



Searches for Supersymmetry at the Tevatron



Squarks / Gluinos

Charginos / Neutralinos

$$B_s \rightarrow \mu^+ \mu^-$$

R-parity Violation

Gauge Mediated SUSY Breaking



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ICHEP, Beijing, August 2004



Increased # of bunches:
 6 (3500 ns)
 \rightarrow 36 (396 ns)

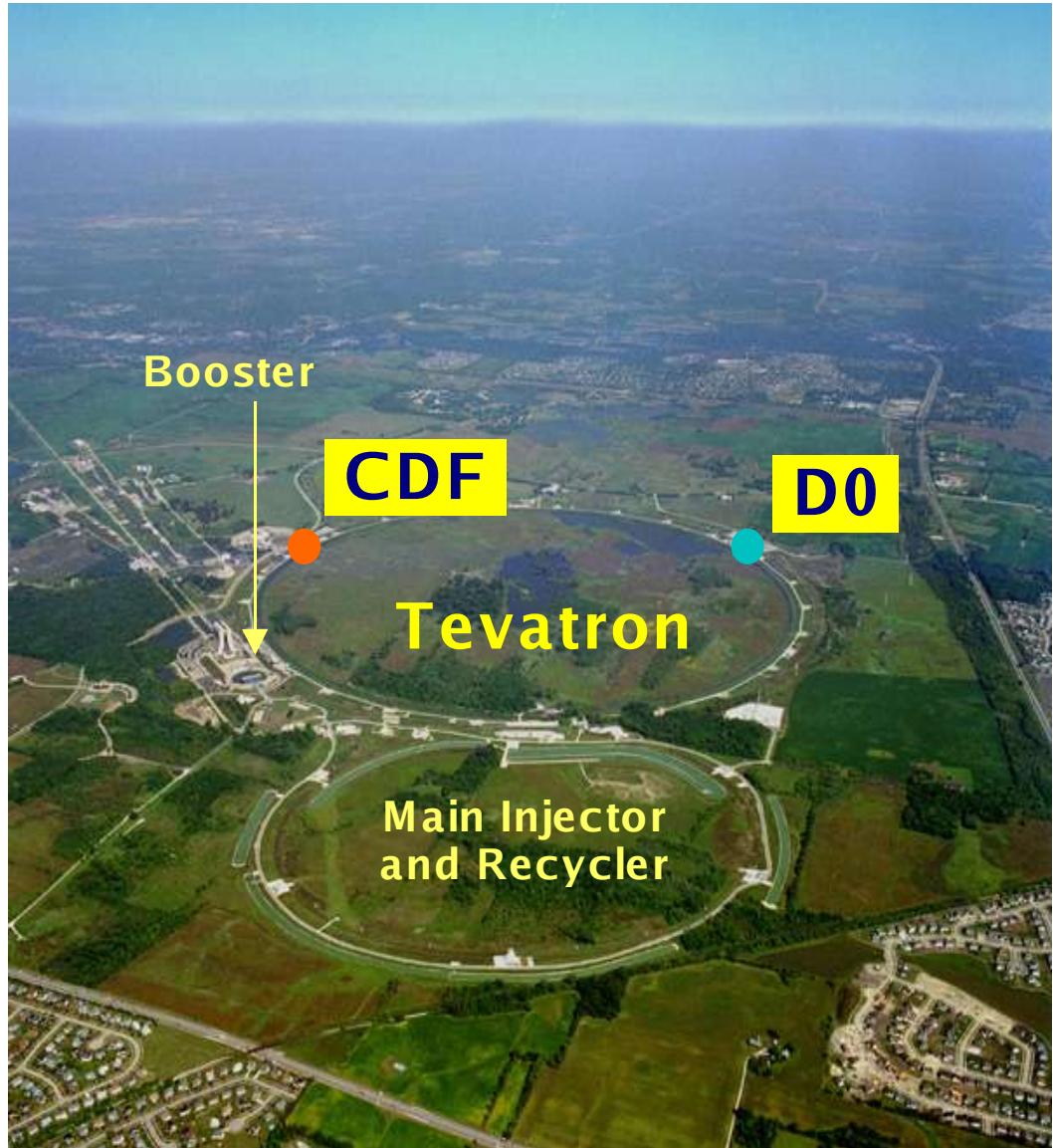
New Main Injector
 storage ring up to 150GeV

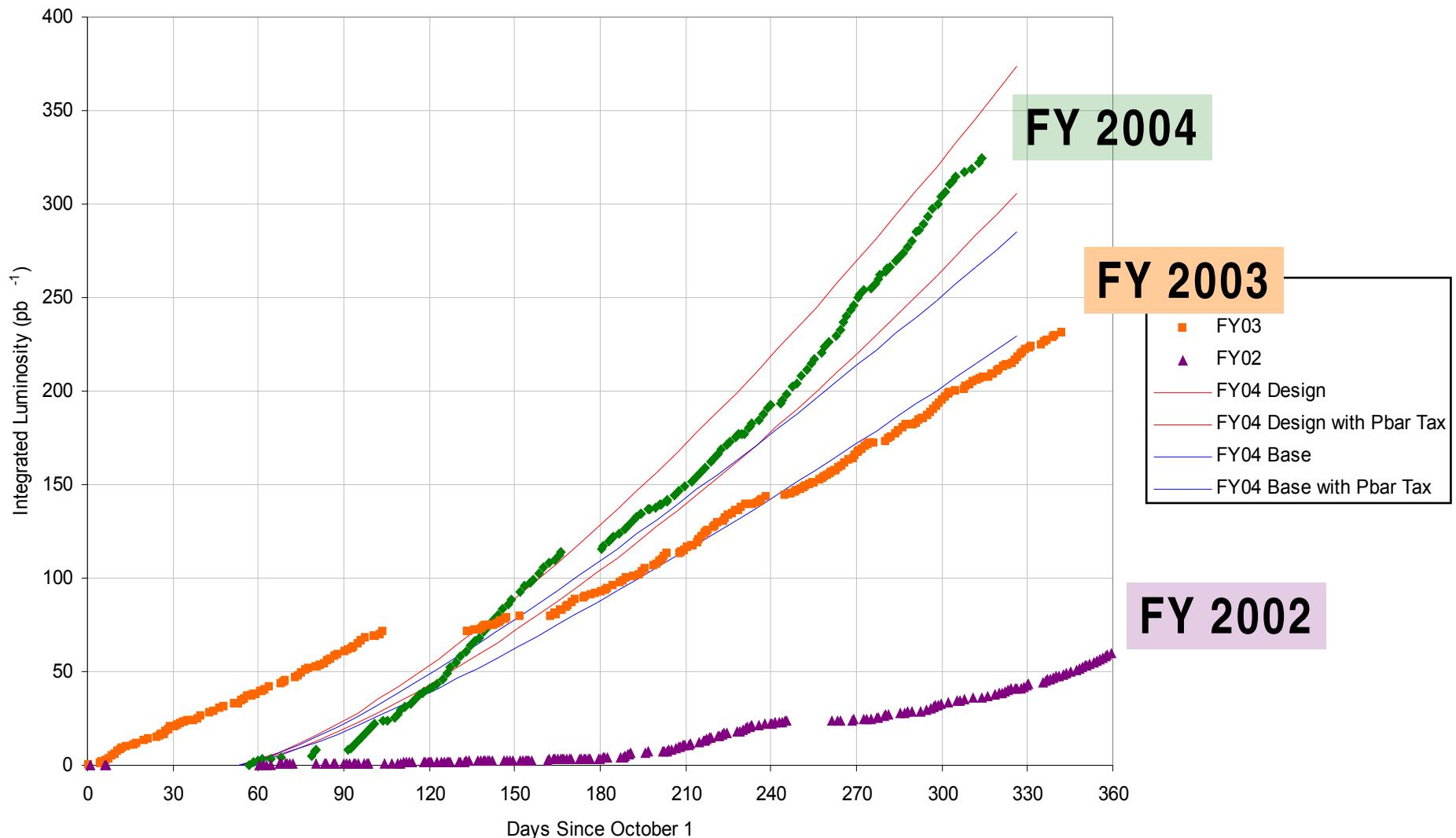
New “Recycler”

(Storage ring for pbar cooling (in commissioning), add e-cooling (installation))

- Run II start March 2001
- Typical peak luminosity
 - $0.16 \cdot 10^{32} \text{ cm}^{-2} \text{s}^{-1}$ (Run I)
 - $\rightarrow 0.8 \cdot 10^{32} \text{ cm}^{-2} \text{s}^{-1}$ (“Run IIa”)
 - $\rightarrow 2-4 \cdot 10^{32} \text{ cm}^{-2} \text{s}^{-1}$ (“Run IIb”)
- Achieved design luminosity for Run II without Recycler this Summer
- $\int L dt \simeq 4 - 8 \text{ fb}^{-1}$ by 2009

$p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ (Run I: 1.8 TeV)





Both experiments collected about 500 pb^{-1} so far in Run II
Analyses shown here use up to 250 pb^{-1}

