

Searches for SuperSymmetry at the TeVatron (Recent Results*)

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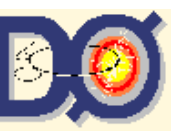
*many
approved
during this
week !



CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

Les Rencontres de Physique
de la Vallée d'Aoste

February 27-March 5, 2005

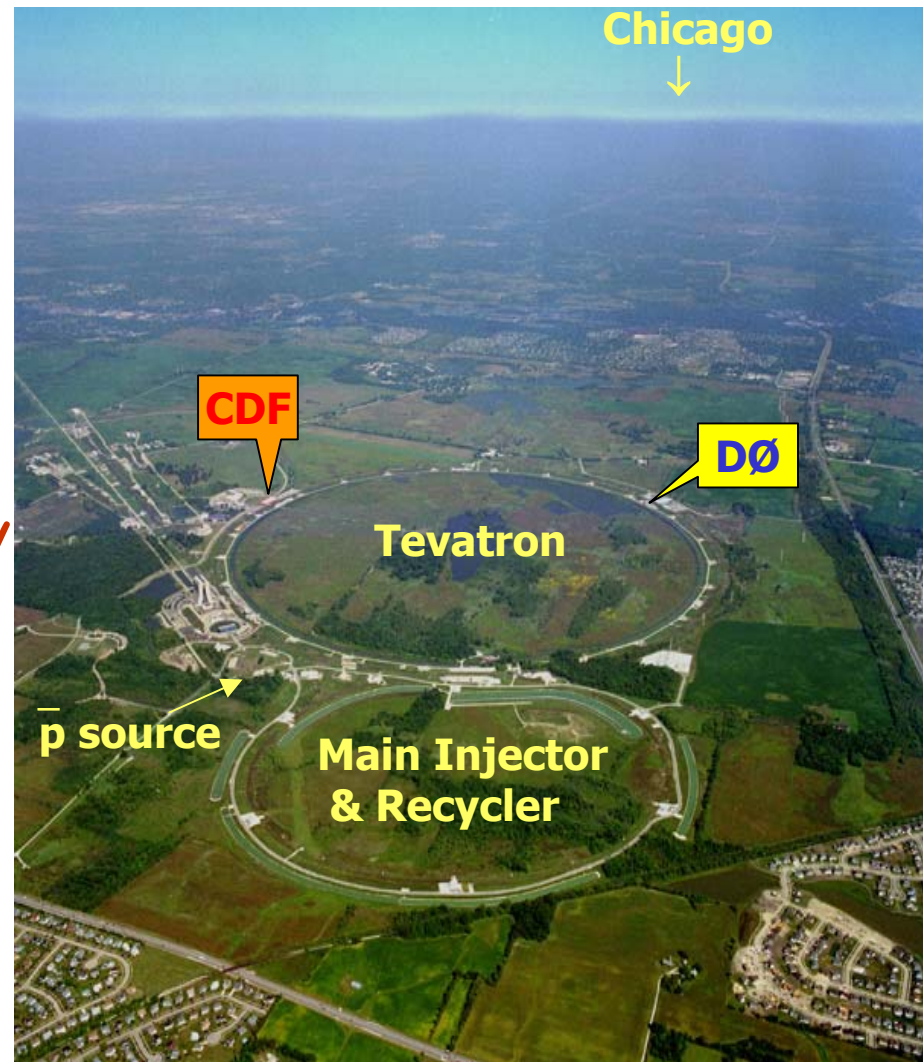


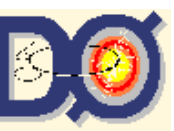
Tevatron at Run II



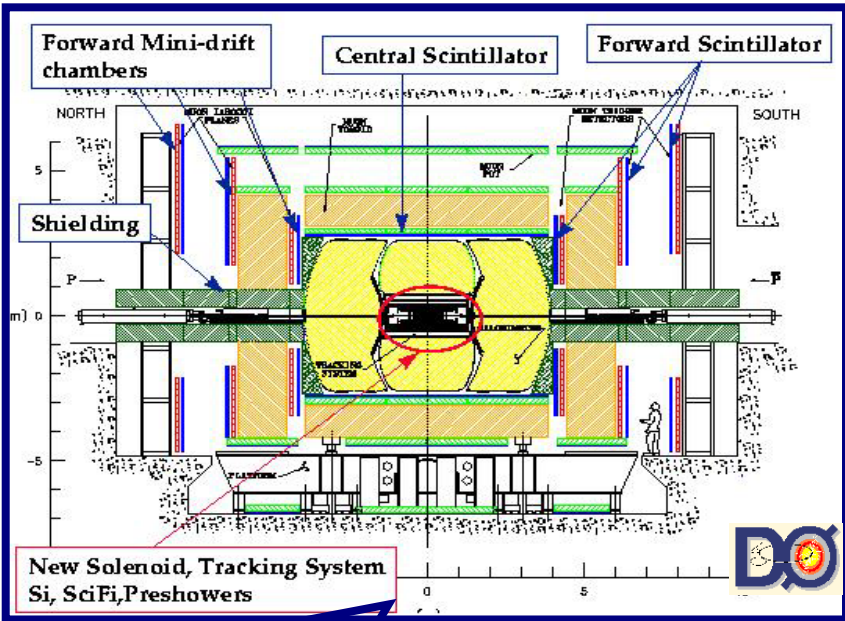
Run II started March 2001

- Higher energy
(1.8 TeV \rightarrow 1.96 TeV)
 \Rightarrow Higher cross sections
(\sim 20-30 % for $\chi^\pm \chi^0$)
- Higher antiproton intensity
6 \times 6 \rightarrow 36 \times 36 bunches
(3.5 μ s \rightarrow 396 ns)
antiproton "recycler"
 \Rightarrow Higher luminosity
- Powerful Trigger Systems
(2.5 MHz \rightarrow 50 Hz)





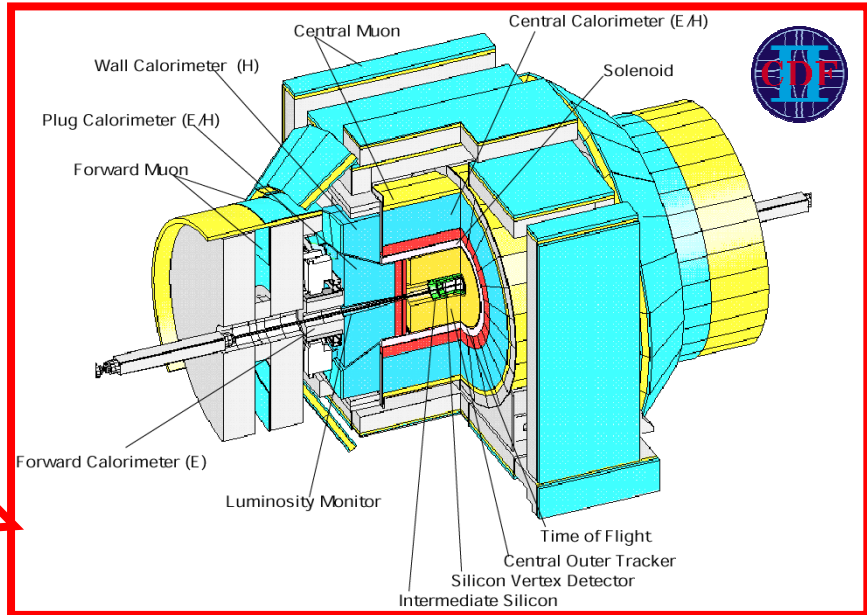
DO and CDF Upgrade

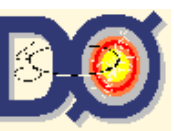


	DO	CDF (Acceptance)
Electron	$ \eta < 3$	$ \eta < 3$
Muon	$ \eta < 2$	$ \eta < 1.5$
Tracking (Si)	$ \eta < 3$	$ \eta < 2$

Tracking in 2T magnetic field (silicon and fibers), Hermetic Calorimeter (Argon), Wide Muon Coverage ...

Tracking in 1.4T magnetic field (silicon and drift chamber), up to 96 hits per tracks, Displaced track trigger...





Luminosity Performance



In 2005:

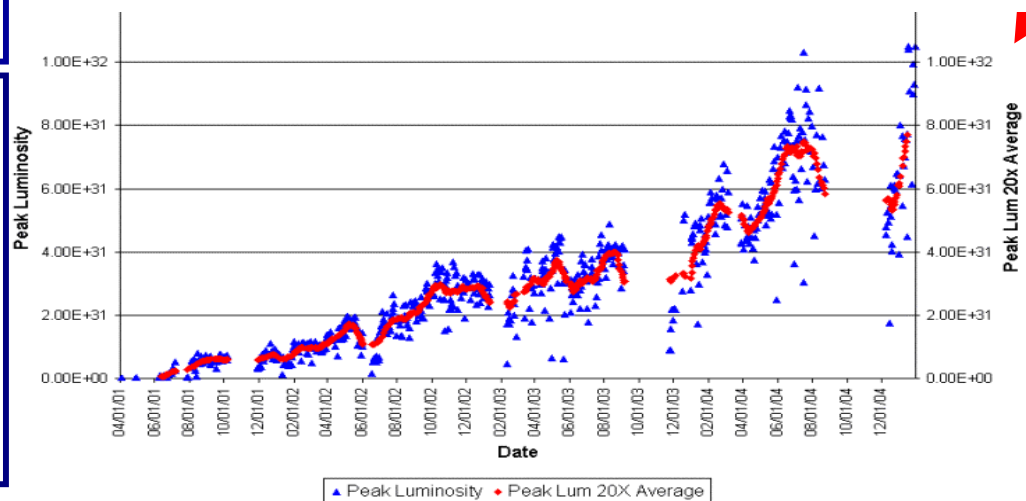
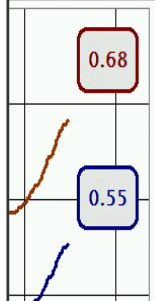
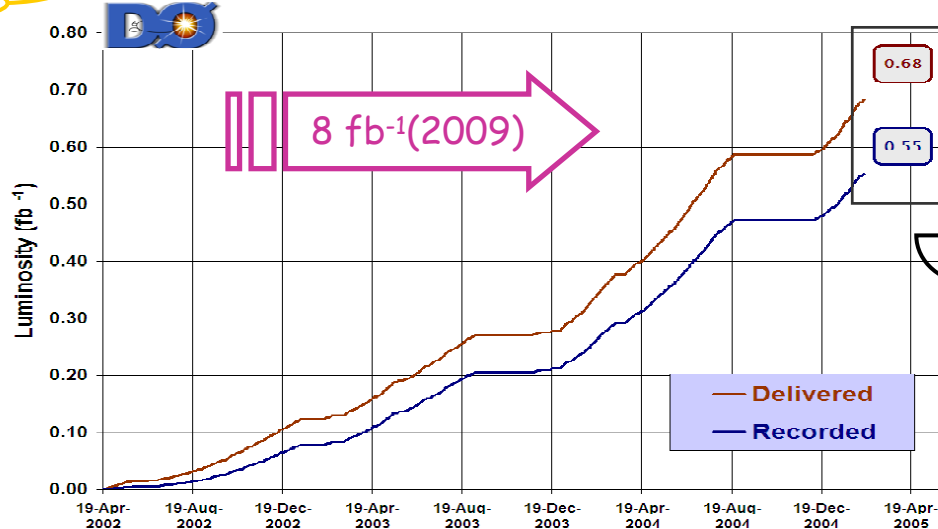
02/23/2005

