Tevatron SUSY Results

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On behalf of the CDF and D0 Collaborations

- **Introduction**
- **Chargino-Neutralino searches**
- **Slepton searches**
- **Gluino-squark searches**
- **Conclusion**

Introduction

SUper SYmmetry

Symmetry of Nature for Boson<->Fermion interchange

- Basic ingredient for unification with gravity (SuperString/M-theory)
- The only nontrivial extension of the Lorentz-Poincaré group
- Provides elegant solution to evade the fine tuning problem

Minimal extension of the SM: MSSM

- every SM particle has ΔS = ±1/2 partner
- R = $(-1)^{3B+L+2S}$ = +1 (SM); = -1 (SUSY)
- 2nd Higgs doublet is needed (treated in the Tevatron Higgs talk)

R = +1

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

$$g \Leftrightarrow \tilde{g}$$

$$\gamma, Z, h, H, A \Leftrightarrow \chi^{0}_{1,\ldots,4}$$

$$W^{\pm}, H^{\pm} \Leftrightarrow \chi^{\pm}_{1,2}$$

R = -1

If SUSY were exact: only 1 additional parameter (μ) needed

SUSY is a broken symmetry since nobody has seen the partners

- many more parameters describe breaking
- with additional hypotheses they are reduced in models treated here, e.g.
  - gravitation mediated (mSUGRA) model to 5 (m_0, $m_{1/2}$, $\tan\beta$, $\mathrm{sgn}\mu$, A_0)
  - gauge mediated (mGMSB) model to 6 (Λ, M_m, N_5, $\tan\beta$, $\mathrm{sgn}\mu$, C_{grav}) parameters

In most cases R-parity is assumed to be conserved:

- since there are severe limits on B- and L-violating processes
- **Then:** SUSY partners are pair produced
  - LSP is stable (neutral and weakly interacting) – dark matter candidate

Basic signature is MET (LSP), + multiple jets or leptons

- from cascade decays of the heavy R=-1 partners

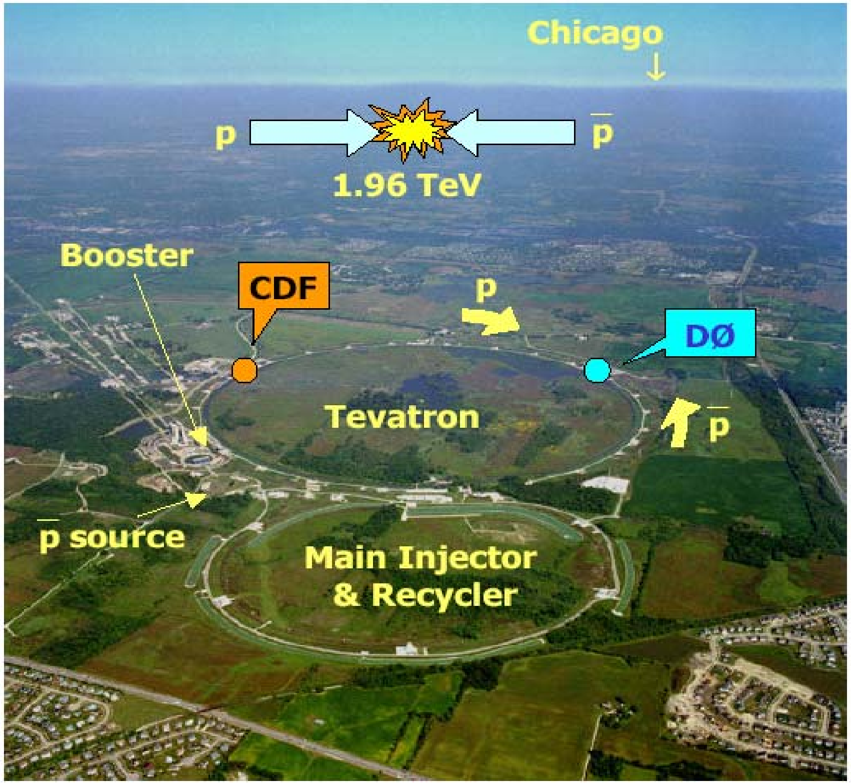
Main bg is t tb, gauge boson production in pair or with jets

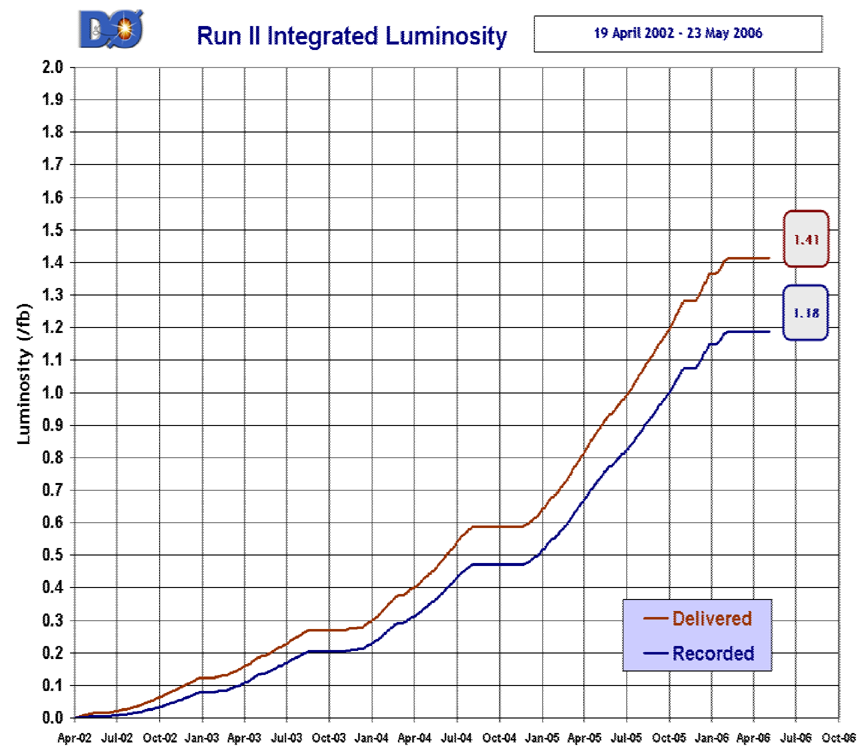
Violation of R-parity is not excluded. This would

- allow single resonant formation of SUSY particles
- produce many more jets/leptons in final state in B- and L-violating processes
- add additional parameters (48 Yukawa couplings)

At the Tevatron both RPC and RPV have been studied

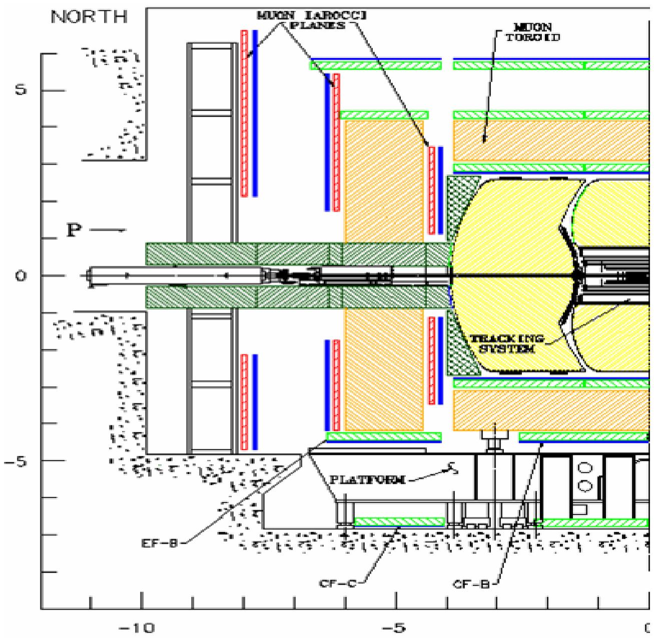
Tevatron



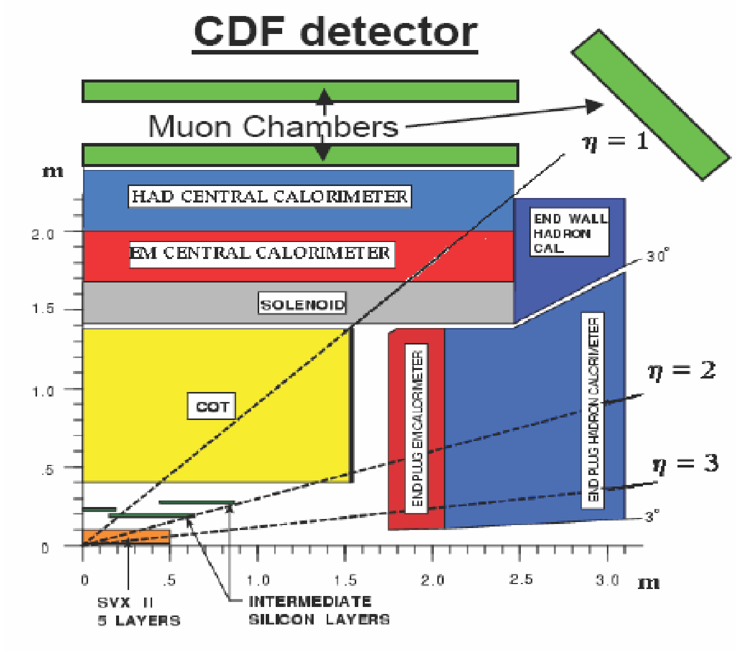


Run IIa ended in March 2006 – full dataset 1.3 fb^{-1} (10x Run I)
Run IIb started in June 2006 – hoping to reach 4-8 fb^{-1} by ~2009

