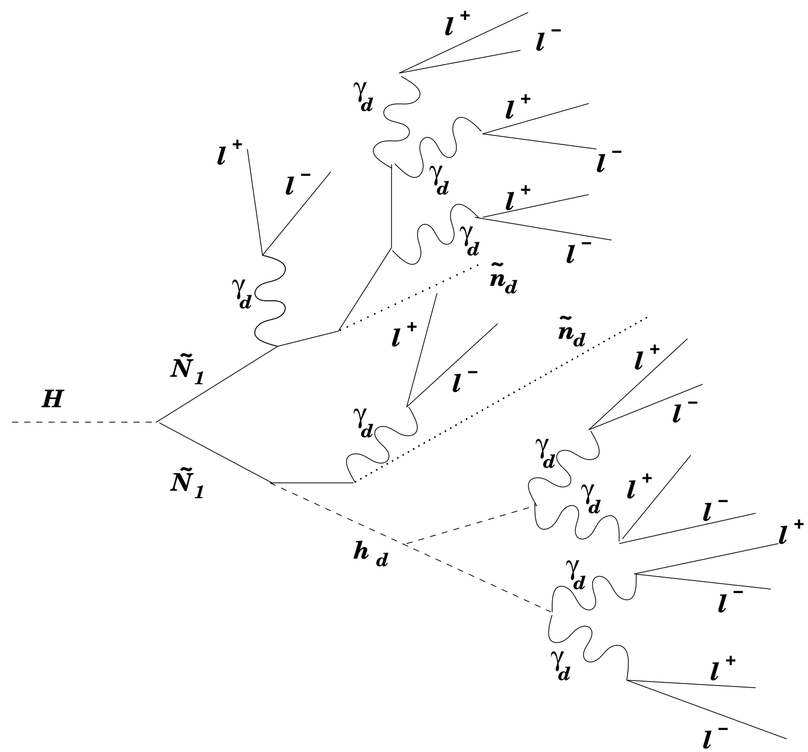
A Search for Low-Energy Leptons and Lepton Jets in W and Z Events at CDF



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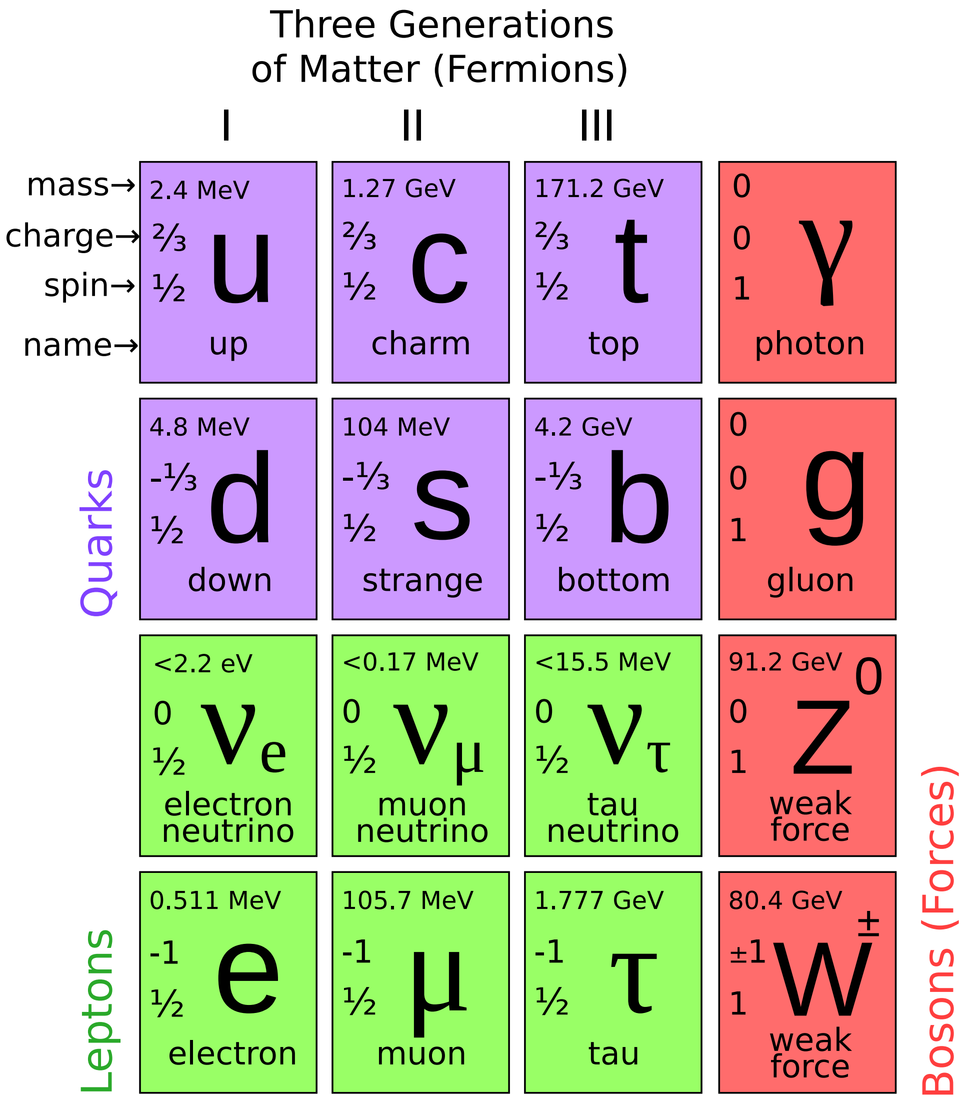
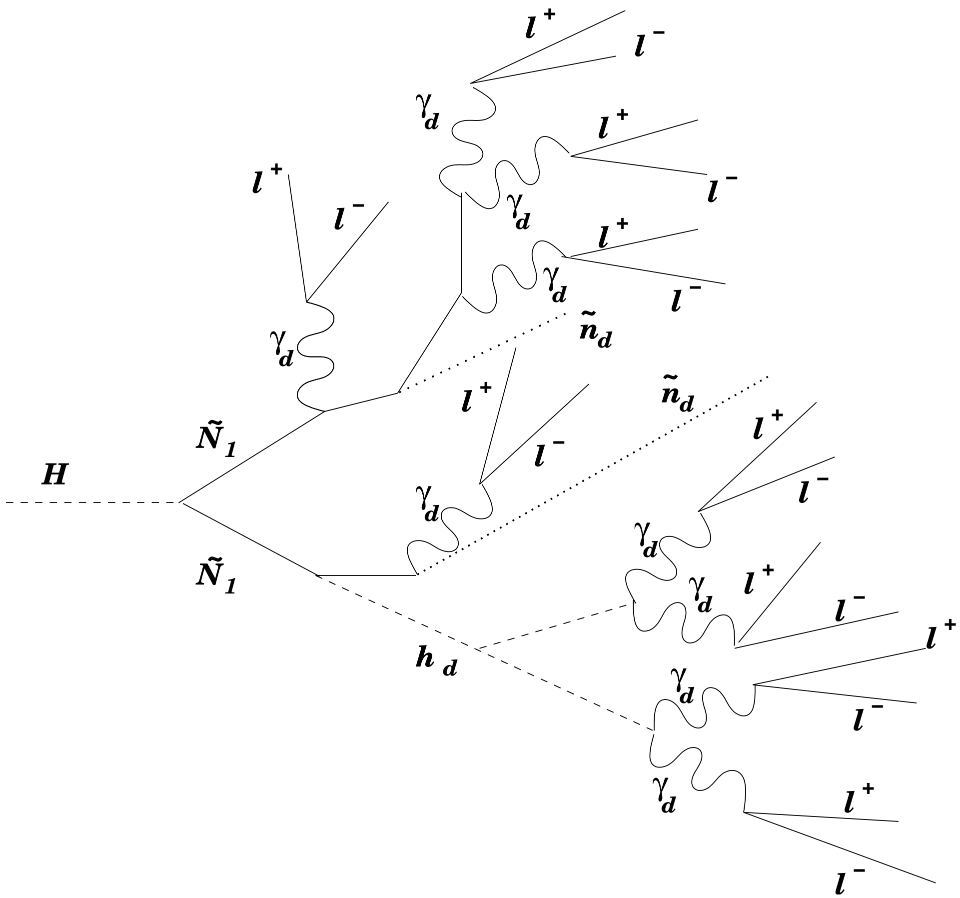
Thesis Defense

The Standard Model



- Matter consists of fermions
- Forces mediated by bosons
- Well tested, but known to be incomplete.
  - Where is the Higgs?
  - What is Dark Matter?
  - Why is there more matter than antimatter?
  - ...
- There must be physics beyond the SM

A Model-Independent Search



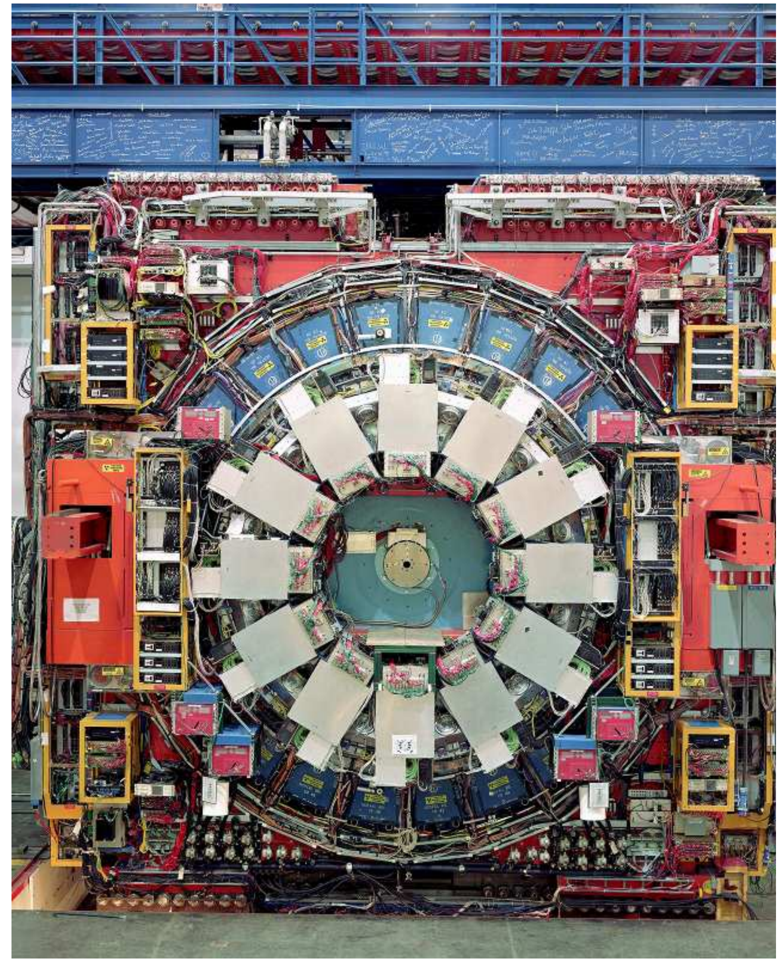
18 Leptons!

