SUSY Without Prejudice : I
Background & Experimental Constraints

"We will restore science to its rightful place…"

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arXiv: 0812.0980

02/11/2009

The MSSM has many nice features, e.g., Dark Matter candidates, but is very difficult to study in any detailed, model-independent manner due to the very large number of soft SUSY breaking parameters (~ 120).

To circumvent this issue, authors generally limit their analyses to a specific SUSY breaking scenario(s) such as mSUGRA, GMSB, AMSB,… which determines the sparticle (e.g., the LSP's) couplings & signatures in terms of a few parameters.

But how well do any or all of these reflect the true breadth of the MSSM?? Do we really know the MSSM as well as we think??

Is there another way to approach this problem & yet remain *more general*? *Some* set of assumptions are necessary to make any such study practical. But what? There are many possibilities.

mSUGRA $\neq$ MSSM !!!

FEATURE Analysis Assumptions :

- The most general, CP-conserving MSSM with R-parity
- Minimal Flavor Violation
- The lightest neutralino is the LSP.
- The first two sfermion generations are degenerate (sfermion type by sfermion type).
- The first two generations have negligible Yukawa's.
- No assumptions about SUSY-breaking or GUT

This leaves us with the pMSSM:

→ the MSSM with 19 real, weak-scale parameters…

What are they??

19 pMSSM Parameters

sfermion masses: m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3}, m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}

gaugino masses: M_1, M_2, M_3

tri-linear couplings: A_b, A_t, A_τ

Higgs/Higgsino: μ, M_A, $\tan\beta$

Note: These are TeV-scale Lagrangian parameters

What are the Goals of this Study???

- Prepare a large sample, ~50k, of MSSM models (= parameter space points) satisfying 'all' of the experimental constraints. A large sample is necessary to get a good feeling for the variety of possibilities. (Done)
- Examine the properties of the models that survive. Do they look like the model points that have been studied up to now???? What are the differences?
- Do physics analyses with these models for LHC, ILC/CLIC, Fermi/GLAST, PAMELA/ATIC, etc. etc. – all your favorites!

→ Such a general analysis allows us to study the MSSM at the electroweak/TeV scale without any reference to the nature of the UV completion: GUTs? New intermediate mass scales? Messenger scales?

How? Perform 2 Random Scans

Linear Priors

10^7 points – emphasize moderate masses

$100\ \text{GeV} \leq m_{\text{sfermions}} \leq 1\ \text{TeV}$

$50\ \text{GeV} \leq |M_1, M_2, \mu| \leq 1\ \text{TeV}$

$100\ \text{GeV} \leq M_3 \leq 1\ \text{TeV}$

$\sim 0.5\ M_Z \leq M_A \leq 1\ \text{TeV}$

$1 \leq \tan\beta \leq 50$

$|A_{t,b,\tau}| \leq 1\ \text{TeV}$

Log Priors

$2\text{x}10^6$ points – emphasize lower masses but extend to higher masses

$100\ \text{GeV} \leq m_{\text{sfermions}} \leq 3\ \text{TeV}$

$10\ \text{GeV} \leq |M_1, M_2, \mu| \leq 3\ \text{TeV}$

$100\ \text{GeV} \leq M_3 \leq 3\ \text{TeV}$

$\sim 0.5\ M_Z \leq M_A \leq 3\ \text{TeV}$

$1 \leq \tan\beta \leq 60$

$10\ \text{GeV} \leq |A_{t,b,\tau}| \leq 3\ \text{TeV}$

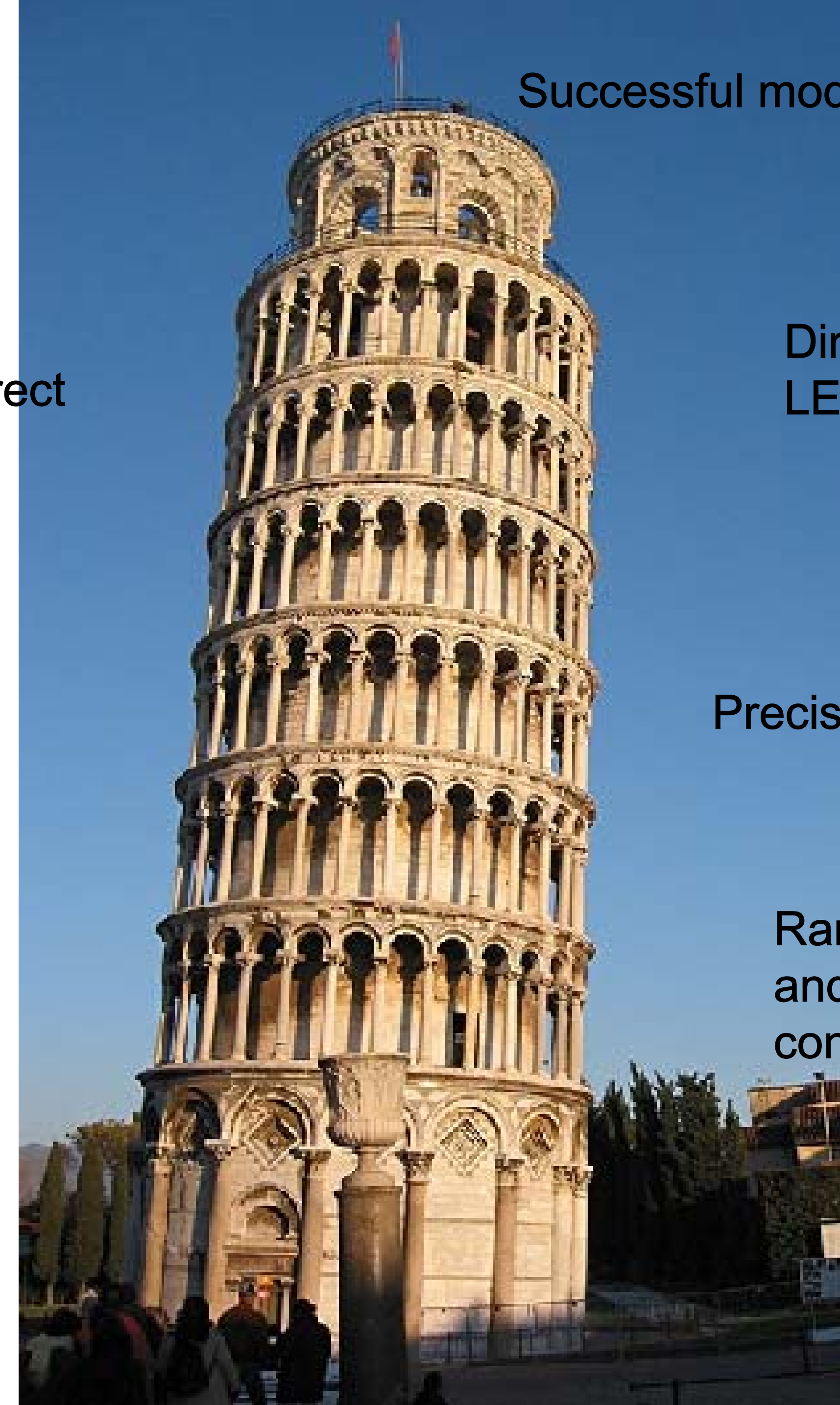
→Comparison of these two scans will show the prior sensitivity.

