ILC in the LHC Era

Jack Gunion
U.C. Davis

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Fundamental physics goals for the LHC and the ILC

1. Discover and understand in detail the mechanism for EWSB.

   Higgs bosons, e.g.

2. Determine if the hierarchy problem has been solved or not.

   SUSY?

3. Discover the dark matter particle(s) and measure the properties of all particles needed for computing the relic density.

   R-parity conserving SUSY for example. Is there an alternative if Hill and Hill are right?

4. Explain electroweak or other baryogenesis using particles seen at the LHC and ILC.

5. Discover a scalar field or other source for dark energy and inflation.

Our prejudices are:

- **that the LHC will reveal the EWSB mechanism, but that the ILC will be needed to fully detail it;**
- **that if dark matter is a WIMP of any kind, the LHC is very likely to see it, and the ILC should provide the needed detailed measurements in many cases — probably also ok if dark matter = axions or axinos;**
- **that it is quite possible that LHC + ILC data will provide the info (e.g. Higgs mass, stop masses, .. in SUSY) needed to assess baryogenesis;**
- **it is probably wishful thinking to believe that the LHC and/or ILC will see very weakly coupled and heavy scalar(s) that might underly dark energy and inflation.**

Of course, maybe dark matter *is* just a cosmological constant whose value might be understood if we make progress on the first items.

Many models have been developed as a result of not having relevant data.

Indeed, theorists have been adopting the Yogi Berra philosophy:

"If you come to a fork in the road, take it!".

There are lots of theorists and there have been lots of years, so there have been lots of (admittedly, interesting) roads taken.

String theory $\Rightarrow 10^{520}$ forks in the road, but most are probably not relevant to our world.

Our marriage to the SM passed through the honeymoon stage long ago, the reassessment stage during the 90's, and has now entered the stage of questioning the relationship. Theorists (and a smaller fraction of the experimentalists, experimentalists being more faithful in general) find the many attractive young models far more appealing. We hope to be able to explore their possibilities sooner rather than later. For some us, time is running out in which to enjoy the fruits of our quest.

To explore the ILC — LHC connection, I will focus on SUSY models with R-parity conservation since they really have a shot at explaining EWSB, dark matter and baryogenesis all at once.

Even within SUSY, it is possible to find models with:

1. **LHC signals that will mandate an ILC500.**

2. **LHC signals that suggest an ILC500 may be very relevant, but without a firm guarantee.**

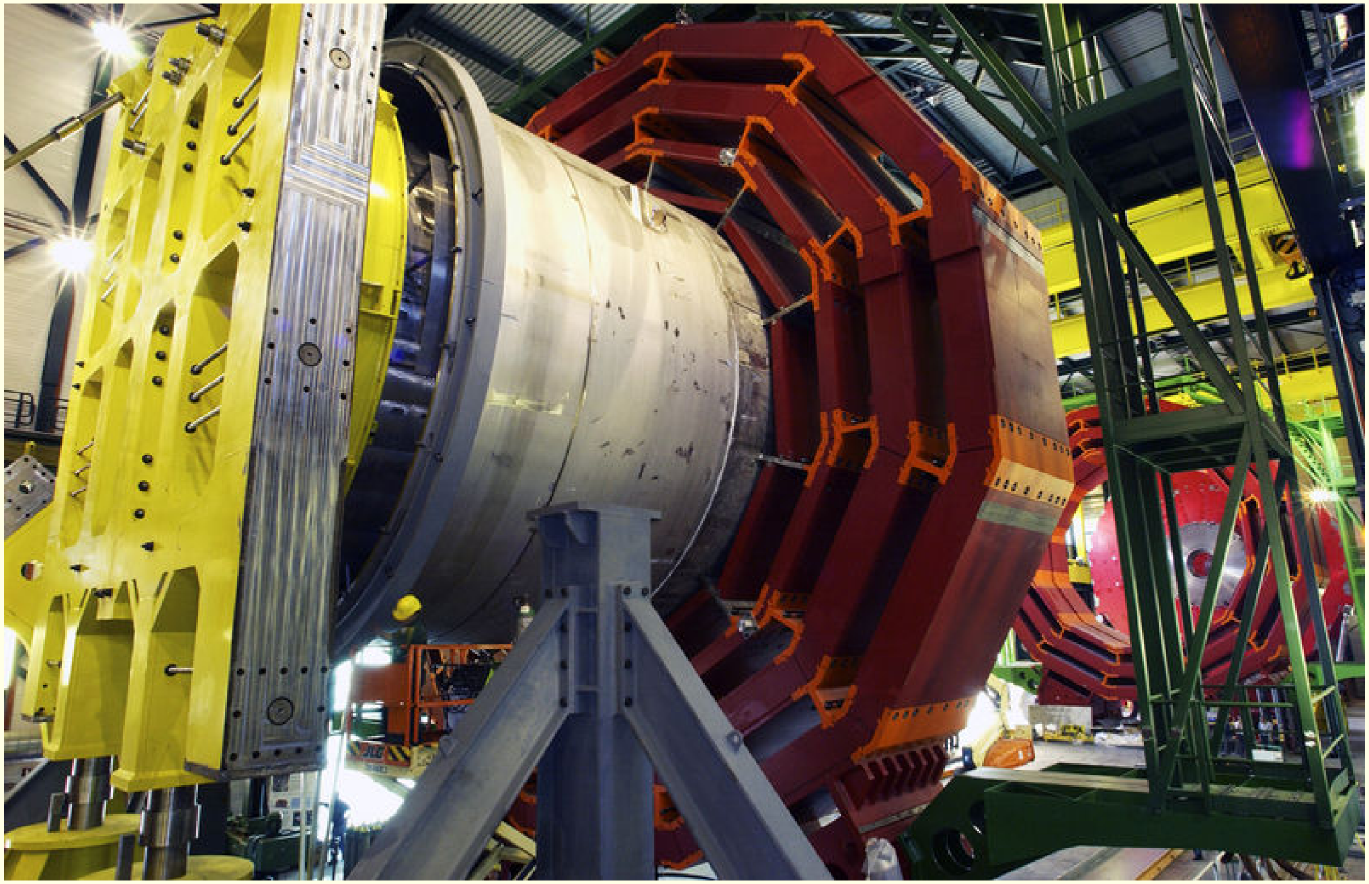
3. **Scenarios in which the LHC sees no new physics, but yet there are truly exciting things that an ILC500 would observe.**

4. **Scenarios with no new physics accessible at either the LHC or ILC500 but that an ILC1000 would be able to explore.**

5. **But I know of no scenario in which neither the LHC nor an ILC1000 would have clear signals, unless the SUSY mass scale is so high that the model is highly fine-tuned.**

Bottom Line: WE NEED DATA!

Fortunately, the LHC is at hand.



The CMS Detector

But what will the LHC detectors see? I am betting on some type of SUSY, probably with R-parity conservation for dark matter.

The MSSM

- Despite the μ problem, the MSSM (but not necessarily the cMSSM which is on the verge of being ruled out) is an important benchmark.
- It gives coupling constant unification, electroweak symmetry breaking via renormalization group evolution from the GUT scale, and dark matter (if R-parity is conserved).
- To get baryogenesis requires a very light $\widetilde{t}_1$ since LEP demands that a SM-like Higgs boson have $m_h \gtrsim 114~\mathrm{GeV}$ (see talk by C. Wagner) — of course, the m_h lower bound forces $\widetilde{t}_2$ to be heavy $\Rightarrow$ large fine-tuning ($i.e.$ sensitivity of m_Z to GUT scale parameters).
- Precision electroweak is not a problem if SUSY is reasonably light and stops are split.

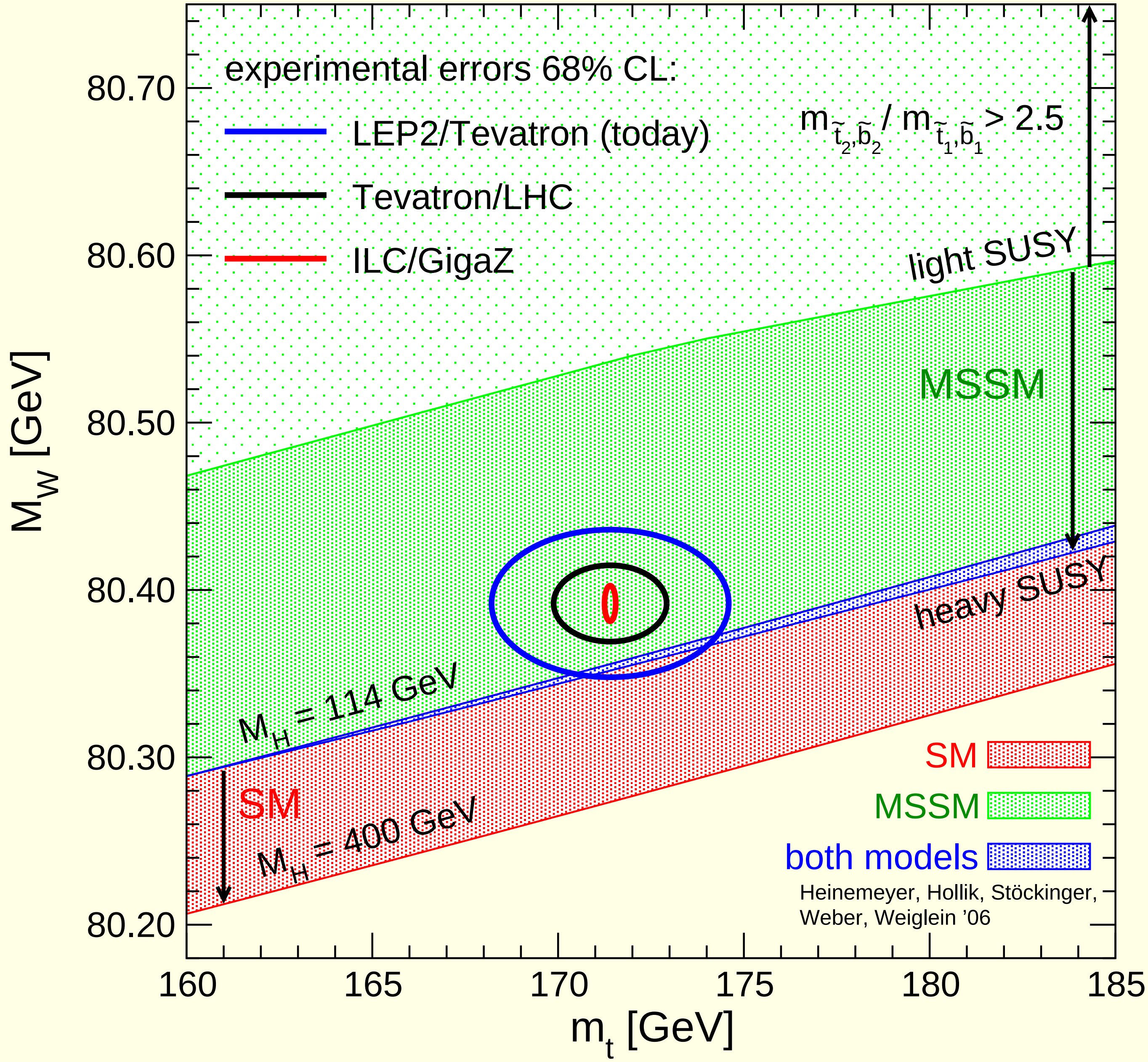


Figure 1: *Precision electroweak constraints in the MSSM context prefer light SUSY, but with big stop mass ratio, but that is good for baryogenesis.*

