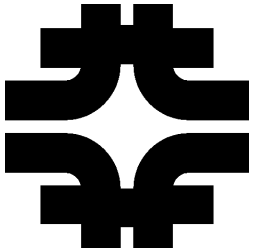


SUSY Searches at Tevatron

Sunil Somalwar

Rutgers University

For CDF & DØ Collaborations

SUSY: Why?

Supersymmetry gives boson partners to fermions and vice versa:

fermion (lepton/quark) → boson superpartner (slepton/squark)

boson (gauge/higgs) → fermion superpartner (gaugino/higgsino).

Doubling the particle spectrum worked very well once before:

Assembling the electron (Murayama, TASI 2000 lectures):

a) **$q=1.6\times10^{-19}$ Coul**

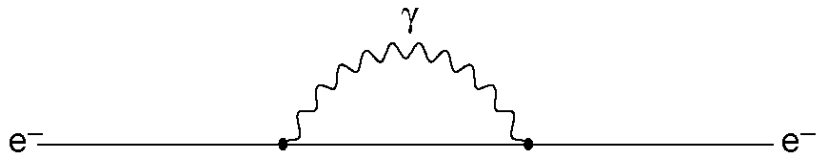
b) **radius = ?** $\hbar c \sim 200$MeV fm = (2TeV)(10^{-19}m) ➔ $r_e < 10^{-19}$m

[(200GeV)(10^{-18}m) ➔ $r_e < 10^{-18}$m (from g_e), LEP 2006: 10 TeV contact interaction ➔ $r_e < 10^{-20}$m]

c) **compress $q=1.6\times10^{-19}$ Coul to $r_e = 10^{-19}$m**

$E_{assembly} \sim +q^2/r_e \sim 10^4$ MeV

but electron mass ~ ½ MeV !



➔ **Delicate cancellation with a *negative* 9999.5 MeV "bare mass"**

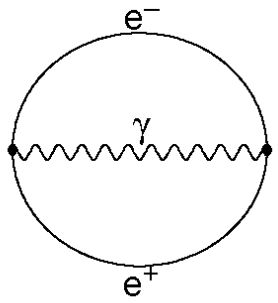
m_e = 0.5 MeV = -9999.5 MeV + 10,000 MeV

OR……

SUSY: Why?

OR…. Double the particle spectrum by adding positron (discovered 1932)

i.e., new physics at ~100fm ~1MeV



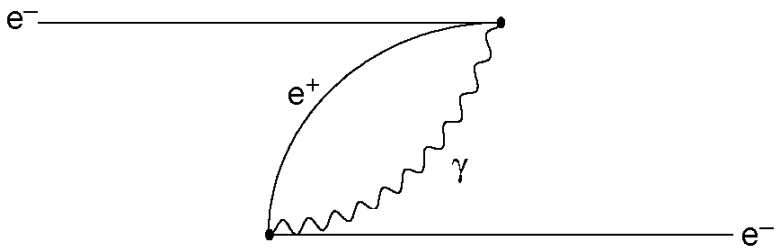
Weisskopf (1939):

$E_{assembly} \sim +q^2/r_e \sim 10^4$ MeV

cancelled by

$E_{vacuum\ pair} \sim -q^2/r$

(due to e^+ from vacuum)

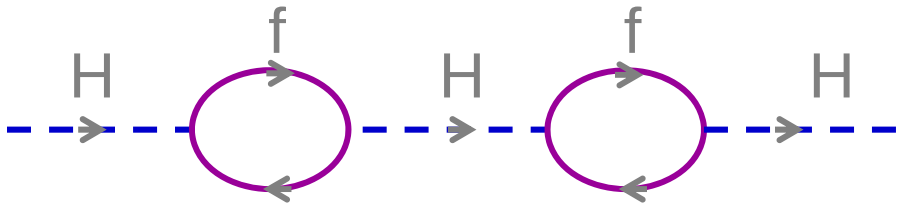


After summing:

$$(m_e c^2)_{obs} = (m_e c^2)_{bare}\left[1 + \frac{3\alpha}{4\pi}\log\frac{\hbar}{m_e c r_e}\right]$$

SUSY: Why?

Today: Higgs has the same problem.



Radiative loops: M_H ~10^{15} GeV (GUT scale), but Higgs mechanism works at m_W,m_Z ~ 100 GeV (Electroweak scale)

Delicate cancellations at 10^{15} GeV

OR

New physics (SUSY) at a TeV scale

stop loops cancel the top loops → "hierarchy problem" solved.

SUSY: Why?

PETER  SUSY

& maybe we can't find either because they eloped into the vacuum ether ….

SUSY: Really?

- Higgs mass(hierarchy problem), gauge unification
- Dark matter candidate
- New complex phases → New CP violation → baryogenesis
- SUSY anticipated the heavy top.

BUT SUSY is badly broken. m(selectron) >> 511 KeV

Newsflash from the ultra-high XeV energy world where supersymmetry is an everyday fact: sNobel prize awarded for discovering that

a) the electrons and selectrons are not massless and

b) their masses are different!

unfortunately….

SUSY: Really?

unfortunately….

A low-temperature physicist got the Snobel Prize.

SUSY Breaking Defines Phenomenology & Search Strategy

- Signatures depend on SUSY breaking, mass hierarchy and mixing

e.g. with R-parity, Stable Lightest Supersymmetric Particle (LSP)

→ Missing E_T (MET) signature (LSP and neutrinos)

→A powerful constraint, but …

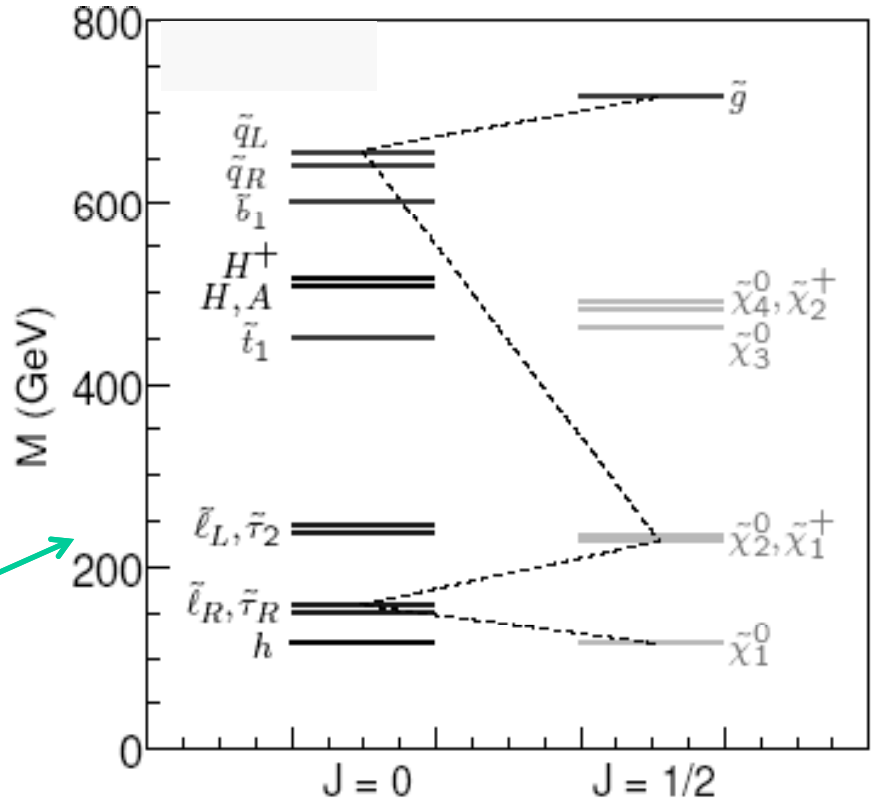
Tevatron:

i) squarks too heavy for 2TeV → small strong cross section

ii) Direct EW competitive (since gauginos lighter than squarks)

LHC:

strong production wins. (→ jetty signals)



Many but not all models:
RGE running →
- Strongly interacting particles heaviest
- Weakly interacting (middle)
- By Hypercharge (lightest)

SUSY Searches: Do the Convenient Thing

Search interpretation problem: full-blown SUSY has too many parameters.

1) mSUGRA is a convenient scenario because it has only(!) 5 parameters

m_0: common scalar mass @ GUT scale, $m_{1/2}$: common gaugino mass @ GUT scale
A_0: common trilinear coupling @ GUT scale, tan(β): ratio of Higgs VEV's
sign(μ): higgsino mass parameter

2) For photonic signatures, GMSB is appropriate. Its parameters:

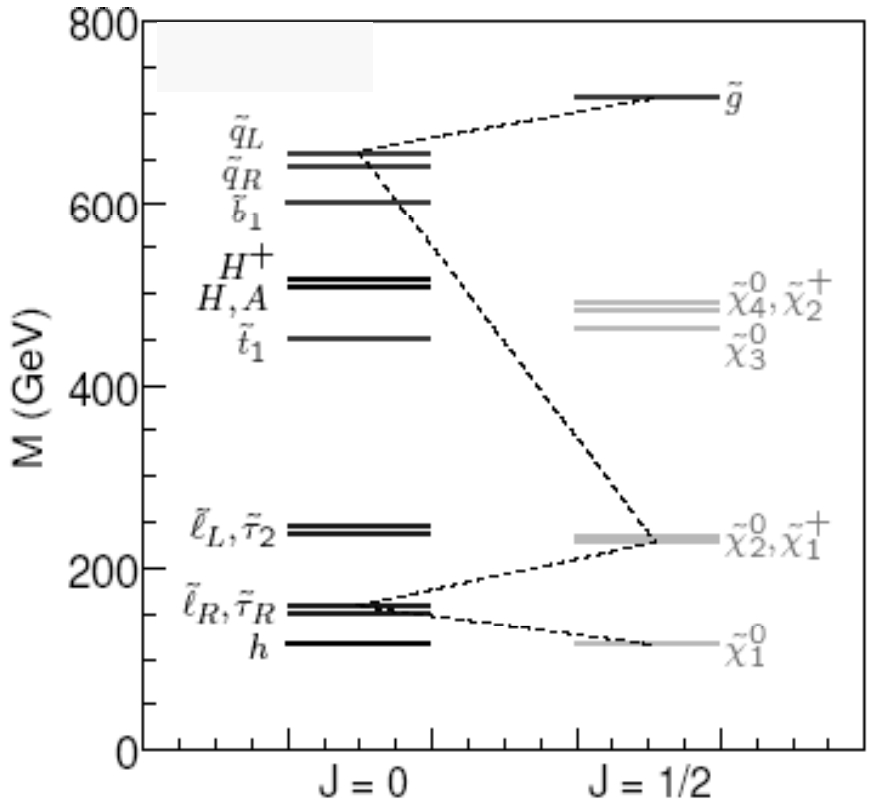
N & M: Number of pairs and mass(es) of messenger, root(F) or Λ: SUSY-breaking mass scale
$\kappa \sim 1$: neutralino-photino mixing, tan(β) & sgn(μ): as above

The theory-experiment disconnect: A noted theorist, upon hearing of CDF trilepton results, "Nice… but no theorist thinks that mSUGRA describes reality."

→ Model-independence desirable. (More on this during trilepton searches).

SUSY Search Goals and Signatures: This Talk

- Chargino-Neutralino: trilepton & missing-ET
- Squarks & Gluinos (incl stop, sbottom, "tau corridor")
  - i. Dilepton+(b) jets+MET
  - ii. Multijet + MET
  - iii. Tau + jets +MET
- Sneutrinos: R-parity violation (e-μ resonances, no jet, *no* MET)
- Light LSP:
  - GMSB (diphoton +MET)
  - Dark photon/Hidden Valley
    - (photon+ close lepton pair + MET)



Signatures important: "Don't worry, we will explain whatever you discover (and there will be multiple explanations)" Scott Thomas

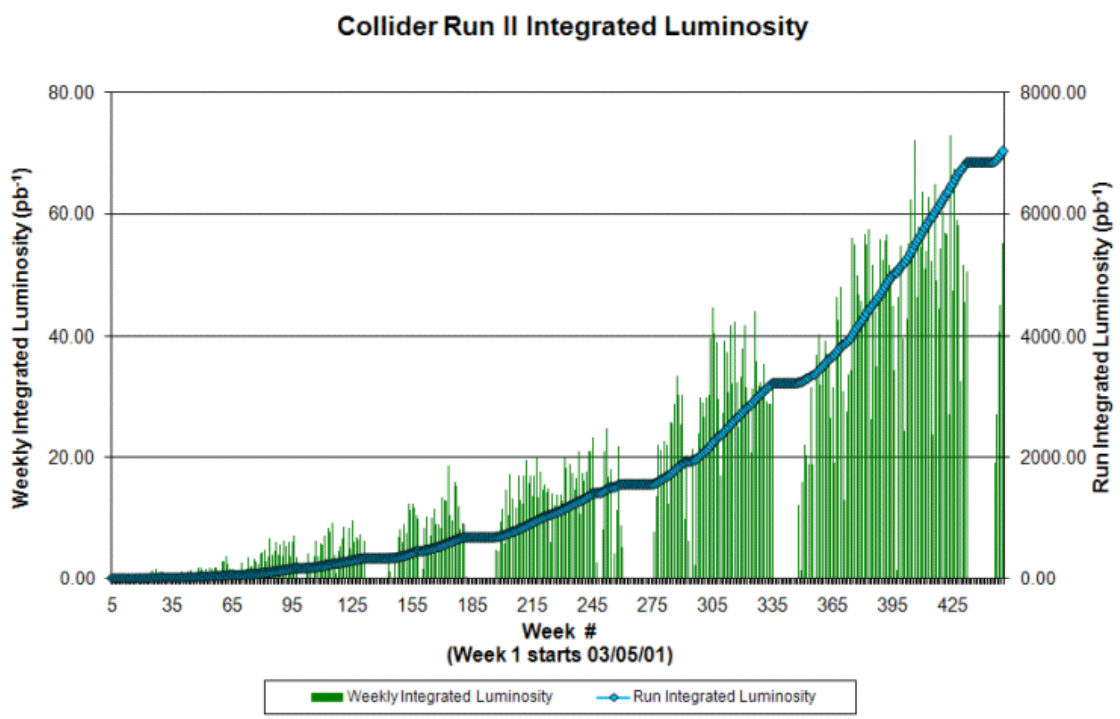
NOT in this talk

- **R-parity is not sacrosanct (Dark Matter could come from somewhere else)**
  If R-parity violated (with L conservation protecting proton lifetime)
  → **Multi-jet (resonance) signature, no LSP/MET** $(\tilde{q})(\tilde{q}) \rightarrow (jjj)(jjj)$
  → **Copious strong production (against QCD background).**

- **SUSY searches in the MSSM context**
  e.g. H/A → ττ

- **FCNC Search $B_{S(d)}$ → μμ , SM BR = 3.9 x 10^{-9} (1x10^{-10})**
  Deviation from SM would indicate new physics, including SUSY as $(\tan\beta)^6$!
  CDF: 3.7 fb^{-1}: BR(*Bs* → *μμ*) < 4.3x10^{-8} , BR(*Bd* → *μμ*) < 7.6x10^{-9} @95% CL
  DØ : ~6 fb^{-1} results anticipated in the near future.