- Some searches are heavily optimized for one particular theory
- We instead search for a general signature that many models have in common: "Many Leptons"
- Previous searches have required high momentum, isolated leptons - could have missed exciting events

A Needle in a Haystack

- The new physics could be produced at a very low rate: 10^{-12} of the collisions at CDF
  - 1 cm square somewhere on the South Side
- We need to reduce the backgrounds and understand the remaining backgrounds very well

Tevatron and CDF Overview

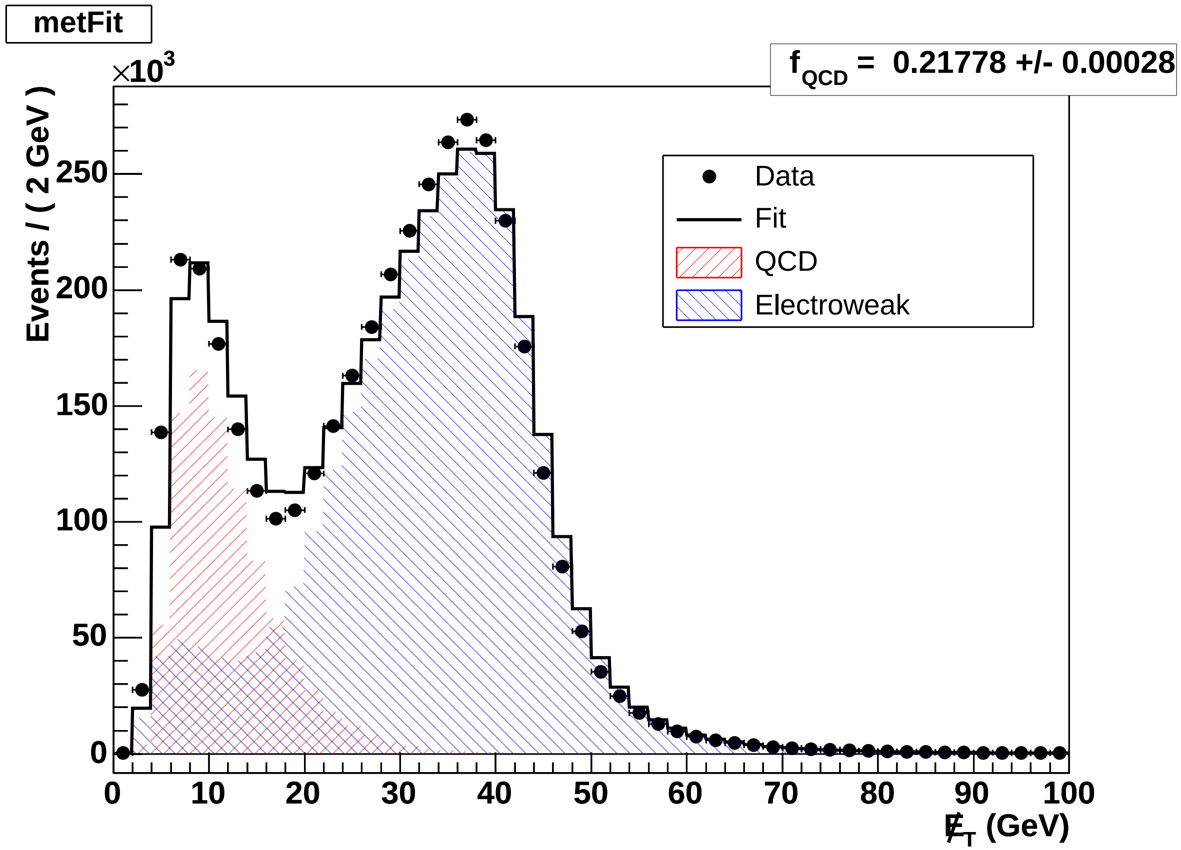


- The Tevatron at Fermilab collides protons and antiprotons at a center-of-mass energy of 1.96 TeV
- CDF is a general-purpose detector collecting data at the Tevatron at Fermilab

Analysis Summary

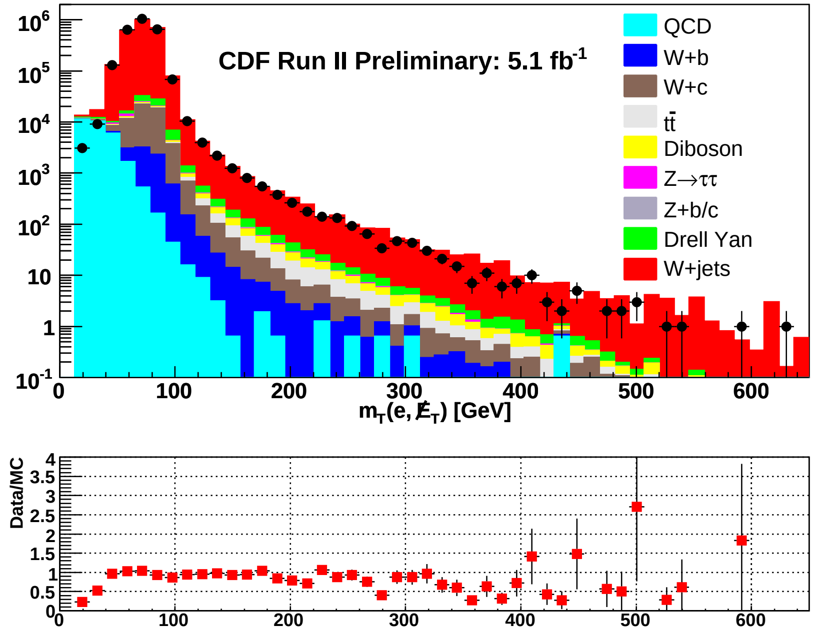
- Used 5.1 fb^{-1} of CDF data, collected from Dec. 2004 to Jan. 2010
- Triggered on W or Z boson production (reduces backgrounds by 10^6)
- Developed "soft" lepton identification - p_T down to 2 GeV for electrons, 3 GeV for muons, no isolation requirement
- Normalize predictions to W/Z + exactly one lepton bin (expected to be dominated by SM processes)
- Count events with multiple additional leptons
- Set limit (or observe excess) based on the number of events with multiple additional electrons and muons

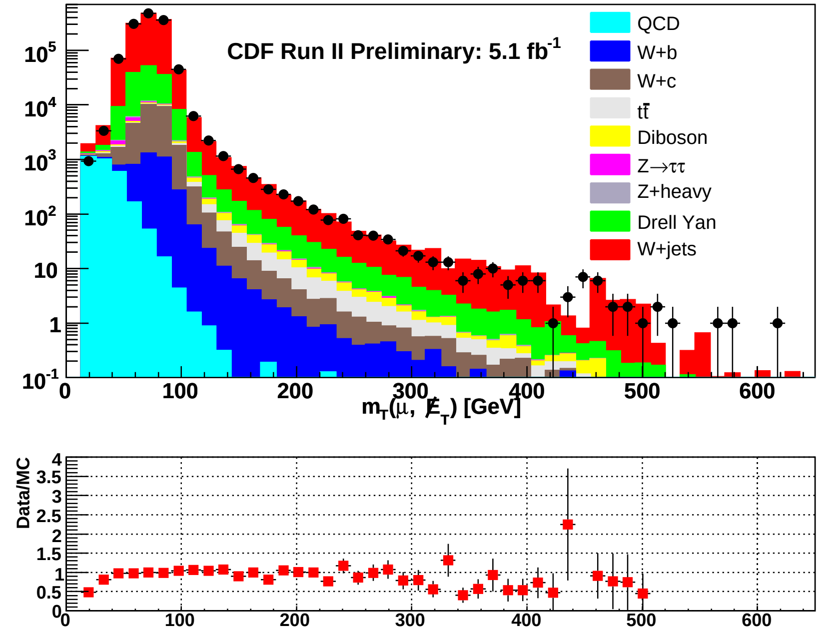
Background Estimation

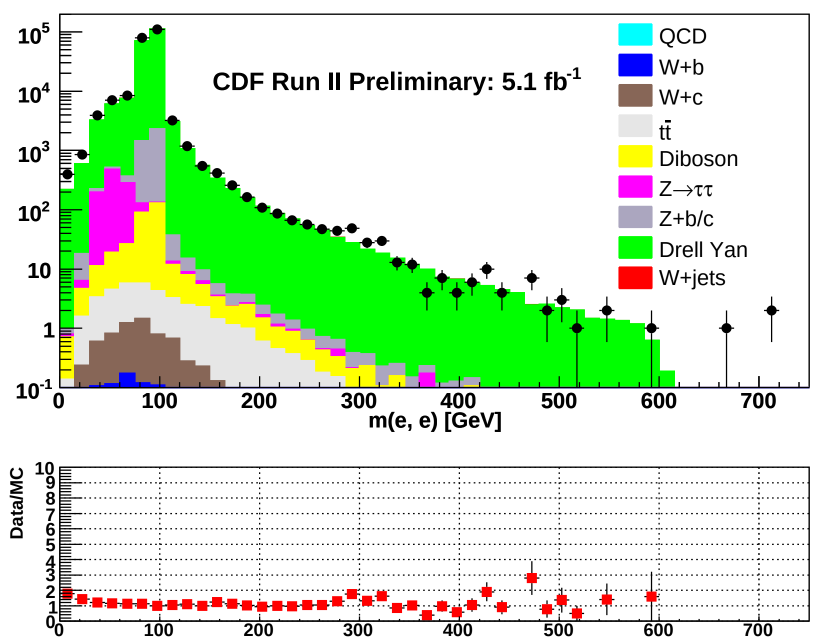


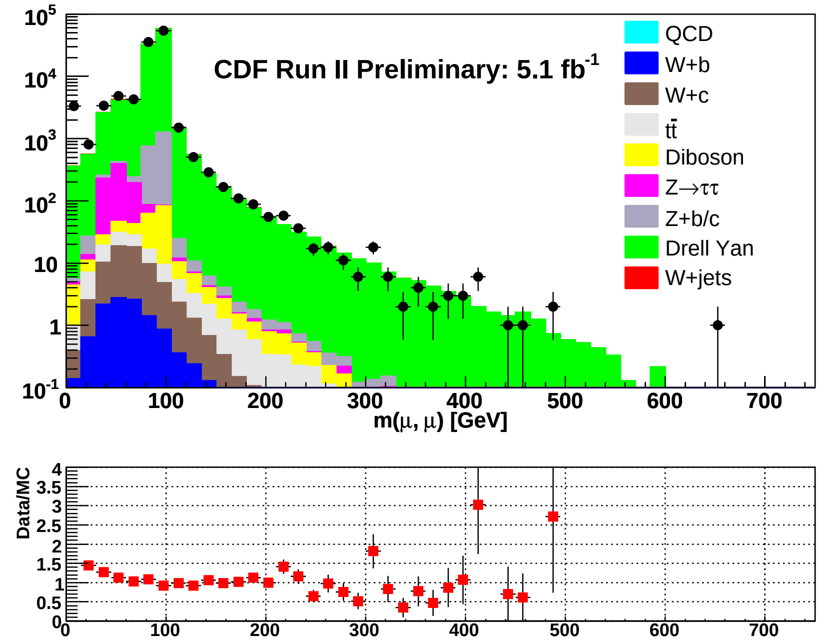
- Electroweak processes are well understood, modeled by Monte Carlo
- QCD processes cannot be modeled: sample acquired from the data
- Fit the $\not\!\!E_T$ distribution to find the fraction of events from electroweak and QCD
- Cut on $\not\!\!E_T$ to remove most QCD