→This analysis required ~ 1 processor-century of CPU time.
this is the real limitation of this study.

Successful models

WMAP & Direct Detection

Direct searches at LEP & Tevatron



g-2

Precision data

Spectrum requirements

Rare decays and flavor constraints

Constraints

- $-0.0007 < \Delta\rho < 0.0026$ (PDG'08)

- $b \to s\,\gamma$: $B = (2.5 - 4.1) \times 10^{-4}$; (HFAG) + Misiak etal. & Becher & Neubert
- $\Delta(g-2)_\mu$??? $(30.2 \pm 8.8) \times 10^{-10}$ (0809.4062)
  $(29.5 \pm 7.9) \times 10^{-10}$ (0809.3085)
  $[\sim 14.0 \pm 8.4] \times 10^{-10}$ [Davier/BaBar-Tau08]

$\to$ $(-10 \text{ to } 40) \times 10^{-10}$ to be conservative..

- $\Gamma(Z \to \text{invisible}) < 2.0$ MeV (LEPEWWG)
  This removes Z decays to LSPs w/ large Higgsino content

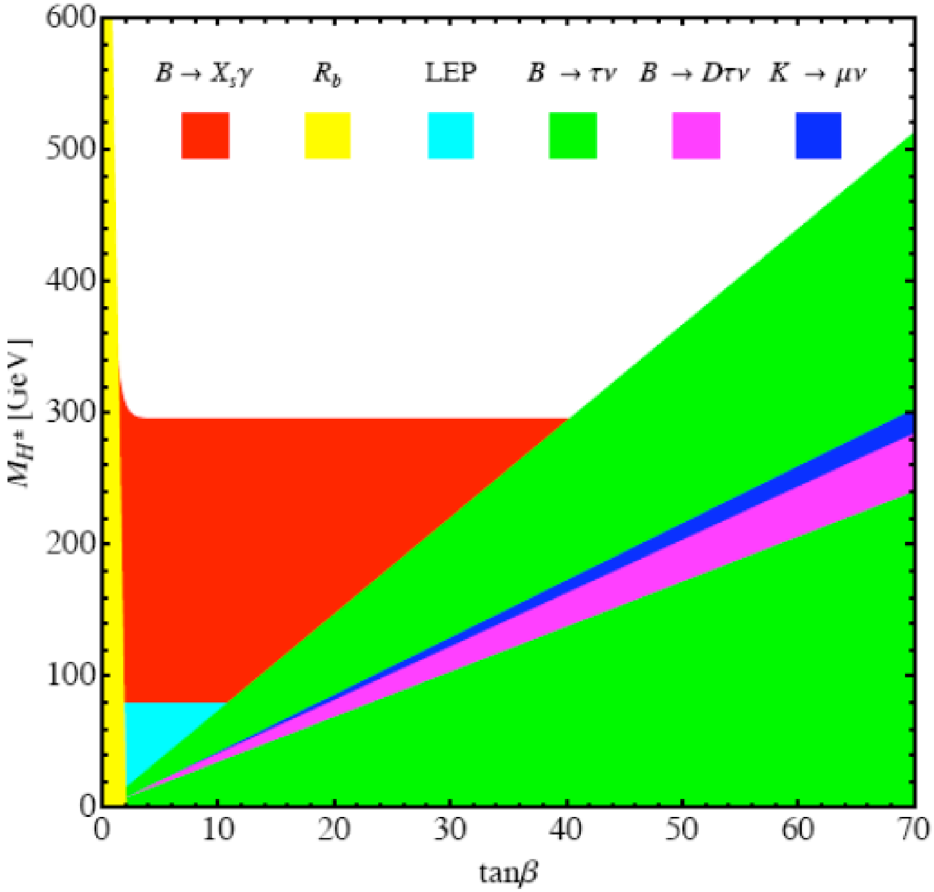
- Meson-Antimeson Mixing : Constrains $1^{st}/3^{rd}$ sfermion mass ratios to be in the range $0.2 < R < 5$ in MFV context

B→τν

Isidori & Paradisi, hep-ph/0605012 &
Erikson etal., 0808.3551 for loop corrections

Bounds on NP by rare decays: example of Two-Higgs-Doublet Model

Haisch,arXiv:0805.2141



New data from Babar and Belle

talks by Baracchini, Hara

* New bounds: $B\to K\nu\bar{\nu}, B\to\mu\nu$

* New HFAG for $B\to\tau\nu$

$BR(B\to\tau\nu) = (1.51\pm0.33)\,10^{-4}$

SM: $\propto |V_{ub}|^2\, f_B^2$

$BR(B\to\tau\nu) = (0.80\pm0.12)\,10^{-4}$

UTfit,2008

$\tan\beta$ suppression expected
in THDM/MSSM

Super-B ($\succeq 50ab^{-1}$) sensitivity

$3-4\%$ Stocchi et al.,arXiv:0710.3799

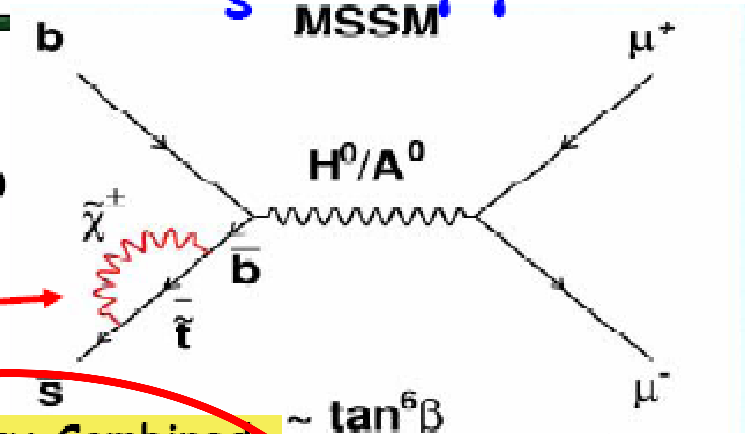
Heavy Flavour Theory, Tobias Hurth (CERN,SLAC)

