Search for SUSY at the Tevatron

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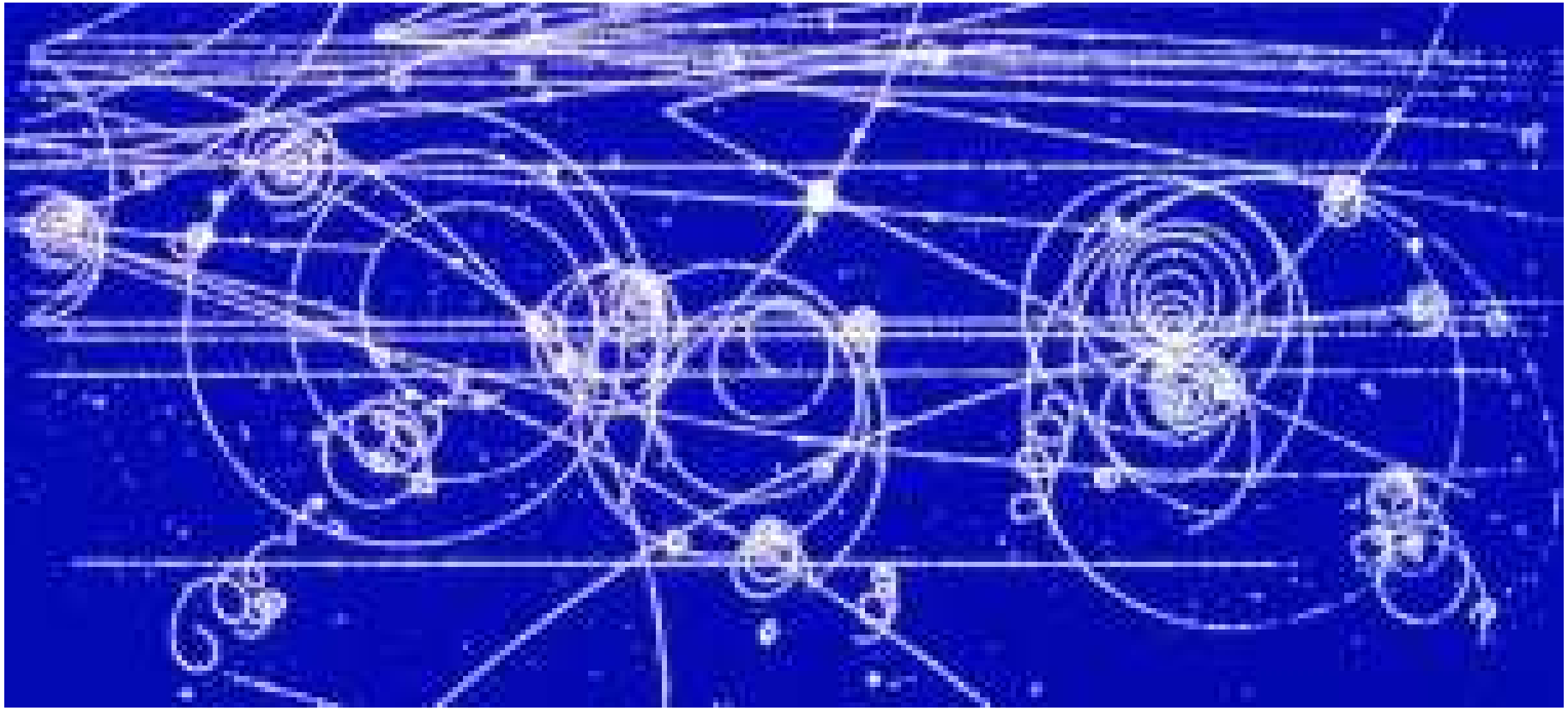
DIS 2009, Madrid, Spain, 26-30 April 2009

For CDF and DØ Collaborations



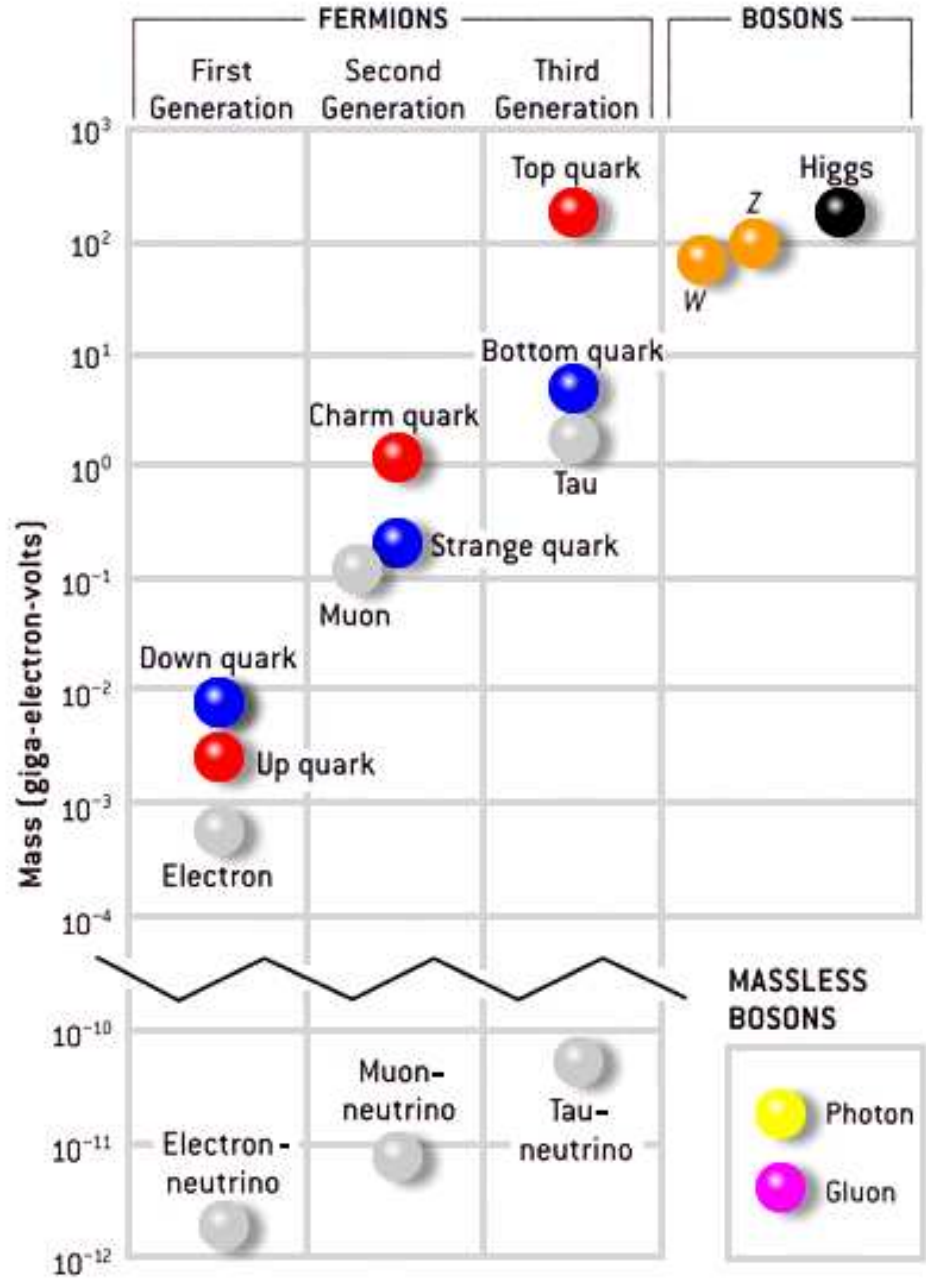
Why

Standard Model (SM)

- The SM describes data from collider experiments very well
- The only particle missing is Higgs boson
  - Directly sensitive to Λ_{UV} (unlike other SM particles)
  - Enormous quantum corrections:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots$$

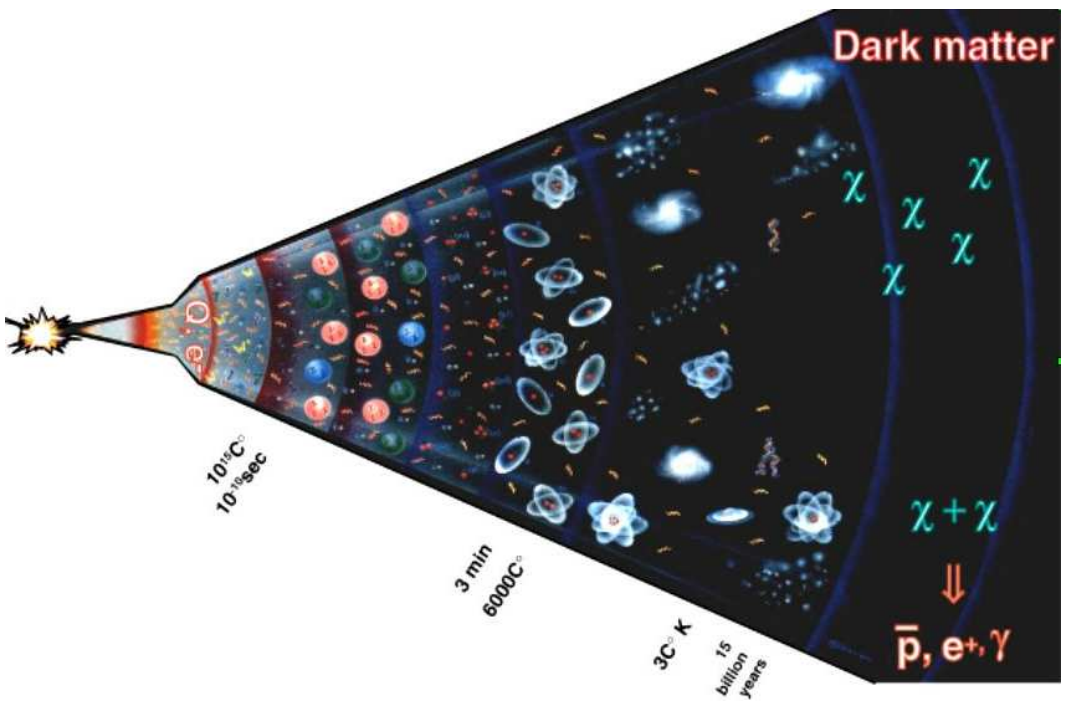
- The predicted high energy behavior is unphysical at the TeV scale
- Didn't predict massive neutrinos
- Cosmology data needs more: Dark Matter Candidate

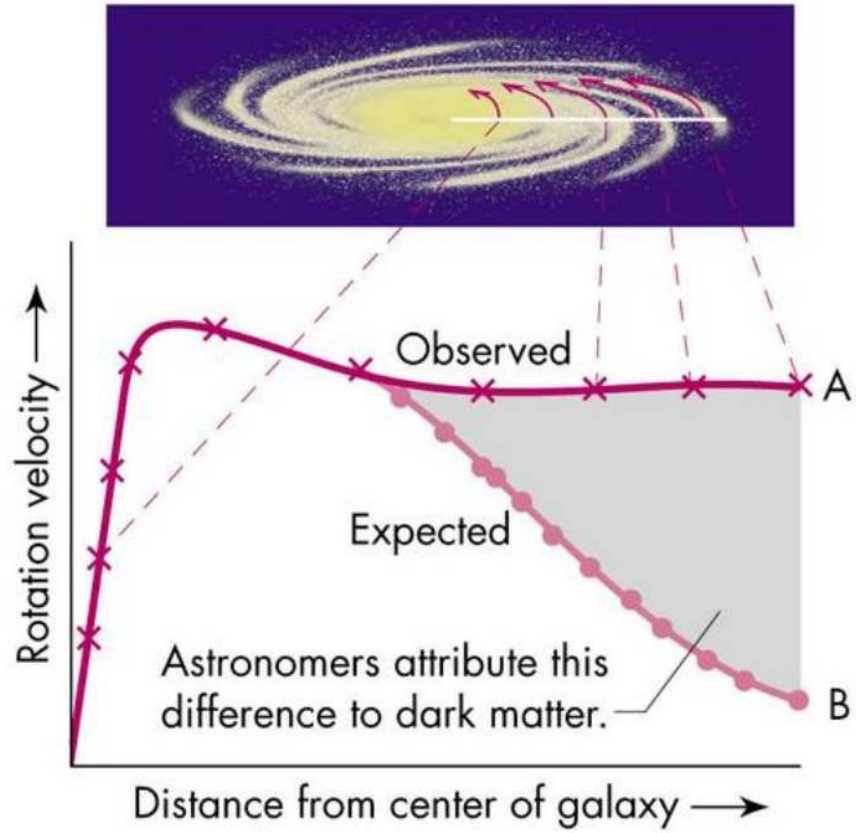


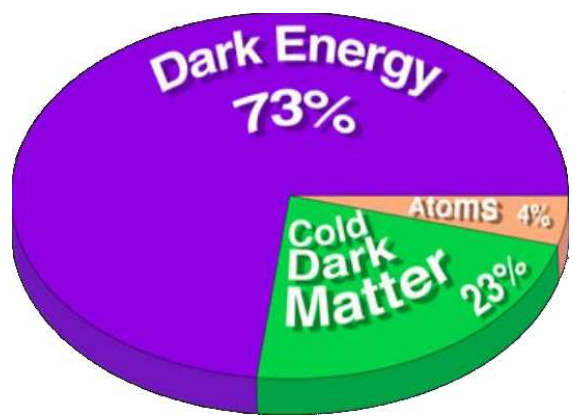
Why

Cosmology

- Galaxy Rotation
- Requires massive stable particles
- The theory should
  - Describe early Universe physics
  - Predict relic density (WMAP data)

