Direct and indirect bounds on Higgs bosons

Georg Weiglein

DESY

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- Introduction
- Direct bounds
- (Some) indirect bounds
- Conclusions $+$ advertisement

Introduction:
Physics of electroweak symmetry breaking

What is the mechanism of electroweak symmetry breaking?

- Standard Model (SM), SUSY, . . . :
  Higgs mechanism, elementary scalar particle(s)

- Strong electroweak symmetry breaking:
  a new kind of strong interaction

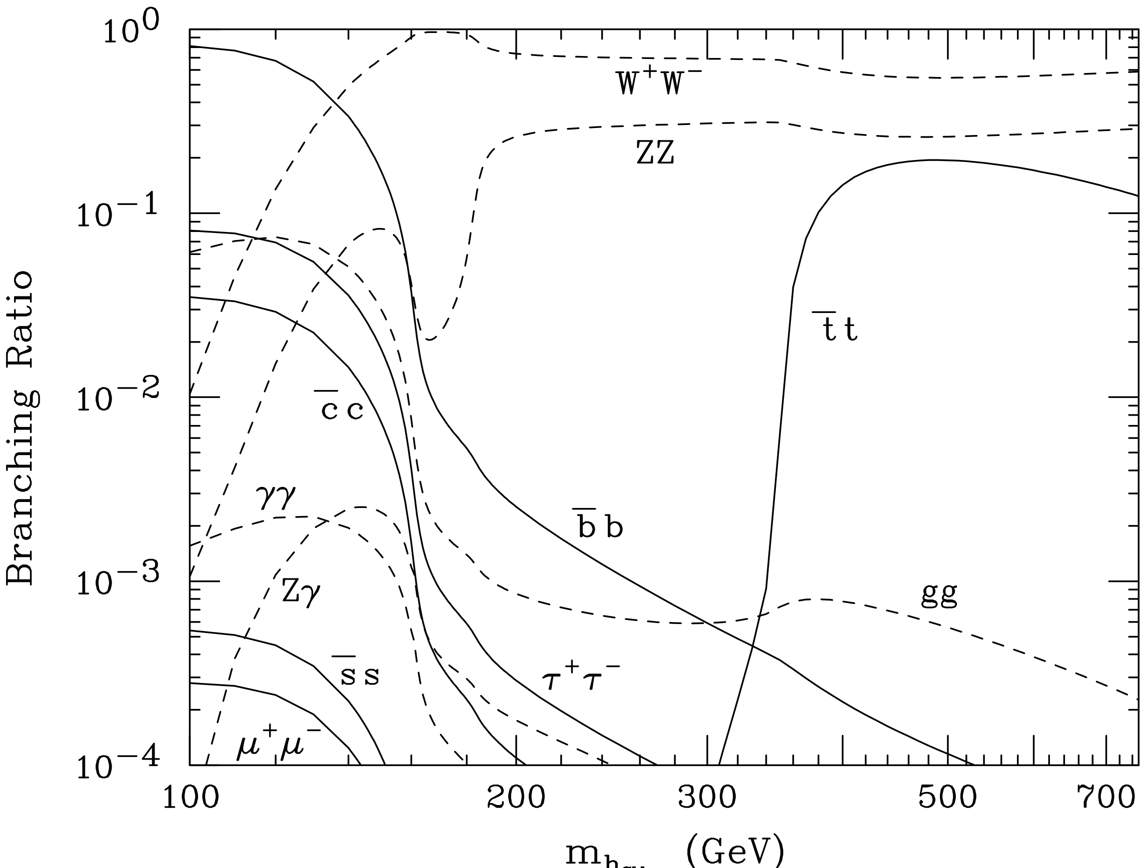
- Higgsless models in extra dimensions: boundary conditions for SM gauge bosons and fermions on Planck and TeV branes in higher-dimensional space

$\Rightarrow$ New phenomena required at the TeV scale

Higgs phenomenology: SM and beyond

Standard Model: a single parameter determines the whole Higgs phenomenology: $M_{\rm H}$

Branching ratios of the SM Higgs:



$\Rightarrow$ dominant BRs:

$M_{\rm H} \lesssim 140$ GeV:
$H \to b\bar{b}$

$M_{\rm H} \gtrsim 140$ GeV:
$H \to W^+W^-, ZZ$

Higgs physics beyond the SM

In the SM the same Higgs doublet is used “twice” to give masses both to up-type and down-type fermions

$\Rightarrow$ extensions of the Higgs sector having (at least) two doublets are quite “natural”

$\Rightarrow$ Would result in several Higgs states

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Example: SUSY in the “decoupling limit”

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Example: SUSY in the “decoupling limit”

But there is also the possibility that none of the Higgs bosons is SM-like

BSM $\oplus$ Higgs phenomenology

- Large enhancement / suppression of standard search channels possible
  Example: large enhancement of $H\bar{b}b$ coupling
  $\Rightarrow$ large suppression of BR($h \to \gamma\gamma$), BR($h \to WW^*$), ...

- New channels, different phenomenology:
  - Experimental evidence for dark matter
    $\Rightarrow$ if dark matter particle is lighter than $M_{\mathrm{H}}/2$
    $\Rightarrow$ large branching fraction into invisible particles
    $\Rightarrow$ large suppression of all other BRs
  - Higgs production in decays of BSM particles
  - $h_i \to h_j h_j$ decays
  - Higgs–radion mixing, ...
  - Higgses with nearly degenerate masses: large interference effects, resonance-type behaviour possible

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

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

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

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

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

Two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

General parametrisation of possible SUSY-breaking terms
$\Rightarrow$ free parameters, no prediction for SUSY mass scale

Hierarchy problem $\Rightarrow$ expect observable effects at TeV scale

Simplest ansatz for SUSY breaking: the Constrained MSSM (CMSSM)

Assume universality at high energy scale ($M_{\rm GUT}$, $M_{\rm Pl}$, ...)
renormalisation group running down to weak scale
require correct value of $M_{\rm Z}$

$\Rightarrow$ CMSSM characterised by

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

CMSSM has been the “favourite toy” for both theorists and experimentalists so far

CMSSM is in agreement with the experimental constraints from electroweak precision observables (EWPO)
$+$ flavour physics $+$ cold dark matter density $+$ ...

The Non-Universal Higgs Model (NUHM)

Universality of soft SUSY-breaking contributions to the Higgs scalar masses is less motivated than universality between squarks and sleptons

$\Rightarrow$ NUHM:

two additional parameters (can be traded for M_A and μ after imposing the electroweak vacuum conditions)

Simplest realisation:

$$m_{H_1}^2 = m_{H_2}^2 \equiv m_H^2$$

Common soft SUSY-breaking contribution to Higgs scalar masses squared: “NUHM1”

Higgs physics in Supersymmetry

"Simplest" extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters

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$\Rightarrow$ Two parameters instead of one: $\tan\beta \equiv \frac{v_u}{v_d}$, $\quad M_\mathrm{A}$ (or $M_{\mathrm{H}^\pm}$)

$\Rightarrow$ Upper bound on lightest Higgs mass, M_h (*FeynHiggs*):
[*S. Heinemeyer, W. Hollik, G. W. '99*], [*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

$$M_\mathrm{h} \lesssim 135\,\mathrm{GeV}$$

Very rich phenomenology

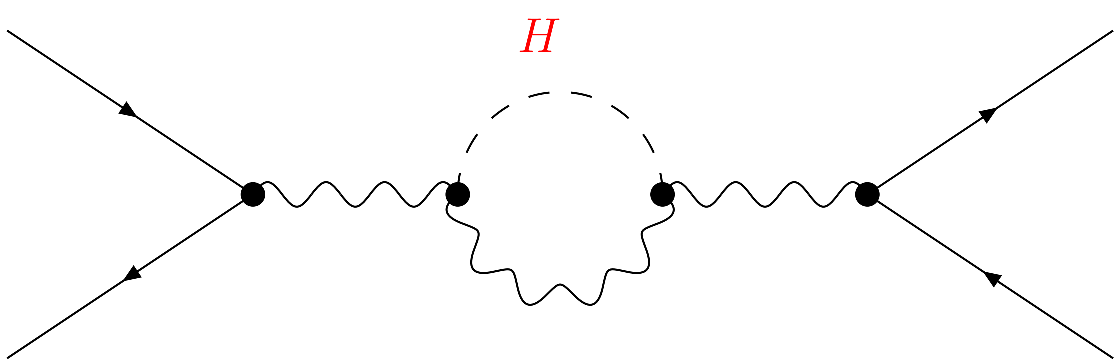
Indirect constraints

EW precision data:
$M_Z, M_W, \sin^2\theta_{eff}^{lept}, \ldots$

Theory:
SM, MSSM, ...