→ B = (55 to 227) x 10^{-6}

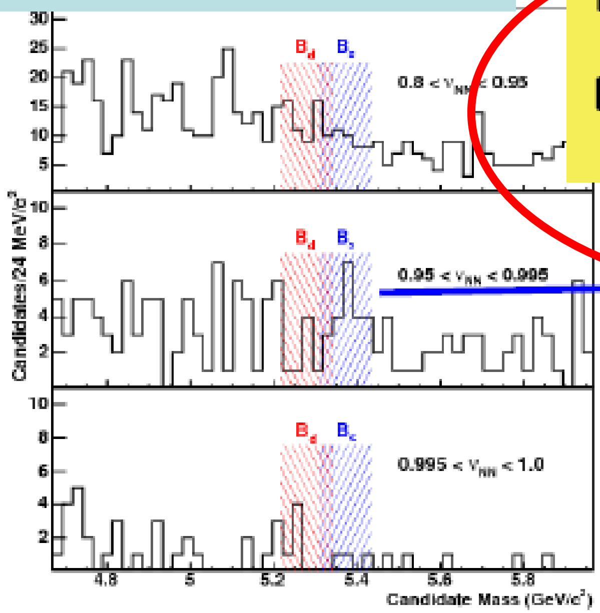
Indirect Search: $B_s \rightarrow \mu\mu$

The search for $B_s \rightarrow \mu\mu$ is perhaps the most sensitive to SUSY since sparticles show up in loops

Especially sensitive at high $\tan\beta$ ($\propto \tan\beta^6$)

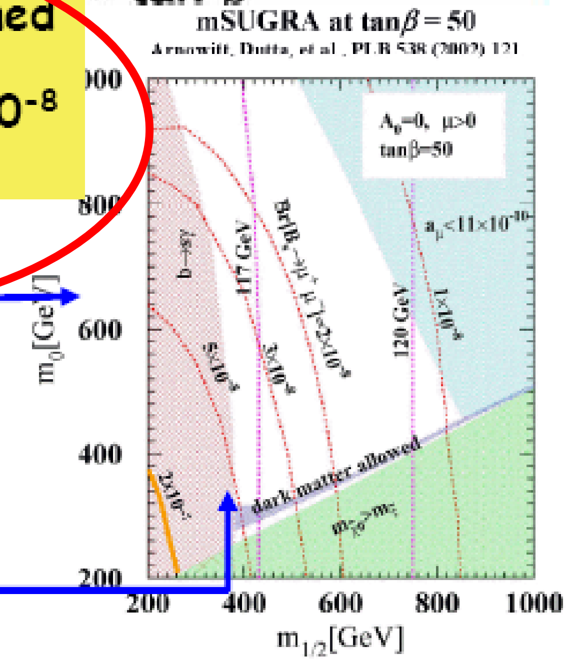


CDF, PRL 100, 101802 (2008)

