Supersymmetry Searches at Tevatron

(Lecture III)

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Outline

- **Supersymmetric models**
- **Run I supersymmetry searches**
- **Run II discovery potential**

China Center of Advanced Science & Technology
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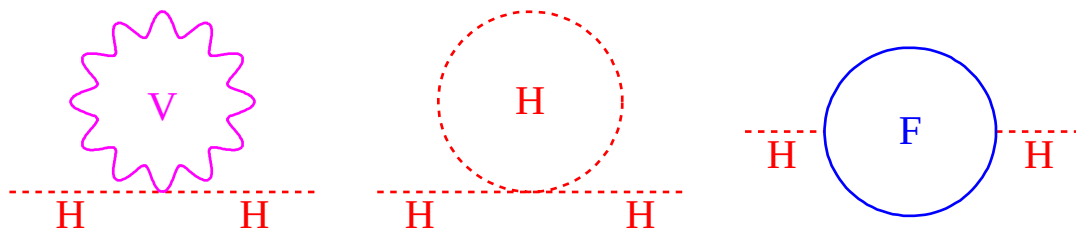
Theoretical Problems

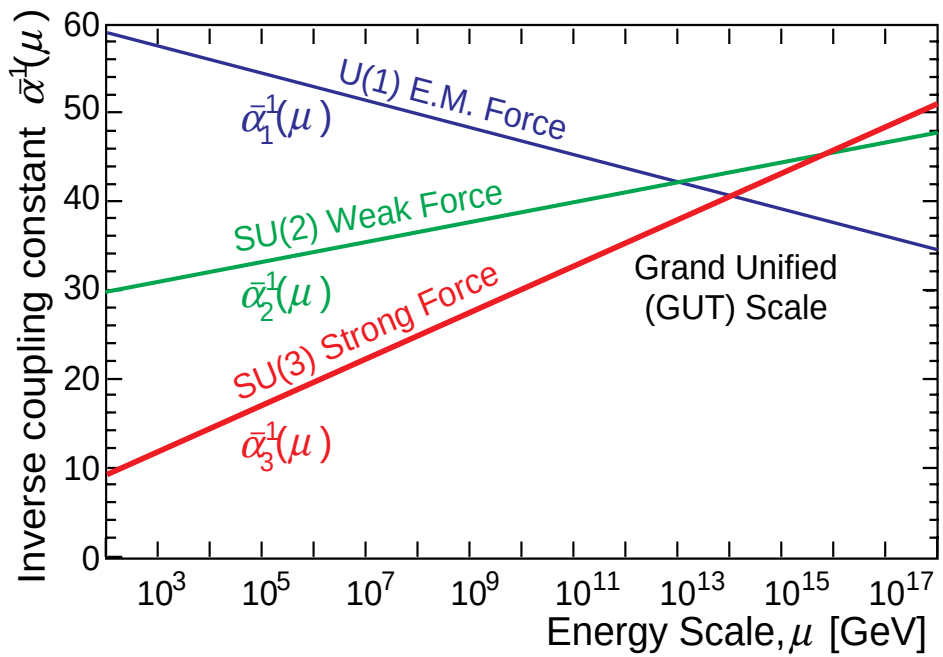
As much as we love the Standard Model, it is unlikely to be a complete theory

Higgs boson mass receives radiative corrections which are quadratically divergent

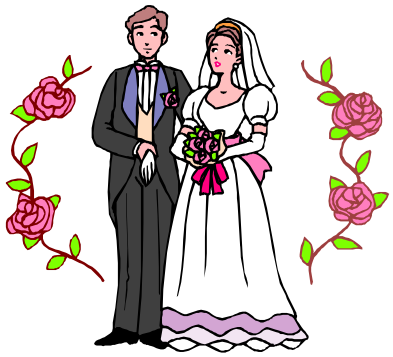


Standard Model does not incorporate gravity

Strong, electromagnetic and weak interactions do not unify at high energies without new physics



A Solution: Supersymmetry



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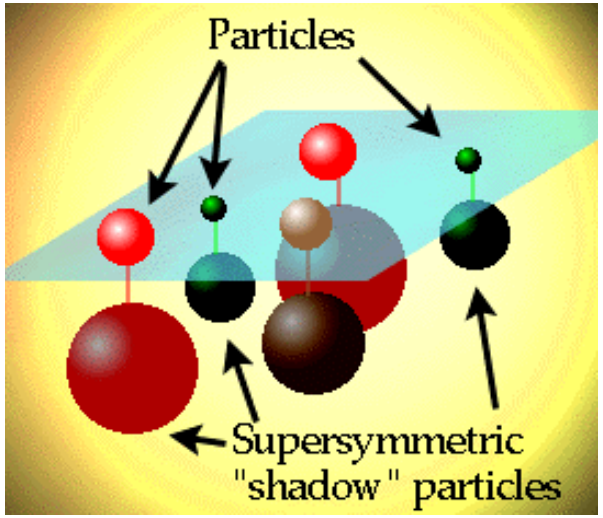
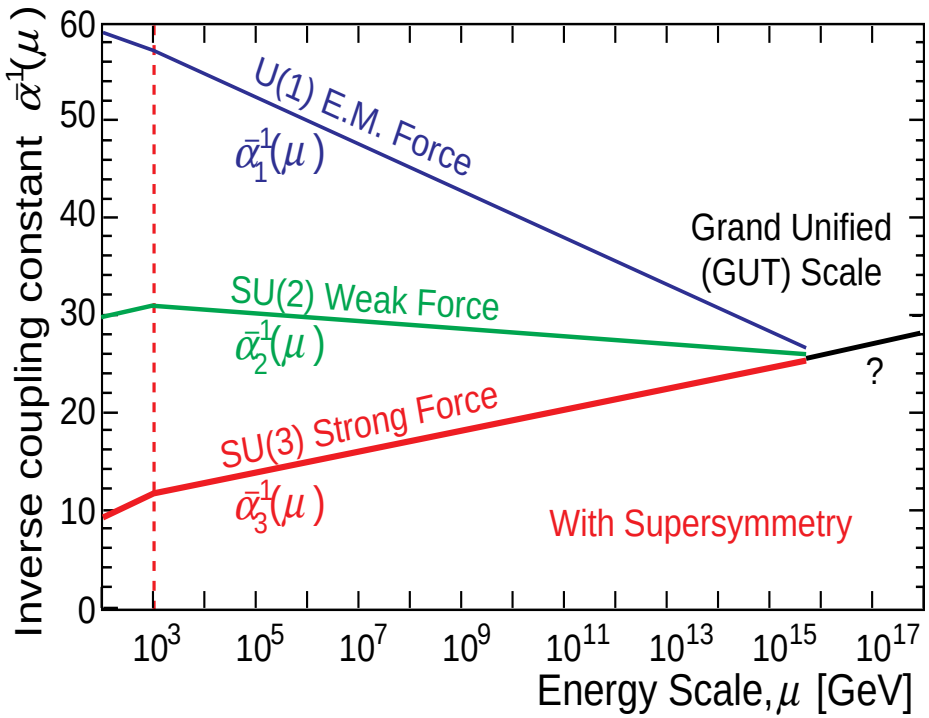


It is a theory popular theoretically but unobserved experimentally

Provides a solution to Higgs mass problem

Offers a path to the incorporation of gravity

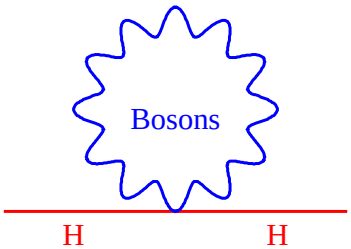
Unifies strong, electromagnetic and weak forces at high energies

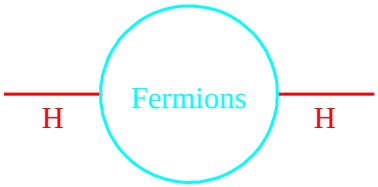


Predicts the radiative breaking of EW symmetry

Constraints from Higgs Mass

Standard Model





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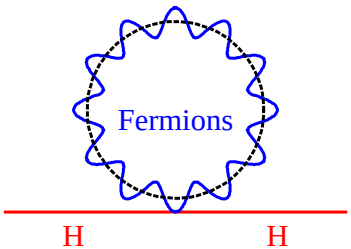
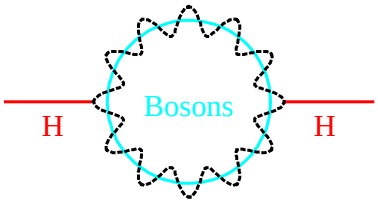
Supersymmetry





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With supersymmetry
fermion and boson loops have opposite signs
there are equal numbers of bosons and fermions

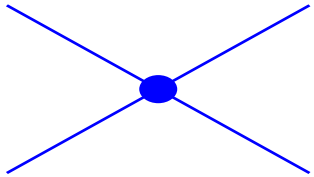
$$\delta m_H^2 = -\left(\frac{g_F^2}{4\pi}\right)\left(\Lambda^2 + m_F^2\right) + \left(\frac{g_B^2}{4\pi}\right)\left(\Lambda^2 + m_B^2\right) \approx O\left(\frac{\alpha}{\pi}\right)\left|m_B^2 - m_F^2\right|$$

The divergence cancels for identical couplings

Supersymmetry mass scale $\lesssim$ 1 TeV
if $\delta m_H^2 \lesssim m_H^2$

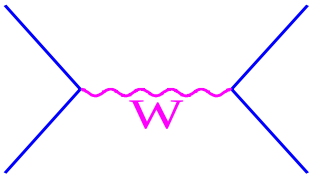
Historical Guidance

W boson was introduced to make $\sigma(e\nu_e \to e\nu_e)$ finite

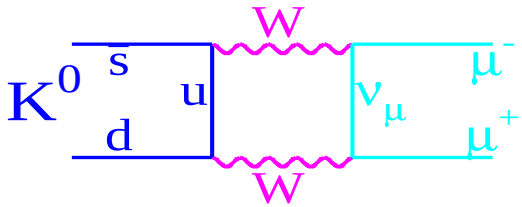


$$\sigma \Rightarrow \frac{G_F^2\, s}{\pi}$$

$\Rightarrow$



$$\sigma \Rightarrow \frac{G_F^2\, M_W^2}{\pi}$$



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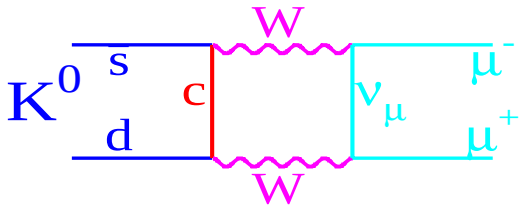

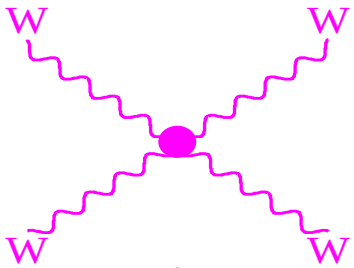

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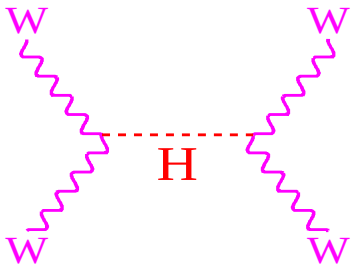


To solve $K^0 \to \mu\mu$ decay problem, the charm quark was postulated

To make $\sigma\left(W_L^+ W_L^- \to W_L^+ W_L^-\right)$ finite, we introduced the Higgs boson

Supersymmetry Models

The simplest supersymmetric model
is the minimal supersymmetric standard model (MSSM)

(1) An extra Higgs doublet of opposite hypercharge
(2) Supersymmetrizing the gauge field

Standard Model Particles

$W^{\pm} H^{\pm}$ γ Z h H A u d e ν .....

$\Downarrow$ $\Downarrow$ $\Downarrow$

$\tilde{\chi}_2^{\pm}$ $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_4^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_1^0$ $\tilde{u}_L$ $\tilde{d}_L$ $\tilde{e}_L$ $\tilde{\nu}_L$ $\tilde{u}_R$ $\tilde{d}_R$ $\tilde{e}_R$ $\tilde{\nu}_R$ $\tilde{}\tilde{}\tilde{}\tilde{}$

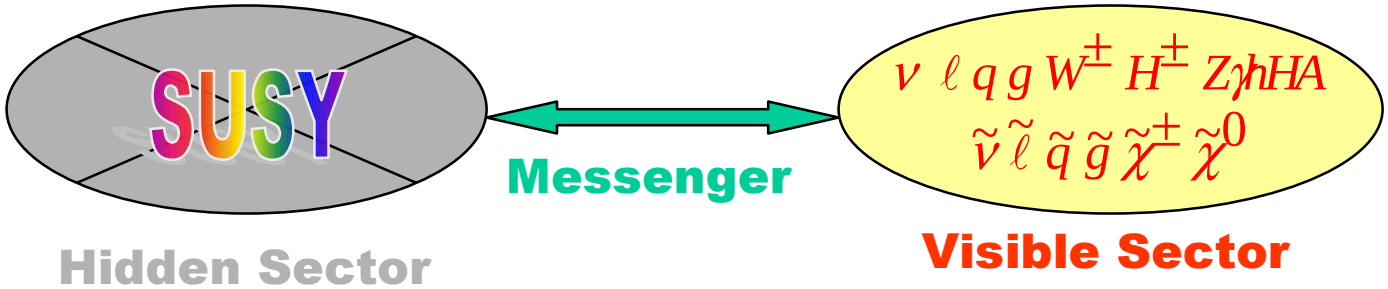
Supersymmetric Particles

For every spin degree of freedom in SM,
there is a supersymmetric spin degree of freedom

Lots of new particles and lots of free parameters
$\Rightarrow$ lots of opportunity

Broken Supersymmetry

Supersymmetry must be broken



The symmetry is assumed to be broken in a hidden sector, a messenger sector mediates the breaking to the visible sector

Different mediation leads to different classes of models

Gravity inspired models

The messenger interaction is of gravitational strength

Gauge mediated models

SM gauge interactions play the role of messenger force

Anomaly mediations, Gaugino mass dominance

Supersymmetry Phenomenology

Supersymmetry phenomenology depends on

(1) Whether R-parity is conserved
(2) What is the lightest supersymmetric particle (LSP)

If R-parity is conserved:

(1) Supersymmetric particles are pair produced
(2) Heavy sparticles decay to lighter sparticles
(3) LSP is stable (no available decay mode)

Cosmological consideration suggests that the LSP is neutral in electric and color charges

LSP candidates are:
Neutralino, scalar neutrino, gravitino, ...

