Supersymmetry at the Tevatron
$\not$results from Run I

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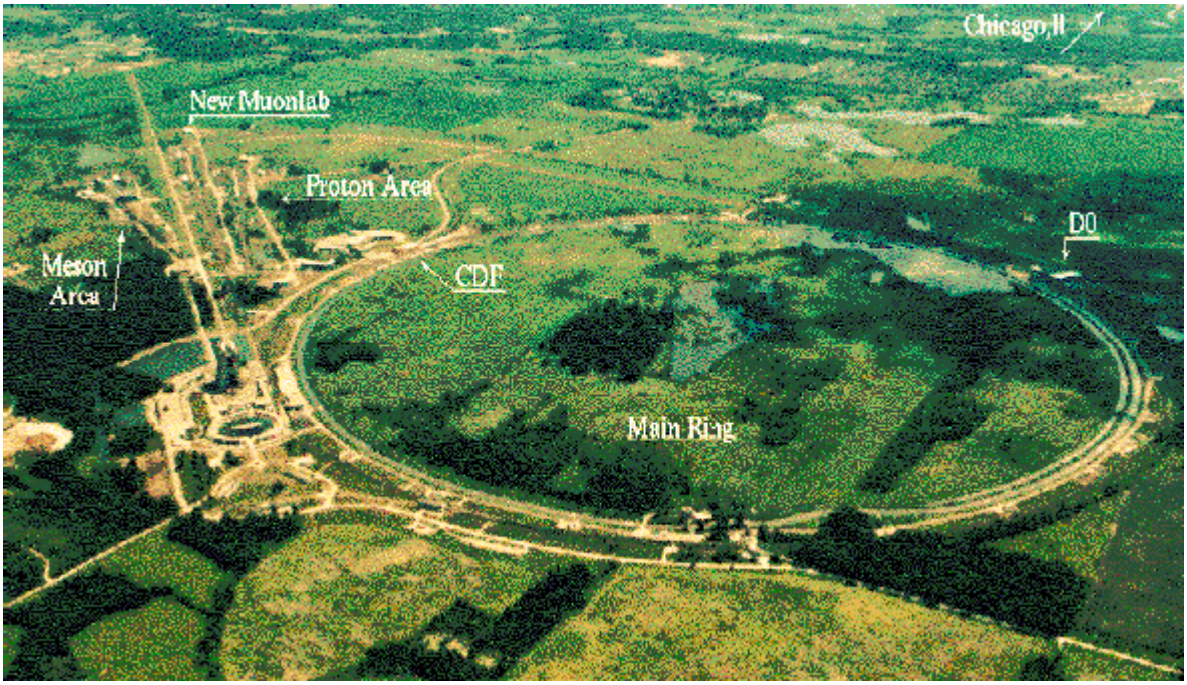
(for the CDF and DØ Collaborations)

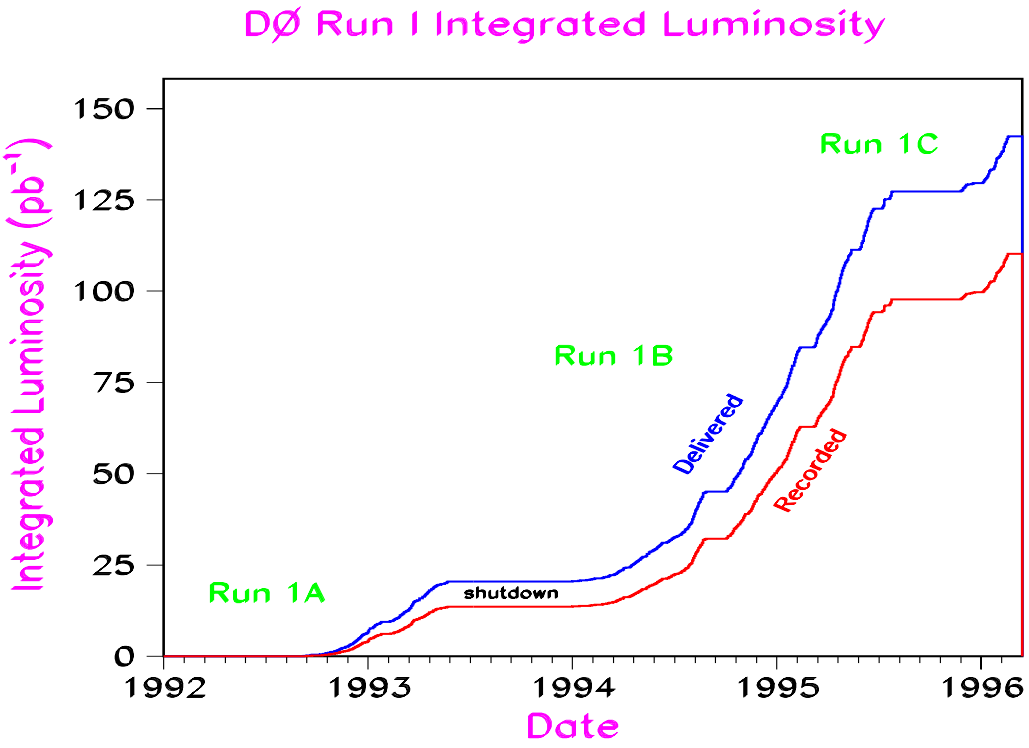
- Introduction
- Searches for Charged Higgs Bosons
- Searches with R-parity Conservation
- Searches with R-parity Violation
- GMSB Supersymmetry Searches

Supersymmetry'99 — Fermilab, June 14, 1999

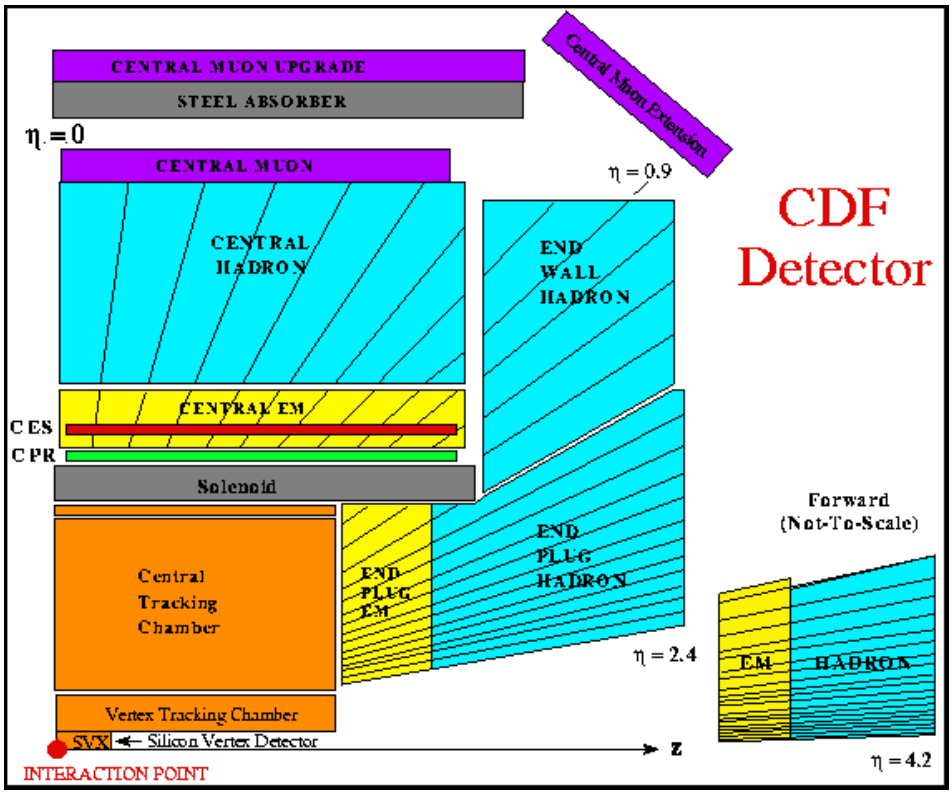
Tevatron Run I Collider



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



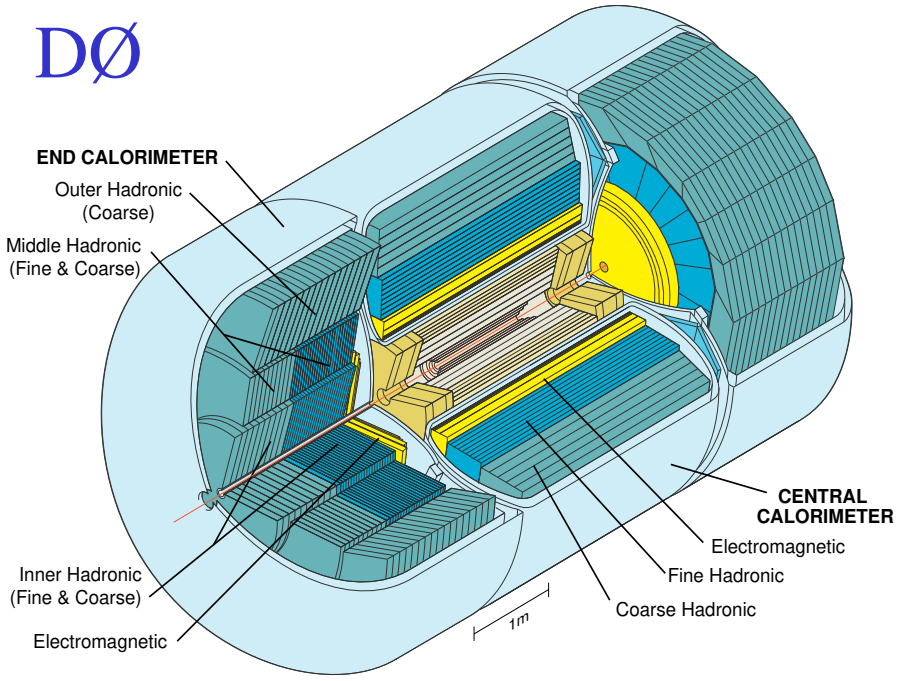
Run I Detectors



Tracking

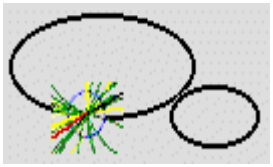
$\ell^{\pm}$ b

DØ



Calorimeter

e / γ $\not\!\!E_T$



Supersymmetry Menu

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

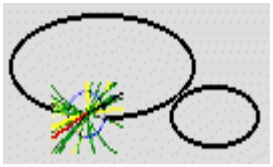
But none is what we have wanted...

