Phenomenological perspectives

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DESY

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- Determination of the properties of the new state at $\sim 126\ \mathrm{GeV}$: present and future
- What does the signal at $\sim 126\ \mathrm{GeV}$ tell us?
- Where is the new physics that stabilises the gauge hierarchy?
- Conclusions

Determination of the properties of the new state at $\sim 126\ \mathrm{GeV}$: present and future

What do we know so far?

What can we find out in the future and how?

Determination of the properties of the state at $\sim 126\ \mathrm{GeV}$

Mass: statistical precision already remarkable with 2012 data

$\Rightarrow$ Need careful assessment of systematic effects
for $\gamma\gamma$ and ZZ^* channels,
e.g. interference of signal and background, . . .

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Spin can in principle be determined by discriminating between distinct hypotheses for spin 0, (1), 2

$\mathcal{CP}$ properties

$\mathcal{CP}$-properties: experimentally much more difficult than spin
Can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables investigated up to now ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

General structure of HVV coupling (from Lorentz invariance):

$$a_1(q_1, q_2)g^{\mu\nu} + a_2(q_1, q_2)\left[(q_1 q_2)\, g^{\mu\nu} - q_1^\mu q_2^\nu\right] + a_3(q_1, q_2)\epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

Pure $\mathcal{CP}$-even state: $a_1 = 1, a_2 = 0, a_3 = 0$,
Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

However, in most BSM models a_3 would be loop-induced and heavily suppressed $\Rightarrow$ Realistic models often predict $a_3 \ll a_1$

$\Rightarrow$ Observables involving HVV coupling provide only limited sensitivity to effects of a $\mathcal{CP}$-odd component

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$\Rightarrow$ Channels involving only Higgs couplings to fermions provide much higher sensitivity

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- The total Higgs width cannot be measured at the LHC without additional assumptions
  $\Rightarrow$ Can in general only determine ratios of couplings, not absolute coupling values

Higgs coupling determination at the LHC

Problem: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\mathrm{prod,\,decay}} \sim g^2_{\mathrm{prod,\,decay}}$):

$$\sigma(H) \times \mathrm{BR}(H \to a + b) \sim \frac{\Gamma_{\mathrm{prod}}\Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{tot}}},$$

Large uncertainty on dominant decay for light Higgs: $H \to b\bar{b}$

⇒ Without further assumtions, total Higgs width cannot be determined

⇒ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

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Deviations from the SM would in general change kinematic distributions

$\Rightarrow$ No simple rescaling of MC predictions possible

$\Rightarrow$ Not feasible for analysis of 2012 data set

$\Rightarrow$ LHC Higgs XS WG: Proposal of “interim framework”

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Assumptions:

- Signal corresponds to only one state, no overlapping resonances, etc.
- Zero-width approximation
- Only modifications of coupling strenghts (absolute values of the couplings) are considered, no modification of the tensor structure as compared to the SM case

  $\Rightarrow$ Assume that the observed state is a $\mathcal{CP}$-even scalar

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Use state-of-the-art predictions in the SM and rescale the predictions with "leading order inspired" scale factors κ_i ($\kappa_i = 1$ corresponds to the SM case)

Note: scaling of couplings is in general not possible if higher-order electroweak corrections are included

In the SM: Higgs sector is determined by single parameter M_{H} ($+$ higher-order contributions)

$\Rightarrow$ Once M_{H} is fixed the Higgs couplings are determined and cannot be varied within the SM

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Which kind of scaling factors should be considered?

In general, scale factors are needed for couplings of the new state to

t, b, τ, W, Z, $\ldots$

$+$ extra loop contribution to $\sigma(gg \to H)$, $\Gamma(H \to gg)$

$+$ extra loop contribution to $\Gamma(H \to \gamma\gamma)$

$+$ additional contributions to total width, Γ_H, from undetectable final states

Total width Γ_H cannot be measured without further assumptions (otherwise only coupling ratios can be determined, not absolute values of couplings)

Proposed "benchmarks" for scale factors κ_i

Different "benchmark" proposals, based on simplifying assumptions to reduce the number of free parameters

1 parameter: overall coupling strength μ

2 parameters: e.g. common scale factor κ_V for W, Z, and common scale factor for all fermions, κ_F

...

For each benchmark (except overall coupling strength) two versions are proposed:

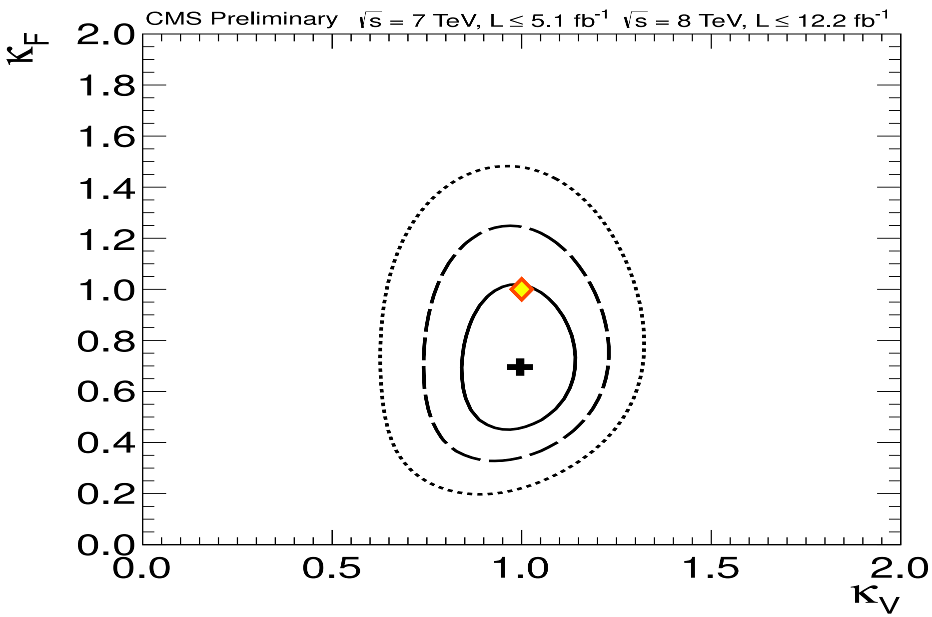
with and without taking into account the possibility of additional contributions to the total width

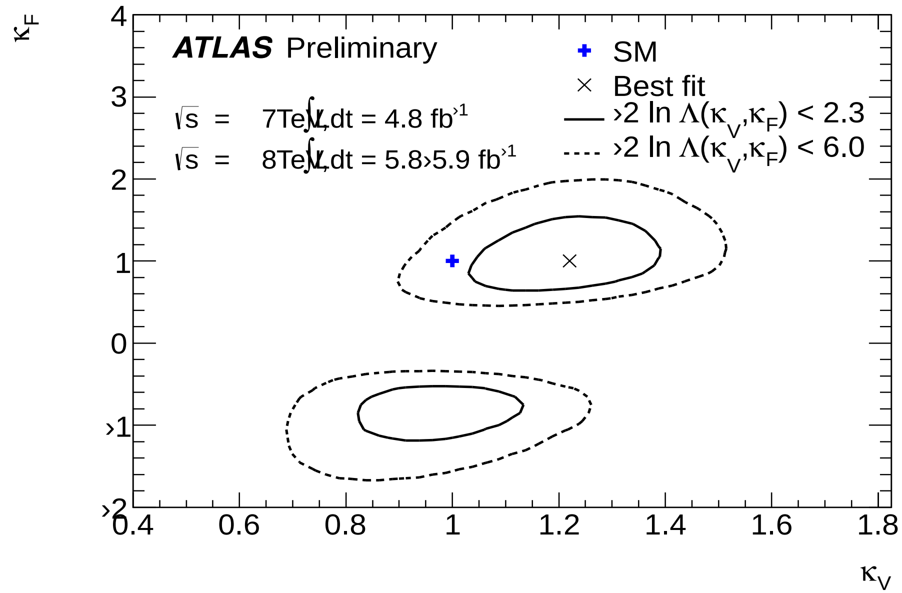
Proposed "benchmarks" for scale factors κ_i

