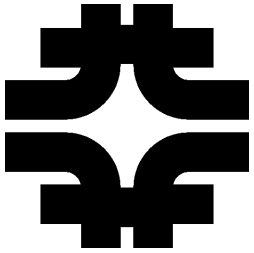

Search for New Physics with Tevatron

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Rutgers University

For CDF & DØ Collaborations

New Physics Searches at the Tevatron: A Partial List

- **SUSY**
  - Chargino-Neutralino
  - Squarks & Gluinos (incl stop & sbottom)
  - Sneutrinos: R-parity violation
  - Light LSP: GMSB, Dark photon/Hidden Valley

- **Non-SUSY**
  - Leptoquarks
  - Resonances (dilepton, diboson)
  - 4th Generation: b'

NOT in this talk

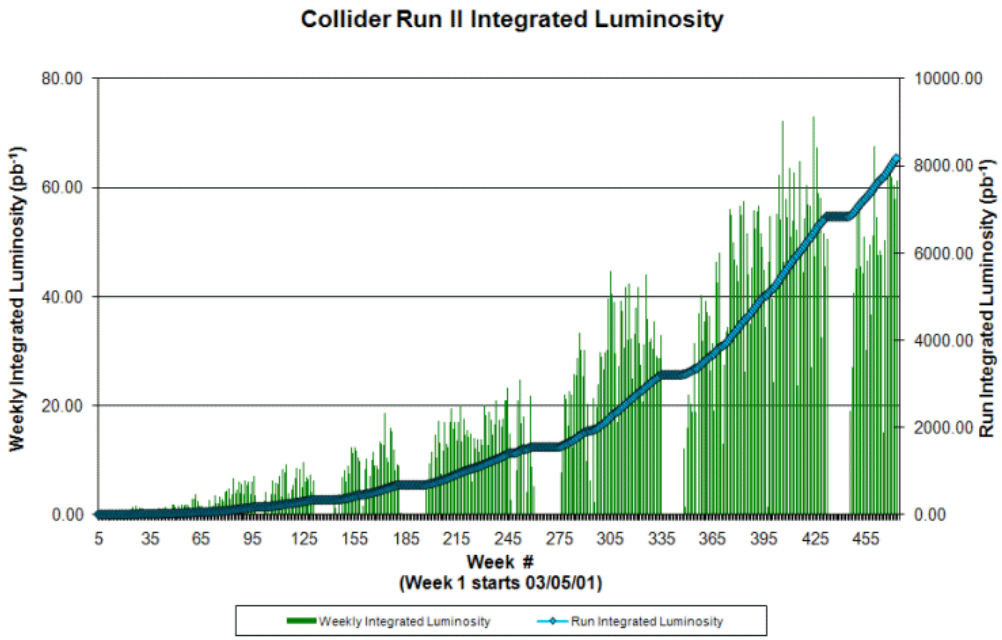
- R-parity is not sacrosanct (Dark Matter could come from somewhere else)
  If R-parity violated (with L conservation protecting proton lifetime)
  → Multi-jet (resonance) signature, no LSP/MET $(\tilde{q})(\tilde{q}) \rightarrow (jjj)(jjj)$
  → Copious strong production (against QCD background).

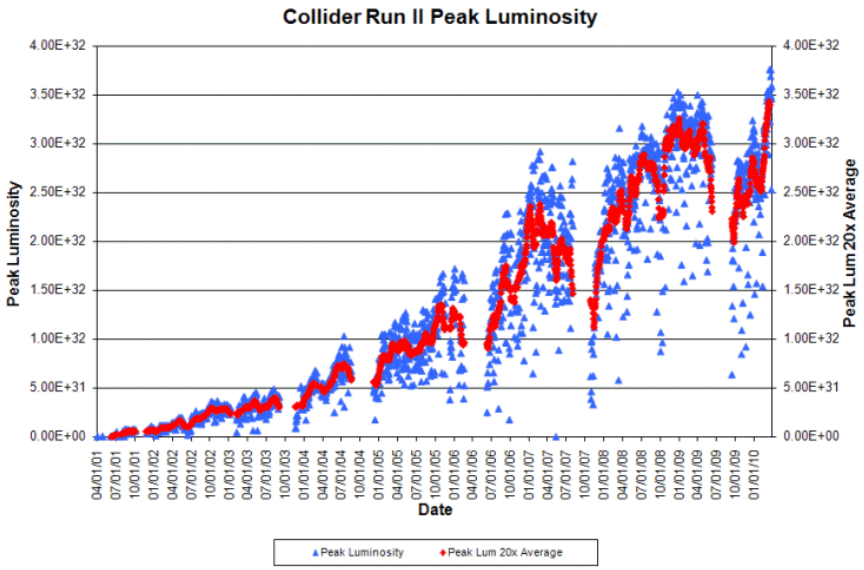
- SUSY searches in the MSSM context e.g. H/A → ττ (talk by Chris Hays)

- New Physics in the top sector (talk by Ford Garberson)

- 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.

Tevatron is Running Very Well

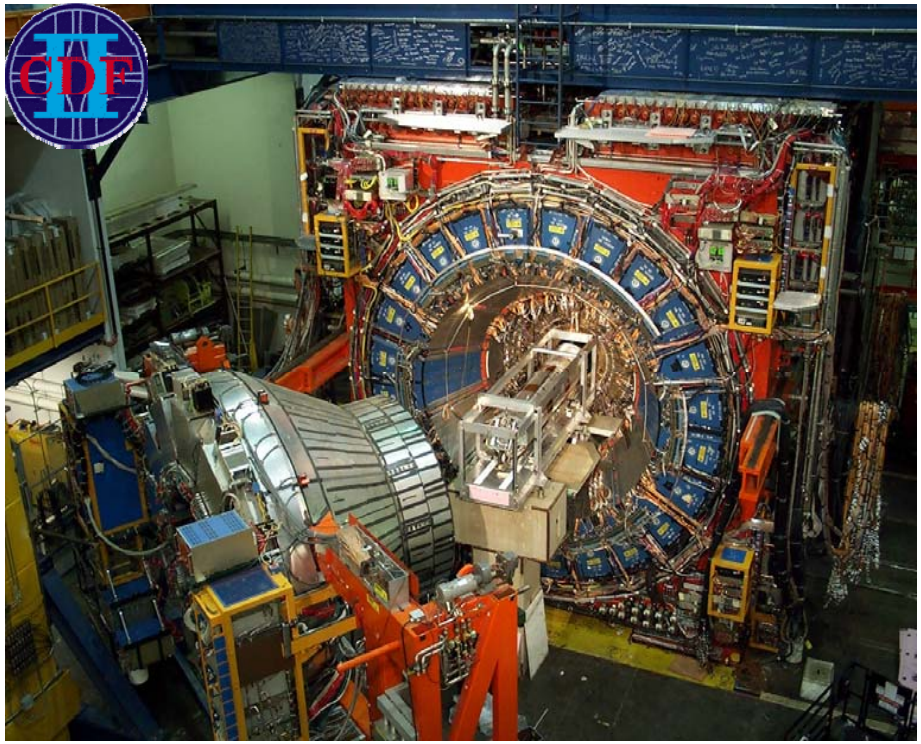




Results in this talk from data up to **5.4 fb^{-1}**

- **>8 fb^{-1} per experiment; >2 fb^{-1} per year, this year shaping up well**
- **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**

SUSY Motivation for Experimentalists

Supersymmetry (fermion/boson symmetry) doubles the particle spectrum.

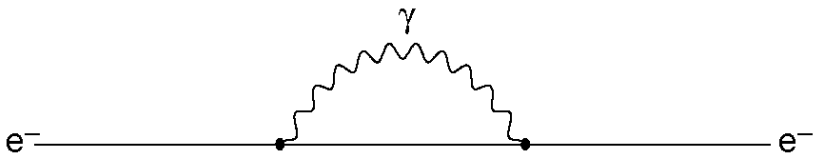
Seems like a huge price, but we do it all the time.

Assembling the electron (Murayama, TASI 2000 lectures):

$q=1.6\times10^{-19}$ Coul , radius $< 10^{-19}$m

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

$E_{assembly} \sim +q^2/r_e \sim 10^4$ MeV but $m_e \sim$ ½ MeV

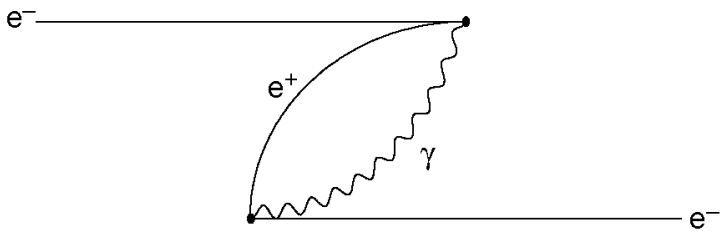


➔ **Large *negative* "bare mass"**

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

FIX: Double the particle spectrum: positron i.e., new physics at ~100fm ~1MeV

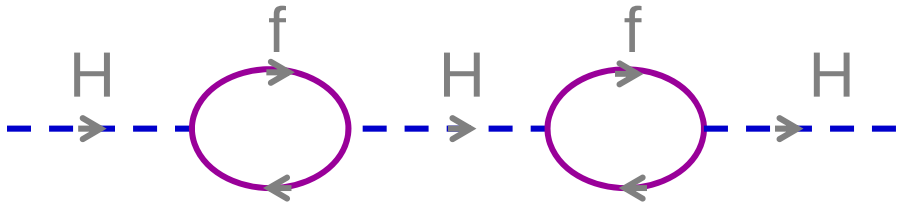
Weisskopf (1939): $E_{assembly} \sim +q^2/r_e$ cancelled by $E_{vacuum\ pair} \sim -q^2/r$ (e^+ from vacuum)



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

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

SUSY (or some new physics) at a TeV scale

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

ALSO: Gauge unification, Dark matter candidate, New complex phases → new CP violation → baryogenesis, SUSY anticipated the heavy top.

- **BUT SUSY is (has to be) badly broken. m(selectron) >> 511 KeV**

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 …

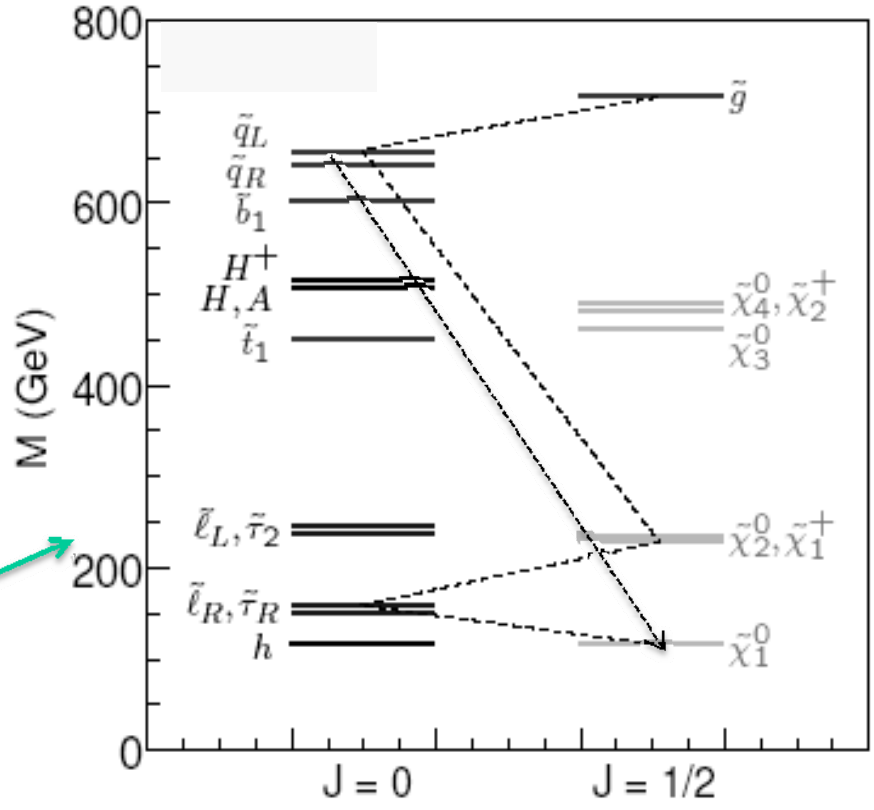
Tevatron:

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

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

LHC:

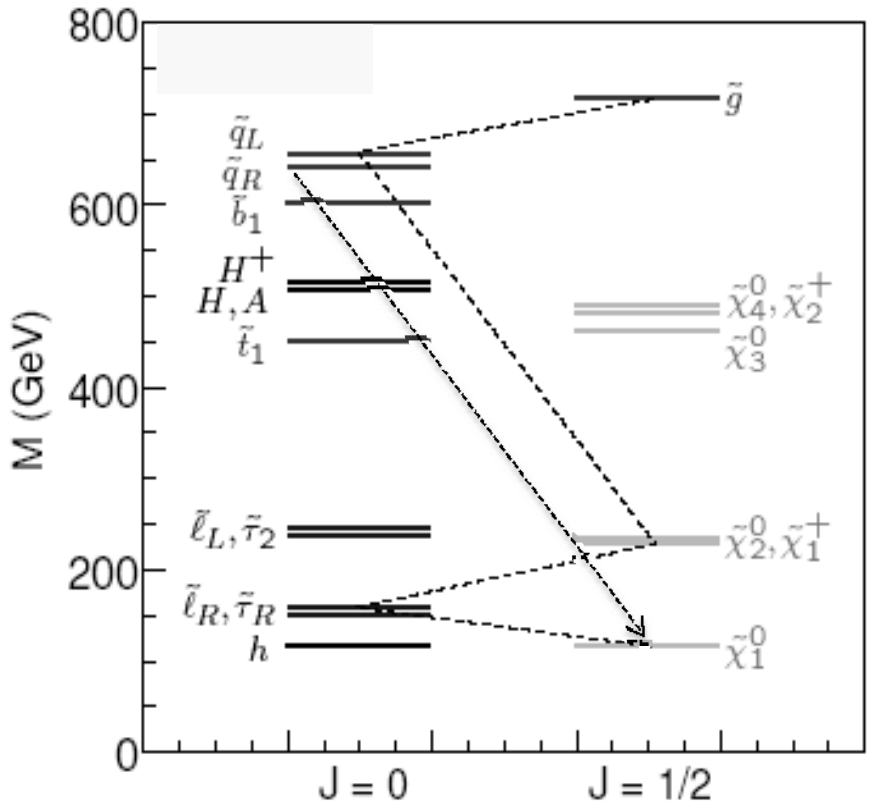
strong production wins. (→ jetty signals)



