Search for new physics at CDF

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We know the SM is not enough

- We know that there are many questions that the SM does not answer
  - Why is the Planck scale and the electroweak 17 orders of magnitude apart?
  - How is gravity incorporated?
  - What is the source of dark matter?
  - Why there is a boson/fermion asymmetry?
  - Why there is a particle/antiparticle asymmetry?
  - Why we have several interactions instead of one unified one?
  - ….
- Most of the questions make the extension or/and modificaton of the SM inevitable
- This leads to an extremely strong interest in searches for new physics
  - Even SM measurements are seen as indirect searches for new physics

How to search for new physics

- Either test a particular theory
  - Either discover or exclude new physics predicted by a current theory (don't over-optimize event selection)
  - Or exclude an *a priori* part of the parameter space of a theory (over-optimize event selection)

- Or search for a signature predicted by many theories or no current theory
  - Be model-independent and prepare for the unexpected

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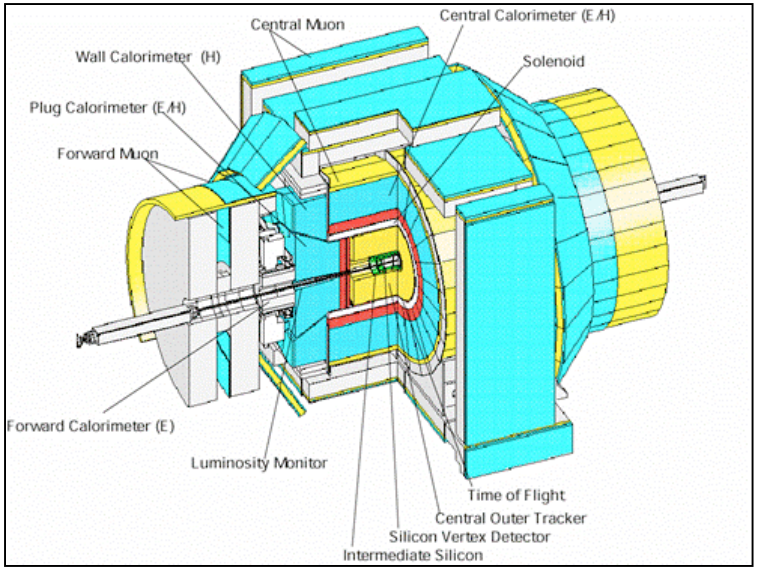
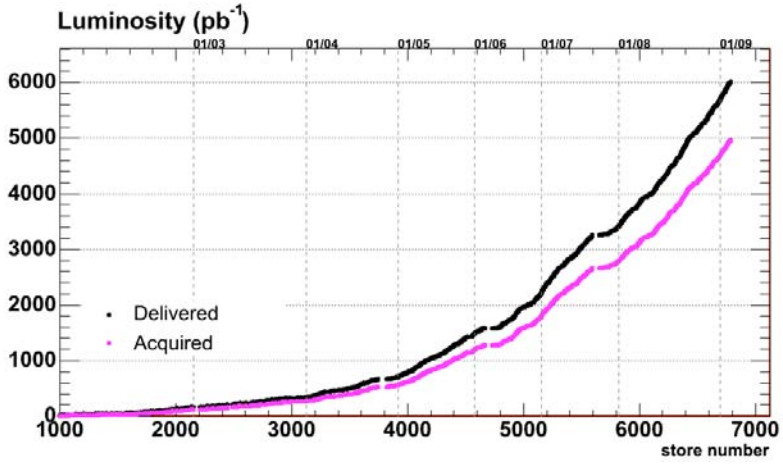
Current CDF Searches

- Searches that test a particular theory
  - SUSY (mSUGRA, GMSB, R-parity violation)
  - Large extra dimensions
  - Heavy GUT bosons

- Or search for a signature predicted by many theories or no theory
  - High-mass events
  - Exotic combinations of objects (γ+jet+MET, …)

The Tevatron and CDF





- **Tevatron is still the highest-energy hadron collider (protons-antiprotons at 1.96 TeV CM)**
- **CDF is a multi-purpose collider detector of leptons, photons, hadrons and MET**
- **Recorded luminosity: > 5 fb^{-1}**
- **Presented in this talk: up to 3 fb^{-1}**

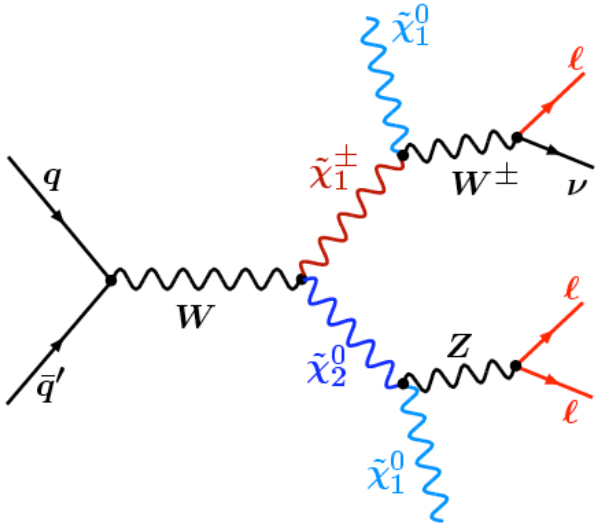
Supersymmetry

- Theory that predicts a boson for any SM fermion and vice-versa
  - The superpartners differ only in their spin
- SUSY is obvioulsly broken, which leads to a new mass-spectrum for sparticles. We study "soft" SUSY breaking
  - mSUGRA (LSP=neutralino), GMSB (LSP=gravitino)
- Removes fine tuning and offers ultra-violet completeness
  - Large radiative corrections of superpartners cancel each-other
- Possibility of force unification
  - Not exactly possible with SM
- Cold dark matter candidate
  - If R-parity is conserved, the lightest supersymmetric
  - particle (LSP) is stable.

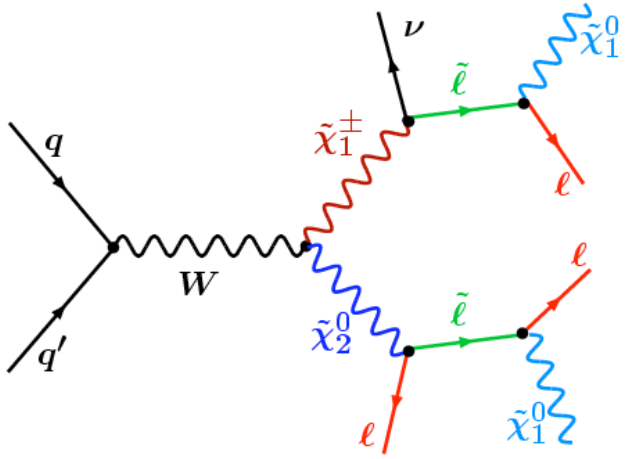
- Possibility of radiative Electroweak symmetry breaking
  - As an alternative to spontaneous breaking

Chargino – Neutralino to Trileptons

- Chargino-Neutralino production and decay to trileptons is a golden SUSY signature
  - Very low SM backgrounds, cross sections of the order of 0.1-1 pb have not been excluded yet



Decays through W/Z favorable for heavy sleptons, but BR to leptons low



Decays through sleptons guarantee final leptons, but also preference to $\tilde{\tau} \rightarrow \tau$

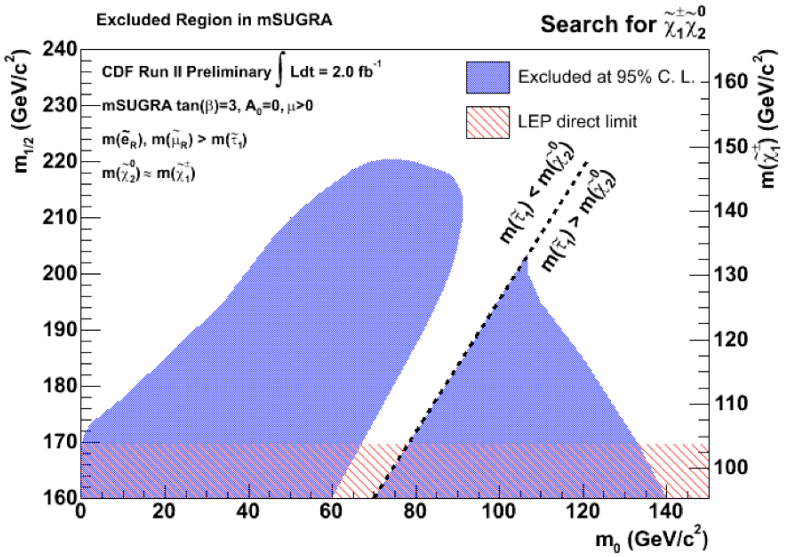
- Signature of interest: ***Three leptons and Missing Transverse Energy*** (MET) due undetected neutralinos (LSP in mSUGRA with R-parity conservation) and neutrinos

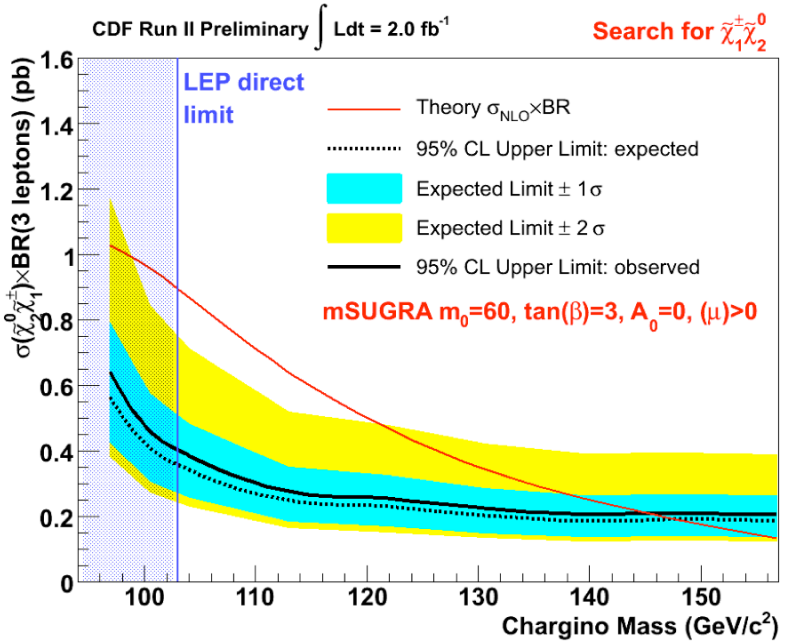
Chargino-Neutralino

- L = 2.0 fb^{-1}
- Signature: (3 leptons or 2 leptons+track) +MET
- Selection (signal region):
  - p_T (15,10/5,5) GeV/c
  - MET>20 GeV (DY and QCD rejection)
  - $N_{jets} \leq 1$ and $H_T < 80$ (top rejection)
  - Z-mass veto (DY rejection)
  - Dilepton Mass above 20 GeV/c^2 (QCD and resonance rejection)
- Trilepton backgrounds:
  - DY+fake, Z+γ, diboson

Analysis	Backg.	Signal	DATA
Trilepton	**0.9 ± 0.1**	4.5 ± 0.6	**1**
Dilepton+Track	**6.9 ± 0.9**	5.5 ± 1.1	**6**

$M(\chi_1^{\pm}) > 145$ GeV/c^2 at 95% CL



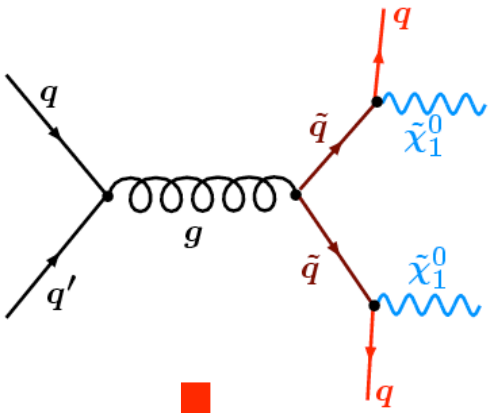


Phys. Rev. Lett. 101, 251801 (2008)

