

Searches for Supersymmetry at the Tevatron

Rencontres de Moriond, QCD

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On behalf of the CDF and DØ Collaborations



Outline

- Brief introduction to SUSY
- SUSY searches at Tevatron
- Some selected analyses in final states :
 - Multi-lepton
 - Jets and Missing Transverse Energy
 - Photons
 - Long-lived
- Summary

Supersymmetry

- A popular extension to the SM
 - Unifies gauge couplings (if $M_{\text{SUSY}} < \text{few TeV}$)
 - Incorporate gravity
 - Solve the “fine-tuning” problem (if $M_{\text{SUSY}} < \text{few TeV}$)
 - Provide a Dark Matter candidate
- Postulate symmetry between boson and fermion particles
 - Every SM particle has a SUSY partner with same quantum numbers except spin (differ by 1/2)

$$e, \nu, u, d, \dots (\text{spin } 1/2) \Rightarrow \tilde{e}, \tilde{\nu}, \tilde{u}, \tilde{d}, \dots (\text{spin } 0)$$

$$\gamma, W^\pm, Z^0, g, \dots (\text{spin } 1) \Rightarrow \tilde{\chi}_{1,2,3,4}^0, \tilde{\chi}_{1,2}^\pm, \tilde{g} \quad (\text{spin } 1/2)$$

- New quantum number : R-parity = $(-1)^{3B+L+2S}$
 - Particles: R=1, SParticles: R=-1

Phenomenology of SUSY

R-parity is conserved :

- SUSY particles are pair produced
- Lightest SUSY Particle (LSP) stable
 - If neutral \Rightarrow
 - escape detection \Rightarrow Missing Energy (MET) signature !
 - candidate for Cold Dark Matter !

R-parity not conserved :

- SUSY particle can be singly produced
- LSP decays to SM particles, no dark matter candidate
- Process would violate either lepton or baryon quantum numbers

- SUSY is broken ($M_{\text{SUSY}} > M_{\text{SM}}$)
- Some SUSY breaking models

mSUGRA

- ~~SUSY~~ mediated by gravity
- LSP most likely is : $\tilde{\chi}_1^0$
- $M_{\tilde{\chi}_1^\pm} \approx M_{\tilde{\chi}_2^0} \approx 2M_{\tilde{\chi}_1^0}$

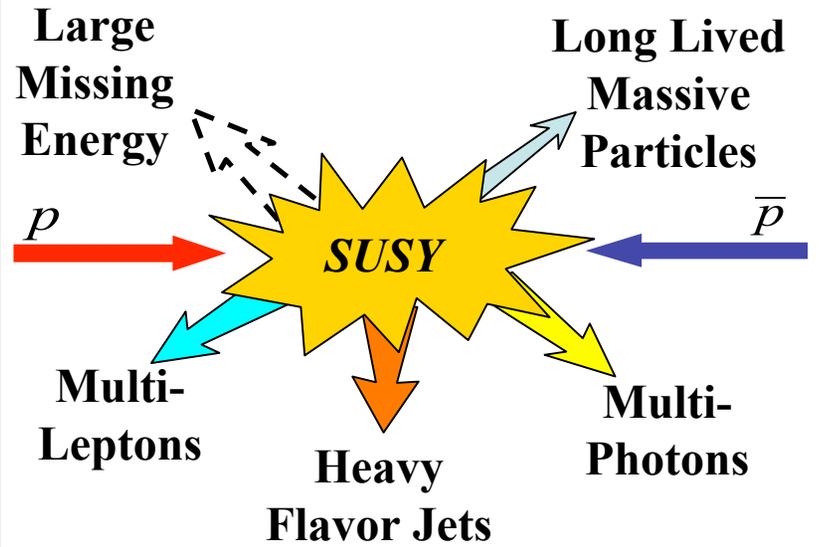
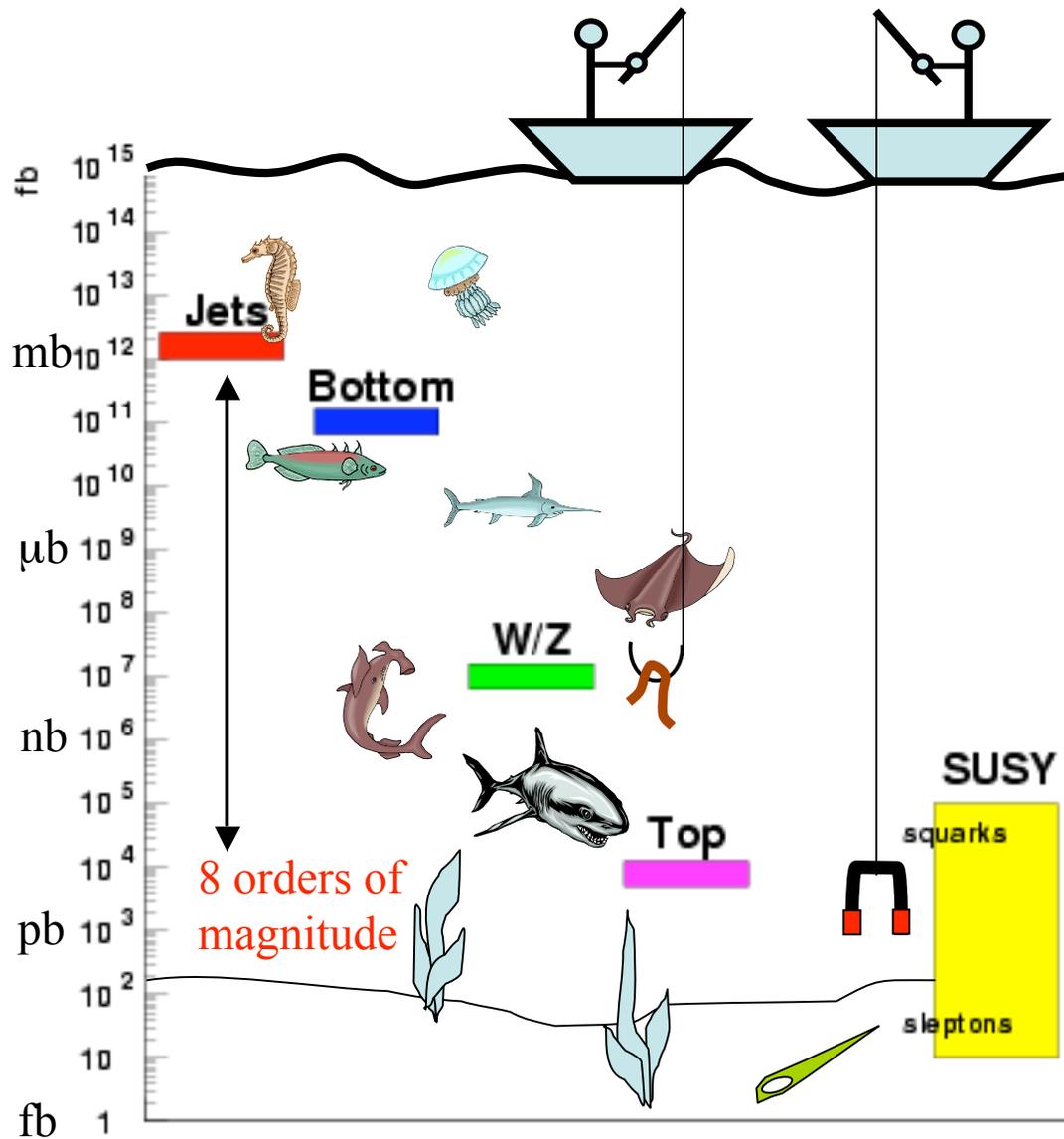
GMSB

- ~~SUSY~~ mediated by gauge fields
- LSP : \tilde{G}
- Phenomenology mostly determined by the NLSP (slepton or neutralino)

SUSY at the Tevatron

- Predicted rates for SUSY are **LOW !!!**

• **Need to look for distinctive signature to distinguish from SM background**



- Present results using data samples : 300 pb^{-1} to 1 fb^{-1}



Searches for Chargino/Neutralino in MET+Leptons



• Pair production of chargino/neutralino can produce multi-lepton and MET in final state (R-parity conservation)

⇒ Very clean, “Gold Plated” signature, but :

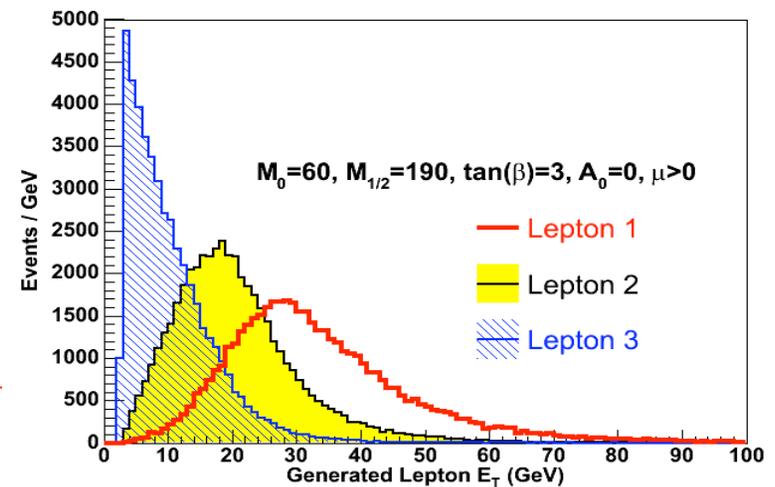
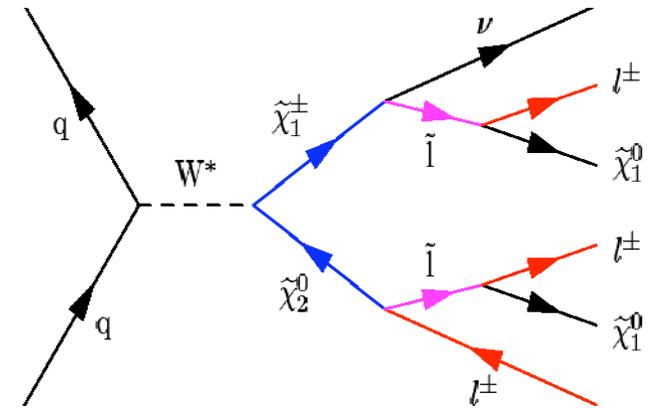
- Low cross section (x BR)
- Soft lepton

⇒ Need large integrated luminosity

⇒ Combine various final states

General search strategy (CDF and DØ) :

- Two isolated leptons (e or μ)
- Additional isolated lepton or track (for Tri-lepton ch.)
- Require some MET
- Veto events where M_{l+l-} in J/ ψ , Υ , Z peaks



Main Background :

- DY, Di-bosons, jets faking leptons, conversions



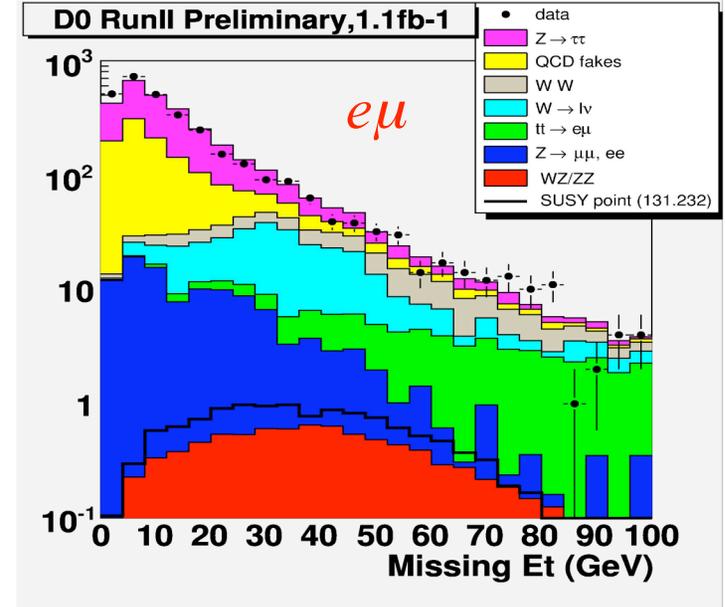
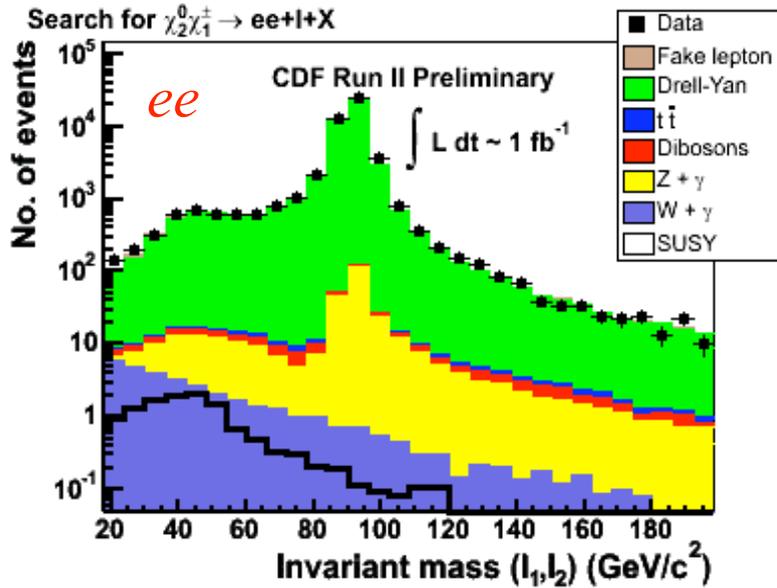
Searches for Chargino/Neutralino in MET+Leptons



