SUSY Searches at the Tevatron

Run I Results and Run II Prospects

On behalf of CDF-DØ collaborations

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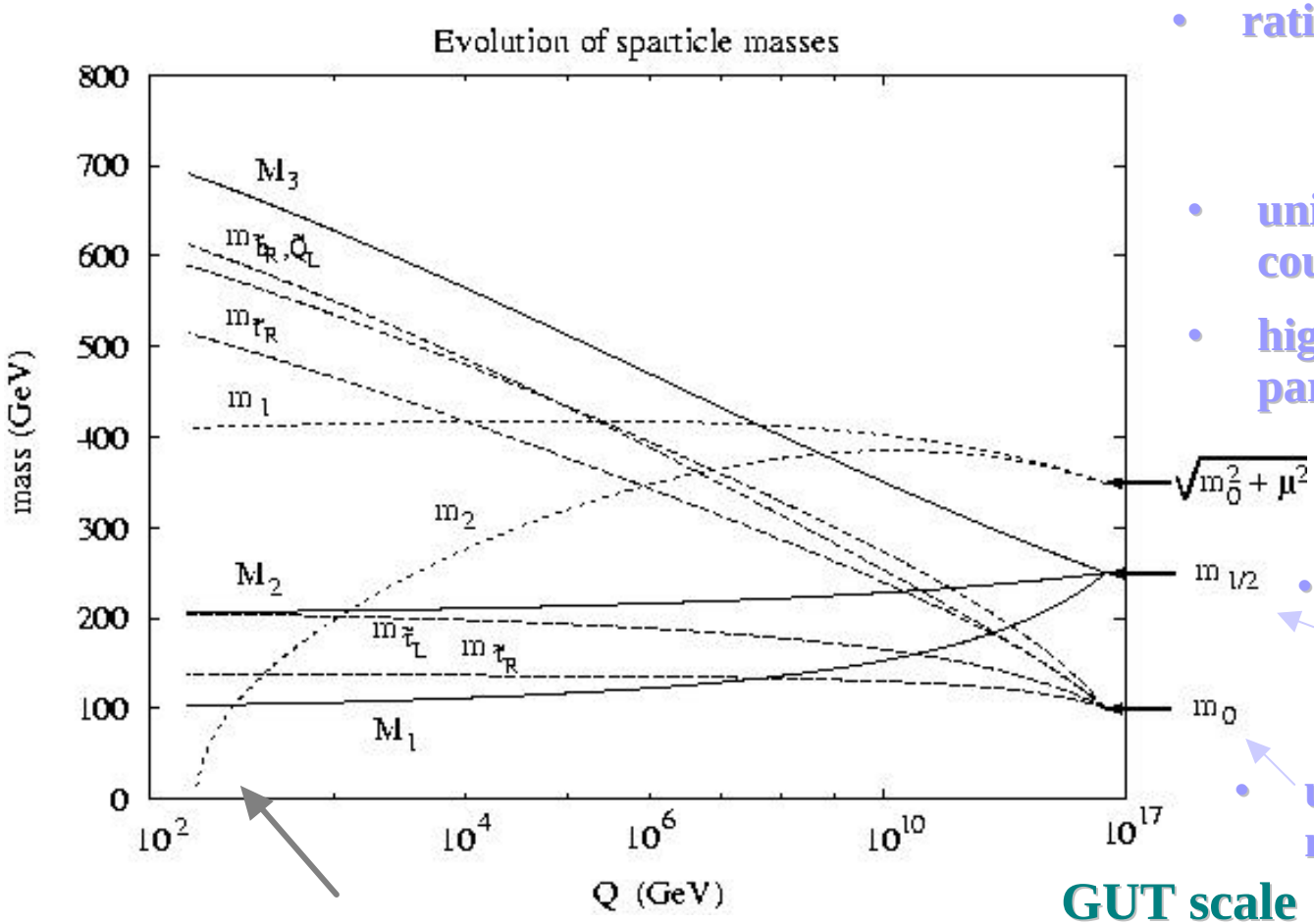
(CPPM-Marseille, France)

The Famous 4 + sign(m) SUGRA Parameters



- ratio of Higgs vev's : $\tan b$
- universal trilinear coupling : A_0
- higgs mixing parameter
- universal gaugino mass
- universal scalar mass

GUT scale

Radiative Electroweak Symmetry Breaking $\Rightarrow |m|$

Mass Relations in SUGRA

$M_{\tilde{g}} \simeq 3\ M_2$ $\qquad m_{1/2} \approx 1.2\ M_2$

$M_{\tilde{\chi}_1^\pm} \simeq M_2$ (gaugino region)

$M_{\tilde{\chi}_1^0} \simeq 0.5\ M_2$ (gaugino region)

Gaugino mass unification

and .....

$M_{\tilde{\nu}}^2 = m_0^2 + 0.77 M_2^2 + 0.5 M_Z^2 cos(2\beta)$

$M_{\tilde{e}_L}^2 = m_0^2 + 0.77 M_2^2 - 0.27 M_Z^2 cos(2\beta)$

$M_{\tilde{e}_R}^2 = m_0^2 + 0.22 M_2^2 - 0.23 M_Z^2 cos(2\beta)$

$M_{\tilde{q}}{}^2 \sim m_0^2 + 10 M_2^2 + O(M_Z^2 cos(2\beta))$

$\pm$ (splitting term)

Sfermion unification

Mixing : mass splitting for $\tilde{t}, \tilde{b}, \tilde{t}$

$A_t - m / \tan b$,

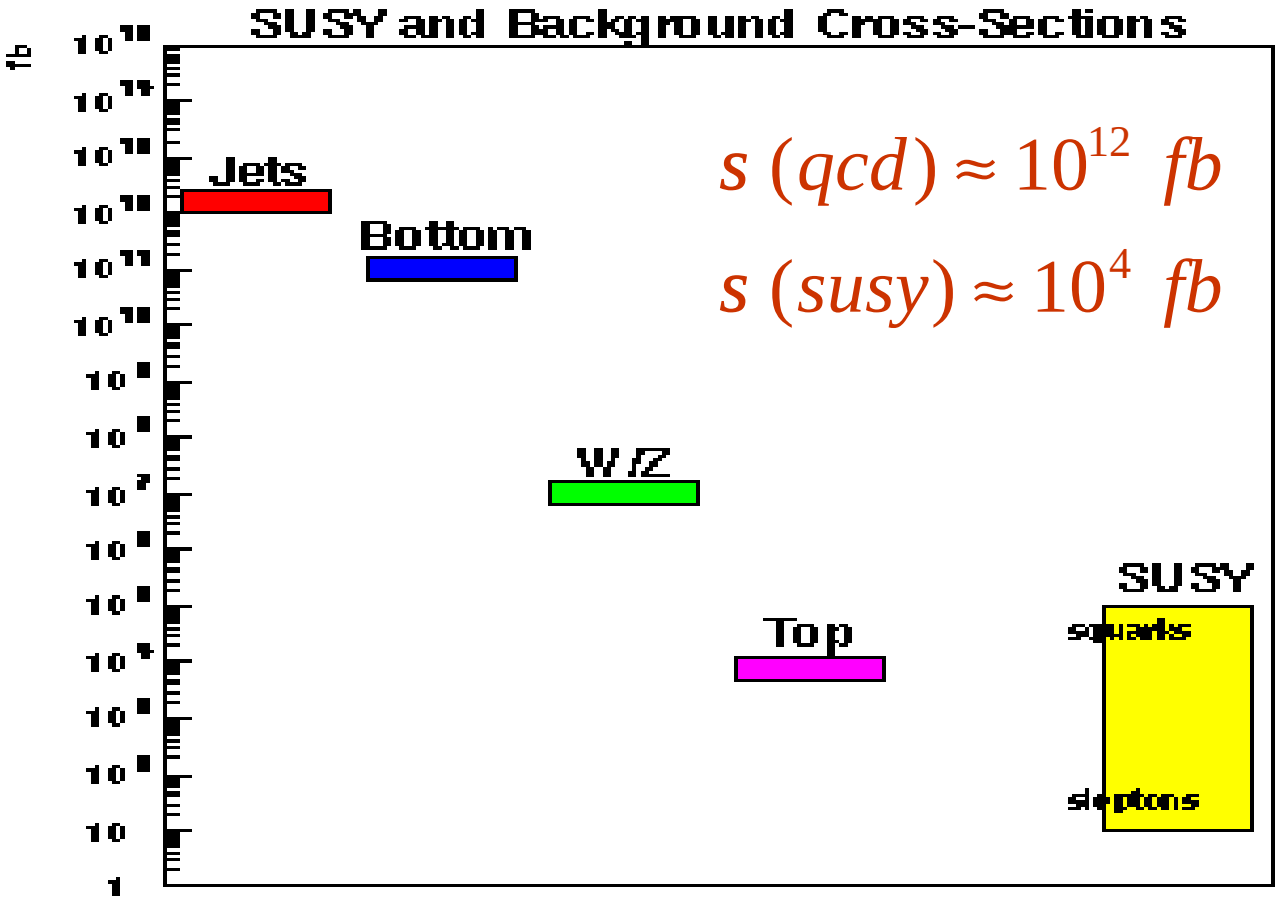
$A_b - m \tan b$,

$A_t - m \tan b$,

RPC = R-Parity Conserved

Background Cross Sections

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



$$s\,(qcd) \approx 10^{12}\ fb$$

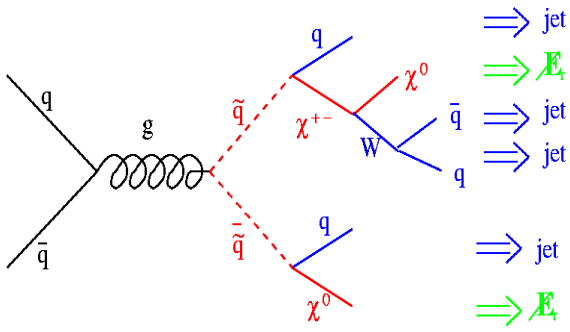
$$s\,(susy) \approx 10^{4}\ fb$$

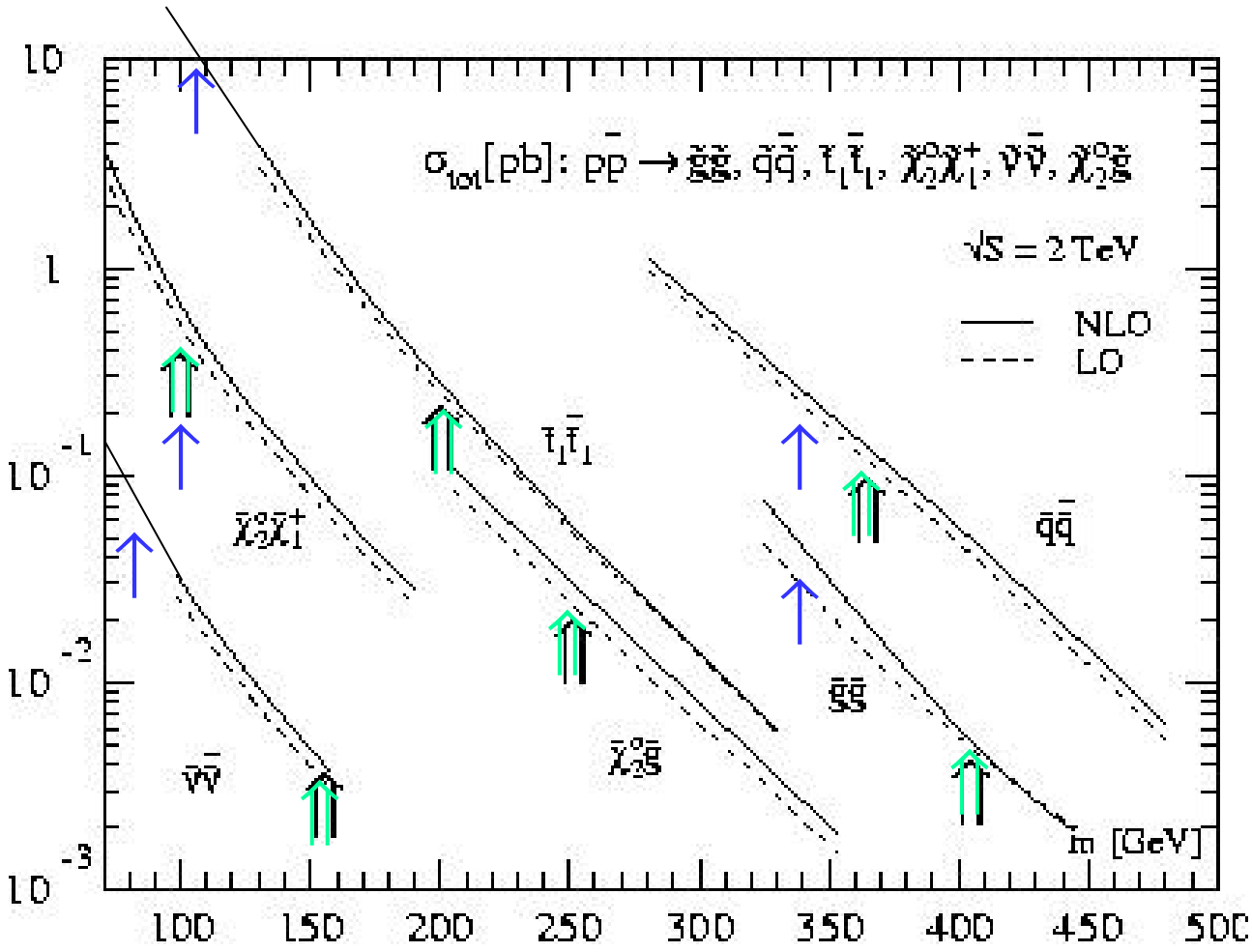
Leptons identification and missing E_T

are the keys

- ✓ Signal efficiency ~ 1-20 % (depends on parameter space)
- ✓ Systematic errors ~ 10-20 % (NLO, PDF, ISR, FSR, jet energy scale,etc.)