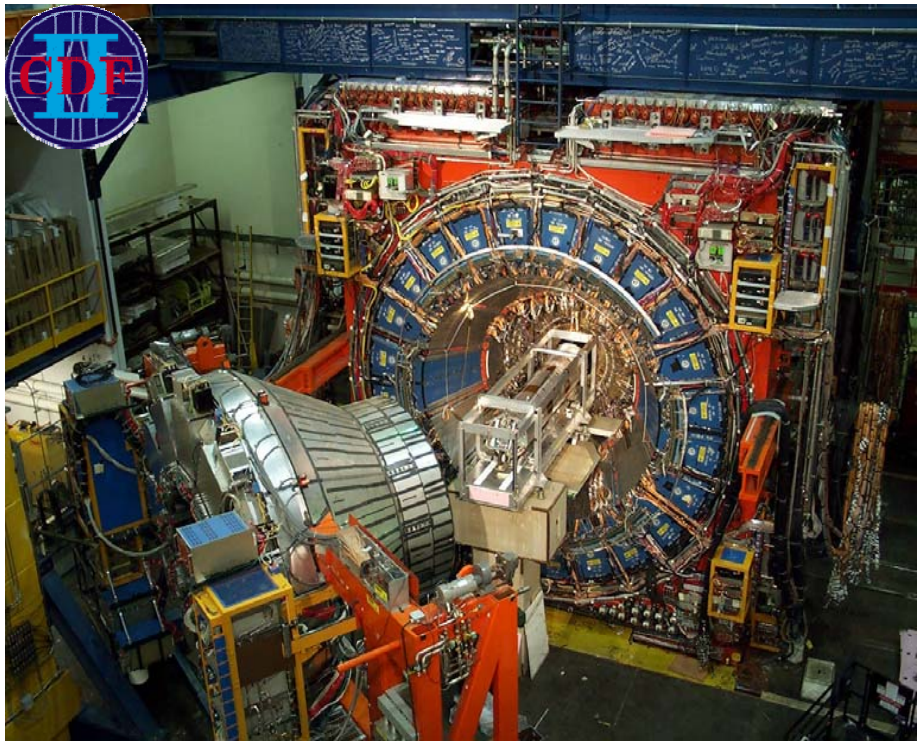
Tevatron is Running Very Well



Results in this talk are from upto 4 fb^{-1} of data

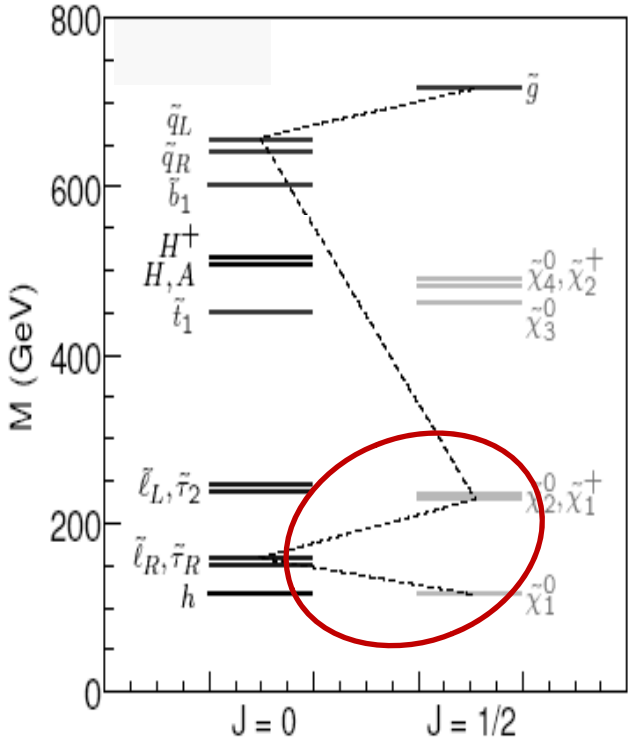
- ~7 fb^{-1} per experiment; ~2 fb^{-1} per year (delivered when no shutdown)
- Routine rates before shutdown: 55-60 pb^{-1} per week
- Peak lumi >300 $\mu b^{-1}/s$
- Expect 10-12 fb^{-1} per experiment by 2011

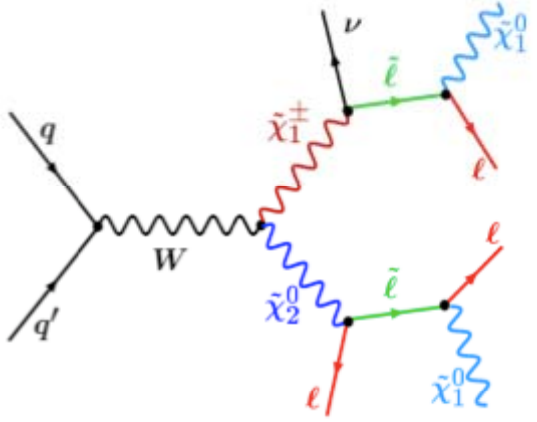
CDF and DØ Experiments

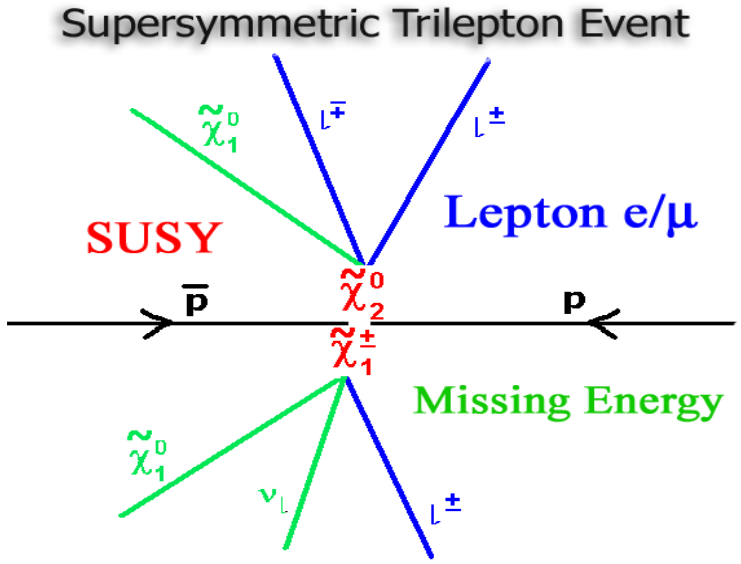


- **Multipurpose detectors — classic design**
  - **"silicon", central tracker, solenoid, calorimeter, muon chambers**
- **Operating well: 80-90% efficiency**
- **Broad physics program**
  - **QCD, EWK, top, B-physics, Higgs searches, searches for new physics**

Charginos & Neutralinos at Tevatron







- Clean "golden mode"
  - 3 isolated leptons
  - Large MET
  - Small SM background

- But small signal
  - Direct Electroweak
  - σ × Br ~ pb

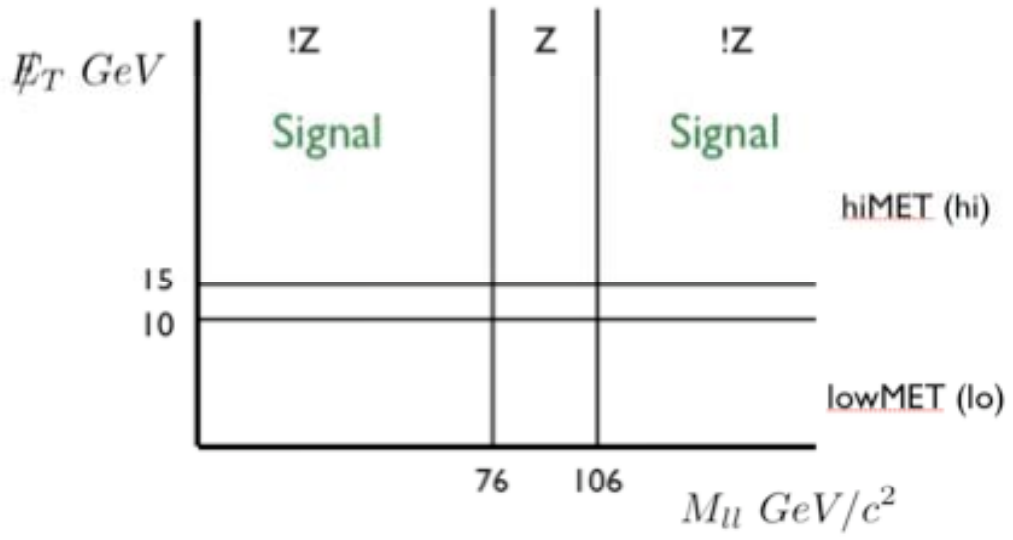
Charginos and Neutralinos with $l^+l^-l^+$

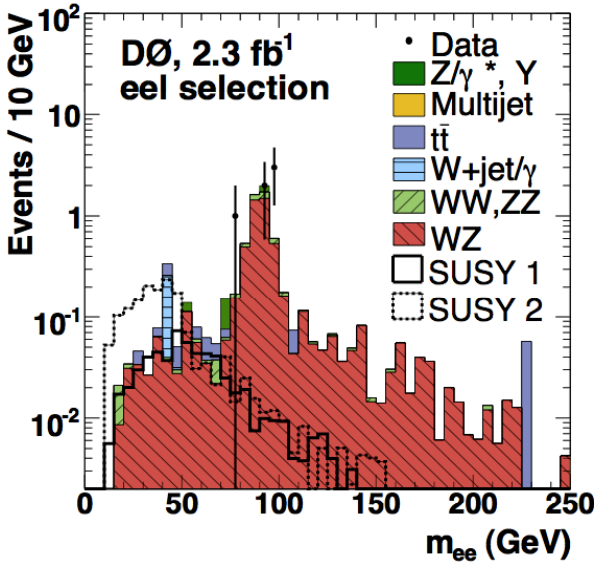
CDF : Multiple exclusive channels

- $l^+l^-l^+$ (l=e,μ), l^+l^- + Track
  - "tight" & "loose" leptons
  - 1st lepton: E_T=15-20 GeV
  - 2nd & 3rd leptons: E_T=5-10 GeV
- Kinematic cuts
  - M_{l+l}, N_{jet}, missing E_T, $\Delta\phi$. . .

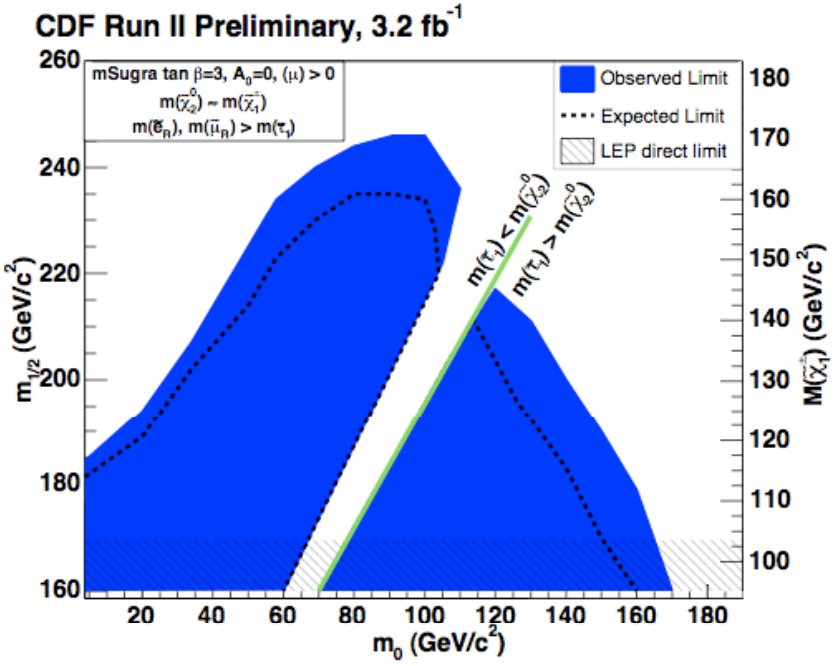
DØ

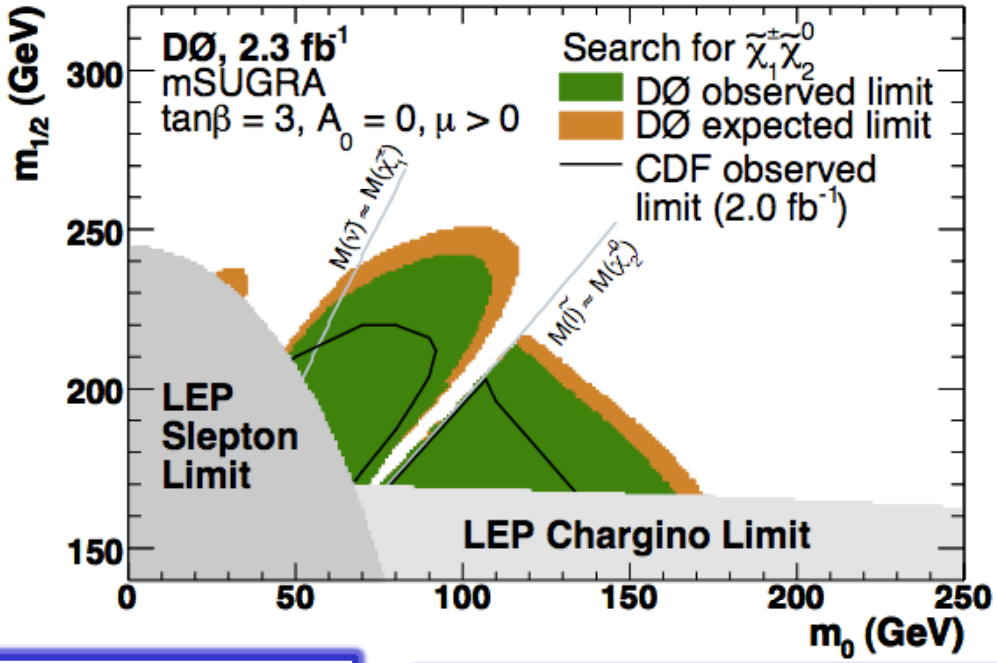
- l^+l^- + Track, μτ+Track, μττ (τ→hadrons)
  - 1st lepton: E_T=12-20 GeV
  - 2nd & 3rd leptons: E_T=4-16 GeV
- Backgrounds
  - WW, WZ, DY, W+γ/jets, ttbar





