Searches in Lepton Final States

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on behalf of the CDF and DØ Collaborations

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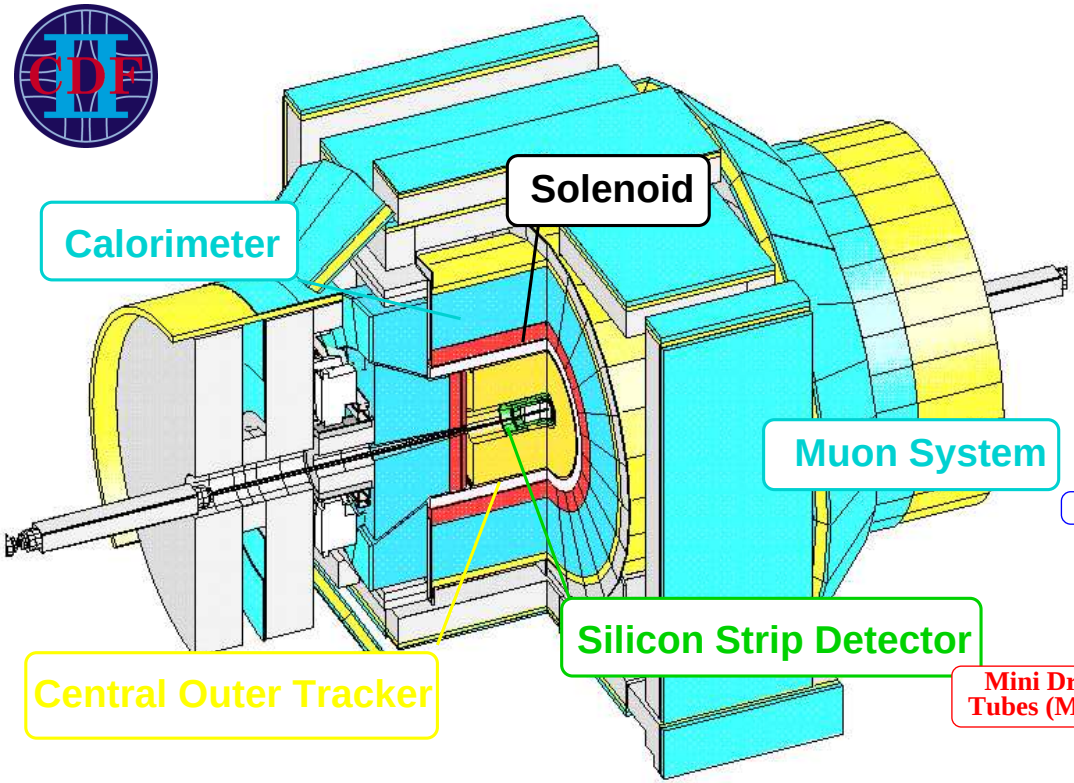
Outline

- Tevatron collider and detectors
- Going beyond the Standard Model
- Supersymmetry
  - ▲ Searches within mSUGRA
  - ▲ SUSY beyond mSUGRA
- Searches for heavy resonances
  - ▲ Extra gauge bosons
  - ▲ Gravitons
- Summary and outlook

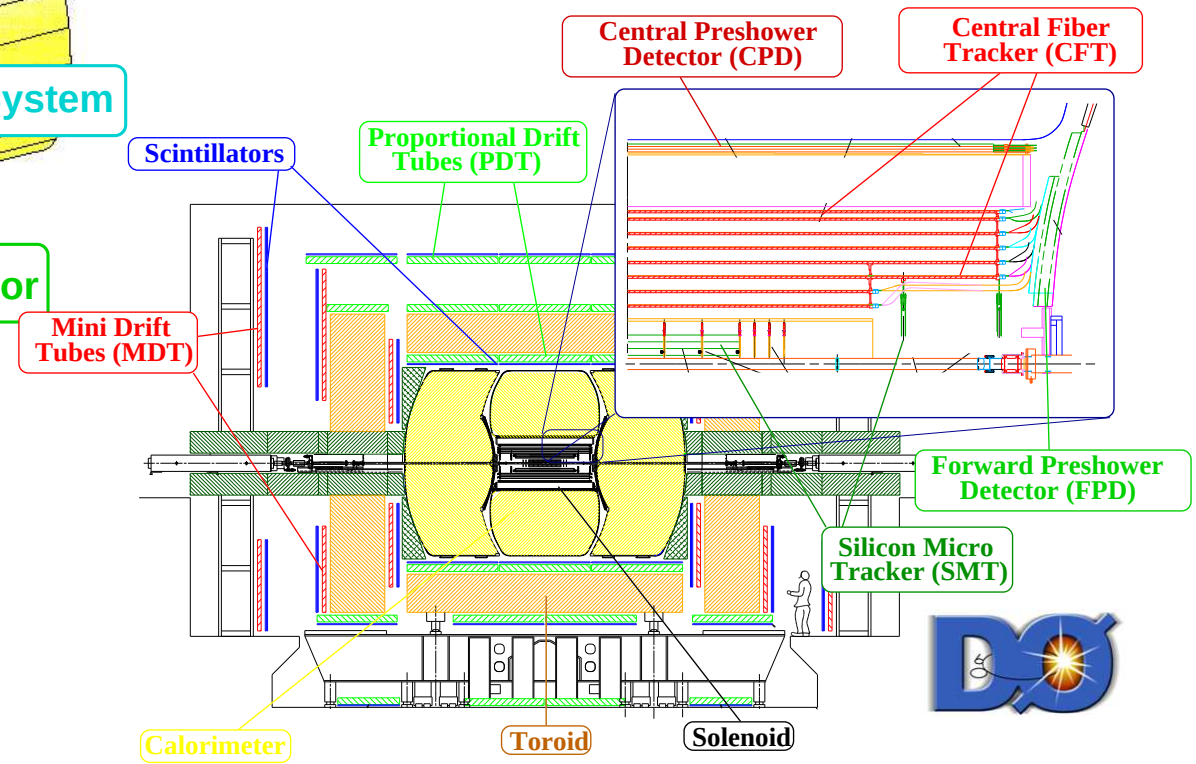
Results presented today

$\int \mathcal{L} dt$ = 1–3 fb^{-1}

The Detectors



- Two multipurpose detectors
  - ▲ Identification of electrons, muons, taus, jets, missing transverse energy
- Fast readout electronics
  - ▲ Bunch spacing 396 ns
- Dedicated trigger systems
  - ▲ Rate reduction from 2.5MHz to 50Hz

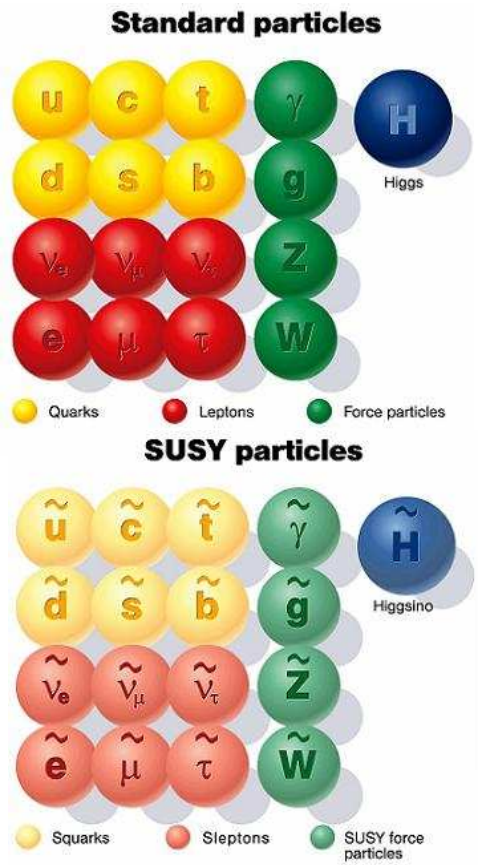


- CDF detector
  - ▲ Large tracking volume (r = 1.5 m)
- DØ detector
  - ▲ Large acceptance for electrons ($|\eta| < 3.2$) and muons ($|\eta| < 2.0$)

Going Beyond the Standard Model

- The Standard Model is very successful...
  - ▲ ...but it cannot answer all questions and has some caveats
    - ⇒ Many ways and attempts to extend the Standard Model

1. Supersymmetry
   - ▲ Extension of the Poincare group
     - ▶ Supersymmetric partner for every SM particle
     - ▶ Charginos, Neutralinos, Sleptons, Sneutrinos,...



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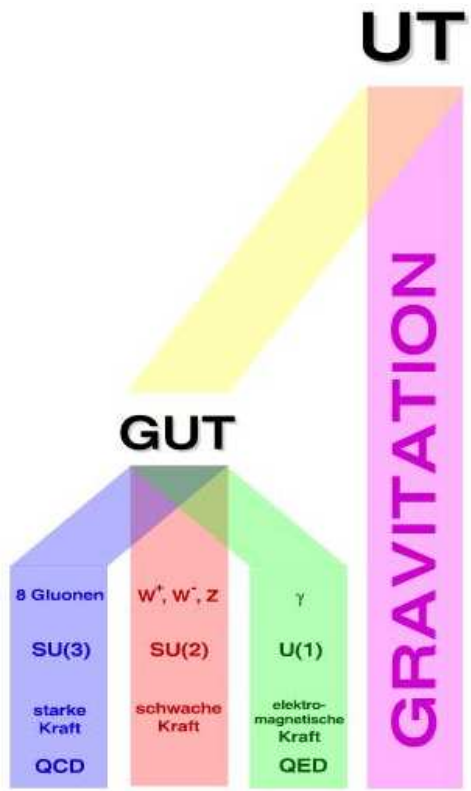
2. Grand Unified Theories
   - ▲ Enlarge gauge group $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$
     - ▶ New additional gauge bosons W′, Z′



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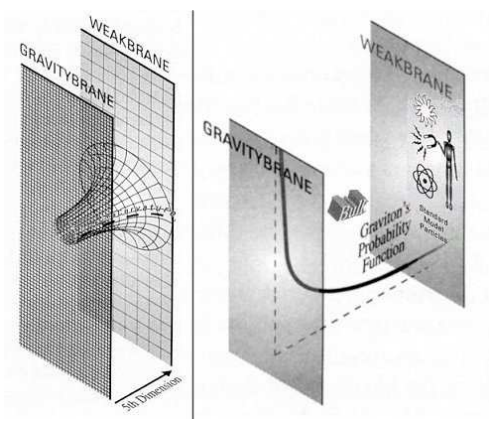
3. Large Extra Dimensions, Randall Sundrum Model
   - ▲ Increase the number of space dimension
     - ▶ KK excitations, RS gravitons,...