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

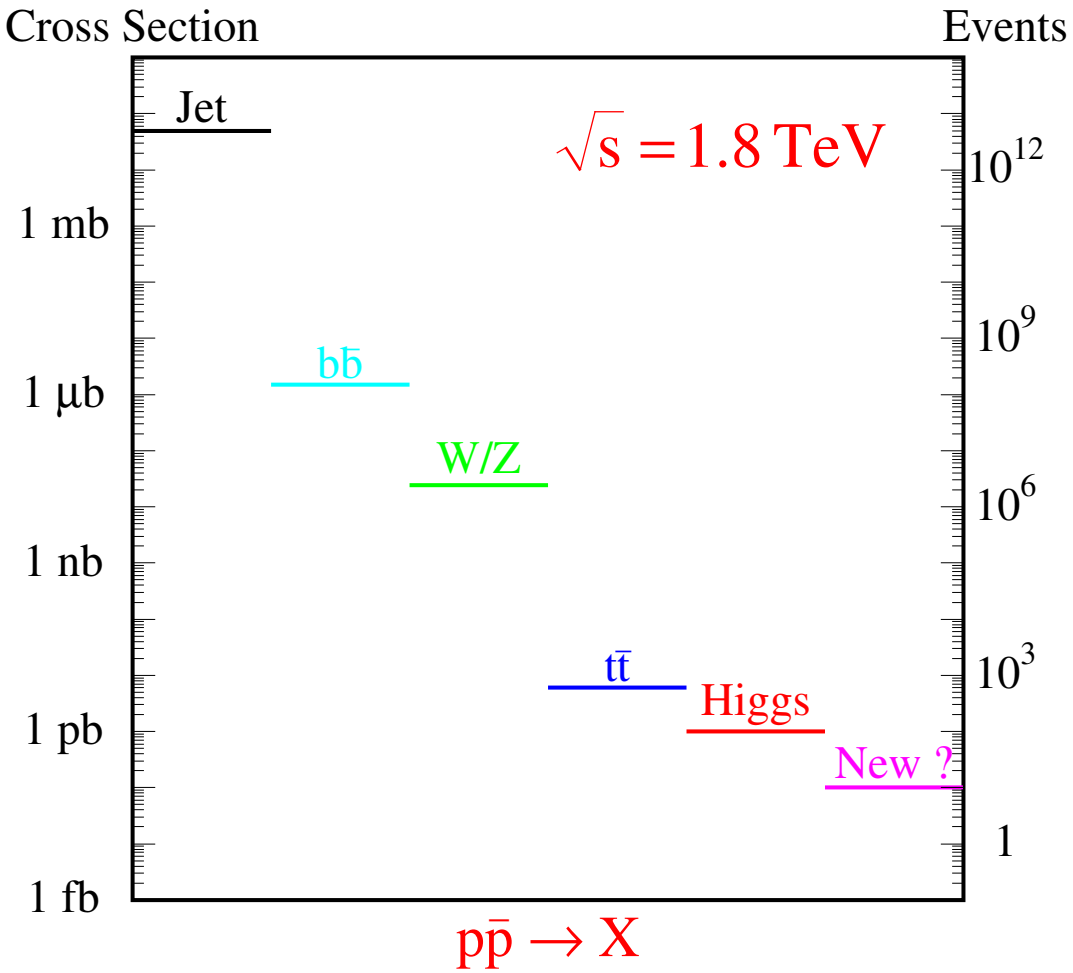
Searches with R-parity violation
dilepton+jets
four-lepton

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

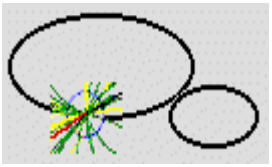
The cross section for new physics is small
compared with dominant Standard Model processes



Leptons (e, μ) and $\not\!\!E_T$ are the keys

- missing $\not\!\!E_T$ resolution
- lepton identification efficiency and fake rate

(DØ e–identification: ~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
$t \to Hb$

Therefore, it will compete with the SM mode
$t \to Wb$

Since $H^{\pm}$ and $W^{\pm}$ decay differently

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

$t \to Hb$ 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

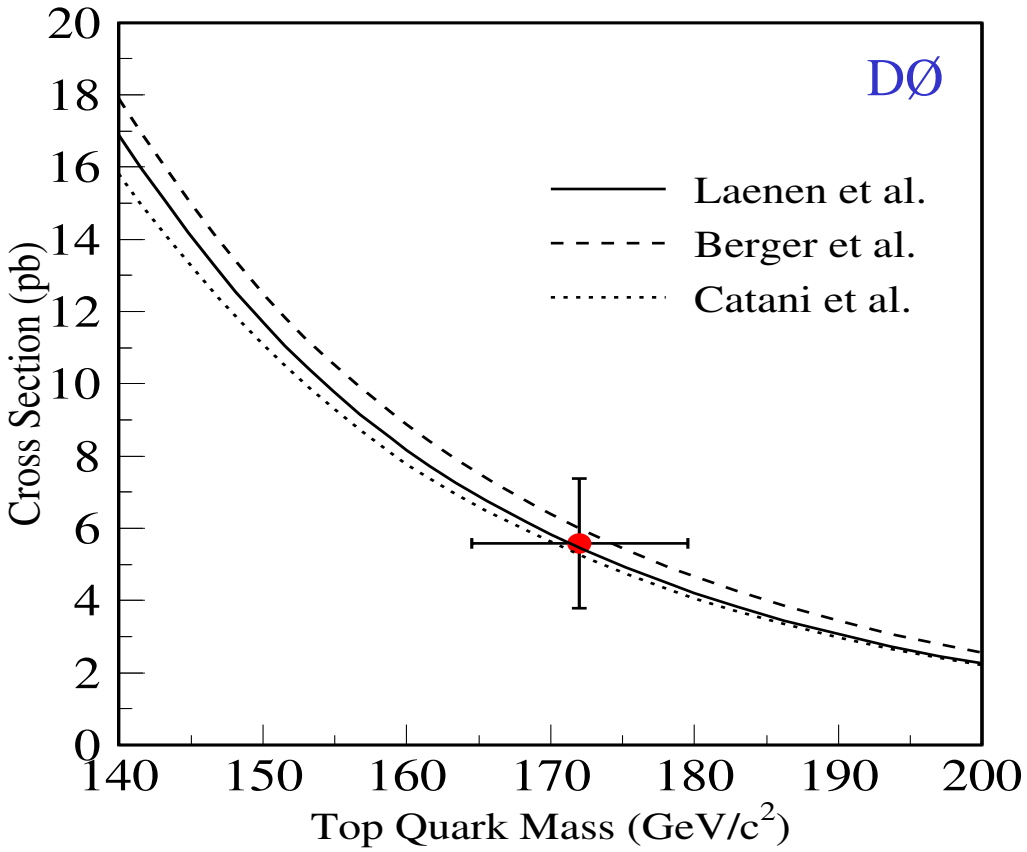
Direct searches at LEP $M_H > 69$ GeV
CLEO has set an indirect limit from $b \to s\gamma$ to be
$M_H > 244 + 63 / (\tan\beta)^{1.3}$

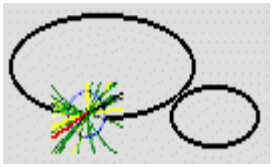
Search for Charged Higgs

DØ searched for charged Higgs bosons
in decays of pair-produced top quarks from
the disappearance of SM *WWbb* signature
hep-ex/9902028

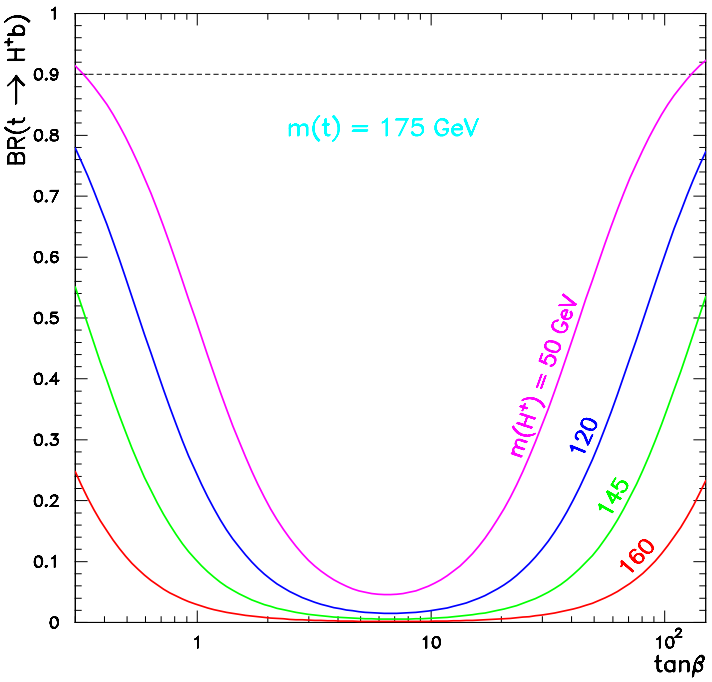
For the top quark analyses, DØ observed
30 events with 11.2±2.0 expected background events

Assuming Br(t→Wb)=100%, the measured top-pair
cross section agrees well with the SM prediction





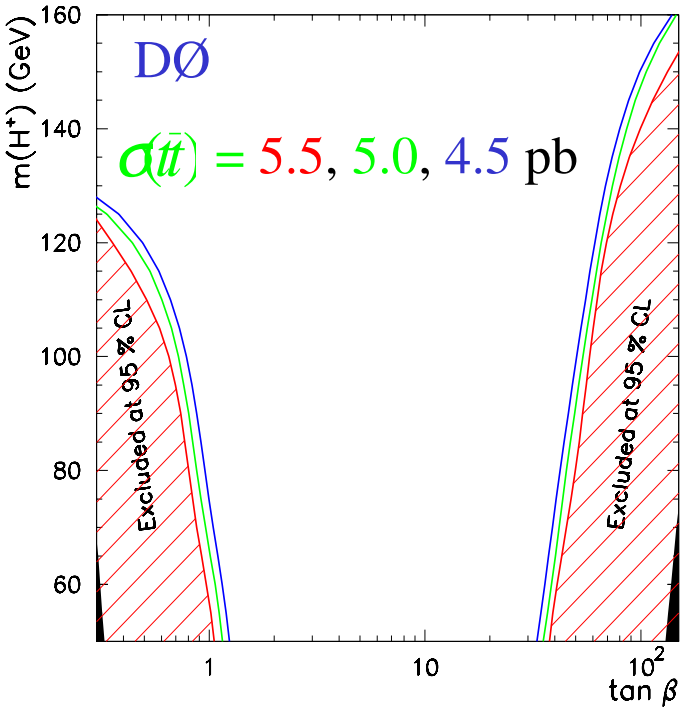
Search for Charged Higgs



Sensitive only to the regions of parameter space with large Br(t→Hb)

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

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



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 $t \to Hb$ decay via tt disappearance

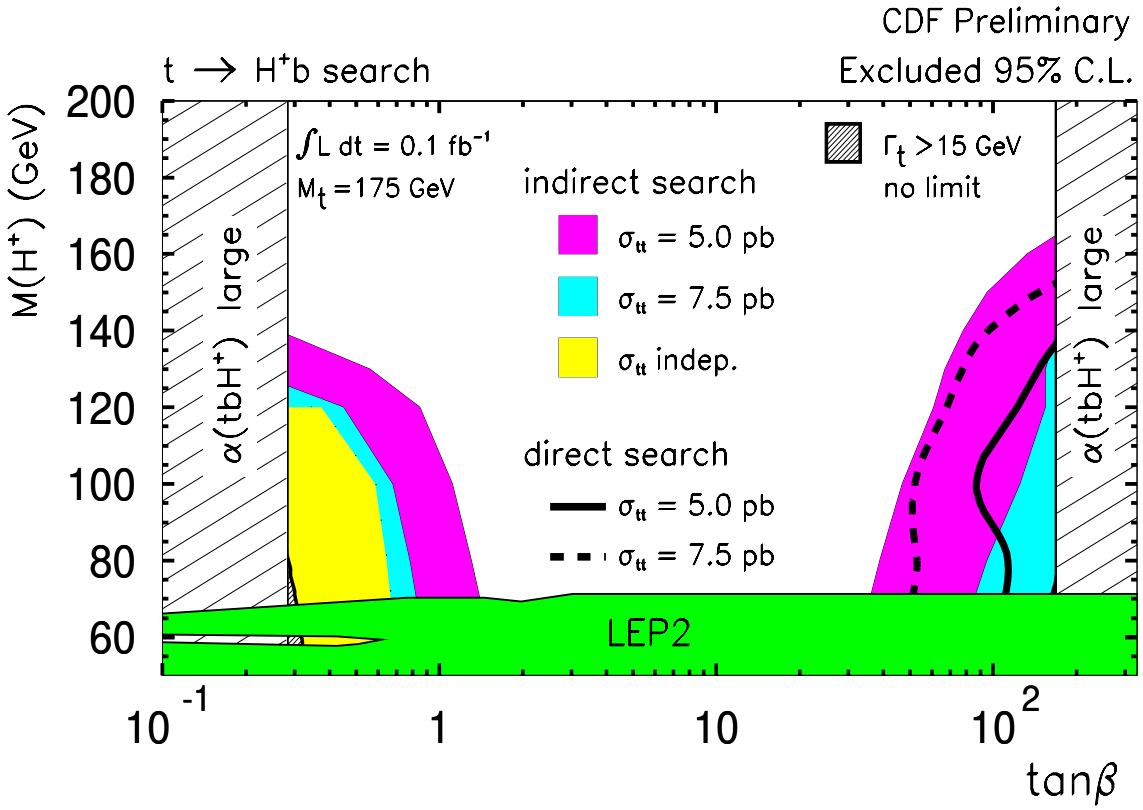
and τ appearance for high tanβ (where $H \to \tau\nu$)
Phys. Rev. D54, 735 (1996)