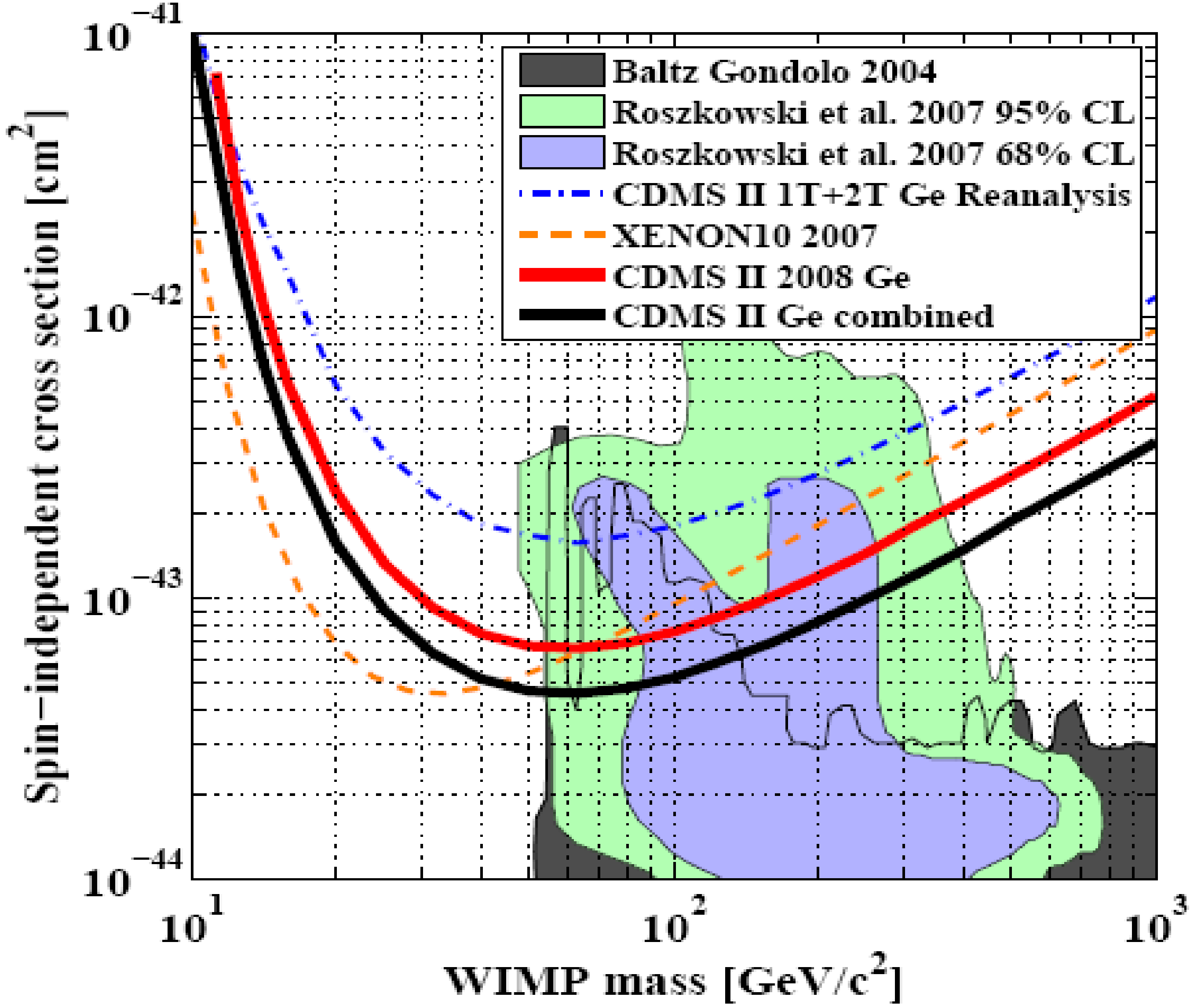


Preliminary Combined CDF/DØ
$BR(B_s \rightarrow \mu\mu) < 4.5\times10^{-8}$ @95%

$BR_{SM}=3.5\times10^{-9}$



Dark Matter: Direct Searches for WIMPs



- CDMS, XENON10, DAMA, CRESST-I,… → We find a factor of ~ 4 uncertainty in the nuclear matrix elements. This factor was obtained from studying several benchmark points in detail & so we allow cross sections 4x larger than the usually quoted limits. Spin-independent limits are completely dominant here.

- Dark Matter density: $\Omega h^2 < 0.1210$ → 5yr WMAP data + We treat this only as an upper bound on the LSP DM density to allow for multi-component DM, e.g., axions, etc. Recall the lightest neutralino is the LSP and is a thermal relic here.

- LEP and Tevatron Direct Higgs & SUSY searches : there are *many* of these searches but they are very complicated with many caveats…. CAREFUL!

Zh, h-> bb, $\tau\tau$

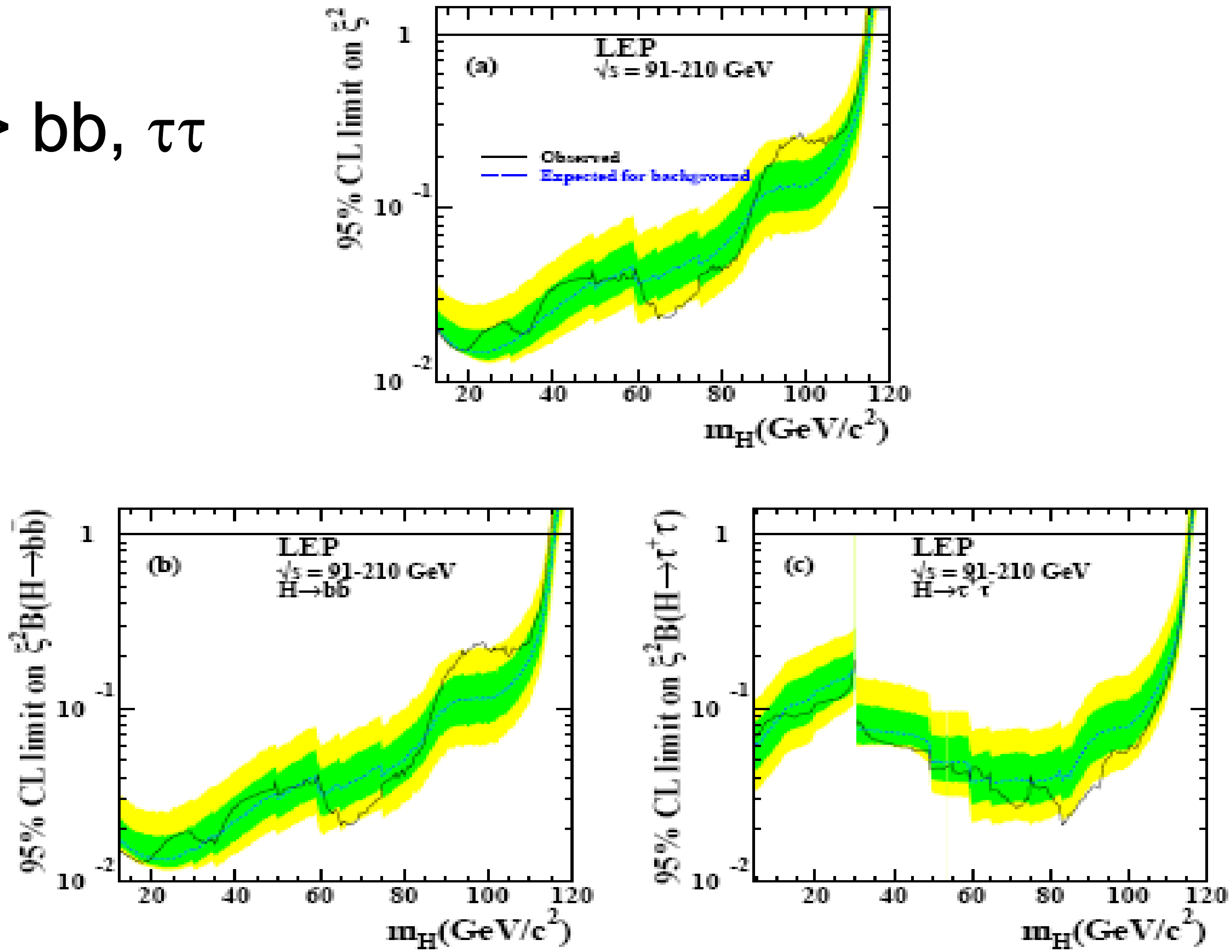


Figure 1: *The 95% c.l. upper bound on the coupling ratio $\xi^2 = (g_{\rm HZZ}/g_{\rm HZZ}^{\rm SM})^2$ (see text). The dark (green) and light (yellow) shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling. (a): For Higgs boson decays predicted by the Standard Model; (b): for the Higgs boson decaying exclusively into $b\bar{b}$ and (c): into $\tau^+\tau^-$ pairs.*

