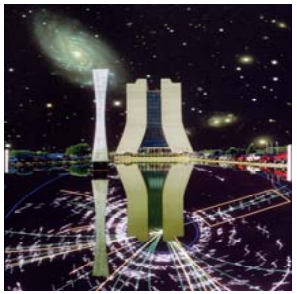
SUSY & Non SM Higgs Searches



Mario Martínez-Pérez

(IFAE-Barcelona)

Outline

- SUSY

- Squark/Gluino Searches
- Search for Chargino/Neutralino
- GMSB Scenario

- Non SM Higgs Searches
- $B_s \to \mu\mu$ vs MSSM

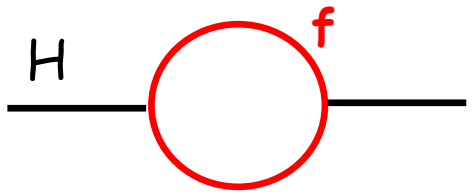
- SUSY @ the LHC
- Final Remarks

Not covered in this talk
- SUSY in ttbar decays
- RPV Searches
- .....

Hierarchy Problem

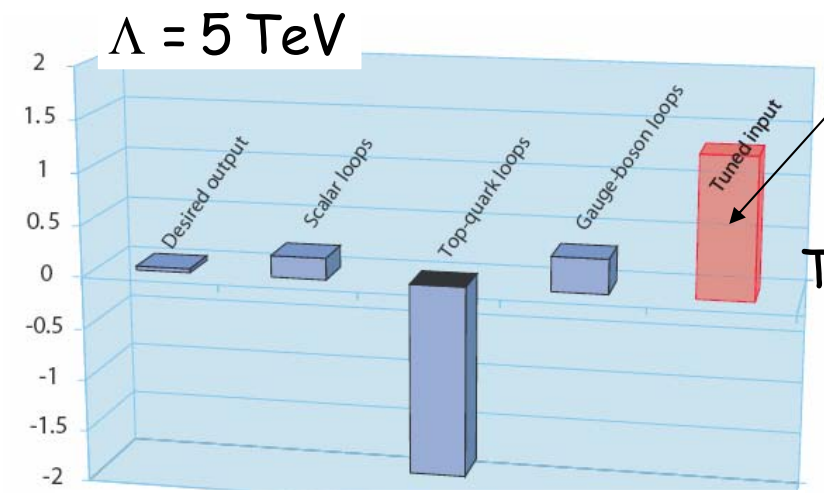
From EWK to Planck scale ?

$$< H > = 174\ GeV \rightarrow m_H^2 \approx O(-100\ GeV^2)$$



$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots]$$

if $\Lambda_{UV} \approx M_{planck} \rightarrow$ fine tuning in 10^{30} !!



relative contributions to ΔM_H^2

(taken from C. Quigg, hep-ph/0704.2232)

Already a serious problem at 5 TeV scale
(cancellation among top, gauge and Higgs loops)

This kind of conspiracy has name in Physics...

SuperSymmetry ?

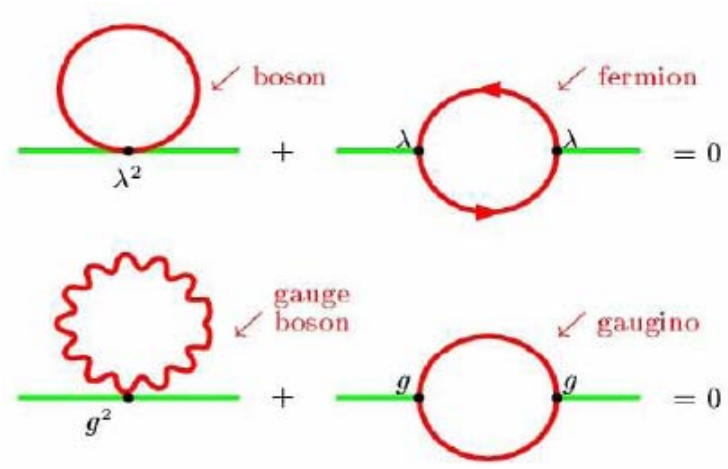
SuperSymmetry in 30"

- Fermion/Boson symmetry

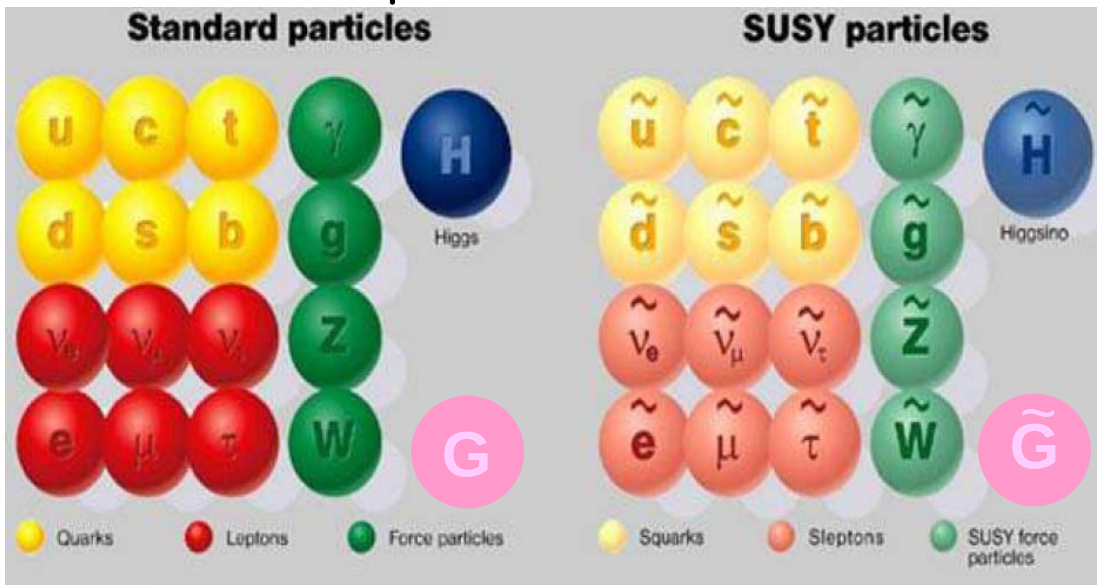
$$Q\,|\,\text{fermion}\rangle = |\,\text{boson}\rangle$$

$$Q\,|\,\text{boson}\rangle = |\,\text{fermion}\rangle$$

Exact cancellation between fermion & boson loops for Higgs (cures the hierarchy problem)



Double Spectra of Particles



..will mix to form mass eigenstates..

Higgs sector with 2 doublets

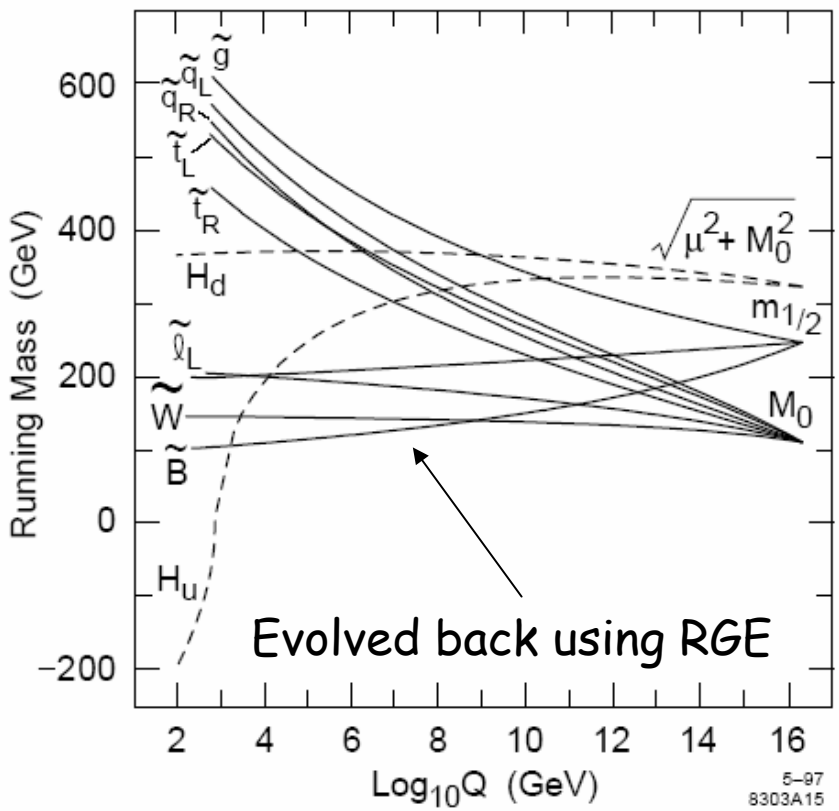
$$H_U, H_D \longrightarrow h, H, A, H^{\pm}$$

..SUSY must be broken..... model-dependent phenomenology

mSUGRA
(gravity mediated SUSY breaking)

SUSY breaking (hidden sector) $\xrightarrow{\text{gravity}}$ MSSM (visible sector)

L_{soft} terms introduce huge number (up to 105) of new parameters



Assuming unification of masses at GUT scale allows to reduce it to 5

m_0: common scalar mass at GUT

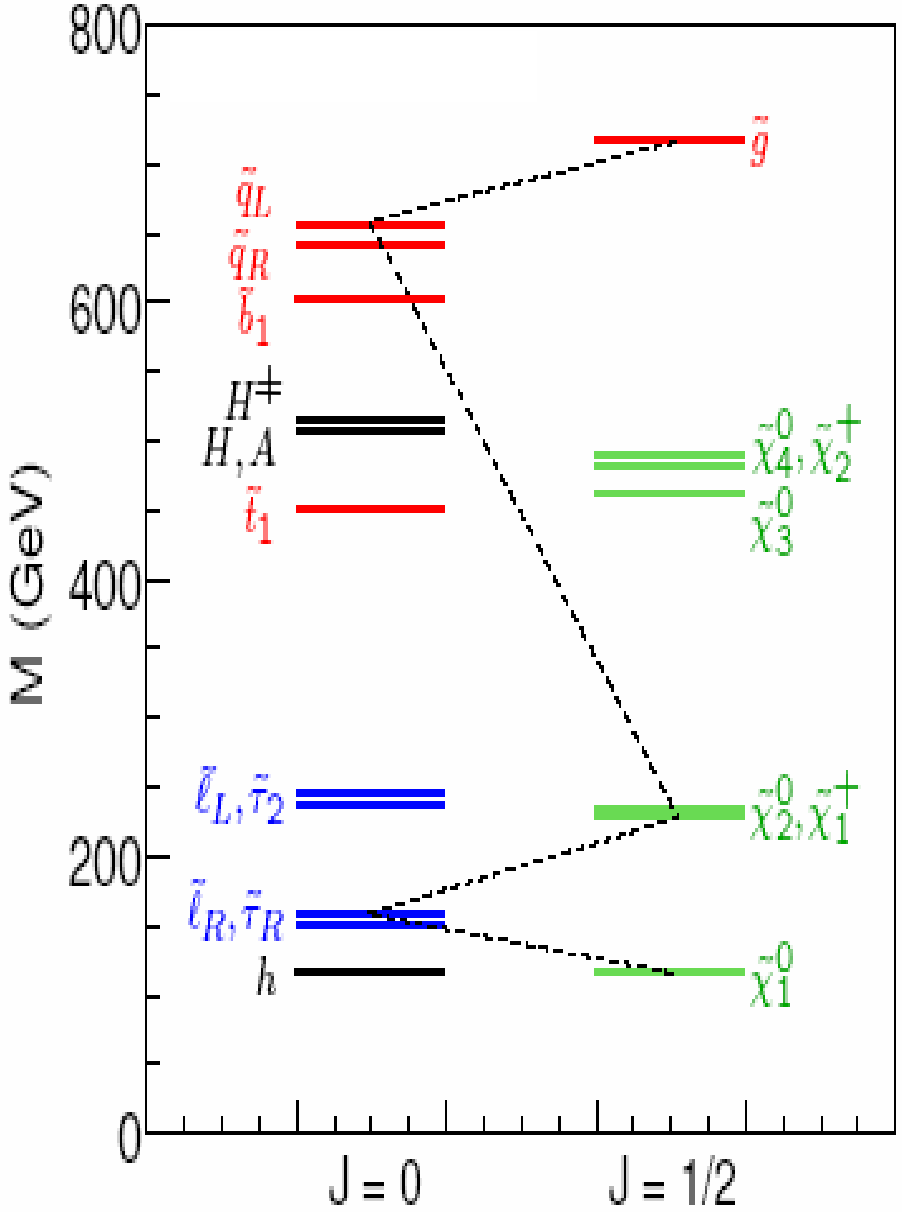
$m_{1/2}$: the common gaugino mass at GUT

$\tan\beta$: $\langle H_U \rangle / \langle H_D \rangle$

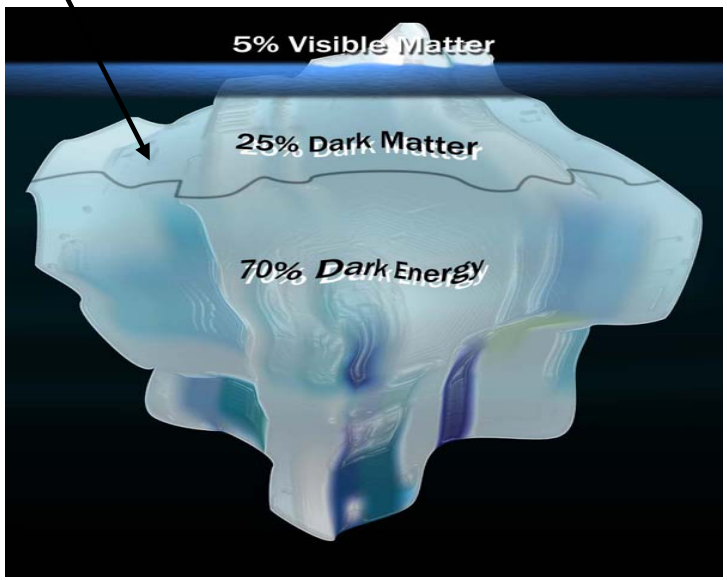
A_0: common (scalar)^3 coupling

Sign(μ): Higgs mass term

Typical mSUGRA Mass Spectra

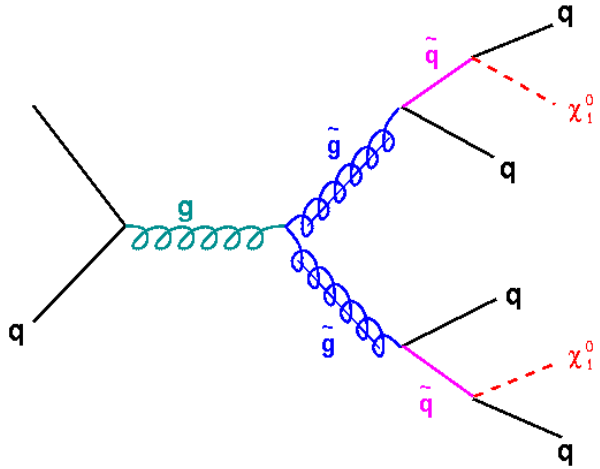


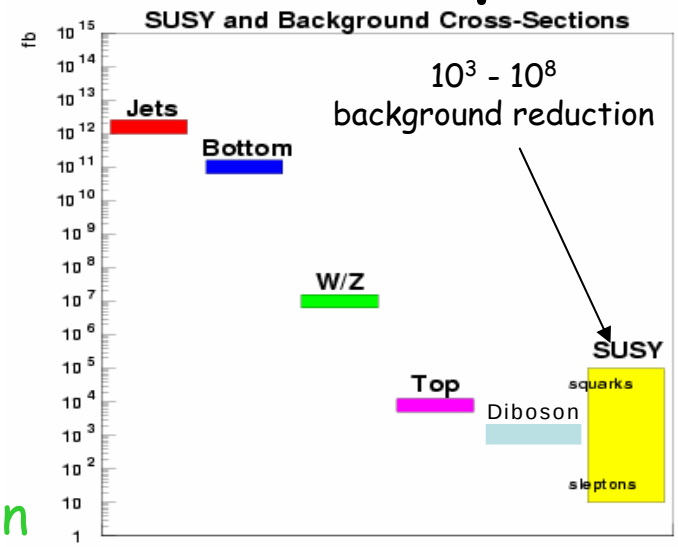
1. Squarks and Gluinos are heavy
2. mixing of third generation leads to light stop/sbottom and stau
3. χ_1^0 will be the LSP (stable if R_p conserved)

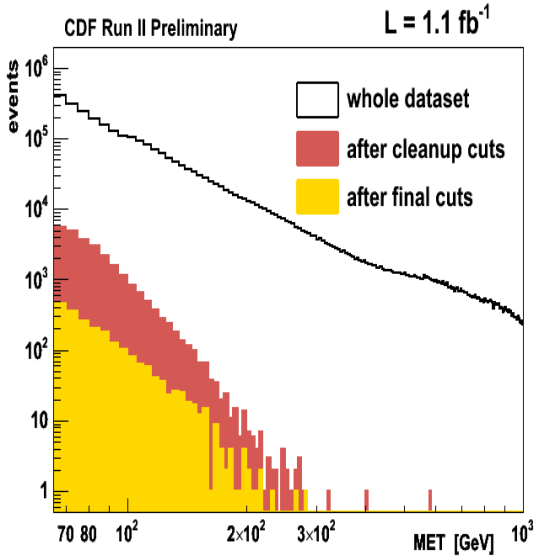


4. One higgs is very light (< 135 GeV)

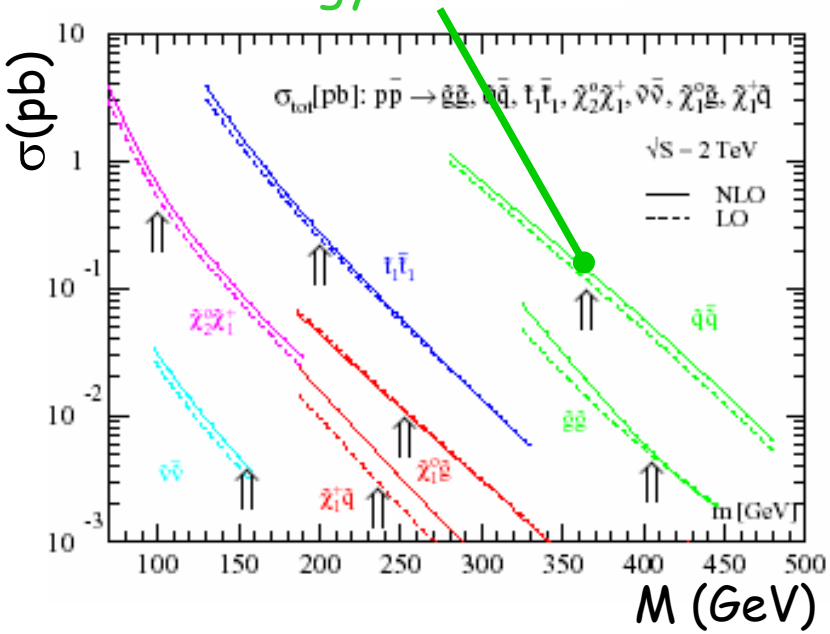
Inclusive Gluino/Squark Search





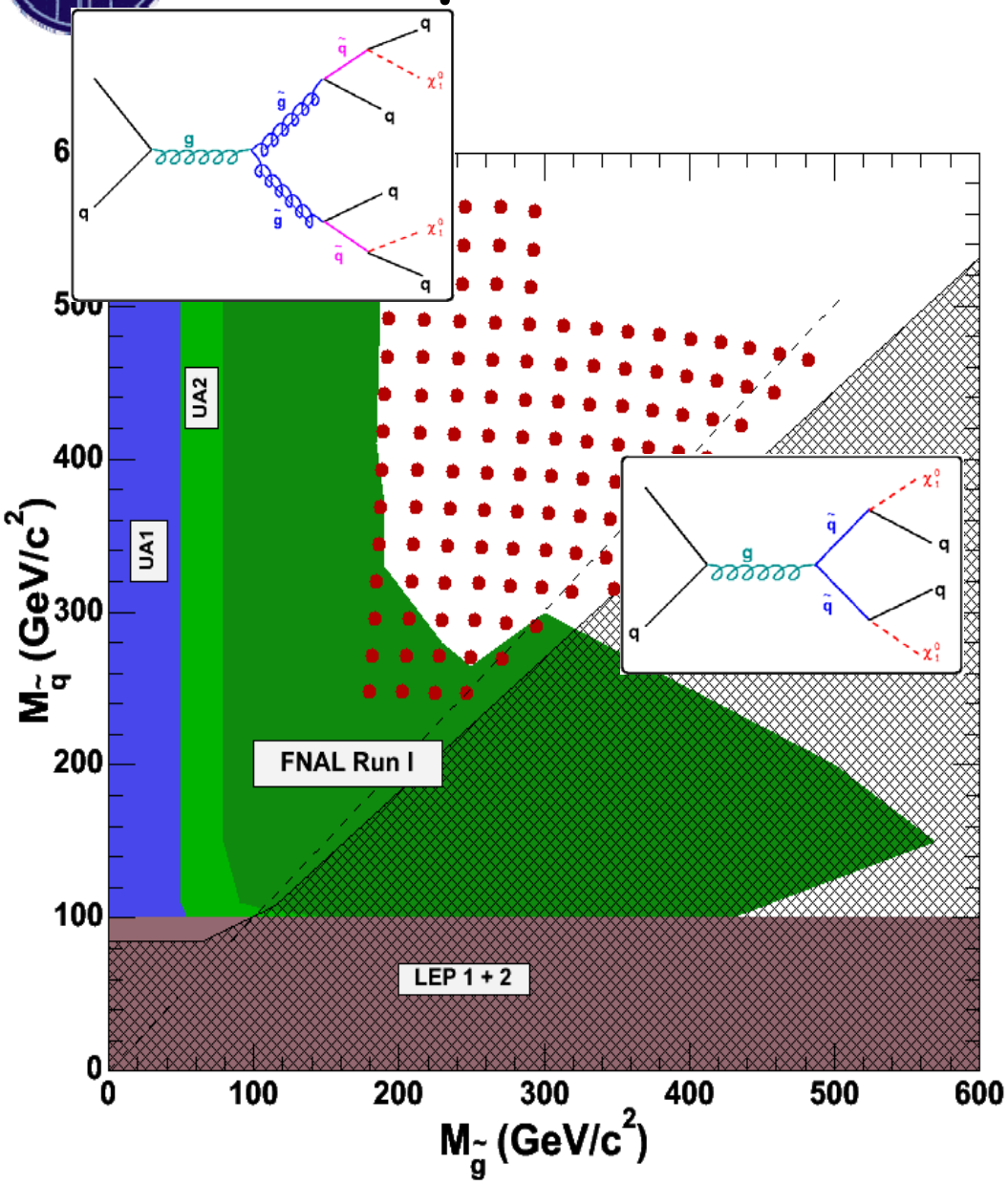


gluino/squark production
at the energy frontier



- Assuming R-parity conservation
- Signature: $\not{E}_T$ + jets
- Understanding of beam backgrounds
- Difficult…multiple SM backgrounds
  - Detector effects
  - top and Z->νν+jets irreducible
  - understanding of QCD & W/Z+jets

Squark/Gluino Searches



- mSUGRA scenario

  $A_0 = 0$

  $\mu < 0$

  $\tan\beta = 5\,(\mathrm{CDF})\,,\ \tan\beta = 3\,(\mathrm{D0})$

  scan in $M_0 - M_{1/2}$ plane

- stop pair production not considered and the squark masses are averaged over 4 (CDF) or 5 (D0) flavors

- Experiments (CDF & D0) carry out searches in different final states

$$\not{E}_T + \geq N_{jet}, \quad N_{jet} = 2 - 4$$

- cuts on $\Delta\phi(\not{E}_T$ - jet) against QCD - jets
- veto against electrons and muons

- optimization across the plane using

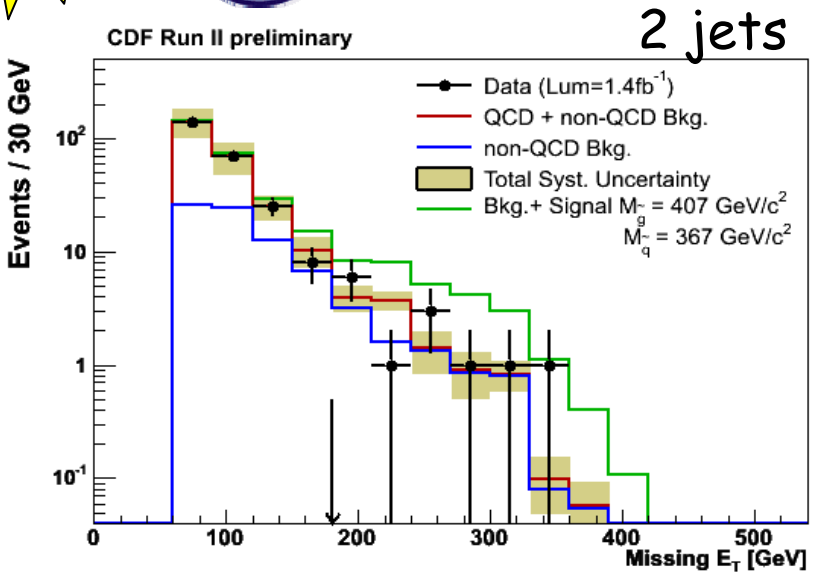
$$\not{E}_T,\ E_T^{jets} \text{ and } H_T \equiv \sum_{jets} E_T^{jet}$$

Squark/Gluino Search

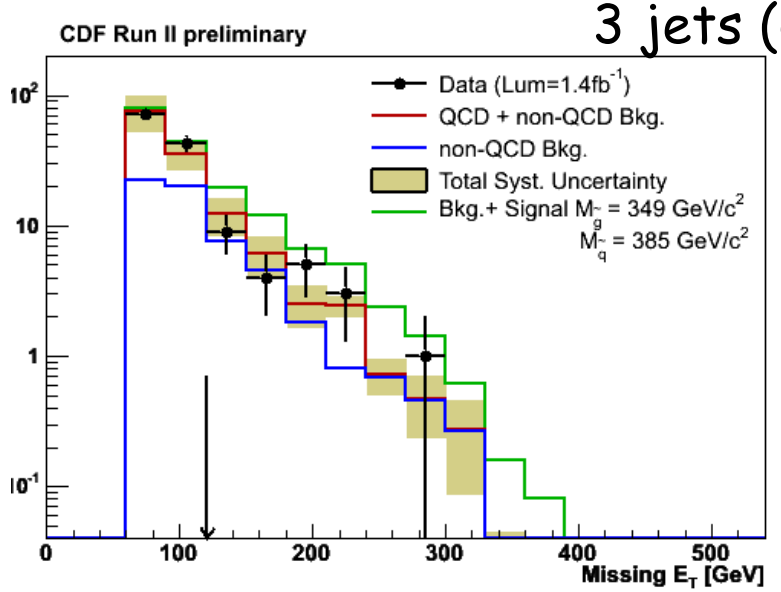
NEW

1.4 fb-1

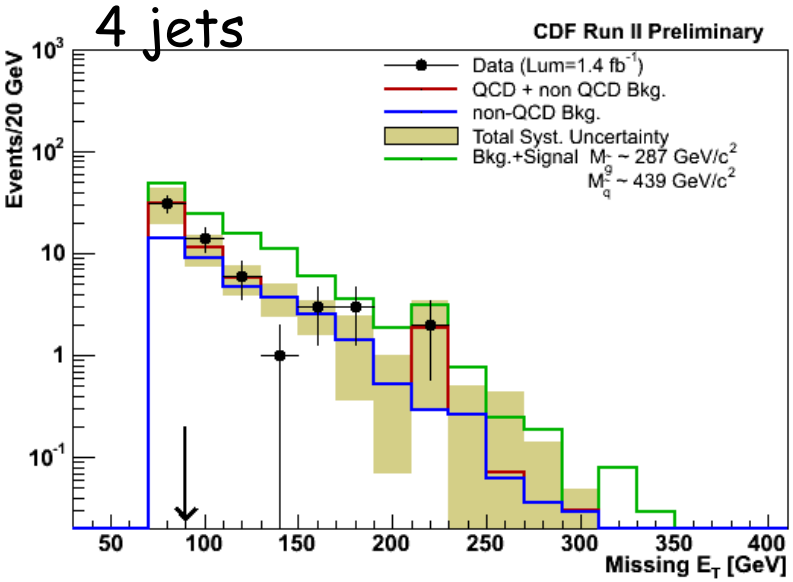
2 jets



3 jets (C)



