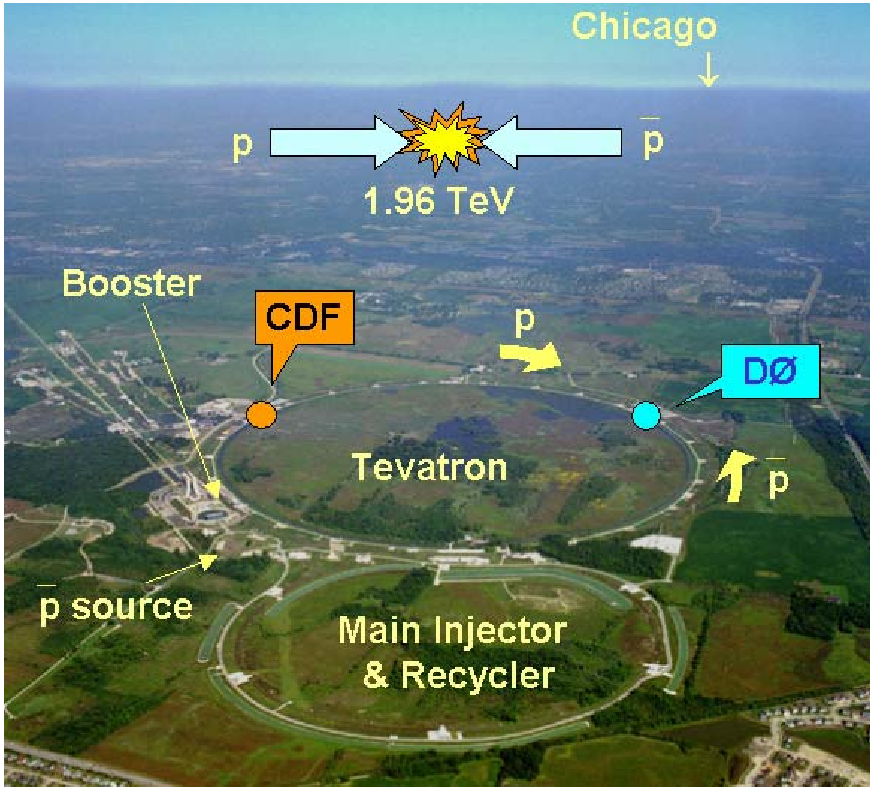
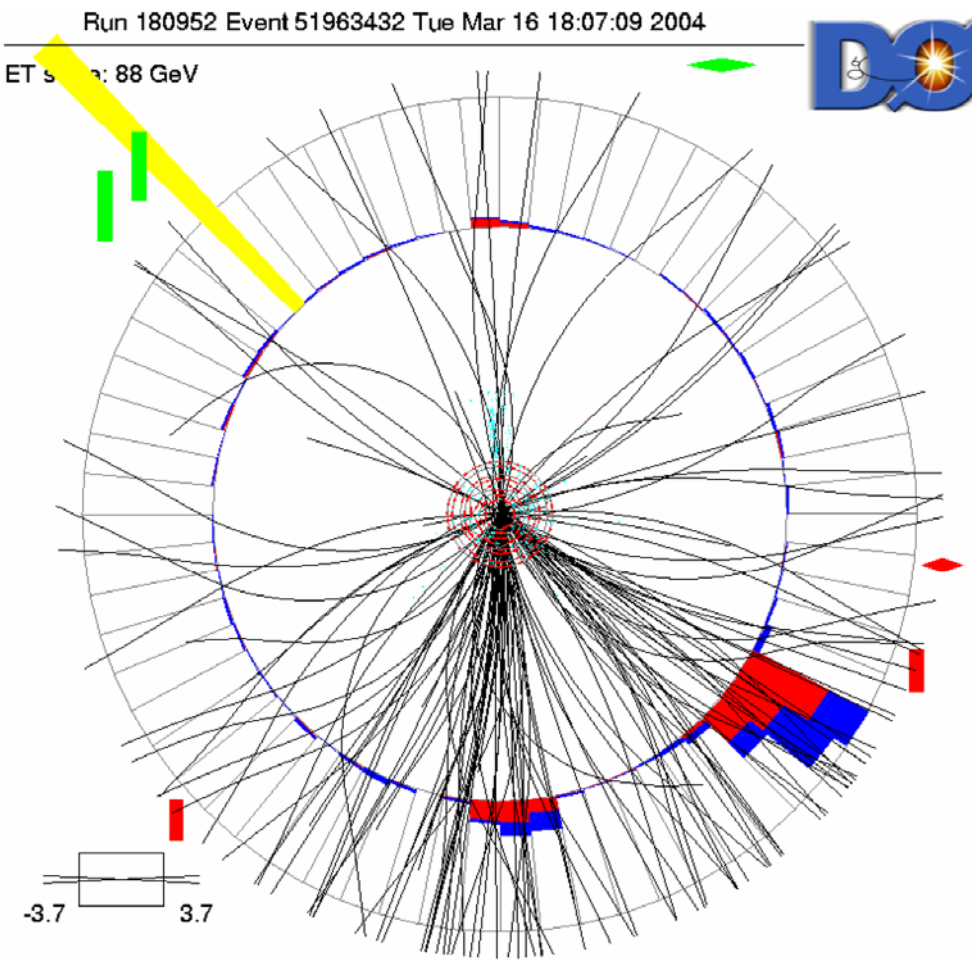
Supersymmetry searches at the Tevatron





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PASCOS 05, Gyeongju, Korea

May 31st, 2005

Outline

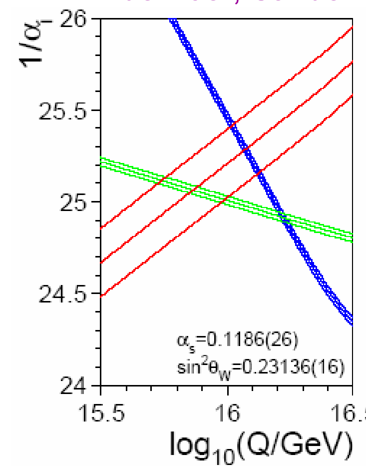
- Introduction
  - Supersymmetry
  - Supersymmetry and colliders
  - Tevatron
- Searches
  - Higgs sector
    - SM Higgs
    - **SUSY Higgs**
  - Indirect sensitivity
    - $B^0_S \rightarrow \mu^+\mu^-$
  - Sparticle sector
    - **Jets + missing E_T**
    - Charged massive stable particles
    - Di-photons + missing E_T / Gauge MSB
    - Flavor tagged jets + missing E_T
    - **Tri-leptons**
- Summary

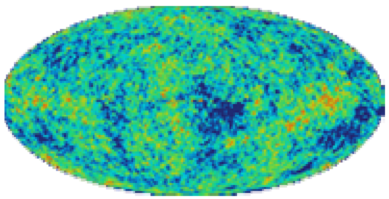
All limits at 95% CL

Supersymmetry

- What is supersymmetry good for ?
- **PA**RTICLE answer
  - Can cure the divergent fermionic loop corrections associated with the Higgs particle (if sparticles not too heavy).
  - Creates lots of new (s)particles to study (1 + 31)
- **S**TRINGS answer
  - A necessary component of most unified theories of the forces.
- **COS**MOLOGY answer
  - Provides a cold dark matter candidate, the neutralino, which can explain measured relic abundance.

de Boer, Sander



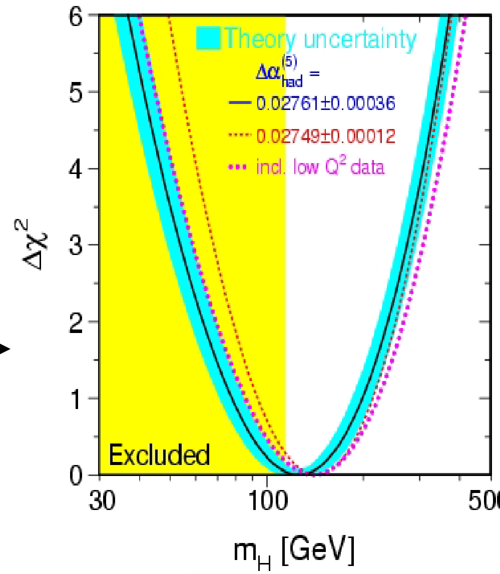


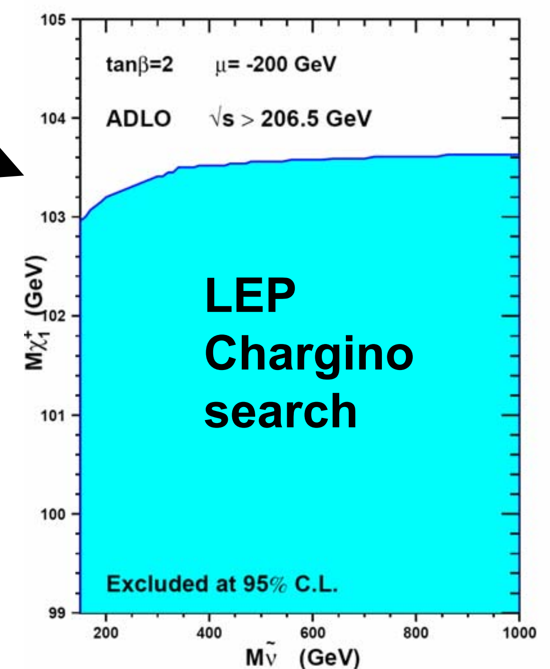
CMB anisotropy (WMAP)

Supersymmetry and Colliders

- Experiments (especially LEP/Tevatron/SLC), have established many aspects of the Standard Model (SM) to great precision.
  - But no direct evidence yet for the Higgs particle (LEP: m_H > 114.4 GeV)
  - SM fits: $m_H = 126\ ^{+73}_{-48}$ GeV
  - Nor direct evidence for production of supersymmetric particles
    - LEP experiments *convincingly* excluded charginos below 103 GeV and sleptons below 95 GeV.
    - Implies lightest neutralino mass exceeds about 50 GeV in typical models
- SUSY models predict lightest Higgs mass below ≈ 135 GeV.
  - Sparticle masses unknown, but expect the chargino to have a mass of $O(m_W)$.

The noose is tightening, or, discovery is perhaps just around the corner

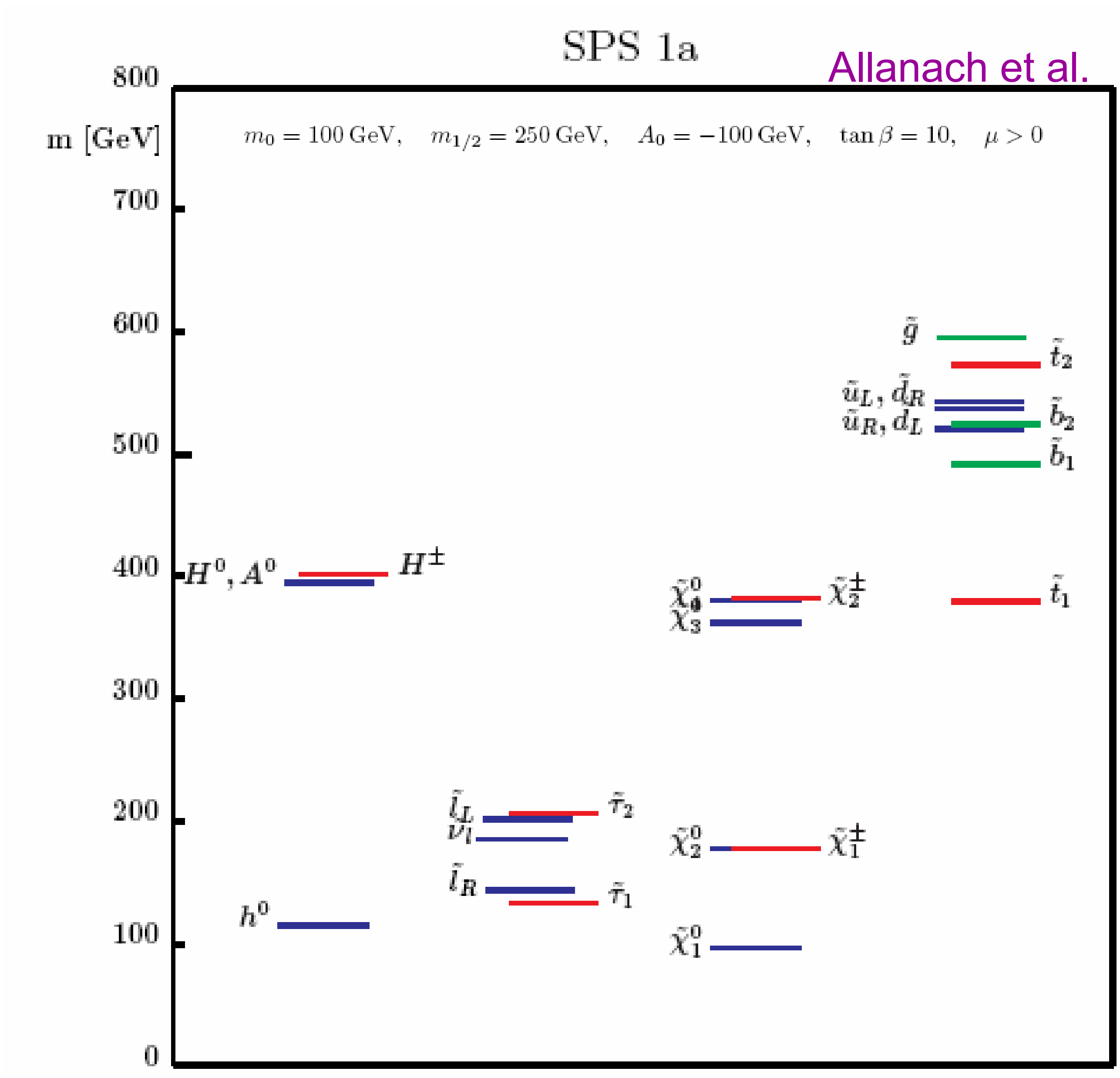




Supersymmetry Models

- How supersymmetry is broken is unknown
  - SUSY breaking could be gravity-mediated, gauge-mediated, anomaly-mediated, …
- General SUSY models have many parameters
  - Results shown today assume R-parity conservation
    - (there are also RPV results)
  - Often, minimal supergravity (mSUGRA) model is used to interpret experimental data. Parameters:
    - m_0 common scalar mass
    - $m_{1/2}$ common gaugino mass
    - $\tan\beta$ ratio of vevs of Higgs fields (v_u/v_d)
    - A_0 common Higgs-sfermion coupling
    - sign(μ) sign(Higgs/Higgsino mass parameter)

Example post-LEP SUSY spectrum



Particular models have well defined relationships between sparticles.

