XIII Lomonosov Conference on Elementary Particle Physics
August 23 – 29, 2007

Search for New Phenomena and non-SM Higgs at the Tevatron

Richard Partridge
Brown University

The Standard Model Remains Standing!

Preview of this talk's conclusions:

- Tevatron searches for New Phenomena show no significant deviations from Standard Model predictions

This is probably not a surprise

- It is a conclusion we have heard far too many times…
- The title of my talk starts with the word "Search"…
- Rumors and news travel faster than airplanes…

Will the SM Continue to Stand?

- While the edifice of the Standard Model remains intact, the foundation is weak
  - The familiar force of gravity is completely absent
  - The SM appears to describe only ~5% of the universe
  - Some divergent loops are not cancelled (hierarchy problem)
  - Large number of seemingly arbitrary parameters
  - Source of baryon asymmetry, integer ratio of quark/lepton charges, strong CP puzzle, etc. etc. etc.

Likely the better question is:

"How Long Will the SM Continue to Stand"

Lessons from the Past

- Nearly all of the major particle physics discoveries in the past ~35 years were predicted by well motivated theoretical arguments now embodied in the SM
  - The converse is not true - not all good theoretical ideas survive!
  - This did not occur in a vacuum – the experimental clues were in place
  - Many successes from requiring calculations to yield sensible results ⇒ gauge theories, cancellation of divergent loops and anomolies, etc.
  - We should listen to our theoretical colleagues!
- The discovery of dark matter and dark energy are perhaps the most notable exceptions
  - Interestingly, these discoveries were made with telescopes rather than particle accelerators
  - New technology can play a significant role in breaking new ground
  - There are limits to theoretical prognostication!

Looking under the Lamp Post

- A successful accelerator search requires:
  - There is enough energy to produce the particle in question
  - There is enough luminosity to produce the particle in sufficient quantity
  - The new particle is distinguishable from backgrounds
  - Experimenters have to look in the right place
- In some sense, we are like the person who has lost their keys at night…our only hope is to look under the lamp posts where there is sufficient "illumination"
- This analogy is especially true for New Phenomena searches at the Tevatron
  - Well motivated theoretical arguments for new physics at the TeV scale
  - But the Tevatron energy / luminosity may not provide enough illumination
  - By contrast, LHC will have the energy / luminosity needed to thoroughly explore the TeV scale

Selected Tevatron Lamp Posts

This talk will focus on a subset of the Tevatron searches:

- Search for supersymmetric particles
  - Squark / gluino
  - Neutralino / chargino
  - Gauge Mediated SUSY
- Search for Non-SM Higgs
  - SM Higgs search covered in talk by Gaston Gutierrez
- Search for excited gauge bosons
- Search for leptoquarks
- Search for extra dimensions

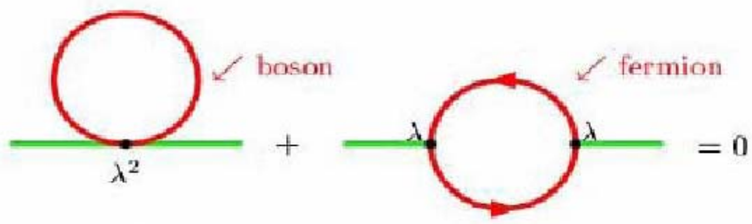
Many details are omitted in this talk – please refer to CDF / DØ publications and web pages for more complete descriptions of these (and other) analyses

SUperSYmmetry

- Supersymmetry imposes a new symmetry between fermions and bosons
- Symmetry is clearly broken – SUSY particles must be heavy if they exist

SM Particles	SUSY Particles			
quarks: q	q	squarks: $\tilde{q}$		
leptons: l	l	sleptons: $\tilde{l}$		
gluons: g	g	gluino: $\tilde{g}$		
charged weak boson: $W^\pm$	$W^\pm$	Wino: $\tilde{W}^\pm$	$\tilde{\chi}^\pm_{1,2}$	chargino
Higgs: H^0	$H^\pm$	charged higgsino: $\tilde{H}^\pm$		
	h^0, A^0, H^0	neutral higgsino: $\tilde{h}^0, \tilde{A}^0$	$\tilde{H}^0$	higgsino
neutral weak boson: Z^0	Z^0	Zino: $\tilde{Z}^0$	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
photon: γ	γ	photino: $\tilde{\gamma}$		

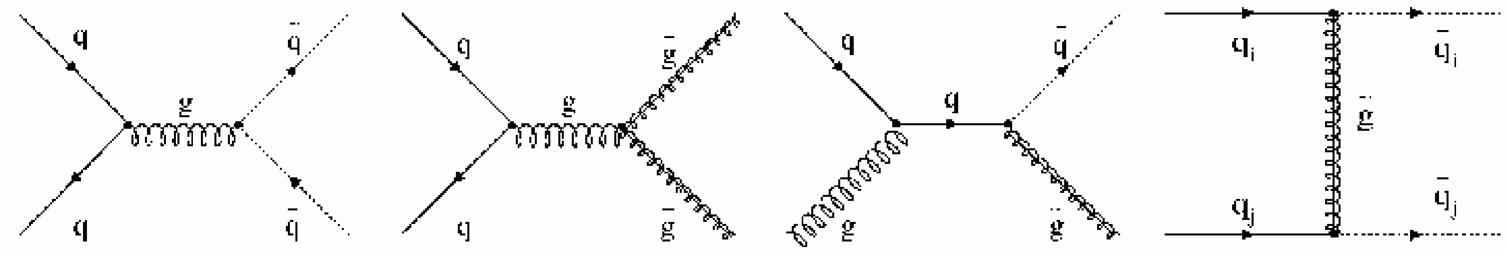
- SUSY potentially resolves a number of open issues in the SM
  - Loop diagrams cancel at all orders (solves the hierarchy problem)



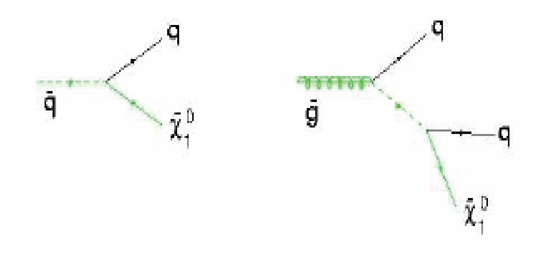
  - If R-Parity is conserved, then lightest SUSY particle is a dark matter candidate
  - Potential to unify coupling constants at the GUT scale (assuming nothing goes wrong in the 13 orders of magnitude between the TeV and GUT scales)
  - Supersymmetry required in some attempts to include gravity (e.g., string theory)

Squark / Gluino Search

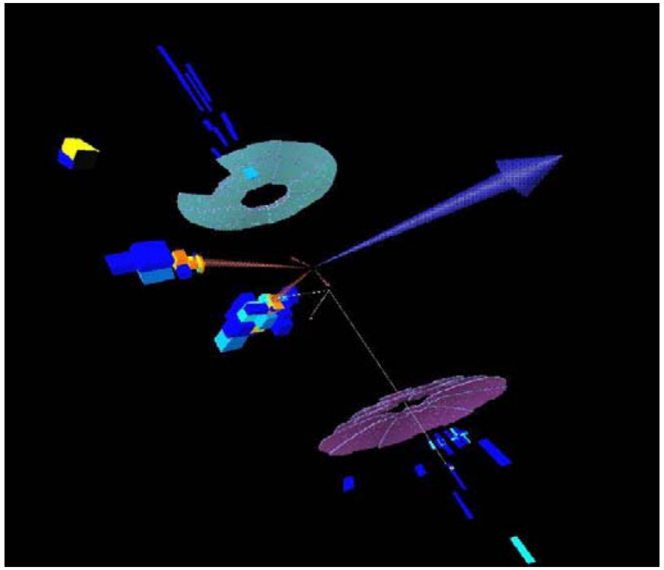
- Squarks and gluinos produced by strong interaction



- For stable neutralino LSP, decays yield final states of Missing E_T and jets



DØ



- Data contains events with missing E_T as high as 368 GeV
- H_T, the scaler sum of jet E_T, is 489 GeV for this event

