Beyond the Standard Model: Searches at the Tevatron

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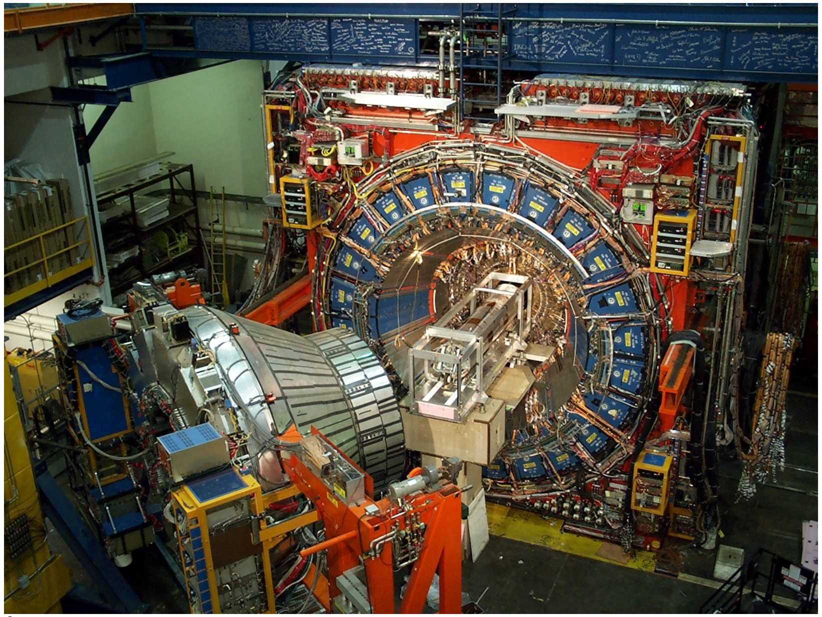
With thanks to the CDF and DØ Collaborations

Introduction

- First off, BSM searches cover a LOT of territory
  - Both in terms of the actual models themselves and the possible signatures from these models
  - If you can imagine it, you can search for it...
- I can't possibly cover every analysis done by CDF and DØ, but I'll try to give a broad overview and hit the highlights
  - I've tried to focus on results with 1 fb^{-1} (or more) of integrated luminosity

The Tevatron

- For the moment, it's still the highest energy collider in the world (at 1.96 TeV)
- DØ (top) and CDF (bottom) are the two general purpose detectors at the Tevatron
- Each experiment has recorded about 5 fb^{-1} of $p\bar{p}$ collision data

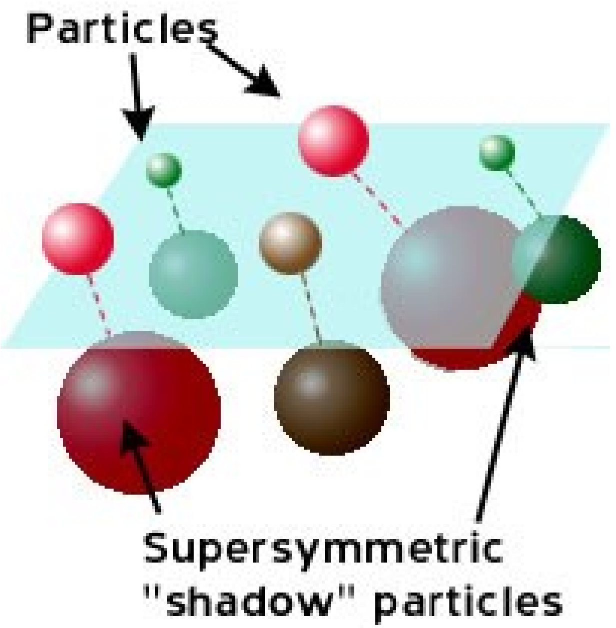


Outline

- Searches for Supersymmetry
  - Trileptons, Squarks/gluinos, RPV, GMSB
- High mass resonance searches
- Extra dimensions searches
  - Larges extra dimensions and Randall-Sundrum gravitons
- Leptoquark and new quark searches
- Generic/Model-independent Searches
- “Other” searches

Supersymmetry

- SUSY predicts that each standard model particle will have a SUSY partner
  - Must be a broken symmetry, or the “sparticles” would have the ~same mass as the SM particles (and we would have seen them by now)
- SUSY phenomenology is driven by how SUSY is broken
  - Most generic has ~100 free parameters
  - Much easier to work with mSUGRA, GMSB, or other SUSY breaking models with ~5 free parameters



General SUSY Properties

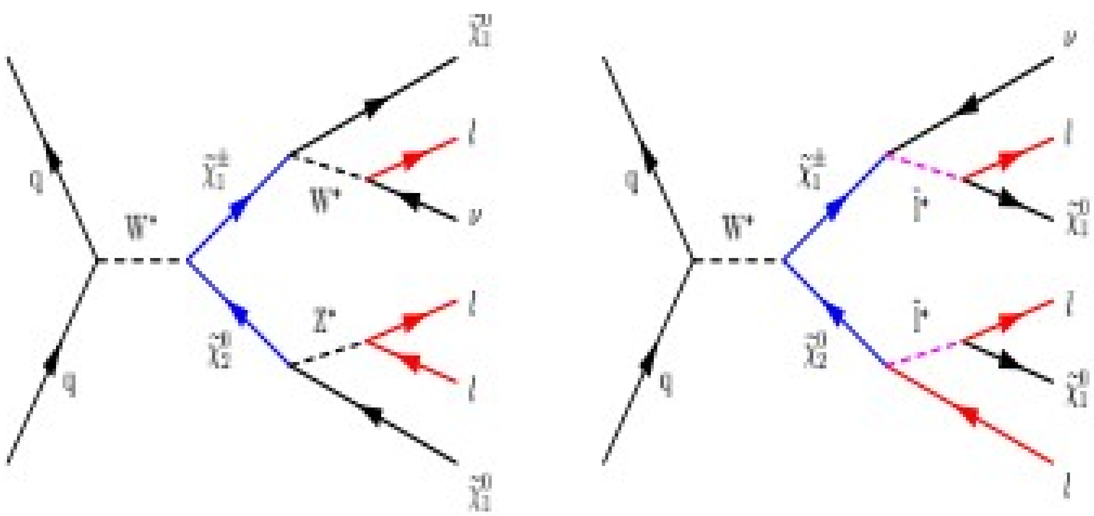
- It's important to remember that SUSY models in themselves represent a huge variety of possible signatures
- There are some general properties (but even these are not set in stone!)
  - Lightest supersymmetric particle (LSP) is stable and neutral (good dark matter candidate)
    - ⇒ produces missing energy (MET) in the detector
  - Heavier SUSY particles decay to SM particles and (eventually) the LSP
    - ⇒ typical signature is SM particles (leptons and/or jets) and missing energy
  - SUSY particles are produced in pairs

General Comment on SUSY Limits

- Generally, SUSY searches produce a limit on either a sparticle's mass (or production cross section) or on the parameters of a particular SUSY breaking model
  - One always has to remember that these limits are made with specific assumptions about the other meaningful parameters of the SUSY model!
  - This also means that it is not always easy to directly compare limits between different experiments (unless they use EXACTLY the same model parameters, which unfortunately is the exception rather than the rule...)

Trileptons

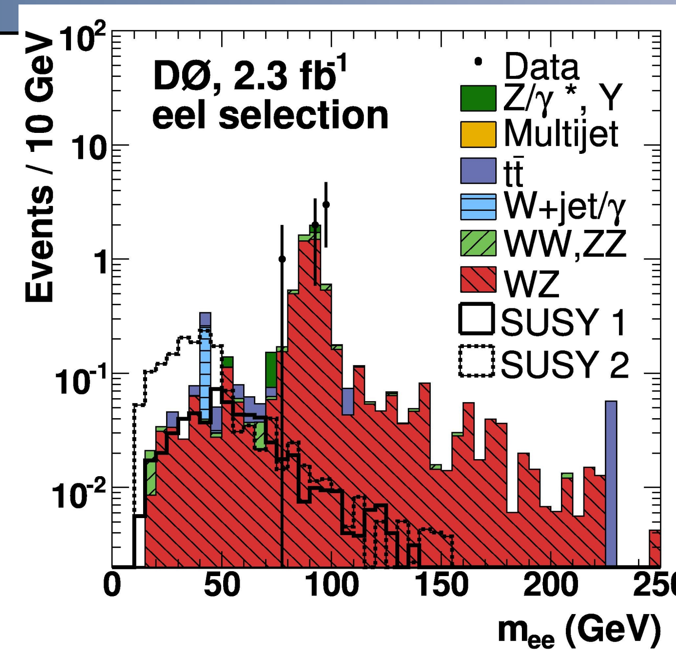
- At a “messy” hadron collider, final states with leptons are relatively clean
  - Both in terms of triggering and separating from multijet backgrounds



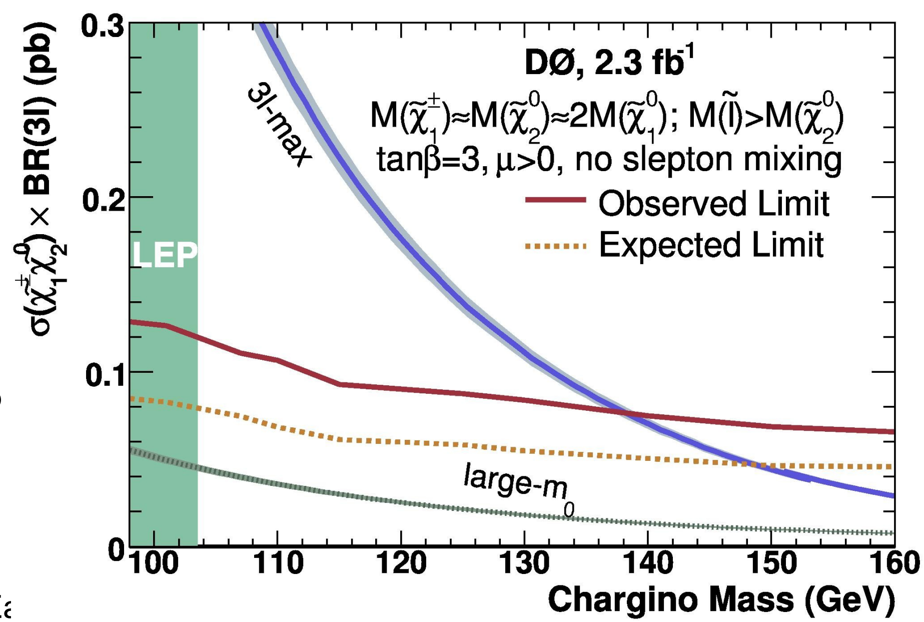
- Chargino/neutralino production (the partners of the charged/neutral SM gauge bosons) typically have a relatively large cross section
- Final state is 3 leptons + MET
  - Branching fraction small, but very clean final state with small backgrounds
  - Lepton pT depends on the mass relationships

DØ Trilepton Search

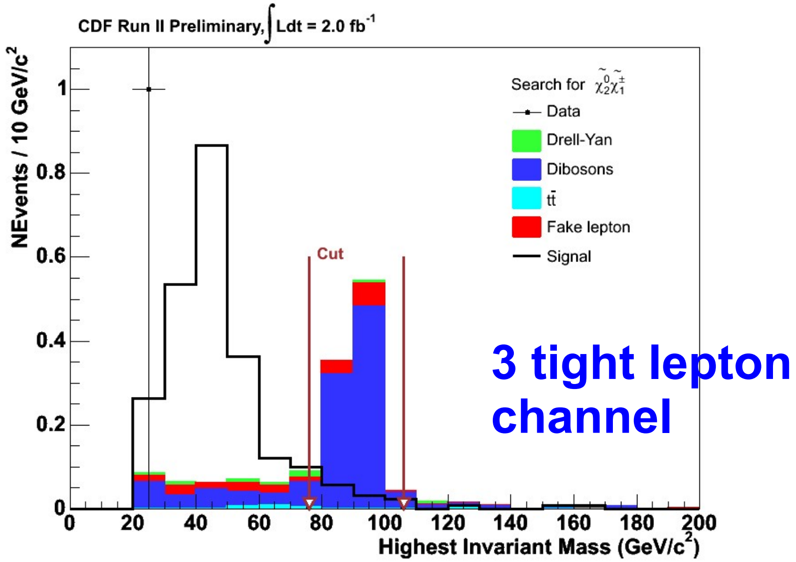
- Combines a μμl, μτl, eμl, μττ, and eel selection
  - l = isolated track in central tracker
- After all selections, obtain 0-4 events in data
  - Expect O(1) SUSY events
  - Consistent with background estimates (dominated by WZ production)
- Limits set on chargino mass (for several models) and for mSUGRA

