"Tell me that you have found no sign of New Physics again, I dare you. I double dare you. Tell me one more goddamn time!"

Implications of SUSY and Higgs Searches for the ILC

Sven Heinemeyer, IFCA (CSIC, Santander)

Hamburg, 05/2013

1. Pre-LHC SUSY predictions for the ILC

2. Impact of SUSY and Higgs searches

3. Conclusions

4. How to go ahead

1. Pre-LHC SUSY predictions for the ILC

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^0_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM $\Rightarrow m_h \leq M_Z$

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Predictions for the ILC

Indirect constraints on M_{SUSY} from existing data?

- Electroweak precision observables (EWPO) ?
- B physics observables (BPO) ?
- Cold dark matter (CDM) ?

$\Rightarrow$ combination of EWPO, BPO, CDM ?

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EWPO M_W : information on $m_{\tilde{t}}$, $m_{\tilde{b}}$ or M_A, $\tan\beta$ or . . .

EWPO $(g-2)_\mu$: information on $\tan\beta$ and/or $m_{\tilde{\chi}^0}$, $m_{\tilde{\chi}^\pm}$ and/or $m_{\tilde{\mu}}$, $m_{\tilde{\nu}_\mu}$

BPO BR$(b \to s\gamma)$: information on $\tan\beta$ and/or $M_{H^\pm}$ and/or $m_{\tilde{t}}$, $m_{\tilde{\chi}^\pm}$

CDM (LSP gives CDM) : information on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ or M_A or . . .

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CDM (LSP gives CDM) : information on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ or M_A or . . .

$\Rightarrow$ combination makes only sense if all parameters are connected!
$\Rightarrow$ GUT based models, . . .

The results presented here are based on:

The "MasterCode"

⇒ collaborative effort of theorists and experimentalists

[*Buchmüller, Cavanaugh, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Marouche, Martinez Santos, Olive, Rogerson, Ronga, de Vries, Weiglein*]

Über-code for the combination of different tools:

– tools are included as subroutines

– compatibility ensured by collaboration of authors of "MasterCode" and authors of "sub tools" /SLHA(2)

– one "MasterCode" for one model . . .

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode

The most studied model: CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

} at the GUT scale

$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

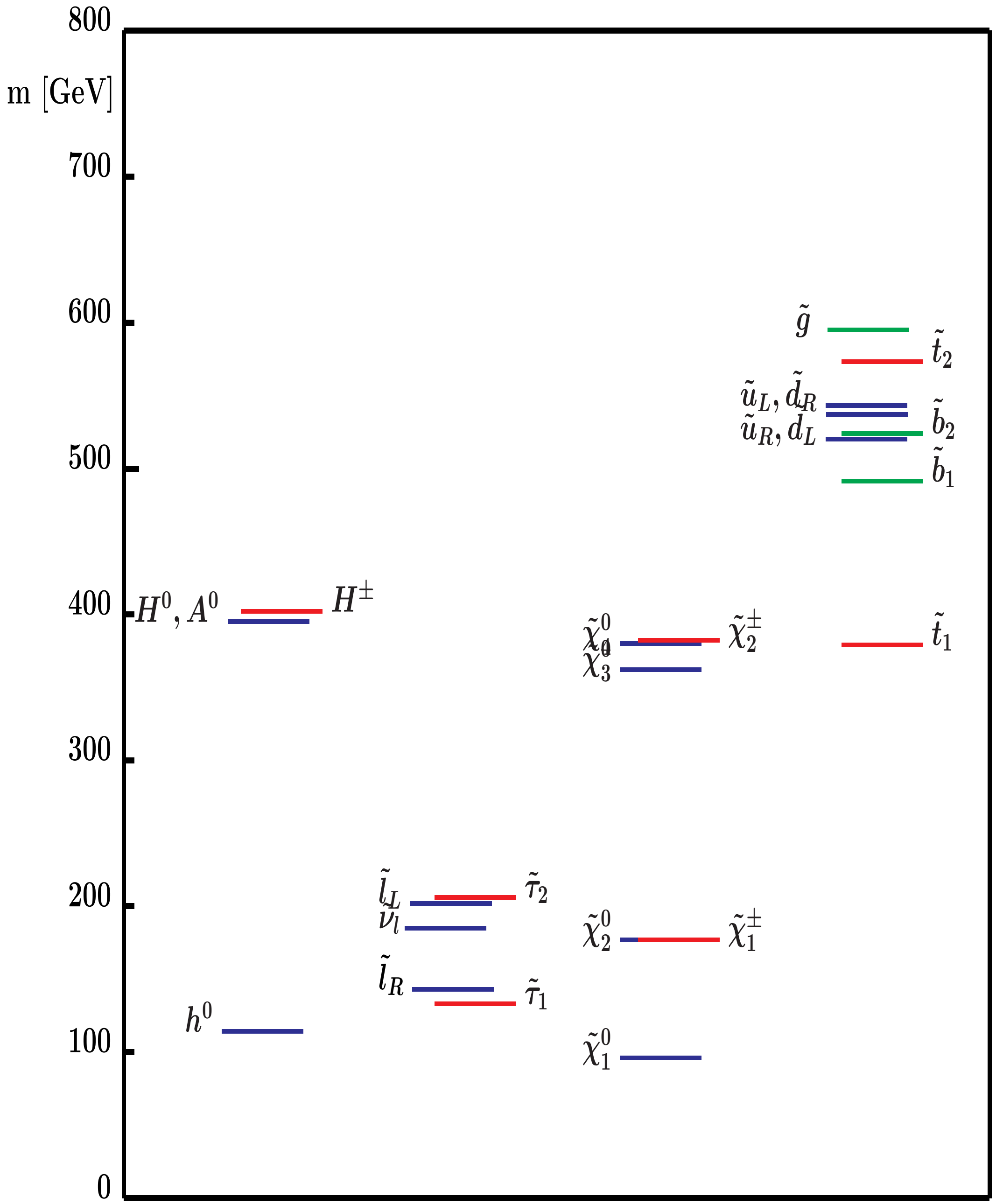
⇒ Lightest SUSY particle (LSP) is the lightest neutralino

“Typical” CMSSM scenario

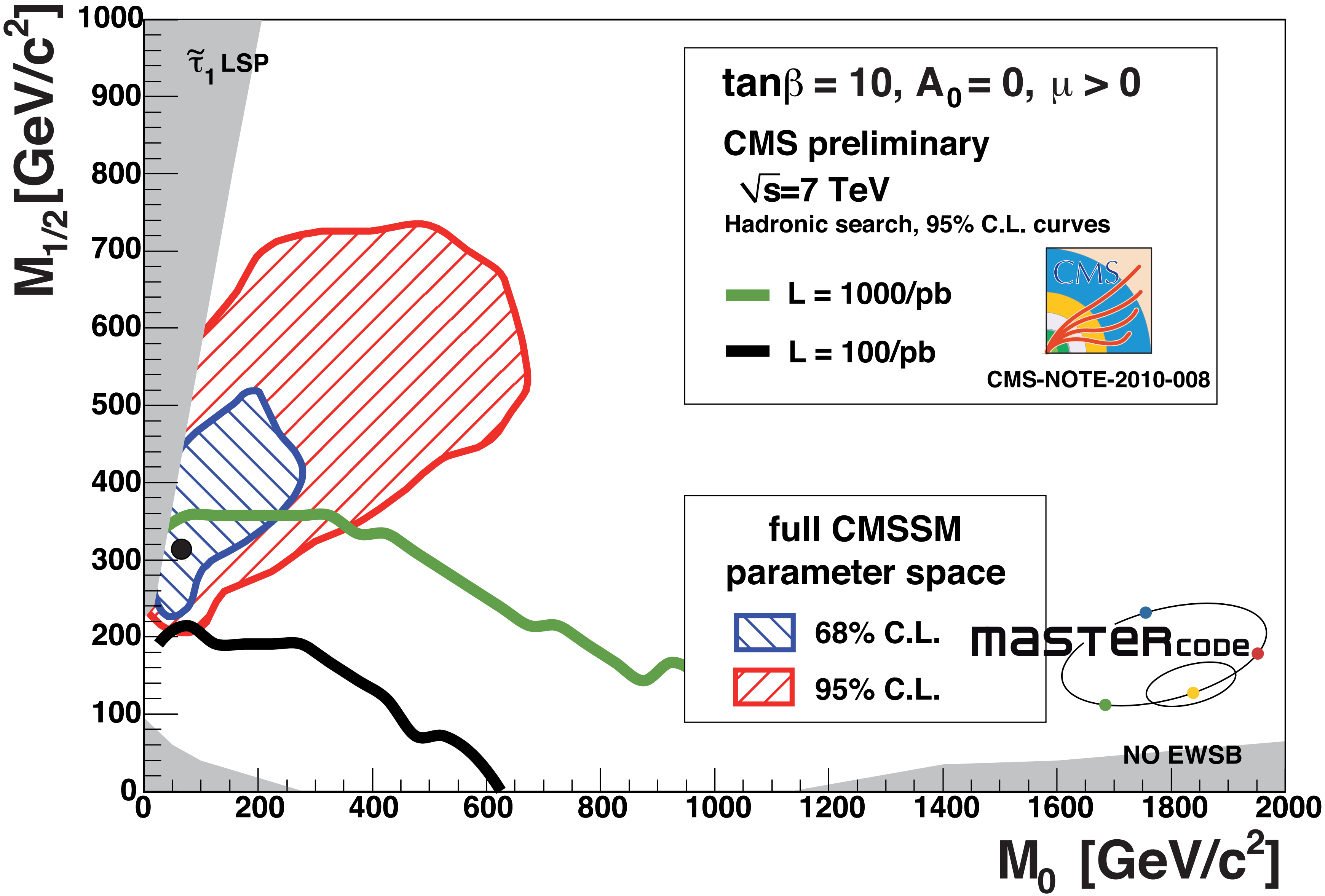
(SPS 1a benchmark scenario):