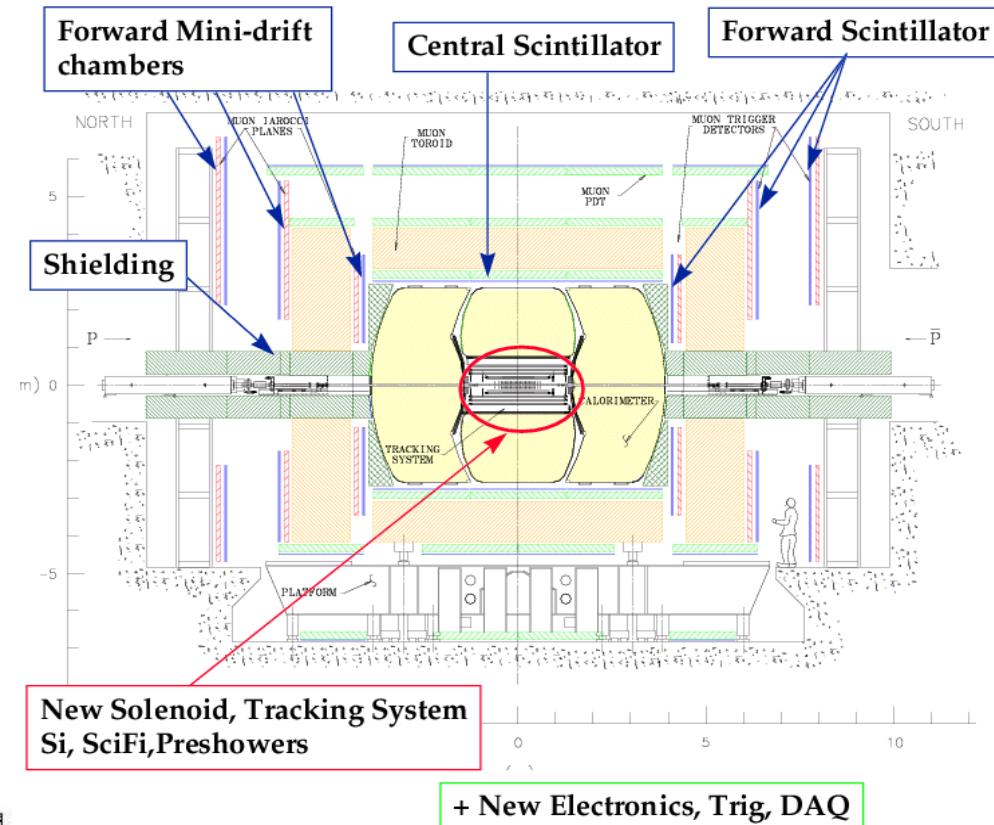
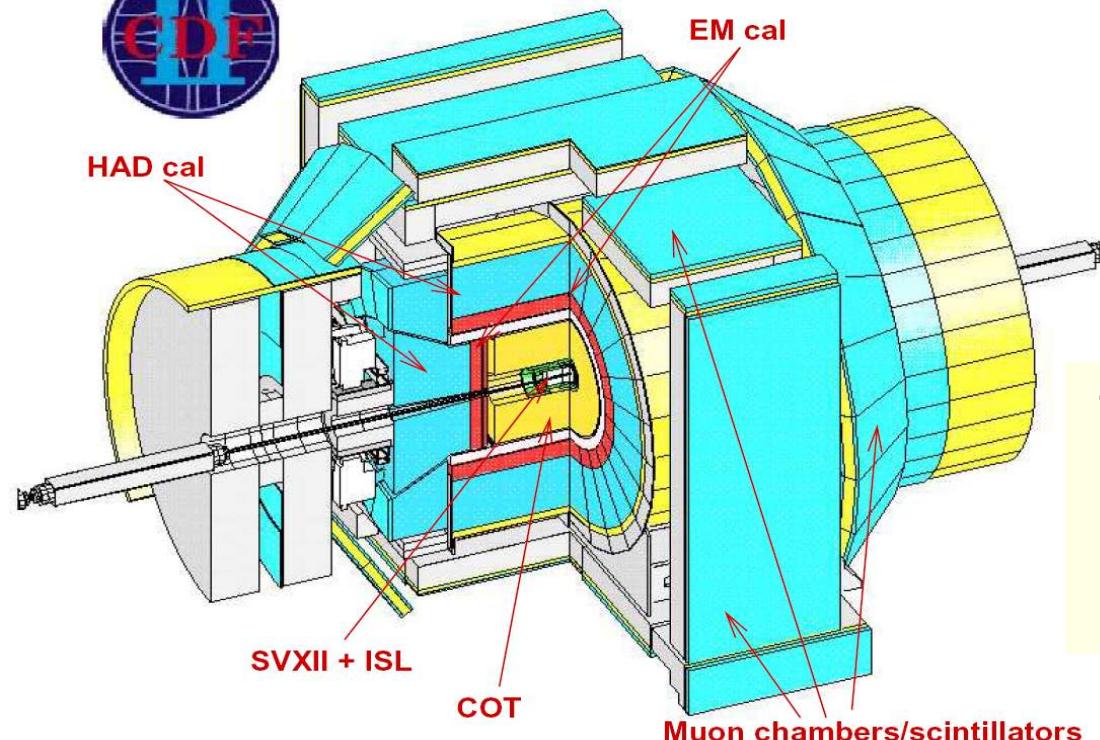
DØ Strengths:

Excellent and wide muon coverage, hermetic calorimetry



CDF Strengths:

Excellent precision tracking,
“deadtimeless” trigger



Two general purpose detectors: **CDF** **DØ**

Electron Acceptance

$|\eta| < 3.0$

Muon Acceptance

$|\eta| < 1.5$

Precision Tracking (Silicon)

$|\eta| < 2.0$

$|\eta| < 3.0$

- Direct searches for SUSY partners at the Tevatron

- ◆ Squarks / Gluinos

- Strong production – large cross sections
- Masses possibly relatively high

- ◆ Charginos / Neutralinos

- Small cross sections
- Chargino mass limit from direct searches at LEP: “only” 103 GeV
- Cascade decays can provide clean signatures

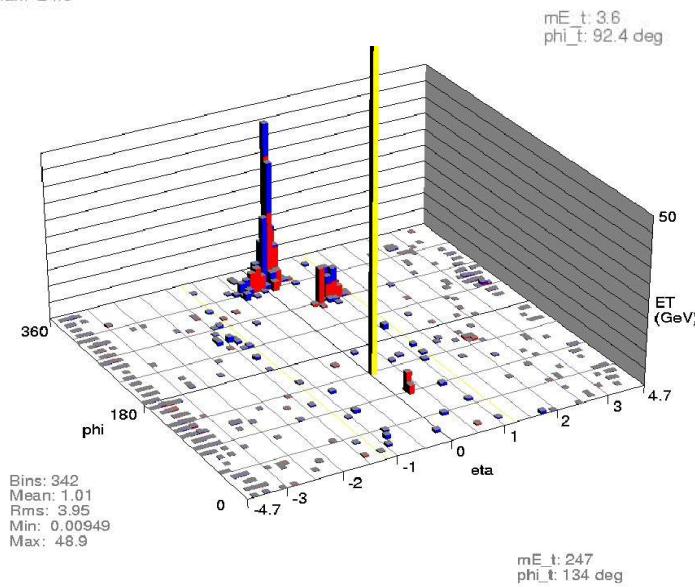
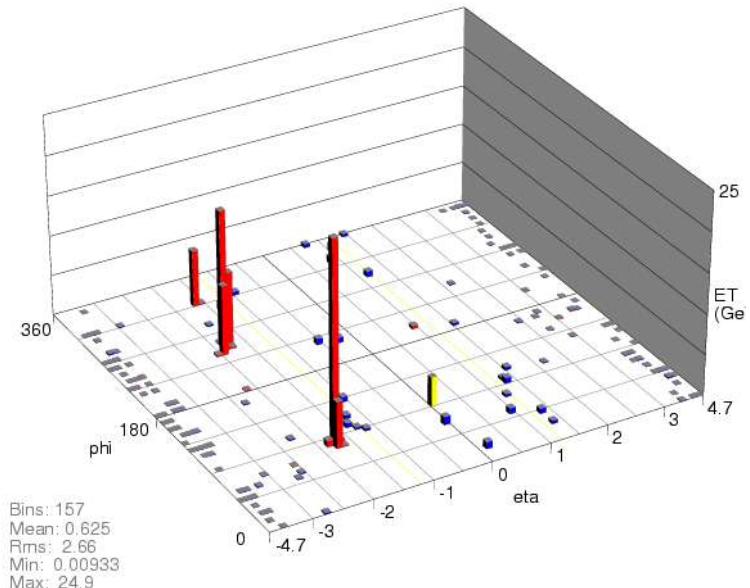
- Signatures vary with model assumptions

- ◆ MSSM with R-parity conserved: Missing E_T (jets + missing E_T , trileptons + missing E_T)

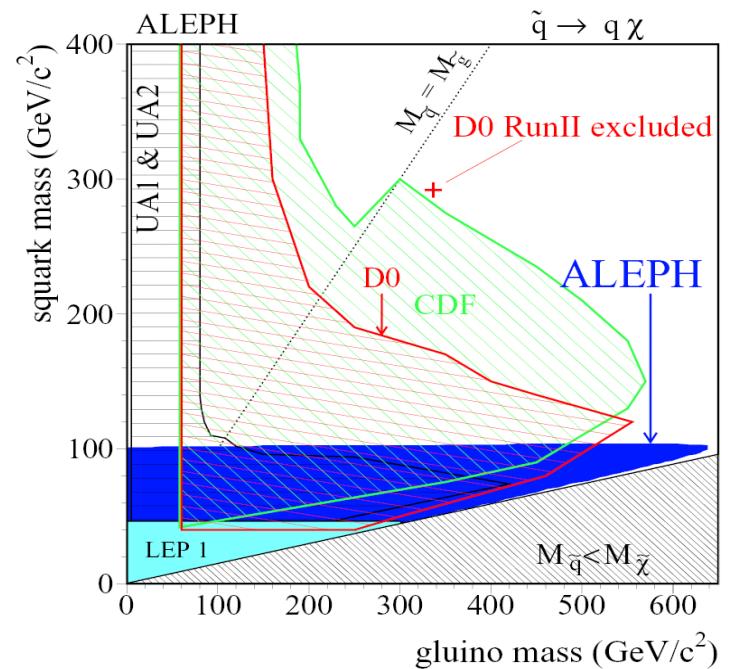
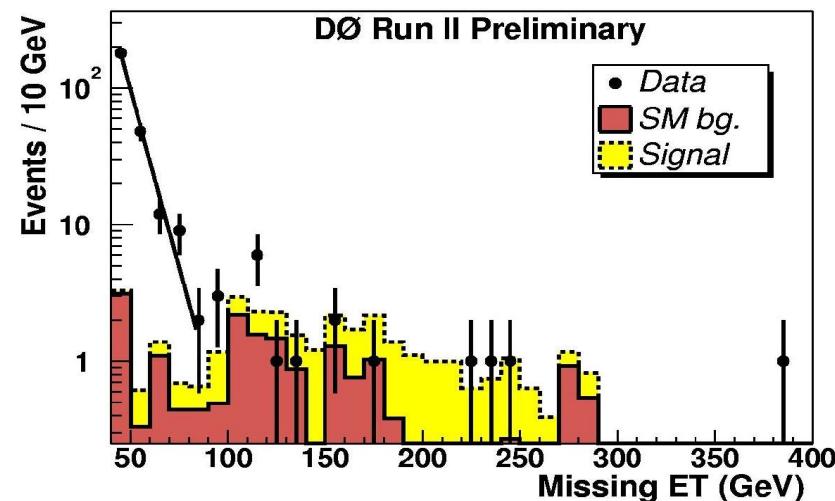
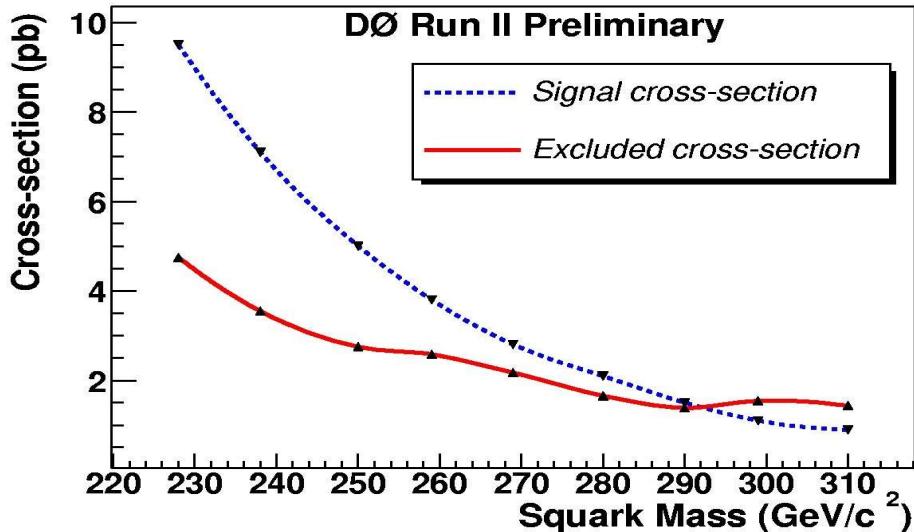
- ◆ MSSM with R-parity violation: Multileptons, leptons + jets

