Searches for Supersymmetry at the Tevatron

Introduction

Squarks and Gluinos → Acoplanar jets

Stop / Sbottom

Charginos and Neutralinos → Trileptons

GMSB → Di-photons + MET

Off the beaten path

Conclusions

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July 21, 2008

The Physics Landscape

There are many possible models of new physics that could easily produce results in 1 fb^{-1}.

While SUSY may be popular, all that is certain is a high probability for some sort of new physics just around the corner :

Radiative corrections to the Higgs mass

Gravitation?

Three generations?

.....

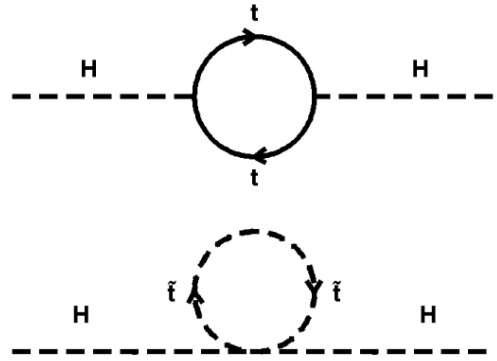
If there is one

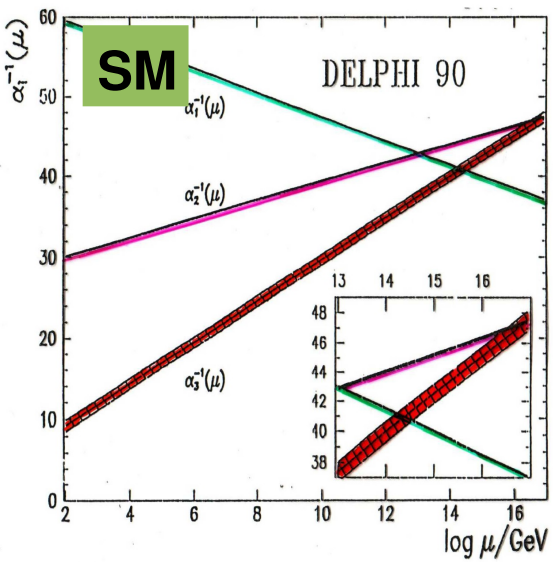
Unification of couplings?

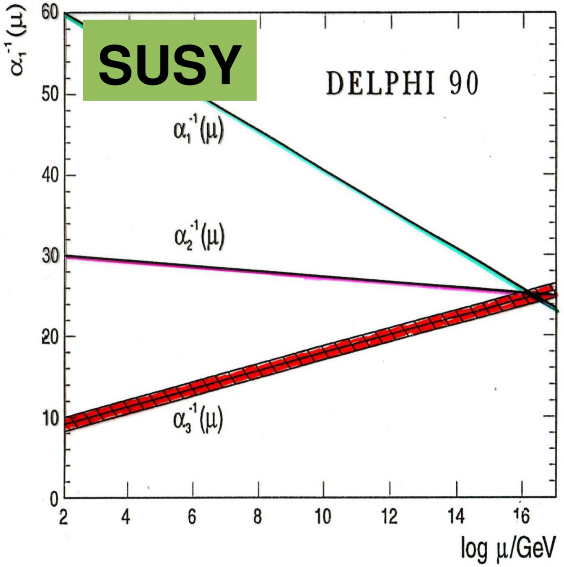
Dark matter?

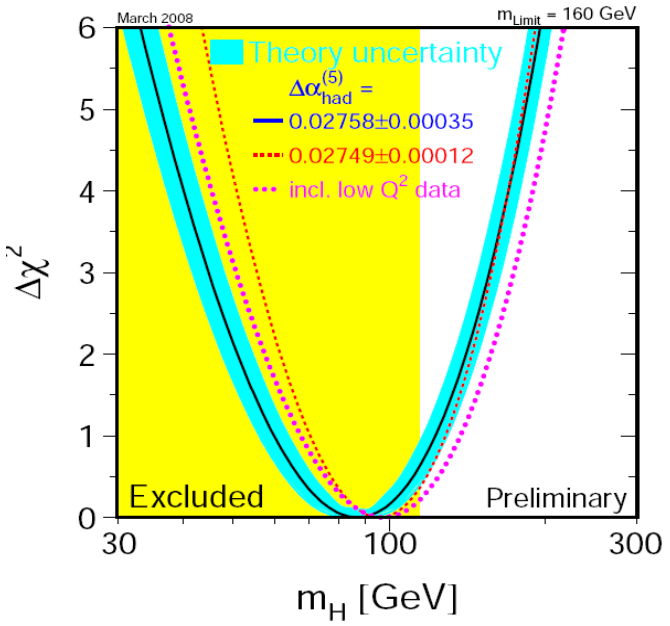
Supersymmetry

- Supersymmetry (SUSY): fundamental symmetry , relating bosons and fermions
- Stabilizing Higgs mass ("fine-tuning")
  - m(Higgs) < 135 GeV (MSSM)
  - In good agreement with expectations from EW fits
- "Running" of couplings is sufficiently modified to allow grand unification at a single scale









http://lepewwg.web.cern.ch/LEPEWWG

- LSP (Lightest SUSY Particle) is candidate for dark matter

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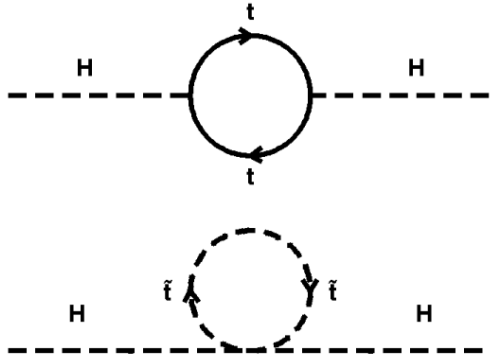

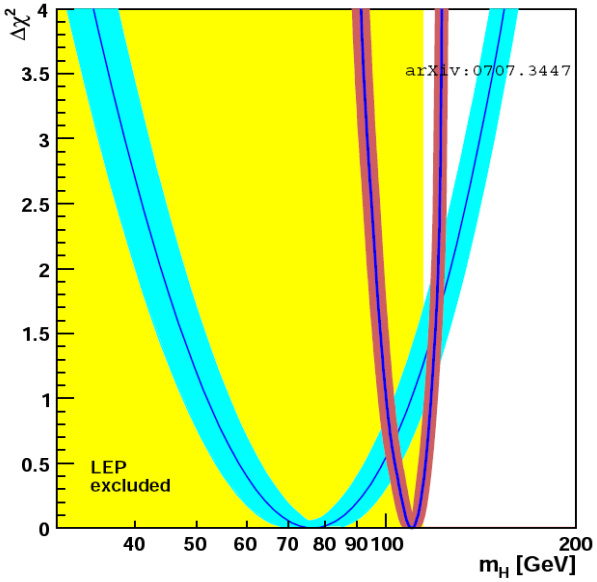

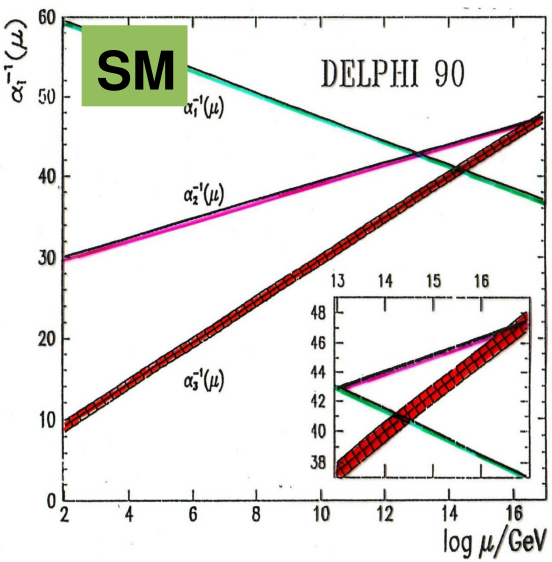

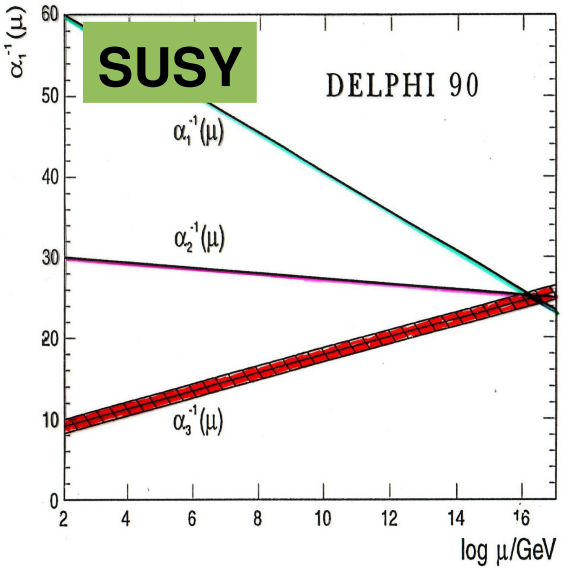

- LSP (Lightest SUSY Particle) is candidate for dark matter

Supersymmetry

Spin 0	1/2	1	3/2	2
Higgs $h^0,H^0,A,H^\pm$	Gluino $\tilde{g}$	Gauge	Gravitino $\tilde{G}$	Graviton G
Sleptons $\tilde{l}$	Leptons	bosons		
Squarks $\tilde{q}$	Quarks			
	Gauginos $\tilde{\chi}^\pm,\tilde{\chi}^0$			

- **Signatures depend on model assumptions** (e.g. MSSM: > 100 parameters)
  - R-parity conservation: $\not{E}_T$ **due to undetected LSP** **R-Parity** $R_p =$ **+ 1 SM, – 1 SUSY**
  - Different models for SUSY breaking mechanism have various phenomenological consequences: **jets, leptons, photons, long-lived particles**
- **Benchmark-Scenarios** allow systematic study of supersymmetric models with realistic effort, simultaneously incorporating experimental and theoretical bounds (e.g. “Snowmass Points and Slopes”)
- LEP searches for charginos, sleptons, higgs: $m(\tilde{\chi}^\pm)>103.5$ GeV, $m(\tilde{l})>95$ GeV, $m(h)>114.4$ GeV

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At least 32 new particles

- **Signatures depend on model assumptions** (e.g. MSSM: > 100 parameters)
  - R-parity conservation: $\not{E}_T$ **due to undetected LSP** **R-Parity** $R_p = \begin{matrix} +1 & \text{SM} \\ -1 & \text{SUSY} \end{matrix}$
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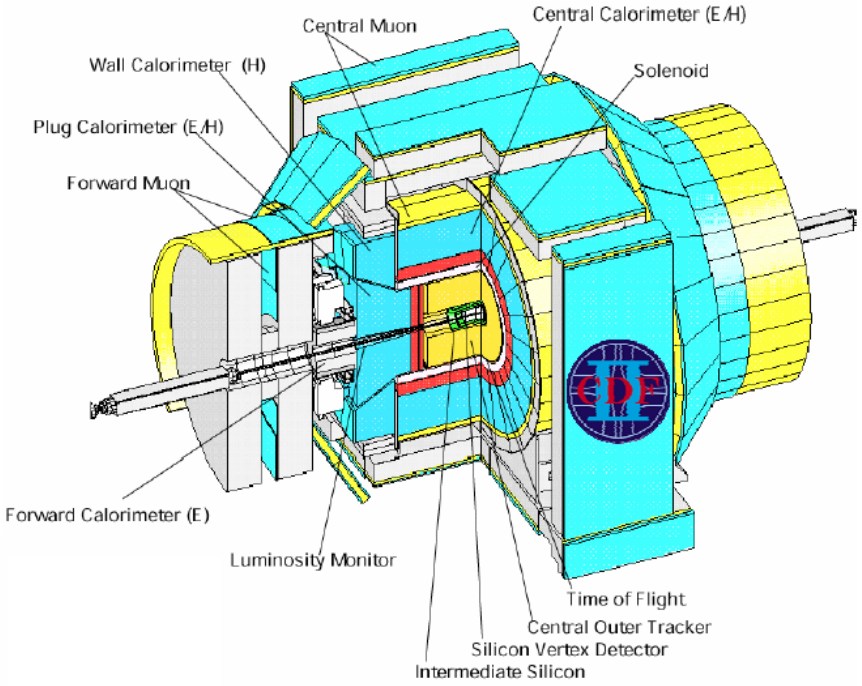
Tevatron: The DØ and CDF Experiments

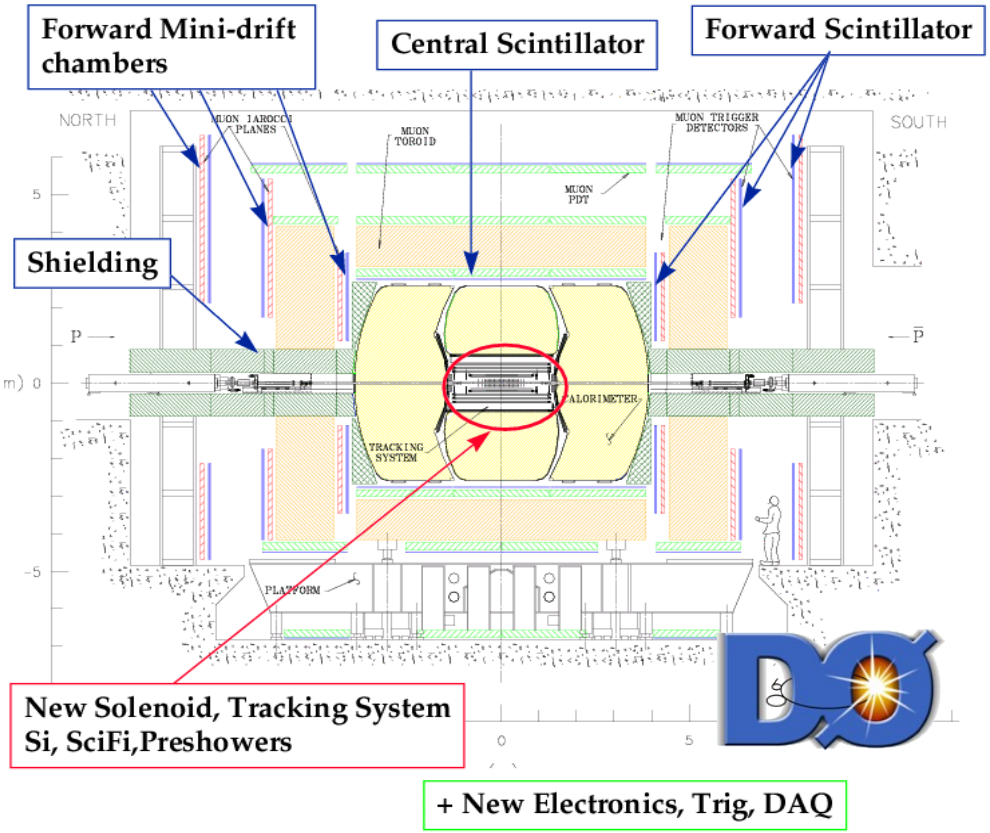
DØ strengths:

Muon system with large acceptance, hermetic calorimetry

CDF strengths:

large Level 1 trigger bandwidth, central tracking



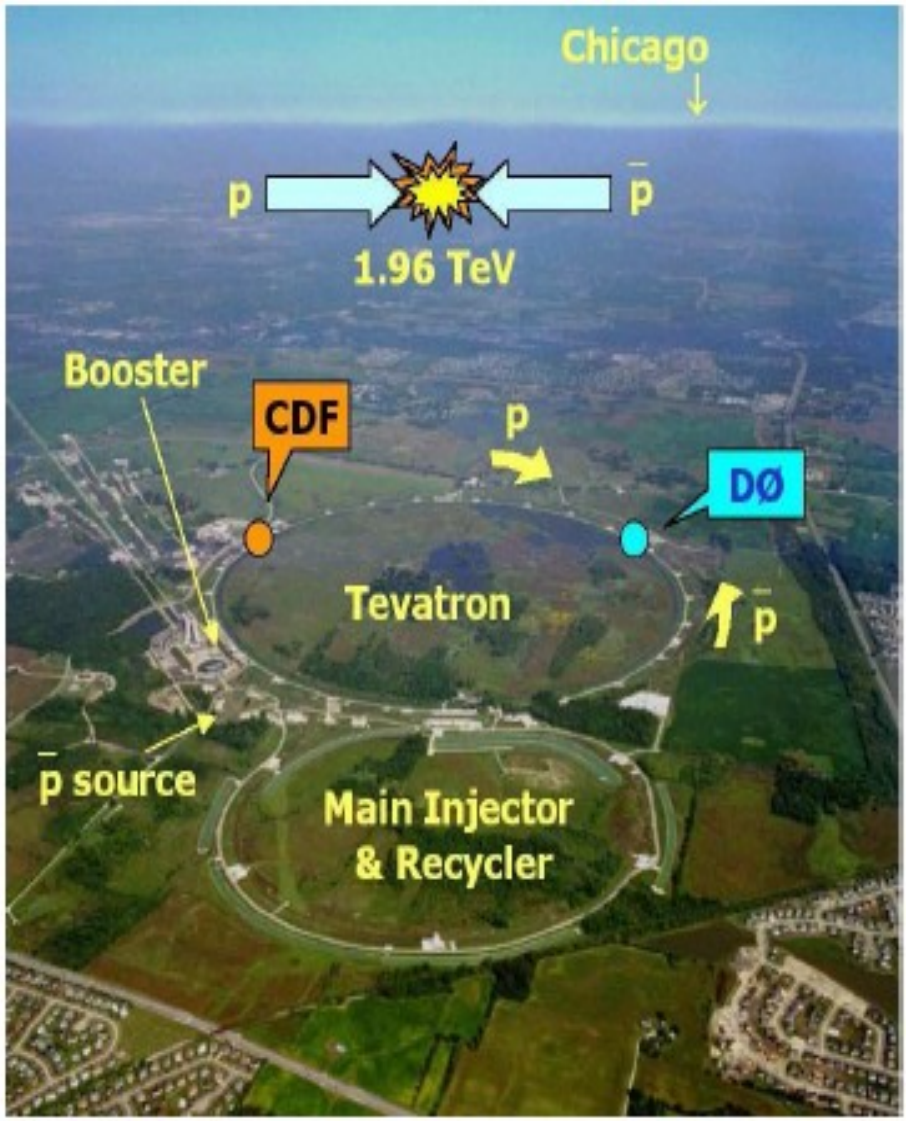


Typically:

Electron acceptance	$\|\eta\| < 2.0 - 3.0$
Muon acceptance	$\|\eta\| < 1.0 - 2.0$
Precision tracking (Si)	$\|\eta\| < 2.0 - 3.0$

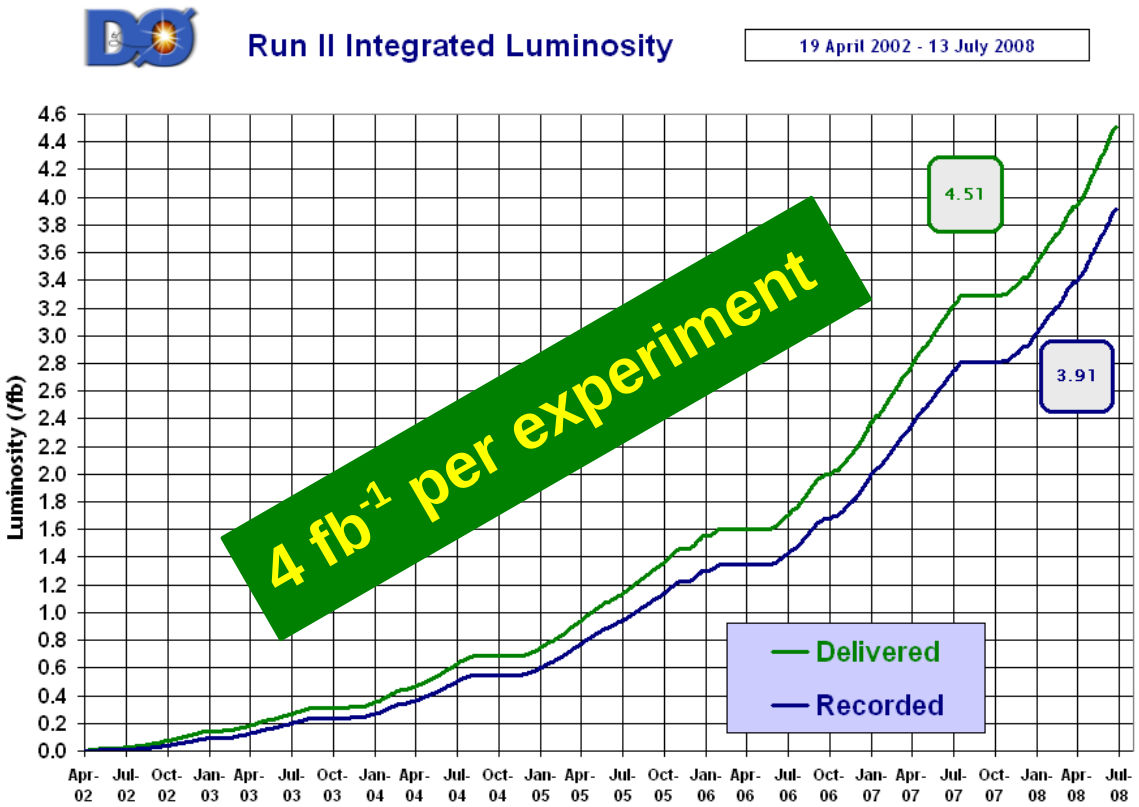
Detectors are well understood and take data with ~80-95% efficiency

Data Samples



Integrated Luminosity:

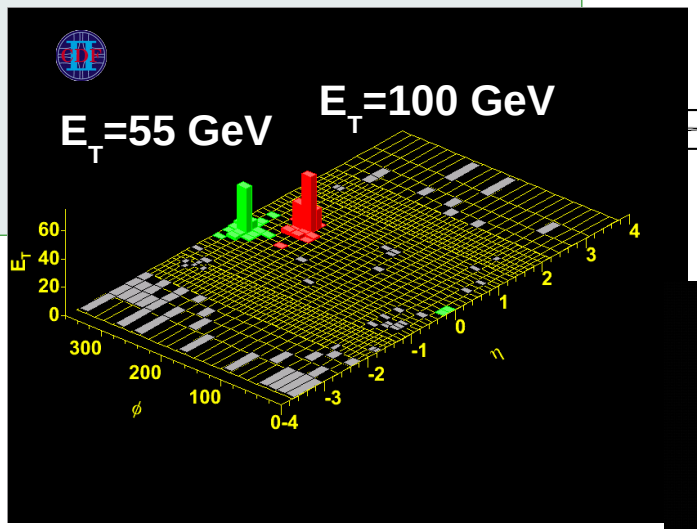
0.1 fb^{-1} / exp.	Run I, 1992-96
1.3 fb^{-1} / exp.	Run IIa, 2002-06
4 – 8 fb^{-1} / exp.	Run IIb, until 2009

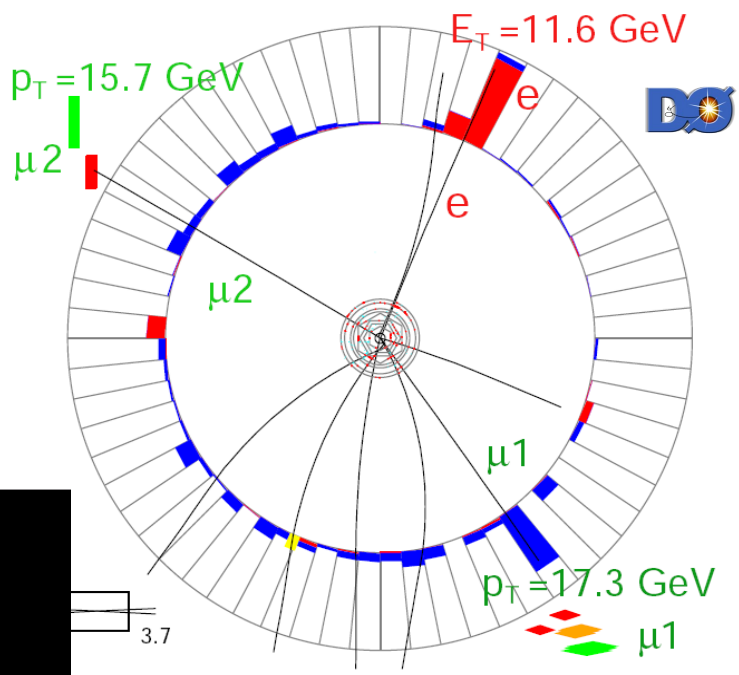


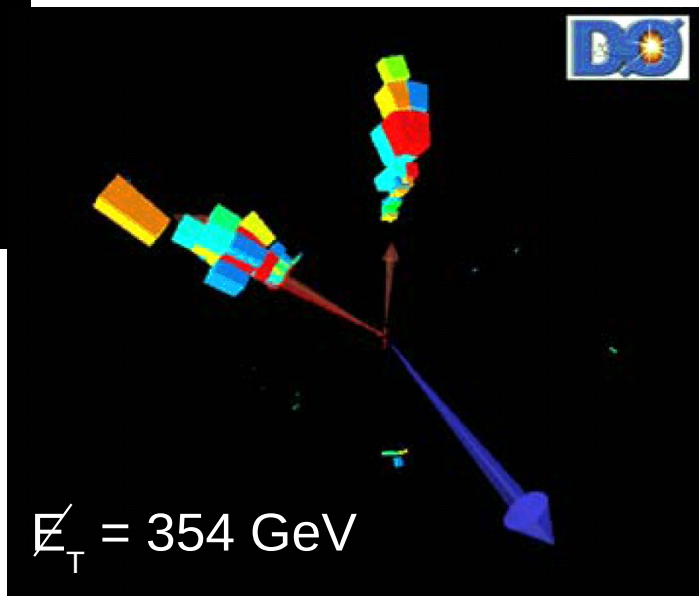
Supersymmetry – Signatures

Studied in great detail is mSUGRA: gravity mediated symmetry breaking, only 4 ½ parameters

- Scalar and gaugino mass at the GUT-scale, **m_0 and $m_{1/2}$**
- Trilinear coupling parameter **A_0**
- **tan β**, ratio of the higgs vacuum expectation values at the electroweak scale
- **sign(μ)**, higgsino mass parameter







Missing transverse energy (LSP)

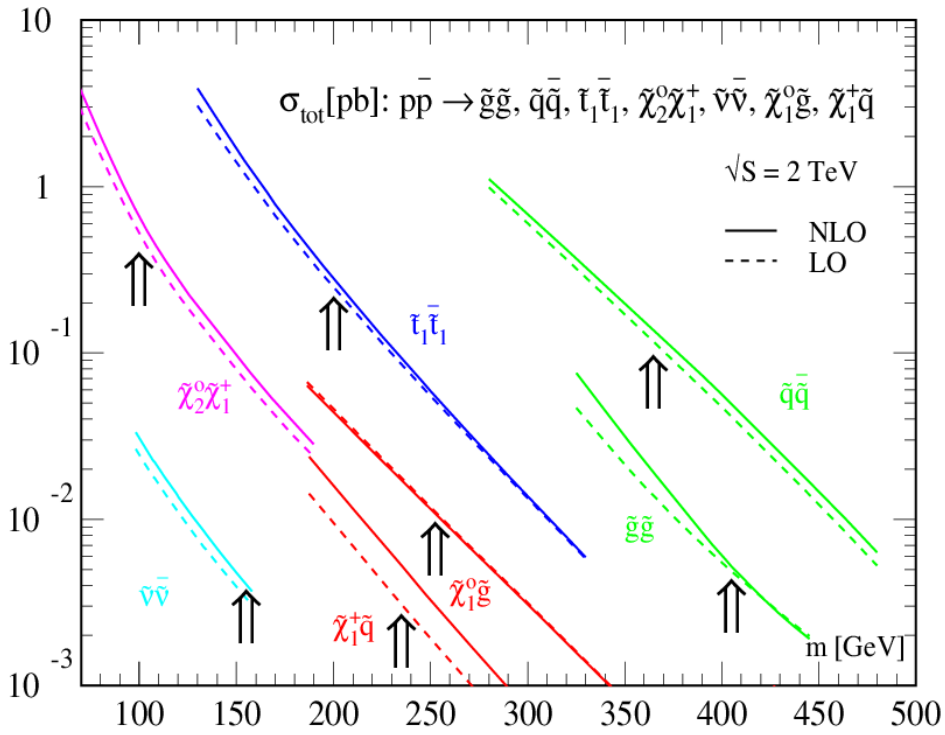
and/or many jets

and/or many leptons from cascade decays

(but: can be soft)

Search Strategies

- **Generic sparticle production**
  - Probe large regions of parameter space
- **Search for sparticles with unusual properties**
  - Small mass differences or couplings
  - Also: different SUSY breaking mechanisms
- SUSY Higgs
- Indirect searches
  - Rare decays
- Global ("model independent") searches



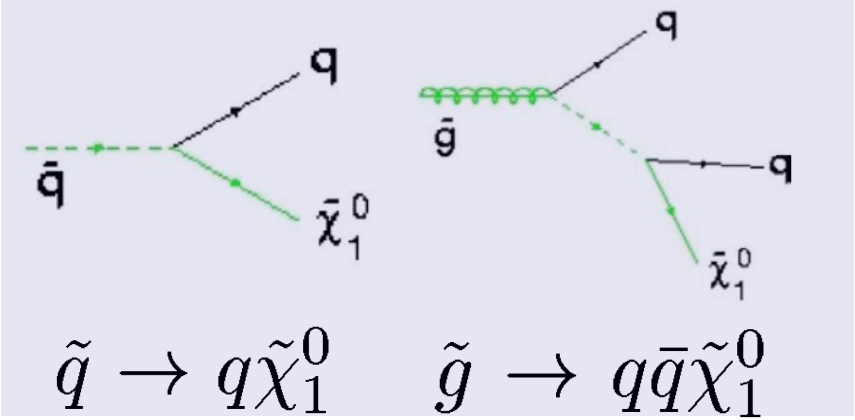
All limits are at 95% CL

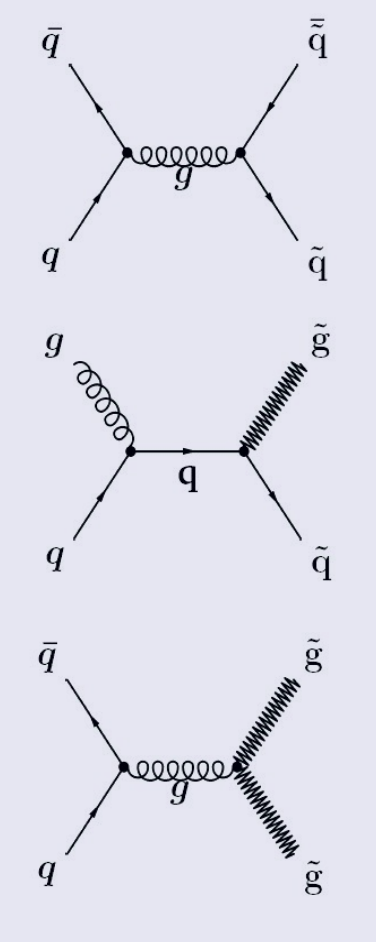
Supersymmetry: Squarks and Gluinos

Hadron collider: LSP assumed stable

large squark-gluino (R_p conserved)

cross sections → ≥ **2 jets + $\not{E}_T$ ("MET")**





Low m_0, m(squark)<m(gluino)

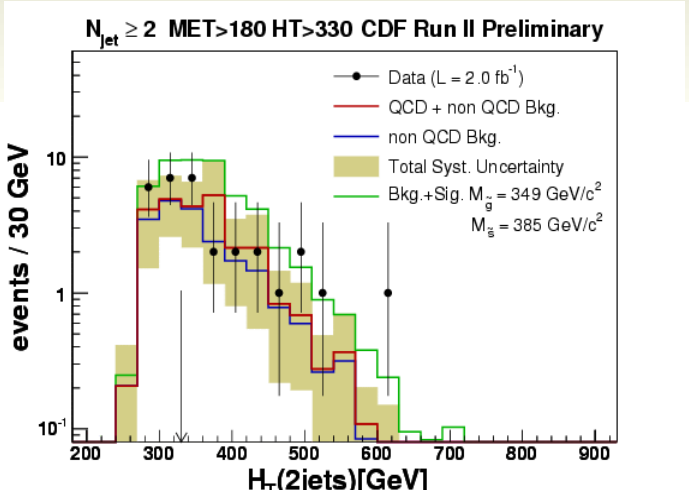
(at least 2 jets)

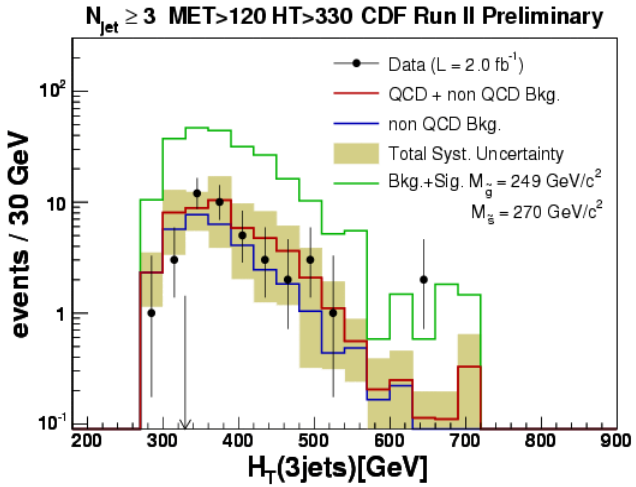
Medium m_0, m(squark)~m(gluino)