Validation of High-p_T Sample

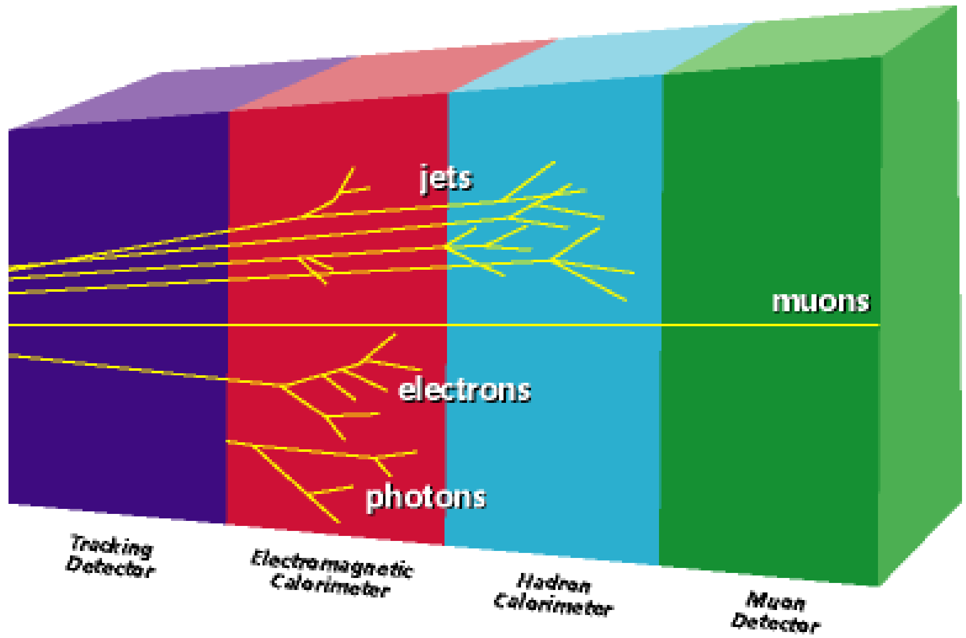






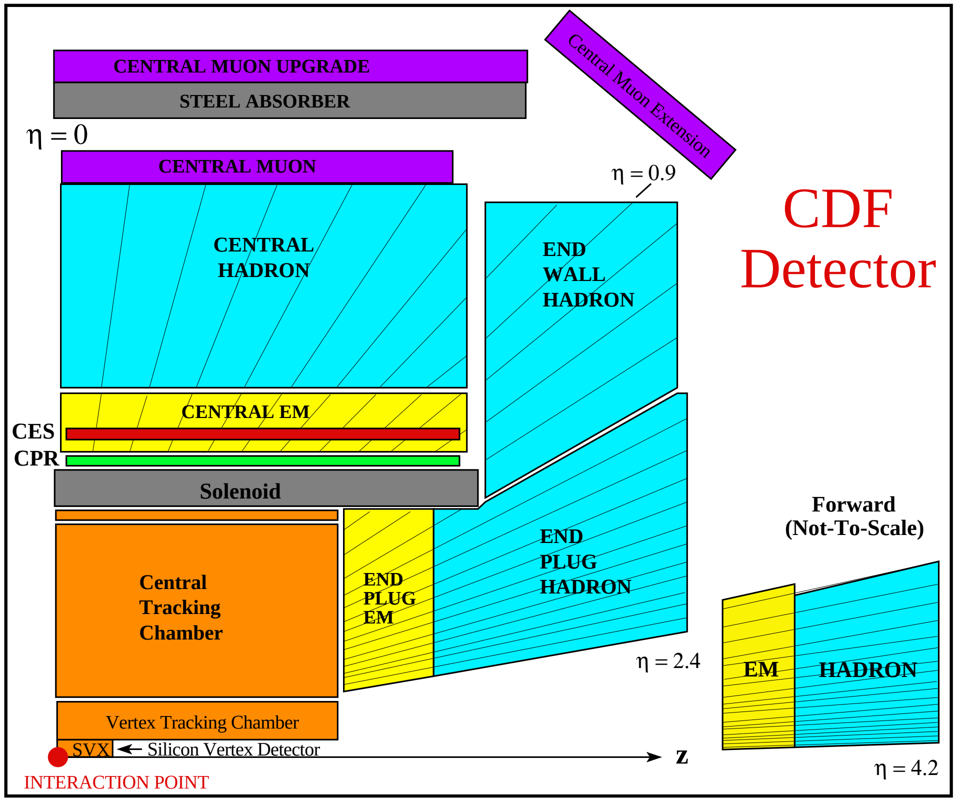


Soft Lepton Identification



- High-energy, isolated leptons are relatively easy to identify
- Low-energy, non-isolated leptons are harder to distinguish from low-energy background
- We use likelihood-based methods to combine many dis

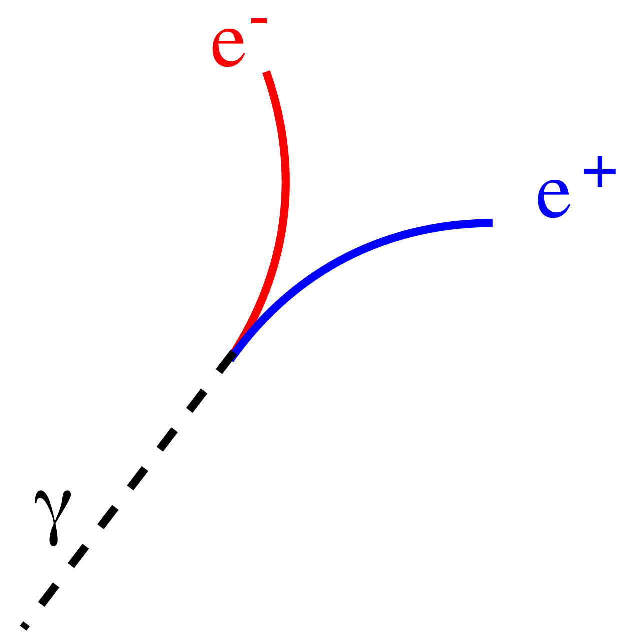
Soft Electrons

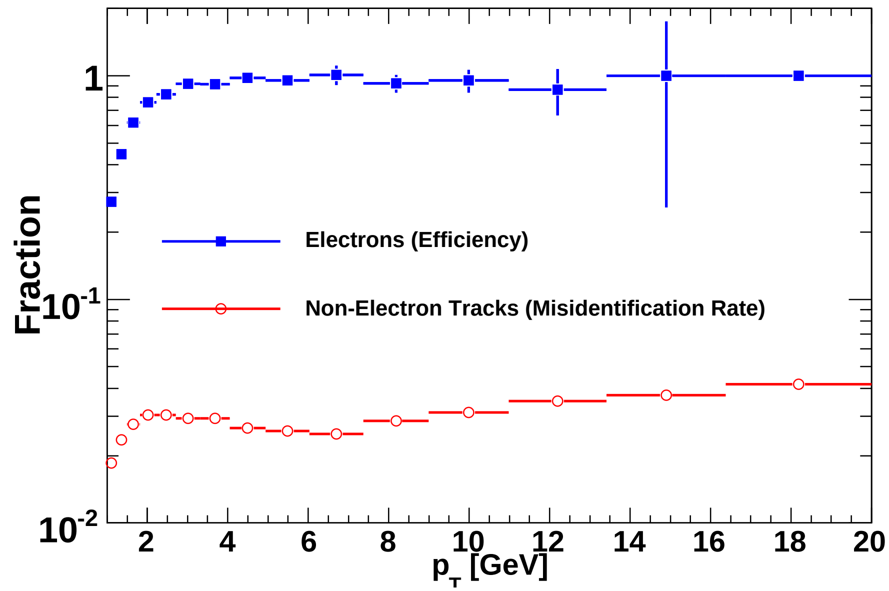


- Likelihood-based ID
  - Tracking chamber dE/dx - more useful at low p_T
  - Energy deposited in preradiator, EM and hadronic calorimeters
  - New algorithm for matching tracks to showermax clusters - improved performance when matching multiple nearby clusters

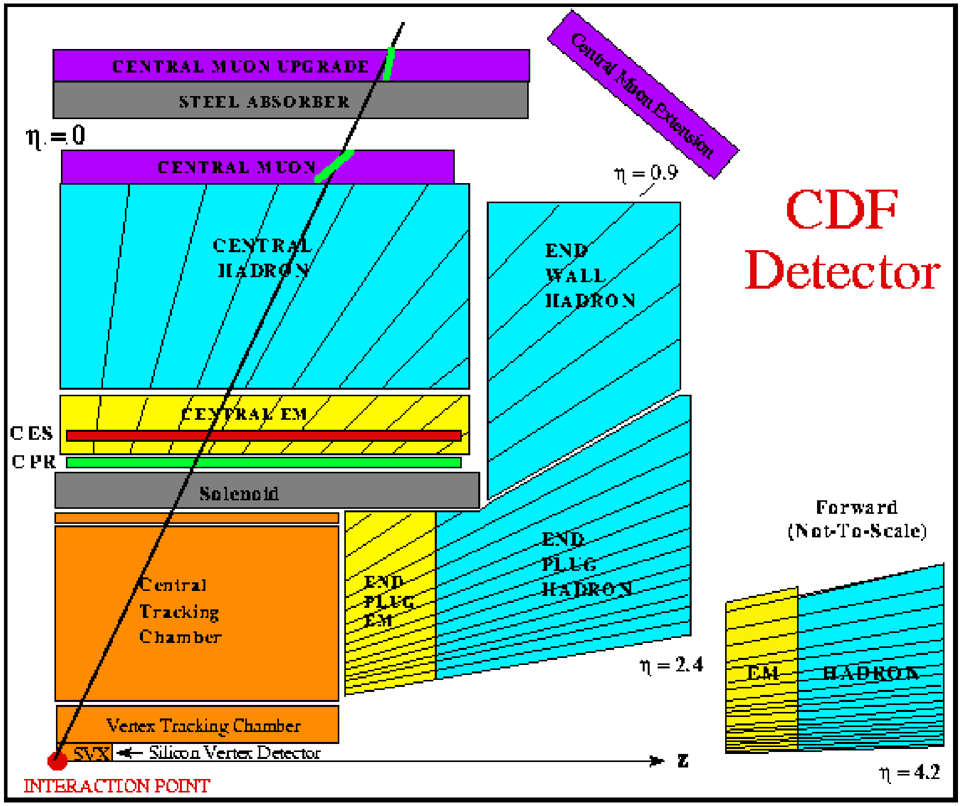
Soft Electron Training

- Sample of real electrons from photon conversions
- Sample of non-electrons from other generic objects with real electrons removed
- Response of likelihood measured in training samples as function of p_T, η, isolation
- Calculated efficiency and fake rate is applied to the MC to predict SM background