$ee+l$

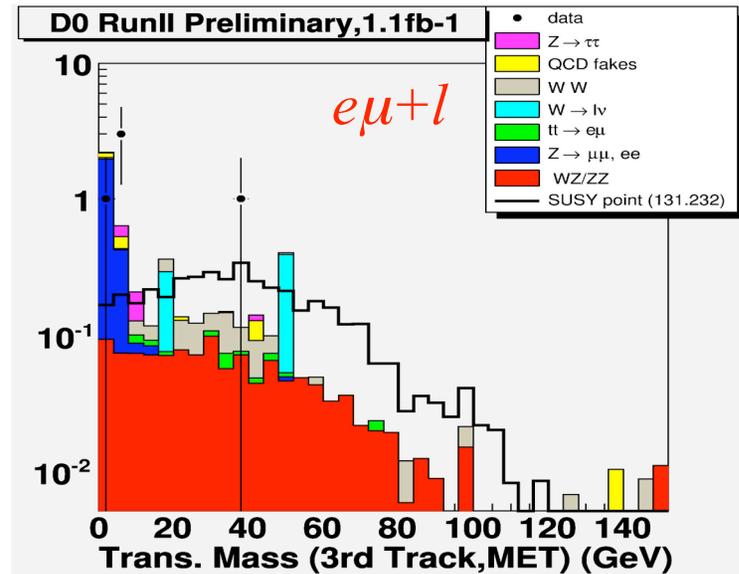
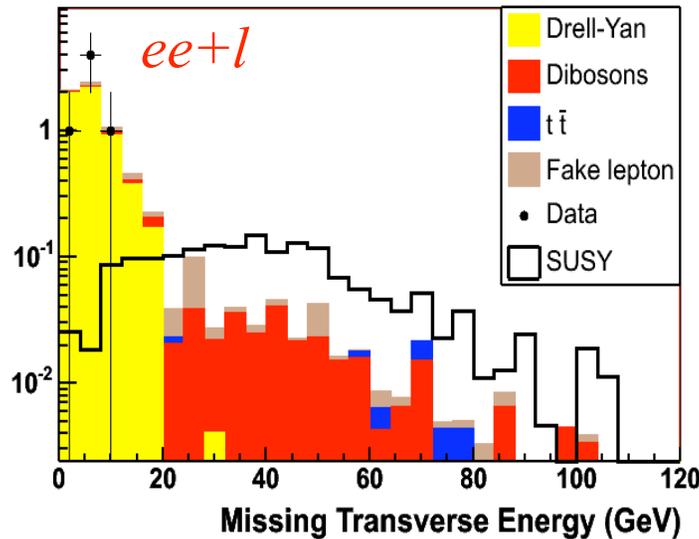
$e\mu+l$

Pre-selection
(req. 2 leptons)



Search for $\chi_2^0\chi_1^\pm \rightarrow ee+l+X$

After almost all selections





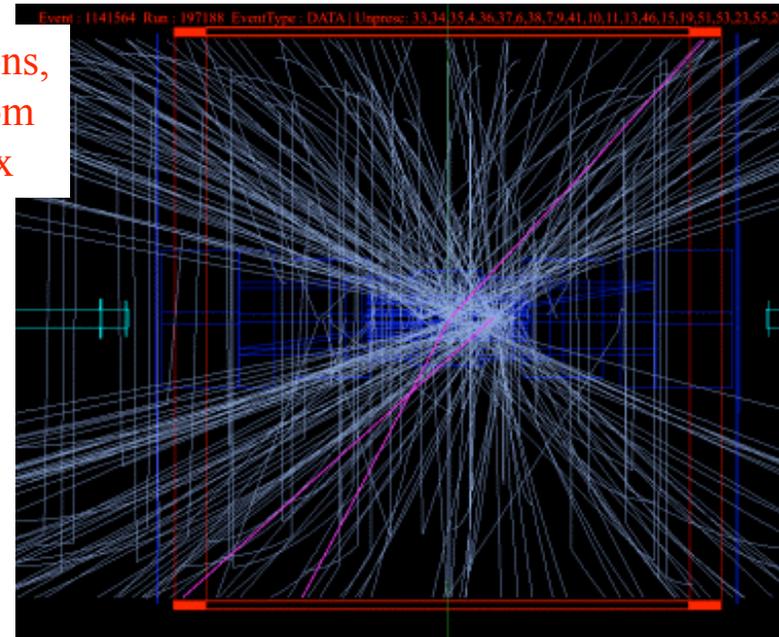
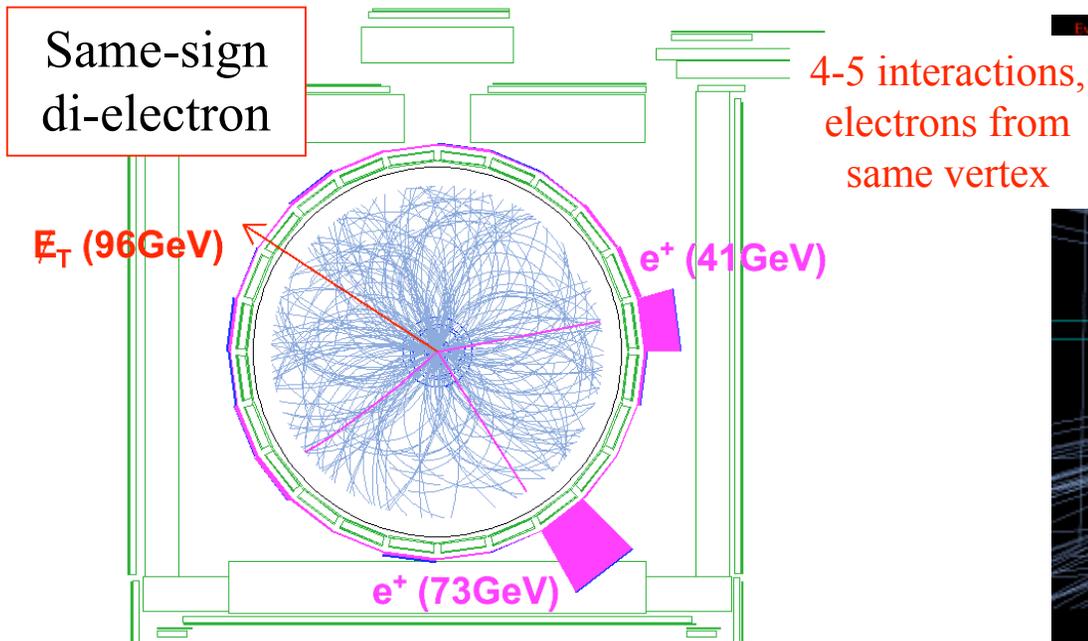
Searches for Chargino/Neutralino in MET+Leptons



CDF	L (fb^{-1})	#Predicted Bkg	#Obs. Data
ee+l (lowpt)	1	0.97 ± 0.28	3
$\mu\mu$ +l (low pt)	1	0.40 ± 0.12	1
ell	1	0.75 ± 0.36	0
μ ll	0.75	1.26 ± 0.27	1
$e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm$	1	7.8 ± 1.1	13

DØ	L (fb^{-1})	#Predicted Bkg	#Obs. Data
ee+l	1.1	0.76 ± 0.67	0
$\mu\mu$ +l	1.1	$0.32^{+0.73}_{-0.03}$	2
$e\mu$ +l	1.1	$0.94^{+0.40}_{-0.13}$	0
$\mu^\pm \mu^\pm$	0.9	1.1 ± 0.4	1

#SUSY signal (per ch) $\sim 0.2 - 4$ events

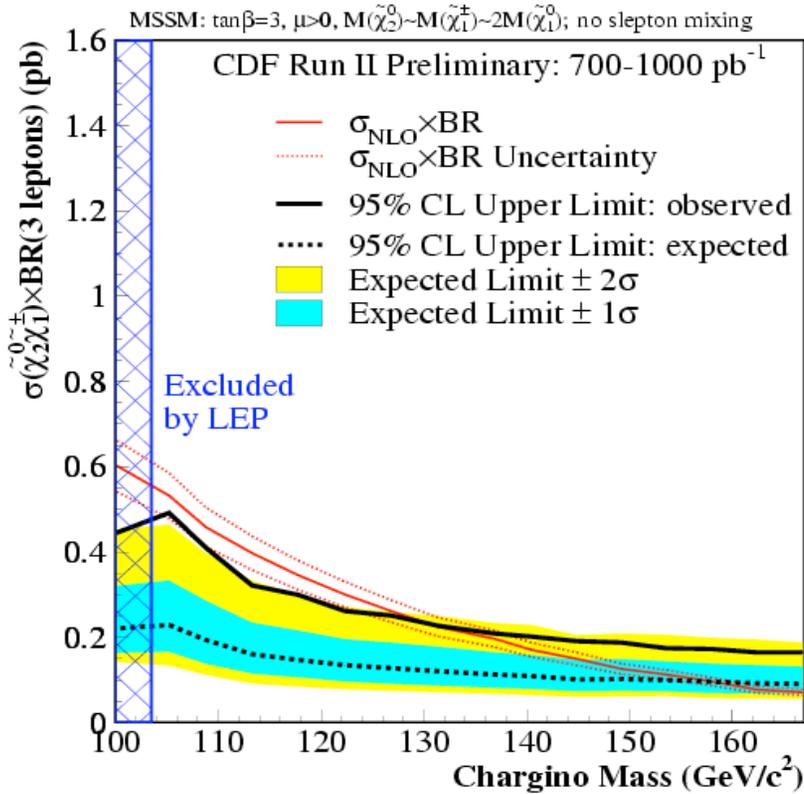




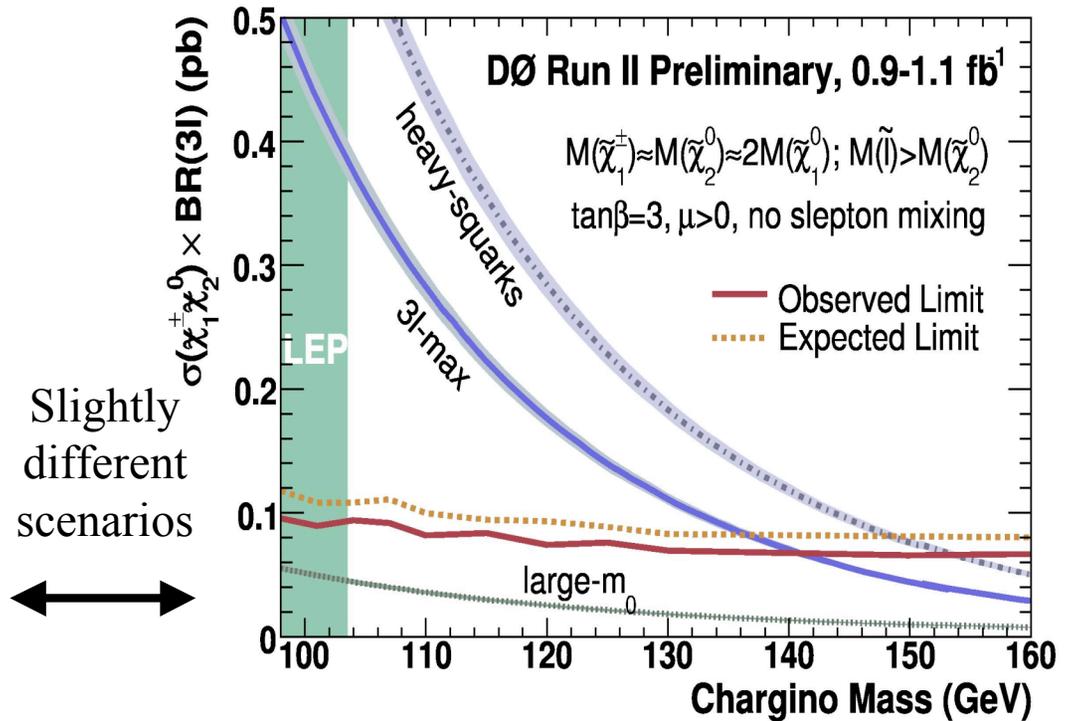
Searches for Chargino/Neutralino in MET+Leptons



- Results of various channels are combined
- Present limits in general scenario : mSUGRA like, low $\tan\beta$, no slepton mixing



- Obs. limit : $M_{\tilde{\chi}_1^\pm} < 130 \text{ GeV}/c^2$
- Exp. limit : $M_{\tilde{\chi}_1^\pm} < 160 \text{ GeV}/c^2$

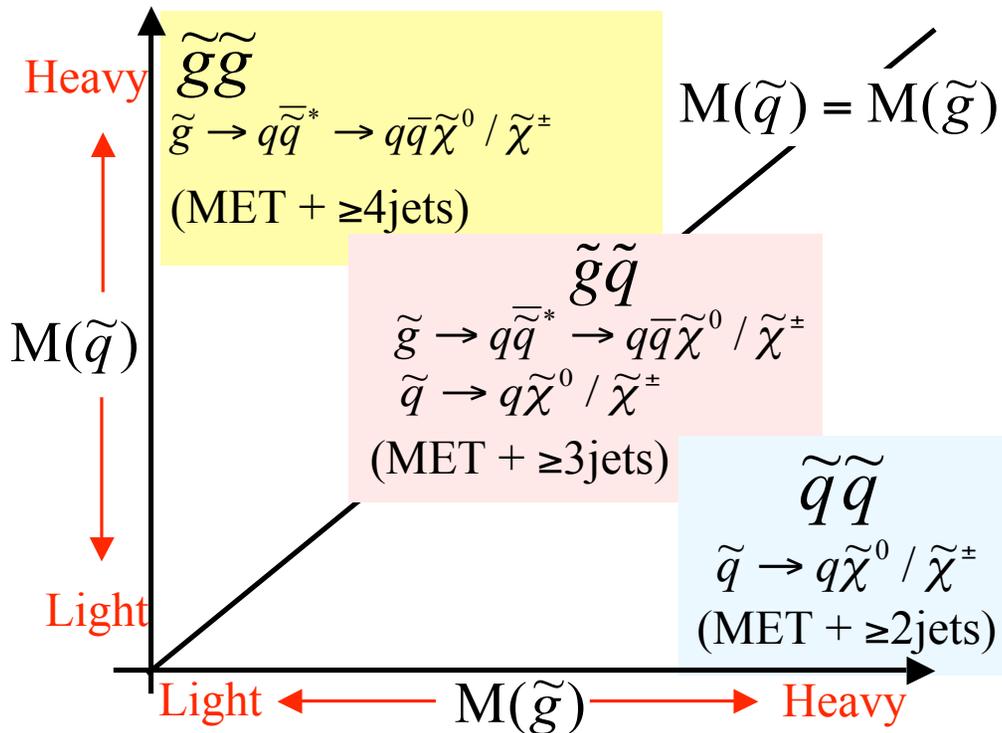
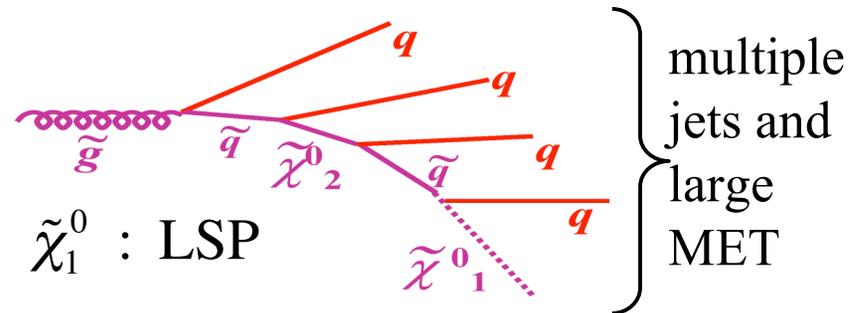