R-parity conservation generally leads to missing E_T signature

Minimal SuperGravity Model

Supersymmetry breaking scale is general of ~ 10^9 TeV

1. **A massive gravitino**
2. **The lightest SM superpartner is the LSP**

mSUGRA assumes scalar and gaugino mass unification at GUT scale

Has four continuous and one discrete free parameters at GUT scale

m_0	common scalar mass parameter
$m_{1/2}$	common gaugino mass parameter
A_0	common trilinear coupling
$\tan\beta$	ratio of V.E.V. of the Higgs doublets
Sign(μ)	sign of higgsino mass parameter

mSUGRA predicts radiative breaking of the electroweak gauge symmetry

Minimal Gauge Mediation Model

Susy breaking scale can be as low as ~ 100 TeV

$\Rightarrow$ **An exceedingly light gravitino**
$\Rightarrow$ **Gravitino is naturally the LSP**

The phenomenology depends on the next lightest supersymmetric particle (NLSP)

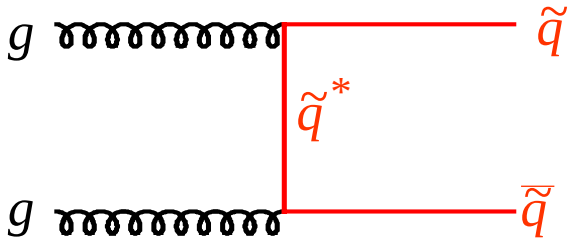
$$\tilde{\chi}_1^0 \rightarrow (\gamma,\ h,\ Z) + \tilde{G} \qquad \tilde{\tau} \rightarrow \tau + \tilde{G}$$

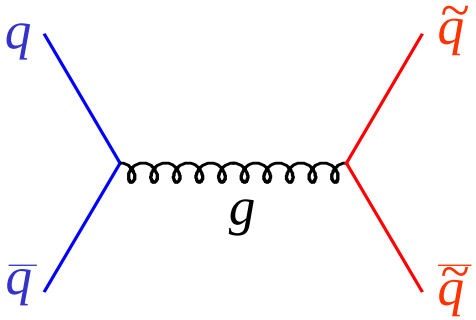
Leading to anomalous production of events with photon/tau and large missing E_T

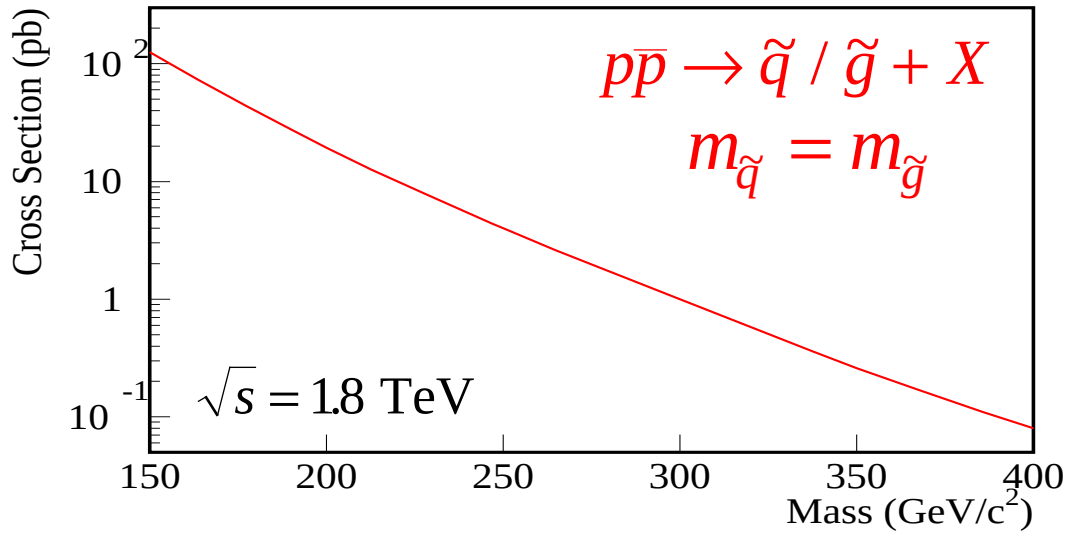
Minimal Gauge Mediation Model (MGM)

Λ	supersymmetry breaking scale
M_m	messenger sector scale
N	number of messengers
$\tan\beta$	ratio of V.E.V. of the Higgs doublets
Sign(μ)	sign of the higgsino mass parameter

Signal Cross Sections



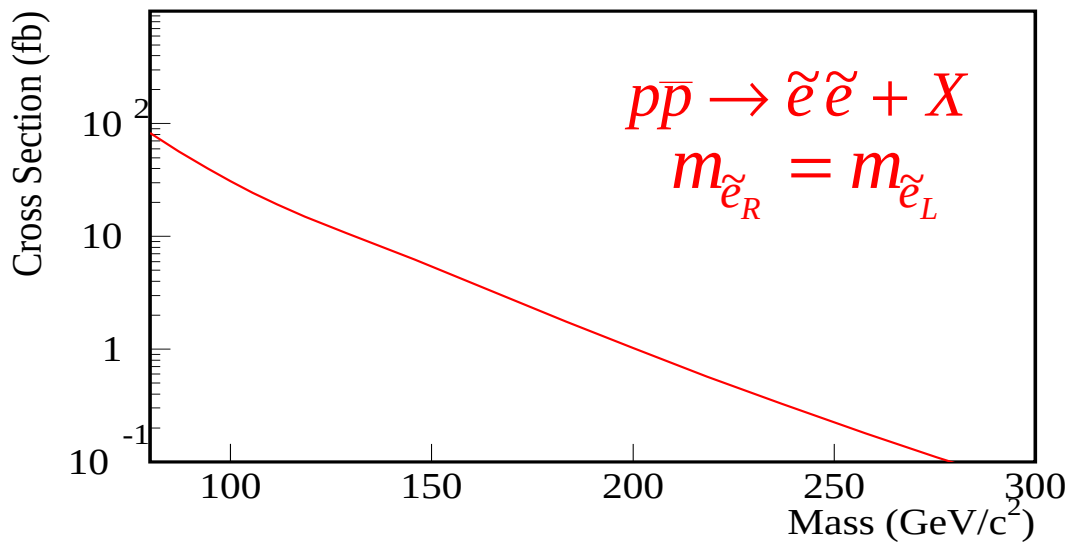




Production has less dependence on susy parameters than decays

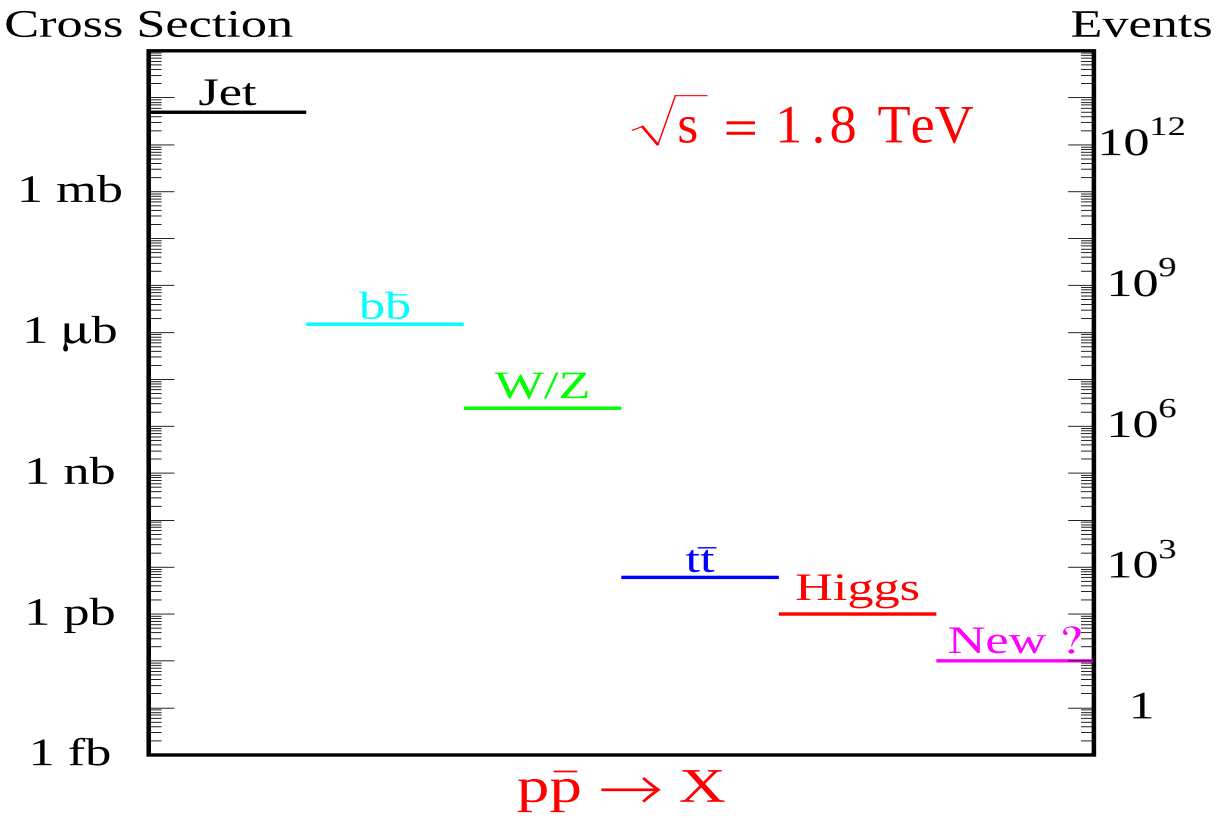
Squarks and gluinos dominant the production at Tevatron if kinematically accessible

Cross sections for scalar leptons are small



Background Cross Sections

The cross section for new physics is small compared with dominant Standard Model processes

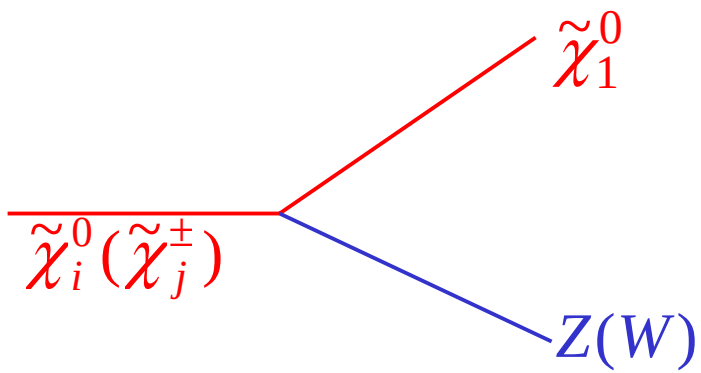


Leptons (e, μ) and missing E_T are the keys

- **missing E_T resolution**
- **lepton identification efficiency**
- **lepton fake rate**

Supergravity Signatures

For most of the parameter space, the lightest neutralino is the LSP and is so assumed for most of the analyses



$$\tilde{\chi}_i^0 \to Z\,\tilde{\chi}_1^0$$
$$\tilde{\chi}_j^\pm \to W\,\tilde{\chi}_1^0$$
$$\tilde{q} \to q\,\tilde{\chi}_1^0$$
$$\tilde{g} \to q\,\tilde{q}$$

$$p\bar{p} \to \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to WZ + \not{E}_T \Rightarrow \ell^{1,2,3} + \not{E}_T + X$$
$$\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm \to WW + \not{E}_T \Rightarrow \ell^{1,2} + \not{E}_T + X$$

$$\begin{aligned} p\bar{p} \to \tilde{q}\bar{\tilde{q}} \to X + \tilde{\chi}_1^0\tilde{\chi}_1^0 &\Rightarrow jets + \not{E}_T \\ + \tilde{\chi}_1^\pm\tilde{\chi}_1^0 &\Rightarrow jets + \not{E}_T + \ell \\ + \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp &\Rightarrow jets + \not{E}_T + \ell^\pm\ell^\mp \\ + \tilde{\chi}_2^0\tilde{\chi}_1^0 &\Rightarrow jets + \not{E}_T + \ell^\pm\ell^\mp \\ + \tilde{\chi}_1^\pm\tilde{\chi}_2^0 &\Rightarrow jets + \not{E}_T + \ell\ell\ell \\ + \ \ldots\ldots \end{aligned}$$

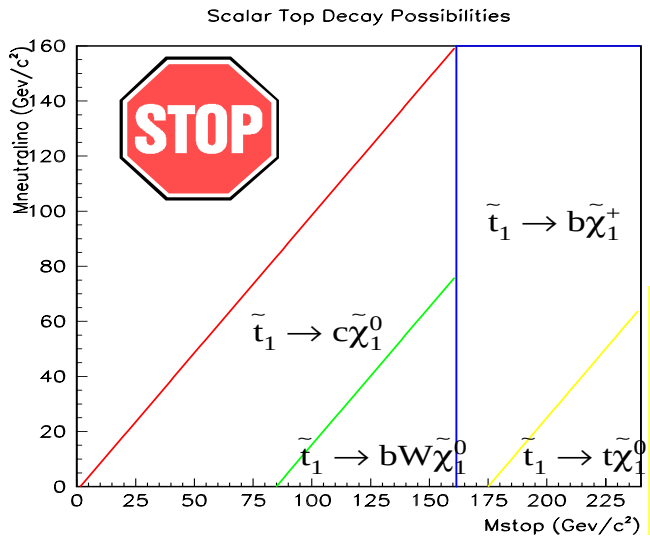
$$p\bar{p} \to \tilde{g}\tilde{g} \to X + \tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \Rightarrow jets + \not{E}_T + \ell^\pm\ell^\pm$$

Signatures:

$$p\bar{p} \to SUSY \Rightarrow \not{E}_T + \ell^n + j^m$$

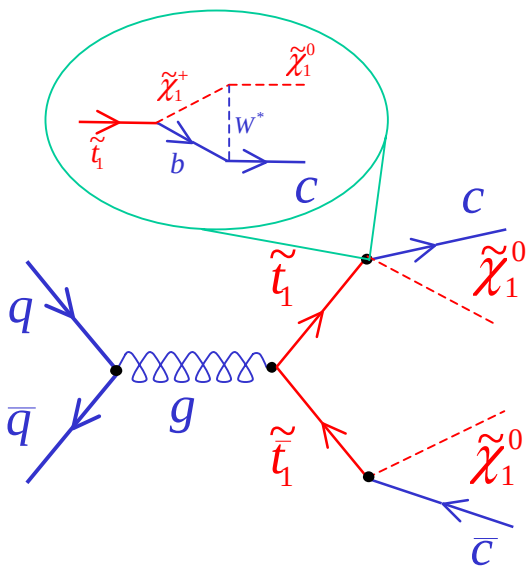
Stop and Sbottom Signatures

In many supersymmetry models, stop (and sbottom) can be significantly lighter than other squarks

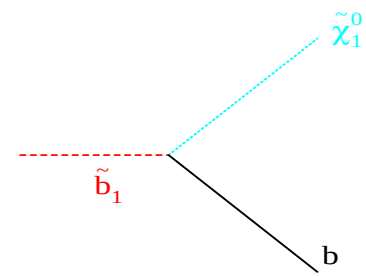


$$\tilde{t}_1 \to b + \tilde{\chi}_1^{\pm} \to Wb + \tilde{\chi}_1^0$$
$$\tilde{t}_1 \to b + \tilde{\chi}_1^{\pm} \to b\ell + \tilde{\nu}$$
$$\tilde{t}_1 \to \tilde{\chi}_1^0 + c$$
$$\tilde{t}_1 \to t + \tilde{\chi}_1^0$$

Signatures:
1) **excess of SM top events**
2) **two acoplanar c-jets with mE_T**
3) **two b-jets, two leptons and mE_T**



Assuming $Br(\tilde{b}_1 \to b\tilde{\chi}_1^0) = 100\%$
pair production of $\tilde{b}_1$ **will yield two acoplanar** b**- jets**

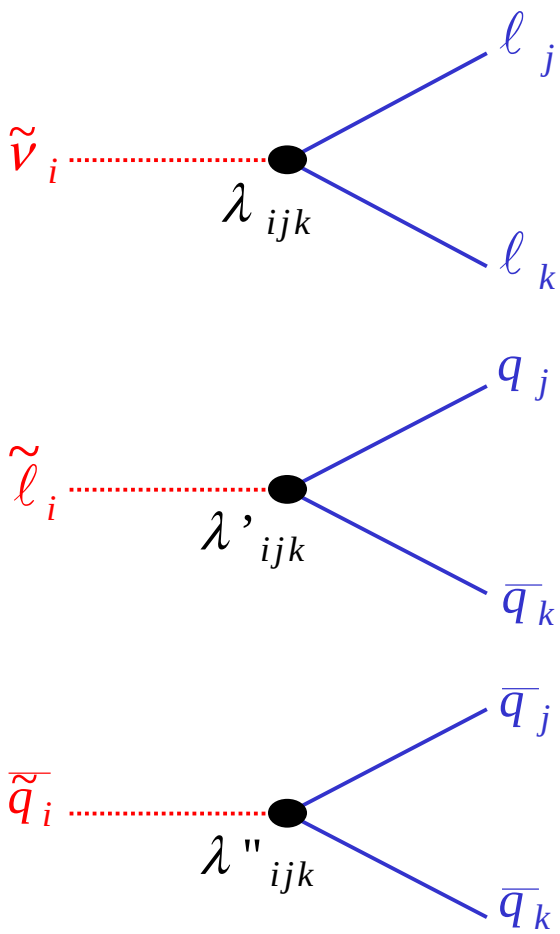


Signatures:
two acoplanar b-jets + missing E_T

(Also expected from WH, ZH)

R-parity Violation Signatures

In addition to the SM interactions, following interactions are allowed



resulting lepton and baryon number violations as well as the R-parity violation

B-violating λ''_{ijk} couplings will lead to multijet events without $\not{E}_T$

The L-violating λ_{ijk} and λ'_{ijk} couplings will give rise to multilepton events

$$\tilde{\chi}_1^0 \to \nu\tilde{\nu}^* \Rightarrow \nu\ell\ell \;\; (\lambda_{ijk})$$
$$\tilde{\chi}_1^0 \to \ell\tilde{\ell}^* \Rightarrow \ell qq \;\; (\lambda'_{ijk})$$