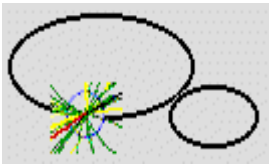
For the τ appearance analyses,
τjjX and acoplanar ττ events were searched

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

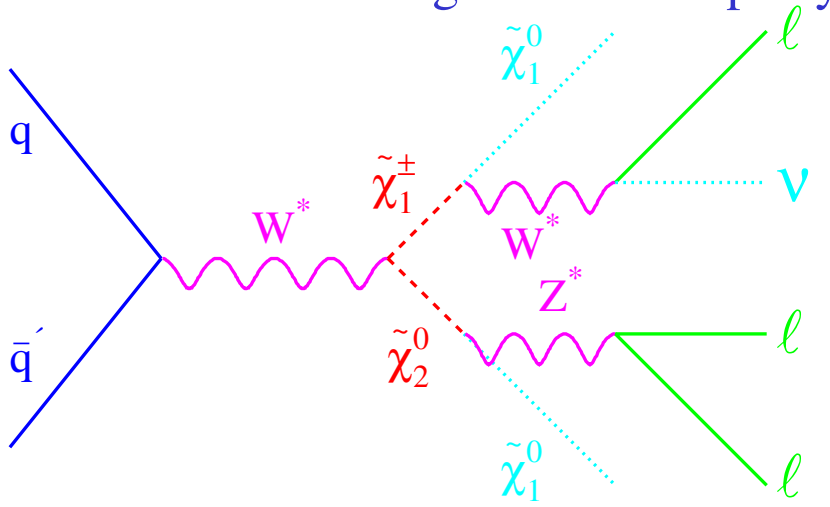
No excess of events





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 $\not{E}_T$, one of the cleanest signature for supersymmetry



Both CDF (106 pb^{-1}) and DØ (~90 pb^{-1}) searched for eee, eeμ, eμμ, μμμ events in Run I

Phys. Rev. Letters 80, 5275 (1998)

Phys. Rev. Letters 80, 1591 (1998)

Selection

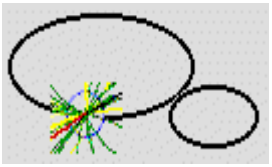
- 3 or more leptons with varying E_T
- require e^+e^- or $\mu^+\mu^-$ (CDF only)
- $\not{E}_T$>10 – 15 GeV
- lepton – lepton correlation cut
- resonance removal

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

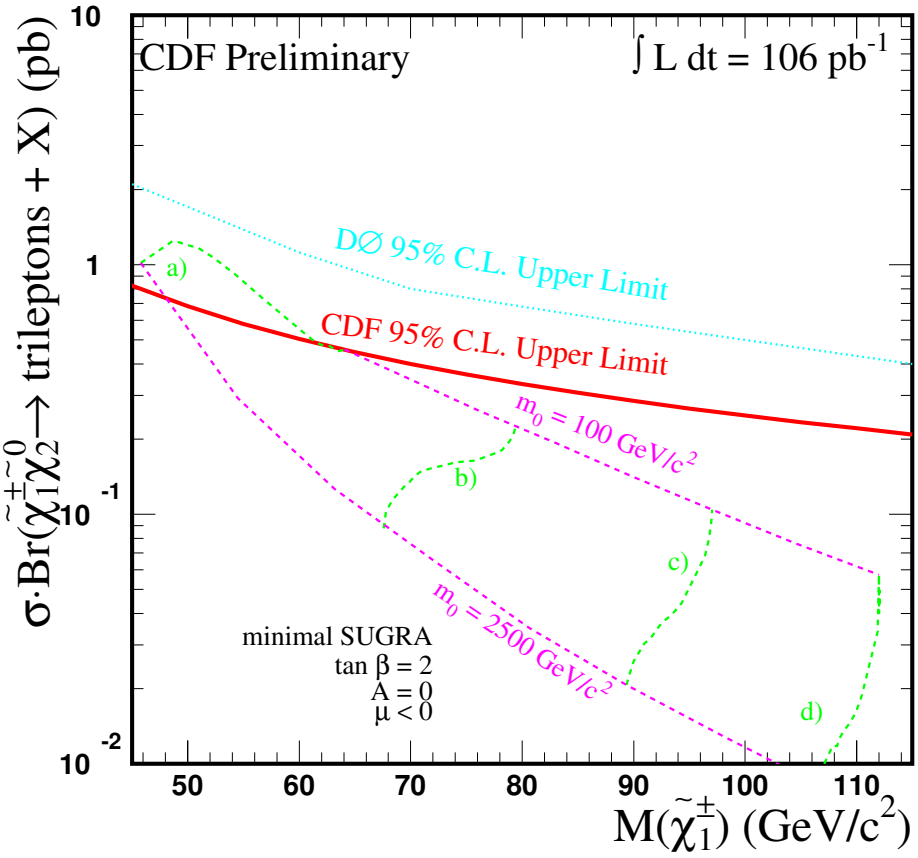


Search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ Production

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

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

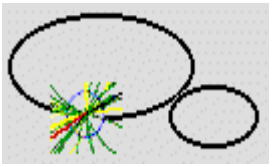
The typical efficiency is 3-12% for CDF and 2-6% for DØ when chargino mass is varied from 50 to 100 GeV



Trilepton for SUSY discovery?

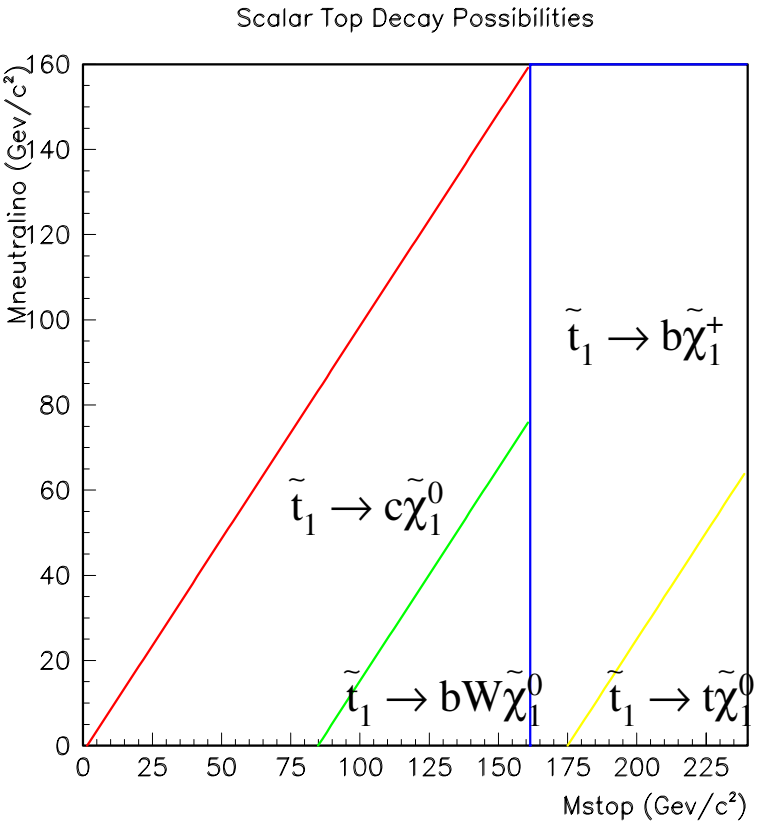
⇩

Dilepton was said top quark discovery

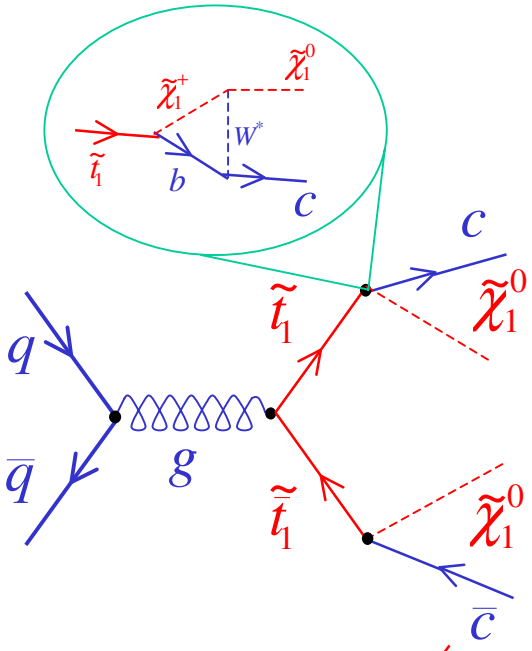


Search for Light Stop

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



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



Signature: two acoplanar charm-jets with $\not\!\!E_T$

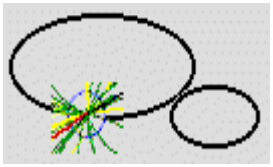
Selection (CDF):

- 2 or 3 jets with E_T>15 GeV
- $\not\!\!E_T$>40 GeV
- $\not\!\!E_T$ – 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)