If additional contributions to Γ_H are allowed
$\Rightarrow$ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

If no additional contributions to $\Gamma(H \to \gamma\gamma)$, Γ_H, . . . are allowed
$\Rightarrow$ κ_γ can be determined in terms of κ_b, κ_t, κ_τ, κ_W
evaluated to NLO QCD accuracy

Example: κ_V, κ_F analyses from CMS and ATLAS





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$\Rightarrow$ An analysis in terms of just κ_V and κ_F (or similar) would be much too restrictive in the future

$\Rightarrow$ It is not very useful to present projections for the HL–LHC in terms of κ_V and κ_F, more general approach needed

Complementary approach: model-specific Higgs phenomenology beyond the SM

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

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"

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Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”

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)
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Detection of a SM-like Higgs with $M_\mathrm{H} \gtrsim 135$ GeV would have unambiguously ruled out the MSSM, signal at ~ 126 GeV is well compatible with MSSM prediction

Future analyses: effective Lagrangian approach, obtained from integrating out heavy particles

Assumption: new physics appears only at a scale $\Lambda \gg M_{\mathrm{h}} \sim 126 \ \mathrm{GeV}$

Systematic approach: expansion in inverse powers of Λ; parametrises deviations of coupling strenghts and tensor structure

$$\Delta\mathcal{L} = \sum_i \frac{a_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{a_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \ldots$$

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$\Rightarrow$ Analyses in terms of SM $+$ effective Lagrangian and in specific BSM models: MSSM, . . . are complementary

What does the signal at $\sim 126\ \mathrm{GeV}$ ***tell us?***

Possible interpretations of the signal at $\sim 126\ \mathrm{GeV}$:

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Dilaton, . . .

$\Rightarrow$ In principle a possible option, but looks increasingly unlikely

One would also expect to see other signatures of the EWSB dynamics in such a case soon . . .

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$\Rightarrow$ A logical possibility, but this would mean that the gauge hierarchy, dark matter, matter–anti-matter asymmetry in the universe, . . . , would all have origins that are not directly related to low-scale physics

Option 2: Higgs boson of an extended Higgs sector in the decoupling limit

Signal at $\sim 126\ \mathrm{GeV}$ would correspond to the lightest Higgs state of an extended Higgs sector, all other Higgses heavy

Deviations from SM predictions for Higgs couplings are inversely proportional to the scale of the heavy Higgses

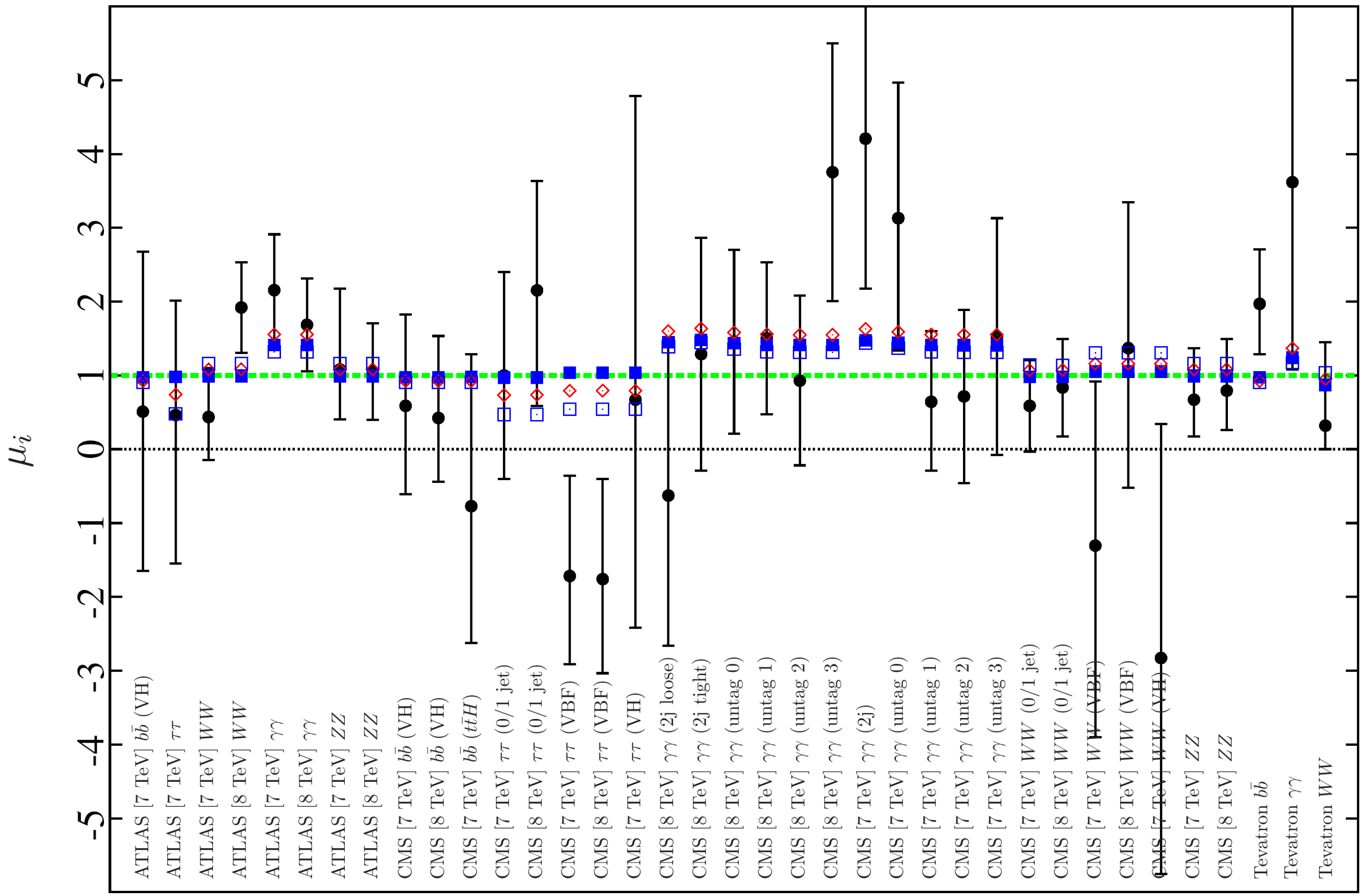
Example:

SUSY Higgs sector in the decoupling limit, $M_{\mathrm{A}} \gg M_{\mathrm{Z}}$

MSSM fit (pre HCP): comparison of SM with MSSM interpretation in terms of light Higgs h

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12]

- LHC / TeV. data, ■ full fit, ⊡ without TeV., ◇ without low. en. obs.



