

Searches for New Physics at the CDF experiment

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On behalf of the CDF collaboration

ASPEN WINTER PARTICLE PHYSICS CONFERENCE

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Tevatron and the CDF experiment

was

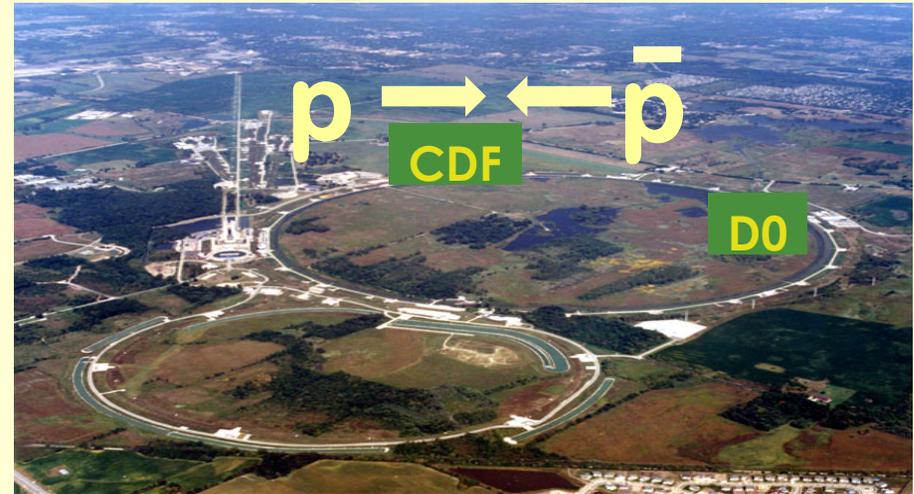
Highest-energy accelerator
currently operational
... but still doing great!

Proton-antiproton: $\sqrt{s} = 1.96 \text{ TeV}$

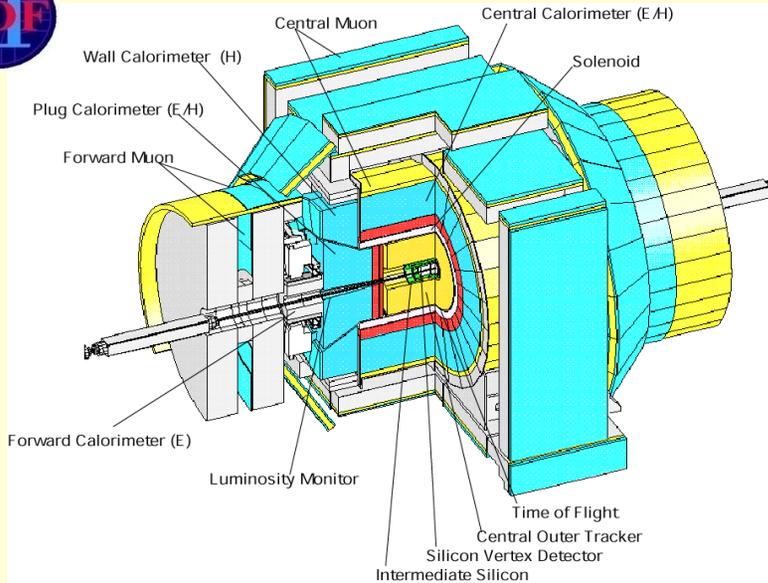
Peak luminosity $\rightarrow > 3.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

Integrated luminosity/week $\rightarrow \sim 70 \text{ pb}^{-1}$

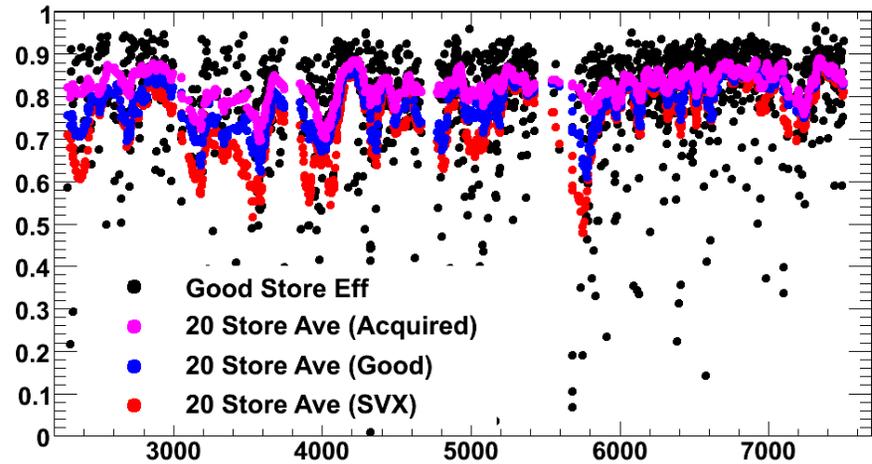
> 7 fb⁻¹ of data



~ 8 years of good data



Data Taking Efficiency



record: 85-90 % of delivered luminosity

Outline

- SUSY searches
 - chargino/neutralino
 - Squarks and gluinos
 - GMSB in diphoton final states
 - RPV SUSY (sneutrinos)

- Search for ExtraDimensions and new Gauge Bosons using resonances
 - DiBoson resonances
 - Dilepton resonances

- Searches for 4th generation quarks (B')

- Conclusions

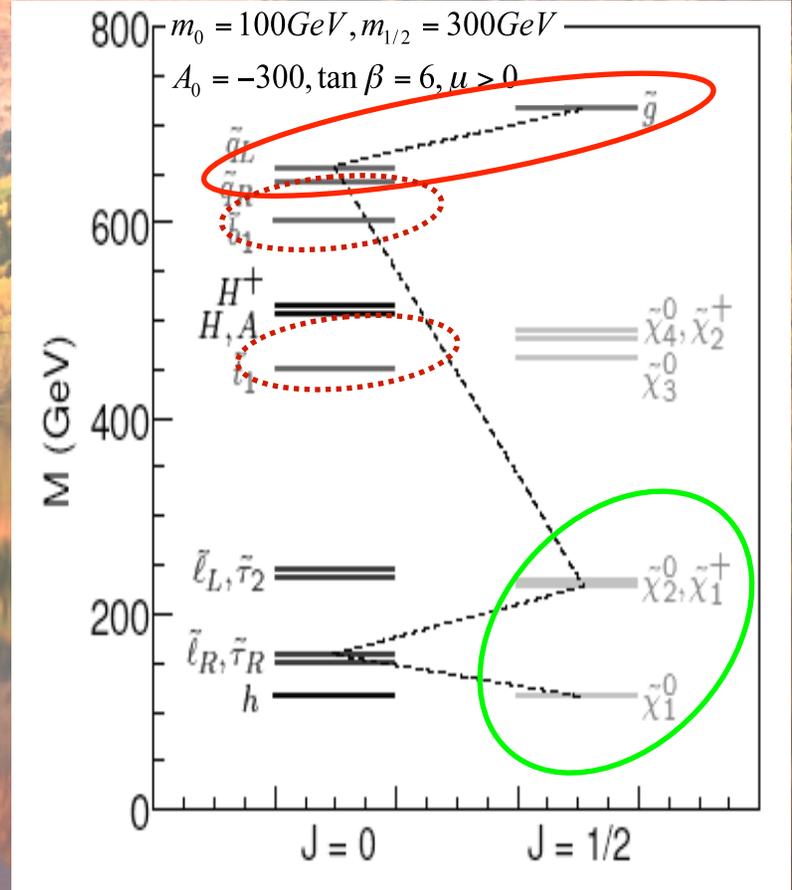
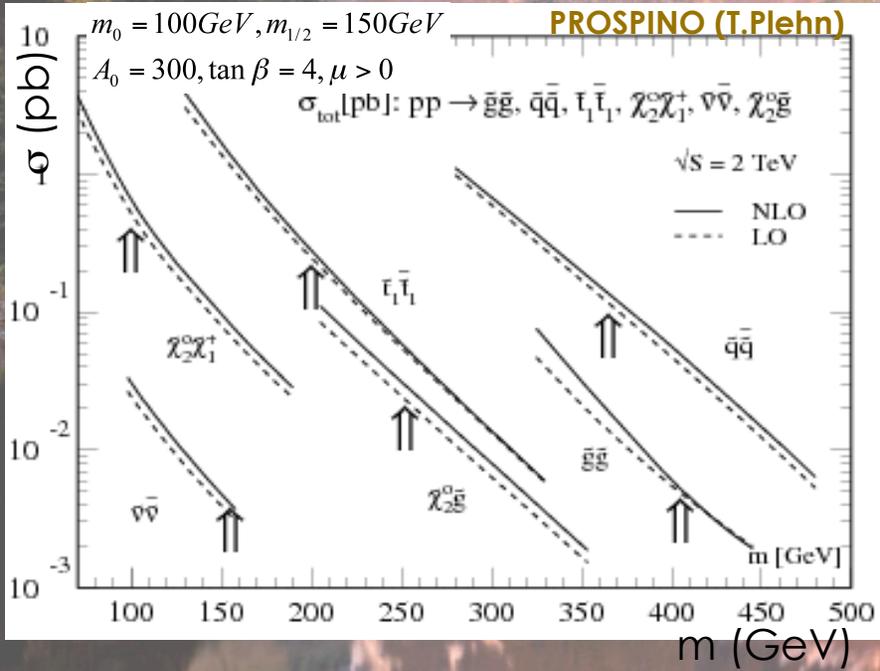


Not in this talk:

- Search for LeptoQuarks
- Signature-based searches
- Search for new physics in Top events (A.Ivanov's talk)
- New physics in B-flavor sector (S.Burdin's talk)
- BSM Higgs (A.Haas's talk)

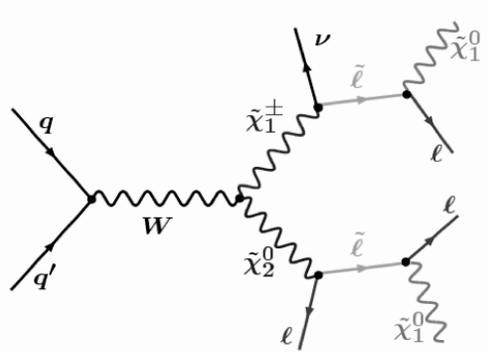
CDF: <http://www-cdf.fnal.gov/physics/exotic/exotic.html>

Supersymmetry



$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ production

“trileptons”



- Assume R_p conservation, $\tilde{\chi}_1^0$ is LSP
- Low cross sections ($\sigma \times Br < 0.5$ pb)
- Very clean signature:
 - Missing E_T due to undetected ν , $\tilde{\chi}_1^0$
 - 3 isolated leptons

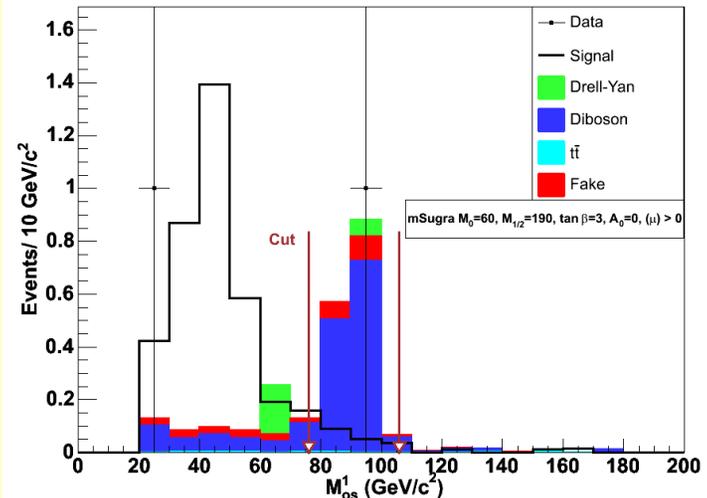


- 3 identified leptons (e, μ)
 - 2 identified leptons + track (l)
- 3.2 fb^{-1} • “Tight” and “loose” e, μ categories

Main backgrounds:

- WW, WZ, Drell-Yan, W+jets, $t\bar{t}$
- Rejection using kinematic selections on:
 M_{l+l-} , N jets, Missing E_T , $\Delta\phi$ between leptons...

Search for $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, CDF Run II Preliminary, 3.2 fb^{-1}



Results

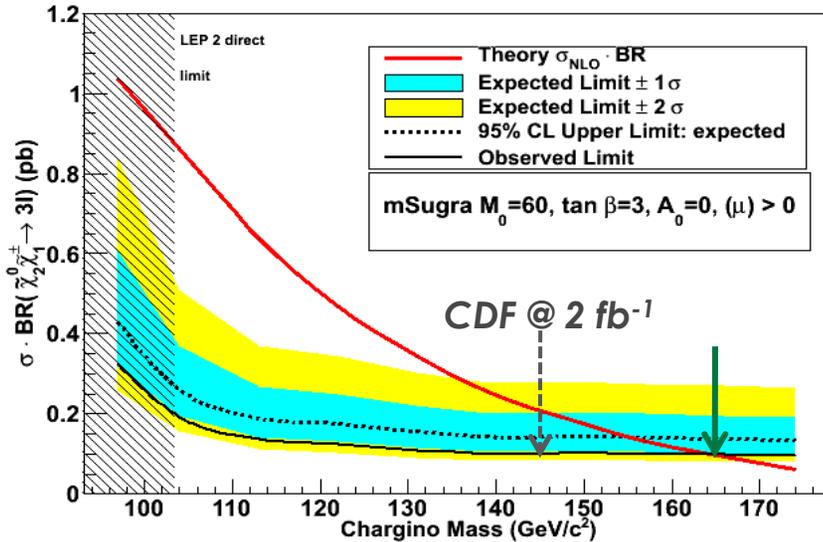
Good agreement between data and SM prediction → **set limit**

Channel	SM expected	Data
Trilepton	1.5 ± 0.2	1
Lepton+trk	9.4 ± 1.2	6

$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ results

$m_0 = 60 \text{ GeV}, \tan \beta=3, A_0=0, \mu>0$

CDF Run II Preliminary, 3.2 fb⁻¹

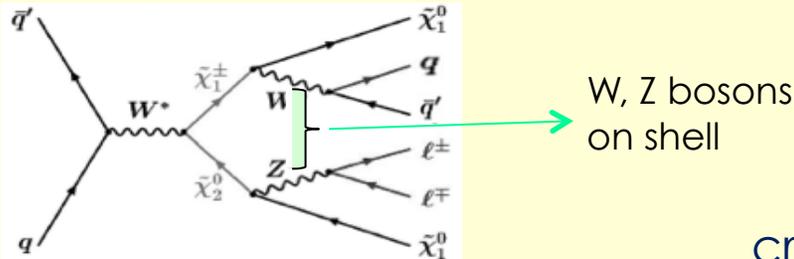


Excludes $m\tilde{\chi}_1^\pm < 164$ (154 Exp.) GeV/c^2

Update@3.2 fb⁻¹ results in [PRL 101, 251801 \(2008\)](#)

