JCET:
Joint Center for TeV Experiment and Theory

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University of Chicago

in collaboration with:

Argonne National Laboratory
Fermi National Accelerator Laboratory
University of Illinois at Urbana-Champaign
Northern Illinois University
Northwestern University
Teachers Academy for Mathematics and Science

Abstract

This is a proposal for a cooperative experiment/theory center based at the University of Chicago. The primary goal of JCET is to provide the intellectual leadership and practical resources which are essential for catalyzing and exploiting major discoveries at TeV colliders.

Name of Organization: University of Chicago

Title of Proposed Project:

Joint Center for TeV Experiment and Theory (JCET)

Proposed Duration: 60 months

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1 Executive Summary

Hadron collider experiments at the Fermilab Tevatron, and in 2006 at CERN's Large Hardron Collider (LHC), are poised to explore the TeV energy regime for the first time, extending the energy frontier by an order of magnitude during the present decade. Concurrently, an explosion of rapid progress and creative activity within elementary particle theory is producing fundamental new insights about gauge theories, superstrings, supersymmetry, gravity, and the physics of extra dimensions. The possibilities for new physics at the TeV scale now appear far richer and more challenging than was suspected even as recently as 3 years ago.

The last period of comparable experimental and theoretical ferment occurred in the early 1970's, swiftly culminating in the development of the Standard Model. Since this era the particle physics community has become much larger and more specialized. Creative approaches are needed to speed up and strengthen information exchange between frontiers of theory and experiment, at a time when the pace of new developments is accelerating on both fronts.

Our proposed Physics Frontier Center (PFC) fills this need in a direct and efficient way, by a joint theory/experiment Center at the University of Chicago, combining forces of 6 major institutions in close proximity to Fermilab. The creation of our Center will coincide with the beginning of Tevatron Run II, with the attention of the world physics community captured by the prospect of major discoveries during this 5-year run. The Joint Center for TeV Experiment and Theory (JCET), will apply its broad and formidable expertise in frontier theory and experiment to identifying, elucidating, and exploiting the full spectrum of new physics opportunities in the TeV regime.

The initial effort is organized around a number of MRC's, each focused on an area of new physics which offers both realistic prospects for dramatic discoveries as well as serious challenges for collider experimenters. These include flexible but focused research efforts on the physics of extra dimensions, supersymmetry, the Higgs boson, and the top quark. New theoretical concepts will be explored and evolved into testable models with explicit experimental signatures. Essential practical physics analysis tools will be developed, taking advantage of the unique cooperative environment between theorists and experimenters, and the stable, focused infrastructure of the Center.

The participants in JCET research programs will consist of (i) faculty-level theorists and experimenters from the 6 participating institutions, (ii) postdocs, students, and visitors supported at these institutions, (iii) postdocs and students supported by Center fellowships, (iv) Center-supported urban high school and undergraduate interns, and (v) long-term Center visitors, both theorists and experimenters, chosen with an eye both to providing critical expertise and to responding to exciting new developments.

JCET will provide a unique opportunity for students and postdocs to be exposed to a much broader view of particle physics and physics education, and to participate meaningfully in major discoveries. Students will stay in contact with a broader range of senior physicists during the full period of thesis research. Center-supported students and postdocs, both in experiment and in theory, will acquire the skills which will be most in demand as the LHC era approaches.

The educational and outreach opportunities for JCET are exceptionally rich, and are fully integrated into our proposal. An inter-disciplinary MRC devoted to statistical treatment of large data sets utilizes our unique ties to the Teachers Academy for Mathematics and Science in Chicago (TAMS), a connection which we will additionally exploit to identify and recruit minority students for our internship program. Other major opportunities arise from the University of Chicago and Fermilab participation in the QuarkNet program, which seeks to actively involve high school students and teachers in the Tevatron and LHC collider experiments.

2 Considerations Unique to this Proposal

2.1 Need for a PFC approach

The primary goal of JCET is to provide the intellectual leadership and practical resources which are essential for catalyzing and exploiting major discoveries at TeV colliders. This goal mandates a Center-based approach. The main factors are:

(1) Size: no existing single group at any university or national lab has enough expertise and resources to tackle this challenge.

(2) Cohesion: informal contacts between theorists and experimenters, or between different experimental collaborations, have not provided the stable base needed to develop comprehensive analysis tools that keep pace with cutting edge theoretical developments. A Center provides a stable base for flexible programs of full-time focused research, and will provide continuity and momentum for analysis.

(3) Focus: the national labs wield impressive resources, but these resources are stretched thin to support the broad and ambitious HEP programs of this decade. A Center will focus new resources in a critical area.

(4) Flexibility: stable Center-based groups, with ample experimental and theoretical expertise, and supplemented by a robust visitor program, can reorganize their efforts quickly and efficiently in response to surprises on either the experimental or theoretical frontiers.

(5) Training: the PFC infrastructure will allow a significantly larger number of students and postdocs, both in experiment and in theory, to obtain the skill-sets which will be in greatest demand during the LHC era. Students will stay in contact with a broader range of senior physicists during the full period of thesis research. Theory students will have regular interaction with senior experimenters, and experimental students will interact with senior theorists.

(6) Outreach: pooled resources will allow coordinated and effective public outreach without compromising research goals.

(7) Education: the Center-based approach allows us to have a truly integrated educational component in our research proposal.

2.2 Unique features

Our proposed JCET center has a number of features which make it uniquely attractive, namely:

(1) Location: we exploit our proximity to Fermilab, home of the Tevatron collider, U.S. CMS, and a Tier-1 LHC data center. The University of Chicago already has strong groups involved in CDF and ATLAS, while the co-PI's from neighboring institutions are active in CDF, DØ , and ATLAS. All of the participating groups, universities, and labs have a long history of cooperation and close informal ties. Visitors, postdocs, and students will want to join us because we are where the action is.

(2) Leverage: by combining strong existing groups in a Center-based approach, with initiatives tying together new theories and new experiment, we will achieve intellectual leadership in both areas for a relatively modest incremental investment of money and organization. The University of Chicago already has a world-class presence in string theory and astrophysics/cosmology, as well as experimental and theoretical particle physics, which will enable the Center to recruit a higher caliber of students, postdocs, and visitors. In addition, the physical plant and administrative framework necessary to support the Center already exists in the Enrico Fermi Institute, where the Center would be situated.' Fermilab and Argonne staff, visitors, and postdocs will participate in Center activities, with no expenditure of Center resources beyond office space and incidentals.

(3) Education: The JCET is ideally placed to mesh with the QuarkNet program, which seeks to actively involve high school students and teachers in the Tevatron and LHC collider experiments. The University of Chicago is already an active QuarkNet center. A major research component of our proposal utilizes our unique ties to the Teachers' Academy for Mathematics and Science in Chicago (TAMS), a connection which we will additionally exploit to identify and recruit minority students for our internship program.

2.3 Timing

The Tevatron is scheduled to start Run II on March 1, 2001. The Fermilab estimate is that in the first year of data taking the collider experiments will get 6 times the data accumulated in the previous Tevatron run. It is urgent that JCET activities are started in time to have robust predictions to compare with the initial data.

2.4 The Path to the Center

An important precursor of the JCET concept was the Run II SUSY/Higgs workshop, held at Fermilab throughout the year 1998. The Workshop was highly successful and had major impact on the thinking at Fermilab for the future. Workshops are of finite duration, and have limited scope and depth. The Center approach provides an opportunity to continue and extend the cooperative activities pioneered in the Workshop in a sustainable way. The Center will build upon the existing relationships between theorists and experimenters through flexible programs of full-time focused research.

3 MRC-A: Extra Dimensions and Quantum Gravity

Participants: Gregory Anderson (Northwestern), Gustaaf Brooijmans, Marcela Carena (Fermilab), Henry Frisch, Jeffrey Harvey (U. Chicago), Joseph Lykken (Fermilab and U. Chicago), Stephen Martin (Northern Ill. U.), Carlos Wagner (Argonne and U. Chicago).
+ 2 PFC-supported faculty-level visitor FTEs per year, + 1 PFC-supported 5-year fellow, + 4 postdocs with other support (2 U. Chicago, 1 Argonne, 1 Fermilab), + 4 students.

One of the most striking predictions of superstring theory is the existence of seven extra spatial dimensions. The physical effects of extra dimensions appear as new particle degrees of freedom called "Kaluza-Klein (KK) modes", which look like more massive copies of ordinary light states. String solutions also contain "branes", which generically have light particles, including gauge bosons and fermions, trapped on their world-volumes. This provides another way to "hide" the existence of extra dimensions, since an observer trapped on a brane cannot directly probe the dimensions transverse to the brane, without overcoming the energy cost set by the brane tension. This observation has led to the "brane-world" hypothesis, that the Standard Model constituents of ordinary matter may be confined to a 3-brane, and thus to a 3+1-dimensional slice of a higher dimensional "bulk" spacetime [1, 2, 3, 4, 5].

The brane-world view of extra dimensions has far-ranging implications for particle physics, gravity theory, astrophysics, and cosmology. Large compact extra dimensions imply a lowering of the effective Planck scale, and the existence of massive Kaluza-Klein graviton modes [6, 7]. These massive spin 2 KK graviton modes may be observable at colliders, either through missing energy signatures (when the KK gravitons are very weakly coupled), or as new difermion or diboson resonances (if the KK gravitons have larger couplings to Standard Model particles), or through their virtual effects on Standard Model processes [8, 9, 10, 11].

Many other new physics signatures are associated with the existence of extra dimensions. Some of the Standard Model particles may probe large extra dimensions, in which case their KK mode excitations can be observable at colliders [12]. In addition there are new scalar particles called "radions" associated with the shape of the extra dimensions and the stability of the brane configurations; radions can have observable effects through *e.g.* mixing with the Higgs boson [13, 14]. If the effective Planck scale is sufficiently low, many new quantum gravity phenomena may be directly accessible at colliders, perhaps accompanied by explicit stringy or braney effects [15, 16, 17].

Our JCET research group will pursue three major overlapping activities.

- Engage with new theoretical ideas and scenarios for extra dimensions as they develop. Explore these using tools, insights, and constraints from string theory and particle physics. Coalesce these ideas into concrete testable models.
- Translate models into explicit experimental signatures, focusing on high p_T collider physics but also being cognizant of constraints or tests involving astrophysics, precision data, and table-top or satellite gravity experiments.
- Develop optimized strategies for experimental data analysis and a broad spectrum multi-channel search for the full range of possible collider signals of extra dimensions, quantum gravity, and related brane physics.

Harvey, Lykken, and Martin Schmaltz (Fermilab), supplemented by members of the UC string theory group, provide our core expertise in brane physics and string theory. Our initial theoretical interest will be the Randall-Sundrum brane scenarios [18, 19, 20] of warped extra dimensions and localized gravity. These scenarios appear to implement a generalization of the AdS/CFT holographic duality, but the precise connections to string theory and supersymmetry are not yet understood [31, 32, 33, 34, 35, 36] By tackling these theoretical issues we will greatly improve our ability to map the warped compactification and localized gravity concepts into realistic models. We will recruit long-term visitors who are among the leaders in this fast-moving field, and organize informal workshops around topics of special importance and timeliness.

One specific theoretical objective is to obtain a phenomenological classification of black holes which could be produced at TeV colliders. This requires us to better understand black hole physics in the regime where the usual semi-classical reasoning may break down, due to the effects of extra dimensions, branes, and a lowered quantum gravity or string scale. Preliminary investigations indicate that there are basic practical issues involving both black hole production and black hole evaporation.

Anderson, Carena, Lykken, Martin, Schmaltz, and Wagner will pursue a broader program of exploring and parametrizing the possible new physics effects of extra dimensions. The goal is to go beyond the simplistic "straw man" models which have so far dominated most of the phenomenological investigations of extra dimensions, by identifying and parametrizing more robust categories of potentially realistic models. Lykken and Schmaltz are already pioneers in this area, while Anderson, Carena, Martin, and Wagner have been leading figures in the exactly analogous effort applied to supersymmetry. Just as for supersymmetry, this sort of activity is essential for stimulating coordinated experimental searches for new physics. In the area of large extra dimensions, we are at present lacking robust parametrized frameworks analogous to "minimal supergravity" or "minimal gauge mediation" in supersymmetry theory. As was discussed recently at a meeting of the Particle Data Group, this situation has led to considerable confusion and frustration in the experimental community. Experimentalists need to know (i) what are the models, (ii) how are they parametrized, (iii) how do we quote exclusion limits, (iv) how do we compare signals and/or exclusion from different collider channels, and (v) how do we compare collider results with results from table-top gravity experiments and from astrophysics. Our JCET team will fill this need in an organized way on the accelerated timescale needed to keep up with rapid developments in both theory and experiment.

Our third major activity involves an interface between theory and experiment at an even more detailed level, developing optimized strategies for data analysis and a broad spectrum multi-channel search for collider signals of extra dimensions, quantum gravity, and related brane physics. This activity will involve the theorists named above in collaboration with (among others) Frisch, Brooijmans, Fermi Fellows Maria Spiropulu and Bruce Knuteson (U. Chicago), and a PFC-funded fellow. Collider signatures will be explored in detail, with full-scale event generation and realistic treatment of physics and detector backgrounds. At the present time event generation for Kaluza-Klein graviton production is available in very limited form as add-ons to Isajet, Herwig, and Pythia (the latter done at Fermilab by Lykken, Spiropulu, and two postdocs). Our JCET team will develop and implement full-scale realistic event generation based upon the robust parametrized frameworks discussed above.

With a solid understanding of the kinematic and topological behavior of the extra-dimensions signal(s) in a ppbar (Tevatron) as well as pp (LHC) collider, the JCET team will study the efficiency of existing triggers and proceed with studies and proposals of new triggers and data streams where needed. The goal being to selectively collect reasonably sized data sets with very high efficiency on the modes we look for. Naturally, JCET will identify the orthogonal triggers that allow a precise estimate of the Standard Model processes under the quantum gravity signals we look for.

Our JCET program will be coordinated with CDF and DØ analysis groups, utilizing Tevatron data as it is acquired in Run II. Among the promising channels to be examined are missing $\mathrm{E_T}$ + jets, missing $\mathrm{E_T}$ + photons, and Drell-Yan lepton pair production. JCET will provide the first dedicated long-term effort to develop realistic physics analysis tools and new triggers related to the physics of extra dimensions. This program is a natural outgrowth of our current research and expertise. Frisch is already leading the CDF group investigating collider signatures of new physics involving photons [21, 22, 23, 24]. Knuteson's thesis developed a new model-independent strategy, 'Sleuth', to look for new physics in a systematic way across a large number of channels, in this case using data from the D0 detector [25]. Spiropulu's ground-breaking blind analysis [26] of missing $\mathrm{E_T}$ + jets channels (for the Run Ib squark/gluino search) gives us unequaled expertise for extra dimensions searches involving missing energy. Brooijmans, as DØ New Phenomena convener, links us to the DØ group actively searching for virtual effects of extra dimensions [27].

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4 MRC-B: The Search for the Higgs Boson

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+ 2 PFC-supported faculty-level long-term visitors per year,
+ 1 PFC-supported 5-year fellow,
+ 3 PFC-supported postdocs,
+ 2 postdocs with other support (1 Fermilab, 1 Argonne)
+ 3 students.

Precision Measurements of Electroweak Observables and the Higgs Boson Mass

The precision measurements of electroweak observables at the Tevatron, the SLD and the LEP experiments are in excellent agreement with the SM predictions [1]. There is, however, no direct experimental evidence for the underlying dynamics responsible for electroweak symmetry breaking. The values of the precision electroweak observables indicate that any physics beyond the standard model, if present at the weak scale, interacts only weakly with the electroweak gauge bosons and that a scalar Higgs boson, with mass of the order of the electroweak scale, should appear in the low energy spectrum as a remanent of the mechanism of electroweak symmetry breaking. The search for the Higgs boson is therefore one of the key open challenges of high energy physics.

Rosner has a continuing interest in the interplay between Higgs mass predictions of the SM and precision electroweak measurements such as atomic parity violation [2]. The discovery of a Higgs boson at masses accessible in the next few years would place strong constraints on the possibility of new physics, such as gauge sector extensions. With help from a PFC postdoc or student Rosner would be able to systematically map out these constraints as a function of Higgs boson mass.

Higgs Boson Searches at Lepton and Hadron Colliders

Searches for the SM Higgs boson have been extensively performed at the

LEP experiments at CERN, which has concluded its running at the end of the year 2000. The absence of a conclusive signal has allowed the CERN experiments to set a lower bound, of the order of 113 GeV, on the Higgs boson mass. The combination of the data collected by the four LEP experiments shows also an excess of events of about 3 standard deviations, consistent with the production of a Standard Model - like Higgs boson with mass in the range 114 - 116 GeV [3]. The LEP data, although suggestive, is not sufficient to provide conclusive evidence of the presence of a light Higgs boson. The next run of the Tevatron collider, to start early in the year 2001, will provide an excellent opportunity to test the presence of such particle and therefore to shed light on the mechanism of electroweak symmetry breaking.

A joint experimental and theoretical study was recently completed [4] with the conclusion that the upgraded Tevatron collider, with a center of mass energy of 2 TeV and with a total integrated luminosity of 10–20 fb^{-1}, would be able to test most of the SM Higgs mass parameter region preferred by precision electroweak data, $m_H \leq 180$ GeV [1]. According to this study, if the Higgs mass were less than 130 GeV, the most relevant search channel is its production in association with a W or Z boson followed by its decay to bottom quarks. If its mass were above 130 GeV, however, the best channel is its production through gluon fusion and its decay to W pairs.

These conclusions rely on assumptions about the detector capabilities, in particular the b-tagging efficiencies and the $b\bar{b}$ invariant mass resolution, as well as on the present understanding of the Standard Model backgrounds. The start of the collection of data by the Tevatron experiments will provide crucial information on these issues. Moreover, much work needs to be done for the complete understanding of the QCD backgrounds. Furthermore, new production mechanisms and decay modes should be explored (see the discussion of Higgs boson production in association with top quark pairs: MRC-D). This entails a strong effort from the theoretical and experimental communities, based on a fluid interaction between theorists and experimenters.