4. Many more not covered here...



Supersymmetry (MSSM)

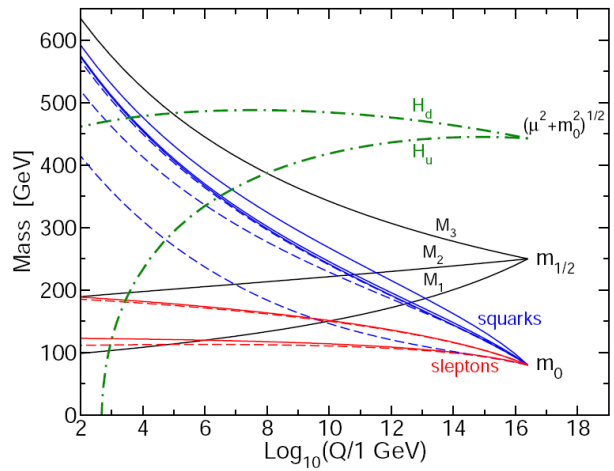
Minimal field content with two Higgs doublets

R–parity = +1			R–parity = –1			R–parity = –1		
Particle	Symbol	Spin	Particle	Symbol	Spin	Particle	Symbol	Spin
Lepton	ℓ	$\frac{1}{2}$	Slepton	$\tilde{\ell}_L, \tilde{\ell}_R$	0			
Neutrino	ν	$\frac{1}{2}$	Sneutrino	$\tilde{\nu}$	0			
Quark	q	$\frac{1}{2}$	Squark	$\tilde{q}_L, \tilde{q}_R$	0			
Gluon	g	1	Gluino	$\tilde{g}$	$\frac{1}{2}$			
Photon	γ	1	Photino	$\tilde{\gamma}$	$\frac{1}{2}$			
Z Boson	Z	1	Zino	$\tilde{Z}$	$\frac{1}{2}$			
W Boson	$W^{\pm}$	1	Wino	$\tilde{W}^{\pm}$	$\frac{1}{2}$	Neutralino	$\tilde{\chi}_i^0$	$\frac{1}{2}$
Higgs	$H^0, H^{\pm}$	0	Higgsino	$\tilde{H}_1^0, \tilde{H}_2^+$	$\frac{1}{2}$	Chargino	$\tilde{\chi}_i^{\pm}$	$\frac{1}{2}$
	h^0, A^0	0		$\tilde{H}_1^-, \tilde{H}_2^0$	$\frac{1}{2}$			

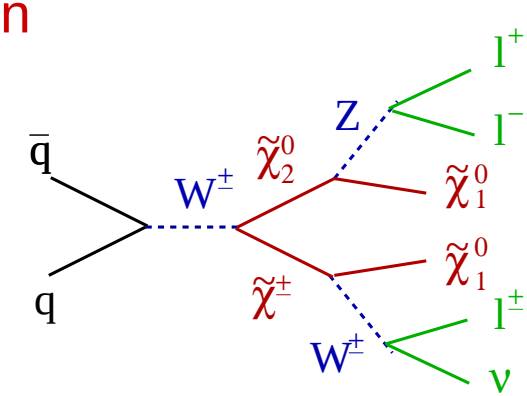
- More than 100 parameters in the MSSM
  - ▲ Can be reduced with reasonable assumptions (unification at GUT scale,...)
- R–parity: R = $(-1)^{3(B-L)+2S}$
  - ▲ If R–parity conserved $\Rightarrow$ Lightest supersymmetric particle is stable

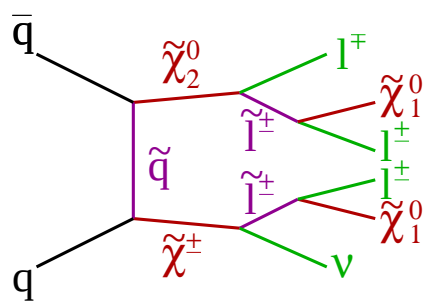
mSUGRA

- One of the most considered models for SUSY searches is mSUGRA
  - ▲ mSUGRA characterized by five parameters
    - ▶ Common scalar mass at GUT scale: m_0
    - ▶ Common Gaugino mass at GUT scale: $m_{1/2}$
    - ▶ Common trilinear coupling at GUT scale: A_0
    - ▶ Ratio of VEV of the neutral Higgs fields: $\tan\beta$
    - ▶ Sign of Higgs mass parameter: sign(μ)
  - ▲ R–parity conservation $\Rightarrow$ stable LSP (Neutralino)



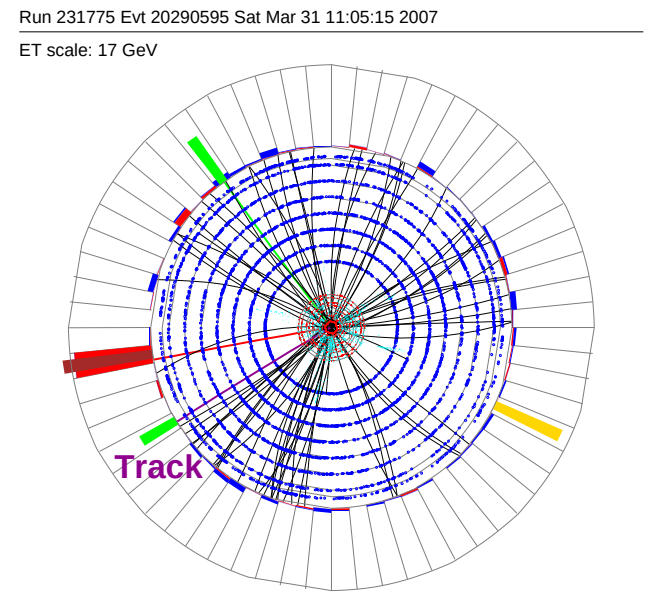
- Main search channels at the Tevatron
  - ▲ Charginos and Neutralinos
    - ▶ Three charged leptons + $\not{E}_T$
  - ▲ Squarks and Gluinos
    (not covered in this talk)
    - ▶ 2–4 jets + $\not{E}_T$
  - ▲ Stop and Sbottom

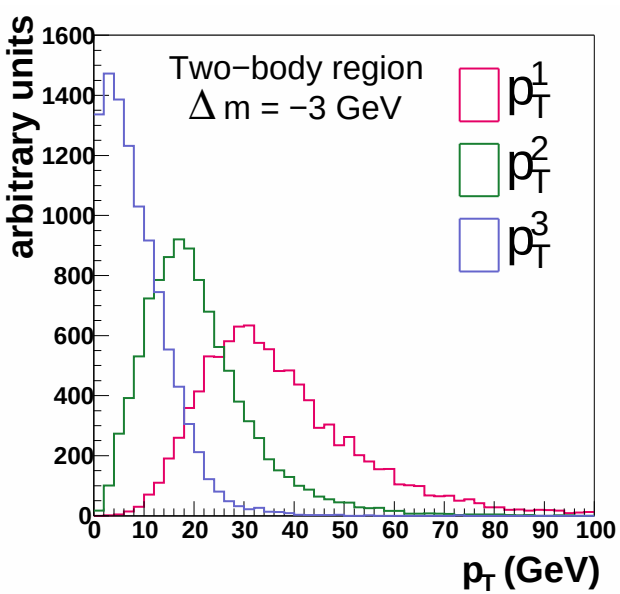




Search for Charginos and Neutralinos

- Trilepton channel is the “golden mode” for Chargino/Neutralino search
  - ▲ Signature: three charged leptons plus missing transverse energy
- Challenges
  - ▲ Leptons have low transverse momenta
  - ▲ Small cross sections: $\sigma \times$BR < 0.5 pb



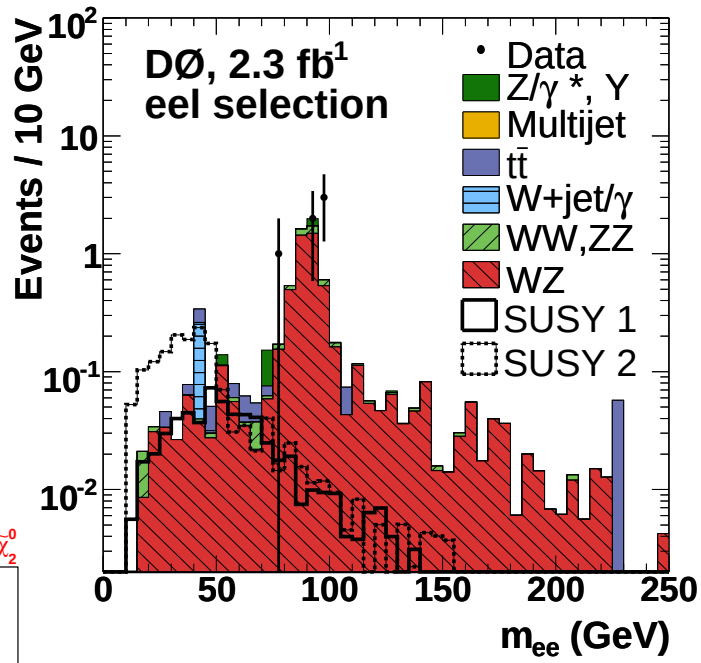


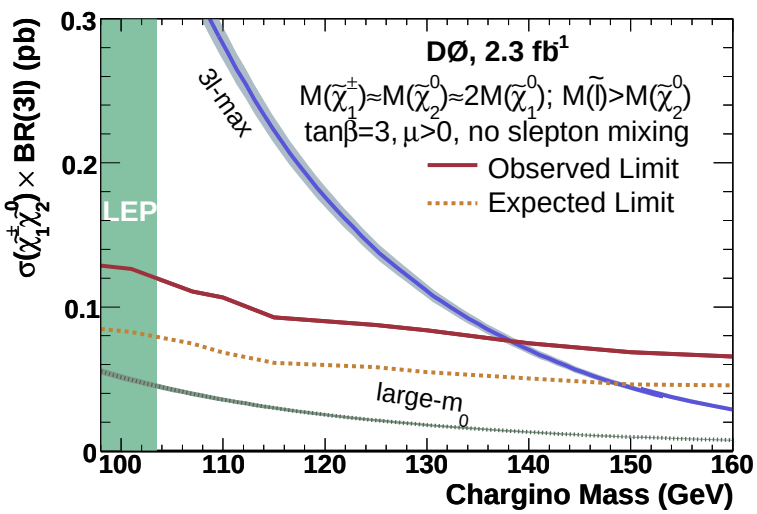
- Selection strategy
  - ▲ Two identified leptons + track
    - ► High efficiency, sensitive to all flavors
  - ▲ Require $\not\!\!E_T$ to account for LSP’s and ν’s
- DØ: Five different final states arXiv:09010646v1
  - ▲ $ee + \ell$, $\mu\mu + \ell$, $e\mu + \ell$, $\mu\tau + \ell$, $\mu\tau + \tau$
- CDF: Several final states PRL 101, 251801 (2008)
  - ▲ Three identified leptons (e, μ) or two leptons (e, μ) plus track