CDF also performed an analysis in the **large m_0 hypothesis**

$\mathcal{L}=2.7 \text{ fb}^{-1}$

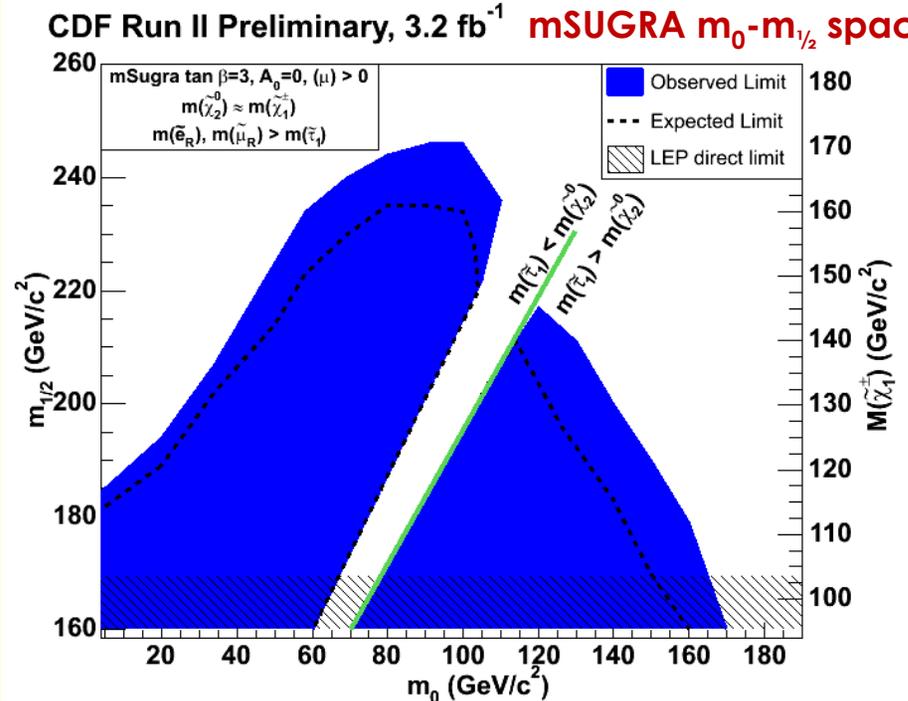


$m(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm) > m(\tilde{\chi}_1^0) + m(W, Z)$

Final state: e^+e^- pairs (Z), at least 2 jets (W) and Missing $E_T (> 40, 50, 60 \text{ GeV})$

cross section upper limits @ 95% CL ~ **1-3 pb**

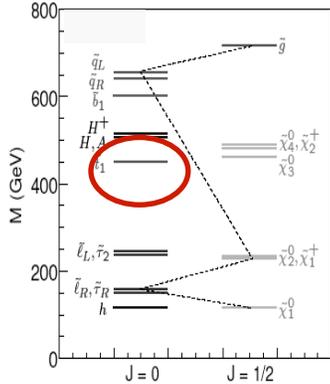
excluded region in $m\text{SUGRA } m_0\text{-}m_{1/2}$ space



Limits depend on relative $\tilde{\chi}_2^0\text{-}\tilde{l}$ masses

- $m_{\tilde{\chi}_2^0} > m_{\tilde{l}}$ increases \mathcal{BR} to e/μ
- $m_{\tilde{\chi}_2^0} \approx m_{\tilde{l}}$ reduces acceptance

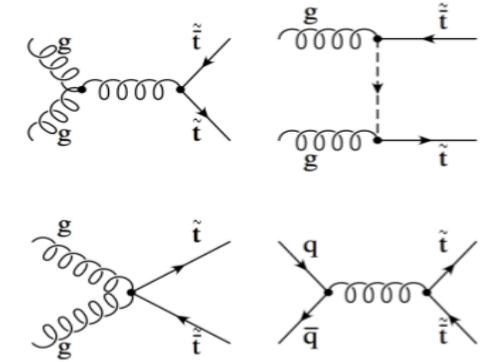
Stop searches



- Lightest of the squarks
- Can be lighter than the top quark:
 - due to the large SM top mass

$$m_{t_{1,2}}^2 = \frac{1}{2}(m_{t_L}^2 + m_{t_R}^2) \mp \frac{1}{2} \sqrt{(m_{t_L}^2 - m_{t_R}^2)^2 + 4m_t^2(A_t - \mu \tan \beta)^2}$$

- 2-, 3-body decays possible



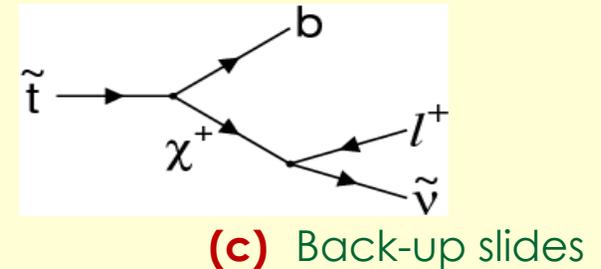
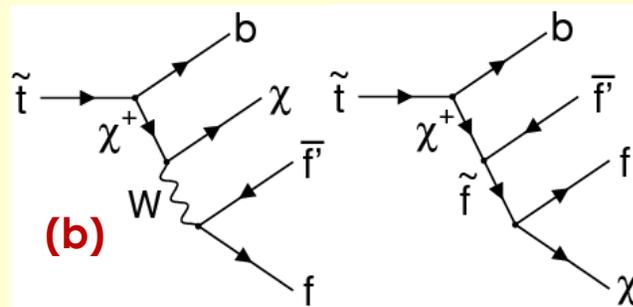
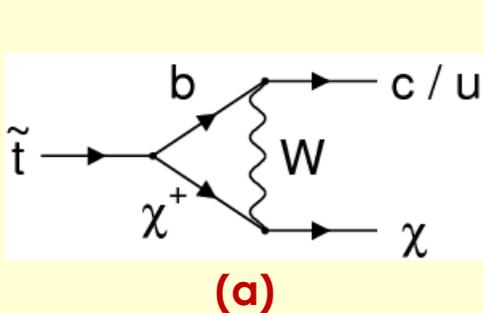
Assumptions for stop searches at the Tevatron:

- R_p conserved, $m_{\text{stop}} < m_{\text{top}}$, LEP2 constraints

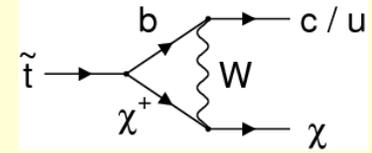
(a) 2-body: $\tilde{t}_1 \rightarrow c \tilde{\chi}_1$ if $m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{t}_1} < m_W + m_b + m_{\tilde{\chi}_0^1}$

(b) 2-body: $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm \rightarrow b W^\pm \tilde{\chi}_0$ if kinematically allowed

(c) 3-body: $\tilde{t}_1 \rightarrow b l \tilde{\nu}$

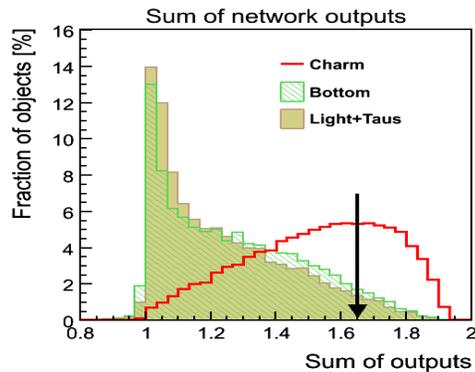
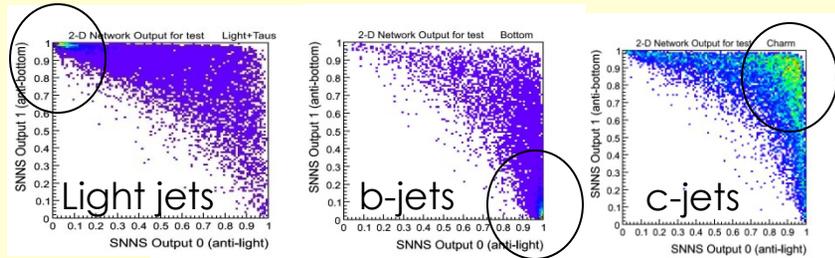


Stop searches: $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$



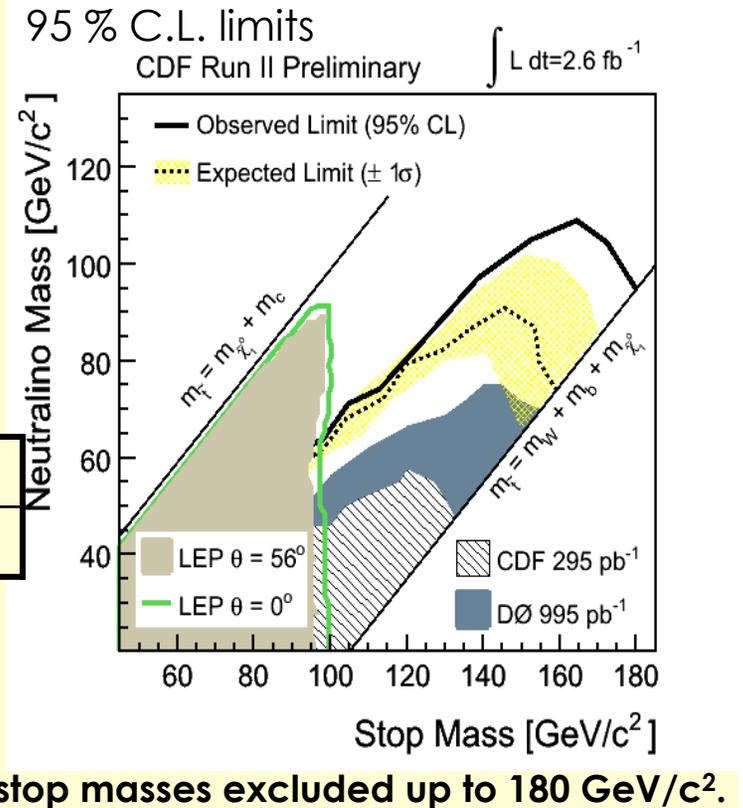
- Assume 100% B.R. in charm + neutralino
- Signature:** 2 c-jets and Missing E_T from χ_1^0
 - at least one jet tagged as heavy flavor (secondary vertex tools)
- Large backgrounds:*
 - QCD dominant: estimated from data as a tag rate

2D NN for Flavour Separator: main tool to enhance the sample with c-jets

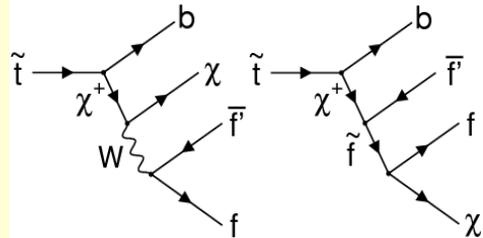


Data	115
Exp	132.0 ± 24.4

Data in good agreement with SM expectation

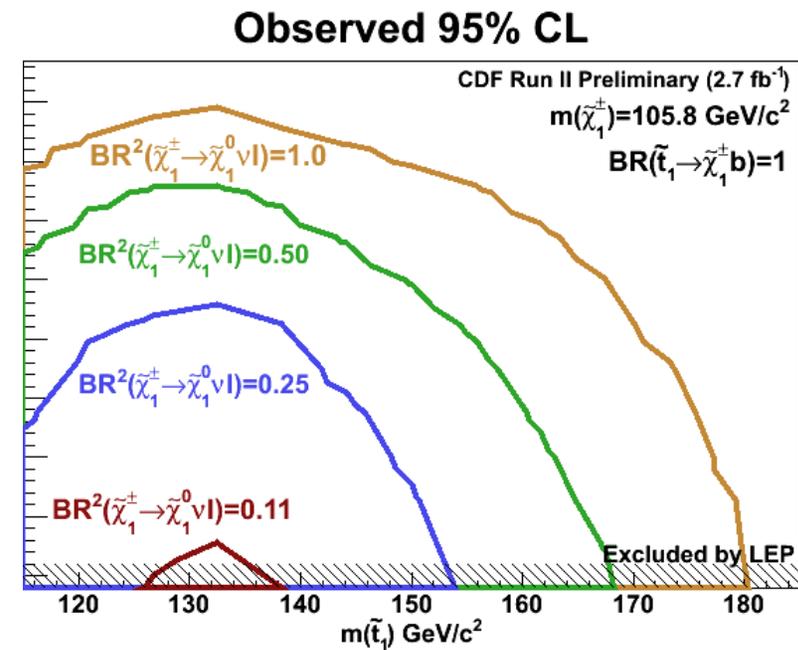
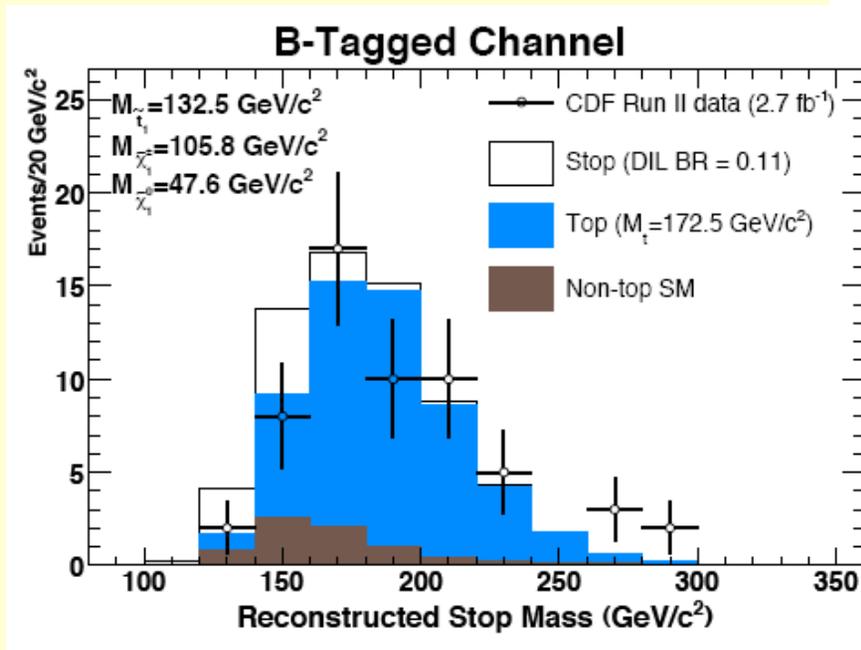