$\Downarrow$

Test of theory at quantum level: loop corrections



$\Downarrow$

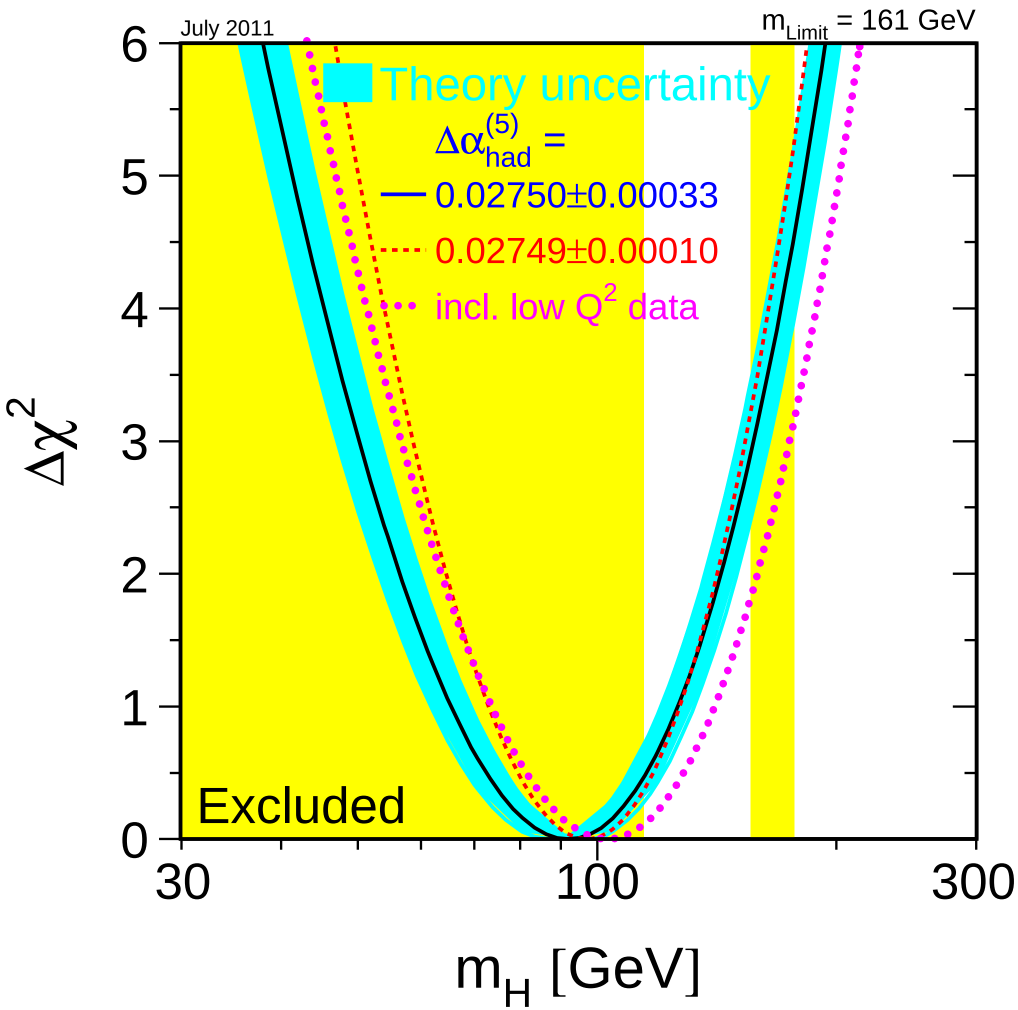
Sensitivity to effects from unknown parameters: M_H, $M_{\tilde{t}}$, ...

Window to “new physics”

Constraints on the SM Higgs from electroweak precision data

Indirect constraint on $M_{H_{SM}}$, no direct search limits included in the fit

[*LEPEWWG '11*]



$\Rightarrow$ Preference for a light Higgs, $M_{H_{SM}} < 161\ \mathrm{GeV}$, 95% C.L.

Direct bounds

Searches for the SM Higgs:

Exclusion limits from LEP, Tevatron, ATLAS, CMS:

Allowed mass range for SM Higgs reduced to
$114\ \mathrm{GeV} \lesssim M_{\mathrm{H_{SM}}} \lesssim 127\ \mathrm{GeV}$
($+$ high mass region above $600\ \mathrm{GeV}$)

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Excess observed by ATLAS and CMS in SM-like Higgs searches near $M_{\mathrm{H_{SM}}} \approx 125 \text{ GeV}$, supported by several channels (in particular $\gamma\gamma$, ZZ^*)

Slight excess observed also at the Tevatron

Direct bounds for BSM Higgses

The direct bounds quoted above apply only to a SM-like Higgs

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$\Rightarrow$ There may be a Higgs signal in a mass region that is excluded for the SM:

- Above 130 GeV
- Below 114 GeV

  Example: a 40 GeV Higgs in the MSSM with complex parameters (CPX scenario) is in agreement with all experimental bounds

HiggsBounds: confronting arbitrary BSM Higgs sectors with search limits from LEP, the Tevatron and the LHC

Limits for different production and decay channels have been presented in two ways:

- For a specific model: SM, MSSM benchmark scen., . . .
  $\Rightarrow$ combination of different channels possible
  difficult to interpret for other models or w.r.t. changes in the input parameters or the theoretical predictions

- As cross section limits for a certain search topology
  $\Rightarrow$ exclusion bounds have to be tested channel by channel
  fairly model-independent and generally applicable
  $\Rightarrow$ Implemented in program *HiggsBounds*
  [*P. Bechtle, O. Brein, S. Heinemeyer, G. W., T. Stefaniak, K. Williams '08, '11*]

Determination of 95% C.L. exclusion region from given cross section limits

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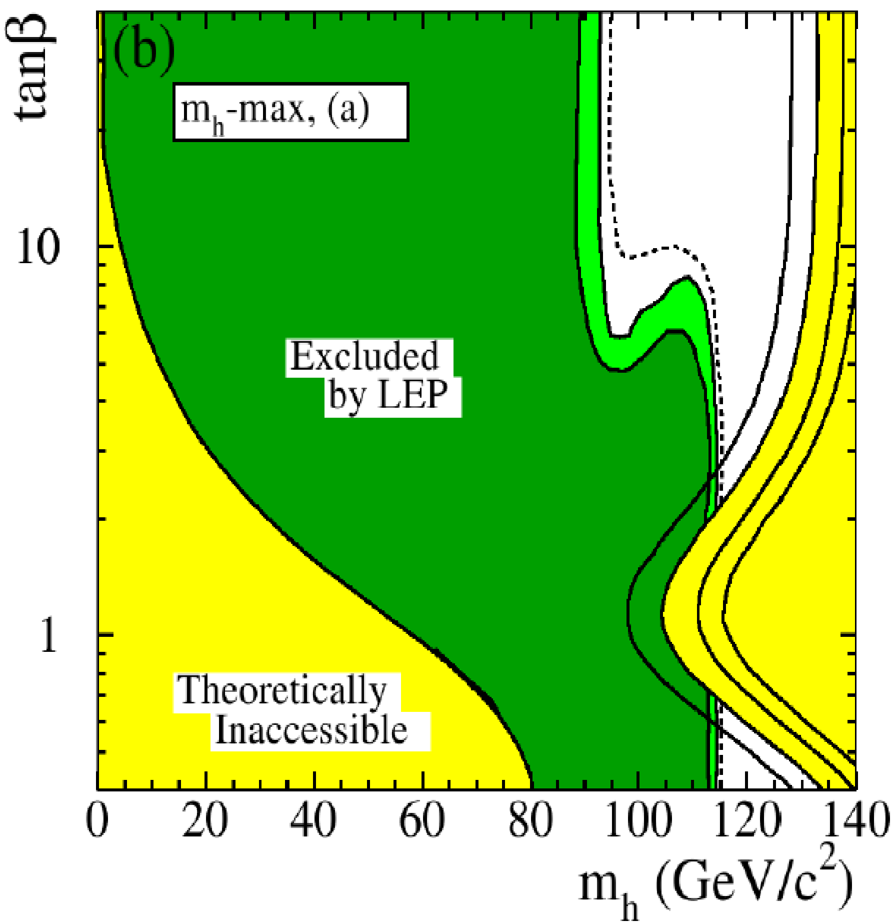
- On the basis of the expected search limits for different channels in a given model one needs to determine for every parameter point the search channel having the highest statistical sensitivity for setting an exclusion limit

