Search for Supersymmetry at the Tevatron

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For the DØ and CDF Collaborations

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Experimental SUSY signatures

- R_p (R-parity) conserving
  - *Lightest Supersymmetric Particle (LSP)* is stable, escapes detector (undetected)
  - Results in large E_T^{Miss}
- R_p violating signatures
  - Often include lepton flavor violating decays

SUSY Breaking Mechanisms:

- Minimal SUGRA: supergravity inspired
  - Simplest and most-studied model
    - Usually leptons and/or jets with E_T^{Miss}
- Gauge-Mediated-SB motivated signatures
  - LSP: Gravitino, various next-LSP (NLSP)
    - Photons if $\tilde{\chi}_1^0$ is the NLSP
    - Run 1 CDF $ee\gamma\gamma E_T^{Miss}$

$$\tilde{\chi}_1^0 \to \gamma\tilde{G}$$

- Anomaly-Mediated-SB motivated signatures
  - Long-lived particles, soft pions
  - Very hard at hadron colliders

Outline

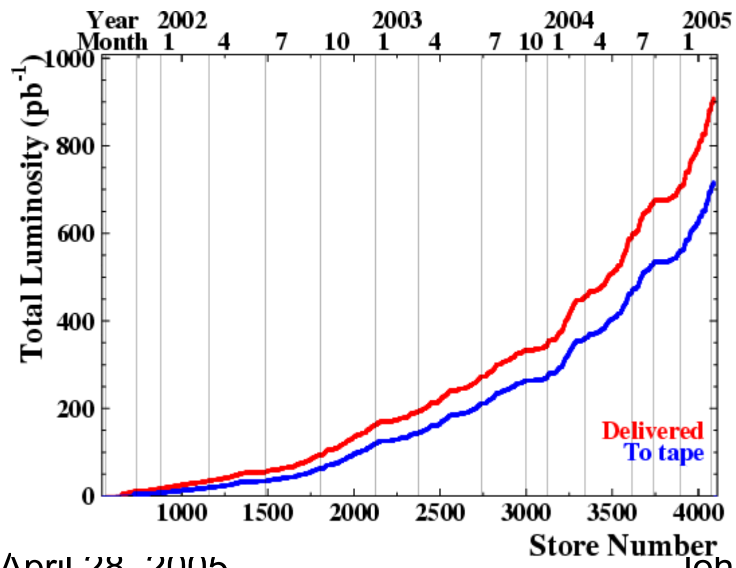
- Neutralino-Chargino Pair
- Squark and gluino
- RPV Sleptons
- RPV Stop
- CHAMP

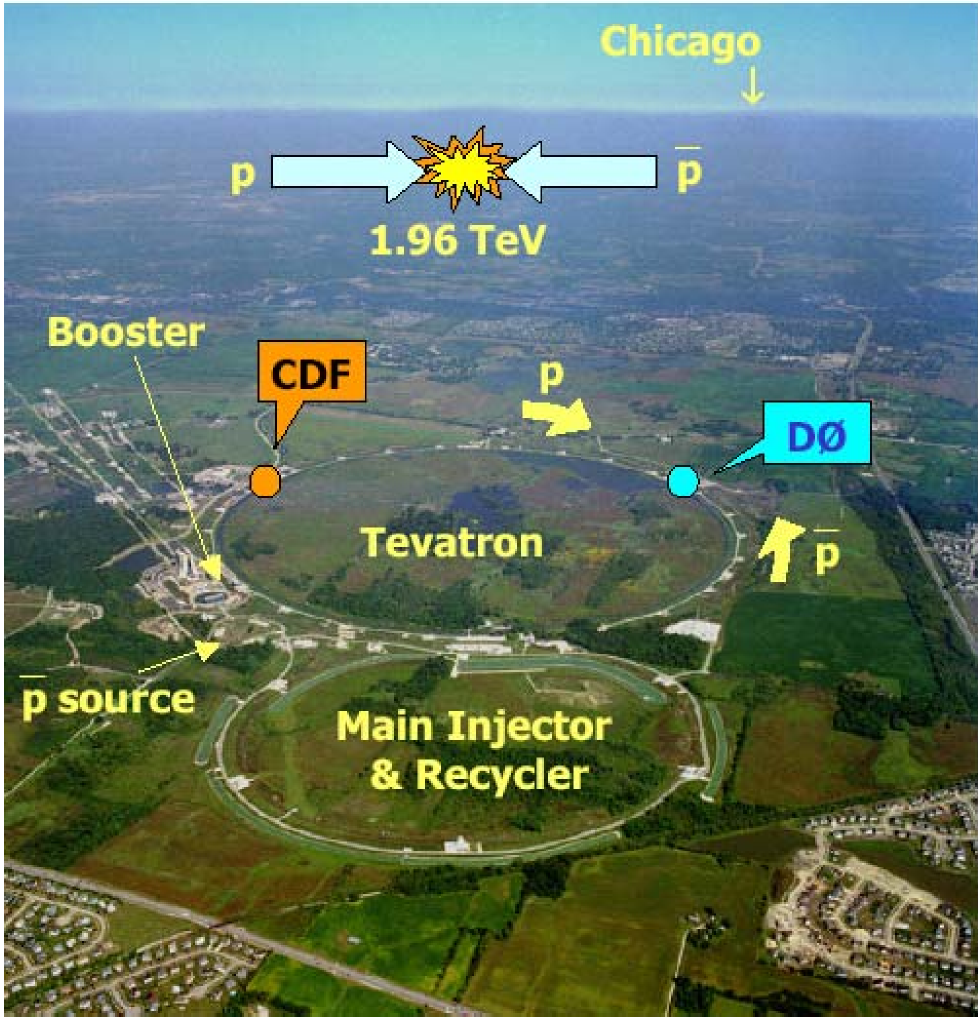
Current best limit on the mass of some SUSY particles:

Gaugino $\tilde{\chi}_1^\pm$	103 GeV/c^2	LEP2
GMSB $\tilde{\chi}_1^\pm$	150 GeV/c^2	DØ
$\tilde{g}$ (any $M_{\tilde{q}}$)	195 GeV/c^2	CDF
$\tilde{q}$ ($M_{\tilde{q}} = M_{\tilde{g}}$)	300 GeV/c^2	CDF

Tevatron Run2 at Fermi National Accelerator Lab

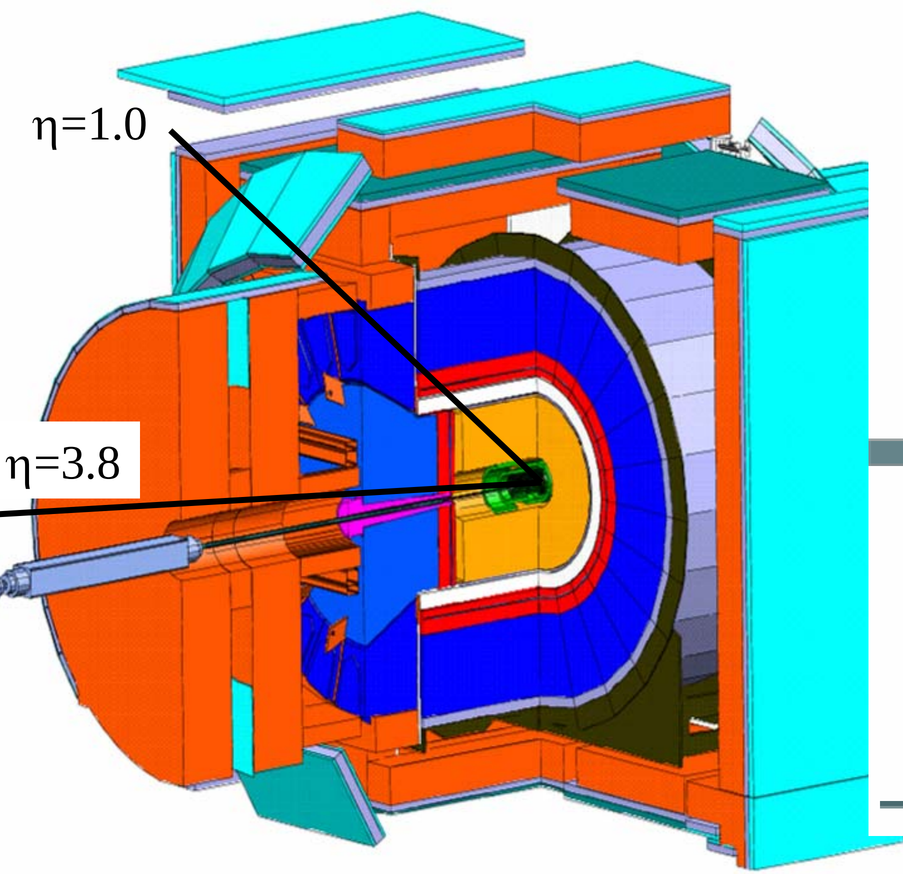
- Tevatron Run2:
  - Energy in C.O.M.: 1.96 TeV
- Now: >600/pb of data on tape for both CDF and DØ.
- Current analyses 200-390/pb
- Run2 goal: 4.4-8.5/fb
  - Take data until 2009
- Tevatron is the ***Energy Frontier*** until the LHC is turned on.

