Direct Accelerator Searches for Supersymmetry

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Outline

- Introduction : Searches for SUSY at colliders
- The experiments at Tevatron and HERA
- Searches for SUSY (R-parity conserved)
    - Squark and Gluino
    - Sbottom
    - Chargino and Neutralino
- Searches for SUSY (R-parity violation)
    - R-parity Violation via LLE Coupling
    - Resonant Slepton Production
    - Resonant Squark Production
    - Bosonic Decays of Stop
- Summary

SUperSYmmetry

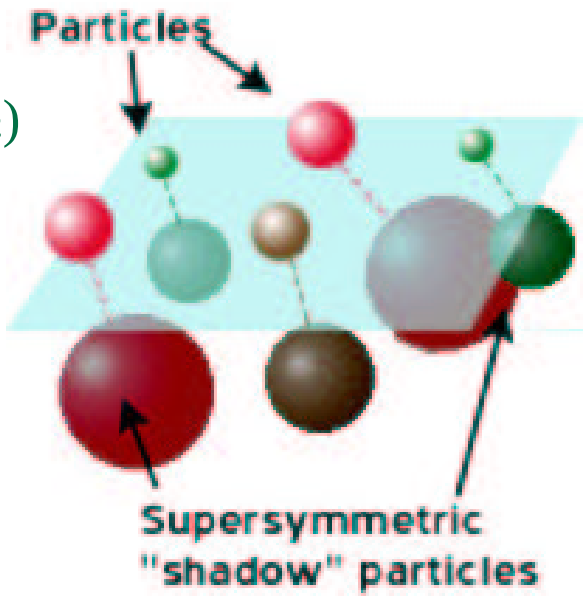
- Postulates symmetry between bosons and fermions
  - Every SM particle has a SUSY partner (spin differ by ½)

$$e,\nu,u,d,\ldots \text{ (spin ½)} \Rightarrow \tilde{e},\tilde{\nu},\tilde{u},\tilde{d},\ldots \textbf{(spin 0)}$$

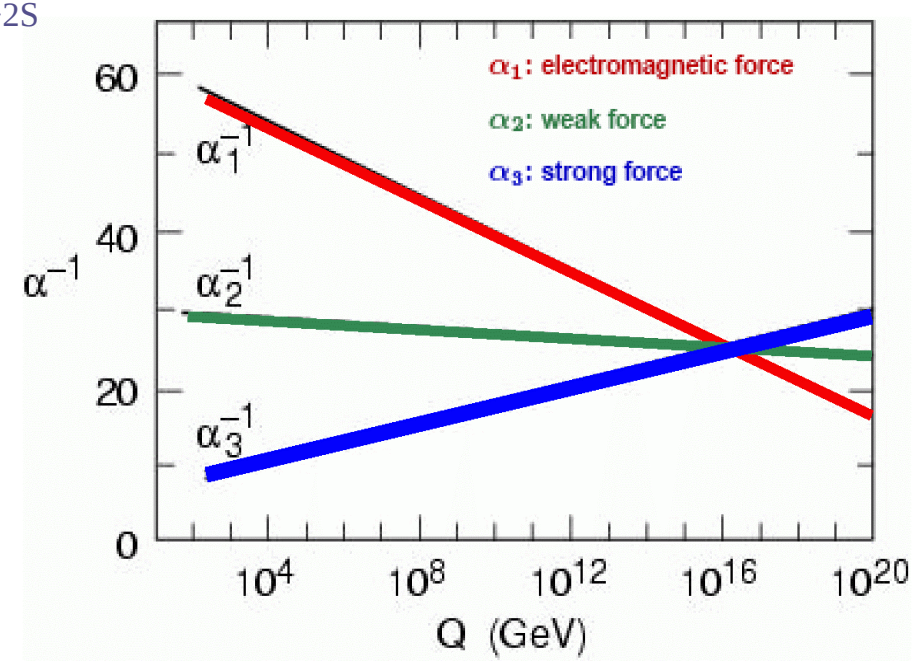
$$\gamma,W^{\pm},Z^{0},g,\ldots \text{ (spin 1)} \Rightarrow \tilde{\chi}^{0}_{1,2,3,4},\tilde{\chi}^{\pm}_{1,2},\tilde{g}\ldots \text{(spin ½)}$$

  - Breaks down the rigid classification :

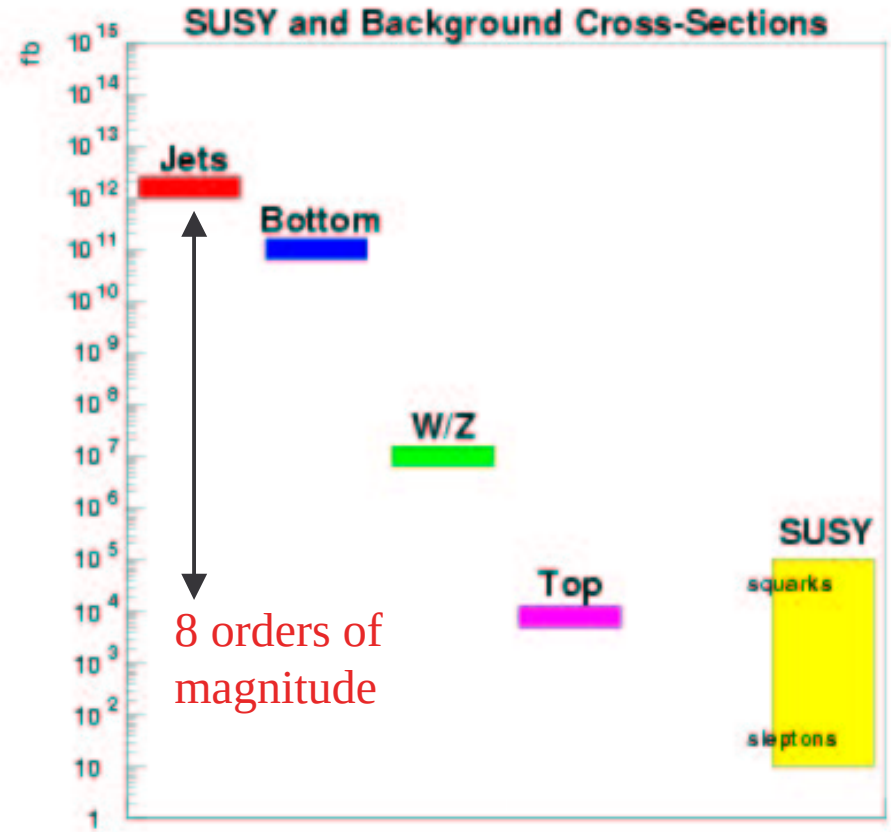
matter ↔ fermions	forces ↔ bosons



- New quantum number : R-parity = $(-1)^{3B+L+2S}$
  - Particles: R=1, SParticles: R=-1
- Can unify gauge couplings
- Can incorporate gravity (SUperGRAvity)
- May have a candidate for dark matter
- SUSY is not an exact symmetry
  - The SM particles and its SUSY partners have same quantum #, except that their masses are different



Look for SUSY at Colliders



(@ Tevatron)

At Colliders:

- Can produce SUSY particles directly
- Controlled environment v.s. indirect search from low energy experiments
- Production rates for SUSY is very small compare to other SM processes
- Challenge for experimentalists :

HOW TO LOOK FOR THEM !!!

- Low production rates, require high luminosity
- Need high detection efficiency
- Suppress background

Phenomenology of SUSY (R-parity)

- Expected SUSY signatures at colliders depend on assumption make about the theory

R-parity is conserved :

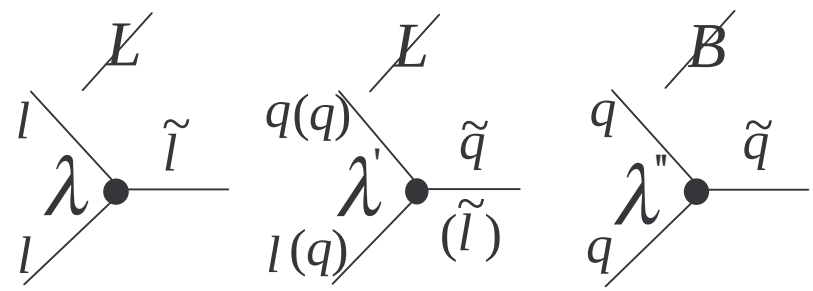
- SUSY particles are pair produced
- Lightest SUSY Particle (LSP) stable
  - If neutral ⇒ dark matter candidate
  - Escape detection ⇒ missing transverse energy ($\not{E}t$)

R-parity not conserved :

- SUSY particle can be singly produced
  ⇒ Larger production rate
- LSP decays to SM particles, no dark matter candidate
- Final states :
  - Not always have large missing energy
  - More jets/leptons

Superpotential of general MSSM with R-parity violation term :

$$W_{\not{R}p} = \underbrace{\lambda_{ijk} L_i L_j E_k}_{\not{L}} + \underbrace{\lambda'_{ijk} L_i Q_j D_k}_{\not{L}} + \underbrace{\lambda''_{ijk} U_i D_j D_k}_{\not{B}}$$



- Assume only one of the coupling is non-zero, to prevent rapid proton decay

Resonant production of SUSY via $\not{R}p$

	λ	λ'	λ''
Expt	LEP	HERA Tevatron	Tevatron

Phenomenology of SUSY (Models)

- MSSM has > 100 parameters ! $\Rightarrow$ Difficult to make prediction
- Some models make some assumption about SUSY breaking
  - To reduce # parameters
  - Thus make the theory more predictable
- Therefore PREDICTION depends on WHAT models used
- Common models used by collider experiments :

mSUGRA

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

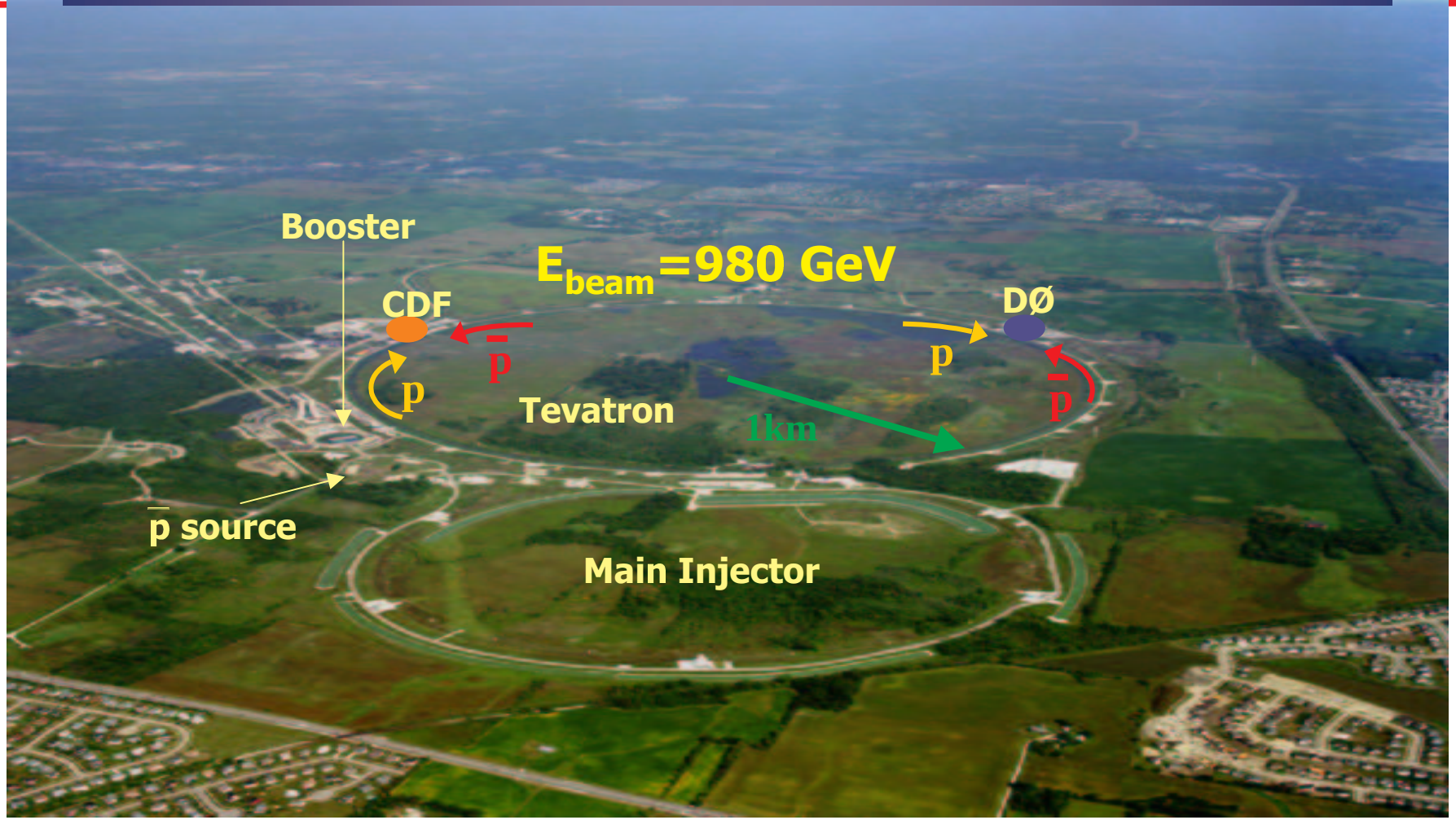
GMSB

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

- These models allow different colliding experiments to have a **common bench mark** to compare results

The Experiments

Fermi National Accelerator Laboratory



Tevatron:

In operation since 1985, major upgrade completed in 2000

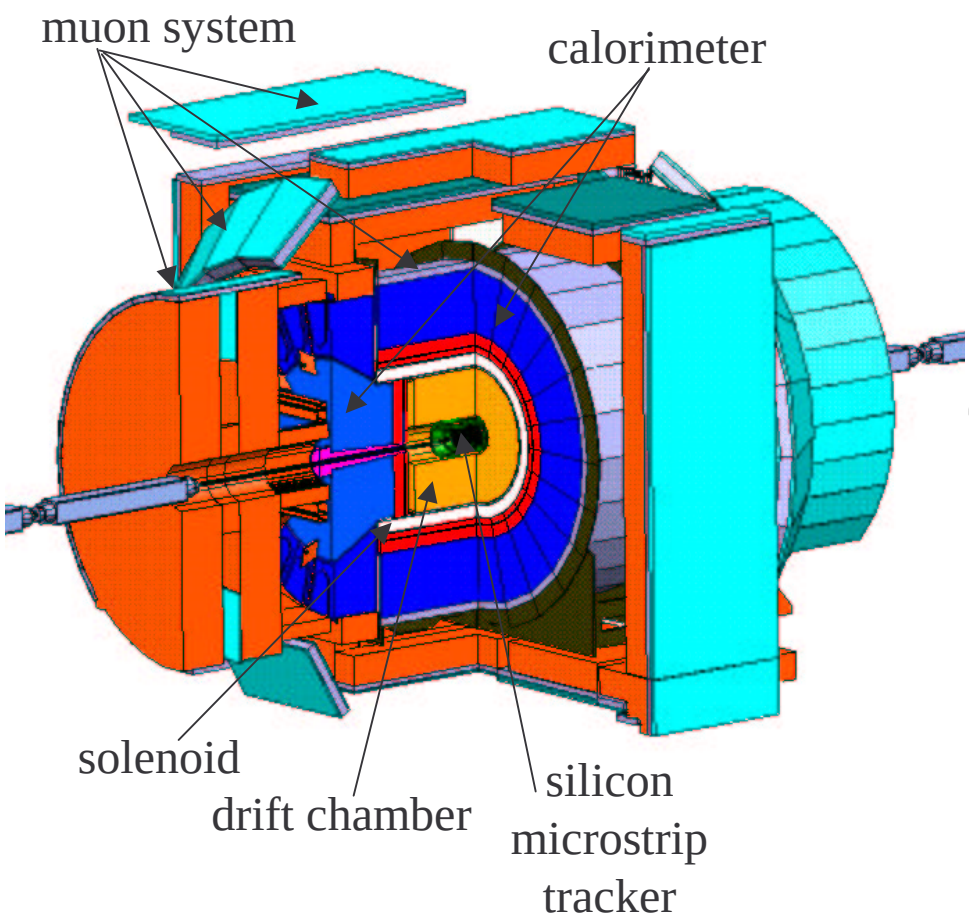
Run II began March 2001, has since delivered ~0.65 fb^{-1}

Design peak instantaneous luminosity ~ 2 E32 $cm^{-2}s^{-1}$ (has achieved 1E32 !)