Frequent assumptions:

1) **R-parity violating LSP decay**
2) **couplings are not too weak or too strong**
3) **terms with similar event topology dominate**

Signatures:

$$p\bar{p} \to SUSY \Rightarrow \ell^n + j^m (+\not{E}_T)$$

Gauge Mediation Signatures

Signatures generally depend on the next-lightest supersymmetric particle (NLSP)

$$\tilde{\chi}_1^0 \to \gamma\tilde{G},\ \ Z\tilde{G},\ \ h\tilde{G}$$
$$\tilde{\ell} \to \ell G$$

$$p\bar{p} \to SUSY \Rightarrow 2\,NLSP + \ell^n + j^m$$
$$\Rightarrow (\not{E}_T + \ell^n + j^m) + \gamma\gamma$$
$$\Rightarrow (\not{E}_T + \ell^n + j^m) + \ell\ell$$
$$\Rightarrow (\not{E}_T + \ell^n + j^m) + \gamma h$$
$$\ldots\ldots$$

Signatures:

$$\gamma\gamma\not{E}_T,\ \ \ell\ell\not{E}_T,\ \ \gamma b\bar{b}\not{E}_T,\ \ldots$$

Depending on their lifetimes, NLSPs can decay at the production vertex, inside and outside detector

$\Downarrow$

displaced photons
hot cells
slow moving particles
kinked tracks

Only two Run I analyses specifically done for GMSB models:

- **light gravitino production**
- **diphoton+mEt events**

Experimental Signatures

Leptonic Signatures

- Single-lepton
  Expected from many SUSY models, large backgrounds from W production
- Di-lepton
  Expected from both R-parity conserving (with mEt) and R-parity violation (w/o mEt) scenarios.
  Like-sign dilepton events will have very small backgrounds.
  A pair of massive stable charged particles could appear as a dilepton event
- Tri-lepton
  Cleanest channel, but very low production cross section
- τ events
  Important for large tanβ scenarios

Jet Signatures

- Heavy-flavor quarks
  Expected from light stop and sbottom production
- Jets
  dominant signature for squarks/gluinos production, huge QCD multijet backgrounds

Photonic Signatures

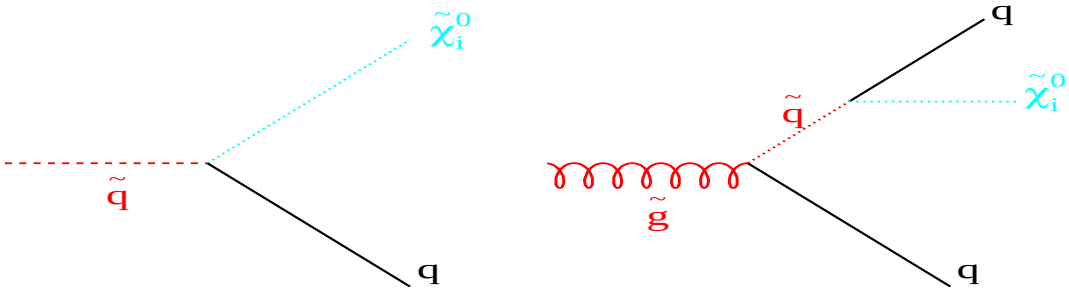
- Single-photon
  Expected from some MSSM and GMSB models
- Di-photon
  Expected from GMSB models

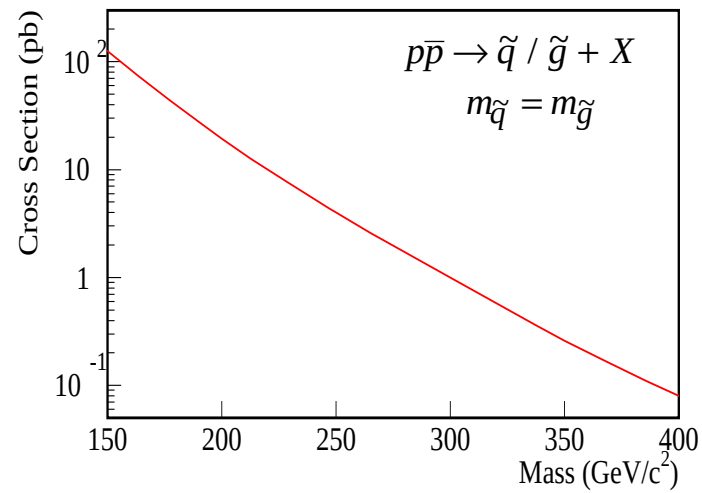
Run I Analyses

- jets+mEt (squarks/gluinos, stop,...)
- single-lepton+jets+mEt
- dilepton+jets (RPV Yukawa coupling)
- .....
- dilepton+jets+mEt (mSUGRA, stop,...)
- trilepton+mEt (charginos/neutralinos, RPV)
- single-photon+jets+mEt (MSSM)
- diphoton+mEt (GMSB)

Squarks and Gluinos

Squarks and gluinos can be copiously produced at Tevatron if they are light





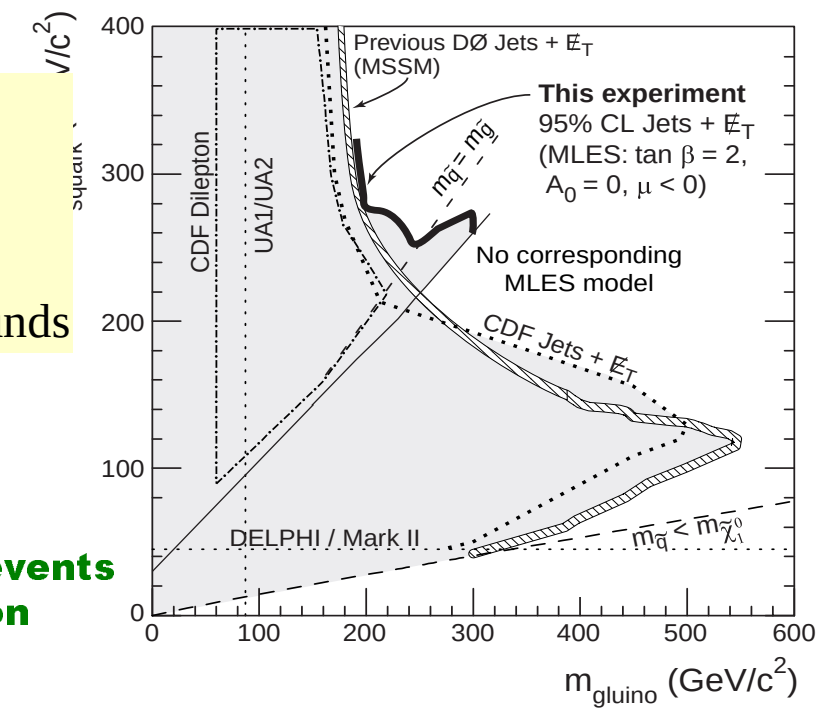
The dominant signature for $p\bar{p} \to \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} + X$ production is therefore $jets + \not{E}_T$

DØ: Phys. Rev. Lett. 82, 29 (1999)

1) ≥ 3 jets with $E_T > 25$ GeV
   $|\eta| < 1.1$ or $1.4 < |\eta| < 3.5$
2) $E_T^{j1} > 115$ GeV
3) $\not{E}_T > 75$ GeV
4) topological cuts to reduce instrumental backgrounds

Final selection criteria for each $(m_0, m_{1/2})$ were determined by choosing H_T and $\not{E}_T$ thresholds that maximized the $S / \delta B$ ratio

The background is dominated by QCD multijet events
No apparent excess is found beyond expectation

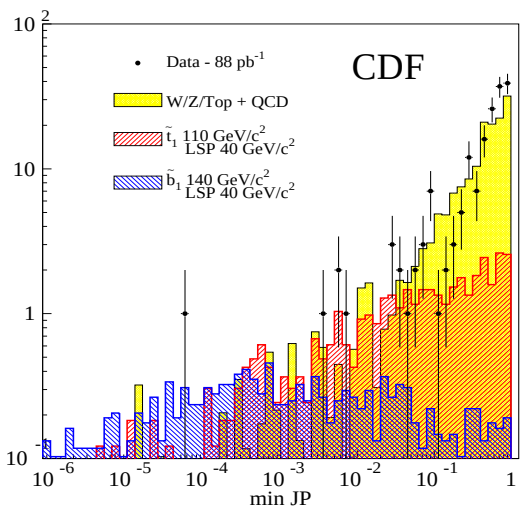


Stop and Sbottom from Jets+mEt

CDF searched for events with heavy-quark jets and large mEt.

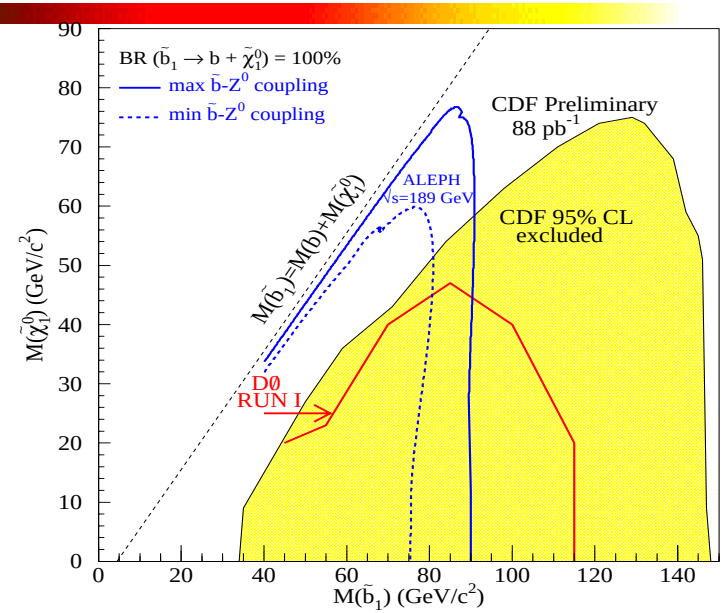
1) 2 or 3 jets with $E_T > 15$ GeV
   no jet with $7 < E_T < 15$ GeV
2) $\not{E}_T > 40$ GeV
3) no identified leptons with $E_T > 10$ GeV
4) topological cuts
5) jet probability < 0.05 for $\tilde{t}_1$ searches
   < 0.01 for $\tilde{b}$ searches

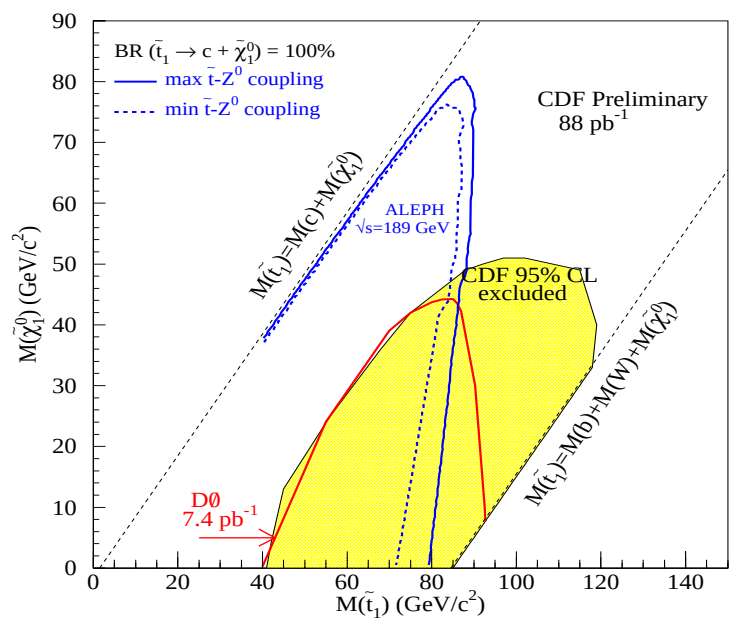
Backgrounds are dominated by W(→τν)+jets and mismeasurements



Stop searches:
11 events observed
~15 expected

Sbottom searches:
5 events observed
~6 expected





Stop from b-jets, lepton and mEt

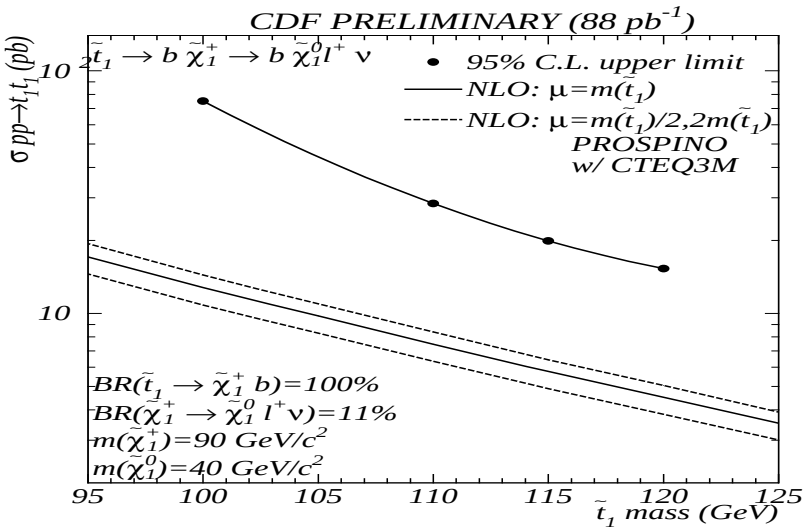
CDF searched for $\tilde{t}_1\bar{\tilde{t}}_1$ production with $\tilde{t}_1 \to b + \tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{\pm} \to W\tilde{\chi}_1^0$ or $\ell\tilde{\nu}$

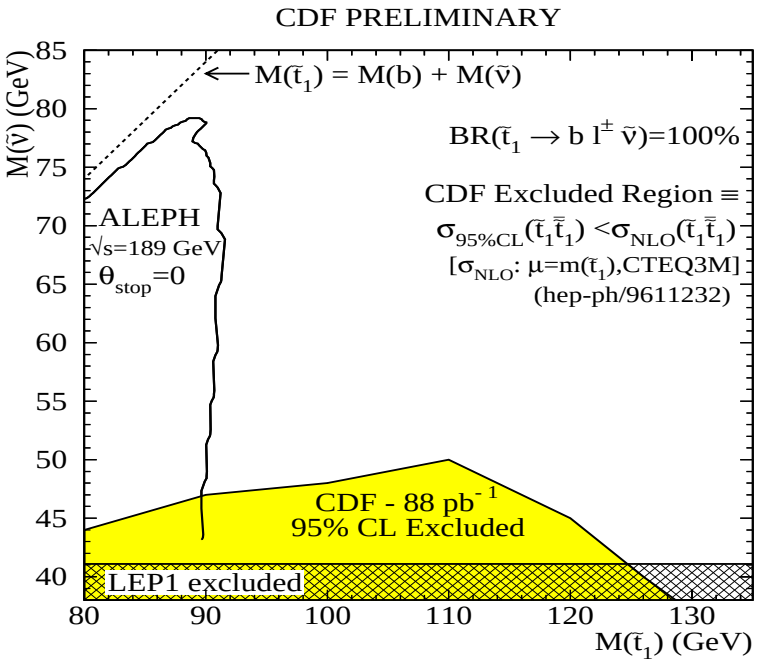
CDF: Phys. Rev. Lett. 84, 5273 (2000)

1) $\geq 2\ell$ with $E_T > 10$ GeV, but not $e^+e^-, \mu^+\mu^-$
2) ≥ 2 jets with $E_T > 12{,}8$ GeV, ≥ 1 vertex tagged
3) $\not{E}_T > 25$ GeV
4) cleanup requirements to reduce mismeasurement backgrounds

