

Supersymmetry at the Tevatron

Results from Run I

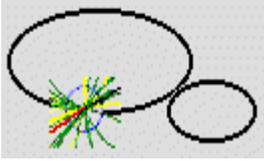
Jianming Qian

The University of Michigan

(for the CDF and DØ Collaborations)

- Introduction
- Searches for Charged Higgs Bosons
- Searches with R-parity Conservation
- Searches with R-parity Violation
- GMSB Supersymmetry Searches

Supersymmetry'99 — Fermilab, June 14, 1999

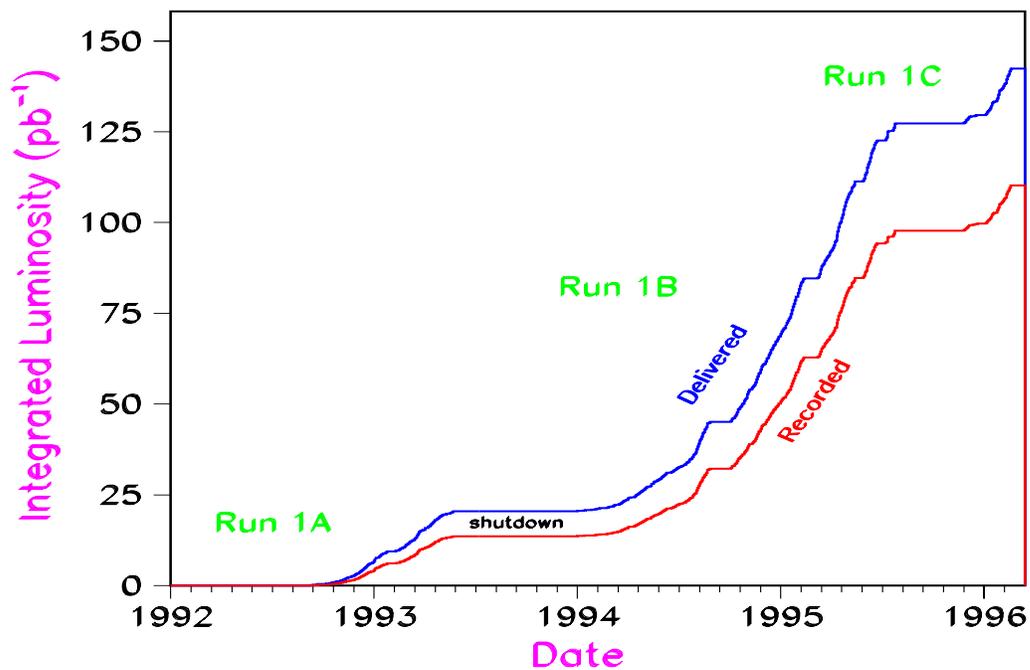


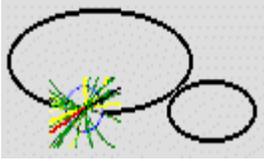
Tevatron Run I Collider



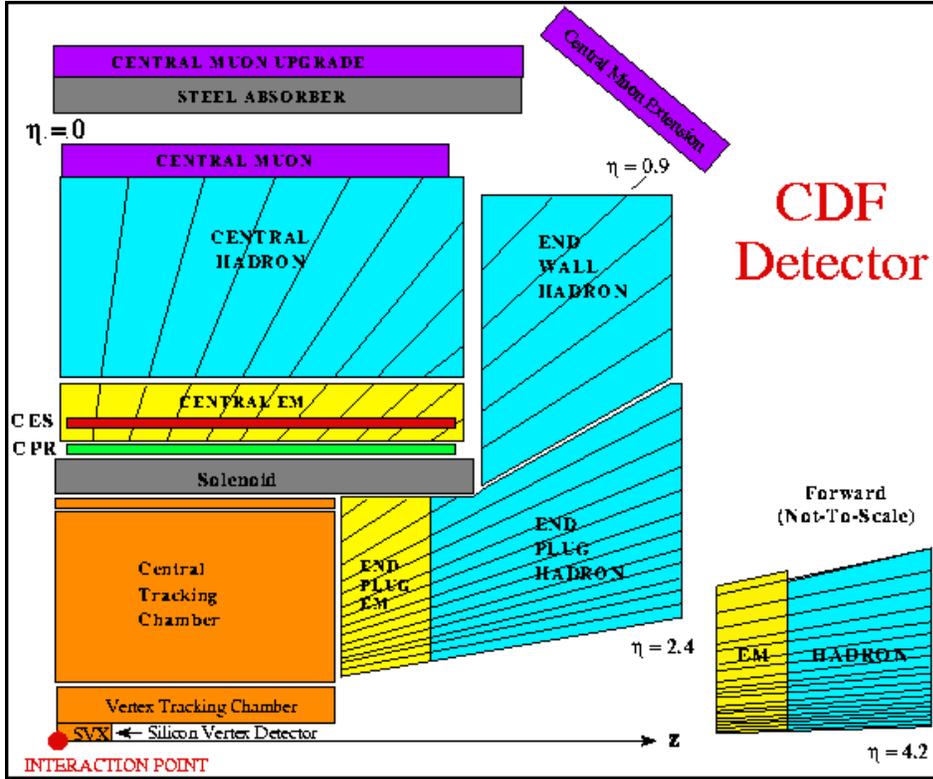
An integrated luminosity of about 100 pb^{-1} was recorded per detector at $\sqrt{s} = 1.8 \text{ TeV}$

DØ Run I Integrated Luminosity

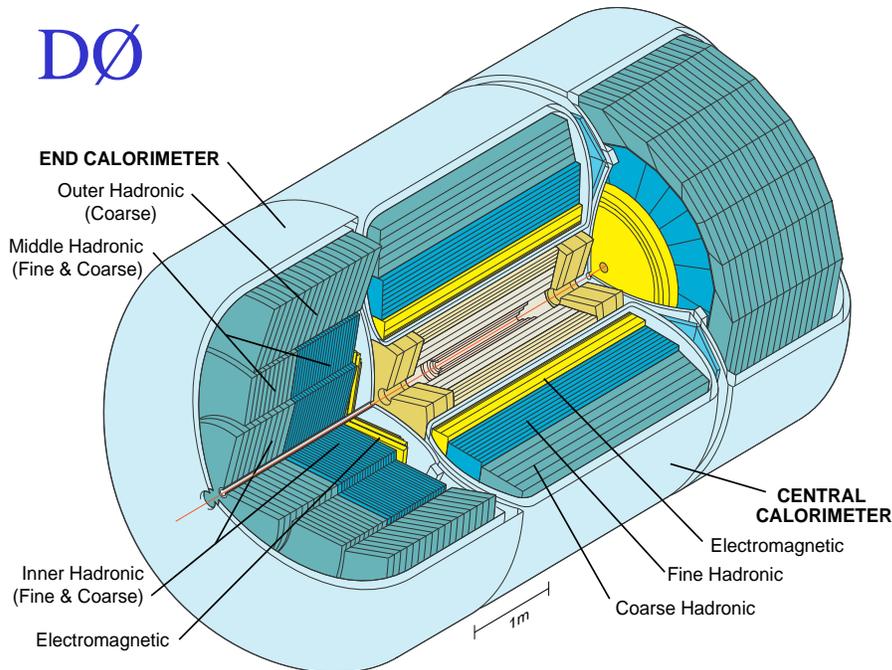




Run I Detectors

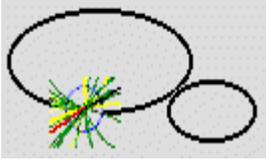


DØ



Calorimeter

$e/\gamma E_T$



Supersymmetry Menu

A lot has been done and published,
~8 publications for CDF and ~11 for DØ

But none is what we have wanted...

The lightest supersymmetric particle (LSP)
is assumed to be
either the lightest neutralino and a light gravitino

Searches with R-parity conservation

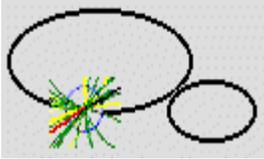
jets
dilepton+jets
trilepton
photonic signatures

Searches with R-parity violation

dilepton+jets
four-lepton

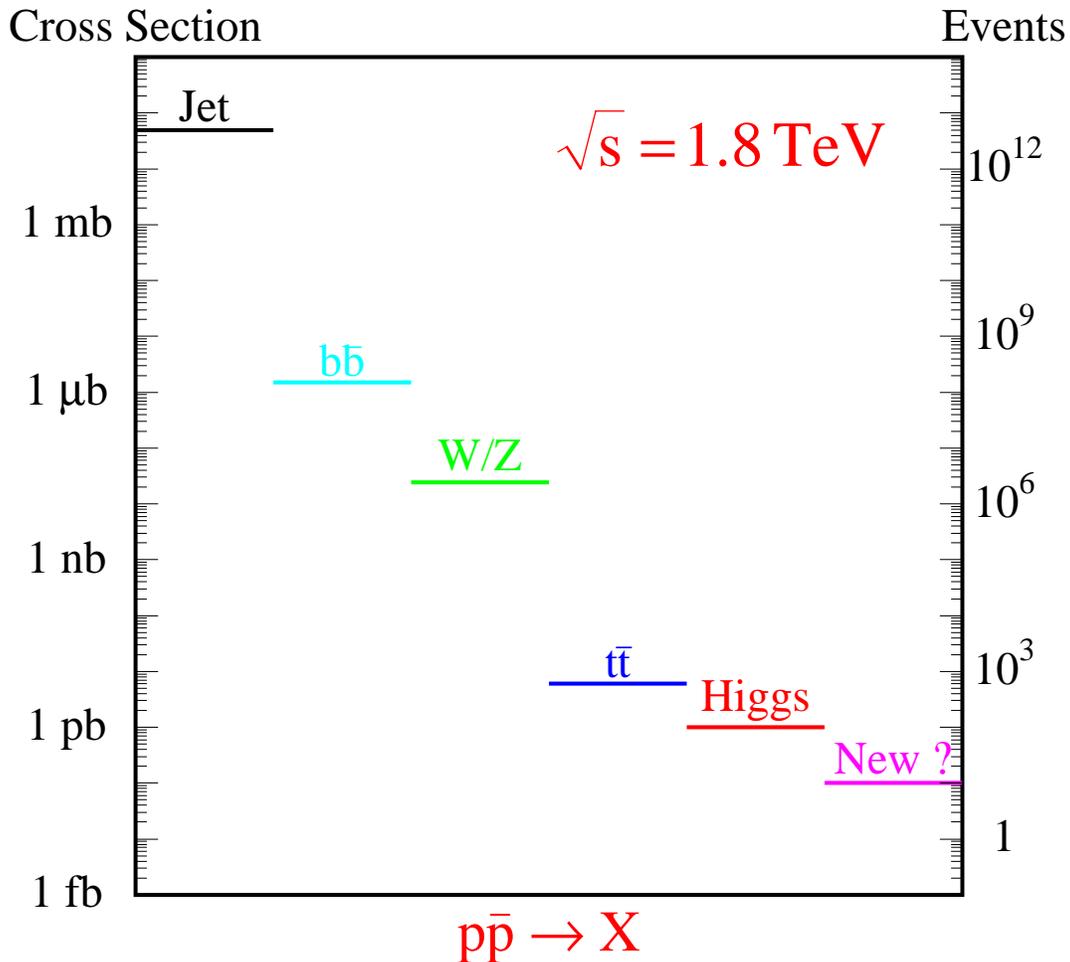
Results are often interpreted in models

- minimal supersymmetric extension of SM (MSSM)
- minimal super-gravity models (mSUGRA)
- models with gauge-mediated supersymmetry breaking (GMSB)



Challenges

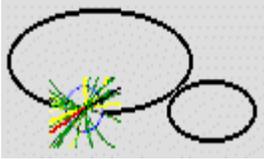
The cross section for new physics is small compared with dominant Standard Model processes



Leptons (e, μ) and \cancel{E}_T are the keys

- missing \cancel{E}_T resolution
- lepton identification efficiency and fake rate

(DØ e-identification: $\sim 75\%$ efficiency and 10^{-4} fake rate)



Search for Charged Higgs

Both CDF and DØ searched for charged Higgs boson production in top quark pair events

If charged Higgs bosons are sufficiently light, they can be produced in top quark decays

$$t \rightarrow Hb$$

Therefore, it will compete with the SM mode

$$t \rightarrow Wb$$

Since H^\pm and W^\pm decay differently

$$W \rightarrow \ell \nu, q\bar{q}' \quad H \rightarrow c\bar{s}, \tau \nu, Wb\bar{b}$$

$t \rightarrow Hb$ will lead to different signatures for top quark pair events

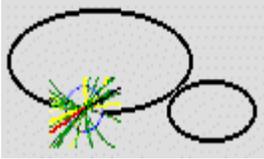
Signature for H production in $t\bar{t}$ events