Susy Cross Sections at Tevatron





⇑ **corresponds to:**

m_1/2 = 150 GeV

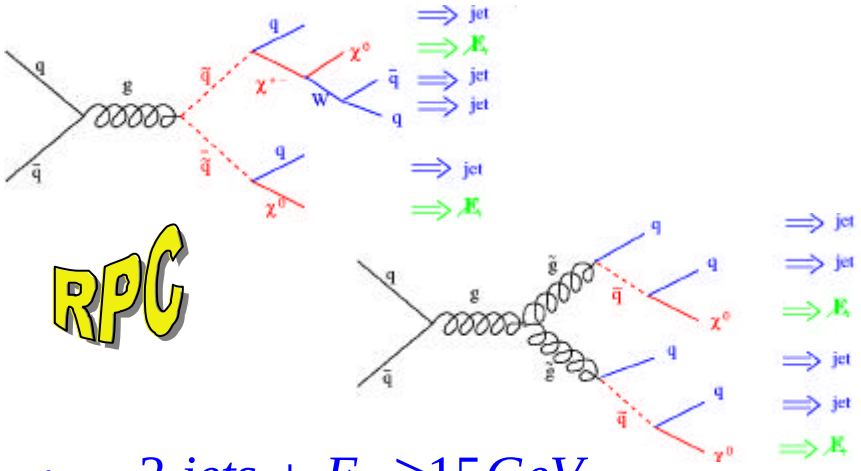
m_0 = 100 GeV

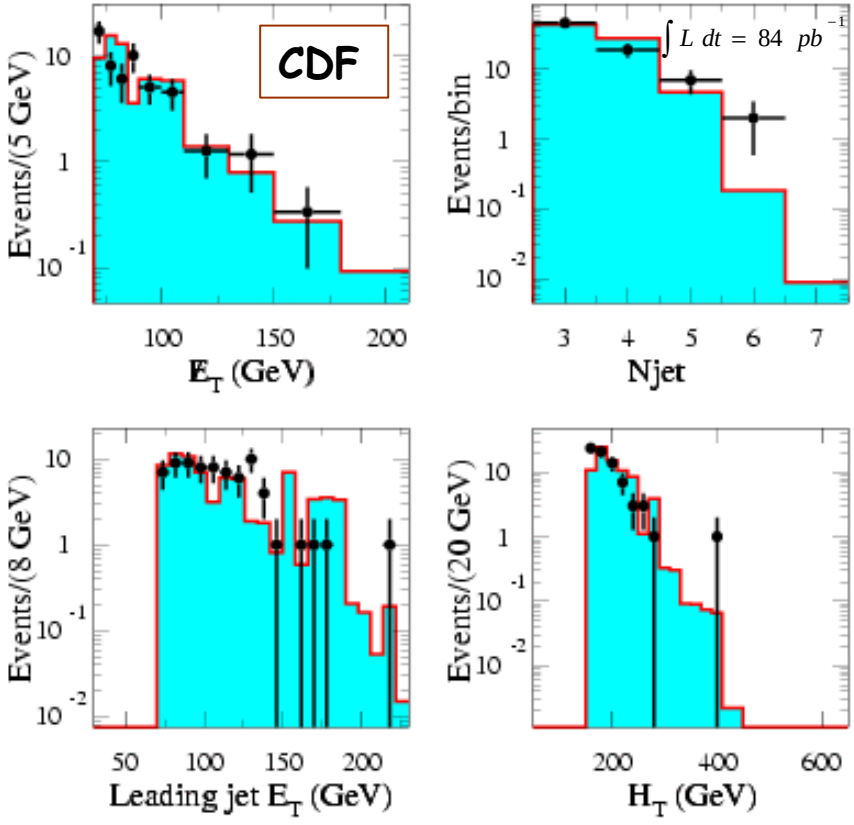
A_0 = 300 GeV

tanβ = 4, μ > 0

↑ **corresponds to present limits**

Squarks and Gluinos : Jets + $\not\!\!E_T$





- $3\ jets + E_T \geq 15 GeV$
- $\not\!\!E_T \geq 70 GeV$
- no isolated tracks
- $H_T = E_{T_2} + E_{T_3} + \not\!\!E_T \geq 150 GeV$

- bacgrounds : QCD, $Z(\rightarrow \nu\bar{\nu}) + > 3$ jets
  $W(\rightarrow \tau\bar{\nu}) + > 2$ jets

- MC predictions for events with more than 3 jets are normalized to observed $Z(\rightarrow ee) + \geq 2$ jets

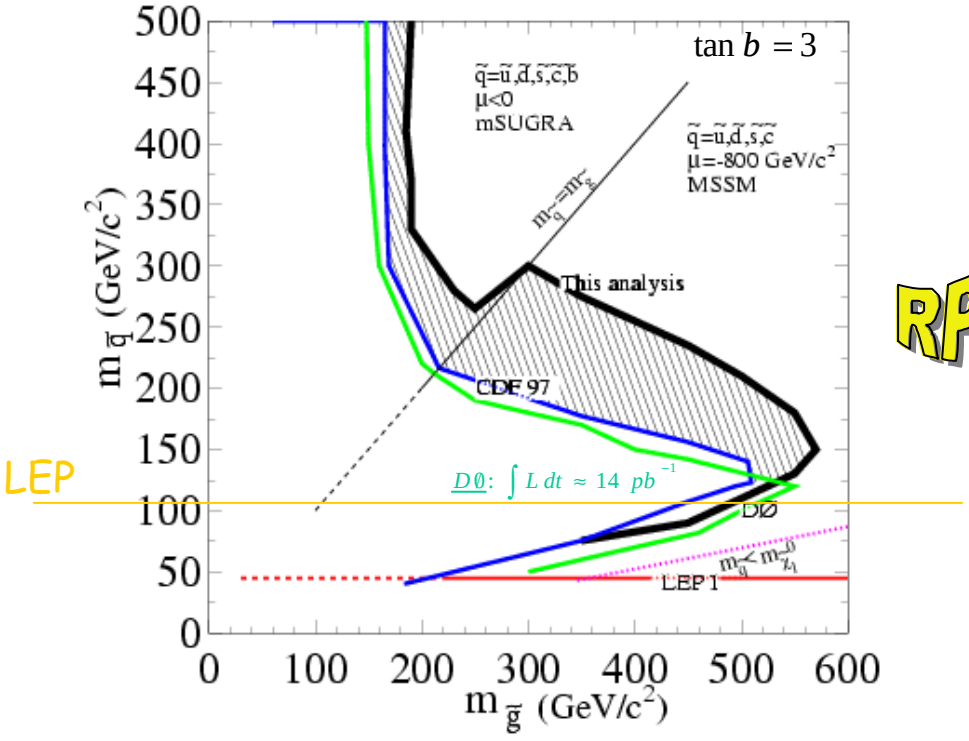
- 74 event in data
- 76 ± 13 expected from SM

- CDF : Phys. Rev. Lett. : 88 (2002) , pp.041801
- DØ : Phys. Rev. Lett. : 83 (1999) no.24, pp.4937

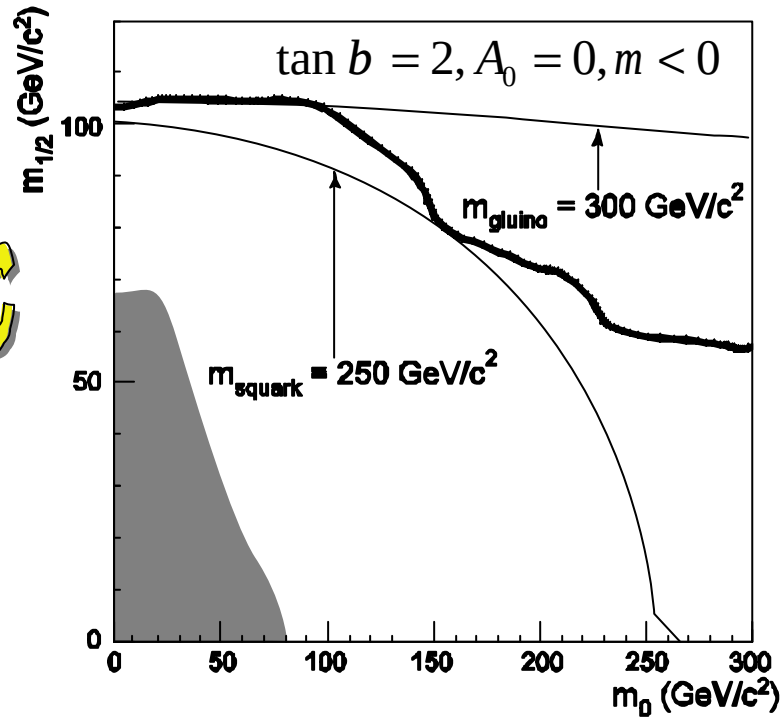
Squarks and Gluinos : Jets + $\not{E}_T$

$\underline{CDF}$: $\int L\,dt = 84\ pb^{-1}$

$\underline{D0}$: $\int L\,dt = 79\ pb^{-1}$



RPC



$m_{\tilde{g}} \geq 300$ GeV $(m_{\tilde{q}} \approx m_{\tilde{g}})$

$m_{\tilde{g}} \geq 195$ GeV $(all\ m_{\tilde{q}})$

$m_{\tilde{g}} \geq 260$ GeV $(m_{\tilde{q}} \approx m_{\tilde{g}})$

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

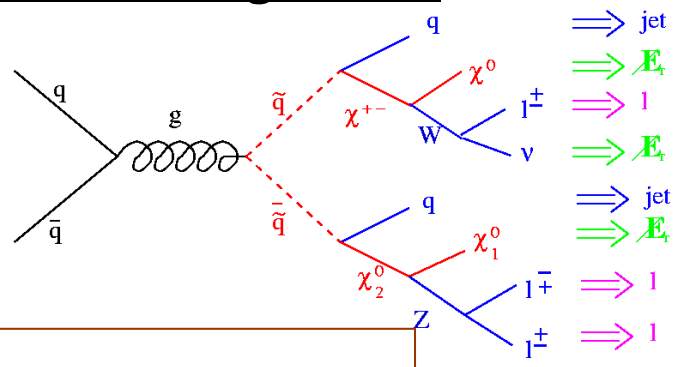
CDF : Phys. Rev. Lett. : 88 (2002) , pp.041801

DØ : Phys. Rev. Lett. : 83 (1999) no.24, pp.4937

Squarks and Gluinos : di-lepton

• CDF dilepton (Like Sign ±±) :

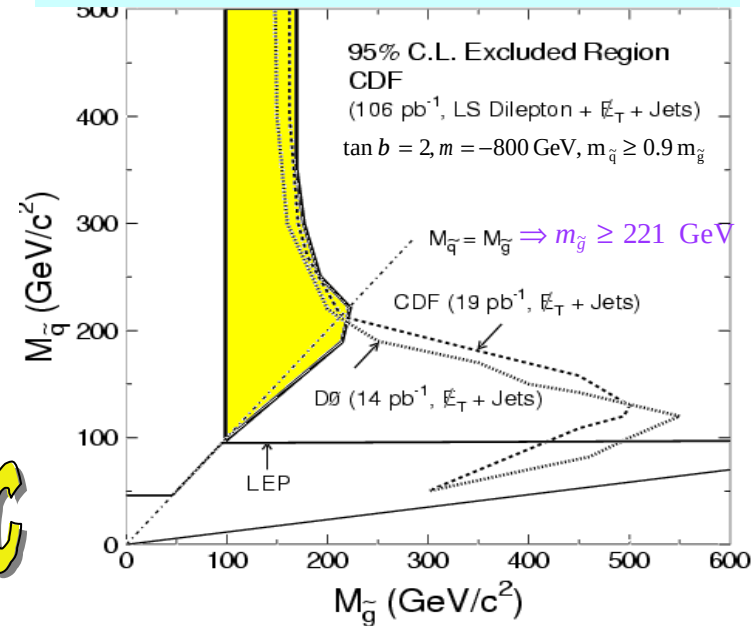
$\int L\,dt = 106\ pb^{-1}$



- 0 event in data
- $0.55 \pm 0.25 \pm 0.08$ expected from SM

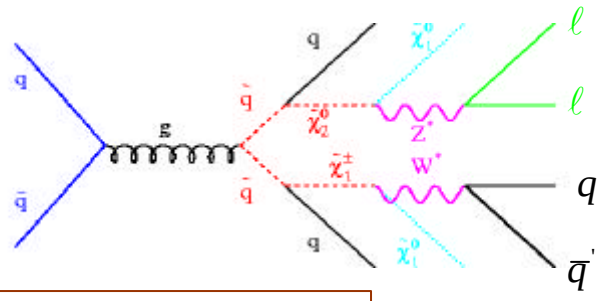
RPC

• CDF : Phys. Rev. Lett. : 87 (2001) , pp.251803

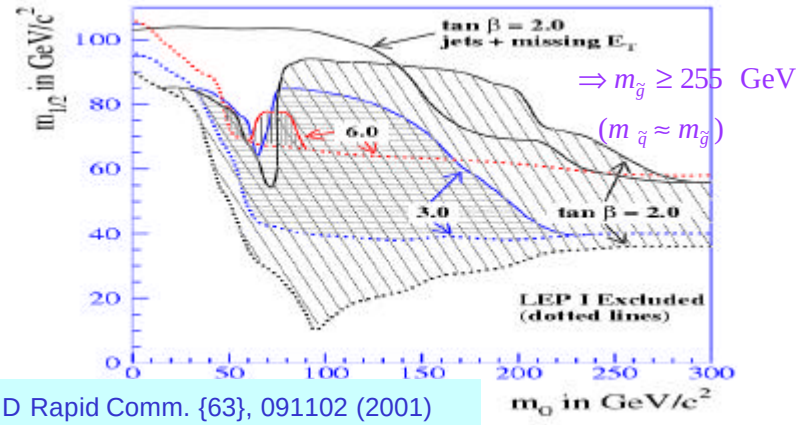


• DØ dilepton :

$\int L\,dt = 108\ pb^{-1}$



- 52 events in data
- 53 expected from SM

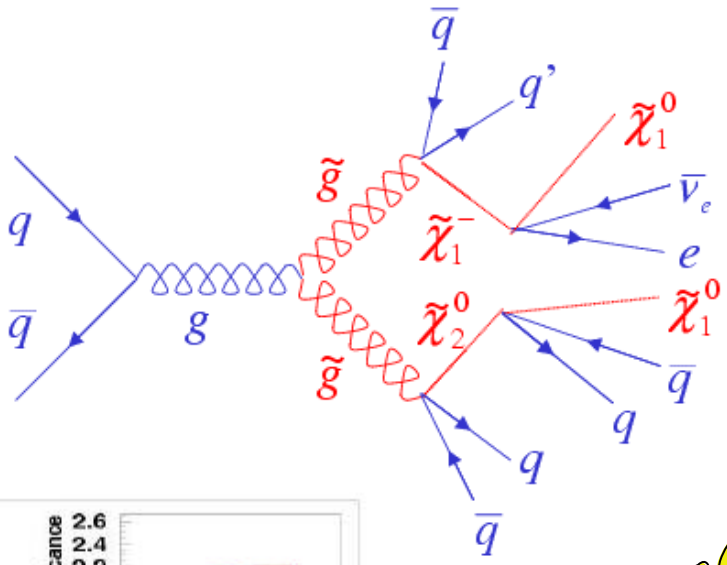


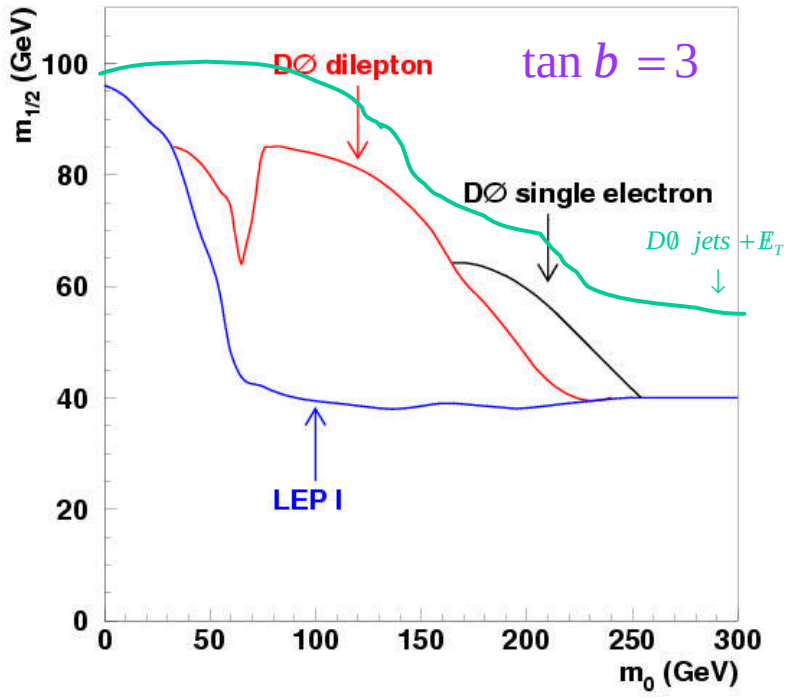
•DØ : Phys. Rev. D Rapid Comm. {63}, 091102 (2001)