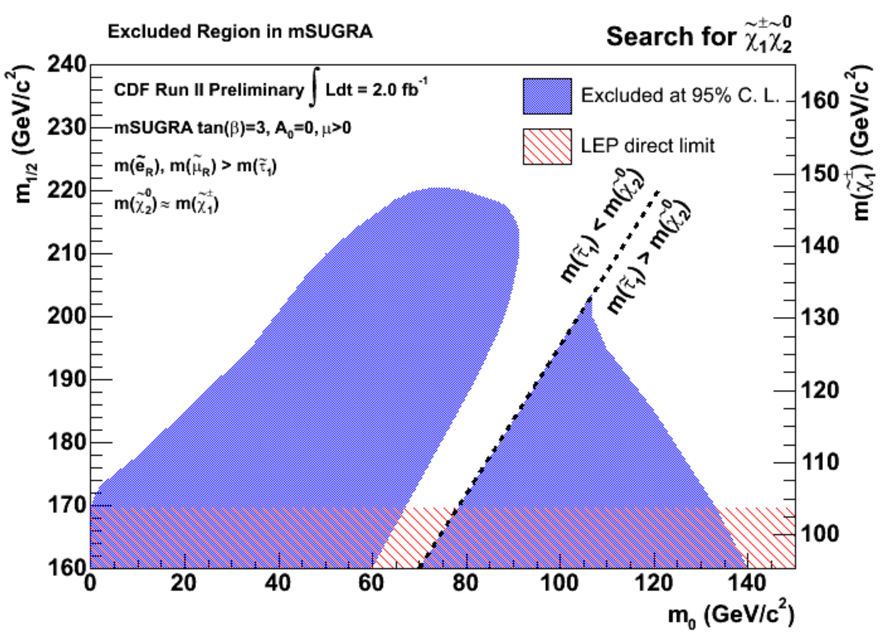


arXiv: 0901.0646, submitted to PLB



CDF Chargino/Neutralino Search with Leptons



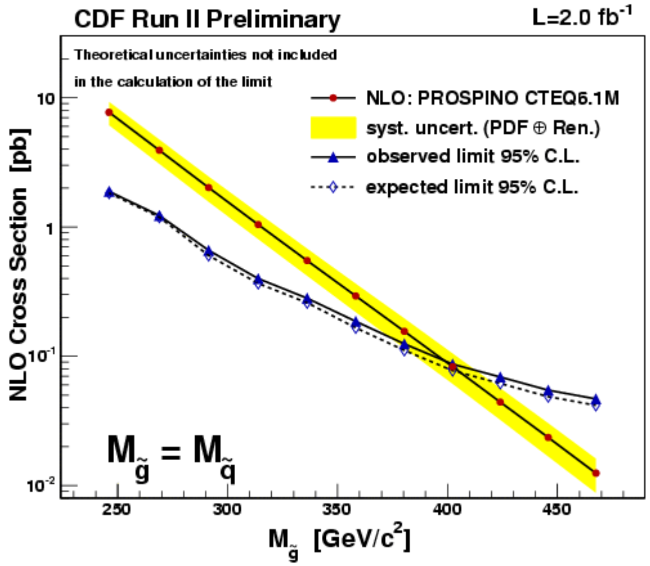


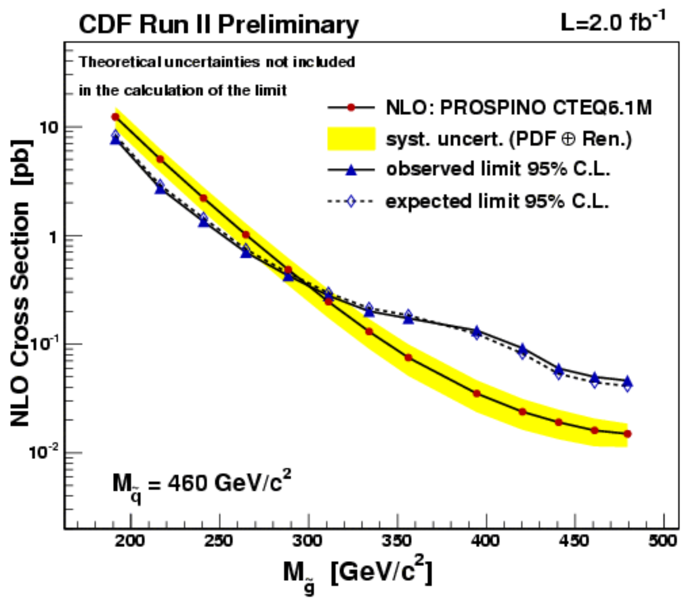
- 5 separate channels (3 tight leptons, 2 tight + 1 loose, 1 tight + 2 loose, 2 tight + 1 track, and 1 tight + 1 loose + 1 track, where “lepton” means e or μ)
- Expect about 6 background events (dominated by SM diboson production) and 4-7 SUSY events, observe 7 events
- Limits set on chargino mass (for several choices of parameters) and on mSUGRA model parameters

Squarks/Gluinos

- The production cross section for squarks and gluinos is typically larger than that for chargino/neutralino production
  - Squarks/gluinos then decay to quarks and gluons and the LSP is produced in the decay chain
    - ⇒ detector signature is multiple jets and missing energy
  - The exact number of jets produced (and the p_T of these jets) is determined by the mass relationships between squarks and gluinos
    - Can produce 2, 3, or 4 (or more) jets (with missing energy from the LSP)

CDF Squark/Gluino Search

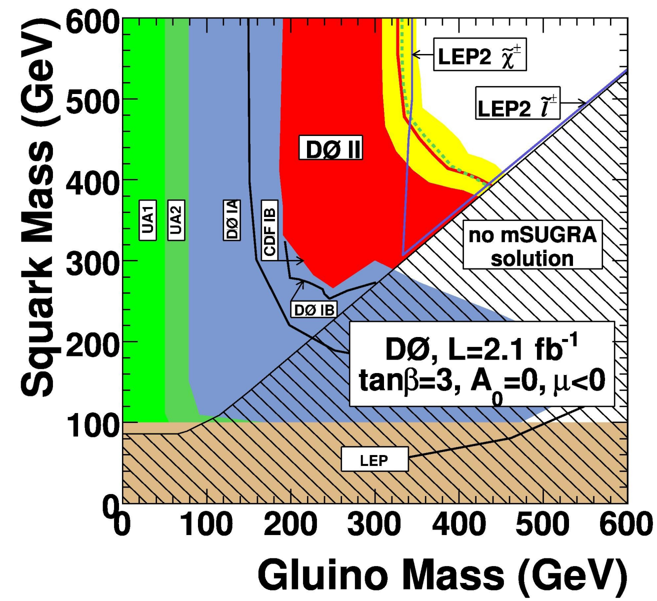


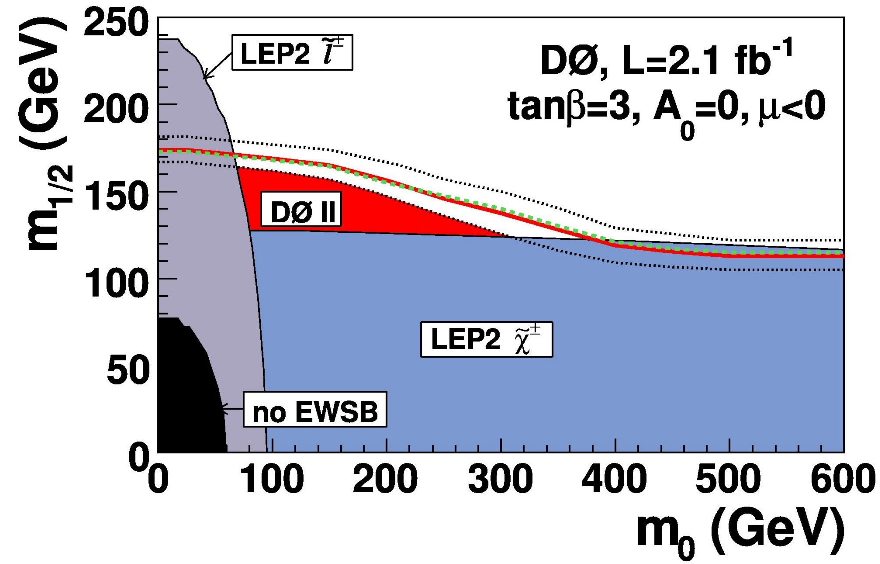


- Divided into 2/3/4 jet (+ MET) final states
- Select 18/38/45 data events, with 16±5/37±12/48±17 expected background events
  - Background dominated by multijets and W/Z+jets
- Set limits on squark and gluino masses, as well as on mSUGRA parameters

DØ Squark/Gluino Search

- Divided into 2/3/4 jet (+ MET) channels
- Selects 11/9/20 events, which is consistent with background estimates
  - Expect ~10 signal events
  - Main backgrounds from Z+jets, W+jets, and ttbar
- Limits set on squark and gluino masses, and mSUGRA parameters





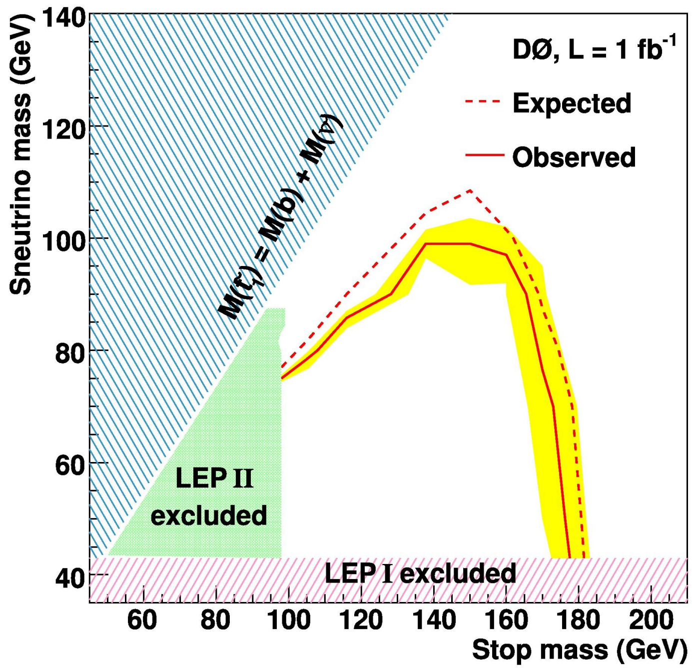
PLB **660**, 449 (2008)

Stop/Sbottom Searches

- Due to mixing, the 3rd generation squarks and sleptons should be the lightest
  - Since stops/sbottoms are lighter than the other squarks, they should have the largest production cross section
  - The decays of the stop and sbottom depend on various mass relationships
  - Possibilities for stop include
    - Stop → *c* + neutralino
    - Stop → *b* + lepton + sneutrino
    - Stop → *b* + W + neutralino
  - Each decay results in a different signature

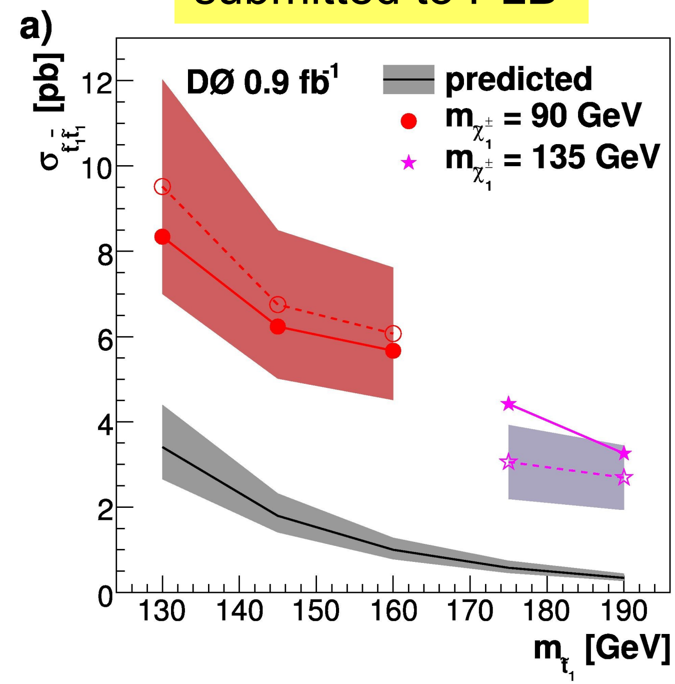
DØ Stop Searches

arXiv: 0811.0459,
submitted to PLB



Assume two stops produced which each decay to$b$+l+sneutrino.
Primary SM backgrounds are ttbar and diboson.
Set limits in stop mass versus sneutrino mass plane.