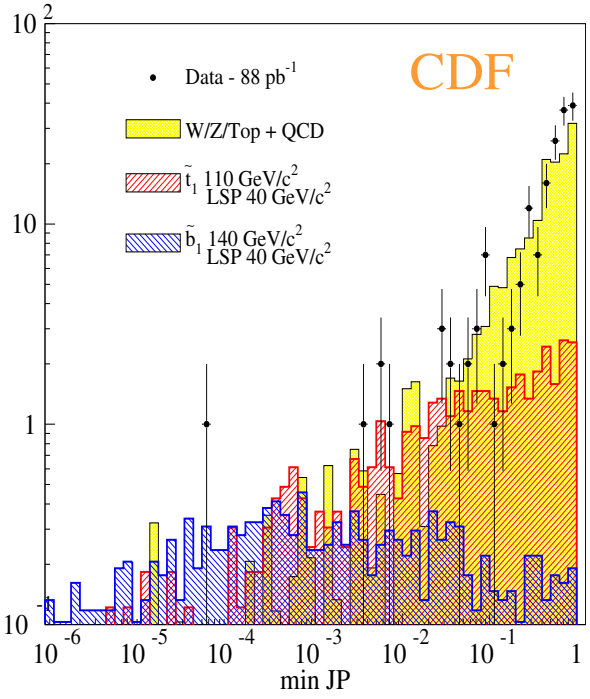


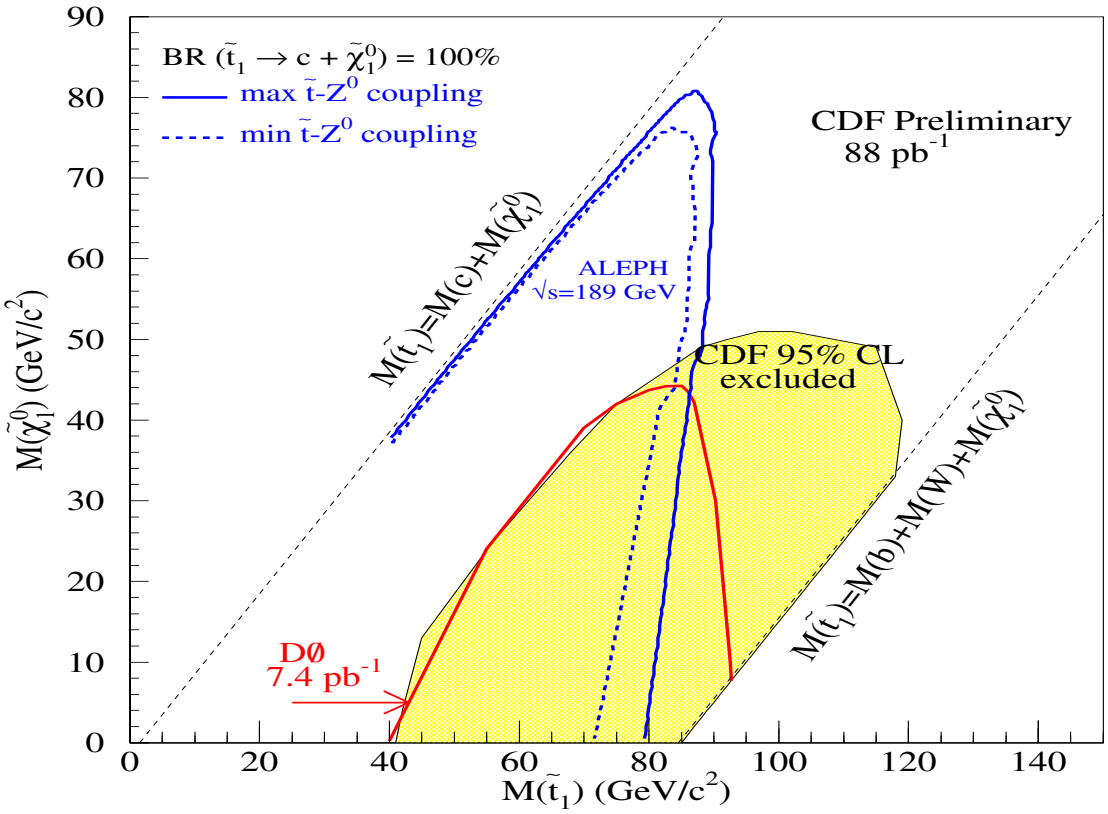
Search for Light Stop

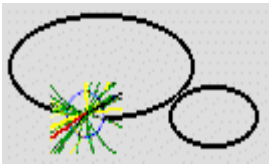
Jet probability constructed using the SVX information to tag charm-jets:
min JP < 0.05

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

No excess of events

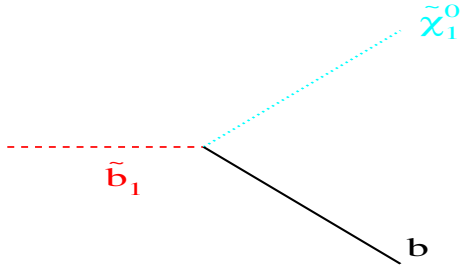






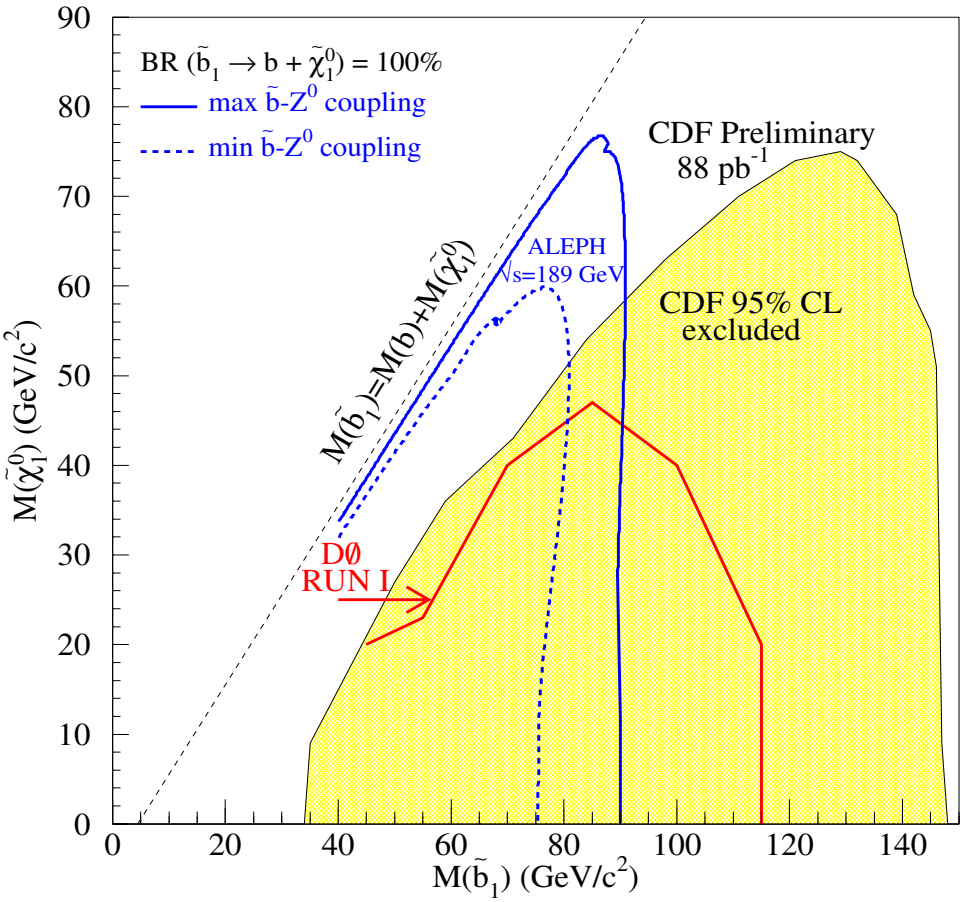
Search for Sbottom

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

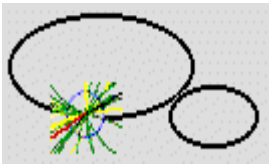


Replacing the charm-tag (min JP < 0.05) with
the b-tag (min JP < 0.01), CDF observed 5 events
with 6±2 expected background events

No excess of events

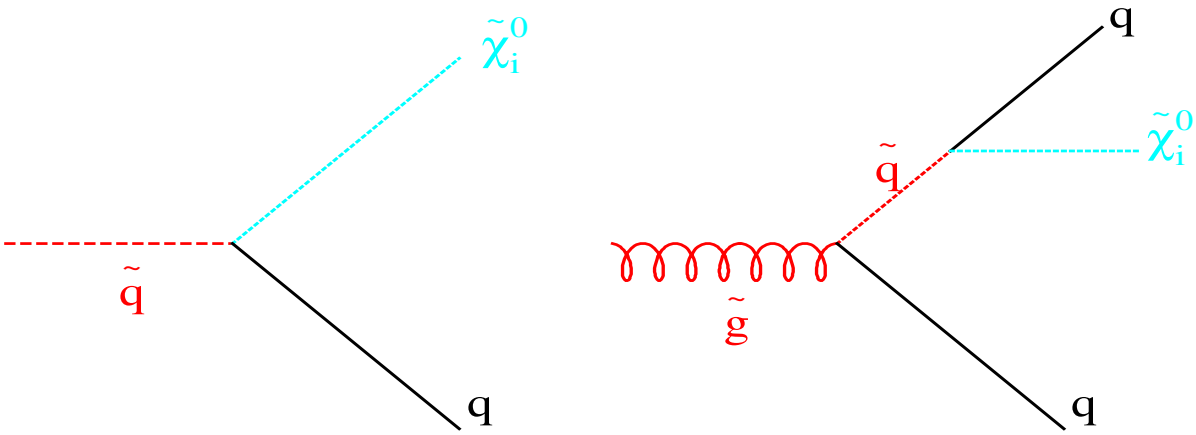


DØ carried out a similar analysis except
that b-jets have to be tagged with less efficient soft-μ



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

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



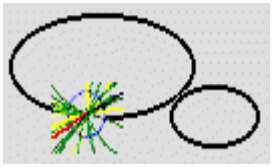
The signature for $p\bar{p} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} + X$ production is therefore jets + $\not{E}_T$ events

DØ (80 pb^{-1}) searched for events with jets+$\not{E}_T$
hep-ex/9902013

Selection:
- 3 or more jets with E_T>25 GeV
- Leading jet E_T>115 GeV
- $\not{E}_T$>75 GeV
- $\not{E}_T$ – jet correlation cut
- optimized $\not{E}_T$ – H_T cut

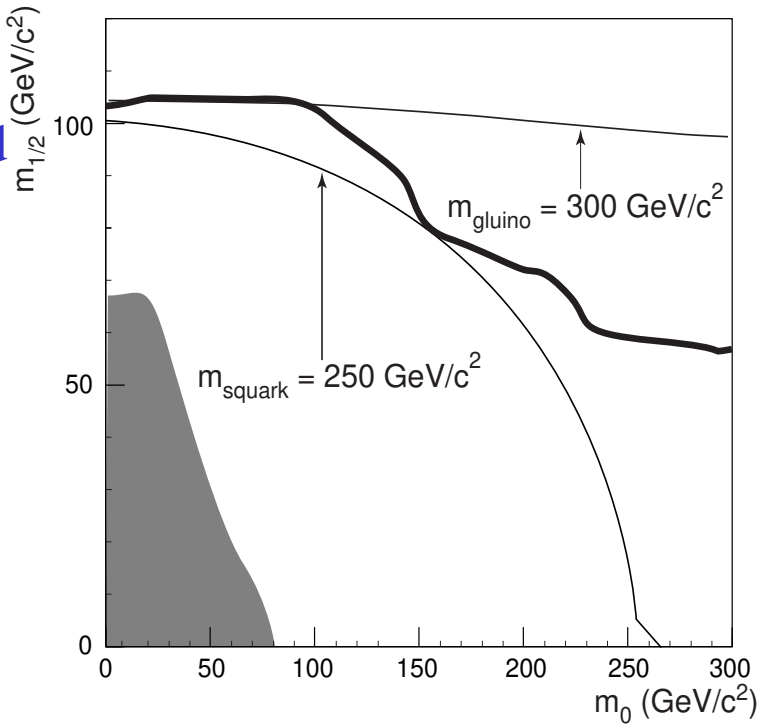
Backgrounds:
- QCD multijet
- top quark pair
- W/Z+jets

Shape analysis to estimate residual QCD background



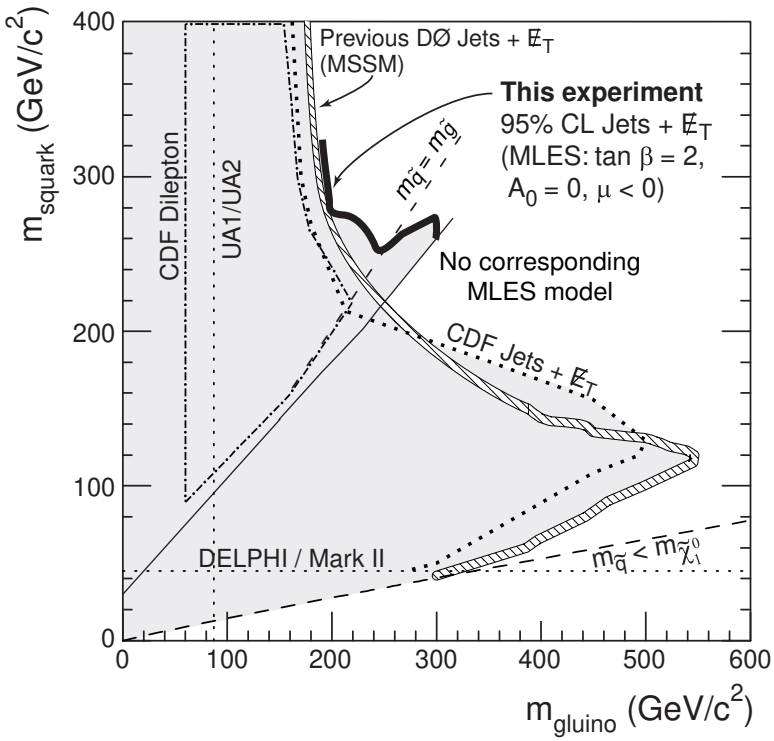
Search for $\tilde{q}$ and $\tilde{g}$

The analysis was optimized for mSUGRA models with A_0=0, tanβ=2, μ<0 using the next-to-leading order cross section by PROSPINO