$\Rightarrow \chi^2$ reduced compared to SM case, better fit probability

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  Relation to weakly-coupled 5-dimensional model (AdS/CFT correspondence)

  Discrimination from fundamental scalar

  - Precision measurements of couplings ($\Rightarrow$ high sensitivity to compositeness scale), $\mathcal{CP}$ properties, . . .
    Does the new state have the right properties to unitarize $W_L W_L$ scattering?
  - Search for resonances
    (light Higgs $\Leftrightarrow$ light resonances?)
- . . .

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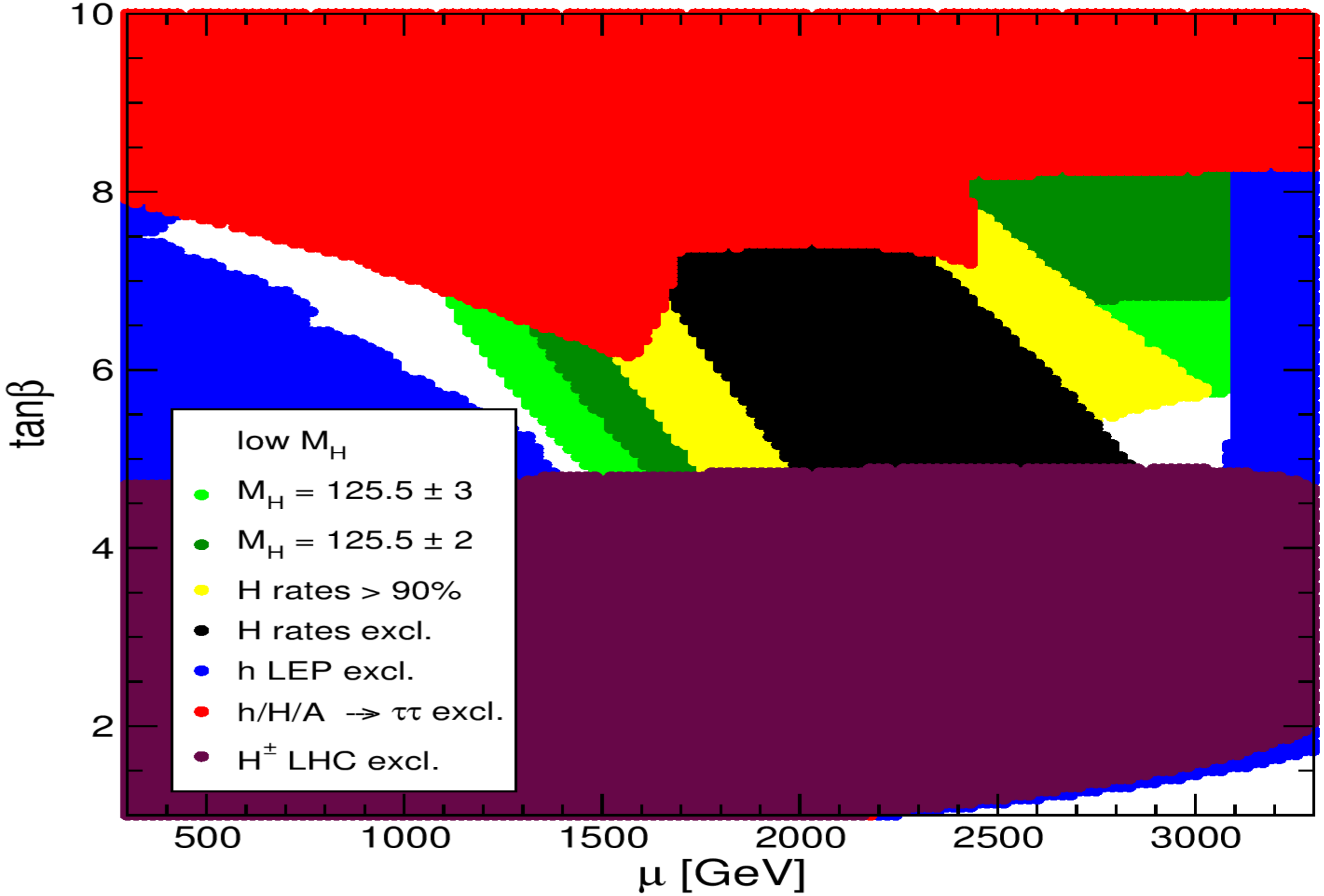
⇒ Observation of a SM-like signal at $\sim 126 \text{ GeV}$ provides a strong motivation to look for non SM-like Higgses elsewhere

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

Low M_H benchmark scenario of the MSSM: signal interpreted as heavy CP-even Higgs H

Approximate treatment of latest CMS limit included

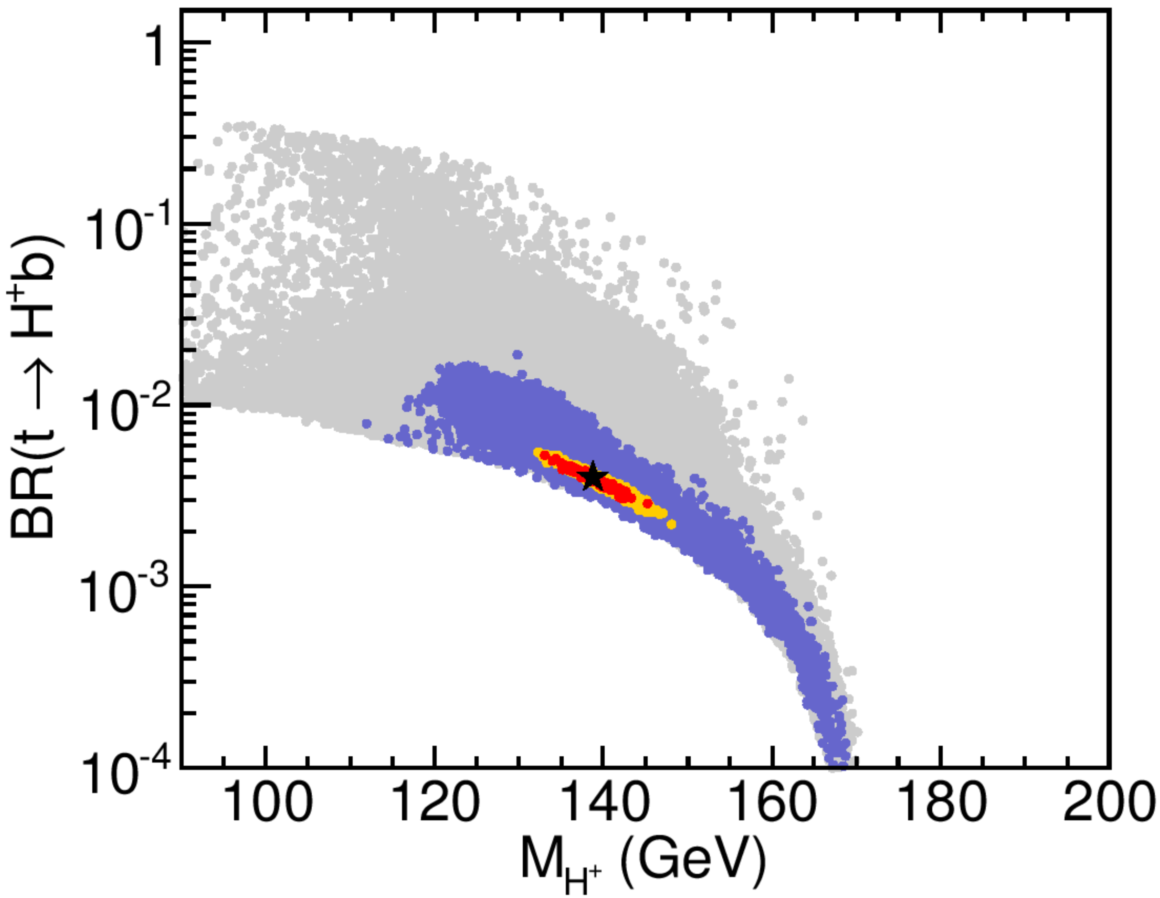
[*M. Carena, S. Heinemeyer, O. Stål, C. Wagner, G. W. '13*]