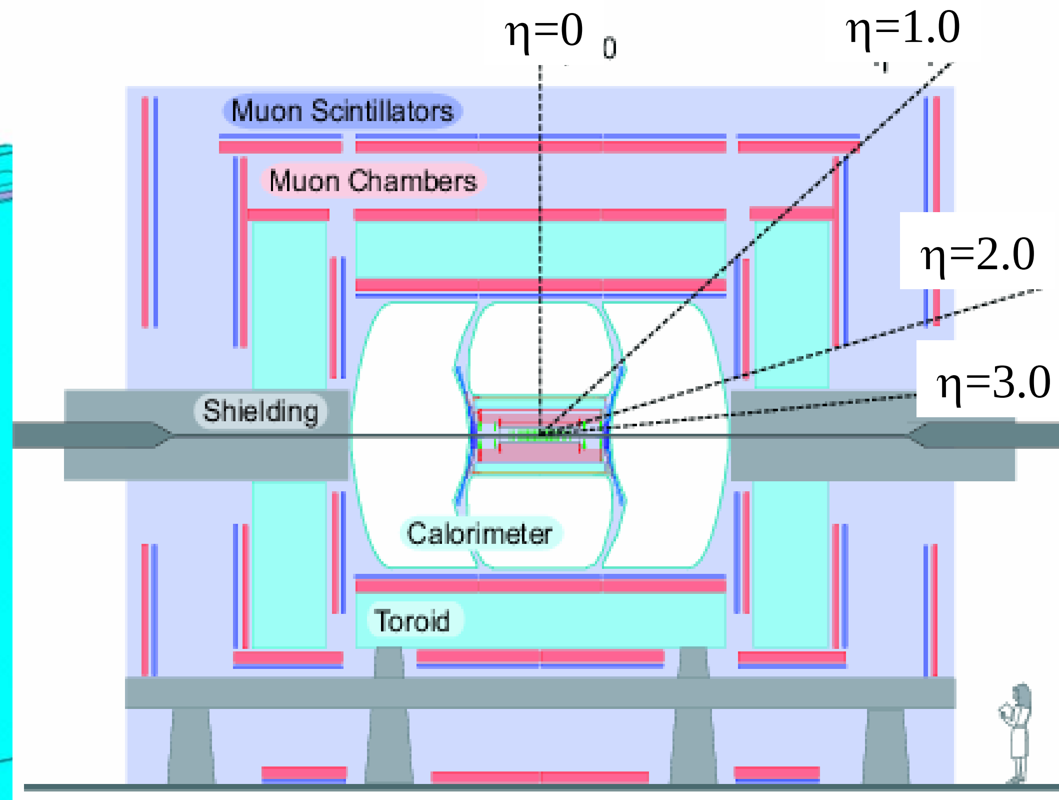




Tevatron Experiments: DØ & CDF

- State-of-art, multi-purpose detectors
  - Excellent particle detection efficiency, coverage, tracking and triggering





Chargino-Neutralino Searches

- Recall:

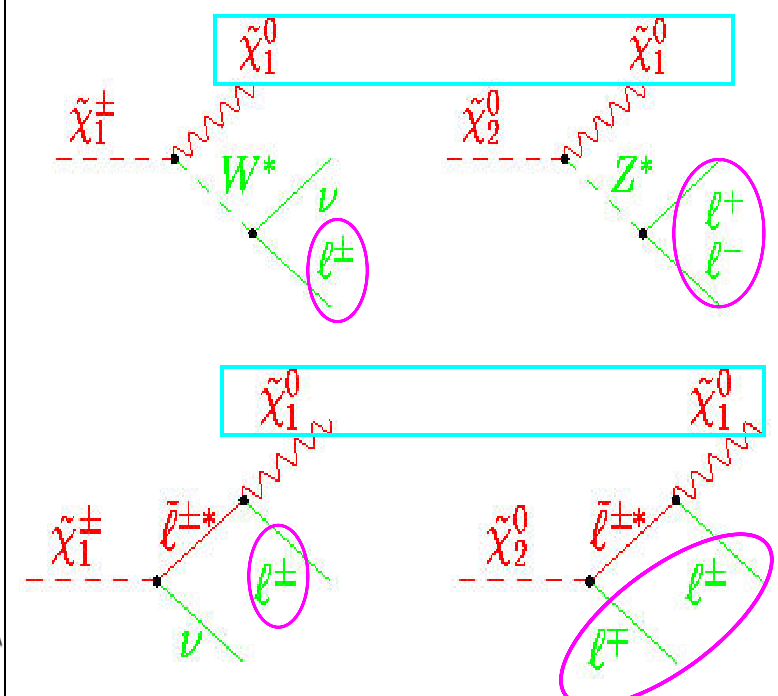
$$\tilde{W}^{\pm}, \tilde{H}^{\pm} \Rightarrow \tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm} \rightarrow \text{“Charginos”}$$

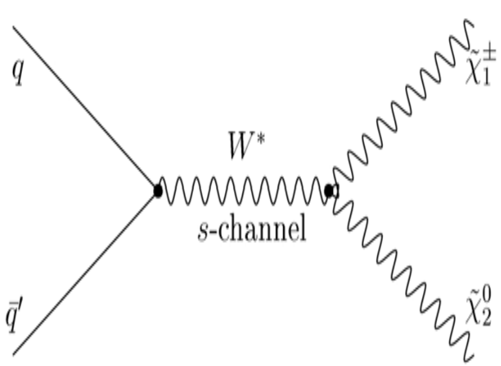
$$\tilde{W}^{0}, \tilde{B}^{0}, \tilde{H}_d^{0}, \tilde{H}_u^{0} \Rightarrow \tilde{\chi}_1^{0}, \tilde{\chi}_2^{0}, \tilde{\chi}_3^{0}, \tilde{\chi}_4^{0} \rightarrow \text{“Neutralinos”}$$

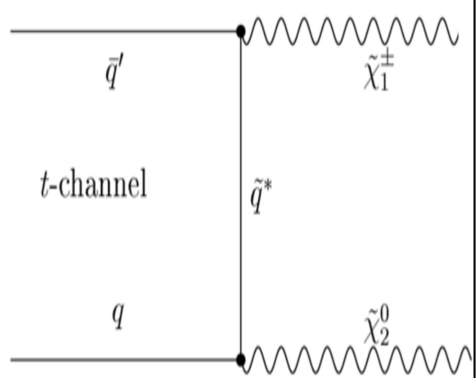
Gaugino, Higgsino content, m(slepton) determines BR’s, coupling strengths

- @ Tev: Look for pair of $\chi_1^{\pm}\chi_2^{0}$
- Final state with 3 leptons, large E_T^{Miss}
- One of the SUSY “golden modes”
  - Striking signature
  - Small SM backgrounds

$$\tilde{\chi}_2^{0}\tilde{\chi}_1^{\pm} \rightarrow l^{\pm}l^{\mp}l^{\pm}\tilde{\chi}_1^{0}\tilde{\chi}_1^{0}X$$







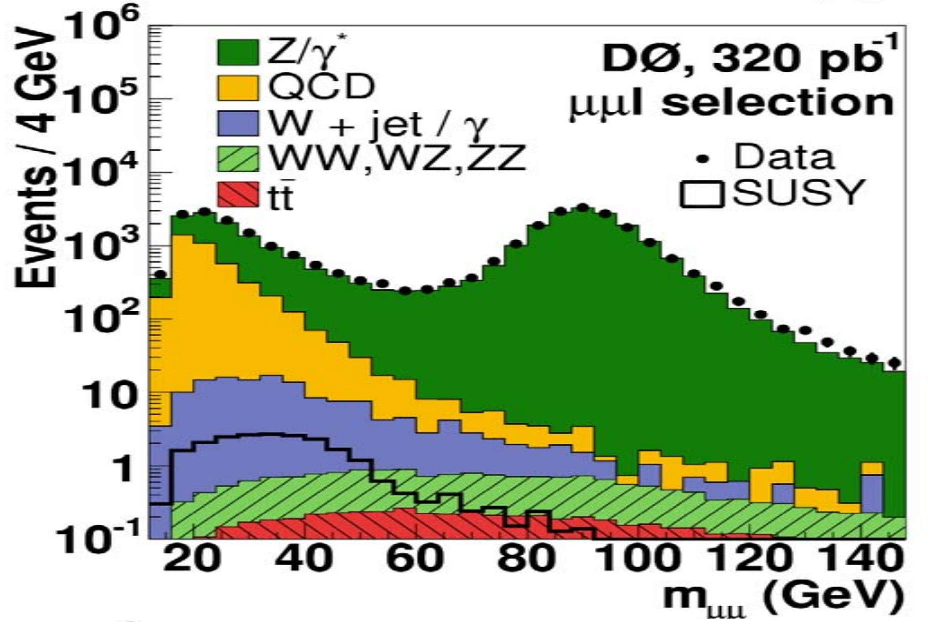
Chargino and Neutralino in $3\ell+E_T^{Miss}$

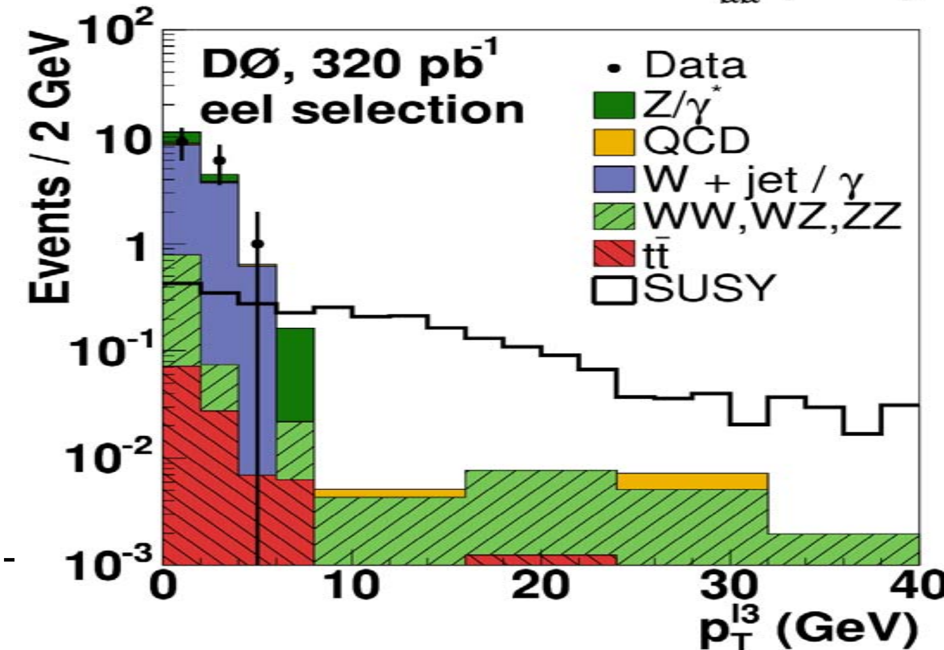
6 analyses

- $2l(l=e,\mu,\tau)$+isolated track or $\mu^{\pm}\mu^{\pm}$
- E_T^{Miss} and topological cuts (M_{ll}, $\Delta\phi$, M_T)

Selection	Bkgnd expected	Observed
ee+l	0.21±0.12	0
eμ+l	0.31±0.13	0
μμ+l	1.75±0.57	2
μ±μ±	0.64±0.38	1
eτ+l	0.58±0.14	0
μτ+l	0.36±0.13	1
SUM	3.85±0.75	4

95%CL: $\sigma\times BR(3l)<0.2$ pb





Chargino Neutralino Limits

"3l-max"

- $m_{\tilde{l}} \geq m_{\tilde{\chi}_2^0}$ (low m_0)
- No slepton mixing

Limits :