- 3l-max ($M_{\tilde{l}} \geq M_{\tilde{\chi}_2^0}$, lep. decay max. enhanced)
- Obs. limit : $M_{\tilde{\chi}_1^\pm} < 141 \text{ GeV}/c^2$

• Exceed LEP's limit in these scenarios

Searches for Squarks/Gluinos in MET+Jets

- \tilde{q}, \tilde{g} can be pair produced at Tevatron
- Decays of \tilde{q}, \tilde{g} may produce multiple jets and large MET (Rp conservation)



• Main Background :

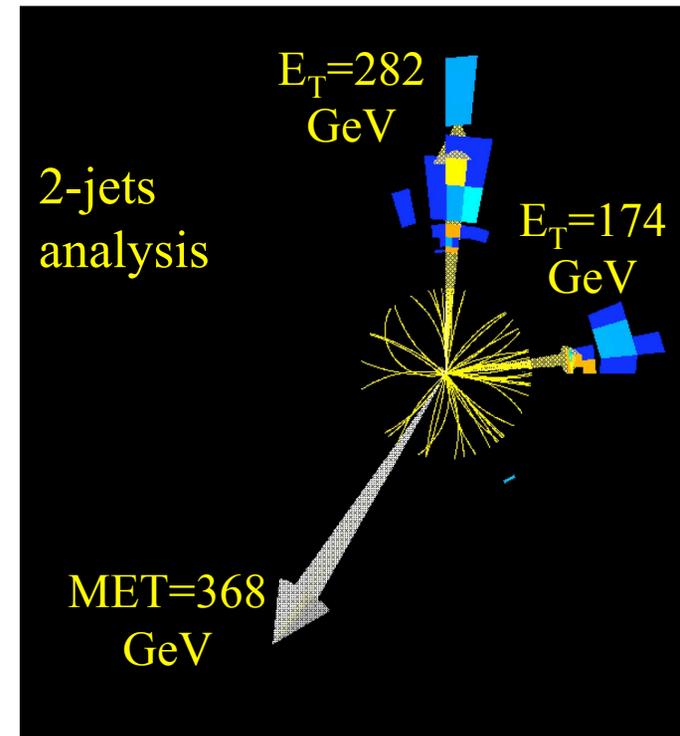
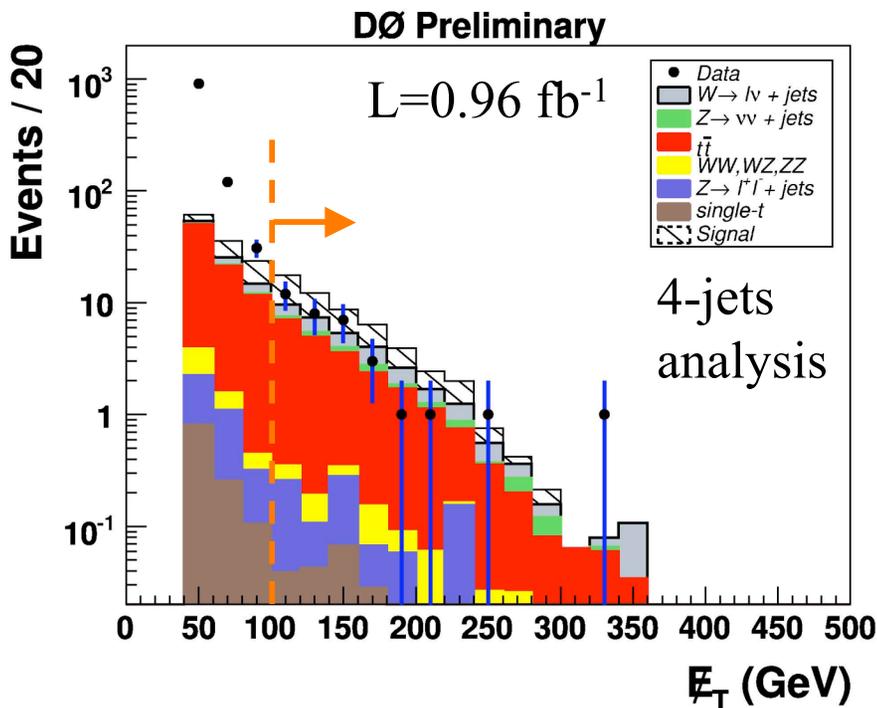
- QCD multi-jet (fake large MET)
- $Z(\rightarrow \nu\nu)$ +jets (irreducible)
- $W(\rightarrow l\nu)$ +jets (missed lepton)
- Diboson, $t\bar{t}$

Searches for Squarks/Gluinos in MET+Jets



- DØ performs separate analyses for each final states ($\geq 2, 3, 4$ jets+MET), to obtain best optimized signal to background separation
- Main selection cuts:
 - Multi-jets + MET
 - Separation of MET direction and jets
 - Lepton veto
 - Large H_T + large MET

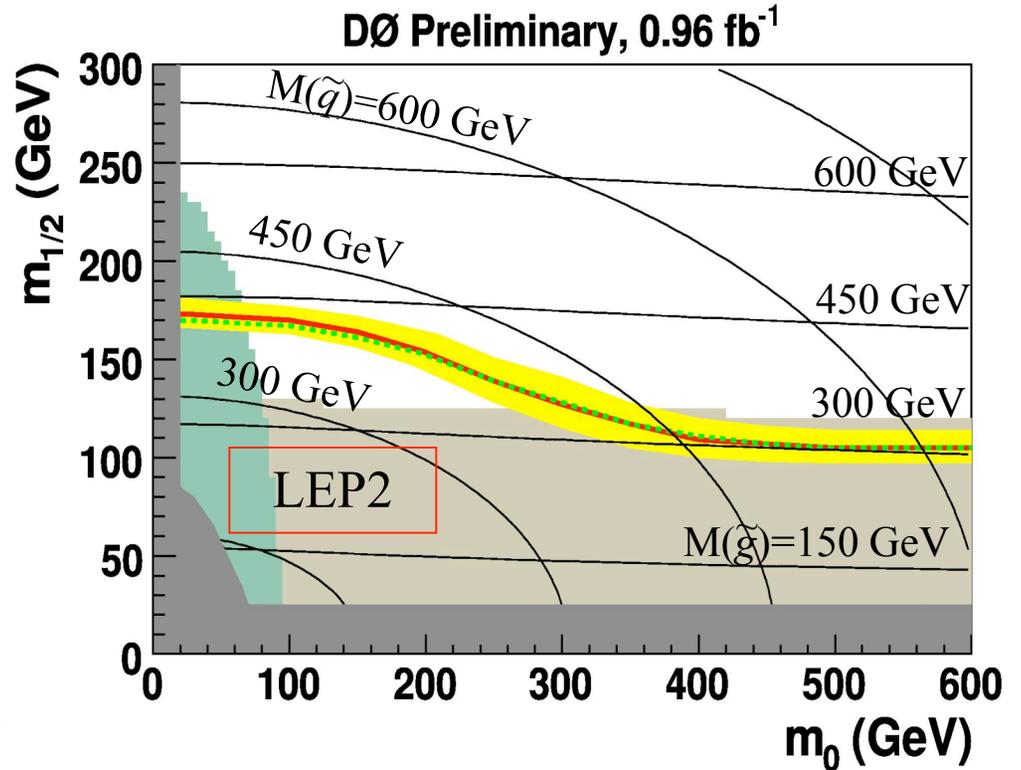
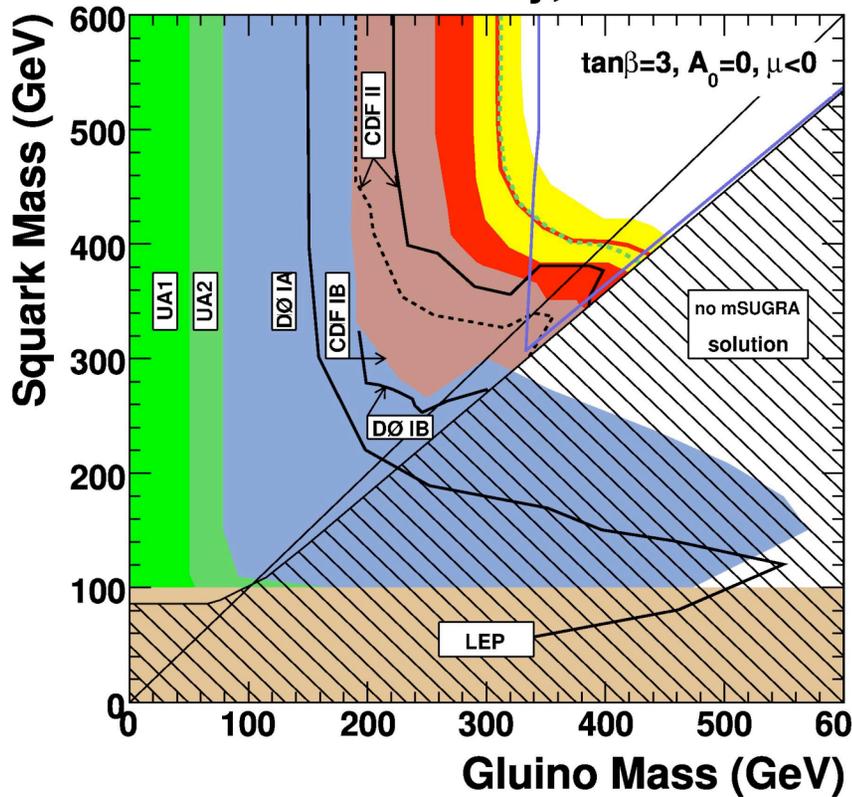
	# obs	# expected
2-jets	5	$7.5^{+1.7}_{-1.5}$
3-jets	6	$6.1^{+1.3}_{-1.2}$
4-jets	34	$33.4^{+5.6}_{-5.0}$



Searches for Squarks/Gluinos in MET+Jets



DØ Preliminary, 0.96 fb⁻¹



- Determine limits in mSUGRA framework
- Red curve : new 95% CL exclusion
- Yellow band : effect from theory cross section uncertainties

- This analysis also constrain the mSUGRA parameters (m_0 : universal scalar mass, $m_{1/2}$: universal gaugino mass)
- Extend limits beyond LEP
- CDF 1fb⁻¹ results coming soon

$$M(\tilde{g}) > 309 \text{ GeV}; M(\tilde{q}) > 391 \text{ GeV}$$

$$M(\tilde{g}) > 402 \text{ GeV (when } M(\tilde{g}) \sim M(\tilde{q})\text{)}$$



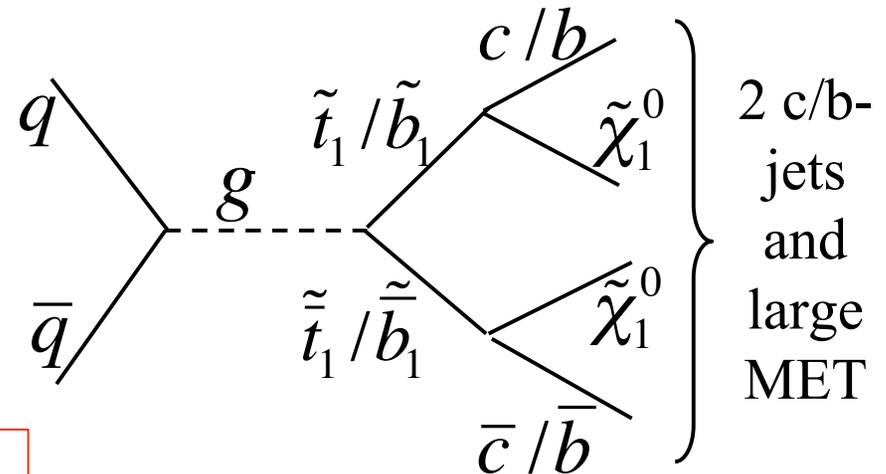
Search for Third Generation Squarks



- Large mixing between the L- and R-handed weak eigenstates
 - Stop : due to large top quark mass
 - Sbottom : large mixing occurs at high $\tan\beta$
- \Rightarrow one of the stop and sbottom quarks can be light

Search for Stop/Sbottom Quarks in MET+Jets

- CDF, DØ searched for stop/sbottom quark pair production
- Assume: $\text{BR}(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0) = 100\%$
 $\text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 100\%$



Main Selection:

- 2,3 jets, with ≥ 1 jet tagged as c/b-jet
- Large MET ($> \sim 50$ GeV)
- Separation of MET direction and jets
- Lepton veto

