Will there be Supersymmetry at the ILC ?

M. E. Peskin
LHC Implications for ...
July 2012

One often hears:

"If SUSY is not found at the LHC before the shutdown, then we will know that SUSY will not be found at the ILC."

People attending this workshop know that this is incorrect. I hope that this will be explained clearly in the report to the European Strategy Study.

First, what is the ILC ?

ILC is an e+e- linear collider based on superconducting RF cavities with design CM energy 500 GeV. The technology extends at least to 1000 GeV. It is likely that construction of ILC would be staged, with a first stage at 250 GeV.

The ILC TDR is being completed this year. ILC is the only proposal for a future e+e- collider that is ready for approval now.

Is there a case for the ILC ?

Heuer: The case for any future collider must be based on what we have learned from LHC.

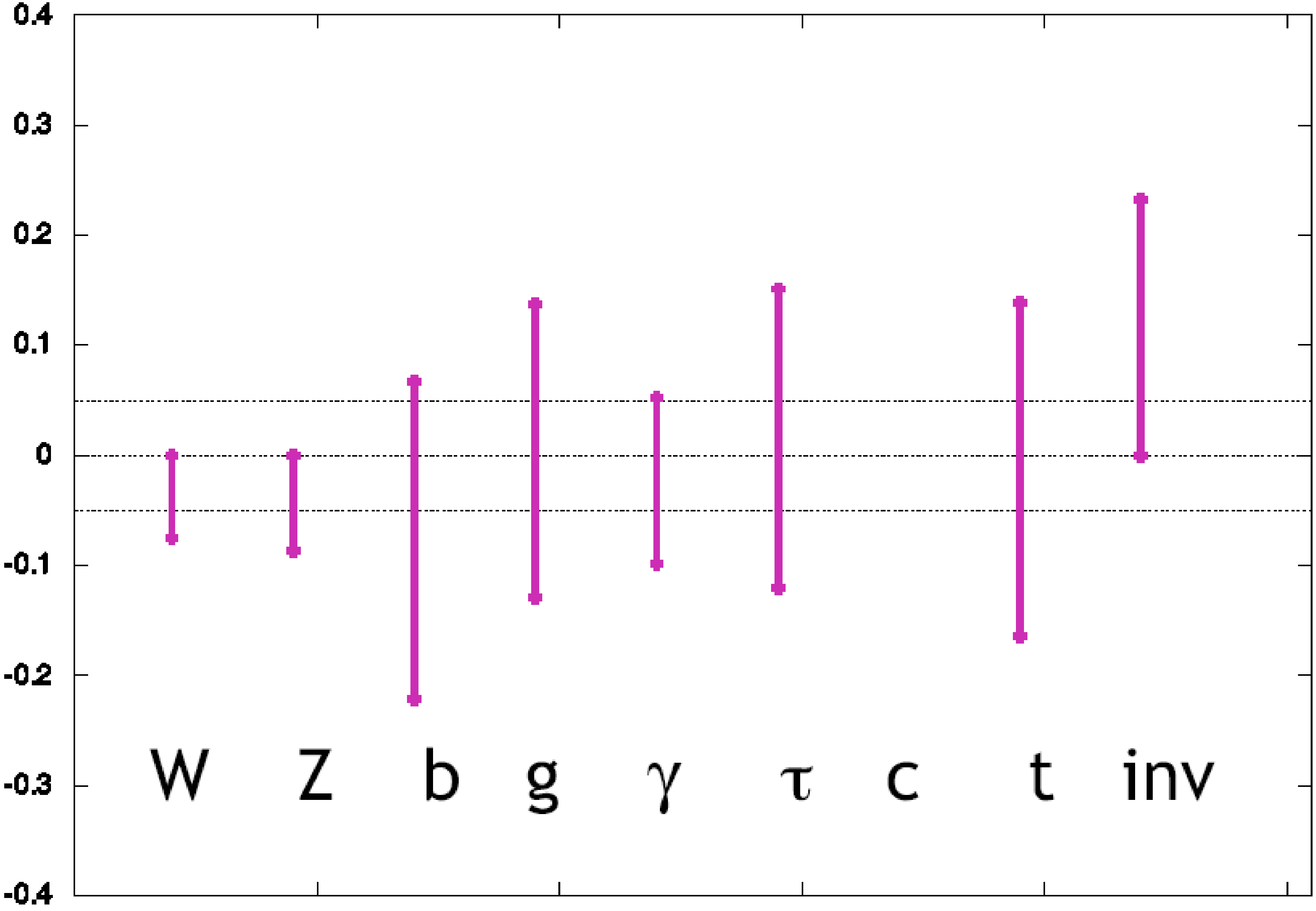
We have now learned something from the LHC, and it strongly motivates proposing the ILC immediately.

The LHC has discovered a boson of mass 125 GeV, coupling to WW, ZZ, and γγ. We thus know that this boson can be studied with precision at the ILC. This is an important program that might be a gateway to knowledge about new physics.

New physics models typically include a Higgs boson similar to the Standard Model Higgs boson, with deviations less than 10% in couplings. The LHC cannot reach this level of precision. The ILC will.