Stop searches: $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm$



- Assume on-shell charginos: $m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}_1} - m_b$
- Signal topology depends on $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm}$
- Signature:** Missing E_T + 2 opposite-sign leptons + 2 b-jets (0 or ≥ 1 tag)
 - \rightarrow Main background: top production (dilepton)
- Reconstruct stop mass with a kinematic fit

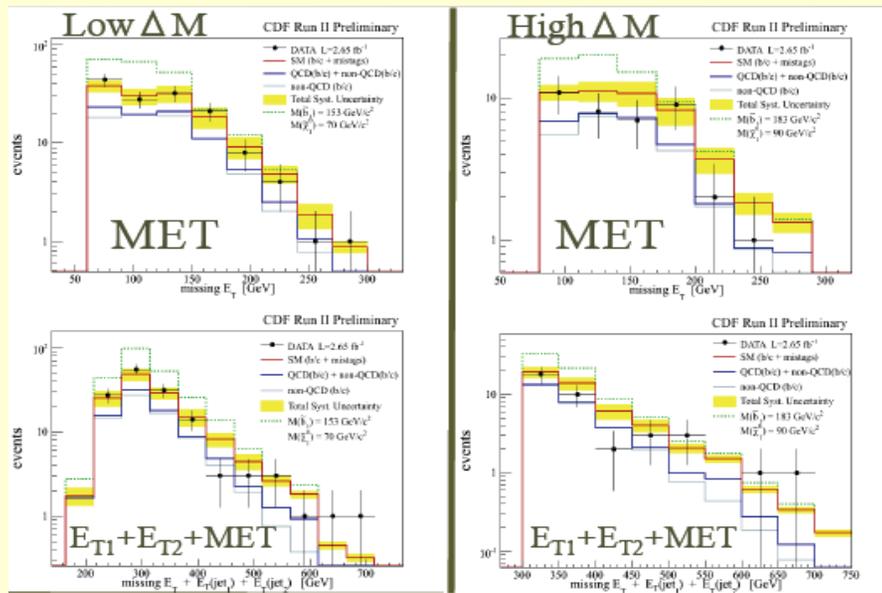
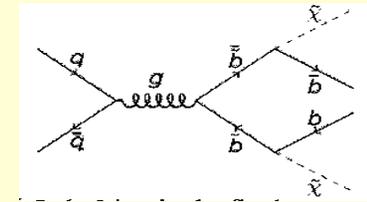
ArXiv:0912.1308v1
Submitted to PRL



Limits for several dilepton BR for $115 < m(\tilde{t}_1) < 197$ GeV,
 $44 < m(\chi_1^0) < 91$ GeV. Fix to $m(\chi_1^\pm) = 105.8$ and 125.8 GeV

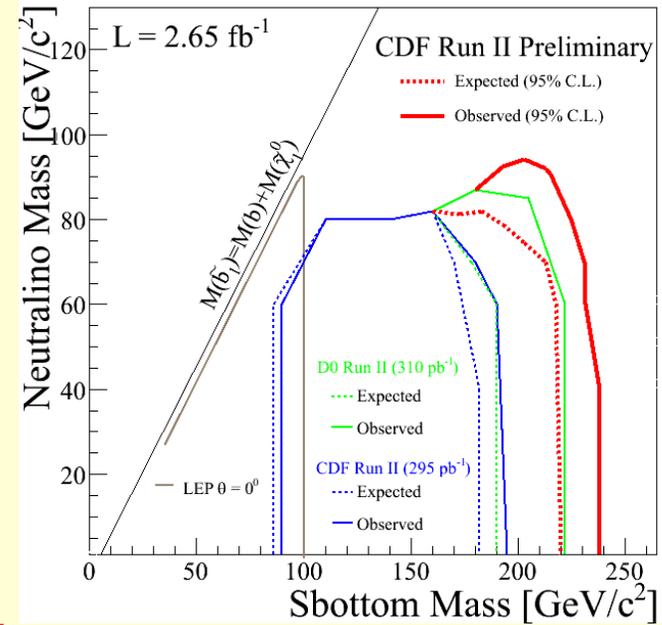
Search for \tilde{b} pair production

- MSSM scenario: $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ (BR=100%)
- Signature of two b-jets and MET ($\tilde{\chi}_1^0$)
- Data-driven estimation of QCD(b/c) and misidentified HF-jets
- Optimization based on kinematics:
 - MET, ΣE_T (jets); b-tagging of at least 1 jet
 - 2 selections implemented to further enhance sensitivity



region	SM expected	Data
Low DM	133.8 ± 25.2	139
High DM	47.6 ± 8.3	38

Data in good agreement with SM expectation

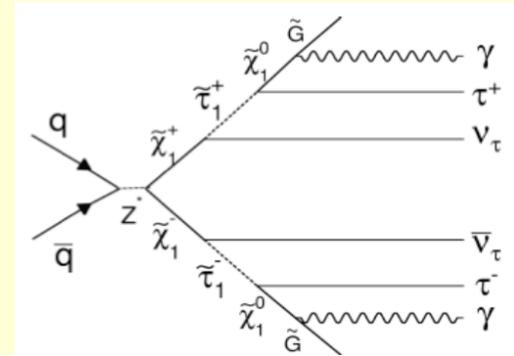


sbottom masses excluded up to 240 GeV/c².

GMSB: $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ in $\gamma\gamma + ME_T$

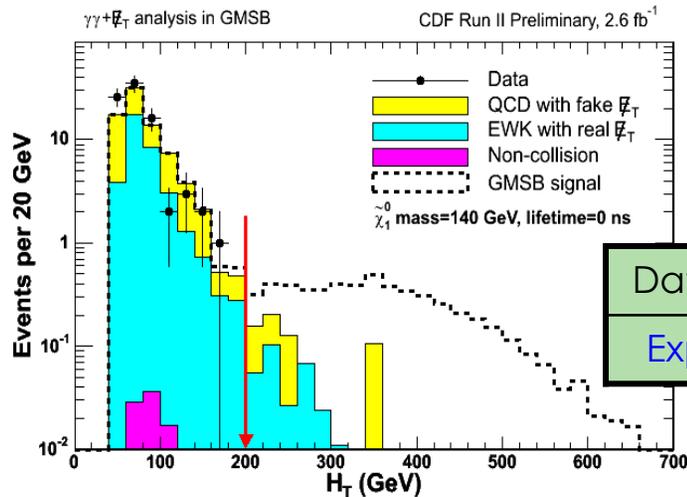
- SUSY breaking at scale Λ (10 -100 TeV)
- Squarks, gluinos and sleptons heavy
- Gravitino very light (\ll MeV) and LSP
- If NLSP is neutralino: $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$

If R_p conserved:
 $\gamma\gamma + ME_T (+X)$
final states



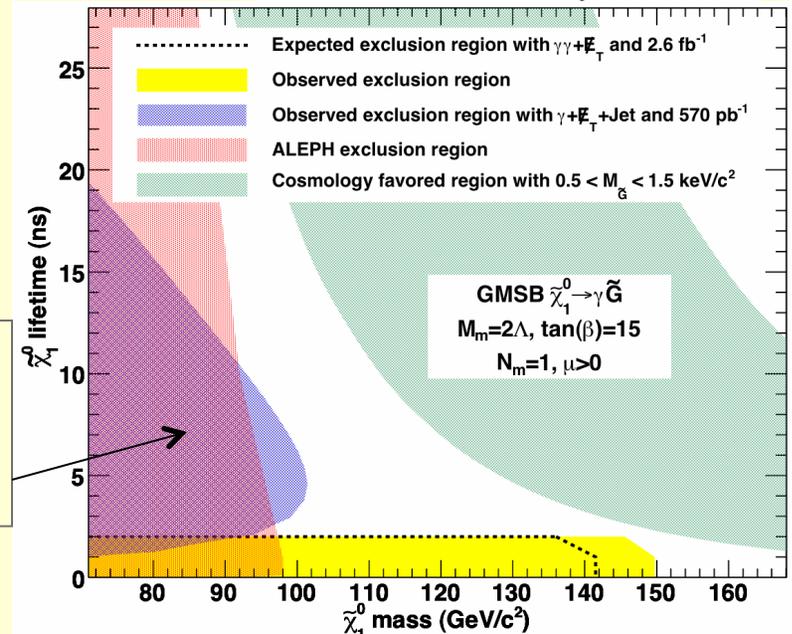
Assume χ_1^0 (NLSP) short-lived

- Optimize $\gamma\gamma + ME_T$ analysis for 0 ns lifetime
- Significant Missing E_T and Large H_T
 $H_T = \Sigma (\text{EM objects}) + E_T^{\text{jets}} + \text{Missing } E_T$
- Very low SM background



single delayed photon
 PRL 99, 121801
 (2007)
 PRD 78, 032015
 (2008)

Data	0 event
Exp	$1.4 \pm 0.3 \pm 0.3$

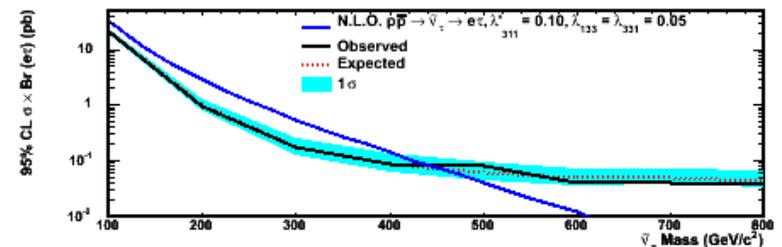
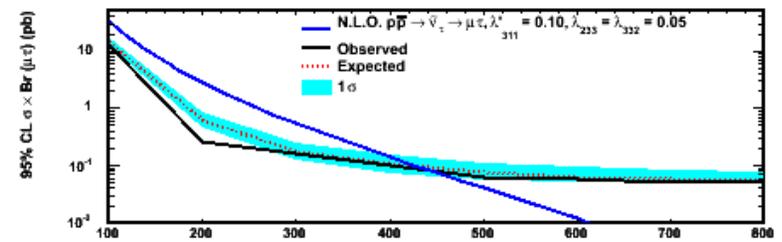
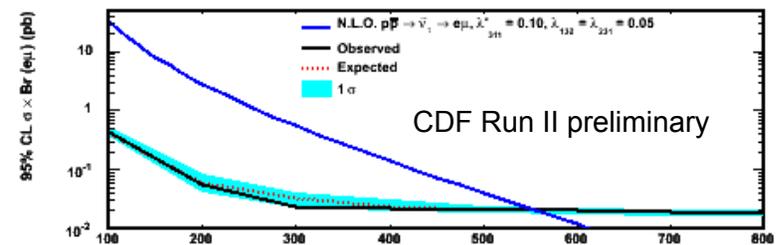
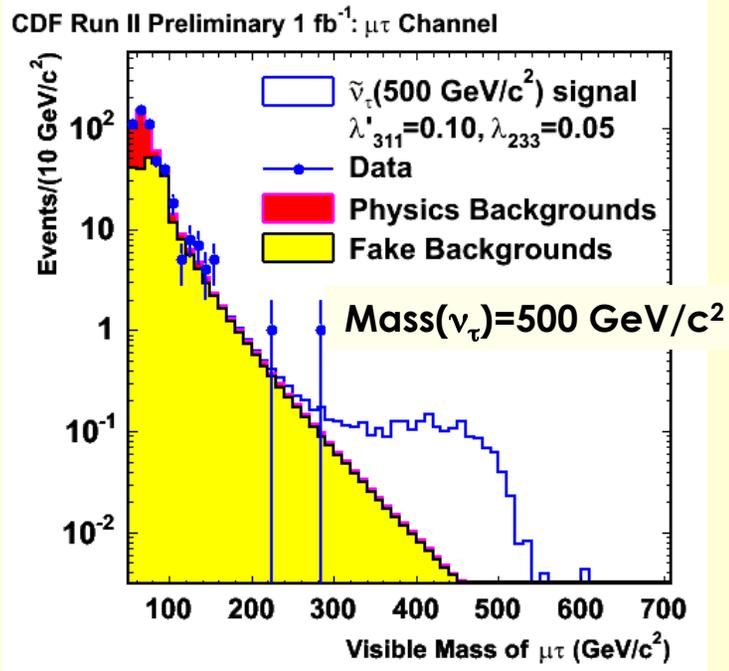
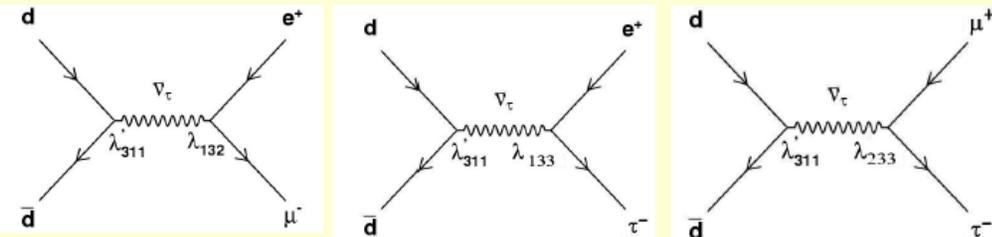


$M(\chi_1^0) > 149 \text{ GeV}/c^2$ for $\tau \leq 2 \text{ ns}$
 (Expected: $M(\chi_1^0) > 141 \text{ GeV}/c^2$)

PRL 104, 011801 (2010)

Search for scalar neutrinos

- Assume R_p violation: possible production of single SuperPartner
- Search strategy:** look at high-mass unlike flavored lepton pairs: $e\mu$, $e\tau$, $\mu\tau$
 - ◇ probe the $\lambda_{ijk} - M_{\text{scalar neutrino}}$ parameter space



$\sigma \times \text{BR}$ upper limits of **0.018 pb ($e\mu$)**, **0.037 pb ($e\tau$)**, **0.052 pb ($\mu\tau$)** for with $\lambda'_{311} = 0.1, \lambda_{132} = \lambda_{133} = \lambda_{231} = 0.05$

Extra-Dimension and new gauge Bosons

Large Extra Dimensions

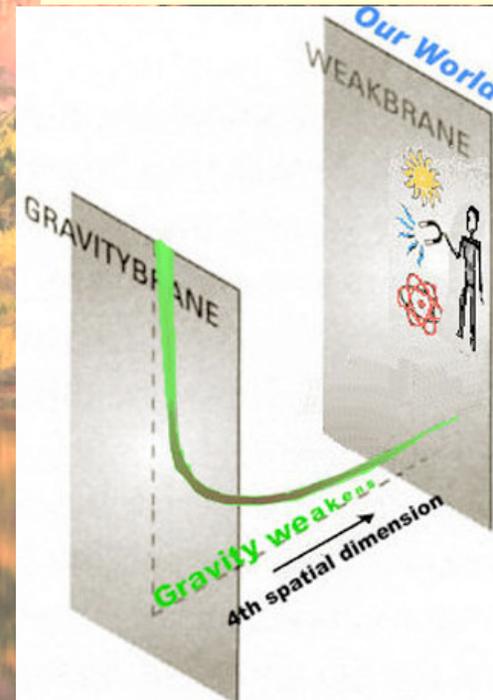


$$\phi(x) = \phi(x + k2\pi R)$$
$$(k = 0, 1, 2, \dots)$$
$$p = k/R$$

Z' and W' bosons

Naturally arise from many SM extensions (GUTS - E6, SO(10), ..., extra dimensions etc..)

