R-parity Violating SUSY Searches at the Fermilab Tevatron

SUSY **98**

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Outline

- R-parity Phenomenology
- Current Constraints on R-parity Violation
- HERA High Q^2 Event Excess Saga
- Tevatron Searches for R-parity Violating SUSY
  - HERA-inspired Searches
  - General Searches
- Summary
- Future prospects

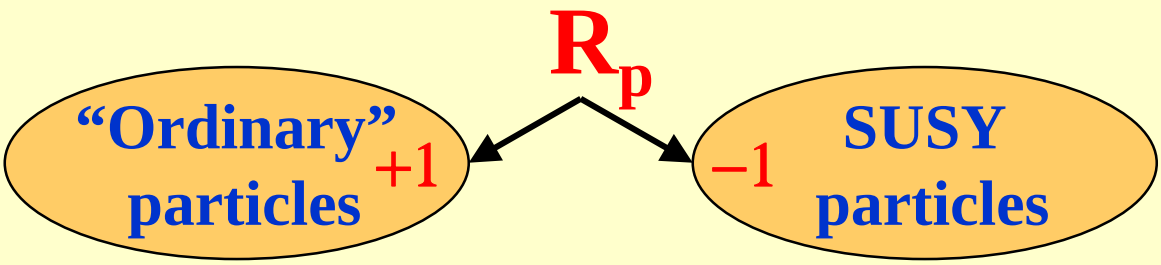
Phenomenology of the R-Parity Violation

SUSY introduces an extra discrete symmetry: R-parity, or R_p:

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

B - baryon number
L - lepton number
S - particle spin

Originated in a footnote[±7] *of classical Farrar-Fayet paper [PL **76B** (1978) 575] - 20 years of R-parity!*



P-parity? - Was taken!; Q-parity? - Excuse my French!; hence - R-parity

RPV couplings describe lepton or baryon number non-conservation (given that the angular momentum is still conserved!)

Full SUSY Superpotential

Superpotential:

$$W = W_{MSSM} + W_{\not{R}_p}$$

$$W_{MSSM} = h^e_{ij} L_i H_1 \overline{E}_j + h^d_{ij} Q_i H_1 \overline{D}_j + h^u_{ij} Q_i H_1 \overline{U}_j + \mu H_1 H_2$$

$$W_{\not{R}_p} = \frac{1}{2}\lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \frac{1}{2}\lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k + \kappa_i L_i H_2$$

i,j,k - generation indices; L,Q are lepton, quark doublets; E,D,U are electron, d-, u-quark singlets; $\lambda, \lambda', \lambda''$ – RPV couplings; κ_i dimensionless mass parameters

Including $SU(2)_L$ and $SU(3)_C$ symmetry requirements we end up with 9+27+9+3 = 48 new terms beyond MSSM

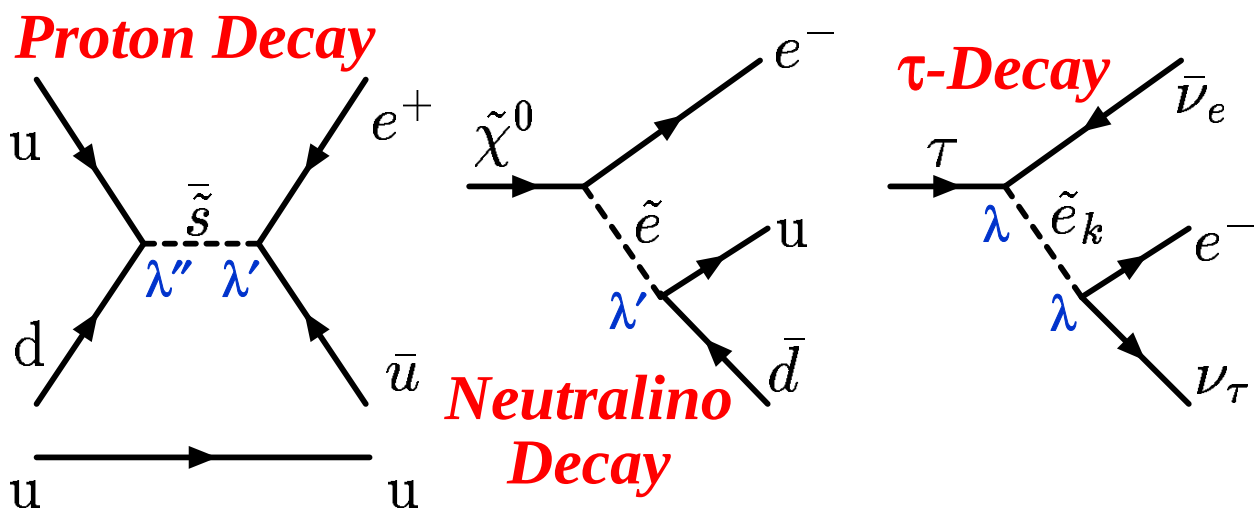
It's conventional to perform (L_i, H_1) rotation:

$$W_{\not{R}_p} = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k$$

Lepton number violation **Baryon number violation**

$$L_{L_i Q_j \overline{D}_k} = \lambda'_{ijk} \Big[-\tilde{e}^i_L u^j_L \overline{d}^k_R - e^i_L \tilde{u}^j_L \overline{d}^k_R - \left(\overline{e}^i_L\right)^c u^j_L \left(\tilde{d}^k_R\right)^* + \tilde{\nu}^i_L d^j_L \overline{d}^k_R + \nu^i_L \tilde{d}^j_L \overline{d}^k_R + \left(\overline{\nu}^i_L\right)^c d^j_L \left(\tilde{d}^k_R\right)^* \Big] + h.c.$$

RPV Decays and Experimental Bounds



Current RPV coupling bounds (mostly 1σ, $\tilde{m} = 100$ GeV): [H.Dreiner, hep-ph/9707435]

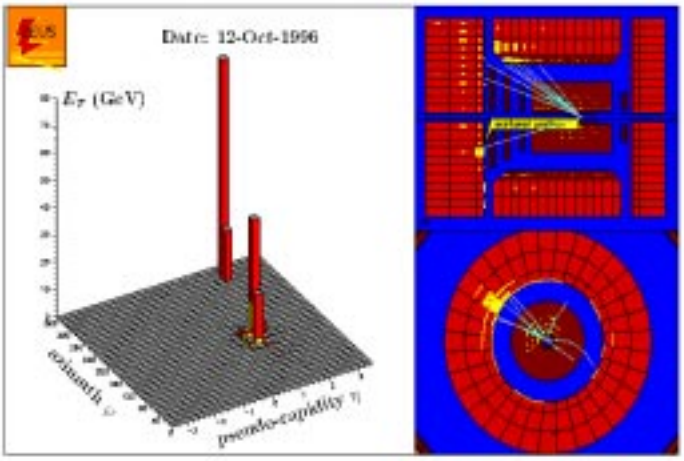
ijk	λ_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ''_{ijk}
121	0.05	111	0.001	211	0.09	311	0.16	112	10^{-6}
122		112	0.02	212		312		113	10^{-5}
123		113		213		313		123	1.25
131	0.06	121	0.035	221	0.18	321	0.20	212	
132		122	0.06	222		322		213	
133	0.004	123	0.20	223		323		223	
231	0.06	131	0.035	231	0.22	331	0.26	312	0.43
232		132	0.33	232	0.39	332		313	
233		133	0.002	233		333		323	