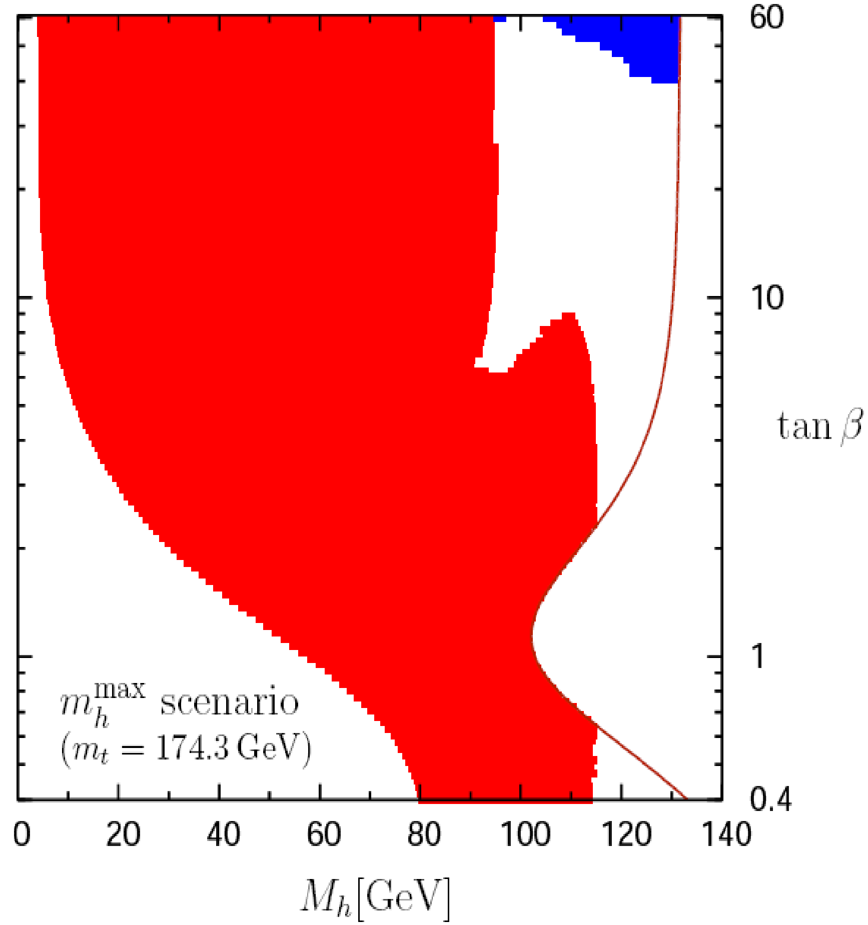
- For this single channel only one needs to compare the observed limit with the theory prediction for the Higgs production cross section times decay branching ratio to determine whether or not the considered parameter point of the model is excluded at 95% C.L.

Example: MSSM $m_{\rm h}^{\rm max}$ *benchmark scenario, comparison of HiggsBounds output with LEP Higgs Working Group results*

Eur. Phys. J. **C 47** (2006) 547
[*LEP Higgs Working Group '06*]

HiggsBounds: $m_{\rm t}$ set to benchmark value, improved $m_{\rm h}$ prediction, Tevatron res. included

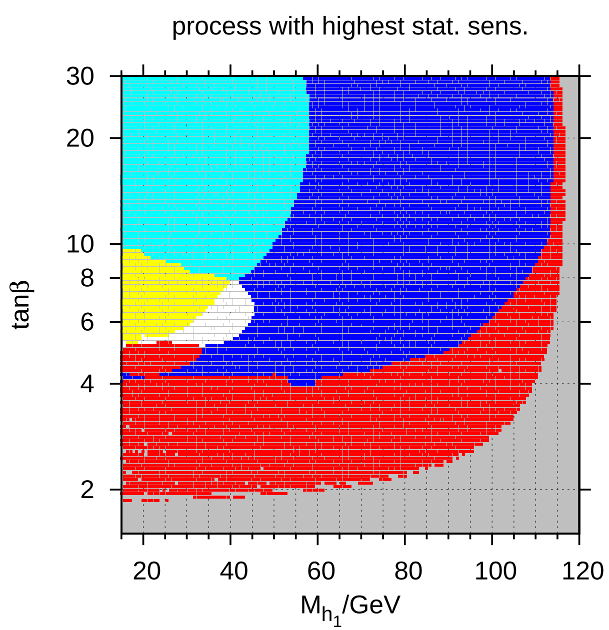




Example: analysis of LEP coverage in CPX scenario with improved theoretical prediction

For every parameter point: determine the search channel with the highest statistical sensitivity for setting an exclusion

[*P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08,'11*]



Channels:

$$({\color{red}\blacksquare}) = (h_1 Z) \longrightarrow (b\bar{b}Z)$$

$$({\color{blue}\blacksquare}) = (h_2 Z) \longrightarrow (b\bar{b}Z)$$

$$(\square) = (h_2 Z) \longrightarrow (h_1 h_1 Z) \longrightarrow (b\bar{b}b\bar{b}Z)$$

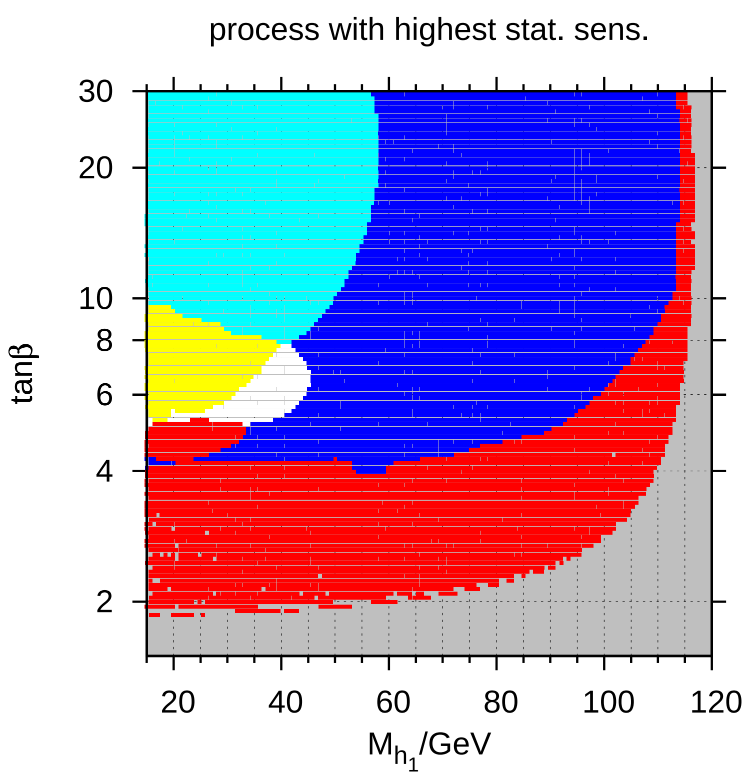
$$({\color{cyan}\blacksquare}) = (h_2 h_1) \longrightarrow (b\bar{b}b\bar{b})$$

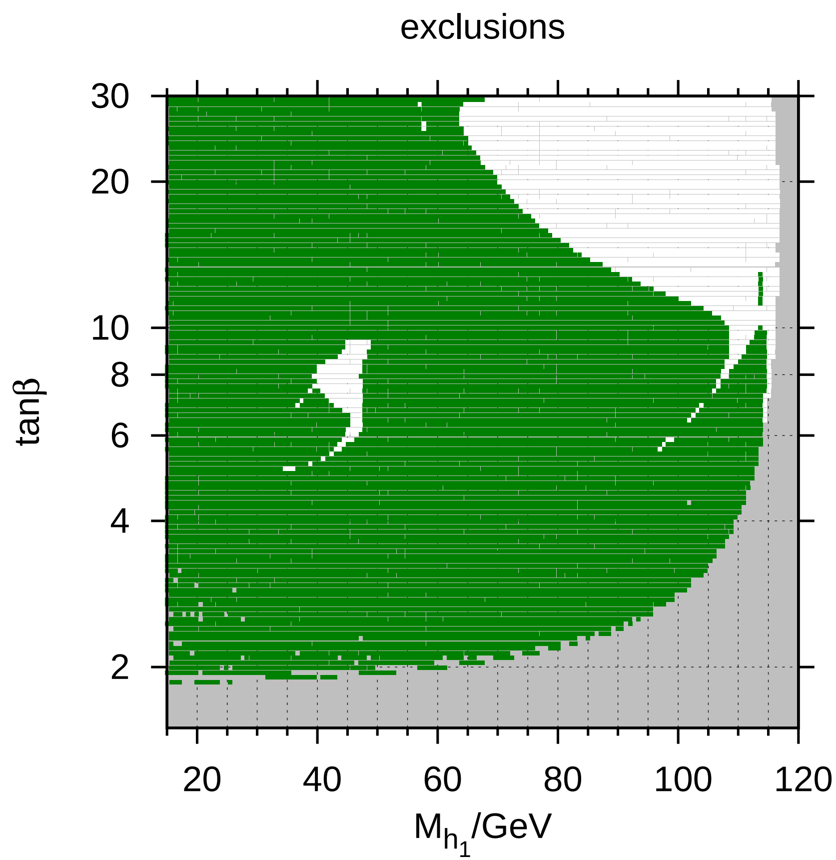
$$({\color{yellow}\blacksquare}) = (h_2 h_1) \longrightarrow (h_1 h_1 h_1) \longrightarrow (b\bar{b}b\bar{b}b\bar{b})$$