• Main Background

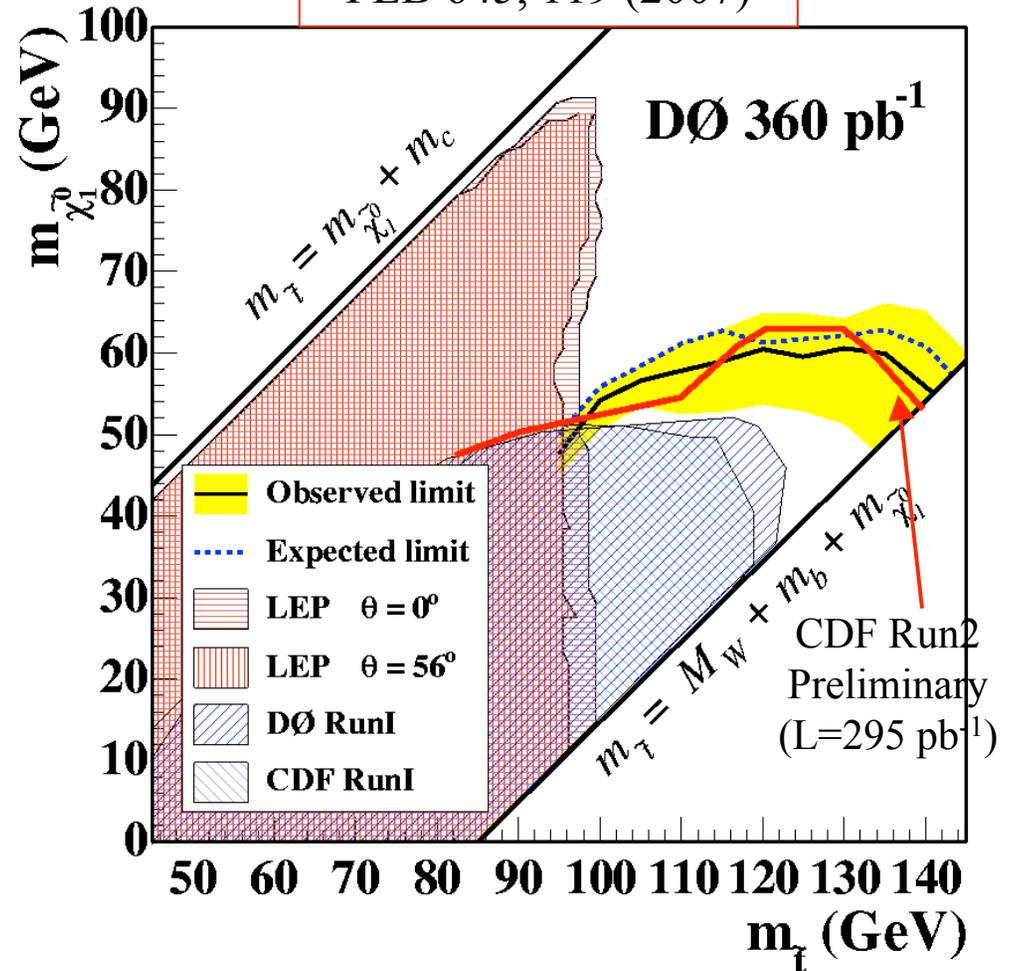
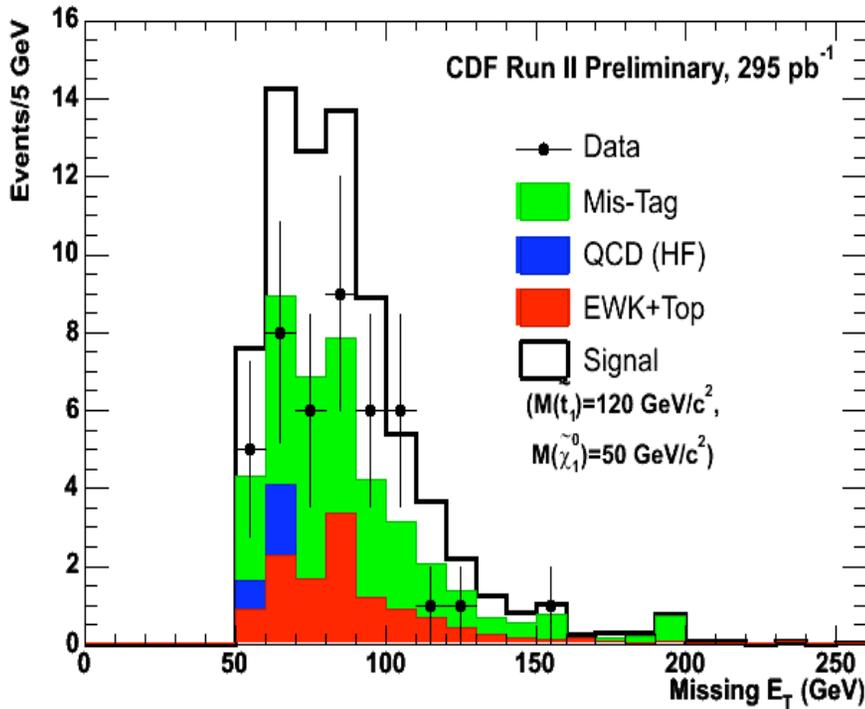
- $Z(\rightarrow \nu\nu) + \text{jets}$, $W(\rightarrow l\nu) + \text{jets}$
- Di-boson, $t\bar{t}$
- QCD multi-jet



Search for Stop Quark



PLB 645, 119 (2007)



Good agreement between Data and SM prediction (after all selection cuts)

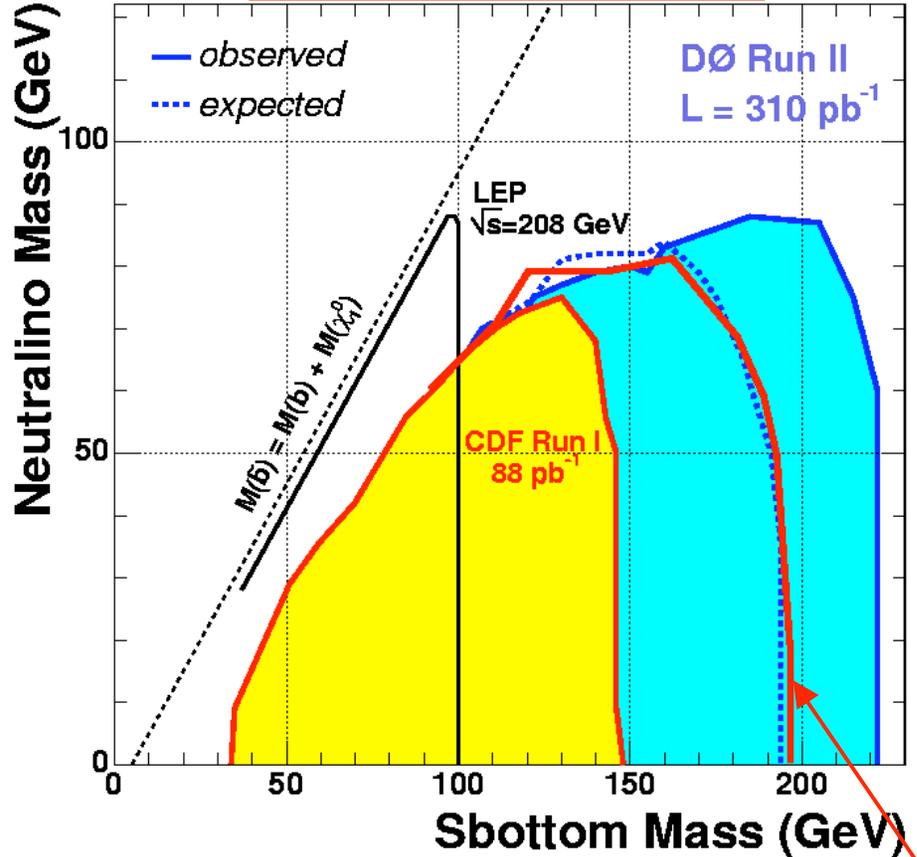
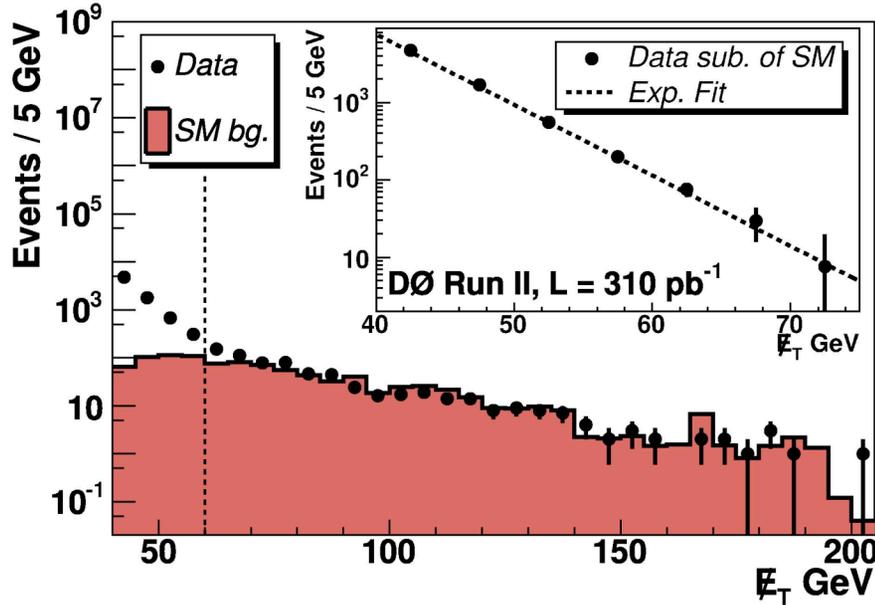
Both CDF and DØ exclude $M(\tilde{t}_1) < \sim 140$ GeV, for $M(\tilde{\chi}_1^0) = 55$ GeV at 95% CL



Search for Sbottom Quark



PRL 97 171806 (2006)



- MET distr. after pre-selection cuts
- Data well described by expected SM contributions (low MET dominated by QCD, not simulated)
- After applying all cuts and b-tagging, found no excess in Data above SM prediction

Exclusion (@ 95% CL) :

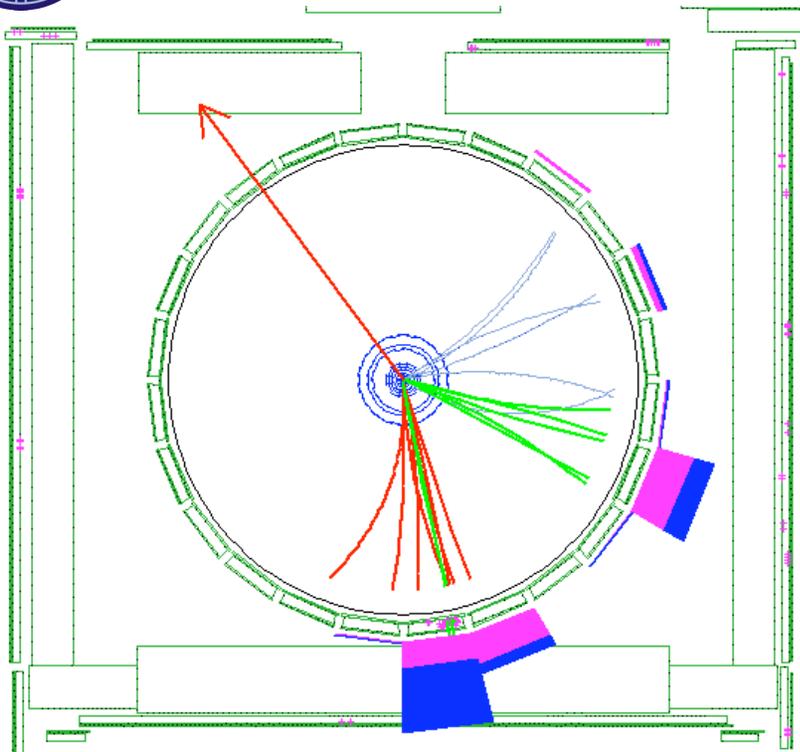
DØ : $M(\tilde{b}_1) < 222$ GeV

CDF : $M(\tilde{b}_1) < 195$ GeV

CDF Run2
Preliminary
(L=295 pb⁻¹)



A Sbottom Candidate Event in CDF

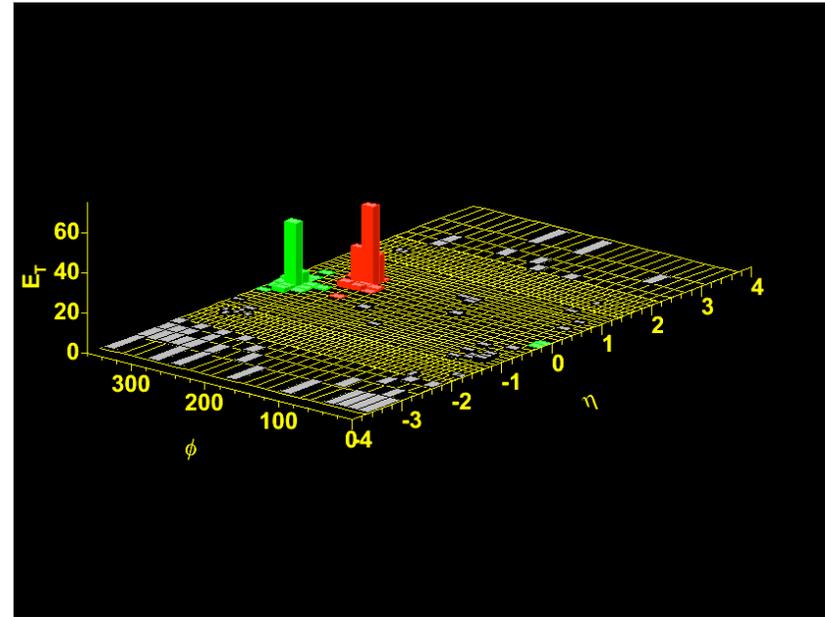


Two b-tagged jets

Jet₁ $E_T = 100.3$ GeV

Jet₂ $E_T = 54.7$ GeV

Missing $E_T = 145$ GeV



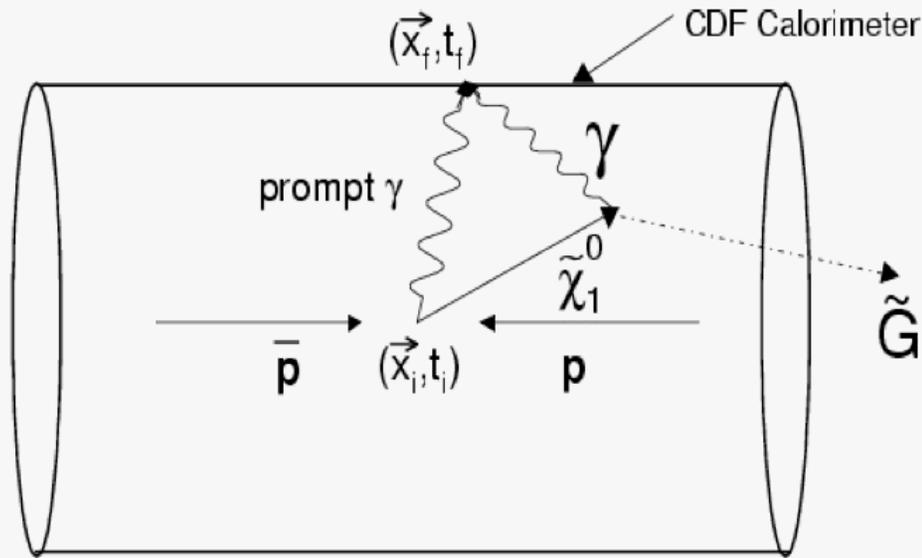
$m_{jj} = 82$ GeV

Could be ZZ ?