Squarks, gluino expected to be most massive. (easiest to produce at a hadron collider)

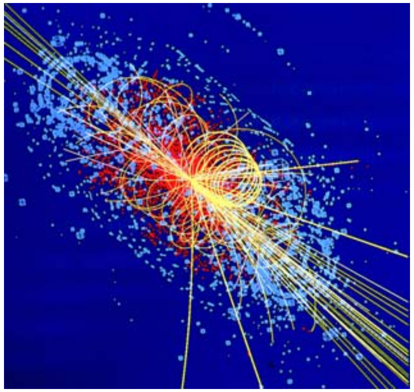
Sparticles with only EW interactions are expected to be much lighter (difficult to produce at hadron colliders, but easy at lepton colliders)

Note: mSUGRA mass splittings are large

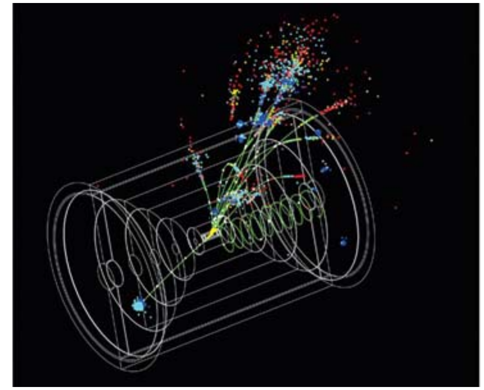
Searching for Supersymmetry at the Tevatron

- *Strongly* interacting sparticles have high cross-sections.
- Focus on search signatures with small contributions from SM processes to achieve reasonable S/B.
- Ensure that the process can fit within the permissible trigger rate (only can record around 50 Hz from 2.5 MHz collision rate).
  - Often means focussing on leptons and very high p_T jets, with high-level real-time trigger algorithms.
- Bottom-line:
  - we search **now** for what we can search for !

Future Colliders

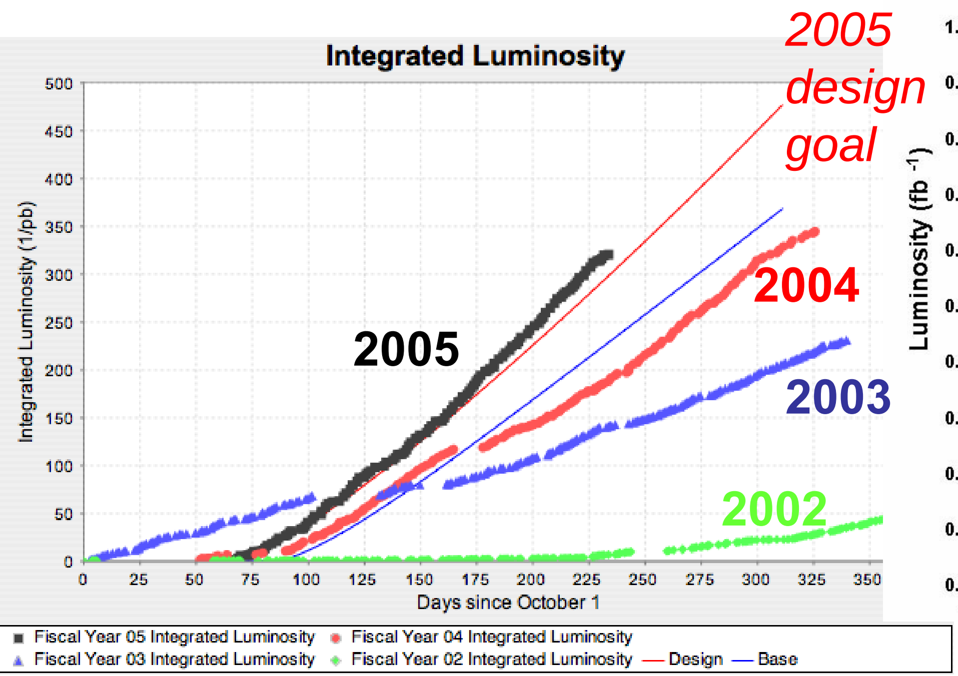


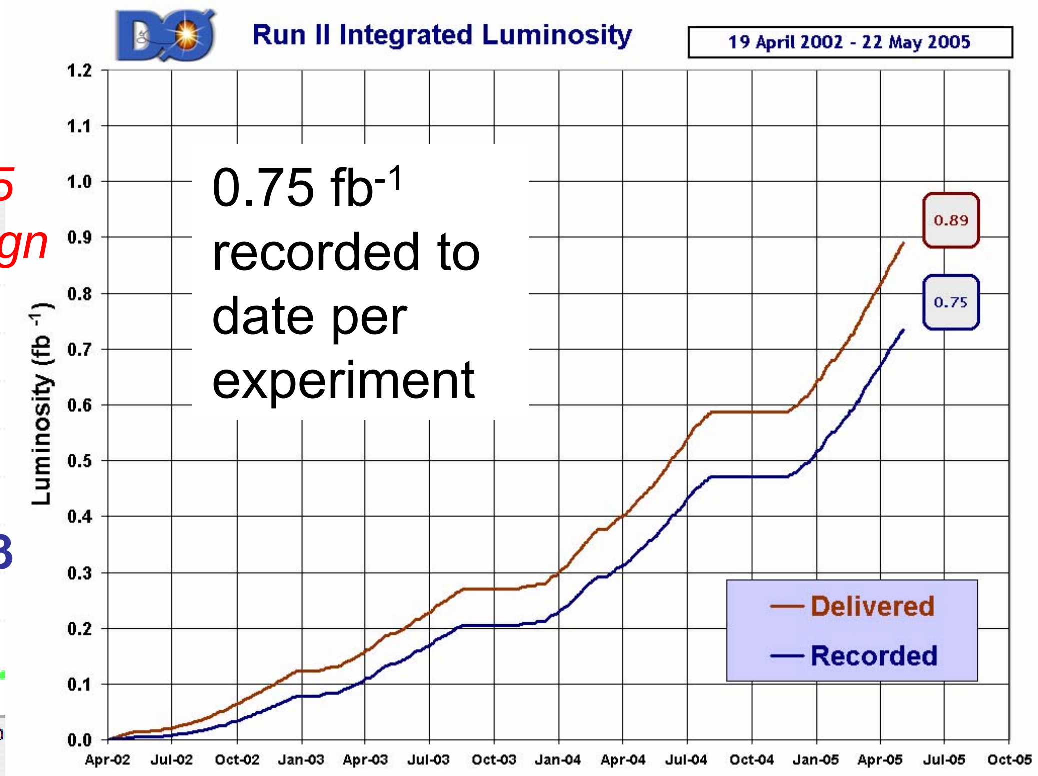
- LHC (pp at 14 TeV)
- Funded, starting soon
- 300 fb^{-1}
- Explore Higgs sector
- Discover strongly interacting sparticles and some cascade products if m < few TeV



- ILC (e^+e^- at 0.2 → >1 TeV)
- Design stage
- 1000 fb^{-1}
- Definitive Higgs studies
- Discoveries and precision measurements of kinematically accessible SUSY particles (especially neutralinos, charginos, sleptons)

Tevatron Integrated Luminosity





Each year, big improvements.

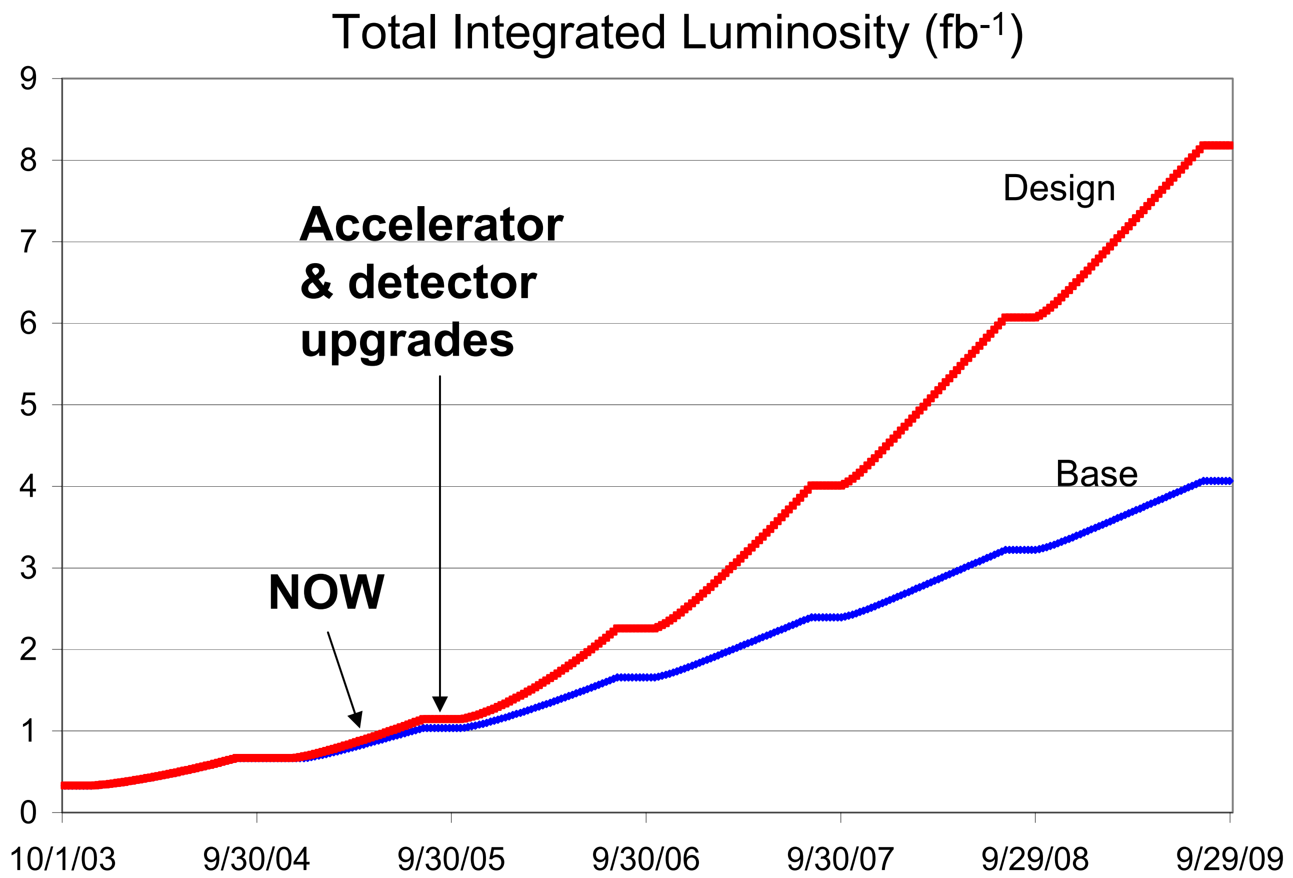
Accelerator performance *exceeding* design goal in 2005

Results shown today typically use 0.32 fb^{-1} from pre-2005 data

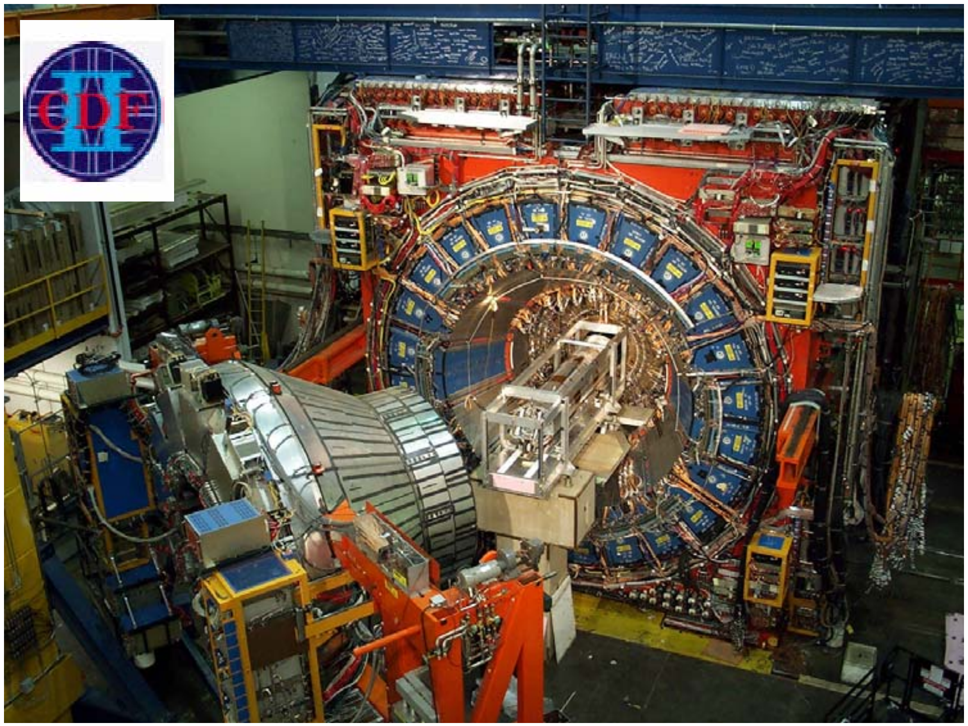
Tevatron prospects

Expecting 8 fb^{-1} per experiment through 2009

(X 25 increase compared to current 320 pb^{-1} results from data collected prior to 2005)



Upgraded Tevatron Detectors



Working well. Upgrades this fall for b-tagging and triggering at high luminosity.

SM Higgs

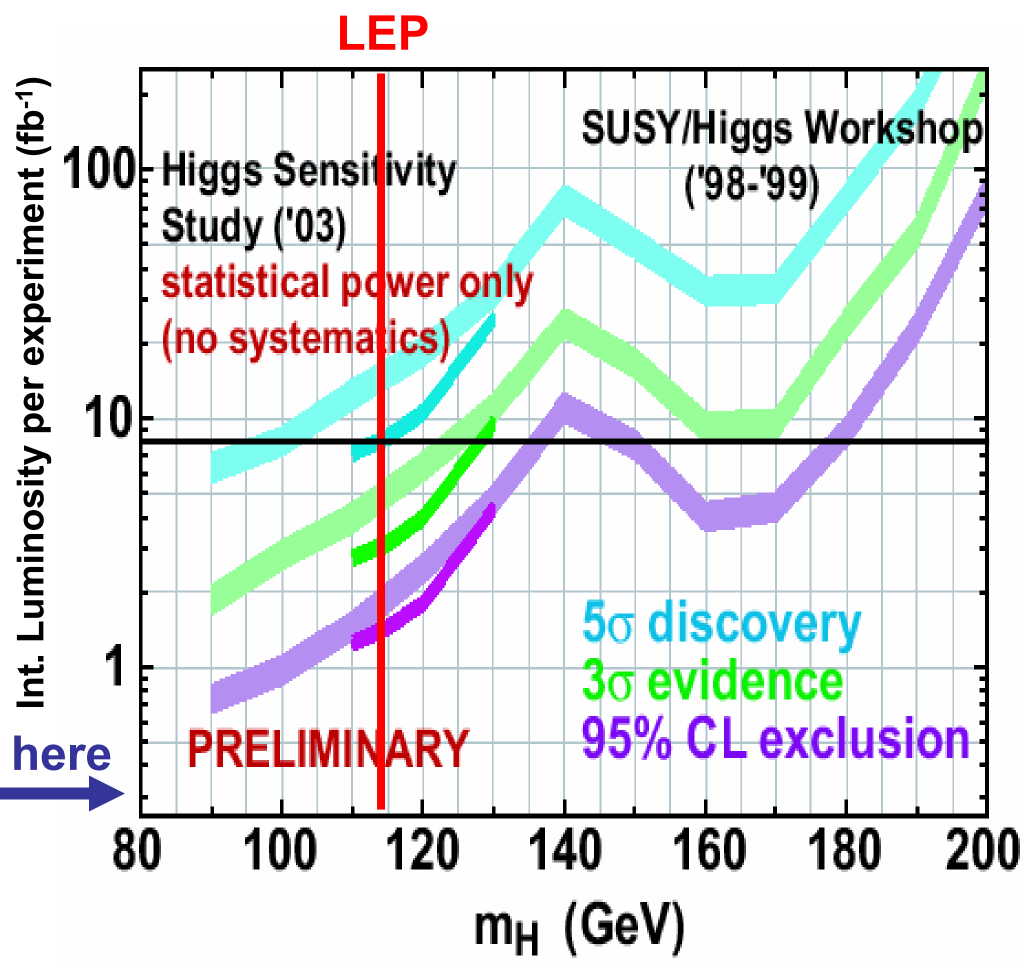
In 2 Higgs doublet models like minimal SUSY, the lightest CP-even Higgs, h, often has properties only subtly different from the SM Higgs.