- Peak luminosity: $107. 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
- Weekly delivered: 8 - 16 pb^{-1}
- Data taking efficiency: 80 - 90%

Physics quality data collected so far :
 $> 550 \text{ pb}^{-1}$
 Analysis shown :
 up to 390 pb^{-1}

Run II Integrated Luminosity

19 April 2002 - 14 February 2005



10^{32}

1. Charginos
and
Neutralinos

2. R-parity
Violation

main search
streams at the
Tevatron

5. Squarks
and
Gluinos

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

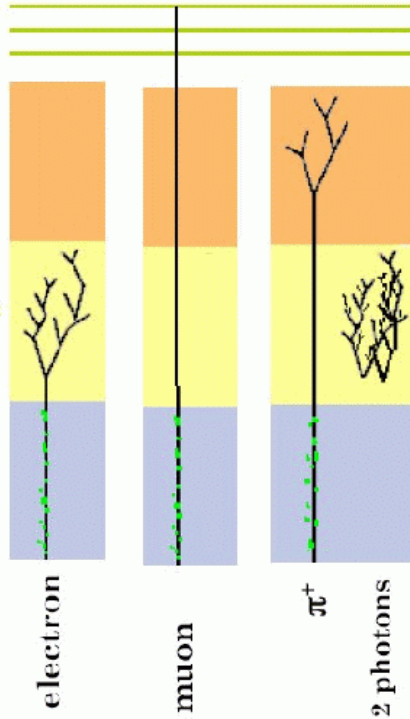
4. GMSB

Muon
Chambers

Hadronic
Calorimeter

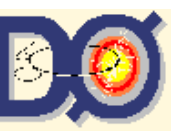
Electromagnetic
calorimeter

Tracking
Detectors



Multi-leptons

- Low production cross sections
- Typically low leptonic branching ratios
- Clean experimental signature



1. Trileptons

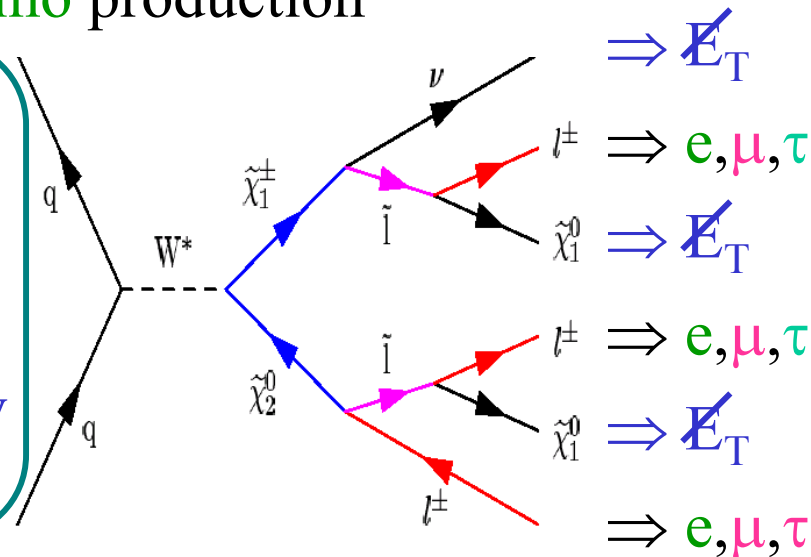
from **Chargino-Neutralino** production

Clean signature but:


- low cross sections ($\sigma \times BR < 0.5 \text{ pb}$)
- soft leptons
- taus (at large $\tan\beta$)

⇒ Needs large integrated luminosity

⇒ Combine various final states



DØ analysis combines **6** final states :

- **ee**l (316 pb^{-1})
- **e μ l** (318 pb^{-1}) 
- **$\mu\mu$ l** (300 pb^{-1})
- **same sign dimuon** (313 pb^{-1})

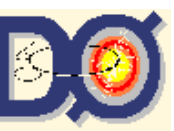
Luminosity uncertainty : $\pm 6.5\%$

+ New Results :

- **e τ l** (325 pb^{-1})
- **$\mu\tau$ l** (326 pb^{-1})

$$\int L dt =$$





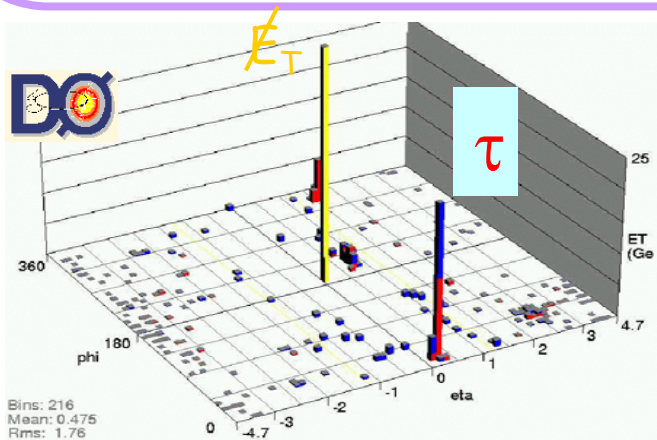
Trileptons (II)

• Trigger :

Inclusive combination of many different triggers with **very tight cuts at low pt** and **many looser versions for higher and higher pt**

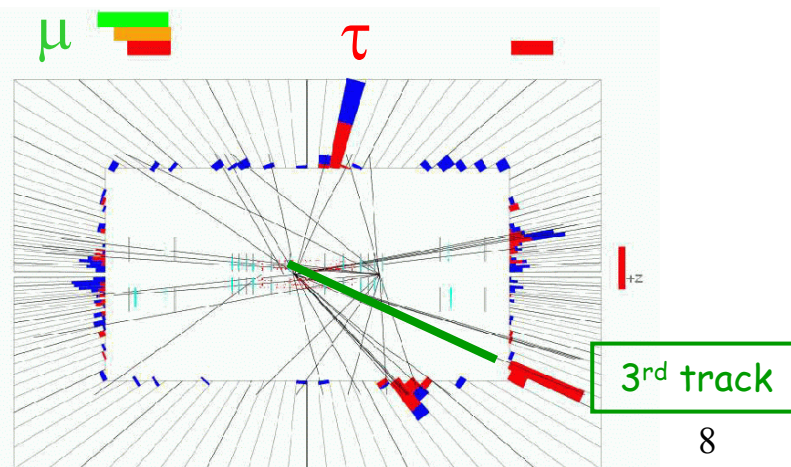
• Offline :

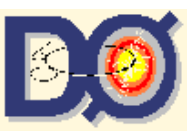
- 2 well identified and isolated e or μ ($P_T \sim 10$ GeV) or τ
 \Rightarrow Increase acceptance by requiring 2 out of 3 leptons
- + Isolated high quality track (= third lepton : e, μ, τ) with $P_T \sim 5$ GeV
- + Transverse Missing energy (= neutrinos, neutralinos) with $\cancel{E}_T \sim 20$ GeV
- + Anti Z cuts (15 GeV < inv. Mass < 60 GeV)
- Or Like-Sign requirements (dimuons)



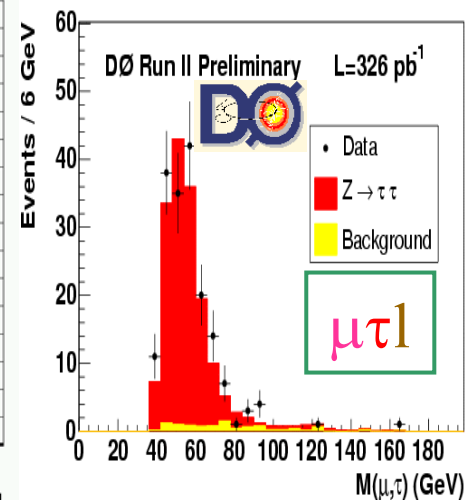
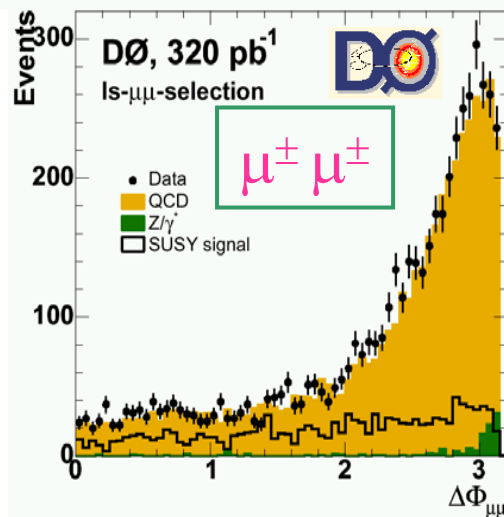
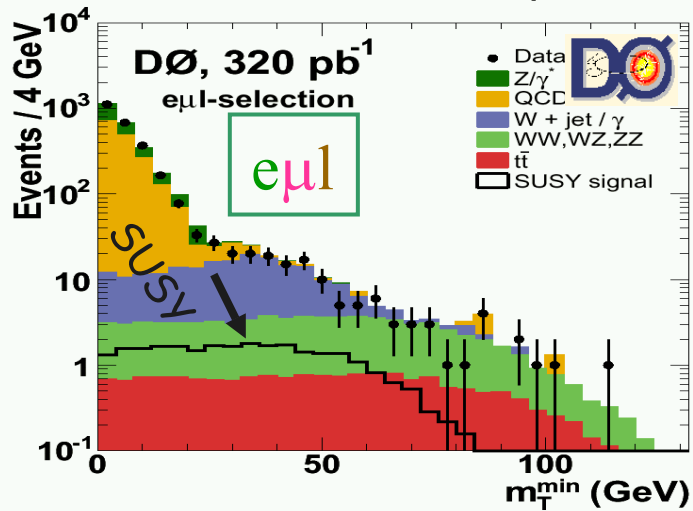
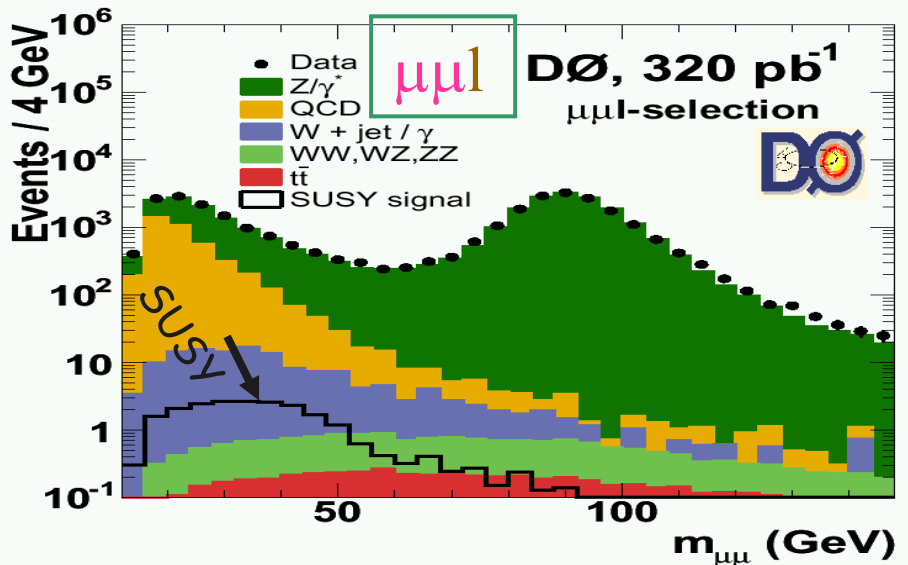
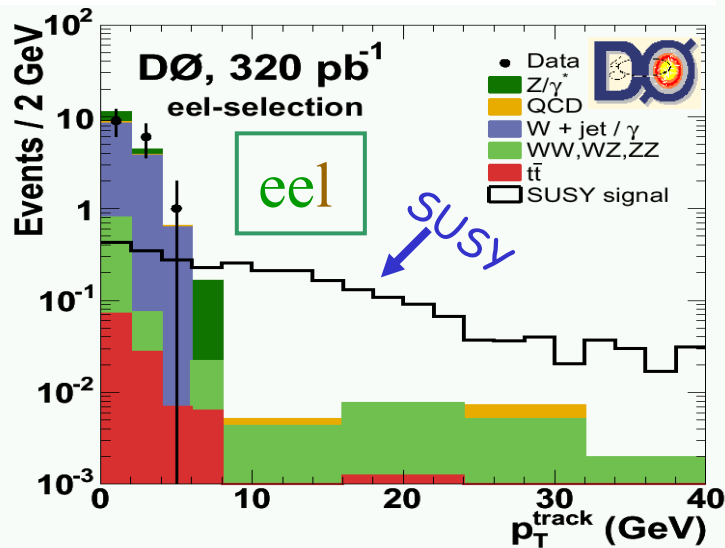
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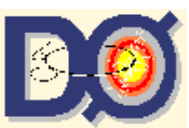
La Thuile