CC universality	double β	$R_l(Z)$	ν_μ DIS	n↔n-bar
$\tau \to e\nu\nu/\mu\nu\nu$	Atomic Parity V.	$\pi \to e\nu/\mu\nu$	$\tau \to \pi\nu$	Indirect
ν_e mass	D^0-D^0-bar mixing	$D^+ \to K^*\mu\nu/K^*e\nu$	Heavy nucleon decay	2σ bounds

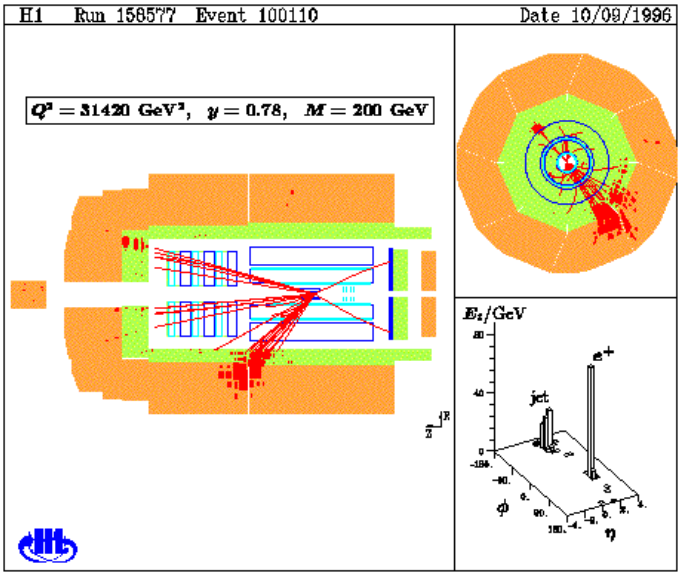
HERA High Q^2 Events

HERA at DESY (Hamburg)

High Q^2 events in 20 pb^{-1} of e^+p data



ZEUS: 4 events (SM: 0.9)



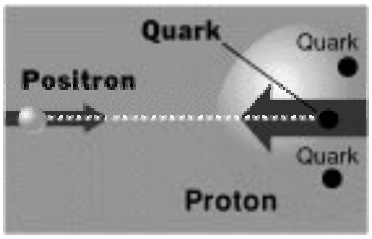
H1: 7 events (SM: 1.0)

New York Times February 25, 1997

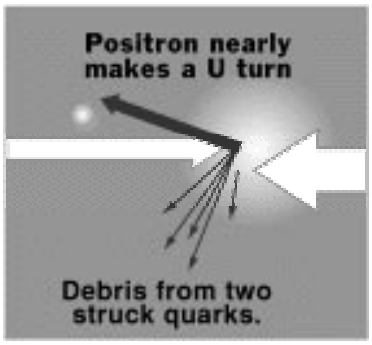
Footprints of a ~~Leptoquark~~?

At the DESY accelerator in Hamburg, Germany a positron (the electron's antimatter counterpart) collides with a quark. In a few spectacular collisions, the positron nearly makes a U turn. One possible explanation is the momentary creation of a strange new particle called a leptoquark.

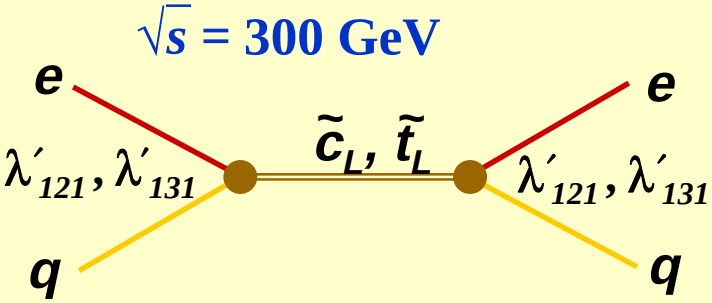
Positron and a quark inside a proton are accelerated close to the speed of light and then collided



The high-energy positron nearly reverses direction, possible evidence of a leptoquark.



HERA High Q^2 Events And RPV SUSY



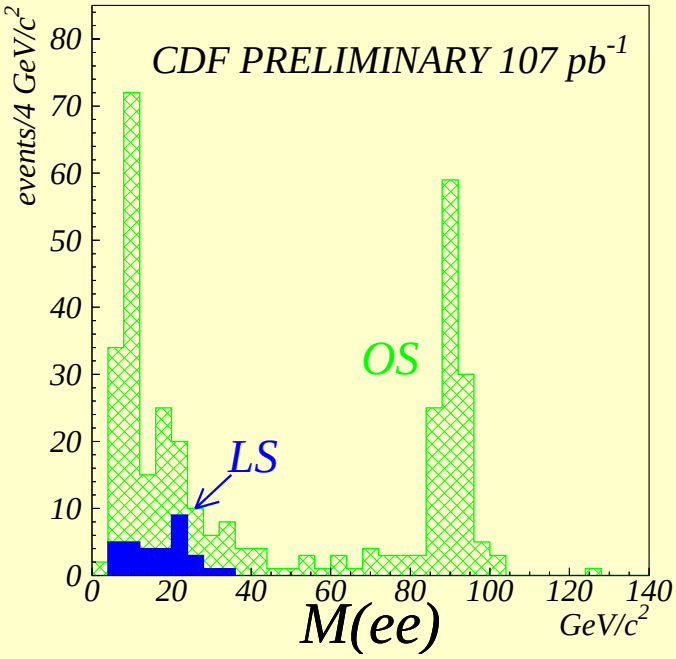
Choudhury/Raychaudhuri PL **B401** (1997) 54, PRD **56** (1997) 1778; **Altarelli et al.** hep-ph/9703276; **Dreiner/Morawitz** hep-ph/9703279; **many others**

Need λ'_{1j1} in order to use valence quarks in the proton; λ'_{111} is severely constrained by neutrinoless double β-decay

- ***After the 1997 data set has been analyzed the significance of HERA anomaly did not improve; in fact, the 1997 data alone does not exhibit any significant excess of high Q^2 events***
- ***Joint analysis of the H1/ZEUS data does not support an explanation of the HERA results with a single narrow s-channel resonance [U.Bassler, G.Bernardi,*** *Z.Phys.* ***C76****, 223 (1997)]*
- ***However, the HEP community attention to the RPV SUSY searches was attracted and a lot of studies in this direction are being done***

