Implications of a 125 GeV Higgs for the ILC

Sven Heinemeyer, IFCA (CSIC, Santander)

Munich, 07/2011

based on collaboration with
J. List, G. Moortgat-Pick, G. Weiglein

1. SUSY predictions for the ILC

2. Impact of a 125 GeV Higgs

3. Conclusions

4. The No-Brainer

1. 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 $M_{\rm SUSY}$ 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 $m_{\tilde{t}}$, $m_{\tilde{\chi}^\pm}$

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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

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

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

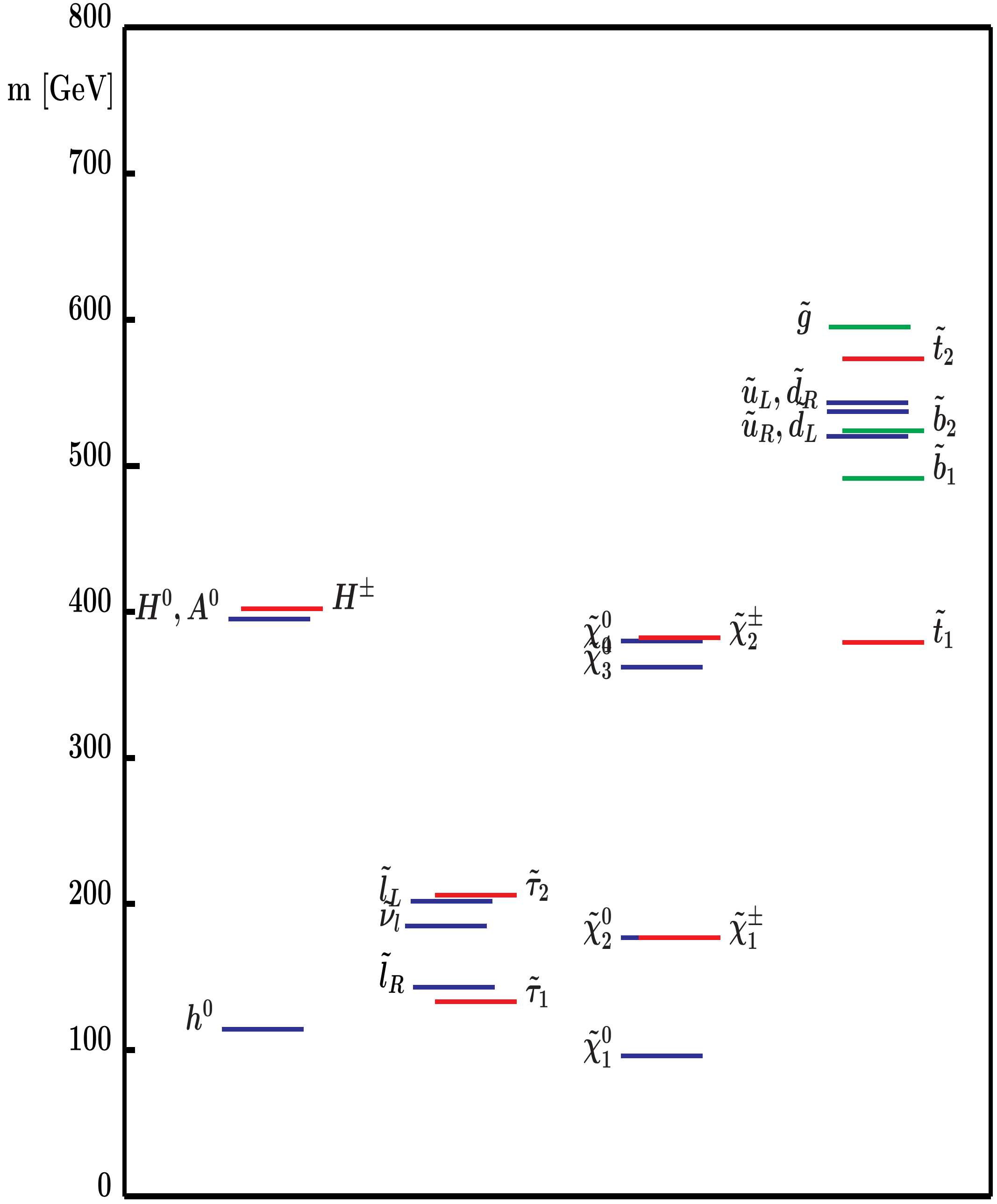
⇒ Lightest SUSY particle (LSP) is the lightest neutralino