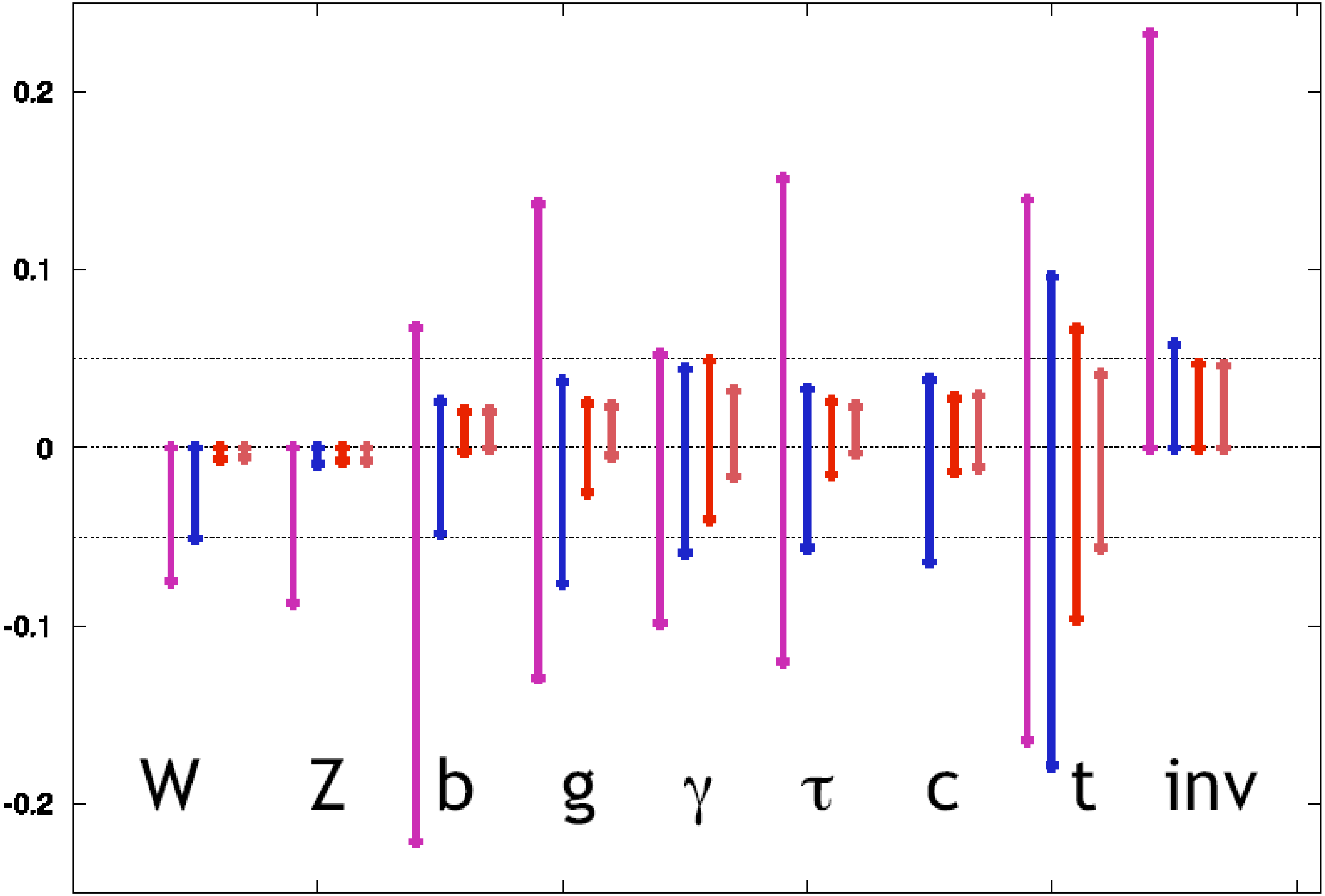
The LHC has not discovered any other new particles. So there is no motivation currently for e+e- at 3 TeV, and there may not be when we have seen more LHC data.

$g(hAA)/g(hAA)|_{SM}-1$ LHC



MEP, arXiv:1207.2516

$g(hAA)/g(hAA)|_{SM}-1$ LHC / HLC / ILC / ILCTeV



MEP, arXiv:1207.2516

These arguments are recognized by members of the government in Japan. There is an opportunity for frontier particle physics in Asia in parallel with the SLHC program.

AAA directorates With Core Members of Federation of Diet Members (2011 Dec.)

AAA public symposium

Promoting Accelerator world, basic science, and ILC

S. Yamashita at KILC12

So, the ILC is already highly motivated.

Now I will address:

Can there be extra motivation coming from the LHC discovery of SUSY in the latter half of this decade ?

It is well understood that, even if only a few SUSY particles are in the range of the ILC, the precision study of these particles can lead to important conclusions.

For model studies of neutralino dark matter, see

Baltz et al   hep-ph/0602187

I apologize that this study needs to be updated with new benchmarks not excluded at LHC.

Are light SUSY particles excluded at the LHC ?

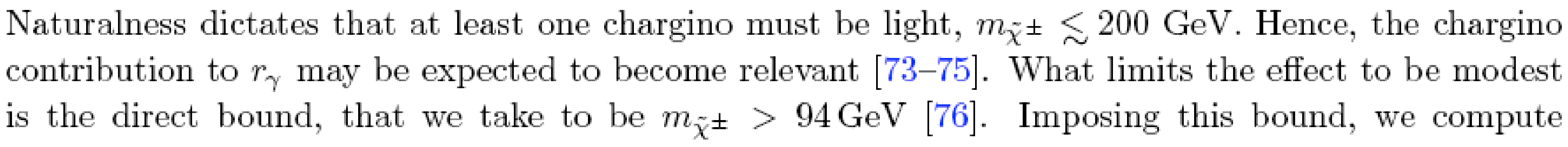
I will first give some sociological evidence against this statement:

1. No theorist who believed in SUSY before 2009 has renounced SUSY in the light of the LHC exclusions. (*)

2. Model builders are still building models with 200 GeV charginos.

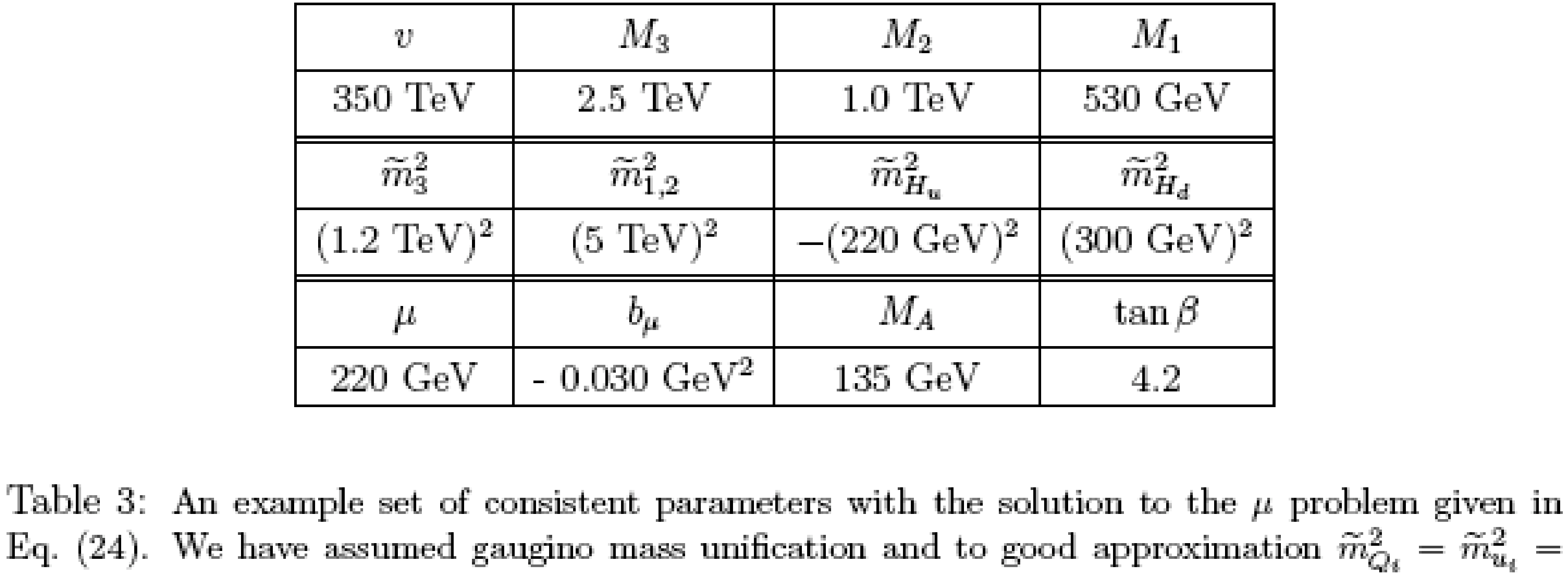
(* Gordy Kane might be considered an exception.)

Blum, D’Agnolo, and Fan, arXiv:1206.5303



Naturalness dictates that at least one chargino must be light, $m_{\tilde{\chi}^\pm} \lesssim 200$ GeV. Hence, the chargino contribution to r_γ may be expected to become relevant [73–75]. What limits the effect to be modest is the direct bound, that we take to be $m_{\tilde{\chi}^\pm} > 94\,\mathrm{GeV}$ [76]. Imposing this bound, we compute