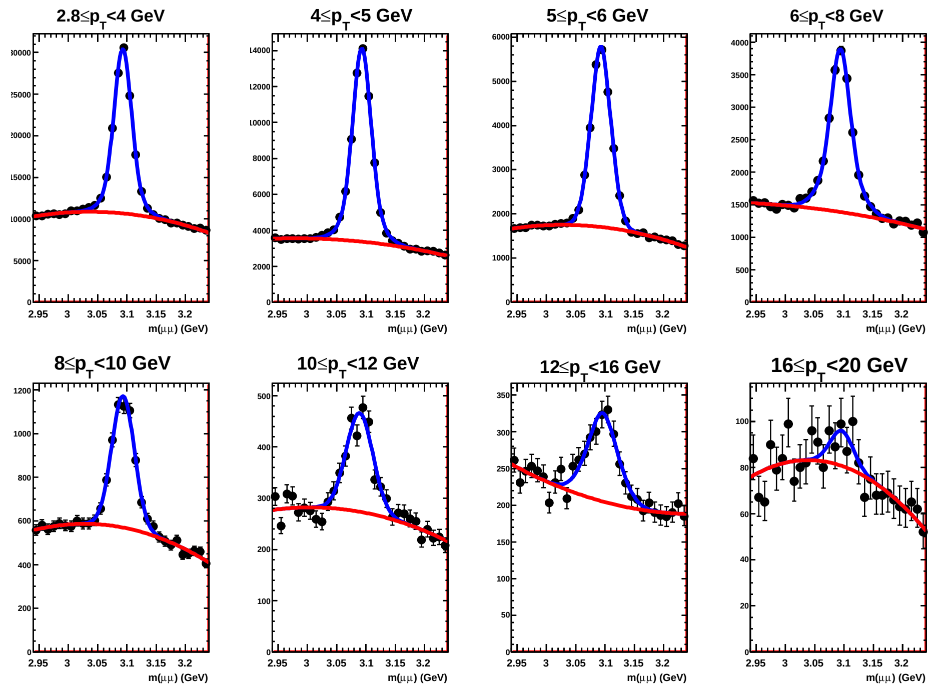
Soft Muons

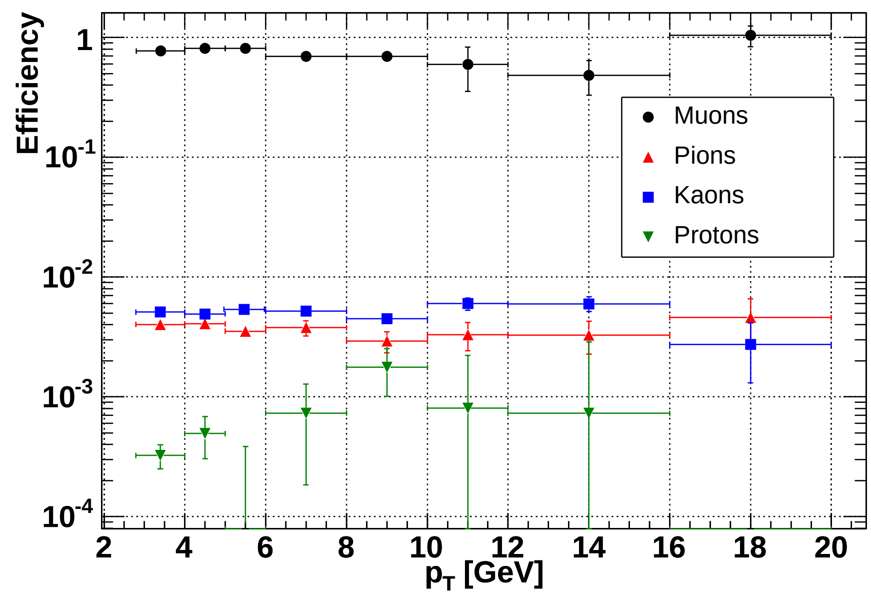


- Used a previously-developed soft muon tagger
- Uses matching between track and hits in muon detectors, e.g. Δx, Δz, $\Delta\phi$

Soft Muon Testing

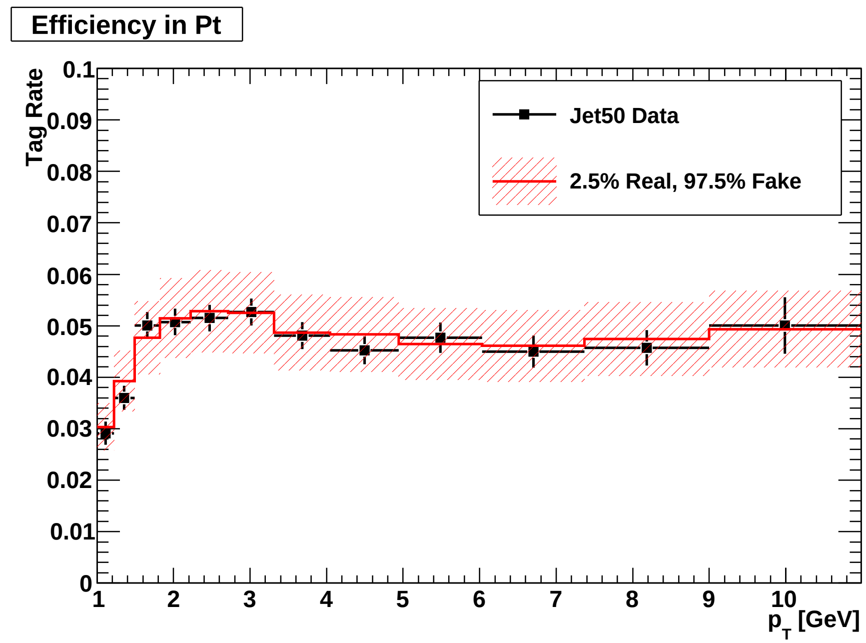
- Likelihood tested on μ, π, K, p
  - Pure sample of muons obtained from J/Ψ decays
  - Pure sample of each background obtained from D^* and Λ decays
- Performance measured as function of p_T and η
- Calculated efficiency and fake rate are applied to the MC to predict SM background

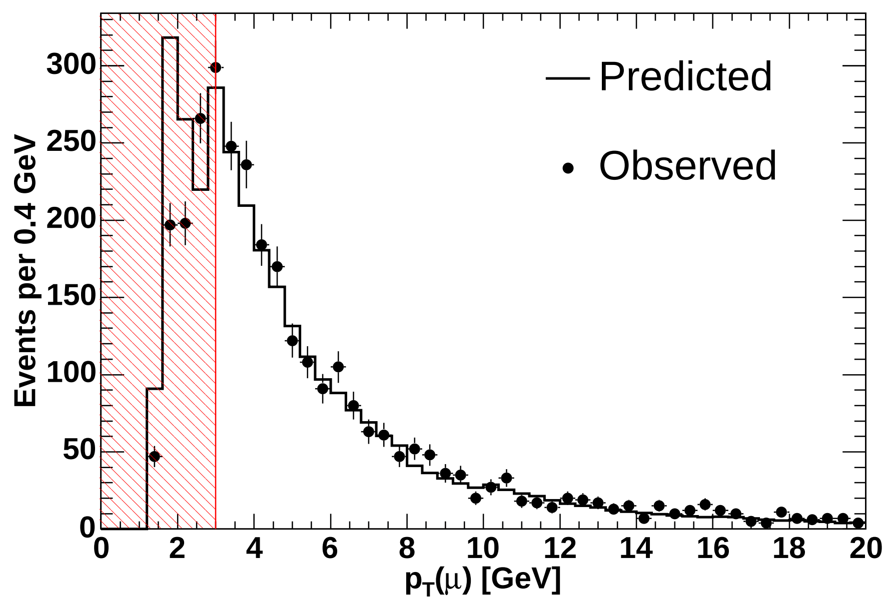




Soft Lepton Validation

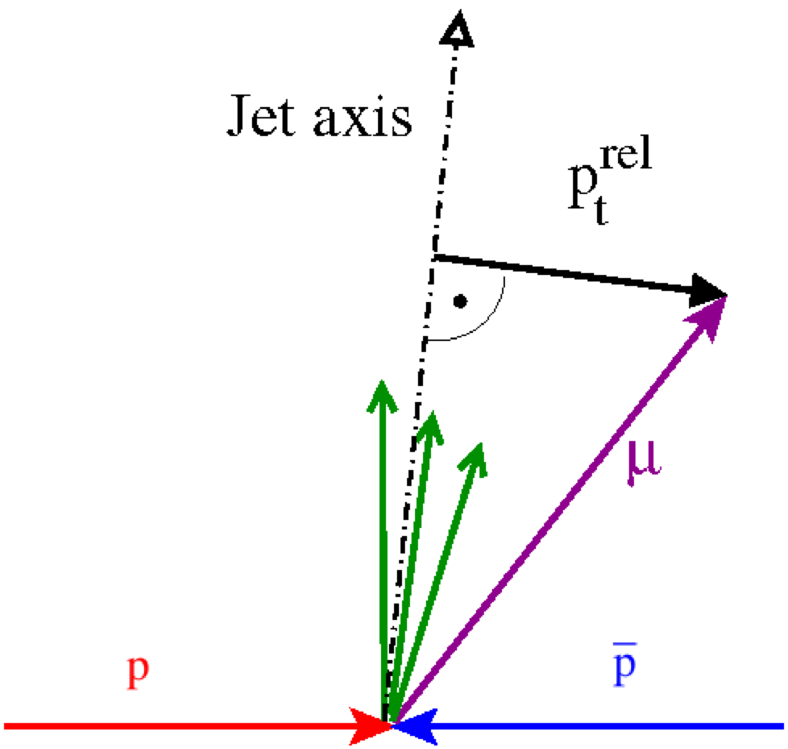
- We validate the soft lepton identification in a different data sample
- Take a sample triggered on high-p_T jets, calculate expected and observed lepton numbers
- For electrons, we predict 6448 and observe 6345 - a difference of 5%.
- For muons, we predict 2220 and observe 2331 - a difference of 5%.