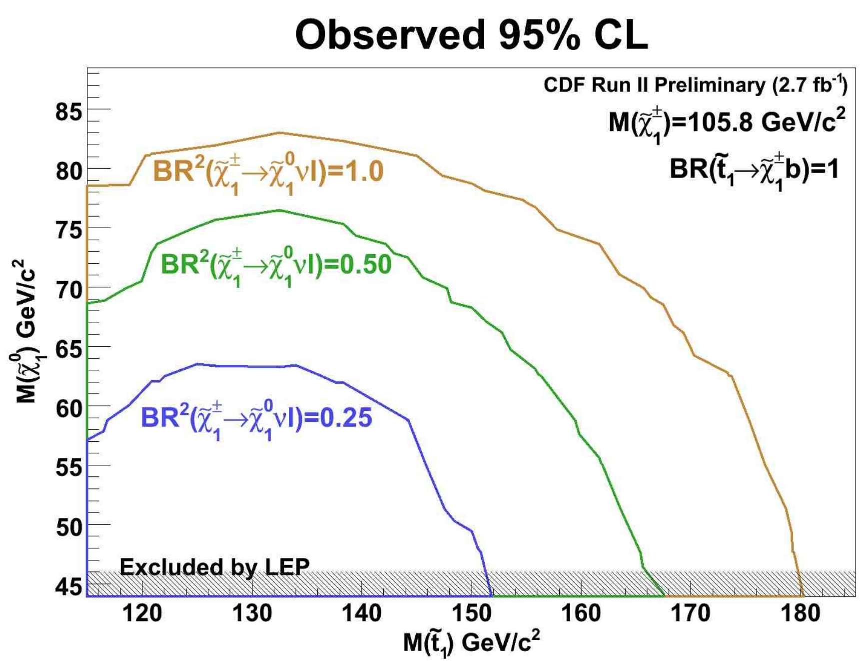
arXiv: 0901.1063,
submitted to PLB



Assume two stops produced which each decay to a b and the lightest chargino (which then decays to a W and the lightest neutralino).
Use kinematic differences to separate from ttbar background.
Set cross section limits for different chargino/neutralino masses.

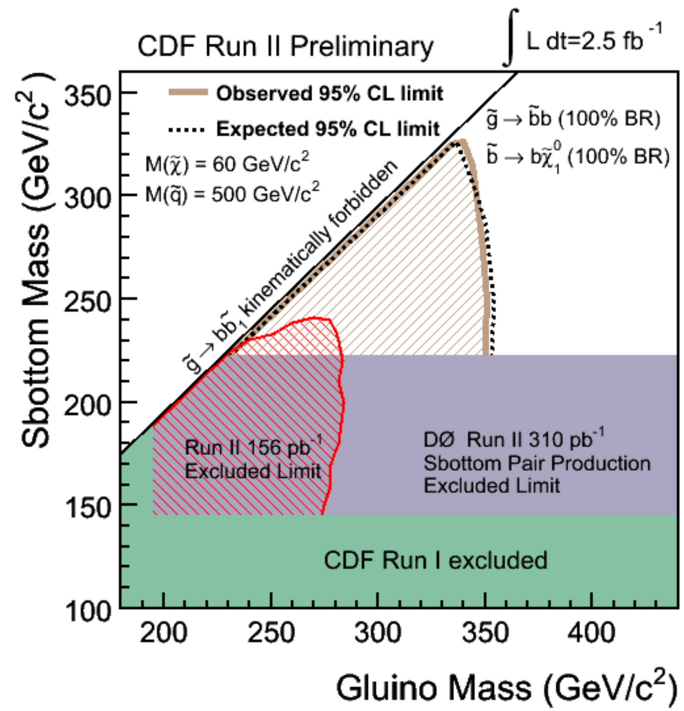
CDF Stop/Sbottom Searches

Pair Production of Stop Quarks Mimicking Top Event Signatures



Assume two stops produced which decay to b+l+ν+neutralino.
Reconstruct stop mass to separate from ttbar.
Set limits in neutralino mass versus stop mass plane.

Gluinio-Mediated Sbottom Production



Two gluinos produced which each decay to 2b quarks and a neutralino, resulting in a 4b+MET final state.
Use a neural net to separate from multijet and mistagged background.
Set limits on gluino cross section versus gluino mass and in gluino/sbottom mass plane.

RPV SUSY

- It is usually assumed that SUSY models conserve *R-parity*
  - Results in stable LSP and sparticles produced in pairs
- But, there is no reason that R-parity needs to be absolutely conserved
  - Can be violated with either lepton- or baryon-number violating terms
  - There are limits from (for example) flavor-changing neutral currents, so the amount of R-parity violation should be small
- With RPV interactions, LSP isn't stable and single SUSY particles can be produced

CDF High-Mass Resonances Decaying to Lepton Pairs

$e\tau$ channel

signal mass (GeV/c^2)	mass cut (GeV/c^2)	SM background events	observed events	exp. signal events	exp. limit (pb)	obs. limit (pb)
100	> 80	332.4 ± 13.1	343	827.1 ± 60.0	21.09	21.16
200	> 160	22.7 ± 1.4	21	116.4 ± 6.8	1.02	0.96
300	> 230	5.0 ± 0.5	5	31.8 ± 1.6	0.19	0.19
400	> 280	2.1 ± 0.4	2	10.9 ± 0.5	0.096	0.092
500	> 310	1.4 ± 0.3	2	3.9 ± 0.1	0.069	0.077
600	> 340	1.0 ± 0.3	0	1.3 ± 0.05	0.055	0.039
700	> 360	0.9 ± 0.2	0	0.4 ± 0.02	0.055	0.040
800	> 360	0.9 ± 0.2	0	0.1 ± 0.004	0.050	0.037

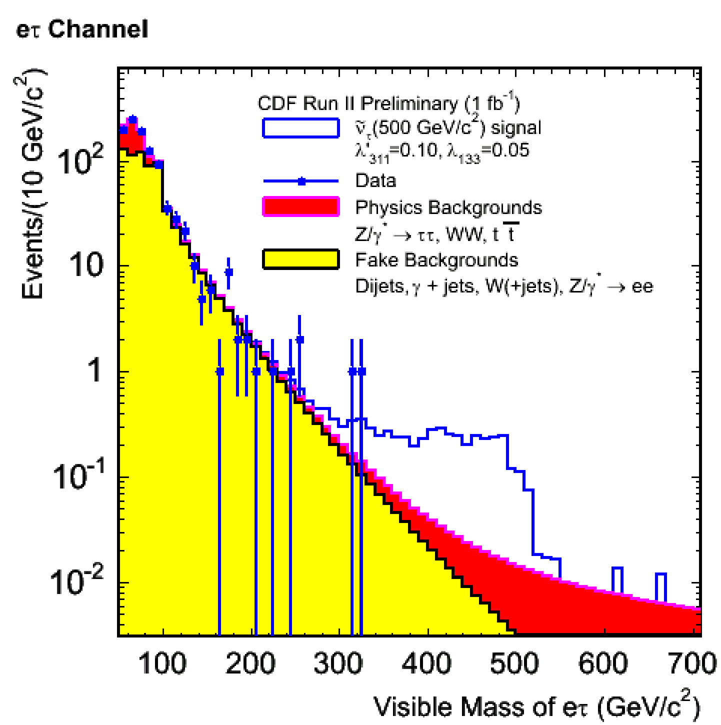
$\mu\tau$ channel

signal mass (GeV/c^2)	mass cut (GeV/c^2)	SM background events	observed events	exp. signal events	exp. limit (pb)	obs. limit (pb)
100	> 80	153.1 ± 10.8	135	548.2 ± 48.8	14.76	13.01
200	> 160	9.3 ± 1.3	2	87.2 ± 5.9	0.66	0.26
300	> 220	2.6 ± 0.5	1	24.1 ± 1.4	0.19	0.16
400	> 240	1.8 ± 0.4	0	8.6 ± 0.4	0.12	0.093
500	> 280	1.0 ± 0.3	0	2.8 ± 0.1	0.081	0.080
600	> 320	0.6 ± 0.2	0	0.91 ± 0.04	0.072	0.056
700	> 350	0.4 ± 0.2	0	0.28 ± 0.01	0.065	0.053
800	> 370	0.4 ± 0.2	0	0.08 ± 0.003	0.062	0.052

$e\mu$ channel

signal mass (GeV/c^2)	mass cut (GeV/c^2)	SM background events	observed events	exp. signal events	exp. limit (pb)	obs.limit (pb)
100	> 90	22.8 ± 2.4	22	3029.2 ± 114.8	0.45	0.43
200	> 190	3.2 ± 0.5	3	405.9 ± 12.8	0.062	0.058
300	> 280	0.6 ± 0.2	0	98.0 ± 2.8	0.032	0.024
400	> 360	0.2 ± 0.2	0	27.9 ± 0.7	0.024	0.022
500	> 450	0.1 ± 0.1	0	8.3 ± 0.2	0.021	0.020
600	> 500	0.06 ± 0.1	0	2.6 ± 0.07	0.021	0.020
700	> 550	0.05 ± 0.09	0	0.9 ± 0.02	0.020	0.020
800	> 600	0.04 ± 0.08	0	0.2 ± 0.01	0.019	0.018

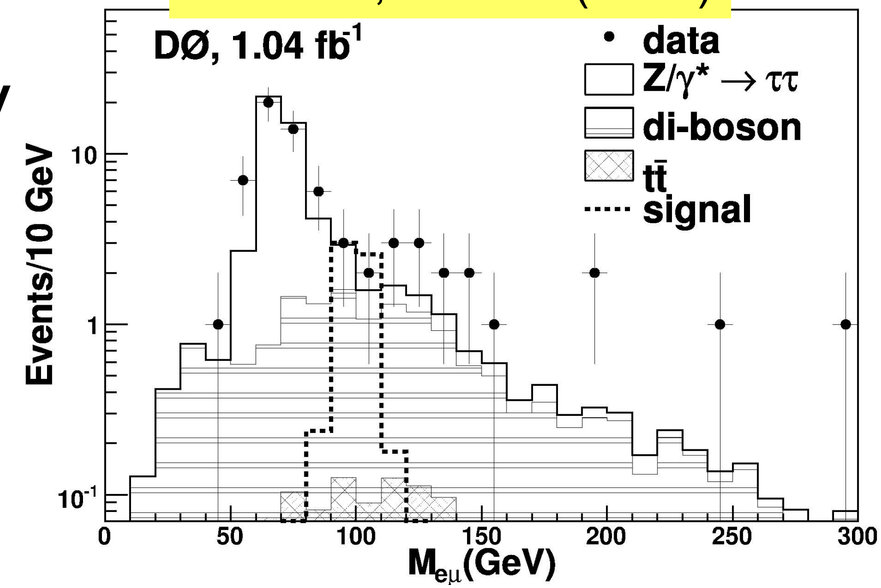
- Single sneutrino produced in lepton-flavor violating RPV interaction, decays to pairs of leptons
- Use eμ, eτ, μτ final states

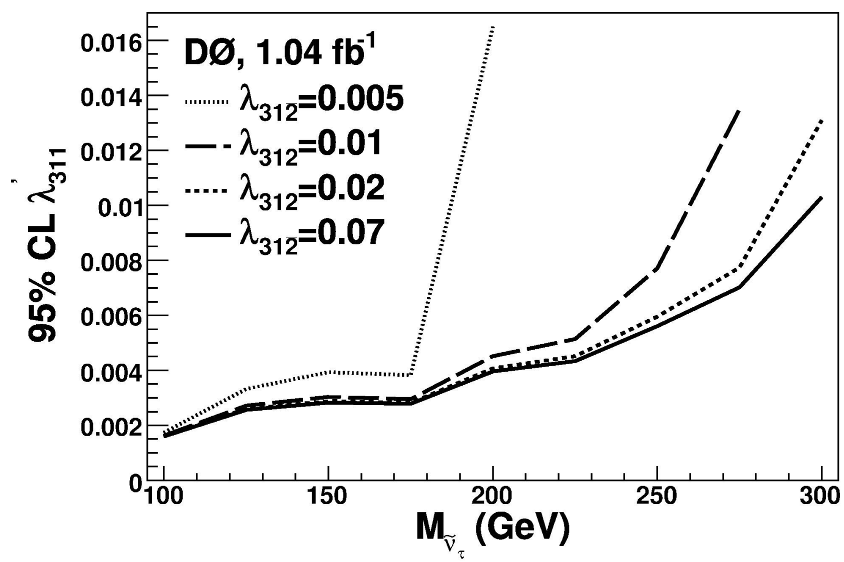


DØ Scalar Sneutrino in eμ

- Produce a single sneutrino via a lepton-number violating RPV interaction, then decays to an electron and a muon.
- Main background is SM diboson production
- Observe 68 events, expect 59.2±5.3 from backgrounds.
- Single would show up as peak in the eμ mass spectrum
- Set limits on two RPV couplings (versus sneutrino mass)

PRL **100**, 241803 (2008)