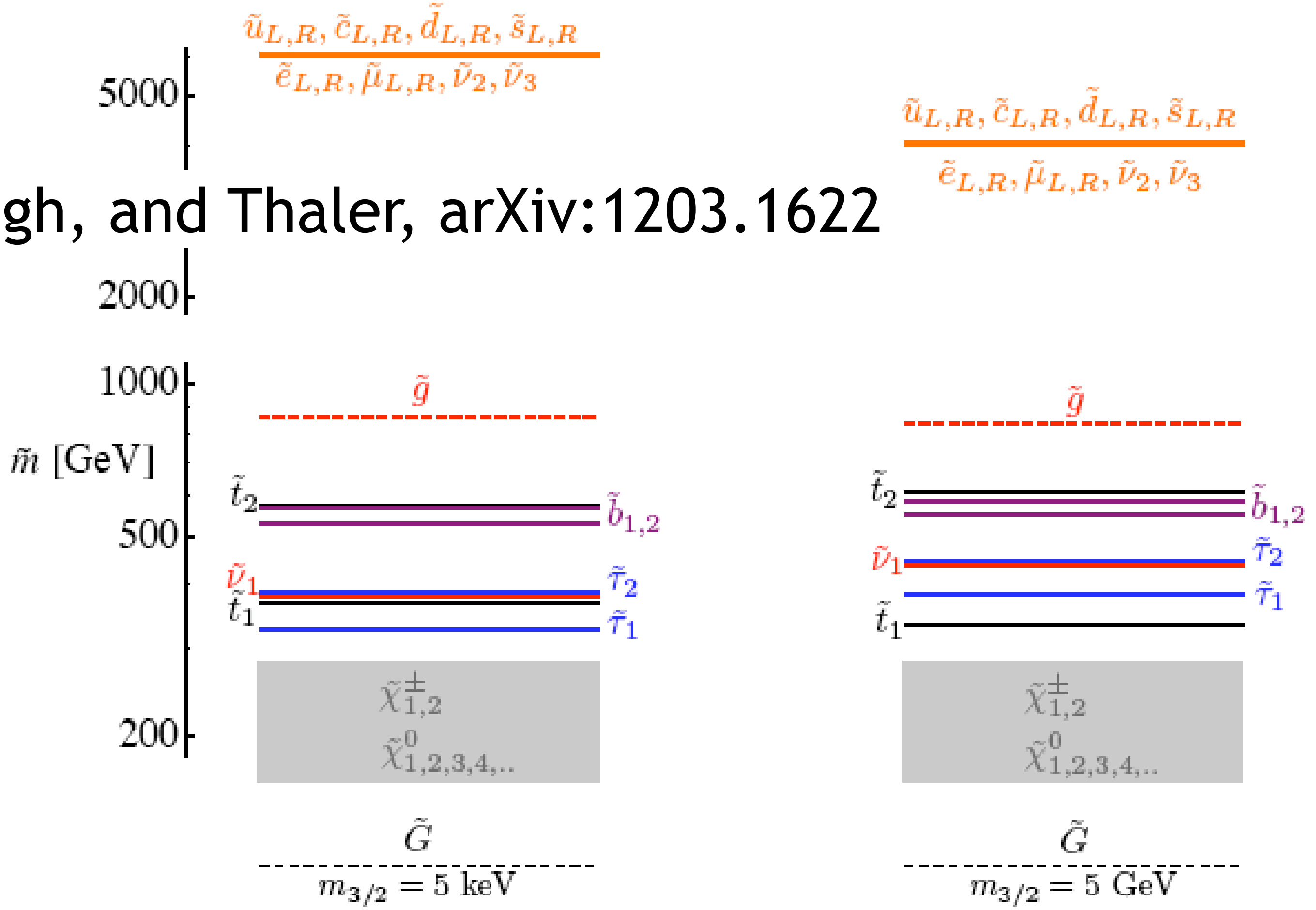
Cohen, Hook, Torroba, arXiv:1204.1337



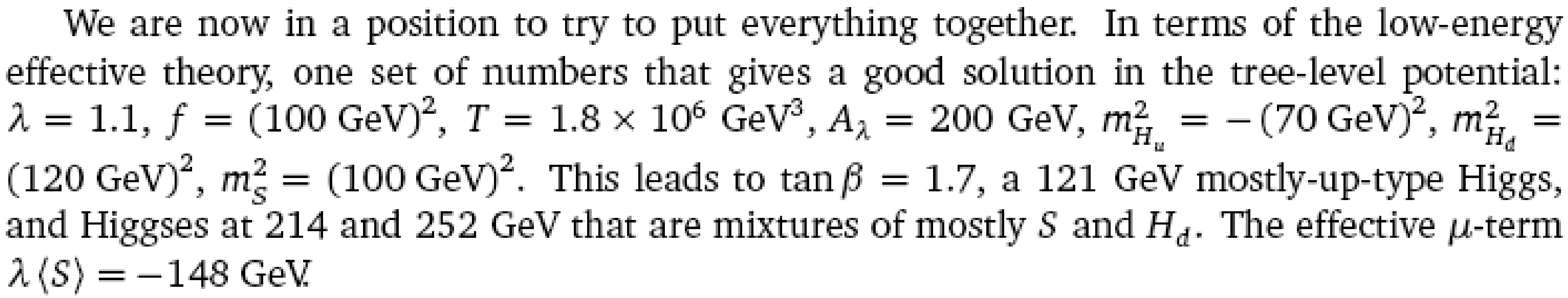
v	M_3	M_2	M_1
350 TeV	2.5 TeV	1.0 TeV	530 GeV
$\widetilde{m}_3^2$	$\widetilde{m}_{1,2}^2$	$\widetilde{m}_{H_u}^2$	$\widetilde{m}_{H_d}^2$
$(1.2\ \mathrm{TeV})^2$	$(5\ \mathrm{TeV})^2$	$-(220\ \mathrm{GeV})^2$	$(300\ \mathrm{GeV})^2$
μ	b_μ	M_A	$\tan\beta$
220 GeV	- 0.030 GeV^2	135 GeV	4.2

Table 3: An example set of consistent parameters with the solution to the μ problem given in Eq. (24). We have assumed gaugino mass unification and to good approximation $\widetilde{m}_{Q_3}^2 = \widetilde{m}_{u_3}^2 =$

Craig, McCullough, and Thaler, arXiv:1203.1622



Randall and Reece, arXiv:1206.6540


We are now in a position to try to put everything together. In terms of the low-energy effective theory, one set of numbers that gives a good solution in the tree-level potential: $\lambda = 1.1$, $f = (100\text{ GeV})^2$, $T = 1.8 \times 10^6\text{ GeV}^3$, $A_\lambda = 200$ GeV, $m^2_{H_u} = -(70\text{ GeV})^2$, $m^2_{H_d} = (120\text{ GeV})^2$, $m^2_S = (100\text{ GeV})^2$. This leads to $\tan\beta = 1.7$, a 121 GeV mostly-up-type Higgs, and Higgses at 214 and 252 GeV that are mixtures of mostly S and H_d. The effective μ-term $\lambda\langle S\rangle = -148$ GeV.

The reason for this is easy to understand. The μ parameter enters directly into the expression for the Z mass in SUSY, so at the very least, small μ is needed for naturalness.

$$m_Z^2 = 2\,\frac{M_{Hd}^2 - \tan^2\beta M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$

This has led to a number of proposals for SUSY spectra with a few particles important for naturalness light and all others much heavier. This strategy has been given the name "natural SUSY". See, e.g.