Although the Tevatron collider can explore the existence of a light Higgs boson in the whole mass range consistent with electroweak precision measurement data, it will be difficult to analyze the precise properties of the Higgs boson in case it is discovered at this collider. The Large Hadron Collider (LHC) at the CERN laboratory in Switzerland, to start operation in the year 2006, will enable to perform a detailed study of the Higgs properties. In particular, recent theoretical studies show that an accurate determination of the decay widths and branching ratios may be obtained [5] at the LHC collider if the Higgs boson is in the mass range accessible at the Tevatron collider. Moreover, the LHC can explore Higgs boson masses up to nearly the TeV scale [6] and therefore it can provide a definitive test of the mechanism of electroweak symmetry breaking.

Supersymmetry and Higgs Physics

If the mechanism of electroweak symmetry breaking is governed by new physics, there will be important implications for Higgs particle searches at present and future colliders. If supersymmetry is realized in nature, new Higgs boson particles will be present. The minimal supersymmetric Standard Model (MSSM) includes two Higgs doublets [7], which acquire different vacuum expectation values, leading to a physical spectrum containing two CP-even Higgs bosons, a charged Higgs boson and a CP-odd Higgs boson. In many cases, only one light Higgs boson remains in the low energy spectrum. The properties of this Higgs boson are well determined as a function of the exact supersymmetry spectrum, the ratio of Higgs vacuum expectation values, $\tan\beta$, and the mass of the heavy Higgs bosons[7].

The lightest Higgs boson mass in the MSSM is restricted to be below 130 GeV [7, 8], if the third generation squarks are not heavier than 1 TeV, independently of the exact supersymmetry breaking parameter space. Moreover, even in the most general supersymmetric extensions, if the gauge and Yukawa couplings values are consistent with a perturbative treatment of the theory up to energies of about the Planck scale, then the lightest Higgs boson mass cannot exceed 200 GeV [9].

The properties of the Higgs particles in the MSSM may be quite different from those of their SM counterpart. Carena and Wagner have performed one of the most complete computations of radiative corrections to the Higgs boson masses and couplings, including two-loop radiative corrections [10]. These computations are presently used by the four LEP collaborations in their combined analyses. Moreover, in their recent analyses they showed the existence of regions of parameter space with strongly supressed (and sometimes enhanced) couplings of the CP-even Higgs bosons to bottom quarks and/or tau leptons [11, 12, 13], which lead to new signatures [13, 14] at the Tevatron and the LHC. Higgs searches at these two colliders are complementary [13]: Whenever the Higgs couplings to bottom quarks are suppressed, rendering the search for the neutral MSSM Higgs bosons at the Tevatron specially difficult, the branching ratio of the Higgs decay channel into photons, which is one of the main signatures expected at the LHC, is importantly enhanced. The correct implementation of these higher order radiative effects in the experimental analyses is crucial to understand possible signatures, or to profit the most in the theoretical understanding of nature in the absence of it.

CP-Violation and Higgs Phenomenology in the MSSM

Very recently, Carena and Wagner [15, 16] also analyzed the possible incidence of unexpected new physics effects induced by the presence of new sources of CP violation associated with the soft supersymmetry breaking parameters of the third generation of squarks. Under these conditions, the three physical MSSM neutral Higgs bosons have no definite CP quantum number, and their couplings to fermions and gauge bosons may become highly non-Standard. One of the most exciting consequences of this scenario is the possible presence of two light Higgs bosons with non-negligible SM-like couplings to the W and Z gauge bosons. Although no clear evidence of this possibility has been found, the LEP data are consistent with such a scenario [17], which could be tested at the next run of the Tevatron collider. Therefore, the presence of new CP violating sources demands a drastic change in the search strategies for Higgs bosons at the Tevatron and the LHC.

Summary of Higgs Physics Analyses

Developing the tools for a detail study of the Higgs phenomenology, which could drastically differ from the Standard Model one, is a very demanding task. The expertise of the scientists who will play an active role at the Center is unique to ensure the successful completion of such project. It is one of the main goals of the Center to study the capabilities of the Tevatron and the LHC to uncover the physics of the Higgs sector and to study its properties. The knowledge acquired through the understanding of the Higgs sector will allow us to get precious information about the physics beyond the standard model. The interface between theory and experiment that we intend to develop at the Center will be of great use for the HEP community as a whole.

Studies for a $\gamma\gamma$-Collider

Our group has broad interests in Higgs physics at future colliders. We will assess the potential of $\gamma\gamma$ colliders to produce large samples of Higgs bosons, and determine how the most important Higgs properties can be measured with a practical machine.

Higgs bosons are produced in the s-channel in $\gamma\gamma$ collisions. The cross sections are sizable, of order 1 pb. The beam energy required is $M_h/2$, which is within the reach of existing e^+e^- collider technologies for $M_h < 300$ GeV. Depending on the details of the generation of the photon beam, the photon energy spectrum can be peaked at 70% of the electron energy. Furthermore, the photon luminosity can exceed that of the original electron beam. A Higgs boson of mass 120 GeV could be produced at a rate of thousands per year with electron beam energies of only 80 GeV. A large sample of clean Higgs events with well understood backgrounds would allow the measurement of several Higgs properties, such as its mass (to' a precision of 100 MeV), its branching ratios, the $\gamma\gamma$ partial width, the total width, and its CP quantum numbers. The possibility of manipulating the beam polarization is promising in this regard. All of these properties would incisively restrict the parameter space of the MSSM.

This is a project where input from both experimentalists and theorists is needed, in part because the phenomenology is not as well developed as in other collider projects. For example, early studies of the isolation of a Higgs signal from a continuum $b\bar{b}$ background obtained very promising results, thanks to the helicity suppression of the $b\bar{b}$ final state. Later, however, it was realized that first-order QCD corrections would not be suppressed, and indeed, background estimates allowing for a $b\bar{b}g$ final state were considerably less optimistic.

We see similar opportunities for experimental-theoretical teamwork in the study of more complicated backgrounds. For example, the hadronic structure of the photon is not well understood, especially at high transverse momentum, yet this will be central to the background calculations for two-jet final states. While new experimental data have greatly improved the situation, more work is needed on the theoretical side to synthesize this information and to model the hadronic interactions of two real photon beams. This problem has not been fully explored in existing feasibility studies for a $\gamma\gamma$-collider.

The environment near the interaction region for a $\gamma\gamma$-collider will be unusual: there will be a dense flux of low-energy photons and electron-positron pairs which will complicate the reconstruction of secondary vertices. (This pertains also to high-luminosity e^+e^- machines.) There are no serious studies of the precise physical consequences of such environment. Again, we see this as a good opportunity for joint theoretical-experimental work in this direction.

Naturally work must proceed with the technical design of a $\gamma\gamma$-collider. The technical work required in this direction will be partially supported by funds coming from the State of Illinois (ICAR).

About the Participants:

Co-PIPD M. Carena was co-convenor of the LEP Higgs Working Group and is co-convenor of the RUN II Tevatron Higgs Working Group. The CO-PIPD's M. Schmitt, C. Wagner and S. Willenbrock have been active members of the RUN II Tevatron Higgs Working Group. Their expertise will be a crucial component for the success of this MRC. Postdoc Tim Tait (Argonne) is also one of the leading young physicists working in the field of Higgs phenomenology at hadron colliders. The Co-PIPD M. Velasco is a leading figure behind the studies of Higgs production at $\gamma\gamma$ colliders.

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5 MRC-C: Supersymmetry and Related Signatures

Participants: Greg Anderson (Northwestern U.), Edmond Berger (Argonne), Gustaaf Brooijmans, Marcela Carena, Ray Culbertson (Fermilab), Henry Frisch (U. Chicago), David Hedin (Northern Illinois U.), Joseph Lykken (Fermilab and U. Chicago), Stephen Martin (Northern Illinois U.), Jonathan Rosner (U. Chicago), Mayda Velasco (Northwestern U.), Carlos Wagner (Argonne and U. Chicago). + 1 PFC-supported faculty-level visitor FTEs per year, + 2 PFC-supported 5-year fellows, + 1 PFC-supported postdoc, + 3 postdocs with other support (1 Northern Illinois U., 1 U. Chicago, 1 Argonne), + 3 students.

While the Standard Model of particle physics provides an excellent description of all low-energy experimental data gathered up to now, there are solid reasons to believe that it must be extended at energies below a TeV or so. The most important of these reasons is that the smallness of the electroweak scale compared to the Planck scale introduces a naturalness problem. This is related to the instability of the Higgs mass scale under quantum corrections. The most promising known solution to this problem is supersymmetry (SUSY), a symmetry which relates bosonic to fermionic degrees of freedom. This implies that each fundamental fermionic particle must have a bosonic partner. It follows that as long as the supersymmetric partners are not too much heavier than the electroweak gauge bosons, the electroweak scale will be stable with respect to quantum corrections.

Local supersymmetry implies invariance under space-time transformations, opening up the possibility of understanding a unification between gravity and the Standard Model gauge interactions. Moreover, if supersymmetric particles are present with masses near the TeV scale, then the extrapolation of the three known gauge couplings to large energies shows that they converge to a common value. The non-observation of supersymmetric particles in past searches implies that supersymmetry, if realized in nature, must be broken. In order to be relevant to the problem of the stability of the electroweak scale, the superpartner masses, which are induced by supersymmetry breaking, should not be larger than a few TeV. This implies that they should perhaps be accessible to searches at Fermilab's Tevatron Run II and certainly at CERN's Large Hadron Collider.

The search for supersymmetry provides many stimulating challenges for experimenters, due to the richness and variety of its possible signatures. With the new era of TeV hadron colliders it is essential to develop the best tools and strategies for SUSY searches. Simulation of SUSY signatures with realistic event generators that include Standard Model processes is a crucial step in this direction. It is equally essential to keep pace with the experimental implications of new theoretical ideas as they develop, to assure that the experimental searches will be sufficiently flexible to detect even the most elusive of signals of supersymmetry. While the structure of supersymmetry as a theory does have a rigid backbone of non-negotiable features, it also has sufficient flexibility to admit a wide variety of different signatures at colliders. Furthermore, the discovery signals for supersymmetry may well be extremely subtle and great care may be required to avoid missing them. The Center approach that we propose is designed to provide the unique interaction between theorists and experimentalists so that the opportunities will not be missed.

If supersymmetry is indeed discovered, the next crucial phase becomes one of characterization and measurement. The goal will be to use the data gathered to answer the key questions: "Is this really SUSY beyond any reasonable doubt? If so, exactly which superparticles have been discovered? What kind of supersymmetry is it?" This is also a situation where communication between experimentalists and theorists is crucial. During the Tevatron Run II era especially, the Center will have the unique ability to provide fast feedback between the two camps. It will be critical to facilitate close discussions on which strategies are possible and which are not, and to use data and theory together to explore new options for measurements. A key argument in favor of our Center is that one would like to have learned how to interact in this way before the first hint of supersymmetry, not have to learn it after.

An important issue in the quest for supersymmetry is the mechanism of supersymmetry breaking. Within the last five years, several new general ideas and many new specific models addressing this problem have been proposed by theorists. Understanding which of these ideas is correct, or whether some new idea is required, will require experimental input. Conversely, the methods used by experimentalists to search for supersymmetry can benefit greatly from understanding the implications of theoretical models. In broad terms, the different scenarios may be characterized by the messenger particles and interactions that mediate between a "hidden sector" where the dynamics of supersymmetry breaking occurs, and the "visible sector" which includes the Standard Model particles. These scenarios include:

- *Supergravity mediation* [1]: This has historically been considered the standard scenario for the study of supersymmetric searches at high energy colliders. The standard signatures are governed by the prompt decay of supersymmetric particles into Standard Model particles, plus missing energy carried away by the Lightest Supersymmetric Particle (LSP). A stable LSP could explain the dark matter required in cosmology.

- *Gauge mediation* [2, 3]: In this case, supersymmetry breaking is mediated by the Standard Model gauge interactions. The LSP in this case is typically the gravitino. The experimental signatures are determined [4, 5]by the decay of the next-lightest supersymmetric particle (NLSP) into its Standard Model partner and a gravitino. The width of this decay is inversely proportional to the fourth power of the supersymmetry breaking scale, and so the experimental signatures may, in principle, serve to allow determination of this scale, and to disentangle the specific scenario realized in Nature.

- *Anomaly-mediated supersymmetry breaking* [6] : This is a novel idea, in which the source of supersymmetry breaking is assumed to be decoupled from the visible sector (for example, by spatial extent in extra dimensions) and supersymmetry breaking is transmitted in a minimal way by gravitational interactions. The Weyl anomaly determines the precise pattern of supersymmetry breaking parameters and the spectrum of gauginos (fermionic superpartners of the Standard Model gauge bosons) is fixed.

We propose to study search methods and definitive features for each of these scenarios far beyond present studies, as well as search for new schemes which may not fit neatly into the above categories.

One area of need is to obtain a refined understanding of backgrounds for supersymmetric events in Tevatron Run II. The possible signatures include trilepton plus missing transverse energy ($\ell^+\ell^-\ell^{\pm'} + \not{E}_{\rm T}$), like-charge dileptons $\ell^+\ell^{+'} + \not{E}_{\rm T}$, and the same signals with additional jets, and signals with lepton vetos together with multi-jets plus missing transverse energy. Berger and collaborators are already leaders in the study of new production mechanisms in supersymmetry that make best use of the relatively restricted energy and phase space of the Tevatron collider [7]. As Run II begins, we will have available an improved understanding of the detector response to each of these signals, and the relevant backgrounds. One factor that we expect to play an important role in our proposed work is the likelihood that the events will be rich in tau leptons. Due to the non-discovery of a Higgs boson at LEP, we can infer that in many parts of the supersymmetry breaking parameter space, the lightest stau is significantly lighter than the other sleptons, and has a larger mixing angle. This tends to increase the *a priori* likelihood that heavier supersymmetric particles will decay through a real or virtual stau, increasing the tau lepton multiplicity. Therefore, it will be crucial to understand how well CDF and D0 can identify taus. Frisch has worked on tau-identification with CDF in top decay and searches for the (SUSY) charged Higgs [8]. We propose that our center will make a significant effort in this area.

There are good theoretical motivations for supposing that stops and sbottoms (the superpartners of the top and bottom quarks) are among the lighter supersymmetric particles. Fortunately, these have provided nice channels for both CDF and D0 in Run I, and in fact are often more straightforward searches than other SUSY channels. Co-PIs Brooijmans and Hedin have been leaders in analyzing these signals for the Tevatron at D0. In Run II, the improvement in b-tagging should allow a very good reach. However, understanding the extent of the improvement will require a significant dedicated investment of time, which our Center will help provide. In particular, JCET can provide calculations and Monte Carlo implementations of such items as polarization effects in three-body decays of squarks and sleptons, especially stops, sbottoms and staus.

In the case of supergravity mediation, it has usually been assumed in both theoretical estimates of signals and experimental that the mass spectrum of superpartners is fixed by a benchmark "minimal supergravity" assumption, which depends on only five parameters [1]. For example, these assumptions make the strong prediction that the bino, wino, and gluino superpartner mass parameters are in the ratio of approximately 1:2:7. However, it has long been recognized that these assumption have a questionable theoretical basis. We propose to conduct a thorough study of the supergravity mediation signatures, but allowing for a much wider variety of mass spectra possibilities.

This has a direct effect on discovery and study methods at the Tevatron and the LHC, because branching ratios and efficiencies to pass experimental cuts can be a dramatic function of new physics mass scales. For example, if the gluino is allowed to be relatively much lighter than is usually assumed, then events with large jet multiplicity may become completely dominant. While some efforts have been made to study such "nonstandard" models of supergravity mediation, we believe that it is crucial to generalize these efforts. It is quite possible that the search strategies needed to discover supersymmetry may be qualitatively different from what has usually been assumed. We propose to concentrate especially on noting and exploiting new and qualitatively different methods, to ensure that no opportunity for discovering and studying supersymmetry is missed. The Center approach to studying this problem will be crucial, as we can bring together a critical mass of theorists (Anderson, Berger, Carena, Lykken, Martin, Rosner, Wagner) and experimentalists (Brooijmans, Culbertson, Frisch, Hedin, Velasco) plus visitors and postdocs who have all worked extensively on the relevant issues of relating theoretical predictions to experimental realities.

The gauge-mediated supersymmetry breaking (GMSB) [5] and anomaly-mediated supersymmetry breaking (AMSB) [6] categories both predict a wide variety of experimental signatures which are, by familiar standards of new physics searches, exotic. This means that the discovery signals are likely to be quite striking, but also may involve techniques and analyses which are new and difficult to fully anticipate. The Center approach will be crucial in maintaining focus on these issues.

In gauge-mediation models, the identity and the decay lifetime of the NLSP determines the signals that will appear at colliders. If the NLSP is a neutral fermion (neutralino) with a short lifetime, then the prediction is for many events with a pair of very energetic and isolated photons together with large missing transverse energy. If the lifetime is longer, then a particularly exciting possibility is that the photons will point back to a position displaced from the interaction point; in principle this allows a determination of the NLSP lifetime. This can be done either by using the fine-grained D0 calorimeters to find the photon shower direction, or possibly by using the material inside the tracking volume as a converter for photons into electron-positron pairs, which can then be analyzed to find the initial direction of the photon very precisely [9]. This is directly related to the supersymmetry breaking scale, one of the most important quantities of interest to theorists.

In order to fully exploit this possibility, it will be necessary to develop rather unique Monte Carlo programs, a task for which our Center will be well-suited.

If the NLSP is a quasi-stable charged slepton or squark, then we expect high energy deposition and anomalous time-of-flight for otherwise muon-like tracks. If the charged NLSP has a short lifetime, then one expects kinks in charged tracks corresponding to its decay into an ordinary lepton and a Goldstino. Understanding the implications of this for Tevatron Run II will require detailed studies of the performance of detector elements. We propose to further existing studies in light of the improved capabilities of the upgraded detectors, including new elements added to both CDF and D0 which will allow triggering on these types of particles. (In particular, CDF has a new TOF system and D0 has added scintillation counters outside the calorimeter.) This could dramatically improve the reach compared to existing studies.