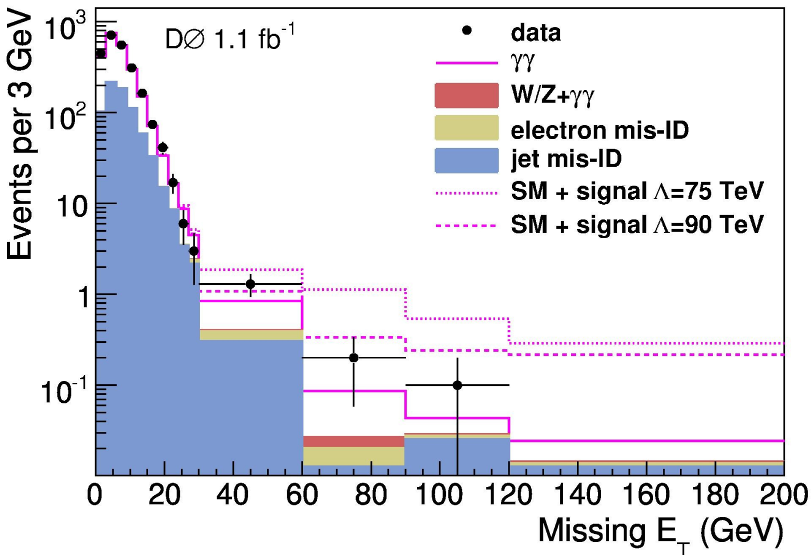
GMSB

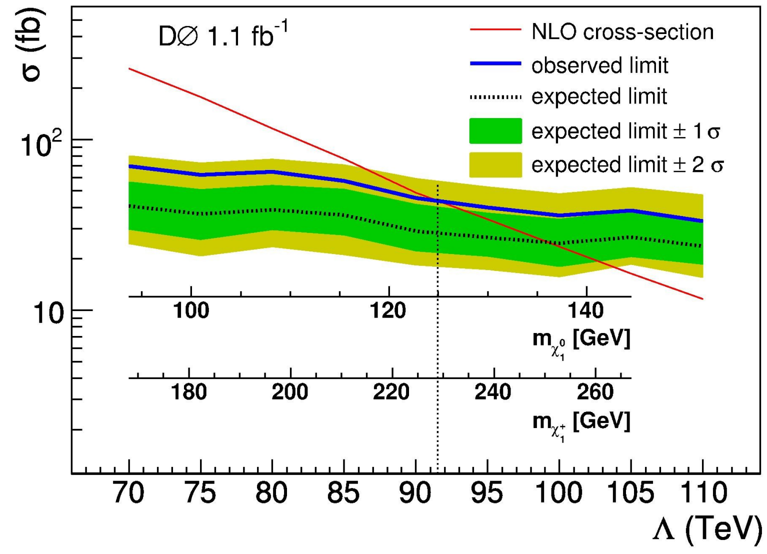
- In gauge-mediate supersymmetry breaking, SUSY is broken in a hidden sector. This breaking is then communicated to the SM via messenger fields and standard gauge interactions.
- The LSP is the gravitino
- SUSY particles will eventually decay to the LSP through the next-to-lightest SUSY particle (NLSP)
  - NLSP can be the lightest neutralino or a slepton (usually the lightest stau)
  - NLSP decays to LSP can be suppressed, resulting in long NLSP lifetimes!

DØ Diphoton Search

- Assume the NLSP is the neutralino, which decays to a photon and a gravitino. This produces a 2 photon + MET signature.
- Most troublesome backgrounds are jets and electrons faking photons
- Set limits on chargino and neutralino masses

PLB **659**, 856 (2008)



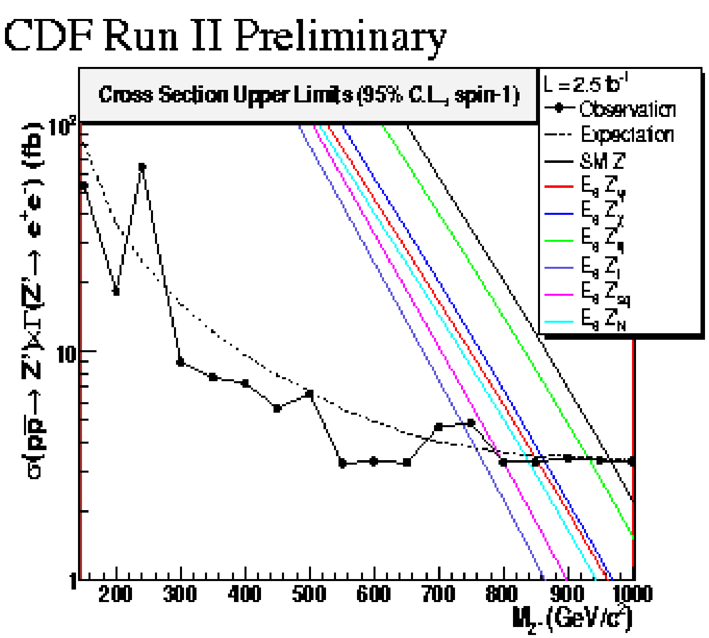


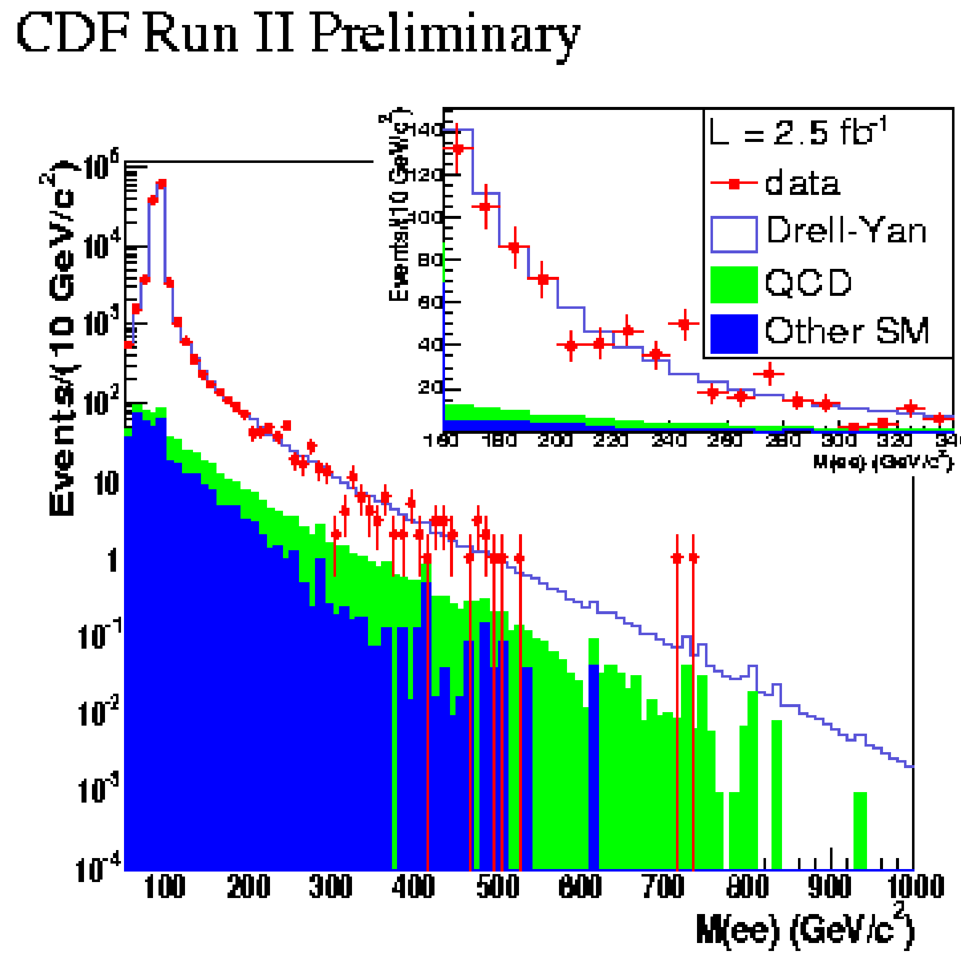
High Mass Resonance Searches

- There are a wide variety of models that predict new particles that would decay to quarks, leptons, or gauge bosons
  - KK states in ED models, excited quarks or leptons, new gauge bosons, etc...
- The general strategy for these searches is to look for deviations from the SM in invariant mass distributions (dilepton mass, dijet mass, diboson mass, etc...)
  - A good, old-fashioned “bump hunt”

CDF Dielectron Resonance Search

- Require two electrons and look for excesses in mass spectrum above 150 GeV
- Dominant backgrounds are SM dielectron production, and dijets and W+jets with the jets misidentified as electrons

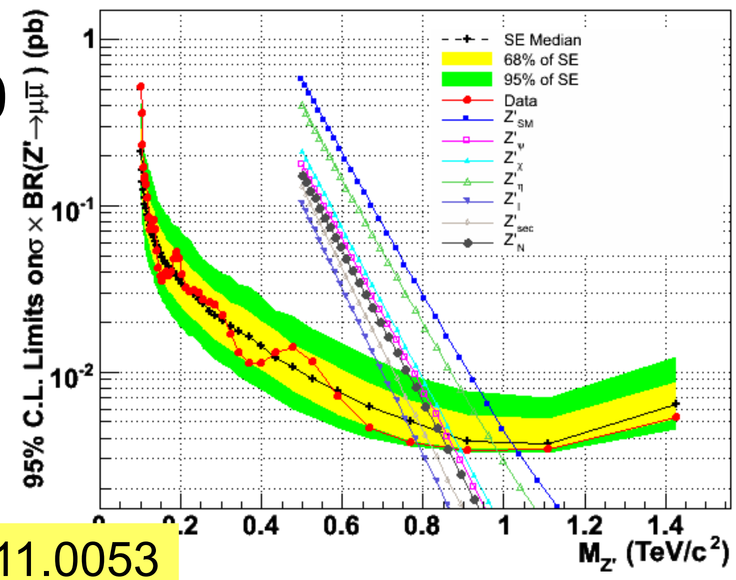




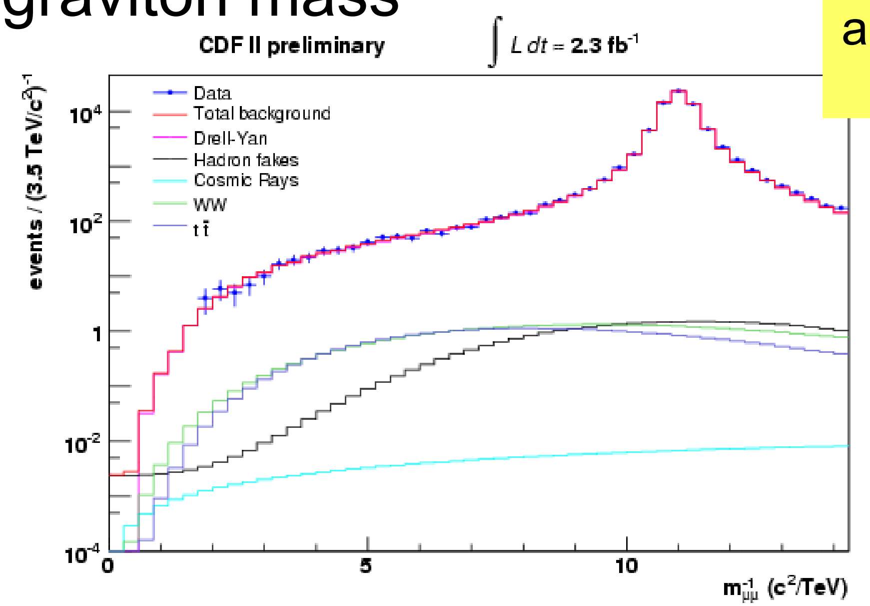
Set limits on a variety of Z' models.
Exclude a Z' with SM couplings below 966 GeV

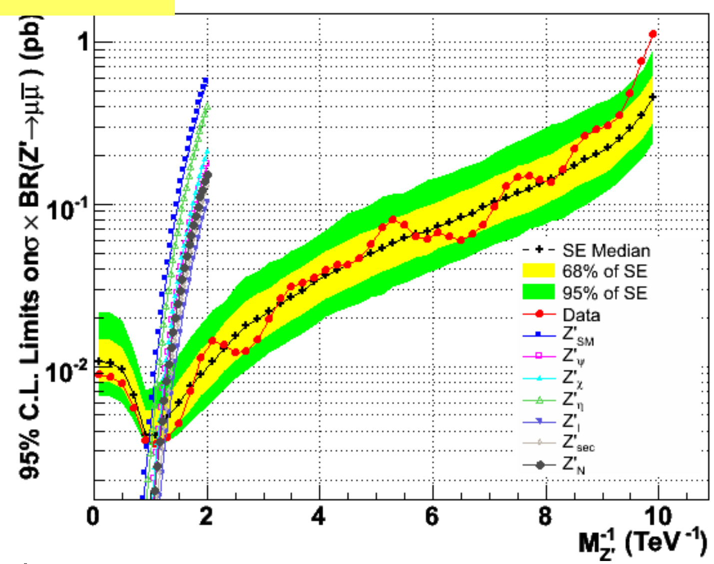
CDF Dimuon Resonance Search

- Look for excesses in dimuon mass spectrum (signal region is above 100 GeV)
  - Actually, search in 1/M, since its more closely related to the resolution
- Set limits on sneutrino, Z', and graviton mass