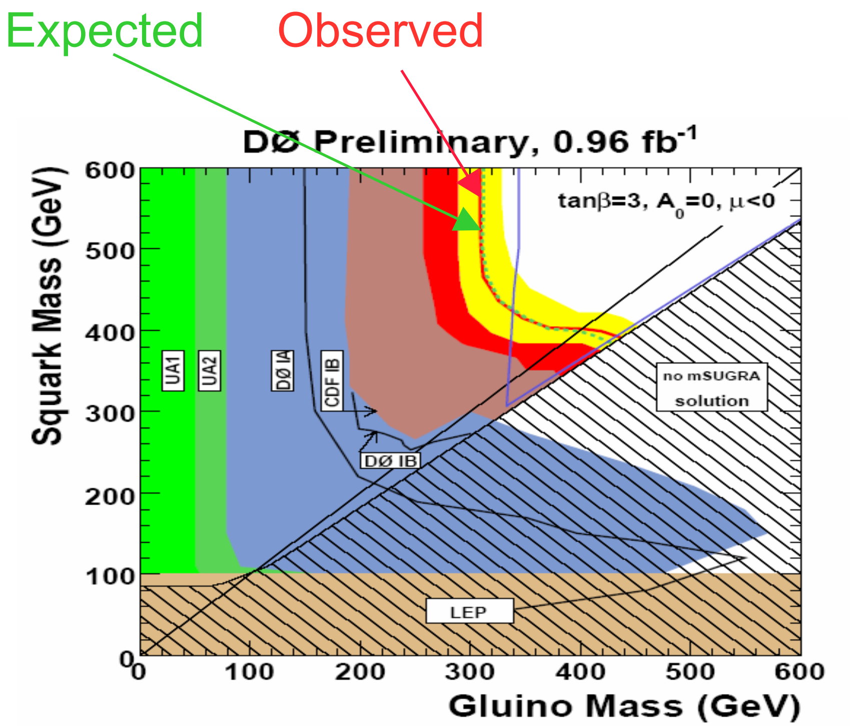
DØ Squark / Gluino Search

- Assume gravity mediated (mSuGRA) SUSY breaking
  - 5 parameters: m_0, $m_{1/2}$, A, tanβ, and sign(μ)
- 3 Separate Analyses
  - low m_0: squark pair production dominates $\Rightarrow$ ≥2 jets + Missing E_T
  - med m_0: squark-gluino production dominates $\Rightarrow$ ≥3 jets + Missing E_T
  - high m_0: gluino-gluino production dominates $\Rightarrow$ ≥4 jets + Missing E_T

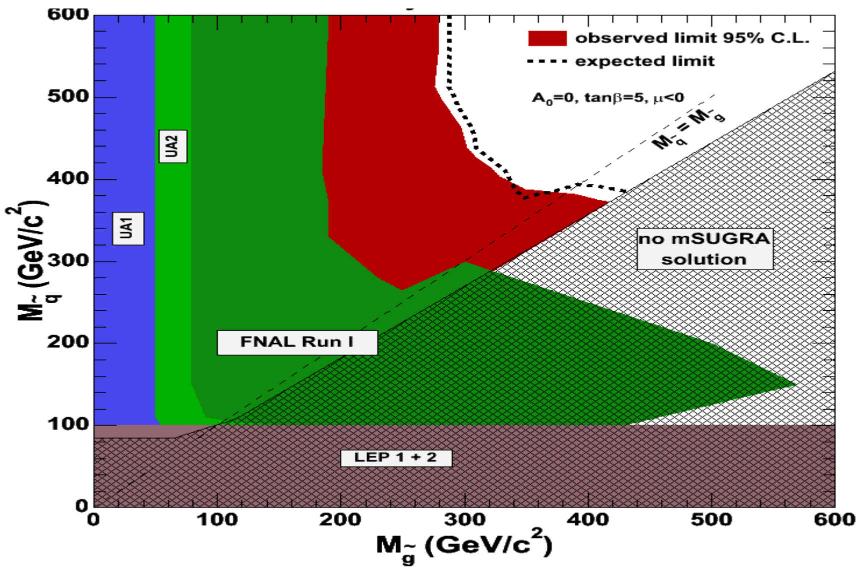
- Final MET/HT cuts :
  - "dijet" : MET > 225 GeV, HT > 300 GeV
  - "3-jets" : MET > 150 GeV, HT > 400 GeV
  - "gluino" : MET > 100 GeV, HT > 300 GeV

	Data	Total background
"Dijet"	5	7.5 ±1.1 (stat) +1.3 -1.0 (syst)
"3 jets"	6	6.1 ±0.4 (stat) +1.3 -1.2 (syst)
"Gluino"	34	33.4 ±0.8 (stat) +5.6 -4.9 (syst)

Squark / Gluino Search Results



Similar analysis by CDF presented at the 2007 Lepton-Photon conference



Yellow band: PDF and scale uncertainties
Limits from lower edge of band

PDF and scale uncertainties not shown
Limits from nominal cross section

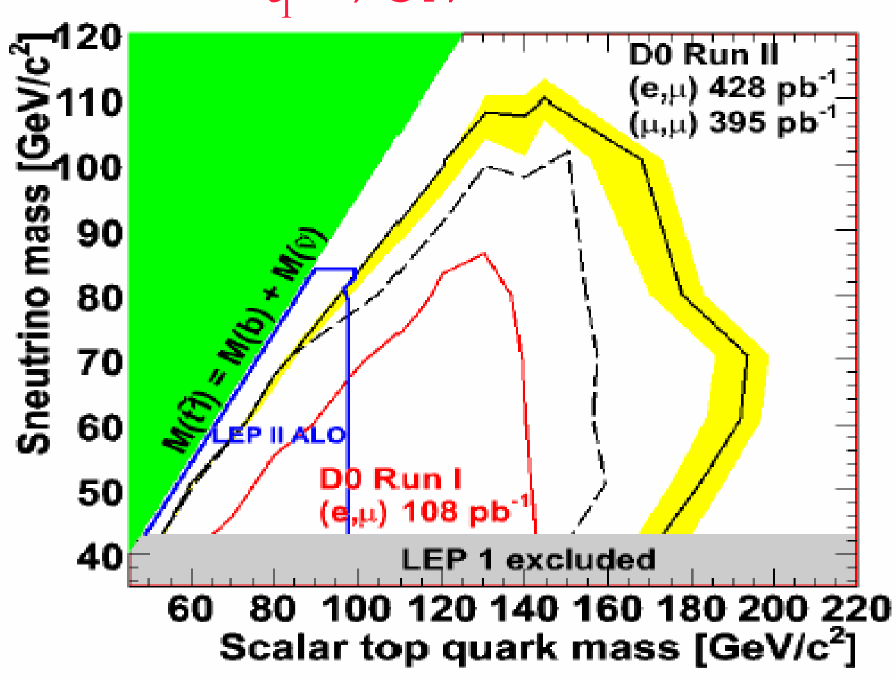
$$m_{\tilde{q}} > 375 \text{ GeV @ 95\% CL}$$
$$m_{\tilde{g}} > 383 \text{ GeV @ 95\% CL}$$
$$m_{\tilde{q}} = m_{\tilde{g}}:\ m > 380 \text{ GeV @ 95\% CL}$$

$$m_{\tilde{g}} > 290 \text{ GeV @ 95\% CL}$$
$$m_{\tilde{q}} = m_{\tilde{g}}:\ m > 380 \text{ GeV @ 95\% CL}$$

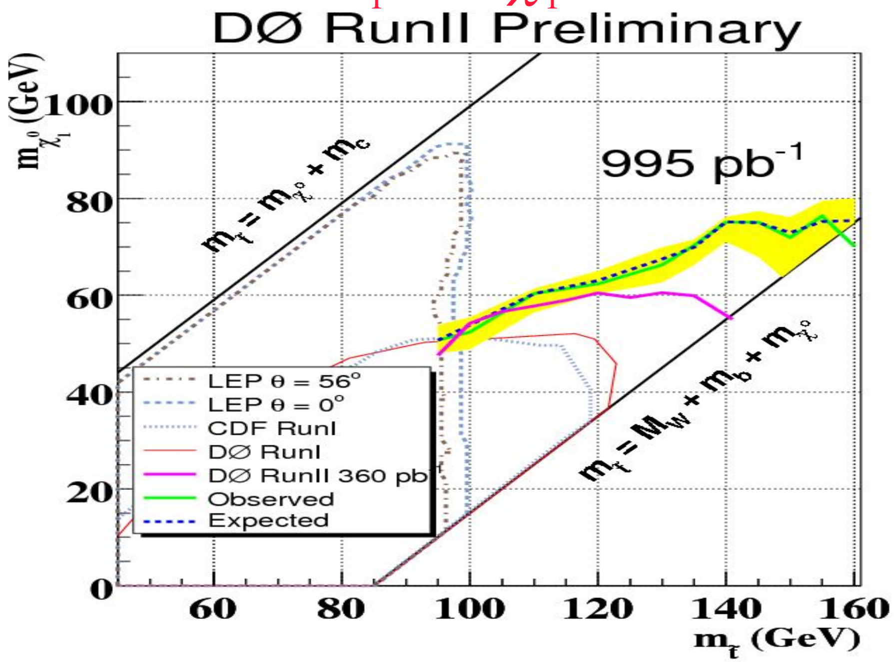
Search for Stop Squarks

- Stop quark can be relatively light
  - Large Yukawa coupling of top quark generates a light stop mass in some models
  - If m(stop) < m(top), decays to top are forbidden
  - Two light stop searches currently limit SUSY parameter space