4 jets



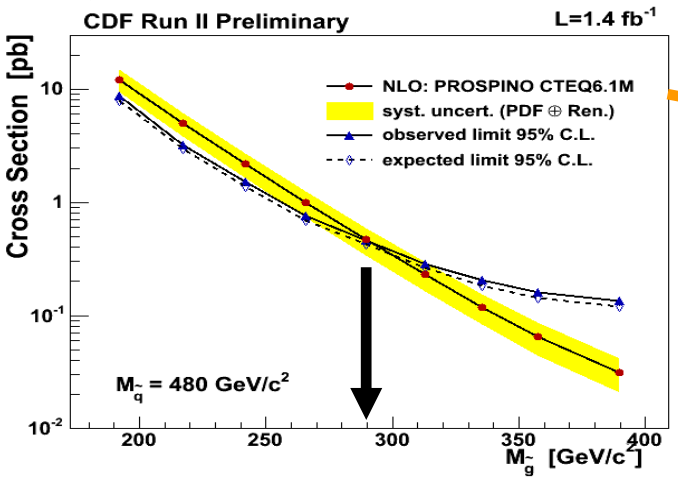
events in 1.4 fb^{-1}	DATA	SM Expected
≥ 4 jets	29	27 ± 2 ± 9
≥ 3 jets (A)	616	607 ± 16 ± 146
≥ 3 jets (B)	166	154 ± 7 ± 44
≥ 3 jets (C)	22	25 ± 2 ± 8
≥ 2 jets	13	11 ± 2 ± 3

harder cuts

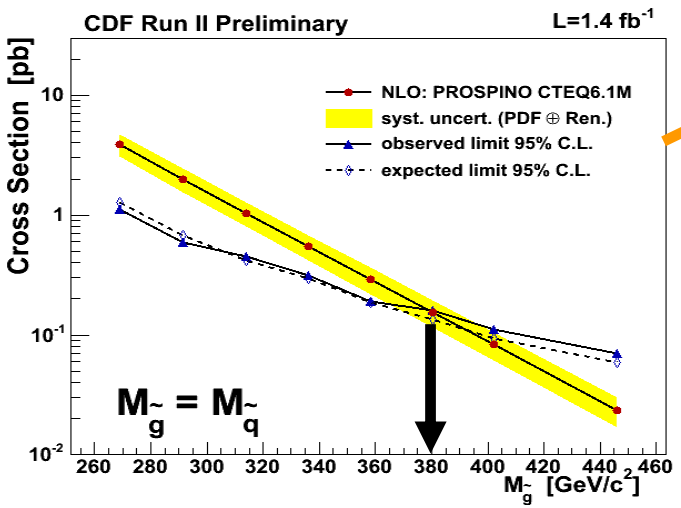
Good agreement with SM predictions

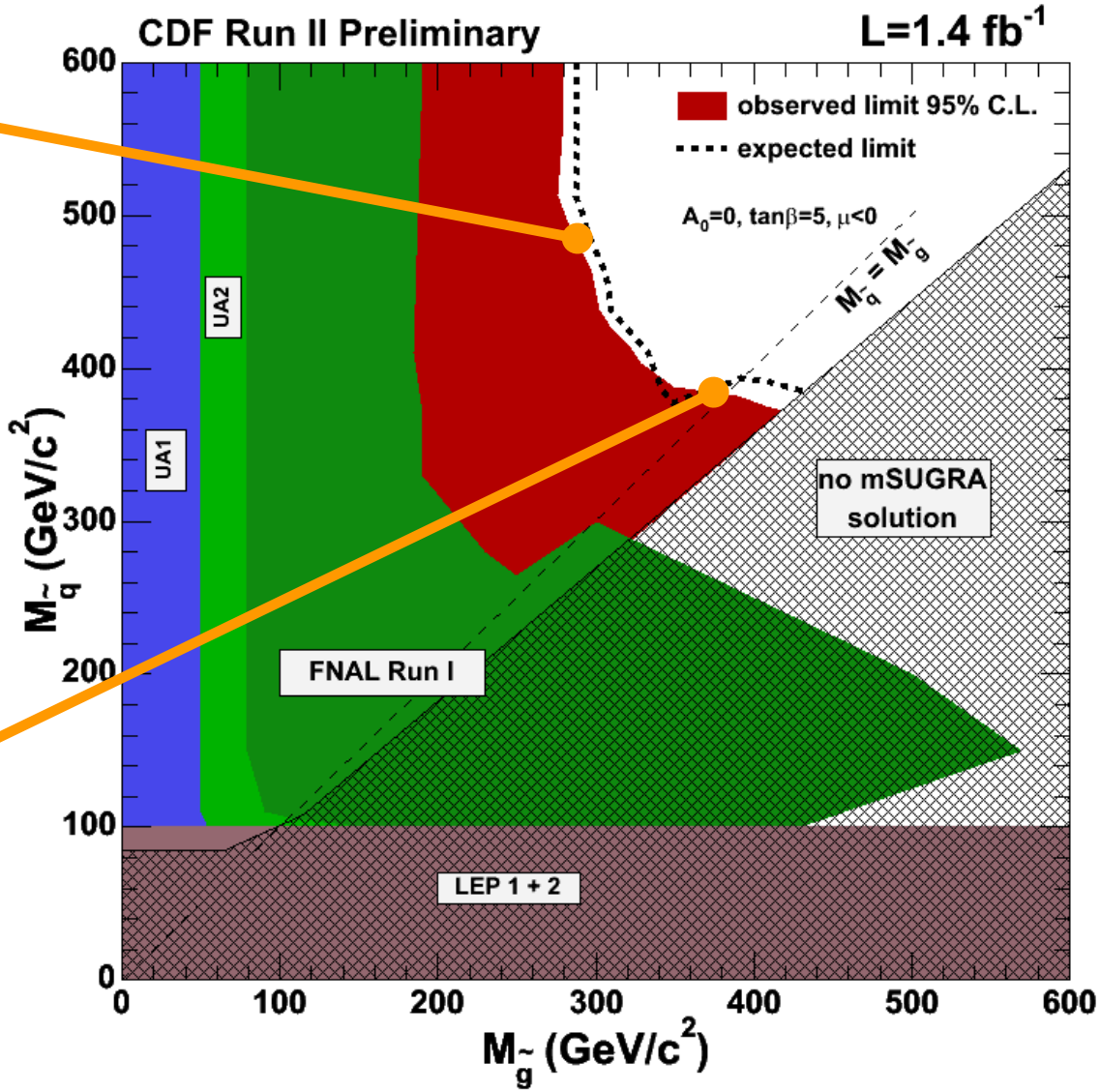
NEW

squark/gluino masses



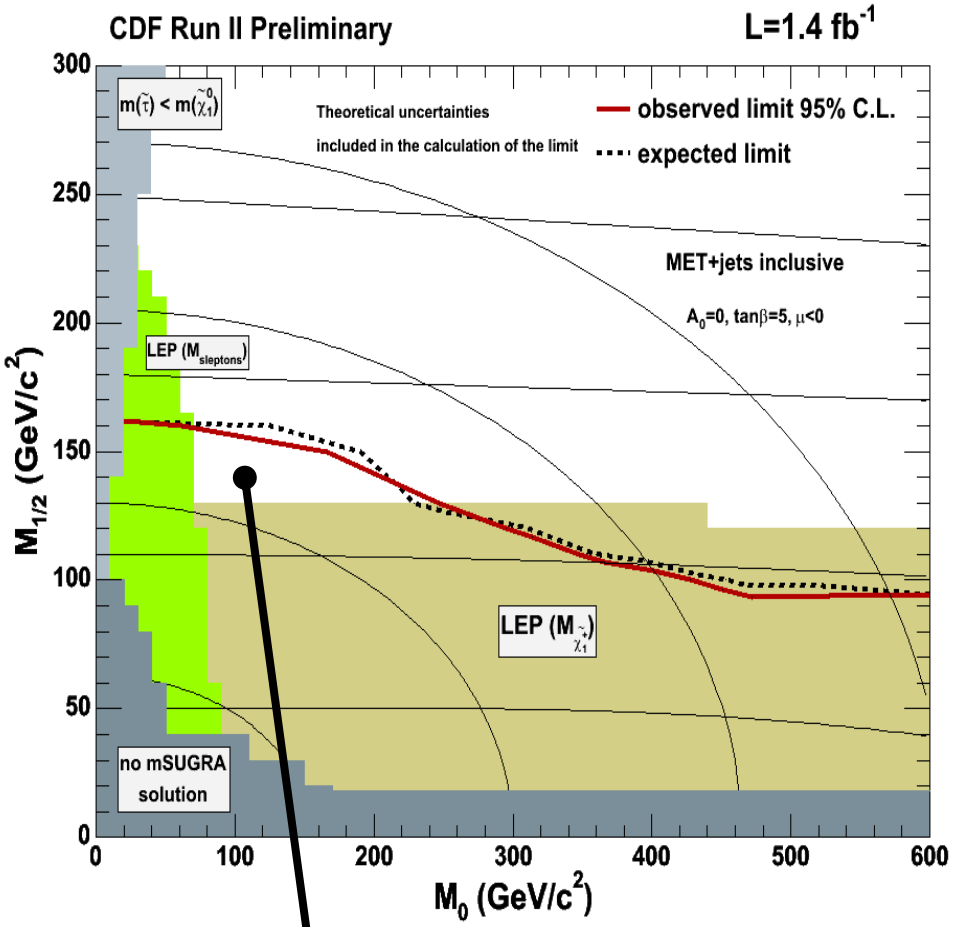
$M_{gluino} > 290$ GeV @ 95% CL

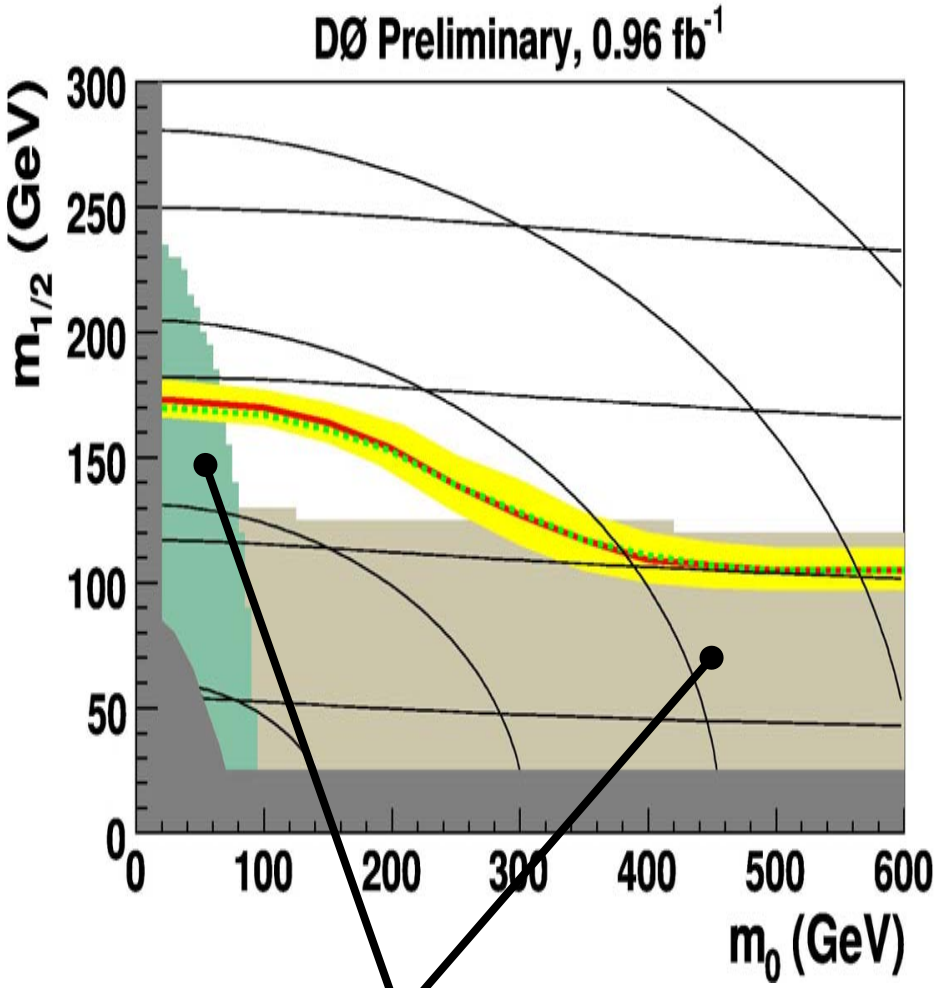




For $M_{gluino} = M_{squark} \Rightarrow M > 380$ GeV @ 95% CL

Limits on mSUGRA parameters



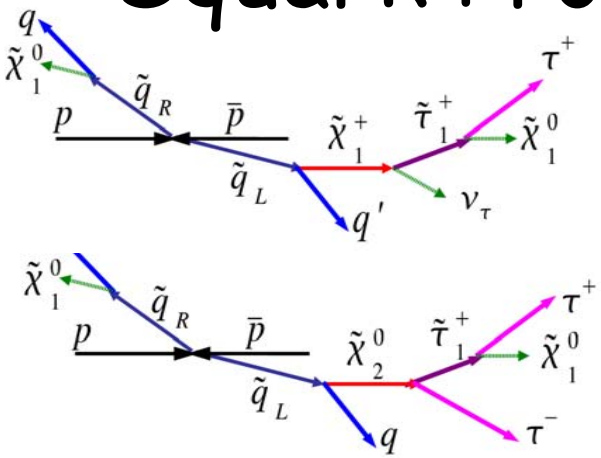


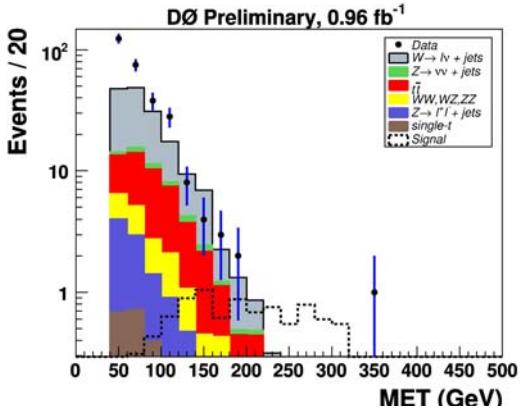
Tevatron results extend the LEP excluded region (LEP indirect limits) at low values of M_0 and $M_{1/2}$

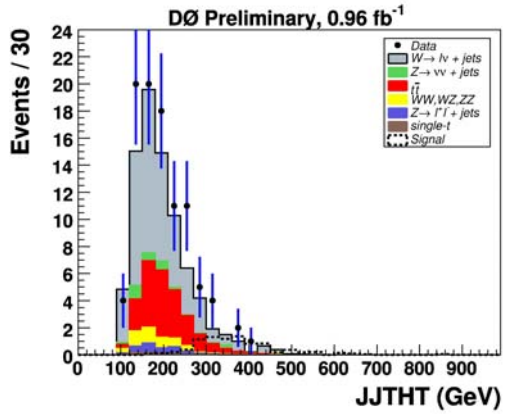
NEW

0.96 fb-1

Squark Production (τ+Jets+MET)







- mSUGRA scenario (enhanced in τ decay)

$$A_0 = -2\,M_0,\ \tan\beta = 15,\ \mu < 0$$

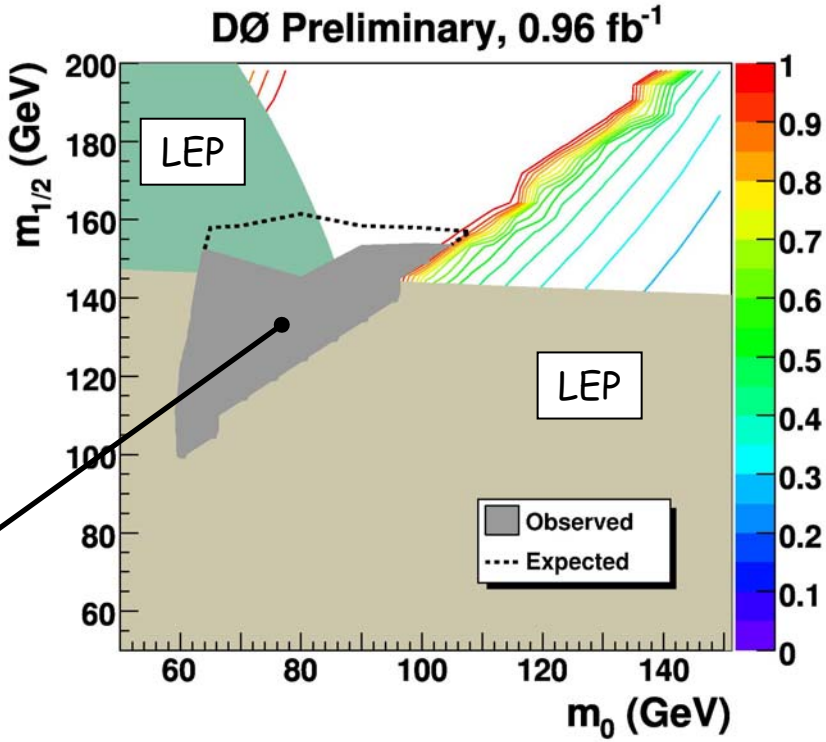
- Jets + MET (similar to inclusive search)
- At least one τ (hadronic decay)
- optimization based on MET and JJTHT

$$\not{E}_T > 175\,\text{GeV},\ \text{JJTH}_T > 325\,\text{GeV}$$

$$\Rightarrow 2\ \text{events}\ (\text{SM}: 1.7 \pm 0.3^{+0.6}_{-0.3})$$

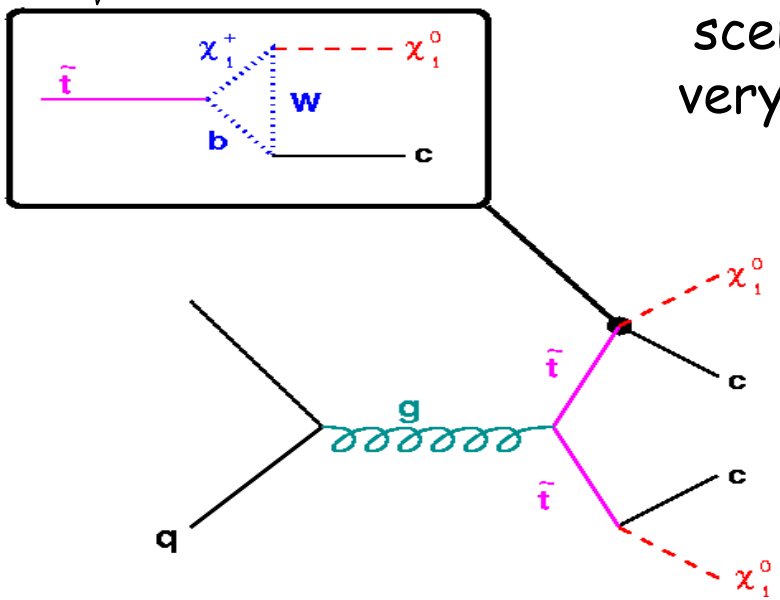
- Translates into a limit on squark mass:

$$M_{\tilde{q}} > 366\ @\ 95\%\ \text{CL}$$



NEW

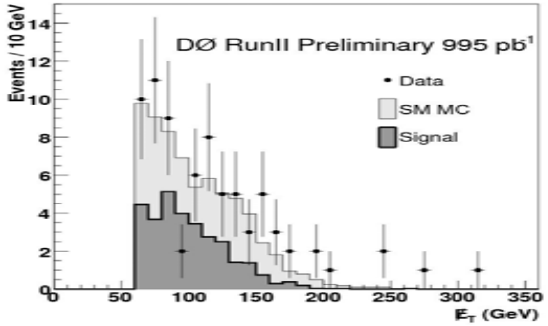
Stop Pair Production



scenario with very light stop →

$\tilde{t}_1 \to c\chi_1^0$ (100%)

$45 < M(\chi_1^0) < 90$ GeV



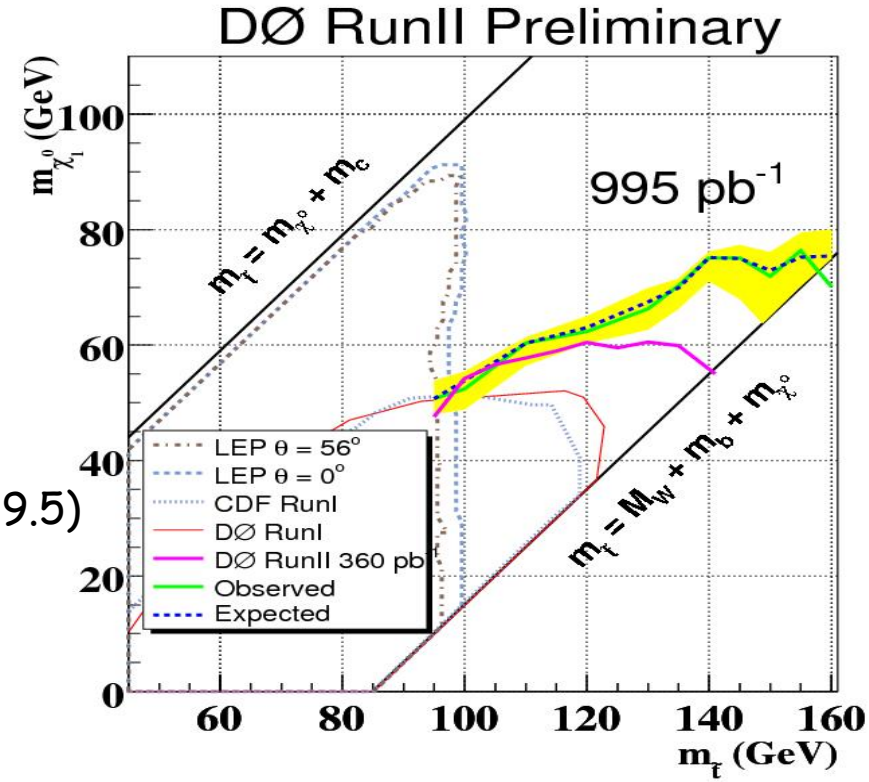
1 fb-1

Cuts optimized for different stop masses

$\not{E}_T > 70$ GeV, $H_T > 140$ GeV

Only 2 jets
At least one c-tag
No isolated leptons
Cuts on $\Delta\phi(\not{E}_T, \text{jet})$ & $\Delta\phi(\text{jet}, \text{jet})$
……

66 events
(SM : 64.2 ± 9.5)



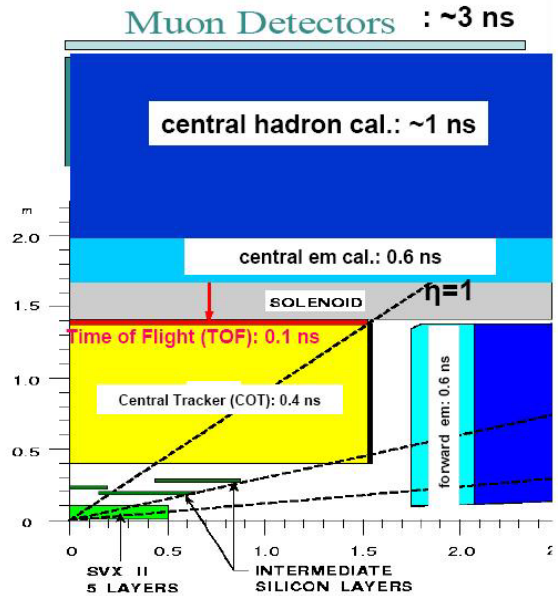
NEW

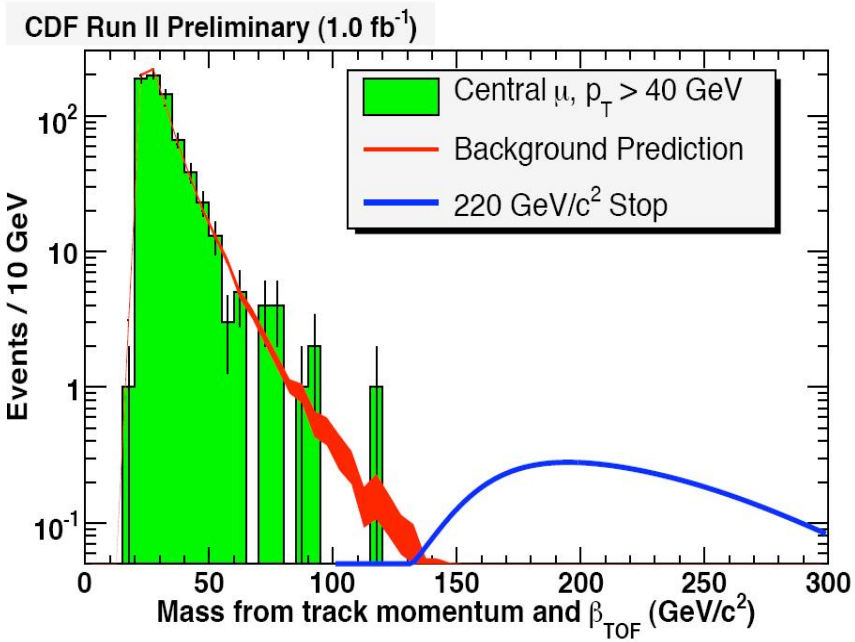
Stable Stop

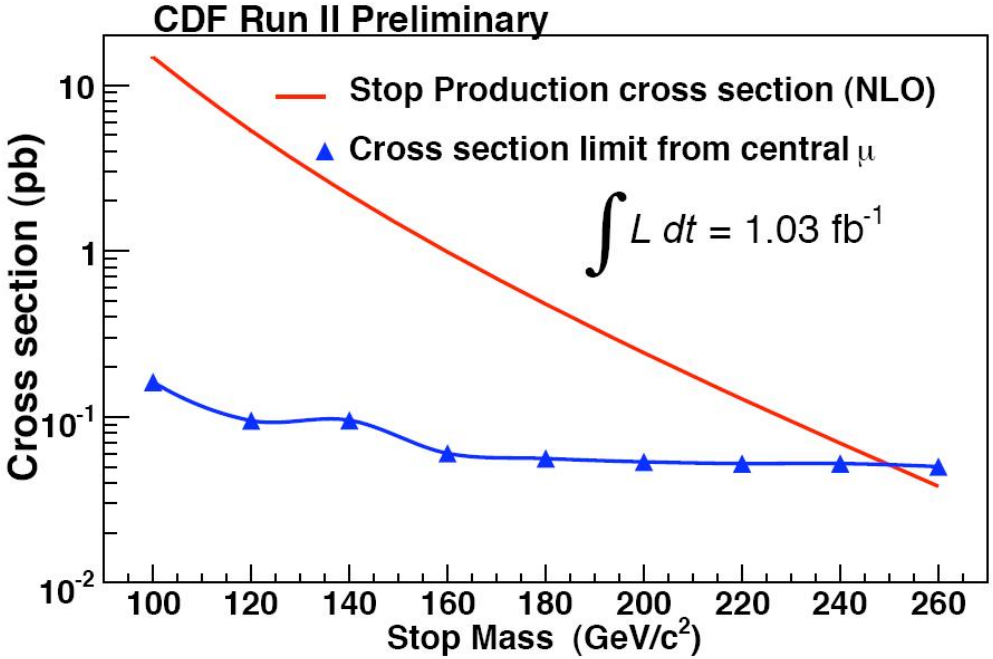
1 fb-1

reconstructed as high-pt muons

$$M_{TOF} = p\sqrt{\frac{1}{\beta^2} - 1}$$





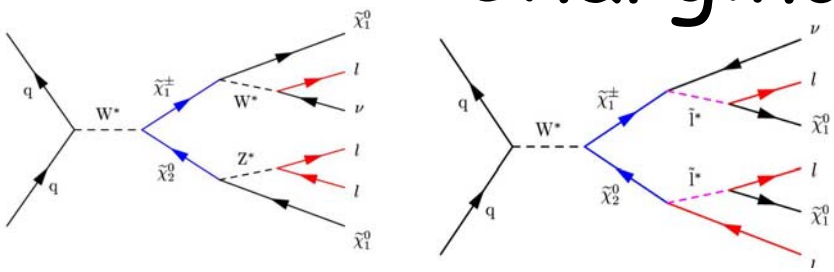


$p_T^{\mu} > 40\ GeV/c,\ |\eta^{\mu}| < 0.6$

$0.4 < \beta < 0.9$

$M(\tilde{t}) > 250\ GeV$ @ 95% CL (stable)

Chargino/Neutralino

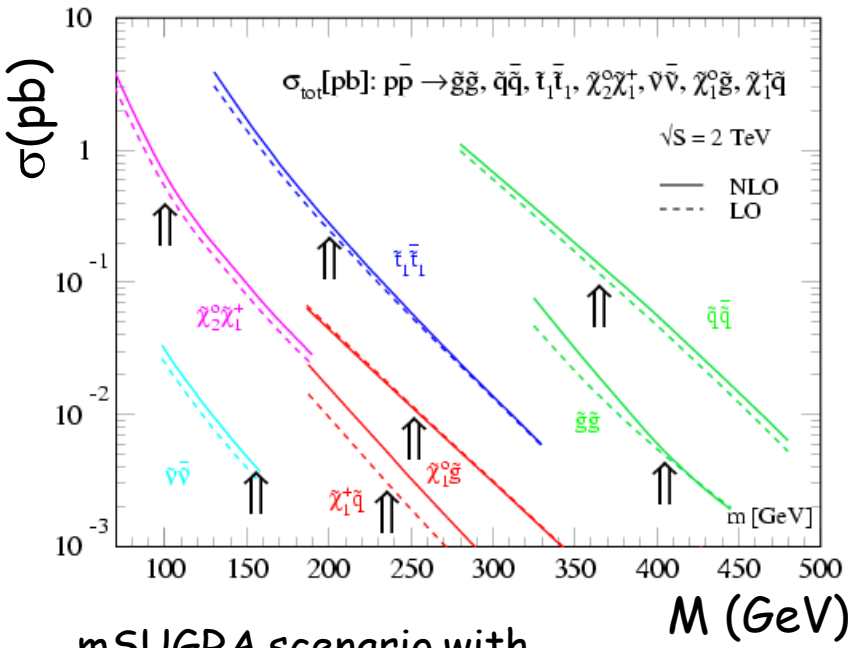


Multiple leptons in the final state
- three leptons + MET
- two like sign leptons

Relative low σxBr(in leptons) but is clean

SM background very much reduced
- Dominated by Drell-Yan, Z/W+γ and Dibosons
- Small contributions from ttbar and bbar

