WP1 Status and Visions - Theory

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First Annual Meeting of ITN HiggsTools
Freiburg, 04 / 2015

Work package WP1: interpretation of data

Data: Measurements of the signal + limits from searches

The discovered signal is so far compatible with a SM-like Higgs, but variety of interpretations possible ⇔ very different underlying physics

Tasks:

- Extraction of model-independent results from data
- Measurement of Higgs properties
- Interpretation of experimental results in different models
- Future European strategy for particle physics

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In fact: from what we know so far, we cannot understand how a Higgs boson could be as light as the one that was discovered
The mass should be affected by physics at high energy scales (e.g. Planck scale, 10^{19} GeV, where gravity is of similar strength as the other interactions)
⇒The mass should have been driven up to high scales

How can a Higgs boson be as light as 125 GeV?

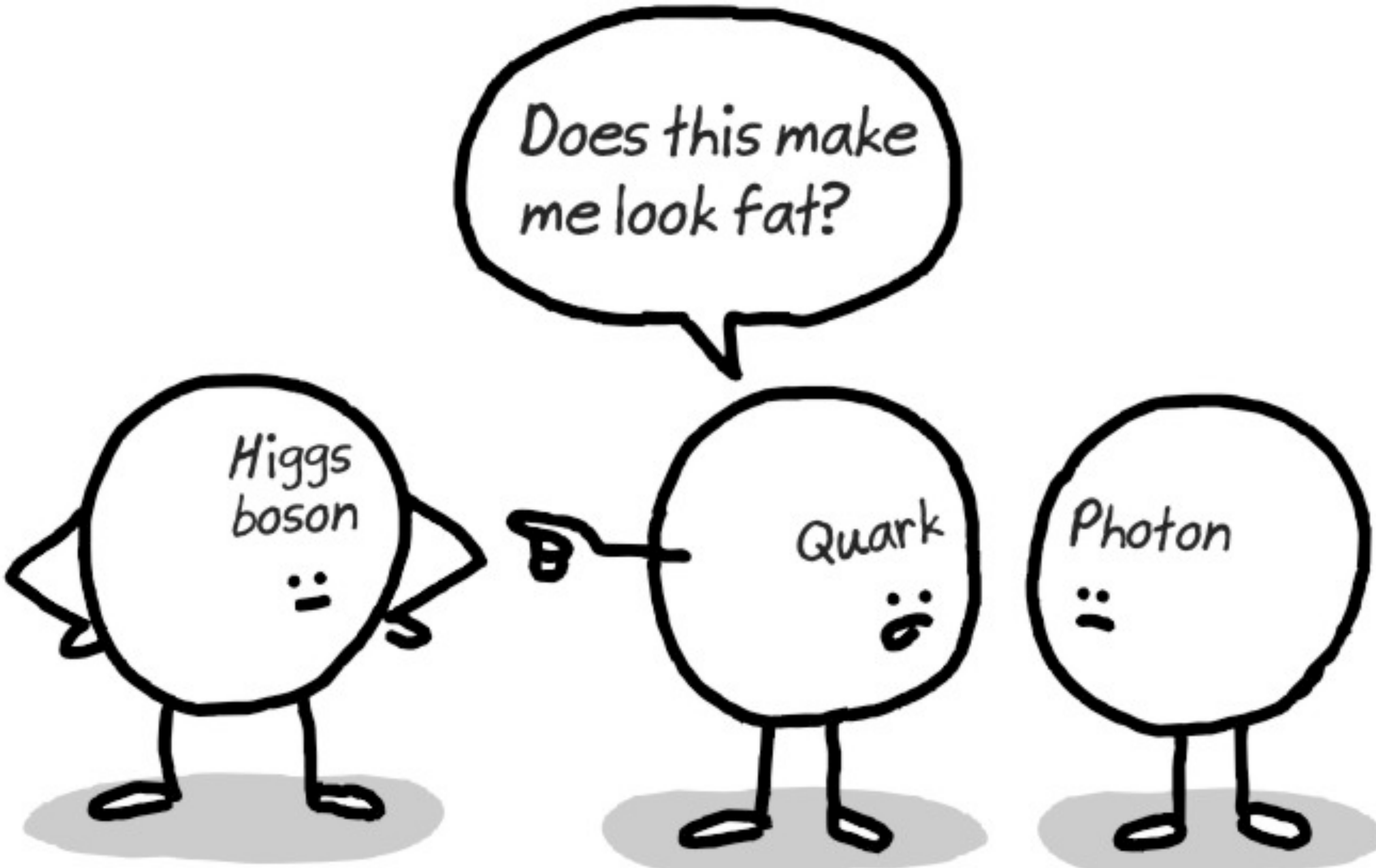
- A new symmetry of nature $\longrightarrow$ Supersymmetry?
- A new fundamental interaction of nature $\longrightarrow$ composite Higgs?
- Extra dimensions of space $\longrightarrow$ impact on gravity on small scales?
- Multiverses $\longrightarrow$ anthropic principle?

What is the quantum structure of the universe?