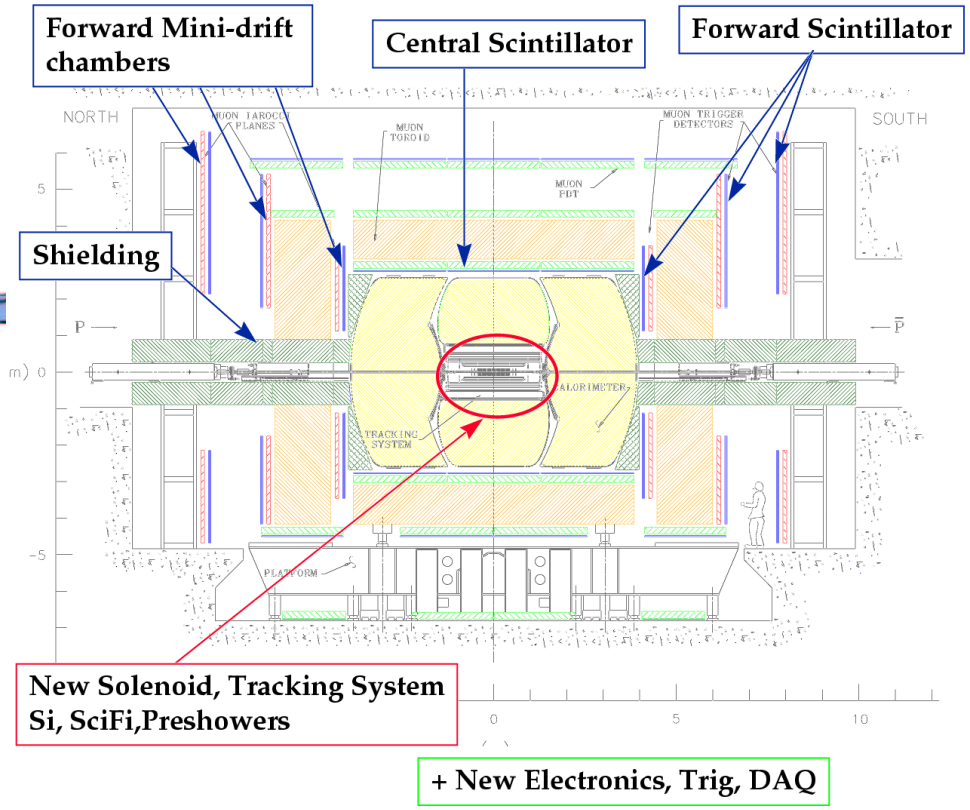
The Tevatron Experiments

Multipurpose detectors :

- Electron, muon, tau identification
- Jet and missing energy measurement
- Heavy-flavor tagging through displaced vertices and soft leptons



CDF



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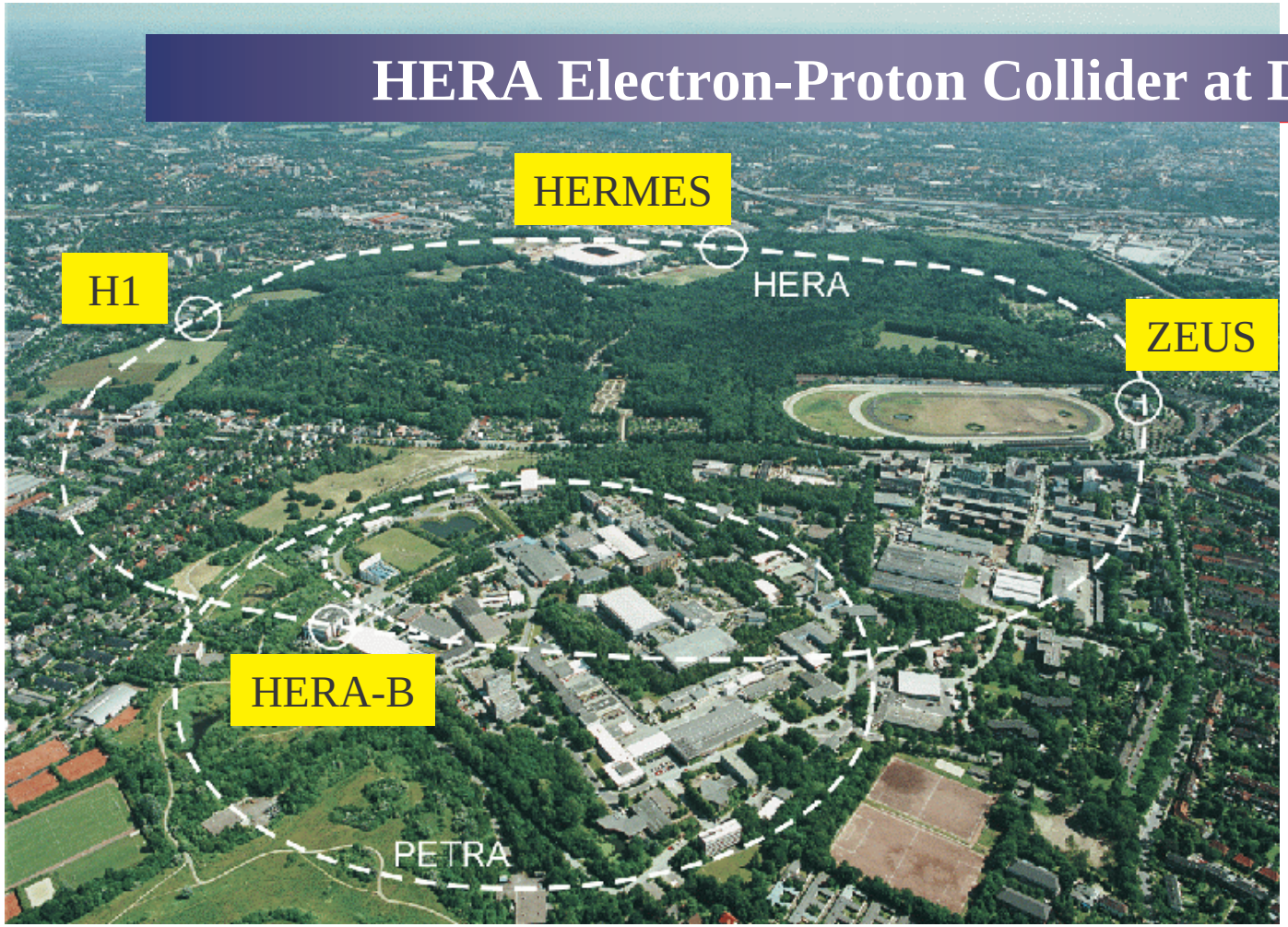
HERA Electron-Proton Collider at DESY



e^+/e^- → ← p

E(e)=27.5 GeV

E(p)=

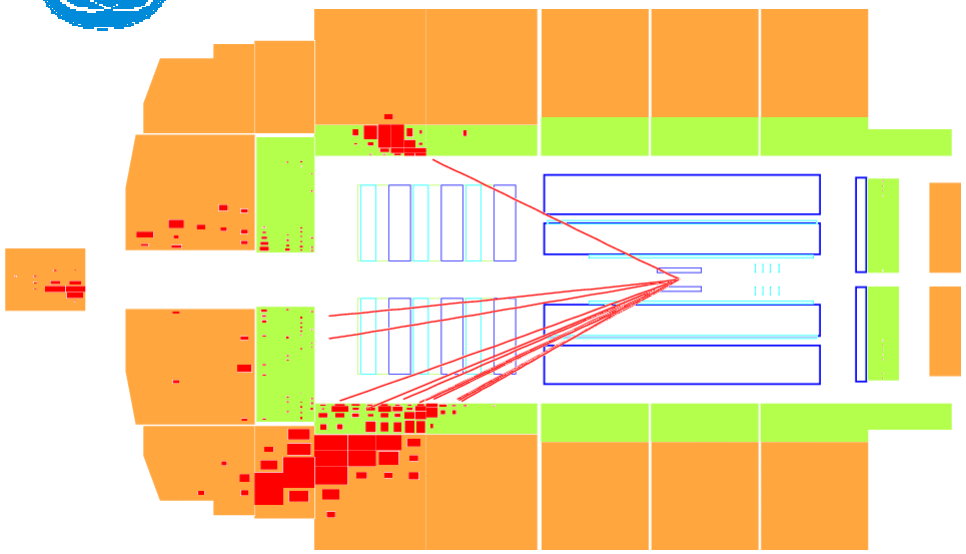
820 GeV (until 1997)

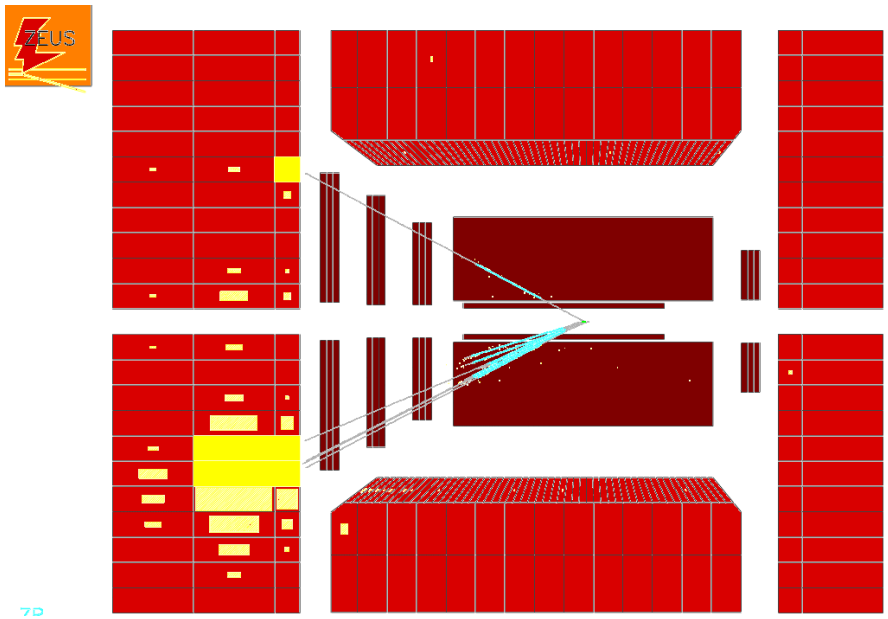
920 GeV (from 1998)

$\sqrt{s} \sim 300$ GeV

- During HERA-1 (1994-200) : H1 and ZEUS collected ~ 0.1 fb^{-1}
- Upgraded ⇒ HERA-2
  - Data taking until 2007 → 0.7 fb^{-1}

The HERA Experiments





Liquid Argon Calorimeter

44000 cells

$\sigma/\sqrt{E}$ = 12% electron

$\sigma/\sqrt{E}$ = 50% hadron

Uranium-Scintillator Calorimeter

6000 cells read out by 12000 PMT's

$\sigma/\sqrt{E}$ = 18% electron

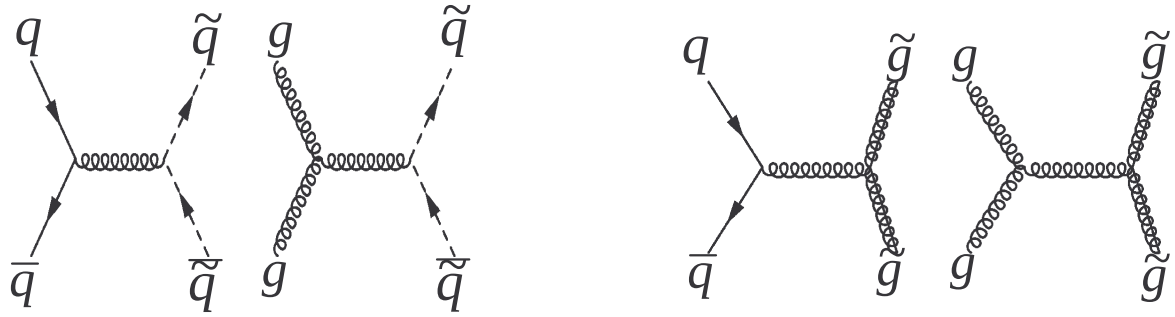
$\sigma/\sqrt{E}$ = 35% hadron

+ tracking, vertex, μ and leading e, p, n detection

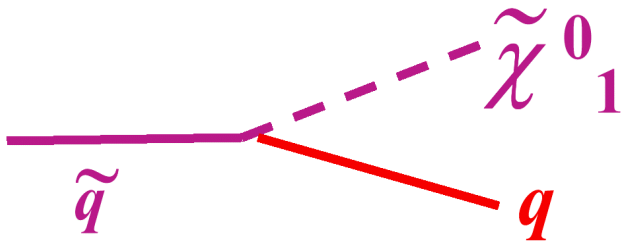
Searches for SUSY (R-parity Conserved)

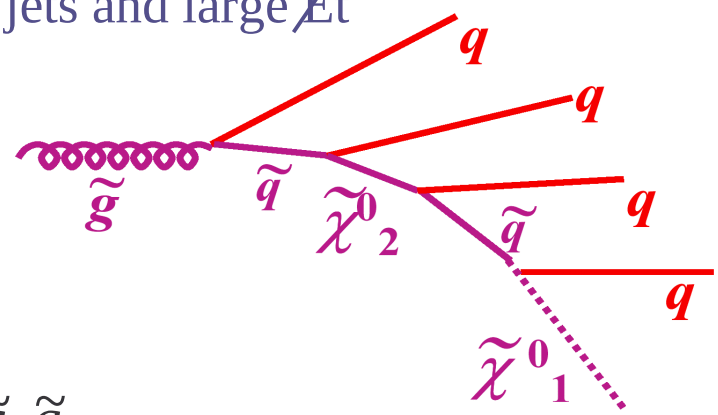
Searches for Squarks and Gluinos in MET + Jets

- Light colored sparticles($\tilde{q},\tilde{g}$) can be copiously pair produced at Tevatron



- Decays of $\tilde{q},\tilde{g}$ may produce multiple jets and large $\not{E}t$





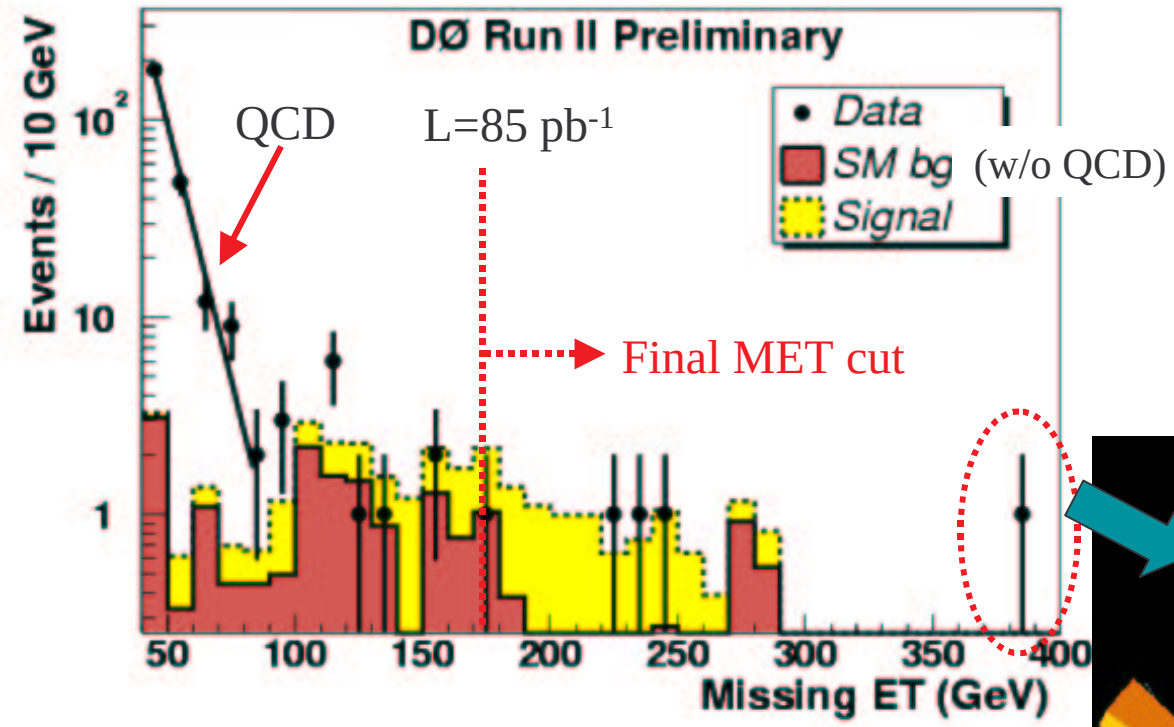
$\tilde{\chi}^0_1$: LSP

- D∅ has performed direct search for $\tilde{q},\tilde{g}$:
  - Using Jets+$\not{E}t$ data sample (~85 pb^{-1})
  - Require ≥2 jets (Et_1>60 GeV, Et_2>50 GeV)
  - Jets to be acoplanar , not pointing in same direction as $\not{E}t$ (reduce QCD multi-jets)