Analyses with L_{int} > 0.3 fb^{-1} are reported here



D0 CDF



Electron ID :
|η|<2.4 (w/ track)
ID eff. ~ 80-90%

Photon ID :
|η|<2.4 (|η|<1.1 w/ CPS)
ID eff. ~ 85%

Electron ID :
|η|<3.6 (|η|<2 w/ track)
ID eff. ~ 80-90%

Photon ID :
|η|<2.8
ID eff. ~ 80%

Jet ID :
cone alg. |η|<4.0

HF tag :
lepton-tag: |η|<2.0
vertex-tag: |η|<2.4

Jet ID :
cone alg. |η|<3.6

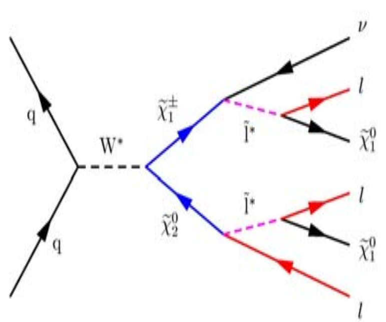
HF tag :
lepton-tag: |η|<1.0
vertex-tag: |η|<1.5

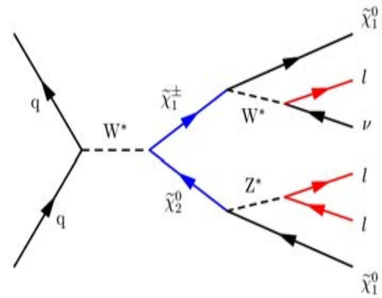
Muon ID :
|η|<2
ID eff. ~ 90-100%

Muon ID :
|η|<1
ID eff. ~ 90-100%

Chargino-Neutralino searches

Chargino ($\chi_1^{\pm}$) and Neutralino (χ_2^0) RPC pair production



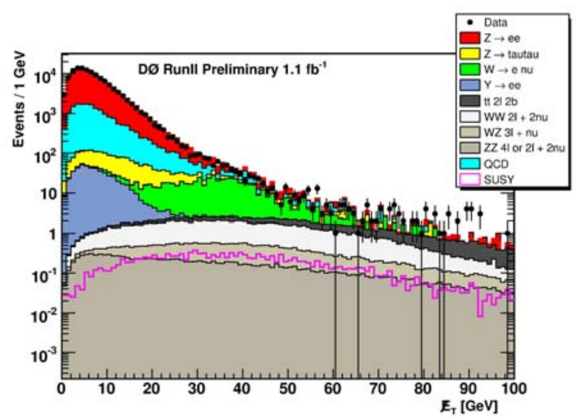


Production also via sq (t-channel)
Decay can be also 2-body
$m_{sl} < m_{\chi 20}, m_{\chi 1+}$

signature: 3l (isolated e,μ,τ or track (3rd l)) + MET
or: 2l (SS e,μ) + MET (if 3rd lepton is too soft)

Both CDF and D0 has searched for this signal on ~1fb^{-1} dataset

Main backgrounds:
Z/γ*+jets
QCD (multijets)
WW,WZ
ttbar

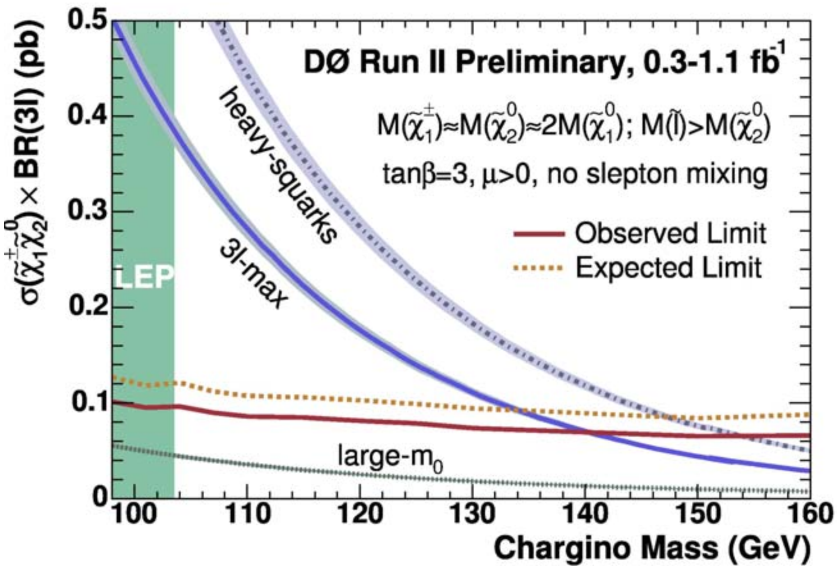


Data are well described at the preselection stage and in control regions
Ex.: D0 eel analysis
$p_T^{e1} > 12$ GeV
$p_T^{e2} > 8$ GeV

Since σ x BR are small several channels are combined

After cuts to supress the background and enhance the signal data are compatible with the expected background in all analyses

DØ Analysis channels	Luminosity (fb^{-1})	Total predicted Background	Observed data
ee+track	1.2	0.82±0.66	0
$\mu\mu$+track	0.3	1.75±0.57	2
eμ+track	0.3	0.31±0.13	0
$\mu^+\mu^+$/ $\mu^-\mu^-$	0.9	1.1 ± 0.4	1
eτ+track	0.3	0.58±0.14	0
$\mu\tau$+track	0.3	0.36±0.13	1



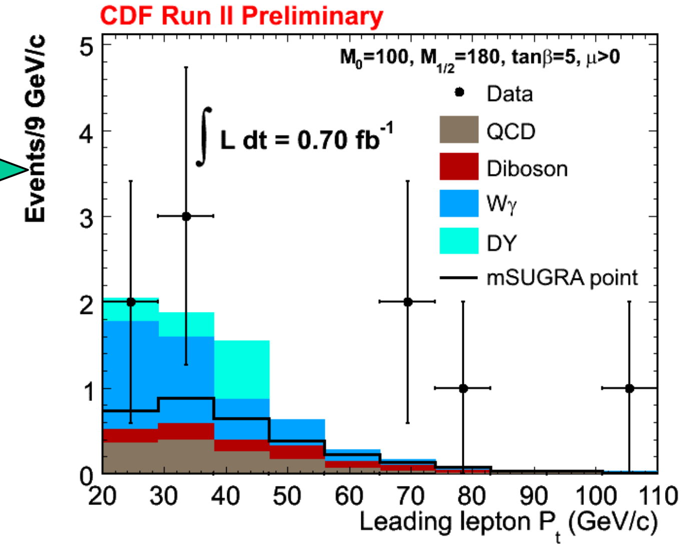
Chargino mass limit in mSUGRA inspired models considerably improved

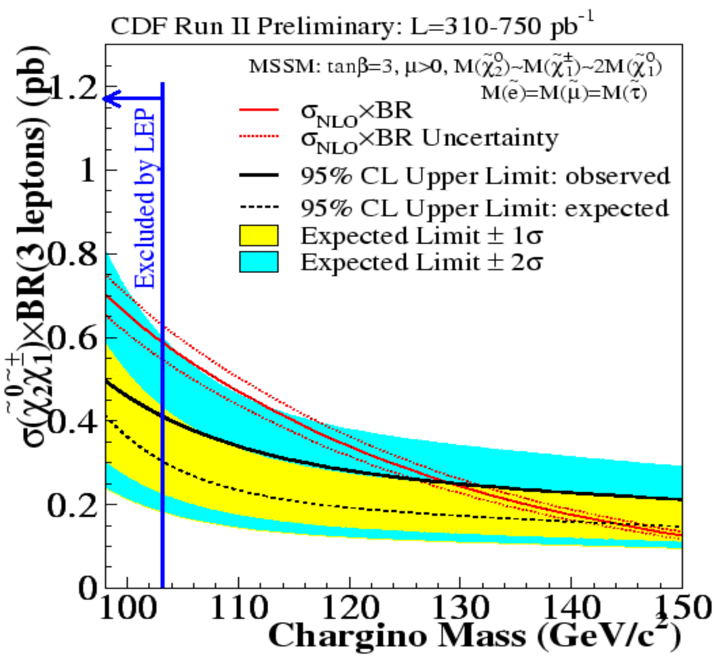
3l-max: M_{sl} slightly above $M_{\chi 20}$ and M_{sl} degenerate: $M_{\chi+}$ > 140 GeV

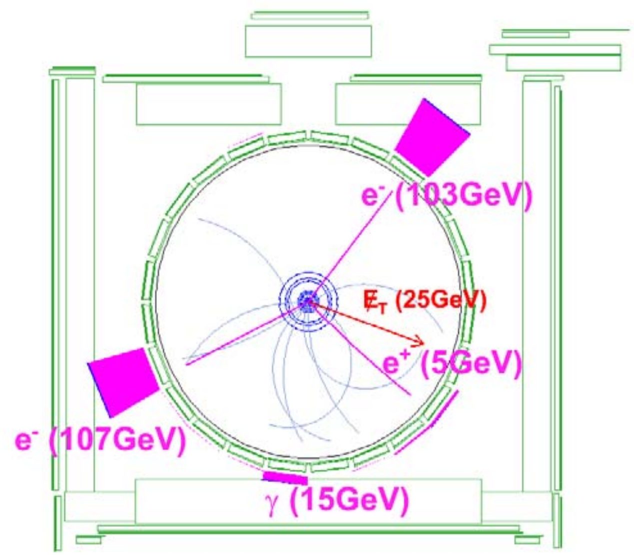
heavy-sq: destructive t-channel contribution minimal: $M_{\chi+}$ > 155 GeV

For large m_0: sl's are heavy and small BR into leptons

CDF Analysis channels	Luminosity (pb^{-1})	Total predicted Background	Observed data
$e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$	710	6.80±1.00	9
$\mu\mu$ +e/μ **(low-p_T)**	310	0.13±0.03	0
ee+track	610	0.48±0.07	1
ee + e/μ	350	0.17±0.05	0
$\mu\mu$ +e/μ	750	0.64±0.18	1
μe +e/μ	750	0.78±0.15	0