SM Higgs search is doubly relevant for SUSY:

a) its existence is a founding principle for SUSY models, and the firmest prediction (m < 135 GeV)

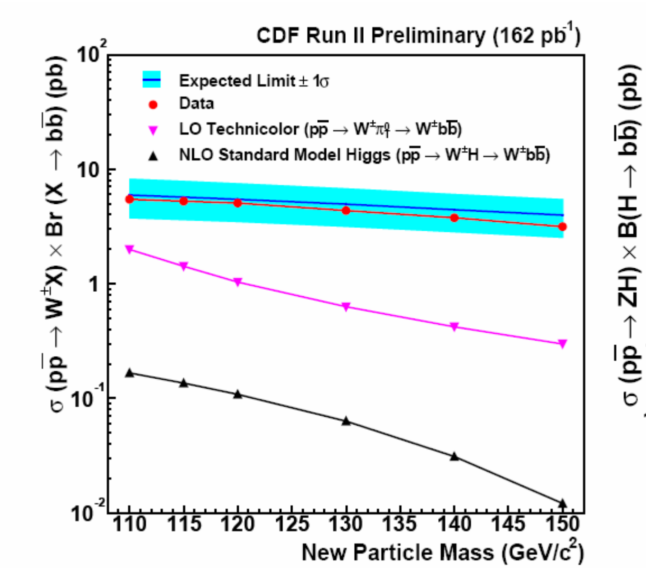
b) SM Higgs results can be translated into constraints on SUSY parameter space

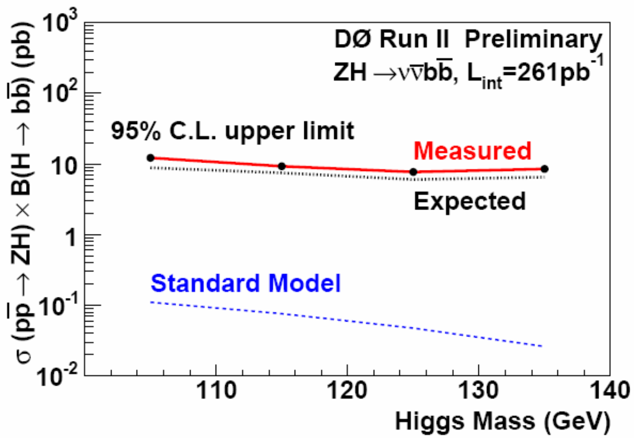
We are here

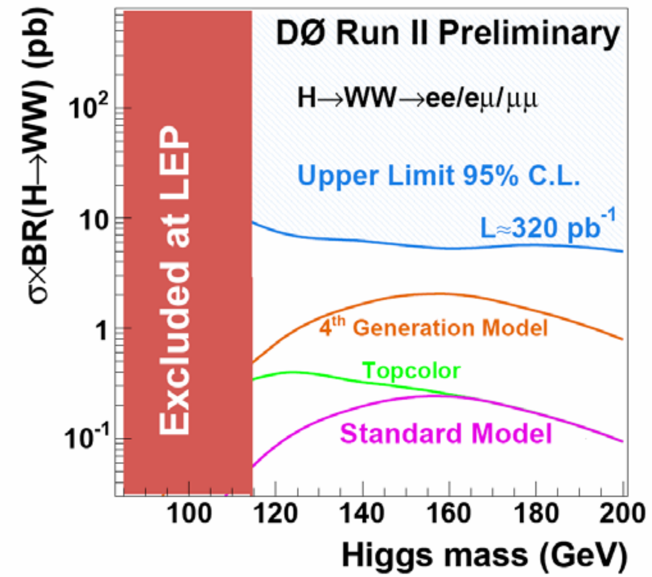


Not enough analyzed data so far to test SM Higgs sector. Analyses are in progress.

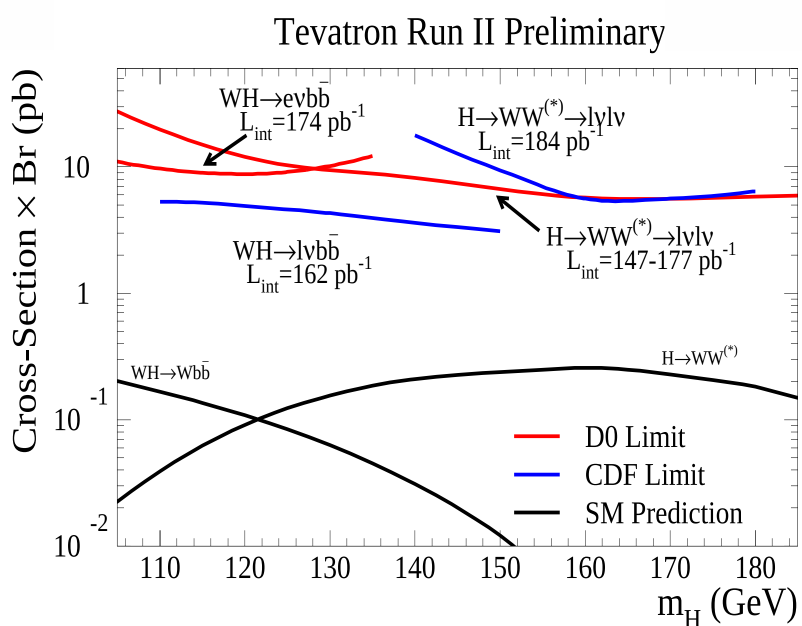
SM Higgs







Searches for WH, ZH, H production



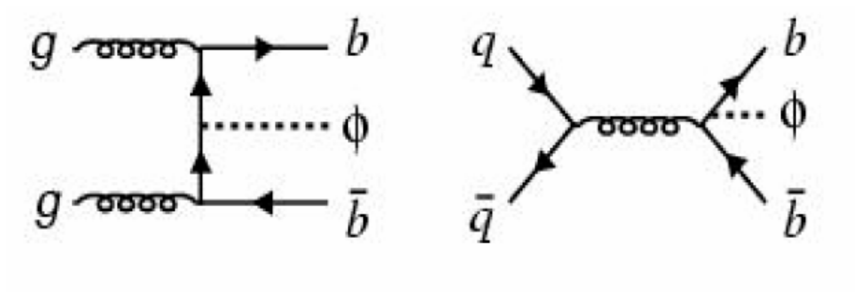
With × 25 data samples, several channels, 2 experiments, improved analyses, we will be testing this in the years ahead

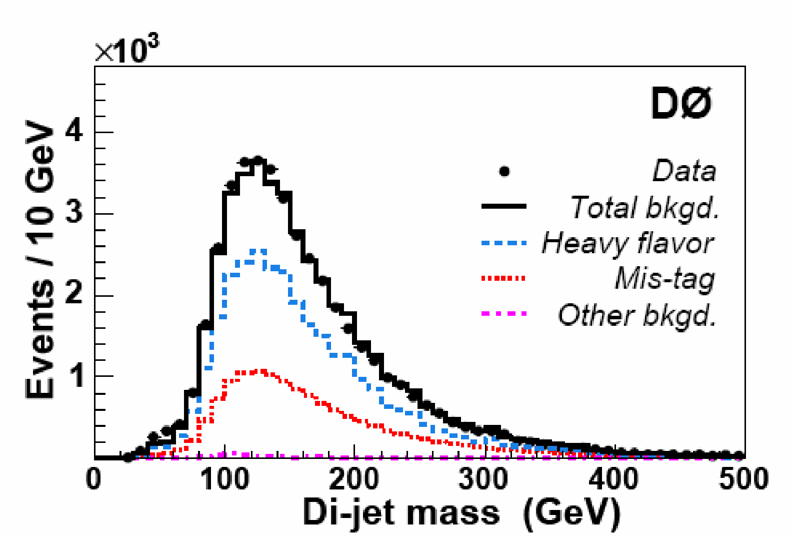
Neutral MSSM Higgs bosons

With ϕ = h, H, A

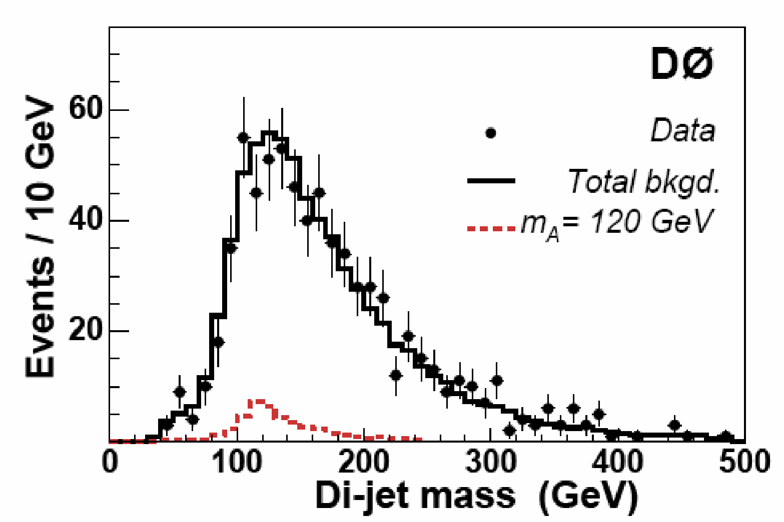
Investigate $\phi \rightarrow b\bar{b}$ decay.

The various bosons may be mass degenerate. Associated production with b has $\sigma \sim \tan^2\beta$





Double b-tagged sample used to test modeling of backgrounds



Triple b-tagged event selection

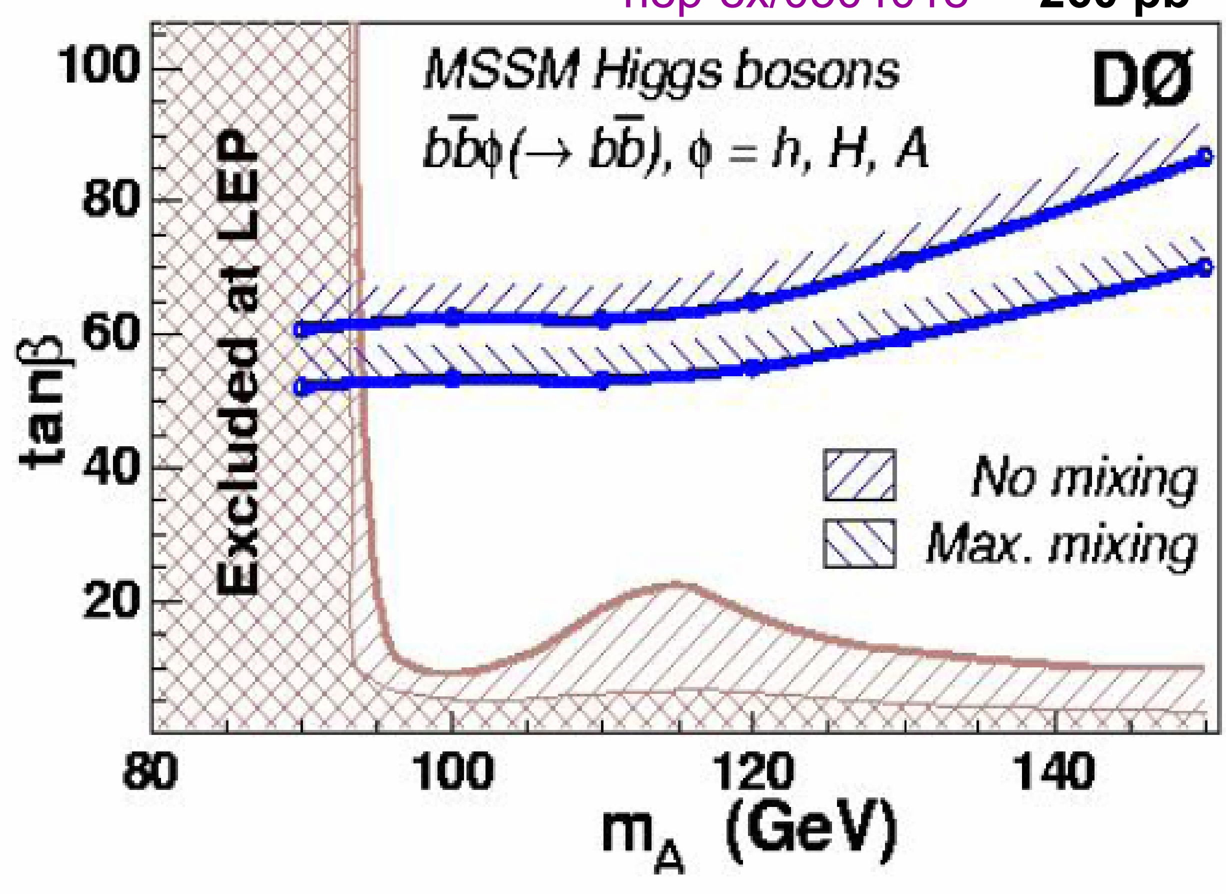
(dotted red curve shows the m_A=120 GeV signal which is excluded at 95% CL)

MSSM Higgs bosons

Cross-sections depend on SUSY parameters, top mass, stop mixing

Using the same reference scenarios as at LEP2, can exclude complementary regions of parameter space at high tanβ

hep-ex/0504018 **260 pb^{-1}**

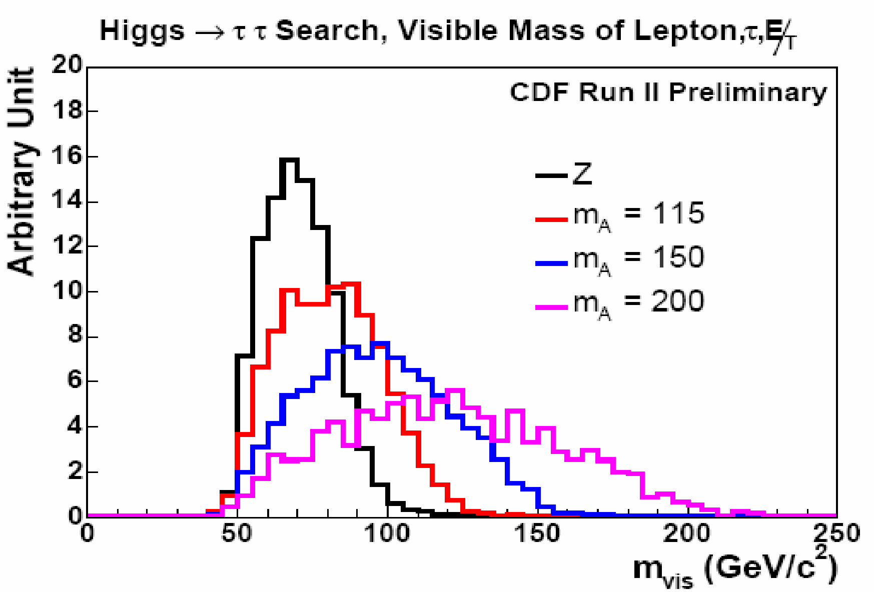


MSSM Higgs ($A \rightarrow \tau\tau$)

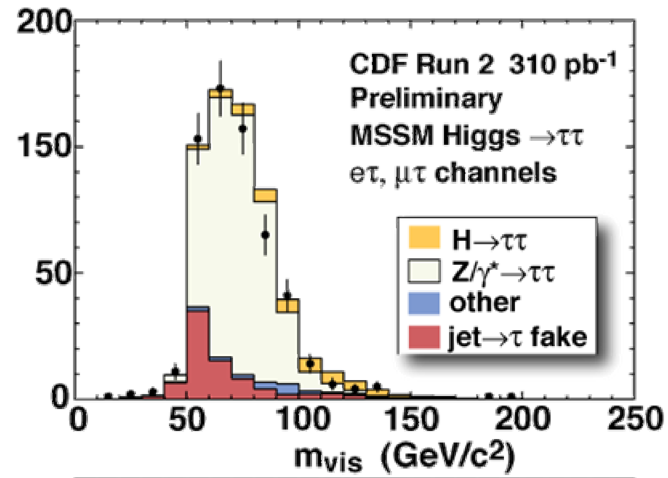
BR($A \rightarrow \tau\tau$) ≈ 8% . (small)

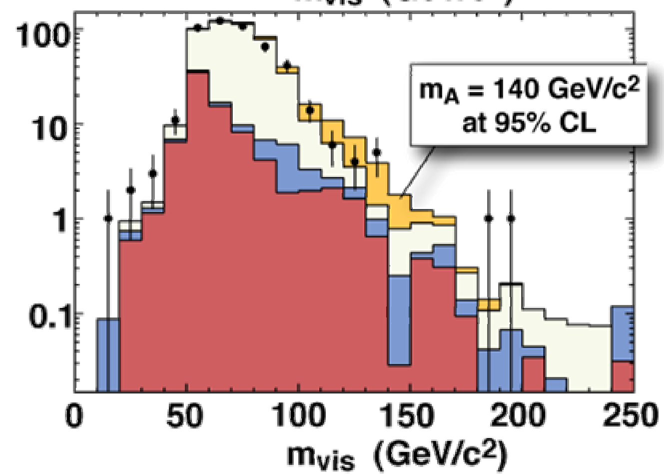
Can use gg fusion production (high cross-section).