Squark-Gluino production and decay

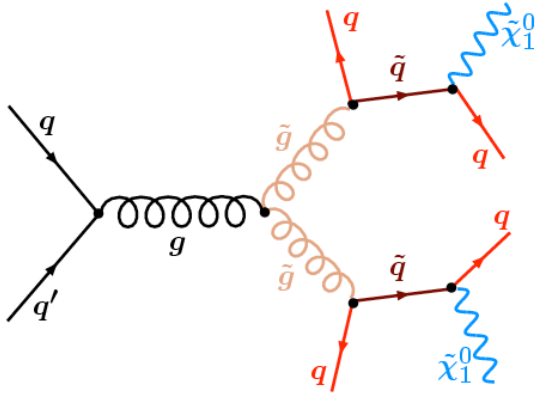
- The dominant squark-gluino production process depends on their mass (σ~0.1-0.2 pb for our sensitivity region)

If $M_{\tilde{q}} < M_{\tilde{g}}$



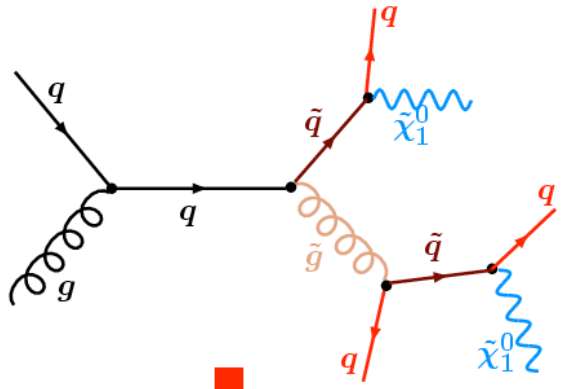
Result: 2 jets and MET

If $M_{\tilde{q}} > M_{\tilde{g}}$



Result: 4 jets and MET

If $M_{\tilde{q}} \approx M_{\tilde{g}}$ then additional contribution:



Result: 3 jets and MET

- Although the production is strong, the analyses are challenging due to QCD-multijet and W/Z+jet backgrounds
  - Solution: break-down analyses in jet-multiplicity bins and optimize separately (using MET and HT←Sum of jet E_T)

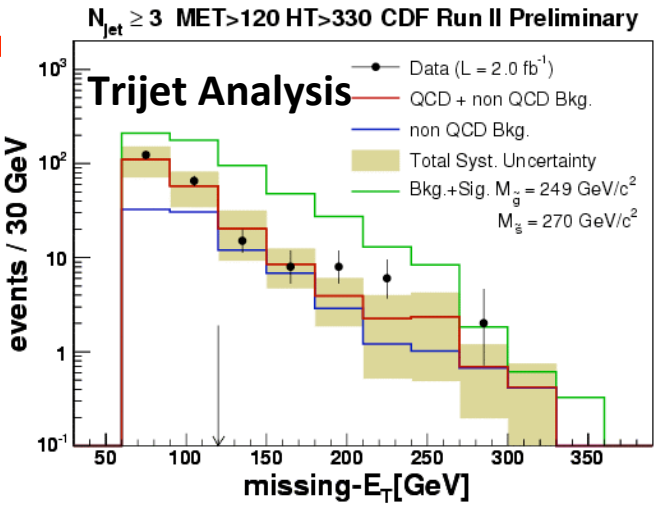
Gluino-Squark

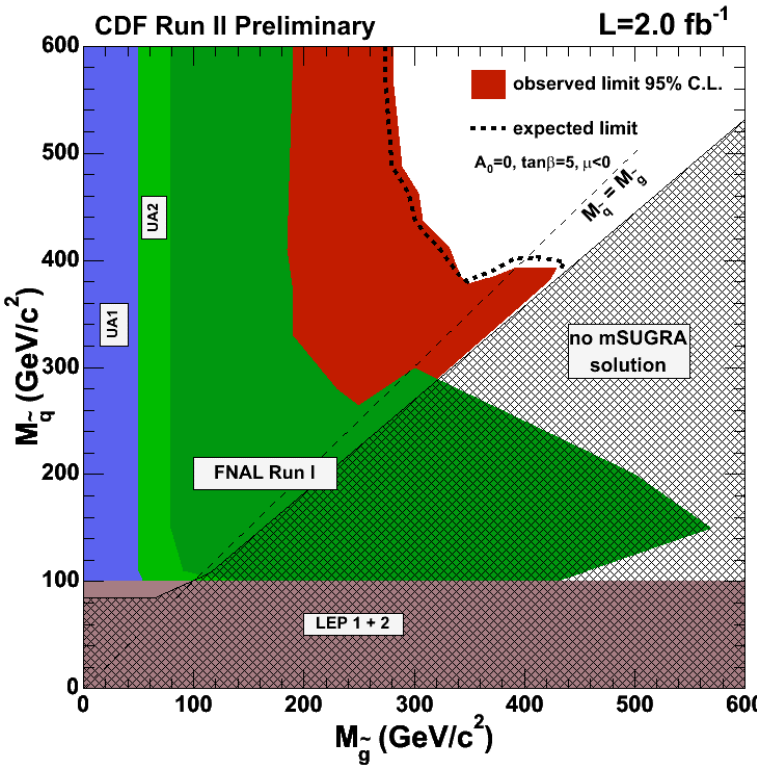
arXiv:0811.2512 [hep-ex]

- L = 2 fb^{-1}
- Signature: Jets + MET
- Selection:
  - High MET (for QCD reduction)
  - lepton-veto (for top and boson reduction)
  - small jet-met angle (for QCD reduction)
  - separate optimized cuts for 3 analyses
- Backgrounds: QCD multijets, Z+jets, W+jets, top, diboson
  - (all MC, for QCD it is normalized to data at low-met)

95% CL: Mass of gluino > 392 GeV/c^2

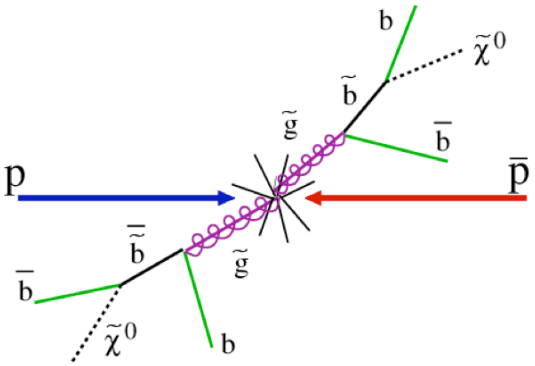
Analysis	HT cut (GeV)	MET cut (GeV)	Jet Et (GeV)	Bckg.	DATA
Dijet	330	180	**165,100**	**16 ± 5**	**18**
Trijet	330	120	**140,100,25**	**37± 12**	**38**
4-jet	280	90	**95,55,55,25**	**48 ± 17**	**45**

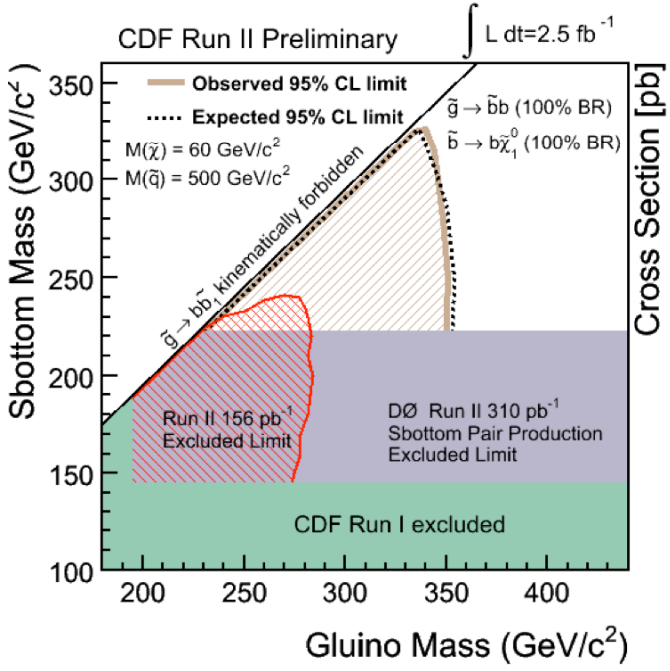


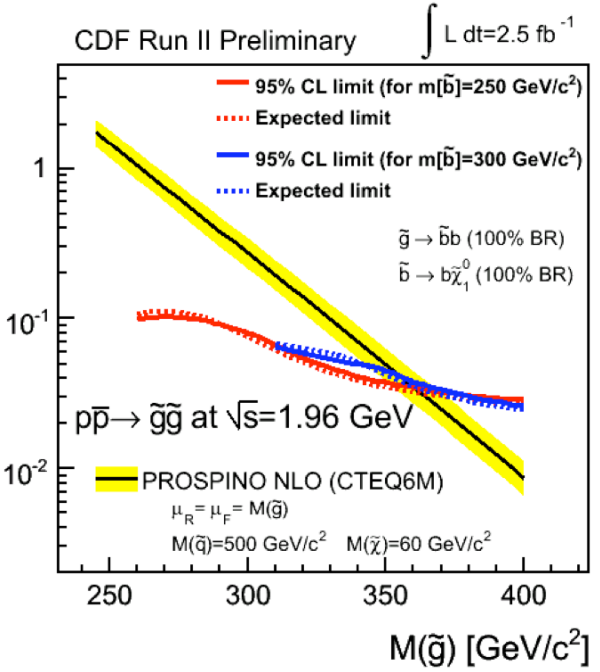


Gluino-mediated sbottom

- L = 2.5 fb^{-1}
- Selection: ≥2 jets (25,35) GeV
  MET > 70 GeV
  either 1 b-jet or ≥2 b-jets
- Study of QCD and EWK control regions
- SM backgrounds: QCD (light and heavy flavor), top pair, W/Z+jets
- For two-b-jet analsis: Expect 2.3 ± 0.8 SM events and observe 2
- M(gluino)>350 GeV at 95% CL