Papucci, Ruderman, Weiler, arXiv:1110.6926
Baer, Barger, Huang, Tata, arXiv:1203.5539

There are less or more extreme natural SUSY scenarios. Let's review them:

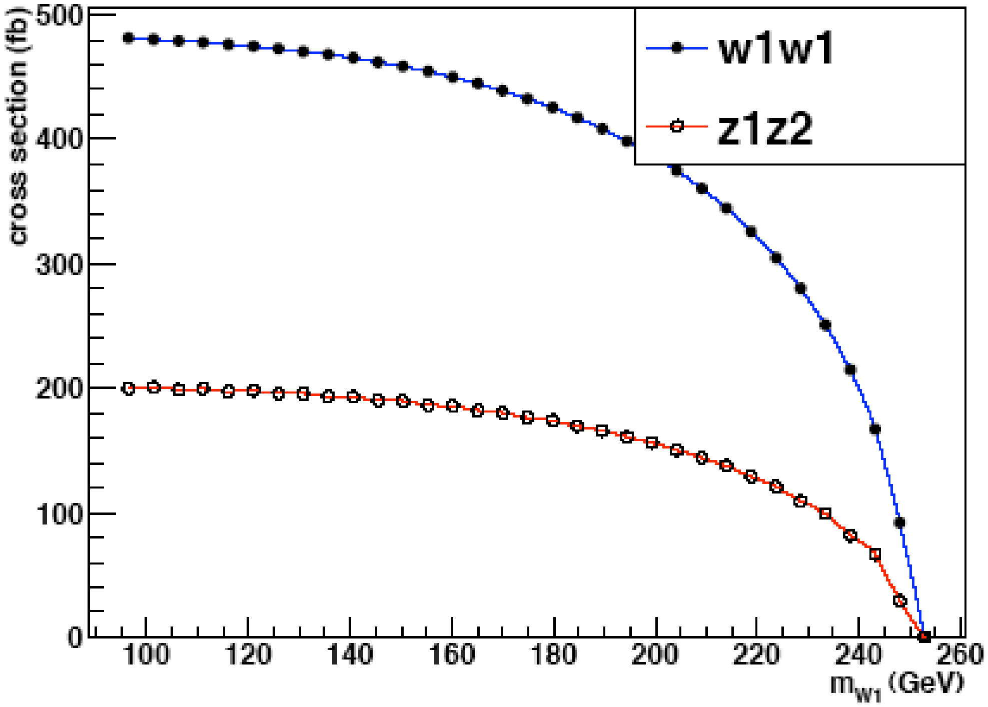
1. Light Higgsino only

This is a sector $\widetilde{\chi}_1^0\ ,\ \widetilde{\chi}_2^0\ ,\ \widetilde{\chi}_1^\pm$

below 200 GeV, with mass splittings of order 10 GeV. It is very difficult for LHC to observe these particles.

At the ILC, the cross sections are large. Observation is not trivial, but Baer, Barger, Huang, arXiv:1107.5581 give a straightfoward set of cuts.

The cross sections are strongly dependent on beam polarization, allowing a test of the Higgsino/chargino mixture.



The Higgsino is not a good dark matter candidate, having too large an annihilation cross section to WW, ZZ.

However, we might need to go to the NMSSM to raise the Higgs mass to 125 GeV.   Then a singlino LSP below the Higgsino can be a good dark matter candidate, with

$$\sigma(\widetilde{S}\widetilde{S} \to W^+W^-) \sim \lambda^4 \sigma(\widetilde{H}\widetilde{H} \to W^+W^-)$$

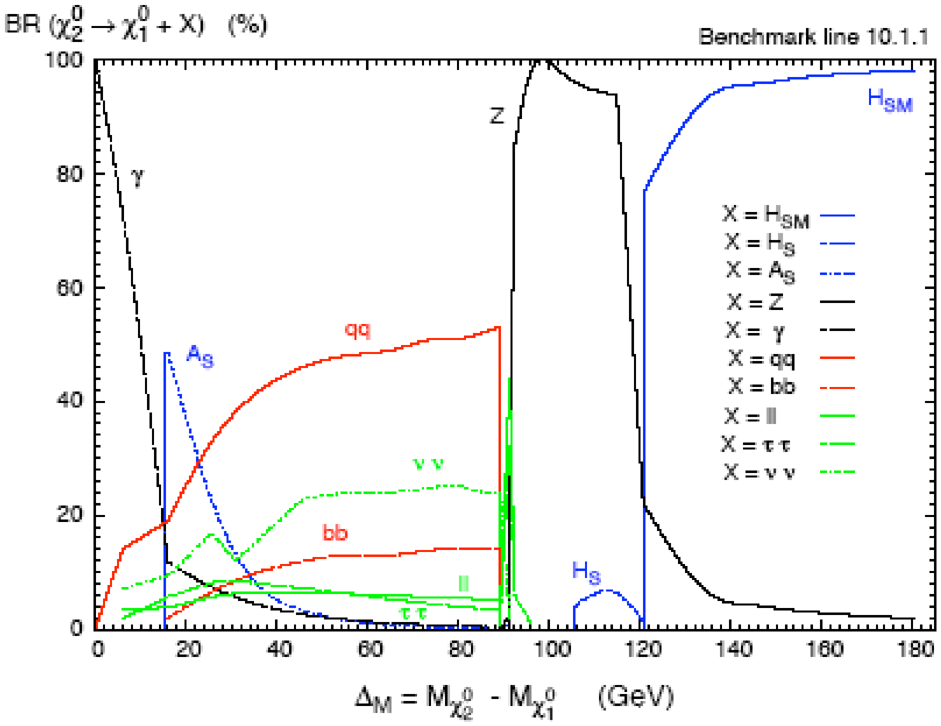
The Higgsino decays to the singlino with

