Recontres Des Moriond

Exotic Searches at the Tevatron

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For the D0 and CDF Collaborations

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RUTGERS
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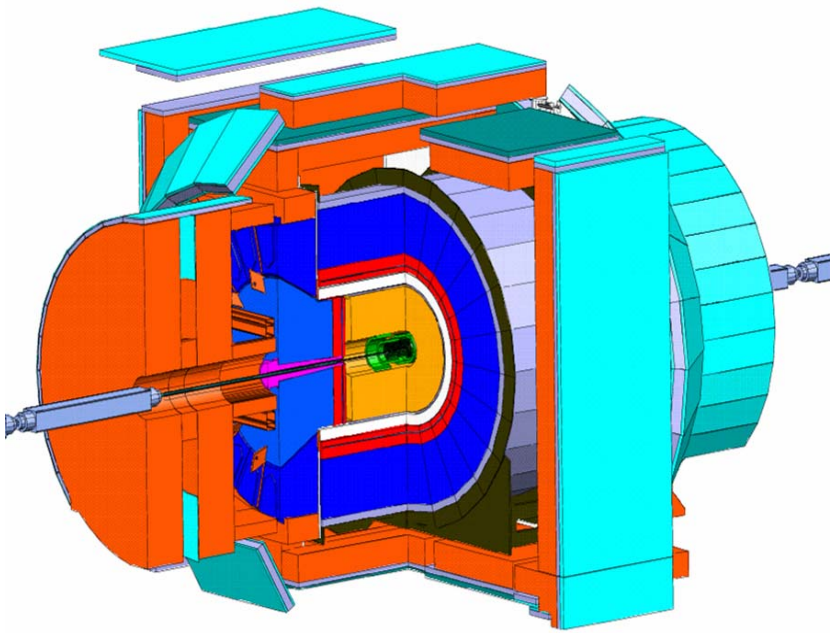
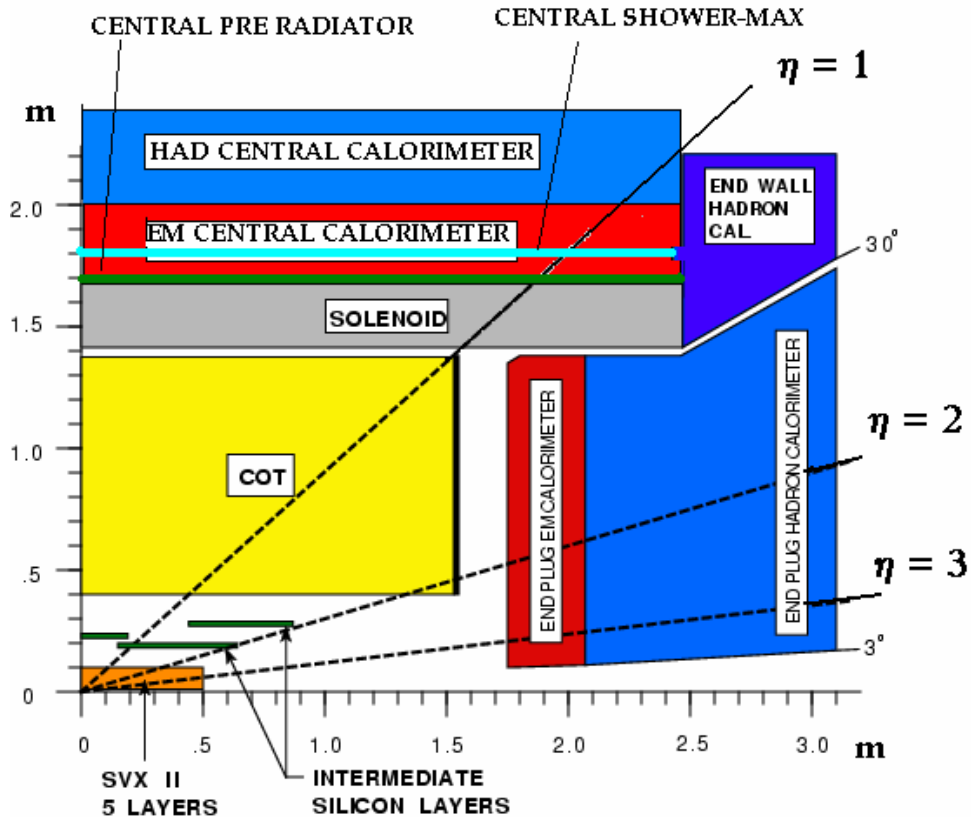
CDF II

Fermi National Accelerator Laboratory

DØ

CDF Detector

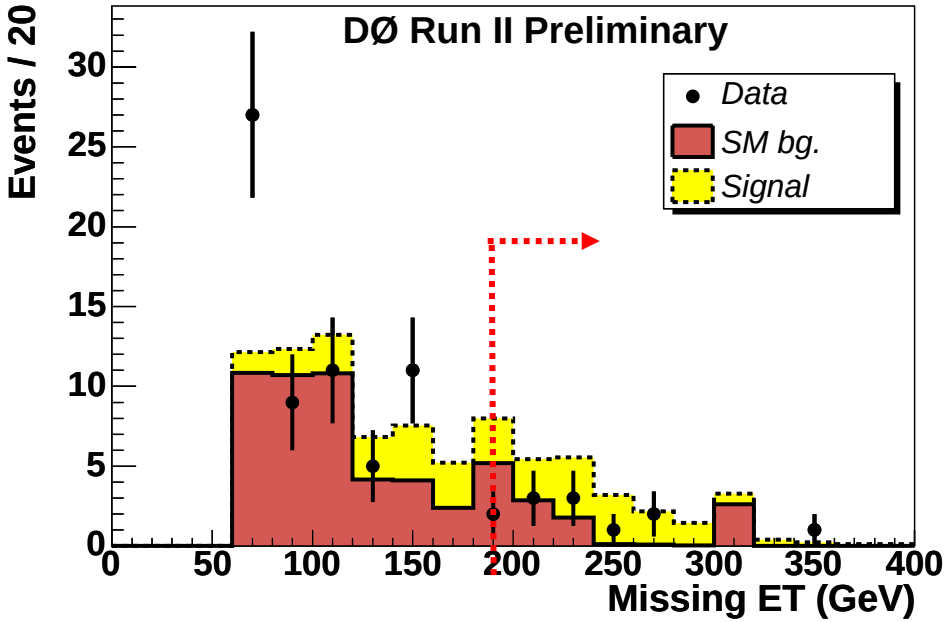


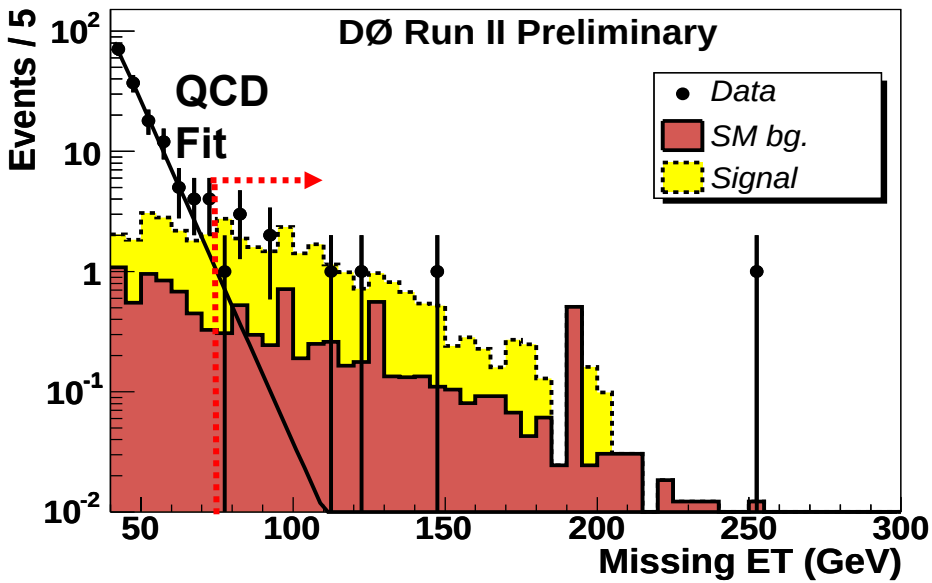


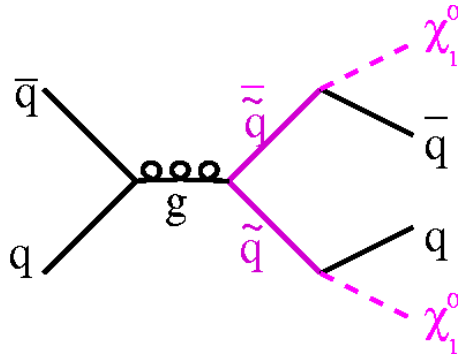
- Extended spatial e, μ coverage
- New plug calorimeter improves also MET measurement

- New displaced vertex trigger (SVT)
- New silicon and gas tracker
- Upgrade of muon system

Squark-gluino Search







1) $\tilde{g}$ heavier than $\tilde{q}$:

$\tilde{q}\tilde{q}$ production dominates,
look for acoplanar dijets

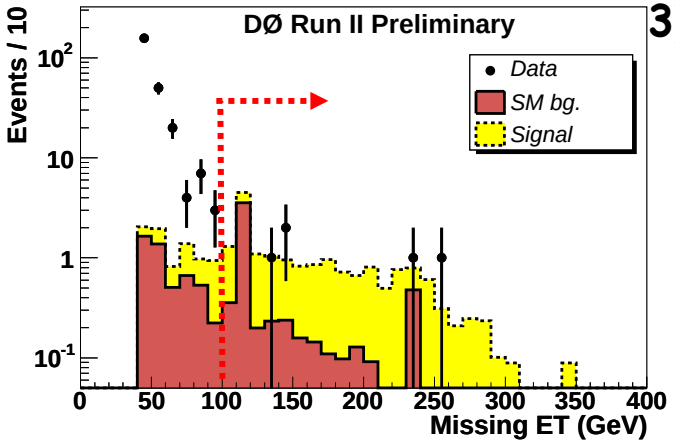
- $\not{E}_T$ > 175 GeV,
- Σ jet E_T > 250 GeV

2) $\tilde{q}$ heavier than $\tilde{g}$:

$\tilde{g}\tilde{g}$ production dominates,
look for multi (>=4) jets

- $\not{E}_T$ > 75 GeV,
- Σ jet E_T > 250 GeV

Squark-gluino Search



3) $\tilde{q}\,\tilde{g}$ similar masses:

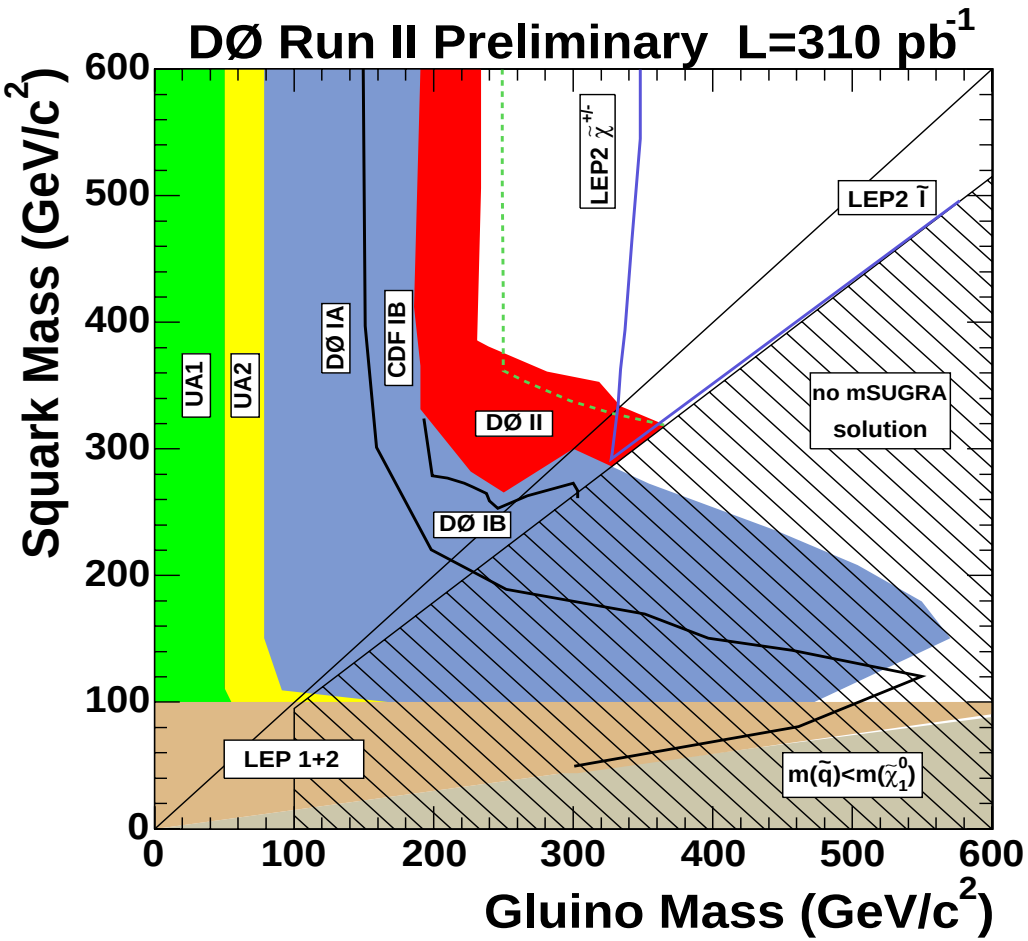
$\tilde{g}\tilde{q}$ production important,
look for 3 jet events

- $\not\!\!E_T$ > 100 GeV,
- Σ jet E_T > 325 GeV

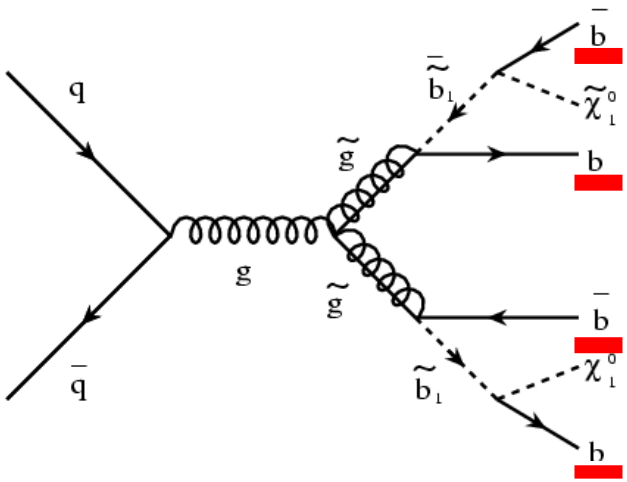
1) $\tilde{q}\tilde{q}$ production (dijets)
Expected 12.8 +- 5.4
Observed 12

2) $\tilde{g}\tilde{g}$ production (>=4 jets)
Expected 7.1 +- 0.9
Observed 10

3) $\tilde{q}\tilde{g}$ production (3 jets)
Expected 6.1 +- 3.1
Observed 5



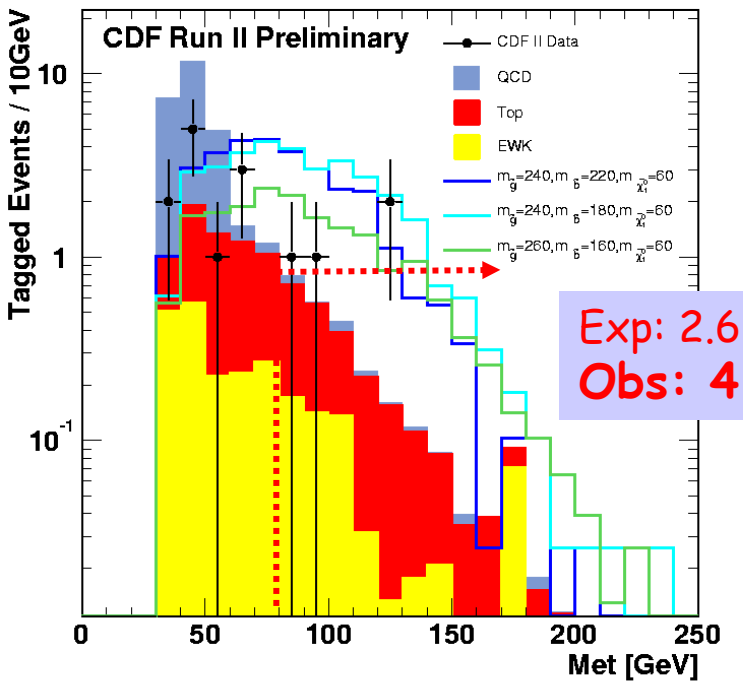
Search for Gluino → Sbottom



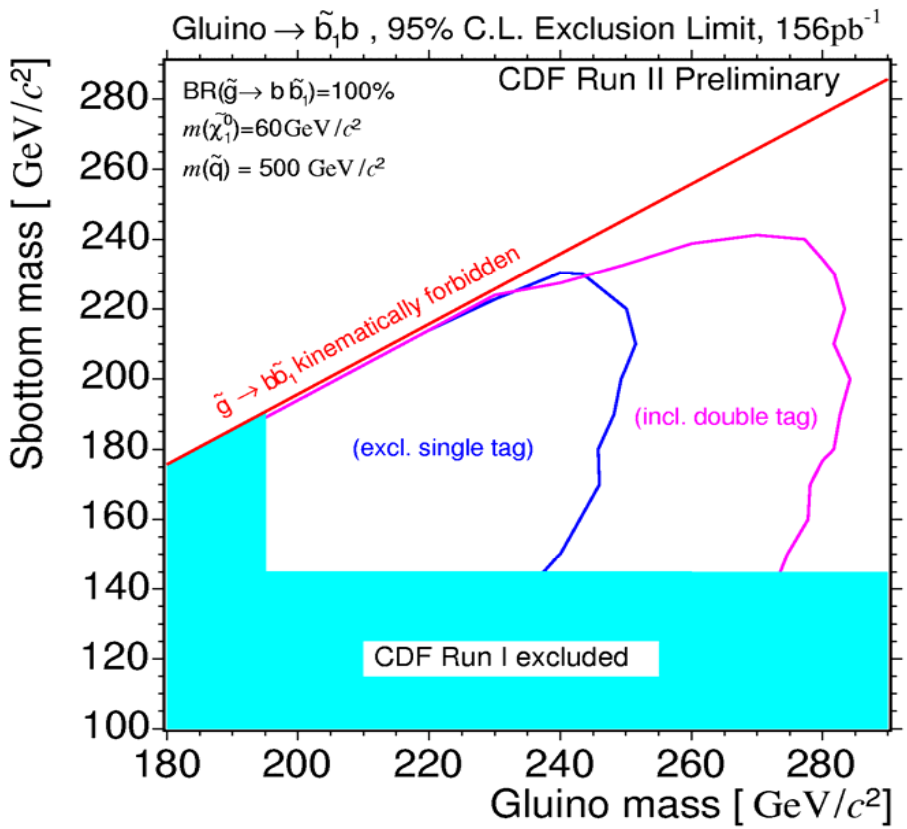
- $\tilde{b}_1$ can be *very light* for large tanβ
- Expect large branching fraction of gluinos to sbottoms.