LEP II: Associated Higgs Production

Z→ hA →4b,2b2τ,4τ

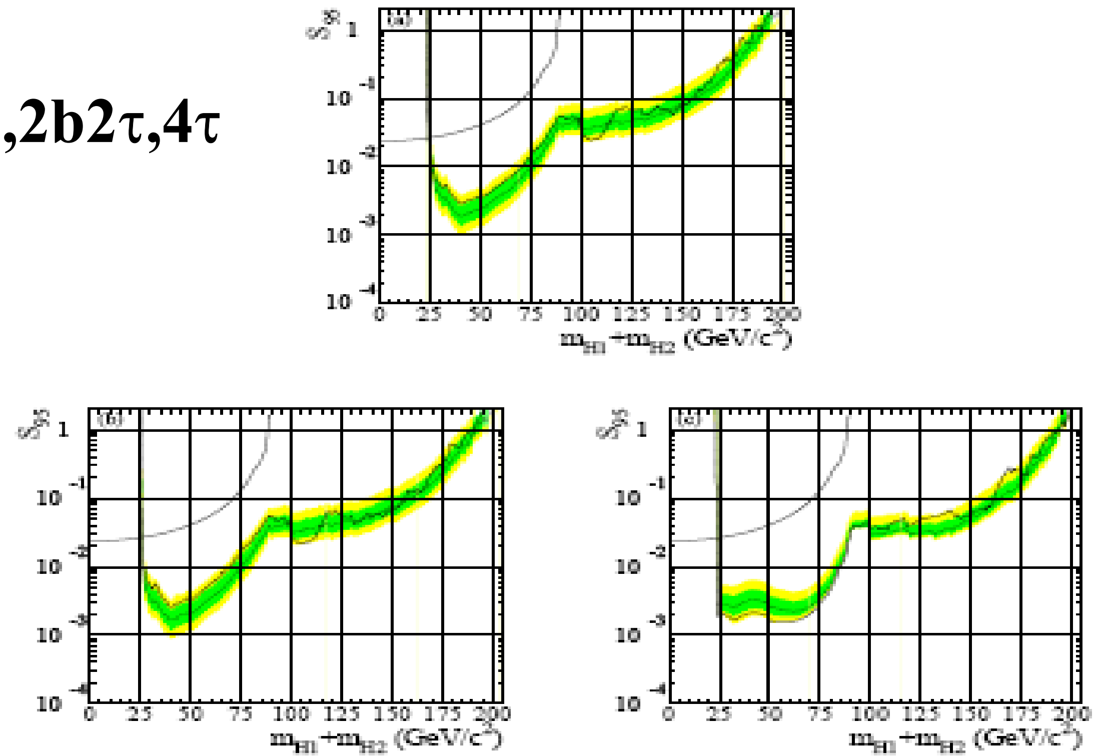
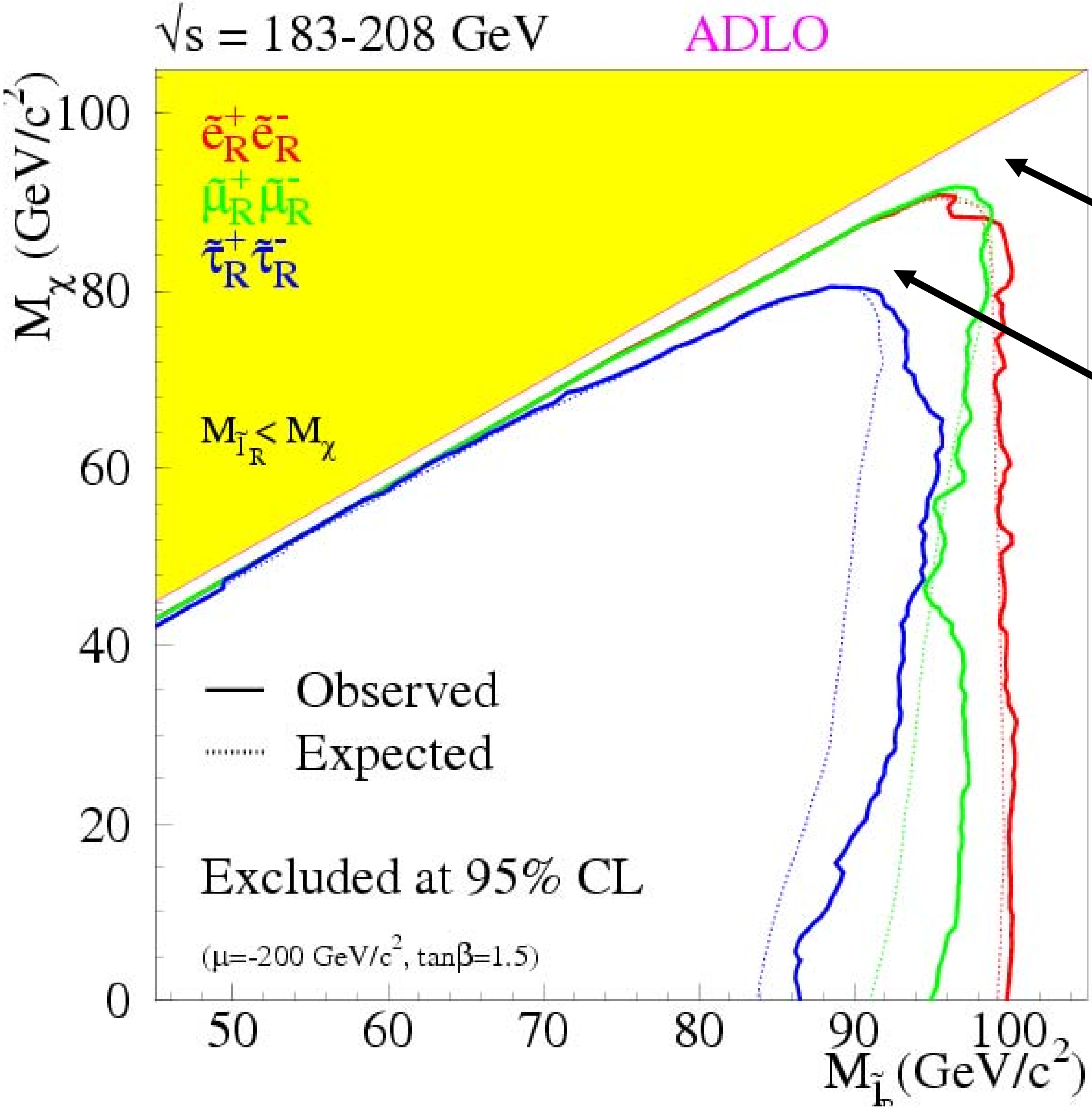