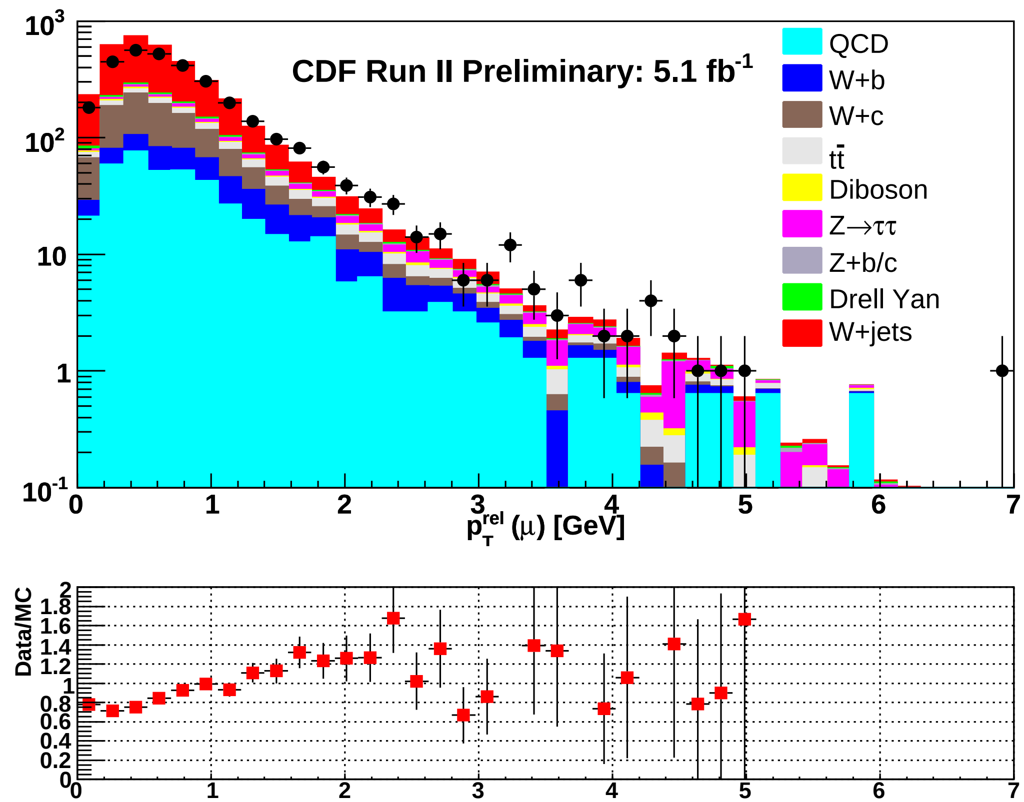


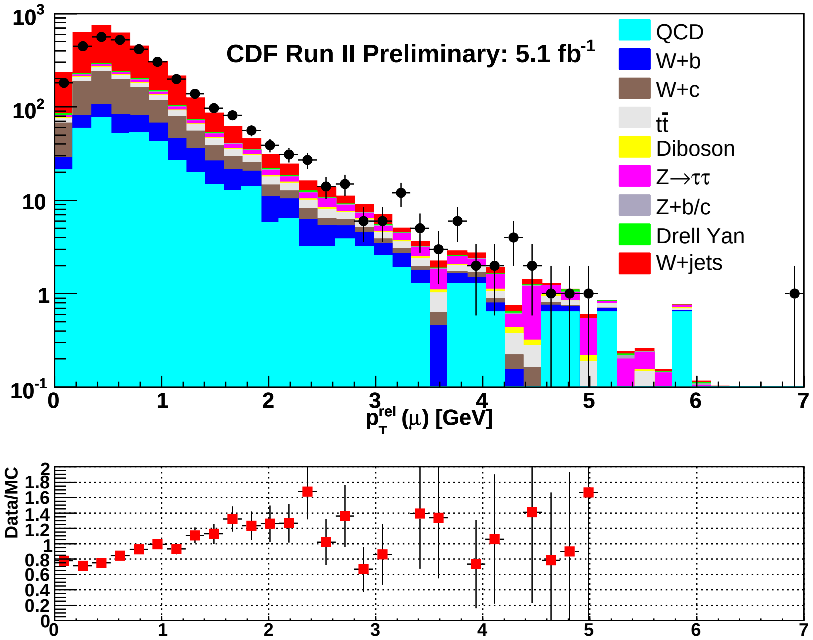


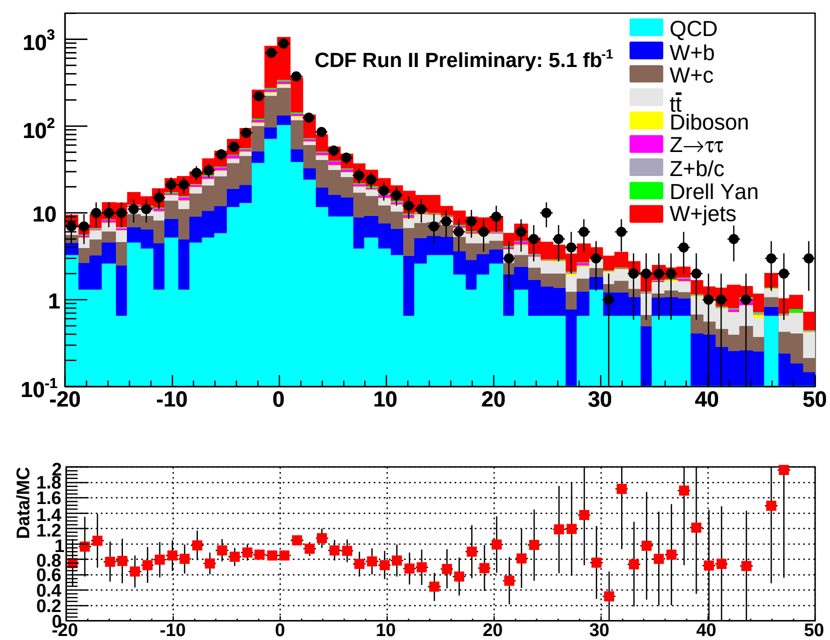
Background Estimation - Heavy Flavor Fraction

- Semileptonic heavy quark decays ($b \rightarrow l\nu c$, $c \rightarrow l\nu s$) are the principal background source of real soft leptons
- We examine distributions sensitive to the heavy flavor fraction in the W/Z + exactly one lepton bin

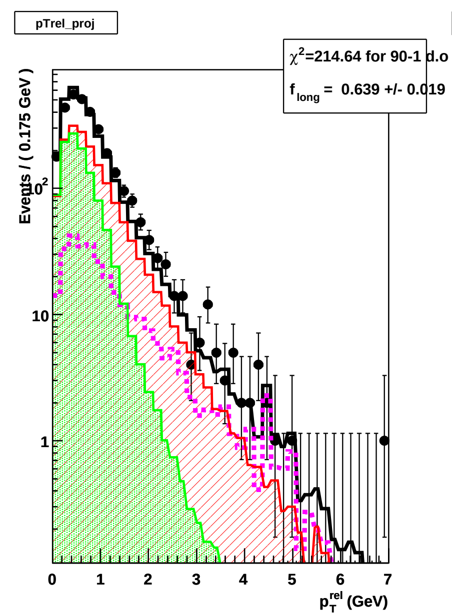


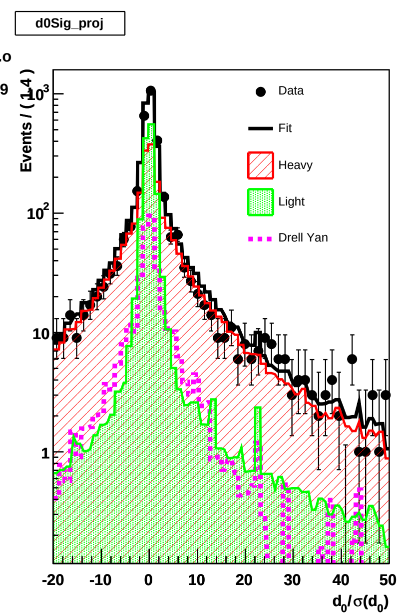






- We fit p_T^{rel} and d_0 of soft muons in the "one additional muon" bin
- We fit to templates from light, heavy, and Drell-Yan processes
- We use the result of this fit to normalize the MC





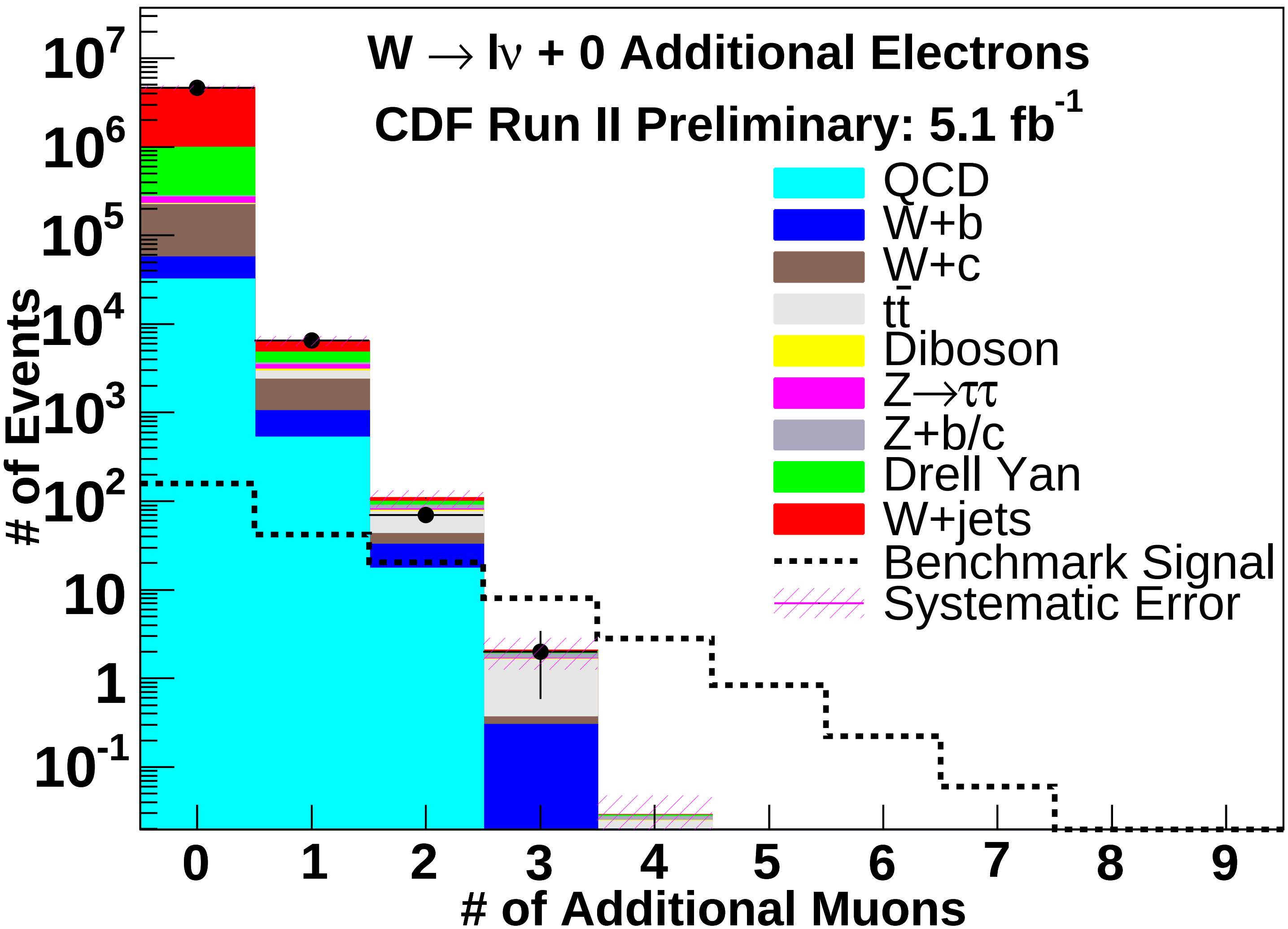
Systematic Uncertainties

Systematic Source	Uncertainty (Percent)	Effect in Large S/B Region (Events)
Trigger Efficiency	±(1.6 - 5.9)%	±0.06
QCD fraction	±26%	0
Soft e real rate	±15%	±0.04
Soft e fake rate	±15%	±0.11
Soft μ real rate	± stat. err. ±8%	±0.64
Soft μ fake rate	±10%	±0.34
Normalization to e or μ	±31% (W), ±39% (Z)	±0.24
Heavy Flavor Fraction	$\pm 5 - 34\%$	±0.25