$\Rightarrow$ Rich phenomenology: all five MSSM Higgs bosons are light

MSSM interpretation in terms of heavy Higgs H: preferred values for $M_{\mathrm{H}^\pm}$ and $\mathrm{BR}(t \to H^+ b)$

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12]



⇒ MSSM interpretation in terms of heavy Higgs H can be probed by charged Higgs searches

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- ILC:
  - Pair production, e.g. SUSY case: $e^+e^- \to hA$ ($+\ t\bar{t}h$ production, . . .)

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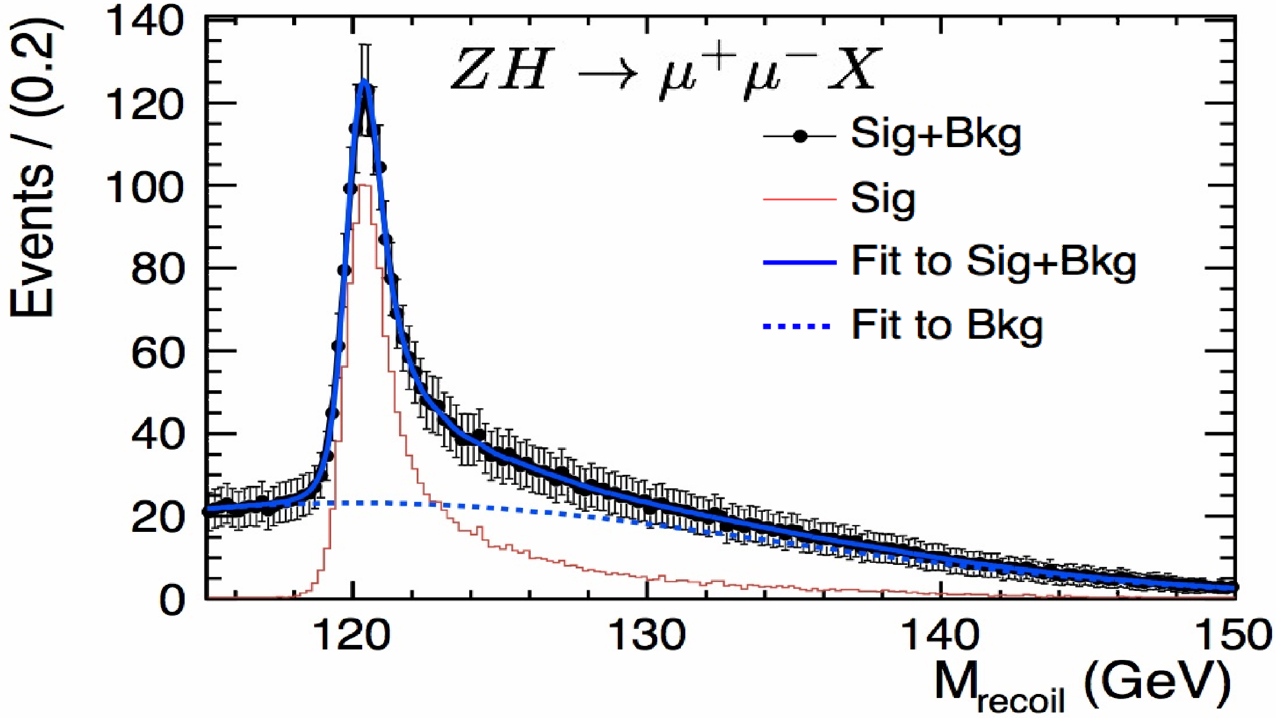
ILC ("Higgs factory") measurements will be crucial for distinguishing between options 0, 1, 2, 3, 4:

- High-precision measurements of couplings to gauge bosons and fermions and of total width without theoretical assumptions
- Decay-mode independent measurement using "recoil" against the Z
  $\Rightarrow$ Absolute measurement of couplings and total Higgs width, model-independent
- Higgs self-coupling $\Leftrightarrow$ experimental access to Higgs potential
- ...

ILC: high-precision measurements of Higgs properties

"Recoil" method: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$ [*R. Poeschl et al. '12*]