- **The MSSM brings up many interesting LHC — ILC connections. In particular, the LHC inverse problem: Can we use LHC data to determine the fundamental Lagrangian parameters?**

  And, can we do so with sufficient accuracy as to allow a meaningful extrapolation to the GUT scale and an accurate calculation of DM density?

  The general picture:

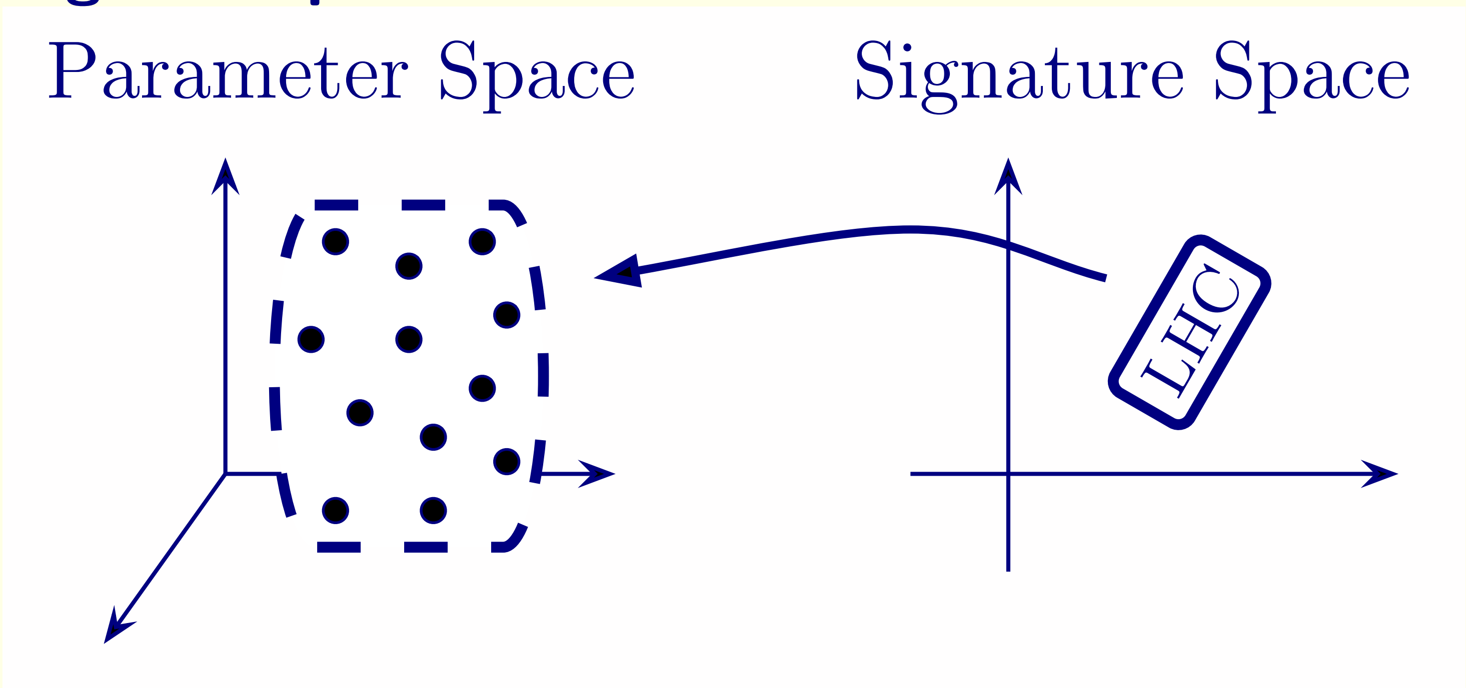


Figure 2: *The likely LHC situation. N. Arkani-Hamed, G. L. Kane, J. Thaler and L. T. Wang, JHEP* **0608***, 070 (2006) [arXiv:hep-ph/0512190].*

This picture presumes that the LHC will have a hard time determining the absolute mass scale. For example, the SPS1a' point (don't ask if you don't know) gives a spectrum of the following type:

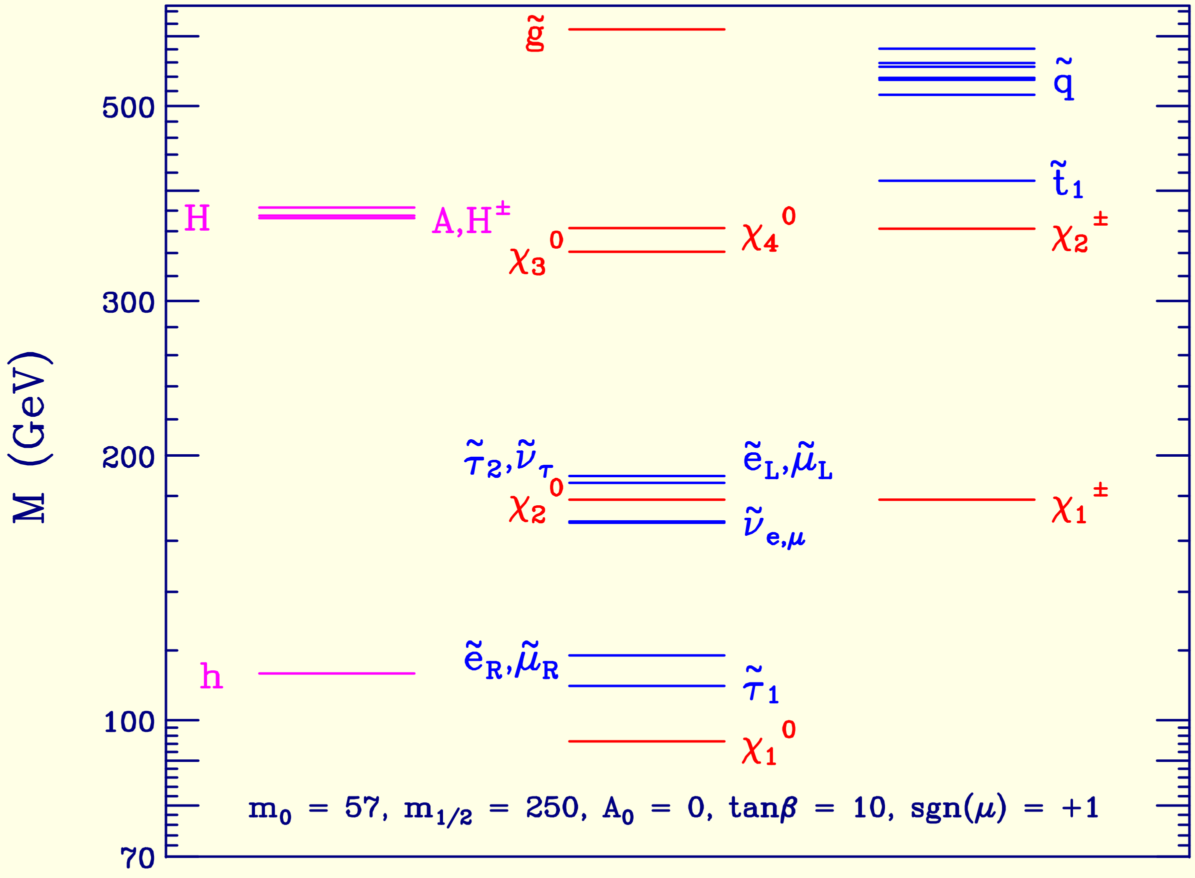


Figure 3: *Mass spectra of an SPS1a'-like point.*

Using lepton spectrum edges and the like, one gets quite a bit of information about the spectrum, but a good determination of the overall mass scale is elusive. $m_{\widetilde{\chi}_1^0}$ sets the overall scale.