No excess of events

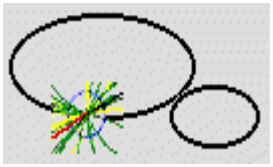
Detection efficiency is typically a few percent for the signal



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

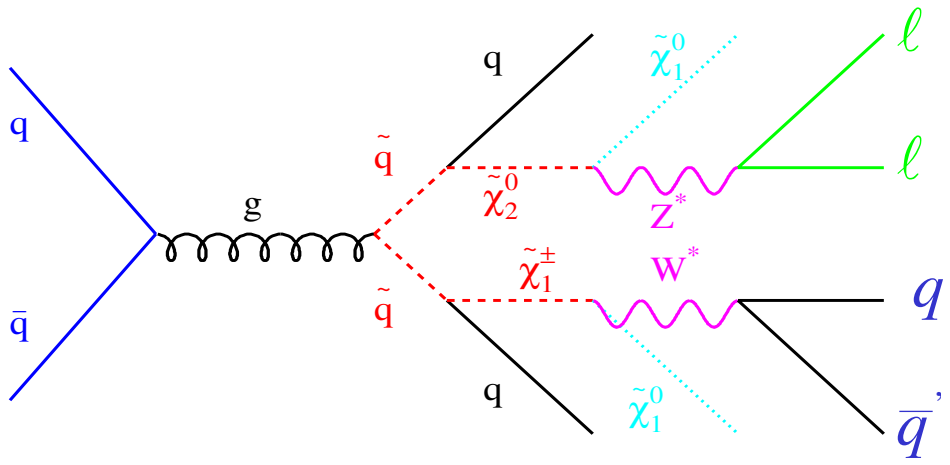
$m_{\tilde{g}} > 260$ GeV

@ 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

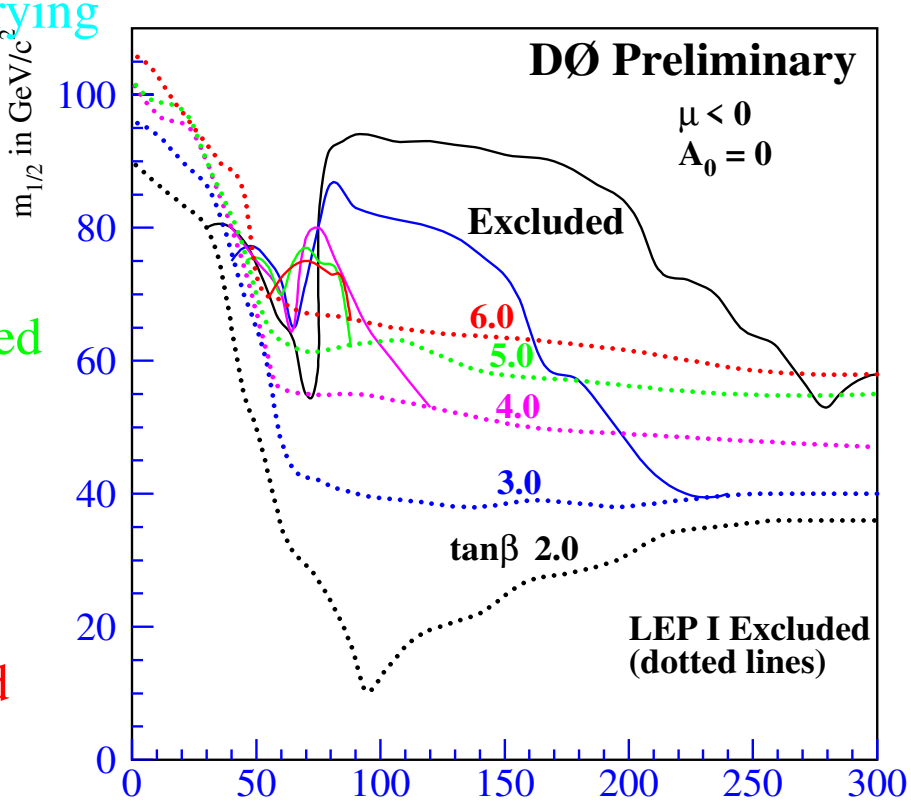
Selection:

- two leptons with varying E_T requirement
- two jets with $E_T^{min} > 20$ GeV
- $\not\!\!E_T$>20, 30, 40 GeV

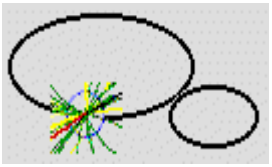
Criteria were optimized for every MC point studied to achieve maximum S-B discrimination

No excess is observed

95% C.L. Excluded Region



(see the parallel session talk by Sailesh Chopra)



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

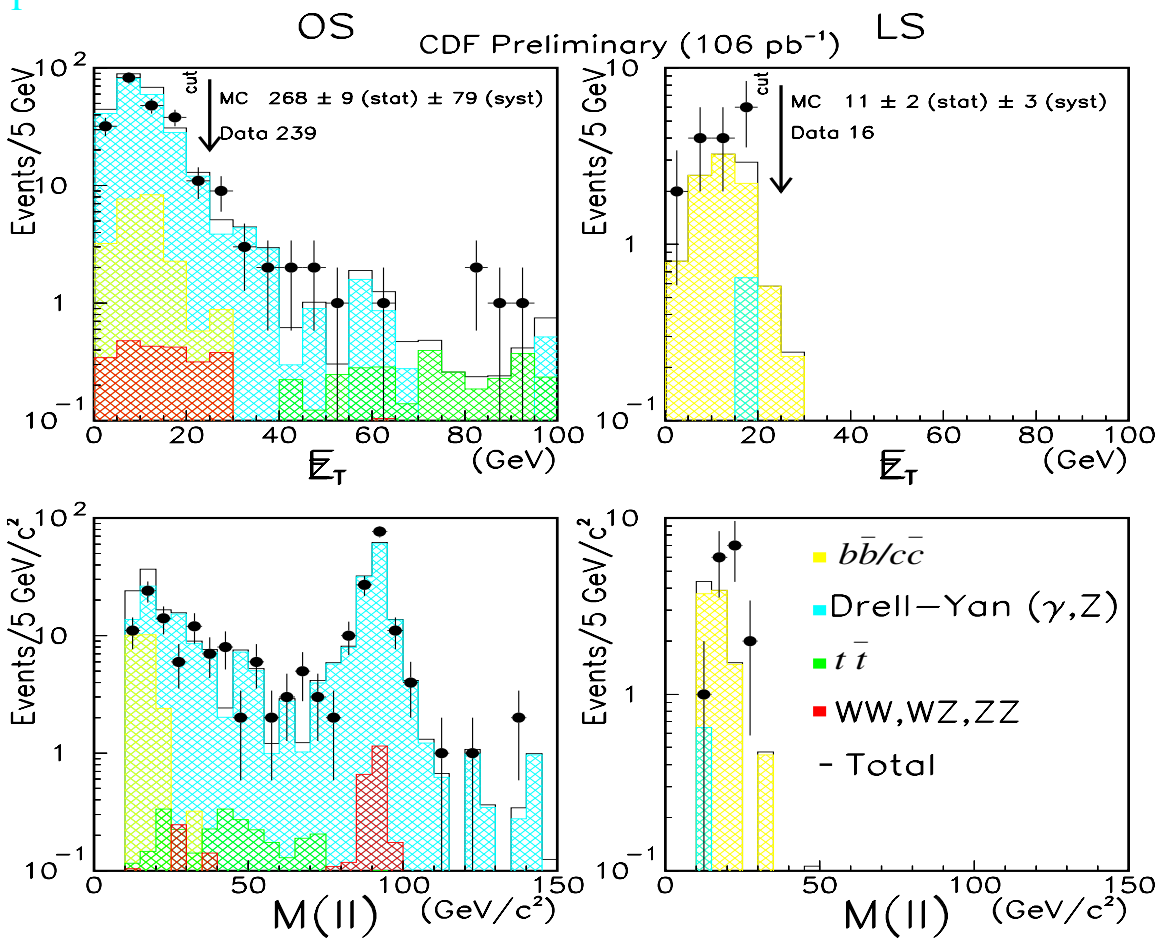
CDF searched for $\ell^{\pm}\ell^{\pm} jj$ events

Selection:

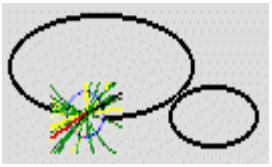
- Two like-sign leptons with E_T>11,5 GeV
- two or more with E_T>15 GeV
- dilepton mass cuts
- $\not\!\!E_T$>25 GeV

Backgrounds:

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



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

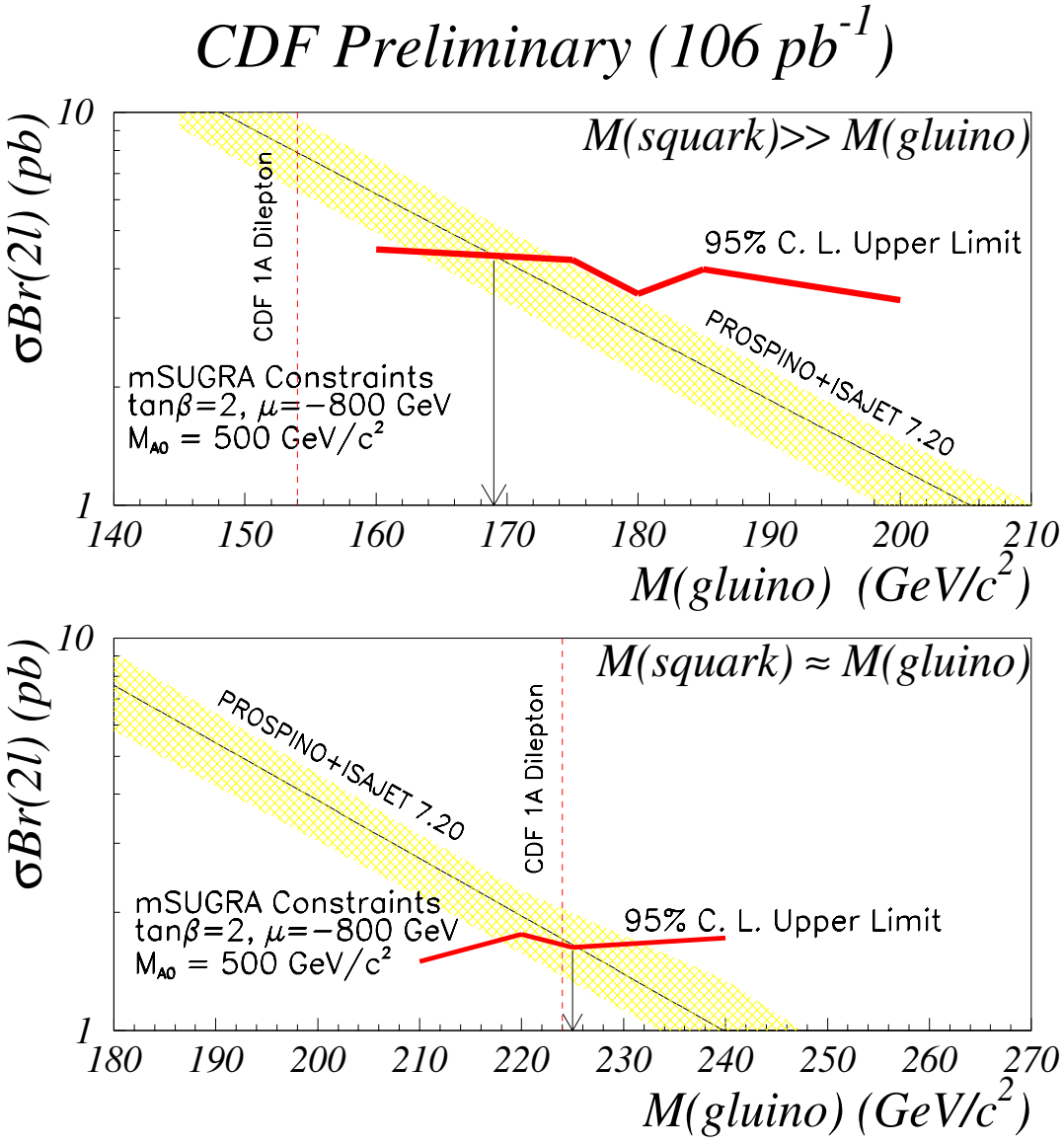


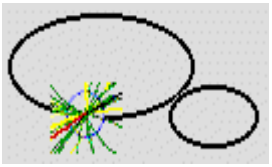
Search for $\tilde{q}$ and $\tilde{g}$

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%





Search for $\not{R}_p$ Supersymmetry

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

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

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

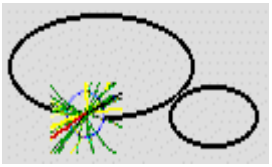
The B - violating λ''_{ijk} couplings will lead to events with multijet without $\not{E}_T$ make it impossible to study at the Tevatron