Trileptons (III)





Trileptons (IV)

$$\int L dt \approx 320 \text{ pb}^{-1}$$

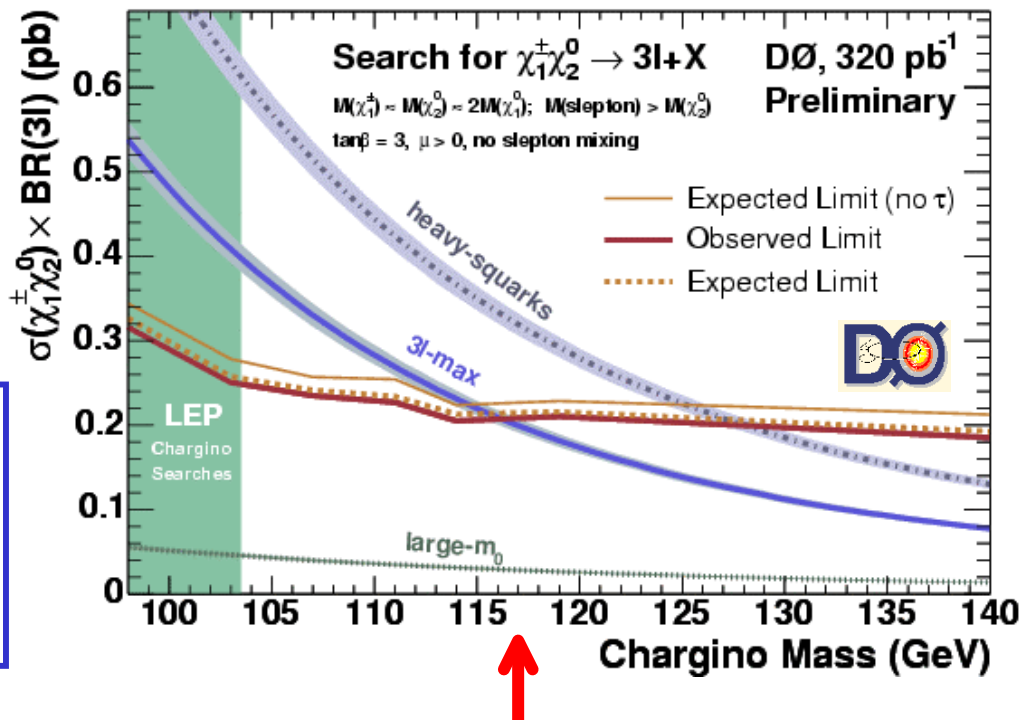


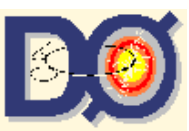
$\chi^\pm \chi^0$	Observed	Standard Model	Signal
eel	0 event	0.21 ± 0.12	1.94 ± 0.17
e μ l	0 event	0.31 ± 0.15	1.50 ± 0.13
$\mu\mu$ l	2 event	1.75 ± 0.57	1.01 ± 0.12
LS $\mu\mu$	1 event	0.66 ± 0.37	0.80 ± 0.20
e τ l	0 event	0.58 ± 0.14	0.36 ± 0.05
$\mu\tau$ l	1 event	0.36 ± 0.13	0.67 ± 0.05

Data : 4
SM : 3.85 ± 0.57 (stat)
 ± 0.49 (sys)



Significant improvement versus LEP :
 $m(\chi^+) > 117.7 \text{ GeV}$
 for $m(\text{slepton}) \approx m(\chi')$



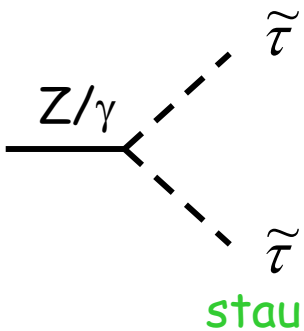


CMSP (stable stau and χ^\pm)

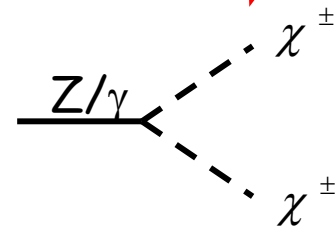
DØ has searched for
Charged Massive Stable Particles



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

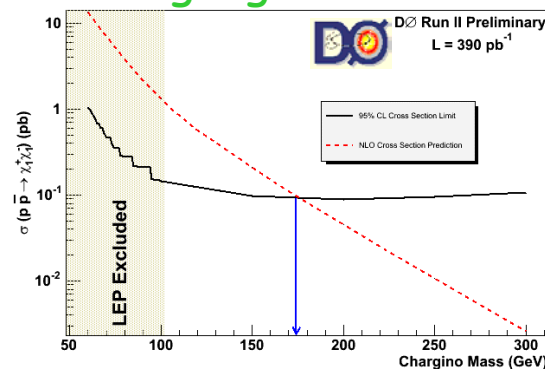
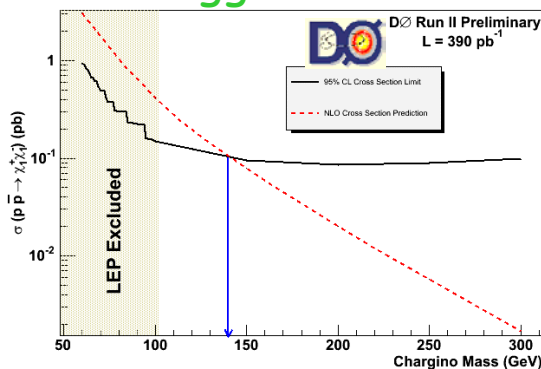
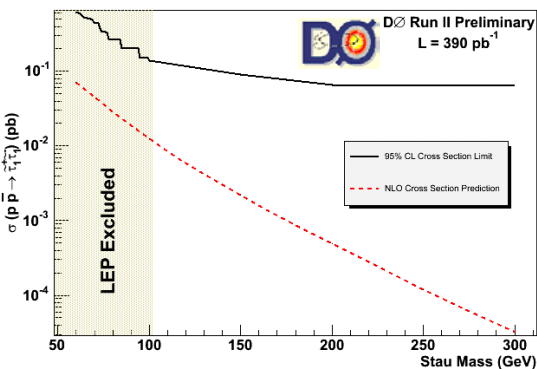


- appear as slow moving high $P_T \mu$
- timing of the muon scintillators used



higgsino-like

gaugino-like

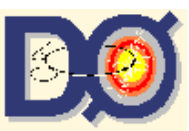


$$\sigma^{\text{limit}} = 0.06 - 0.62 \text{ pb}$$

$$m_{\chi^+} > 140 \text{ GeV}$$

World best limit

$$m_{\chi^+} > 174 \text{ GeV}$$



2. R-parity violation : RPV



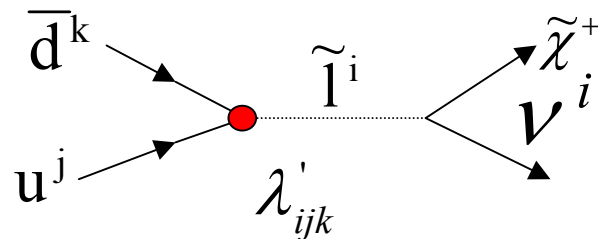
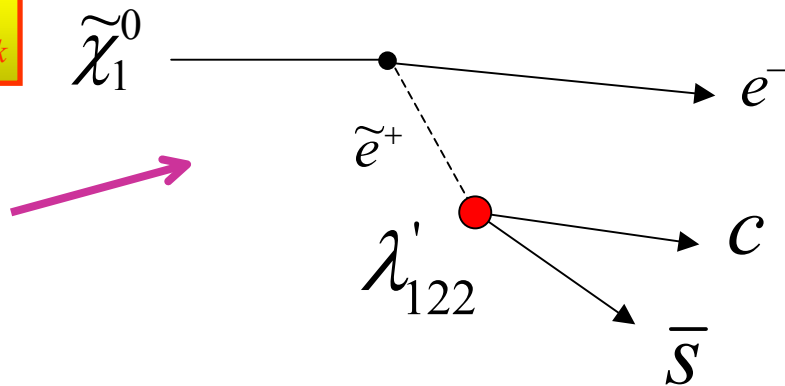
$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Experimental signatures :