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

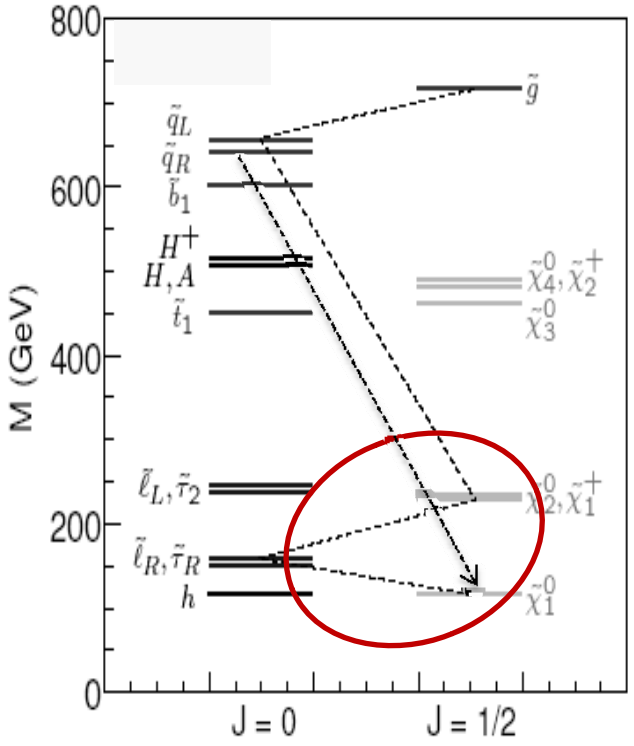
SUSY Search Goals and Signatures

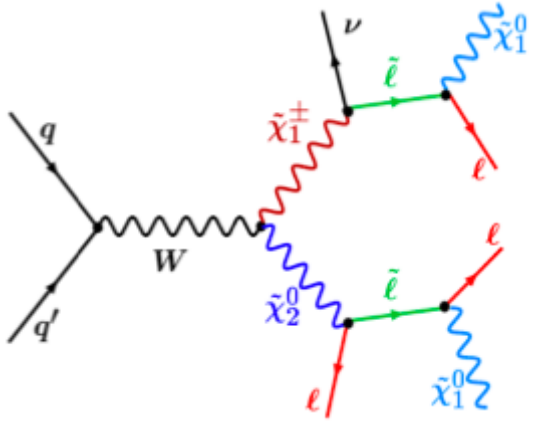
- Chargino-Neutralino: trilepton & missing-ET
- Squarks & Gluinos (incl stop, sbottom, "tau corridor")
  - i. Dilepton+(b) jets+MET
  - ii. Multijet + MET
  - iii. Tau + jets +MET
- Sneutrinos: R-parity violation (e-μ resonances, no jet, *no* MET)
- Light LSP:
  - GMSB (diphoton +MET)
  - Dark photon/Hidden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

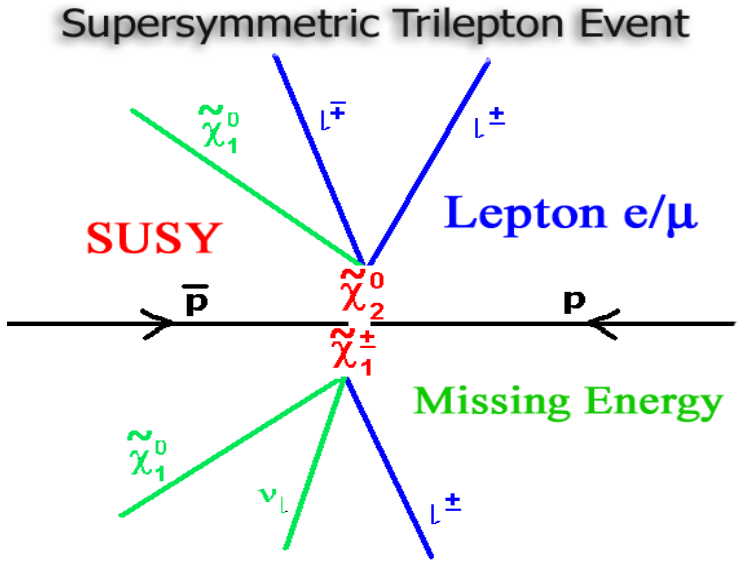


Signatures important: "Don't worry, we will explain whatever you discover (and there will be multiple explanations)" Scott Thomas

Charginos & Neutralinos at Tevatron







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

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

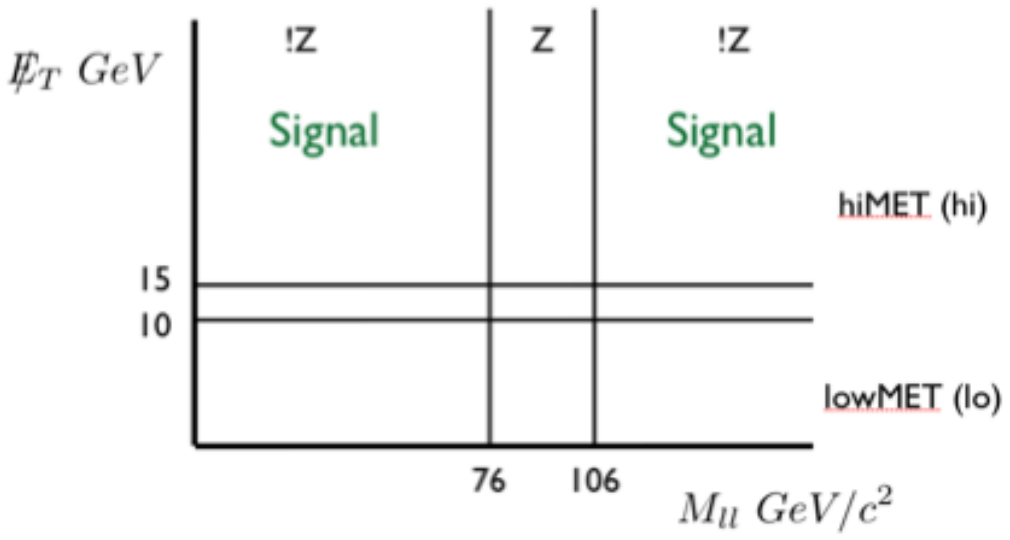
Charginos and Neutralinos with $l^+l^-l^+$

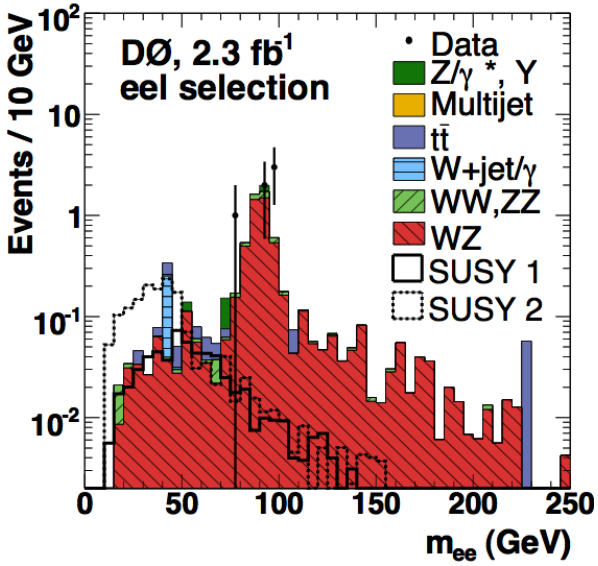
CDF : Multiple exclusive channels

- $l^+l^-l^+$ (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, $\Delta\phi$. . .

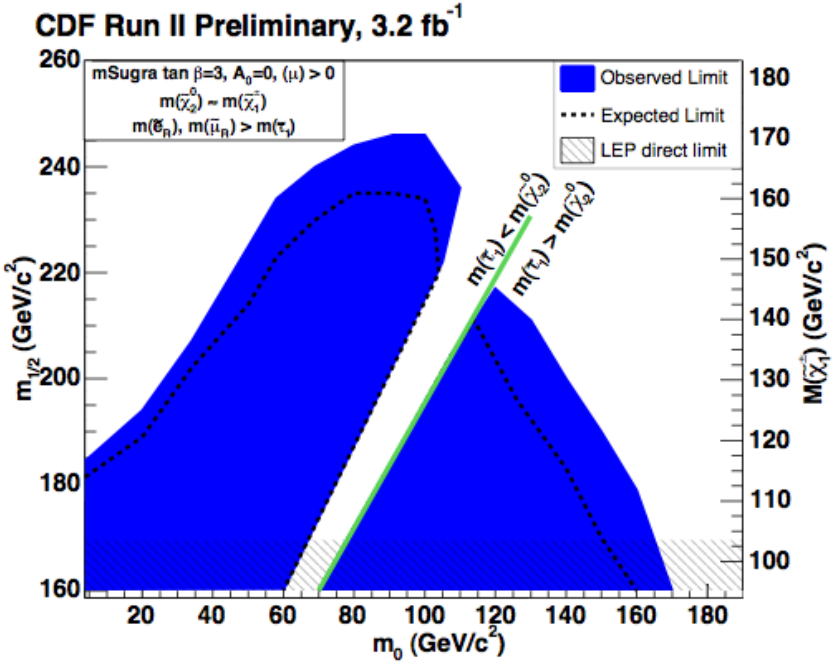
DØ

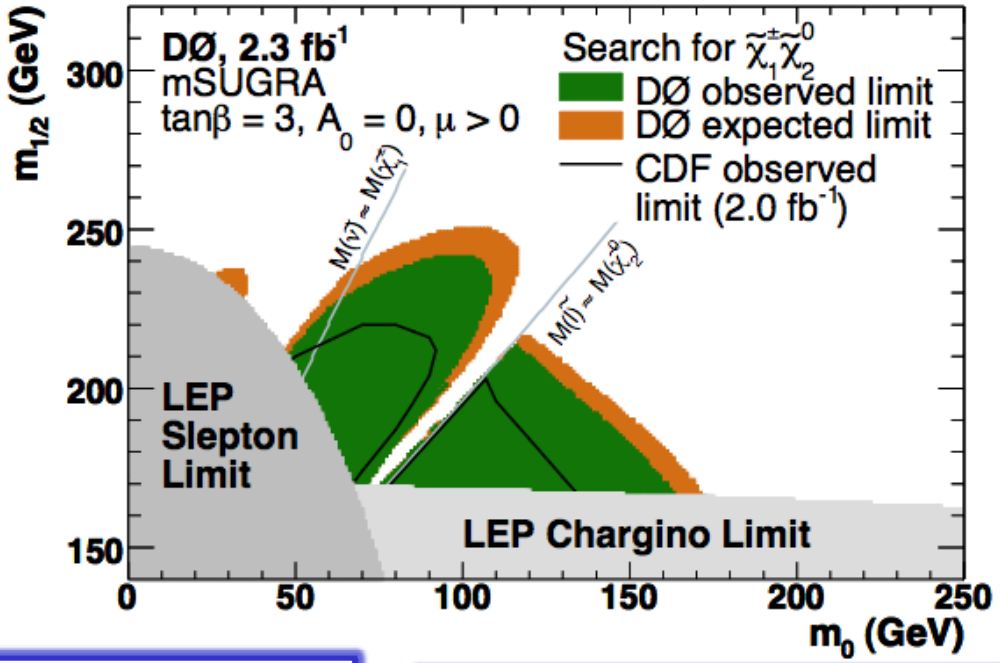
- l^+l^- + Track, μτ+Track, μττ (τ→hadrons)
  - 1st lepton: E_T=12-20 GeV
  - 2nd & 3rd leptons: E_T=4-16 GeV
- Backgrounds
  - WW, WZ, DY, W+γ/jets, ttbar