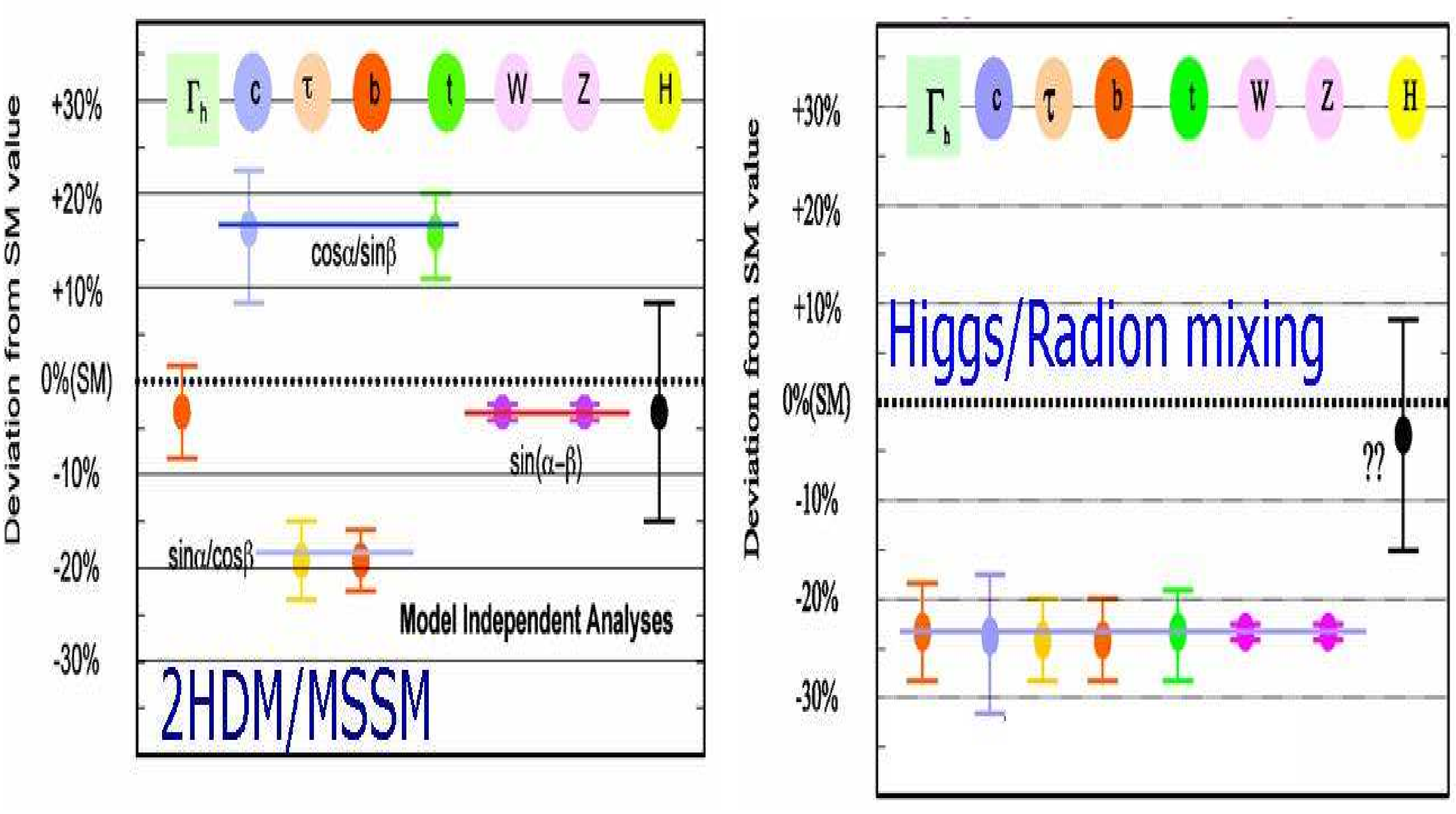


Measurement of mass, couplings, $\mathcal{CP}$ properties, self-coupling, ... + high sensitivity to additional Higgses

$\Rightarrow$ Identification of the underlying nature of electroweak symmetry breaking

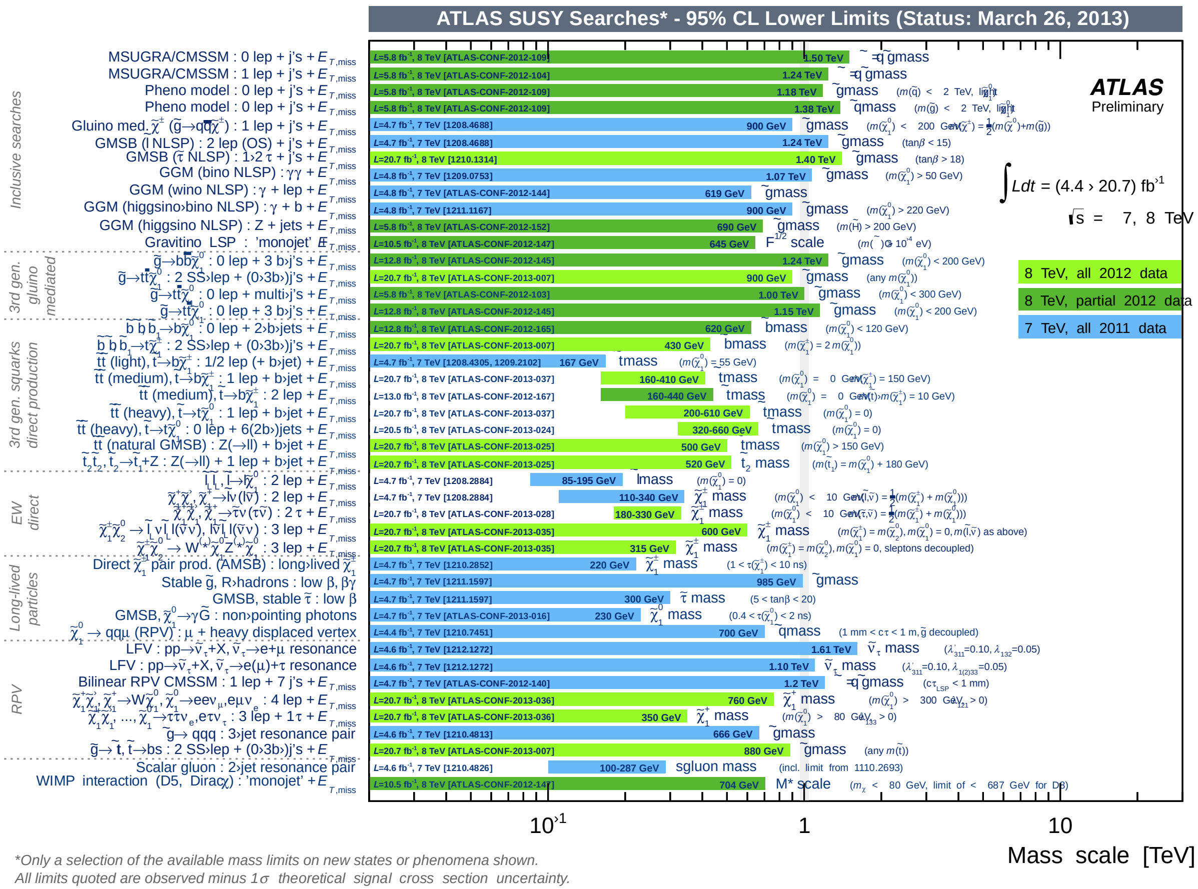
The quest for identifying the underlying physics

Discrimination between different kinds of underlying physics via precision measurements of Higgs couplings



Where is the new physics that stabilises the gauge hierarchy?

Large number of searches, many limits, . . . *[ATLAS Collaboration '13]*



Interpretation in specific scenarios, e.g. CMSSM, and in "simplified models"

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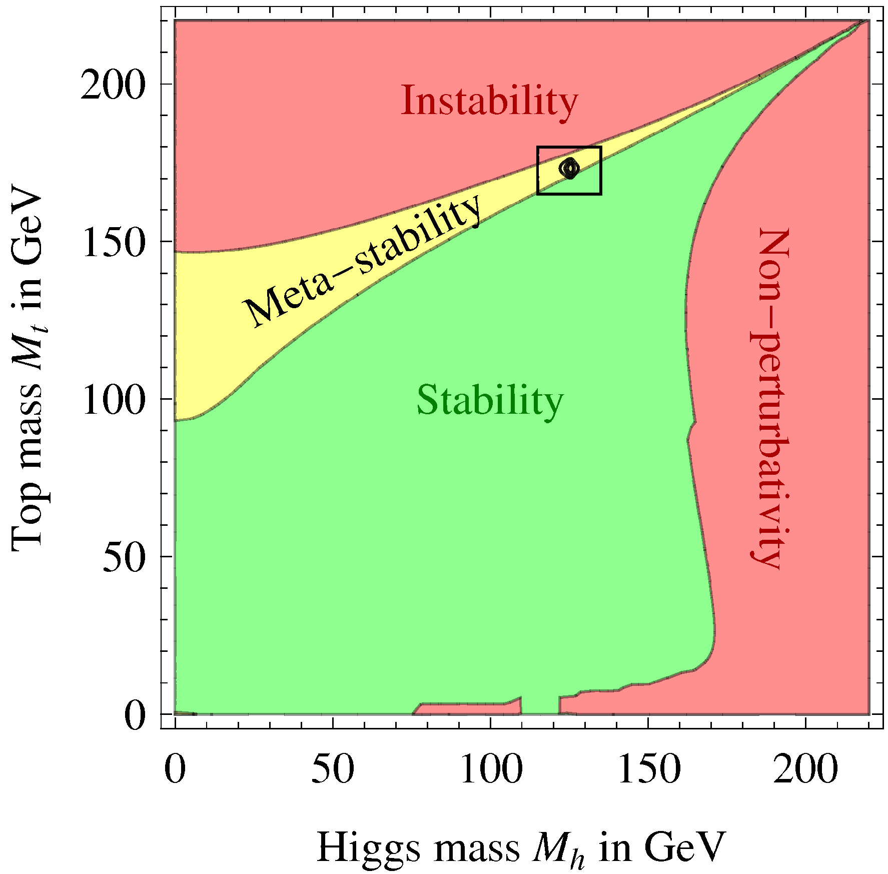
Do we live in a metastable vacuum?