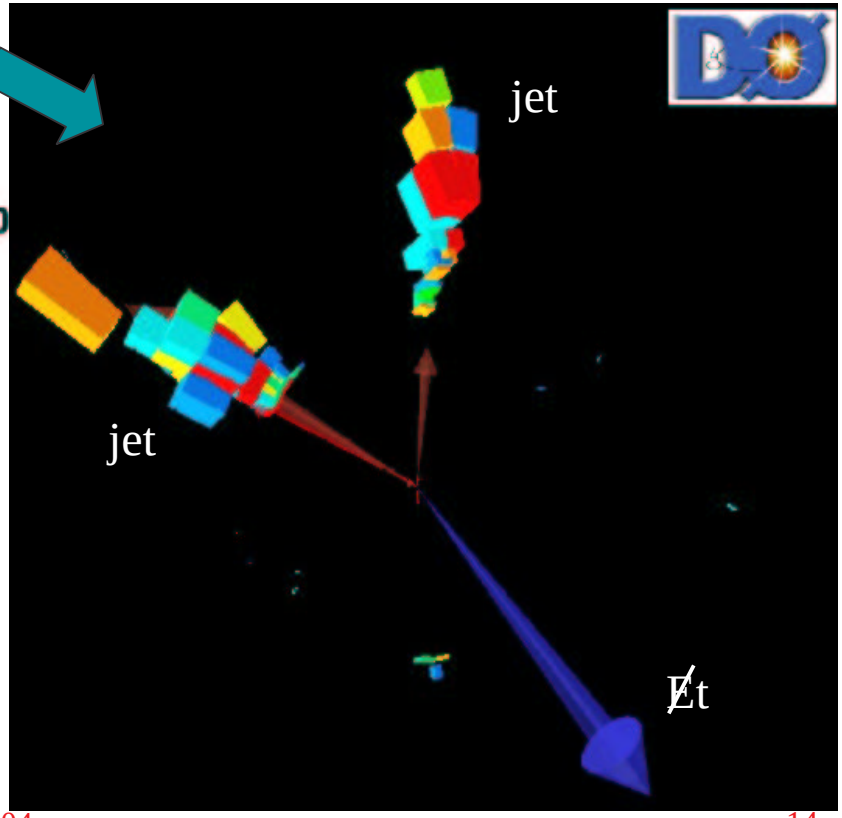
- No isolated leptons (e,μ)
- $\not{E}t$ > 175 GeV
- $H_T = \sum_i Et^i_{jet} > 275$ GeV

Reduce W/Z+jets

Searches for Squarks and Gluinos in MET + Jets



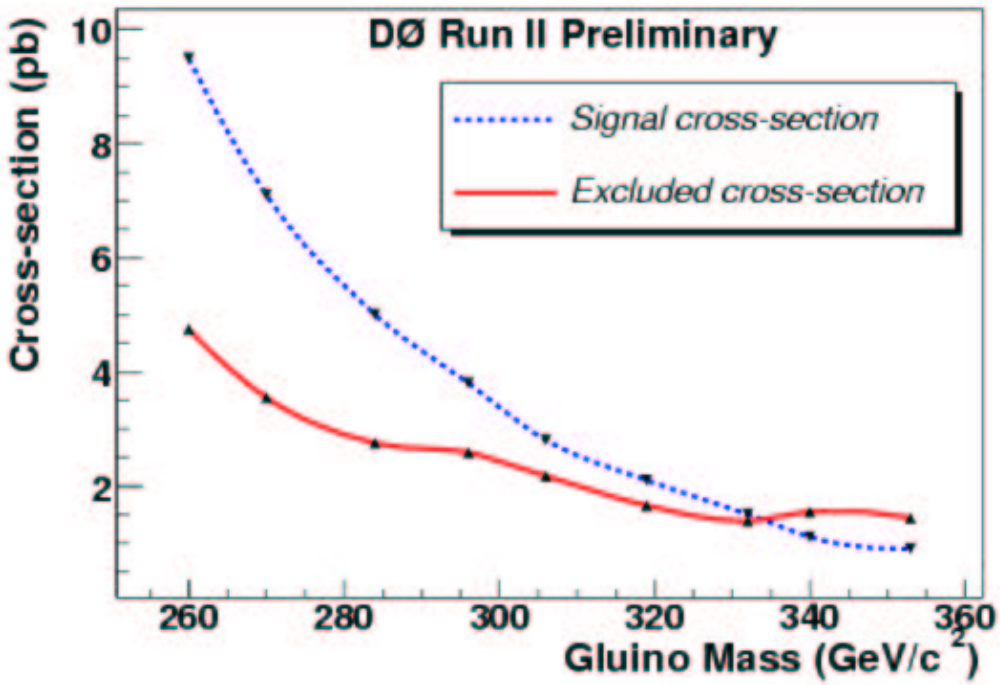
- A large $\not{E}t$ event (w/ 2 large Et jets)
  - $\not{E}t$ = 381 GeV
  - Et_1=289 GeV, Et_2=117 GeV

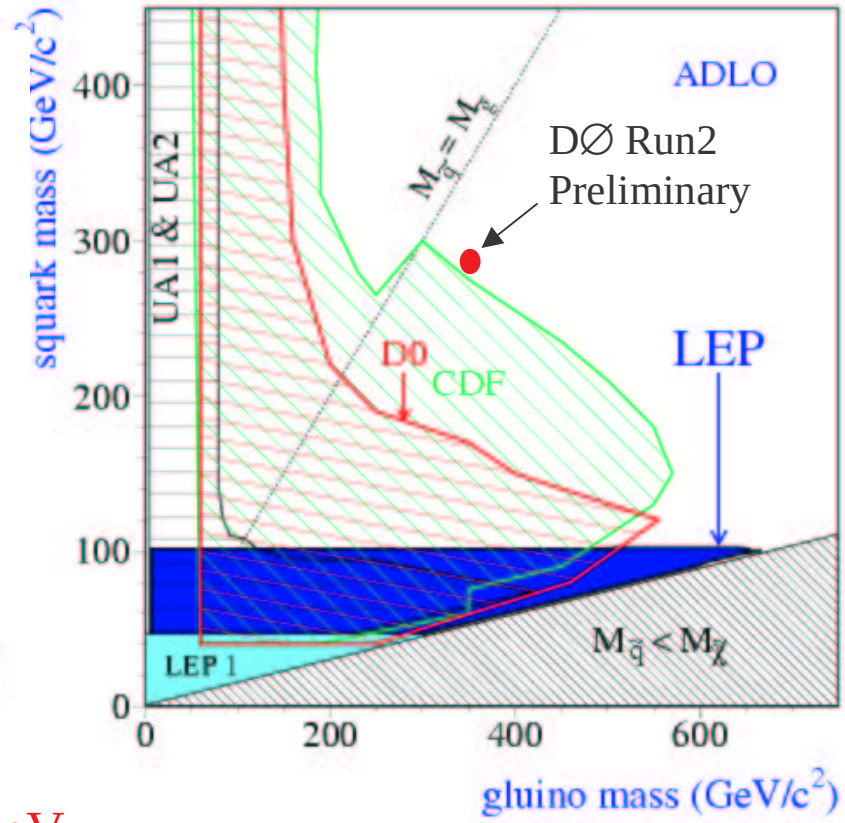


- Observed 4 events, expect 2.7±1.0 (stat)
- SM background mostly from :
  - $Z(\rightarrow\nu\nu)$+jets
  - $W(\rightarrow\tau\nu)$+jets

Searches for Squarks and Gluinos in MET + Jets

- Interpret results in mSUGRA scenario :
  - m_0=25 GeV, tanβ=3, A_0=0, μ<0
- Signal efficiency : ~2 - 7 % ($m_{1/2}$ = 100-140 GeV)

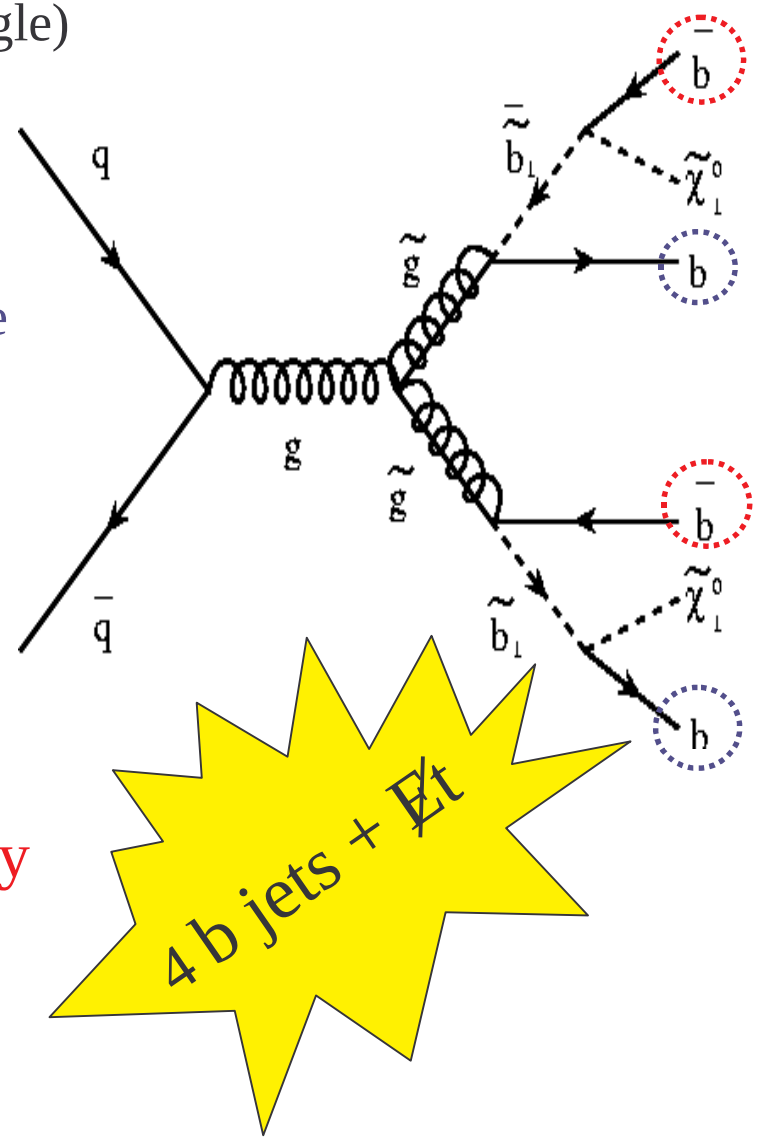




- Set gluino (squark) mass limit at 333 (292) GeV
- **Have extended Run1 limit !**

Searches for Sbottom from Gluino Decay (MET + Jets)

- The 3rd generation squarks could be light due to large mixing of the mass eigen-state
  - $\tilde{q} = \tilde{q}_L \cos\theta_{\tilde{q}} + \tilde{q}_R \sin\theta_{\tilde{q}}$ ($\theta_{\tilde{q}}$: mixing angle)
- Large top mass → light stop
- At large tanβ → light sbottom
- At Tevatron the gluino pair production rate is large
- If $M_{\tilde{q}}\,(\text{light flavor}) > M_{\tilde{g}} > M_{\tilde{b}} > M_{\tilde{\chi}_1^0}$
  - $\tilde{g} \rightarrow \bar{b}\tilde{b}_1$
  - $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ ($\tilde{\chi}_1^0$: LSP)

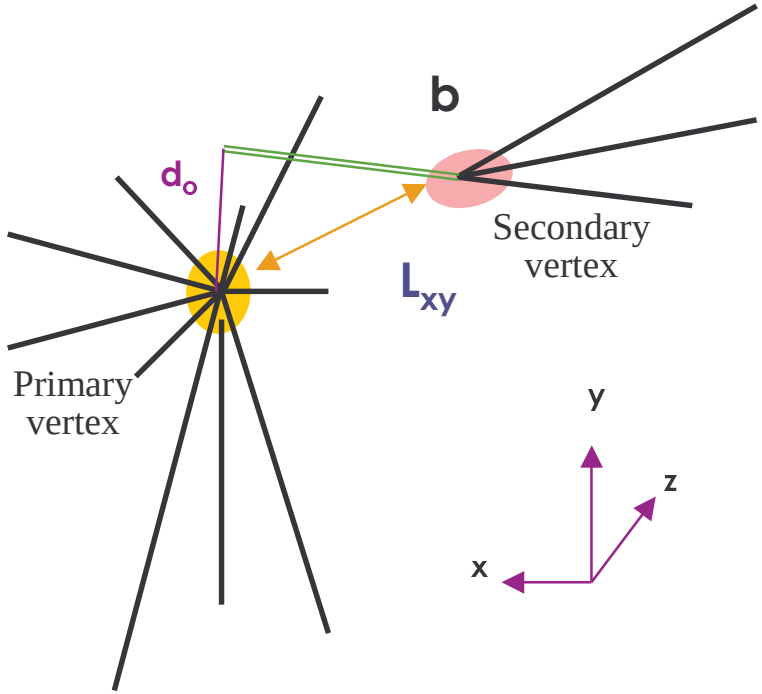


CDF search for Sbottom from Gluino decay

Assuming : $BR(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 100\%$

Searches for Sbottom from Gluino Decay (MET + Jets)

- Data sample: MET+2jets (156 pb^{-1})
  - Require ≥ 1 jet b-tagged (displaced from primary vertex)



Backgrounds :

QCD multi-jet :

- Reduced by requiring:
  - Large $\not{E}t$ ($\not{E}t$>80 GeV)
  - Jets not pointing in MET direction
- Estimate contribution from MC and fake tagging rate measured in data

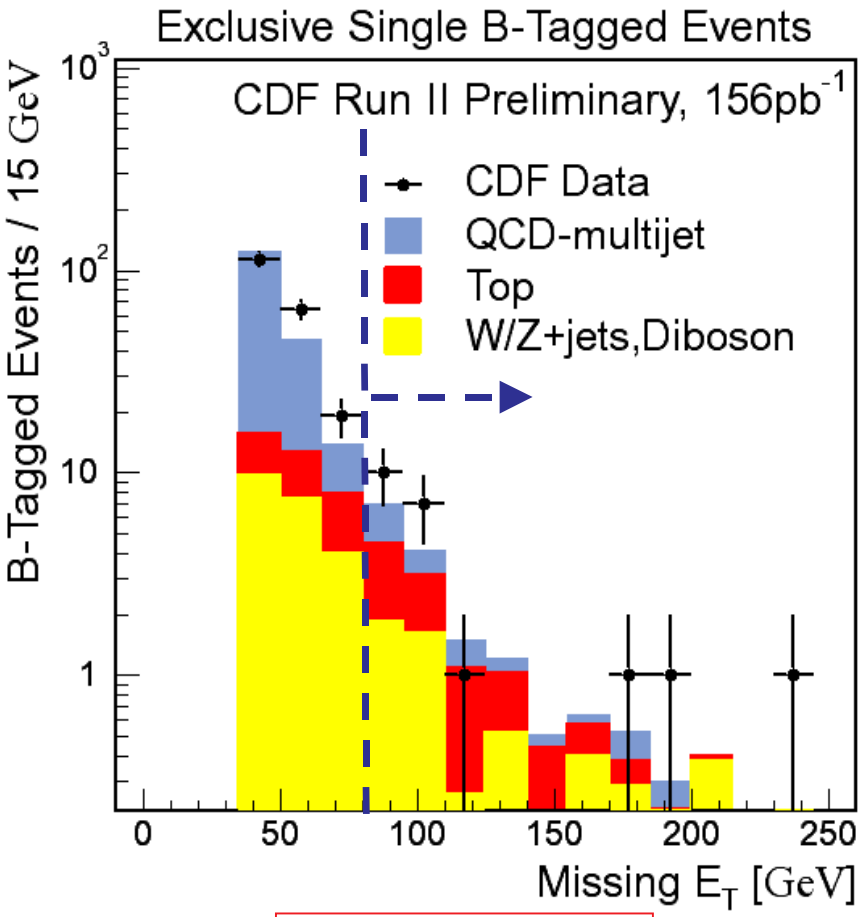
Electroweak : W/Z+jets, Diboson

- Reduced by requiring:
  - Tag b jets
  - No isolated lepton
- Estimate contribution from MC

t-tbar : t→Wb

- Reduced by requiring:
  - No isolated lepton
- Estimate contribution from MC

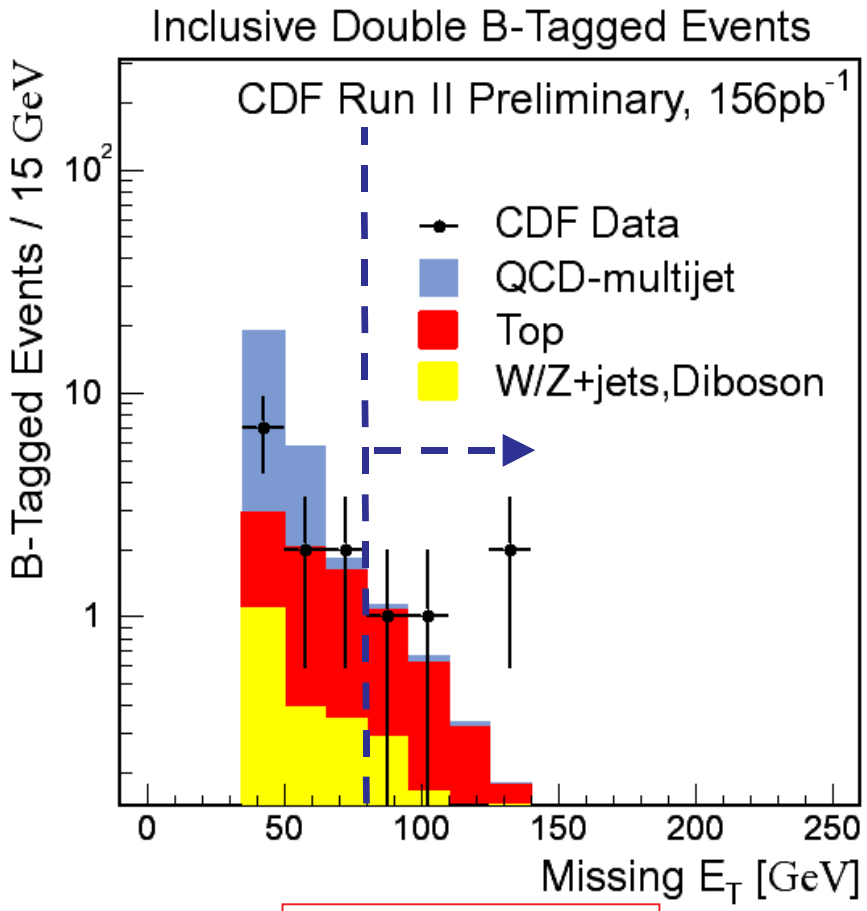
Searches for Sbottom from Gluino Decay (MET + Jets)