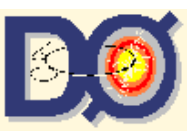
- **Pair production** and **RPV decays of LSP**
 - λ and λ' couplings
- **Resonant sparticle** production
 - λ' and λ'' couplings

RPV consequences :

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



LSP is not anymore a candidate for dark matter



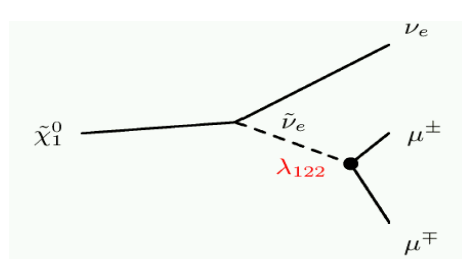
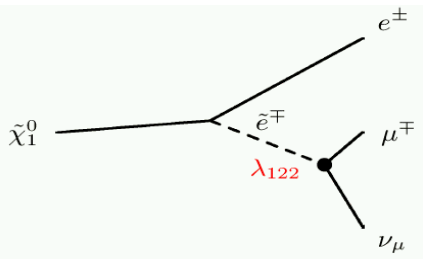
RPV with $\lambda_{ijk} L_i L_j E_k$ coupling

DO has searched for multilepton final states arising from SUSY particle pair production with SUSY particle pair production with R-parity violating decays of two neutralino LSP's

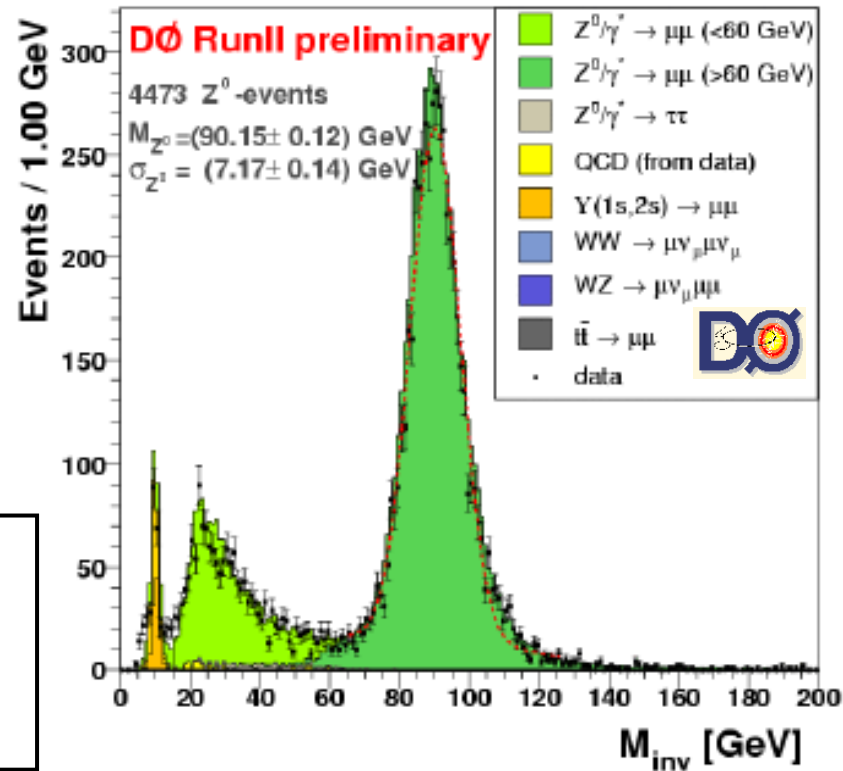
The couplings considered :

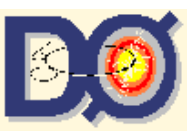
$\lambda_{121} \Rightarrow eeee, eee\mu$ or $ee\mu\mu + \nu\nu$

$\lambda_{122} \Rightarrow \mu\mu\mu\mu, \mu\mu\mu e$ or $\mu\mu ee + \nu\nu$



Three isolated rather soft (i.e neutralino mass expected small $\approx 50-90$ GeV) e or μ + Missing E_T + channel-dependent cuts (e.g. anti Z)





RPV with $\lambda_{ijk} L_i L_j E_k$ (II)

$$\int L dt = 160 \text{ pb}^{-1}$$

$$\lambda_{122}: 2 \text{ (data)} / 0.6 \pm 1.9 \text{ SM}$$

 \Rightarrow

$$m_{\chi^+} > 165 \text{ GeV}$$

$$\int L dt = 238 \text{ pb}^{-1}$$

$$\lambda_{121}: 0 \text{ (data)} / 0.5 \pm 0.4 \text{ SM}$$

 \Rightarrow

$$m_{\chi^+} > 181 \text{ GeV}$$

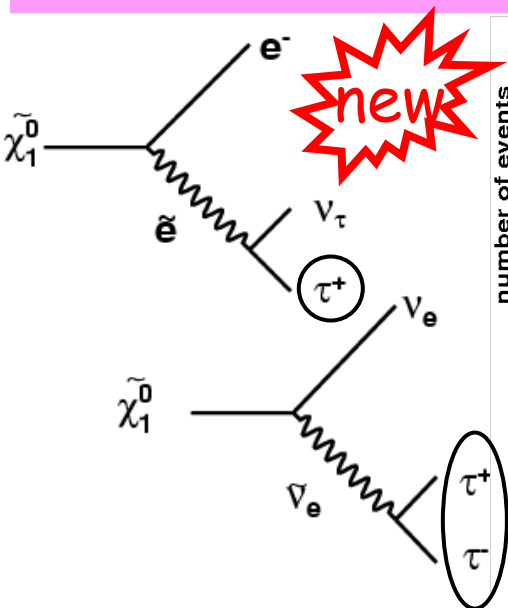
$$\int L dt = 200 \text{ pb}^{-1}$$

$$\lambda_{133}: 0 \text{ (data)} / 1.0 \pm 1.4 \text{ SM}$$

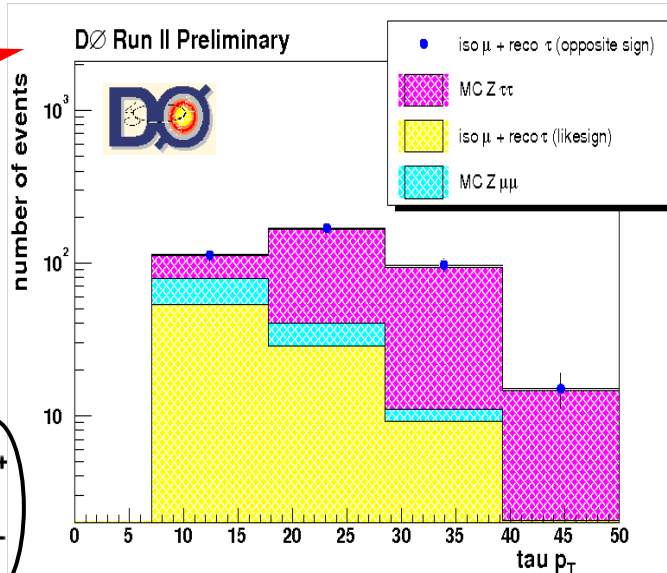
 \Rightarrow

$$m_{\chi^+} > 118 \text{ GeV}$$

with $\tau \rightarrow \text{hadrons} + \nu$:

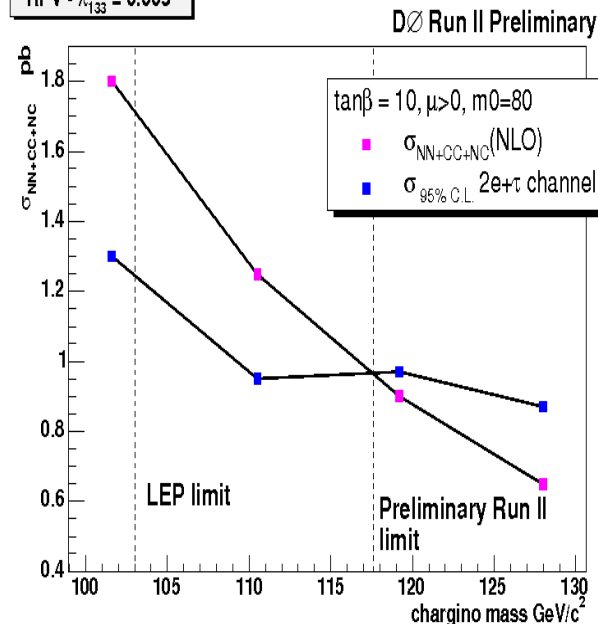


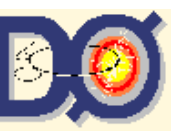
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La Thuile 2005