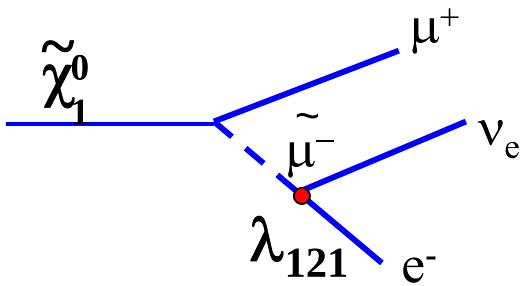






Chargino ($\chi_1^{\pm}$) and Neutralino (χ_2^0) pair production

Lightest neutralino (χ_1^0) is allowed to decay via RPV $\lambda_{ijk} L_i L_j E^c_k$



More leptons (less MET) than in RPC case
→ better sensitivity

One assumes 1 non-zero coupling at a time
λ_{121}, λ_{122} (CDF,D0), λ_{133} (D0)
sufficiently large that decay w/o displaced vertex

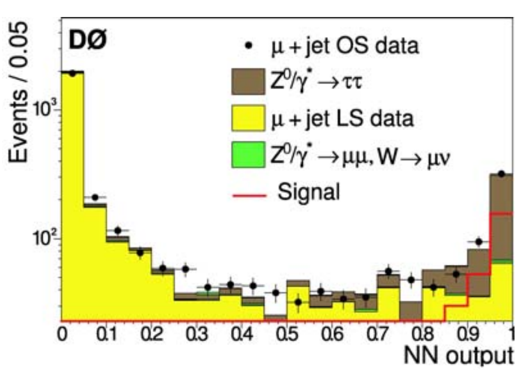
CDF has searched events with 4 leptons has found 0 with expected bg: 0.008±0.004

D0 has found 0 events

in channels:	**eel**	**μμl (l= e, μ)**	**eeτ**
with bg:	**0.9 ±0.4**	**0.4 ±0.1**	**1.3 ±1.8**

mSUGRA limits by D0 (L = 0.36 fb^{-1})
CDF has obtained somewhat smaller limits

τ identification validated in Z→ τ τ

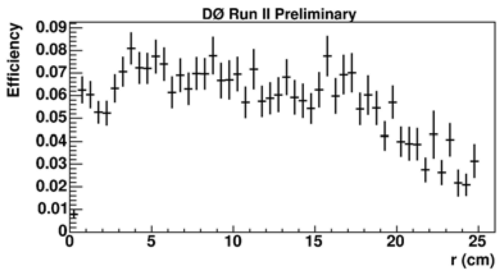


Coupling	sign(μ)	$m(\tilde{\chi}^0_1)$	$m(\tilde{\chi}^{\pm}_1)$
λ_{121} ($m_0 = 1$ TeV, $\tan\beta = 5$)	>0	119	231
λ_{122}	>0	118	229
λ_{133}	>0	86	166
λ_{121} ($m_0 = 1$ TeV, $\tan\beta = 5$)	<0	117	234
λ_{122}	<0	115	230
λ_{133} ($m_0 = 100$ GeV, $\tan\beta = 5$)	>0	105	195
λ_{133} ($m_0 = 100$ GeV, $\tan\beta = 20$)	>0	115	217

Longlived neutralino (χ_1^0) pair production

If λ_{122} sufficiently small χ_1^0 may live long producing a displaced vertex in 5-20 cm from the interaction points by the $\mu\mu$ pair
NuTeV has reported 3 events of $\mu\mu$ pairs

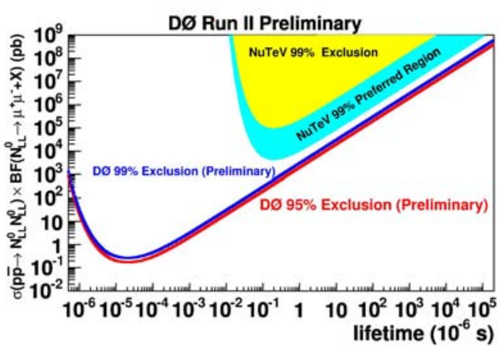
D0 has adequate vertex reconstruction acceptance x efficiency determined with K_s



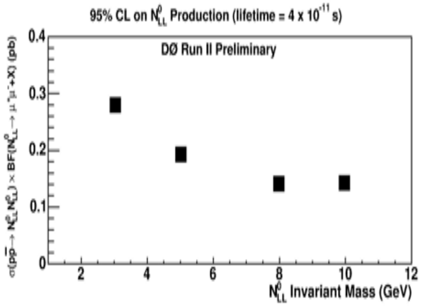
Observed: 0 events
2 muons p_T>10 GeV, cosmic veto, good vertex in 5 < r_T < 20 cm
DCA > 0.01 from any other vertex
Background: 0.75±1.6 (w/ syst) estimated from data extrapolating from 0.3 < r_T < 5 cm and inverting the DCA cut
Systematics estimated by changing the selection criteria

The obtained 95(99)% xsection upper limit excludes the interpretation of the NuTeV events as being longlived neutralinos

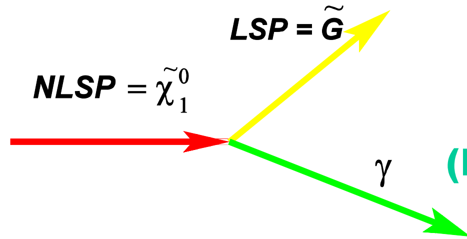
$M_{\chi 10}$=5GeV



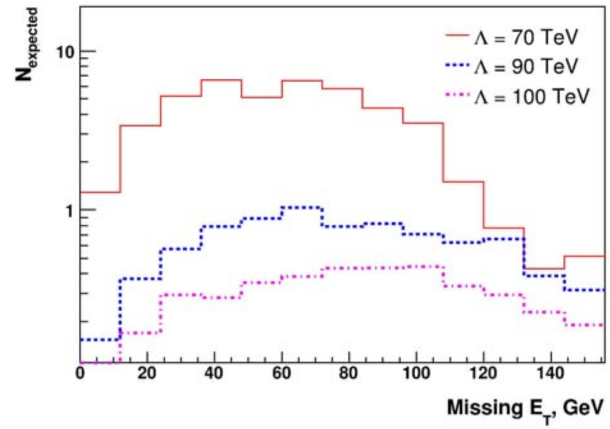
L=0.38 fb^{-1}



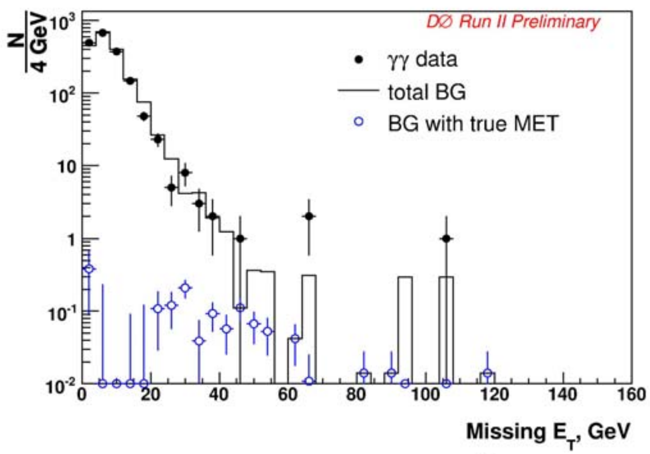
GMSB



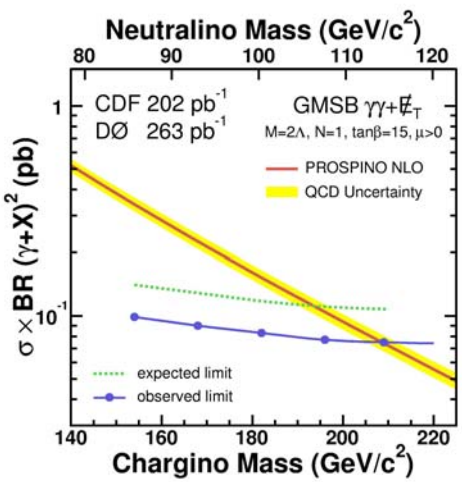
Expected signal
vs M=2Λ messenger mass scale
(N_5=1, tanβ=15, μ>0, C_{grav}→short lifetime)



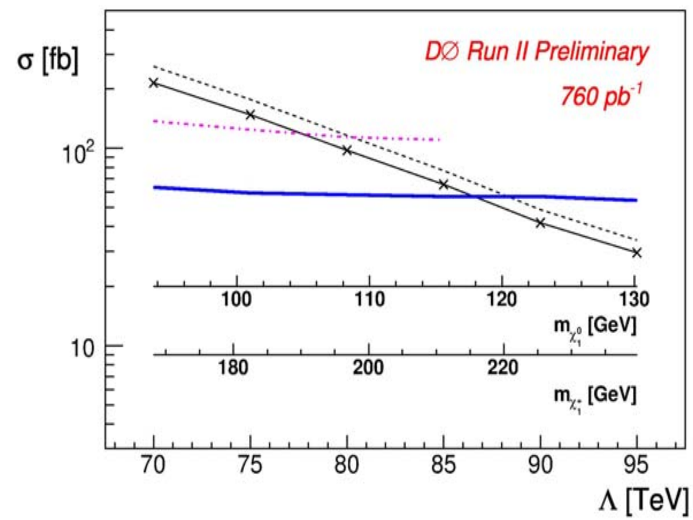
Select 2 photons p_T > 25 GeV (1 w/ PS hit)



Signal is at high MET:
MET > 45 GeV
Data: 4 Bg: 2.1±0.7

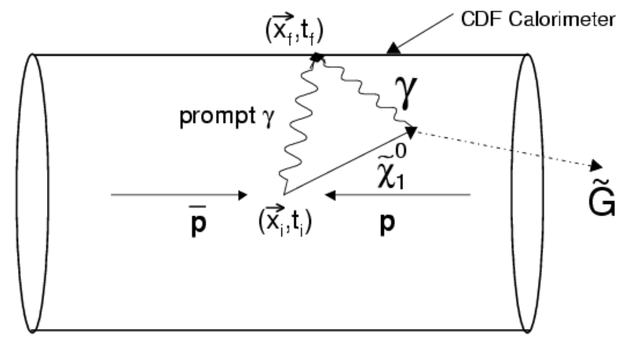


Previous CDF-D0 combined limit improved by D0:
$m_{\chi10}$ > 120 GeV
$m_{\chi1\pm}$ > 220 GeV