➡ M($\tilde{\chi}_1^{\pm}$)>116 GeV/c²

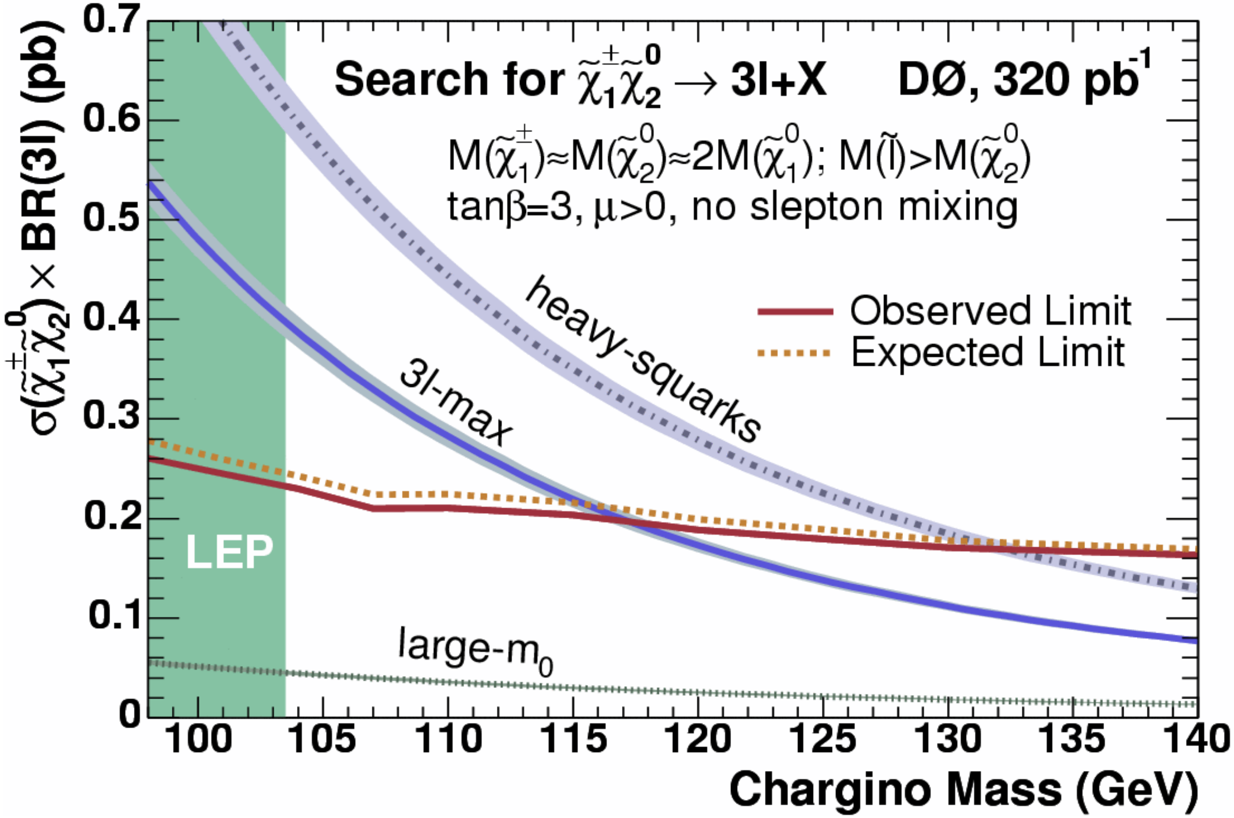
"Heavy Squarks"

- $m_{\tilde{q}} >> m_{\tilde{l}}$

➡ M($\tilde{\chi}_1^{\pm}$)>128 GeV/c²

"Large m_0"

- M($\tilde{l}$)>>M($\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$)
- No sensitivity



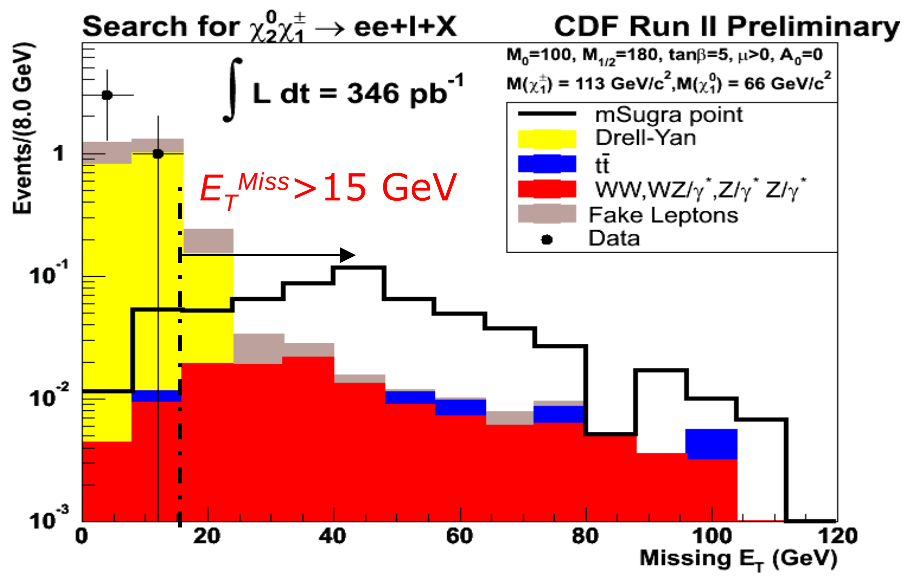
Start testing above LEP limit for mSugra—but LEP Model Independent !

- adding τ's improves sensitivity
- Limit: σxBR ~ 0.2 pb
- hep-ex/0504032

The "golden mode" at CDF

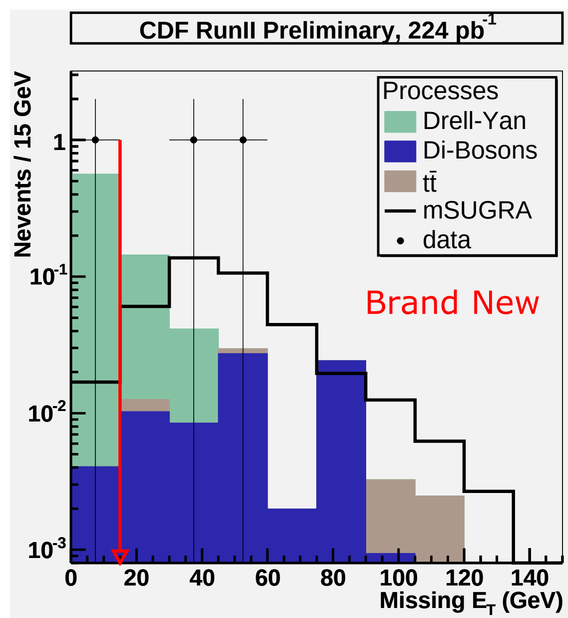
SELECTION:

- 2 electrons + ℓ, $|\eta| < 1$
- ℓ can be e, μ, or track, as low as 4 GeV
- blind analysis approach
- employs advanced kinematic cuts



2 triggers: E_T>20 GeV E_T>10 GeV

Process	ee+ℓ	ee+track
mSugra	0.5	0.5
Bkgnd Expected	0.16±0.07	0.36±0.27
OBSERVED	0	2



M_0=100 GeV/c²
$M_{1/2}$=180 GeV/c²
tan(β)=5
μ>0
A_0=0

⇩

$$m_{\tilde{\chi}_1^\pm} = 113\,\mathrm{GeV/c^2}$$

$$m_{\tilde{\chi}_1^0} = 66\,\mathrm{GeV/c^2}$$

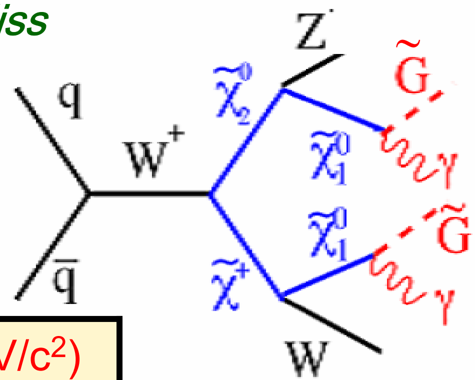
First pass through the data complete !!

Plenty of room to improve:

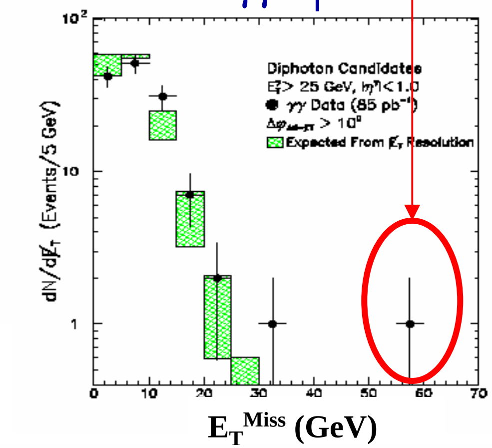
- include forward electrons and muons
- dimuon channels coming soon
- combine results from channels

Chargino-Neutralino in $\gamma\gamma + E_T^{Miss}$

In GMSB: 2 photons+E_T^{Miss}



Motivated from CDF-I $ee\gamma\gamma E_T^{Miss}$ event

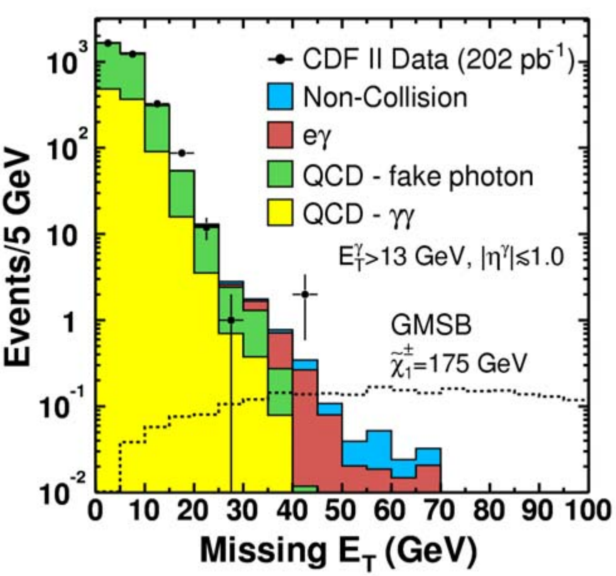


CDF/DØ Event selection:

-2 photons E_T > 13/20 GeV

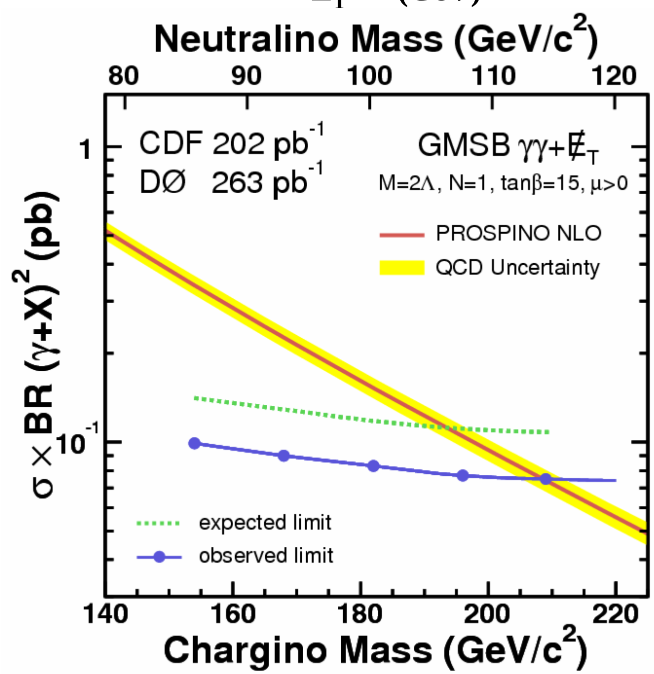
-E_T^{Miss}>45/40 GeV

	Bkgd Exp.	Obs	Limit $m_{\tilde{\chi}^+}$ (GeV/c^2)
D0	3.7±0.6	2	195
CDF	0.3±0.1	0	167



CDF and D0 combined result: $m(\tilde{\chi}_1^\pm)$>209 GeV/c^2

hep-ex/0504004



Gluino-squark searches in hadronic channels

- Large strong-interaction cross sections
- Typically searches in jets + E_T^{Miss} *for light squarks*
  - Large E_T^{Miss} *used to* suppress bkgds
- Large mixing produces unique signature for the 3rd family sqarks
  - Flavor tagging generally used.
- Large mixing also allows the 3rd family sqarks to be light:
  - Stop: due to large m_t.
  - Sbottom: due to large *tan*β.

$$p\bar{p} \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$$

$$\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}$$

generic ($\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}$) specific ($\tilde{t}, \tilde{b}$)

Lightest squark: $\tilde{t}_1(\text{low}\tan\beta)$, $\tilde{b}_1(\text{high}\tan\beta)$

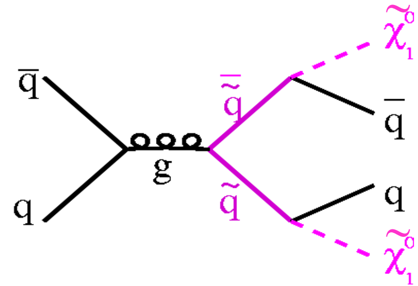
Target w/special searches

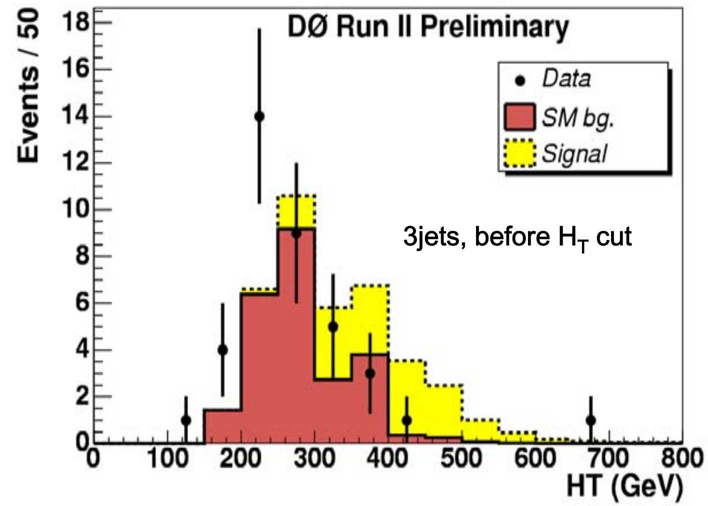
Squarks and Gluinos in jets+E_T^{Miss}

- In mSUGRA:

  Njets+ E_T^{Miss} selection

  - 3 analyses





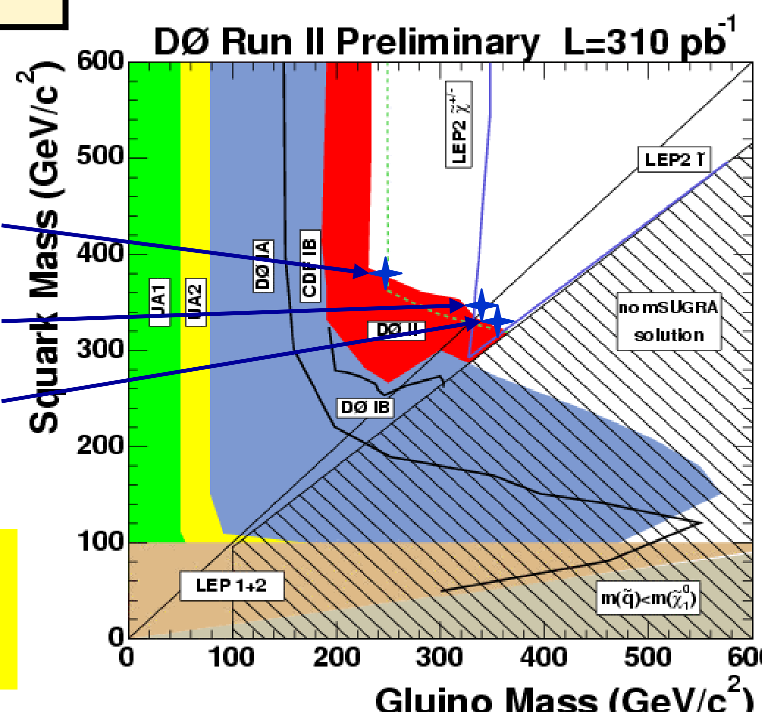
#jets(P_T (GeV))	$H_T = \sum P_t^{jet}$	E_T^{Miss}	Bkgd Expected	OBS
2jets(60,50)	250 GeV	175 GeV	12.8±5.4	12
3jets(60,40,25)	325 GeV	100 GeV	6.1±3.1	5
4jets(60,40,30,25)	175 GeV	75 GeV	9.3±0.5	10

Limits ($\tan\beta=3$, $A_0=0$, $\mu<0$, q= $\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{b}$):

➡ 4j : M_0=500 GeV-> $M(\tilde{g})$> 233 GeV/c², σ~3pb

➡ 3j : $M(\tilde{g})= M(\tilde{q})$ -> $M(\tilde{q})$ > 333 GeV/c², σ~0.6pb

➡ 2j : M_0=25 GeV -> $M(\tilde{q})$ > 318 GeV/c², σ~0.7pb

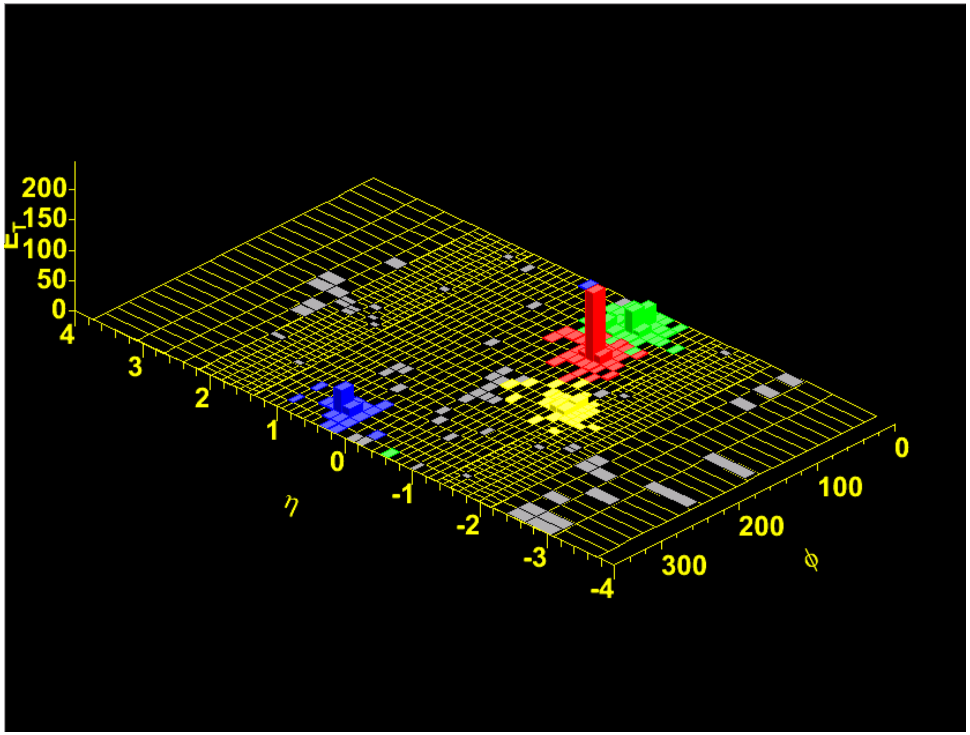


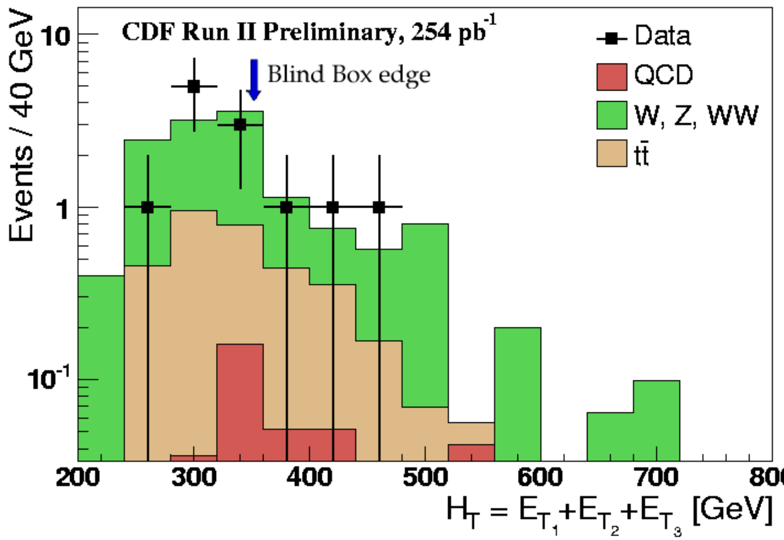
Extended LEP mSUGRA reach for $M(\tilde{q})<M(\tilde{g})$