Participants Culbertson and Martin were among the co-conveners of Ref. [5], and will bring experience with these signals to the proposed PFC. The recent revival of interest in GMSB is at least partly due to the CDF work done by Culbertson and Frisch, in conjunction with David Toback, on the now well-known $ee\gamma\gamma \not{E}_t$ event. In Run II we will use signature-based methods we have developed in Run I [10, 11], with new methods to be developed in MRC-E, to systematically search final states involving two neutral bosons, i.e. $\gamma\gamma$, γZ, ZZ, γh, Zh, hh, each categorized as to what other objects are in the events (e.g. leptons, b-quarks, number of jets, ...). The Standard Model predictions for these channels are of interest in their own right because they form the dominant backgrounds for top quark and Higgs searches, as well as providing control samples to test both the theoretical understanding and the modeling of the detector. There are many variations on these signals, as outlined in [5], which we propose to study in the greater detail that they deserve.

In collider experiments a muon is defined as a particle that penetrates the multiple collision lengths of steel absorber in the muon system in a way that is consistent with the expected multiple scattering given the measured momentum. It is possible, however, that there exists a long-lived light sbottom squark, or a light stau slepton, or other relatively light new particle, that would be identified as a muon[12]. For example, a light gluino could decay $\tilde{g} \rightarrow b\tilde{b}$, with the $\tilde{b}$ being (mis)identified as a muon[13]. If the new particle were light enough to be relativistic, the identification of the particle as a muon rests solely on the assumption that no other charged stable nonstrongly interacting particle heavier than the electron exists. (For heavy stable particles both ionization (dE/dx) and time-of-flight can be used to measure the mass. See Refs.[14], for example).

One interesting characteristic of stable or long-lived heavy hadrons containing superpartners penetrating a calorimeter is that the light quark partner would be repeatedly stripped from the squark, which then would reclothe itself from quarks from interactions in the material. The particle would consequently sometimes be neutral and sometimes charged, depending on the flavor of the (up or down) quark or antiquark picked up. This would have two consequences. One is that the standard 'extrapolator' routines used by the experiments to extrapolate the measured vector momentum through the magnetic field in the calorimeter to the muon chambers behind would give the incorrect extrapolation. A second is that because the calorimeter is made of matter, and consequently there are more u quarks than $\bar{u}$ quarks at values of x corresponding to the velocity of the heavy particle, there could be a net positive charge asymmetry in the hadrons misidentified as muons. With better statistics, and a better understanding of how heavy stable or long-lived particles would be detected, these channels will be of interest in the upcoming run.

Anomaly-mediation models usually predict that the lightest supersymmetric particles are a nearly degenerate pair of charged and neutral fermions, the supersymmetric partners of the electroweak isospin gauginos (winos). The charged wino should be very slightly heavier than the neutral one, and can decay after a macroscopic distance inside the detector into the neutral wino and a very soft pion. Then the unique signatures include the highly-ionizing tracks of a quasi-stable wino. The resulting signals at Run II of the Tevatron require further study to determine their viability and the reach that can be obtained. In addition, the theoretical groundwork for anomaly mediation (and related models) remains unsettled, and will be the subject of our investigations. It is quite possible that with an improved theoretical understanding, we will be able to pin down the experimental signatures better, again highlighting the usefulness of a coordinated effort between theorists and experimentalists.

These are not the only possibilities for long-lived particles predicted in particular supersymmetric models. Recently Martin has proposed [15] that in models which solve the strong-CP and μ problems at an intermediate scale, the LHC may be able to detect the decays of extremely long-lived neutralinos, with decay lengths greatly exceeding the size of the detectors. This relies on the high rates available at the LHC. In other versions of this type of model, the predictions seem to closely mimic those of gauge-mediated models with a stau NLSP. We propose to study the general issues of a very slowly decaying NLSP, to evaluate the best strategies for detecting or placing limits on this phenomenon both at the Tevatron and the LHC. Another area in which our proposed Center will be active is in exploring the possibilities presented by R-parity violation. Berger and collaborators have recently [16] explored the possibility of single top-squark production, and further work along these lines should be pursued.

Principled naturalness criteria play an important role in shaping our expectations about the tenable ranges of masses for new particles. In the absence of direct evidence of new physics at an accessible scale above $v = 246$ GeV, naturalness considerations are one of the few tools at our disposal for placing upper limits on the scales of possible new physics. Naturalness is the original and principal motivation for weak-scale supersymmetry, and superpartners cannot be arbitrarily heavy if this motivation is to remain intact.

A significant portion of the literature devoted to naturalness studies apply criteria which do not have a reliable correspondence to fine-tuning. Although reliable quantitative fine-tuning measures exist [17], explicit studies have only been carried out for the most traditional versions of supergravity-mediated supersymmetry breaking. We propose to complete a series of rigorous naturalness studies for a broader collection of SUSY models. For example, this will be done for models based on gauge-mediated, anomaly-mediated, and non-universal supergravity-mediated scenarios. Moreover, we intend to extend the application of principled naturalness criteria beyond the MSSM, *e.g.* to the NMSSM and to theories containing additional matter content. These studies will be important as they will lead to a sense of how much variation there is in the naturalness of different versions of low energy supersymmetry. Such studies provide some guidance as to what spectrums are most tenable, and as a result what signals are most deserving of prioritized study. As a unique feature of the Center, these investigations can then be directly compared with parallel efforts which will investigate and seek to improve the reach of the LHC and Tevatron in the various models.

Recent experimental observations including the discovery of neutrino flavor oscillations, make it imperative to explore consequences of theories that go beyond the Standard Model and its minimal SUSY extension. Berger and Rosner have been collaborating in this area during the past year, joined by a postdoc (David E. Kaplan) and a PhD student (Troy André) and funded by a Seed Grant administered jointly by the University of Chicago and Argonne. One such approach to pursue is a grand unified model based on the symmetry group E_6. This theory contains the SM gauge group as a subgroup but allows a wide variety of patterns of non-zero neutrino masses and flavor mixing [18]. Anderson has been developing new E_6-based model building tools [19] to construct predictive theories of flavor which have implications for neutrino physics and for CP violation in the B system, as well as for sparticle decay signatures at colliders. We propose to extend and continue this analysis, as well as extending earlier analyses which sought to identify probes of the flavor structure of superpartner masses by studying their decay patterns.

Among the new testable consequences in high energy collisions at the Tevatron and LHC are the existence of new heavy quarks. Unlike the existing quarks, these would be singlets under weak isospin. The non-supersymmetric E_6 models and certain gauge-mediated supersymmetric scenarios can share some common experimental features [20], so it is important to develop and contrast the properties of these theories prior to experimental observations. This provides another compelling motivation to refine our understanding of supersymmetry breaking, and to develop calculations of expected production cross sections and event signatures. Rosner is a leading expert on E_6 unification, and recently proposed a mechanism [21] by which mixing between a heavy exotic quark and the bottom quark can account for the striking inequality in mass $m_b \ll m_t$. André has already been working on experimental signatures of the heavy exotic quarks. Berger, Rosner, and André expect to predict cross sections, event yields, and transverse momentum distributions for production of exotic quarks and of other states in both E_6 and supersymmetric models. Of decisive importance for discovery, or for placing limits on the presence of exotic quarks and top squarks, is to establish the differences that these manifest in both production and decay from states of the Standard Model and of other candidate theories.

There are several areas of overlap between this MRC and the others in our proposed Center. First, it is possible that the Higgs boson will manifest itself first in supersymmetric events. In gauge-mediated models of supersymmetry breaking, if the NLSP is a neutralino with a large higgsino content, then one may find events with displaced energetic isolated photons and tagged bottom-quark jets. It is therefore possible, but so far not well-studied, that the Higgs boson can be studied by finding it in decays of the NLSP in gauge-mediation models, thus overlapping with MRC-B. Another area of overlap occurs in the area of MRC-A, the phenomenology of large extra dimensions. These two ideas are of course not mutually exclusive. If low-energy supersymmetry and large extra dimensions coexist, then the signatures could be quite different than what one might have imagined only taking the two ideas separately. We propose to continue to explore the implications of this. Finally, we note that the analysis of supersymmetry could clearly benefit greatly from MRC-E, the development of signature-based searches. The possibility of exploiting these overlaps is a particular strength of the proposed Center.

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6 MRC-D: Top Quark Physics

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+ 1 PFC-supported faculty-level visitor FTE per year, + 1 PFC-supported 5-year fellow, + 3 postdocs with other support (1 U. Chicago, 1 Argonne, 1 U. Illinois), + 3 students.

The top quark was discovered at Fermilab in 1995 [1]. However, very little is known about the top quark relative to the other quarks and leptons, due to the small number of events that were gathered in Run I of the Tevatron. For example, the number of top quark events recorded by CDF in the final state $W+$ 4 jets (where the W decays leptonically), with one or more identified b jets, was only about 25 [2]. This final state has relatively little background and provides an excellent sample from which to reconstruct the top quark mass. All of the measurements of the properties of the top quark from Run I have substantial statistical uncertainties, and many of the systematic uncertainties are also large due to small control samples.

This situation is going to change dramatically during this decade, beginning with Run II of the Tevatron in March 2001 and continuing with the commissioning of the LHC in 2006. For example, in Run IIa of the Tevatron (2 fb^{-1}), CDF and DØ will each record about 1000 $W+$ 4 jets events with one or more b tag. This is due mostly to the factor of 20 increase in integrated luminosity, but also to the increased energy of the collider and the increased acceptance for top quark events from the detector upgrades. Run IIb, with the goal of 15 fb^{-1}, will yield about 7500 such events. The LHC will be a true top factory, providing about 1.5 million such events during the first few years of low-luminosity running (30 fb^{-1}). Thus we will have at our disposal a large number of top quarks with which to make precision studies of its properties.

The top quark is the only known fermion whose mass is near the electroweak scale, so a precision study of its properties is imperative. The top quark could be involved with the mechanism of electroweak symmetry breaking or of fermion mass generation (or both), and this could be revealed by a close scrutiny of its properties. These ideas are embodied in Topcolor [3] and extended Technicolor models [4], and predict specific signals in top quark

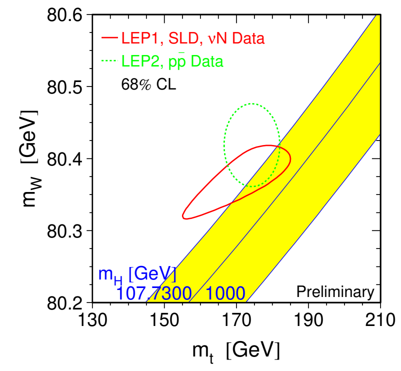

Figure 1: M_W *vs.* m_t, with lines of constant Higgs mass.

production and decay. Even if the top quark should ultimately prove to be a normal fermion, the study of this very heavy quark will be interesting because many of these studies are novel and have no analogue in light fermions.

Here we describe a program of top quark studies at the Tevatron and the LHC. The participants in this MRC have considerable experience with and interest in top quark physics. Frisch, Lecompte, and Liss are members of the CDF collaboration, which co-discovered (with DØ) the top quark; Liss was co-convenor of the top quark group at that time. Berger, Rosner, and Willenbrock have made a variety of contributions to the theory and phenomenology of the top quark. Willenbrock has also co-organized two workshops on top quark physics [5, 6]. We intend to provide a focal point for top quark studies at the Tevatron and the LHC.

6.1 Mass, width, and strong interactions

A Mass

The top quark mass is interesting in its own right and as an ingredient in precision electroweak physics. As the uncertainty in the W mass decreases, it is desirable to have a corresponding decrease in the uncertainty in the top quark mass. This is illustrated in Fig. 1. An uncertainty of 20 MeV in the W mass is a realistic goal for Run IIb (15 fb^{-1}) at the Tevatron [7]. The corresponding uncertainty desired in the top quark mass, obtained by projecting onto a line of constant Higgs mass in Fig. 1, is about 3 GeV. A measurement of the W mass to an accuracy of 15 MeV appears possible at the LHC [8]; this corresponds to an uncertainty of 2 GeV in the top quark mass. A precision measurement of the top quark mass will be especially interesting if the central value of the direct measurements in the M_W *vs.* m_t plot of Fig. 1 remains in conflict with the lower bound on the Higgs mass.

The top quark mass was measured in Run I to be $m_t = 174.3 \pm 5.1$ GeV [9, 10]. The single largest source of uncertainty in the top quark mass is the systematic uncertainty due to gluon radiation. Reducing that uncertainty will require a coordinated effort between theorists and experimentalists. What is required is an accurate modeling of the emission of gluon radiation in top quark events [11]. This must be supplemented by measurements of the gluon radiation in top quark events to build confidence that the theoretical model is correct.

One of the interesting features of gluon radiation in top quark events is the presence of a "dead cone" [12, 13]. This refers to the suppression of soft gluon emission in the direction of the top quark. This effect has been observed in bottom-quark production, but only as a decrease in hadron multiplicity [14]. The large mass of the top quark allows this effect to be observed as a depletion of jets in the direction of the top quark. It is an example of an effect that can be used to build confidence in our understanding of final-state gluon radiation in top quark events.

It will also be necessary to carefully model initial-state radiation. It may be possible to use electroweak processes such as W, Z production, and even WW, WZ, and ZZ production, to isolate the effects of initial state radiation. These are color-singlet processes, as opposed to $t\bar{t}$ production, which is color octet, but the dominant collinear radiation is universal.

At the LHC, the statistical sample will be large enough to contemplate an accuracy in the top quark mass of 1 GeV or less. Nonperturbative QCD will become relevant, despite the fact that the top quark decays faster than the typical strong-interaction time scale, Λ_{QCD}^{-1}. For example, it is known that the pole mass of a quark is an ambiguous concept due to nonperturbative QCD [15], and this is also true for the top quark [16]. Thus it will be important to ensure that the quantity which is being measured experimentally has a well-defined theoretical interpretation.

B Spin correlation

The top quark lifetime is much less than the time it takes for the strong interaction to flip its spin, $(\Lambda_{QCD}^2/m_t)^{-1}$ [17]. This is a unique property of the top quark, not shared by any other quark. Therefore the spin of the top quark at production will manifest itself directly in the angular distribution of its decay products. Although the top quark is produced unpolarized by the strong interaction, the spins of the top and the antitop are correlated [18, 19]. There is a particular basis, dubbed the "off-diagonal" basis [20], in which the spins are 100% correlated in the process $q\bar{q} \to t\bar{t}$, which dominates at the Tevatron. Including the process $gg \to t\bar{t}$, the spin correlation in this basis is expected to be 84%. The spin correlation at the LHC is only 31%, but the much greater statistics should make it possible to observe.

The limited sample of top quarks in Run I did not allow for an observation of the spin correlation [21]. The statistics of Run II should allow for the first observation of this effect. It will require collaboration between theorists and experimentalists to optimize the sensitivity of the measurement. Furthermore, the spin correlation can be used as a tool to test the $V - A$ structure of the weak decay of the top quark [22]. This needs to be implemented into several popular Monte Carlo events generator to become of practical use.

C Dilepton events

The CDF sample of top events with two high-p_T leptons (dilepton sample) [23] has from the very first been questioned as to whether some of the events come from sources other than top quark pairs. For example, one event has three high-p_T isolated leptons, very unusual for the decay of a top quark pair. With the smallness of the present sample, studies have been unable to prove whether the sample is anomalous or not.

Many of these studies have concentrated on comparing measured distributions of kinematic variables with the corresponding standard-model distributions. A much more powerful method is to do a kinematic fit to the events for the mass and momenta of the top quark; such a multi-variate fit incorporates all of the information of the data, and also returns a figure-of-merit that is interpretable in terms of probability.

One needs to understand very well the kinematics of top production and decay, as well as the kinematics of the backgrounds, to understand the systematic uncertainties associated with such a multi-variate fit. In particular, if there are discrepancies with the top hypothesis, having a close-knit team of theorists and experimentalists to understand the subtleties of the standard-model predictions will be crucial. For example, it was thought that supersymmetry had been discovered at the CERN $Sp\bar{p}S$ Collider ('mono-jets') in the early '80's; a careful study (by theorists!) [24] showed that the backgrounds had been underestimated, and the data were consistent with the standard model.

D Cross section

The top quark is unique in being the only known fermion heavier than the W and Z gauge bosons. This gives it the possibility of decaying into lighter, but still very massive new particles, such as the SUSY neutralinos or the top or bottom squarks, for example. In addition, new particles that couple to mass, such as Higgs bosons, will preferentially decay into the heavy third-generation quarks and leptons.

A consequence of these properties of the top quark is that in many models there is additional top production beyond the standard model, due to the production and decay of new particles [25]. This would lead to an apparently enhanced production cross section. On the other hand, there may be new decay modes of the top quark, such as $t \to \tilde{t}\tilde{\chi}^0_1$, that would diminish the branching ratio into the dominant decay channel $t \to Wb$ [25]. A precision measurement of the top cross section times the square of the branching ratio $t \to Wb$ would thus be a test of many models of new physics.

The measurements of cross sections at hadron colliders have traditionally been normalized to the total proton-proton or proton-antiproton cross-section. This itself is difficult to measure, with a 10% discrepancy between measurements at $\sqrt{s} = 1.8$ TeV, for example [26]. The dominant uncertainties in the measurement of the top cross section are from this luminosity uncertainty, and from initial- and final-state radiation of jets [27, 28].

A substantially more precise way to measure the top cross section may be to normalize to an electroweak cross section such as the W or Z cross section [29, 30]. In addition, if much higher statistics are available (as will be at the LHC), precise measurements can be made of the ratio of top production to other cross sections of similar invariant mass to $t\bar{t}$, such as WW, WZ, and ZZ production.

The cross section for $t\bar{t}$ pair production is measured to be approximately 5 pb at 1.8 TeV [31, 32], in good agreement with expectations of resummed perturbative QCD [33, 34, 35] It should be (arguably[1]) possible in the future to measure the ratio $R_{t\bar{t}} = \sigma(t\bar{t})/\sigma(Z)$ to close to the present precision of the measurement of the cross section ratio $R_W = \sigma(W)/\sigma(Z)$. The present measured value of R_W has an approximately 2% uncertainty [36]. Measuring the ratio $R_{t\bar{t}} = \sigma(t\bar{t})/\sigma(Z)$ to 2% would give an uncertainty of $0.2 \times 5 = 100$ fb on $\sigma_{t\bar{t}}$, assuming that new physics affects $t\bar{t}$ production substantially more than Z production. This measurement would also check the branching ratio of $t \to Wb$ at the 2% level if there is agreement with the standard model, ruling out some models with light top or bottom squarks.