[*G. Degrassi et al. ’12*]



The hierarchy problem: SM Higgs mass is affected by large corrections ($\sim \Lambda^2$) from physics at high scales

Now that a Higgs-like state with a mass of ~ 126 GeV has been discovered, the question what protects its mass from physics at high scale becomes even more pressing

"Hierarchy problem": $M_{\text{Planck}}/M_{\text{weak}} \approx 10^{17}$

How can two so different scales coexist in nature?

Via quantum effects: physics at M_{weak} is affected by physics at M_{Planck} $\Rightarrow$ Instability of M_{weak}, would imply that all physics is driven up to the Planck scale

$\Rightarrow$ Expect new physics to stabilise the hierarchy

E.g. SUSY: Large corrections cancel out because of symmetry fermions $\Leftrightarrow$ bosons

What has actually been excluded?
Let's consider the old SPS 1a benchmark point

A look back to the pre–LHC days:

Global fits in constrained SUSY models (CMSSM, . . .):

Best fit point was close to SPS 1a (LM1, . . .) benchmark point:

Low scale SUSY point

$\Rightarrow$ "plain vanilla" SUSY

$\Rightarrow$ "best case scenario" for LHC and LC

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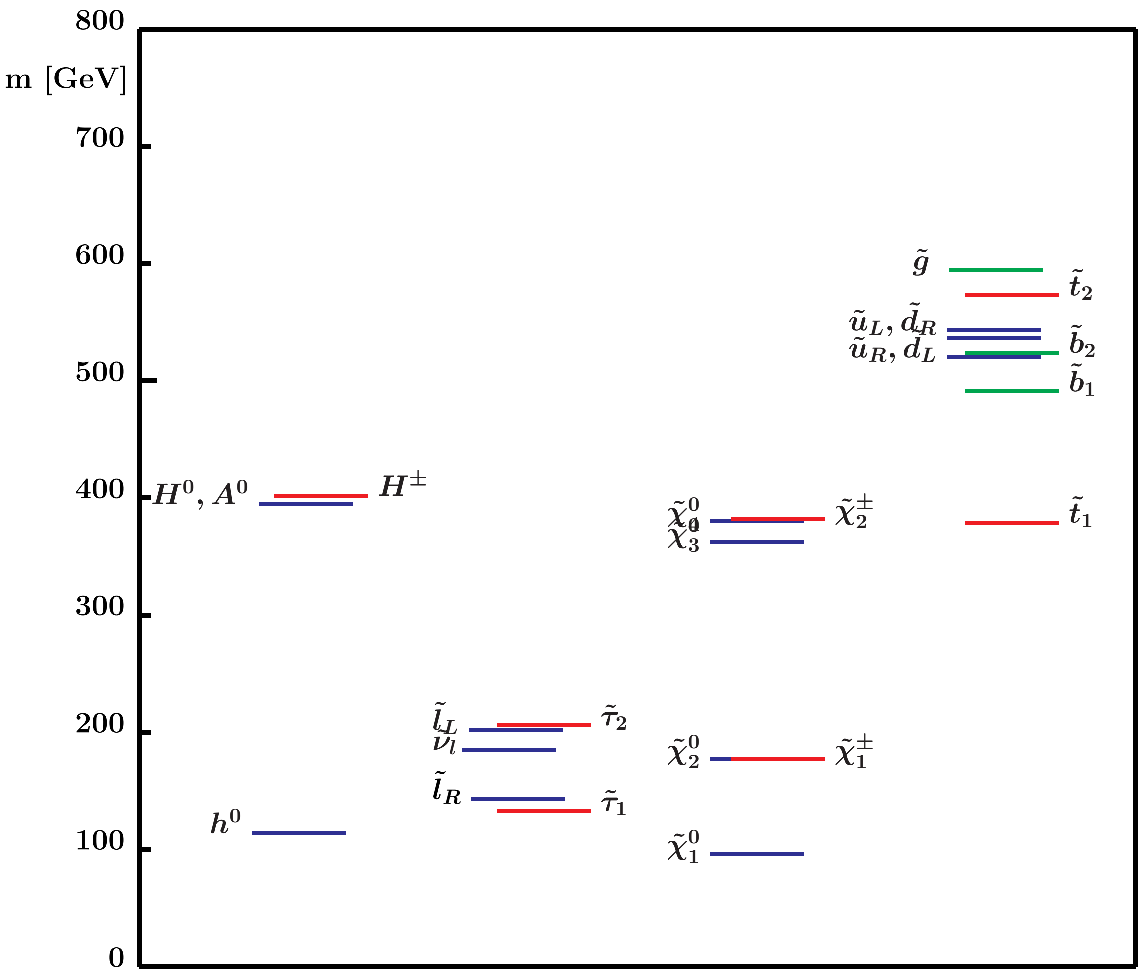
Preference for light SUSY scale was mainly driven by $(g-2)_\mu$

⇒ light $\tilde{e}$, $\tilde{\mu}$, $\tilde{\chi}$, . . . : light electroweak SUSY particles

Particle spectrum of the SPS 1a benchmark point



⇒ all SUSY masses below 600 GeV

⇒ “plain vanilla” SUSY at its best

My favourite question to ATLAS and CMS SUSY hunters

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Question:

Is it possible to exclude such a scenario with the present data

- from direct production of third generation squarks?
- from direct production of electroweak SUSY particles?

Sensitivity to effects of new physics from high-precision measurements at the ILC

- Measurements in the Higgs sector
- Top physics
- Electroweak precision observables ($\sin^2\theta_{\rm eff}$, $M_{\rm W}$, ...)