⇒ Distinctive signature: 4 b-jets and $\not\!\!E_T$

Inclusive double tagged events



Exp: 2.6 +- 0.7
Obs: 4

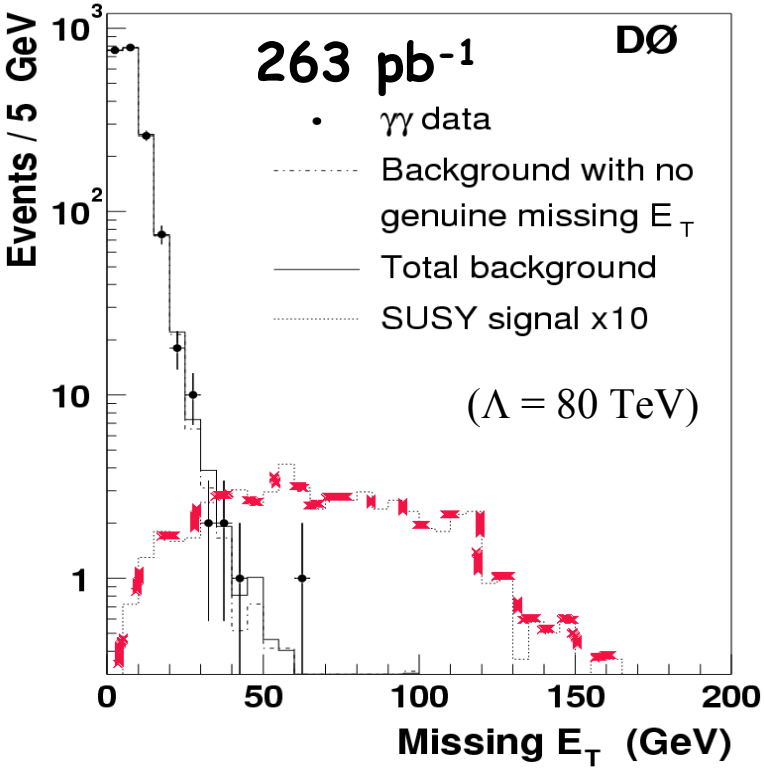


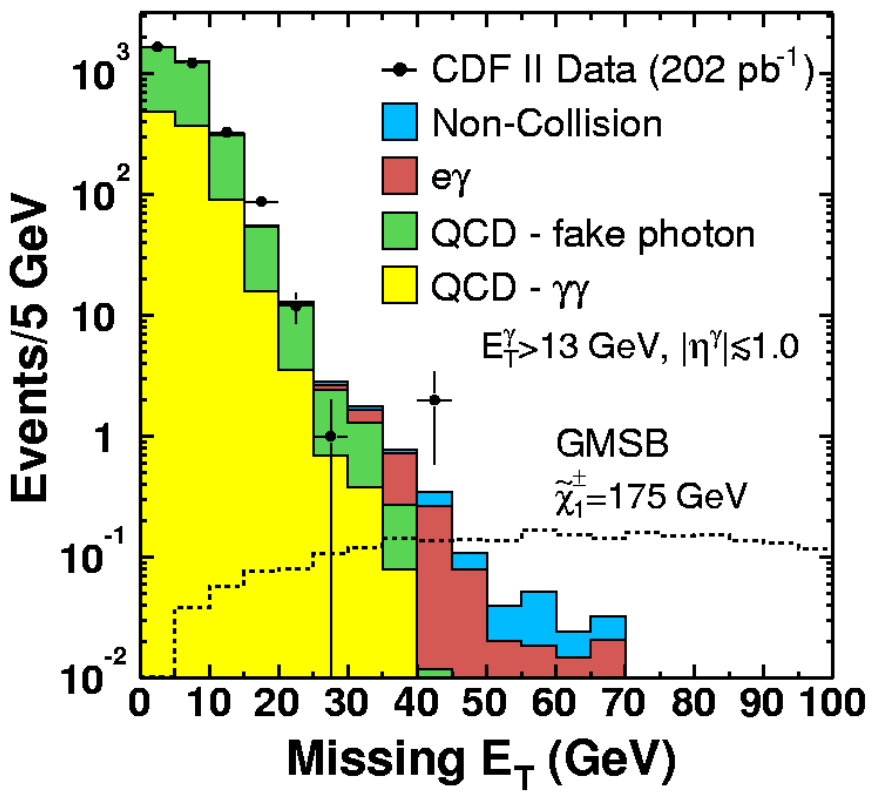
Diphotons+Missing Energy

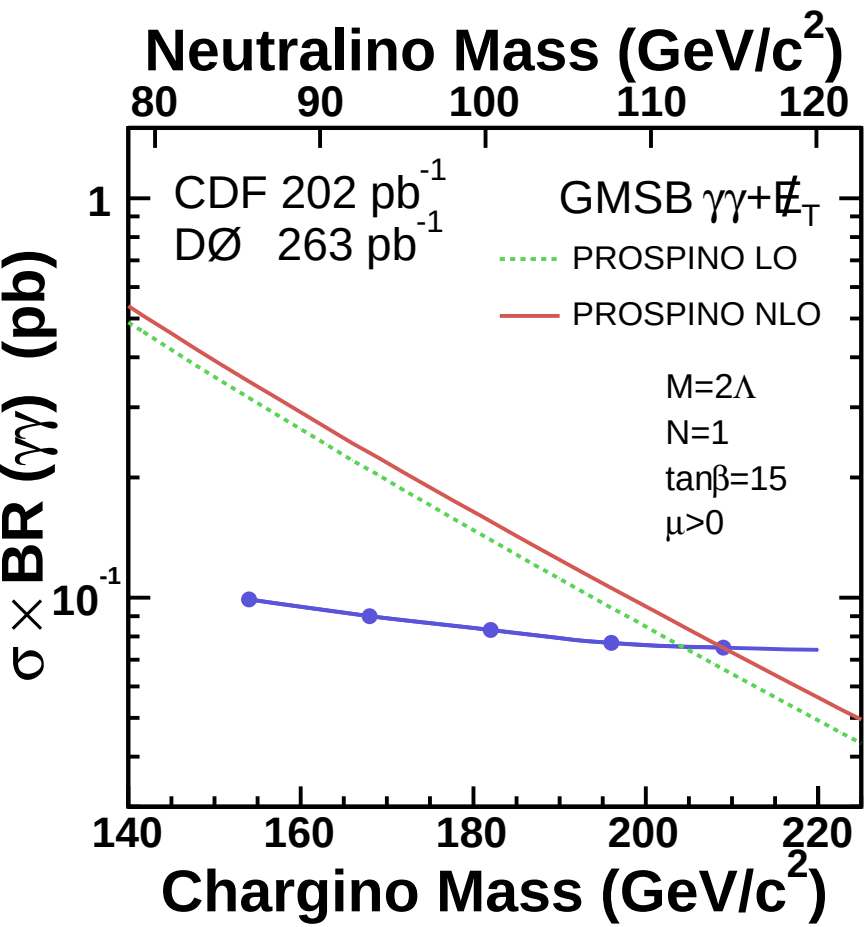
NLSP $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$ LSP

Typical GMSB signature from $\tilde{\chi}_1^0$ decay
Gaugino pair production → lightest neutralino

Signature: 2 energetic photons + $\not{E}_T$







D0: $E_T(\gamma)$ >20 GeV, $\not\!\!E_T$ >40 GeV

Expect: 3.6±0.6 events

Obs: 2

Phys. Rev. Letters 94, 041801 (2005).

Current results:

CDF $m(\tilde{\chi}_1^{\pm})$ > 167 GeV

D0 $m(\tilde{\chi}_1^{\pm})$ > 195 GeV

DF: $E_T(\gamma)$ >13 GeV, $\not\!\!E_T$ >45 GeV

xpect: 0.3±0.1 events

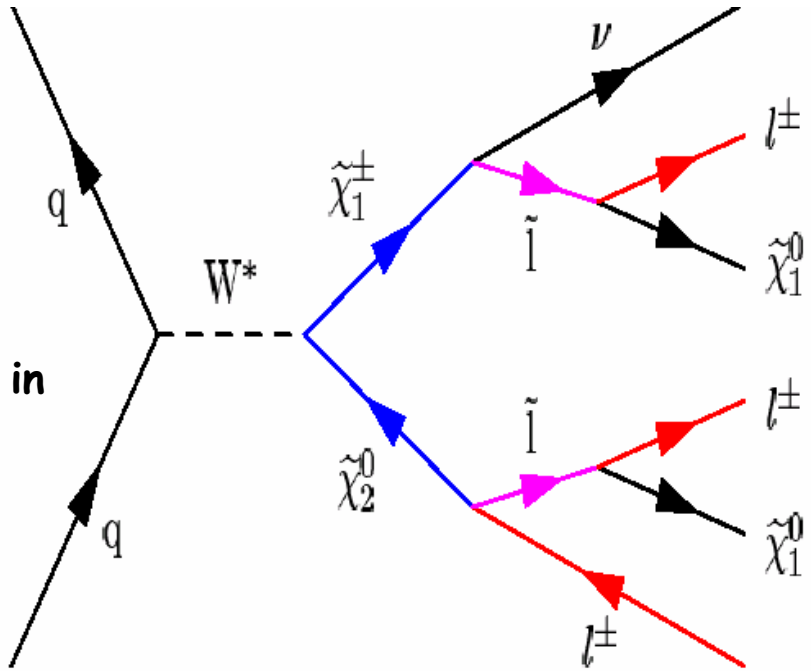
Obs: 0

Accepted by Phys Rev. D.

SUSY tri- & di-lepton searches

Trilepton signature is one of cleanest SUSY signatures

- Chargino-Neutralino production
- Decay to WZ (or sleptons) + 2 LSP
- Low SM background
- But also : Small x-section
  - Leptonic Br are enhanced if slepton masses are close to gaugino (i.e. χ^{+-}_1 in mSUGRA) masses.



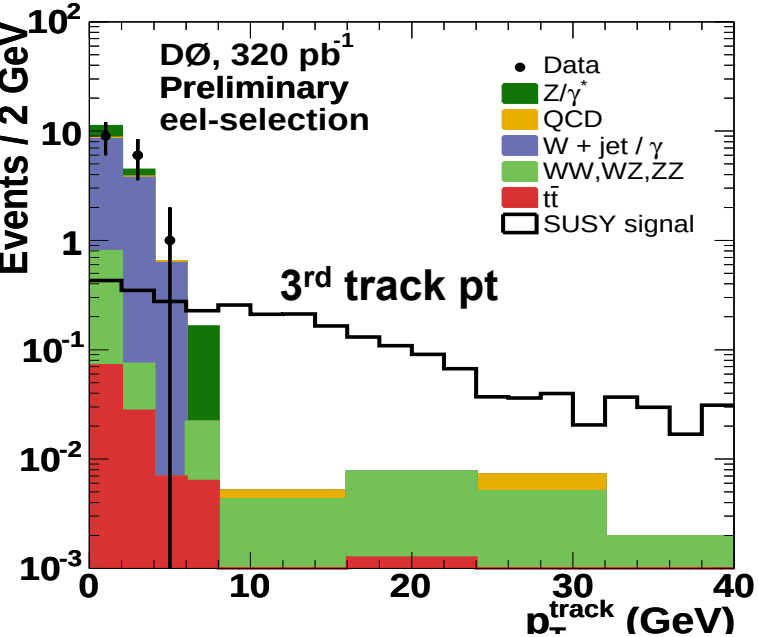
Classic tri-lepton SUSY signature:

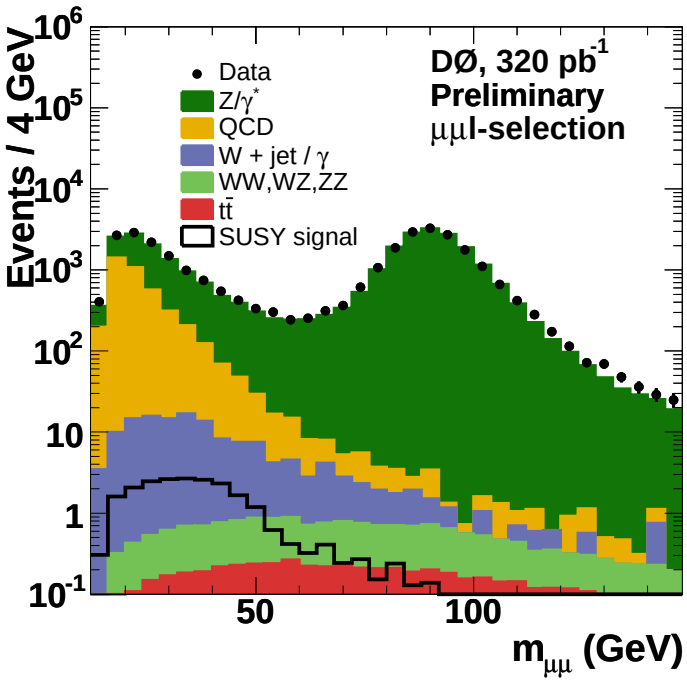
2 *like-sign* leptons signatures available

Strategy:

Combine eel, μμl, eμl, $\mu^{+-}\mu^{+-}$, τ(τ,l)l

SUSY Trileptons





1) eel:

p_T 1,2,3 > 12, 8, 4 GeV

$\not{E}_T \times p_{T3}$ > 220 GeV^2

Expected BG: 0.21+- 0.12
Observed: 0

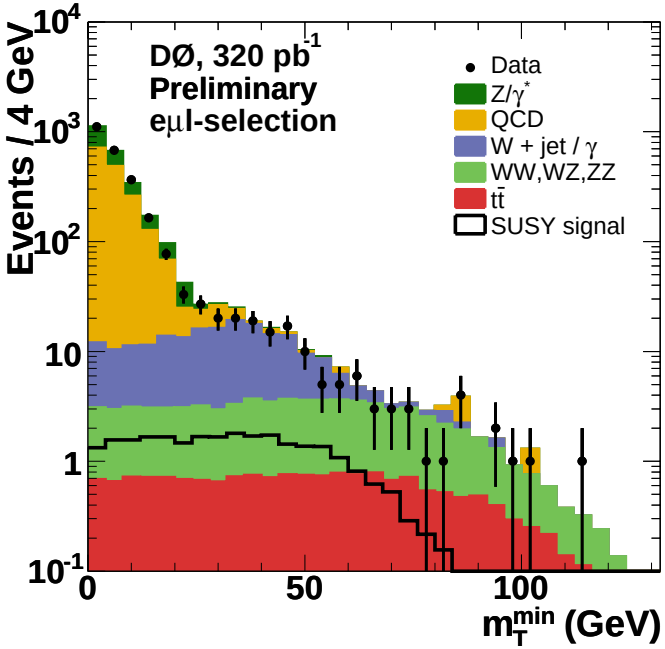
2) μμl:

p_T 1,2,3 > 11, 5, 3 GeV

$\not{E}_T \times p_{T3}$ > 150 GeV^2

Expected BG: 1.75 +- 0.57
Observed: 2

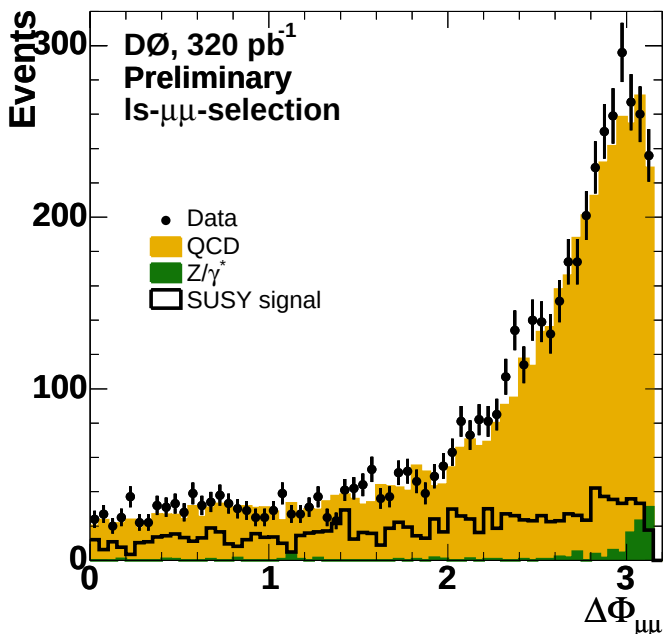
SUSY Trileptons



3) eμl:

p_T 1,2,3 > 12, 8, 7 GeV

Expected BG: $0.31\ ^{+0.15}_{-0.12}$
Observed: 0

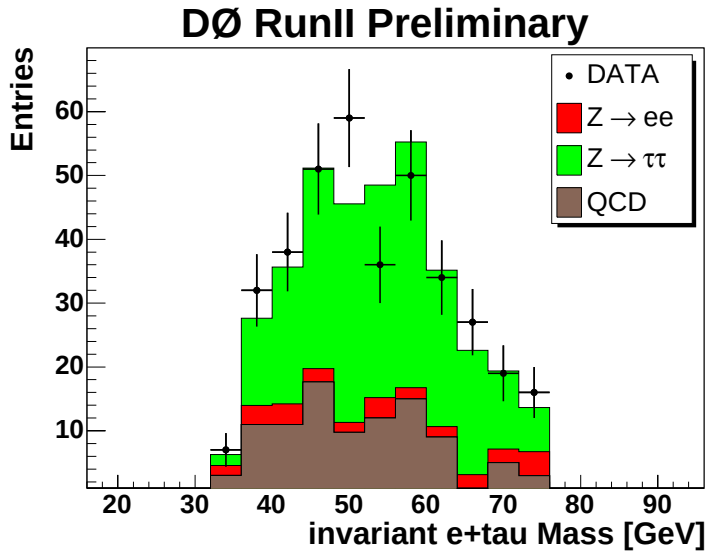


4) like-sign μμ:

p_T 1,2 > 11, 5 GeV
$E_T \times p_{T2}$ > 300 GeV^2

Expected BG: 0.66 +- 0.37
Observed: 1

SUSY Trileptons, with τ



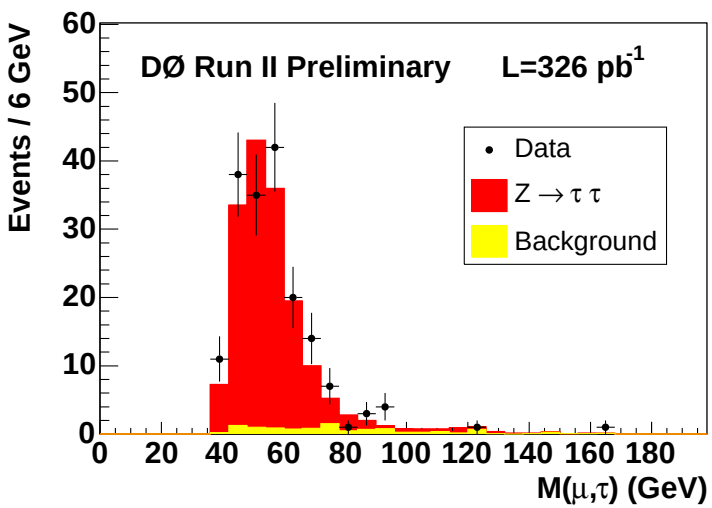
5a) eτl: τ → hadronic decay

p_T 1,2,3 > 8, 8, 5 GeV

$E_T \times p_{T(track)}$ > 350 GeV²

Expected BG: 0.582 $^{+0.112}_{-0.105}$

Observed: 0



5a) μτl: τ → hadronic decay

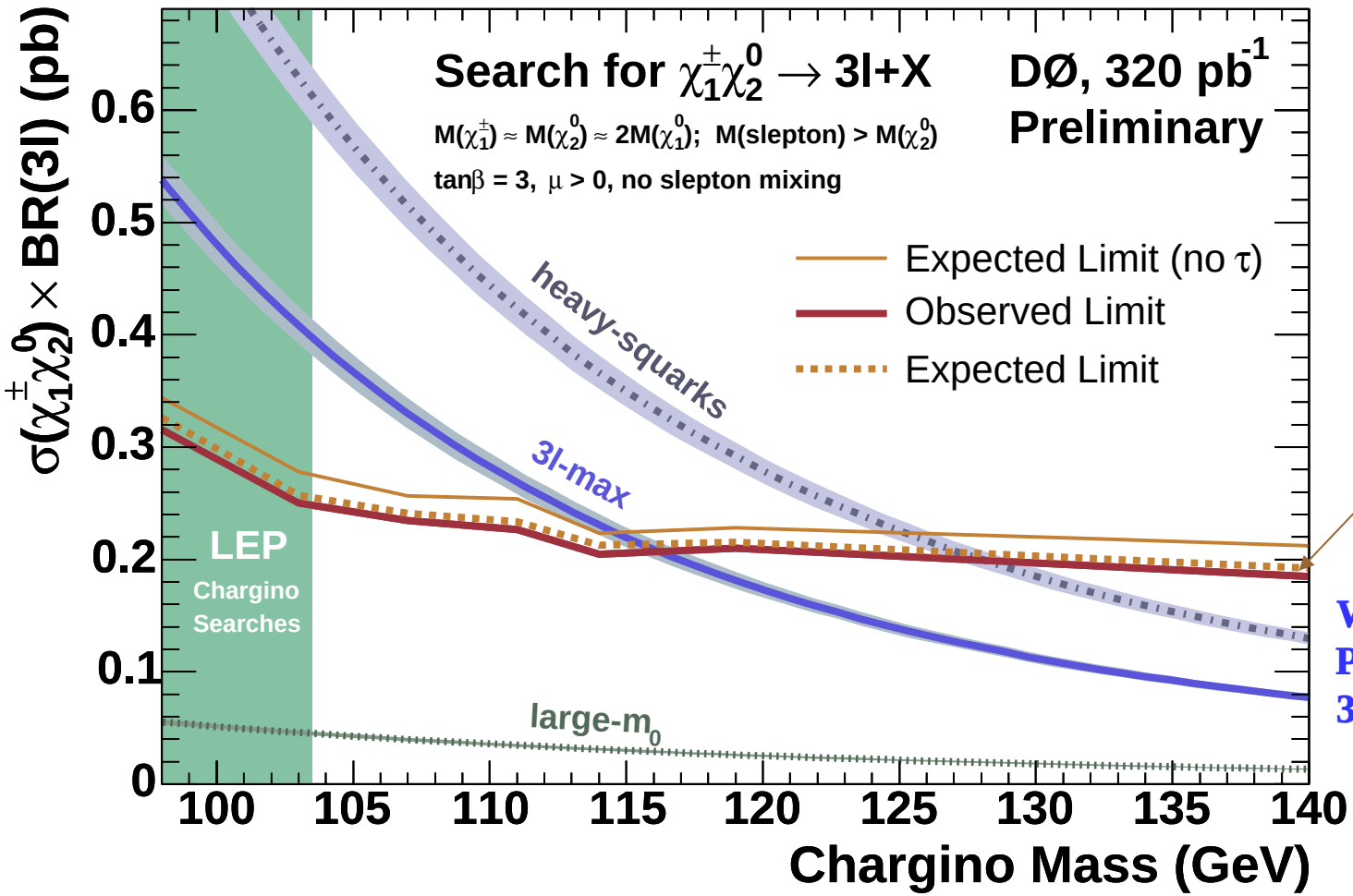
p_T 1,2,3 > 14, 7, 4 GeV

$E_T \times p_{T(track)}$ > 250 GeV²

Expected BG: 0.36 +- 0.12

Observed: 1

SUSY Trileptons, Combined Result

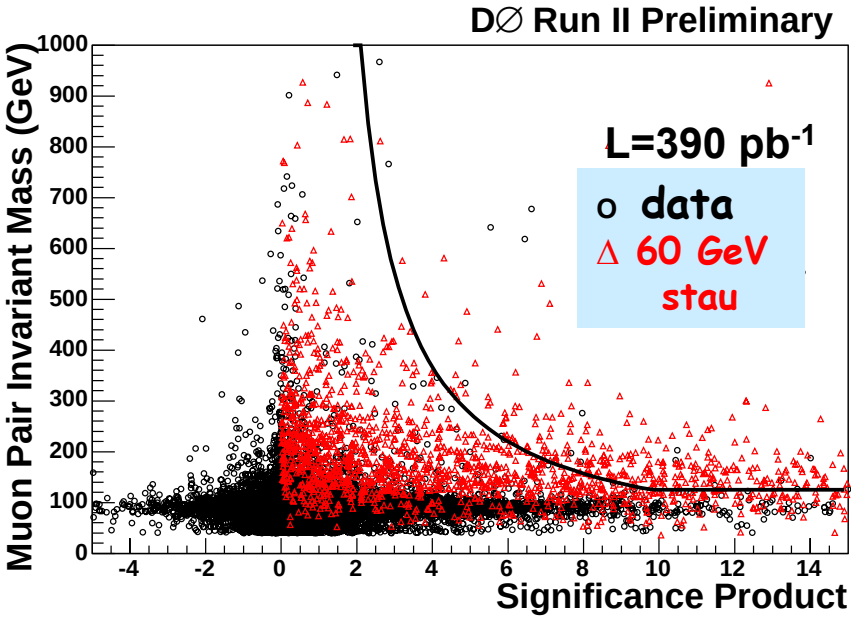


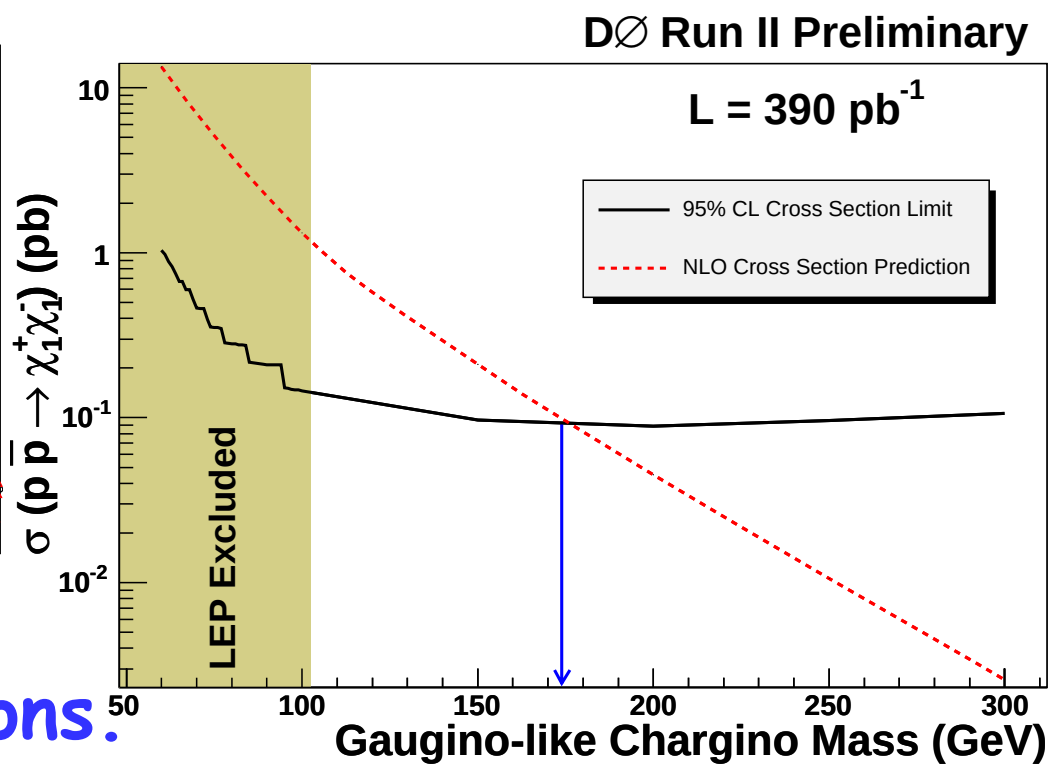
τ helps!

W. Beenakker et al., Phys. Rev. Lett. 83, 3780 (1999)

Huge improvement on Run 1 (~1.5 pb limit)

Charged Massive Particles





CHAMPS look like muons:

- inv mass, speed inconsistent with beam-production.
- speed significance = $\frac{1-\text{speed}}{\sigma_{(\text{speed})}}$
- significance > 0 for both muons

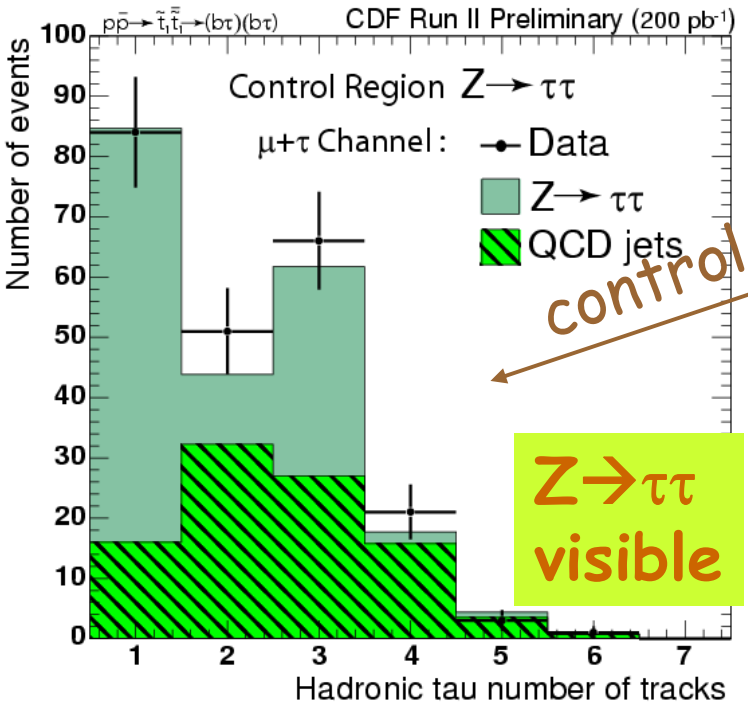
Gaugino-like chargino > 174 GeV/c^2
Higgsino-like chargino> 140 GeV/c^2

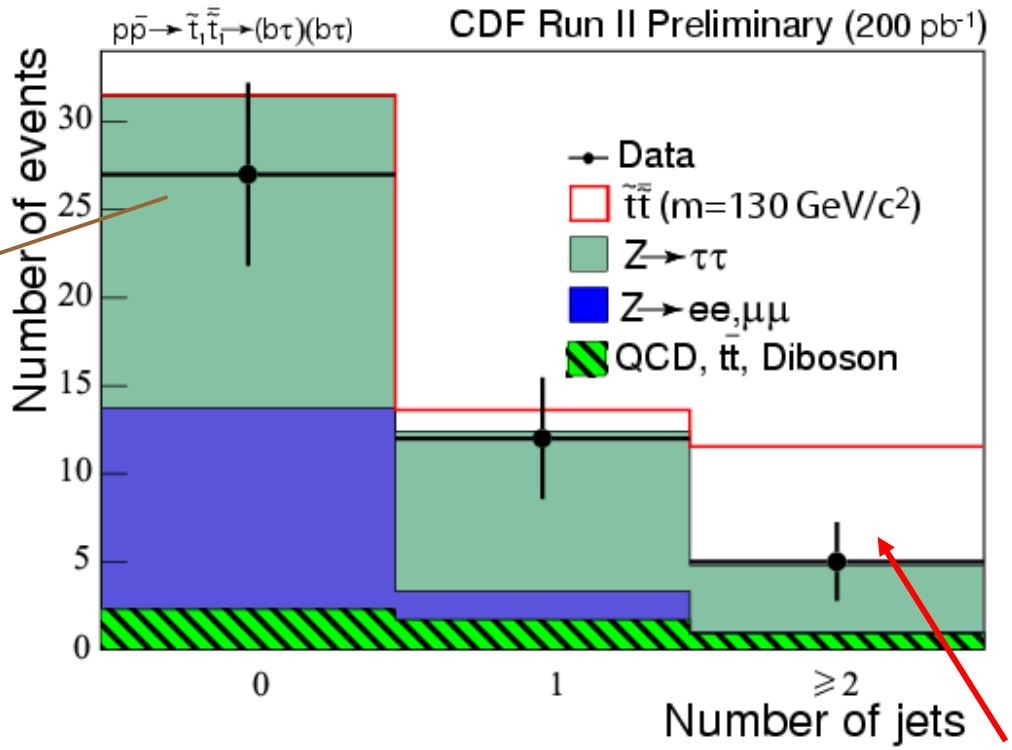
CDF Champs search: (85 pb^{-1})
M_stop > 108 GeV/c2

SuperSymmetry (RPV)

$p\bar{p} \rightarrow \tilde{t}\,\tilde{t} \rightarrow b\tau\, b\tau$

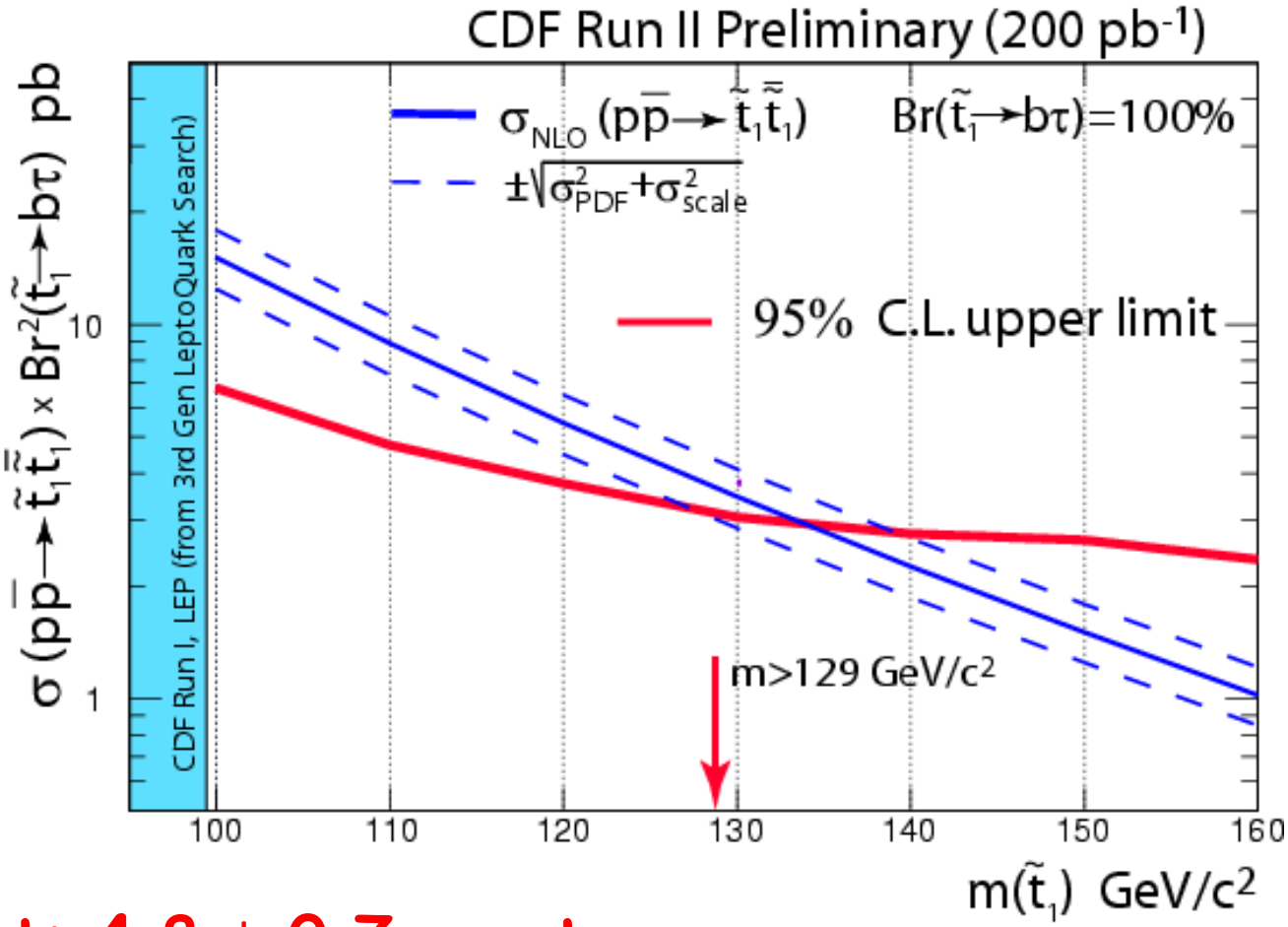
No large $\not{E}_T$ requirement possible!





Biggest background: Real τ from Z→ττ

SuperSymmetry (RPV)



Expect: 4.8 ± 0.7 events

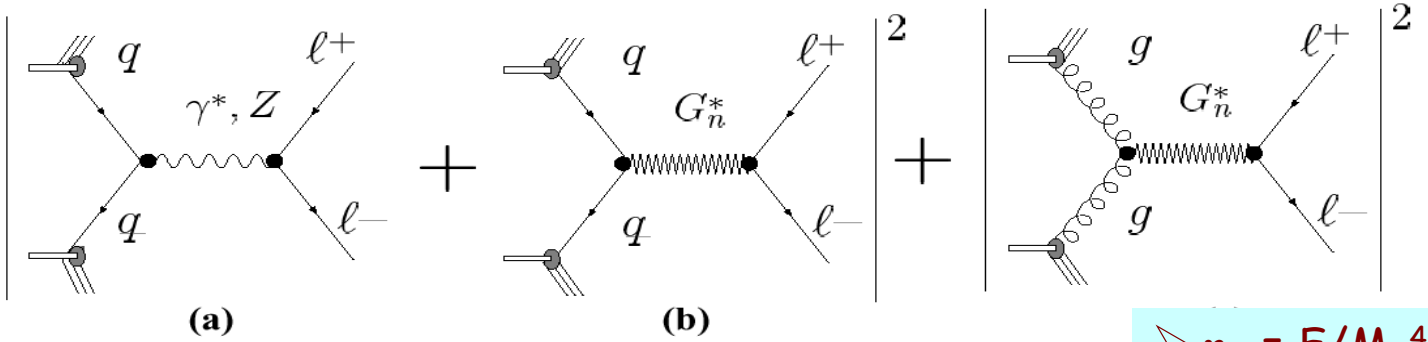
Obs: 5

$m(\tilde{t}_1) > 129\ GeV/c^2$

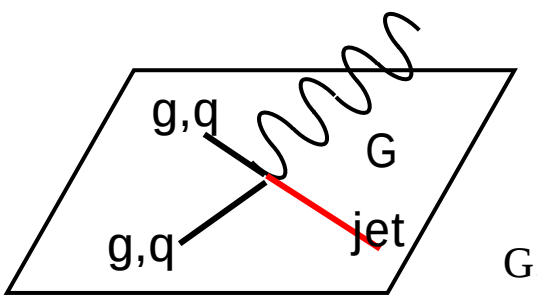
3rd Gen. LQ also ruled out at m>129 GeV/c²

Large Extra Dimension (LED)

- **Dilepton and diphoton channels:**



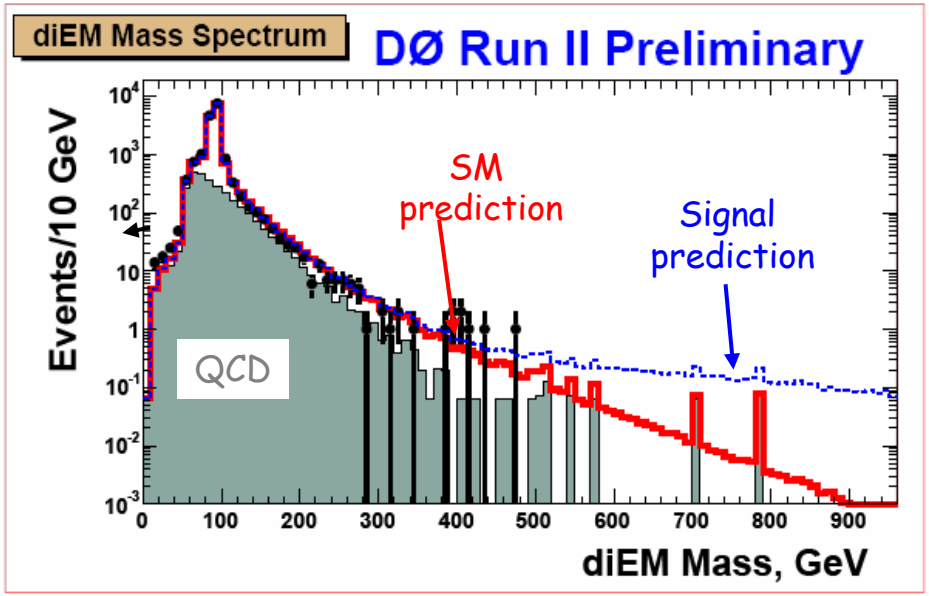
- **Monojet channel where a jet recoils against the graviton which leaves the usual 3D dimension.**

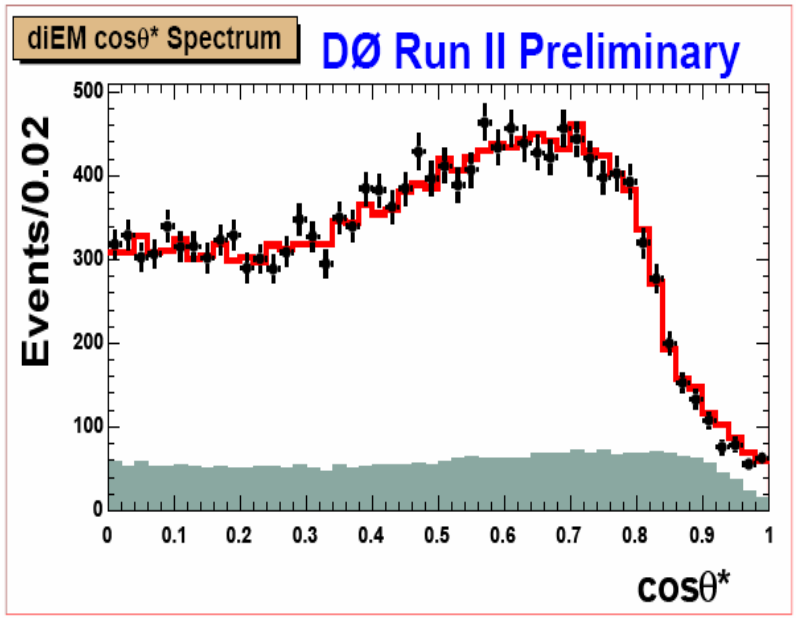


- $\eta_G = F/M_S^4$
- F is a *model dependent* dimensionless parameter ~ 1:
- **GRW**: F = 1
- **HLZ**:
  F = $\log(M_s^2/M^2)$, n =2
  F = 2/(n-2), n > 2
- **Hewett**:
  F = 2 λ/π, $\lambda = \pm 1$
  M_s is UV cutoff = $M_{PL(3+n\ dim)}$

G. Giudice, R. Rattazzi, and J. Wells, Nucl. Phys. **B544**, 3 (1999)
T. Han, J. Lykken, and R. Zhang, Phys. Rev. D **59**, 105006 (1999)
J. Hewett, Phys. Rev. Lett. **82**, 4765 (1999).