- ◆ GMSB (with Neutralino NLSP): Diphotons

Run 180116 Event 4428470 Thu Apr 8 10:57:08 2004

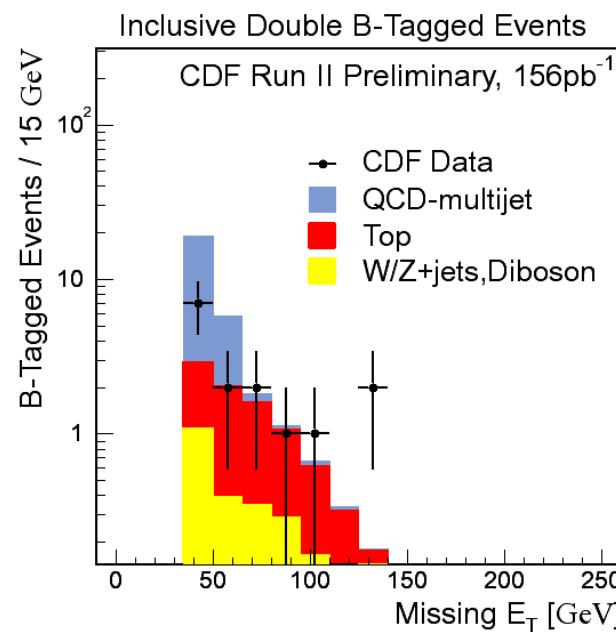
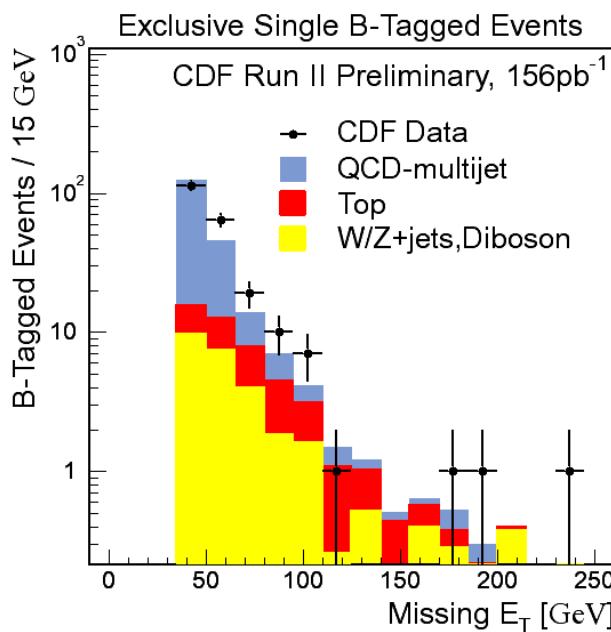
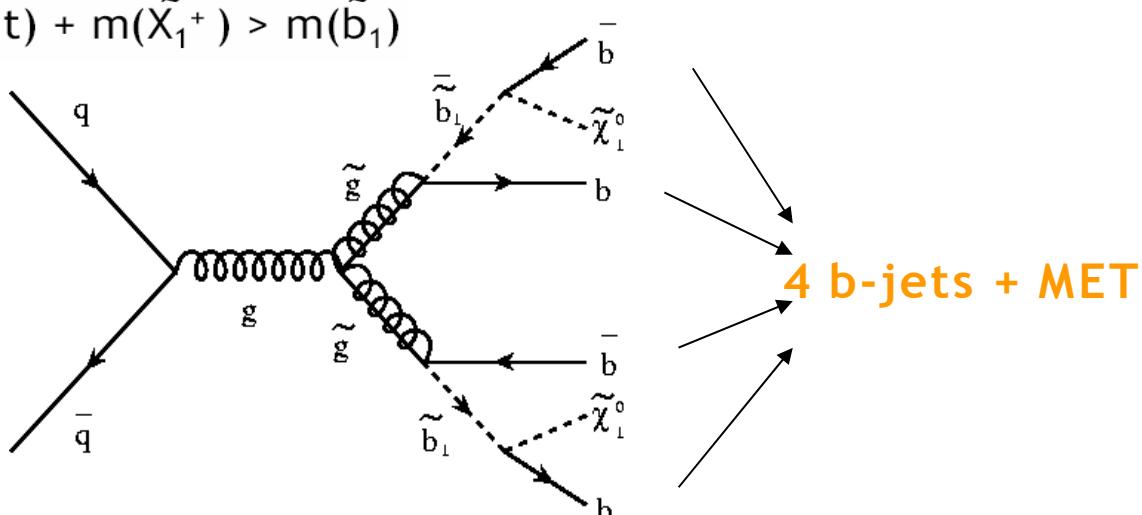


- $p\bar{p}$ collider: strong production of squarks / gluinos → **large cross section**
- **Signature** (squarks lighter than gluinos):
 $\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0 q\tilde{\chi}_1^0$ (2 jets + E_T)
- Massive background from multijet production,
 $Z + \text{jets}$ (with $Z \rightarrow \nu\nu$)
- Tight cuts: $E_T > 175 \text{ GeV}$, $H_T > 275 \text{ GeV}$
- DØ, $\int L dt = 156 \text{ pb}^{-1}$
 - ◆ 4 events observed, 2.7 ± 1.0 expected
 - ◆ Limits improved beyond Run I



- Sbottom may be light
 - ◆ Assume $\text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 100\%$, R_p conserved
 - ◆ Assume $m(\tilde{g}) > m(\tilde{b}_1) > m(\tilde{\chi}_1^0)$, $m(t) + m(\tilde{\chi}_1^+) > m(\tilde{b}_1)$
- Exploit **b-tagging** and **kinematics**
 - ◆ 3 jets $> 15 \text{ GeV}$, $E_T > 80 \text{ GeV}$
 - ◆ $\Delta\phi(E_T, \text{jets}) > 40^\circ$
 - ◆ b-jet secondary vertex tag

$$\int L dt = 156 \text{ pb}^{-1}$$



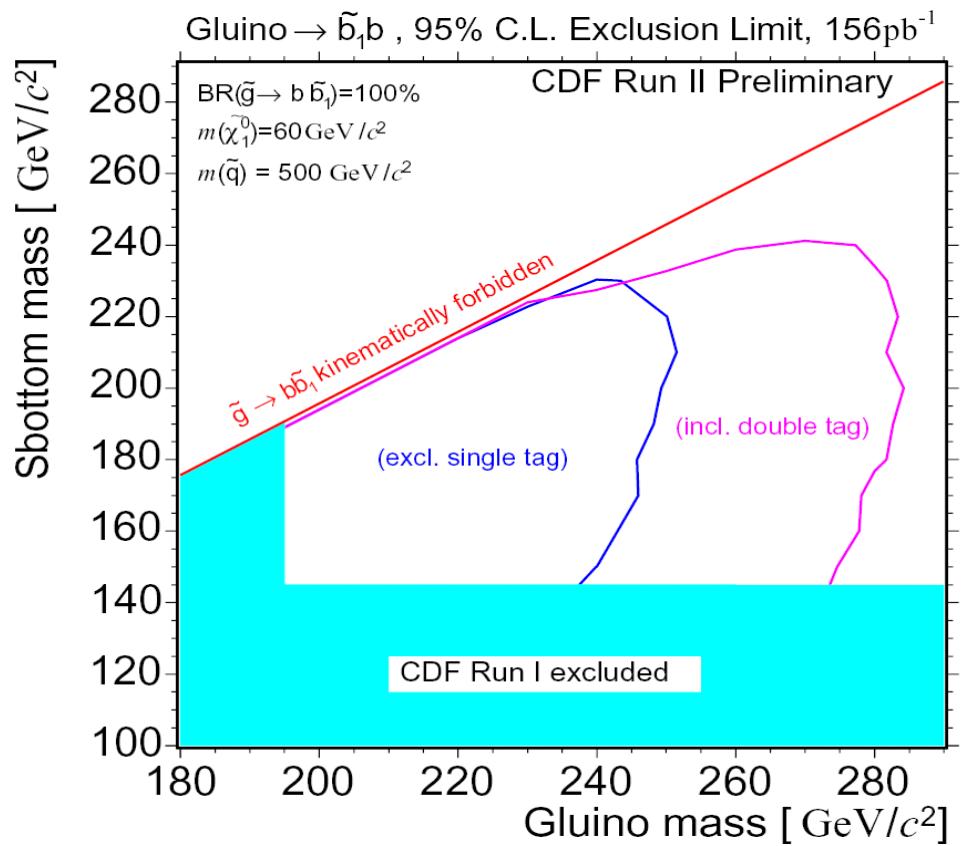
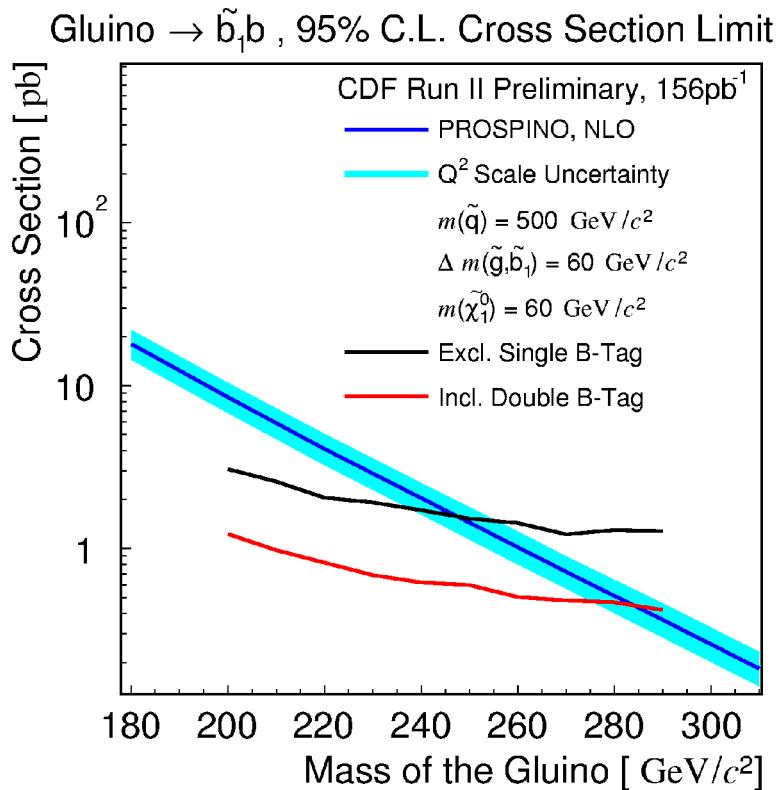
Single b-tag:

- observe 21 events
- expect 16.4 ± 3.7

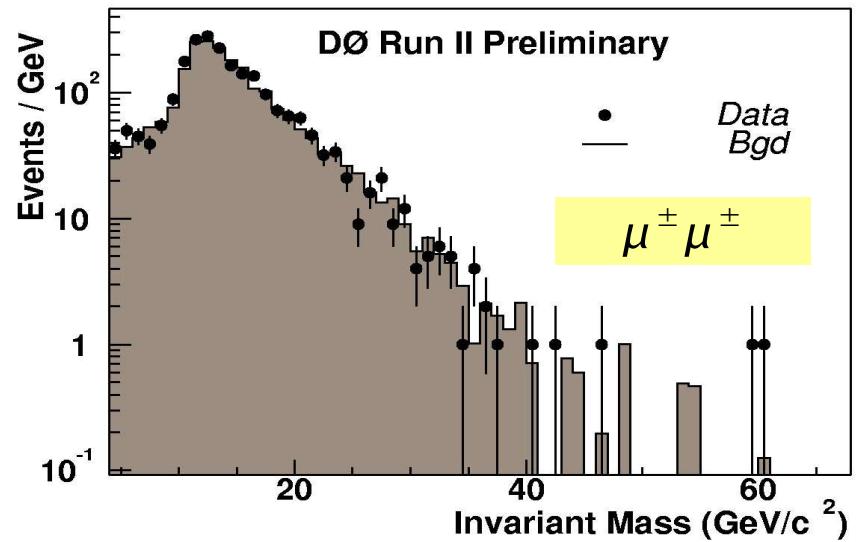
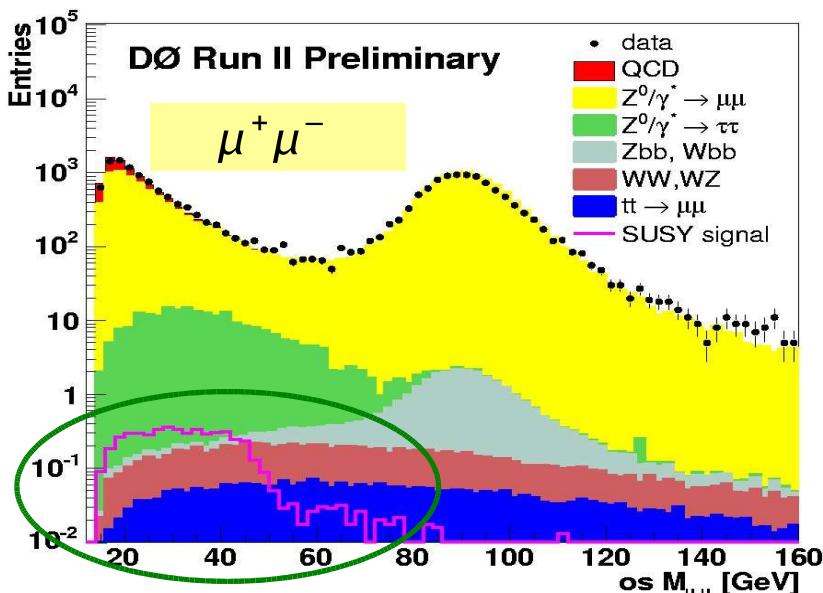
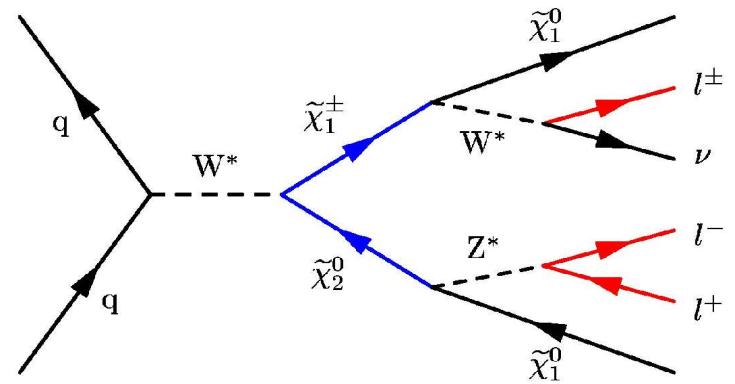
Double b-tag:

- observe 4 events
- expect 2.6 ± 0.7

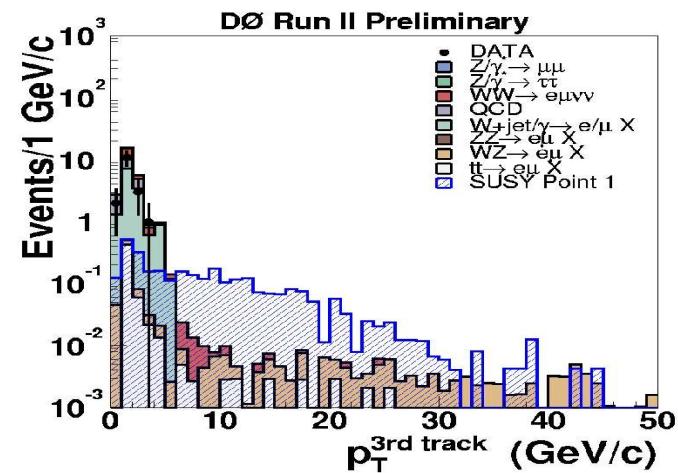
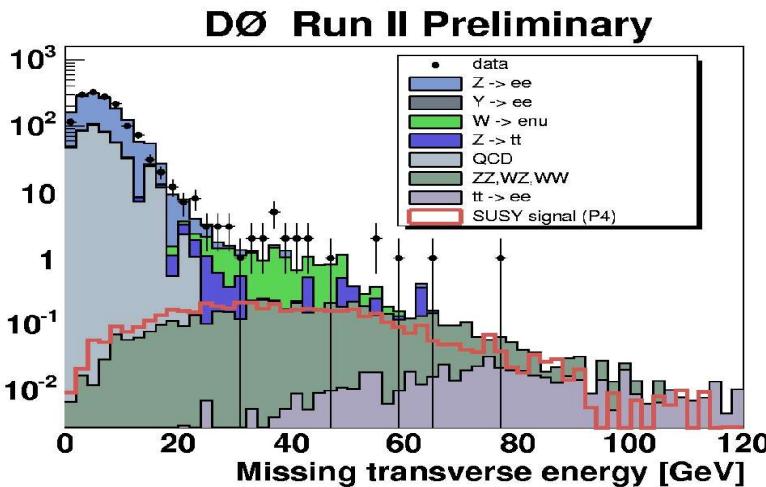
Large region excluded in the $m(\text{sbottom}) - m(\text{gluino})$ plane



- Golden channel: leptonic cascade decays → three leptons + missing E_T
- Challenges
 - ◆ Small event rates ($\sigma \times BR < 0.5\text{pb}$)
 - ◆ Leptons with low transverse momenta
- DØ: Four selections, $\int L dt = 147 - 249 \text{ pb}^{-1}$
 - ◆ ee + track, e μ + track, $\mu\mu$ + track, $\mu^\pm\mu^\pm$
- Backgrounds: WW, WZ, W γ