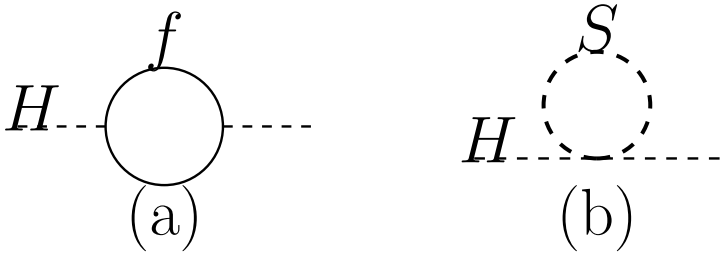






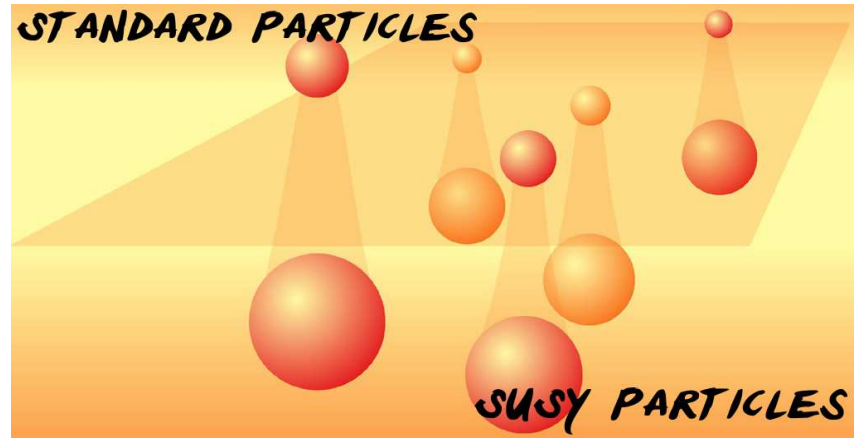
SUSY

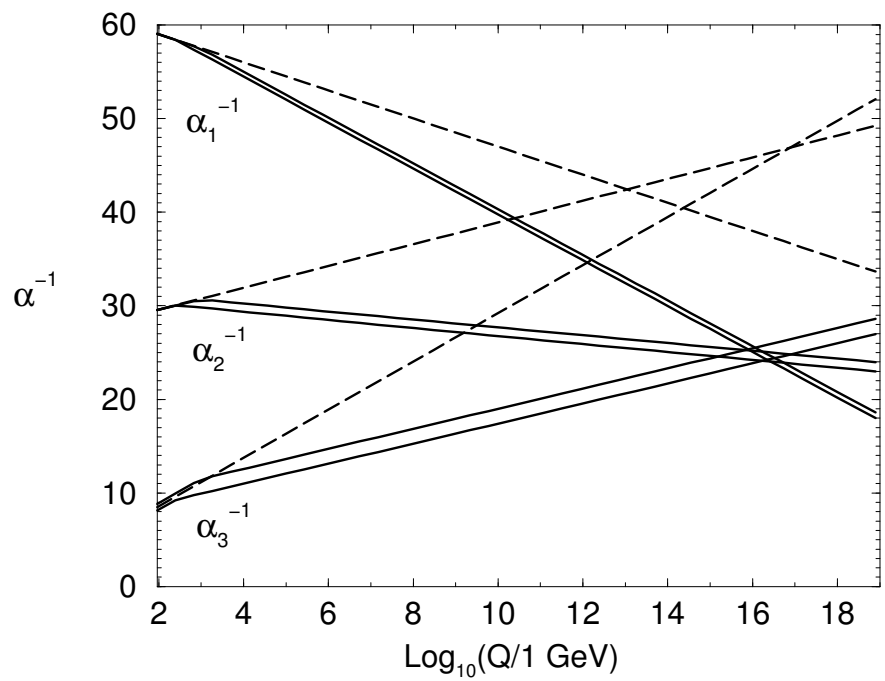
- Higgs boson mass quantum corrections



$$\Delta m_H^2 = \frac{1}{8\pi^2}(\lambda_S - |\lambda_f|^2)\Lambda_{\rm UV}^2 + \ldots$$

- $Q|\text{Boson}\rangle = |\text{Fermion}\rangle$,
  $Q|\text{Fermion}\rangle = |\text{Boson}\rangle$
- R-Parity: $P_R = (-1)^{3(B-L)+2s}$
  1 for SM, -1 for superpartners
- R-parity is conserved:
  - The SUSY particles produced in pairs
  - Dark Matter candidate
- Supersymmetry is broken
- 32 new particles, 105 new parameters



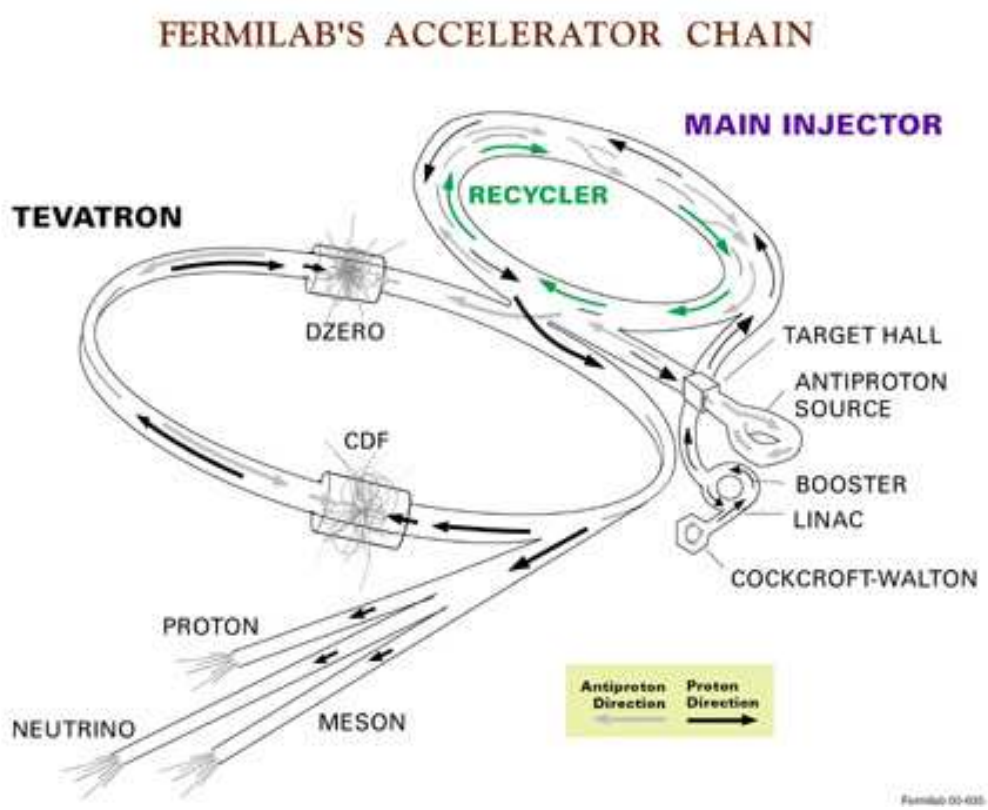


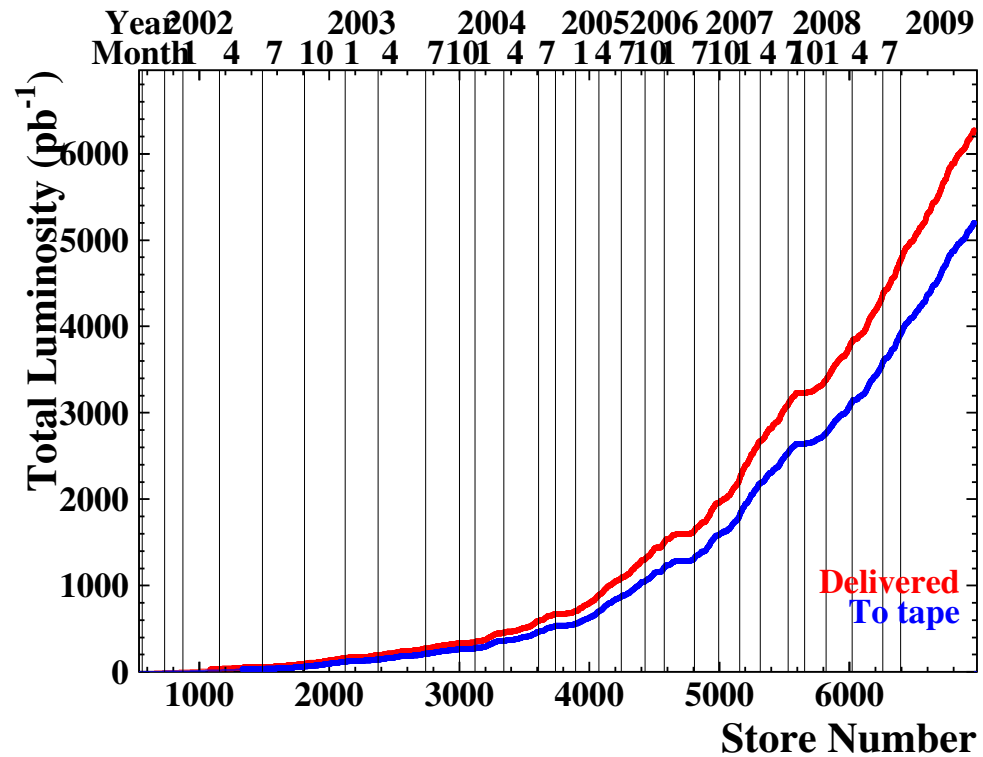
SUSY

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	H_u^0 H_d^0 H_u^+ H_d^-	h^0 H^0 A^0 $H^\pm$
squarks	0	−1	$\widetilde{u}_L$ $\widetilde{u}_R$ $\widetilde{d}_L$ $\widetilde{d}_R$	(same)
			$\widetilde{s}_L$ $\widetilde{s}_R$ $\widetilde{c}_L$ $\widetilde{c}_R$	(same)
			$\widetilde{t}_L$ $\widetilde{t}_R$ $\widetilde{b}_L$ $\widetilde{b}_R$	$\widetilde{t}_1$ $\widetilde{t}_2$ $\widetilde{b}_1$ $\widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L$ $\widetilde{e}_R$ $\widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L$ $\widetilde{\mu}_R$ $\widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L$ $\widetilde{\tau}_R$ $\widetilde{\nu}_\tau$	$\widetilde{\tau}_1$ $\widetilde{\tau}_2$ $\widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0$ $\widetilde{W}^0$ $\widetilde{H}_u^0$ $\widetilde{H}_d^0$	$\widetilde{\chi}_1^0$ $\widetilde{\chi}_2^0$ $\widetilde{\chi}_3^0$ $\widetilde{\chi}_4^0$
charginos	1/2	−1	$\widetilde{W}^\pm$ $\widetilde{H}_u^+$ $\widetilde{H}_d^-$	$\widetilde{\chi}_1^\pm$ $\widetilde{\chi}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

Where: Tevatron

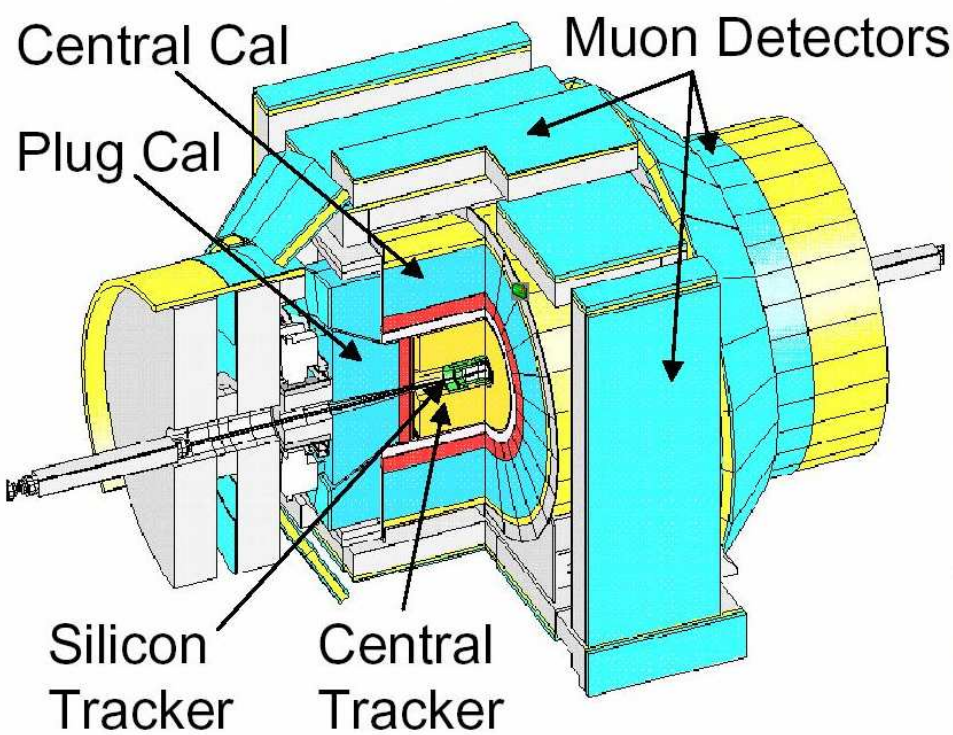
- $p\bar{p}$ **Collisions**
- $\sqrt{s}$=**1.96** TeV
- $\mathcal{L}_{peak}$ = **3.7**$\times 10^{32}$ **cm**$^{-2}$**s**$^{-1}$