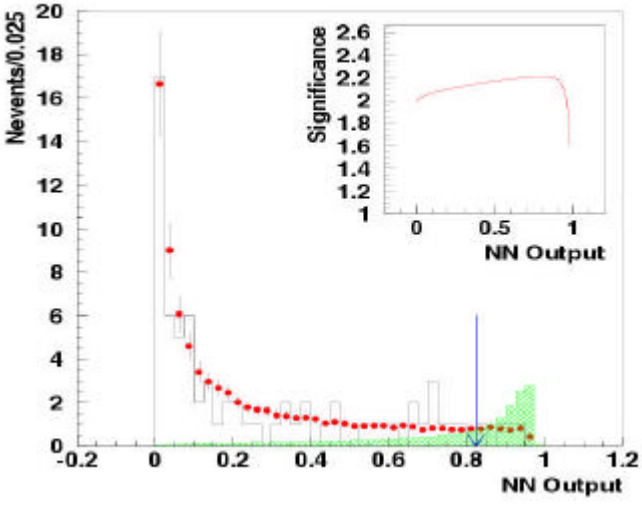
Single-Electron at DØ

$$e^{\pm} + (\geq 4\ jets) + \not{E}_T$$

• DØ : submitted to PRL, hep-ex/0205002







RPC

$$\int L\,dt = 92.7\ pb^{-1}$$

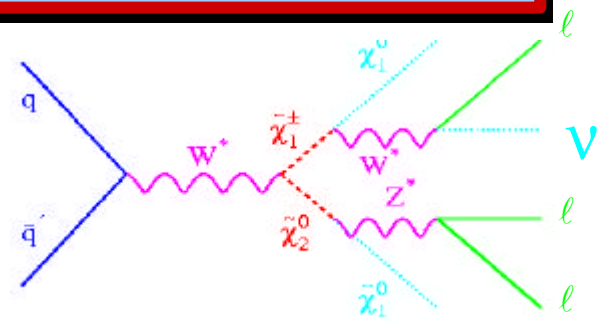
- **t t : 16.8 ± 5.2**
- **WW + ³ 2 jets : 1.4 ± 0.3**
- **QCD Multijet: 19.1 ± 4.7**
- **W + ³ 4 jets : 43.0 ± 7.6**

80.3 ± 10.4 expected from SM

72 events in the data

Chargino and Neutralino

$\tilde{c}_2^{\,0}\,\tilde{c}_1^{\pm}$ to trilepton events with $\not{E}_T$ is one of the cleanest signature for susy



Run I

- 0 event in data
- 1.5 ± 0.5 expected from SM in CDF
- 1.2 ± 0.2 expected from SM in DØ

$$m(\tilde{c}_1^{\pm}) \approx m(\tilde{c}_2^{\,0}) = 2m(\tilde{c}_1^{0})$$

$$\Rightarrow \quad m(\tilde{c}^{\pm}) \succ 70\ GeV$$

RPC

- CDF : Phys. Rev. Lett. : 80 (1998), 1591
- DØ : Phys. Rev. Lett. : 80 (1998), 5275

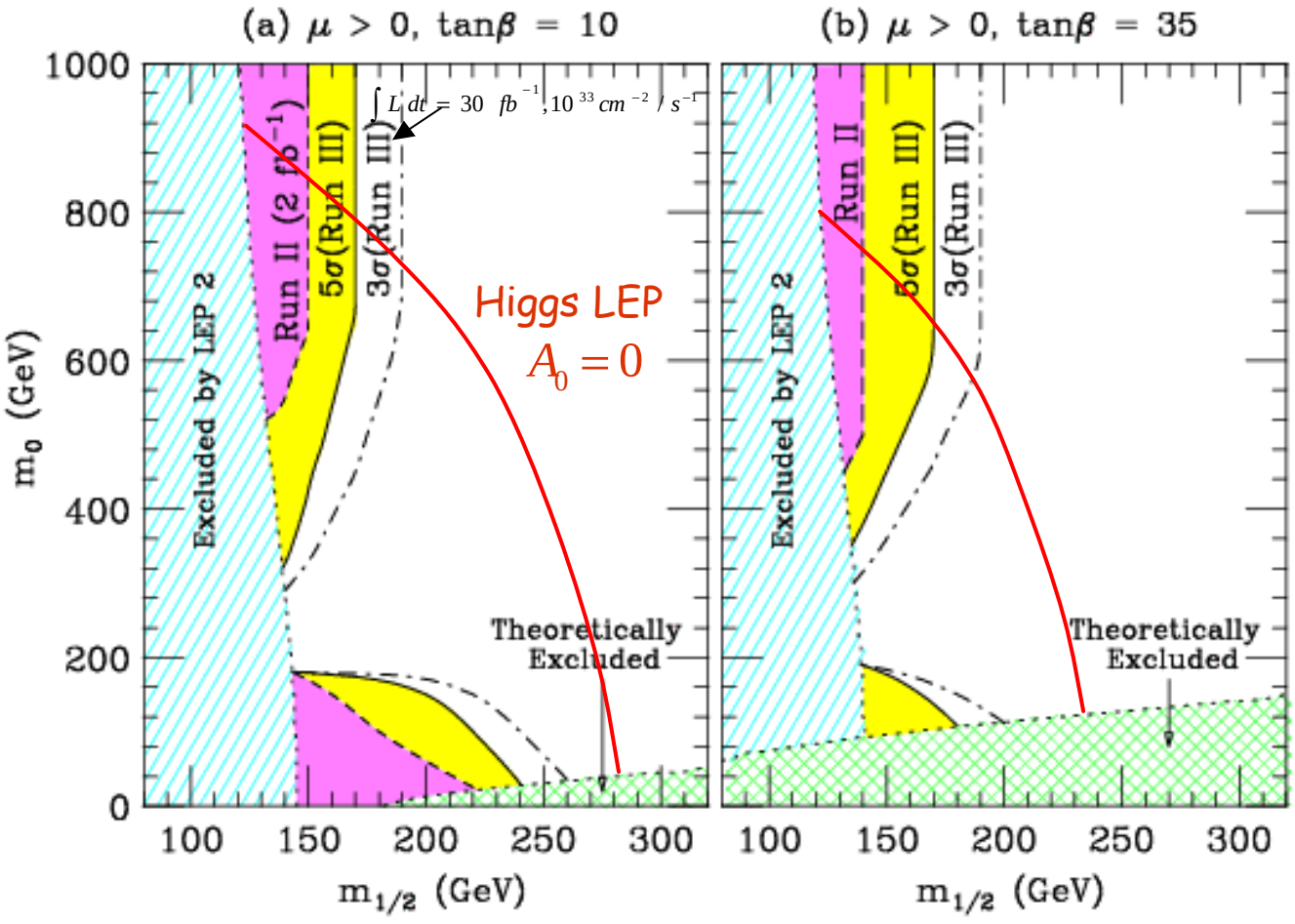
Prospects Run II

- lll (l=e or mu) :
  - Golden channel for susy discovery at Tevatron
  - Low bkg ~ 0.5 fb, easy to trigger
- lltau (tau identification = narrow jet) :
  - Bkg ~ 5-60 fb depending on cuts
- Like Sign dilepton :
  - Complementary in the region where 1 soft lepton

Chargino and Neutralino : RunII

Pure Trilepton (e,m)

- Sugra report, hep-ph/0003154
- LEP SUSY WG, summer 2001



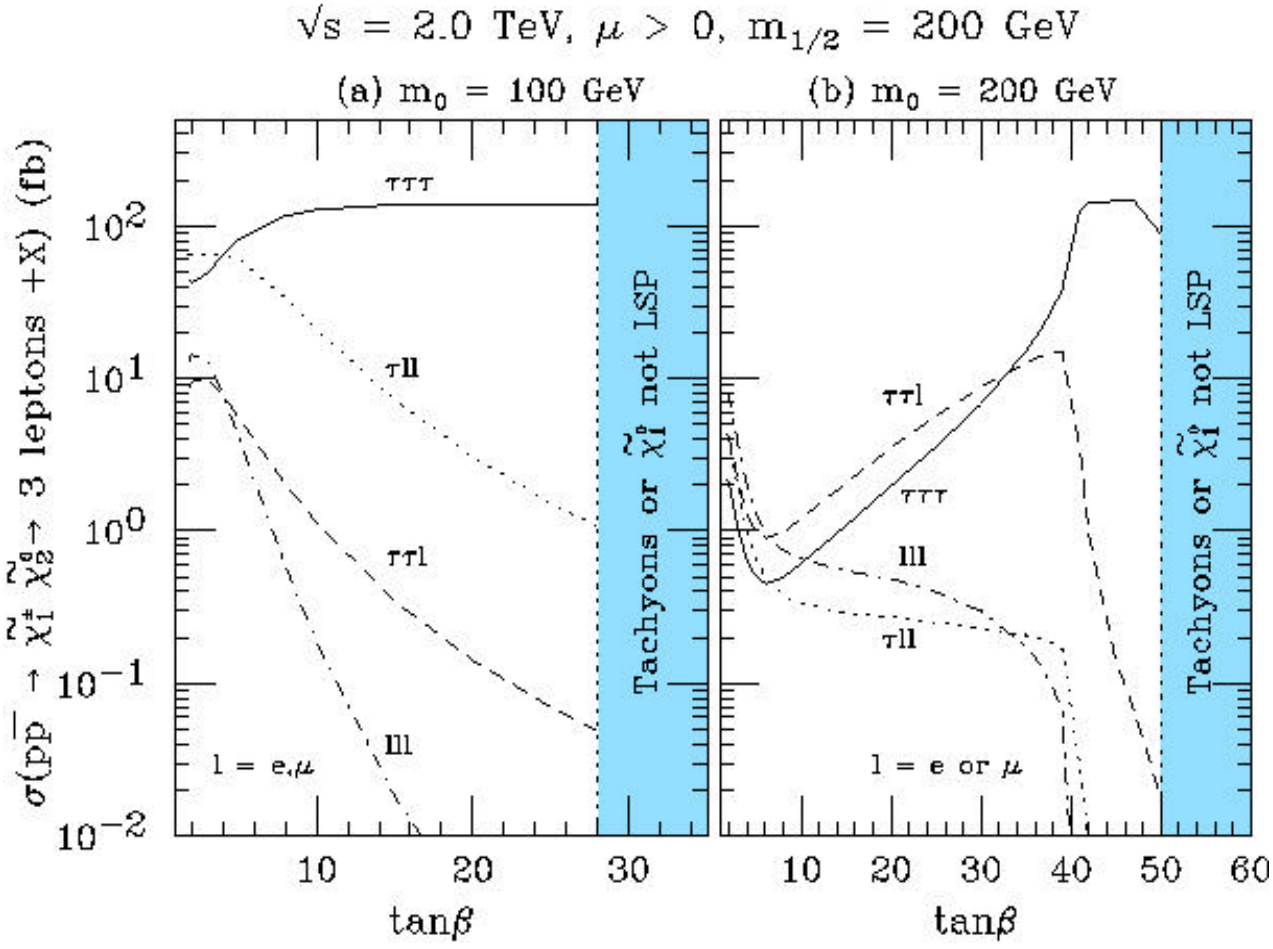
Tevatron may probe a substantial region not accessible at LEP2

RPC

Chargino and Neutralino

Tau identification is vital !

- Sugra report, hep-ph/0003154



Search for the $\tilde{t}$ at DØ

MSSM, light $\tilde{n}$ LSP scenario

$$BR(\tilde{t} \rightarrow b\, l \tilde{n}) = 100\ \%$$

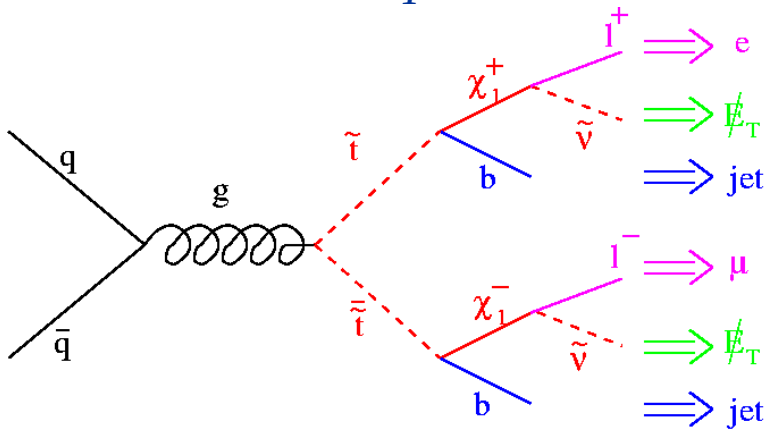
$$\int L\, dt = 108\ \ pb^{-1}$$

- $\geq 1\, electron \quad (E_T > 15\ GeV\ ,\ |h| < 2.5)$
- $\geq 1\, muon \quad (p_T > 15\ GeV\ ,\ |h| < 1.7)$
- $\not{E}_T > 20\ GeV$
- $15^o < |j_e - j_m| < 165^o$

  $(\ fake\ \ e\ \ from\ \ QCD\ \ \ jets\ )$
- $|h_e + h_m| > 2$

RPC

$$e + m + \not{E}_T + X$$



Selection Results

- 10 event in data
- 13.7 ± 1.5 expected from SM
- 13.2 ± 2.3 expected from signal

  $(m_{\tilde{t}} = 120\ GeV\ ,\ m_{\tilde{n}} = 60\ GeV\ )$

• Phys. Rev. Lett. {88}, 171802 (2002)