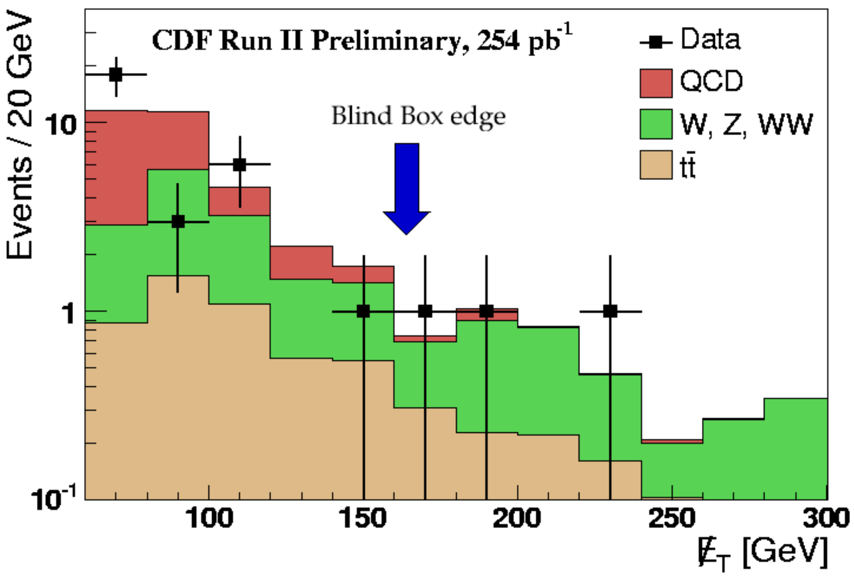
Gluino-Squark in jets + E_T^{Miss}

Brand new result!

- ≥3 jets (125, 75, 25 GeV)
- E_T^{Miss}>165 GeV, H_T>350 GeV
- Expect 4.2 ± 1.1 bkgnd events; SUSY: 0.7-4.8. (Blind analysis approach)
  - Observe 3 events in data
  - Scan parameter space, set limit soon

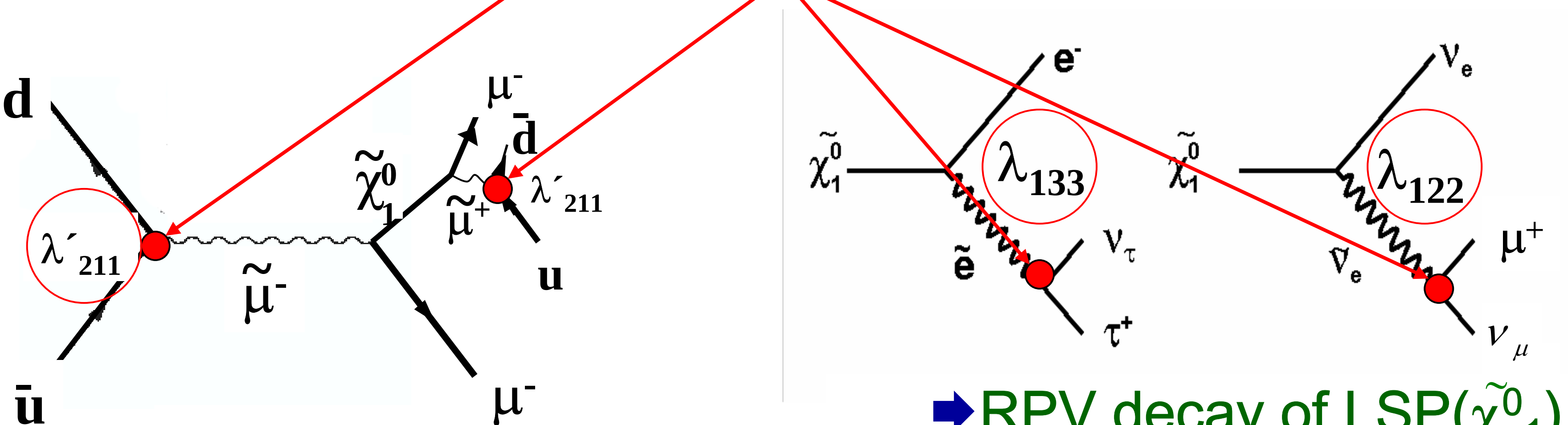






RPV Sleptons

- RPV tested in Production and Decay of SUSY particles



➡ Resonant sparticle production

➡ λ'_{ijk} coupling

➡ Selection:

2jets+2 isolated μ's

- λ'_{211}

➡ RPV decay of LSP($\tilde{\chi}^0_1$)

➡ λ_{ijk} coupling

➡ Selection:

$3\ell+E_T^{Miss}$+channel-dependent cuts

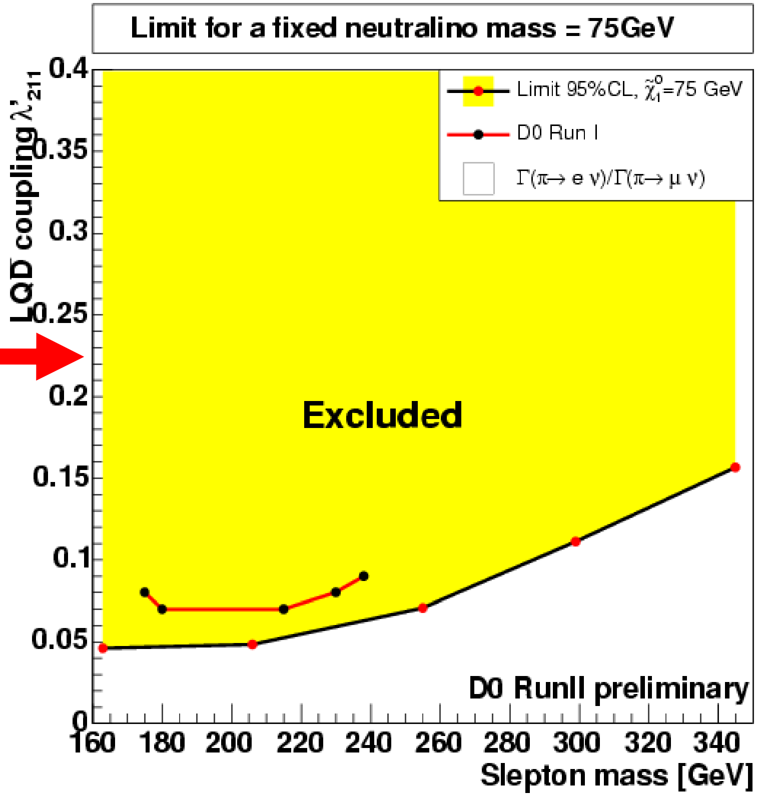
- λ_{121} -> eeee,eeeμ,eeμμ+νν
- λ_{122} -> μμμμ, μμμe,μμee+νν
- ➡ λ_{133} -> ττττ, τττe, ττee+νν

RPV Slepton limits

- (L=154 pb^{-1}) : λ'_{211}

  σ~2pb

EXP	OBS
1.1±0.4	2



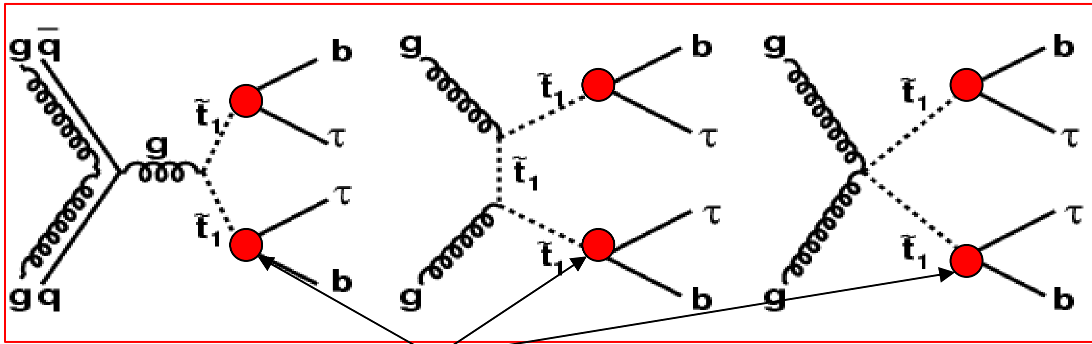
- (L=160 pb^{-1}) : λ_{122}
  - M($\tilde{\chi}_1^0$)>90GeV/c², M($\tilde{\chi}_1^\pm$)>165 GeV/c²
- (L=238 pb^{-1}) : λ_{121}
  - M($\tilde{\chi}_1^0$)>95GeV/c², M($\tilde{\chi}_1^\pm$)>181 GeV/c²
- (L=200 pb^{-1}) : λ_{133}
  - M($\tilde{\chi}_1^0$)>66GeV/c², M($\tilde{\chi}_1^\pm$)>118 GeV/c²

All channels with μ>0
Typical σ~0.1pb

Chan.	tan(β)	Exp.	Obsv.
eel	5	0.6±1.9	2
μμl	5	0.5±0.4	0
eeτ	10	1.0±1.4	0

Stop in RPV SUSY (I)

- Assume
  - BR($\tilde{t}_1 \rightarrow b\tau$) ~ 100%
- Search for :

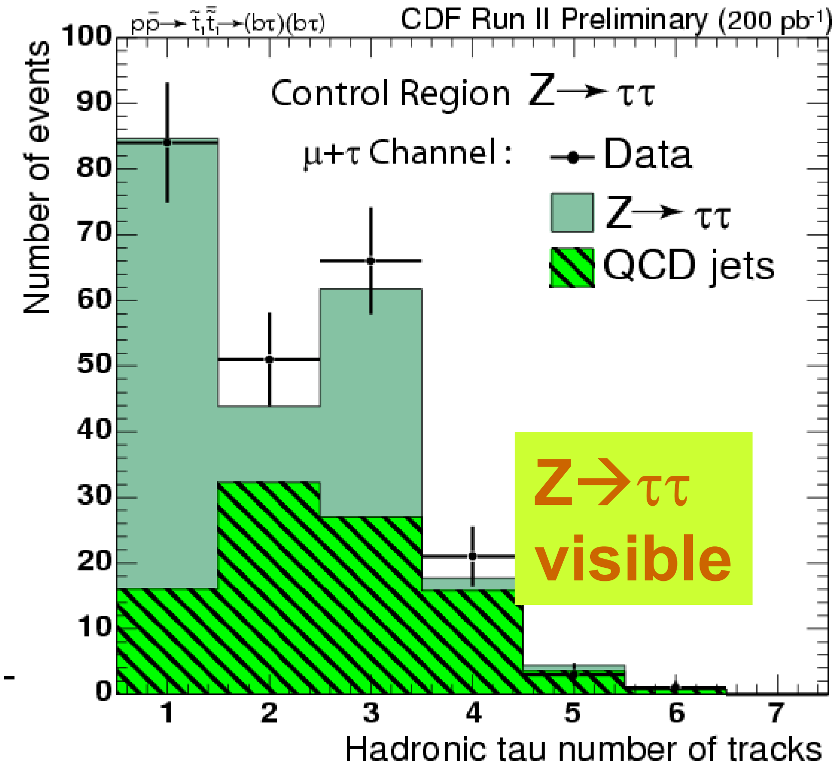


$$qq, gg \rightarrow \tilde{t}_1 \bar{\tilde{t}}_1 \rightarrow b\tau_{\mathrm{had}} \bar{b} \tau_{\mathrm{lep}}$$