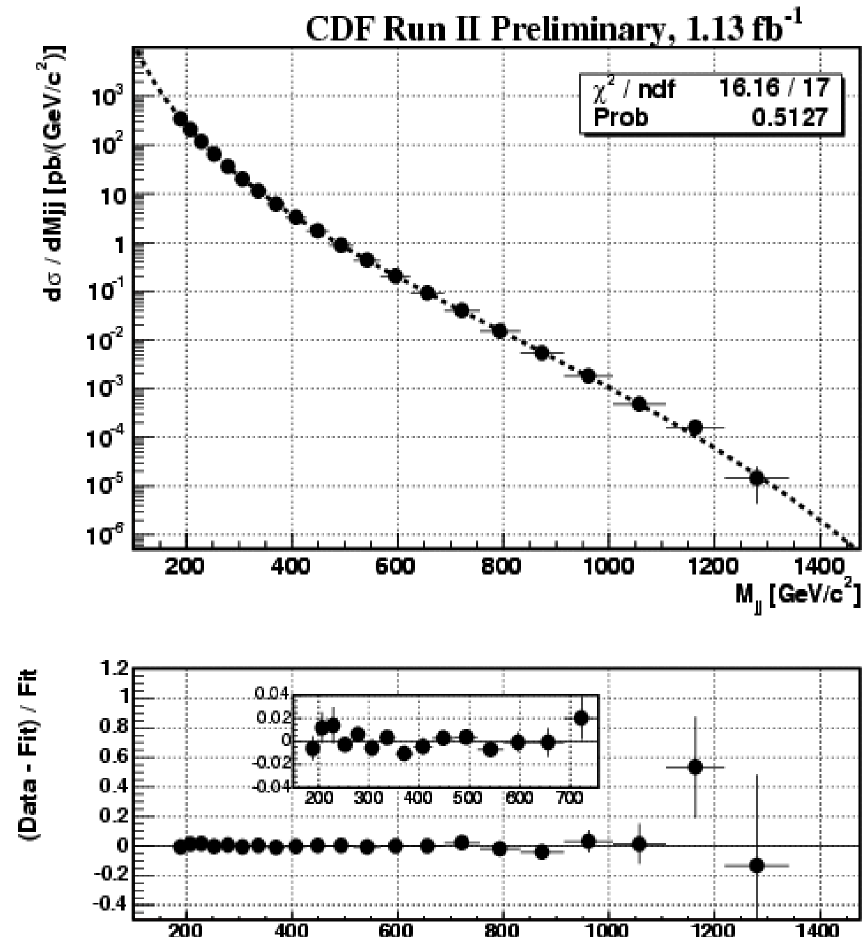
arXiv: 0811.0053





CDF Dijet Resonance Search

- Choose 2 high-pT jets, look at mass spectrum above 180 GeV
- Fit dijet mass (use functional form from pythia and herwig simulation). Look for bumps in data minus fit plot
- Set limits on excited quarks, W', Z', and gravitons
- Excludes excited quarks from 260-870 GeV, W' from 280-840 GeV, and Z' from 320-740 GeV



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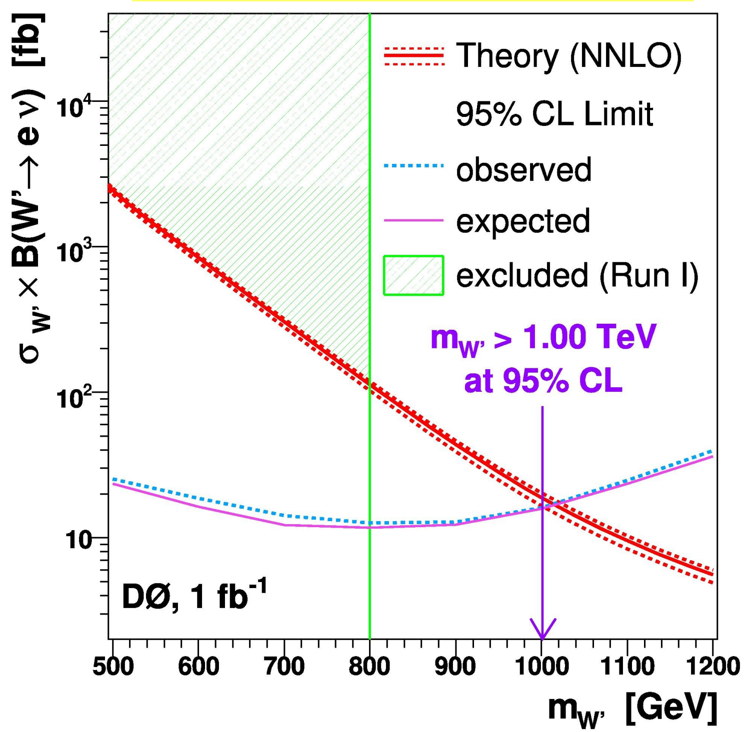
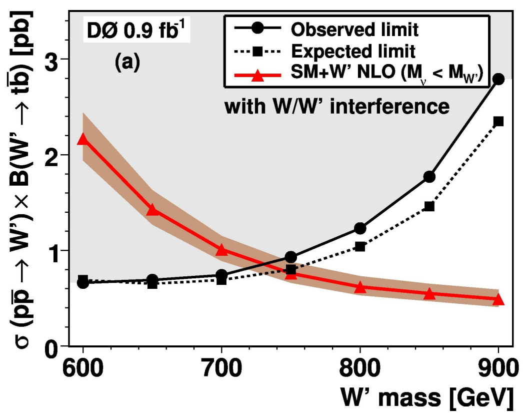
DØ W' Searches

PRL **100**, 031804 (2008)



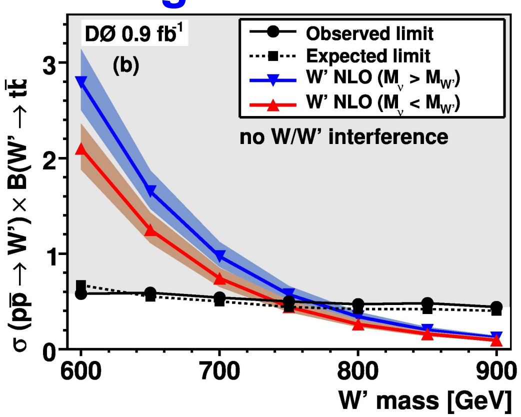
Look for electron+MET signature.
Look for excess in tail of transverse mass Distribution.
Exclude W' with SM couplings below 1 TeV

Left handed W'



PRL **100**, 211803 (2008)

Right handed W'



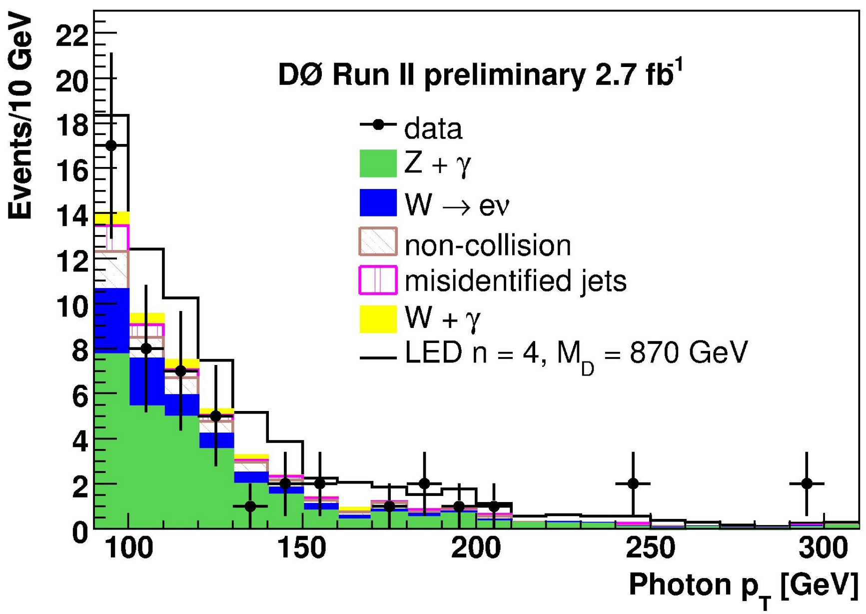
Look for W' decaying to *tb* (results in same signature as single top)
Look at mass of two leading jets, charged lepton, and neutrino.

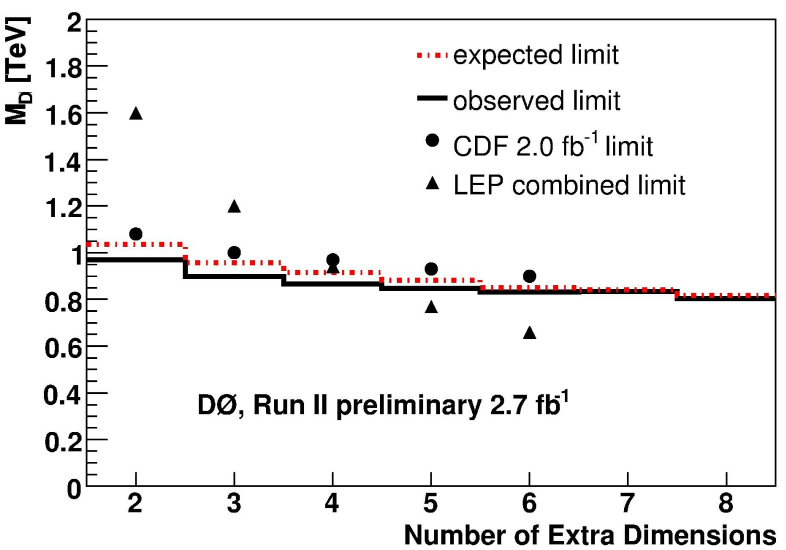
Extra Dimensions Searches

- This is one method of explaining why gravity is so much weaker than the other forces ("hierarchy problem")
- In ADD models, the SM particles are confined to our usual 3 spacial dimensions, while gravity can propagate in extra dimensions
  - Gravity propagates in $4+\delta$ dimensions, where δ is the number of extra dimensions
  - This renders the effective Planck scale small, even though the fundamental mass scale can be close to the weak scale
- "Large" extra dimensions (LED) must be compactified to have escaped detection by precision gravity experiments
  - Any particle that travels in these extra dimensions will have quantized momentum, resulting in a tower of energy states known as Kaluza-Klein (KK) modes

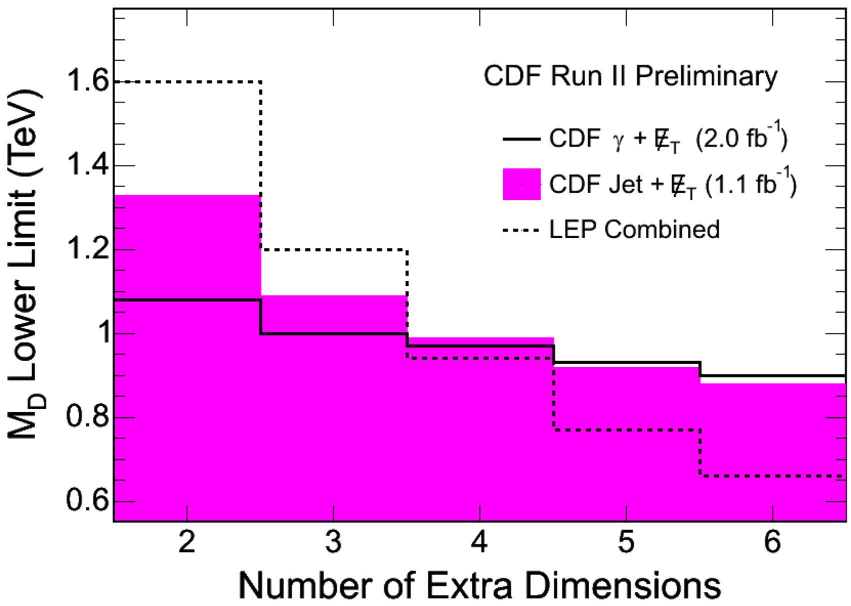
DØ Monophoton Search

- A Kaluza-Klein graviton is produced in association with a photon. The graviton escapes detection, leaving a monophoton signature in the detector
- Use "photon pointing" to require a vertex to within 10cm
  - Use to reject instrumental backgrounds (cosmics, beam halo, misidentified jets)
- No significant excess is observed, so limits are set on the number and size of extra dimensions





CDF Photon + MET Search



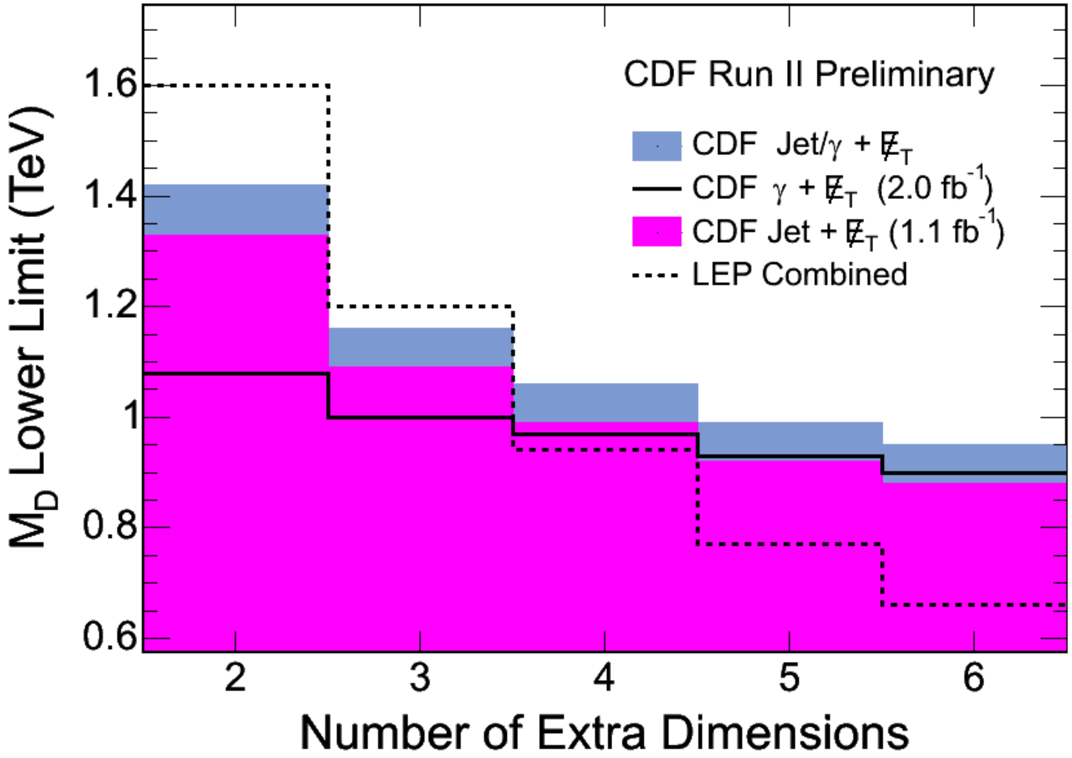
CDF RunII Preliminary, 2.0 fb^{-1}			
N LED	α (%)	σ^{95}_{obs} fb	M_D^{obs} GeV
2	7.2	84.7	1080
3	7.2	84.7	1000
4	7.6	80.4	970
5	7.3	82.7	930
6	7.2	84.4	900