Search limits for MSSM with complex parameters (CPX scenario)

Channels (*HiggsBounds*)
$(\square) : (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$

Excluded region from LEP, 95% C.L. [*K. Williams, H. Rzehak, G. W. '11*]





⇒ Confirmation of the "hole" in the LEP coverage

⇒ Very light Higgs boson is not excluded

Implications of the results from the SM Higgs searches for SUSY

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The SUSY relations imply an upper bound on the mass of the light $\mathcal{CP}$-even Higgs, M_h

$\Rightarrow$ In the MSSM: $M_\mathrm{h} \lesssim 135~\mathrm{GeV}$

Implications of the results from the SM Higgs searches for SUSY

The SUSY relations imply an upper bound on the mass of the light $\mathcal{CP}$-even Higgs, M_h

$\Rightarrow$ In the MSSM: $M_\mathrm{h} \lesssim 135$ GeV

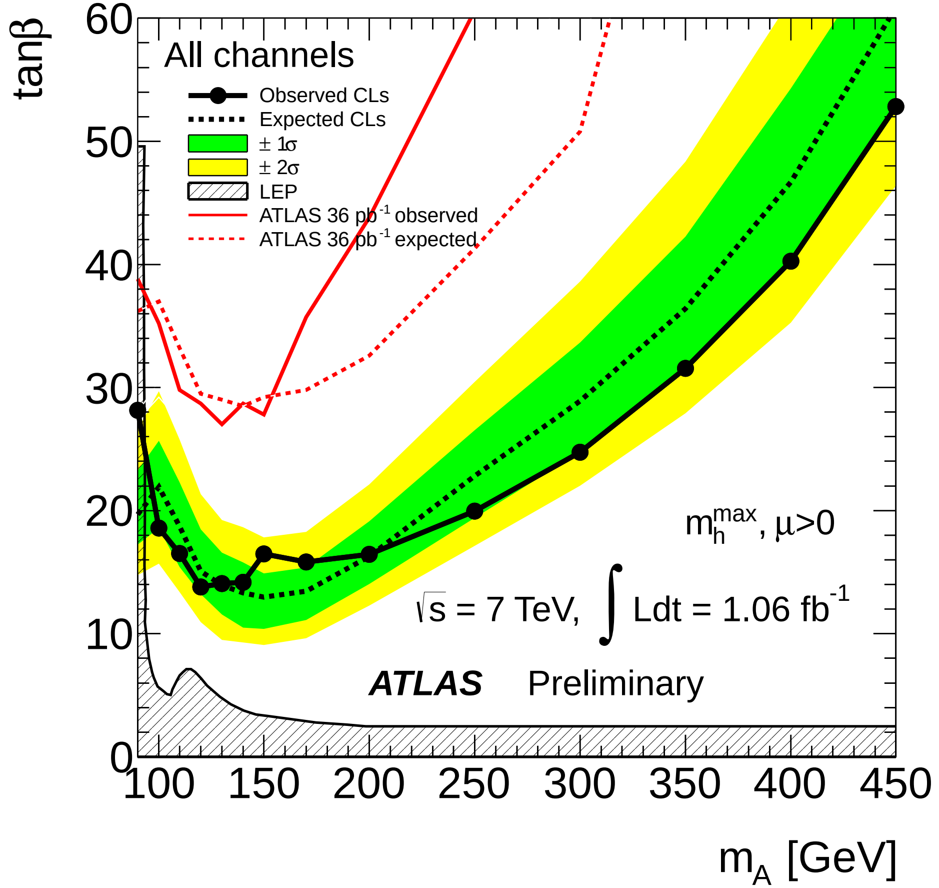
- The detection of a SM-like Higgs with $M_\mathrm{H} \gtrsim 135$ GeV would have unambiguously ruled out the MSSM

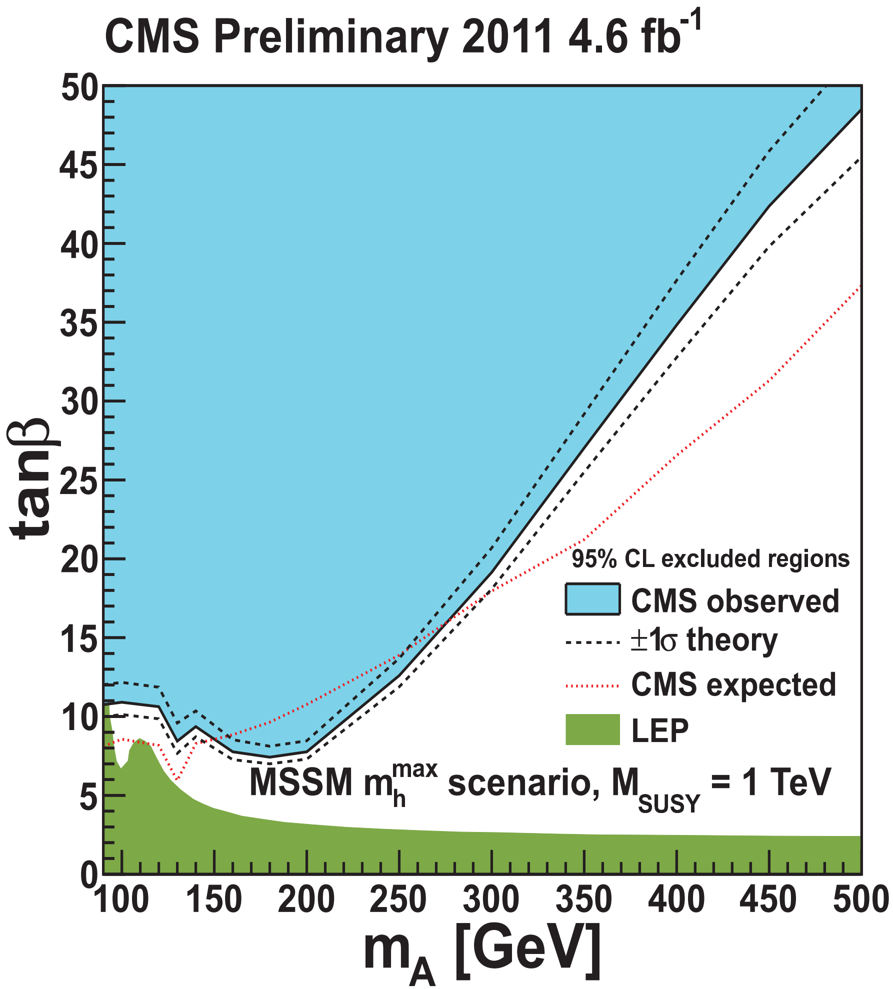
  Region above the upper bound of the MSSM is meanwhile ruled out for a SM-like Higgs

- Unexcluded low-mass region corresponds to the mass range predicted for the light $\mathcal{CP}$-even Higgs of the MSSM

Search for the heavy SUSY Higgs bosons H, A: limits in the M_A–$\tan\beta$ plane

[*ATLAS Collaboration '11*] [*CMS Collaboration '11*]





⇒ Large coverage in M_A–$\tan\beta$ plane

LHC + LEP start to narrow down the region of very low M_A

MSSM interpretation of latest Higgs search results from ATLAS and CMS

Statistical significance of reported excess near 125 GeV is not yet conclusive

In the following: investigate MSSM interpretation of assumed Higgs signal at $125 \pm 1 \text{ GeV}$

Intrinsic theoretical uncertainties from unknown higher-order corrections, $\Delta M_{\rm h}^{\rm intr} \sim 2 \text{ GeV}$, and parametric uncertaintes (variations of $m_{\rm t}$ by $\pm 1\sigma$) taken into account

Interpretation of an assumed Higgs signal at $\sim 125 \text{ GeV}$ *in terms of the light MSSM CP-even Higgs* h

Assumed signal would imply a lower bound on $M_{\rm h}$

$\Rightarrow$ Set parameters entering via higher-order corrections such that $M_{\rm h}$ is maximised ($m_{\rm h}^{\rm max}$ benchmark scenario)