Charginos and Neutralinos with $l^+l^-l^+$





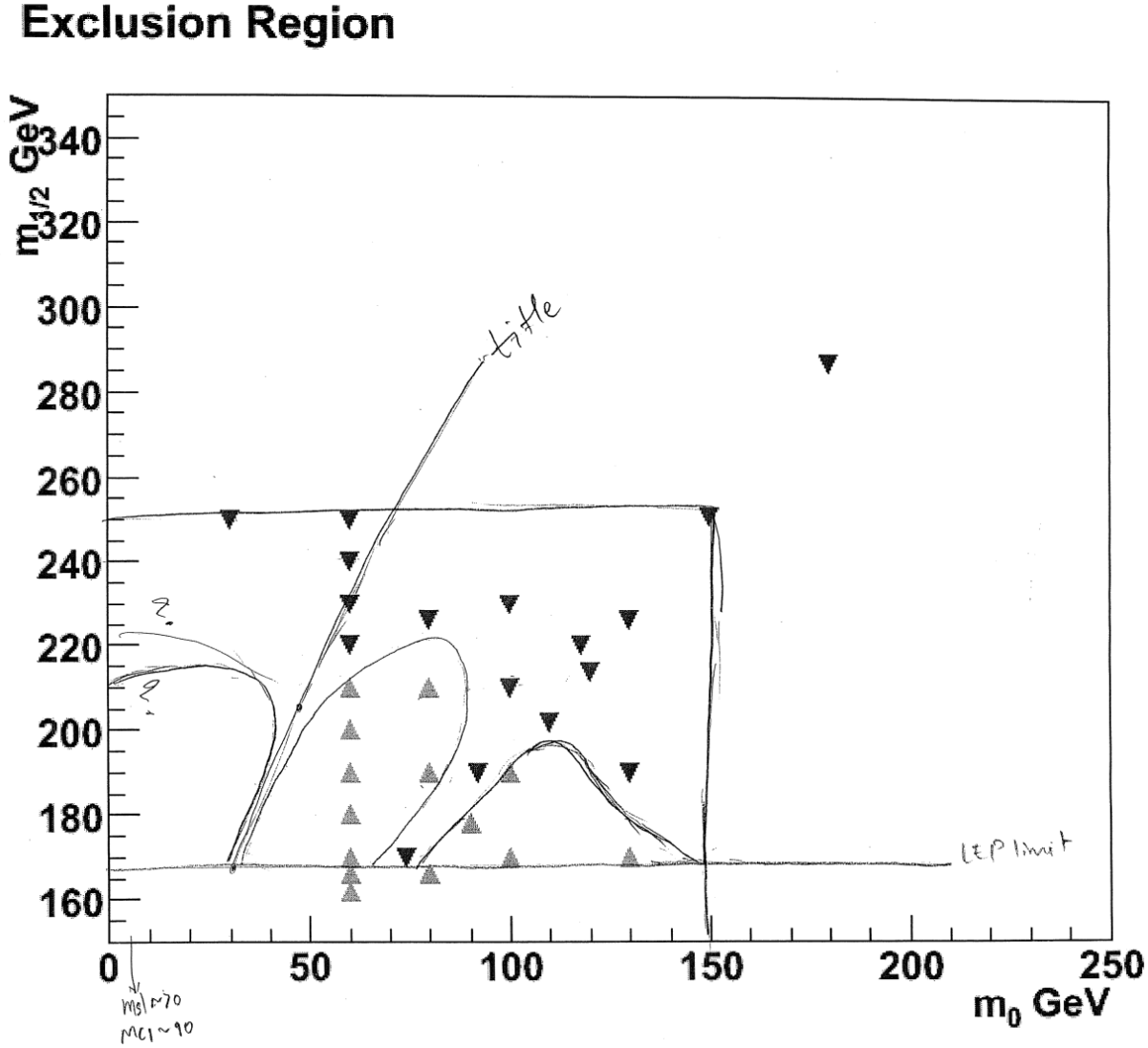
CDF & D0: M($\chi^{\pm}$) limits ~160GeV/c^2

D0 (1.0-2.3 fb^{-1})			CDF (3.2 fb^{-1})		
Channel	SM	Data	Channel	SM	Data
Low p_T	5.4±0.6	9	$l^+l^-l^+$	1.5±0.2	1
High p_T	3.3±0.4	4	l^+l^-+trk	9.4±1.4	6

- **CDF**
  - 2 fb^{-1} PRL 101,251801(2008)
  - 3.2fb^{-1} prelim
- **D0**
  - 2.3 fb^{-1} PLB 680, 34 (2009)

Early Exclusion

2 fb^{-1}

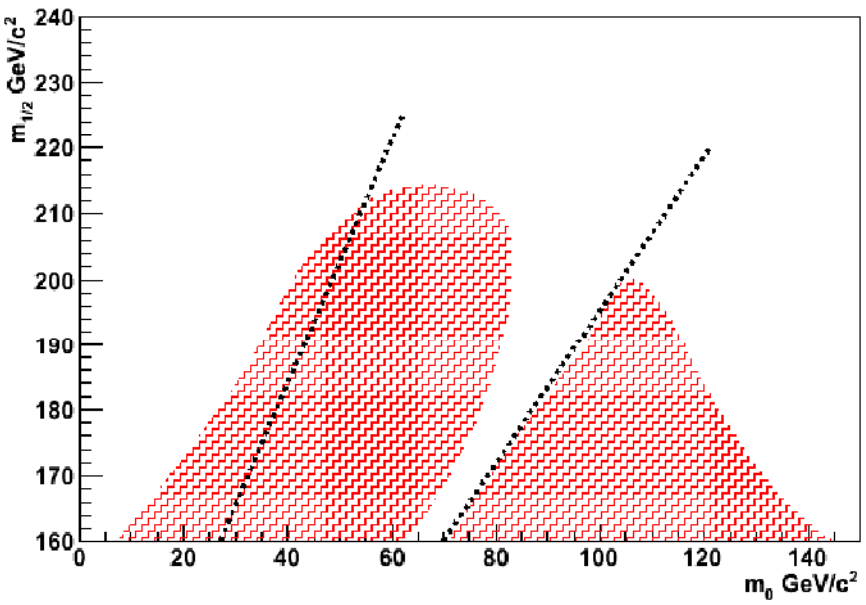


Tripletons: Breaking Away From mSUGRA

- **What if A_0 = 100 or tan(β) = 15? Other models?**
  - **Split channels by number of τ 's (0,1,2,3)**
  - **Provide four [σB]'s for each channel**
  - **Sensitivity independent of branching ratios**

Exclusion region obtained from the model independent formulation agrees well with experiment.

Fit spreadsheet available electronically.



"Addressing the Multi-Channel Inverse Problem at High Energy Coliders: A Model Independent Approach to the Search for New Physics with Trileptons."Dube, Glatzer, Somalwar, Sood, Thomas arXiv:0808:1605, submitted to PRD.

So Far

Chargino-Neutralino (Direct weak production)

- 3 leptons(e/mu) & missing-E_T
- 2 leptons + track/tau & missing-E_T

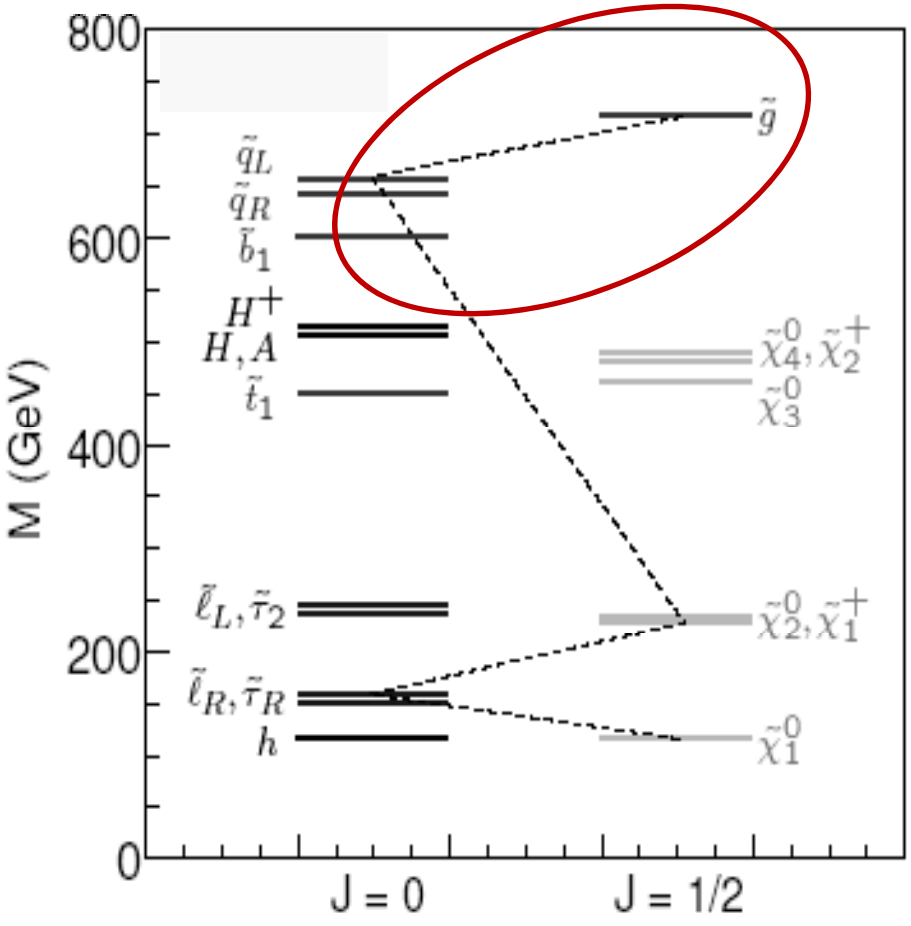
Now:

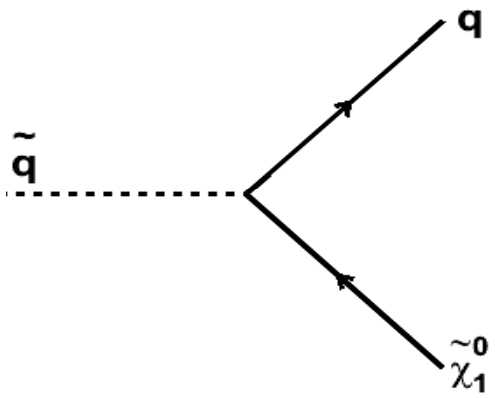
- hadronic production (higher masses)
- Squarks and gluinos
- Specific squarks

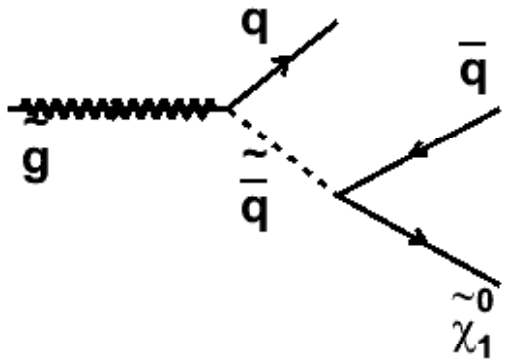
Later:

- Photons: GMSB and Hidden Valley

Squarks & gluinos with n-Jet & MET







- Number of jets
- Missing-E_t
- H_t (=Σ jet E_t's)

Squarks & gluinos with n-Jet & MET

•Number of jets, Missing-E_t and H_t (=Σ jet E_t's)

Std Model Contributions

2 or more jets: W+jets, QCD, Z (invisible)+jets, top

4 or more jets: top, QCD, W+jets, Z (invisible)+jets

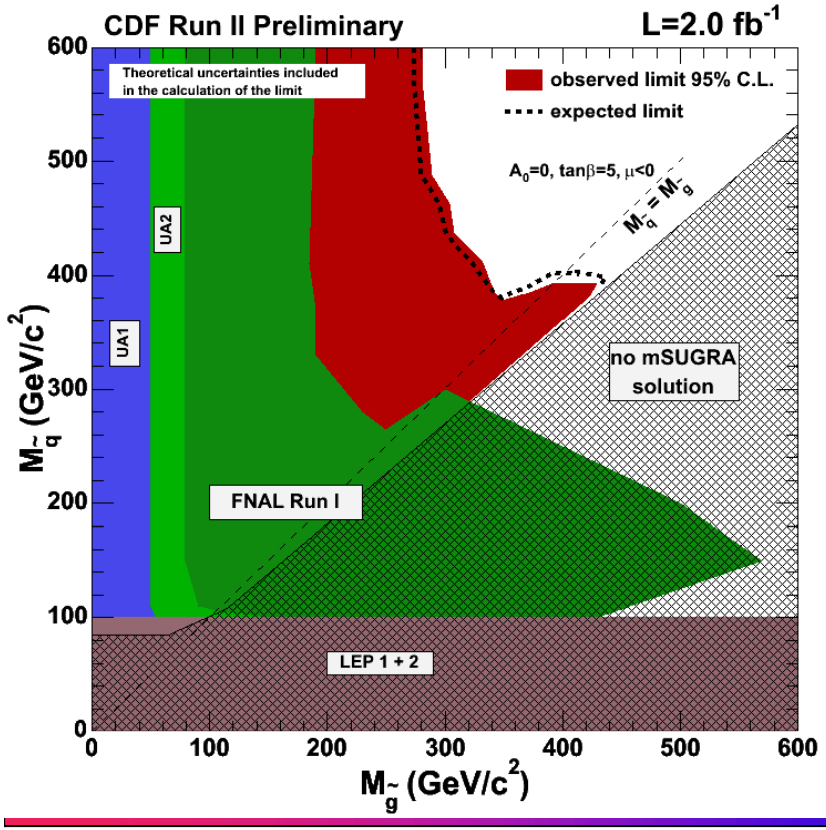
	CDF $(2\ \text{fb}^{-1})$		DØ $(2.1\ \text{fb}^{-1})$	
Analyses	**Expected**	**Observed**	**Expected**	**Observed**
2-jets	16 ± 5	18	$11 \pm 1^{+3}_{-2}$	11
3-jets	37 ± 12	38	$11 \pm 1^{+3}_{-2}$	9
4-jets	48 ± 17	45	$18 \pm 1^{+6}_{-3}$	20

