Searches for Supersymmetry at the Tevatron

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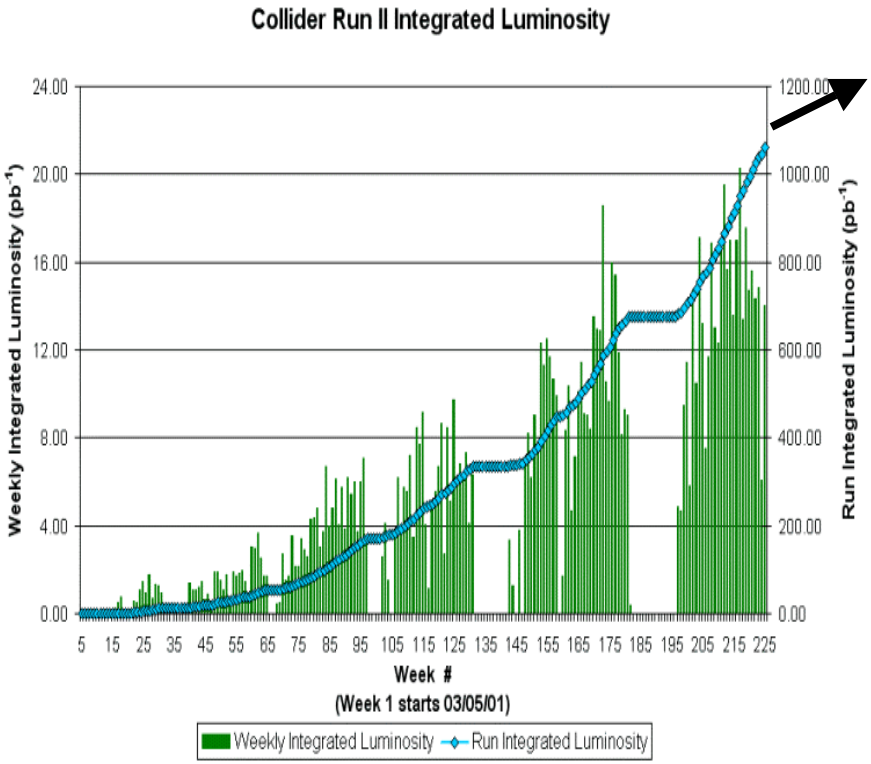
For the D0 and CDF collaborations

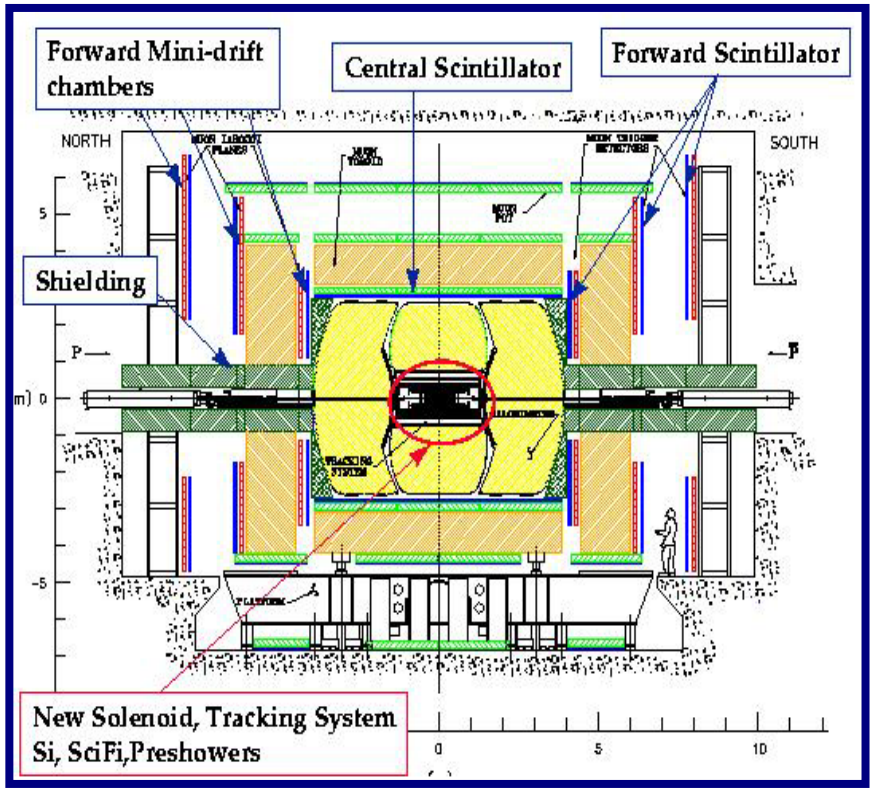
- *Introduction*
- *Searches for Charginos and Neutralinos (RPC)*
- *Searches for Charginos, Neutralinos or Sleptons (RPV)*
- *Searches for Squarks and Gluinos (RPC)*
- *Searches for Squarks (RPV)*
- *Searches for* $B_s \rightarrow \mu^+ \mu^-$
- *Conclusion*

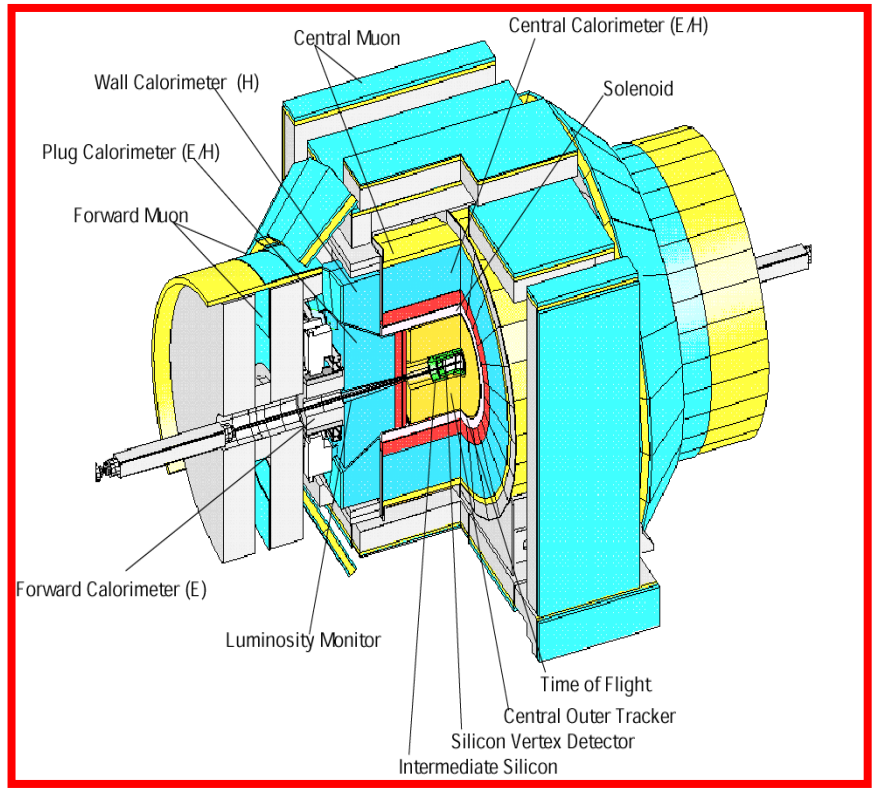
Tevatron at Fermilab – Run II



- Higher energy
  (1.8 TeV → 1.96 TeV) =>
  Higher cross sections
- Higher antiproton intensity
  6×6 → 36 × 36 bunches(3.5 μs → 396 ns)
  antiproton "recycler" => Higher luminosity
- RunII goal: ≈9 fb-1 in 2009

D0 CDF





Both general purpose detectors well understood and highly efficient with:

Excellent calorimeters and muon chambers coverage

Precision tracking (Silicon Vertex Detector)

Analyses presented here use up to ≈390 pb-1

Some SUSY parameters : reminder

❖Every SM particle has $\Delta S = ½$ partner:

$$q\,,\,l \Leftrightarrow \tilde{q}\,,\,\tilde{l} \qquad g \Leftrightarrow \tilde{g}$$

$$\gamma\,,Z\,,h,H\,,A \Leftrightarrow \tilde{\chi}^0_{1,\ldots,4} \qquad W^{\pm},H^{\pm} \Leftrightarrow \chi^{\pm}_{1,2}$$

❖$R=(-1)^{3B+2L+S} = +1$ (SM) ; $= -1$ (SUSY)

LSP is stable if R parity is conserved (RPC)

Small violation of R parity is not excluded (RPV)=> additional couplings and LSP decays in SM particles

❖SUSY breaking Mechanisms 2 models treated here:

Graviton mediated model (mSUGRA)

mo common scalar mass

$m_{1/2}$ common gaugino mass

tan β ratio of Higgs Vacuum expectation Values

sign(μ) sign of Higgsino mass term

A_0 trilinear coupling

LSP = $\tilde{\chi}^0_1$

Gauge mediated model (GMSB)

(new chiral supermultiplets: messengers)

Λ SUSY breaking scale

M_m messenger mass (2 Λ)

N_5 number of messengers

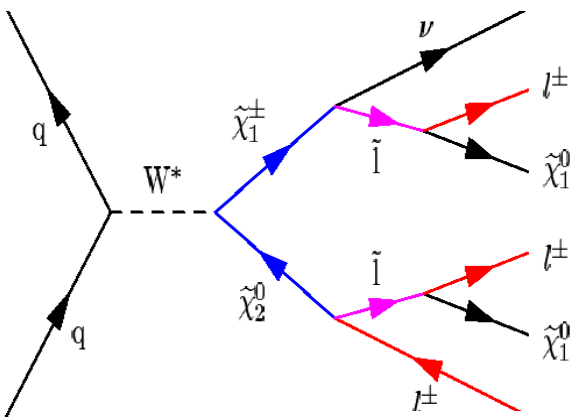
tan β and sign(μ)