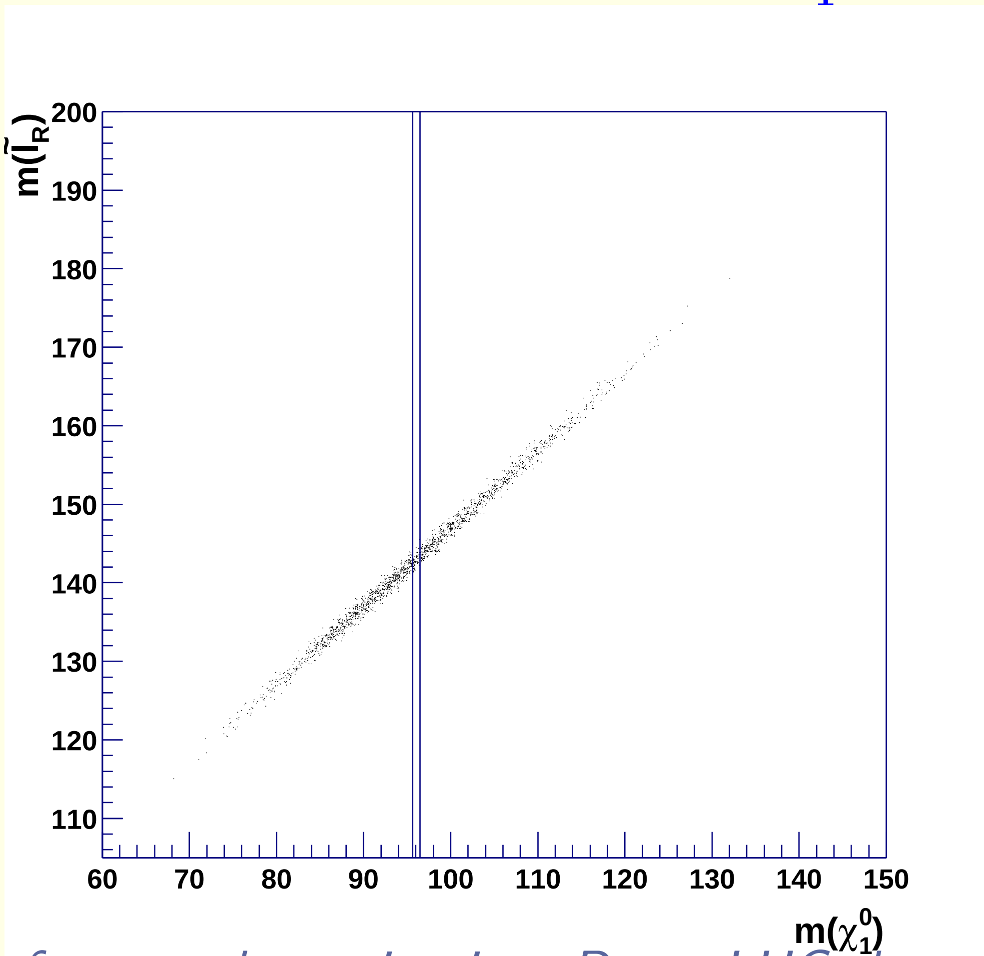


Figure 4: *Accuracy for $m_{\widetilde{\chi}_1^0}$ determination. Dots=LHC alone $\Rightarrow \Delta m_{\widetilde{\chi}_1^0} \sim 4.3\,\mathrm{GeV}$. Vertical band=ILC. G. Weiglein et al. [LHC/LC Study Group], Phys. Rept.* **426***, 47 (2006) [arXiv:hep-ph/0410364]. Note: Errors assume you are at the SPS1a' dot.*

The overall result of mass determinations done the usual way, assuming you are at the correct dot:

Table 1: *The RMS values of the mass distribution in the case of the LHC alone, and combined with measurements from the ILC1000. All numbers in GeV.*

	LHC	LHC+LC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\ell}_L}$	5.0	0.2 (LC input)
Δm_{τ_1}	5-8	0.3 (LC input)
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	7-12	5-11
$\Delta m_{\bar{\tilde{t}}_1}$	7.5	5.7
$\Delta m_{\bar{\tilde{t}}_2}$	7.9	6.2
$\Delta m_{\tilde{g}}$	8.0	6.5

The ILC threshold scans are crucial to getting the accuracy needed for DM precision calculations.

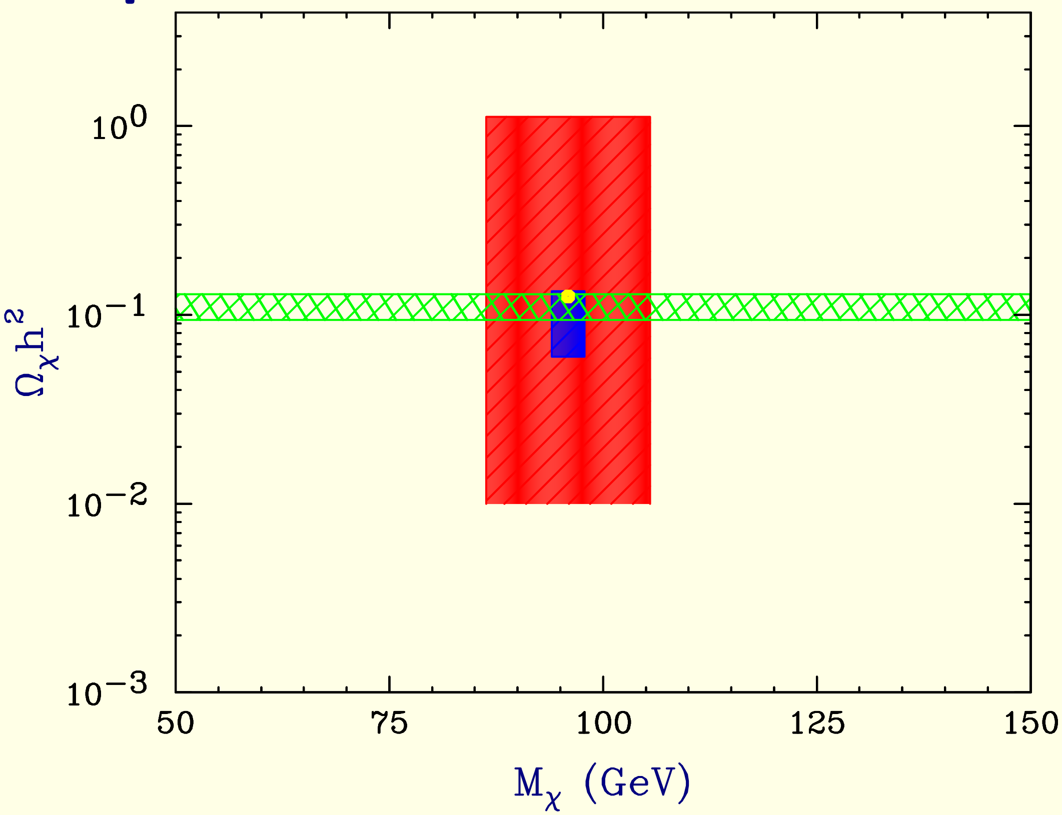


Figure 5: *Accuracy of WMAP (horizontal green shaded region), LHC (outer red rectangle) and ILC (inner blue rectangle) in determining* M_χ*, the mass of the lightest neutralino, and its relic density* $\Omega_\chi h^2$*. The yellow dot denotes the actual values of* M_χ *and* $\Omega_\chi h^2$ *for point B'. A. Birkedal, et al.hep-ph/0507214*

Both LHC (for the heavier colored sparticles) and ILC data are crucial to achieving the accuracy necessary to meaningfully assess GUT scale boundary conditions.

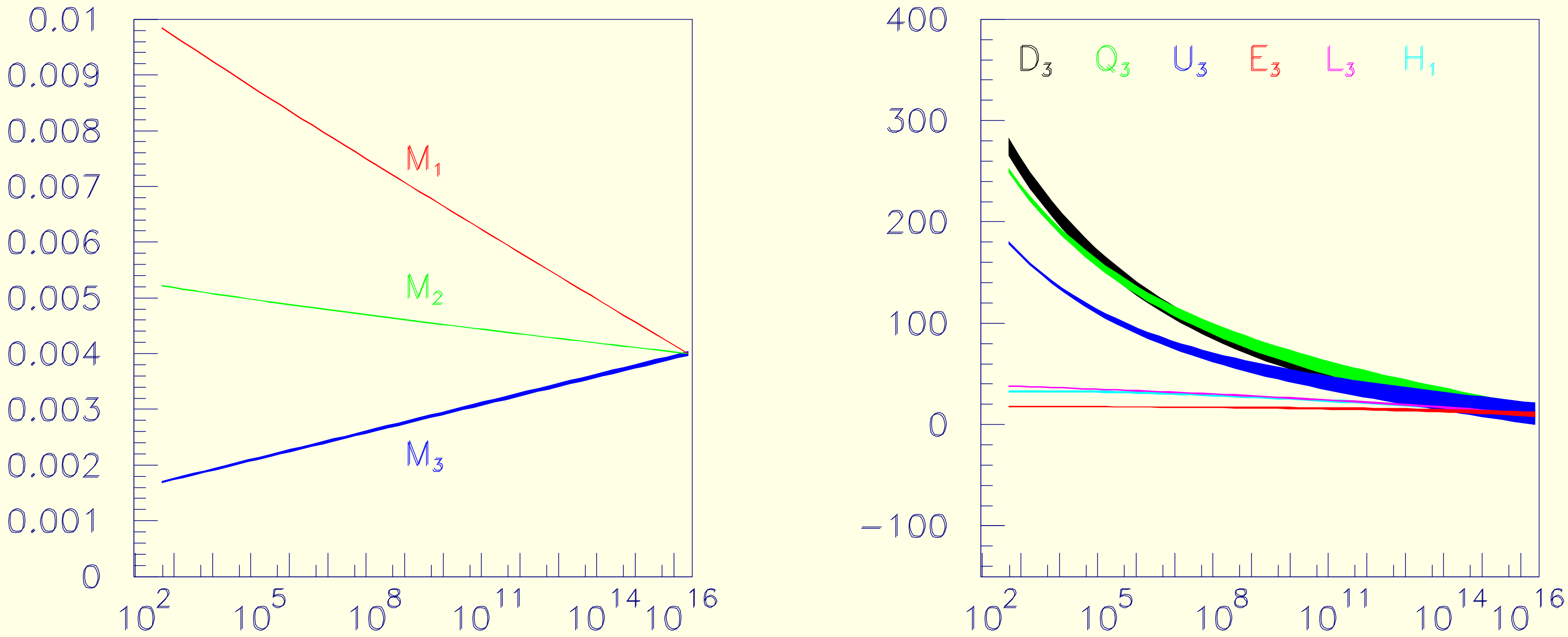


Figure 6: *Evolution to the GUT scale using LHC + ILC1000 measurements. On the left,* $\boldsymbol{1/M_i}$ *[GeV^{-1}] is plotted vs.* $\boldsymbol{Q}$(GeV). *On the right,* $\boldsymbol{M^2_{\tilde{j}}}$ *[$\mathbf{10^3}$ GeV^2] for 3rd soft masses squared are plotted vs.* $\boldsymbol{Q}$(GeV).