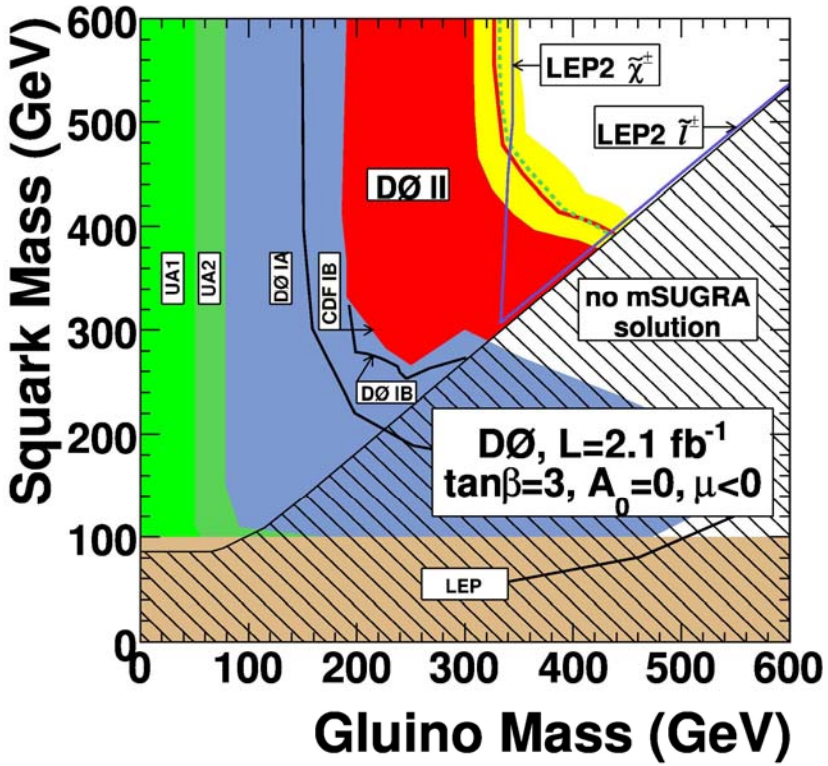
Squarks & gluinos with n-Jet & MET

Gluino: m> 280 GeV/c^2 for all m(squark) (CDF) PRL 102,121801(2009)

308 GeV/c^2 (DØ) PLB 660, 449 (2008)

Squarks 380 GeV/c^2 for all gluino masses





Squark Production in jets+τ_h+MET

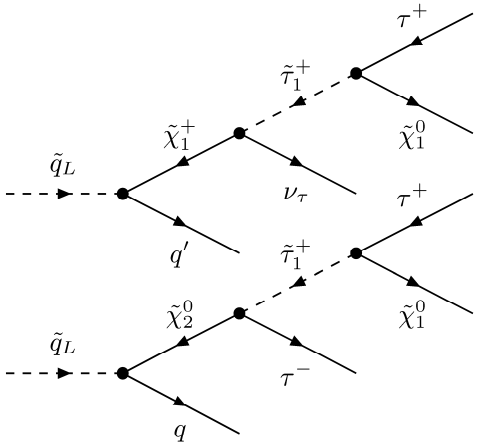
- "Tau corridor"
  - Stau is lightest slepton

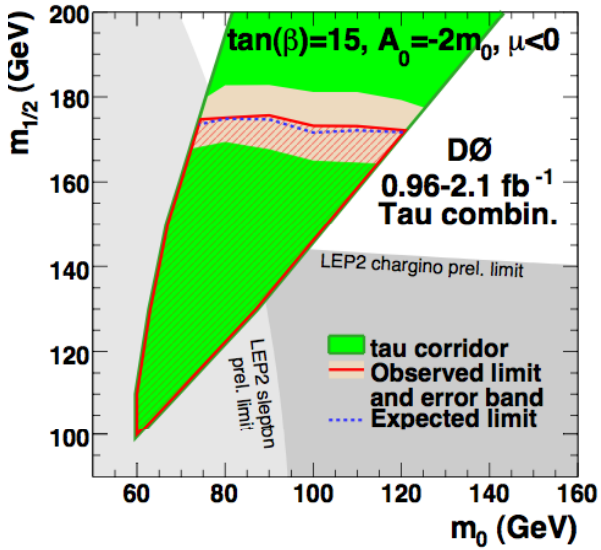
$$M(\tilde{\tau}_1) < M(\tilde{\chi}_1^{\pm}),\ M(\tilde{\chi}_2^0)$$

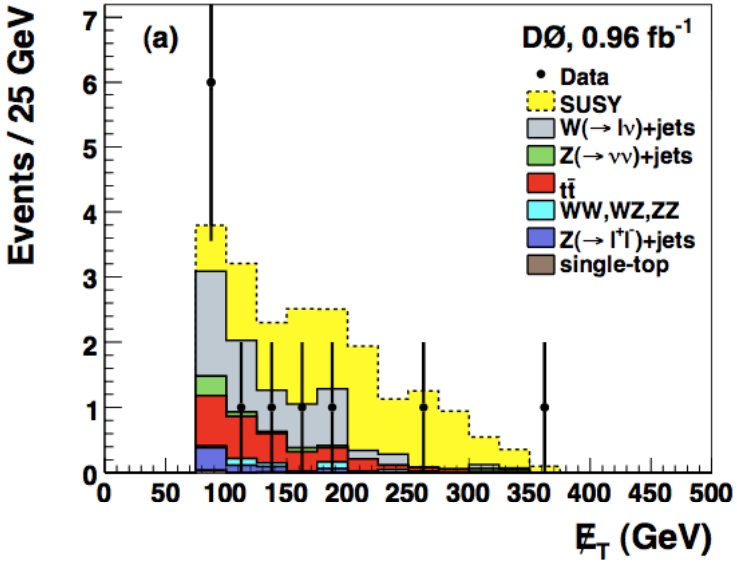
  - M(squark)<M(gluino)

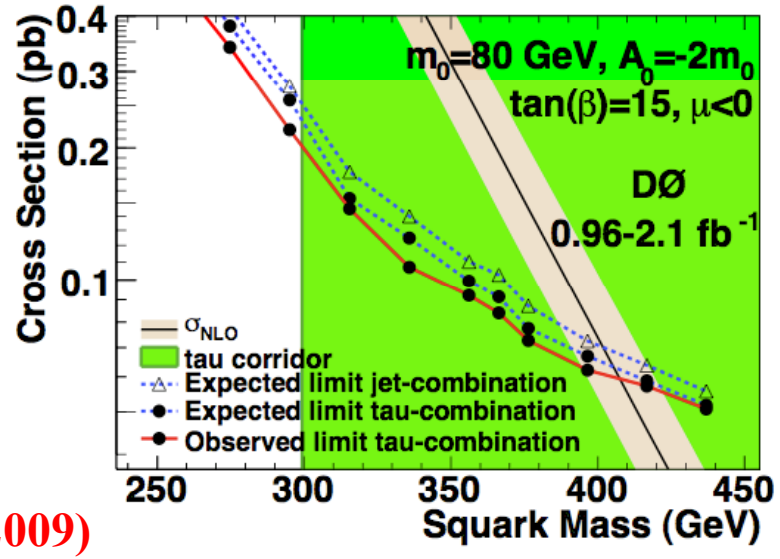
$$p\bar{p} \to \tilde{q}_R\tilde{q}_L,\ \tilde{q}_R \to q\tilde{\chi}_1^0$$

- Final state: jets+$\tau_{(h)}$+MET
  - Not studied before



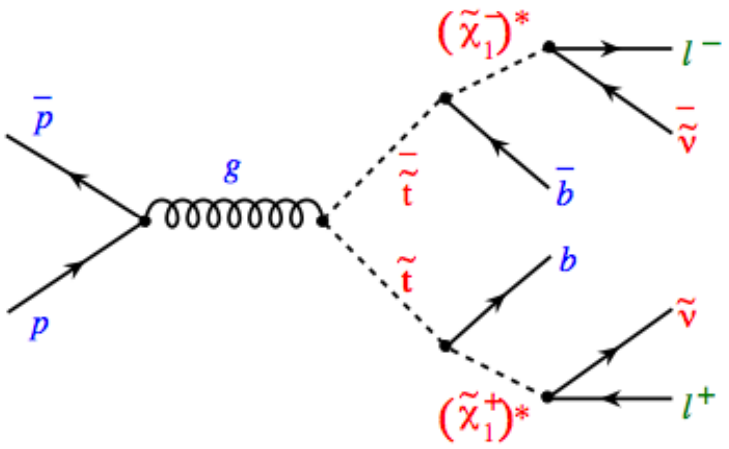






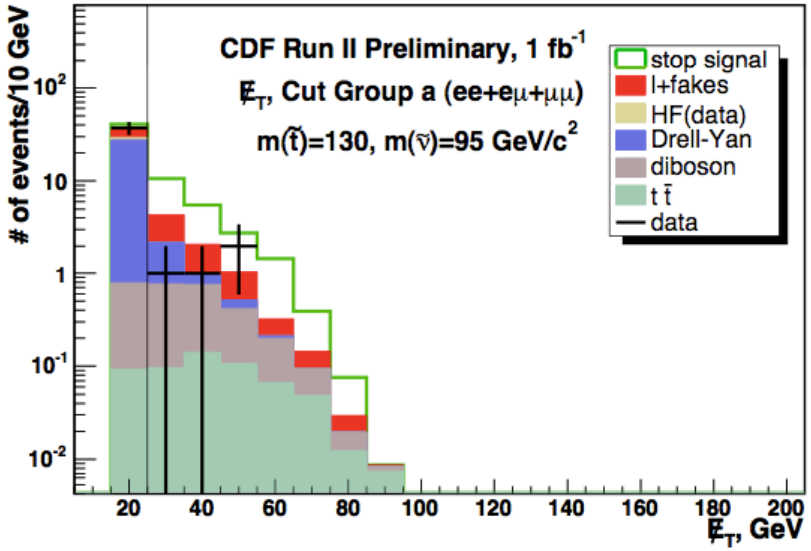
PLB 680,24 (2009)

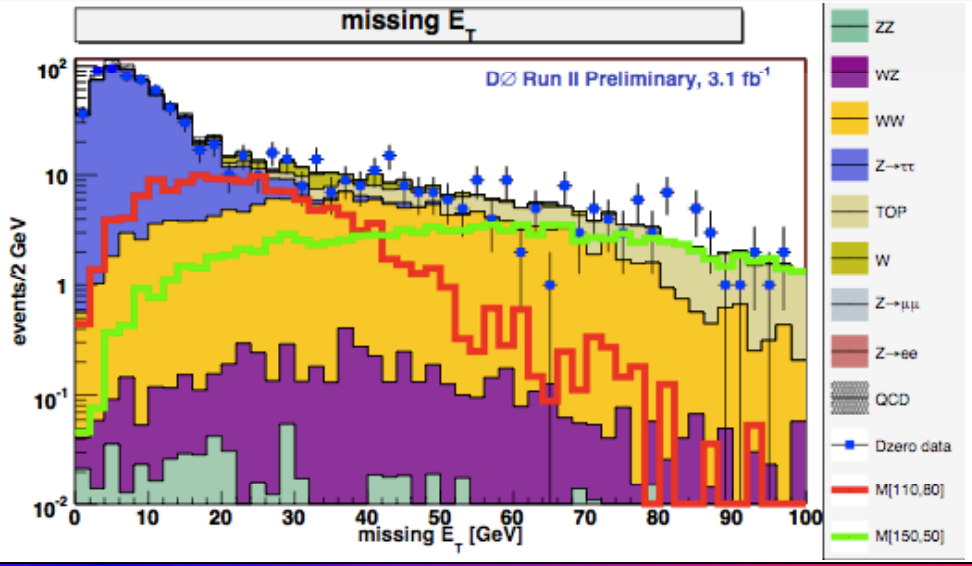
Stop→$l^{\pm}$+b+sneutrino in l^+l^-+jets+MET



$\tilde{t}_1 \rightarrow bl\tilde{\nu}$

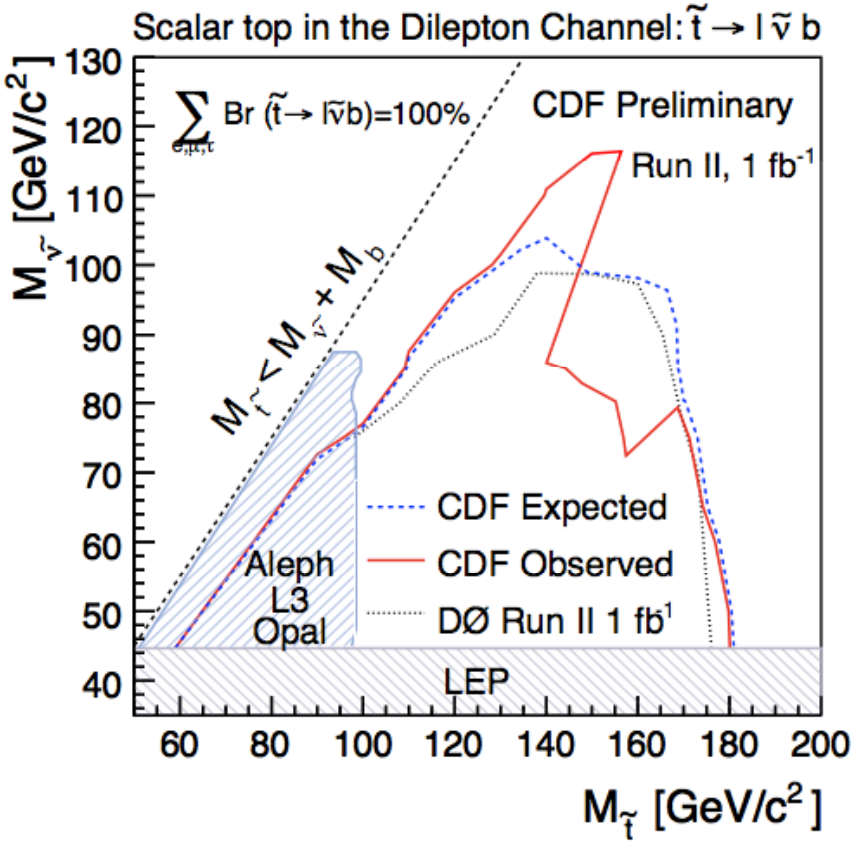
- **Stop light** (big L-R mixing, level repulsion➔see-saw)
- **sneutrino is LSP**
- **Topology: Δm=m(stop)-m(sneutrino)**
- **Final state:**
  - **CDF (1 fb^{-1}): l^+l^-+N_{jet}>1+MET (ll=ee, μμ, eμ)**
  - **D0 (3.1 fb^{-1}): $e^+\mu^-$+(jets)+MET**