At present the theoretical calculations of the production cross section $\sigma(t\bar{t})$ have uncertainties far above the 2% level, even though some of the initial-state radiative corrections will cancel in the ratio. We intend to improve substantially the theoretical uncertainty on this ratio, and hence on the predicted top cross section.

E Width

The top quark decays rapidly into Wb, with a predicted width of $\Gamma_t = 1.39$ GeV [37]. The partial width $\Gamma(t \to Wb)$ can be measured indirectly via single-top quark production (see section B). However, with enough statistics, it may be possible to make a *direct* measurement of the *total* width. The Wb invariant-mass distribution is described by a Breit-Wigner, which gives a power-law behavior above the pole. If the invariant mass, or a related quantity, is measured with a resolution that is Gaussian, for invariant masses many widths above the pole the power law of the Breit-Wigner distribution dominates the exponential of the Gaussian resolution, and so the width can be directly measured from the tail of the mass spectrum. This is the method that is now used to directly measure the width of the W boson [38, 39, 40] For this method to work the resolution must be well understood. It may be advantageous to trade statistics for resolution by picking a variable related to the Wb invariant mass which has well-understood resolution, rather than the invariant mass itself. One such variable, for example, is the invariant mass of

[1] While the future measurement is substantially more difficult, the Run II detectors have much better acceptance and b-tagging, and with higher statistics much better control of the systematic uncertainties.

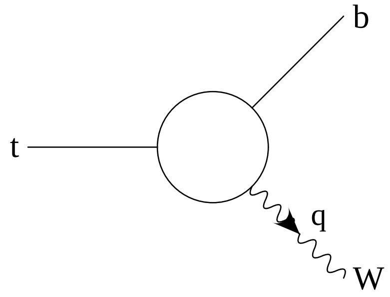

Figure 2: top quark decay via the charged-current weak interaction.

a lepton from the W decay and a lepton from the semi-leptonic decay of the b quark in fully-reconstructed top decays. Because the resolution for electrons and muons is well-measured in W, Z, J/ψ and Υ decays, the resolution in this invariant mass will be well understood. We will explore the feasibility of such methods to directly measure the top width. The W width, which is comparable to the top width, will complicate the extraction of the top width.

6.2 Weak interactions

The top quark is distinguished from the other fermions by its large mass. Since fermions acquire their mass via the spontaneous breaking of the weak interaction, the weak interactions are an especially interesting place to probe for nonstandard interactions. Below we discuss the two ways to access the weak interactions of the top quark at hadron colliders: decay and production.

A Decay

The top quark decays via the charged-current weak interaction. The most general form for the top quark charged current (see Fig. 2) is [41]

$$\begin{aligned}\bar{u}(b)\Gamma^\mu u(t) &= \frac{g}{2\sqrt{2}} V_{tb}\bar{u}(b)[F_L^1\gamma^\mu(1-\gamma_5) + F_R^1\gamma^\mu(1+\gamma_5) \\ &\quad -\frac{i}{M}F_L^2\sigma^{\mu\nu}q_\nu(1-\gamma_5) - \frac{i}{M}F_R^2\sigma^{\mu\nu}q_\nu(1+\gamma_5)]u(t) \quad (1)\end{aligned}$$

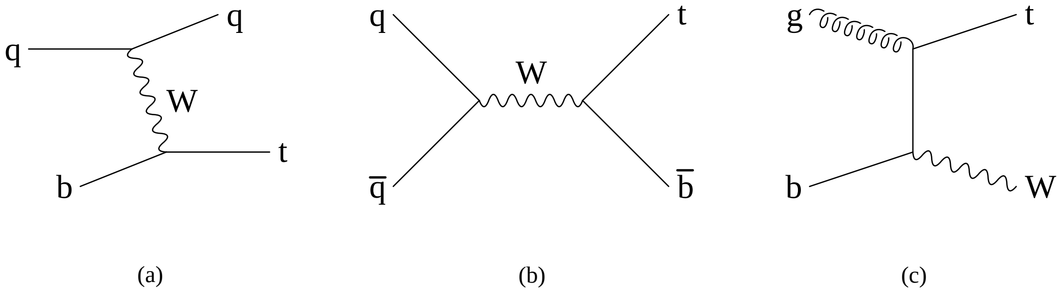

Figure 3: Single-top quark production via (a) t-channel W exchange, (b) s-channel W exchange, and (c) associated production with a W.

where q is the four-momentum of the W boson, M is a mass scale, and the form factors $F^{1,2}_{L,R}(q^2)$ are evaluated at $q^2 = M_W^2$. These form factors are the analogues of the "Michel parameters" of the muon. The standard model (at tree level) predicts $F_L^1 = 1$, $F_R^1 = F_L^2 = F_R^2 = 0$.

In Run I, the decay of the top quark was studied only crudely, due to limited statistics. It was learned that the top quark decays to a longitudinal W boson with a branching ratio of $0.91 \pm 0.37 \pm 0.13$, in agreement with the expectation of 0.70. It was also learned that the branching ratio to a positive-helicity W boson is 0.11 ± 0.15, in agreement with the expectation of zero [42]. No theoretical interpretation of these measurements was made.

Much more precise measurements of top quark decay will be possible in Run II and at the LHC. This suggests the challenge of measuring the "Michel parameters" of the top quark with the greatest possible accuracy. This requires a coordinated effort between theorists and experimentalists. The measurements of the branching ratio to longitudinal and positive-helicity W bosons are examples of the measurements that will be necessary to isolate all four form factors, but they are not sufficient. The $t\bar{t}$ spin correlation, discussed above, may be a useful tool. Optimizing the analysis will be a challenge that only a coordinated effort can meet.

B Single top

The only parameter in the top quark charged-current weak interaction, Eq. (1), that cannot be accessed via top quark decays is the overall strength of the interaction, parameterized by V_{tb}. This is because there is no known way to measure the lifetime (or equivalently, the width) of the top quark at a hadron collider (except possibly the method proposed in section E).

Fortunately, there is another way to measure the overall strength of the interaction: measure the "single top" production cross section, which occurs via the weak interaction. There are three processes of interest, as shown in Fig. 3. The process in Fig. 3a involves the t-channel exchange of a W boson, which promotes a b quark in the proton sea to a top quark [44, 45, 46]. The process in Fig. 3b involves the s-channel exchange of a W boson, and is similar to the Drell-Yan process [47, 48]. The process in Fig. 3c involves the production of a single top quark in association with a W boson [49, 50]. There are upper bounds on the s- and t-channel processes from Run I [43]; the associated-production process is only significant at the LHC.

The single-top cross sections at the Tevatron and LHC are significant. The largest cross section is from the t-channel process, Fig. 3a; it is about 1/3 times the pair-production cross section. However, the backgrounds to single top are much more severe than they are to top quark pair production. Thus an accurate knowledge of all backgrounds (the most severe being $Wb\bar{b}$ and $t\bar{t}$) is essential to isolate the signal. The backgrounds must be measured in regions away from the signal in order to build confidence in the theoretical calculations. The single-top processes may also be useful to measure the top quark charged-current form factors, Eq. (1) [49].

6.3 Yukawa and other interactions

At present the top quark is of great interest in its own right, but it will not be long before it becomes a significant background to other processes of interest. What is less appreciated is that the top quark can also be used as a tool to discover new physics. Here we discuss three realizations of this observation.

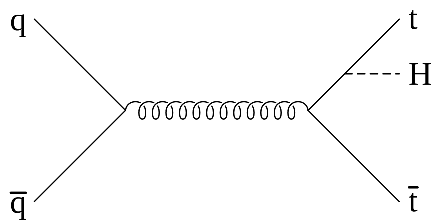

Figure 4: Higgs boson production in association with a top quark pair.

A $t\bar{t}H$

The hunt for the Higgs boson is one of the great quests of hadron colliders this decade (see MRC-B). The top quark can play a useful role in this search, both within the standard model and beyond. For example, almost all of the parameter space of the supersymmetric standard model is covered by Higgs signals that involve the top quark [8]. Here we discuss the associated production of the Higgs boson in association with a top quark pair, as shown in Fig. 4.

The associated production of a Higgs boson with a top quark pair is of interest as a means to measure the top quark Yukawa coupling to the Higgs boson. This coupling is related to the mechanism which provides the top quark with mass when the electroweak symmetry is spontaneously broken, so it is of particular interest.

The associated production of the Higgs boson with a top quark pair is relevant at both the LHC [8] and the Tevatron [51]. It can be used to search for a Higgs boson in the mass range where it dominantly decays to $b\bar{b}$. The backgrounds are significant, however, and the final state ($WbW\bar{b}b\bar{b}$) is quite complicated. It has been found that to reduce the background to an acceptable level, and to avoid a large combinatoric background due to the presence of four b quarks in the final state, one must reconstruct the t and $\bar{t}$ with high efficiency. This is a great challenge, one that will require experience with ordinary $t\bar{t}$ events, as discussed in section 6.1 of this MRC. Thus the Higgs search in this channel benefits from integrating it with the general study of the top quark. The backgrounds (the largest being $t\bar{t}b\bar{b}$) require collaboration between theorists and experimentalists, as they must

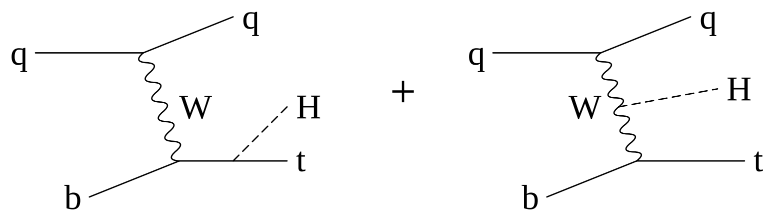

Figure 5: Higgs boson production in association with a single top quark.

be calculated accurately and measured away from the Higgs signal to build confidence in their precision.

If the Higgs boson is heavy enough that it decays principally to W^+W^-, then the final state is $WbW\bar{b}WW$, which leads to an even more complicated final state after the W bosons decay. This signal is even more challenging to extract from backgrounds. There has been no serious study of this signal to date. At the Tevatron, there are only a handful of events with 15 fb^{-1}, but there are of order 30 trilepton events with 30 fb^{-1} at the LHC.

B tH

A generalization of the above process is to search for the Higgs boson produced in association with a single top quark [52, 53]. The largest cross section comes from the t-channel process shown in Fig. 5. The Higgs boson can be radiated off the top quark or the t-channel W. The two contributions are comparable and of the opposite sign, so there is significant destructive interference. This makes the signal more difficult to observe, but also provides the only known way to test the relative sign of the coupling of the Higgs boson to the top quark and the W boson.

This process has been considered when the Higgs decays to a pair of photons [52]. Since the dominant decay of the Higgs boson in this mass region is to $b\bar{b}$, this suggests searching for the final state $qWbb\bar{b}$. There are about 75 such events at the LHC with 30 fb^{-1}. However, there are large backgrounds to this signal from top quark pair production, so it will be especially challenging to extract. The analysis will benefit from the experience gained from the study of the $t\bar{t}H$ process.

C $W_R \to t\bar{b}$

If right-handed W's exist, it is possible that the corresponding right-handed neutrinos N are too heavy to permit the decays $W_R \to lN_l$. The decays $W_R \to q\bar{q}'$ should still be permitted, however. The signature $W_R \to t\bar{b}$ was suggested by Rosner and Takasugi some time ago as one possible channel in which a distinctive signal could be detected [54]. The utilization of this channel for a realistic search will require close interaction between theorists and experimentalists in order to map out likely backgrounds and details of signatures.

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for the central value (but in good agreement for the uncertainty!). The top cross sections are normalized to this number, and hence share the problem of systematic disagreements at the 10% level, precluding a precision measurement.

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7 MRC-E: Tools and Methods for Signature-Based Searches

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7.1 Introduction

We have a unique opportunity to make a paradigm shift in the way many searches for new physics will be performed at the Tevatron and LHC. Nearly all experimental searches to date have been model-driven, in which one starts with a particular scheme and tests that hypothesis against data[1]. While this is a reasonable strategy when the number of competing candidate theories is small, this strategy becomes unwieldy when the number of competing candidate theories is large. During the process of assembling the final pieces of the standard model — discovering the W and Z^0 bosons at CERN in 1983, and the top quark at Fermilab in 1995 — pursuing a model-driven strategy made good sense, since the properties of these particles (except their precise mass) were predicted. We find ourselves now in a completely different situation.

The standard model is a remarkable intellectual achievement, but leaves many fundamental questions unanswered. The pieces of the puzzle of the nature of the fundamental constituents of nature that we have just fit into place — the W and Z bosons and the top quark — were inside the standard model, and their signatures were thus precisely predicted. In contrast, we know very little about the properties of the new pieces that we may identify in the next decade, and this fundamentally changes the nature of the challenge.

It is very possible, even likely, that upcoming discoveries will look quite different from expectations built on current models. The recent explosion of interest in extra dimensions is an excellent example of how rapidly the most popular models of new physics can change. We are in a situation in which the number of potentially interesting models proposed on the high energy phenomenology e-print archive in one year is far greater than the number of models that CDF or DØ will be able to test in all of Run II at the Tevatron.

We consequently propose to devote substantial effort in pursuing "signature–based searches". In this scenario, data analysis is based on a signature rather than a model of production of new particles. A signature is a set of selection criteria on collider data which define a data set. In particular, signatures are often specified by the number of charged leptons (e, μ, and τ); neutrinos and other undetectectable particles, observed as missing transverse momentum ($\not{E}_t$); light quarks (u and d) and gluons detected as jets; heavy quarks (charm, bottom and top); and the gauge bosons (W,Z^0, and γ) in certain kinematic regions, such as having large transverse momentum or large invariant mass or total energy. Two examples of signatures are: a) 2 opposite–sign electrons with $E_t > 20$ GeV, or b) 3 jets with $E_t > 20$ GeV and significant missing E_t.

For clarity, we note that in our terminology, models are completely predictive theories of new particle production and decay. For example, a supersymmetric (SUSY) model might list several assumptions for SUSY parameters such as values for $\tan\beta$ and μ and assumptions for renormalization group equations, unification, and the order to which the cross sections are calculated. This model then determines particle masses, production cross sections, and decay branching ratios. Most models contain some variation on the masses of the particles or the branching ratios which can lead to different signatures in different regions of parameter space.

7.2 Systematic Calculation of Standard Model Backgrounds.

The paradigm of signature–based searches operating in parallel in a large number of signatures requires a much more general and comprehensive understanding of standard model backgrounds than has so far been obtained. The importance of this more comprehensive understanding weaves throughout this proposal, as it is impossible to discover evidence of "new" physics, be it extra dimensions, supersymmetry, or states from higher groups such as E_6, etc., unless one has a very clear idea of what the the "old" physics is.

The goal of Run II is to accumulate at least 15 fb^{-1}per detector, a factor of 150 more than the accumulation in Run I. With this increased reach of the Tevatron, many signatures that involved the multiple production of fundamental bosons and fermions, such as $t\bar{t}W$, WW+jets, $W\gamma$+ jets, γbc+ jets,and $t\bar{t}b\bar{b}$, for example, will be accessible for detailed analysis. These are also signatures in which one expects new physics, such as the Higgs boson ($t\bar{t}b\bar{b}$), the stop squark (γbc+ jets, possibly), technicolor, (γbc), to show up. The calculation of the Standard Model rates for these processes is absolutely necessary for the convincing detection of anything new. In addition, these processes will have to be implemented in at least two Monte Carlo programs, so that there are detailed predictions of what the detectors will see, with redundancy to prevent errors.

An additional factor is the development of flavor identification in detectors at hadron colliders. We have come very far from the early days of collider physics when a jet was just a jet. We now can 'tag' both b-quarks and c-quarks. The new detectors for Run II represent a major increase in capability beyond their respective Run I detectors; we expect to be able to routinely separate b and c quarks from each other and from light quarks and gluons. There are new capabilities for strange quarks as well, as well as indications that gluon jets can be separated from jets from light quarks on a statistical basis. And lastly, there will be many more events with top quarks in them (we produced about 500 $t\bar{t}$ pairs per detector last run- next run we expect 75,000 pairs produced per detector). The ability to measure the flavor of quark jets means that there is a whole class of processes that needs more precise understanding and calculations: events with $b\bar{b}$ pairs, $c\bar{c}$ pairs, or, for example, $b\bar{b}c\bar{c}$ production (this latter is a background in the signatures involving bc, a possible charged Higgs signature, as well as charged technicolor and SUSY decays).

This will be an ongoing process as analyses become more sophisticated as Run II proceeds. However, based on the needs uncovered by the Run I analyses, we have made a partial list of channels and signatures where Standard Model calculations of the requisite precision do not yet exist. We are working as a group to augment and tune this list; after we have a prioritized list, the next task will be to assemble interested parties to work on individual channels. One important aspect to have related calculations done with the same input values and other assumptions: for example, the production of a top quark-antiquark pair with a photon or with a W boson can serve as control samples for a search for Higgs production in association with a $t\bar{t}$ pair.

Our (partial) wish-list follows as an illustration (the signal channels to which these are the Standard Model backgrounds are left to the reader to fill in; for example, the semileptonic decay of a top quark gives the signature of $W+4$ jets – if we wish to work to order α_s, we need to have predictions of W+0,1,2,3,4,5 jets):

Table 1.

Single boson	Diboson	Triboson	Heavy flavor
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}+\leq 3j$	$WW+b\bar{b}+\leq 3j$	$WWZ+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 3j$	$WW+c\bar{c}+\leq 3j$	$W\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$ZZ+b\bar{b}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{b}+\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$		$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}+\leq 3j$	$\gamma\gamma+b\bar{b}+\leq 3j$		
$\gamma+c\bar{c}+\leq 3j$	$\gamma\gamma+c\bar{c}+\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}+\leq 3j$		
	$WZ+c\bar{c}+\leq 3j$		
	$W\gamma+\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

Table 1: A list of standard model processes that may need to be understood in order to discern evidence of new physics in Run II. The notation Z is used here to indicate full Z/γ^* interference; γ is used to indicate a real photon.

In addition to calculations of high-p_T cross-sections and angular distributions for specific channels as listed above, there are a number of more general properties of $\bar{p}p$ interactions that need to be better understood and modeled for fully exploiting the Tevatron and the LHC, some of them involving difficult non-perturbative QCD calculations.