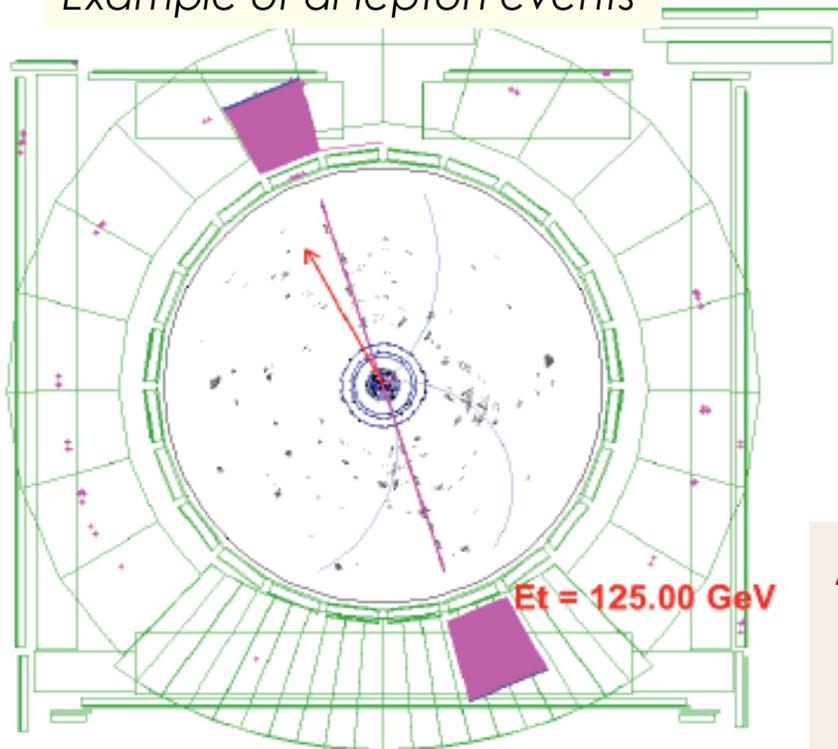
Randall-Sundrum



Search for high mass resonances

- **Di-lepton** resonances have a strong track record for discovery
→ J/ψ , Y , Z
 - Enlarge the possible final states looking also in **dijet, ditop or dibosons!**
- Construct the pair invariant mass and look for any excesses in the high mass spectrum

Example of di-lepton events



Advantage

Sensitive to many BSM scenarios:

- Extra-Dimensions
- Extended SUSY-GUT groups (SO(10), E6, E8... leading to additional gauge bosons, Z' and W')
- R-parity violating SUSY and more...

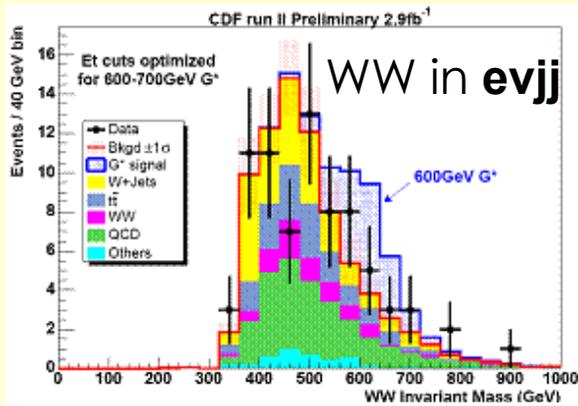
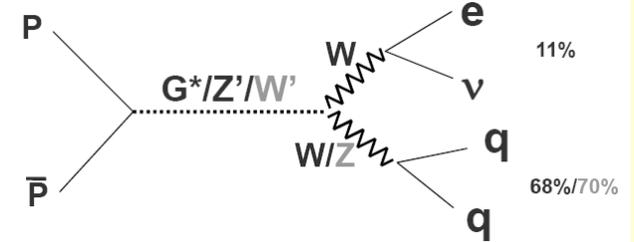
At CDF all modes have been explored!

See also: A.Ivanov's talk (ditop),
K.Hatakeyama's talk (dijet)

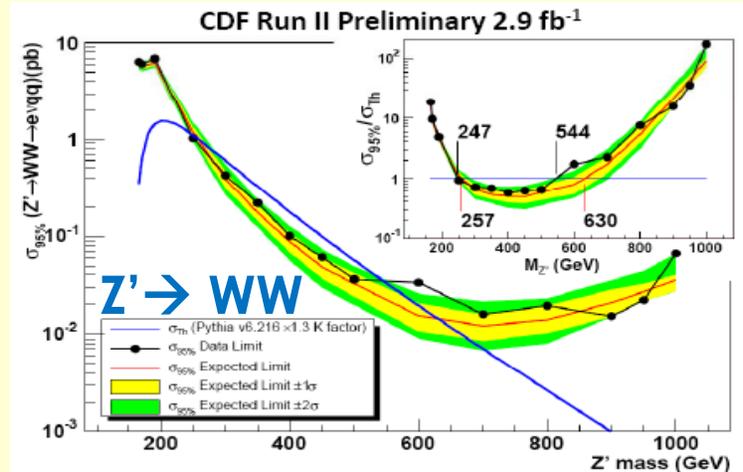
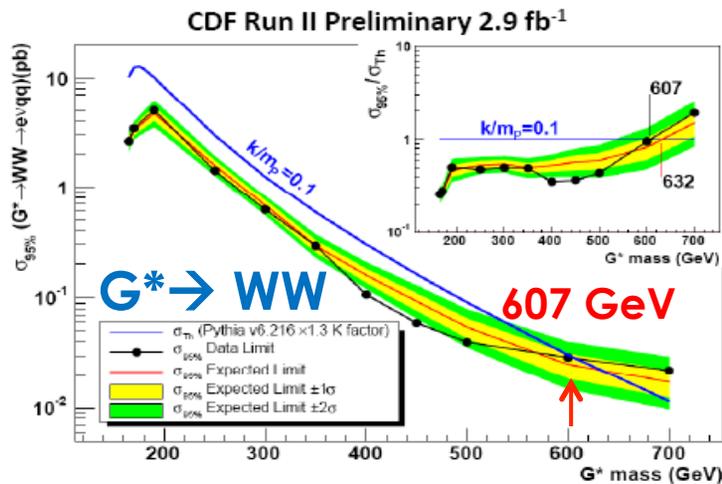
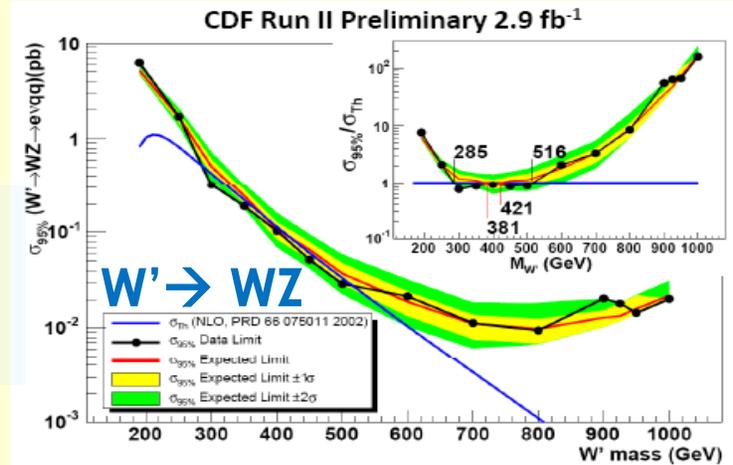
Diboson resonances (I)

- Clean final states + mass constraints
- Final state: electron+MET+ 2jets
- Interpretation given in different models, optimized for expected resonance mass

$\mathcal{L}=2.9 \text{ fb}^{-1}$



$W \rightarrow \nu e$ with two solutions
 Dijets in [65,95] (for WW)
 Dijets in [70,105] (for WZ)
 3-jet events also considered



Diboson resonances (II)

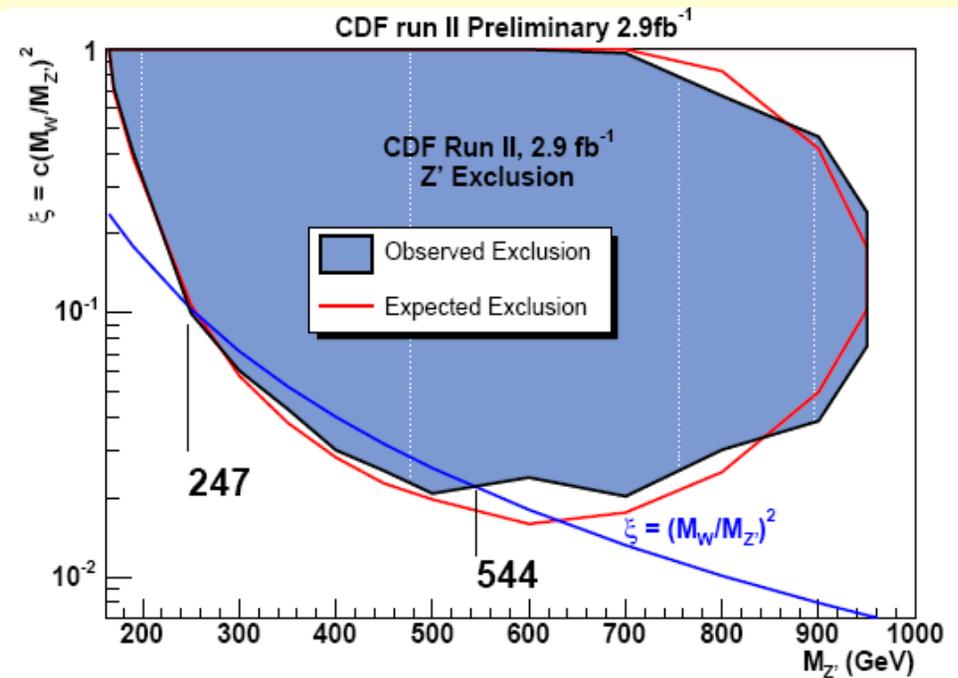
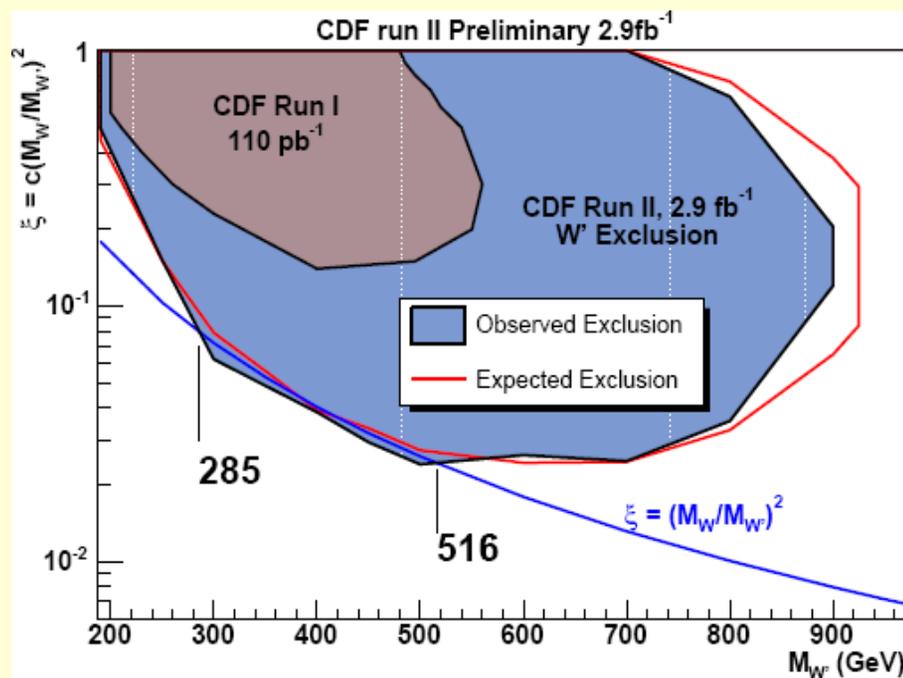
Couplings of $V^\pm W^\pm Z^0$ or $V^0 W^+ W^-$ suppressed by a mixing factor $\xi = c \cdot (M_W/M_V)^2$ (where $V = W'^\pm$ or Z'^0): $g \cos \theta w \rightarrow \xi g \cos \theta w$

\rightarrow Plots shown before refer to: $c=1$, $\xi = (M_W/M_V)^2$

Studies of diboson decay modes directly probe this coupling strength.