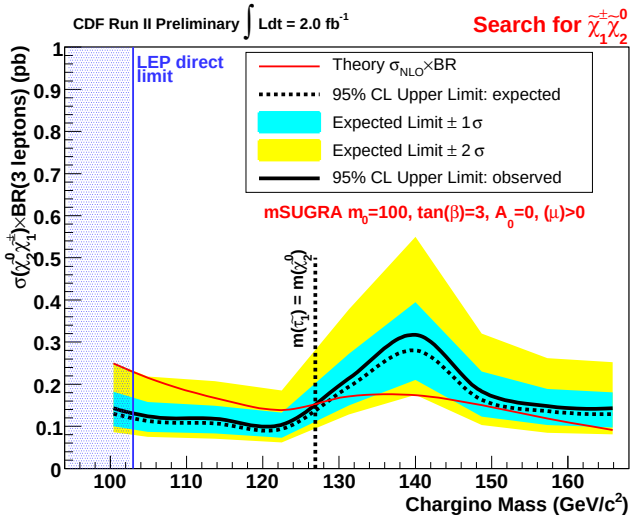
Trilepton Results

DØ $\int \mathcal{L}dt$ = 2.3 fb^{-1}	Background	Data	CDF $\int \mathcal{L}dt$ = 2.0 fb^{-1}	Background	Data
low p_T	5.4±0.6	9	Trilepton	0.88±0.14	1
high p_T	3.3±0.4	4	Lepton+track	5.5±1.1	6

- Main background: Diboson production (WZ, WW)
- Other contributions: Drell Yan, W→ $\ell\nu$, $t\bar{t}$





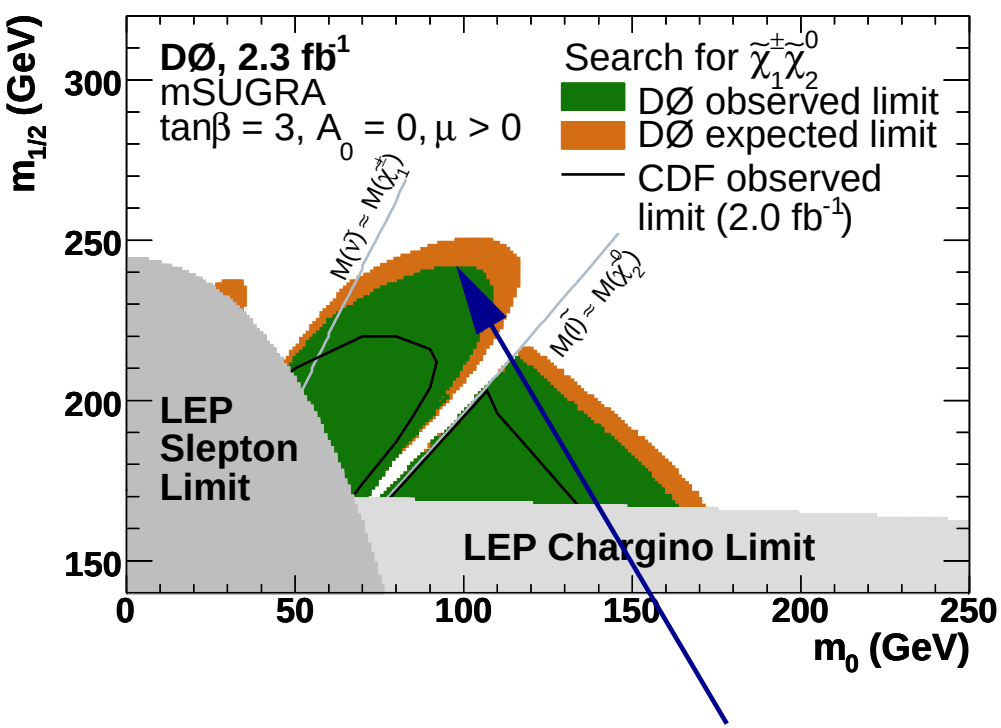


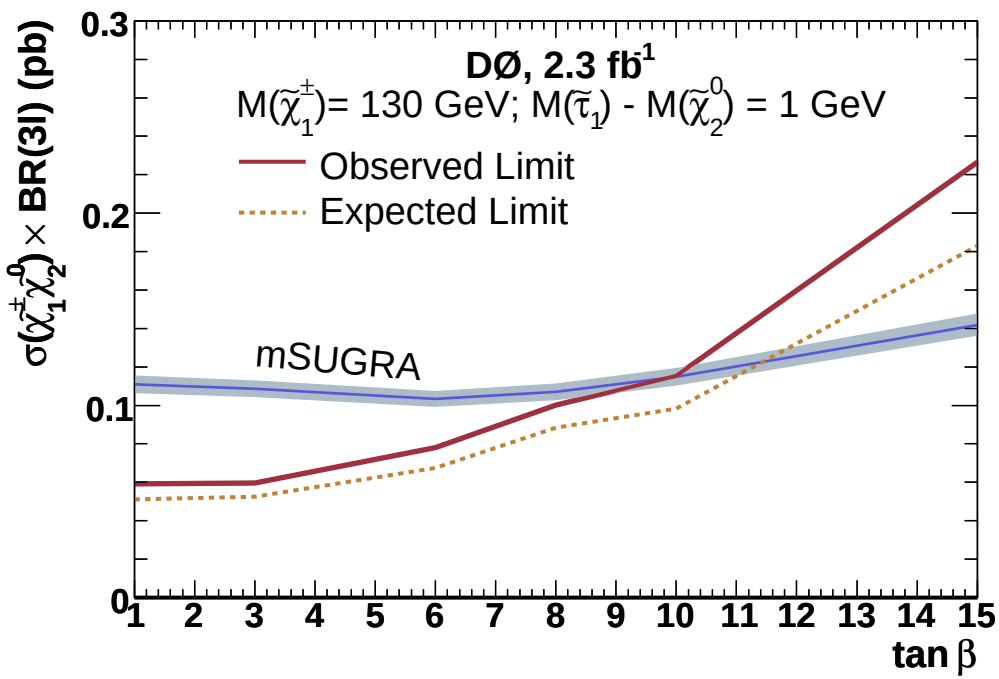
- Chargino mass limits (CDF)
  - ▲ $m_{\tilde{\chi}_1^\pm} > 145$ GeV (m_0 = 60 GeV)
  - ▲ $m_{\tilde{\chi}_1^\pm} > 127$ GeV (m_0 = 100 GeV)

- Chargino mass limits (DØ)
  - ▲ $m_{\tilde{\chi}_1^\pm} > 138$ (145) GeV ("3ℓ–max": $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx 2m_{\tilde{\chi}_1^0}$)

Trilepton Results (2)

- Extend limits in m_0–$m_{1/2}$ plane and for different $\tan\beta$



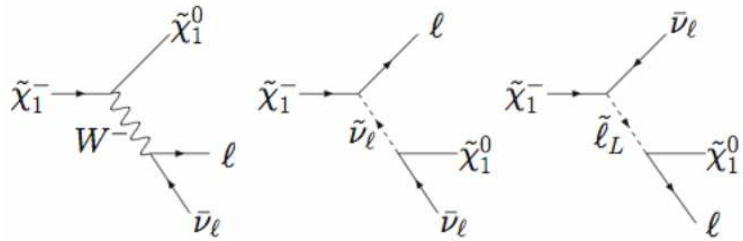


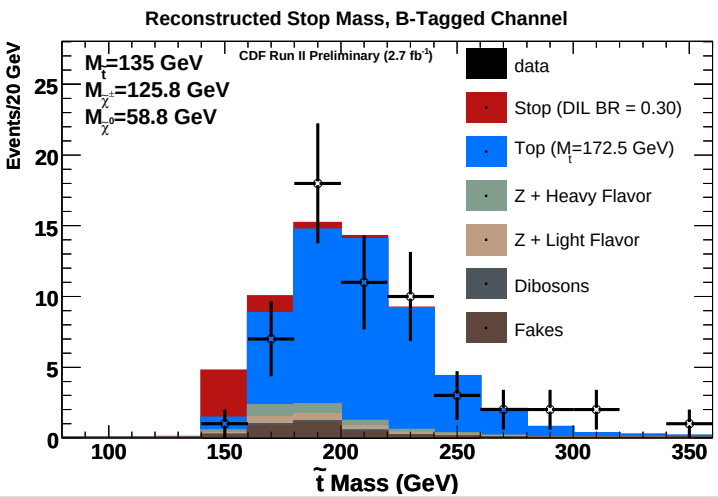
- Exclude Charginos with masses up to 167 GeV
- Probe Charginos masses up to 178 GeV
- Can exclude Charginos of 130 GeV up to $\tan\beta$ = 9.6

Search for $\tilde{t}_1\tilde{t}_1 \to b\bar{b}\ell\ell'\tilde{\chi}_1^0\tilde{\chi}_1^0\nu\bar{\nu}$

- Kinematic assumptions
  - $m_{\tilde{t}_1} < m_t$: 115 GeV $< m_{\tilde{t}_1} <$ 185 GeV
  - $m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}_1} - m_b$: 106 GeV $< m_{\tilde{\chi}_1^\pm} <$ 126 GeV
  - $\tilde{\chi}_1^0$ is LSP: 44 GeV $< m_{\tilde{\chi}_1^0} <$ 89 GeV