- **But, one can do better at the LHC than using only the edge techniques.** **JG, McElrath, Cheng, Marandella, Han, in preparation — see talk by McElrath**

  Consider the chain decay sequence:

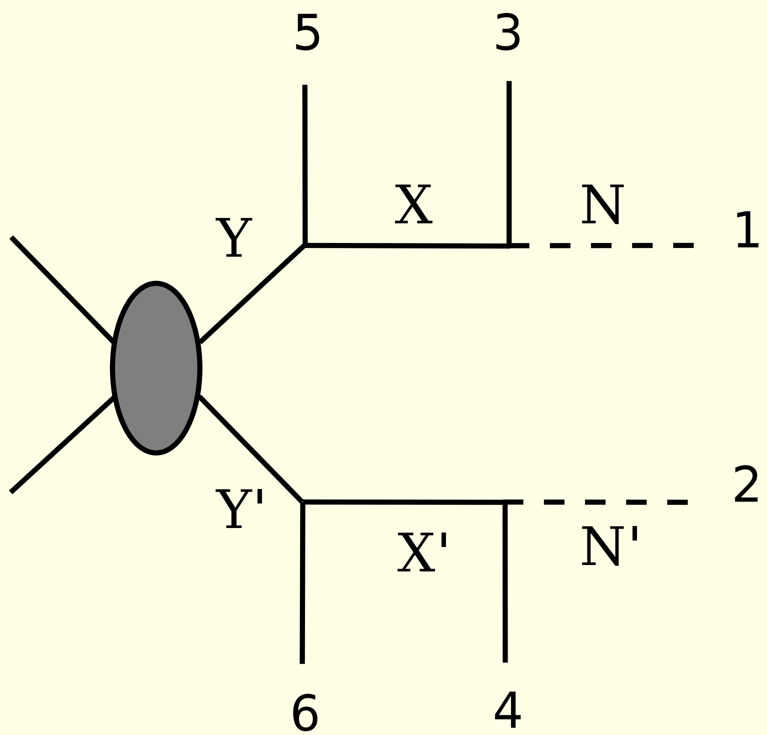


Figure 7: *A typical chain decay topology.*

This topology can be applied to many processes with 4 visible and 2 invisible particles.

For example, suppose $M_Y = M_{Y'}$, $M_X = M'_X$, and $M_N = M'_N$.

Examples that fit this:

$$\begin{aligned}
t\bar{t} &\rightarrow bW^+bW^- \rightarrow bl^+\nu bl^-\bar{\nu} \\
\tilde{\chi}^0_2\tilde{\chi}^0_2 &\rightarrow l\tilde{l}l\tilde{l} \rightarrow ll\tilde{\chi}^0_1 ll\tilde{\chi}^0_1 \\
\tilde{q}\tilde{q} &\rightarrow q\tilde{\chi}^0_2 q\tilde{\chi}^0_2 \rightarrow ql\tilde{l}ql\tilde{l} \rightarrow qll\tilde{\chi}^0_1 qll\tilde{\chi}^0_1 \\
\tilde{t}\bar{\tilde{t}} &\rightarrow b\tilde{\chi}^+\bar{b}\tilde{\chi}^- \rightarrow bW^+\tilde{\chi}^0_1\bar{b}W^-\tilde{\chi}^0_1
\end{aligned}$$

The third entry above is the SPS1a' case of interest.

In our approach, we take each event and determine from available constraints and the visible energies of the leptons the values of M_X, M_Y and M_N that are allowed. After overlapping the allowed regions for many events we look for the values of these masses that maximize the number of consistent events, obtaining a plot like

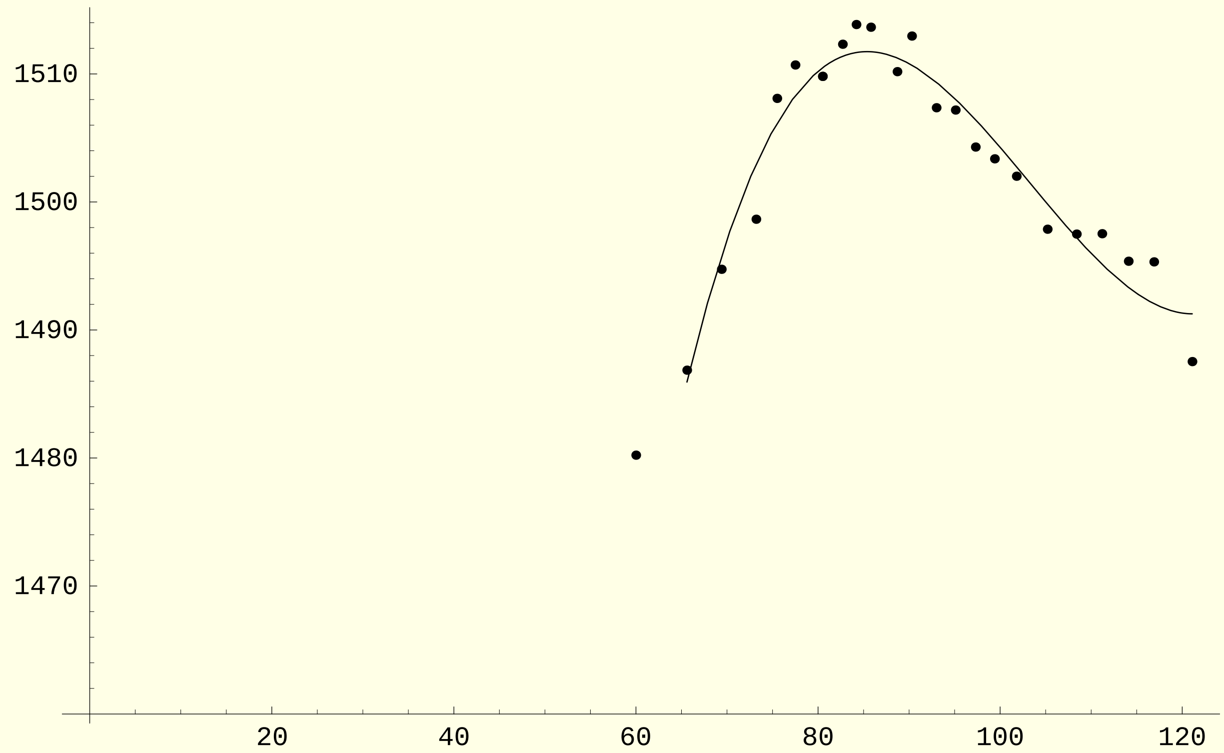


Figure 8: *Number of events consistent with M_N choice as a function of M_N.*

Remarkably, the point at which the turnover occurs gives M_N (and M_X and M_Y) to within ~ 1 GeV. (Resolutions, backgrounds, ... have been included. Bias of this turnover location for given model must be studied to achieve this accuracy.)

Presumably, the experimental groups will actually end up doing even better in the end.

A $\sim$ GeV accuracy for the absolute mass scale should be sufficient to eliminate the 'slider' degeneracies of the LHC inverse solutions.

Such accuracy for the more massive states will aid enormously in the GUT extrapolation.

The ability to get an absolute mass scale out of LHC data could be quite crucial for determining whether the ILC500 is sufficient or one needs to go to ILC1000.

- **Higgs detection in the MSSM**

There is certainly a no-lose theorem in the CP-conserving case.

However, if CP violation in the Higgs sector is introduced, some interesting holes open up. M. Carena, J. R. Ellis, S. Mrenna, A. Pilaftsis and C. E. M. Wagner, Nucl. Phys. B 659, 145 (2003) [arXiv:hep-ph/0211467].

The figure on the next page shows various regions of coverage.

- **The light grey region is theoretically excluded,**
- **and the two medium grey regions are excluded by LEP .**
- **The two darkest shades of grey are**
  (a) the 5-σ discovery region at the LHC using $t\bar{t}H_i \to b\bar{b}$ (100 fb^{-1});
  (b) the 3-σ evidence region at the Tevatron using $W/ZH_i \to b\bar{b}$ (5 fb^{-1});

(c) the 5-σ discovery region at the LHC using $WW \to H_i \to \tau^+\tau^-$ (30 fb^{-1}); and
(d) the 5-σ discovery region at the LHC using $H_i \to \gamma\gamma$ with 100 fb^{-1} of luminosity.

- The phases of $A_t = A_b$ and $m_{\widetilde{g}}$ are shown at the top.

- There is a small hole.

  In these regions of parameters, one of two phenomena occurs.

  (1) The neutral Higgs boson with dominant couplings to the W and Z bosons can decay predominantly into channels which contain either two neutral Higgs bosons, or a neutral Higgs boson and a Z boson. The lighter Higgs boson has only feeble couplings to the W and Z bosons and top quarks, and escapes detection both at LEP and the hadron colliders.

  The danger of Higgs to Higgs decays has a long history in the

NMSSM, to which we shortly turn, beginning with J. F. Gunion, H. E. Haber and T. Moroi, Snowmass 96 [arXiv:hep-ph/9610337], followed by B. A. Dobrescu and K. T. Matchev, JHEP 0009, 031 (2000) [arXiv:hep-ph/0008192]. **The danger arises for Higgs masses below $2m_W$ because of the very tiny $b\bar{b}$ width if its couplings to $b\bar{b}$ are not highly enhanced.**

(2) All three neutral Higgs bosons can share the coupling to W and Z bosons and the top quark, resulting in three marginal signal excesses.