$\tilde{t}_1 \rightarrow bl\tilde{\nu}$

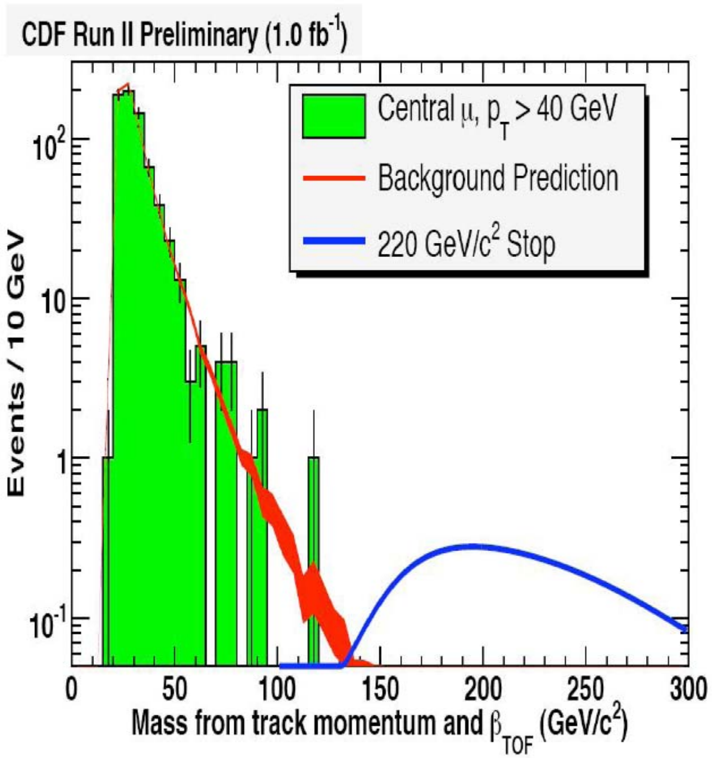


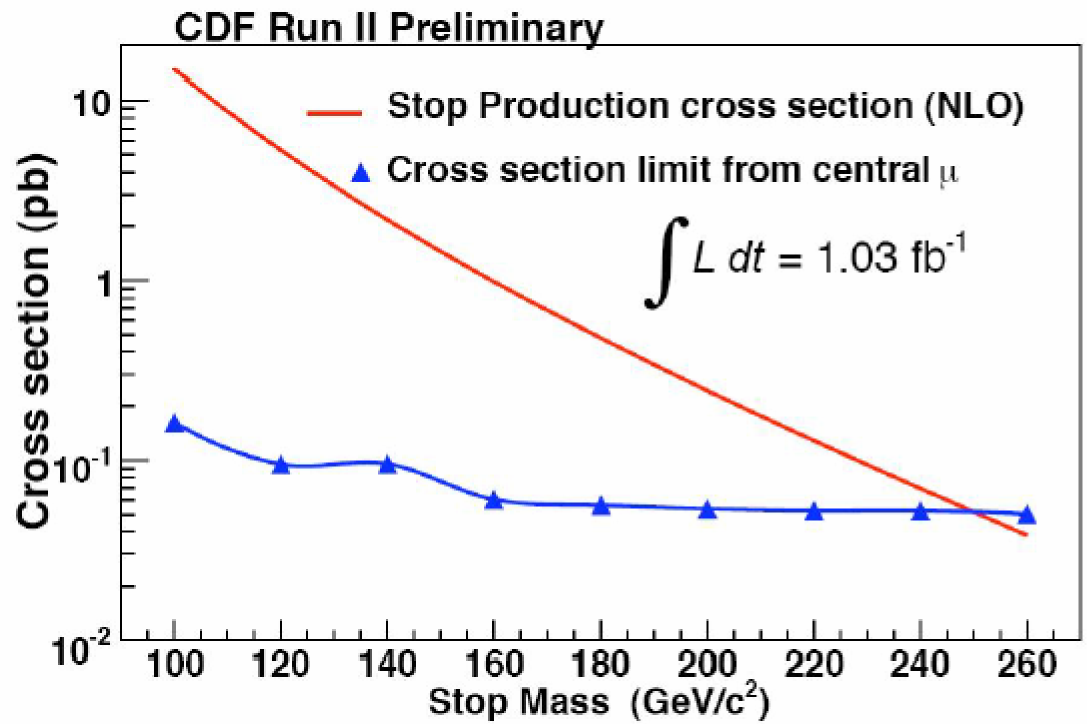
$\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$



CDF Search for Stable Stop Squarks

- If the Stop Squark is the lightest SUSY partner, then it will appear as a stable particle
  - Stop reconstructed as a muon
  - Calculate particle mass from TOF and momentum measurements

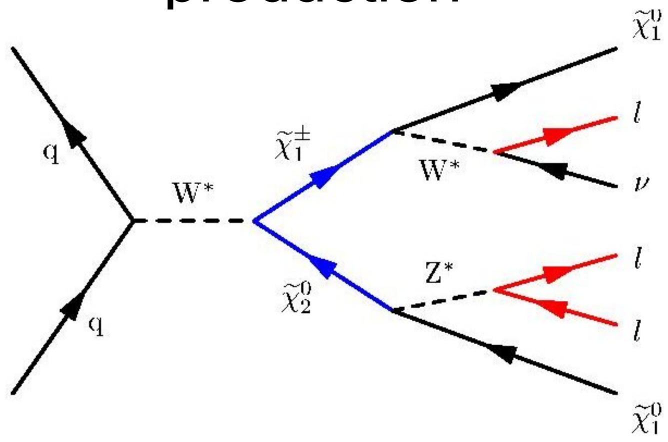




$m_{\tilde{t}}(stable) > 250 \text{ GeV} @ 95\% \text{ CL}$

Chargino / Neutralino Search

- Triple gauge boson coupling leads to $\chi_2^0 \chi_1^+$ production
  - Small BR for 3 lepton final states
  - Clean signature with little background
  - "trilepton" and like-sign dilepton signatures