LED with ee & γγ





➢ **Fit Mee, Mγγ and cosθ*, extract $\eta_G^{95\%}$**

$\eta_G = 0.00 \pm^{0.12}_{0.00}$ TeV^{-4} $\quad$ $\eta_G = -0.08 \pm^{0.08}_{0.18}$ TeV^{-4}

$\eta_G^{95\%} = 0.292$ TeV^{-4} $\quad$ $\eta_G^{95\%} = -0.432$ TeV^{-4}

for $\lambda > 0$ $\quad$ for $\lambda < 0$

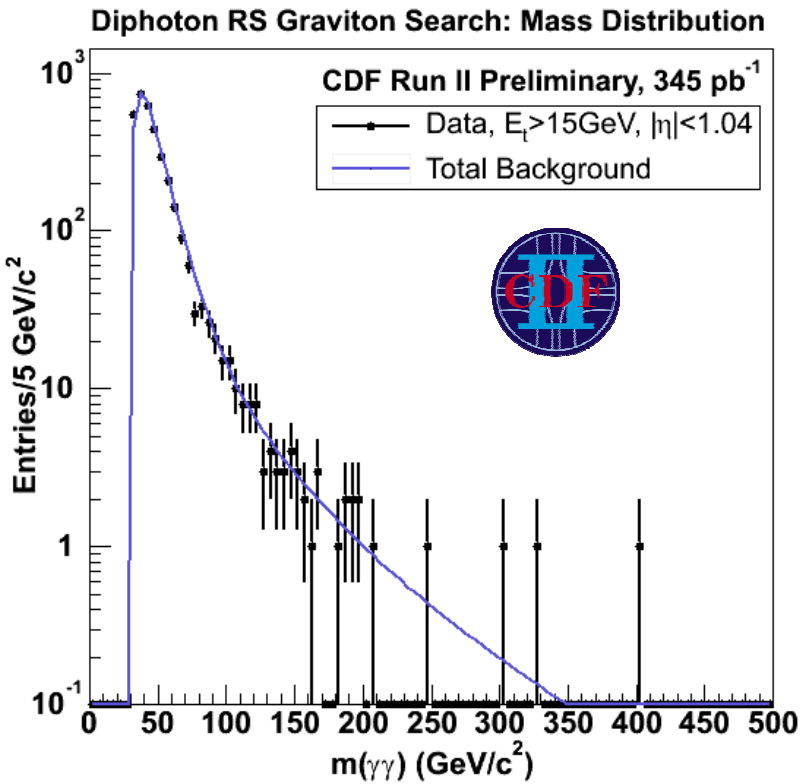
Limits on Fundamental Planck Scale, in TeV

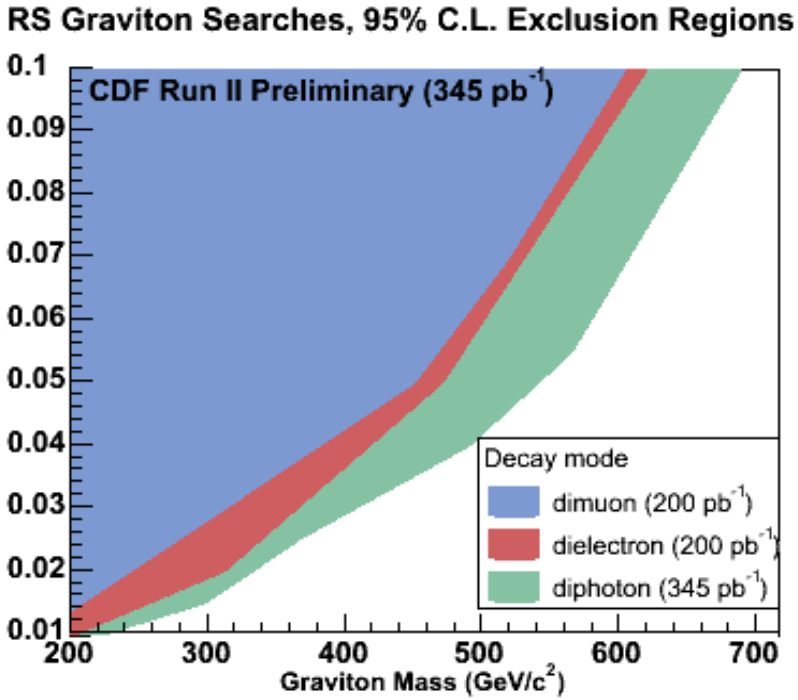
	GRW	HLZ for n =						Hewett
		2	3	4	5	6	7	λ = +1/-1
DØ RunII	1.36	1.56	1.61	1.36	1.23	1.14	1.08	1.22/1.10
DØ RunI + Run II	1.43	1.67	1.70	1.43	1.29	1.20	1.14	1.28/NA

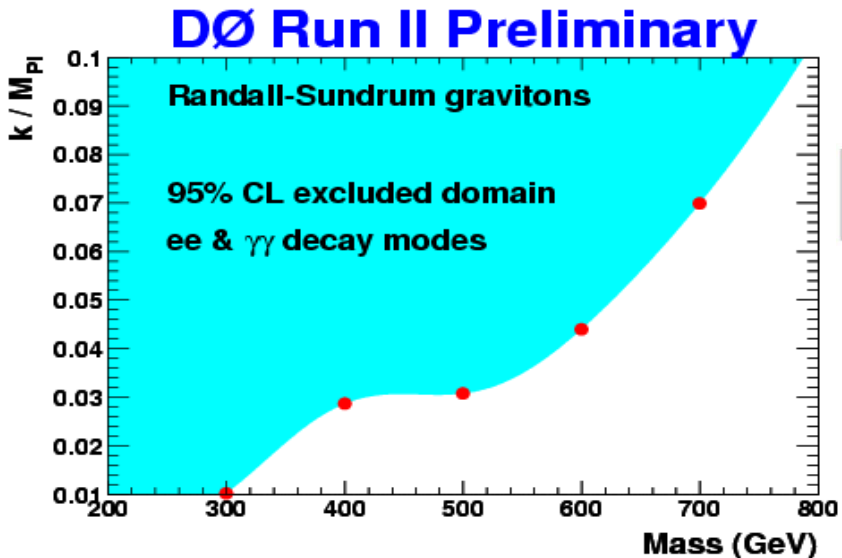
ED with di-photons

$p\bar{p} \rightarrow G \rightarrow \gamma\gamma$

L. Randall and R. Sundrum,
Phys. Rev. Lett. **83**, 3370 (1999).



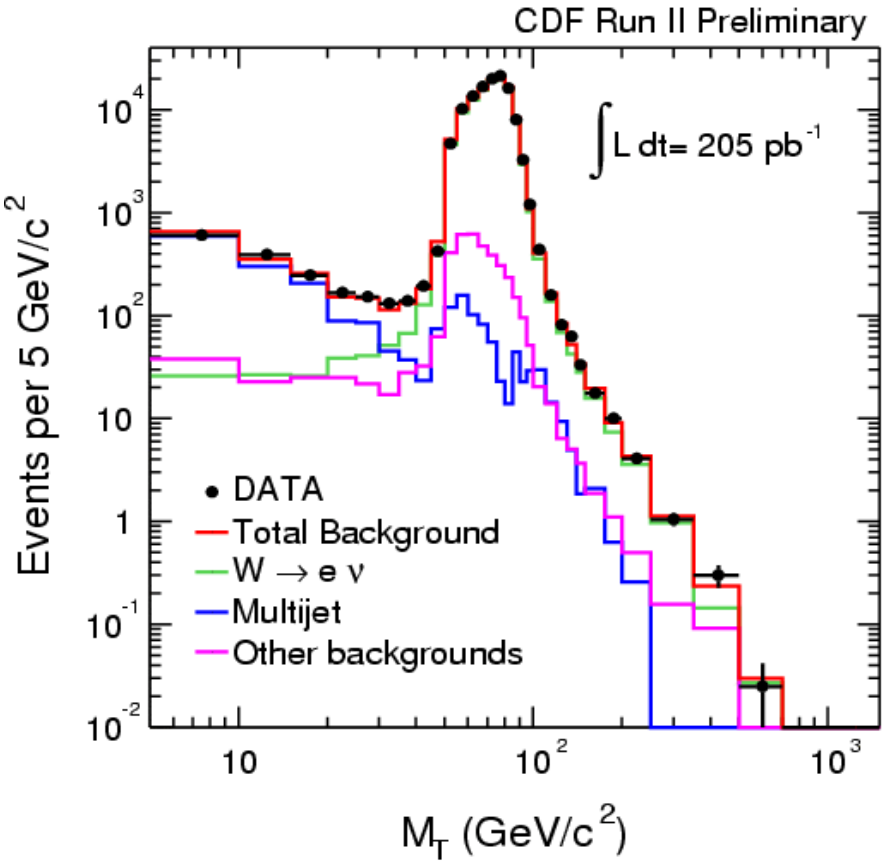


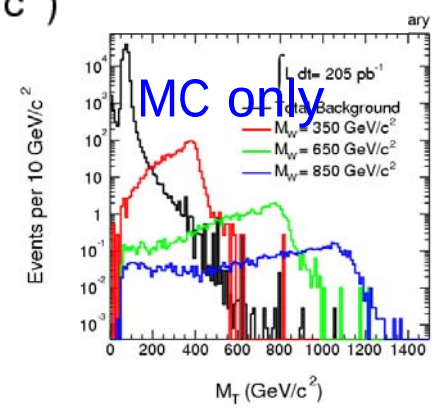


W' search in eν channel

- W': additional charged heavy vector boson
- appears in theories based on the extension of the gauge group
- e.g. Left-right symmetric models: $SU(2)_R \longrightarrow W_R$
- assume: the neutrino from W' decay is light and stable.
- signature:

high p_T electron + high $\not{E}_T$



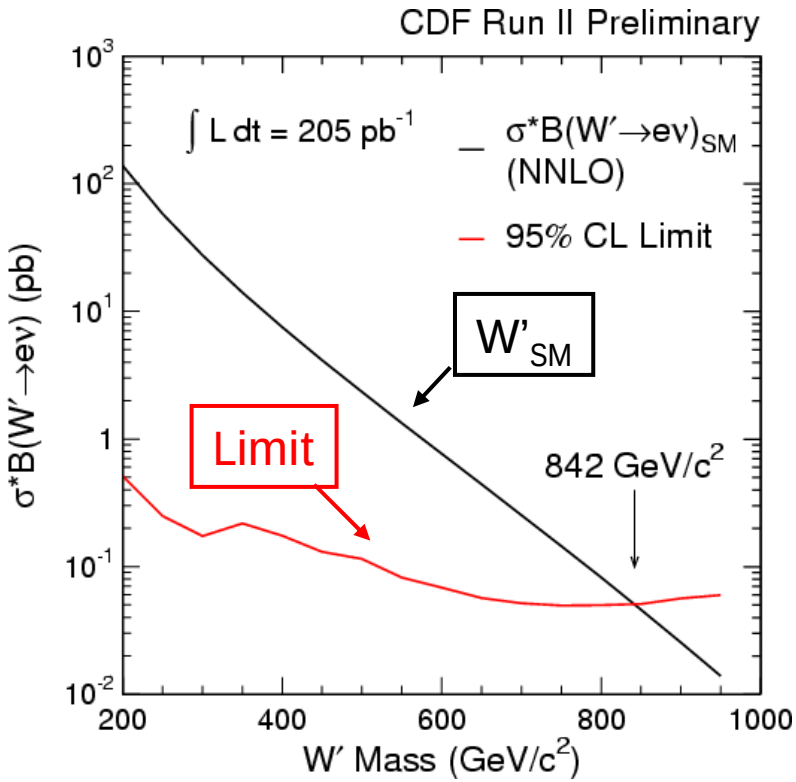


W' search (cont.)

- No events above SM expectation, set limits on W' production rate
- use binned likelihood fitting method
- two types of systematics are examined as a function of M_T:
  - affect **event rate**

    (dominant: PDF, ~14%)
  - affect **the shape**

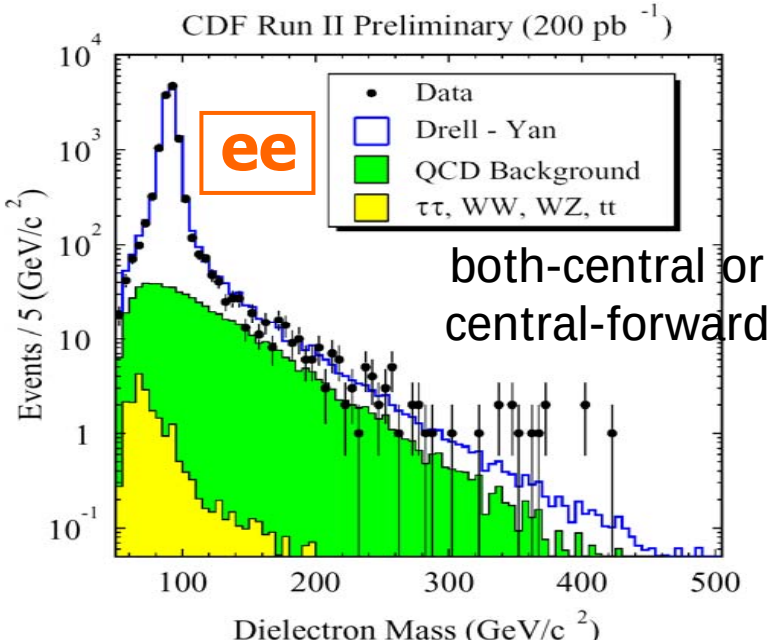
    (dominant: electron energy scale, ~16%)
- σ*B(W' → eν) limit: ~ 50 – 100 fb for M(W') > 500 GeV/c^2 at 95% CL.



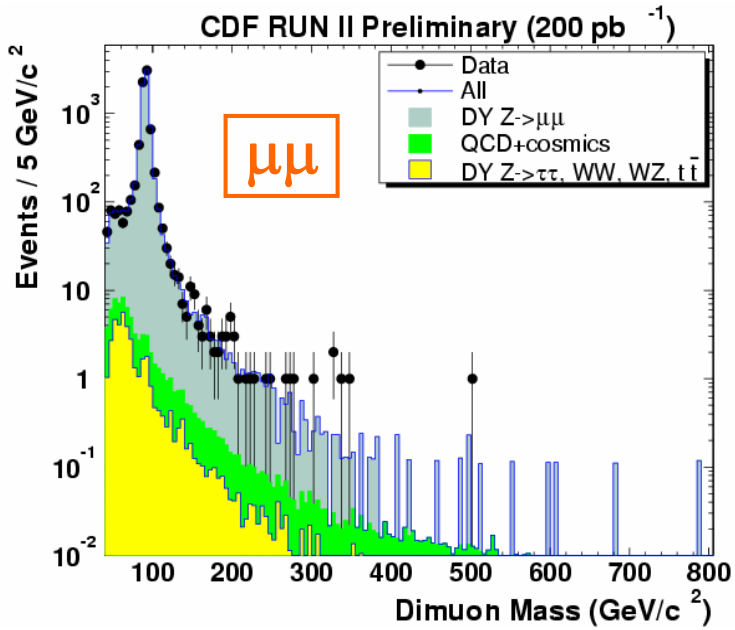
Limit: $M(W'_{SM}) > 842$ GeV/c^2

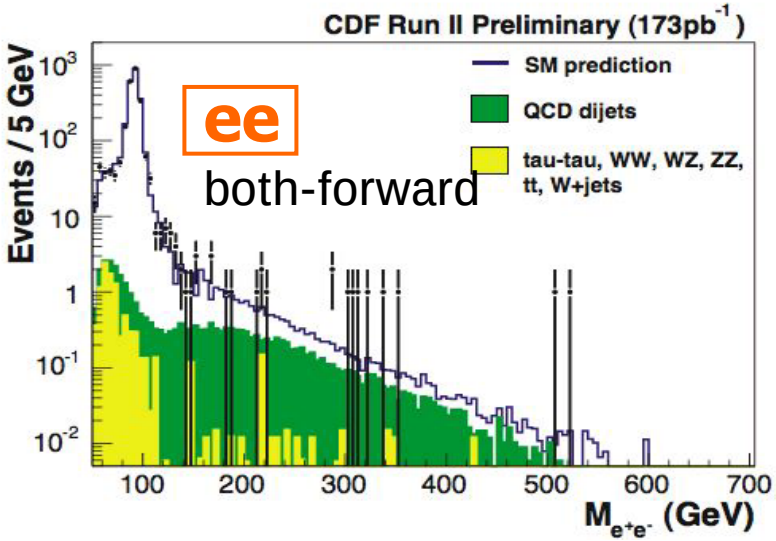
Run I results (with the same assumptions):
$M(W'_{SM}) > 754$ GeV/c^2

Searches in high mass dileptons (cont.)