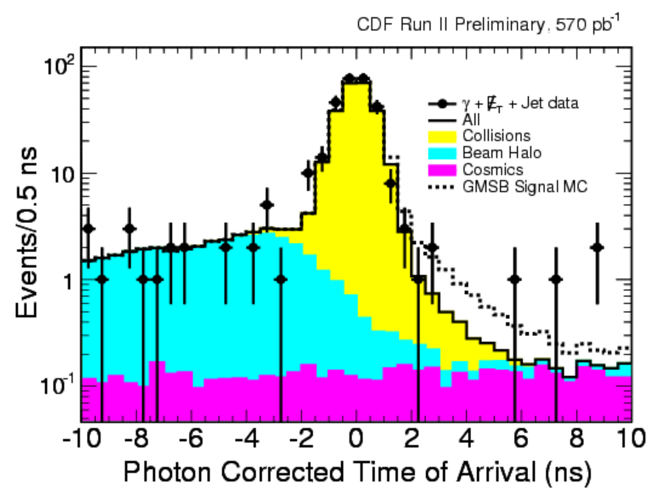
GMSB

N_5=1, tanβ=15, μ>0, M=2Λ

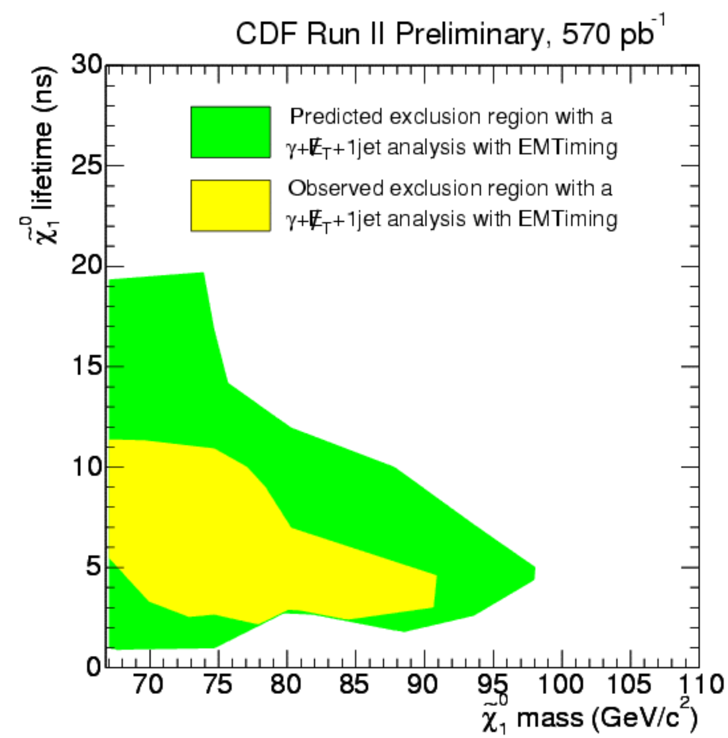


CDF searches for longlived NLSP χ_1^0

by looking for a « late » photon of p_T>30 GeV
in the calorimeter
accompanied with MET (G) (> 50 GeV) and
with a jet (from the other SUSY particle) of p_T>30 GeV



t_0 is the arrival time of prompt particles in the calorimeter
time resolution ~0.6 ns

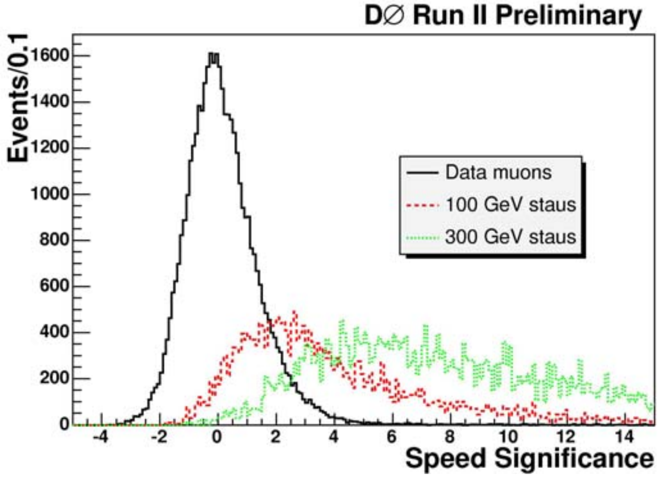


With an optimal timing cut of 1.5 ns
one observes 10 data events
expecting 7.6 ±1.9 background events

AMSB

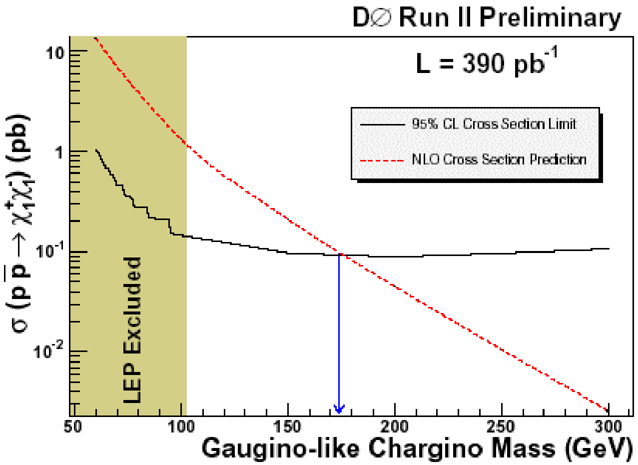
D0 has studied chargino pair production if $M_{\chi\pm} - M_{\chi 10}$ <~ 150 MeV

These charginos live long (CMSP)
appear as muons in the detector,
but they are slower: v~p/E
→arrive later in the muon detector
Speed significance (sps): $(1-v)/\sigma_v$ (σ_t~2-3ns)



Select: 2 muons p_T>15 GeV
at least 1 muon isolated
cosmic ray veto
sps > 0 for both muon
cut optimized in the $M_{\mu\mu}$ vs sps_1*sps_2 plane
depending on the CMSP mass

Background are muons of missmeasured time: estimated from data Z→ μ μ



Data is compatible with expectation of the SM
No event observed beyond M_{CMSP}>100 GeV
typical background: 0.60±0.05
(depending slightly on the mass)

Exclude $M_{\chi\pm}$ < 174 GeV (gaugino-like)

Slepton searches

GMSB

D0 limits for CMSP is applied to long lived stau (NLSP) pair production

With the parameters:

Λ = 19→100 TeV,

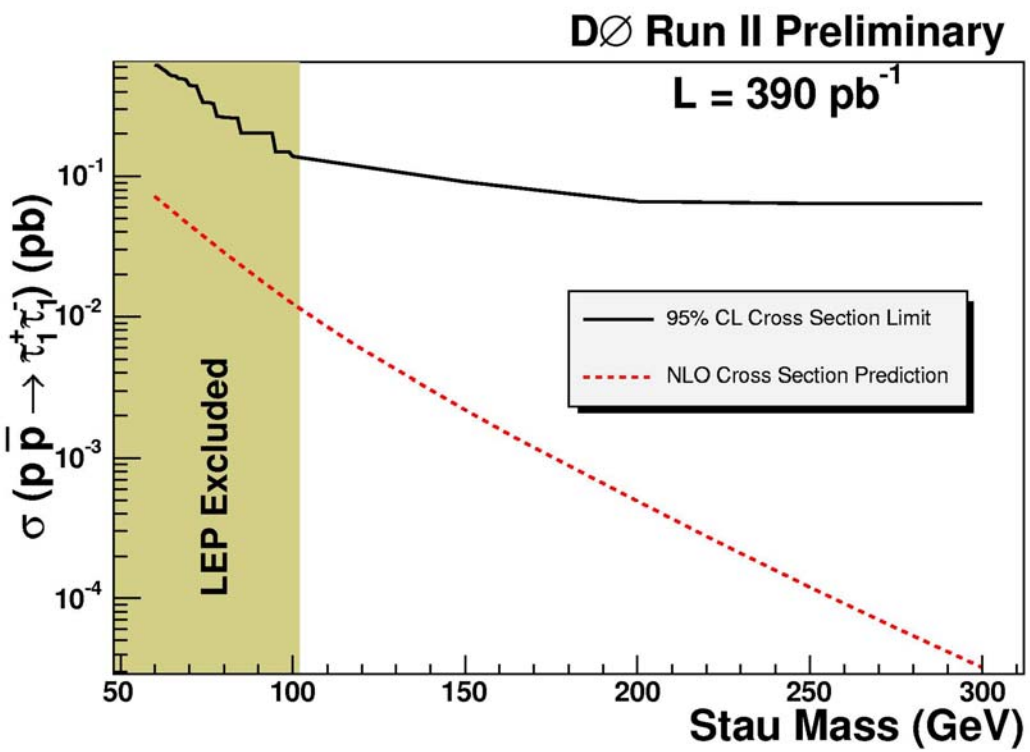
M_m = 2 Λ,

N_5=3,

$\tan\beta$=15,

μ>0,

C_{grav}=1

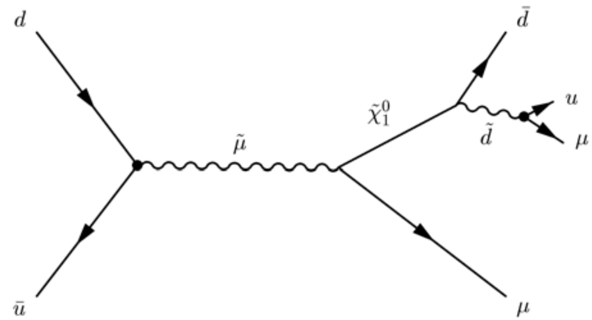


95% upper limits

of stau pair production

no mass limit yet

Resonant smu/snu$_\mu$ search in RPV production and LSP (χ_1^0) decay via non-zero $\lambda'_{211}L_2Q_1D^c_1$ term