- **Similar holes arise for various other phase choices.**
- **Only the ILC (ILC500 is fine) can absolutely guarantee Higgs detection in all CPX scenarios.**

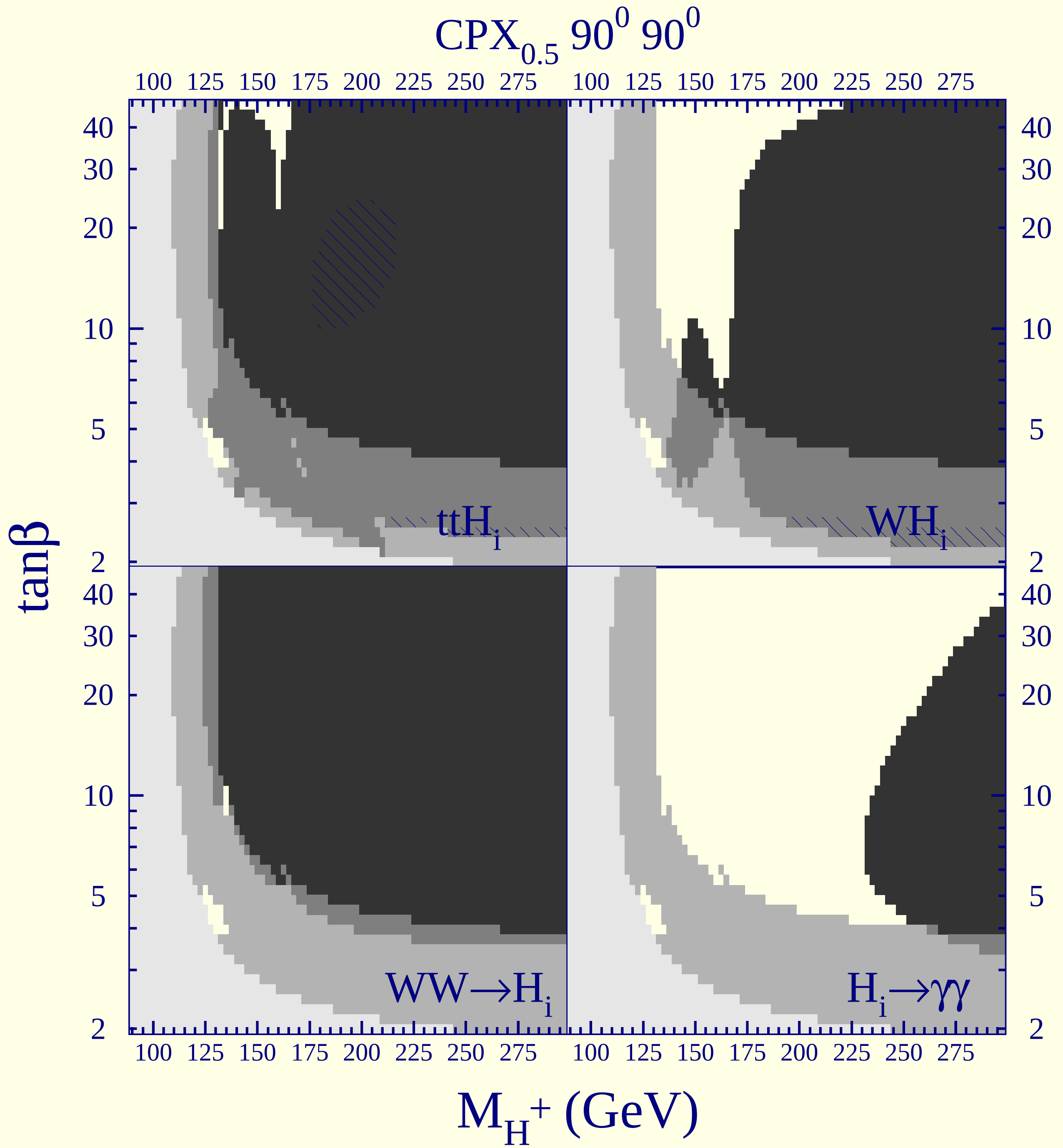


Figure 9: *Coverage of the $M_{H^{\pm}}$–$\tan\beta$ plane in the CPX scenario with $M_{\rm SUSY} = 0.5$ TeV and for the $A_t = A_b$ and $m_{\widetilde g}$ phases shown at top.*

The Next-to-Minimal Supersymmetric Model

Some electroweak priors

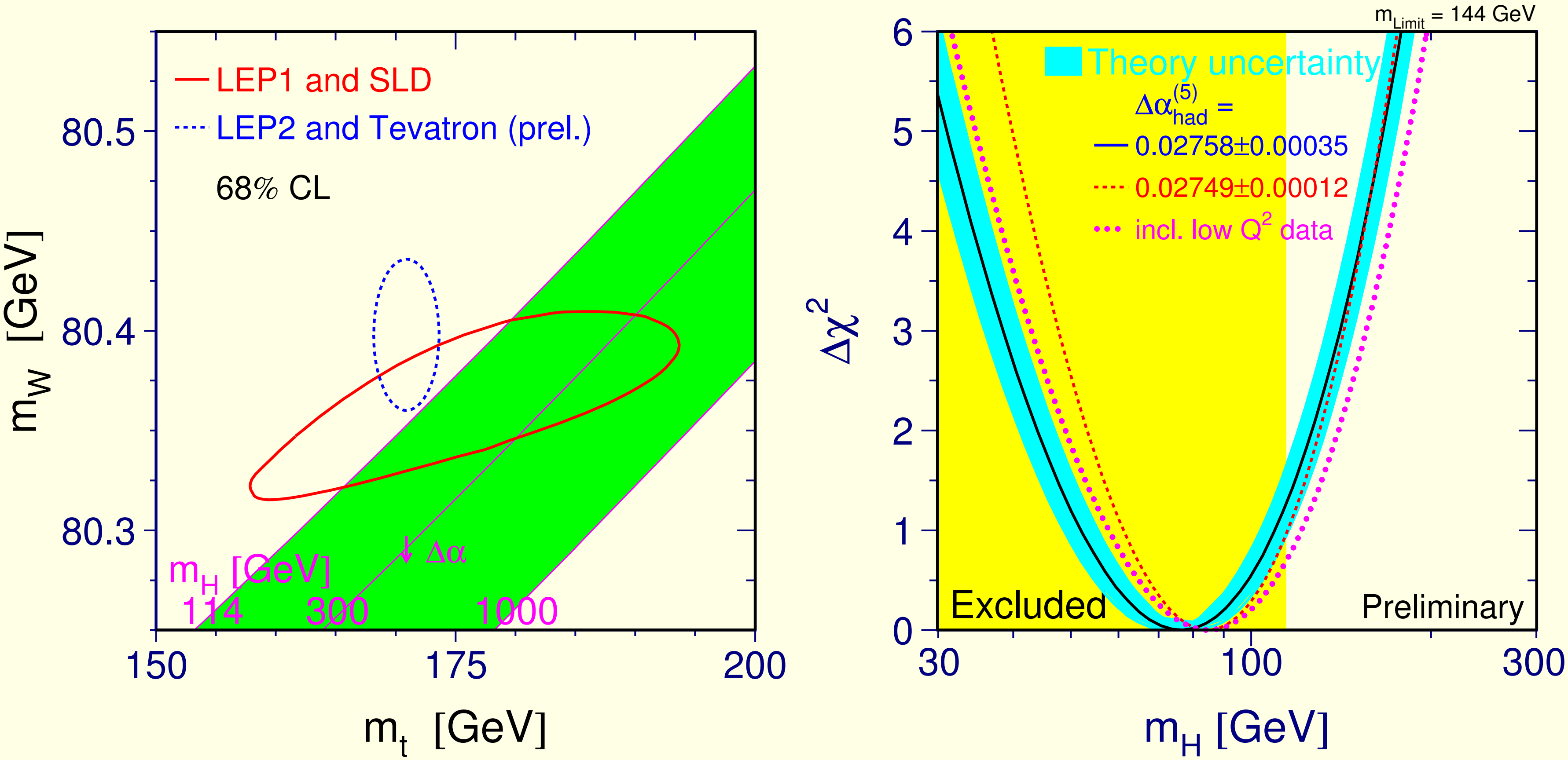
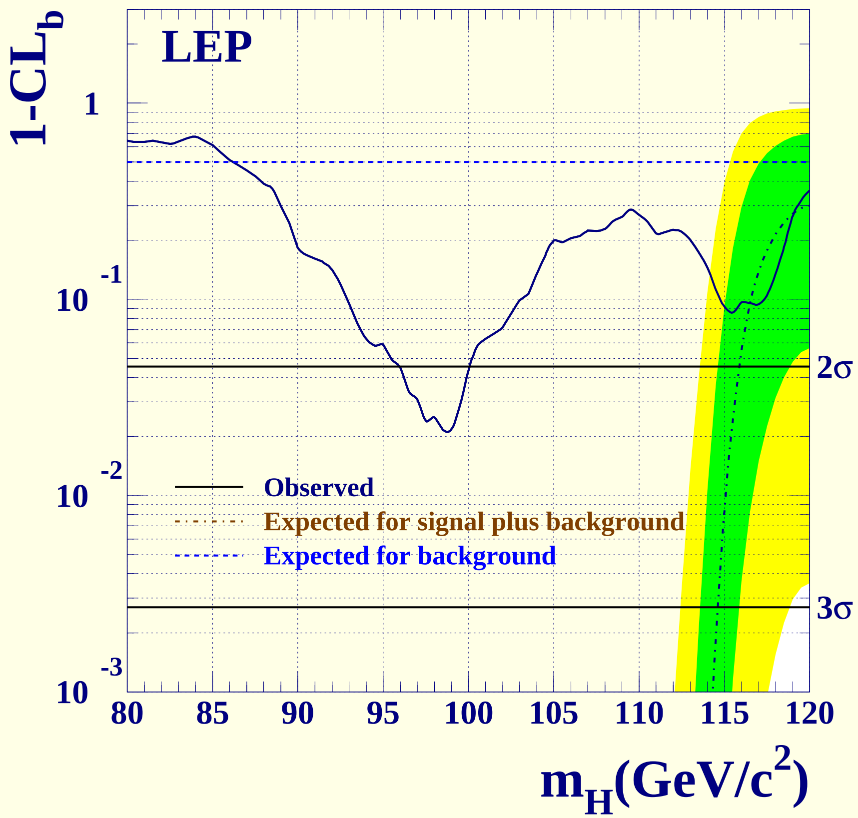