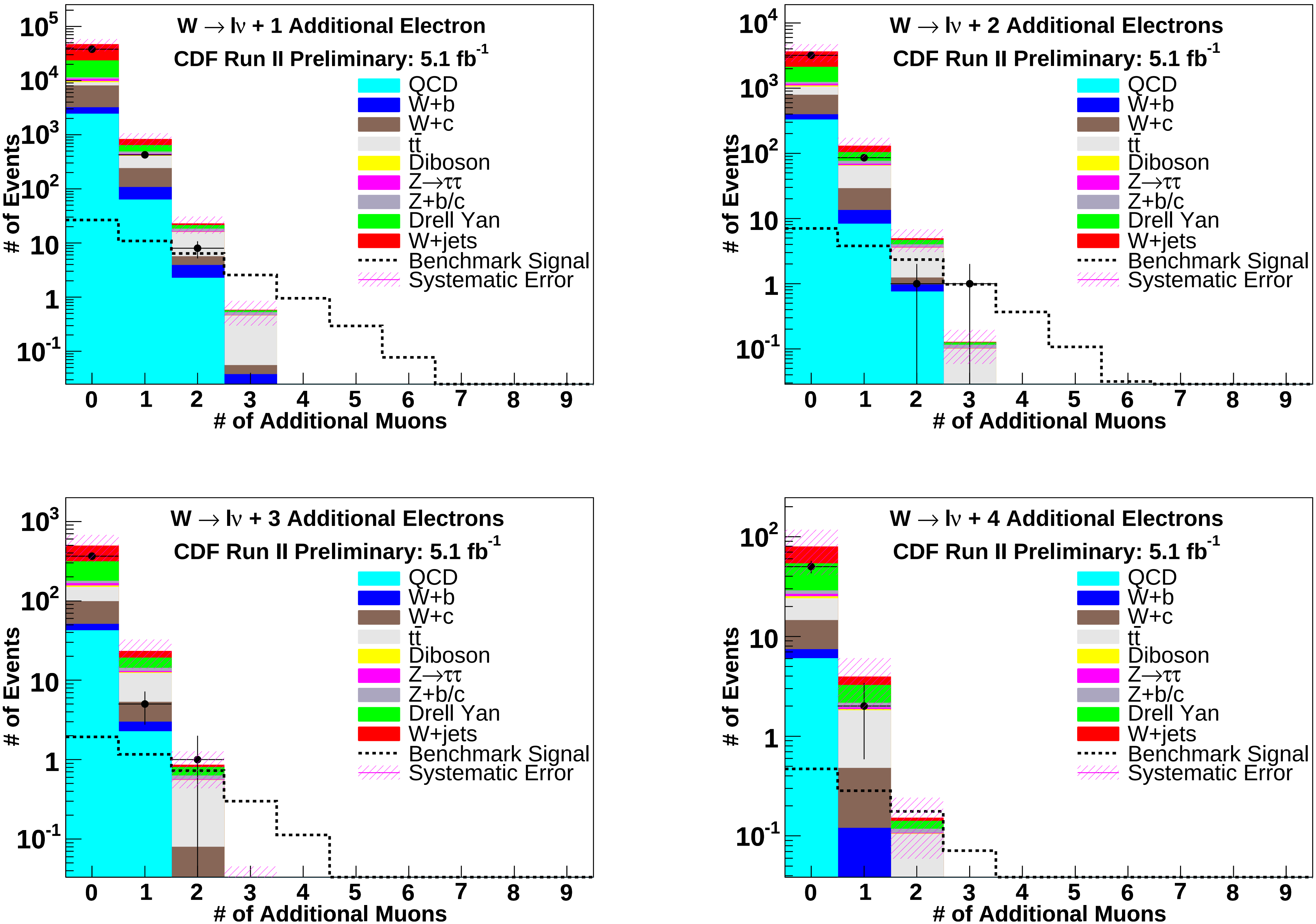
- The "Large S/B Region" is W/Z + 3 or more muons.
- Compare the effects to 2.9 expected SM background events.

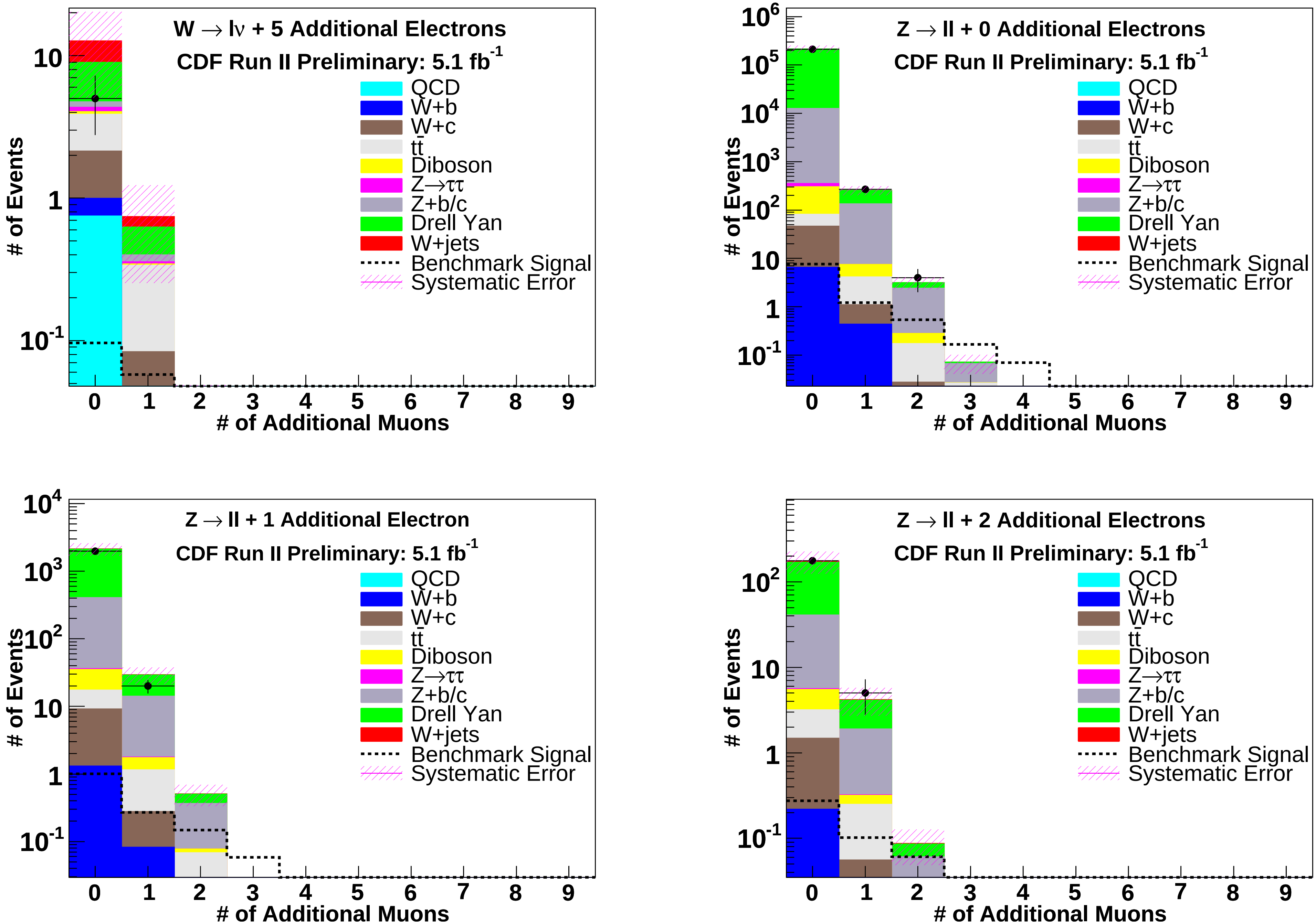
Results

- 2D plot of N_μ vs. N_e, presented in slices of N_e
- Most sensitive in muons, due to photon conversion background

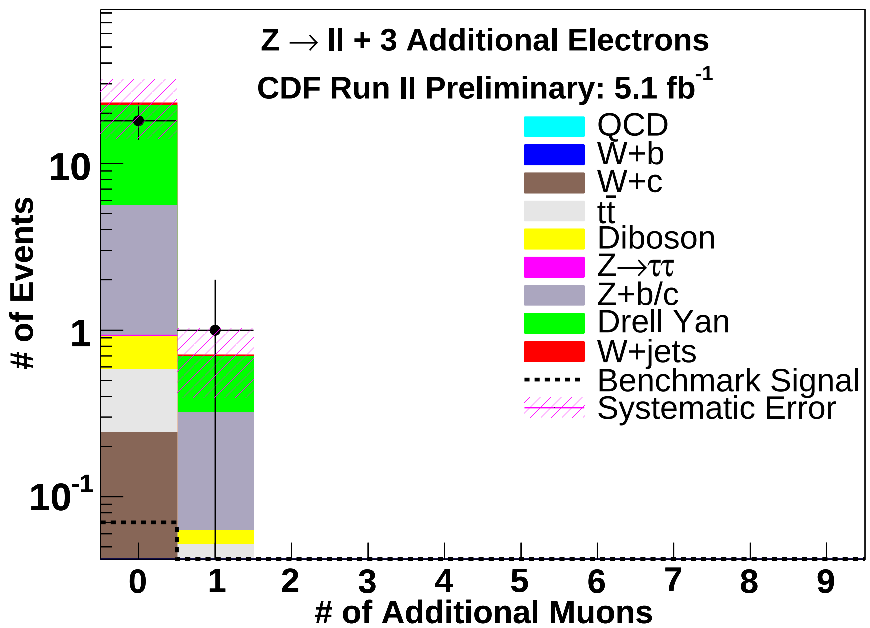


Results

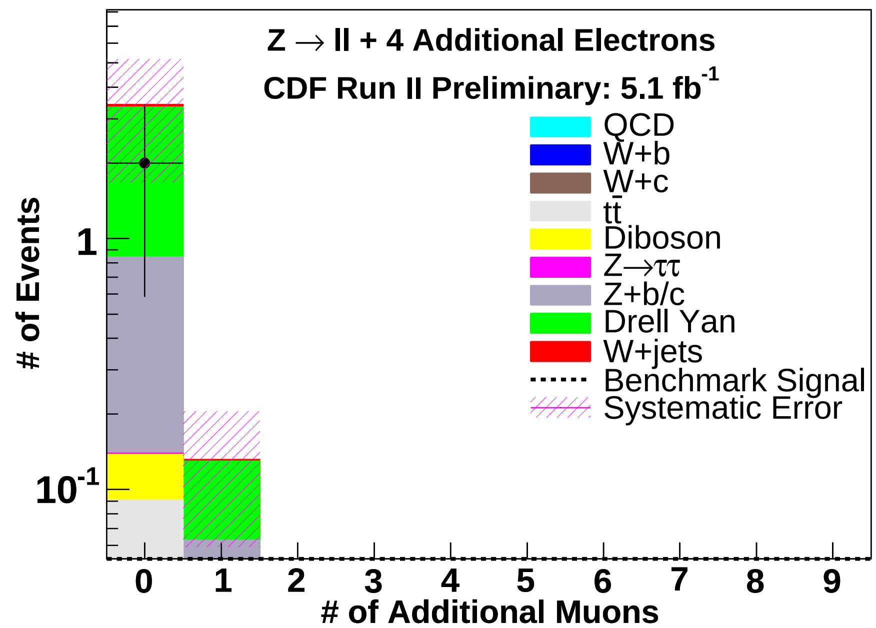

W → lν + 1 Additional Electron
CDF Run II Preliminary: 5.1 fb^{-1}
W → lν + 2 Additional Electrons
CDF Run II Preliminary: 5.1 fb^{-1}
W → lν + 3 Additional Electrons
CDF Run II Preliminary: 5.1 fb^{-1}
W → lν + 4 Additional Electrons
CDF Run II Preliminary: 5.1 fb^{-1}
QCD
W+b
W+c
$t\bar{t}$
Diboson
Z→ττ
Z+b/c
Drell Yan
W+jets
Benchmark Signal
Systematic Error
# of Events
# of Additional Muons