Long list of tuned cuts to kill SM contributions



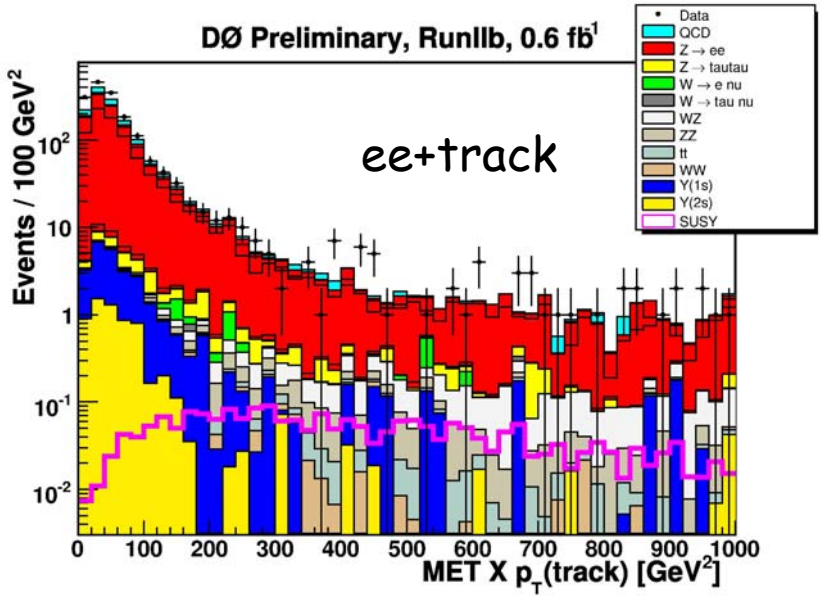
mSUGRA scenario with

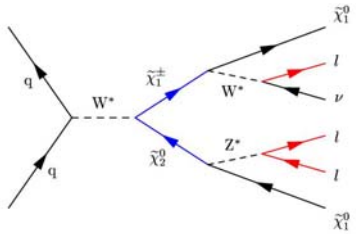
$\tan\beta = 3, A_0 = 0, \mu > 0$

$M(\chi_2^0) = M(\chi_1^\pm) = 2M(\chi_1^0)$

no slepton mixing

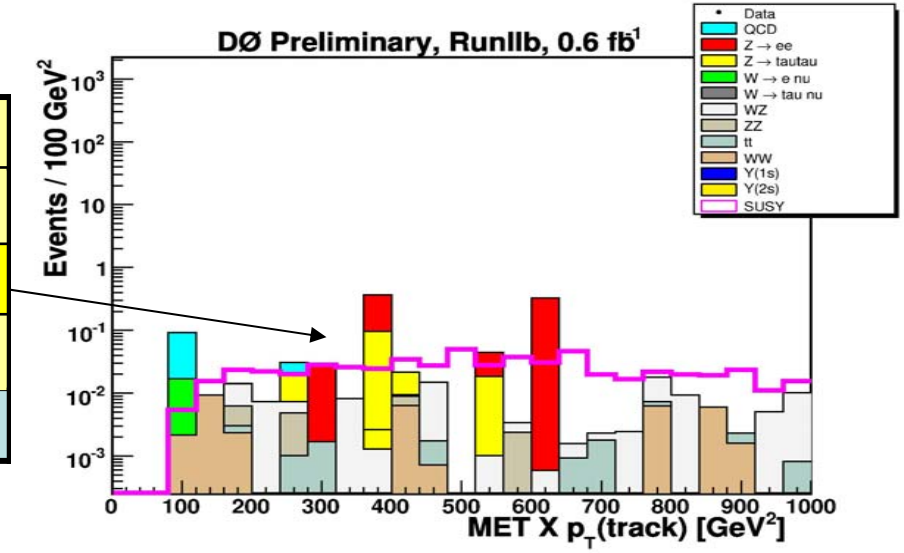
dependency on χ_2^0 and $\chi_1^\pm$ decay Br($\rightarrow$leptons)





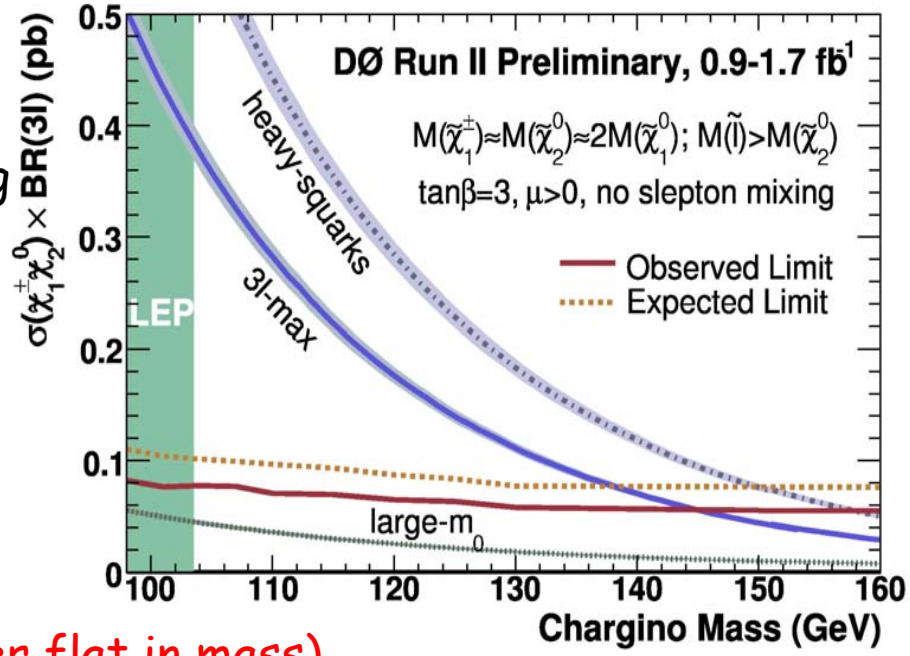
Chargino/Neutralino

trileptons	SM expect.	DATA
μμ+track	$0.32^{+1.34}_{-0.32}$	2
NEW ee+ track	1.0 ± 0.3	0
eμ+l	0.9 ± 0.4	0
Like sign μμ	1.1± 0.4	1

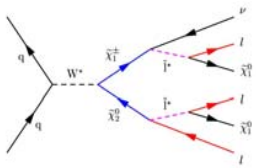


Run IIa + Run IIb ➡ 1.7 fb-1

Improved limits compared to LEP results in mSUGRA scenarios with no slepton mixing



- heavy-squarks: maximal cross section
- 3l-max: enhanced leptonic decays
- large-m0: W/Z exchange dominates
- New observed limit: σxBr < 0.1 pb (rather flat in mass)

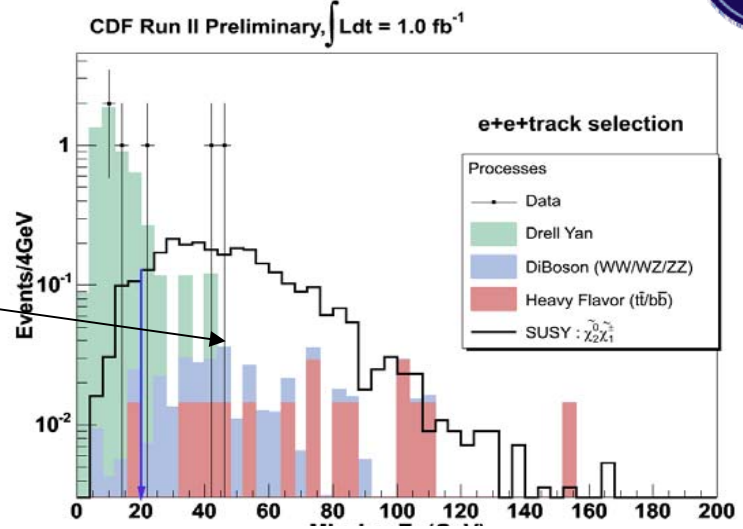


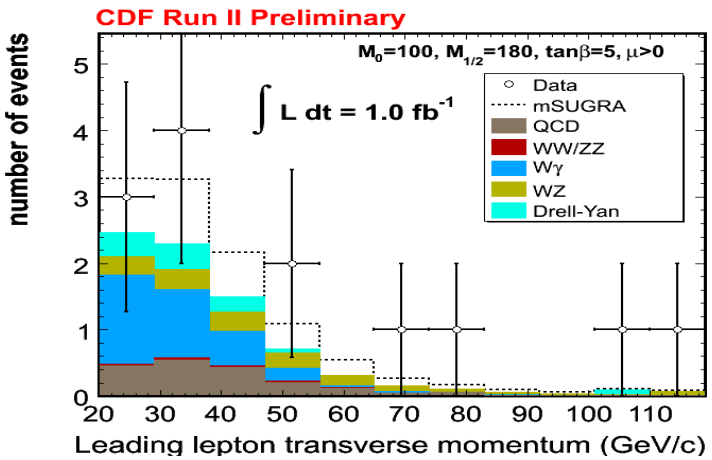
Chargino/Neutralino

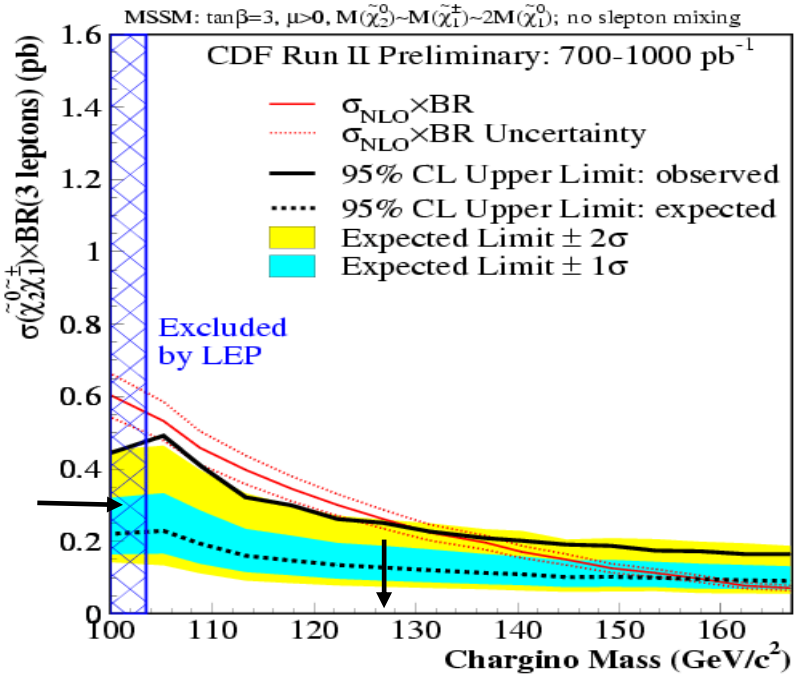
1 fb-1

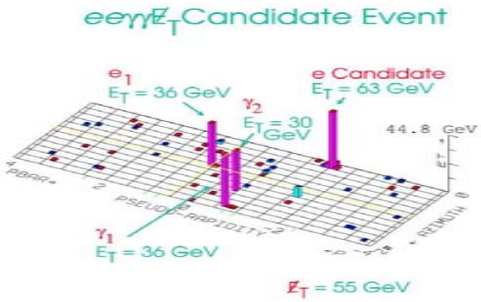
trileptons	SM expect.	DATA
μμ+l (low pt)	0.4 ± 0.1	1
ee+ track	1.0 ± 0.3	3
μ+ll	1.2 ± 0.2	1
e+ll	0.8 ± 0.4	0

LS leptons	SM expect.	DATA
ee	2.9 ± 0.5	4
eμ	4.0 ± 0.6	8
μμ	0.9 ± 0.1	1









GMSB

(gauge mediated SUSY breaking)

SUSY breaking (hidden sector) → Gauge Fields → MSSM (visible sector)

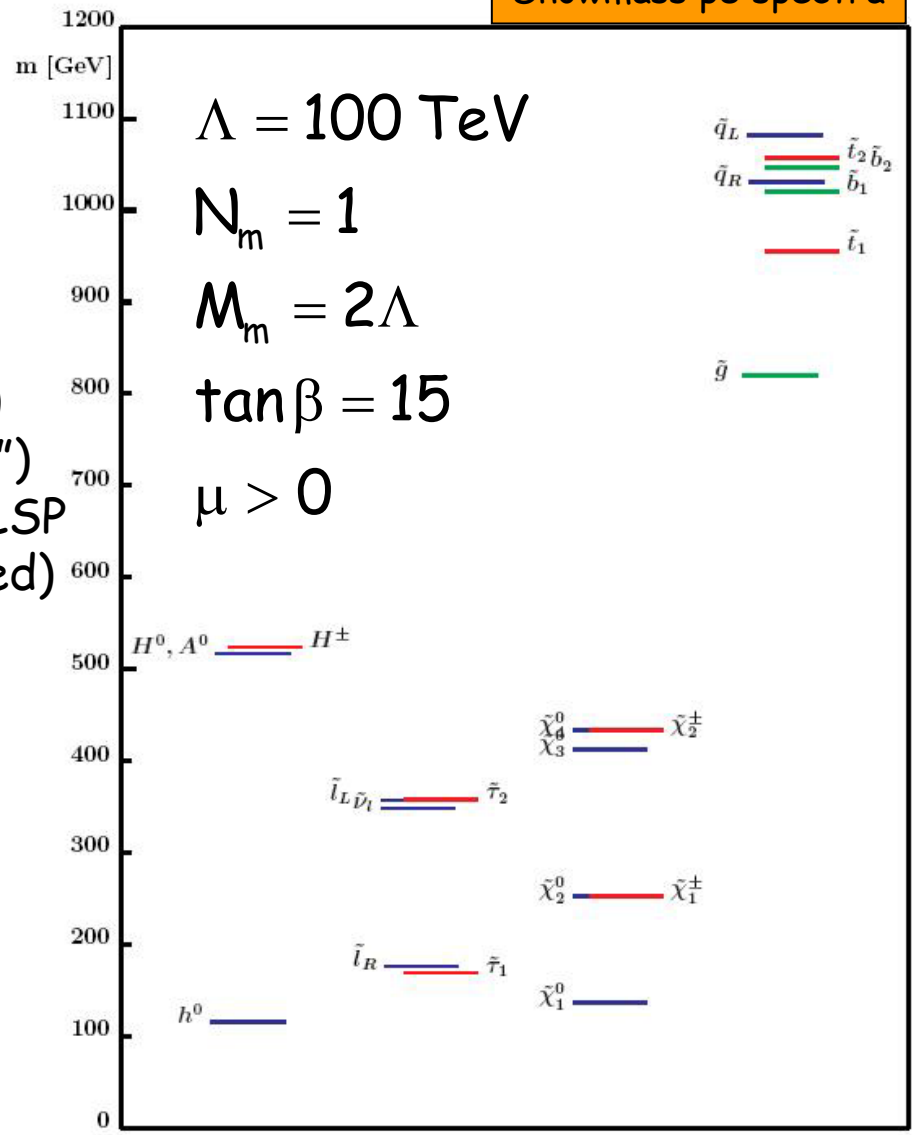
- SUSY breaking at scale Λ (10 -100 TeV)
- Mediated by Gauge Fields ("messengers")
- Gravitino is very light (~ KeV) and the LSP
- Neutralino is NLSP (its lifetime not fixed)

$$\chi_1^0 \rightarrow \tilde{G}\gamma$$

•Rp conservation (2 NLSP in final state)

$$\gamma\gamma + \not{E}_T + X$$

Snowmass p8 spectra

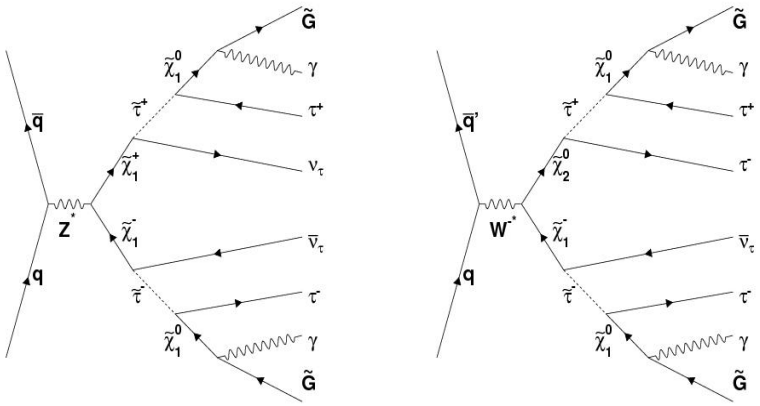


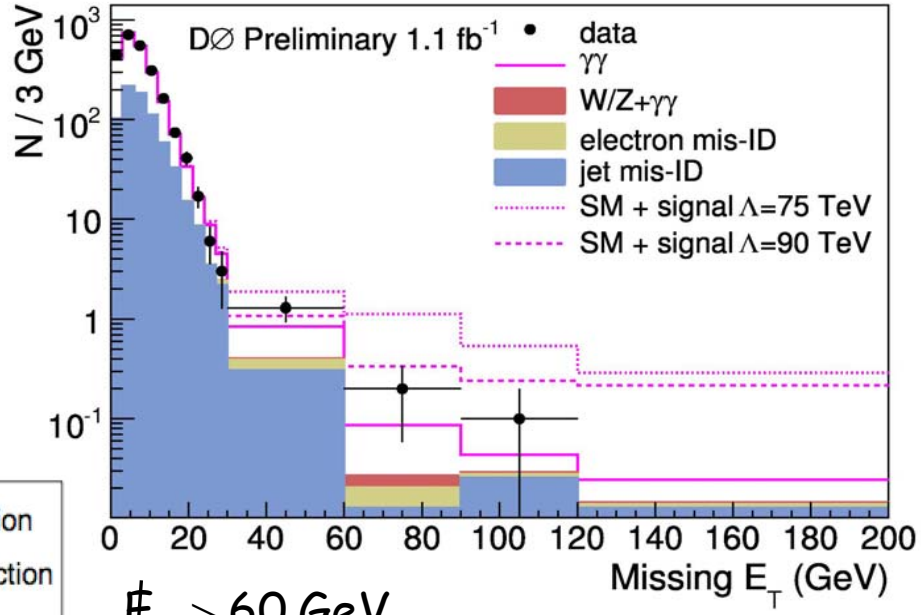
(taken from N. Ghodbane et al., hep-ph/0201233)

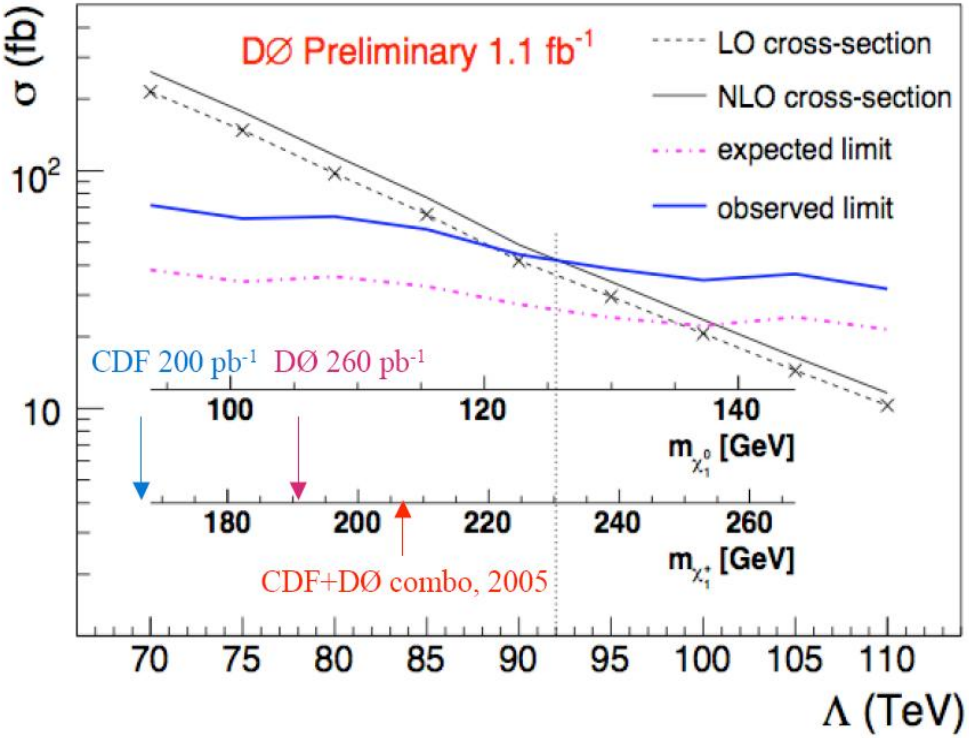
NEW

γγ+MET (GMSB)

1.1 fb-1







$\not{E}_T > 60$ GeV

2 photons ($p_T^\gamma > 25$ GeV, $|\eta^\gamma| < 1.1$)

$\Delta\varphi(\not{E}_T, \text{jet}) < 2.5$

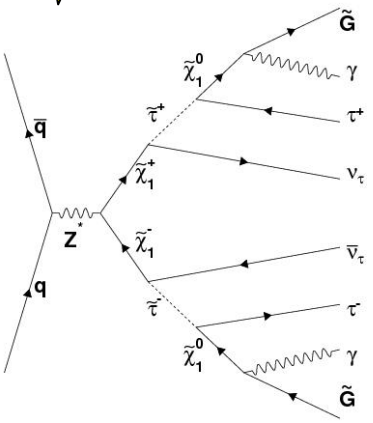
3 events (SM : 1.6 ± 0.4)

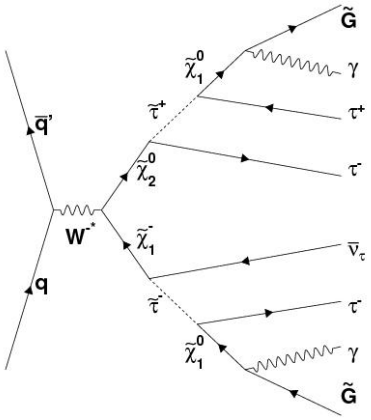
$\Lambda > 92$ TeV @ 95% CL

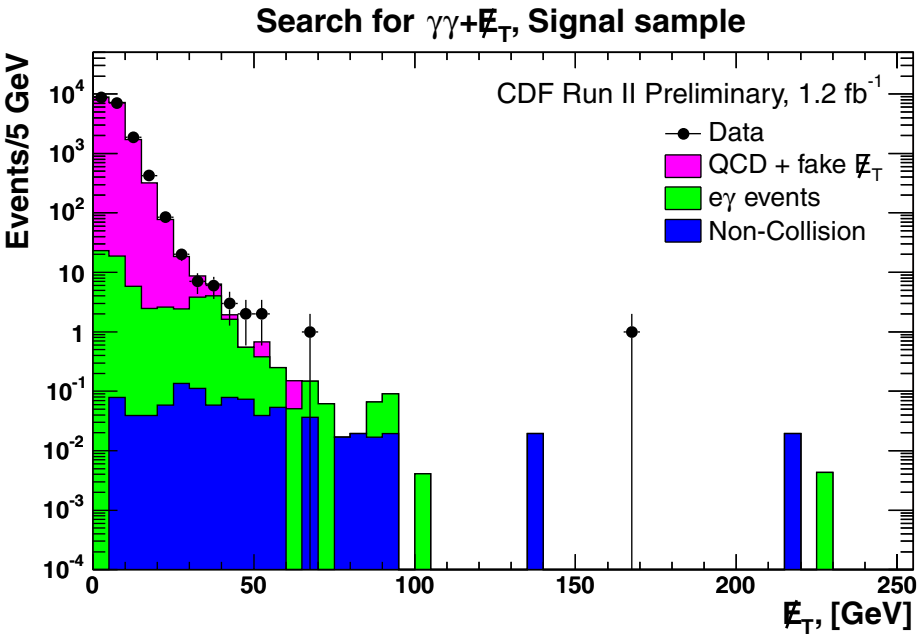
$M(\chi_1^0) > 126$ GeV, $M(\chi_1^+) > 231$ GeV

NEW

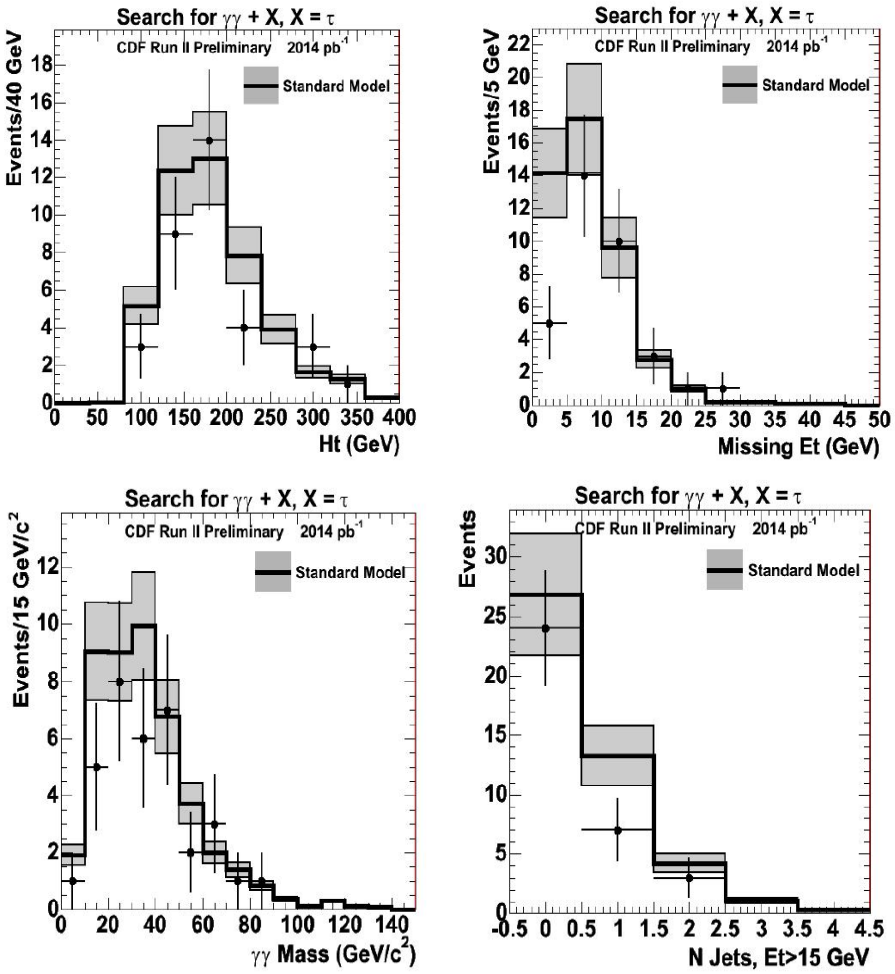
γγ+MET & γγ+τ







2 fb^{-1}

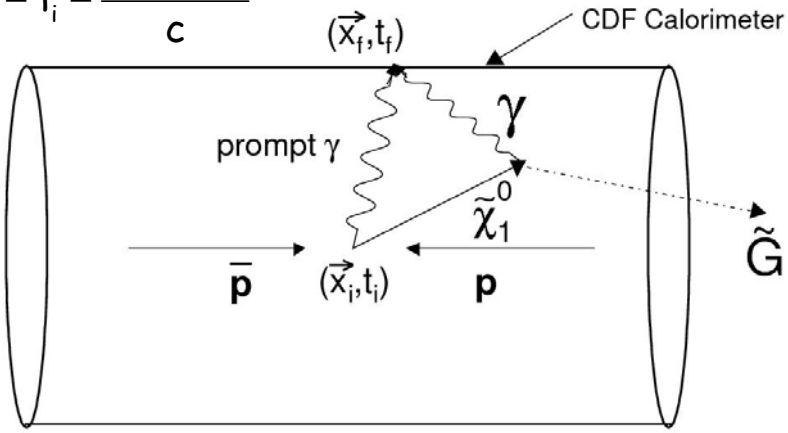


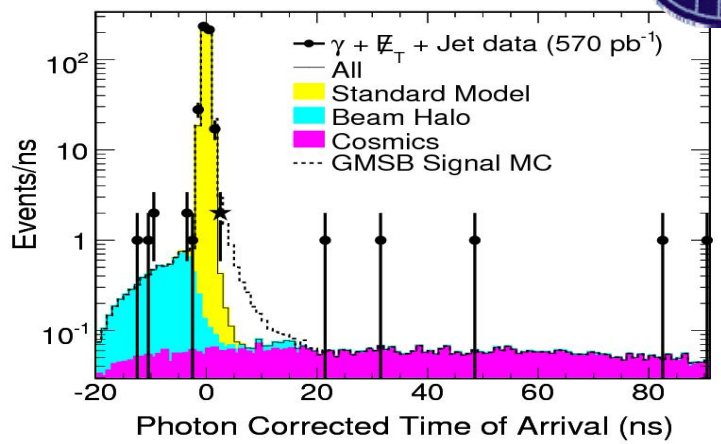
Signature-based search: Good agreement with SM predictions

0.6 fb-1

Delayed Photons (GMSB)

$$t_c^\gamma \equiv t_f - t_i - \frac{|\vec{x}_f - \vec{x}_i|}{c}$$





$\not{E}_T > 40$ GeV

a photon ($p_T^\gamma > 25$ GeV, $|\eta^\gamma| < 1.1$)

a jet ($E_T^{jet} > 35$ GeV, $|\eta^{jet}| < 2$)

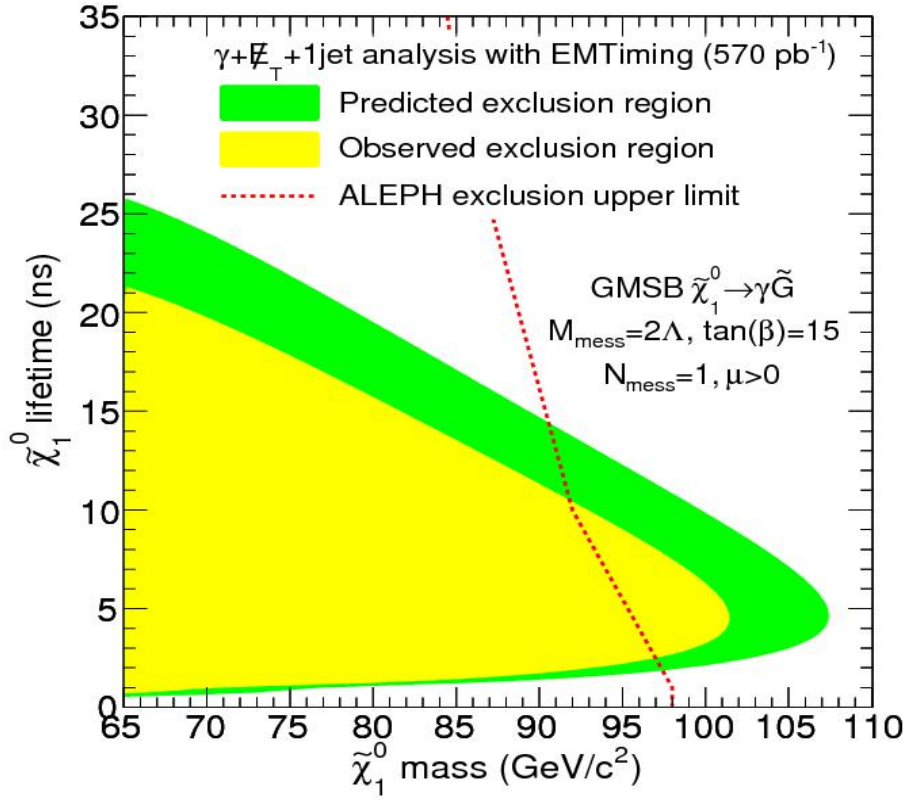
$\Delta\varphi(\not{E}_T, \text{jet}) > 1$

