UNFINISHED BUSINESS IN PARTICLE PHYSICS

J. Rosner – University of Chicago – March 31, 2011

Great progress in past 50 years in consolidating results of particle physics into a "Standard Model."

Then: A small "zoo" of particles could be listed on wallet cards: neutron, proton, pi meson, "strange" relatives

Four fundamental forces: strong, weak, electromagnetic interactions; gravity. Weak interactions violated parity (mirror symmetry).

Now: we understand over 400 particles in terms of a few basic constituents. Weak and electromagnetic forces are unified. We see and understand CP symmetry violation.

Today: Where we stand; some unsolved questions

- What distinguishes weak interactions from electromagnetism?
- What explains the pattern of quark masses and couplings?
- Why does the Universe have more matter than antimatter?
- What makes up all but 4.6% of the Universe?

IN MEMORY OF BRUCE WINSTEIN

Bruce's tireless and unselfish devotion to his colleagues and physics will be missed.

Bruce and his colleagues made the first definitive measurement verifying the Kobayashi-Maskawa theory of CP violation, for which KM shared the 2008 Nobel Prize with Yoichiro Nambu

Bruce then turned his efforts to measuring polarization in the cosmic microwave background, which will provide information on the earliest moments of the Universe.

These efforts are already bearing fruit through results of the QUIET experiment in Chile.

Bruce lives on through his many postdocs and students.

UNFINISHED BUSINESS?

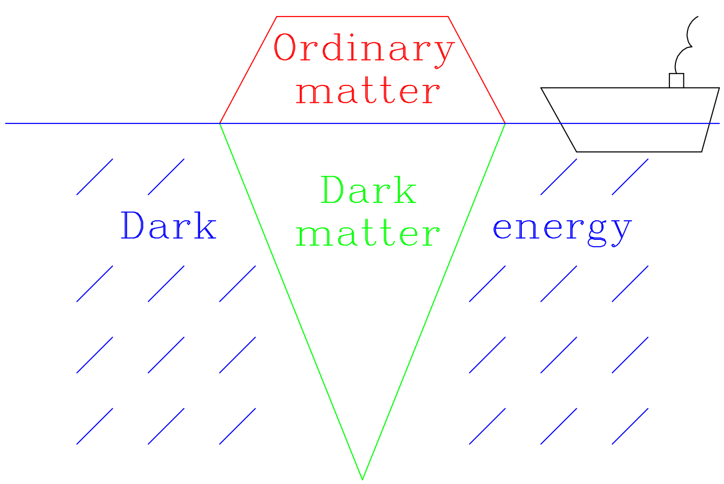
April Fool's joke #1: I thought I was retiring (but ...)

April Fool's joke #2: "Unfinished" is an understatement

In some views, only one piece of the Standard Model remains to be found - the Higgs boson

Bosons: spins $(0, 1, \ldots)\hbar$; fermions: spins $(1/2, 3/2, \ldots)\hbar$

Majority view: *Supersymmetry*: Every particle has a partner differing by 1/2 unit of spin. Keeps Higgs light.



Today: We may be seeing a *small fraction* of what remains to be discovered

This talk: partly a warm-up for tomorrow's symposium

SOME HISTORY

Recollections span 50 years; some of you will see next 50

Hope for as much progress in next 50 years as last 50

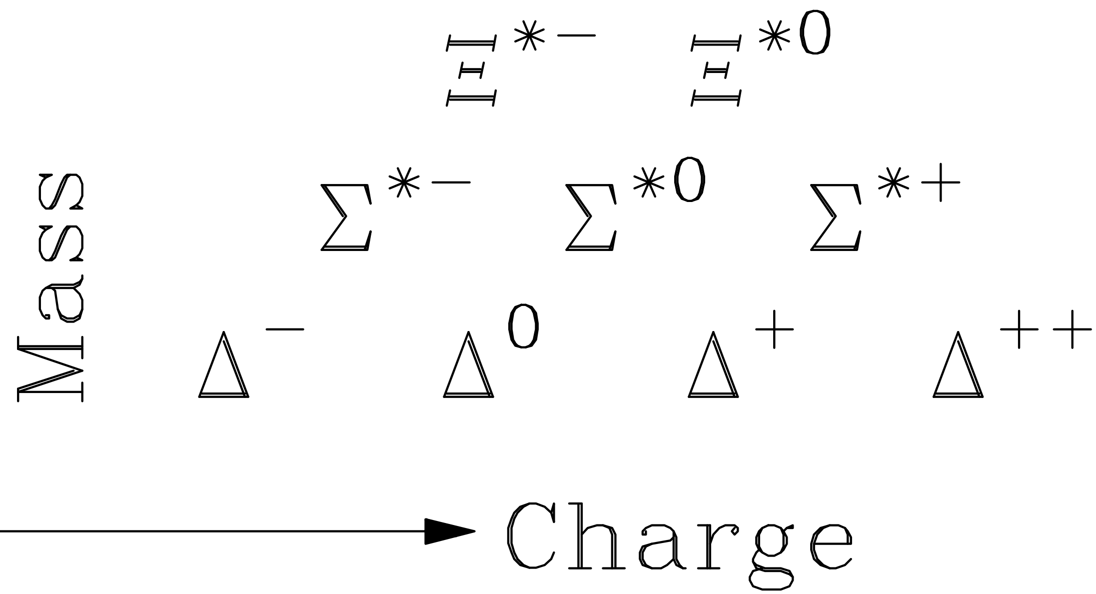
Looking back:	Looking ahead:
Build particles out of quarks	Understand quark, lepton pattern
Unifying the forces	Are there more forces?
Quarks have 3 $colors$	Other hidden "charges"?
More quarks	Still more quarks?
CP violation seen, explained	Understand baryon asymmetry

Mid-50s: experiments at the Chicago Cyclotron, located two (soon one) building(s) north of here

Short-lived particle called the Δ was found to exist in four charge states: Δ^{++}, Δ^{+}, Δ^{0}, Δ^{-}

Δ AND RELATIVES

The Δ particles (mass about 1.3 times a proton's) were found to have heavier relatives in the early 1960s:



Murray Gell-Mann and Yuval Ne'eman used an algebraic technique based on the group SU(3) to characterize these 9 particles, predicting a tenth "Ω^-" atop the pyramid