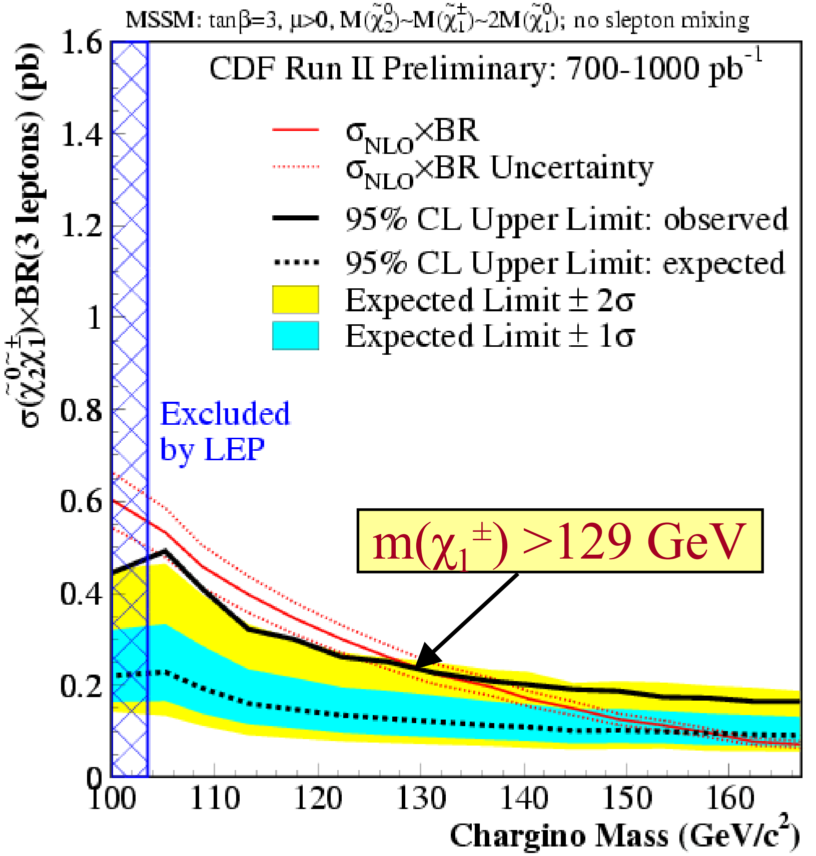
CDF Trileptons	Background	Data
$\mu\mu + \ell$ (low p_T)	0.4 ± 0.1	1
ee + track	1.0 ± 0.3	3
$\mu + \ell\ell$	1.2 ± 0.2	1
$e + \ell\ell$	0.8 ± 0.4	0
$e^\pm e^\pm$	2.9 ± 0.5	4
$e^\pm \mu^\pm$	4.0 ± 0.6	8
$\mu^\pm \mu^\pm$	0.9 ± 0.1	1

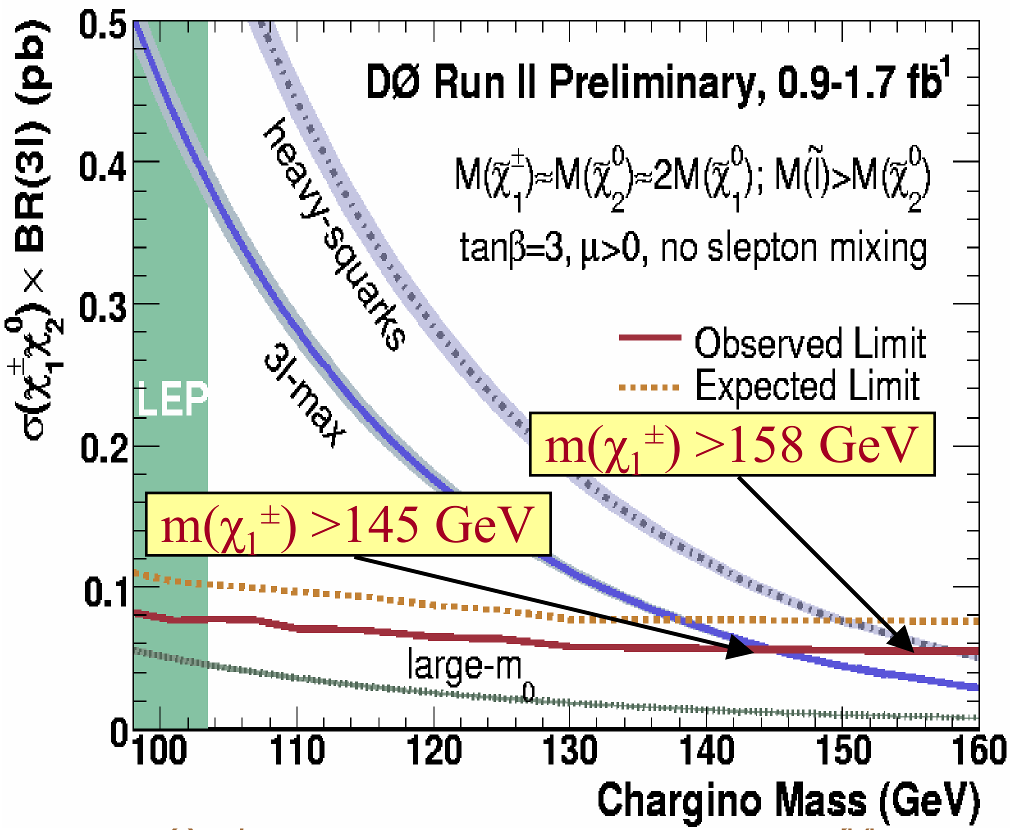
DØ Trileptons	Background	Data
$\mu\mu$ + track	0.32 ± 1.34	2
ee + track	1.0 ± 0.3	0
$e\mu$ + track	0.9 ± 0.4	0
$\mu^\pm \mu^\pm$	1.1 ± 0.4	1

- No significant excess – combine channels to form cross section limits

Chargino / Neutralino Search

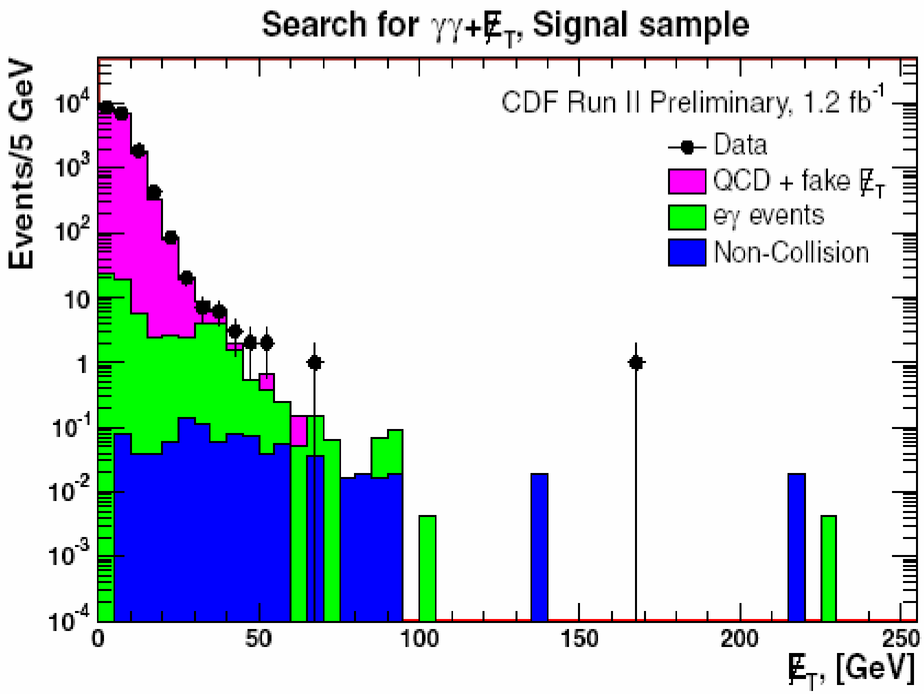
- SUSY predictions are model dependent
  - CDF: $\tan\beta = 3,\ A_0 = 0,\ \mu > 0,\ m_0 = 70\ \text{GeV}$
  - DØ: $\tan\beta = 3,\ A_0 = 0,\ \mu > 0,\ m(\tilde{\ell}) > m(\chi_2^0)$