Search for $\tilde{t}$ $\tilde{n}$ LSP

- **CDF $bl\tilde{n}$ analysis:**
  - 1 electron or 1 muon (E_T >10 GeV)
  - 2 jets (>12 GeV and 8 GeV)
  - $\not{E}_T$ > 25 GeV + b - tagging

  e = 5.7 %

  81 events in data

  87.3 ± 8.8 expected from SM
- **DØ $bl\tilde{n}$ analysis:**
  - 1 electron & 1 muon (E_T >15 GeV)
  - no jets required
  - $\not{E}_T$ > 20 GeV

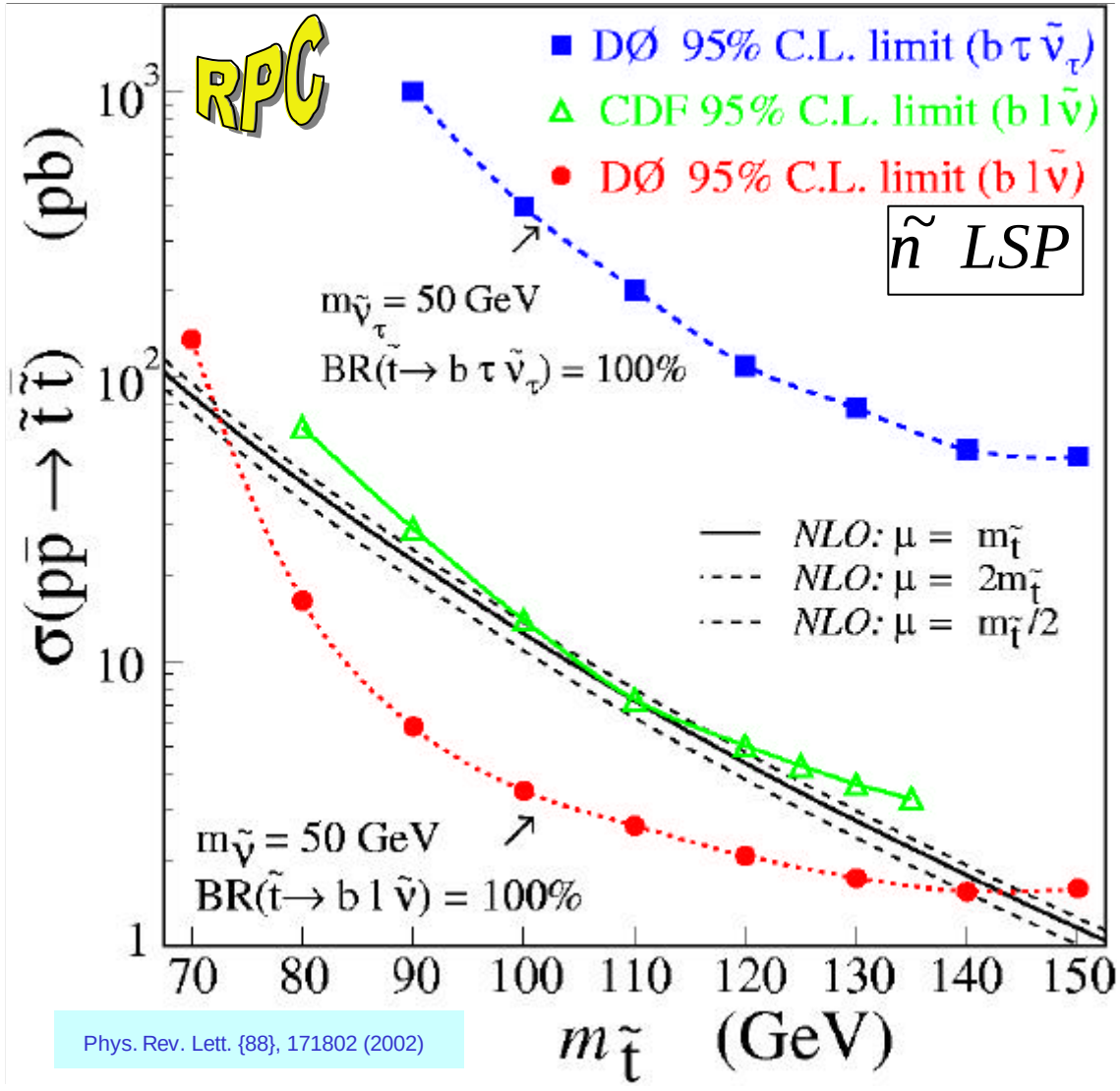
  e = 4 %

  10 events in data

  13.7 ± 1.5 from SM
- **DØ $bt\tilde{n}_t$ analysis:**
  - use electron & muon decay of t

  e = 0.6 %

  2 ± 0.3 from expected signal

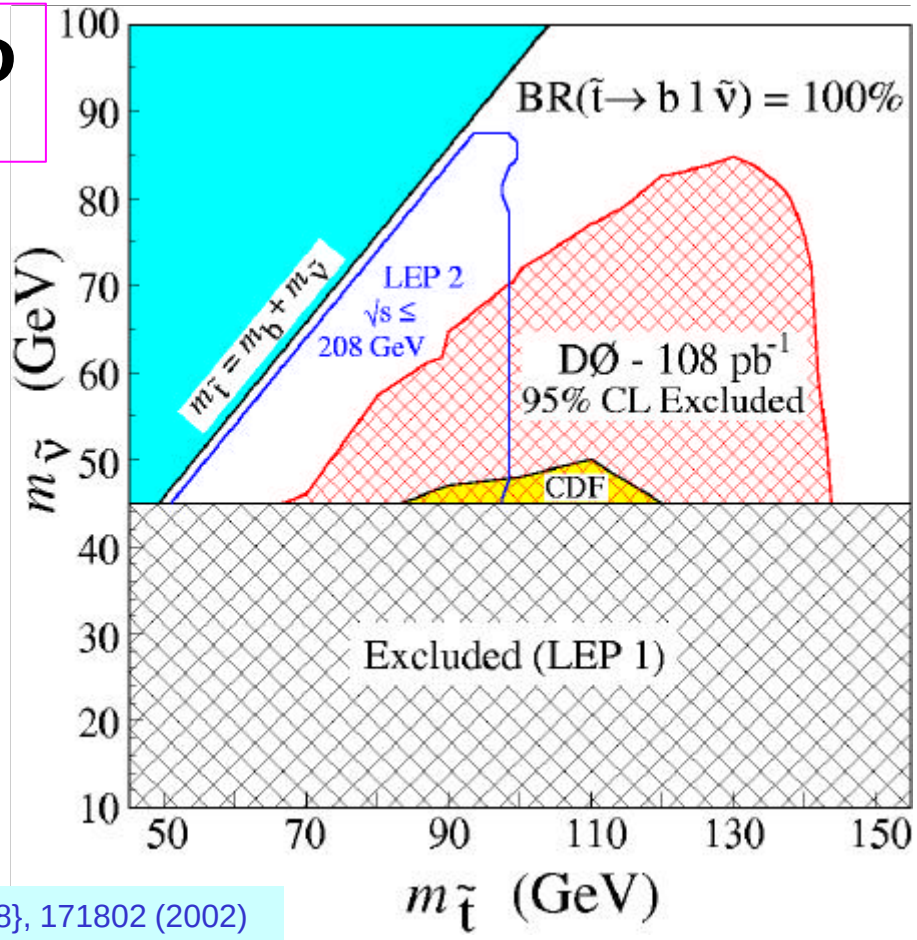


Phys. Rev. Lett. {88}, 171802 (2002)

Search for $\tilde{t}$ $BR(\tilde{t} \rightarrow b l \tilde{n}) = 100\ \%$

Interpretation of Run I Result

$\tilde{n}$ *LSP*



$m_{\tilde{n}} < 60\ GeV$

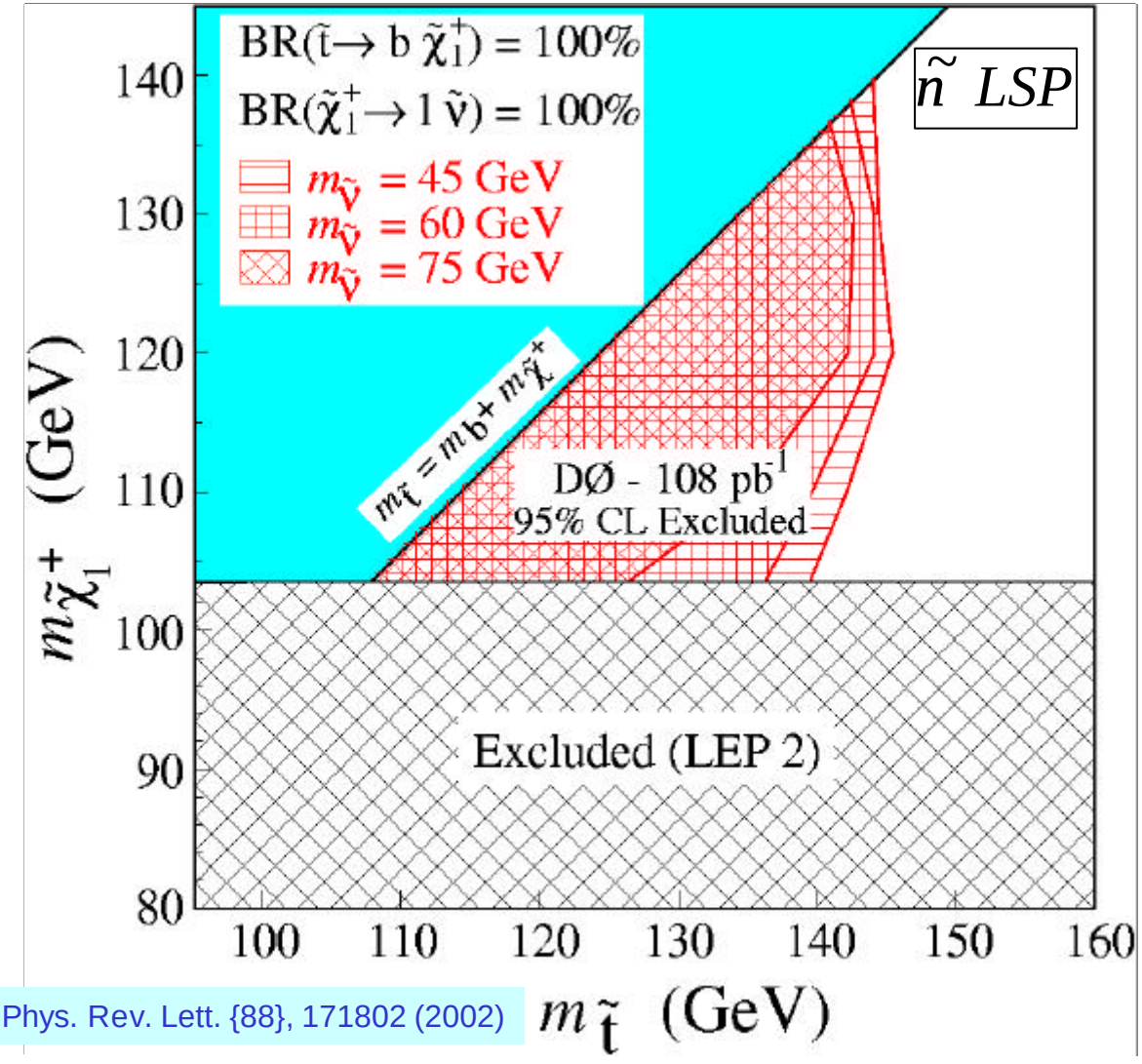
$\Downarrow$

$m_{\tilde{t}} > 140\ GeV$

RPC

• Phys. Rev. Lett. {88}, 171802 (2002)

Search for 2 Body Decay of $\tilde{t}$ at DØ



• Phys. Rev. Lett. {88}, 171802 (2002)

$$m_{c_1^{\pm}} < m_{\tilde{t}}$$

$$\Downarrow$$

RPC

2 body decay

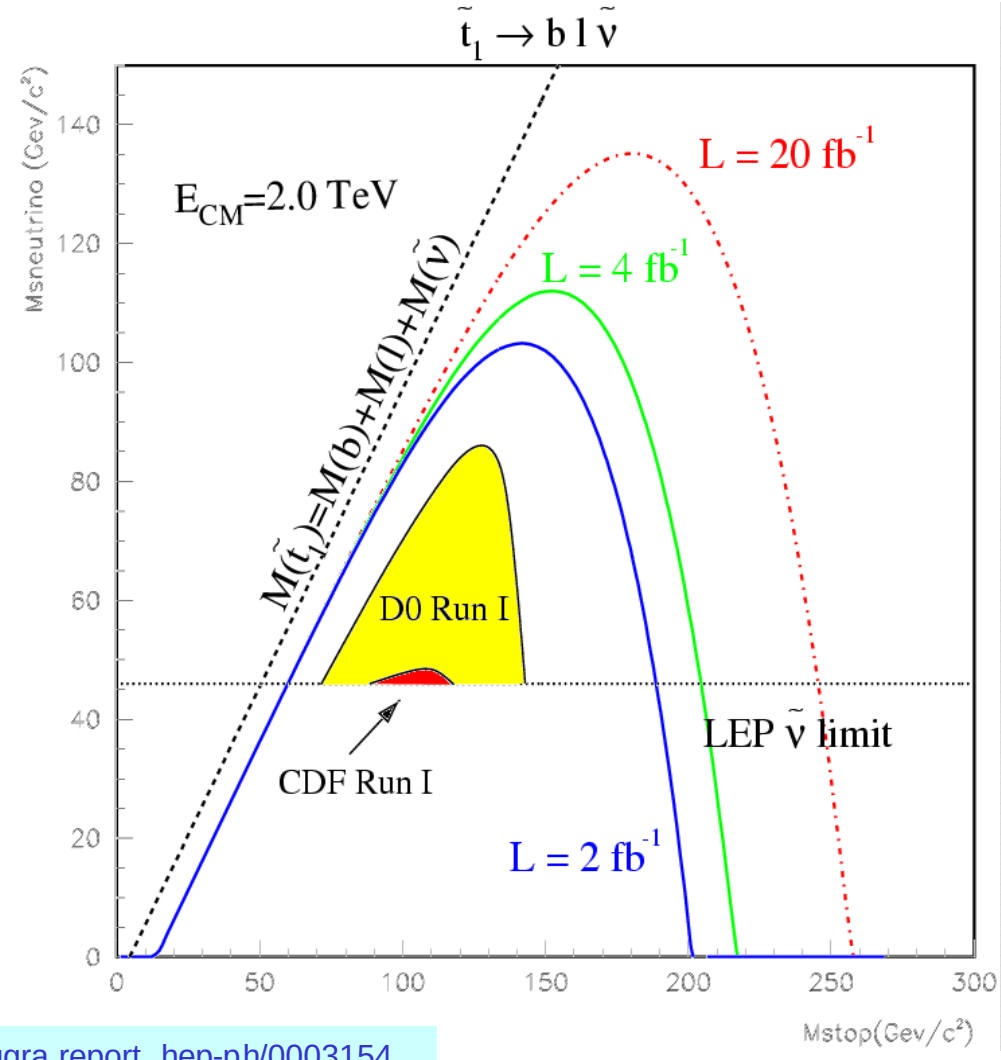
$$\tilde{t} \to \tilde{b}\, c_1^{\pm}$$

excluded region,

as a function of

stop and chargino masses

Run II Prospects for $\tilde{t}$ $\tilde{n}$ LSP



$$BR(\tilde{t} \rightarrow b\, l\, \tilde{n}) = 100\ \%$$

Run IIa (2 fb-1)