- disappearance of standard $WWbb$ signature
- anomalous τ lepton production

Direct searches at LEP $M_H > 69$ GeV

CLEO has set an indirect limit from $b \rightarrow s\gamma$ to be

$$M_H > 244 + 63 / (\tan \beta)^{1.3}$$



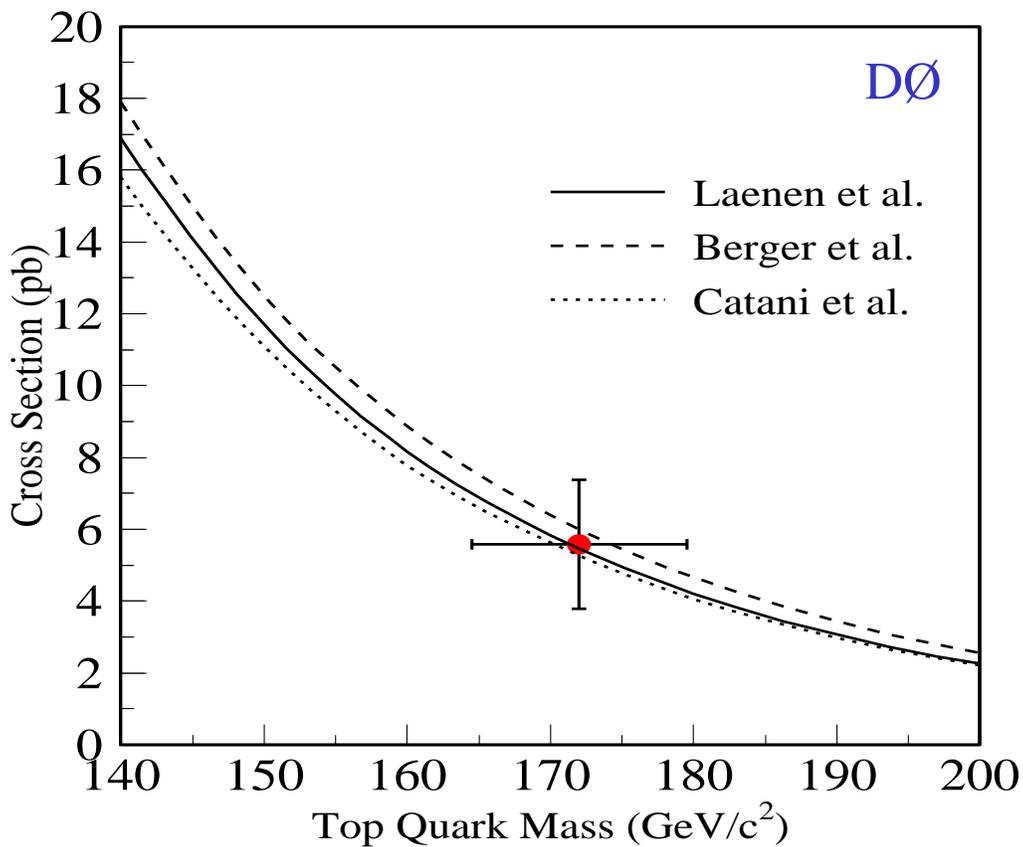
Search for Charged Higgs

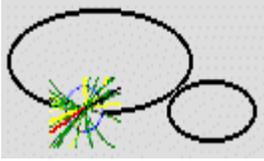
DØ searched for charged Higgs bosons
in decays of pair-produced top quarks from
the disappearance of SM $WWbb$ signature

hep-ex/9902028

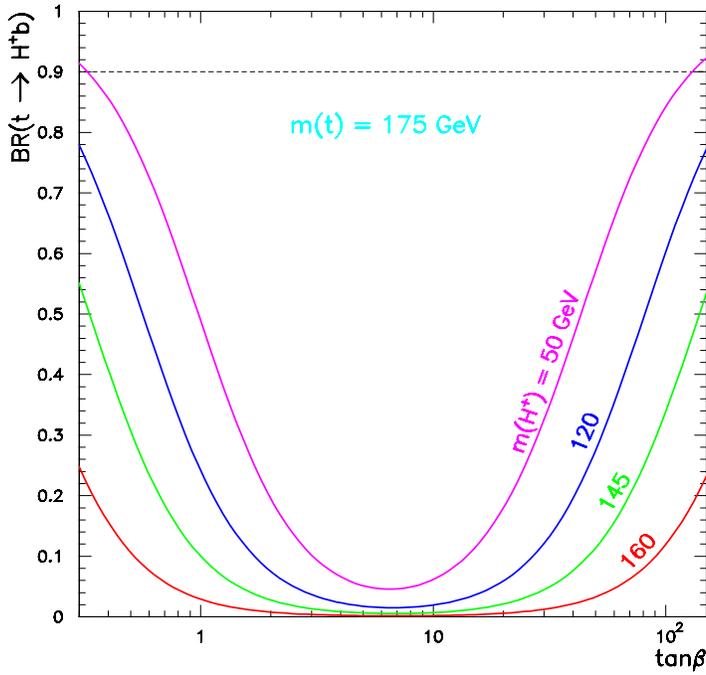
For the top quark analyses, DØ observed
30 events with 11.2 ± 2.0 expected background events

Assuming $\text{Br}(t \rightarrow Wb) = 100\%$, the measured top-pair
cross section agrees well with the SM prediction





Search for Charged Higgs

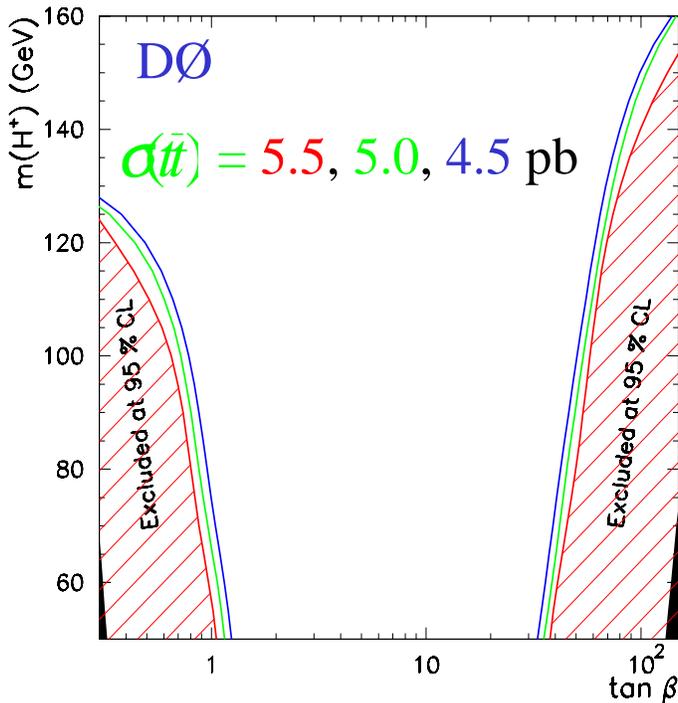


Sensitive only to the regions of parameter space with large $\text{Br}(t \rightarrow Hb)$

Sensitive only to topologies different from $WWbb$ of the SM top quark pair

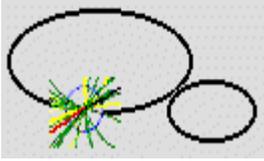


$$H \rightarrow c\bar{s}, \tau\nu$$



The analysis was restricted to the regions with valid leading-order calculations

How much disappeared depends on how much expected



Search for Charged Higgs

CDF also searched for $t \rightarrow Hb$ decay via $t\bar{t}$ disappearance

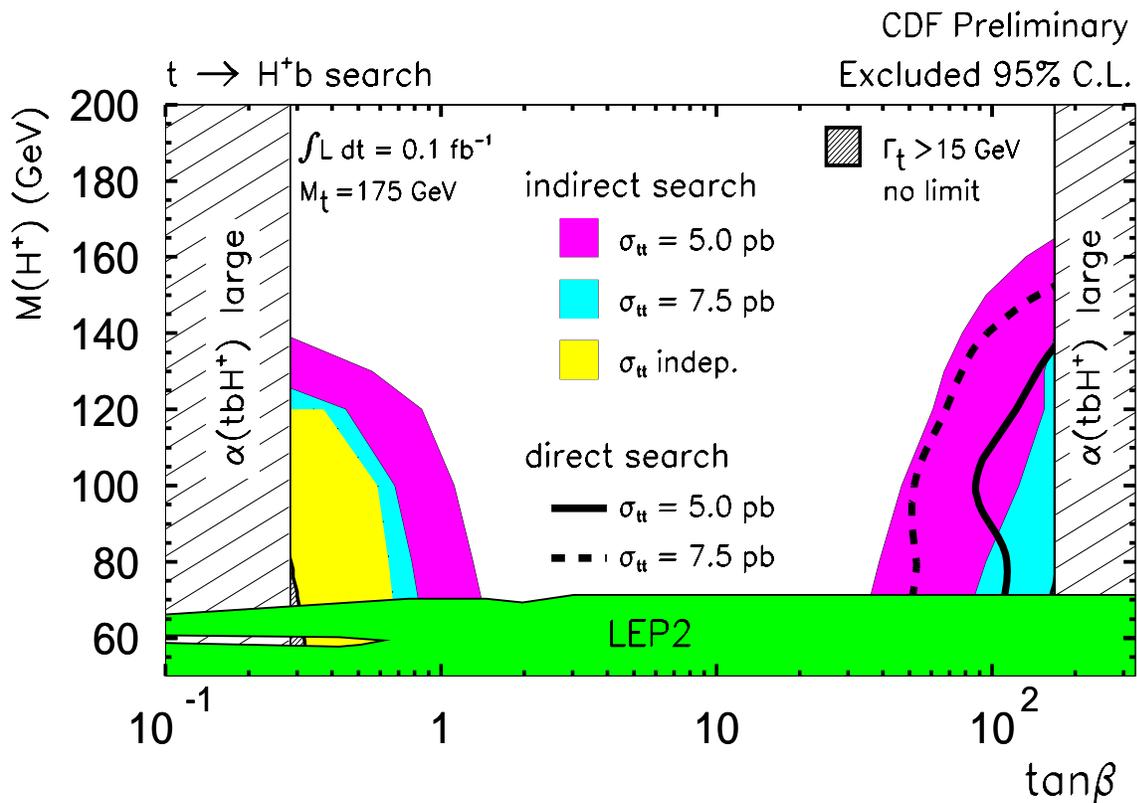
and τ appearance for high $\tan\beta$ (where $H \rightarrow \tau\nu$)
Phys. Rev. D54, 735 (1996)

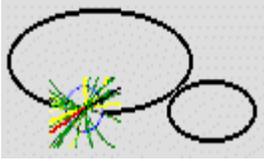
For the τ appearance analyses, $tj\bar{j}X$ and acoplanar $\tau\tau$ events were searched

The major backgrounds are fake taus, W +jets, Z +jets and WW , WZ , ZZ productions

7 events were observed with 7.4 ± 2.0 events expected

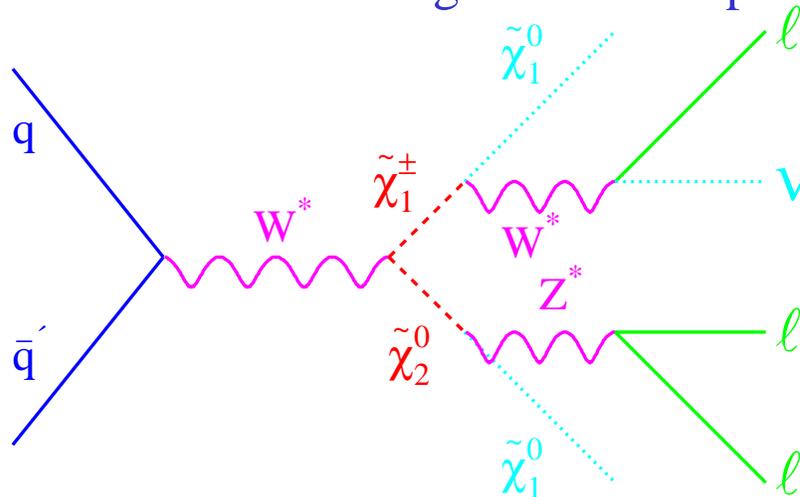
No excess of events





Search for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ Production

Production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ will lead to trilepton events with \cancel{E}_T , one of the cleanest signature for supersymmetry



Both CDF (106 pb^{-1}) and DØ ($\sim 90 \text{ pb}^{-1}$) searched for eee , $ee\mu$, $e\mu\mu$, $\mu\mu\mu$ events in Run I

Phys. Rev. Letters 80, 5275 (1998)

Phys. Rev. Letters 80, 1591 (1998)

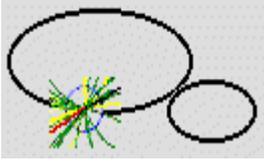
Selection

- 3 or more leptons with varying E_T
- require e^+e^- or $\mu^+\mu^-$ (CDF only)
- $\cancel{E}_T > 10 - 15 \text{ GeV}$
- lepton – lepton correlation cut
- resonance removal