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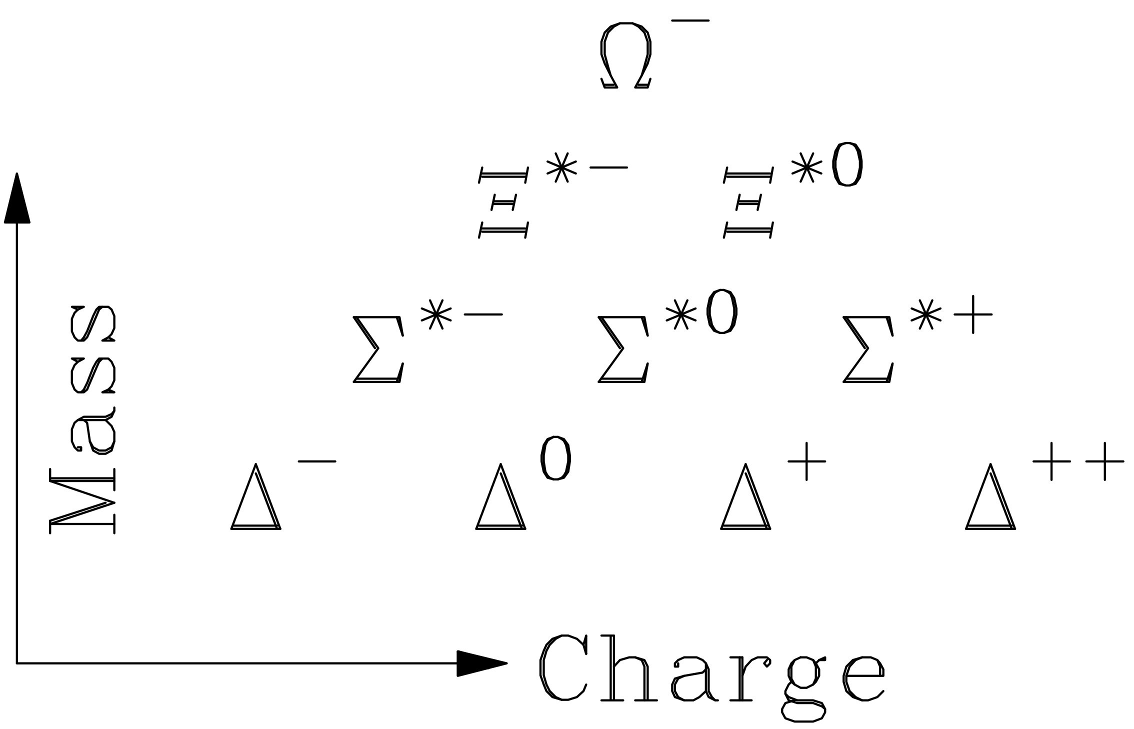
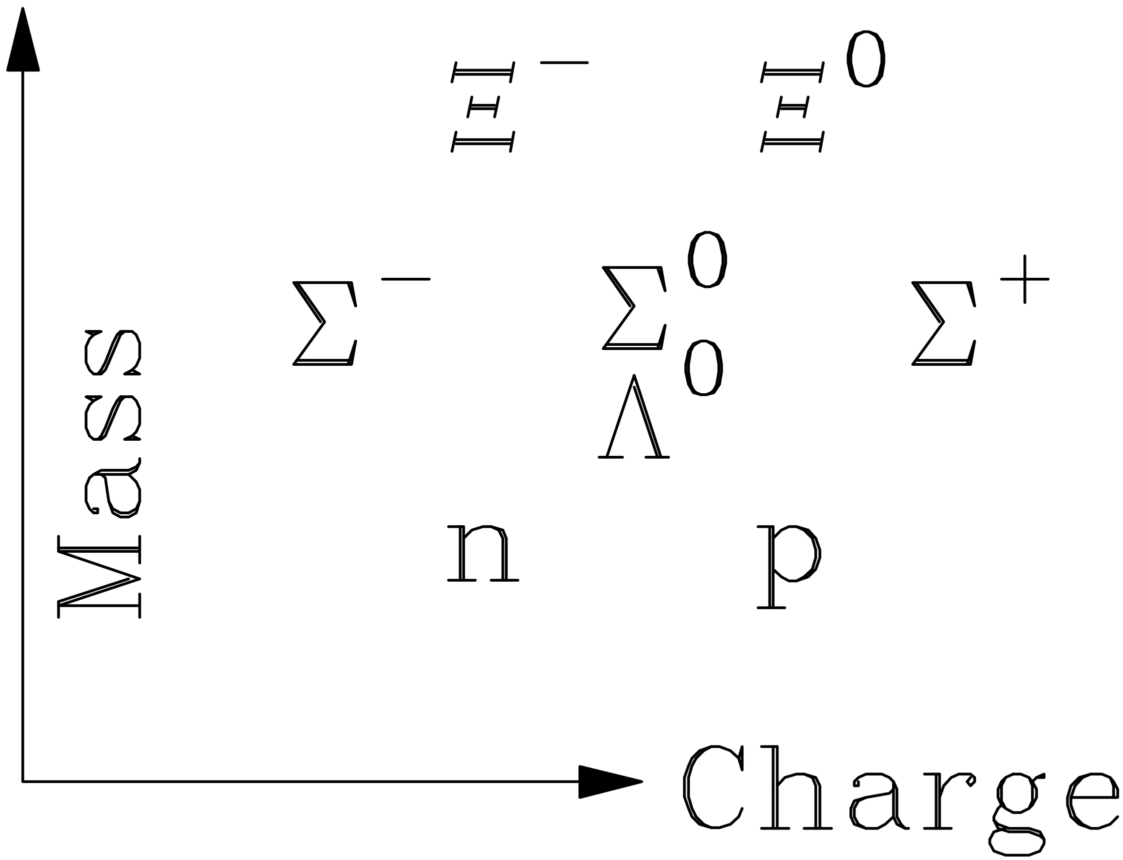


Murray Gell-Mann and Yuval Ne'eman used an algebraic technique based on the group SU(3) to predict a tenth particle "Ω^-" atop the pyramid: Discovered in 1964

THE "EIGHTFOLD WAY"

The proton ('p') and neutron ('n') were also predicted to belong to a larger family of eight particles, hence the name