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



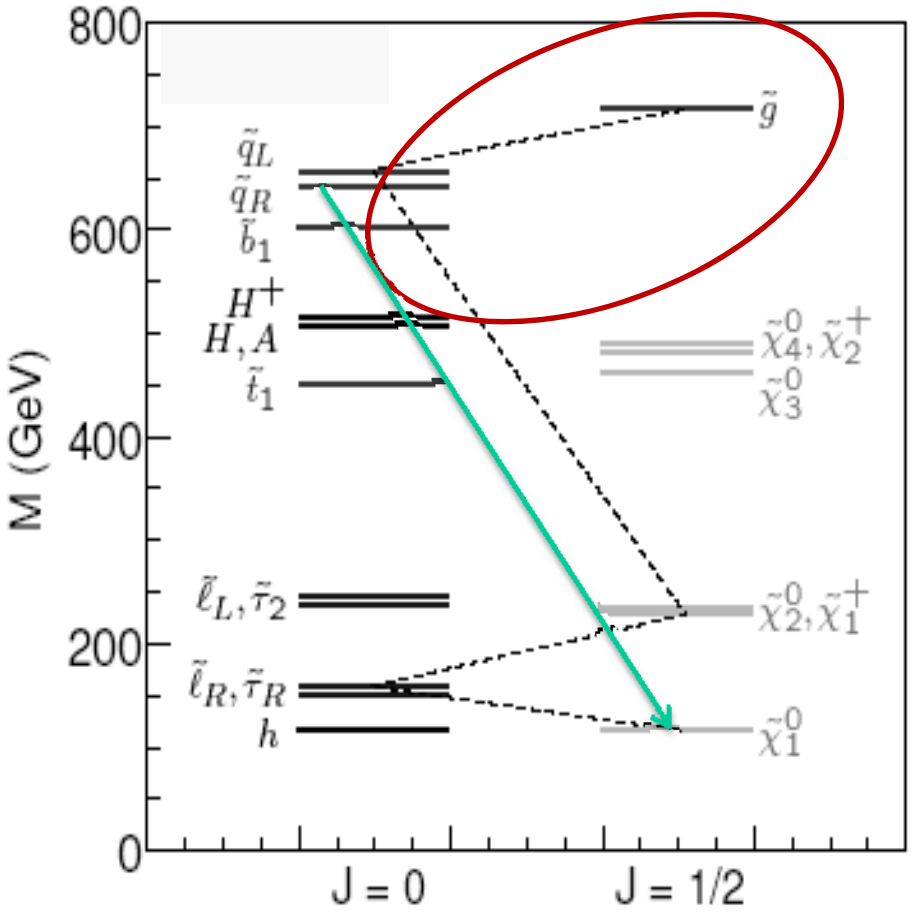


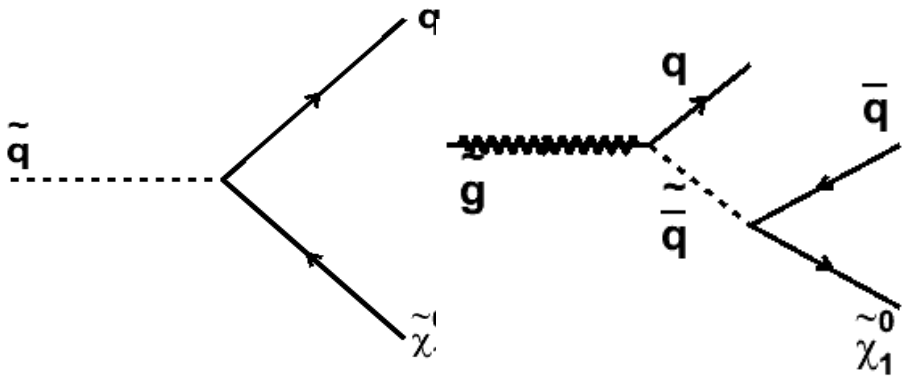
CDF & D0: M($\chi^{\pm}$) limits ~160GeV/c^2

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

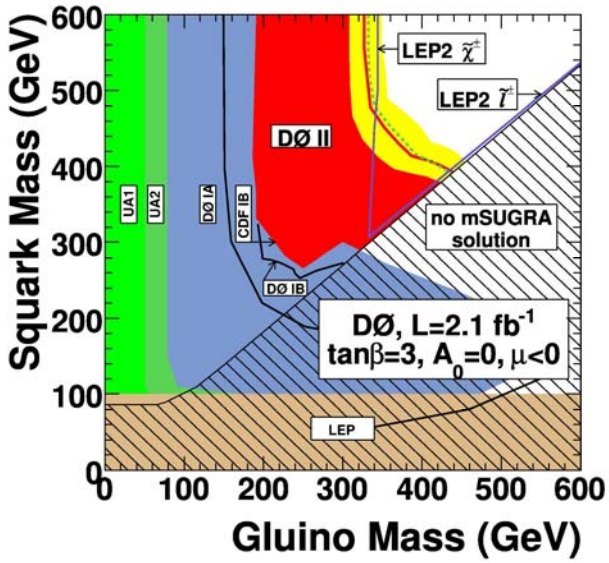
- **CDF**
  - 2 fb^{-1} PRL 101,251801(2008)
  - 3.2fb^{-1} prelim
- **D0**
  - 2.3 fb^{-1} PLB 680, 34 (2009)

Squarks & gluinos with n-Jet & MET





No of jets, Missing-E_t, H_t(=Σ jet E_t)

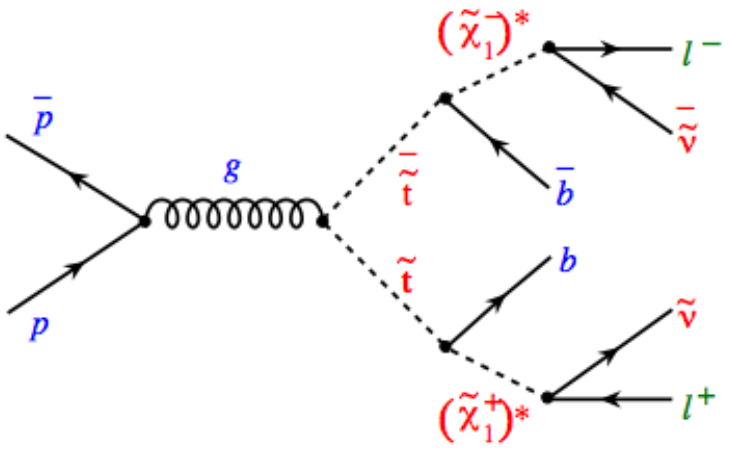


CDF& DØ Limits:

gluino ~300 GeV/c^2, squarks ~380 GeV/c^2

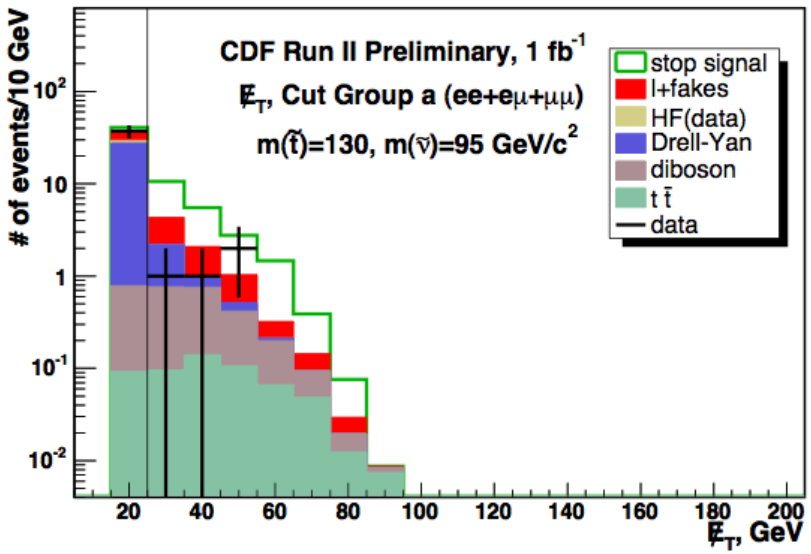
PRL 102,121801(2009) & PLB 660, 449 (2008)

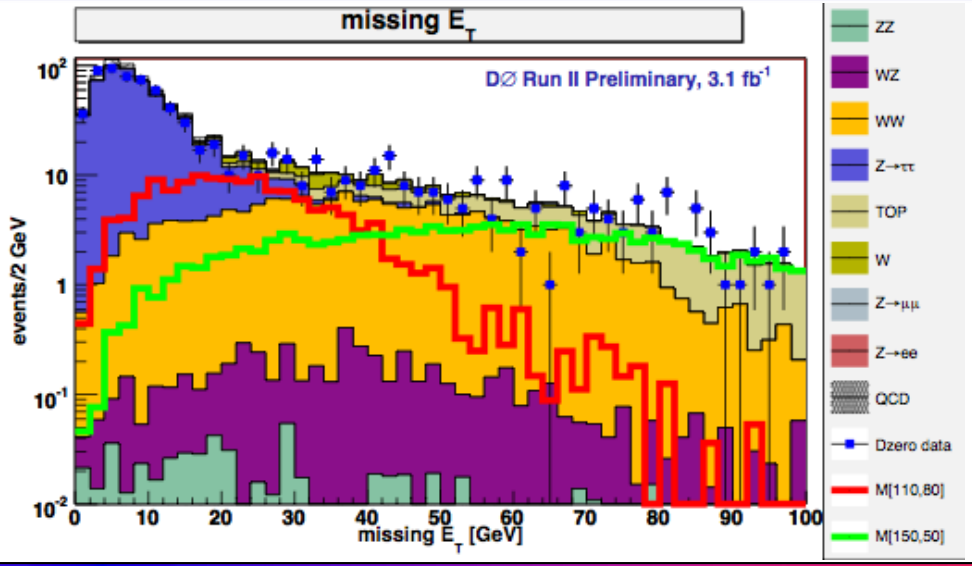
Stop→$l^{\pm}$+b+sneutrino in l^+l^-+jets+MET



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

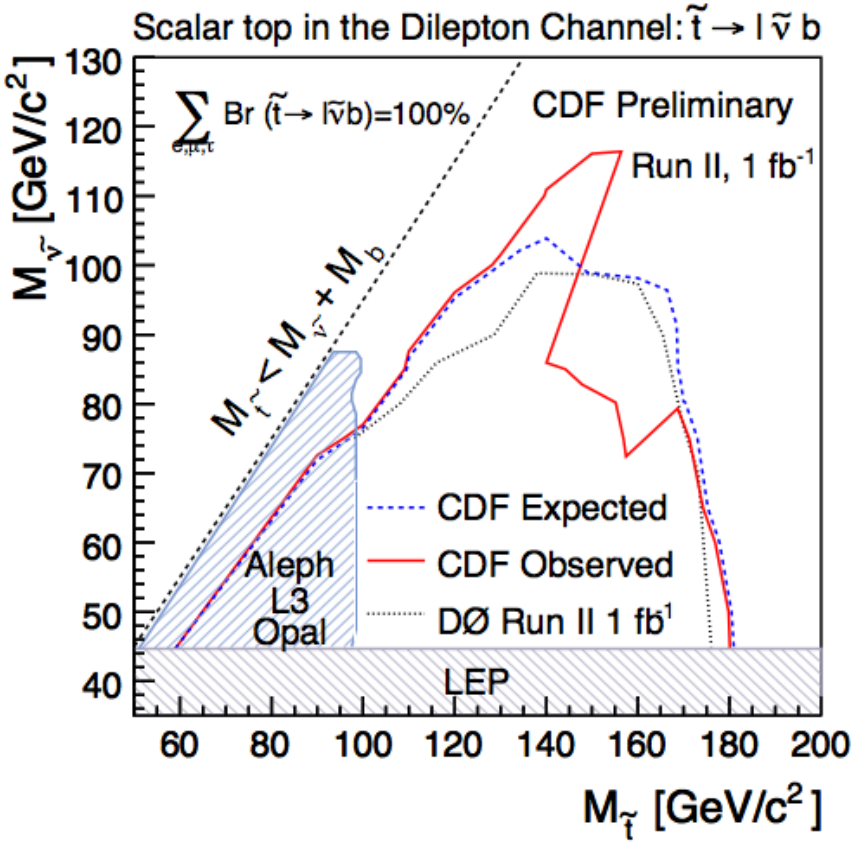
- **Stop light** (big L-R mixing, level repulsion➔see-saw)
- **sneutrino is LSP**
- **Topology: Δm=m(stop)-m(sneutrino)**
- **Final state (note soft leptons):**
  - **CDF (1 fb^{-1}): l^+l^-+N_{jet}>1+MET (ll=ee, μμ, eμ)**
  - **D0 (3.1 fb^{-1}): $e^+\mu^-$+(jets)+MET**

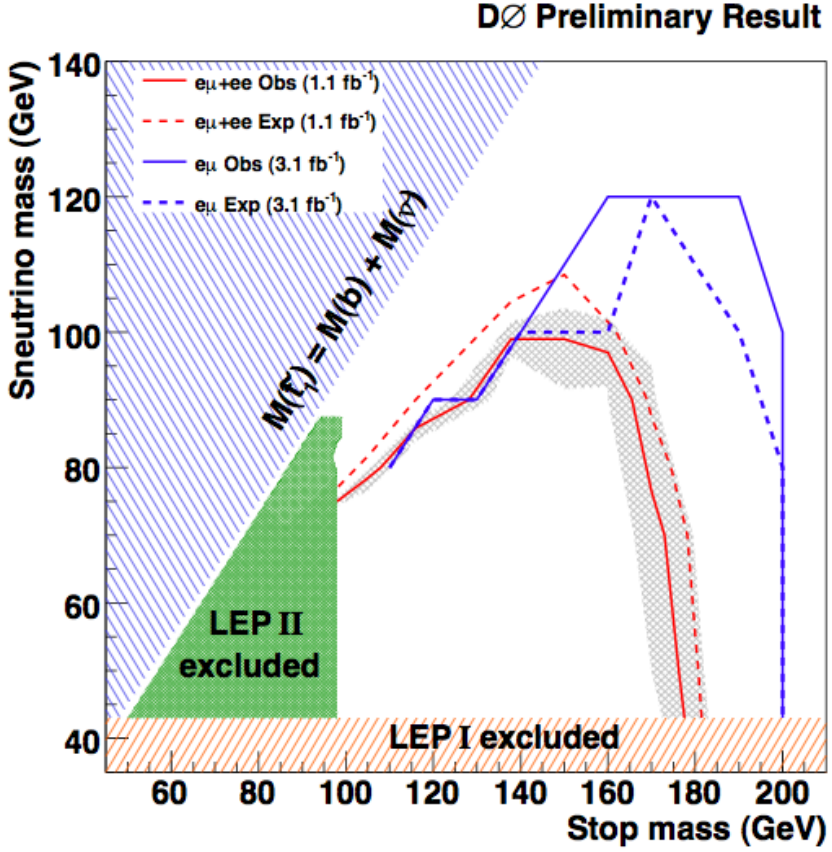




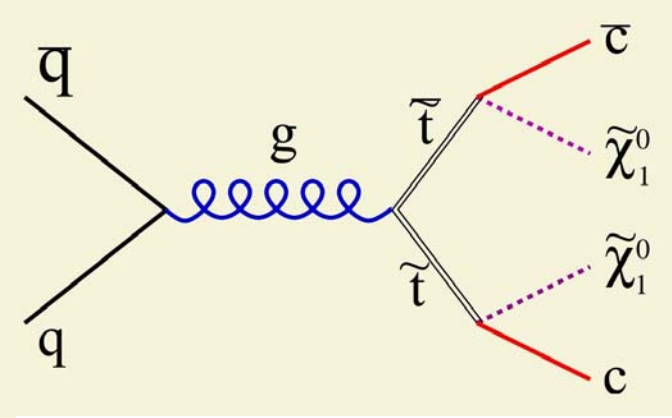
Stop→$l^{\pm}$+b+sneutrino in $l^{+}l^{-}$+jets+MET