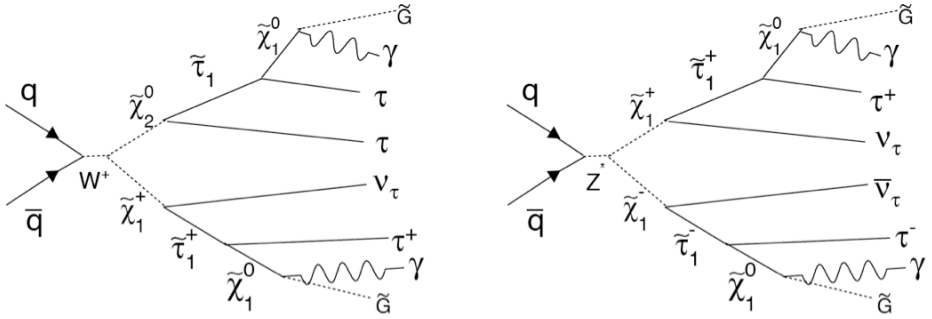


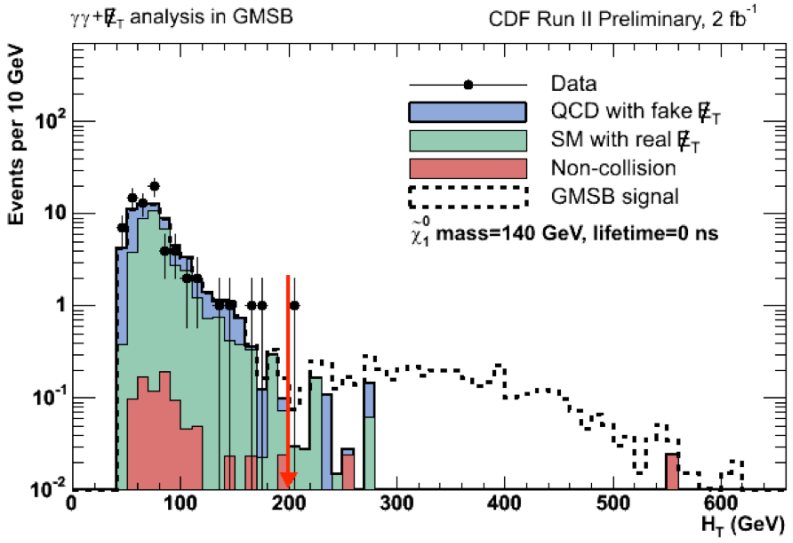


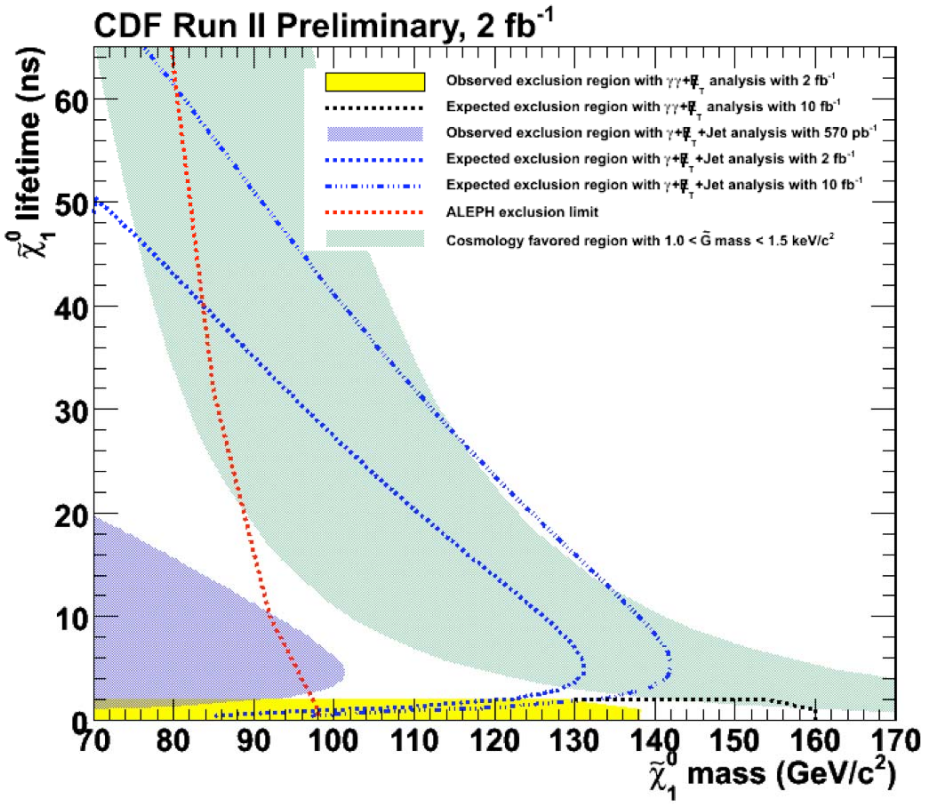


GMSB χχ→γγ+MET

- L = 2 fb^{-1}
- Selection: 2γ (E_T>13 GeV)
  MET significance > 3
  H_T >200 GeV, Δφ(γ,γ)<π-0.15
- SM backgrounds: electroweak with real MET (67%), QCD with fake MET(17%), non-collision
- Expect 0.6 ± 0.3 SM and observe 1
- **Set limits on lightest neutralino and its lifetime**

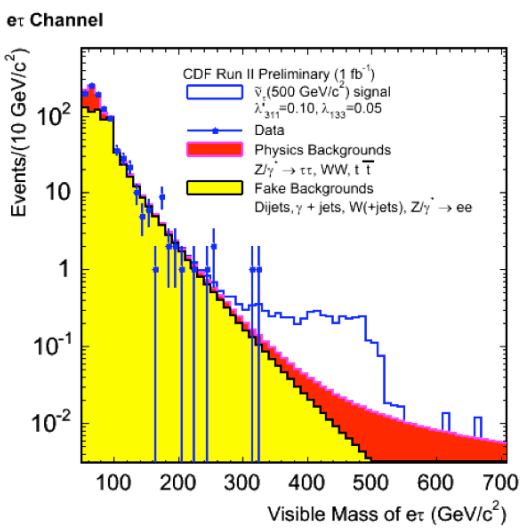


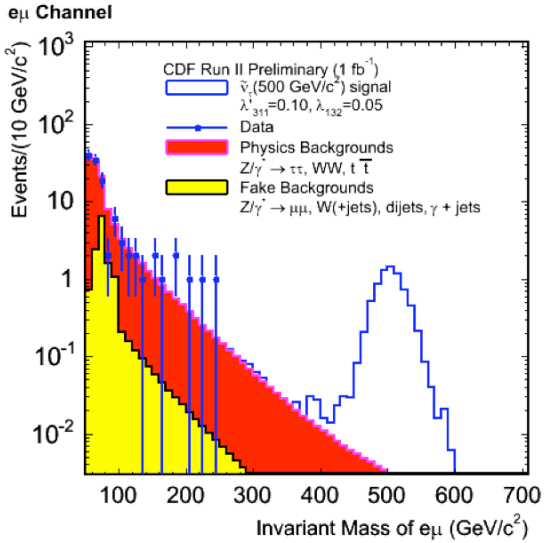


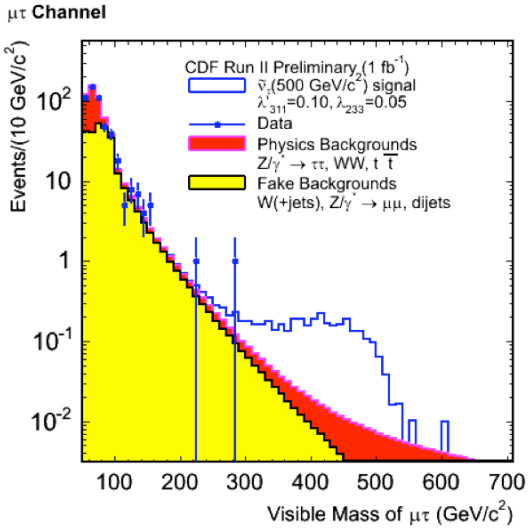


R-parity violating sneutrino→eμ or eτ or μτ

- L = 1 fb^{-1}
- Selection: eμ, eτ, μτ (e,μ:pT>20, τ:pT>20 GeV/c)
- SM backgrounds: Z→ττ, diboson, tt, W/Z+ fakes
- Control regions: 50-110 GeV/c^2
- Benchmark Signal regions: $M_{e\mu}$>500, $M_{e\tau}$>310, $M_{\mu\tau}$>280 GeV/c^2
- Observation consistent with SM expectation
- **Set limits on RPV sneutrinos**





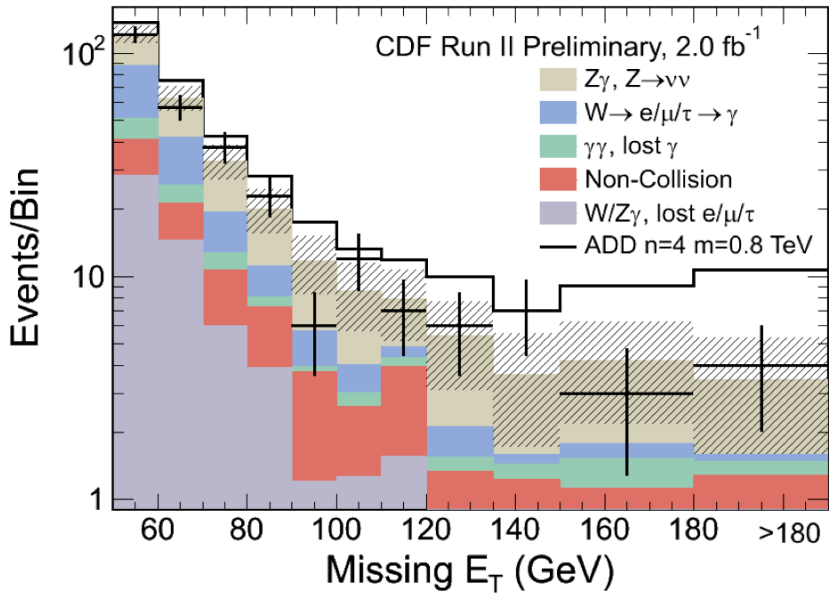


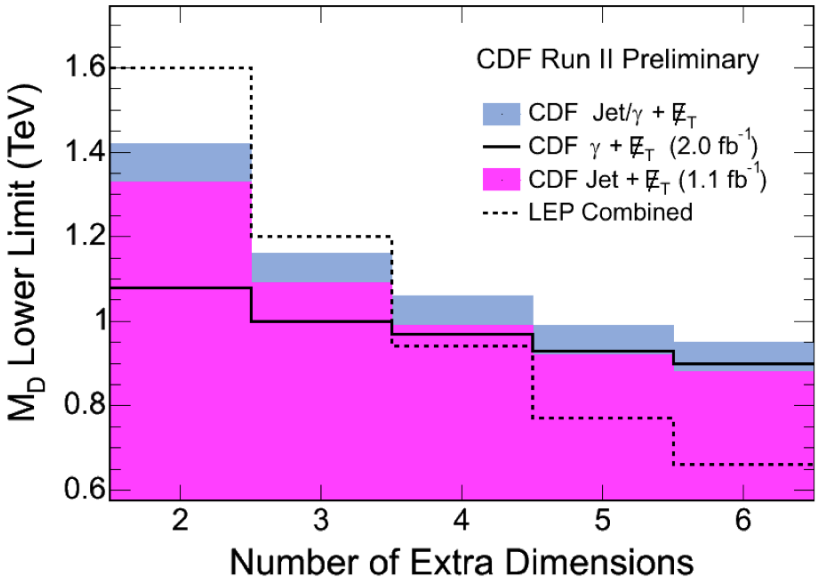
Channel	Mass cut (GeV/c^2)	SM Expected	Observed
eμ	500	0.1 ± 0.1	0
eτ	310	1.4 ± 0.3	2
μτ	280	1.0 ± 0.3	2

Extra dimensions (γ+MET)

- $\underline{L = 2\ fb^{-1}}$
- Signal: G+γ →MET + γ
- Selection: E_γ > 90 GeV
  MET > 50 GeV
  No jets(tracks) above 15(10) GeV
- SM backgrounds: Z+γ→νγ(54%), cosmics (20%),W+γ (10%), W→fake γ (6%),γγ (5%)
- Expect 46.7 ± 3 SM and observe 40
- **Set limits on number and mass-scale of Large extra dimensions (combined with the jet+MET analysis)**

Phys. Rev. Lett **101**, 181602 (2008)