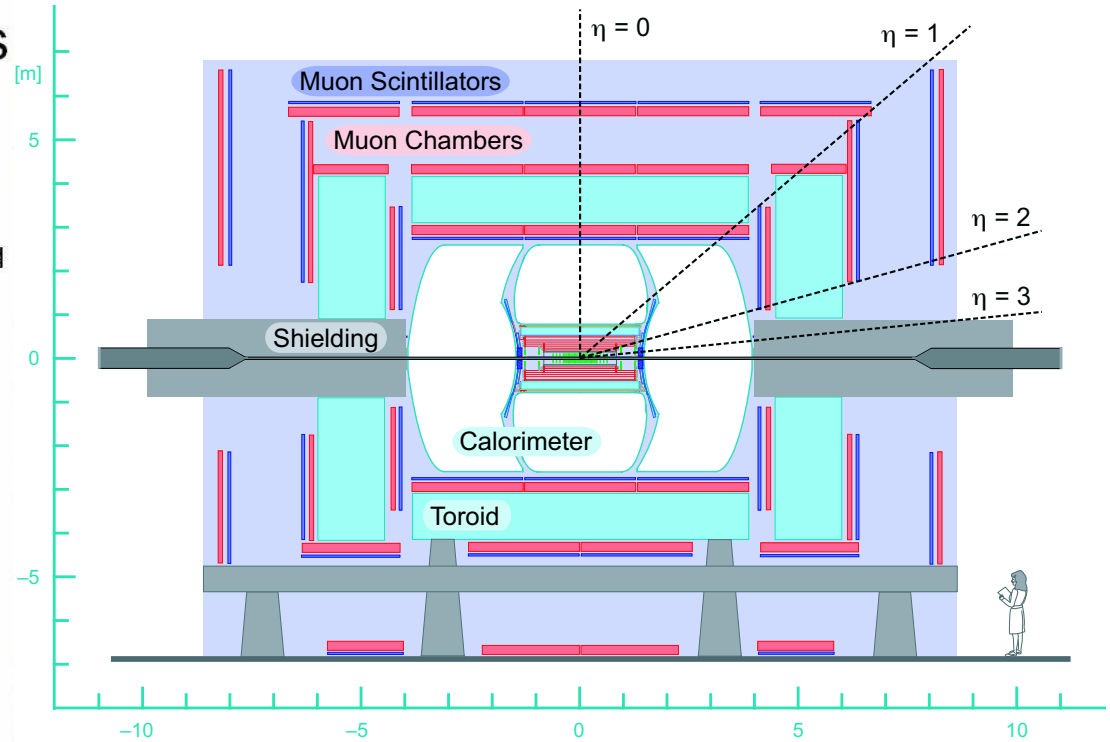


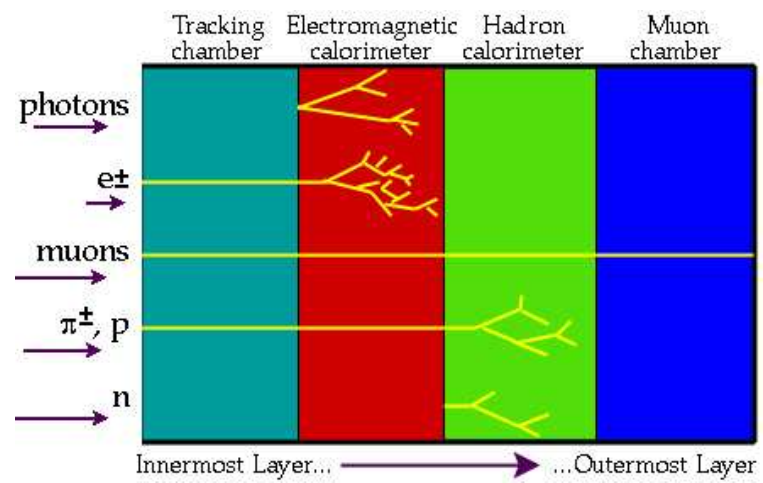


- >6 fb^{-1} delivered, >5 fb^{-1} on tape
- In this talk: up to 4.1 fb^{-1} results

Where: CDF and $D\emptyset$



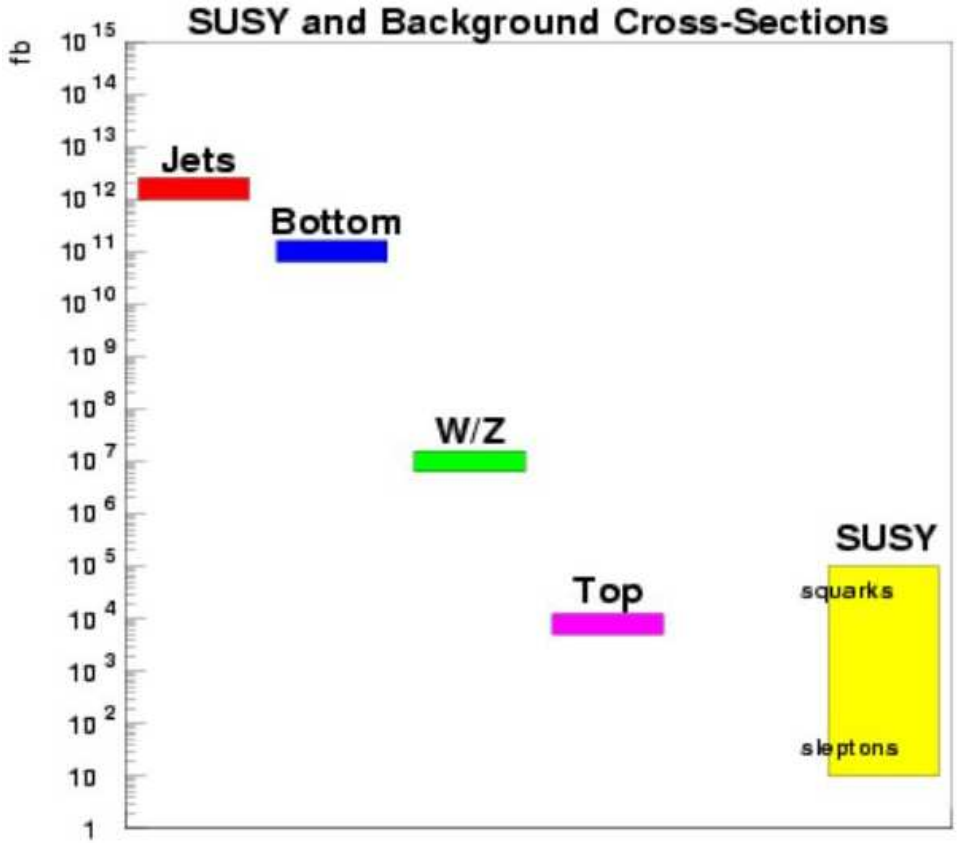




Detectors and identified objects:

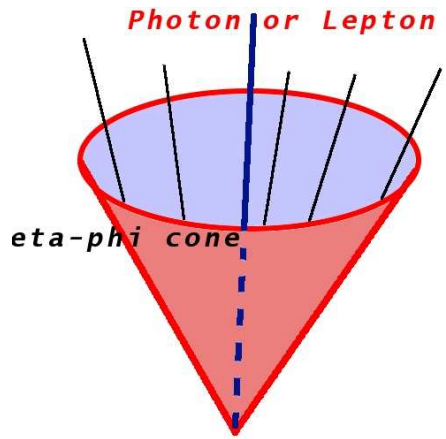
- Trackers: e, μ, jets
- Calorimeters: e, μ, jets, $\not{E}_T$
- Muon Detectors: μ, soft $\mu's$ from jets

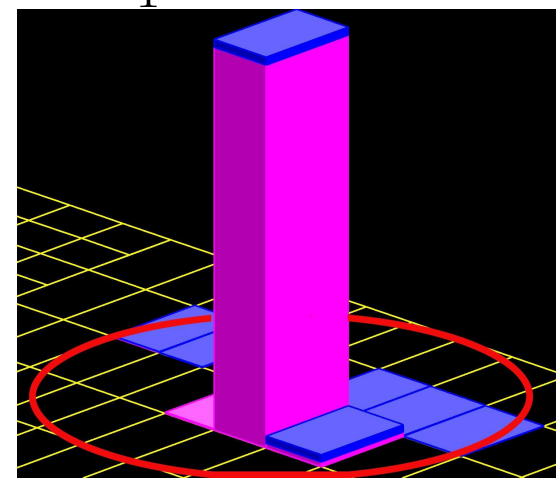
Physics



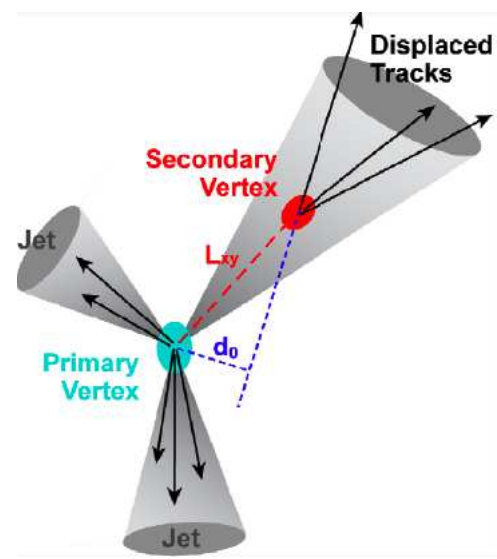
Tracking Iso: $\sum \mathrm{p}_{\mathrm{T}}^{track}$ in $\eta - \phi$

Calorimeter Iso: $\sum \mathrm{E}_{\mathrm{T}}^{tower}$ in $\eta - \phi$





Jet with a displaced vertex:
"b-tag", "HF-jet"



Data-driven backgrounds are crucial

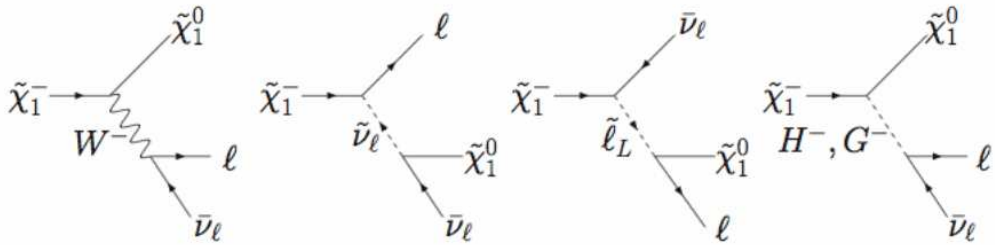
- Jets misID as leptons
  - Isolation etc.
- Fake $\not\!\!E_{\mathrm{T}}$ (mismeasured jet, lost μ)

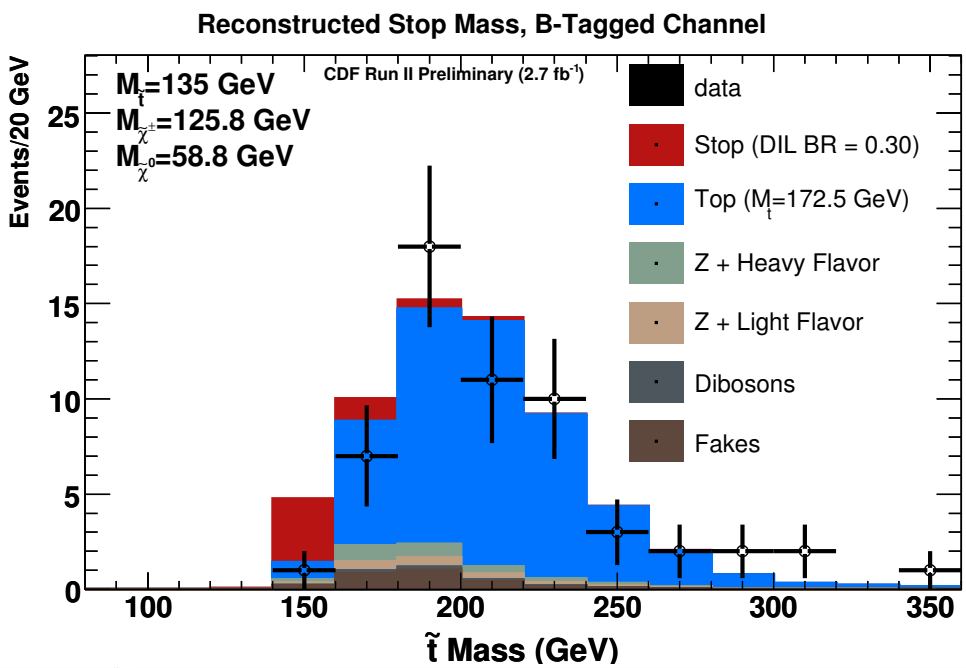
Physics

- Stop
  Top sample is large and pure, top dileptons are under control
- Sbottom
  4 b-quarks in the final state
- RPV $\tilde{\nu}_{\tau}$
  Single sparticle production is allowed
- Direct production of the Gauginos
  Lighter, EWK production cross sections, leptonic final states
- Squarks and Gluinos:
  Heavy, but strong production cross-section
- CHAMPs (Charged MAssive Stable Particles)
  "slow moving muons"