- **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**

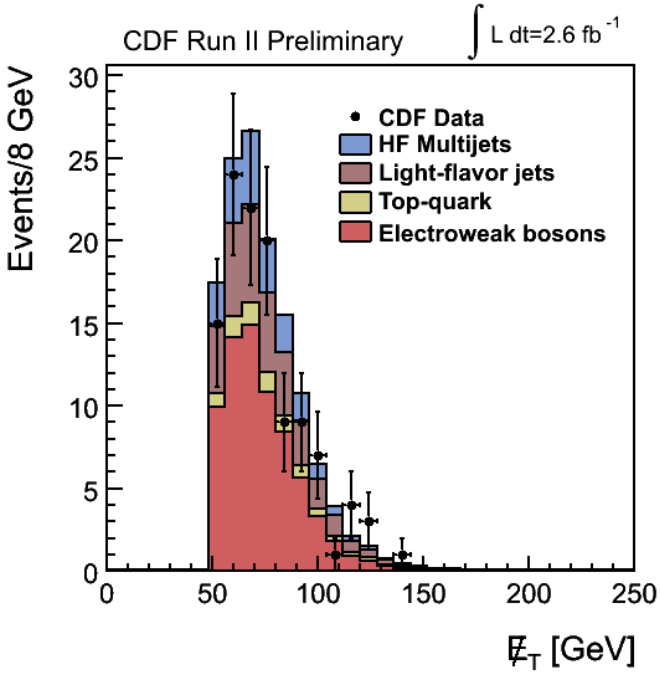




Stop search with charm-tagging



- (RGE running induces stop-charm mixing)
- 2 jets, missing-ET, >1 tagged jet
- Large backgrounds



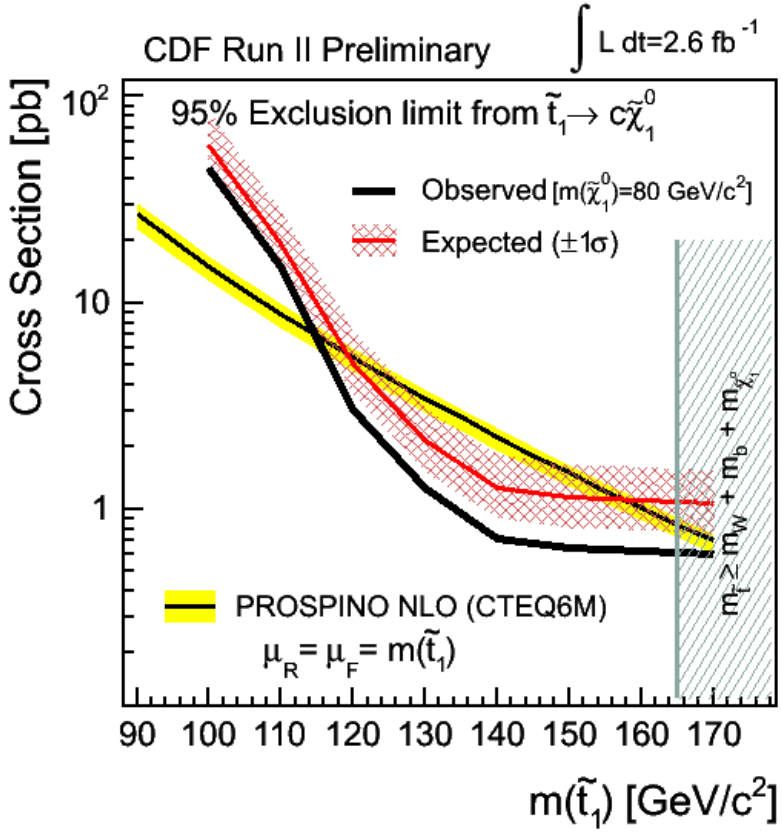
CDF Run II Preliminary 2.6 fb^{-1}

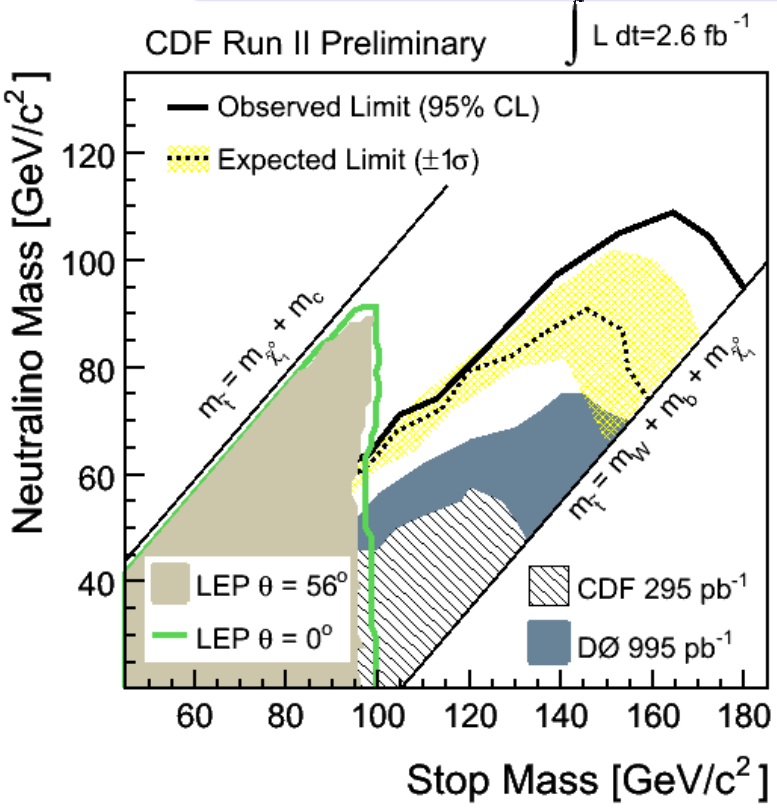
	Final Region
W/Z + jets production	60.9 ± 26.6
Diboson production	10.7 ± 1.9
Top pair production	4.6 ± 1.3
Single top production	3.2 ± 0.8
HF QCD Multijets	20.4 ± 15.2
Light-flavour contamination	32.2 ± 12.7
Total expected	132.0 ± 24.4
Observed	115
Signal m($\tilde{t}$)=125, m($\tilde{\chi}^0$)=70	90.2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

Kinematic Exclusion (up to 180 GeV/c²)

