SUSY at Accelerators (other than the LHC)

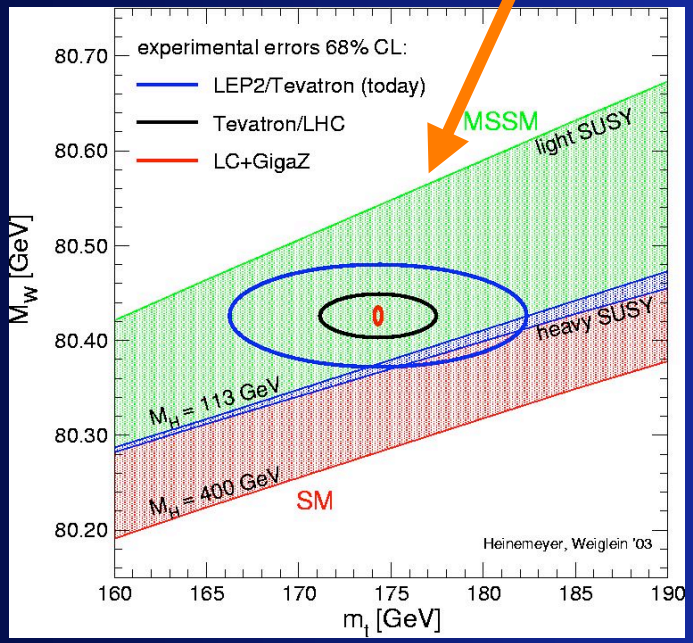
Beate Heinemann, University of Liverpool

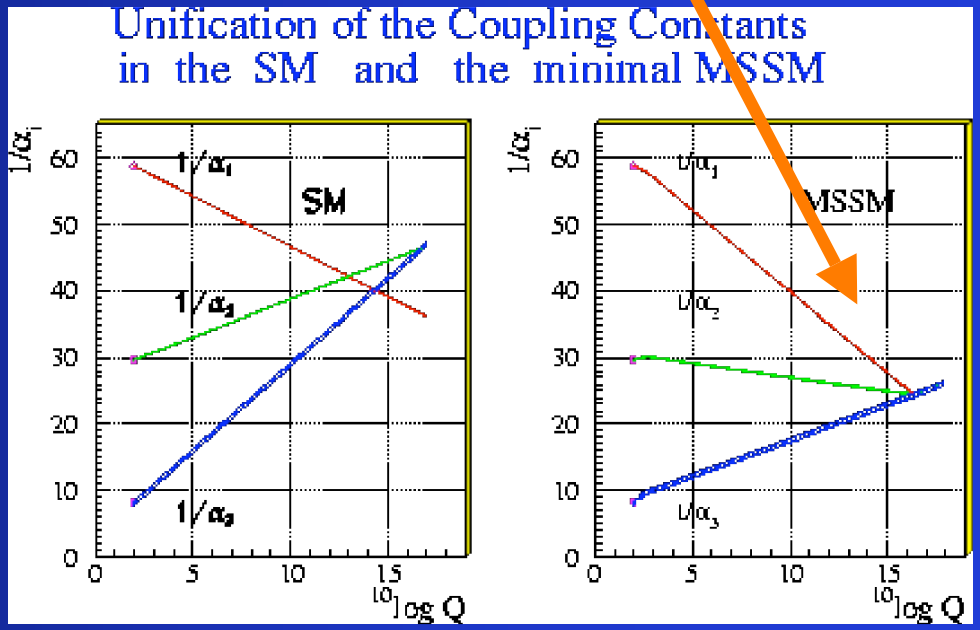
- Introduction
- Final LEP Results
- First Tevatron Run 2 Results
- Summary and Outlook

IDM 2004, Edinburgh, September 2004

Why do we like SUSY?

- Theoretical motivations
  (e.g. solves the hierarchy problem (M_{Pl}/m_{EW}), includes gravity, …)
- Good agreement with EW precision data and gauge coupling unification





- Provides a natural Cold Dark Matter candidate

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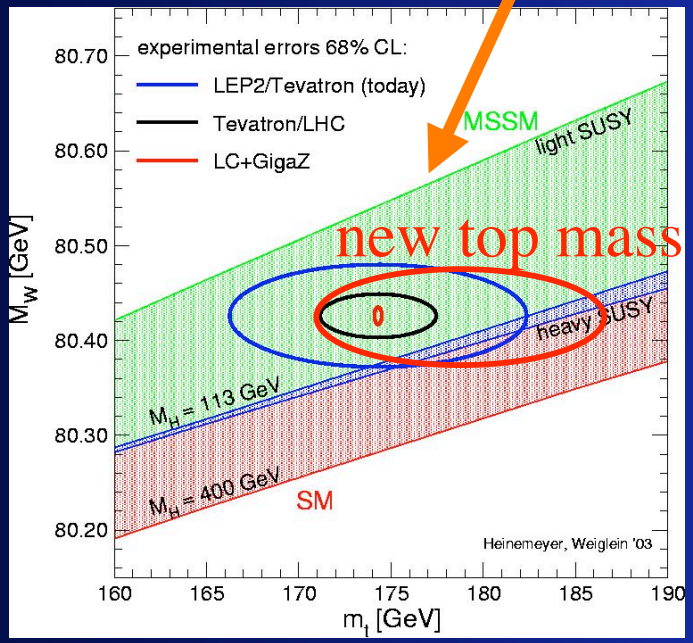

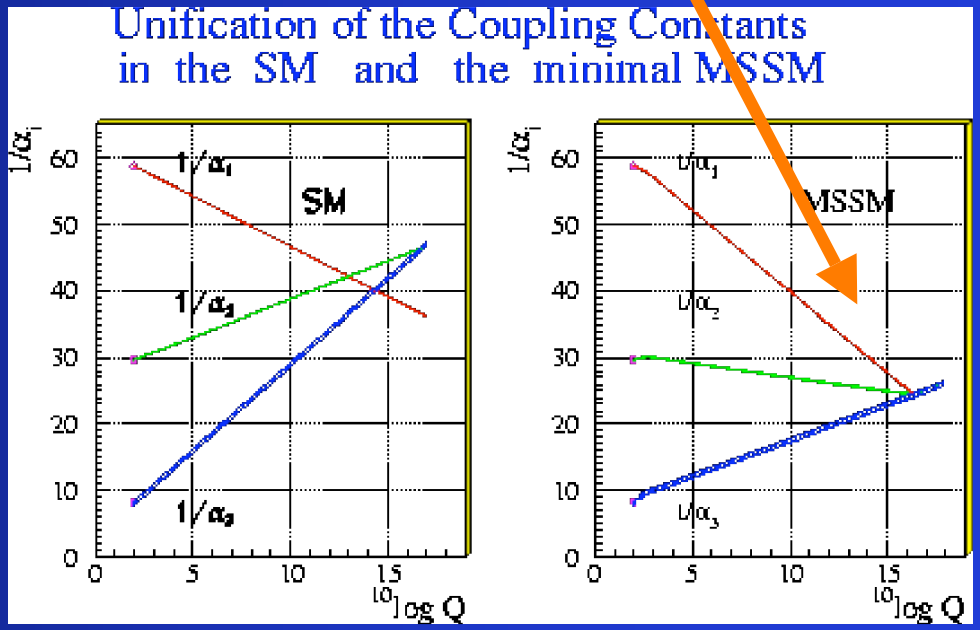

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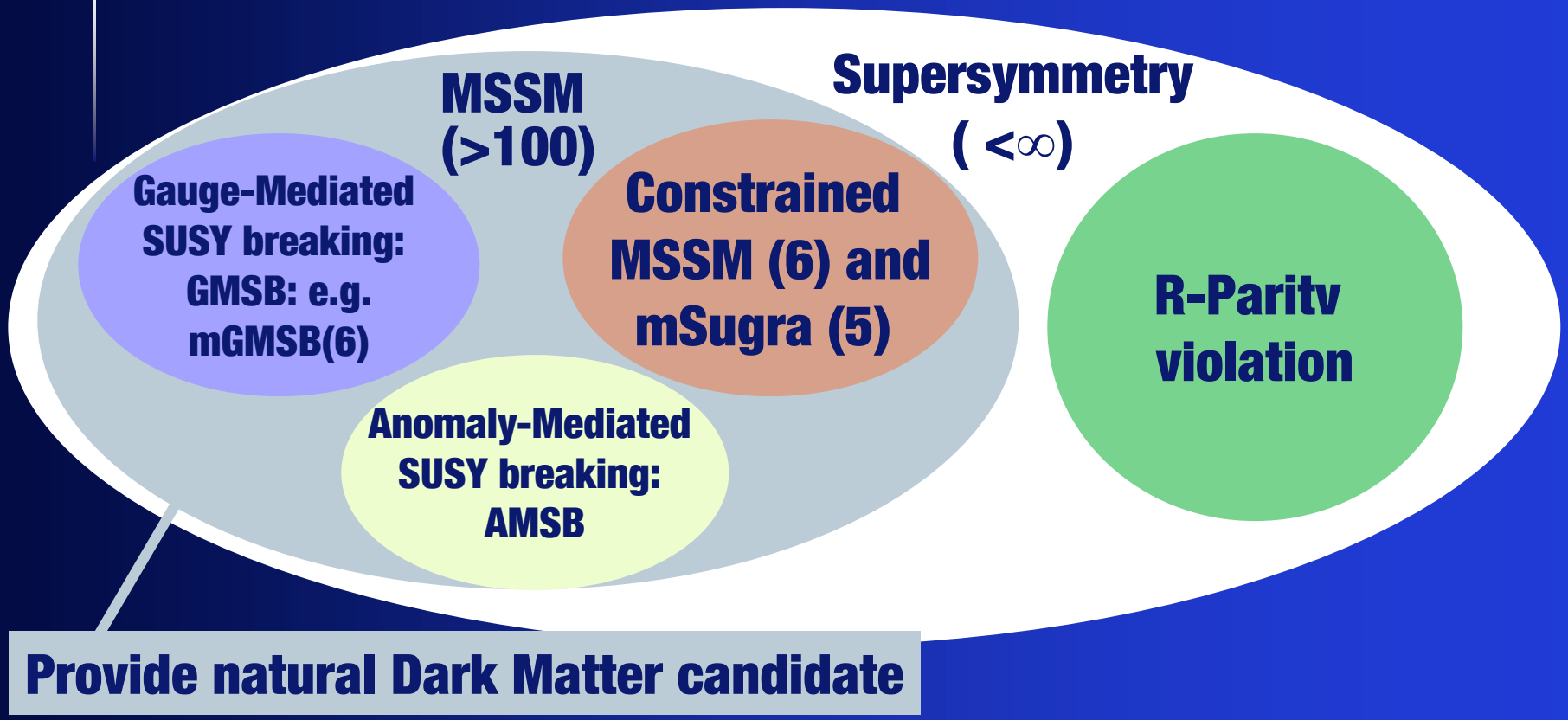
Supersymmetric Models