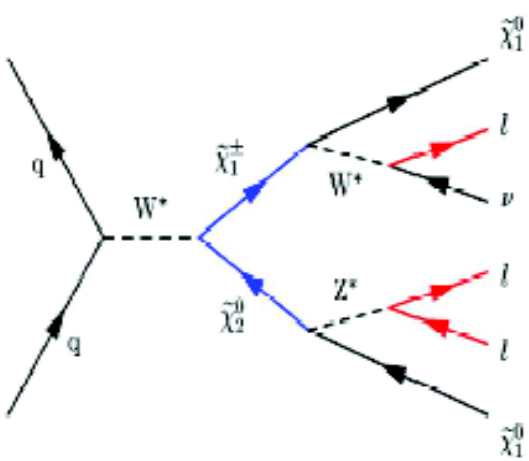
C_{grav} = factor multiplying effective mass of gravitino

LSP = $\tilde{G}$ NLSP = $\begin{cases} \tilde{\chi}^0_1 \rightarrow \tilde{G}\gamma \\ \tilde{\tau} \end{cases}$

Charginos and Neutralinos in 3 *leptons* + E_t^{miss}

$$\tilde{\chi}_2^0 \tilde{\chi}_1^{\pm} \rightarrow l^{\pm} l^{\mp} l^{\pm} \tilde{\chi}_1^0 \tilde{\chi}_1^0 X$$





Final state : 3 *leptons* + large E_t^{miss}

Clean signature but small event rates (σxBr<0.5pb) and leptons with low P_T

6 analyses $\int L\,dt \approx 320\ pb^{-1}$

ee or $\mu\mu$ or e μ (P_T cuts ≈10 GeV)

or e τ or $\mu\tau$ (had.decay of the τ :NN) + *lepton*

(isolated high quality track with P_T cut ≈ 5 GeV)

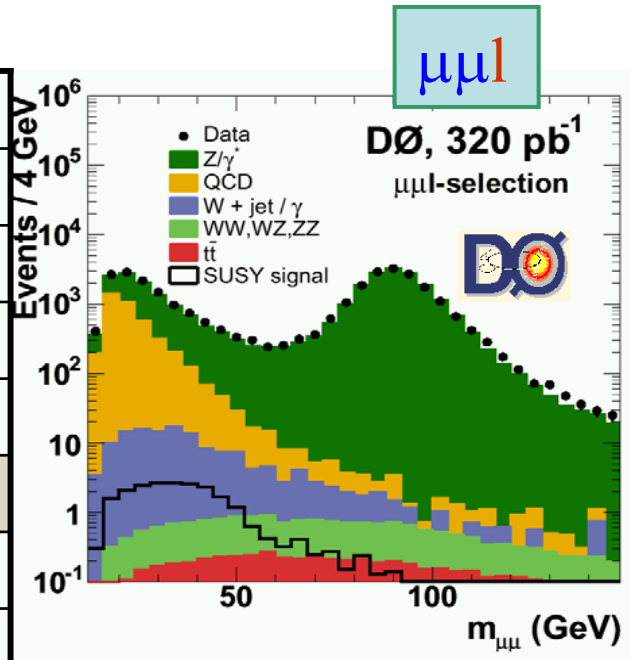
or 2 μ like sign (P_T cuts ≈10GeV)

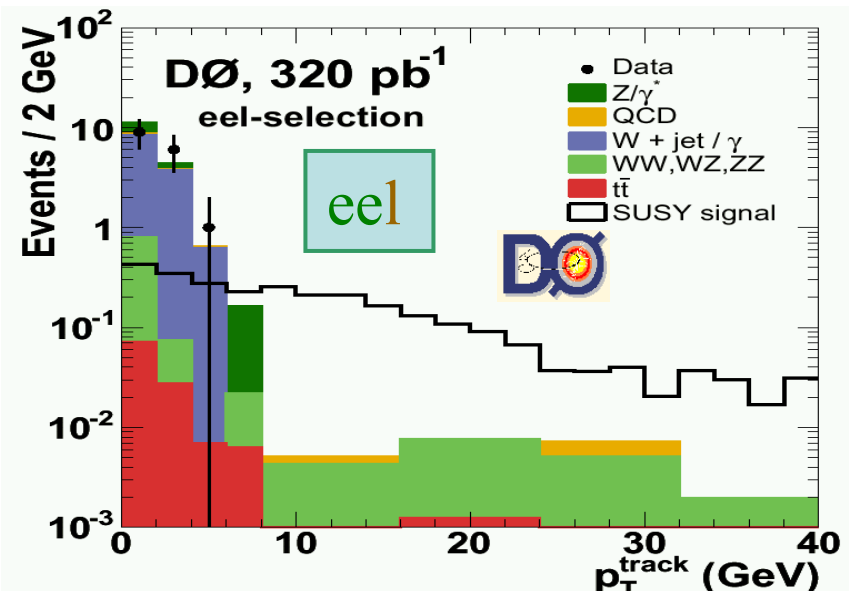
+ E_T^{miss} > 22GeV

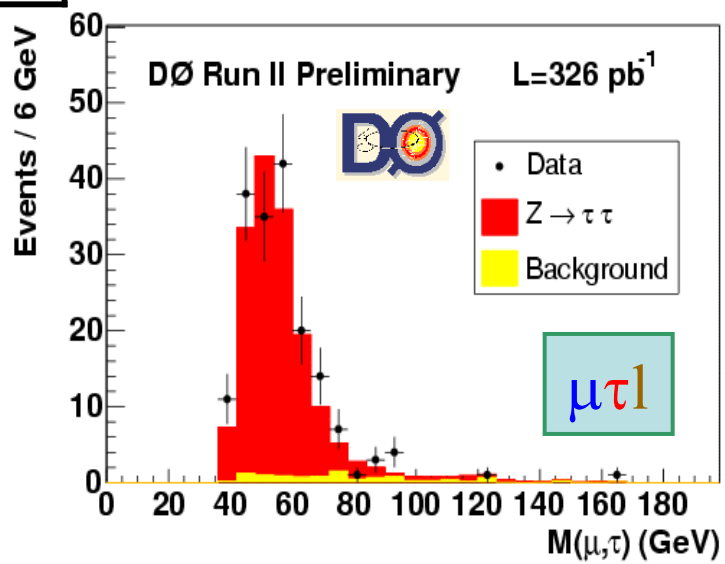
+ anti Z cuts

Search for Charginos and Neutralinos in 3 *leptons* + E_T^{miss}

Channel	Observed	SM expected
e e + *l*	0	0.21±0.12
e μ + *l*	0	0.31±0.13
μ μ + *l*	2	1.75±0.57
Same sign μ μ	1	0.66±0.37
Sum	3	2.93±0.54±57
e τ + *l*	0	0.58±0.14
μ τ + *l*	1	0.36±0.13







mSUGRA Search for Charginos and Neutralinos

hep-ex/0504032 analyses eel, μμl, eμl, μ±μ±

σ x Br(3l) is mainly a function of
$M(\tilde{\chi}^{\pm})$ **and** $M(\tilde{l})$

❖3l-max: low m0 - leptonic BR is maximally enhanced for $M(\tilde{l}) \geq M(\tilde{\chi}_2^0)$

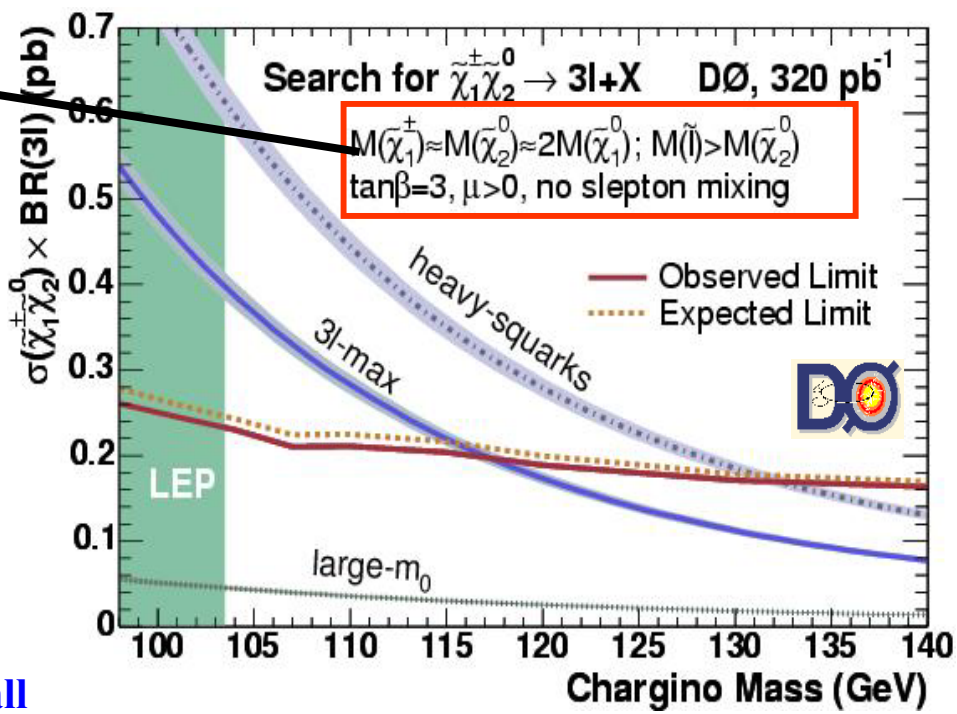
$M(\tilde{\chi}_1^{\pm}) > 117$ GeV

❖heavy-Squarks: $M(\tilde{q}) >> M(\tilde{l})$ → cross section is maximal

$M(\tilde{\chi}_1^{\pm}) > 132$ GeV

❖large m_0: large $M(\tilde{l})$ →

W/Z exchange graph is dominant → small leptonic BR



Including the eτl and μτl analyses gives better sensitivity:

❖limit improves by 10% for tanβ=3

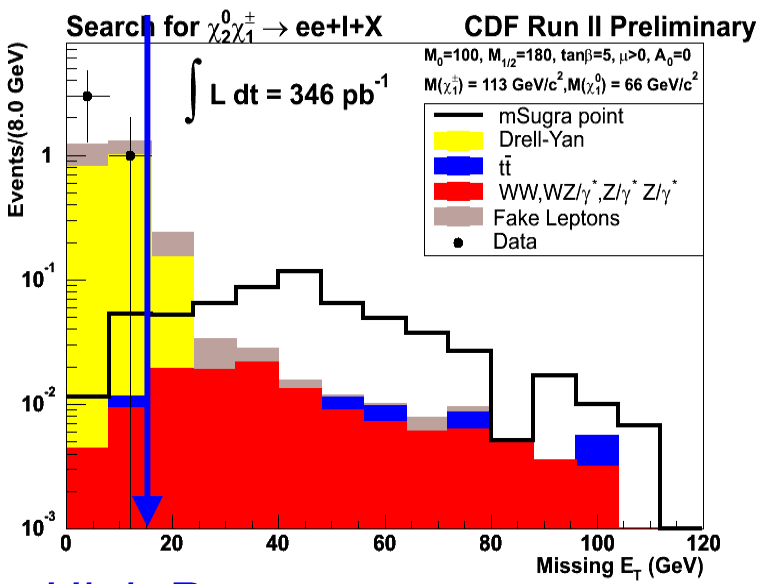
❖more expected at large tanβ, where the τ's dominate the final state

Charginos and Neutralinos in 3 *leptons* + E_t^{miss}

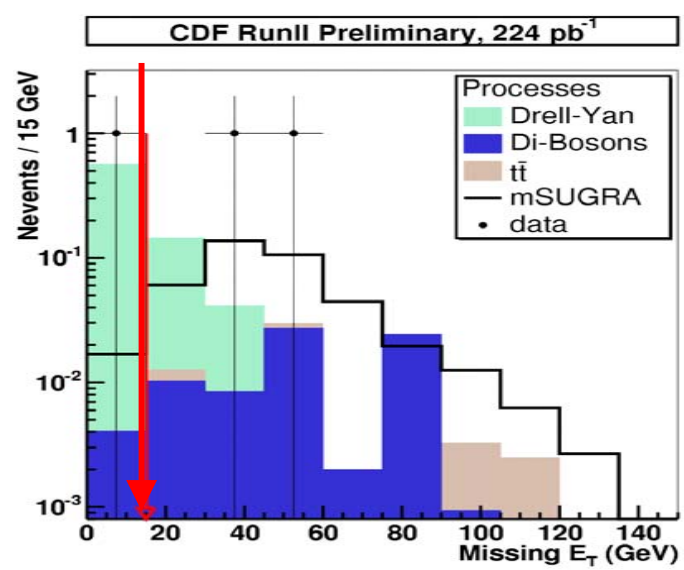
2 analyses: ee + *l*

	P_T(e1,e2) GeV	P_T(*l*3) GeV	E_T^{miss} GeV	Lumi pb^{-1}	SM exp.	Obs.
High P_T	> (20,8)	e or μ > (4)	>15	346	0.16 ±0.07	0
Low P_T	> (10,5)	track > (4)	>15	224	0.36 ±0.27	2

m_0 =100 GeV, $m_{1/2}$ =180GeV, tan(β)=5, μ>0 → 0.5 events



High P_T

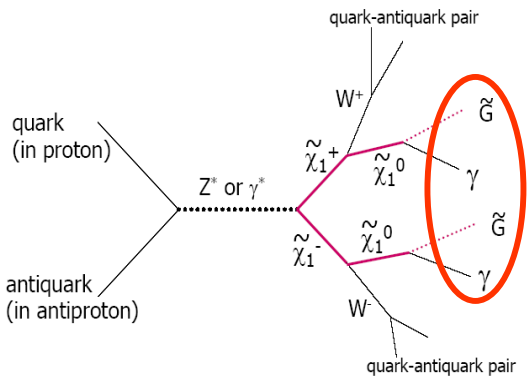


Low P_T

μ channel will be include soon

GMSB Chargino and Neutralino in $\gamma\gamma$ + E_T^{miss}

(263 pb^{-1}) – (202 pb^{-1}) Combination : hep-ex/0504004



D0/CDF Selection:

2 photons

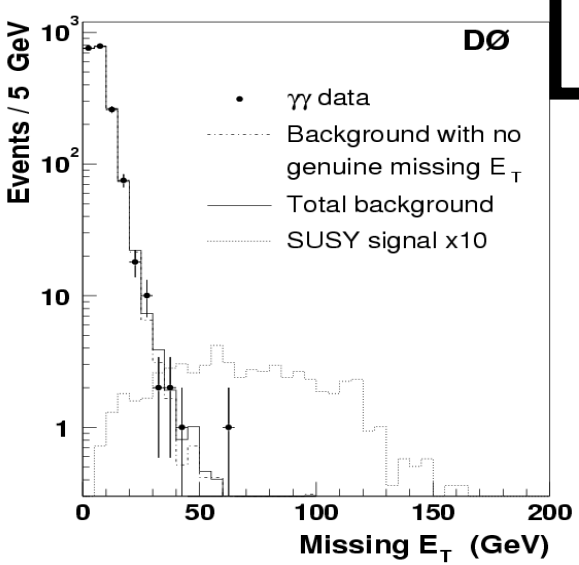
$E_T(\gamma)$> 20 / 13 GeV

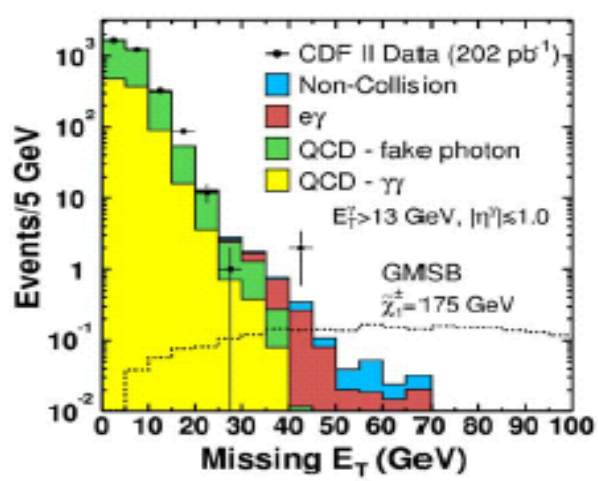
E_T^{miss} > 40 / 45 GeV

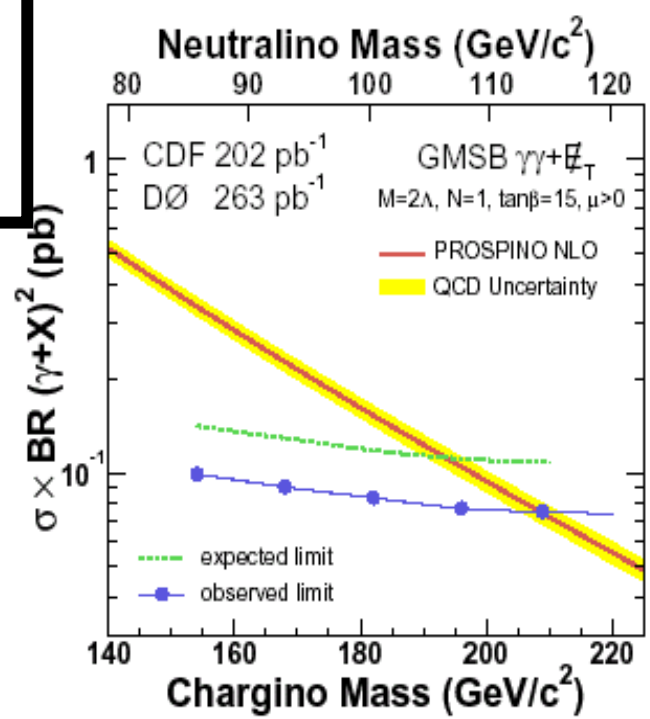
	Obs	Exp. SM	$M(\chi^{\pm})$ (GeV)
D0	2	3.7±0.6	>195
CDF	0	0.3±0.1	>167

$M(\chi^{\pm})$>209 GeV/c2

$M(\chi^0)$>114 GeV/c2







$M_m=2\Lambda$, $N_5=1$, $\tan\beta=15$, $\mu>0$

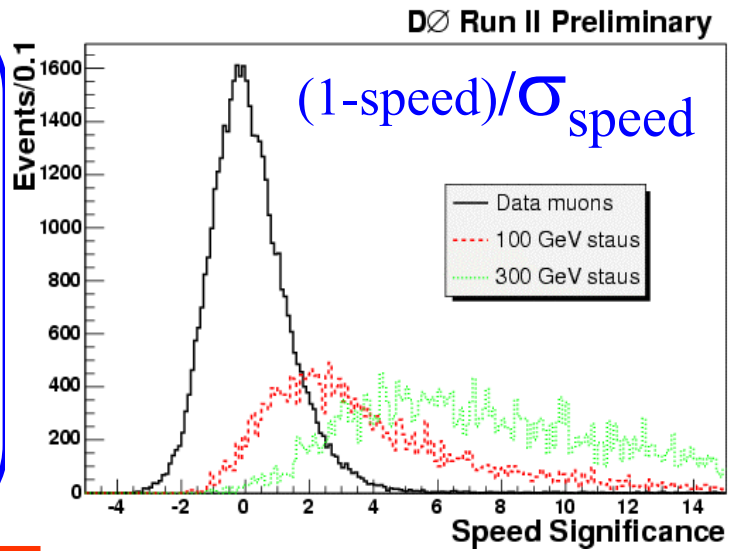
Production of a pair of CMSP ("stable" $\tilde{\tau}$ or $\chi^{\pm}$)

Charged Massive Particles with $c\tau$ >10m

- appear as slow moving high P_T μ
  - P_T>15 GeV + isolation
- timing of the muon scintillators used
  - Speed significantly slower than c

0 candidate expected: 0.66±0.6event

no SM background



Limits:

$\int L\,dt \approx 390\ pb^{-1}$

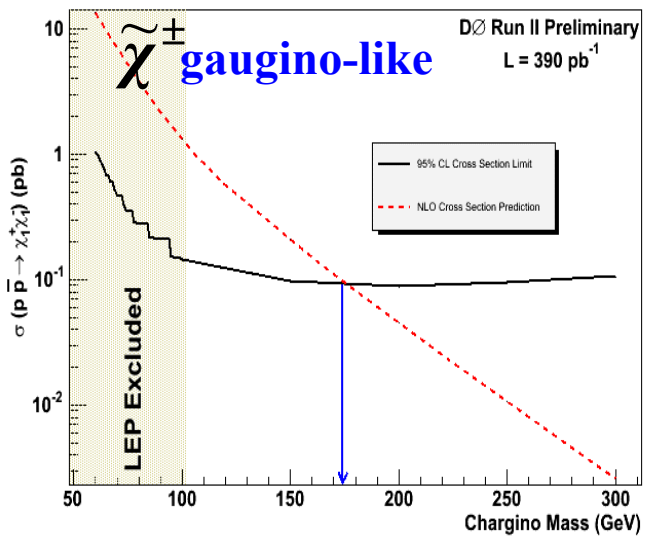
GMSB: CMSP is $\tilde{\tau}$

σ^{limit}=0.06-0.62 pb not sensitive yet

AMSB: CMSP is $\tilde{\chi}^{\pm}$ $\left(\Delta M(\tilde{\chi}_1^{\pm} - \tilde{\chi}_1^{0}) < 150\,MeV\right)$

Higgsino-like: $m_{\chi^+} > 140$ GeV

Gaugino-like: $m_{\chi^+} > 174$ GeV



M.C Cousinou – HCP 2005

R-parity violation : RPV

Additional terms in the superpotential:

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

L_i (Q_i) are the lepton(quark) $SU(2)_L$ doublet superfields

E_j (D_j, U_j) are the electron (down and up quark) $SU(2)_L$ singlet superfield

λ , λ' , λ'' are Yukawa couplings

- **RPV** decay **of LSP** ($\tilde{\chi}_1^0$)

λ_{ijk} **coupling** ⟷ **Lifetime of LSP**

- **Resonant sparticle production**

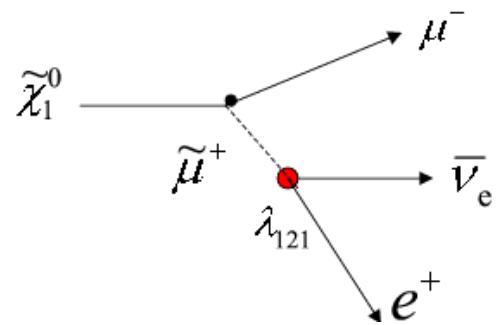
λ'_{ijk} **coupling**

***RPV** consequences on experimental signatures :*

- SUSY signature can be very different
  - Less missing E_T
  - More leptons and jets
- Sparticle may be produced by RPV couplings as single Sparticle

RPV $\lambda_{ijk} L_i L_j \bar{E}_k$ coupling

$$\tilde{\chi}^{\pm}\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 + X \rightarrow 4l + E_T^{miss} + X$$

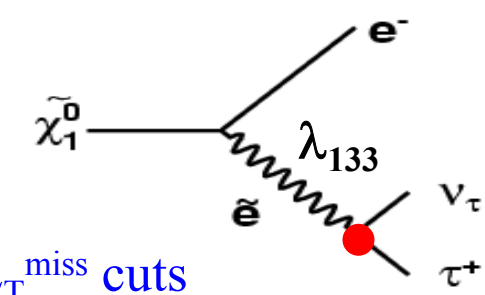


The couplings considered :

$\lambda_{121} \Rightarrow$ eeee, eeeμ or eeμμ + νν

$\lambda_{122} \Rightarrow$ μμμμ, μμμe or μμee + νν

$\lambda_{133} \Rightarrow$ ττττ, τττe or ττee + νν



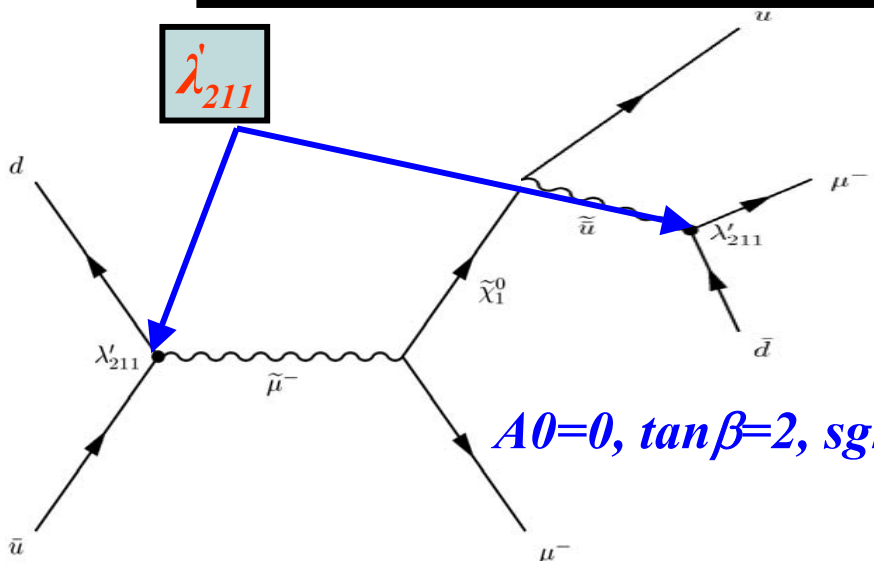
Selection:

3 isolated leptons + low P_T cut on 3rd lepton + loose E_T^{miss} cuts

	Lumi. Int. (pb-1)	Data	SM exp.	parameters	$M(\tilde{\chi}_1^{\pm}) >$ (GeV)
eel (l=e, μ)	238	0	0.5±0.4	m0=250 GeV,tanβ=5,A0=0, μ>0	181
μμl (l=e, μ)	160	2	0.6±1.9	m0=250 GeV,tanβ=5,A0=0, μ>0	165
eeτ_{had}	200	0	1.0 ±1.4	m0=80 GeV,tanβ=10,A0=0, μ>0	118

RPV $\lambda'_{211} L_2 Q_1 \bar{D}_1$ coupling

$\int L\,dt = 154\ pb^{-1}$

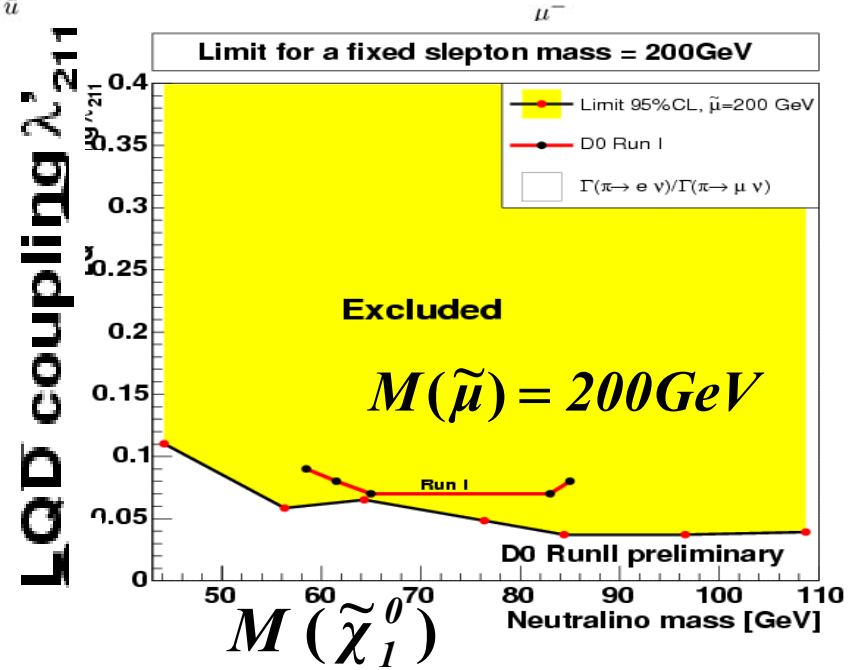


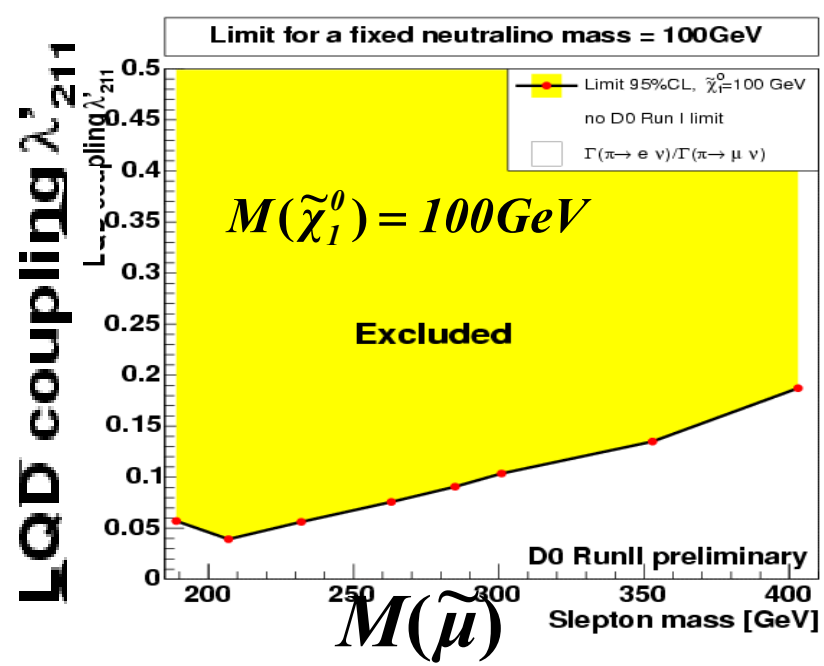
the invariant masses of the $\tilde{\chi}_1^0$ and $\tilde{\mu}$ can be reconstructed