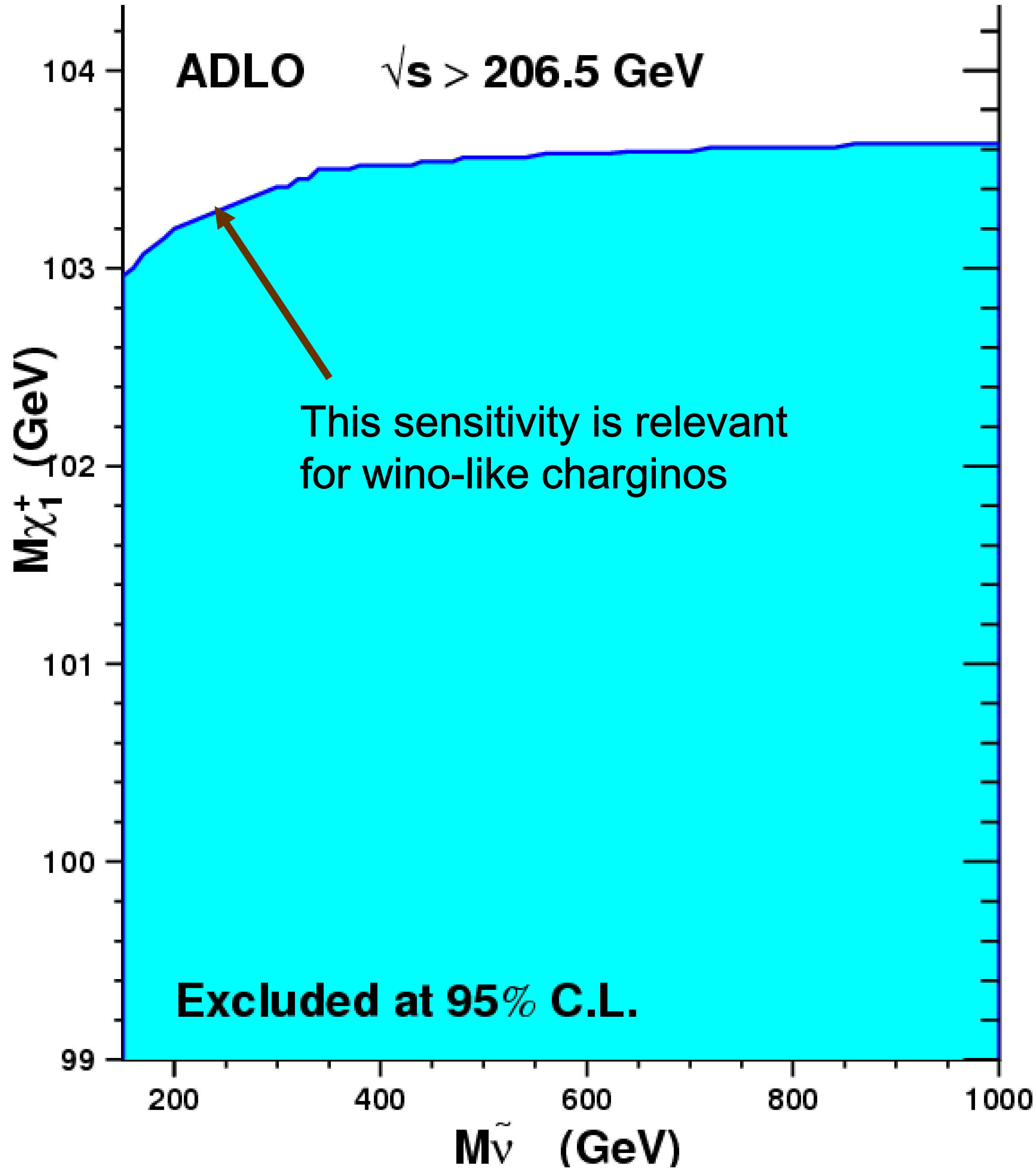
Figure 3: Model-independent 95% c.l. upper bounds, S_{95}, for various topological cross sections motivated by the pair-production process $e^+e^- \to \mathcal{H}_2\mathcal{H}_1$, for the particular case where $m_{\mathcal{H}_2}$ and $m_{\mathcal{H}_1}$ are approximately equal. Such is the case, for example, in the CP-conserving MSSM scenarios for $\tan\beta$ greater than 10. The abscissa represents the sum of the two Higgs boson masses. The full line represents the observed limit. The dark (green) and light (yellow) shaded bands around the median expectation (dashed line) correspond to the 68% and 95% probability bands. The curves which complete the exclusion at low masses are obtained using the constraint from the measured decay width of the Z boson, see Section 3.2. Upper plot: the Higgs boson decay branching ratios correspond to the m_h-max benchmark scenario with $\tan\beta$=10, namely 94% $\mathcal{H}_1 \to b\bar{b}$, 6% $\mathcal{H}_1 \to \tau^+\tau^-$, 92% $\mathcal{H}_2 \to b\bar{b}$ and 8% $\mathcal{H}_2 \to \tau^+\tau^-$; lower left: both Higgs bosons are assumed to decay exclusively to $b\bar{b}$; lower right: the Higgs bosons are assumed to decay, one into $b\bar{b}$ only and the other one into $\tau^+\tau^-$ only. For the case where both Higgs bosons decay to $\tau^+\tau^-$, the corresponding upper bound can be found in Ref. [31], Figure 15.

RH Sleptons



Note the holes where the leptons are too soft…

We need to allow for a mass gap w/ the LSP & also in the squark case when soft jets are possible..light guys may slip through



Large mass gap chargino search

Depends on the sneutrino mass in the t-channel if less than ~ 160 GeV due to interference if large wino content

Some 'light' charginos may slip through as search reach is degraded

Tevatron Constraints : I   Squark & Gluino Search

- This is the first SUSY analysis to include these constraints

- 2,3,4 Jets + Missing Energy (D0)

TABLE I: Selection criteria for the three analyses (all energies and momenta in GeV); see the text for further details.

Preselection Cut	All Analyses		
$\not{E}_T$	≥ 40		
|Vertex z pos.|	< 60 cm		
Acoplanarity	$< 165°$		
Selection Cut	"dijet"	"3-jets"	"gluino"
Trigger	dijet	multijet	multijet
jet$_1$ p_T[a]	≥ 35	≥ 35	≥ 35
jet$_2$ p_T[a]	≥ 35	≥ 35	≥ 35
jet$_3$ p_T[b]	–	≥ 35	≥ 35
jet$_4$ p_T[b]	–	–	≥ 20
Electron veto	yes	yes	yes
Muon veto	yes	yes	yes
$\Delta\phi(\not{E}_T, \text{jet}_1)$	$\geq 90°$	$\geq 90°$	$\geq 90°$
$\Delta\phi(\not{E}_T, \text{jet}_2)$	$\geq 50°$	$\geq 50°$	$\geq 50°$
$\Delta\phi_{\min}(\not{E}_T, \text{any jet})$	$\geq 40°$	–	–
H_T	≥ 325	≥ 375	≥ 400
$\not{E}_T$	≥ 225	≥ 175	≥ 100

[a]First and second jets are also required to be central ($|\eta_{\text{det}}| < 0.8$), with an electromagnetic fraction below 0.95, and to have CPF0 ≥ 0.75.
[b]Third and fourth jets are required to have $|\eta_{\text{det}}| < 2.5$, with an electromagnetic fraction below 0.95.