$2\text{ ns} < t_c^\gamma < 10\text{ ns}$

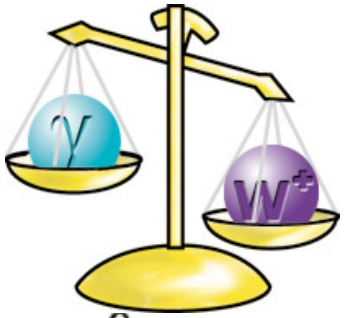
vertex & cosmics rejection

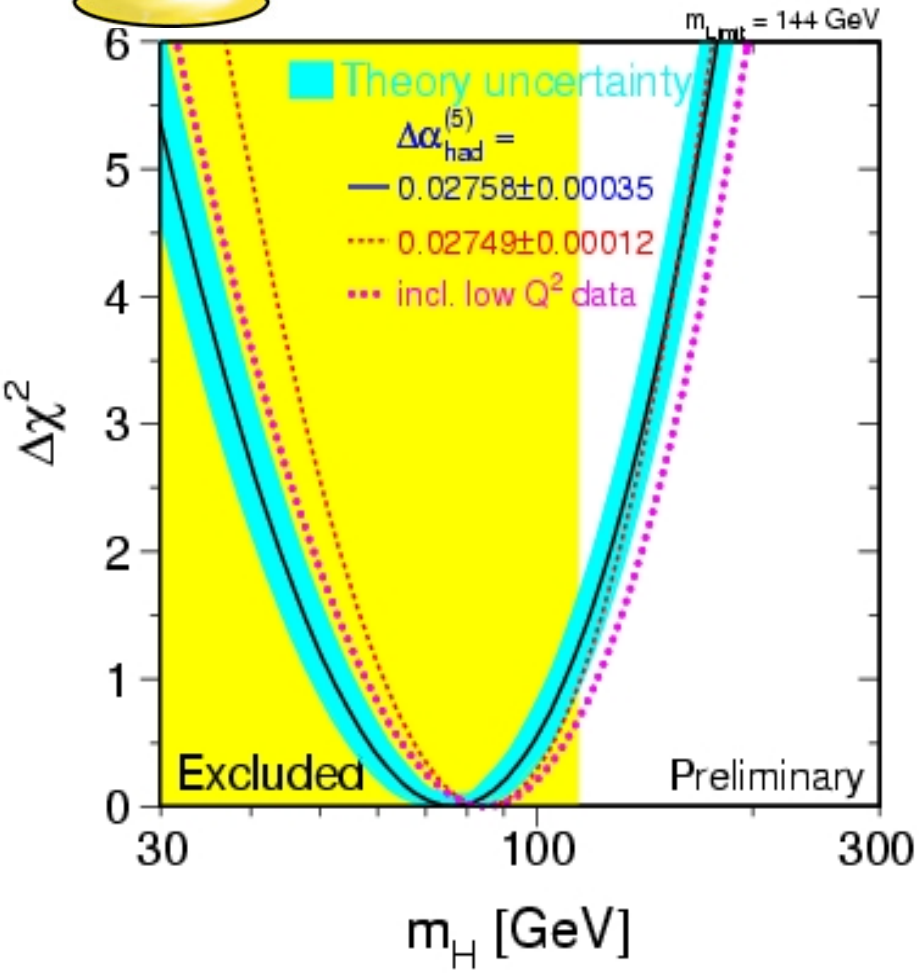
2 events (background : 1.3 ± 0.7)

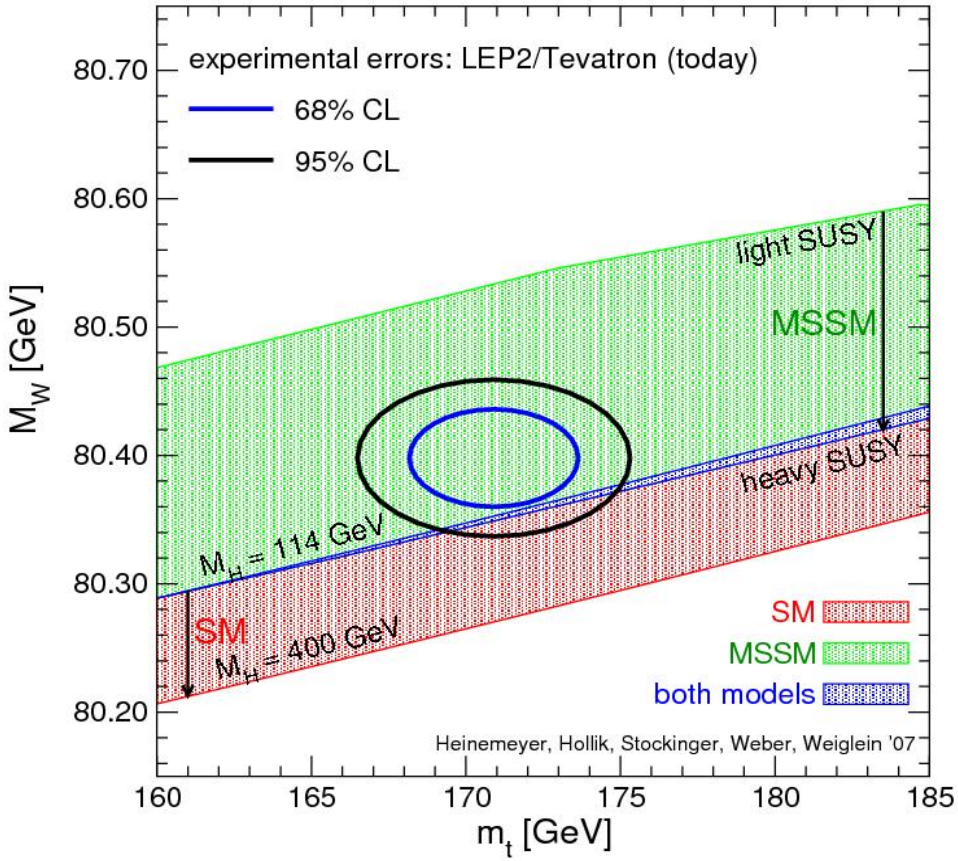
$M(\chi_1^0) > 101$ GeV @ 95% CL (with $\tau_{\chi_1^0} = 5$ ns)



Electroweak Fits
(indirect Higgs Mass constrains)



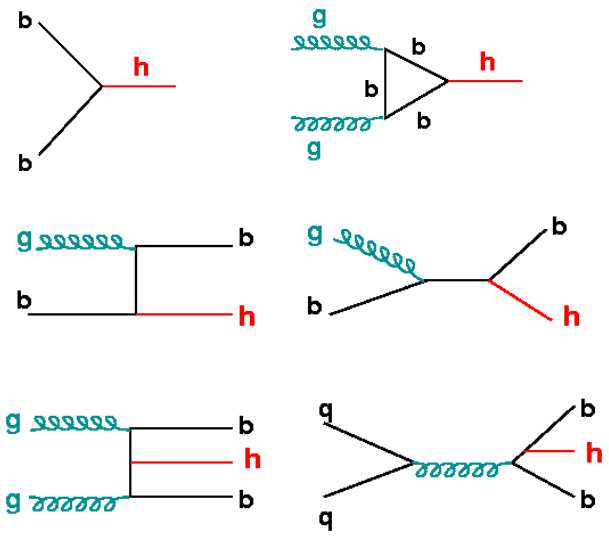




Measured top and W masses favor low values for M_H
(dangerously entering MSSM regime)

MSSM Higgs

$H_U, H_D \longrightarrow h, H, A$ and $H^{\pm}$



$\tan\beta = \langle H_U \rangle / \langle H_D \rangle$

Tree level: M_A and $\tan\beta$ as parameters

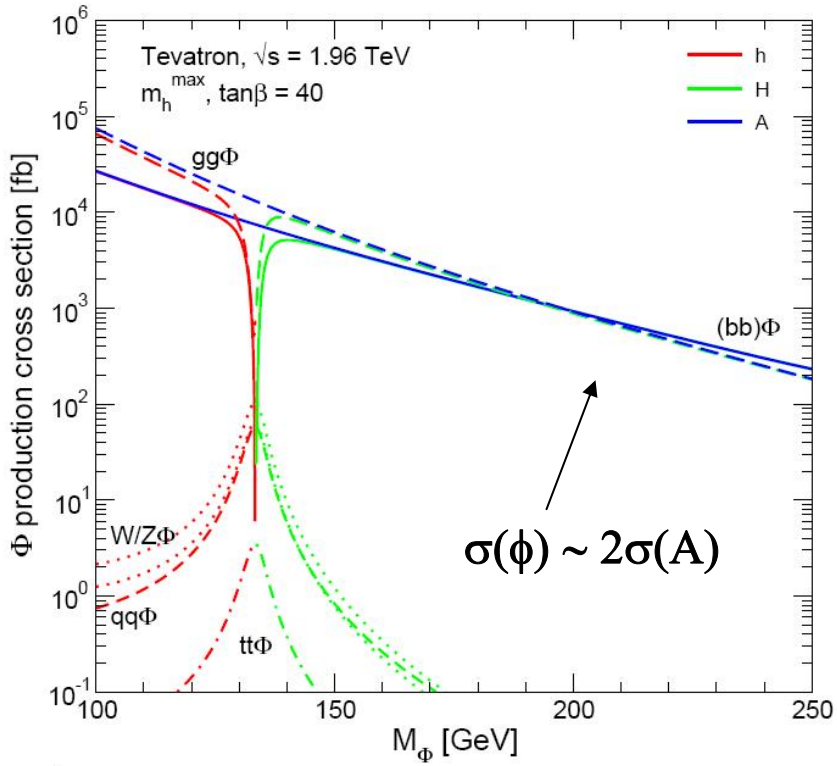
enhanced coupling to down - type fermions

(low M_A and high $\tan\beta$)

MSSM Higgs production cross section boosted compared to SM at large $\tan\beta$

$$\sigma(b\bar{b}A) \times \mathrm{BR}(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

$$\sigma(gg, b\bar{b} \to A) \times \mathrm{BR}(A \to \tau^+\tau^-) \simeq \sigma(gg, b\bar{b} \to A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2+9},$$

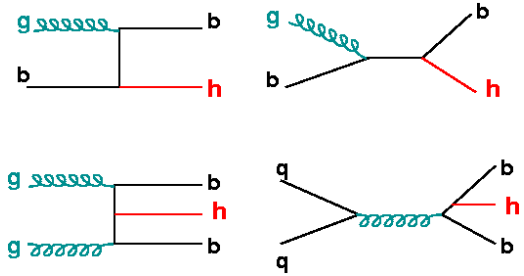


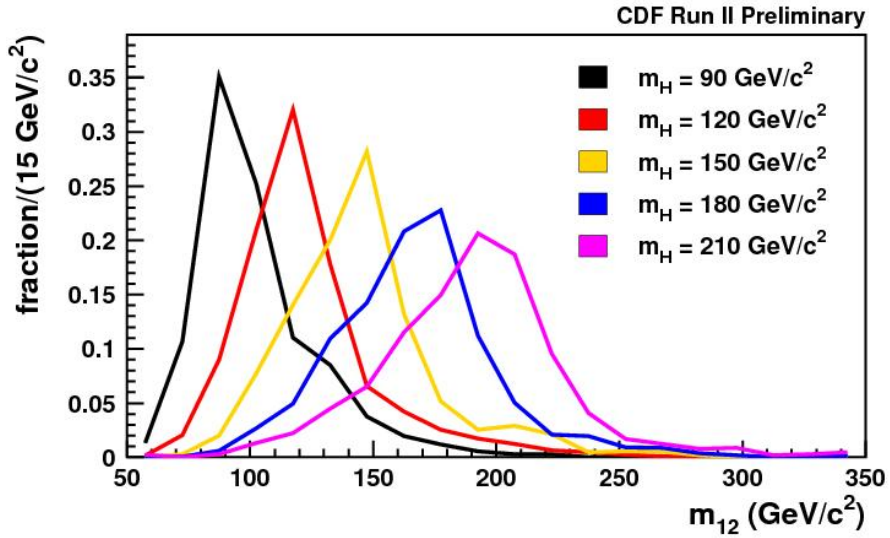
At low masses

$Br(h \to bb) \sim 90\%$, $Br(h \to \tau\tau) \sim 10\%$

NEW

$\phi b(b) \to bb\, b(b)$





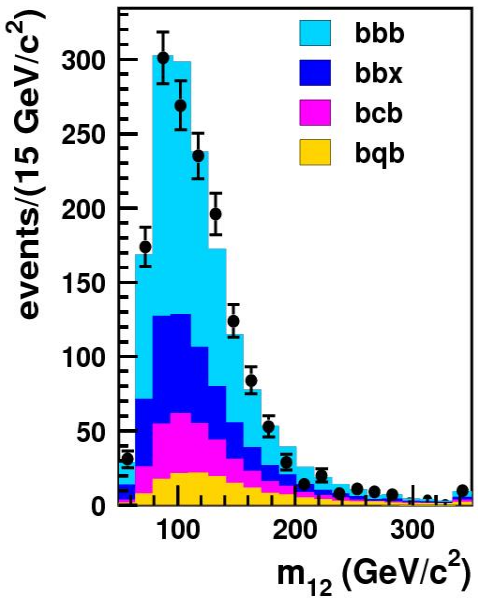
3 b-tagged jets in the final state

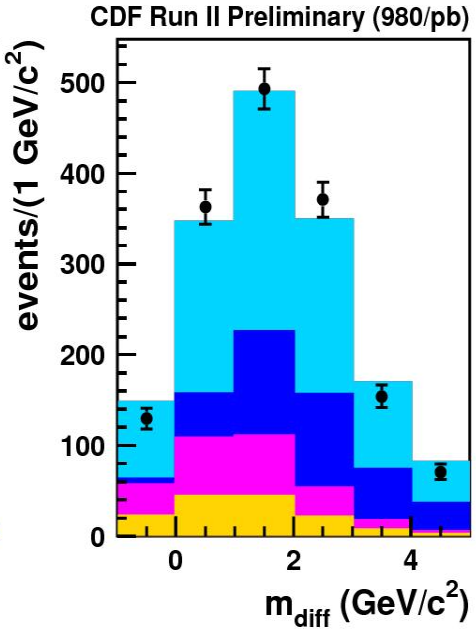
Two variables for discrimination

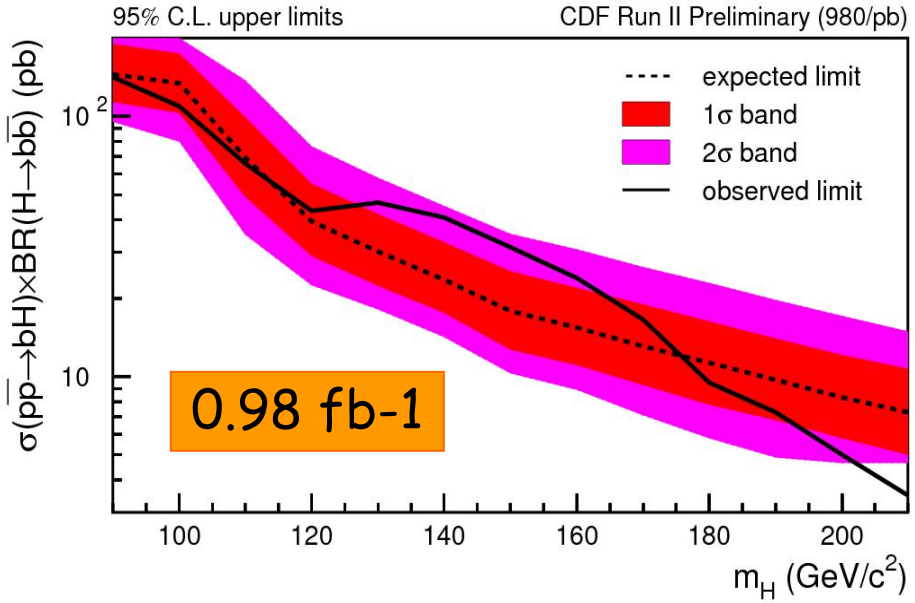
M_{12} (invariant mass two leading jets)

$$M_{diff} \equiv M_{vertex}^{jet1} + M_{vertex}^{jet2} - M_{vertex}^{jet3}$$

Data fitted to templates for flavor mixing



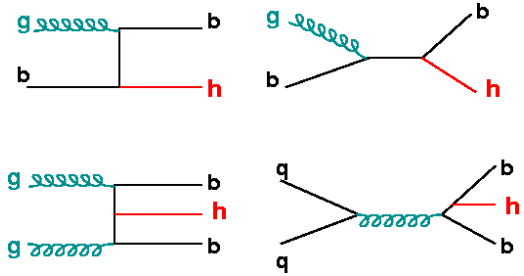


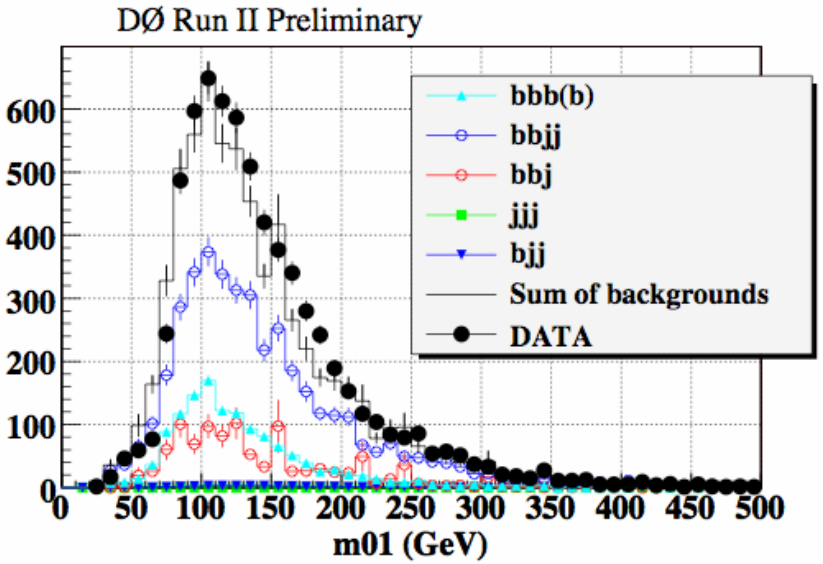


observed limit within 2σ of expected

0.9 fb-1

ϕb(b)->bb b(b)

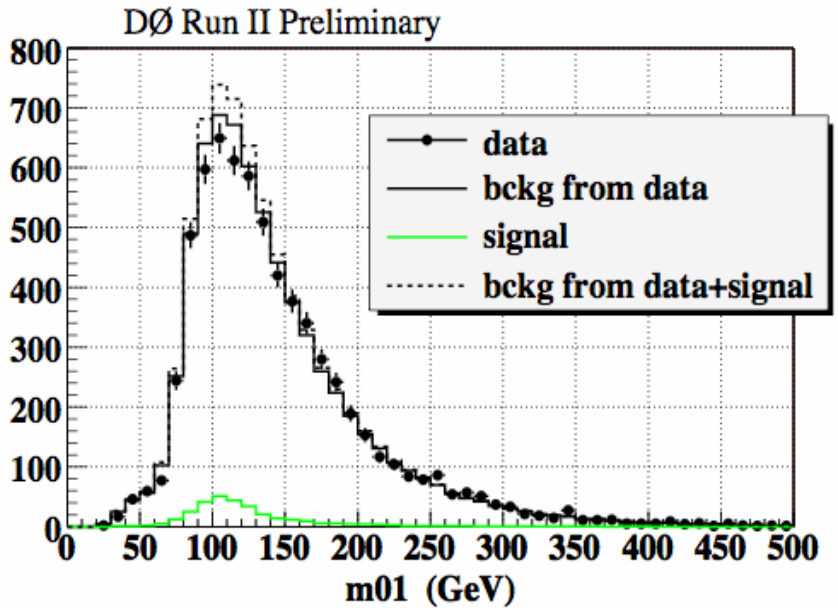


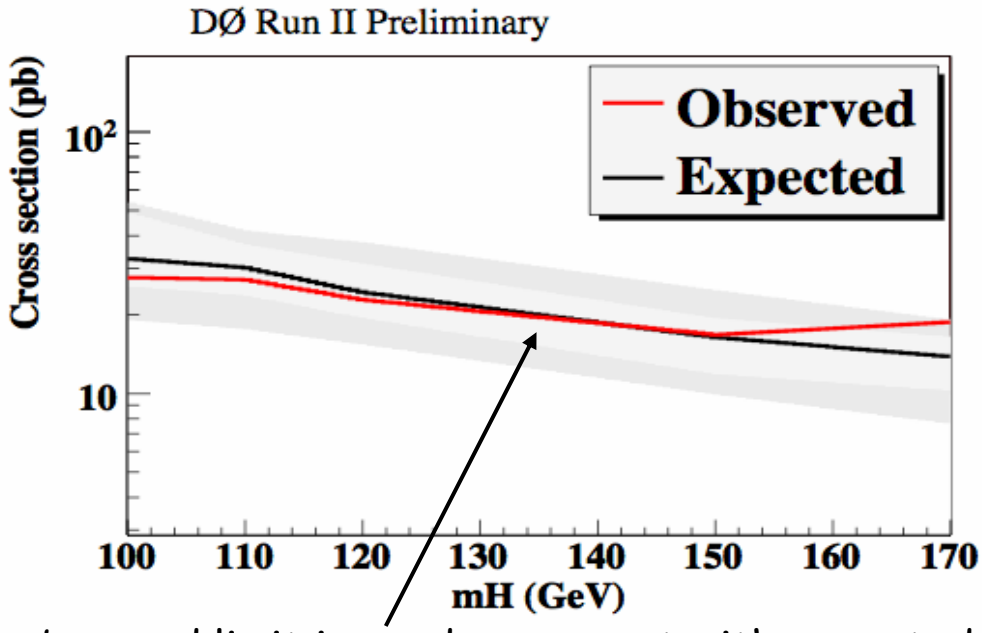


Use doubled-tags in data to compute b-tag probability for a third jet

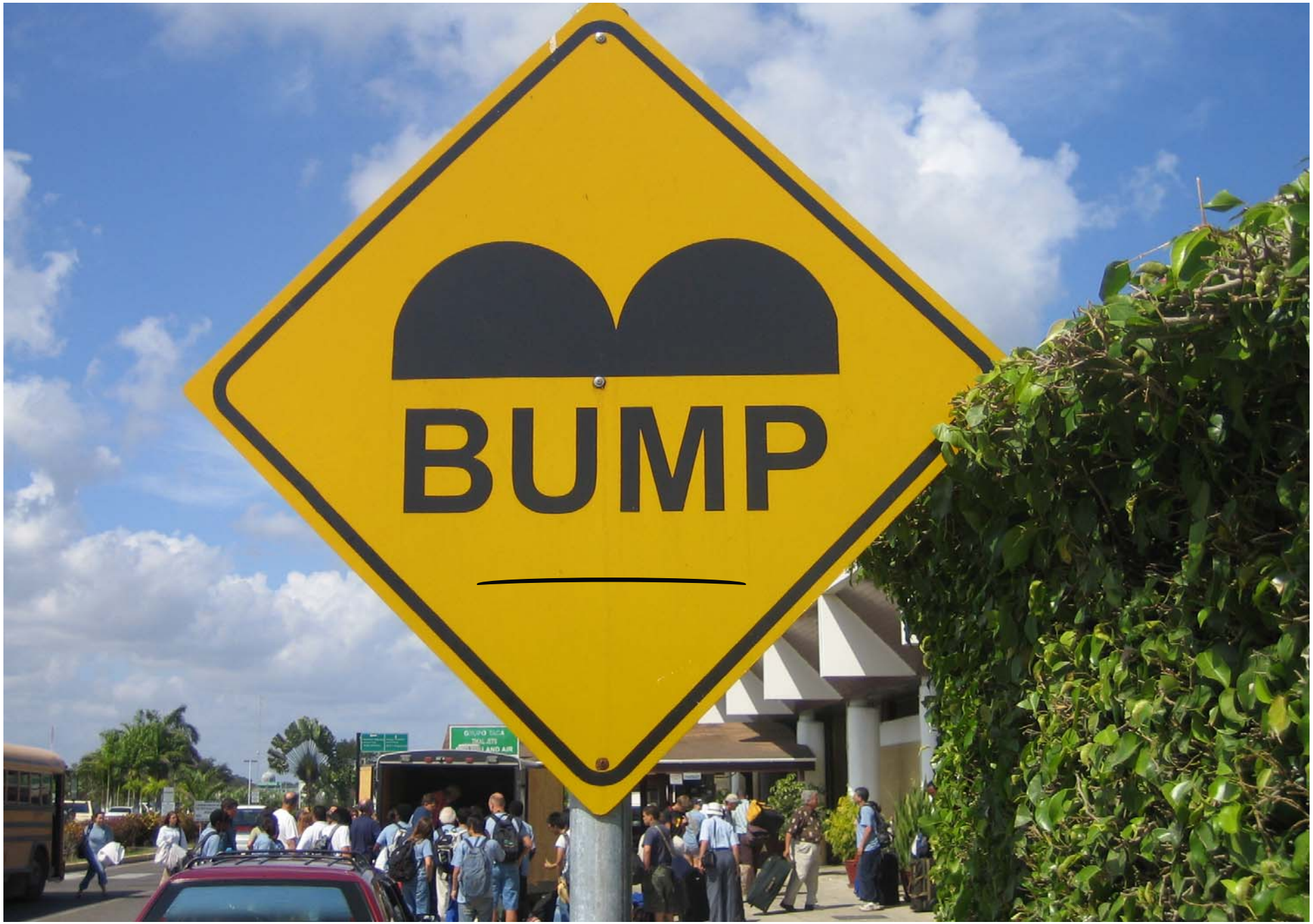
3 b-tagged sample then normalized to data outside signal region (separately for each H mass point)

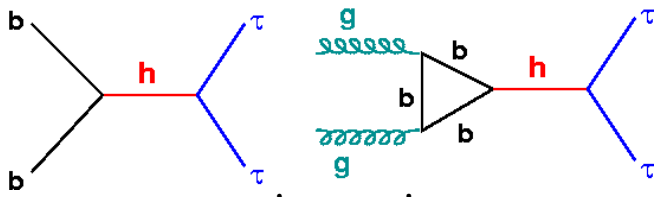
Validation using MC samples (relative contributions taken from ALPGEN)





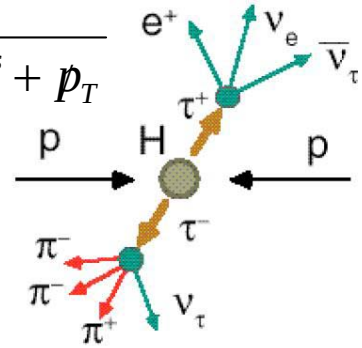
observed limit in good agreement with expected