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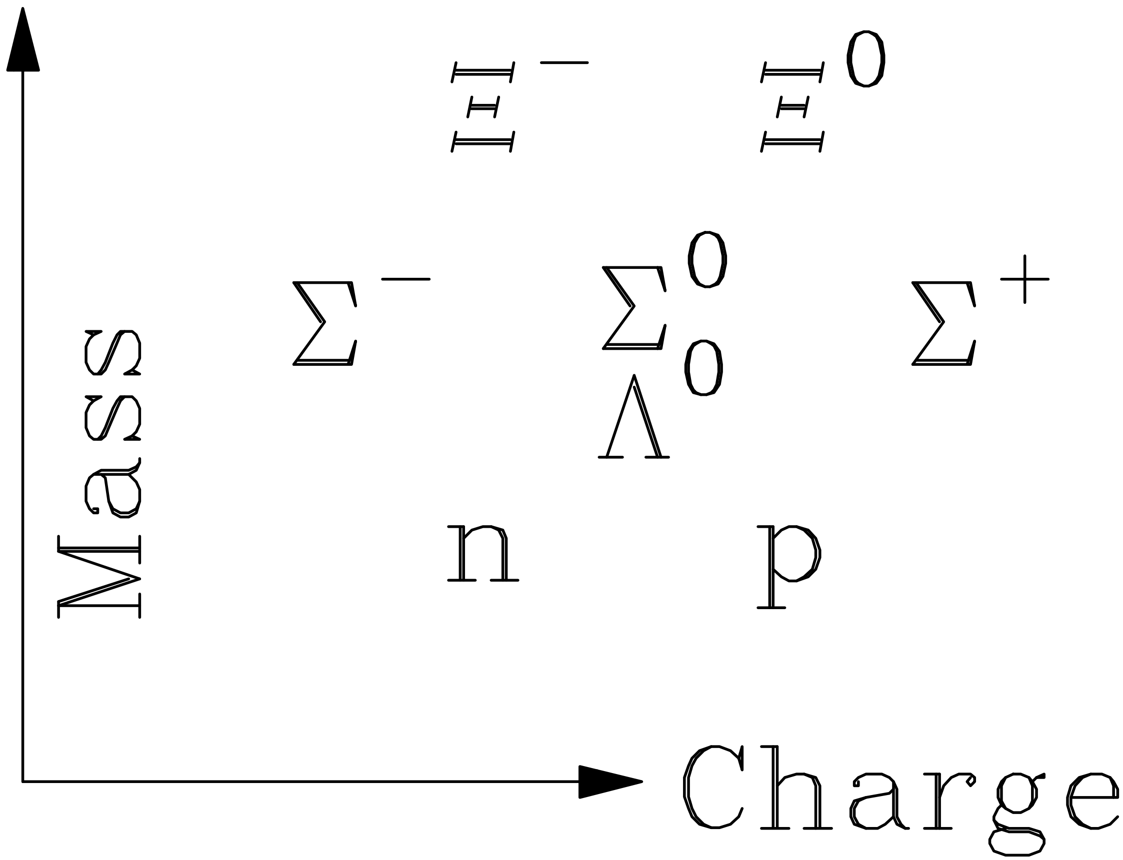
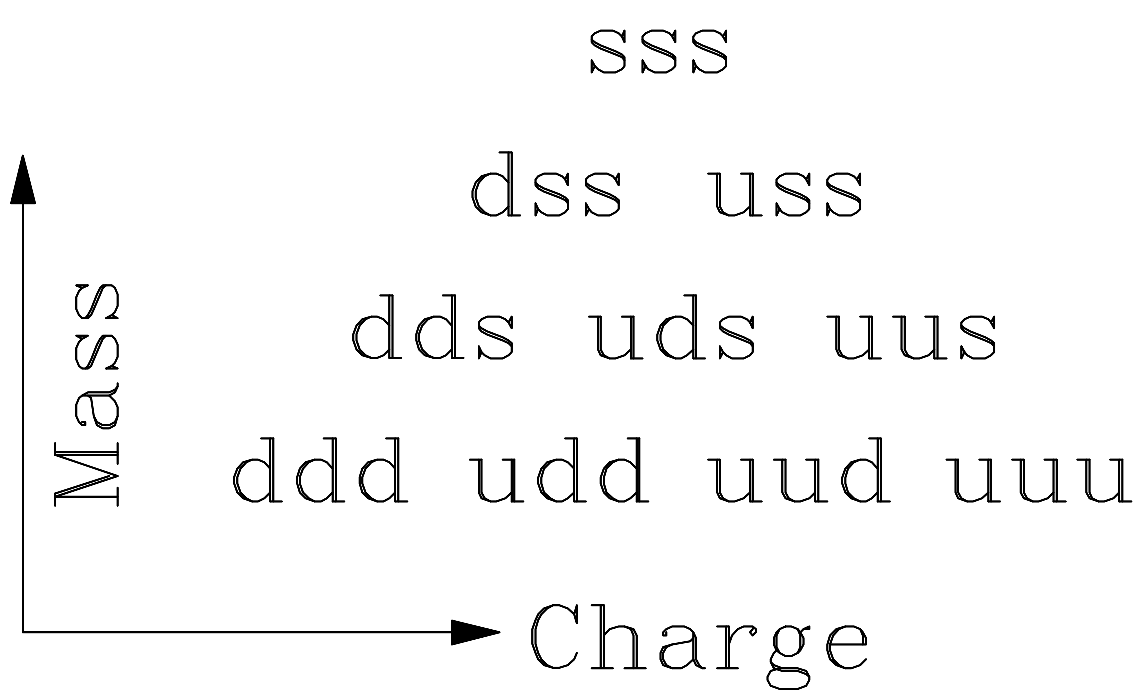


Fermi: "Young man, if I could remember the names of all these particles I would have been a biologist."

QUARKS FOR Δ AND RELATIVES

Gell-Mann, G. Zweig: three quarks ("Three Quarks for Muster Mark," *Finnegans Wake*) called u ('up'), d ('down'), and s ('strange', heavier than u, d)



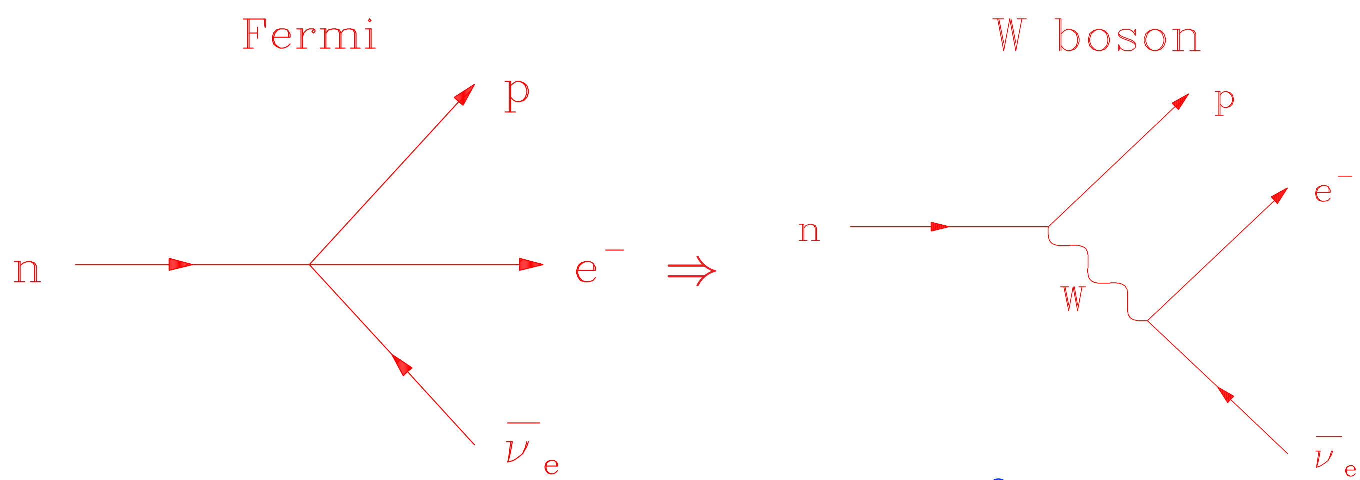
Quark charges: $Q(u) = 2/3$, $Q(d) = Q(s) = -1/3$

Explained many new particles: H. Lipkin, R. Dalitz, 1966 International Conference on High Energy Physics, Berkeley

SIMPLIFYING FORCES

Fermi (1934): Weak-interaction theory based on a four-fold interaction

Exchange of an intermediate particle makes theory more like electromagnetism (photon exchange); self-consistent at high energy



Charged W's would be accompanied by a W^0

Photon could not be W^0; $W^{\pm}$ couplings are not mirror-symmetric

Glashow (1961): solved the problem by adding a Z^0 $(M_Z > M_W)$

Weinberg-Salam (1967-8): $W^{\pm}$, Z^0 get masses via Higgs mechanism

$W^{\pm}$ and Z^0 discovered at CERN in 1983; extensively studied

THE CHARMED QUARK

Lepton "doublets": $\begin{pmatrix} \nu_e \ (1956) \\ e^- \ (1897) \end{pmatrix}, \begin{pmatrix} \nu_\mu \ (1962) \\ \mu^- \ (1937) \end{pmatrix}$ (no strong interactions)

These doublets particpate in weak interactions, e.g., $n \to pe^- \bar{\nu}_e$

1964: Bjorken–Glashow, ...: quark–lepton analogy, $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}$ with weak interactions involving the transitions

$$u \leftrightarrow d' = d\cos\theta + s\sin\theta, \ \ c \leftrightarrow s' = -d\sin\theta + s\cos\theta \quad (\theta \simeq 13^\circ)$$

So charmed quarks would decay mainly to *strange* quarks.