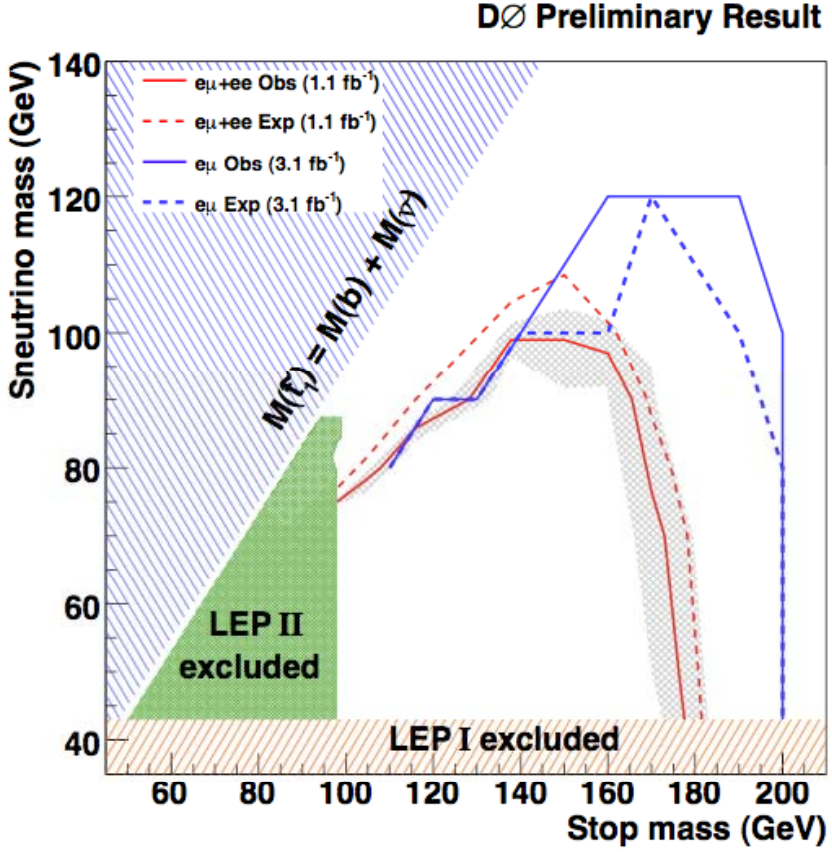




Stop→$l^{\pm}$+b+sneutrino in $l^{+}l^{-}$+jets+MET

- **Results at large Δm=m(stop)-m(sneutrino)**
  - **D0 (3.1 fb^{-1}): m(stop)>200 GeV**
  - **CDF (1 fb^{-1}): m(stop)>180 GeV**



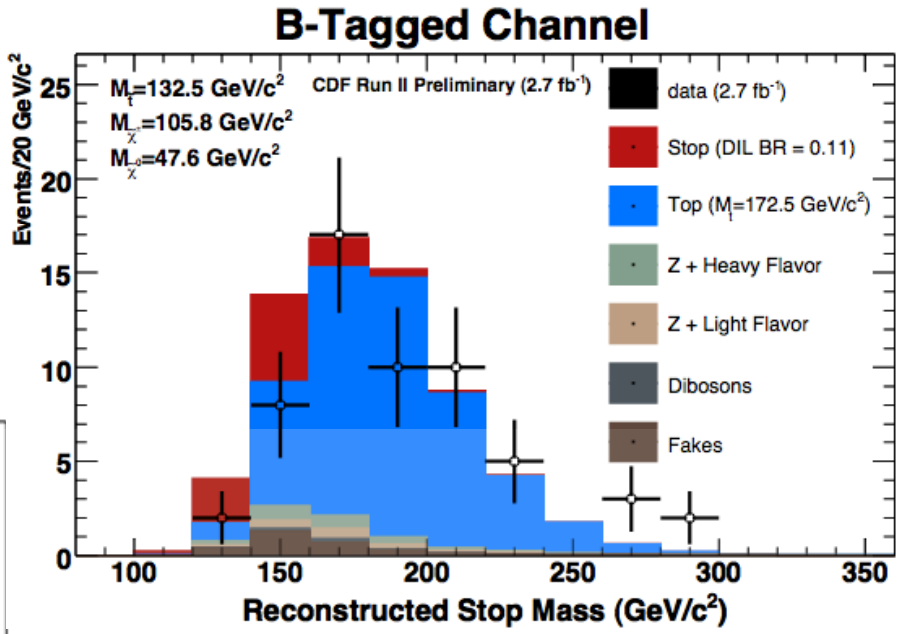


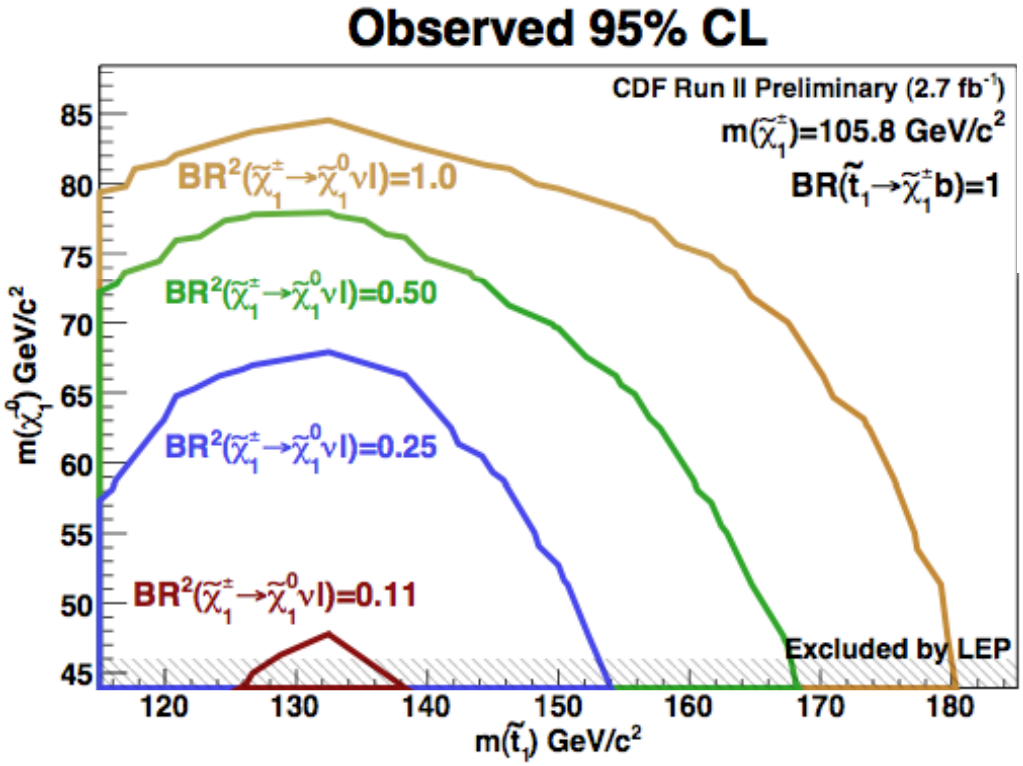
Stop Decays Mimicking Top Signature

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{\chi}_1^0 l\nu$$

Usual ttbar selection:

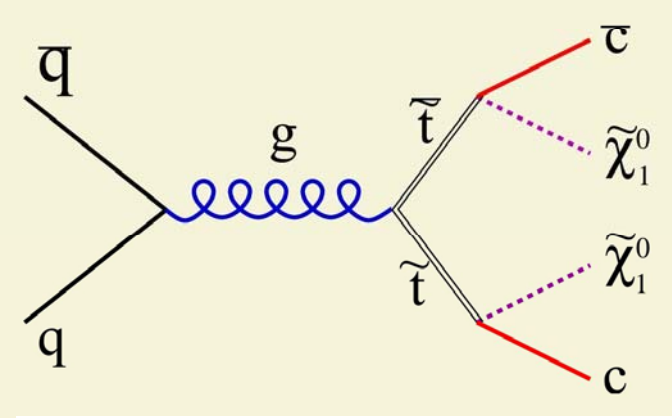
- l^+l^-+bb+MET (l=e, μ)



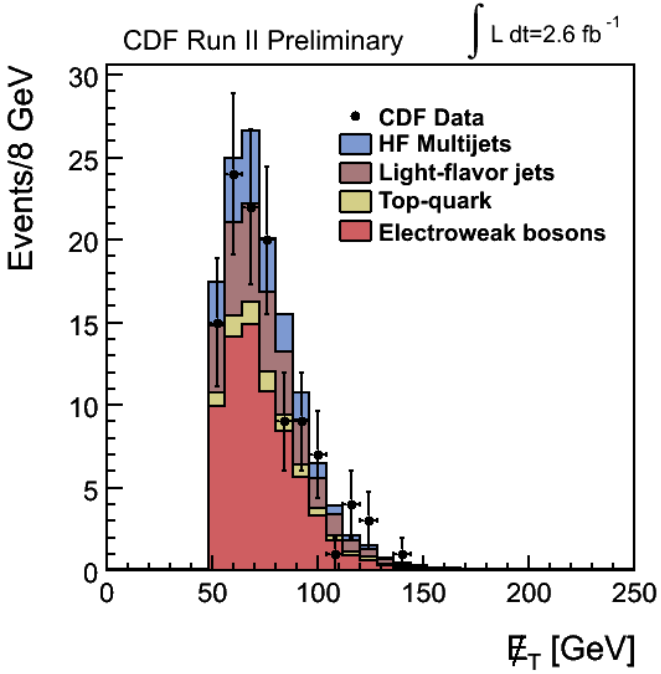


1. $\tilde{\chi}_1^0$ is the LSP
2. $m_{\tilde{t}_1} \lesssim m_t$
3. $m_{\tilde{\chi}_1^+} < m_{\tilde{t}_1} - m_b$

Stop search with charm-tagging



- 2 jets and missing-ET
- At least one tagged jet



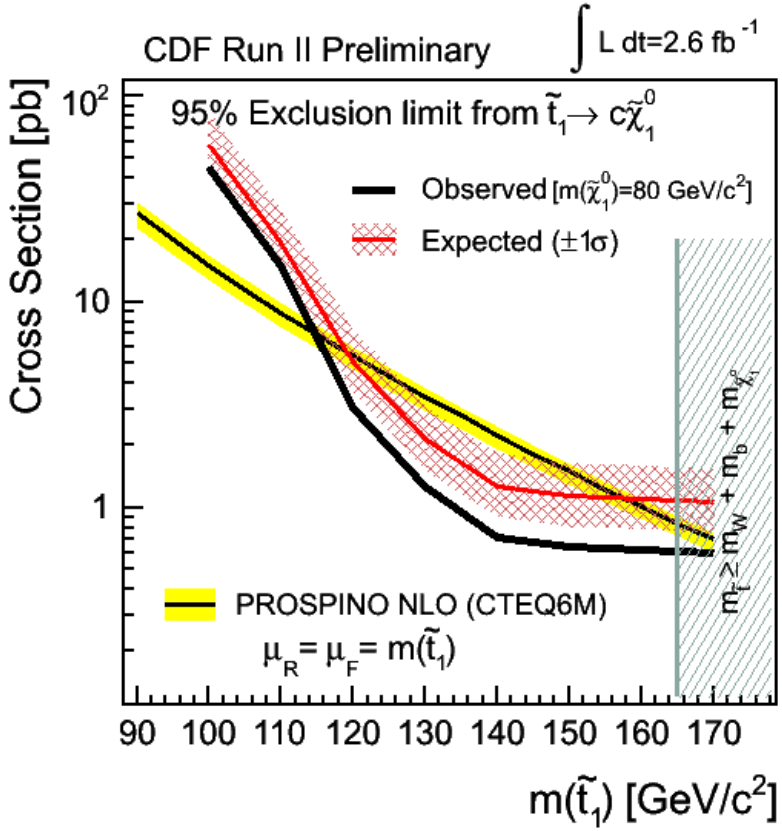
CDF Run II Preliminary 2.6 fb^{-1}

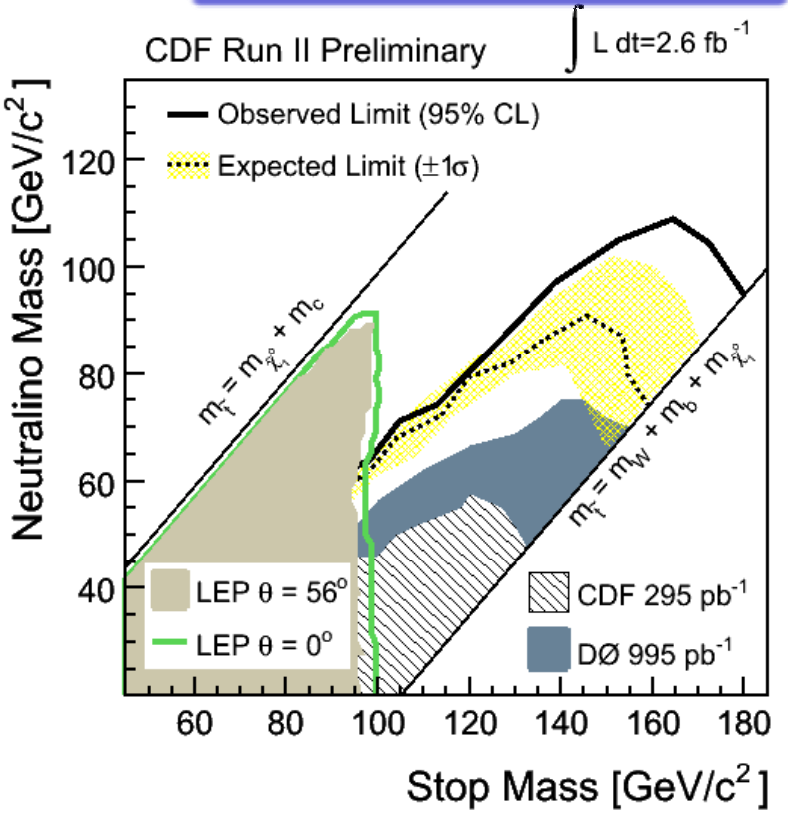
	Final Region
W/Z + jets production	60.9 ± 26.6
Diboson production	10.7 ± 1.9
Top pair production	4.6 ± 1.3
Single top production	3.2 ± 0.8
HF QCD Multijets	20.4 ± 15.2
Light-flavour contamination	32.2 ± 12.7
Total expected	132.0 ± 24.4
Observed	115
Signal m($\tilde{t}$)=125, m($\tilde{\chi}^0$)=70	90.2 ± 23.9
Signal m($\tilde{t}$)=135, m($\tilde{\chi}^0$)=70	78.0 ± 20.7
Signal m($\tilde{t}$)=115, m($\tilde{\chi}^0$)=70	82.4 ± 21.8