BUMP

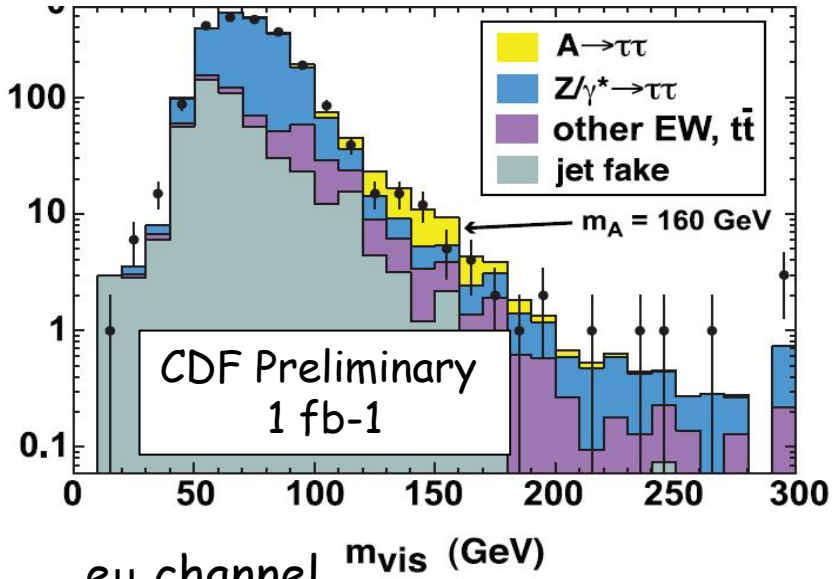


$\phi \to \tau\tau$

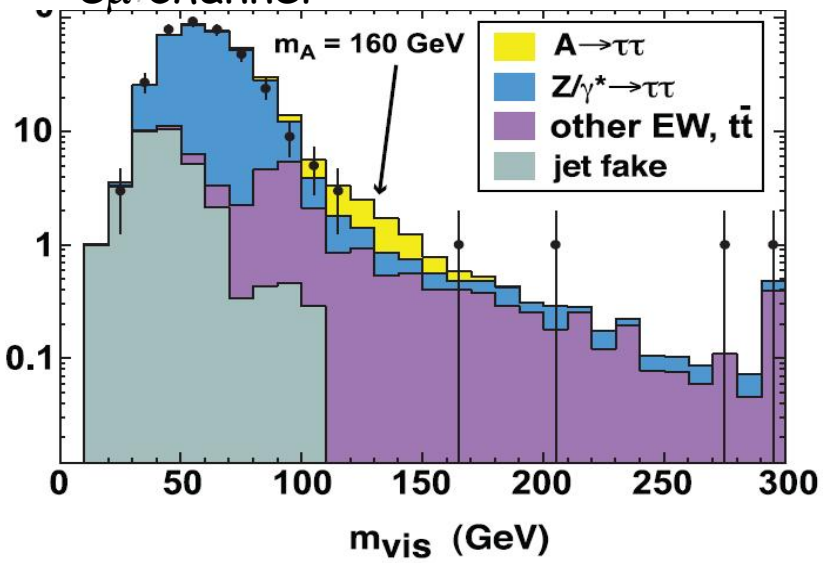
$$m_{vis} = \sqrt{p_{\tau_1}^{vis} + p_{\tau_2}^{vis} + p_T}$$



eτ,μτ channel



eμ channel



2 tau candidates

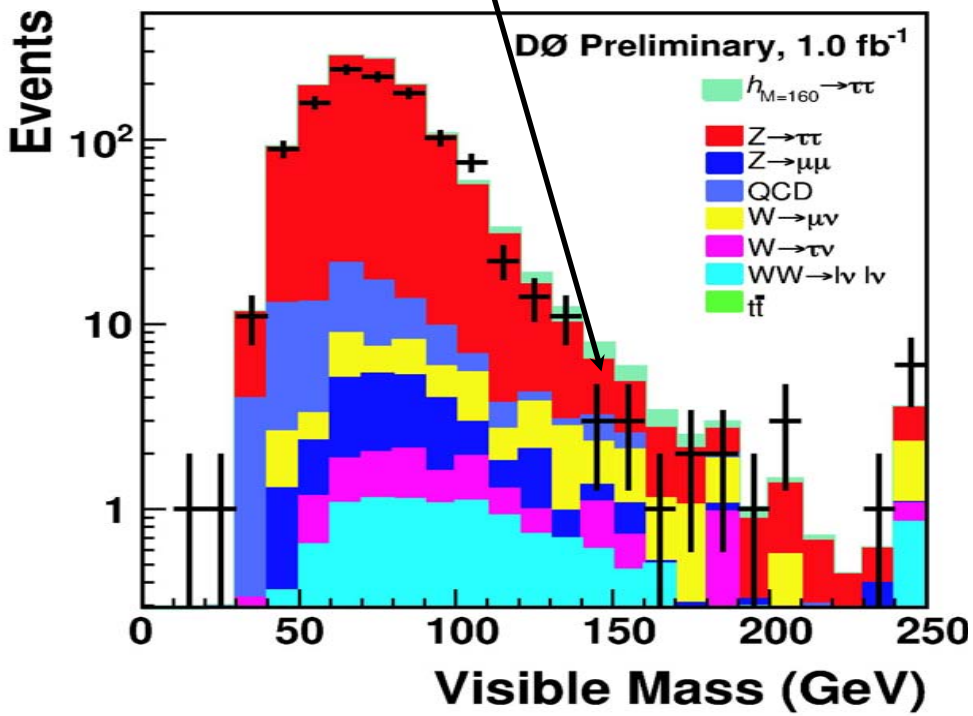
One hadronic or leptonic (CDF) decay

One leptonic decay (opposite charge)

(CDF: e,μ) (D0: μ)

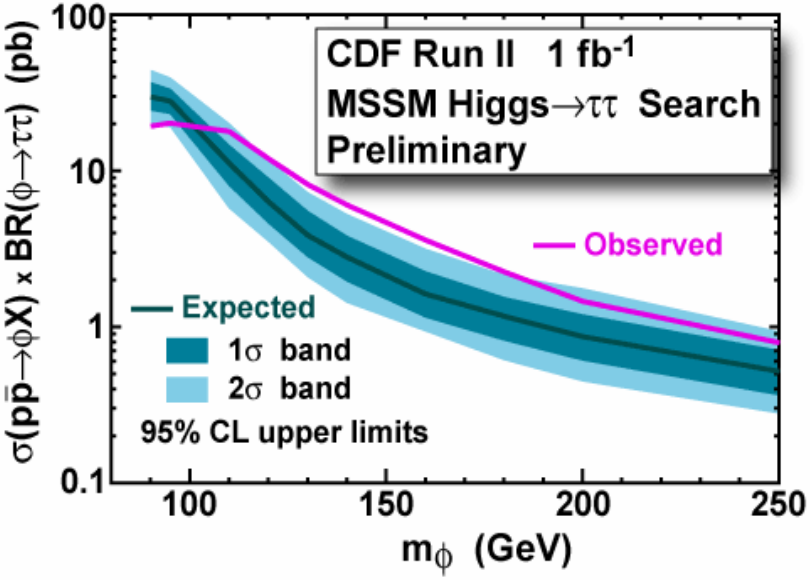
small excess in CDF eτ+μτ channel (<2σ effect)

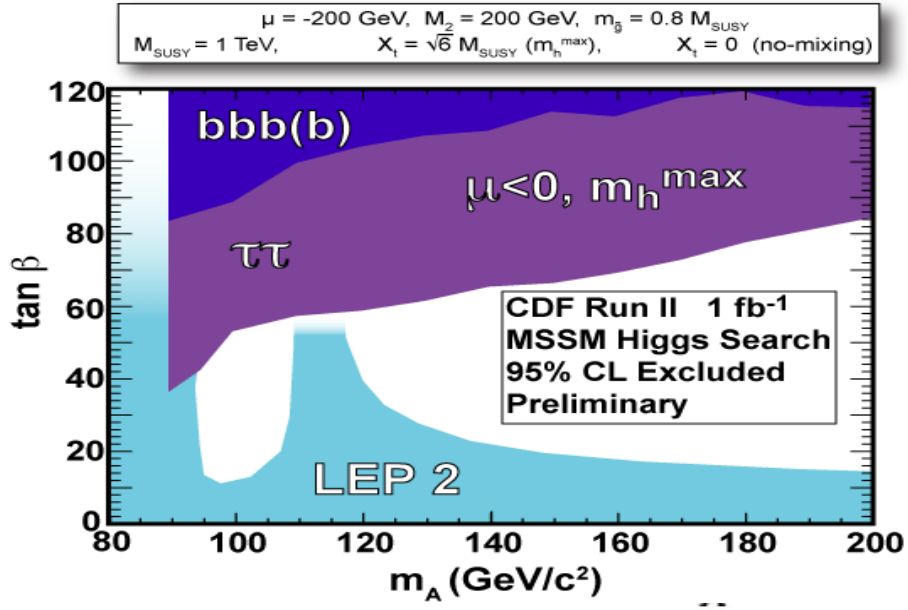
- Not observed in CDF eμ channel
- D0 analysis in good agreement with SM

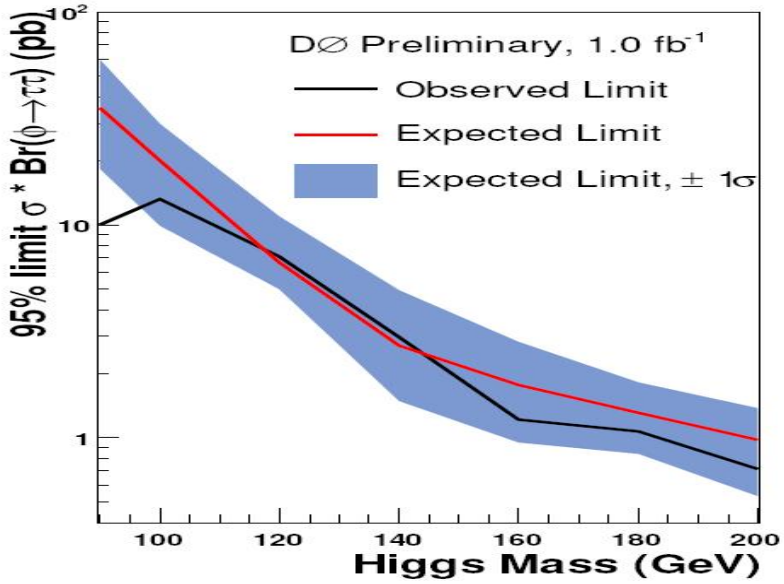


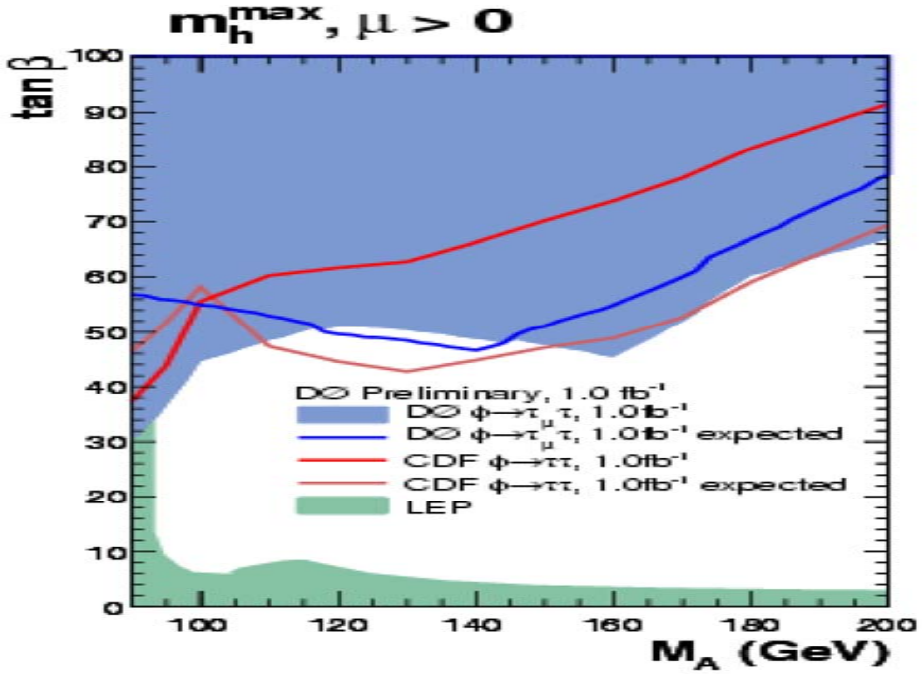
$\phi \to \tau\tau$

1 fb-1









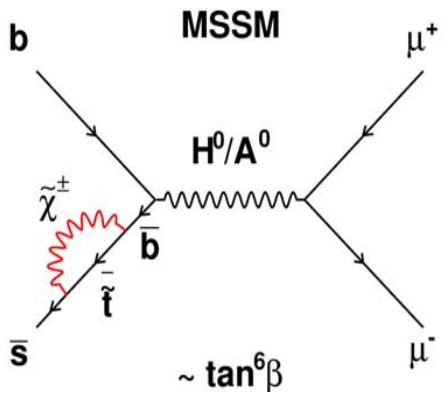
NEW

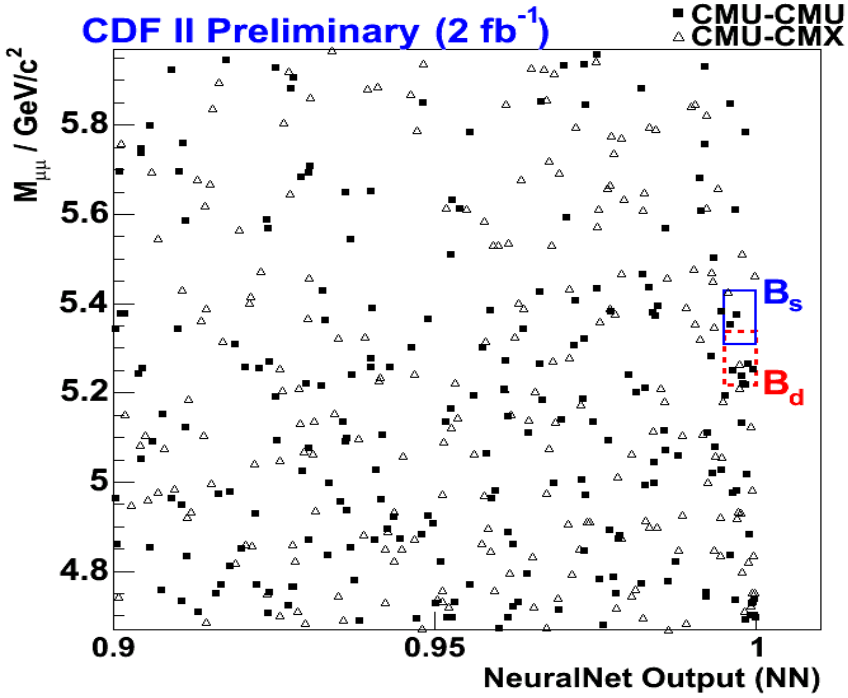
$B_s \to \mu^+\mu^-$

2 fb^{-1}

SM prediction $\Rightarrow Br(B_s \to \mu^+\mu^-) \sim 3.42 \times 10^{-9}$

SUSY $\to$ big enhancement $\to$ ($\sim \tan^6\beta$)





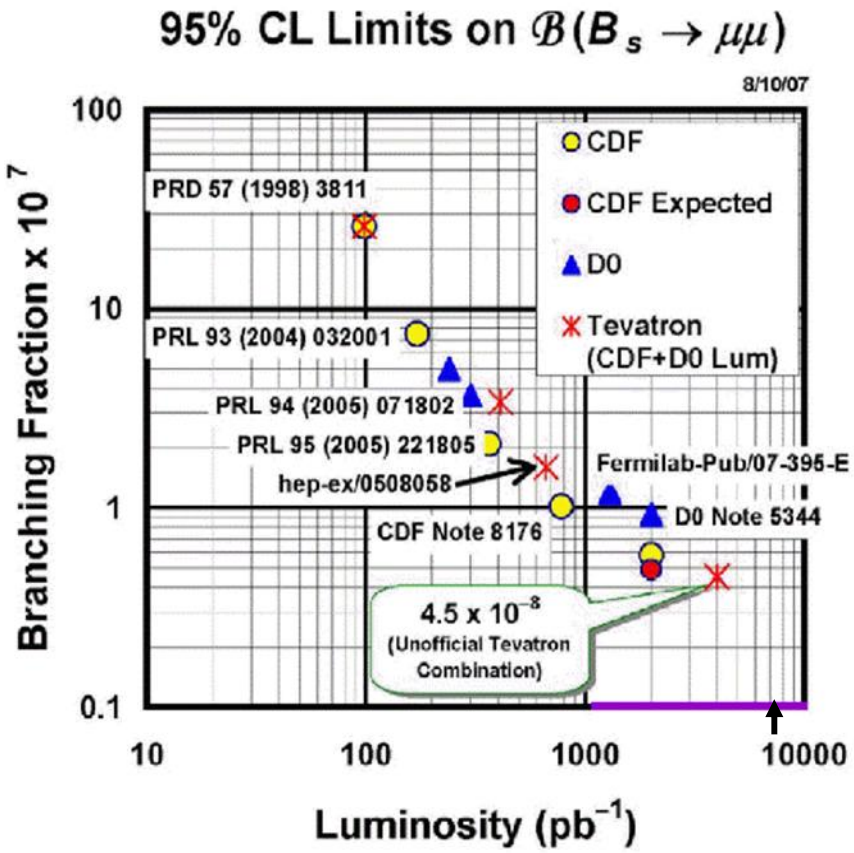
CDF analysis:

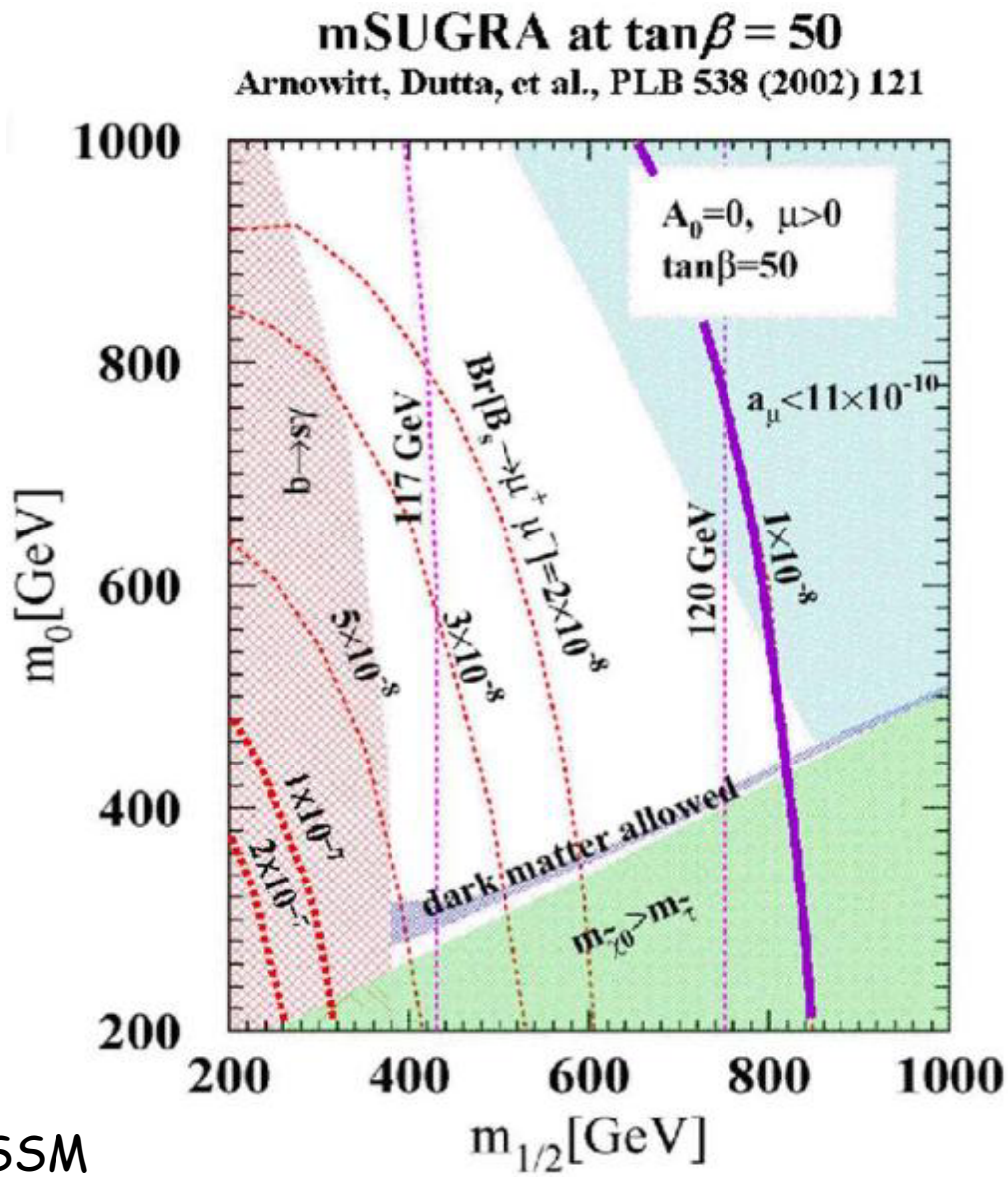
- Can distinguish Bs from Bd$\to\mu\mu$
- Using Neural Net to extract signal
- Improve sensitivity by including NN output and $M_{\mu\mu}$ in limit calculation

Bs window → 3 events
Bd window → 6 events
No significant excess !

$Br(B_s \to \mu\mu) < 5.8 \times 10^{-8}$ @ 95% CL
$Br(B_d \to \mu\mu) < 1.8 \times 10^{-8}$ @ 95%CL

B_s vs MSSM





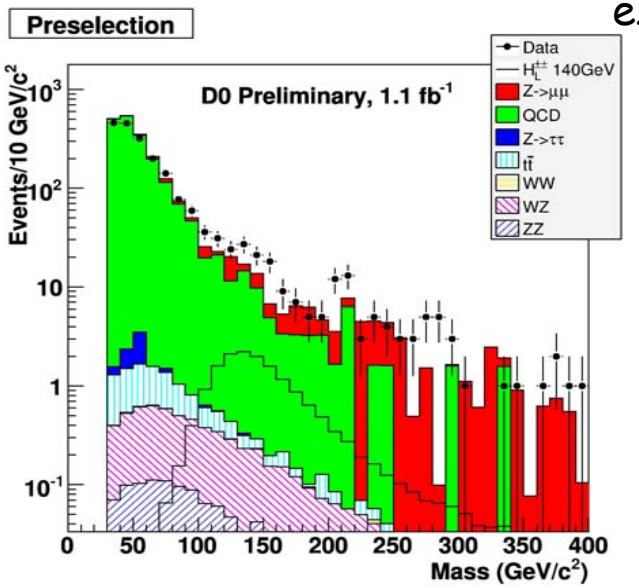
This measurement shows its potential to introduce strong constraints on MSSM

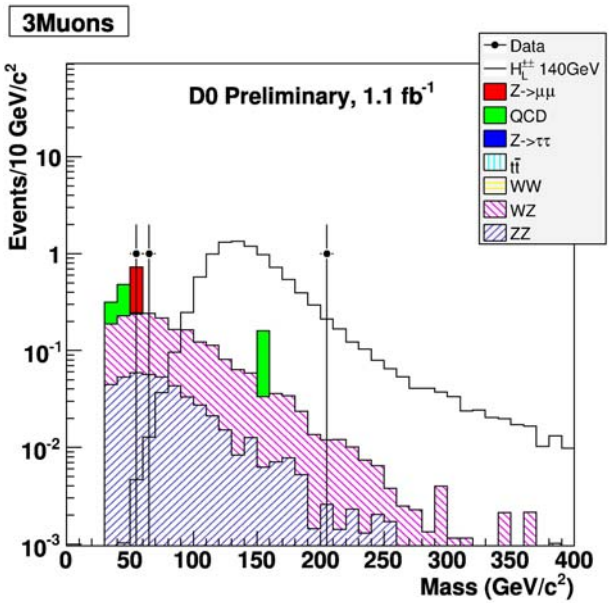
NEW

1.1 fb-1

Doubly Charged Higgs

exotic extensions of Higgs sector with higher isospin multiplets





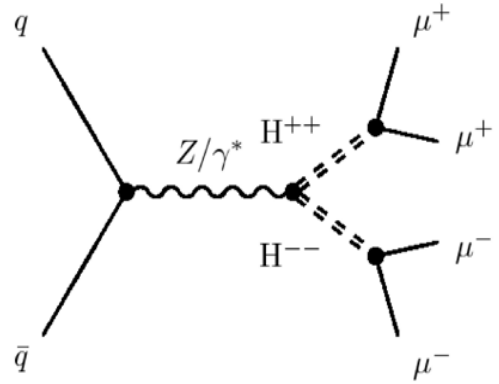
- 2 like-sign muons
  - $p_t > 15$ GeV
  - $|\eta| < 2$
  - isolated
  - $\Delta\varphi_{\mu\mu} < 2.5$
  - $M\mu\mu > 30$ GeV
- A third muon

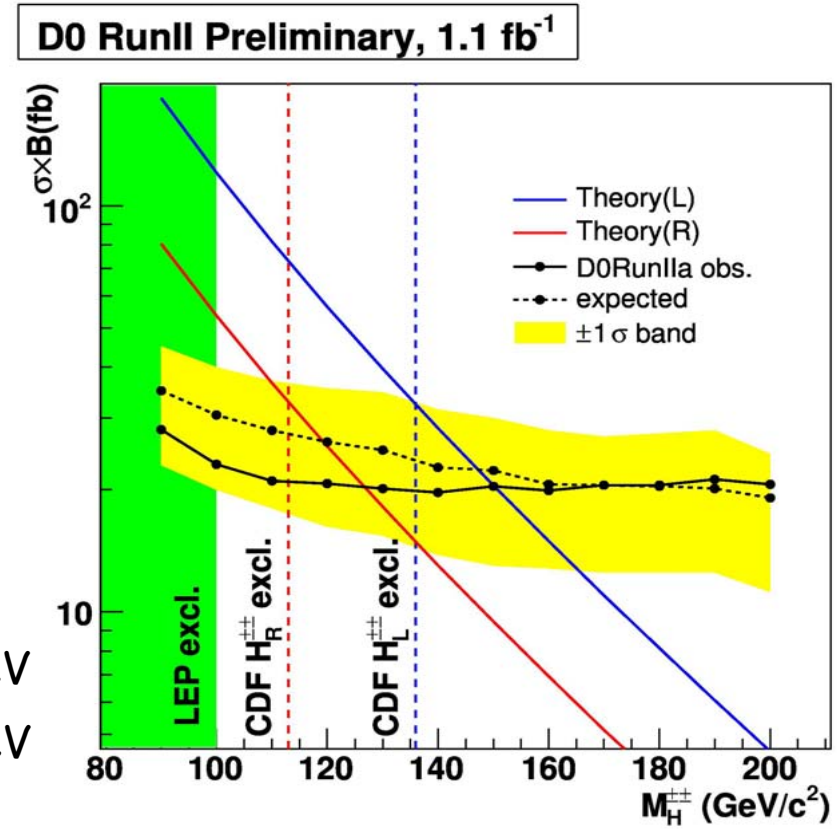
3 events

(SM : 3.1 ± 0.5)

$M(H_L^{\pm\pm}) > 150$ GeV

$M(H_R^{\pm\pm}) > 126$ GeV





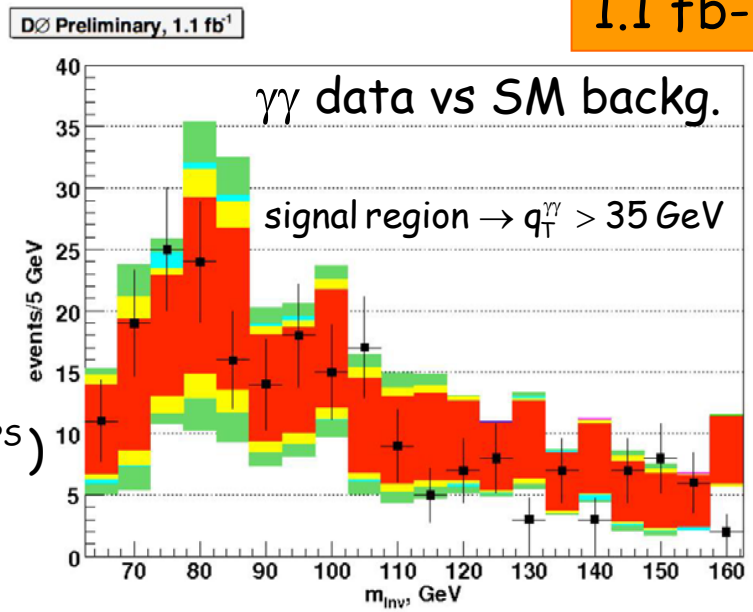
NEW Fermiophobic Higgs in 2γ+X

1.1 fb-1

$$p\bar{p} \to VV \to h_f \to \gamma\gamma + X$$
$$p\bar{p} \to h_f W^{\pm}(Z) \to \gamma\gamma + X$$

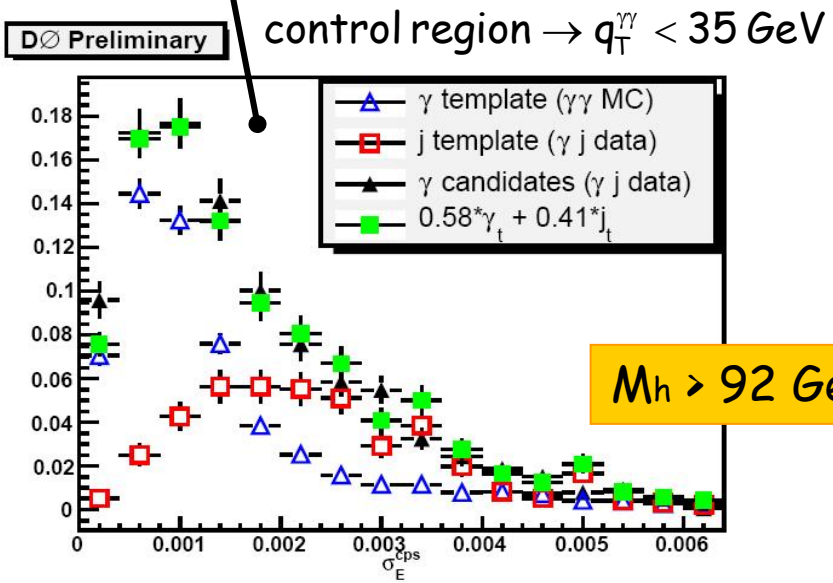
2 photons ($p_T^{\gamma} > 25$ GeV, $|\eta^{\gamma}| < 1.1$)

background from $\gamma\gamma$, γ + jet and jet + jet

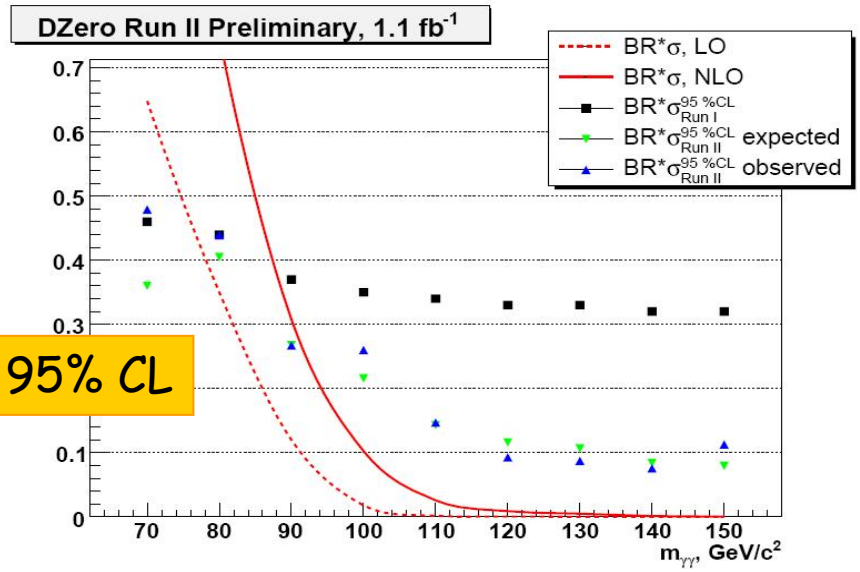


2D fits to templates of EM shower profiles (σ_E^{CPS})