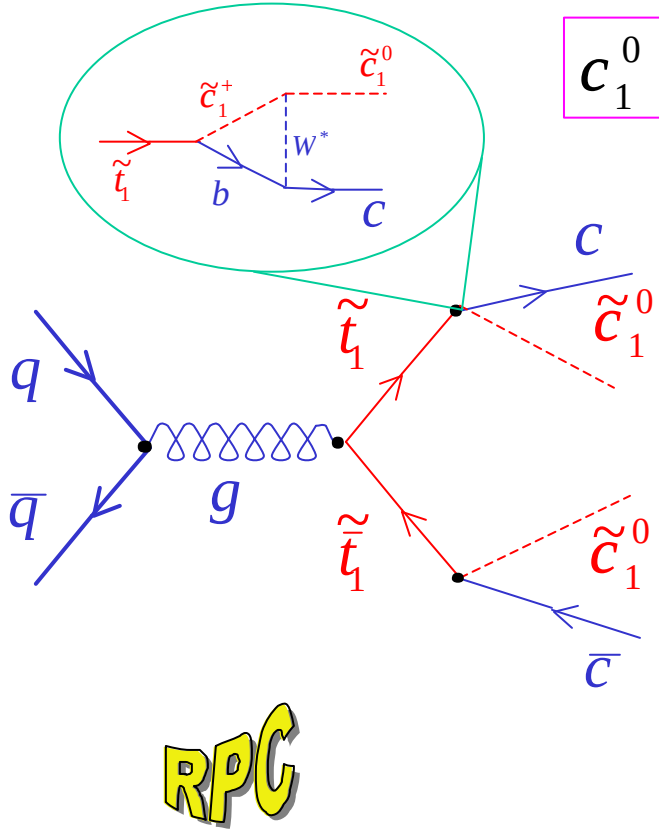
➔ 50 GeV above Run I

t **channel sensitivity to be checked**

RPC

• Sugra report, hep-ph/0003154

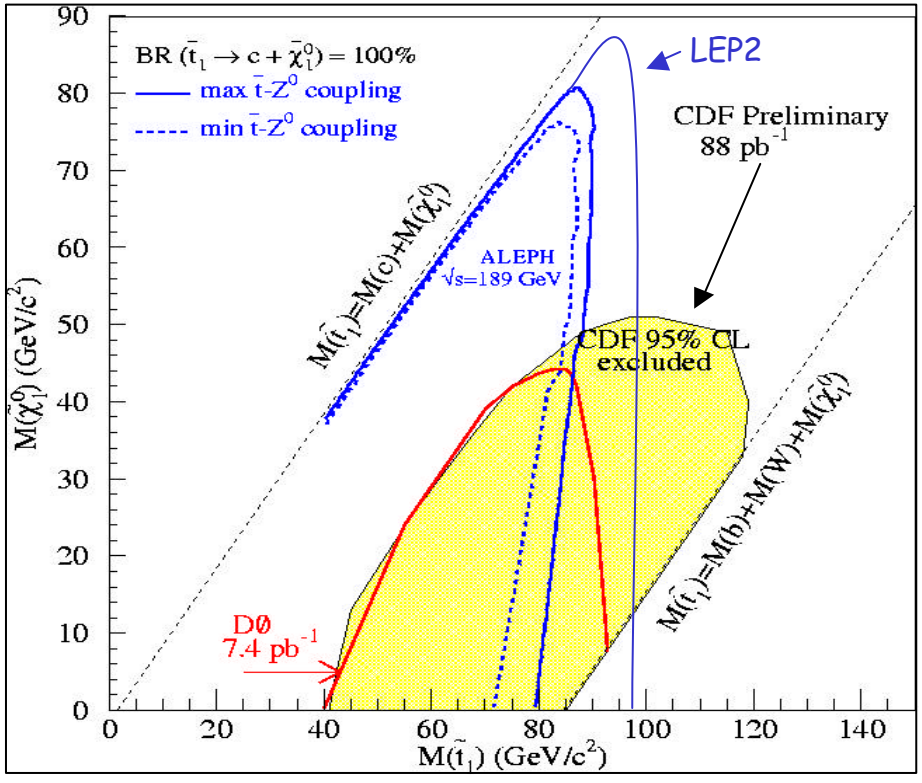
Search for $\tilde{t}$ with Jets + $\not{E}_T$



c_1^0 LSP

$$BR(\tilde{t} \rightarrow c c_1^0) = 100\ \%$$

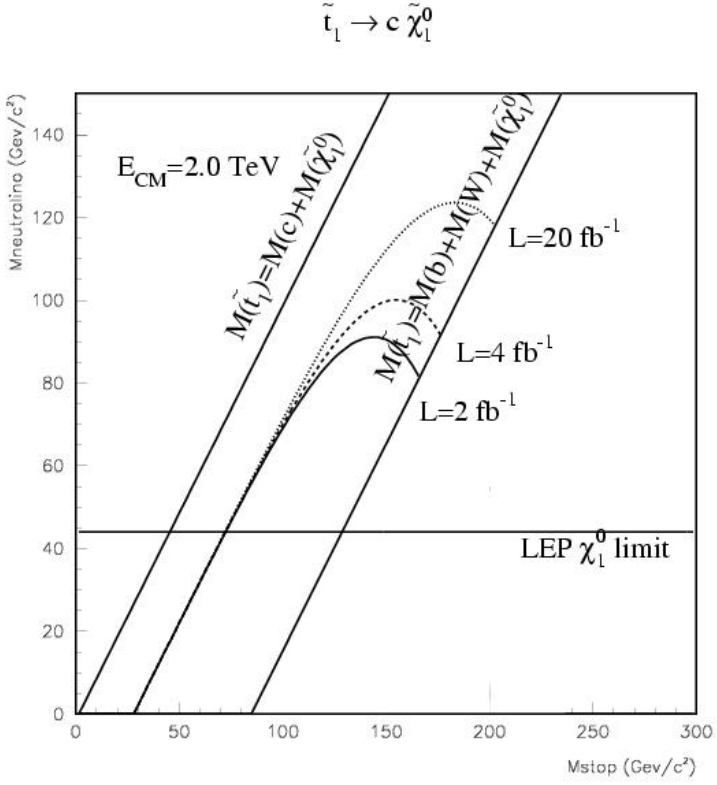
Interpretation of Run I Result



- CDF : Phys. Rev. D. 53, 1051 (1996)
- LEP SUSY WG, summer 2001

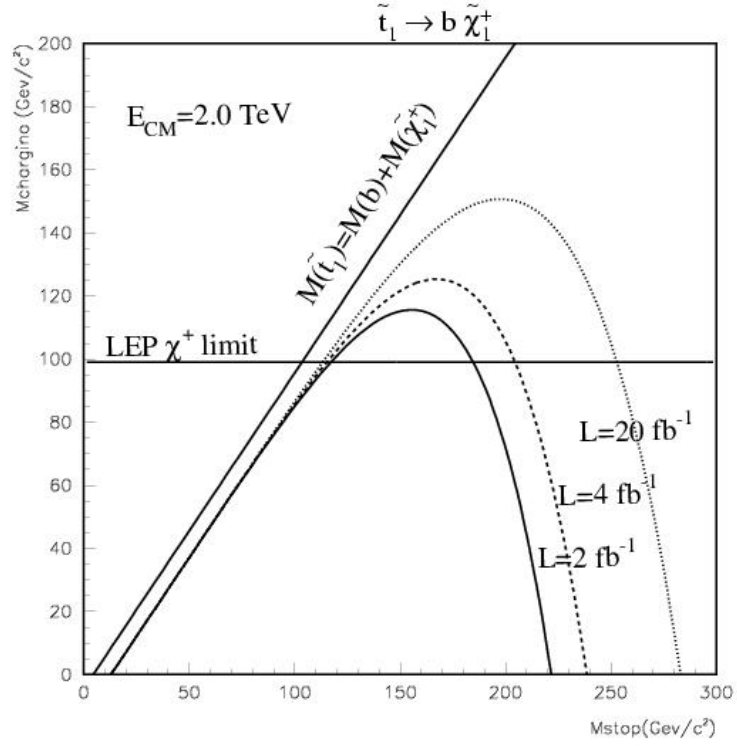
Prospects for $\tilde{t}$ at Run II c_1^0 LSP

$\tilde{t} \rightarrow c\, c_1^0$



Reach : $m_{\tilde{t}} \approx 160\, GeV$

$\tilde{t} \rightarrow b\, c^+ \qquad c^+ \rightarrow ln\, c_1^0$



Reach : $m_{\tilde{t}} \approx 190\, GeV$

for $t \rightarrow \tilde{t}\, c_1^0$

see :

FERMILAB-Pub-2000-288-E

• Sugra report, hep-ph/0003154

Search for $\tilde{b}$ with Jets + $\not{E}_T$ at CDF

searches for events with heavy-quark jets and large $\not{E}_T$

- 2 or 3 jets ($E_T > 15$ GeV)
- $\not{E}_T > 40$ GeV
- no identified leptons with $E_T > 15$ GeV
- b – tagging

RPC

$$BR(\tilde{b} \to b\, c_1^0) = 1$$

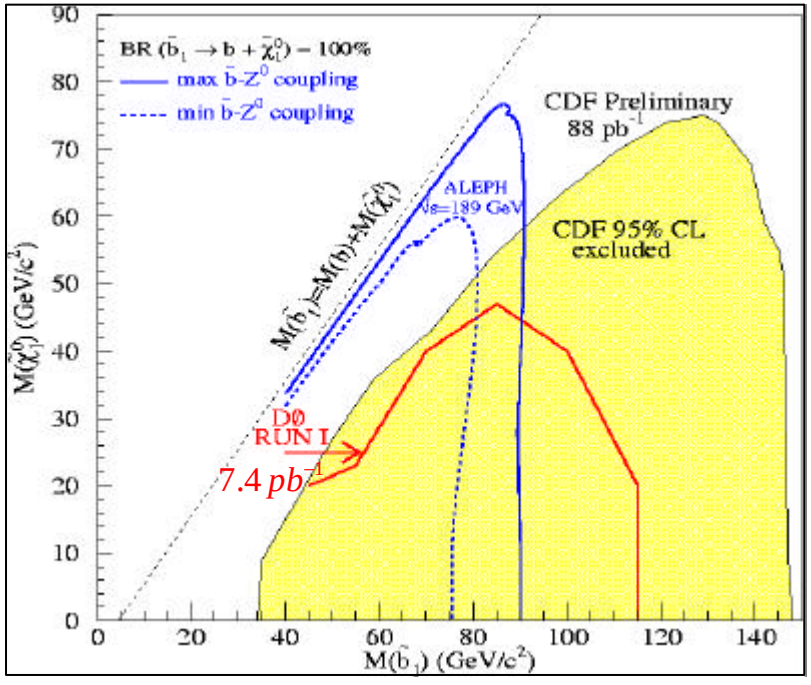
Backgrounds are dominated by $W(\to t\nu) +$ jets and mismeasurements

- CDF : Phys. Rev. Lett. 84, 5704 (2000)
- DØ : Phys. Rev. Lett. 76 (1996), 2222

$\tilde{b}$ Selection Results

- 5 event in data
- ~ 6 expected from SM

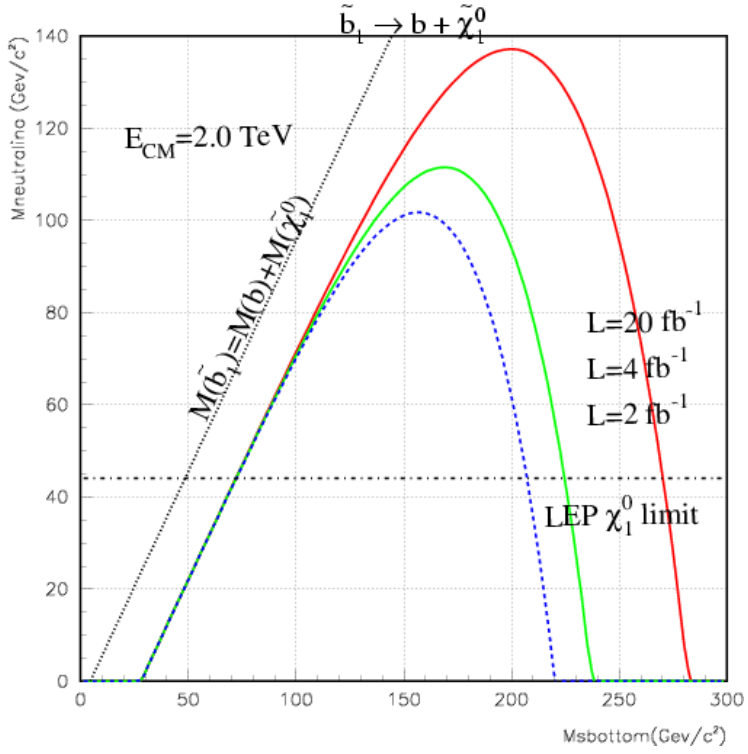
Interpretation of Run I Result



Prospects for $\tilde{b}$ at Run II

$$BR(\tilde{b} \rightarrow b\, c_1^0) = 100\ \%$$

Reach : $m_{\tilde{b}} \approx 210\, GeV$



this reach may be changed if :

$$\tilde{b} \rightarrow b c_2^0$$

$$c_2^0 \rightarrow l\bar{l}\, c_1^0$$ (small bkg)

tagging of b-jets is important !