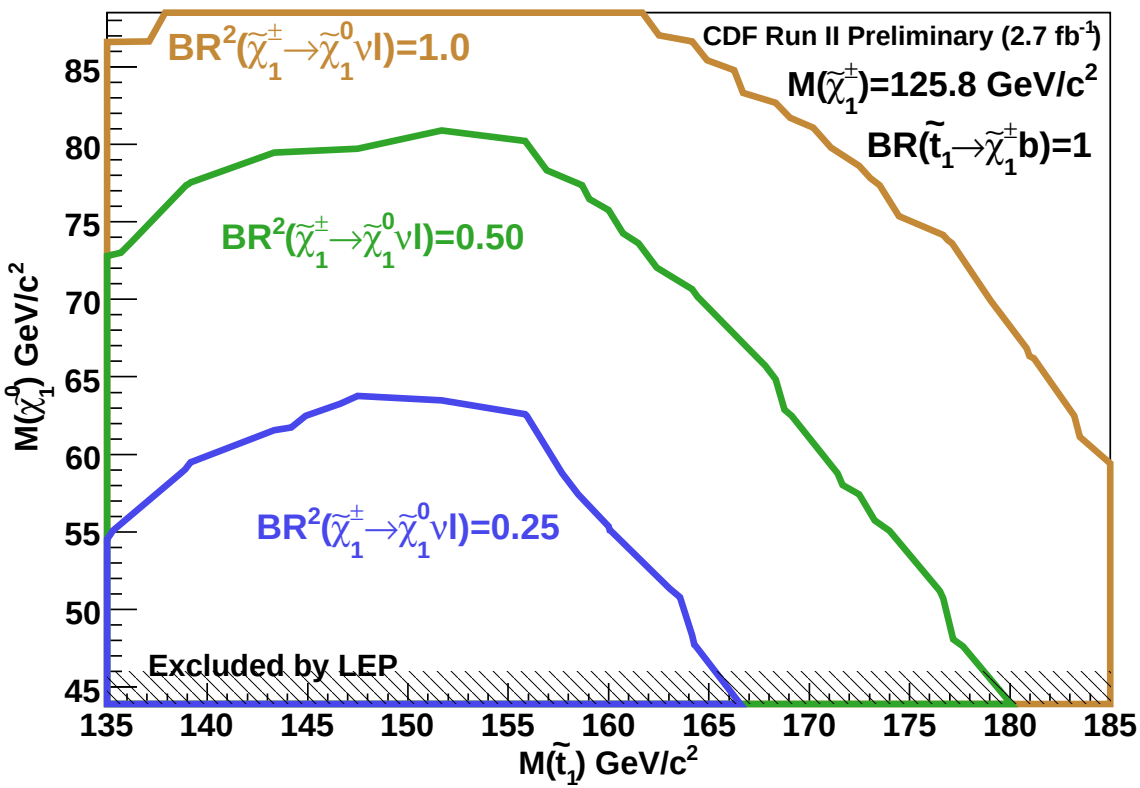
Decay of $\tilde{\chi}_1^\pm$ from $\tilde{t}_1 \to \tilde{\chi}_1^\pm b$ decay





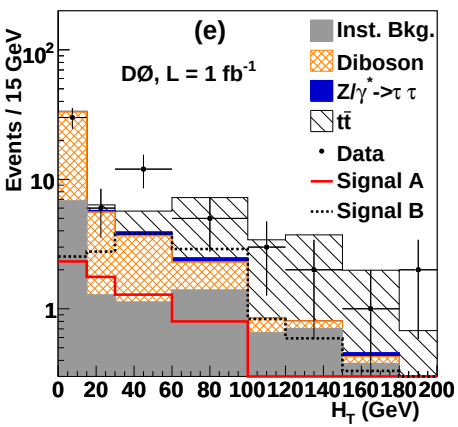
	ee	$\mu\mu$	$e\mu$	Sum
Signal	1.1	1.4	3.0	5.5
Background	14.2	12.4	29.4	56.0
Data	15	12	30	57

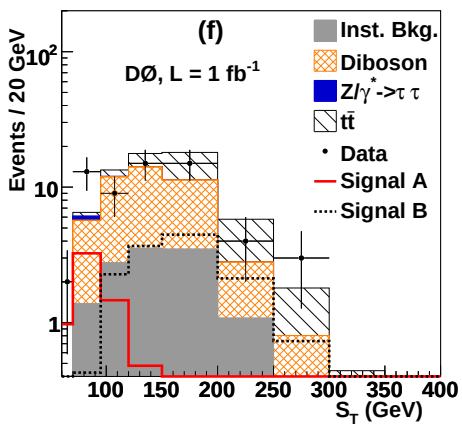
Observed 95% CL



Search for $\tilde{t}_1\tilde{t}_1 \to b\bar{b}\ell\ell'\tilde{\chi}_1^0\tilde{\chi}_1^0\nu\bar{\nu}$ (2)

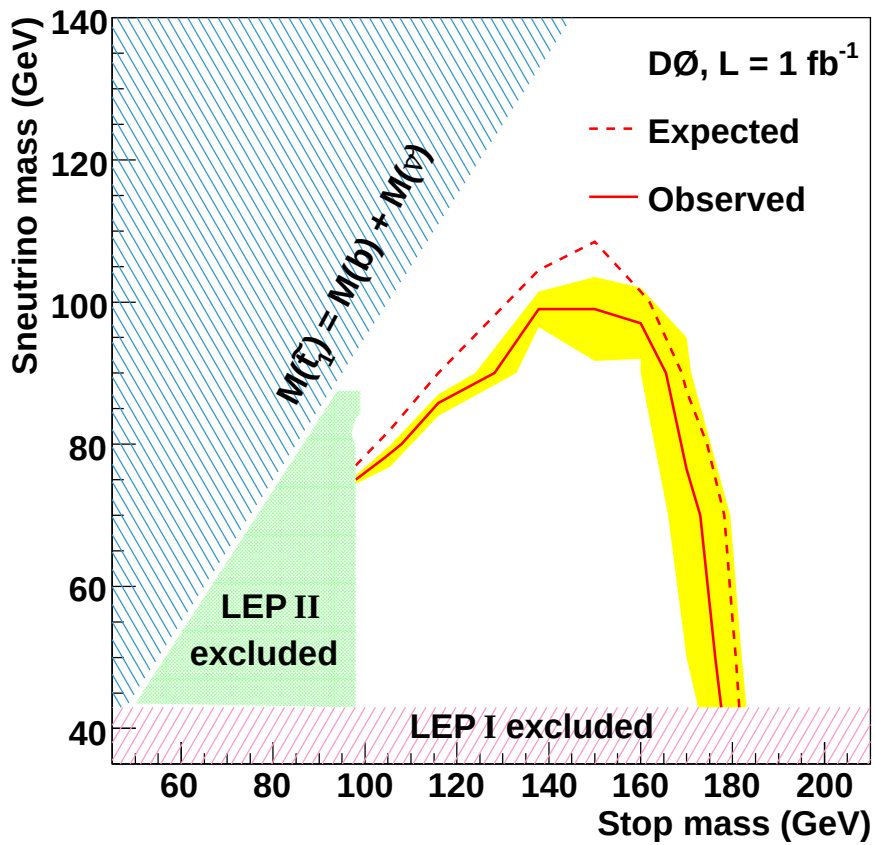
- Use topological variables to discriminate signal from background
  - H_T: scalar sum of jet transverse momenta
  - S_T: scalar sum of lepton transverse momenta and $\not{E}_T$





H_T (GeV)	S_T (GeV) 0–70 Bkg	0–70 Data	70–120 Bkg	70–120 Data	>120 Bkg	>120 Data
0–15	0.3	1	13	15	19	12
15–60	0.09	1	4.2	6	8	11
60–120	0.06	0	1.6	1	9	8
>120	0.01	0	0.9	0	7	6

arXiv.org:0811.0459

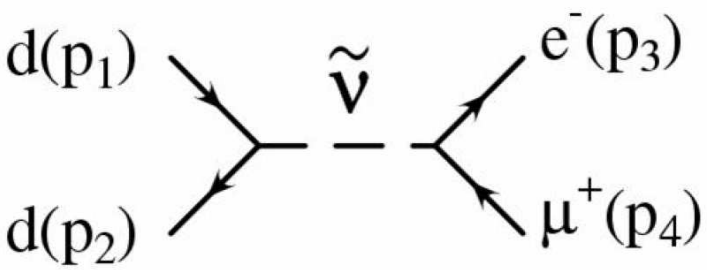


Search for Sneutrino Resonances

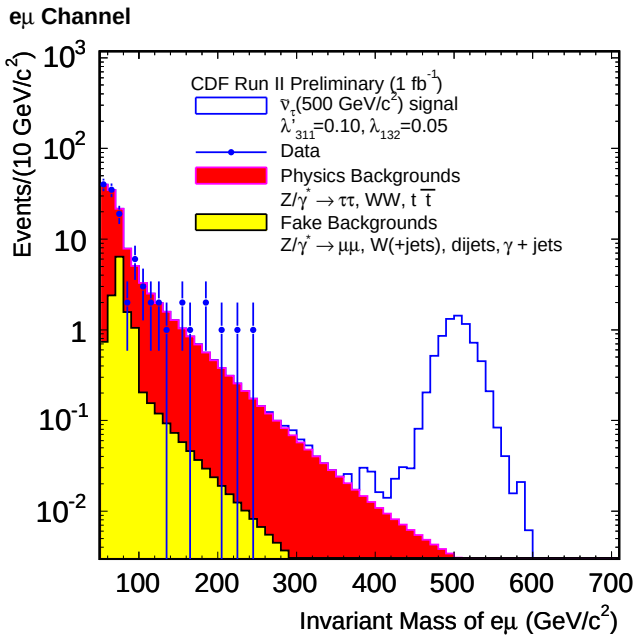
- Consider R parity violating model with superpotential