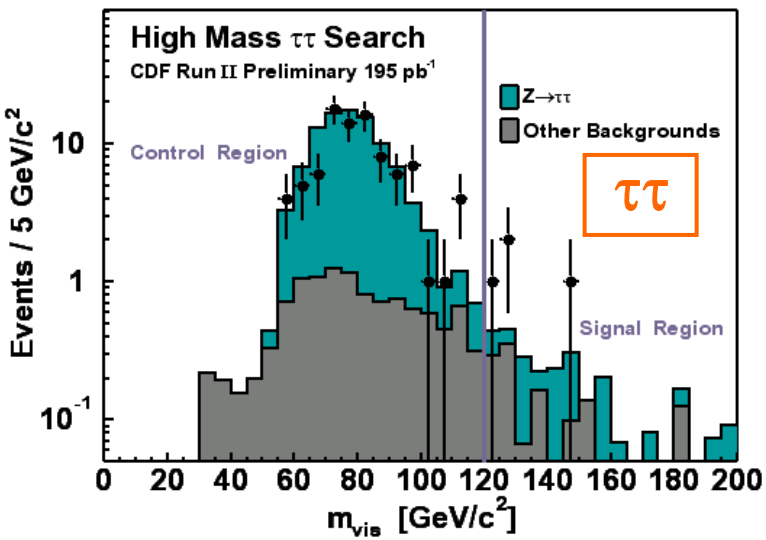


both-central or central-forward



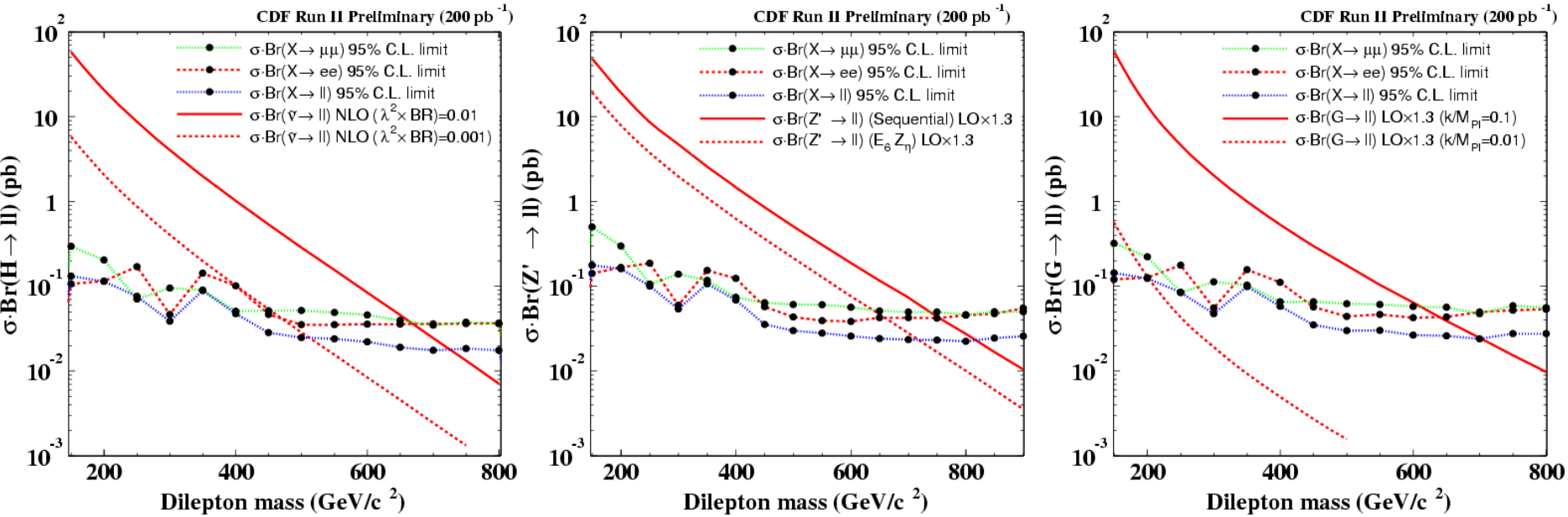


both-forward



σ*BR Limits (X→ ee or μμ)

spin-0 spin-1 spin-2



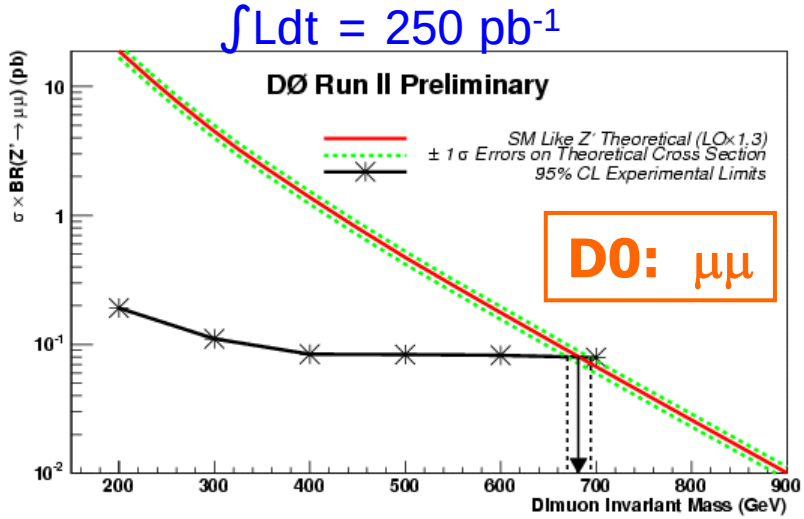
σ*Br(X → μμ) 95% CL limit

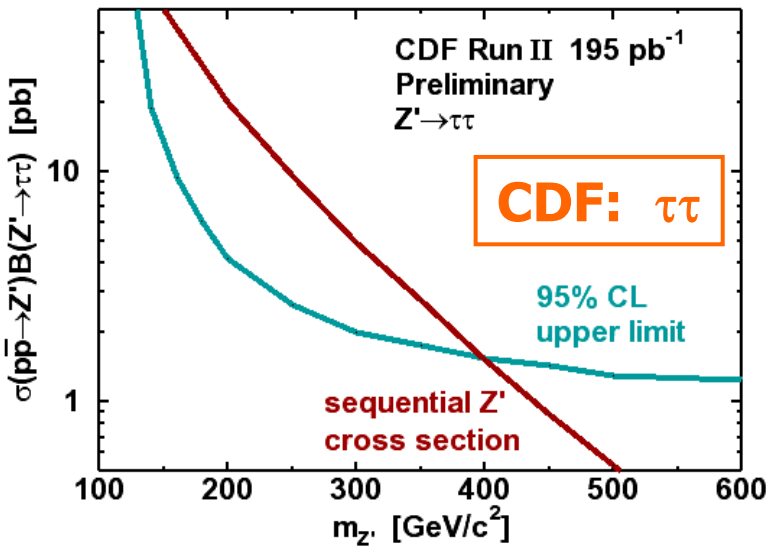
σ*Br(X → ee) 95% CL limit

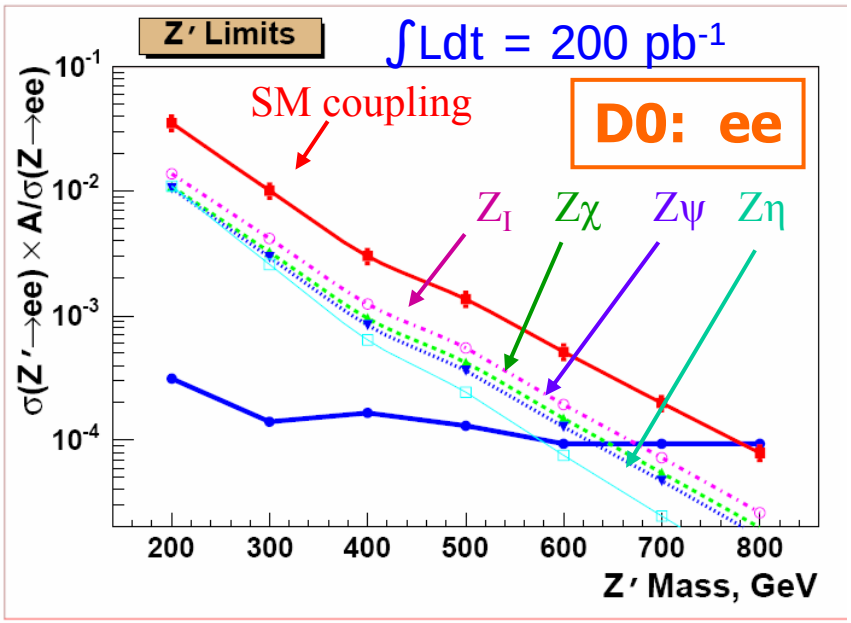
ee, μμ combined limit

- σ*Br limit: ~ 25 fb for all spins for the high mass region (M_{ll} > 600 GeV)
- These limit curves can be compared with many models
- Individual channel limits are still very important - lepton universality ?

Spin-1, Z' limits







z' mass limits (in GeV/c^2)

SM Couplings	ee	μμ	ee+μμ	ττ
CDF :	750	735	815	394
DØ:	780	680		

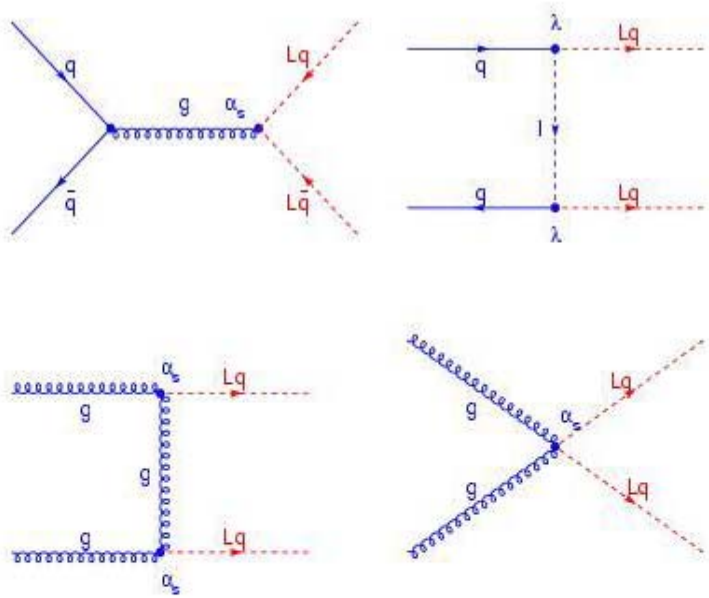
E_6	Z_I	Zχ	Zψ	Zη	
CDF:	610	670	690	715	(ee+μμ)
DØ:	575	640	650	680	(ee)

Leptoquarks (direct searches)

Carry both lepton (L) and baryon (B) numbers
Couple to quark and lepton **of the same generation**

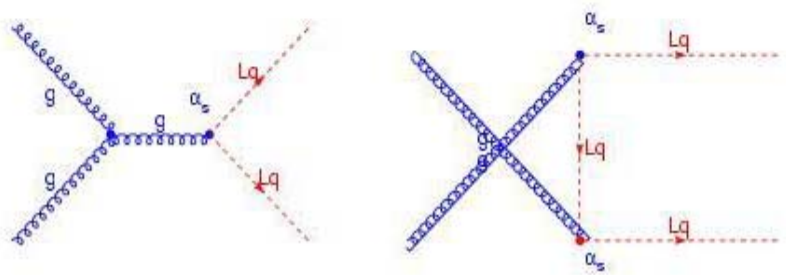
At the TeVatron they are pair produced

3 generations



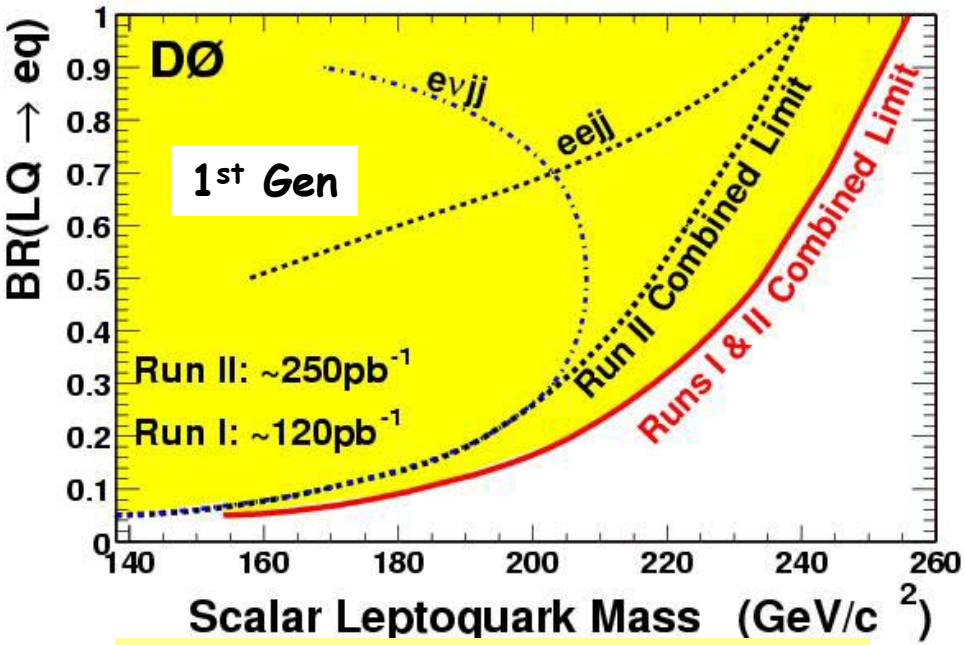
Their decay is controlled by β = **BR (LQ→lq)**

Experimental signature:
high P_T isolated lepton(s) (β=1)
***or* $\not{E}_T$ + 2 jets (β=0)**



1st, 2nd and 3rd Generation LQ

channels: eejj, evjj, (νvjj)

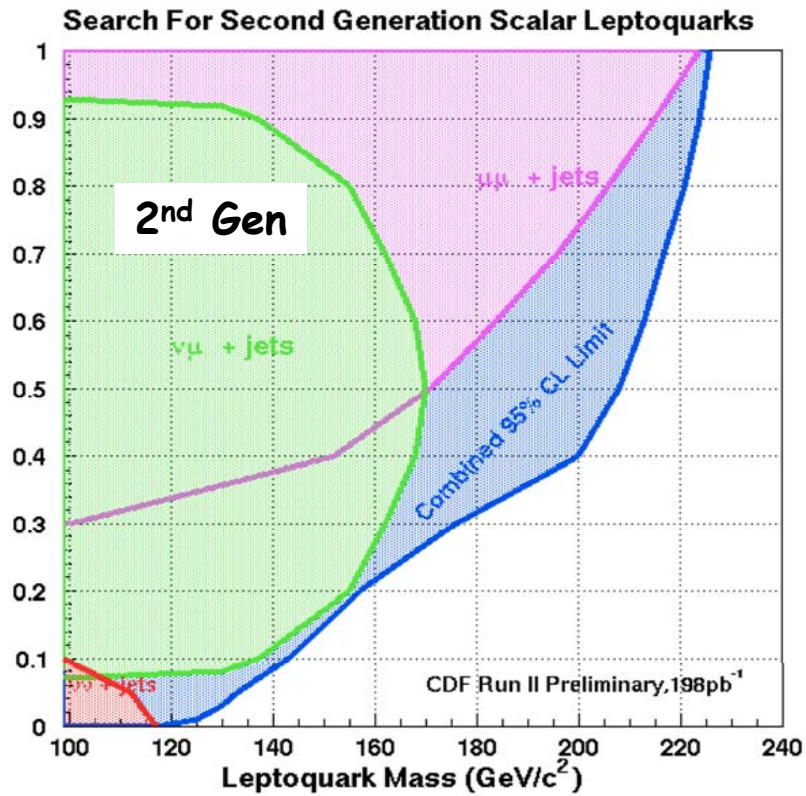


for β=1,

D0: Run I + II, M_{LQ} > 256 GeV/c^2

CDF: Run II, M_{LQ} > 235 GeV/c^2

channels: μμjj, εvjj, vvjj



for β=1,

D0: Run I, M_{LQ} > 200 GeV/c^2

CDF: Run II, M_{LQ} > 224 GeV/c^2

3rd Gen. LQ ruled out by CDF at m>129 GeV/c^2 (β=1)

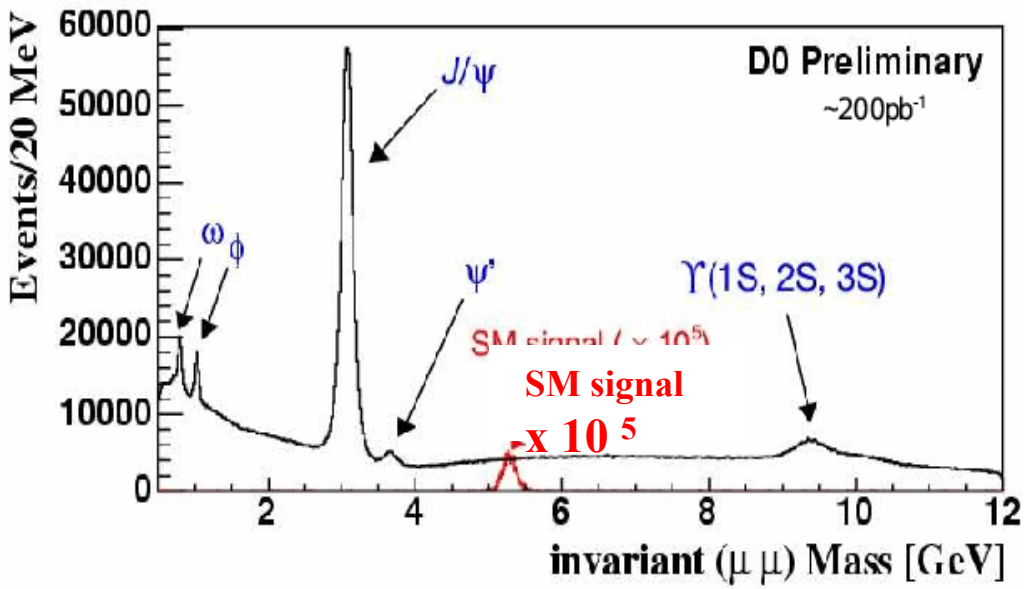
See the RPV stop search

$B_s \rightarrow \mu\mu$

Complementary to other SUSY searches, *indirect*
BR could be enhanced from new physics:
loop decays (MSSM, mSugra) or direct ($\not{R}_P$)

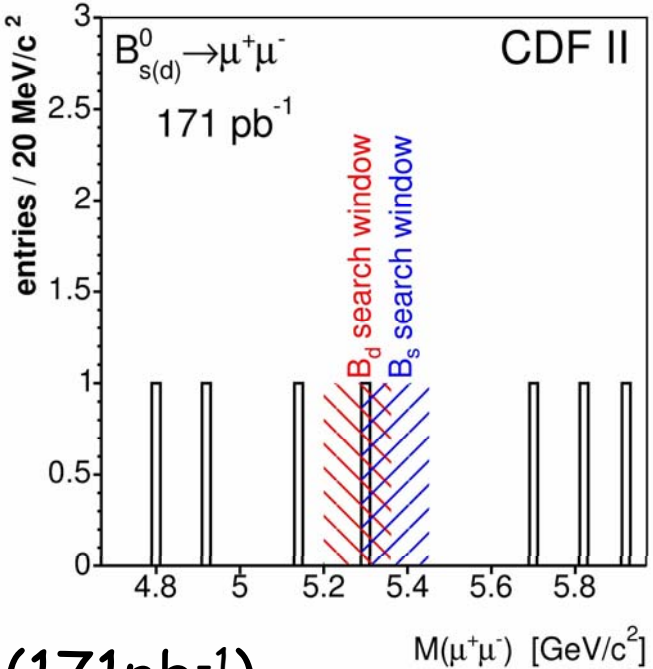
Challenging: SM prediction is 3.4×10^{-9} ...