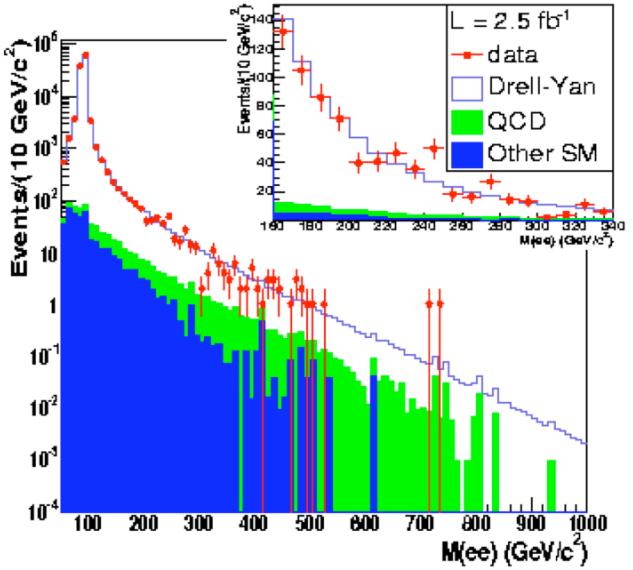


Search for high-mass X→ee or μμ resonance

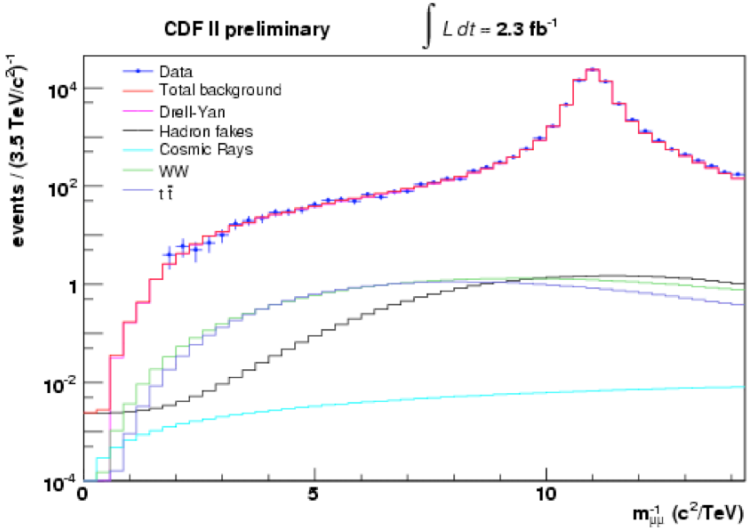
- L = 2.3-2.5 fb^{-1}
- Possible signal investigated
  - Spin 0 (RPV sneutrino)
  - Spin 1 (Z')
  - Spin 2 (Randall-Sundrum Graviton)
- Selection: 2 μ (2e), opposite charge, p_T>30 (25) GeV/c
- Backgrounds: **Drell-Yan**, diboson, tt, fakes

- ee →Observation consistent with expectation with the exception of the 241 GeV/c^2 window
  - "local" 3.8 σ
  - Probability to see that from 150 GeV - 1 TeV is 0.6% (2.5 σ)
- μμ→Observation consistent with expectation

- Set limits for different bosons:
  - **M(Z'$_{SM}$)>1030 (966) GeV/c^2** using μμ (ee)
  - **M(Graviton)>921 (850) GeV/c^2** for k=0.1M_{Pl} using μμ (ee)
  - **M(sneutrino)>866(397) GeV/c^2** for λBR=0.01(0.0001)



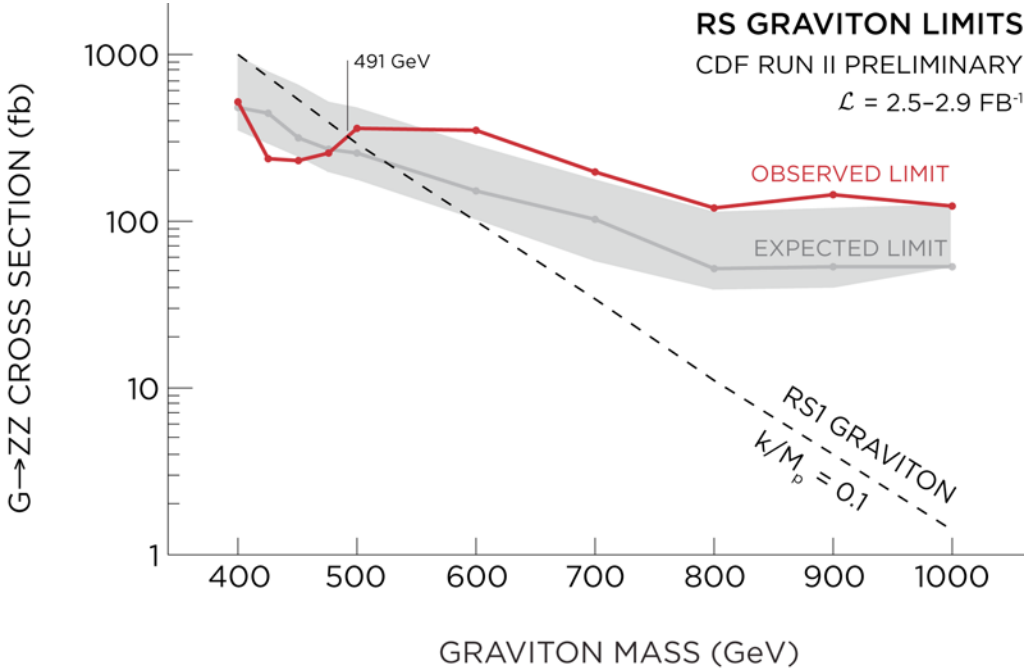
Phys. Rev. Lett. 102, 031801 (2009)

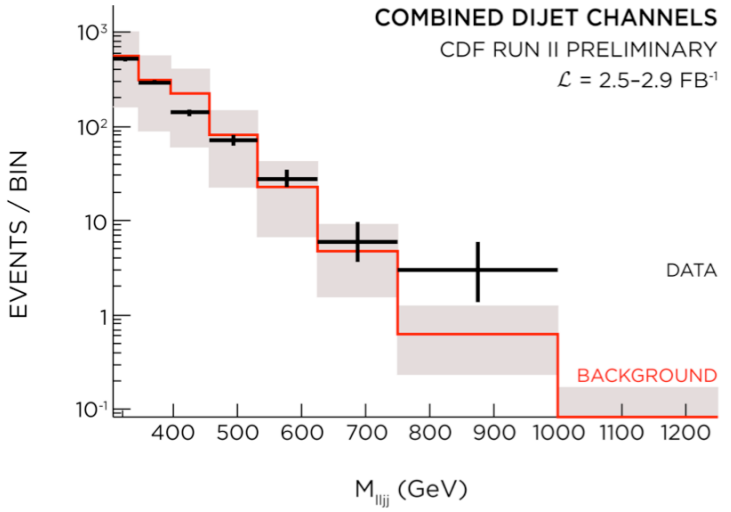


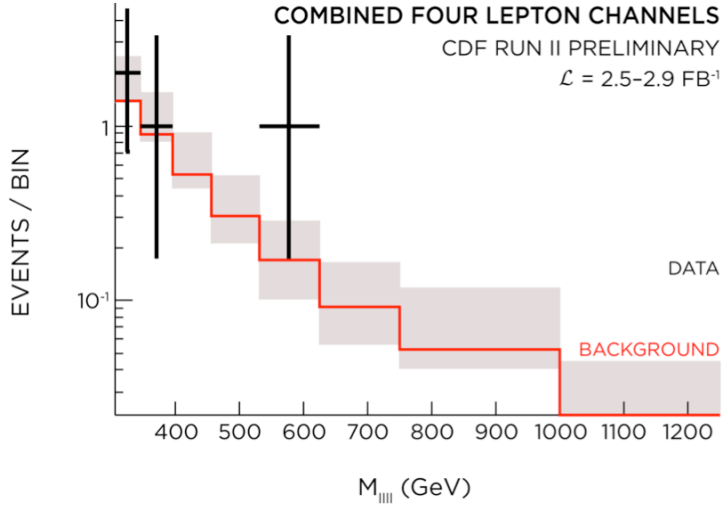
arXiv:0811.0053v1 [hep-ex]

Search for high-mass X→ZZ resonance

- L = 2.5-2.9 fb^{-1}
- Signature: X→ZZ→ℓℓℓℓ or ℓℓjj, ℓ=e or μ
- Selection: ee(μμ) of 5,20 (2 or 10, 20) GeV/c
- SM backgrounds: W+jets, Z+jets, QCD, diboson
- Signal region: based on the recontructed Z-mass probability and M_X>300 GeV/c^2
- Observation consistent with expectation
- **Set limits for spin-2 graviton at 491 GeV/c^2**







Summary

- We are searching (almost) everywhere for new physics
- We have not found any significant discrepancy from Standard Model expectations

BUT

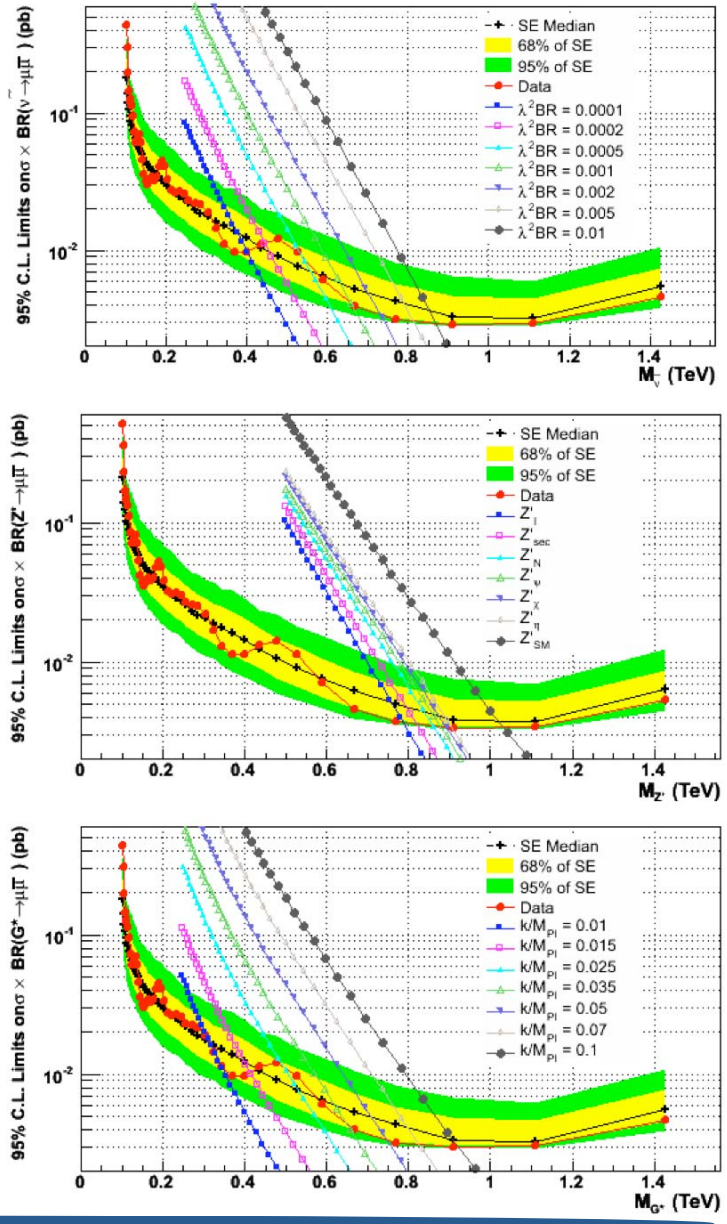
- We are excluding significant regions of theoretical parameter space
- We master our understanding of the Standard Model backgrounds in all possible phase spaces
- We keep running and improving our analyses looking for a discovery
- We develop tools and methods to be used at LHC