λ'_{333}

selection: 1ℓ (ℓ=e,μ)+ 1τ + ≥ 2 jets

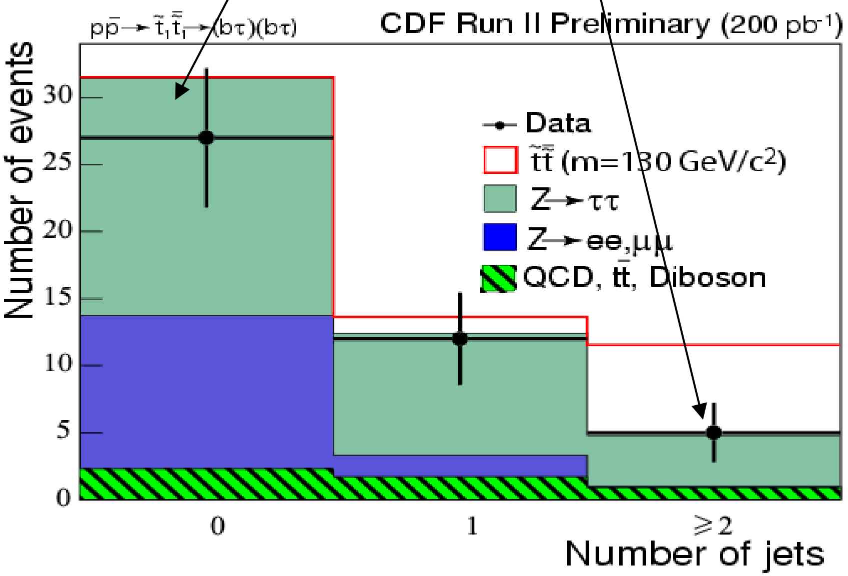
Largest background:
Real τ from Z→ττ
→ Check in 0 jet bin
control region

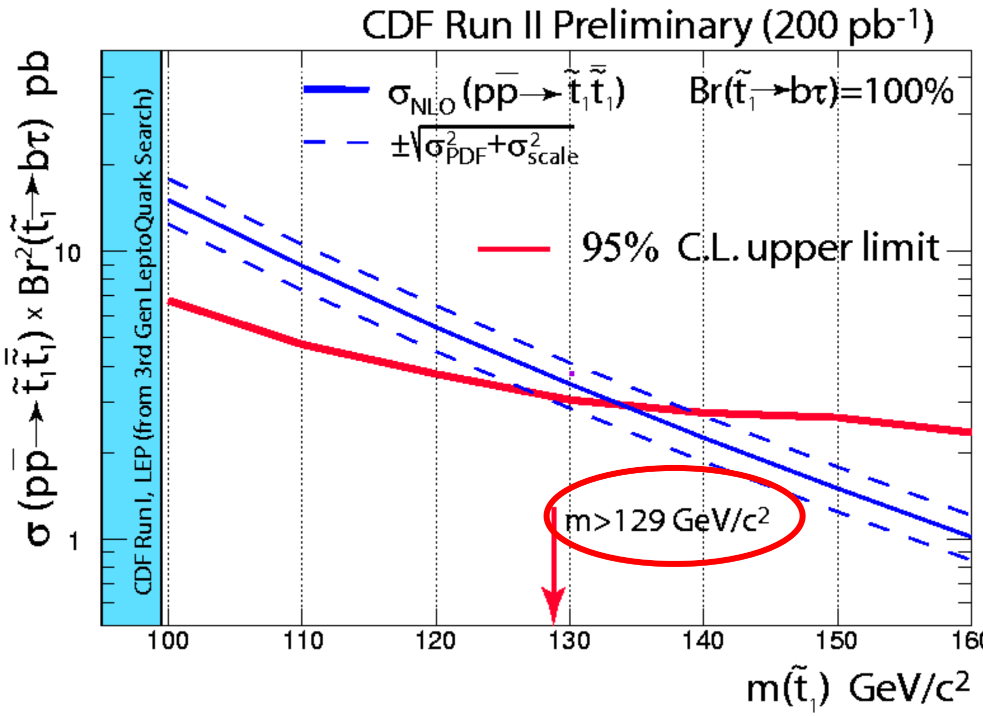


Stop in RPV SUSY (II)

- *Control region* looks good
- Measure in *signal region*

	$e+\tau$	$\mu+\tau$	SUM
Expect. BG	2.6±0.6	2.2±0.5	4.8±0.7
Observed	2	3	5

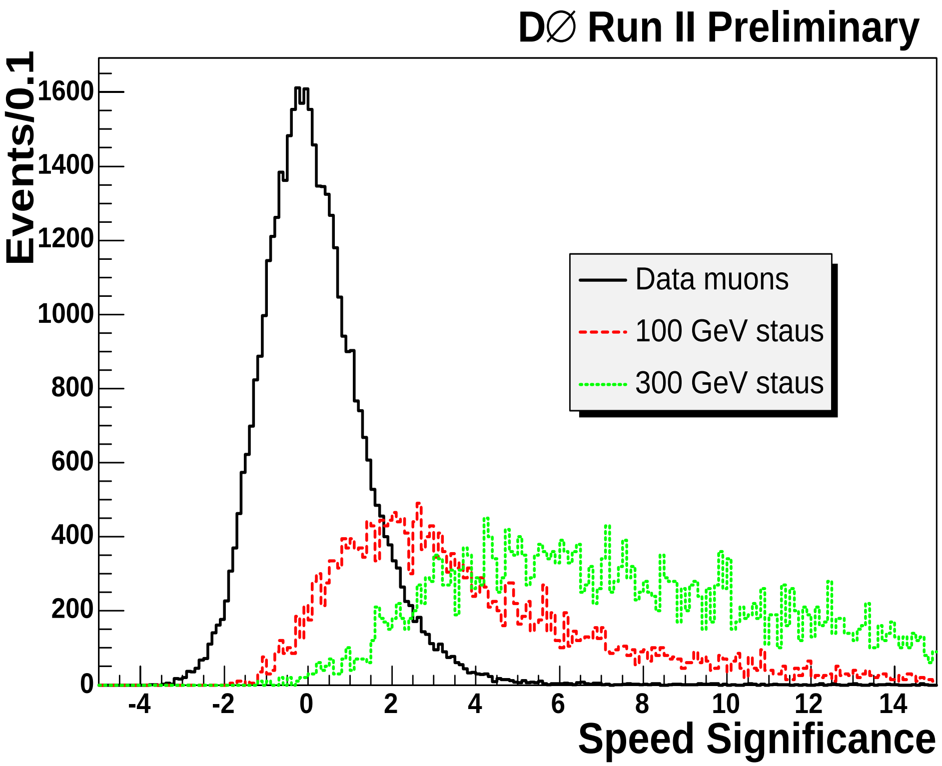




- **Limit: m(stop)>129 GeV/c^2**
- **Typical σ~3pb**

CHAMPs

- Look for particle that is
  - charged
  - Massive: v<<c
  - Lifetime long enough to decay outside detector ($c\tau$>10 m)
- Massively ionizing
- Event Selection:
  - 2 muons p_T> 15 GeV/c, isolated
  - Speed *significantly* slower than c



$$S_v = \frac{1-\text{speed}}{\sigma_{\text{speed}}}$$

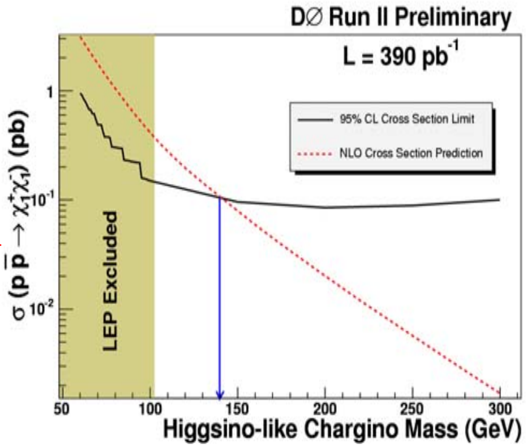
Champs

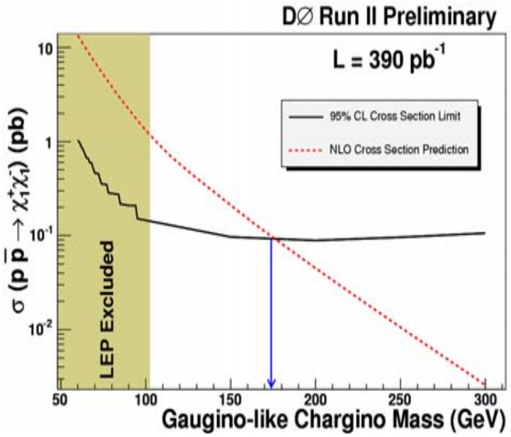
- Estimate backgrounds from data
  - 2D Plane: $M_{\mu\mu}$ vs. $S_v^1 \times S_v^2$
- SUSY interpretation: Set limits for (quasi)-stable staus, charginos
  - Stau: GMSB-like models (σ~0.01pb, m=100GeV) – not yet sensitive
  - Charginos: AMSB-like models (σ~0.05pb, m=100GeV)

Expected bgknd	OBSERVED
0.66±0.06	0

Limits in AMSB: champ=$\tilde{\chi}^{\pm}_1$

- Higgsino like:
  - o $M(\tilde{\chi}^{\pm}_1)>140$ GeV/c^2
- Gaugino like:
  - o $M(\tilde{\chi}^{\pm}_1)>174$ GeV/c^2