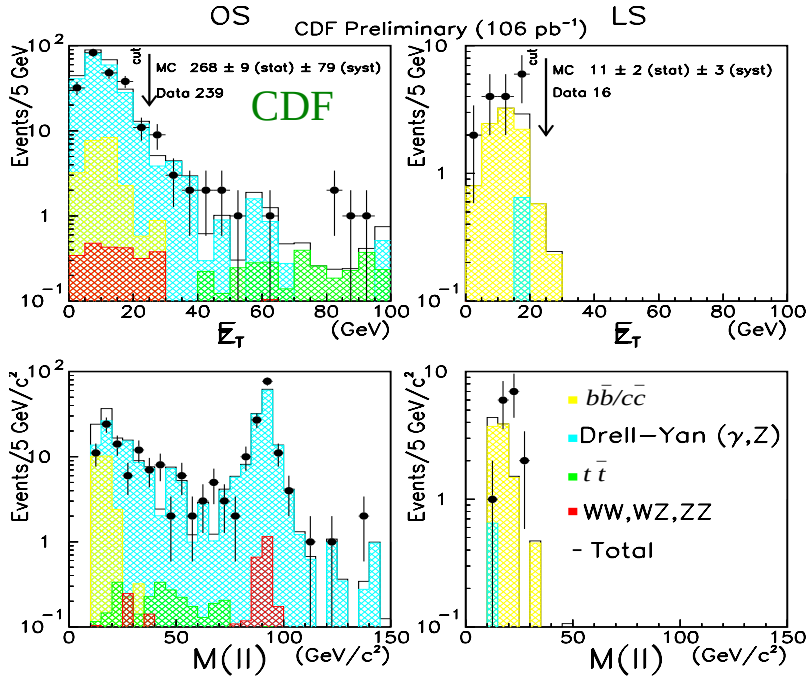
81 events were observed compared with 87.3±8.8 expected from background processes dominated by W+jets, tt, bb and fakes

Unbinned likelihood fit to kinematic distributions to extract potential stop signal. Results are consistent with no stop production





Dilepton (±±) from Squarks and Gluinos



Like-sign dileptons are expected from

$$p\bar{p} \rightarrow \tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} \Rightarrow \ell^{\pm}\ell^{\pm} jj \not{E}_T + X$$

1) $2\ell^{\pm}\ell^{\pm}$ with $E_T > 11{,}5$ GeV
2) ≥ 2 jets with $E_T > 15$ GeV
3) dilepton mass cut
4) $\not{E}_T > 25$ GeV

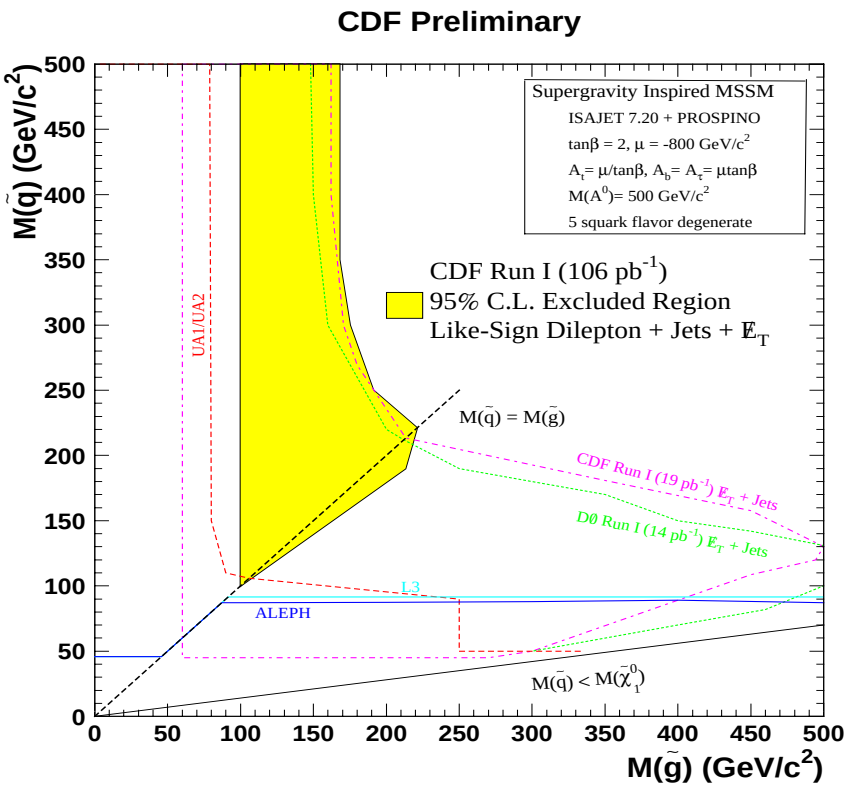
Backgrounds:

- **Drell-Yan**
- **heavy quarks**
- **dibosons**

No like-sign events were observed while 0.6±0.3 events were expected from known processes.

19 opposite-sign events passed the similar selection.

The null results is used to constrain squark/gluino production within the SUGRA-inspired MSSM and assuming 5 degenerate squarks.
The efficiency for the signal is about 1%.

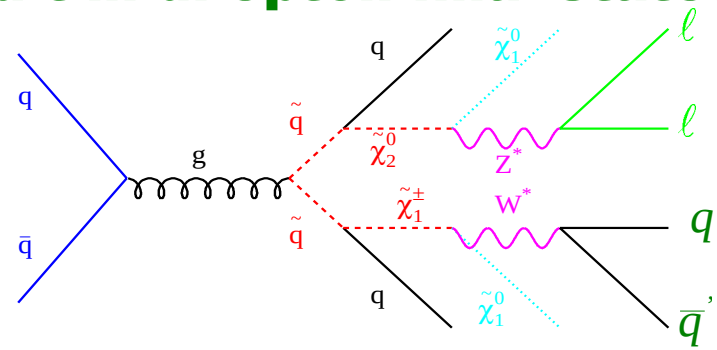


Dilepton from mSUGRA

Squarks and gluinos can also result in dilepton final states

$$p\bar{p} \rightarrow SUSY \Rightarrow \ell\ell jj + \not{E}_T$$

1) two leptons (e, μ) with varying E_T cut
2) two or three jets with varying E_T cut
3) missing E_T greater than 20 or 30 GeV



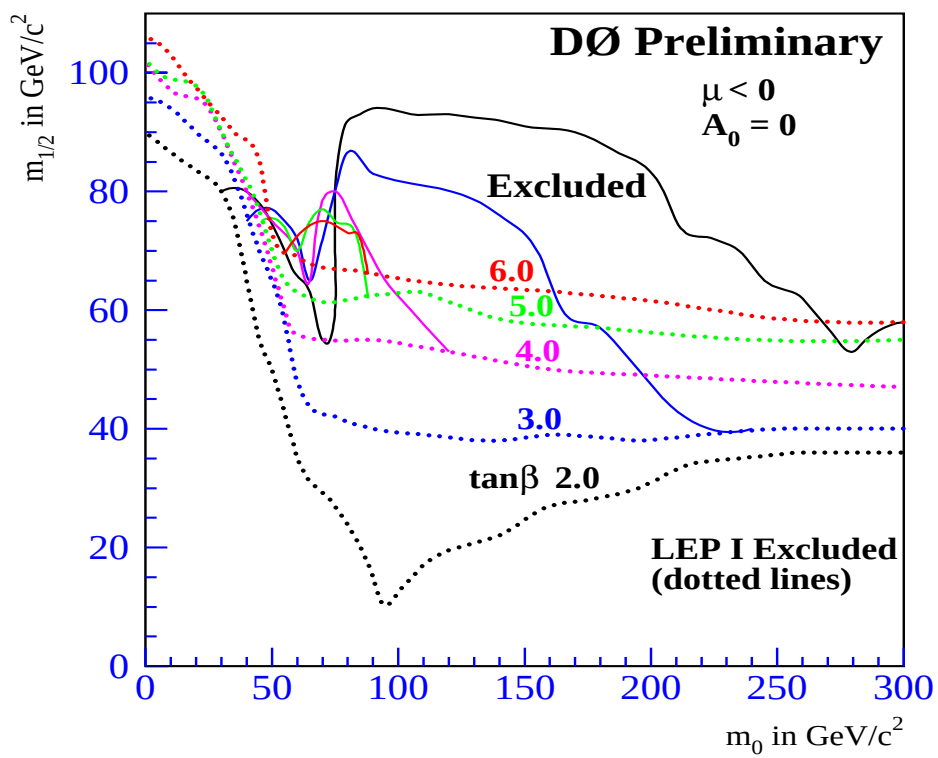
Event selection was optimized for different point in the mSUGRA parameter space.
However typically εB~0.05%

The background sources
- **Z and ttbar production**
- **instrumental backgrounds**

The numbers of observed events are consistent with those expected from background processes

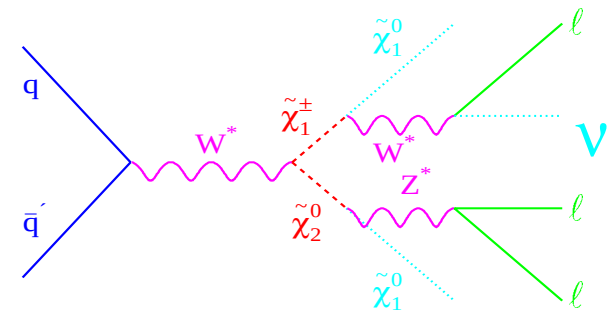
The null results are interpreted within the mSUGRA framework

95% C.L. Excluded Region



Charginos and Neutralinos

Production of $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ will lead to trilepton events with $\not{E}_T$, one of the cleanest signature for supersymmetry



Both CDF and DØ searched for trilepton (e, μ) events in RunI

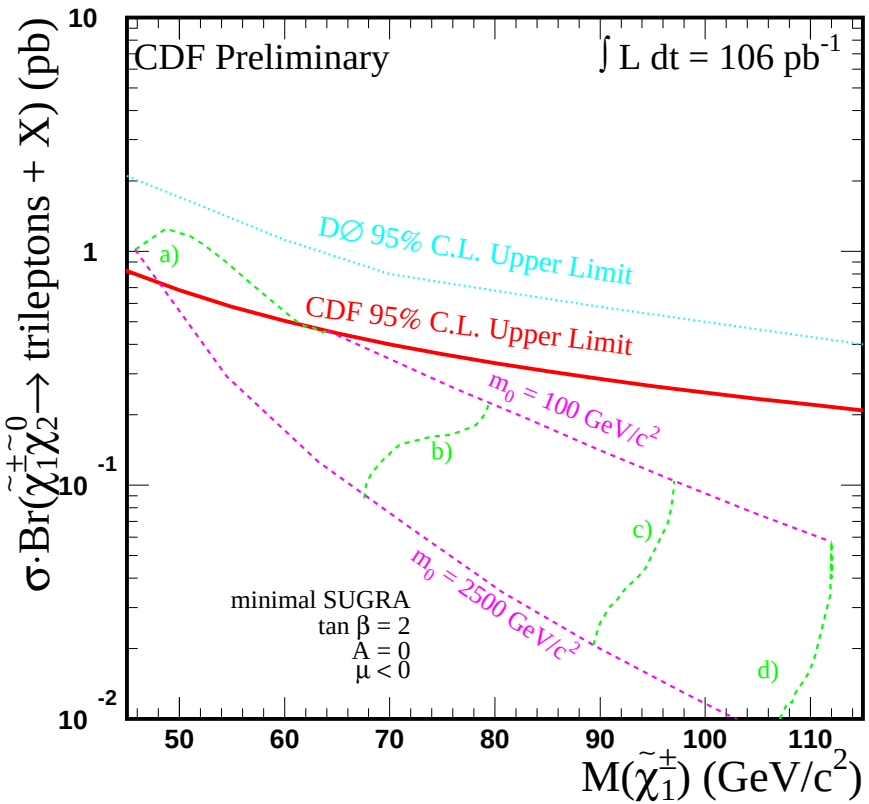
PRL 80, 1591 (1998); 80, 5275 (1998)

1) $\geq 3\ell$ (e, μ) with $E_T > 5-11$ GeV
2) require e^+e^- or $\mu^+\mu^-$ (CDF only)
3) $\not{E}_T > 10-15$ GeV
4) $\ell\ell$ topology and mass cuts

No events were observed in either experiment. CDF expected to see 1.2±0.2 events while DØ estimated to have 1.3±0.4 events from background processes

The null results were interpreted in the framework of MSSM models which give $m_{\tilde{\chi}_1^{\pm}} \approx m_{\tilde{\chi}_2^0} \approx 2m_{\tilde{\chi}_1^0}$

The efficiency is typically 3-12% for CDF and 2-6% for DØ when chargino mass is varied from 50 to 100 GeV



Single-Photon Final State

DØ (99 pb^{-1}) searched for single-photon events with two or more jets and large missing E_T

Phys. Rev. Letters 82, 29 (1999)

Within the MSSM, the radiative decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \gamma$ dominates in some regions of parameter space

1) $E_T^\gamma > 20$ GeV, $|\eta^\gamma| < 1.1$ or $1.5 < |\eta^\gamma| < 2.5$
2) ≥ 2 jets with $E_T^j > 15$ GeV, $|\eta^j| < 2.0$
3) H_T and $\not{E}_T$ requirements to reduce backgrounds

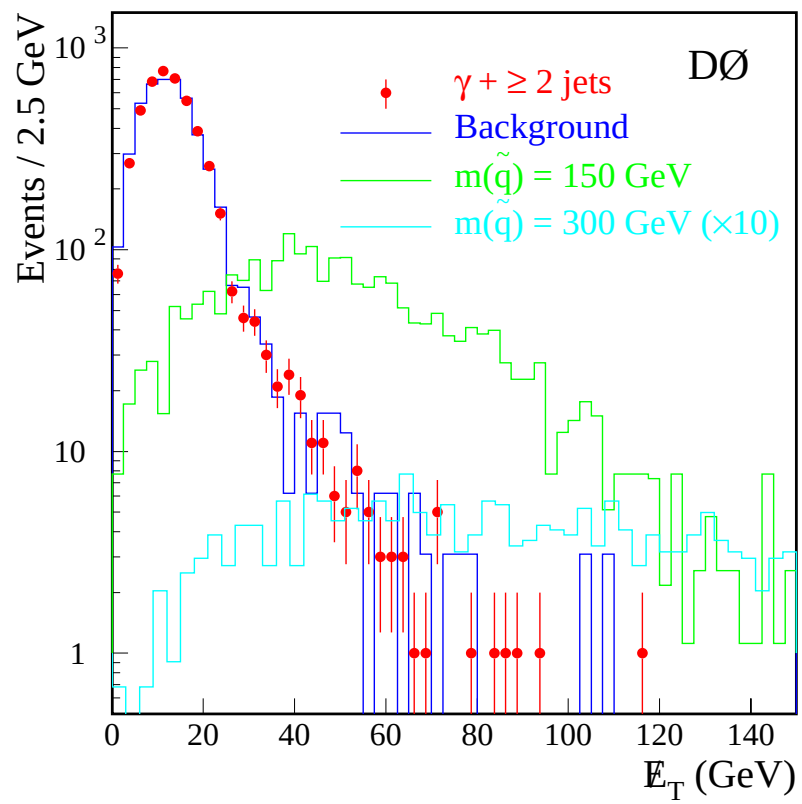
Production of supersymmetric particles at Tevatron would lead to anomalous events of photons with large missing E_T

Major background from missing E_T mismeasurement

The missing E_T distributions of signal and control samples agree very well

For mEt>25 GeV, 318 events were selected with 320±20 events expected

The null results are interpreted assuming $p\bar{p} \to \tilde{q} / \tilde{g} \Rightarrow \tilde{\chi}_2^0 + X \Rightarrow \gamma j j \not{E}_T + X$



Dilepton (±±) from R-parity Violations

Like-sign dileptons are expected from

$$p\bar{p} \to \tilde{g}\tilde{g} \to (\bar{c}\tilde{c}_L)(\bar{c}\tilde{c}_L) \Rightarrow \bar{c}\bar{c}(e^{\pm}d)(e^{\pm}d)$$

$$p\bar{p} \to \tilde{q}\bar{\tilde{q}} \to (\bar{q}\tilde{\chi}_1^0)(q\tilde{\chi}_1^0) \Rightarrow q\bar{q}(q\bar{q}'e^{\pm})(q\bar{q}'e^{\pm})$$