Select events with one τ decaying leptonically, the other τ decaying hadronically and a high degree of isolation



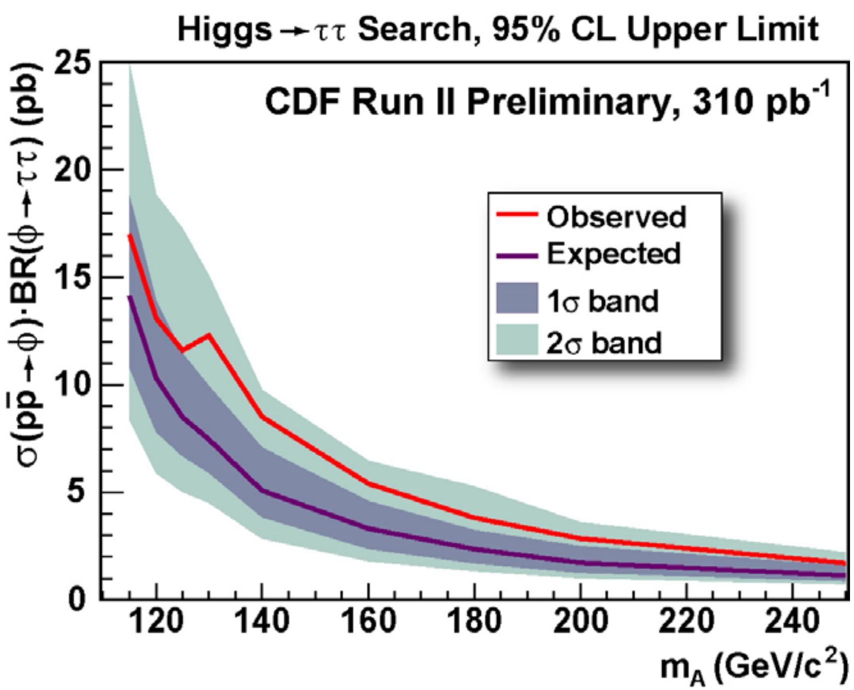
Form a mass-like discriminating variable using the lepton, hadron(s) and missing E_T



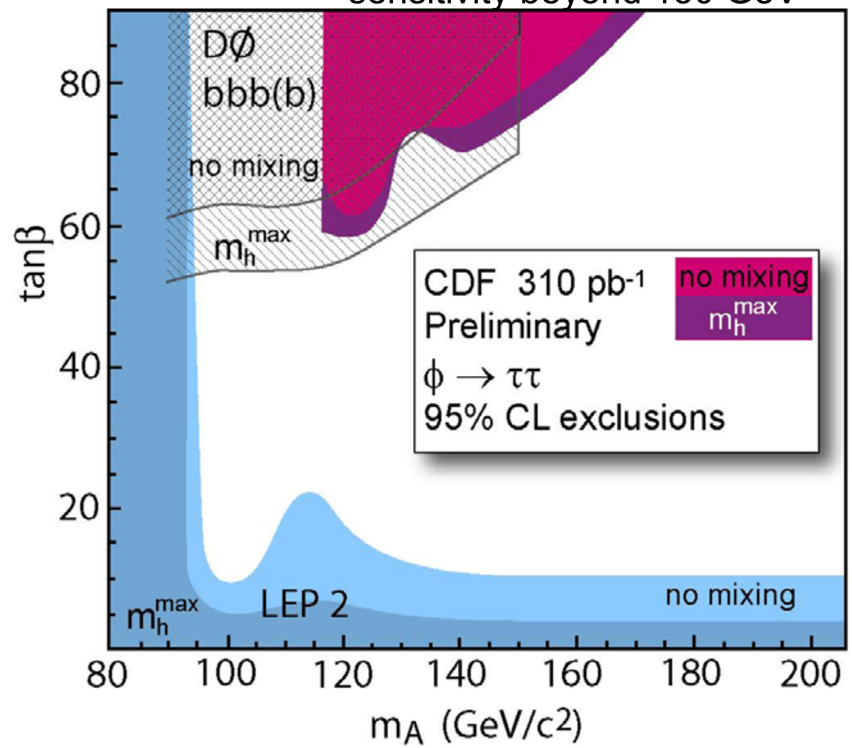


Selected events are consistent with SM sources dominated by $Z \rightarrow \tau\tau$

MSSM Higgs Limits



Note: DØ limits (260pb^{-1}) do have sensitivity beyond 150 GeV



σ.B limits not so stringent at low mass near the Z; improve at higher mass

MSSM scenarios used by CDF not directly comparable with LEP2 and DØ. CDF uses μ=+200 GeV,

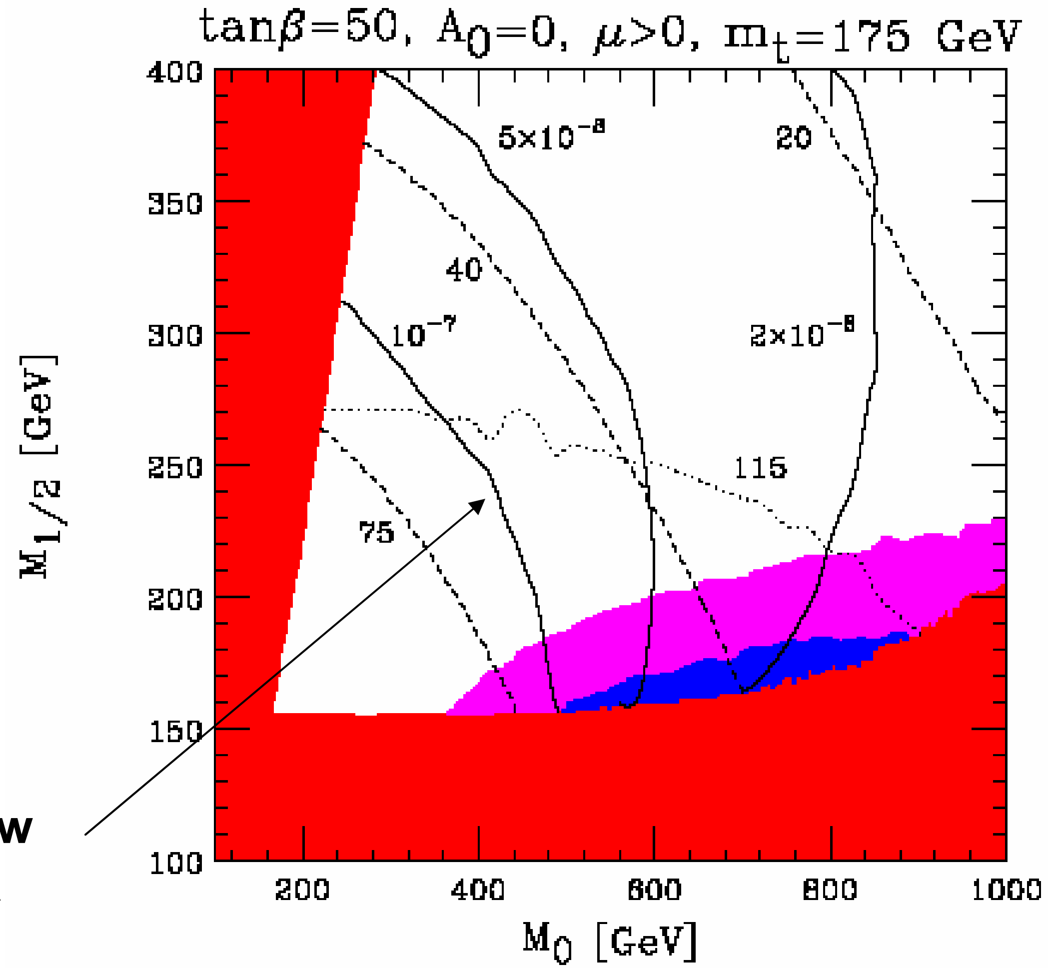
LEP2/DØ use μ=-200 GeV.

$B_s^0 \to \mu^+\mu^-$

Well-known that some observables have sensitivity to SUSY at the loop level, eg b→s γ, $(g\text{-}2)_\mu$

Promising channel at Tevatron, $B^0_s \to \mu^+\mu^-$, (FCNC mode with SM BR of 3.5×10^{-9}).

SUSY sensitivity ~ $\tan^6\beta$

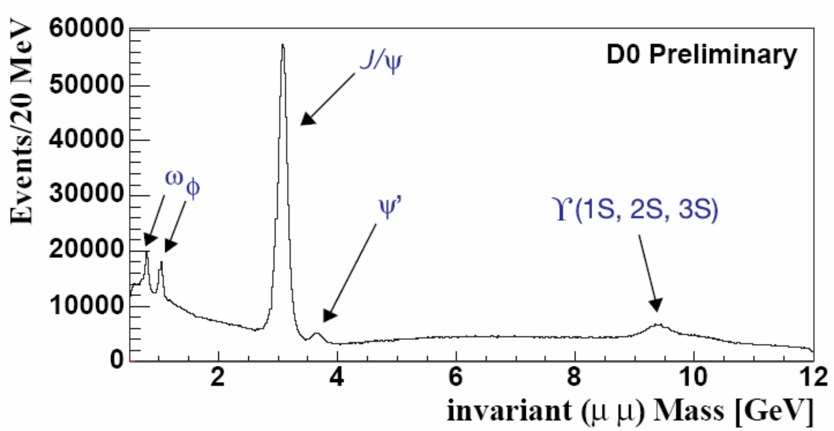


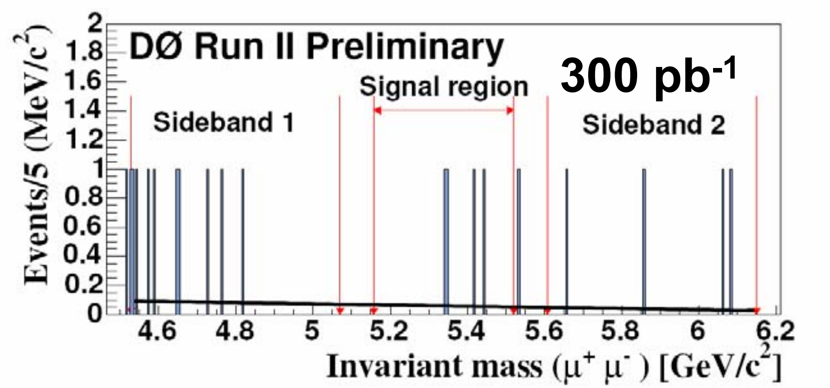
Solid contours show the BR in mSUGRA

Dedes et al, hep-ph/0207026

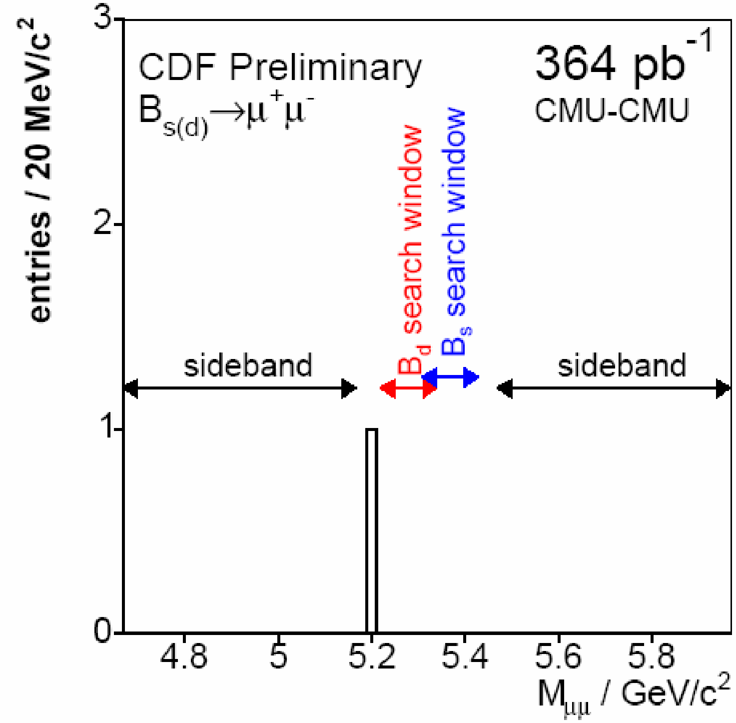
$$B_s^0 \rightarrow \mu^+\mu^-$$

Muons ? We can do them !