Search for SUSY in Delayed Photon Signature

- CDF search for heavy long lived particle decaying (inside detector) into γ
 - Focus on GMSB model where lifetime of $\tilde{\chi}_1^0$ (NLSP) is free parameter



- In GMSB, gravitino \tilde{G} is LSP (escape undetected)
- If $\tilde{\chi}_1^0$ is NLSP, then $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
- Final state consists of γ +Missing E_T +X in SUSY production under GMSB

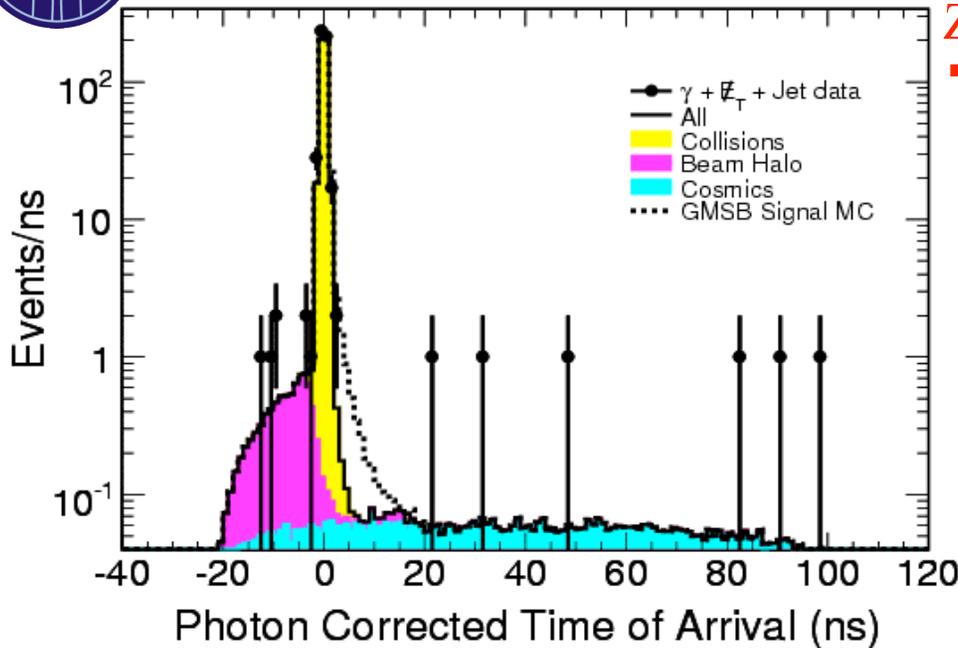
- $\tilde{\chi}_1^0$ is long lived and decays into γ and \tilde{G}
- γ from $\tilde{\chi}_1^0$ decay will arrive at face of detector with time delayed relative to promptly produced γ

- Select events with γ +MET+jet signature :
 - $E_T(\gamma) > 30 \text{ GeV}$
 - $E_T(\text{jet}) > 35 \text{ GeV}$
 - $\text{MET} > 40 \text{ GeV}$
- Arrival time of γ is measured by the timing system of the EM calorimeter

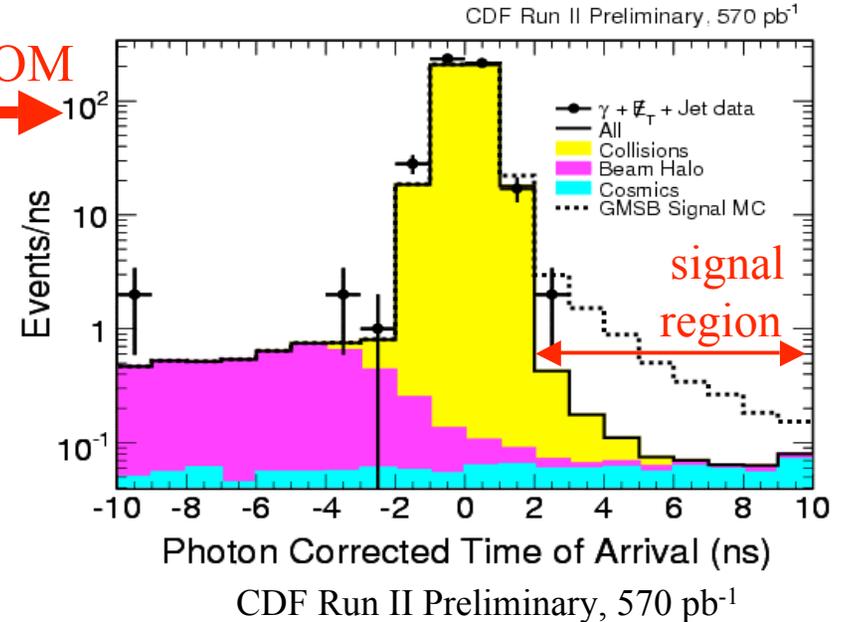


Search for SUSY in Delayed Photon Signature

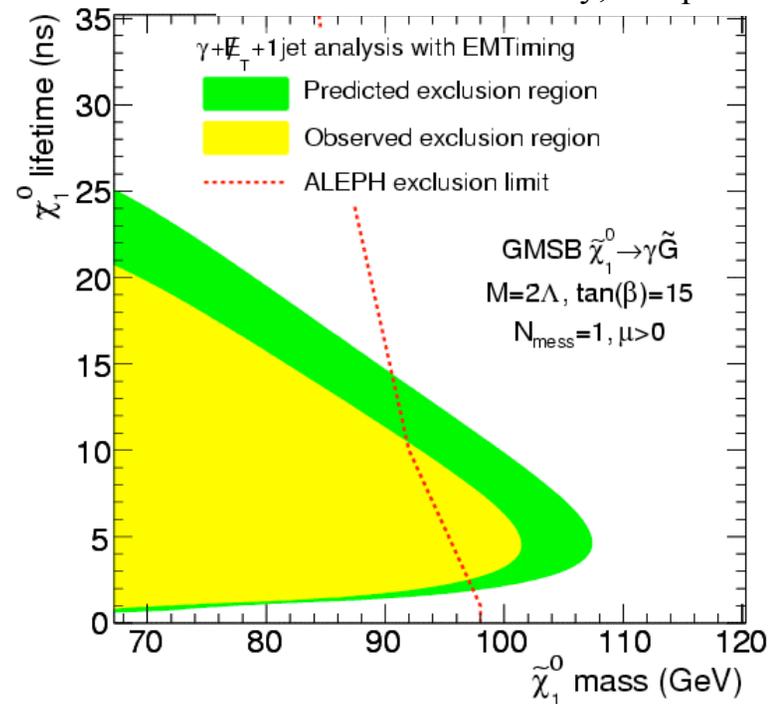
CDF Run II Preliminary, 570 pb⁻¹



ZOOM



- γ time corrected for TOF assuming coming from interaction point
- Signal window 2-10 ns
- Predict 1.3 ± 0.7 BG events
- Observe 2 events
- Set exclusion in $M(\tilde{\chi}_1^0)$ and $\tilde{\chi}_1^0$ lifetime plane

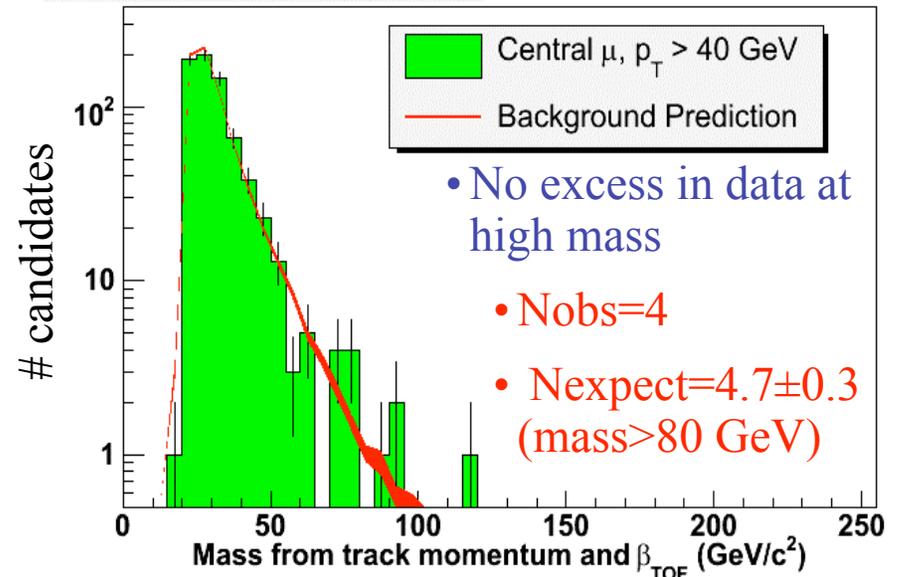




Search for CHARGE Massive Particles (CHAMPs)

CDF Run II Preliminary (1.0 fb⁻¹)

- Search for long lived particles :
 - massive, carry charge
 - decay outside detector
- CHAMPs particles: Slow moving, very penetrating (“slow muon”)
- Look for “muon” like particle penetrate through calorimeter to the muon chambers
- Time-of-Flight (TOF) detector to measure β
- Track momentum and β to calculate mass

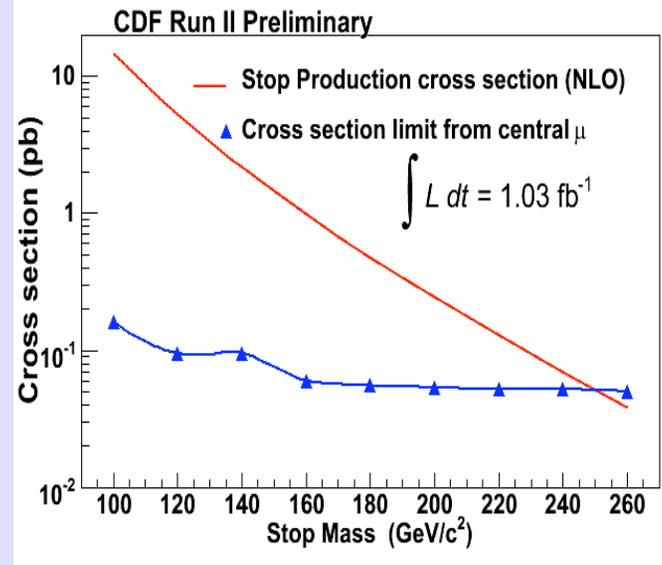


Main background :

- Cosmic
- Instrumental effect :
 - Mis-measurement :
 - Interaction time and arrival time at TOF
 - Track momentum

Limit :

- Interpret results in SUSY model w/ one compactified Extra Dimension (R. Barbieri, L.J. Hall, and Y. Nomura, PRD 63, 105007 (2001))
 - LSP : stop quark
- Exclude stable stop quark $M(\text{stop}) < 250 \text{ GeV}$



CHARGE Massive Particles (CHAMPs)



- Search pair production of Charged Massive stable particles that are slow moving