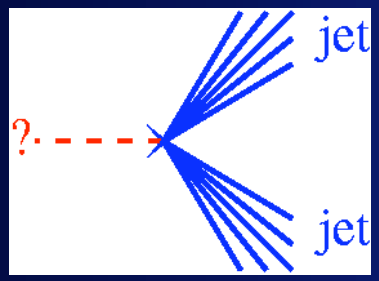
Provide natural Dark Matter candidate

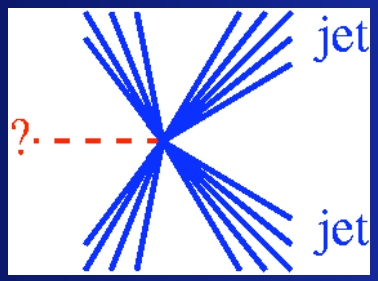
Will focus on MSSM (mSUGRA and GMSB):

- provide natural dark matter candidate
- have most experimental results

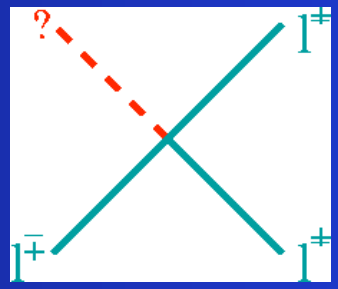
How to look for SUSY

- LSP = lightest neutralino (or sneutrino or stau)
- Typical search : NLSP → LSP + (SM particles), LSP undetected : $\not{E}_t$
- Sensitivity:
  - LEP: $m_{NLSP} \sim \sqrt{s}/2 \leq 103.5$ GeV
  - Tevatron: 100- 500 GeV (depends on particle)
- Example topologies:

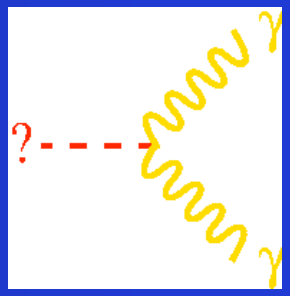




squarks, gluinos

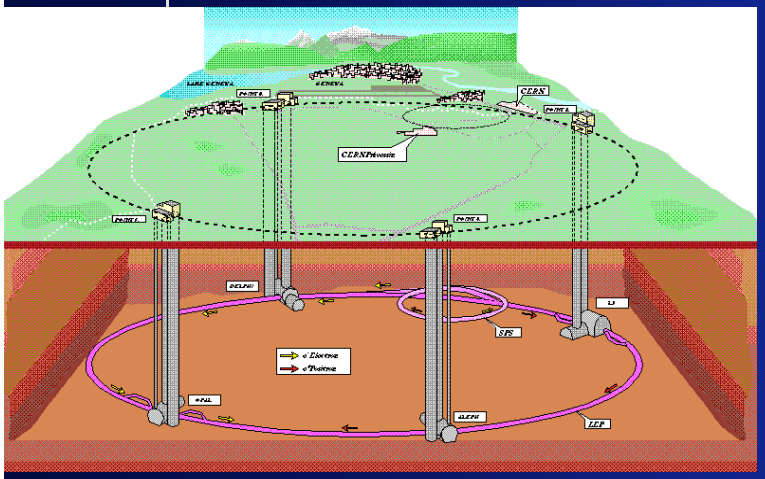


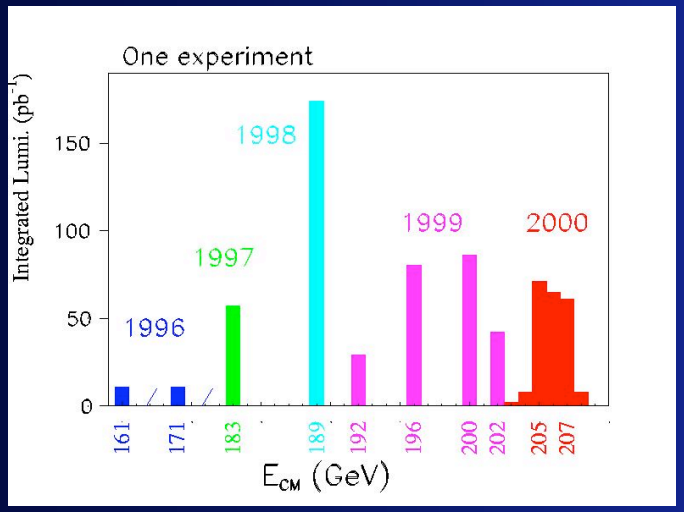
chargino+neutralino



GMSB

LEP II: Geneva



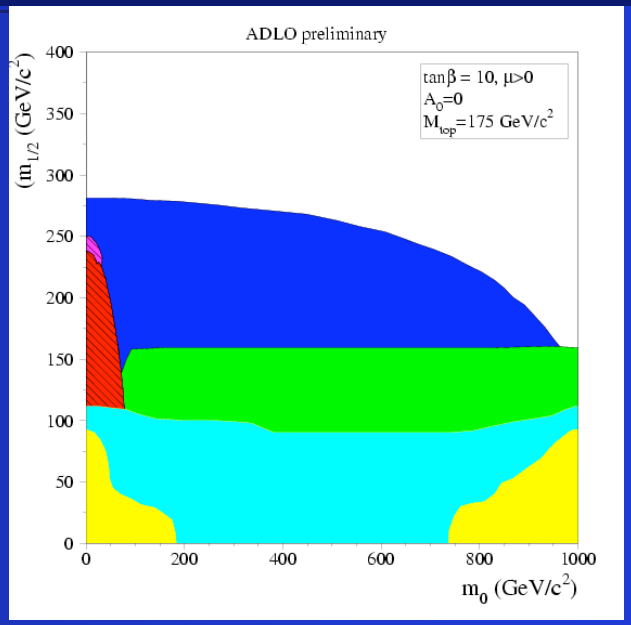


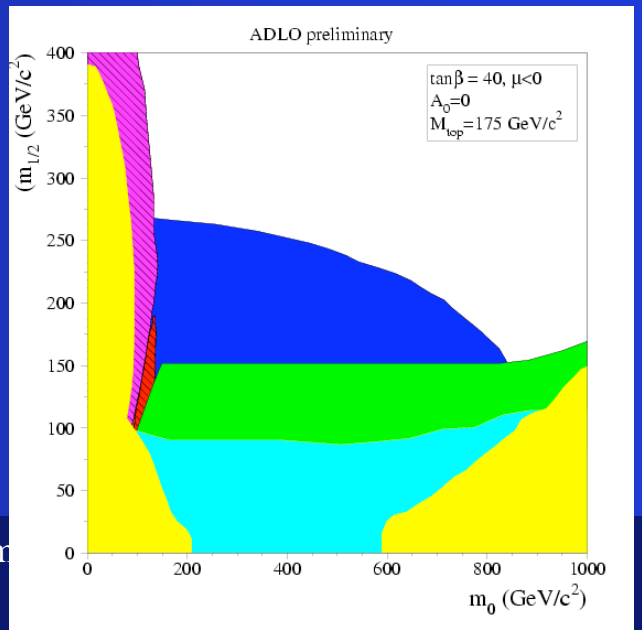
- e+e- collider at CERN:
  Energies 160-207 GeV
  (~140 pb^{-1} / exp at $E_{cm} \geq 206$ GeV)
- 4 experiments:
  - ALEPH, DELPHI, L3, OPAL
  - particle identification $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$, γ, b, c
  - Trigger efficiency ~ 100 % for $E_{vis} > 5$ GeV
- Accelerator and Experiments exceeded expectations for performance

LEP: final mSUGRA limits

- Theoretically excluded
- LEP1 EWK precision measurements
- Chargino searches
- Selectron and stau searches
- Higgs Search: Zh
- Heavy stable stau

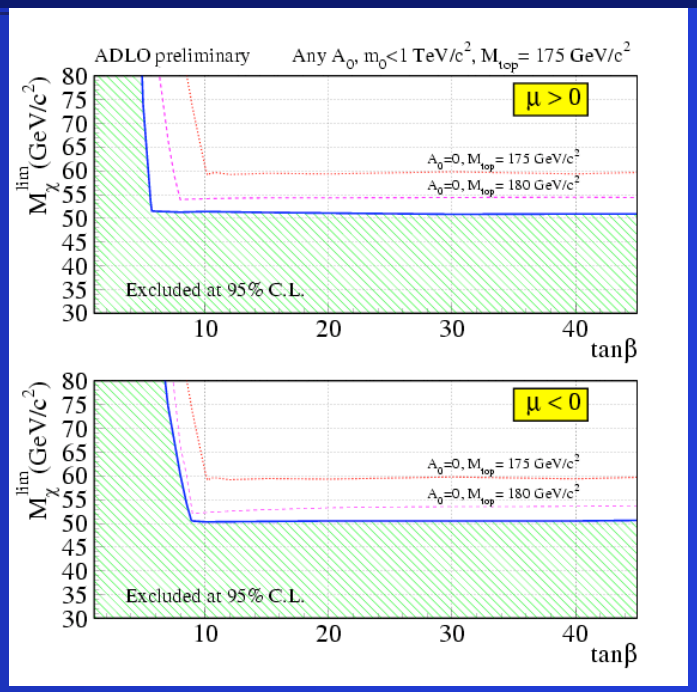
m_0: Common scalar mass at GUT scale
$m_{1/2}$: Common gaugino mass at GUT scale
A_0: Common trilinear scalar interaction at GUT scale
$\tan\beta$: Ratio of Higgs vevs
Sign of μ (Higgsino mass parameter)

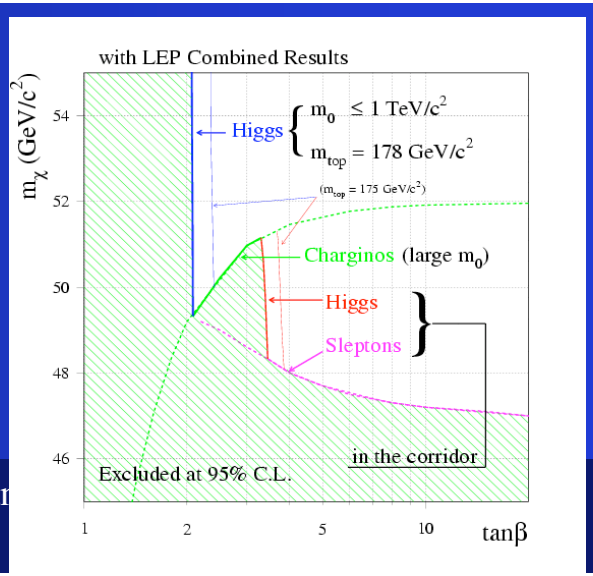




LEP: summary of LSP limits

- Interplay of several searches:
  - Charginos: in a large part of the parameter space
    $m_\chi \sim M_1 \approx M_2/2 \sim m_{\chi^\pm}/2$
  - Sleptons: M_i appear in their masses through the RGEs
  - Higgs boson: through stop quark masses in radiative corrections
- mSUGRA:
  - $M(\chi_1^0)$>50-60 GeV
  - $\tan\beta \geq 4$
- Constrained MSSM
  - $M(\chi_1^0)$>46-50 GeV
  - $\tan\beta \geq 2$