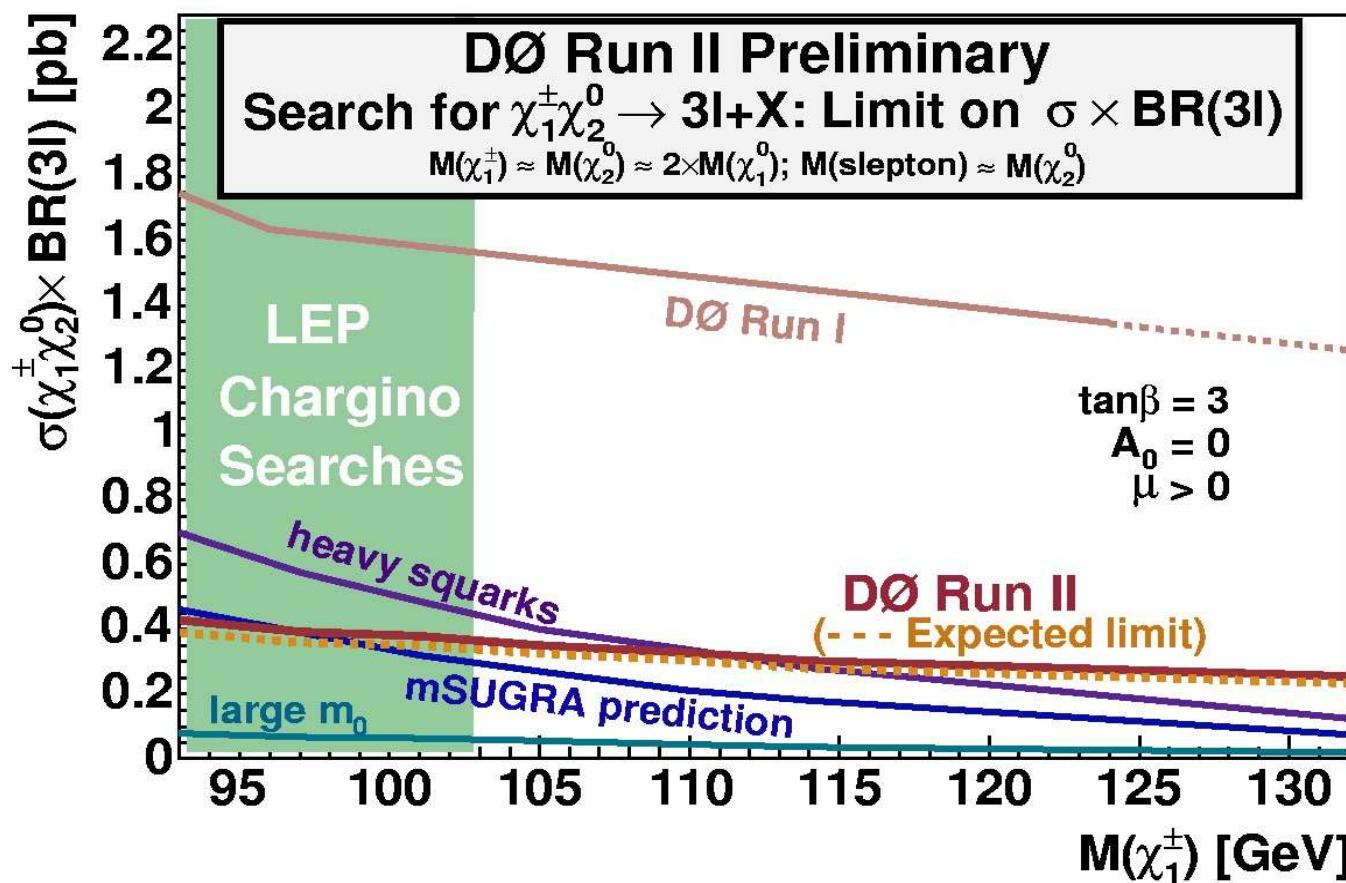


- **Selection:** two well identified leptons plus
 - ◆ Significant missing transverse energy
 - ◆ Additional isolated track (except for like-sign dimuons)
 - Very low cut on track p_T (3 to 5 GeV), **efficient for e, μ and τ** (including hadronic τ -decays)



Selection	Observed	SM Bgrd.	Signal ($m_{\text{ch}} = 100 \text{ GeV}$)	$\int L dt$
ee + track	1 event	0.7 ± 0.5	1.83 ± 0.11	249 pb^{-1}
e μ + track	0 events	0.3 ± 0.3	1.25 ± 0.09	235 pb^{-1}
$\mu\mu$ + track	1 event	1.8 ± 0.5	1.12 ± 0.13	221 pb^{-1}
$\mu^\pm\mu^\pm$ (LS)	1 event	0.1 ± 0.1	0.36 ± 0.04	147 pb^{-1}

- Take overlaps into account for combination
- Close to reaching sensitivity for mSUGRA beyond LEP limits, significant improvement on Run I limits
- Exclude chargino masses below 97 GeV with comparable chargino, neutralino, and slepton masses



“mSUGRA”: maximize leptonic BR ($m(\text{slepton}) \approx m(\chi_2^0) \rightarrow \text{sfermion decays dominate}$)

“Large m_0 ”: Decays via W^*/Z^* dominate \rightarrow leptonic BR small

“Heavy squarks” (relaxing mass unification): enhanced cross section (destructive interference with squark-exchange suppressed)

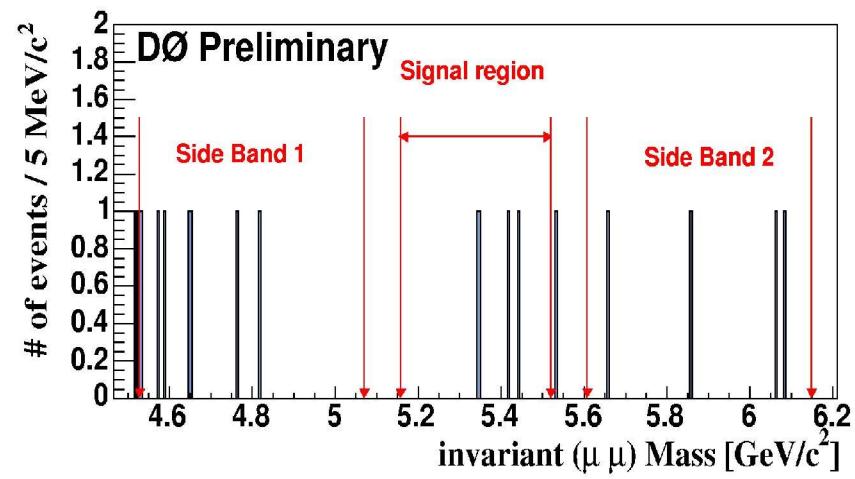
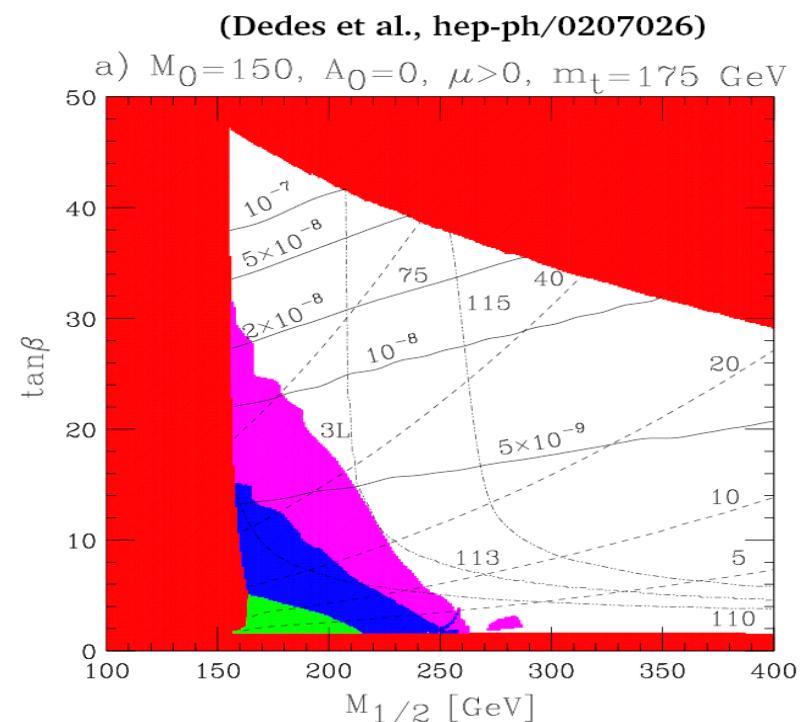
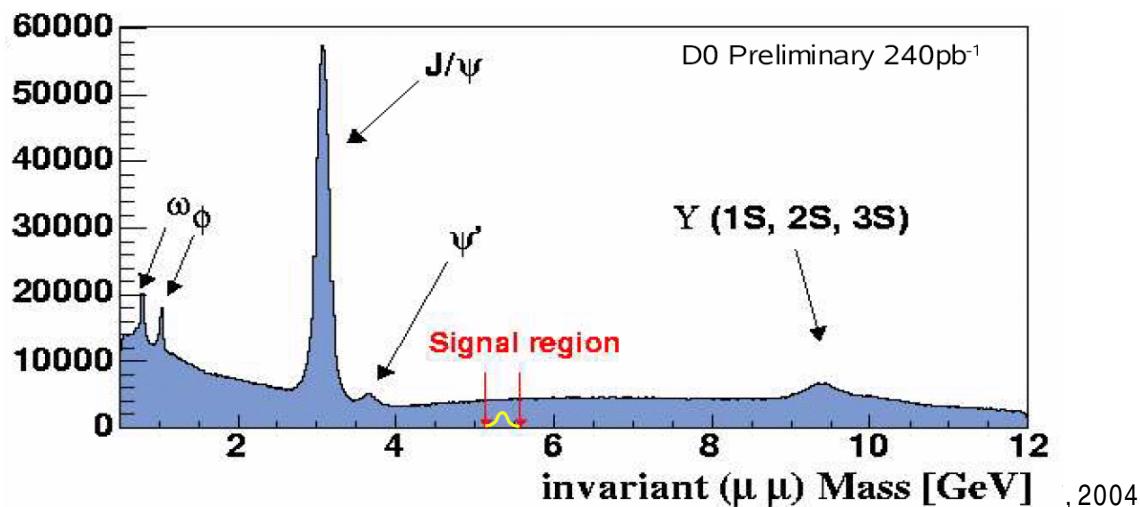
- SM prediction: $\text{BR}(B_s \rightarrow \mu^+ \mu^-) = 3.8 \cdot 10^{-9}$
- Can be enhanced by non-SM contributions
 - SUGRA: $\sim (\tan \beta)^6$ – significant at large $\tan \beta$
 - Complementary to trilepton search
- Tevatron: large production rate for B_s
- Selection: two isolated muons, displaced vertex
- Results at 95% CL



CDF (171 pb⁻¹): $\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 7.5 \cdot 10^{-7}$



D0 (240 pb⁻¹): $\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 4.6 \cdot 10^{-7}$

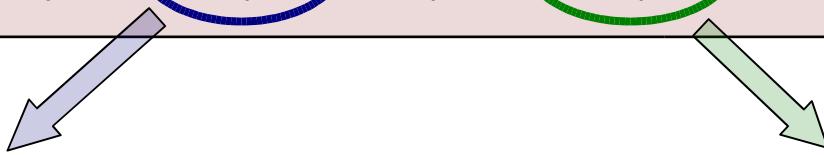


R - parity: $R_P = (-1)^{3B+L+2S}$

S is the particle spin,
B is the baryon number,
L is the lepton number

$$W = W_{MSSM} + W_{R_P}$$

$$W_{R_P} = \frac{1}{2} \lambda_{ijk} \varepsilon_{ab} L_i^a L_j^b E_k^c + \lambda'_ {ijk} \varepsilon_{ab} L_i^a Q_j^b D_k^c + \lambda''_{ijk} \varepsilon_{xyz} U_i^{cx} D_j^{cy} D_k^{cz} + \kappa_i \varepsilon_{ab} L_i^a H_2^b$$



i,j,k = 1,2,3 generation indices

R_P violated in decay
 \rightarrow multi lepton final state

Resonant production
 \rightarrow two muon and two jets final state

Chiral superfields:

L: lepton doublet superfield

E: lepton singlet superfield

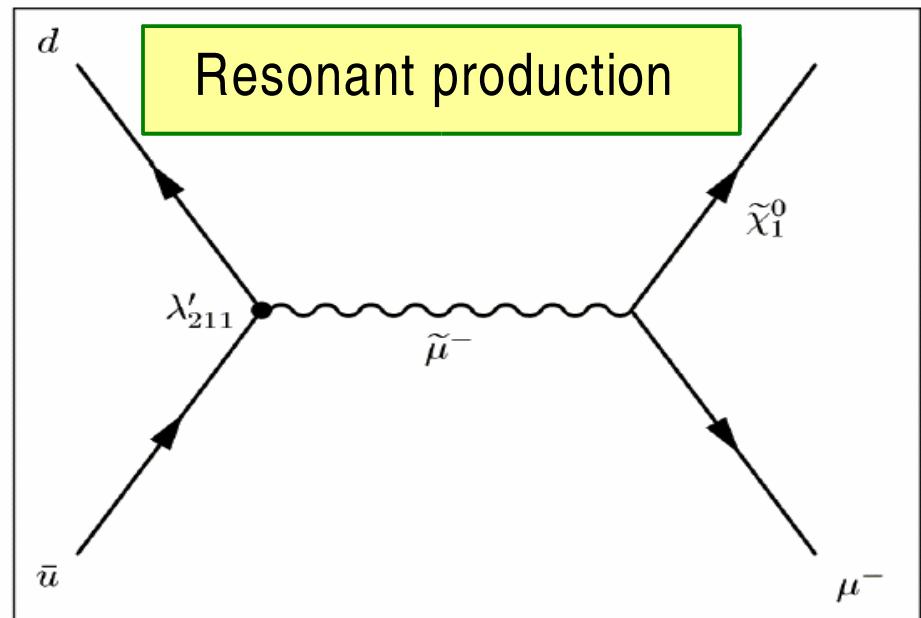
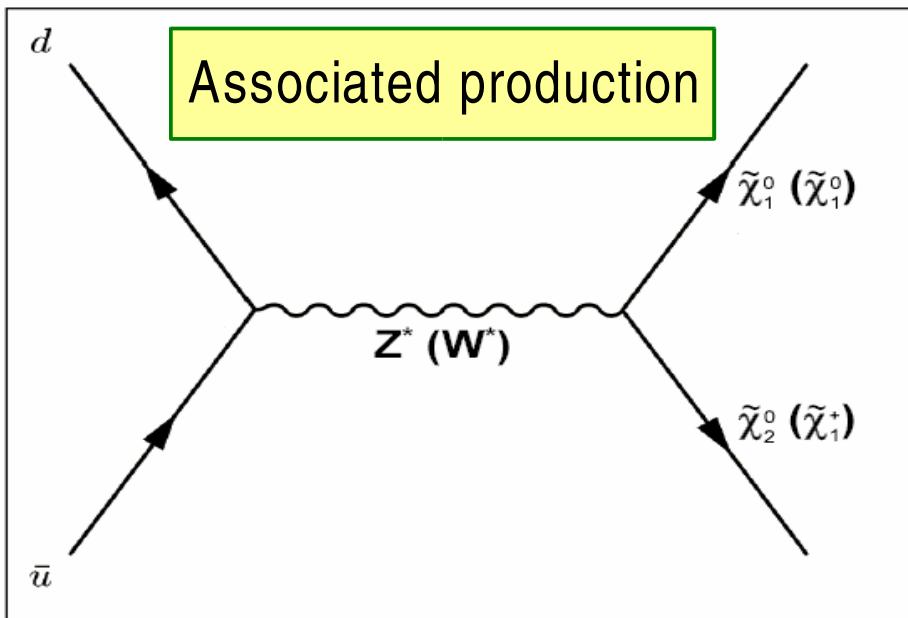
Q: quark doublet superfield

D: down-like quark singlet superfield

}

Resonant production at hadron colliders

$\lambda, \lambda', \lambda''$: Yukawa couplings

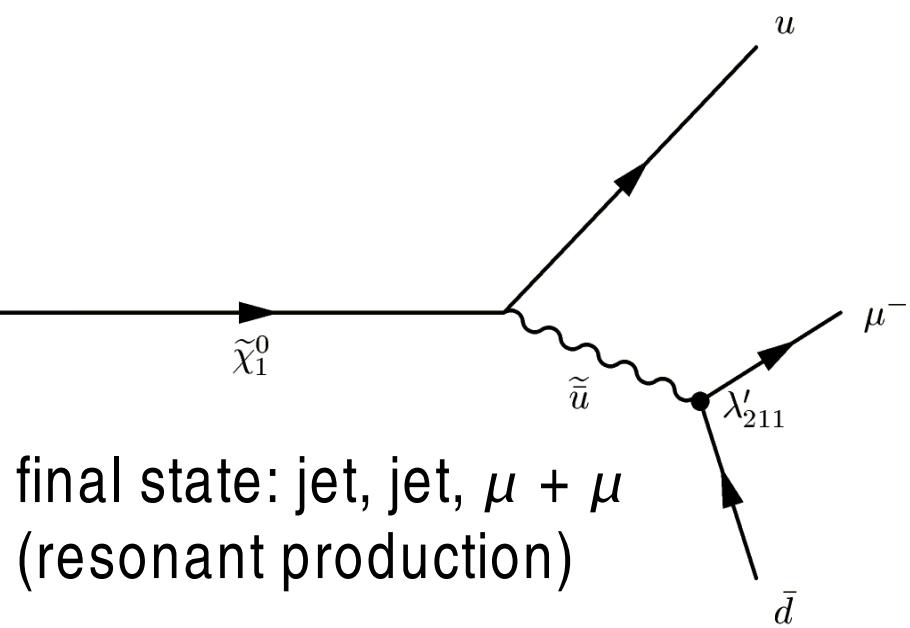


- R-parity conserved
- Search for decays via the R-parity violating LLE couplings λ'_{121} , λ'_{122}
- Final states with 4 leptons or more; analyses ask for at least 3 leptons.

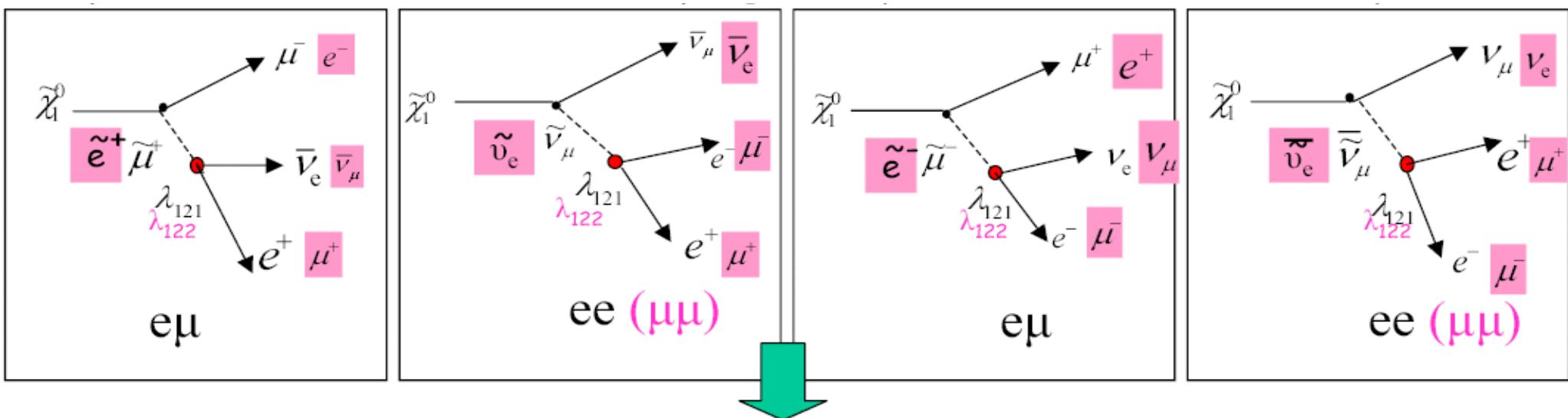
→ R-parity violating $\tilde{\chi}_1^0$ decay (λ'_{211})
 → Dimuon and dijet final state

Other modes:

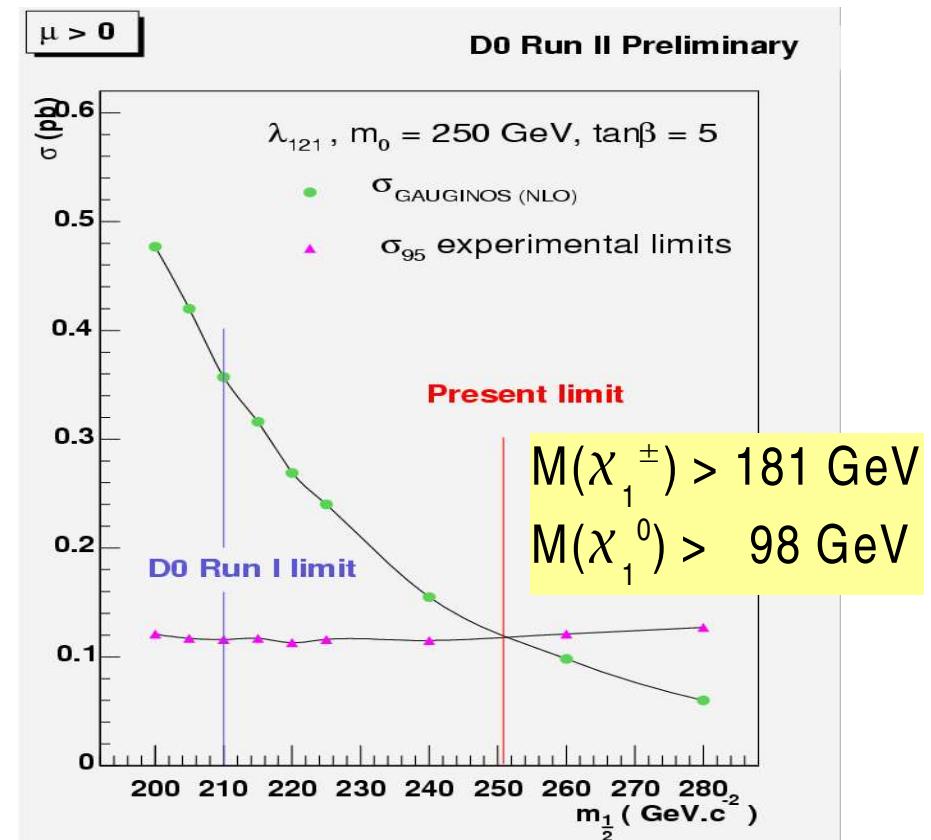
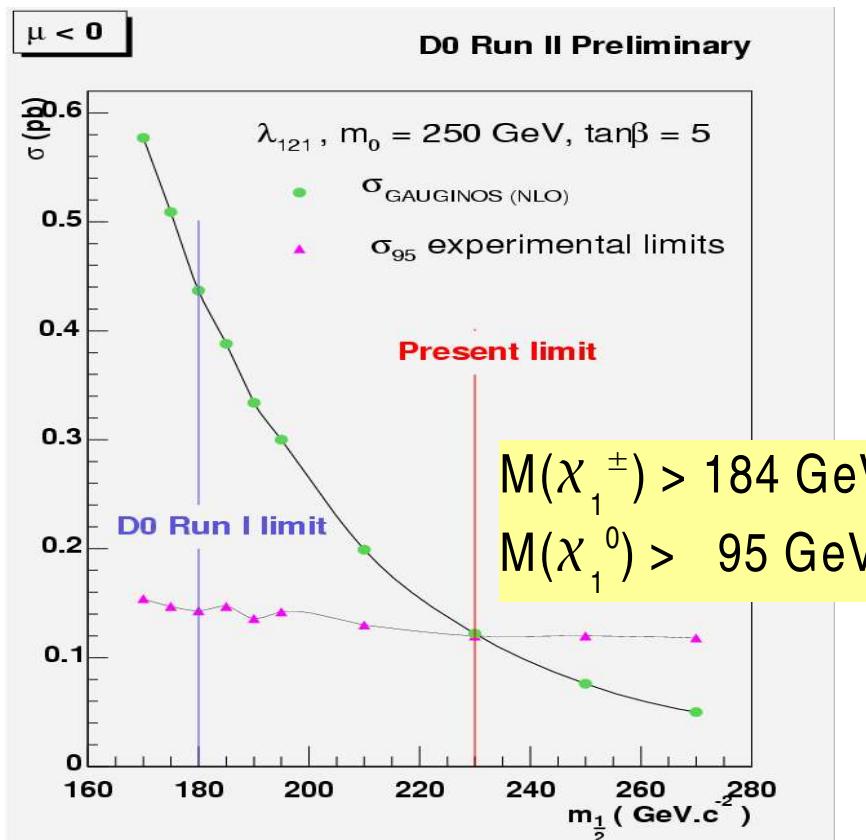
- sneutrino resonance
 → dijet, muon & missing E_T final state
- t-channel slepton exchange