(at least 3 jets)

High m_0, m(squark)>m(gluino)

(at least 4 jets)





Important backgrounds:

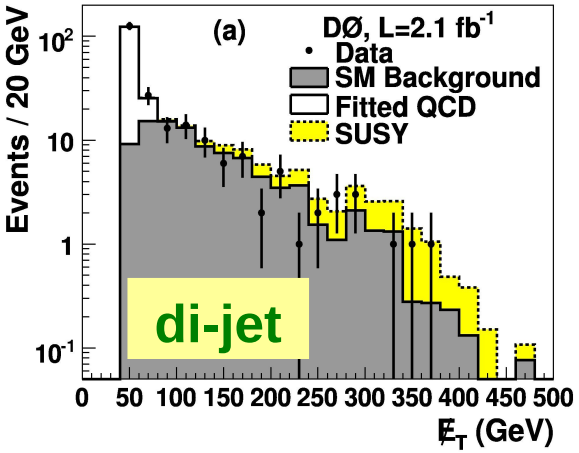
- $Z \rightarrow \nu\nu$ + jets
- Top pairs
- W+jets

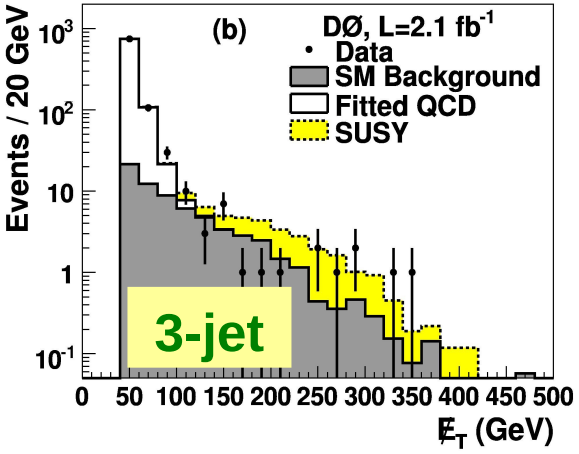
Suppressed using:

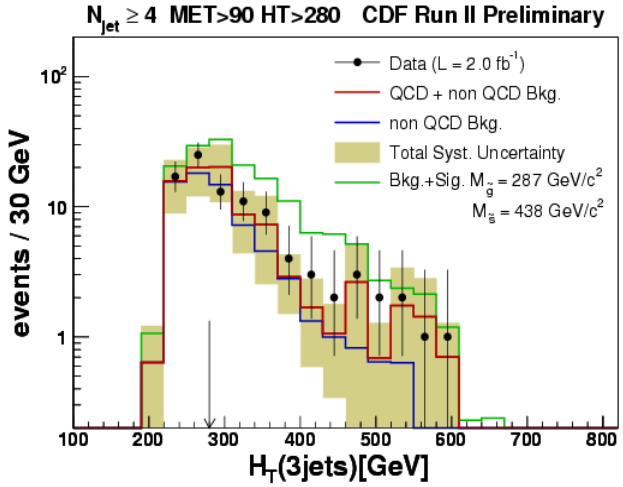
- Jet p_T
- MET
- total energy (H_T)
- angular correlations

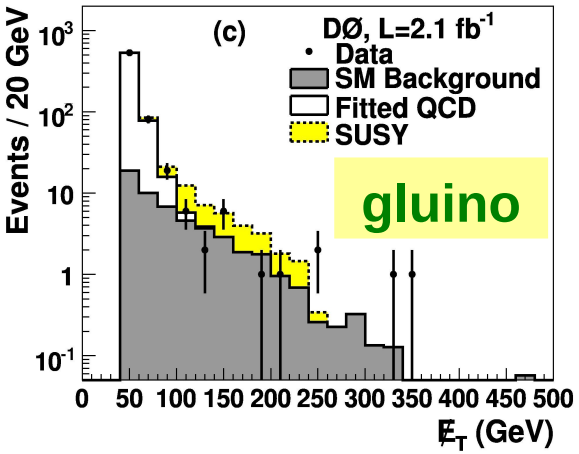
Optimize for multiple SUSY points

No data excess observed

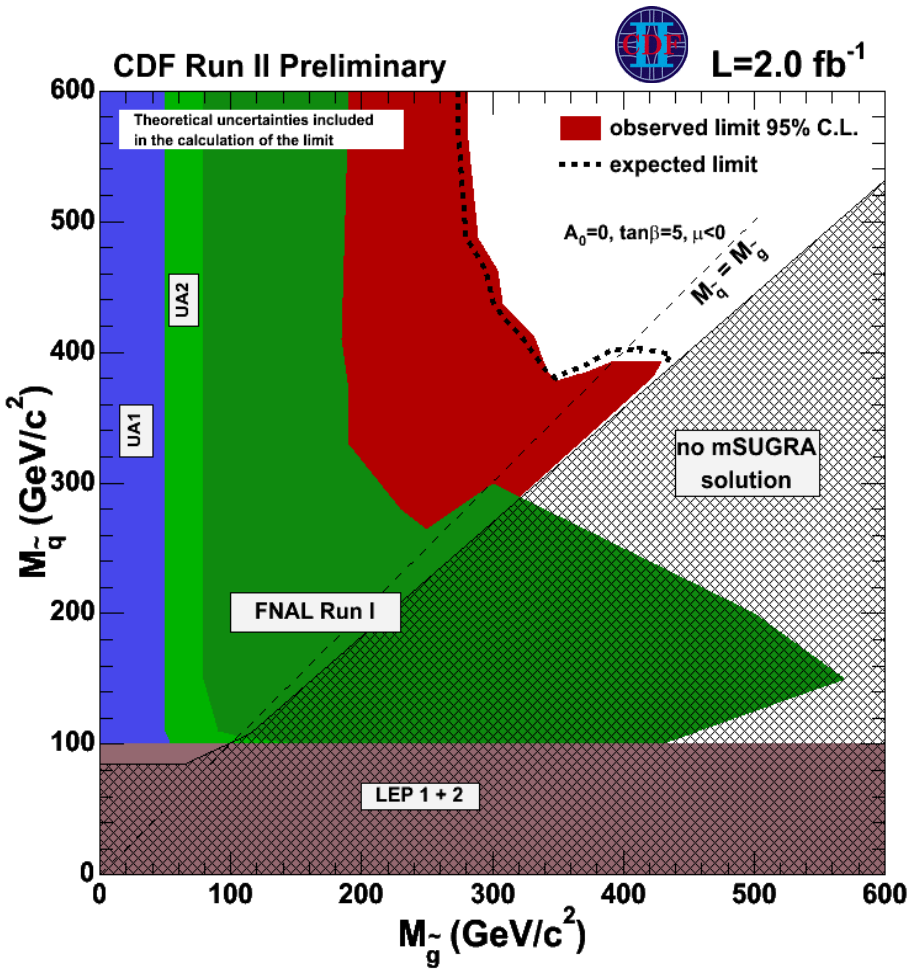


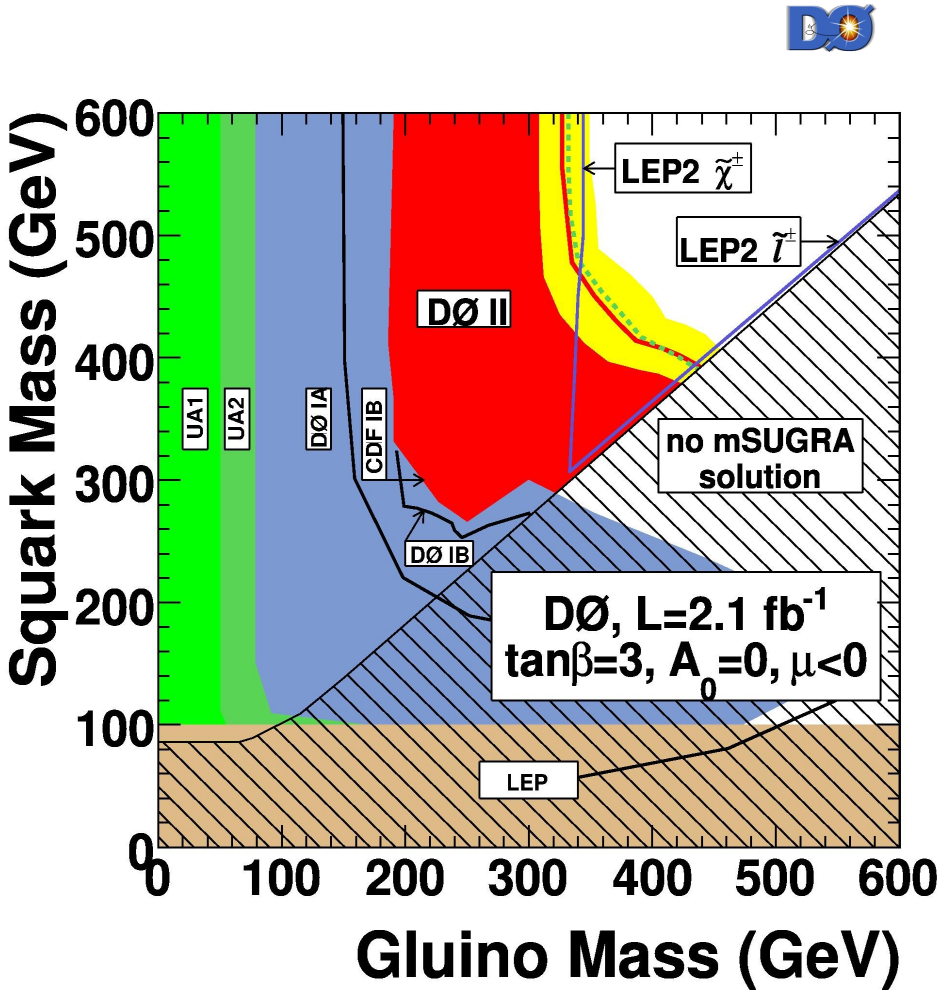






Squarks and Gluinos: Mass Limits





M > 392 GeV [M($\tilde{q}$)=M($\tilde{g}$)]
M($\tilde{g}$) > 280 GeV

M($\tilde{q}$) > 392 GeV
M($\tilde{g}$) > 327 GeV

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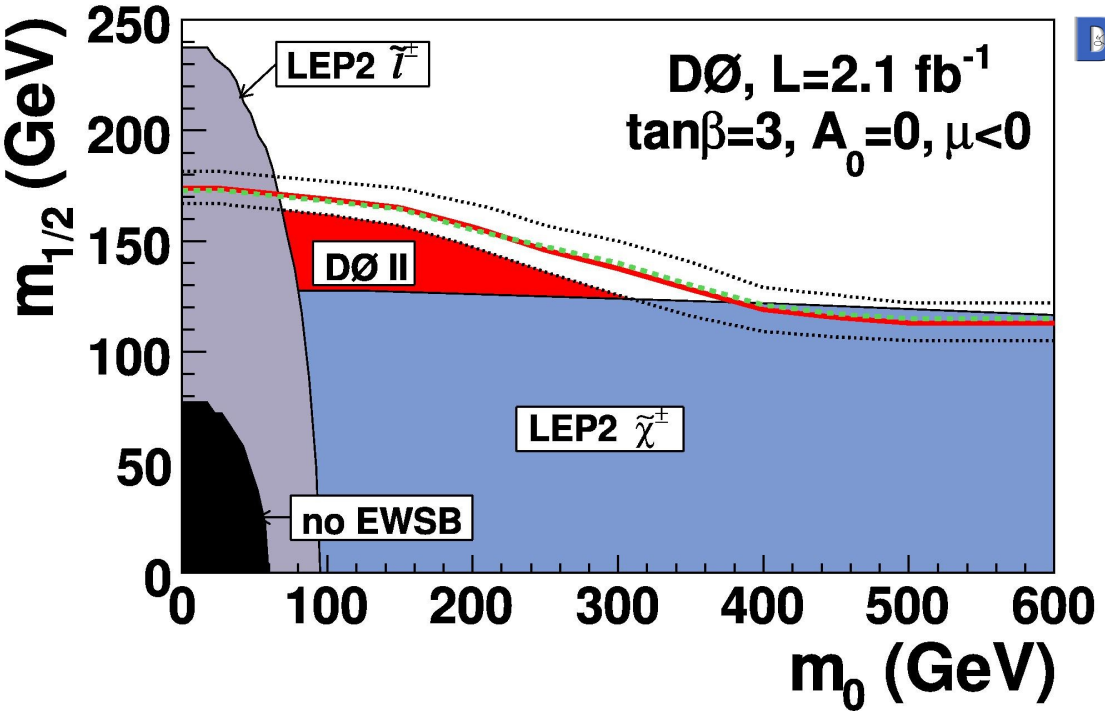
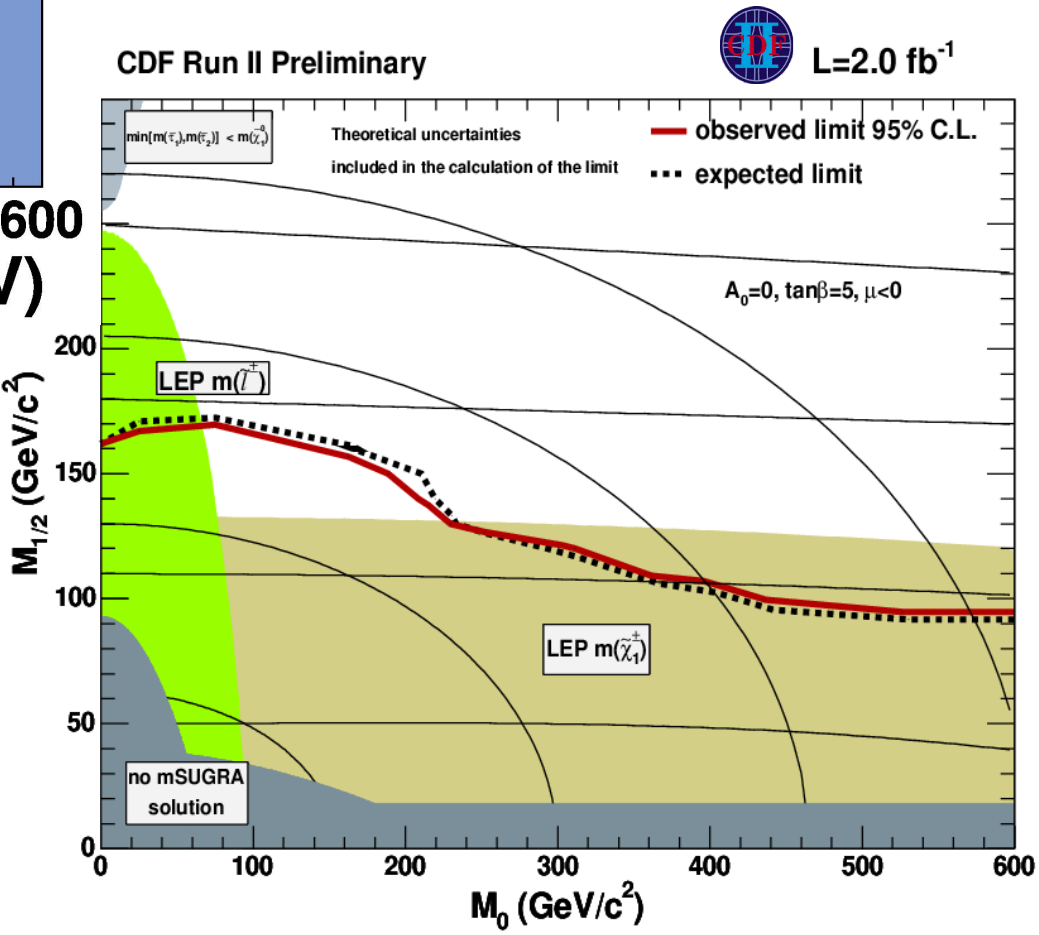
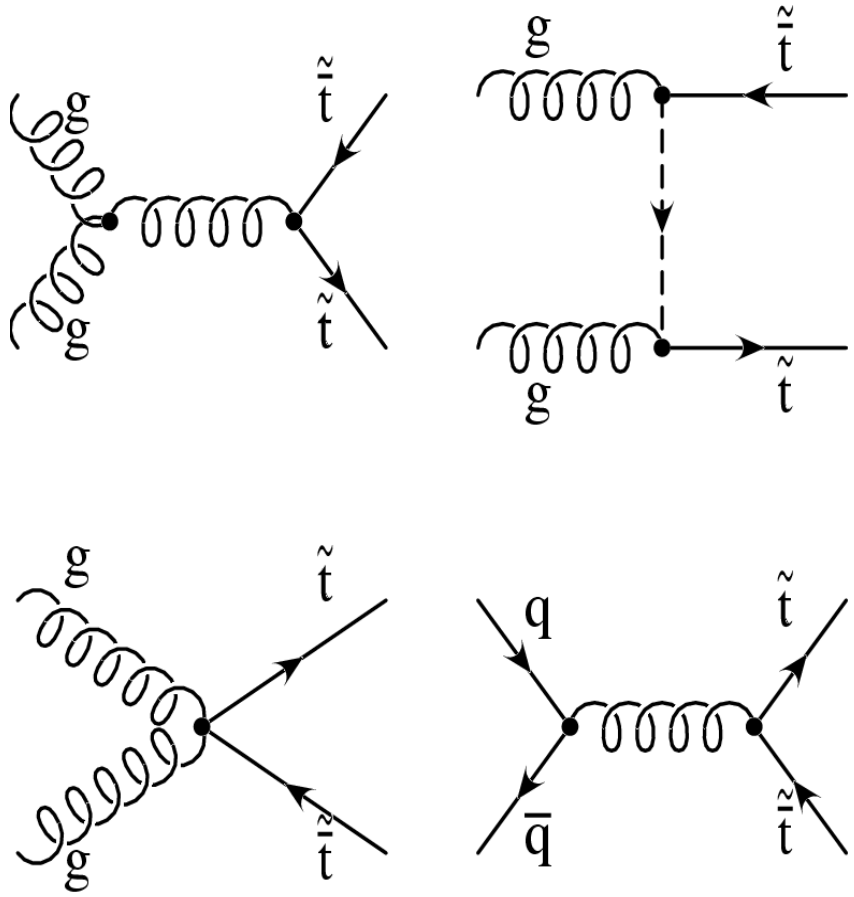
Squarks and Gluinos: Limits in m_0 vs. $m_{1/2}$