Multiple analyses keyed to look for:

Squarks-> jet +MET
Gluinos -> 2 j + MET

The search is based on mSUGRA type sparticle spectrum assumptions which can be VERY far from our model points.. the pMSSM easily survives!

D0 benchmarks

TABLE II: For each analysis, information on the signal for which it was optimized (m_0, $m_{1/2}$, $m_{\tilde{g}}$, $m_{\tilde{q}}$, and nominal NLO cross section), signal efficiency, the number of events observed, the number of events expected from SM backgrounds, the number of events expected from signal, and the 95% C.L. signal cross section upper limit. The first uncertainty is statistical and the second is systematic.

Analysis	$(m_0, m_{1/2})$ (GeV)	$(m_{\tilde{g}}, m_{\tilde{q}})$ (GeV)	σ_{nom} (pb)	$\epsilon_{\text{sig.}}$ (%)	$N_{\text{obs.}}$	$N_{\text{backgrd.}}$	$N_{\text{sig.}}$	σ_{95} (pb)
"dijet"	(25,175)	(439,396)	0.072	$6.8 \pm 0.4^{+1.2}_{-1.2}$	11	$11.1 \pm 1.2^{+2.9}_{-2.3}$	$10.4 \pm 0.6^{+1.8}_{-1.8}$	0.075
"3-jets"	(197,154)	(400,400)	0.083	$6.8 \pm 0.4^{+1.4}_{-1.3}$	9	$10.7 \pm 0.9^{+3.1}_{-2.1}$	$12.0 \pm 0.7^{+2.5}_{-2.3}$	0.065
"gluino"	(500,110)	(320,551)	0.195	$4.1 \pm 0.3^{+0.8}_{-0.7}$	20	$17.7 \pm 1.1^{+5.5}_{-3.3}$	$17.0 \pm 1.2^{+3.3}_{-2.9}$	0.165

TABLE III: Definition of the analysis combinations, and number of events observed in the data and expected from the SM backgrounds.

Selection	"dijet"	"3-jets"	"gluino"	$N_{\text{obs.}}$	$N_{\text{backgrd.}}$
Combination 1	yes	no	no	8	9.4 ± 1.2 (stat.) $^{+2.3}_{-1.8}$ (syst.)
Combination 2	no	yes	no	2	4.5 ± 0.6 (stat.) $^{+0.7}_{-0.5}$ (syst.)
Combination 3	no	no	yes	14	12.5 ± 0.9 (stat.) $^{+3.6}_{-1.9}$ (syst.)
Combination 4	yes	yes	no	1	1.1 ± 0.3 (stat.) $^{+0.5}_{-0.3}$ (syst.)
Combination 5	yes	no	yes		kinematically not allowed
Combination 6	no	yes	yes	4	4.5 ± 0.6 (stat.) $^{+1.8}_{-1.3}$ (syst.)
Combination 7	yes	yes	yes	2	0.6 ± 0.2 (stat.) $^{+0.1}_{-0.2}$ (syst.)
At least one selection				31	32.6 ± 1.7 (stat.) $^{+9.0}_{-5.8}$ (syst.)