Figure 10: *Perhaps we really should believe in a light SM-like Higgs!*



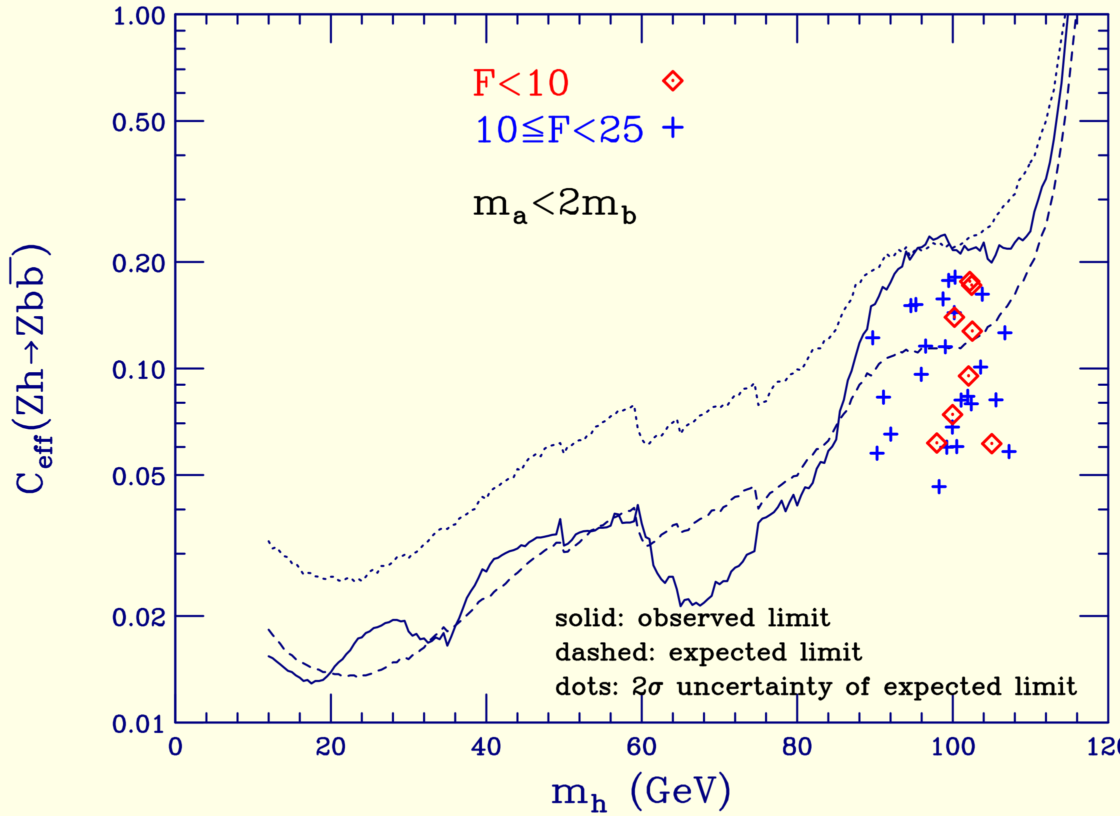


Figure 11: *There is an observed vs. expected* $\boldsymbol{2.6\sigma}$ *discrepancy that is fit perfectly if there is a Higgs with* $\boldsymbol{m_h \sim 100}$ GeV *having close to SM* $\boldsymbol{ZZh}$ *coupling, but* $\boldsymbol{B(h \to b\overline{b}) \sim 1/10}$ *the SM value.*

The NMSSM can fit all these priors, solves the hierarchy problem and has many very attractive features. R. Dermisek and J. F. Gunion,

Phys. Rev. D 75, 075019 (2007) [arXiv:hep-ph/0611142]. Phys. Rev. D 73, 111701 (2006) [arXiv:hep-ph/0510322]. Phys. Rev. Lett. 95, 041801 (2005) [arXiv:hep-ph/0502105].

- The MSSM μ parameter problem is solved using $\mathcal{L} \ni \lambda \widehat{S}\widehat{H}_u\widehat{H}_d$ with $\mu_{\rm eff} = \lambda\langle S\rangle$.
- Gauge coupling unification and RGE EWSB is just as in the MSSM.
- Fine-tuning (F) is absent if the light h_1 has SM-like VV and $f\overline{f}$ couplings and if $m_{h_1} \sim 100~{\rm GeV}$ ($\tan\beta \gtrsim 5$) — SUSY sparticles, especially the stops and gluino, should be close to being observable at the Tevatron.
- This fits precision EWSB very nicely.
- It is natural for the lightest CP-odd Higgs, a_1, to be such that $B(h_1 \to a_1a_1) \sim 0.8$ and $m_{a_1} < 2m_b$ so that $a_1 \to 2\tau$ or

$2\ jets$ (which evades LEP limits on $e^+e^- \to Z + b's$).[1]

- LEP analyses have not constrained this scenario as of yet, but the $Z + 4\tau$ mode is now being actively pursued for the relevant h_1 mass range.

What will the LHC see?

- Light SUSY (needed for low fine-tuning).
- But it will not see the h_1 in the usual channels ($e.g.$ $h_1 \to \gamma\gamma$, $\ldots$).
- LHC analyses must be sensitive to $h_1 \to a_1 a_1 \to 4\tau$ (if $m_{a_1} > 2m_\tau$ *for which there is some fine-tuning preference*) or $h_1 \to a_1 a_1 \to 4\ jets$ (if $m_{a_1} < 2m_\tau$).

[1]Note: Since the $h_1 b\overline{b}$ coupling is so small, it does not take much $h_1 a_1 a_1$ coupling for the $h_1 \to a_1 a_1$ to be the dominant decay since $m_{h_1} < 2m_W$. There are many papers that make use of the small $\Gamma(h_1 \to b\overline{b})$ to allow dominance of other decays.

Possibilities:

– $WW \to h_1 \to a_1 a_1 \to 4\tau$, WW fusion production.
– $t\bar{t}h_1 \to t\bar{t}4\tau$.
– $pp \to pp + h_1 \to pp + 4\tau$ diffractive channel.
– While there is real hope for the above 4τ channels, the corresponding cases with 4τ replaced by $4\ jets$ are probably impossible at the LHC.

Even if the LHC sees the Higgs signal, the ILC will be crucial to really detail the h_1.

- The Higgs-power of the ILC resides in the fact that the $e^+e^- \to ZX$ missing-mass M_X spectrum will have strong Higgs peak regardless of how the h_1 decays.

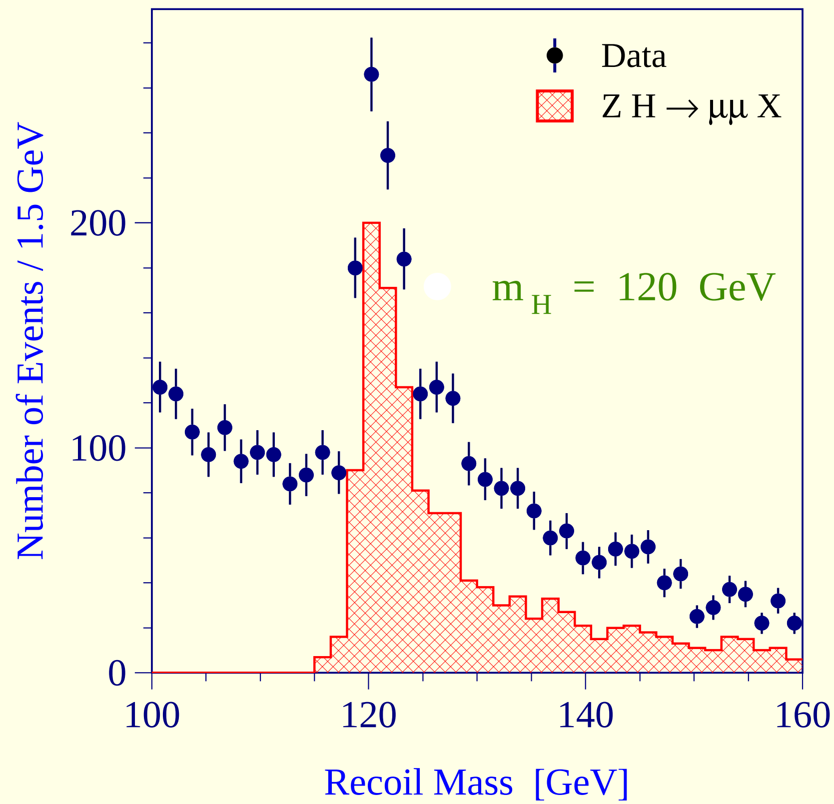


Figure 12: Decay-mode-independent Higgs M_X peak in the $Zh \to \mu^+\mu^- X$ mode for $L = 500~\mathrm{fb}^{-1}$ at $\sqrt{s} = 350~\mathrm{GeV}$, taking $m_h = 120~\mathrm{GeV}$..

There are lots of events in just the $\mu^+\mu^-$ channel (which you may want to restrict to since it has the best mass resolution).

- **Can then check $h_1 \to b\bar{b}$ and $h_1 \to a_1 a_1 \to 4\tau$ branching ratios for consistency with the model.**

- **Can study the a_1 decays as well, and probably get a good determination of many a_1 properties ($e.g.$ how much singlet).**

Other benefits:

- **Light SM-like h_1 as well as the $\lambda A_\lambda S H_u H_d$ coupling makes baryogenesis highly viable, especially if the stop squarks are not particularly heavy (as preferred for low fine-tuning).**

- **There is a new dark matter scenario in which the $\widetilde{\chi}_1^0$ is very light but annihilates sufficiently via the a_1 resonance — can we measure the a_1 and $\widetilde{\chi}_1^0$ properties sufficiently accurately to check?** J. F. Gunion, D. Hooper and B. McElrath, Phys. Rev. D 73, 015011 (2006) [arXiv:hep-ph/0509024].

- **There is a new task for the B factories: look for $\Upsilon \to \gamma a_1 \to$**

$\gamma 2\tau, \gamma 2\ jet$. R. Dermisek, J. F. Gunion and B. McElrath, arXiv:hep-ph/0612031.