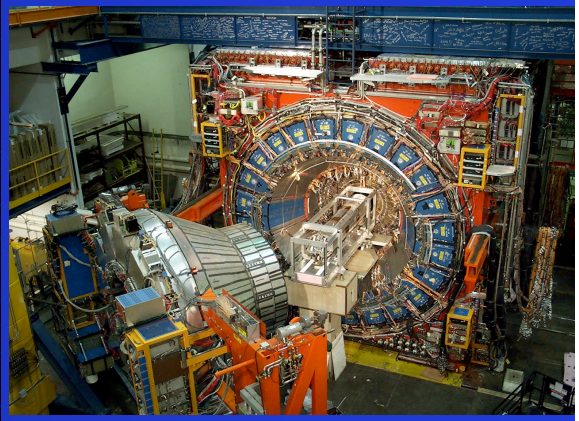


Tevatron Run II

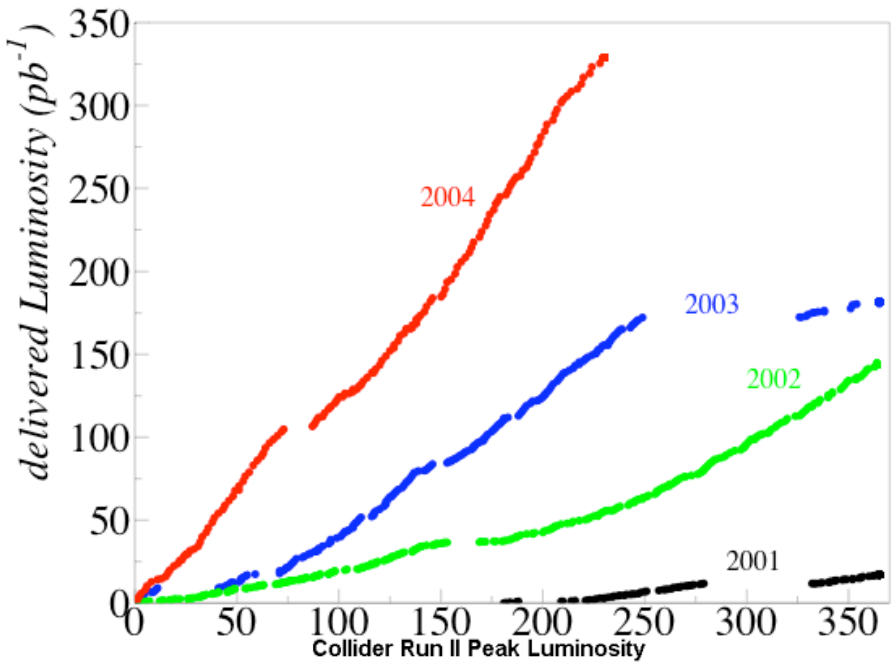
- Upgrade completed in 2001
- Accelerator:

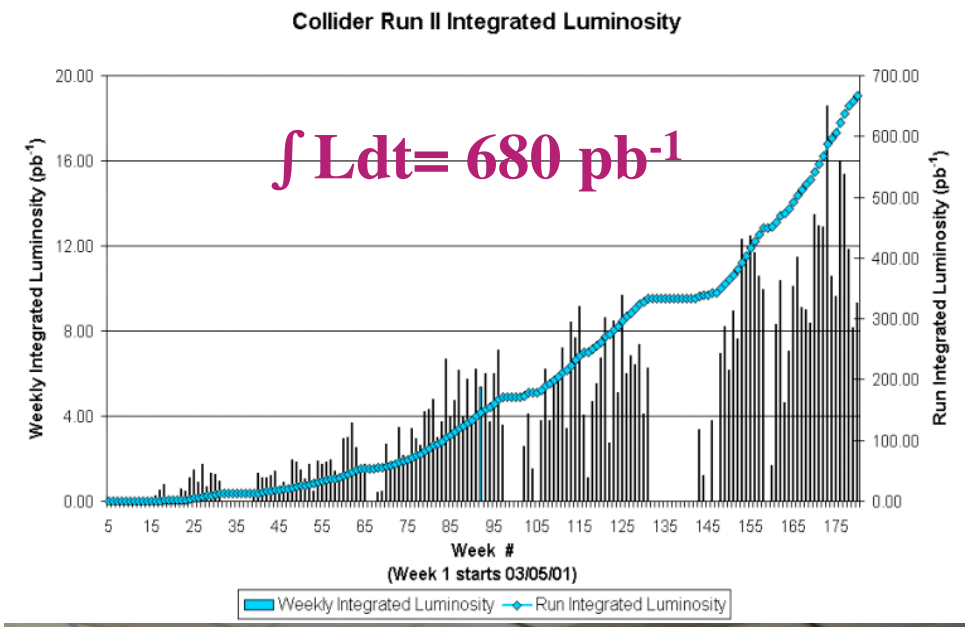
	$\sqrt{s}$(TeV)	Δt(ns)	L($cm^{-2}\ s^{-1}$)
Run I	1.8	3500	2.5×10^{31}
Run II	1.96	396	1.0×10^{32}

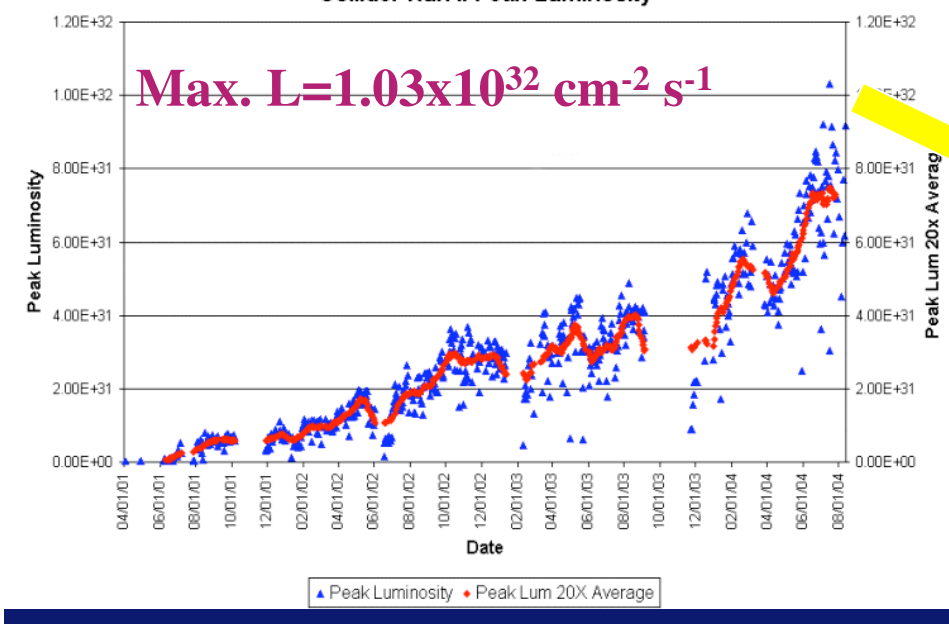
- Experiments CDF and D0
- About 500 pb^{-1} of good data on tape => expect 2 fb^{-1} (4-9 fb^{-1}) by 2006(2009)
- Analysed about 200 pb^{-1}



Tevatron Performance

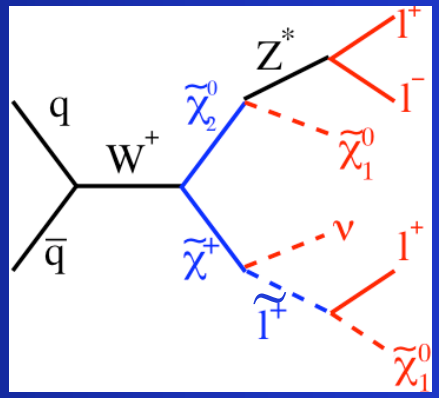


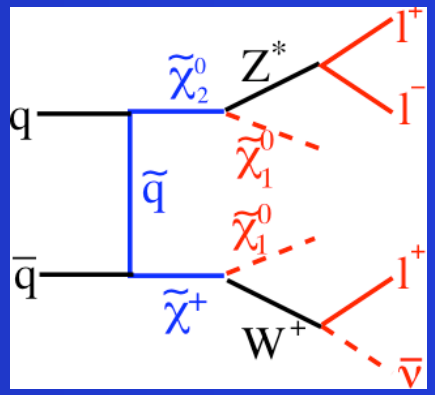




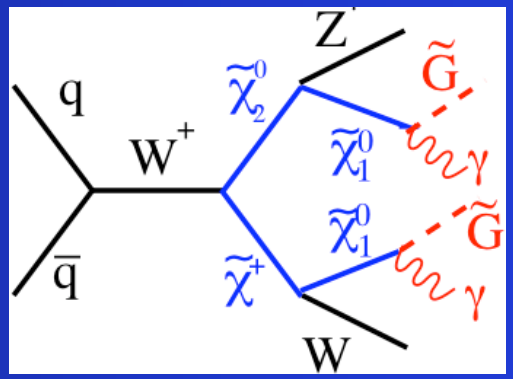
Charginos and Neutralinos

- mSUGRA inspired
  - Neutralino LSP
  - 3 leptons + $\not{E}_t$





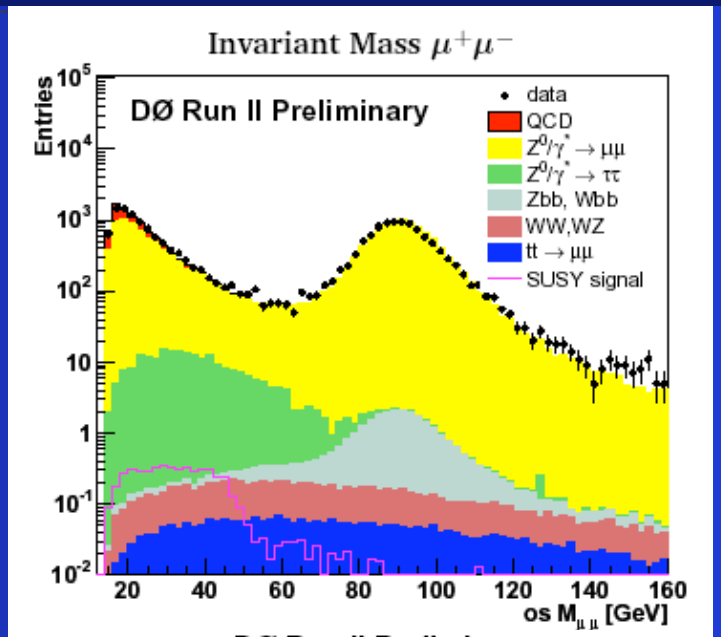
- GMSB inspired:
  - Gravitino LSP m($\tilde{G}$) ~O(keV)
  - Here: Neutralino (NLSP)->$\tilde{G}\gamma$
  - 2 photons + $\not{E}_t$ + X