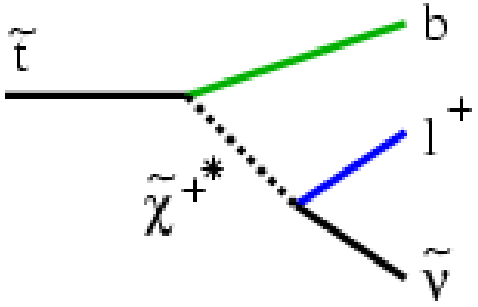
Stop (and Sbottom)

- Third generation “special”
  - Stop could be the lightest squark
- Pair production through strong interaction
- Numerous search channels
- Depend on dominant decay mode



Dileptons	Heavy flavor+MET	Stable, charged particles
ee, eμ, μμ	bb+MET	
+2b+MET	cc+MET	

Stop in eμ + 2b + MET



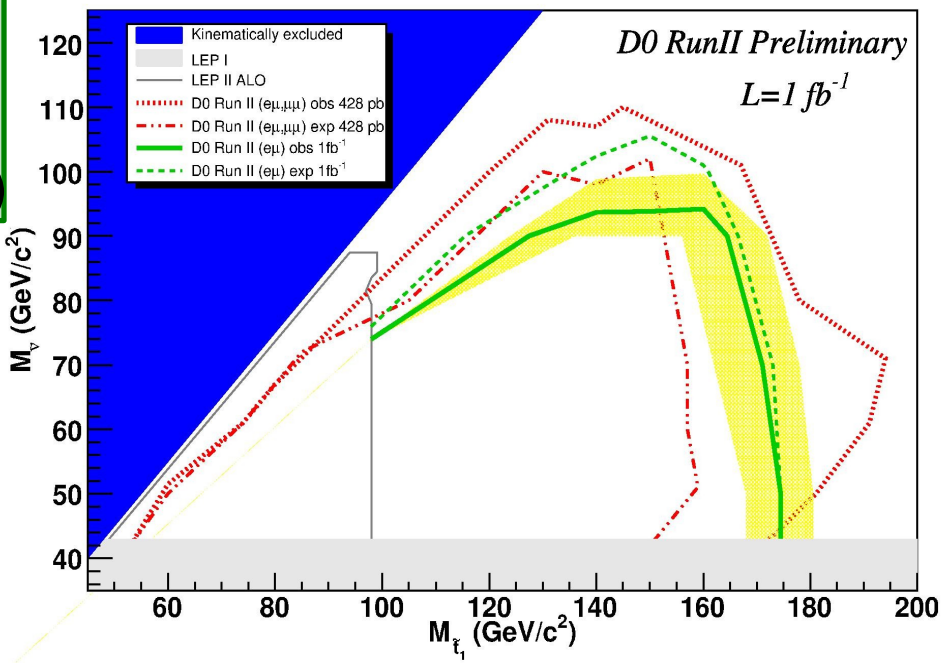
Stop pair production:

Two isolated leptons,

missing E_T,

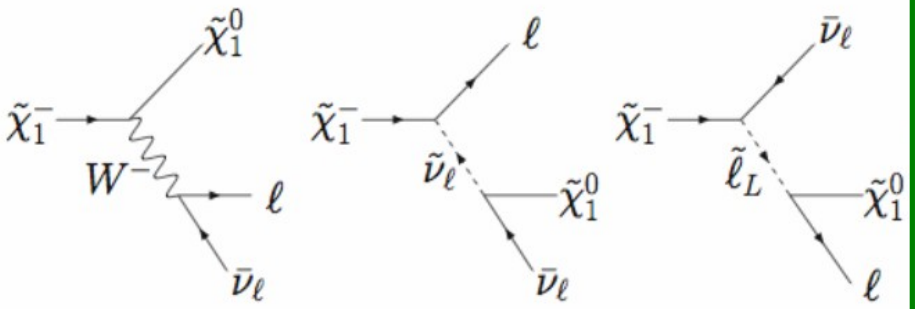
two b-jets (can be soft)

- Decay mode stop → b ℓ $\tilde{\nu}$
- Sneutrino is NLSP
- Update in eμ channel
  - Highest dilepton branching fraction
  - Low backgrounds

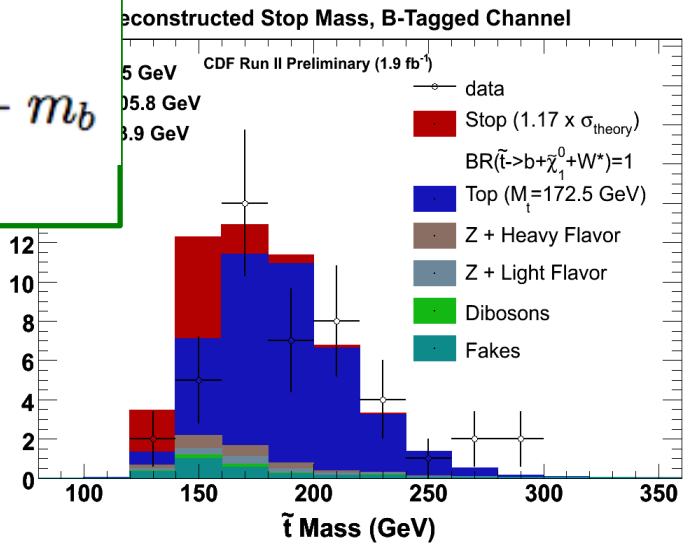


Σ p_T (jets) (GeV)	$p_T(\mu) + p_T(e) + MET$ (GeV)					
	0-70		70-120		>120	
	Data	Bkgd	Data	Bkgd	Data	Bkgd
0-15	1	0.3±0.3	15	13±2	12	19±2
15-60	1	0±0	6	4.2±0.9	11	8±1
60-120	0	0±0	1	1.6±0.6	8	9±1
>120	0	0.0±0.0	0	0.9±0.4	6	7±1

Stop → $b\tilde{\chi}_1^{\pm} \rightarrow b\,\ell\,\tilde{\chi}_1^0$



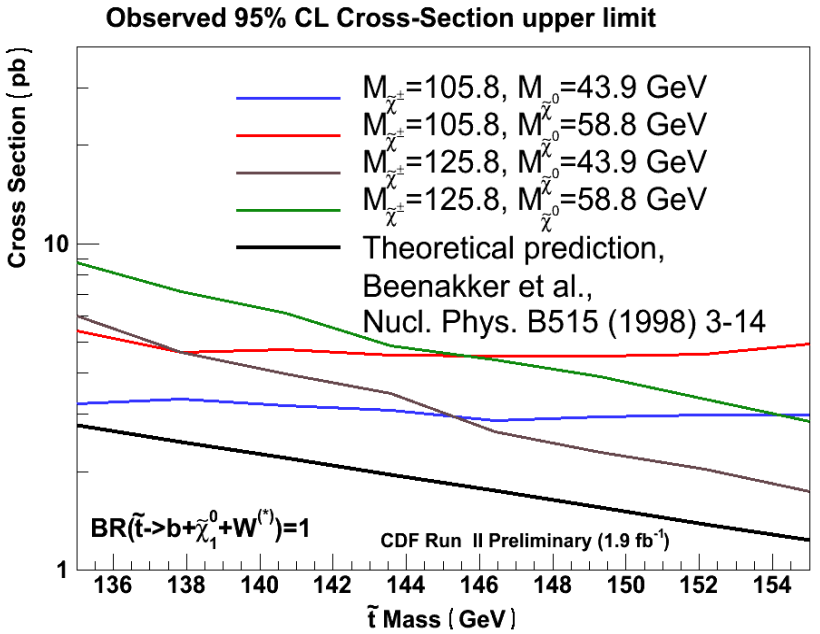
1. $\tilde{\chi}_1^0$ is the LSP
2. $m_{\tilde{t}_1} \lesssim m_t$
3. $m_{\tilde{\chi}_1^+} < m_{\tilde{t}_1} - m_b$



- Stop mass = 135 – 155 GeV
  - several chargino/neutralino mass points

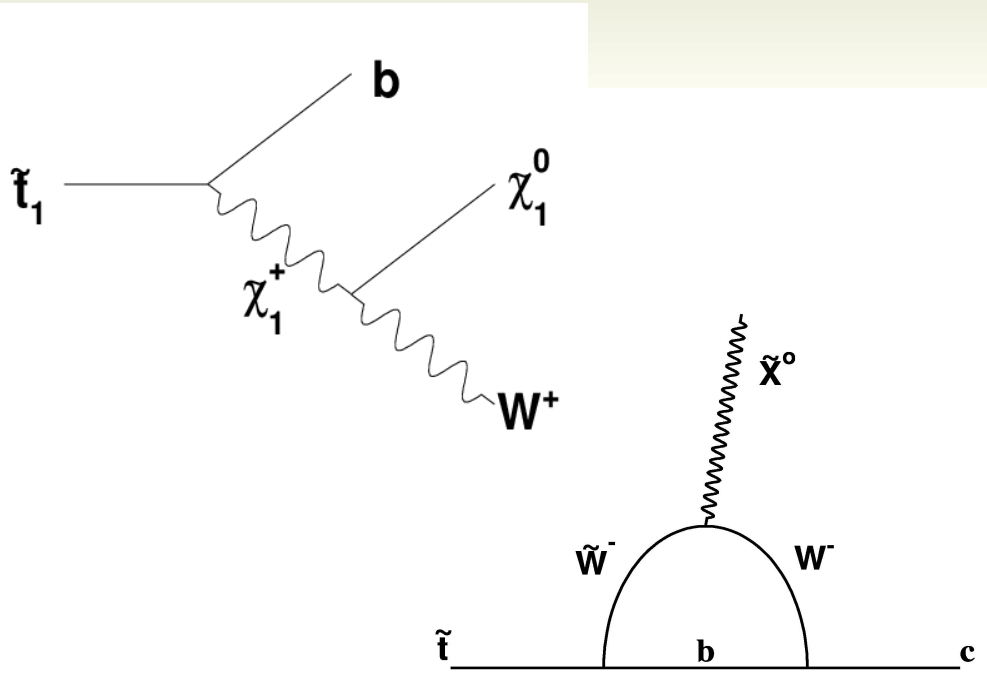
	Background	Data
ee	10.62±1.49	10
μμ	9.46±1.27	11
eμ	22.46±2.88	24
l l	42.53±5.56	45

no evidence of stop signal

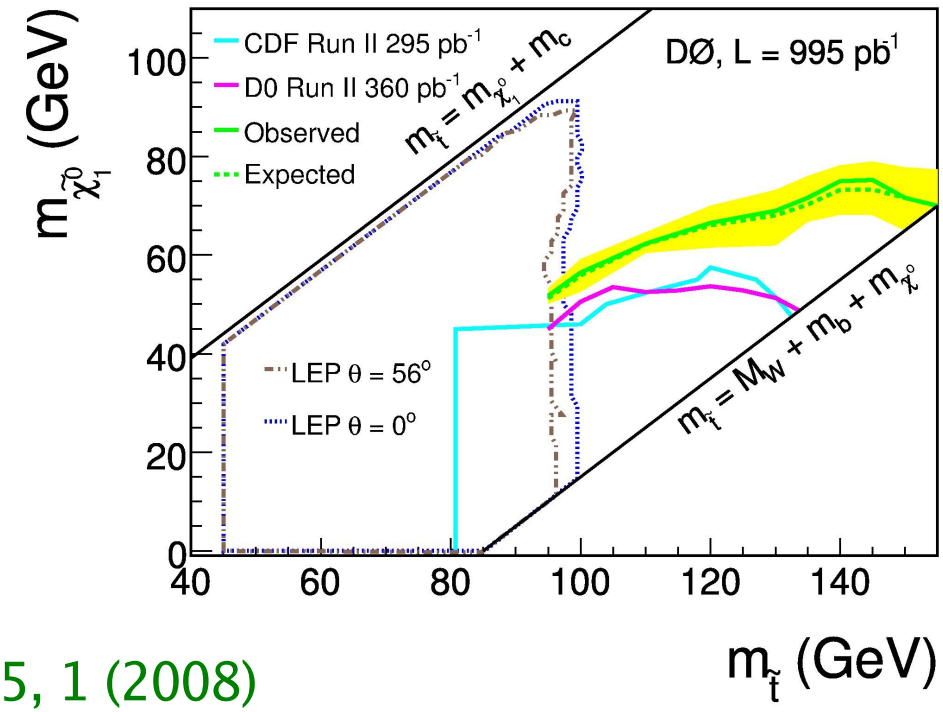


Stop in $c\bar{c}$ + MET

- Decay mode stop → c + $\tilde{\chi}_1^0$
  - $m_{\tilde{t}} < m_b + m_{\tilde{\chi}_1^+}$
  - $m_{\tilde{t}} < m_W + m_b + m_{\tilde{\chi}_1^0}$
- Search for acoplanar charm jets (using b-tagging based on lifetime)
- Optimize selection vs. m(stop)



stop mass	background	data
95-130 GeV	85.3±1.8 +12.8 -13.0	83
135-145 GeV	59.0±1.6 +8.5 -8.8	57
150-160 GeV	66.6±1.1 +9.6 -10.0	66



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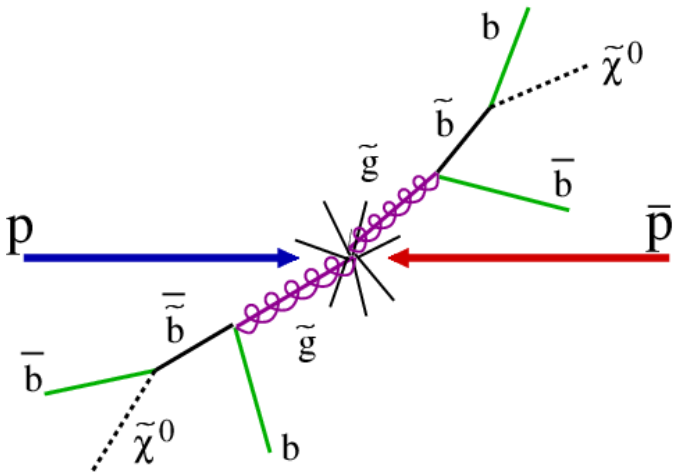
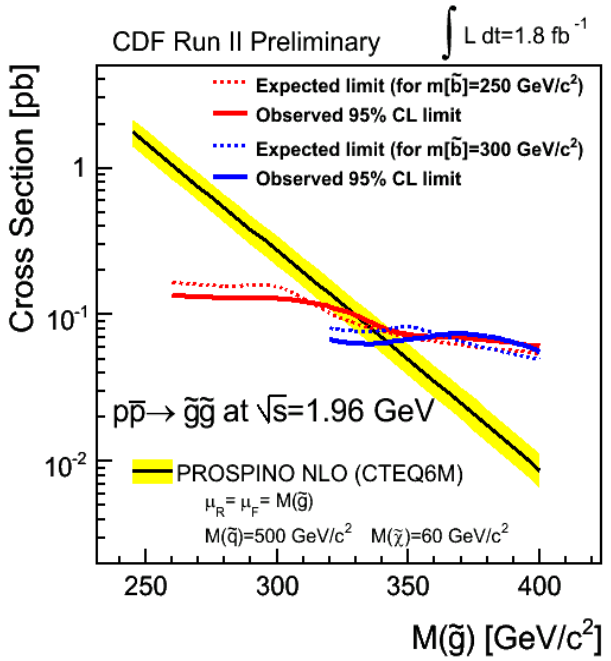
Sbottom in Gluino Production