Backgrounds

- WZ, ZZ
- Zb, Wbb
- top pair
- Z/ γ +fake lepton

No events were observed in either experiment
The expected # of background events is 1.2 ± 0.2 for CDF
and 1.3 ± 0.4 for DØ

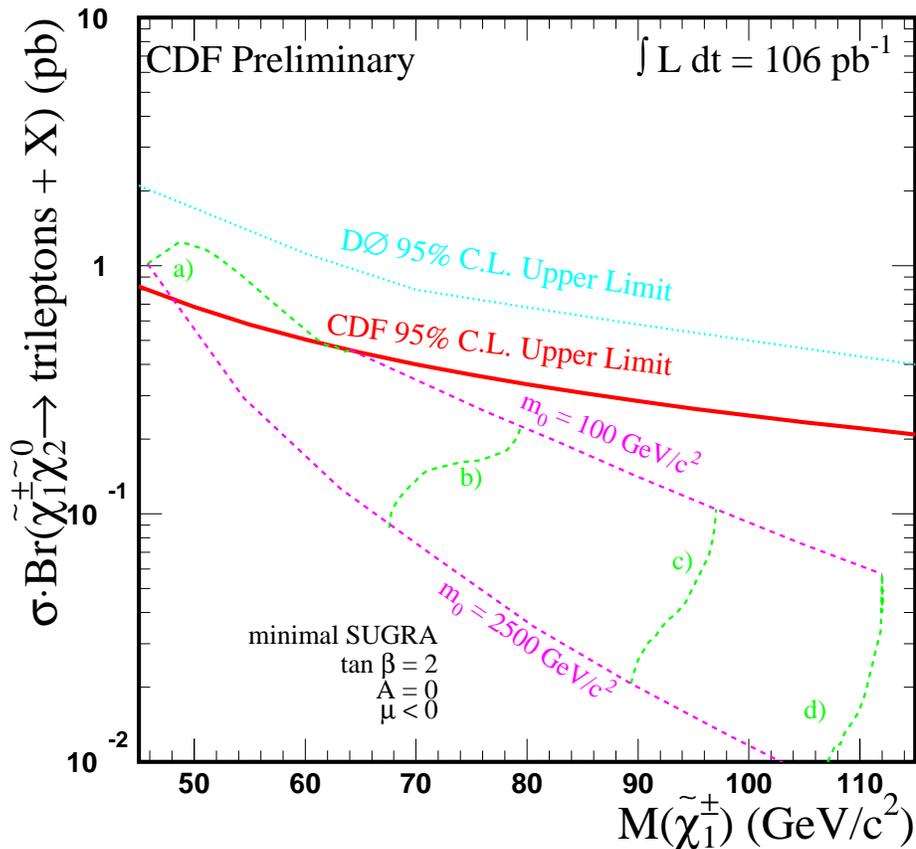


Search for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ Production

The null results were interpreted within the framework of MSSM models which give

$$M_{\tilde{\chi}_1^\pm} \approx M_{\tilde{\chi}_2^0} \approx 2M_{\tilde{\chi}_1^0}$$

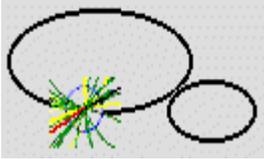
The typical efficiency is 3-12% for CDF and 2-6% for DØ when chargino mass is varied from 50 to 100 GeV



Trilepton for SUSY discovery?



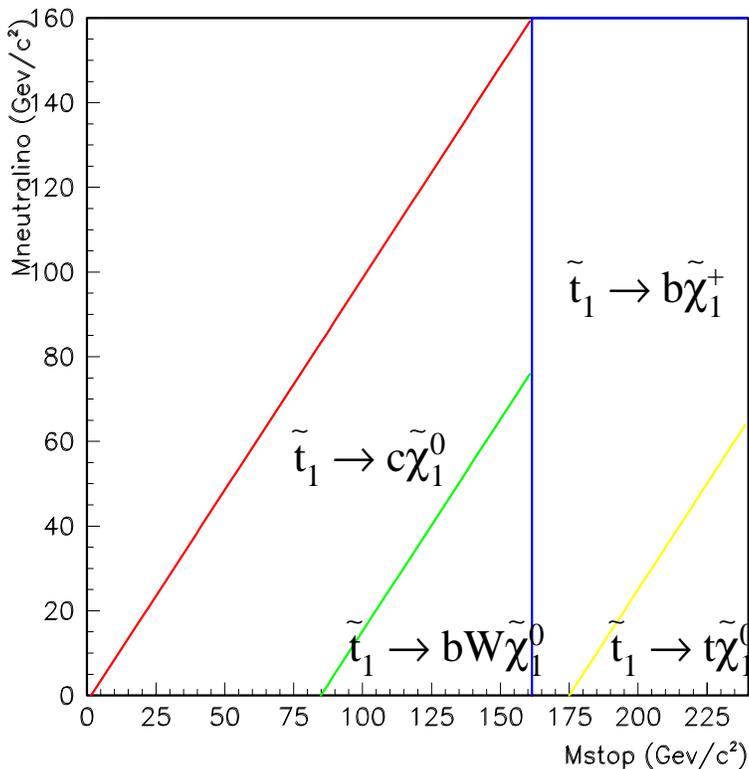
Dilepton was said top quark discovery



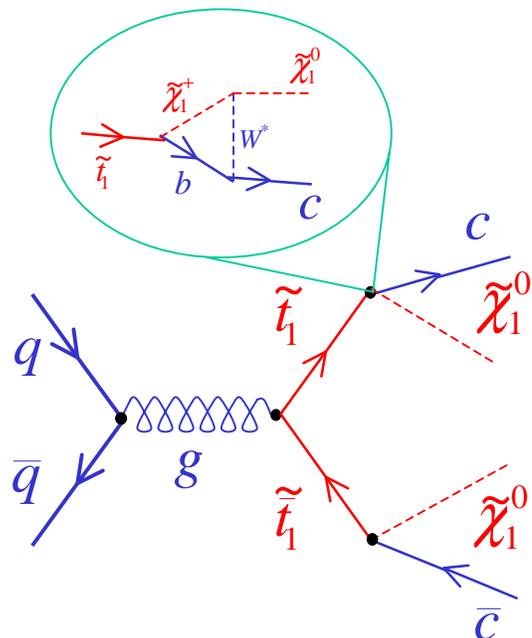
Search for Light Stop

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

Scalar Top Decay Possibilities



If $m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_t$
and $m_{\tilde{t}_1} < m_{\tilde{\chi}_1^+} + m_b$ then
 $Br(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0) = 100\%$



Signature: two acoplanar charm-jets with \cancel{E}_T

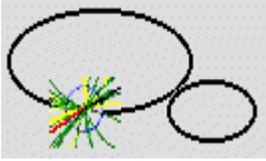
Selection (CDF):

- 2 or 3 jets with $E_T > 15$ GeV
- $\cancel{E}_T > 40$ GeV
- \cancel{E}_T – jet correlation cut
- jet – jet correlation cut
- at least one charm-tagged jet

Backgrounds:

- W+jets and Z+jets
- top
- diboson
- QCD multijet

(see the parallel session talk by Stephen Worm)

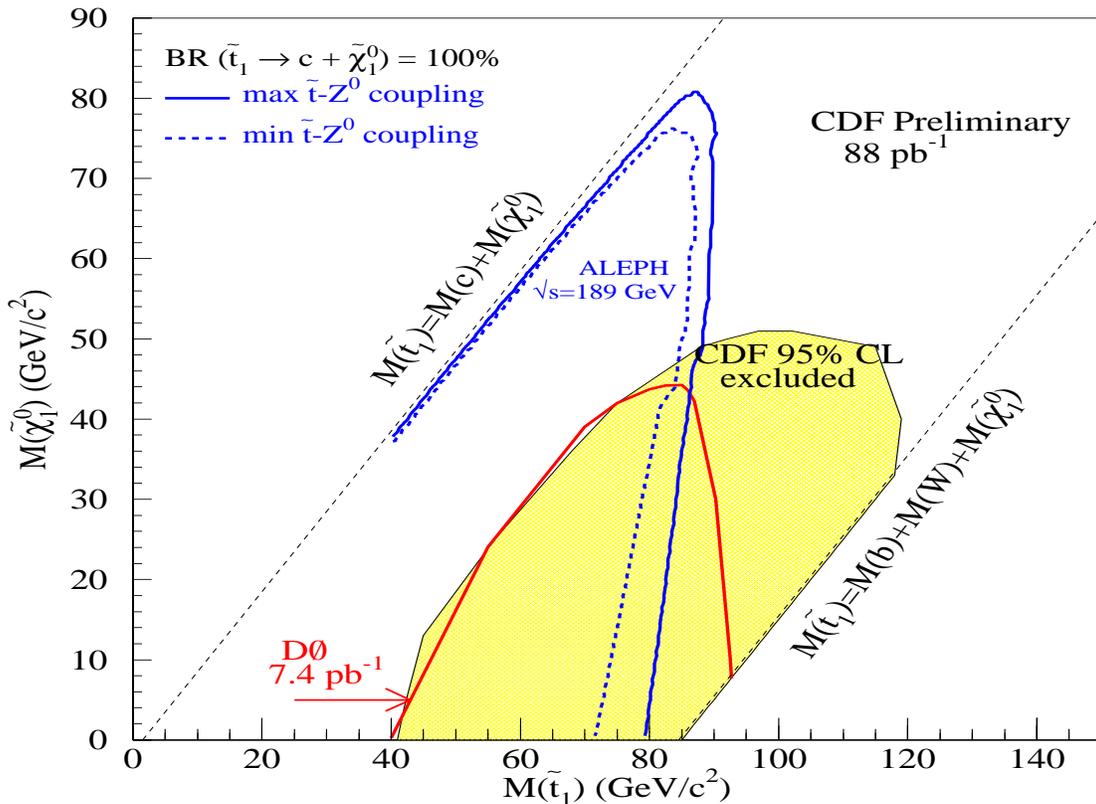
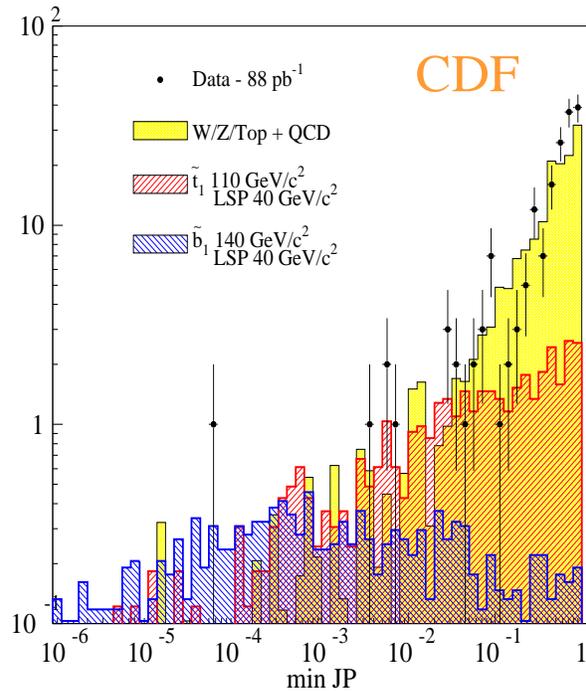


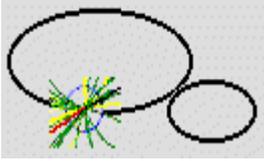
Search for Light Stop

Jet probability constructed using the SVX information to tag charm-jets:
 $\min JP < 0.05$