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

Back-up

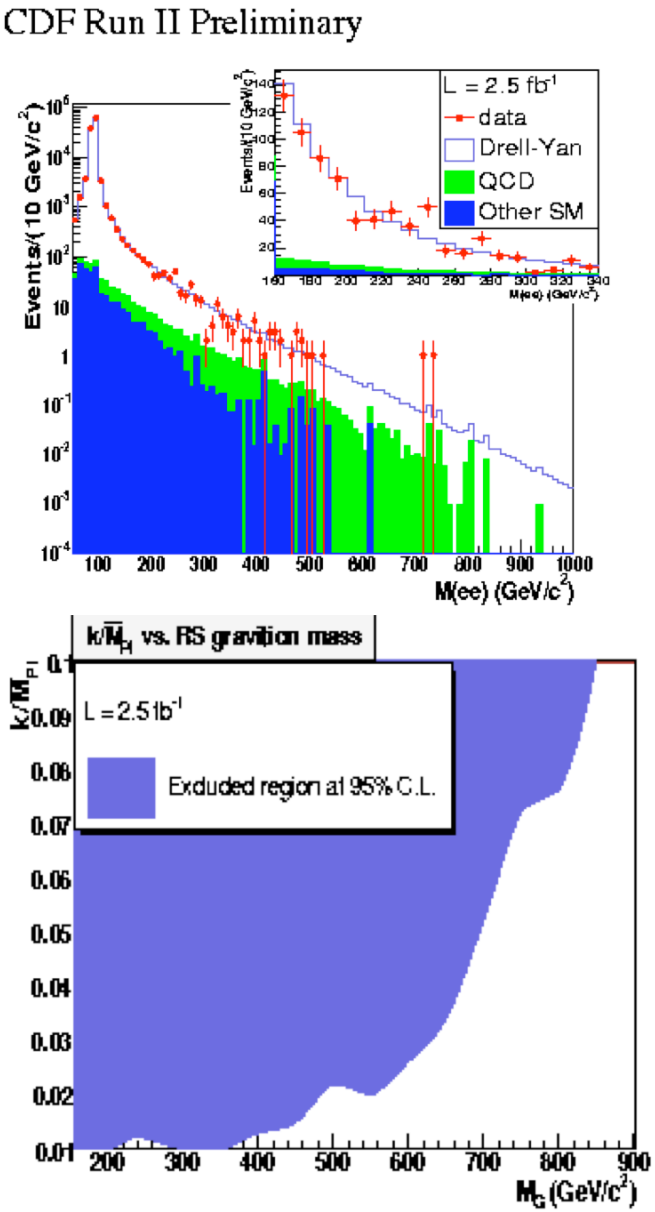
Search for high-mass X→μμ resonance

- L = 2.3 fb^{-1}
- Possible signal investigated
  - Spin 0 (RPV sneutrino)
  - Spin 1 (Z')
  - Spin 2 (Randall-Sundrum Graviton)
- Selection: 2 μ, opposite charge, p_T>30 GeV/c
- Backgrounds: **Drell-Yan**, diboson, tt, fakes
- Strategy: Normalize dimuon background template to the data from 70-100 GeV/c^2 and look for resonance at the high mass tail (> 100 GeV/c^2)
- Observation consistent with expectation
- Set limits for different bosons:
  - **M(sneutrino)>866(397) GeV/c^2** for λBR=0.01(0.0001)
  - **M(Z')>1 TeV/c^2**
  - **M(Graviton)>921(293) GeV/c^2** for k=0.1M_{Pl}(0.01M_{Pl})



Search for high-mass X→ee resonance

- L = 2 fb^{-1}
- Possible signal investigated
  - Spin 1 (Z')
  - Spin 2 (Randall-Sundrum Graviton)
- Selection: 2 e, opposite charge, p_T>25 GeV/c
- Backgrounds: **Drell-Yan**, diboson, tt, fakes
- Scan procedure: Use likelihood ratio L_b/L_{s+b} and scan the dielectron mass spectrum from 150 GeV/c^2 to 1 TeV/c^2
- **Observation consistent with expectation with the exception of the 241 GeV/c^2 window**
  - "local" 3.8 σ
  - Probability to see that from 150 GeV - 1 TeV is 0.6% (2.5 σ)
- Set limits for different bosons:
  - **M(Z')>966 GeV/c^2**
  - **M(Graviton)>850GeV/c^2** for k=0.1M_{Pl}(0.01M_{Pl})



Lepton+photon+MET+b-jet

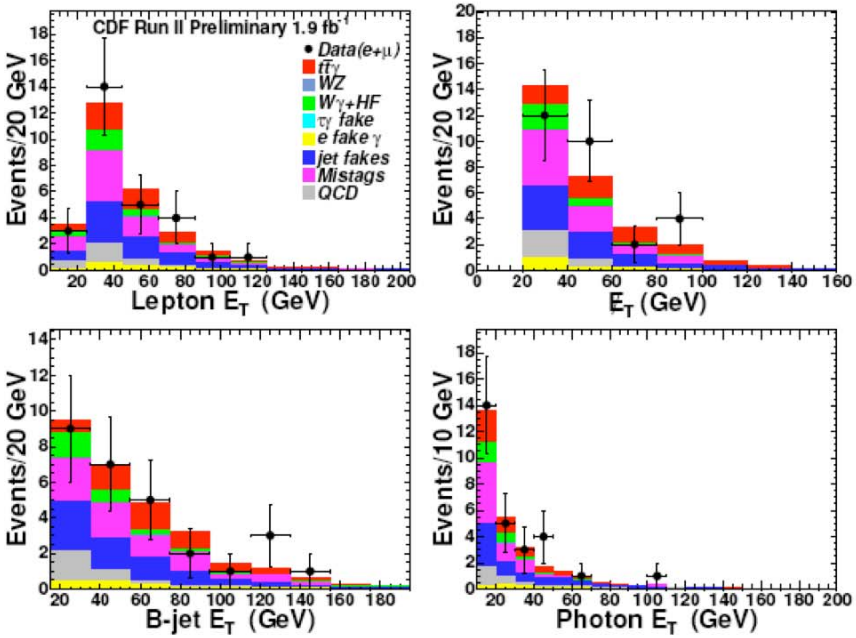
Motivation

- Extension of $\ell\gamma \not\!\!E_T$
- Signature with b and t, W and γ
- $t\bar{t}\gamma$: control sample for $t\bar{t}H$ (LHC), Q(top)

Results

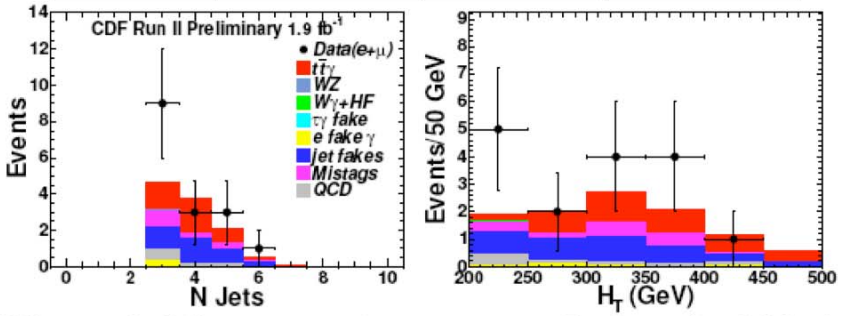
CDF Run II Preliminary, 1.9fb^{-1}

$\ell\gamma \not\!\!E_T b$	$e\gamma \not\!\!E_T b$	$\mu\gamma \not\!\!E_T b$	$(e+\mu)\gamma \not\!\!E_T b$
Expected	16.8 ± 2.2	$11.1^{+1.7}_{-1.4}$	$27.9^{+3.6}_{-3.5}$
Observed	16	12	28

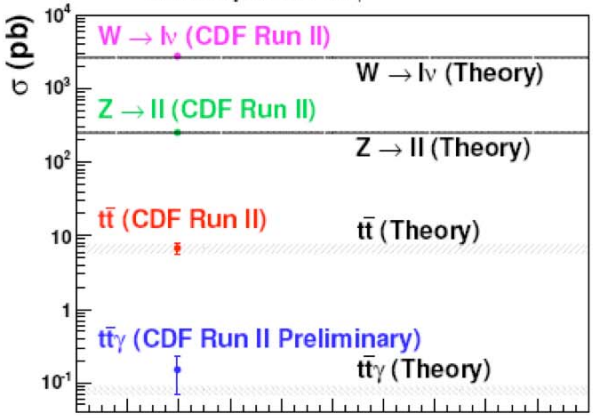


CDF Run II Preliminary, 1.9fb^{-1}

$t\bar{t}\gamma$	$t\bar{t}\gamma(e)$	$t\bar{t}\gamma(\mu)$	$t\bar{t}\gamma(e+\mu)$
Predicted	$6.7 \pm 1.4(tot)$	$4.4^{+1.3}_{-0.8}(tot)$	$11.1^{+2.3}_{-2.1}(tot)$
Observed	8	8	16



The probability, assuming no true $t\bar{t}\gamma$ Standard Model (SM) signal, for the background alone to produce at least as many events (16) as observed in data, is 1% (2.3 σ). Assuming SM $t\bar{t}\gamma$ production, we calculate the $t\bar{t}\gamma$ cross-section to be $\sigma_{\text{semileptonic } t\bar{t}\gamma} = \mathbf{0.15 \pm 0.08}$ pb. SM prediction is $\sigma^{\text{SM}}_{\text{semileptonic } t\bar{t}\gamma} = \mathbf{0.080 \pm 0.011}$ pb.

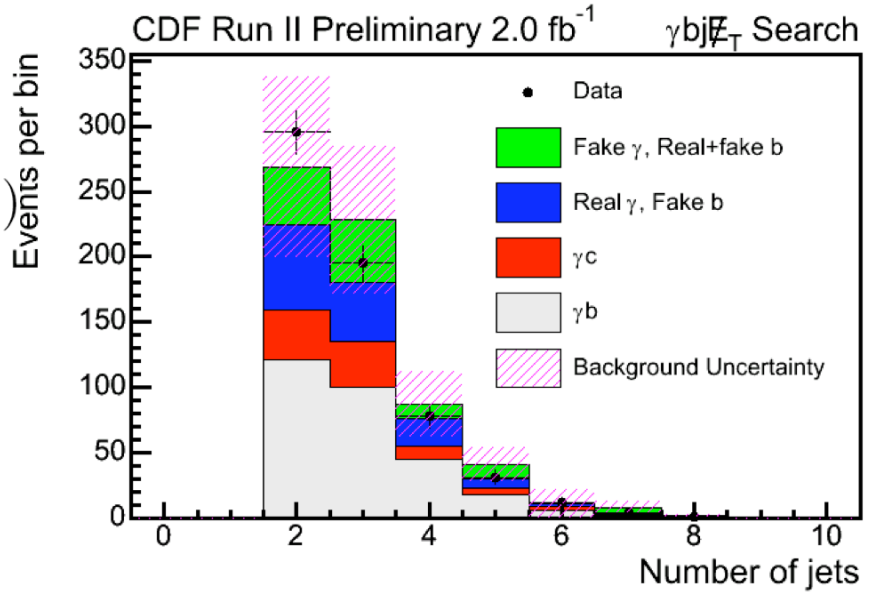


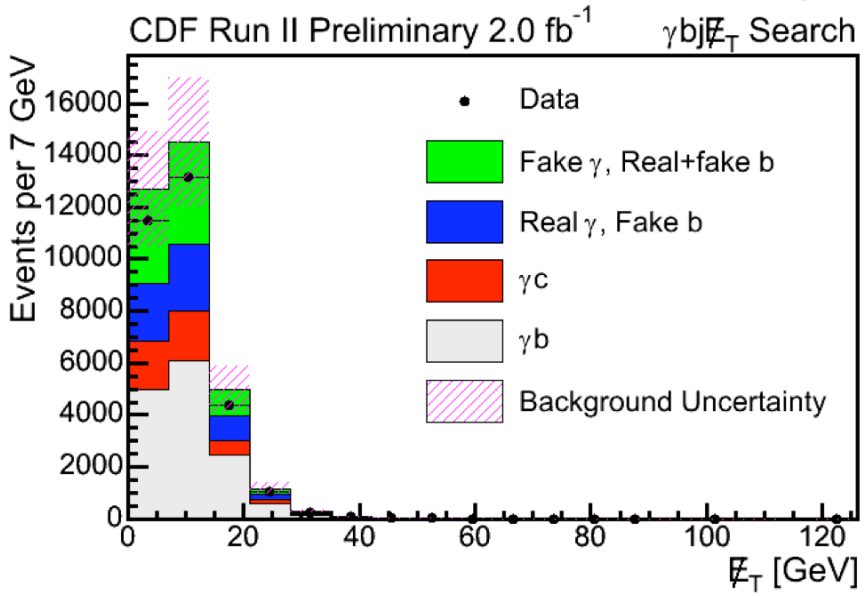
Photon+jet+MET+b-jet

- L = 2 fb^{-1}
- Possible signal

$$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow (\bar{b}\tilde{t})(\gamma\tilde{\chi}_1^0) \rightarrow (\bar{b}c\tilde{\chi}_1^0)(\gamma\tilde{\chi}_1^0) \rightarrow (\gamma\bar{b}c\not{E}_T)$$