2 jets and 2 isolated μ and P_T(jet,μ)~20 GeV
efficiency ~ 0.5-0.6%

A0=0, tanβ=2, sgn(μ)=-1

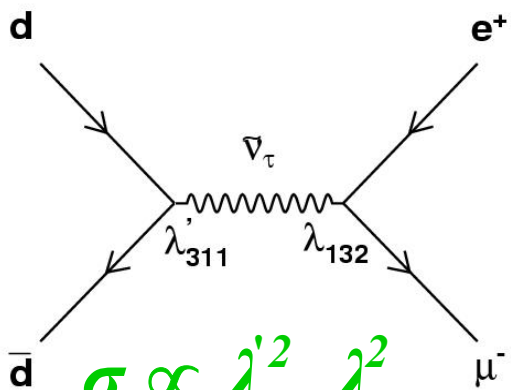
2 (data) / 1.1 ± 0.4 SM





RPV Search for Scalar Neutrino (1)

$\int L\,dt \approx 344\ pb^{-1}$



$\sigma \propto \lambda'^2_{311}\lambda^2_{132}$

e (E_T>20 GeV) + μ (P_T>20 GeV) + opposite charged

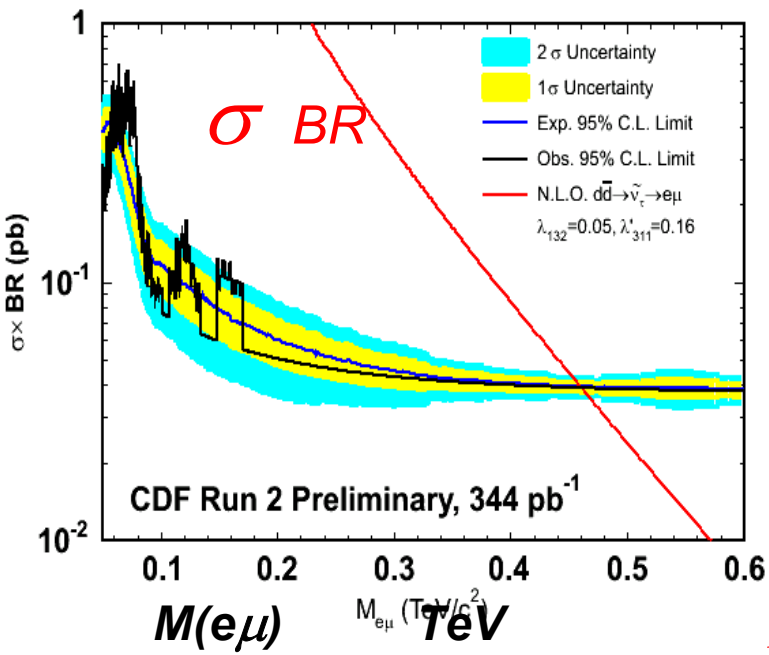
Acceptance ~ 25% (M(e μ)= 350 GeV)

Mass resolution ~15 GeV for M(e μ)=300 GeV

Data: 77 events - SM exp.: 71.3±1.8(stat)

with M(e μ)>100 GeV :

Data:5 events - SM exp.:8.0±1.1(stat)

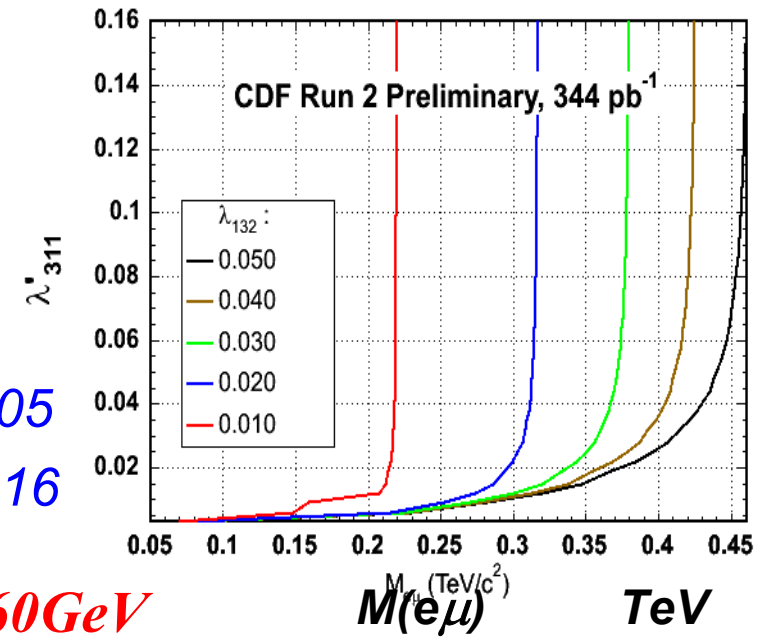


M(eμ) TeV

λ_{132}=0.05

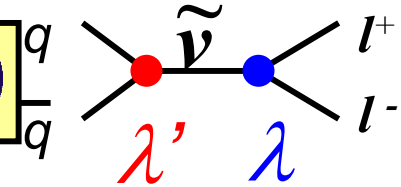
λ'_{311}=0.16

$M(\tilde{\nu}) > 460GeV$



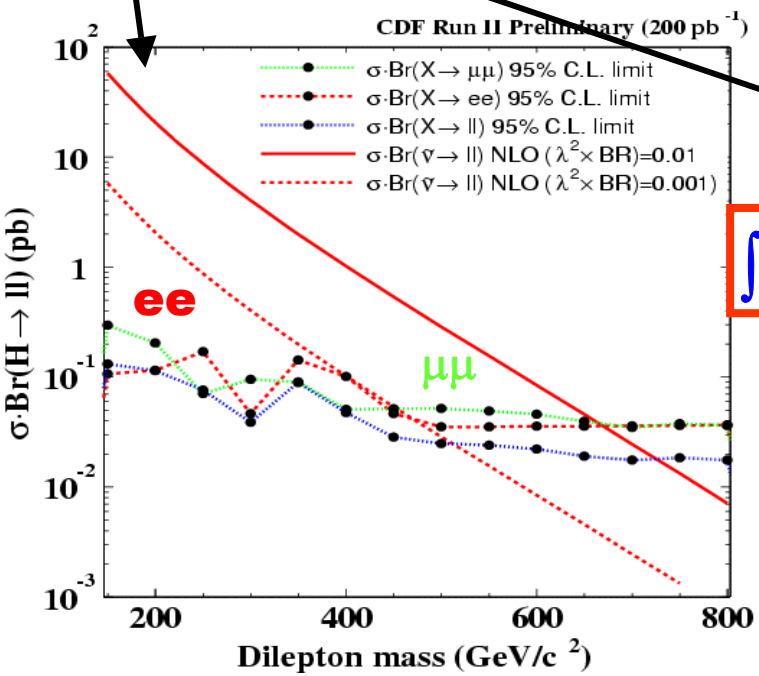
M(eμ) TeV

RPV Search for Scalar Neutrino (2)

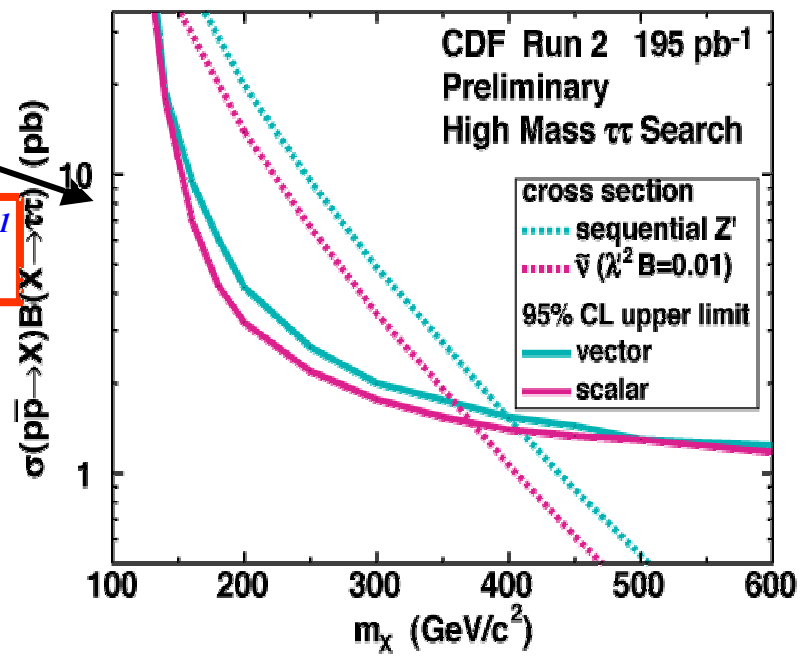


Channel	Cuts (GeV)	Obs.	SM exp.	$M(\tilde{\nu}) >$ (GeV)
ee	$E_T(e)>25 + M(ee)>500$	0	0.5 ± 0.1	725
μμ	$P_T(\mu)>20 + M(\mu\mu)>500$	1	1.2 ± 0.1	
$\tau_h\tau$	$P_T(\tau_h)>25 + E_T^{miss}>15 + M_{vis}>120$	4	2.8 ± 0.5	377

Limit at 95%CL
If $\lambda'^2 \cdot Br = 0.01$



$\int L dt \approx 200\ pb^{-1}$



Squarks and Gluinos

$M(\tilde{g}) >> M(\tilde{q})$

low m_0

$M(\tilde{q}) \cong M(\tilde{g})$

intermediate m_0

$$q\bar{q} \rightarrow \tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$$

$M(\tilde{q}) >> M(\tilde{g})$

high m_0

$$\tilde{q} \rightarrow q\chi^0$$

$$\tilde{g} \rightarrow q\tilde{q} \rightarrow qq\chi^0$$

m_0 310 pb^{-1}	# jets (P_T GeV)	$H_T=\Sigma\lvert\vec{P}_t^{jet}\rvert$ (GeV)	E_T^{miss} (GeV)	Exp. SM	Obs.
Low values	2 jets (60,50)	>250	>175	12.8±5.4	12
Int. values	3 jets (60,40,25)	>325	>100	6.1±3.1	5
High values	4 jets (60,40,30,25)	>250	>75	7.1±0.9	10
254 pb^{-1}	3 jets (125,75,25)	>350	>165	4.2±1.1	3