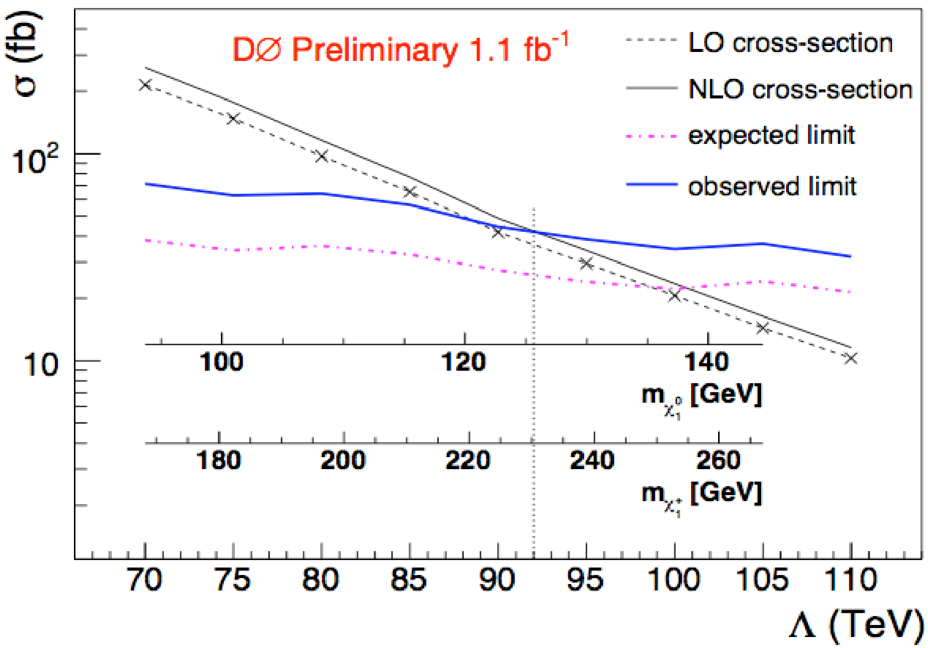




Search for Gauge Mediated SUSY

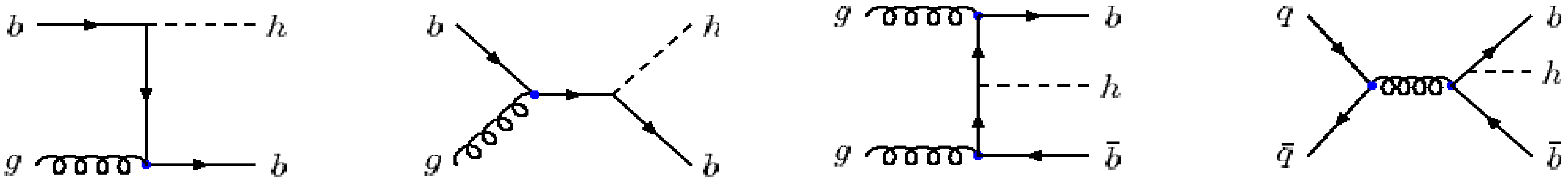
- SUSY breaking at scale Λ mediated by gauge fields
- Gravitino is LSP, neutralino or stau is NLSP
  - Neutralino NLSP decays to gravitino $\chi_1^0 \rightarrow \gamma \tilde{G}$
  - Stau NLSP signature is massive long-lived charged particles
- No excess seen; DØ combined stau/γγMET limit: $\Lambda > 92$ TeV

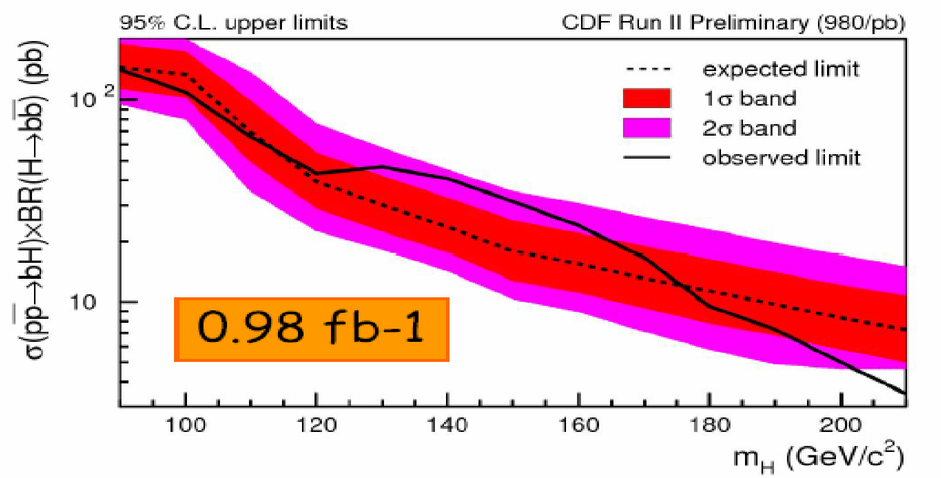


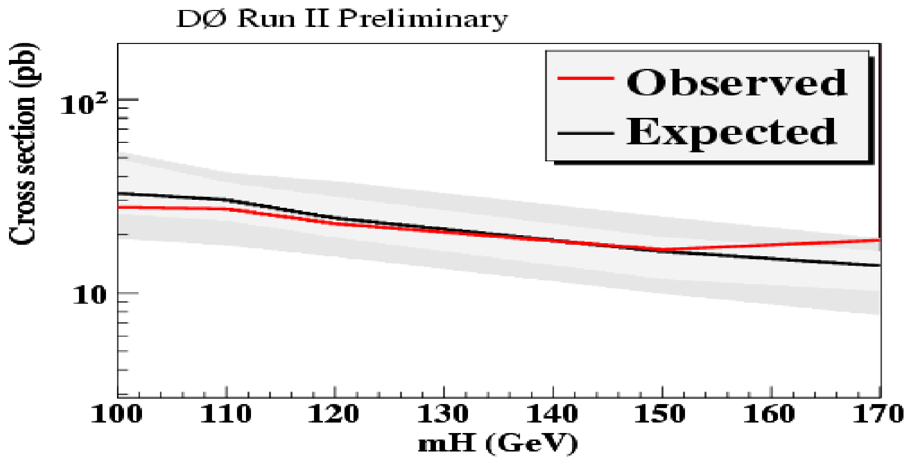


Search for SUSY Higgs in 3b Final State

- Minimal supersymmetry has 2 Higgs doublets H_u, H_d
  - 5 Higgs bosons: h, H, A, H^+, H^-
  - At tree level, two independent parameters: m_A and $\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle$
  - For large $\tan\beta$, production cross section enhanced by a factor $\tan^2\beta$
  - Light Higgs BR ~90% bb, ~10% $\tau\tau$
  - Look for Higgs in 3b final state