Data Sample: 88 pb^{-1}
 Events observed: 11
 Expected background: 15 ± 4

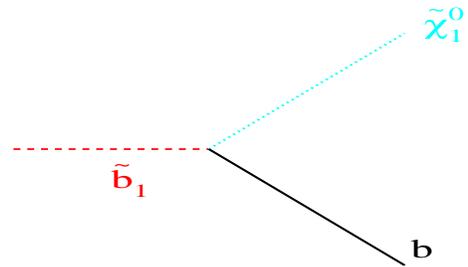
No excess of events





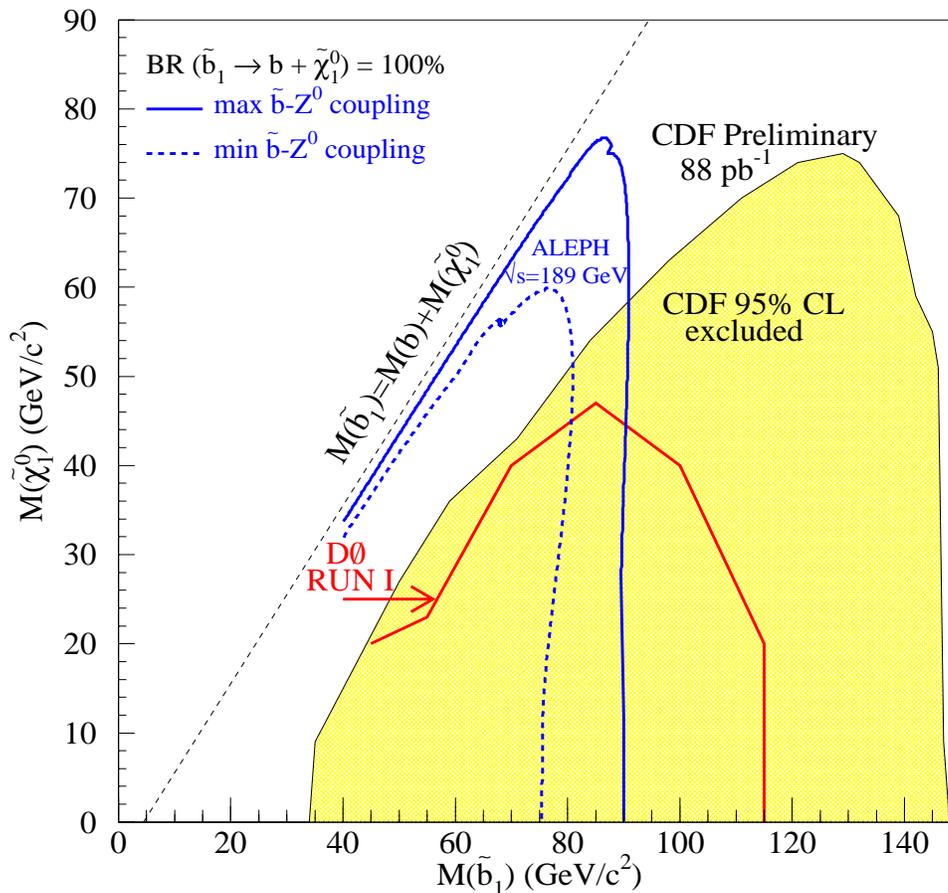
Search for Sbottom

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

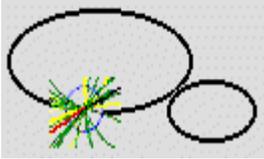


Replacing the charm-tag (min JP < 0.05) with
 the b-tag (min JP < 0.01), CDF observed 5 events
 with 6 ± 2 expected background events

No excess of events

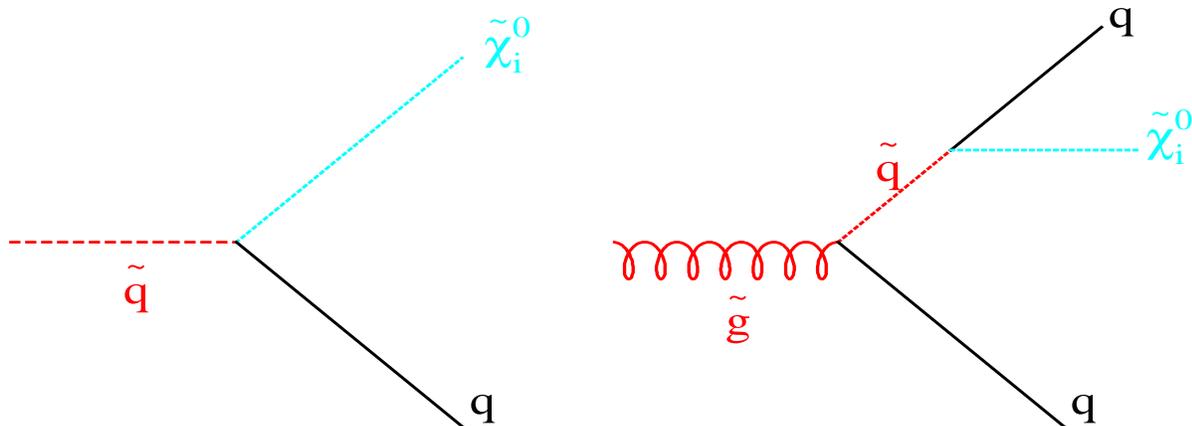


DØ carried out a similar analysis except
 that b-jets have to be tagged with less efficient soft- μ



Search for \tilde{q} and \tilde{g}

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



The signature for $p\bar{p} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} + X$ production is therefore jets + \cancel{E}_T events

DØ (80 pb⁻¹) searched for events with jets + \cancel{E}_T
hep-ex/9902013

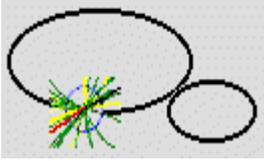
Selection:

- 3 or more jets with $E_T > 25$ GeV
- Leading jet $E_T > 115$ GeV
- $\cancel{E}_T > 75$ GeV
- \cancel{E}_T – jet correlation cut
- optimized \cancel{E}_T – H_T cut

Backgrounds:

- QCD multijet
- top quark pair
- W/Z+jets

Shape analysis to estimate residual QCD background



Search for \tilde{q} and \tilde{g}

The analysis was optimized for mSUGRA models with $A_0=0$, $\tan\beta=2$, $\mu<0$ using the next-to-leading order cross section by PROSPINO

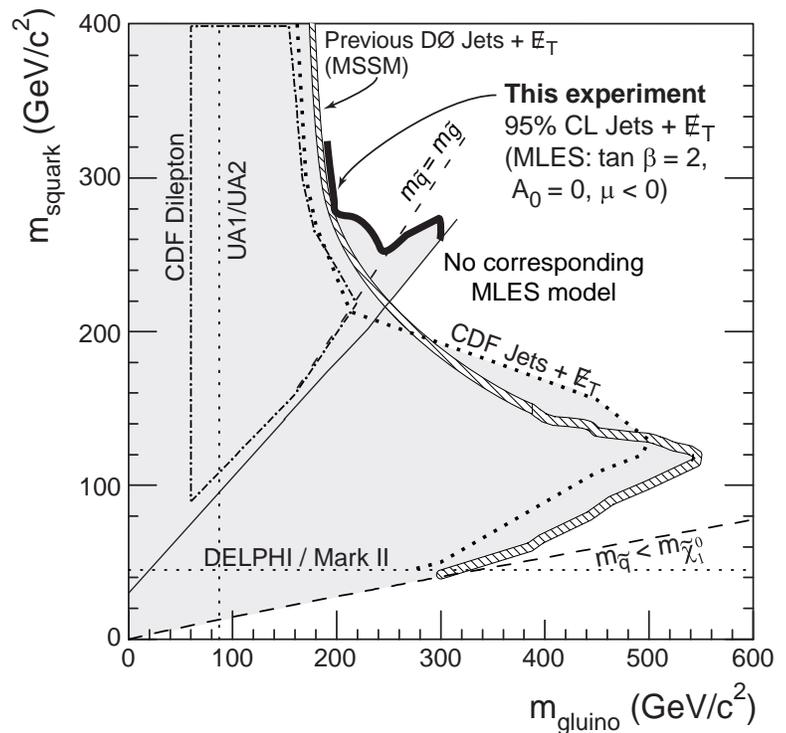
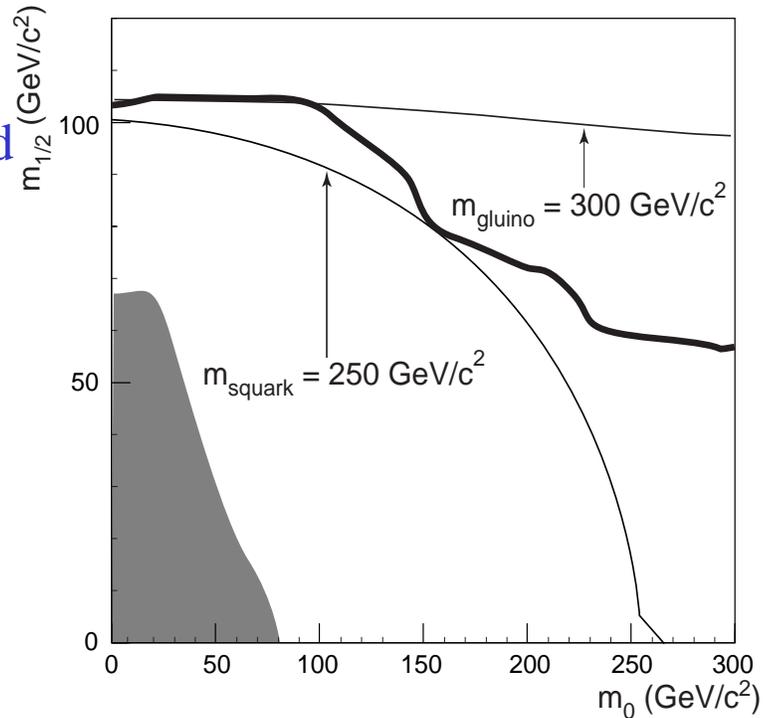
No excess of events

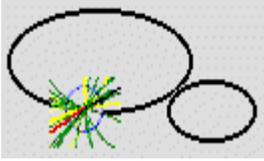
Detection efficiency is typically a few percent for the signal

$$m_{\tilde{q}} > 250 \text{ GeV}$$

$$m_{\tilde{g}} > 260 \text{ GeV}$$

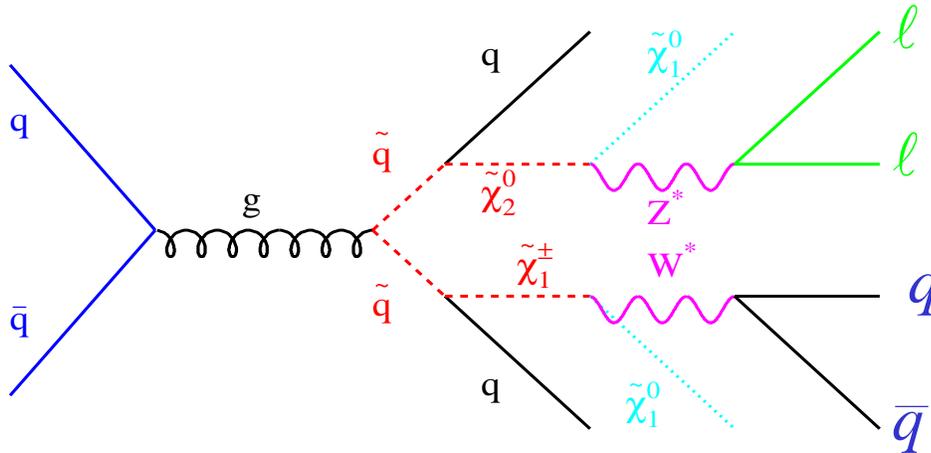
@ 95% C.L.





Search for \tilde{q} and \tilde{g}

Squarks and gluinos can also result in dilepton final states



Signature: dilepton accompanied by two jets

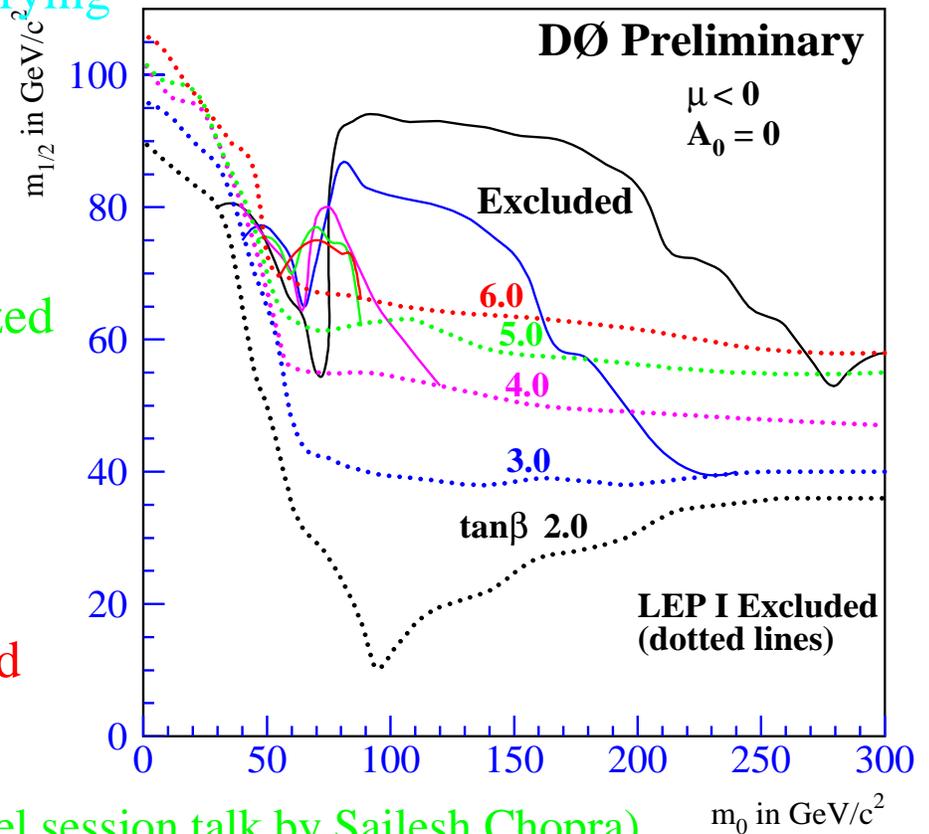
Selection:

- two leptons with varying E_T requirement
- two jets with $E_T^{\min} > 20$ GeV
- $E_T > 20, 30, 40$ GeV

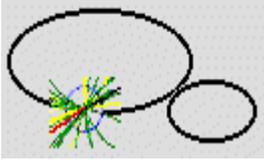
Criteria were optimized for every MC point studied to achieve maximum S-B discrimination

No excess is observed

95% C.L. Excluded Region



(see the parallel session talk by Sailesh Chopra)



Search for \tilde{q} and \tilde{g}

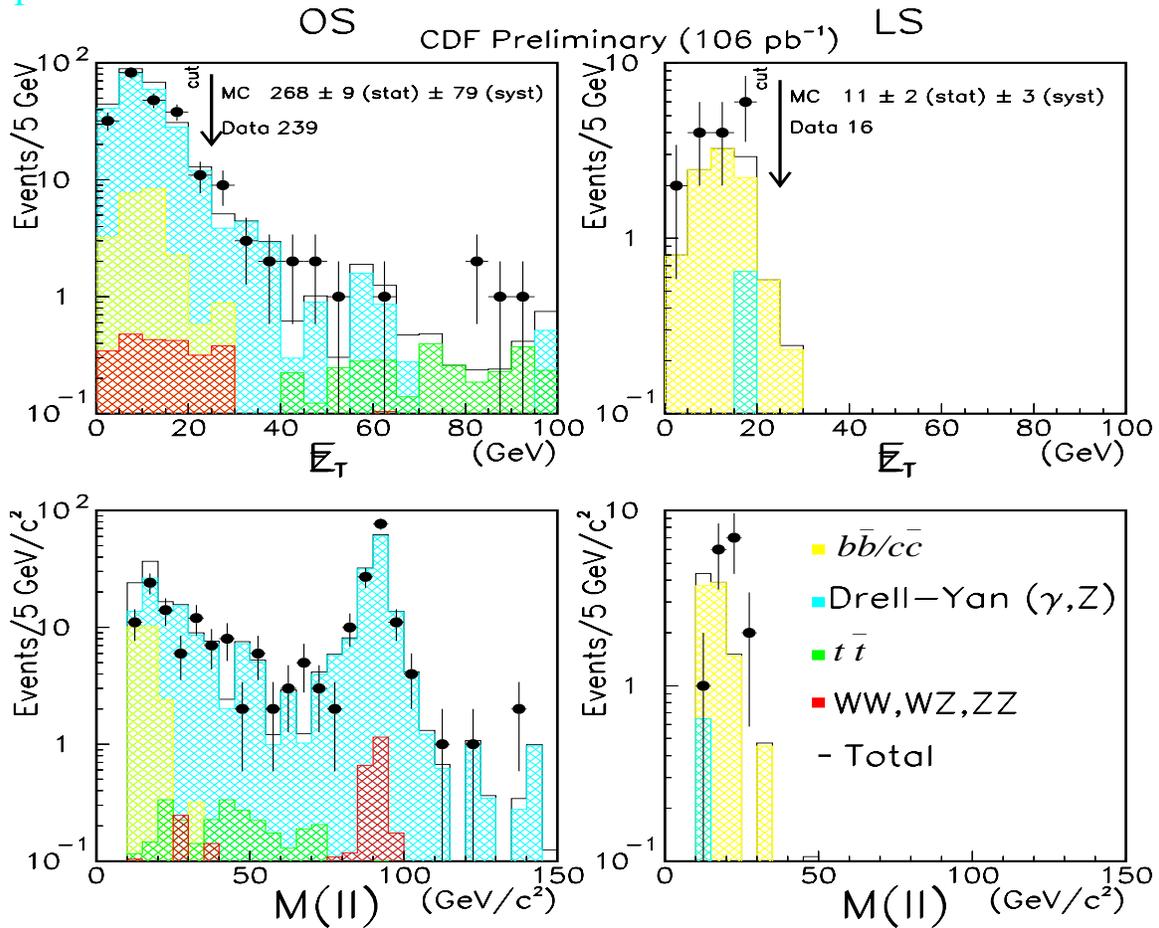
CDF searched for $\ell^\pm \ell^\pm jj$ events

Selection:

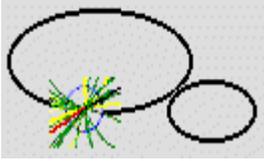
- Two like-sign leptons with $E_T > 11.5$ GeV
- two or more with $E_T > 15$ GeV
- dilepton mass cuts
- $\cancel{E}_T > 25$ GeV

Backgrounds:

- Drell-Yan
- top, bottom, charm
- diboson



0 events observed with 0.6 ± 0.3
events expected from the backgrounds



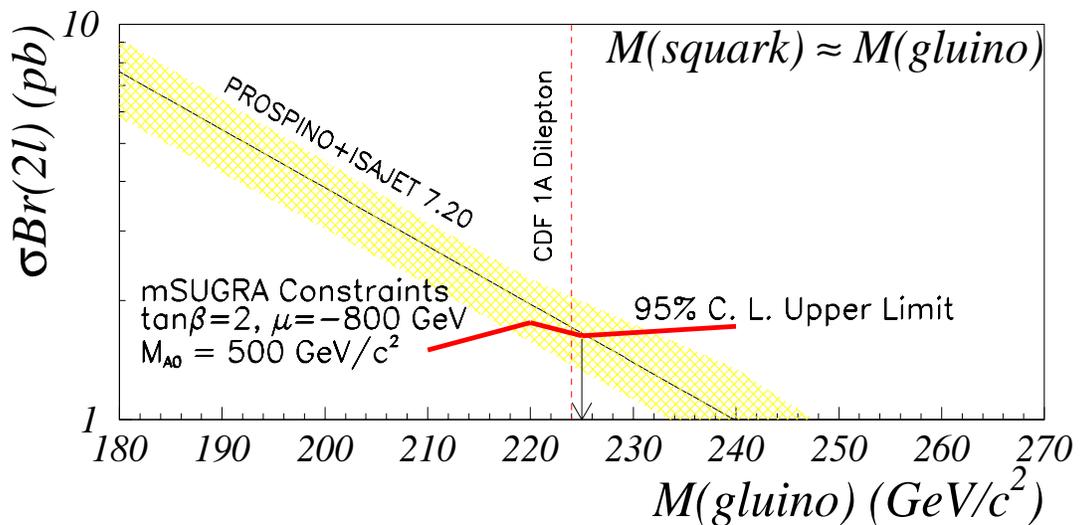
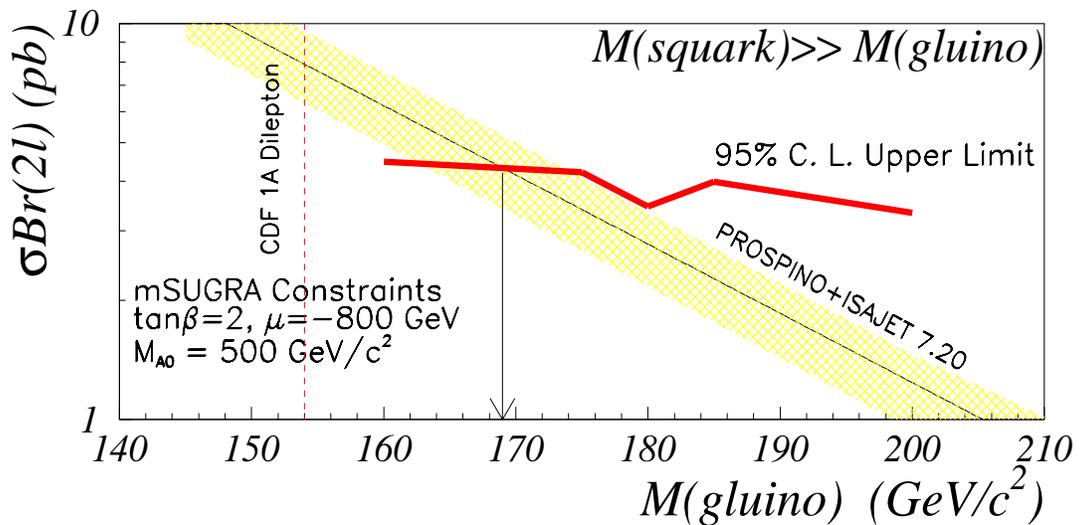
Search for \tilde{q} and \tilde{g}

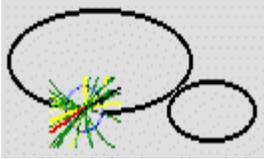
Interpreted in terms of $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} \rightarrow \ell^\pm \ell^\pm jj$ production assuming 5 degenerate squarks

Leptons are produced in the decays of $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ cascaded from \tilde{q} and \tilde{g}

The total efficiency for the signal varies from 0.6% to 2.0%

CDF Preliminary (106 pb^{-1})





Search for R_p Supersymmetry

The gauge and Lorentz symmetries allow to add the following terms to the superpotential

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

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

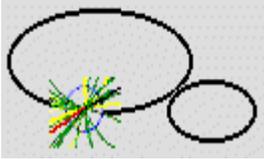
The B - violating λ''_{ijk} couplings will lead to events with multijet without E_T make it impossible to study at the Tevatron

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

Both CDF and DØ have searched for R-parity violating supersymmetry in leptonic final states

Assumptions:

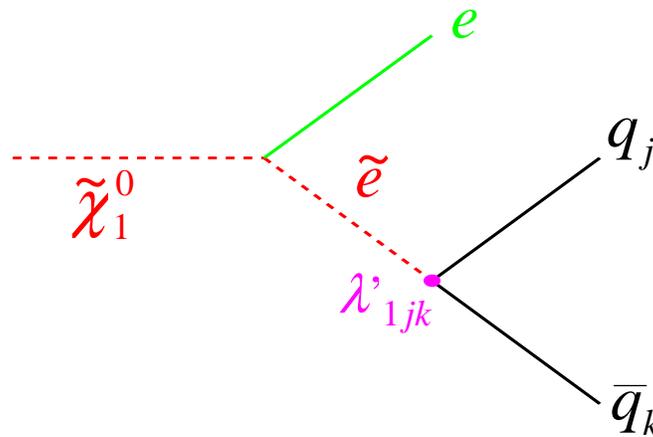
- Among all possible terms, only those R-parity violating terms with the same event topology dominate
- R_p -violating decays of \tilde{c} and $\tilde{\chi}_1^0$ are considered
- The couplings are strong so that R_p -violating decays occur within the detector



Search for R_p Supersymmetry

DØ studied the case that all R_p couplings are small except λ'_{1jk} within the framework of mSUGRA

$$p\bar{p} \rightarrow SUSY \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow ee + jets$$



Signature: two electrons accompanied by four jets

Selection:

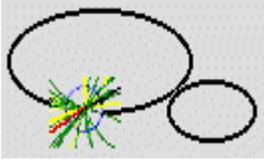
- 2 or more electrons with $E_T > 10, 15$ GeV
- 4 or more jets with $E_T > 15$ GeV
- $m_{ee} < 76$ GeV or $m_{ee} > 106$ GeV
- $H_T > 150$ GeV

Backgrounds:

- Drell-Yan
- $Z \rightarrow \tau\tau \rightarrow ee$
- $t\bar{t} \rightarrow ee$
- Instrumental

In a sample of 96 pb^{-1} , 2 events were observed with 1.8 ± 0.3 events expected from the background