For example, the identification of high-p_T photons that are directly produced is difficult due to the large background rate of photons from π^0 and η decays. Direct photons are expected to be isolated from nearby particles, in general, in contrast to the π^0's, which in general are produced in jets. It has been proposed[2] that the probability of a jet fragmenting to an isolated π^0 can be estimated by measuring the probability of fragmentation to an isolated charged pion. There are, however, corrections due to the fragmentation to other charged particles such as kaons and protons- these corrections need to be calculated.

Another example involves details of color flow and particle production in the underlying event. Photon identification involves a veto against tracks from particles pointing at the electromagnetic cluster, as another background to photons comes from electrons. QCD studies, for which the p_T of the photon is low (typically less than 40 GeV), set the cut against tracks at 1 GeV, rather arbitrarily. In Run I we have already observed photons with energies above 200 GeV, and expect many more such events in Run II. For these high p_T photon candidates,, the track veto at 1 GeV may be cutting into the efficiency; we need a way to set this cut from basic principles as well as from control samples. The control sample we use is a sample of high-p_T $Z^0 \to e^+e^-$ decays; for each event we reconstruct the direction of the Z, and and measure the spectrum of tracks pointing along the Z momentum. However, there will be corrections due to the difference between the underlying events in Z and γ production, and these need to be calculated.

In this effort JCET is absolutely critical. The incentive structure currently built into theoretical particle physics tends to reward those who focus on more abstract topics, with little reward given for work leading to a better understanding of standard model backgrounds. The scope of the needs (e.g. Table 1) will require new calculational tools and Monte Carlo programs. It is likely that a different way of attacking these problems, involving both experimentalists and theorists, is necessary. Recognizing the extreme importance of having better standard model background estimates, JCET can provide focus, continuity and support to encourage the important work still left to do within the context of the standard model — work that could end up being as crucial to the discovery of new physics at the Tevatron and the LHC.

7.3 Further Development of Strategies and Tools for Signature–based Searches

The development of signature–based searches at hadron colliders is new. In the past several years there has been an initial discussion of some of the ideas in the literature[3, 4], and one carefully worked example has been published[5]. Other publications with aspects of these concepts are in preparation[6, 7, 8, 9]. But the problems are difficult, and a great deal of development of ideas and the necessary tools remains to be done. With the close connection between theorists and experimentalists, as well as between LHC and Tevatron experiments, JCET will be in a unique position to develop signature–based searches into much more sophisticated tools than these present first-generation analyses.

In these first-generation signature–based searches we have found that it is possible to abstract general characteristics of an extremely large class of models. In particular, most models incorporating new phenomena predict the presence of events at large transverse momenta, where "large" is relative to standard model and instrumental backgrounds. We can then look for "regions of excess at large transverse momenta" in an essentially model-independent way. Members of this proposal have been active in the development of these ideas, both at CDF [3, 4, 8, 9] and at DØ [5, 6, 7].

This is a fundamentally new approach that addresses questions far beyond high energy physics. In many fields of research the practitioner analyzes data with only a somewhat vague idea of the signal she or he expects to find. Once an anomaly is discovered, she then faces the extremely difficult question of whether the anomaly is statistically significant. The difficulty of this question lies in the near impossibility of determining the *trials factor* — how many places could an equally interesting signal have appeared, but did not? This question is faced by astrophysical researchers looking for evidence of clustering in cosmic ray data, by epidemiologists attempting to identify clustering of disease, by nuclear scientists looking for resonances of potentially unknown width and mass, and by the layperson whenever faced with a seemingly startling "coincidence." We have realized that with a rigorous definition of the space of potentially interesting signals — a space that can be loosely defined as the space of candidate signal consisting of "regions of excess at large transverse momentum" — the trials factor can be explicitly evaluated, providing a well-defined quantification of the "interestingness" of any candidate signal[5].

There are many potential advantages to this approach. In addition to providing a means for systematically searching a much broader space of potentially interesting physics, this approach enables an *a posteriori* measure of the degree of interest of an anomaly spotted through other (less systematic) means. The focus also becomes much more data–based, and the analysis of the entire data set is emphasized. Certain "model blinders" that are common in specific searches, leading at times to a desire to cut out interesting (six-lepton) events in order to improve limits on a specific (three-lepton) model, are all but eliminated by adopting a data-driven strategy. Time and resources that have in the past gone to the incremental improvements of limits on specific new models are instead devoted to better understand the standard model and instrumental backgrounds to a broader section of the data. If we happen to be guessing wrong about where new physics is likely to show itself in the next decade, a model-independent analysis of the type we propose is likely to be our only hope at discovery.

Although the direction of necessary change is well-understood, hammering out the details of how such a model-independent analysis should be performed will require close cooperation between experimentalists, who know best what their equipment will allow, and theorists, who know best the wide variety of possibilities that may reveal themselves in Run II. This effort requires input from numbers of people on both sides of the table, and there currently exists no good forum for this exchange. The collaboration that JCET would enable is key to this enterprise, which will require clever ideas of many kinds from many different heads.

7.4 Confrontation of Theory by Experiment- the Interface Between Signature–based Limits and Model–based Predictions

A shift by experimentalists toward signature–based limits will allow a new model-driven approach to data analysis, and in fact a fundamentally new way of publishing data. A physicist wishing to check a particular model against data from any high energy physics collider is generally hopelessly lost — the information provided in publications is usually insufficient for an outsider to derive independent conclusions. This is an unfortunate but necessary consequence of our current two-dimensional method of publishing, as a few sheets of paper is simply an insufficiently rich medium for publishing the rich data that we work so hard to collect.

We propose the publishing of data through the World Wide Web in a form that allows a physicist to easily use any aspect of that data to test any particular model she wishes. This can be done by carefully defining the web page as the interface between the model-builder and the experiment, with the generation of signal Monte Carlo and specification of interesting variables placed in the hands of the model-builder, and the detector simulation, data, and standard model and instrumental background estimates in the hands of the experiment. Once the data and background estimates have been understood of our attack), these are "published" through the web to enable extensive testing of specific models. The automation of model-testing that we propose will drastically reduce the time required to test any particular model. In addition, automation will allow us to move toward a goal of being able to apply limits in many signatures to a given model, and thus make a multi-dimensional exclusion in parameter space that takes into account how signatures change as the parameters change. The additional flexibility that this will allow in our analysis of data should be enormous. We expect that this idea is likely to be adopted by other high energy physics experiments, and imagine that in the future it may evolve into a publication standard used even by fields outside physics.

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8 MRC-F: Determining Factors in Math and Science Education

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+ 1 Masters student (Northern Ill.)
+ 4 undergraduates (2 U. Chicago),
+ 2 High School interns (1 U. Chicago)

8.1 Introduction

This MRC has two major components, with the first focussed on quantitative statistical assessment of interventions in math and science education (Subsection 8.2). This component has three distinct yet closely related strands: 1) assessment of program impact on students, 2) determining readiness of schools for intervention, and 3) quantitative determination of program factors in successful schools. The second component of this MRC involves developing a model for the transfer of these and other research results to the daily working and policy-making of individual schools, an area that has received little attention but one we believe is critical (Subsection 8.3). Lastly, synergies with the other MRC's in this proposal are discussed in Subsection 8.4.

A Background

Ten years ago, The Teachers Academy for Mathematics and Science (referred to as TAMS or the "Academy") was conceived and initiated by physicists and local parents and educators. Initially funded by the NSF and DOE, the Academy is now fully supported by the State of Illinois and private funds at a level of more than six million dollars annually. The Academy seeks to train a critical mass of elementary school teachers in mathematics and science, as well as parents and the leadership team (e.g. principals, local school board members, etc.) at a large number of individual schools. The Academy does this by implementing a comprehensive, school-wide, three-year program that consists of three major components for teachers.

First, the program involves classroom instruction addressing both math and science content as well as teaching pedagogy. This is done using methods appropriate for teachers who instruct elementary level students (In Chicago these teachers are non-specialists; 17,000 teachers regularly teach math and science in the Chicago Public Elementary Schools, very few with any training in math and science). Second, extensive classroom support in each individual teacher's classroom is provided, including long-term follow-up with biweekly visits to the classroom by TAMS specialists. This assists teachers in transferring their increased knowledge into practice in their own classrooms with their students. And finally, the Academy distributes appropriate classroom teaching materials and student manipulatives, including access to computer technology. A more detailed description of the Academy's program can be found on the TAMS web site at http://www.tams.org.

By the State's request, TAMS has now extended its work from Chicago to schools in other areas of Illinois including, among others, Joliet and Aurora, which are in close proximity to Argonne and Fermi National Laboratories respectively. To date, the Academy has worked with 114 elementary schools and 3,000 teachers in Chicago and four other urban centers in Illinois. The Academy purposely chooses to work with schools who teach an ethnically diverse population of students (currently 61.0% of the students in Academy schools are African-American, 30.3% Hispanic, 6.1% Caucasian, 2.6% Asian, and 88.8% receive reduced priced lunch, a common measure of low-income families.).

B Program Results

i Student Results Urban schools in Illinois, as well as in the nation as a whole, face diverse and complex challenges[1][2][3]. Improvements in the situation require that the problems can be broken down and approached systematically. The more widespread use of standard-based tests and better data sets will offer the opportunity to attack these challenges through rigorous statistical methods.

One measure of student achievement in Illinois is the Illinois Goal Assessment Program (IGAP). The IGAP is a standardized test based on goals set by the Illinois State Board of Education. Elementary students are tested in third, sixth, and eighth grades for mathematics, and fourth and seventh

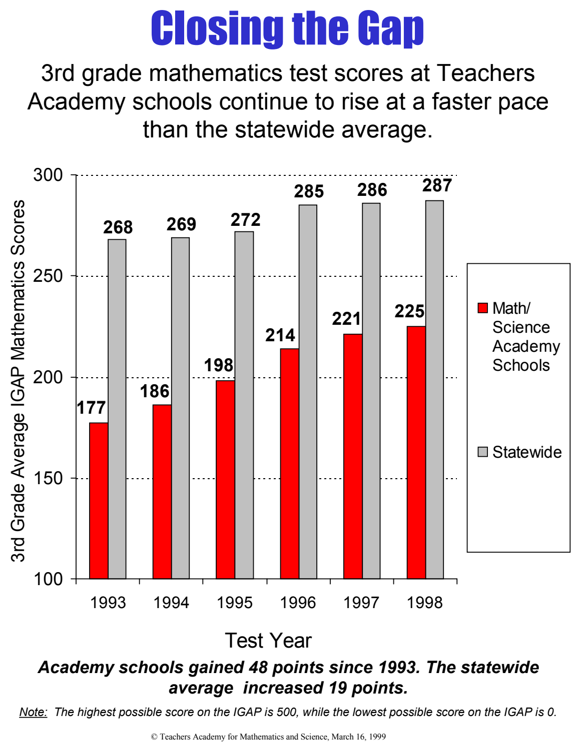

Figure 6: A comparison of the rate of improvement in 3rd grade mathematics test scores at TAMS schools versus the statewide average.

grades for science. Scores are reported by school and grade as average scores[2] on a scale from 0 to 500. A sampling of the Academy's results are included here. Teachers Academy schools, while starting at a lower initial point, have improved substantially more rapidly than other schools statewide. On average from 1993-1998, 3rd grade mathematics students at Academy schools have gained 48 points (from 177 to 225) compared to 19 points on average (from 268 to 287) for other schools in the state (see Fig. 1). It is important to note that by design the Academy works with some of the lowest performing schools in the state where educational support mechanisms are most needed.

[2]The numbers given in the following charts are average scores/school.

Additionally, the Academy has seen sustained improvements over time. Figure 2 shows results for third grade students who were tested three years later in the 6th grade. In contrast to the data in Figure 6, for which the total number of schools which had participated in the mathematics and science programs was held constant over the years, the graph in Figure 7 includes schools in three-year comparisons tabulated by when they entered the Academy. All comparisons: 1990-1993, 1991-1994, 1992-1995, 1993-1996, 1994-1997, and 1995-1998 indicate sustained improvement over time and show marked, positive differences in comparison to the state's third to sixth grade increases over the same time spans (the corresponding state gains are 4, 2, 4, 3, 4, and 3 points respectively). These comparisons are statistically significant, 1994-1997 ($p<.01$) and 1995-1998 ($p<.05$).

Science achievement also improved (see Fig. 3). The average IGAP science scores of seventh graders at Academy schools rose from 1993-1998 by 38 points (from 168 to 206), to be compared to a 9-point gain (from 244 to 253) by their peers at other schools statewide. The gain in TAMS schools in the last year of the study (1997-1998) was most pronounced, with a 19 point gain versus the statewide gain of eight (8) points. Both comparisons are statistically significant at the $p<.01$ level.

Science scores of a given cohort of students (i.e. a longitudinal study) also show substantial gains over time. From fourth grade to seventh grade the largest gain experienced was in the most recent 3-year time period from 1995 to 1998. In 1995, when Academy school fourth graders were tested they scored an average of 159 points. Three years later, in seventh grade, they gained 48 points to score an average of 207 points (see Fig. 4). The same comparison for the state yielded a 10 point gain, from 250 to 260. This difference is statistically significant ($p<.01$).

In addition to the overall average, individual Academy schools showed impressive double-digit gains from fourth grade in 1995 to seventh grade in 1998. Out of 45 schools with 4th and 7th grade scores available, 43 experienced double-digit gains. The other two schools had double-digit losses for the same time period. In comparison, 70% of the other statewide schools showed double-digit gains, 10% single-digit gains, 19% losses, and 1% no change. Overall, six of the top 25 gaining schools in the state out of the 645 in this three-year comparison were Academy schools (see Fig. 5).

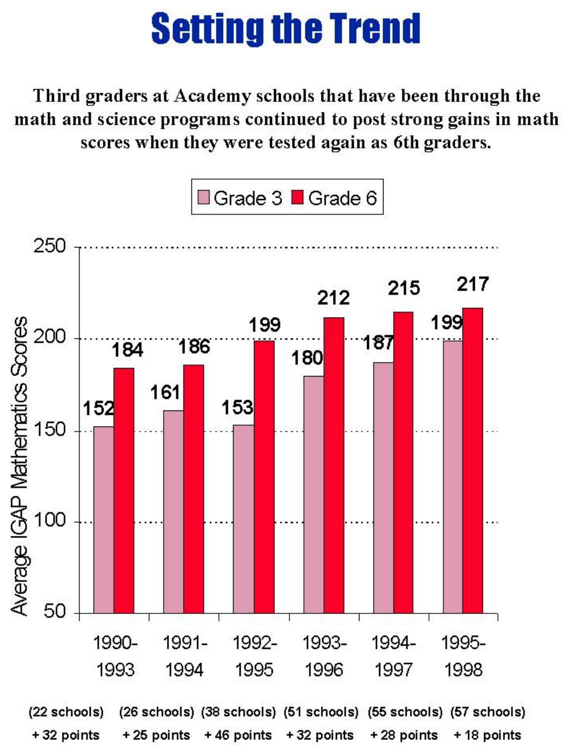

Figure 7: The average IGAP scores of students who have gone through the math and science programs in TAMS schools tested in the 3rd grade and again in 6th grade.

ii Teacher Results In addition to gains in student achievement, teachers who have been exposed to the Academy's professional development program have improved their own knowledge. A 29-item open-ended basic math and science skills test, with a maximum total of 40 points, was administered before and after the intervention. Inferential comparisons were made only for the teachers who had a matched set of data (i.e. both a pretest and post-test). Because this comparison was made only for a subset of teachers, it is important to compare mean scores for all participating teachers for the pretest (mean = 11.4), and the post-test (mean = 22.9) to determine if the comparison data were biased due to sampling attrition. The means for these larger groups were slightly smaller than the mean scores for those teachers where a pretest–post-test comparison was possible (although within measurement uncertainties). Teachers in the East St. Louis School District showed a 98.3% improvement on the skills tests, while teachers in the Joliet School District showed a 32.3% gain in one year. Briefly, the following table and figure highlight some of the gains for the two districts as well as the distribution of scores[3]:

District/Score Ranges	**Pretest**	**post-test**
East St. Louis[4]	Number of Teachers	Number of Teachers
0 to 9.5	41.5%	1.0%
10 to 14.5	27.4%	7.7%
15 to 19.5	17.0%	21.2%
20 to 29.5	13.2%	61.5%
30 or more	0.9%	8.7%
Average Score (40 max.)	11.9	23.6
Joliet[5]		
0 to 19.5	38.2%	14.8%
20 to 24.5	29.4%	22.2%
25 to 29.5	29.4%	18.5%
30 or more	2.9%	44.4%
Average Score (40 max.)	21.4	28.3

Table 2: Scores from a Pretest/Post-test comparison for teachers from East St. Louis and Joliet who had completed training with TAMS.

[3]More detailed statistical results from this study, or any of the analyses mentioned in this proposal, can be obtained from the Academy. Note pretest and post-test totals might not add to exactly 100% due to rounding.

C Overview of the Proposed Research: The DataSets

Inspired by these preliminary results, TAMS requested and received access to large data sets from the Boards of Education of Chicago and the State of Illinois in order to investigate more rigorous methods of educational research. These data sets encompass approximately 6 million student records, as well as data on more than 3,000 schools, over 10 years. These data sets contain student test score data, school and student demographic information, and teacher statistics. This information will be combined with internal Academy databases involving programmatic data such as teacher attendance rates in the Academy's program, teacher and student content knowledge and attitudinal measures, and both quantitative and qualitative classroom observations. This component's approach echoes the call of The President's Council of Advisors on Science and Technology (PCAST) which stated, " (a) large-scale, rigorously controlled program of research and evaluation will ultimately be necessary"[4]. More detail is provided below in Section 8.2.

The second major component of this MRC is the development of models for transfer of research results into tangible efforts at individual schools. Teachers and school administrators rarely have the expertise, tools, or personnel to help them analyze data[7]. As a result they traditionally rely on intuitive decision-making much more often than other professionals do in similar sized organizations[8]. The focus of this component is supported by recent reports of The National Academy of Evaluation (NAE)[5] and the National Research Council (NRC)[6] whose strategic goals call for: 1) tying "research to practice"; 2) focusing on "critical transitions in the lives of low-income students"; and 3) "linking teachers' professional development and teaching practices with improved student learning". This component will also be described in detail below, in Section 8.3

The funding of this MRC will help pay for: 1) the preparation of the large data sets for statistical analysis, 2) the analysis of these data along multiple research strands, 3) the dissemination of the results at the city, state, and national levels, and 4) the transfer and use of the knowledge gained in a manner useful to educational practitioners in Academy schools.