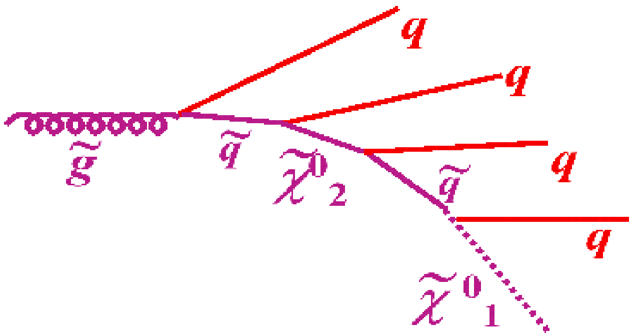


In Conclusion…

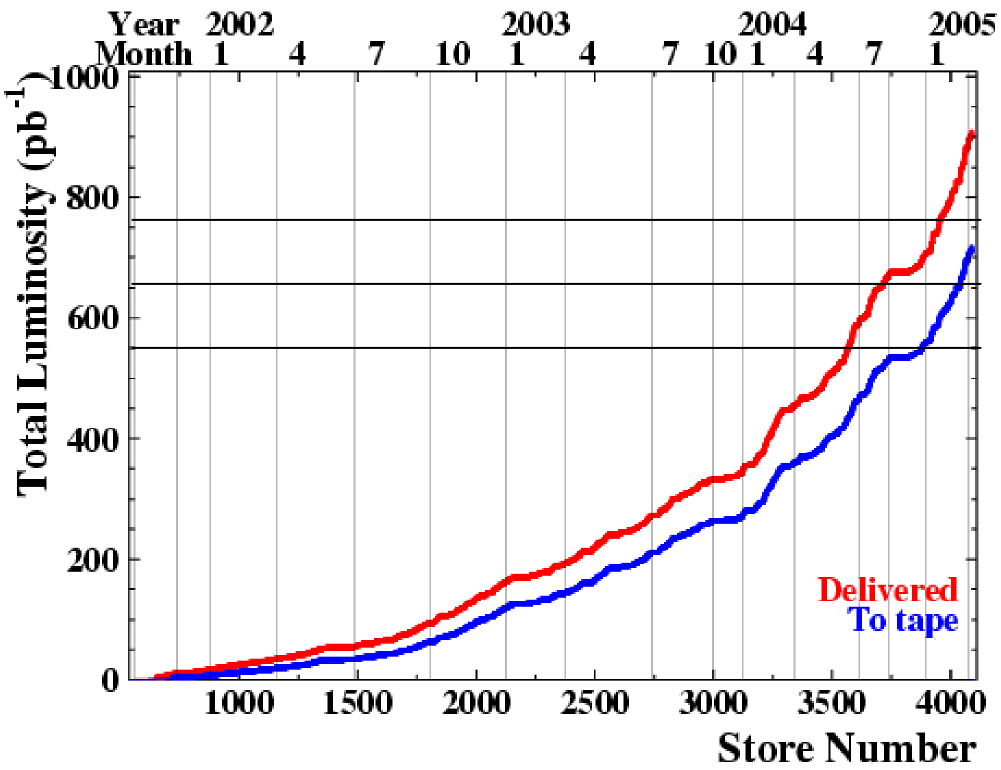
- SUSY promising venues for new physics
- D0 and CDF both mounting extensive program
  - Gluino-squark (limit above Tevatron Run1)
  - Chargino-neutralino (limit above LEP's in certain param. space)
  - R-parity violating modes
  - Stop, sbottom
  - Excluding new regions in parameter space
- Stay tuned for more data, more channels, …

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

Backup Slides

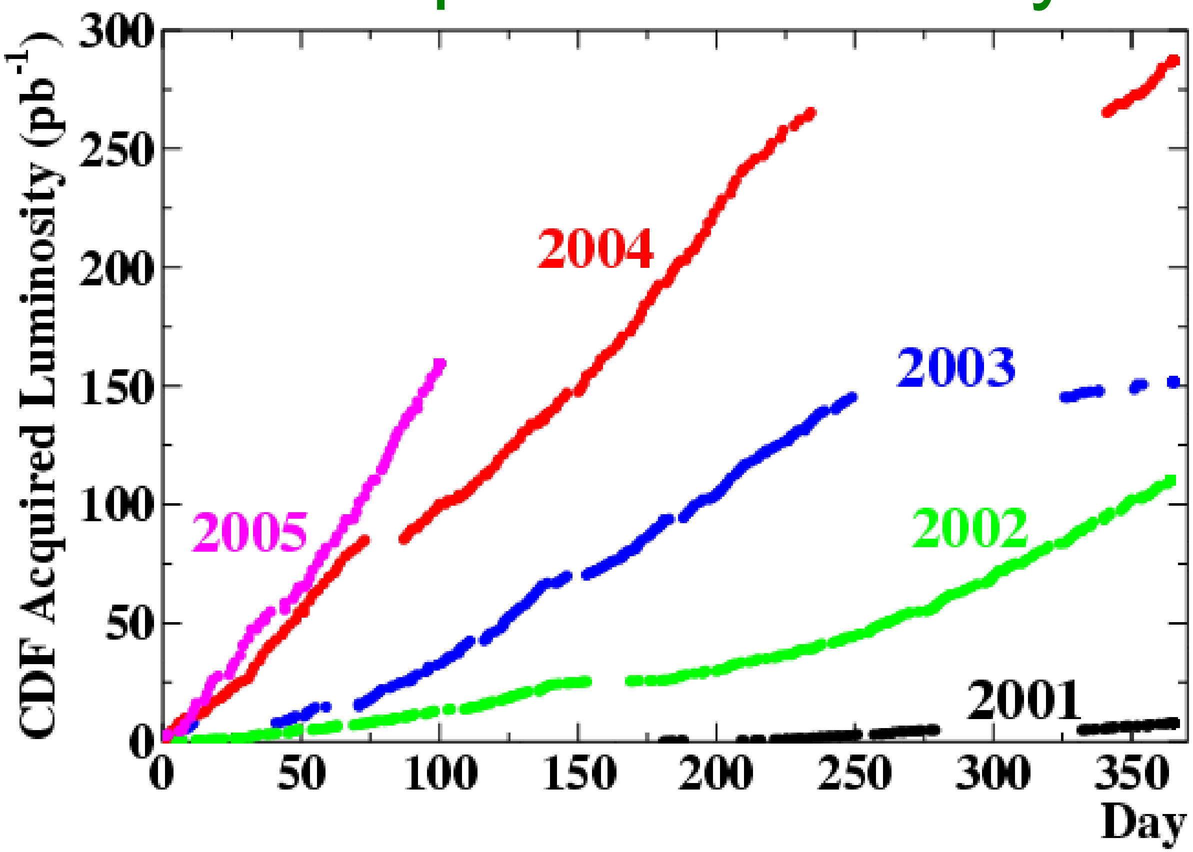


Delivered Luminosity



- Current record initial luminosity >12×10^{32}/cm^2/s
  - Frequent records before shutdown
  - Goal: 300/pb delivered in FY04 was reached
- Run analyses currently using ~240/pb-390/pb
- Run 2 goals: "Base:" 4.4 fb^{-1}. "Design:" 8.5 fb^{-1}

CDF Acquired Luminosity



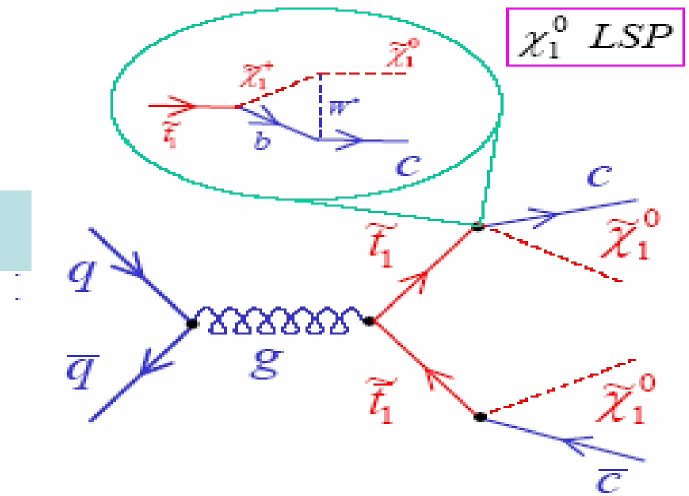
CDF Run II	Time (hr)	Init Lum (E30)	Efficiency (%)
Average	17.2	33.2	72.5
Record	62.4	118.8	98.5