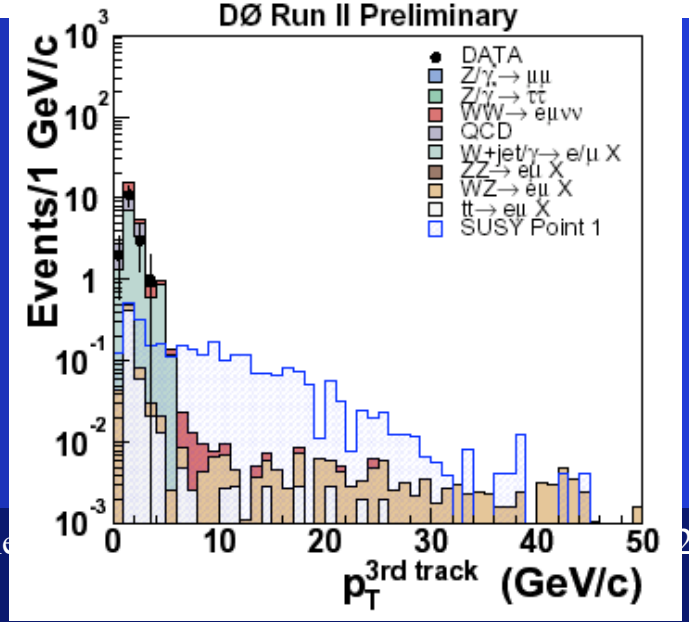


3 leptons + $\not{E}_T$

- Challenge:
  - σxBR low (<0.5 pb)
  - Backgrounds large
- Selection
  - 2 l (l=e,μ) + isolated track or $\mu^\pm\mu^\pm$
  - Significant $\not{E}_T$
  - Topological cuts

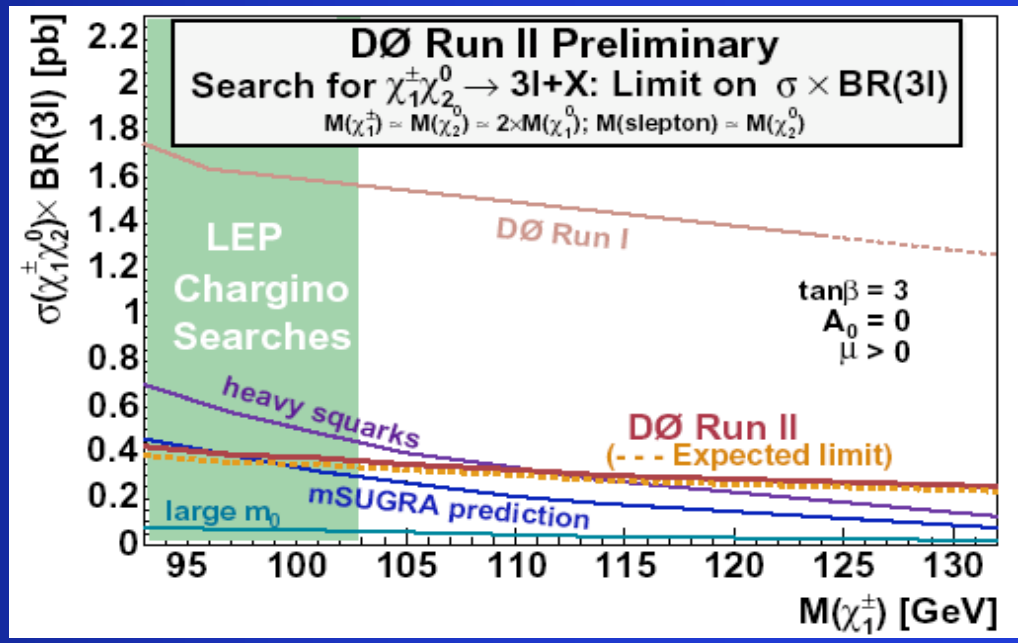
selection	background	observed
eel	0.7±0.5	1
eμl	0.3±0.3	0
$\mu\mu$l	1.8±0.4	1
$\mu^\pm\mu^\pm$	0.1±0.06	1





mSUGRA: 3-lepton result

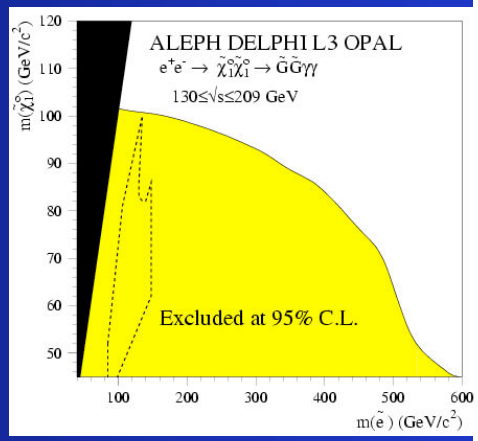
- Combined result:
  - σxBR<0.3-0.4 pb
- Theory comparison
  - mSugra: $m(\chi^{\pm})>97$ GeV
    - $\tan\beta=3$, $A_0=0$, $\mu>0$
    - $M(\chi^{\pm})\approx M(\chi^0_2)\approx 2M(\chi^0_1)$
  - Heavy squarks: $m(\chi^{\pm})>111$ GeV
    - Reduce destructive interference
  - Large m_0:
    - Sleptons heavy
    - Very difficult

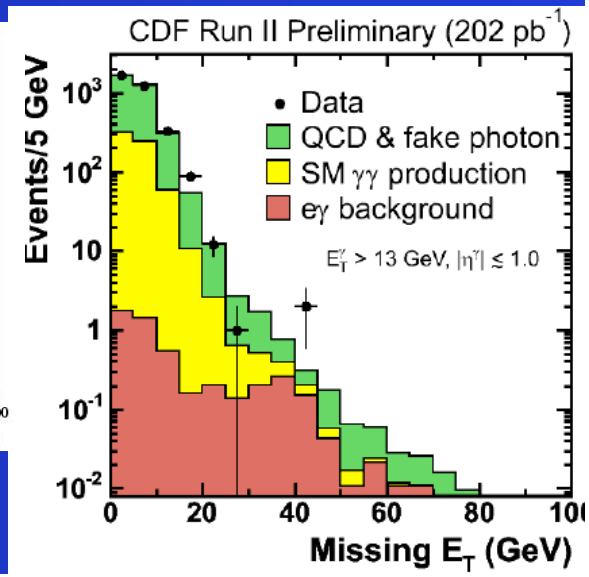


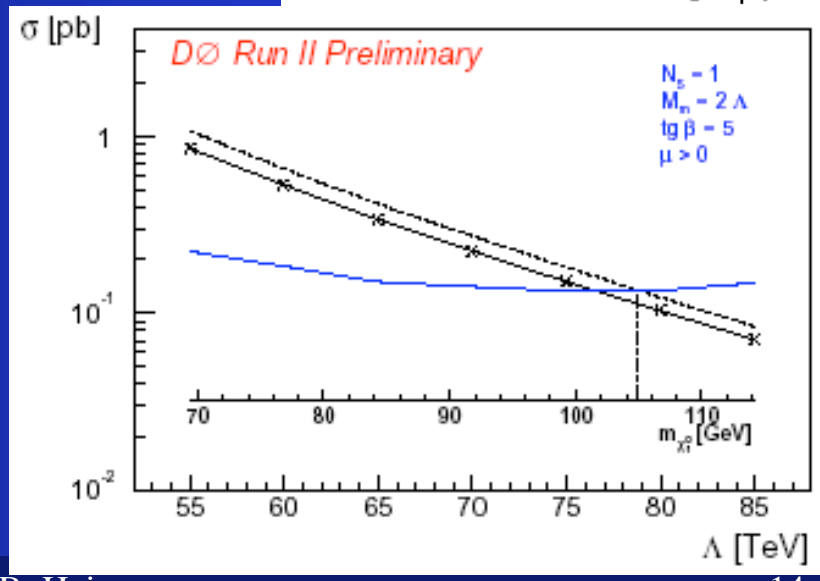
Will extend sensitivity beyond LEP with just 25% more data:
Two times more already on tape!

GMSB: $\gamma\gamma+\not{E}_t$

- Assume χ^0_1 is NLSP:
  - Decay to $\tilde{G}+\gamma$
  - $\tilde{G}$ light M~O(1 keV)
  - Inspired by CDF $ee\gamma\gamma+\not{E}_t$ event: now ruled out by LEP
- D0 (CDF) Inclusive search:
  - 2 photons: E_t > 20 (13) GeV
  - $\not{E}_t$ > 40 (45) GeV



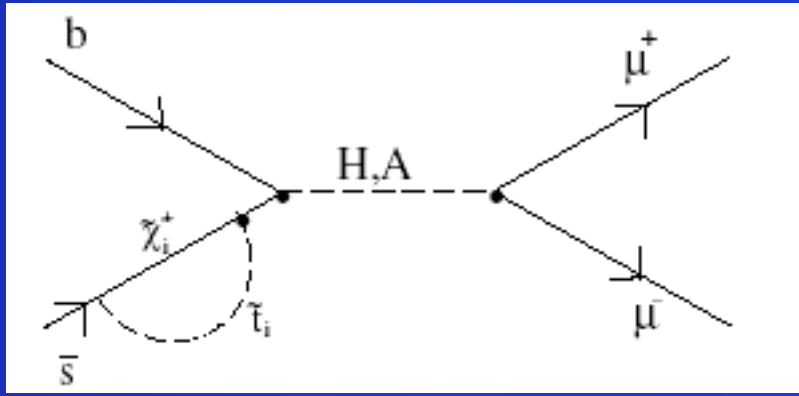


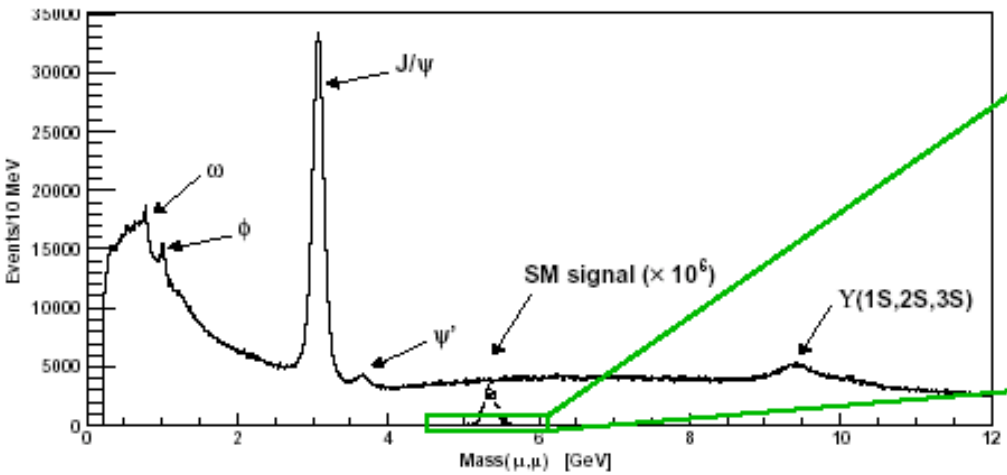


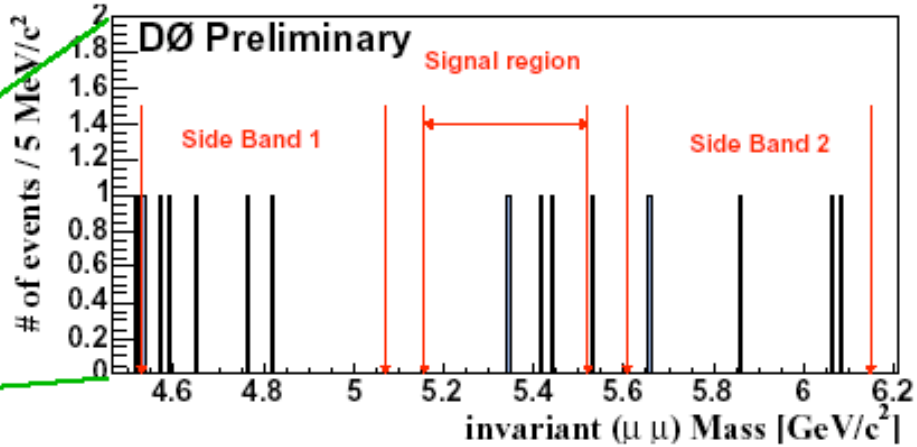
	Exp.	Obs.	$M(\chi^+_1)$
D0	2.5±0.5	1	>192 GeV
CDF	0.3±0.1	0	>168 GeV