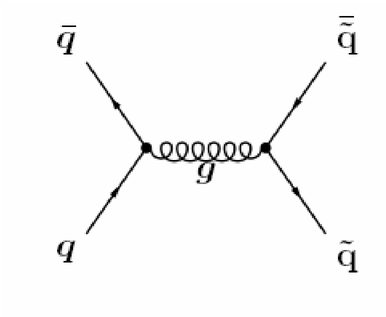
=> BR < 3.7 × 10^{-7}



=> BR < 2.0 × 10^{-7}

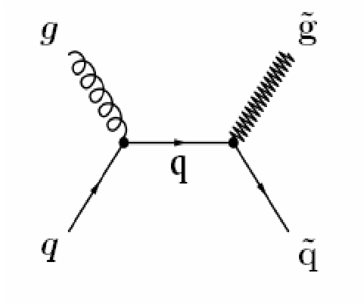
Will provide powerful test of high tanβ SUSY as more data is collected

Jets + Missing E_T

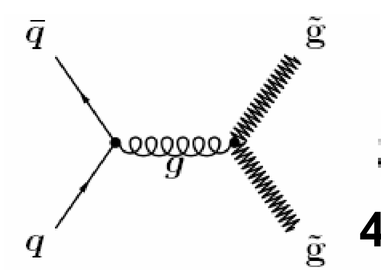


$\tilde{q} \to q\chi$

2-jets + MET



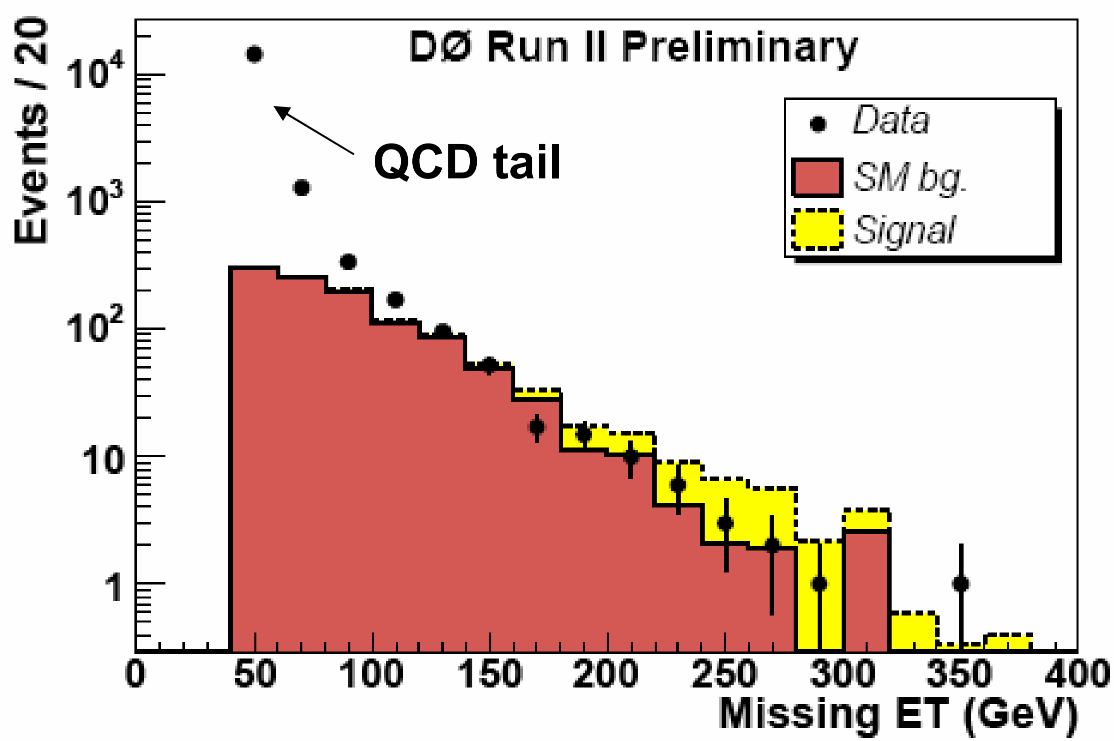
3-jets + MET



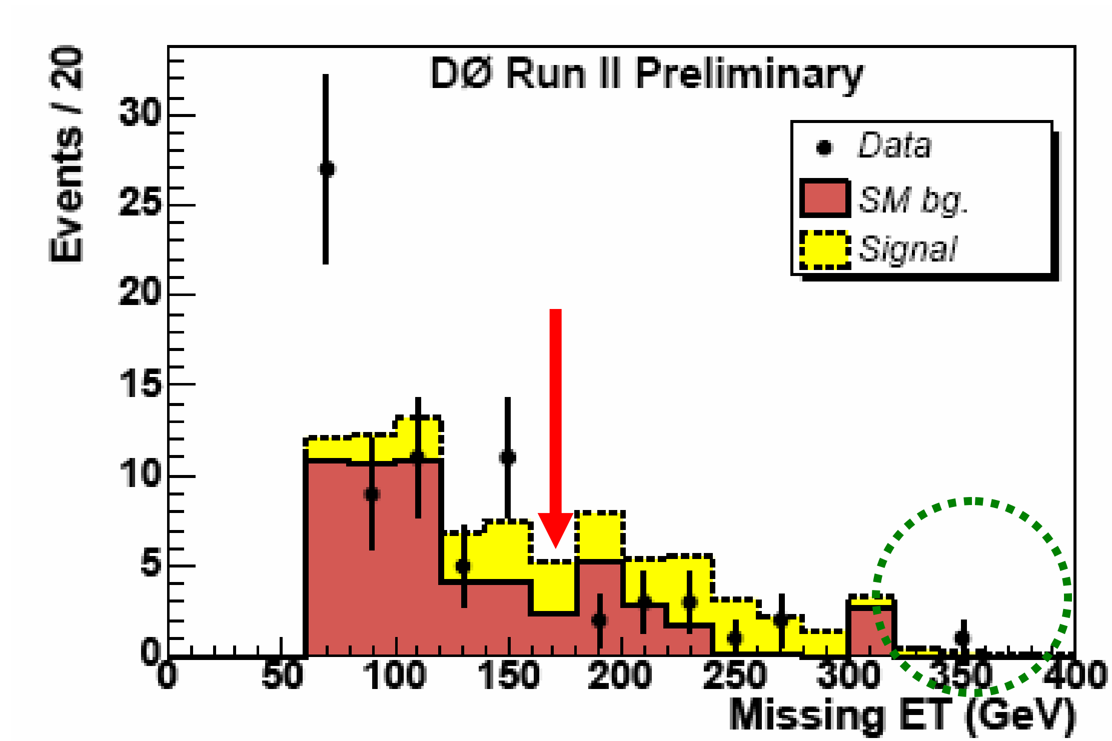
$\tilde{g} \to q\bar{q}\chi$

4-jets + MET

Pre-selected data from special jets + MET trigger



Example: 2-jets + Missing E_T Analysis



Signal has squark mass = 318 GeV

Final selection criterion: require MET > 175 GeV.

Observe 12 events.

Signal efficiency, ε = 7%

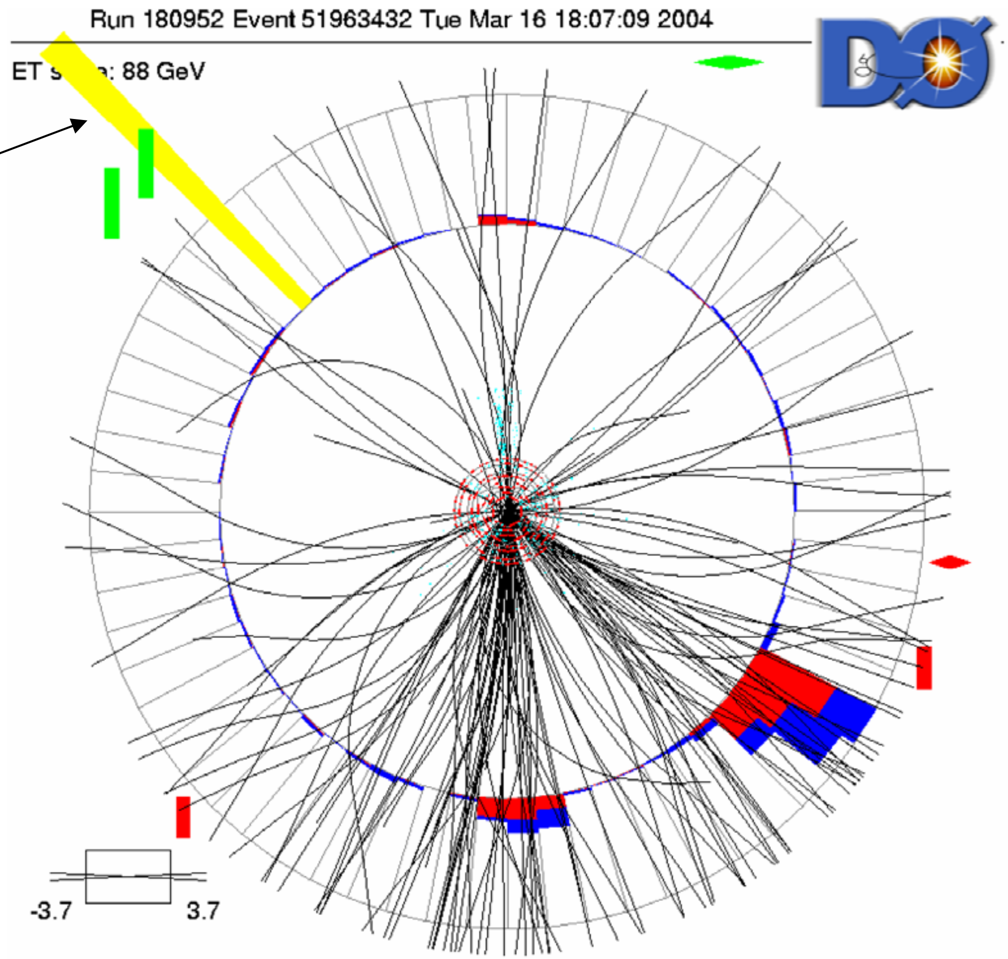
Expect 12.8 ± 5.4 from SM sources:

- **$Z \rightarrow \nu\,\nu$ + jet jet : 5.2 ± 3.7**
- **$W \rightarrow l\,\nu$ + jet jet : 6.3 ± 3.8**
- **t tbar : 1.4 ± 0.1**
- **QCD : negligible**

N.B. If SUSY lives at high MET it may be discovered. (need high mass splitting between squarks and neutralino(s))