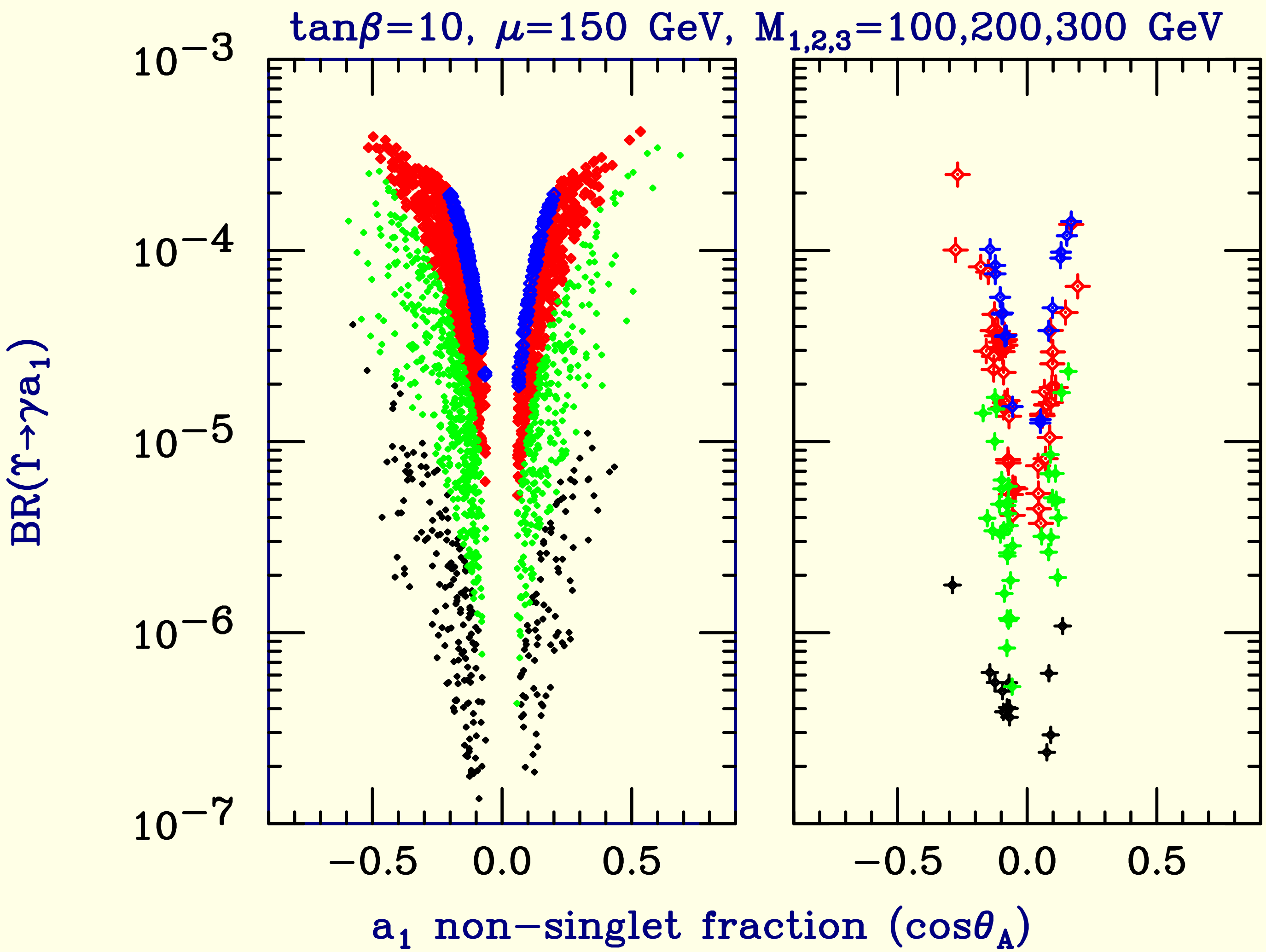


Figure 13: $B(\Upsilon \to \gamma a_1)$ for NMSSM scenarios with various ranges for m_{a_1}. (**blue**= $< 2m_\tau$, **red**=$[2m_\tau, 7.5]$, **green**=$[7.5, 8.8]$, **black**=$[8.8, 9.2]$) **The lower bound on $B(\Upsilon \to \gamma a_1)$ arises basically from the LEP requirement of $B(h_1 \to a_1 a_1) > 0.7$.**

Bottom line:

- **The LHC will be needed for SUSY spectrum and initial Higgs discovery.**

- **The ILC will be needed to really verify h_1 properties and to check whether dark matter works, $i.e.$ the $\widetilde{\chi}_1^0$ and possibly (depending upon $m_{\widetilde{\chi}_1^0}$) the a_1 properties.**

- **Must continue LEP data reanalysis.**

- **B factory data on Υ resonances should be used to constrain or observe $\Upsilon \to \gamma a_1$.**

- **Many of these same conclusions apply to other MSSM extensions such as ....**

Extended NMSSM-like models

- **Strings like lots of singlets.**
- **In the SUSY context, you could have many singlets, which leads to many $h_1 \to aa$ type decays, not to mention $h_1 \to \widetilde{\chi}\widetilde{\chi}$ decays.**
- **One particular model is the $U(1)'$ Extended MSSM.** T. Han, P. Langacker and B. McElrath, Phys. Rev. D 70, 115006 (2004) [arXiv:hep-ph/0405244].
  - **This model has an extra $U(1)'$ gauge group added to the MSSM along with a singlet S as well as 3 other $S_{1,2,3}$; all are charged under the $U(1)'$, but not under the SM groups. S gives the μ parameter as in the NMSSM.**
    The model has some attractive features, but also a lot of complexity. Some problems and features are:

- The lightest Higgs with WW couplings can be heavy because of extra D-term contributions to its mass.
- The lightest Higgs need not have WW couplings. If it doesn't, then it is usually somewhat singlet in nature.
- Gauge coupling unification would appear to require significant extra matter at high scales.
- A more complete model would be required to assess fine-tuning with respect to GUT-scale parameters.
- There are 4 light a_k^0's and these are definitely important in Higgs decays, especially for a light singlet-like Higgs with suppressed couplings to SM particles, but also for the heavier SM-like Higgs if it has mass below $2m_W$.
- There are many neutralinos, some of which are singlet-like and very light, but coupled to the Higgs so that $h_i \to \widetilde\chi_j^0 \widetilde\chi_k^0$ is often a dominant or at least important channel, again especially for the lighter singlet-like Higgs boson.

* **The decays of the lightest a_1 can be dominated by neutralino pairs.**

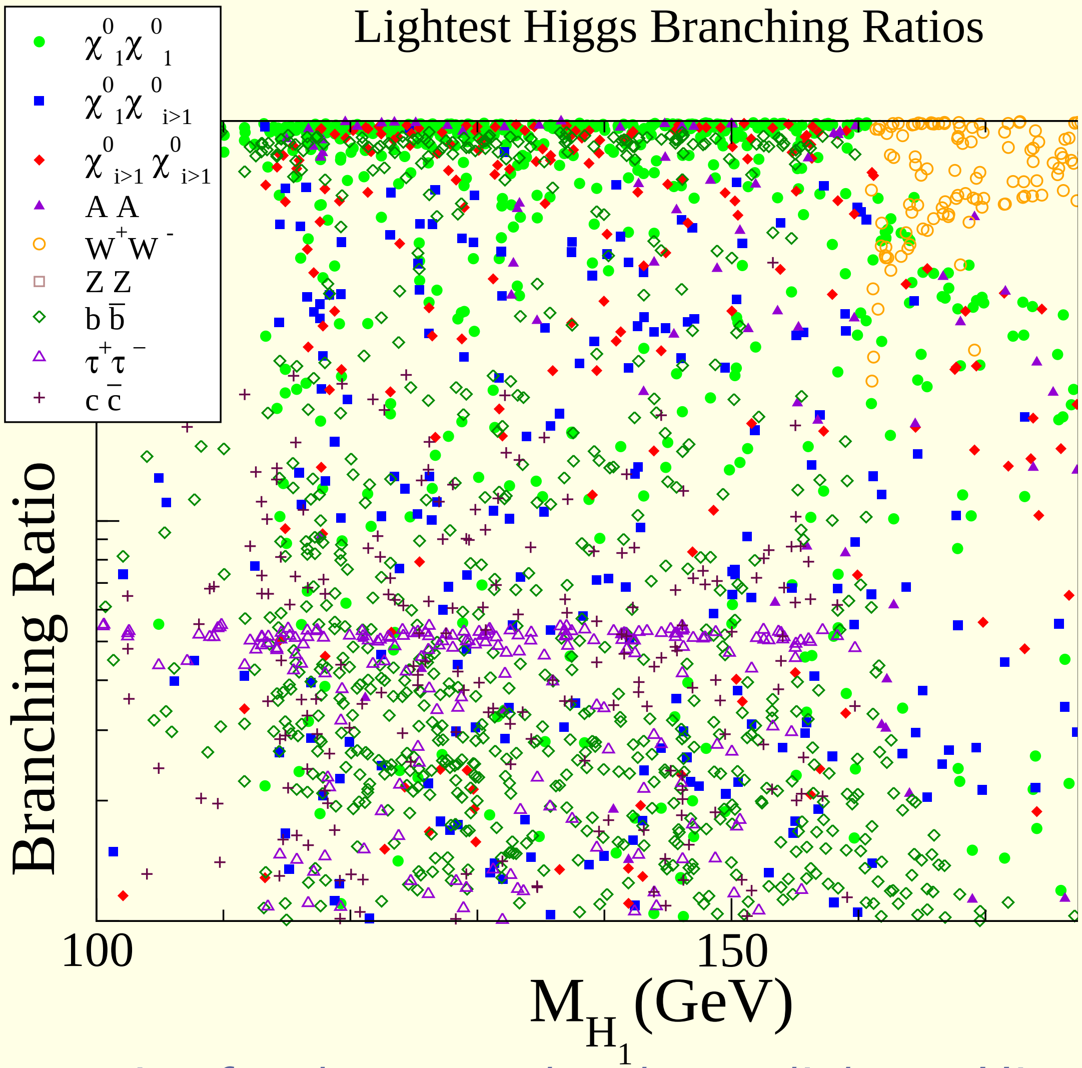


Figure 14: *Branching ratios for the somewhat heavy lightest Higgs with substantial WW coupling.*

- **A lot more work is needed on this kind of model with regard to baryogenesis, dark matter, gauge coupling unification (possibly problematical), ... to fully assess.**

Bottom line:

- **The LHC is very likely to miss the Higgs because of the many channels it would appear in.**

  High $\tan\beta$ could come to the rescue and allow $b\overline{b}h_2 + b\overline{b}a_2 \to b\overline{b}\tau^+\tau^-$ detection. (There are Tevatron hints from CDF and anti-hints from D0.)