1 b-tag

Observed : 21

Expect : 16.4 ± 3.7

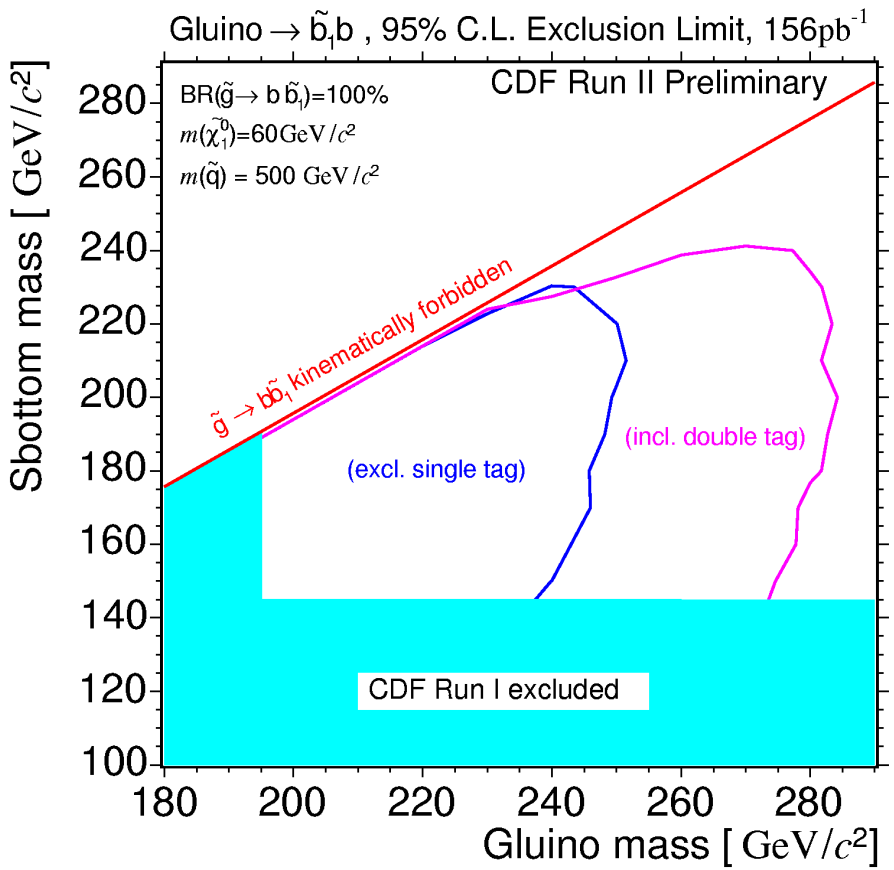


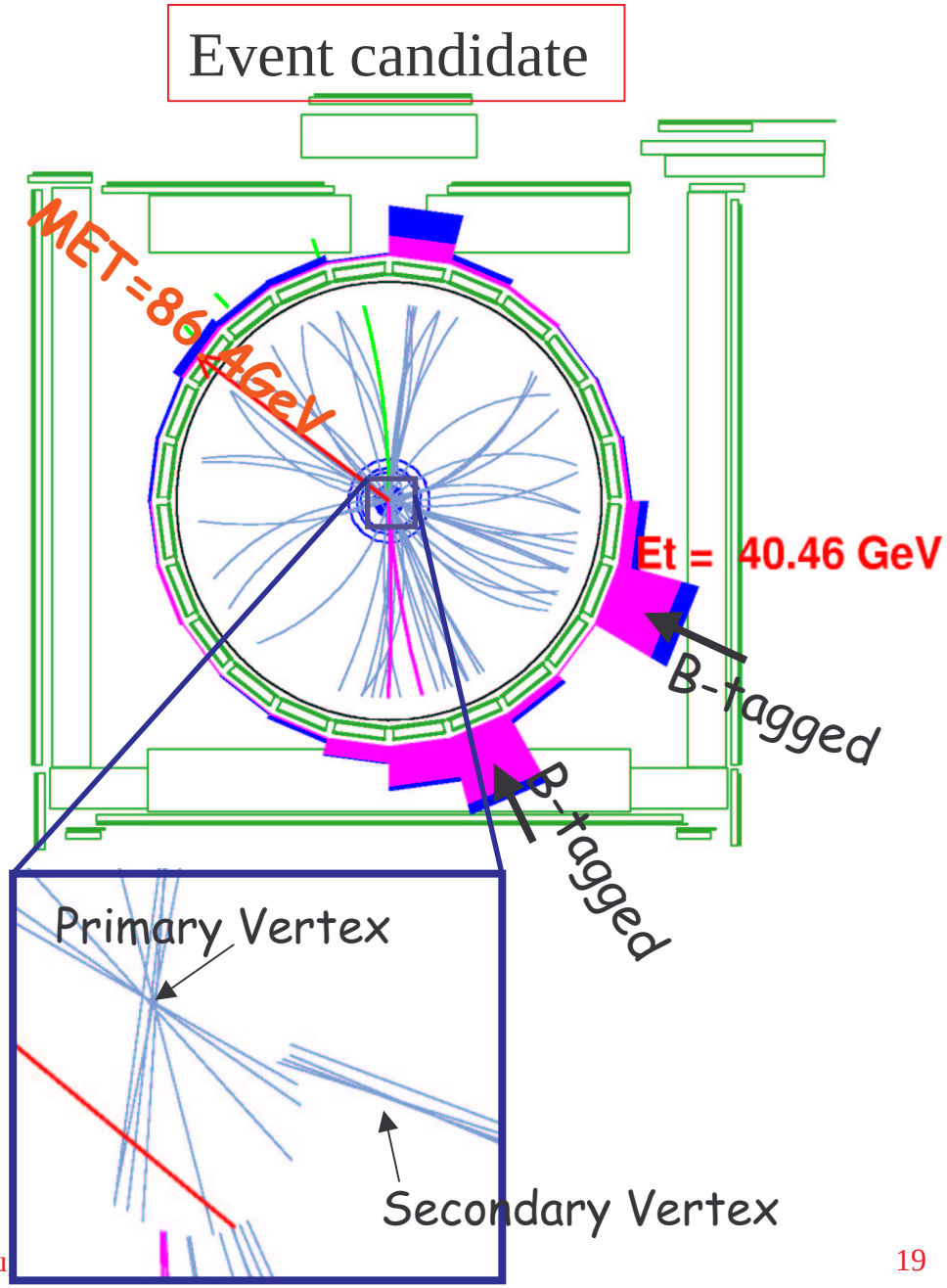
≥2 b-tag

Observed : 4

Expect : 2.6 ± 0.7

Searches for Sbottom from Gluino Decay (MET + Jets)



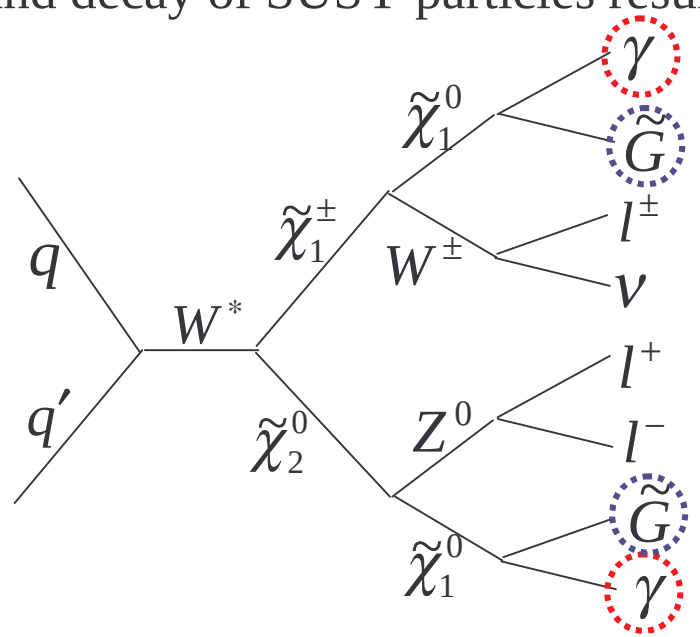


- Extended CDF Run1 limit
- Better limit from double tag due to better background suppression, while keeping similar acceptance as single tag
- M($\tilde{g}$)=240 GeV, M($\tilde{b}_1$)=180 GeV

Acceptance: ~8%(1 b-tag), ~9% (≥2 b-tag)

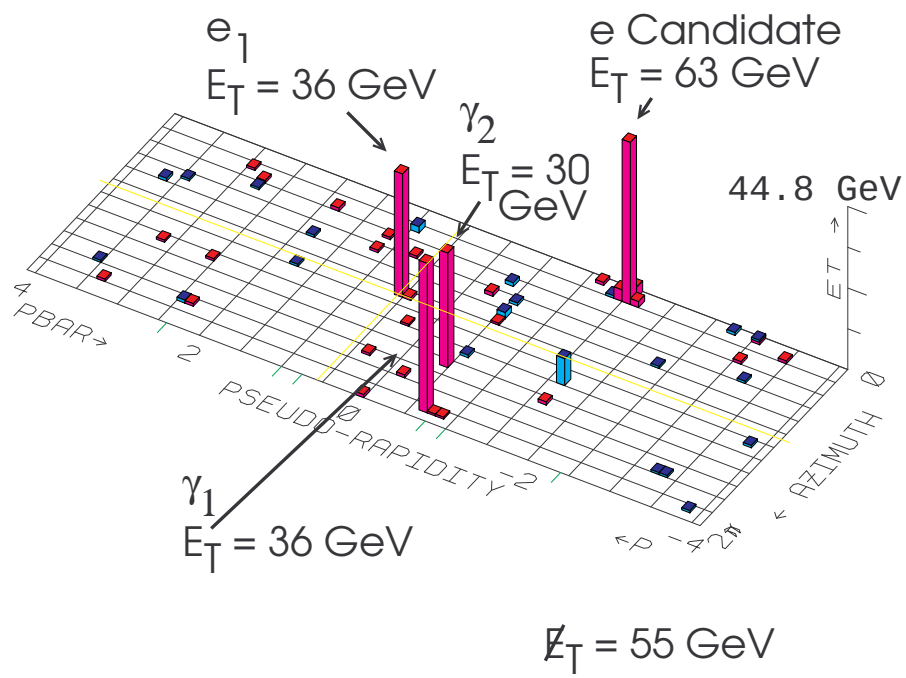
Inclusive DiPhoton Search

- In Run1 CDF observed an event with $ee\gamma\gamma + \not{E}t$ in the final state
- Di-photon + $\not{E}t$ signature is rare in SM processes
- Possible SUSY scenario for such event :
  - GMSB:
    - $\tilde{G}$ is LSP, NLSP is $\tilde{\chi}_1^0$ or $\tilde{l}$
    - If $\tilde{\chi}_1^0$ is NLSP, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$
    - If R-parity is conserved, pair production and decay of SUSY particles results :



CDF Run1

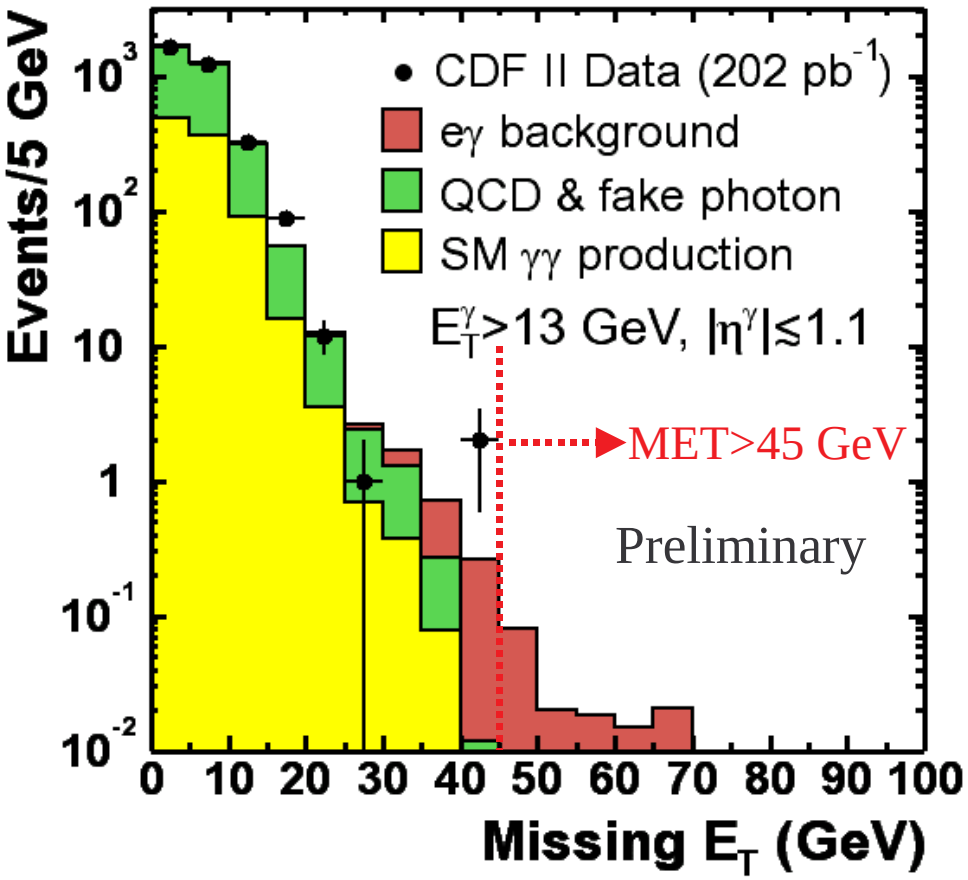
$ee\gamma\gamma\not{E}_T$ Candidate Event

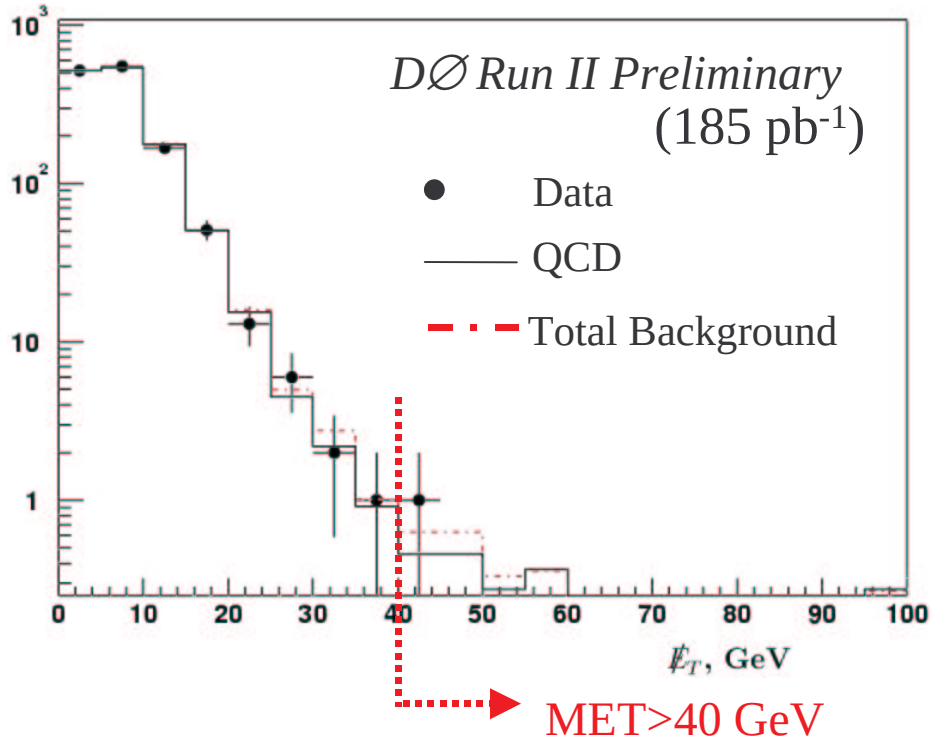


Final state : $\gamma\gamma + \not{E}t + X$

Inclusive DiPhoton Search

•Performed extensive search for events w/ $\gamma\gamma + \not{E}t$ signature by CDF and DØ in Run2