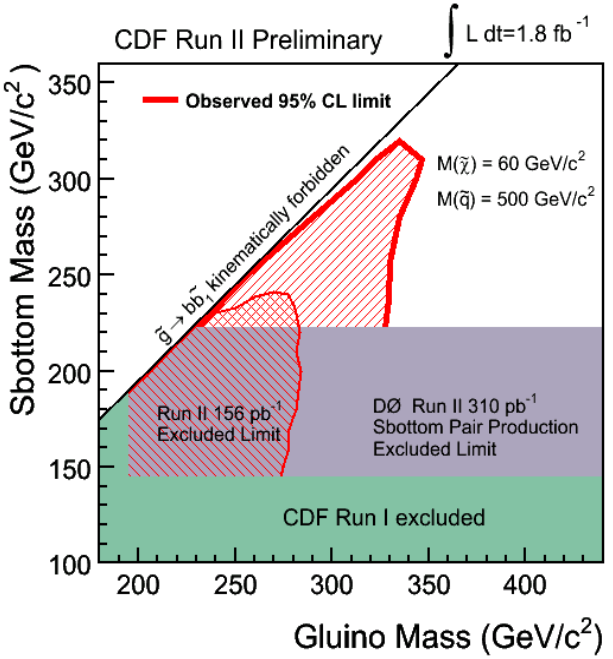


- Pair production of gluinos
- Gluino decays to sbottom + bottom
- Sbottom decays to bottom + neutralino



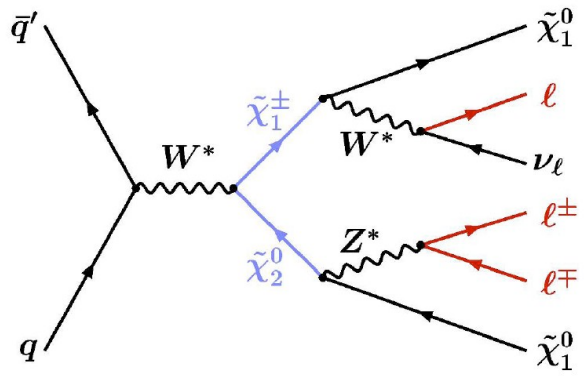
- Search for events with multiple jets (at least one b-tagged) and MET
- Two regions of $\Delta M = M(\tilde{g}) - M(\tilde{b})$

	Large Δm	Small Δm
Background	22.7 ± 4.6	22.0 ± 3.6
Data	25	19

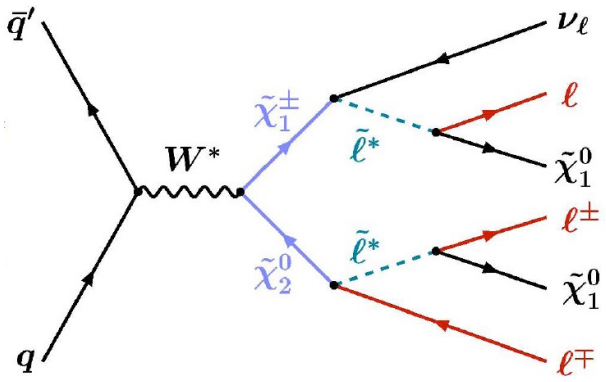


Charginos / Neutralinos: Trilepton Final State

Heavy sleptons:



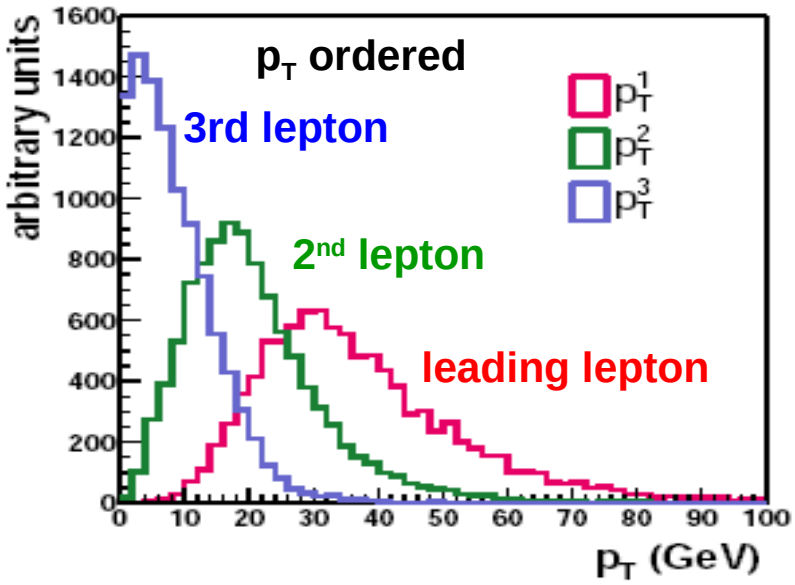
Light sleptons:



- Gaugino pair production via EW interaction
  - Small cross sections, ~0.1 – 0.5 pb
- Charginos and neutralinos decay via gauge bosons or sfermions to LSP and SM particles.
- R-parity conserving models ⇒ LSP stable
- LSP escapes detection in the detector
- SUSY signature
  - 2 electrons or muons
  - Third lepton
  - Large missing E_T

Very clean signature, but small cross sections

Charginos / Neutralinos: Trileptons



- Three search techniques
  - 3 identified leptons (l=e or μ)
  - 2 leptons + isolated track
  - Two same sign leptons
- Allows for some additional acceptance
  - Taus and low p_T leptons

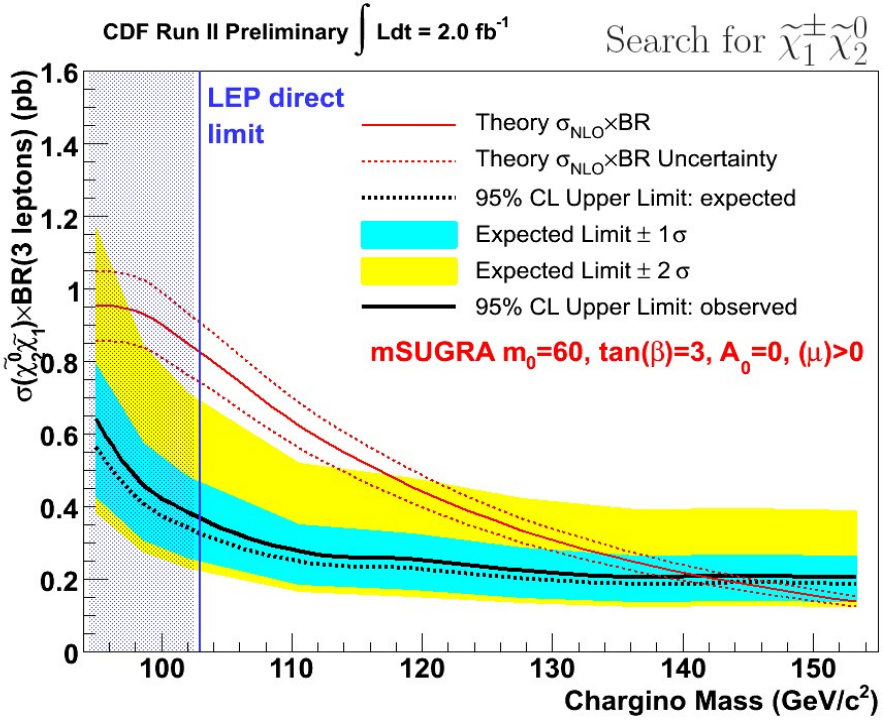
CDF	Background	Data
3 tight	0.49±0.04±0.08	1
2 tight, 1 loose	0.25±0.03±0.03	0
1 tight, 2 loose	0.14±0.02±0.02	0
Total trilepton	0.88±0.05±0.13	1
2 tight, 1 track	3.22±0.48±0.53	4
1 tight, 1 loose, 1 trk	2.28±0.47±0.42	2
Total dilepton+track	5.5±0.7±0.9	6

2.0 fb^{-1}

DØ	Background	Data
ee*l*	1.8±0.8	0
μμ*l*	0.3+1.3-0.3	2
eμ*l*	0.9±0.4	0
$\mu^+\mu^+$	1.1±0.4	1
l = lepton or track		

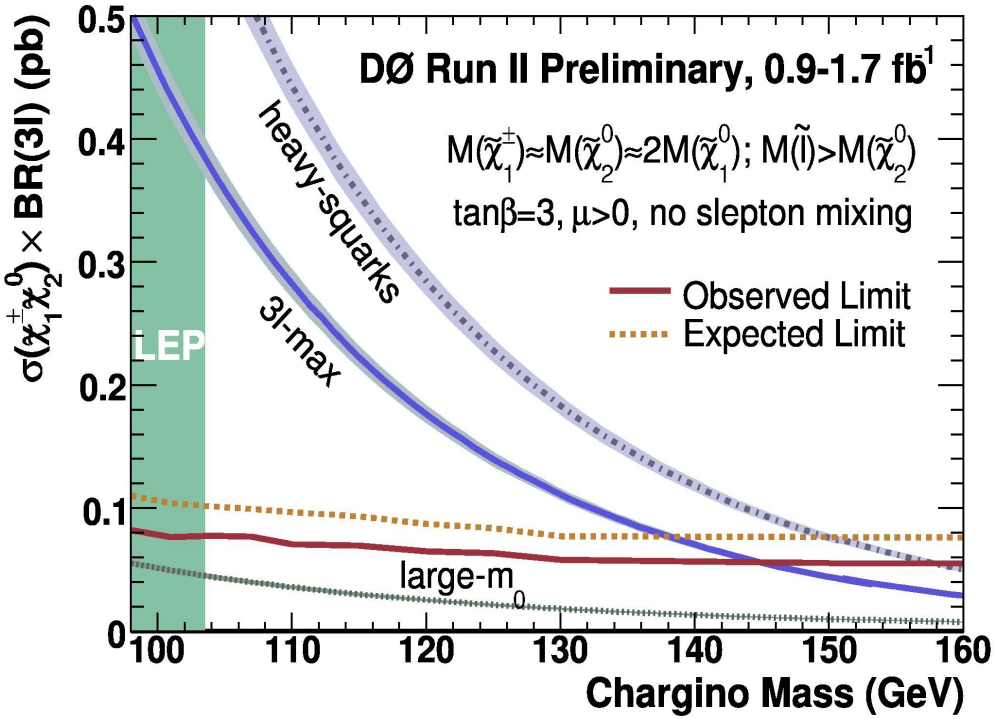
0.9 1.7 fb^{-1}

Charginos / Neutralinos: Limits



$M(\tilde{\chi}_1^{\pm}) > 140$ GeV

mSUGRA



$M(\tilde{\chi}_1^{\pm}) > 145$ GeV

mSUGRA, no slepton mixing

GMSB in Di-photons

Gauge Mediated SUSY Breaking: Gravitino G is LSP

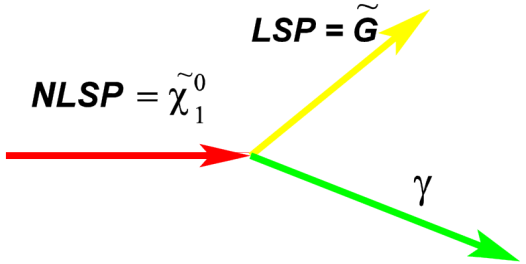
Possible scenario: neutralino NLSP, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$

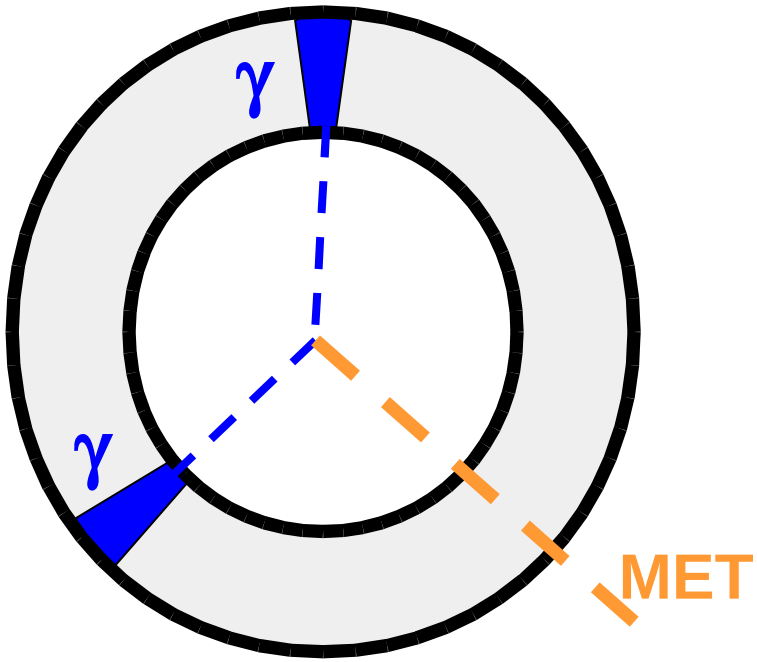
→ Chargino / neutralino production leads to final state $\gamma\gamma + \not{E}_T$

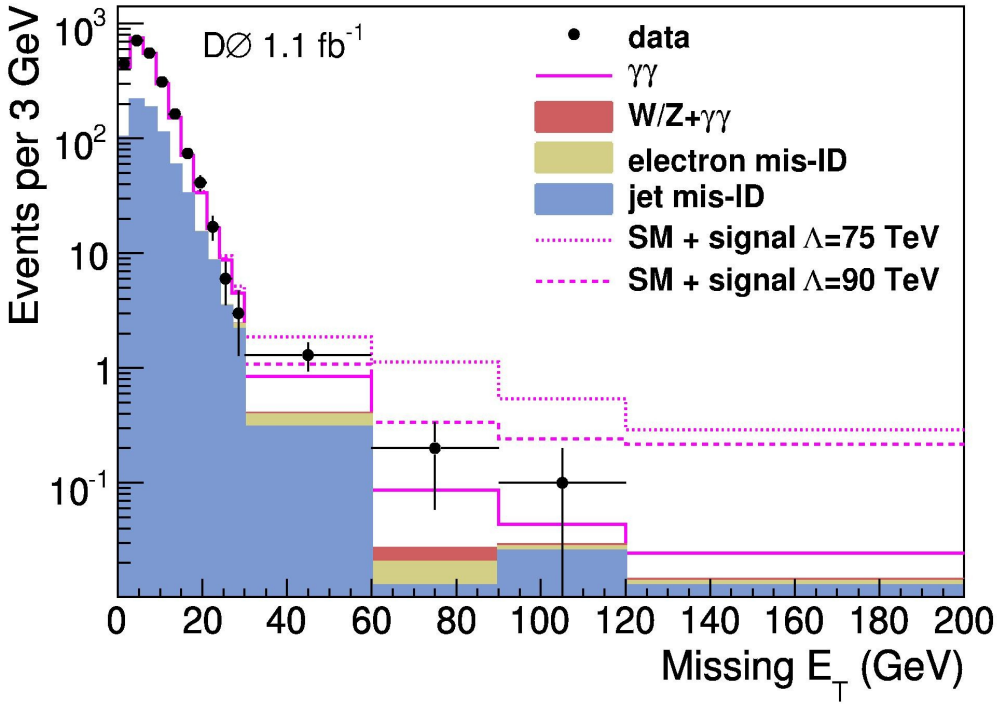
→ Inclusive search for 2 photons plus $\not{E}_T$

