SUSY SEARCHES AT THE TEVATRON

Xavier Portell
(On behalf of CDF and D0 Collaborations)

HCP (Duke, NC) May 2006

THE TEVATRON

p-pbar collider:

36x36 bunches at 396 ns crossing time

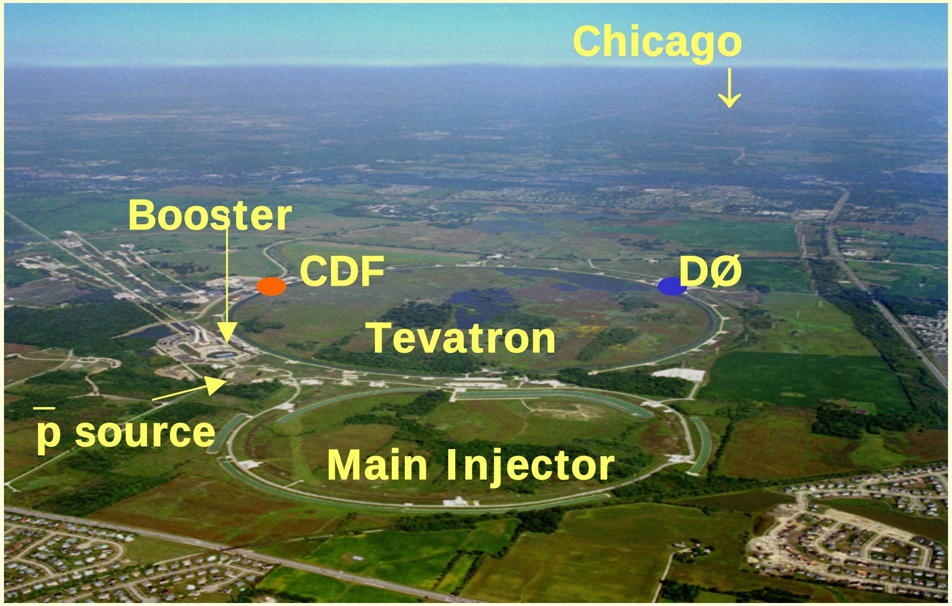
→ $\sqrt{s}$ = 1.96 TeV (Run I →1.8TeV)

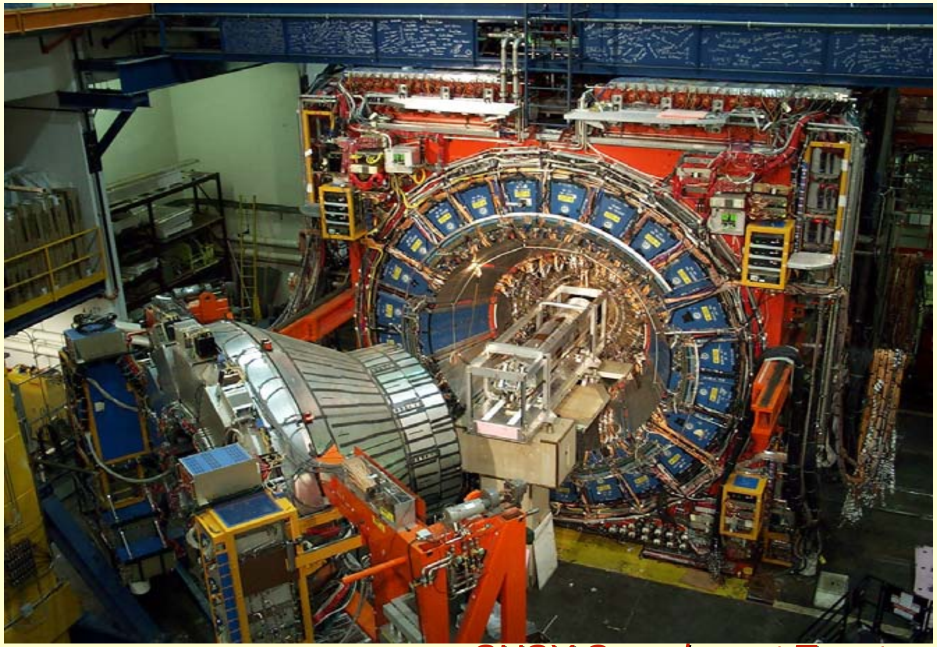
Tevatron, CDF and D0 were highly upgraded in Run II.

Great performance: 1.6 fb^{-1} delivered

1.3 fb^{-1} to tape

Data collecting efficiencies ~ 85%





WHY DO WE NEED SUSY?

The SM works very well... but there exist some unresolved problems:

- Mass hierarchy problem
- Unification
- Dark Matter
- Matter-antimatter asymmetry

SUSY: **Q|Boson> = Fermion**
Q|Fermion> = Boson

The introduction of SUSY have very interesting implications:

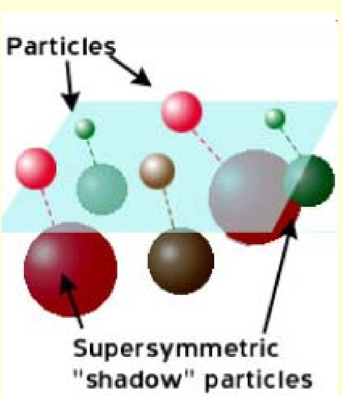
✓ Solves the hierarchy problem

✓ Unification of forces at GUT scale

✓ Provides a Dark Matter candidate

✓ ...

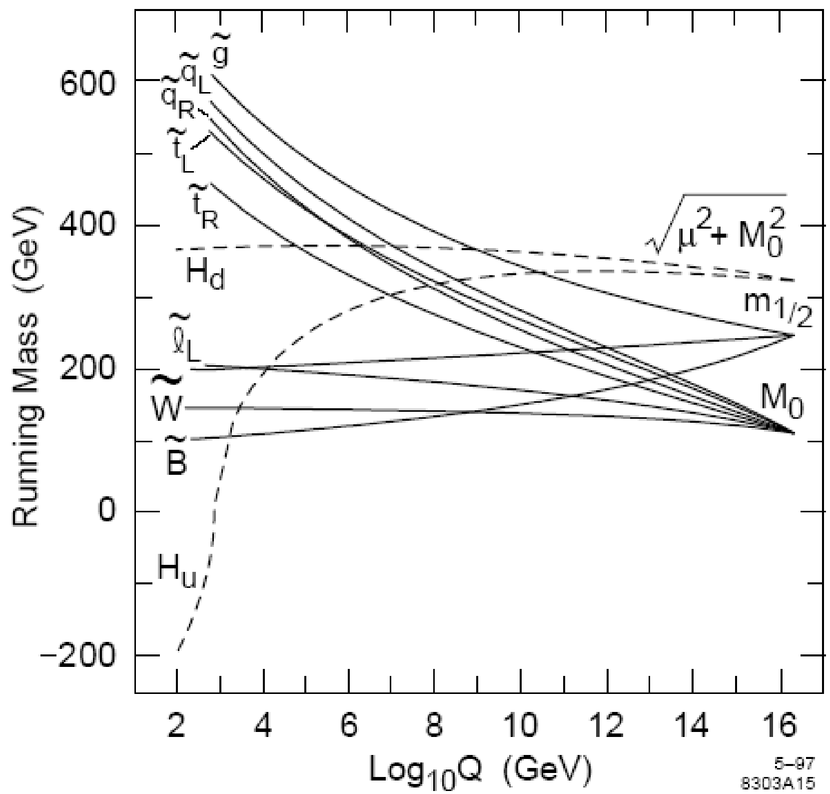
But SUSY also imply new undiscovered particles...



$[u,d,c,s,t,b]_{L,R}$	$[e,\mu,\tau]$	$[\nu_{e,\mu,\tau}]$	Spin $\frac{1}{2}$
$[\tilde{u},\tilde{d},\tilde{c},\tilde{s},\tilde{t},\tilde{b}]_{L,R}$	$[\tilde{e},\tilde{\mu},\tilde{\tau}]$	$[\tilde{\nu}_{e,\mu,\tau}]$	Spin 0
g	$W^{\pm}, H^{\pm}$	$\gamma, Z, H_1^0 H_2^0$	Spin1/Spin 0
$\tilde{g}$	$\tilde{\chi}^{\pm}_{1,2}$	$\tilde{\chi}^0_{1,2,3,4}$	Spin $\frac{1}{2}$

SUSY BREAKING

Symmetry → Need to be broken → determines phenomenology



One of the preferred models: mSUGRA

- New superfields in the “hidden” sector
- Interact gravitationally with MSSM
- Soft SUSY breaking
- Only 5 parameters at SUSY scale

m_0: common scalar mass at GUT

$m_{1/2}$: the common gaugino mass at GUT

tanβ: Ratio of Higgs vaccum expectation values

A_0: Trilinear coupling

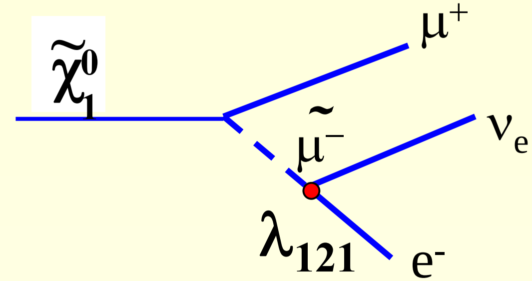
Sign(μ): Higgs mass term

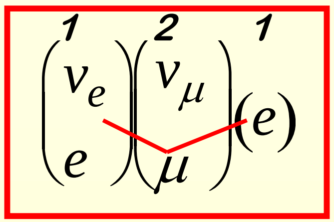
R-PARITY

Most general SUSY lagrangian → Leptonic and Baryonic number violation in the superpotential

$$W_{RPV} = \lambda_{ijk} L^i L^j \overline{E}^k + \lambda'_{ijk} L^i Q^j \overline{D}^k + \lambda''_{ijk} \overline{U}^i \overline{D}^j \overline{D}^k + \varepsilon_i L_i H_2$$

- λ and λ' violate leptonic number and λ'' the baryonic number
- *ijk* denote the families involved





New quantum number: $R_p=(-1)^{3(B-L)+2s}$

SM particles: Rp=1

Superpartners: Rp=-1

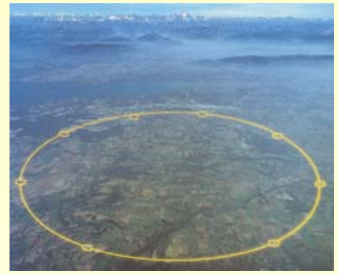
When Rp is conserved:

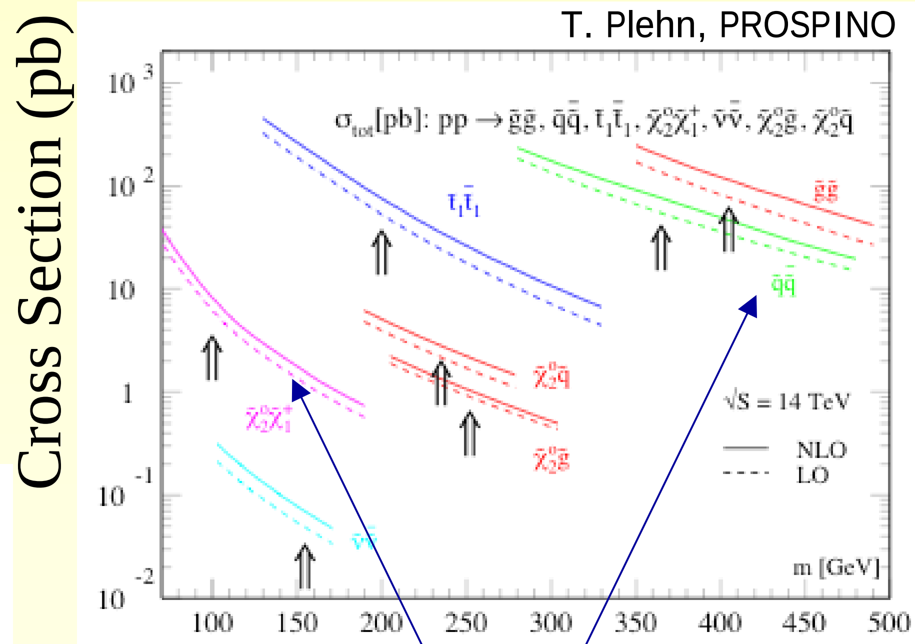
- **Superpartners are pair produced**
- **Lightest SUSY Particle (LSP)** ← Dark Matter candidate!

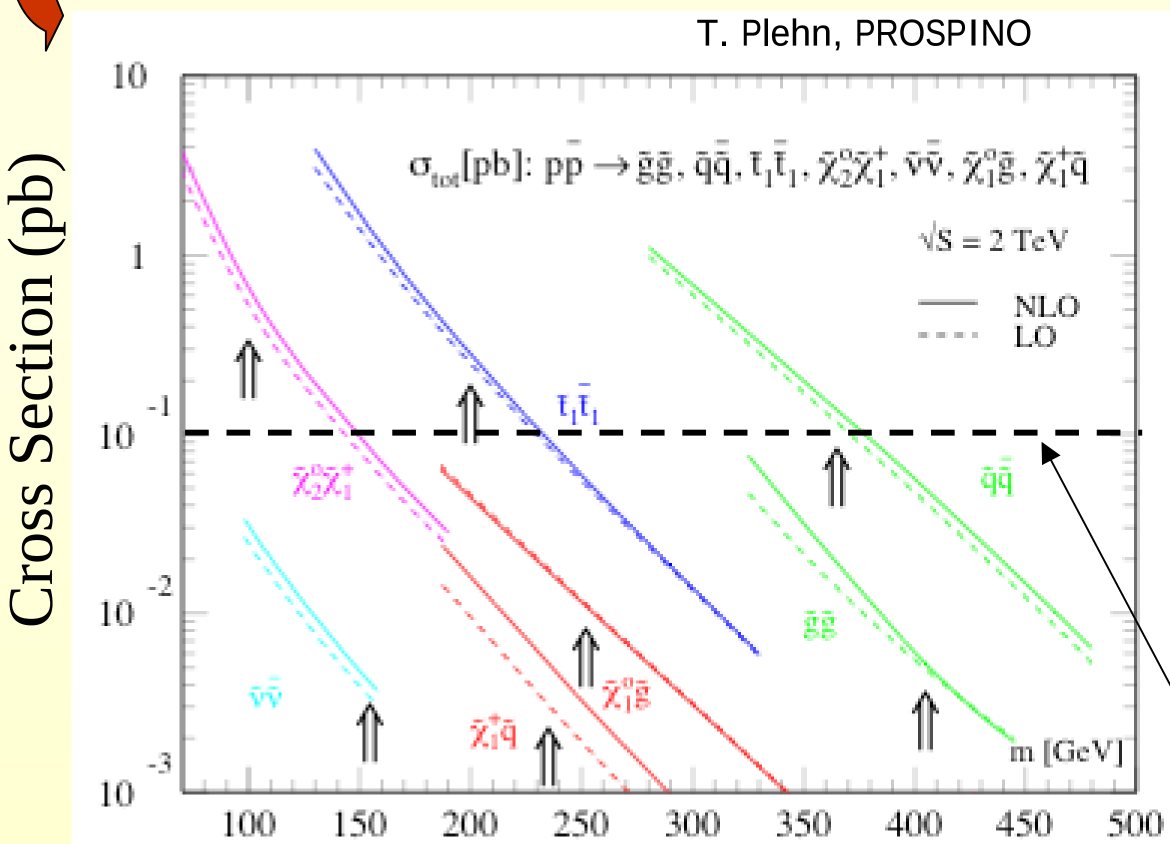
WHY AT THE TEVATRON?

Tevatron: 1.96 TeV

LHC: 14 TeV







$\tilde{q}, \tilde{g}$ → increase by 3-4 orders of magnitude w.r.t. Tevatron.

$\tilde{\chi}^{\pm}_1\ \tilde{\chi}^0_2$ → comparable to Tevatron (and with more background).

Good prospects for finding SUSY at the Tevatron!