R-Parity Violating SUSY at the Tevatron

At the Tevatron SUSY particles could be produced in pairs via strong interactions (e.g., via s-channel gluon exchange)



HERA-motivated RPV searches:

$$p\bar{p} \to \begin{cases} \tilde{c}_L \bar{\tilde{c}}_L, \tilde{t}_L \bar{\tilde{t}}_L \xrightarrow{R_p} \left(l^+ d\right)\left(l^- \bar{d}\right) \\ \tilde{c}_L \bar{\tilde{c}}_L, \tilde{t}_L \bar{\tilde{t}}_L \to \left(c\tilde{\chi}_1^0\right)\left(\bar{c}\tilde{\chi}_1^0\right) \xrightarrow{R_p} c\left(q\bar{q}'l^\pm\right)\bar{c}\left(q\bar{q}'l^\pm\right) \\ \tilde{g}\tilde{g} \to \left(\bar{c}\tilde{c}_L\right)\left(\bar{c}\tilde{c}_L\right) + c.c. \xrightarrow{R_p} \bar{c}\left(dl^+\right)\bar{c}\left(dl^+\right) + c.c. \end{cases}$$

General RPV searches:

$$p\bar{p} \to \begin{cases} \tilde{q}\bar{\tilde{q}} \to \left(q\tilde{\chi}_1^0\right)\left(\bar{q}\tilde{\chi}_1^0\right) \xrightarrow{R_p} q\left(q\bar{q}'l^\pm\right)\bar{q}\left(q\bar{q}'l^\pm\right) \\ \tilde{\chi}_1^0\tilde{\chi}_1^0 \xrightarrow{R_p} \left(q\bar{q}'l^\pm\right)\left(q\bar{q}'l^\pm\right) \end{cases}$$

RPV in Gluino Pair Production (CDF)

$$p\bar{p} \rightarrow \tilde{g}\tilde{g} \qquad \lambda'_{121}$$

$$\tilde{g} \rightarrow \bar{c}\tilde{c}_L + c\bar{\tilde{c}}_L \xrightarrow{R_p} \bar{c}e^+d + ce^-\bar{d}$$

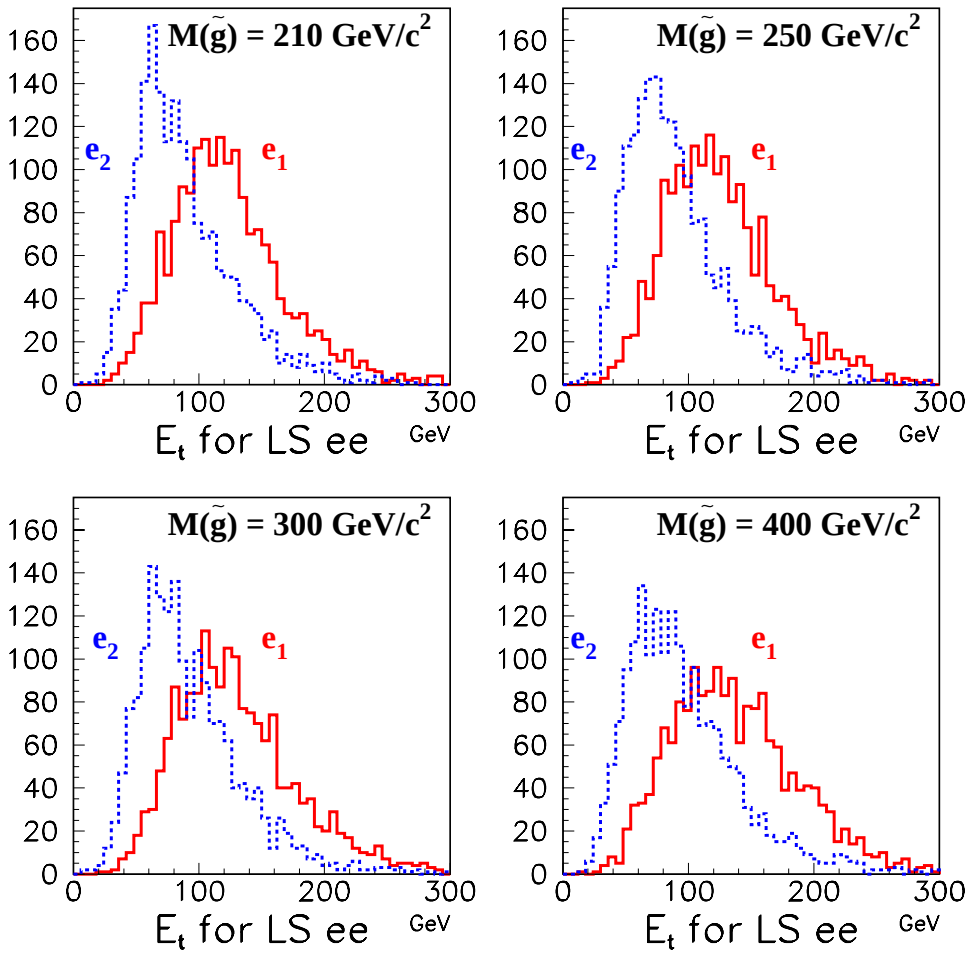
$$p\bar{p} \rightarrow \left(e^+e^+ \text{ or } e^-e^-\right) + jets$$

- Model:
  - Choudhury/Raychaudhuri PRD **56** (1997) 1778
  - $M(\tilde{u}_R^i) = M(\tilde{d}_R^i) = M(\tilde{u}_L^\alpha) \equiv M(\tilde{q}),\ i = 1,2,3;\ \alpha = 1,3$
  - $M(\tilde{d}_L^i)^2 = M(\tilde{u}_L^i)^2 - M(u^i)^2 + M(d^i)^2 - M(W)^2 \cos 2\beta;\ \tan\beta = 2$
  - $M(\tilde{q}) > M(\tilde{g}) > M(\tilde{c}_L) = 200\ \text{GeV}$
- Cuts:
  - 2 e^+e^+ or e^-e^- with $E_T > 15$ GeV, $|\eta_e| < 1.1$
  - ≥2 jets with $E_T > 15$ GeV, $|\eta_j| < 2.4$
  - Missing E_T veto ($\not{E}_T/\sqrt{\Sigma E_T} < 5\ \text{GeV}^{1/2}$)
- Data:
  - No events in 107 pb^{-1}

RPV in Gluino Pair Production (cont'd)

- Signal Monte Carlo:

ISAJET 7.20 + CDF Detector Simulation (QFL')