Indirect Search: $B_s \to \mu\mu$

- BR($B_s \to \mu\mu$):
  - SM: 3.5×10^{-9} (G. Buchalla, A. Buras, Nucl. Phys. B398, 285)
  - SUSY:
    - 3 order of magnitude enhancement (Arnewitt et al., Phys. Lett. B538, 121)
    - $\propto \tan^6\beta$ (G. Kane et al., hep-ph/0310042)
- Selection:
  - 2 muons, displaced vertex+other







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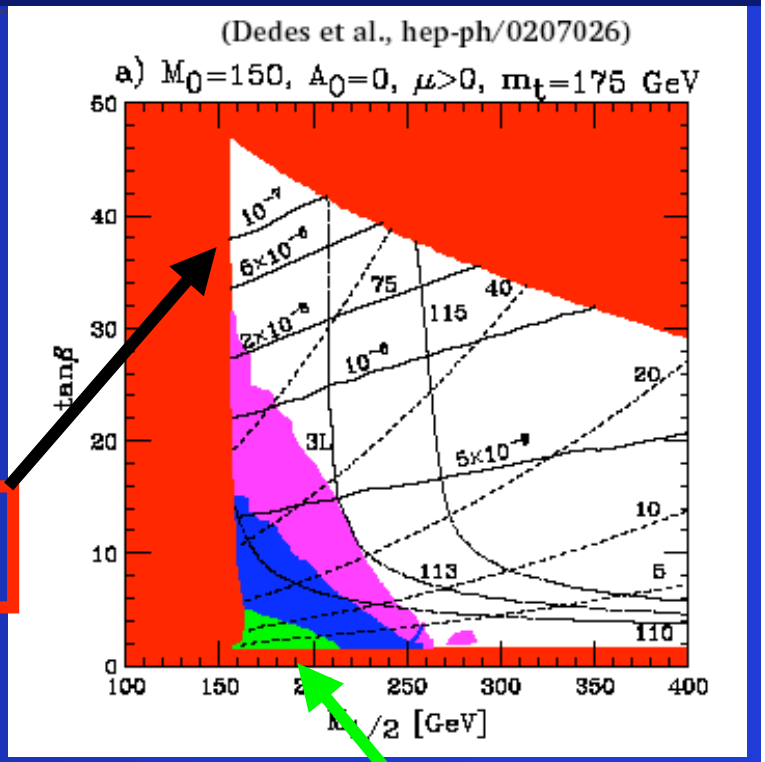


1×10^{-7}

Trileptons: $2fb^{-1}$

	D0 (prel.)	CDF
expected	3.7±1.1	1.1±0.3
observed	4	1
BR@90% C.L.	$<3.8\times10^{-7}$	$<5.8\times10^{-7}$

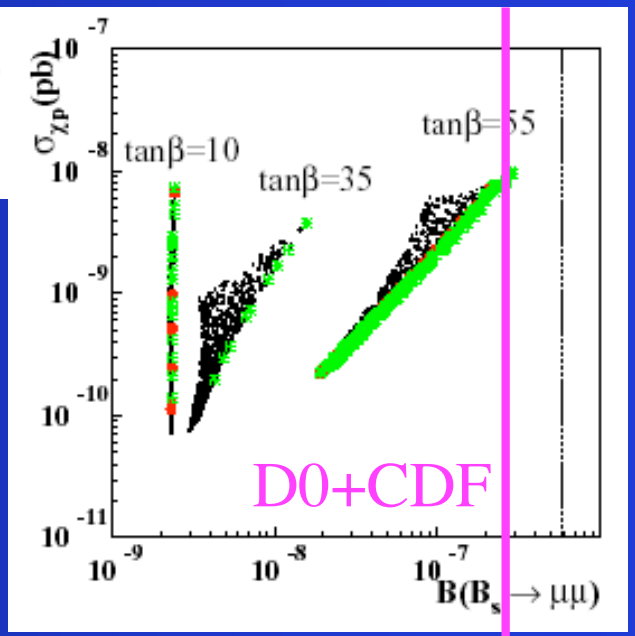
Combined CDF+D0: $BR<2.6\times10^{-7}$

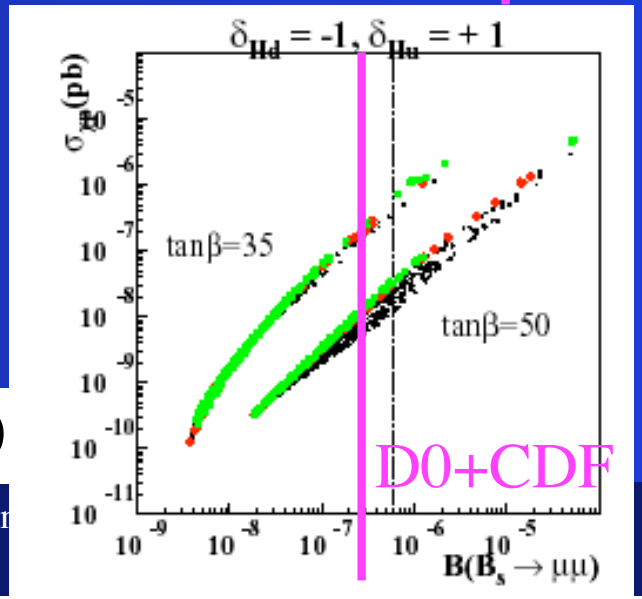
Bs->μμ vs DM cross section

Less than, within, Greater than 2 σ of WMAP,

(P. Ko, SUSY 04)

- Probe SUSY parameter space consistent with WMAP data:
  - mSUGRA: just touching…
  - Non-minimal models (Cerdano, Munoz): already constraining
- Bs->μμ in competition with direct DM detection experiments





M_0=300 GeV, A_0=0

Bs->μμ vs DM cross section

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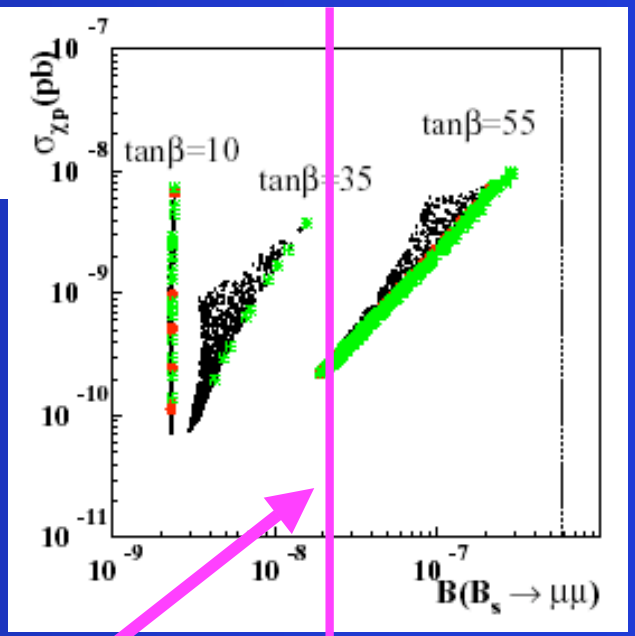
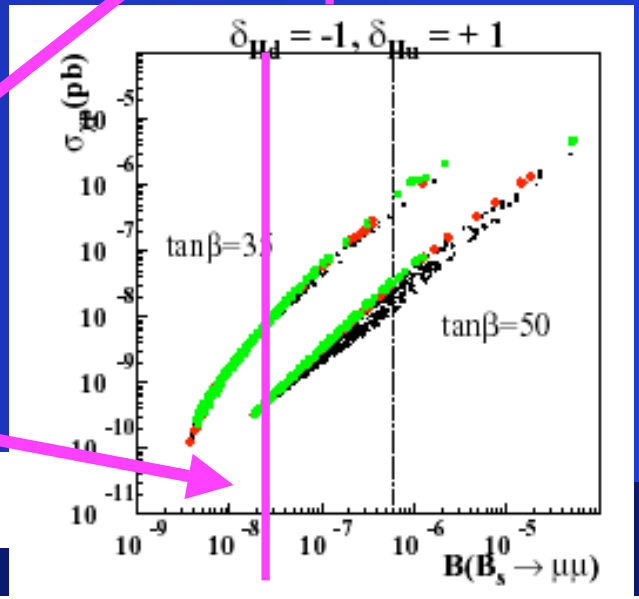
- Bs->μμ in competition with direct DM detection experiments
- Will achieve: $<2\times10^{-8}$