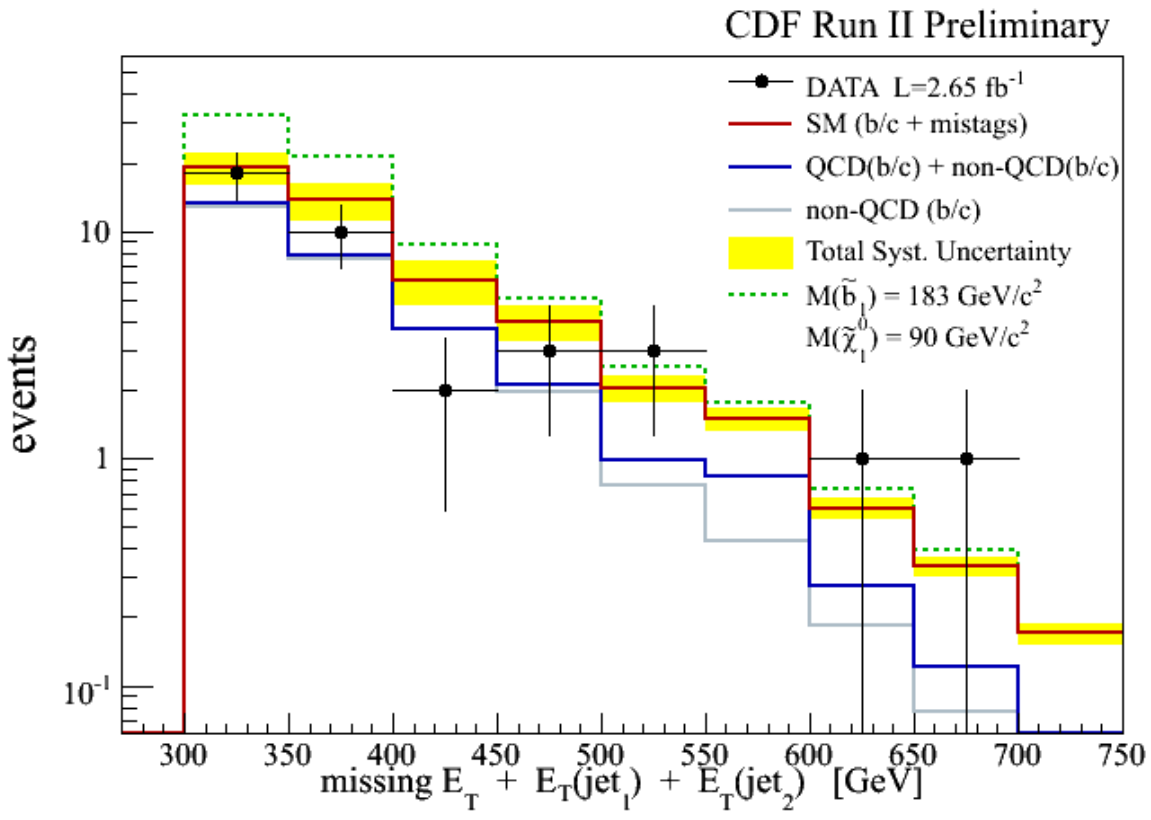




Sbottom at the Tevatron

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

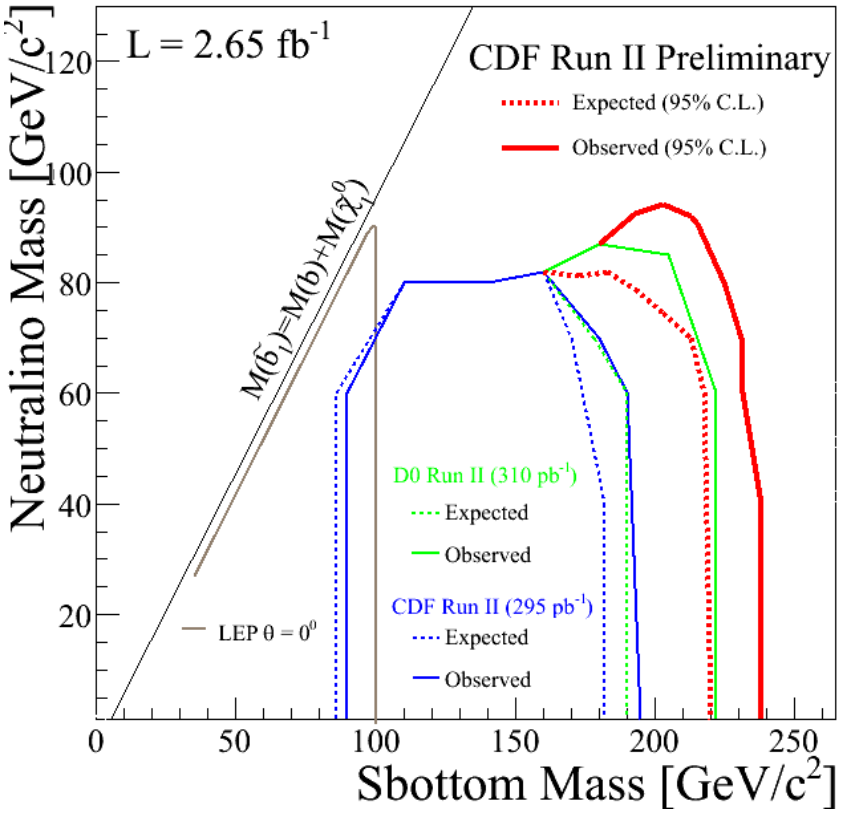
cf: later leptoquarks

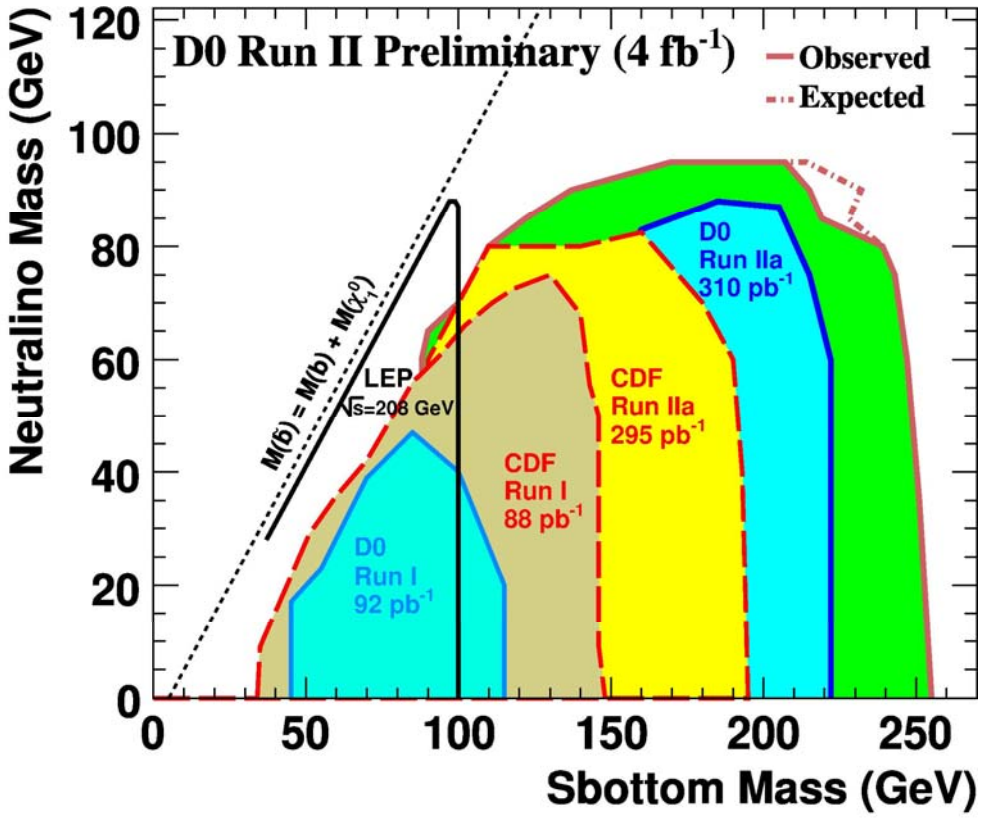


- Sbottom could be the lightest colored sparticle at high tan(β).
  (same level repulsion see-saw as stop)
- Strategy: missing-E_T, Sum jet E_T, b-tagging (& optimization)

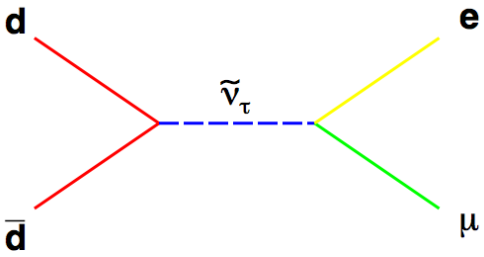
Sbottom at the Tevatron

Mass limit approaching 250 GeV/c^2





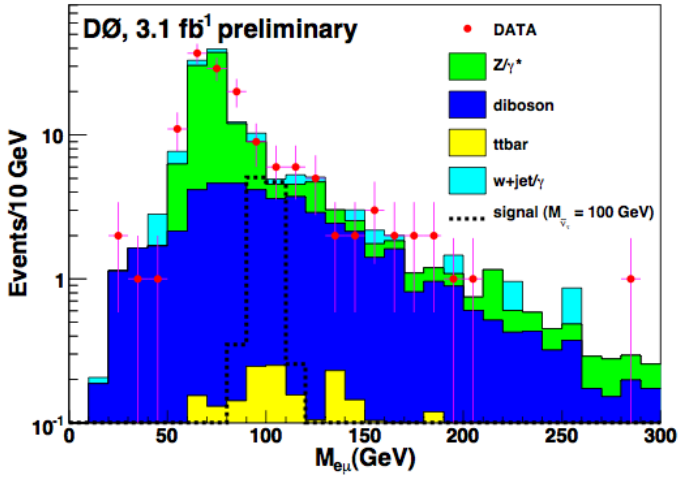
R-Parity Violating Sneutrinos

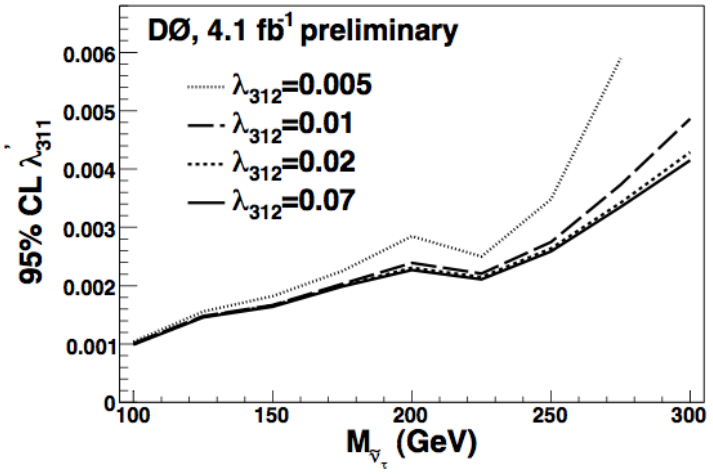


- R_p violation → No MET
  - production of single sparticle
- High-mass $e^+\mu^-$ resonances
  - Striking signature
  - Veto(!) events with MET & jets
  - Backgrounds: $Z/\gamma^* \rightarrow \tau\tau \rightarrow e\mu$, dibosons

DØ 4.1 fb^{-1} →

CDF: eμ,μτ, eτ 1 fb^{-1} (PRL 100, 241803 (2008))





SUSY 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

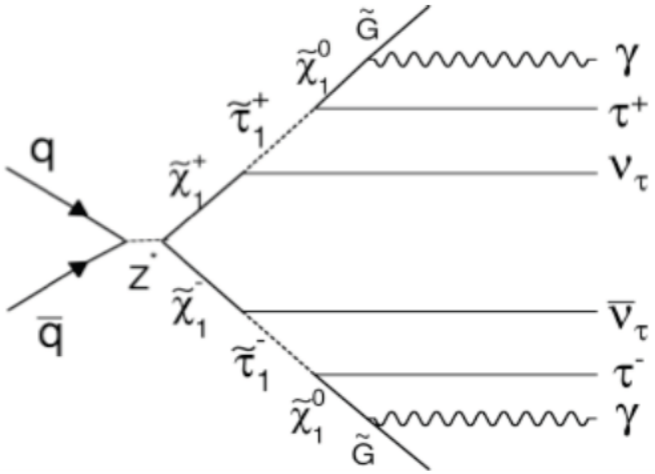
Specific slepton: Sneutrinos (no MET/jets)

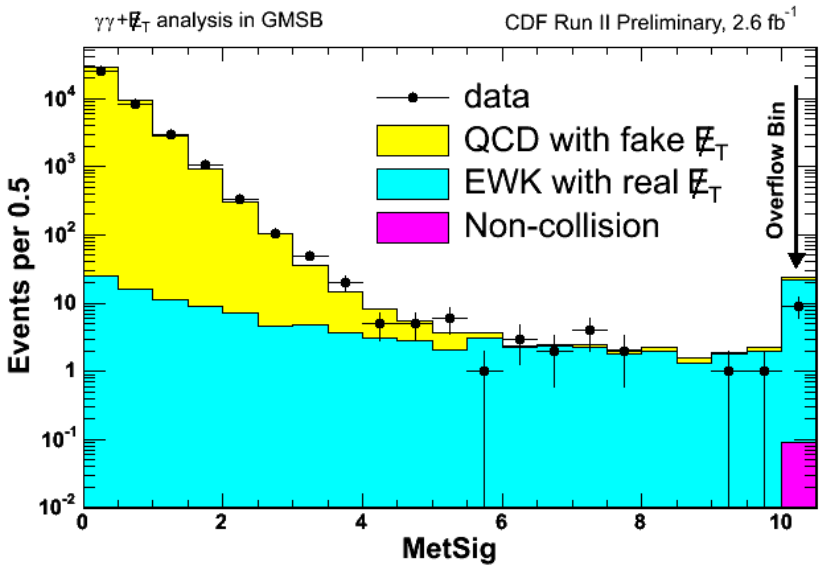
Now: photons

GMSB (very light LSP, photons and MET)

Hidden Valley SUSY (GMSB like, but peculiar signature)

Limits on GMSB in γγ+MET



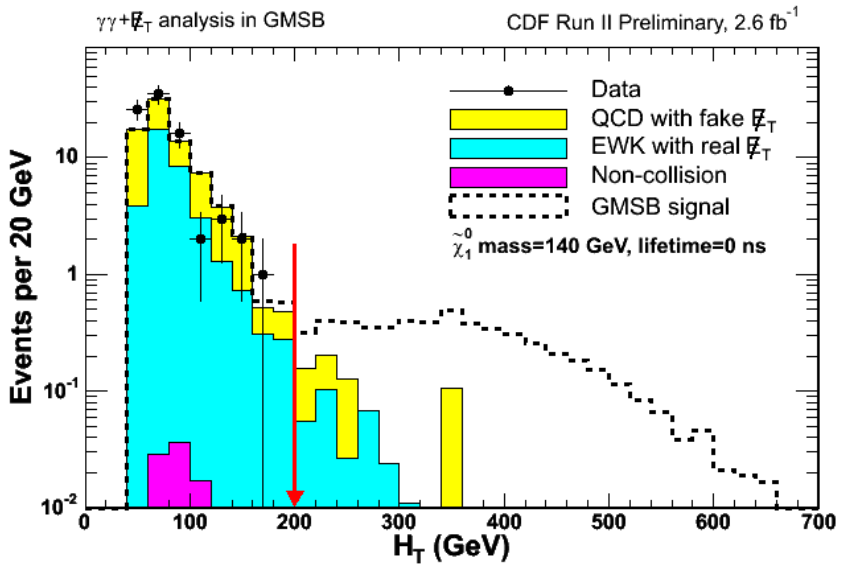


MET-significance based on energy resolution

- **Gauge-Mediated SUSY Breaking**
  - GMSB comes closest to a complete theory of 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