Glashow–Iliopoulos–Maiani (1970): $m_c \simeq 2$ GeV$/c^2$; M. K. Gaillard and B. W. Lee (1973): role of charmed quark in electroweak theory

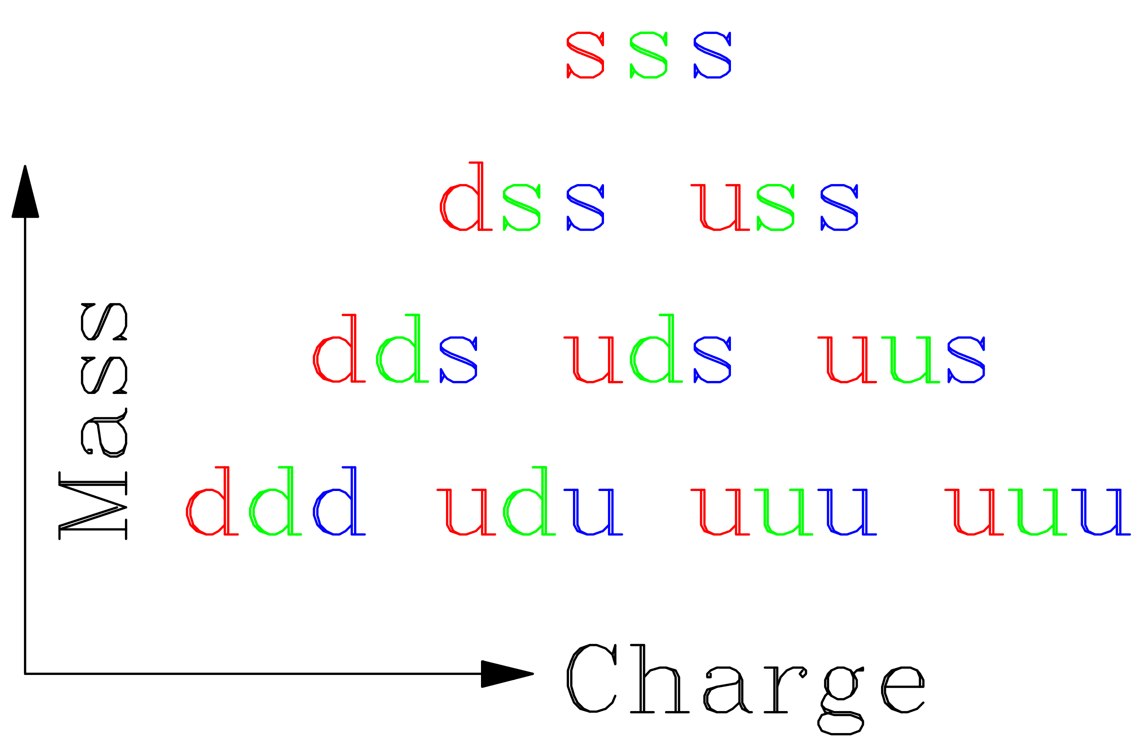
1974: Charmed quark c identified via $J/\psi = c\bar{c}$. $J =$ "Ting" (co-discoverer). *Charmonium* ($c\bar{c}$) spectrum is still evolving

1975-6: Particles with one charmed quark. Today: rich spectrum

QUARKS HAVE COLOR

The *Pauli exclusion principle* prevents any fermions (like quarks) from occupying the same quantum state, as in $\Delta^{++} = uuu$ with all u-quark spins parallel

Solved by endowing quarks with *colors* R, G, B (~ 1972)



Color is a *charge* seen by *gluons* (strong force carriers)

CP SYMMETRY VIOLATION

Before 1957 all of the following were thought valid:

Charge reversal C (exchange particles with antiparticles)

Parity P (mirror symmetry)

Time reversal T

Gradual erosion of separate invariances

1957: Weak interactions violate C and P, conserve CP and T

1964: Neutral K meson decays violate CP (J. Cronin, V. Fitch, ...)

CPT invariance hard to violate; CP violation then $\Rightarrow T$ violation

Proposals for CP violation in K decays:

Superweak (Wolfenstein, 1964): New interaction

Kobayashi-Maskawa (KM): standard weak interaction; ≥ 6 quarks

3RD QUARK-LEPTON FAMILY

At the same time as charm: the τ lepton (M. Perl, 1974)

Quark-lepton analogy:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \Rightarrow \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

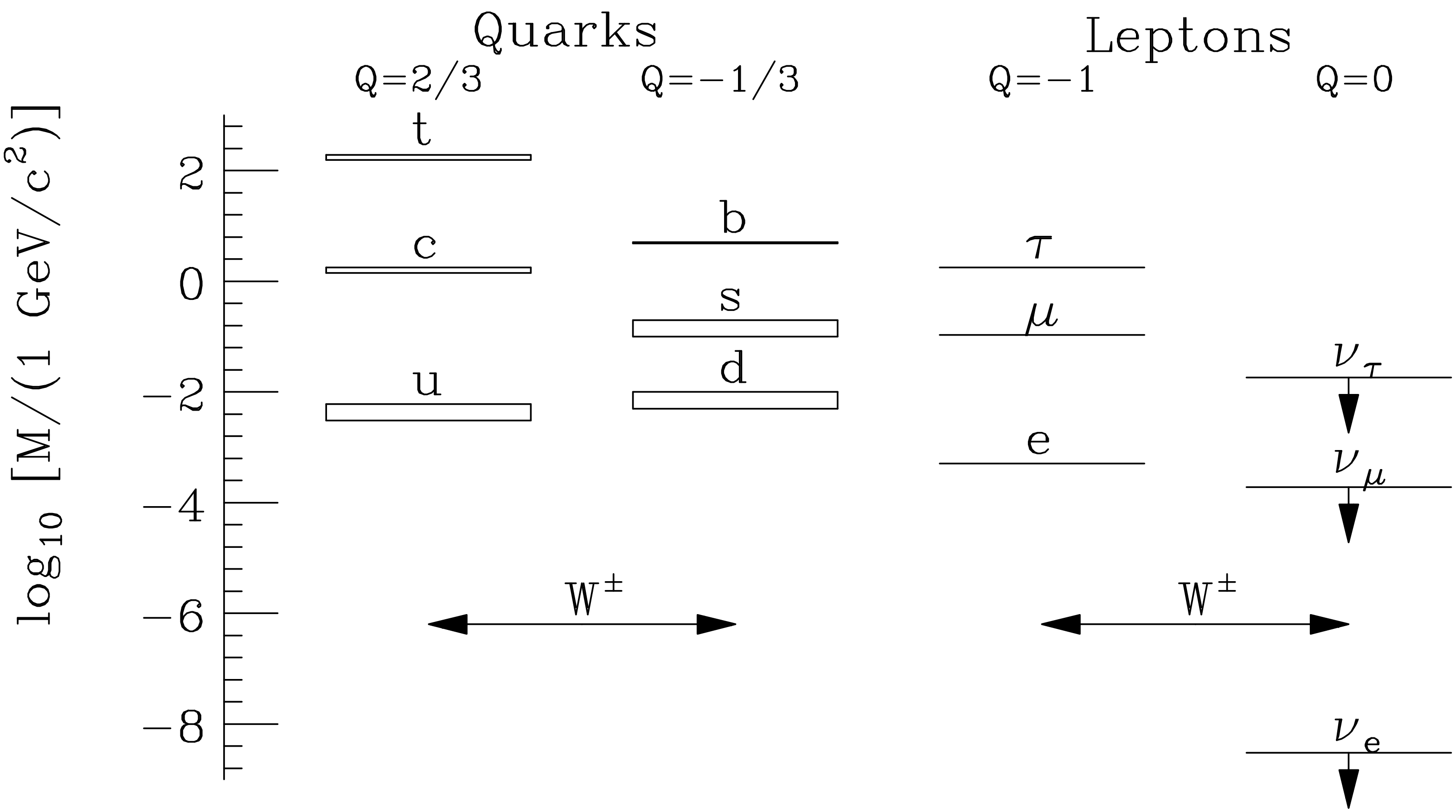
Third lepton pair (ν_τ, τ^-) $\Rightarrow$ third quark pair (t [top], b [bottom]), predicted by Kobayashi and Maskawa.