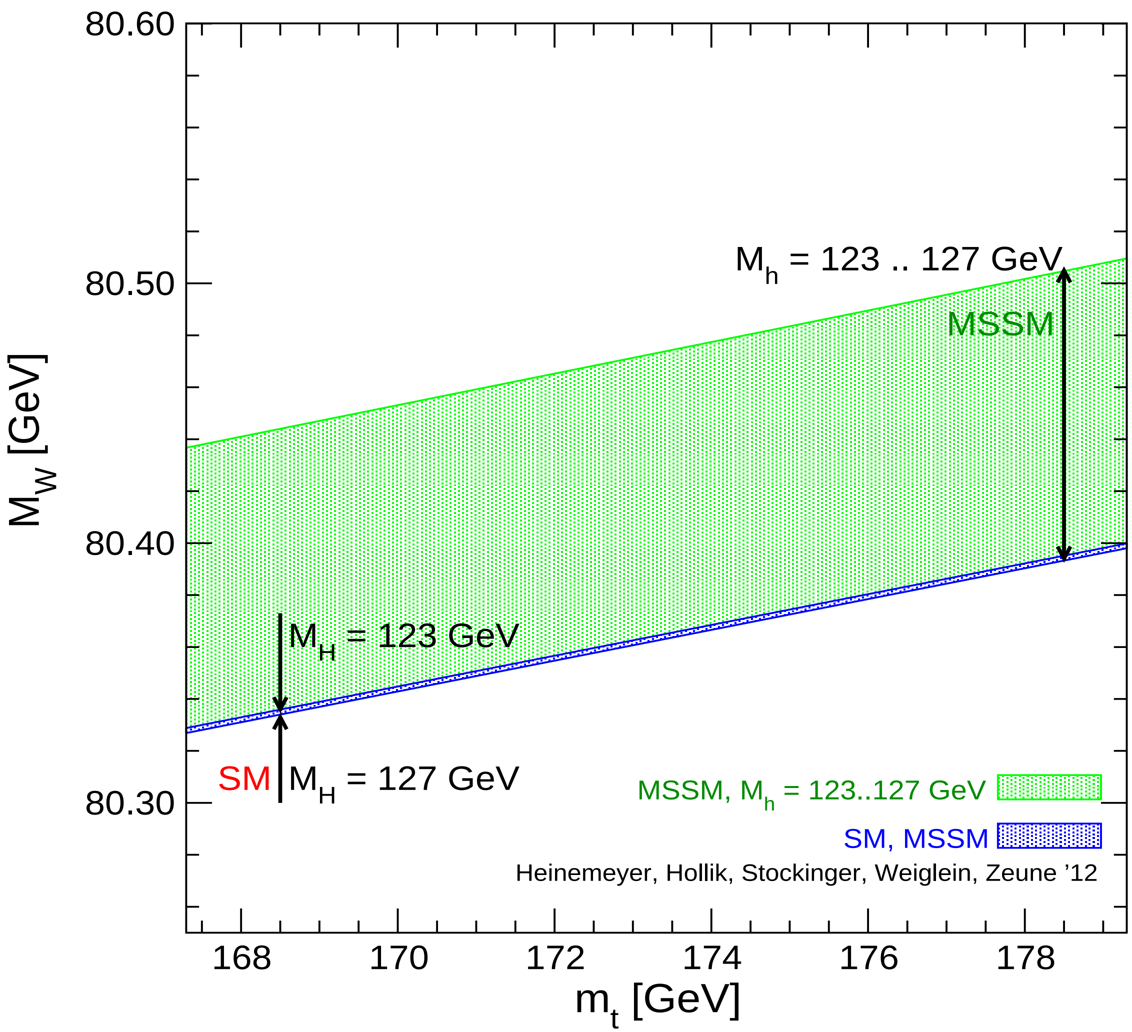
Example: $M_{\rm W}$–$m_{\rm t}$ correlation

ILC:

- High-precision measurement of $m_{\rm t}$, relation between measured quantity and theoretically well-defined parameter is known with sufficient accuracy
- Precise measurement of $M_{\rm W}$ (continuum and WW threshold)

Example: prediction for M_W (parameter scan), SM vs. MSSM (signal interpreted as light CP-even Higgs, h)

Prediction for M_W in the SM and the MSSM:



[S. Heinemeyer, W. Hollik, D. Stöckinger, G. W., L. Zeune '12]

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SM: M_H varied

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

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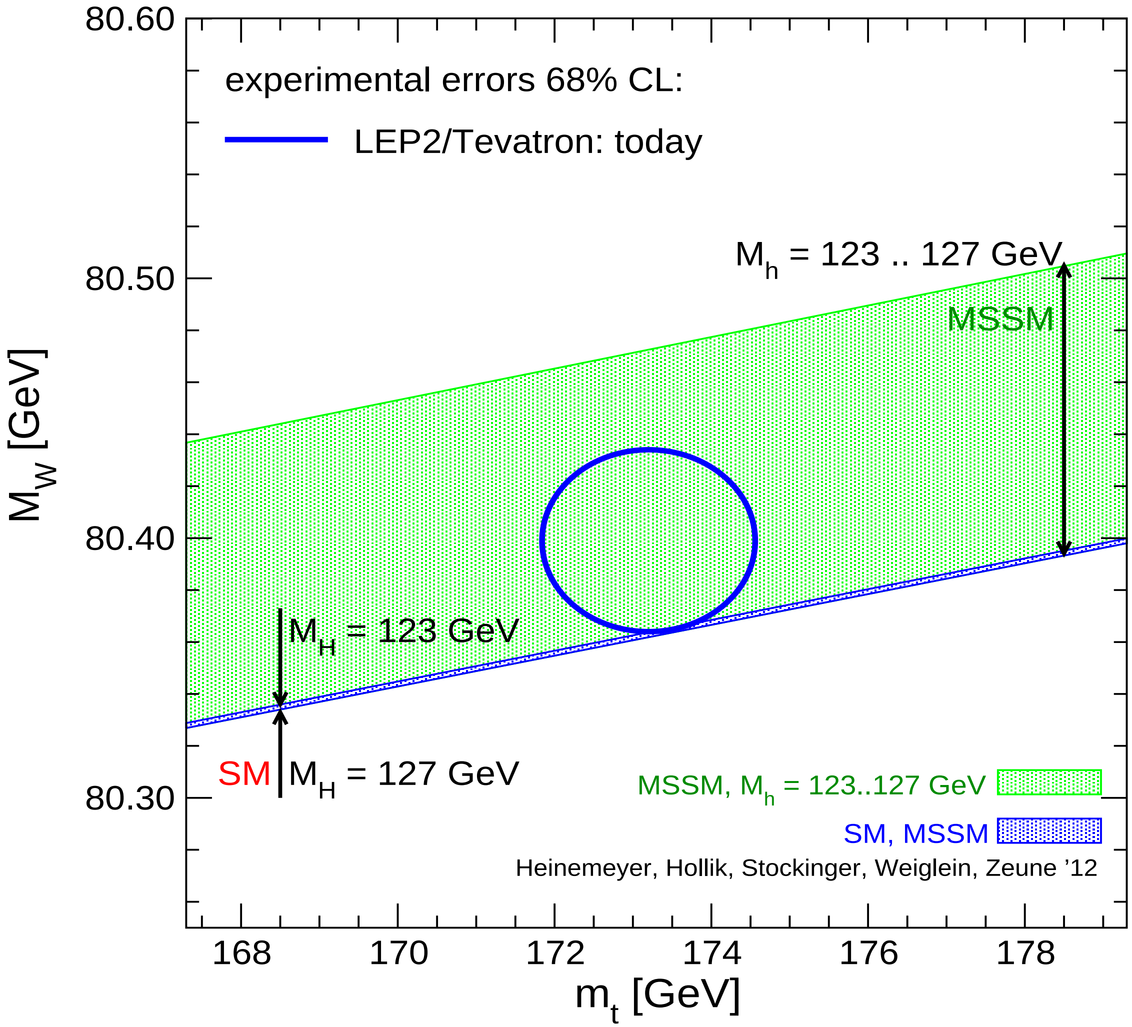