8.2 Assessment of the Effectiveness of Interventions in Math and Science Education

The large datasets, once they have been prepared for analysis, will allow the quantitative investigation of a number of questions. We discuss the three we have selected in turn below.

A Impact of Intervention on Student Performance

One research strand of this MRC is to develop rigorous and sophisticated statistical models for measuring the impact of interventions within schools. One of the biggest challenges of this type of research involves addressing the question of how the impact of an intervention can be measured in the absence of adequate comparison groups, which is often the case. With the assistance of the former Corporate Statistician for the CNA Insurance Companies, Yakov Avichai, the Academy has begun evaluating the impact of the Academy's work with teachers using techniques from the insurance industry to solve the problem of not having adequate control samples[9]. This is particularly important for the Academy since its target population consists of the poorest performing schools and those with high concentrations of low income students. The goal has been to analyze the impact of the Academy intervention on 7th grade science score differentials on state standardized student test scores between 1994 and 1999.

Ideally, one would select a set of comparable schools to those that were exposed to the Academy's program and proceed with a straightforward comparison. This, however, is not feasible given the available information (and sample sizes) and is doubtfully achievable in the foreseeable future. Instead, we have developed a multivariate regression model of all schools that controlled for key independent variables, namely, 1993 science scores (baseline score), 1998 math and reading scores (prior year's scores), English language proficiency scores, low income measure, school enrollment, and ethnicity variables[6]. The multivariate fit[7] enabled us to calculate the expected results for Academy schools in the general environment and compare them with the actual results. In other words, the expected value is the score the Academy school would be expected to achieve if it performed as well as non-Academy schools with similar demographics and initial achievement levels. These results are shown in Table A.

[6] These variables were used because they were readily available in the data. Determining the ideal variables and refining the model using the newly constructed datasets are goals of this MRC.

[7] The standardized β coefficients for each variable described above were -1.2, 0.23, 1.0, 0.36, 0.14, 0.22, -0.30 respectively. The constant was -3.39. For this exploratory analysis a less stringent range of significance levels was accepted for the coefficients. All were significant at the $p<.05$ level except the low income measure which was significant only at $p<.20$ level.

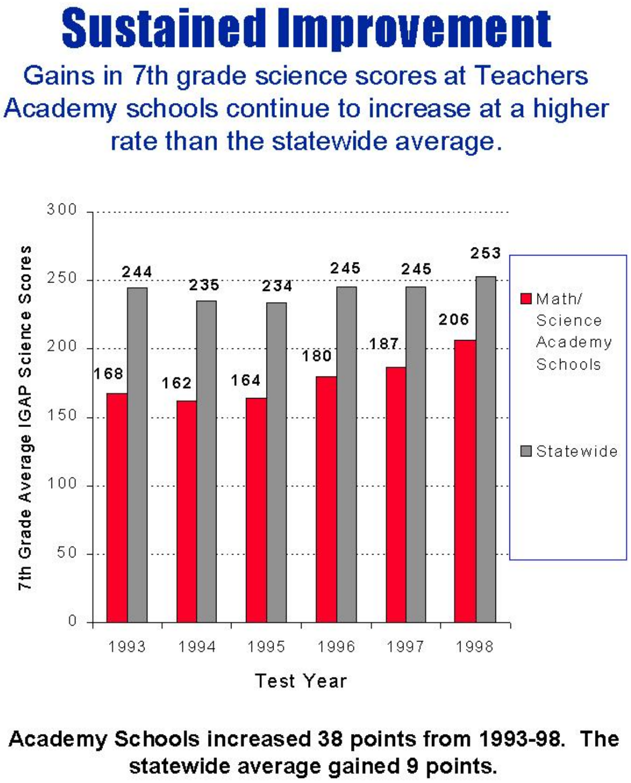

Figure 8: IGAP science scores for 7th graders at TAMS schools and statewide as a function of year tested.

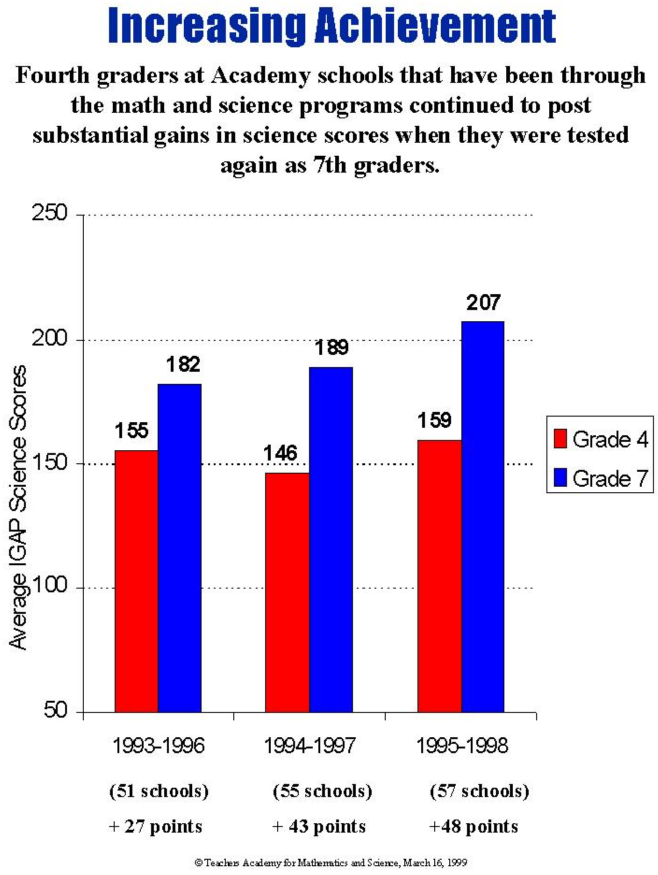

Figure 9: Average IGAP scores for three cohorts of 4th graders who have been through the TAMS math and science programs, tested in the 4th grade and again as 7th graders.

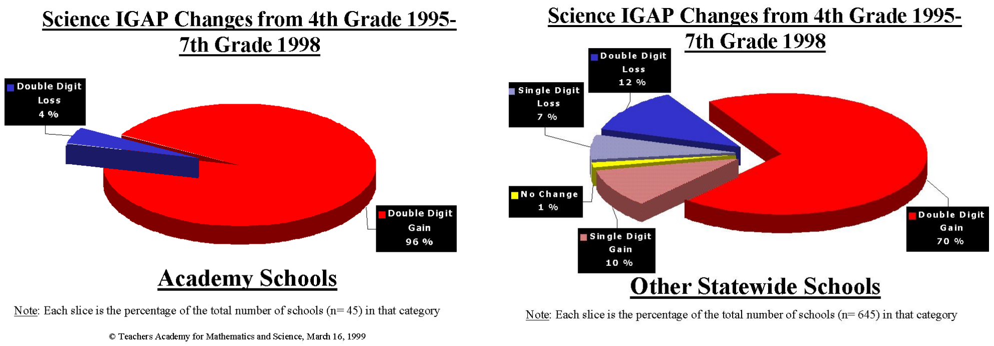

Figure 10: The distribution in changes in the average science IGAP scores between the 4th grade in 1995 and the same students in the 7th grade in 1998 in TAMS schools (left) and other schools statewide (right).

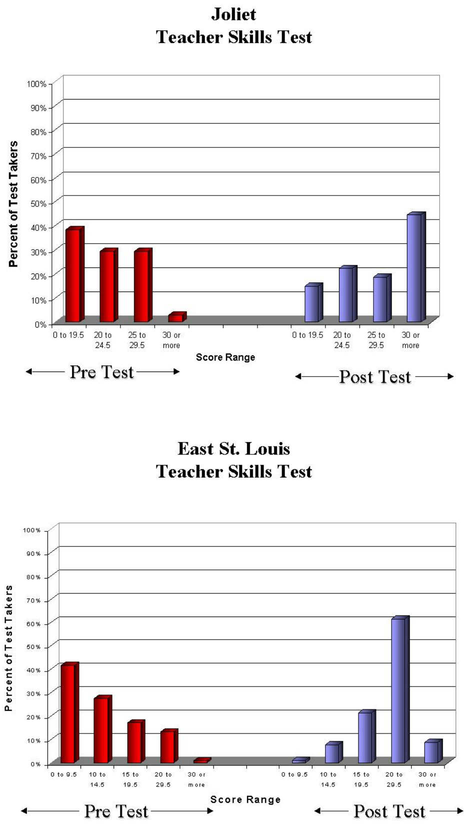

Figure 11: Pretest and post-test scores on a teacher skills test for teachers from East St. Louis (left) and Joliet (right).

School	Actual	Expected	Academy Effect
CATHER ELEM SCHOOL	33.85	1.22	32.63
MORSE ELEM SCHOOL	.	.	.
REVERE ELEM ACCELERATED SCHOOL	33.59	10.22	23.37
ASHE ELEM SCHOOL	.	-0.01	.
SCHILLER ELEM SCHOOL	25.33	8.99	16.34
SCHMID ELEM SCHOOL	15.47	-16.66	32.13
WHITE ELEM SCHOOL	3.27	-5.07	8.34
MADERO MIDDLE SCHOOL	-1.1	-39.87	38.77
ADDAMS ELEM SCHOOL	50.85	-19.71	70.56
EBINGER ELEM SCHOOL	23.71	-11.59	35.3
EVERS ELEM SCHOOL	-51.32	6.67	-57.99
GRAY ELEM SCHOOL	-5.7	-38.4	32.7
HAINES ELEM SCHOOL	41.02	21	20.02
MCCORKLE ELEM SCHOOL	28.5	-1.9	30.4
MCKAY ELEM SCHOOL	.	.	.
MORRILL ELEM MATH & SCI SCHOOL	-9.39	-31.84	22.45
PRESCOTT ELEM SCHOOL	67.92	-38.43	106.35
WHITTIER ELEM SCHOOL	.	.	.
BEETHOVEN ELEM SCHOOL	17.49	25.88	-8.39
BYFORD ELEM SCHOOL	.	.	.
JOHNSON ELEM SCHOOL	-4.71	-7.77	3.06
MARSH ELEM SCHOOL	35.15	0.11	35.04
OVERTON ELEM SCHOOL	.	27.94	.
PULASKI ELEM COMMUNITY ACADEMY	17.16	-25.39	42.55
LEE ELEM SCHOOL	-19.2	-11.73	-7.47
CARVER MIDDLE SCHOOL	3.91	-0.88	4.79
BYRD ELEM COMMUNITY ACADEMY	10	1.78	8.22
LAWRENCE ELEM SCHOOL	20.69	-6.42	27.11
RUGGLES ELEM SCHOOL	14.28	-11.5	25.78
SONGHAI ELEM LEARNING INSTITUTE	-12.58	0.6	-13.18
CARTER ELEM SCHOOL	17.79	1.97	15.82
DOUGLAS ELEM COMMUNITY ACADEMY	48.61	-0.73	49.34
PERSHING ELEM HUMANITIES MAGNET	-3.21	-29.24	26.03
JAMES WARD ELEM SCHOOL	23.26	-22.12	45.38
POE ELEM CLASSICAL SCHOOL	.	.	.
SENN METRO LIB ARTS & TECH HS	7.84	.	.
NICHOLSON ELEM MATH & SCIENCE	27.64	9.07	18.57
CHALMERS ELEM SCHOOL	33.26	-2.07	35.33
FERNWOOD ELEM SCHOOL	32.87	11.53	21.34
GRESHAM ELEM SCHOOL	22.8	7.88	14.92
HALE ELEM SCHOOL	5.14	-6.52	11.66
KILMER ELEM SCHOOL	-9.66	-30.26	20.6
MONROE ELEM SCHOOL	38.09	-45.14	83.23
PULLMAN ELEM SCHOOL	3.66	1.43	2.23
RYDER ELEM MATH & SCI SPEC SCHOOL	22.87	6.91	15.96
LANGSTON HUGHES ELEM SCHOOL	11.29	-11.77	23.06
MAYS ELEM ACADEMY	.	.	.
OWENS ELEM COMMUNITY ACADEMY	.	.	.
BETHUNE ELEM SCHOOL	4.58	-14.91	19.49
DONOGHUE ELEM SCHOOL	16.63	5.49	11.14
JUNGMAN ELEM SCHOOL	.	.	.
MOOS ELEM SCHOOL	32.06	-31.59	63.65
ROQUE DE DUPREY ELEM SCHOOL	39.53	-34.45	73.98
BRENTANO ELEM MATH & SCIENCE ACAD	44.58	-18.52	63.1
ANDERSEN ELEM COMMUNITY ACADEMY	14.95	-1.99	16.94
HERZL ELEM SCHOOL		1.16	5.84
RAVENSWOOD ELEM SCHOOL	41.94	-8.69	50.63
AVERAGE =	**17.5**	**-7.8**	**26.5**[8]
# of Positive Schools			**42**
# of Negative Schools			**4**

Table 3: 7^{th} grade science regression results for Academy Schools. Note some individual cases do not have values due to missing data.

With these techniques we were able to document a 26-point differential (15% gain) versus comparable schools attributable to the Academy's intervention while controlling for different socioeconomic conditions. Additionally, positive effects were seen in 91% of the participating Academy schools. We should point out that this methodology can be modified and adapted to work for assessing any intervention, being in no way tied exclusively to the specific TAMS programs. In addition, it allows determination of which factors are important to gains in student achievement, even in the face of high mobility, broad socioeconomic variation (e.g. Hispanic vs Afro-American populations), and other factors that make the usual assessment so difficult.

As part of the proposed research we will explore the nature and causes of the random variability that is the background for student performance data. We will treat the identified background effects explicitly in our models. In this manner this strand can be thought of as analogous to several of the other MRC's in this proposal which propose to isolate "interesting" signatures from background. This proposal will allow for the extension of these models to include additional independent variables such as program attendance rates, number of teachers receiving the program, and duration of the program as well as to individual student-level as opposed to the current measure of school-level performance. Additionally the proposed research will examine the effects on students of having certain patterns of well-trained elementary teachers. For instance, does having a few well-trained teachers in earlier years have a sustained effect in future years? Is this effect greater than having well-trained teachers later in a student's education? Does having several well-trained teachers in consecutive years produce a cumulative effect on student performance? The answers to these questions can have important policy implications in decisions involving where to apply resources in order to achieve the greatest impact.

B Determination of School Readiness for Intervention

The allocation of limited resources is an important problem in math and science educational reform interventions. A second research strand of this MRC is development of mathematical models which address the question of how to select schools in order to best utilize the limited resources available. This question is important because there are both direct and indirect costs associated with selecting for an intervention or program schools that for a variety of reasons may be unreceptive or uncooperative. In addition to the direct financial costs to the program, there are also indirect human costs associated with selecting unreceptive or uncooperative schools. These costs involve the loss of program services and benefits to equally needy children in more receptive environments. Also, when limited resources are spent in unreceptive settings, these children are denied access to the potential benefits the program can provide their schools. In effect, this line of research addresses the readiness question, that is, which schools are not currently ready, at this point in time, to benefit from the intervention program. We note that this is a problem that does not occur for the more common small pilot intervention programs, but is a problem that needs to be addressed in any program committed to systemic change in a large school system.

The TAMS program is an intensive, whole-school activity. The literature on successful professional development and organization change is clear in this area[10]; schools need to understand the purpose of the professional development activities and trust its representatives so that they will "buy-in" to the process. There are several stages of preparedness and readiness for school change and its essential that the school's stage matches that necessary for the provider's program[11]. The first part of the TAMS intervention program is to work with schools to bring them to a developmental stage where the school could benefit from the Academy's program. It is important to note that while the Academy is committed to working with schools that are among the most challenging (i.e. schools with high concentrations of low income students, historically underprivileged groups, and low levels of student achievement), unfortunately this group of potential clients is quite large (there are 500 public elementary schools in Chicago alone). Thus, it is impractical to reach all of them at any one time, and this necessitates choosing some over others. The proposed research addresses the very practical question of how to do make school selection decisions in a systematic fashion to minimize risk to Academy resources while still selecting schools with extensive needs. Early efforts along this research strand appear promising.

C Successful School Factors

The third research strand of this MRC involves quantitative identification of program factors that make schools successful. This involves quantifying the requisite level of teacher participation. There are two elements to this quantification. The first will quantify teacher participation in terms of number of teachers at an individual school to receive the program (i.e. the critical mass). The second will quantify teacher participation in terms of the number of hours of the program attended by each teacher (i.e. intensity) over a given period of time (i.e. duration).

This strand of the proposed research will allow us to directly address a number of important programmatic issues and questions. For example, how much teacher participation is needed to affect student test score performance? That is to say, does reaching 50% of total teachers in a school make a difference in student performance? Or does one need to reach 75% of teachers in a school? Or does one need to involve even a higher percentage? How much of a difference in student performance do these different levels of participation produce? Additionally, the proposed research will allow us to examine how successful one-on-one visits to teacher classrooms are in increasing students' academic performance as measured on standardized tests? The answers to these questions are important because they are generalizable to other educational professional development initiatives, and because they have serious implications for scalability and reproducibility of math and science programs in other geographical locations. Hence, the results of this strand of the MRC's proposed research should be beneficial to both policy makers and educational practitioners.

8.3 Building Schools' Internal Capacity for Data-driven Improvement

In order to induce change in educational systems it is crucial to translate beneficial research into effective practice. A second component of this MRC focuses on timely and expeditious transfer of research results to individual school communities. Teachers and school administrators rarely have the expertise, tools, or personnel to help them analyze data[7]. As a result they rely on intuitive decision-making much more often than other professionals do in similar sized organizations[8]. As part of the proposed MRC the Academy will initiate a pilot project in 3 schools. The objective of this pilot project will be to implement a process that will assist schools in the development of their own internal capabilities to use data for decision-making.

Many educators still have little experience using and looking at data.