1977 (Fermilab): Υ family of spin–1 $b\bar{b}$ particles produced in proton-proton interactions, decaying to e^+e^-, $\mu^+\mu^-$

Rich $b\bar{b}$ spectroscopy (Quigg); "B" mesons containing a single b quark (Cornell, early 1980s). Decays of particles with b quarks: an active field (Gronau).

Top (1994): Fermilab Tevatron collided protons with antiprotons to produce $t\bar{t}$ pairs; mass $M_t \simeq 171$ GeV$/c^2$.

THE QUARKS AND LEPTONS



All the quarks and leptons? Attention has turned to the pattern of weak charge-changing transitions among them.

CP violation in B and K decays yields consistent picture, including different CP violation parameters in $K \to (\pi^0\pi^0, \pi^+\pi^-)$ (B. Winstein and collaborators)

THE HIGGS BOSON

Electroweak theory needs ≥ 1 spinless particle (*Higgs boson*) with definite couplings to W and Z and whose couplings to quarks and leptons generate masses and mixings. Not yet found; $M(H) \geq 114$ GeV/c^2

Precise electroweak measurements, e.g., in experiments at LEP (CERN e^+e^- collider) or the Tevatron (Fermilab $\bar{p}p$ collider), favor Higgs boson not far above present limits (through effects in loop Feynman diagrams)

Searches under way for the Higgs boson at Fermilab and the CERN Large Hadron Collider (LHC). Decay modes under consideration include $b\bar{b}$, $\tau^+\tau^-$, and $\gamma\gamma$. If it is heavy enough to decay to W^+W^- or ZZ its decay signatures are easier to distinguish from backgrounds, and a narrow mass range 158–173 GeV/c^2 has already been excluded

OUTSTANDING BETS

Electroweak theory requires a Higgs boson

Henry Frisch and I have bet Frank Merritt and Mark Oreglia a dinner at Cedars that the Higgs will not be found by Jan. 17, 2013.

Life will be *more* interesting if Higgs boson is not found in predicted mass range; could mean we are still missing some quarks/leptons.

Are neutrinos their own antiparticles?

I have bet Stuart Freedman $10.00 that the answer will be known to be "yes" by October 1, 2014; he bets we will know "no". Carlos Wagner is holding the $$$ and is free to invest in the meantime.

If so, a Sakharov (1967) condition is satisfied for the Universe to contain more matter than antimatter. The other two are CP violation (seen) and a period out of thermal equilibrium (hard to avoid)

Today: bets on supersymmetry taken

I bet we know much *less* than half the particle spectrum

DARK MATTER

Colliding galaxy clusters, galactic rotation velocities, galactic velocities in clusters, cosmic microwave background, gravitational lensing, . . . imply there is "dark" matter, 5 times as abundant as ordinary matter

Ordinary matter exists in many stable forms: p, n (in nuclei), e^-, three ν flavors, photons, gluons. Expect dark matter to exhibit at least as much variety.

Dimension (4) of space-time and rank (4) of "Standard Model" (electroweak + strong group) are much less than the maximum number of dimensions (10) in superstring theories or rank of groups (16 or more) in such theories.

A TeV-scale effective symmetry of (Standard Model) $\otimes$ G, where G is a new symmetry, can be richer than supersymmetry, where the known spectrum is "only" doubled (plus some extra Higgs bosons)

EXTENDING OUR REACH

Possible types of matter:

Type of matter	Std. Model	G	Example(s)
Ordinary	Charged	Uncharged	Quarks, leptons
Mixed	Charged	Charged	Superpartners
Shadow	Uncharged	Charged	E_8' of $\mathrm{E}_8 \otimes \mathrm{E}_8'$

"Charged" means the interactions of the symmetry group (Standard Model or G) "see" the particles

"Shadow" matter is challenging because our usual probes (strong and electroweak interactions) are blind to it

As we already have information from gravity on dark matter, it is natural to follow it up by learning how it is distributed on local, galactic, and cluster scales

In many scenarios, at sufficient energy (TeV?) one can produce the mixed or shadow particles in pairs

MORE UNIFICATION?

Theory oc color ("Quantum Chromodynamics") $\Leftrightarrow$ SU(3) (3×3 unitary matrices with determinant 1)

Electroweak theory $\Leftrightarrow$ SU(2) $\times$ U(1) ($\leftarrow$ phase rotations)

Georgi and Glashow put these together into an SU(5):

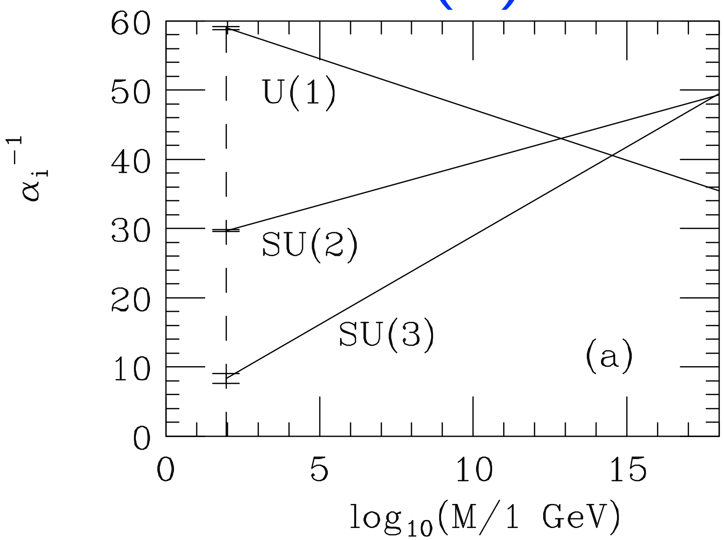
$$\left[\begin{array}{ccc|cc} & & & \mathrm{X} & \mathrm{Y} \\ & \mathrm{SU}(3) & & \mathrm{X} & \mathrm{Y} \\ & & & \mathrm{X} & \mathrm{Y} \\ \hline \bar{\mathrm{X}} & \bar{\mathrm{X}} & \bar{\mathrm{X}} & \multicolumn{2}{c}{\mathrm{SU}(2)} \\ \bar{\mathrm{Y}} & \bar{\mathrm{Y}} & \bar{\mathrm{Y}} & & \end{array}\right] \longrightarrow \left[\;\mathrm{SU}(5)\;\right]$$

New bosons X, Y cause proton decay, must be heavy

Coupling strengths vary with mass scale

NOT QUITE!