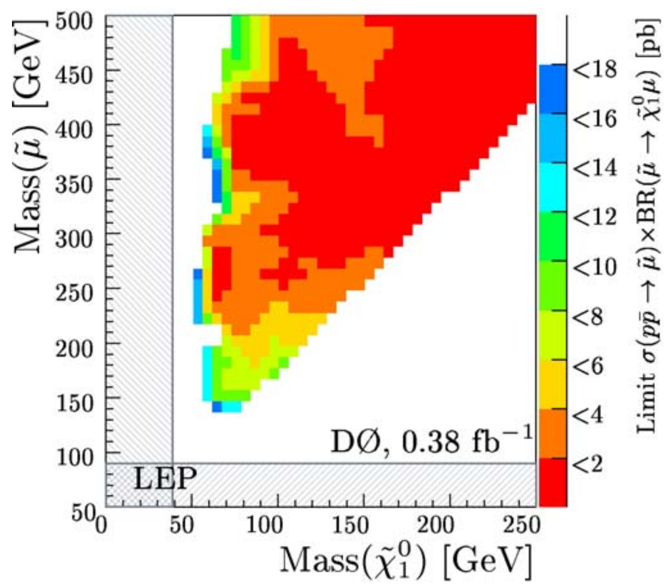


$$d\bar{d} \to \tilde{\nu}_\mu \to \chi_1^\pm \mu^\mp \qquad \chi_1^\pm \to \chi_1^0 qq'$$

$$d\bar{u} \to \tilde{\mu} \to \chi_{2,3,4}^0 \mu \qquad \chi_{2,3,4}^0 \to \chi_1^0 qq'q''\ldots$$

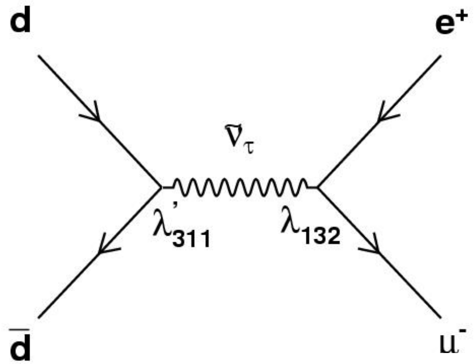
$$d\bar{u} \to \tilde{\mu} \to \chi_1^0 \mu \qquad \chi_1^0 \to \mu q\bar{q}$$

Select :
2 isolated muons
p_T^1>15, p_T^2>8 GeV
>1 jet p_T>15 GeV
Reconstruct:
χ_1^0 (leading μ +2j)
sl (2 μ+all jet)
No signal observed:
good agreement with SM
Exclusion for mass and coupling derived

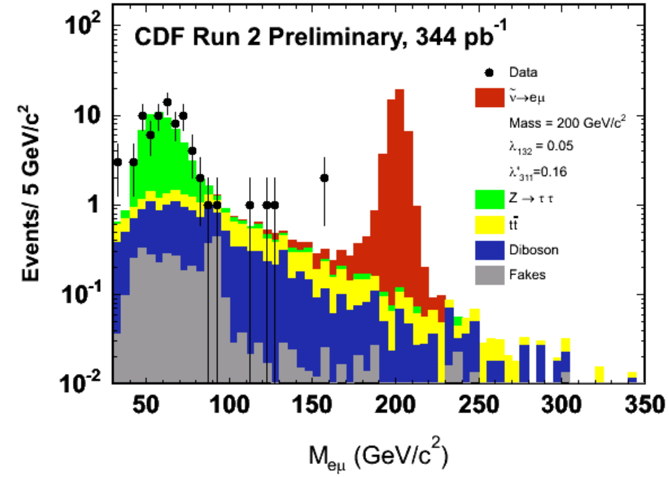


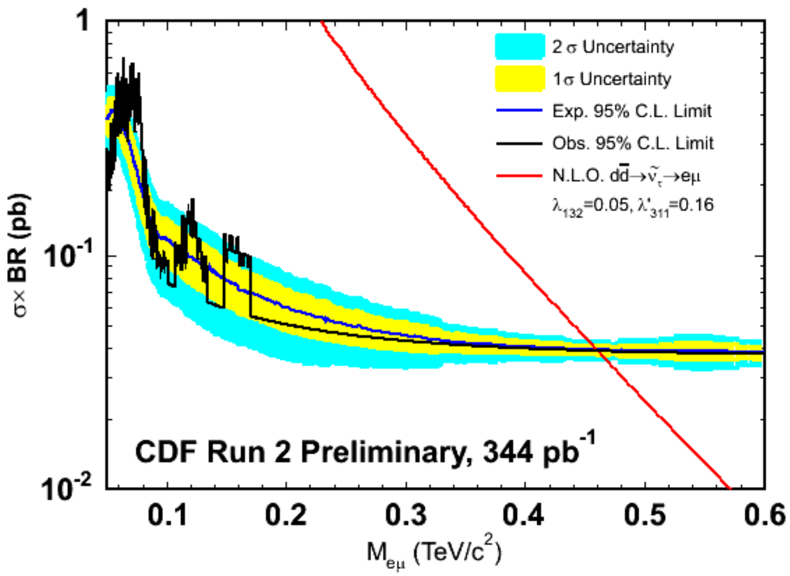
Max. excluded sl mass [GeV]	For min. λ_{211} coupling strength
210	0.04
340	0.06
363	0.10

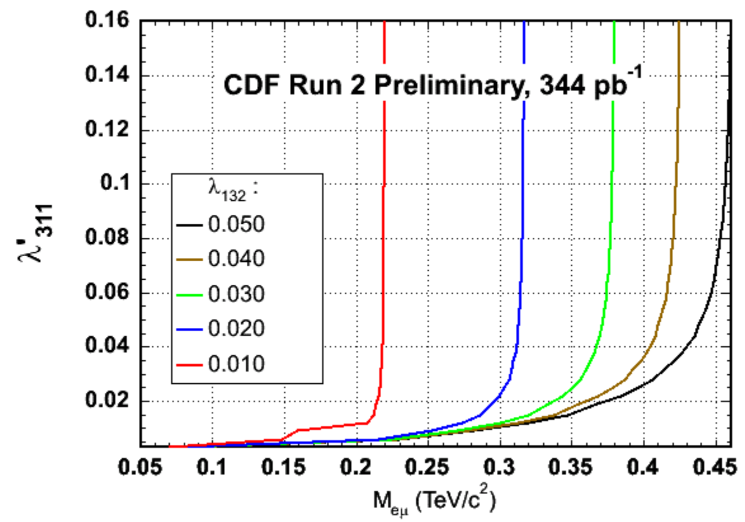
Resonant snu$_\tau$ search in RPV production ($\lambda'_{311}L_3Q_1D^c_1$) and decay ($\lambda_{132}L_1L_3E^c_2$)



Select :
Isolated muon p_T>20 GeV
electron p_T>20 GeV
Reconstruct: snu$_\tau$ (e-mu)
No signal observed:
good agreement with SM
Exclusion for mass
and coupling derived







Gluino-squark searches

Search for generic Squarks and Gluinos in the multi-jet -- MET topology (D0)

Search for high MET and $H_T = \Sigma_{jet} E_T$ events in 3 regions of mSUGRA

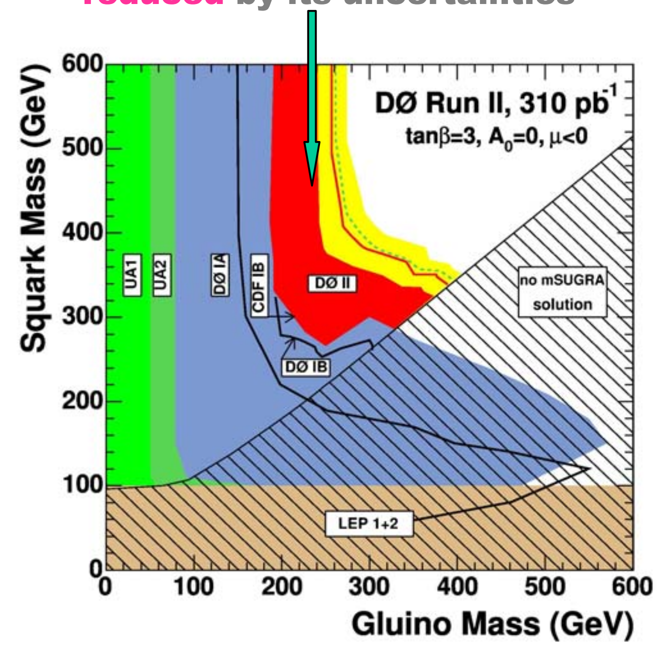
Small m_0: $M_{sq} < M_{gl}$ 2 acoplanar jets (>60,50 GeV) H_T>275, MET>175 GeV
$M_{sq} \sim M_{gl}$: 3 jets (>60,40,30 GeV) H_T>350, MET>100 GeV
Large m_0: $M_{gl} < M_{sq}$ 4 jets (>60,40,30,20 GeV) H_T>225, MET> 75 GeV

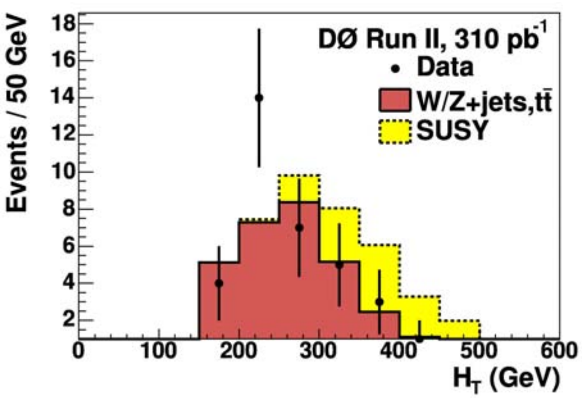
Data and SM bg are in agreement

	Data	SM bg
2jet:	6	$4.8^{+4.5}_{-2.1}$
3jet:	4	$3.9^{+1.5}_{-1.3}$
4jet:	10	$10.3^{+2.4}_{-2.9}$