Lifetime unknown

Assume here: prompt







GMSB in Di-photons

$M(\tilde{\chi}_1^0) > 125$ GeV

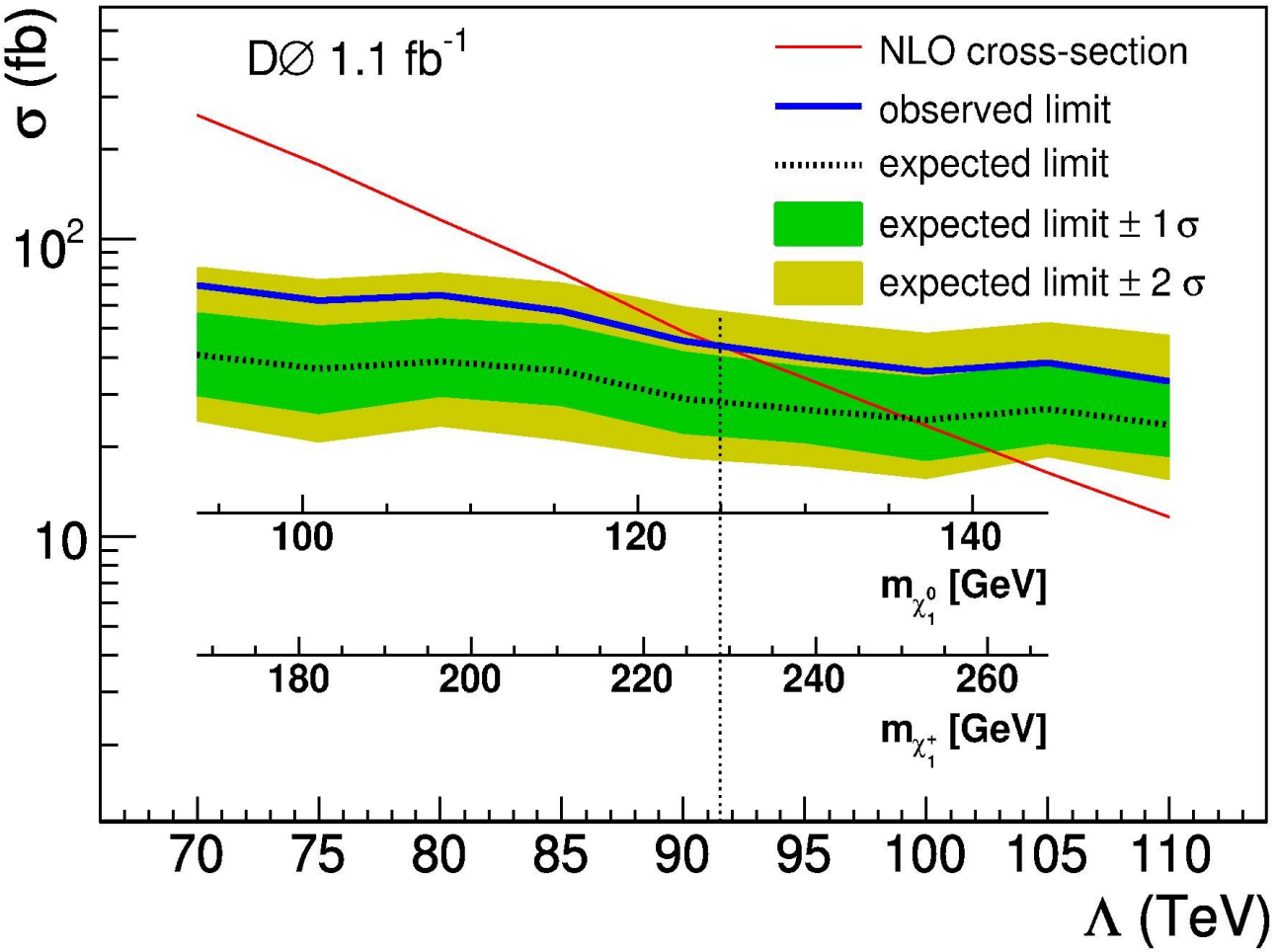
$M(\tilde{\chi}_1^\pm) > 229$ GeV

Previous CDF and DØ combination:

$M(\tilde{\chi}_1^0) > 114$ GeV

$M(\tilde{\chi}_1^\pm) > 209$ GeV

(N_5=1, M_m=2, tanβ=15, μ>0)



PLB 659, 856 (2008)

“Other” SUSY

No dark matter candidate

or

addition to basic SUSY

or

...

R-Parity Violation

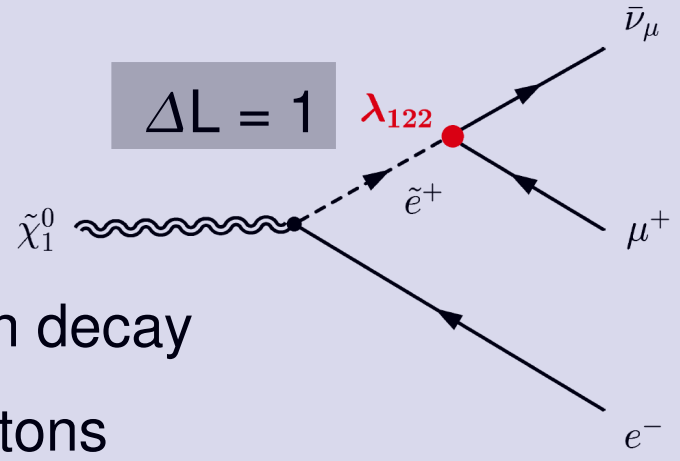
R-parity: $R_P = (-1)^{3B+L+2S}$ **+ 1 SM** **– 1 SUSY**

S Spin
B Baryon number
L Lepton number

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

Violation of R-parity → **45 additional parameters** (Yukawa couplings)

λ_{ijk} (9) $\Delta L = 1$



R_P violated in decay

Many leptons

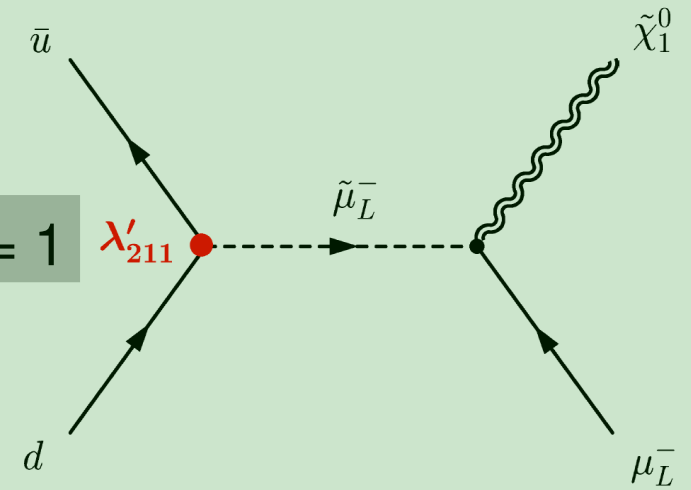
λ''_{ijk} (9) $\Delta B = 1/3$

Experimentally and theoretically constrained (p decay etc.)

LSP no candidate for dark matter in RPV models

λ'_{ijk} (27) Resonant production

Leptons and jets

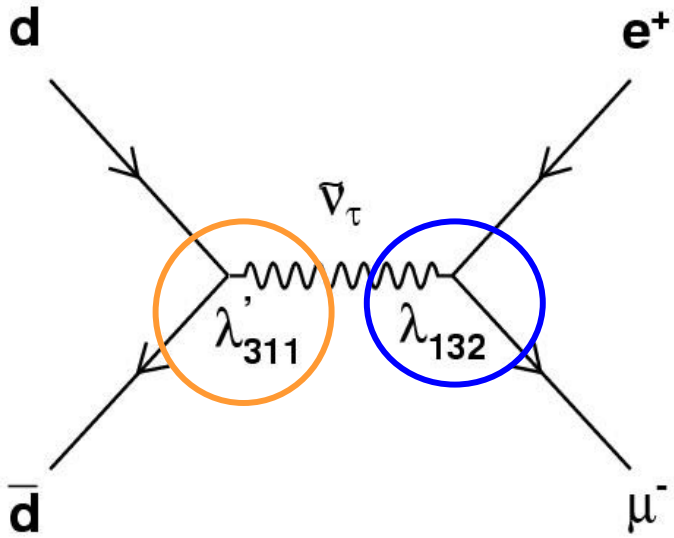


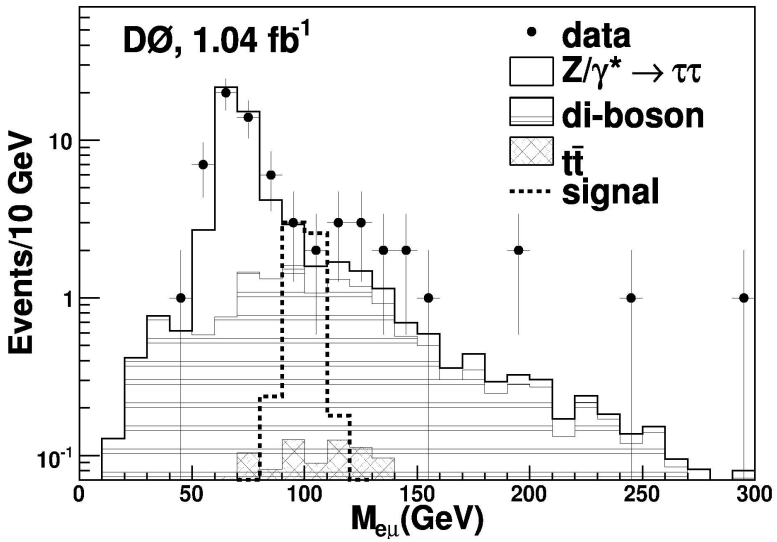
$\Delta L = 1$

- Can cause small BF or long lifetimes
- Or resonances

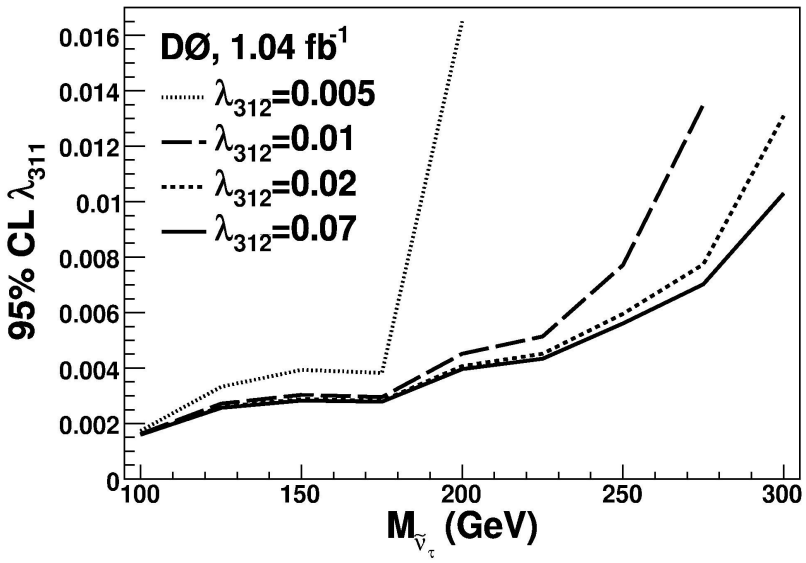
RPV Sneutrinos

- Single sneutrino production
- RPV for production and decay
  - Different couplings λ'_{311} and λ_{132}
- Search for eμ resonance





Data:
68
SM:
59.2 ± 5.3



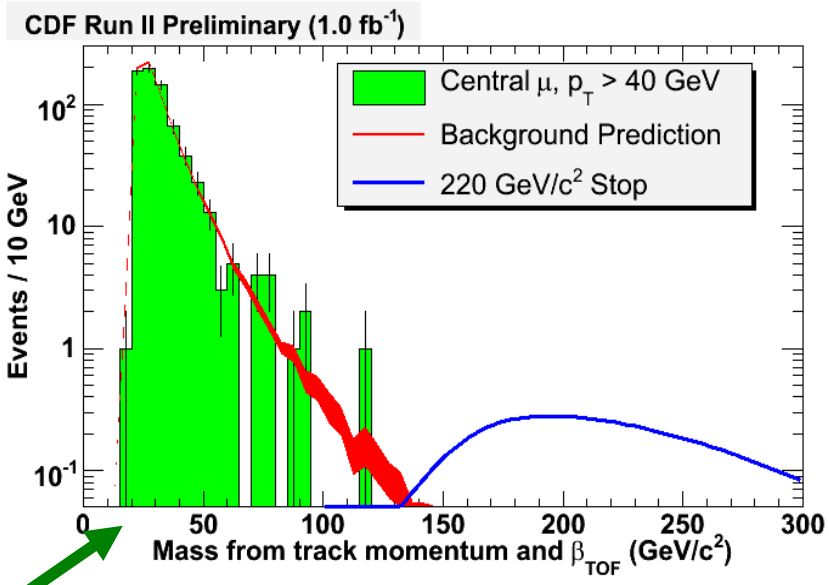
PRL 100, 241803 (2008)

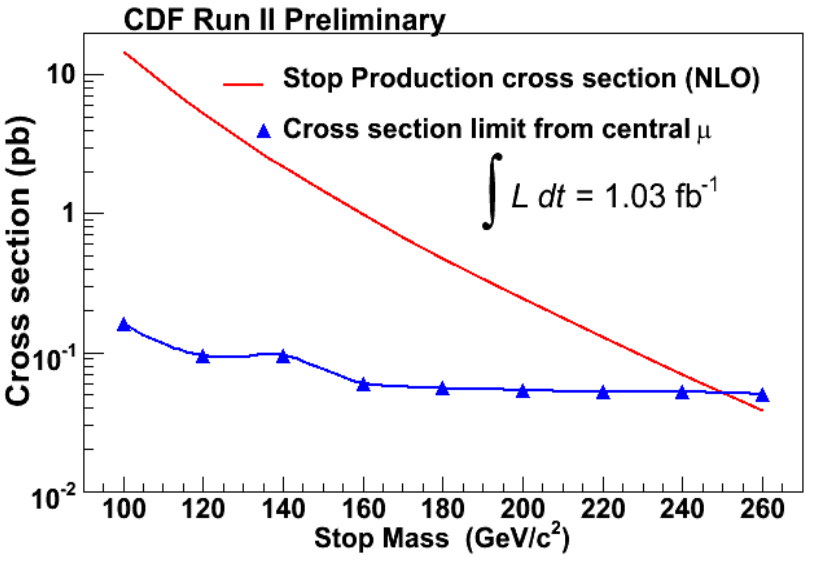
Long-lived Stop

- Generic search for CHAMPS – charged, massive, stable particles
- In SUSY for example long-lived stop – escapes detector before decay
- Signature: slow-moving, muon-like particle
  - Measure mass:

time of flight → velocity + momentum → mass

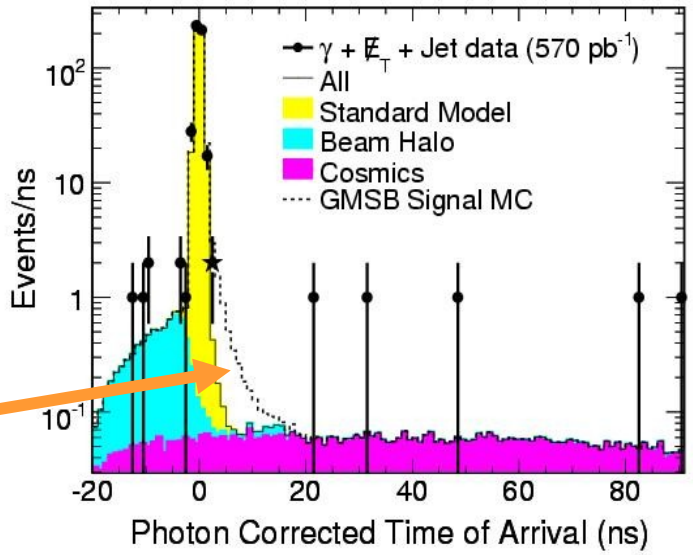
- No standard model background
  - Use data to estimate background in signal region
- **M(stop) > 250 GeV**

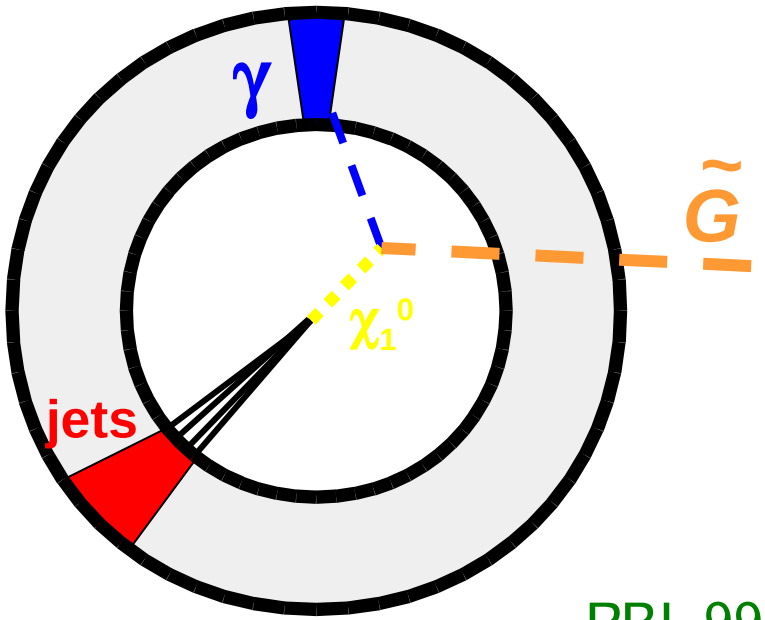




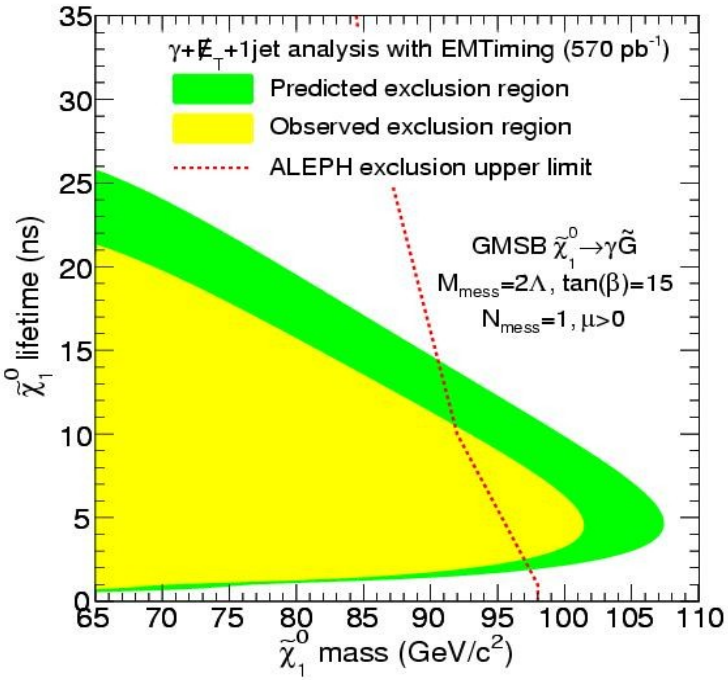
Long-lived Neutralinos

- GMSB SUSY
  - $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$ (same as diphoton)
  - $\tilde{\chi}_1^0$ is long-lived
- Search for γ+jets+MET events
- Measure arrival time of photon
  - Optimize for τ = 5 ns