Higgs particle provides access to the non-trivial structure of the vacuum

$\Rightarrow$ Answers to those questions are among the prime goals of the upcoming runs of the LHC and a future e^+e^- collider

Higgs physics: what do we want to know?



Higgs physics: what do we want to know?

- What is the underlying nature of the observed signal and which role does it play in the physics of electroweak symmetry breaking?
  Fundamental / composite? Extended Higgs sector? ...

- Are there additional Higgs states?
  Could be heavier but also lighter than the state at 125 GeV

- Does the observed state unitarise WW scattering?
  Are there signs of a new strong interaction? Resonances? ...

- Higgs self-coupling: the ``holy grail" of Higgs physics
  Quantum structure of the vacuum? ...

- Does the observed signal provide access to further new physics?
  Decay into a pair of dark matter particles? ...

Higgs physics: how do we find out?

- High-precision studies of the properties of the observed signal
- Search for additional Higgs states above but also below 125 GeV
- Test unitarisation in different processes
- Explore Higgs self-coupling in different ways: different processes have different sensitivities to new physics, H → h(125) h(125), ...
- Explore interplay of Higgs physics and other new physics: h(125) as a final state in new physics processes, h(125) → $\chi\chi$, ...
- ...

Extended Higgs sectors: possible deviations from the Standard Model

SUSY as a test case: well motivated, theory predictions have been worked out to high level of sophistication

"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

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

$\Rightarrow$ Upper bound on lightest Higgs mass, M_h:

Lowest order: $M_h \leq M_Z$

Including higher-order corrections: $M_h \lesssim 135\,\text{GeV}$
(for TeV-scale stop masses)

Interpretation of the signal at 125 GeV within the MSSM?

Interpretation of the signal in extended Higgs sectors (SUSY), case I: signal interpreted as light state h

- Most obvious interpretation: signal at about 125 GeV is interpreted as the lightest Higgs state h in the spectrum

- Additional Higgs states at higher masses

- Differences from the Standard Model (SM) could be detected via:

  - properties of h(125): deviations in the couplings, different decay modes, different CP properties, ...

  - detection of additional Higgs states: $H, A \to \tau\tau$, $H \to hh$, $H, A \to \chi\chi$, ...

Interpretation of the signal in terms of the light MSSM Higgs boson

- Detection of a SM-like Higgs with $M_H > 135$ GeV would have unambiguously ruled out the MSSM (with TeV-scale masses)

- Signal at 125 GeV is well compatible with MSSM prediction

- Observed mass value of the signal gives rise to lower bound on the mass of the CP-odd Higgs: $M_A > 200 \text{ GeV}$

- $\Rightarrow M_A \gg M_Z$: ``Decoupling region" of the MSSM, where the light Higgs h behaves SM-like

- $\Rightarrow$ Would not expect observable deviations from the SM at the present level of accuracy

The quest for identifying the underlying physics

In general SUSY / 2HDM-type models one expects % level deviations from the SM couplings for BSM particles in the TeV range, e.g.

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \text{GeV}}{m_A}\right)^4$$

$$\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2 .$$

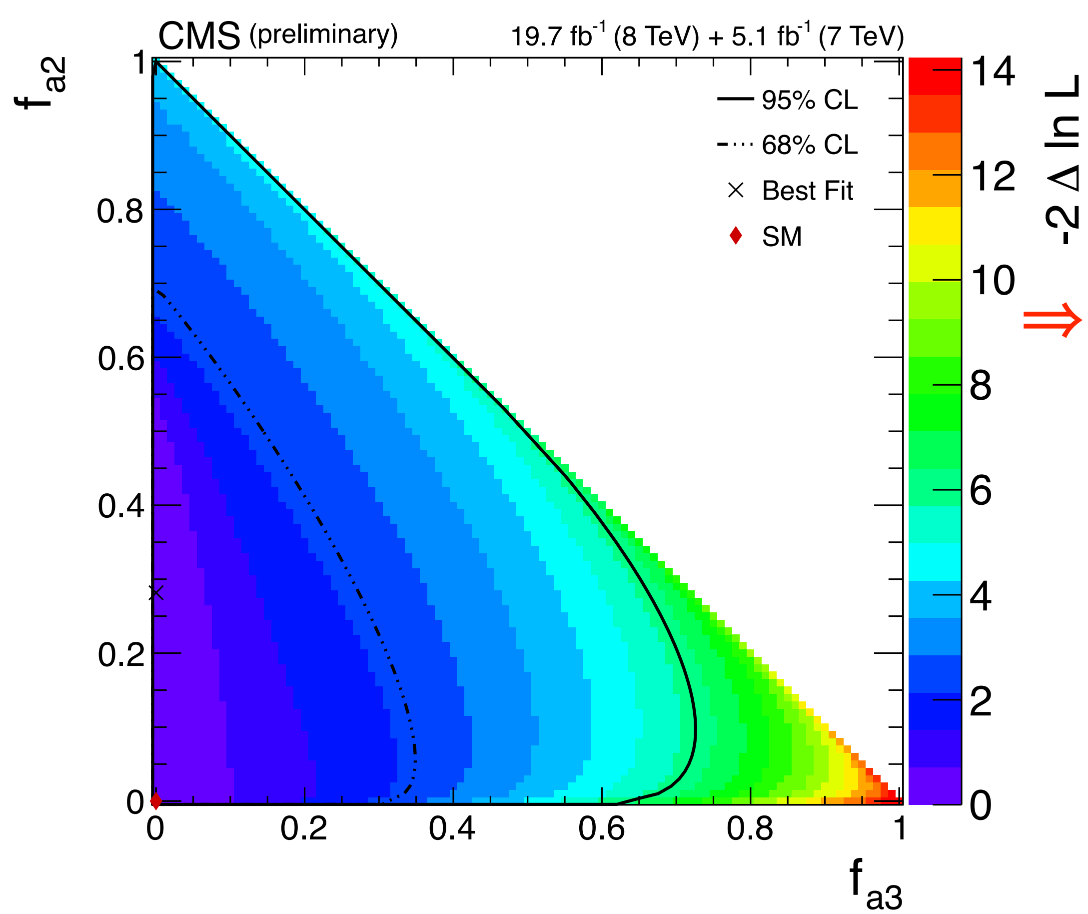
⇒ Need very high precision for the couplings