“Typical” CMSSM scenario

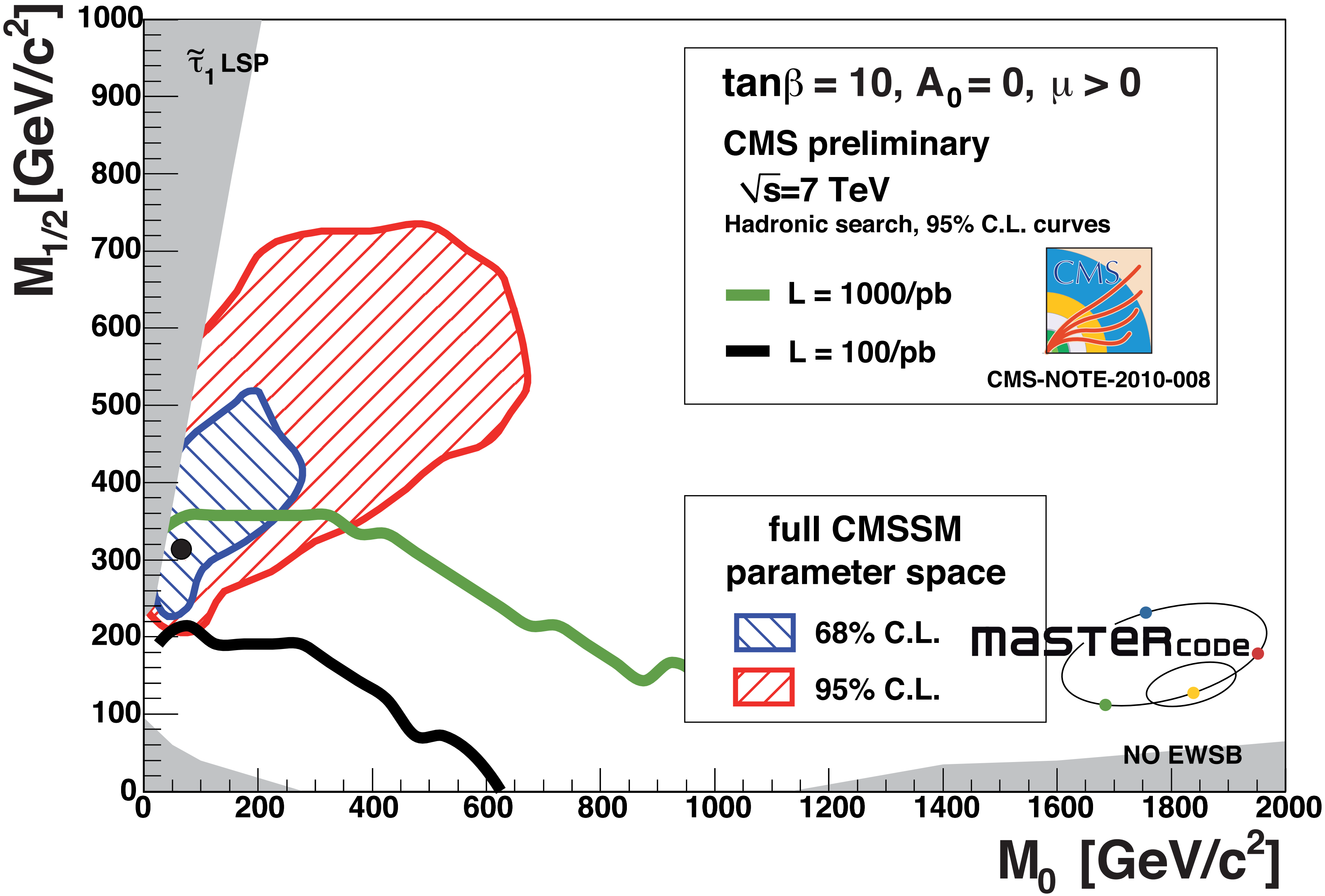
(SPS 1a benchmark scenario):

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 of a 125 GeV Higgs

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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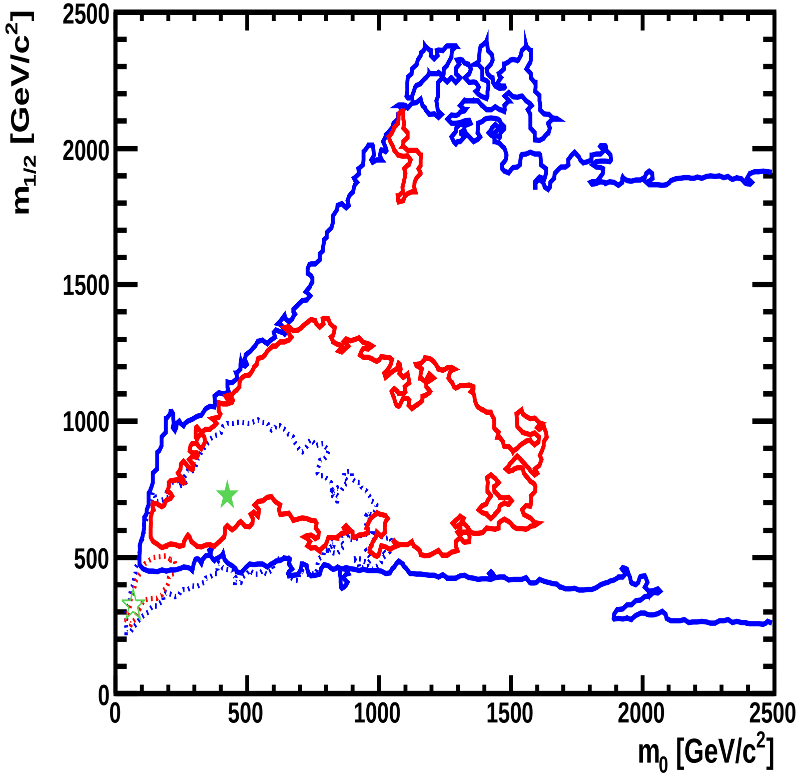
$\Rightarrow$ Implications for the ILC?

$\Rightarrow$ not as trivial as you might think!

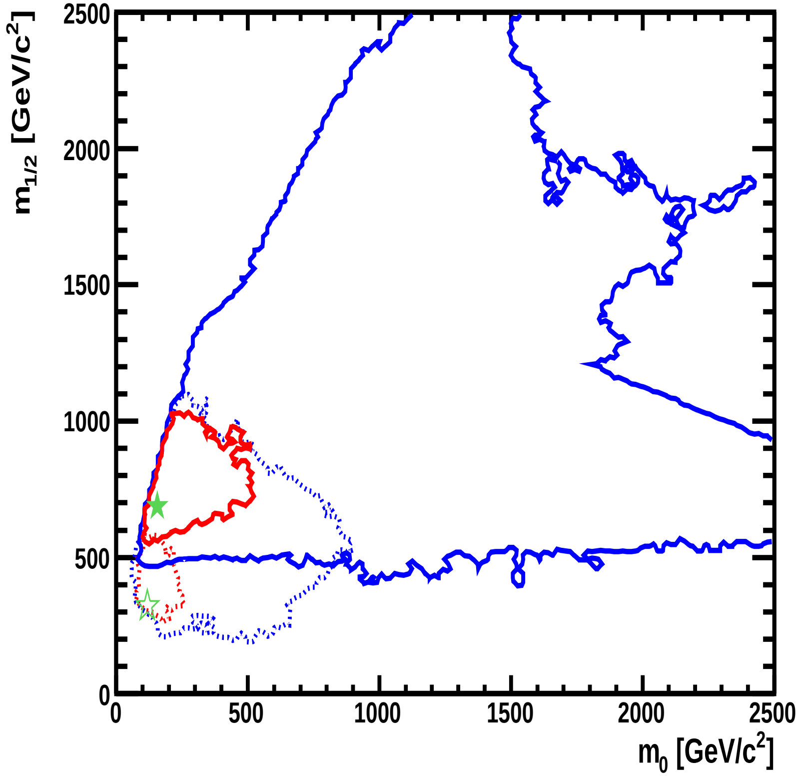
m_0-$m_{1/2}$ plane including 1/fb of LHC data:

[2011]

CMSSM



NUHM1



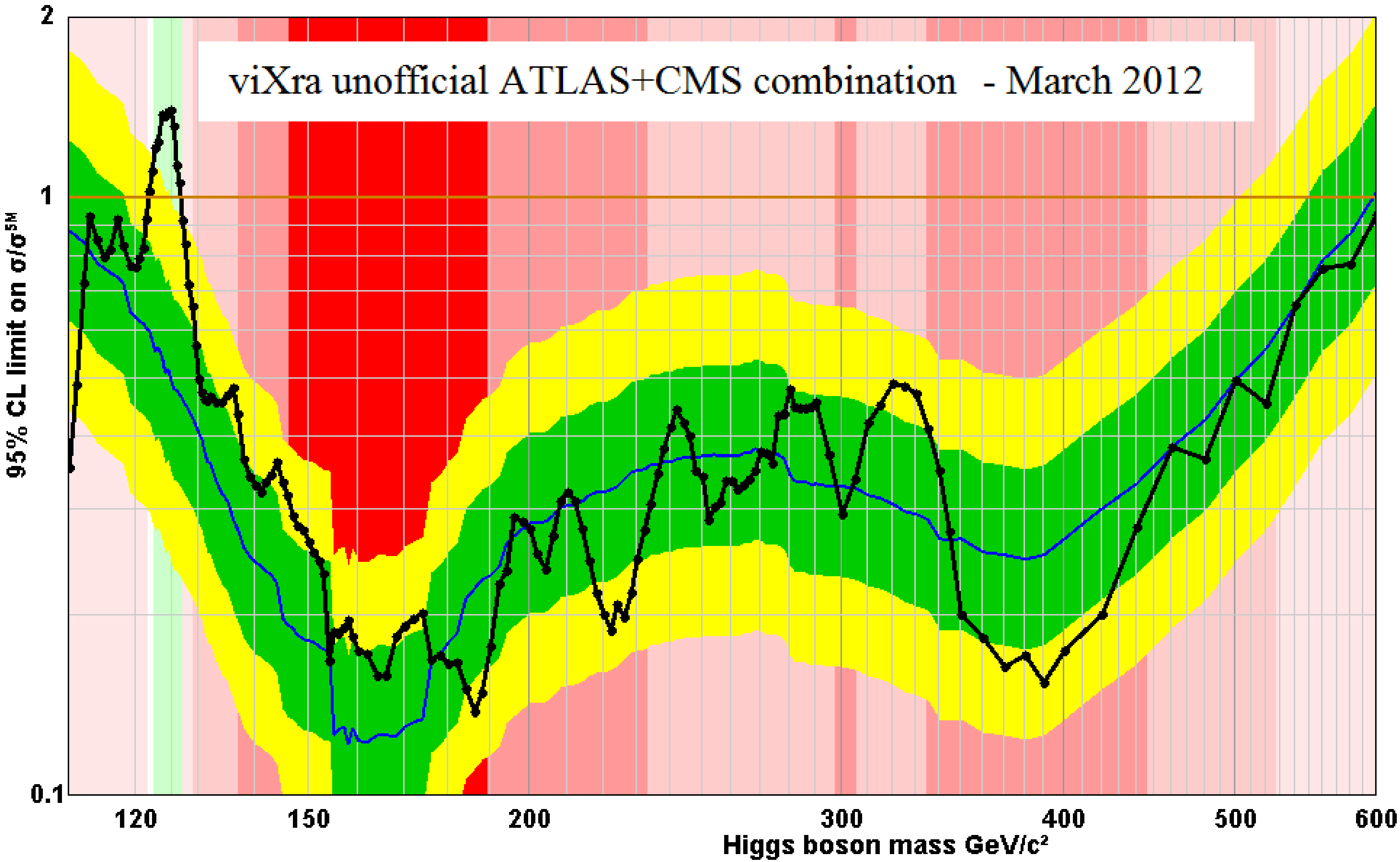
dotted: pre-LHC/Xenon, solid: post-LHC (1 fb^{-1})/Xenon

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

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

⇒ shift to higher masses

Unofficial(!) LHC combination for SM-like Higgs searches:



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: $\frac{\mathrm{e}\, m_t}{2 M_W s_\mathrm{W}}, \frac{\mathrm{e}\, m_t^2}{M_W s_\mathrm{W}}, \ldots$

$\Rightarrow$ Dominant one-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

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

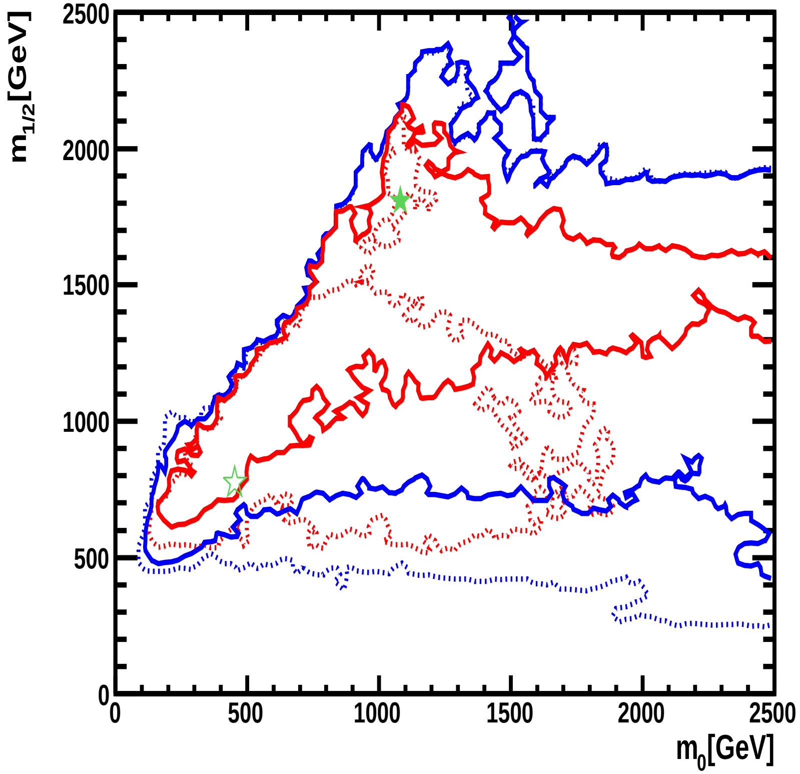
Present status of M_h prediction in the MSSM:

Complete one-loop and 'almost complete' two-loop result available

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

[2011]

CMSSM



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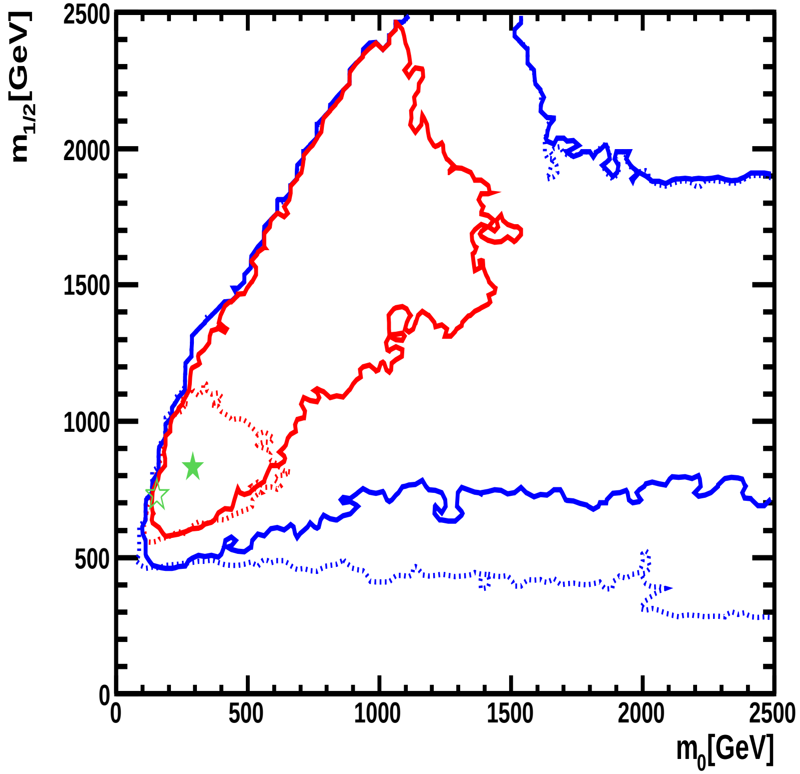

dotted: pre-Higgs, solid: post-Higgs

$\Rightarrow$ shift to even higher masses

even larger allowed ranges . . .

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}	28.8/22	15%	780	450	-1100	41	119
$M_h = 125$	30.6/23	13%	1800	1080	860	48	–
NUHM1	20.8/18	29%	340	110	520	13	119
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Not finding SUSY early does not make the ILC looks bad,

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And requires SUSY realizations that are in agreement with
– higher colored mass scales (LHC limits)
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The LHC searches (mainly) for colored particles,
the ILC is (also) searching for uncolored particles!

Any inference from one sector to the other is strongly model dependent!

$\Rightarrow$ look for other models...?