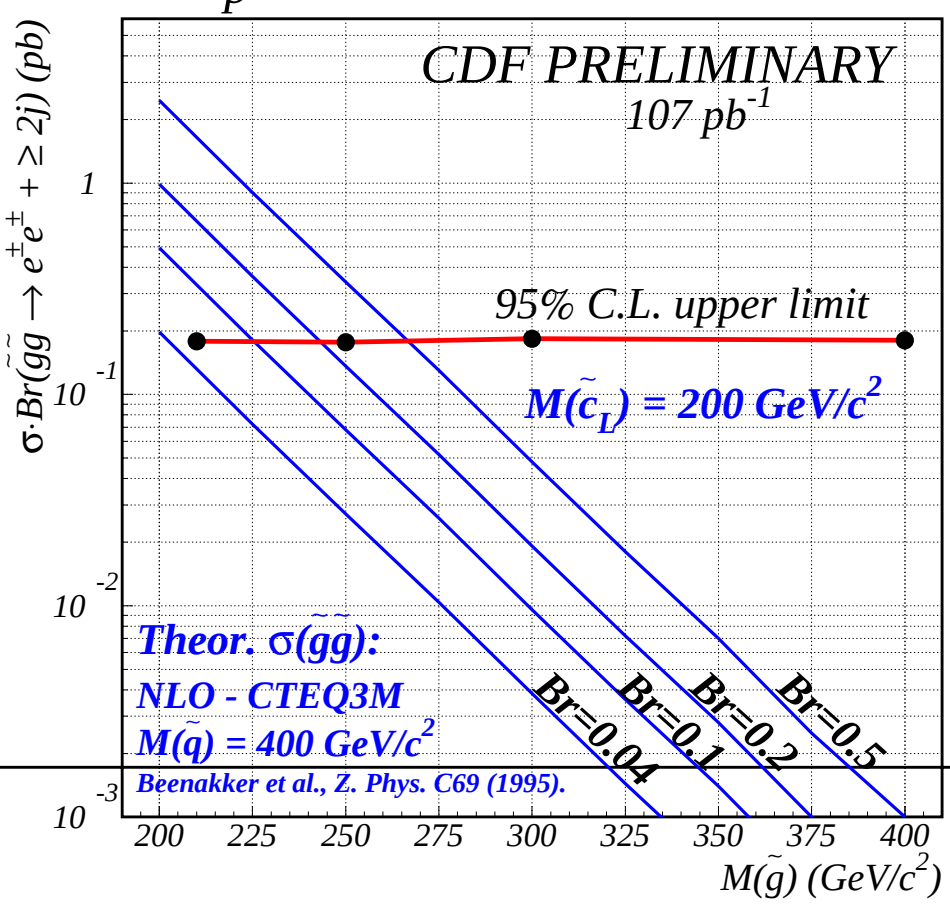
R-parity violating decays

- Backgrounds:
  - semileptonic b- and c-decays; negligible

RPV in Gluino Pair Production (cont'd)

- Limits:
  - Based on NLO $p\bar{p} \rightarrow \tilde{g}\tilde{g}$ calculations by Beenakker et al. Z.Phys. **C69** (1995) 163

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

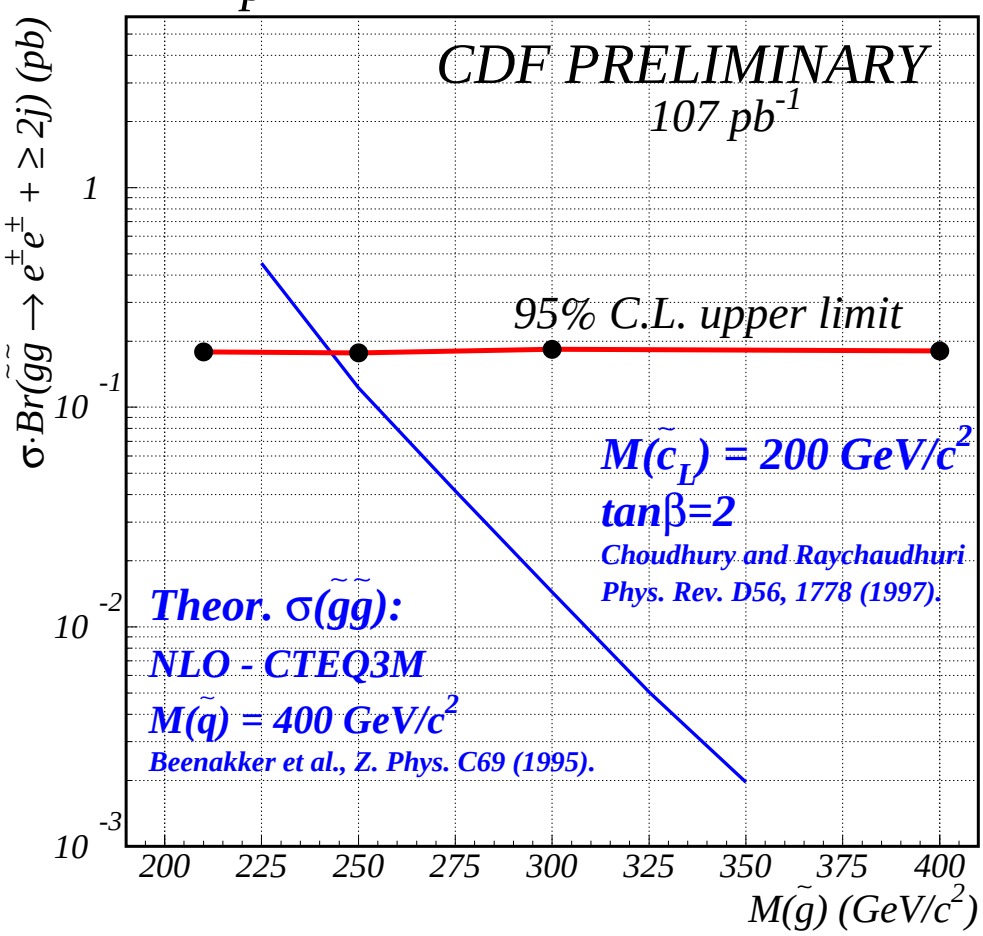


$$Br \equiv BR\left(\tilde{g}\tilde{g} \rightarrow e^{\pm}e^{\pm} + \geq 2\,jets\right)$$

RPV in Gluino Pair Production (cont'd)