Highest Missing E_T 2-jet candidate

MET



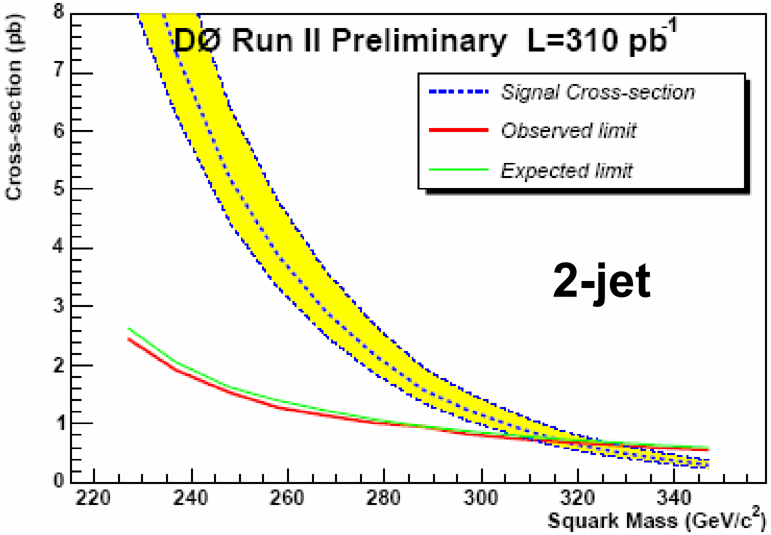
Transverse view along the beam-axis

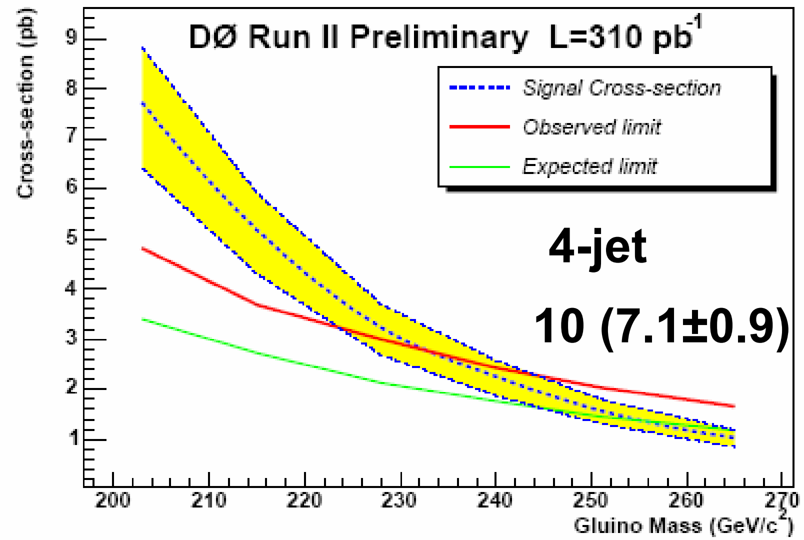
MET: 354 GeV

p_T^{j1} : 264 GeV

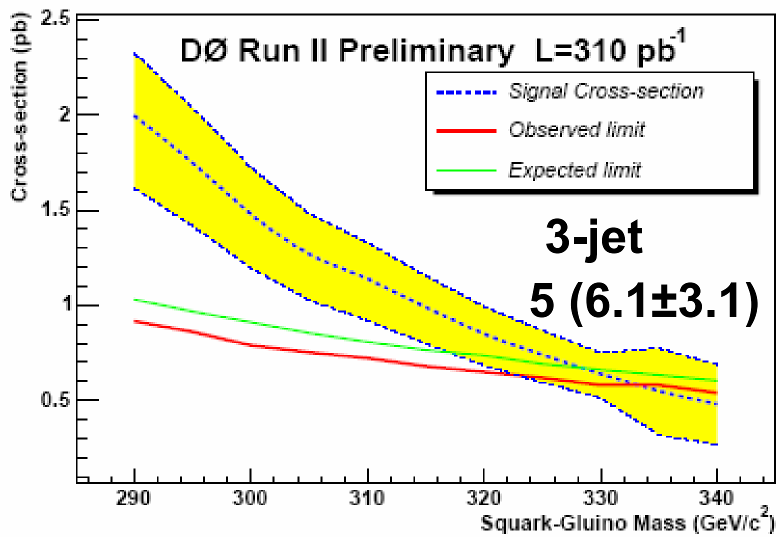
p_T^{j2} : 106 GeV

Jets + Missing E_T

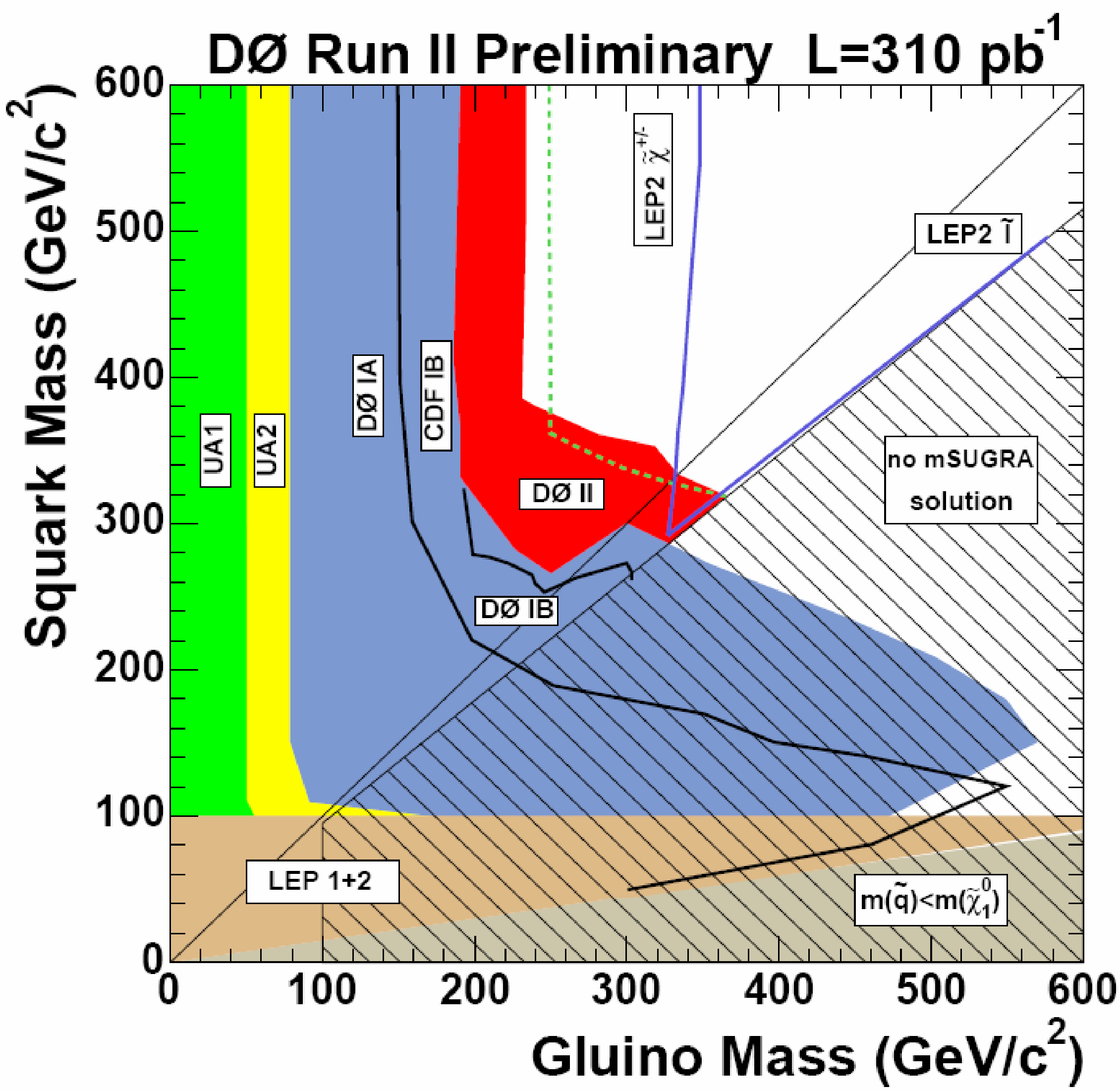




Signal cross-sections for tanβ=3, A_0=0, μ<0



Jets + Missing E_T



Red region is now excluded with D0 RunII data.

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

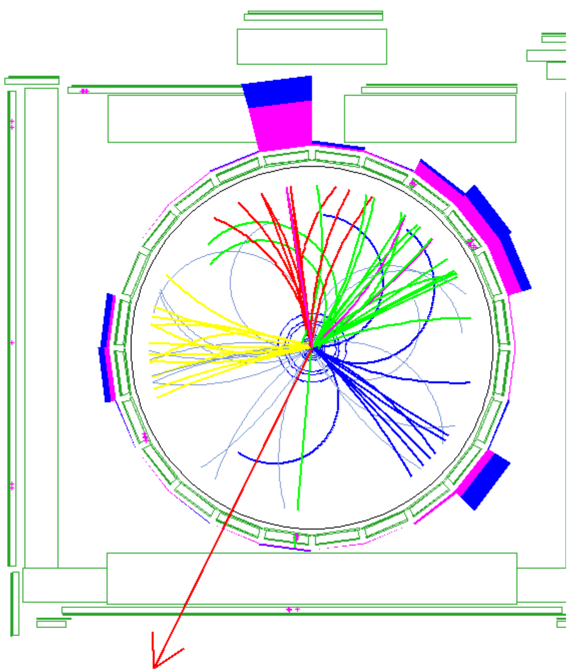
Green line: expected limit

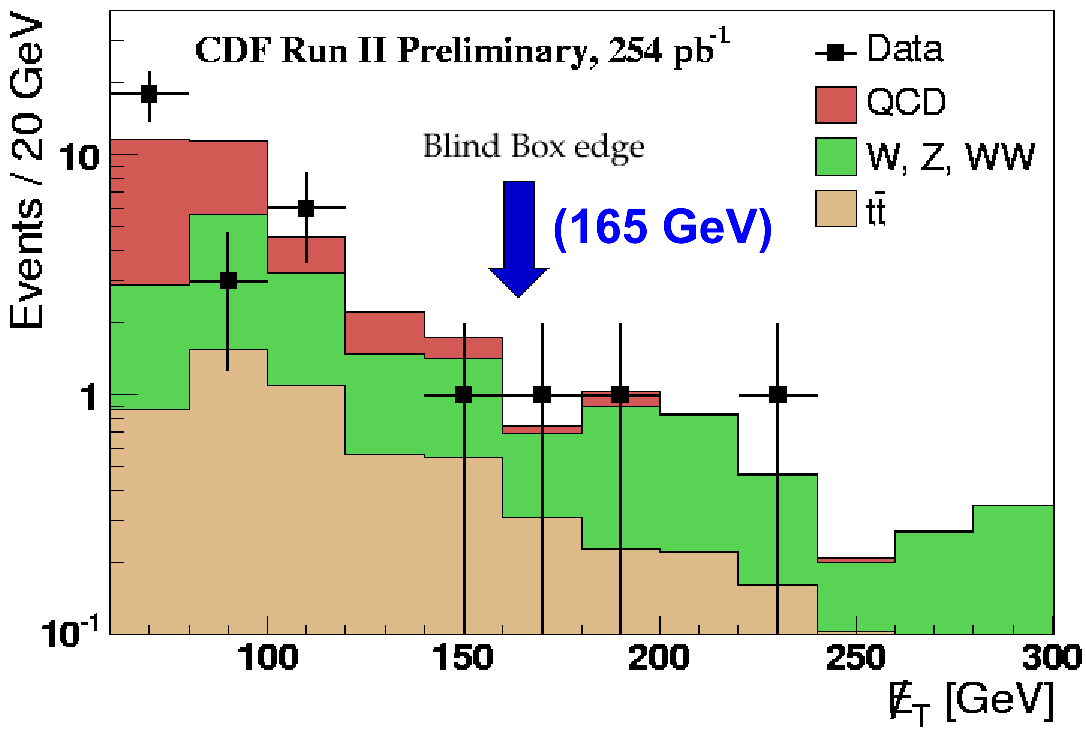
Starting to probe new kinematic regions.

M > 322 GeV for $M_{squark} = M_{gluino}$

More model independent interpretation in progress

Jets + Missing E_T



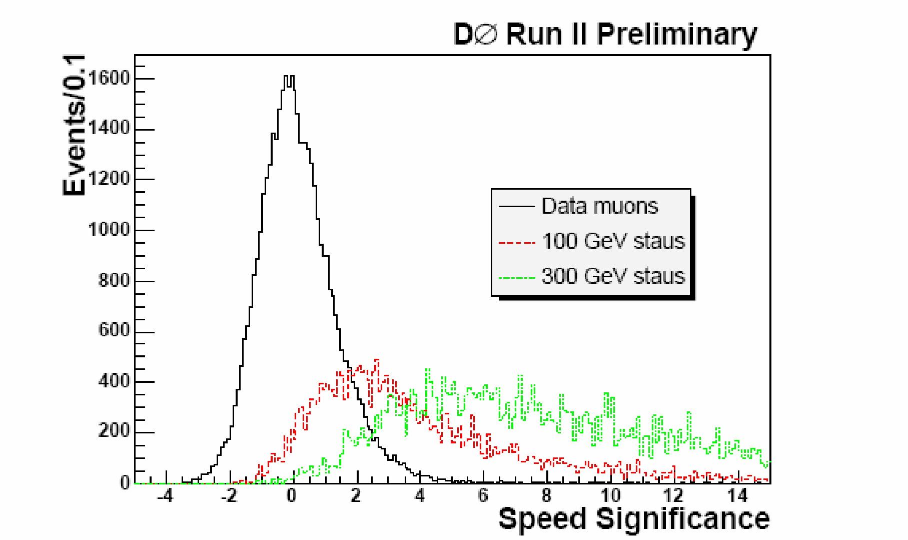


Require ≥ 3 jets. E_T > 25 GeV.

Observe 3 events, expect 4.1 ± 1.5 from SM

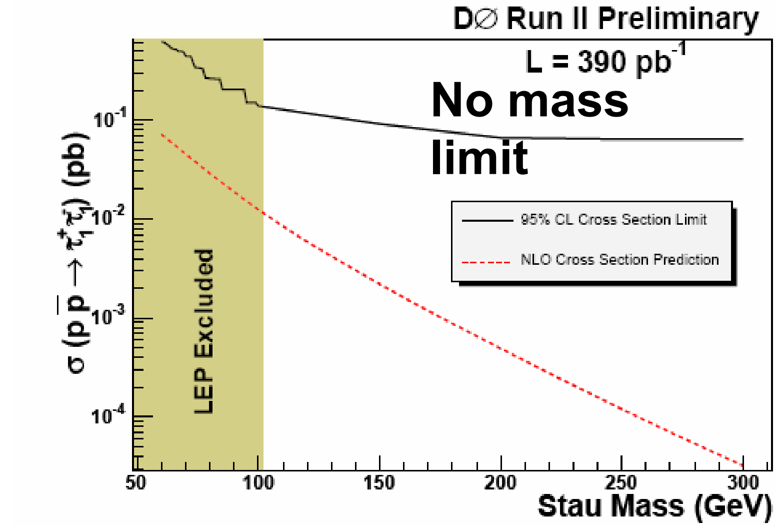
Charged Massive Stable Particles

Charged supersymmetric particles may not decay within the detector.
Experimental signature: pair of penetrating slow tracks as measured with muon scintillator hits, with p_T exceeding that expected from $Z \to \mu^+\mu^-$

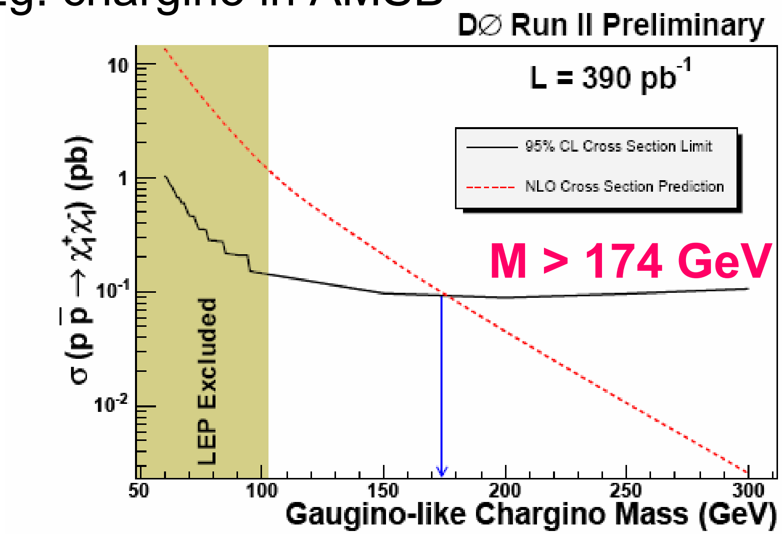


For m > 100 GeV: 0, (0.66±0.06), $\varepsilon \approx 6\%$

Eg. stau NLSP in GMSB



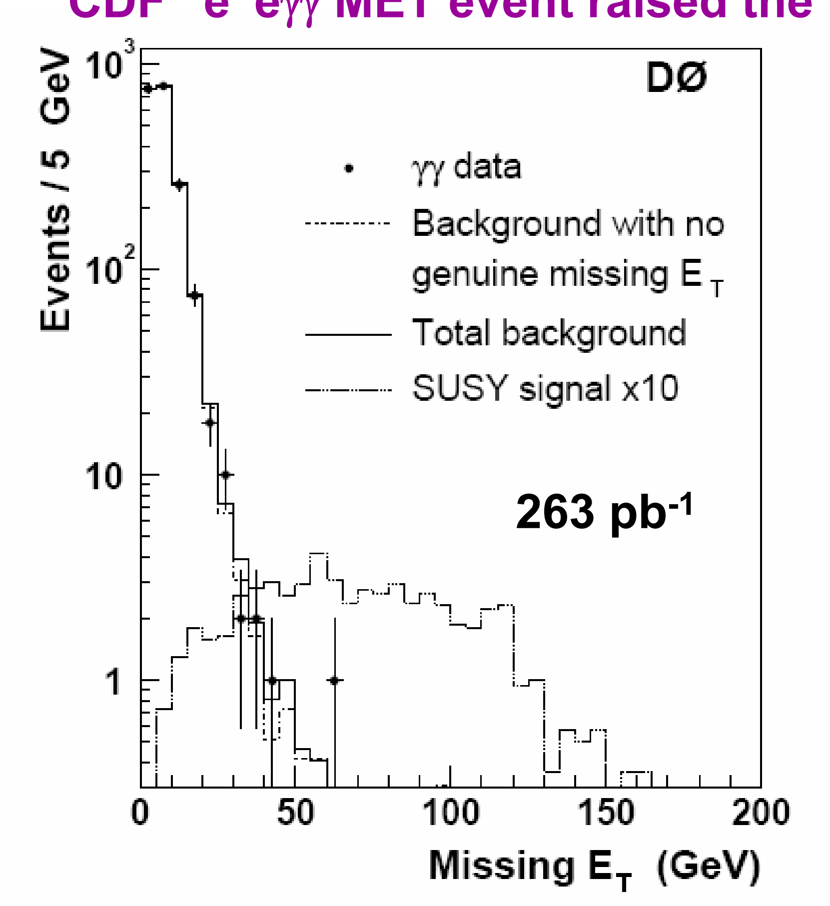
Eg. chargino in AMSB

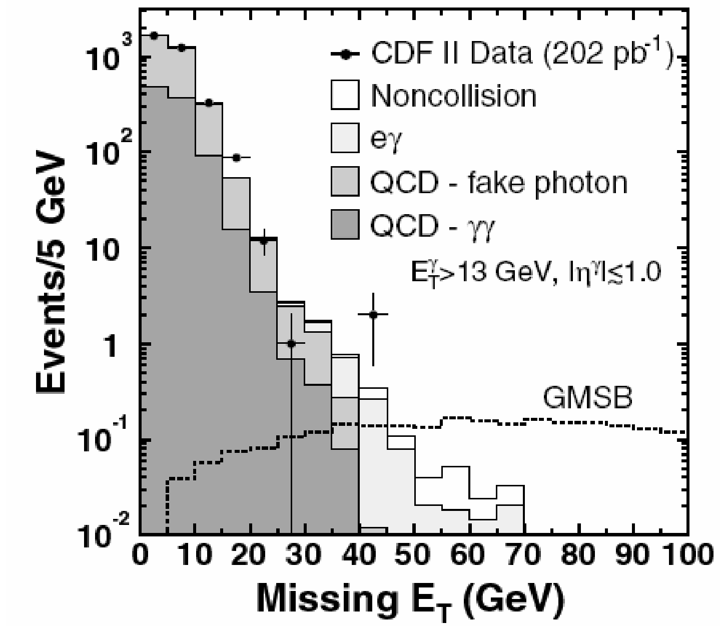


$\gamma\gamma$ + Missing E_T

Distinctive signature in Gauge-Mediated SB. Can also occur in no-scale supergravity and MSSM models.