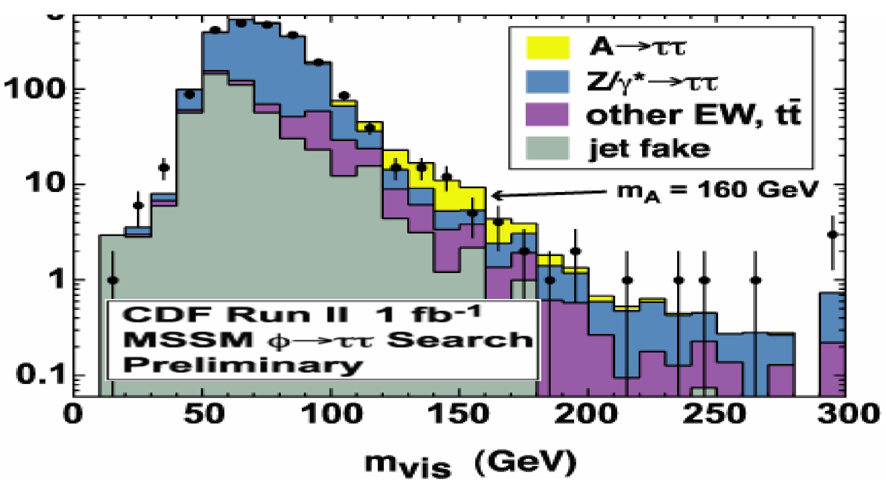


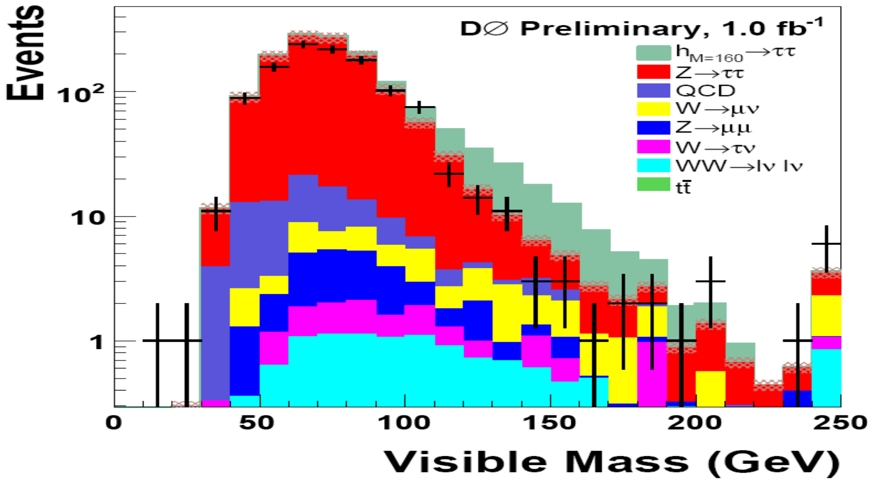


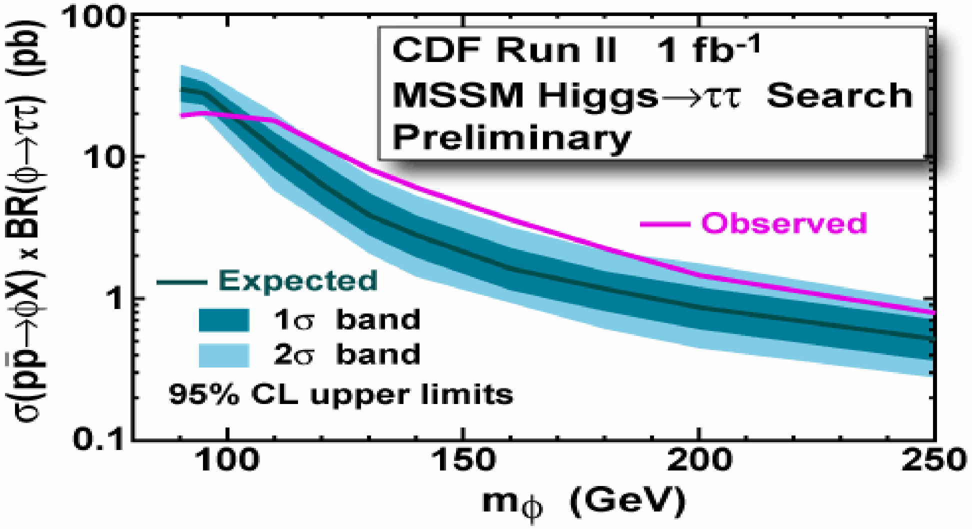


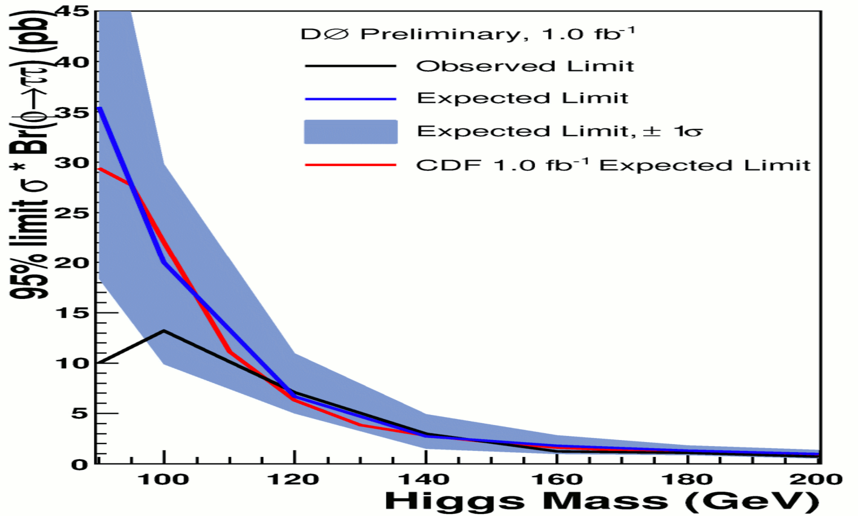
Search for SUSY Higgs in ττ Channel

- CDF has ~2σ excess for m_ϕ~150 GeV; not seen by DØ



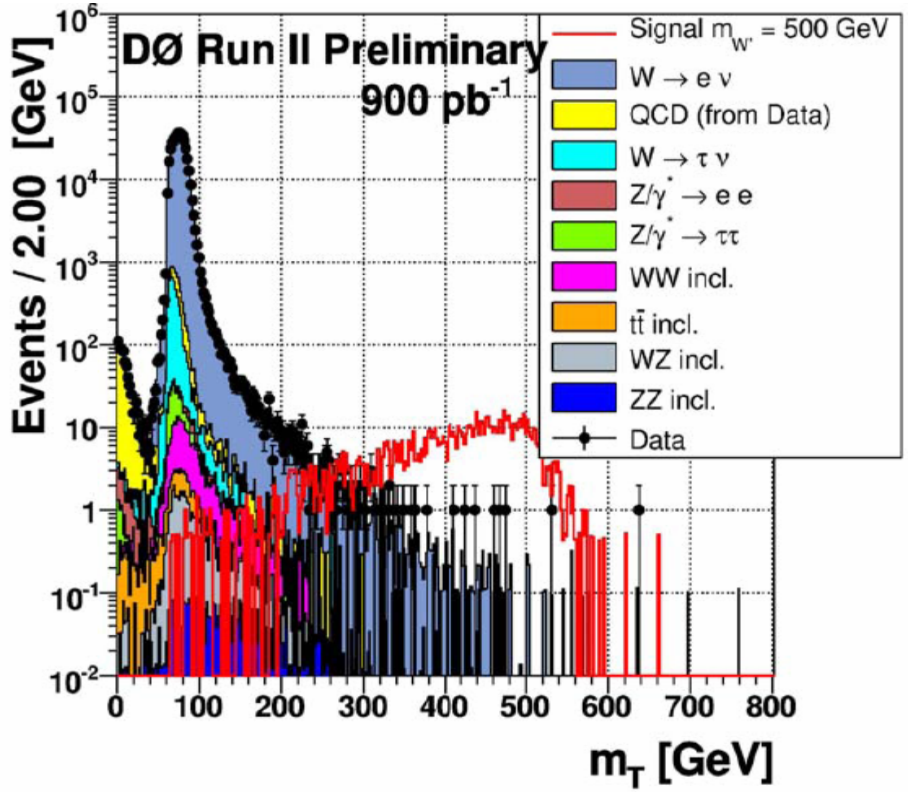




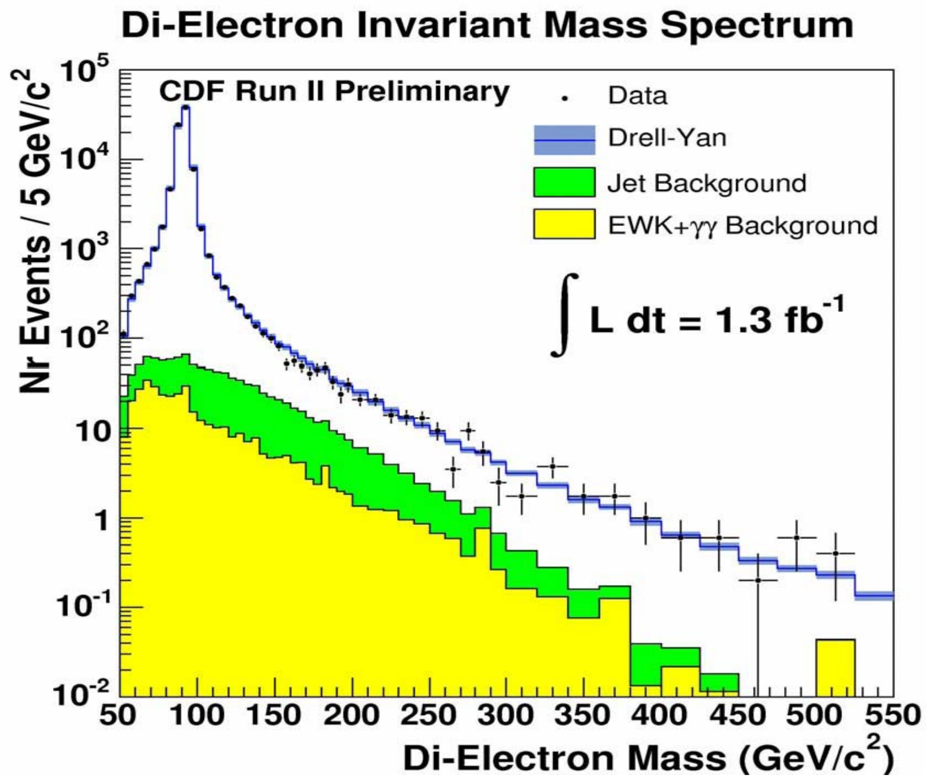


Search for Excited Gauge Bosons

- Additional gauge bosons predicted by many theories
- No evidence for W' or Z' in Tevatron data
  - Set mass limits assuming SM couplings