100 events per fb^{-1}

OUTLINE

R
P
C

SQUARKS AND GLUINOS

MET+jets

CHARGINOS AND NEUTRALINOS

3-leptons

GMSB CHARGINO/NEUTRALINO

$\gamma\gamma$ + MET

R
P
V

STOP

b-jets and taus

CHARGINO/ NEUTRALINO

4-leptons

INDIRECT

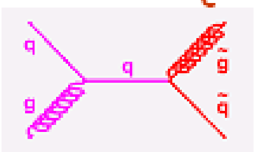
INDIRECT SEARCHES:

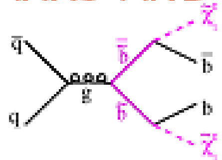
$B_S \rightarrow \mu\mu$

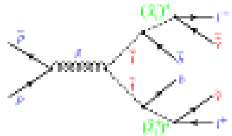
OUTLINE

R
P
C

SQUARKS AND GLUINOS







MET+jets

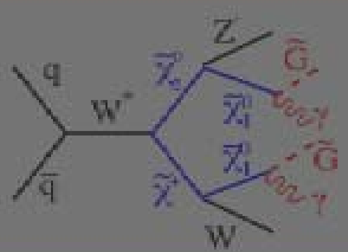
$M_{gl} \sim M_{sq} > 300\ GeV/c^2$ $M_{sb} > 145\ GeV/c^2$ $M_{st} > 140\ GeV/c^2$

CHARGINOS AND NEUTRALINOS

3-leptons

$M_{charg} > 103\ GeV/c^2$

GMSB CHARGINO/NEUTRALINO

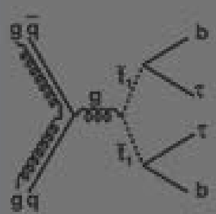


$\gamma\gamma$ + MET

$M_{charg} > 209\ GeV/c^2$ $M_{neutr} > 115\ GeV/c^2$

R
P
V

STOP



b-jets and taus

$M_{stop} > 122\ GeV/c^2$

CHARGINO/NEUTRALINO

4-leptons

$M_{neutr} > 45\ GeV/c^2$

INDIRECT

INDIRECT SEARCHES: $B_S \rightarrow \mu\mu$

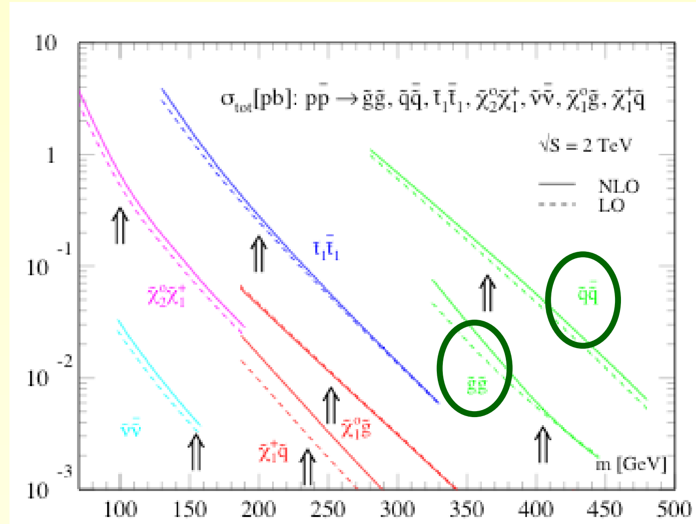
Dimuon events

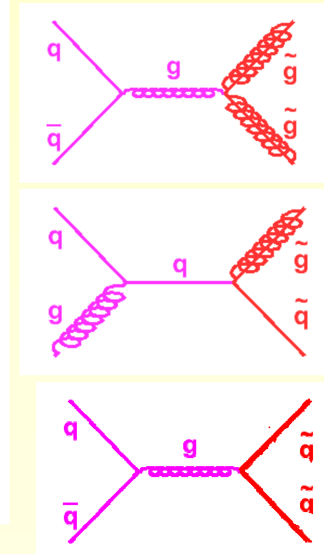
$BR(Bs \rightarrow \mu\mu) < 2.0 \cdot 10^{-7}$

SQUARKS AND GLUINOS

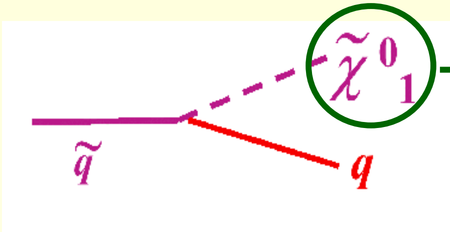
DIRECT SQUARK-GLUINO PRODUCTION:

Strong interaction: large production expected



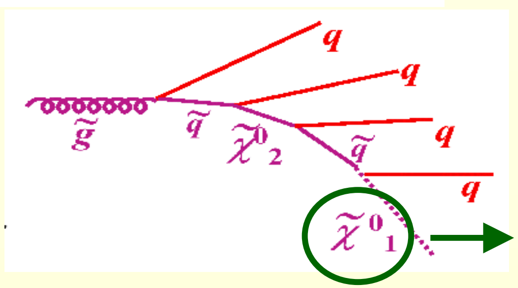


DECAY:



→ Missing E_T

Multiple jets



→ Missing E_T

Missing E_T (MET) + jets

- Always 3 or more jets
- Optimization for three different ranges of gluino masses.

Optimized for three cases:

2-jets (when Mgl>Msq)

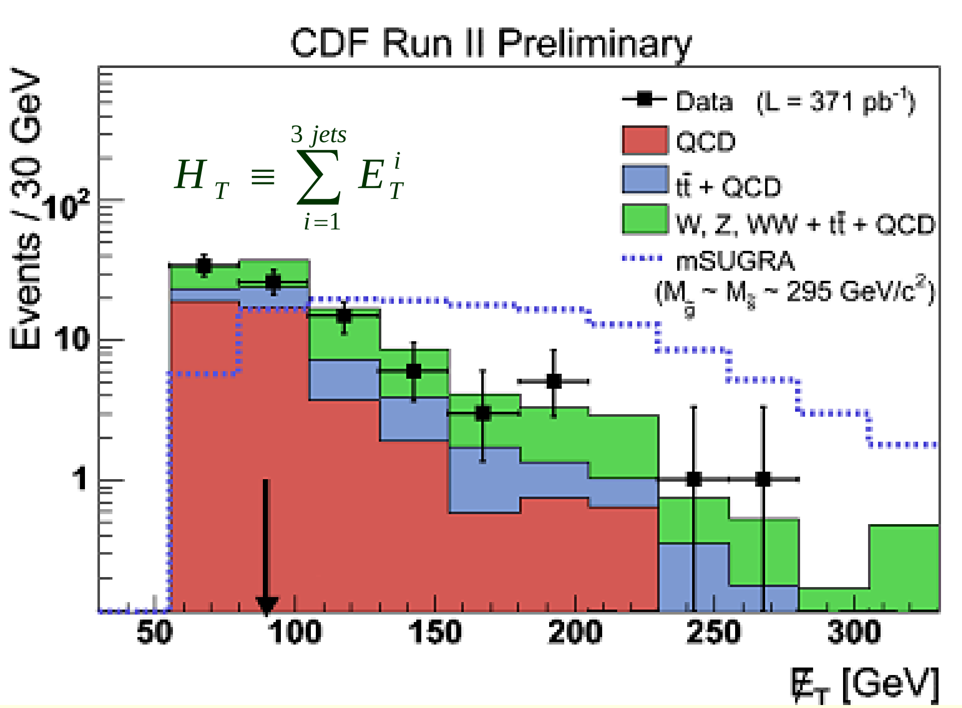
3-jets (when Mgl~Msq)

4-jets (when Mgl<Msq)

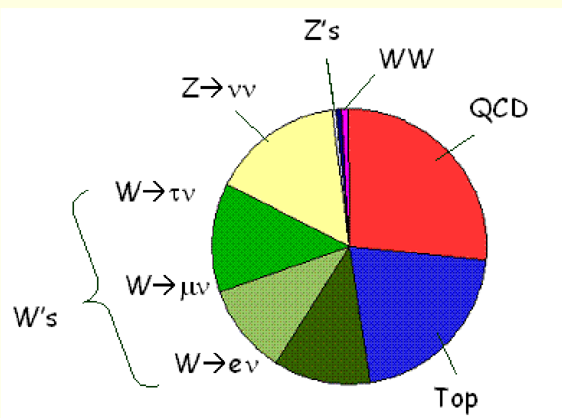
Studied an mSUGRA scenario with first **4 flavors degenerate** (sbottom/stop not considered)

Backgrounds are challenging (specially QCD)

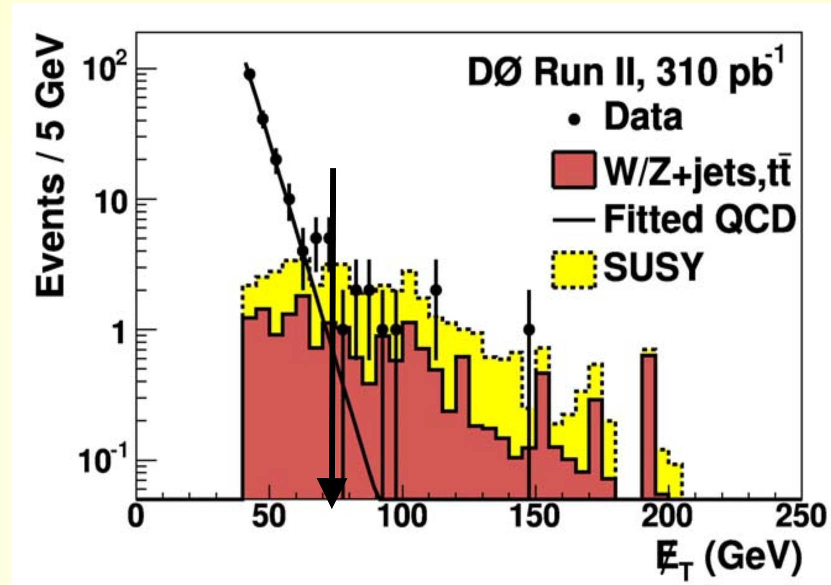
SQUARKS AND GLUINOS



Distributions after all cuts for CDF and D0 agree with data in all cases.

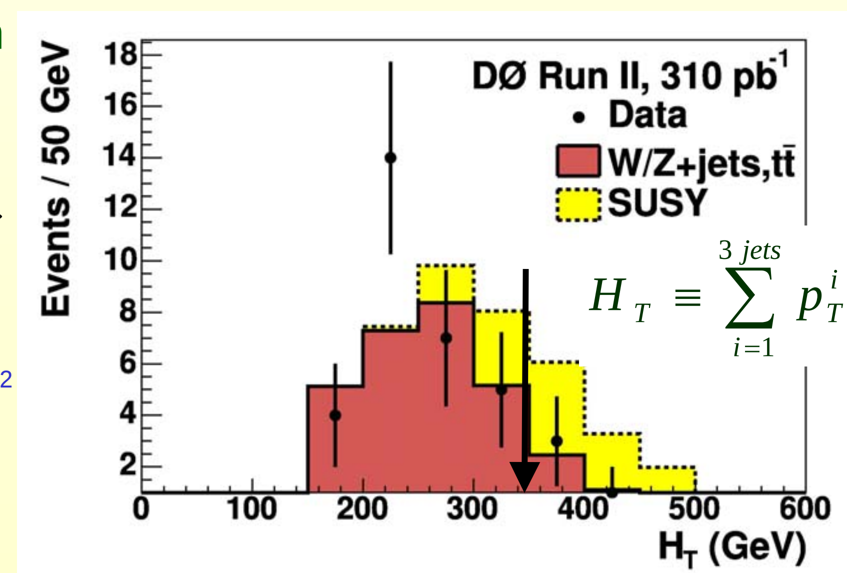


CDF background contributions after all the cuts.



4-jet optimization

M_{gl}~240 GeV/c^2



3-jet optimization

M_{gl}~M_{sq}~330 GeV/c^2

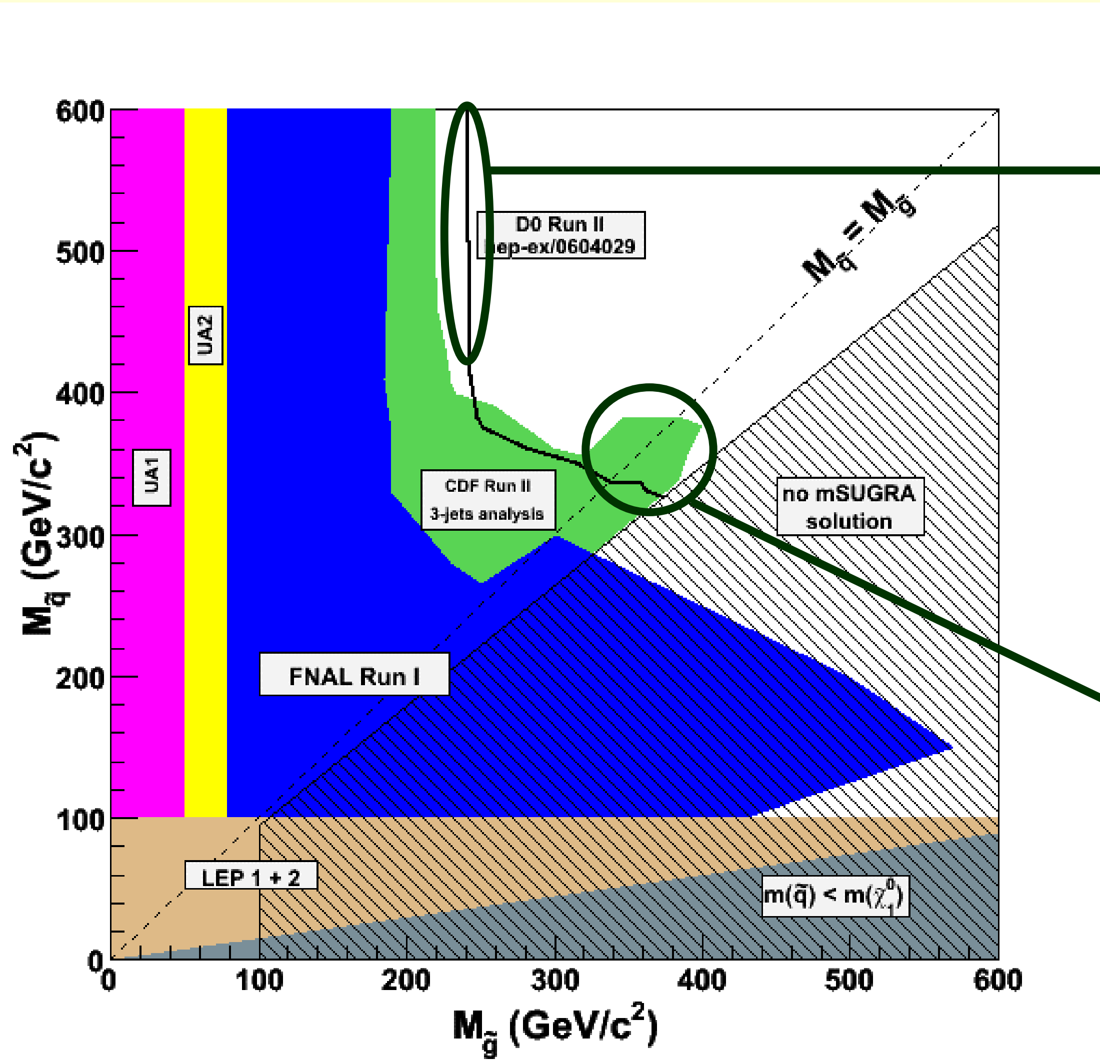
SQUARKS AND GLUINOS: LIMITS

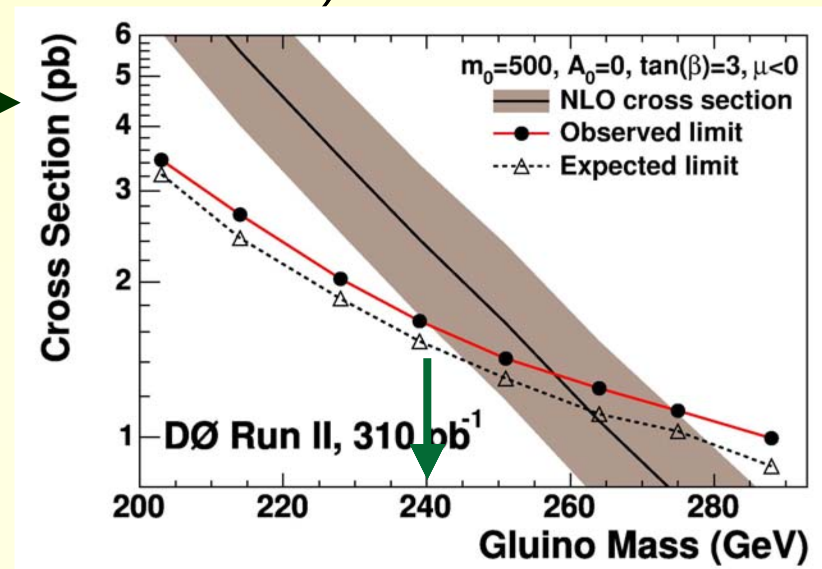
D0: 310 pb^{-1}, $A_0=0$, $\mu<0$ and $\tan\beta=3$