- Monophoton + MET signature
- No excess of is observed, so limits are set on the cross section and on M_D, the fundamental mass scale

CDF RunII Preliminary, 2.0 fb^{-1}		
Channel	$\gamma E_T > 50$ GeV	$\gamma E_T > 90$ GeV
$W \to e \to \gamma$	47.3 ± 5.1	2.6 ± 0.4
$W \to \mu/\tau \to \gamma$	19.1 ± 4.2	1.0 ± 0.2
$W\gamma \to \mu\gamma \to \gamma$	33.1 ± 10.2	1.7 ± 1.2
$W\gamma \to e\gamma \to \gamma$	8.0 ± 3.0	0.8 ± 0.7
$W\gamma \to \tau\gamma \to \gamma$	17.6 ± 1.6	2.5 ± 0.2
$\gamma\gamma \to \gamma$	18.9 ± 2.3	2.3 ± 0.6
cosmics	36.4 ± 2.5	9.8 ± 1.3
$Z\gamma \to \nu\nu\gamma$	99.7 ± 9.5	25.2 ± 2.8
Total	280.1 ± 15.7	46.7 ± 3.0
Data	280	40

CDF Photon/jet + MET

- LED models can also produce a signal of one or more high p_T jets with MET
- Combine with the 1.0 fb^{-1} jet+MET search to improve the limit

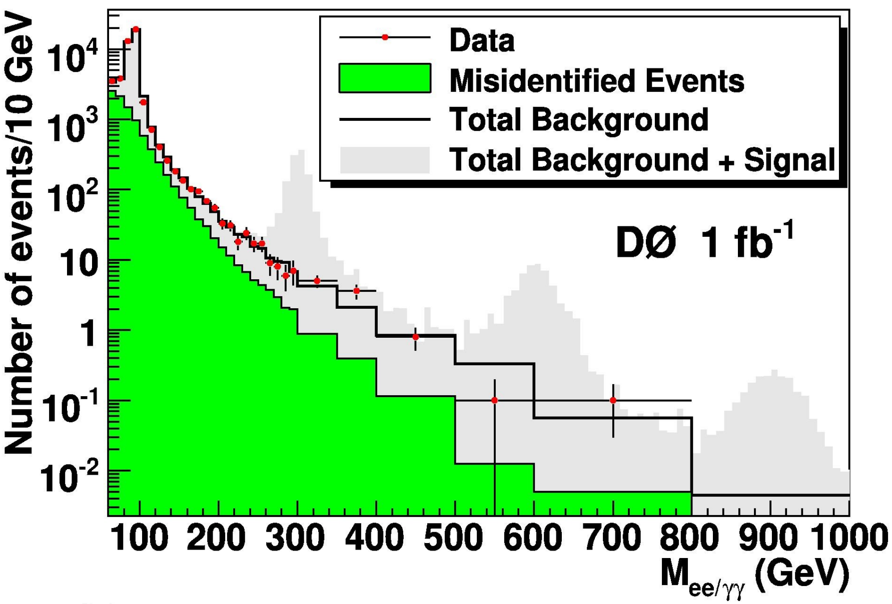


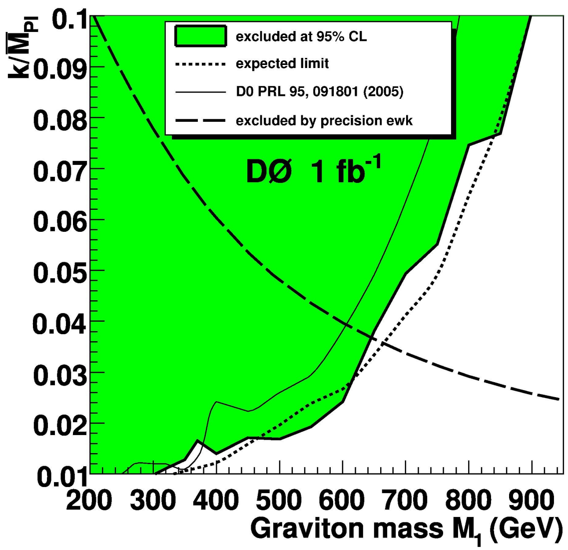
CDF RunII Preliminary, Jet/γ+$\not{E}_T$		
N LED	σ^{95}_{obs} fb	M^{obs}_D GeV
2	26.3	1420
3	38.7	1160
4	46.9	1060
5	52.7	990
6	56.7	950

DØ Randall-Sundrum Graviton Search in Di-EM

- In Randall-Sundrum (RS) ED models, the SM particles are confined to a 3-brane and gravity originates at another 3-brane. Only gravitons propagate in the bulk between these branes
- Use 1.0 fb^{-1} of data to search for KK excitations of the graviton that decays to a pair of electrons or photons
- Count events in a sliding window (varies from 20 to 220 GeV) in the invariant mass distribution (optimized from simulation) for graviton masses from 200 to 950 GeV

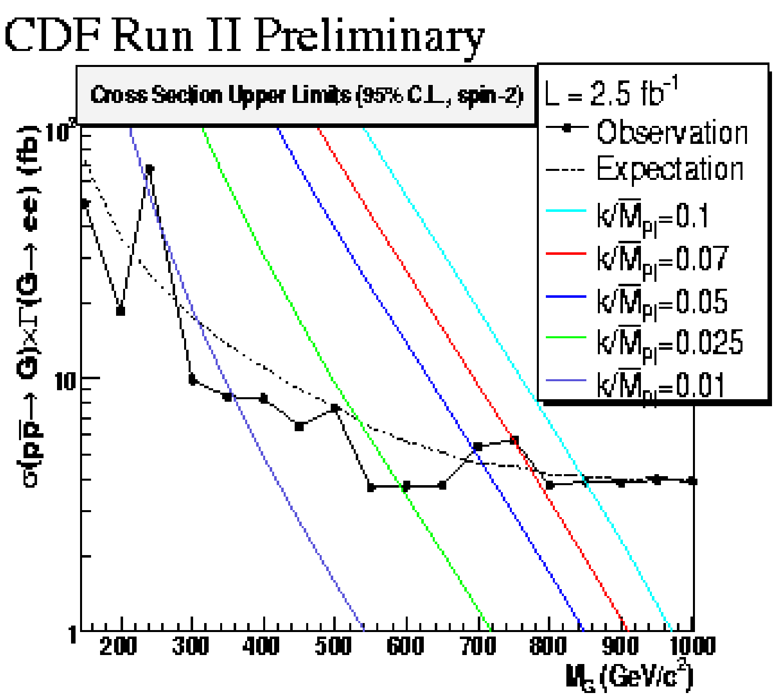
PRL **100**, 091802 (2008)



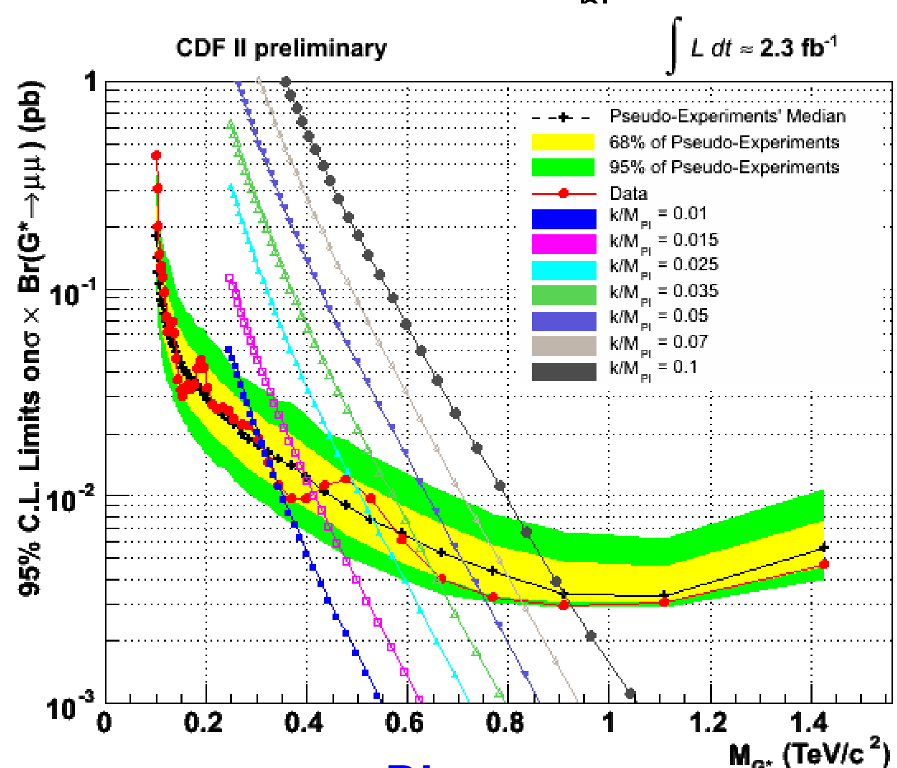


CDF High Mass RS Graviton Searches

- Interpret high mass ee and μμ searches in terms of RS gravitons
- Look for decays of KK excitations of the graviton decaying to dileptons
- Set limits on graiviton mass as function of k/M_{Pl}



Dielectrons

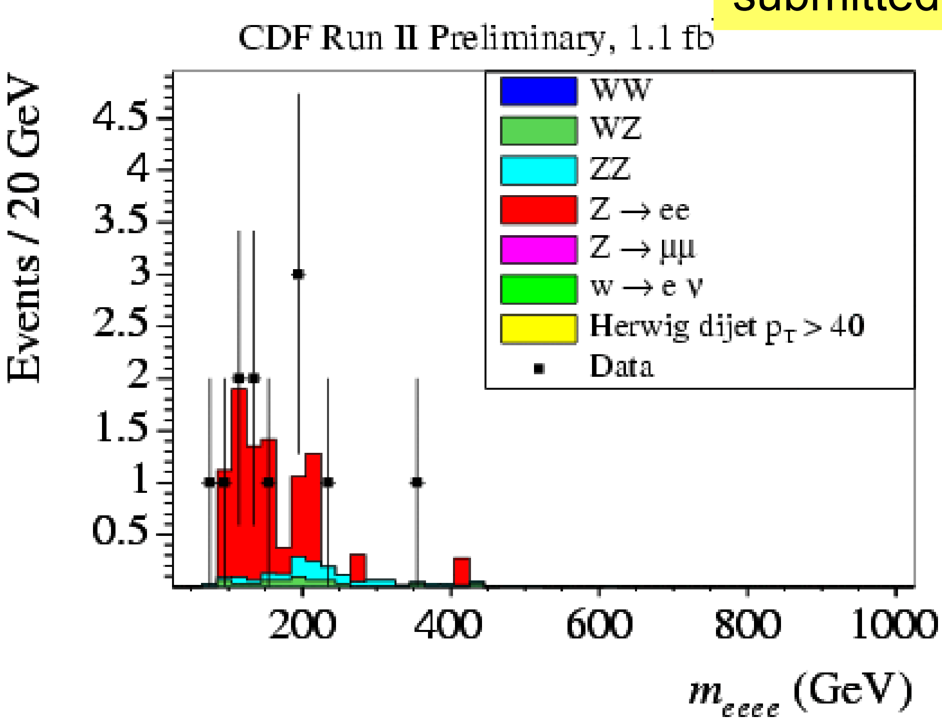


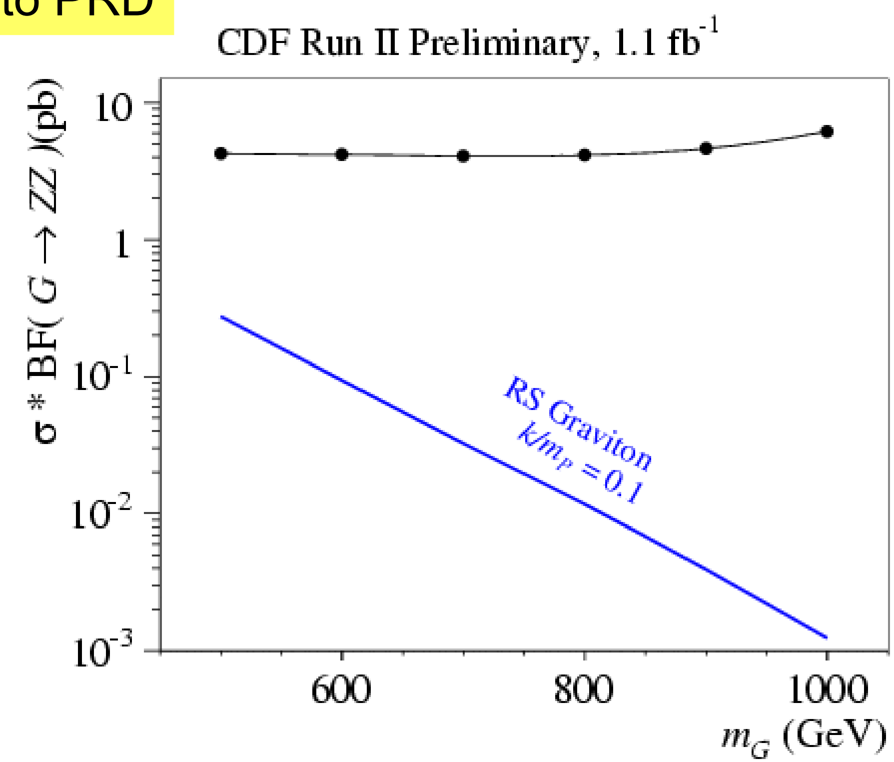
Dimuons

CDF ZZ Search

- RS Graviton could also decay to a pair of Z bosons
- Look for ZZ decaying to *eeee*
- Observe 12 *eeee* events, none in signal region (m_{eeee} > 400 GeV), expect 0.028 ±0.009 ±0.011 background events in signal region