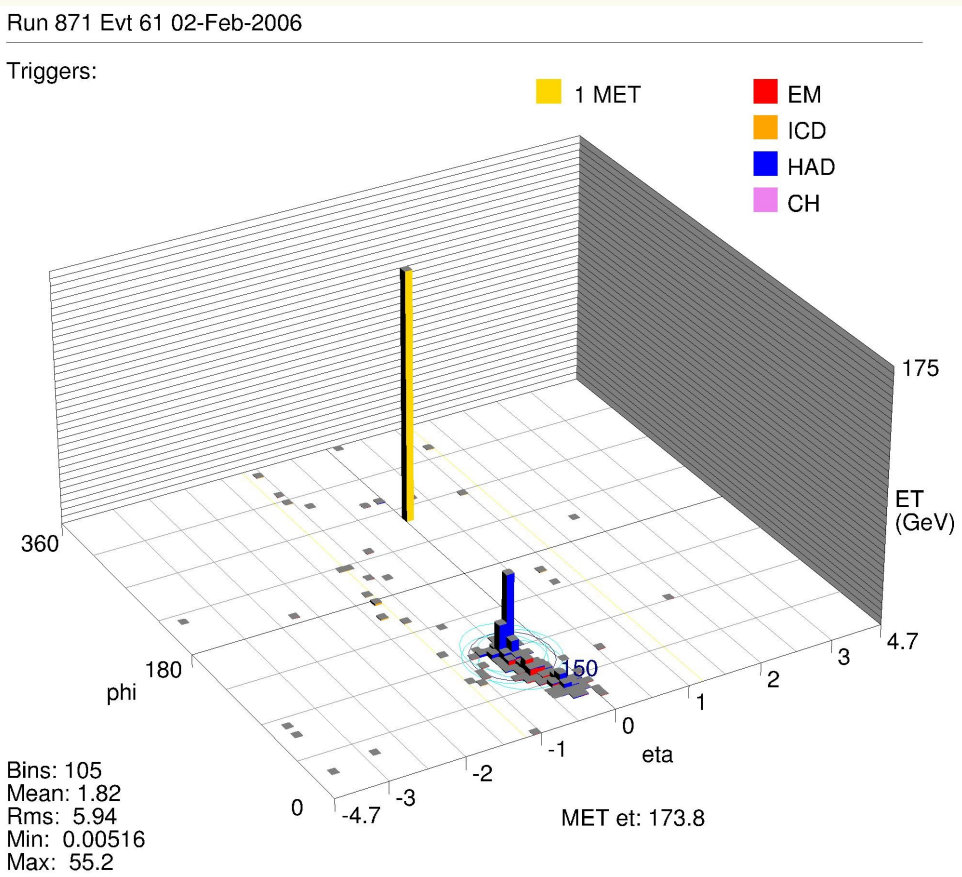


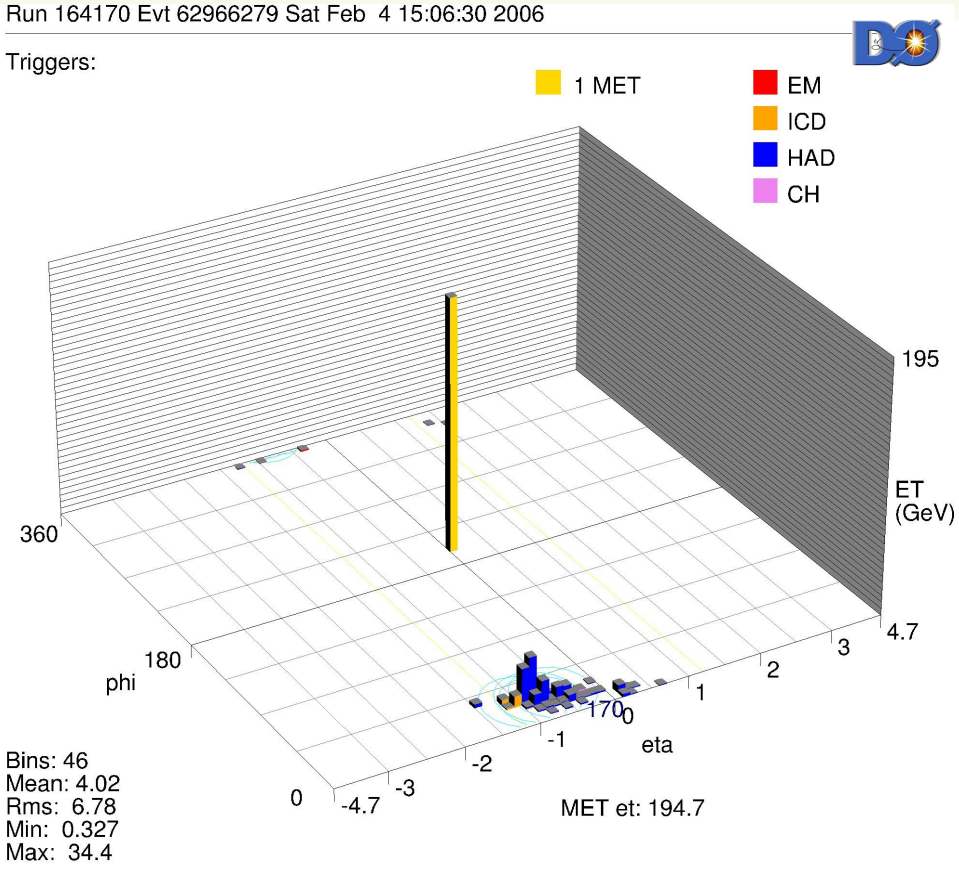
Data:
2
SM:
1.25 ± 0.66



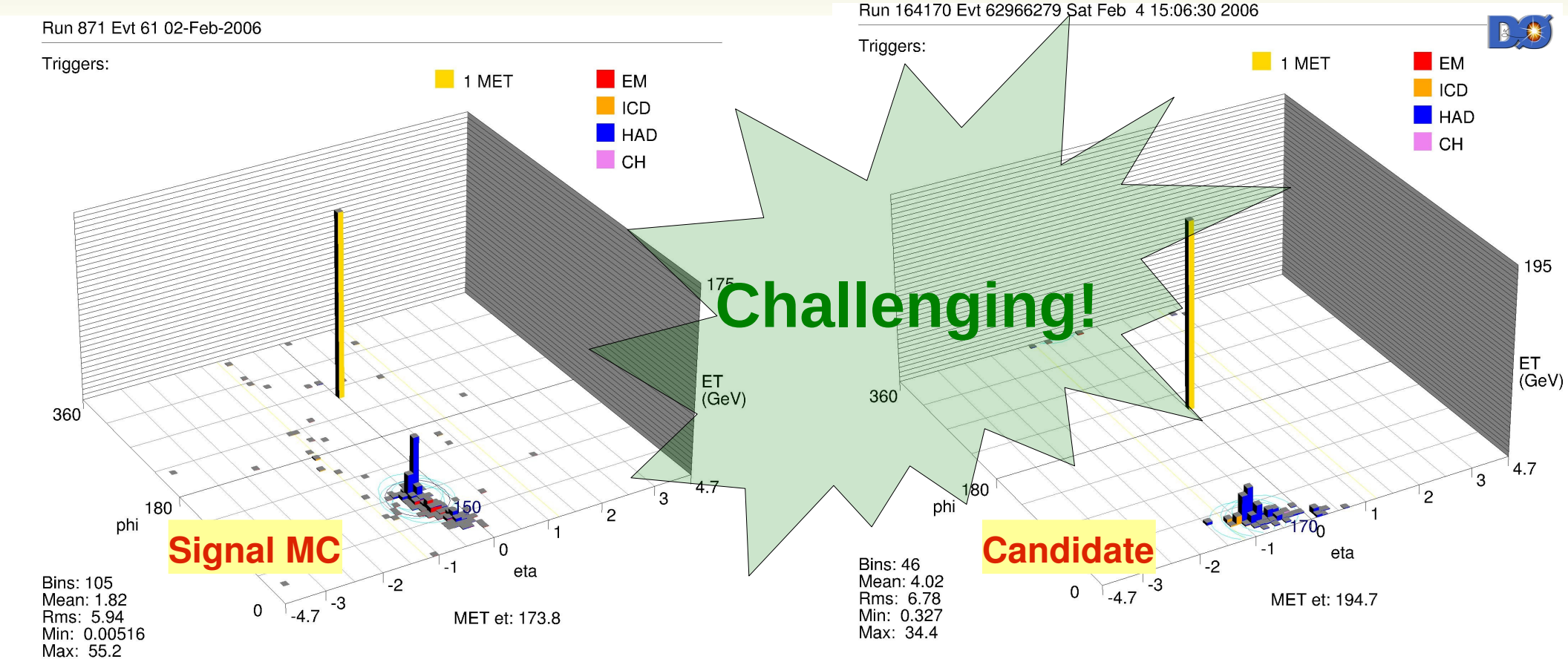
PRL 99, 121801 (2007)

“Stopping Gluinos”





“Stopping Gluinos”



- Gluinos hadronize into *R-hadrons*. Charged R-hadrons can lose all their kinetic energy through ionization and come to rest (“split SUSY” → heavy squarks, light gauginos)
  - **Lifetime between 10 ns and 100 sec,** decay into jets + $\not{E}_T$ (LSP)
  - **~500 “stopped gluinos” in 2 fb^{-1}** for m(gluino) = 300 GeV

"Stopping Gluinos"

PRL 99, 131801 (2007)

Backgrounds (a selection):

– Cosmic muons, beam halo, detector effects, diffractive events, ... mostly estimated from data

Additional difficulties:

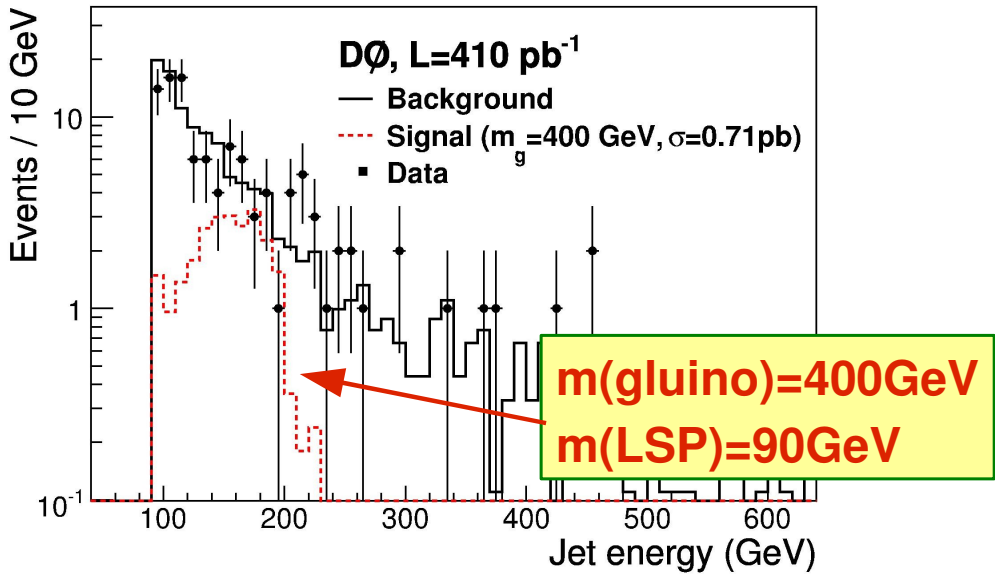
– Energy depositions are out-of-time relative to bunch crossing (→ signal shaping and discrimination)

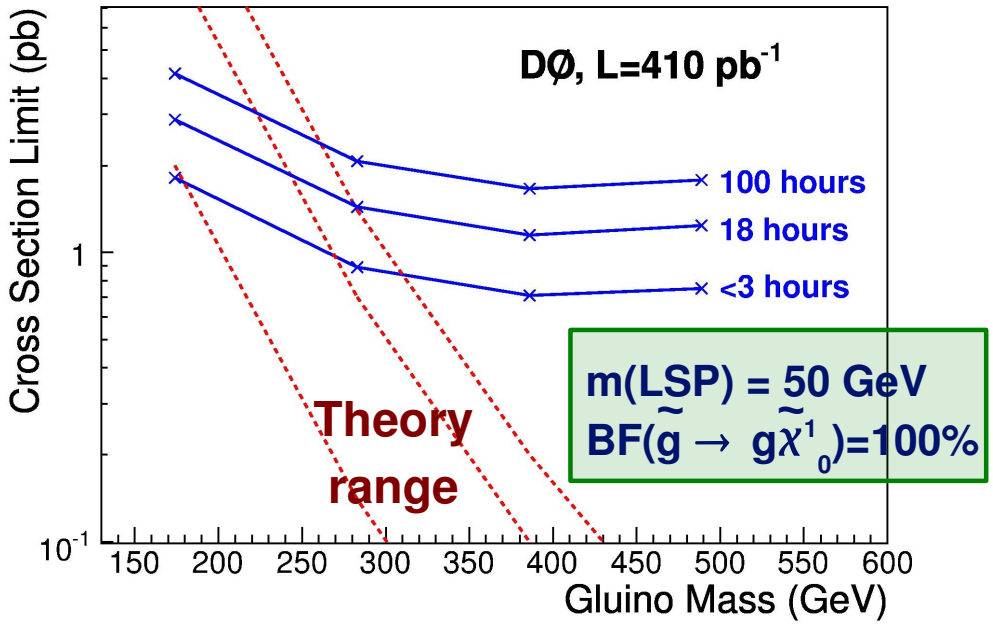
– Trigger

Data compatible with background expectation

Intervals in jet energy translated into gluino mass for a certain LSP mass

$$E = (M_g^2 - M_{LSP}^2)/2M_g$$





Other SUSY Searches

- Numerous BSM Higgs searches
- B_s (and B_d) into $\mu\mu$
- Squarks in jets+tau+MET
- Stop in b+tau
- Stop admixture to top in lepton + jets
- Long-lived neutralinos decaying to dimuons
- 2^{nd} generation slepton resonances
- RPV SUSY in trileptons
- Long-lived charginos and staus
- Long-lived particles decaying into electron or photon pairs
- ...