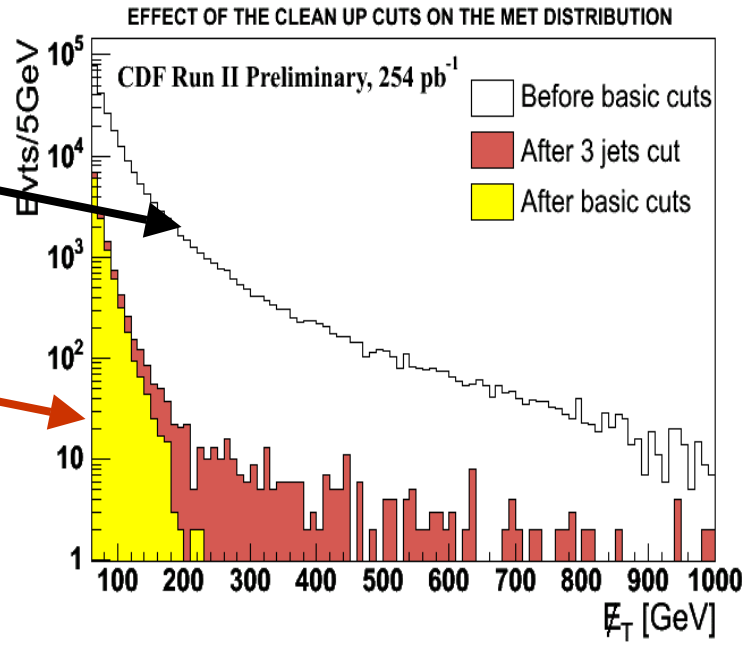
mSUGRA Squarks – Gluinos in jets + E_T^{miss}

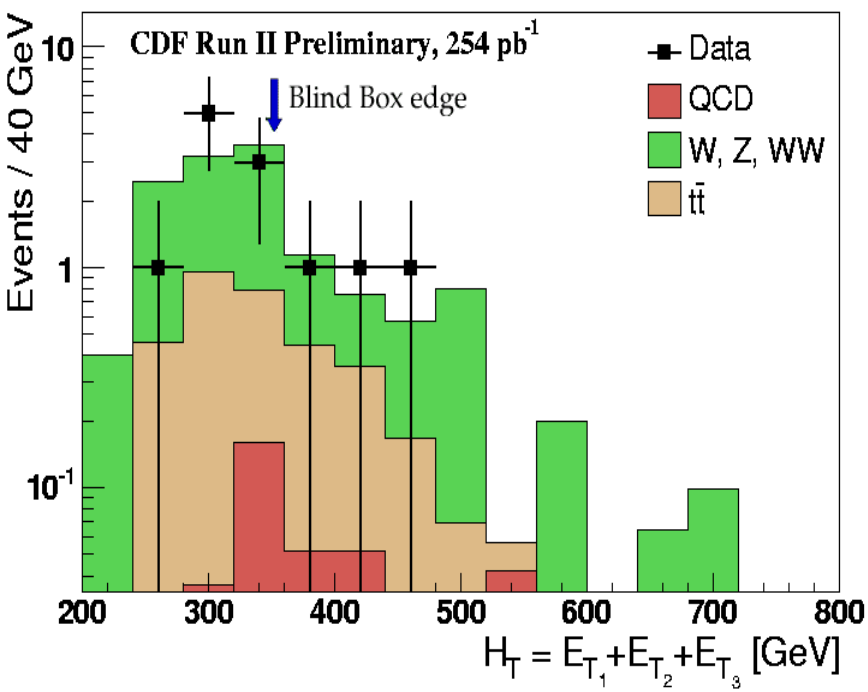
Enormous QCD background !

Missing E_T mis-measurements:

- ***Jet energy mis-measured***
- ***Beam halos-hot towers…***

after E_T^{miss} cleaning cuts:



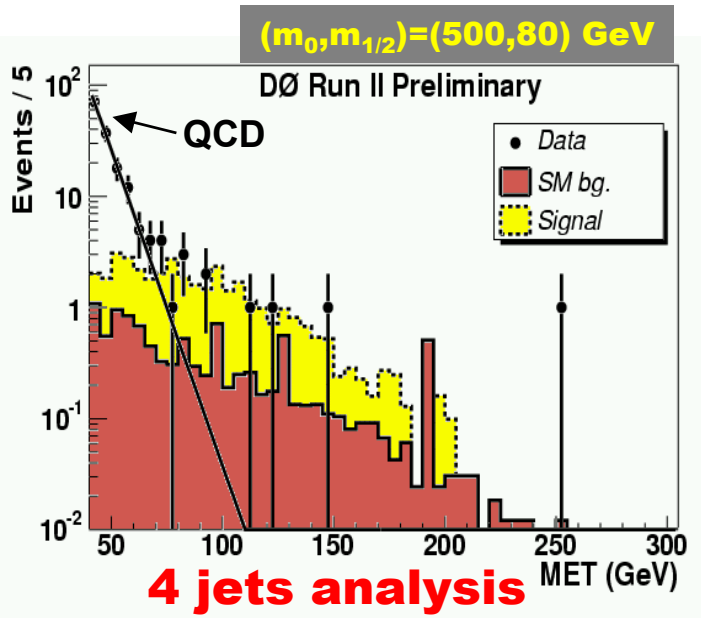


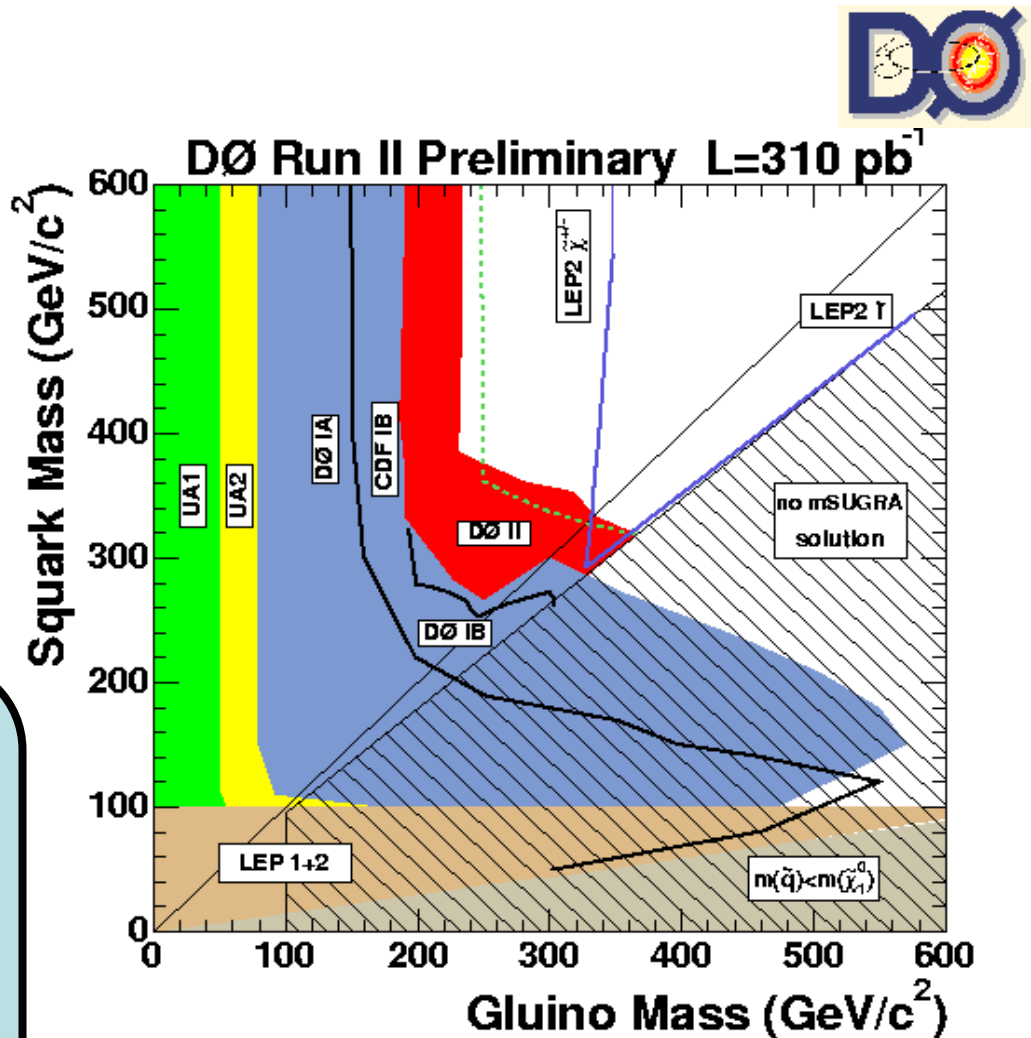
No charged leptons + E_T^{miss} non aligned with jets

Data: 3 SM exp. 4.2±1.1 events

Expect ~ 0.7 - 4.8 events for M(q,g)~380 GeV

mSUGRA Squarks – Gluinos in jets + E_T^{miss}





m(squark) > 318 GeV
(m_0= 25 GeV)
m(gluino) > 233 GeV
(m_0= 500 GeV)
m(gl)=m(sq) > 333 GeV

Search for Gluino decaying in Sbottom Bottom

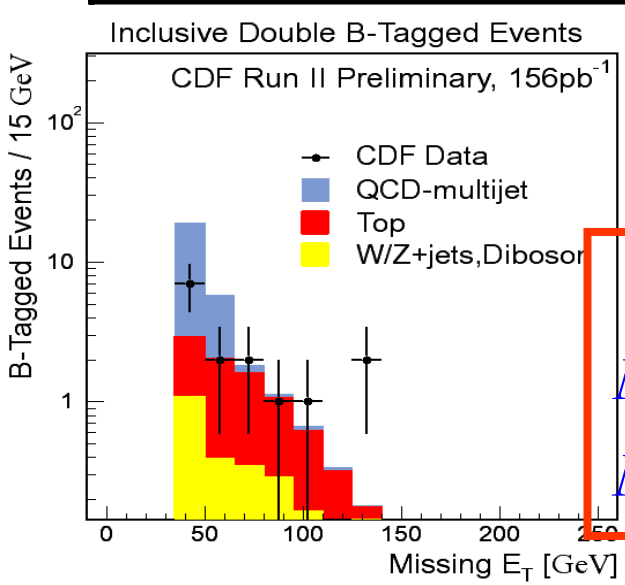
Assumption : **the $\tilde{b}$ is lighter that the $\tilde{g}$**