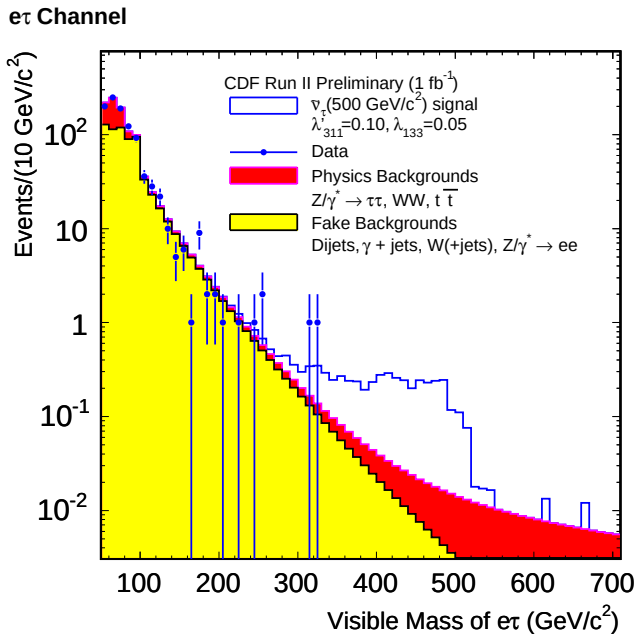
$$W = \frac{1}{2}\varepsilon_{ab}\lambda_{ijk}\hat{L}_i^a\hat{L}_j^b\hat{E}_k + \varepsilon_{ab}\lambda'_{ijk}\hat{L}_i^a\hat{Q}_j^b\hat{D}_k + \frac{1}{2}\varepsilon_{\alpha\beta\gamma}\lambda''_{ijk}\hat{U}_i^\alpha\hat{D}_j^\beta\hat{D}_k^\gamma + \varepsilon_{ab}\delta_i\hat{L}_i^a\hat{H}_2^b$$

- All RPV couplings other than λ'_{311} and $\lambda_{321} = \lambda_{312}$ are set to zero



- CDF $\int \mathcal{L}dt$ = 1 fb^{-1}
  - ▲ Search in $e\mu$, $e\tau$ and $\mu\tau$ final states
- Use invariant mass ($e\mu$) or visible mass ($e\tau$, $\mu\tau$) to extract limits

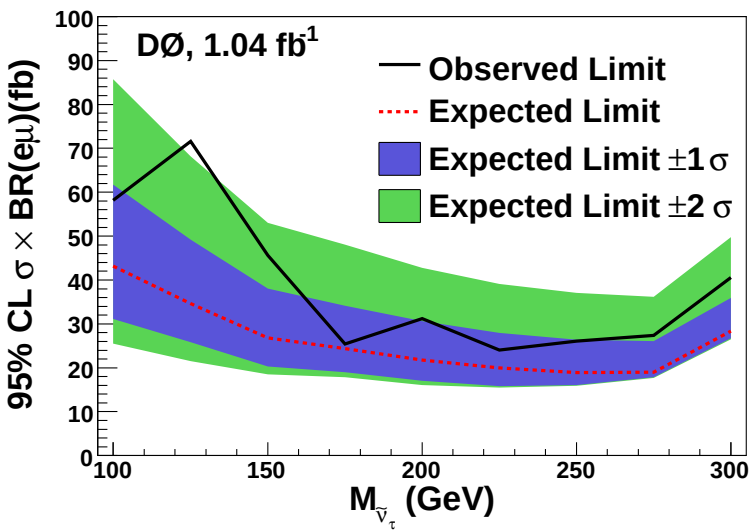


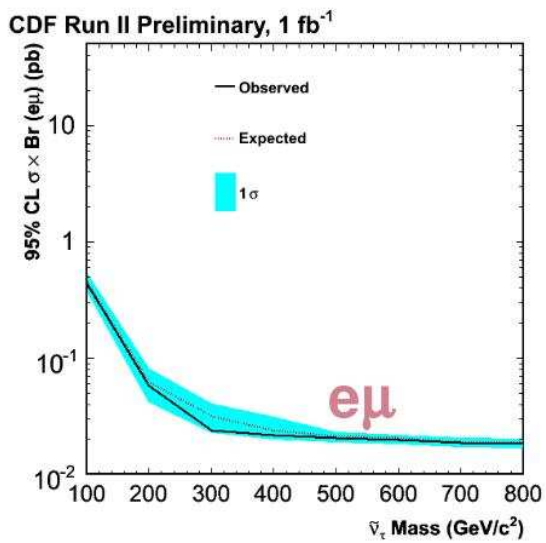


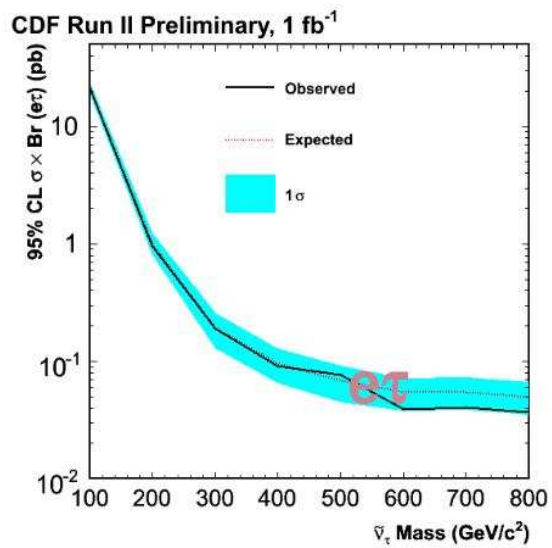
Search for Sneutrino Resonances (2)

PRL 100, 241803 (2008) DØ	$e+\mu$
Background	59.2
Data	68

CDF	$e+\mu$	$e+\tau$	$\mu+\tau$
$m_{e\mu}, m_{vis}$	$>$ 500 GeV	$>$ 310 GeV	$>$ 280 GeV
Background	0.1	1.4	1.0
Data	0	2	2



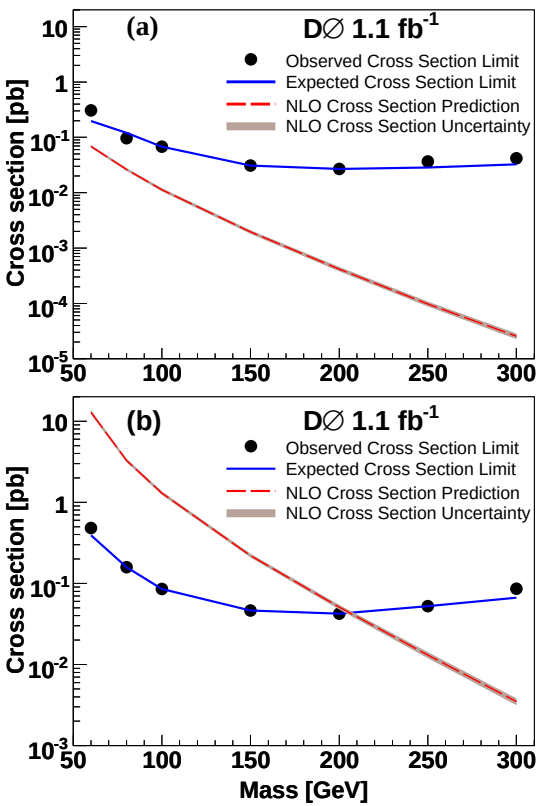




- Cross section limits
  - ▲ Exclude $\sigma\times$BR in the range of 10^{-2} to 10^{-1} pb

Search for CHAMPS

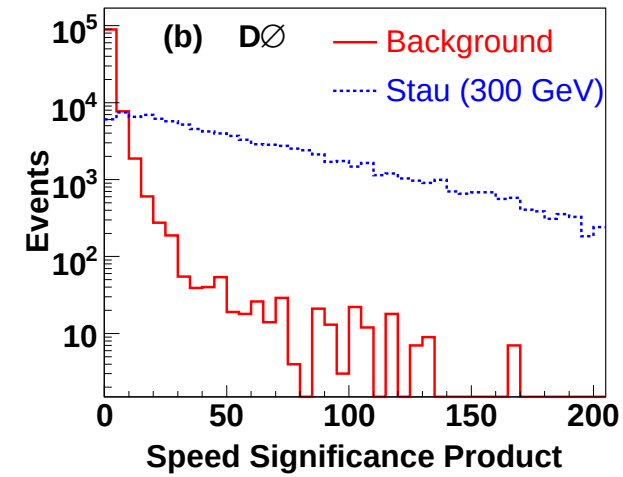
- Search for Charged Massive Stable Particles
  - Pair produced staus or charginos
    - Signature in the detector: “slow muons”
    - Use time-of-flight information and invariant mass to distinguish signal and background