Principals and teacher leaders will be assisted by the Academy's School Data Specialists in how to use data to assess needs. The pilot project will also be designed to facilitate an inquiry cycle using the newly acquired data sets; as well as assist the principals, teachers, school board members, and other school leaders in using data to develop school improvement efforts that are tied directly to teaching and student achievement. This will give principals and teachers the opportunity to development their ability to gather, analyze, and use data in an appropriate manner. The process[12] will begin with the development of a 'dynamic school profile'. This profile will contain templates, tools and processes that can be used by schools to guide their improvement efforts. It will contain guiding questions and specific elements, trends and needs that staffs and stakeholders could look for in the data. As a result, schools will develop an effective school improvement plan, and an increased capacity to continually use data to improve student achievement. From the results we achieve in the pilot, we will seek funds to modify and adapt this into a well-documented and publicly available program scalable for a larger number of schools, supported by State, other Federal (non-JCET), or private funds.

8.4 Synergies

The statistical tools, presentation and interpretation of data, and the infrastructure necessary for handling of large data sets have much in common with those used in physics data analysis. In fact, the availability of powerful computing facilities available to us through several of the other JCET institutions will give us the ability to create the initial master data sets much faster and more efficiently than on our own. In addition, University of Chicago and Fermilab physicists have been closely involved with this effort through the TAMS Program Committee, on which they serve. This close cooperation has already proved to be highly profitable for both those that come from an education background and from a physics background. Some of the regular seminars of JCET will be devoted to statistical and educational topics; the exposure of young physicists (including the undergraduates at the JCET institutions) to this will, in our experience, induce further involvement and outreach in their subsequent careers. Additionally the Academy works with schools in locations geographically close to all the universities and national laboratories involved in this collaboration, allowing for interaction between the physics and educational components of the Center. The Center will also be an arena in which visitors from all over the country will be introduced to effective math and science education and cutting-edge educational research.

8.5 Summary

In summary, the research strands of this MRC address questions of how to measure the impact of a math and science program in a rigorous statistical manner, how to select potential sites while minimizing the associated risk, and how to quantitatively determine the essential factors in a school necessary for systemic improvement in student performance in mathematics and science. Additionally, this MRC addresses the need to transfer this research to practice and build research capacity within individual schools themselves. The Academy believes that, taken as a whole, this research will make a substantial and unique contribution to the educational research literature as well as to practitioners, policy makers, and the public at large. Furthermore, it provides a unique opportunity to involve research scientists and science students, both graduate and undergraduate, in the realities of the complex challenges (and possible solutions) of math and science education in urban elementary schools.

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9 Outreach

The institutions represented in this proposal are in a unique position of having long-standing and deep ties to a large urban school system. The PI is one of the founders of TAMS, a state-funded organization devoted to whole school change in the teaching of mathematics and science at the K-8 level in an urban environment. TAMS has shown quantitative substantial gains in test scores on average in the schools in which it has been involved. The University of Chicago and Fermilab are still strongly involved in the TAMS operations. There are two faculty members from UC on the Board of Trustees (Frisch and David Oxtoby, who is Dean of the Physical Sciences Division); Herman White from Fermilab is both on the Board and is Chair of the TAMS Program Committee, on which Frisch and Oxtoby also serve. The role of TAMS in 'Education, Human Resources, Diversity, and Outreach' is described in some detail in MRC-F; we refer the reader to that section for the major thrust of JCET in this area. Based on the results and impact on the state-level here in Illinois, we believe that with the effort described in MRC-E, JCET has the possibility to make substantial improvements in the delivery and effectiveness of math and science education on a national level.

Beyond our strong efforts in teacher training, we will pursue an initiative which has not been possible on an institution-by-institution basis, but could be done under the umbrella of the PFC. The number of minority students who enter physics is tiny. We would like to identify exceptional minority high-school students in the Chicago-area schools and hire them in the summer to work with the experimental groups in this proposal. We have a proof that this can work from one example; one of us (Frisch) learned of an exceptional student from the Director of TAMS, who heard him deliver the valedictory speech at his 8th grade graduation. The student was hired for the summer to measure cross-talk in CDF trigger cables, which he did creatively and superbly. He then worked for several summers more with the UC group, maintaining contact during the school year as well. He is now entering UIC, with the intent to get a PhD in nanotechnology. As he comes from one of the worst neighborhoods in the city, there is every reason to believe that this experience can be repeated and expanded.

Finding and keeping in touch with such remarkable kids is not easy. We have the contacts necessary to do so. Mentoring them is also very time-intensive; there are many stresses and pressures on their lives to pull them away from their goals. With a consortium of institutions we can form a critical mass, and the overhead of identifying and tracking the students can be pooled. The main emphasis would be on teaching them electronics and computing as skills, along with the healthy scepticism and enthusiasm that jointly come with being a physicist, while at the same time maintaining ties to their local communities.

There are also ongoing individual efforts at each of the institutions. These will benefit from the interaction fostered by JCET's heavy involvement in education, in particular through the contacts made through TAMS with an exceptionally large cohort of teachers and students, and with the business community of Chicago through the TAMS Board of Trustees.

For example, U. Chicago and Fermilab are also active members of QuarkNet, which involves high-school science teachers in High Energy research. Through TAMS we have made additional contacts with teachers in the Chicago public schools, and are working to involve them with QuarkNet.

The University of Illinois Department of Physics has a long-standing and strong commitment to community outreach. Willenbrock has run the Department's "Saturday Physics Honors Program", a series of Saturday morning presentations for high school students given each fall. Both Liss and Willenbrock have been regular presenters. We anticipate that the activities of the Center, both in Urbana and elsewhere, will dovetail nicely with existing Illinois outreach programs, providing a natural pool of actively engaged and interested people to turn the local high school students on to the excitement of forefront research in physics. The Illinois Physics Department has also been heavily involved with the Illinois Science Teachers Association, and the faculty, including Liss, have been regular participants in ISTA conferences. The existence of the Center will provide a natural way for us to widen the pool of participants beyond faculty at U of I.

NIU plans on expanding its outreach effort to the area of increasing the awareness of Fermilab's activities to communities in the northern Illinois region which may be impacted by possible extensions of the Fermilab program. Starting in Summer 2001, NIU graduate students with an interest in education will be employed using state funds to work on developing brochures, posters, videos and other materials which can be distributed when visiting schools or community centers. This will be coordinated with previous and continuing activities at Fermilab and other Illinois universities.

The high energy theory group at Northwestern University has been pioneering the use of the world-wide-web for classroom learning and educational outreach. The Virtual Physics Laboratory is a developing collection of physics applets for use both in undergraduate physics instruction and educational outreach. This Java applet collection is visited by hundreds of students a day, and has received unsolicited positive feedback from both high school teachers and University professors from around the world. The Virtual Physics Laboratory can be found at:

http://www.physics.nwu.edu/ugrad/vpl/index.html

We plan to incorporate the Virtual Physics Laboratory as one of the major outreach components of an interactive JCET web-site. Development of web-based resources related to JCET activities will help us to draw in and involve talented students, while simultaneously increasing the visibility of JCET in the local, national, and international community.

JCET can play an important role in growing and strengthening these activities at each of the individual institutions, as well as providing a center where educators, scientists, statisticians, teachers, and undergraduate and graduate students from many institutions can interact through seminars and discussions.

10 Synergies and Common Infrastructure

Each of the MRC's in our proposal is intimately related to the others. The searches for both the Higgs and supersymmetry depend on understanding the Standard Model backgrounds of top and gauge boson production. The development of systematic strategies and statistical tools for signature-based searches cuts across all the work. Many of the questions, such as the presence and kinematic properties of b-quarks in complicated final states, are in common. The emphasis on precise Standard Model calculations, as the necessary understanding to discover new physics, highlights the need for overlapping efforts between physicists with a broad set of skills and experience. The Monte Carlo development will also be in common, exploiting the stable infrastructure of the Center. The boundaries between research groups will be kept fluid, to maximize the synergies, flexibility, and overlap of Center activities. Weekly MRC group meetings, joint seminars, and informal workshops, will also help ensure that JCET functions as the physical locus of the on-going research. A strong visitor program gives us the opportunity to invite selected experts to assist on specific problems, calculations, or development of analysis tools.

JCET will provide an environment where students and postdocs will be exposed to a much broader view of particle physics and physics education than is available in each of our universities separately. The Center provides a mechanism to introduce our students, both graduate and undergraduate, experimental and theoretical, to the leading theorists interested in experiment from departments all over the country. It also provides a unique opportunity for theory students to learn the realities and complexities of experiments and data analysis.

JCET will be housed at the Enrico Fermi Institute of the University of Chicago; this is where seminars and meetings would be held, where all of us, including those from other institutions, would have dedicated offices and computer facilities, and where financial and logistical support would be located. Among other possibilities, existing space close to the experimental group could be renovated to provide 8 offices of 3 desks each in the HEP building; nearby space can support 3 or 4 more such offices. The building has an excellent conference room for seminars on its 3rd floor. The building is wired for ethernet; high band-width links to Fermilab (for Collider data) and Argonne (for computing and data storage) are already installed. The University, which manages Argonne, has encouraged use of Argonne's computer facilities; we will explore JCET use of these for the TAMS data analyses.

National Scope: The Center is intended to be a resource to universities across the nation, empowering the faculty at each by giving them access to Center-developed analysis tools, technical expertise, and interaction with a wider group working on the same problems. The universities in our consortium already benefit from proximity to Fermilab, where the experiments will be running for the next 5 years. The Center will provide the opportunity for physicists from more distant institutions to visit for a semester or quarter, in a university-based Center environment that is also within easy reach of the experiments.

The health of the theoretical community interested in measurable phenomena has been of concern in the field. Recent exciting developments, relating powerful ideas from string theory to phenomena which may be directly accessible at TeV colliders, have created an opportunity to strengthen the university-based data-driven community. There are fundamental questions being addressed, with exciting experimental prospects.

Fellowships: An essential element of the Center will be Fellowships and internship programs. These will include graduate fellowships for students interested in the intersection of frontier theory and experiment, and post-doctoral fellowships for young scientists working on theoretical problems that interface with data and thus require longer time-scales. Each of these is under-represented in our field, and is an area with which we have already been involved. The prestige and exposure of a widely-advertised fellowship, much like the Fermi Fellowships at Chicago, will help bring in excellent candidates at each of these levels. We propose the following fellowships:

1. **The Robert G. Sachs Fellowships in HEP:** 6 post-PhD 5-year fellowships in fundamental physics, either theory or experiment, but with the focus on work that can benefit from the added time and access to Center physicists;

2. **The Maria Goeppert-Mayer Graduate Fellowships:** 8 fellowships for incoming admitted graduate students at any of the participating institutions.

Each of these will be widely advertised, and competitively judged by a committee consisting of one representative from each participating institution. Special emphasis will be put on attracting candidates who are women or members of other under-represented groups.

In addition to the Fellowships, we will have internship programs for under-represented groups, both from high school and from college. **The JCET High School Summer Interns Program:** 6 summer jobs for urban high-school students; **The JCET Undergraduate Interns Program:** support for 6 undergraduate students 12-15 hours a week during the year, and summer.

11 Shared Experimental Facilities

The purpose of JCET, of course, is to allow universities to fully utilize a national experimental facility, Fermilab, whose use is shared by many universities and institutions around the world. It is the proximity of our four universities to Fermilab and the Tevatron Collider, which will be the highest energy accelerator in the world until the LHC comes online in 2006, that is the main motivator of this collaboration. Because the thrust of this proposal is to strengthen the theoretical infrastructure needed to exploit the physics at Fermilab, no other shared experimental facilities are being proposed to be established, unless one includes the physical location of JCET and the computing infrastructure among all the institutions.

JCET will be located at the Enrico Fermi Institute of the University of Chicago; this is where seminars and meetings would be held, where all of us, including those from other institutions, would have dedicated offices and computer facilities, and where financial and logistical support would be located. Existing space close to the experimental group could be renovated to provide 7 offices of 3 desks each in the HEP building; a large open space on the north end of the building surrounded by windows would support an inviting place to sit and discuss, with couches, comfortable chairs, tables, and black-boards. Two carrels of four computers each in the room would provide a place for undergraduates and day visitors to work. This is an interesting reversion to the previous use of the room; before terminals were in individual offices, we found that a communal computing room fostered a great deal of interaction between members of different experimental groups.

The building has an excellent conference room for seminars on its 3rd floor. We are considering adding a smaller meeting room on the 2nd floor to accomodate the extra load of meetings and discussions from JCET. At present teleconferencing is done through an older setup with a relatively small screen in an adjacent building of the Enrico Fermi Institute; we plan on adding additional capability for JCET in one of the two rooms mentioned above.

University architects have looked at the preliminary plans, and have estimated the renovation costs. The plans and even the costs have received a positive response so far in negotiations with the Dean's Office.

The HEP building is already wired for 100-base-T Ethernet; high bandwidth links to Fermilab (for Collider data) and Argonne (for computing and data storage) are already installed. The University, which manages Argonne, has encouraged use of Argonne's computer facilities; we will explore JCET use of these for the TAMS data analyses.

Maintenance and operation of the physical facilities will be managed through the Enrico Fermi Institute and the University exactly as is done at present. The computer infrastructure at UC will be maintained by an additional computer person, working for the present HEP system manager. We have requested 0.5 FTE on this proposal, with the other 0.5 FTE to be provided by the University. We are presently running more than 50 nodes; the additional 25 or so for JCET will not make any qualitative changes in the operation, other than the load involved with having many visitors with different habits and desires.

12 Collaborations with Other Sectors

JCET is a collaboration of four universities (the University of Chicago; the University of Illinois, Urbana-Champaign; Northern Illinois University; and Northwestern University) a 501-C3 (not-for-profit) organization (TAMS), and two national laboratories, one of which is multi-purpose (Argonne) and the other focussed on High Energy Physics (Fermilab). In addition JCET will serve as a national and international resource for other universities and institutions working on analysis of data at Fermilab and the LHC.

The Teachers Academy for Math and Science has extensive and close connections with several other sectors not commonly available to most working scientists. Co-PI Lourdes Monteagudo is a member of the Illinois State Board of Education, and has served as Deputy Mayor for Education of the City of Chicago. The Board of Trustees has connections to other educational institutions, with active members from the Archdiocese of Chicago, the Chicago Public Schools and the Chicago Academy of Sciences. The biggest sources of teachers coming into the Chicago system are represented also with Trustees from Chicago State University and Roosevelt University.

The Board of Trustees has on it major figures in the business world of Chicago, such as Robert Malott (former CEO of FMC Corporation), Richard Morrow (former Chairman of Amoco), and Carolyn Murphy (former Senior Vice-President of CNA Insurance) who play a very active role in policy.

The discussion of reform of science and math teaching policy, the focus of TAMS, thus takes place in a broad context with participants representing both stakeholders and those in positions to change policy at the City and State level. This allows unique opportunities, such as the access to the large datasets described in MRC-F, the fruitful collaboration with Yakov Avichai, the former Corporate Statistician for the CNA Insurance Companies, and the testing of techniques at new sites such as in East St. Louis, Aurora, and

Joliet, which was done at the request of the State of Illinois. The involvement of TAMS in JCET should lead to more such opportunities involving the other JCET institutions and the other educational, business, and govermental organizations represented on the TAMS Board.

13 International Aspects

Because High Energy Physics is highly international, we have begun exploring possible connections to strong university groups with similar interests abroad. Our thoughts are: 1) to broaden the pool from which we search for the 'best and brightest' applicants for graduate and postgraduate fellowships; 2) to attract students into the field by broadening the scope on which we advertise the existence of these fellowships; and 3) to tap into theoretical expertise that exists elsewhere. In return, we can offer the international community opportunities for working on highly exciting physics, including graduate student training at the Tevatron at a time when CERN has closed down the LEP accelerator and is building the LHC. The opportunity at the Tevatron to take data, analyze it, and extract physics could play an important role in the continuing development of an international view of accelerator usage in Europe, the FSSR, and Asia in the next 5 years. The Tevatron is the training ground for the LHC, and there will be at least one generation of European graduate students who would greatly benefit from being on running experiments at the Tevatron.

In addition, the ties that are created during this next 5-year period by Europeans coming to the US will serve us well during the LHC era, as it will then be at CERN and other European institutions that American graduate students will get their training. Close ties with several first-rate European universities could allow a sharing of graduate student education that would be much richer than just sending students to the laboratories alone (much of one's education depends on the sharing of learning with fellow students, we believe; close ties to other students on a broader basis has to be a good thing, as well as the contact with a broader spectrum of more senior physicists).

To understand the issues and gauge the reaction from other countries to the JCET proposal, we have made initial contacts with a few institutions we believe could be interested. If JCET is approved we envisage possibly widening these contact to include several more universities in Europe, the

FSSR, South America, and Africa. We have had substantive conversations with Nicola Cabibbo, Carlo Dionisi, Lucia Zanello, and Fabio Zwirner from the University of Rome, and Giorgio Bellettini from the Scuola Normale in Pisa. They have expressed strong interest and support, and we are exploring modes of operating that would allow us to collaborate on areas in the MRC's of common interest. In addition, we have been in contact with Lev Okun of ITEP (Moscow) in similar discussions, again with a very positive reaction to the goals and style of JCET. In each of these cases the hoped-for dominant mode would be to have visitors and to advertise widely in these countries for applicants for the Fellowships.

At this point we do not propose to enter into formal agreements with any international institutions. In the expected case that one or more of these collaborations pans out, however, we would add appropriate members to the Fellowship and Visitor Committees from these countries. More formal agreements could be made at a later time if circumstances make them appropriate.

14 Management

The grant would be administered by the PI through the Univ. of Chicago Office of Sponsored Research, as is now done for the present NSF HEP grant, with subcontracts to the other institutions (unless the NSF prefers to deal directly with each institution). Frisch has recently stepped down as PI of the HEP grant, and would be willing to assume the responsibility of the PFC; the level of effort in administrating the PFC should be comparable to that of the umbrella grant (the amount of money and number of people involved are comparable, although there are no theorists on the HEP grant). We are requesting 30% of an 'FSR', a person in our Local Business Center who provides faculty accounting support. This request is based on a University policy in the Physical Sciences Division; the justification of this is given in NSF Bulletin 94-15.

Decision-making would be by consensus, as is done both in the big experimental CDF and D0 collaborations and, for example, among the eight Co-PIs of the UC grant, with one Co-PI of the PFC per institution participating. We anticipate there will be regular (but not frequent) meetings to discuss major issues and decisions after the initial startup. We are well-used to cooperating using Email and video-conferencing, and as we are close meetings are not difficult.