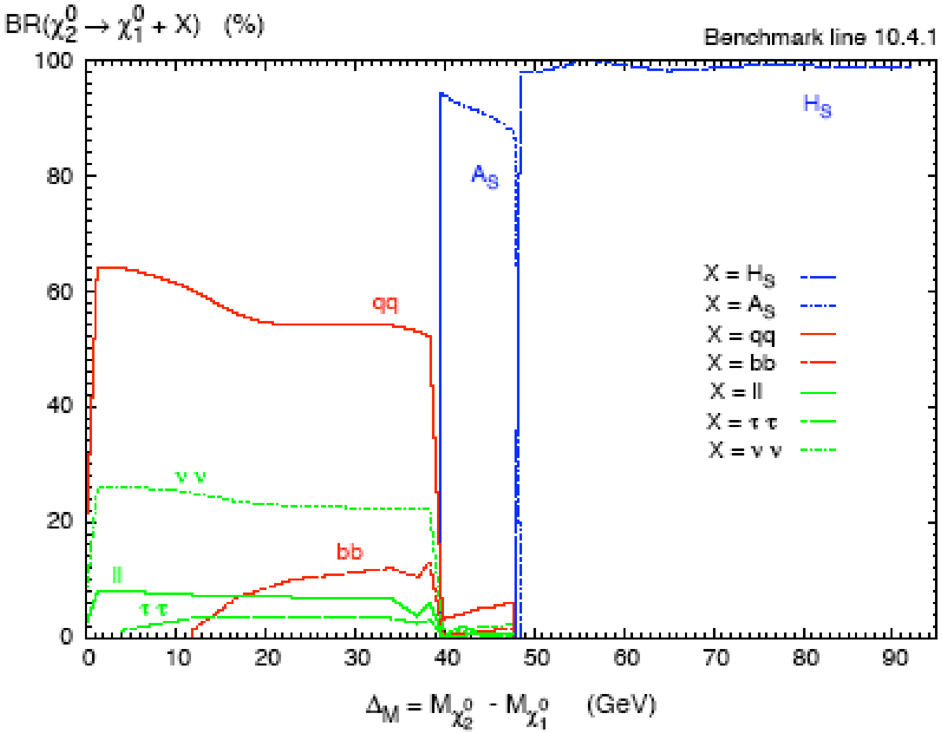
$$\Gamma(\widetilde{H}) \sim \lambda^2 \cdot \mathrm{GeV}$$

This can be measured down to tens of MeV in a threshold scan.

λ can also be determined using precision measurements of the 5 neutralino mass eigenvalues.

The Higgsino has a rich pattern of decay modes, none of which pass LHC triggers.





Das, Ellwanger, Teixeira,
arXiv:1202.5244

2. Light sleptons

In constrained frameworks, the sleptons and squarks are at the same mass scale. In more general contexts, this is unnecessary.

There are currently no model-independent limits on sleptons beyond LEP.

There are many reasons why light sleptons are motivated:

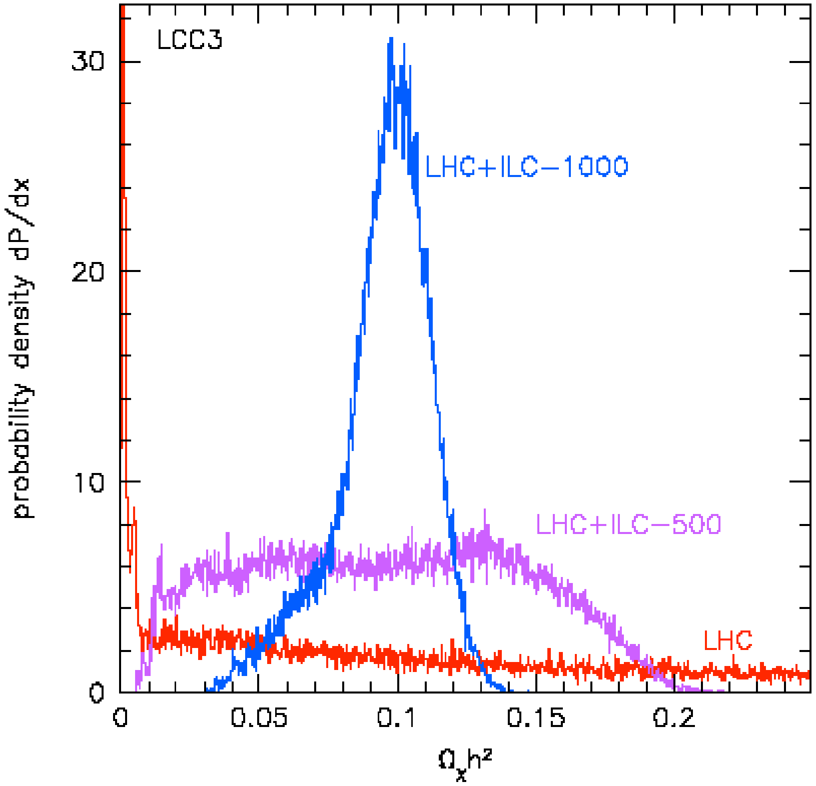
Stau coannihilation mechanism for dark matter. This forces

$$m(\widetilde{\tau}) \approx m(\widetilde{H})$$

SUSY contribution to muon g-2.