Observed : 0

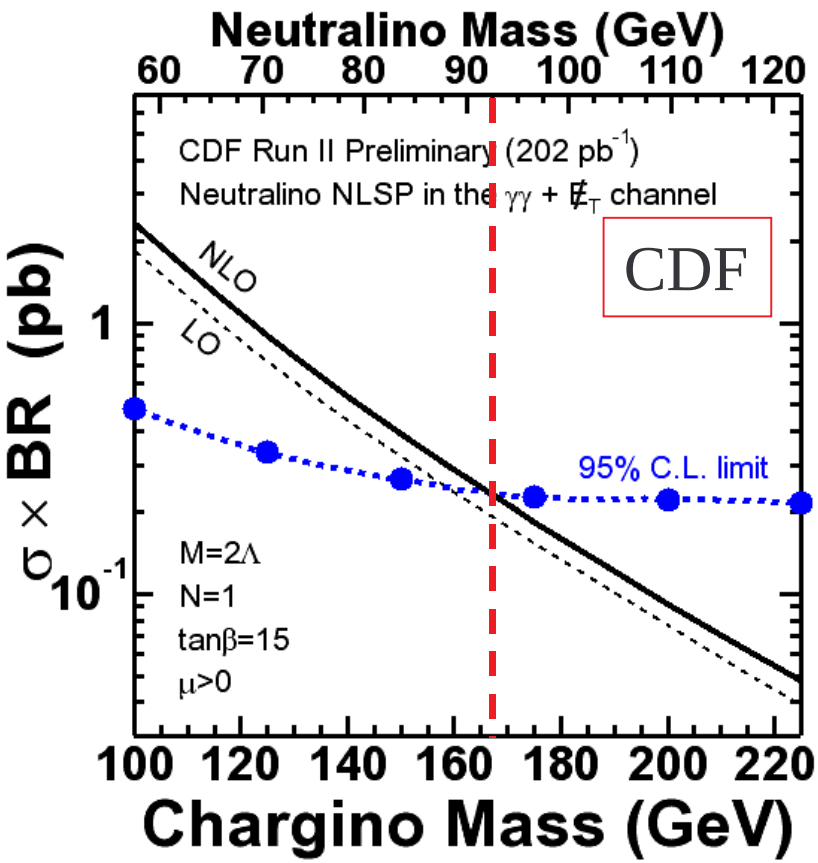
Expect : 0.27±0.12

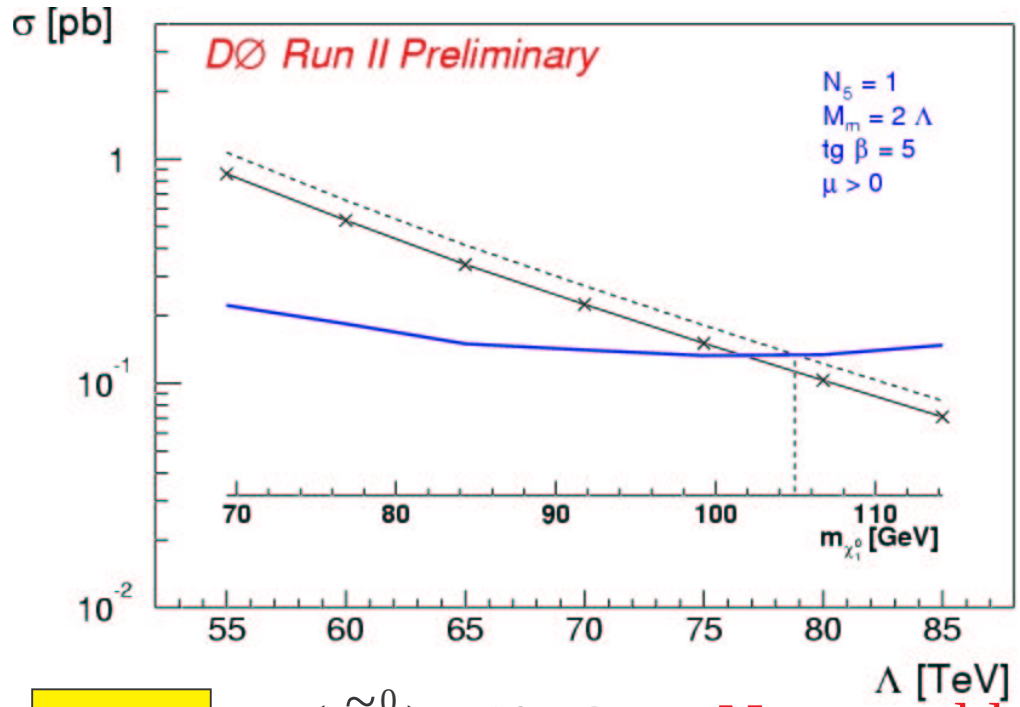
Observed : 1

Expect : 2.5±0.5

Inclusive DiPhoton Search

- SM contributions to $\gamma\gamma + \not{E}t$:
  - Fake $\not{E}t$:
    - QCD w/ direct γ, or jets mis-ID as γ
    - DY w/ both *e* mis-ID as γ
    - Non-collision: Cosmic/beam-related (losses/halo)
- True $\not{E}t$:
  - $W\gamma \rightarrow e\nu\gamma$ (lost track)
  - $Wj \rightarrow e\nu j$ (lost track, jet fake as γ)
  - $Z \rightarrow \tau\tau \rightarrow ee + X$ (lost track)
  - $t\bar{t}, WW, WZ$





DØ limits

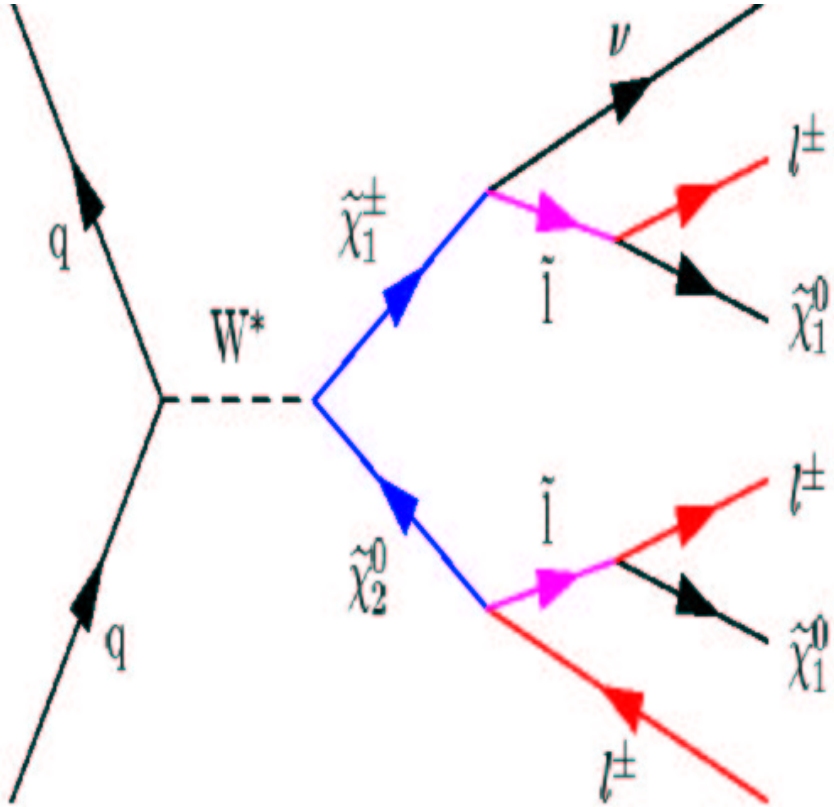
- $M(\tilde{\chi}_1^0) > 105$ GeV
- $M(\tilde{\chi}_1^+) > 192$ GeV

New world best limit !

Searches for Chargino/Neutralino in Tri-Lepton

- Pair production of chargino/neutralino can produce multi-lepton and $\not{E}t$ in final state
- Small contributions from SM processes in this signature

  ⇒Very clean, "Gold Plated" signature to find SUSY

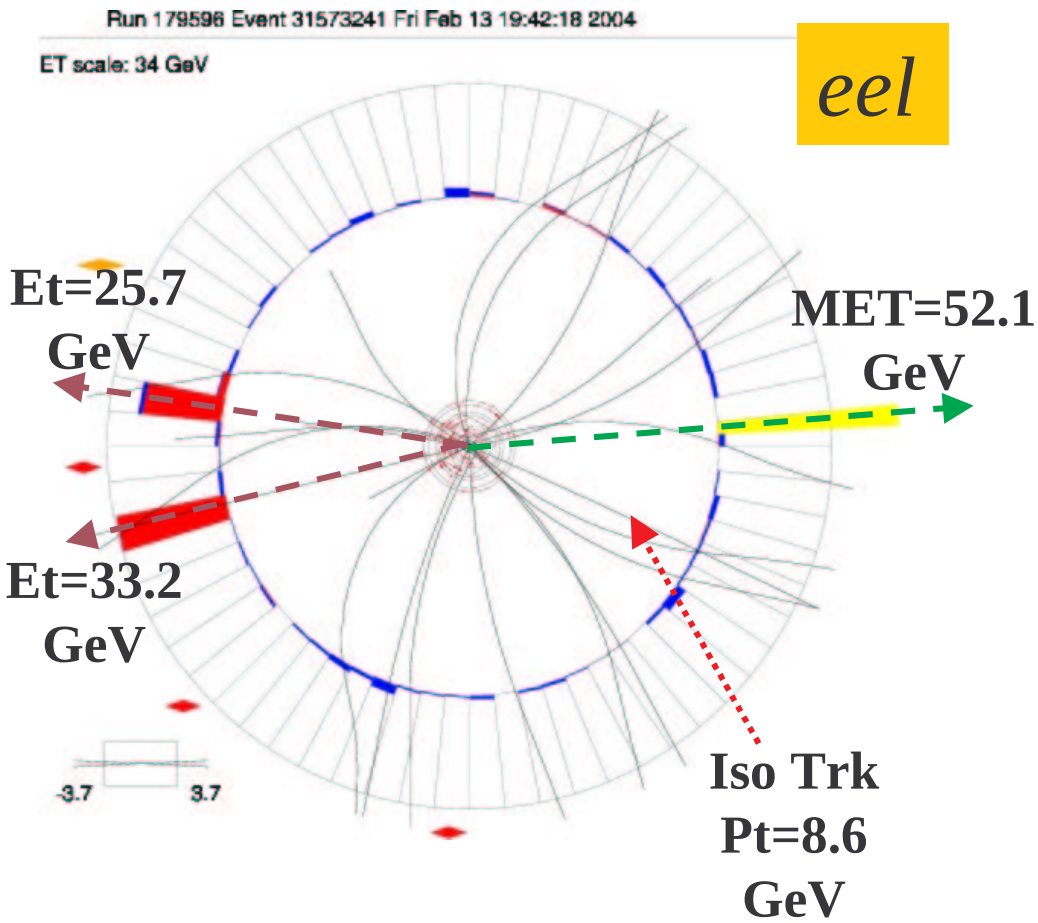


- Searches at DØ:
  - $e + e$ + lepton
  - $e + \mu$ + lepton
  - $\mu + \mu$ + lepton
  - Like sign di-muon ($\mu^+\mu^+$, $\mu^-\mu^-$)
- Search optimized for mSUGRA parameter space near LEP 2 limit :
  - $\tan\beta=3$, $A_0=0$, $\mu>0$
  - $m_0=[72,88]$ GeV, $m_{1/2}=[165,185]$ GeV
- Search using data ~ 147 – 249 pb^{-1}

Searches for Chargino/Neutralino in Tri-Lepton

	eel	*eμl*	*μμl*	LS *μμ*
Data Sample L (pb^{-1})	249	235	221	147
Pt of 2 charged leptons (GeV)	Pt(e1) > 12 Pt(e2) > 8	Pt(e) > 12 Pt(μ) > 8	Pt(μ1) > 15 Pt(μ2) > 5	Pt(μ1) > 10 Pt(μ2) > 5
Iso Trk Pt (GeV)	> 3	> 5	> 3	
$\not{E}$t (GeV)	> 20	> 20	> 22	> 15
Other Cuts				
# Observed	1	0	1	1
# Expected	0.68±0.40±0.32	0.29±0.33±0.02	1.83±0.40±0.21	0.13±0.06±0.02
Dominant Background	$\gamma^*/Z \rightarrow e^+e^-$ W+γ WW/WZ	WZ W+γ W+jets	$\gamma^*/Z \rightarrow \mu^+\mu^-$ $\gamma^*/Z \rightarrow \tau^+\tau^-$	WZ $b\bar{b}$ ZZ
# Signal (mSUGRA scanned region)	0.7 - 2.3	0.4 – 1.8	0.3 – 1.4	0.1 – 0.4

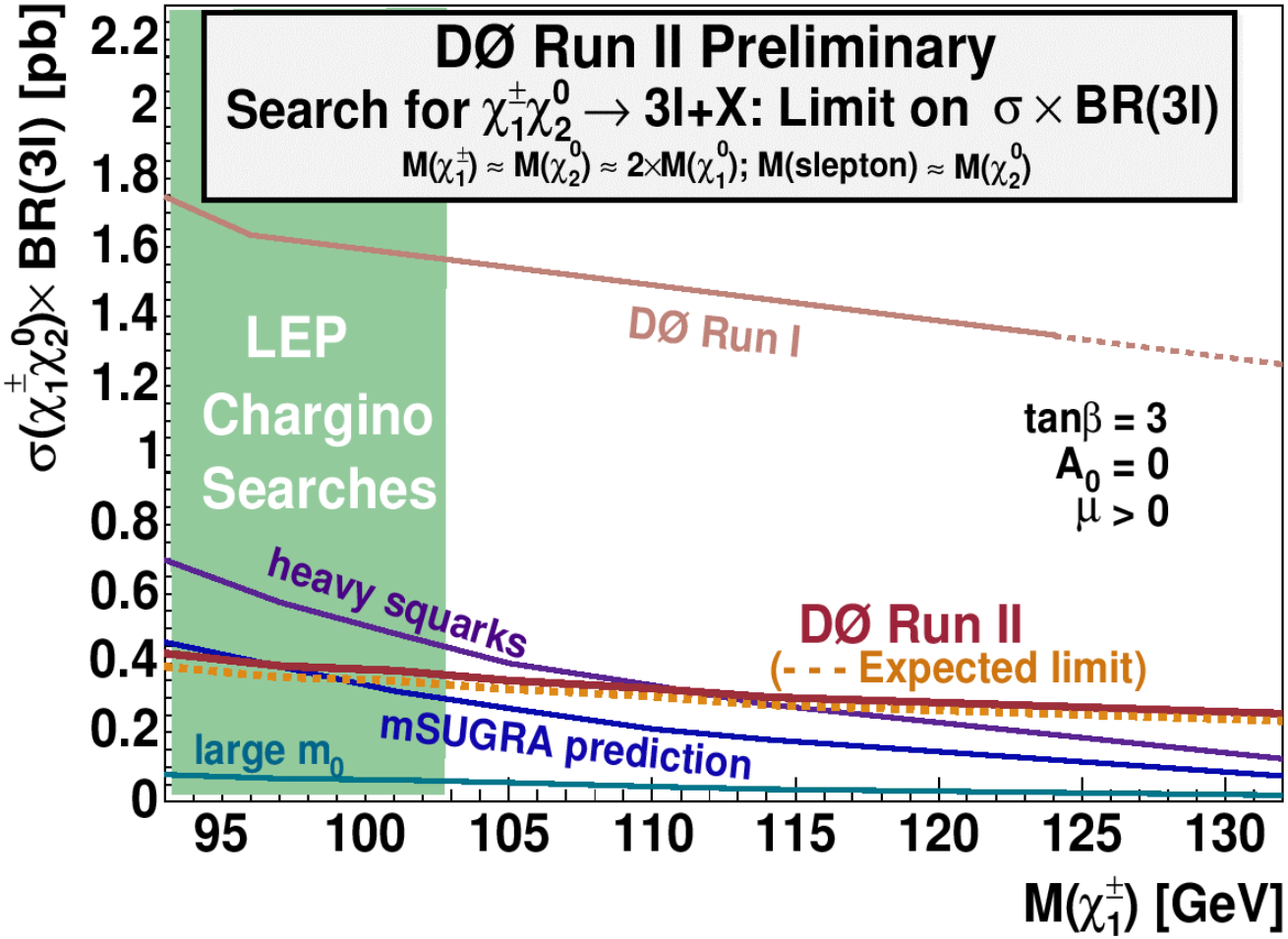
Searches for Chargino/Neutralino in Tri-Lepton



An event candidate from *e*+*e*+*l* search

Searches for Chargino/Neutralino in Tri-Lepton

- Combined results from each analysis
  - ⇒Improve sensitivity
- Significant improvement over Run1 Tevatron results
- Excluded chargino mass below 97 GeV (in mSUGRA model)
  - Closed to LEP2 limit
  - Can reach same sensitivity w/ 25% more data !!!