Stop search with charm-tagging

- Charm-tagging to reduce b-jet backgrnd.
- Neural Networks

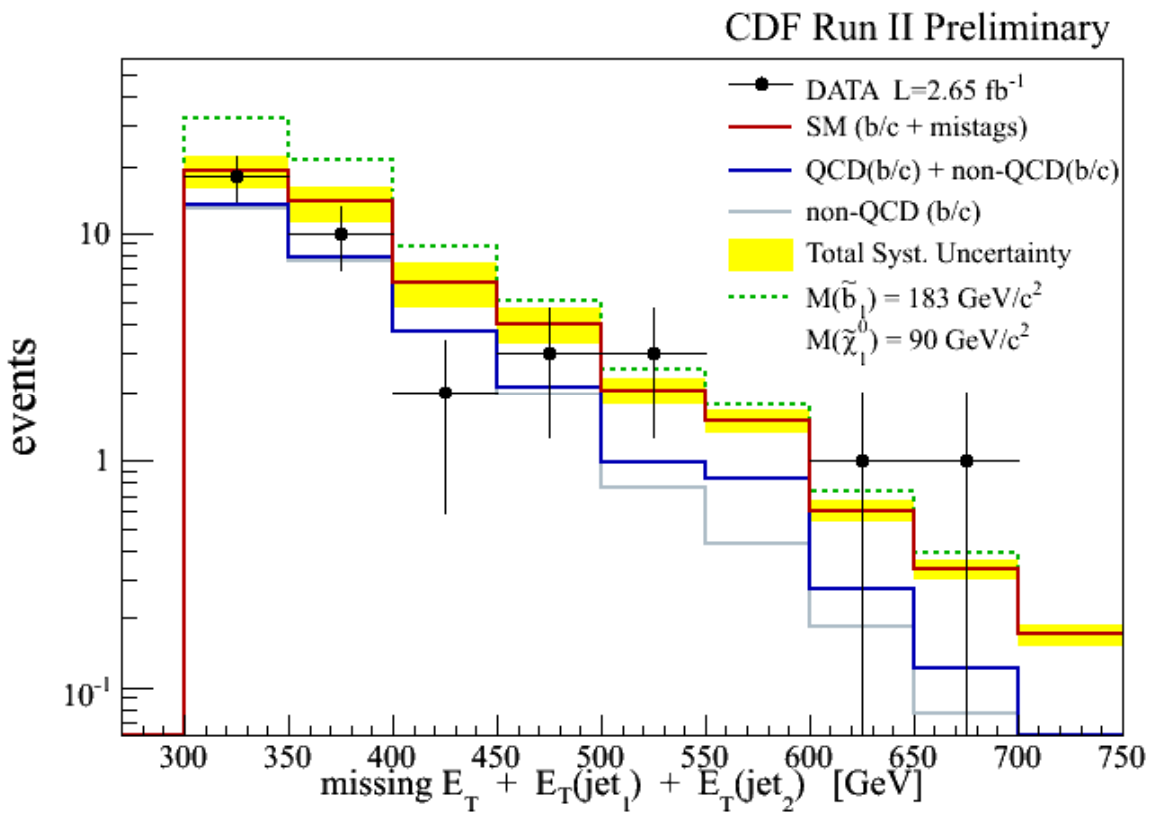
Kinematic Exclusion (up to 180 GeV/c²)





Sbottom at the Tevatron

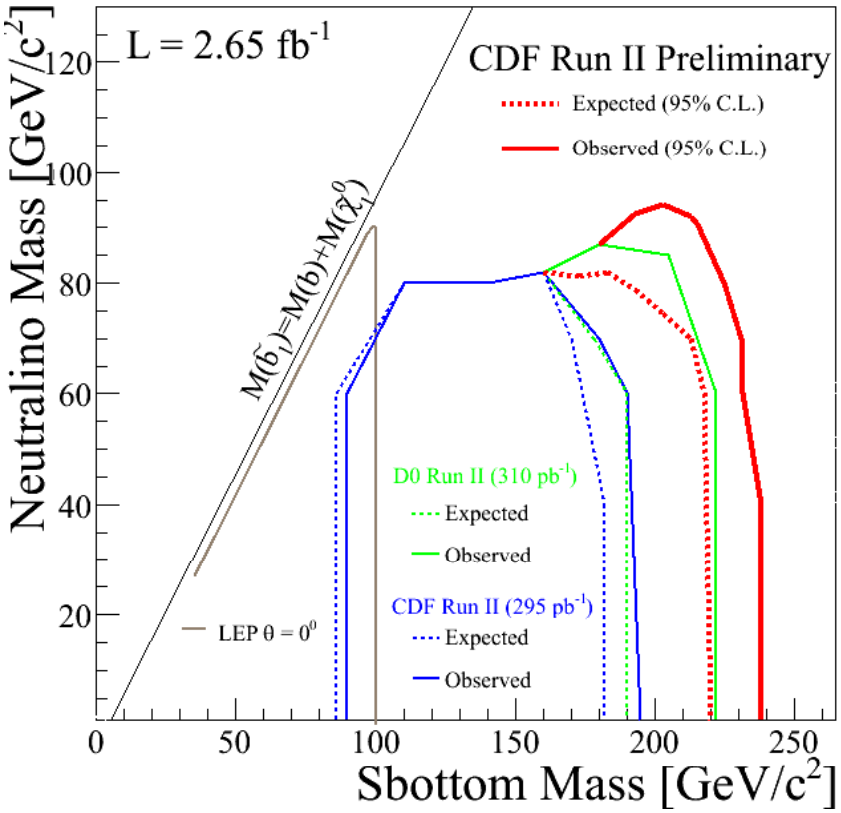
$$p\bar{p} \longrightarrow \tilde{b}_1\bar{\tilde{b}}_1 \longrightarrow (b\chi^0)\,(b\chi^0)$$

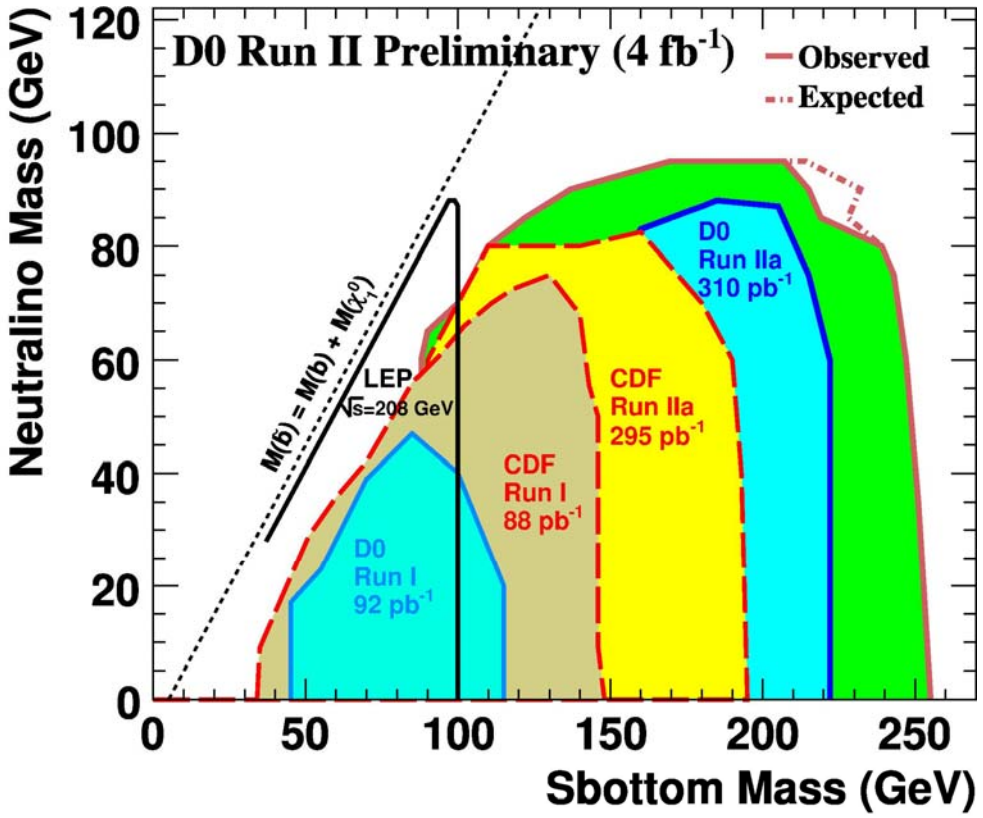


- Sbottom could be the lightest colored sparticle at high tan(β).
  (same level replusion see-saw as stop)
- Strategy: missing-E_T, Sum jet E_T, b-tagging (& optimization)

Sbottom at the Tevatron

Mass limit approaching 250 GeV/c^2



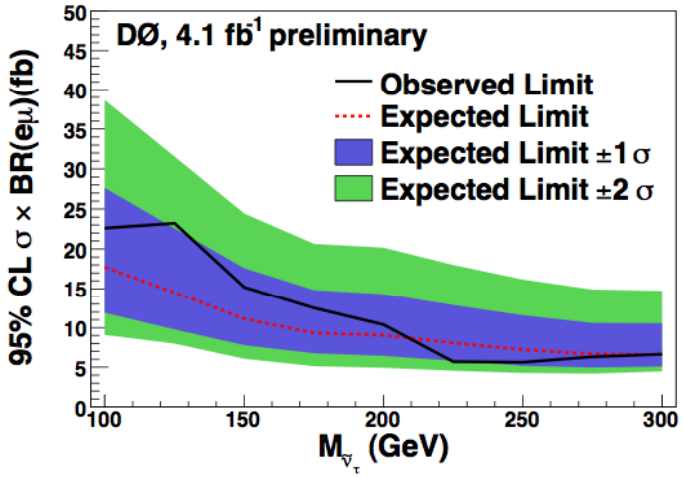


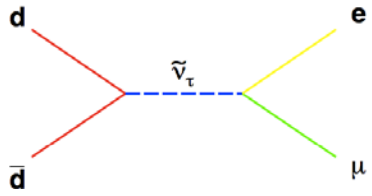
Sneutrinos

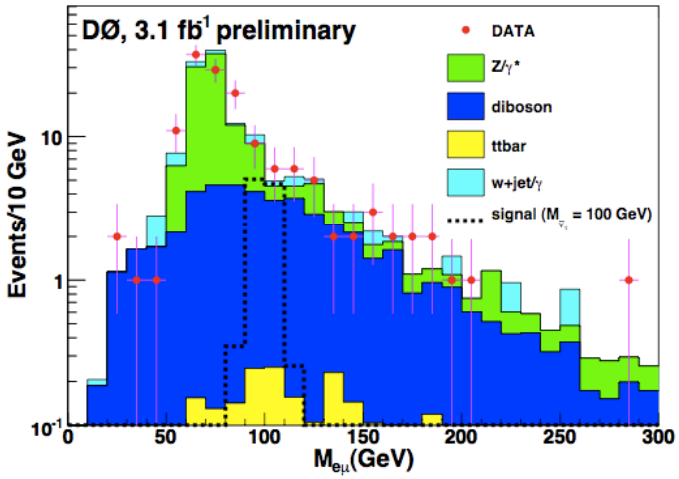
- Assume R_p violation
  - production of single sparticle
- High-mass $e^+\mu^-$ resonances
  - Striking signature
  - Veto events with MET & jets
  - Backgrounds: $Z/\gamma^* \rightarrow \tau\tau \rightarrow e\mu$, dibosons

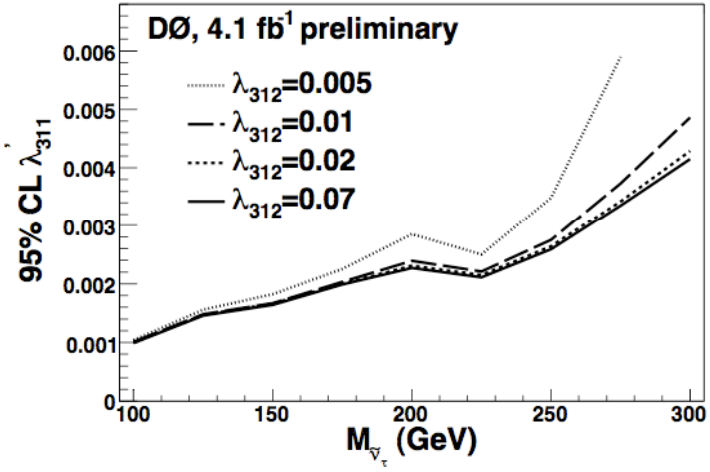
1 fb^{-1} analysis: PRL 100, 241803 (2008)