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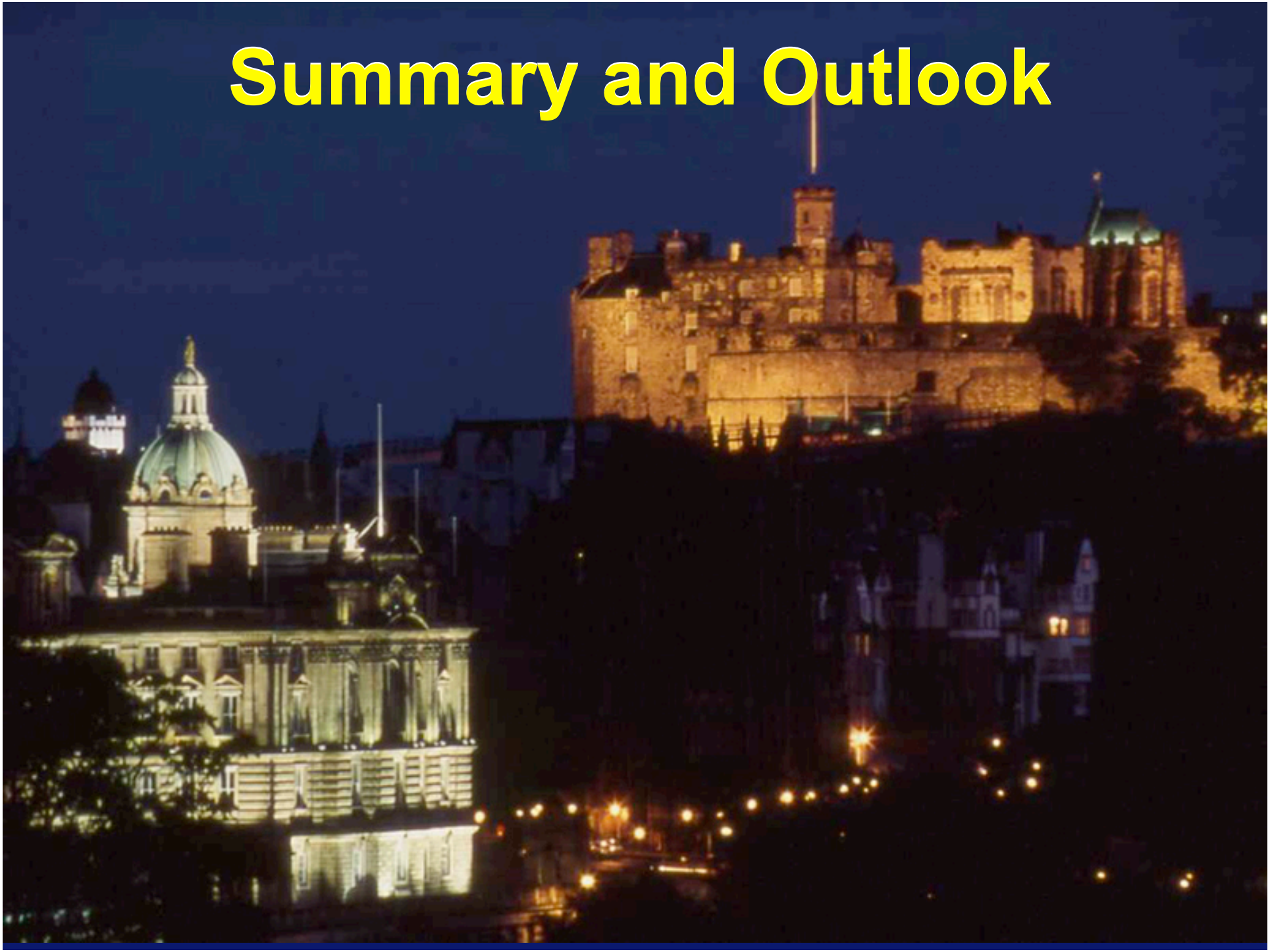
Summary and Outlook



Summary and Outlook

- LEP severely constrained mSUGRA and beyond:
  - LSP mass >50 GeV
  - Chargino mass>103.5 GeV

Summary and Outlook

- Tevatron Run 2 has started and is running:
  - 1st result available: direct and indirect
  - Have started to constrain parameter space
  - Expect 20-50 times more data by start of LHC: 4-9 fb^{-1}

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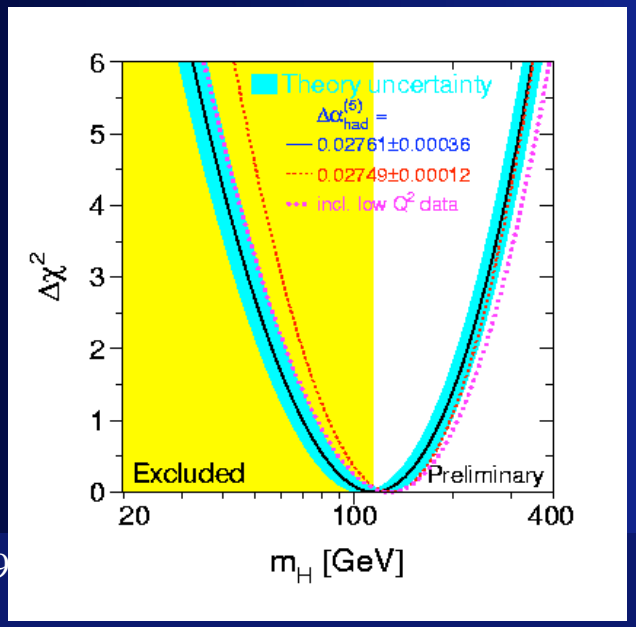
Hope we don't have to wait for the LHC to find Dark Matter at colliders!

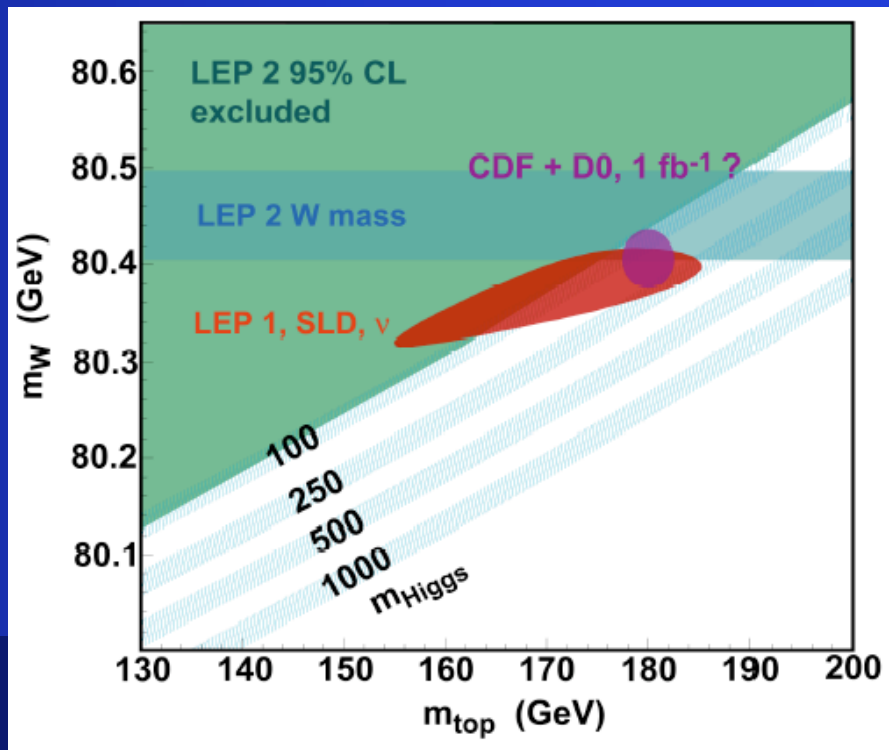
Backup Slides

The Higgs boson

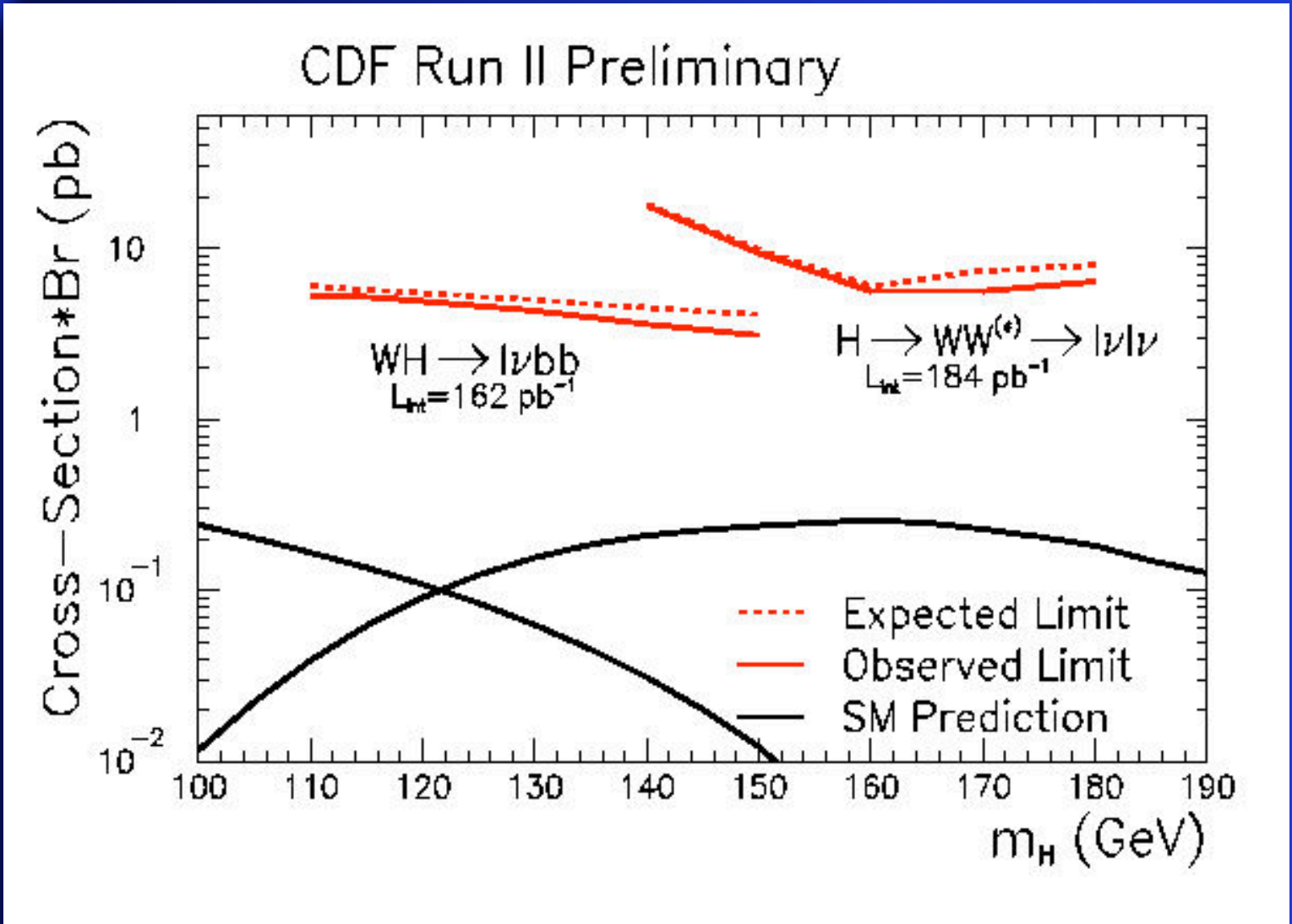
- Precision measurements of
  - M_W =80.412 ± 0.042 GeV/c^2
  - M_{top}=178.0 +- 4.3 GeV/c^2
- Prediction of higgs boson mass within SM due to loop corrections
  - Most likely value: 114 GeV
- Direct limit (LEP): m_h>114.4 GeV