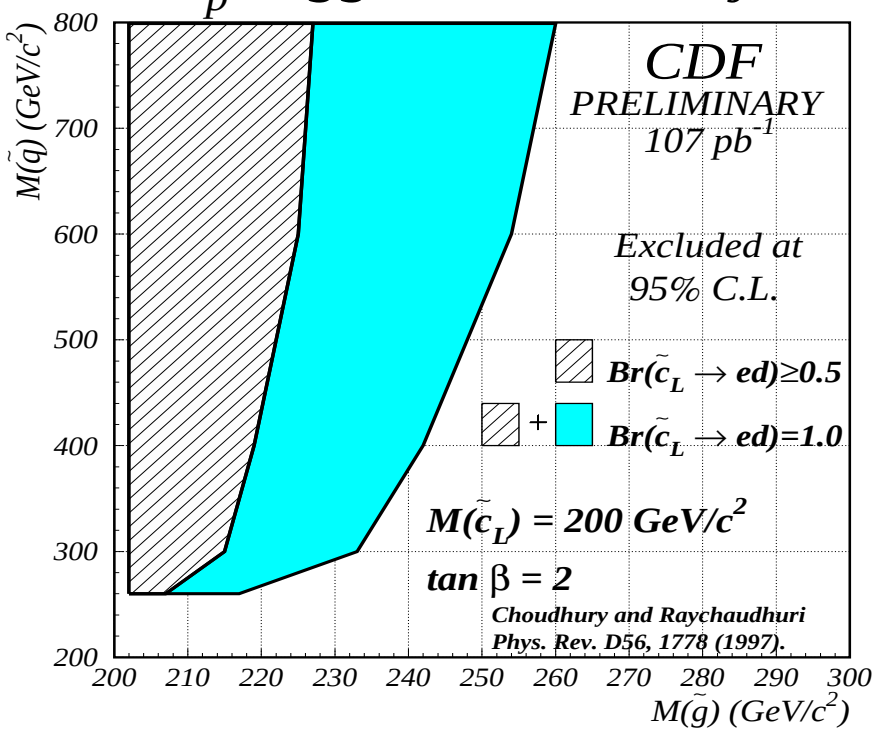
CDF: Phys. Rev. Lett. 83, 2133 (1999)

1) $e^{\pm}e^{\pm}$ with $E_T > 15$ GeV
2) ≥ 2 jets with $E_T > 15$ GeV
3) no significant $\not{E}_T$

No event observed while 0.3±0.3 background events expected

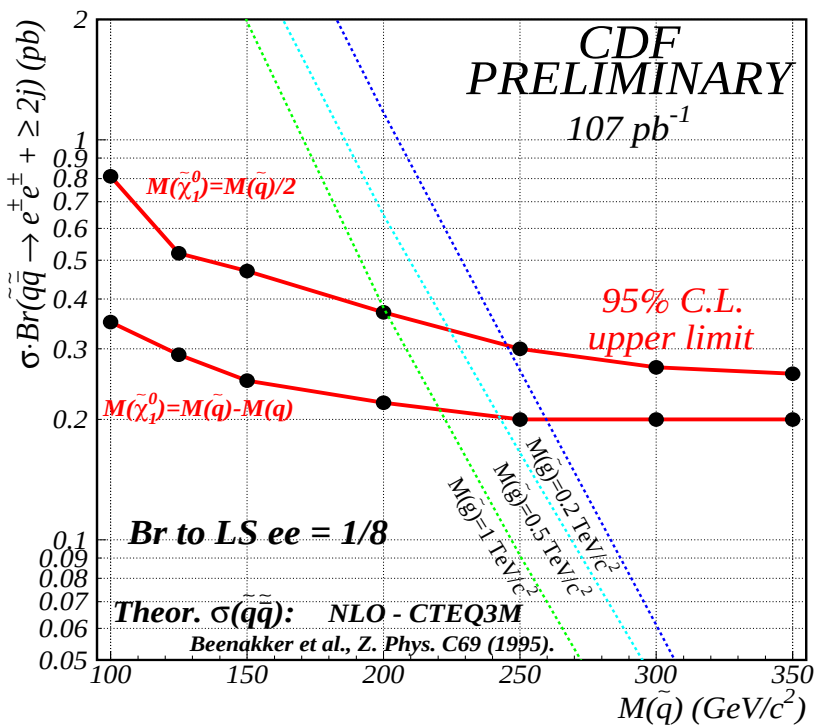
Motivated in part by HERA excess and probes λ'_{121} R-parity violating coupling

$$\not{R}_p \quad \tilde{g}\tilde{g} \to e^{\pm}e^{\pm} + \geq 2j$$



$$M(\tilde{\chi}_1^{\pm}) > M(\tilde{q}) > M(\tilde{\chi}_1^0)$$

$$\not{R}_p \quad \tilde{q}\bar{\tilde{q}} \to q\,\tilde{\chi}_1^0\,\bar{q}\,\tilde{\chi}_1^0 \to e^{\pm}e^{\pm} + \geq 2j$$

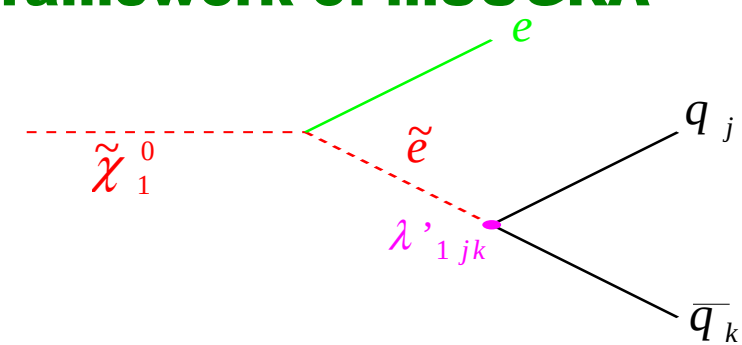


Dilepton from R-parity Violations

Dzero Studied the case that all RPV couplings are small except λ'_{1jk} within the framework of mSUGRA

DØ: Phys. Rev. Lett. 83, 4476 (1999)

$$p\bar{p} \rightarrow SUSY \Rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow eejjjj$$

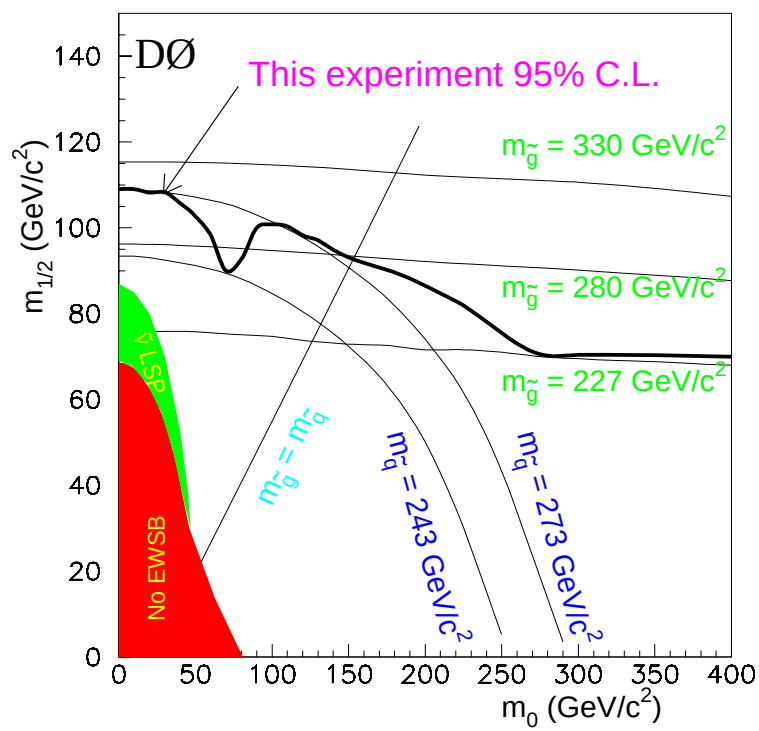


1) $E_T^{e1} > 15$ GeV, $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$
2) $E_T^{e2} > 10$ GeV, $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$
3) ≥ 4 jets with $E_T^j > 15$ GeV, $|\eta| < 2.5$
4) M_{ee} not consistent with M_Z

Backgrounds are dominated by Drell-Yan process and mismeasurement

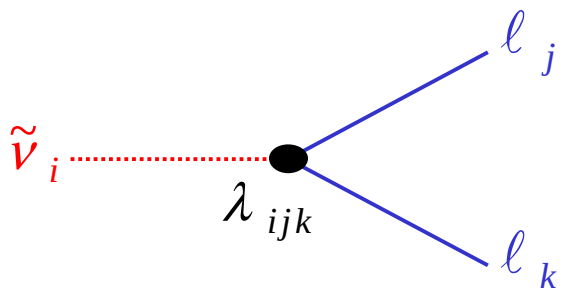
Two events observed with 1.8±0.4 events expected from backgrounds

The analysis assumes $\tilde{\chi}_1^0$ LSP and only the LSP decays through R-parity violating interactions



Trilepton from R-parity Violations

The lepton number violating terms in the R-parity violating Lagrangian will result events with four-leptons



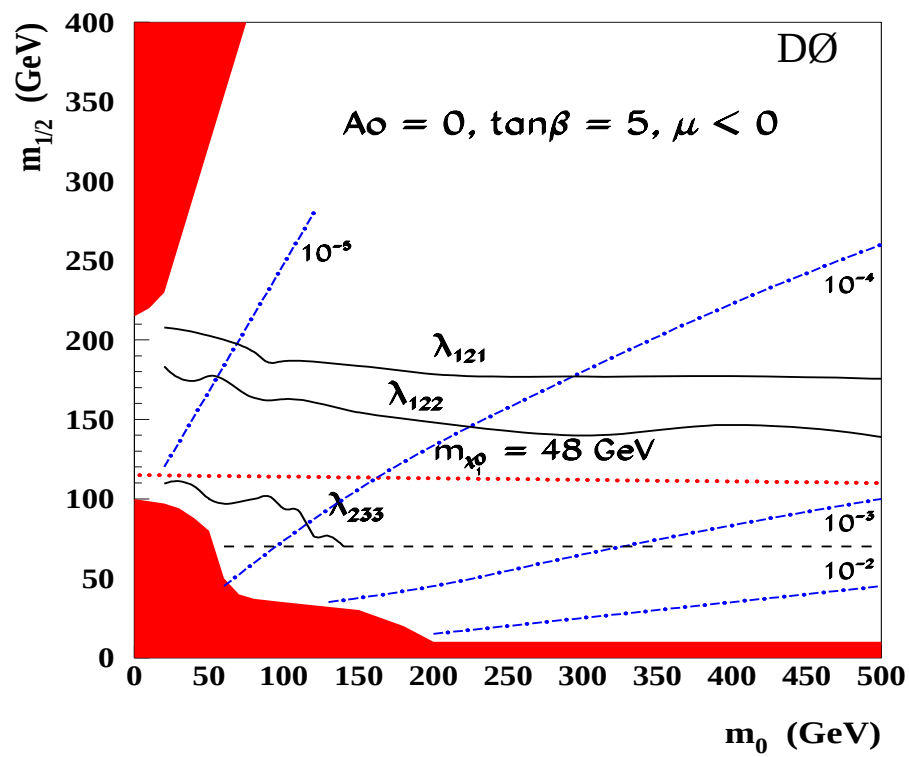
DØ has reinterpreted the trilepton analysis of charginos and neutralinos searches in the RPV framework

The analysis assumes

1) $\tilde{\chi}_1^0$ is the LSP
2) the LSP decays through RPV

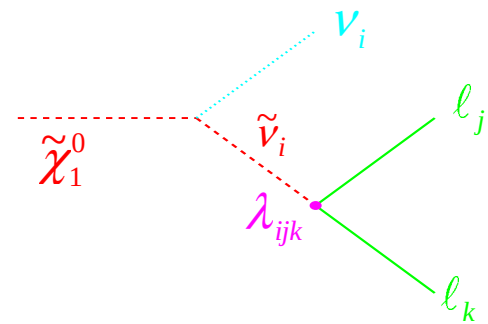
The analysis is sensitive to
1) the 1st and 2nd lepton family
2) couplings $10^{-4} < \lambda_{ijk} < 10^{-3}$

The sensitivity is measured using mSUGRA model assuming R-parity violations



Four-lepton from R-parity Violations

CDF searched four-lepton events from R-parity violating process with a dominant λ_{121} in the mSUGRA framework



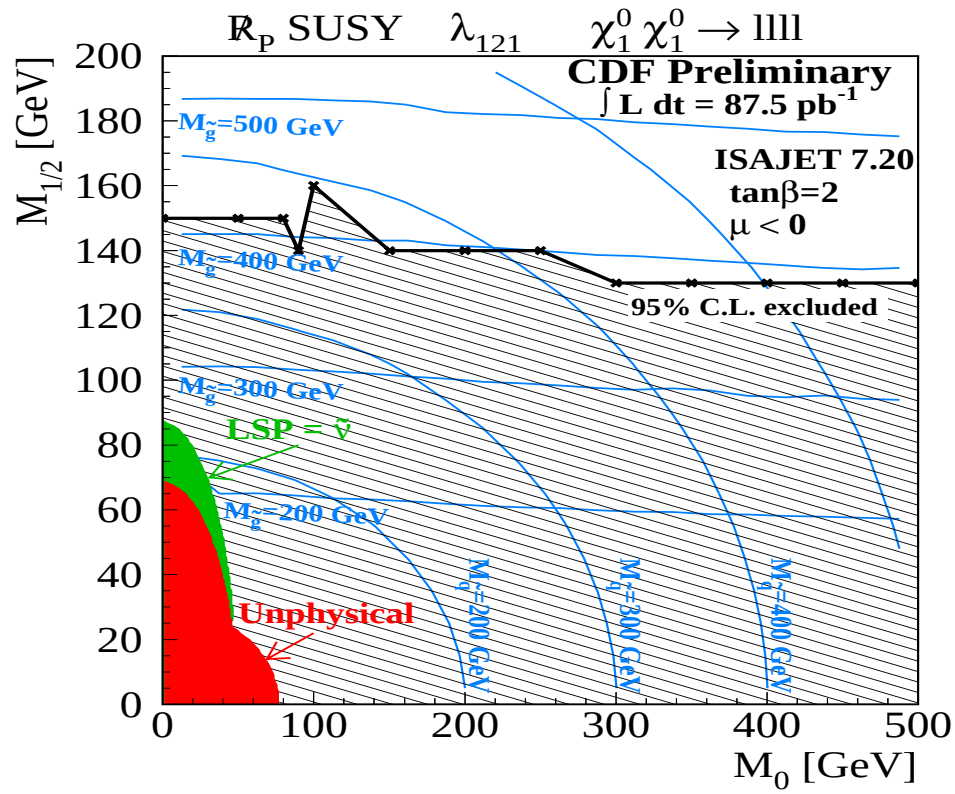
$$p\bar{p} \to SUSY \Rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \ell\ell\ell\ell + X$$

1) $E_T^{\ell} > 12,5,5,5$ GeV
2) $\Delta R^{\ell\ell} > 0.4$

One event observed while 1.3±0.4 events expected from SM (bb,cc,...) and instrumental backgrounds

There were 185 tri-lepton events in the data

Efficiency for the signals varies between 10–20% for most of the parameter space of interest

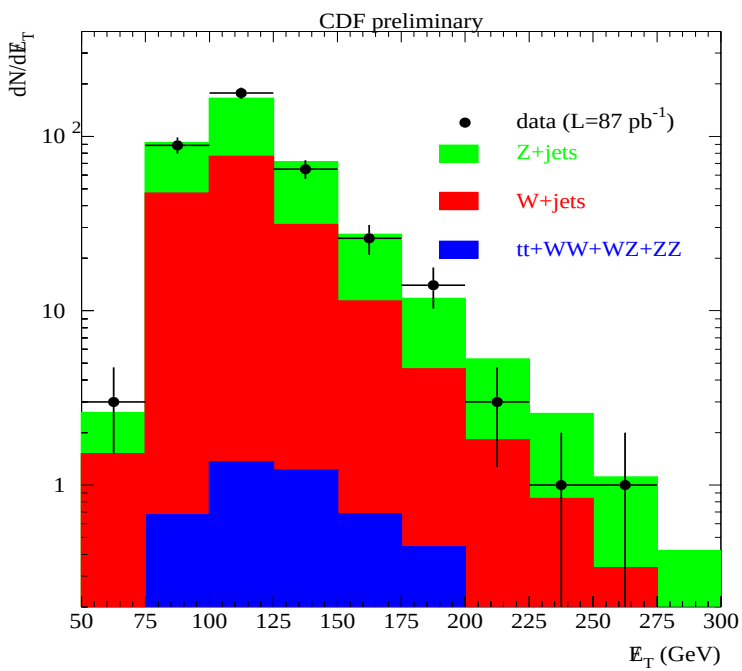


Monojet from Gravitino Production

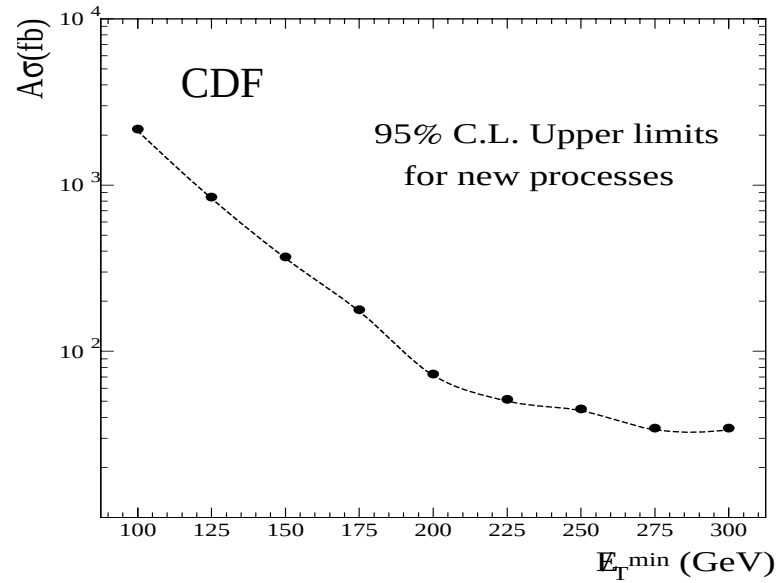
If the gravitino is light and all other super-partners are heavy, it could be the only super-partner produced at Tevatron, resulting monojet events with large mEt

$$q\bar{q} \to \tilde{G}\tilde{G}g$$
$$qg \to \tilde{G}\tilde{G}q$$
$$gg \to \tilde{G}\tilde{G}g$$

1) leading jet with $E_T > 80$ GeV
2) at least one central jet with $E_T > 10$ GeV
3) $\not{E}_T > 50$ GeV
4) no high p_T leptons
5) topological cuts to reduce mismeasurement backgrounds



Backgrounds are dominated by W/Z+jets production. No excess was observed.