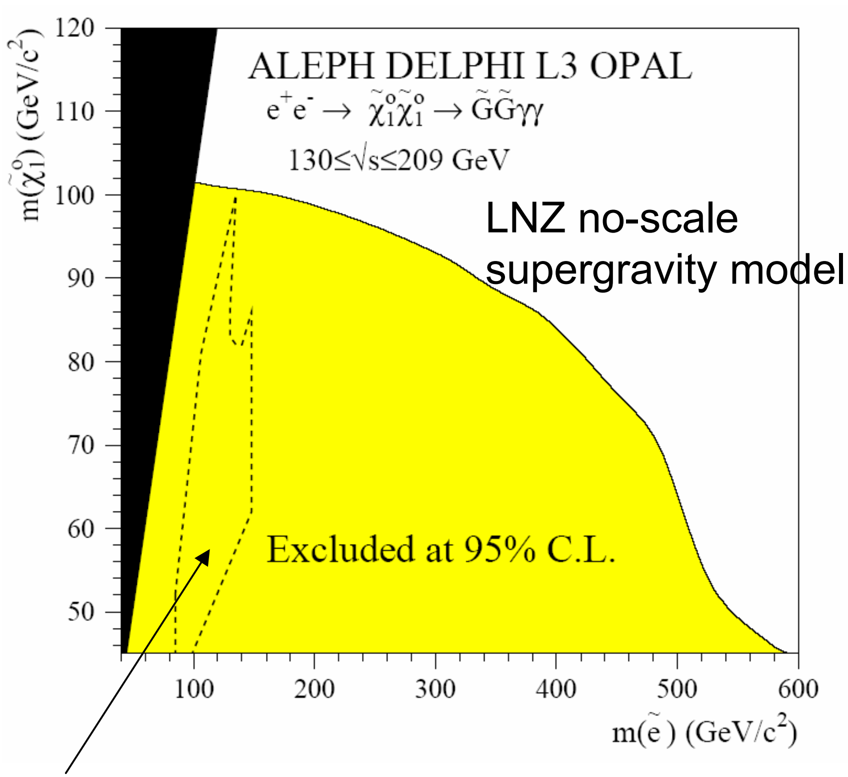
CDF "e"e$\gamma\gamma$ MET event raised the profile of these channels



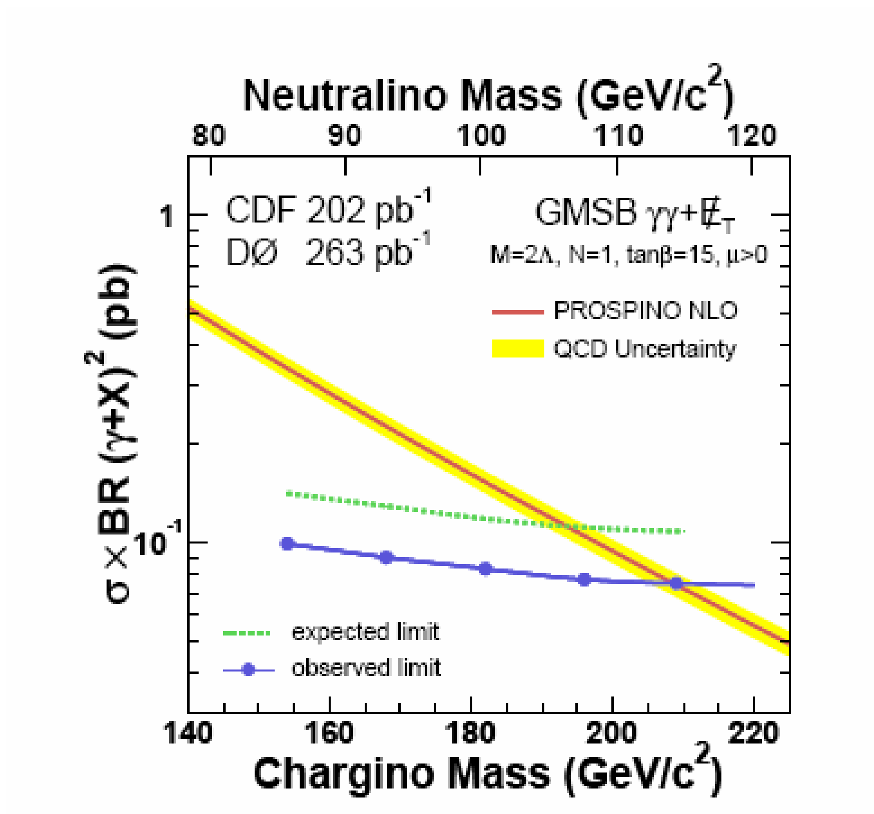


No evidence with much increased data-sets from CDF and DØ of anomalies.

Model limits from $\gamma\gamma$ + Missing E_T



Region favored by CDF ee$\gamma\gamma$ event.



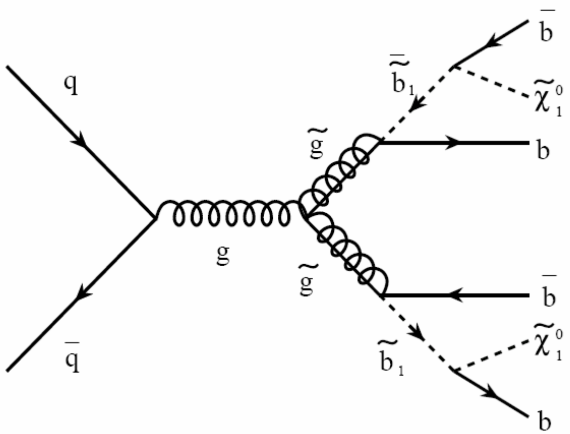
Chargino Mass limits

CDF: 167 GeV, DØ: 195 GeV

Combined: 209 GeV

Gluino/light sbottom

For large tanβ, lighter sbottom may be of low mass and accessible at Tevatron



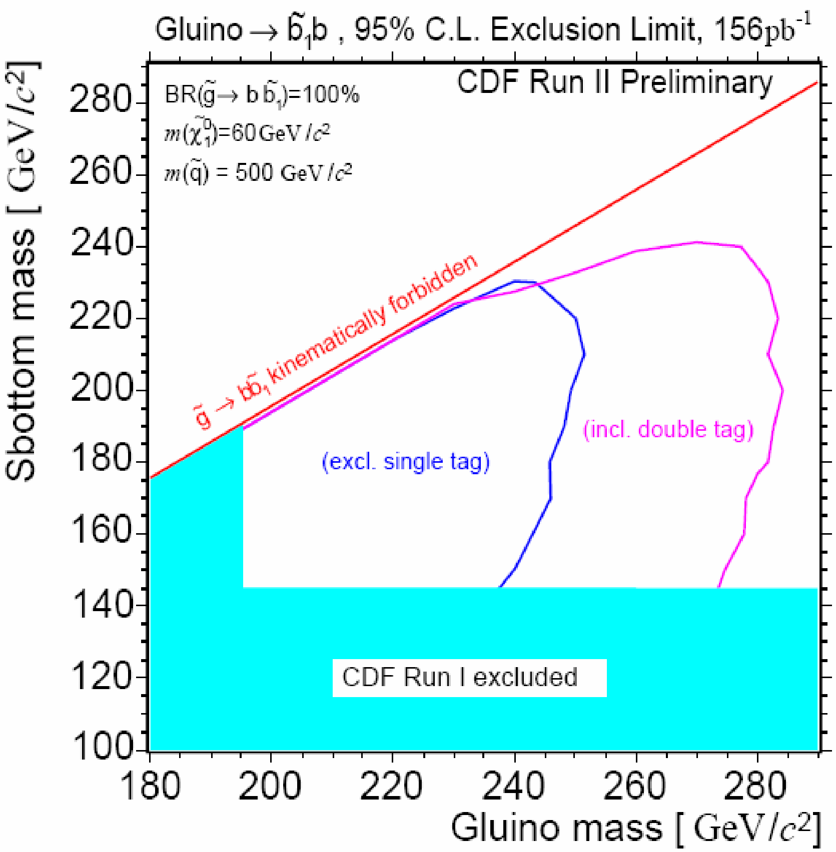
Can do b-tagging. Search for multi-jet (≥ 3) events with b-tags.

Two of the jets may be soft.

Two analyses:

Exclusive single tag: 21 (16.4±3.6)

Inclusive double tag: 4 (2.6±0.7)



Note: results depend on neutralino mass

Stop

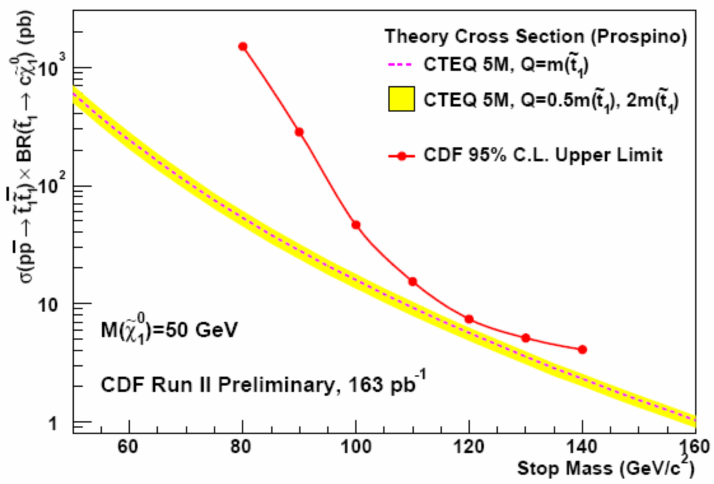
Search for stop pair production with $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$

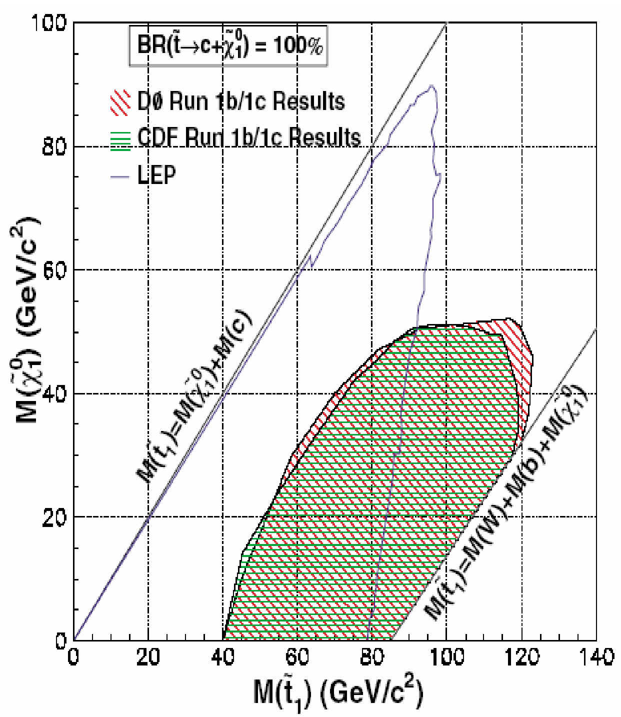
Signature: Heavy-flavor tagged di-jets with missing E_T

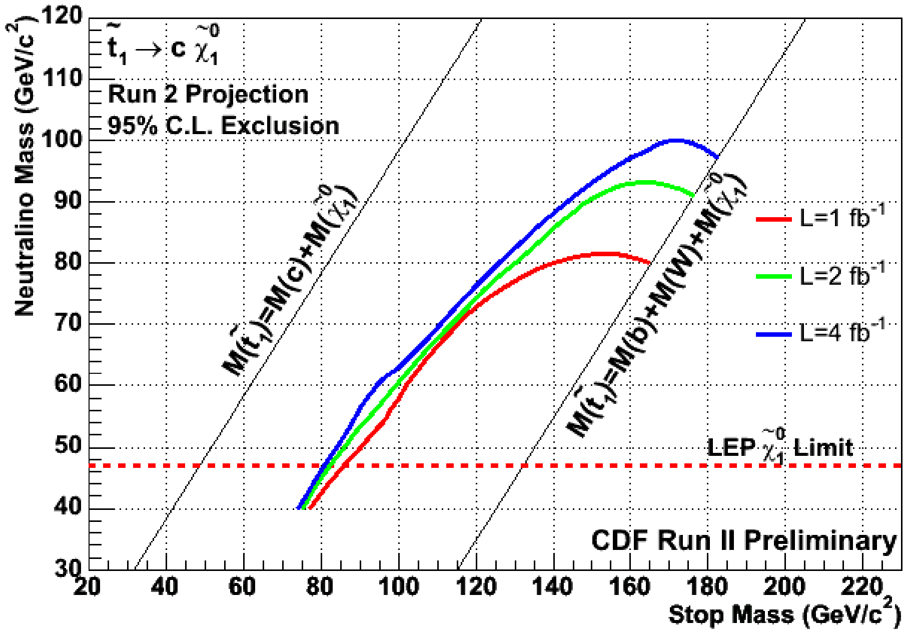
Observe 11 events.