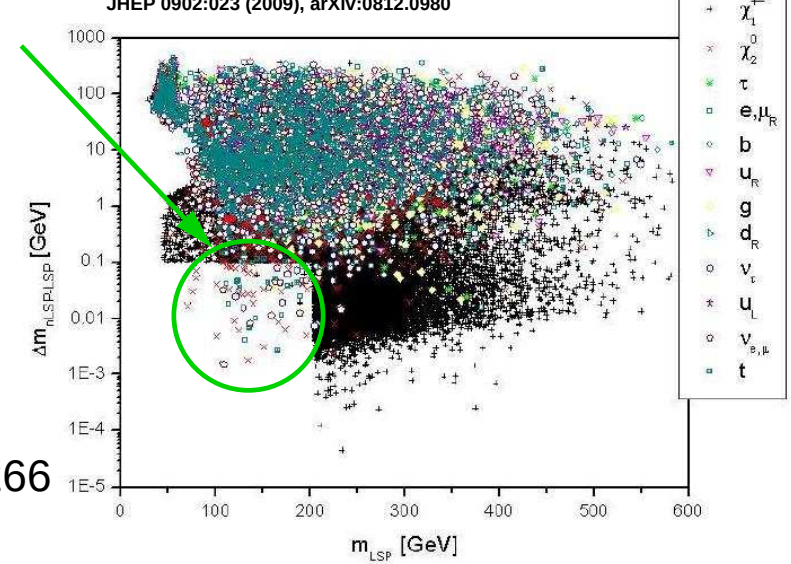
arXiv:0809.4472

Chargino mass limits	
Gaugino–like	206 GeV
Higgsino–like	171 GeV

- CHAMP search can ex–clude a larger fraction of models in the pMSSM



C. F. Berger, J. S. Gainer, J. L. Hewett, T. G. Rizzo
JHEP 0902:023 (2009), arXiv:0812.0980

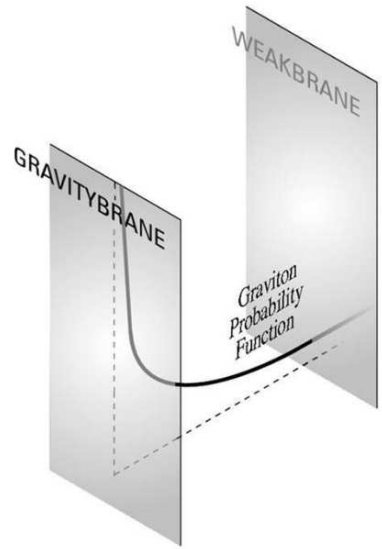


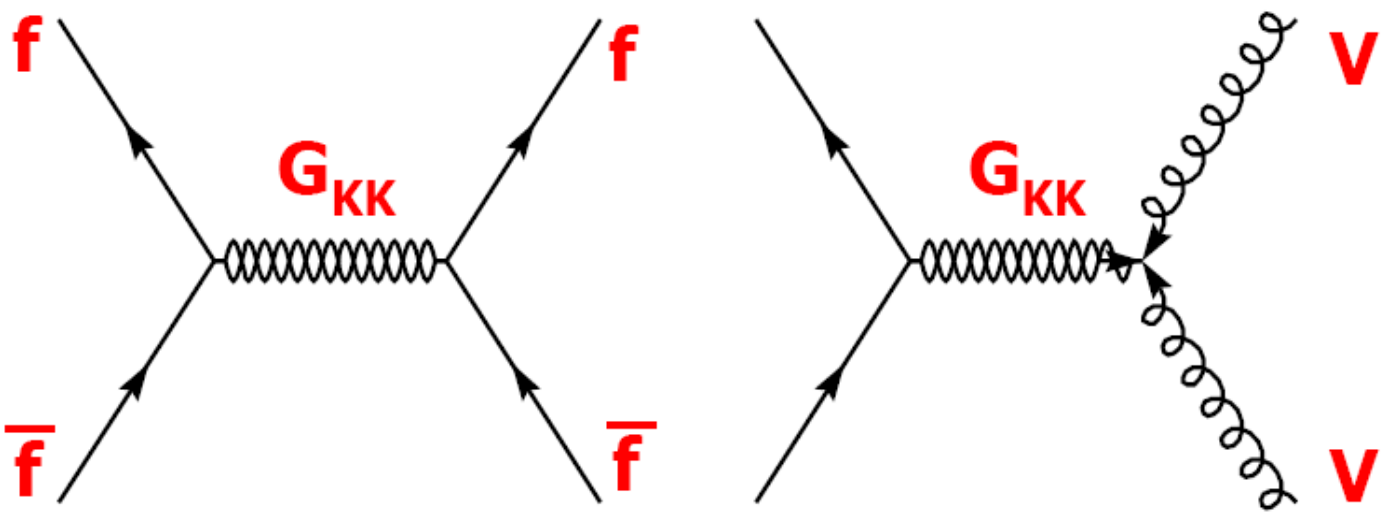
CDF CHAMP search: arXiv:0902.1266

- $m_{\tilde{t}} > 250$ GeV
- $\sigma < 48$ fb (10 fb) for strongly (weakly) interacting CHAMP

Extra Dimensions

- Extra dimension models come in various flavors
  - ▲ Large extra dimension, universal extra dimensions,...
  - ▲ Today: only Randall Sundrum model
    - ► Only one additional dimension
    - ► Weak scale generated from large scale through expo–nential hierarchy
    - ► Exponential hierarchy arises from background metric
  - ▲ Excitations lead to heavy gravitons
  - ▲ Can decay into pair of fermions or bosons





Additional Gauge Bosons

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  - ▲ Large extra dimension, universal extra dimensions,...
  - ▲ Today: only Randall Sundrum model
    - ▶ Only one additional dimension
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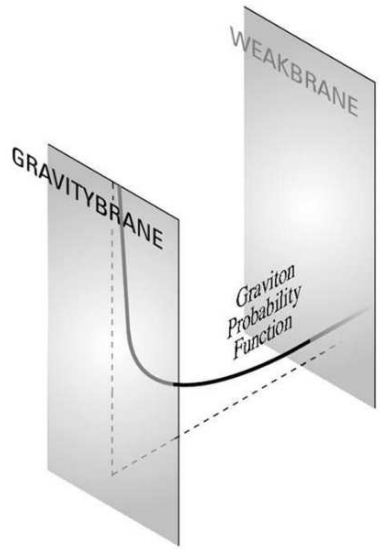
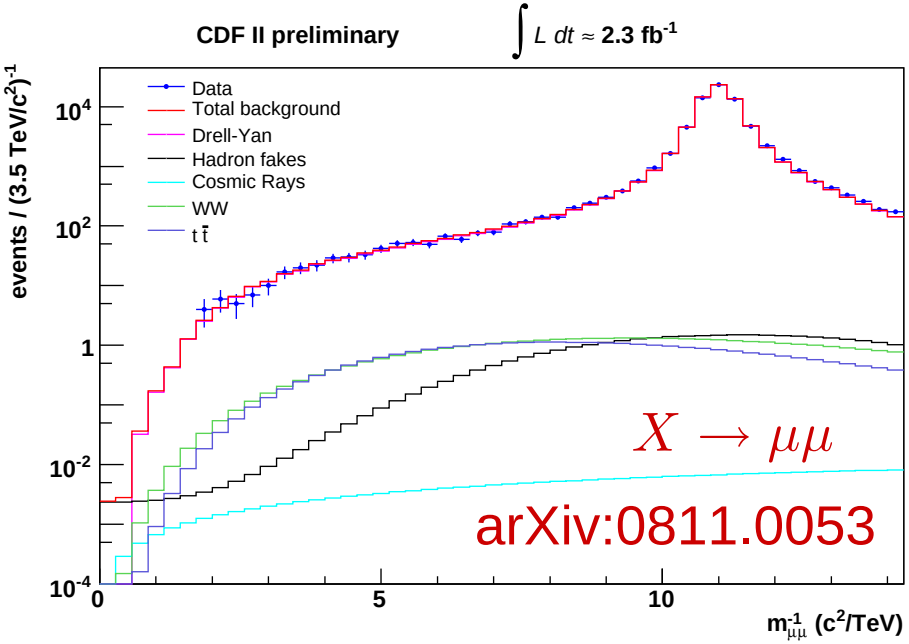
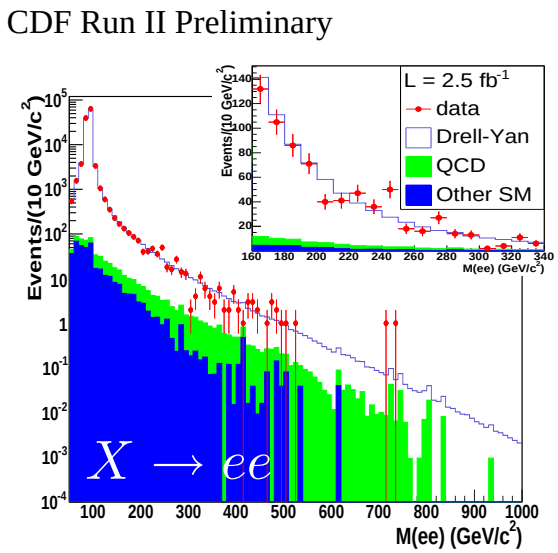


- Embed SM gauge group in larger groups: SU(5), SO(10), E_6,...
  - ▲ U(1) gauge groups can survive to reasonable low energies
    $\Rightarrow$ Additional neutral gauge vector bosons: Z'
- Other models also predict new heavy gauge bosons
  - ▲ Left–right symmetric models: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  - ▲ Little Higgs models

Search for High Mass Resonances

- High mass resonance in dilepton final state
  - Spin 0: Sneutrino $\tilde{\nu}$
  - Spin 1: Heavy gauge boson Z'
  - Spin 2: RS graviton G^*
- Search for deviations from SM prediction at high invariant dilepton mass





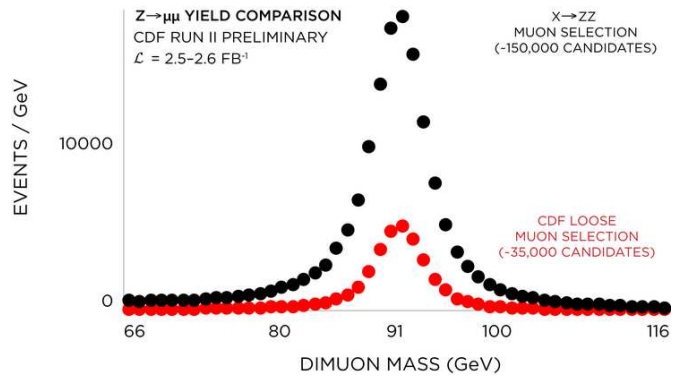
PRL 102, 031801 (2009)

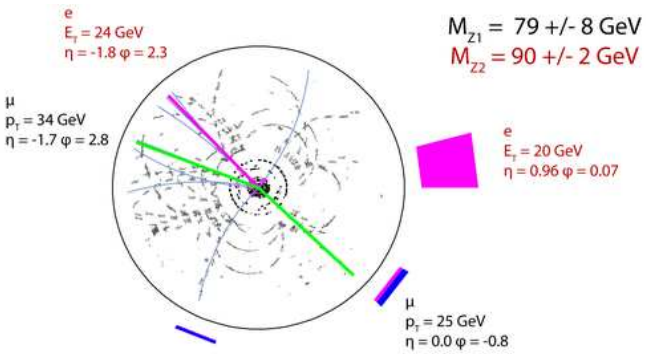
Mass limits in GeV			
		ee	$\mu\mu$
$\tilde{\nu}$	$\lambda^2 \cdot BR = 0.01$		810
Z'	SM like	966	1030
G^*	$k/M_{Pl} = 0.1$	850	921
2.5σ excess at m_{ee} = 240 GeV			

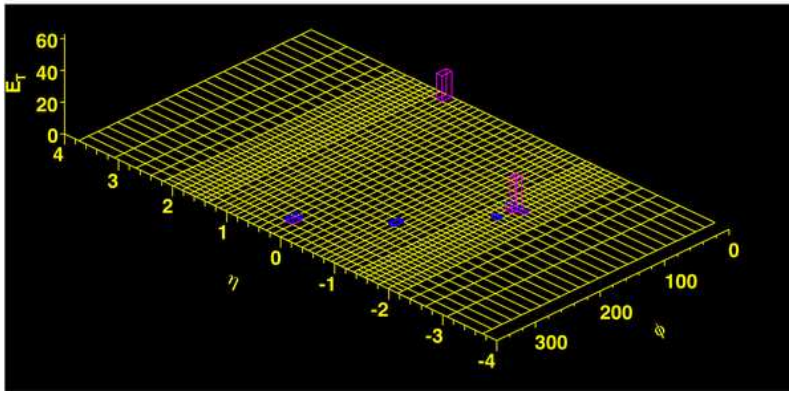
- DØ search for W' with $\int \mathcal{L}dt$ = 1 fb^{-1}: $m_{W'} >$ 1000 GeV