$\lambda'_{311}=0.12\ \lambda_{213}=0.07$







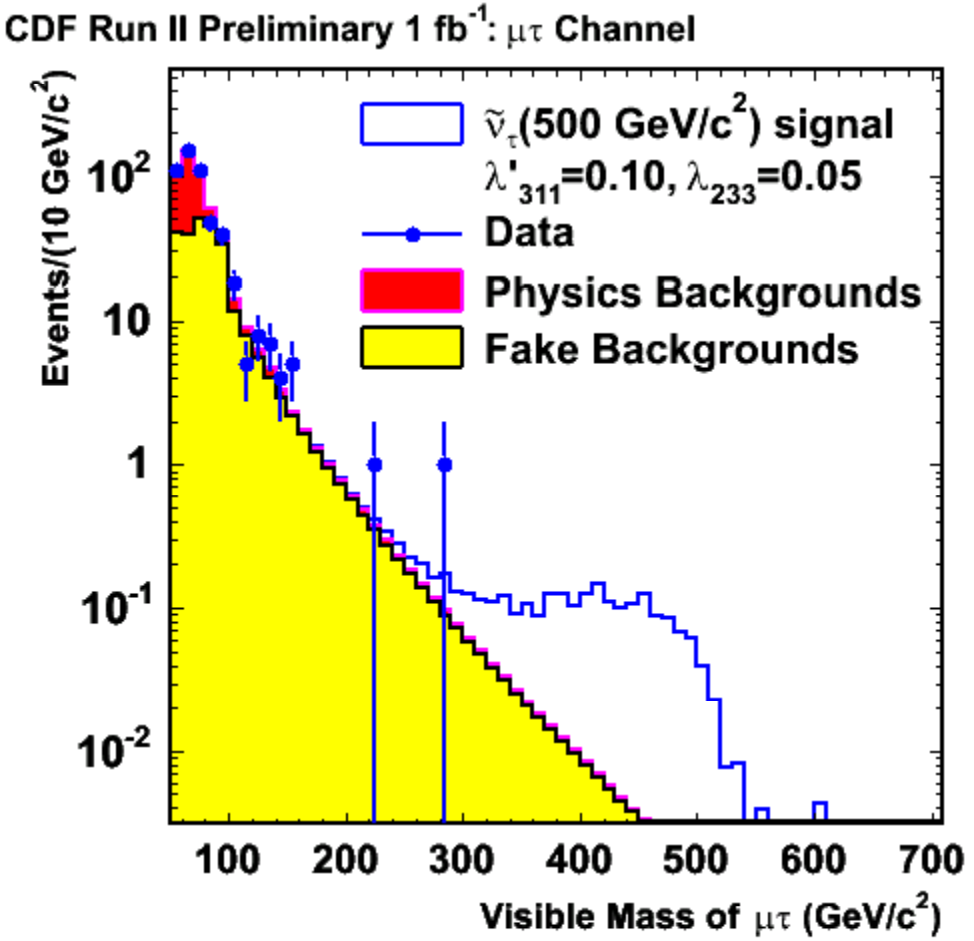


Sneutrinos (including τ channels)

CDF: Highmass eμ,μτ, eτ resonances (1 fb^{-1})

SM processes	eμ channel
	M > 480GeV/c^2
$Z/\gamma^* \rightarrow \tau\tau$	0.002 ± 0.002
$Z/\gamma^* \rightarrow \mu\mu$	0.0005 ± 0.0003
$W \rightarrow \mu\nu(+\text{jets})$	¡0.0001
WW	0.01± 0.001
$t\bar{t}$	0.002±0.002
Dijets and γ +jets	0.002±0.002
Total SM background	0.02±0.003±0.01
Expected signal	1.8 ± 0.05 ±0.2
Observed Events in data	0

Paper under Collaboration Review Shortly



So Far

Chargino-Neutralino (Direct weak production)

3 leptons(e/mu) & missing-E_T

2 leptons + track/tau & missing-E_T

Hadronic production (higher masses)

Squarks and gluinos

Specific squarks: stop and sbottom (jets, maybe leptons and MET)

RP Violation

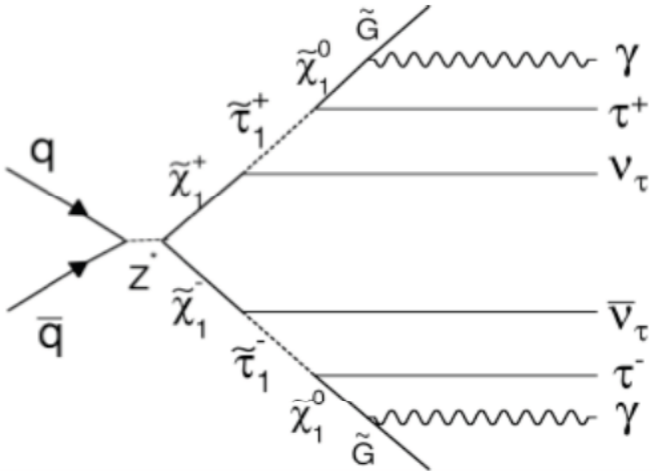
Specific slepton: Sneutrinos (no MET/jets)

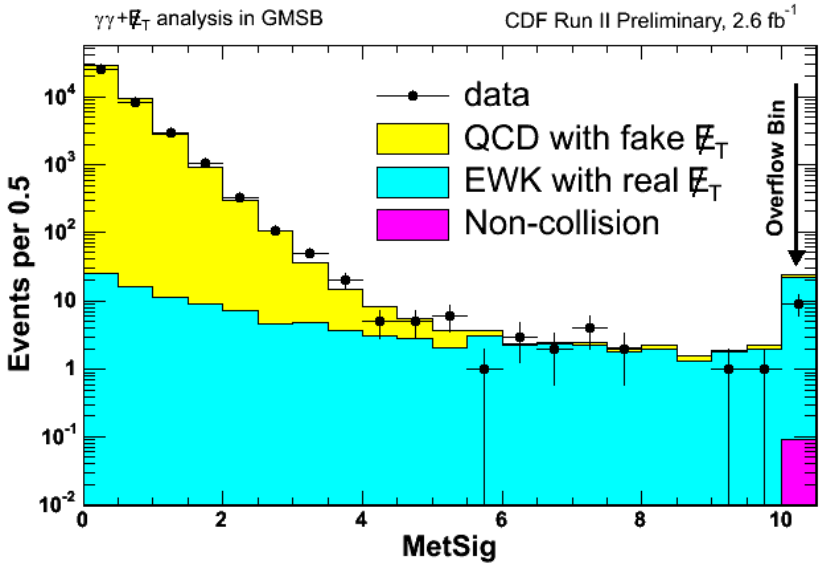
Now: photons

GMSB (very light LSP, photons and MET)

Hidden Valley SUSY (GMSB like, but peculiar signature)

Limits on GMSB in γγ+MET



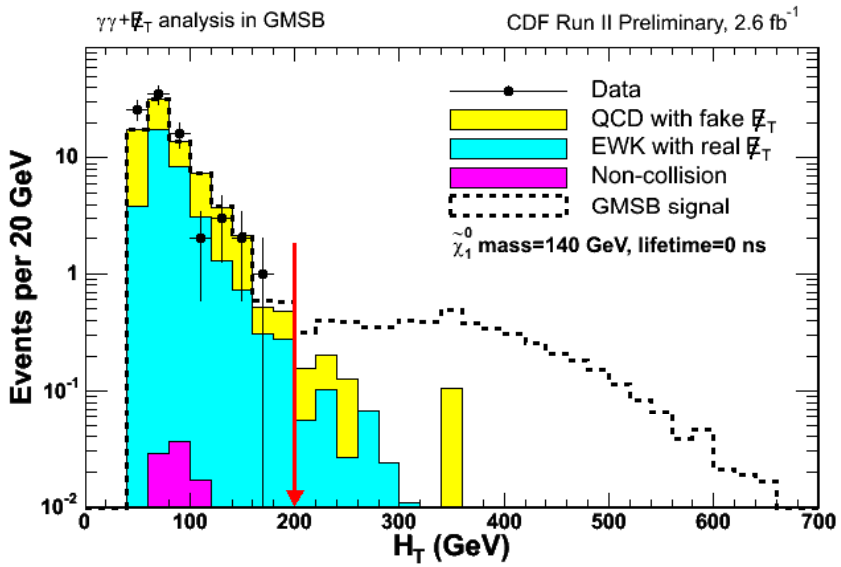


MET-significance based on energy resolution

- **Gauge-Mediated SUSY Breaking**
  - **SUSY breaking scale:10-100 TeV**
  - **Heavy squarks, gluinos, sleptons**
  - **Gravitino LSP (<<MeV)**
  - **Neutralino or slepton NLSP**
  - **If χ^0 NLSP: $\chi^0 \rightarrow \gamma G$ (Br=100%)**

- **3D optimization:**
  - **MET-significance, H_T, $\Delta\varphi_{\gamma\gamma}$**
    - **$H_T = E_T(\gamma 1) + E_T(\gamma 2) + MET + \ldots$**
- **Backgrounds**
  - **$Z\gamma\gamma \rightarrow \nu\nu\gamma\gamma$, $W\gamma \rightarrow \nu\gamma\gamma_{fake}$**

Limits on GMSB in γγ+MET

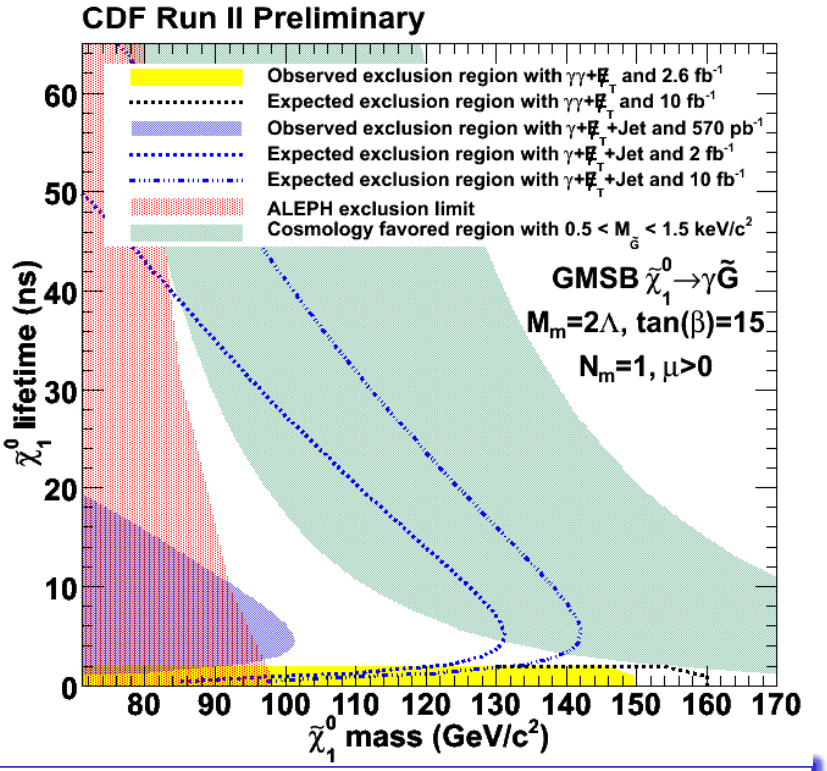


$H_T=E_T(\gamma 1)+E_T(\gamma 2)+MET+...$

After MET-sig>3 & $\Delta\varphi_{\gamma\gamma}<3$

Data: no events observed

Background Source	Expected Rate±Stat±Sys
Electroweak	$0.77\pm0.21\pm0.22$
QCD	$0.46\pm0.22\pm0.10$
Non-Collision	$0.001^{+0.008}_{-0.001}\pm0.001$
Total	$1.23\pm0.30\pm0.24$



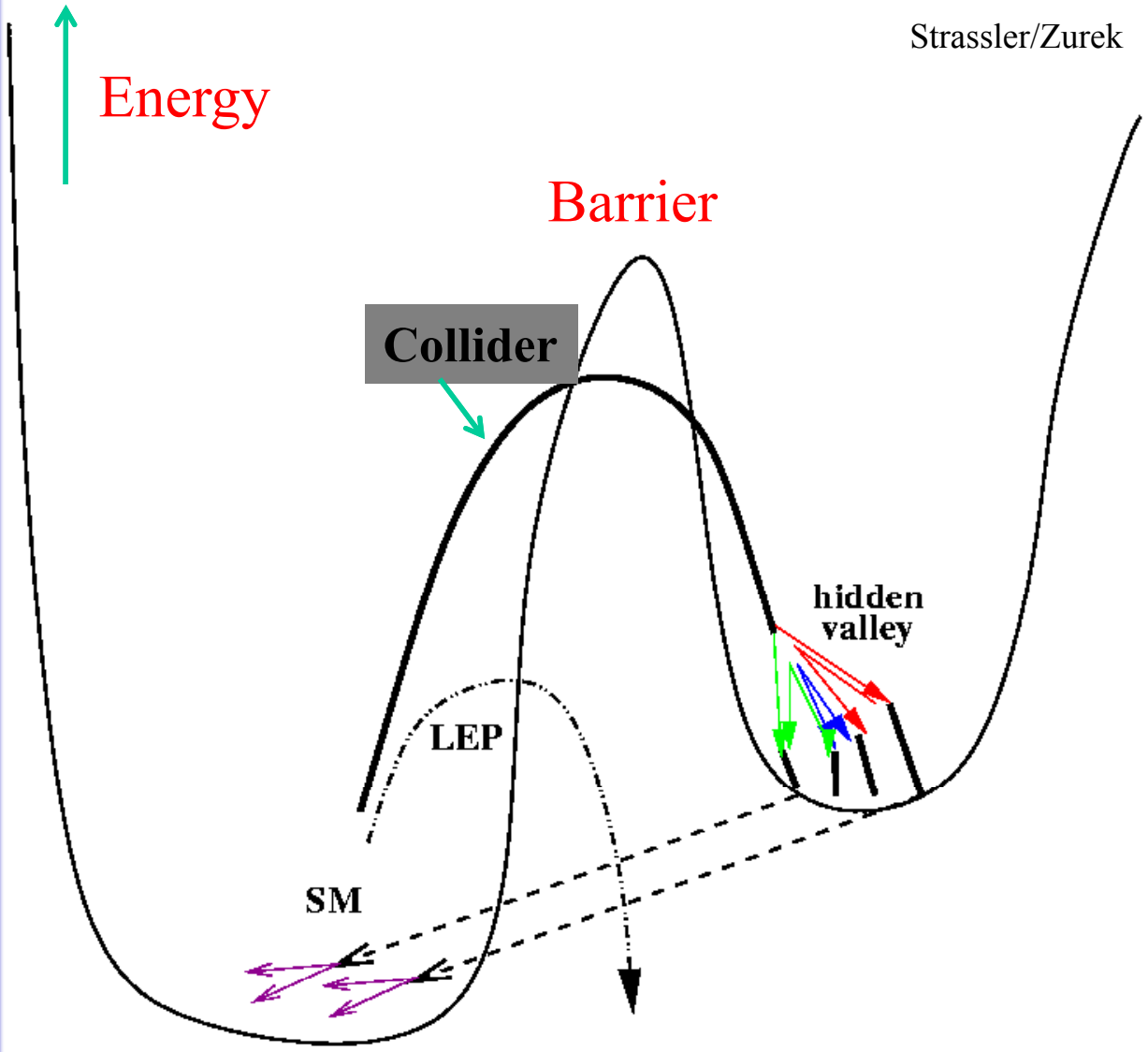
- 95% CL limits in neutralino mass & lifetime plane
  - Neutralino mass>149 GeV/c^2
  - Submitted to PRL arXiv:0910.3606

Supersymmetric Hidden Valley → Dark Photons

- DAMA/LIBRA anomaly, e^+ from galactic center: INTEGRAL
- cosmic e^-/e^+: PAMELA, ATIC..