W → lν + 5 Additional Electrons
CDF Run II Preliminary: 5.1 fb-1
Z → ll + 0 Additional Electrons
CDF Run II Preliminary: 5.1 fb-1
Z → ll + 1 Additional Electron
CDF Run II Preliminary: 5.1 fb-1
Z → ll + 2 Additional Electrons
CDF Run II Preliminary: 5.1 fb-1
QCD
W+b
W+c
tt̄
Diboson
Z→ττ
Z+b/c
Drell Yan
W+jets
Benchmark Signal
Systematic Error
# of Events
# of Additional Muons

Results



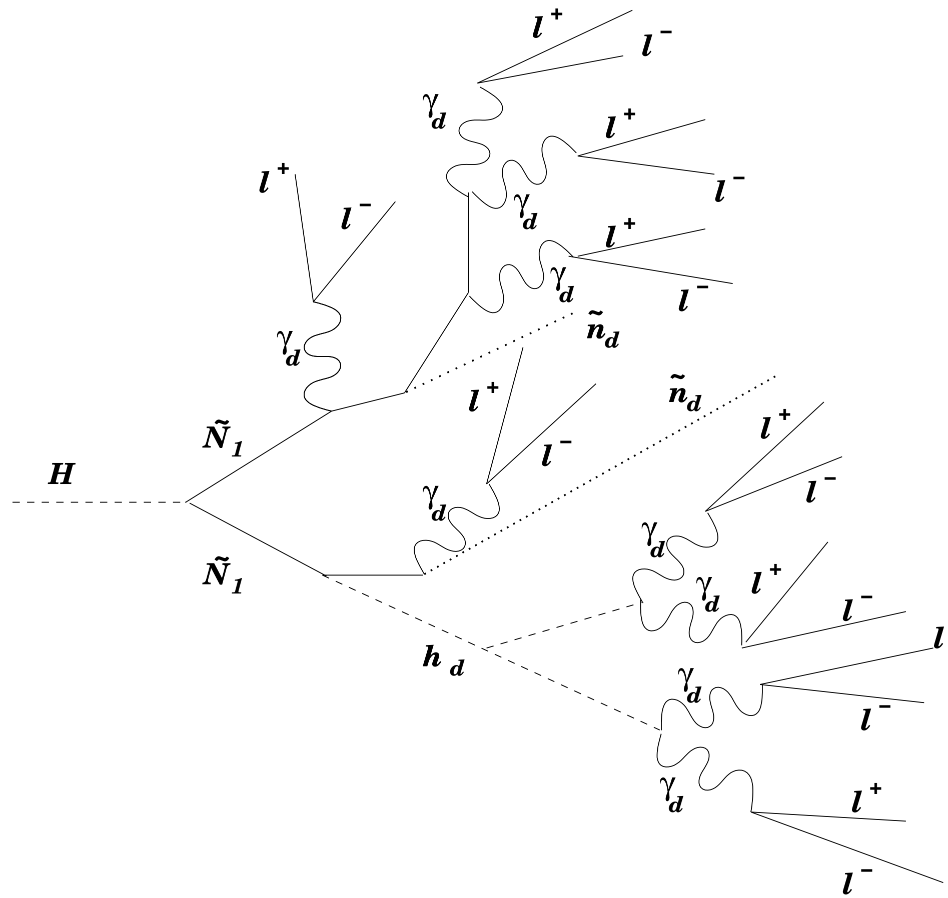
Z → ll + 3 Additional Electrons
CDF Run II Preliminary: 5.1 fb^{-1}
QCD
W+b
W+c
$t\bar{t}$
Diboson
Z→ττ
Z+b/c
Drell Yan
W+jets
Benchmark Signal
Systematic Error
# of Events
# of Additional Muons



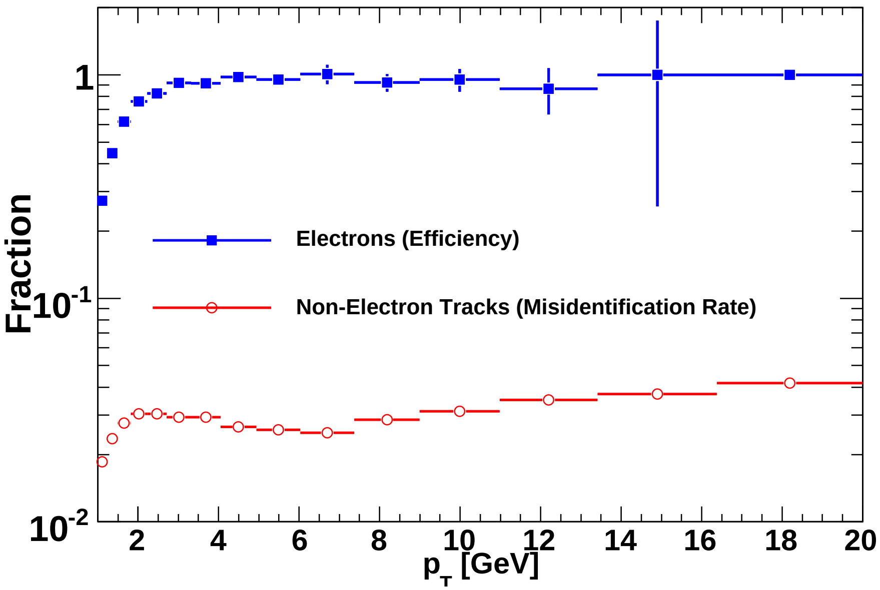
Z → ll + 4 Additional Electrons
CDF Run II Preliminary: 5.1 fb^{-1}
QCD
W+b
W+c
$t\bar{t}$
Diboson
Z→ττ
Z+b/c
Drell Yan
W+jets
Benchmark Signal
Systematic Error
# of Events
# of Additional Muons

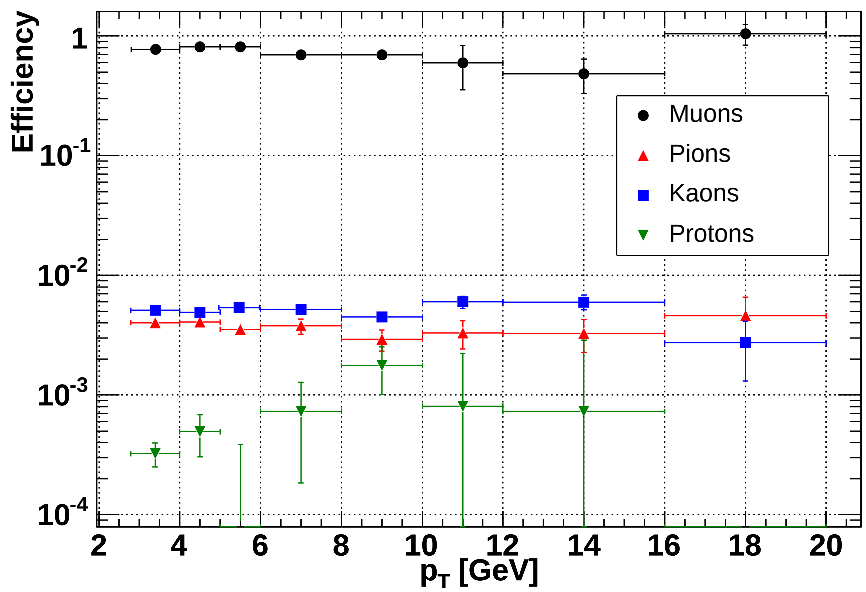
Overview of Benchmark Model

- Adaptation of Neutralino Benchmark Model from A. Falkowski *et al*, arXiv:1002.2952 [hep-ph]
- Particular parameters from Matt Reece (Princeton) and Lian-Tao Wang (U. Chicago)
- Can explain electron and positron cosmic ray excesses (PAMELA, H.E.S.S., Fermi) as DM annihilation
- Leptons are low-energy and non-isolated
- Ruled out at 99.7% confidence



Limits on Other Models

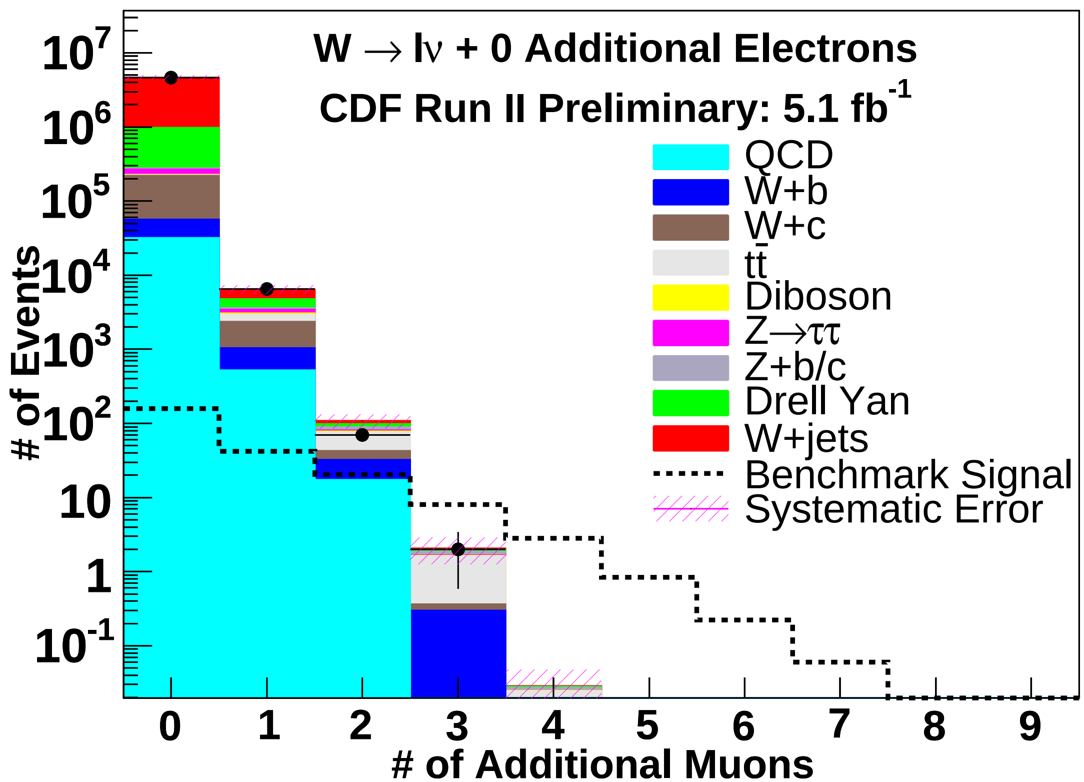




- Take any model, find number of extra leptons it produces
- Use the soft lepton identification efficiency to calculate how many we would find
- Use the number of events we actually found to set a limit

Conclusions

- First analysis of its kind at CDF: counting low-energy objects in a sample triggered on high-energy objects
- Any model that produces multiple leptons can be tested
- Three events with three muons, none with four