$\Rightarrow$ Lower bounds on $M_{\rm A}$, $\tan\beta$

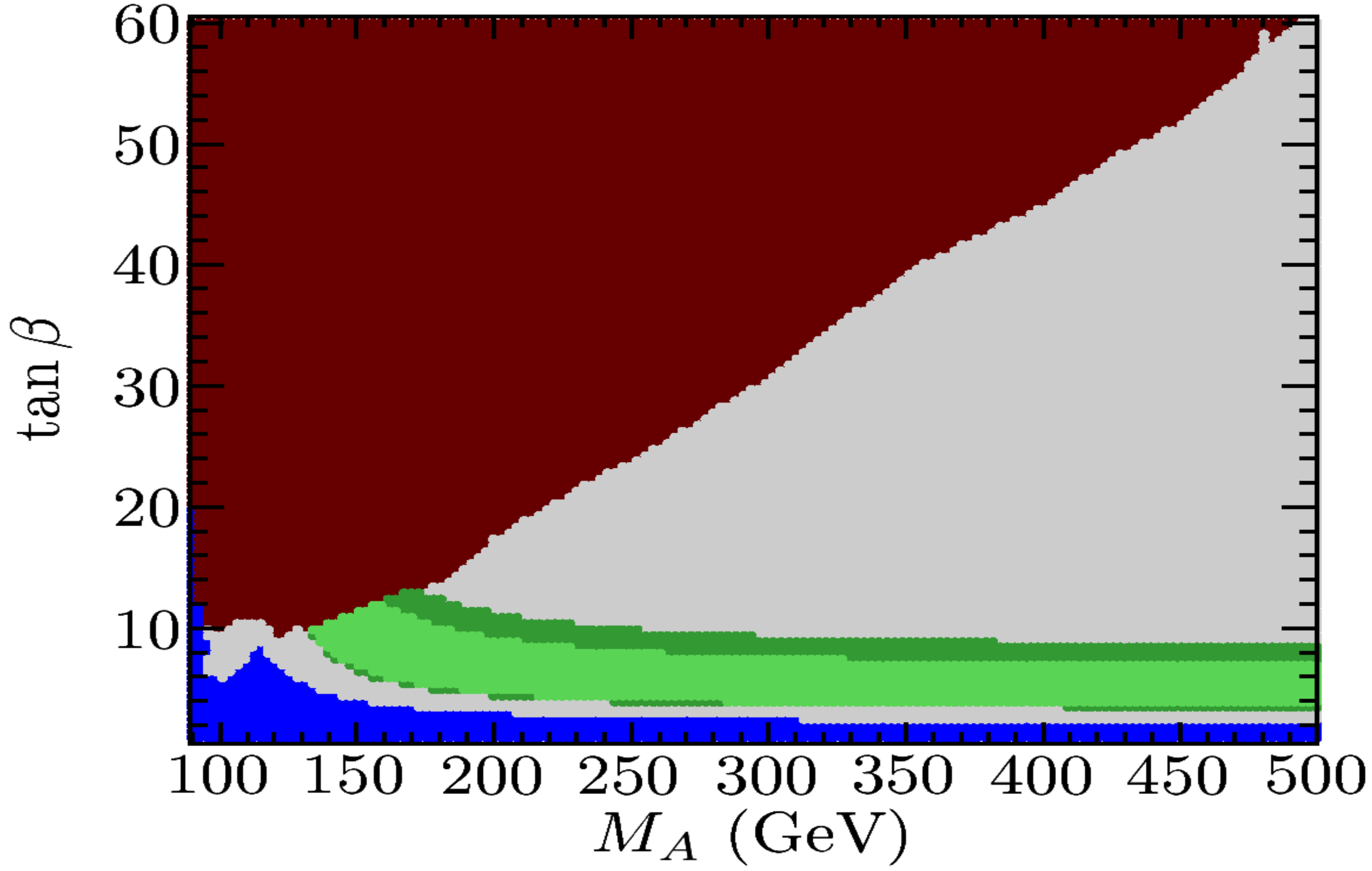
Search limits from LEP and from LHC $H, A \to \tau^+\tau^-$ search taken into account:

HiggsBounds

[*P. Bechtle, O. Brein, S. Heinemeyer, G. W., T. Stefaniak, K. Williams '08, '11*]

Lower bounds on M_A *and* $\tan\beta$ *from assumed Higgs signal at* ~ 125 GeV

Green region: compatible with assumed Higgs signal with / without m_t variation [*S. Heinemeyer, O. Stål, G. W. '11*]

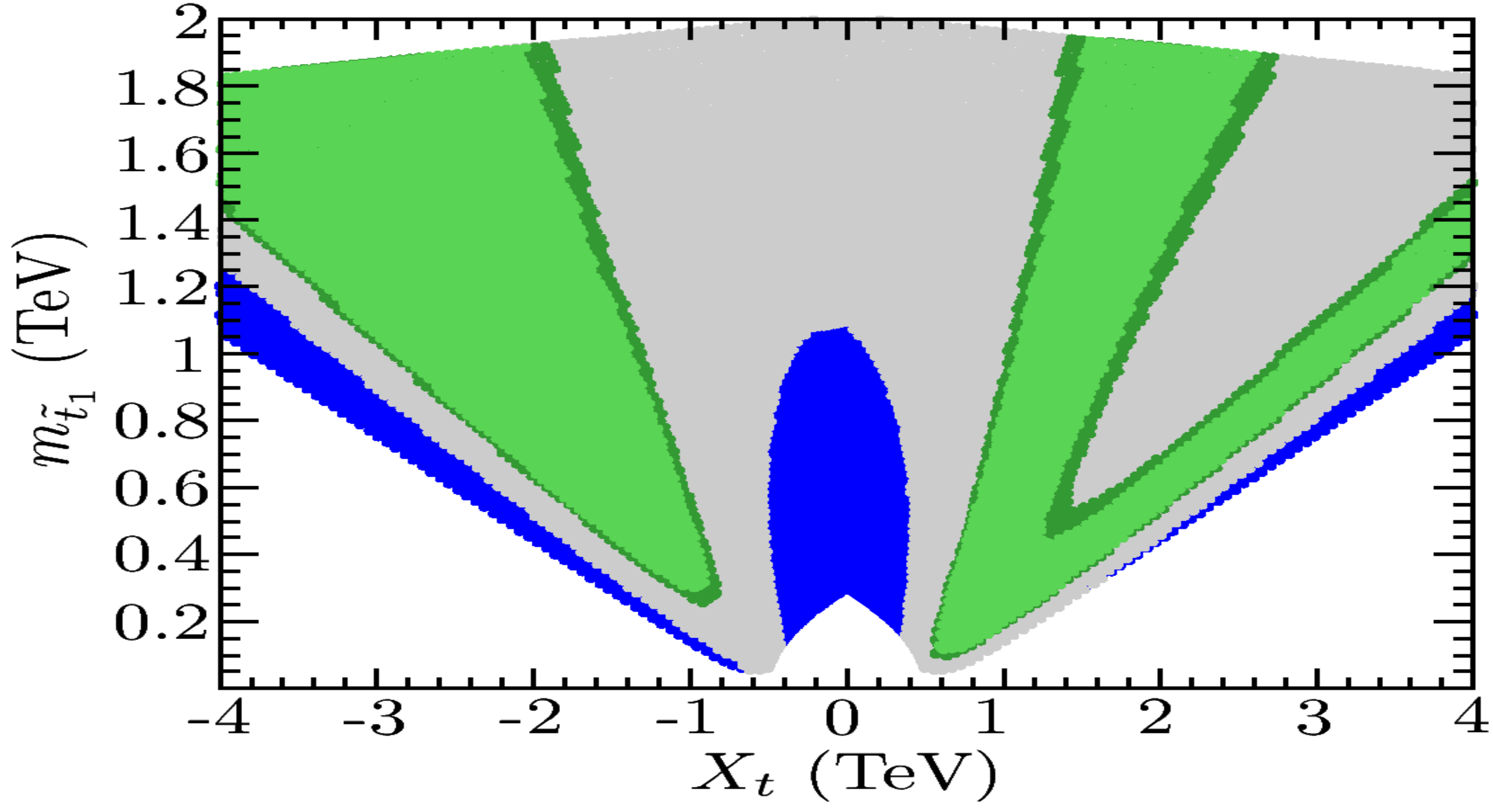


$\Rightarrow \tan\beta \gtrsim 3$, $M_\mathrm{A} \gtrsim 130$ GeV, $M_{\mathrm{H}^\pm} \gtrsim 152$ GeV

Lower bound on the lightest stop mass from assumed Higgs signal at ~ 125 GeV

M_A, $\tan\beta$ chosen in decoupling region: $M_A = 1$ TeV, $\tan\beta = 20$

[S. Heinemeyer, O. Stål, G. W. '11]