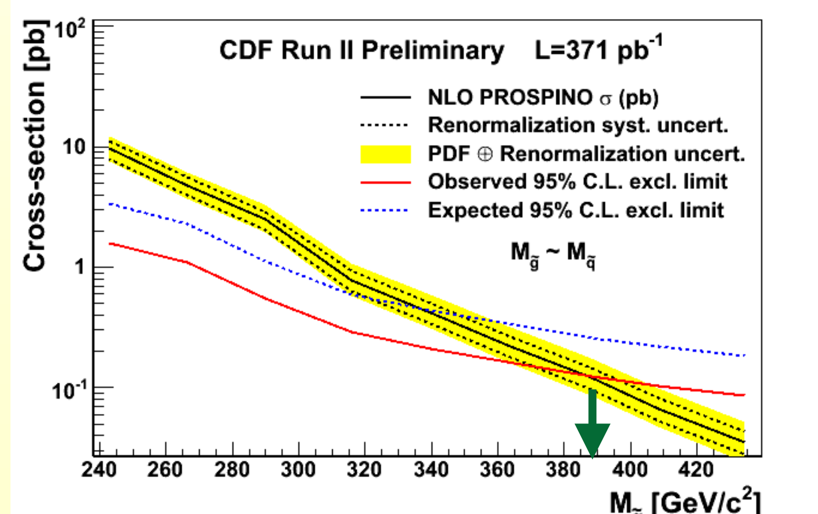
CDF: 371 pb^{-1}, $A_0=0$, $\mu<0$ and $\tan\beta=5$

CDF: Includes the theoretical uncertainties when calculating the observed limit

D0: Reduce theoretical cross section by 1σ (more conservative)







$M_{gl} > 387$ GeV/c^2 (when $M_{gl} \sim M_{sq}$)

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

3rd GENERATION SQUARKS

SUSY: Predicts left- and right-handed scalar partner eigenstates for each SM fermion

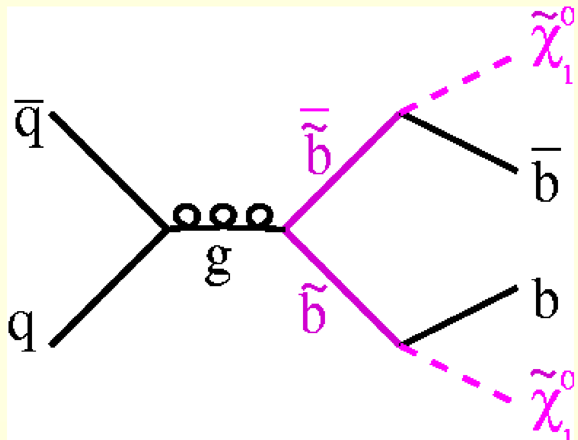
As 3rd generation is heavier, stop and sbottom could be the lightest SUSY particles.

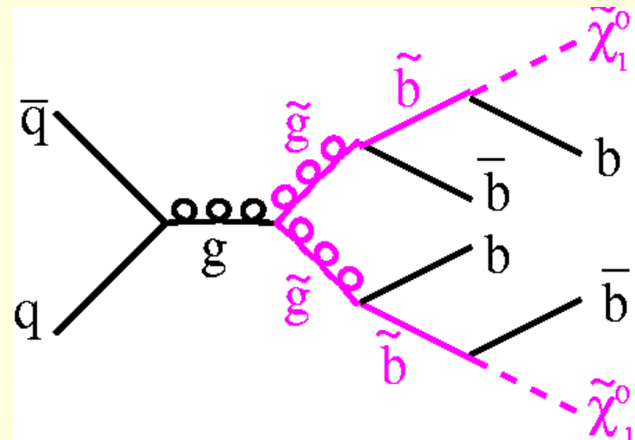
$$m^2_{\tilde{t}1,2} = \frac{1}{2}(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R}) \mp \frac{1}{2}\sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4m_t(A_b - \mu\tan\beta)^2}$$

Important to have **specific analyses** for them!

SBOTTOM

Signatures of 2 or 4 b-jets and MET

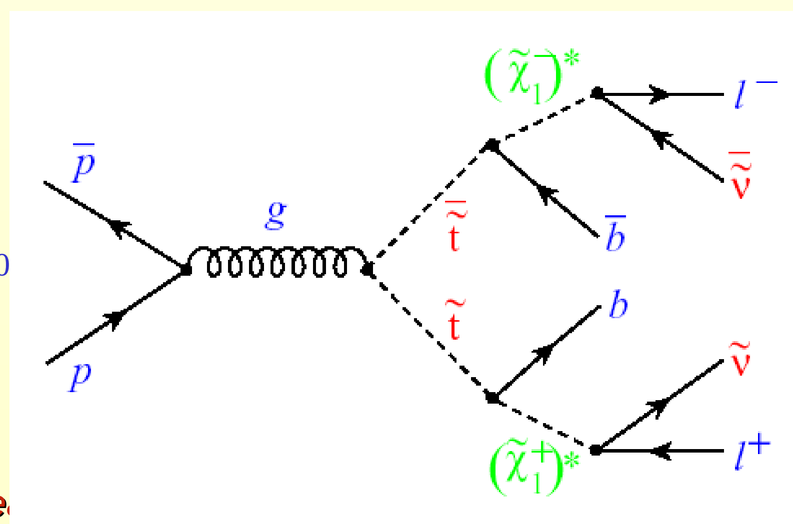




STOP

Depending on the mass:

- Heavy: $\tilde{t} \rightarrow t\tilde{\chi}^0$
- Medium: $\tilde{t} \rightarrow b\tilde{\chi}^{\pm} \rightarrow bW\tilde{\chi}^0$
- Light: $\tilde{t} \rightarrow c\tilde{\chi}^0$



A Light stop is preferred (consistent with baryogenesis)

Balazs, Carena, Wagner (hep-ph/0403224)

Soft jets (experimental challenge)

SBOTTOM

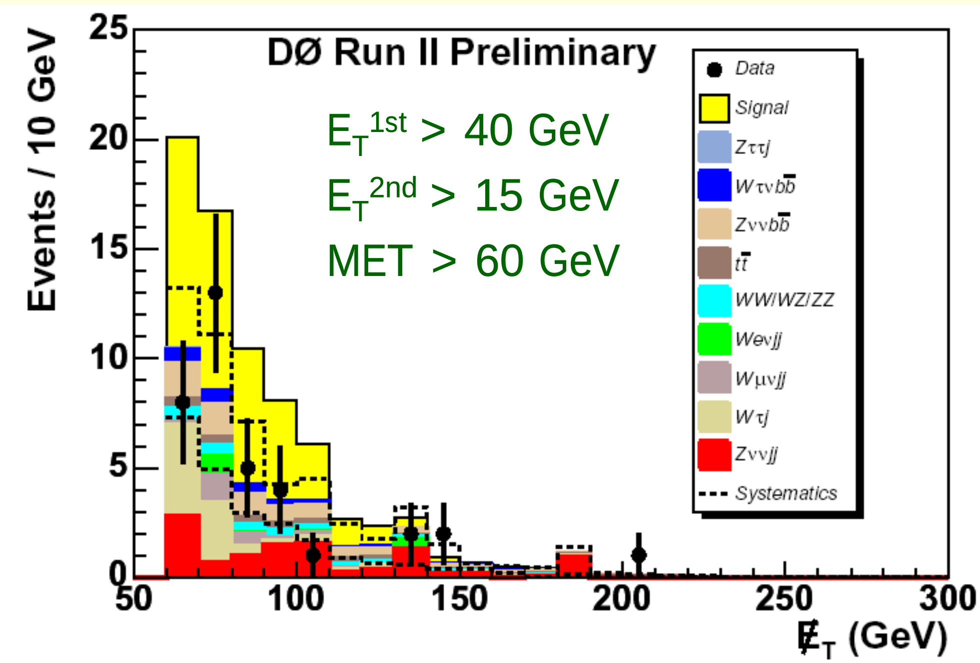
SELECTION CRITERIA

✓ At least two jets, one b-tagged.

✓ Three different jet/MET thresholds (increasing sbottom mass):

E_T^{1st} > 40-70 GeV E_T^{2nd} > 15-40 GeV

MET > 60-100 GeV

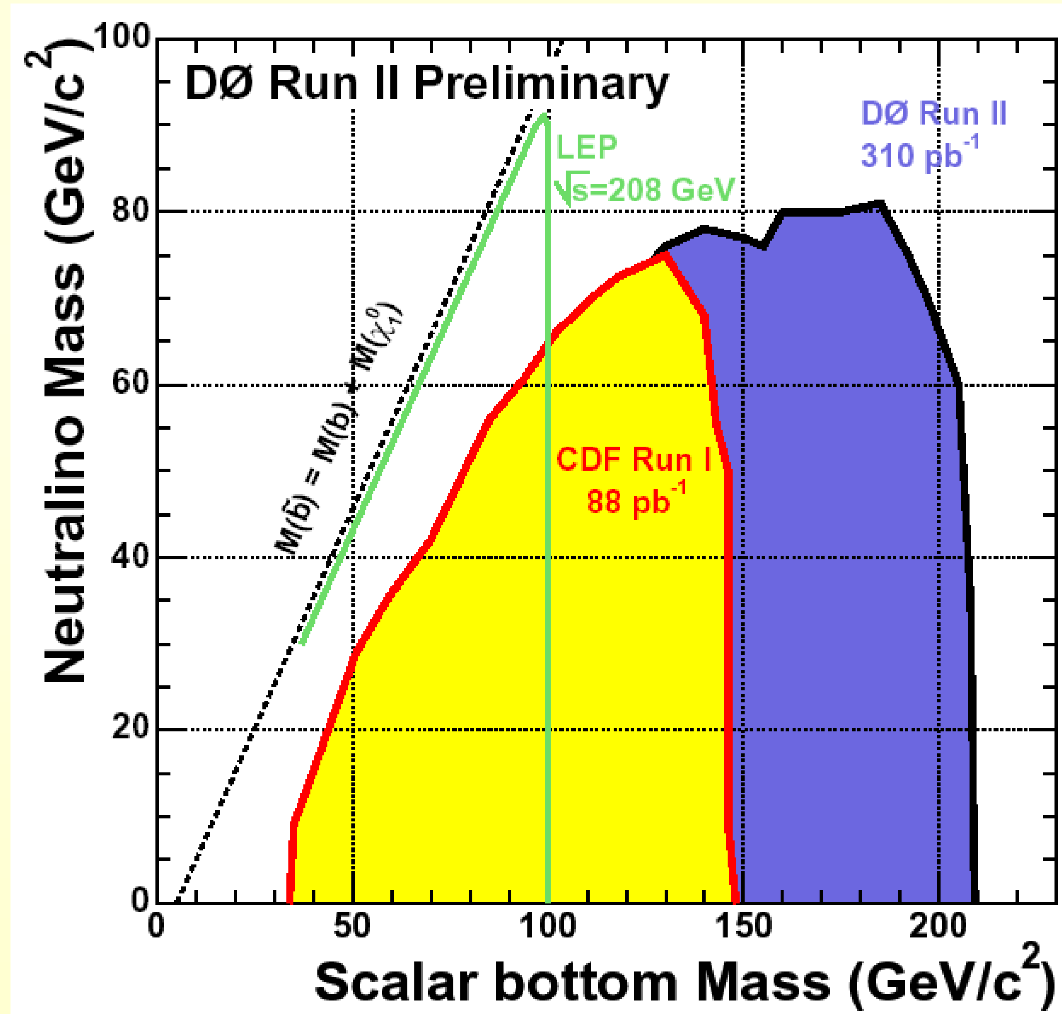


↳ $(m_{\tilde{b}}, m_{\tilde{\chi}_1^0}) = (140, 80)$ GeV/c^2

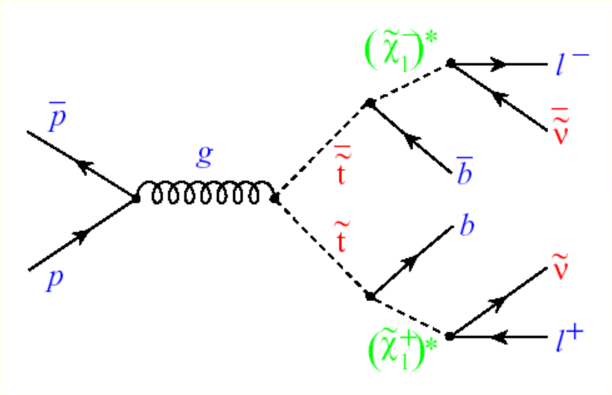
RESULTS

✓ Good agreement data/MC

✓ Exclude sbottom masses up to 200 GeV (depending on neutralino mass)



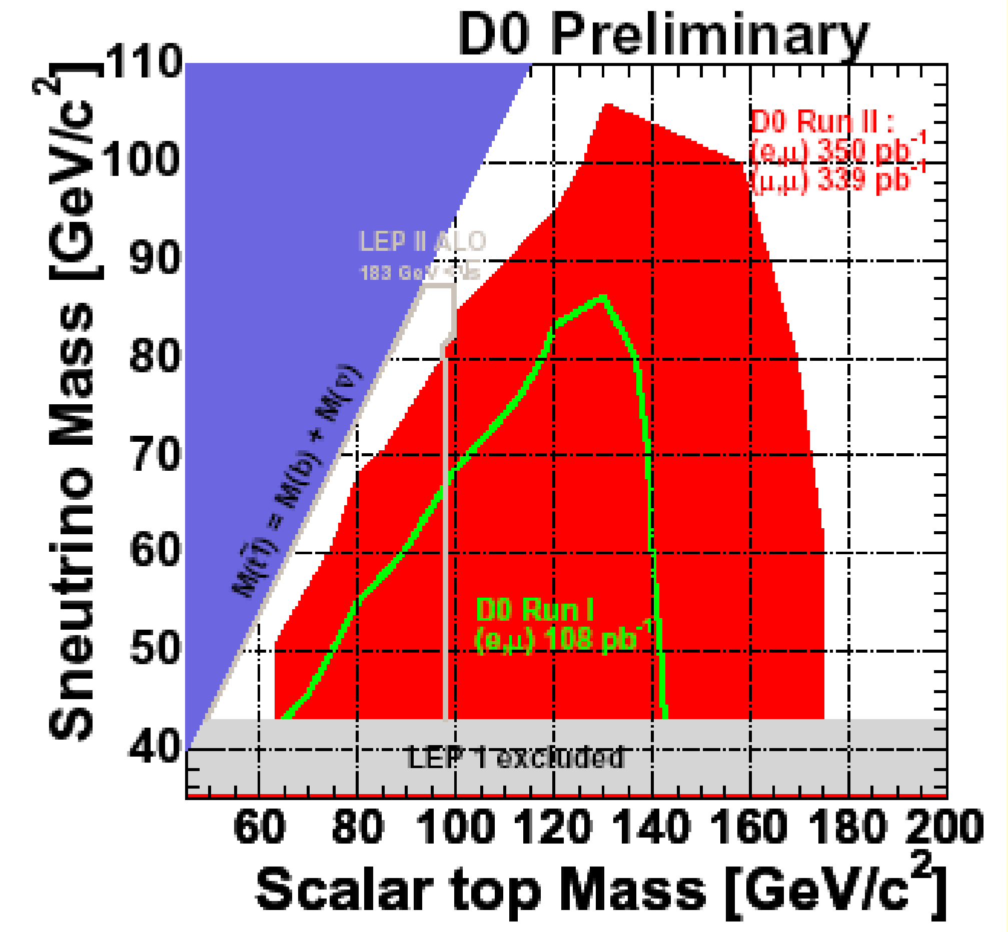
STOP



- ✓ D0: 2 different analyses to improve sensitivity: eμ, μμ
- ✓ eμ analysis: optimized for different Δm= (Mstop – Msneutrino) values
- ✓ Missing E_T > 15 GeV
- ✓ Topological cuts