- *Previous studies:*

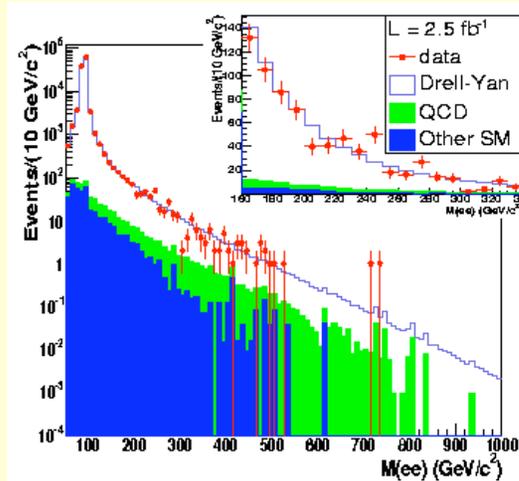
CDF Run I (PRL 88,071806, (2002)) for W' , ξ limits for Z' never studied.



Di-lepton resonances

Dielectron:

- Central ($|\eta_{1,2}| < 1$) or Central-Forward ($|\eta| < 2$) e^+e^- pair with $E_T > 25$ GeV
- Resonance search performed in mass range 150-1000 GeV/c^2
- No evidence for NP

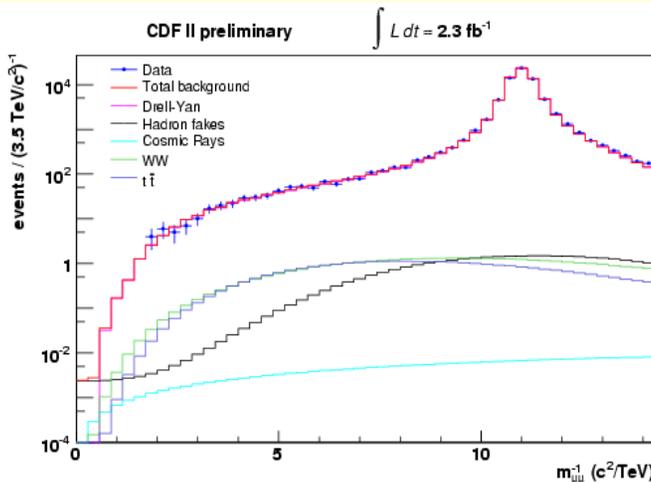


PRL 102, 031801 (2009)

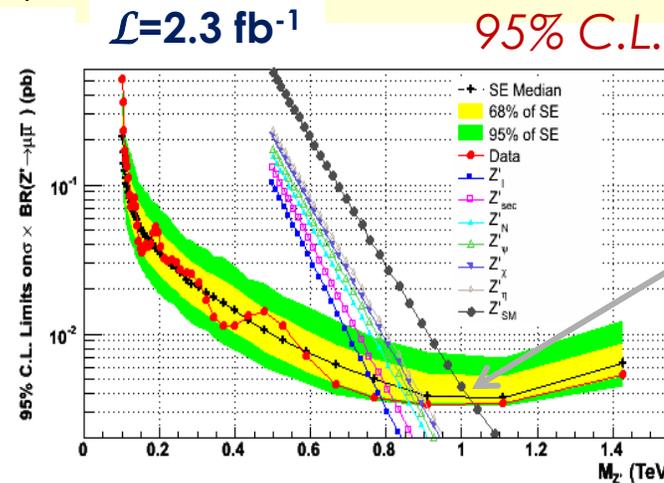
Exclude:

$M(G^*) < 850 \text{ GeV}/c^2$ for $k/M_{PI} = 0.1$
 $SM\text{-like } Z' > 966 \text{ GeV}/c^2$

Dimuon: Search in $1/m_{\mu\mu}$ (constant detector resolution) **PRL 102, 091805 (2009)**



Data and SM exp. in good agreement



95% C.L. limits in different models

Sneutrino (spin 0)
 $m > 397 - 866 \text{ GeV}/c^2$

Z' (spin 1)
 $m > 1.03 \text{ TeV}/c^2$ (SM-like)

RS G* (spin 2)
 $m > 293 - 921 \text{ GeV}/c^2$

Update with 5 fb^{-1} and alternative method will be ready soon!

4th generation

	2.4 MeV $\frac{2}{3}$ $\frac{1}{2}$ u up	1.27 GeV $\frac{2}{3}$ $\frac{1}{2}$ c charm	171.2 GeV $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 γ photon
Quarks	4.8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon
	<2.2 eV 0 $\frac{1}{2}$ ν_e electron neutrino	<0.17 MeV 0 $\frac{1}{2}$ ν_μ muon neutrino	<15.5 MeV 0 $\frac{1}{2}$ ν_τ tau neutrino	91.2 GeV 0 1 Z weak force
Leptons	0.511 MeV -1 $\frac{1}{2}$ e electron	105.7 MeV -1 $\frac{1}{2}$ μ muon	1.777 GeV -1 $\frac{1}{2}$ τ tau	80.4 GeV ± 1 1 W [±] weak force
				Bosons (Forces)

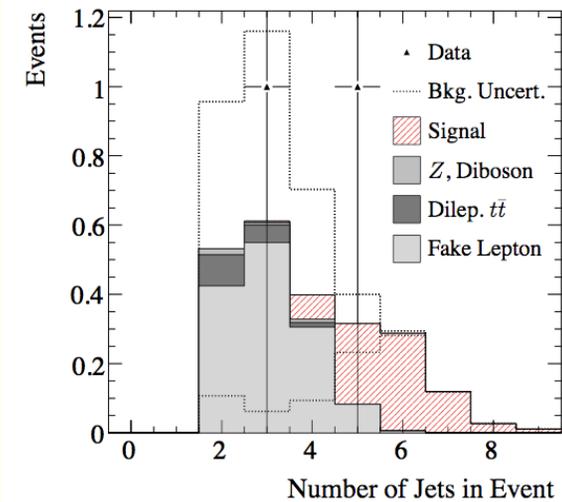
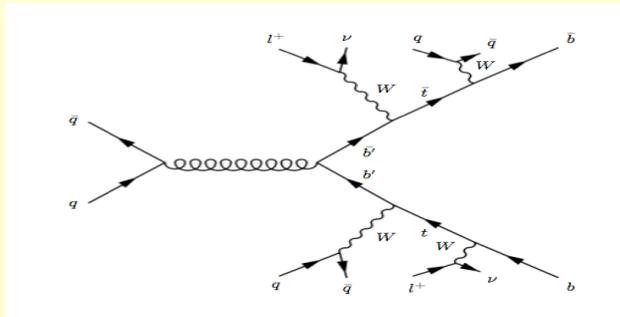
Why nothing here?

(* for results on t' searches, see A.Ivanov's talk

Search for $B' \rightarrow Wt$

Submitted to PRL ArXiv: 0912.1057

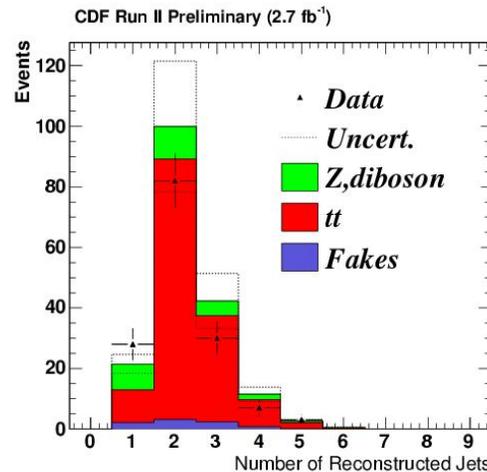
- Final state: 2 same-sign e/μ , b-jets and MET



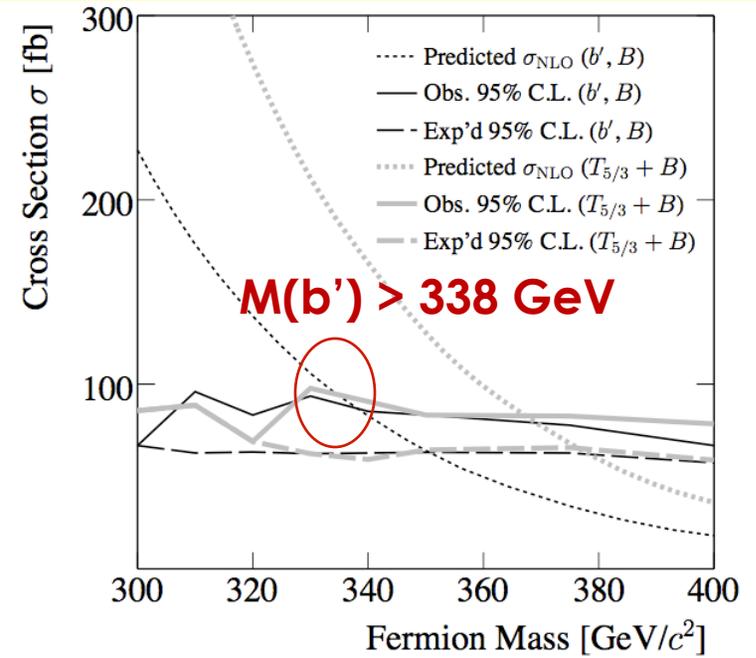
- Low SM bkg (misreconstructed leptons dominates)

Validation of predictions for DY and top bkg performed in opposite-sign leptons region

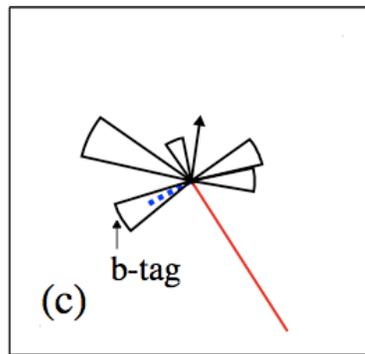
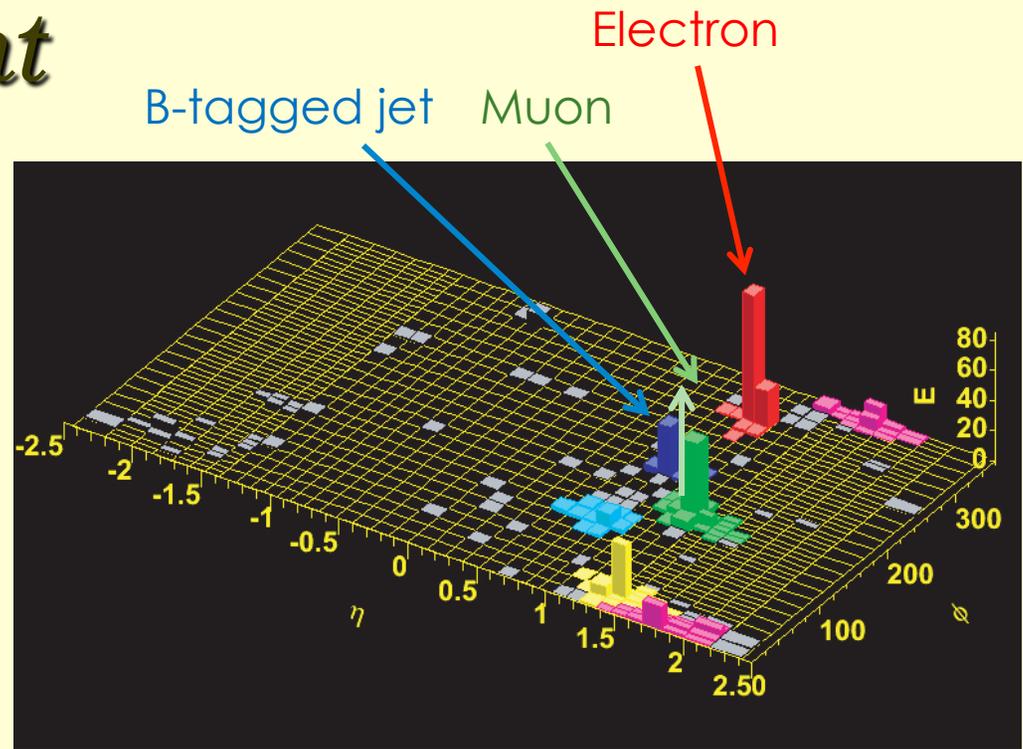
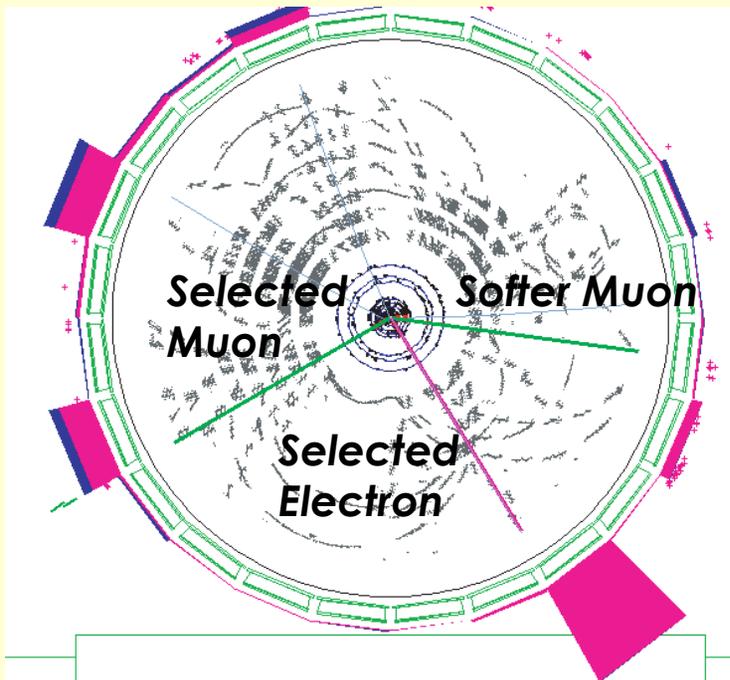
1 b-jet $E_T > 20$ GeV
 MET > 20 GeV
 OS leptons $p_T > 20$ GeV



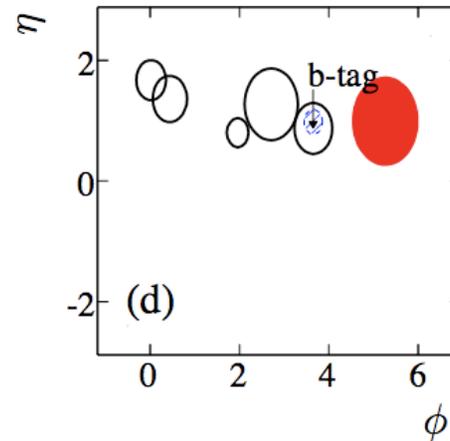
- Good agreement between data and SM estimations (2 vs 1.6 ± 1.4 events) \rightarrow