Acknowledgements

Thanks to everyone who helped with this analysis

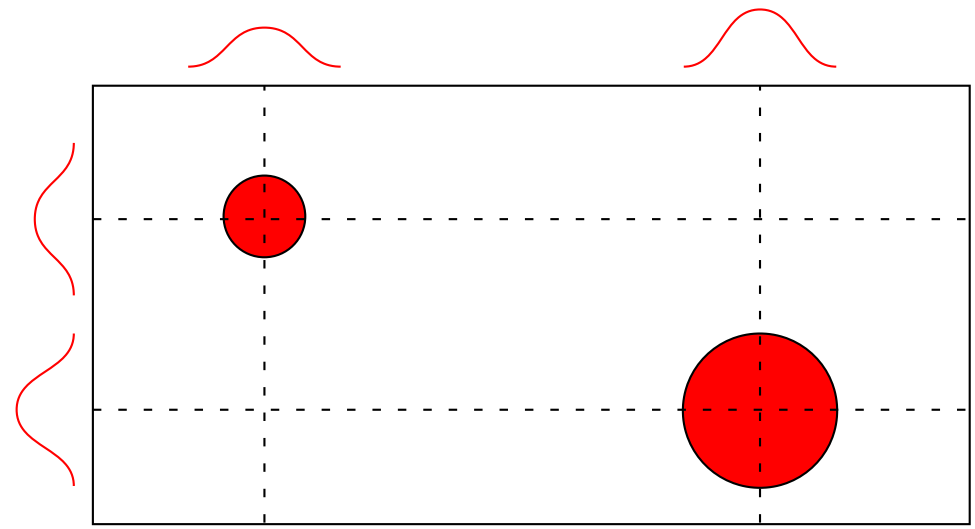
- My advisor, Henry Frisch
- My coworkers, Dan Krop and Carla Pilcher
- My colleauges, who are too many to count
- My thesis committee, Jim Pilcher, Bob Rosner, and Carlos Wagner

Backup Slides

2D CES Algorithm

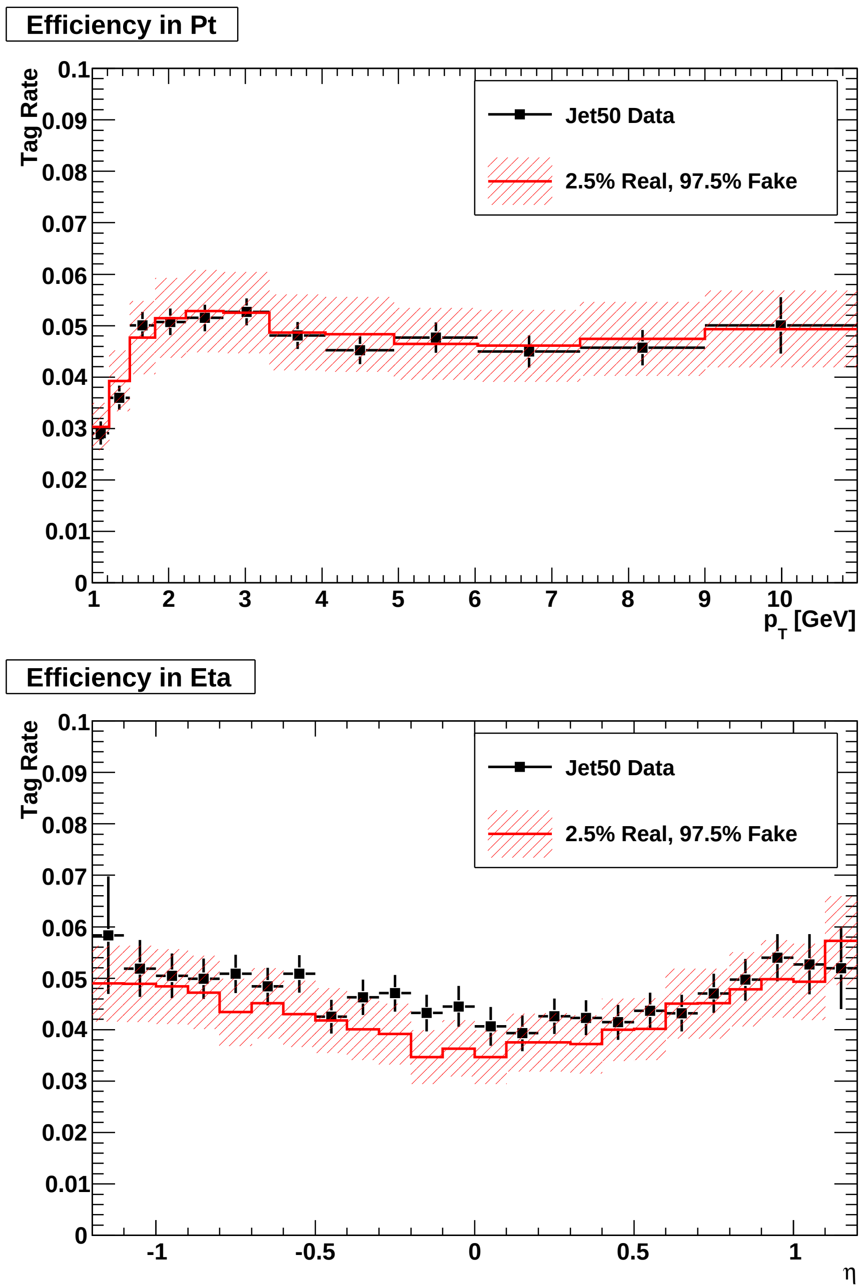
New algorithm for matching tracks to showermax clusters (created by Pasha Murat):

- Calibrate alignment of each wedge, response of each strip and wire
- Match strip and wire clusters into 2D showers
- Better energy and spatial resolution
- Very useful when two clusters are at the same x or z



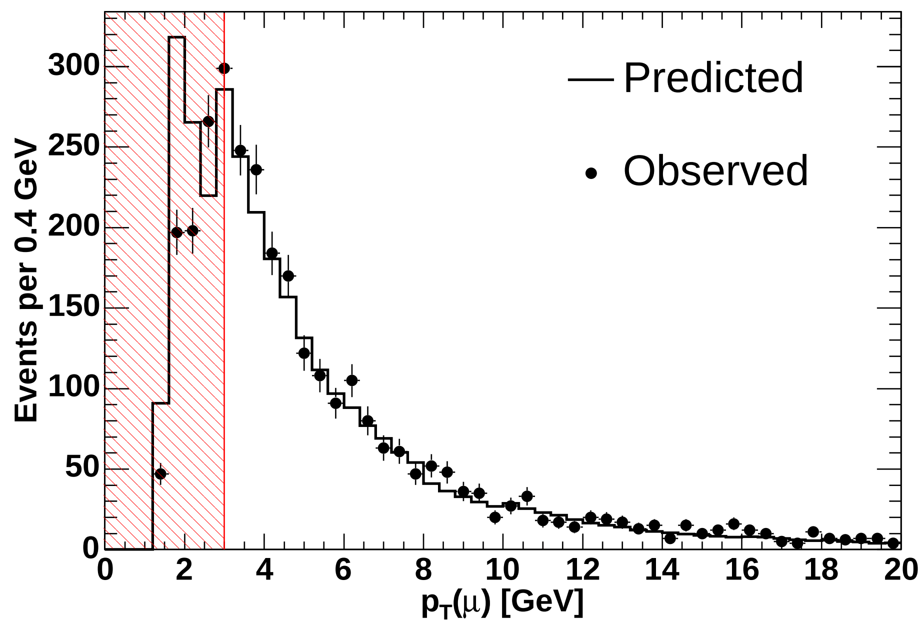
Soft Electron Systematic Uncertainty

- We use the `JET50` sample as a cross-check of the parameterizations
- We calculate an expected ID probability for each candidate track and compare it to the actual ID rate
- We calculate an expected 6448 identified electrons and observe 6345 - a 1.6% difference
- We assign a 15% systematic uncertainty to cover the observed shape differences in p_T and η
- We let the real ID rate and the mis-ID rate vary independently by this factor



Soft Muon Systematic Uncertainty

- We validate the fake rates by applying the matrix to taggable tracks in JET100 data and comparing the predicted and observed distributions.
- We see good agreement above range-out region, $p_T > 3$ GeV.
- We predict 2220 observed muons and observe 2331 - a difference of 5%.
- We assign a systematic uncertainty of twice the difference, or 10%.



Background Estimation - Normalization

- We scale the background estimate to the one additional lepton bin
  - Expected to be dominated by Standard Model (heavy flavor, Drell-Yan, etc.)
- Since we performed the heavy flavor fit in the 'one additional muon' bin, the MC is already normalized there
- There is a mismatch between data and MC in the 'one additional electron' bin of about 35%
- In events that have at least one additional electron, we add a systematic uncertainty to cover that difference

Results Summary - W

Bins with < 0.25 events expected in BG and signal, and none observed, are not shown.

N_e	N_μ	Predicted SM Background	Predicted Dark Higgs Signal	Observed
0	0	4623512 ± 315244	158	4673896
0	1	6463 ± 807	42	6498
0	2	109 ± 24	21	70
0	3	2.1 ± 0.79	8.0	2
0	4	0.029 ± 0.019	2.8	0
0	5	0.00026 ± 0.00023	0.83	0
1	0	46055 ± 11387	27	37778
1	1	824 ± 230	11	425
1	2	23 ± 7.8	6.4	8
1	3	0.58 ± 0.27	2.6	0
1	4	0.010 ± 0.0074	0.95	0
1	5	0.00011 ± 0.00011	0.29	0

Results Summary - W (continued)

N_e	N_μ	Predicted SM Background	Predicted Dark Higgs Signal	Observed
2	0	3600 ± 1085	7.1	3184
2	1	129 ± 43	3.8	86
2	2	4.9 ± 1.8	2.3	1
2	3	0.13 ± 0.067	0.97	1
2	4	0.0031 ± 0.0024	0.37	0
3	0	491 ± 185	1.9	366
3	1	23 ± 9.3	1.2	5
3	2	0.85 ± 0.42	0.72	1
3	3	0.028 ± 0.017	0.30	0
4	0	79 ± 38	0.47	50
4	1	3.9 ± 2.1	0.28	2
5	0	13 ± 7.6	0.096	5
5	1	0.74 ± 0.49	0.058	0
6	0	2.0 ± 1.5	0.015	0

Results Summary - Z

N_e	N_μ	Predicted SM Background	Predicted Dark Higgs Signal	Observed
0	0	215219 ± 36886	7.6	211448
0	1	255 ± 52	1.2	270
0	2	3.2 ± 0.89	0.54	4
1	0	2145 ± 447	1.0	1975
1	1	30 ± 8.1	0.27	20
1	2	0.51 ± 0.18	0.15	0
2	0	175 ± 50	0.28	176
2	1	4.2 ± 1.5	0.10	5
3	0	23 ± 9.0	0.070	18
3	1	0.71 ± 0.31	0.031	1
4	0	3.4 ± 1.8	0.019	2
5	0	0.52 ± 0.35	0.0044	0

Dark Sector Hidden Higgs Model

- SUSY Parameters: $\mu = 149$ GeV, $m_{\tilde{N}_1} = 13$ GeV, $m_{\tilde{N}_2} = 286$ GeV, $\tan(\beta) = 3.5$, $\sin(\alpha) = -0.28$
  - SUSY LSP: $m_{\chi_0} = 10$ GeV
- $m_H = 120$ GeV
- Dark Sector:
  - $m_{\chi_d} = 1$ GeV, $m_{\gamma_d} = 300$ MeV
  - $\gamma_d \to e^+e^-$ (52.5%)
  - $\gamma_d \to \mu^+\mu^-$ (46.6%)
  - $\gamma_d \to \pi^+\pi^-$ (0.9%)
- Model the χ_0 decay to dark sector:
  - $\chi_0 \to \chi_d + 2\gamma_d$ (33%)
  - $\chi_0 \to \chi_d + 3\gamma_d$ (33%)
  - $\chi_0 \to \chi_d + 4\gamma_d$ (33%)