19 events were observed with mEt>175 GeV while 22 were expected. This leads to

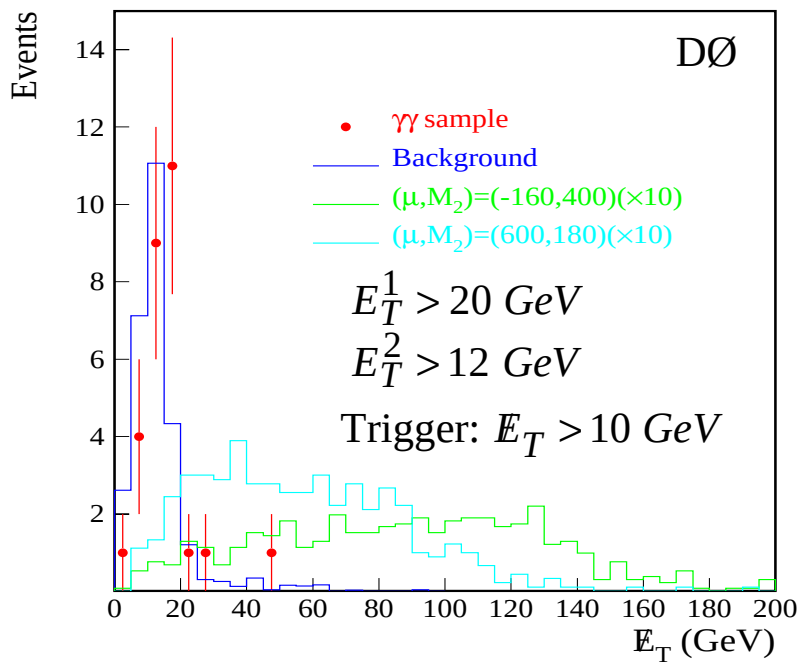
$$\sqrt{F} > 217 \text{ GeV} \Rightarrow m_{\tilde{G}} \geq 1.1 \times 10^{-5} \text{ eV}$$

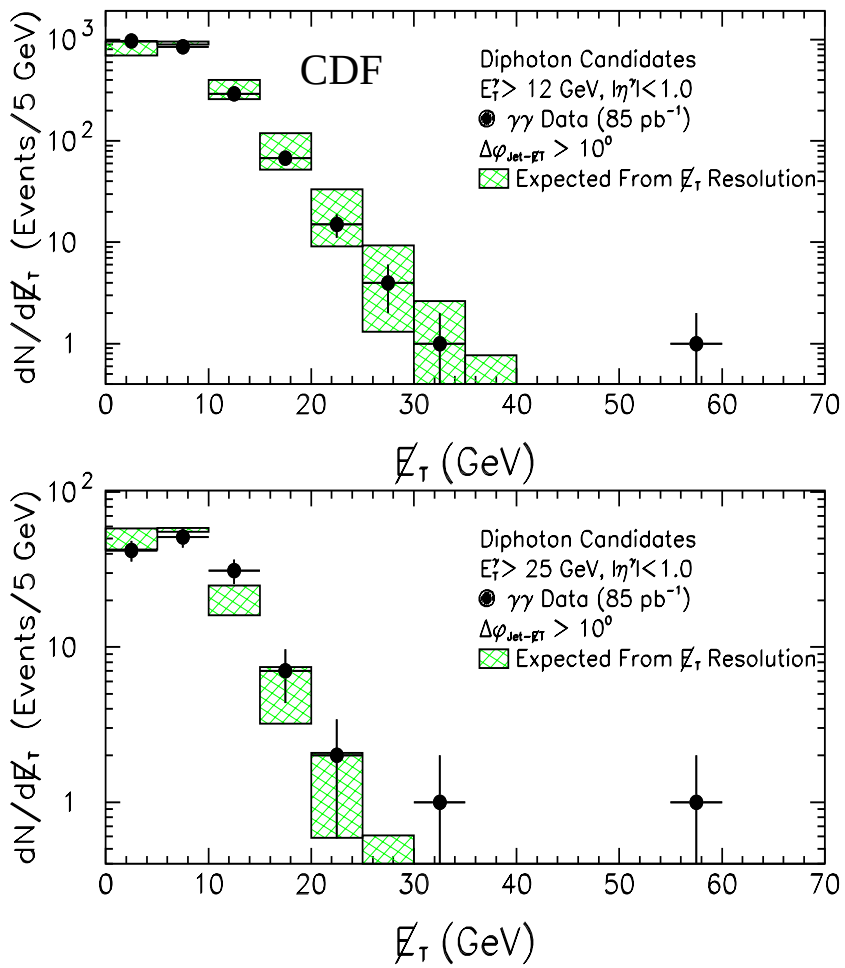
Diphoton from Neutralino Decays

Both CDF and Dzero searched for $p\bar{p} \to \gamma\gamma \not{E}_T + X$ events and no significant excess was found

CDF: PRD 59, 092002 (1999) DØ: PRL 80, 442 (1998)

They are expected from $p\bar{p} \to SUSY \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X$ with $\tilde{\chi}_1^0 \to \gamma + \tilde{G}$ decays

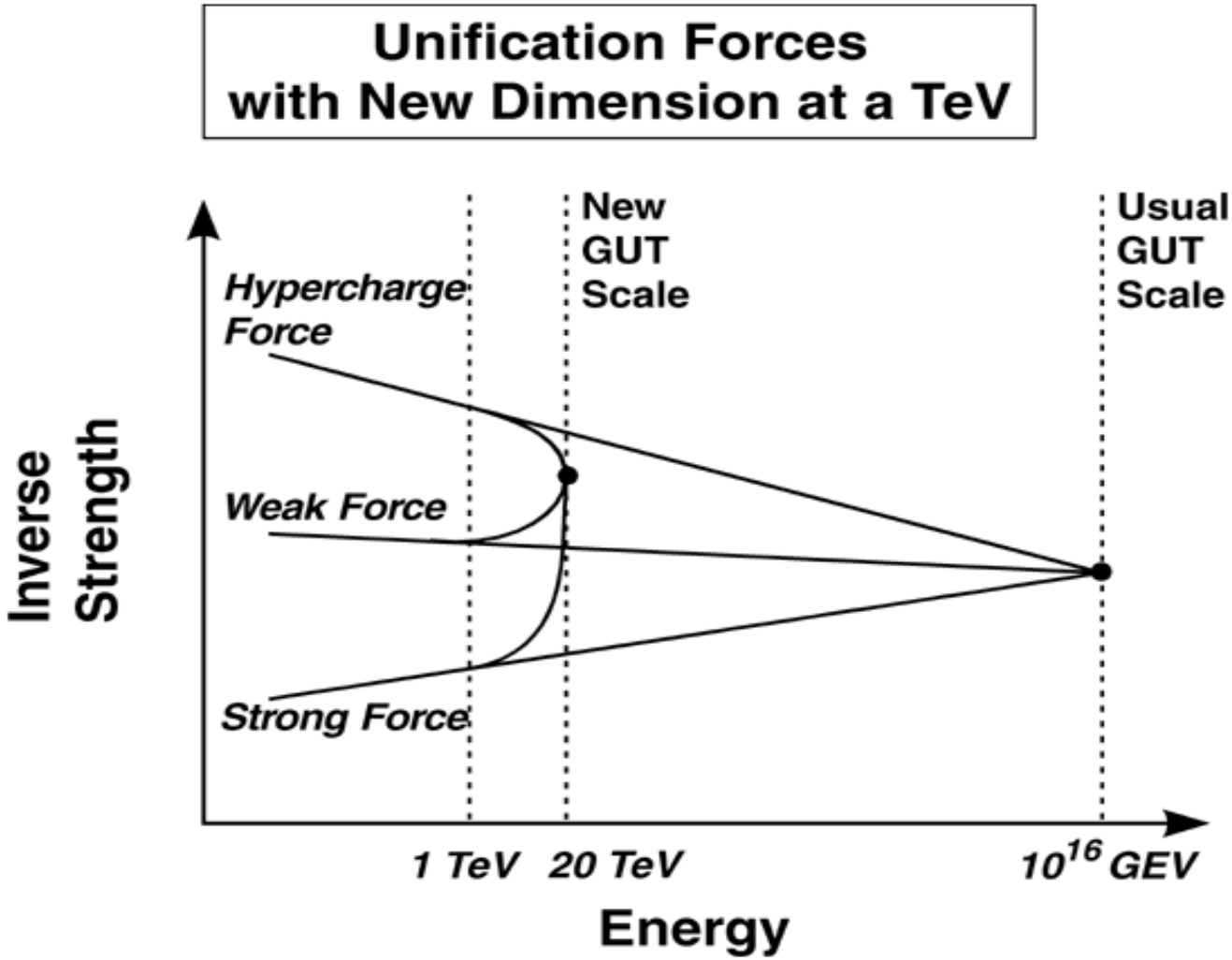




Events with two photons and large missing E_T are rare

Large Extra Dimensions

The large extra dimensions are introduced to solve the hierarchy problems of the standard model by effective lowering the Planck scale



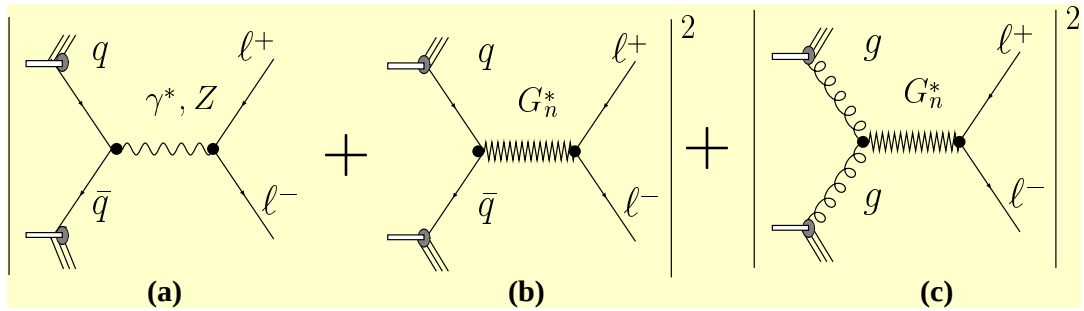
Compactification radius

$$R \propto \frac{1}{M_S}\left(\frac{M_{Pl}}{M_S}\right)^{\frac{2}{n}}$$

n: # of extra dimensions
M_{Pl}: Planck scale
M_S: effective Planck scale

Dielectron and Diphoton Final State

The existence of large extra dimensions will modify both the mass and the angular distributions of dilepton and diphoton events



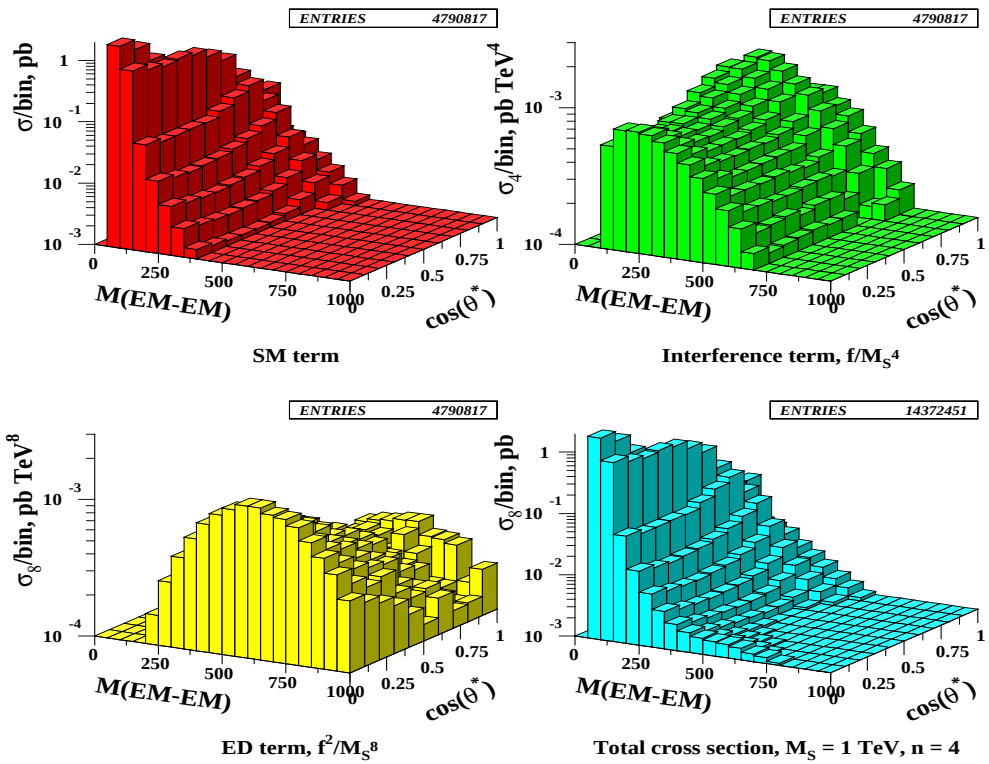
DØ has searched for virtual graviton effects in the final state with two electromagnetic clusters, combining dielectron and diphoton final states in the analysis to eliminate cross Misidentifications between electrons and photons

$$p\bar{p} \rightarrow (ee, \gamma\gamma) + X$$

$$\frac{d^2\sigma}{dM\, d\cos\theta^*} = f_{SM}(M, \cos\theta^*) + f_{\text{int}}(M, \cos\theta^*)\eta + f_{KK}(M, \cos\theta^*)\eta^2$$

where $\eta = \dfrac{F}{M_S^4}$

MC Simulation of the ED signatures



Selection of Di-EM Final State

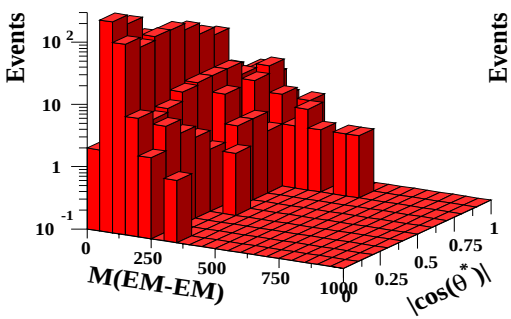
1) two electromagnetic clusters with $E_T > 45$ GeV, $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$
2) $\not{E}_T < 25$ GeV

The non-separation between electrons and photons yield very high efficiency (79%) for di-EM final states