arXiv: 0801.1129, submitted to PRD



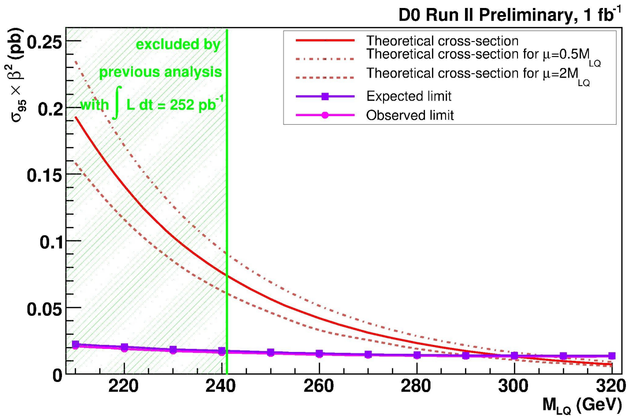


Leptoquark Searches

- Leptoquark are particles that would carry both lepton and baryon number
- Leptoquarks decay to a quark and a charged lepton or a quark and a neutrino
  - Assumption is usually that leptoquarks only decay to quarks/leptons of a single generation
  - β is the branching fraction to a charged lepton and a quark
- Assuming leptoquarks are pair-produced, signatures are lljj, or lνjj, or ννjj
  - All quarks/leptons from the same generation

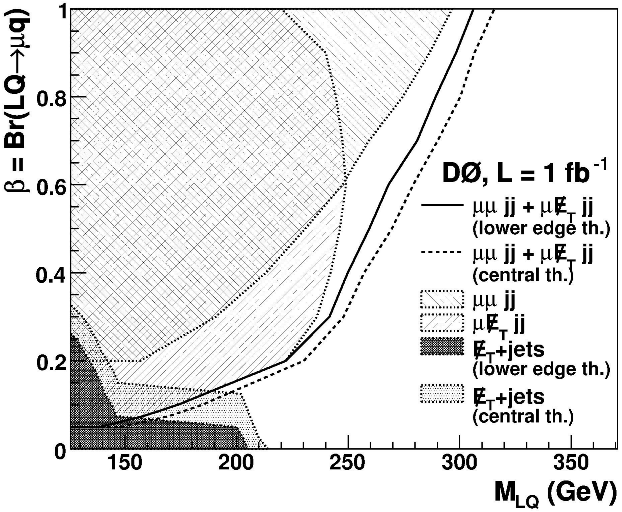
DØ Leptoquark Results

1st generation scalar LQ, 1 fb^{-1}



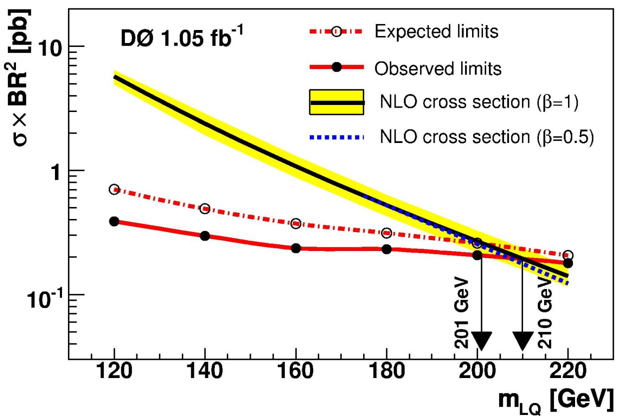
Exclude m_{LQ} < 292 GeV for $\beta = 1$

2nd generation scalar LQ, 1 fb^{-1}



PLB **671**, 224 (2009)
m_{LQ} > 316 GeV ($\beta = 1$)
m_{LQ} > 270 GeV ($\beta = 0.5$)

3rd generation scalar LQ, 1.1 fb^{-1}

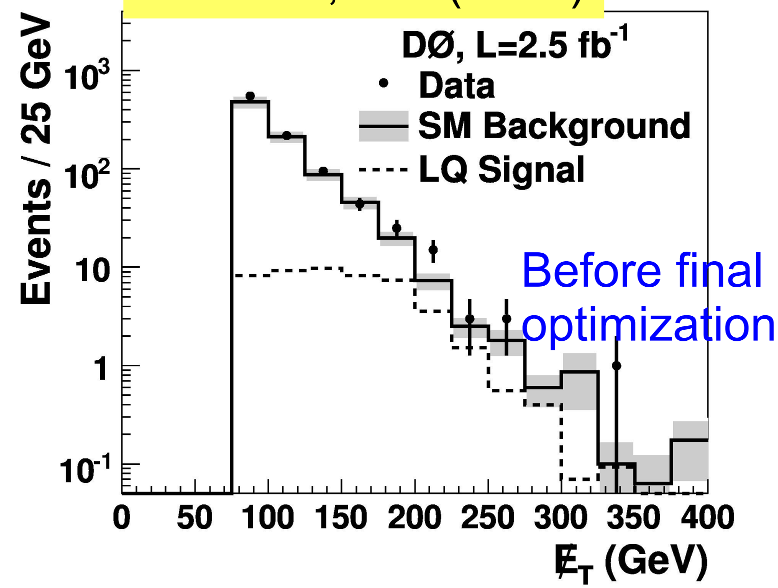


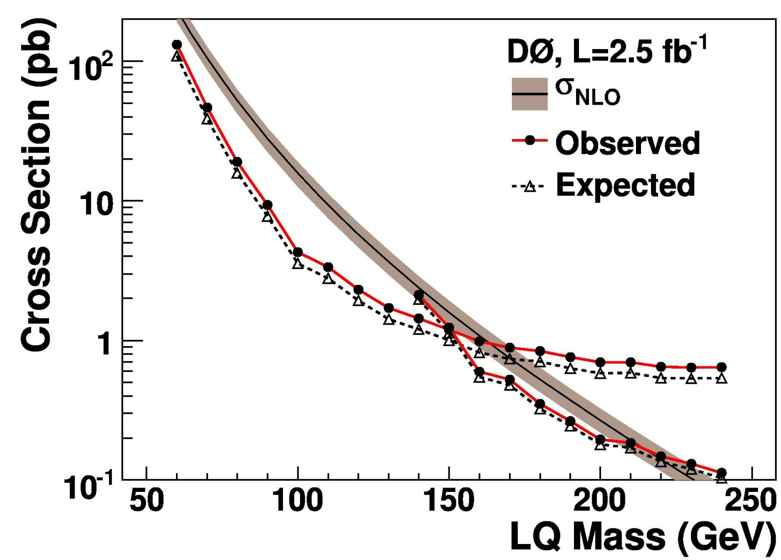
PRL **101**, 241802 (2008), m_{LQ} > 210 GeV ($\beta = 1$)

DØ Leptoquarks in Acoplanar Jets

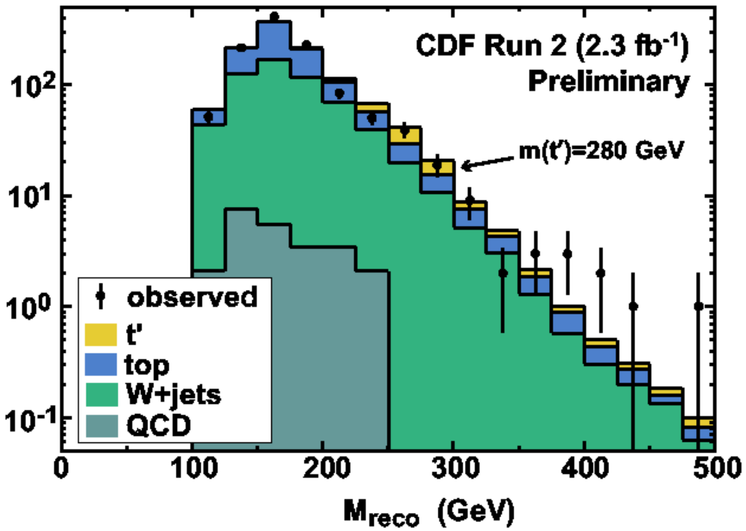
- Assume leptoquarks are pair produced and decay to a quark and a neutrino (β=0)
  - Results in 2 jets + MET signature
- Set limits on scalar leptoquark (of a single generation) of 205 GeV
  - (Analysis also sets limits on T-odd quarks in Little Higgs models)

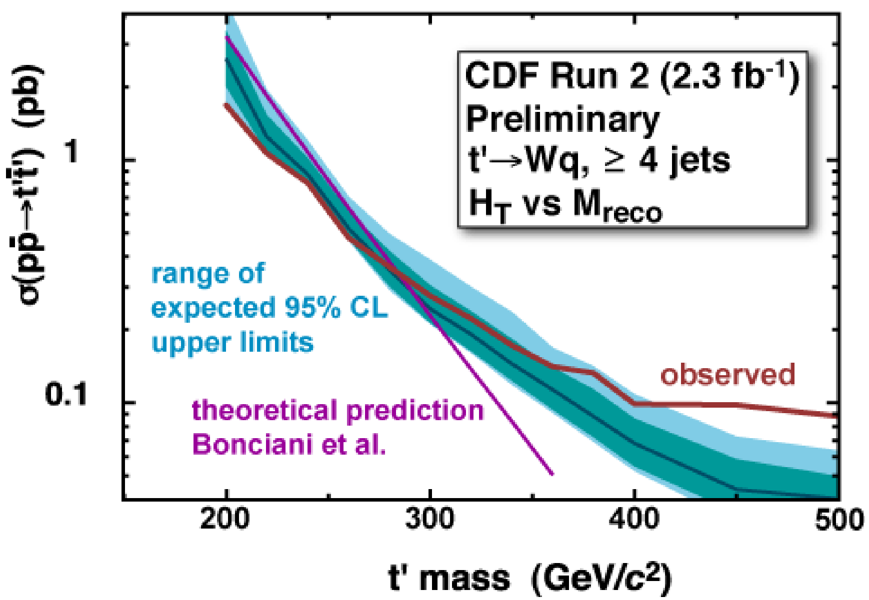
PLB **668**, 357 (2008)





CDF t' Quark Search





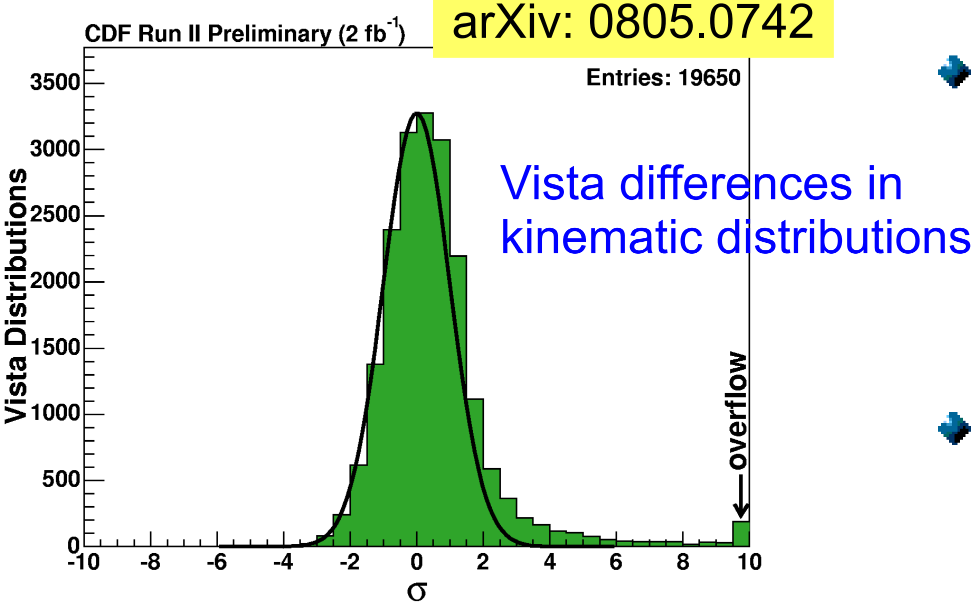
- Search for new 4th generation quarks
- Assume
  - Pair produced
  - Mass large than top
  - Decays (promptly) to Wq
- Analysis very similar to ttbar analysis
  - Reconstruct t' mass
- Exclude t' with mass below 284 GeV