The sneutrino usually decays into neutrino and neutralino (MET)

Optimization	Background	Data
eμ (Δm low)	23.0 ± 3.1	21
eμ (Δm high)	40.7 ± 4.4	42
μμ	2.9 ± 0.4	1



Numbers compatible with SM

Great improvement with respect to Run I (excluding up to the top mass)

OUTLINE

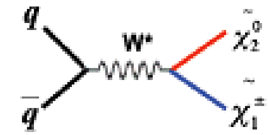
RPC

SQUARKS AND GLUINOS

MET+jets

$M_{gl} \sim M_{sq} >$ ~~300~~ 387 GeV/c² $M_{sb} >$ ~~145~~ 220 GeV/c² $M_{st} >$ ~~140~~ 175 GeV/c²

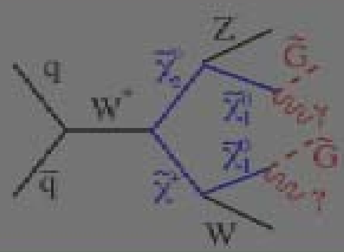
CHARGINOS AND NEUTRALINOS



3-leptons

$M_{charg} > 103$ GeV/c²

GMSB CHARGINO/NEUTRALINO

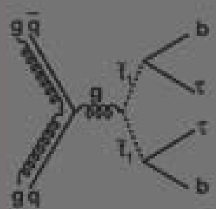


$\gamma\gamma$ + MET

$M_{charg} > 209$ GeV/c² $M_{neutr} > 115$ GeV/c²

RPV

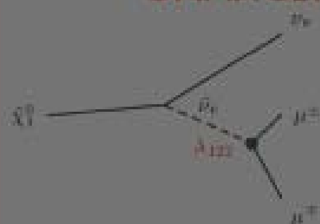
STOP



b-jets and taus

$M_{stop} > 122$ GeV/c²

CHARGINO/NEUTRALINO

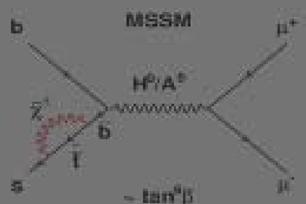


4-leptons

$M_{neutr} > 45$ GeV/c²

INDIRECT

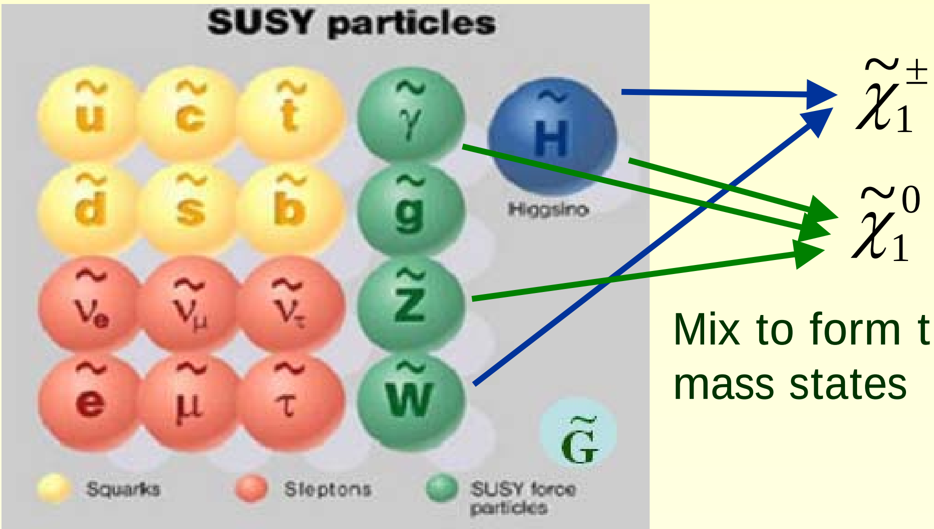
INDIRECT SEARCHES: $B_S \rightarrow \mu\mu$



Dimuon events

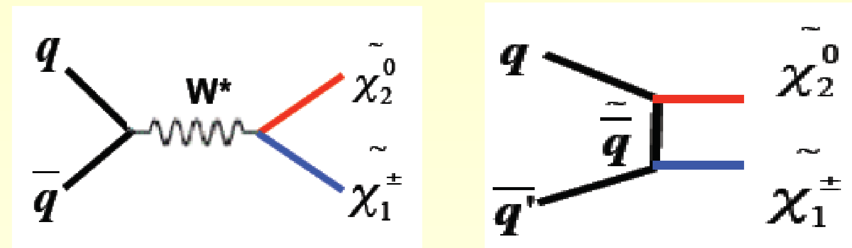
$BR(Bs \rightarrow \mu\mu) < 2.0 \cdot 10^{-7}$

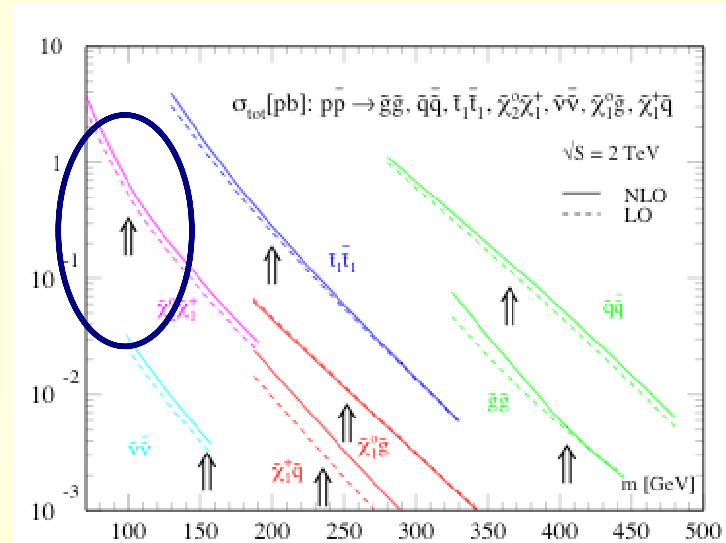
CHARGINOS AND NEUTRALINOS

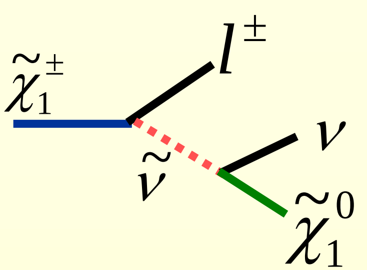


Mix to form the mass states

PRODUCTION

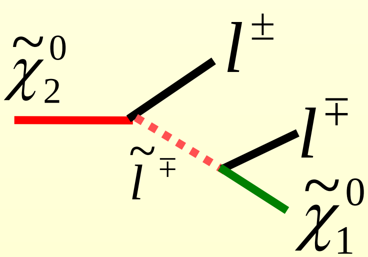






Always one lepton from $\tilde{\chi}^{\pm}_1$

+ Missing E_T



Always two leptons from $\tilde{\chi}^0_2$

In mSUGRA:

$M_{\tilde{\chi}^{\pm}_1} \sim M_{\tilde{\chi}^0_2} \sim 2\, M_{\tilde{\chi}^0_1}$

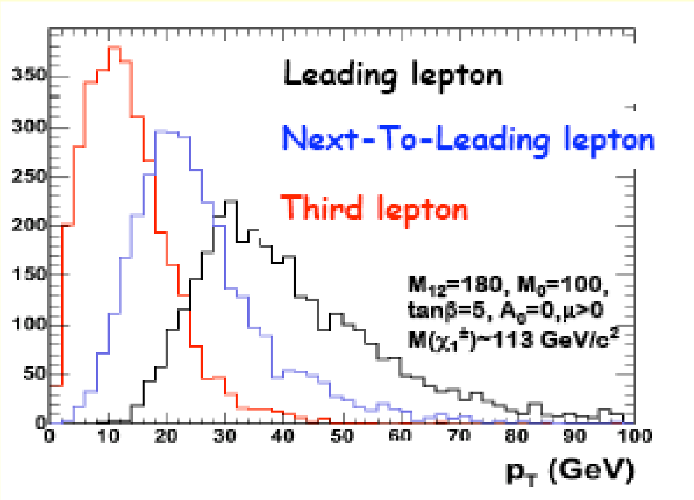
We have always 2 like-sign leptons (one from each superpartner)

Clean signature and relatively high cross sections

GOLDEN CHANNEL

CHARGINOS AND NEUTRALINOS

The third lepton tends to be very soft

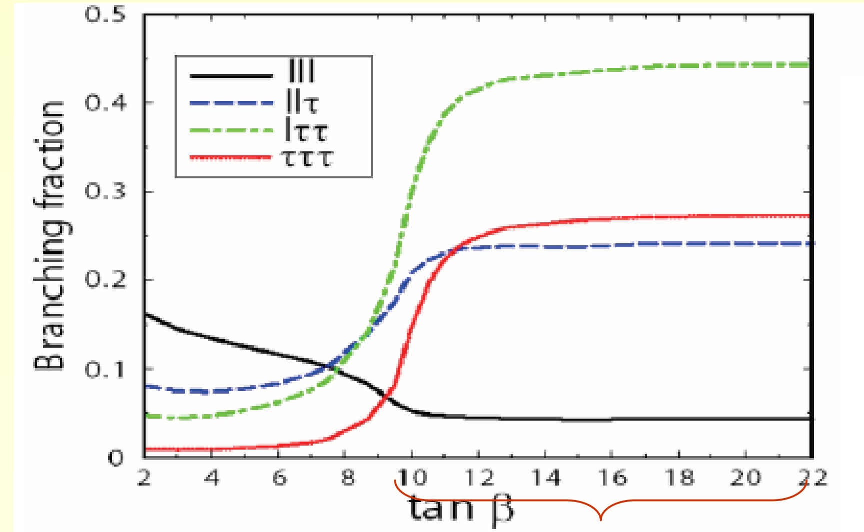


Cuts in lepton P_T:

P_T^{1st}~20 GeV/c

P_T^{2nd}~10 GeV/c

tanβ determines the lepton flavor composition

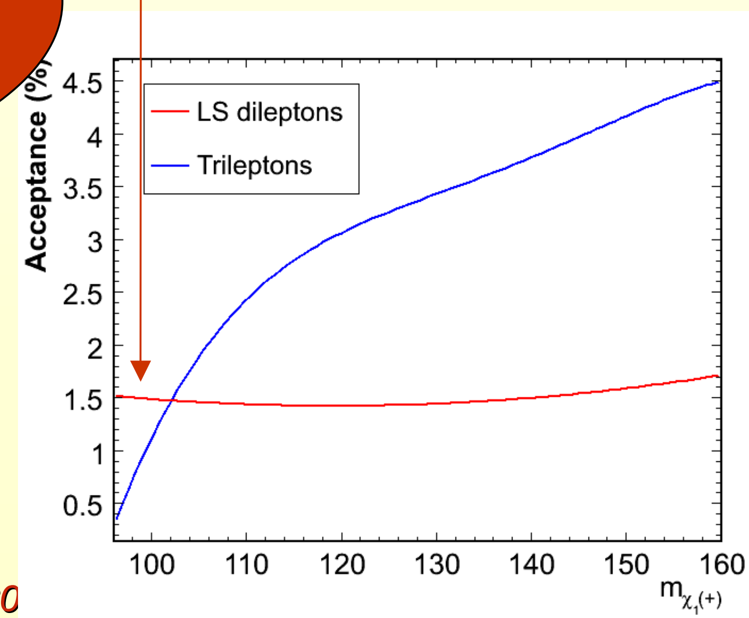


taus dominate

IMPORTANT ANALYSES VARIETY

- **3 leptons (ee+l, μμ+l, eμ/μe+l)**
- **2 leptons + track**
- **2 like-sign (LS) leptons (ee,μμ,eμ)**

Low p_T zone



Different trigger paths and cut optimizations for e/μ and tracks in general

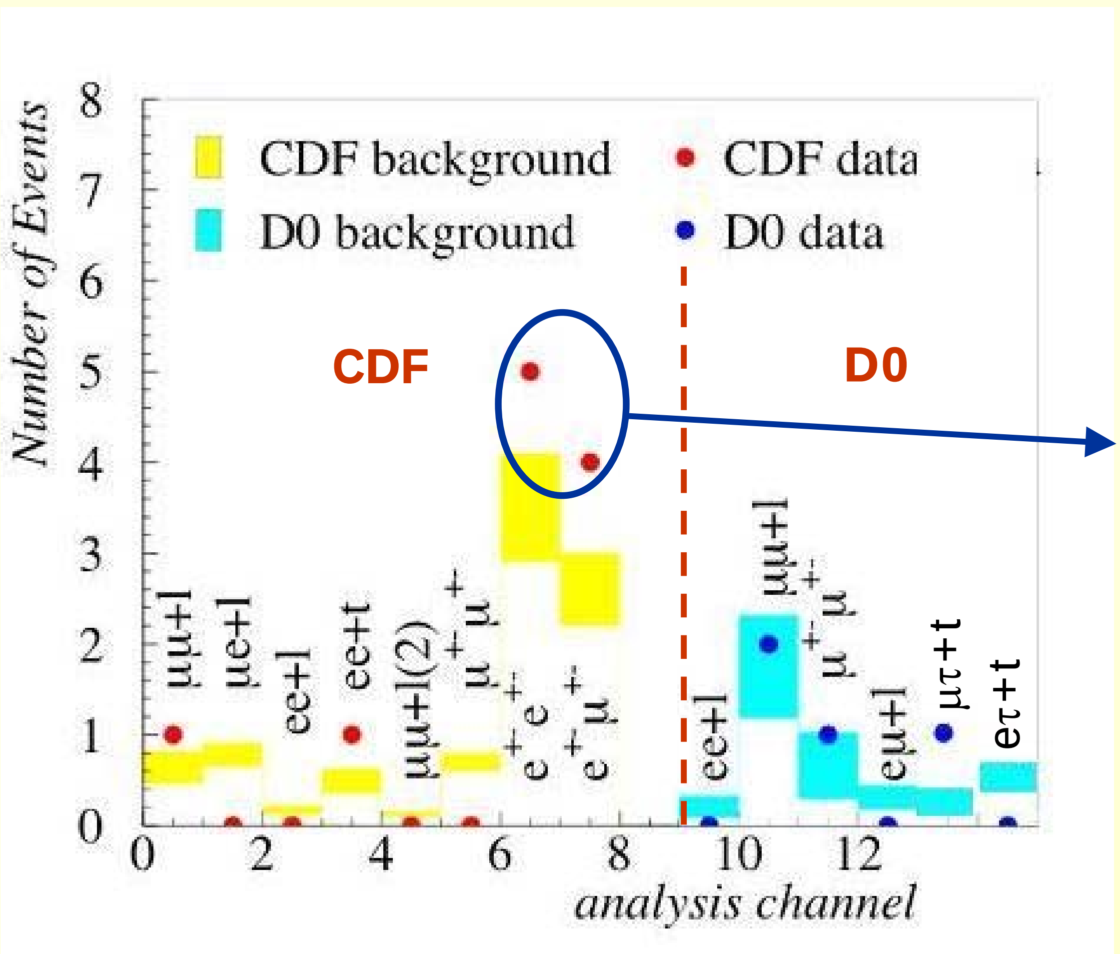
CHARGINOS AND NEUTRALINOS

Requirements to reduce SM background

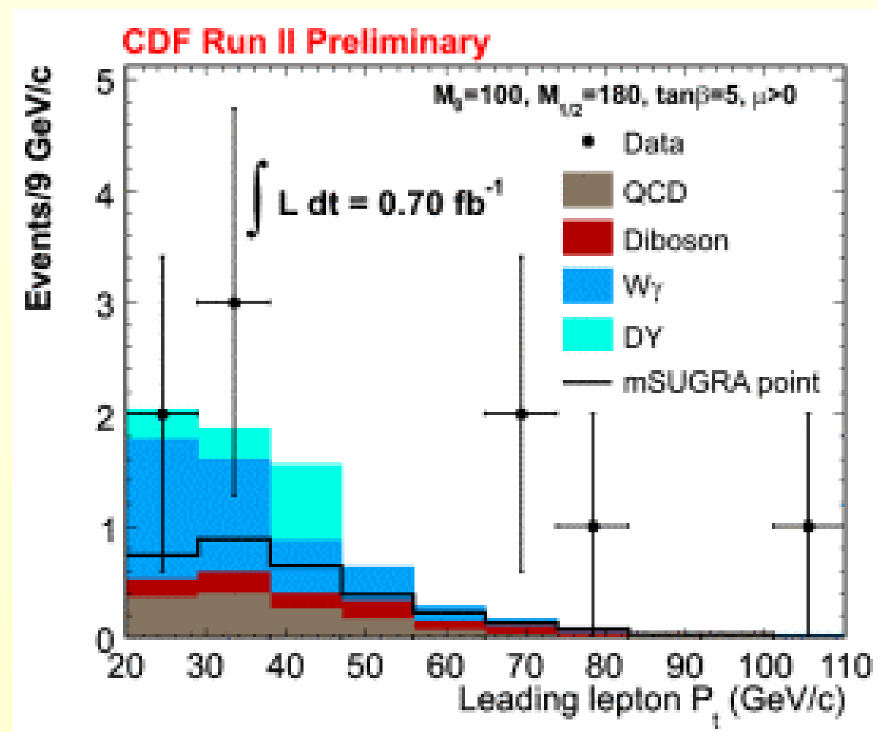
(DY, diboson, conversions…)