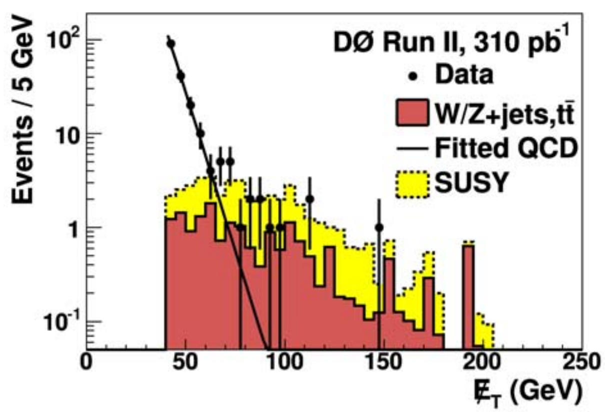
Calculate limits:

Theoretical cross section reduced by its uncertainties





"3-jet"



"4-jet"

M_{gl} > 241 GeV/c^2 ; M_{sq} > 325 GeV/c^2

1^{st} and 2^{nd} generation Squarks and Gluinos in the jet-MET topology (CDF) optimized for 3 jets

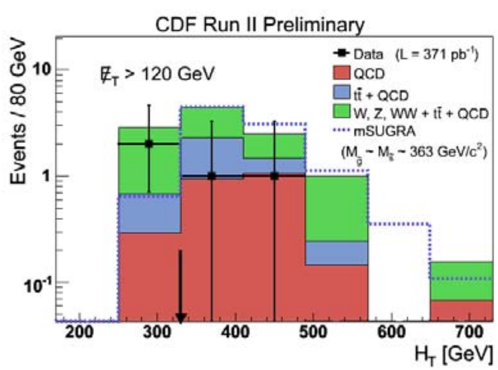
A: $E_T^1 >$ 95 GeV ; $E_T^2 >$ 55 GeV ; $E_T^3 >$ 25 GeV ; MET > 75 GeV ; $H_T >$ 230 GeV
B: $E_T^1 >$ 120 GeV ; $E_T^2 >$ 70 GeV ; $E_T^3 >$ 25 GeV ; MET > 90 GeV ; $H_T >$ 280 GeV
C: $E_T^1 >$ 140 GeV ; $E_T^2 >$ 100 GeV ; $E_T^3 >$ 25 GeV ; MET > 120 GeV ; $H_T >$ 330 GeV

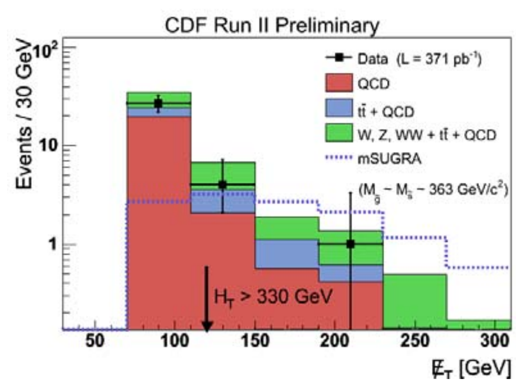
$M_{\tilde{g}}$

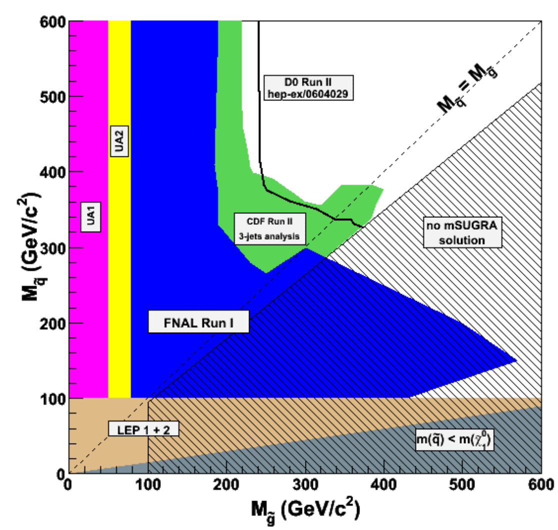
Data and MC agrees in all 3 zones

	ZONE A	ZONE B	ZONE C
DATA	185	40	2
MC	211 ± 7 ± 44	56 ± 3 ± 14	8.2 ± 1.2 ± 2.6

ZONE C





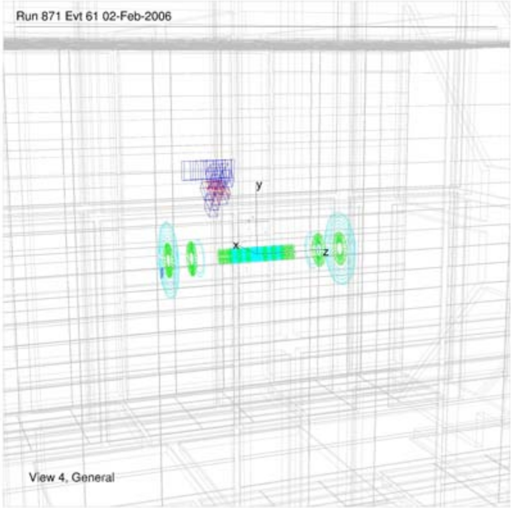


$M_{gl} >$ 387 GeV/c² (when $M_{gl} \sim M_{sq}$)

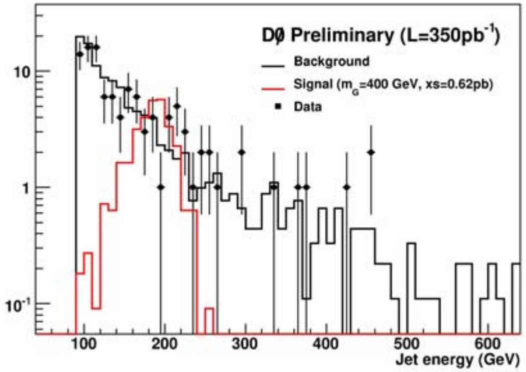
Stopping gluinos

In Split-SUSY s-scalars are heavy
gluinos are light, copiously produced
longlived: fragment into (charged) R-hadrons
loose energy - stop in the detector and decay

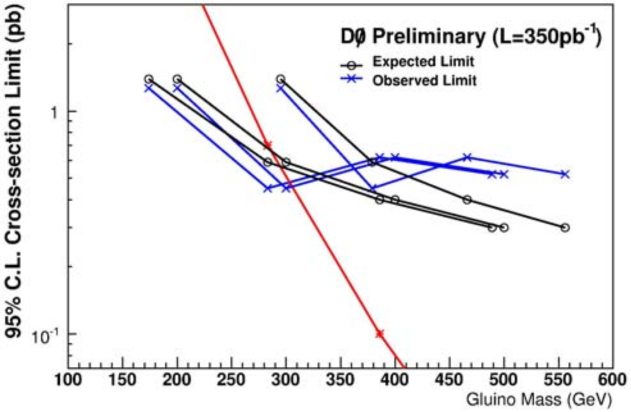
Search for $\tilde{g} \rightarrow g + \chi_1^0$ decay
w/o underlying event



Data selection
- Trigger on jet
- No signal in luminosity monitors
- No reconstructed vertex
- No reconstructed cosmic muons
- Jet in $|\eta|<0.9$, 90 GeV < E < 900 GeV
- η and φ widths of the jet >0.08 (wide jets)
- Background mainly due to cosmic muons w/o reconstructed muons
- Estimated from narrow jet events: P(nomu) = 0.1



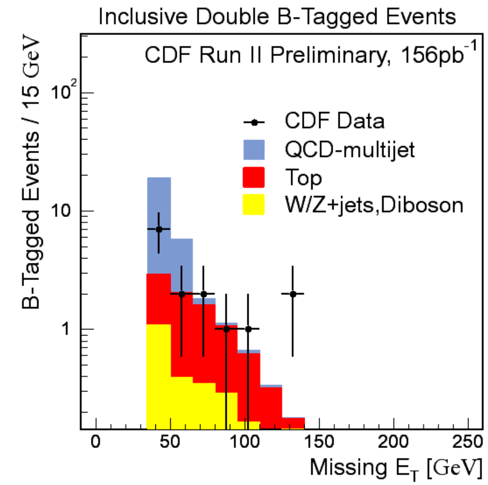
No excess in data
over expected background
Determine cross section
and mass limit vs
$M_{\chi 10}$=50,90,200 GeV



Search for s-bottom quarks from gluino pair-production

$p\bar{p} \to \tilde{g}\tilde{g};\ \tilde{g} \to \tilde{b}+b;\ \tilde{b} \to b+\chi_1^0$ **4 b-jets and MET**

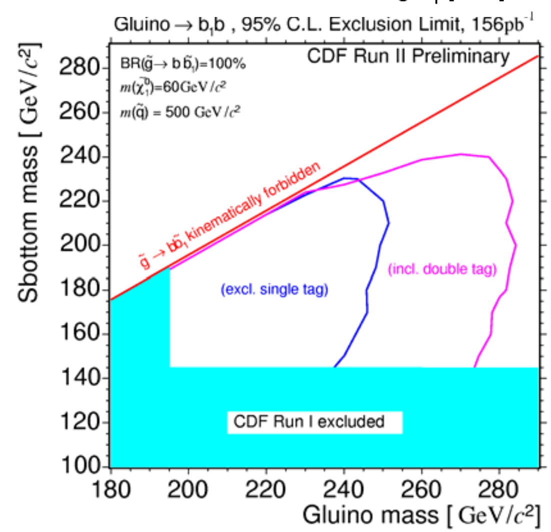
Require: 3 jets with E_T>15 GeV, $|\eta|$<2
at least 2 jets with b-tag
MET>80 GeV



Data agrees with SM background
Verified in 3 control regions, dominated by W/Z+jet, QCD and top production

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

Table 24: Number of expected and observed events in signal region.