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:

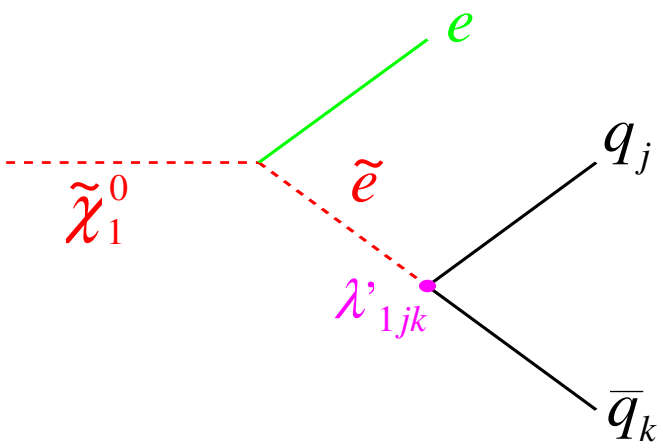
- Among all possible terms, only those R-parity violating terms with the same event topology dominate
- R_p-violating decays of $\tilde{c}$ and $\tilde{\chi}_1^0$ are considered
- The couplings are strong so that R_p-violating decays occur within the detector



Search for R_p Supersymmetry

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

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



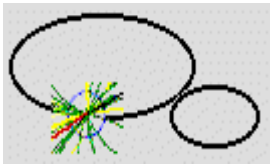
Signature: two electrons accompanied by four jets

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
- $Z \rightarrow \tau\tau \rightarrow ee$
- $tt \rightarrow ee$
- Instrumental

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

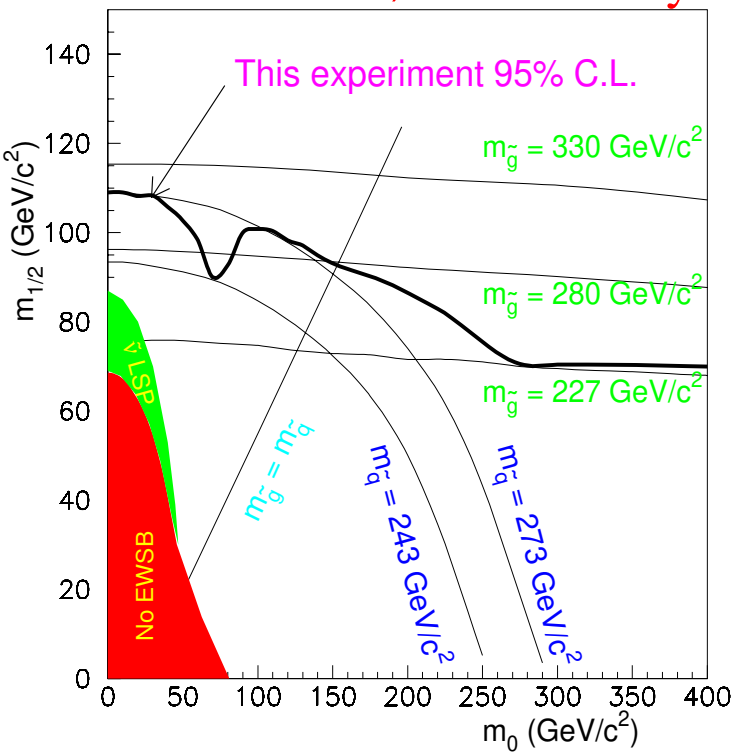
No excess of events



Search for $\not{R}_p$ Supersymmetry

DØ Preliminary

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

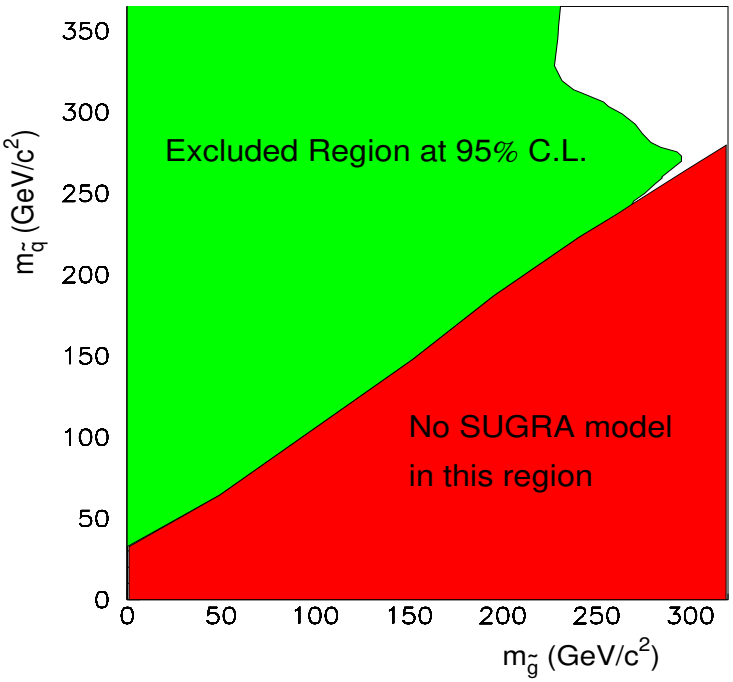


The typical $\varepsilon \cdot$Br is about 2% for the signal

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

$m_{\tilde{g}} > 230$ GeV

@ 95% C.L.

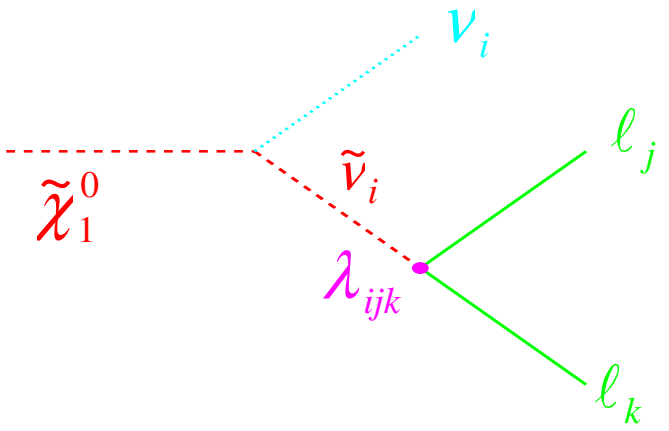


(see the parallel session talk by Sailesh Chopra)

Search for R_p Supersymmetry

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

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

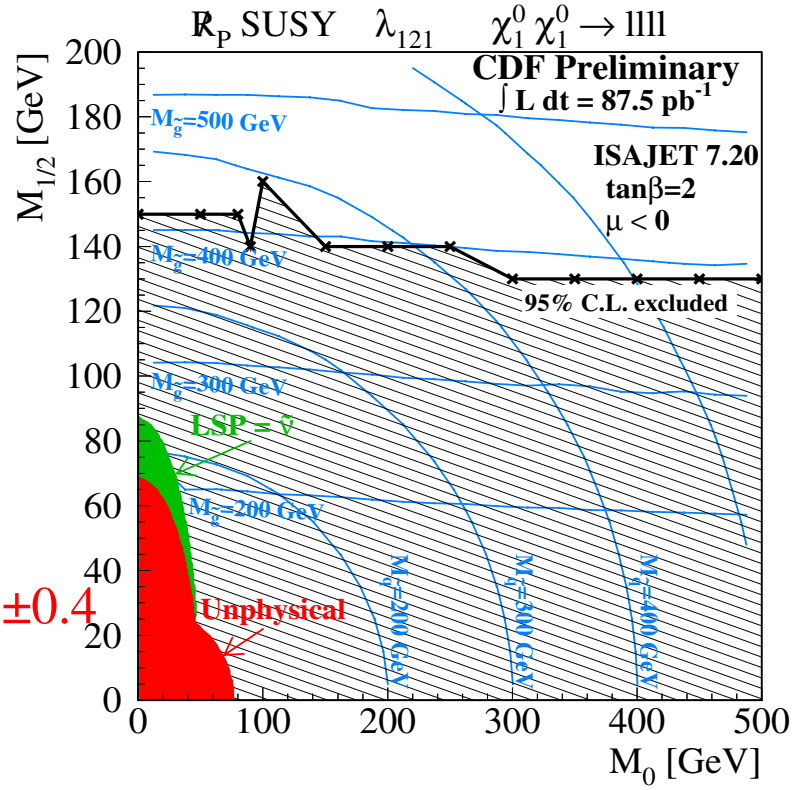


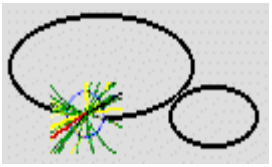
Signature: Events with four leptons

Selection:
- 4 leptons with
  E_T>12 (1), 5 (3) GeV
- ΔR_{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 $\not R_p$ Supersymmetry

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

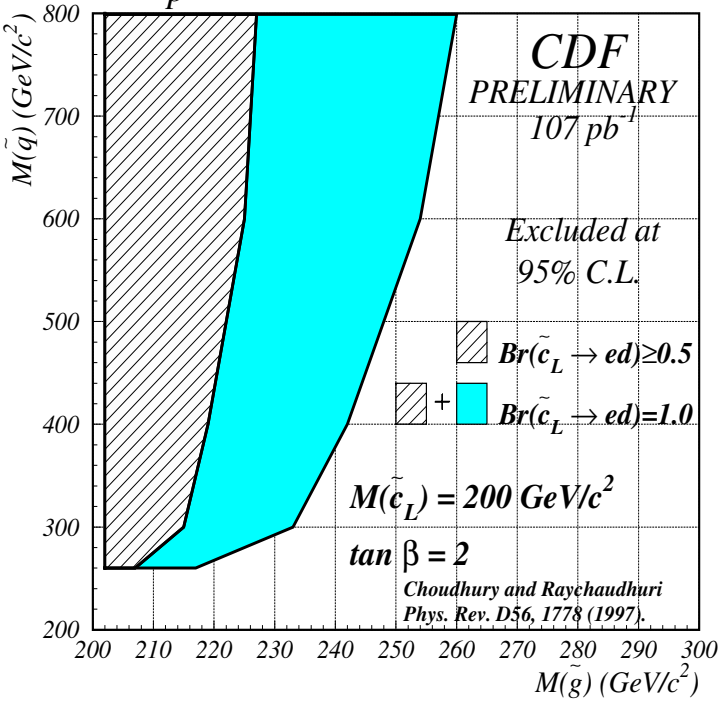
$$p\bar{p} \to \tilde{g}\tilde{g} \to (\bar{c}\tilde{c})(\bar{c}\tilde{c}) \Rightarrow \bar{c}\bar{c}(\ell^+ d)(\ell^+ d) \quad (m_{\tilde{c}} = 200\ \text{GeV})$$