- Minimum p_T for the 2 leading leptons
- Dilepton mass and angle cuts (avoid Z and Drell-Yan)
- Small jet activity
- Missing transverse energy significant

Observed / Expected Events

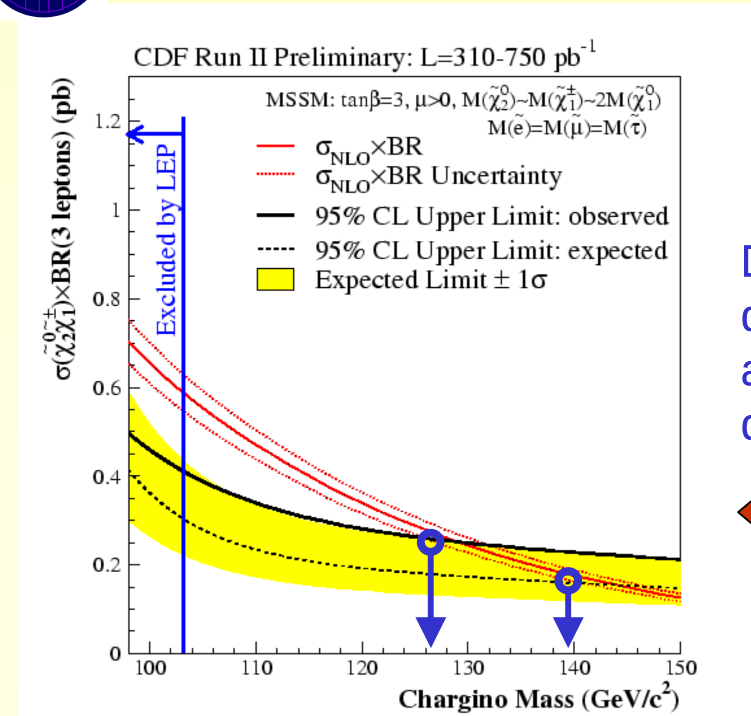


All is compatible with SM…



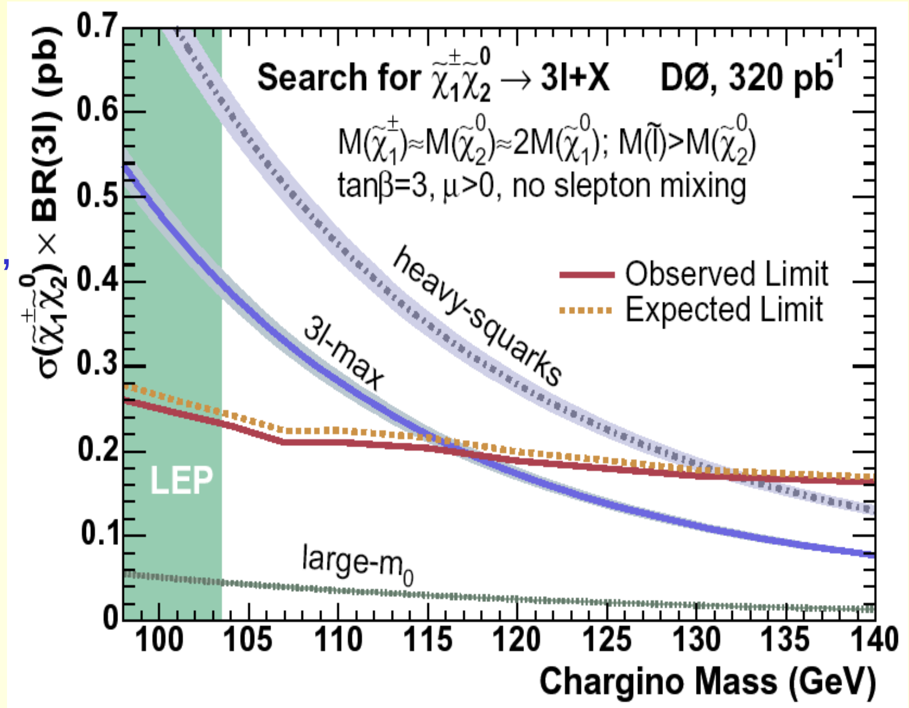
CHARGINOS AND NEUTRALINOS

Low tanβ and slepton mass degenerate



$M_{\tilde{\chi}_1^\pm}$ > 127 GeV/c²

Low tanβ and no slepton mixing



$M_{\tilde{\chi}_1^\pm}$ > 117 GeV/c²

Different luminosities, different number of analyses and slightly different scenarios

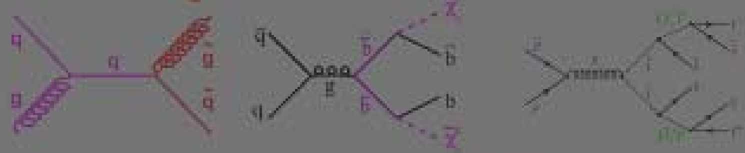
Results are model dependent (for e.g. with slepton mixing the acceptance is worse and there are no new constraints yet)

- Beyond LEP (in these scenarios)
- More luminosity is being added
- Already implementing some improvements...

OUTLINE

RPC

SQUARKS AND GLUINOS



MET+jets

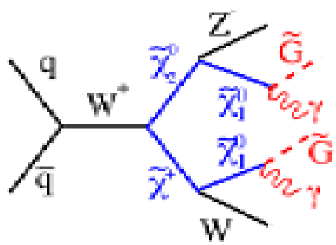
$M_{gl} \sim M_{sq} >$ 387 GeV/c² $M_{sb} >$ 220 GeV/c² $M_{st} >$ 175 GeV/c²

CHARGINOS AND NEUTRALINOS

3-leptons

$M_{charg} >$ 127 GeV/c²

GMSB CHARGINO/NEUTRALINO

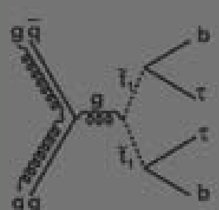


$\gamma\gamma$ + MET

$M_{charg} > 209$ GeV/c² $M_{neutr} > 115$ GeV/c²

RPV

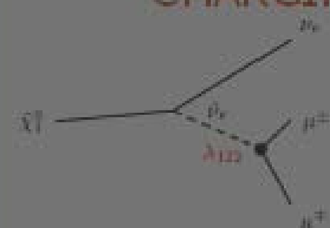
STOP



b-jets and taus

$M_{stop} > 122$ GeV/c²

CHARGINO/NEUTRALINO

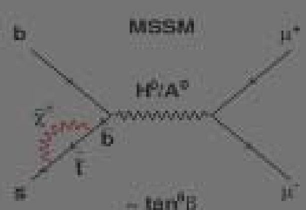


4-leptons

$M_{neutr} > 45$ GeV/c²

INDIRECT

INDIRECT SEARCHES: $B_S \rightarrow \mu\mu$

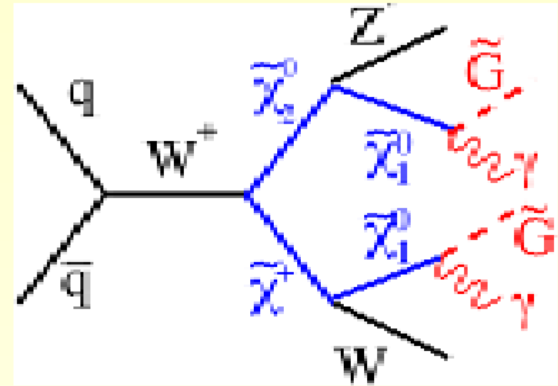


Dimuon events

$BR(B_s \rightarrow \mu\mu) < 2.0 \cdot 10^{-7}$

GMSB: $\gamma\gamma$+MET

In Gauge Mediated Supersymmetry Breaking (GMSB) model the neutralino is the NLSP and the gravitino the LSP (~1 keV/c^2).



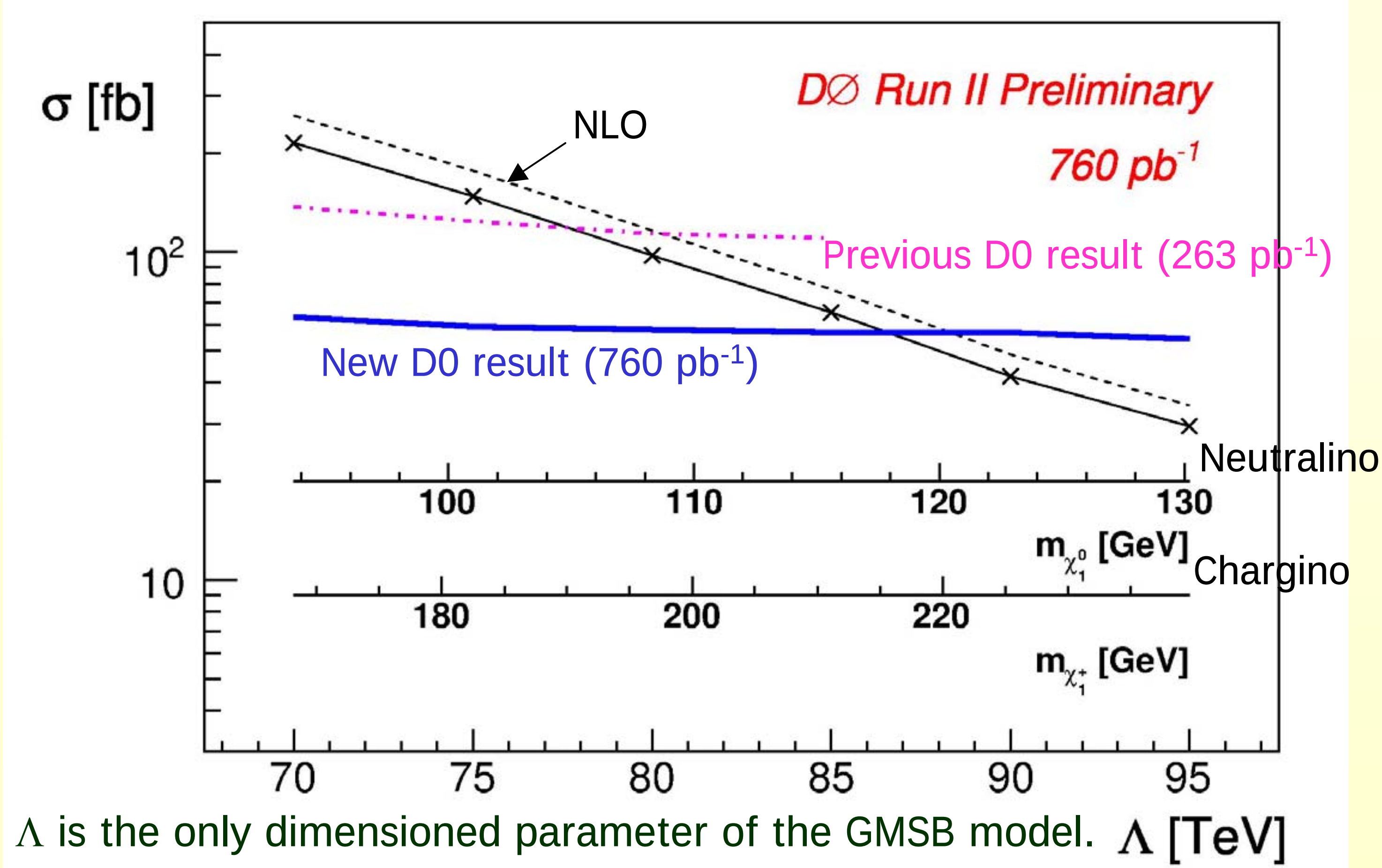
D0 with 760 pb^{-1}:

- ✓ 2 photons (E_T>25 GeV)
- ✓ MET > 45 GeV

SM expect: 2.1 events

Observation: 1 event

New constraints for this process

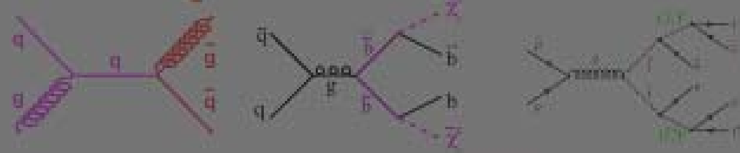


Λ is the only dimensioned parameter of the GMSB model.

OUTLINE

RPC

SQUARKS AND GLUINOS



MET+jets

$M_{gl} \sim M_{sq} >$ ~~[illegible]~~ GeV/c^2 387

$M_{sb} >$ ~~[illegible]~~ GeV/c^2 220

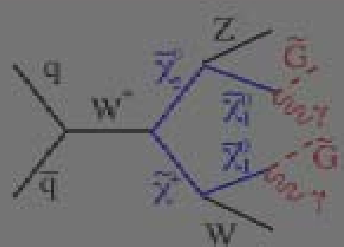
$M_{st} >$ ~~[illegible]~~ GeV/c^2 175

CHARGINOS AND NEUTRALINOS

3-leptons

$M_{charg} >$ ~~[illegible]~~ GeV/c^2 127

GMSB CHARGINO/NEUTRALINO

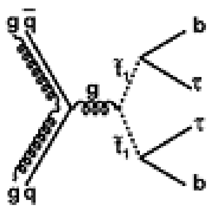


$\gamma\gamma$ + MET

$M_{charg} >$ ~~[illegible]~~ GeV/c^2 220 $M_{neutr} >$ ~~[illegible]~~ GeV/c^2 120

RPV

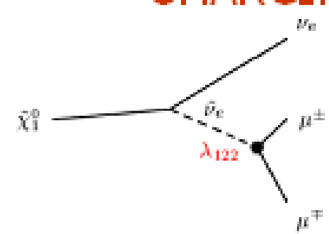
STOP



b-jets and taus

$M_{stop} > 122$ GeV/c^2

CHARGINO/NEUTRALINO

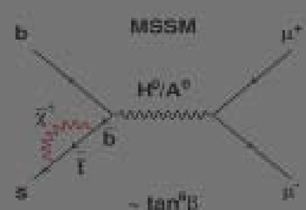


4-leptons

$M_{neutr} > 45$ GeV/c^2

INDIRECT

INDIRECT SEARCHES: $B_S \rightarrow \mu\mu$



Dimuon events

$BR(Bs \rightarrow \mu\mu) < 2.0 \cdot 10^{-7}$

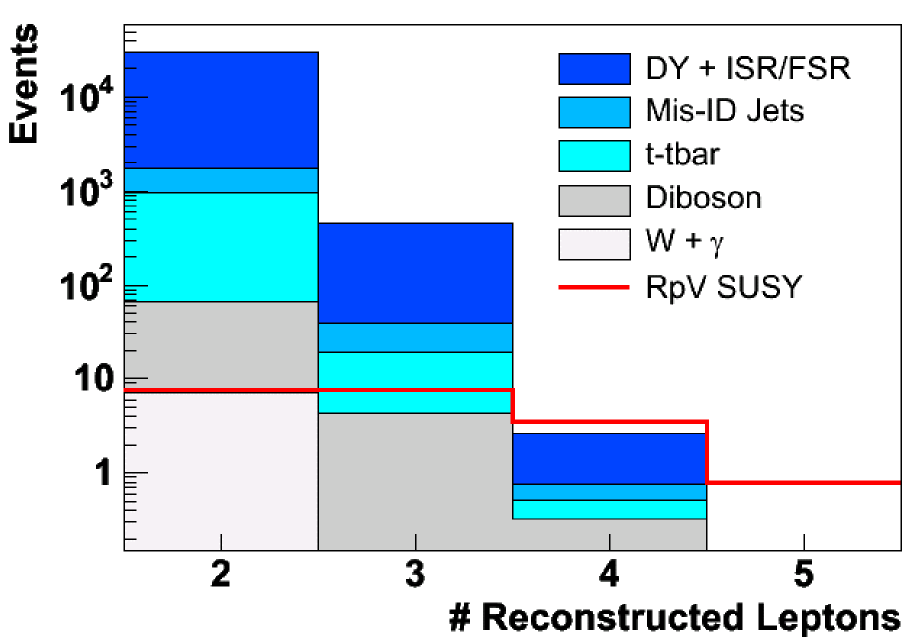
RPV: CHARGINO/NEUTRALINO

ASSUMPTIONS

- ✓ Only first term of W_{RPV} is considered (protect proton lifetime)
- ✓ Charge current universality → $|\lambda|<0.135$ GeV
- ✓ RPV vertex: only in the last decay.
- ✓ The decay is inside the detector
- ✓ In general: $\lambda_{121} > \lambda_{122} >> \lambda_{133}$
  - ➢ CDF: performing analyses only in λ_{121} and λ_{122}
  - ➢ D0: analysing also λ_{133} (high tanβ, low m_0)

$$W_{RPV} = \lambda_{ijk} L^i L^j \overline{E}^k + \ldots$$

i,j,k denote the leptonic families involved.