CDF had 430/pb on tape at the start of 2004 shut-down

Light Stop in mSugra

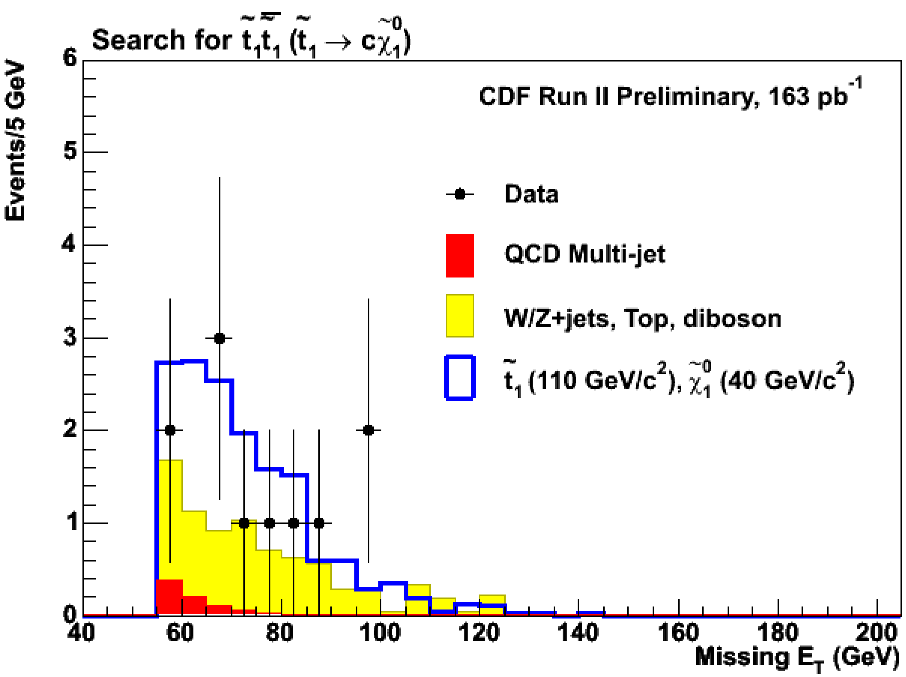
In mSugra with stop NLSP, assume

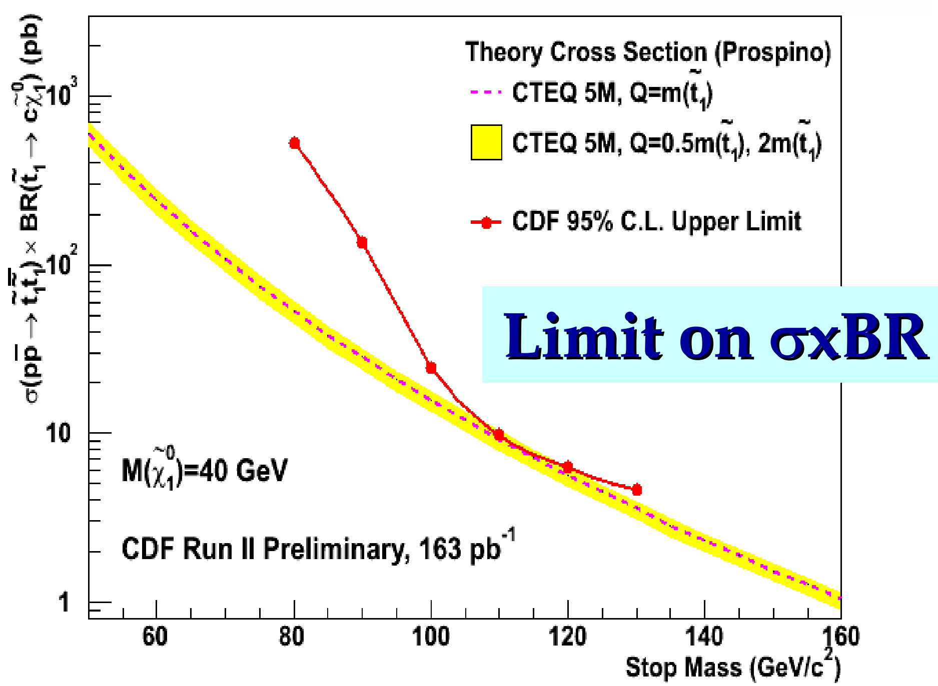
$$BR(\tilde{t}_1 \to c\tilde{\chi}_1^0) \sim 100\%, m_{\chi_1^0} = 40\text{GeV}/c^2$$



selection: *2 jets, large E_T^{Miss}, no l, charm tag*

	Expected	Observed
Pre-tag	105 ± 12	119
Tag (silicon)	8.3 ± 2.3	11



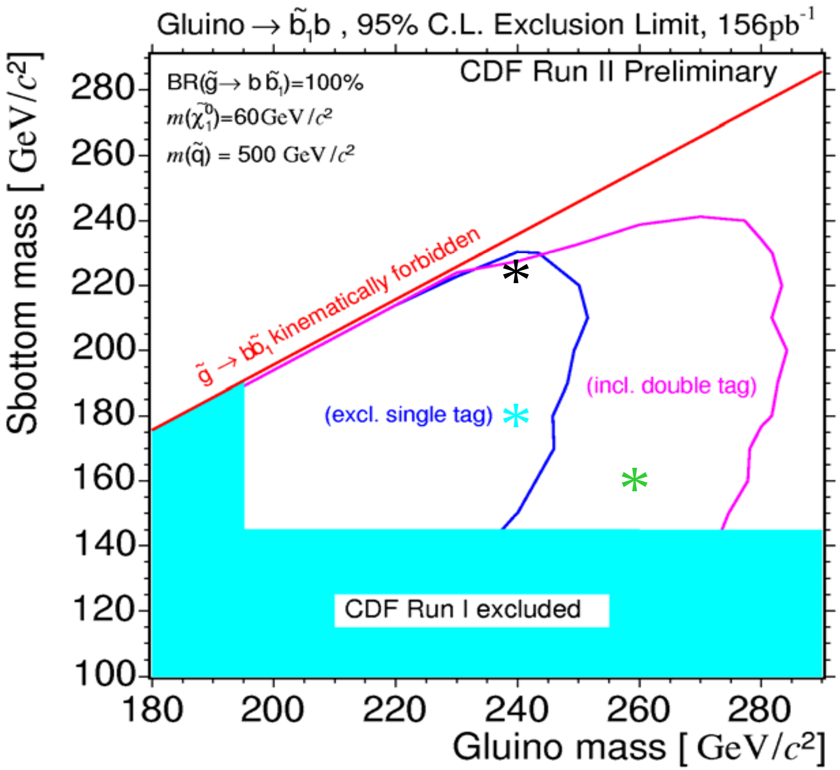


Search for Gluino → Sbottom

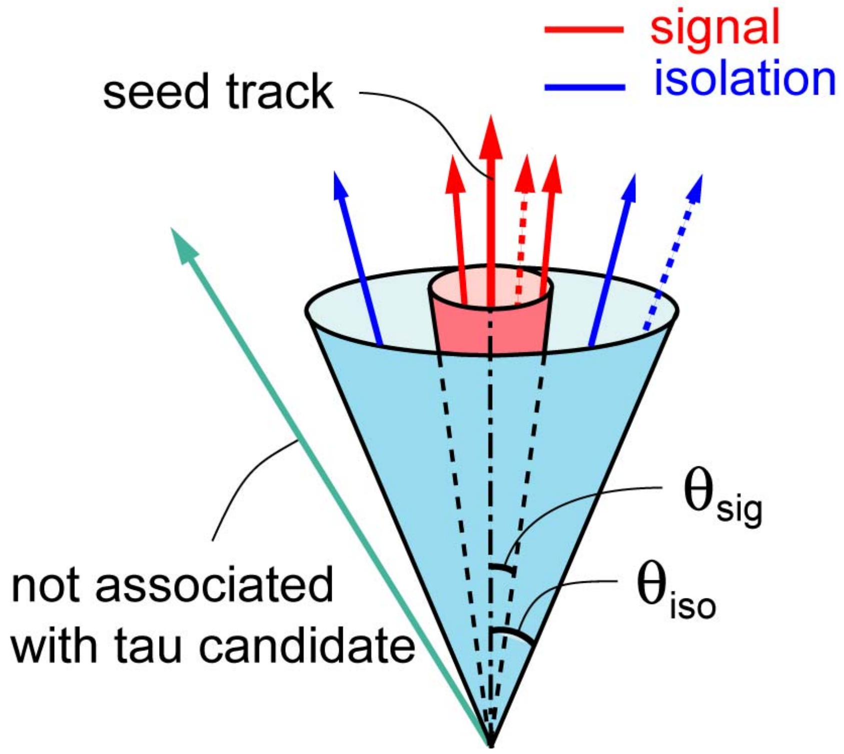
$$\tilde{g}\tilde{g} \rightarrow \tilde{b}_1\bar{\tilde{b}}_1 b\bar{b} \rightarrow b\bar{b}b\bar{b}\,\tilde{\chi}_1^0\tilde{\chi}_1^0$$

- Striking signature: four b's in final state + large E_T^{Miss}.
- Identify *b* quark jets to reduce dijet backgrounds
  - Use displaced tracks to tag
- Efficiency of B-tagging depends on
  - m(gluino) – m(sbottom)
- Set limits as fcn(m_{gluino}, $m_{sbottom}$)

n_{tag}	Bkgnd	Obs.
=1	16.4 ± 3.7	21
>=2	2.6 ± 0.7	4



Tau Idenfication at the Tevatron



CDF Tau Reconstruction

- Characteristic 1,3 track enhancement in signal cone
- Net charge 1
- Low π^0 multiplicity
- m < 1.8 GeV
- No energetic tracks, π^0's in isolation annulus

DØ uses Neural Network to identify hadronic τ. Variables:

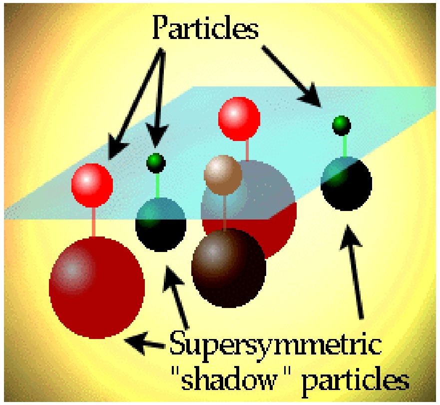
- Shower shape
- Cluster Isolation
- Electromagnetic fraction

Jet data, Zee MC are input to NN as the backgrounds and $Z\tau\tau$ MC is the signal.

NN Efficiency is 84% for τ's from Z.

Supersymmetry

- Based on fundamental symmetries
- String theories are supersymmetric
- Solves some technical problems of Standard Model
- How: double particle spectrum!
  - Worked before: postulate positron for quantum electro dynamics
- Introduce "super-partners" with different spin
  - Makes theory self-consistent
  - Also provides dark matter candidate
- But: where are they?
  - M(positron)=M(electron)
  - But not so for selectron
  - SUSY is broken!
- Should be visible in near future, at Tevatron collider or at next generation (LHC)



$$e \Updownarrow \tilde{e}$$

Particle	Super-partner
e,ν,u,d	$\tilde{e},\tilde{\nu},\tilde{u},\tilde{d}$
γ,W,Z,h	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^{\pm},\tilde{\chi}_1^0 \ldots \tilde{\chi}_4^0$

Dark Matter Candidate → $\tilde{\chi}_1^0$

$$m_{\tilde{l}} > 100\ \mathrm{GeV}/c^2$$

$$m_{\tilde{\chi}_1^0} > 43\ \mathrm{GeV}/c^2, m_{\tilde{\chi}_1^{\pm}} > 104\ \mathrm{GeV}/c^2$$

$$m_{\tilde{g}/\tilde{q}} > 195(300)\ \mathrm{GeV}/c^2$$

R-parity

- Global symmetry of MSSM
- All analyses presented so far assume R_p is conserved
  - Kills (*B*-*L*) violating terms of Lagrangian
    - No proton decay ✓
    - no flavor-violating decays ✓
  - LSP is stable: good dark matter candidate ✓
- What if R_P is **not** conserved?
  - Global symmetries are theoretically shaky
- Introduce new terms in MSSM
- Can produce *single* sparticles
- No stable LSP: no dark matter candidate, no E_T^{Miss}.
  - *But no one says SUSY has to solve all our problems…*

$$\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$$

$\lambda_{ijk}, \lambda'_{ijk}$ → Lepton-number violating terms

λ''_{ijk} → Baryon-number violating terms