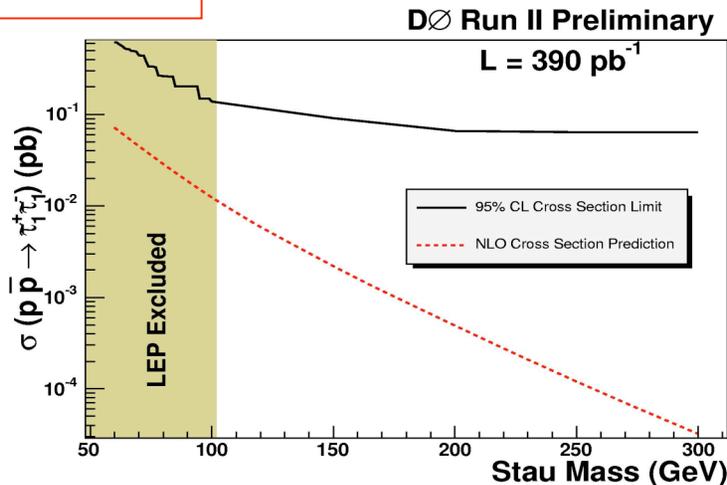
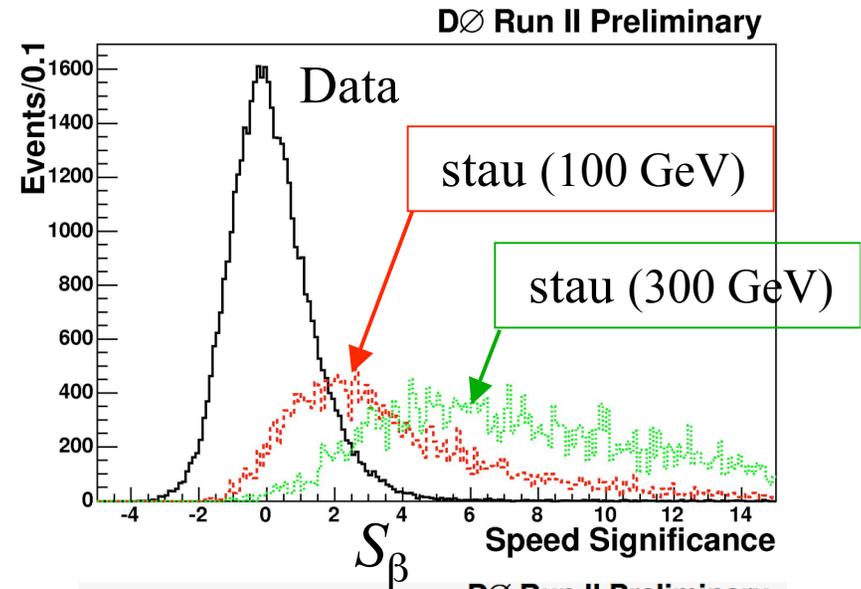
- Select 2 μ -like high- P_T candidates

- Slow : $S_\beta = \frac{1-\beta}{\sigma_\beta}$ is large
- Large di-muon mass

- Est. background from data

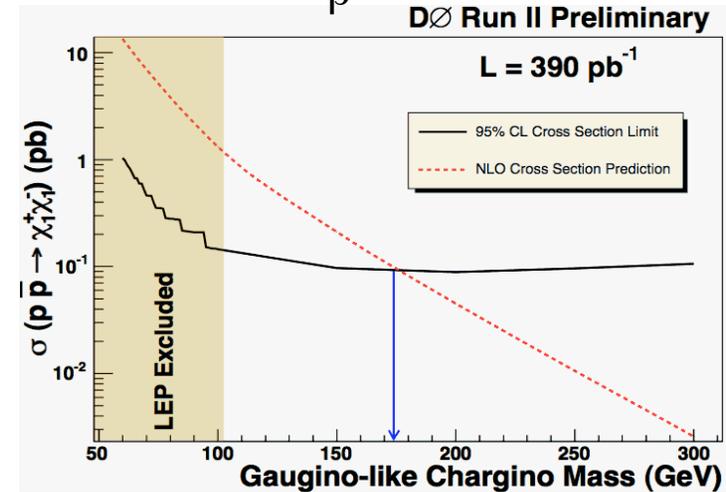
#Exp.	#Obs.
0.66 ± 0.06	0

Limits:



GMSB model:

- Assume CHAMPs = $\tilde{\tau}$ (NLSP)
- Upper limit s : 0.06 pb to 0.62 pb

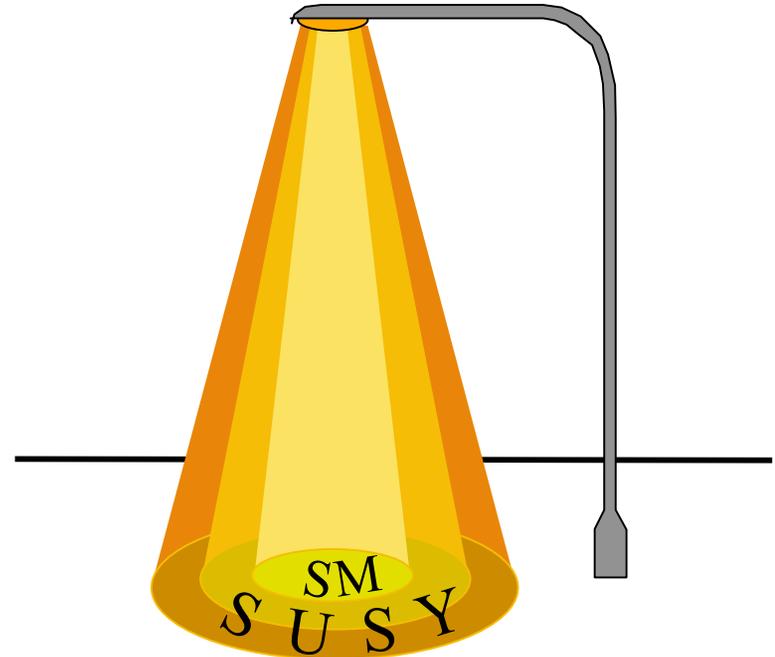
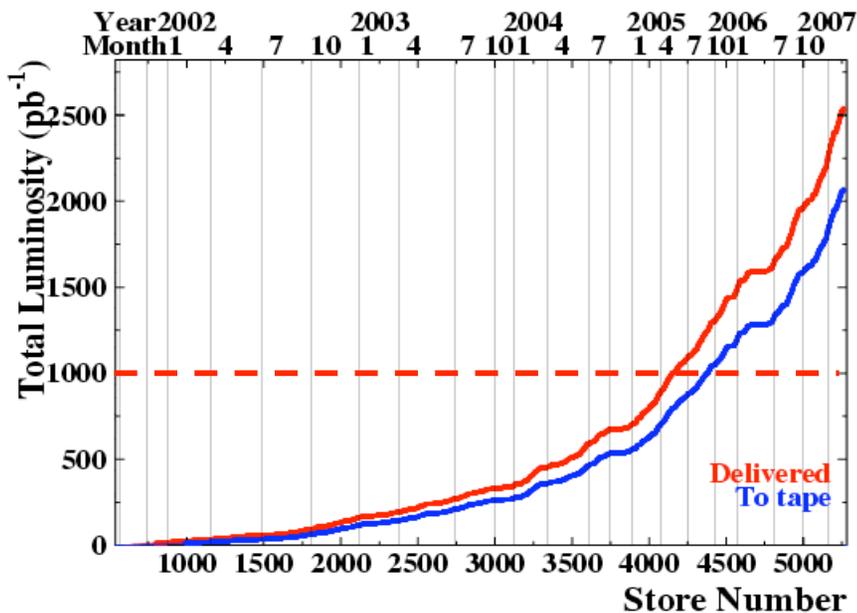


Stable Chargino model (small $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$):

- Assume CHAMPs = $\tilde{\chi}_1^\pm$ (gaugin-like)
- $M(\tilde{\chi}_1^\pm) > 174 \text{ GeV}$

Summary

- SUSY is a promising venue for New Physics
- CDF and DØ are mounting extensive program to search for it and other physics Beyond the Standard Model
- Just finished analysing 1 fb-1 data, and still have much more in the bag
- New Physics/SUSY may be just hiding in the shadow now ... can be observed with brighter “light” !!!