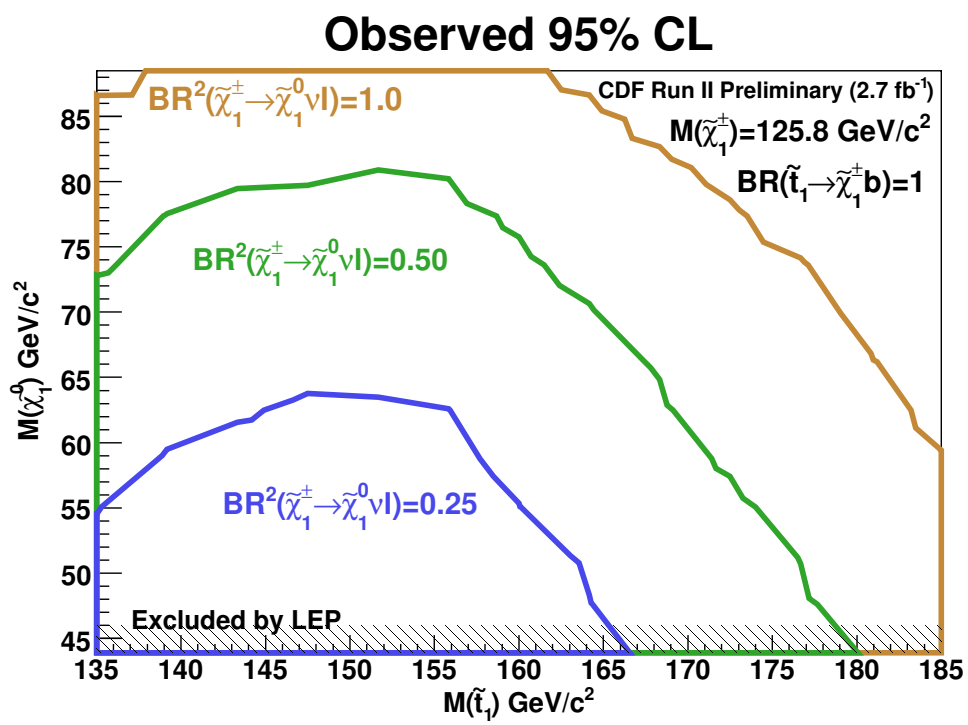
Physics: Stop

- $\tilde{t} \to b\tilde{\chi}_1^{\pm} \to b\tilde{\chi}_1^0 \ell\nu \; (m_{\tilde{t}_1} < m_t)$
- on-shell charginos
- $t\bar{t}$ sample: $\ell\ell \not{E}_T + 2\, b - jets$



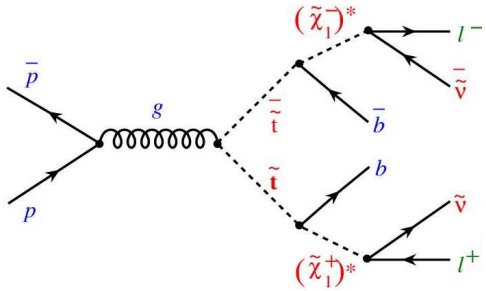


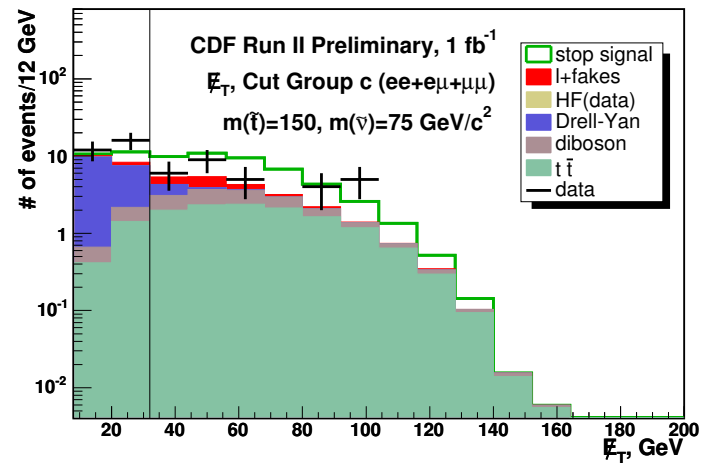
Source	ee	$\mu\mu$	$e\mu$	ll
Total	14.2 ± 2.0	12.4 ± 1.6	29.4 ± 3.8	56.0 ± 7.3
stop	1.1 ± 0.3	1.4 ± 0.4	3.0 ± 0.7	5.5 ± 1.2
Data	15	12	30	57



Physics: Stop

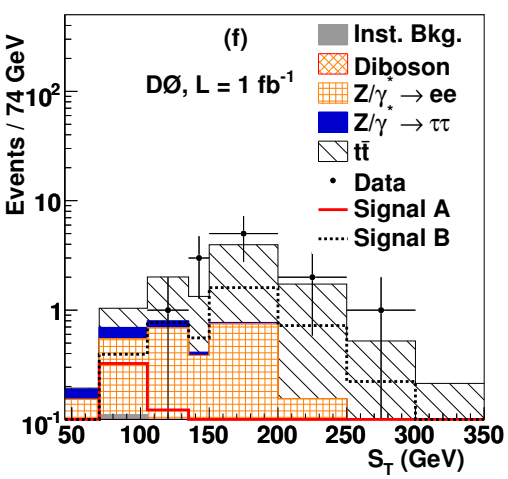
- $\tilde{t} \to \ell b \tilde{\nu}$ $(m_{\tilde{\chi}_1^\pm} > m_{\tilde{t}})$
- $D\emptyset$ ee, $e\mu$
- CDF ee, $e\mu$, $\mu\mu$

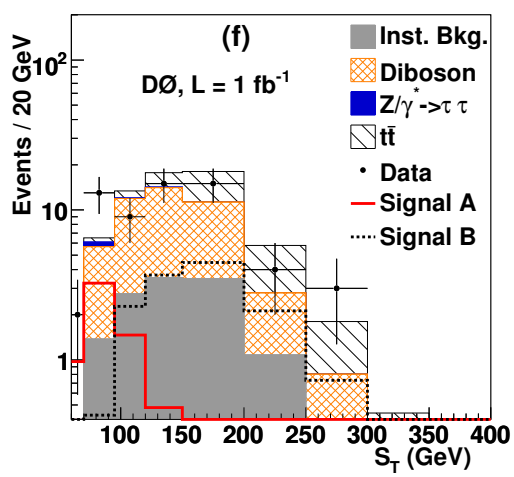




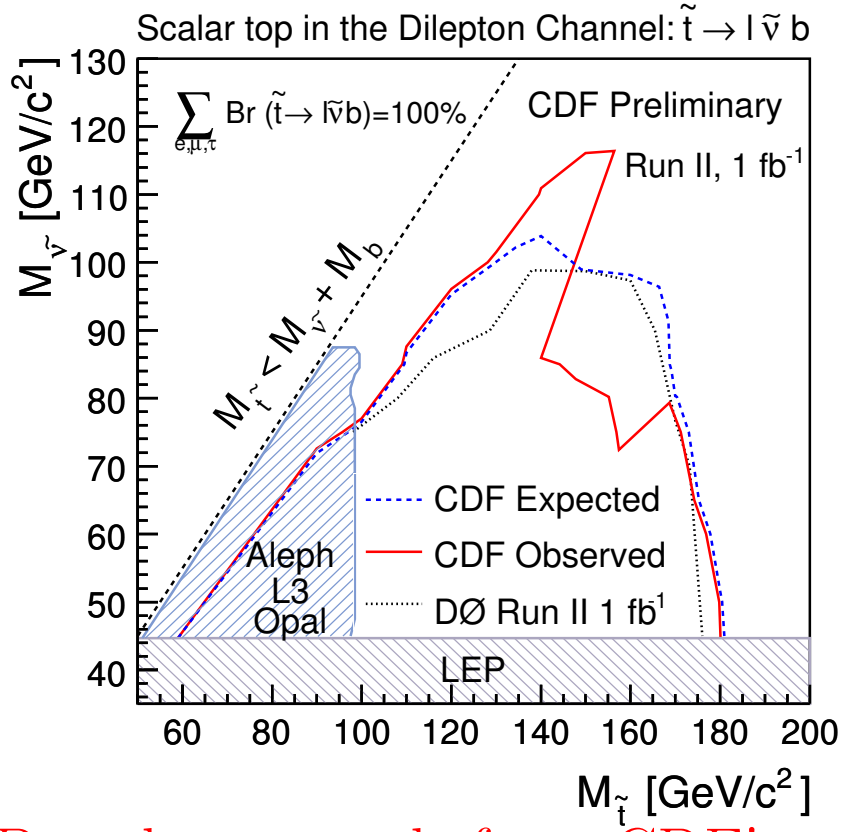
$D\emptyset$: arXiv 0811.0459 (accepted to PLB)

channel	Data	Exp. Bkg.	Sig. A	Sig. B
$e\,e$	12	12.2 ± 0.4	0.6	4.6
$e\,\mu$	61	65 ± 4	6.0	16.1





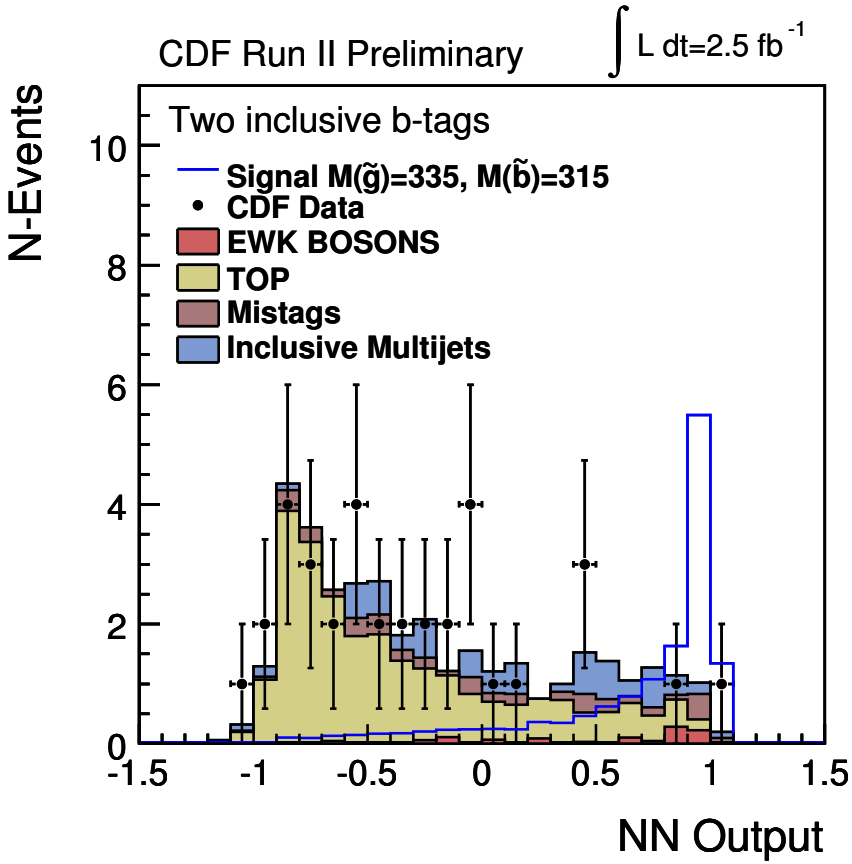
A/B: $m(\tilde{t}, \tilde{\nu}) = (140, 110)/(170, 90)\ GeV$

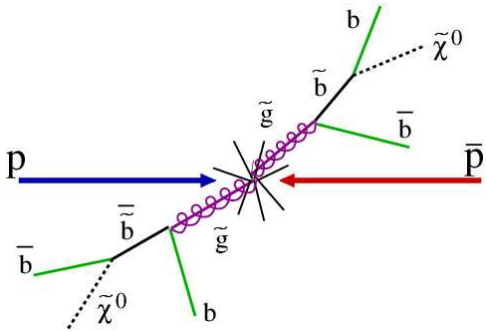


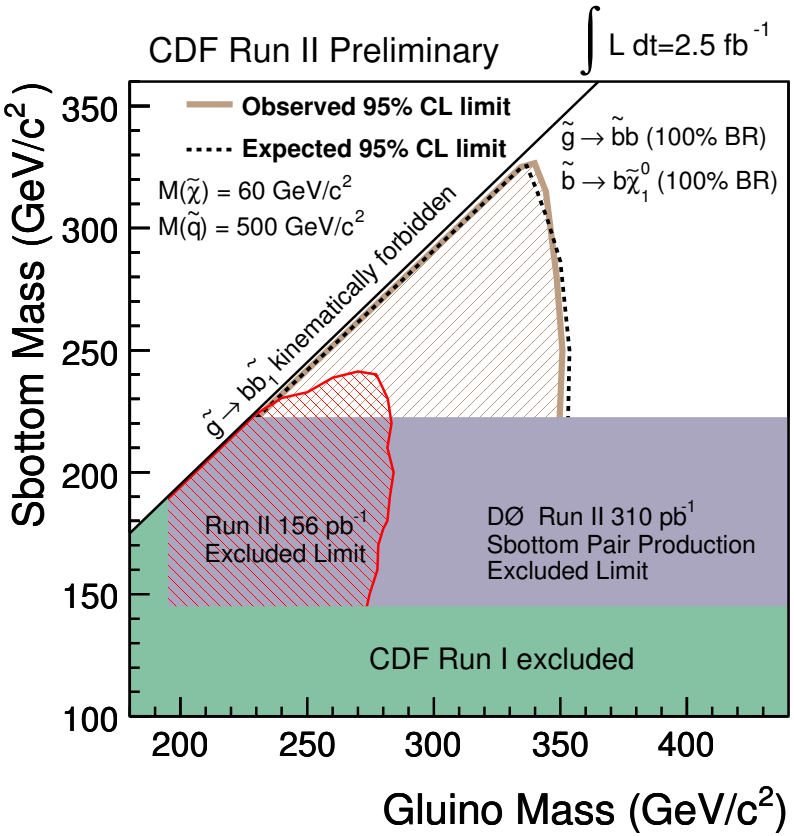
Brand new result from CDF!