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

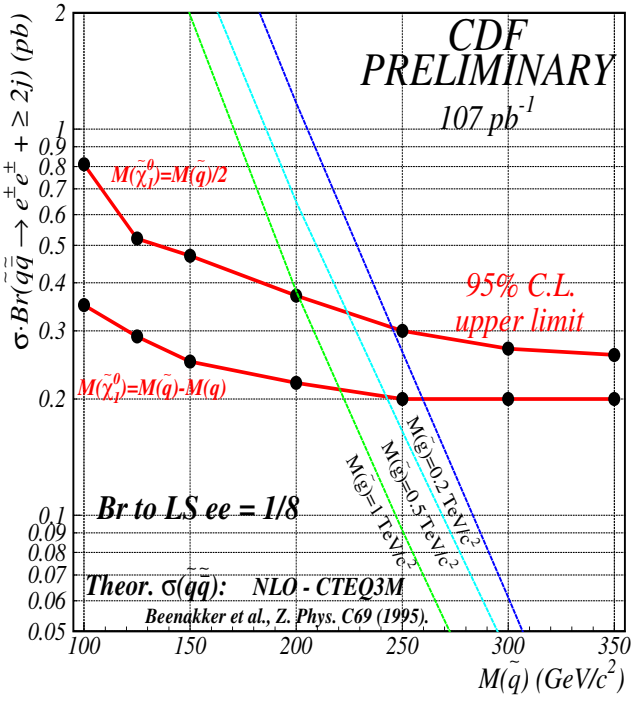
Selection
- two like-sign electrons with E_T>15 GeV
- two or more jets with E_T>15 GeV
- no significant $\not\!\!E_T$

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

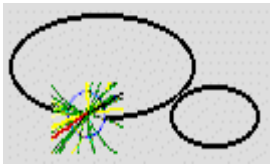
$\not R_p \quad \tilde{g}\tilde{g} \to e^{\pm}e^{\pm} + \geq 2j$



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



(See the parallel session talk by Maxwell Chertok)

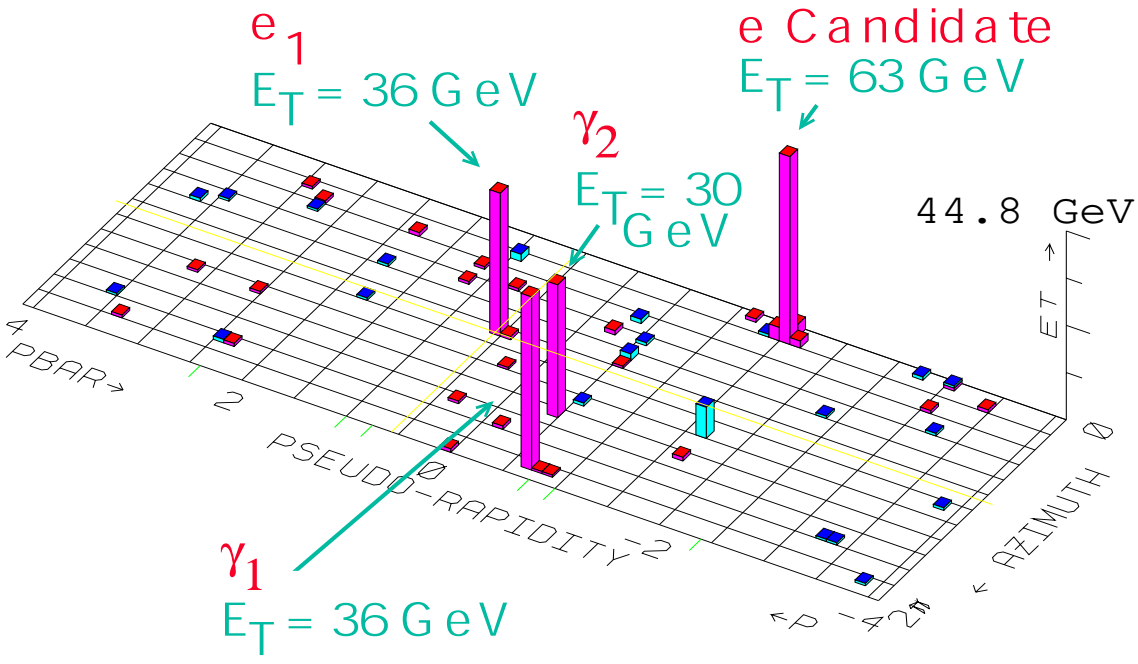


CDF $ee\gamma\gamma\not{E}_T$ Event

Much publicity has accompanied the CDF event.

It is unusual because isolated leptons, photons, and especially large $\not{E}_T$ are rare in the Standard Model

$ee\gamma\gamma\not{E}_T$ Candidate Event



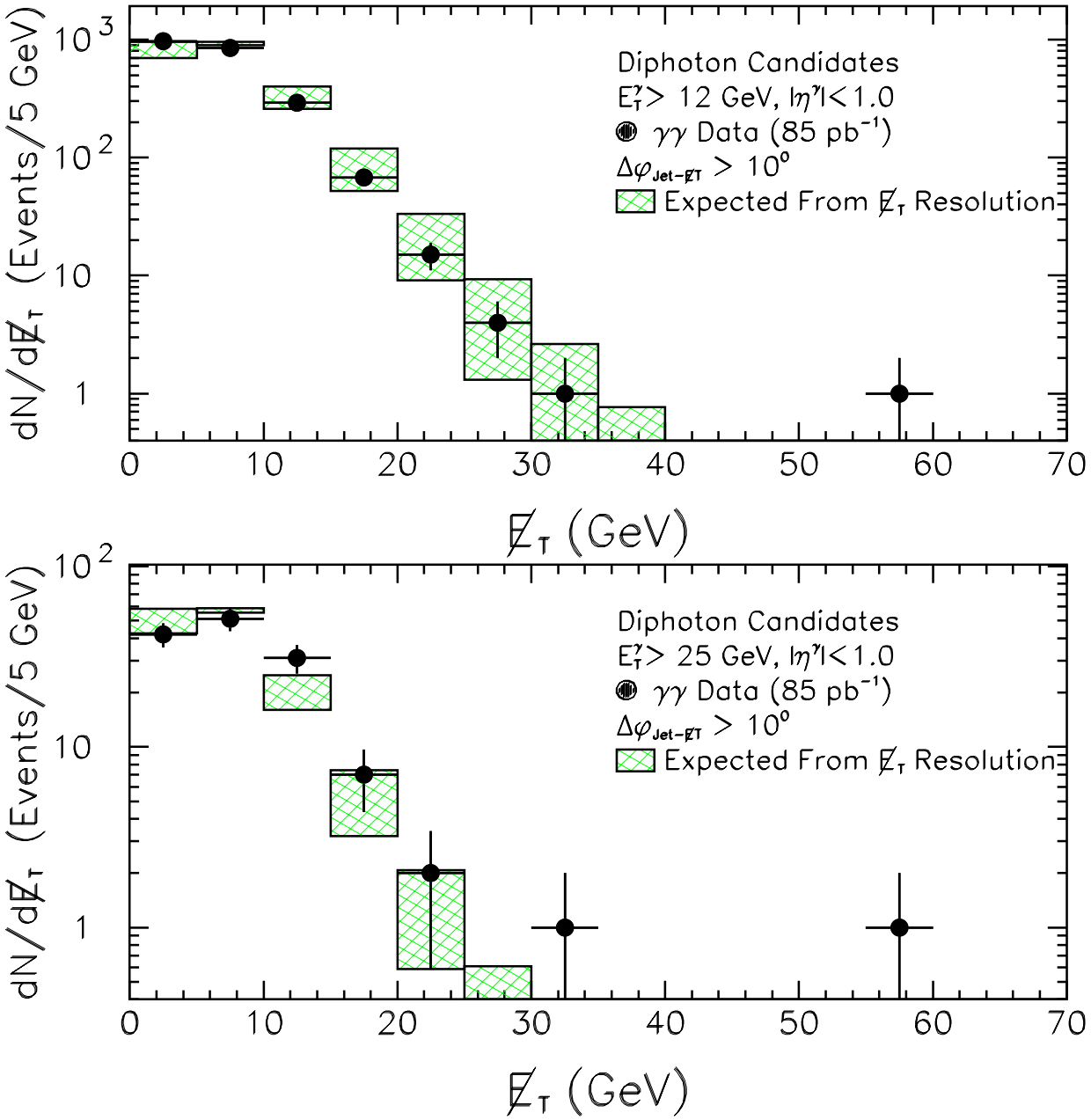
$\not{E}_T$ = 55 GeV

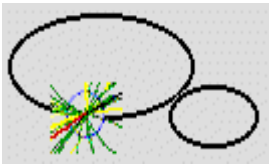
The probability for the event to be resulted from known process is small.
Phys. Rev. Letters 81, 1791 (1998)

It generated considerable theoretical interest

Search for $\gamma\gamma \not{E}_T$ Events

CDF studied the $\not{E}_T$ 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=$\tilde{\chi}_1^0$

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

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

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

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

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

decays was also proposed as an explanation of the event

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

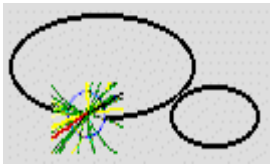
Kane et al., Phys. Rev. D55, 1372 (1997)

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

$\gamma \not{E}_T$+jets events are expected from

$p\bar{p} \rightarrow \tilde{q}/\tilde{g} \rightarrow \tilde{\chi}_2^0$+X processes



Search for $\gamma\gamma \not{E}_T$ Events

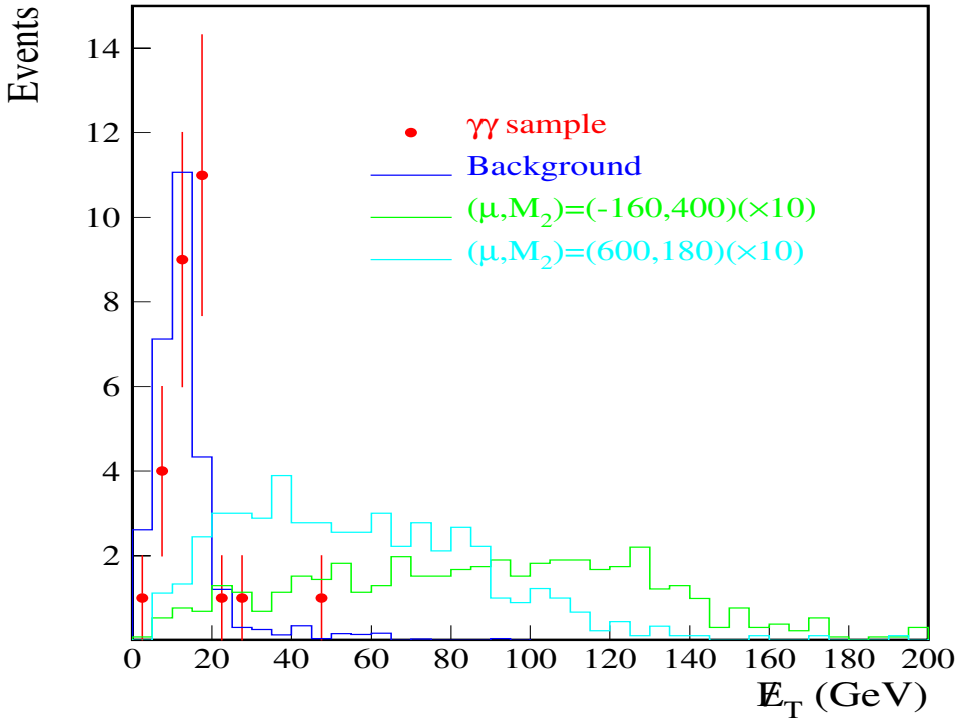
DØ (106 pb^{-1}) searched for diphoton events with large transverse energy imbalance

Phys. Rev. Letters 80, 442 (1998)