SPS home page:

`www.ippp.dur.ac.uk/∼georg/sps`



Pre-LHC prediction in the CMSSM:



⇒ best-fit point and part of 68% C.L. are can be tested in 2011

2. Impact Higgs and SUSY searches

Obvious idea:
(so far) negative search results for SUSY particles and
high (125 GeV) M_h measurement yield

new χ^2(LHC, SUSY, M_h) contribution

Assumption for Higgs:

$$M_h = 125 \pm 1(\text{exp.}) \pm 1.5(\text{theo.}) \text{ GeV}$$

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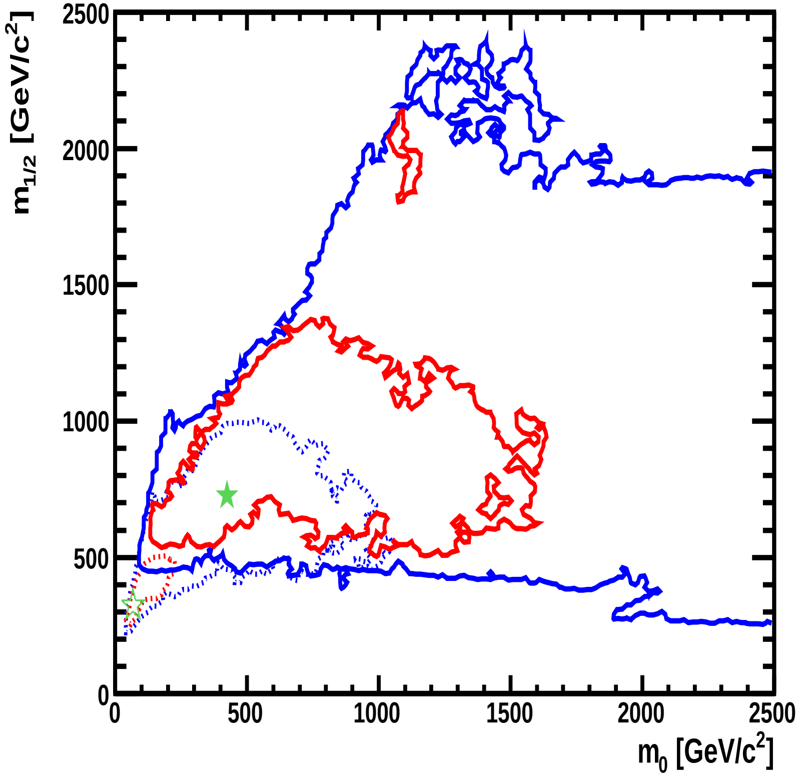
⇒ Implications for the ILC?

⇒ not as trivial as you might think!

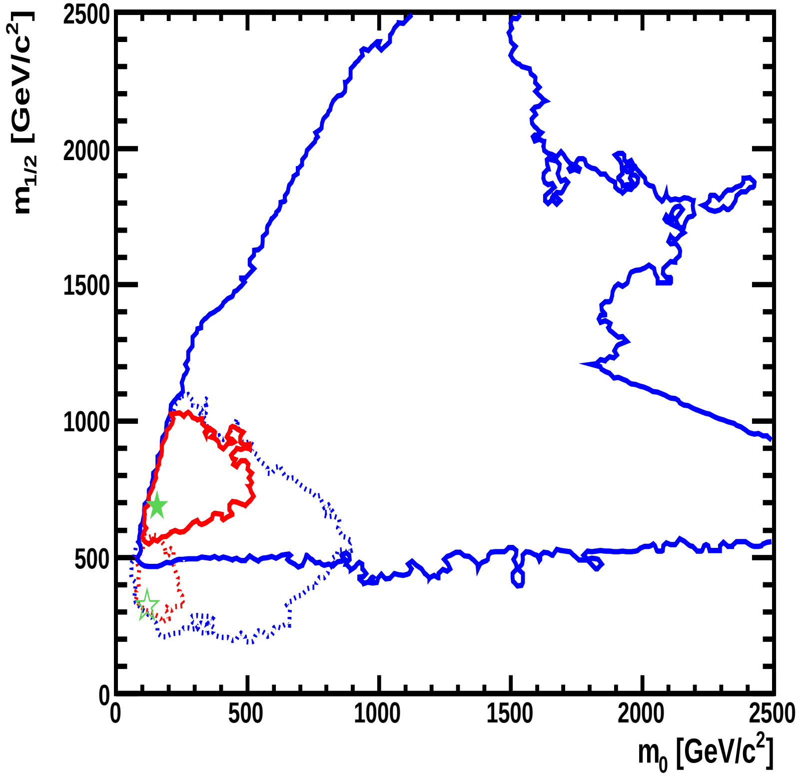
m_0-$m_{1/2}$ plane including 1/fb of LHC data:

[2011]

CMSSM



NUHM1



dotted: pre-LHC/Xenon, solid: post-LHC (1 fb^{-1})/Xenon

⇒ new best-fit point within old 95% CL area

⇒ hardly any overlap between old and new 68% CL areas

⇒ shift to higher masses

The lightest MSSM Higgs boson

MSSM predicts upper bound on M_h:

tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches!

Large radiative corrections:

Yukawa couplings: $\frac{e\, m_t}{2 M_W s_W}, \frac{e\, m_t^2}{M_W s_W}, \ldots$

$\Rightarrow$ Dominant one-loop corrections:

$$\Delta M_h^2 \sim G_\mu m_t^4 \left[\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right], \quad M_S^2 = M_{\tilde{t}_{L,R}}^2 + m_t^2$$

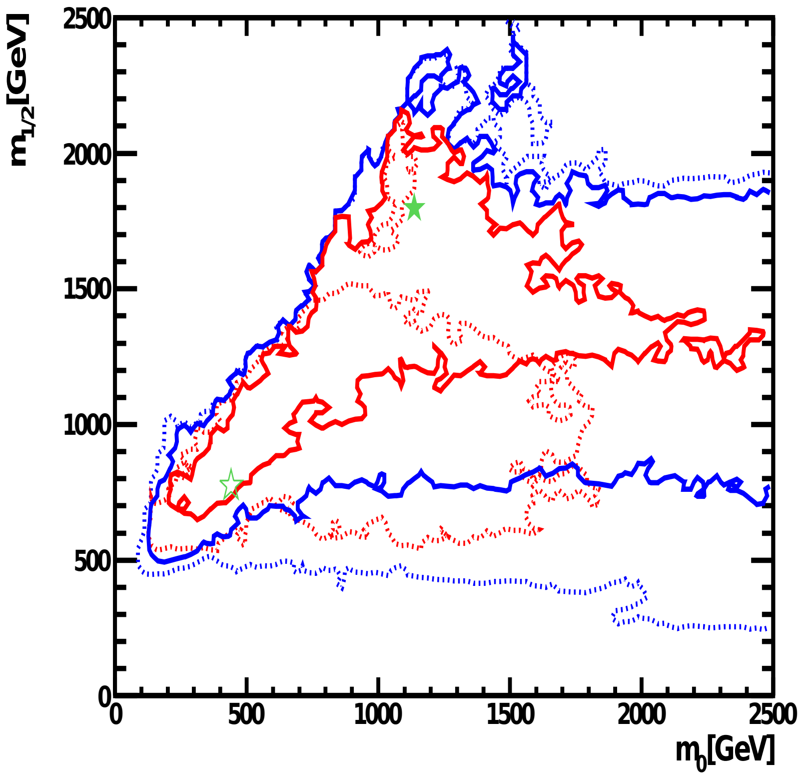
The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

large stop mixing: M_S can be low, $\mathcal{O}$(500 GeV)
small stop mixing: M_S pushed to TeV scale
CMSSM, NUHM1: stop mixing tends to be small(er)