Physics: Sbottom (from gluino decay)

- $\tilde{g} \to \tilde{b}\bar{b}$, $\tilde{b} \to b\tilde{\chi}_1^0$
- $\not{E}_T + 4\ b - jets$, 2.5 fb^{-1} (CDF)
- 2 NN (small and large $\Delta m_{\tilde{g}\tilde{b}}$)
- 1 and 2 b-tags samples



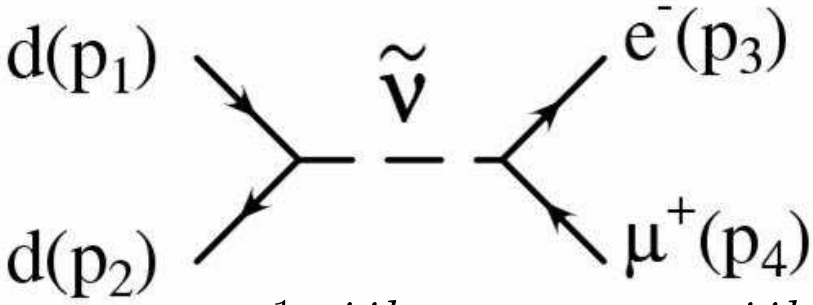


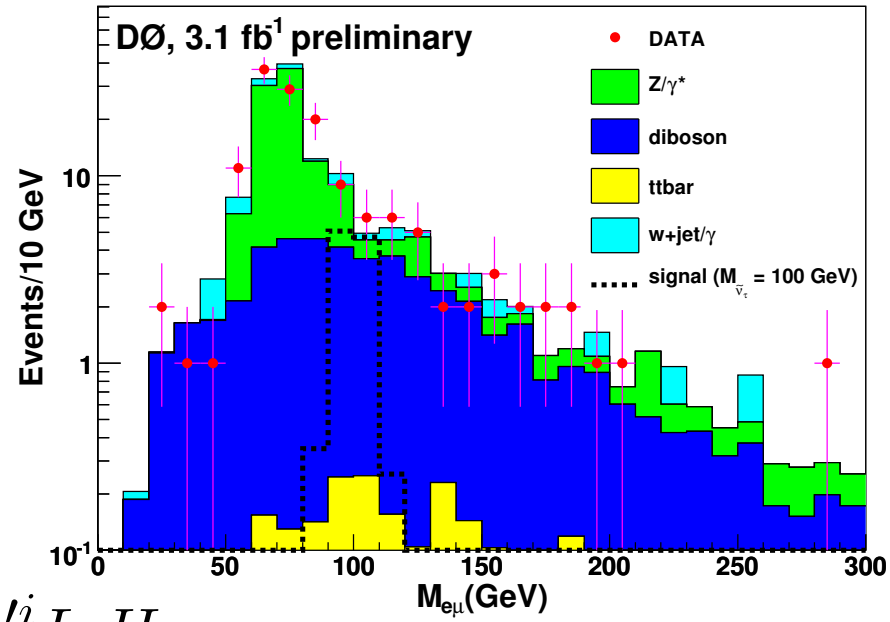


DØ PRL 97 171806 (2006), 310 pb^{-1}

Physics: RPV $\tilde{\nu}_\tau$

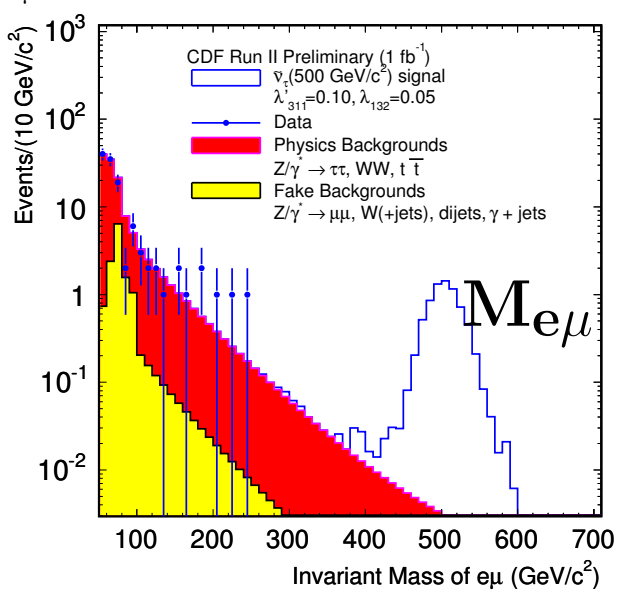
- CDF @ 1 fb^{-1}: $e\mu$, $\mu\tau$,$e\tau$
- $D\emptyset$ @ 4.1 fb^{-1}: $e\mu$



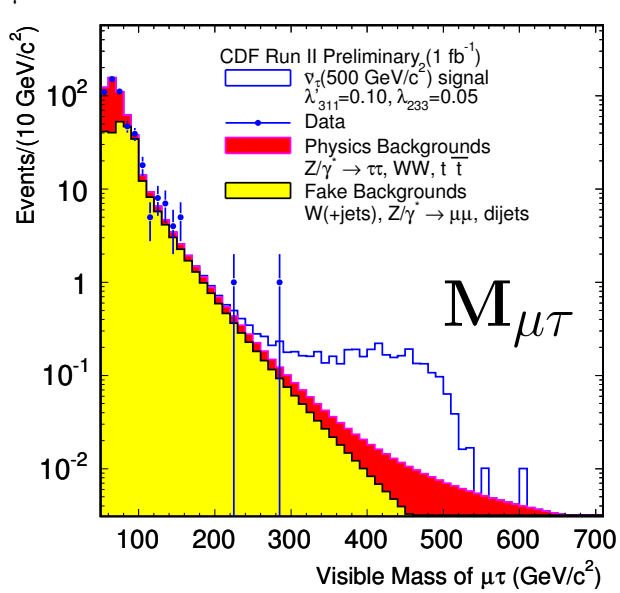


$$W_{\Delta L=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu'^i L_i H_u$$

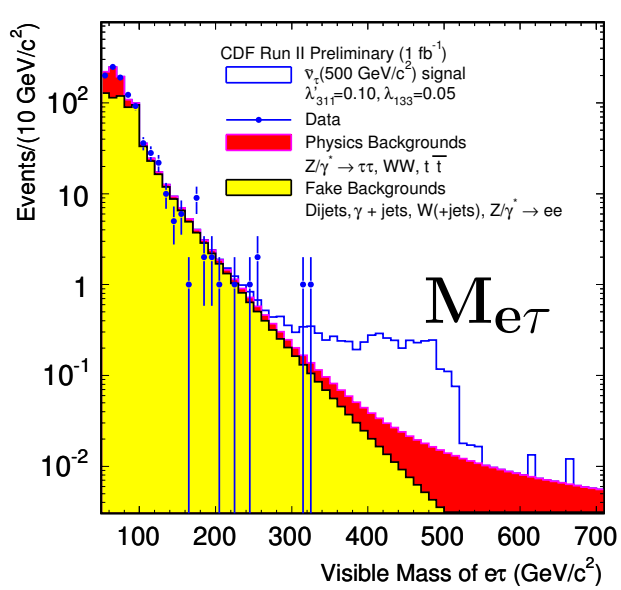
eμ Channel



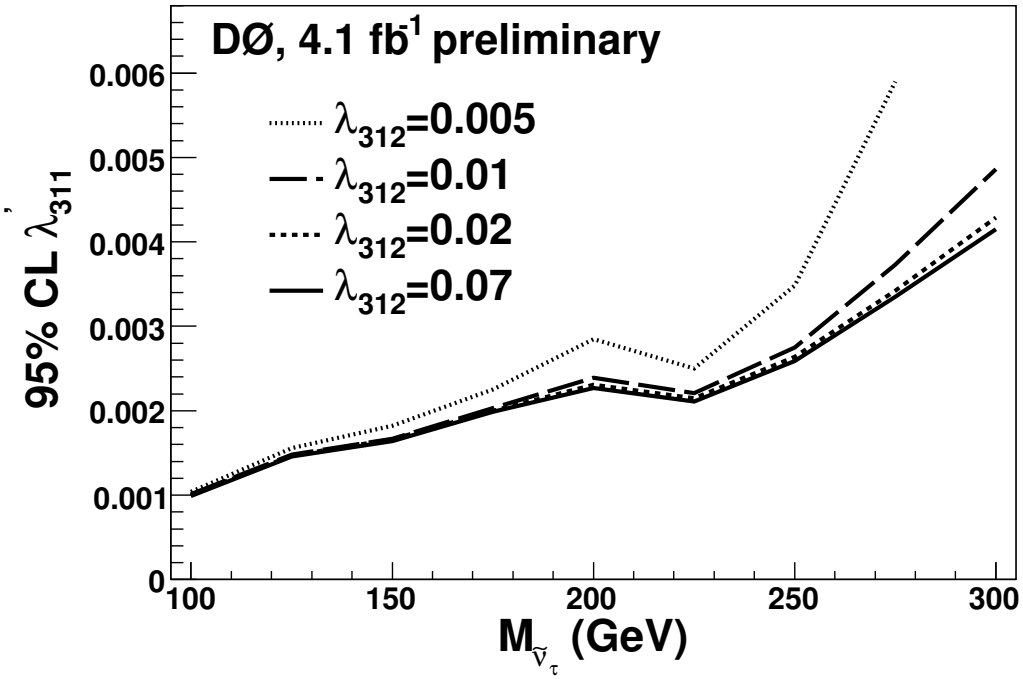
μτ Channel

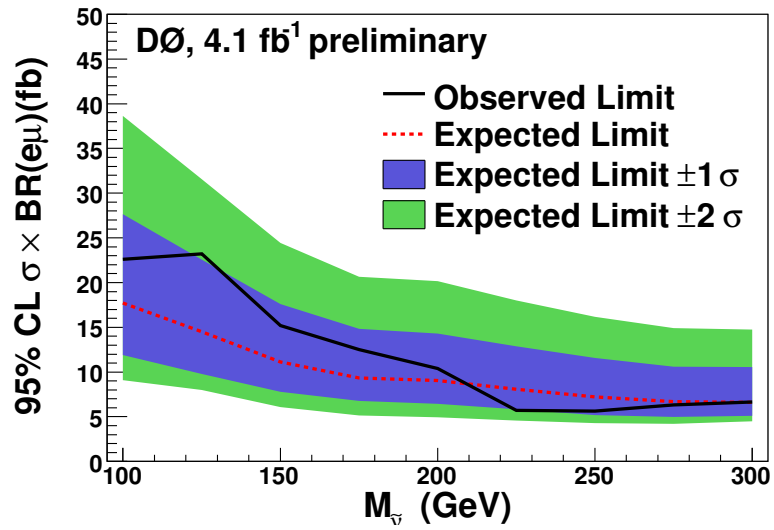


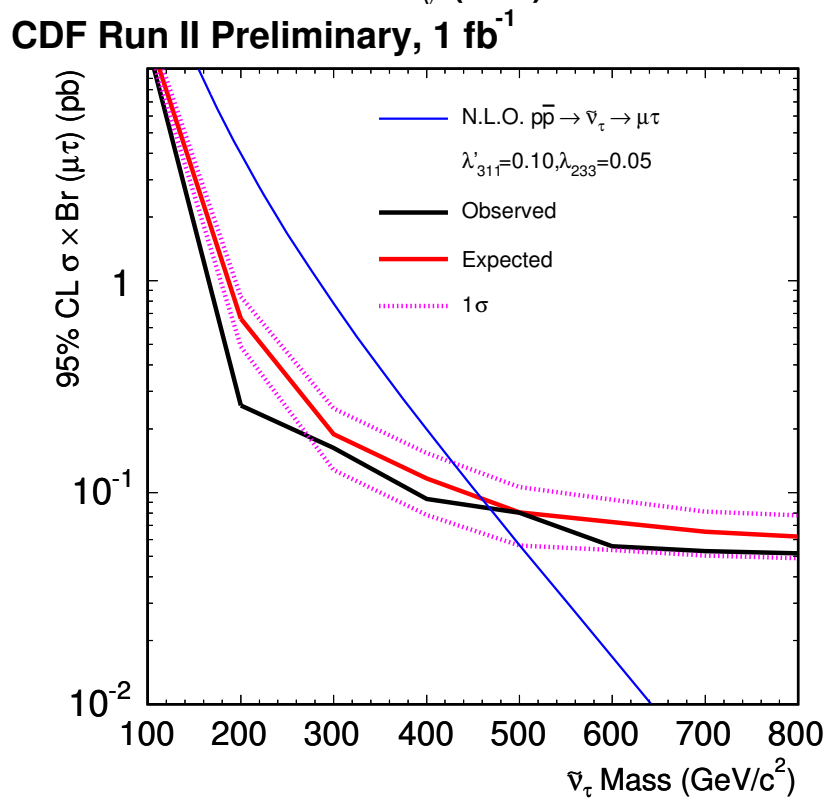
eτ Channel



Physics: RPV $\tilde{\nu}_\tau$



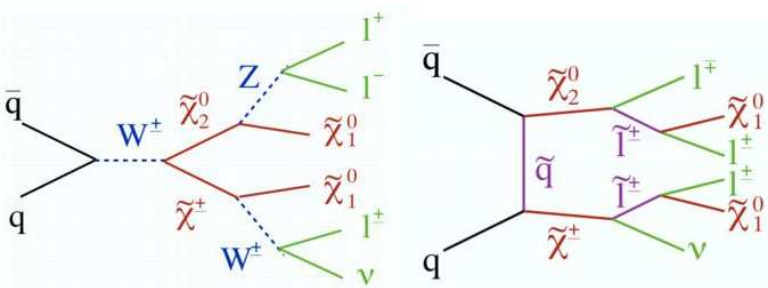




DØ:

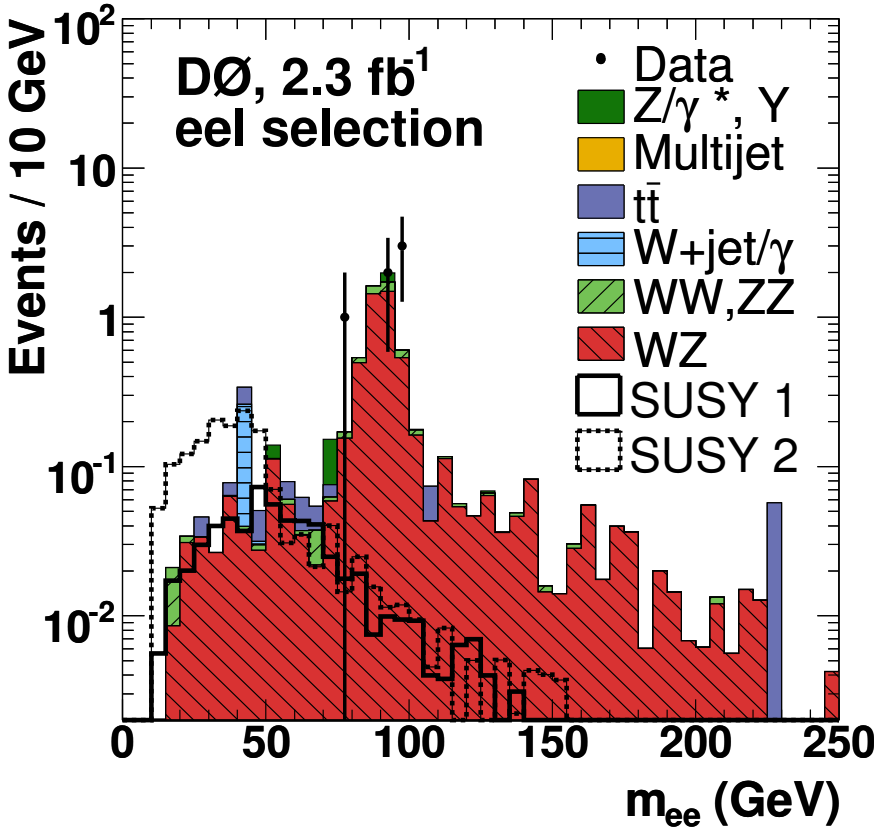
- All RPV couplings are null but λ'_{311} and $\lambda_{321} = \lambda_{312}$
- $\lambda'_{311} \leq 0.12$, $\lambda_{321} \leq 0.07$ for $M_{\tilde{\nu}_\tau} < 100GeV$

Physics: Chargino/Neutralino



DØ: arXiv 0901.0646

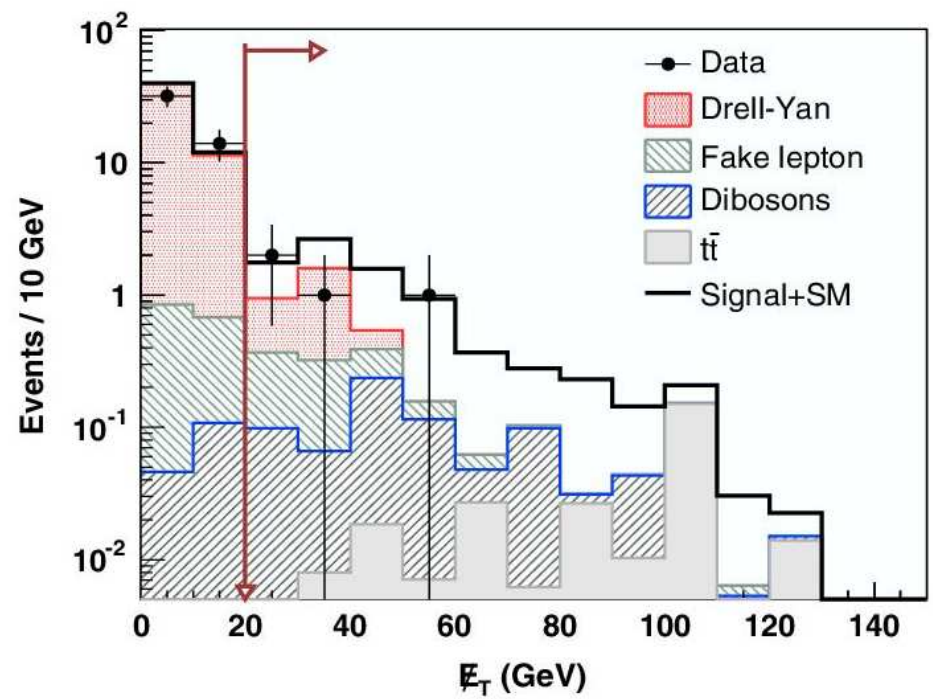
- ee, $\mu\mu$, $e\mu$, $\tau\mu$ + trk(e,μ,τ) + $\not\!\!E_T$



CDF: PRL **101**, 251801 (2008)

- 3 leptons (e, μ) + $\not\!\!E_T$
- 2 leptons (e, μ) + trk(e,μ,τ) + $\not\!\!E_T$

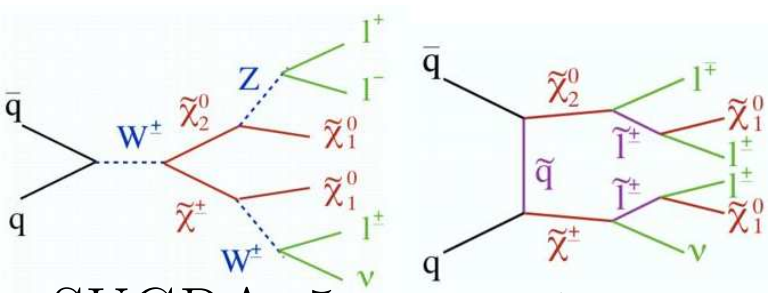
CDF 2fb^{-1}, dilepton+trk:



7 vs 6.4±1.1 (all channels)

fake ℓ 1.4, DY 3.0, dibosons 1.6, $t\bar{t}$ 0.5

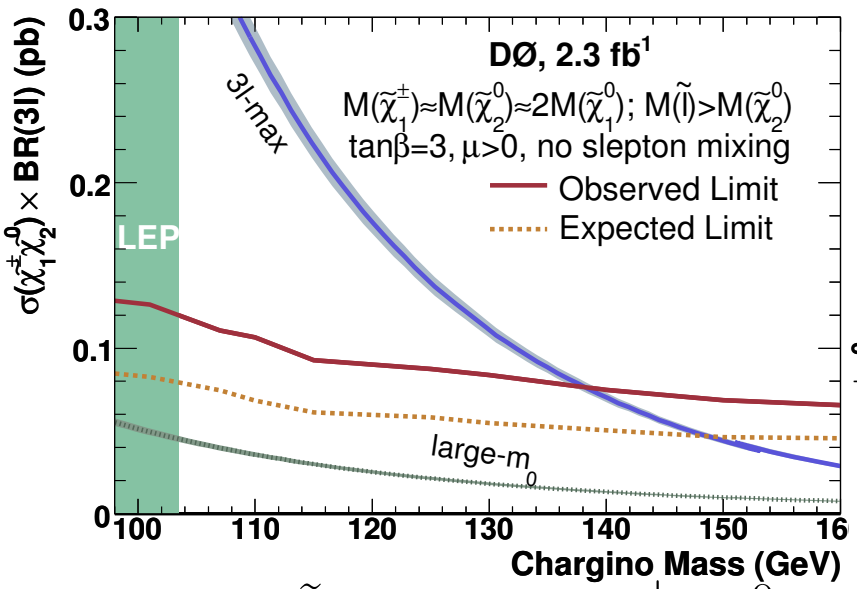
Physics: Chargino/Neutralino



mSUGRA: 5 parameters

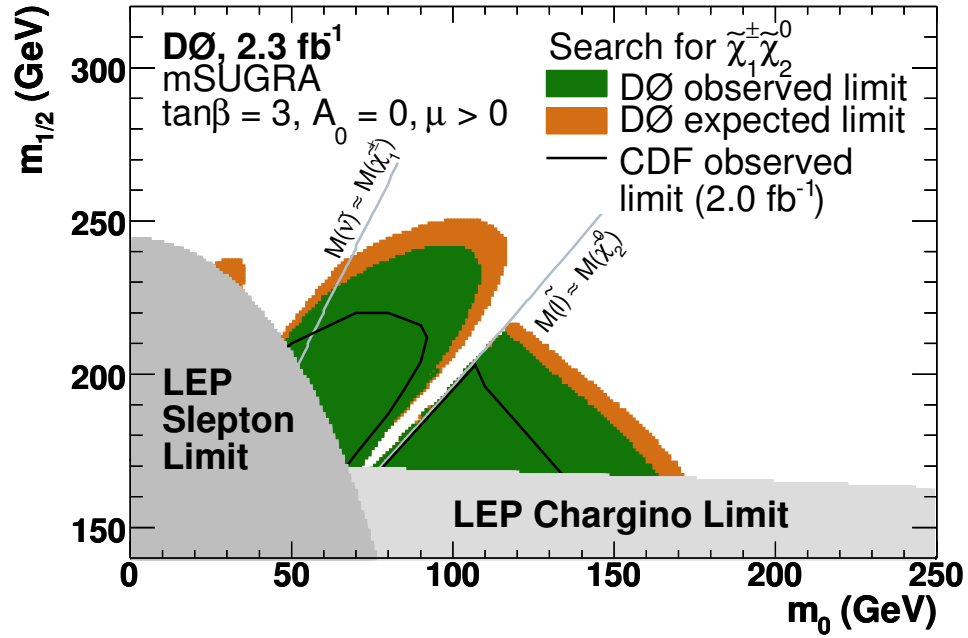
m_0, $m_{1/2}$, $\tan\beta$, A^0, sign(μ)

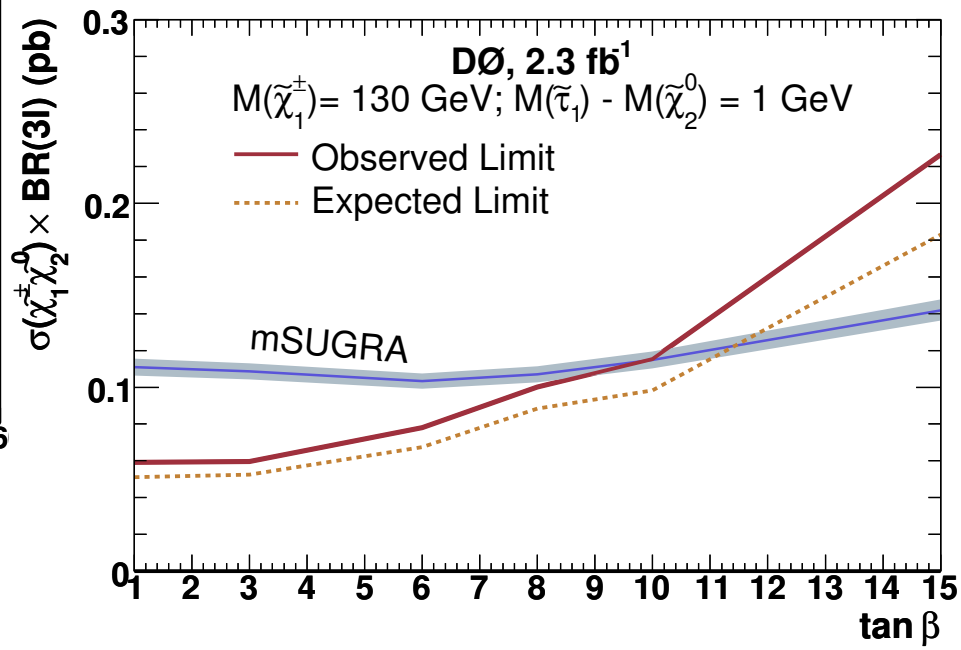
$A^0 = 0$, $\tan\beta = 3$, $\mu > 0$



3ℓ-max: $m(\tilde{\ell}, \tilde{\nu}) > m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0)$,