RPV $\cdot \lambda_{133} = 0.003$

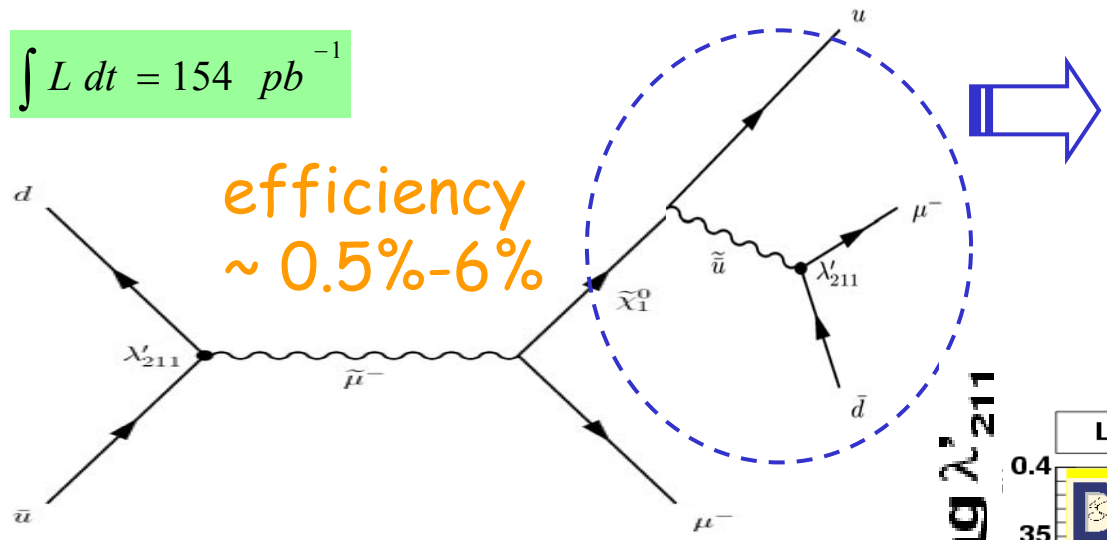




RPV with $\lambda'_{211} L_i Q_j D_k$

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

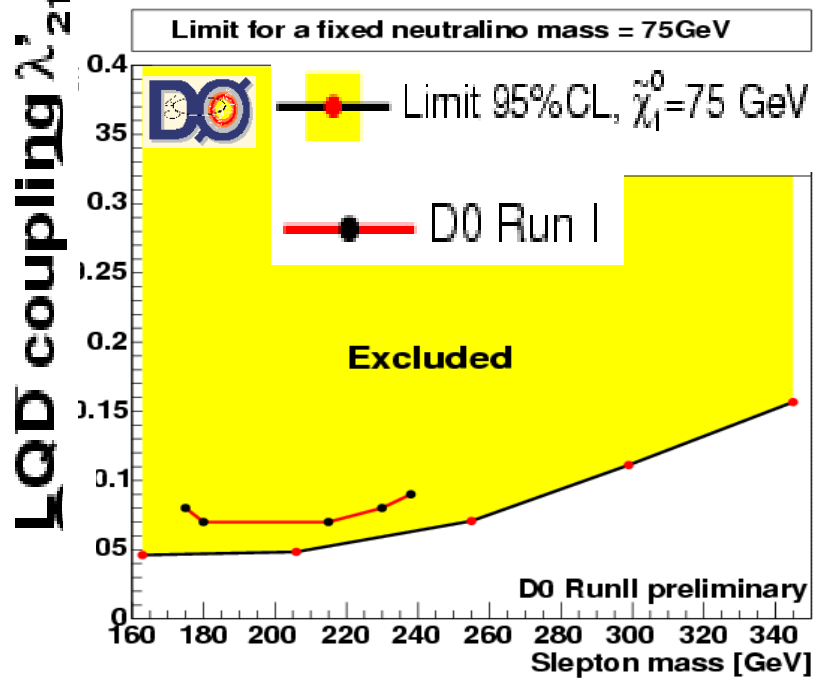
efficiency
~ 0.5%-6%

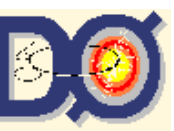


Neutralino and smuon invariant mass reconstruction possible

- 2 jets
- 2 isolated μ
- $P_T(e, \mu) \sim 20 \text{ GeV}$

λ'_{211} : 2 (data) / $1.1 \pm 0.4 \text{ SM}$



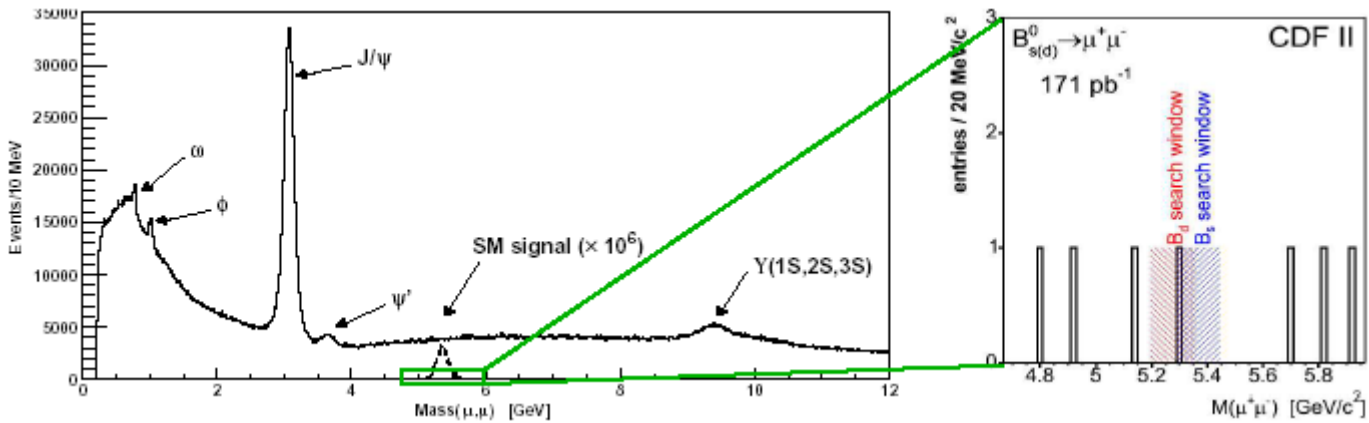


3. $B_s \rightarrow \mu^+ \mu^-$

- In SM, tiny BR $\sim 3.5 \cdot 10^{-9}$ (and 25 times smaller for B_d)
- But in SUSY, enhancement $\sim (\tan\beta)^6$ factor

Select $\mu\mu$:

- from displaced vertices
- look inside a mass window:



$$\int L dt = 240 \text{ pb}^{-1}$$

$$\int L dt = 171 \text{ pb}^{-1}$$

BR($B_s \rightarrow \mu+\mu-$) :

- $< 4.6 \cdot 10^{-7}$
- $< 7.5 \cdot 10^{-7}$

Combined @90% CL
 $BR(B_s \rightarrow \mu+\mu-) < 2.7 \cdot 10^{-7}$

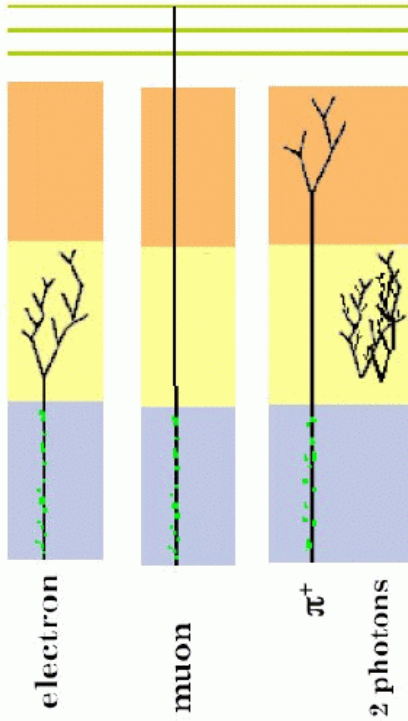
start to probe ...

Muon
Chambers

Hadronic
Calorimeter

Electromagnetic
calorimeter

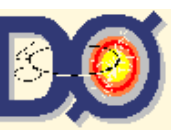
Tracking
Detectors



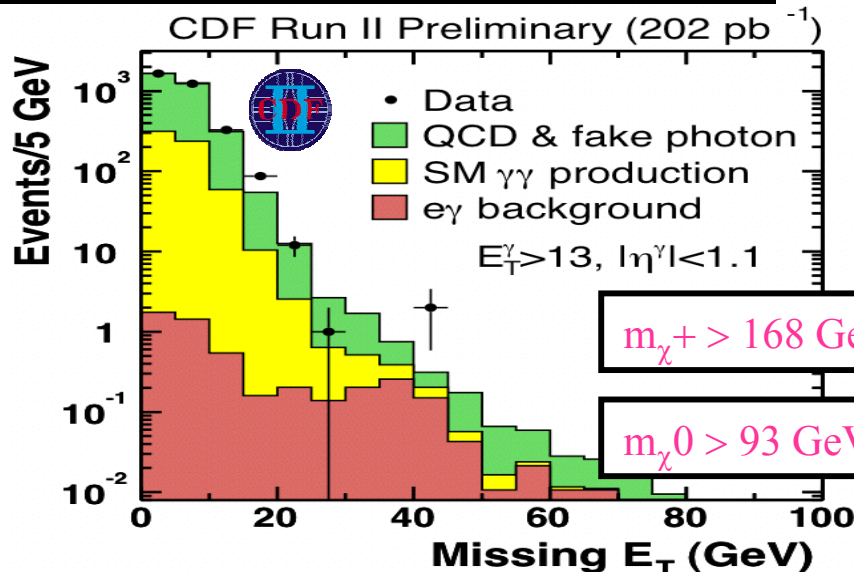
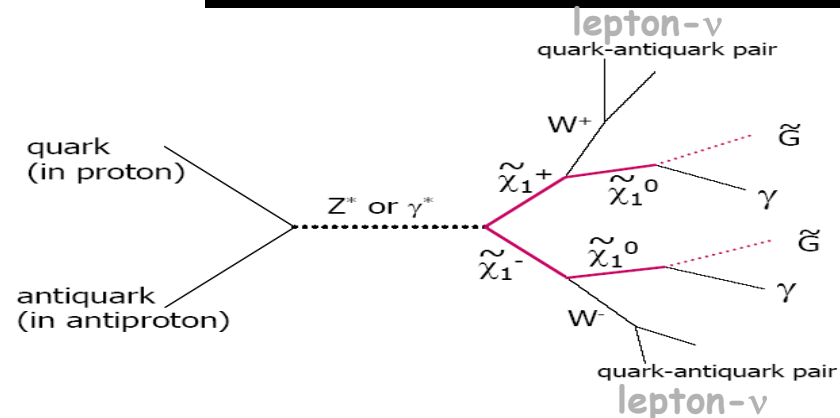
$\gamma\gamma$

+

missing E_T



4. GMSB with χ^0 NLSP



$\int L dt = 263 \text{ pb}^{-1}$ $\int L dt = 202 \text{ pb}^{-1}$

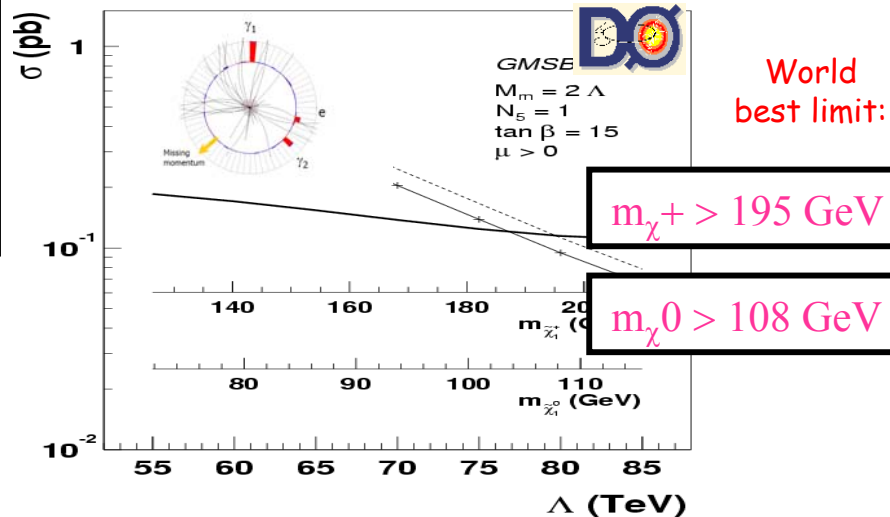
DØ and CDF searched for inclusive final state with 2 $\gamma\gamma$ + Missing E_T