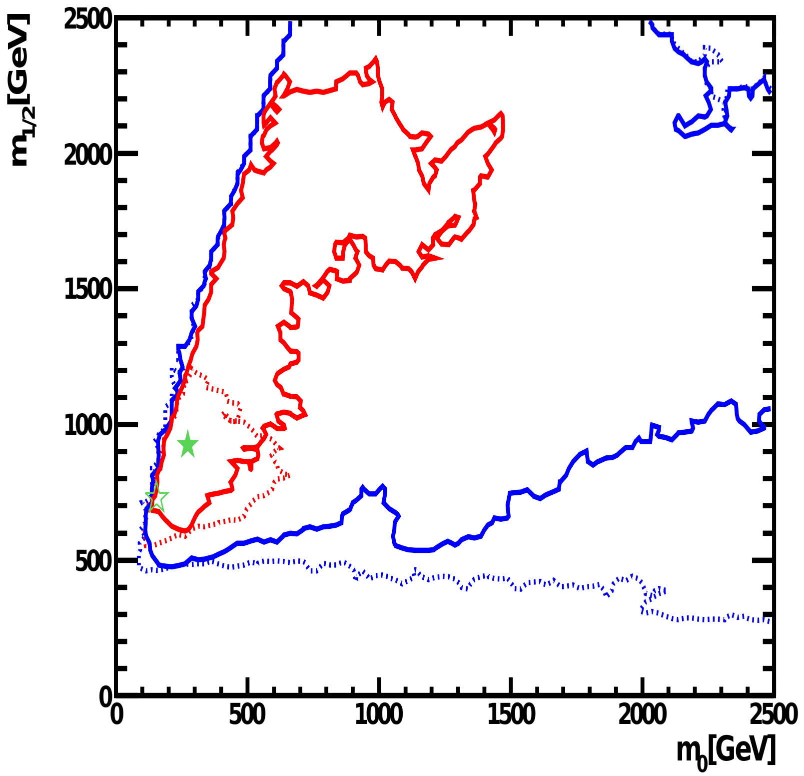
m_0-$m_{1/2}$ plane including "Higgs measurement":

[2011]

CMSSM



NUHM1



dotted: pre-Higgs, solid: post-Higgs

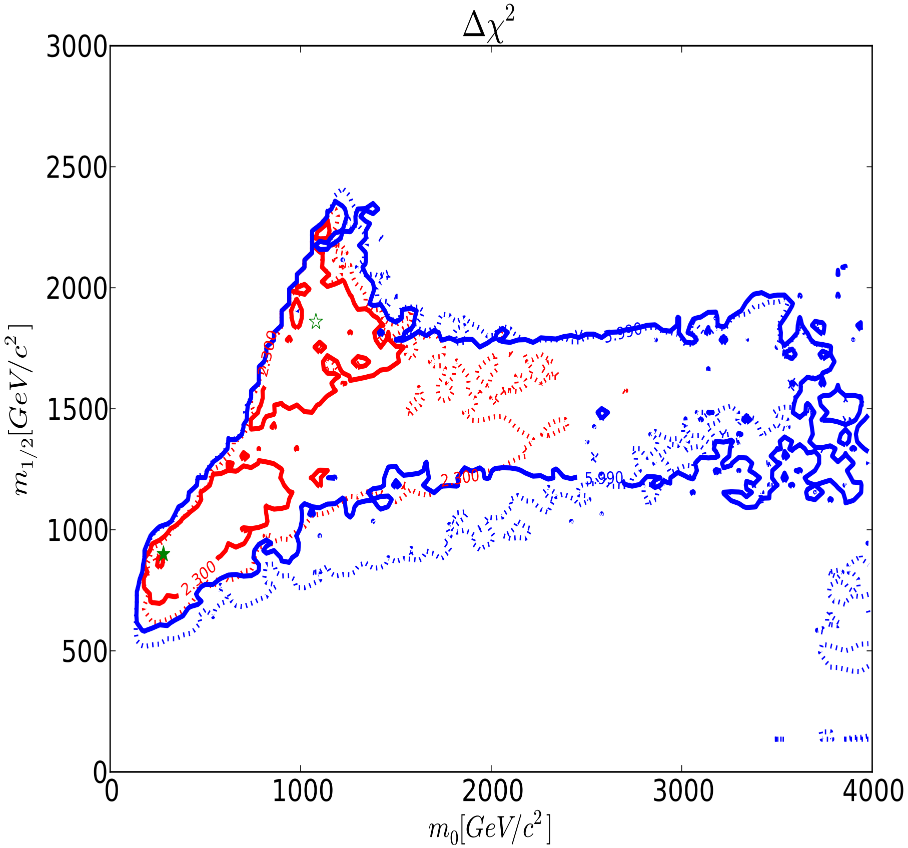
⇒ shift to even higher masses

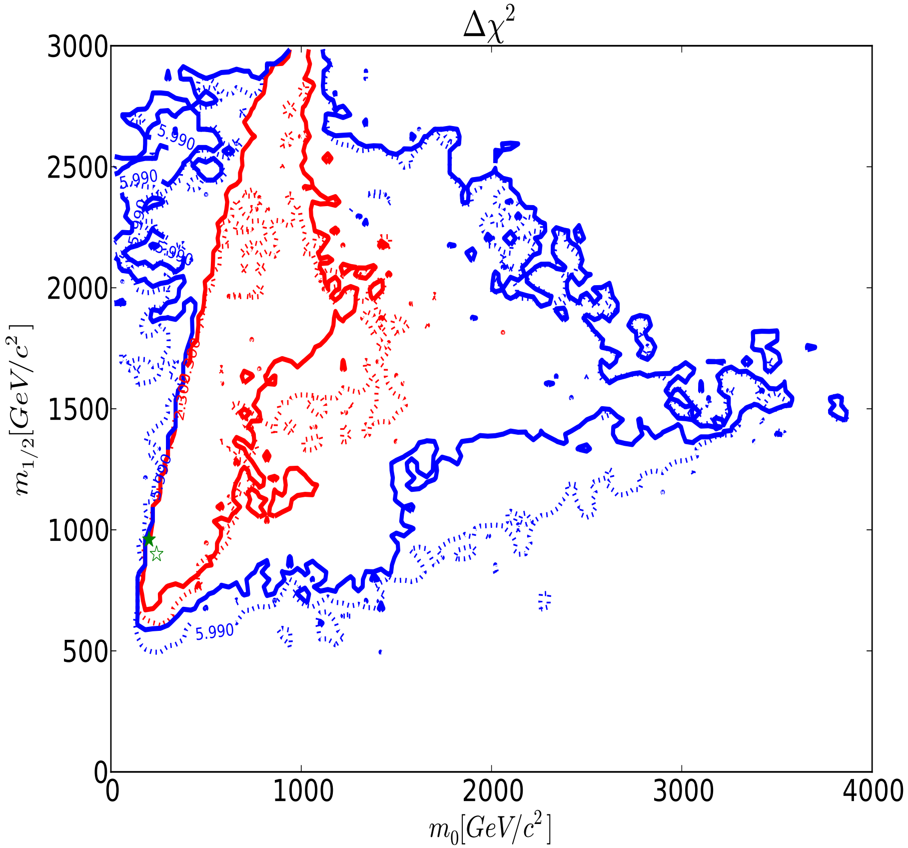
⇒ how "bad" is this for the ILC?

m_0-$m_{1/2}$ plane including 5/fb of LHC data + Higgs:

[2012]