No excess of events

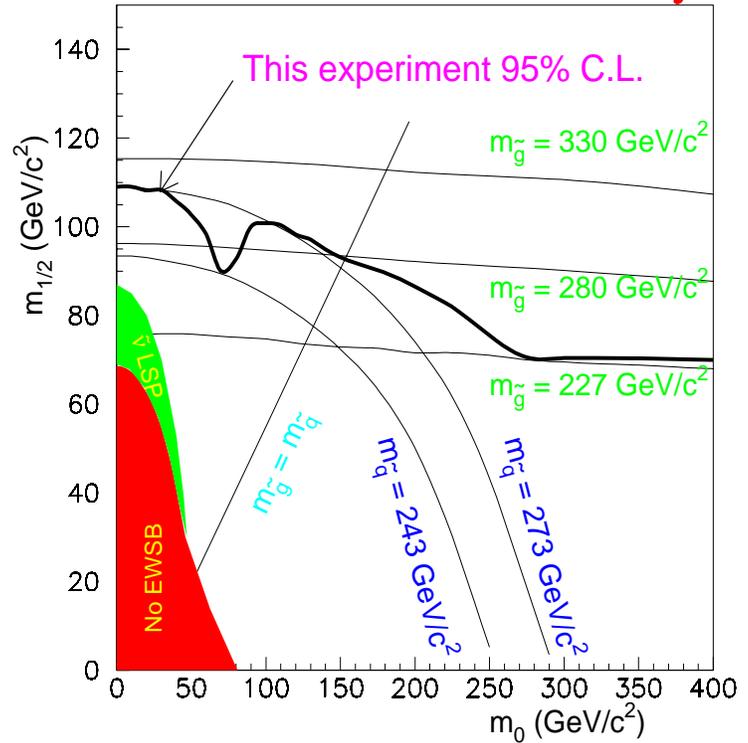


Search for R_p Supersymmetry

DØ Preliminary

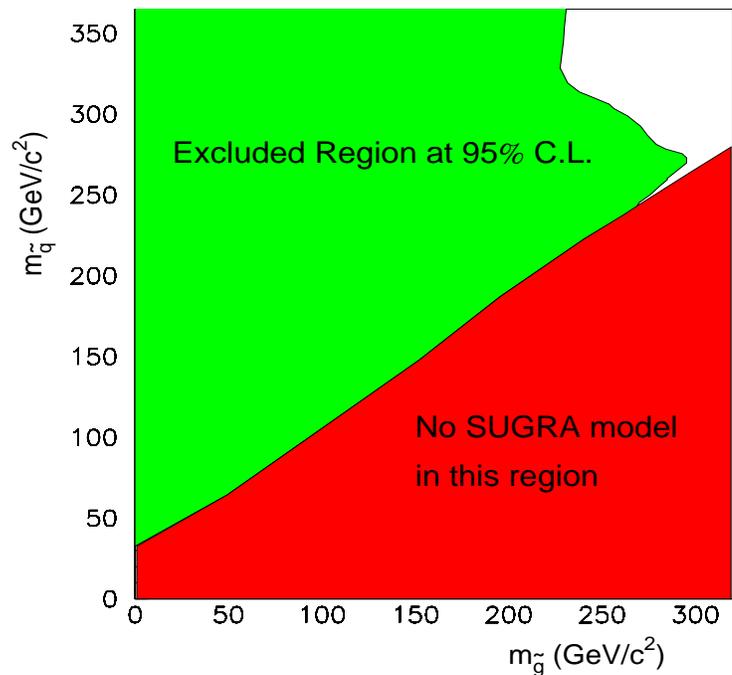
The null results were interpreted in the minimal super-gravity models with $A_0=0$, $\tan\beta=2, 6$, and $\mu<0$ and varying m_0 and $m_{1/2}$

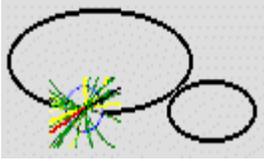
The typical $\varepsilon \cdot \text{Br}$ is about 2% for the signal



$m_{\tilde{q}} > 250 \text{ GeV}$
 $m_{\tilde{g}} > 230 \text{ GeV}$
 @ 95% C.L.

(see the parallel session talk by Sailesh Chopra)

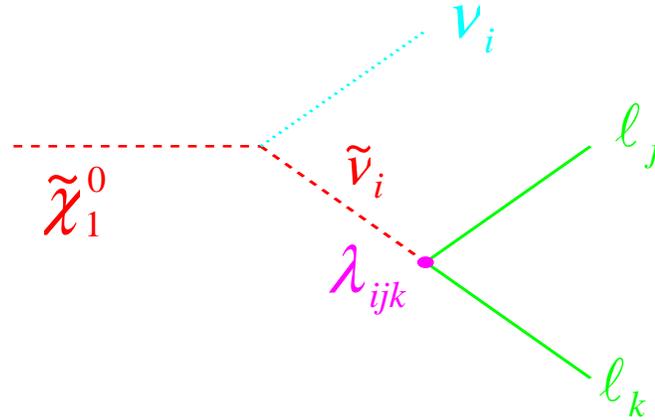




Search for R_p Supersymmetry

CDF studied the case with a dominant λ_{121}
in the mSUGRA framework

$$p\bar{p} \rightarrow SUSY \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow llll + X$$



Signature: Events with four leptons

Selection:

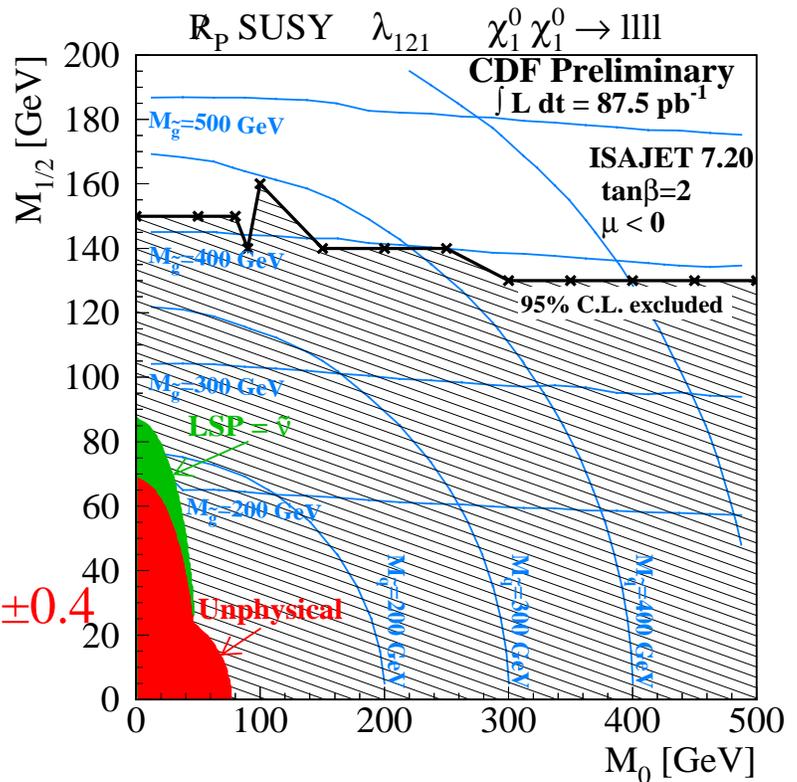
- 4 leptons with $E_T > 12$ (1), 5 (3) GeV
- $\Delta R_{ll} > 0.4$
- no isolation

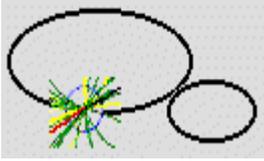
Backgrounds:

- $b\bar{b} / c\bar{c}$
- Instrumental

Event observed: 1

Expected BG events: 1.3 ± 0.4





Search for R_p Supersymmetry

CDF searched like-sign dielectron events with two jets
(Fermilab Pub-98/374-E)

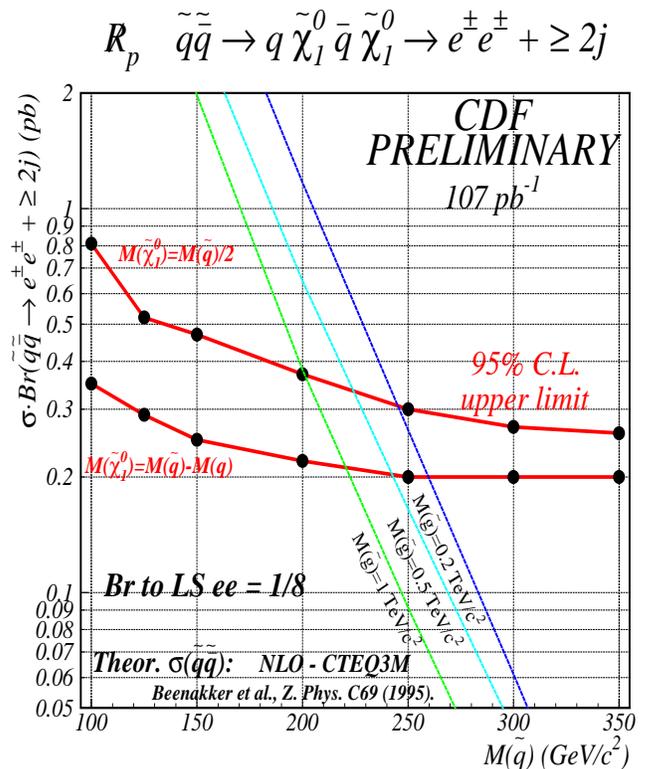
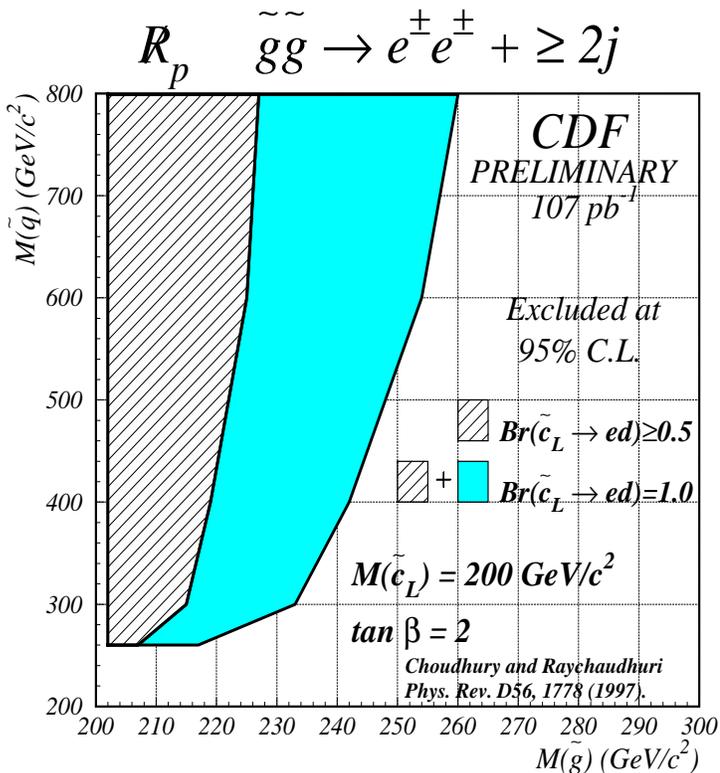
$$p\bar{p} \rightarrow \tilde{g}\tilde{g} \rightarrow (\bar{c}\tilde{c})(\bar{c}\tilde{c}) \Rightarrow \bar{c}\bar{c}(\ell^+d)(\ell^+d) \quad (m_{\tilde{c}} = 200 \text{ GeV})$$

$$p\bar{p} \rightarrow \tilde{q}\tilde{q} \rightarrow (\bar{q}\tilde{\chi}_1^0)(q\tilde{\chi}_1^0) \Rightarrow q\bar{q}(q\bar{q}', \ell^\pm)(q\bar{q}', \ell^\pm)$$

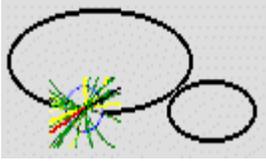
Selection

- two like-sign electrons with $E_T > 15 \text{ GeV}$
- two or more jets with $E_T > 15 \text{ GeV}$
- no significant \cancel{E}_T

No event observed in a sample of 107 pb^{-1}
consistent with the estimated # of background events



(See the parallel session talk by Maxwell Chertok)

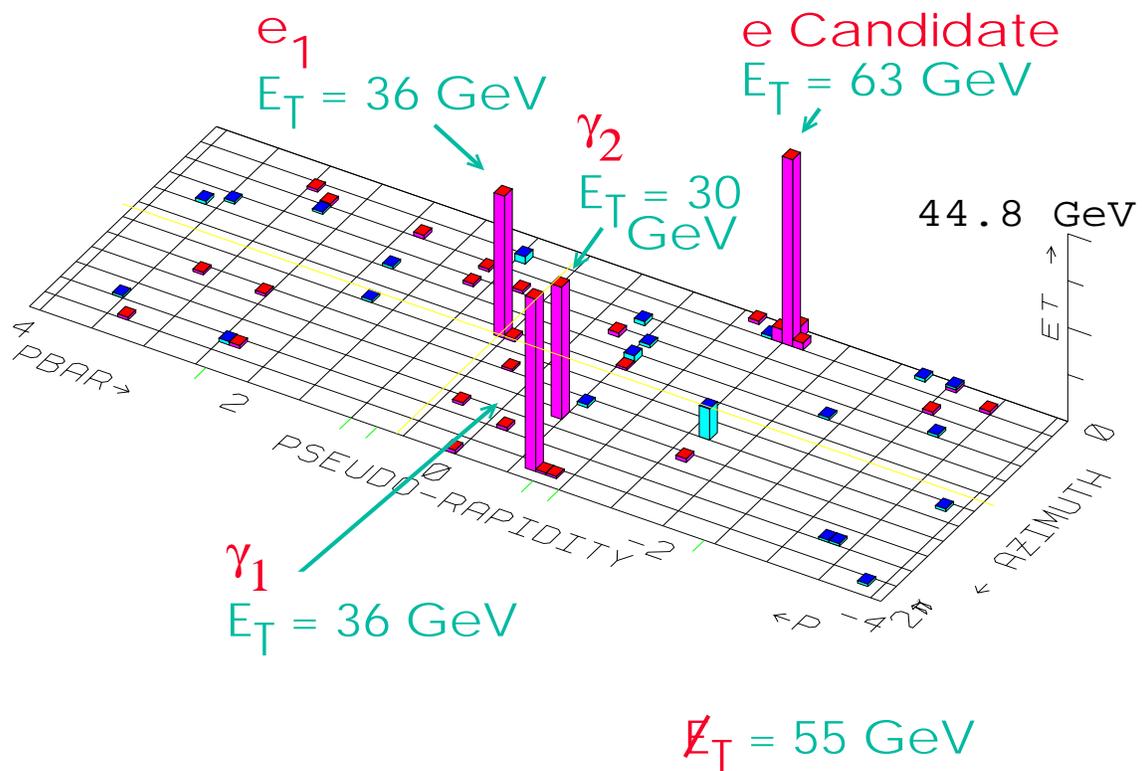


CDF $e\bar{e}\gamma\gamma\cancel{E}_T$ Event

Much publicity has accompanied the CDF event.