- Sugra report, hep-ph/0003154

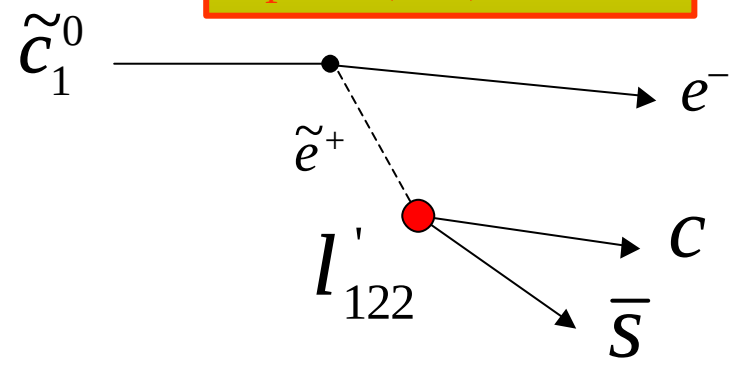
R-parity violation : RPV

- SUSY potential: $W_{SUSY} = W_{MSSM} + W_{RpV}$ R-parity violating SUSY (RPV)

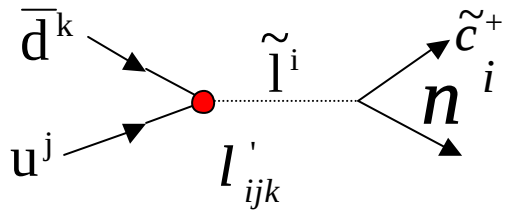
With $W_{RPV} = l_{ijk} L_i L_j \overline{E}_k + l'_{ijk} L_i Q_j \overline{D}_k + l''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k$

$R_P = (-1)^{3B+2S+L}$

(45 new Yukawa couplings)



- Pair production and RPV decays of LSP
  - l and l' couplings
- Resonant sparticle production
  - l' and l'' couplings
- Top decay via RPV
  - l' and l'' couplings



DØ *hypothesis:*

- mSUGRA framework
- $\tilde{c}_1^0$ LSP
- Only <u>one</u> Yukawa coupling $(l_{ijk}, l'_{ijk}, l''_{ilk})$ dominates

RPV : Consequences & Exp. Constraints

RPV consequences :

- The Lightest Susy Particle (LSP) decays either
  - inside the detector (with or without a displaced vertex)
  - outside the detector (similar to RPC analysis)
- Susy signature can be very different
  - Less missing Et
  - More leptons and jets
- sparticle may be produced by RPV couplings as single sparticles
- LSP is not anymore a candidate for dark matter

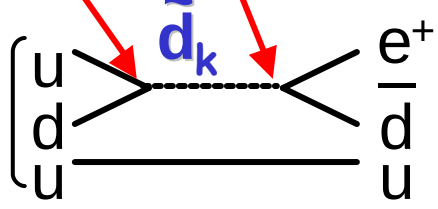
2σ limits for $\tilde{m}$ = 100 GeV

Barger et al., Phys. Rev. D40 (89)
Ledroit, Sajot GDR-S-008 (98)
Allanach et al., PRD 60 (99)

RPV constraints :

ex: proton decay

$l''_{11k} \cdot l'_{11k} < 10^{-22}$



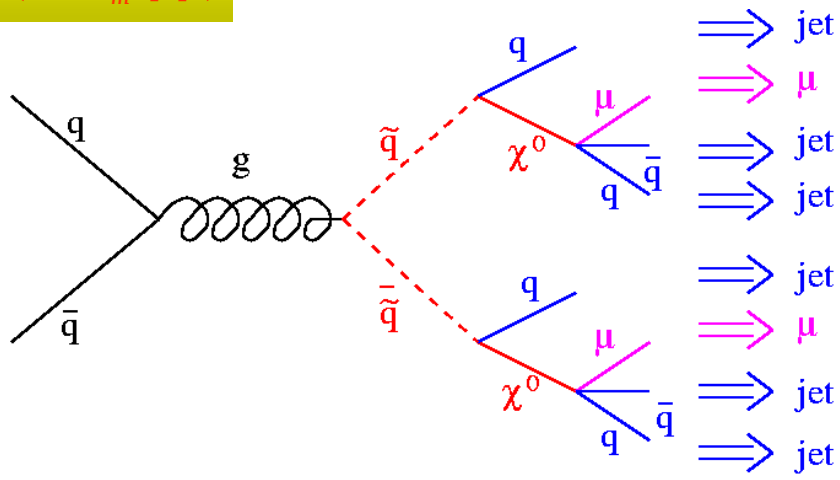
ijk	λ_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ''_{ijk}
121	0.05	111	$5.2\ 10^{-4}$	211	0.06	311	0.12	112	10^{-6}
122	0.05	112	0.02	212	0.06	312	0.12	113	10^{-5}
123	0.05	113	0.02	213	0.06	313	0.12	123	1.25^*
131	0.062	121	0.04	221	0.18	321	0.52	212	1.25^*
132	0.062	122	0.04	222	0.18	322	0.52	213	1.25^*
133	0.006	123	0.04	223	0.18	323	0.52	223	1.25^*
231	0.07	131	0.02	231	0.18	331	0.45	312	0.50
232	0.07	132	0.28	232	0.45	332	0.45	313	0.50
233	0.07	133	$1.4\ 10^{-3}$	233	0.15	333	0.45	323	0.50

RPV Search at DØ in $2m + 4$ *jets*

- LSP decay via $l'_{2jk} L_2 Q_j \overline{D}_k \Rightarrow c_0 \rightarrow mqq' \ (\text{or } n_m qq')$

- RPC conserving production, RPV decays

$$\int L\,dt = 77.5 \pm 4 \ pb^{-1}$$



Selection Results

- 0 event in data
- $0.18 \pm 0.03 \pm 0.02$ expected from SM
  $(Drell-Yan, t\bar{t},\ Z \rightarrow m^+m^- + jets,\ Z \rightarrow t^+t^- \rightarrow m^+m^- + jets)$
- 3.8 ± 0.4 expected from signal
  $(m_0 = 100 \text{ GeV}, m_{1/2} = 90 \text{ GeV})$

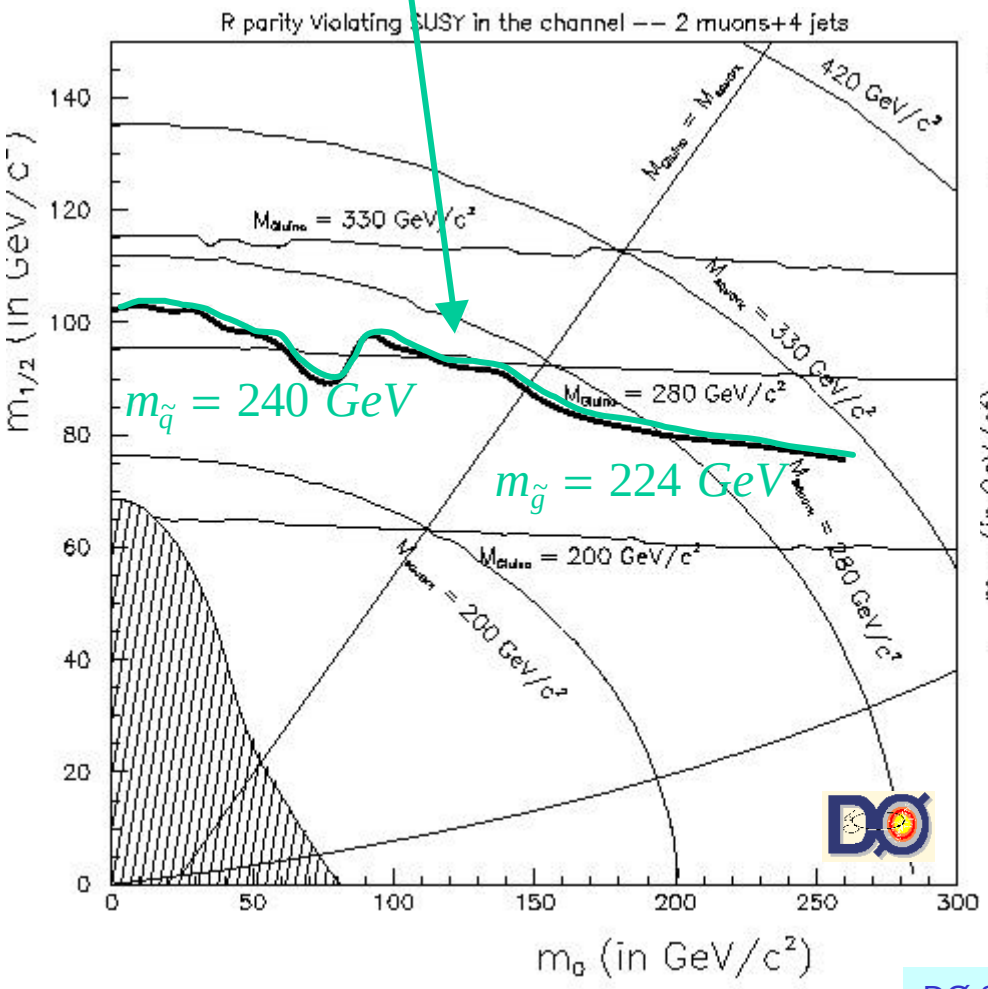
RPV Search at DØ in $2m + 4$ *jets*

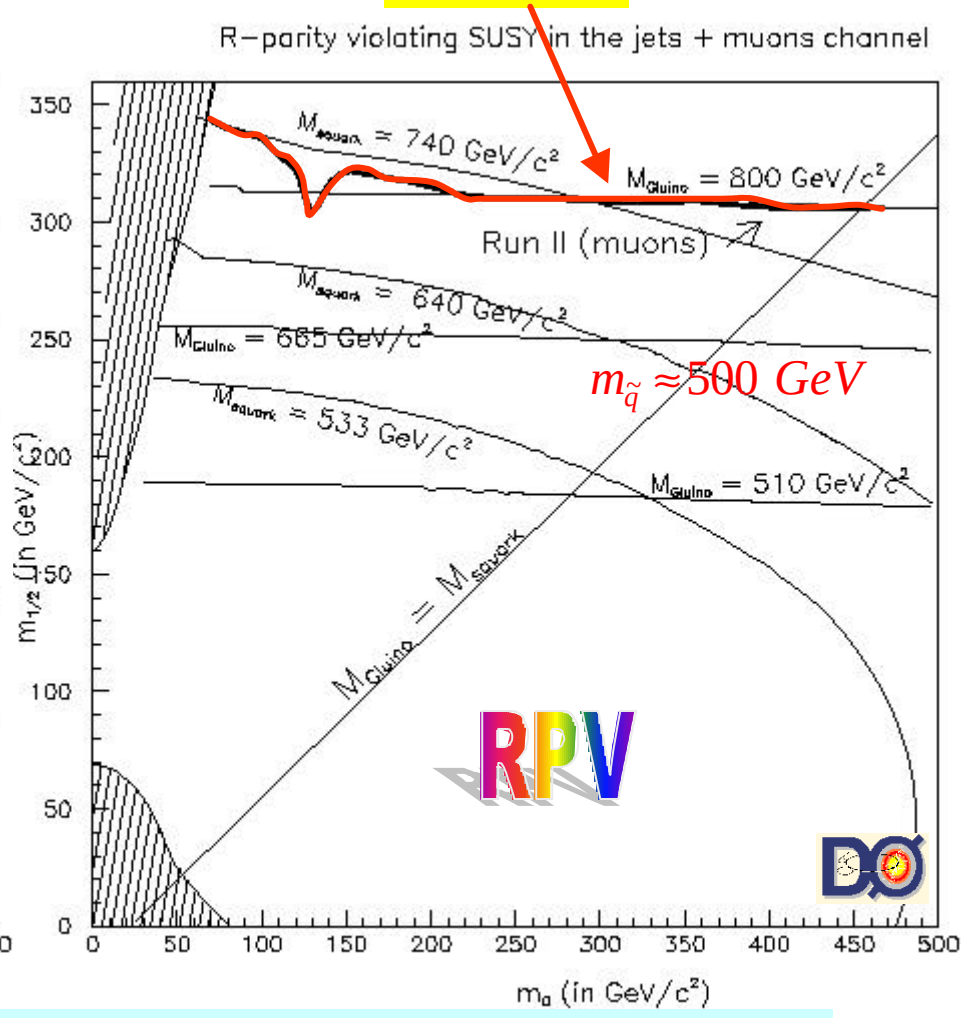
Interpretation

Run I

$A_0 = 0, m < 0, \tan b = 2$

Run II (2fb^{-1})

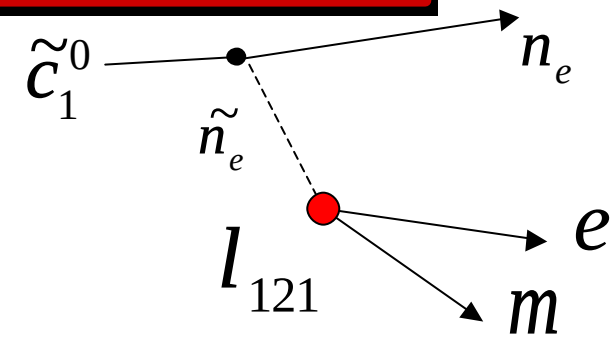


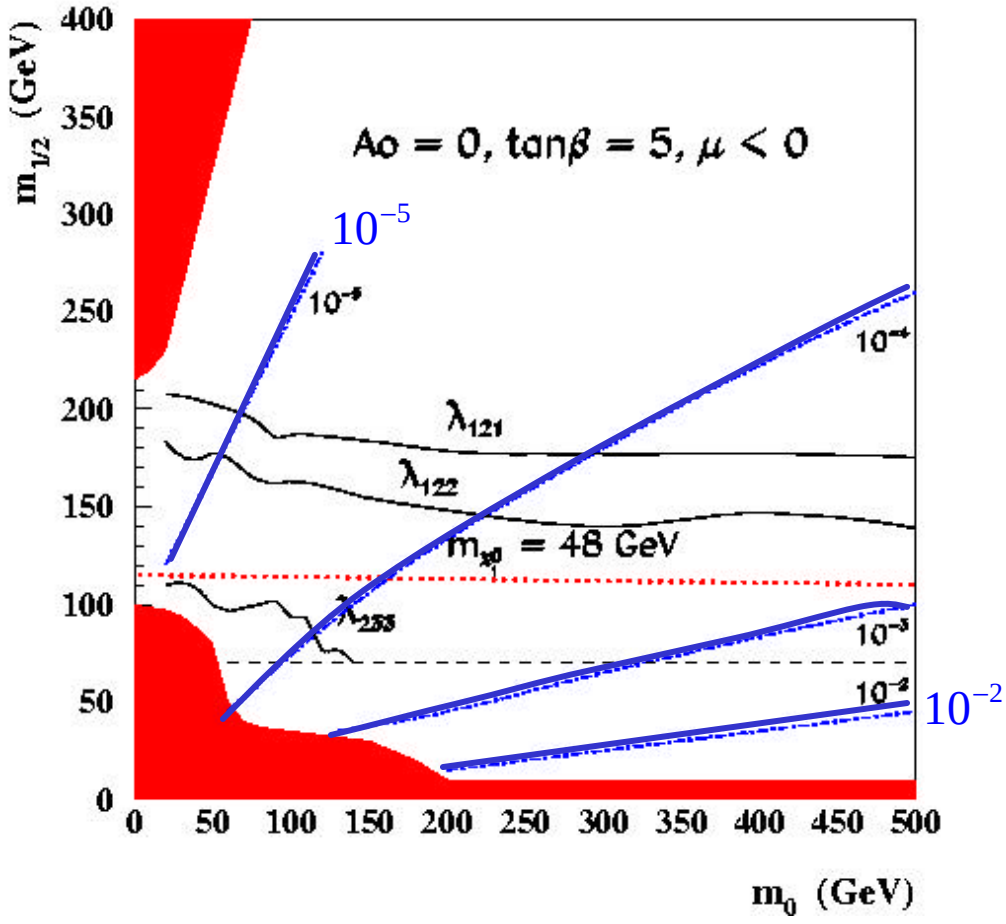


DØ Submitted to PRL, Phys. Rev. Lett. / hep-ex/0111053

Multileptons Channel at DØ

Final State : ^{3} eee,eem,emm,mmm + $\not{E}_T$





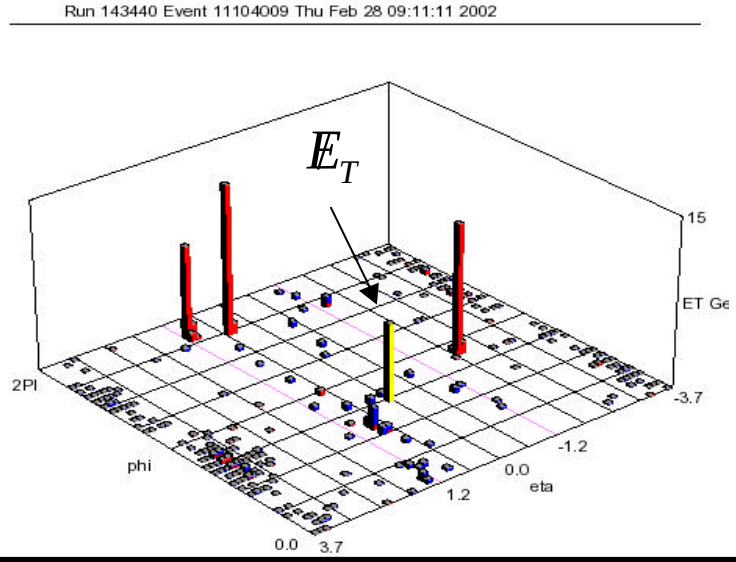
dominant coupling :