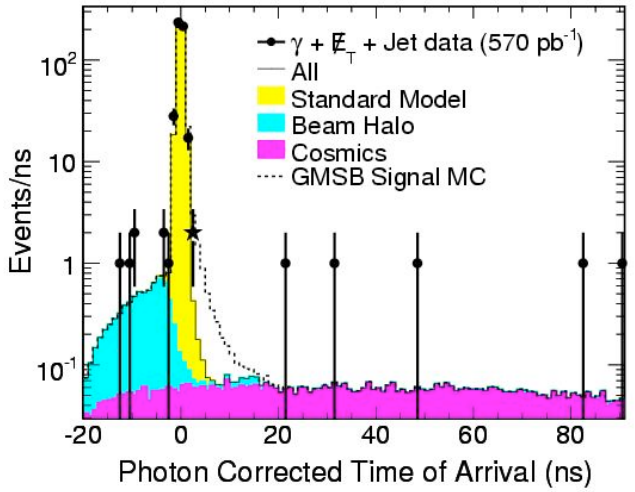
- Selection: 2 jets > 15 GeV (at least one b-tagged), 1 photon > 25 GeV, jet-jet and jet-photon separation of ΔR>0.4
- Backgrounds: multijets+(real/fake) photon+fake MET
  - b-tag can be real or fake
- Estimate fake-γ from shower shapes
- Estimate real-γ/real-b from MC
- Estimate real-γ/fake-b with mistag matrix
- Observation consistent with expectation
  - Expect 637 ± 139 from SM and observe 617

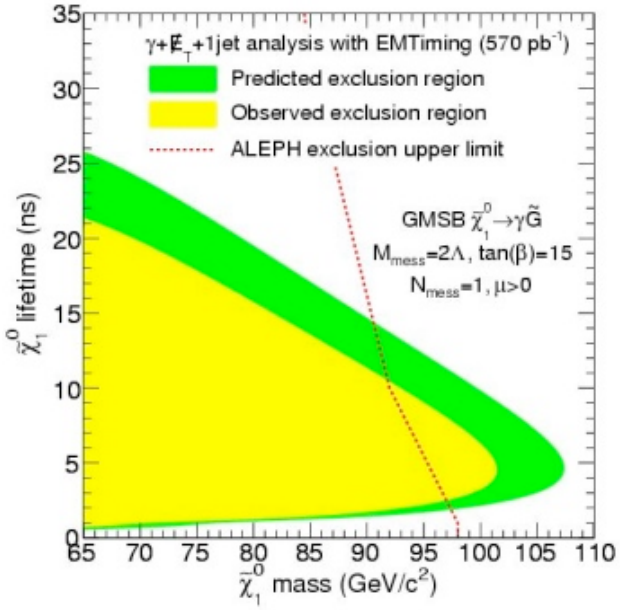




Long-lived neutralinos

- L = 570 pb^{-1}
- Looking fro neutralino to gamma+gravitino
- The photon is "delayed" since it is originated from the decay of the neutralino
- Signature: photon + jet + MET
- Investigated GMSB signal
  - M_mess = 2 Lambda, tanbeta=15, mu>0 N_mess = 1
- Backgrounds:
  - Collision: γ+jet+fake-MET, di-jet + fake-MET, W → e ν
  - Non-collision: cosmic rays and beam effects
- Preselection:
  - photon ET> 30 , met ET> 30, jet ET>30 GeV
  - Geometric separation of muon hits and gamma (cosmic reduction)
  - Delayed signal 2 ns – 10 ns
  - Selection optimized for neutralino mass of 100 GeV/c^2 and lifetime of 5 ns
- Optimization of final cuts
  - MET>40, JET_ET>35, Δϕ(Jet-met)>1 rad, 2 ns <t<10 ns.
- m(neutralino)>101 GeV for lifetime of 5 ns.





PRL 99, 121801 (2007)

stop → b + chargino

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

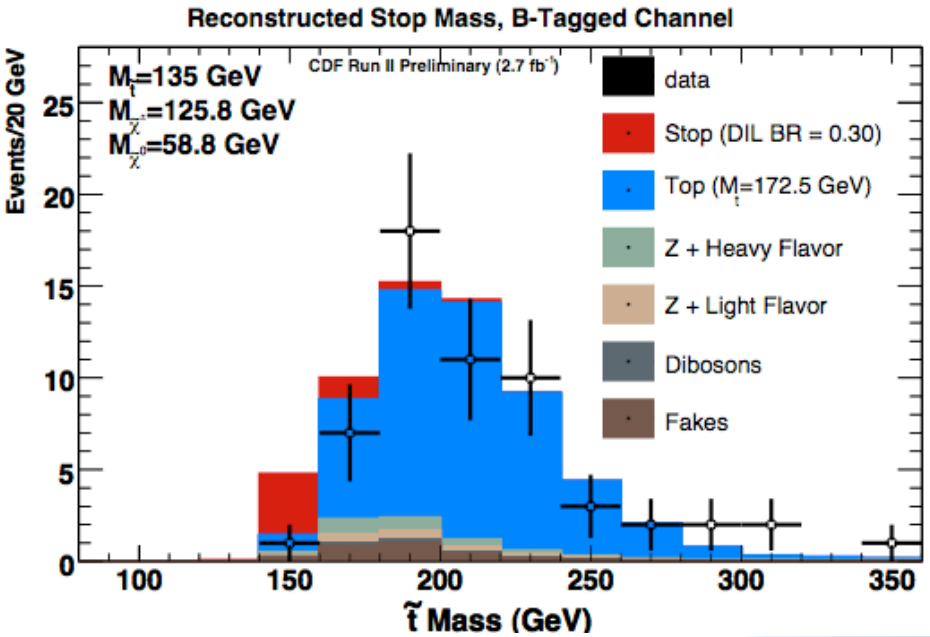
Under the assumptions:

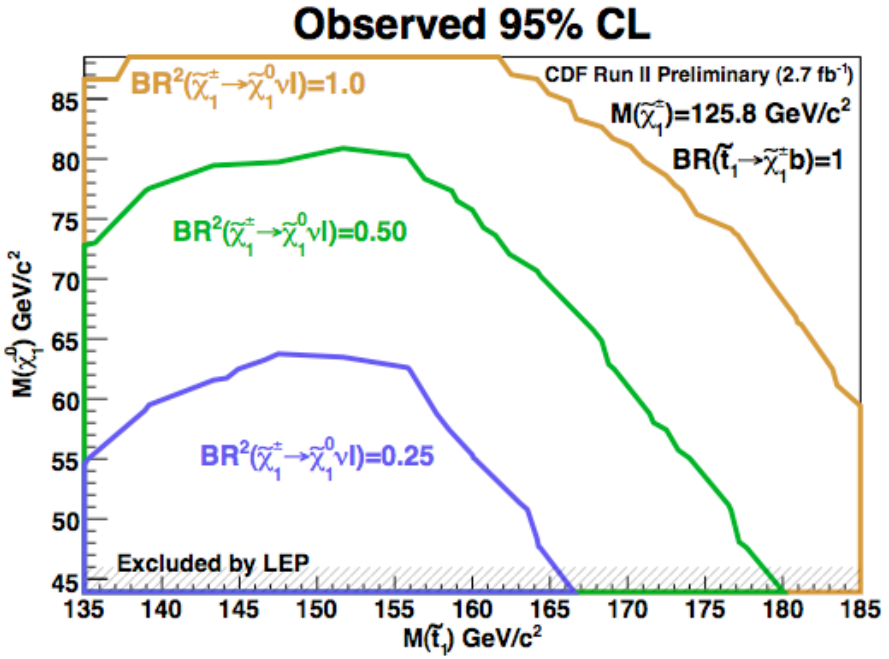
$\tilde{\chi}_1^0$ is the LSP, and $\tilde{q}, \tilde{\ell}, \tilde{\nu}$ are heavy

$m_{\tilde{t}_1} \lesssim m_t$

$m_{\tilde{\chi}_1^+} < m_{\tilde{t}_1} - m_b$

- L = 2.7 fb^{-1}
- Selection: 2 leptons p_T > 20 GeV/c
  2 jets E_T>12,15 GeV
  MET > 20 GeV
  ≥b-tag and no-b-tag channels
- SM backgrounds: top pair (85%), QCD (light and heavy flavor)
- Expect 56 ± 7 SM and observe 57

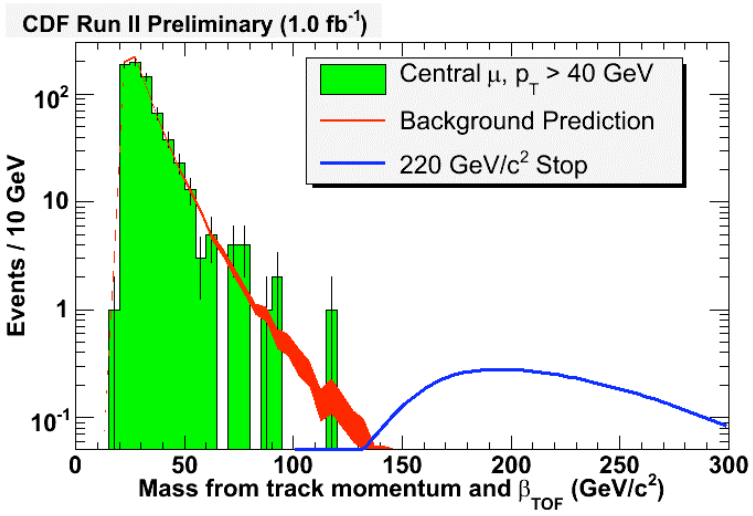


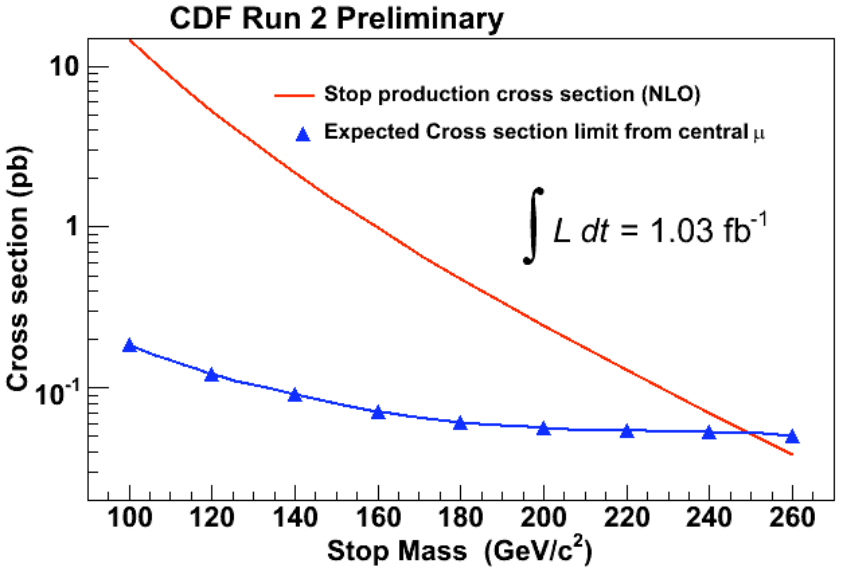


Long-lived top as CHAMP

- $L = 1.0\ fb^{-1}$
- Slow particle signature : slowly-moving highly-ionizing highly-penetrating particle
  - Will look like muon with possible calorimetry energy deposition
- Goal: Measure Time of Flight mass of tracks
- Shape of TOF mass determined by beta-resolution, measured with W→ev
- Backgrounds: Cosmics, multiple interactions

Stop Mass (GeV/c²)	Bckg.	DATA	$\sigma_{95\%}$ (fb)
100	**4.7**± 0.3	**4**	160
120	**1.9**± 0.2	**1**	90
260	**(2.6** ± 0.5)10^{-2}	**0**	50