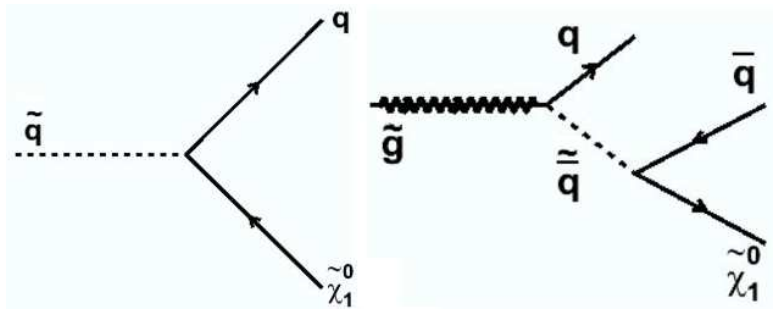
no $\tilde{\ell}$ mixing





Physics: Squark/Gluino

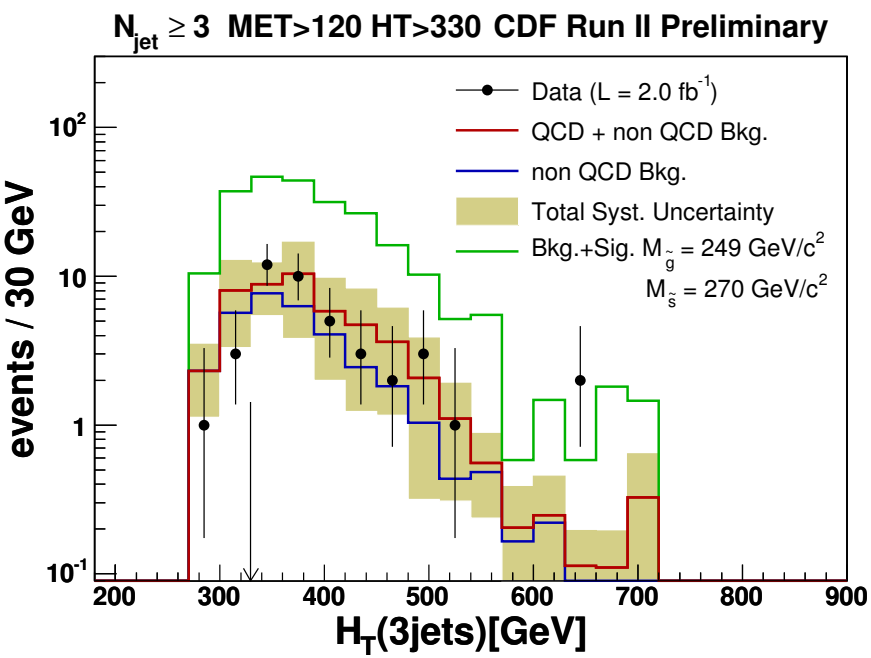
- squark $\tilde{q} \to q\tilde{\chi}_1^0$, gluino $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$
- 2 jets + $\not\!\!E_T$: $m_{\tilde{q}} < m_{\tilde{g}} \Rightarrow \tilde{q}\tilde{q}$
- 3 jets + $\not\!\!E_T$: $m_{\tilde{q}} \sim m_{\tilde{g}} \Rightarrow \tilde{q}\tilde{g}$
- 4 jets + $\not\!\!E_T$: $m_{\tilde{q}} > m_{\tilde{g}} \Rightarrow \tilde{g}\tilde{g}$
- Reject leptons. Main backgrounds: QCD, $Z \to \nu\bar{\nu}$+j, $W \to \ell\nu$+j, $t\bar{t}$

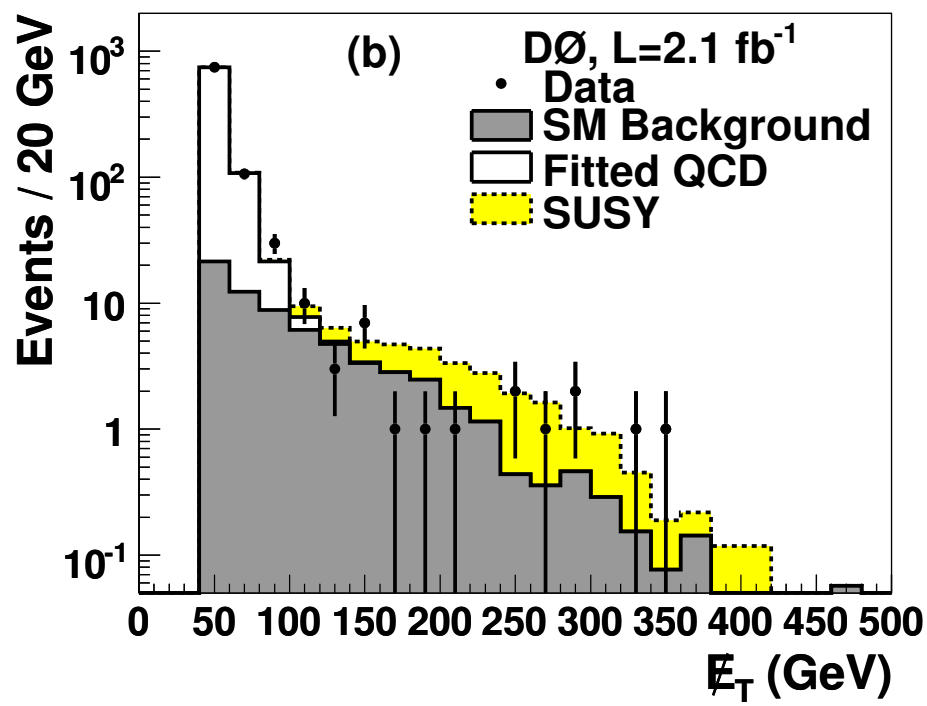


DØ: Phys. Lett. B 660 , 449 (2008)

2j: low-m_0, 3j: $m_{\tilde{q}} \approx m_{\tilde{g}}$, 4j: high-$m_0$

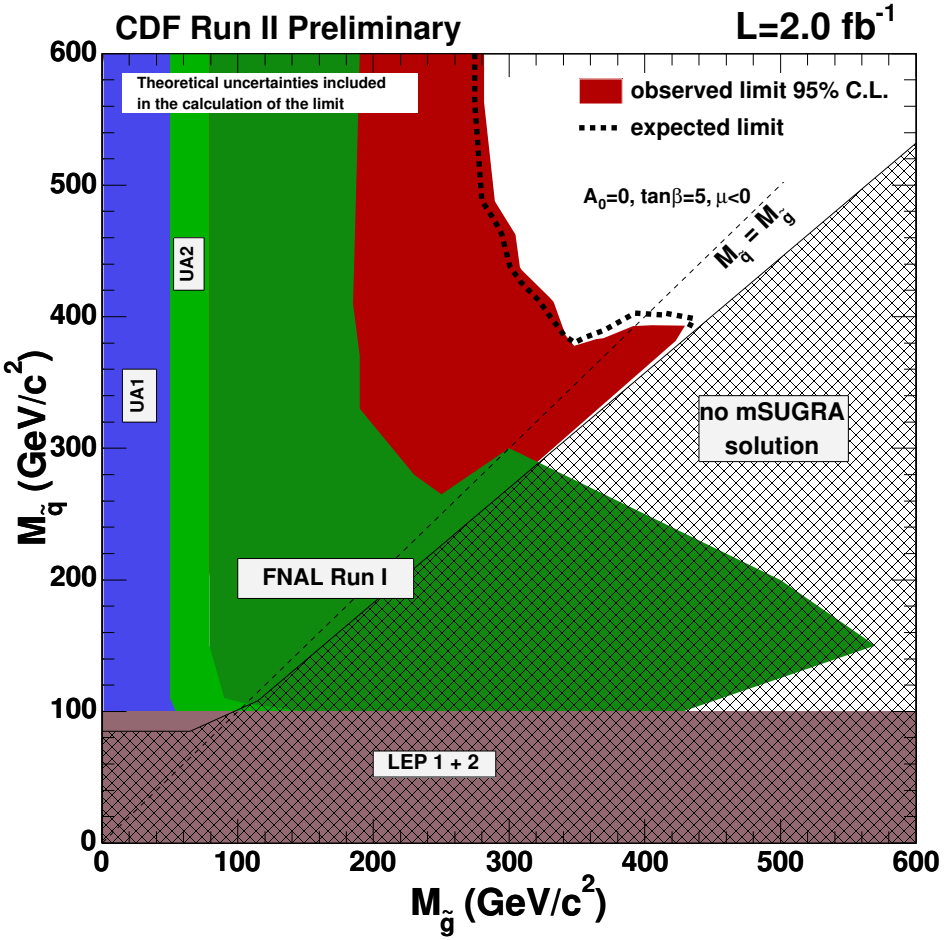
CDF: PRL 102, 121801 (2009)



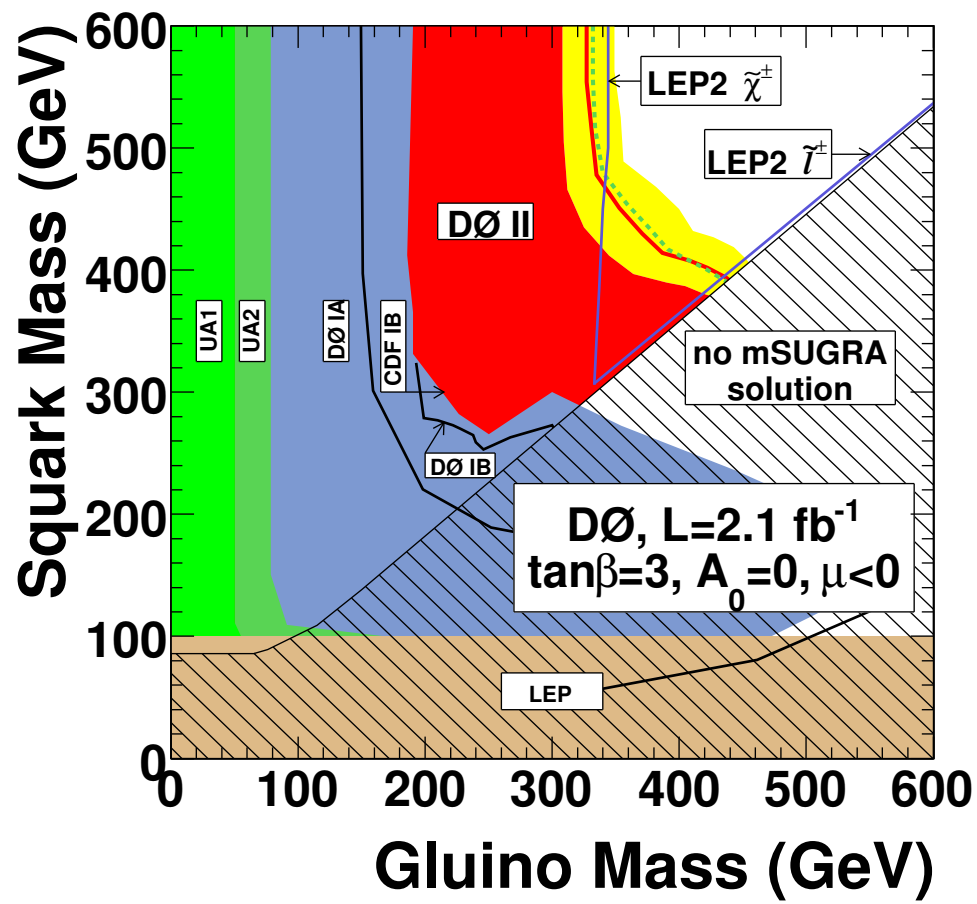


Physics: Squark/Gluino

CDF: PRL 102, 121801 (2009)



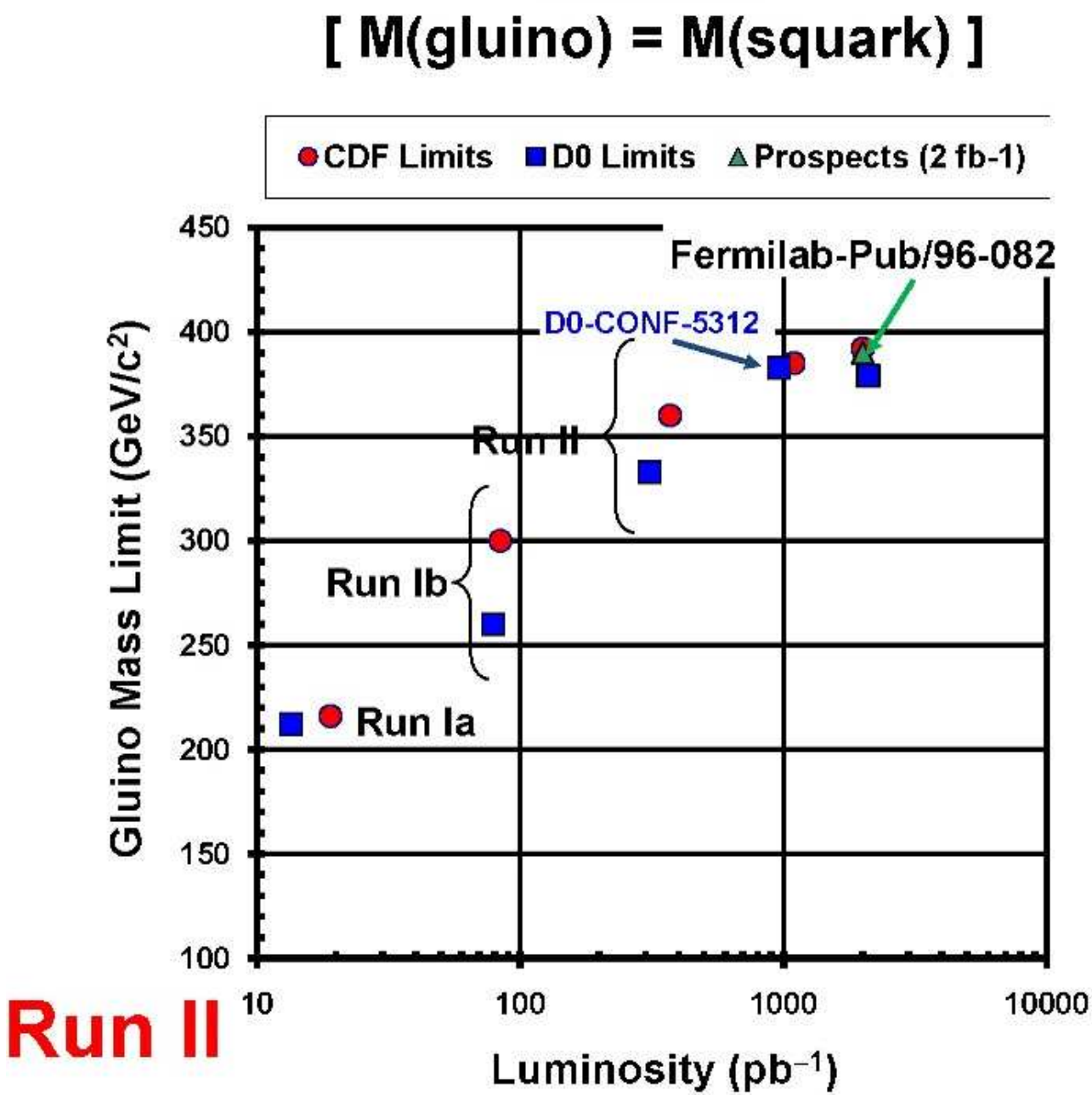
$m_{\tilde{q}} > 379\ GeV$
$m_{\tilde{g}} > 308\ GeV$