- Limits:
  - Based on additional assumption of Choudhury/Raychaudhuri BR value

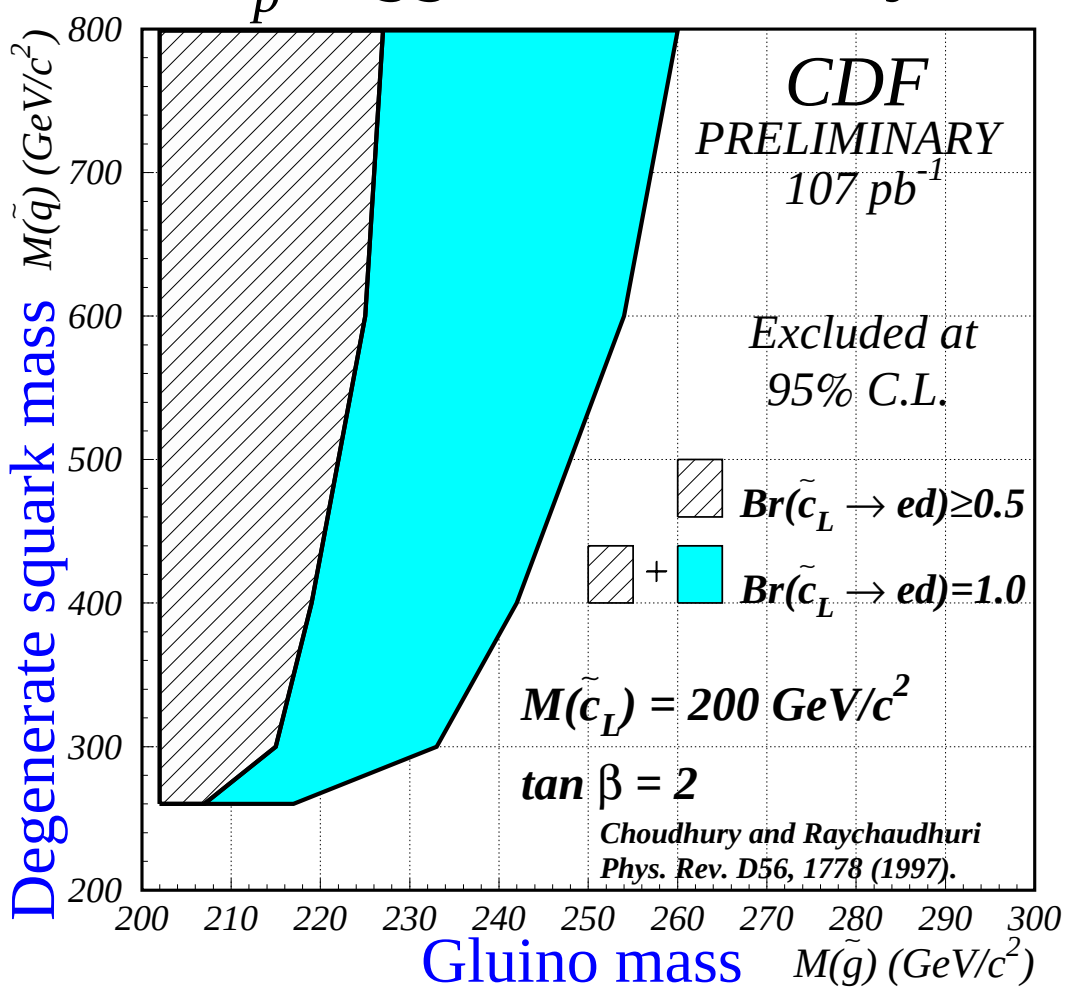
$$\not{R}_p \quad \tilde{g}\tilde{g} \rightarrow e^{\pm}e^{\pm} + \geq 2j$$



RPV in Gluino Pair Production (cont'd)

- Limits in $M(\tilde{g})$ vs. $M(\tilde{q})$ plane :
  - Br = 1: $\tilde{c}_L$ can be LSP (with RPV decay)
  - Br < 1: $\tilde{\chi}^0_1$ can be LSP

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



RPV in Squark Pair Production (CDF)

$$p\bar{p} \to \tilde{q}\bar{\tilde{q}} \to \left(q\tilde{\chi}_1^0\right)\left(\bar{q}\tilde{\chi}_1^0\right) \xrightarrow{R_p} q\left(q\bar{q}'e^{\pm}\right)\bar{q}\left(q\bar{q}'e^{\pm}\right)$$

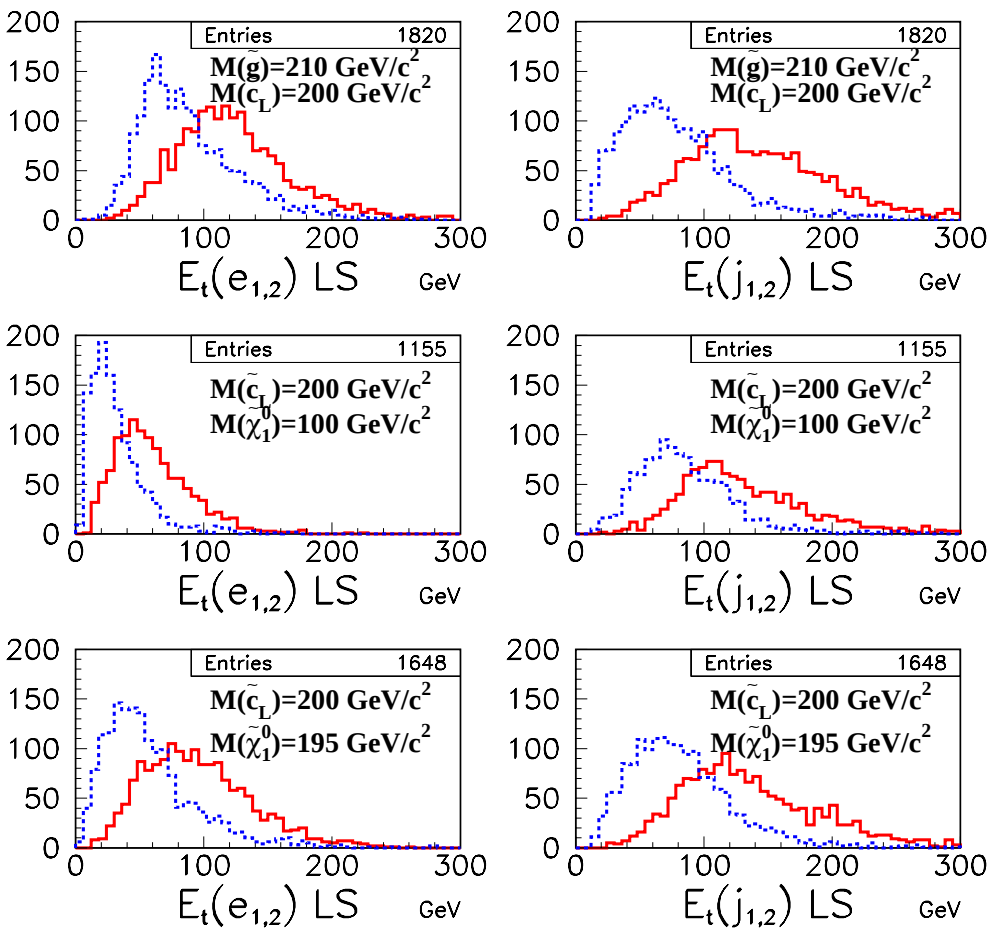
$$p\bar{p} \to \left(e^+e^+ \text{ or } e^-e^-\right) + jets \qquad \boxed{\lambda'_{1ij}}$$