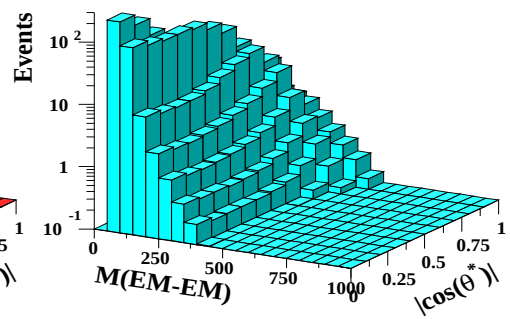
1282 events were selected from a sample of 127 pb^{-1}

Background sources:
- **Drell-Yan dielectron**
- **$\gamma\gamma$ production**
- **instrumental**

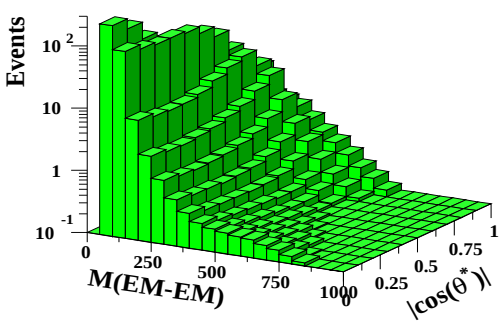
DØ (2000), Run I, 127 pb^{-1}



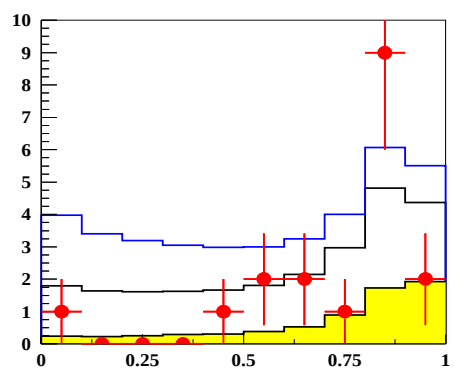
Data



Total background

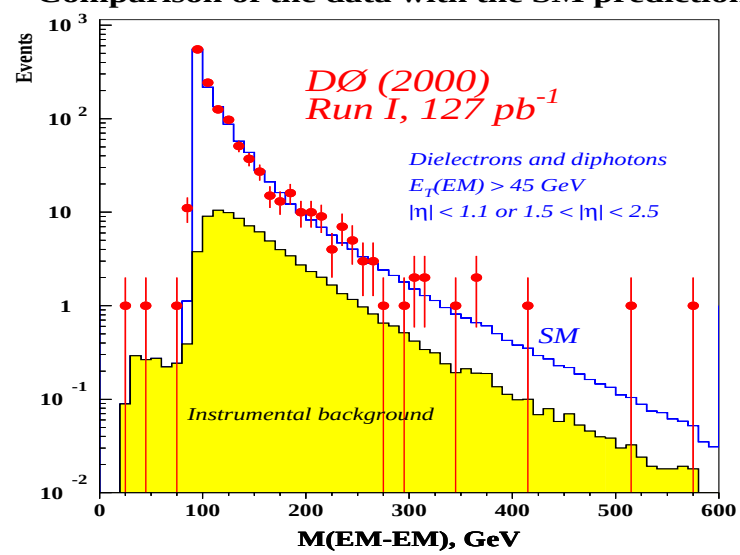


SM+ED signal, M_S = 1 TeV, n = 4



$|\cos(\theta^*)|$, M(EM-EM) > 250 GeV

Comparison of the data with the SM predictions



Limits on LED Scale

The kinematic distributions of di-EM final states are well described by the sum of the SM and instrumental backgrounds

No evidence for large extra dimensions

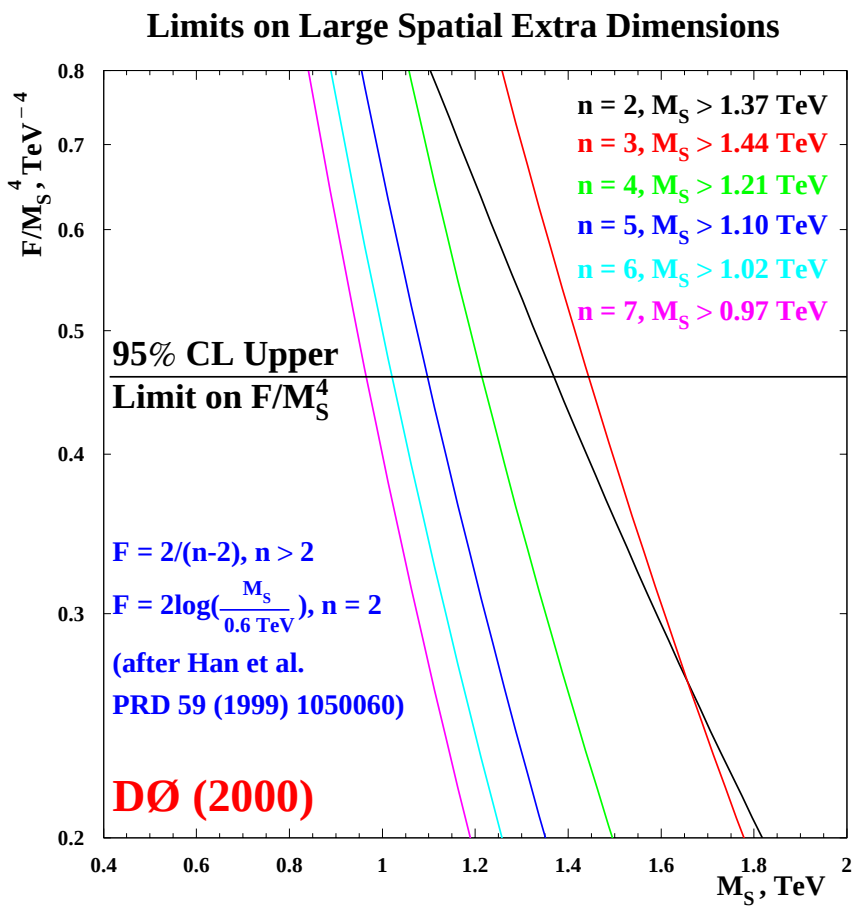
The leading-order distributions were augmented with

- **initial state radiation effect with a transverse kick**
- **K-factor correction to account for the NLO effect.**

The total systematic error is estimated to be about 19%.

Binned maximum likelihood fit to extract the limits.

$M_S > 1.4$ TeV (n = 2)
1.4 TeV (n = 3)
1.2 TeV (n = 4) @ 95% C.L.



Squark and Gluino in Run II

Squarks and gluinos will remain to be copiously produced if kinematically accessible

- Though leptonic events are also expected, the final state with multijet and large mEt remains to the dominant signature of squark and gluino production except for isolated regions of SUGRA parameter space.

- For large tanβ values, gluino, chargino and neutralino decays to third generation particles are significantly enhanced.

- Better understanding of mEt tail of multijet events and developing a robust method to accurately estimate multijet backgrounds are critical for squark and gluino searches in Run II.

- It is important to have good tau-lepton and b-quark trigger and identification capabilities.

Run II improvements:

1) mEt resolution improvement
   - more hermetic detector (CDF)
   - better vertexing (DØ)
2) Advanced analysis methods and generally improved tools

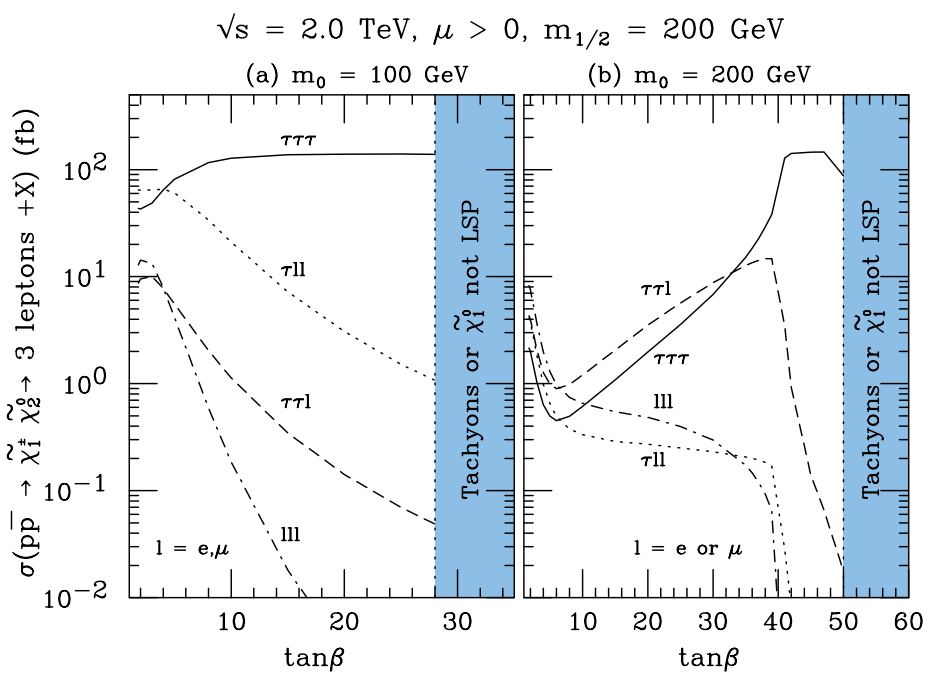
With 2 fb^{-1}, the upgraded Tevatron should be able to probe $m_{1/2}$ up to ~150 GeV, corresponding to a gluino mass of ~400 GeV if m_0<200 GeV

Chargino and Neutralino in Run II

In mSUGRA model, $\tilde{\ell}, \tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0, \tilde{\chi}_2^0$ are typically less massive than $\tilde{q}, \tilde{g}$.

So the $p\bar{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 + X$ production is one of the most promising channels for the searches at Tevatron

At large $\tan\beta$, the lighter tau slepton $\tilde{\tau}_1$ is lighter than $\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}$. Then, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ can dominantly decay into final states with τ via $\tilde{\tau}_1$



The signature is therefore trilepton events with large tau content

Major backgrounds:
- **W+jets, Z+jets, WZ,...**
- **(WZ background is irreducible)**

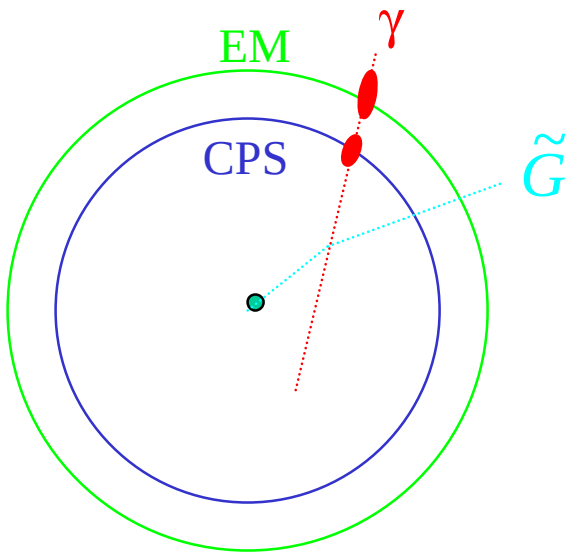
Key to success:
- **large acceptances and high efficiencies for high and low p_T leptons including the tau lepton**

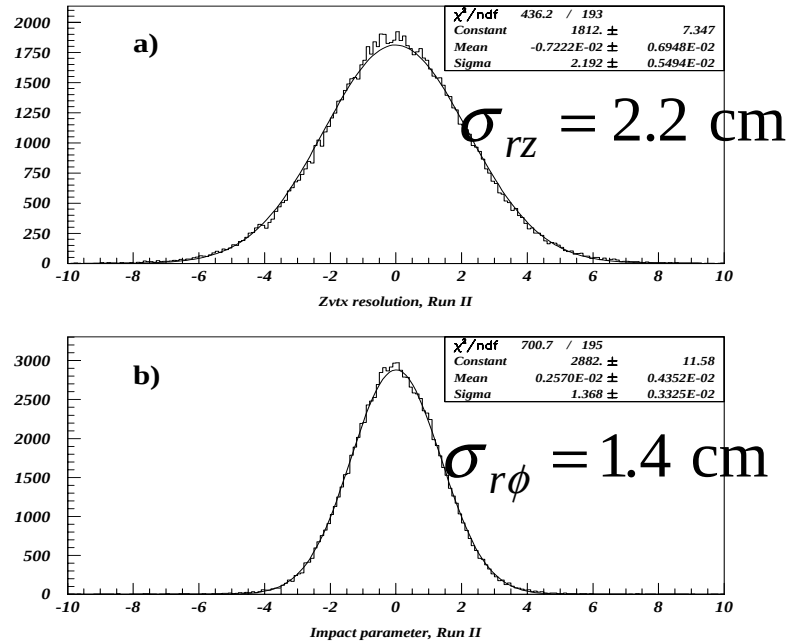
Run II improvements:
1) **extended detector coverage for leptons to improve acceptances**
2) **lepton charge measurement and better muon momentum measurement to reduce backgrounds (DØ)**
3) **major effort on tau identification built upon Run I experiences**

For small to medium values of tanβ values, maximum chargino mass reach of ~200 GeV is achievable at Tevatron Run II

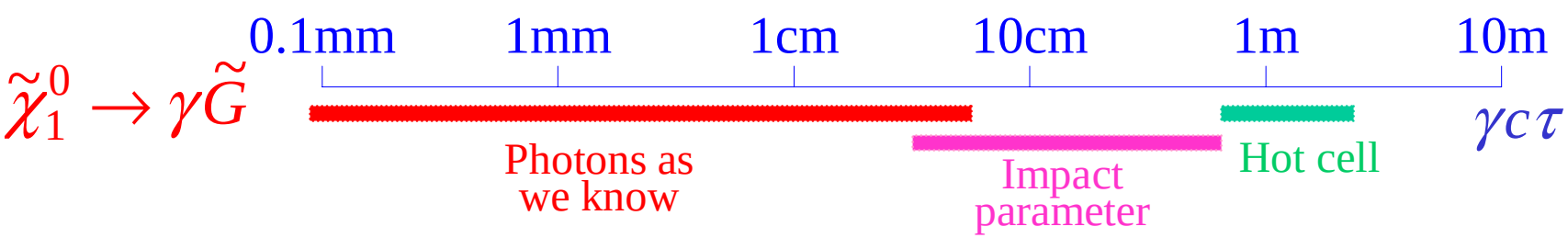
Long-lived Neutralino

The upgraded DØ detector will enable us to identify non-vertex pointing photons by matching clusters in the EM calorimeter and preshower detectors



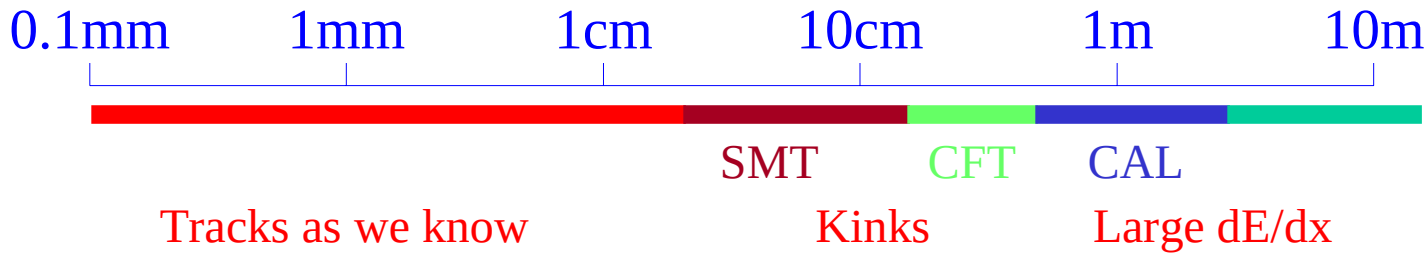


Providing unique tools in searching for long-lived neutralinos



Long-lived Slepton

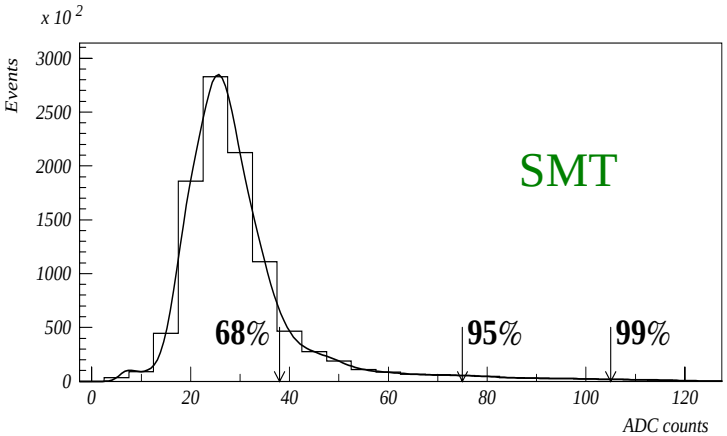
$\tilde{\ell} \rightarrow \ell \tilde{G}$