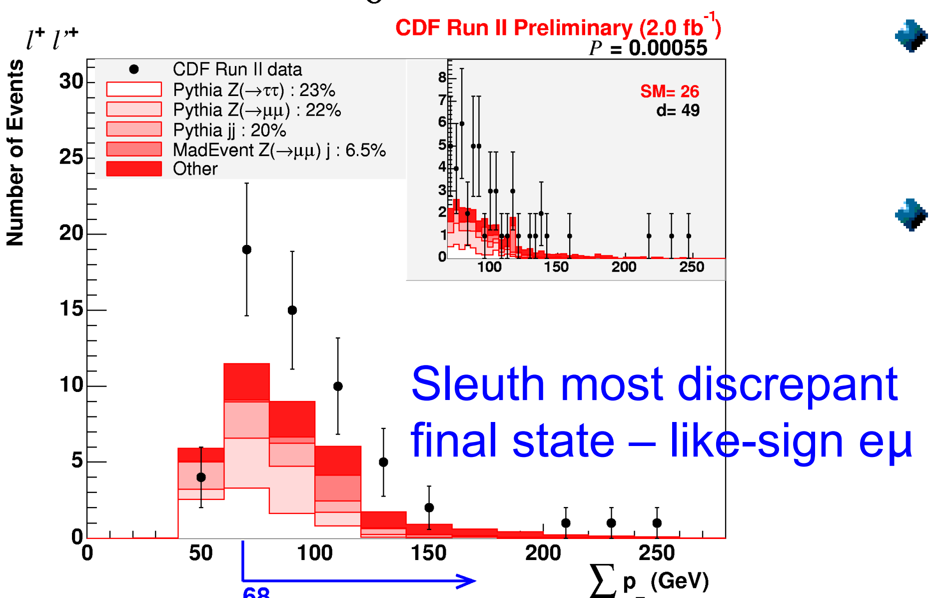
Model Independent Searches

- It is impossible to look for every possible signature of BSM physics
  - How can we be sure there isn't some new physics lurking in our data that we just haven't looked for?
- “Generic” searches try to do a global search of an experiment's data
- Divide data into many different final states
- Use MC to describe everything you know (i.e. the standard model)
  - Do a global fit of several “fudge factors”
- Look for discrepencies (in number, shapes, and “bumps”) in various distributions
- Have to make sure the statistics are handled correctly!

CDF Model Independent Search

arXiv: 0805.0742





- "Vista" looks at gross features of data and is sensitive to new physics with large cross sections
- "Sleuth" looks for excesses in high-p_T tails
- There is also a dedicated "bump hunter"
- No significant discrepancies from the SM are found

Long Lived Particle Searches

- Particles passing through entire detector
  - Requires detailed knowledge of timing and trigger
  - CDF has preliminary result on stable stops using their TOF detector
  - DØ has a result (arXiv:0809.4472, submitted to PRL) on stable staus and stable charginos using timing in the muon system
- Particles decaying inside the detector
  - DØ has a result on neutral long lived particles that decay to muons inside the central tracker (PRL **97**, 161802 (2006))
  - DØ has a result on electrons/photons with highly displaced vertices (PRL **101**, 111802 (2008))

Other "Exotic" Searches

- DØ has a search for stopped gluinos (PRL **99**, 131801 (2007))
  - Gluino stops in the calorimeter, then decays to a jet. Jet is in arbitrary direction and not in time with beam crossing
  - Requires detailed knowledge of the calorimeter
- CDF search for magnetic monopoles (PRL **96**, 201801 (2006))
  - Small data set taken with special trigger. Requires special tracking
  - Requires detailed knowledge of tracking systems

Other Searches

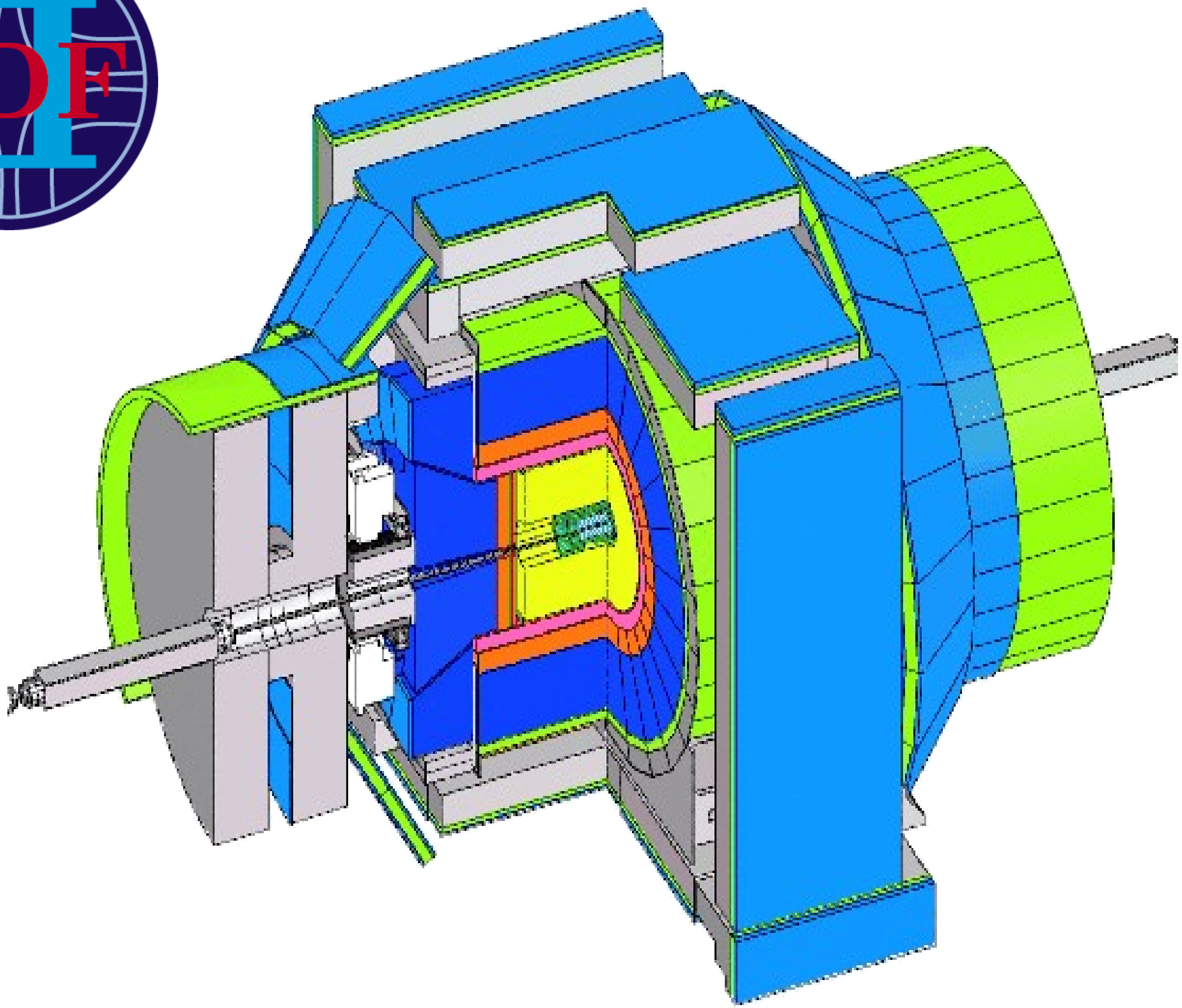
- There are a lot of searches that have been performed by CDF and DØ that I didn't have time to discuss
  - Technicolor
  - Excited quarks/leptons
  - BSM Higgs
  - New (low mass) hadrons
  - Anomalous couplings
  - Little Higgs

Summary

- A great many BSM searches have been performed at the Tevatron, but there are many more that could be done
  - A piece of advice – contact theorists/phenomenologists and the other experiments early in the game!
- Each experiment has websites with all public results:
  - http://www-cdf.fnal.gov/physics/exotic/exotic.html
  - http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm
- Expect updated results (for the winter conferences) soon!

Backup Slides

CDF Detector



Electron acceptance:
$|\eta| < 2.0$

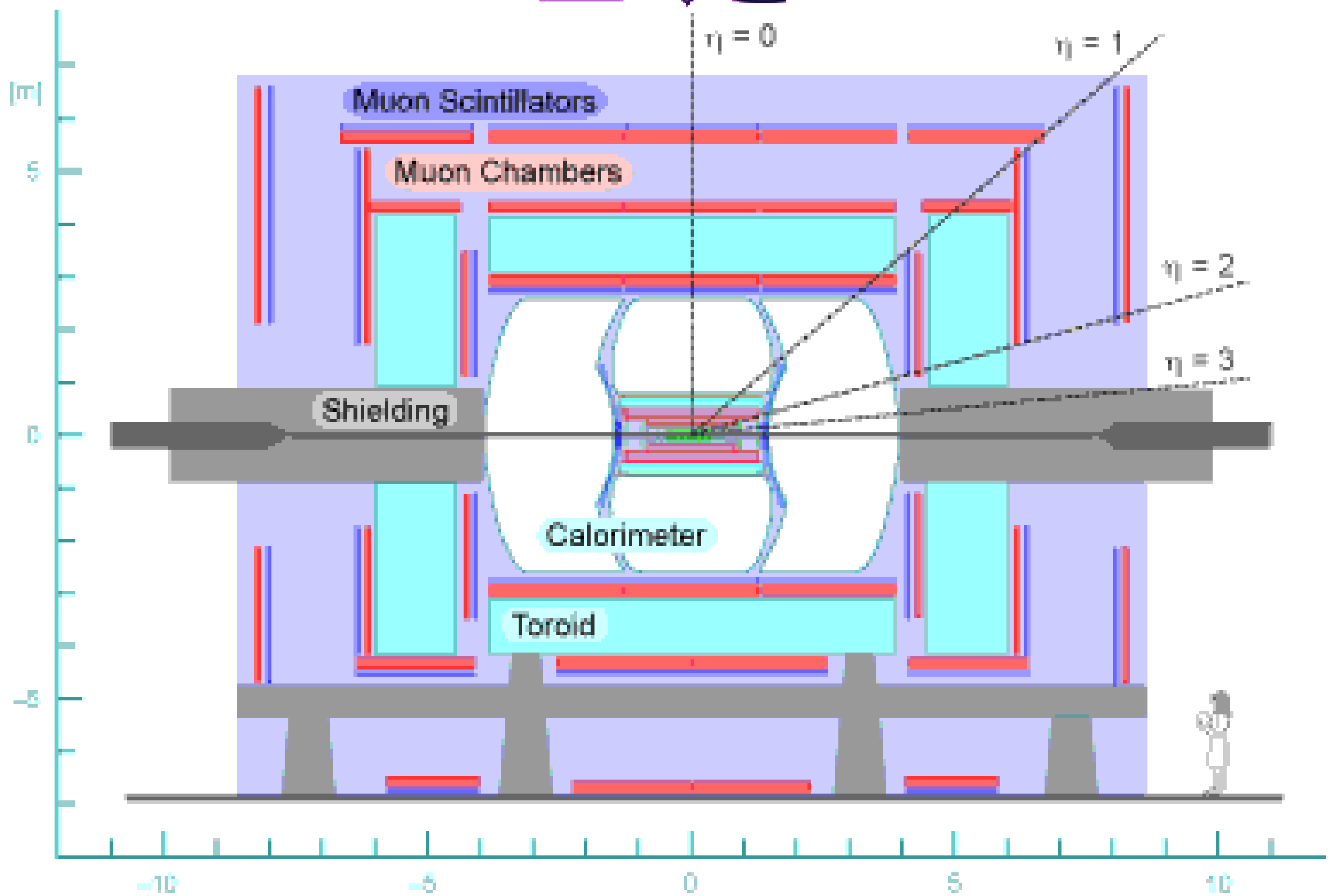
Muon acceptance:
$|\eta| < 1.5$

Silicon tracking:
$|\eta| < 2.0$

Calorimetry:
$|\eta| < 3.6$

Excellent tracking!

DØ Detector



Electron acceptance:
$|\eta| < 3.0$

Muon acceptance:
$|\eta| < 2.0$

Silicon tracking:
$|\eta| < 3.0$

Calorimetry:
$|\eta| < 4.2$

Excellent muon system and calorimeter!

DØ Integrated Luminosity