A pair of $\tilde{\chi}_1^0$ → at least 4 leptons and two neutrinos

Also optimizing for 3 leptons to improve acceptance

Only one RPV at a time
- $\lambda_{121} \neq 0$ → eeee, eeeμ, eeμμ
- $\lambda_{122} \neq 0$ → μμμμ, μμμe, μμee

➡ Low background just for asking 4 leptons or more!

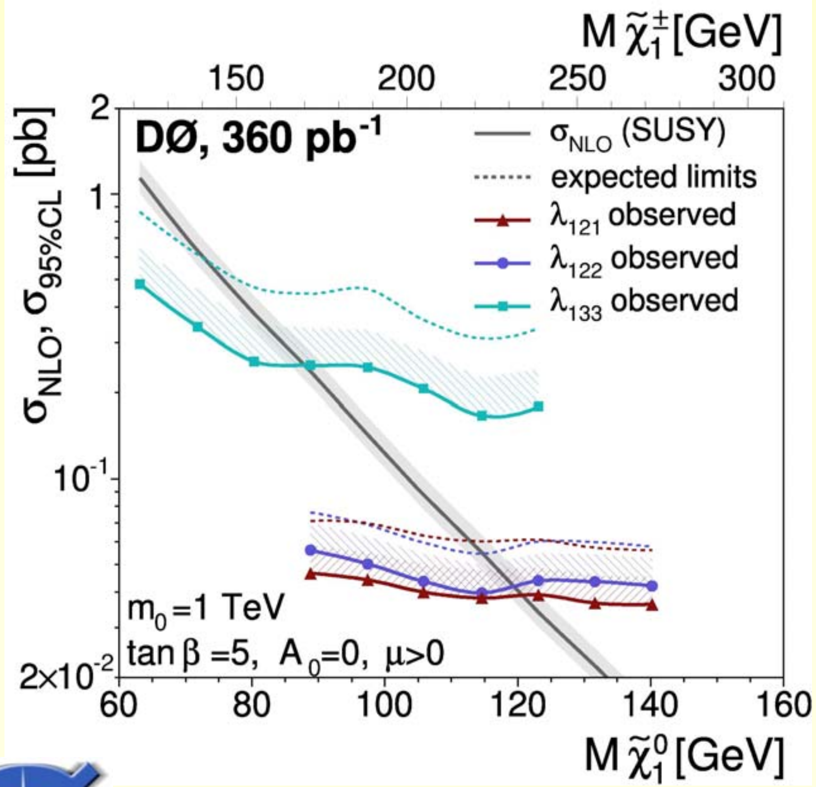
RPV: 4 LEPTONS

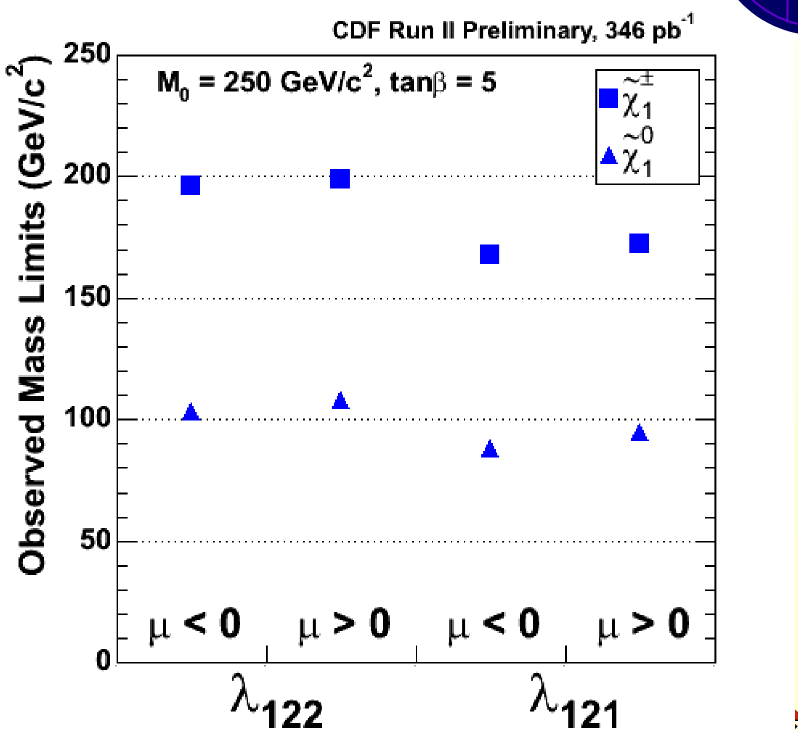
Trilepton Signal Regions		
Dataset	**λ_{121} : eel**	**Λ_{122}: μμl**
Background	2.9 ± 0.8	1.8 ± 1.0
RpV SUSY	3.8 ± 0.4	4.0 ± 0.4
Data	**5**	**1**

Probability to see >=5 with 2.9 ± 0.8 is 17%

≥ 4 Signal Region	
Dataset	**Signal**
Background	0.008 ± 0.004
RpV SUSY	1.5 ± 0.3
Data	**0**

Very low background!

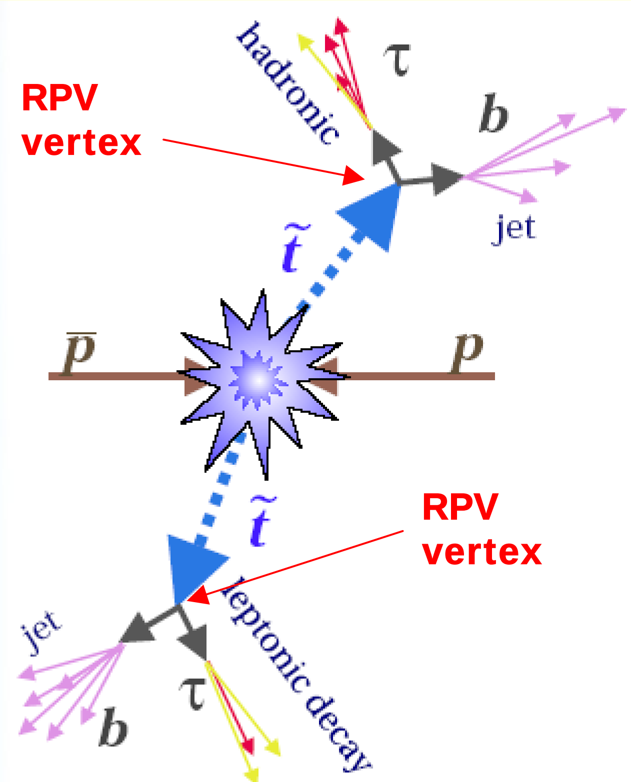




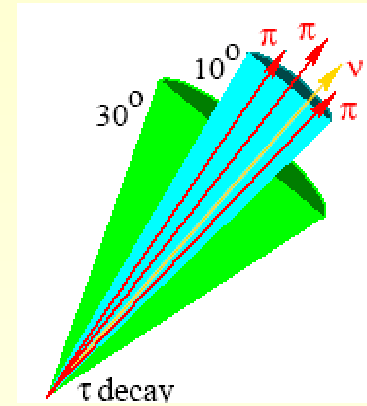
No event found after cuts

m_0=1TeV ; tanβ=5				m_0=100GeV ; tanβ=20
Dataset	**λ_{121} : eel**	**λ_{122}: μμl**	**λ_{133}: eeτ**	**λ_{133}: eeτ**
Background	0.9 ± 0.4	0.4 ± 0.1	1.3 ± 1.7	1.3 ± 1.7
m $\tilde{\chi}_1^0$ (GeV/c²)	119	118	86	115
m $\tilde{\chi}_1^{\pm}$ (GeV/c²)	231	229	166	217

RPV: STOP



- 2 b-jets
- 1 τ hadronic (64.8%)
- 1 τ semi-leptonic (35.2%)



CHALLENGE: τ identification

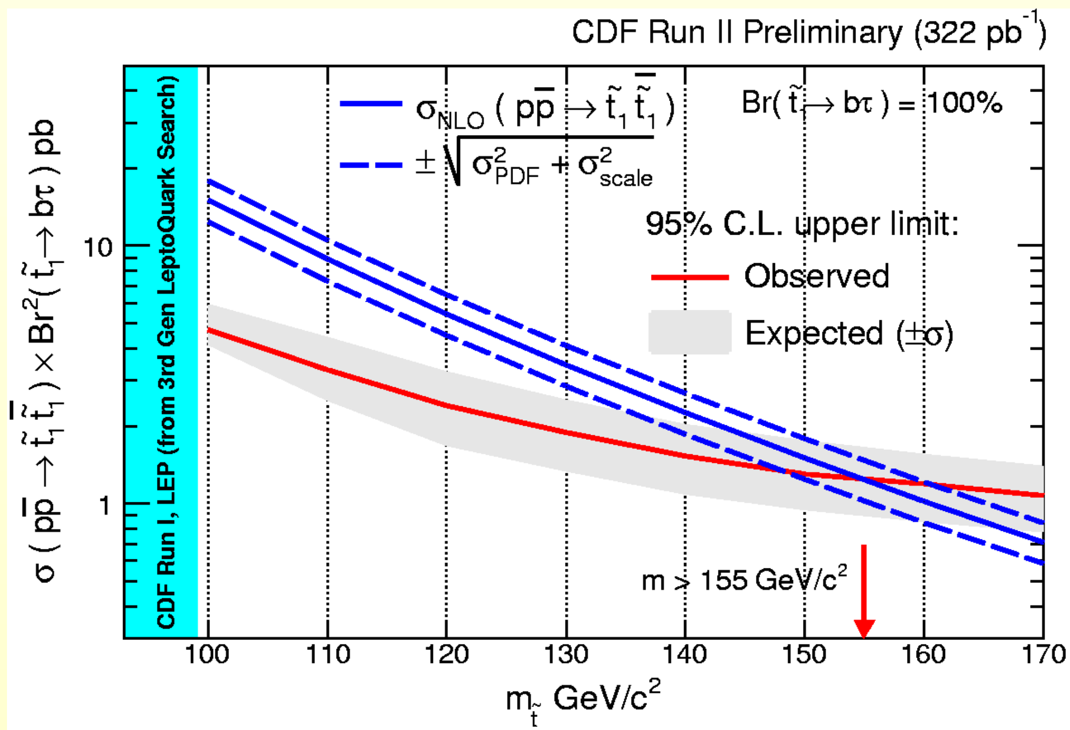
Jets and leptons → τ misidentification

Used Z→ττ for hadronic τ ID: Eff ~ 56%

Expected events: 2.2

Observed events: 2 (1e + 1μ)

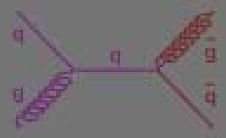
New mass limits are obtained with 322 pb^{-1}

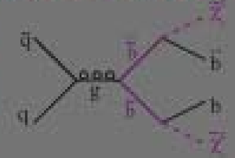


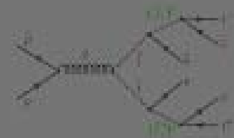
OUTLINE

RPC

SQUARKS AND GLUINOS







MET+jets

$M_{gl} \sim M_{sq} >$ ~~[illegible]~~ GeV/c² 387

$M_{sb} >$ ~~[illegible]~~ GeV/c² 220

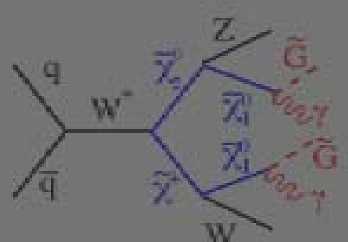
$M_{st} >$ ~~[illegible]~~ GeV/c² 175

CHARGINOS AND NEUTRALINOS

3-leptons

$M_{charg} >$ ~~[illegible]~~ GeV/c² 127

GMSB CHARGINO/NEUTRALINO

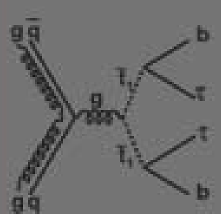


$\gamma\gamma$ + MET

$M_{charg} >$ ~~[illegible]~~ GeV/c² 220 $M_{neutr} >$ ~~[illegible]~~ GeV/c² 120

RPV

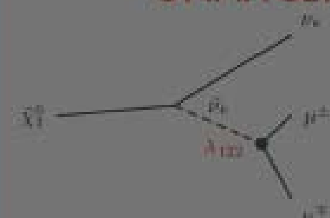
STOP



b-jets and taus

$M_{stop} >$ ~~[illegible]~~ GeV/c² 155

CHARGINO/NEUTRALINO

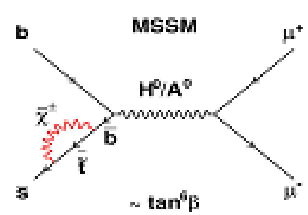


4-leptons

$M_{neutr} >$ ~~[illegible]~~ GeV/c² 120

INDIRECT

INDIRECT SEARCHES: $B_S \rightarrow \mu\mu$



Dimuon events

$BR(Bs \rightarrow \mu\mu) < 2.0 \cdot 10^{-7}$

INDIRECT SEARCHES: $B_S \rightarrow \mu\mu$

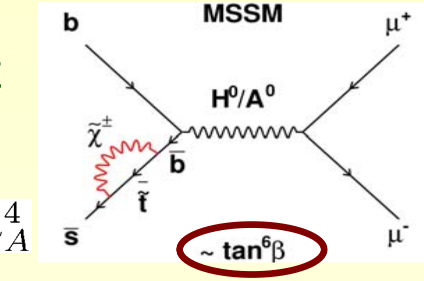
SM: $B_s \to \mu\mu$ is heavily suppressed:

$$BR(B_s \rightarrow \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

(Buchalla & Buras, Misiak & Urban)

SUSY: BR enhancement by 1-3 orders of magn.