Expect $8.3^{+2.3}_{-1.7}$ from SM

⇒ set limits

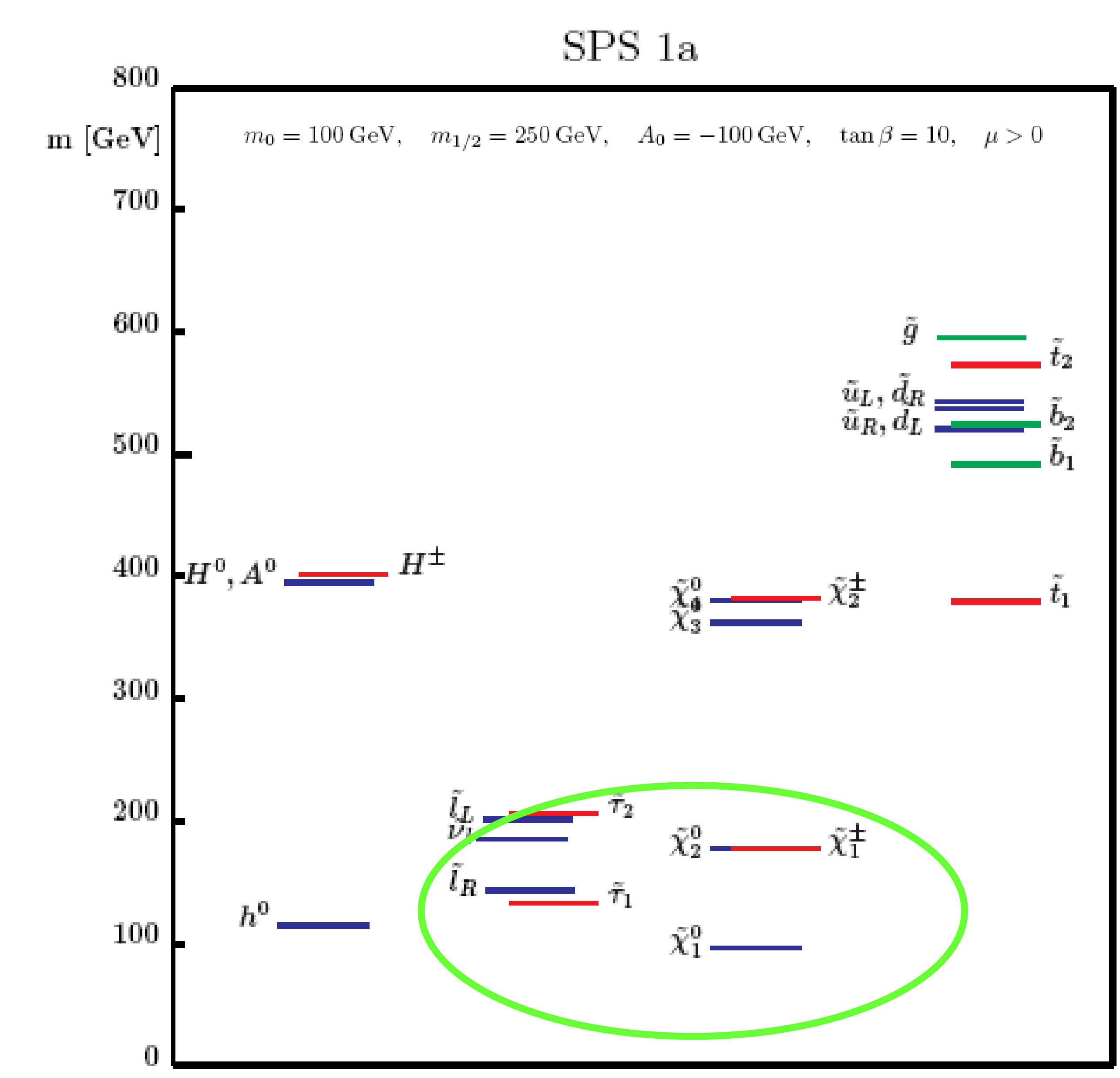






LEP and Tevatron RunI already exclude low mass region

Tri-leptons Search

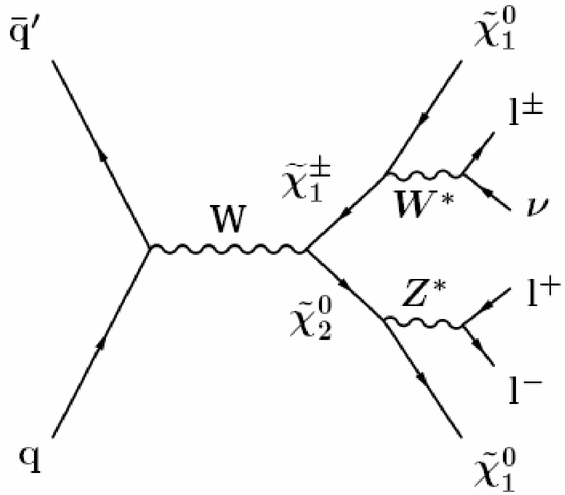


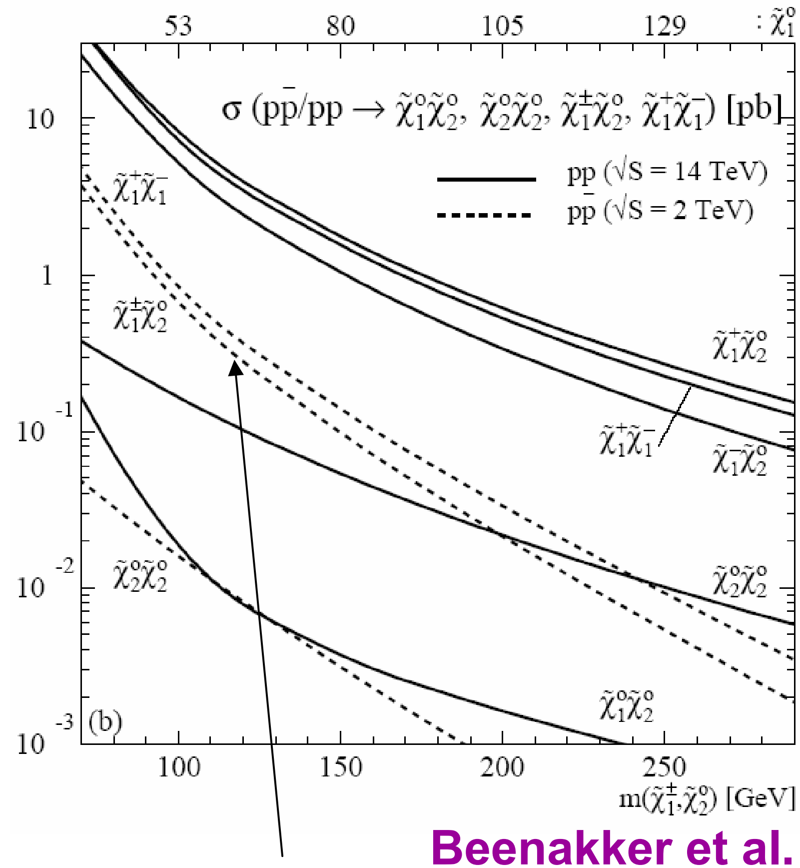
Remember, the lightest SUSY particles are probably not strongly interacting.

Best chance for observing these at Tevatron with current luminosities is if leptonic signatures are enhanced.

This is quite possible if the sleptons are also light

Tri-leptons Intro





Beenakker et al.

Golden signature of production of chargino+neutralino is tri-leptons + missing E_T .

Normal BRs of W, Z lead to 3% of WZ giving tri-leptons (including taus).

BR can be enhanced greatly if the sleptons are light.

If staus are significantly lighter than other sleptons, tri-lepton signature will have enhanced fraction of taus.

Example cross-sections. Note that cross-section depends also on the chargino and neutralino couplings.

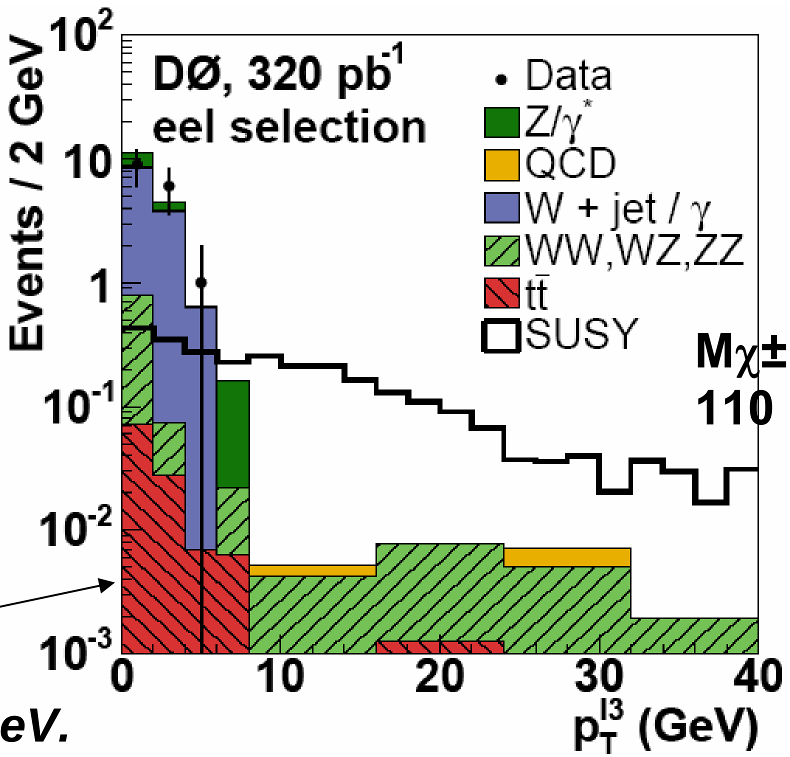
Tri-leptons Channels

D0 has searched in 6 different channels:

eel, eμl, μμl, LS μμ, (eτl, μτl)

For most channels only 2 of the 3 leptons are subject to explicit lepton identification criteria retaining efficiency for one τ.

Premium on triggering and identifying low-p_T leptons.



Mχ± = 110 GeV

Most-sensitive: eel

p_T thresholds are (12, 8, 4) GeV.
Require MET * p_T^{l3} > 220 GeV^2

Selection	Expected Background	Observed	Signal ($m_{\tilde{\chi}^\pm}$=110 GeV)
$ee\ell$	0.21±0.12	0	1.9±0.2
$e\mu\ell$	0.31±0.13	0	1.6±0.1
$\mu\mu\ell$	1.75±0.57	2	1.3±0.2
ls-$\mu\mu$	0.66±0.37	1	0.7±0.1
$e\tau\ell$	0.58±0.14	0	0.4±0.1
$\mu\tau\ell$	0.36±0.13	1	0.7±0.1
Combined	3.87±0.81	4	6.6±0.3

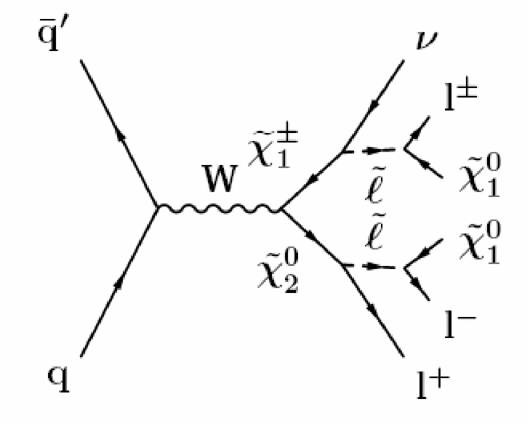
Submitted to PRL

(hep-ex/0504032)

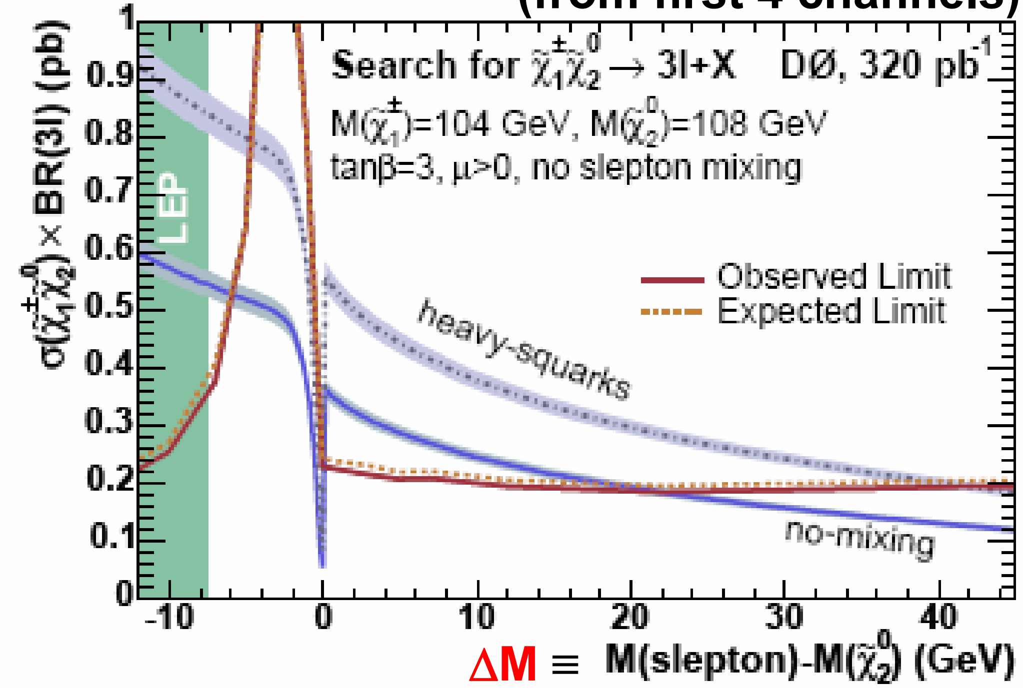
Preliminary

Tri-leptons

If sleptons are light, BR(3l) can be substantial.



(from first 4 channels)



The efficiency of these searches is highly dependent on the softest lepton p_T which depends on the mass splittings when ΔM < 0.

(that is why the σ.B limit varies with ΔM)

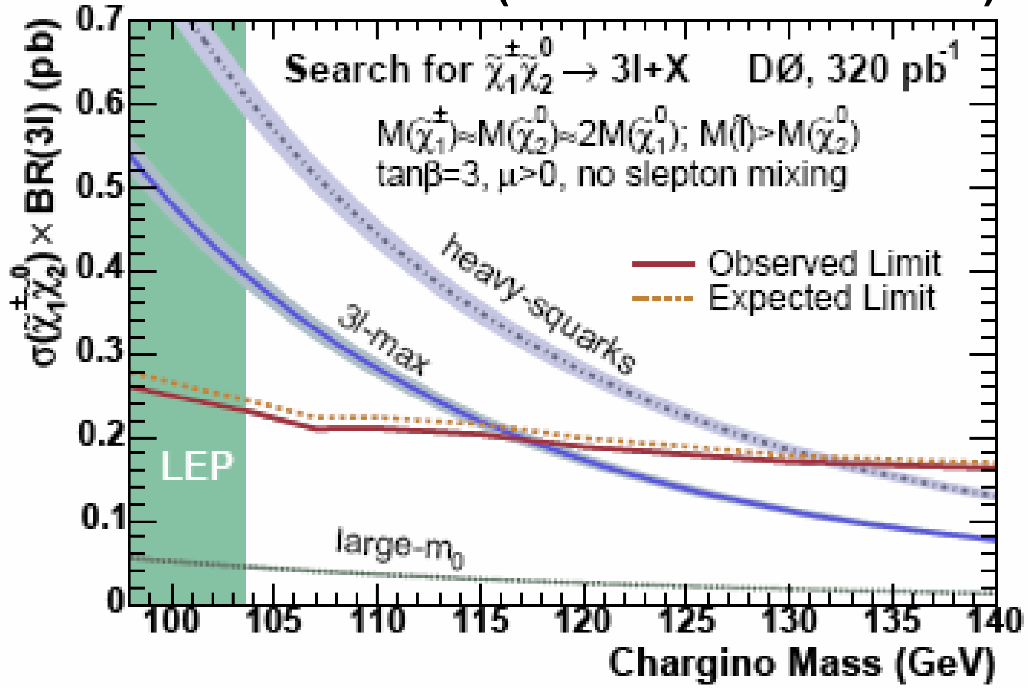
"No slepton mixing" = Mass degenerate lighter sleptons => equal BR to e,μ,τ

For some slepton masses, 104 GeV charginos are excluded for tanβ=3 and μ>0. (blue line > red line)

Cross-section depends also on squark mass (t-channel contribution)

Tri-leptons Chargino Limits

(from first 4 channels)



Model-dependent constraints on charginos beyond the masses probed at LEP

3l-max: $m_{\chi\pm}$ > 117 GeV
Heavy-squarks: $m_{\chi\pm}$ > 132 GeV

σ.B limit improved by about a factor of 10 from DØ RunI

For ΔM>0, the slepton mass which maximizes BR(3l) via 3-body decays was found : “3l-max” curve.

For ΔM≫0, W/Z exchange dominates : “large-m_0” curve, no mass limits yet.

Summary

- RunII Tevatron ($\sqrt{s}$=1.96 TeV), with analyzed data-sets per experiment around 0.3 fb^{-1}, is **now** *exploring new ground* beyond Run I (0.1 fb^{-1} at $\sqrt{s}$=1.8 TeV) with much improved detectors and triggers
- So far, no clear signals for physics beyond the SM
- Much more data foreseen in the next few years (**X 25**)
- Considerable **discovery** potential for sparticles above 100 GeV
- Stay tuned to SM Higgs, MSSM Higgs, jets+Missing E_T, tri-leptons and the unexpected in the next few years
  - More details, updates and other results (eg. top) see:
  - http://www-cdf.fnal.gov/physics/physics.html
  - http://www-d0.fnal.gov/results/index.html