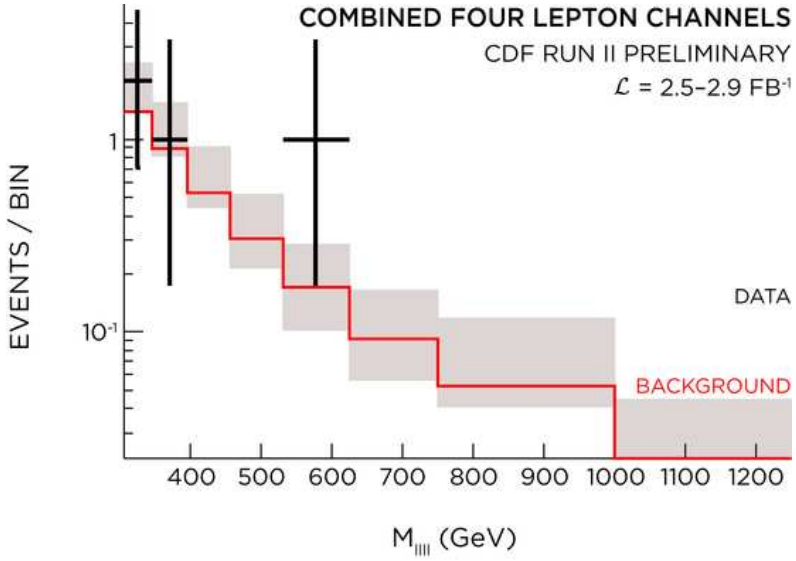
Search for High Mass Resonances (2)

- High mass resonance can also decay in pair of Z bosons
  - ▲ Intermediate mass region: $eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$
  - ▲ High mass region: $eejj$, $\mu\mu jj$
- Loosen lepton requirements to increase acceptance









Mass limit in RS model with $k/M_{Pl} = 0.1$

$M_{G^*} > 491$ GeV

Conclusion

- Summary
  - ▲ Tevatron, CDF and DØ are performing well
    - ▶ Already collected more than 5 fb^{-1} of data
    - ▶ Nearly factor two and more of data than used in results presented here
  - ▲ Searches probing new regions so far not accessible
    - ▶ New limits well beyond previous results
- Tevatron will continue to search for new physics in so far uncovered territory

- For more information please refer to

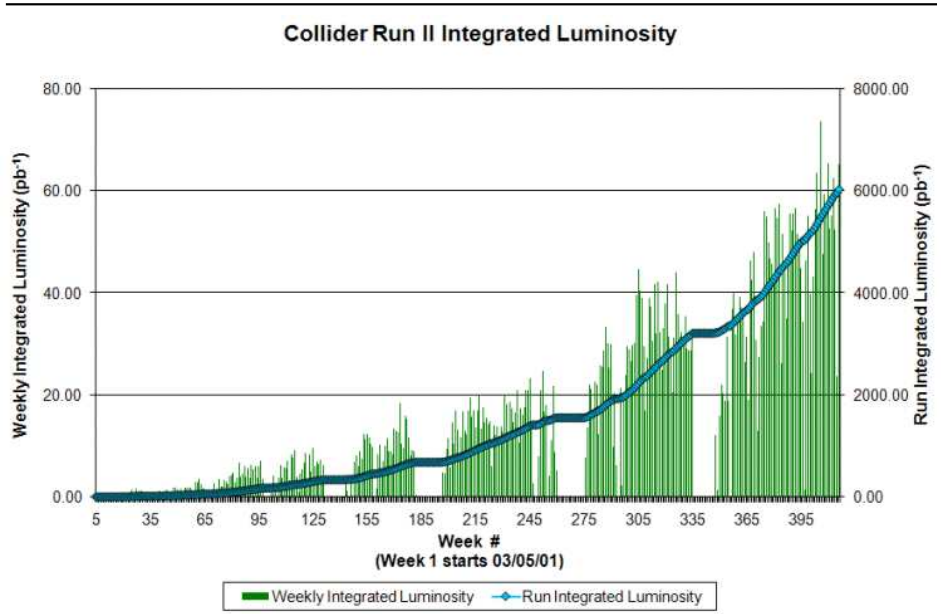
CDF `http://www-cdf.fnal.gov/physics/exotic/exotic.html`
DØ `http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm`

BACKUP SLIDES

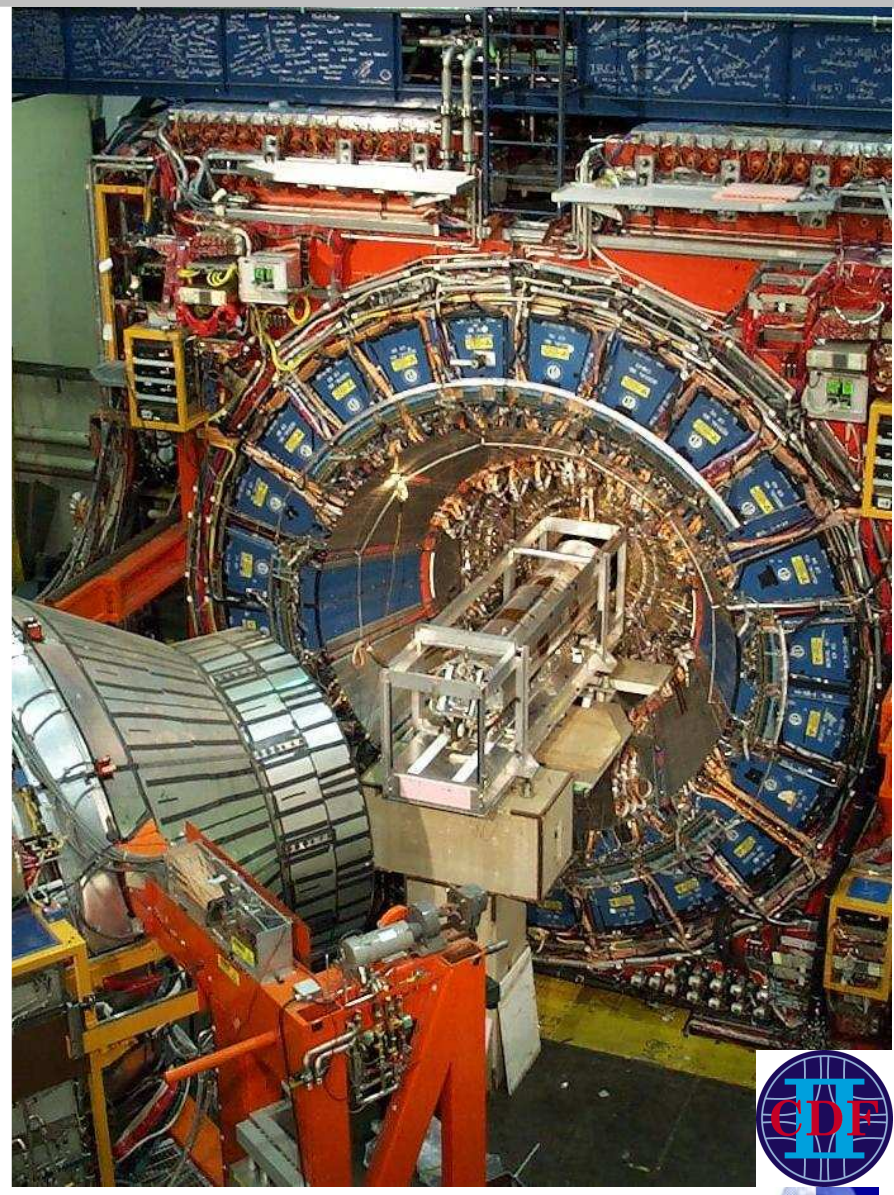
Tevatron

- $p\bar{p}$ collisions at center of mass energy of $\sqrt{s}$ = 1.96 TeV

	Run I	Run IIa	Run IIb
$\sqrt{s}$ (TeV)	1.8	1.96	1.96
Bunches	6×6	36×36	36×36
Bunch spacing (ns)	3500	396	396
Luminosity ($cm^{-2}s^{-1}$)	$1.6 \cdot 10^{30}$	$9 \cdot 10^{31}$	$3 \cdot 10^{32}$

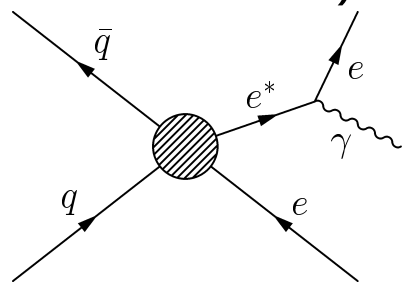


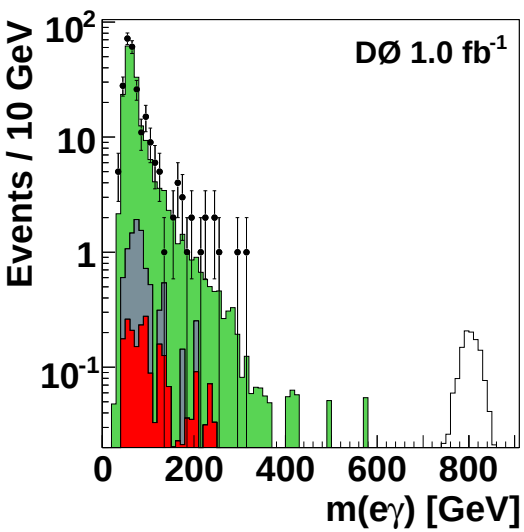
The Detectors (cont'd)