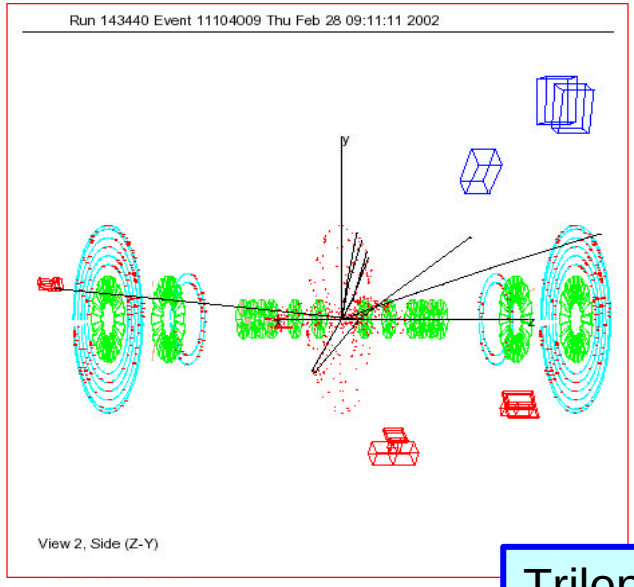
$$(l_{121}, l_{122}, l_{233})$$

DØ, PRL 80, 1592 (1998)
DØ, Phys. Rev. D, Rapid. Comm. 62, 071701 (2000)

eee Candidate Event

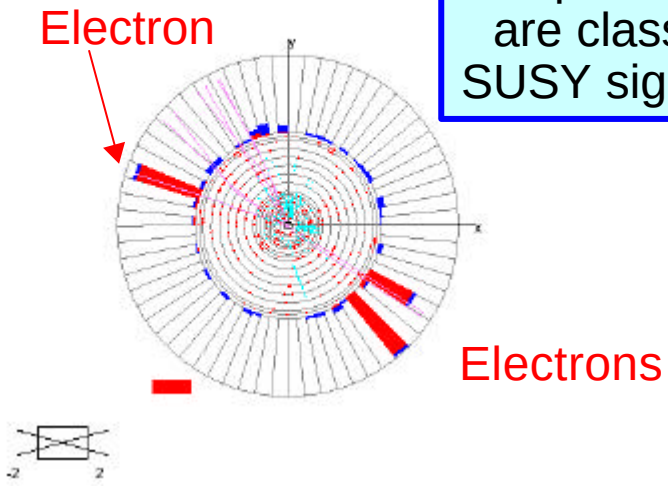
DÆ Run 2 Preliminary





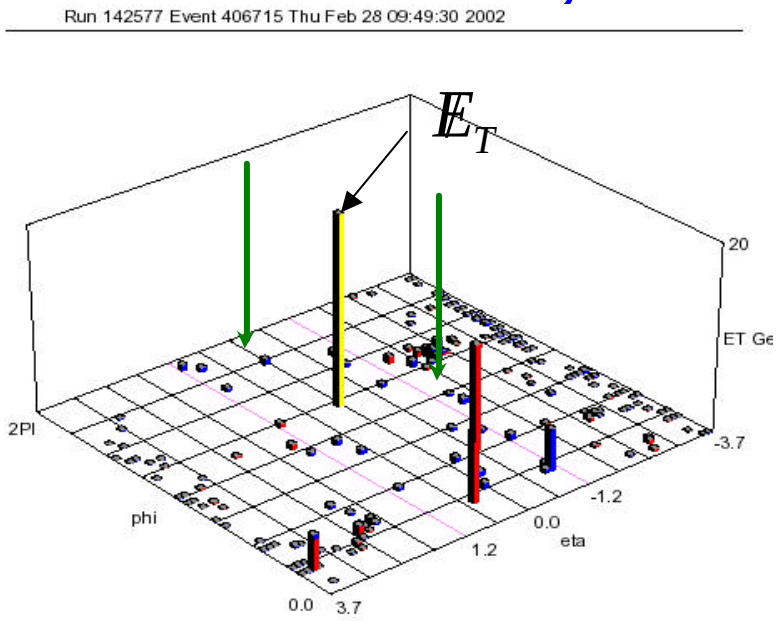
Trilepton events are classical SUSY signature

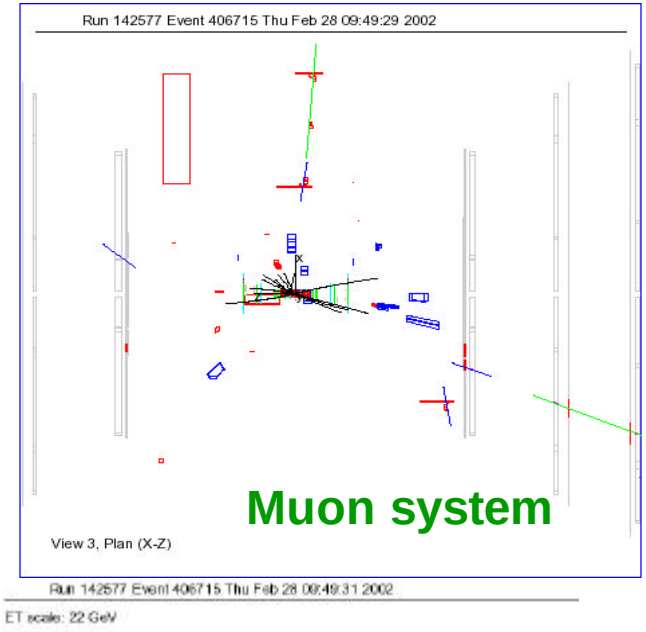
e1	e2	e3
E_T = 17.9 GeV p_T = 0.52 GeV h = 0.43 j = 5.42 Charge = +1	E_T = 13.9 GeV p_T = 10.9 GeV h = -1.94 j = 2.80 Charge = +1	E_T = 13.2 GeV p_T = 15.1 GeV h = 1.06 j = 5.72 Charge = -1
m_{e1e2} = 55.7	m_{e1e3} = 10.8	m_{e2e3} = 63.5
m_{e1e2e3} = 85.2 GeV/c²	$\not{E}_T$ =10.7 GeV	



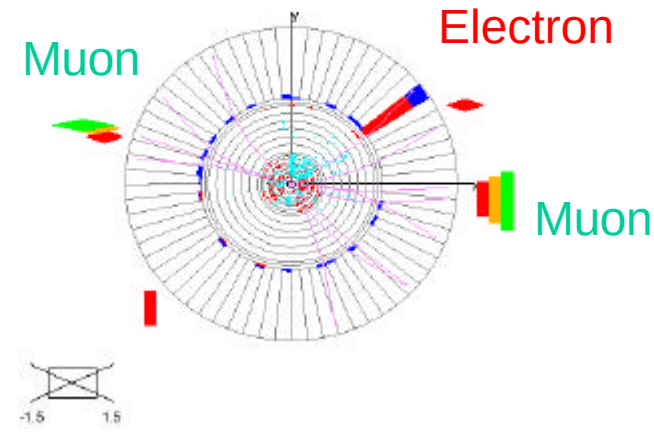
emm Candidate Event

DÆ Run 2 Preliminary





e	m1	m2
E_T = 19.2 GeV h = 0.40 j = 0.63 No track match	p_T = 28.2 GeV h = -0.10 j = 6.20 Charge = -1	p_T = 9.82 GeV h = -1.48 j = 2.88 Charge = 1
	m_{mm} = 41.5 GeV/c^2	
$\not{E}_T$ =31.8 GeV		



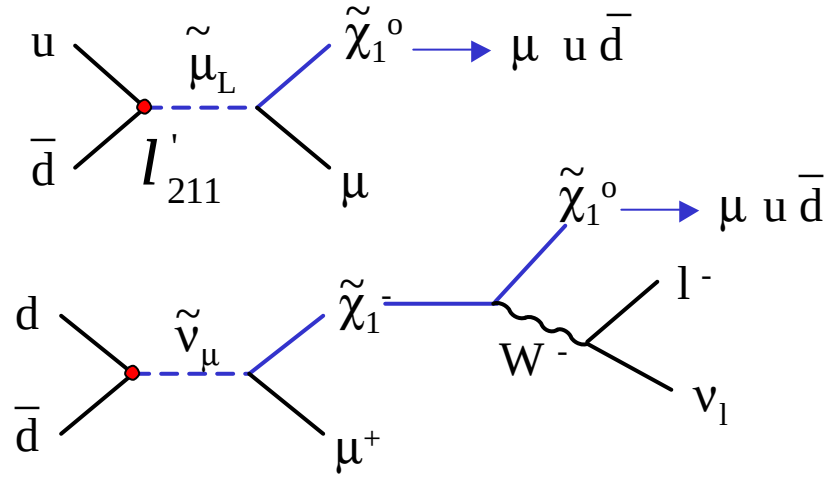
RPV Search at DØ Via Resonant $\tilde{l}$

Final State : 3 2 m + 2 jets

coupling $l'_{211} > 0.06 \frac{m_{\tilde{d}}}{100}$

- resonant prod via RPV
- decay of LSP via RPV

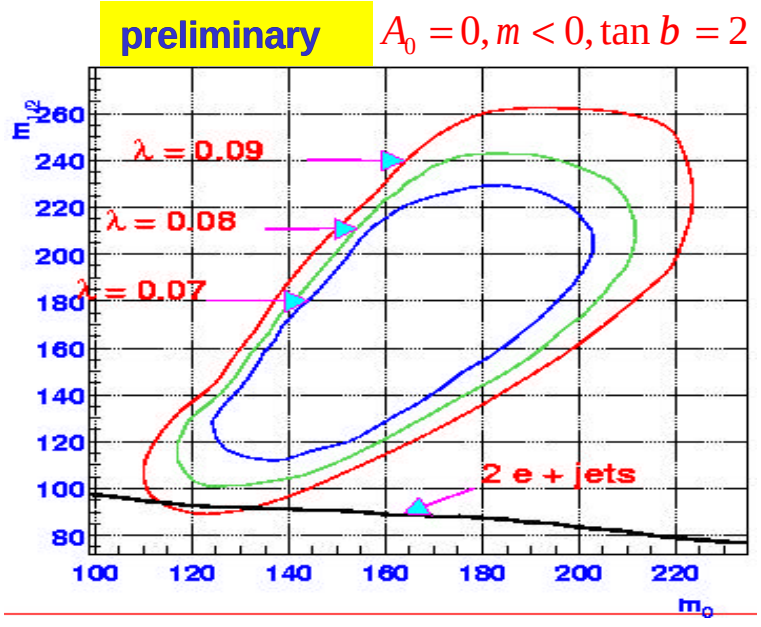
$$\int L\, dt = 94 \pm 5\ pb^{-1}$$



Selection Results

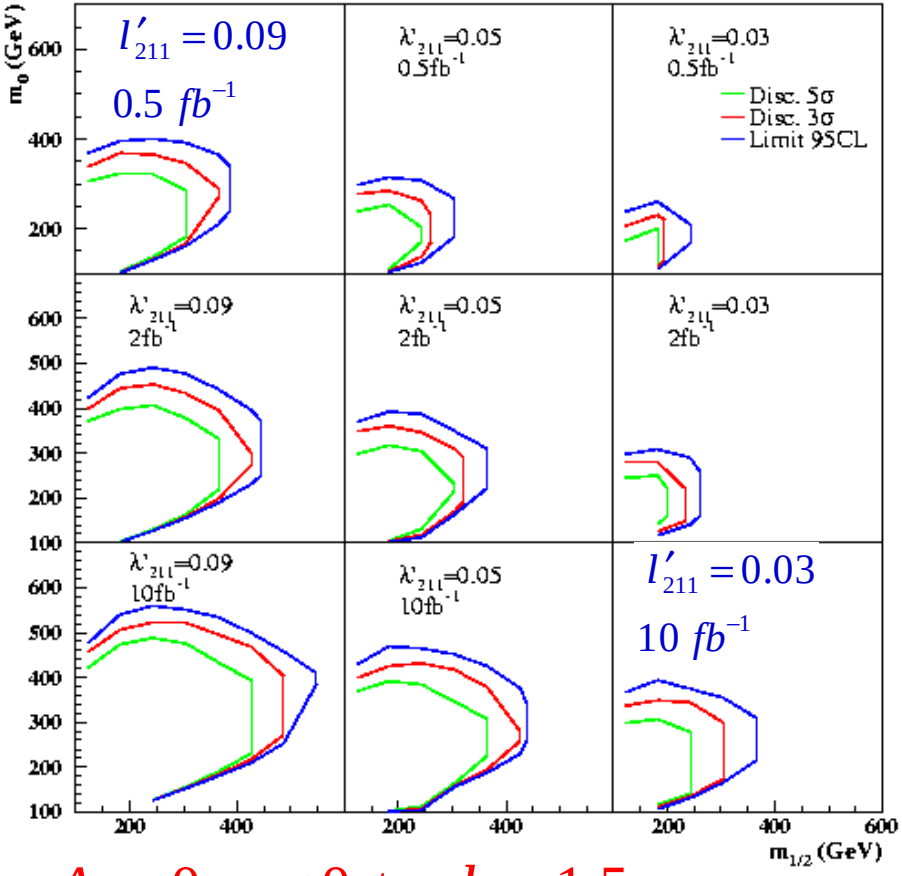
$m_{\tilde{n},\tilde{m}} \geq 260\ \text{GeV}$