$m_{\tilde{g}} \approx m_{\tilde{q}}$: $m_{\tilde{g}} > 392\ GeV$
any $m_{\tilde{q}}$: $m_{\tilde{g}} > 280\ GeV$
$m_{\tilde{q}} < 378\ GeV$: $m_{\tilde{g}} > 423\ GeV$

DØ: Phys. Lett. B 660 , 449 (2008)

Physics: Squark/Gluino

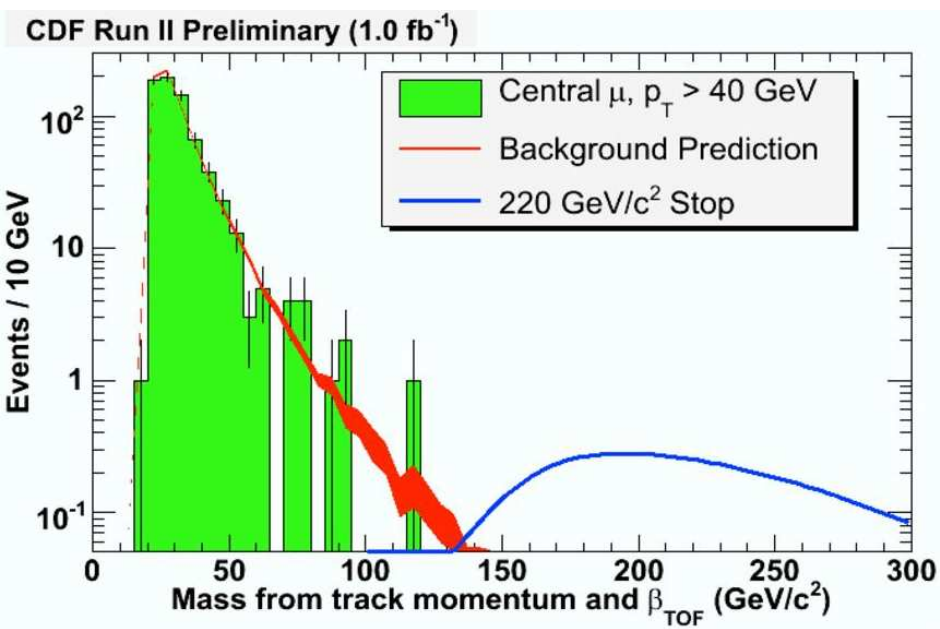


Physics: CHAMPs

- Charged MAssive Stable Particles
- Appear as "slow moving muons"
- stop, stau, chargino, ...

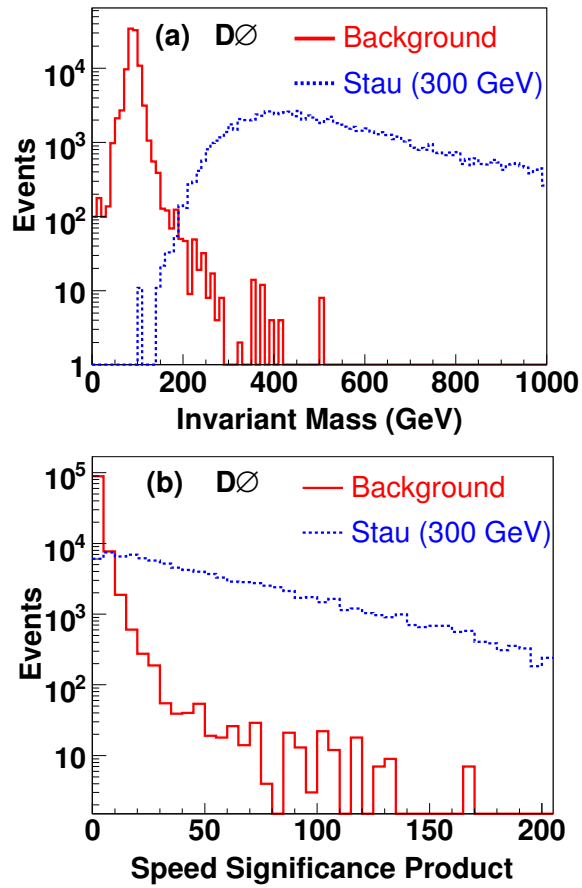
CDF: arXiv 0902.1266, sub.to PRL

- Time of Flight (TOF) detector
- Tracking
- $W \to e\nu$, $Z \to ee$ for TOF studies



DØ: arXiv 0809.0472, sub.to PRL

- Timing in μ system $\Rightarrow$ the speed
- $M(\mu\mu)$
- 1)$Z\mu\mu$, 2)$(1-\bar{v})/\sigma_v < 0$



Physics: CHAMPs

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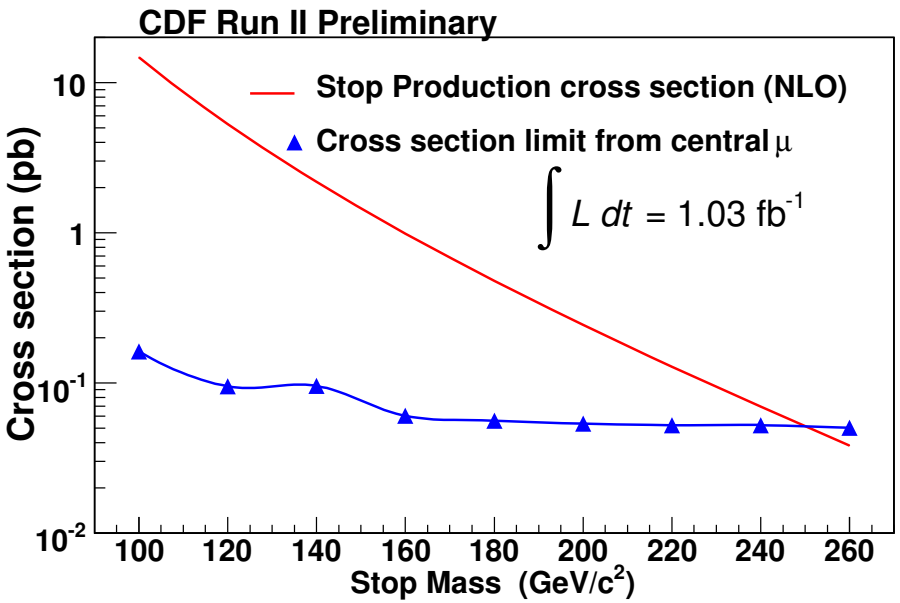
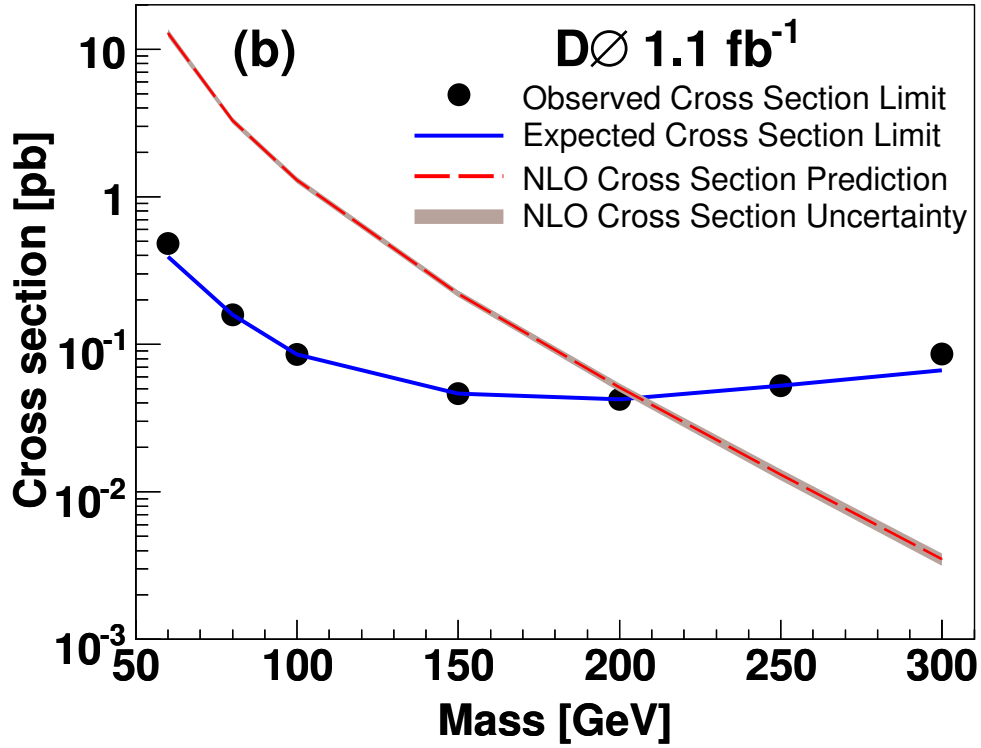


Same result implies:

- $\sigma^{ch} < 10fb$ at 95% CL for $p_T^{ch} > 40GeV$, $|\eta^{ch}| < 1$, $0.4 < \beta^{ch} < 0.9$

DØ: arXiv 0809.0472, sub.to PRL



Limits for chargino mass for pair produced gaugino-like charginos

Summary

- **Supersymmetry is not discovered... yet**
- **Tevatron, CDF, $D\emptyset$ are running very well**
- **Data sample is getting bigger**
  - **Expect 2-3 times more data to analyze**
  - **Can look at the rarer signatures**
  - **Keep digging and pushing limits**
- **CDF Exotics:**
  http://www-cdf.fnal.gov/physics/exotic/exotic.html
- **$D\emptyset$ Exotics:**
  http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm

Summary

- **Keep your eyes open for the unexpected :)**

Summary

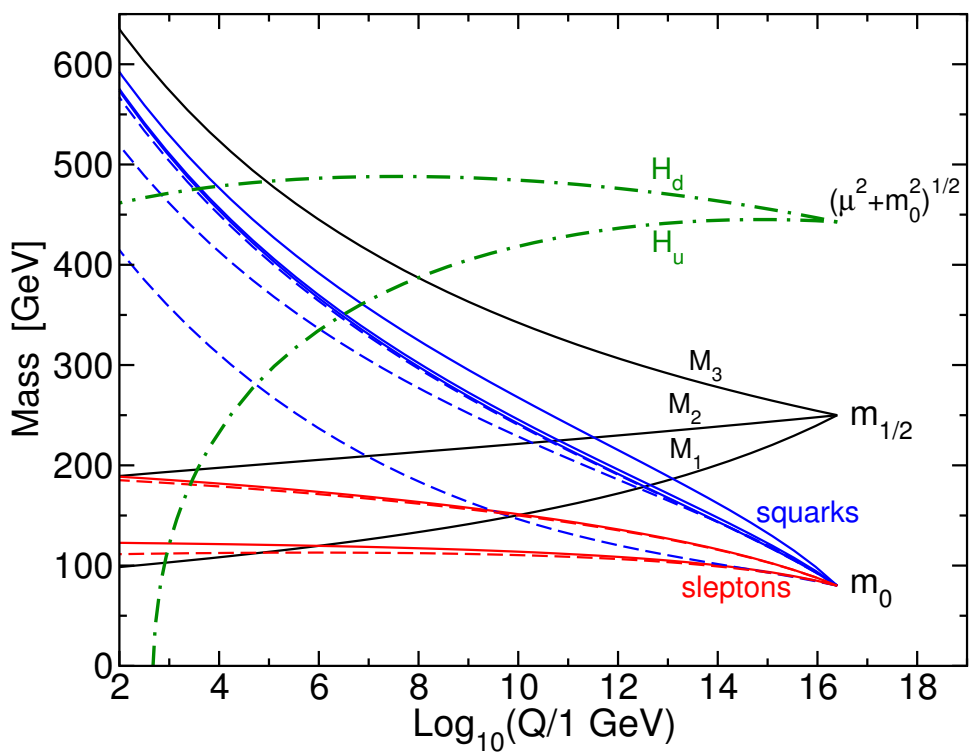
- **Stay tuned!**

SUSY particle	Scenario	Mass Limit (GeV)
Squark and Gluino	mSUGRA, low tanβ	≈ 400
Sbottom	$\mathrm{Br}(\tilde{g} \to \tilde{b}\bar{b}) \approx 100\%$	≈ 300
Stau	RPV, $\lambda'_{311} \neq 0$, $\lambda_{321} = \lambda_{312} \neq 0$	≈ 200
Chargino	mSUGRA, $3\ell - max$ scenario	≈ 140
Stop	Long life-time (CHAMP)	≈ 250

BACKUP SLIDES

mSUGRA

mSUGRA

In mSUGRA, symmetry breaking is via gravitational interactions and the SUSY parameter space is reduced to only 5 parameters:

- m_0: the universal scalar mass at the grand unification scale Λ_{GUT}
- $m_{1/2}$: the universal gaugino mass at Λ_{GUT}
- A_0: the universal trilinear coupling at Λ_{GUT}
- $\tan\beta$: the ratio of the vacuum expectation values of the two Higgs fields
- μ: the sign of the Higgs-mixing mass parameter