Conclusions

- A vibrant program searching for supersymmetry continues – have shown new(er) results in selected areas of “standard” and “non-standard” SUSY
- With 4 fb^{-1} collected, updates promising
- All results and more available at
  http://www-d0.fnal.gov/Run2Physics/WWW/results.htm
  http://www-cdf.fnal.gov/physics/exotic/exotic.html

Backup

Stop and Sbottom in cc(bb) + MET

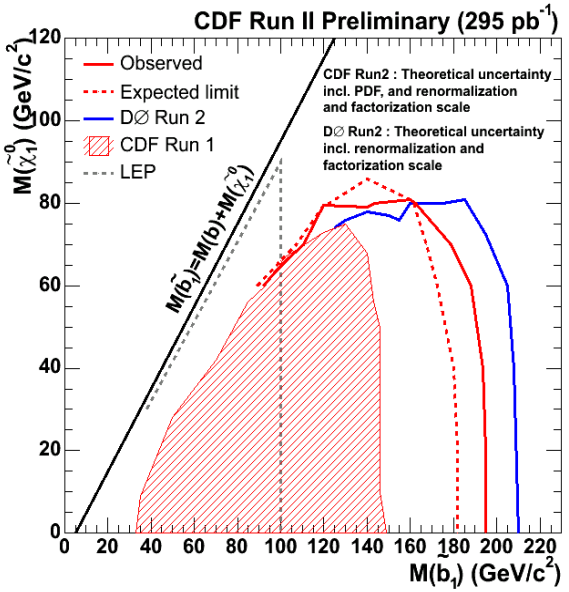
- Pair production of stop or sbottom

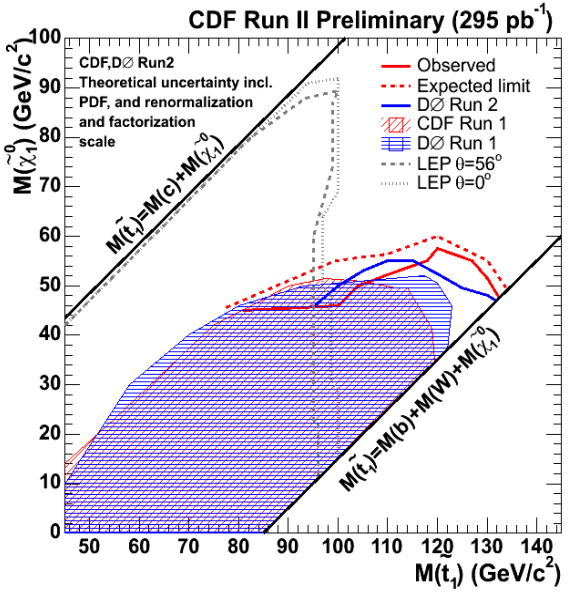
  stop → c + $\tilde{\chi}_1^0$ sbottom → b + $\tilde{\chi}_1^0$

- Signature
  - two energetic jets + MET
  - one heavy flavor tagged jet
- Optimize selection for each channel in three mass regions

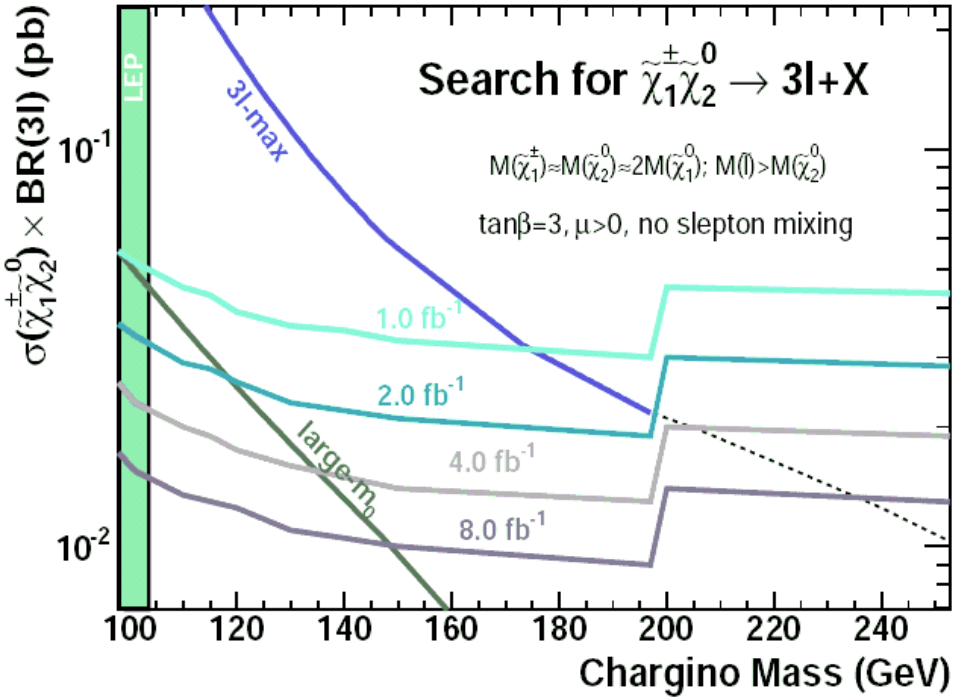
stop	<100	100-120	>120
bkgd	137±6.2±14.6	94.9±5.0±9.9	42.7±2.6±4.6
data	151	108	43
sbottom	<140	140-180	>180
bkgd	55.0±4.2±5.9	17.8±1.7±1.6	4.7±2.1±0.5
data	60	18	3

PRD 76, 072010 (2007)





Charginos / Neutralinos: Outlook

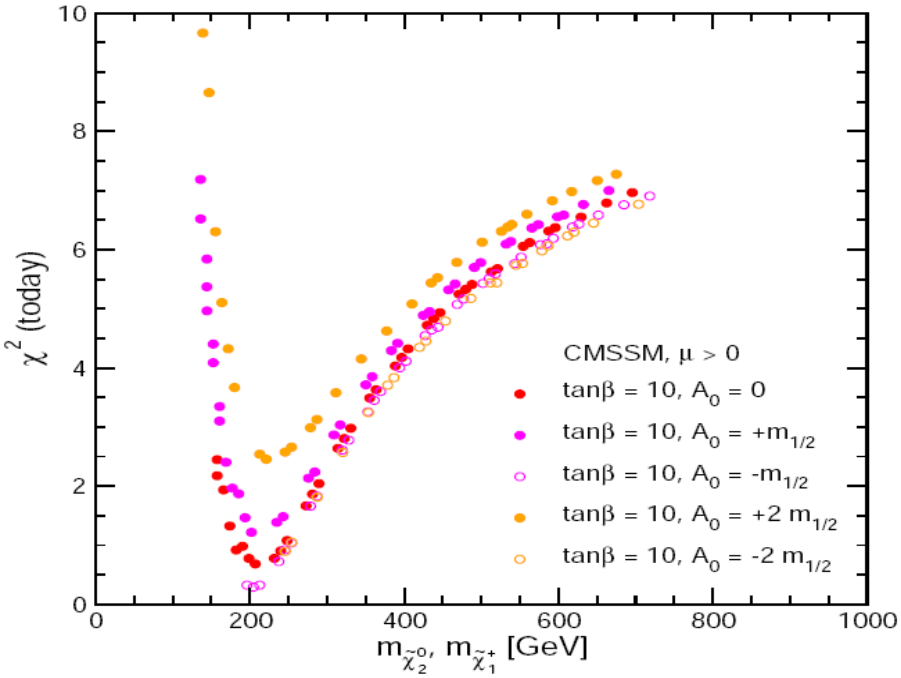


Expected sensitivity (Tevatron combined)

$m(\tilde{\chi}^{\pm}) \simeq 200$ GeV with 2 fb^{-1} in (optimistic) "3l-max"-scenario

Fit of an MSSM to experimental data (CDM, m_W, $(g-2)_\mu$, BF($b \rightarrow s\gamma$), $\sin^2\theta_{eff}$)

$m(\tilde{\chi}^{\pm}) \simeq 200$ GeV for $\tan\beta = 10$



Ellis, Heinemeyer, Olive, Weiglein

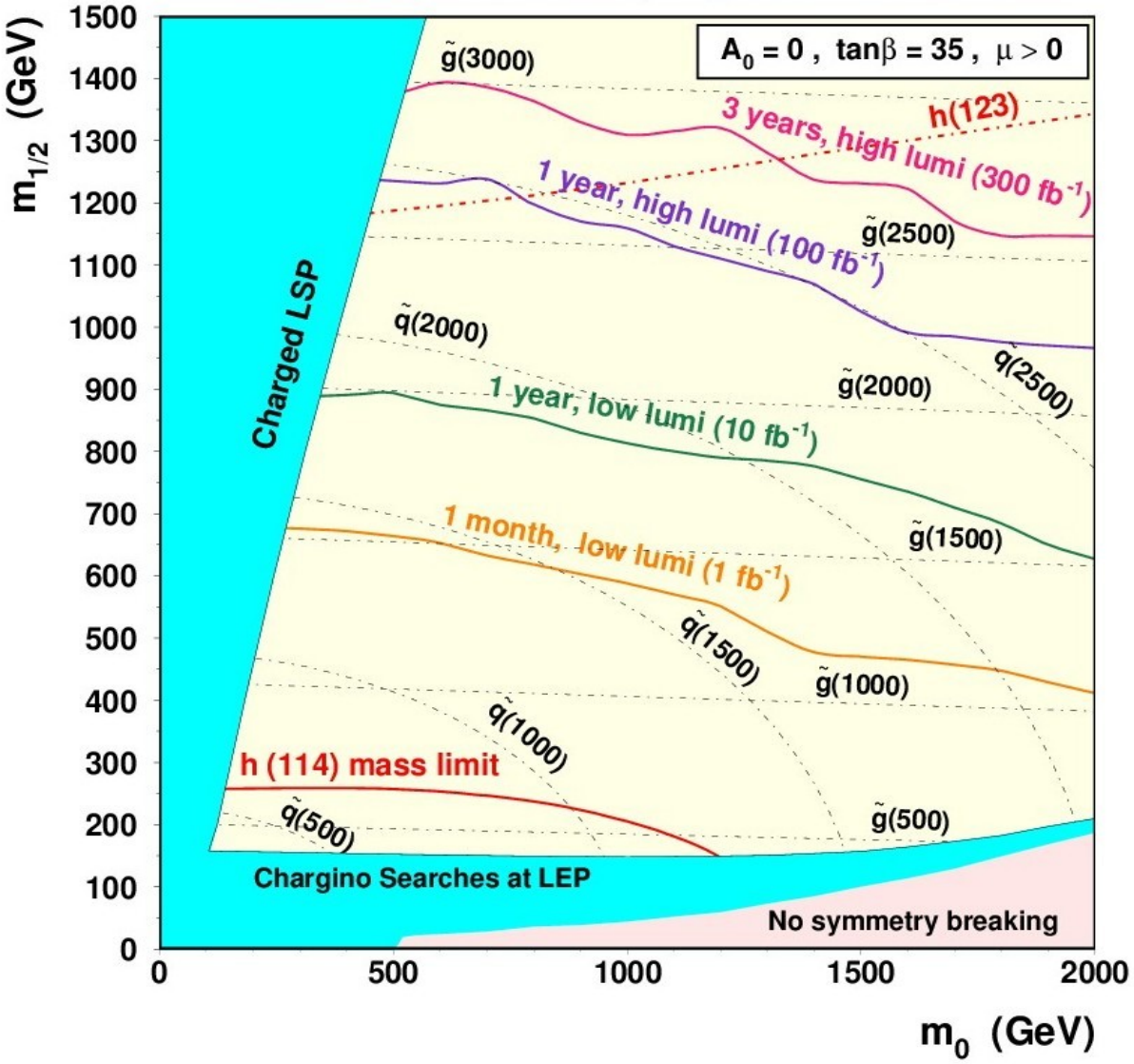
Squarks / Gluinos at the LHC

For large masses: expect S / B > 10, i.e. sensitivity depends mostly on signal,

little on SM backgrounds

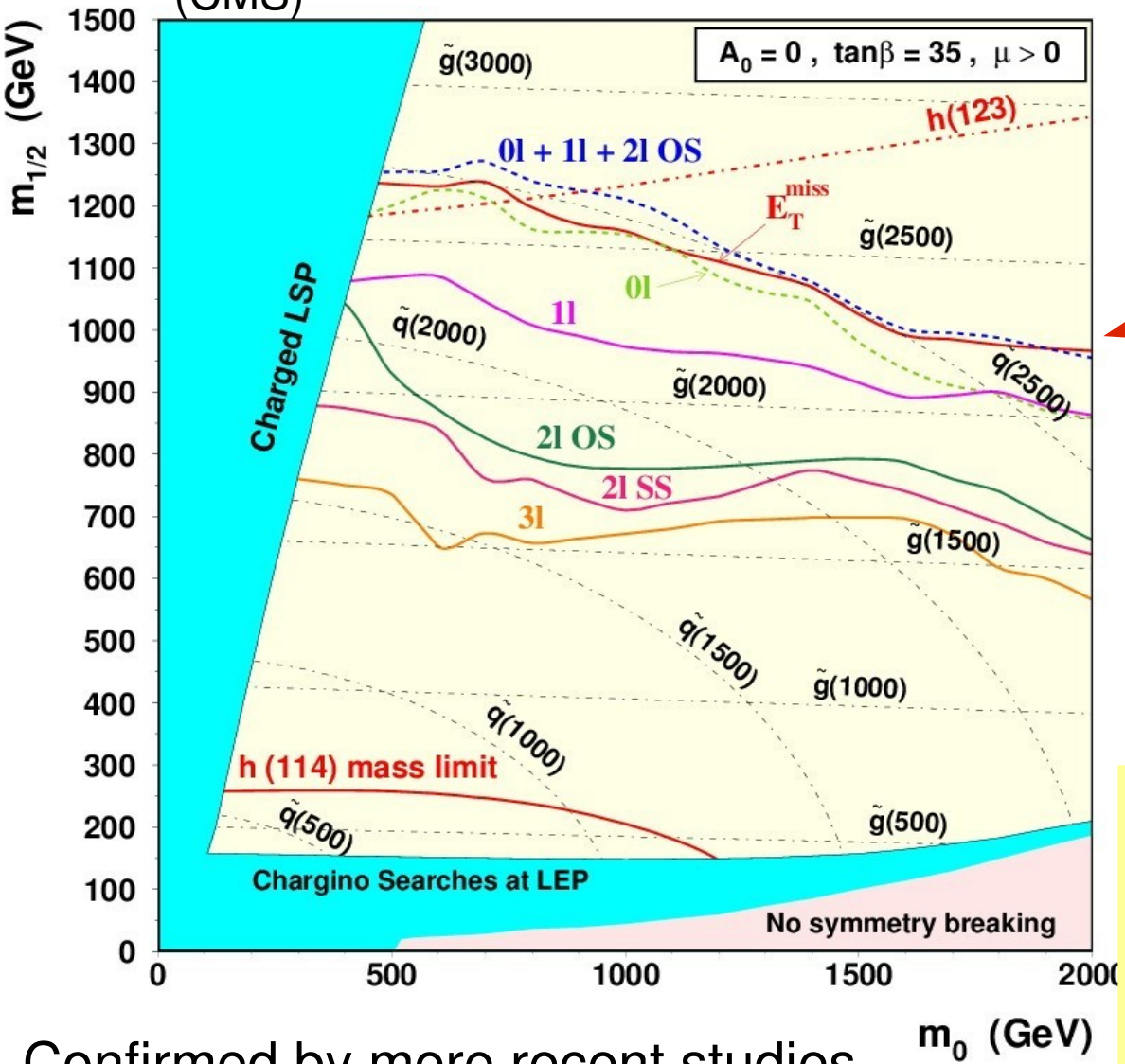
1 fb^{-1}	⇒	M ≃ 1500 GeV
10 fb^{-1}	⇒	M ≃ 2000 GeV
100 fb^{-1}	⇒	M ≃ 2500 GeV

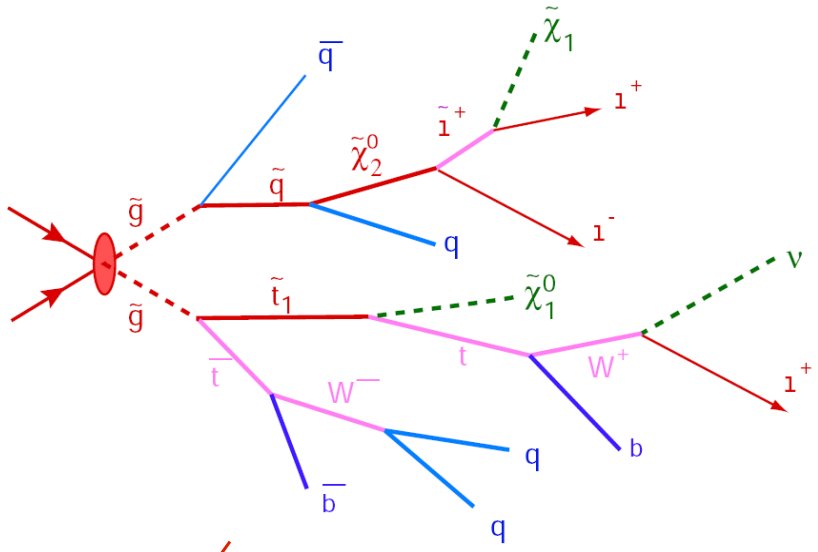
Tev Run II: max. 500 GeV



Inclusive SUSY search (mSUGRA) at the LHC

Expected sensitivity (5 σ) with 100 fb^{-1} (CMS)





Jets + $\not{E}_T$

Jets + $\not{E}_T$ + lepton veto

One lepton

Two opposite charge leptons

Two like-sign leptons

Trileptons

In large areas of the (mSUGRA) parameter space sensitive with different signatures

Confirmed by more recent studies