Better prediction with expected improvements on W and top mass precision



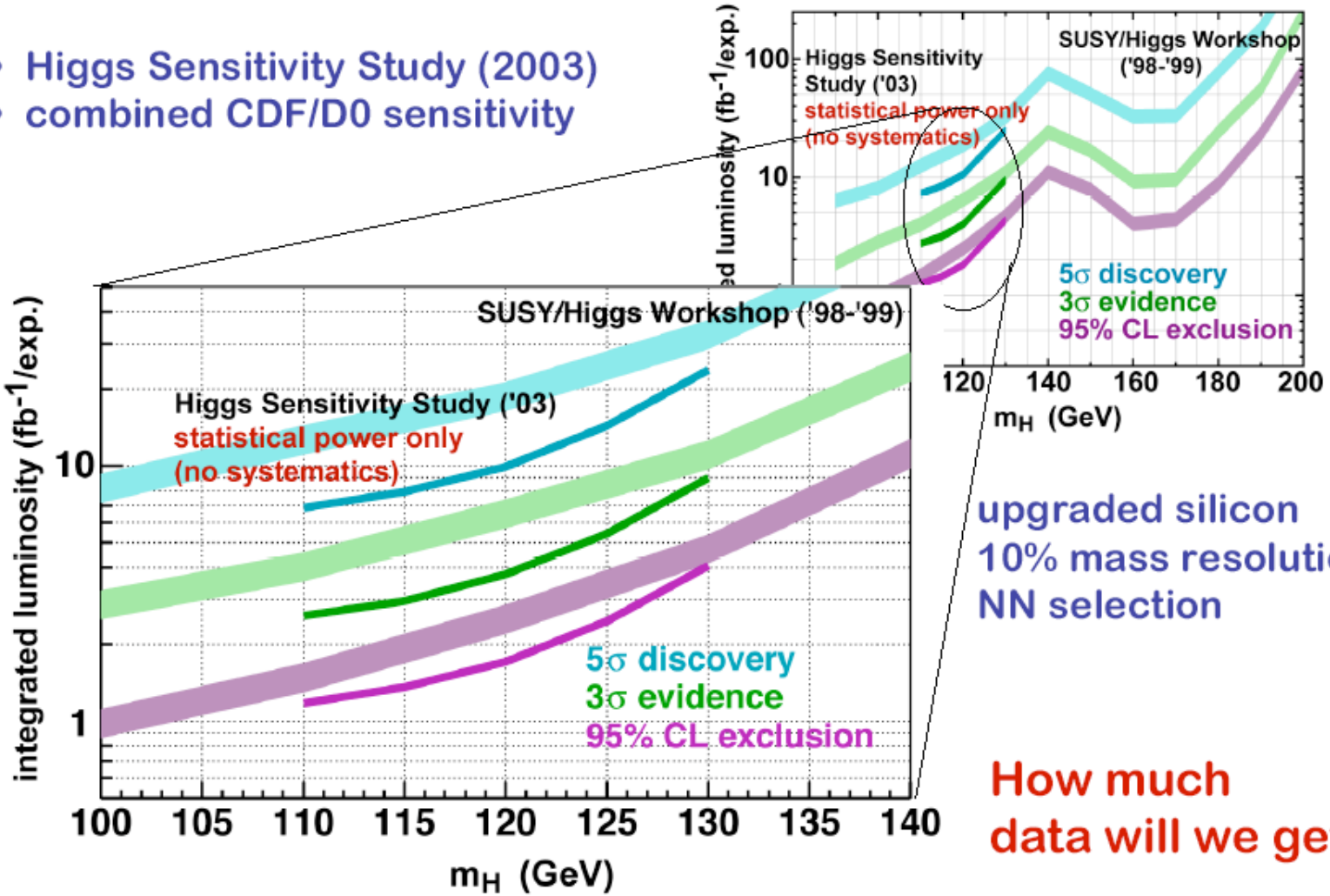


Summary of CDF Higgs Searches



Higgs Discovery at Tevatron?

- Higgs Sensitivity Study (2003)
- combined CDF/D0 sensitivity

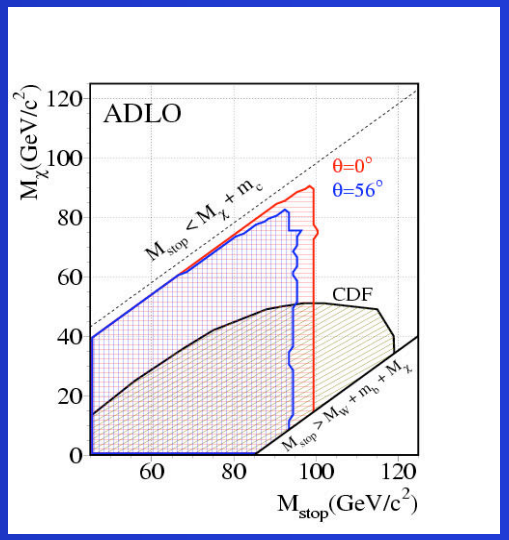


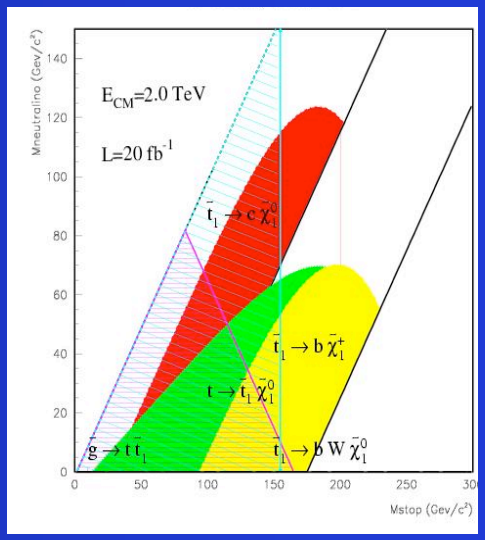
upgraded silicon
10% mass resolution
NN selection

How much data will we get?

Squarks

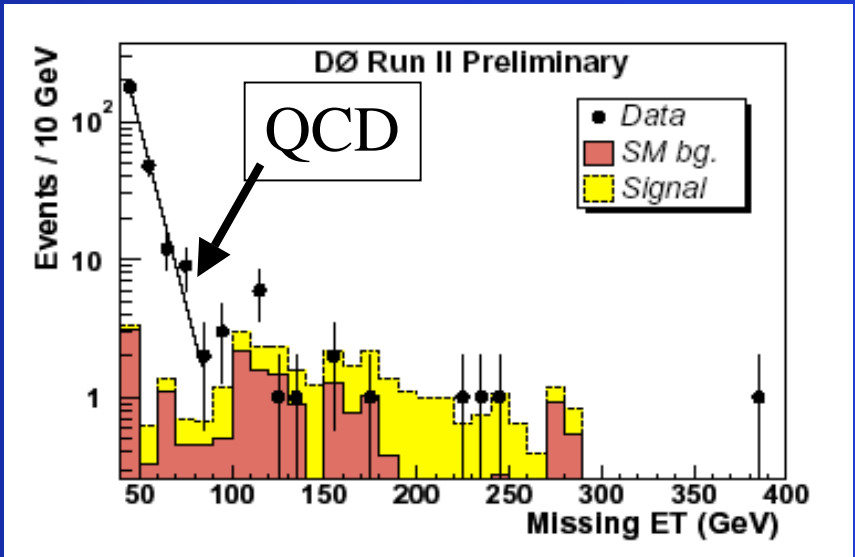
- Typical signature:
  - Jet and $\not{E}_t$
- Interesting:
  - Mixing of mass eigenstates
    - 3rd generation squarks (stop, sbottom) could be very light (<200 GeV)
  - Large production cross sections at Tevatron

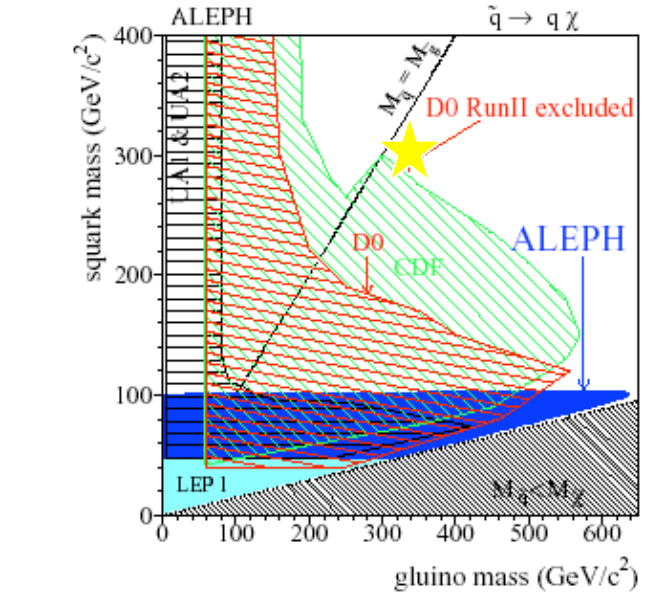




Generic Squarks and Gluinos

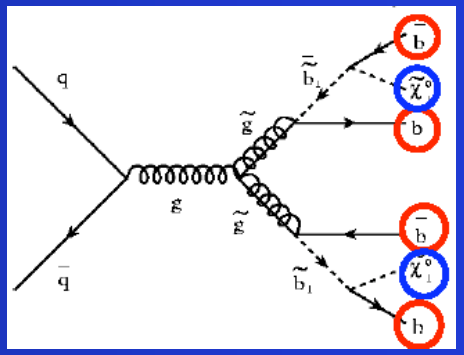
- Signature: $\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0 q\tilde{\chi}_1^0$
  - 2 jets and $\not{E}_t$
  - $\sum P_t^{jet} > 275$ GeV
  - $\not{E}_t > 175$ GeV
- Observe: 4, Expect: 2.7±1.0
- mSugra
  - Fix: m_0=25 GeV, tanβ=3, A_0=0,μ<0
  - Exclude: m(q/g) < 292/333 GeV
- Improves Run I limits:
  - Include more data
  - Scan parameter space

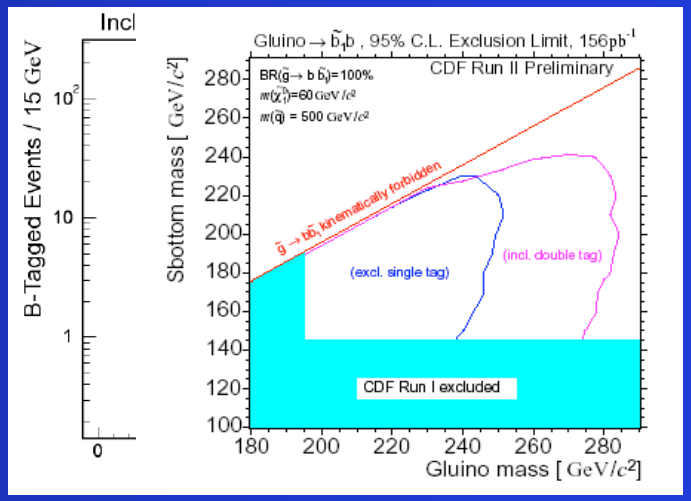




Bottom Squarks

- High tanβ scenario:
  - Sbottom could be light
- This analysis:
  - Gluino rather light: 200-300 GeV
  - BR($\tilde{g}$->$\tilde{b}$b)~100% assumed
- Spectacular signature:
  - 4 b-quarks + $\not{E}_T$
- Require b-jets and $\not{E}_T$>80 GeV