(1) $E_T^{\gamma 1} > 20$ GeV $\quad |\eta| < 1.1$ or $1.5 < |\eta| < 2.0$

(2) $E_T^{\gamma 2} > 12$ GeV $\quad |\eta| < 1.1$ or $1.5 < |\eta| < 2.0$

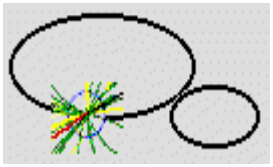
(3) $\not{E}_T > 25$ GeV



Principal Backgrounds

multijet, direct photon, Wγ, W+jets, Z→ee

Two events survived with 2.3±0.9 expected from background processes



Search for $\gamma\gamma\not{E}_T$ Events

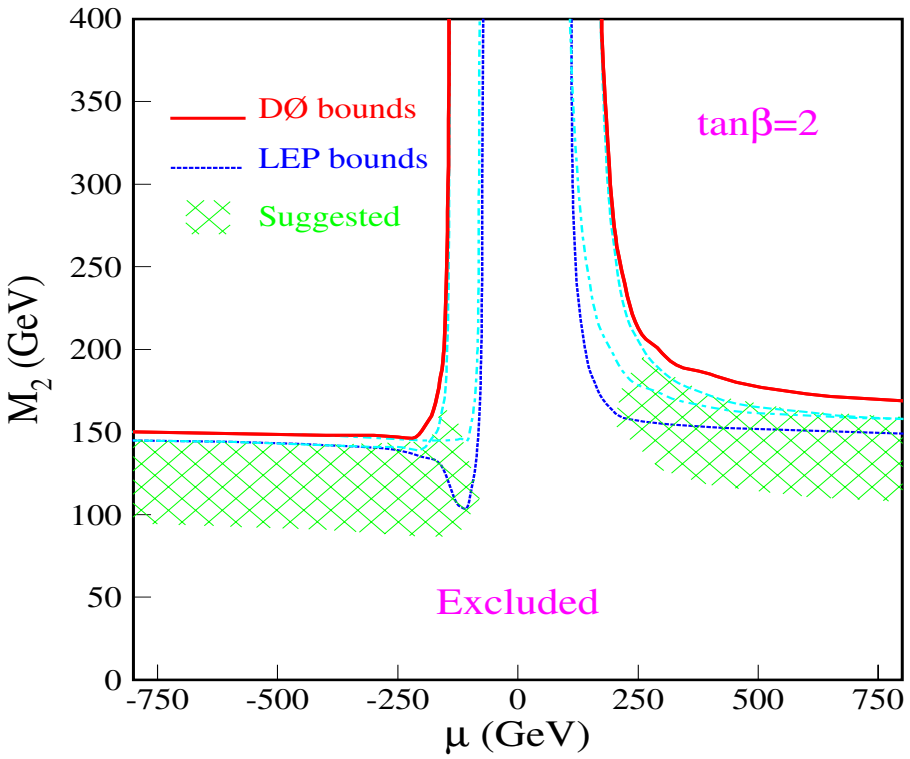
The null results were interpreted
in terms of chargino and neutralino pair production

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

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

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



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

Insensitive to the tanβ value assumed

Search for $\gamma \not{E}_T$+≥2-Jets Events

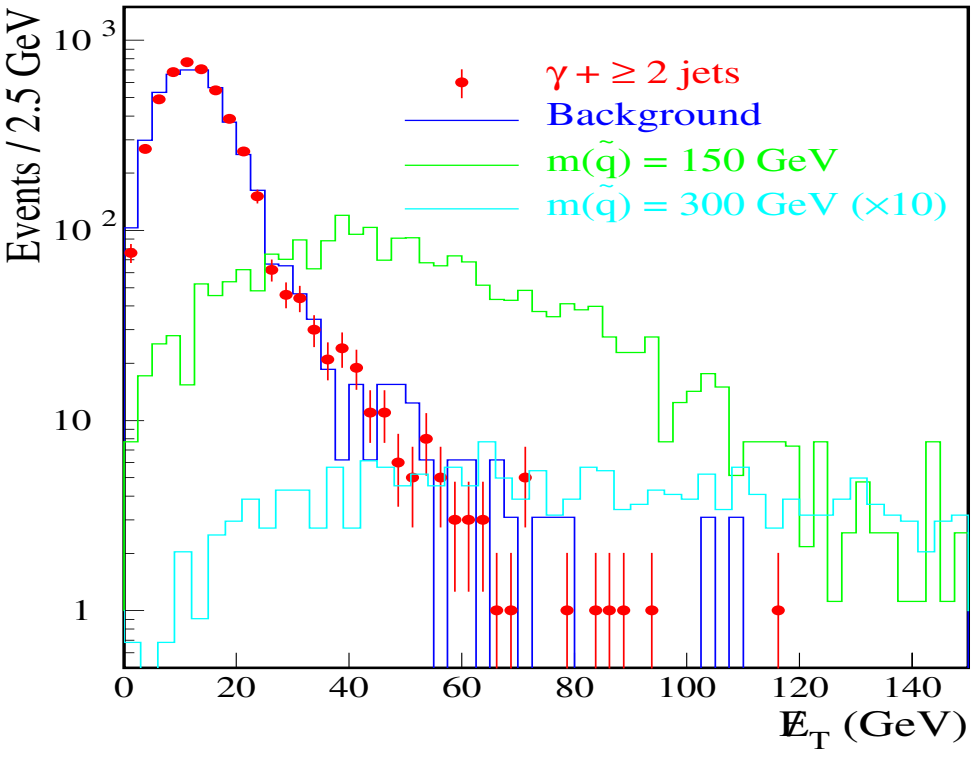
DØ (99 pb^{-1}) also searched for single-photon events with jets and large missing transverse energy

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 $|\eta| < 2.0$

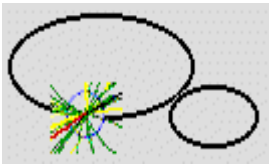
(3) $\not{E}_T > 25$ GeV



Principal Backgrounds

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

318 events selected with 320±20 events expected

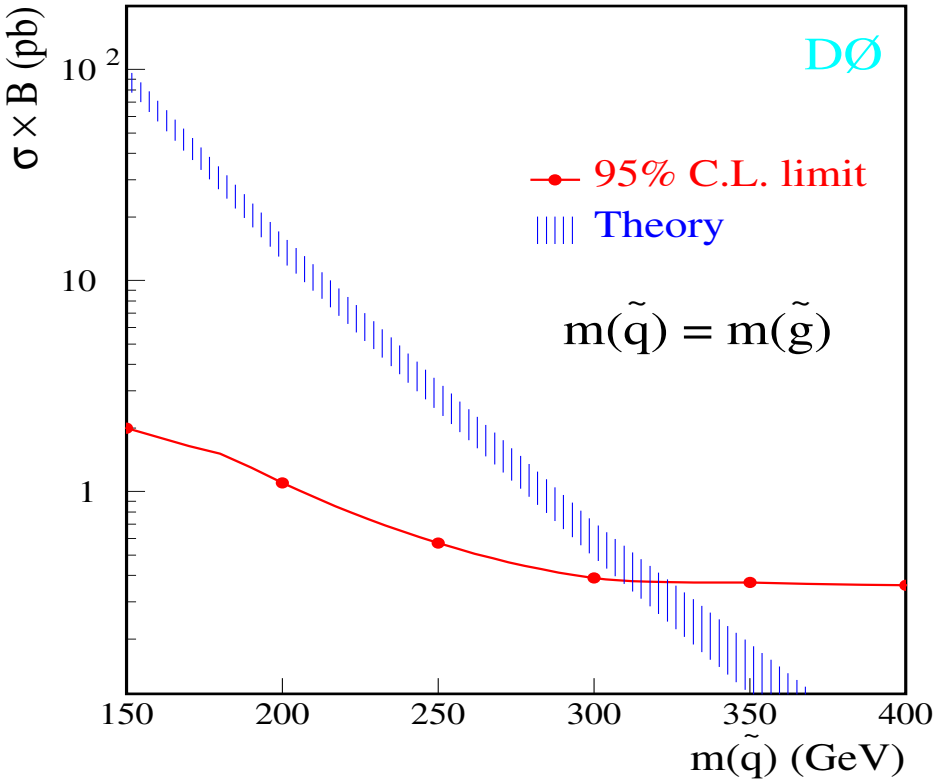


Search for $\gamma \not{E}_T$+≥2-Jets Events

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 $\not{E}_T$–H_T plane

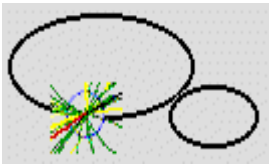
For the optimized cuts $\not{E}_T$>45 GeV and H_T>220 GeV 5 events were observed while 8±6 events were expected



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

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

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



Search for a Light $\tilde{G}$

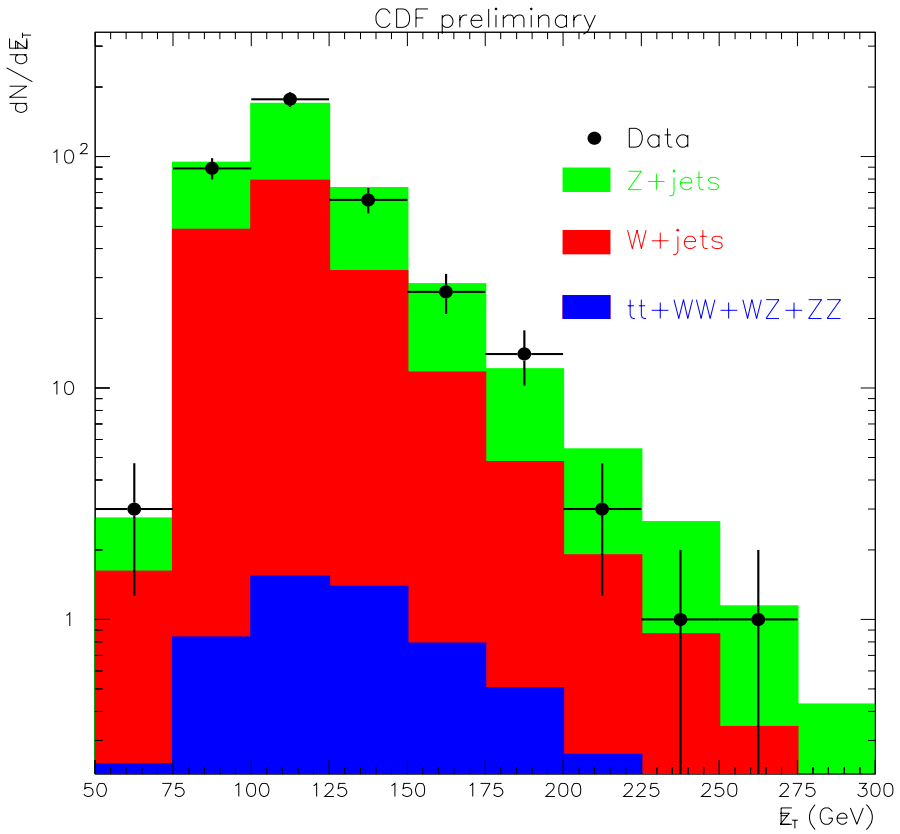
If the gravitino is light and all other super-partners are heavy, $\tilde{G}$ could be the only super-partner produced at Tevatron

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

Signature: high E_T monojet events

Selection:
- E_T>80 GeV for leading jet
- $\not\!\!E_T$>200 GeV
- lepton veto and cleanup

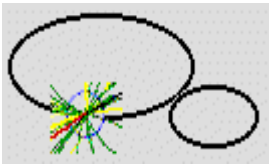
Backgrounds:
- W/Z+jets
- top, diboson



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 $\not\!\!E_T$ final states

- jets + $\not\!\!E_T$ analyses: $\tilde{t}_1$ $\tilde{b}$ $\tilde{q}$ $\tilde{g}$ $\tilde{G}$
- $\ell\ell$ + jets + $\not\!\!E_T$ analysis: $\tilde{q}$ $\tilde{g}$
- $\ell\ell$ + jets analysis: R_p
- $\ell\ell\ell$ + $\not\!\!E_T$ analyses: $\tilde{\chi}^{\pm}$ $\tilde{\chi}^0$
- $\ell\ell\ell\ell$ analysis: R_p
- γ + jets + $\not\!\!E_T$ analysis: $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$
- $\gamma\gamma$ + $\not\!\!E_T$ 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

Sresults = Exclusions (Run I)

Results = Discoveries (Run II?)