CMSSM NUHM1





dotted: 1/fb+Higgs, solid: 5/fb+Higgs

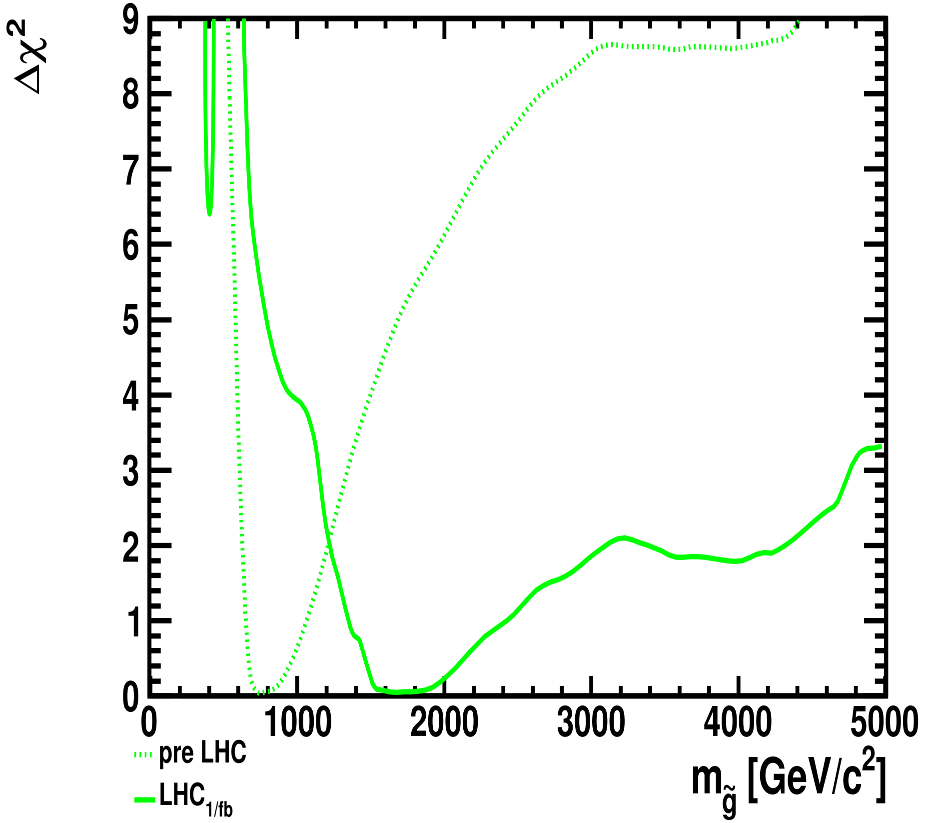
⇒ small shift to even higher masses

⇒ how “bad” is this for the ILC?

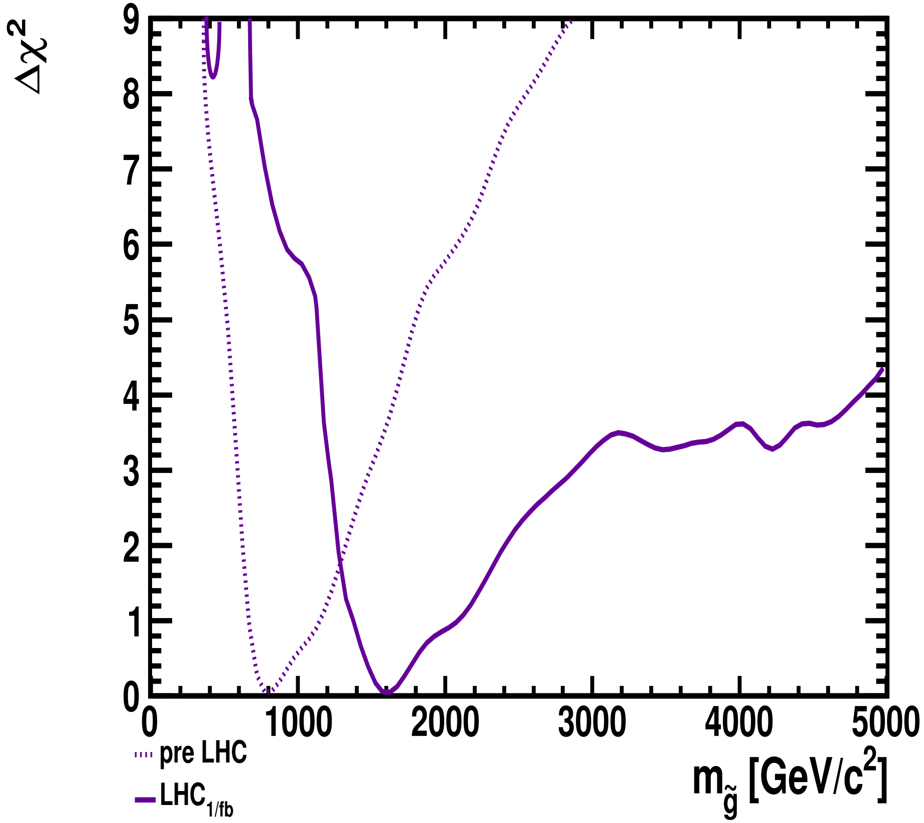
Starting point of the cascade: gluino (incl. 1/fb of LHC data)

[2011]

CMSSM



NUHM1



dotted: pre-LHC/Xenon, solid: post-LHC (1 fb^{-1})/Xenon

$\Rightarrow$ substantial upward shift

What is happening to the χ^2?

Low energy data (mostly $(g-2)_\mu$) favors low SUSY mass scales

LHC data favors higher SUSY scales

M_h “measurement” moves the fit to even higher scales

$\Rightarrow$ tension, reflected in rising χ^2:

Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	$M_h^{\text{no LEP}}$ (GeV)
CMSSM	21.5/20	37%	360	90	-50	15	111
LHC 1 fb^{-1}	31.0/23	12%	1800	1140	1370	46	–
LHC 5 fb^{-1}	32.8/23	8%	1890	1070	1020	16	–
NUHM1	20.8/18	29%	340	110	520	13	119
LHC 1 fb^{-1}	28.9/22	15%	920	270	1730	27	–
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Probabilities still ok, but this might change with more data.

Not finding SUSY early does not make the ILC looks bad,
makes some very constrained models look bad!

An MSSM Higgs at 125 GeV makes CMSSM/NUHM1 “less likely”

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CMSSM/NUHM1: close connection between colored and uncolored sector!