Published limit is based only on inclusive double b-tag events

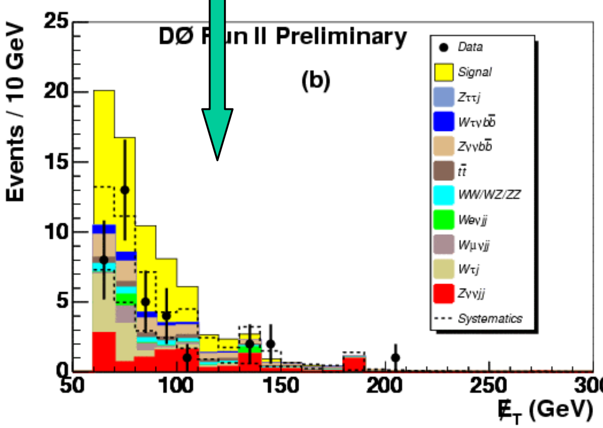
Search for pair-production of s-bottom quarks

$$p\bar{p} \rightarrow \tilde{b}\,\tilde{\bar{b}};\ \tilde{b} \rightarrow b + \chi_1^0$$

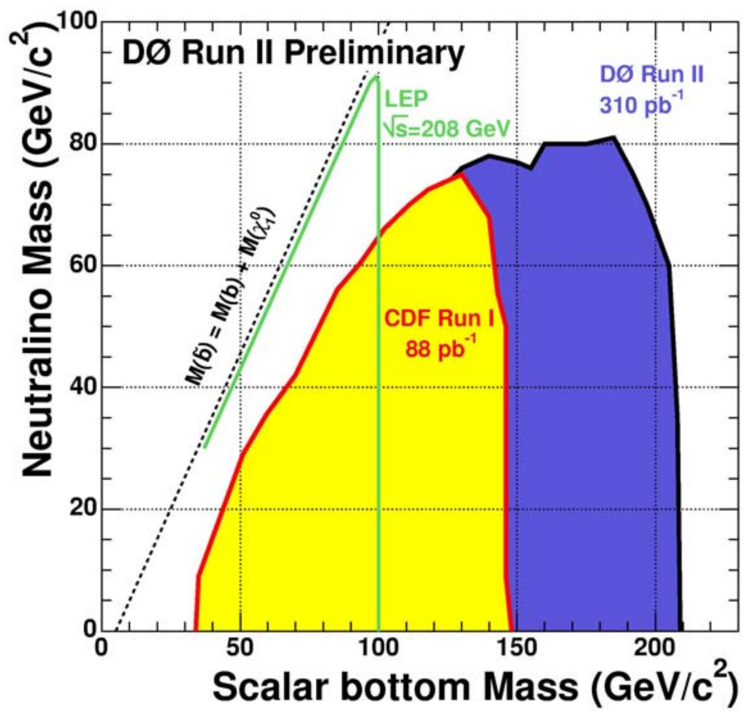
2 acoplanar b-jets and MET

Require: 2 jets with acoplanarity Δφ< 165°
E_T^1>40 GeV, E_T^2>15 GeV, $|\eta^1|$<0.9
at least 1 jet with b-tag
MET>80 GeV
Isolated lepton veto

Data agrees with SM background w/ and w/o b-tagging

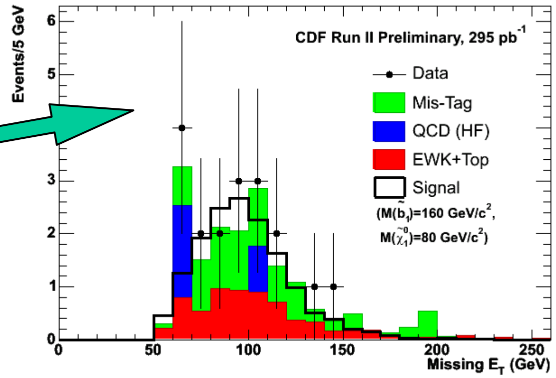


Final E_T^j and MET cuts are increased as function of the s-bottom mass

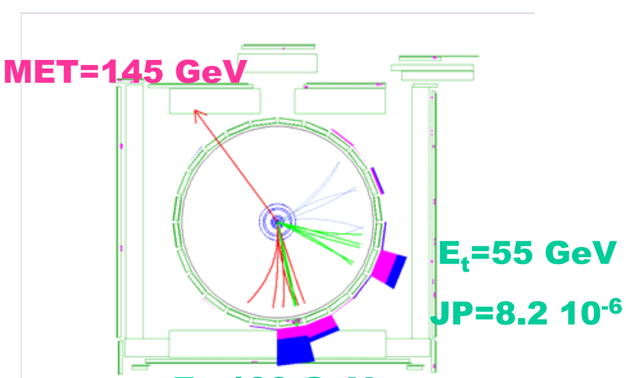


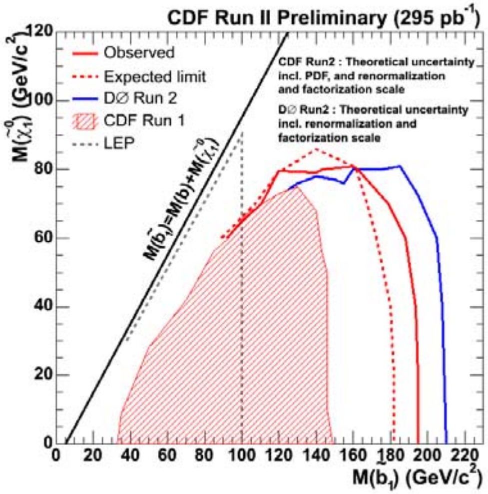
CDF selection for the same channel: $p\bar{p} \rightarrow \tilde{b}_1\bar{\tilde{b}}_1 \rightarrow b\tilde{\chi}_1^0\bar{b}\,\tilde{\chi}_1^0$

- 2 or 3 jets
  - E_t cuts on 1st and 2nd leading jets vary depending on M_{sb}
- MET>50 GeV or higher depending M_{sb}
- 1st and 2nd leading jets not back-to-back
- Jets not pointing along direction of MET
- ≥1 jet tagged JetProbability < 1%



	Low M_{sb}	Medium M_{sb}	High M_{sb}
SM (Total)	55.0±7.24	17.8±2.31	4.67±0.67
Data	60	18	3



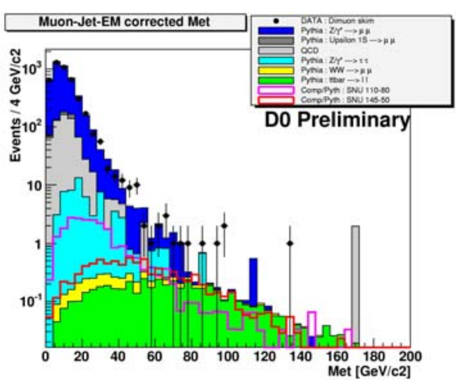


Search for pair-production of stop quarks decaying into b+l+snu (l=e,μ)

Stop may be the lightest squark due to large mixing thanks to large top mass
Its 3-body decay into b+l+snu through virtual chargino dominates for light snu
D0 has studied bbeμ+MET and bbμμ+MET final states in MSSM framework

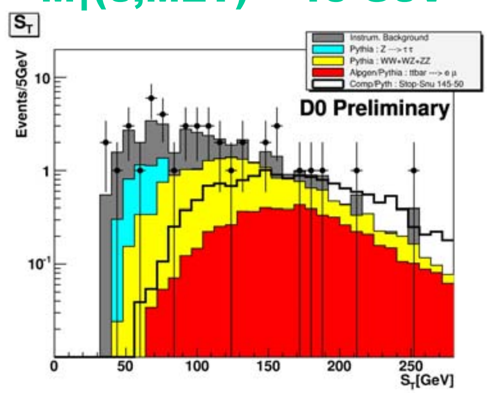
Main selection for μμ:
- 2 isolated OS muons
  - cosmic veto
  - $p_T^1>8$GeV, $p_T^2>6$GeV
- At least 1 jet $p_T>15$ GeV
  - leading jet b-tagged
- MET>MinMET($\Delta\Phi(\mu_1$,MET))
- Mμμ outside the Z mass region

Data is compatible with SM

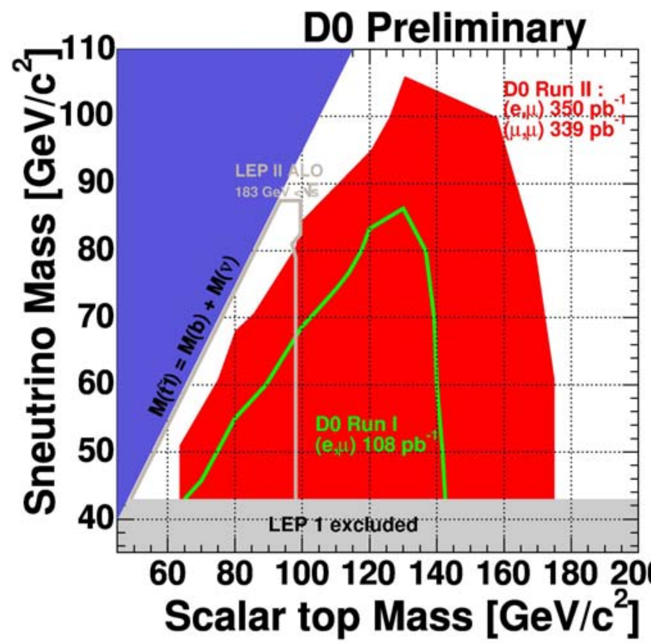


Exclusion limit determined on $H_T=\Sigma p_T^j$

Main selection for eμ:
- >=1 isolated electron
  - $p_T^e>12$ GeV
- >=1 isolated muon
  - $p_T^\mu>8$ GeV
- MET > 15 GeV
  - not in the direction of the leptons
- M_T(e,MET) > 15 GeV