Sidebands and same-sign data used to optimize cuts and check background estimates

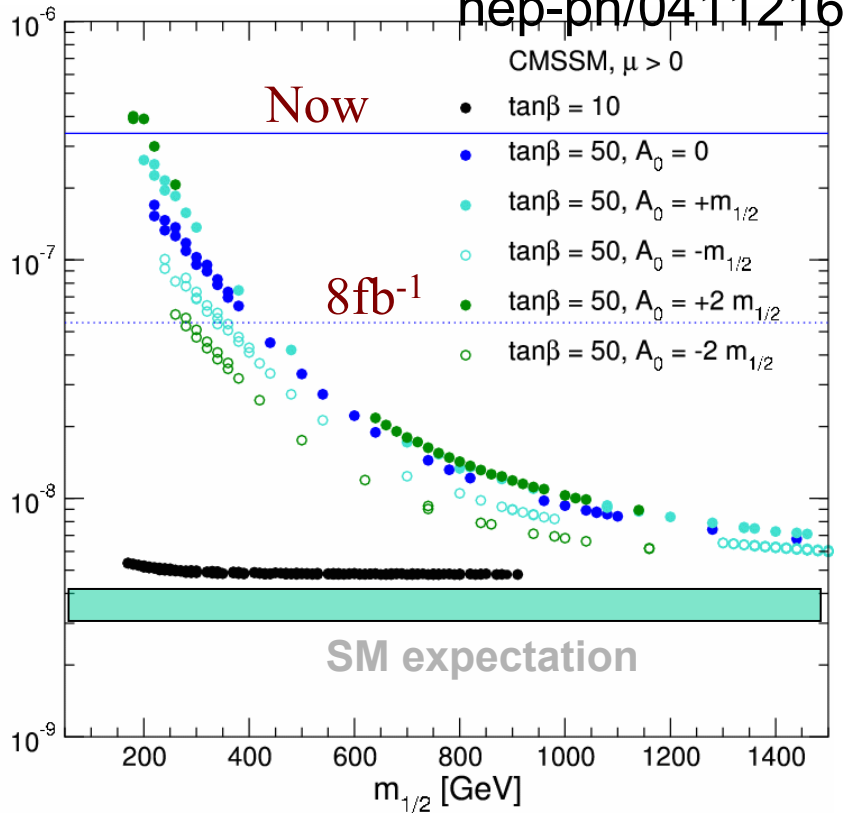


Use lifetime information to reduce backgrounds

Bs $\rightarrow \mu\mu$



hep-ph/0411216



CDF (171pb^{-1})

Expect: 1.05 ± 0.30

Obs : 1

D0(240pb^{-1})

Expect: 3.7 ± 1.1

Obs: 4

Combined: 90% CL

$BR(B_s \rightarrow \mu\mu) < 2.7 \times 10^{-7}$

$BR(B_d \rightarrow \mu\mu) < 1.5 \times 10^{-7}$ (CDF)

Summary and Conclusions

- Presented: some of the more recent preliminary results
  - ✓ Surpassed the sensitivity and results of Run I
  - ✓ Limits shown either exceed any published results of direct searches or are the first limits ever!
- Limits shown with 200 – 300 pb^{-1} of data
  - We have about **600 pb^{-1}** of data on tape (per detector)
  - We will eventually get **2 to 4 fb^{-1}**
- **Interesting regions of parameter space (for many models) are now in reach.**

Many new exciting results from Tevatron experiments and more coming soon!

http://www-cdf.fnal.gov/physics/exotic/exotic.html

http://www-d0.fnal.gov/Run2Physics/WWW/results/np.html

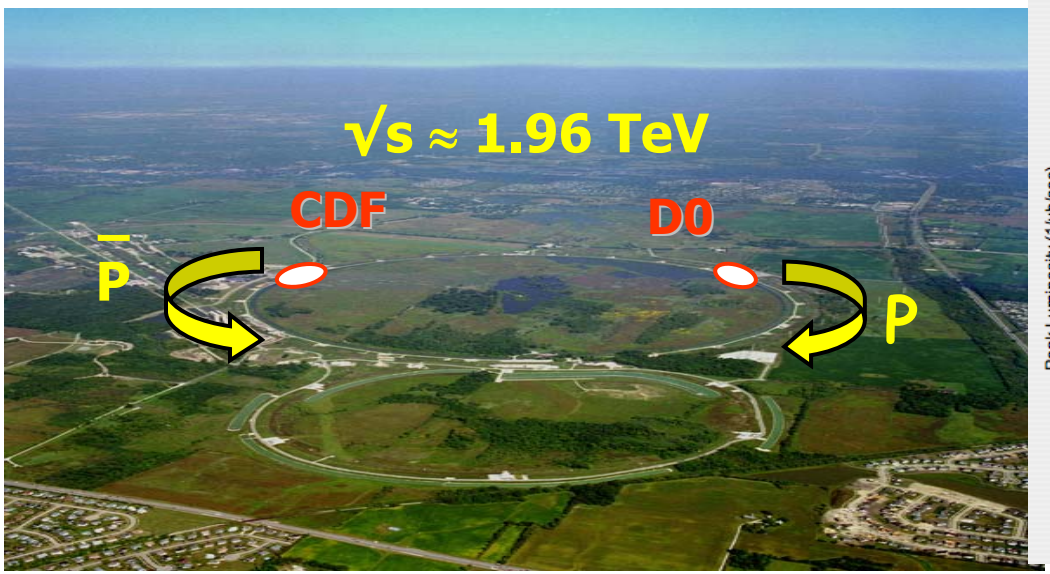
Backup

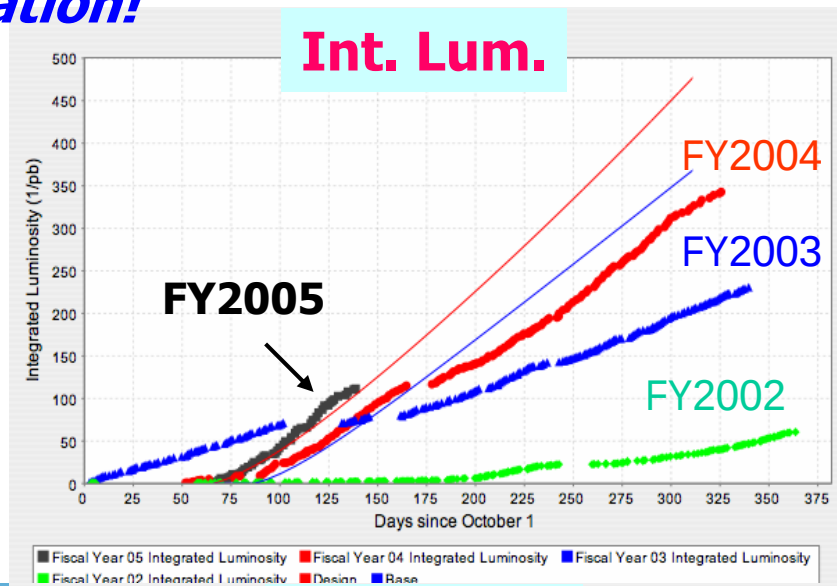
Run II Tevatron Performance

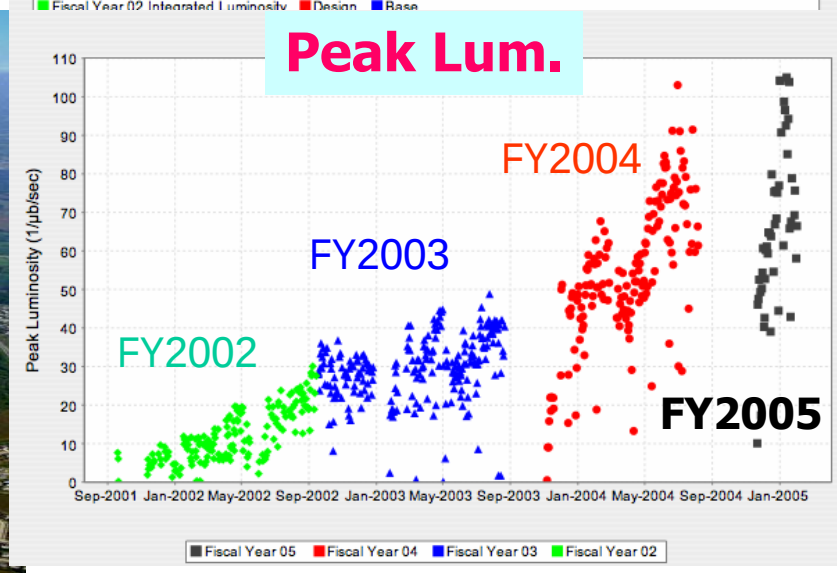
Highest Energy Collider in Operation!

→ **place to search for new physics**

- **Operating extremely well with recycler.**
- **highest Lum: 1.052 e32 $cm^{-2}sec^{-1}$,Jan,2005**
- **single store high :5.05 pb^{-1}, Jan,2005**
- **Analyses presented here are using up to**



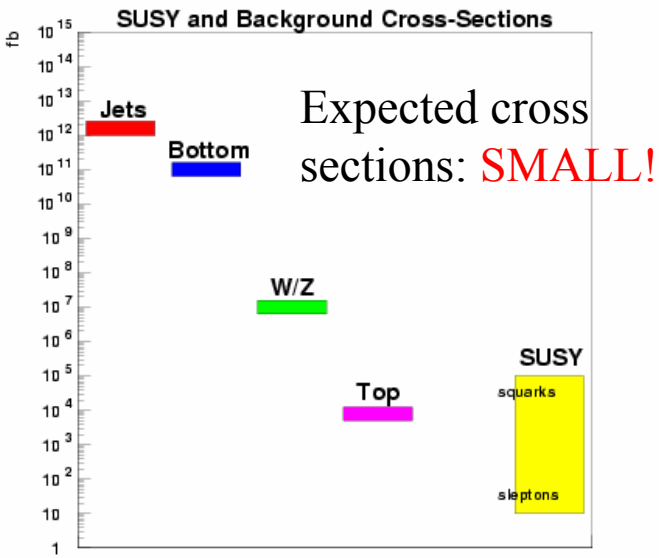




Supersymmetry at the Tevatron

Looking for supersymmetric partners of SM particles

Excesses in SM-like channels and SUSY-only signatures



Expected cross sections: SMALL!

Frameworks used:

-Minimal Supersymmetric extention of the SM (MSSM)

-minimal Supergravity (mSugra)

- Gauge mediated Supersymmetry Breaking (GMSB)

New quantum number: $R_P = (-1)^{B+L+2s}$ $\begin{cases} +1 & \text{SM} \\ -1 & \text{SUSY} \end{cases}$

Lepton Signatures

Also plentiful in SUSY both R_P and $\not{R}_P$

- cascade decays from charginos, neutralinos, sleptons

$$\tilde{\chi}_1^{\pm} \to \nu l \tilde{\chi}_1^0, \quad \tilde{\chi}_2^0 \to \tilde{l}\, l, \quad \tilde{l} \to l\, \tilde{\chi}_1^0$$

Most models predict low p_T, non-central leptons
High tanβ SUSY models predict τ-signatures

- Standard Trileptons (D0)
- RPV Stops (CDF)
- RPV Smuons (D0)
- $B_s \to \mu\mu$ (both)

Extra Dimensions (ED)

Alternatives to SUSY for solving the hierarchy problem (M_{EW} << M_{Plank} ?)

- Focus on:
- Models with n extra spatial dimensions

Large ED (ADD): Arkani-Hamed, Dimopoulos, Dvali, Phys Lett B429 (98)

n>0 (n>2) compactified

$M^2_{PL} \sim R^n M_s^{n+2}$, Ms: string scale

TeV-1 ED (DDG): Dienes, Dudas, Gherghetta, Nucl Phys B537 (99)

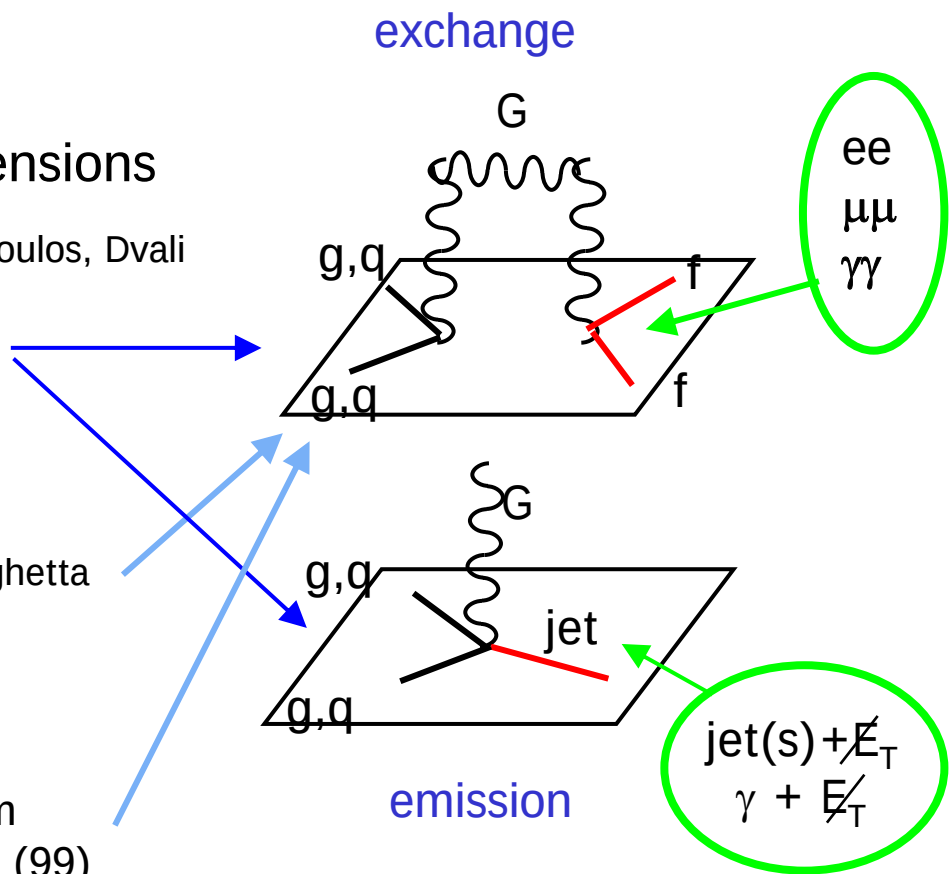
n>=1 (n=1)

M_c: compactification scale

Warped ED (RS): Randall, Sundrum, Phys Rev Lett 83 (99)

n=1, highly curved

k/M_{Pl}, k: curvature scale

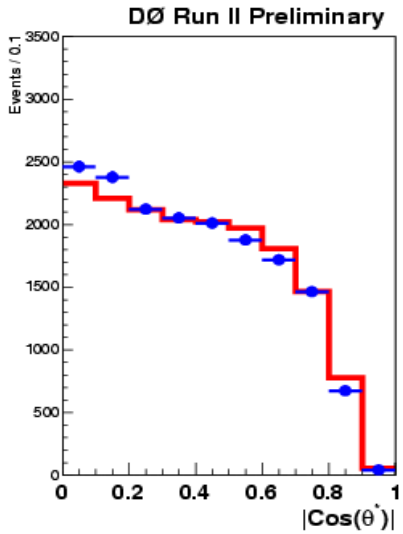


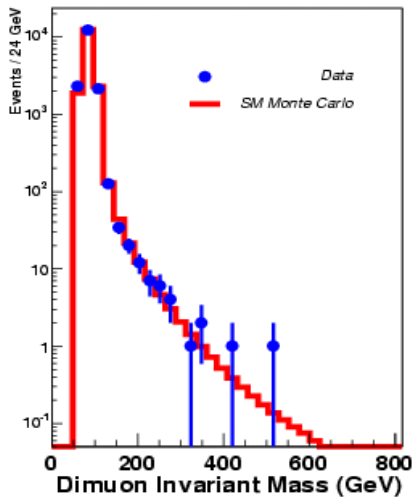
LED with μμ

- Event selection
  - pT > 15 GeV for both muon objects
  - Isolated tracks
  - M(mumu) > 50 GeV
  - Cosmics removed
  - Weighted average PT correction

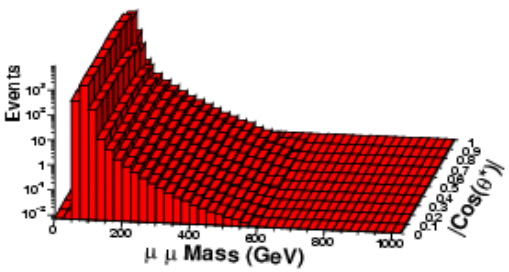
Observed events ~ 17,000 events

DØ ∫Ldt = 250 pb^{-1}

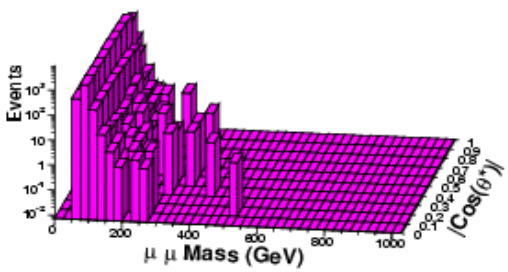




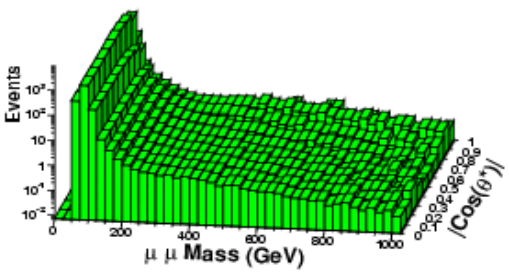
Standard Model Monte Carlo



Data



SM + ED terms (η_G=3.0 TeV^{-4})



DØ Run II Preliminary

No deviation from SM in data

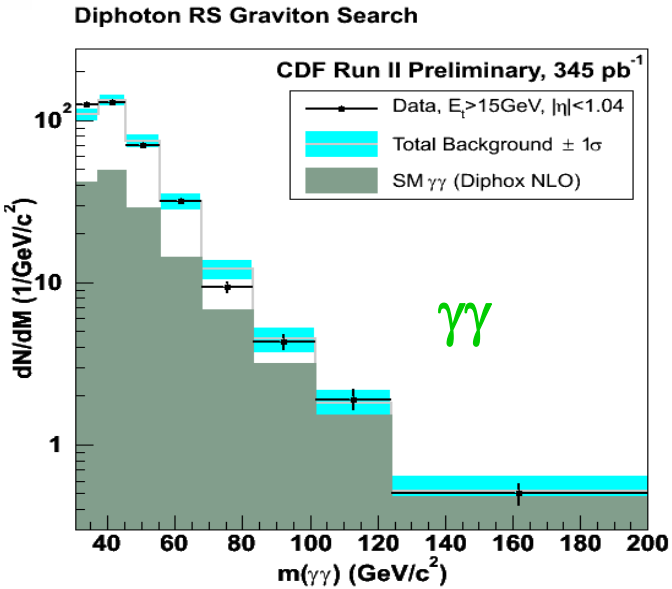
$$\eta_G = 0.00 \pm^{0.33}_{0.00} \text{ TeV}^{-4}$$

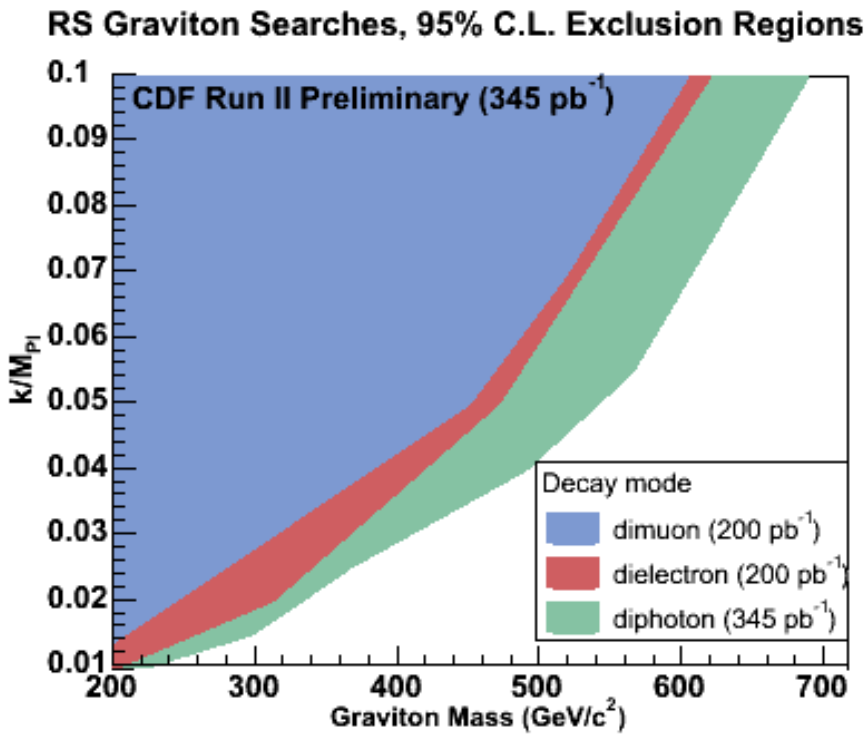
$$\eta_G^{95\%} = 0.71 \text{ TeV}^{-4}$$

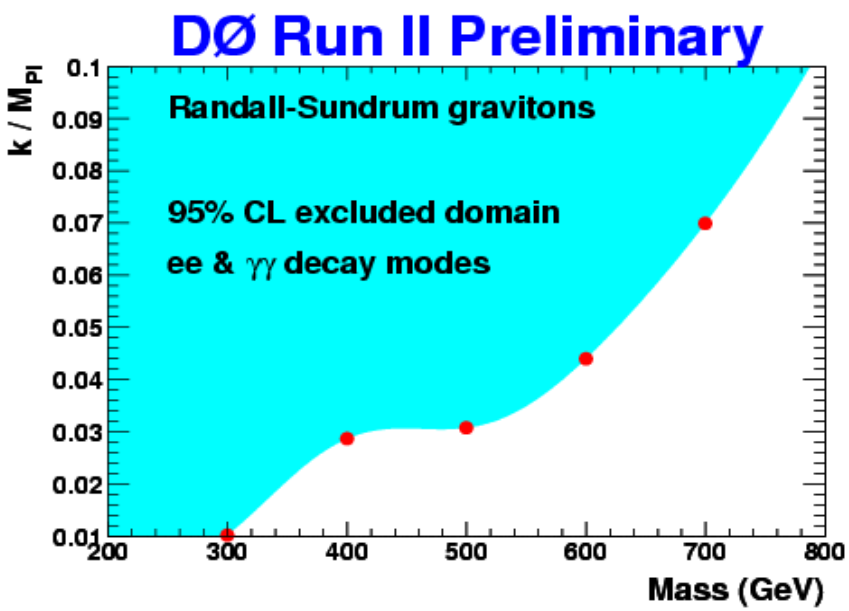
GRW	HLZ for n =						Hewett
	2	3	4	5	6	7	λ = +1/-1
1.09	1.00	1.29	1.09	0.98	0.91	0.86	0.97/0.95