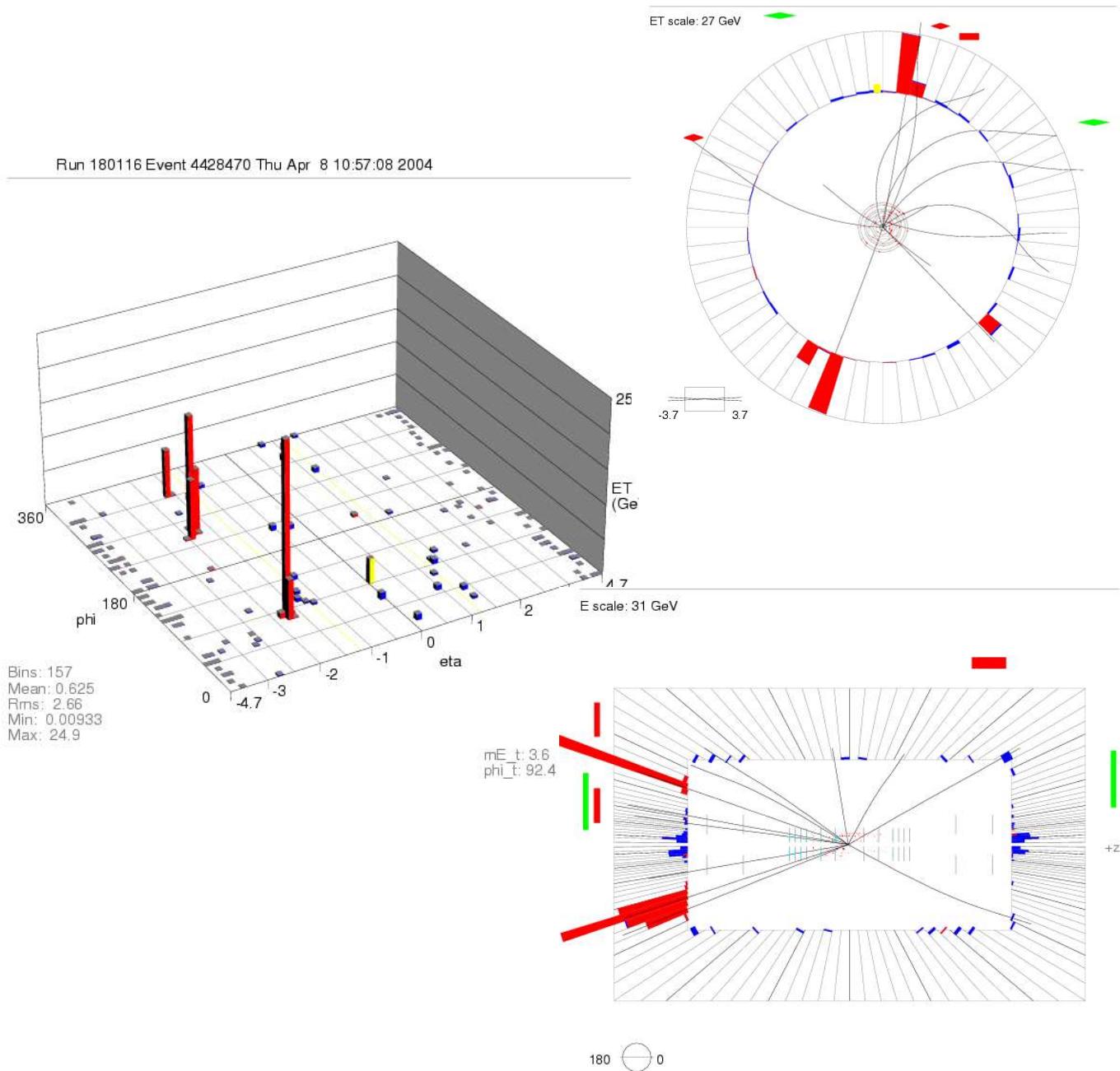
- Only 1 neutralino in **resonant** channel
 - $\mu \mu$ jet jet final state, no missing E_T
- Pair produced neutralinos decay via LLE couplings λ_{ijk} into 2 charged leptons and 1 neutrino
 - More than one possible final state for each coupling
 - Missing E_T



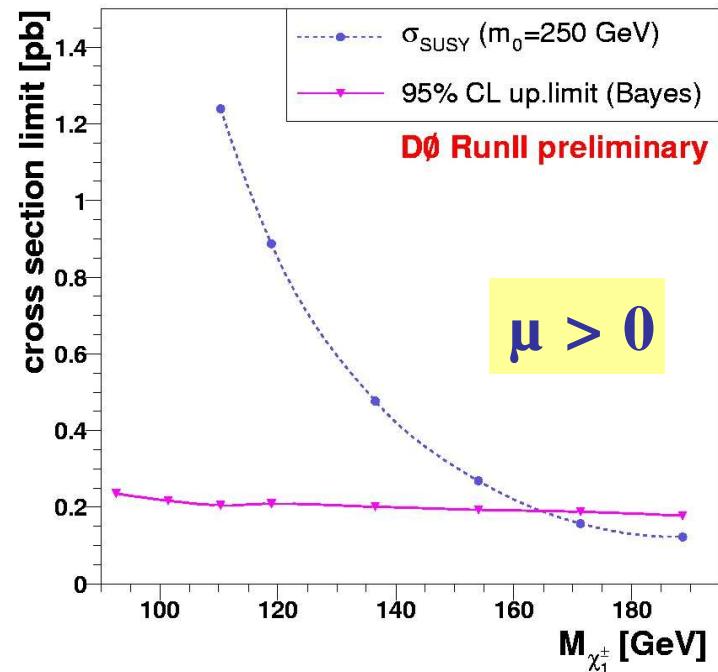
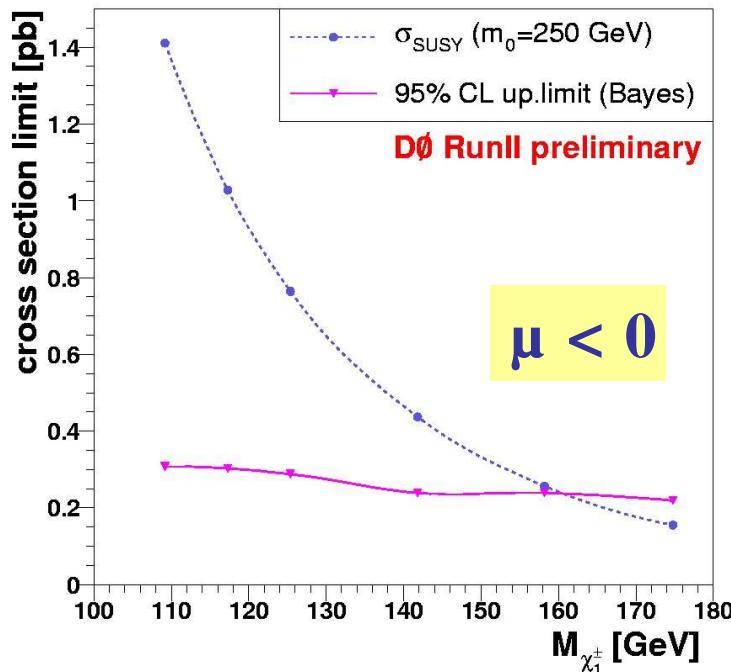
- D0, $\int L dt = 238 \text{ pb}^{-1}$
- Selection: two isolated electrons + additional low- p_T electron or muon, $E_T' > 15 \text{ GeV}$
- **Observe 0 events, SM expectation 0.45 ± 0.43**
- Cross section limit as function of $m_{1/2}$ for $m_0 = 250 \text{ GeV}$, $\tan\beta = 5$, $A_0 = 0$



	Event #2
Runnum	180 116
Evtnum	4 428 470
type	eee
MET	8.3
# of muons (pt, eta, phi)	1 (nseg = -2) (17.4, 1.99, 2.02)
Mee 1-2, 2-3, 1-3 (M_{123})	63.4, 17.7, 31.9 (73.1)
Pt 1, 2, 3	35.6, 28.4, 9.1
Eta 1, 2, 3	-1.78, -1.83, -1.64
Phi 1, 2, 3	1.39, 4.36, 5.50
Charge 1, 2, 3	+1, -1, -1