2 (data) / 3.7 ± 0.6 SM



0 (data) / 0.3 ± 0.1 SM

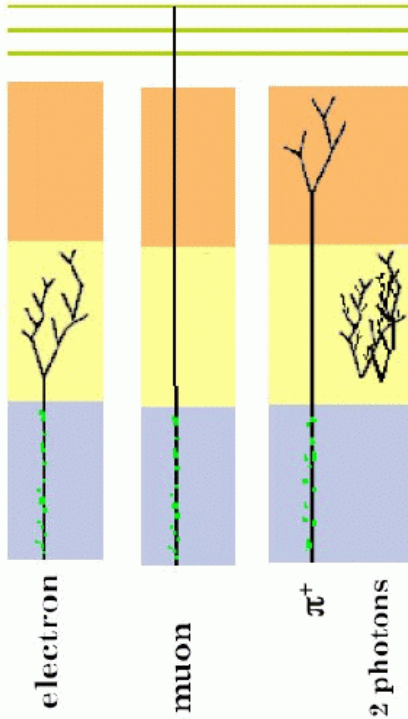


Muon
Chambers

Hadronic
Calorimeter

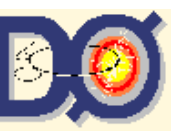
Electromagnetic
calorimeter

Tracking
Detectors



Multijet
+
missing E_T

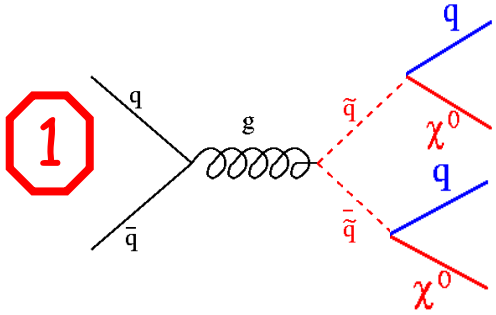
- Large production cross sections
- Large experimental backgrounds



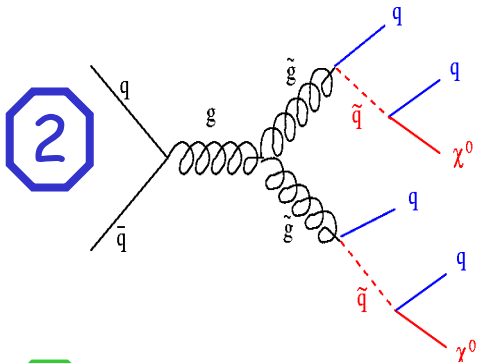
5. Generic squarks/gluinos

DØ has searched for generic squarks-gluinos

1 $m(\tilde{g}) > m(\tilde{q})$
 2 $m(\tilde{q}) > m(\tilde{g})$
 3 $m(\tilde{q}) \approx m(\tilde{g})$

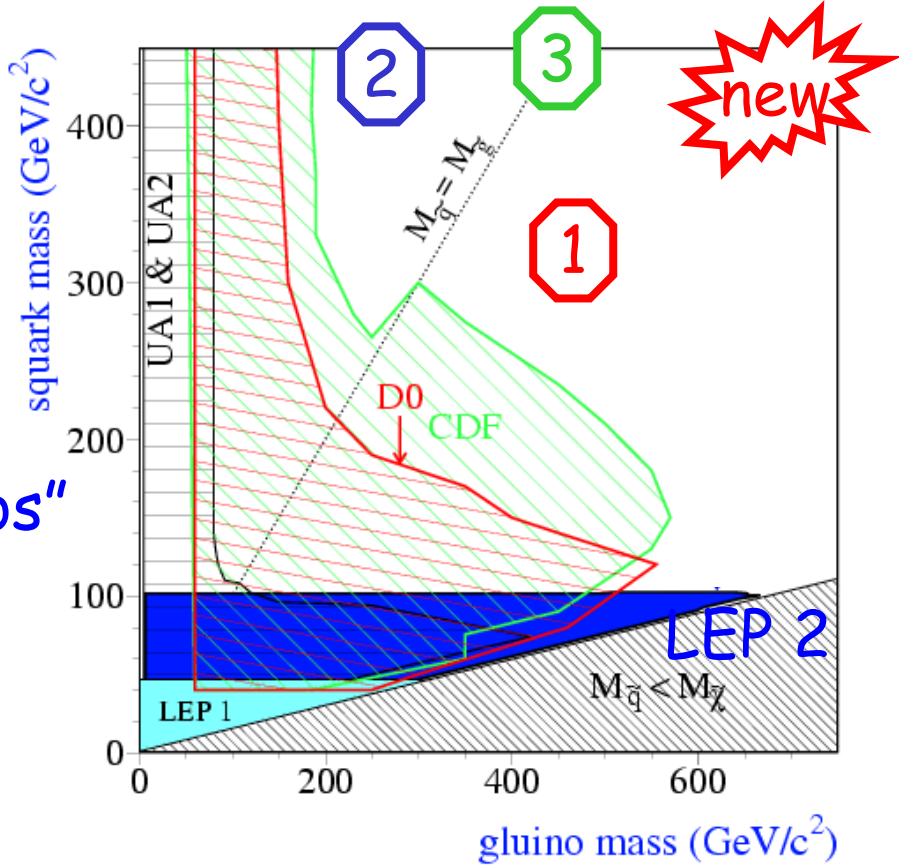


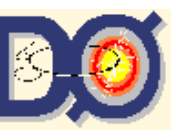
"dijet"



"gluinos"

3 $\tilde{q}\tilde{g} \Rightarrow \geq 3 \text{ jets}$





Generic squarks/gluinos (II)

Example of the "gluinos" analysis

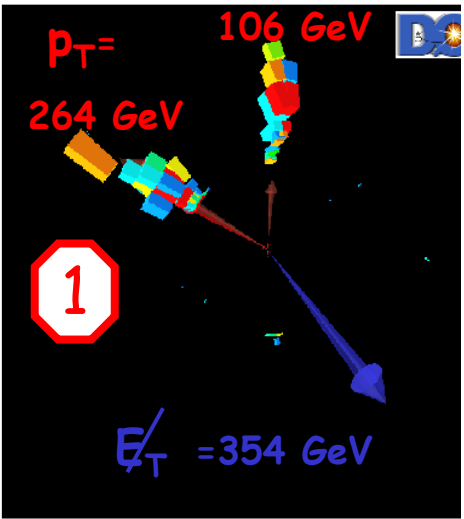
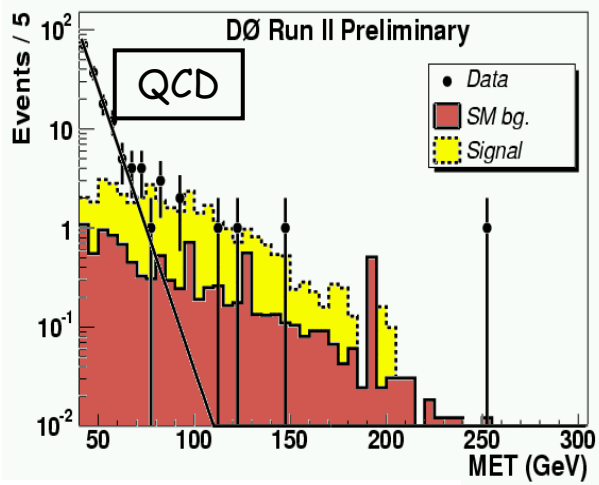
2

- Sum of jet $p_T > 250$ GeV
- Missing $E_T > 75$ GeV

- Main backgrounds left:
- $(Z \rightarrow \nu\nu) + \text{jets}$
 - Top

10 (data) / 7.1 ± 1.6 SM

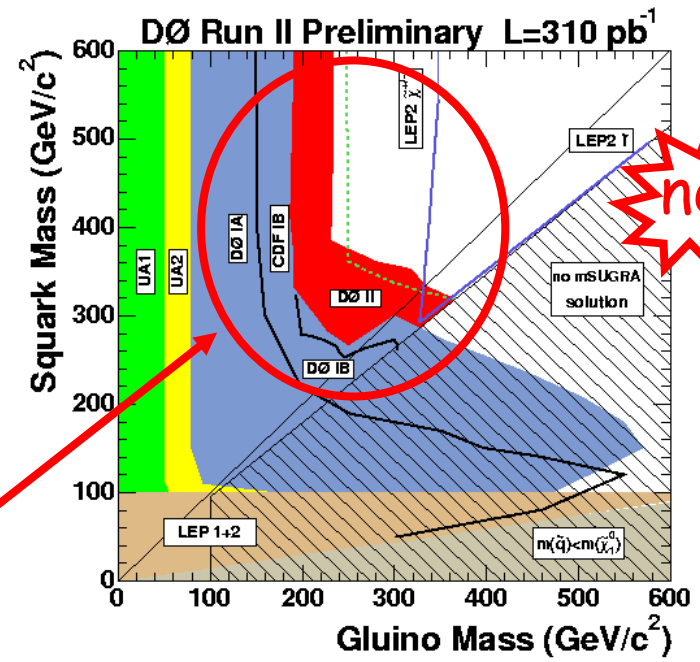
$$\int L dt = 310 \text{ pb}^{-1}$$



1

Significant improvement over CDF-Run I :

- $m(\text{squark}) > 318 \text{ GeV}$ ($m_0 = 25$)
- $m(\text{gluino}) > 233 \text{ GeV}$ ($m_0 = 500$)
- $m(\text{gl}) \sim m(\text{sq}) > 333 \text{ GeV}$



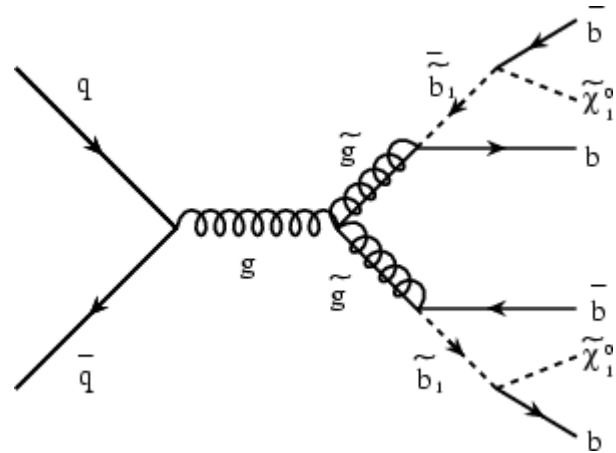


Sbottom

CDF has searched for sbottom in gluino decays (assuming $m_{sb1} \ll m_{squarks}$)