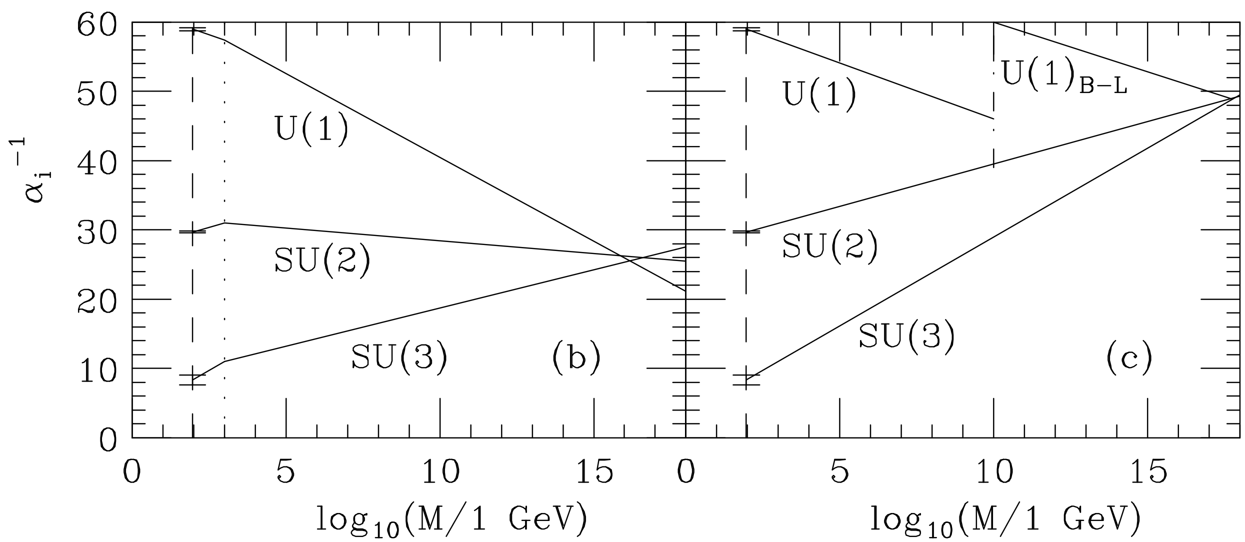
SU(5)



Coupling strengths don't unify at same mass scale

If unification enforced: wrong W/Z mass ratio; proton too short-lived

Supersymmetry Bigger unified group

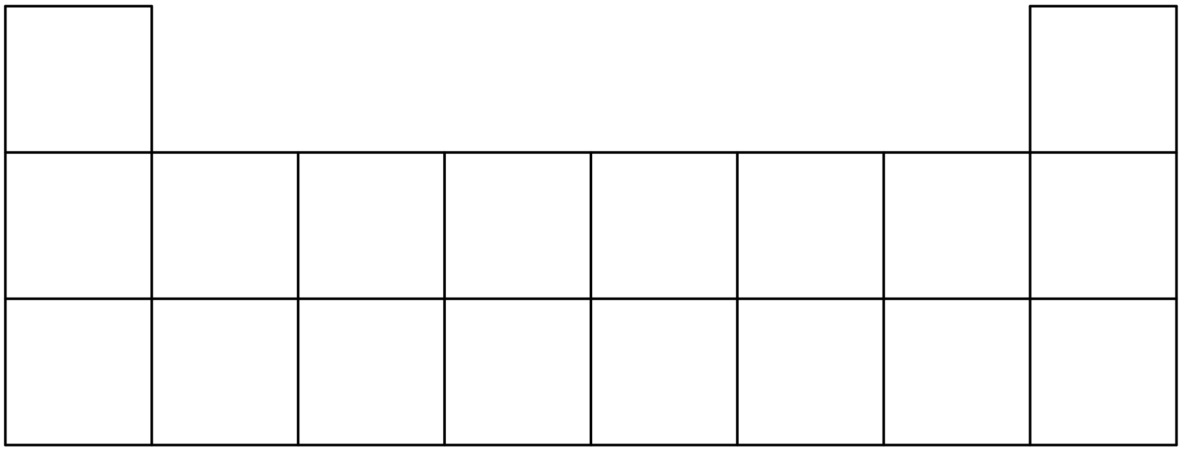


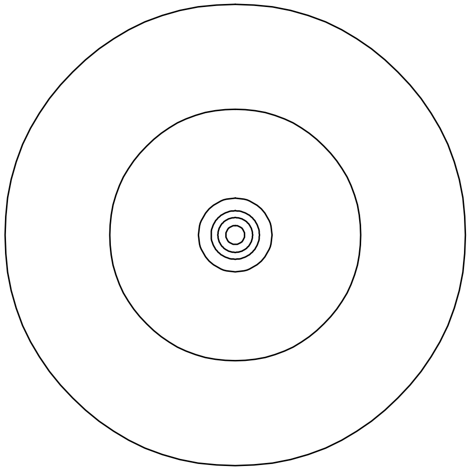
(b) More particles: change couplings vs mass scale