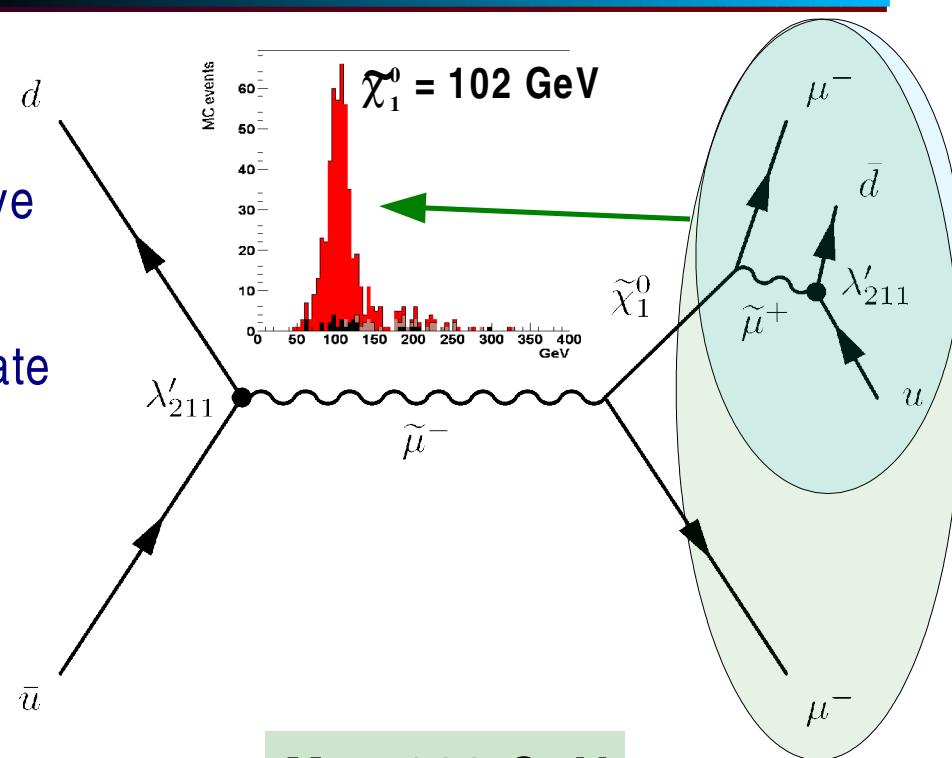
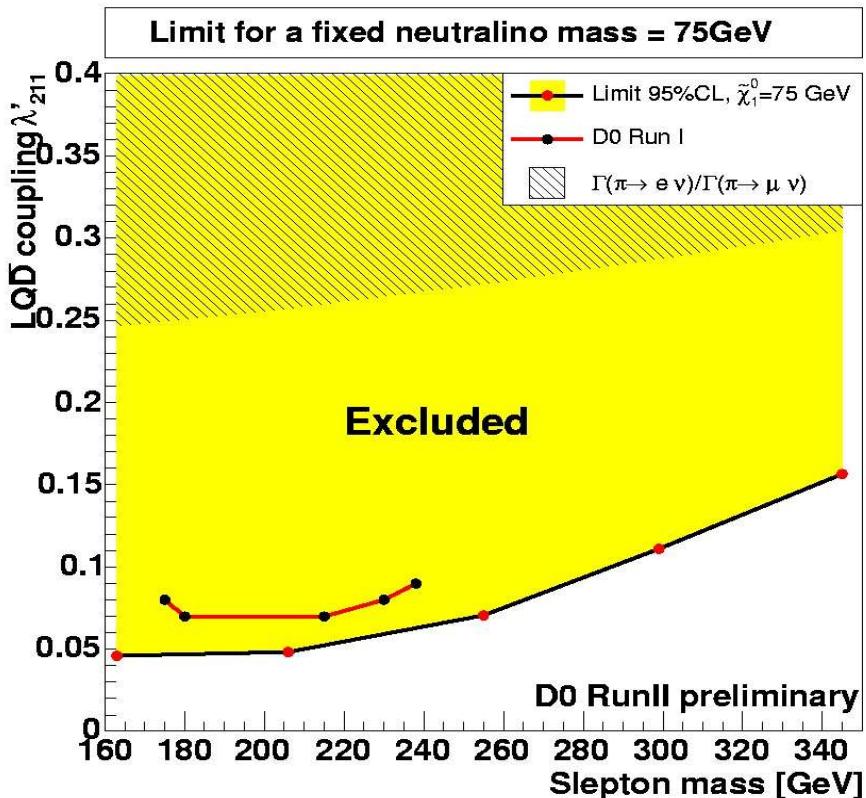


- D $\bar{0}$, $\int L dt = 160 \text{ pb}^{-1}$
- Selection: two isolated muons + additional low- p_T electron or muon (down to 3 GeV)
- Optimized two-dimensional cuts in E_T , lepton- p_T , invariant mass
- **Observe 2 events, SM expectation 0.63 ± 1.93**
- Cross section limit for $m_0 = 250 \text{ GeV}$, $\tan \beta = 5$, $A_0 = 0$

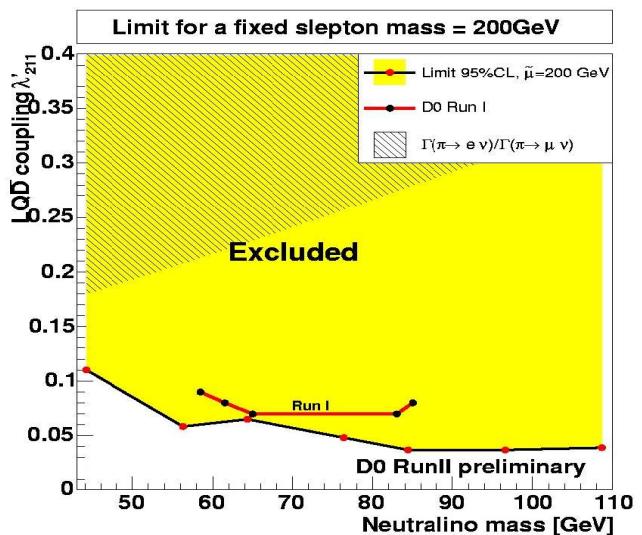


- D0, $\int L dt = 154 \text{ pb}^{-1}$
- 2 jets above $\sim 20\text{GeV}$, 2 isolated muons above $\sim 20\text{GeV}$ (depending on point under study)
- Reconstruct **neutralino** and **smuon** candidate invariant mass

$$M_{\tilde{\chi}_1^0} = 75 \text{ GeV}$$



$$M_{\tilde{\mu}} = 200 \text{ GeV}$$



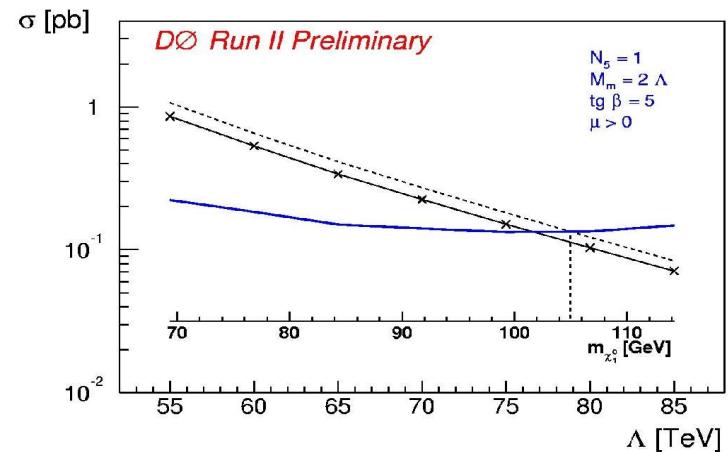
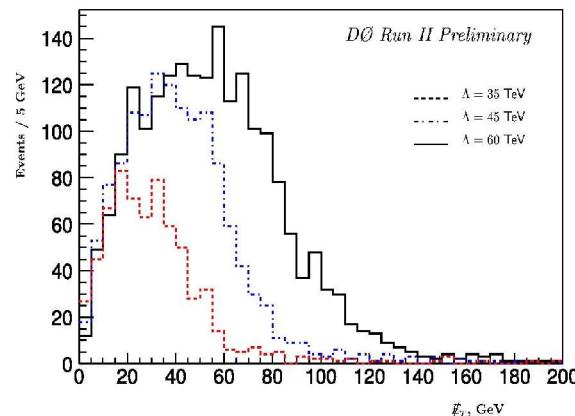
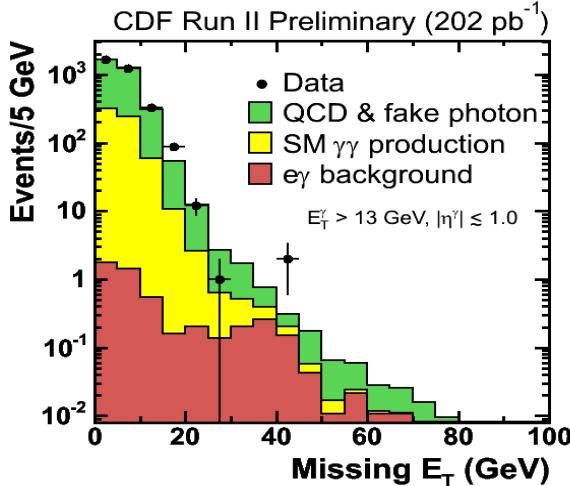
Gauge Mediated SUSY Breaking: Gravitino \tilde{G} is LSP

Assuming Neutralino NLSP: $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$



→ Chargino/Neutralino production leads to final states containing $\gamma\gamma + E_T$

→ Inclusive search for 2 photons plus E_T



Selection: Two central photons with $E_T > 13$ GeV (CDF) / $E_T > 20$ GeV (DØ)
 Optimized cut $E_T > 45$ GeV (CDF) / $E_T > 40$ GeV (DØ)

Observe 0 / 1 events (CDF / DØ), expect 0.3 / 2.5 events from “fakes”

For $N_5 = 1$, $M_m = 2\Lambda$, $\tan\beta = 5(15)$, $\mu > 0$:

DØ (185 pb⁻¹): $m_{\tilde{\chi}_1^0} > 105$ GeV, $m_{\tilde{\chi}^\pm} > 192$ GeV

CDF (202 pb⁻¹): $m_{\tilde{\chi}_1^0} > 93$ GeV, $m_{\tilde{\chi}^\pm} > 168$ GeV



Publication with more data under way

- Tevatron collider and experiments are running well
- Experiments recorded about 0.5 fb^{-1} , analyses shown here based on up to $\simeq 250 \text{ pb}^{-1}$
- $B_s \rightarrow \mu^+ \mu^-$ results starting to constrain large $\tan\beta$ region
- Searches for supersymmetric particles improve on Run I limits and have entered uncharted territory
 - ◆ MSSM with R-parity conserved: Missing E_T (jets + missing E_T , trileptons + missing E_T)
 - ◆ MSSM with R-parity violation: Multileptons, leptons + jets (λ_{121} , λ_{122} and λ'_{211})
 - ◆ GMSB (with Neutralino NLSP): Diphotons