Searches for SUSY (R-parity Violation)

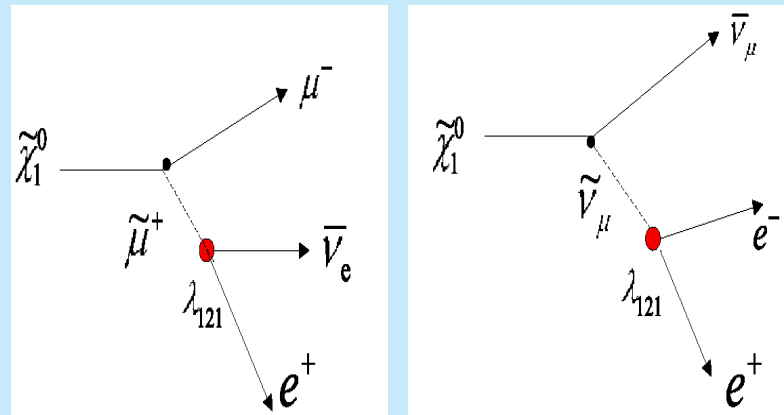
Search for SUSY with R-parity Violation

- For this search, DØ looked for :
  - Rp conserved SUSY production
  - Sparticles cascade decay into light $\tilde{\chi}_1^0$ (LSP)
  - $\tilde{\chi}_1^0$ $\not{R}$p decays via λ_{121} or λ_{122}
  - Each case assume all other $\not{R}$p couplings are negligibly small

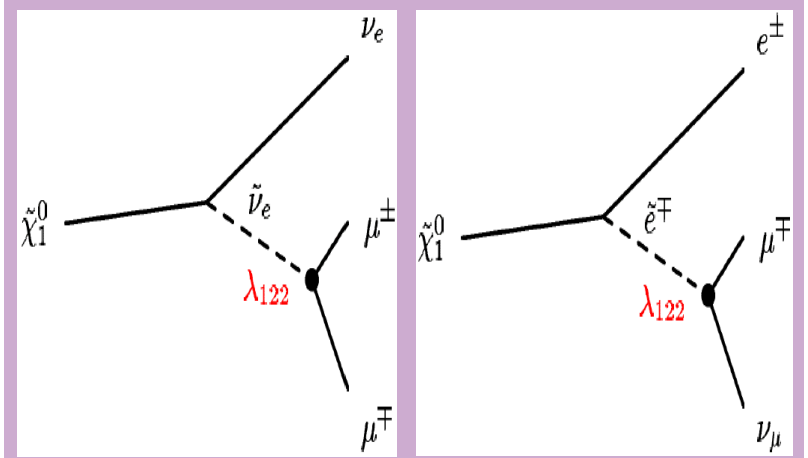
$\Rightarrow$ Final state : 4 charged leptons + $\not{E}$t (from ν)

	λ_{121}	λ_{122}
# e or μ in final state	$\geq 2\ e$	$\geq 2\ \mu$
Select Evts w/	$e + e + l(e,\mu)$ moderate $\not{E}$t	$\mu + \mu + l(e,\mu)$ moderate $\not{E}$t
# Observed	0	2
# Expected	0.45±0.43	0.63±1.93
Dominant SM background	$\gamma^*/Z \rightarrow e^+e^-$ $\gamma^*/Z \rightarrow \tau^+\tau^-$	$\gamma^*/Z \rightarrow \mu^+\mu^-$ $\gamma^*/Z \rightarrow \tau^+\tau^-$

λ_{121} L=238 pb^{-1}

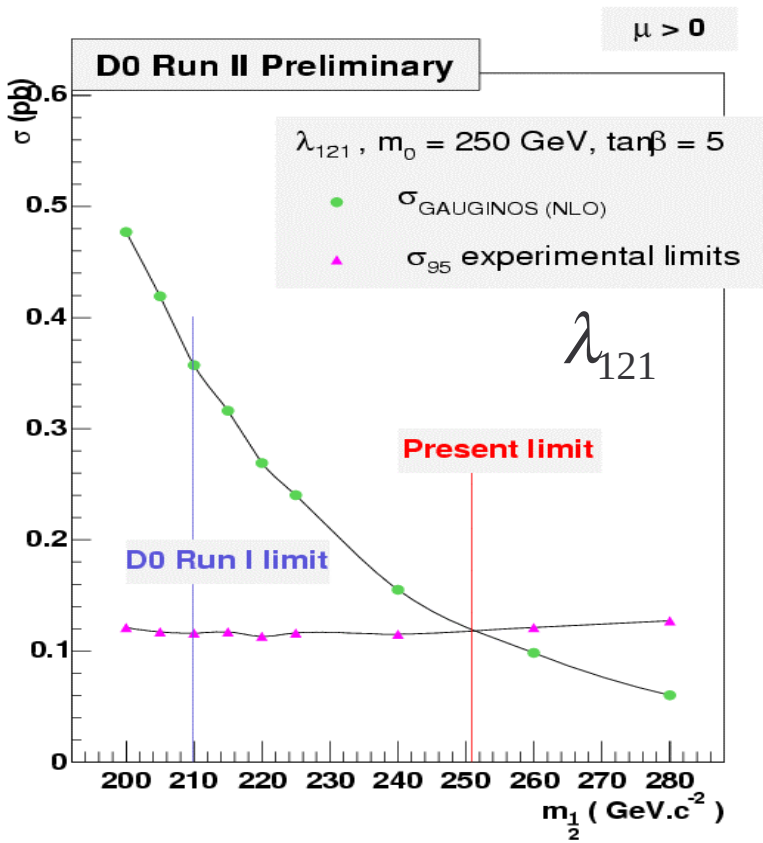


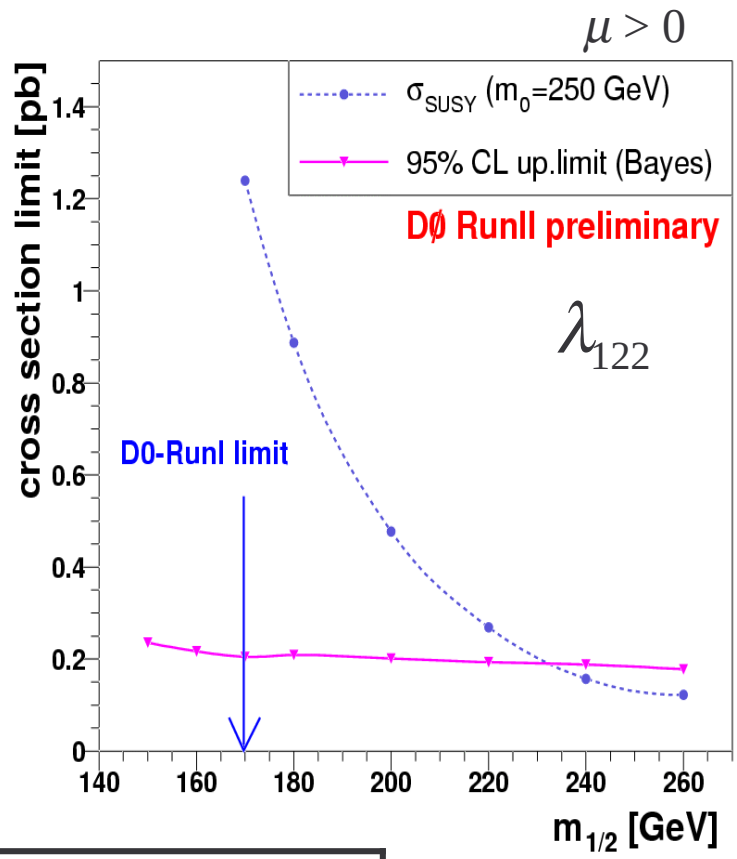
λ_{122} L=160 pb^{-1}



Search for SUSY with R-parity Violation

- Both analyses interpret results in mSUGRA framework :
  - m_0=250 GeV, A_0=0, tanβ=5, $\mu > 0, < 0$





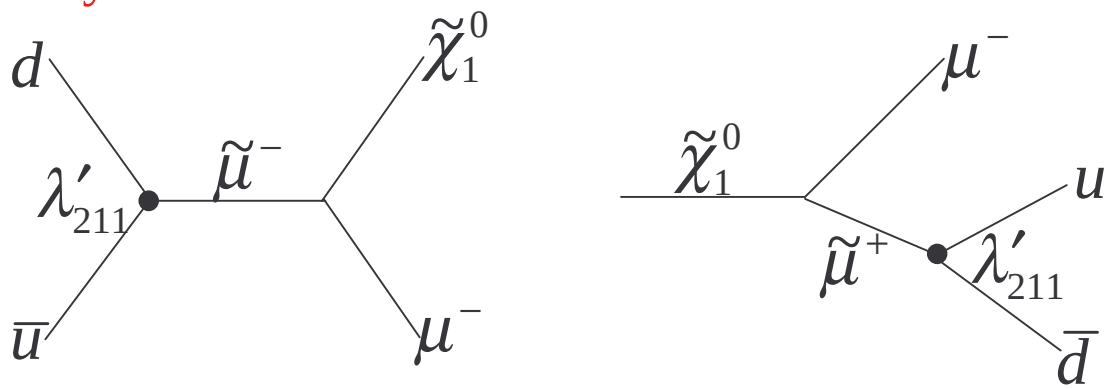
⇒ Limit :

	λ_{121}	λ_{122}
$\mu < 0$	$m_{1/2} < 231$ GeV	$m_{1/2} < 205$ GeV
$\mu > 0$	$m_{1/2} < 251$ GeV	$m_{1/2} < 230$ GeV

Significant improvement over Run1 !

Search for Resonant Slepton Production

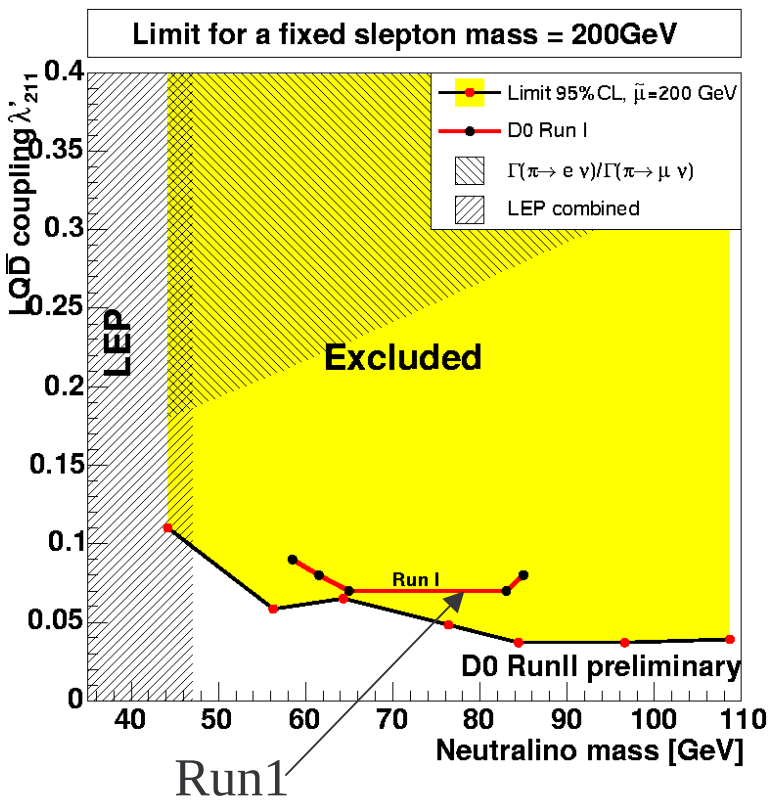
- Single resonant slepton can be produced at Tevatron via λ' $\not{R}$p coupling
- D∅ search for smuon ($\tilde{\mu}$) assuming $\lambda'_{211} \neq 0$, and all other $\not{R}$p couplings are negligibly small
- Consider only :

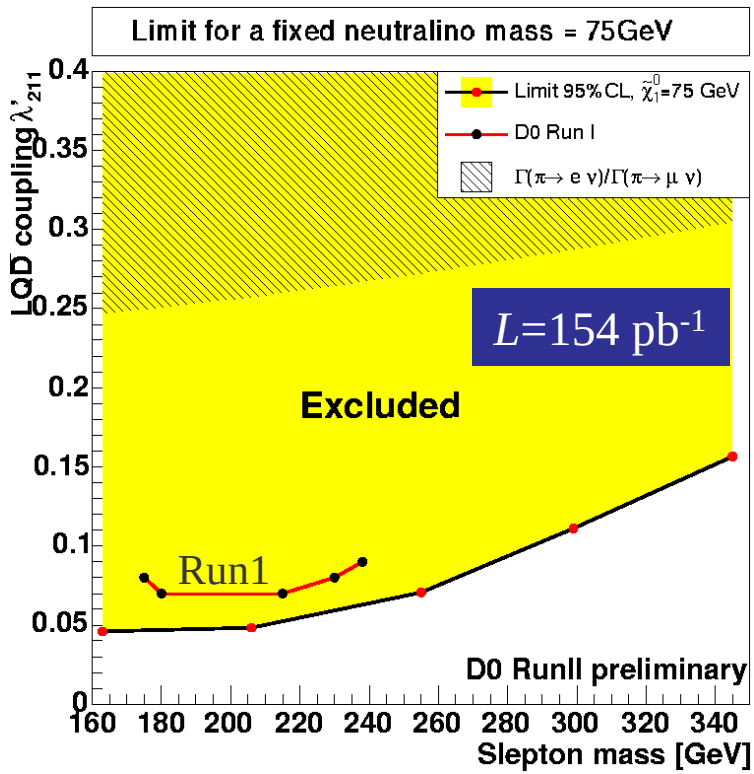


  - Search for events with final states : 2 μ + 2 jets
  - Applied separate sets of cuts which are optimized for specific points in SUSY parameter space
  - Cut on reconstructed invariant mass M($\mu\mu$jj) ($M_{\tilde{\mu}}$), and M(μjj) ($M_{\tilde{\chi}_1^0}$) to help suppress background

Search for Resonant Slepton Production

- Signal efficiency : ~0.5% - 6%
- Observed agreement between data and SM expectation for all SUSY parameter points explored
  - Dominant SM background : γ^*/Z + 2 jets, W+jets, and Di-boson



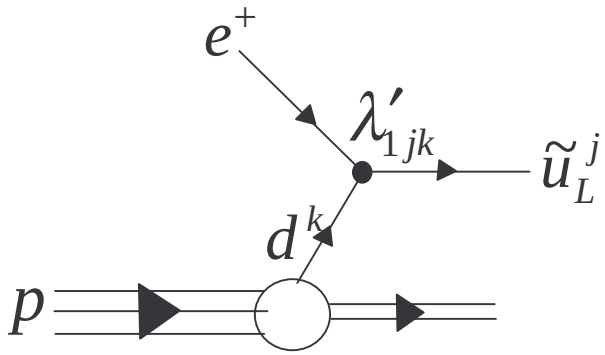


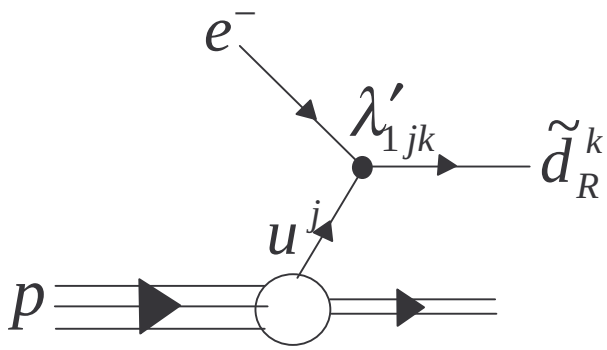
- Limits set in mSUGRA framework
- **Extended exclusion region well beyond Run1 !**

Searches for Resonant Squarks at HERA

•If R-parity not conserved :

$\Rightarrow$ resonant squark can be produced at HERA





$e^+p \Rightarrow$ most sensitive to λ'_{1j1} (j=1,2,3)

- e+ couples to quark (Q=-2/3 or –1/3)
- At high Bjorken-*x*
  - Particle density $f(d) > f(\bar{u})$
- Produce mainly $\tilde{u}_L$ type ($\tilde{u}_L$, $\tilde{c}_L$, $\tilde{t}_L$)

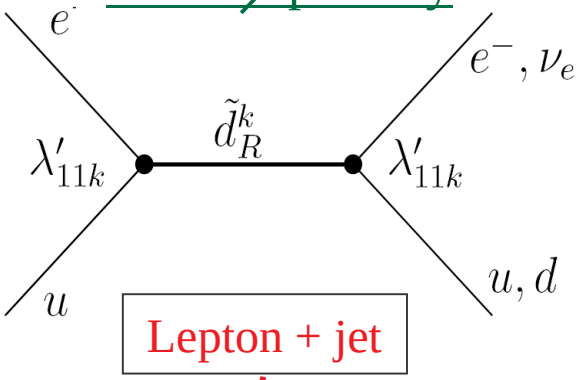
$e^-p \Rightarrow$ most sensitive to λ'_{11k} (k=1,2,3)

- e- couples to quark (Q=+2/3 or +1/3)
- At high Bjorken-*x*
  - Particle density $f(u) > f(\bar{d})$
- Produce mainly $\tilde{d}_R$ type ($\tilde{d}_R$, $\tilde{s}_R$, $\tilde{b}_R$)

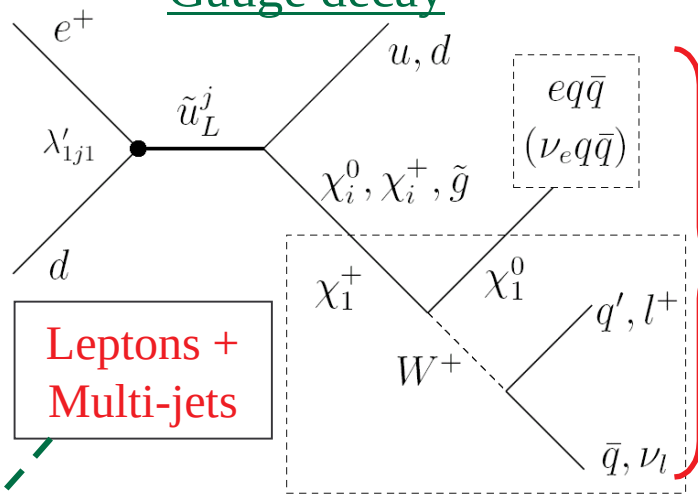
Using data from e^+p and e^-p allow to probe all flavors of squark production via R-parity violation