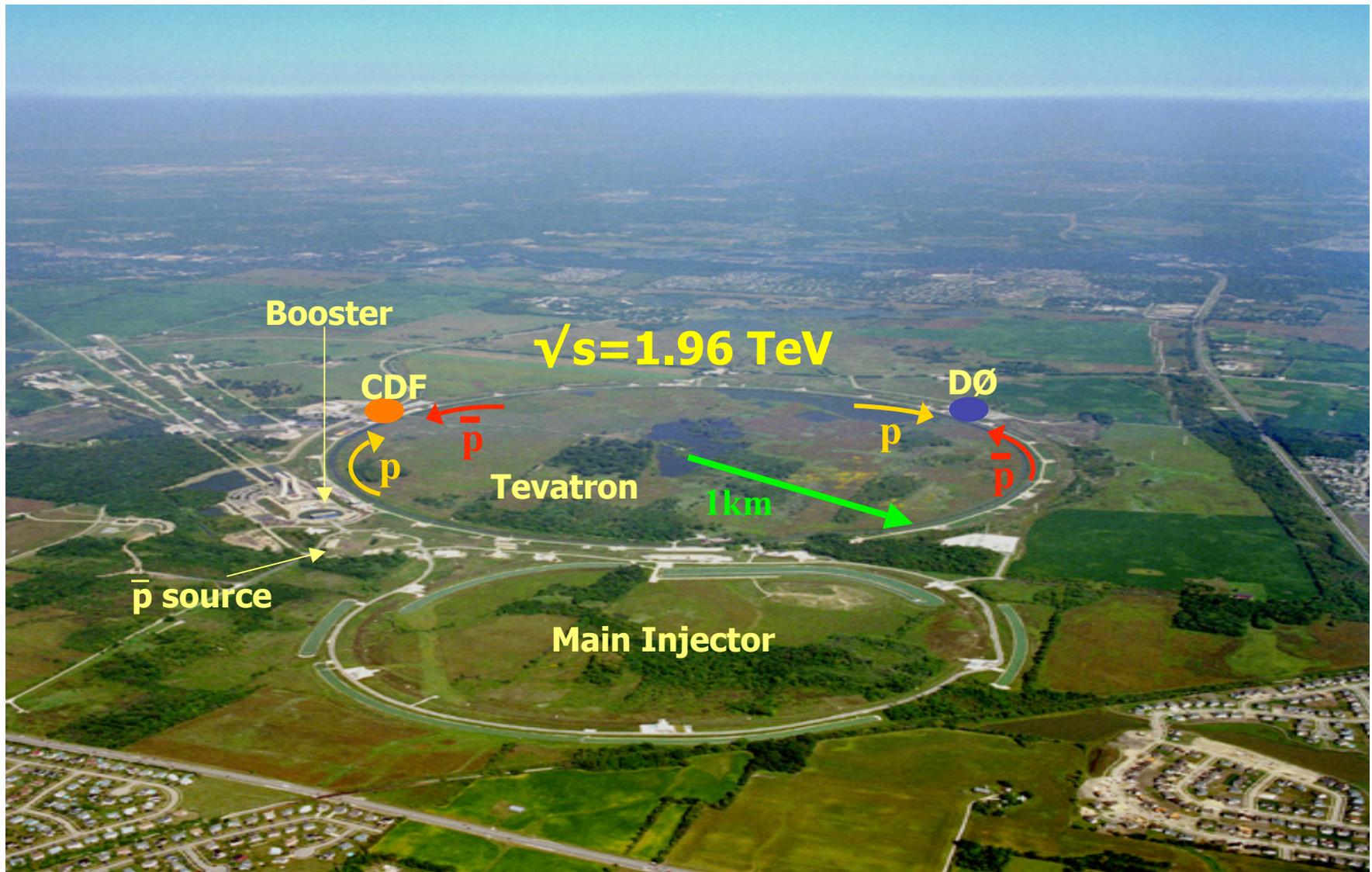


<http://www-cdf.fnal.gov/physics/exotic/exotic.html>

<http://www-d0.fnal.gov/Run2Physics/WWW/results/np.html>



Tevatron

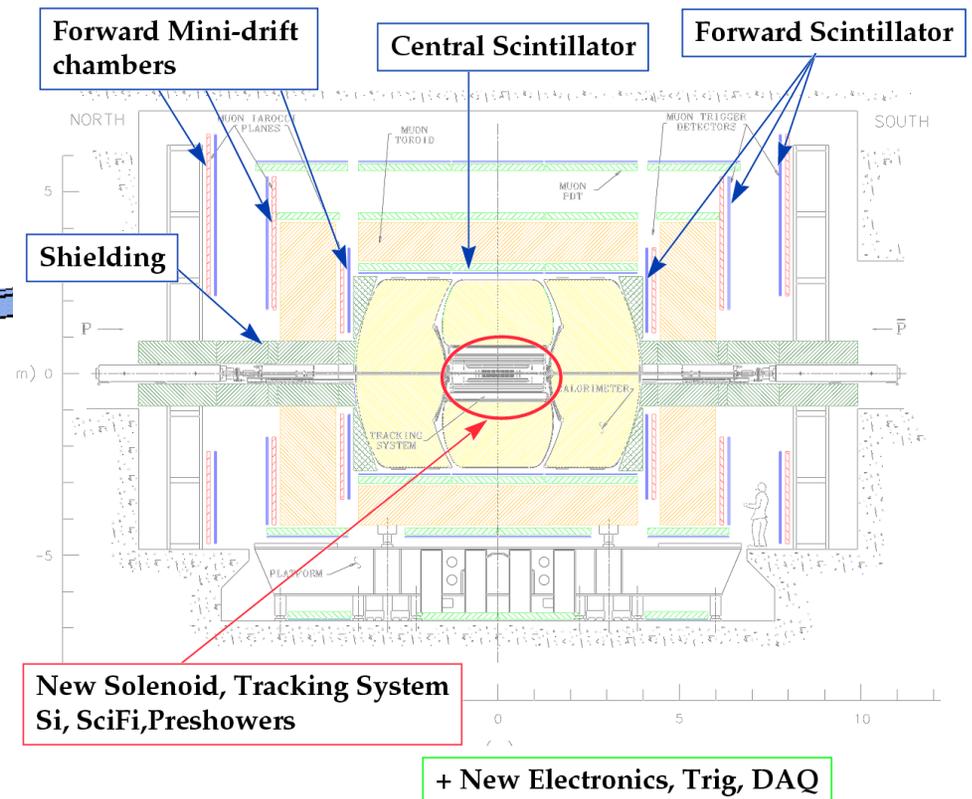
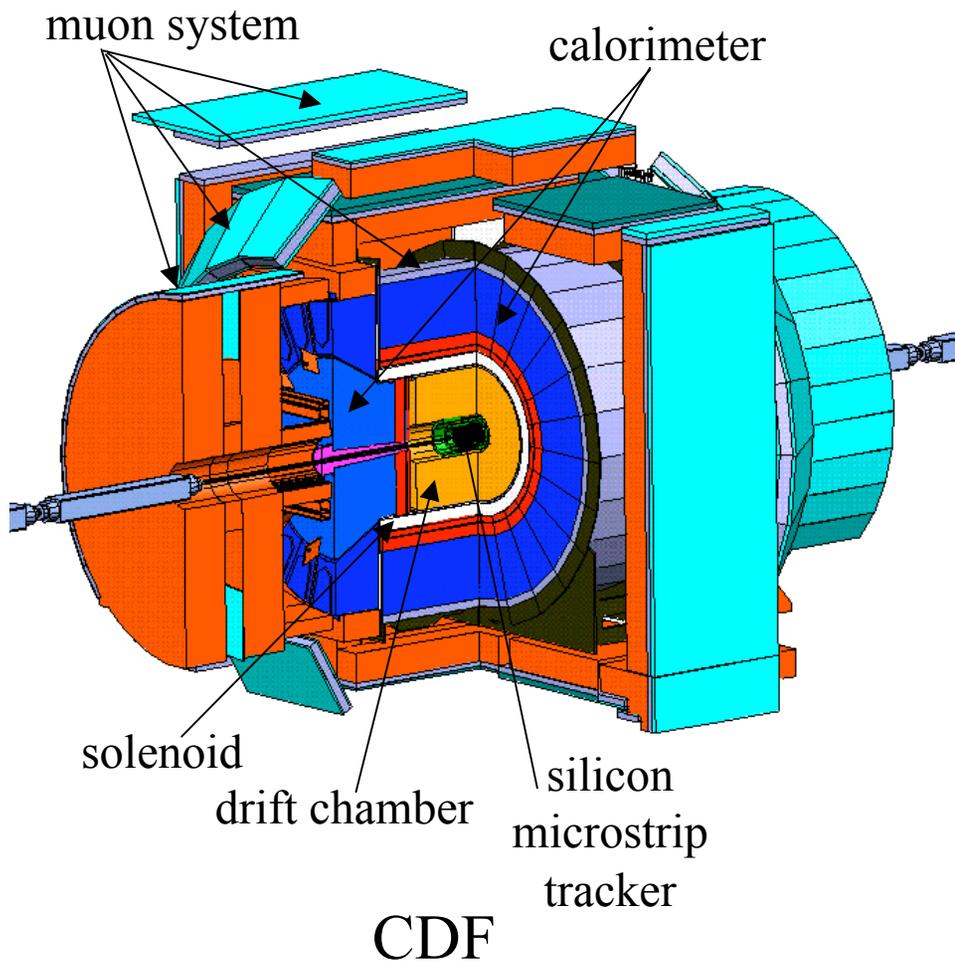


The Tevatron Experiments

Multipurpose detectors :

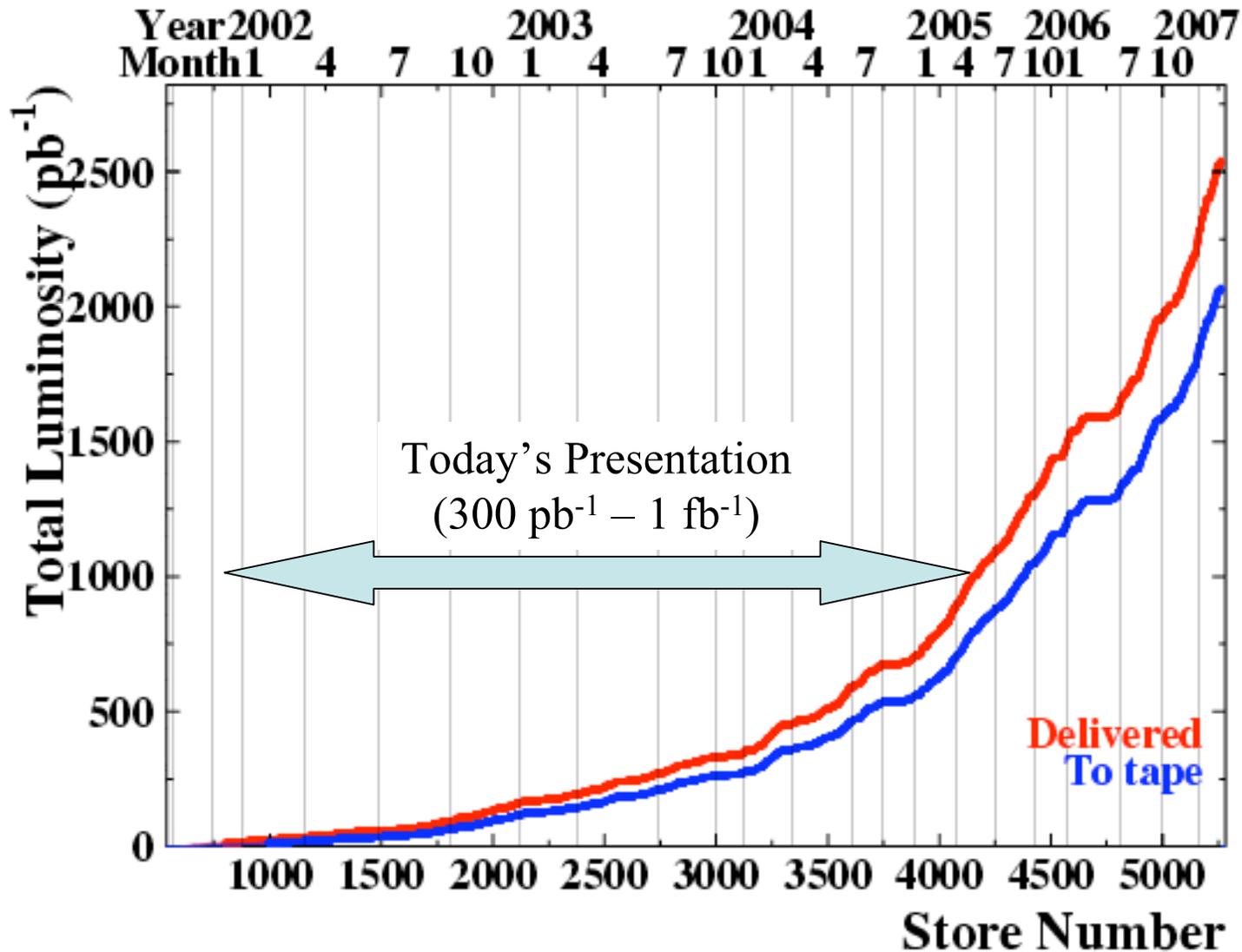
- Electron, muon, tau identification
- Jet and missing energy measurement

- Heavy-flavor tagging through displaced vertices and soft leptons



DØ

Tevatron Run2

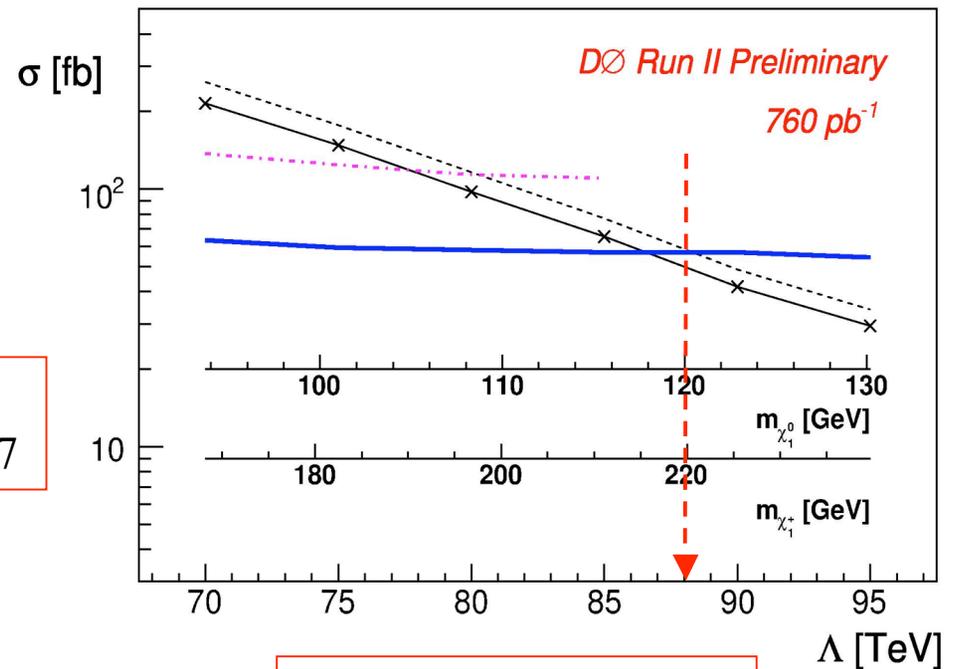
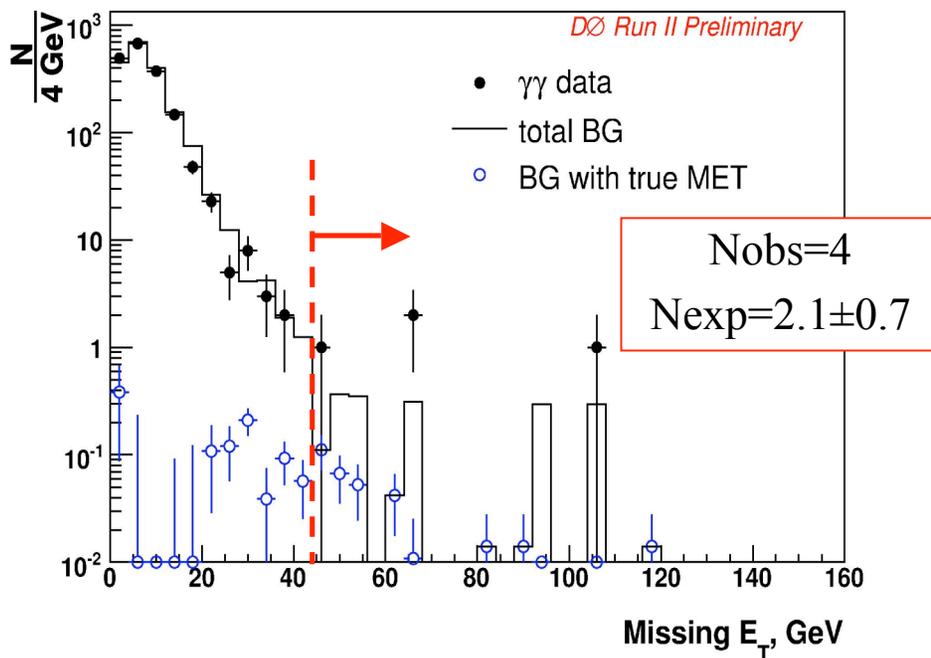


- Tevatron delivered total integrated lumi $\sim 2.5 \text{ fb}^{-1}$
- CDF/DØ collected $\sim 2 \text{ fb}^{-1}$ data

Search for SUSY in MET+Di-Photon



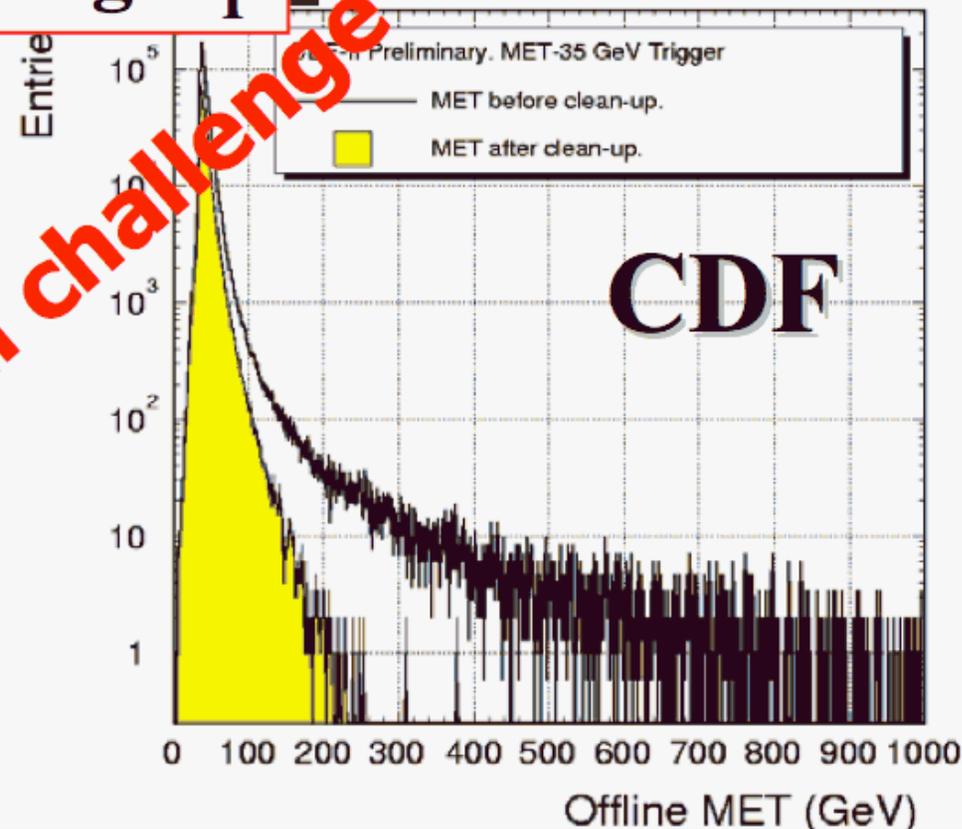
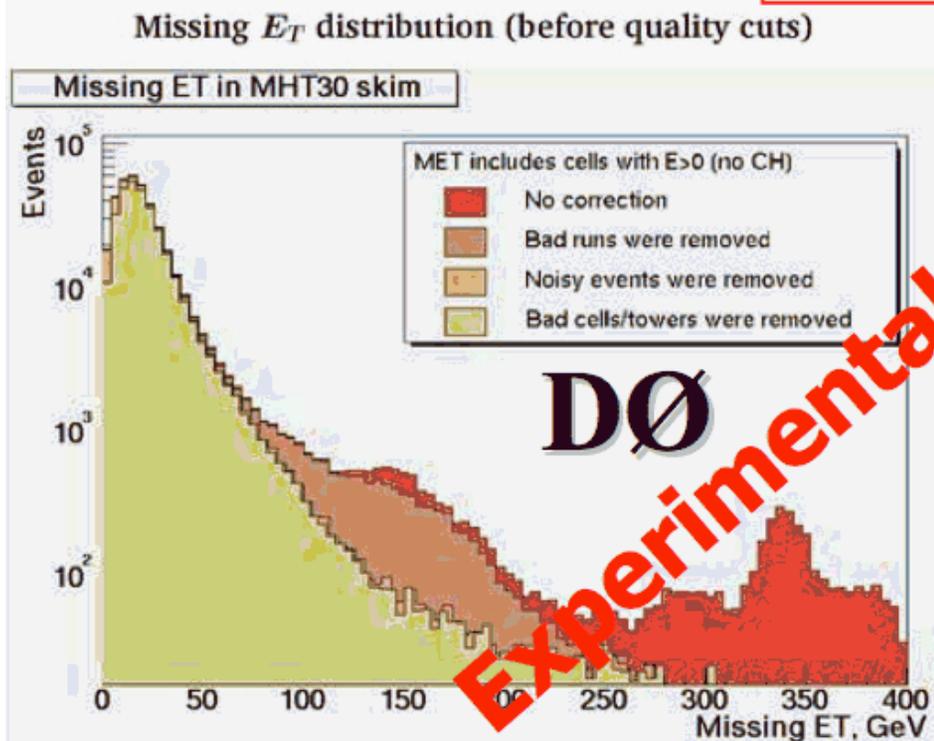
- In GMSB, gravitino \tilde{G} is the LSP (escape undetected)
- If $\tilde{\chi}_1^0$ is NLSP, then $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
 - ⇒ Thus in SUSY production under GMSB, final state will consist of $\gamma\gamma + \text{Missing Et} + X$
- DØ searched for GMSB SUSY in $\gamma\gamma + \text{Missing Et}$ signature
 - 2 photons, $E_t > 25 \text{ GeV}$
 - Missing $E_t > 45 \text{ GeV}$