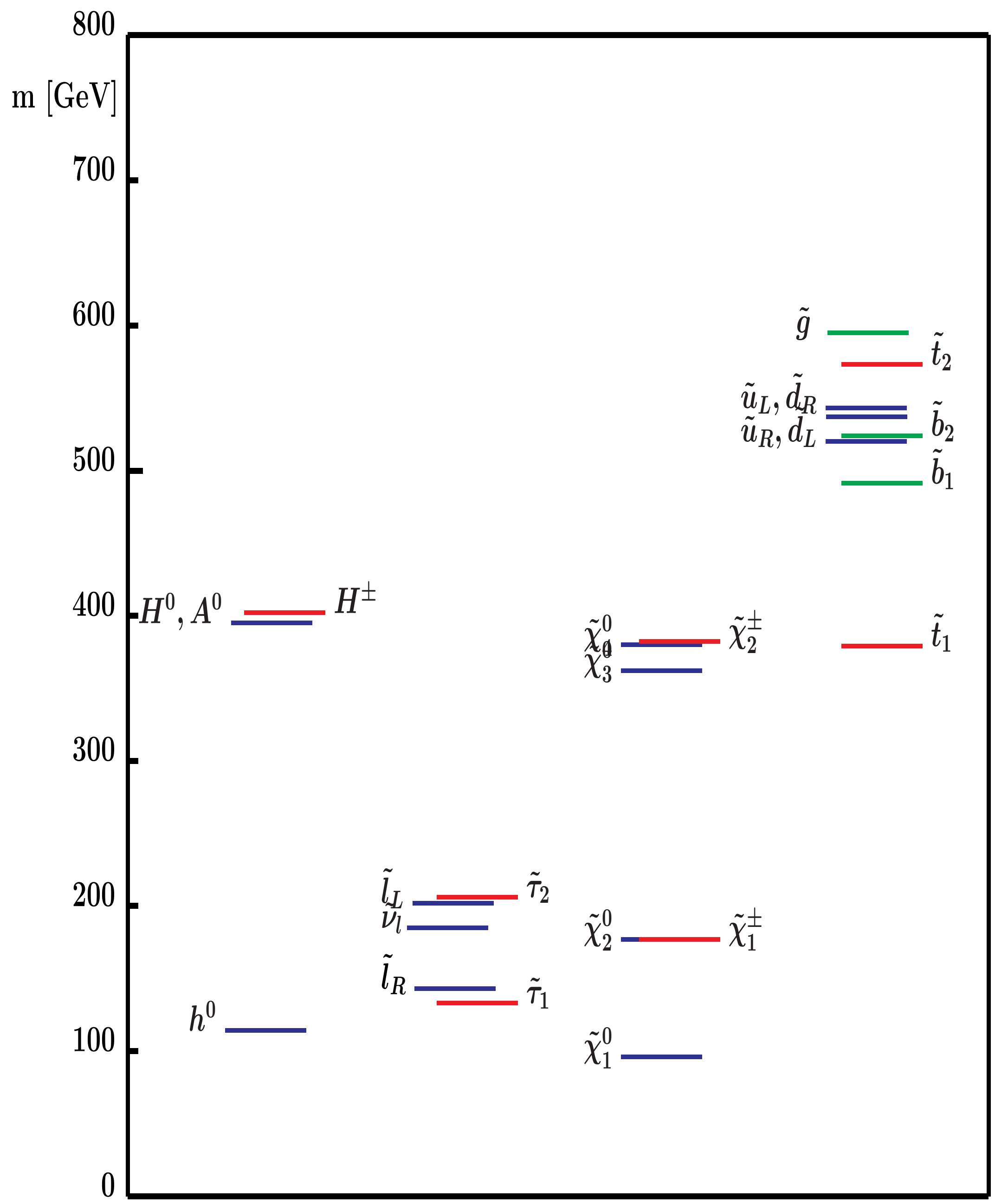
Needed: New SUSY realizations that are in agreement with
– higher colored mass scales (LHC limits)
– lower uncolored mass scales (EWPO; $(g-2)_\mu$) $\Rightarrow$ oder models?!

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

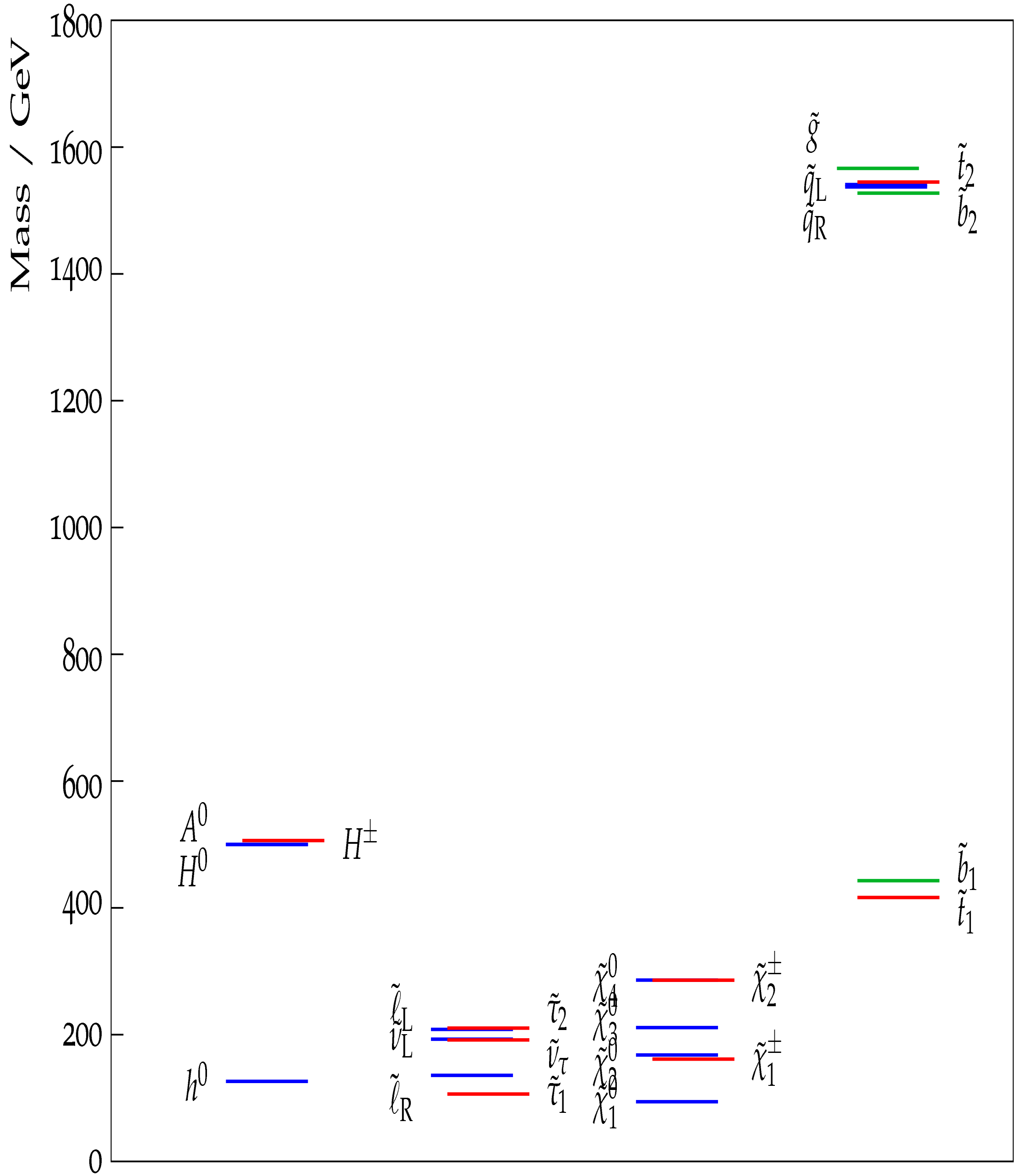
all the sectors



SPS1a variant (I)

colored and uncolored

sector decoupled:



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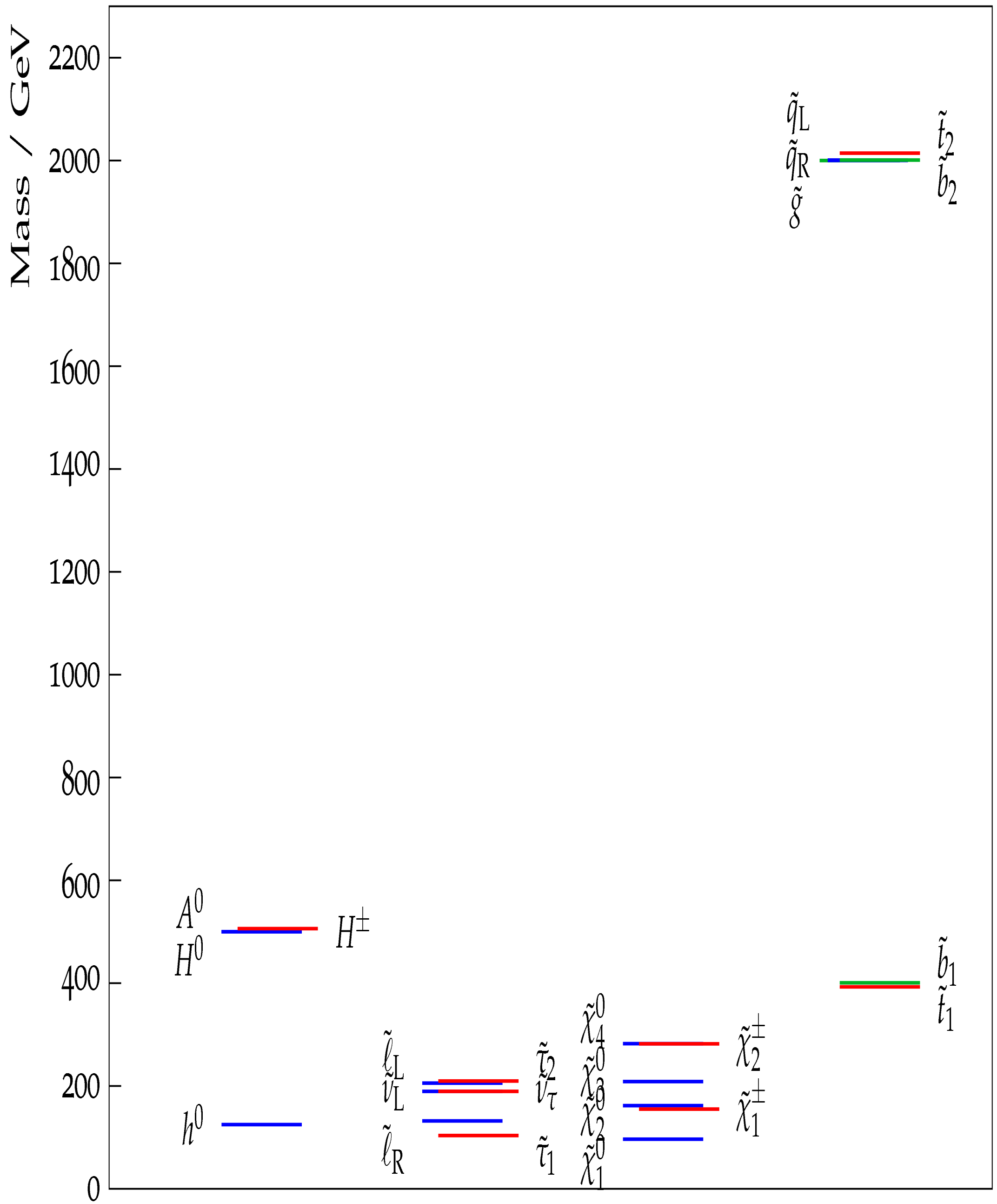