(separation between photons and jets)



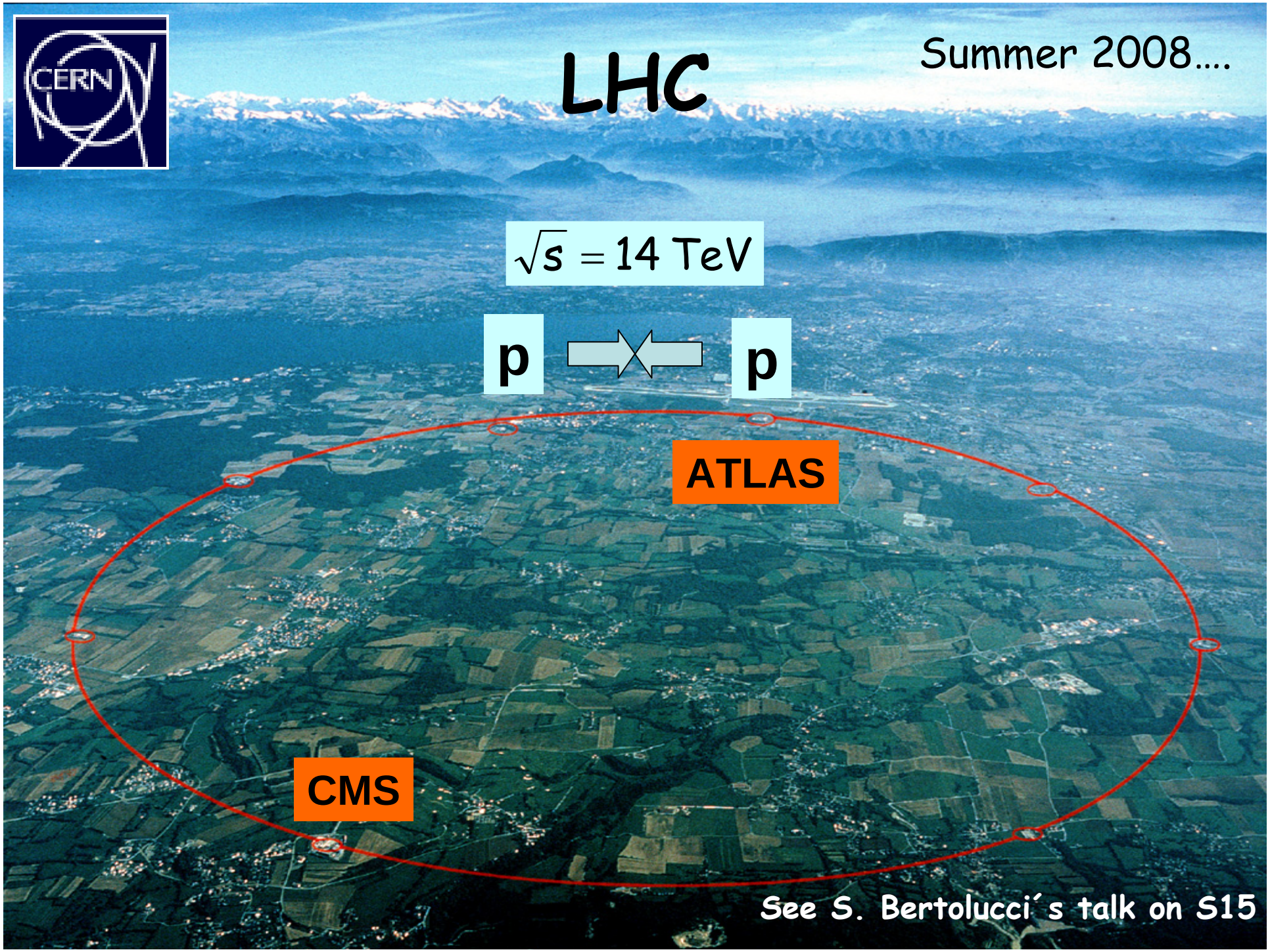
$M_h > 92$ GeV @ 95% CL



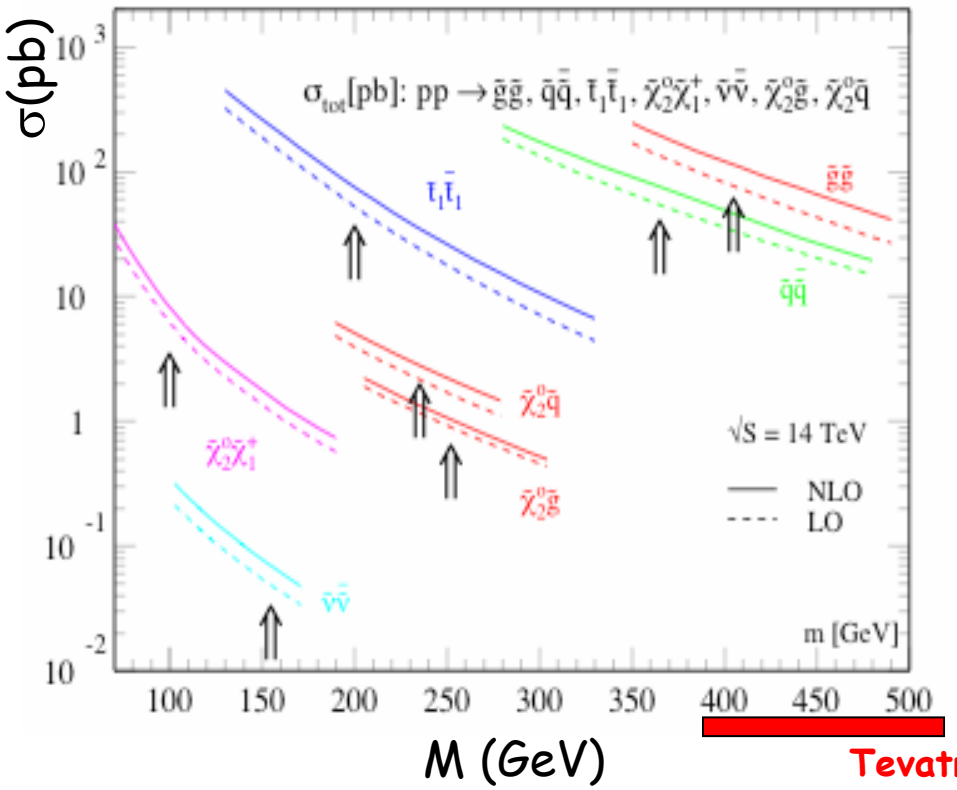
Well....

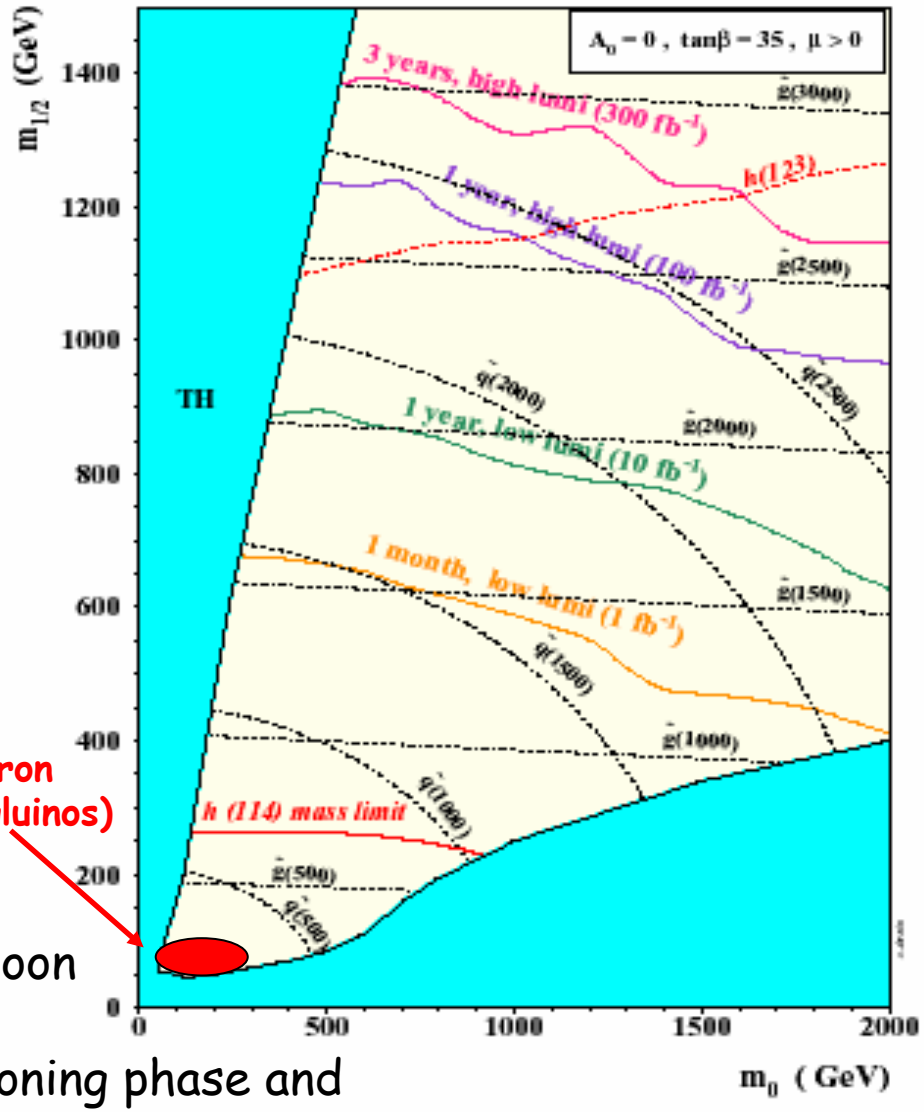
No significant excess compared to SM ...yet

Tevatron will deliver a total of 6-7 fb-1 by the end of FY2009


LHC
Summer 2008....
$\sqrt{s} = 14$ TeV
p
p
ATLAS
CMS
See S. Bertolucci´s talk on S15

SUSY Searches at the LHC





Tevatron (squark/gluinos)

The LHC is built to discover SUSY
If it is there, we will find it relatively soon

But…do not underestimate the commissioning phase and the work needed to understand the SM backgrounds….

Final Notes

Very broad and strong program for SUSY searches at the Tevatron.

No significant excess w.r.t SM yet..

Experiments have presented results with up to 2 fb-1 of data analyzed.

Tevatron will deliver up to 6-7 fb-1 of data by the end of FY2009.

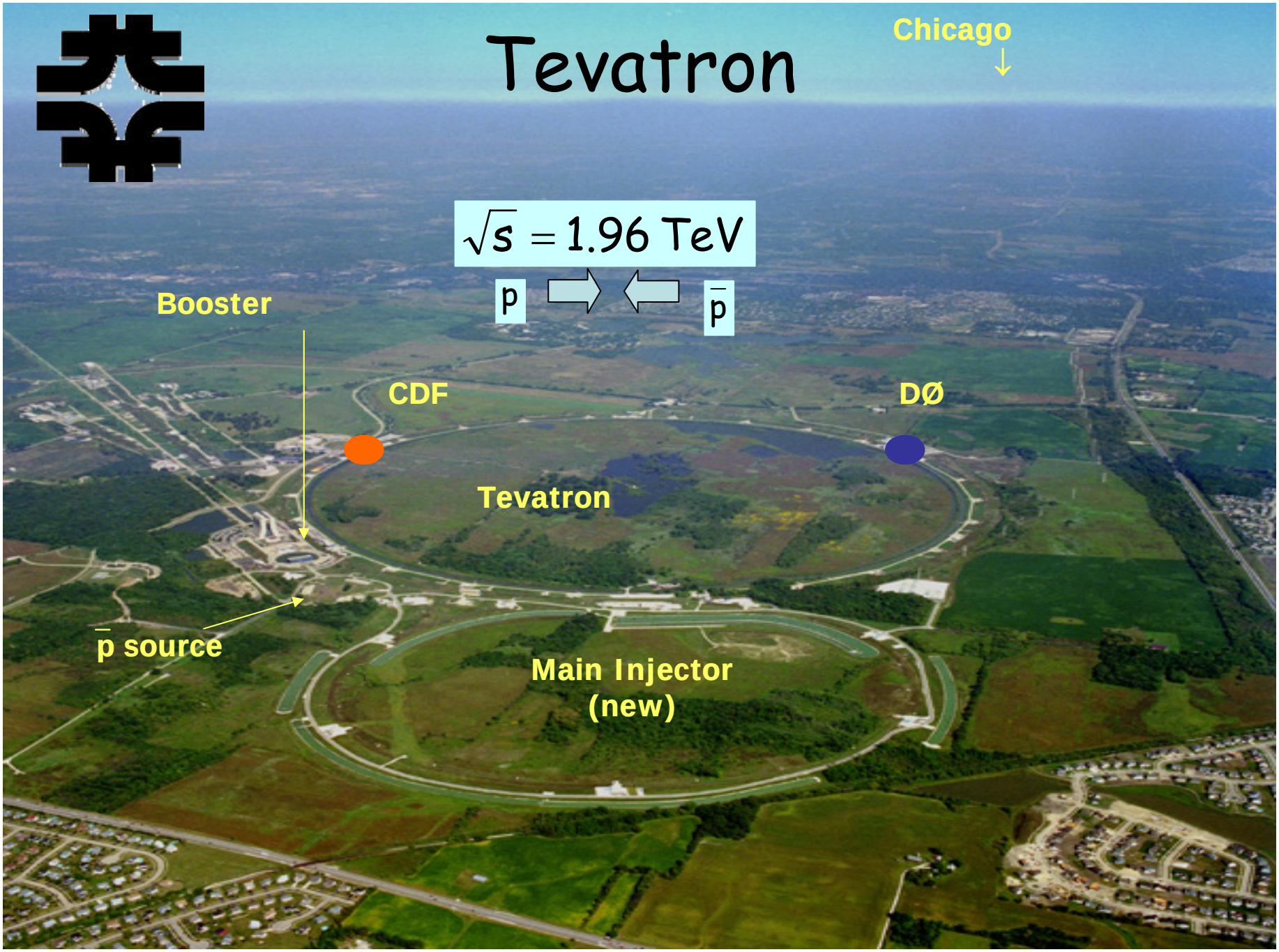
LHC starts operations on summer 2008 with great potential for an "early" discovery.

The next two years will be very exciting…

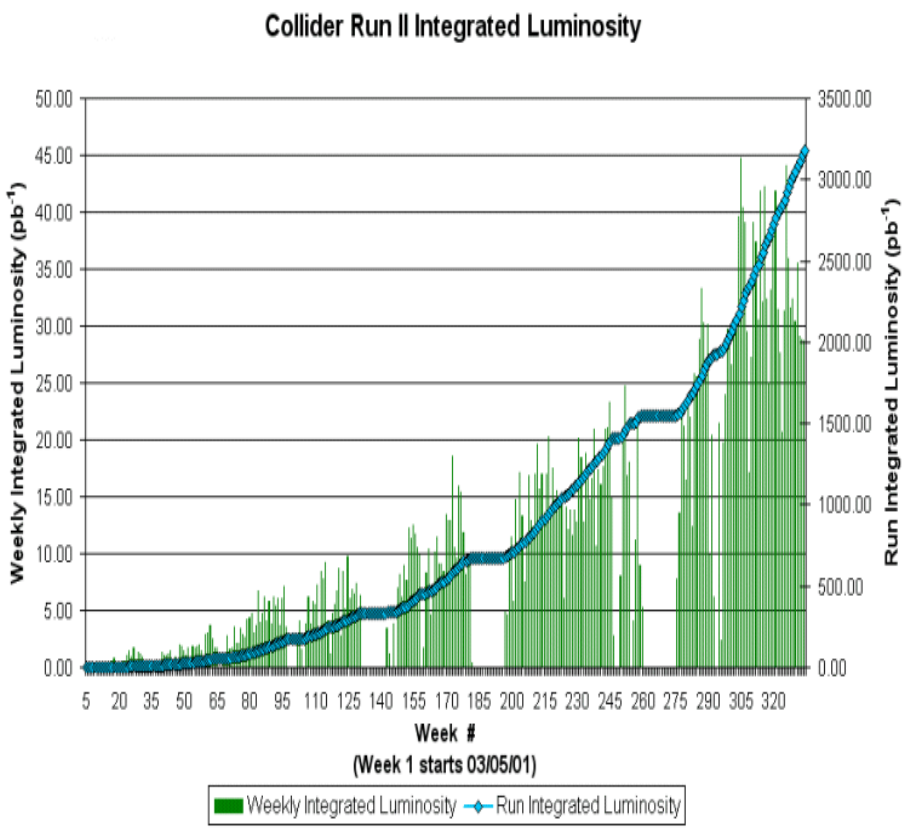
(First SUSY discovery by LP'09 ?!)

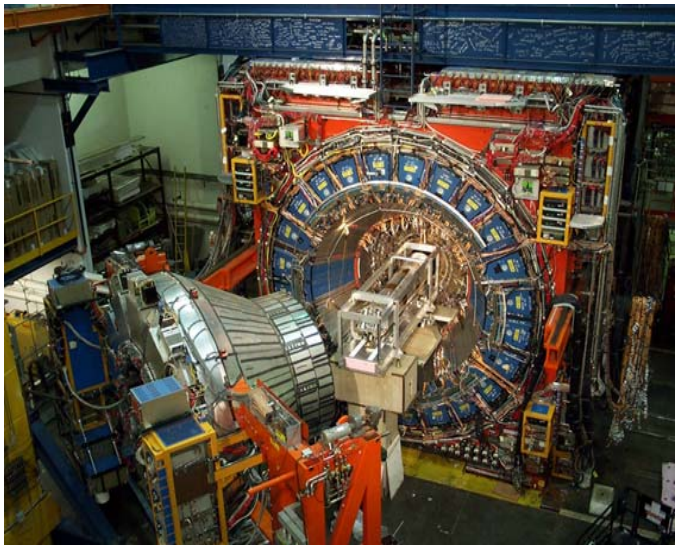
Backup Slides

Tevatron


Chicago
$\sqrt{s} = 1.96$ TeV
p
$\bar{p}$
Booster
CDF
DØ
Tevatron
$\bar{p}$ source
Main Injector
(new)

Tevatron/CDF&DØ



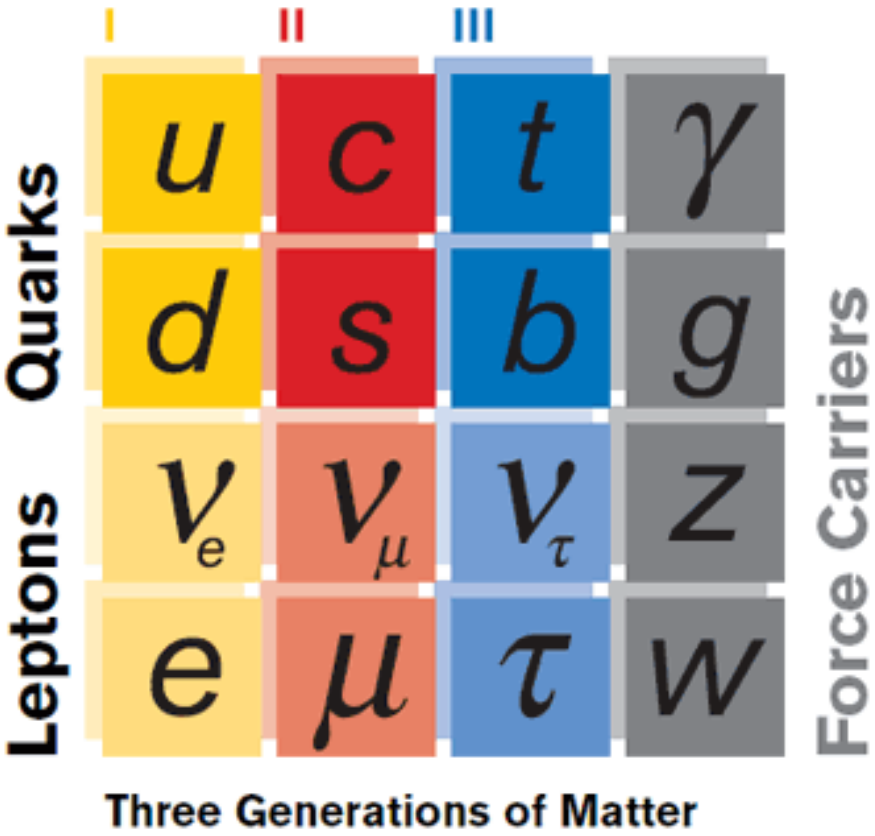


Tevatron: 3.2 fb-1 delivered

CDF & DØ recording physics quality data with very high efficiency (~85%)

The Standard Model

(i.e., the need for new physics)

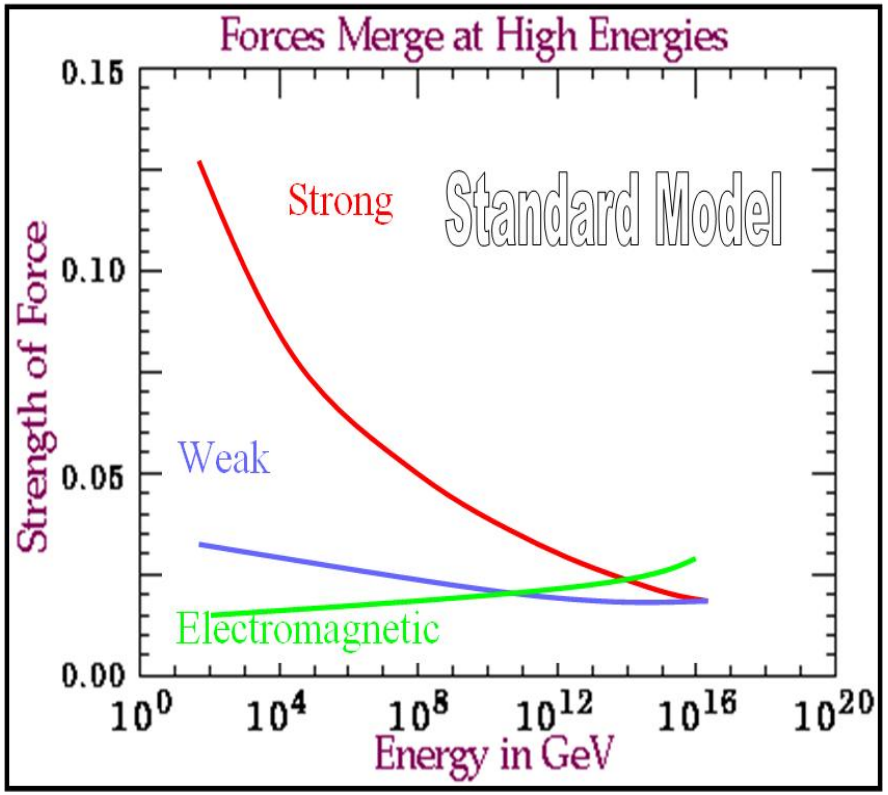


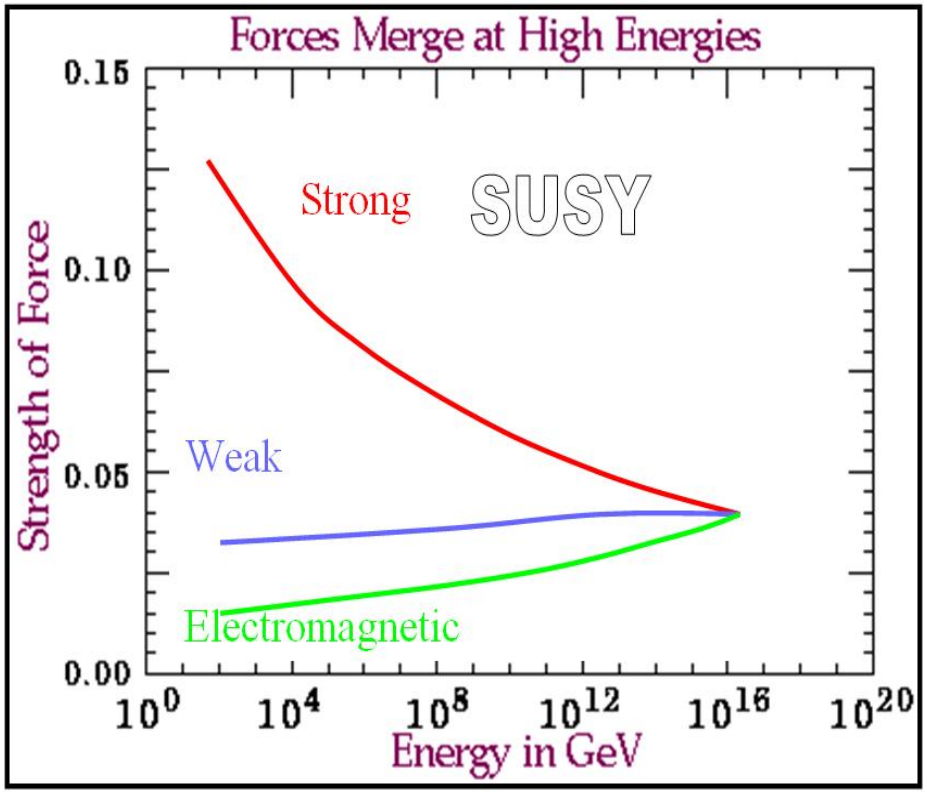
- Who ordered 3 generations?
- Origin of Masses?
- What about Gravity?
- Unification at Large Scale?
- Hierarchy Problem !
- Dark Matter in the Cosmos?
- Matter/Anti-Matter
- .....

New Physics (!)