(c) Larger group: symmetry breaking at > 1 scale

CERN LHC will search for Z's implied by bigger groups

SEEING A PATTERN





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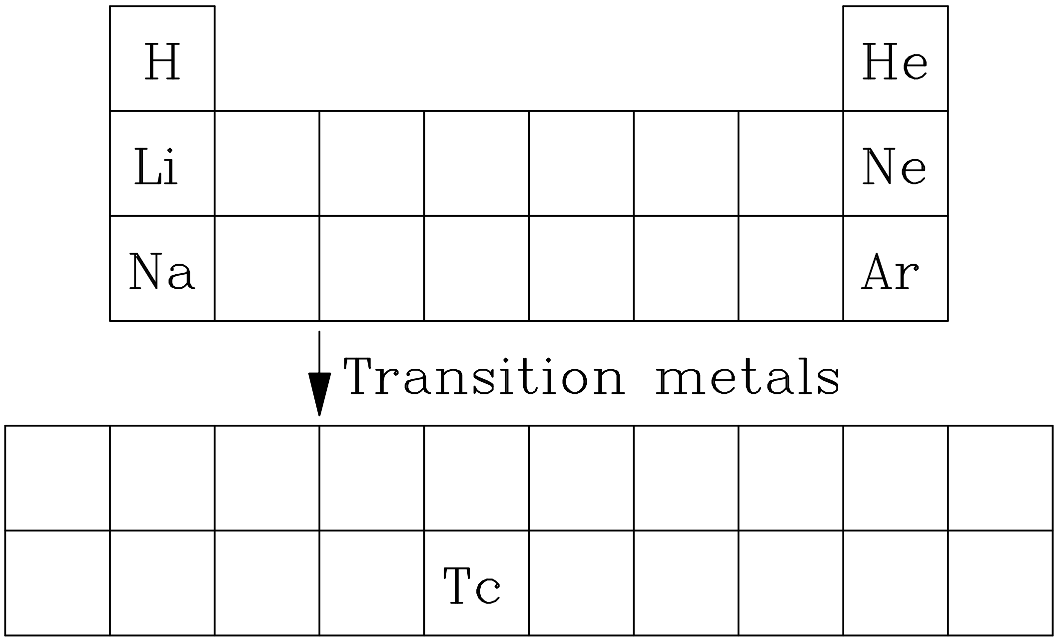
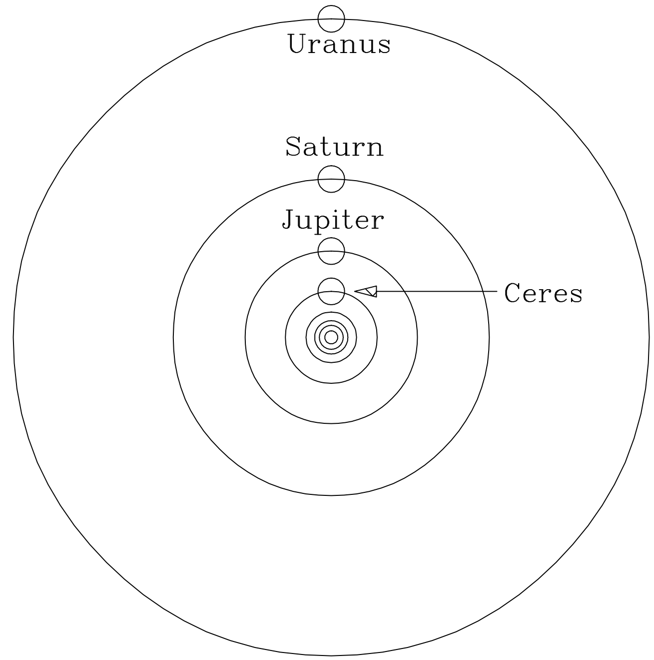


Periodic Table of the Elements



Planetary orbits

Each element: different nuclear charge; electron shells govern chemistry; Technetium predicted

Bode: $a(\mathrm{AU}) = 0.4 + 0.3k$
$(k = 0, 1, 2, 4, 8, \ldots)$
$\Rightarrow$ orbits of Ceres, Uranus

Bode's Law failed to predict Neptune's orbit; Pluto where Neptune should have been; other dwarf planets don't fit; no dynamics

Simulations: similar relations; $\Leftrightarrow$ "anarchy" in quark-lepton masses

EXTRA Zs, QUARKS?

More tomorrow from Langacker, Robinett on extra Zs that might be accessible at the LHC

"Grand unified" groups beyond SU(5) have them: SO(10) has what we named Z_χ; E$_6$ has Z_χ and Z_ψ

Theories with extra dimensions, building on old work of Kaluza and Klein, can have excitations of known particles, usually equally spaced in mass, perhaps in the TeV region

Extra quark and lepton families can signal their presence via loop Feynman diagrams, affecting:

• W/Z mass ratio (allowing for Higgs boson to be much heavier than standard calculations)

• Particle-antiparticle mixing (particularly for "strange beauty" mesons B_s and $\bar{B}_s$), with D0 Collaboration at Fermilab calling Standard Model prediction into question

STUFF TO WATCH

Caution! None of this might be "New Physics" ...

Anomalous magnetic moment of the muon; deviations from Standard Model very easy to achieve in supersymmetry (or any theory with new particles in loop Feynman diagrams)

Top quark production at Tevatron shows an unexpected forward-backward asymmetry; tops tend to follow protons and antitops antiprotons. LHCb can look.

The D0 Collaboration at the Tevatron reports an excess of $\mu^-\mu^-$ pairs over $\mu^+\mu^+$ pairs ($\Rightarrow$ matter-antimatter asymmetry?) More mundane physics not yet ruled out

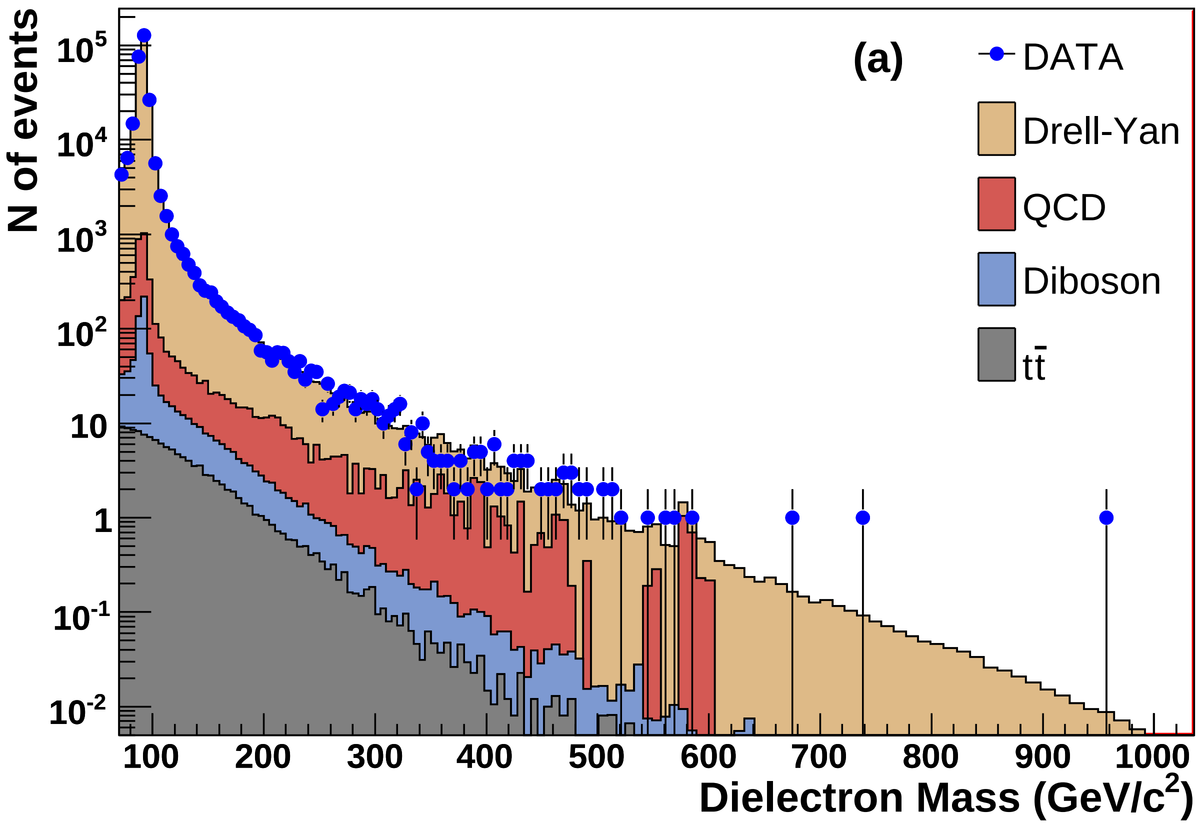
Our colleague Juan Collar and collaborators have a low-energy signal in a dark matter detector (COGENT) which might or might not be dark matter

The CDF Collaboration has one high-mass e^+e^- pair

CDF Z' SEARCH

T. Aaltonen *et al.*, arXiv:1103.4650

Plot number of events vs effective mass of e^+e^-



Probability of event at 960 GeV/c^2 is only about 1%

EXPERIMENTAL PROSPECTS

Analyzing data: CLEO (Cornell, studying charm); BaBar at SLAC (Stanford); still running: Tevatron at Fermilab; Belle at KEK (Japan), to be upgraded.