Final state: **4 b jets + large E_T^{miss}**

At least 3 jets E_T>15 GeV + E_T^{miss} > 80 GeV

+ angular cuts between jets and E_T^{miss}

	Obs.	Exp. SM
Excl. Single b tag	21	16.4 ± 3.7
Incl. double b tag	4	2.6 ± 0.7

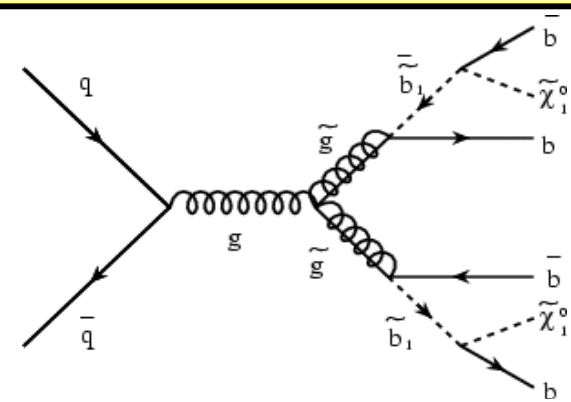


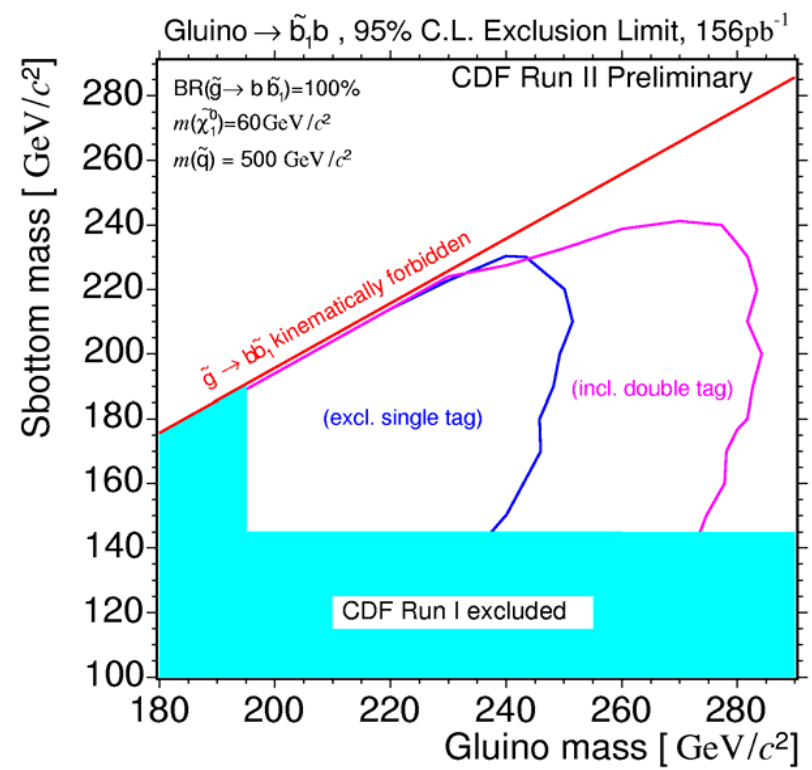
$$\int L\,dt = 156 \quad pb^{-1}$$

95% C.L

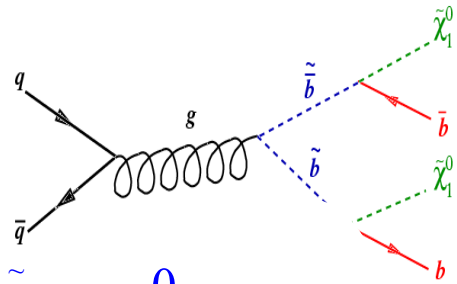
$$M(\tilde{g}) > 280\,GeV$$

$$M(\tilde{b}) > 240\,GeV$$



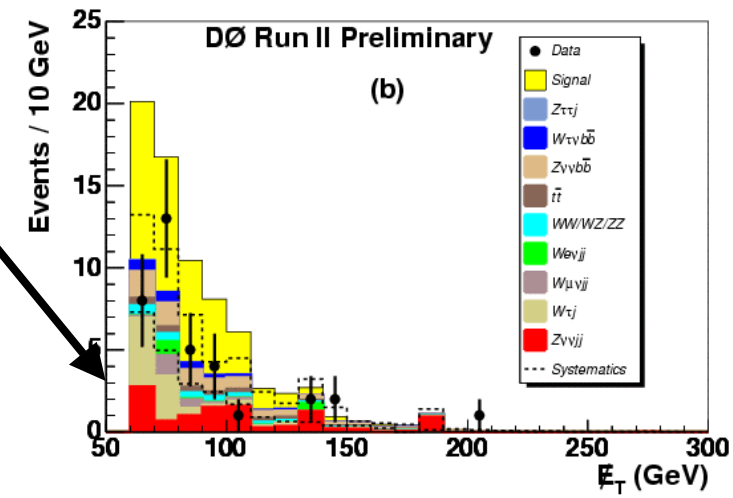


Direct Production of $\tilde{b}\bar{\tilde{b}}$ decaying in $b\bar{b}\tilde{\chi}_1^0\bar{\tilde{\chi}}_1^0$



$$BR(\tilde{b} \rightarrow b\chi_1^0) = 100\ \%$$

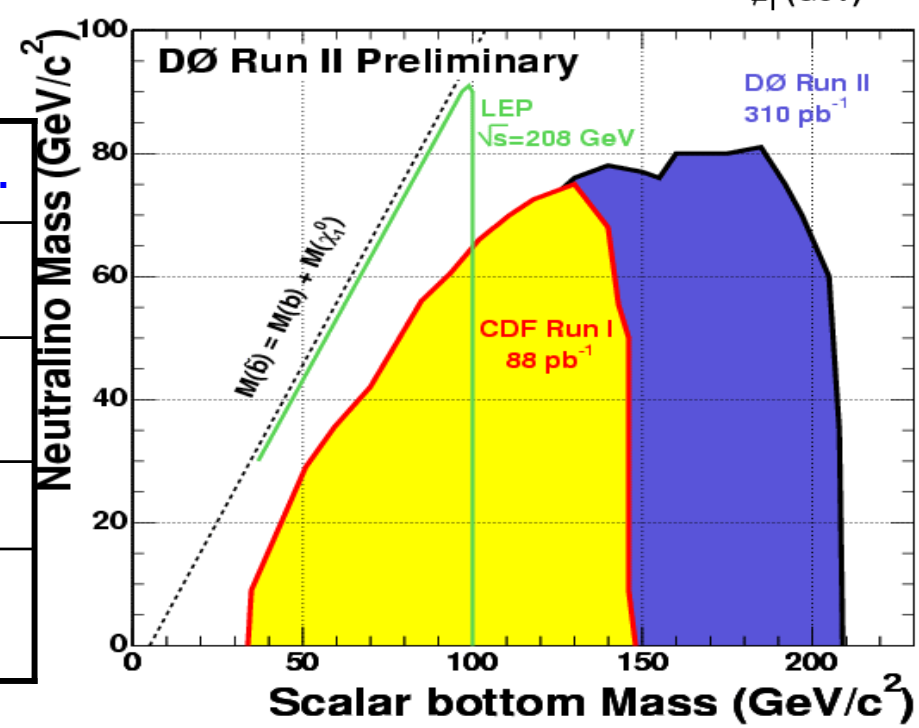
2 b-jets + $\not{E}_T$



Selection:

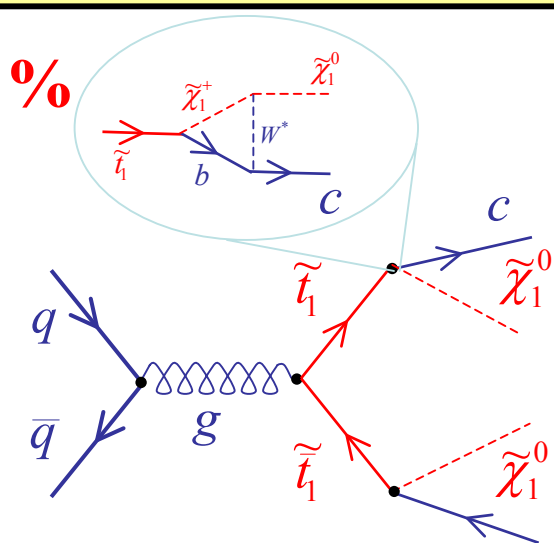
2 jets acoplanars (+3rd jet) + E_T^{miss} cut + single b-tag + lepton veto

$M(\tilde{b})$	Low val.	Med.val.	High val.
E_T(j1,j2) (GeV)	>(40,15)	>(40,15)	>(70,40)
E_T^{miss} (GeV)	>60	>80	>100
Data	36	15	2
SM exp.	38.6±2.8	19.6±1.7	4.4±0.4