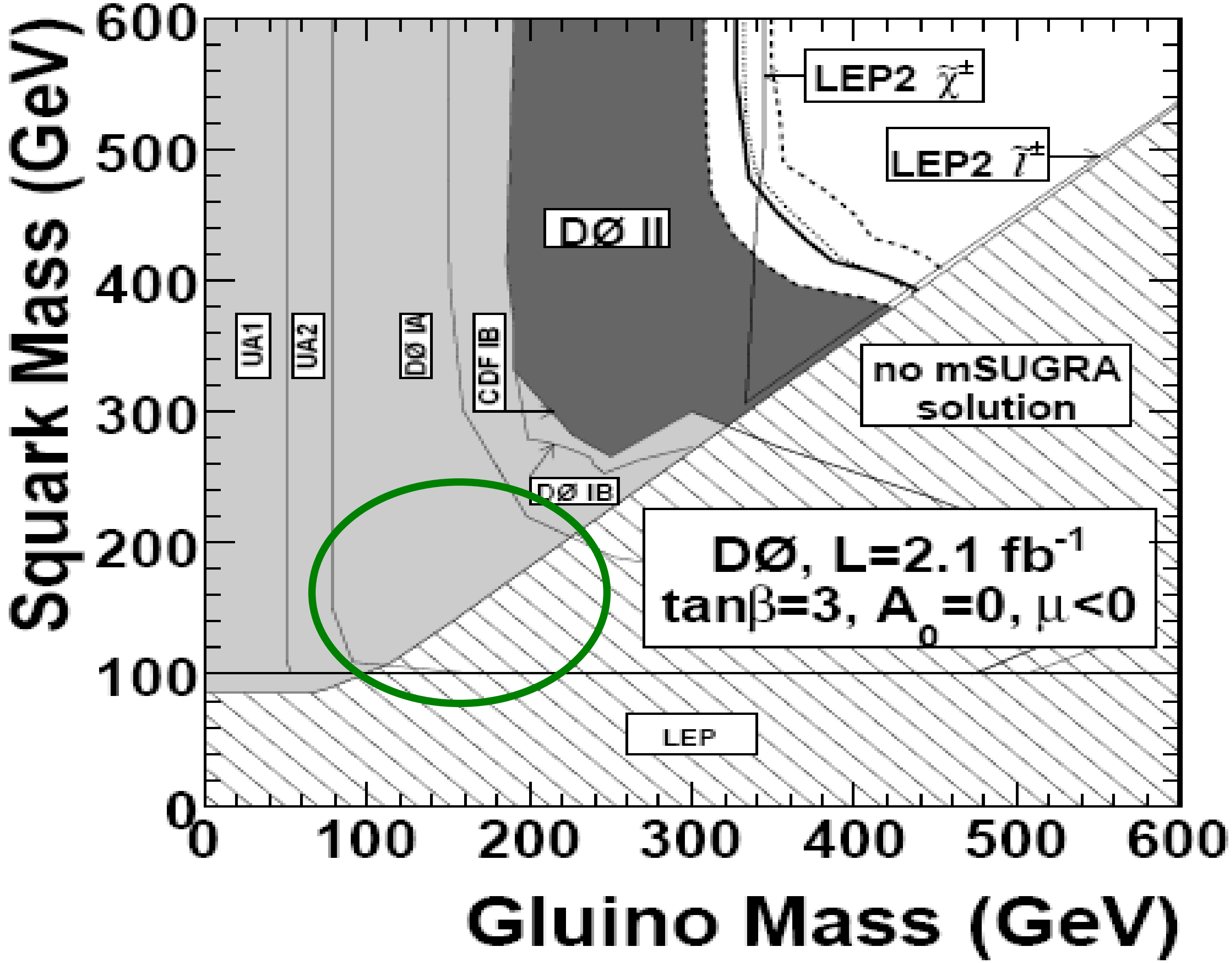
Combos of the 3 analyses

→ Feldman-Cousins 95% CL Signal limit: 8.34 events

SuSpect -> SUSY-Hit -> PROSPINO -> PYTHIA -> D0-tuned PGS4 fast simulation (to reproduce the benchmark points)…

redo this analysis ~ 10^5 times !

This D0 search provides strong constraints in mSUGRA.. squarks & gluinos > 330-400 GeV…our limits can be *much weaker* on both these sparticles as we'll see !!



Tevatron II: CDF Tri-lepton Analysis

CDF RUN II Preliminary $\int \mathcal{L}dt = 2.0\ \text{fb}^{-1}$: Search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$

Channel	Signal	Background	Observed
3tight	2.25 ± 0.13(stat) ± 0.29(syst)	0.49 ± 0.04(stat) ± 0.08(syst)	1
2tight,1loose	1.61 ± 0.11(stat) ± 0.21(syst)	0.25 ± 0.03(stat) ± 0.03(syst)	0
1tight,2loose	0.68 ± 0.07(stat) ± 0.09(syst)	0.14 ± 0.02(stat) ± 0.02(syst)	0
Total Trilepton	4.5 ± 0.2(stat) ± 0.6(syst)	0.88 ± 0.05(stat) ± 0.13(syst)	1
2tight,1Track	4.44 ± 0.19(stat) ± 0.58(syst)	3.22 ± 0.48(stat) ± 0.53(syst)	4
1tight,1loose,1Track	2.42 ± 0.14(stat) ± 0.32(syst)	2.28 ± 0.47(stat) ± 0.42(syst)	2
Total Dilepton+Track	6.9 ± 0.2(stat) ± 0.9(syst)	5.5 ± 0.7(stat) ± 0.9(syst)	6

Table 3: Number of expected signal and background events and number of observed events in 2 fb^{-1}. Uncertainties are statistical(stat) and full systematics(syst). The signal is for the benchmark point described in section 5.

We need to perform the 3 tight lepton analysis ~ 10^5 times

We perform this analysis using CDF-tuned PGS4, PYTHIA in LO plus a PROSPINO K-factor

→ Feldman-Cousins 95% CL Signal limit: 4.65 events

- This is the first SUSY analysis to include these constraints

The non-‘3-tight’ analyses are not reproducible w/o a better detector simulation

Tevatron III: D0 Stable Particle (= Chargino) Search

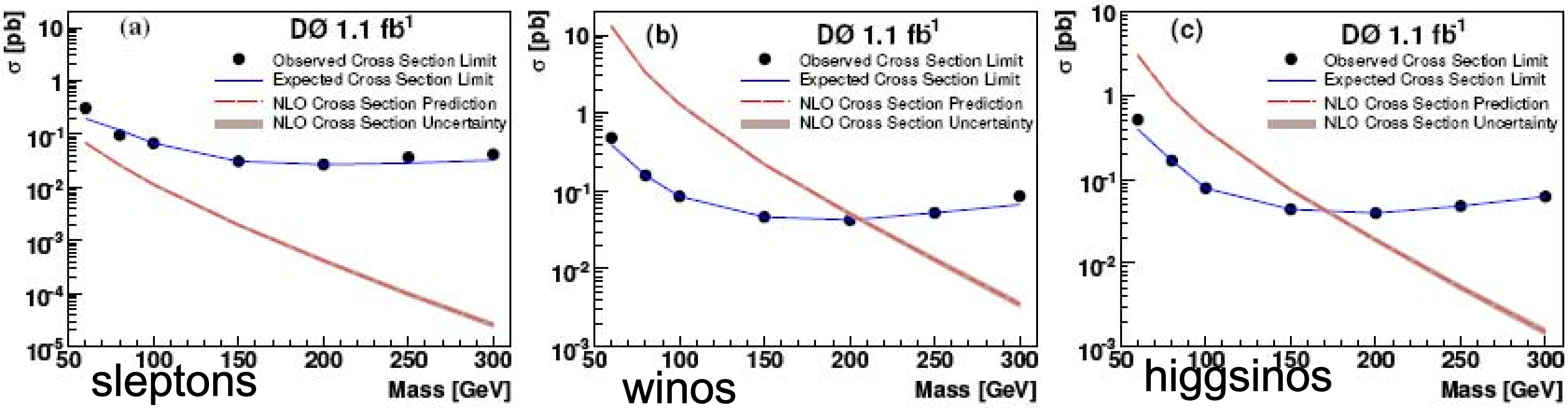


FIG. 2: The observed (dots) and expected (solid line) 95% cross section limits, the NLO production cross section (dashed line), and NLO cross section uncertainty (barely visible shaded band) as a function of (a) stau mass for stau pair production, (b) chargino mass for pair produced gaugino-like charginos, and (c) chargino mass for pair produced higgsino-like charginos.

Interpolation: $M_\chi > 206\ |U_{1w}|^2 + 171\ |U_{1h}|^2$ GeV

This is an *incredibly* powerful constraint on our model set as we will have many close mass chargino-neutralino pairs. This search cuts out a huge parameter region as you will see later.

- No applicable bounds on charged sleptons..the cross sections are too small.
- This is the first SUSY analysis to include these constraints

Summary…so far..

- This is the first large scale study of the 19 parameter pMSSM studying millions of points in parameter space…this is far more general than any other study yet performed

- We have made a conservative set of assumptions within a fixed framework

- Essentially the entire spectrum of experimental constraints have been employed--including for the first time those from the Tevatron which required fast detector simulation

- And so…

RESULTS ???

See JoAnne's Talk

Happy Birthday, Galileo!   Feb. 15, 1564