→ ~1 GeV dark gauge boson ~ 1 GeV mixes with the photon

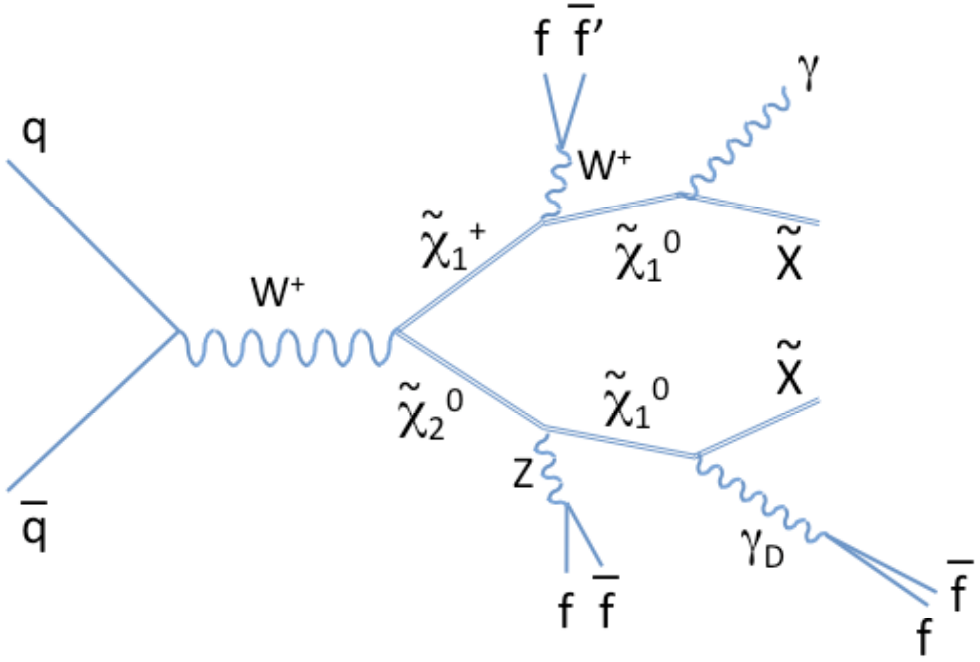
- Signature: two very close leptons



SUSY Hidden Valley Dark Photons

- phenomenology is similar to GMSB
  - Cascade to LSP; LSP→hidden sector
    - Photon + dark LSP (darkino)
    - Dark photon (γ_D) + darkino (MET)
    - γ_D→fermions

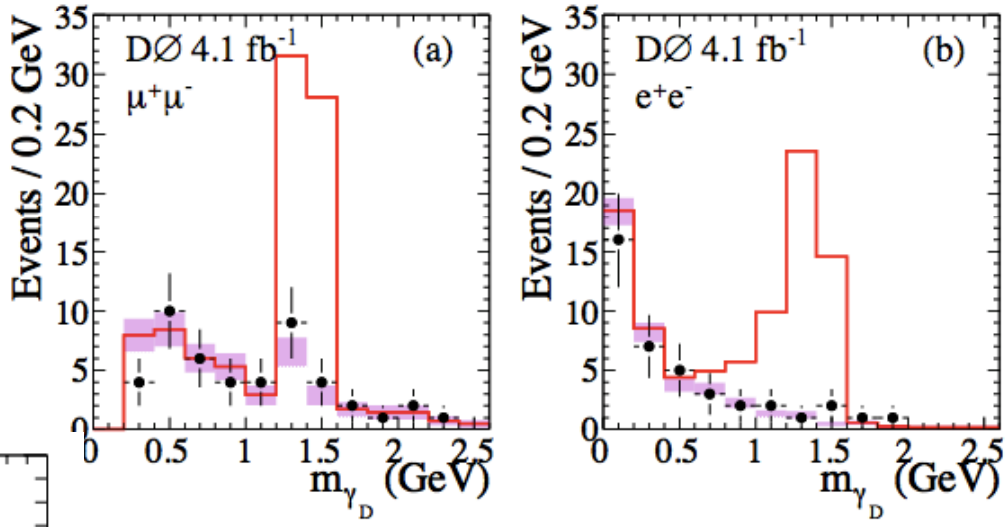
- Look for:
  - γ, MET, two closely spaced leptons
- Main background
  - Multijets, W+γ/jets



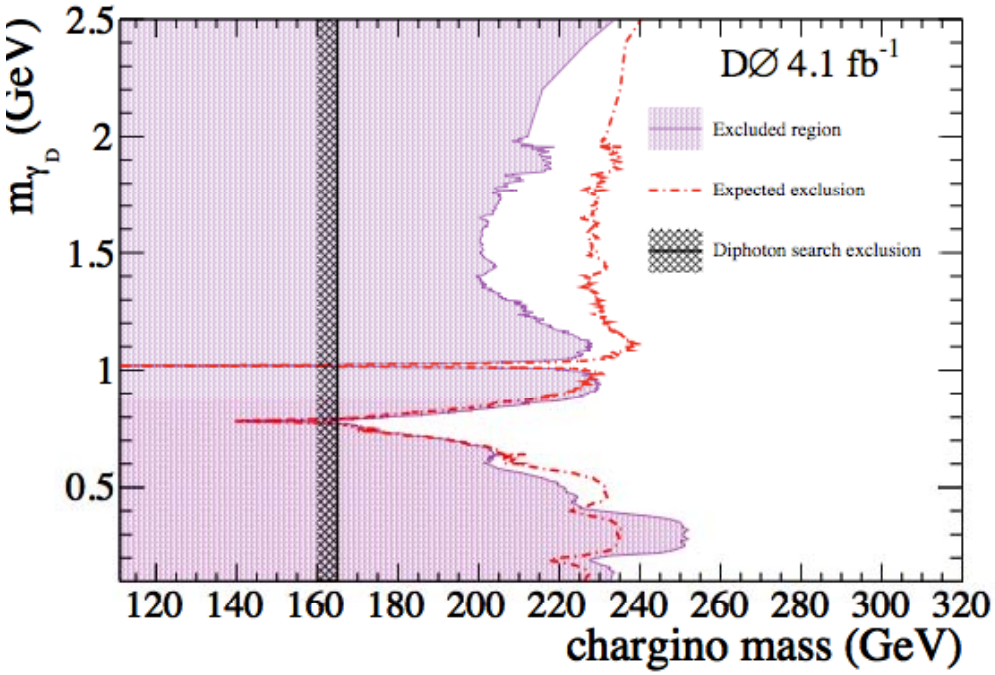
Dark Photons

Dilepton masses. →

Purple bands from contol regions.



μμ ee



Phys. Rev. Lett. 103, 081802 (2009)

Summary

- CDF and DØ have rigorous SUSY program
  - New results on "classic" analyses: stop, trileptons
  - Both experiments exploring new signatures and techniques
- With ~6 fb^{-1} on tape & ~5 fb^{-1} coming, expect more results
- More unconventional searches during the LHC era?
  - Close lepton pairs, delayed/slow particles, CHAMPS….
  - Operational collaborations with theorists
- More CDF and DØ results at

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

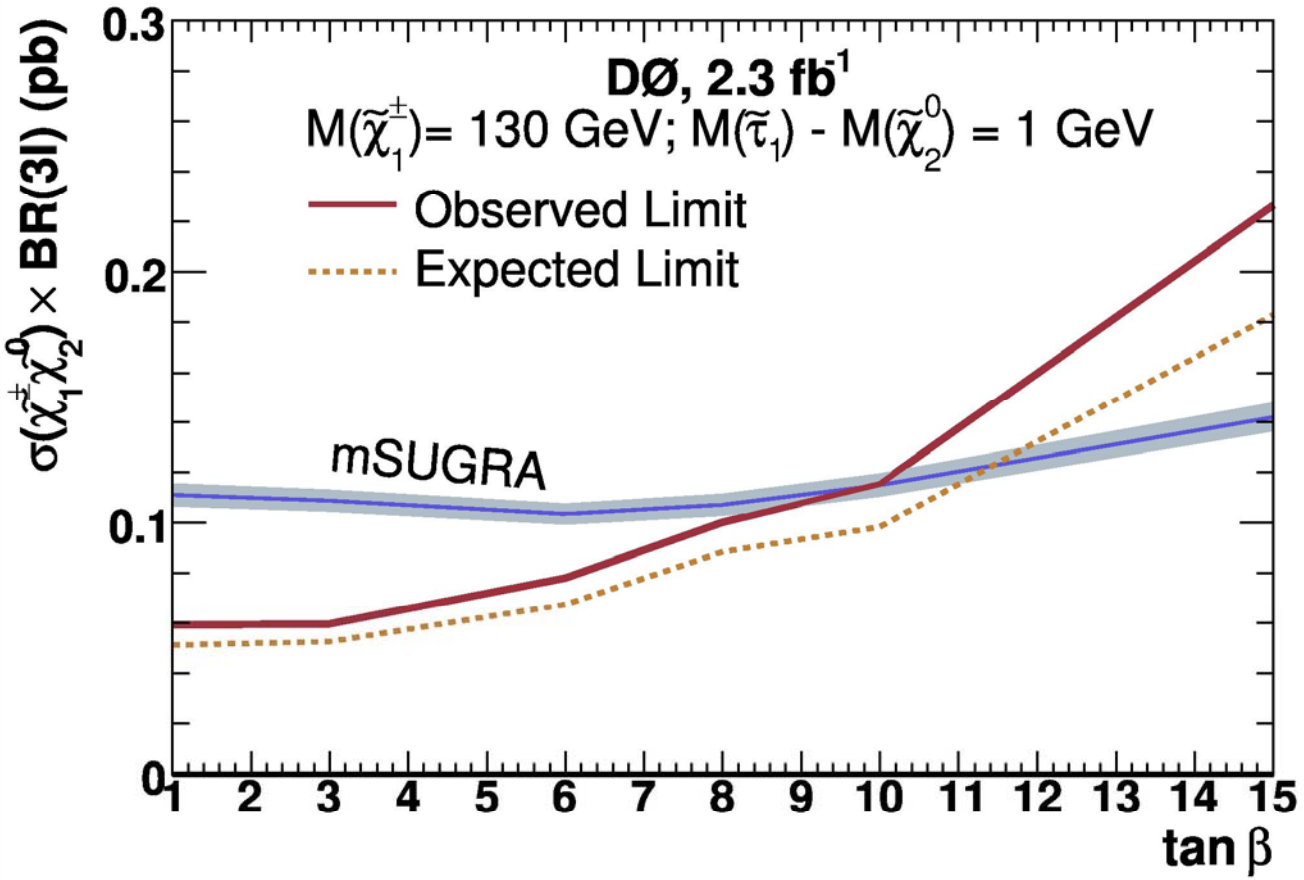
http://www-cdf.fnal.gov/physics/exotic/exotic.html

Backup

Charginos and Neutralinos with $l^+l^-l^+$

- Trileptons is a low tan(β) search: benchmark scenario illustration

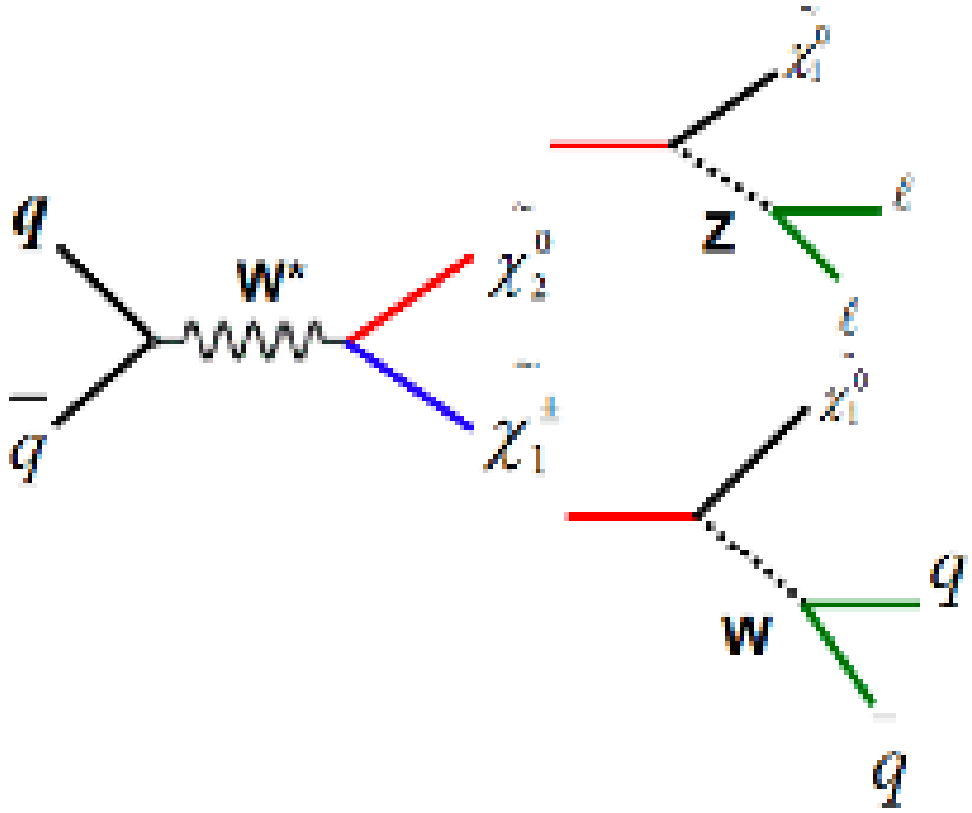
- Notice the low chargino mass: tan(β) range very small when chargino mass close to the upper limit.
- τ coverage key



Charginos & Neutralinos (contd)

- Heavy Gauginos
  - If $M(\chi_2^0)-M(\chi_1^0)>M_Z$ & $M(\chi_1^\pm)-M(\chi_1^0)>M_W$
  - Final state with Z, W and large MET
- One of the trilepton analysis control regions

  (high MET dilepton)
- Not too competitive at the Tevatron (chargino/neutralino ~twice the W/Z mass)



Heavy Chargino & Neutralino in Z+W+MET

- Final state: $Z \rightarrow e^+e^-$, 2 jets ($W \rightarrow qq'$), and MET>40, 50, 60 GeV
  - Final state not explored before
- Main backgrounds: Z+jets & ttbar
- Results for MET>40 GeV
  - Data: 7; SM Bckg: 6.41±0.92