- **The LHC would probably see lots of SUSY, unless all colored sparticles are heavy (not preferred by fine-tuning).**

- **The ILC would absolutely be required to detail the SUSY spectrum and generally sort things out.**

SUSY with a wino LSP

This possibility is quite independent of the EWSB scenario, but does have some impact on dark matter.

- **Many soft-SUSY-breaking boundary conditions can lead to near degeneracy of the $\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^\pm$.**

  This cropped up in early string scenarios (C. H. Chen, M. Drees and J. F. Gunion, Phys. Rev. D 55, 330 (1997) [Erratum-ibid. D 60, 039901 (1999)] [arXiv:hep-ph/9607421]. C. H. Chen, M. Drees and J. F. Gunion, Phys. Rev. Lett. 76, 2002 (1996) [arXiv:hep-ph/9512230]. **)**

  And it arises for the AMSB (anomaly-mediate SUSY breaking) boundary conditions contained within the earlier string models (L. Randall and R. Sundrum, Nucl. Phys. B 557, 79 (1999) [arXiv:hep-th/9810155]. G. F. Giudice, M. A. Luty, H. Murayama and R. Rattazzi, JHEP 9812, 027 (1998) [arXiv:hep-ph/9810442]. **)**

There are many interesting phenomenological implications, and SUSY detection can be much more difficult at a hadron collider. (J. L. Feng, T. Moroi, L. Randall, M. Strassler and S. f. Su, Phys. Rev. Lett. 83, 1731 (1999) [arXiv:hep-ph/9904250]. J. F. Gunion and S. Mrenna, Phys. Rev. D 62, 015002 (2000) [arXiv:hep-ph/9906270]. J. F. Gunion and S. Mrenna, Phys. Rev. D 64, 075002 (2001) [arXiv:hep-ph/0103167]. See also the presentation by Kai Wang, this meeting.)

- Strict AMSB $\Rightarrow M_1 : M_2 : M_3 \sim 2 : 1 : 7$, so the gluino is about 7 times heavier than the $\widetilde\chi^0_1$ (which is close in mass to $\widetilde\chi^\pm_1$).

- The really dangerous situation for a hadron collider, including the LHC, is the case in which

1. colored sparticles are relatively heavy (as natural for AMSB-like b.c.)
2. μ is large, so that $\widetilde\chi^0_3$ and $\widetilde\chi^0_4$ are heavy, so that one must

rely on light gaugino $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_1^0$ production.

3. Maximally bad mass difference:

$$\Delta m_{\widetilde{\chi}} \equiv m_{\widetilde{\chi}_1^{\pm}} - m_{\widetilde{\chi}_1^0} \sim few \text{ GeV} . \quad (1)$$

This is the natural result if one starts with AMSB-like b.c. at tree-level and then inputs the one-loop corrections.
In this case,

$$\widetilde{\chi}_1^{\pm} \to \widetilde{\chi}_1^0 + \pi' s \quad \text{or} \quad \widetilde{\chi}_1^{\pm} \to \widetilde{\chi}_1^0 \ell \nu \quad (2)$$

promptly (so can't use vertex detection or stable track or ...) and the π's or ℓ are quite soft. (The $\widetilde{\chi}_1^0 \ell \nu$ state has $BR \sim 0.1$.)

In this scenario,

1. $\widetilde{\chi}_1^{\pm} \widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^+ \widetilde{\chi}_1^-$ production rates are not large enough to give a dramatic excess of anything.

2. one loses the like-sign di-lepton and tri-lepton signals.
3. without a γ or jet tag, missing energy will tend to cancel between the two sides of the event.
4. no convincing case for discovery of SUSY at the LHC has been made. The most thorough study I know of is for strict AMSB (so that the gluinos and squarks are still being produced at a non-trivial rate)

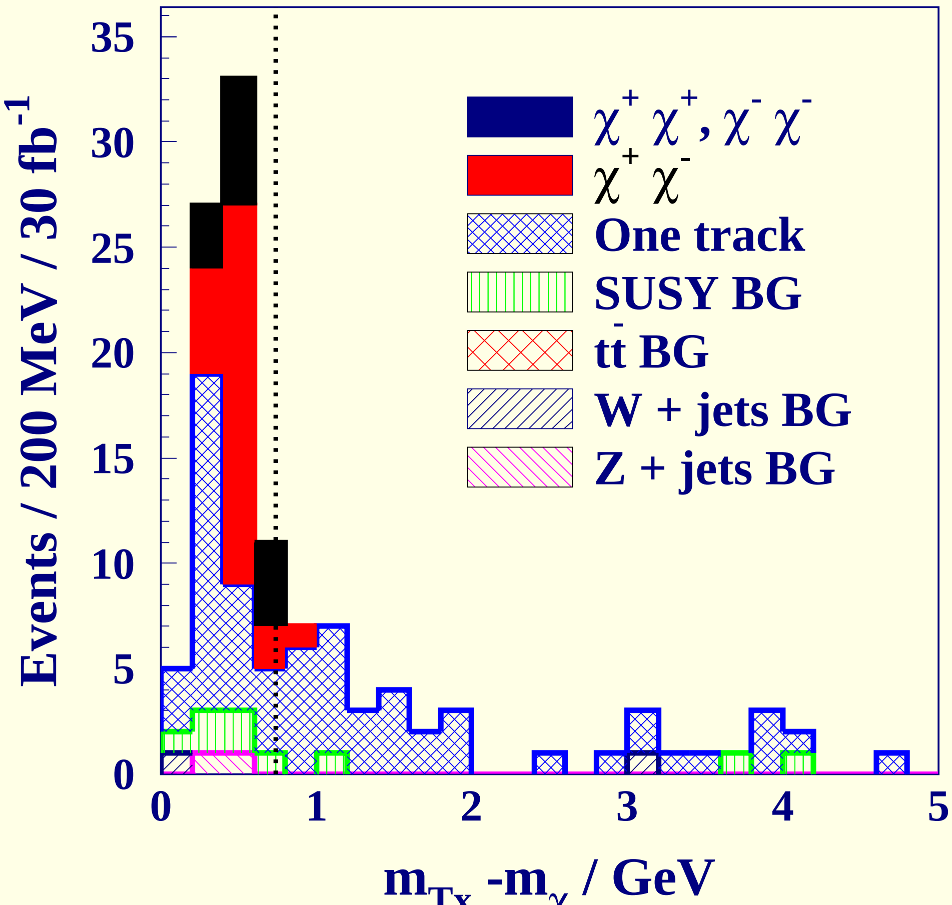


Figure 15: *The ATLAS result of A. J. Barr, C. G. Lester, M. A. Parker, B. C. Allanach and P. Richardson, JHEP* **0303***, 045 (2003) [arXiv:hep-ph/0208214]. Here,* $m_{\widetilde\chi_1^\pm} \sim 100~\mathrm{GeV}$ *(quite low) and* $\Delta m_{\widetilde\chi} \sim 766~\mathrm{MeV}$. *A jet-tag is employed.*

I do not find this result for $m_{\widetilde\chi_1^\pm} \sim m_{\widetilde\chi_1^0} \sim 100~\mathrm{GeV}$ very comforting.

Double the mass scale and there are big problems.

5. Once $\Delta m_{\widetilde{\chi}} \gtrsim 5-7~\mathrm{GeV}$, there may be enough energy in the soft pion 'jets' that progress can be made — see talk by Kai Wang.
6. Generally speaking, the ILC may be necessary for SUSY discovery, and if $m_{\widetilde{\chi}_1^\pm} \sim m_{\widetilde{\chi}_1^0} > 250~\mathrm{GeV}$ this will require ILC1000.

Bottom line:

Could the LHC fail to see SUSY because of AMSB-like b.c. *AND* fail to see the Higgs because of unexpected decays coming from an extended scalar etc. sector like the NMSSM with $m_{a_1} < 2m_\tau$ (so that Higgs detection will probably not be possible.)

This would be a scenario with no LHC signal for which the ILC1000 (but, maybe not the ILC500) would see a lot of spectacular things (h_1, a_1, $\widetilde{\chi}_1^\pm$, $\widetilde{\chi}_1^0$ at the least).

Models with axions and axinos

There is no time to review these, but I recommend L. Covi, L. Roszkowski, R. Ruiz de Austri and M. Small, JHEP 0406, 003 (2004) [arXiv:hep-ph/0402240].

This possibility for dark matter has many attractive features and could yield a situation in which the $\widetilde{\chi}_1^0$ appears to have too much relic density, but this density is degraded by $m_{axino}/m_{\widetilde{\chi}_1^0}$ when the NLSP's ultimately decay after being produced in the early universe.

See also the talk of H. Baer.

Conclusions

1. **In most reasonable SUSY models with R-parity conservation (so as to address dark matter), the LHC will see both Higgs boson signals and missing energy that can be associated with dark matter.**

However,

2. **Beware of an NMSSM-like or CPX-like Higgs sector.**

   In the NMSSM case, work on the 4τ modes at the very least. LEP analyses might have impact.

   Is there anything to be done for the $4\ jet$ modes?

   In the CPX case, there are no known improvements to be made at the LHC, but one should try to close the hole using extended LEP analyses.

3. AMSB-like b.c. remain worrisome.

Further work by the ATLAS and CMS collaborations may increase the robustness of the marginal signals.

Bottom line:

There are no guarantees for the LHC without the ILC.