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

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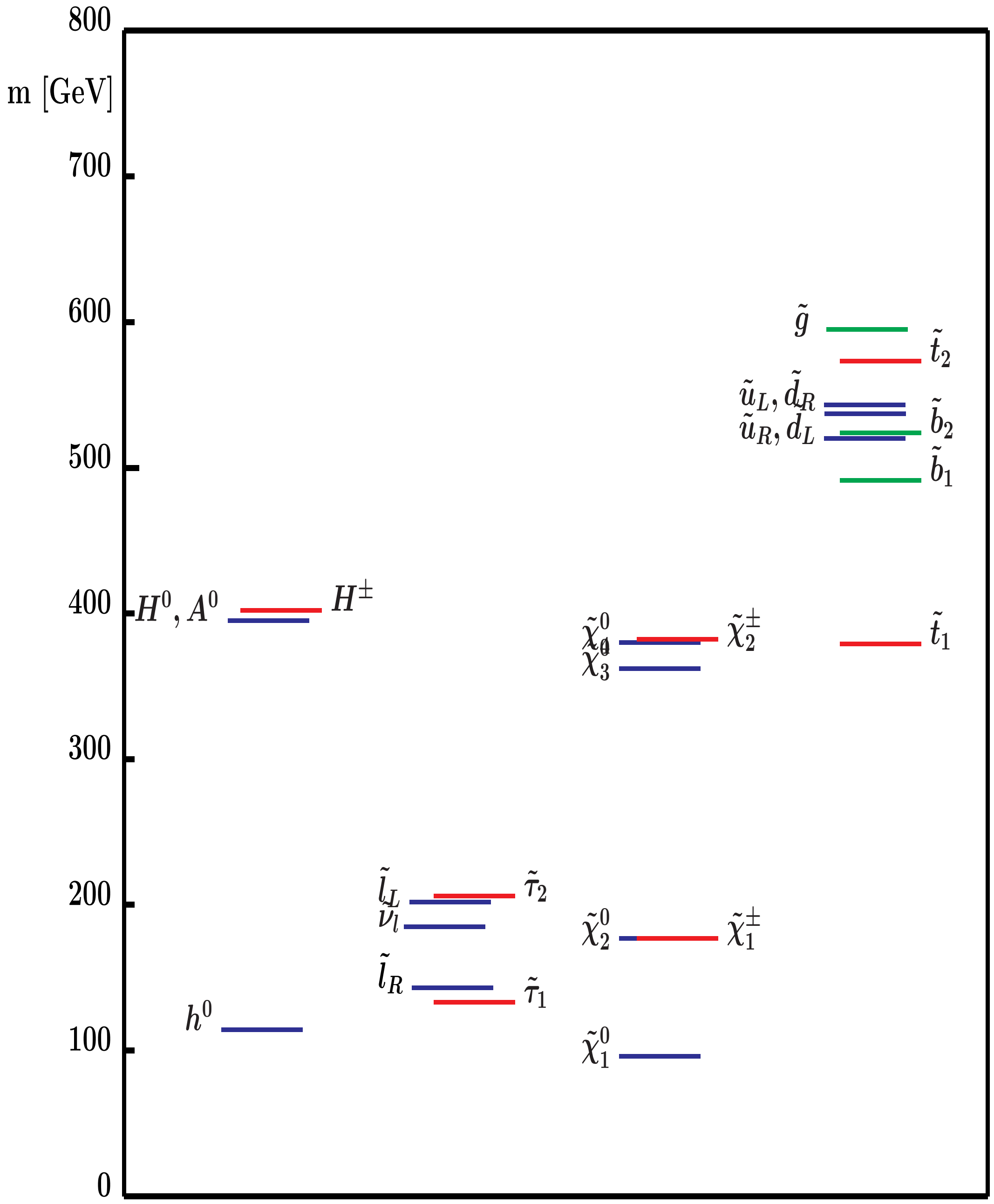
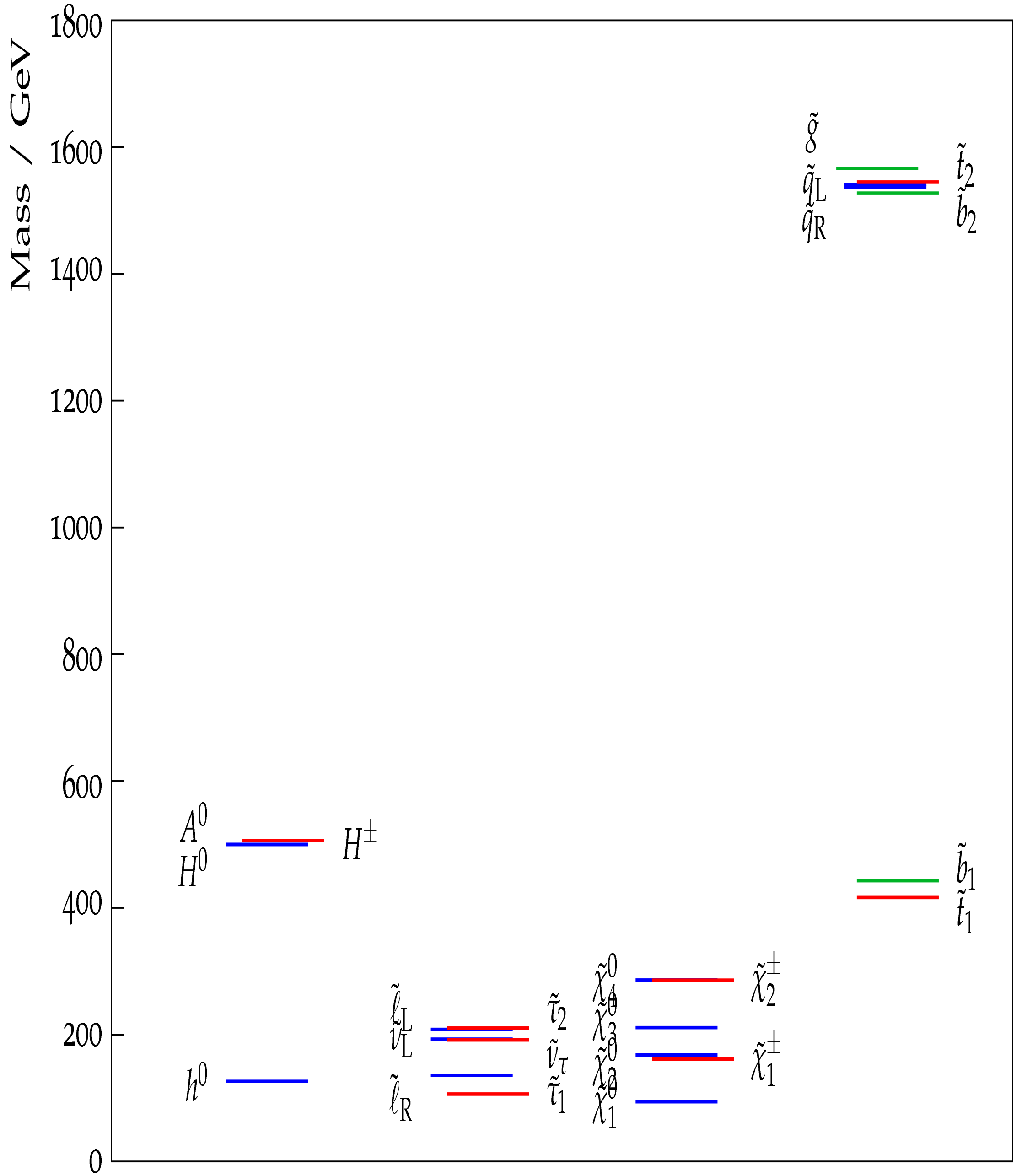


SPS1a variant (I)

colored and uncolored

sector decoupled:



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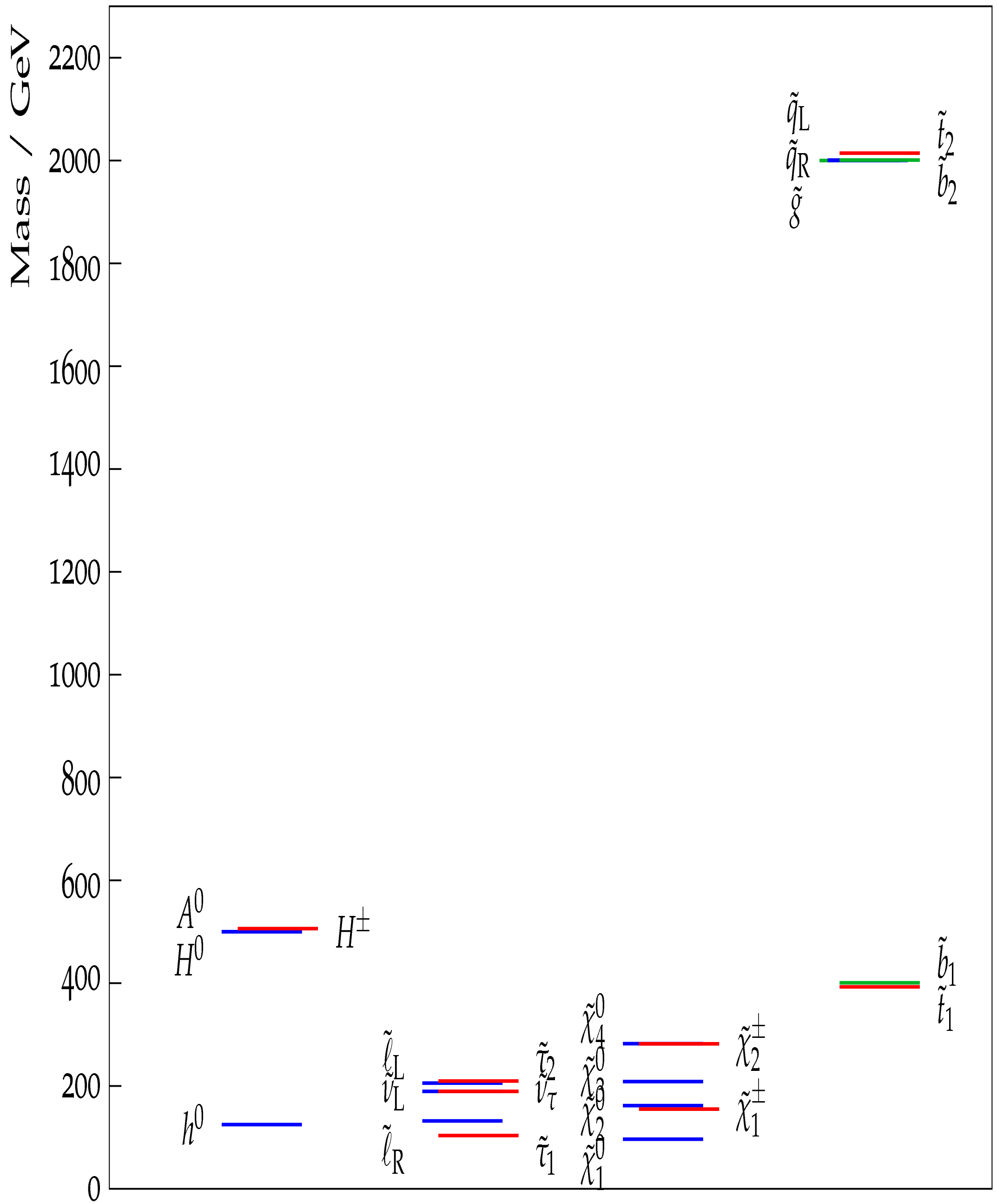

Focus point, gaugino mediation, cosmologically motivated

[*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. The No-Brainer

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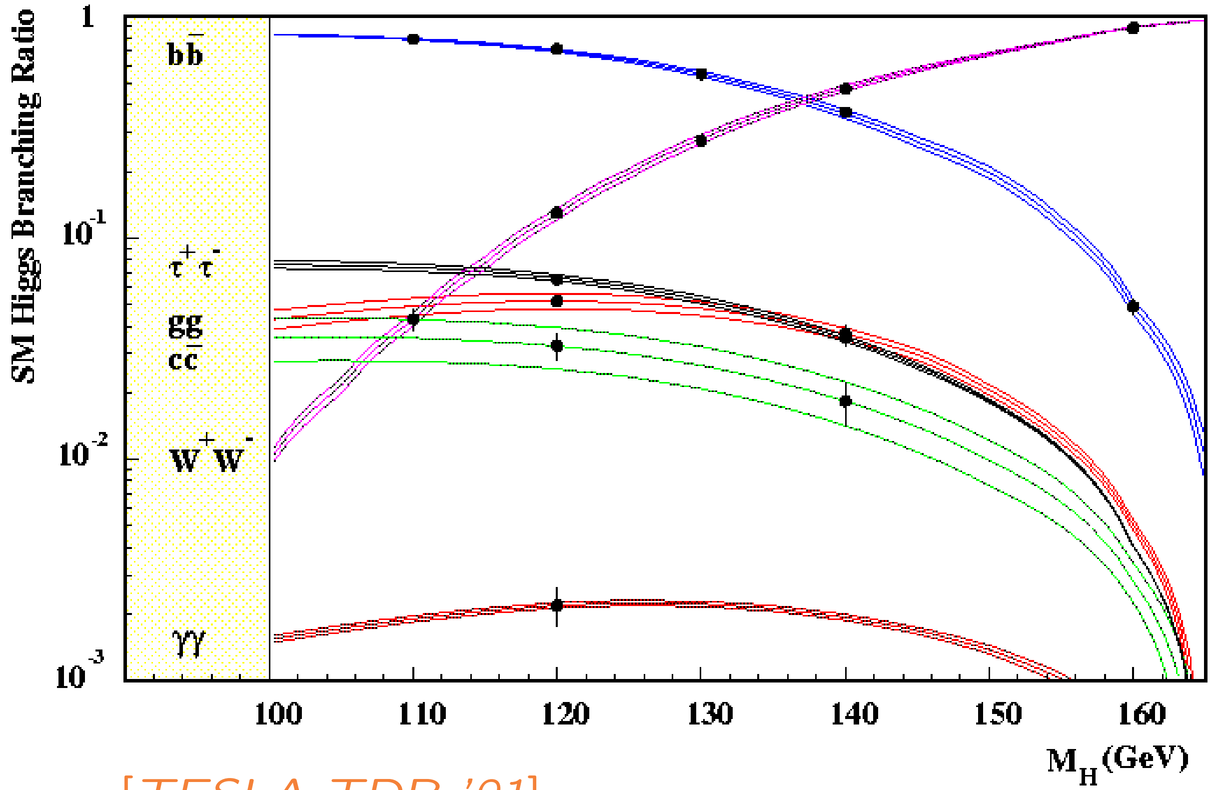
Higgs physics at the ILC:

SM Higgs @ ILC:
Precise measurement of:

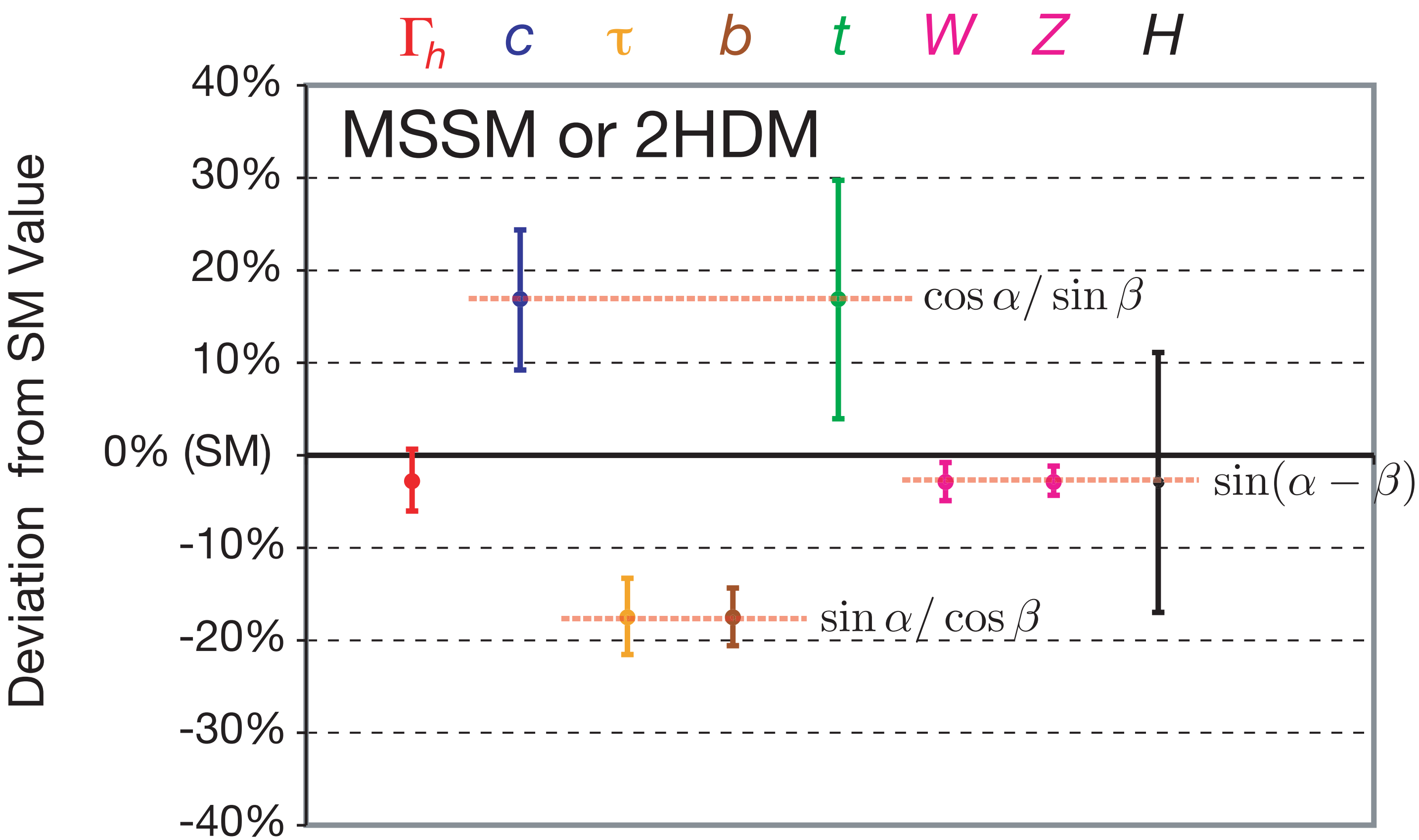
1. Higgs boson mass, $\delta M_H \approx 50$ MeV
2. Higgs boson width (direct/indirect)
3. Higgs boson couplings, $\mathcal{O}$(few%) $\Rightarrow$
4. Higgs boson quantum numbers: spin, . . .



[*TESLA TDR '01*]

Example: Higgs couplings in the MSSM:

"Normal(?)" MSSM scenario:



⇒ measurable deviations (at least in some parts of the parameter space)

The decoupling limit:

For $M_A \gtrsim 150$ GeV:

The lightest MSSM Higgs
is SM-like

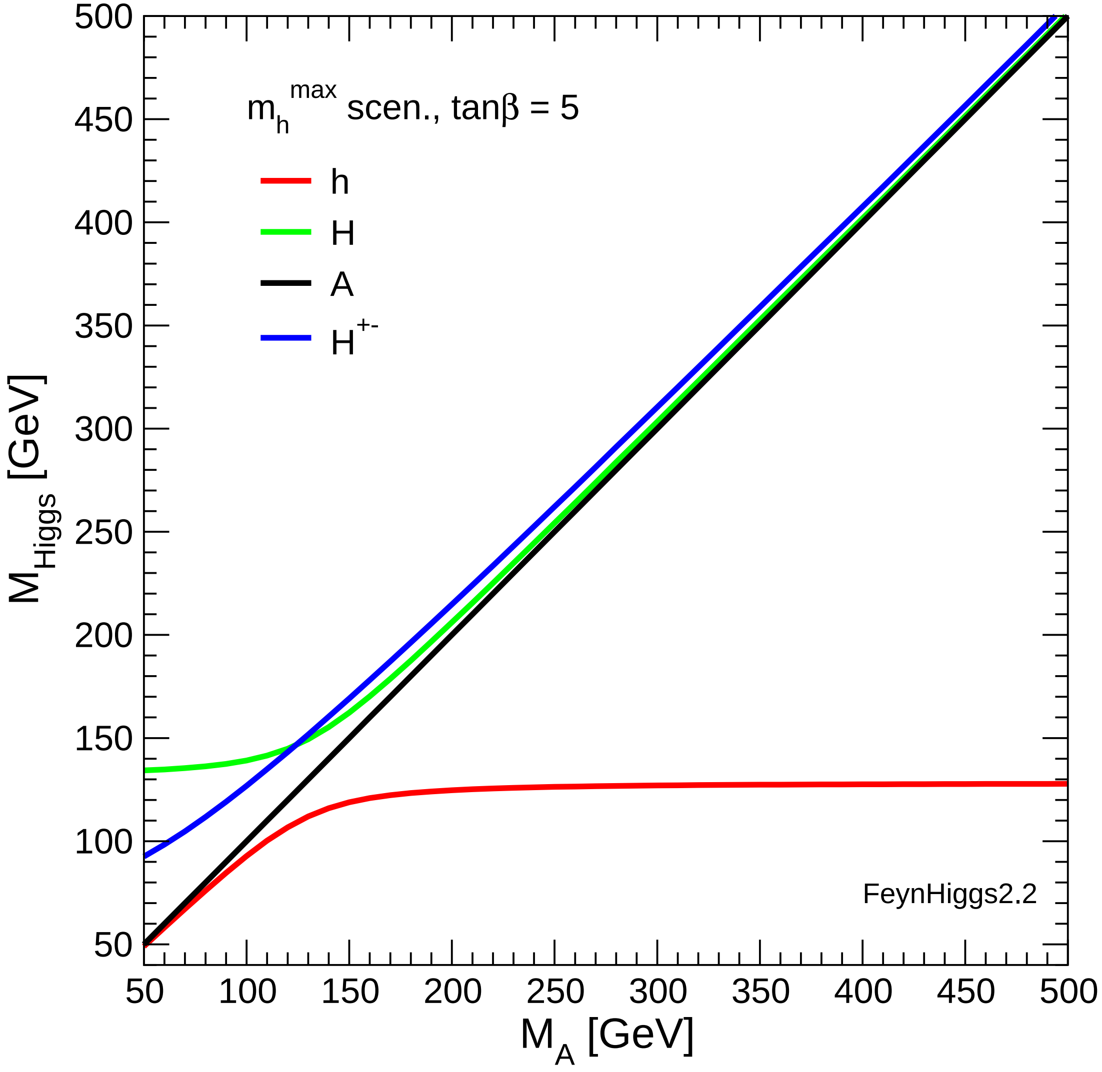
$\Rightarrow$ SM analysis applies!

The heavy MSSM Higgses:

$M_A \approx M_H \approx M_{H^\pm}$

$\rightarrow$ coupling to gauge bosons ~ 0

$\Rightarrow$ no decay $H \rightarrow WW^{(*)}$, . . .



Indirect determination of unknown Higgs sector parameters

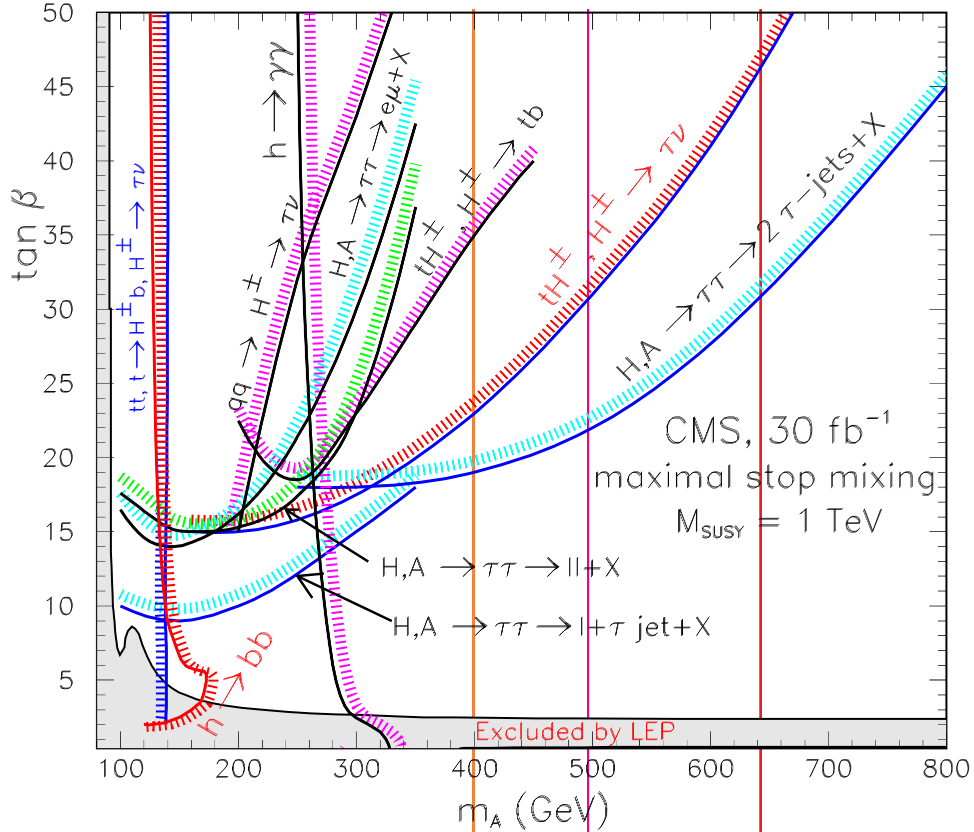
LHC/ILC reach for MSSM Higgs bosons:

LHC:

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

H, A : unreachable parts

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



ILC:

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

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

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

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

$\sqrt{s} = 1000$ 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

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How to go ahead?

(if not strongly discouraged by 2012 data . . .)

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- ILC as a Higgs (and top) factory
- Staged approach?
  - start at lower energies to produce $\mathcal{O}\left(10^5\right)$ Higgs bosons
  - go to higher energies for top physics
  - go to higher energies for TeV scale exploration
- go to other options: GigaZ, $\gamma\gamma$, . . .

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$\Rightarrow$ best case scenario the ILC!

$\Rightarrow$ Let's use our Annus mirabilis in our favor!!