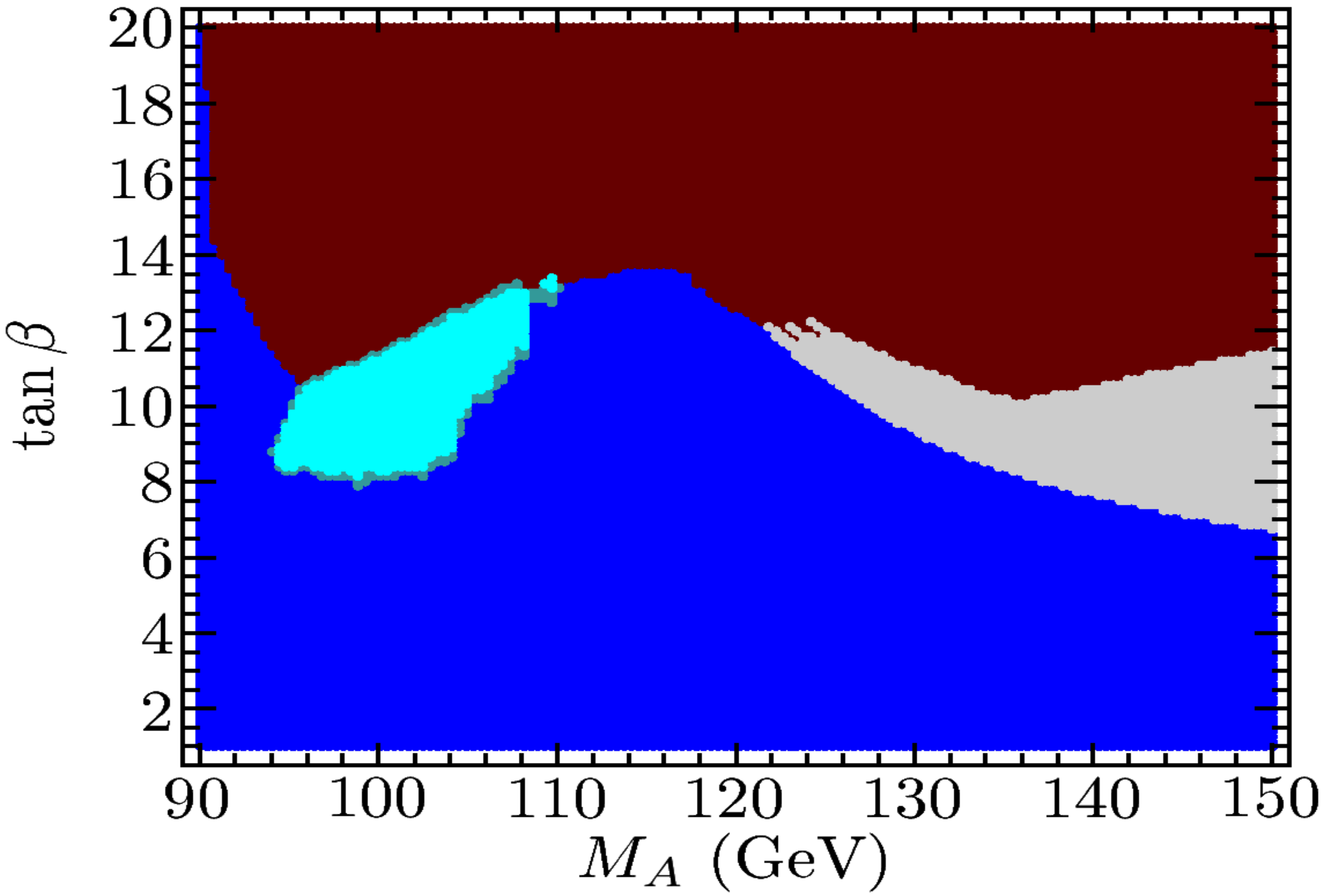
$\Rightarrow m_{\tilde{t}_1} > 100\ (250)$ GeV for positive (negative) X_t

Compatibility with assumed signal would be difficult in constrained models: mGMSB, mAMSB, …

Interpretation of an assumed Higgs signal at ~ 125 GeV
in terms of the heavy MSSM CP-even Higgs H

Scan over $M_{\rm A}$, $\tan\beta$, $M_{\rm SUSY}$, $X_{\rm t}$

[*S. Heinemeyer, O. Stål, G. W. '11*]



$\Rightarrow$ possible for low $M_{\rm A}$, moderate $\tan\beta$

Interpretation of an assumed Higgs signal at $\sim 125~\mathrm{GeV}$ ***in terms of the heavy MSSM CP-even Higgs*** H

The light Higgs h in this scenario has a mass that is always below the LEP limit of $M_{\mathrm{H_{SM}}} > 114.4~\mathrm{GeV}$ (with reduced couplings to gauge bosons, in agreement with LEP bounds)

Could have, for instance, $M_{\mathrm{H}} \sim 125~\mathrm{GeV}$, $M_{\mathrm{h}} \sim 98~\mathrm{GeV}$ (slight excess observed at LEP at $M_{\mathrm{h}} \sim 98~\mathrm{GeV}$)

$\Rightarrow$ It is important to extend the LHC Higgs searches to the region below $114~\mathrm{GeV}$!

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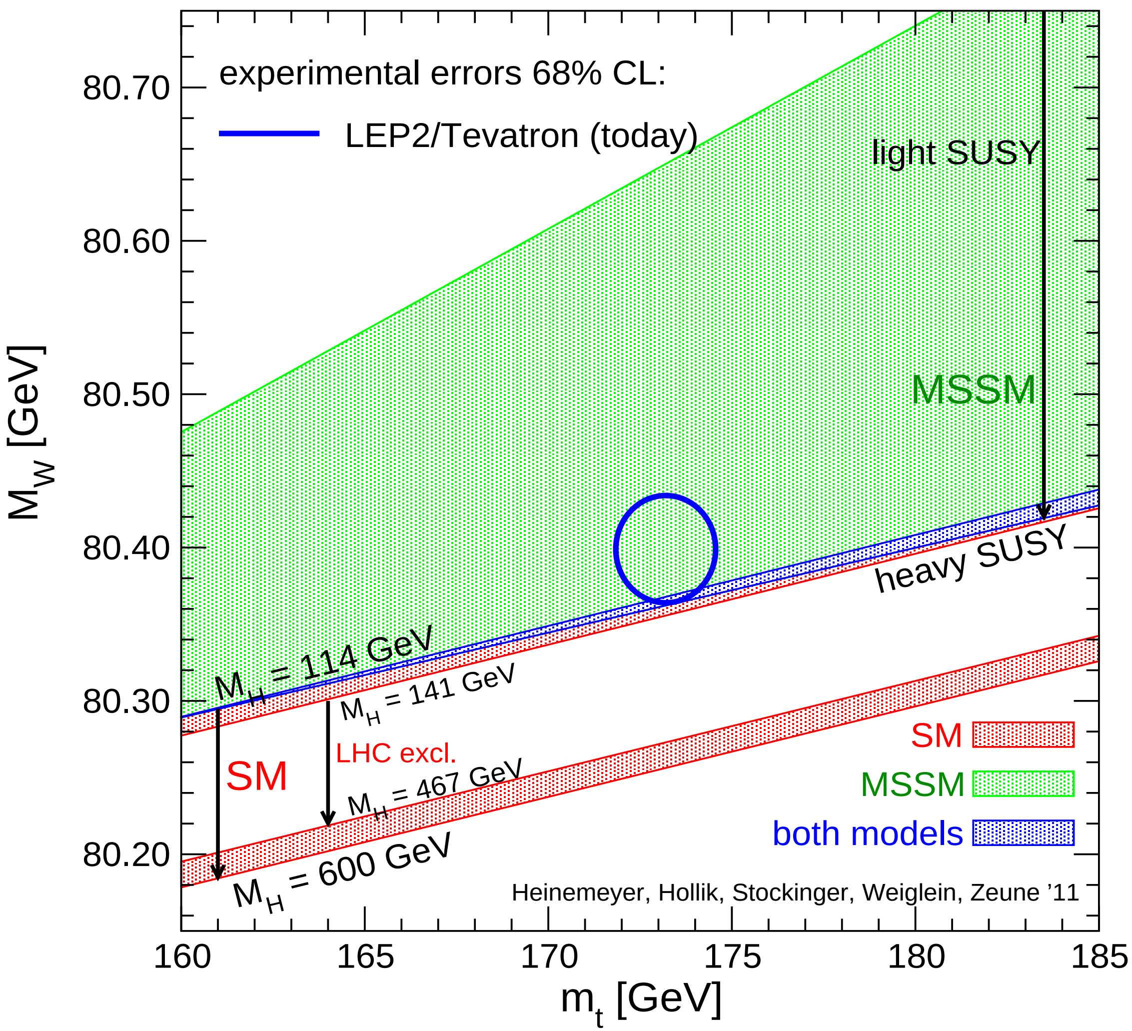
The best way of experimentally proving that an observed state is not the SM Higgs is to find in addition (at least one) non-SM like Higgs!