Lower limits on the fundamental Plank scale, M_S in TeV

Randall-Sundrum Graviton (ee + μμ+ γγ)





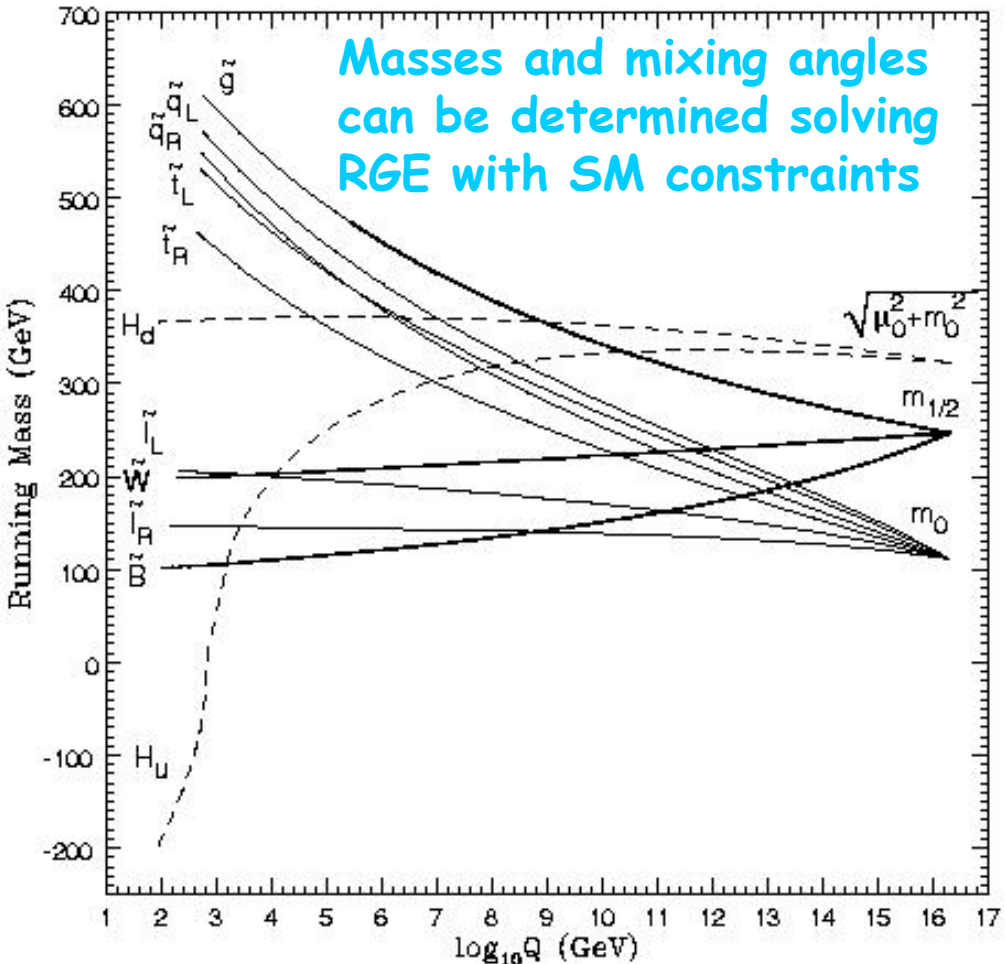


ll has largest acceptance at low mass

γγ has largest acceptance at high mass

BR(G→γγ) = 2 * BR(G→ee)

mSUGRA



Typical mass spectrum in mSUGRA

- Many results below are interpreted in mSUGRA framework
- Simplest SUSY model – good benchmark

- Requires only 5 parameters

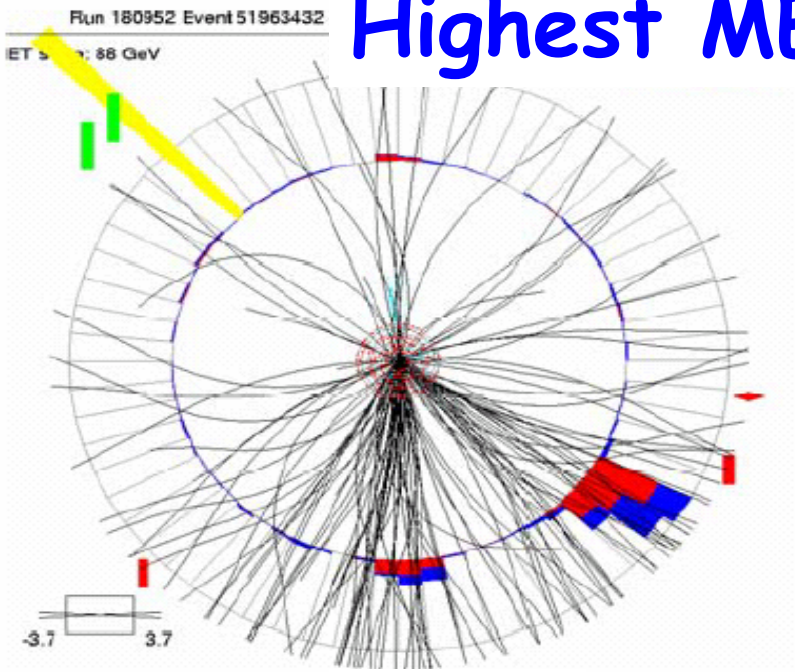
$$M_0, M_{1/2}, \tan(\beta), sign(\mu), A_0$$

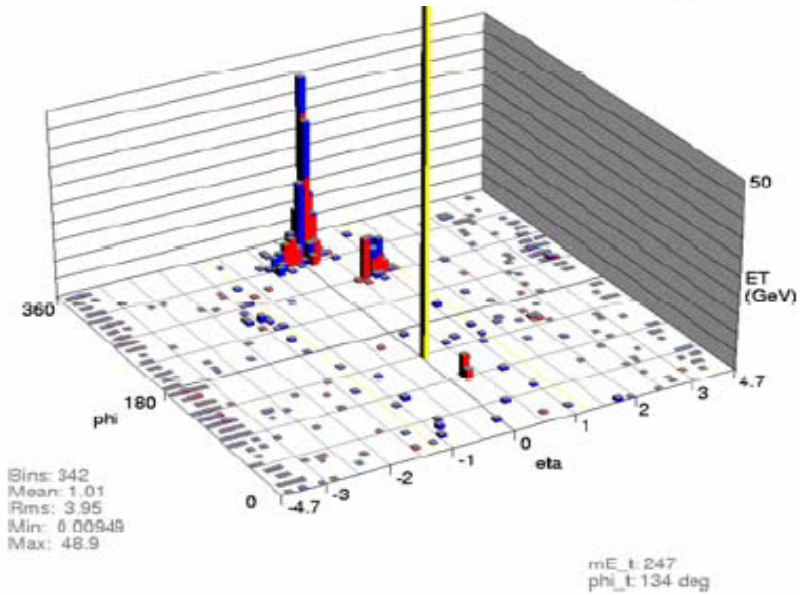
- (Very) restricted by LEP

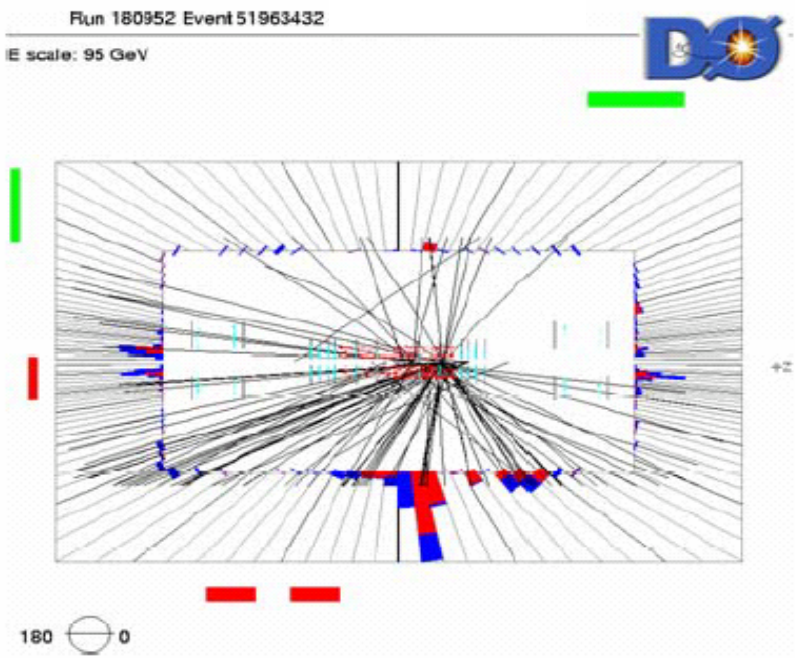
- Squarks and gluinos generally not expected to be lighter than others

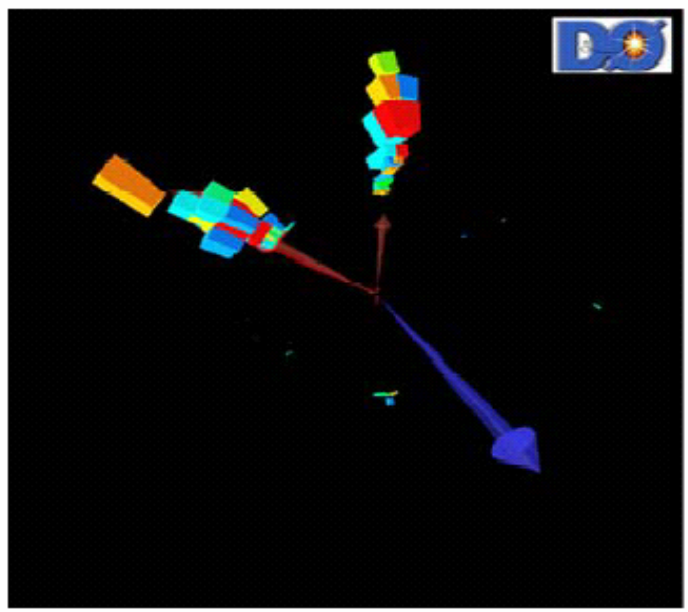
- However, large parameter space can accommodate various mass spectra

Highest MET event



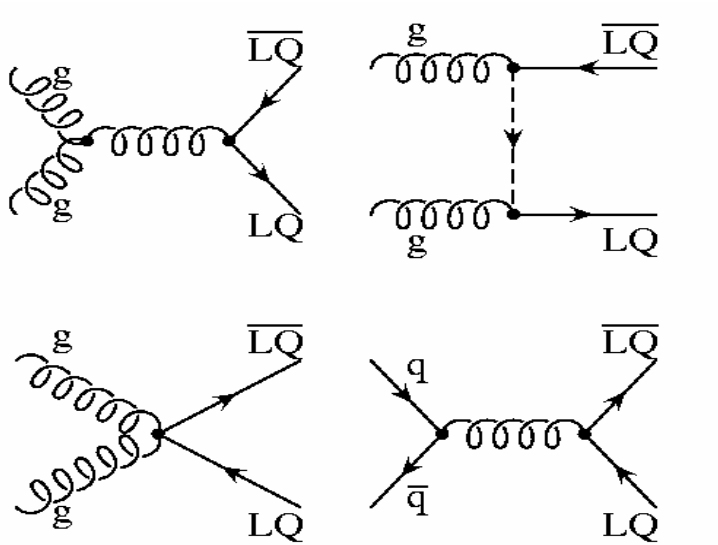


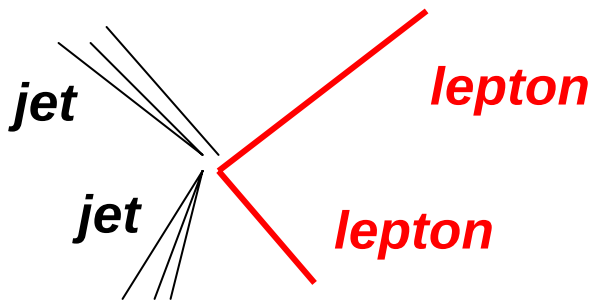




Leptoquarks

- LQ are coupled to both quarks and fermions
  - Predicted in many Grand Unification extensions of SM
  - Carry both lepton and color quantum numbers
- Family diagonal coupling to avoid FCNC beyond CKM mixing





$$(lq)(lq)$$

Searched first generation LQ in channels : eejj and eνjj

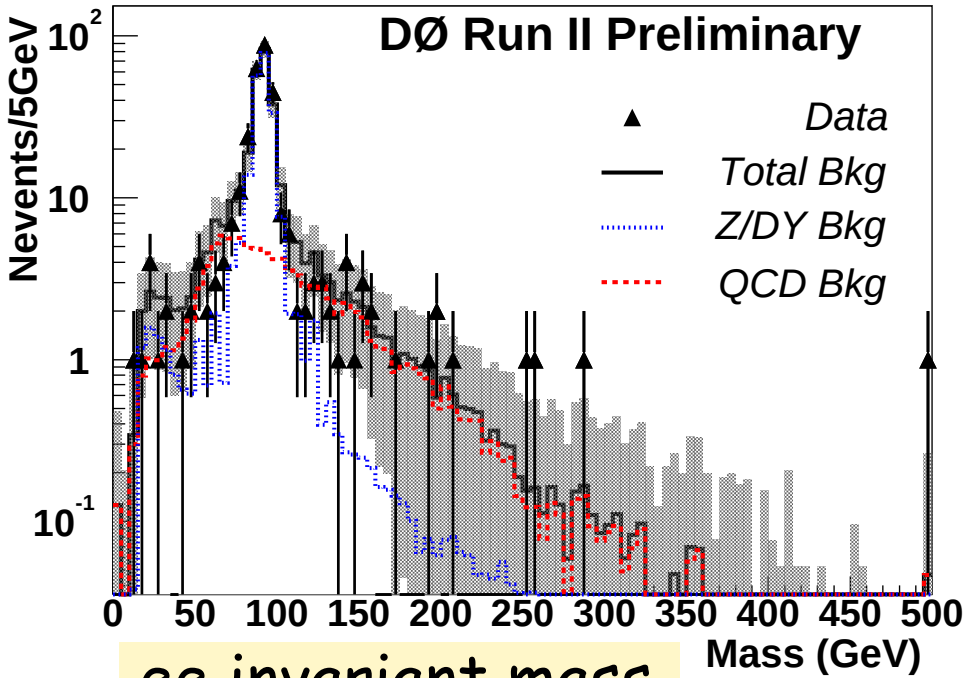
First generation LQ : eejj channel

- Background:

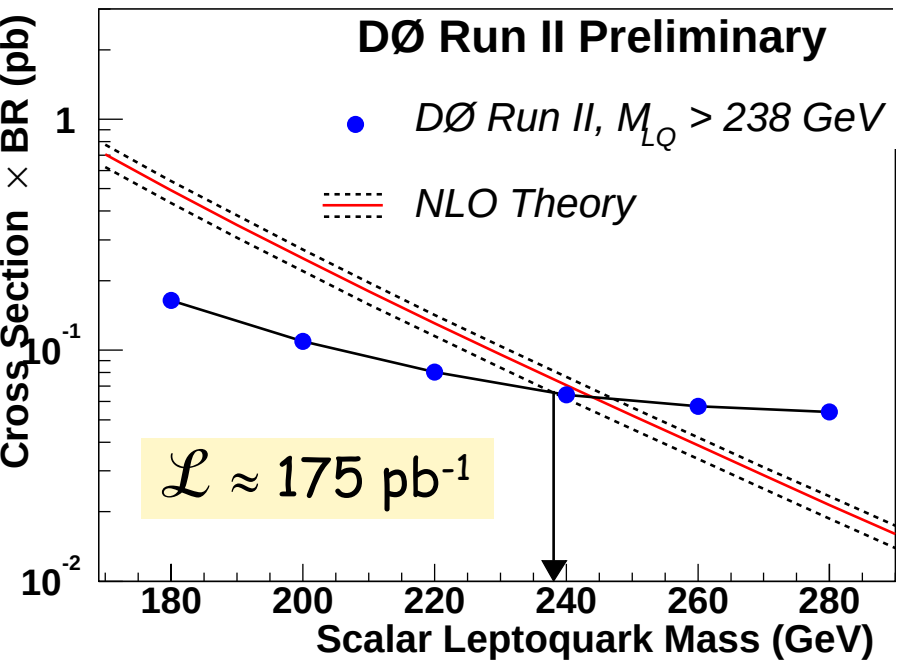
→ Drell-Yan/Z + jets,

→ QCD (with 2 fakes EM)

→ $t\bar{t}$



ee invariant mass



Selections

→Electrons : Et > 25 GeV

→Jets : Et > 20 GeV, |eta|<2.4

→Z veto

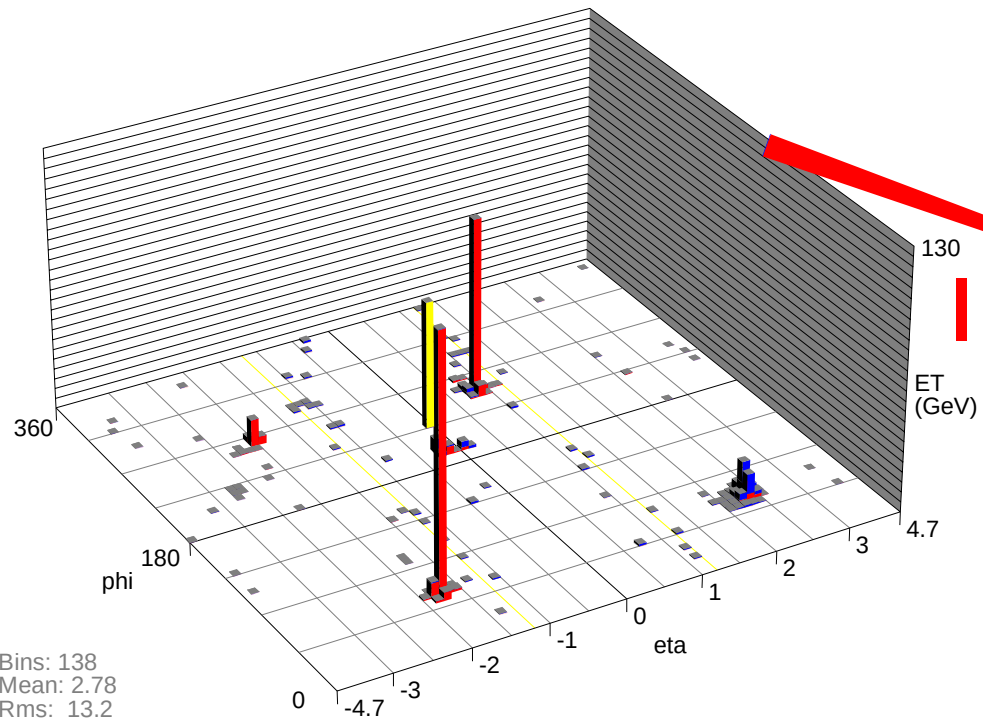
→S_T > 450 GeV

Signal Eff = 12 – 33 %

eejj candidate event

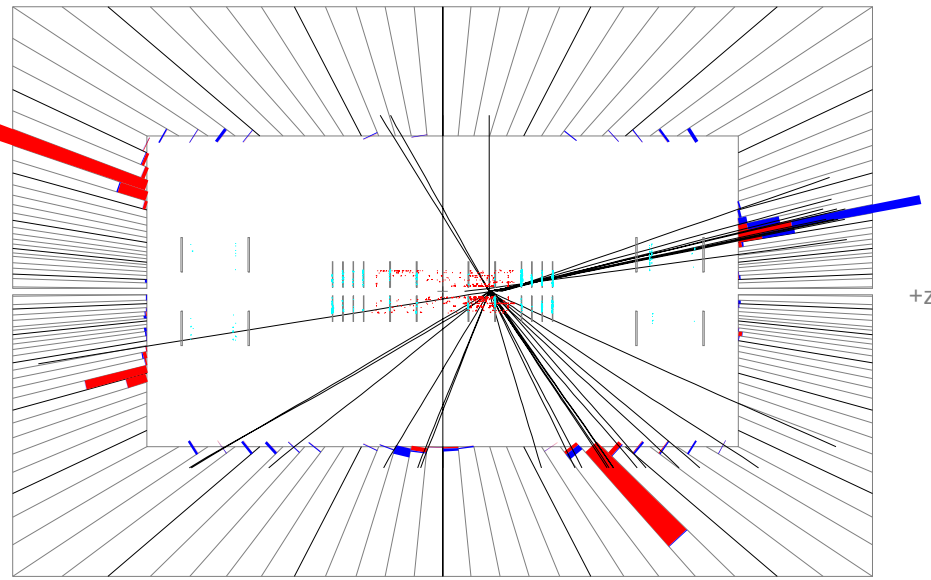
Invariant mass 475 GeV/c^2, cos θ^* = 0.01