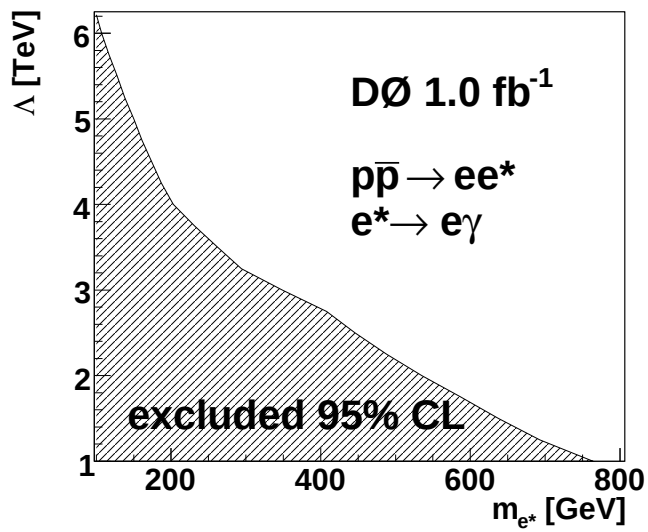


Excited Electrons

- Quarks and leptons could have a substructure PRD 77, 091102 (2008)
  (as so many other particles that once were believed to be fundamental)
  $\Rightarrow$ Excited states, eg e^*
  - ▲ Production and decay
    - ▶ Contact interaction with compositeness scale Λ
    - ▶ Decay via CI or gauge interection (eg $e^* \rightarrow e\gamma$)







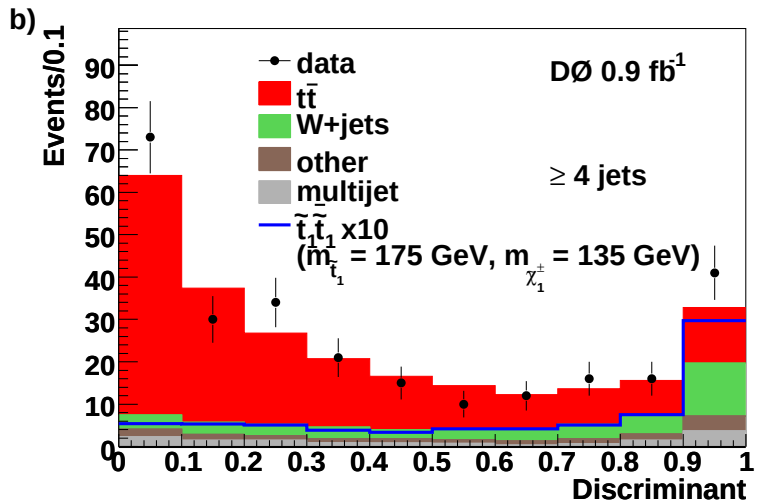
	Bkg	Data
Total	239	259
m_{e^*} = 200 GeV	0.52	1
m_{e^*} = 500 GeV	0.12	0
m_{e^*} = 1000 GeV	$0.17 \cdot 10^{-3}$	0

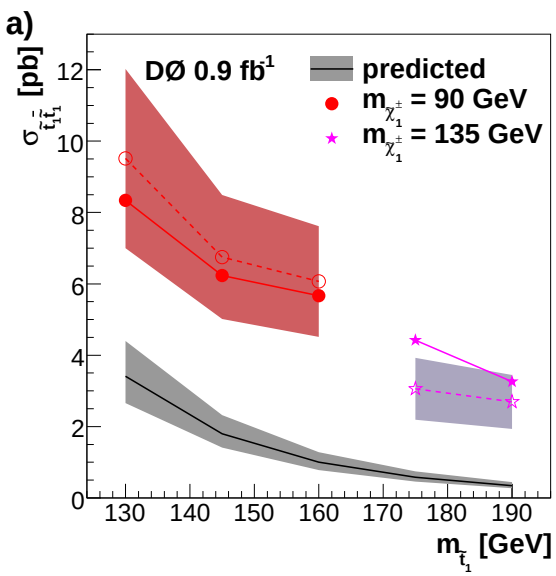
- Exclude excited electrons with masses below m_{e^*} = 756 GeV for Λ = 1 TeV
- Neglecting CI $\Rightarrow m_{e^*} > 989$ GeV

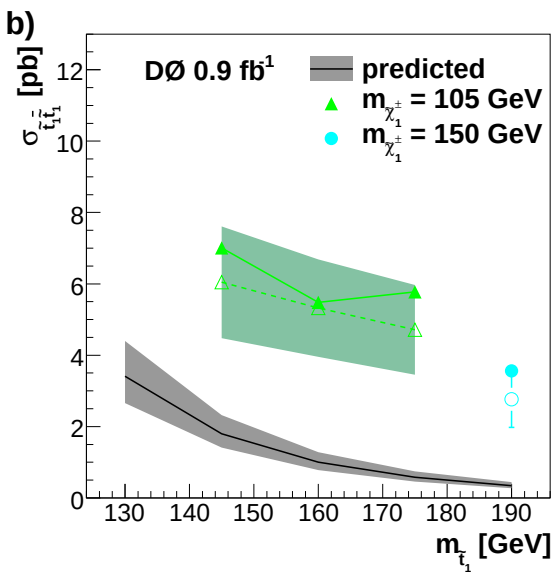
Search for Stops in Lepton+Jets

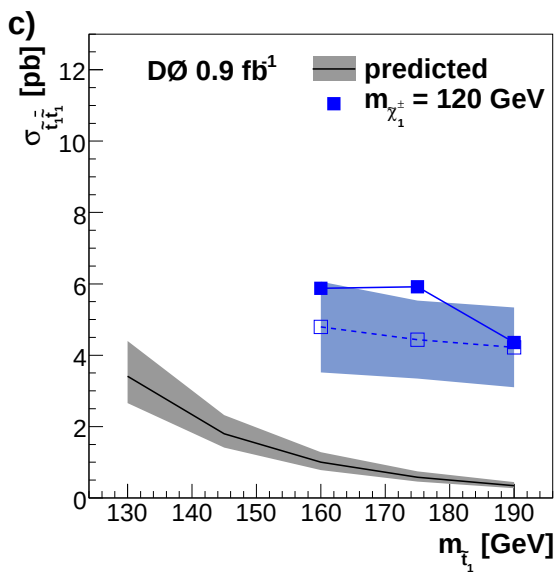
- Use $t\bar{t}$ selection in lepton+jets channel to search for stop quarks arXiv:0901.1063
- To discriminate $t\bar{t}$ from stop signal build Likeli–hood discriminant

	= 3 jets		$\geq$ 4 jets	
	e+jets	μ+jets	e+jets	μ+jets
Signal	3.2	2.2	2.9	2.1
Background	186.2	157.2	138.1	116.0
Data	193	163	133	135







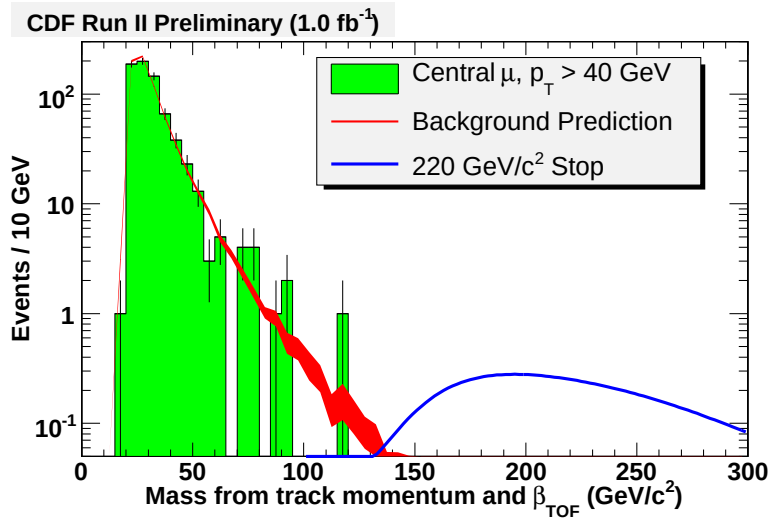


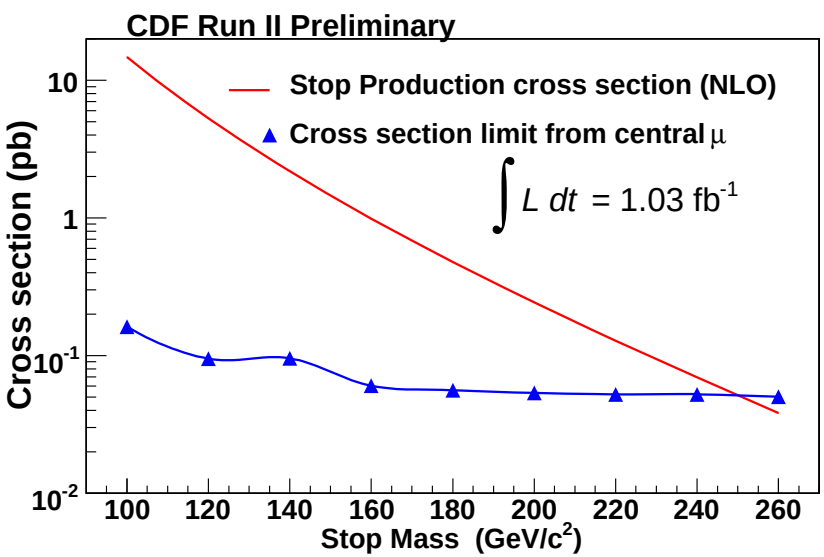
Search for CHAMPS (2)

- Search for long lived Charged Massive Particles

arXiv:0902.1266

  - ▲ Long lifetime, does not decay in detector
  - ▲ Highly ionizing and penetrating
- Signature in the detector: "slow muon"
  - ▲ Use time–of–flight system to measure β of the particle
  - ▲ Measure momentum in the tracker
  - ▲ Combine β and momentum measure–ment to get mass of the particle





- Cross section limit can be interpreted in SUSY models with one compactified extra dimension
  - ▲ In these models Stop is the LSP
- Mass limit: $m_{\tilde{t}} > 250$ GeV

Multimuons

- Study of multimuons events with large impact parameter arXiv:0810.5357v2
  - Predict number of dimuon events in loose sample starting from tight sample
    - Tight sample: Hits in 2 innermost silicon layers + at least 2 additional hits
    - Loose sample: At least 3 silicon hits

$$N_{loose} = N_{tight} \cdot \frac{\varepsilon_{loose}}{\varepsilon_{tight}}$$

- Measurement
  - N_{tight} = 143743 events
    $\Rightarrow N_{loose}^{pred}$ = 518417 events
  - But N_{loose}^{obs} = 590970 events
    $\Rightarrow$ Excess of N = 72553 events
- These event are referred as "ghost events"
  - No explanation for total excess