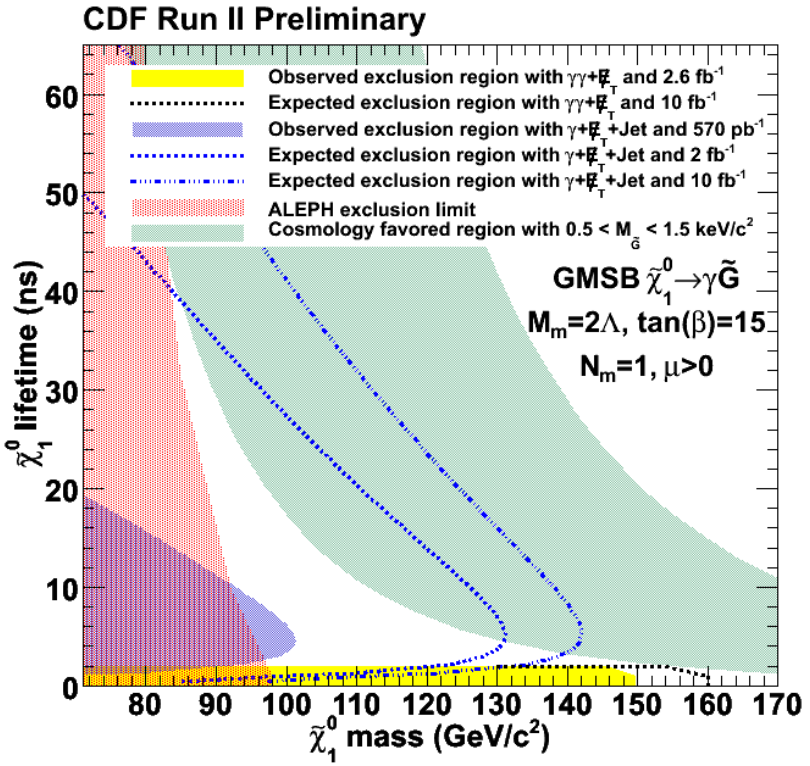


$H_T=E_T(\gamma 1)+E_T(\gamma 2)+MET+...$

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	$1.23\pm0.30\pm0.24$



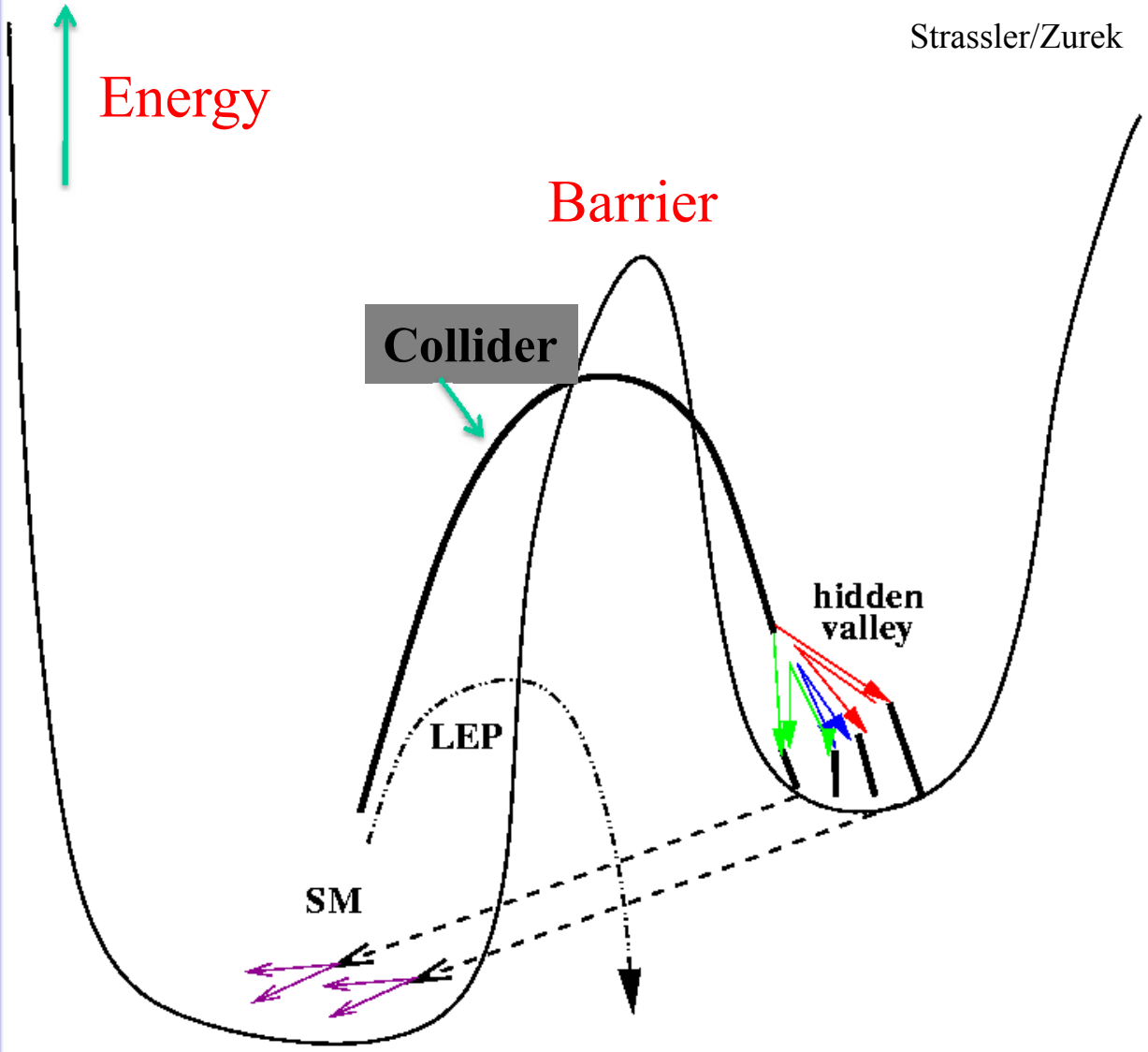
- 95% CL limits in neutralino mass & lifetime plane
  - Neutralino mass>149 GeV/c^2
  - PRL 104 011801 (2010)

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

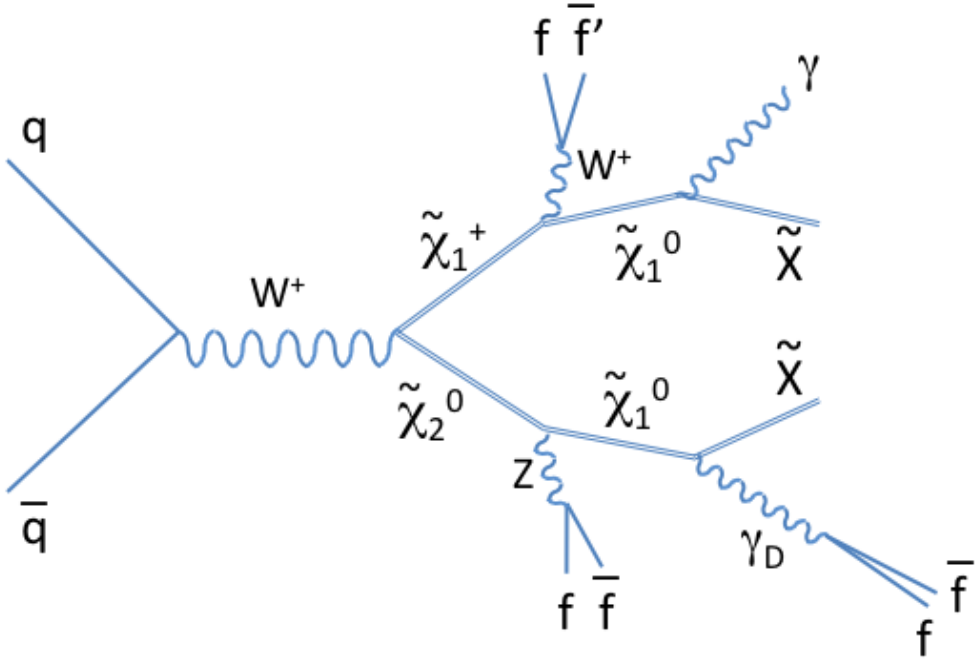
- Signature: two very close leptons



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



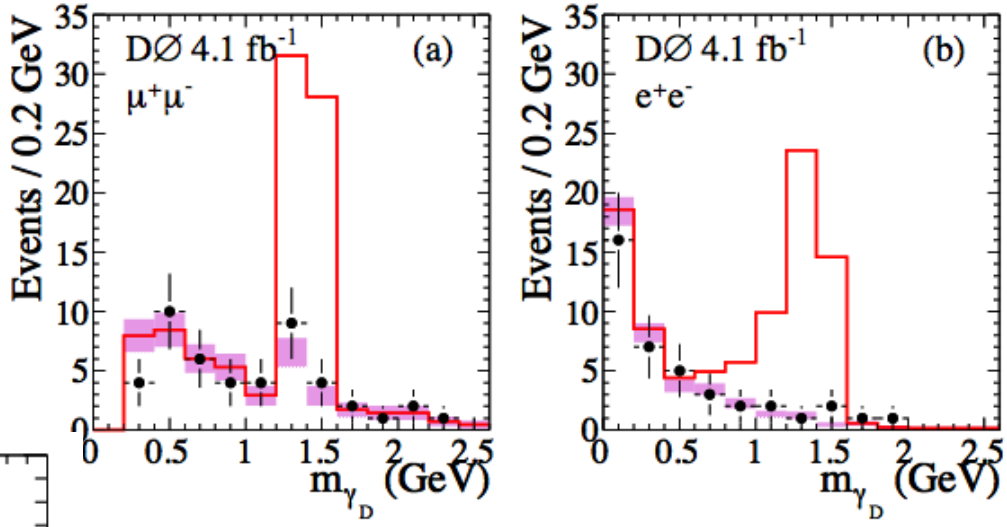
Dark Photons

Dilepton masses. →

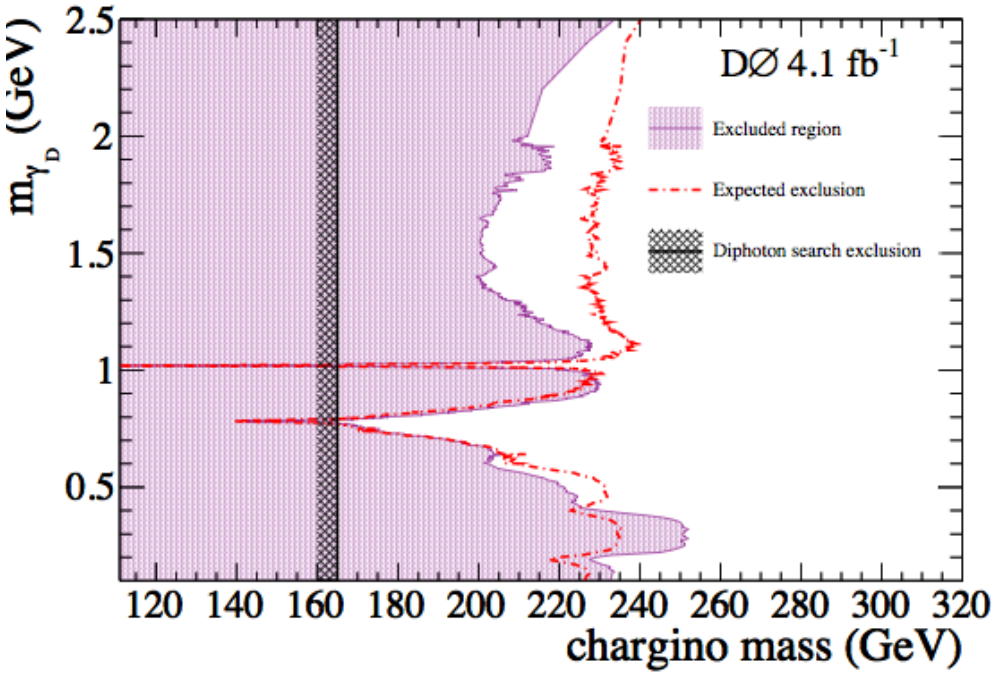
Purple bands from contol regions.

&

1.4GeV γ_D



μμ **ee**



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

Goodbye Susy

Though we never knew you at all
You had the grace to hold yourself
While those around you searched (& searched)

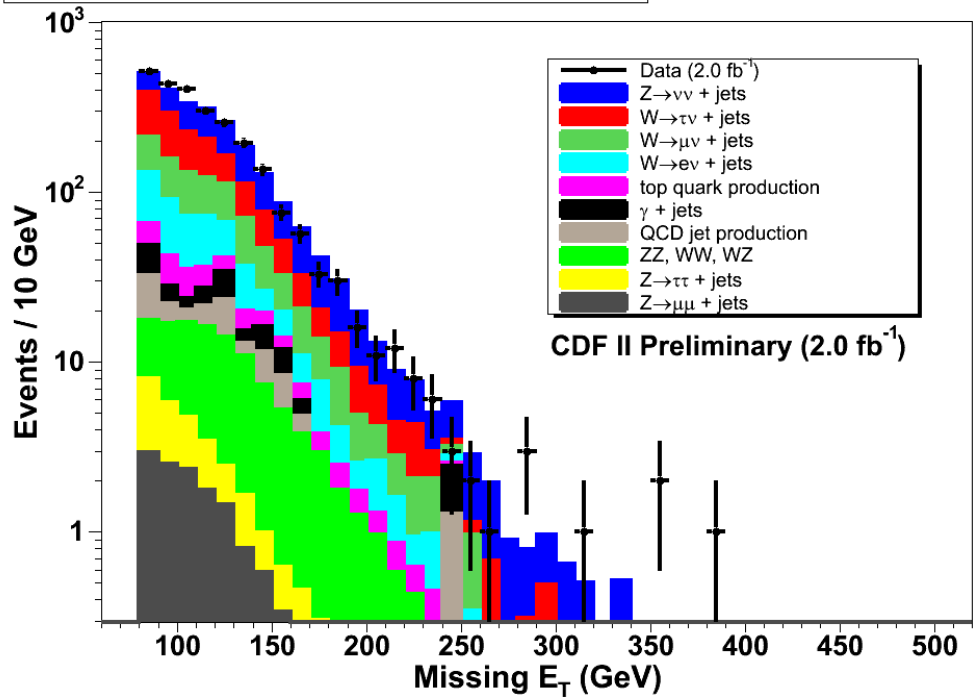
- **Leptoquarks**
- **Resonances (dilepton, diboson)**
- **b'**

Leptoquarks
Connecting the lepton and quark sectors

qqνν: 2jets plus MET

2 Jets with E_T > 30 GeV, No 3rd Jet with E_T > 15 GeV
Scalar Jet H_T > 125 GeV, Missing E_T > 80 GeV

Missing E_T for Low Kinematic Region



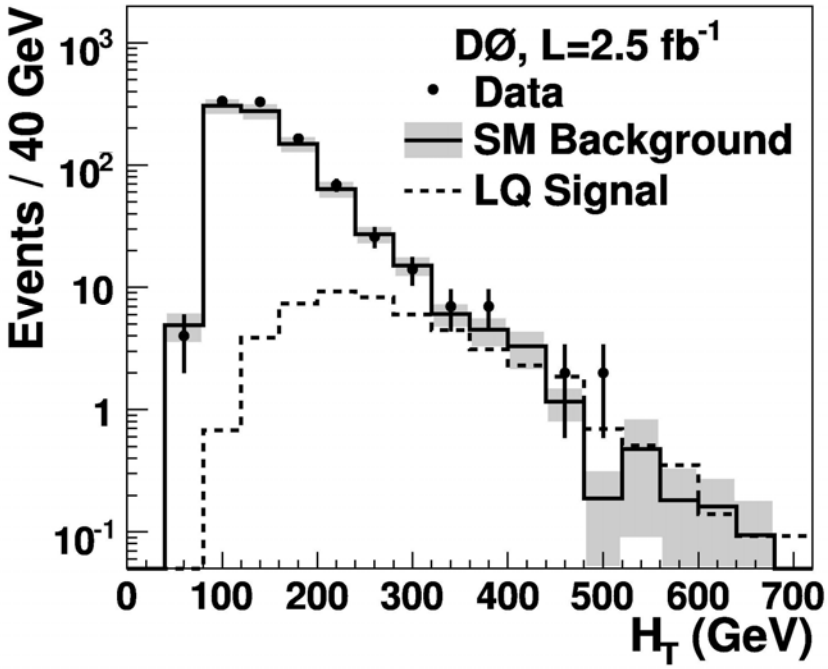
Leptoquark Generation	1st or 2nd	3rd
Lower Mass Limit (GeV)	190	178
σ(pb) limit	0.29	0.44

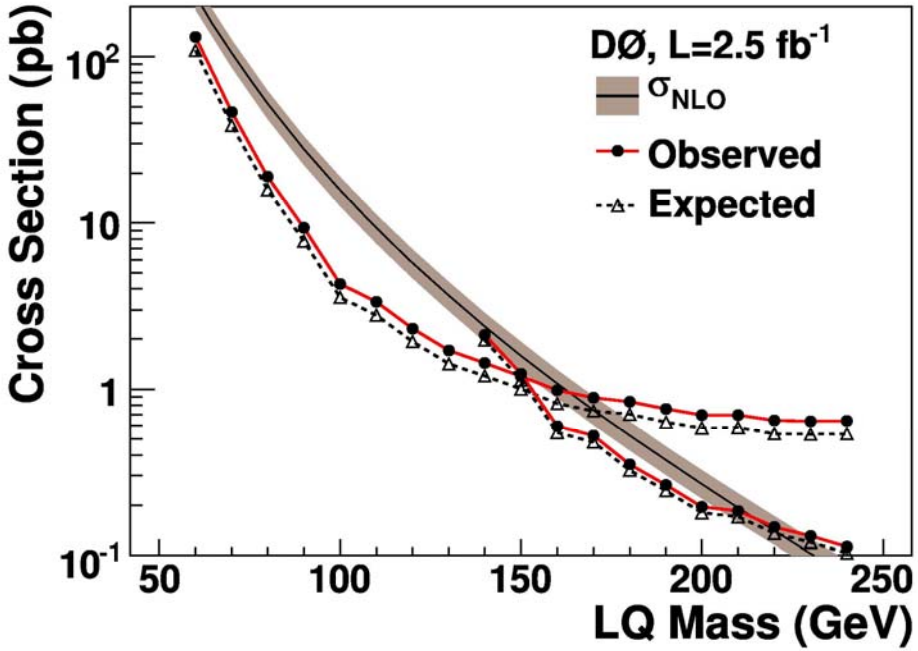
(High Kin region: more HT and MET)

SUSY's back!
Squark pair production with leptonic-hadronic R-parity violation.