- Model:
  - Light stop is considered separately from 5 other mass degenerate squarks
  - $M(\tilde{\chi}_1^{\pm}) > M(\tilde{q}) > M(\tilde{\chi}_1^0)$ (suppresses $\tilde{q} \to q\tilde{\chi}_1^{\pm}$)
  - $M(\tilde{\chi}_1^{\pm}) \approx 2M(\tilde{\chi}_1^0)$ (gaugino mass unification argument)
  - $M(\tilde{\chi}_1^{\pm}) > M(\tilde{t}_1) - M(b)$ (ensures $BR\left(\tilde{t}_1 \to c\tilde{\chi}_1^0\right) = 1$)
- Cuts (same as in gluino analysis):
  - 2 e^+e^+ or e^-e^- with $E_T > 15$ GeV, $|\eta_e| < 1.1$
  - ≥2 jets with $E_T > 15$ GeV, $|\eta_j| < 2.4$
  - Missing E_T veto ($\not{E}_T/\sqrt{\Sigma E_T} < 5$ GeV$^{1/2}$)
- Data:
  - No events in 107 pb^{-1}

RPV in Squark Pair Production (cont'd)

- Signal Monte Carlo:

ISAJET + CDF Detector Simulation

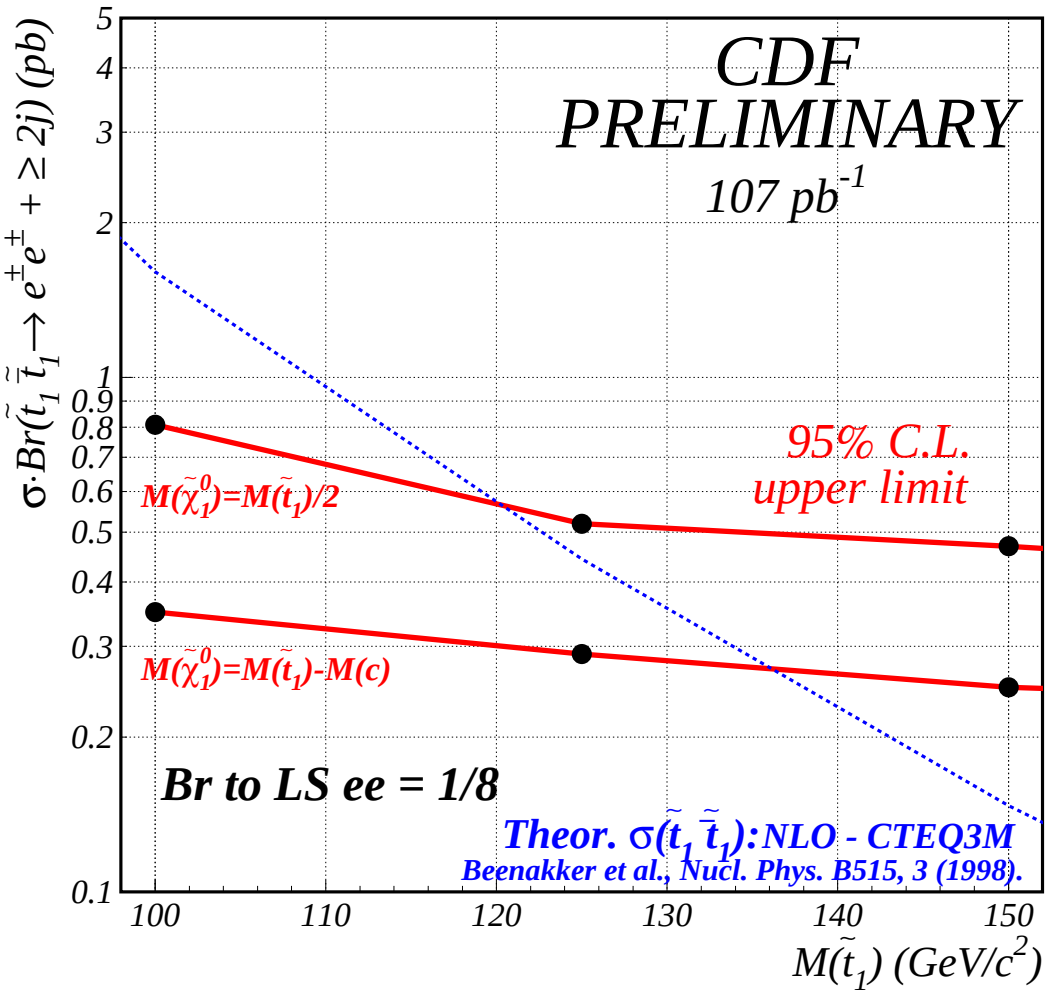


- Backgrounds:
  - semileptonic b- and c-decays; negligible

RPV in Squark Pair Production (cont'd)

- Limits:
  - Based on NLO $p\bar{p} \rightarrow \tilde{t}\,\bar{\tilde{t}}$ calculations by Beenakker et al. NP **B515** (1998) 3

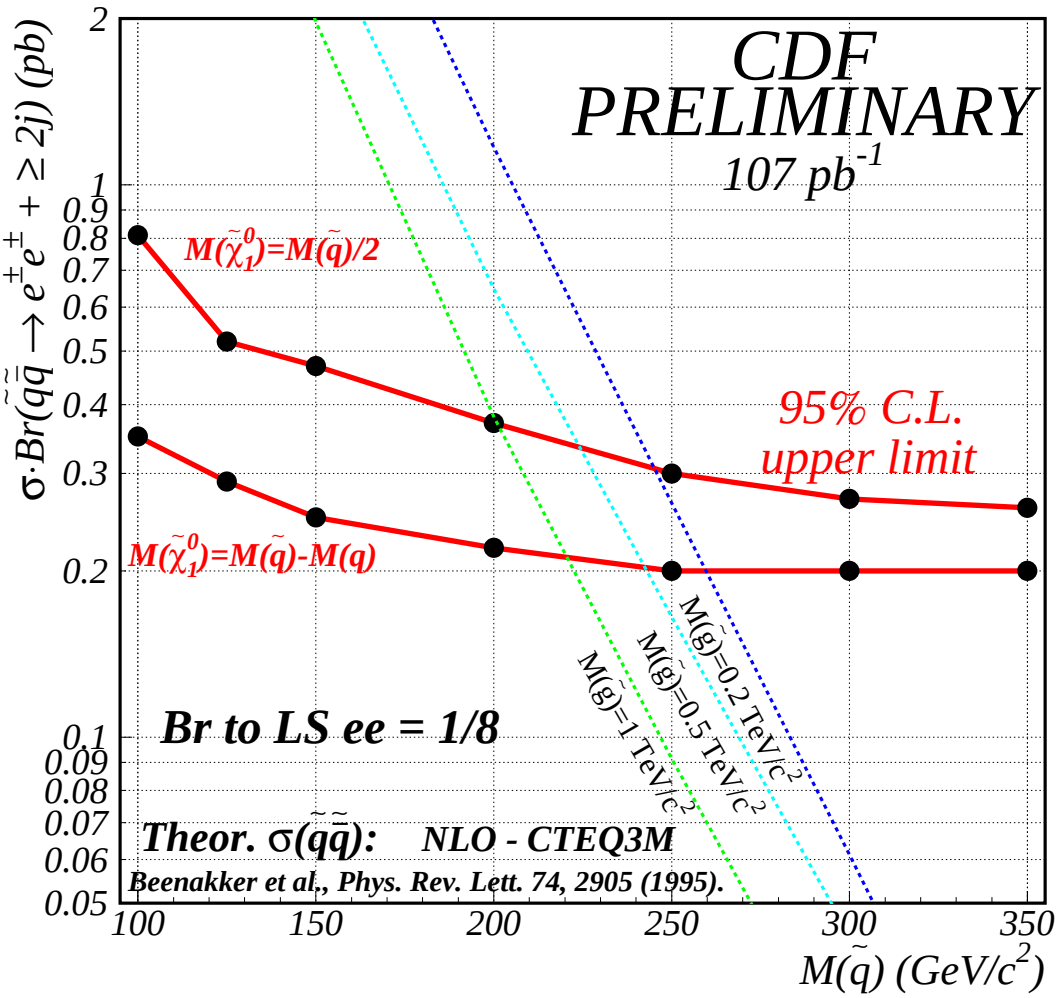
$$\not{R}_p \quad \tilde{t}_1\,\bar{\tilde{t}}_1 \rightarrow c\,\tilde{\chi}_1^0\,\bar{c}\,\tilde{\chi}_1^0 \rightarrow e^{\pm}e^{\pm} + \geq 2j$$