Neutrino experiments at Fermilab, CERN, reactors in China and France will probe mass and mixing pattern.

BES-III in China will extend CLEO's charm studies

LHC has recapitulated 30 years of Standard Model results in a few months and is poised for new discoveries by ALTLAS, CMS, ALICE, and LHCb (rich b quark physics)

Plans for a new lepton collider await LHC results

Non-accelerator experiments include Pierre Auger Array (Argentina), IceCube and ANITA searching for neutrino interactions in South Pole Ice, and HESS and VERITAS looking for astrophysical TeV gamma ray sources.

SUMMING UP

In the past 50 years we have seen tremendous progress in particle physics with the construction of a "Standard Model" of weak, electromagnetic, and strong interactions.

Major discoveries included CP violation and a theory of it, three new species of quark (charm, bottom, and top), the τ lepton and its neutrino, the weak force carriers W and Z, and verification of QCD (Quantum Chromodynamics), the theory of the strong interaction.

Pushing beyond the Standard Model, we see a pattern of neutrino masses and mixings differing significantly from that of quarks.

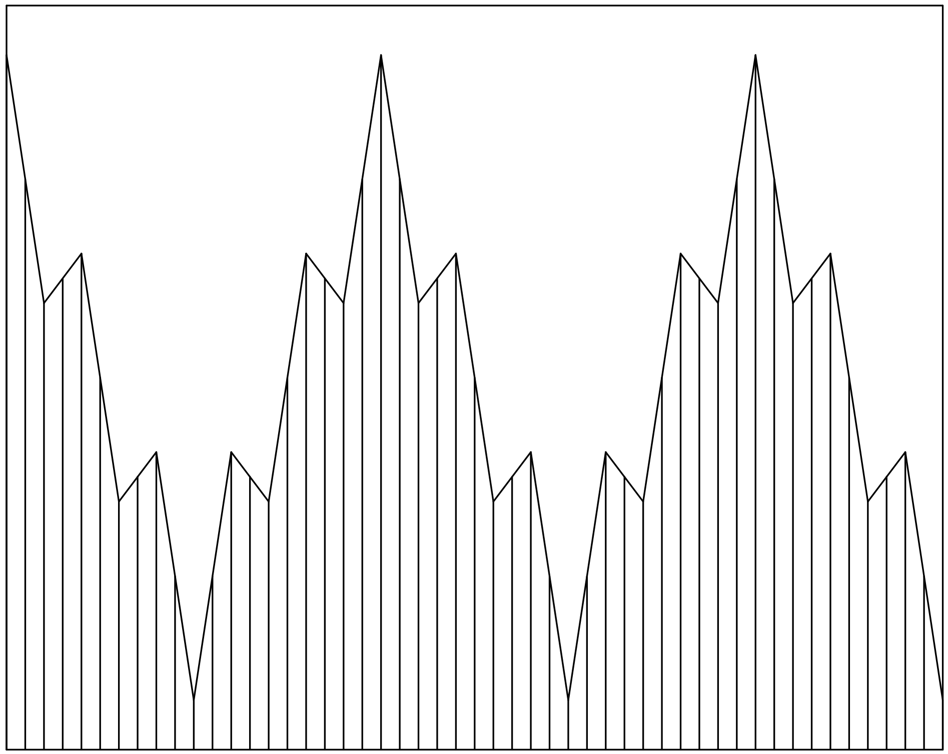
We still seek the Higgs boson, a key to understanding electroweak symmetry breaking. We can describe quark and lepton masses and mixings but don't understand them. We do not know the nature of dark matter; is it the lightest supersymmetric particle?

We look forward to answers to these questions in the coming decade.

Thanks: colleagues for many enjoyable collaborations; DOE for constant support; U of M and U of C for great places to do science

SURPRISES?

Exploring a cave in Pennsylvania with our college outing club, I came upon a room full of stalactites:



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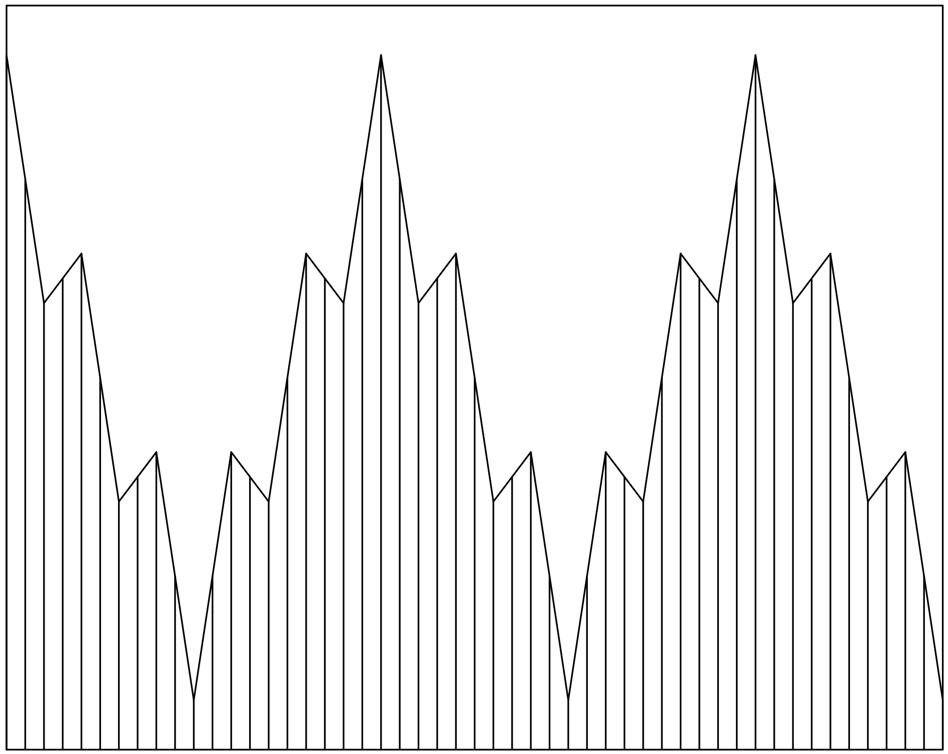

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I was looking out the cave's entrance at pine trees against a night sky glowing with Aurora Borealis