5-jet $e + \mu + e$ event



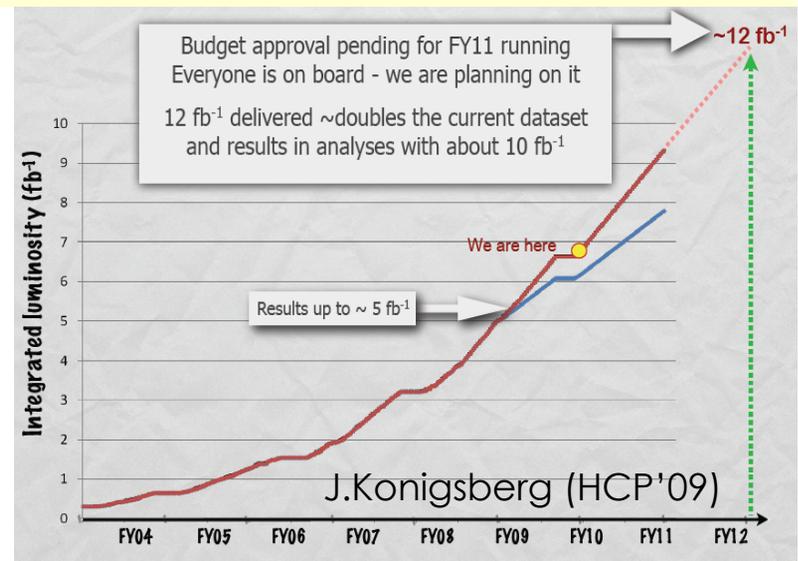
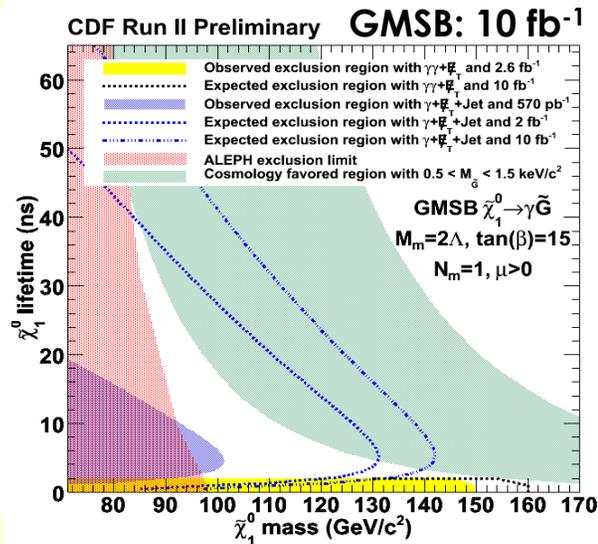
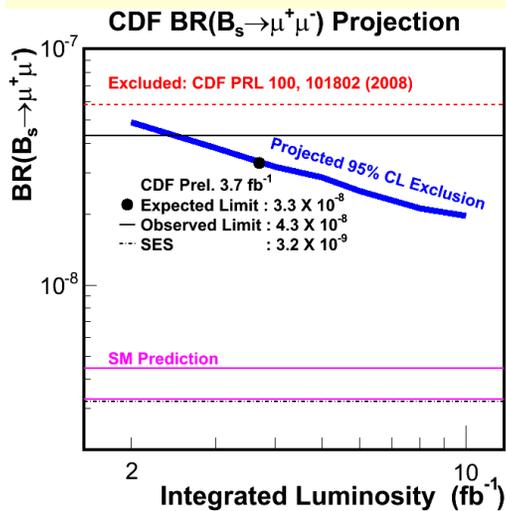
$r-\phi$ Projection



Jet
Electron
Muon

Conclusions

- CDF has a wide and rich program of BSM searches:
 - Continuously on-going updates of existing results using more sophisticated techniques and more data
 - More results expected for rest of Winter conferences 2010
- No evidence of new physics yet, but.. expect to collect and analyze up to 10 fb^{-1} of data in the next years → **Very promising projections**
- Can be competitive with LHC for the next 2-3 years







Back-up

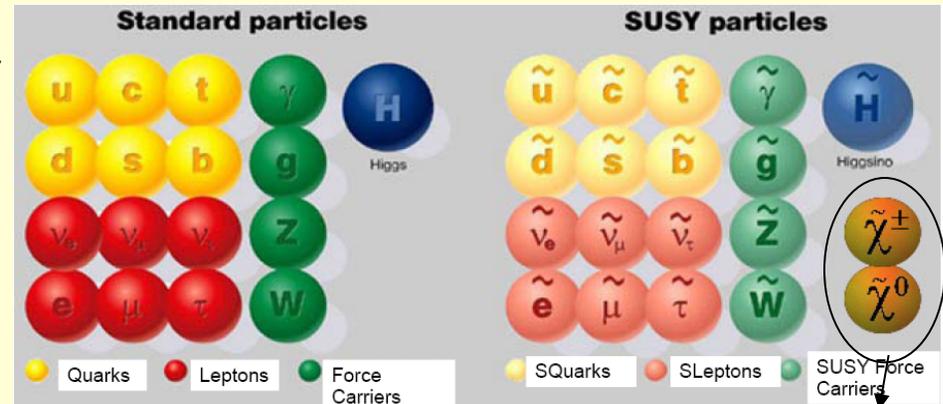
Supersymmetry in 30''

- The Standard Model is theoretically incomplete
 - Require fine tuning, account only for 4% of energy in Universe

- SUSY: New spin-based symmetry relating fermions and bosons:

$$Q | \text{Boson} \rangle = \text{Fermion}$$

$$Q | \text{Fermion} \rangle = \text{Boson}$$

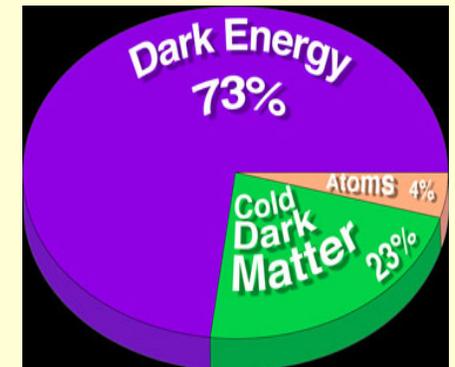


gaugino/higgsino mixing

→ Naturally solves the hierarchy problem

- Define R-parity = $(-1)^{3(B-L)+2s}$
 - R = 1 for SM particles
 - R = -1 for MSSM partners

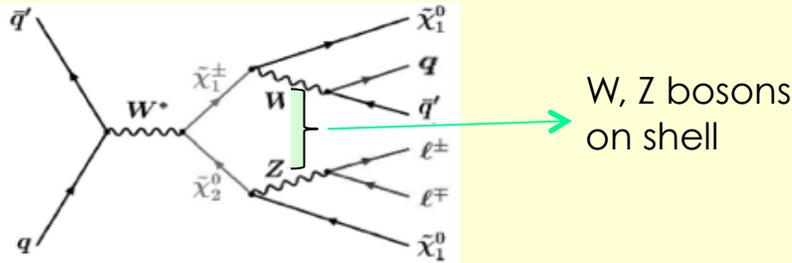
If conserved, provides
Dark Matter Candidate
(Lightest Supersymmetric Particle)



- No SUSY particles found yet
 - SUSY must be broken → > 100 parameters even in “minimal” models

Heavy $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$ production

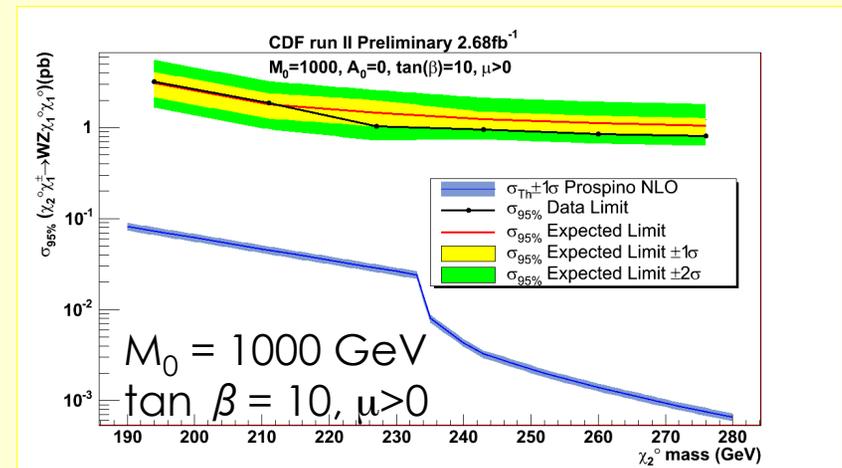
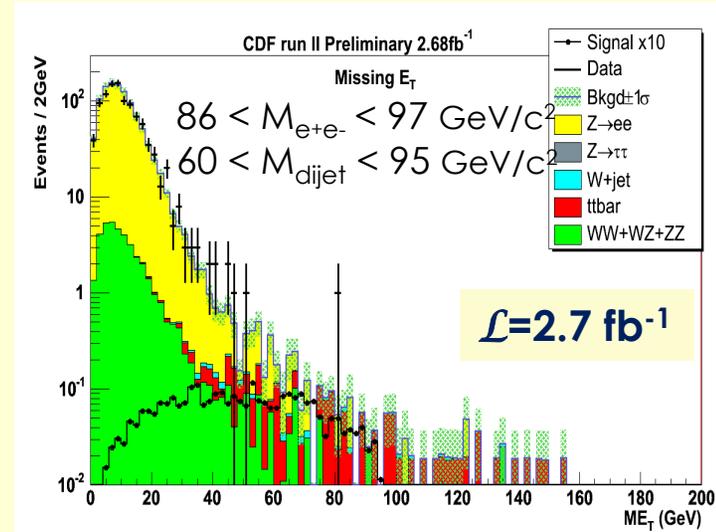
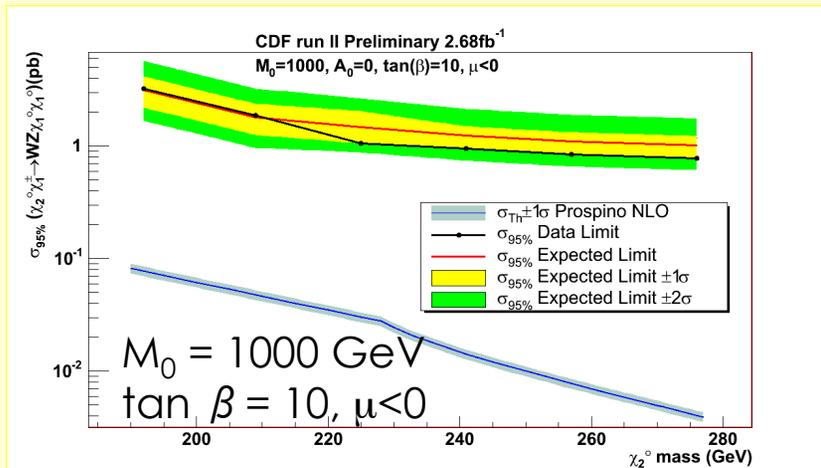
- Assume: $m(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm) > m(\tilde{\chi}_1^0) + m(W, Z)$



- Final state: e^+e^- pairs (Z), at least 2 jets (W) and Missing E_T ($> 40, 50, 60$ GeV)
- Main Background: Z+jets

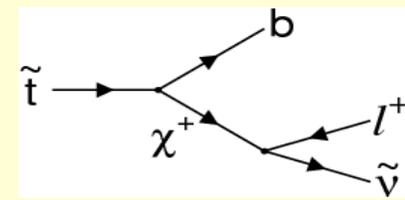
Missing $E_T > 40$ GeV:

Data: 7, SM Expected: 6.41 ± 0.95

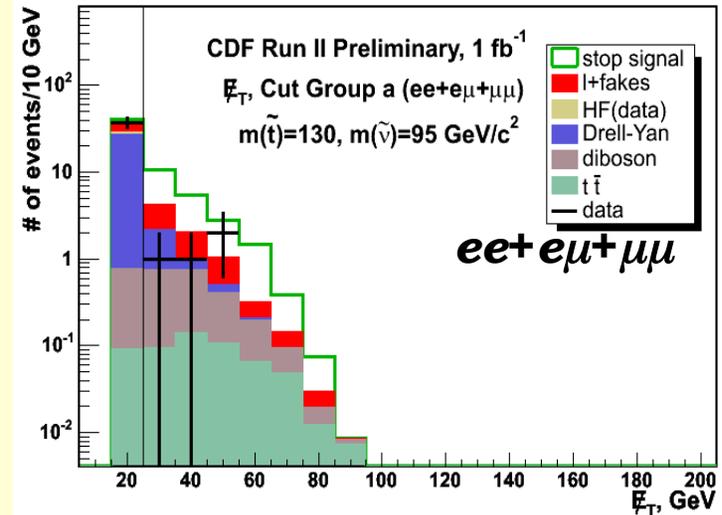
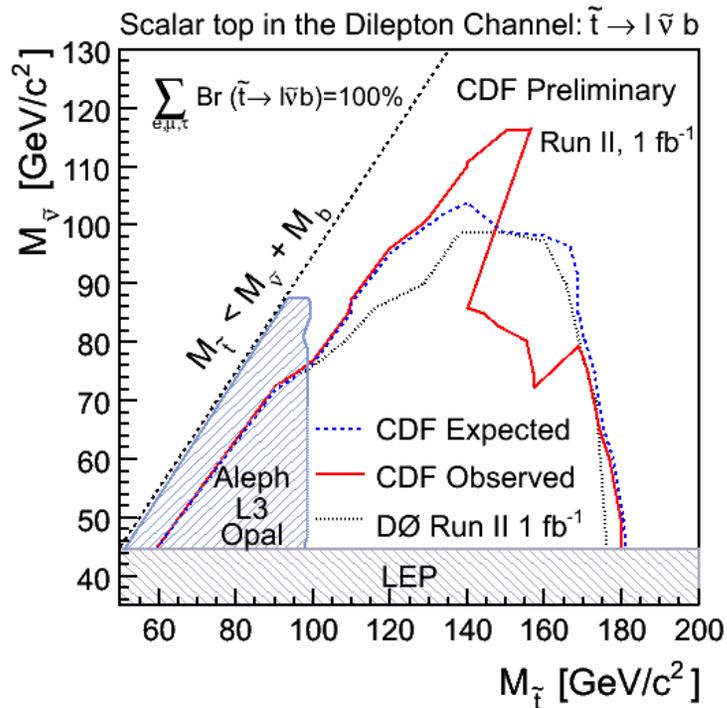


observed cross sections $\sim 1-3$ pb

Stop searches: $\tilde{t}_1 \rightarrow b l \tilde{\nu}$



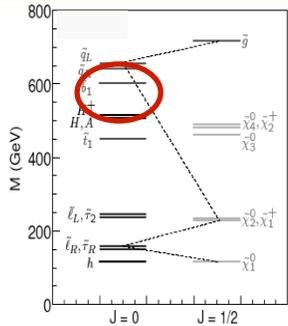
- Assume sneutrino is LSP
- Signal topology depends on $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\nu}}$
- Signature:** Missing E_T + 2 opposite-sign leptons (soft) + 2 b-jets