Squarks : Decay Modes

Direct $\not{R}$p decay



Gauge decay

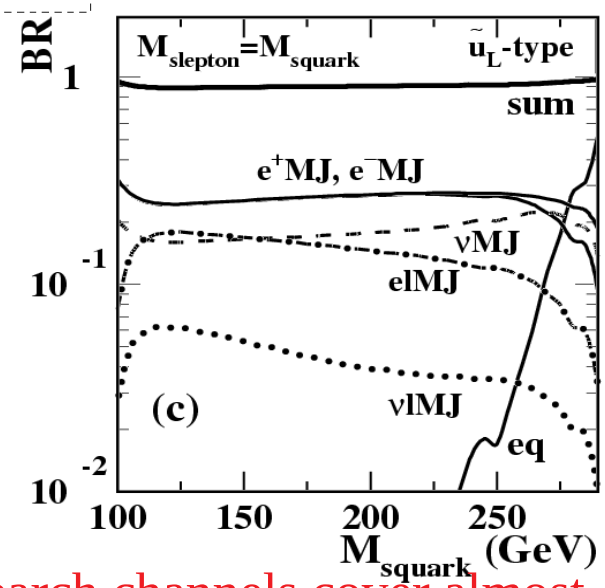


LSP $\not{R}$p decay

$$\tilde{\chi}_1^0 \rightarrow e^{\pm} qq' (\nu qq')$$

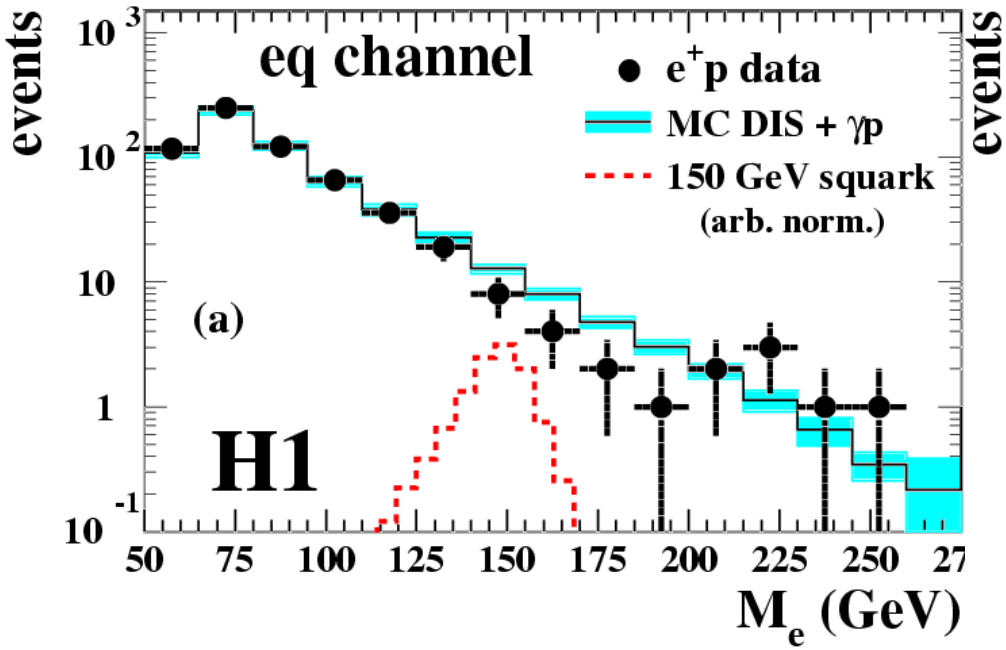
Leptons +
Multi-jets

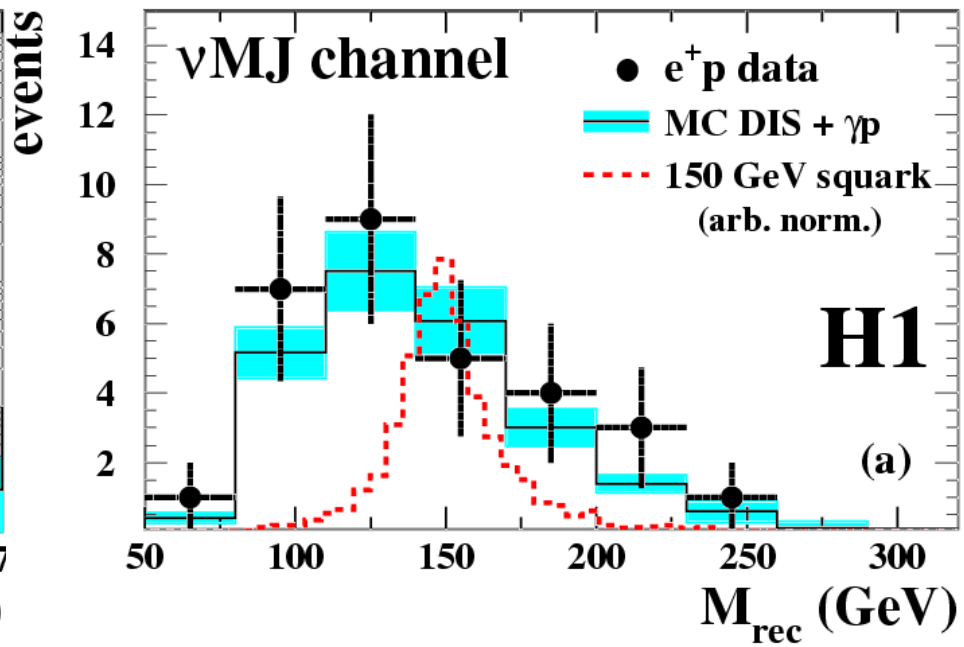
Channel	e^+p collisions Data	e^+p collisions SM expectation	e^-p collisions Data	e^-p collisions SM expectation
eq	632	628 ± 46	204	192 ± 14
νq	—	—	261	269 ± 21
eMJ ("right" charge)	72	67.5 ± 9.5	20	17.9 ± 2.4
eMJ ("wrong" charge)	0	0.20 ± 0.14	0	0.06 ± 0.02
$eeMJ$	0	0.91 ± 0.51	0	0.13 ± 0.03
$e\mu MJ$	0	0.91 ± 0.38	0	0.20 ± 0.04
νeMJ	0	0.74 ± 0.26	0	0.21 ± 0.07
νMJ	30	24.3 ± 3.6	12	10.1 ± 1.4
$\nu\mu MJ$	0	0.61 ± 0.12	0	0.16 ± 0.03



Search channels cover almost entire branching ratios for both *u* and *d* type squarks

Searches for Resonant Squarks at HERA (H1)





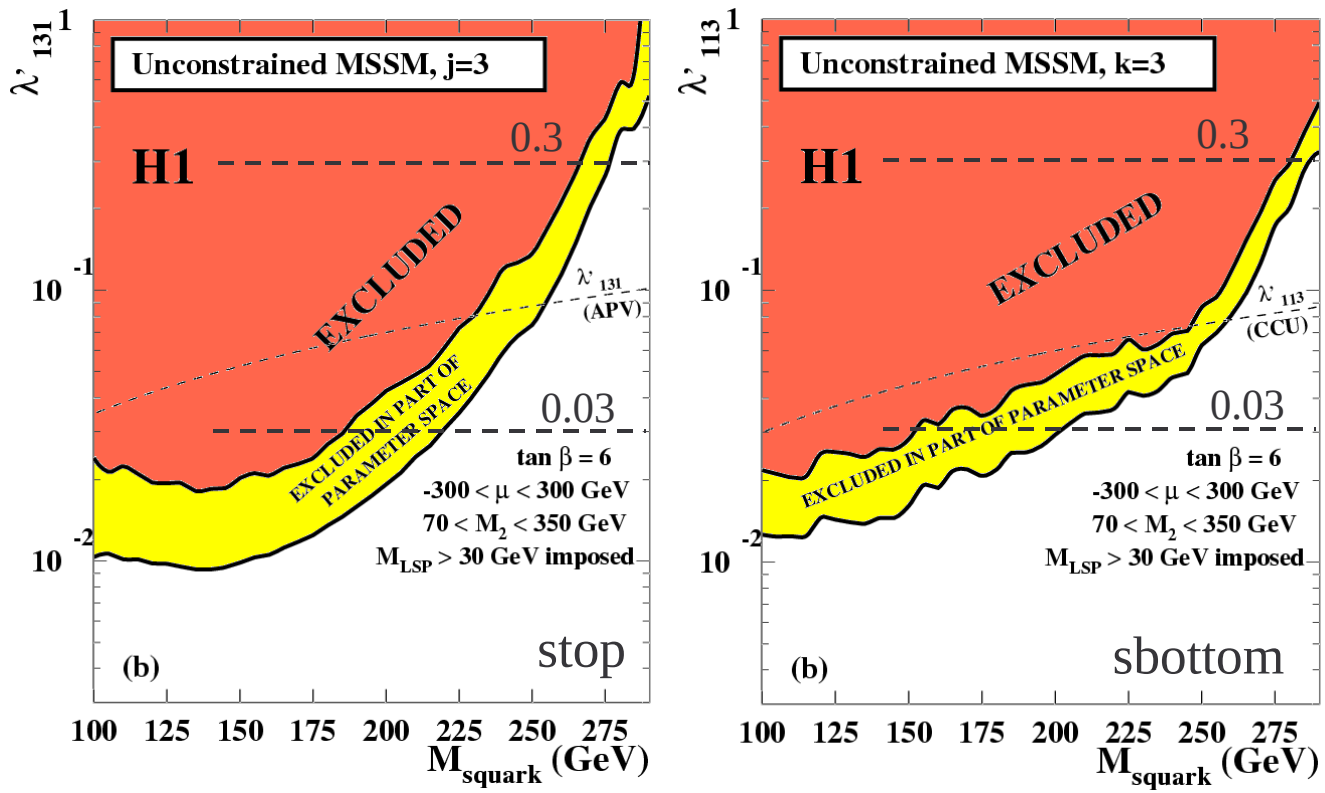
Interpret Results in MSSM

A version of MSSM :

- Assume gaugino mass terms unify at GUT scale to a common $m_{1/2}$
- Degenerate squark mass, degenerate slepton mass (90 GeV)

Scan over these parameters :

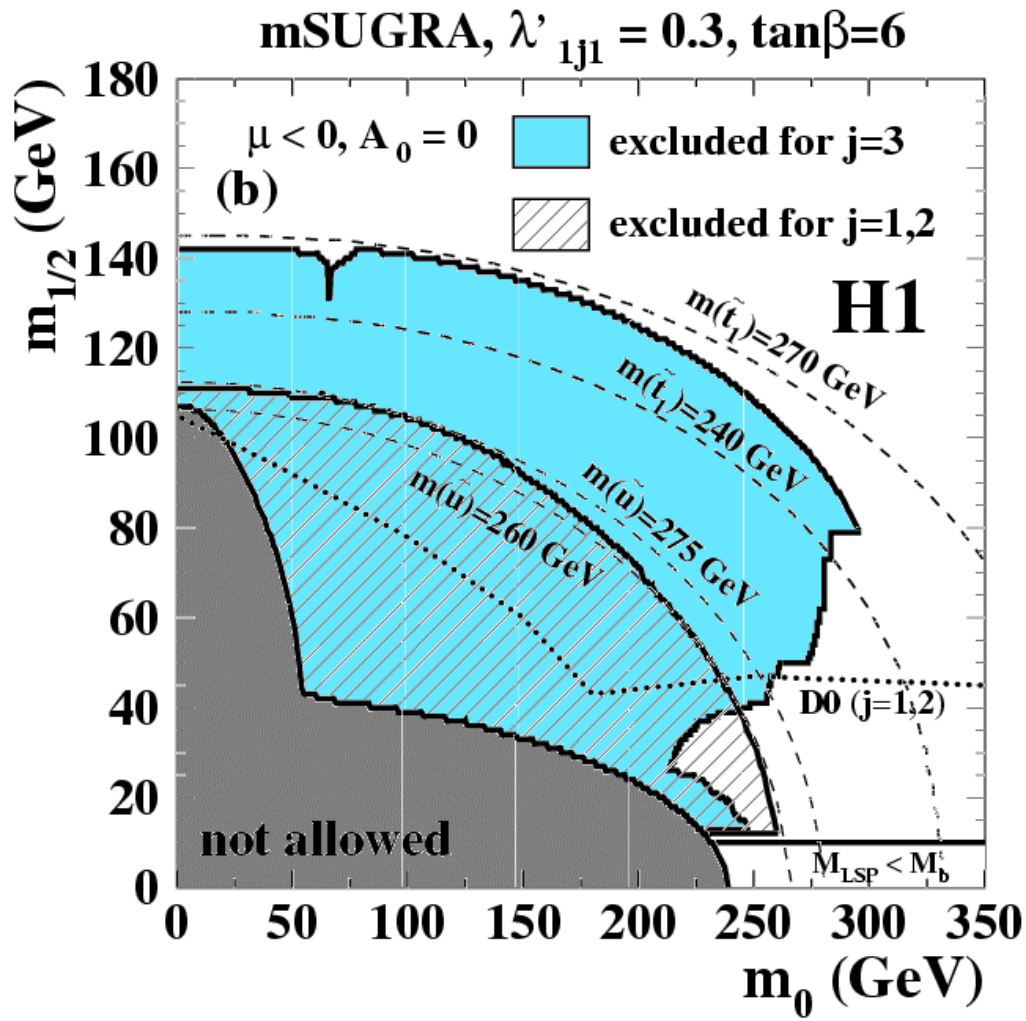
- tanβ=6,
- -300<μ<300 GeV,
- 70<M_2<350 GeV



- For $\lambda' = 0.3$ (e.m. strength), ruled out squark mass below ~280 GeV
- For $\lambda' = 0.03$, rule out squark mass below ~220 GeV

Interpret Results in mSUGRA

- Assume a fixed value of λ', set limit on mSUGRA parameters (m_0, $m_{1/2}$)
- Due to mixing in the stop sector that results in small mass,
  - Allow to probe large values of m_0 and $m_{1/2}$
- For λ' = 0.3, exclude squark mass below 275 GeV

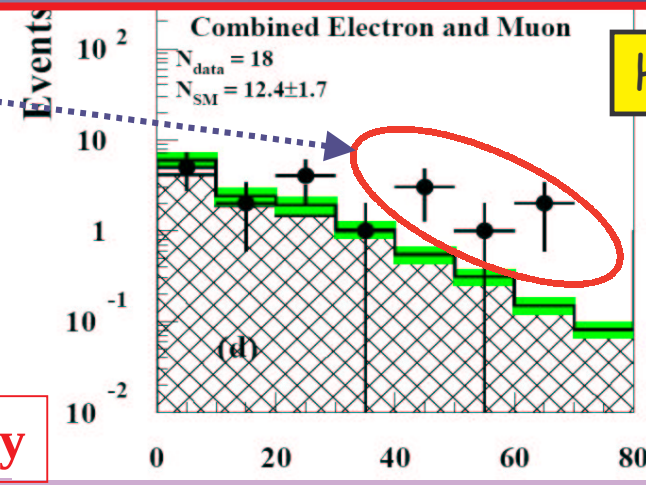


hep-ex/0405070

Bosonic Stop Decay

- H1 observed **excess of isolated high pt lepton (e,m) and large $\not{E}t$**
- One possible explanation : Production and decay of scalar top quark

(T. Kon et al, Mod. Phys. Lett. A12 (1997) 3143.)

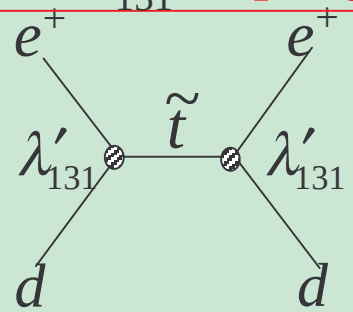


H1: e & μ

not confirmed by ZEUS

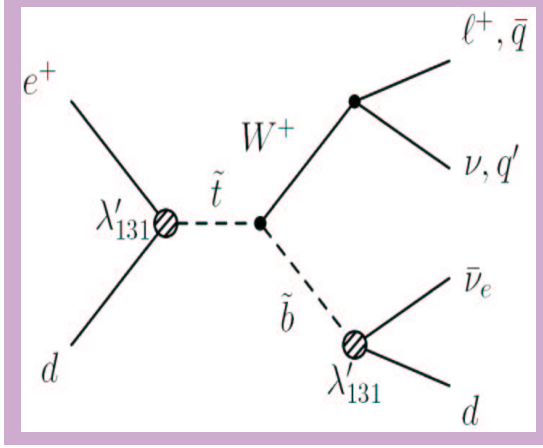
???