To keep the focus, we anticipate not having all institutions having the same level of support at the same time, with the time-average being equitable. Priorities will be determined by physics considerations, again as is done in the collaborations we are familiar with. These will be the hardest decisions we will have to face, but we are confident that they can be worked out amicably (the experience with the UC HEP grant has shown that it can be done, even with too much demand for too few resources).

We envisage having just two committees, one for Fellowships, and one for Visitors. Each would have a Chair, chosen by the Director in consultation with the co-PI's, and one person from each JCET institution. The terms would be of one year. The duties of the Fellowship committee would be to widely advertise the Fellowships, rank the applicants, and select the Fellows. The Visitor committee is to to provide balance and breadth to the acceptance of applications from visitors to JCET.

We have considered having a Board of Trustees and a Visiting Committee, but have come to the conclusion during the preparation of this proposal that we are a broad group with plenty of diversity, and will thus provide our own checks and balances. This will save significant time and money. We will make the annual review by the NSF a time of detailed presentation of the activities of the Center as we do for the Chicago umbrella grant– this has proven very valuable in the past for determining strengths and weaknesses.

15 Results of Prior NSF Support

We summarize here only the research supported by the NSF, as requested. However we note that there are other results obtained by members of this proposal with funding from a wide variety of sources that are germane to the expertise needed for JCET.

15.1 University of Chicago

Of the theory faculty on this proposal funded through Chicago, Harvey is supported by the NSF, and Rosner by the DOE. The major findings of the research of J. Harvey over the last few years are:

1. The discovery of an important consistency condition for M theory, the

theory that unifies all string theories. In particular, the mechanism for canceling inconsistencies (anomalies) of the M theory fivebrane was discovered and applied to problems of black hole entropy and the physics of what are called “little string” theories which involve string like excitations of the fivebrane.

2. A new algebraic structure in string theory based on interactions of BPS (supersymmetric) states was discovered. This structure and the mathematics needed to formulate it has played an important role in the study of string compactification.
3. The use of techniques of non-commutative geometry to simplify and broaden our understanding of D-branes in string theory. In particular, it was shown that D-branes can be constructed exactly as solitons of open string field theory, and that this clarifies why the charges of D-branes are classified by K-theory.
4. A number of additional topics were also investigated including non-perturbative effects in M theory, the role of anomalies in D-brane physics, the application of string coupling duality to non-supersymmetric string theories, and the formulation of string models with few moduli.

Some of the major experimental results from prior NSF support at Chicago in which Frisch has played a strong role are: the discovery of ‘direct leptons’ (one of the first signs of the charm quark), the first measurement of the intrinsic internal momentum of quarks inside the proton, one of the first measurements of ‘anomalous’ hadron production at large P_T (one of the first signs of point-like structure), the best limits at the time on the flux of magnetic monopoles, the invention of large superconducting coincidence detectors, the invention of large-scale superconducting gradiometers, the construction and operation of the Level 1 and Level 2 calorimeter triggers and the trigger framework for CDF, the construction and operation of the ‘Beam-Beam-Counter’ luminosity systems for the CDF detector at Fermilab, the development of the CDF ‘Express Line’ (the mode of rapid access to the data for CDF), the precision measurements of the W boson mass and width, including the first direct measurement of the width, the discovery of the top quark (Frisch supervised two Ph.D theses and played a role in the ’Evidence’ paper and the trigger and data definition), the revival of interest in photons as a signature of supersymmetry through studies of anomalous events and signature-based searches, and the construction and commissioning of the new

Level 1 trigger and critical parts of the innovative SVT system to trigger on b-quarks for Run II. Frisch has been a Co-convenor of the Electroweak, Exotic, and Trigger Groups of CDF, and is presently a Co-convenor of the 'High-Level Objects' group for Run II.

Prior NSF support has also resulted in the education of a number of first-rate young experimentalists; recent former students and postdocs from the UC CDF subgroup are now faculty members at Illinois, Maryland (2), Michigan (3), Texas A&M, UT Austin, Rutgers, UCLA(2), UC Santa Barbara(2), and the University of Athens, as well as Wilson Fellows at Fermilab(2), and a DESY Fellow. Two of these started as undergraduates with the group. A list of the postdoctoral alumni from all of the experimental subgroups on the NSF grant in the last 13 years, with their current positions is given in Table 4. A large number of undergraduates have been supported both by the NSF 'umbrella' grant and by the UC REU program. The lively and intense intellectual environment inside the EFI is perhaps part of the success of so many of our students and postdocs (their natural talent is of course the main factor).

15.2 Northern Illinois University

The NIU high energy experimental and theoretical high energy physics efforts are supported in part by NSF grants.

Since 1995, the research effort of Hedin has been supported by the NSF, under contract PHY-9803785. Hedin's primary research activity is the DØ experiment at Fermilab. The DØ detector is a large, general-purpose detector designed to take full advantage of the energy of the Fermilab proton-antiproton collider. Data collected from 1992 to 1996 (Run I) have produced over 90 published papers. These papers describe the discovery of the top quark and measurements of its properties, searches for new phenomena such as leptoquarks and quark compositeness, high-precision measurements of the W and Z bosons, and QCD studies of light and heavy quark production and fragmentation. During Run I, Hedin had the primary responsibility for muon software and identification, and was the coordinator of the B physics group from 1991-1994. More recently, he was the primary author on papers which used the channel with 2 b quarks and missing energy to search for charge-1/3 third generation leptoquarks and scalar bottom quarks. Since 1997, Hedin's major emphasis has been the upgrade of the DØ detector. He has been responsible for constructing new trigger elements for the muon system and is co-convenor of the muon identification group. An important aspect of this effort has been the involvement of ten graduate and sixteen undergraduate students during the previous five years. Undergraduate research has been supported by the NSF REU program, and Fermilab and University funds, and has included projects such as the design and construction of components of the muon upgrade and new silicon detector and software development. About 60% of these students are now in graduate programs in physics, engineering and biology while the remainder are either high school teachers or employed in industry.

The research effort of Martin has been supported since 1999 under contract PHY-9970691. Martin's primary research efforts have been in the areas of supersymmetry phenomenology and theory. His achievements during this time have included a comprehensive study of the signals for gauge-mediated supersymmetry breaking and related low-scale supersymmetry breaking models for Fermilab's Tevatron in Run II, written with co-PI Culbertson and others. Martin has shown that dimensionless (hard) supersymmetry-breaking terms can play a crucial role in determining the correct vacuum in supersymmetric models. This leads to new possibilities for simultaneously solving the μ problem, the strong CP problem, and the problem of the origin of R-parity. In a related paper, he showed that models of this type can have a rare but potentially spectacular signal at the Large Hadron Collider from delayed decays of neutral fermions into visible states. His most recent work is a thorough study of the possibility that supersymmetric gauge theories can be governed by ultraviolet-stable fixed points. This provides for a possible solution to the supersymmetric flavor problem, and in some circumstances could lead to collider signals which are qualitatively similar to gauge-mediated models.

15.3 The Teachers' Academy for Math and Science

The Teachers' Academy for Math and Science (TAMS) was founded in 1990 with NSF and DOE funding. To date, the Academy has worked with 114 elementary schools in Chicago and four other urban centers in Illinois in an intensive teacher retooling program that emphasizes whole-school change and long-term followup. Quantitative assessment has shown an improvement in student test scores in 91% of the schools. The State of Illinois has taken over support of TAMS at the 6.5M$/year level; at their wishes the Chicago operation has been expanded into other urban centers, in particular East St. Louis, Aurora, and Joliet. TAMS has formed a forum where state, business, education, scientists, the national laboratories, and community leaders regularly discuss and evolve policy for math and science education in Illinois. A much more extensive discussion of the results of TAMS, which would not have been created without NSF support, is given in MRC-E.

16 Budget Description

Budget Description

We have prepared budgets for Years 1-5, presented in the Summary Proposal Budget Form 1030. We have simply budgeted the out-years by a 3% increase in the direct costs of personnel over those in Year 1 to allow for inflation. In what follows we describe the entries line-by-line.

A. **Senior Personnel** No costs are requested for support of the 18 senior personnel at any of the 7 institutions.

B. **Other Personnel**

   (a) **Postdoctoral Associates** This item is to fund the 3 PFC Senior Fellows who will be resident at UC. These 5-year positions are, in general, for accomplished postdoctoral theoretical physicists who do not yet have a faculty job, but are some years past the Ph.D. We have assumed a salary of $70K per year, comparable to a good junior faculty job. We intend this very visible and prestigious position to be a highly-successful feeder for faculty jobs, as are the Enrico Fermi Fellowships at the Institute. The costs for three other PFC Senior Fellows, one per university, are listed under ‘Subawards’ below. No ‘usual’ postdocs will be funded by the Center; these will be funded from current other support.

   (b) **Other Professionals** We have requested 0.5 of an FTE computer system manager to install, maintain, and assist Center personnel and visitors with the computer cluster system here. We have found that new personnel often have custom software or individual computing habits, and it is labor-intensive to make them comfortable and productive on a new system (we run Linux on PC's, for example). We will support the other 0.5 FTE from other funds.

(c) **Graduate Students** We have requested support for 6 graduate students at UC; the costs for 3 additional students at the other institutions, one per university, are listed under 'Subawards' below. We will institute Graduate Fellowships to attract top students interested in both experiment and theory to the Center.

(d) **Undergraduate Students** These funds are to support 9 PFC undergraduates who would be strongly involved with ongoing research in physics and in education at the Center. Previous undergraduates working with the UC CDF group have been very successful, for example publishing in Physical Review Letters, and becoming tenured physics faculty at universities, among other successes. At present we turn away many undergraduates due to lack of funds and supervisory time; the Center will have the resources to mentor a group this size. We assume 8$/hr, and 15 hrs/wk for 32 weeks (school year), and 37.5 hrs/wk for 10 weeks (summer).

(e) **Secretarial, Clerical** This item is for 0.5 FTE secretarial help. We assume 18$ per hour, based on present pay scales at UC.

(f) **Other** The dominant item here, $169,000, is for Center Visitors. We assume that there will be 3 senior (e.g. senior faculty at other institutions) visitors per year, each for 6 months. We would pay half salary for these. We similarly assume that there will be 3 junior (e.g. junior faculty at other institutions) visitors per year, each for 6 months. We would pay 3/4 salary for these. In addition we will support 3 PFC High School Interns at the Center; we have assumed 7$/hr for 10 weeks of 37.5 hrs/wk during the summer for each. Lastly, we have included $11,200 for 0.3 of an FSR (Faculty Service Representative) to administer finances, orders, etc. for the Center.

C. **Fringe Benefits** Fringe benefits at UC are calculated at a rate of 20.6% for the first year. Successive years assume a 0.5% increase per year in the rate.

D. **Equipment** We have requested funds for 15 PC's running Linux for new Center personnel and visitors. These will be clustered along with our present cluster of more than 40 nodes in the HEP building. The cost per station of \$3000 includes enough disk to hold large datasets locally on the user's 'desktop', a good monitor, and enough memory to run Pythia and detector simulations efficiently. Because each PC costs less than \$5000 these are normally charged as supplies; we have negotiated with the University that a single purchase of identical machines that are to be clustered for the same purpose can be charged as equipment if the total is over the (federally mandated) 5K\$ threshold.

In addition we have requested \$10,000 for video conferencing equipment.The Enrico Fermi Institute currently has a small video-conferencing setup bought on UC seed money, but the Center will rapidly overload it. The technology is changing rapidly in this area, and it is not clear what will be the way to go at the time of a future decision. We have guessed that 10K\$ is appropriate for a wall-sized display and projection system with connections to a dedicated PC and/or the Internet.

E. **Travel** We have requested funds for 15 domestic trips to attend conferences at 1K\$ each. In addition we have requested 15K\$ of domestic travel for seminar speakers. We have requested 5 foreign trips at 3K\$ each for young Center physicists to attend foreign conferences.

F. **Participant Support Costs** This item would support 2 LHC-Junior Fellows, young European physicist visitors working on the LHC experiments who wish to get experience with real data and data-taking at the Tevatron. Funds are requested for 3K\$ per month each for living expenses; 3K\$ per visitor is also requested for domestic travel. Foreign travel and some fraction of base salary would be paid by the appropriate foreign institution. The connections made here will pay off in the future when LHC data-taking begins.

G. **Other Direct Costs**

   (a) **Materials and Supplies** The largest item here is 40K\$ for computer peripherals, networking devices, computing supplies (printer paper, media, etc.). We estimate 20K\$ of office supplies, Xeroxing costs, etc. We have requested 20K\$ for software licenses, software maintenance and some minimal hardware maintenance (e.g. on printers). In addition we estimate other miscellaneous maintenance (e.g. Xerox machine, teleconferencing equipment, fax machines, etc.) at 5K$.

(b) **Publication Costs** We have requested 20K$ for page charges and outreach publications and literature for schools and students.

(c) **Consultant Services** The budget includes 9K$ for a contract with S.T.A.G.E.S, a Chicago firm experienced in urban math and science education reform and which works closely in the high schools, that will help us find a pool of top high school candidates for the PFC High School Intern program.

(d) **Computer Services** None.

(e) **Subawards** The proposal includes subawards in the first year of $431,960 for the Teachers' Academy of Math and Science, $335,371 for the University of Illinois at Urbana–Champaign, $336,000 for Northern Illinois University, and $xxx,xxx for Northwestern University. The TAMS subaward breaks down as follows: costs for Senior Personnel: none; Other Professionals: 4 data analysts at $44,000 per year to work with the large new datasets from the City and State; 1 secretarial position at $29,000. Fringe benefits at 24% come to $48,960. The total of salaries, wages, and fringe benefits is $252,960. The request for equipment is for 4 PC's at 3K$ each, plus 2K$ each in peripherals and networking, and 2K$ each, in commercial statistical software packages and other commercial software, totaling 28K$. Domestic travel (for conferences, largely) comes to 14K$. Participant support for 20 participants in PFC workshops and conferences is 20K$. Materials and supplies are estimated to be 20K$; publication costs 2K$. There is a substantial budget of 75K$ for consultants in corporate-world statistics, psychometrics, organizational change, and leadership development. Other costs estimated at 25K$ are associated with the school-based data-driven program. Indirect costs are calculated at 30%; these will be paid by TAMS from State and other sources, and are not charged.

The other three subawards are to UIUC, NIU, and Northwestern. Each contains 30K$ for half-salary for 6 months of a senior PFC visitor, and 26.25K$ for three-quarters-salary for 6 months of a junior PFC visitor. The PFC Fellow at each institution has a salary of 70K$; we assume the graduate Student Fellow costs 19.2K$ in base salary. We also include one undergraduate and one High School intern per institution, at the rates described above. We have used the correct fringe benefit rate and indirect costs at each institution. For materials and supplies at each institution we take 3 computers at 3K$ each, 5K$ of office supplies, xeroxing, etc., 5K$ of computer peripherals and supplies, 4 K$ for communications, 0.5K$ postage, and 3K$ publication costs.

(f) **Other** This item is the tuition for 6 graduate students at UC. Tuition is charged at 62.5% of the stipend, per prior agreement with the NSF by the Division of Physical Sciences.

H. **Total Direct Costs** This is the sum of A through G.

I. **Indirect Costs** The indirect rate is 51% on a base of 947K$. In addition, each subaward is charged at an indirect rate of 51% on the first 25K$ (i.e. about 12.5K$), for a total of 51K$ for the 4 subawards.

J. **Total Direct and Indirect Costs**

K. **Residual Funds** None

L. **Amount of this Request** The total is $x,xxx,xxx for the first year. Subsequent years have been calculated with a 3% increase in salary, and the assumption that fringe and benefits and overhead rates increase by 0.5% per year.

M. **Cost sharing Proposed Level** The total proposed cost sharing for the first year is $xxx,000. This consists of $260,000 from the University of Chicago (see accompanying letter of support from David Oxtoby, Dean of the Physical Sciences Division), $242,128 from TAMS (see accompanying letters of support from Lourdes Monteagudo, Executive Director and Leon Lederman, Chairman of the Board), and $66,661 from NIU, $50,306 from UIUC, and $xx,000 from Northwestern University (see accompanying letter of support from David Buchholtz, Chair of the Physics Dept). As no funds go to ANL or Fermilab we have not asked for matching funds from these Laboratories, but we have support in kind from them (see accompanying letter of support from Michael Witherell, Fermilab Director).

Name	Title	Institution	Date Left UC
Ray Culbertson	Wilson Fellow	Fermilab	1/00
Douglas Glenzinski	Wilson Fellow	Fermilab	9/99
Tsuyoshi Nakaya	Assistant Professor	Kyoto University	9/99
Peter Wilson	Wilson Fellow	Fermilab	6/99
Aaron Roodman	Assistant Professor	SLAC	8/98
Andre Turcot	Research Fellow	University of Michigan	8/98
Harold Evans	Assistant Professor	Columbia University	9/97
Milciades Contreras	Financial Analyst	Bank of America	9/96
Elliott Cheu	Assistant Professor	University of Arizona	9/96
David Wagner	Research Associate	University of Colorado	7/96
Greg Sullivan	Assistant Professor	University of Maryland	9/95
Sarah Eno	Associate Professor	University of Maryland	8/93
Marshall Miller	Research Associate	Inst. of Transp. Studies, UC Davis	2/93
Sunil Somalwar	Associate Professor	Rutgers University	12/92
Joseph Kroll	Assistant Professor	U. Penn	11/92
Tony Barker	Associate Professor	University of Colorado	7/92
Mike Roney	Assistant Professor	University of Victoria	10/91
Claudio Campagnari	Associate Professor	UCSB	9/91
David Strom	Associate Professor	University of Oregon	9/91
Rene Ong	Professor	University of Calif., Los Angeles	7/91
Hitoshi Yamamoto	Professor	University of Hawaii	1/91
Tony Liss	Professor	University of Illinois	3/89
Myron Campbell	Professor	University of Michigan	10/89
Jay Hauser	Associate Professor	UCLA	6/89
Dan Amidei	Associate Professor	University of Michigan	7/88
Yau W. Wah	Professor	University of Chicago	10/87

Table 4: Former UC experimental postdoctoral Research Associates within the last 13 years, current position, and date they left.