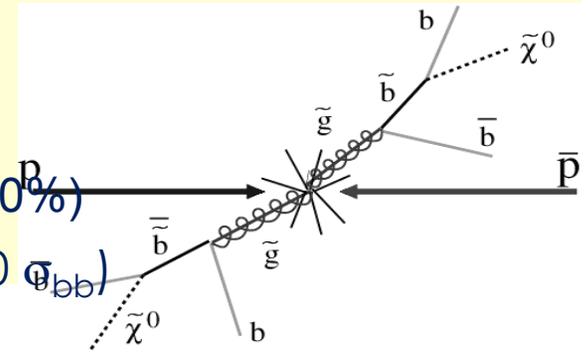
- 1 fb⁻¹ CDF data:** ee, eμ, μμ
- Assuming 100% B.R. to leptons and family symmetry, eμ is the most sensitive channel

**For large Δm , exclusion above top mass:
 $m_{\tilde{t}_1} < 180 \text{ GeV}$**

\tilde{g} -mediated \tilde{b} production



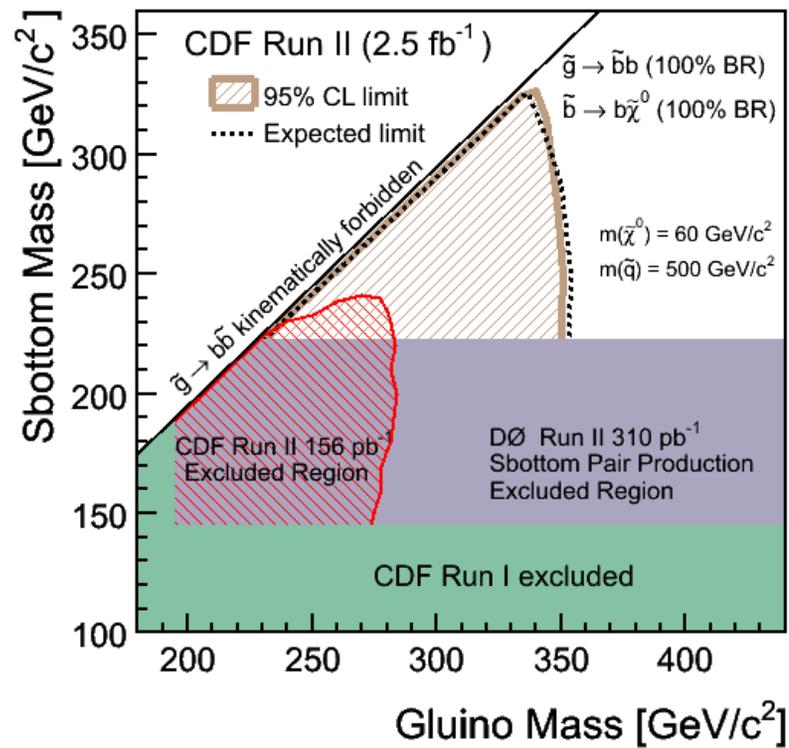
- Light sbottom in large mixing scenarios
- Dedicated searches for \tilde{b} production
- If $m(\tilde{b}) < m(\tilde{g})$ (assuming B.R. ($b \rightarrow b \chi^0$) = 100%)
Search for b from gluino decays $\tilde{\sigma}_{gg} \sim 10 \sigma_{bb}$



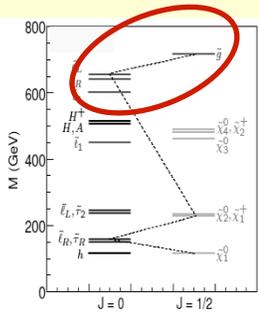
- Final state: Missing E_T + 4 b-jets
- Use b-tagging algorithm to identify at least 2 b-jets
- 2 Neural Network to reject background (top and QCD-multijets)

2 optimization regions depending on g - b mass difference

PRL 102, 221801 (2009)

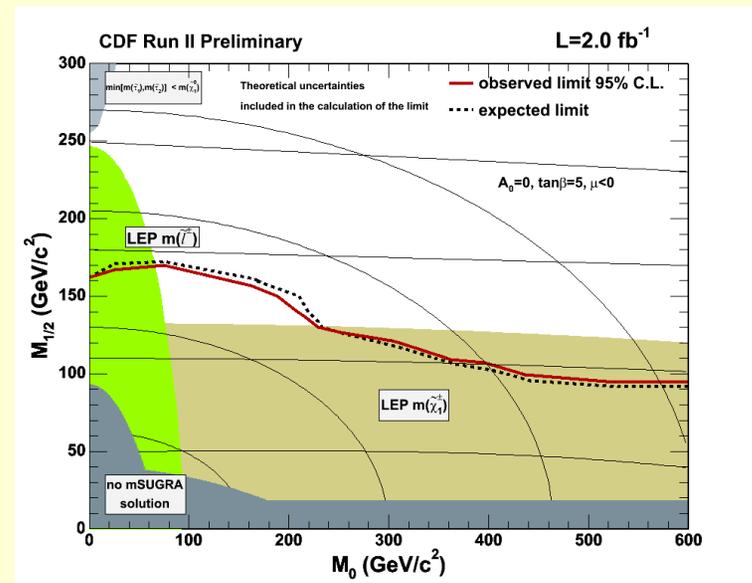
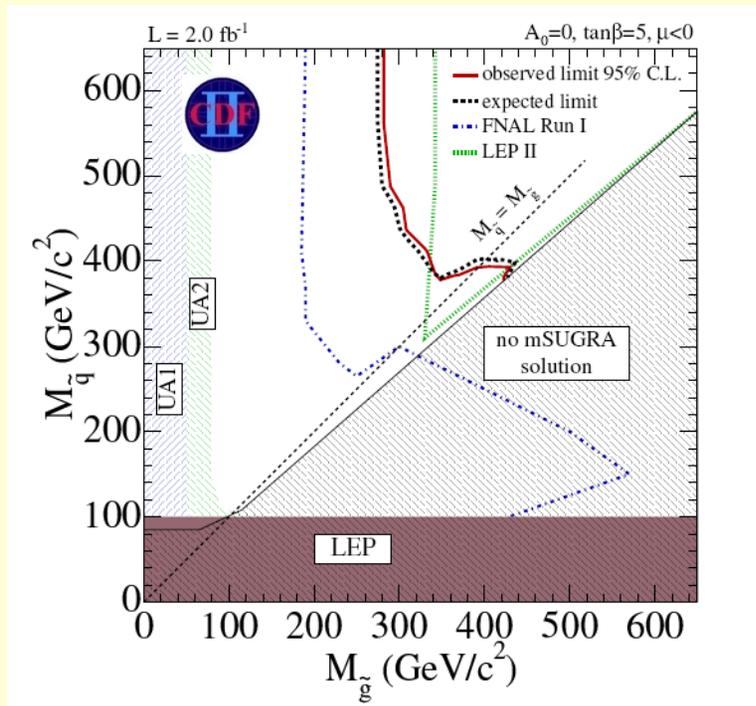
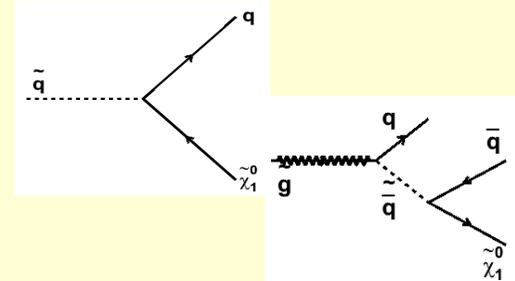


Search for squarks and gluinos



□ Search for squark and gluino pair production in final states with 2, 3, or 4 jets and Missing E_T

- 2 jets + E_T : $\tilde{q}\tilde{q} \rightarrow qq\chi_1^0\chi_1^0$ ($m_{\tilde{q}} < m_{\tilde{g}}$)
- 3 jets + E_T : $\tilde{q}\tilde{g} \rightarrow qqg\chi_1^0\chi_1^0$ ($m_{\tilde{q}} \sim m_{\tilde{g}}$)
- 4 jets + E_T : $\tilde{g}\tilde{g} \rightarrow qqgq\chi_1^0\chi_1^0$ ($m_{\tilde{q}} > m_{\tilde{g}}$)



PRL 102, 121801 (2009)

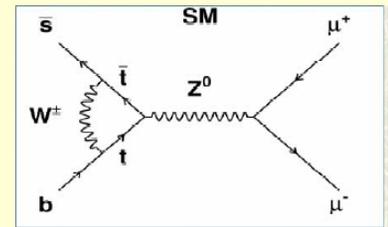
probing sparticle masses $\sim 400 \text{ GeV}/c^2$

Indirect searches: $B_s \rightarrow \mu\mu$

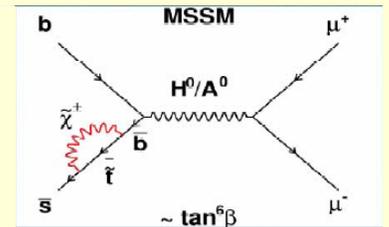
Sensitive to new physics: SUSY particles show up in loops (or direct decays if R_p violation)

CDF (3.7 fb⁻¹): $\text{Br}(B_s \rightarrow \mu\mu) < 4.3 \times 10^{-8}$ @ 95% CL
(Expected limit: 3.3×10^{-8})

SM: BR = 3.42×10^{-9}



SUSY enhance $\sim (\tan\beta)^6$

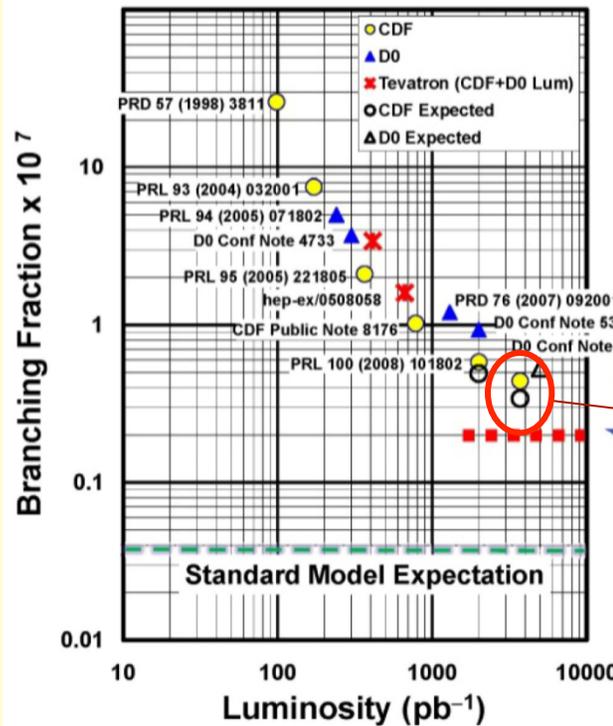


For analysis details see [S.Burdin's talk](#)

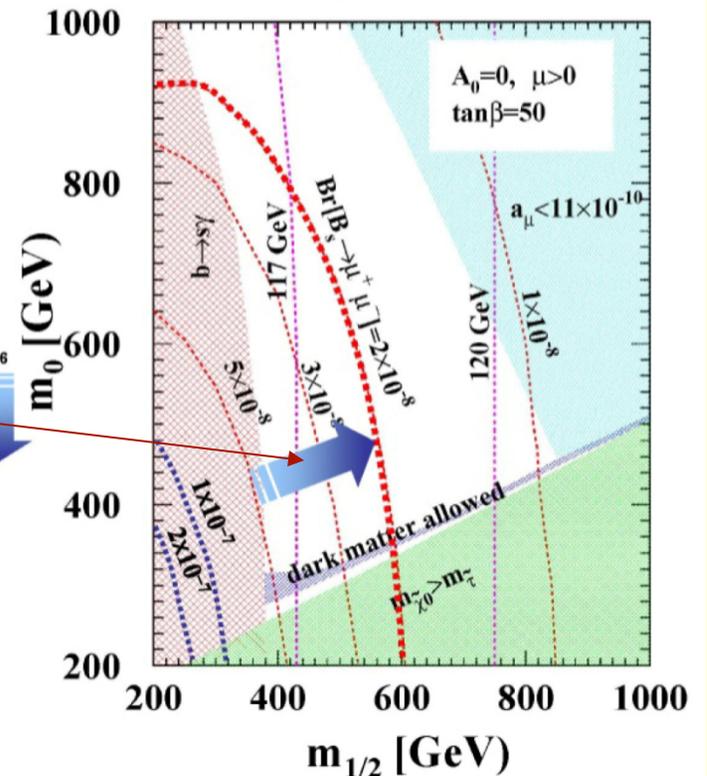
95% CL limit projection show reach to 2×10^{-8} before 10 fb^{-1}

Next step: 6 fb^{-1}

95% CL Limits on $\mathcal{B}(B_s \rightarrow \mu\mu)$



mSUGRA at $\tan\beta = 50$
Arnowitz, Dutta, et al., PLB 538 (2002) 121



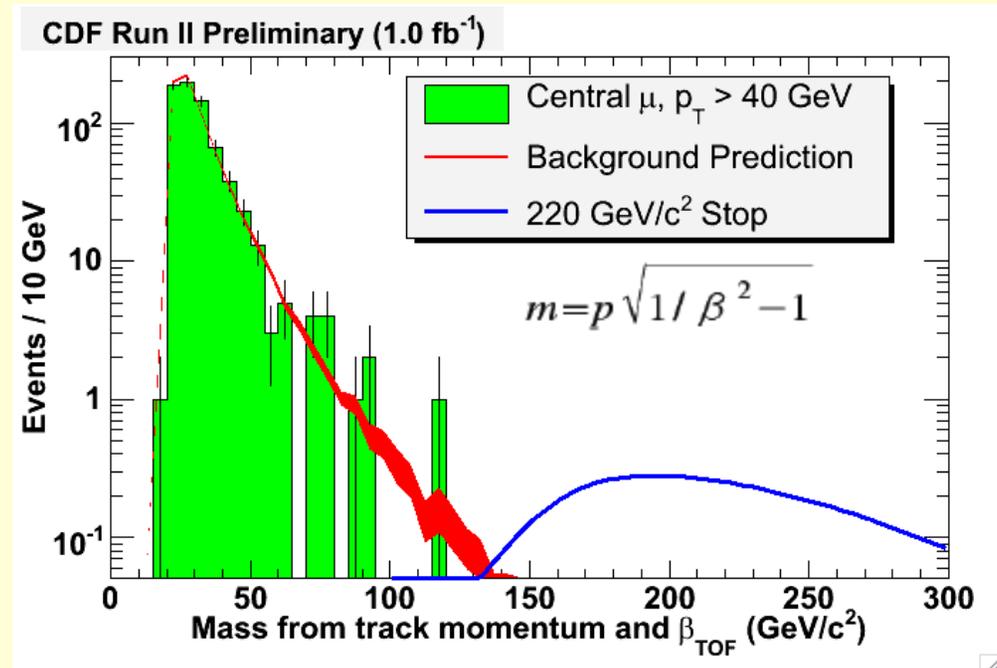
Charged massive stable particles

Long-lived charginos are expected
in some **AMSB** models

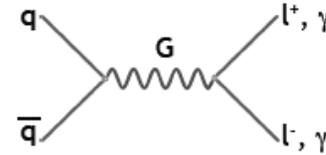
with a “wino-LSP” (small $\chi^\pm - \chi_1^0$ mass difference)
They would appear like slowly-moving muons
⇒ Make use of the **time of flight information**

CDF: Interpretation for strongly interacting charged massive particles, such as stops with a small stop- χ mass difference **$m(\text{stop}) > 250 \text{ GeV}$**

PRL 103, 021802 (2009).