RPC Search for pair production of Stop

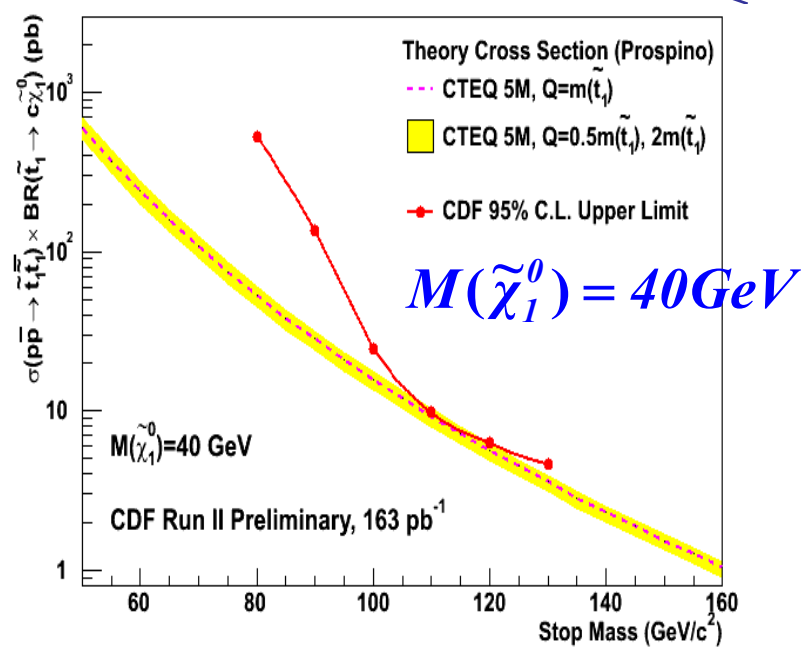
If $\tilde{t}_1$ is the lightest $\tilde{q}$ → $BR(\tilde{t} \to c\chi_1^0) = 100\ \%$



2 jets $E_T \geq 35,25$ GeV + $E_T^{miss} \geq 55$ GeV
+ e.g anti QCD back to back jets
+ no isolated lepton $p_T^{e,\mu} \geq 10$ GeV, anti τ
+ double heavy-flavor-tagging

$\int L\,dt = 163\ pb^{-1}$

11 (data) / 8.3 ± 2.0 SM



Limit from CDF RunI (88pb^{-1}) :
$M(\tilde{t}) > 140\,GeV$ for $M(\tilde{\chi}_1^0) = 40GeV$

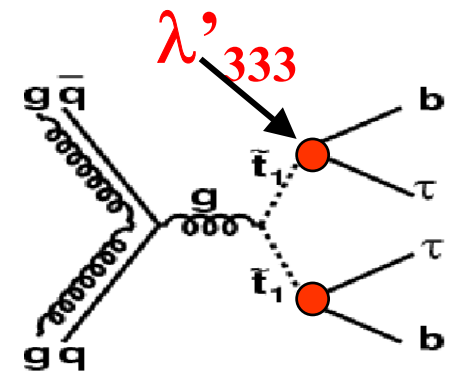
Due to:
Higher E_T^{miss} trigger threshold
and larger systematic uncertainties:
Jet Energy Scale correction (6%-33%)
Tagging heavy flavor jets (13%)

RPV Search for Stop decaying in b + τ

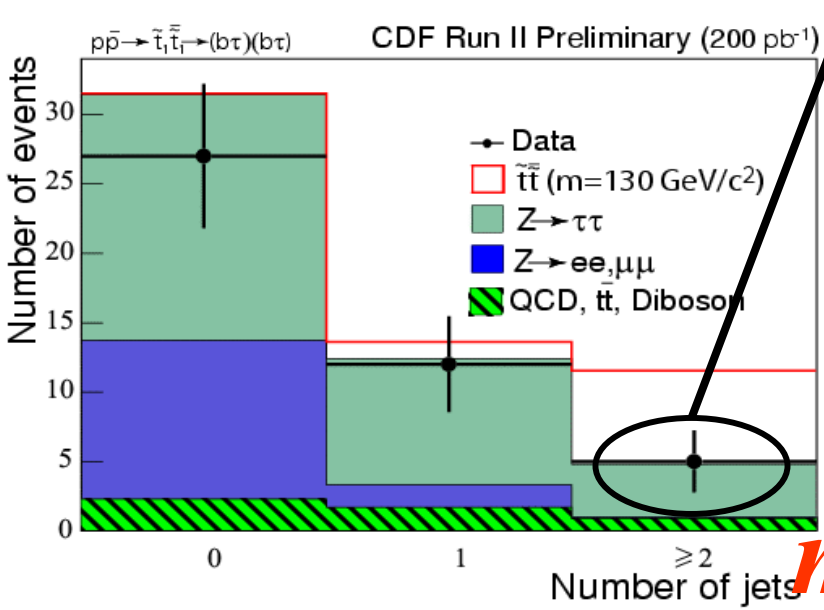
Search for $\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow b\tau_{had}\bar{b}\tau_{lep}$ BR($\tilde{t} \rightarrow b\tau$) ≈ 100%

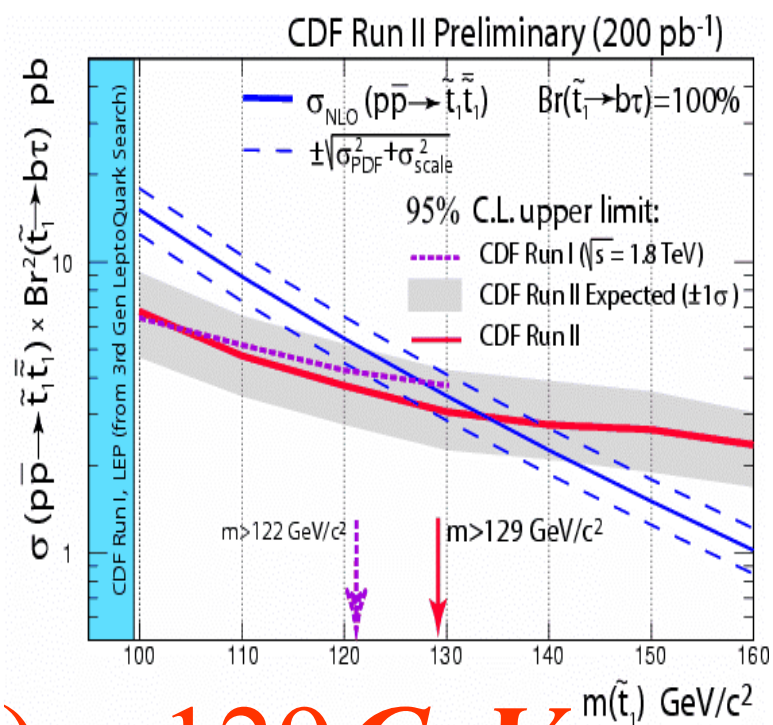
Selection: **1*l*** (*l*=e, μ P_T>10GeV) + **1**τ_{had} (P_T>15GeV)

+ ≥ 2 jets + $M_T(l, E_T^{miss}) < 35$ GeV (to remove W)



$\int Ldt \approx 200 pb^{-1}$	eτ	μτ	all
Exp. SM	2.6±0.6	2.2±0.5	4.8±0.7
observed	2	3	5





$m(\tilde{t}) > 129\,GeV$

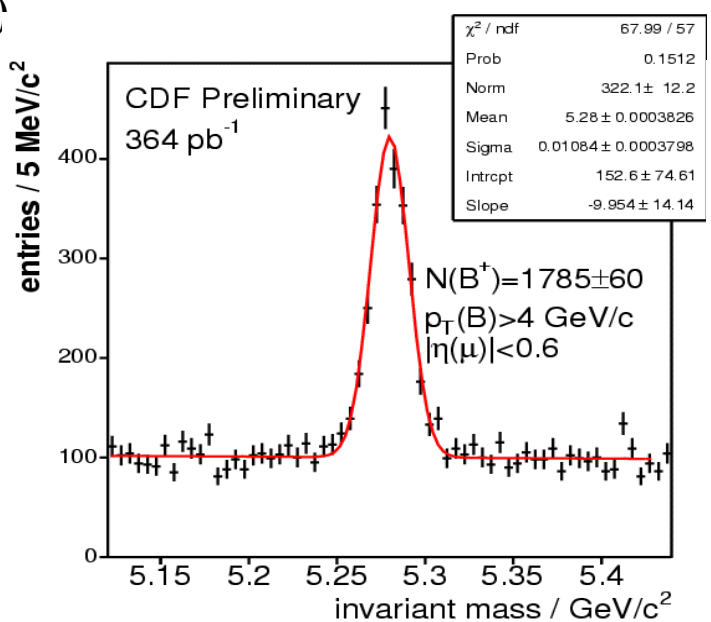
$B_s \rightarrow \mu^+\mu^-$

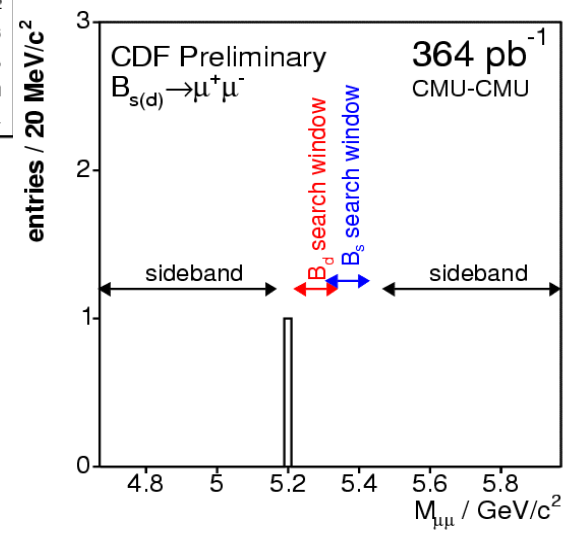
In SM, small BR ~ 3.5 10^{-9}

but in SUSY, enhancement ~ $(\tan\beta)^6$ factor

- Select $\mu^+\mu^-$ (P_T> 2-3GeV) from displaced vertices
- Count events inside a $M(\mu\mu)$ mass window (±100MeV around the B_S mass)

  →0 event
- Normalize the upper limit to the number of $B^{\pm} \longrightarrow J/\Psi\, K^{\pm}$ events





at 90%C.L	Lum. (pb-1)	BR($B_s \rightarrow \mu+\mu-$)
CDF	364	< 1.5 10^{-7}
DØ	300	< 3.0 10^{-7}

Conclusions

CDF and D0 have both covered many SUSY particles searches using an integrated luminosity of about 350pb^{-1}

- *Substantial improvement wrt Run I*
- *Limits above LEP's in certain parameters space*

We are now analysing the 1 fb^{-1} data, hoping for a discovery ,

otherwise there will be substantial improvement of the limits (see the Tevatron Connection Workshop talks (June 24-25))