Stable stop mass > 250 GeV/c² at 95% CL

R-parity violation

- R-parity violating part of Lagrangian

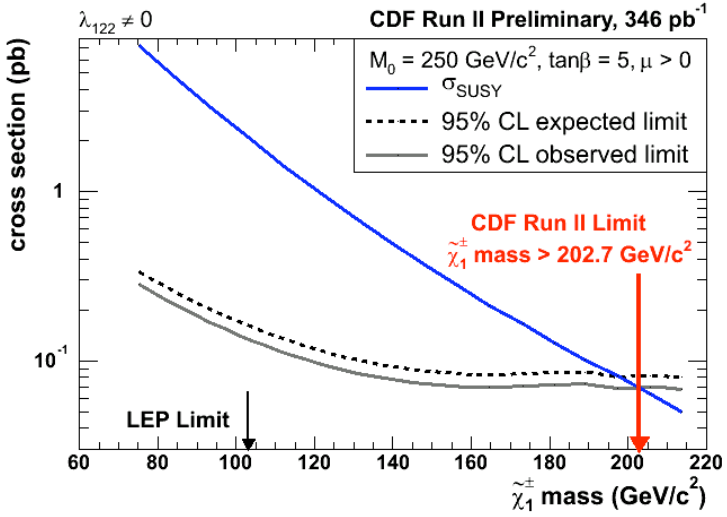
Investigated at the Tevatron

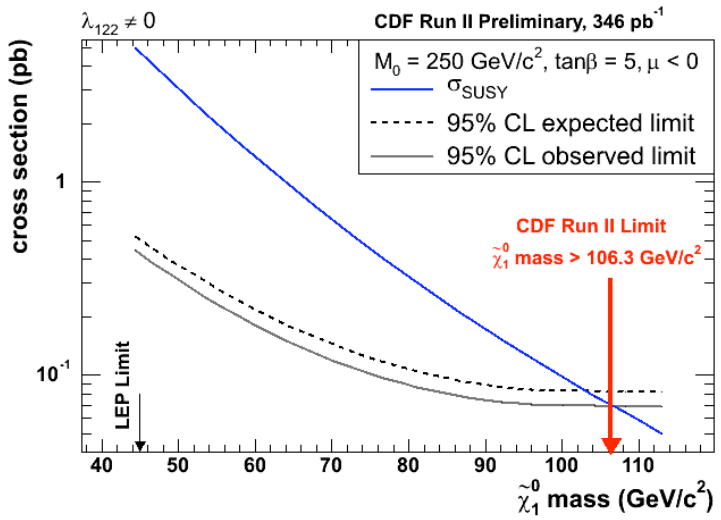
$$L_{RPV} = \frac{1}{2}\varepsilon_{\alpha\beta}\lambda_{ijk}L_i^{\alpha}L_j^{b}E_k + \varepsilon_{\alpha\beta}\lambda'_{ijk}L_i^{\alpha}Q_j^{b}D_k +$$
$$\frac{1}{2}\varepsilon_{\alpha\beta\gamma}\lambda''_{ijk}U_i^{\alpha}D_j^{b}D_k^{\gamma} + \varepsilon_{\alpha\beta}\mu_i L_i^{\alpha}H_u^{b}$$

- μLH → neutrino masses
- LLE and LQD → lepton number violation
- UDD → baryon number violation

- We set limits on the couplings λ,λ'

R parity violation with multileptons





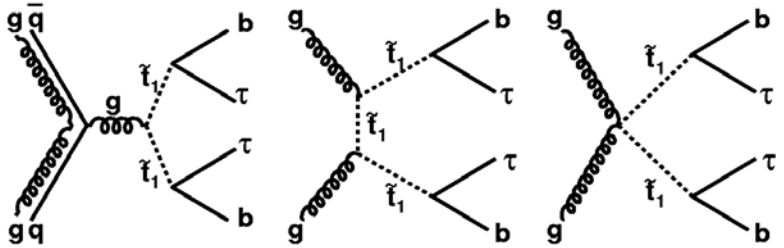
PRL 98, 131804 (2007)

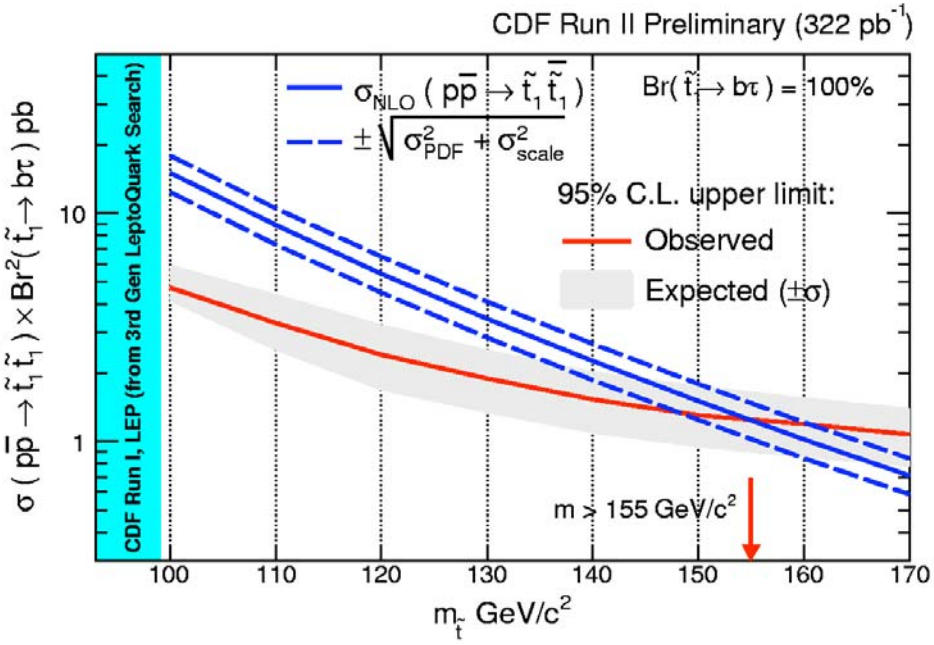
- L = 346 pb^{-1}
- Search for anomalous production of 3 or ≥ 4 leptons
- Both electrons and muons are used

Mass Limits				
	$M_{\tilde{\chi}^0_1}$ (GeV/c^2)		$M_{\tilde{\chi}^{\pm}_1}$ (GeV/c^2)	
SUSY Scenario	Expected	Observed	Expected	Observed
λ_{121} and μ > 0	105.0	101.5	191.9	185.3
λ_{121} and μ < 0	101.1	97.7	192.2	185.6
λ_{122} and μ > 0	107.7	110.4	197.5	202.7
λ_{122} and μ < 0	102.7	106.3	195.3	201.9

RPV stop to tau + b

- L = 322 pb^{-1}
- Process: two stops produced, each of which decay to tau + b with a BR~β
  - Selection for one hadronic and one leptonic tau
- Signature: lepton + narrow jet + 2 jets
- SM Backgrounds: QCD (bb, γ+jet) and W/Z+jets
- Selection:
  - Electron or muon with p_T > 10 GeV/c
  - Hadronic tau with p_T > 15 GeV/c
  - Conversion, cosmic removal and Z → τ τ vetos
  - Signal region (blind) N_{jets} >2 and $M_T(\ell, MET)$<35
- Expected ~2±0.5 e+τ_h and observed 1
- Expected ~1±0.5 μ+τ_h and observed 1
- For β=1, m_{stop} >151 GeV/c^2 at 95% CL





Phys.Rev.D **77**, 052002 (2008)

Stop-sbottom

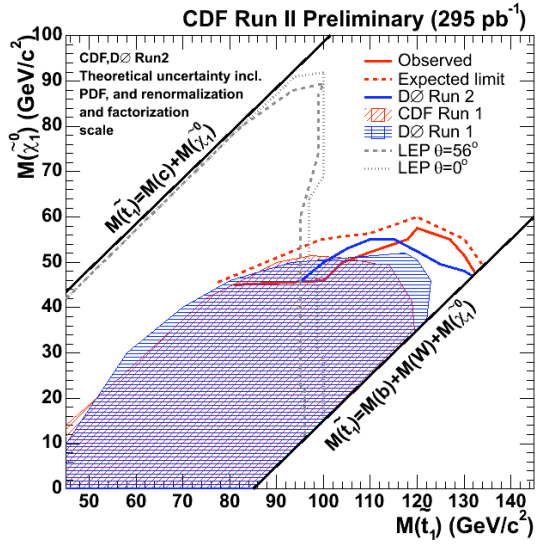
- L = 295 pb^{-1}
- Expected σ of 50 pb to 0.25 pb for stop and sbottom masses from 80 to 200 GeV/c^2
- Signature: c+cbar+MET and b+bbar+MET
- Three mass ranges for each of the sbottom and stop analyses
- Backgrounds:
  - QCD multijet (from data, normalized to low-MET and MET//jet regions)
  - W/Z+jet, single top, ttbar, diboson.

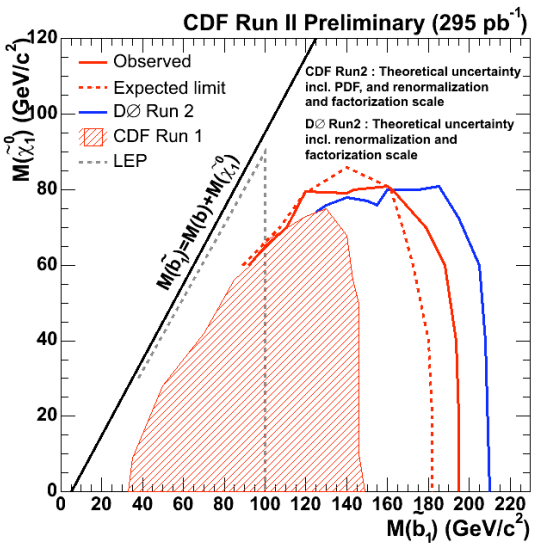
- Selection:
  - Charged particle and EM fraction cut (reduces cosmics, beam-hallo, fake jets, wrong PV selection)
  - MET>50 GeV, no additional jets, no collinear jet and met and jets not collinear or back-to-back (for QCD reduction)
  - Lepton veto and high jet track multiplicity (for W/Z+jets reduction)
  - HF tagger (efficiency 40% and 17% for b and c – 1% and 5% mistag)
- After cuts the highest source of background is Mistag and HF multi-jet
  - the latter goes to zero for the high mass region of search)

	M_{stop} <100	M_{stop} 100-120	M_{stop} >120
SM	137±16	95 ± 11	43 ± 5
DATA	151	108	43

	$M_{sbottom}$ <140	$M_{sbottom}$ 140-180	$M_{sbottom}$ >180
SM	55 ± 7	18 ± 2	4.7 +2.2/-0.7
DATA	60	18	3

Phys. Rev D **76**, 072010 (2007)





Supersymmetry breaking and spectrum

- "Minor detail": We haven't discovered new particles with same masses as our known SM particles and only a spin difference
- So if SUSY is a symmetry of nature, it has to be broken at a higher energy-scale and the effects are mediated to the electroweak scale.
- In Minimal SUSY (MSSM), supersymmetry is broken by introduction of extra Lagrangian terms
  - Soft SUSY Breaking
- Minimal Supergravity (mSUGRA) is MSSM with some extra boundary conditions and assumptions
  - SUSY breaking is mediated by gravity
  - LSP is the Neutralino
  - Only 4 parameters and a sign (m_0 , $m_{1/2,}$ tanβ, A, μ)
- Alternatively, in Gauge Mediated SUSY Breaking (GMSB), SUSY breaking is mediated by gauge fields
  - LSP is the Gravitino

How to get SUSY MC signal

- Assuming on shell produced SUSY particles, use only 2→ 2 decays:
  - Select a SUSY point (e.g., mSUGRA)
  - Get the spectrum (e.g., using SOFTSUSY)
  - Get Branching Ratios (e.g., using SDECAY)
  - Feed spectrum and BR to generator with fragmentation (e.g., PYTHIA)
  - Feed PYTHIA generated events to detector simulator (e.g., GEANT)
  - Correct using the NLO cross-section (e.g., from PROSPINO)