RPV in Squark Pair Production (cont'd)

- Limits:
  - Based on NLO $p\bar{p} \rightarrow \tilde{q}\bar{\tilde{q}}$ calculations by Beenakker et al. PRL **74** (1995) 2905

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



RPV in Neutralino Pair Production (DØ)

$$p\bar{p} \to \cdots \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X \to (e\tilde{e})\,(e\tilde{e}) + X \xrightarrow{R_p} e\,(q\bar{q}')\; e\,(q\bar{q}') + X$$

$$p\bar{p} \to ee + \geq 4 jets$$

λ'_{1ij}

- Model:
  - Neutralino is the LSP
  - Neutralino decays inside the fiducial volume, i.e. $\lambda' \gtrsim 10^{-3}$
  - SUGRA framework: m_0, $m_{1/2}$, tan(β)=2, ~~A_0~~, sing(μ)<0
  - $\lambda'_{122} \neq 0$ (sensitive to other combinations too)
- Cuts:
  - ≥2e with E_T > 15,10 GeV, $|\eta_e|$ < 1.1, 1.5 < $|\eta_e|$ < 2.5
  - ≥4 jets with E_T > 15 GeV, $|\eta_j|$ < 2.5
  - Z(ee)-veto (M_{ee} < 76 GeV or M_{ee} > 106 GeV)
  - $H_T = \Sigma E_T^j + \Sigma E_T^e$ > 150 GeV
- Data:
  - 2 events in 96 pb^{-1}

RPV in Neutralino Pair Production (cont'd)

- Backgrounds:
  - Drell-Yan with ≥4 jets (ISAJET 7.13)
  - $t\bar{t} \to ee$ + jets (HERWIG 5.7)
  - $Z(\tau\tau)$ +jets $\to$ ee + jets (ISAJET 7.08)
  - WW + jets $\to$ ee + jets (PYTHIA 5.6)
  - QCD multijets (Data)
- Signal:
  - ISAJET 7.13 $\begin{cases} \tilde{\chi}_1^0\tilde{\chi}_1^0;\ \tilde{q}\bar{\tilde{q}} \to \tilde{\chi}_1^0\tilde{\chi}_1^0 + X;\ \tilde{g}\tilde{g} \to \tilde{\chi}_1^0\tilde{\chi}_1^0 + X \\ \tilde{q}\tilde{g} \to \tilde{\chi}_1^0\tilde{\chi}_1^0 + X;\ \bar{\tilde{l}}\tilde{l} \to \tilde{\chi}_1^0\tilde{\chi}_1^0 + X \end{cases}$

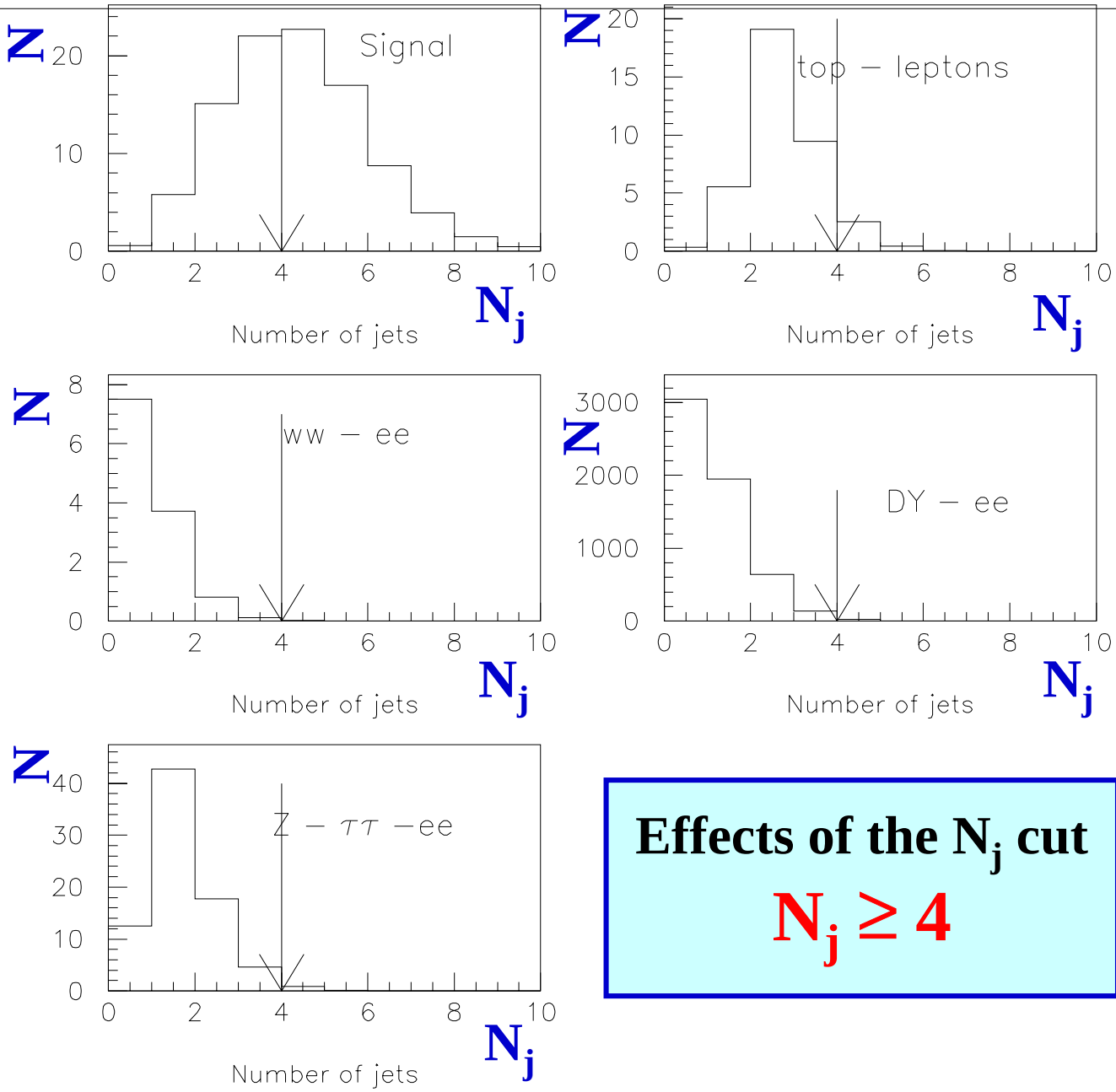
BR fractions: H.Dreiner, M.Guchait, D.P.Roy [PRD **49** (1994) 3270]