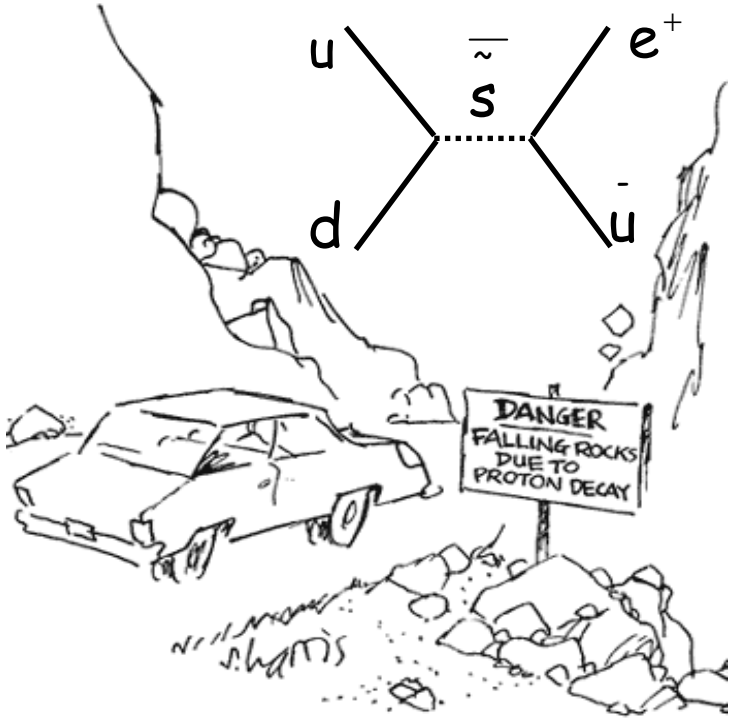
O(TeV) scale phenomenology

Unification of Forces…





R-Parity



Most general superpotential includes terms
Violating Baryon number and Lepton number

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

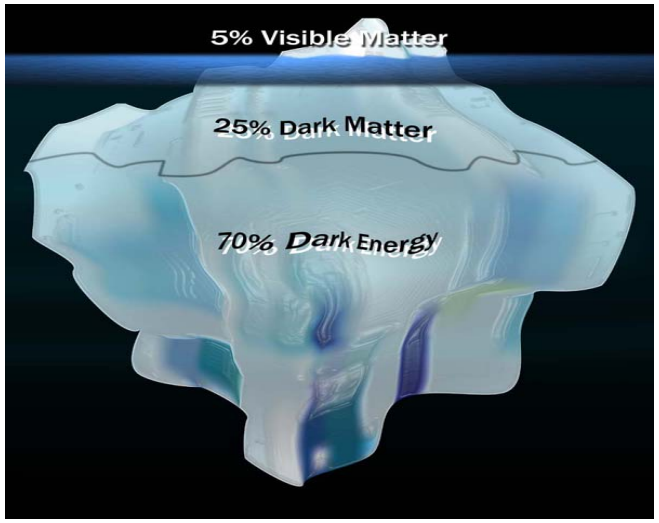
$$W_{\Delta B=1} = \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

New symmetry is postulated…

$$R_p = (-1)^{3(B-L)+2s}$$

$R_p = +1$ (particles)

$R_p = -1$ (sparticles)

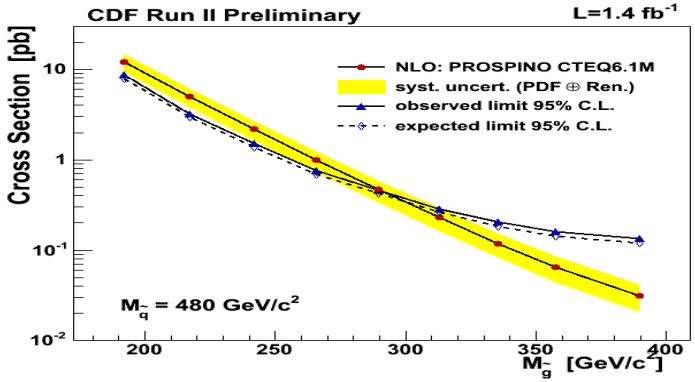


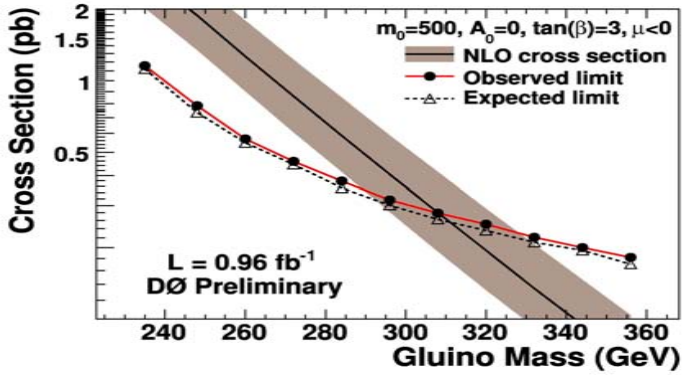
- SUSY particles produced in pairs
- The lightest SUSY particle stable (χ_1^0)
- Valid candidate for Dark Matter

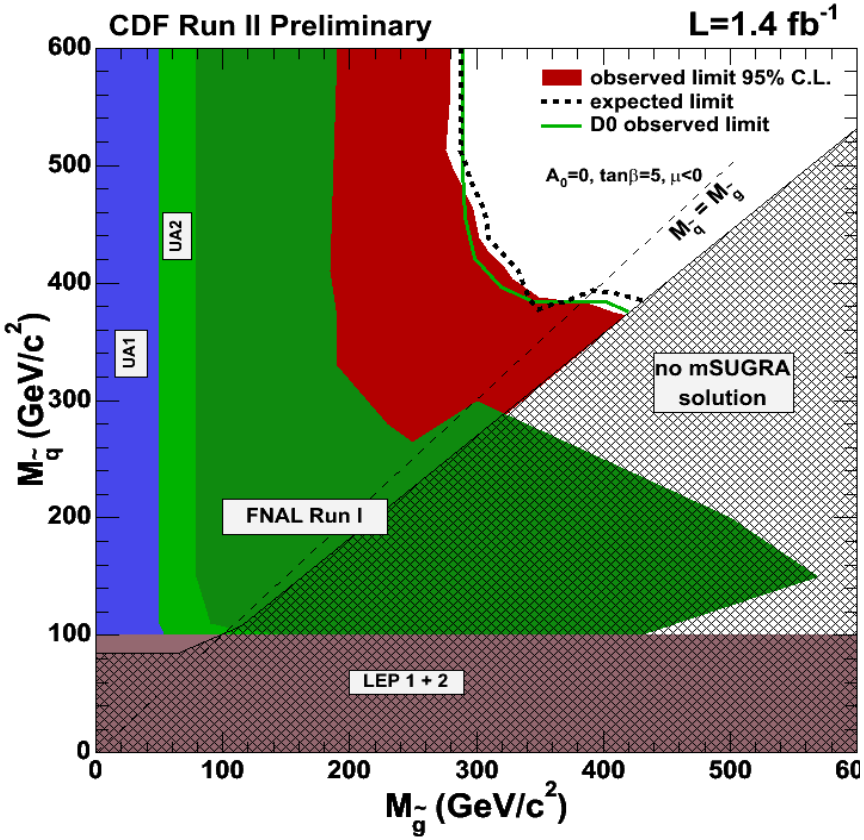
- Distinctive Signature at Colliders

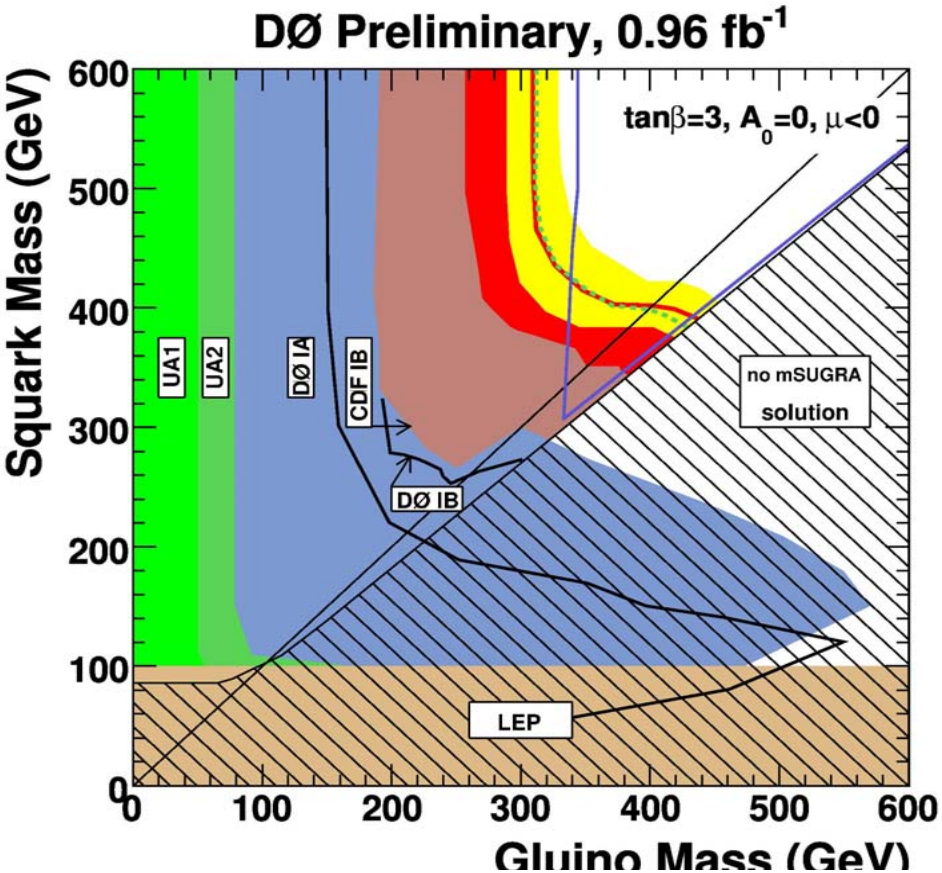
Large Missing E_T

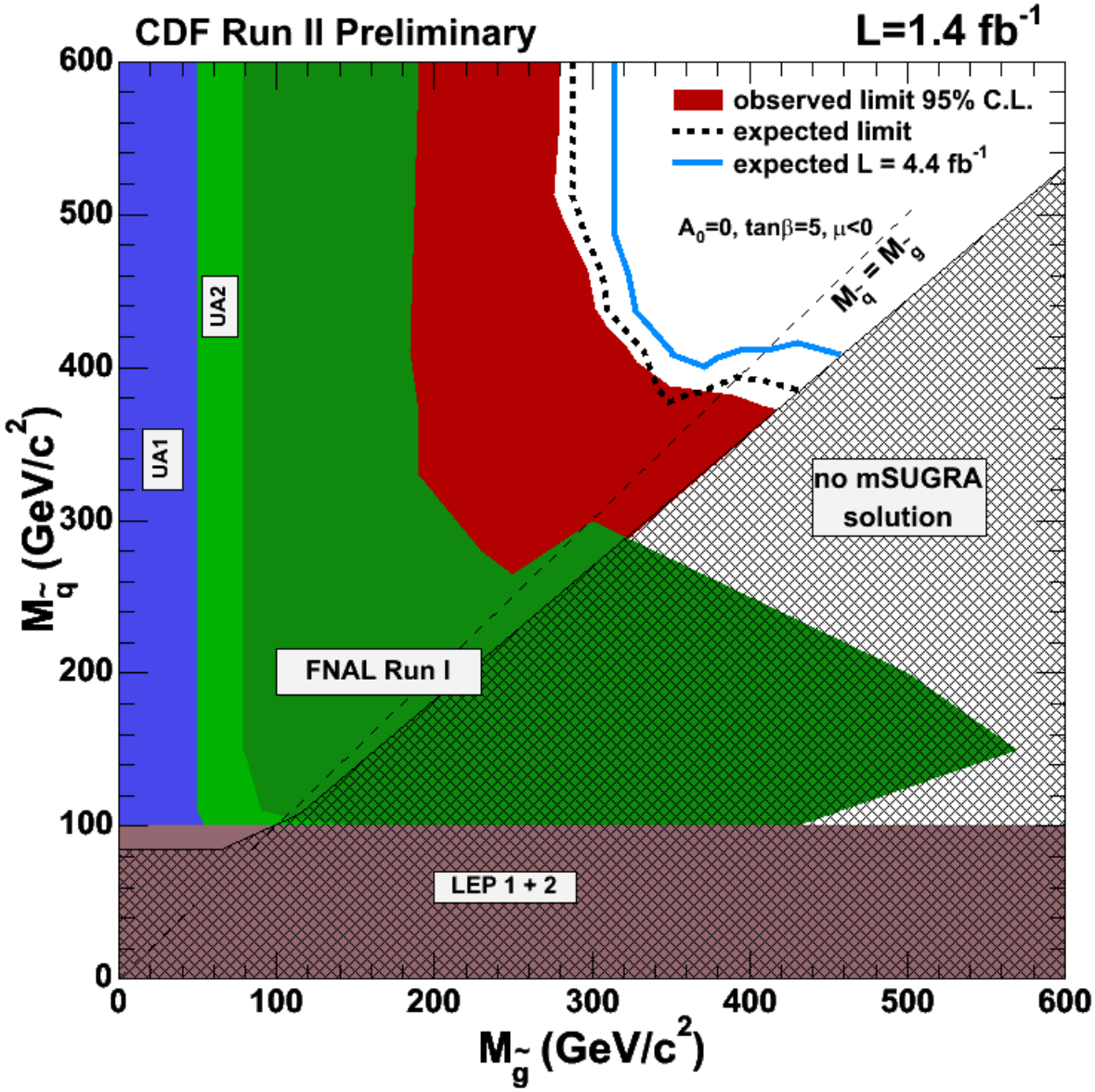
NEW Limits on squark/gluino masses





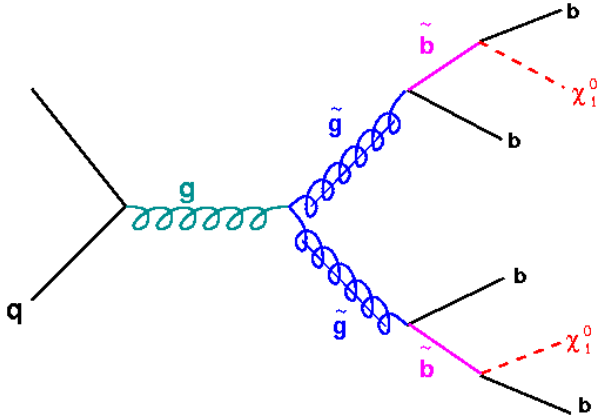





CDF Run II Preliminary
L=1.4 fb^{-1}
observed limit 95% C.L.
expected limit
expected L = 4.4 fb^{-1}
A_0=0, tanβ=5, μ<0
$M_{\tilde{q}} = M_{\tilde{g}}$
UA1
UA2
FNAL Run I
LEP 1 + 2
no mSUGRA solution
$M_{\tilde{q}}$ (GeV/c^2)
$M_{\tilde{g}}$ (GeV/c^2)
0
100
200
300
400
500
600

PRL 96 171802 (2006)

Sbottom from Gluino Decays



$$\tilde{q}_L\,\tilde{q}_R \xrightarrow{\text{mixing}} \tilde{q}_1\,\tilde{q}_2$$

scenario where substantial mixing leads to a sbottom mass eigenstate lighter than gluino

$\tilde{g} \to \tilde{b}_1 b$ (100%)

$\tilde{b}_1 \to b\chi_1^0$ (100%)

$M(\chi_1^0) > 60$ GeV

$\not{E}_T > 35$ GeV

At least three jets

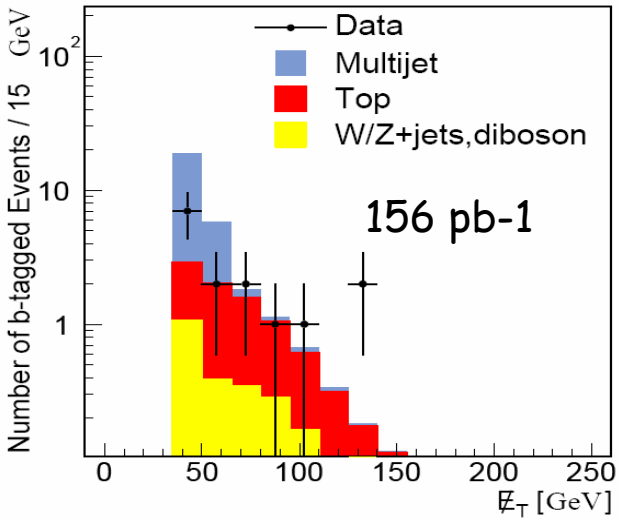
$E_T^{jet} > 15$ GeV

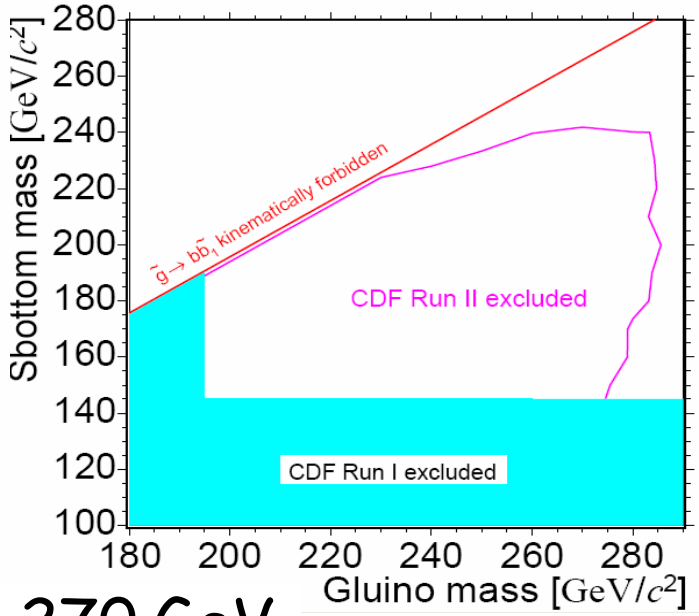
$|\eta^{jet}| < 2$

At least two b-tags

No isolated leptons

Cuts on $\Delta\phi(\not{E}_T, \text{jet})$





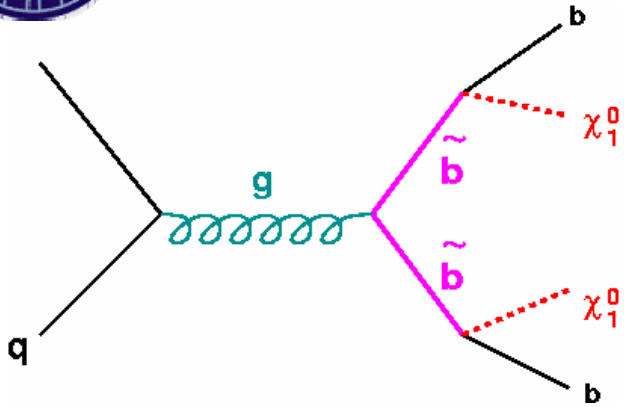
$\not{E}_T > 80$ GeV $\begin{cases} \text{4 events} \\ (\text{SM}: 2.6 \pm 0.7) \end{cases}$

$M_{\tilde{g}} > 270$ GeV

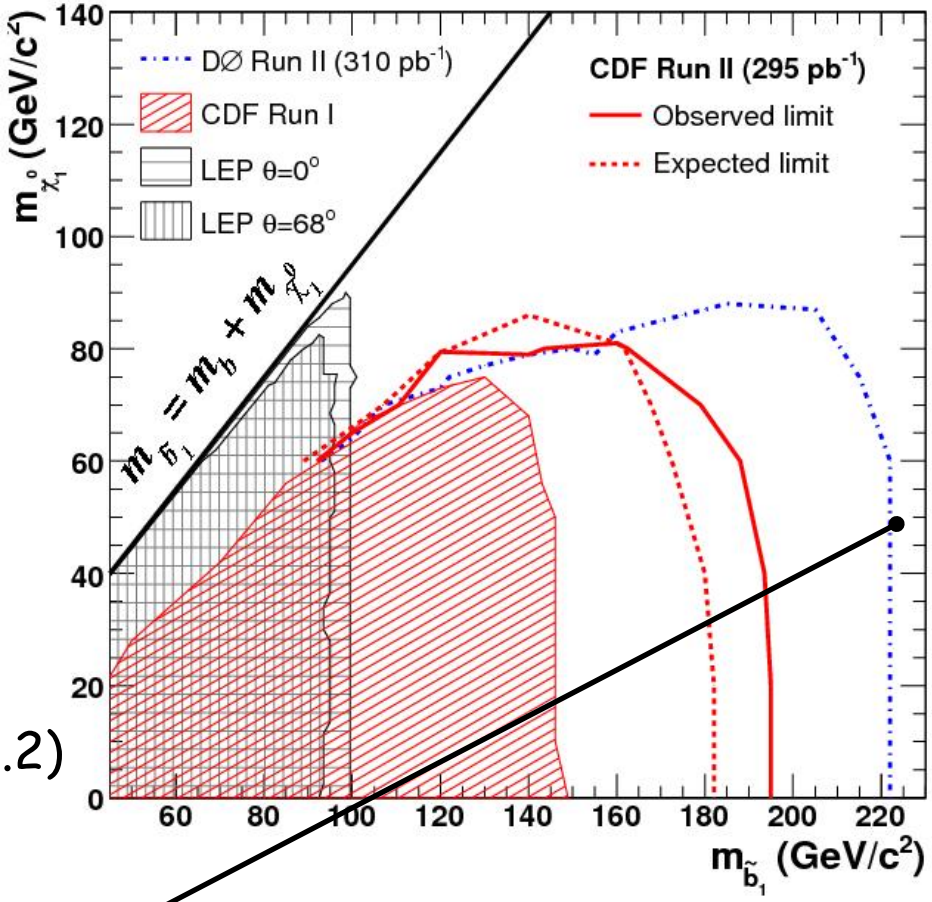
$M_{\tilde{b}_1} > 220$ GeV

@95%CL

Sbottom Pair Production



$\tilde{b} \rightarrow b\chi_1^0$ (100%)



$\not{E}_T > 80$ GeV

At least two jets

$P_T^{jet} > 100\ (50)$ GeV/c

$|\eta^{jet}| < 1.1\ (< 2)$

At least one b-tag

No isolated leptons

Cuts on $\Delta\phi(\not{E}_T, \text{jet})$

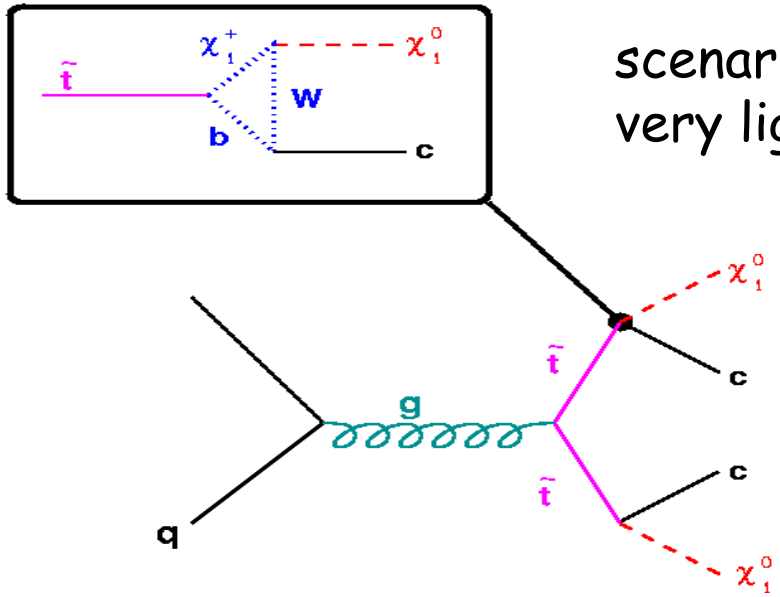
0 events

(SM : 3.2 ± 0.2)

$M_{\tilde{b}} > 222$ GeV/c^2 @ 95% CL

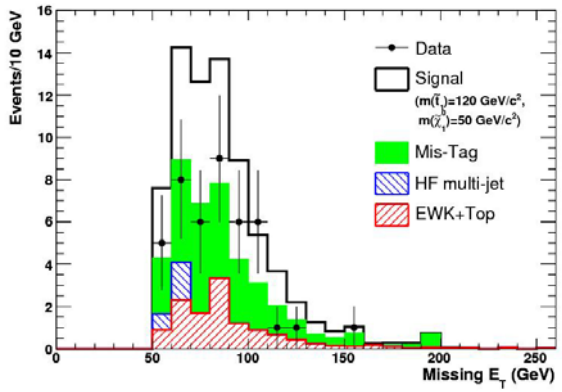
CDF Collab., Submitted to PRD

Stop Pair Production



scenario with a very light stop $\longrightarrow$ $\tilde{t}_1 \to c\chi_1^0$ (100%)

$M(\chi_1^0) > 40$ GeV

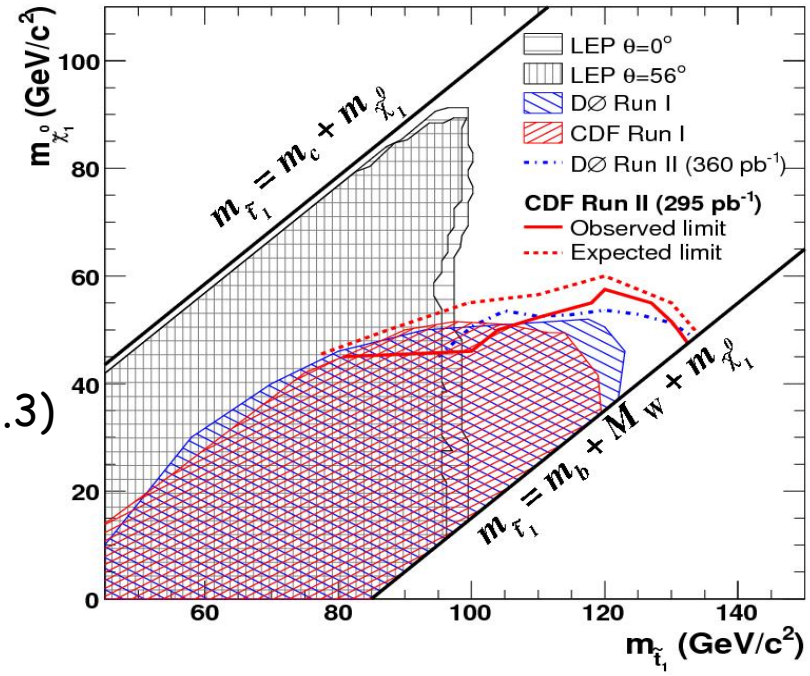


Cuts optimized for different stop masses

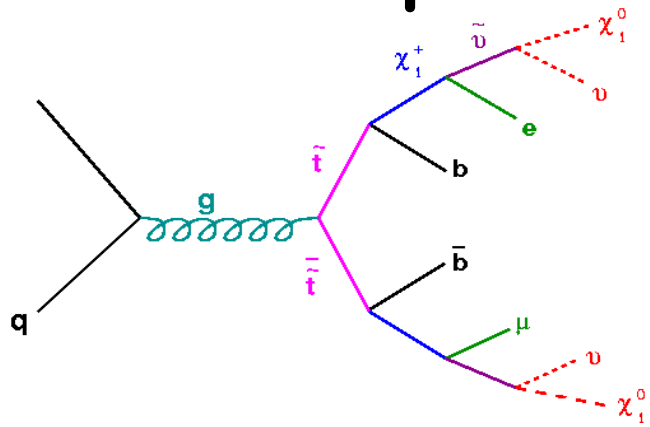
$\not{E}_T > 50$ GeV

2 or 3 jets
At least one c-tag
No isolated leptons
Cuts on $\Delta\phi(\not{E}_T, \text{jet})$ & $\Delta\phi(\text{jet}, \text{jet})$
……

43 events
(SM : 42.7 ± 5.3)



Stop Pair Production (II)



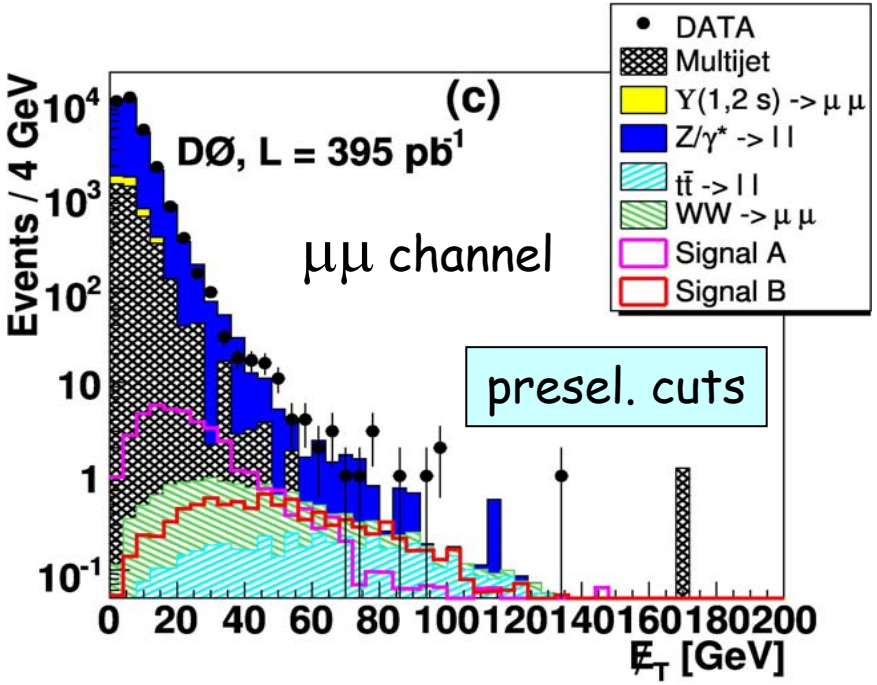
$\tilde{t}_1 \rightarrow b\, l\, \tilde{\nu}$

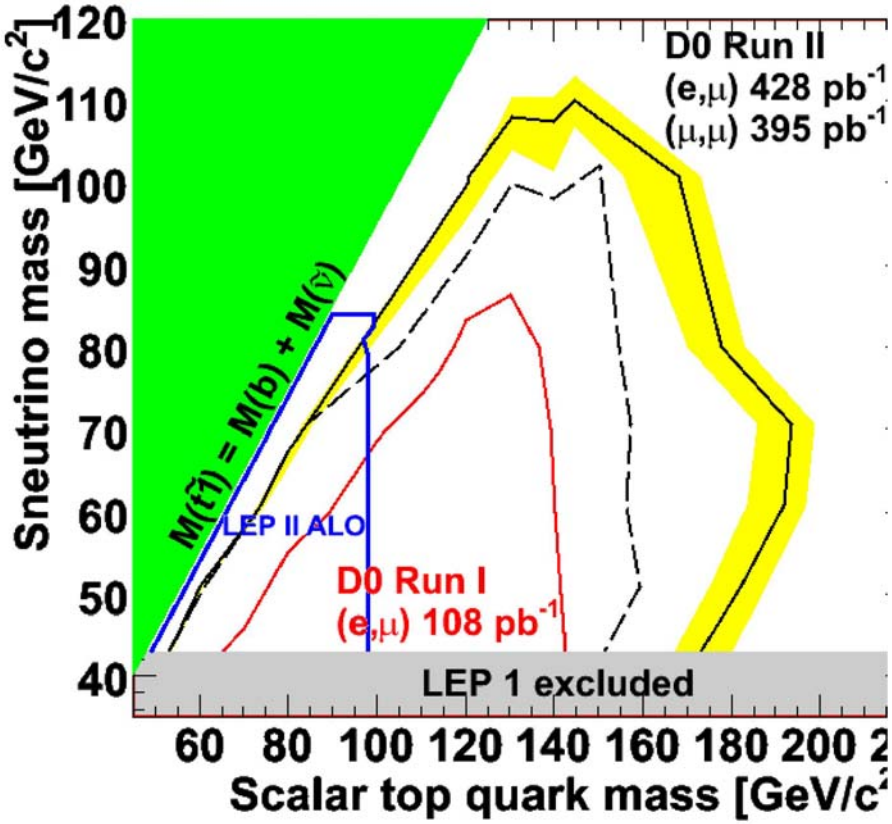
$Br(\chi_1^+ \rightarrow l\tilde{\nu}) = 1$

$e\mu$ and $\mu\mu$ channels

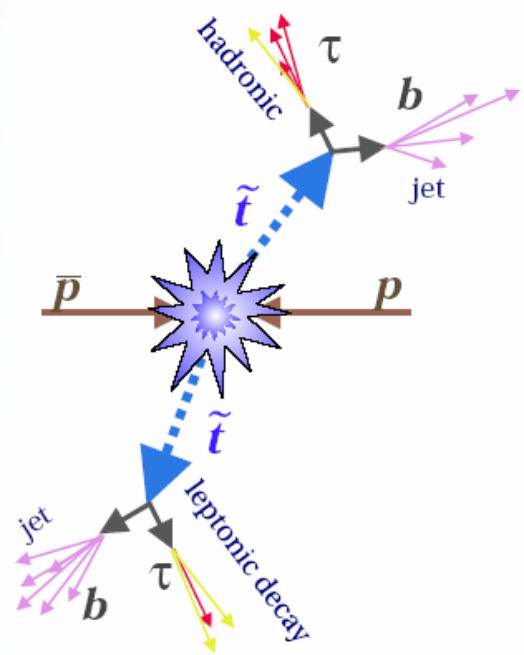
$e\mu \rightarrow 34$ events $(SM: 37.1 \pm 2.7 \pm 0.9)$

$\mu\mu \rightarrow 1$ event $(SM: 2.9 \pm 0.4 \pm 0.1)$





Stop Production (RPV in decay)