It is unusual because isolated leptons, photons, and especially large \cancel{E}_T are rare in the Standard Model

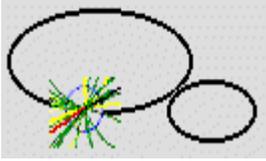
$e\bar{e}\gamma\gamma\cancel{E}_T$ Candidate Event



The probability for the event to be resulted from known process is small.

Phys. Rev. Letters 81, 1791 (1998)

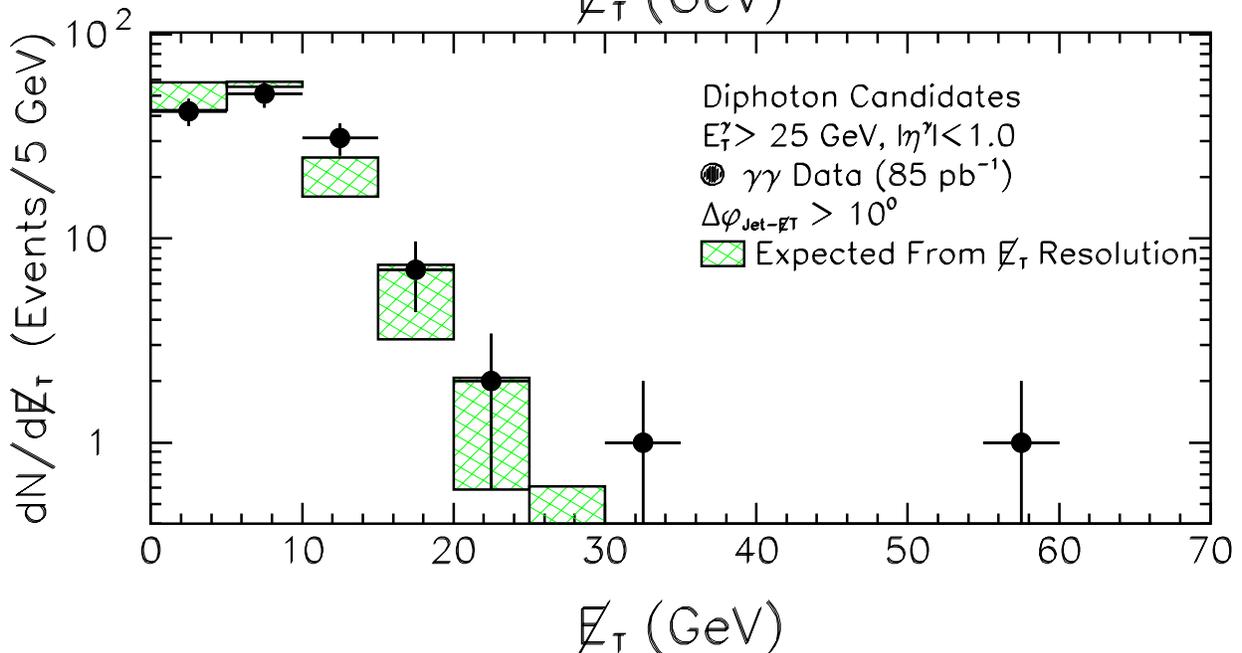
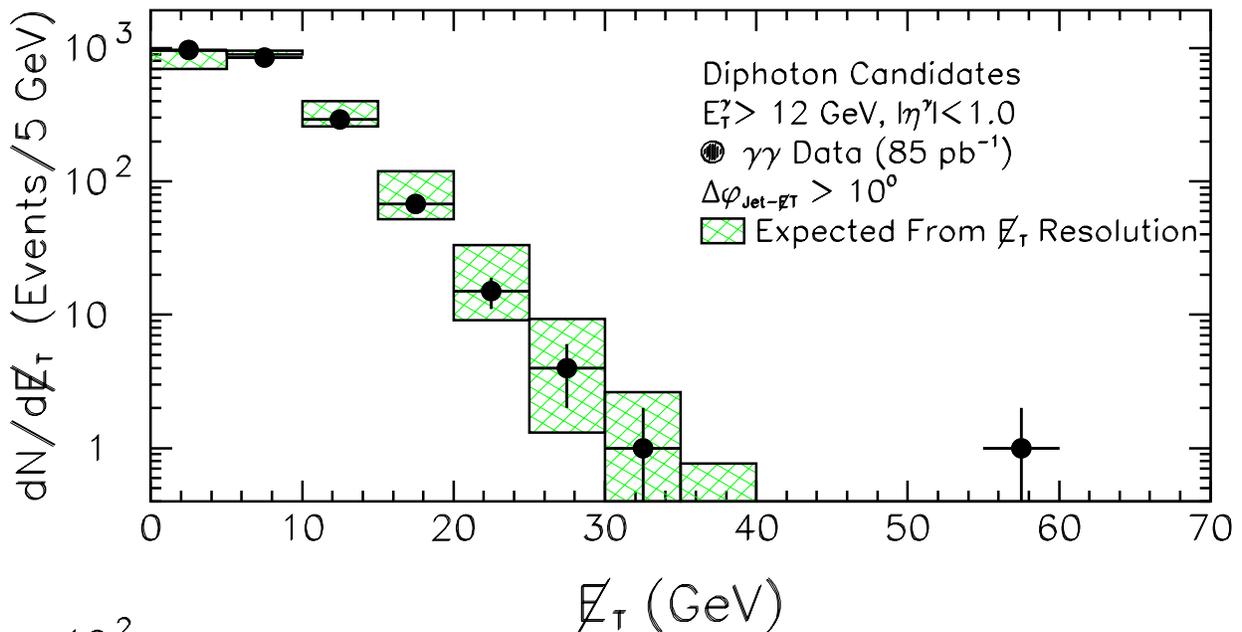
It generated considerable theoretical interest

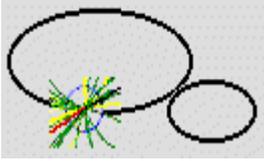


Search for $\gamma\gamma\cancel{E}_T$ Events

CDF studied the \cancel{E}_T distributions of diphoton events
these distributions agree well with the expectations

Phys. Rev. D59, 092002 (1999)





Photon in Supersymmetry

In Gauge Mediated Models with NLSP= $\tilde{\chi}_1^0$
 $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$

$$p\bar{p} \rightarrow \tilde{\chi}^+ \tilde{\chi}^- \rightarrow W^+ W^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$p\bar{p} \rightarrow e\bar{e} \rightarrow e\bar{e} \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

were proposed as possible explanations of the event
 Ellis et al., PLB 394 (1997), Ambrosanio et al., PRD 54, 5395 (1996), ...

Pair production of any supersymmetric particles
 will result in $\gamma\gamma E_T + X$ events
 if both $\tilde{\chi}_1^0$ decay inside the detector



Within the framework of MSSM with the LSP= $\tilde{\chi}_1^0$,
 a class of models with dominant

$$\tilde{e} \rightarrow e + \tilde{\chi}_2^0 \text{ and } \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \gamma$$

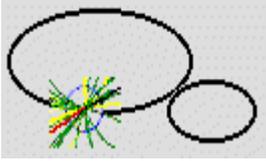
decays was also proposed as an explanation of the event

$$p\bar{p} \rightarrow \tilde{e}\tilde{e} \rightarrow e\bar{e} \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow e\bar{e} \gamma \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

Kane et al., Phys. Rev. D55, 1372 (1997)

$\gamma\gamma E_T$ events are expected from
 $p\bar{p} \rightarrow \tilde{e}\tilde{e}, \tilde{\nu}\tilde{\nu}, \tilde{\chi}_2^0 \tilde{\chi}_2^0 + X$ processes

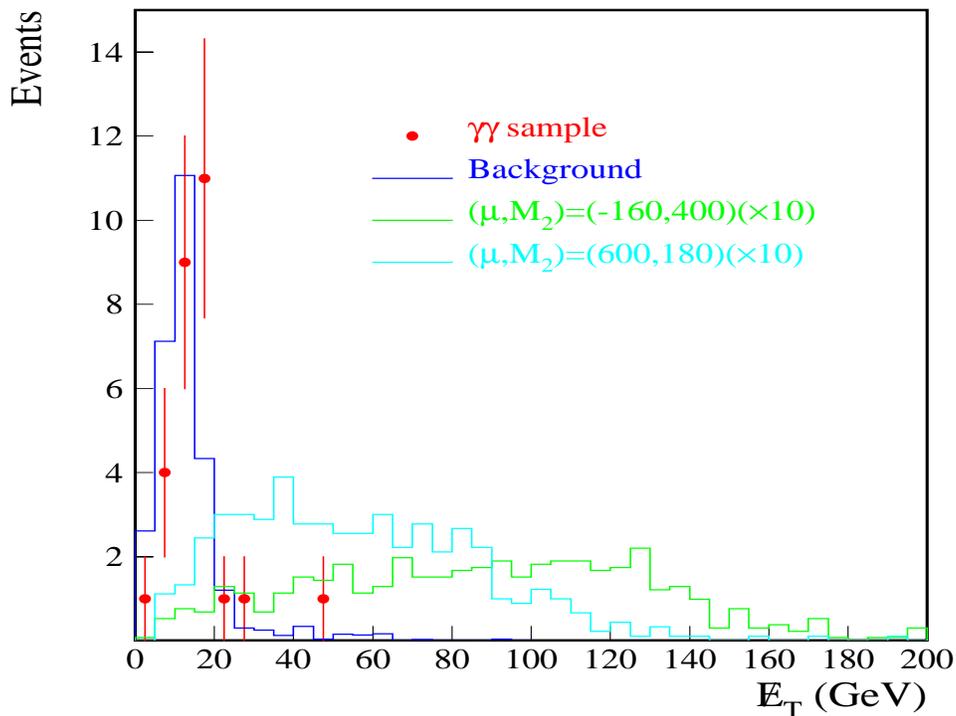
$\gamma E_T + \text{jets}$ events are expected from
 $p\bar{p} \rightarrow \tilde{q}/\tilde{g} \rightarrow \tilde{\chi}_2^0 + X$ processes



Search for $\gamma\gamma\cancel{E}_T$ Events

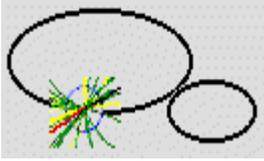
DØ (106 pb⁻¹) searched for diphoton events with large transverse energy imbalance
Phys. Rev. Letters 80, 442 (1998)

- (1) $E_T^{\gamma^1} > 20$ GeV $|\eta| < 1.1$ or $1.5 < |\eta| < 2.0$
- (2) $E_T^{\gamma^2} > 12$ GeV $|\eta| < 1.1$ or $1.5 < |\eta| < 2.0$
- (3) $\cancel{E}_T > 25$ GeV



Principal Backgrounds
multijet, direct photon, $W\gamma$, W +jets, $Z \rightarrow ee$