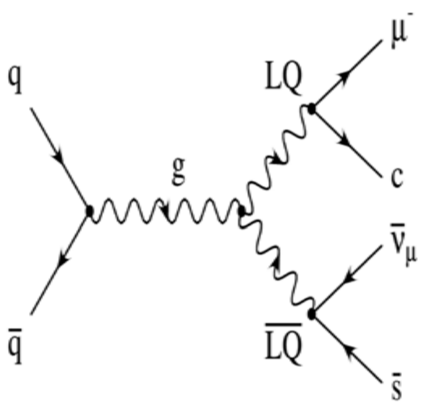
$m_{W'} > 965$ GeV @ 95% CL



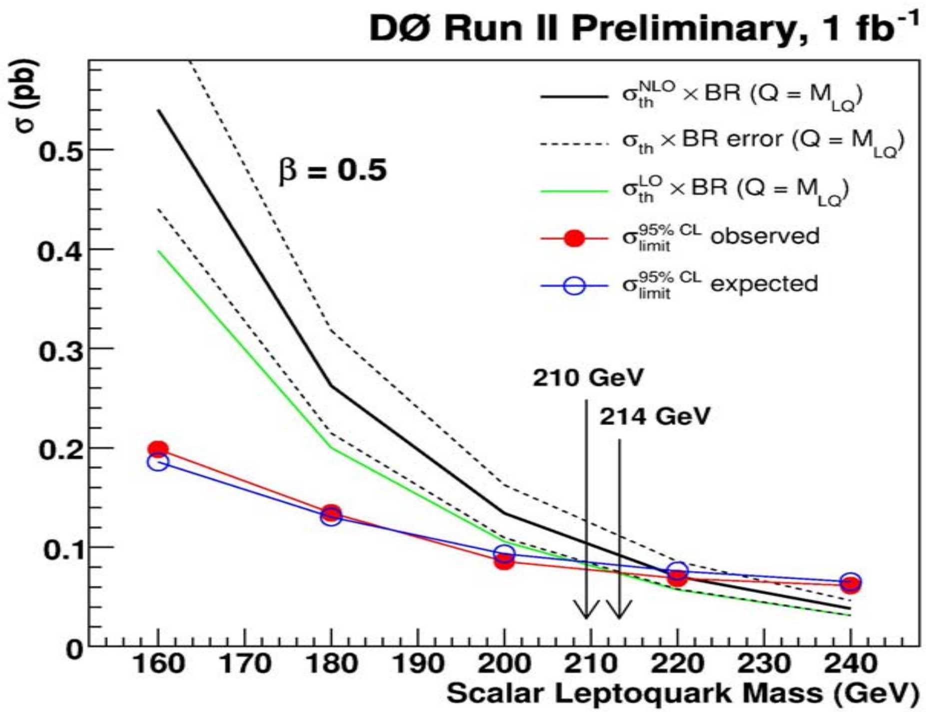
$m_{Z'} > 923$ GeV @ 95% CL

Search for 2nd Generation Leptoquarks

- Models providing a natural explanation for the parallels between quarks and leptons often require leptoquarks
- DØ search for scaler leptoquarks in the $\mu\nu jj$ final state



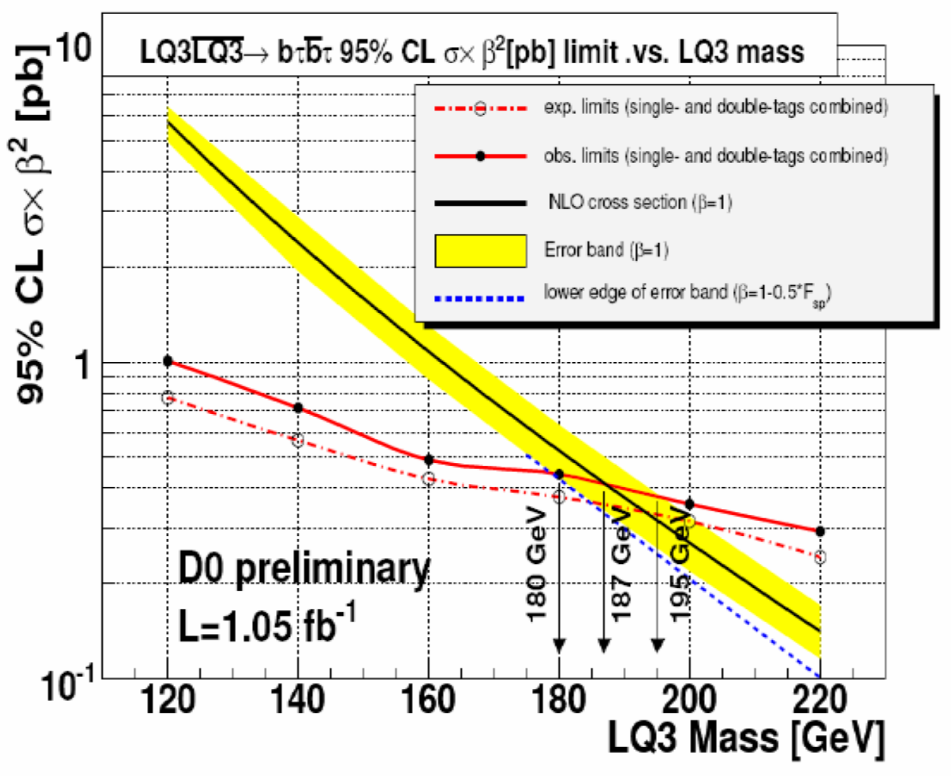
$$BR(LQ \to \ell q) = \beta$$
$$BR(LQ \to \nu q) = 1 - \beta$$



$$m_{SLQ2} > 214\ \mathrm{GeV}\ @\ 95\%\ \mathrm{CL\ for}\ \beta = 0.5$$

Search for 3rd Generation Leptoquarks

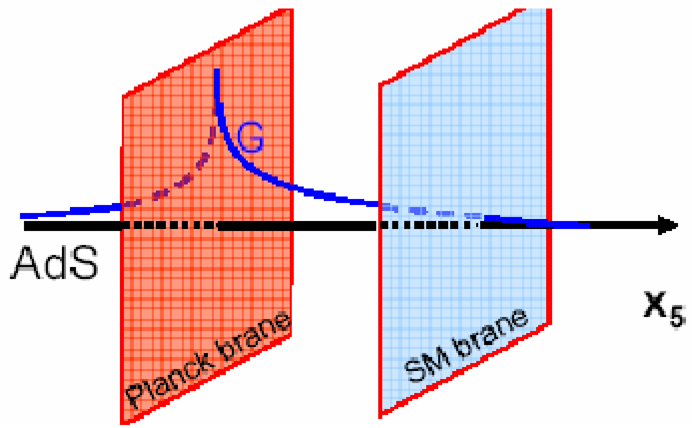
- New DØ search in the bbττ channel
  - LQ → $t\nu_\tau$ kinematically suppressed