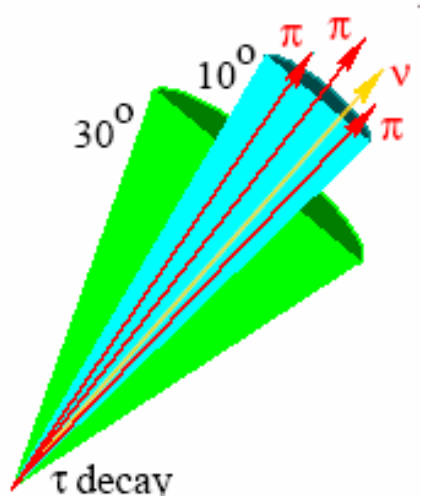
$Br(\tilde{t}_1 \rightarrow b\tau) = 100\%$

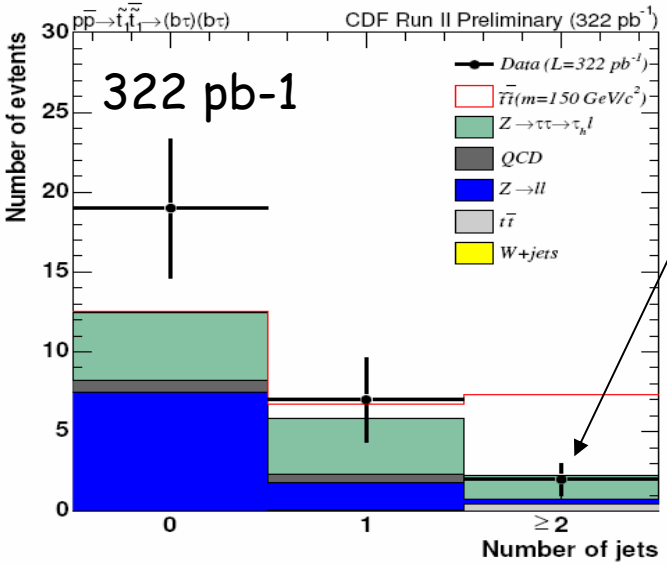
- One high-pt lepton (e or μ)
- One hadronic τ decay
- At least two jets

$E_T^{jet} > 20\ GeV$

$|\eta^{jet}| < 2.4$

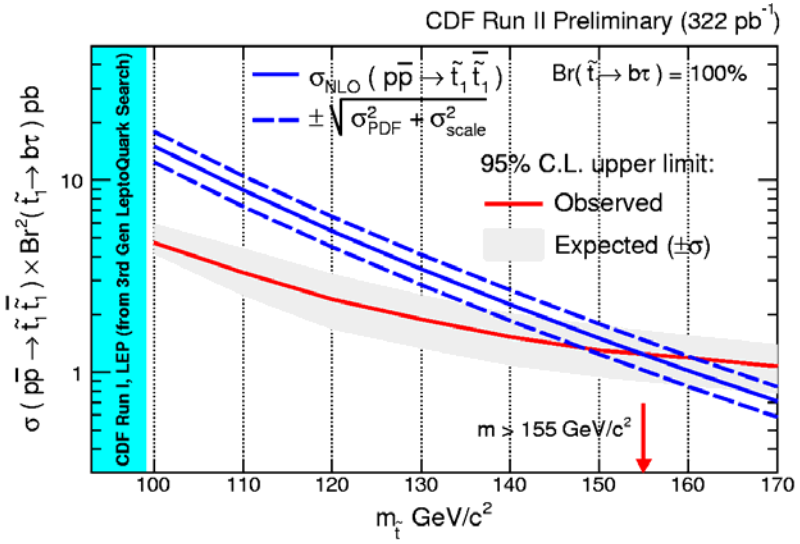
- $M_T(l, \not{E}_T) < 35\ GeV$
- $P_T^{lep} + P_T^{\tau_h} + \not{E}_T > 110\ GeV$



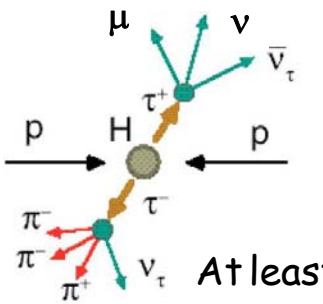


2 events

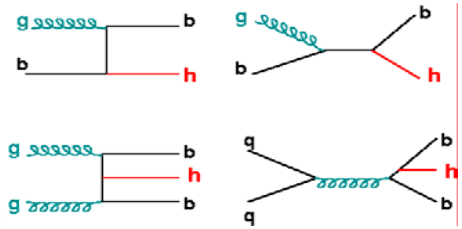
$(SM: 2.3^{+0.5}_{-0.2})$



$M_{\tilde{t}_1} > 155\ GeV$ (@ 95% CL)



$\phi \to \tau\tau$ b(b)



At least one jet ($E_T^{jet} > 15\,GeV, |\eta^{jet}| < 2.5$)

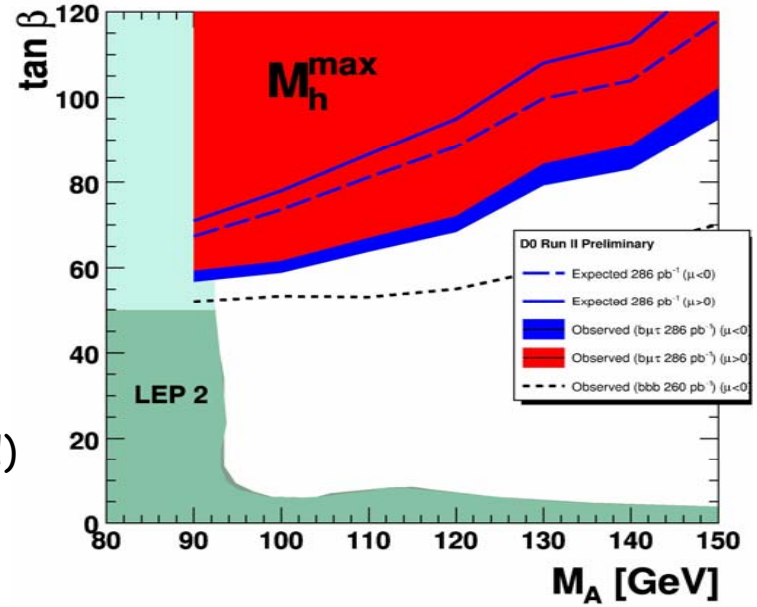
central isolated muon : $p_T^{\mu} > 12\,GeV/c$

one hadronic tau candidate

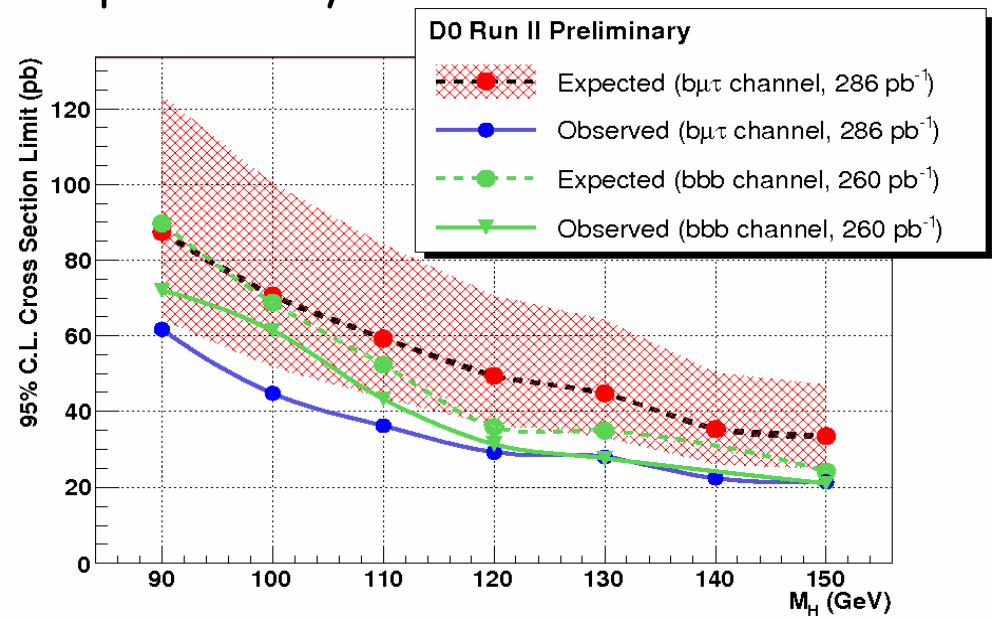
$\tau^{\pm} \to \pi^{\pm}\upsilon_\tau \Rightarrow$ 0 events (1.2 ± 0.2 expected)

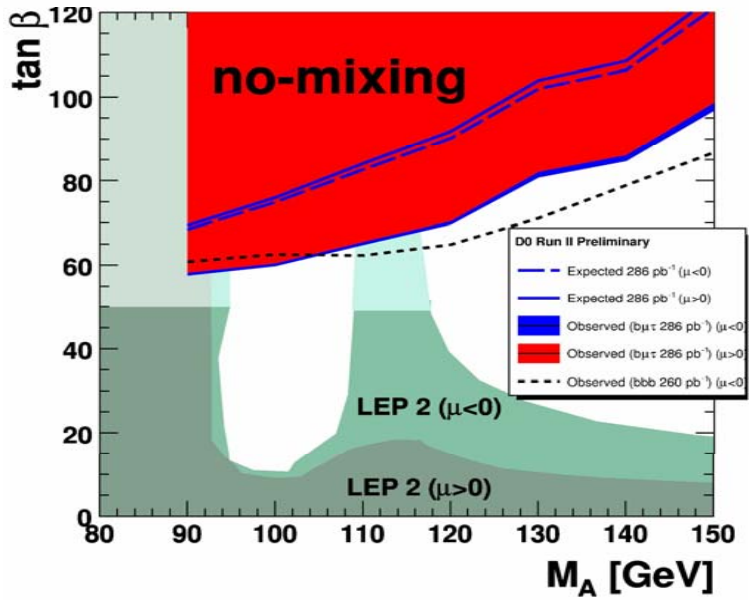
$\tau^{\pm} \to \pi^{\pm}\upsilon_\tau\pi^0 \Rightarrow$ 1 event (2.6 ± 0.3 expected)

$\tau^{\pm} \to h^{\pm}h^{+}h^{-}\upsilon_\tau(\pi^0) \Rightarrow$ 2 events (2.5 ± 0.2 expected)

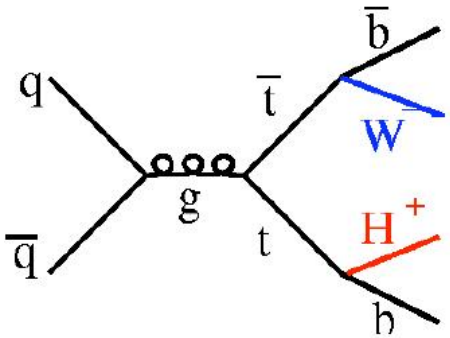


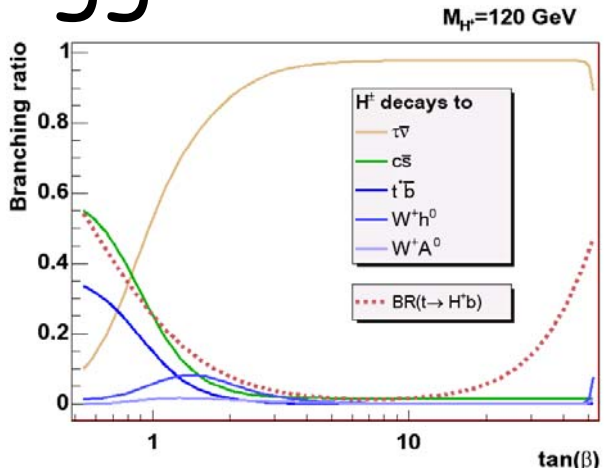
Complementary to other channels

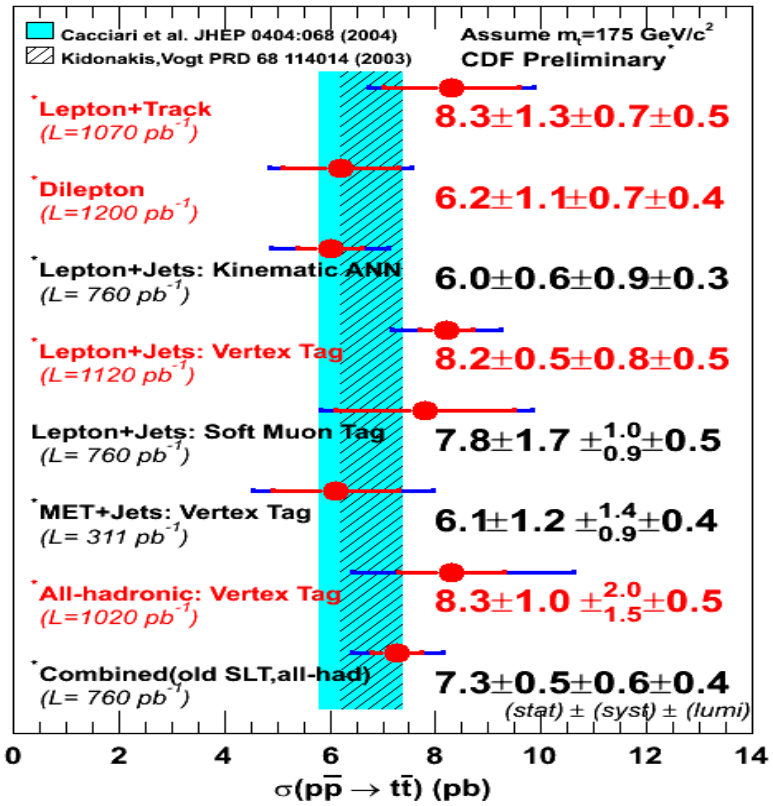


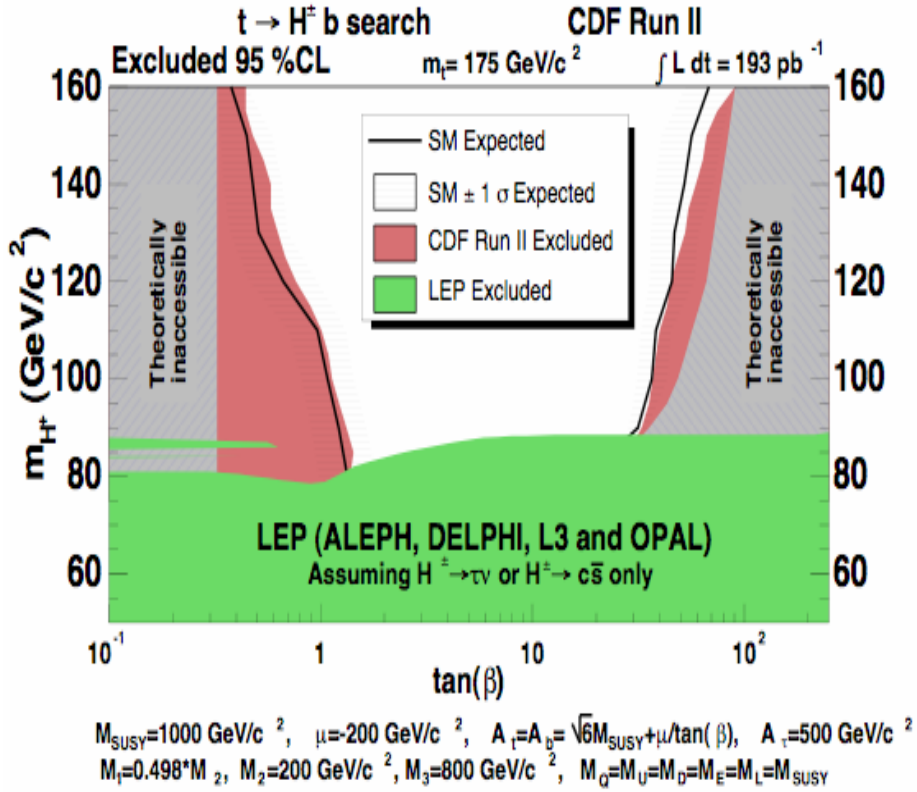


Charged Higgs







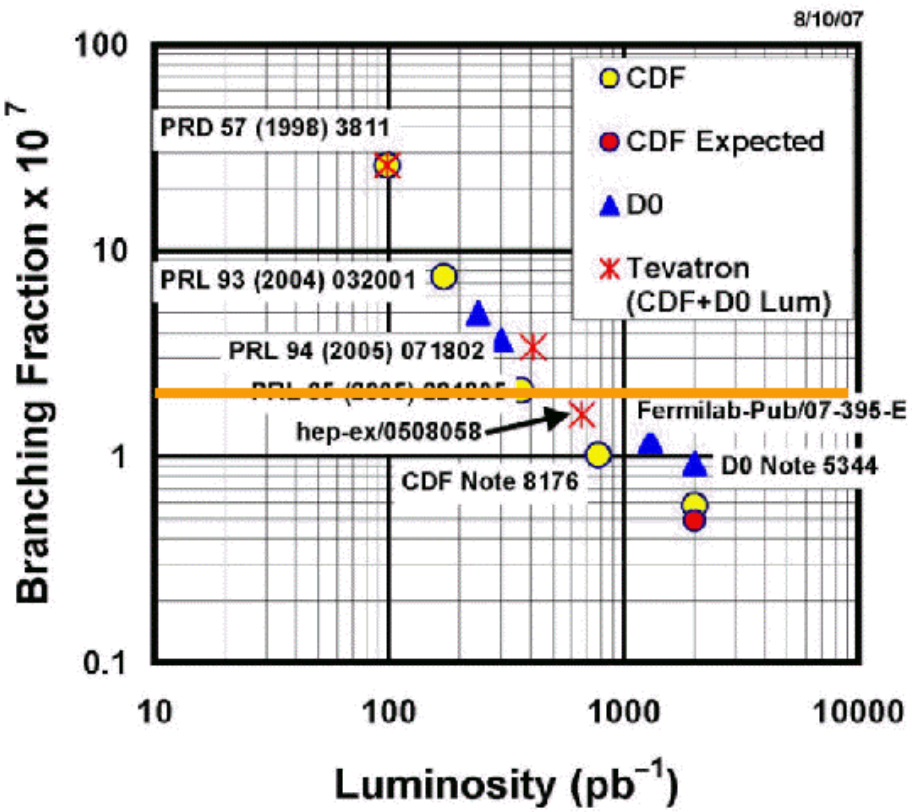


Higgs would modify the observed relative population of different channels

$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection

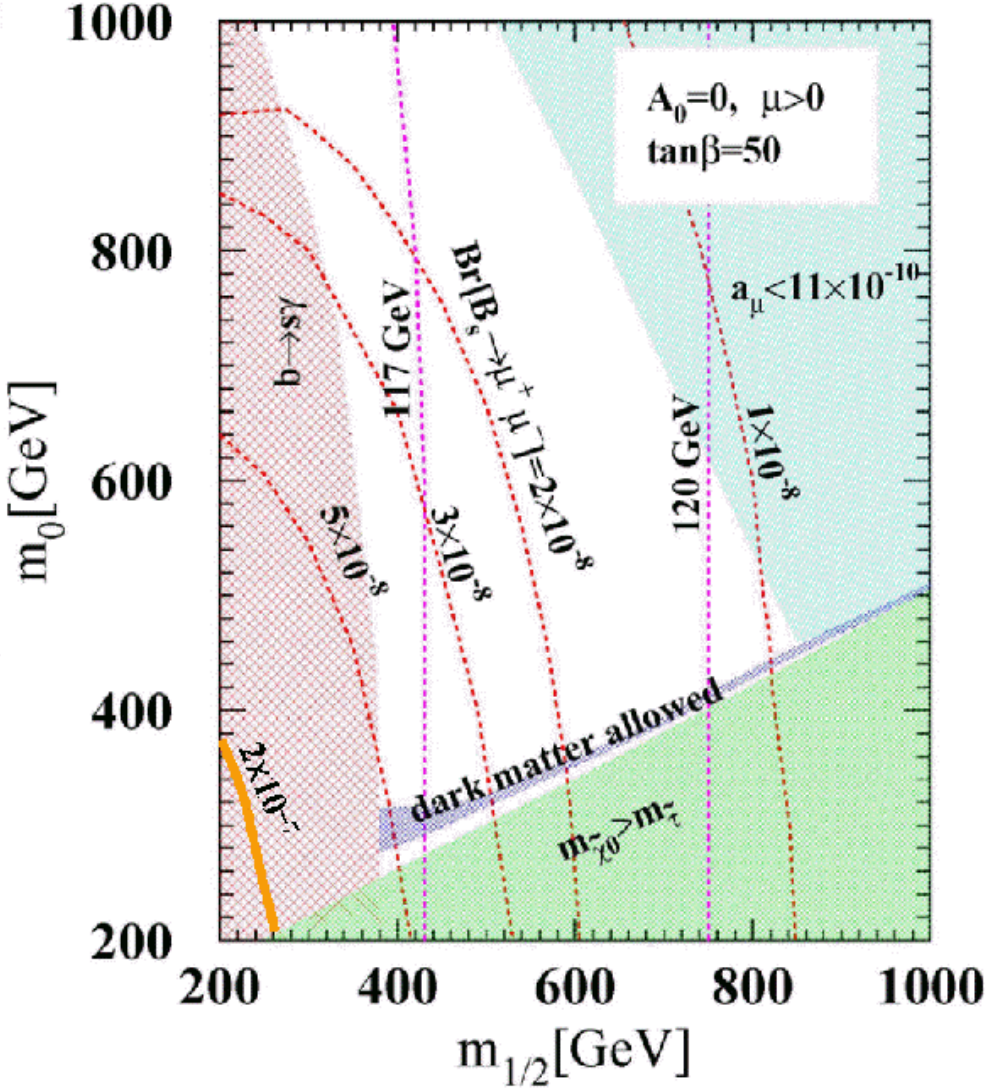
$\mathcal{B}_{SM} = 3.4 \times 10^{-9}$ $\mathcal{B}_{SUSY} \propto (\tan\beta)^6$

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



mSUGRA at $\tan\beta = 50$

Arnowitt, Dutta, et al., PLB 538 (2002) 121



Fermiophobic Higgs in 3γ+X

$$p\bar{p} \to h_F H^{\pm} \to h_F h_F W^{\pm} \to \gamma\gamma\gamma(\gamma) + X$$

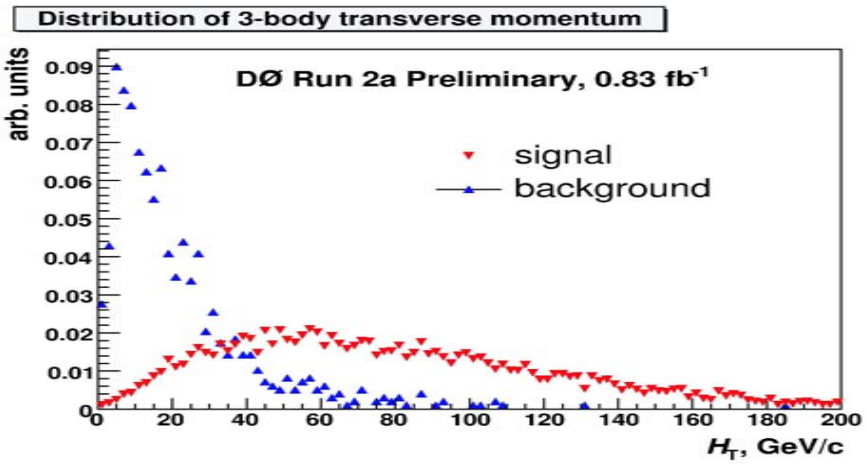
3 photons ($p_T^{\gamma} > 30, 25, 15$ GeV, $|\eta^{\gamma}| < 1.1$)

Backgrounds :

$\gamma\gamma\gamma$, $Z\gamma$, $W\gamma\gamma$, 3jets, 2jets + γ and jet + 2γ

$\gamma\gamma\gamma$ backg. estrapolated from $\gamma\gamma$ data

rest estimated using measured fake rates

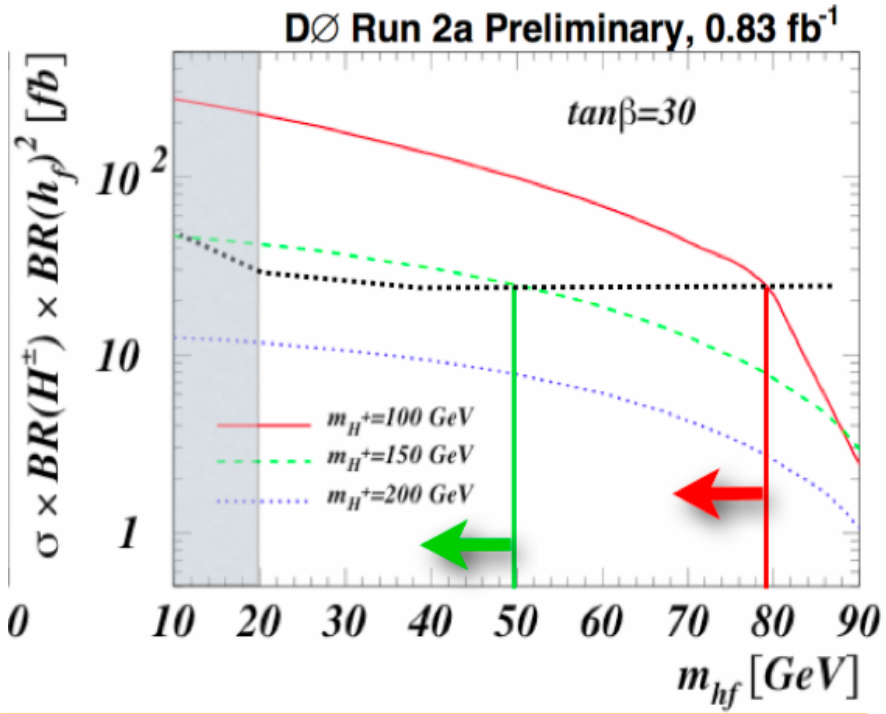


After $H_T > 25$ GeV/c :
0 events (SM backg: 1.1)

In scenario :

$M_{h_f} < 90$ GeV, $M_{H^{\pm}} < 200$ GeV, $\tan\beta > 1$

$Br(h_f \to \gamma\gamma) \approx 1$, $Br(H^{\pm} \to h_f W^{\pm}) \approx 1$



$M_{h_f} > 50$ GeV @ 95% CL ($M_{H^{\pm}} < 150$ GeV and $\tan\beta = 30$)

$M_{h_f} > 80$ GeV @ 95% CL ($M_{H^{\pm}} < 100$ GeV and $\tan\beta = 30$)

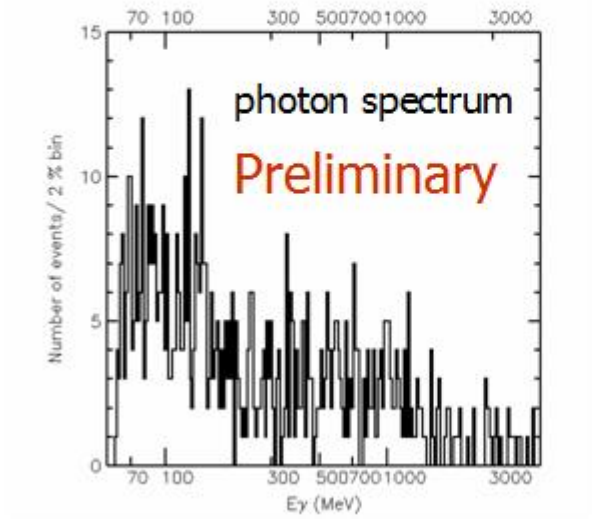
Radiative Decays to Higgs?

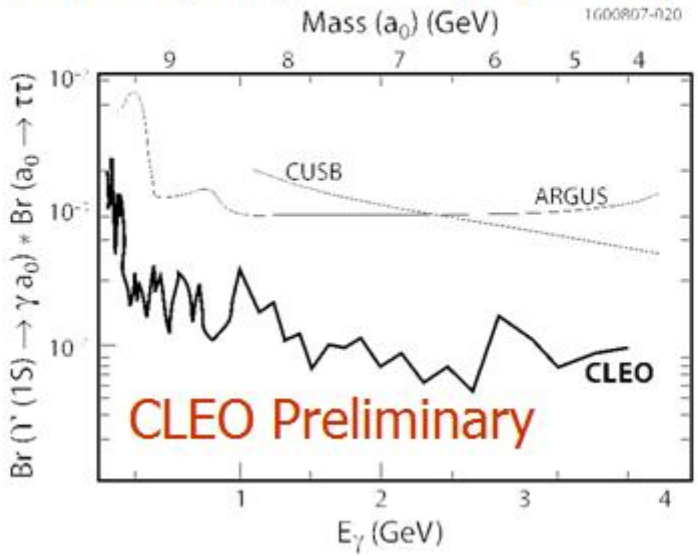
Dermisek, Gunion, McElrath propose adding to the MSSM a non-SM-like pseudoscalar higgs a_0 with $m_{a0} < 2m_b$ [hep-ph/0612031] "NMSSM"

- "natural," avoids fine tuning
- evades the LEP limit M_h>100 GeV since $h \rightarrow a_0 a_0$, but $a_0 \not\rightarrow bb$ and LEP sought b jets
- $a_0 \rightarrow \tau^+\tau^-$ should predominate if $m_{a0} > 2m_\tau$
- Should be visible in $\Upsilon \rightarrow \gamma\, a_0$

Experimentally, CLEO seeks monochromatic γ

- Use $\Upsilon(2S) \rightarrow \pi\pi\Upsilon(1S)$ tag to eliminate $e^+e^- \rightarrow \tau\tau\gamma$ background
- Flag presence of τ pair with two 1-prong τ decays (one lepton), missing energy





ULs improved an order of magnitude or more

Rules out many, but not all NMSSM models