$$BR(B_s \rightarrow \mu^+\mu^-) \propto \tan^6\beta / m_A^4$$

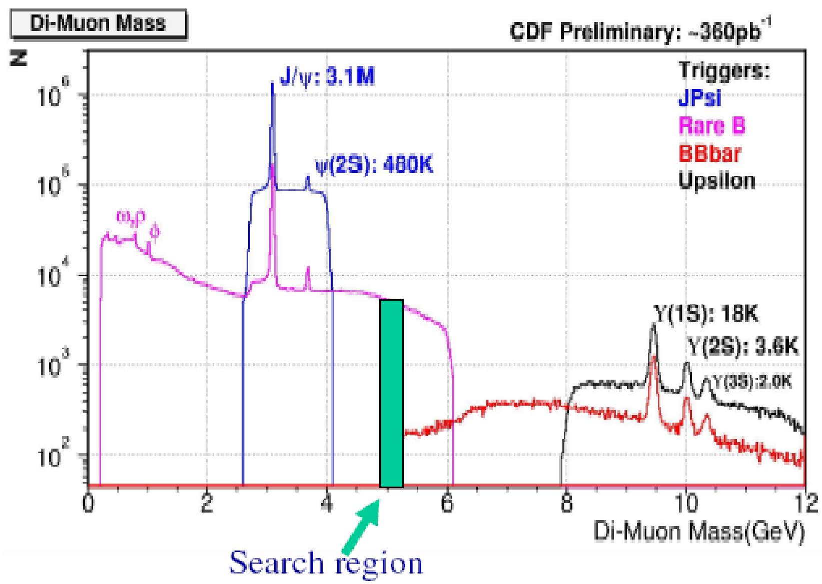


(Babu, Kolda: hep-ph/9909476+ many more)

New CDF result: 780 pb^{-1}

Using $B^+ \rightarrow J/\psi\ K^+$ for normalization

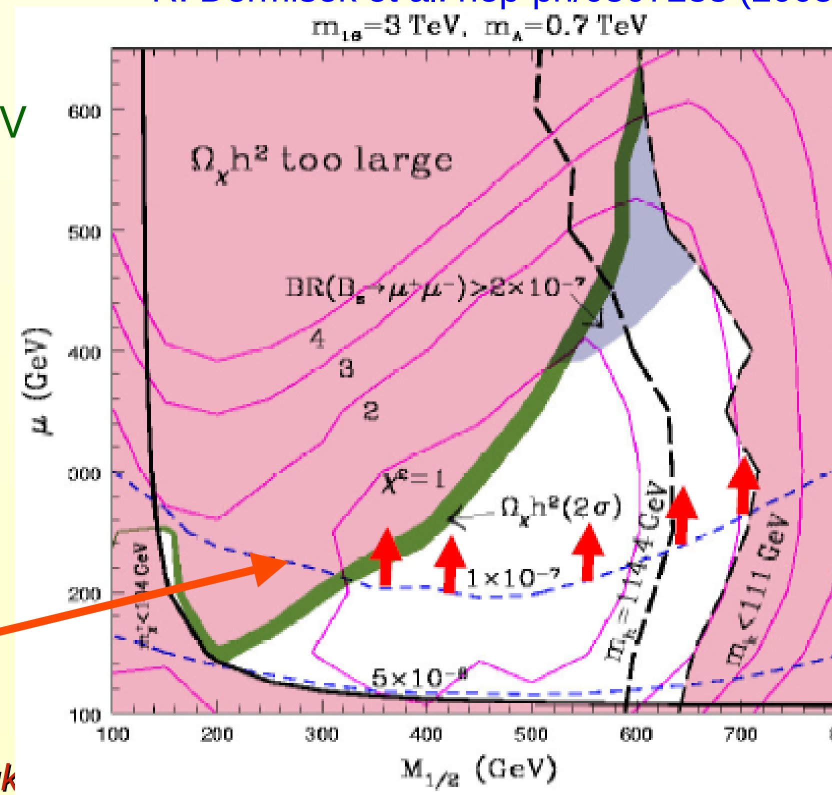
$$BR(B_s \rightarrow \mu^+\mu^-) = \frac{N_{Bs}}{N_{B+}} \frac{\alpha_{B+} \cdot \varepsilon_{B+}^{total}}{\alpha_{Bs} \cdot \varepsilon_{Bs}^{total}} \frac{f_{b \rightarrow B+}}{f_{b \rightarrow Bs}} BR(B^+ \rightarrow J/\psi K^+) BR(J/\psi \rightarrow \mu^+\mu^-)$$



High resolution!

$\sigma(M\mu\mu) \sim 0.23$ MeV

R. Dermisek et al. hep-ph/0507233 (2005)



Found 1 event; expected background 0.9±0.3

New limits at 95% C.L:

BR($B_s \rightarrow \mu\mu$) < 1.0·10^{-7}

DISCLAIMER

Due to time constraints I couldn't cover all the analyses for both detectors.

Some of the most interesting analyses, not covered here, are:

- Stopped gluinos (split SUSY) (350 pb^{-1})
- Long lived charginos (AMSB) (380 pb^{-1})
- Resonant slepton production (RPV) (380 pb^{-1})
- sneutrino→eμ (RPV) (344 pb^{-1})

You can find them all at the CDF or D0 webpages:

http://www-cdf.fnal.gov/physics/exotic/exotic.html

http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm

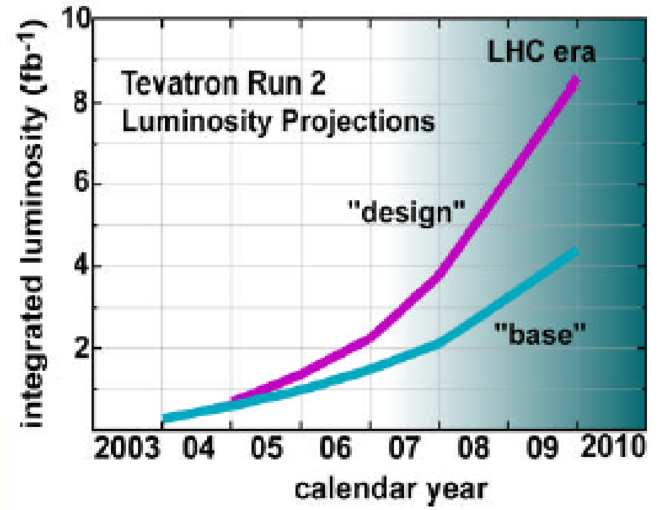
SUMMARY

- Tevatron and detectors are performing very well:
  - ✓ 1.6 fb^{-1} delivered (collected: 1.3 fb^{-1})
  - ✓ Upgrades have been performed during this shutdown
  - ✓ This week Tevatron will start again fully operational and 2 fb^{-1} benchmark is getting closer.

- Plenty of SUSY analyses going on at CDF/D0 detectors. They are being improved with the addition of new data.

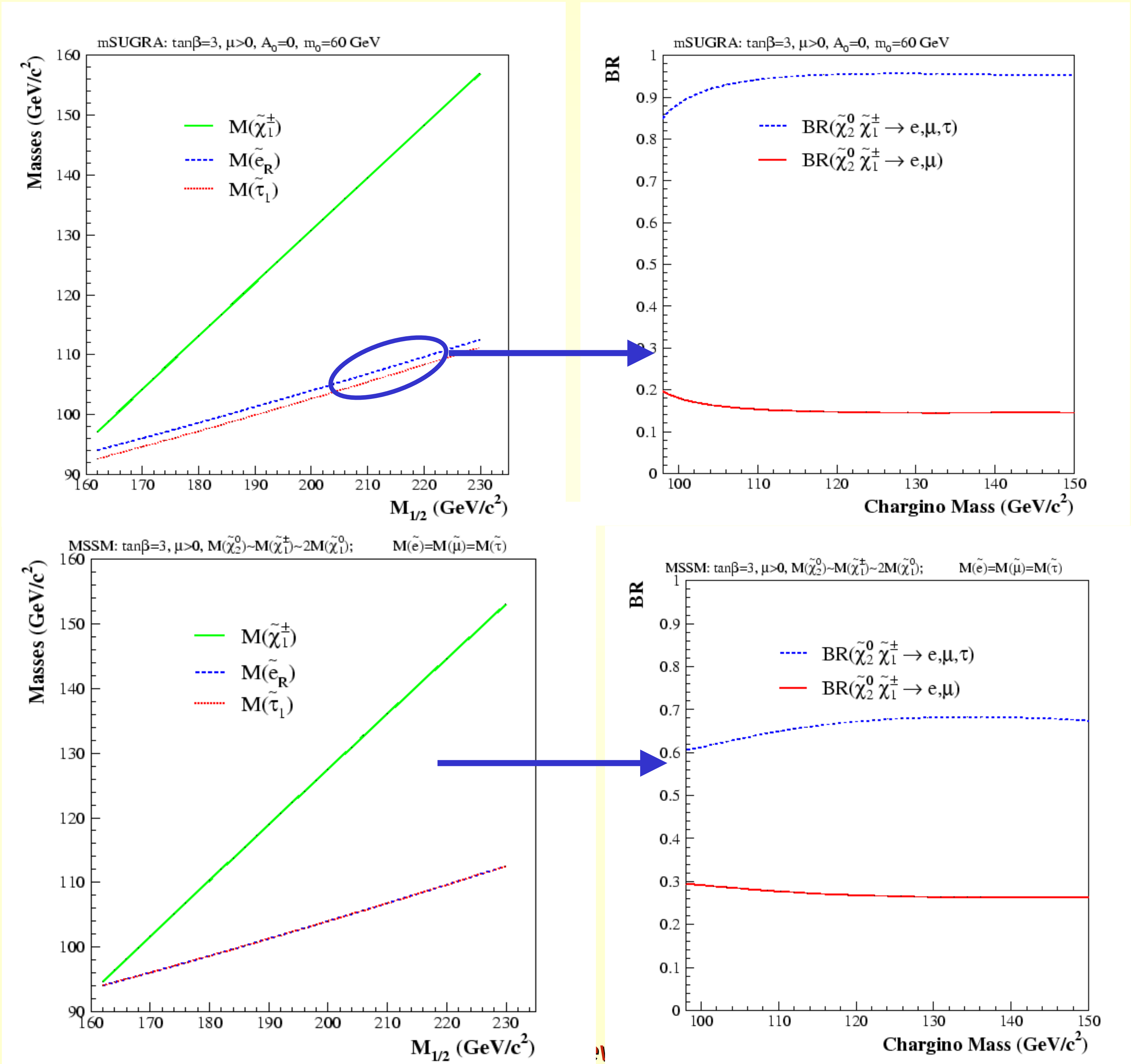
- No SUSY particles have been discovered yet but both direct and indirect analyses are constraining the SUSY parameter space.

Tevatron will keep constraining the SUSY parameters until the LHC era… and perhaps a surprise is found!



BACKUPS

Different 3-Leptons Scenarios



In Standard mSugra the BR into taus is enhanced

↓

smaller acceptance

CDF 3-Leptons Analyses

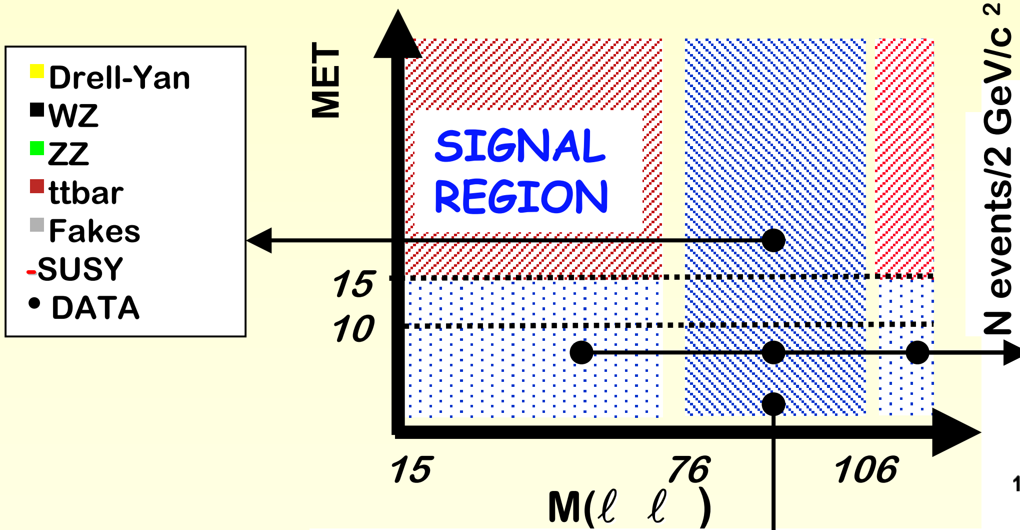
CHANNEL	LUM	TRIGGER PATH
$e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$	710	High p_T Single Lepton
$\mu\ell$ + e/μ	750	High p_T Single Lepton
ee + e/μ	350	High p_T Single Lepton
μμ + e/μ	310	Low p_T Dilepton
ee + track	610	Low p_T Dilepton

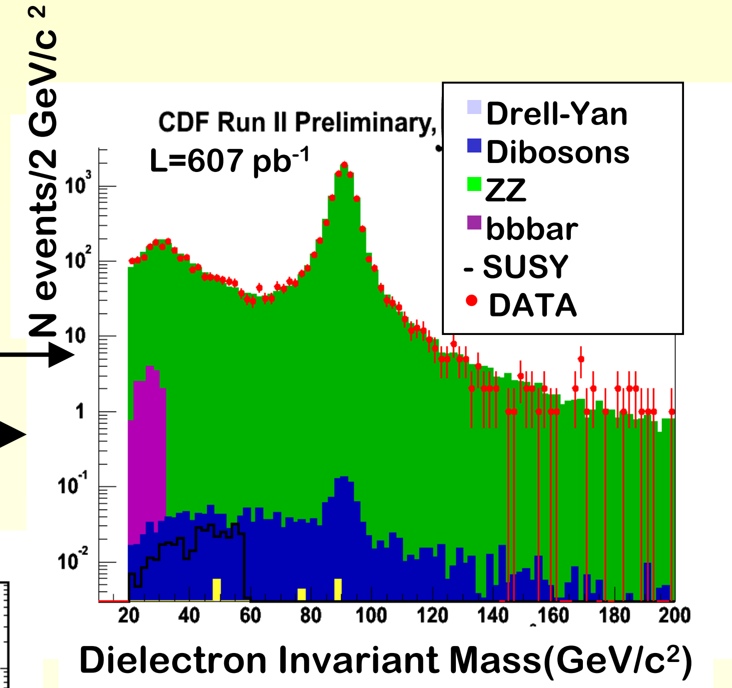
No third lepton requirement
=> Higher acceptance

Use e/mu only
=>Very small backgrounds

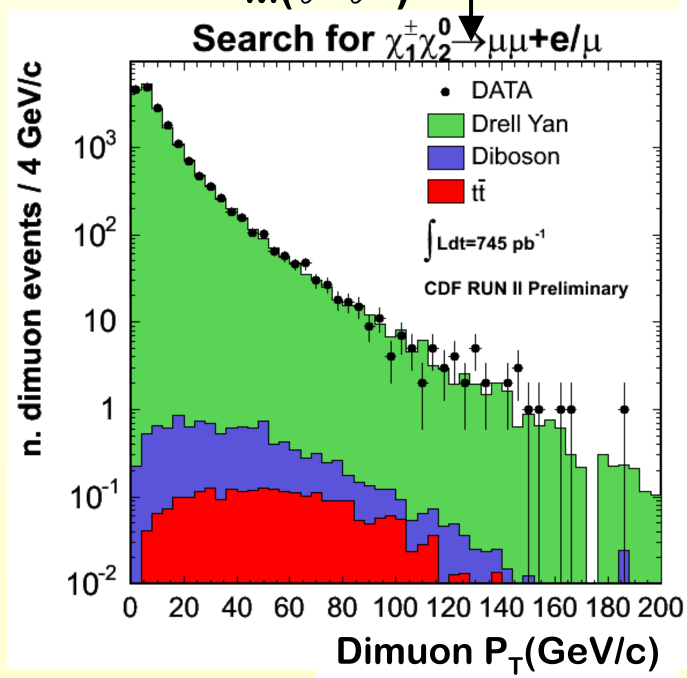
Sensitive to taus as 3rd lepton
=> Keeps acceptance at high tanβ