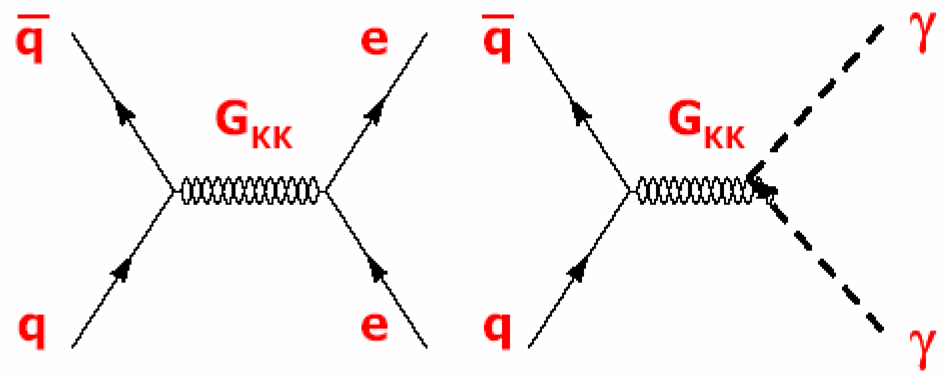


$$m_{SLQ3} > 180\text{ GeV @ 95\% CL}$$

Search for Extra Dimensions

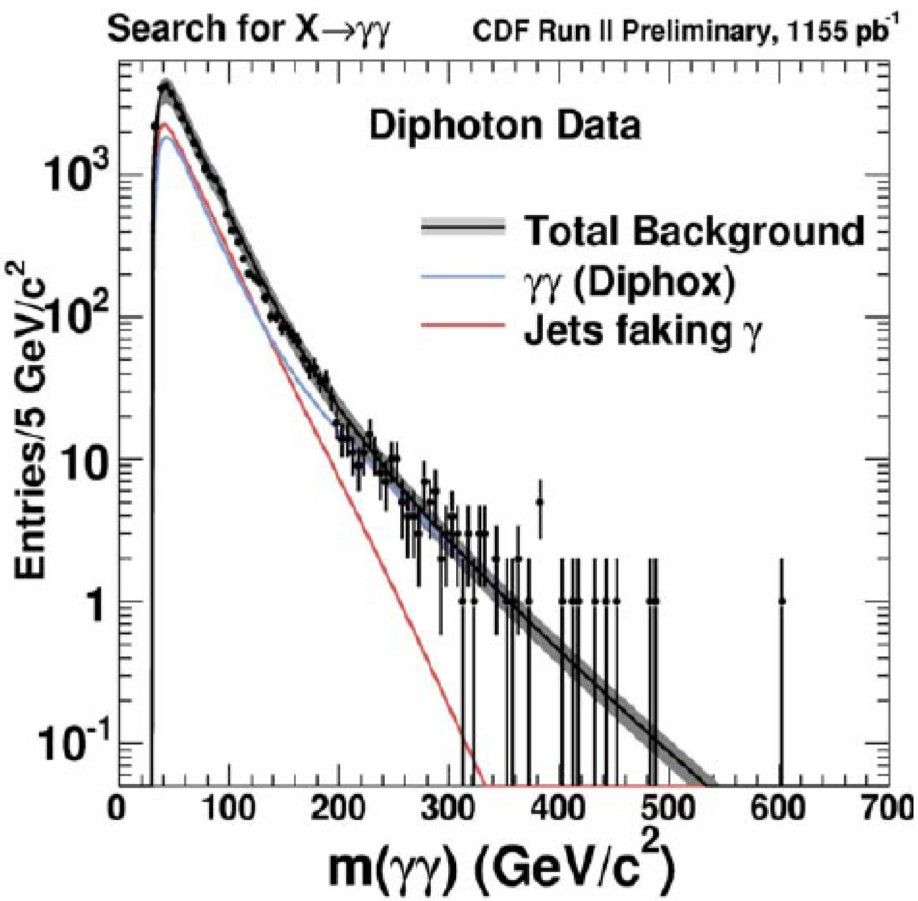
- Alternative solution to the hierarchy problem
- Randall-Sundrum model:
  - Gravity on a 3+1D Planck brane
  - Planck brane separated from the SM brane by a warped 5th dimension
  - Only gravitons propagate in the region between branes
  - Graviton wave function falls exponentially - gravity weak on SM brane
  - Kaluza-Klein excitations with ~1 TeV spacing, couple to SM particles

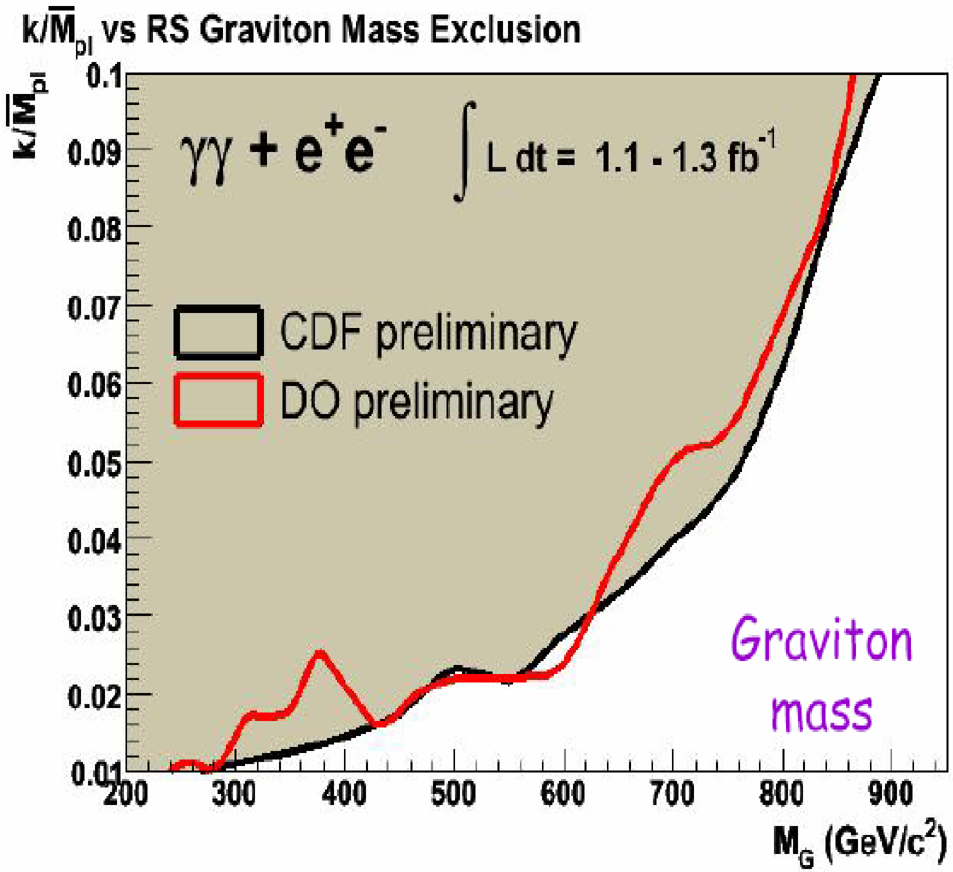




Search for Extra Dimensions

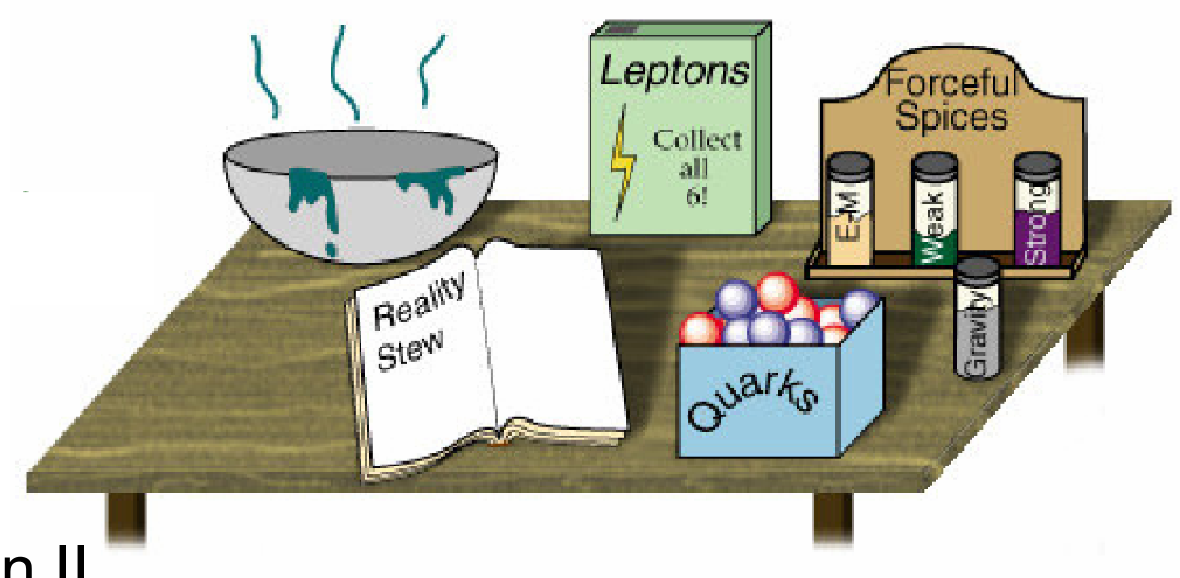
- Signature: narrow resonances in $\gamma\gamma$ or ee final state
  - No resonance seen; set limit on coupling and graviton mass





Conclusions

- Still cooking with the same old ingredients
- Most searches shown from ~1 fb^{-1} samples
- Sensitivity of many searches will improve with luminosity
- Expect ~6-8 fb^{-1} in Run II
- LHC is on the horizon – the sooner we come up with new ingredients the better



(stolen from talk by C. Magass)