Leptoquarks

Two jets with $p_T > 35$, Scalar Jet $H_T > 125$ GeV, Missing $E_T > 75$ GeV

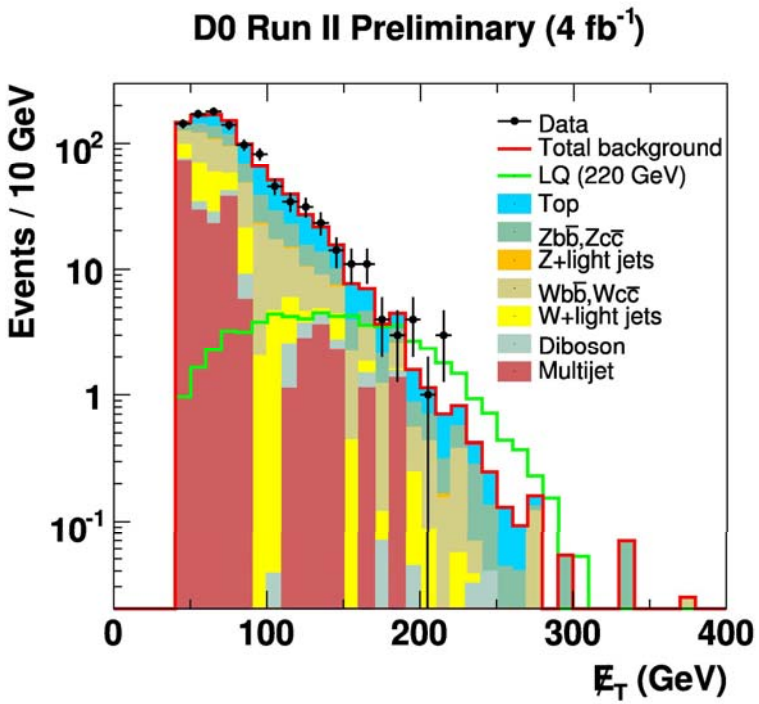


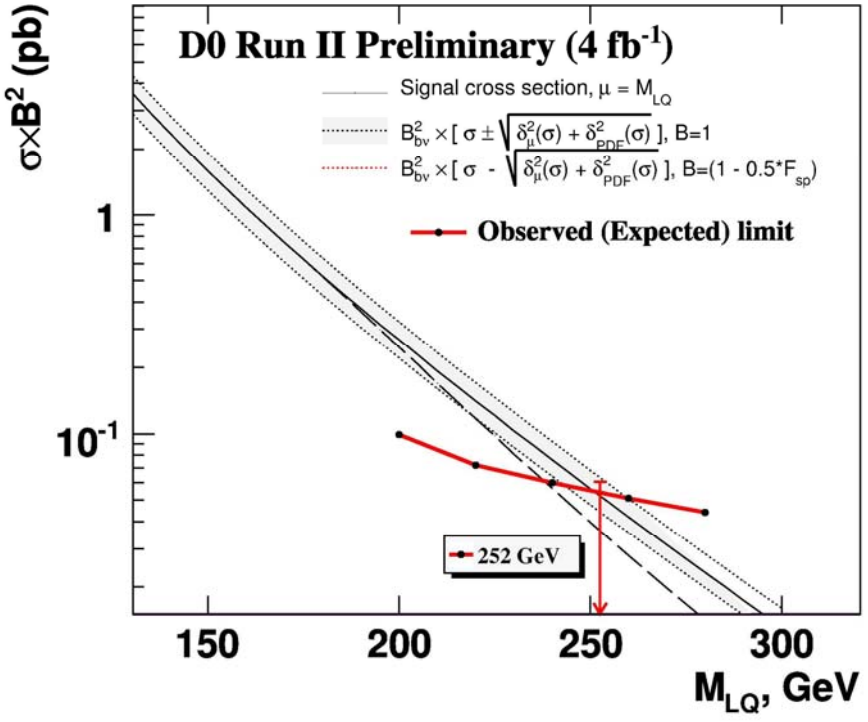


m > 205 GeV

Leptoquarks

…. Then add b-tagging to target the third generation:



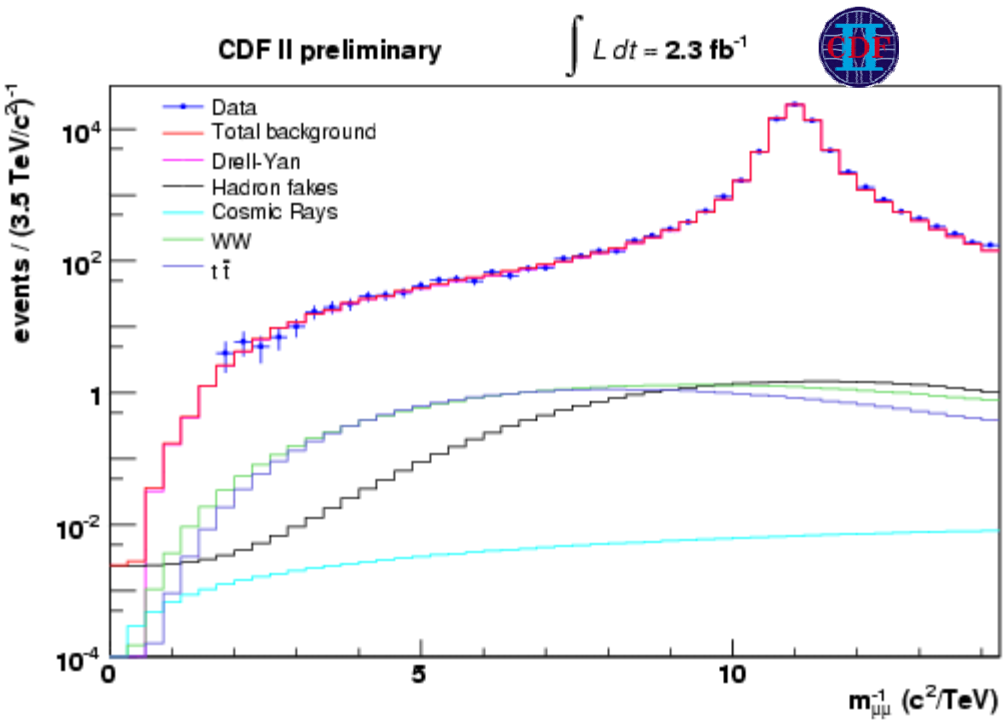


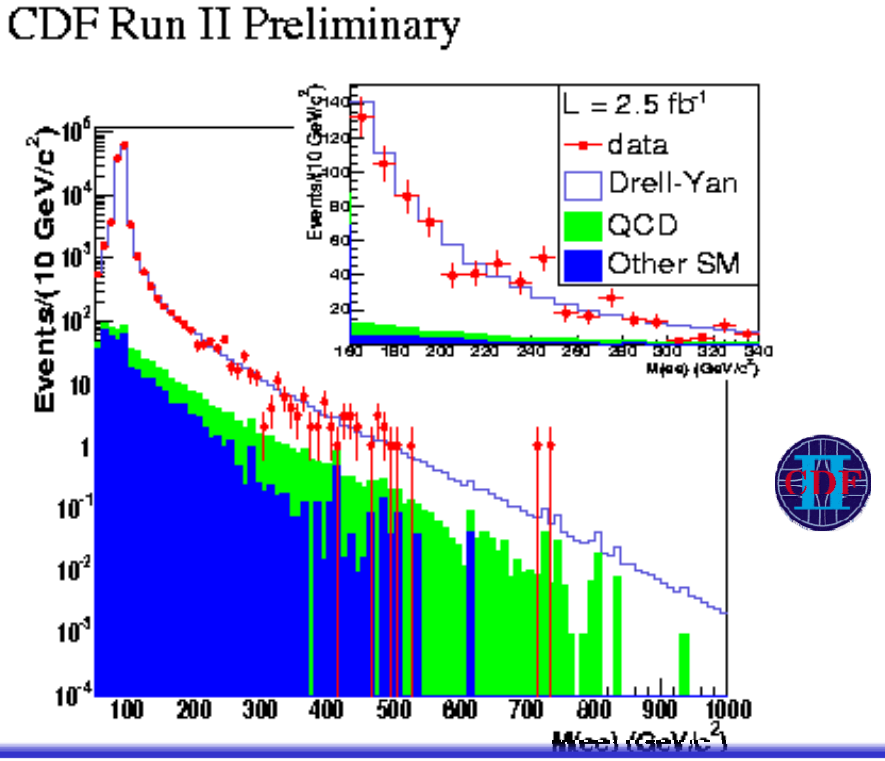
cf: sbottom search earlier

m > 252 GeV

Susy is still here: 3rd generation RPV couplings could enhance this signature

Dilepton Resonances





Inverse mass of two high-pt muons

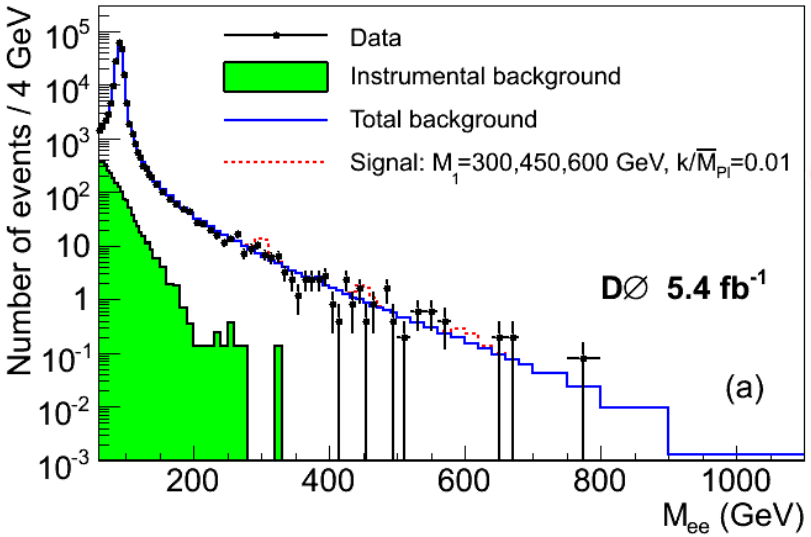
- M(Z') > 1030 GeV

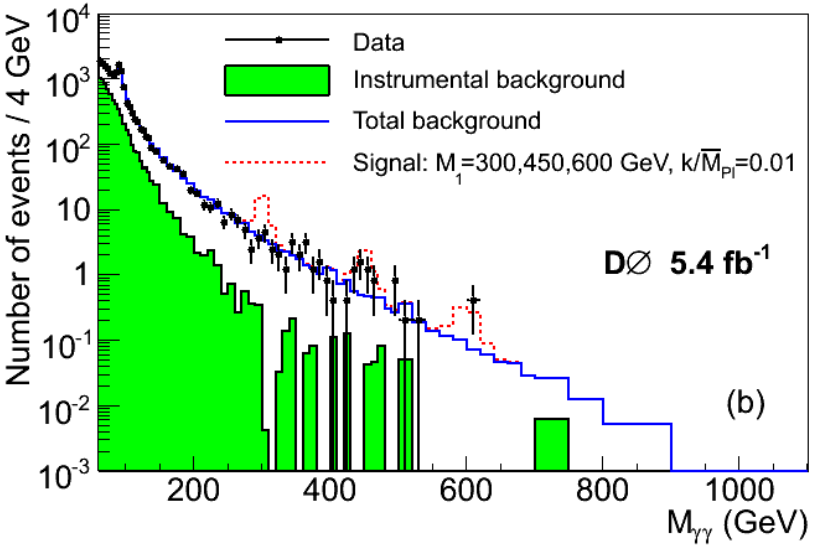
mass of two high-pt electrons

- M(Z') > 961 GeV

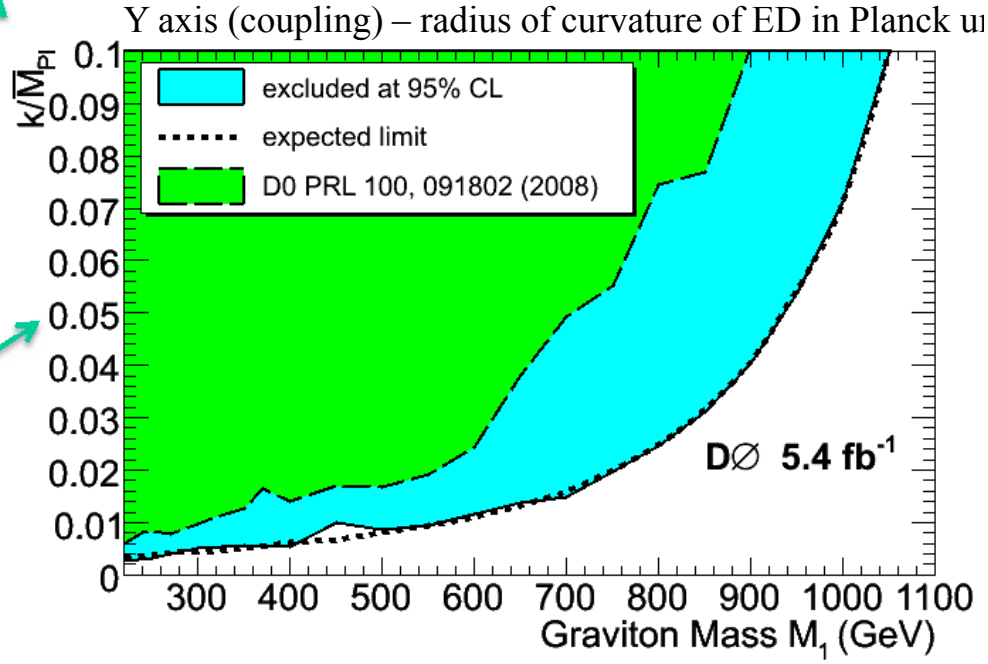
M(Z') > 950 GeV

RS Graviton





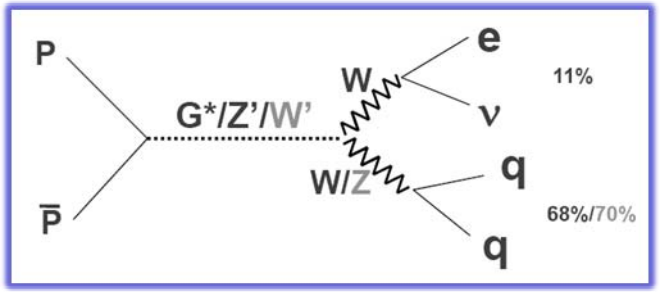
Extra Dimensions - Massive gravitons



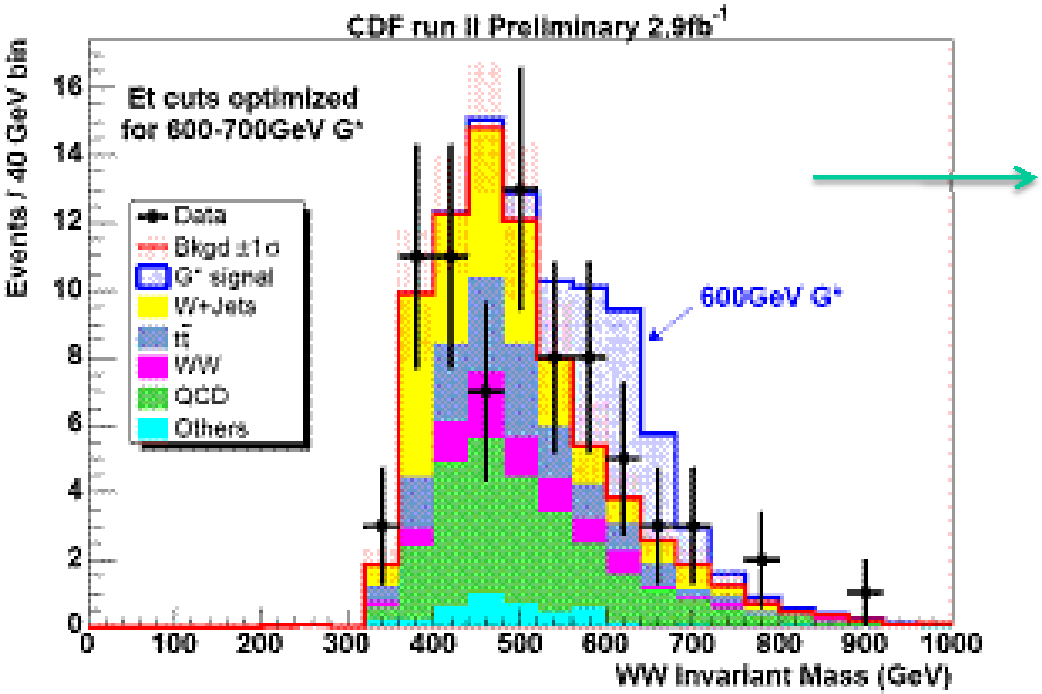
Graviton KK excitation mass limits:
560 - 1040 GeV for 0.01 ≤ k/MPl ≤ 0.1

Diboson Resonances

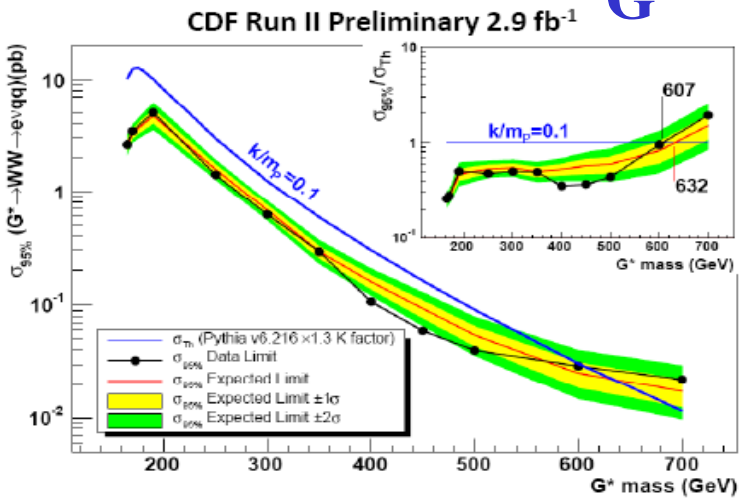
e.g. if dilepton resonances indicate an RS graviton, then G* → WW



electron +2 jets + MET

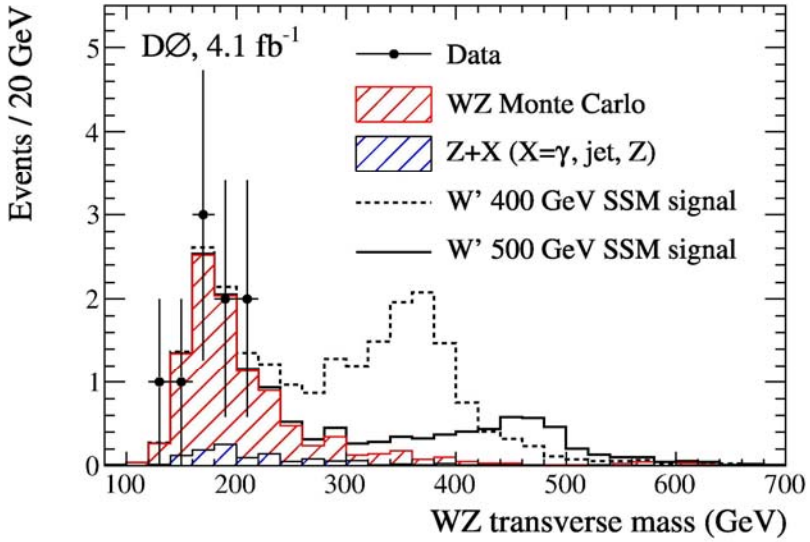


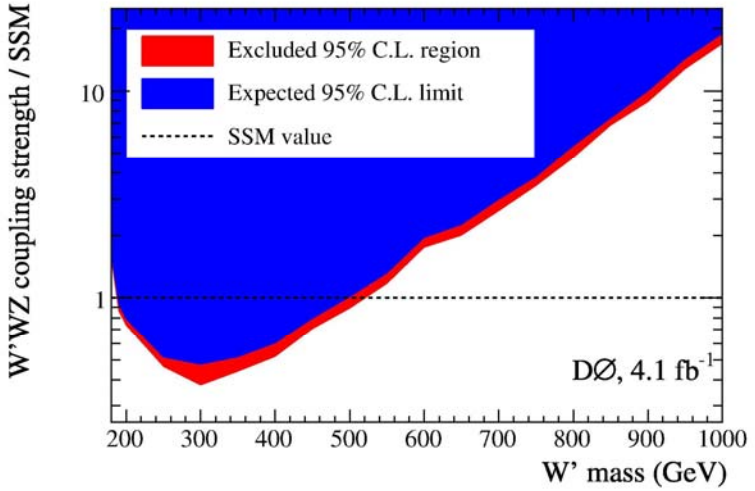
G*



Diboson Resonances

W' → WZ → lνll



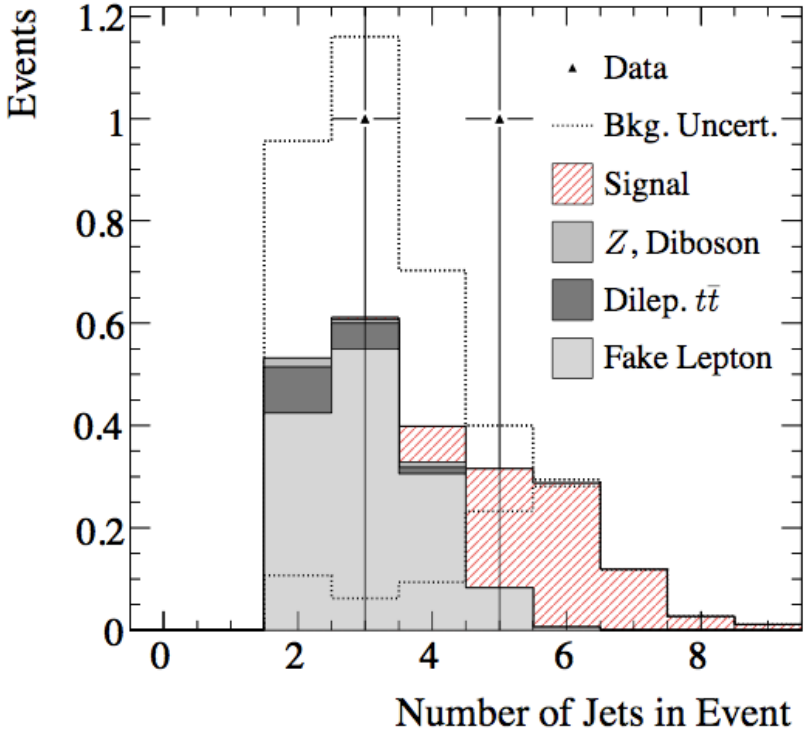


W' excluded between 188 and 520 GeV (assuming SM coupling scaled by mass)(SequentialSM)

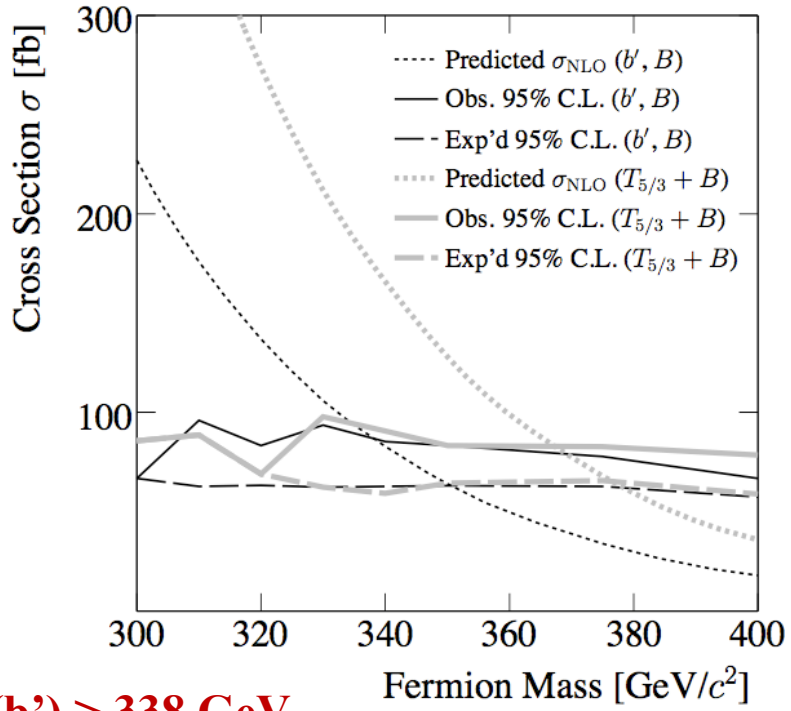
4th Generation: Heavy Fermion b'

- ppbar → b' b'→ (Wt)(Wt) → (WWb)(WWb) **Signature: l^+l^+ b MET**

Avoiding LEP EW bounds →
a) Rt handed massive neutrino, large Yukawa, cancellations
b) 4th generation/anti-generation → mass not from EWSB



← 2 events observed, 1.6+-1.4 expected



CDF: Submitted to PRL ArXiv: 0912.1057 **M(b') > 338 GeV**

Summary

- CDF and DØ have r(v)igorous New Physics program
  - New results on "classic" analyses: stop, trileptons
  - Both experiments exploring new signatures and techniques
- With 7-8 fb^{-1} on tape & 3-4 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