- 5 events in data
- 5,34 ± 0.07 expected from SM
- 7.44 ± 0.07 expected from signal
  ($m_0 = 200$ GeV, $m_{1/2} = 240$ GeV, $m < 0$, $\tan b = 2$, $l' = 0.09$)



RPV Search at DØ Via Resonant $\tilde{l}$: Prospect Run II

Final State : 3 m + 2 jets



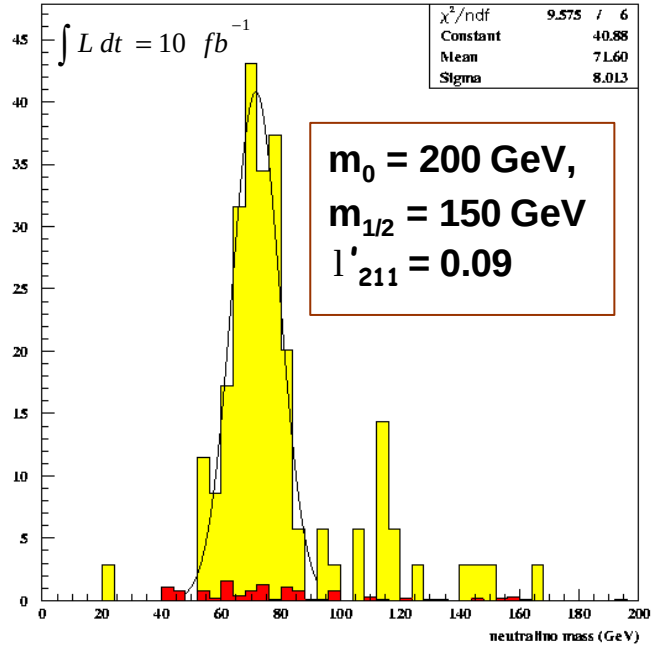
$A_0 = 0, m < 0, \tan b = 1.5$

Deliot et al., EPJ C 19 (01) 155

c_1^0 mass reconstruction possible !

- Fast MC simulation: $m(c_1^0) = 77.7$ GeV
- Reconstruction : 2 jets and softer muon

$m(c_1^0) = 71 \pm 9$ GeV

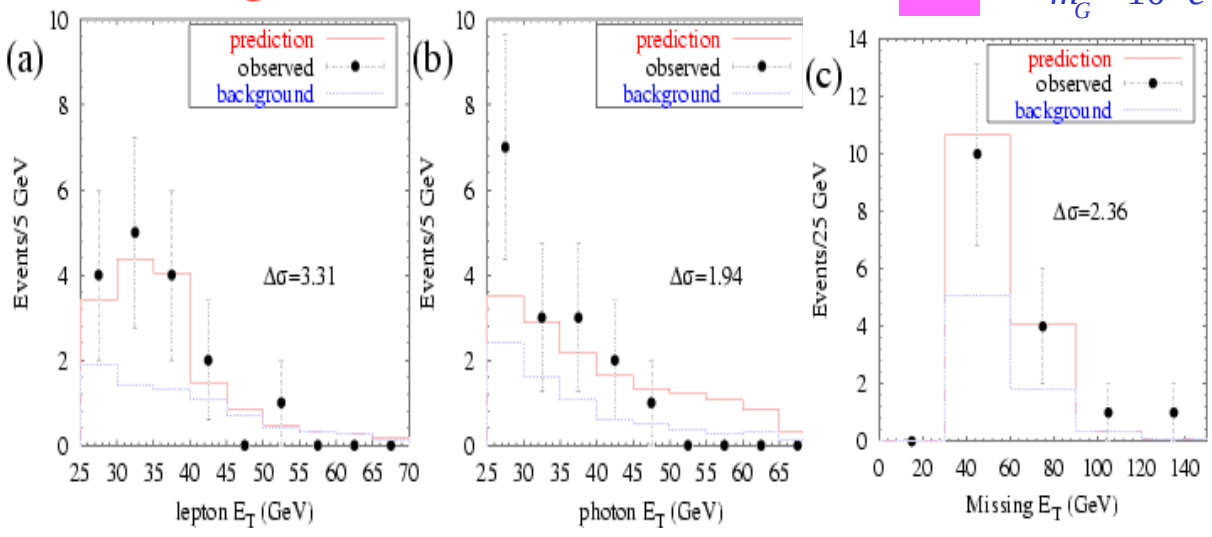


$mg\not{E}_T$ events in CDF RunI : RPV + GMSB ?

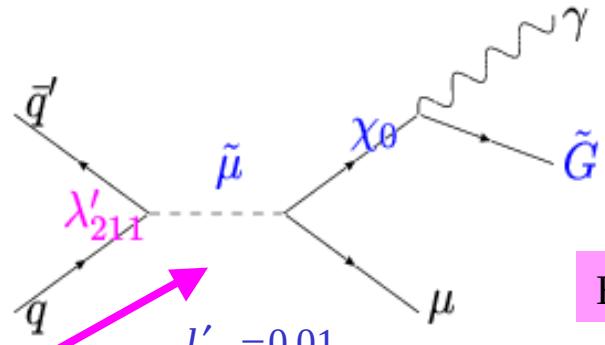
Search for : leptons, photons and missing transverse $\not{E}_T$

$$\int L\,dt = 86.3\ pb^{-1}$$

Channel	Background	N_{obs}	$P(N > N_{obs})$
$\mu\gamma\not{E}_T$	4.5±0.5	11	0.0054



• B.C. Allanach, S. Lola, K. Sridhar, hep-ph/0112321



?

$l'_{211} = 0.01$

$\tan b = 10$

$m_{\tilde{G}} = 10^{-3} eV$

$E_T > 25 GeV$

ISASUGRA7.58 & HERWIG6.301

Example-fit Points

$\Downarrow$

$$BR(\tilde{m} \to m c_1^0) = 0.984$$

$$BR(c_1^0 \to g\tilde{G}) = 0.975$$

$$m_{\tilde{e}_L, \tilde{m}_L} = 130.8\ GeV$$

$$m(c_1^0) = 86.8\ GeV$$

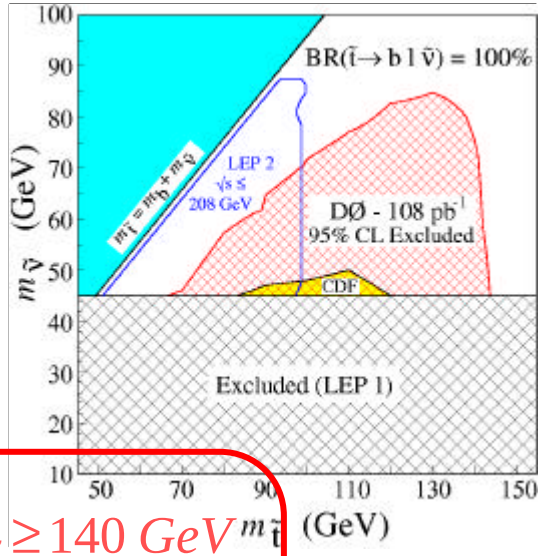
$mg\not{E}_T$: discrepancy with SM bkg

$eegg\not{E}_T$: also

RPV with light gravitino can explain them

RunII conclusive : expect 70-193 events

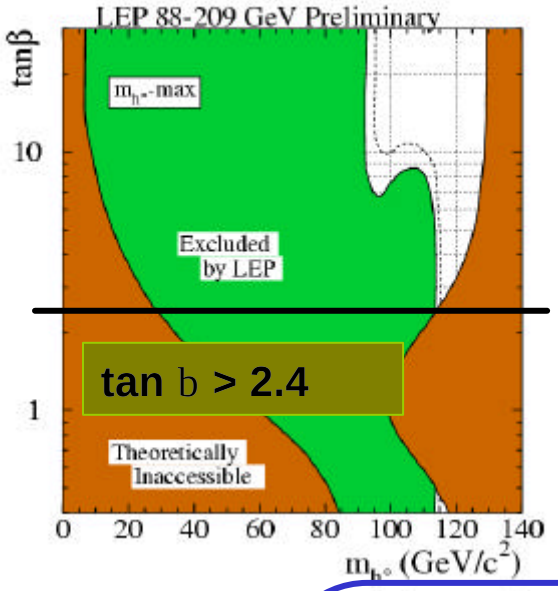
Summary Limits (LEP+Run I Tevatron)



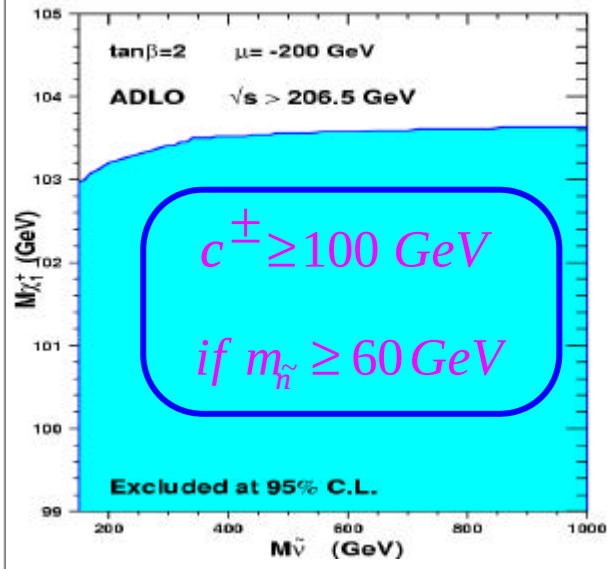
$m_{\tilde{t}} \geq 140\ GeV$

$if\ m_{\tilde{n}} \leq 60\ GeV$

from Higgs boson searches at LEP

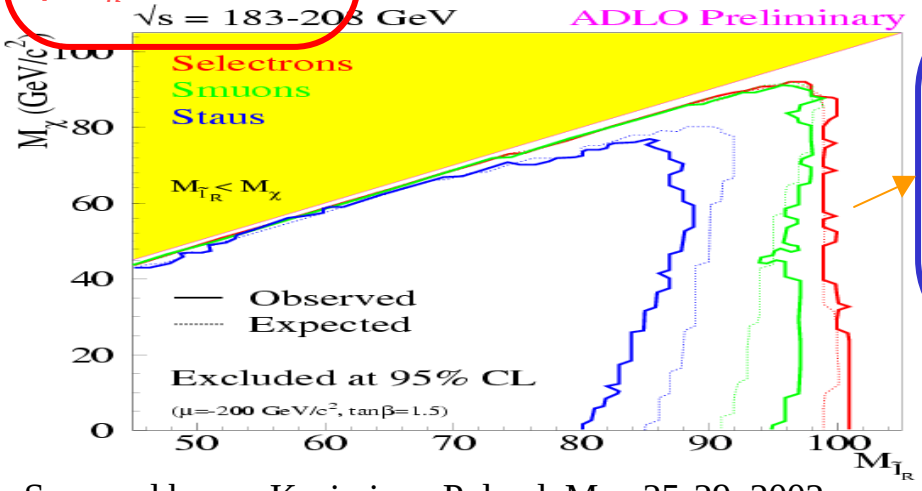


tan b > 2.4



$c^{\pm} \geq 100\ GeV$

$if\ m_{\tilde{n}} \geq 60\ GeV$



$m_{\tilde{e}} \geq 100\text{–}90\ GeV$

↓

$m_{\tilde{\nu}} \geq 75\text{–}60\ GeV$

$m_{\tilde{m}} \geq 95\ GeV$

$c_1^0 \geq 50\text{–}46\ GeV$

$c_2^0 \geq 103\text{–}100\ GeV$

$m_{\tilde{b}} \geq 140\ GeV$

$if\ m_{c_1^0} \leq 60\ GeV$

$m_{\tilde{q}} \approx m_{\tilde{g}} \geq 330\ GeV$

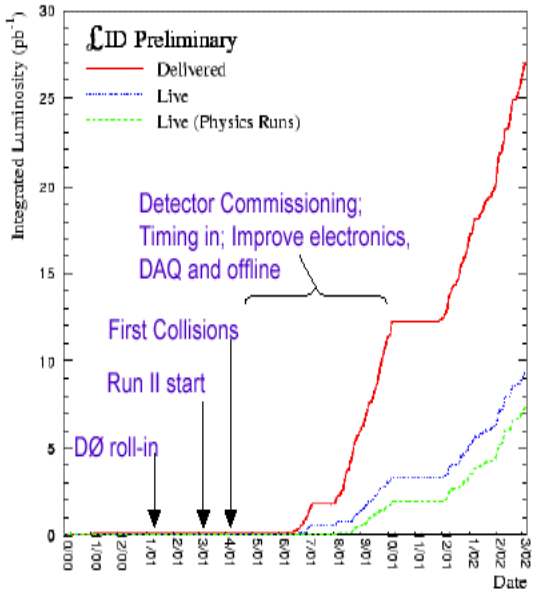
Summary

- Lots of searches in Run I (and LEP, Hera, etc …)
- Still only half of (susy) particles have been found … ☺
- In e+e- machines limits are kinematic – Tevatron is limited by $\int L\,dt$ & $\sqrt{s}$
- Run II : CDF & DØ are **taking data**
  - so far ~ 10 pb-1 on tape, 30 pb-1 delivered,
  - 300 pb-1 expected before the end of 2002.

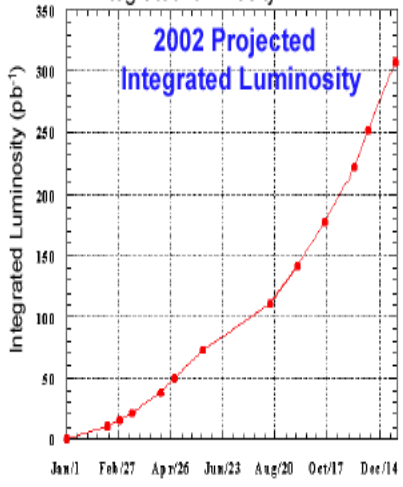
RunIIa expected reaches :

$$m_{\tilde{q}} = m_{\tilde{g}} \approx 400\,GeV \qquad m_{c^{\pm}} \approx 200\,GeV$$

$$m_{\tilde{t}\to c\tilde{c}_1^0} \approx 160\,GeV \qquad m_{\tilde{t}\to b\tilde{n}} \approx 190\,GeV$$



- Refine reconstruction algorithms
- …
- Also looking forward to more integrated luminosity!!!



- Best discovery channel at Tevatron Run II : $\tilde{c}_2^{\,0}\tilde{c}_1^{\pm}$ in 3 leptons topology, di-leptons (multijets more criticals due to NLO corrections …)