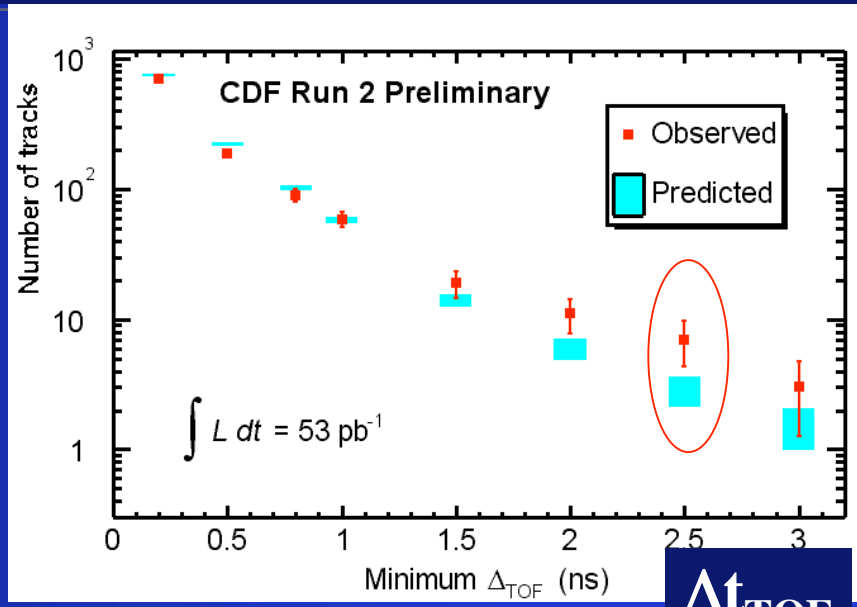
Expect:2.6±0.7

Observe: 4

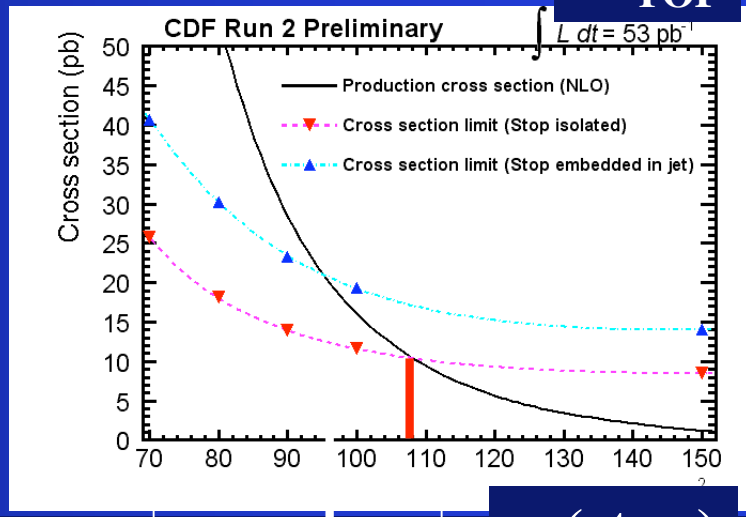
Exclude new parameter space in gluino vs. sbottom mass plane

Stop Quarks

- Model:
  - any charged massive particle (e.g. stop, stau) with long lifetime: "quasi-stable"
  - Assume: fragments like b-quark
- Signature
  - Use Time-Of-Flight Detector:
    - $R_{TOF} \approx 140$cm
    - Resolution: 100ps
  - Heavy particle=> v<<c
  - $\Delta t_{TOF} = t_{track} - t_{event}$ = 2-3 ns
- Result for Δt_{TOF} >2.5 ns:
  - expect 2.9±3.2, observe 7
- σ<10-20pb at m=100 GeV
  $M(\tilde{t})$>97-107 GeV @ 95%C.L.



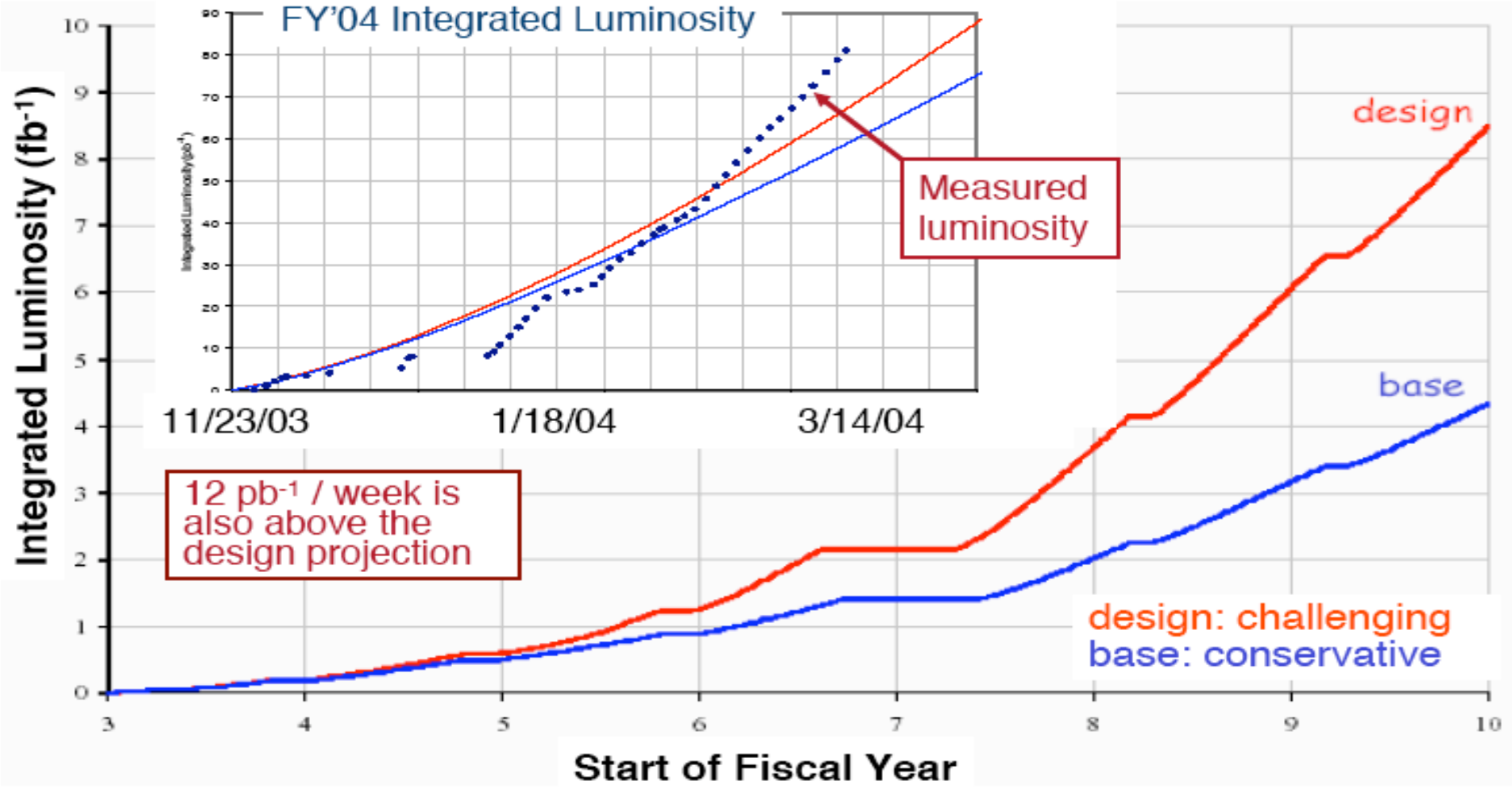
Δt_{TOF}



LEP: 95 GeV

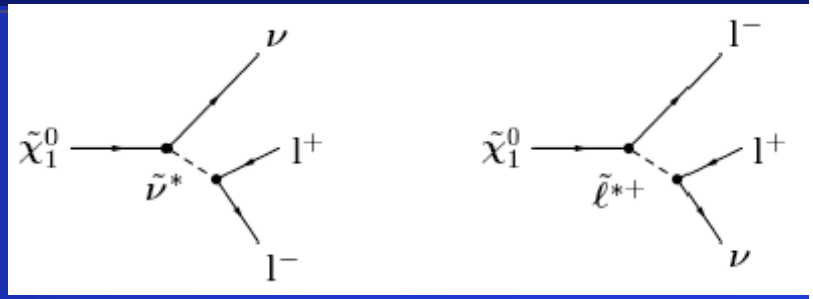
m(stop)

Luminosity Perspectives

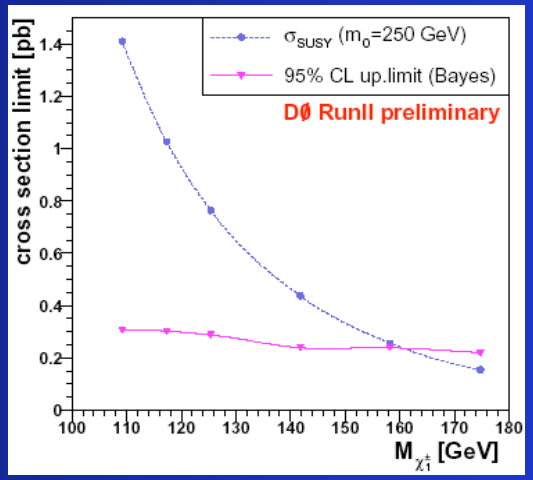


RPV Neutralino Decay

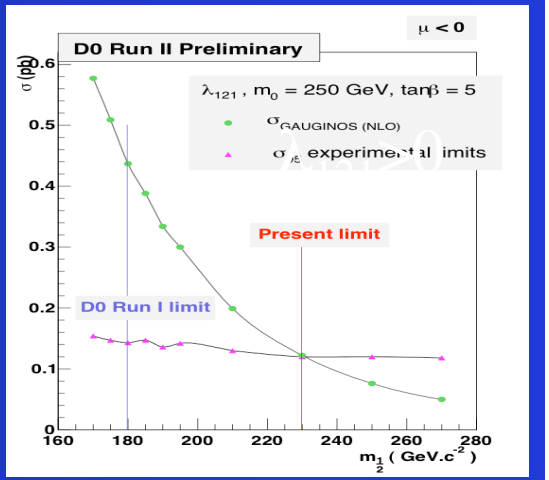
- Model:
  - R-parity conserving production => two neutralinos
  - R-parity violating decay into leptons
  - One RPV couplings non-0: λ_{122} , λ_{121}
- Final state: 4 leptons + $\not{E}_t$
  - eee, eeμ, μμe, μμμ
  - 3rd lepton P_t>3 GeV
  - Largest Background: $b\bar{b}$
- Interpret:
  - M_0=250 GeV, tanβ=5



D0 result	Obs.	Exp.
eel (l=e,μ)	0	0.5±0.4
μμl (l=e,μ)	2	0.6+1.9-0.6



$m(\tilde{\chi}^+_1)$ >160 GeV



$m(\tilde{\chi}^+_1)$ >183 GeV