Two events survived with 2.3 ± 0.9 expected
from background processes



Search for $\gamma\gamma E_T$ Events

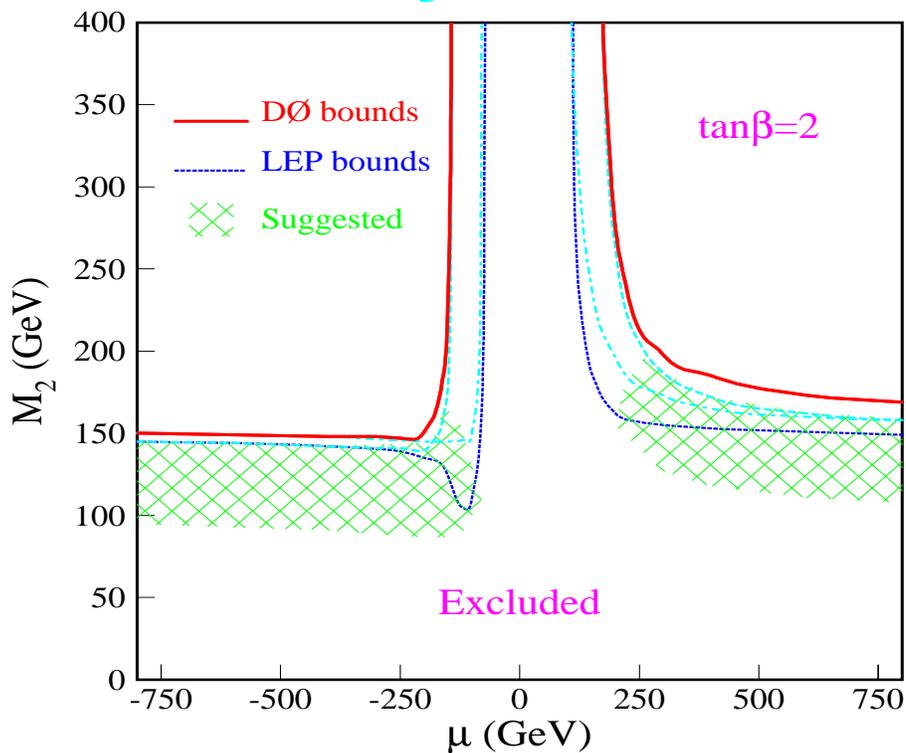
The null results were interpreted in terms of chargino and neutralino pair production

$$p\bar{p} \rightarrow \tilde{\chi}_i \tilde{\chi}_j \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X \rightarrow \gamma\gamma \tilde{G} \tilde{G} + X$$

within the framework of MSSM with LSP = \tilde{G}

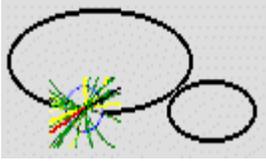
The (μ, M_2) parameter space were explored assuming gaugino mass unification at the GUT scale

$$M_1 = \frac{5}{3} M_2 \tan^2 \vartheta_w$$



$$M_{\tilde{\chi}_1^\pm} > 150 \text{ GeV @ 95\% C.L.}$$

Insensitive to the $\tan\beta$ value assumed

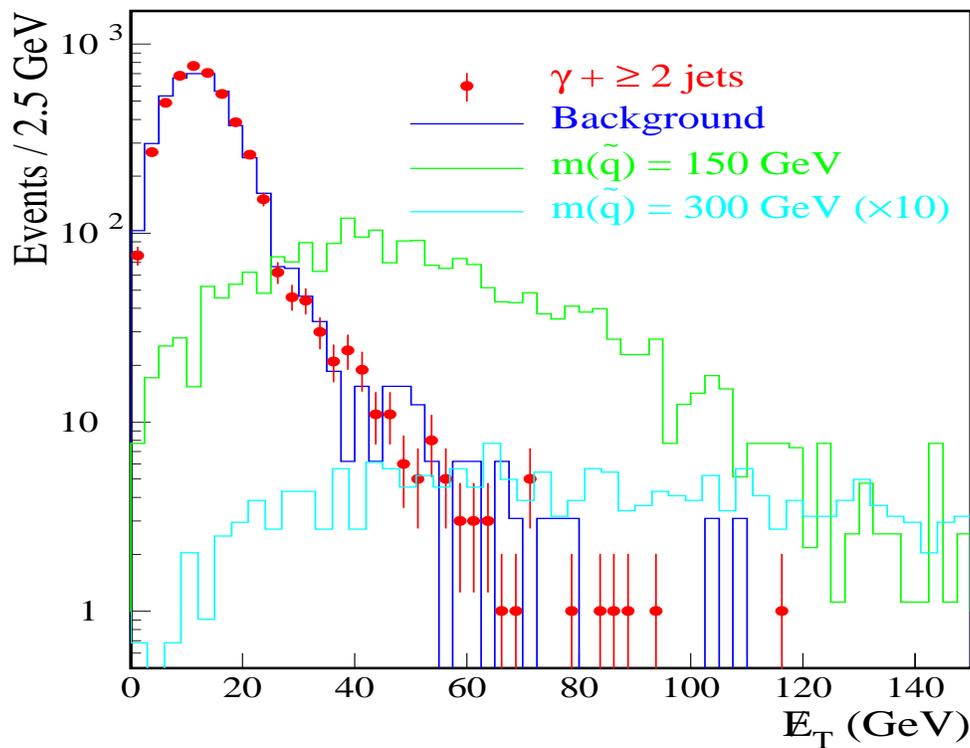


Search for $\gamma E_T + \geq 2$ -Jets Events

DØ (99 pb⁻¹) also searched for single-photon events with jets and large missing transverse energy

Phys. Rev. Letters 82, 29 (1999)

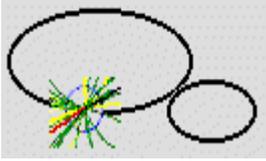
- (1) $E_T^\gamma > 20$ GeV, $|\eta| < 1.1$ or $1.5 < |\eta| < 2.0$
- (2) $N_j \geq 2$, $E_T^j > 20$ GeV with $|\eta| < 2.0$
- (3) $E_T > 25$ GeV



Principal Backgrounds

QCD direct photon and multijet, W+jets, etc...

318 events selected with 320 ± 20 events expected

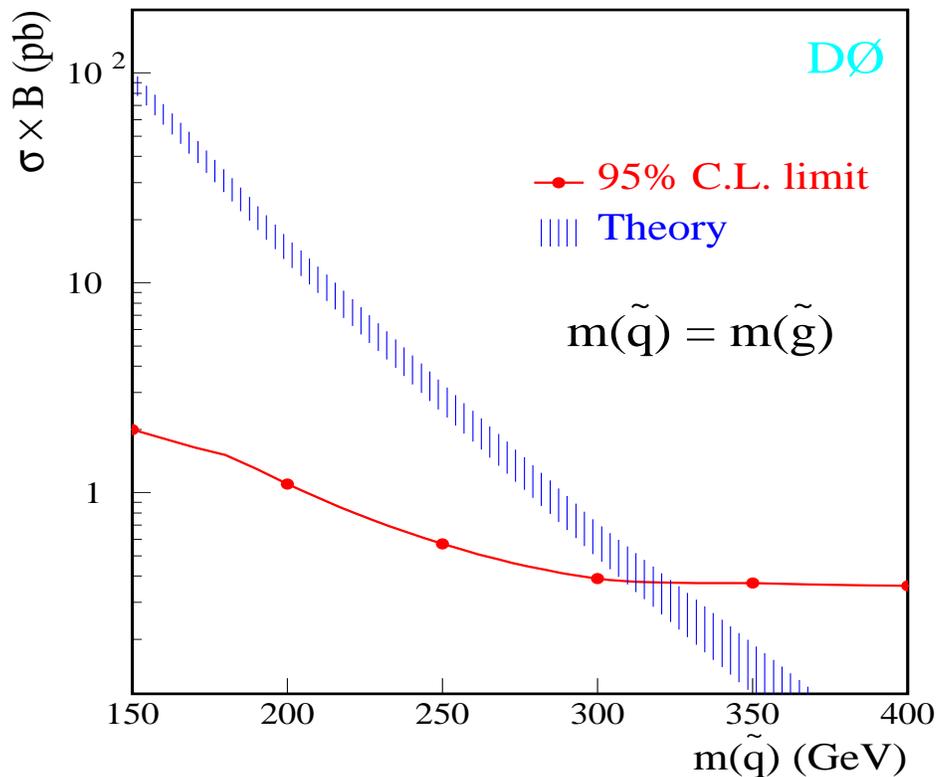


Search for $\gamma E_T + \geq 2$ -Jets Events

The analysis was interpreted in terms of squark/gluino production within the model with dominant $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \gamma$ decay

To increase the sensitivity to supersymmetry, event selection was optimized in E_T - H_T plane

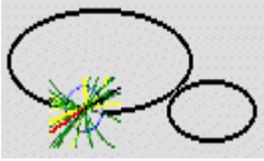
For the optimized cuts $E_T > 45$ GeV and $H_T > 220$ GeV 5 events were observed while 8 ± 6 events were expected



$$m_{\tilde{q}} > 310 \text{ GeV } (m_{\tilde{q}} = m_{\tilde{g}})$$

$$m_{\tilde{q}} > 240 \text{ GeV (heavy } m_{\tilde{g}}) @ 95\% \text{ C.L.}$$

$$m_{\tilde{g}} > 240 \text{ GeV (heavy } m_{\tilde{q}})$$



Search for a Light \tilde{G}

If the gravitino is light and all other super-partners are heavy, \tilde{G} could be the only super-partner produced at Tevatron

$$q\bar{q} \rightarrow \tilde{G}\tilde{G}g \quad qg \rightarrow \tilde{G}\tilde{G}q \quad gg \rightarrow \tilde{G}\tilde{G}g$$

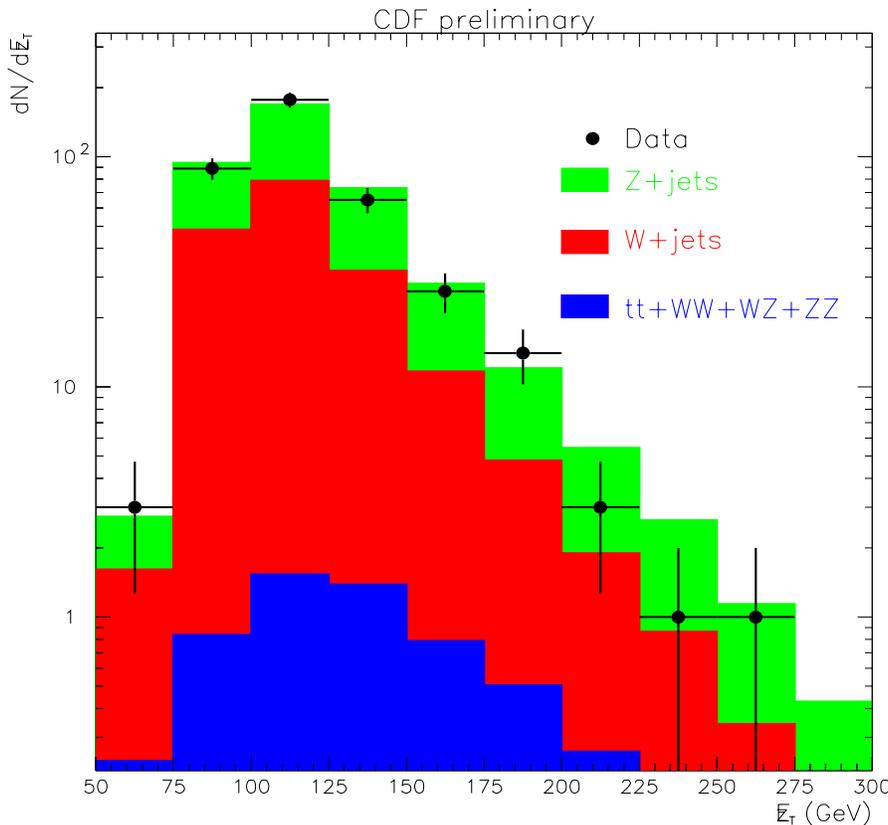
Signature: high E_T monojet events

Selection:

- $E_T > 80$ GeV for leading jet
- $\cancel{E}_T > 200$ GeV
- lepton veto and cleanup

Backgrounds:

- W/Z+jets
- top, diboson

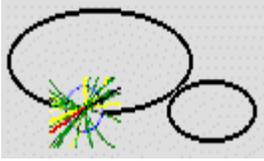


Five events
observed while
 10 ± 3 events are
expected

$$\sqrt{F} > 221 \text{ GeV}$$

$$m_{\tilde{G}} > 1.2 \times 10^{-5} \text{ eV}$$

(See the parallel session talk by Andrea Castro)



Summary

Both CDF and DØ have searched for supersymmetry in leptonic and \cancel{E}_T final states

- jets + \cancel{E}_T analyses: \tilde{t}_1 \tilde{b} \tilde{q} \tilde{g} \tilde{G}
- ll + jets + \cancel{E}_T analysis: \tilde{q} \tilde{g}
- ll + jets analysis: R_p
- lll + \cancel{E}_T analyses: $\tilde{\chi}^\pm$ $\tilde{\chi}^0$
- $llll$ analysis: R_p
- γ + jets + \cancel{E}_T analysis: $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$
- $\gamma\gamma$ + \cancel{E}_T analyses: $\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$

There are still a number of analyses going on
the effort is now being shifted toward Run II

No evidence **against** Supersymmetry

Results = Exclusions (Run I)

Results = Discoveries (Run II?)