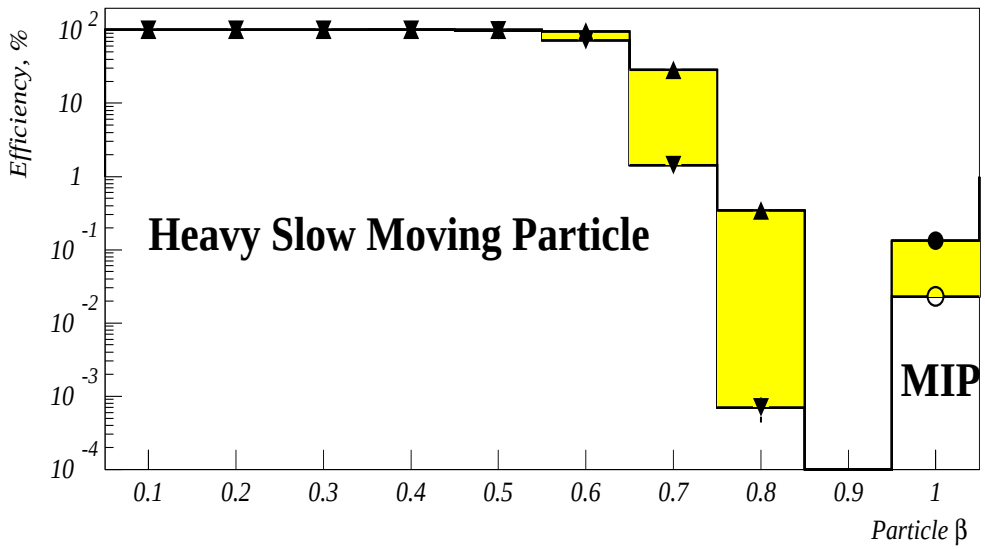


Tools for massive stable charged particles (MSP)

dE/dx information from

1) **Silicon**
2) **Fiber tracker**
3) **Preshowers**
4) **Calorimeter**





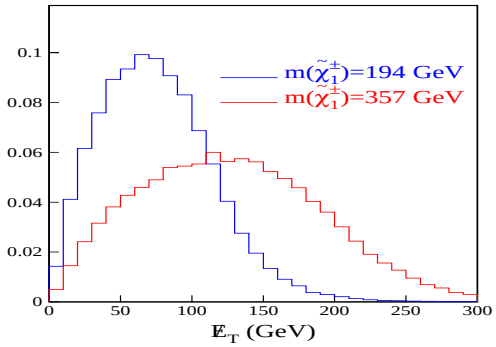
An efficiency of 68% for MSP and a rejection factor of 10 for MIP are assumed

Neutralino as the next LSP

$$p\bar{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0} \to \tilde{\chi}_1^{0}\tilde{\chi}_1^{0} + X$$
$$\Rightarrow \gamma\gamma \not{E}_T + X \text{ (prompt } \tilde{\chi}_1^0 \to \gamma\tilde{G})$$
$$\Rightarrow \gamma jj \not{E}_T + X \text{ (delayed } \tilde{\chi}_1^0 \to \gamma\tilde{G})$$

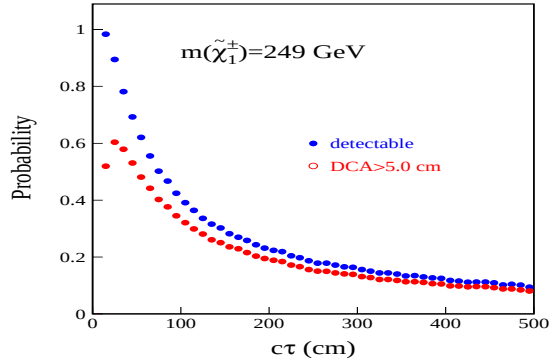
$\gamma\gamma \not{E}_T + X$

- **Cuts: ≥2γ, E_T>20 GeV, $\not{E}_T$>50 GeV**
- **Backgrounds**
  - **0.4 fb (QCD)**
  - **0.2 fb (Fakes)**
- **Efficiency: 15–30%**
- **5σ reach: $M_{\tilde{\chi}_1^{\pm}} < 260$ GeV**

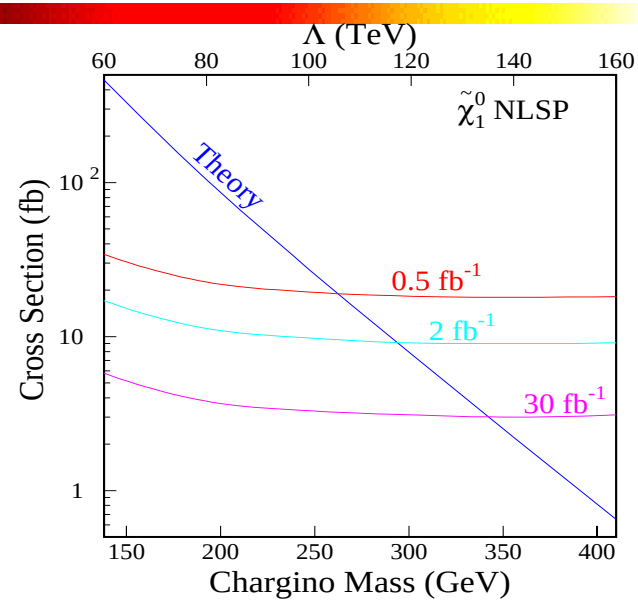


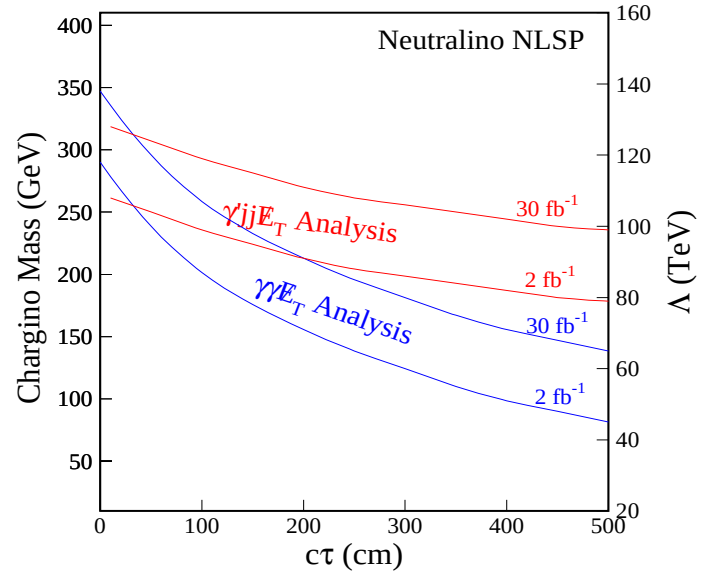
$\gamma jj \not{E}_T + X$

- **Cuts: ≥1γ', E_T>20 GeV, $\not{E}_T$>50 GeV**
- **Backgrounds: 0.3 fb**
- **Efficiencies: varies**

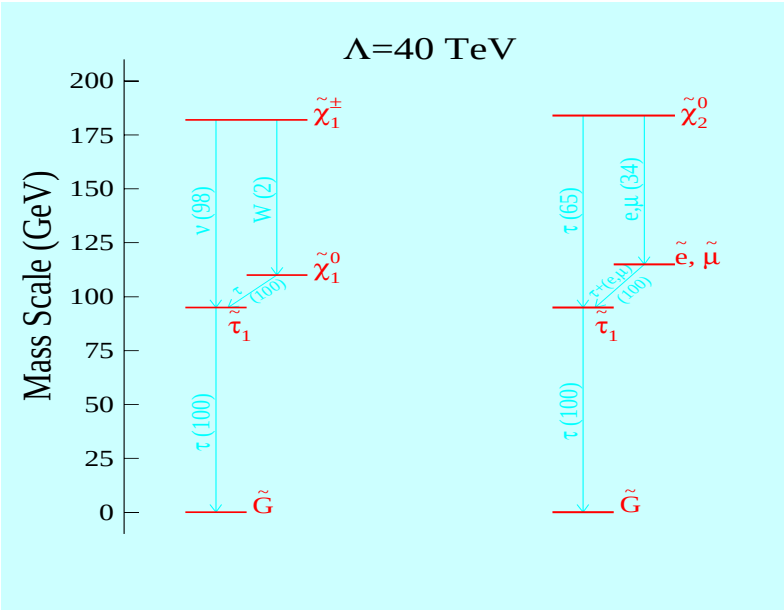


[JQ: hep-ph/9903548]





Stau as the next LSP



Prompt $\tilde{\tau}_1 \to \tau \tilde{G}$

$\ell\ell\ell j \not{E}_T$

Cuts: $p_T^{\ell} > 15,5,5$ GeV, $E_T^j > 20$ GeV, $\not{E}_T > 20$ GeV

$\ell^{\pm}\ell^{\pm} jj \not{E}_T$

Cuts: $p_T^{\ell} > 15$ GeV, $E_T^j > 20$ GeV, $\not{E}_T > 25$ GeV

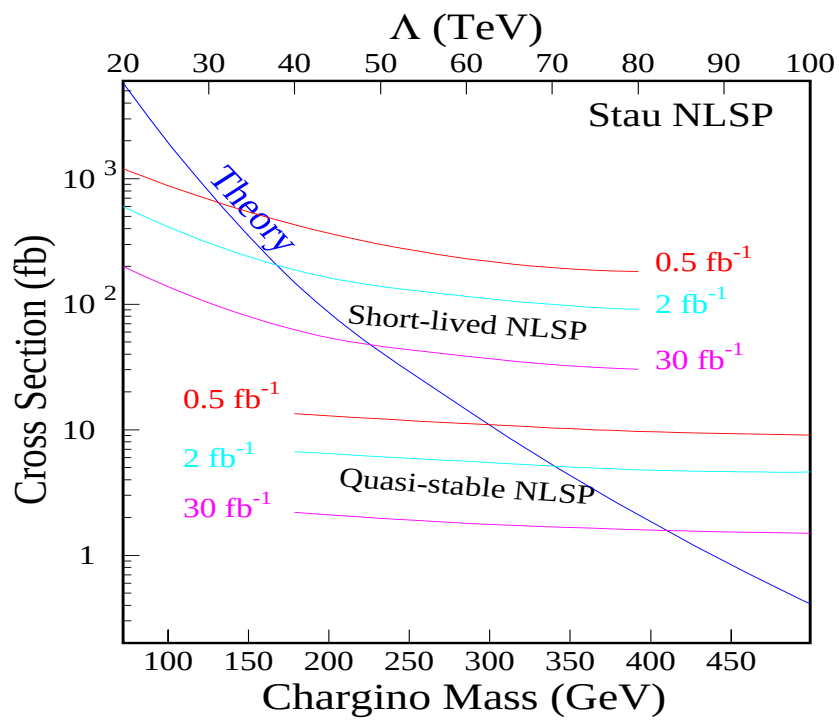
Background: 0.7 fb
Efficiency: 0.5–3.5%

Quasi-stable $\tilde{\tau}_1$

$\ell\ell + dE/dx$

Cuts: $p_T^{\ell} > 50$ GeV, $M_{\ell\ell} > 150$ GeV, dE/dx

Background: 0.5 fb
Efficiency: 35–55%



This scenario should benefit the most
From a robust tau identification

Slepton and Higgsino co-NLSPs

$\tilde{\ell} \rightarrow \ell \tilde{G}$

Prompt: $\ell\ell\ell j \not{E}_T + X$

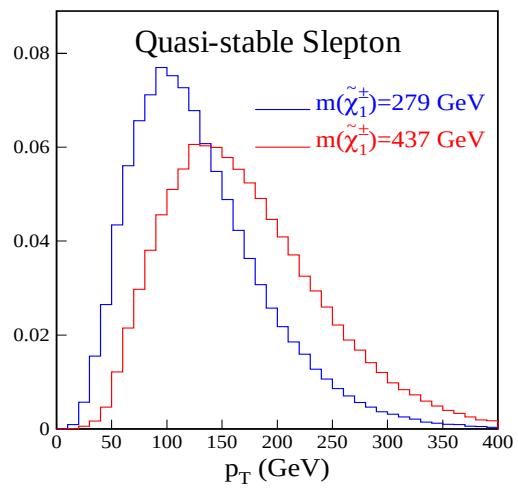
Efficiency: 1-15%

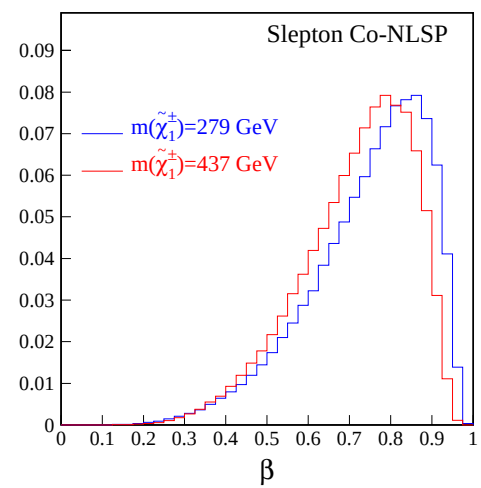
5σ reach: $M_{\tilde{\chi}_1^\pm} < 250$ GeV

Quasi-stable: $\ell\ell + dE/dx$

Efficiency: 30-50%

5σ reach: $M_{\tilde{\chi}_1^\pm} < 330$ GeV





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

$\tilde{\chi}_1^0 \rightarrow h \tilde{G}$

Prompt decay

$\Rightarrow \gamma b j \not{E}_T + X$ events

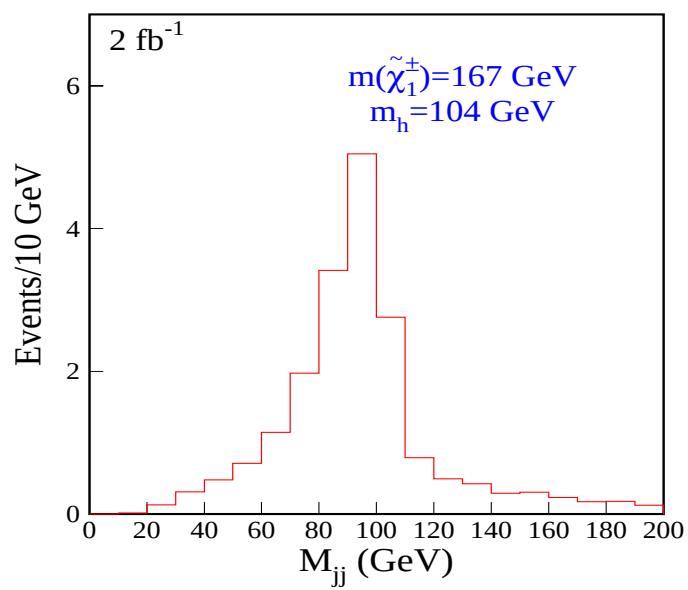
$\geq 1\gamma$ with $E_T > 20$ GeV

≥ 2j with $E_T > 20$ GeV

≥ 1 tagged b-jet

$\not{E}_T > 50$ GeV

Backgrounds: 0.4 fb using $P(j \rightarrow b) = 10^{-3}$

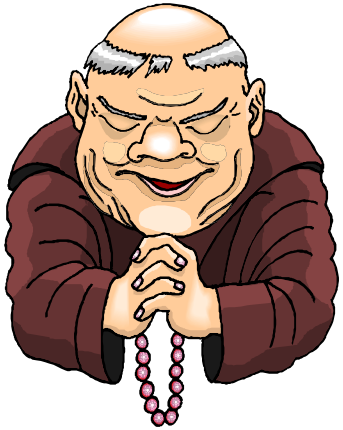


For $\int Ldt = 2$ fb^{-1} and $m_h = 105$ GeV Expect 20 signal events with a few background events

Summary & Outlook

We have carried out extensive searches for physics beyond standard model in Run I. Nothing against or for supersymmetry has been found.

We will continue the searches in Run II and expect to explore gluino mass up to 400 GeV and chargino mass up to 200 GeV.

Supersymmetry may not be the right theory. Hopefully we can discover whatever is new out there in the process.

To make discovery, we need help, not only from theorists, but most importantly from the Nature.