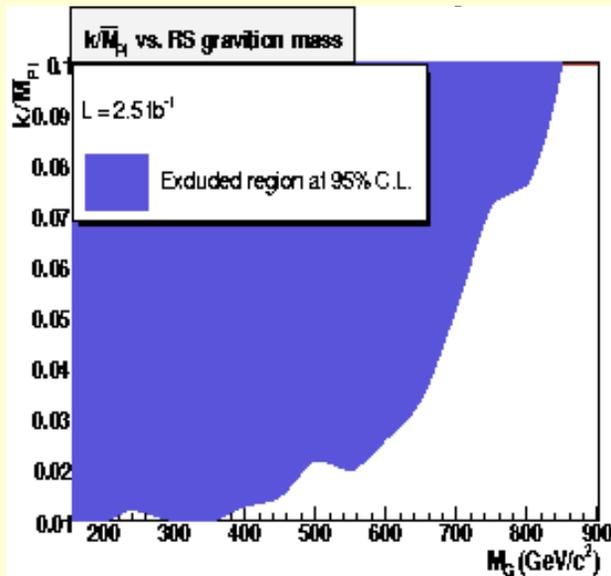
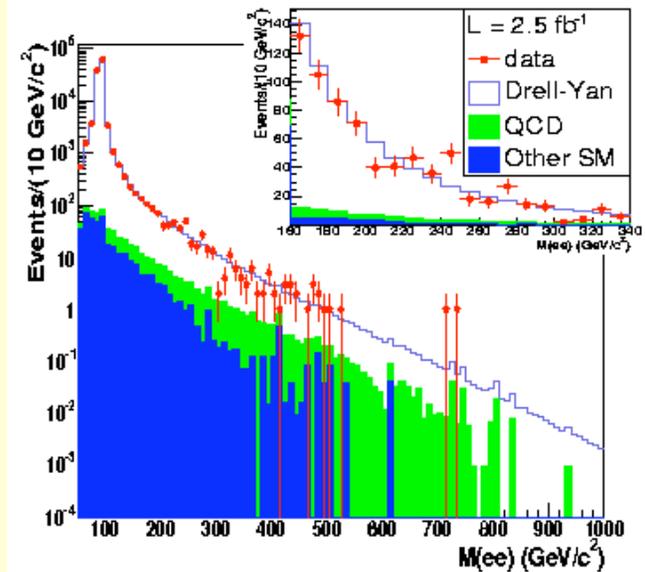
Search for High Mass e^+e^- Resonances



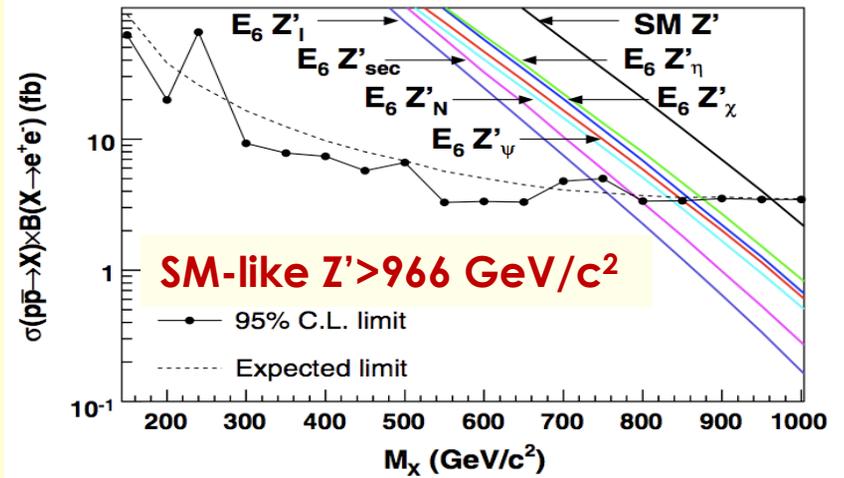
- Central-Central ($|\eta_{1,2}| < 1$) or Central-Forward ($|\eta| < 2$) e^+e^- pair with $E_T > 25$ GeV

Major Backgrounds:

- Drell-Yan, QCD (including W+jets)
- Resonance search performed in mass range 150-1000 GeV/c^2
- No evidence for resonances → **set limits**

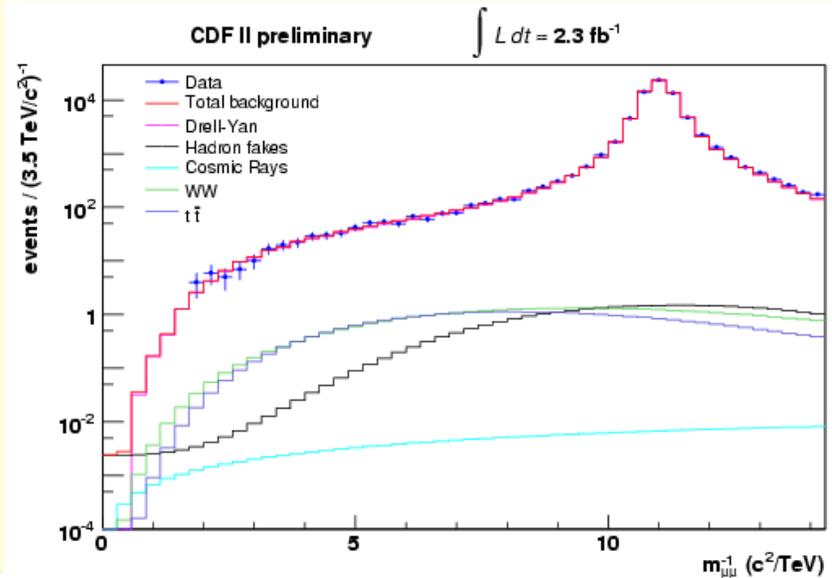


Exclude $M(G^*)$ below **850 GeV/c^2** for $k/M_{Pl}=0.1$

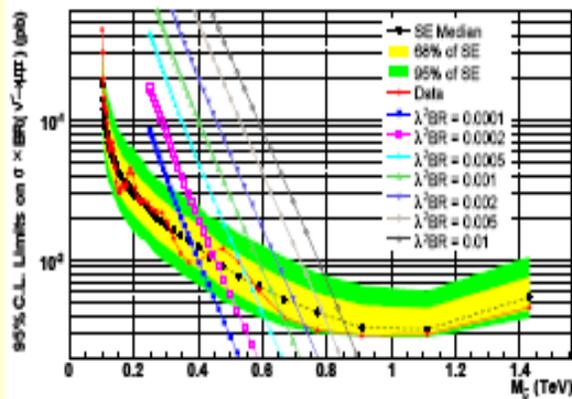


Di-muon resonances

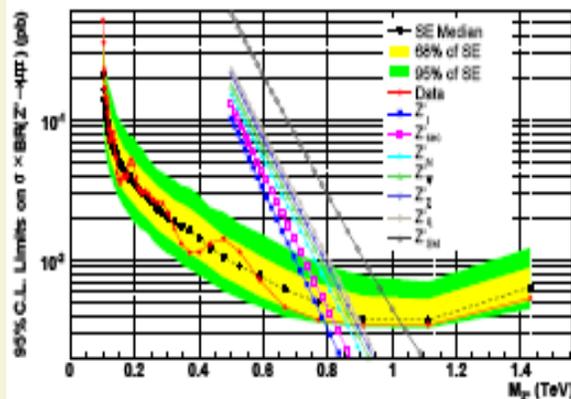
- Resonance decaying to dimuon have spin 0, 1 and 2
- Search in $1/m_{\mu\mu}$ in which detector resolution is $\sim \text{const}$:
 \rightarrow 17% inverse mass resolution at 1 TeV
- Data and SM expectation in very good agreement



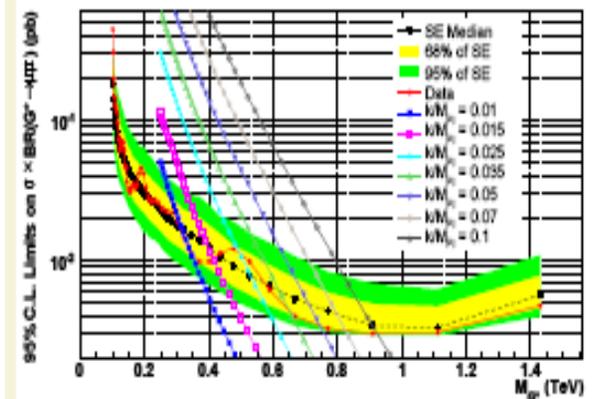
95% C.L. limits in different models



Sneutrino (spin 0)
 $m > 397 - 866 \text{ GeV}/c^2$



Z' (spin 1)
 $m > 1.03 \text{ TeV}/c^2$ (SM-like)

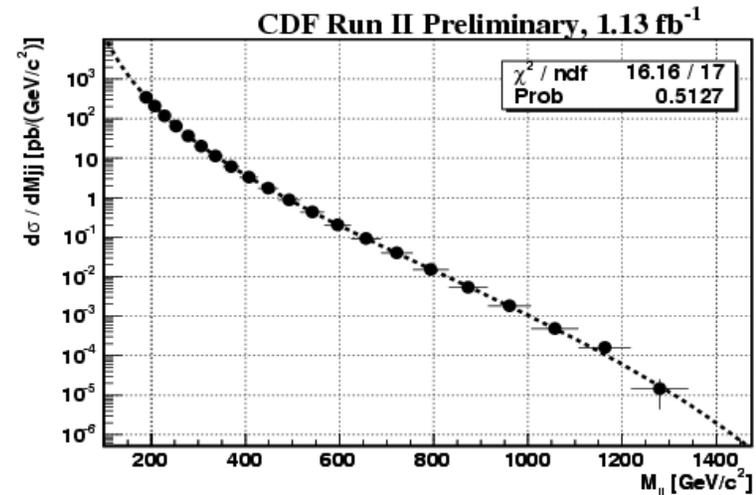


RS G^* (spin 2)
 $m > 293 - 921 \text{ GeV}/c^2$

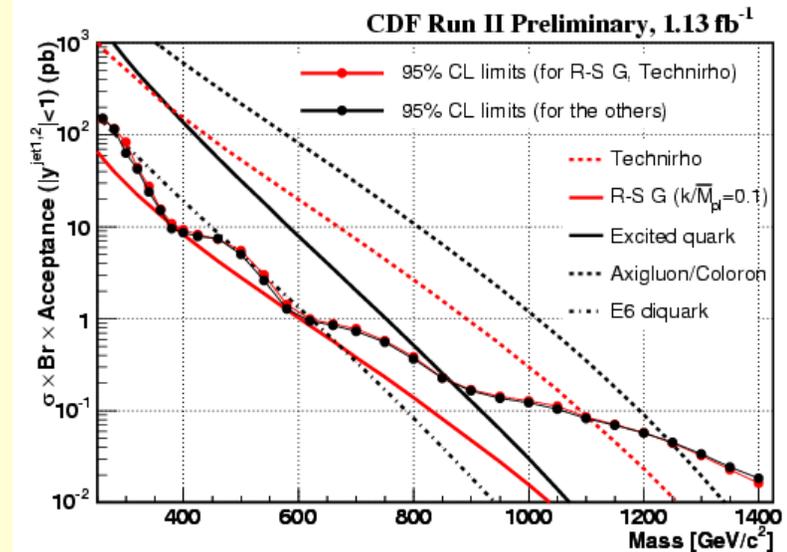
Update with 5 fb^{-1} and alternative method will be ready soon!

Search for High Mass Di-jet Resonances

- Many Models with new particles decaying into di-jets
 - Axiglons, excited quarks, W' and Z' , di-quarks in E_6 , RS gravitons, etc.
 - SM couplings for W'/Z'
 - $k/M_{pl}=0.1$ for R-S graviton
- Events with $N_{jet} \geq 2$, $|y| < 1.0$, $M_{jj} > 180$ GeV/c^2



Observed mass exclusion	Model
260-870 GeV/c^2	Excited quark
260-1110 GeV/c^2	Color-octet technirho
260-1250 GeV/c^2	Axigluon & coloron
260-630 GeV/c^2	E_6 diquark
260-840 GeV/c^2	W' (SM couplings)
260-740 GeV/c^2	Z' (SM couplings)



PRD 79, 112002 (2009)