(Some) indirect bounds

Prediction for M_W (parameter scan): SM vs. MSSM

Prediction for M_W in the SM and the MSSM:



[*S. Heinemeyer, W. Hollik, D. Stöckinger, G. W., L. Zeune '11*]

MSSM: SUSY parameters varied

SM: M_H varied

Tevatron result for m_t interpreted (perturb.) as pole mass

$\Rightarrow$ Slight preference for MSSM over SM

Global fits in constrained SUSY models

Take into account information from

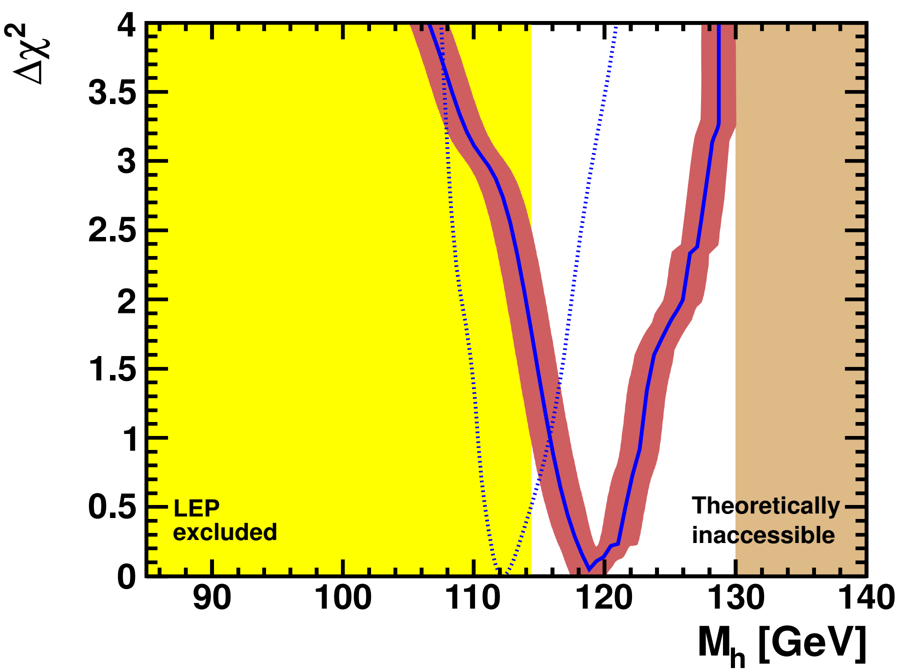
- Electroweak precision observables: M_W, $\sin^2\theta_{\mathrm{eff}}$, Γ_Z, $\ldots$
- $+ (g-2)_\mu$
- + Cold dark matter (CDM) density (WMAP, . . .)
- + B-physics observables:
  $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$, $\mathrm{BR}(B \to \tau\nu)$, $\ldots$

$\Rightarrow$ Fits using frequentist or Bayesian statistical methods

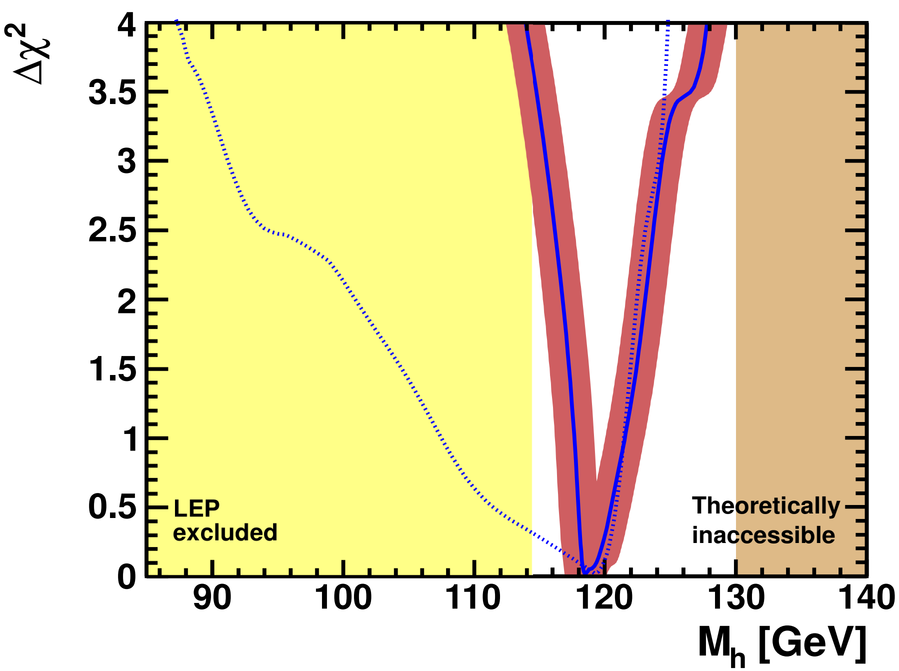
Indirect prediction for the Higgs mass in CMSSM, NUHM1: pre-LHC vs. LHC2011

χ^2 fit for M_h, without imposing direct search limit

CMSSM:



NUHM1:



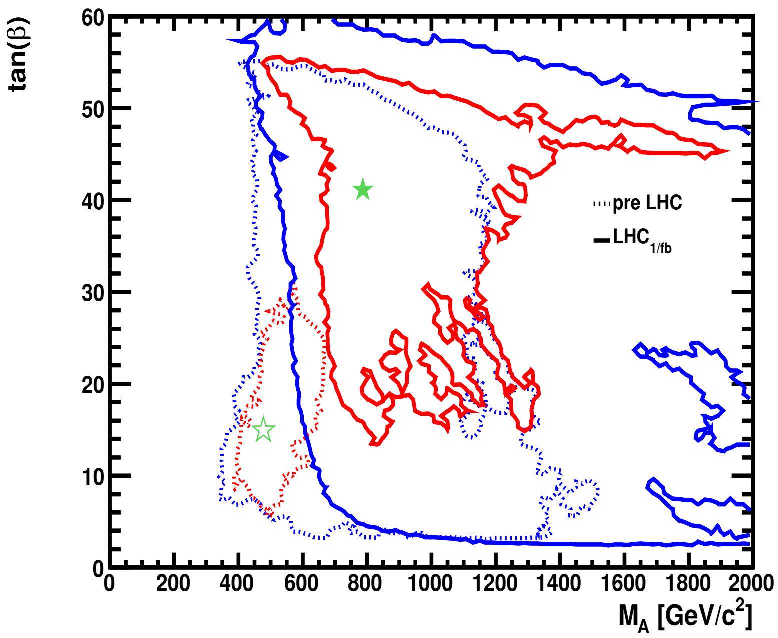
$\Rightarrow$ Compatibility with LEP limit improves with the inclusion of LHC SUSY search limits

Fit without $(g-2)_\mu$, best fit value for M_h:
CMSSM: $M_\mathrm{h} \sim 125$ GeV, NUHM1: $M_\mathrm{h} \sim 127$ GeV

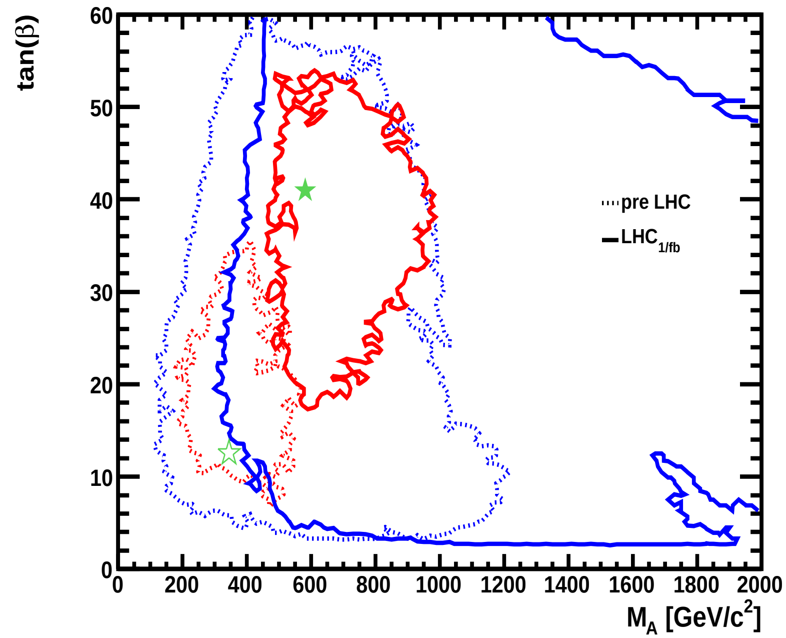
Indirect constraints on M_A and $\tan\beta$ in CMSSM, NUHM1: pre-LHC vs. LHC2011