- Background Summary:
  - D-Y: 0.42 ± 0.15 (stat) ± 0.16 (syst) events
  - tt: 0.08 ± 0.01 (stat) ± 0.03 (syst) events
  - $Z(\tau\tau)$: 0.08 ± 0.02 (stat) ± 0.02 (syst) events
  - WW: negligible
  - QCD: 1.27 ± 0.24 (stat) events
  - Total: 1.8 ± 0.2 (stat) ± 0.3 (syst) events

(consistent with two events observed)

RPV in Neutralino Pair Production (cont'd)

- Signal vs. Background MC:

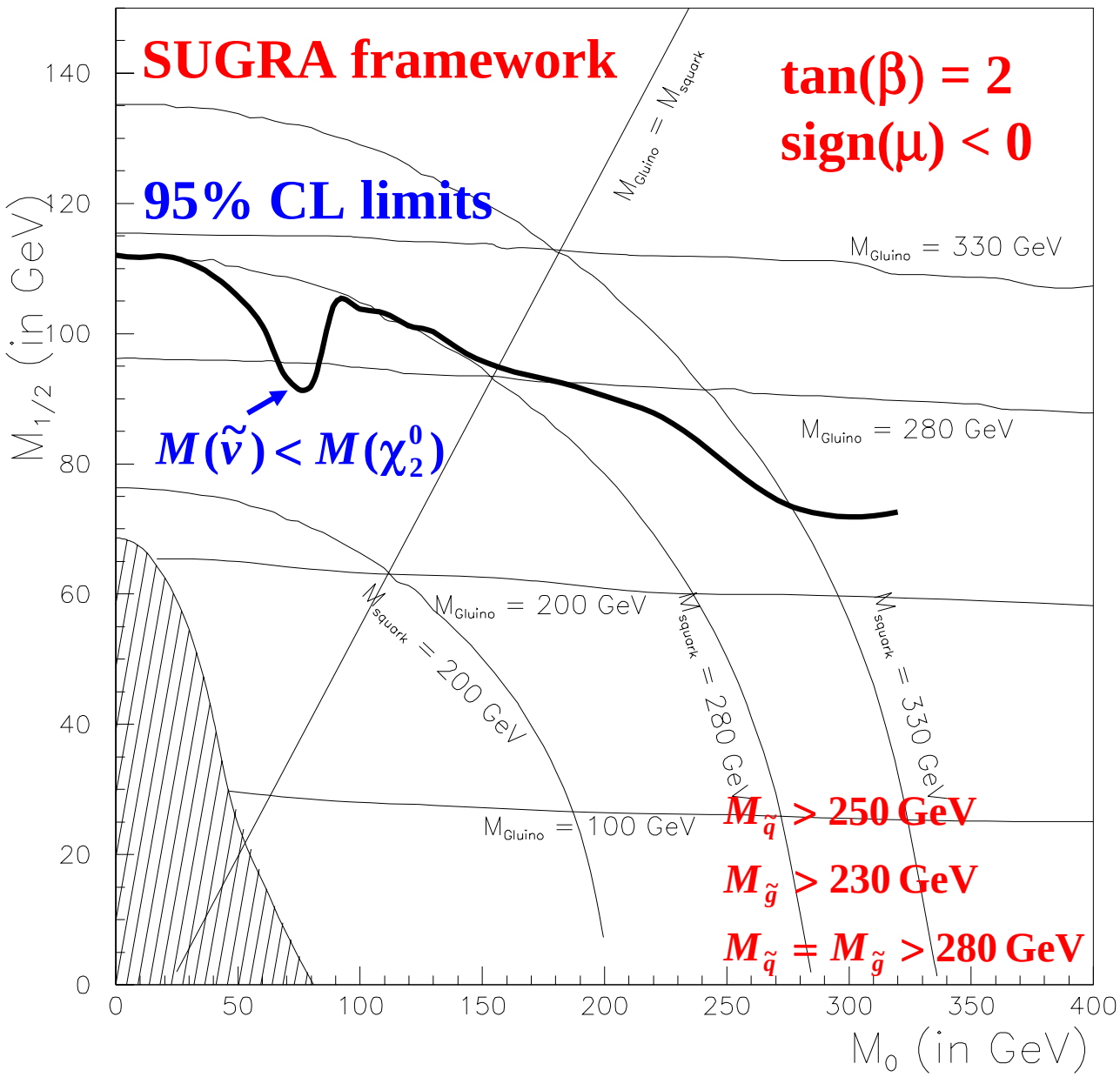


Effects of the N_j cut

$N_j \geq 4$

RPV in Neutralino Pair Production (cont'd)

- Limits:
  - Based on LO cross section from ISAJET



Summary

- Both CDF and DØ have already started searches for RPV SUSY
- The following HERA-inspired analyses were performed:
  - Search for RPV in gluino decays
  - Search for RPV in squark and stop decays
- The following general analysis was performed:
  - Search for RPV in neutralino decays
- They resulted in the new limits on gluino and squark masses as well as SUGRA parameters

Future Prospects

- Both the CDF and DØ teams are working on the RPV analysis in the $\mu\mu$+X channel
- A lot of theoretical interest to the RPV SUSY searches is very promising (cf. Run II SUSY/Higgs Workshop)
- Run II with twenty times higher luminosity and enhanced machine energy will open a very rich field of various SUSY searches
- After all, there is no a priori reasons to believe that R_p has to be conserved