CDF 3-Leptons Control Regions



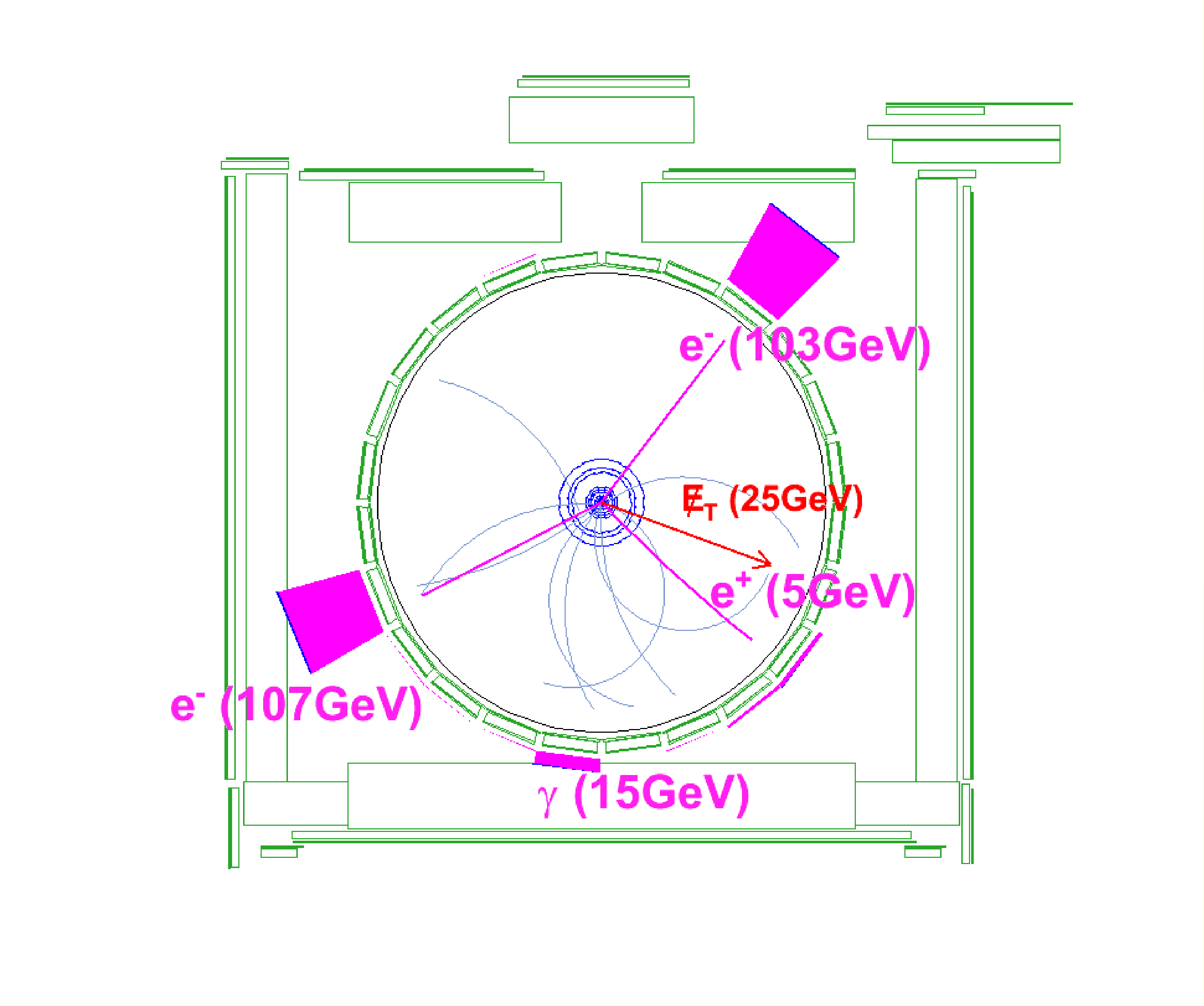


MET (GeV)

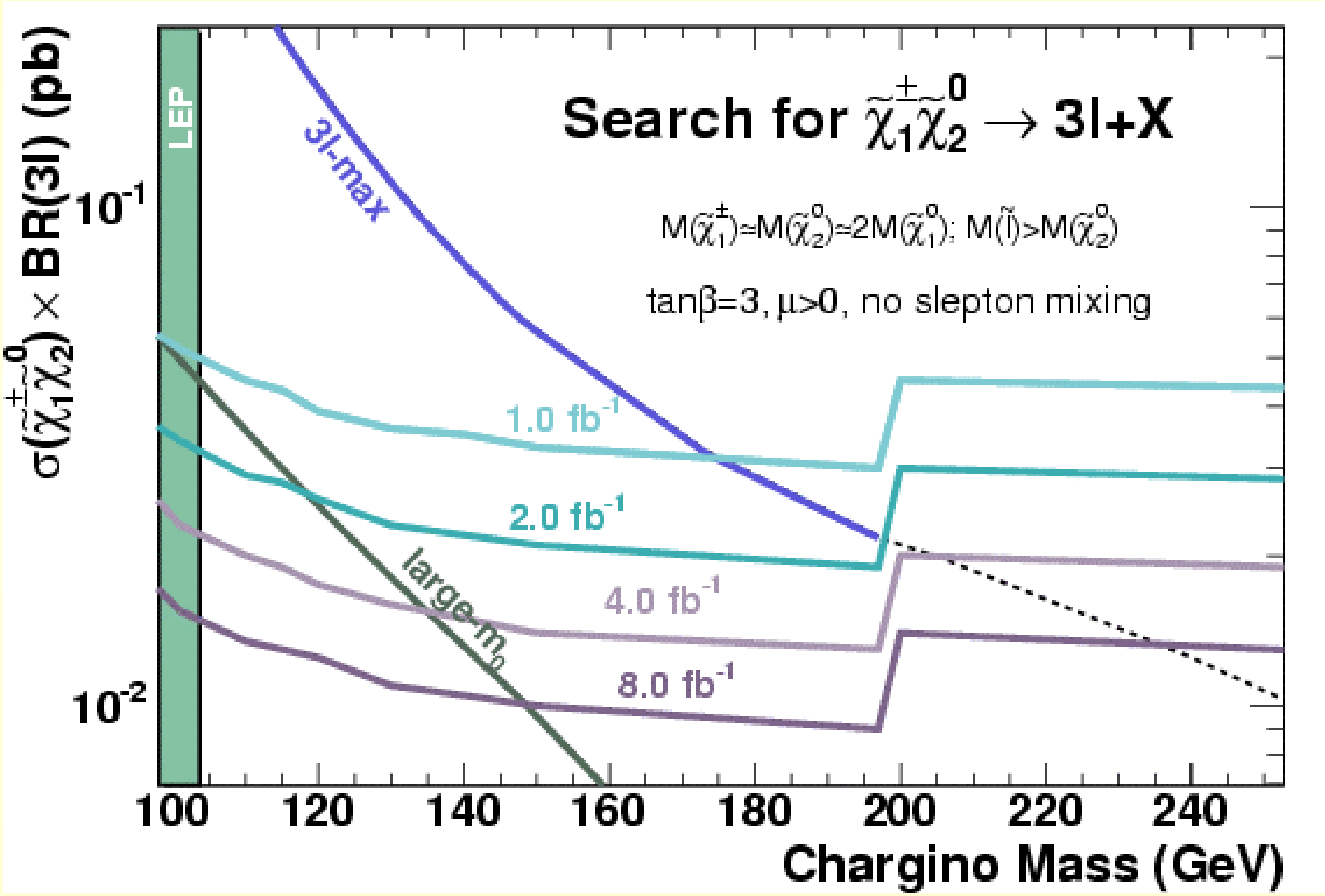


LS-dilepton analysis has additional Control Regions to test conversion removal

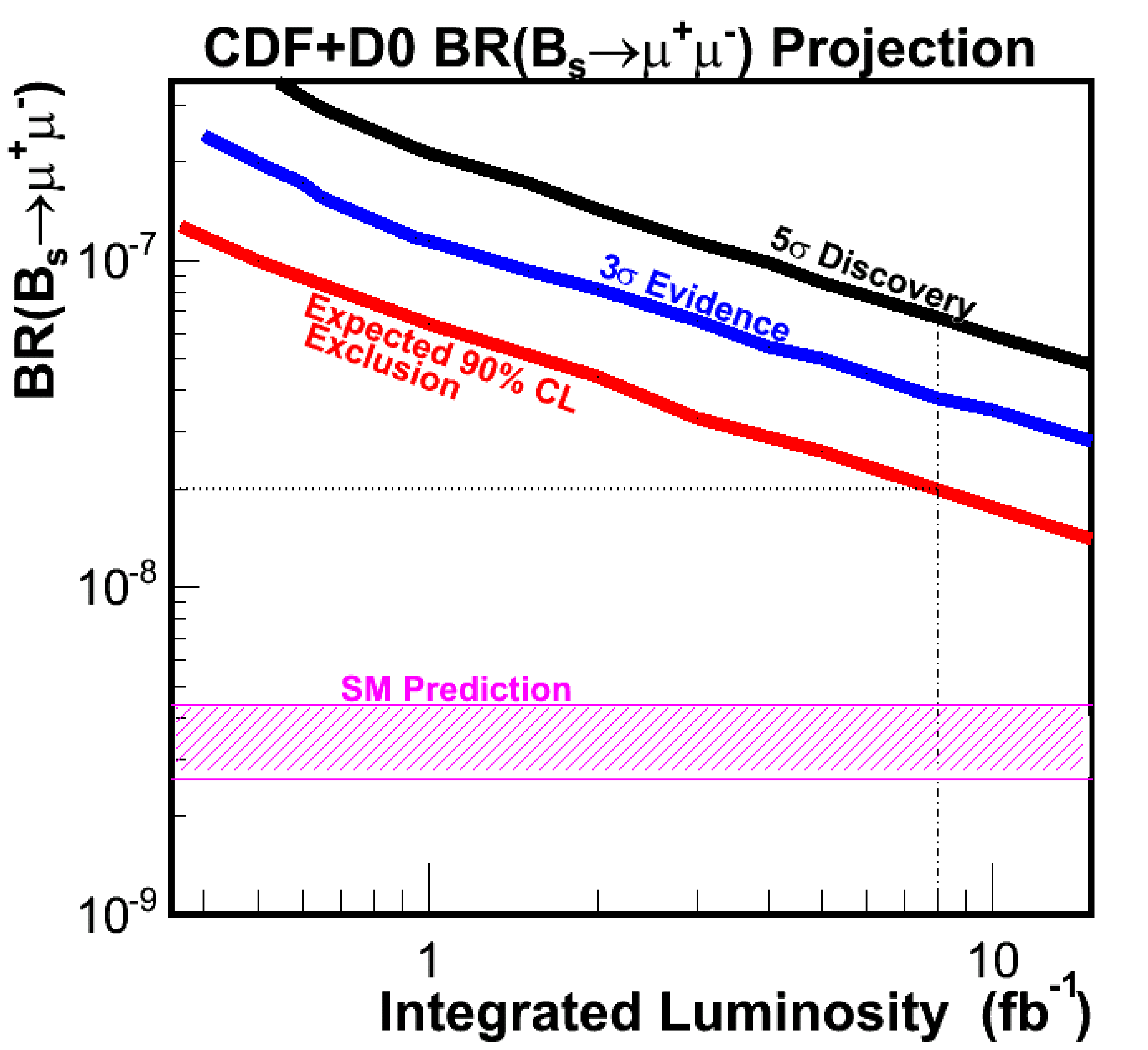
CDF 3-electron Event

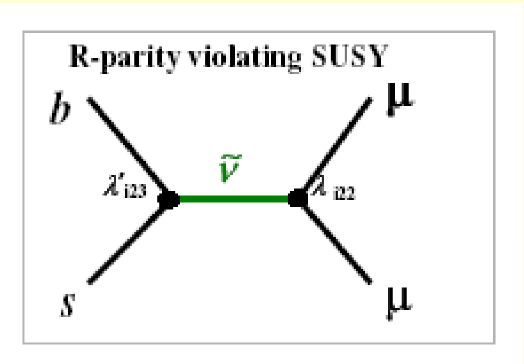


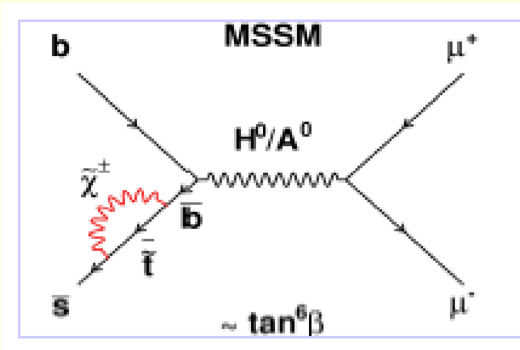
3-LEPTONS: PROJECTIONS



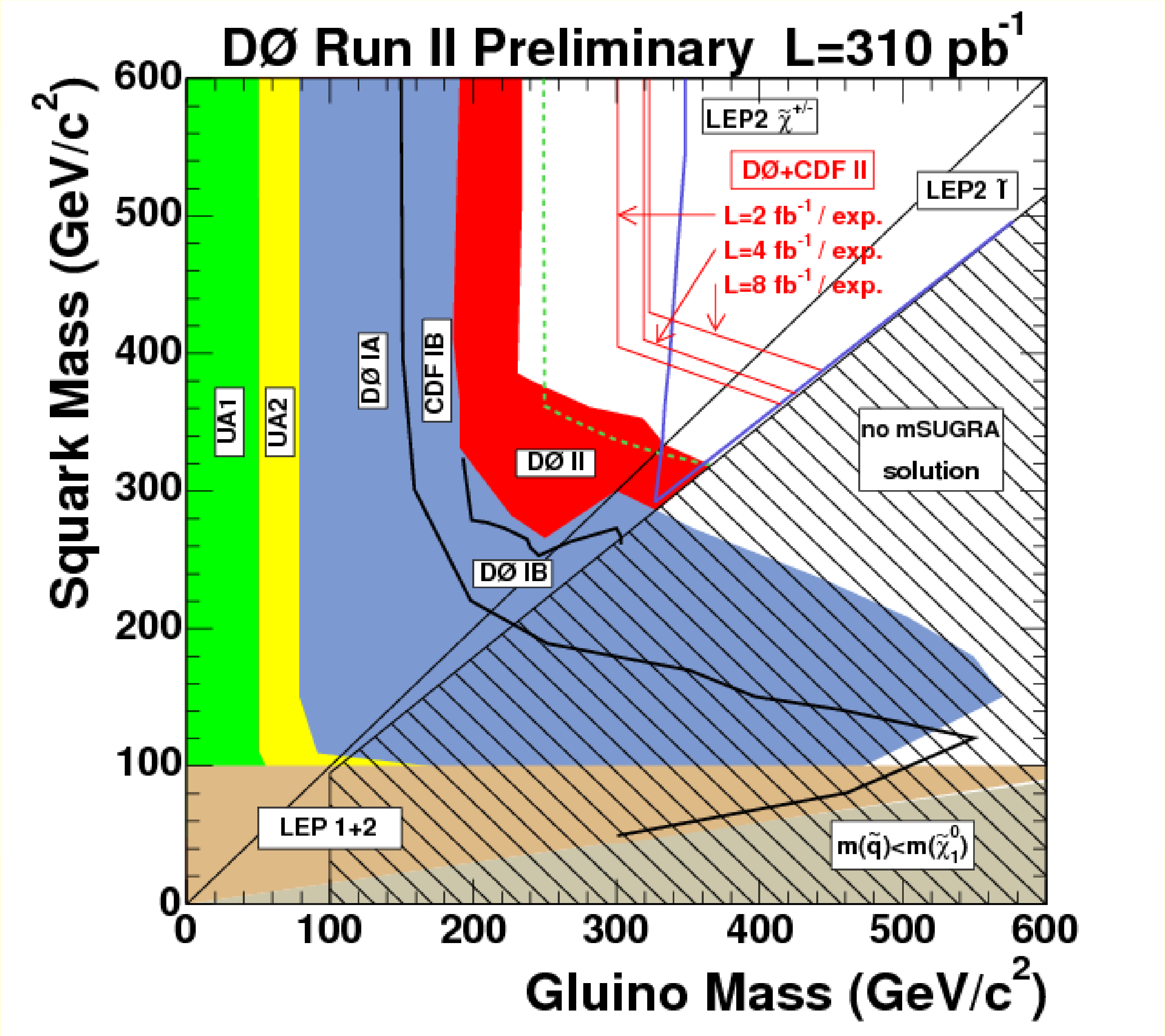
Bs→μμ: PROJECTIONS







SQUARKS/GLUINOS: FUTURE



SQUARKS AND GLUINOS