[O. Buchmueller, R. Cavanaugh, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, J. Marrouche, D. Martínez Santos, K. Olive, S. Rogerson, F. Ronga, K. de Vries, G. W. '11]

CMSSM:



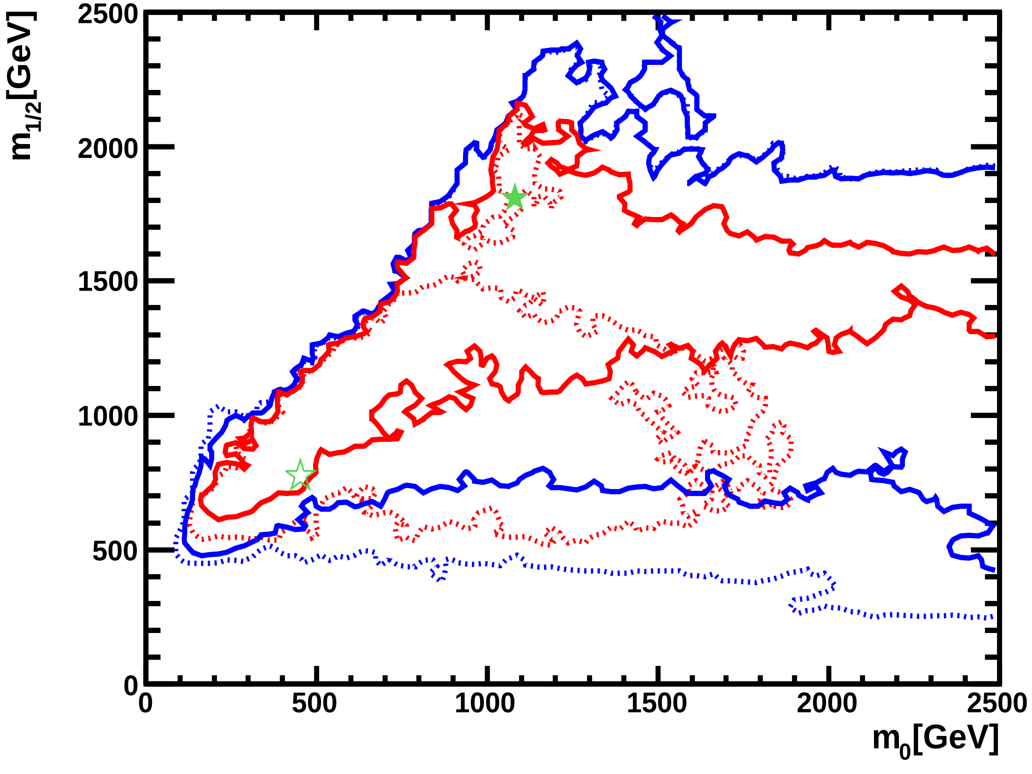
NUHM1:



$\Rightarrow$ Shift to higher values of $\tan\beta$ and M_A

Implications of an assumed Higgs signal at ~ 125 GeV *in the CMSSM*

[O. Buchmueller, R. Cavanaugh, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, J. Marrouche, D. Martínez Santos, K. Olive, S. Rogerson, F. Ronga, K. de Vries, G. W. '11]



$\Rightarrow$ Shift to higher mass scales, reduced fit probability

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- An excess in the search for a SM-like Higgs should serve as a strong motivation to look for non-SM-like Higgses elsewhere
- Combination of direct and indirect bounds will be a powerful tool for discriminating between different interpretations and for identifying the underlying physics

Advertisement: ***Workshop "Implications of LHC results for TeV-scale physics"***

Kick-off meeting:

29/08/2011–02/09/2011, CERN, $\gtrsim 200$ participants

$\Rightarrow$ Discuss impact of experimental results on future strategy for particle physics

Results will be summarised in a document to be submitted as input for the 2012 update of the European Strategy for Particle Physics (in time for “Orsay-type” meeting of strategy update, 09/2012)

Main organisers:

O. Buchmueller, P. De Jong, A. De Roeck, J. Ellis, C. Grojean, S. Heinemeyer, J. Hewett, K. Jakobs, M. Mangano, F. Teubert, G. W.

Workshop "Implications of LHC results for TeV-scale physics"

Three working groups:

- WG1: Signals of electroweak symmetry breaking

  Conv.: *S. Heinemeyer, M. Kado, C. Mariotti, G. W., A. Weiler*

- WG2: Signatures with missing energy

  Conv.: *R. Cavanaugh, J. Hewett, S. Kraml, G. Polesello*

- WG3: Other signatures of possible BSM physics

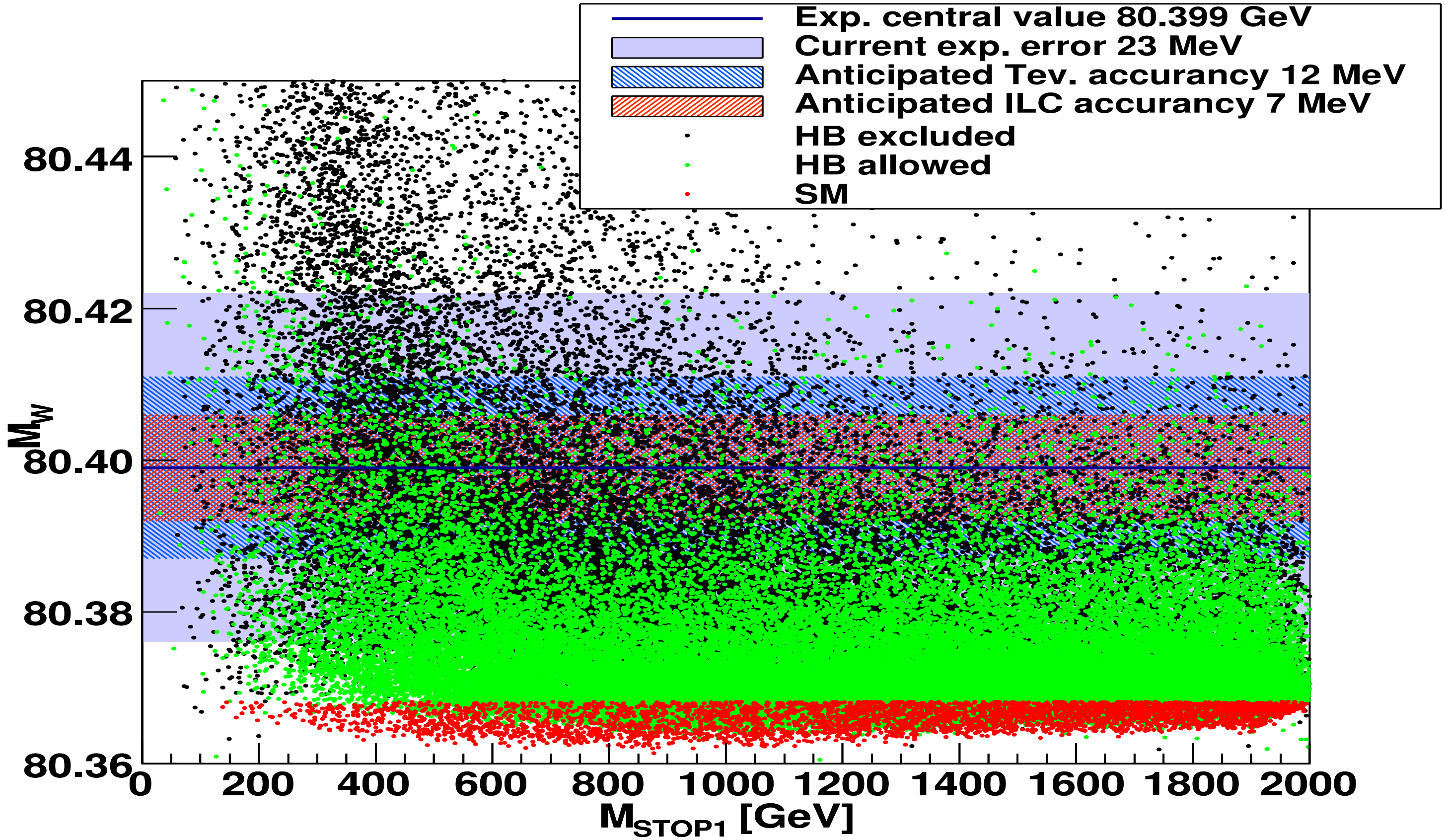
  Conv.: *C. Grojean, D. Martinez, J. Santiago Perez, P. Savard, S. Worm*

$\Rightarrow$ It is now the right time to join in to this activity!

Backup

Current experimental result for M_W and future projections vs. predictions in the MSSM and the SM ($M_{H_{SM}} \lesssim 130$ GeV)

[*L. Zeune, G. W. '11*]



⇒ High sensitivity for discriminating SM / new physics

NB: The density of points has no physical significance