⇒ 4 b-jets + Missing E_T

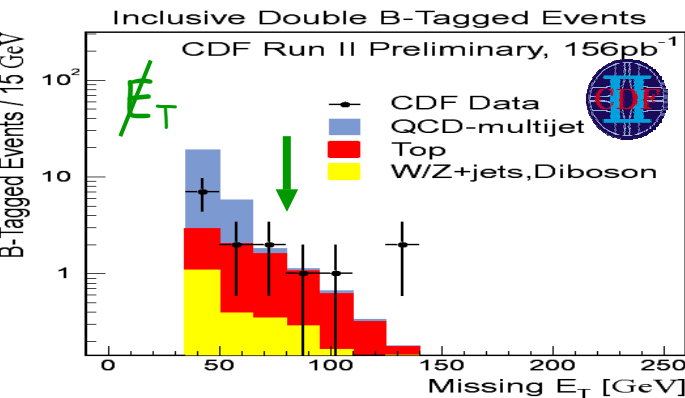
$$\int L dt = 156 \text{ pb}^{-1}$$



Process	Exclusive Single B-Tag	Inclusive Double B-Tag
EWK	$5.66 \pm 0.76(stat) \pm 1.72(sys)$	$0.61 \pm 0.21(stat) \pm 0.19(sys)$
TOP	$6.18 \pm 0.12(stat) \pm 1.42(sys)$	$1.84 \pm 0.06(stat) \pm 0.46(sys)$
QCD	$4.57 \pm 1.64(stat) \pm 0.57(sys)$	$0.18 \pm 0.08(stat) \pm 0.05(sys)$
Total Predicted	$16.41 \pm 1.81(stat) \pm 3.15(sys)$	$2.63 \pm 0.23(stat) \pm 0.66(sys)$
Observed	21	4

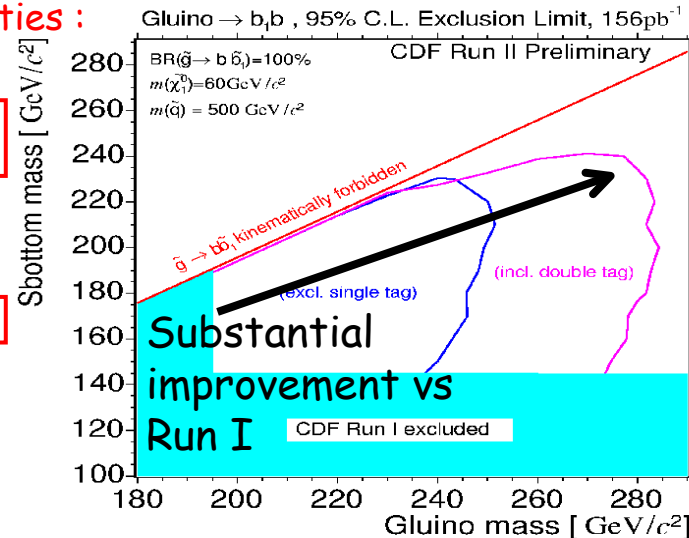
• Main systematic uncertainties :

Luminosity	6.0%
Tagging efficiency	14.0%
Energy scale	25.0%
Trigger efficiency	2.5%
PDF uncertainty	2.0%
Scale factor	-
Cross-section	11.5%
Lepton veto	2.0%
$\Delta\phi$ cuts	0.5%
Total	31.5%



A. Duperrin

La Thuile 2005



Stop

CDF has searched for **stop** in various decays and models



$$\int L dt = 53 \text{ pb}^{-1}$$

CHAMPS
(charged massive particles)

RPC
 $\tilde{t} \rightarrow c \chi_1^0$

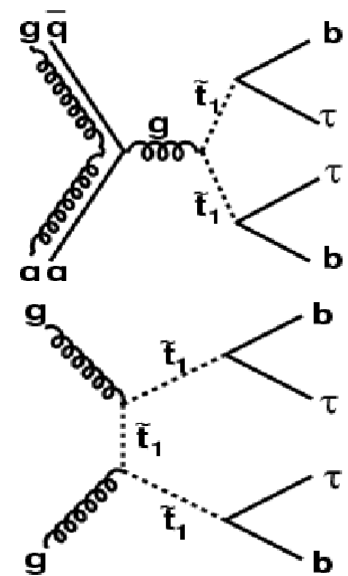
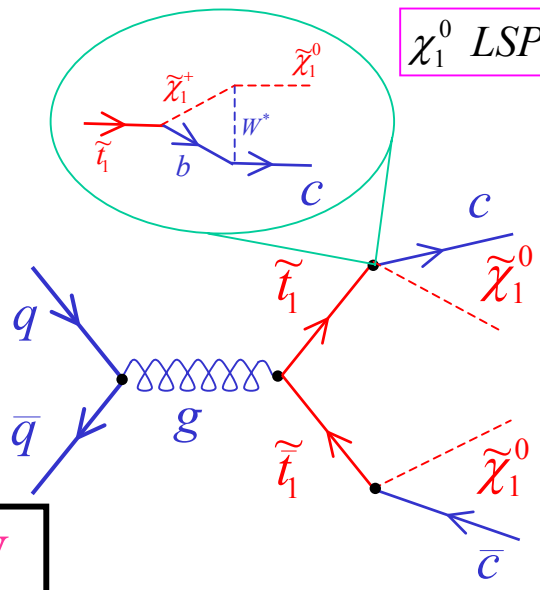
RPV
 $\tilde{t} \rightarrow b \tau$

- Search for long-lived charged particles using Time-of-Flight system
- Particles behave like slow, but high P_T muons

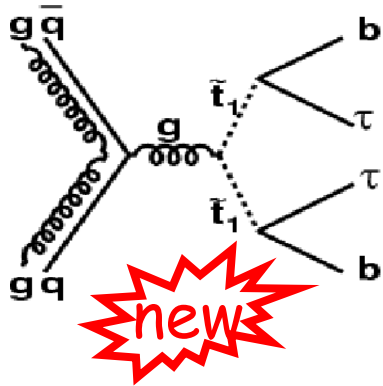
7 (data) / $2.9 \pm 3.1 \text{ SM}$

- Result interpreted for isolated (meta) stable stop \Rightarrow

$$m_{\text{stop}} > 108 \text{ GeV}$$



Stop (RPV $\tilde{t} \rightarrow b\tau$)



$$BR(\tilde{t} \rightarrow b\tau) = 100\%$$

$\Rightarrow \geq 2$ jets + e/μ + τ hadronic + Missing E_T

with :

- $\tau_h \rightarrow$ hadrons + ν
- $\tau_l \rightarrow l\nu_l \nu_\tau$ ($l=e,\mu$)

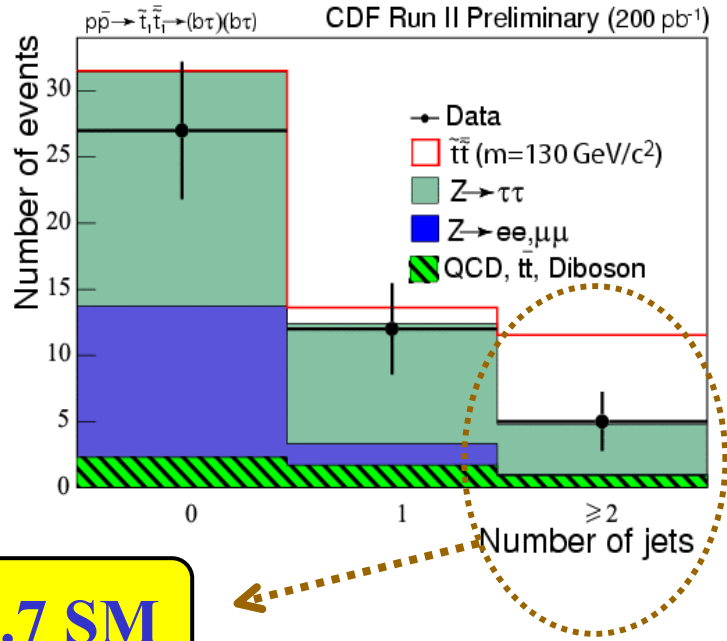
electron or muon $p_T^{e,\mu} \geq 10$ GeV
 + at least one τ_h candidate $p_T^\tau \geq 15$ GeV
 + jets (isolated from e,μ) $E_T \geq 15$ GeV
 + $m(\text{lepton}, \text{Missing } E_T) \leq 35$ GeV
 + e.g. anti Z

Main backgrounds left:

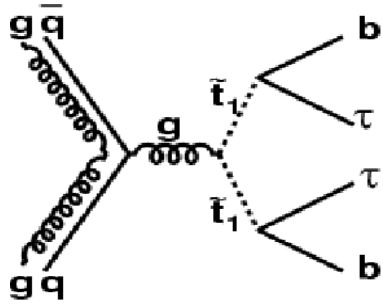
- QCD (bb, γ +jets)
- vector bosons + jets

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

5 (data) / 4.8 ± 0.7 SM



Stop (RPV $\tilde{t} \rightarrow b\tau$) (II)