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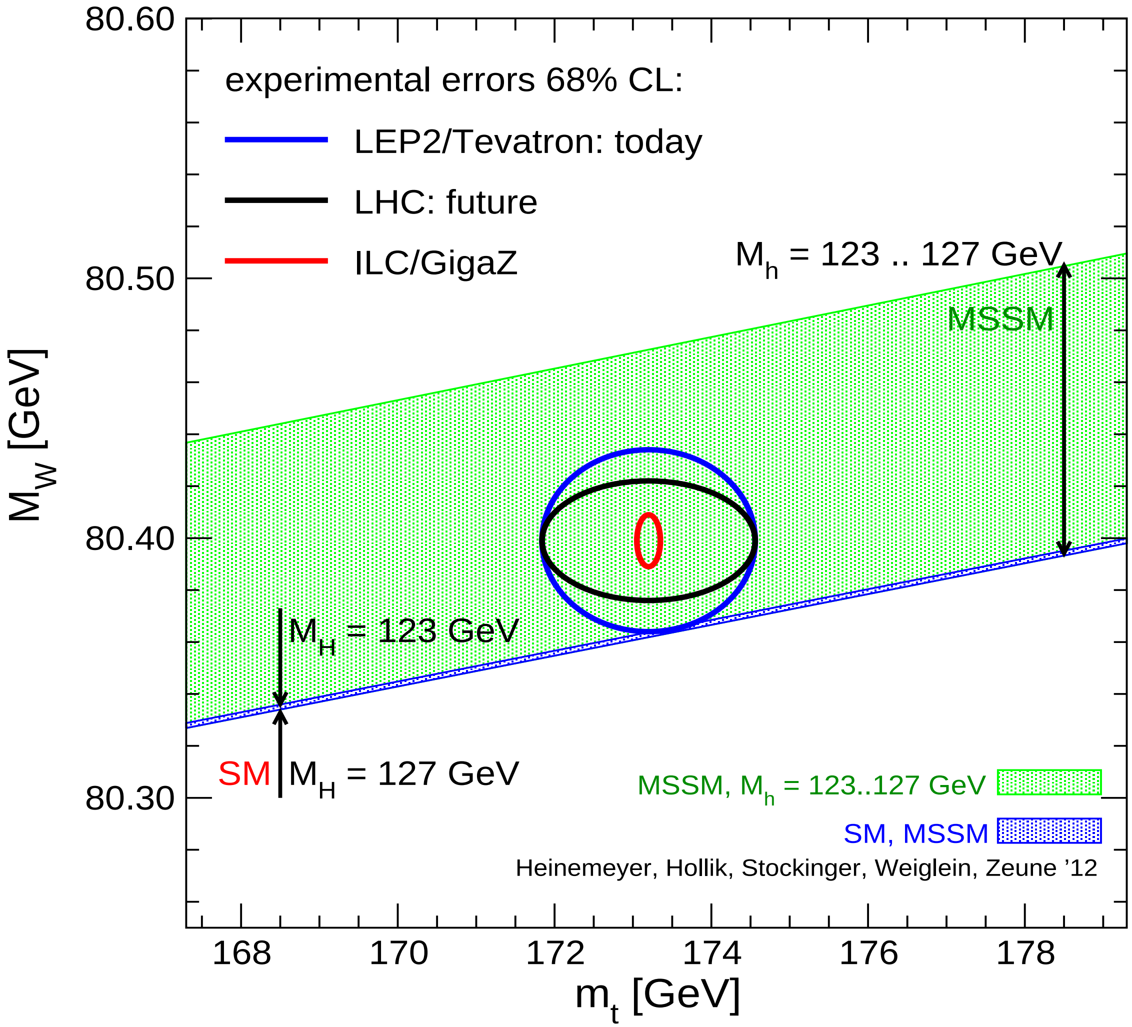

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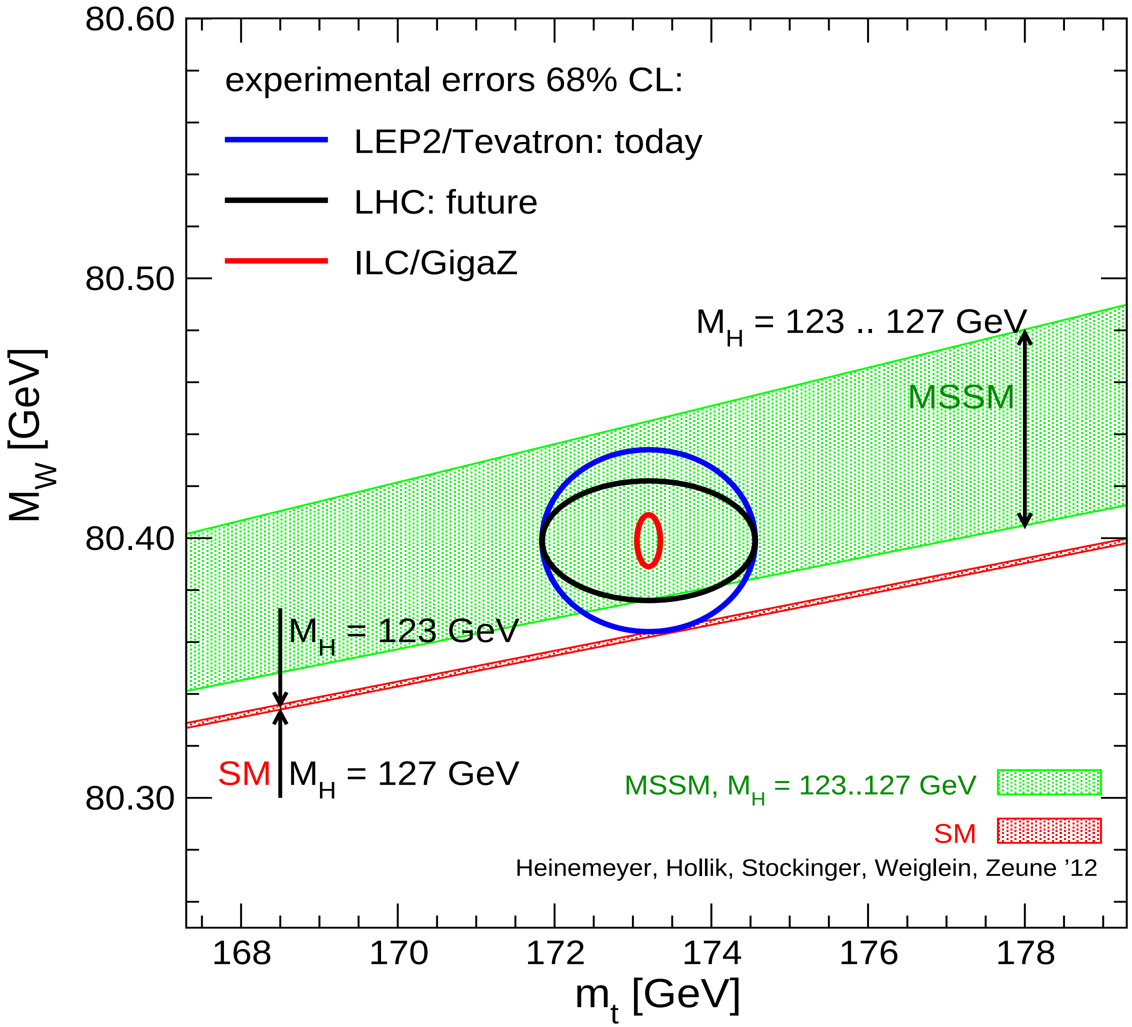

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$\Rightarrow$ High sensitivity to possible effects of new physics

Conclusions

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- Precision measurements provide high indirect sensitivity for effects of new physics