Focus point, gaugino mediation, cosmologically motivated

[W. Buchmüller et al. '12]

particle	$(23, 23, 9)$ model	$(17, 23, 9)$ model	$(28, 28, 11)$ model
h_0	123	123	124
χ_1^0	205	205	164
$\chi_1^\pm$	207	206	166
χ_2^0	208	207	167
$\tilde{\tau}_1$	1530	550	1890
H^0	1470	1110	2200
A	1480	1120	2200
$H^\pm$	1480	1120	2200
χ_3^0	2500	1800	2700
χ_4^0	3800	3800	4100
$\chi_2^\pm$	3800	3800	4100
$\tilde{g}$	3800	3800	4200
$\tilde{t}_1$	2500	2300	2700
$\tilde{u}_1$	3700	3500	4000
$\tilde{d}_1$	3400	3400	3700

Table 1: Some selected masses in GeV, computed with SOFTSUSY, for three models with messenger indices $(N_1, N_2, N_3) = (23, 23, 9)$, $(17, 23, 9)$, and $(28, 28, 11)$. The first has $m_{\rm GM} = 200$ GeV, $\mu = 240$ GeV, and $\tan\beta = 50$; the second, $m_{\rm GM} = 200$ GeV, $\mu = 250$ GeV, and $\tan\beta = 52$; and the third, $m_{\rm GM} = 180$ GeV, $\mu = 180$ GeV, and $\tan\beta = 44$.

3. Conclusinos

- SUSY is (still) our(?) best bet for physics beyond the SM
- During the absence of a signal this is restricted to GUT based models
  $\rightarrow$ CMSSM, NUHM1, . . .
- Our tool: MasterCode: EWPO, BPO, CDM, LHC, M_h, . . .
- pre-LHC/Higgs predictions: relatively low mass scales
- post-LHC predictions: somewhat higher mass scales
  CMSSM, NUHM1, . . . still fit . . .
  with somewhat lower probability
- post-Higgs predictions: even higher mass scales
  CMSSM, NUHM1, . . . do not fit well . . .
- A Higgs at 125 GeV requires SUSY realizations that are
  – higher colored mass scales (LHC limits)
  – lower uncolored mass scales (EWPO; $(g-2)_\mu$)

  $\Rightarrow$ Better prospects for the ILC . . .

4. How to go ahead

My personal view:

Finding a particle that is compatible with a light (SM-like?) Higgs boson is the **best case** scenario for the ILC

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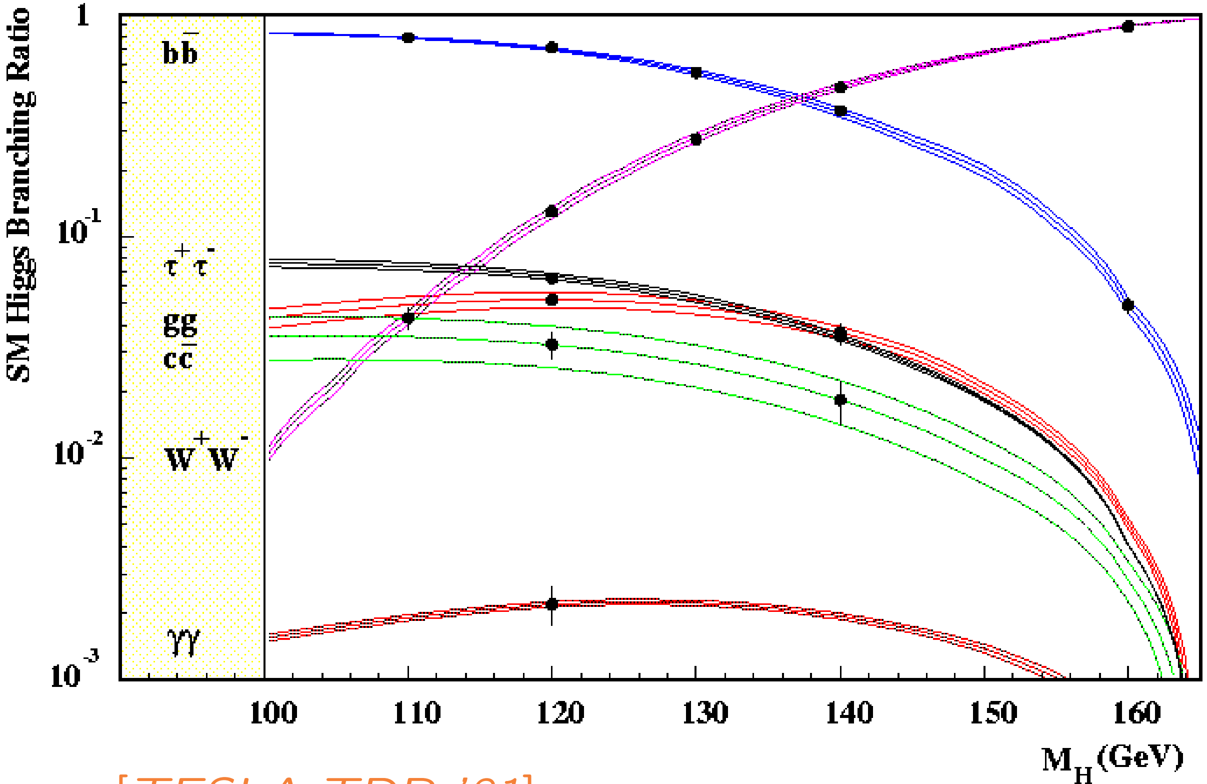
My personal view:

Finding a particle that is compatible with a light (SM-like?)
Higgs boson is the **best case** scenario for the ILC

Higgs physics at the ILC:

SM Higgs @ ILC:
Precise measurement of:

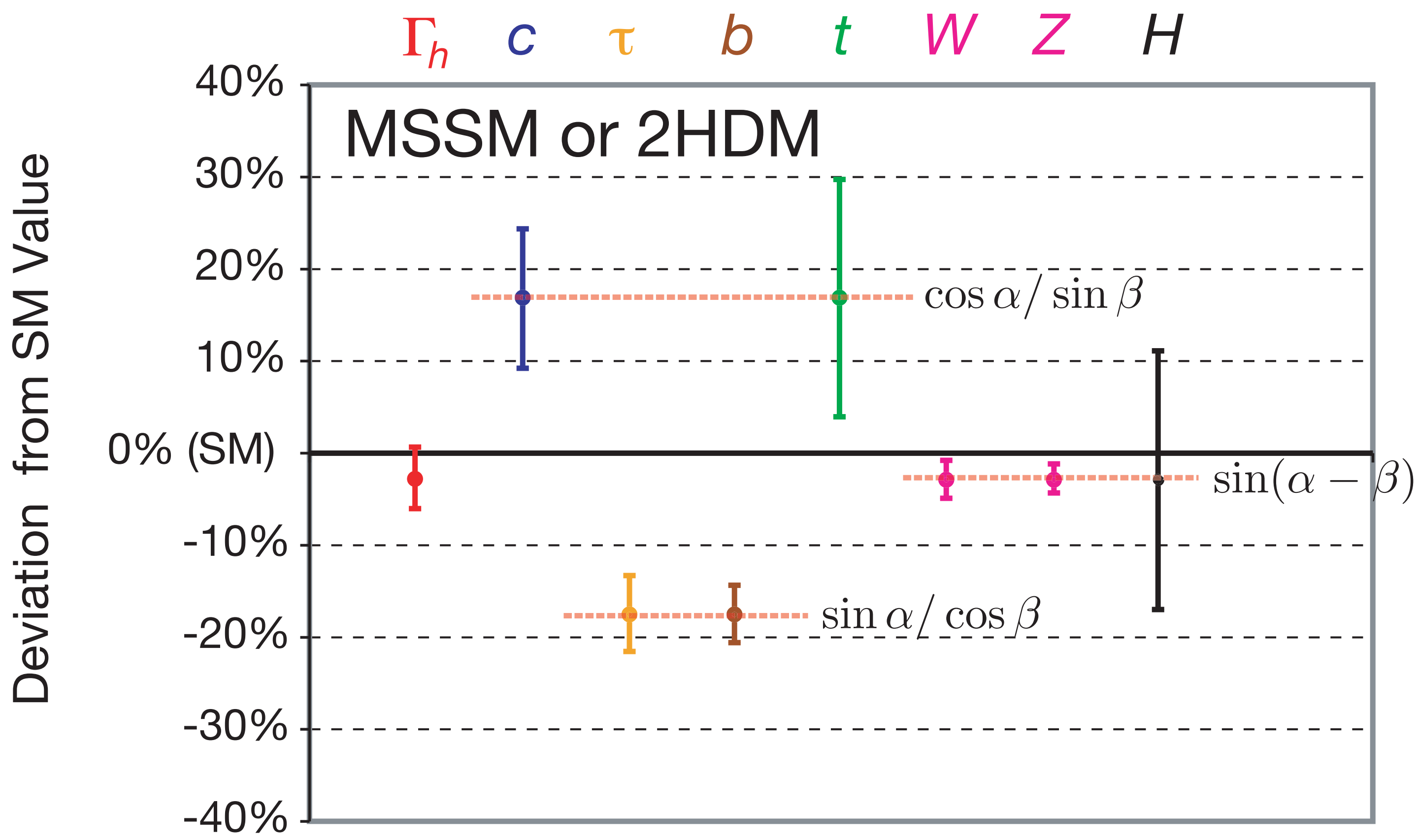
1. Higgs boson mass,
   $\delta M_H \approx 50$ MeV
2. Higgs boson width
   (direct/indirect)
3. Higgs boson couplings,
   $\mathcal{O}$ (few%) ⇒
4. Higgs boson quantum
   numbers: spin, . . .



[*TESLA TDR '01*]

Example: Higgs couplings in the MSSM:

"Normal(?)" MSSM scenario:



$\Rightarrow$ measurable deviations (at least in some parts of the parameter space)

Indirect determination of unknown Higgs sector parameters

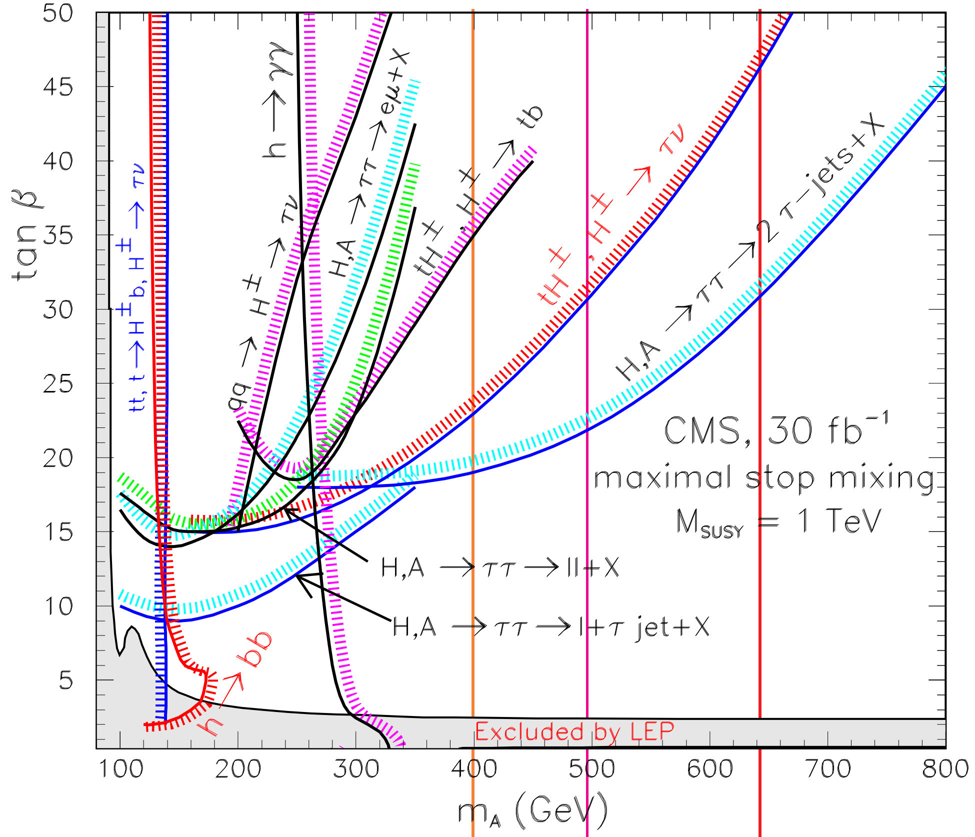
LHC/ILC reach for MSSM Higgs bosons:

LHC:

h : all $M_A - \tan\beta$ plane

H, A : unreachable parts

CMS, 30 fb^{-1}, $m_h^{\rm max}$ scenario: $\Rightarrow$



ILC: $\sqrt{s} = 800$ GeV

$\sqrt{s} = 1000$ GeV

ILC:

kinematic limit: $M_A \lesssim \sqrt{s}/2$

$\to \sqrt{s} = 800$ GeV

$\to \sqrt{s} = 1000$ GeV

$\gamma\gamma$:

kinematic limit: $M_A \lesssim 0.8\sqrt{s}$

$\gamma\gamma$: $\sqrt{s} = 800$ GeV

Q: Is it possible to extend the reach for heavy Higgs bosons ?

A: Yes, by direct and indirect measurements

Q: Is $M_h \sim 125.5$ GeV the only possible interpretation?

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A: No!

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In principle also possilbe:

$$M_h < 125.5 \text{ GeV}$$
$$M_H \approx 125.5 \text{ GeV}$$

Q: Is $M_h \sim 125.5$ GeV the only possible interpretation?

A: No!