Stop decay directly via λ'_{131} coupling



Final state = e + jet

Bosonic Decay



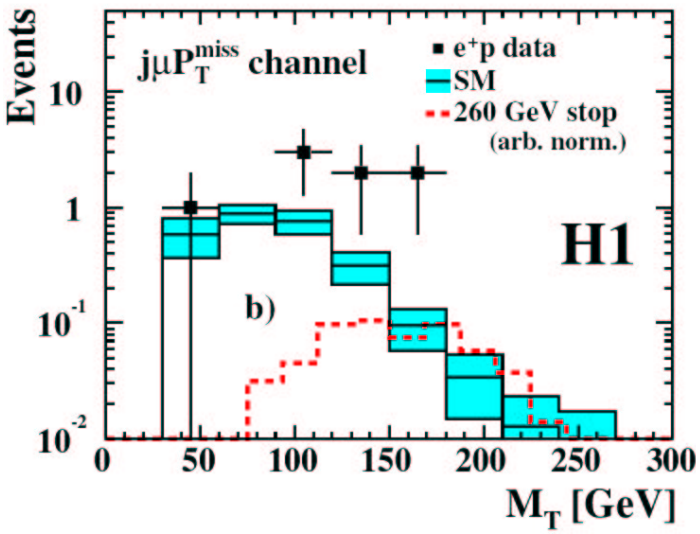
- If $M_{\tilde{t}} > M_{\tilde{b}} + M_W$, and stop decay to gauginos kinematically forbidden
  - Final state = 3jets + $\not{E}t$

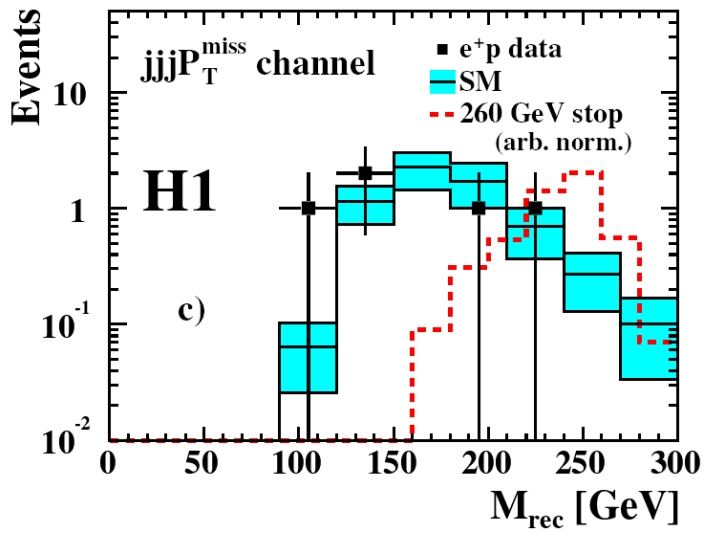
    or = jet + lep + $\not{E}t$

- H1 search for events with these decay signature

H1	j e $\not{E}t$	j μ $\not{E}t$	j j j $\not{E}t$	e j
data	3	8	5	1100
SM exp.	3.8 ± 0.9	2.7 ± 0.5	6.2 ±1.7	1120 ± 131

Bosonic Stop Decay



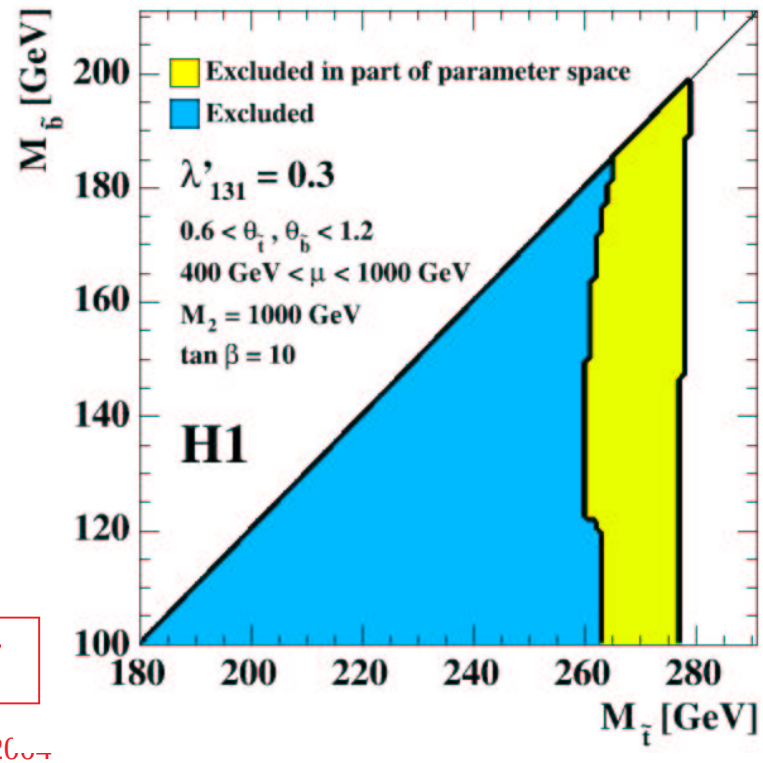


- Excess in j+μ+MET is not confirmed in other channels

Exclusion Limits in MSSM

(assume GUT relation between M_1,M_2,M_3)

- Results from 4 channels are combined
- Set exclusion in the (M_{stop} , $M_{sbottom}$) plane
- For λ'_{131} = 0.3, exclude stop mass up to 275 GeV



hep-ex/0403027

Summary

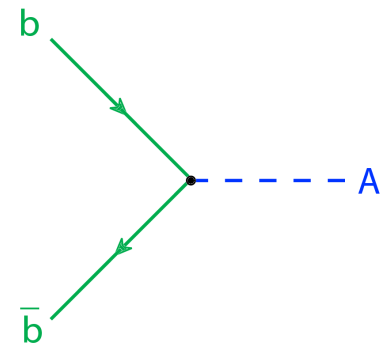
- So far nature has declined to flood us with new phenomena
- Many new SUSY search results from Tevatron and HERA are the world's most sensitive !
- More new data are still being analysed
- Both machines (Tevatron and HERA) will deliver more luminosities over the next N years
    - Recently the peak luminosity at Tevatron has reached ½ of its designed capability
- Its going to be ***very exciting*** at both laboratories in the coming years

Celebration of achieving L=1.0 E32 $cm^{-2}s^{-1}$

Search for MSSM Higgs in Di-Tau

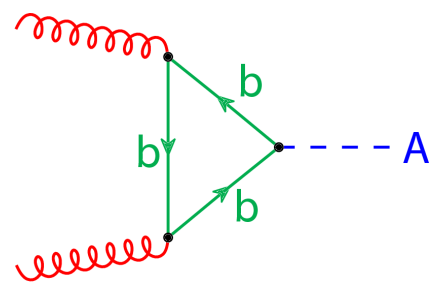
- At hadron collders MSSM Higgs production can be enhanced if tanβ is large
  - Due to coupling of Higgs to b quark ∝ $(\tan\beta)^2$
- $BR(A \to \tau^+\tau^-)$ ~ 10%

  $BR(A \to b\bar{b})$ ~ 90%

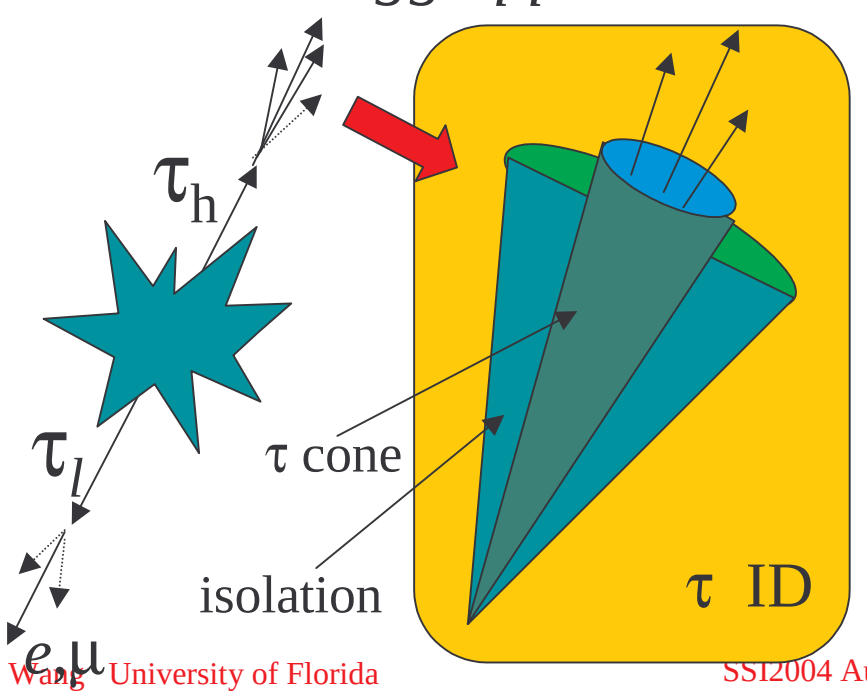


- But $gg/q\bar{q} \to A \to b\bar{b}$

  have to overcome large QCD background



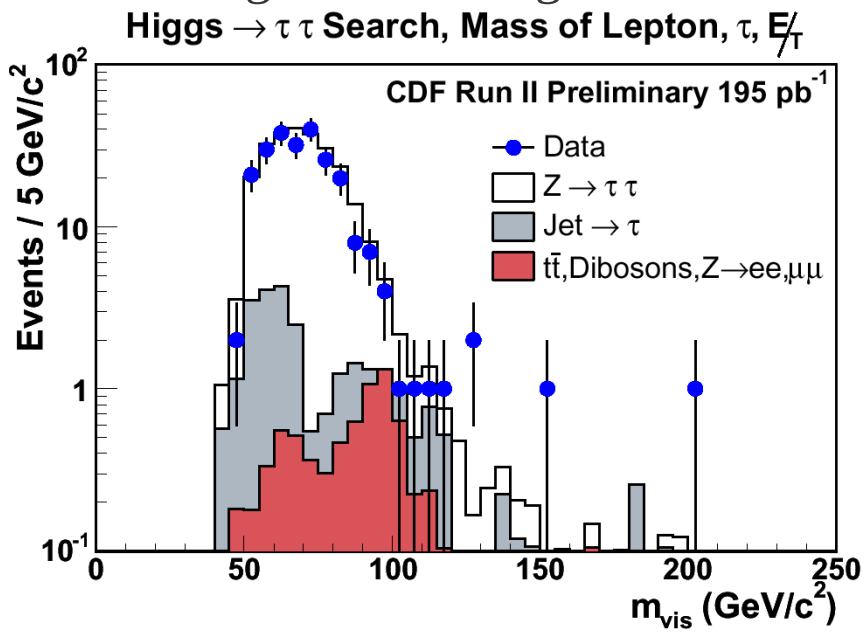
- CDF search for $gg/q\bar{q} \to A \to \tau^+\tau^-$ (~195 pb^{-1})

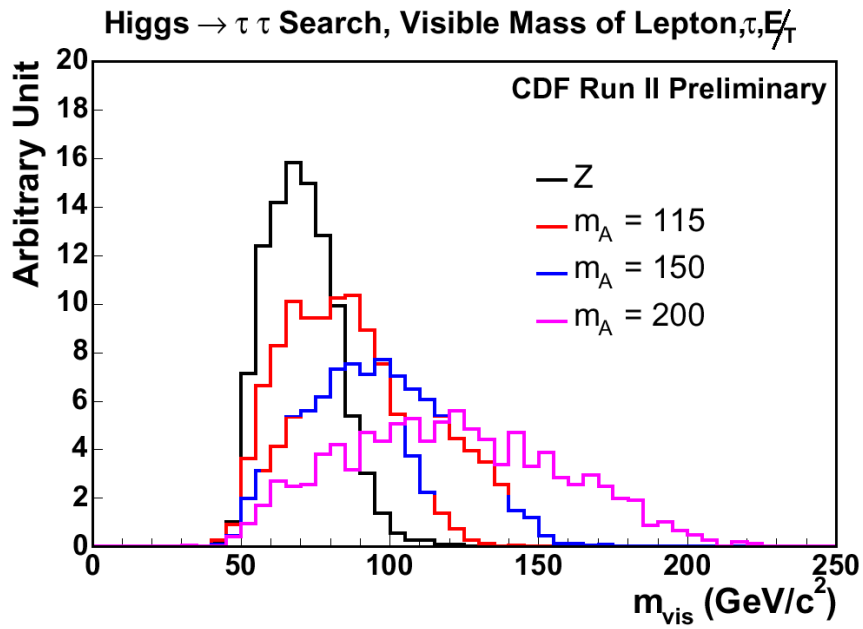


- Select events : 1 leptonic τ decay (e,μ) , one hadronic τ decay

Search for MSSM Higgs in Di-Tau

•Use partial mass reconstructed $M_{vis}(l,\tau_h^{vis},MET)$ distribution to discriminate between background and signal





•SM background from $Z\rightarrow\tau\tau$, jets mis-ID as t, $Z\rightarrow ee/\mu\mu$

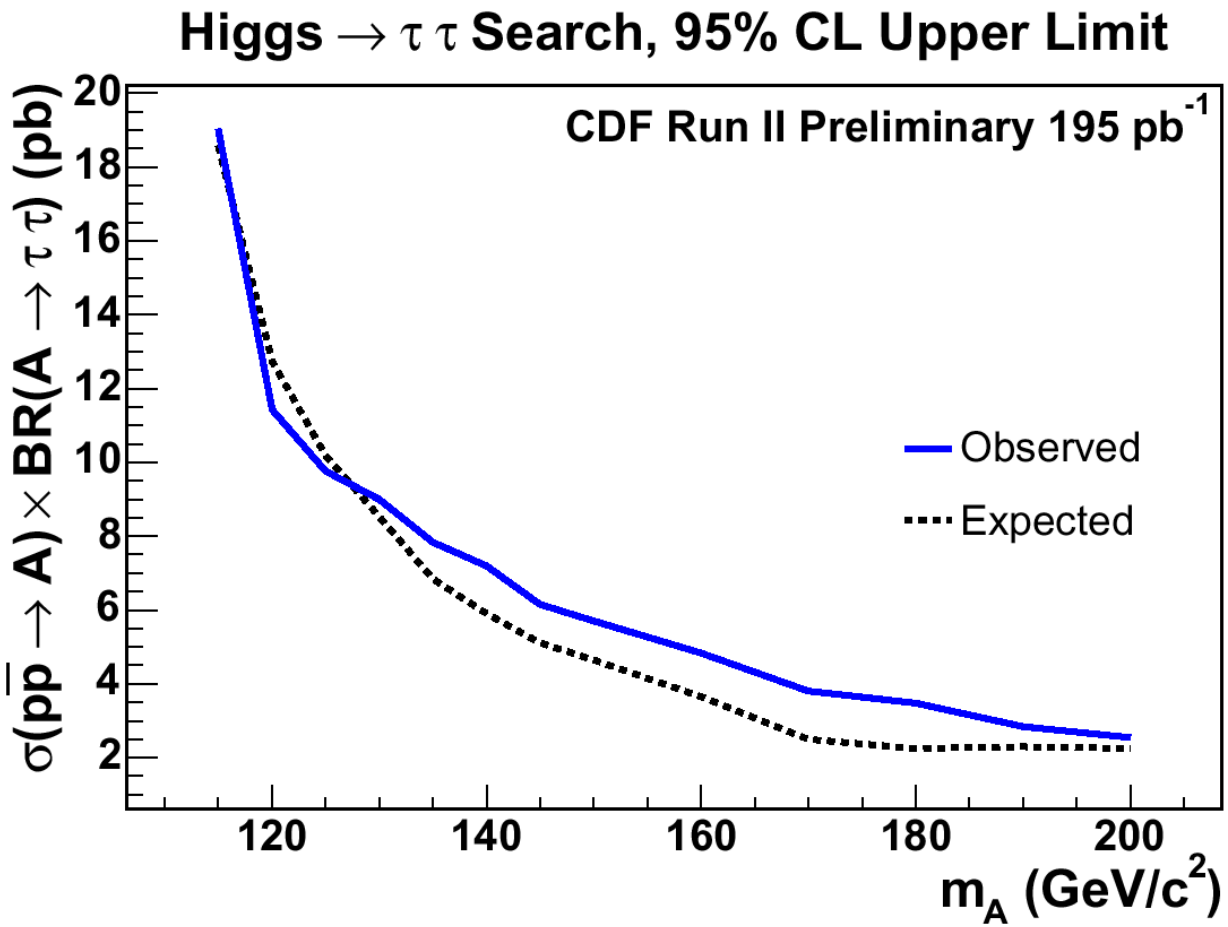
•Good understanding of $Z\rightarrow\tau\tau$

•Measure $\sigma(Z\rightarrow\tau_e\tau_h) = 242\pm48(\text{stat})\pm26(\text{syst})\ \pm15(\text{lumi})$ pb (preliminary)
theory $\sigma(Z\rightarrow ll)_{NNLO} = 251$ pb

•Observe no significant excess of events

•Use mass templates to set limit on $A\rightarrow\tau^+\tau^-$ production cross section

Search for MSSM Higgs in Di-Tau



- Almost ~1 order of magnitude larger than MSSM cross section at tanβ = 30
- Will improve sensitivity after including other final states
  - $A \rightarrow \tau_e \tau_\mu$
  - $A \rightarrow \tau_h \tau_h$