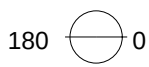
Run 165239 Event 97182072



Run 165239 Event 97182072

E scale: 134 GeV





mE_t: 63.4
phi_t: 226 deg

Jet Energy Scale Corrections

- Correct the measured energy:

$$E_{corr} = \frac{E_{meas} - E_O}{R_{jet} S_{cone}}$$

Offset: electronic noise, uranium noise, underlying event

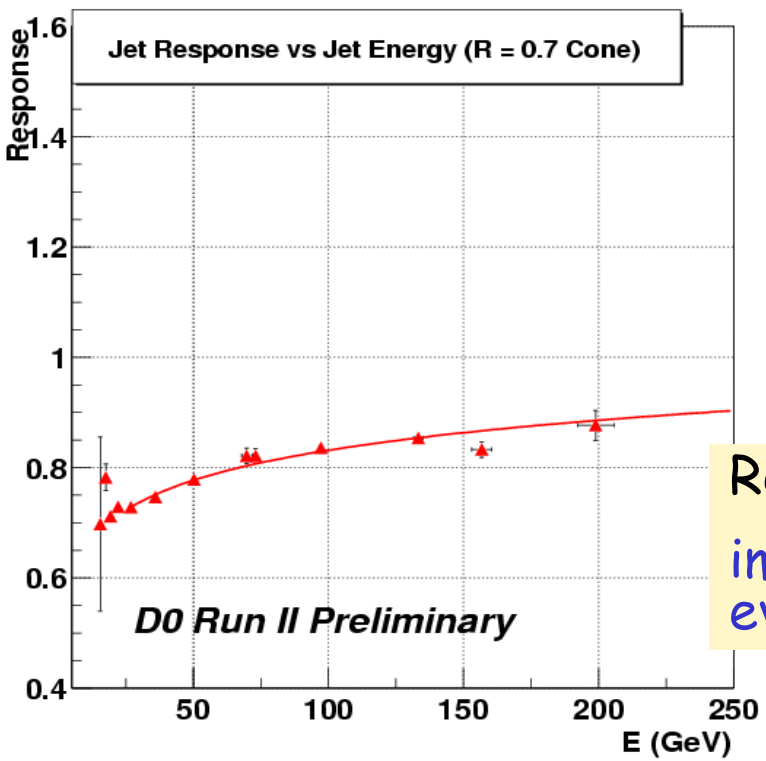
zero bias and minimum bias events (data)

out of cone Showering:

energy density in ring around the jet axis (data)

Response: $E_{meas}/E_{deposit} \neq 1$

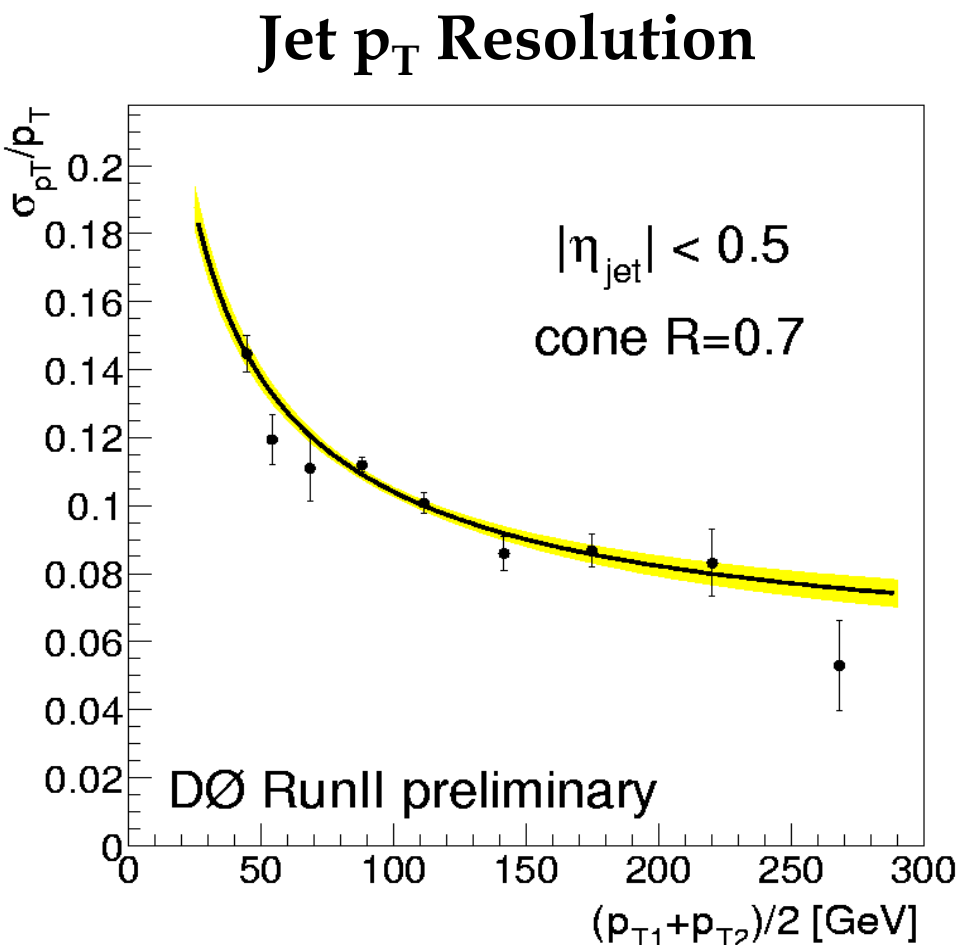
imbalance energy in γ +jet events (data)



Jet Resolution

- Jet P_T resolution:

→ using energy asymmetry in dijet events



$$A = \frac{p_T^{jet1} - p_T^{jet2}}{p_T^{jet1} + p_T^{jet2}} \qquad \frac{\sigma_{p_T}}{p_T} = \sqrt{2}\sigma_A$$

parametrized as:

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{N^2}{P_t^2} + \frac{S^2}{P_t} + C^2}$$

$N = 0.0 \pm 2.2$, $S = 0.902 \pm 0.045$,
$C = 0.052 \pm 0.008$

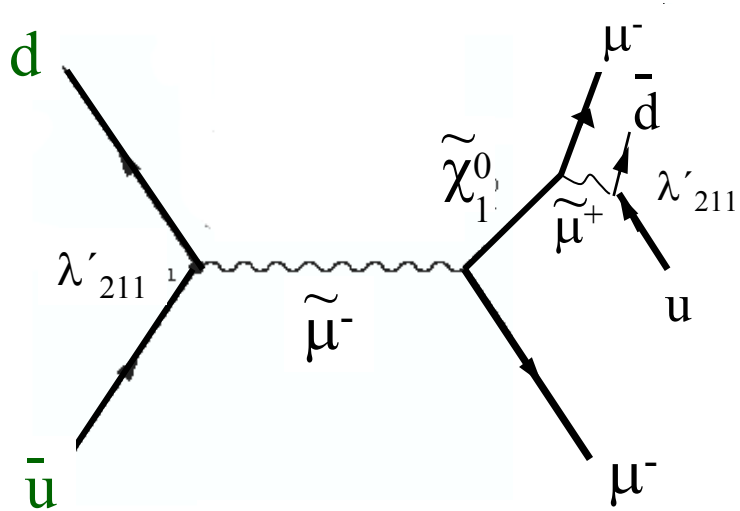
Resonant Smuon Production

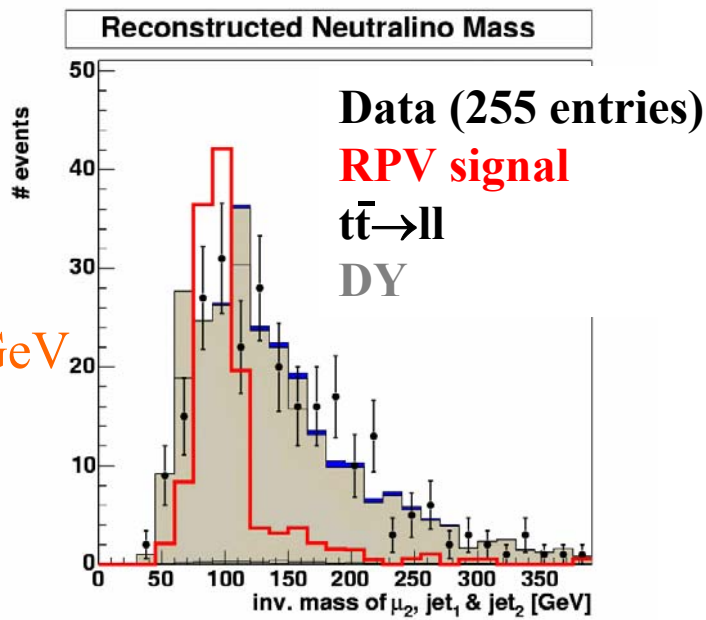
$\tilde{\mu}$ produced via $\not{R}_P$

$\tilde{\chi}_1^0$ decay

Result: 2 muons, 2 jets, and *no* $\not{E}_T$

i.e. possible to reconstruct mass chain





Mass: 102 GeV

Assume prompt $\tilde{\chi}_1^0$ decay

Soft leptons and jets:

- $p_T(\mu_2) \geq 10$ GeV
- p_T (leading jet) ≥ 25 GeV

Can reconstruct $\tilde{\chi}_1^0$ and $\tilde{\mu}$ masses

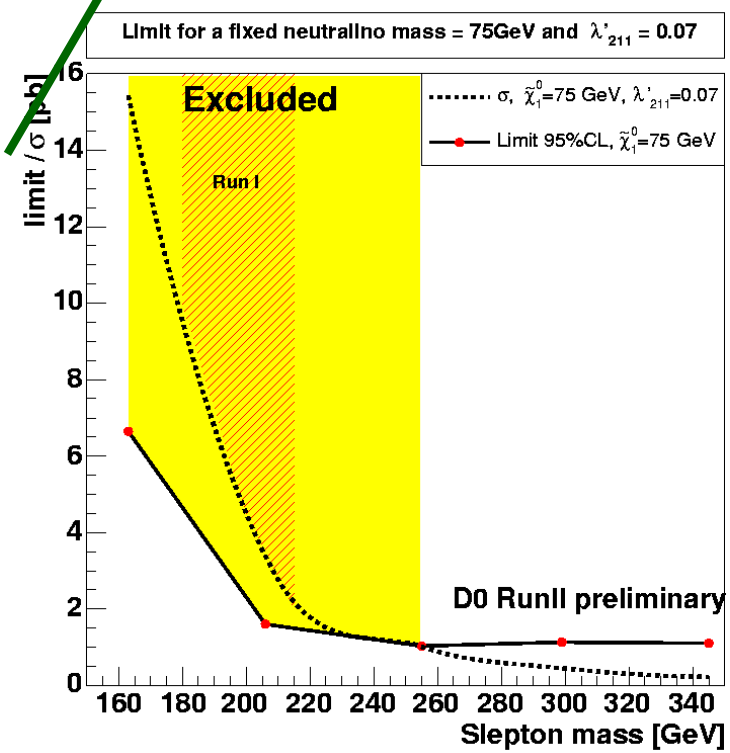
Use this to suppress backgrounds

In 154 pb^{-1} :

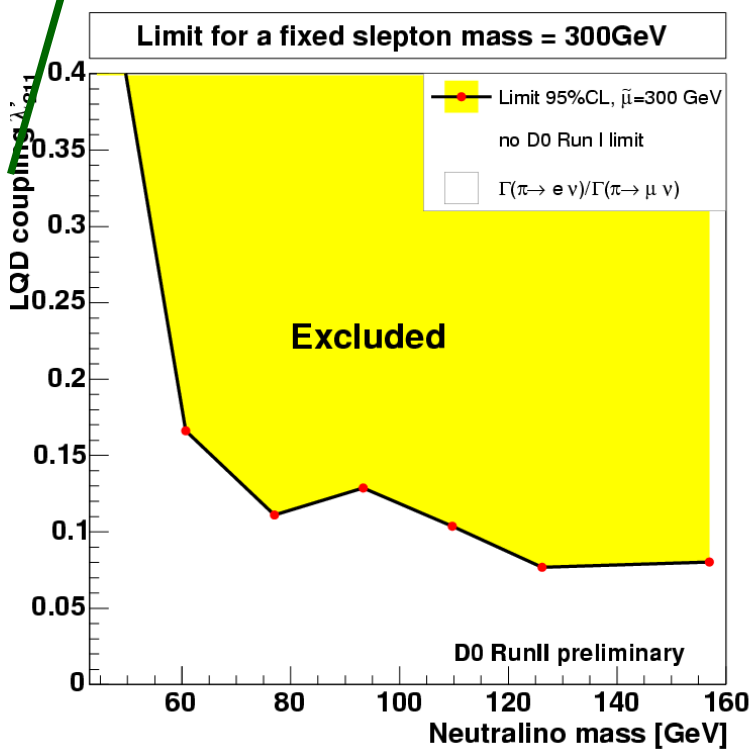
See 2 events

Expect 1.2 ± 0.3 from backgrounds

Limit on cross section



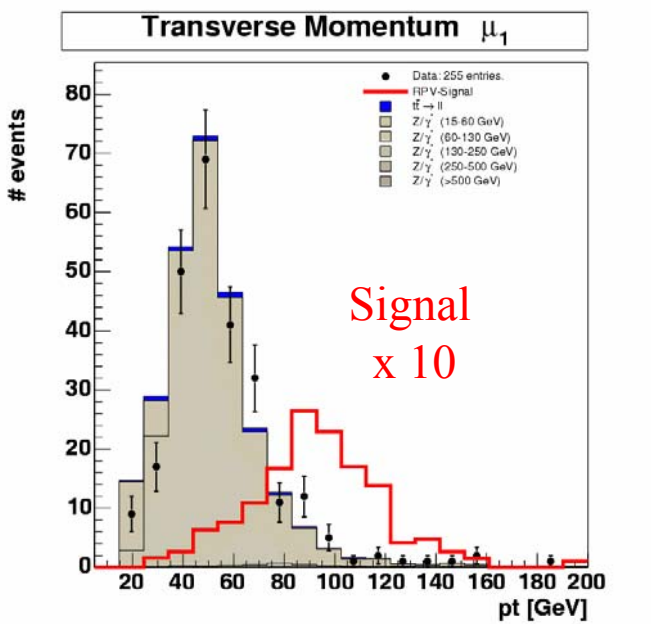
Limit on λ'_{211} coupling

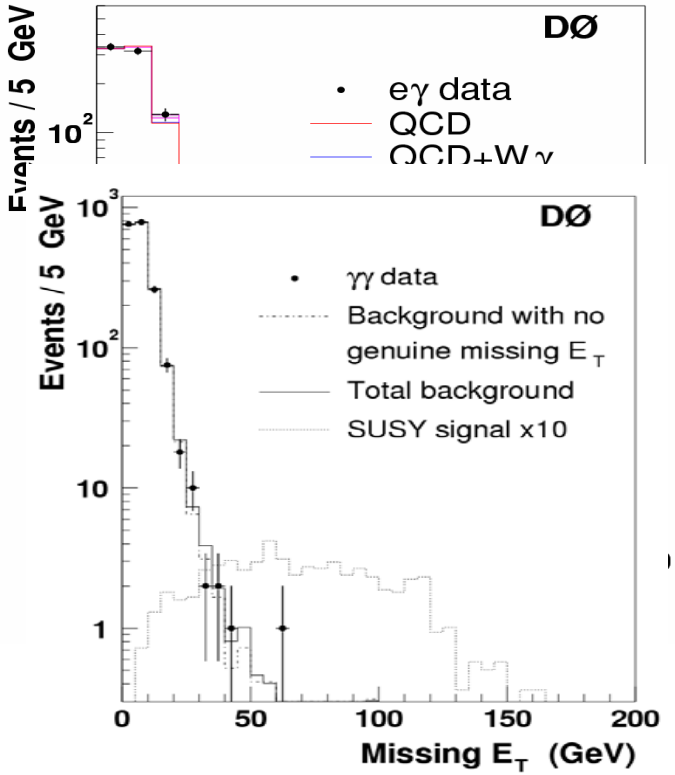


More data is on the way, almost 500 pb^{-1} for 2005

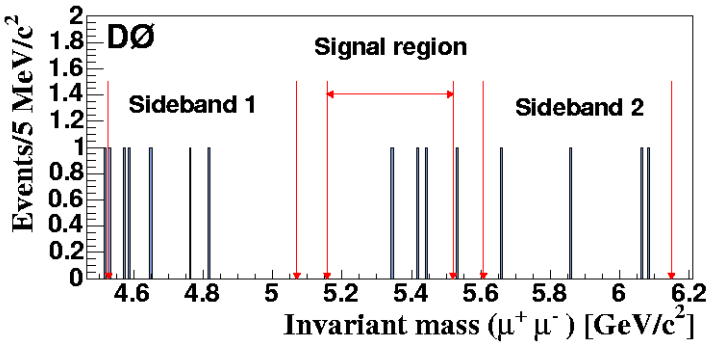
➡ Lots of room to make discoveries before LHC

Diphoton + Smuon backup





Run II $B_s \rightarrow \mu\mu$



CDF: (171 pb^{-1})

$c\tau > 200\ \mu m$

$\Delta\varphi(B_s, \text{vertex}) < 0.1$ rad

mass window: 3σ

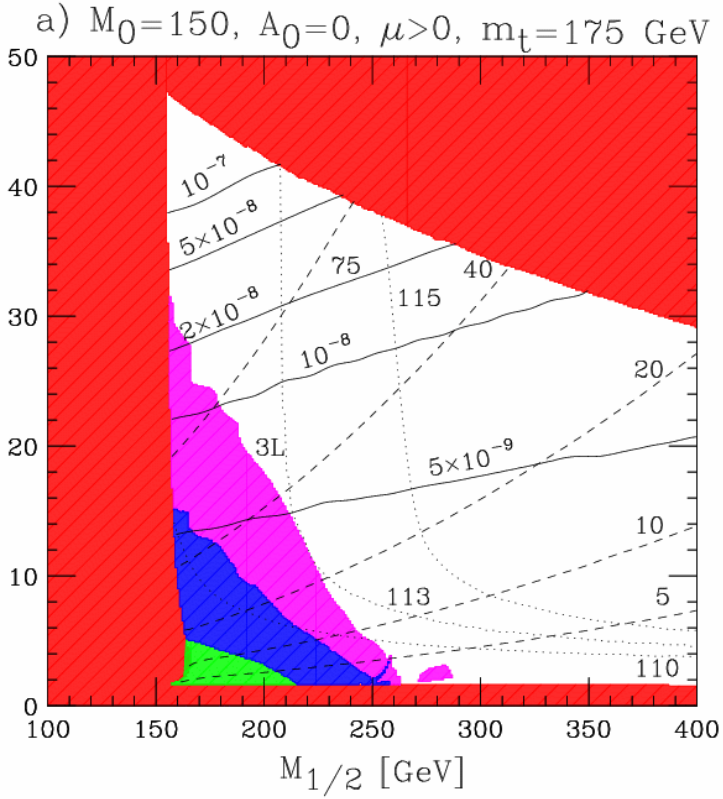
D0: (240 pb^{-1})

$L_{xy}/\delta L_{xy} > 18.47$

$\Delta\varphi(B_s, \text{vertex}) < 0.2$ rad

mass window: 2σ

		B_s	
CDF	$< 5.8 \cdot 10^{-7}$	$1.5 \cdot 10^{-7}$	(90% CL)
D0	(240 pb^{-1})	$< 3.8 \cdot 10^{-7}$	
Combined:		$< 2.7 \cdot 10^{-7}$ @ 90% CL	



Stop to tau b backup