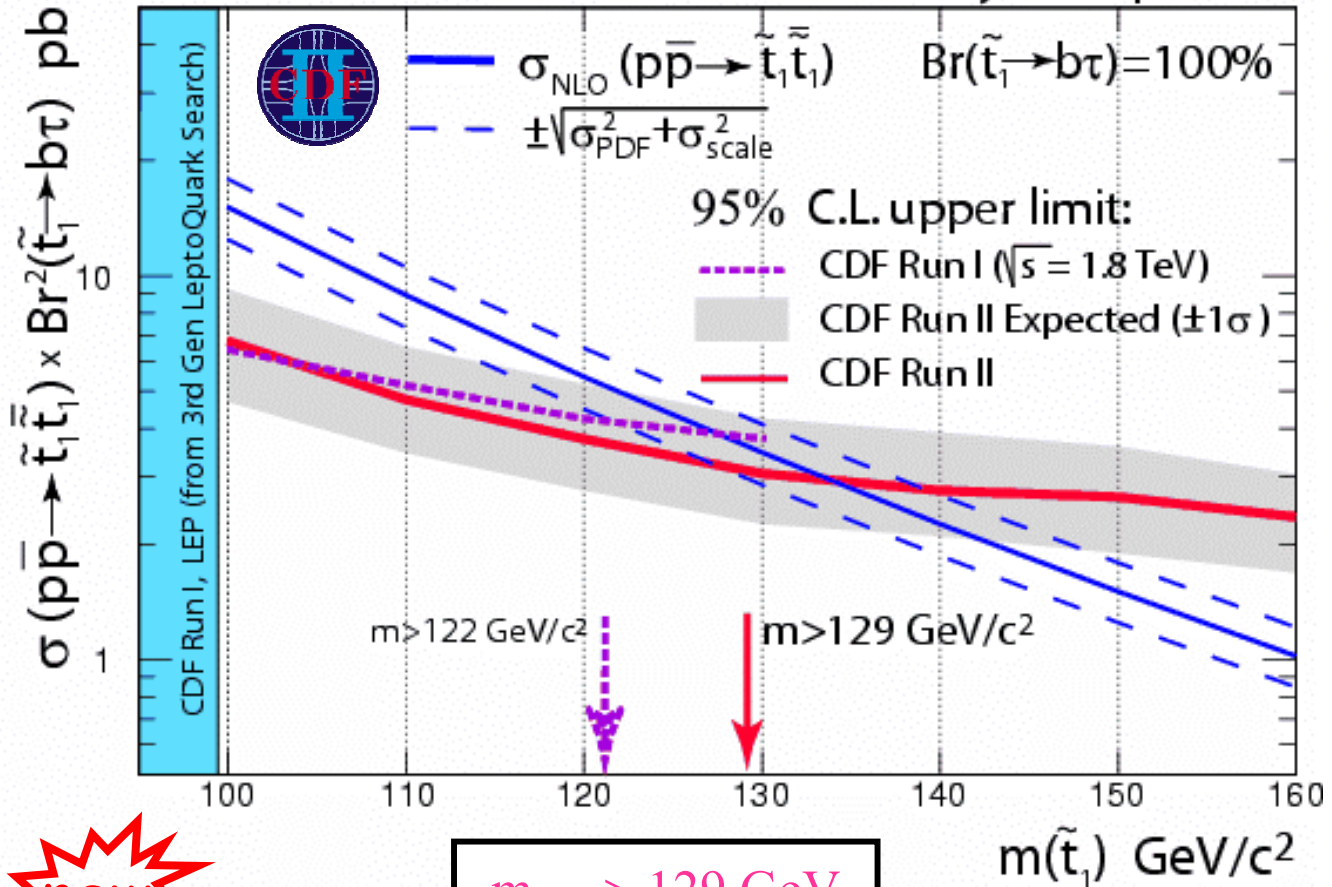


can also be interpreted as pair production of the 3rd generation of scalar leptoquark

LQ $\rightarrow b\tau$

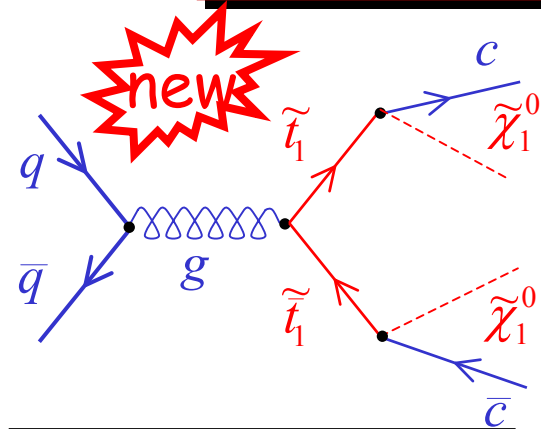
new

CDF Run II Preliminary (200 pb⁻¹)



$m_{\text{stop}} > 129 \text{ GeV}$

Stop (RPC $\tilde{t} \rightarrow c \chi_1^0$)

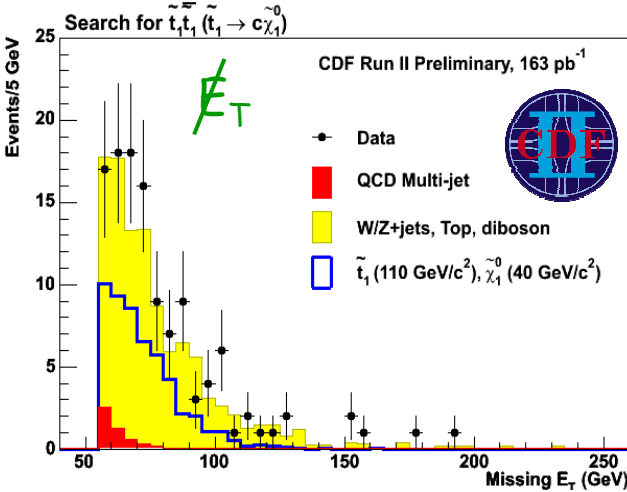


\Rightarrow 2 acoplanar jets + Missing E_T

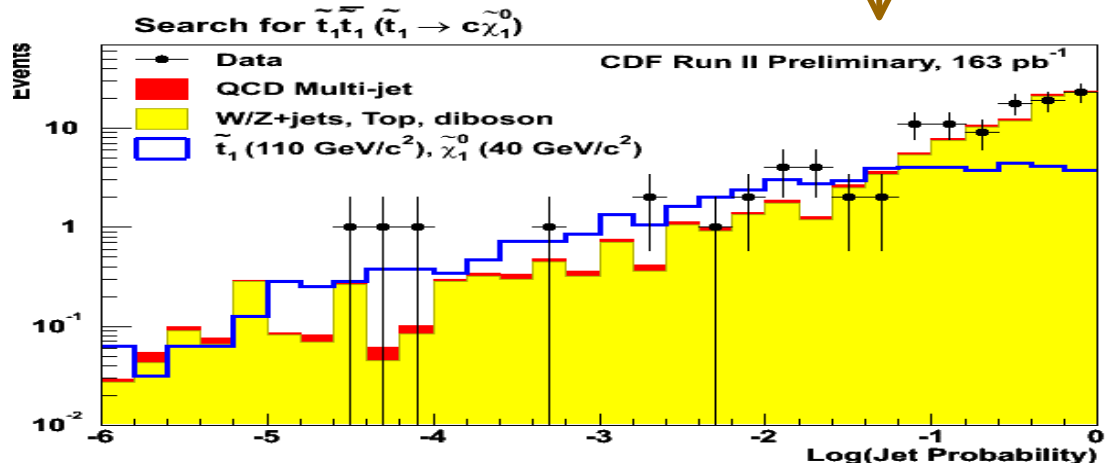
$BR(\tilde{t} \rightarrow c \chi_1^0) = 100\%$ χ_1^0 LSP

Main backgrounds:
($Z \rightarrow \nu\nu$) + 2 jets

- + 2 jets $E_T \geq 35, 25$ GeV (central $|\eta| \leq 1, 1.5$)
- + Missing $E_T \geq 55$ 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

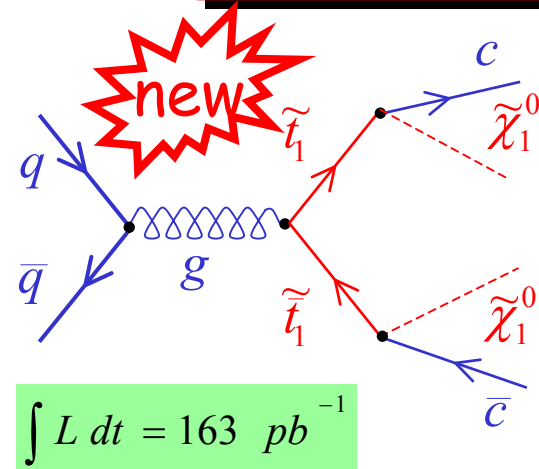


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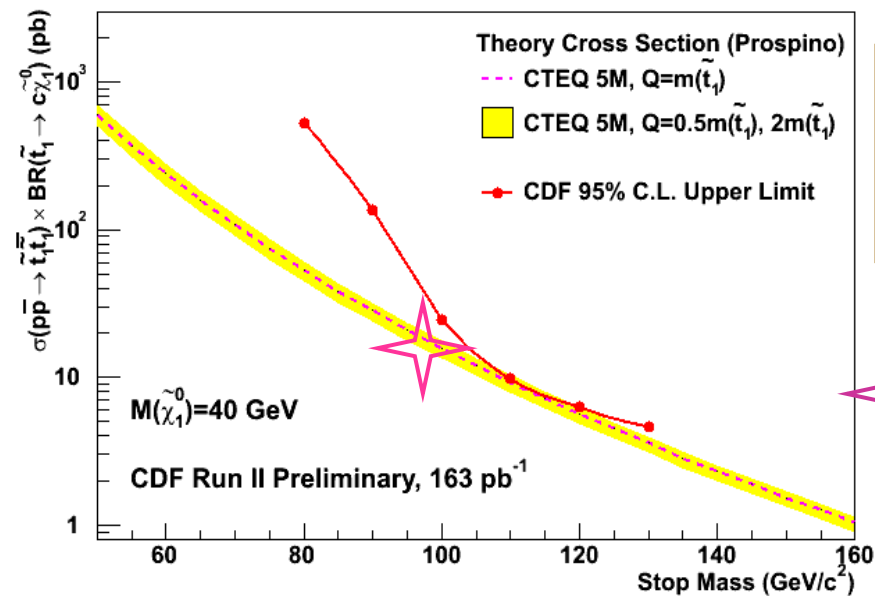
La Thuile 2005

Stop (RPC $\tilde{t} \rightarrow c \chi_1^0$) (II)



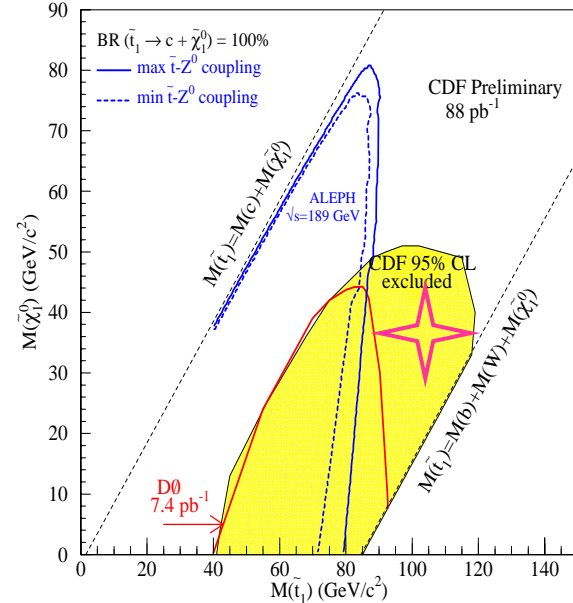
Major sources of **systematic uncertainties**:
background arises from **Jet Energy Scale**
correction (6%-33%) + **tagging** heavy flavor
jets (13%)

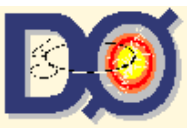
11 (data) / 8.3 ± 2.0 SM



does not
exclude
(yet) Run I

$m_{\chi^0} = 40 \text{ GeV}$
 $m_{\text{stop}} = 100 \text{ GeV}$





Conclusions



- **Tevatron** collider, **CDF** and **D0** are running well
- Analysis shown here based on up to **390 pb⁻¹** (200 pb⁻¹ more data are already being analyzed now!)
- Still only half of **SUSY** particles have been found ...
- But already many new results are derived which **significantly improve on existing limits** (ex : **B⁰_s → μ⁺μ⁻** results starting to constrain **high tan β region**)
- In La Thuile **2009**, expect **8 fb⁻¹** (reasonably optimistic)
- Still **many years** to expand the frontiers of discoveries of New Phenomena for CDF and D0 experiments