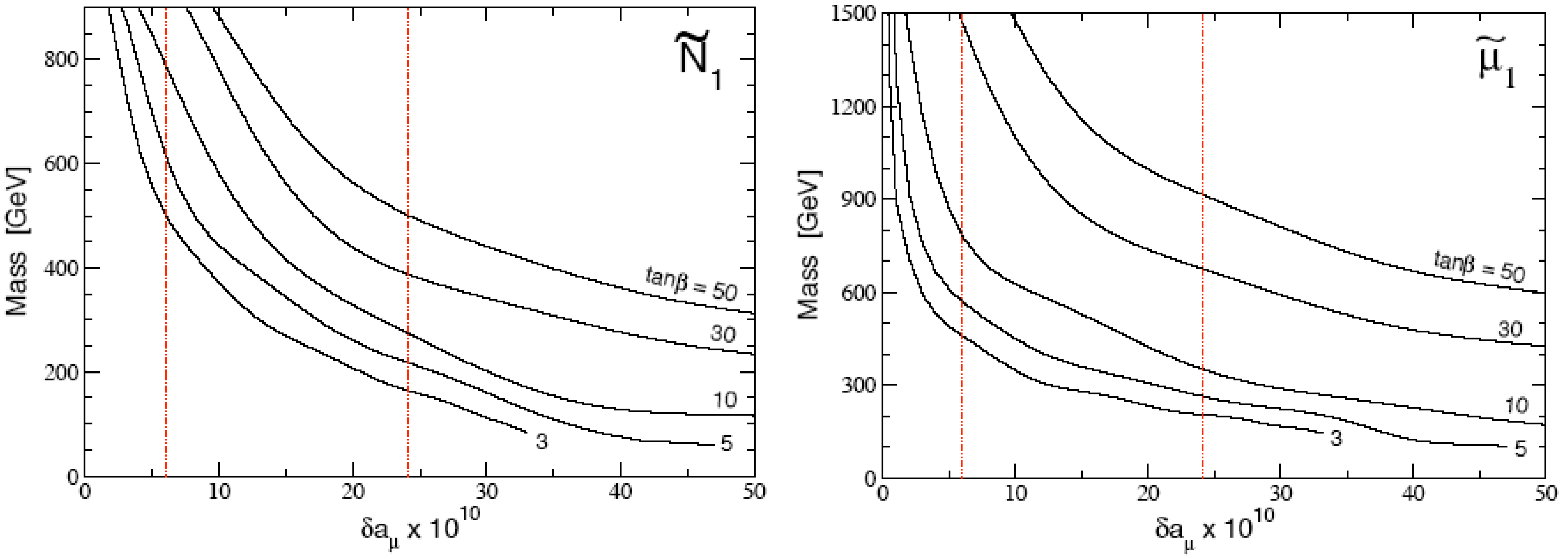
Stau contribution to $\Gamma(h \to \gamma\gamma)$ (Carena et al.)

Stau coannilation was studied in Baltz et al. as the benchmark point LCC3. This point is now excluded on the basis of its quark/gluon sector, which is irrelevant to the dark matter mechanism.



In the study of LCC3, running at 1000 GeV was needed to study the $\widetilde{e}_R$, $\widetilde{\mu}_R$ and to determine $\tan\beta$. These measurements would still be available at energies close to 500 GeV in a scenario with heavy colored particles.

The muon g-2 requires very light sleptons only if $\tan\beta$ is small. However, that is possible if the Higgs mass is boosted to 125 GeV by NMSSM interactions.



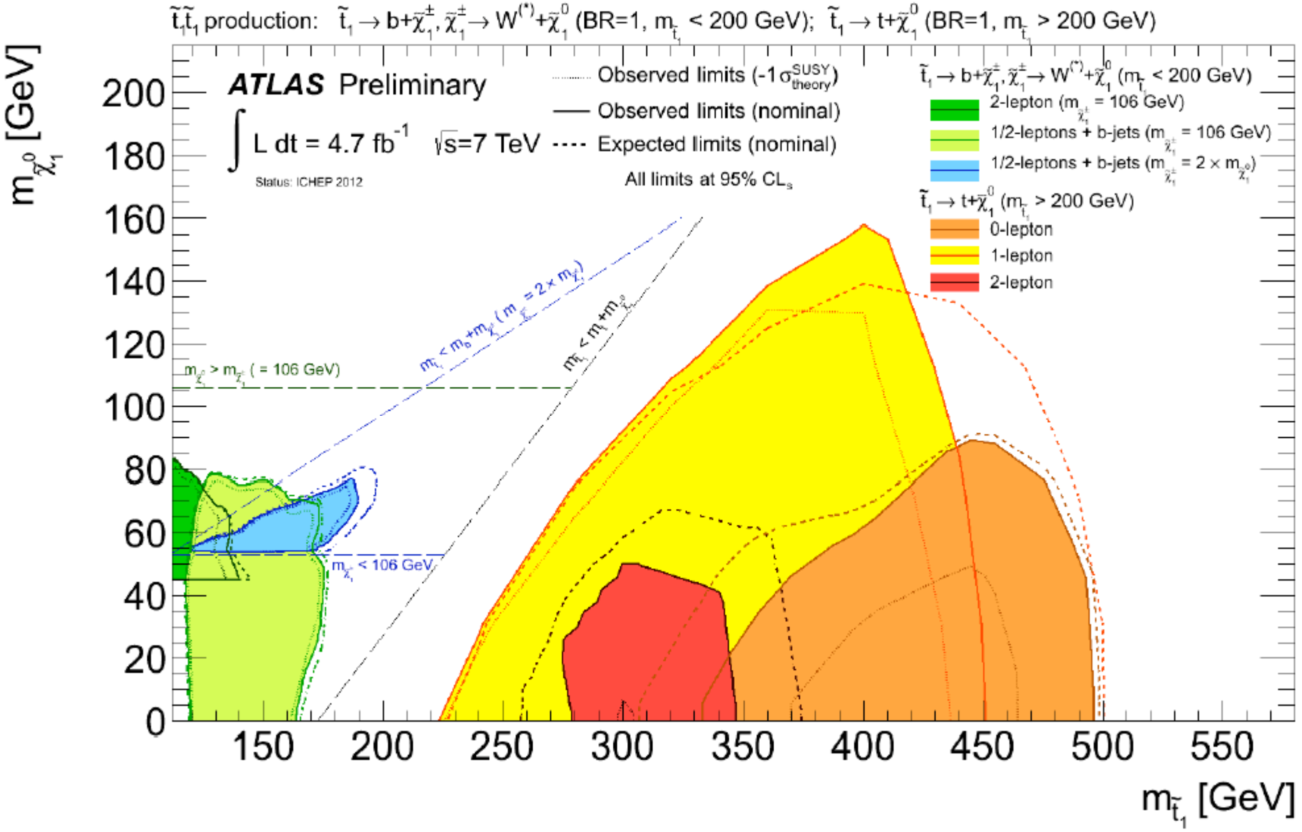
Bounds on the neutralino and smuon masses from muon g-2 anomalies: Byrne, Kolda, and Lennon, hep-ph/0208067 .