- Assuming the whole 2→ 6 decays of most processes (e.g., chargino-neutralino), which is more accurate:
  - Use the complete 2→6 matrix element (e.g., from MADGRAPH)
  - Get the spectrum (e.g., using SOFTSUSY)
  - Integrate using proper phase-space to generate events (e.g., using MADEVENT)
  - Feed the generated events to program with fragmentation (e.g., PYTHIA)
  - Feed PYTHIA generated events to detector simulator (e.g., GEANT)
  - Correct using the NLO cross-section (e.g., from PROSPINO)

Particles we (think we) look for

- There are scalar leptons (sleptons) and quarks (squarks)

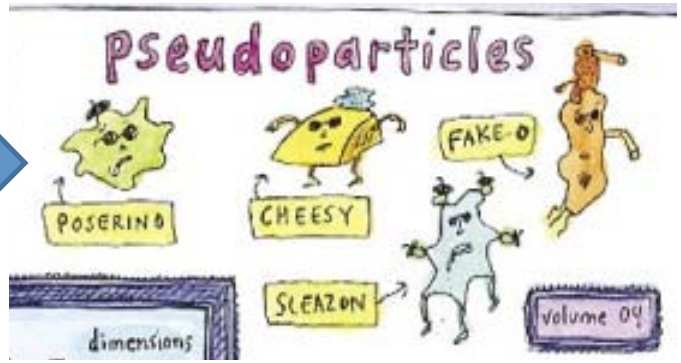
$$l, \nu, q \rightarrow \tilde{l}, \tilde{\nu}, \tilde{q}$$

- There are fermionic gluons (gluinos) and fermionic gauge bosons and higgses that mix to give charginos and neutralinos

$$g \rightarrow \tilde{g} \qquad W, Z, \gamma, \text{higgs sector} \rightarrow \chi^{0}_{1-4}, \chi^{\pm}_{1,2}$$

- We present today direct searches for chargino-neutralino, squark, gluino, stop/sbottom production

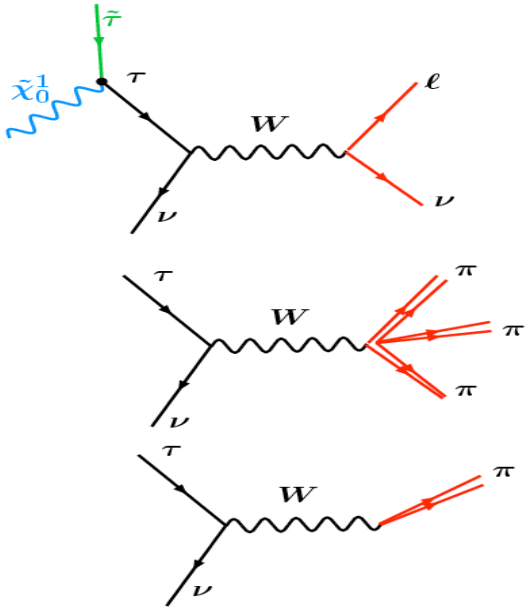
- Of course, we may discover something completely unanticipated in the process !



Cartoons by Roz Chast

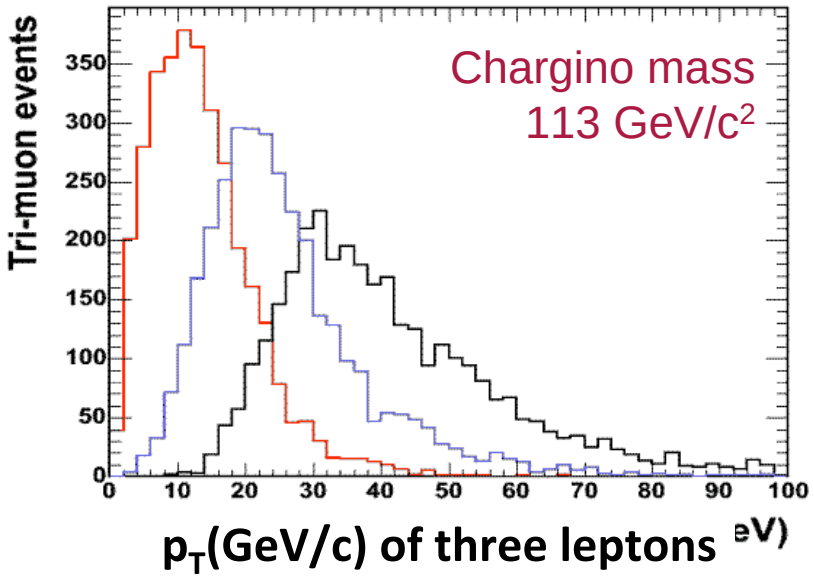
Soft leptons and isolated tracks

- Staus are expected to be the lightest sleptons
  - They will decay to one or three charged hadrons resulting to one or three tracks
  - Or, they will decay to soft leptons



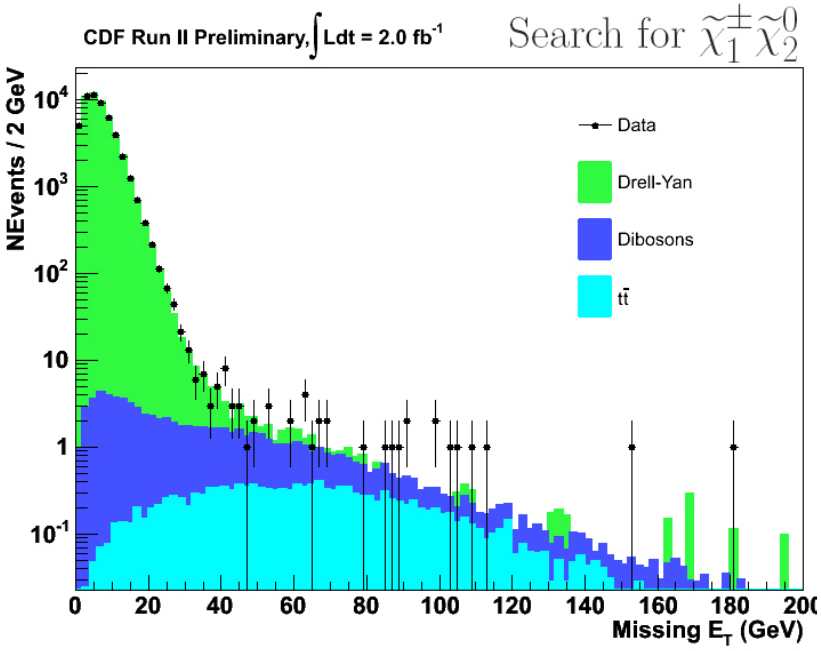
- For this reason, we include isolated tracks to reconstruct some of the "hadronic" taus

p_T of leptons can be really low
(we consider momenta > 5 GeV/c)

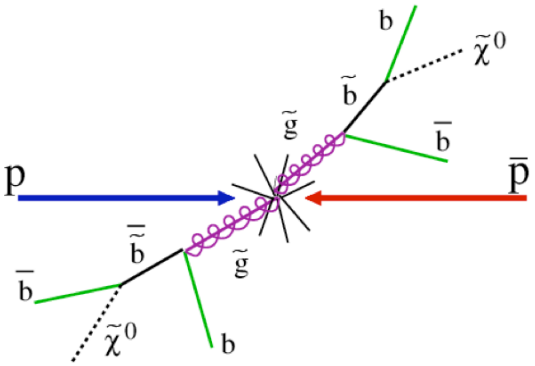
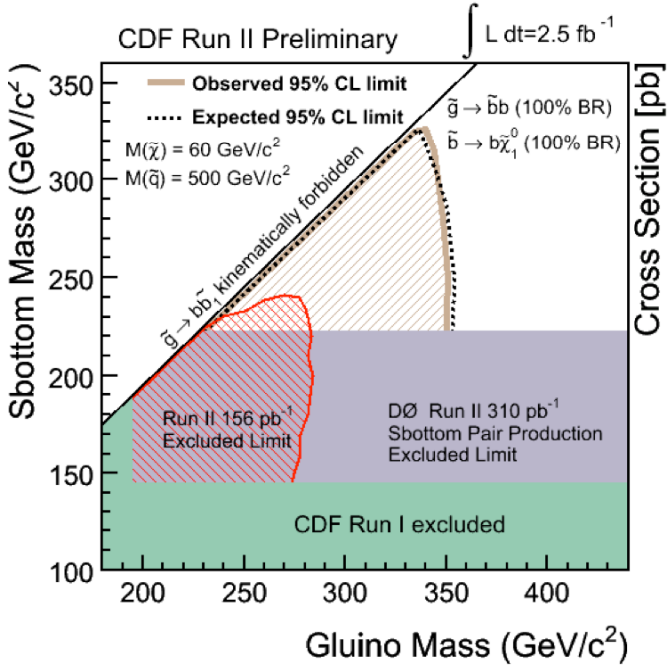
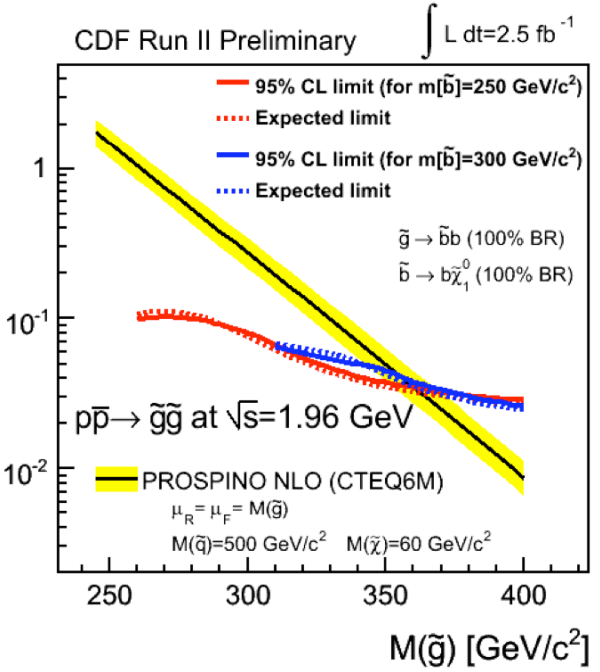


Chargino-Neutralino

- L = 2.0 fb^{-1}
- Signature: (3 leptons or 2 leptons+track) +MET
- Selection (signal region):
  - p_T (15,10/5,5) GeV/c
  - MET>20 GeV (DY and QCD rejection)
  - $N_{jets} \leq 1$ and $H_T < 80$ (top rejection)
  - Z-mass veto (DY rejection)
  - Dilepton Mass above 20 GeV/c^2 (QCD and resonance rejection)
- Trilepton backgrounds:
  - DY+fake, Z+γ, diboson



- Control regions in MET vs $M_{\ell\ell}$ phase-space
  - Both dilepton and trilepton control regions show excellent agreement between SM backgrounds and observation

Gluino-mediated sbottom

- L = 2.5 fb^{-1}
- Selection: ≥2 jets (25,35) GeV
  MET > 70 GeV
  either 1 b-jet or ≥2 b-jets
- Study of QCD and EWK control regions
- Two signal hypotheses used for optimization:
  A: Large Δm: M(gluino) = 335 GeV/c^2, M(sbottom) = 260 GeV/c^2, M(neutralino) = 60 GeV/c^2
- **B: Small Δm: M(gluino) = 335 GeV/c^2, M(sbottom) = 315 GeV/c^2, M(neutralino) = 60 GeV/c^2**
- SM backgrounds: QCD (light and heavy flavor), top pair, W/Z+jets
- For two-b-jet analsis:For optimization A (B) Expect 4.5 ± 1.4 (2.3 ± 0.8) SM events and observe 5 (2)
- M(gluino)>350 GeV at 95% CL