$M(\tilde{\chi}_1^\pm) > 220 \text{ GeV}$

Non-Collision MET Background

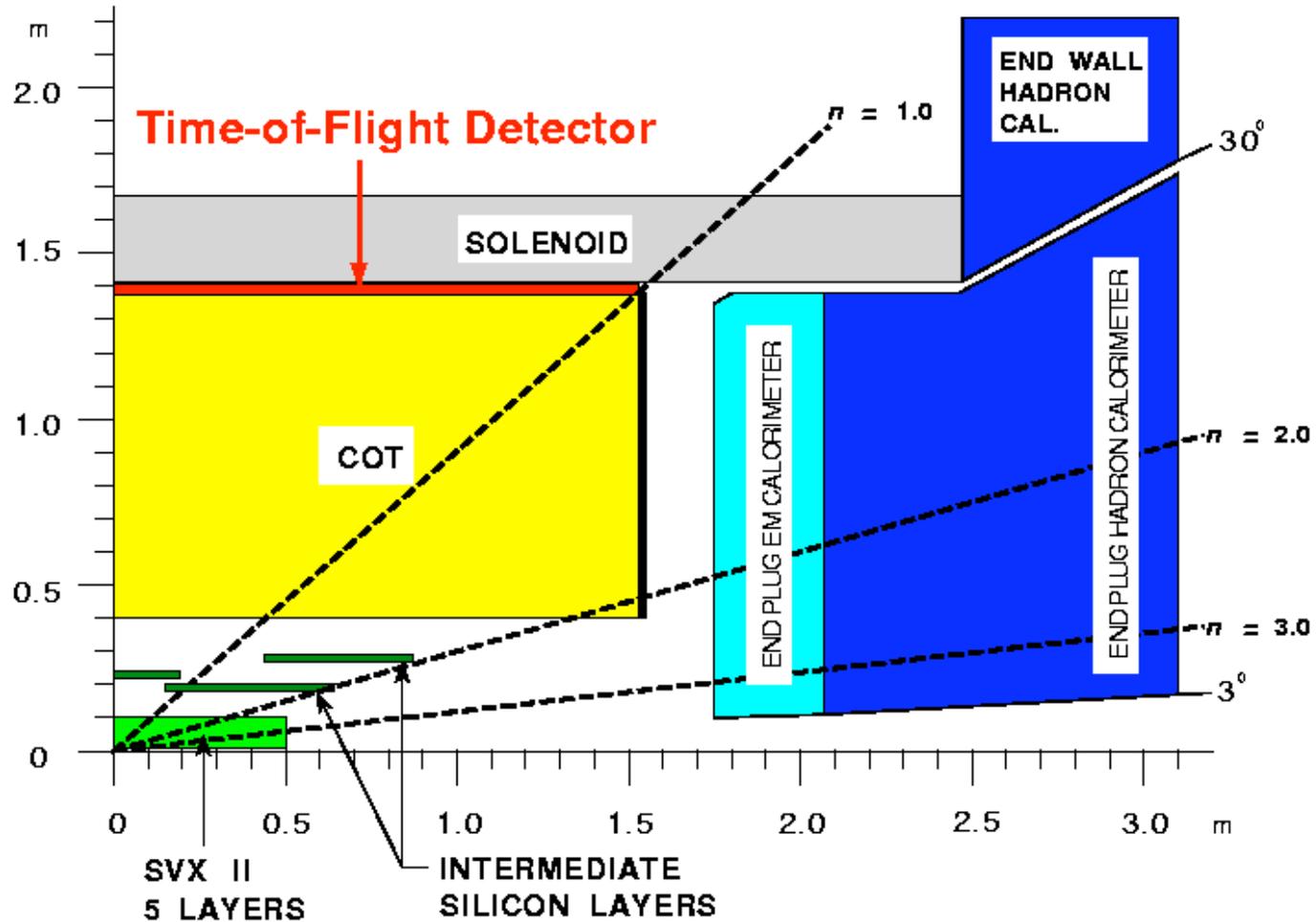
Missing E_T

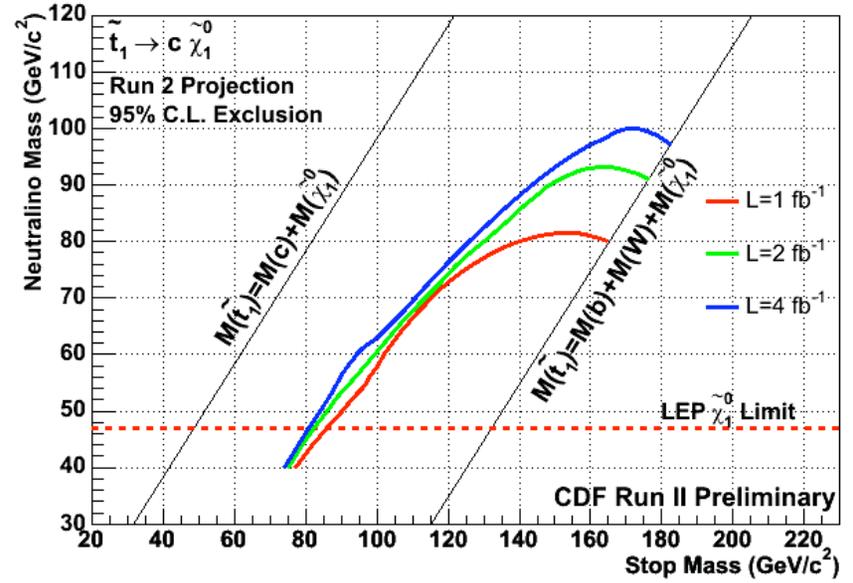
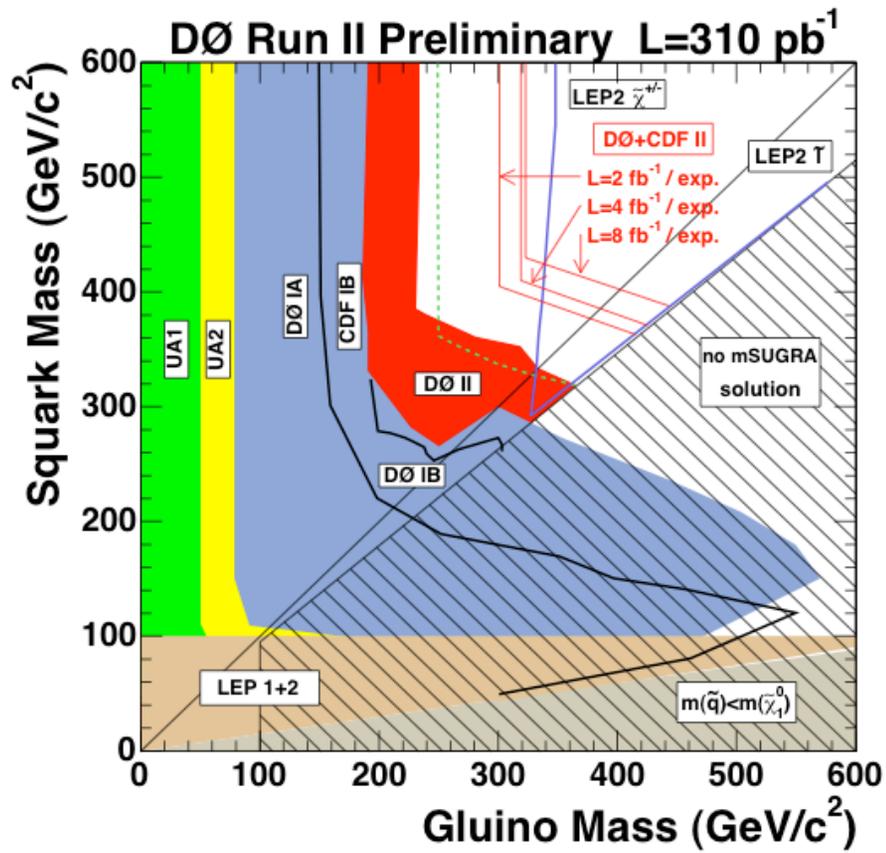


Experimental challenge



Time-of-Flight System





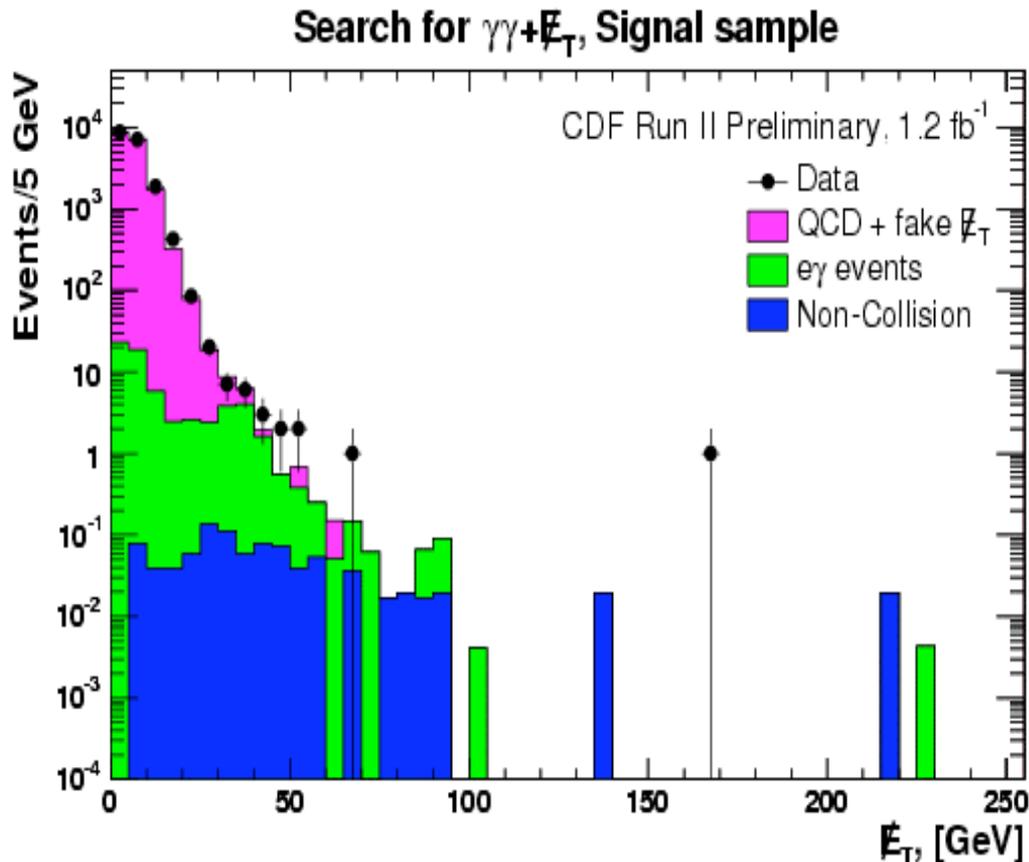


Search for SUSY in MET+Di-Photon

• In GMSB, gravitino \tilde{G} is the LSP (escape undetected)

• If $\tilde{\chi}_1^0$ is NLSP, then $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$

⇒ Thus in SUSY production under GMSB, final state will consist of $\gamma\gamma + \text{Missing Et} + X$



• CDF search for New Physics in $\gamma\gamma + \text{Missing Et}$ signature

• Signature base search, not optimized for any particular model

• Require 2 central photons with $E_T > 13 \text{ GeV}$

• Observe no excess at high MET

• DØ previous search (760 pb⁻¹) observe no excess, set limit $M(\tilde{\chi}_1^\pm) > 220 \text{ GeV}$