3. Light stop

There has been much discussion at this workshop along the lines:

Light stop is highly motivated by naturalness of SUSY.

Light stop is difficult to observe at the LHC. Current limits are weak. Cases such as $m(\widetilde{t}) \approx m_t$, $m(\widetilde{\chi}) \sim 200$ GeV, competing decay channels subvert these limits.



So, why not

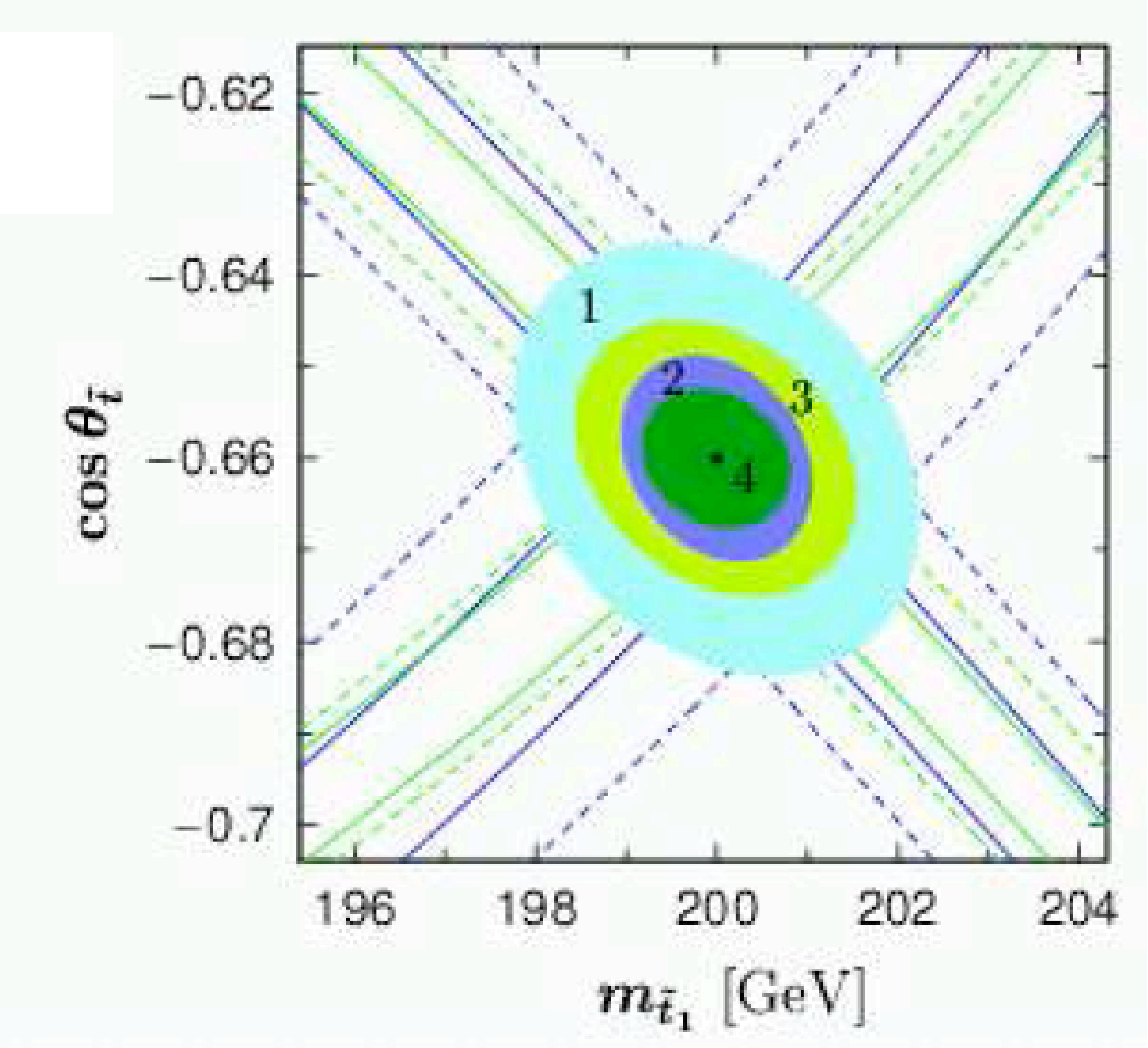
$$m(\widetilde{t}) < 250\ \text{GeV}$$

?

I remind you that measurement of the polarized cross sections

$$\sigma(e^-_L e^+_R \to \widetilde{t}_1 \widetilde{t}^*_1)\ ,\ \sigma(e^-_R e^+_L \to \widetilde{t}_1 \widetilde{t}^*_1)$$

determines the stop mixing angle. This is crucial information for understanding whether m(h) = 125 GeV is possible within the MSSM.



Bartl et al.

4. Light s-everything

More generally, we have discussed at this workshop many mechanism for weakening SUSY exclusions at the LHC. The strongest constraints come from direct decays from a heavy colored parent to the LSP. If these are removed by some mechanism, for example,

$$m(\widetilde{q}_L) \ll m(\widetilde{q}_R), m(\widetilde{g})$$

multiple degenerate weakinos
compressed spectrum
singlino LSP

we could still have a large squark sector below 400 GeV.

Light SUSY scenarios have a common feature:

There must be a large mass gap between the gluino and the light SUSY particles.

So, when we eventually reach the gluino at LHC 14 TeV, the generic jet+MET observables will begin to work and SUSY will be discovered unambiguously.

The light SUSY sector will still be hard to explore at the LHC. We will feel lucky that we are already constructing the ILC !