Exclusion limit determined on $S_T=p_T^e+p_T^\mu$+MET and #Non Isolated Tracks



Combined limit extends significantly regions excluded earlier

Search for pair-production of stop quarks decaying into $c+\chi_1^0$

This decay mode dominates for $m_c+m_{\chi10} < m_{st} < m_b + M_W + m_{\chi10}$

Basic event topology

2 acoplanar c-tagged jets

$p_T^1>40$ GeV, $p_T^2>20$ GeV optimized

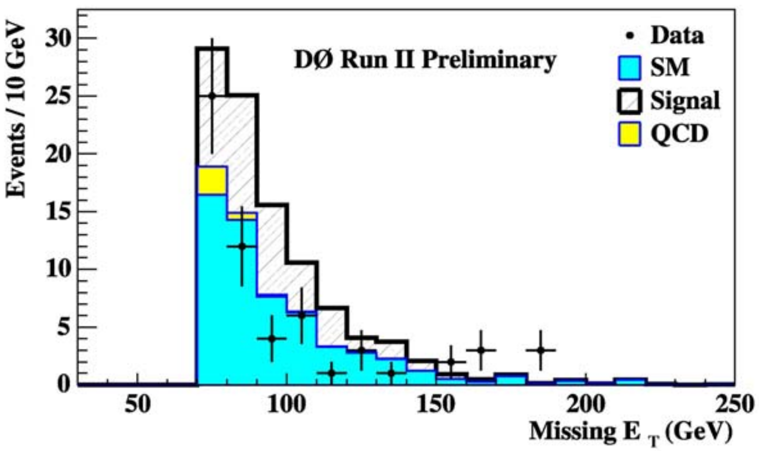
$\Delta\varphi(j_1,j_2) < 165^o$

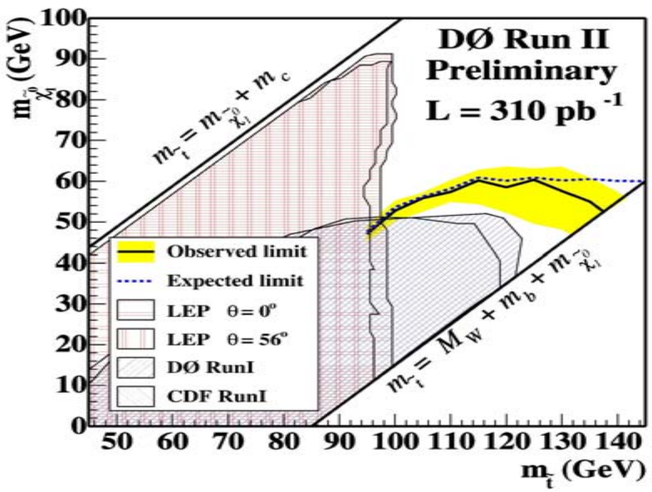
MET > 40 GeV optimized for m_{st}-$m_{\chi10}$ pairs

get minimal <CLs>, expected signal confidence in absence of signal

QCD background is small

extrapolated from low MET





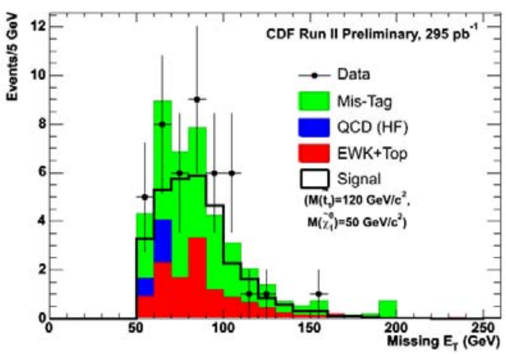
In general data agrees with the SM prediction
A visual scan of the high MET events did not reveal any anomaly

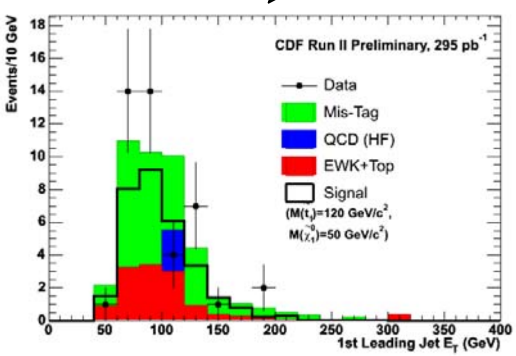
Obtained limit on m_{st} @ 95% improves significantly domains excluded earlier

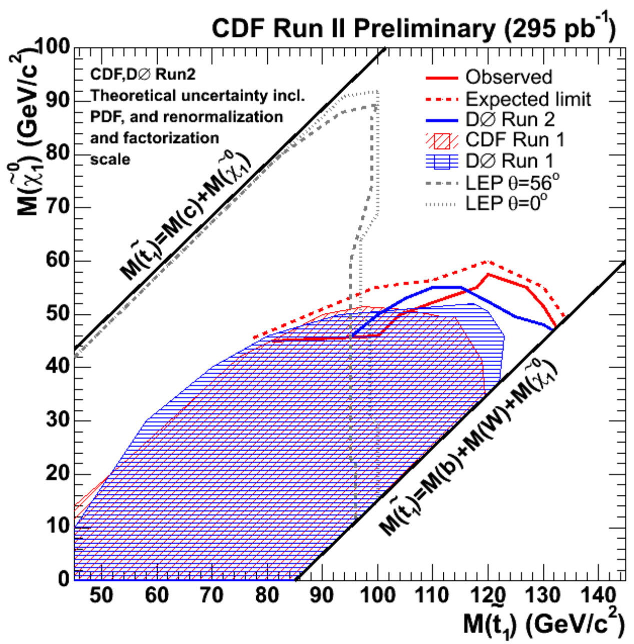
CDF selection for the same channel: $p\bar{p} \to \tilde{t}_1\bar{\tilde{t}}_1 \to c\tilde{\chi}_1^0 \bar{c}\tilde{\chi}_1^0$

- **2 or 3 jets**
  - E_t cuts on 1st and 2nd leading jets vary depending on M_{st}
- **MET>50 GeV or higher depending M_{st}**
- **1st and 2nd leading jets not back-to-back**
- **Jets not pointing along direction of MET**
- **≥1 jet tagged JetProbability < 5%**

	Low M_{st}	Medium M_{st}	High M_{st}
SM (Total)	137±15.8	94.9±11.1	42.7±5.28
Data	151	108	43







Search for pair-production of stop quarks decaying into b+τ via RPV (λ'_{333})

Basic event topology:

1 τ decays leptonically: isolated e or μ

1 τ decays hadronically: track + em cluster

$N_{jet} > 1$

$S_T = p_T^l + p_T^\tau + MET > 110$ GeV

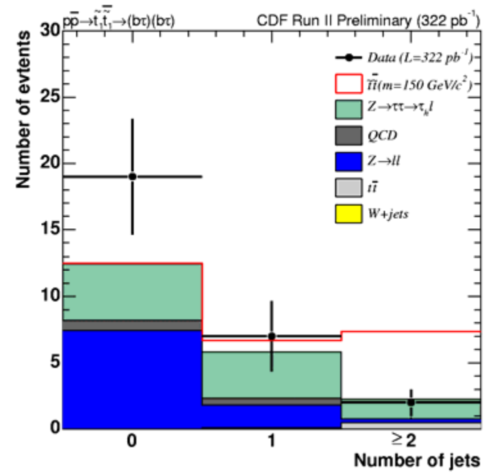
against QCD and Z→ $\tau\tau$ background

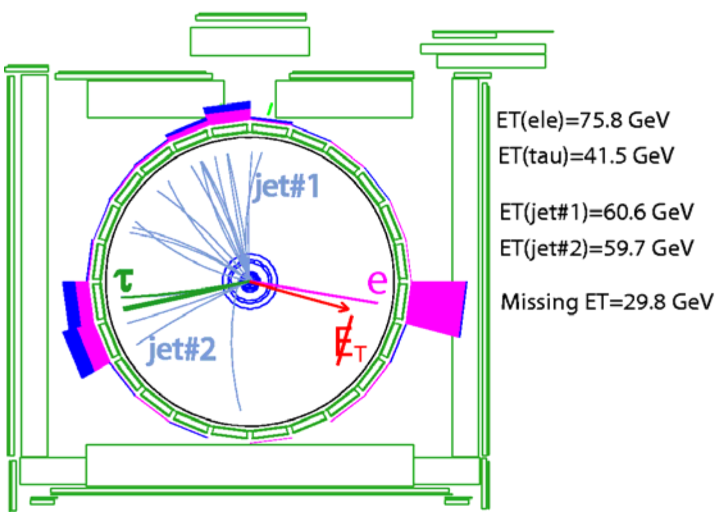
M_T(l,MET) < 35 GeV

against W+jet background

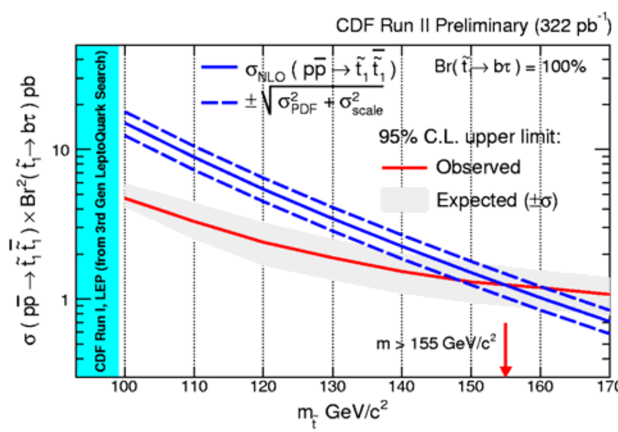
M_{ll} outside Z mass region

2 events seen $2.26^{\pm 0.46}_{0.22}$ expected from SM





L=0.32 fb^{-1}



Upper limit of cross section x BR(100%) derived

Mass limit: M_{st} > 155 GeV obtained

also valid for 3rd generation LQ_3

Conclusions

Thanks to the Tevatron
the regions where there is no need to look for SUSY
have increased considerably

The former LEP and Run I mass limits
have been significantly extended

The searches continue with increasing luminosity,
with better performing detectors,
exploring event topologies
with ever increasing sophistication
in a friendly competition between the two experiments