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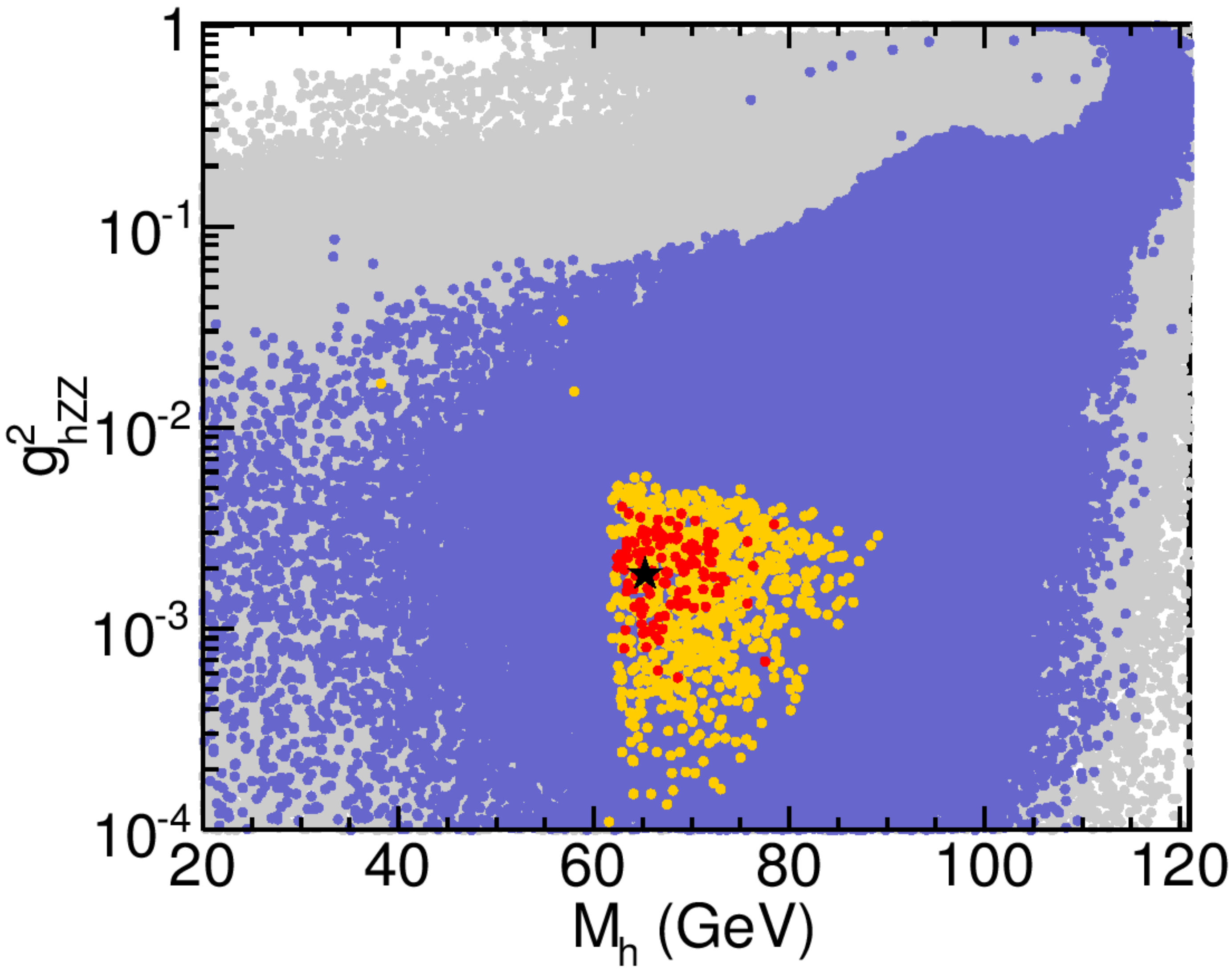
$$M_h < 125.5 \text{ GeV}$$
$$M_H \approx 125.5 \text{ GeV}$$

Consequences:
– all Higgs bosons very light
– easy(?) discovery of additional Higgs bosons at the LHC

Constraints:
– direct searches for the lightest $\mathcal{CP}$-even Higgs
– direct searches for the heavy neutral Higgses
– direct searches for the charged Higgses
– flavor constraints (BR($B_s \to \mu^+\mu^-$) etc.)

Where is the light Higgs in the "heavy Higgs case"?

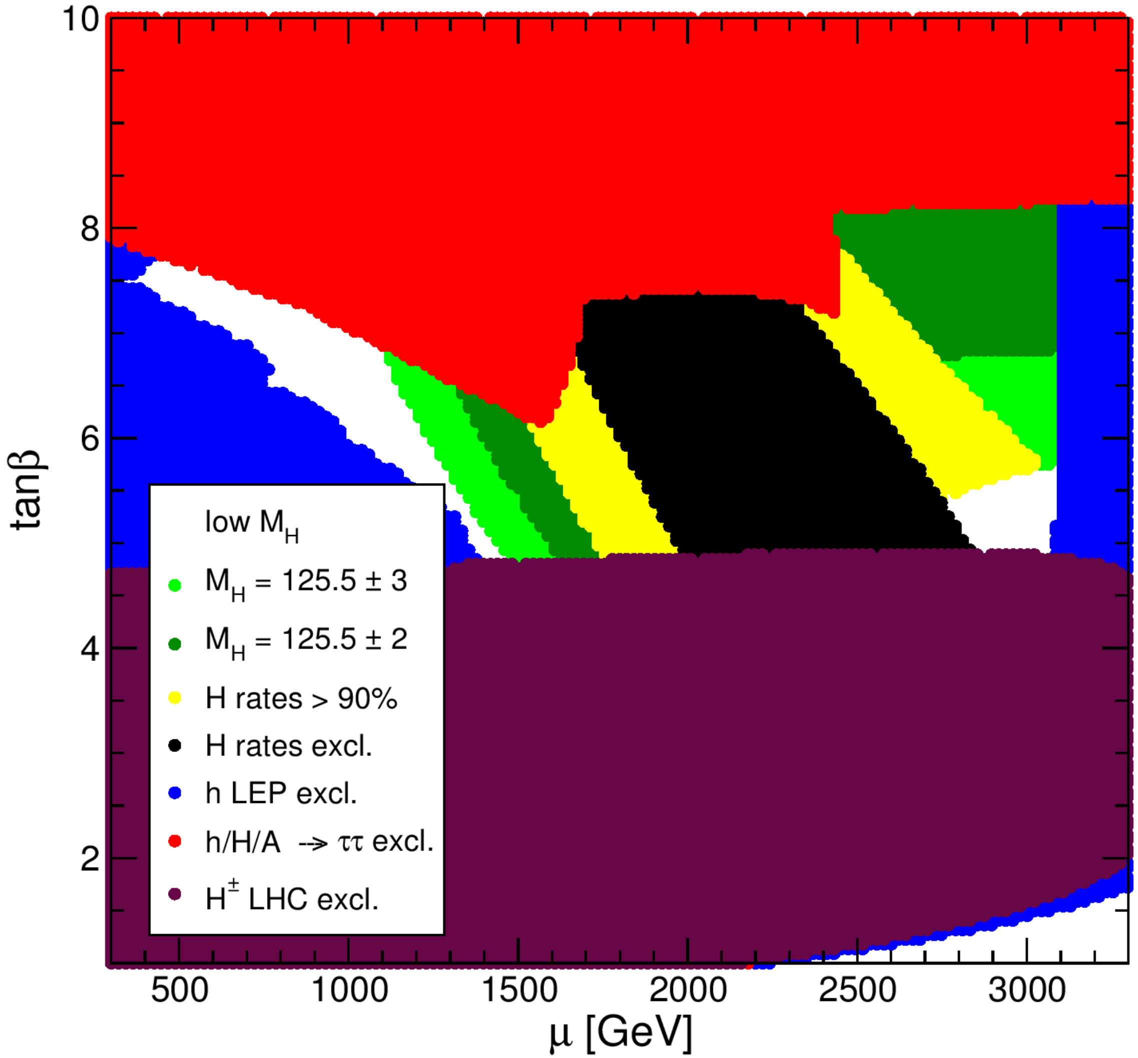
[*P. Bechtle, S.H. O. Stål, T. Stefaniak, G. Weiglein, L. Zeune '12*]



⇒ low M_h values, strongly reduced couplings

low-M_H scenario:

[M. Carena, S.H., O. Stål, C. Wagner, G. Weiglein '13]



$m_t = 173.2$ GeV,

$M_A = 110$ GeV,

$M_{\rm SUSY} = 1500$ GeV,

$M_2 = 200$ GeV,

$X_t^{\rm OS} 2.45 M_{\rm SUSY}$

$A_b = A_\tau = A_t$,

$m_{\tilde{g}} = 1500$ GeV,

$M_{\tilde{l}_3} = 1000$ GeV .

$\Rightarrow M_H \approx 125.5$ GeV can in principle be realized

Is such a light Higgs detectable at the LHC and/or ILC?

LHC:

– $H \to hh$ forbidden for $M_h \gtrsim 63$ GeV

– so far no LHC searches for a Higgs with $M_h \lesssim 100$ GeV

– Possible: SUSY $\to$ SUSY h , e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$

ILC:

– good production mode: $e^+e^- \to hA$

– good production mode: $e^+e^- \to t\bar{t}h$

$\Rightarrow$ could be a unique opportunity for the ILC!

My personal view:

> Finding a particle that is compatible with
> a light (SM-like?) Higgs boson
> is the **best case** scenario for the ILC

How to go ahead?

(if not strongly discouraged by final analysis of 2012 data . . .)

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(if not strongly discouraged by final analysis of 2012 data . . .)

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- Staged approach?
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  - go to higher energies for top physics
  - go to higher energies for TeV scale exploration
- go to other options: GigaZ, $\gamma\gamma$, . . .

My personal view:

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⇒ best case scenario the ILC!

⇒ Let's use our Annus mirabilis in our favor!!