Precision studies of the detected signal

CP properties: compatible with pure CP-even state (SM case), pure CP-odd state excluded, only very weak bounds so far on an admixture of CP-even and CP-odd components

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3}$$

[CMS Collaboration '14]



Loop suppression of a_3 in many BSM models

⇒ Even a rather large CP-admixture would result in only a very small effect in f_{a3}!

⇒ Extremely high precision in f_{a3} needed to probe possible deviations from the SM

The Snowmass report sets as a target that should be achieved for f_{a3} an accuracy of better than 10^{-5}!

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 ($\Gamma_{\text{prod, decay}} \sim g^2_{\text{prod, decay}}$):

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

Total Higgs width cannot be determined without further assumptions

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

Determination of couplings and CP properties need to be addressed together

Deviations from the SM: in general both the absolute value of the couplings and the tensor structure of the couplings (affects $\mathcal{CP}$ properties) will change

$\Rightarrow$ Determination of couplings and determination of $\mathcal{CP}$ properties can in general not be treated separately from each other

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”

``Interim framework” for analyses so far

Simplified framework for analysis of LHC data so far; deviations from SM parametrised by ``scale factors” $\varkappa_i$.

Assumptions:

- Signal corresponds to only one state, no overlapping resonances, etc.
- Zero-width approximation
- Only modifications of coupling strengths (absolute values of the couplings) are considered

⇒ Assume that the observed state is a CP-even scalar

Beyond the $\varkappa$ framework

Goal: Find the best interface where experiment and theory can meet

- Effective Lagrangian approach, obtained from integrating out heavy particles

  Assumption: new physics appears only at a scale $\Lambda >> M_H$

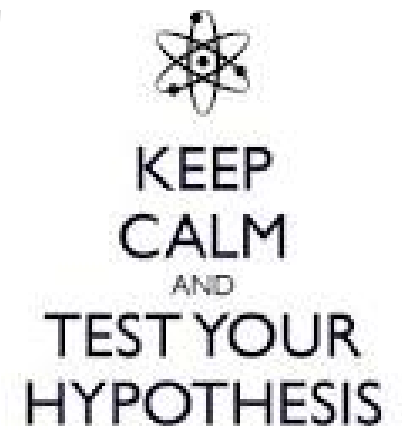
  Systematic approach, expansion in inverse powers of Λ; parametrises deviations of coupling strengths and tensor structure

  Possibility that some BSM particles could be light is not included $\Rightarrow$ analysis in specific models needed

Effective Lagrangian approach

Assumptions:

[G. Passarino '14]



✗ one Higgs doublet (flexible)
✗ linear realization (flexible)
✗ no *light dof* + *decoupling (rigid)*
✗ UVC weakly-coupled and ren. (flexible)
✗ Neglecting $\mathbf{dim} = \mathbf{8}$ and NNLO EW $\mapsto$
3 *TeV* $< \Lambda <$ **5 *TeV***

⇒ Limited range of validity

Pseudo-observables

- Worked very well at LEP
- Much more involved at the LHC
  - To which extent is unfolding possible?
  - Which pseudo-observables, which assumptions?
  - ...
- Masses and couplings are pseudo-observables
  Model dependence of masses is relatively small, model dependence of couplings is relatively large

Also needed besides quantities that try to incorporate information from several channels

- Signal strengths and limits on σ x BR for individual channels
  - Both extrapolated to full solid angle
  - Fiducial cross sections
- ...

Tools for testing theoretical models against the results from Higgs physics (signal + limits)

- *HiggsBounds [P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, K. Williams '08, '12, '13]*

- *HiggsSignals [P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein '13]*

- *Lilith [J. Bernon, B. Dumont '15]*

- *...*

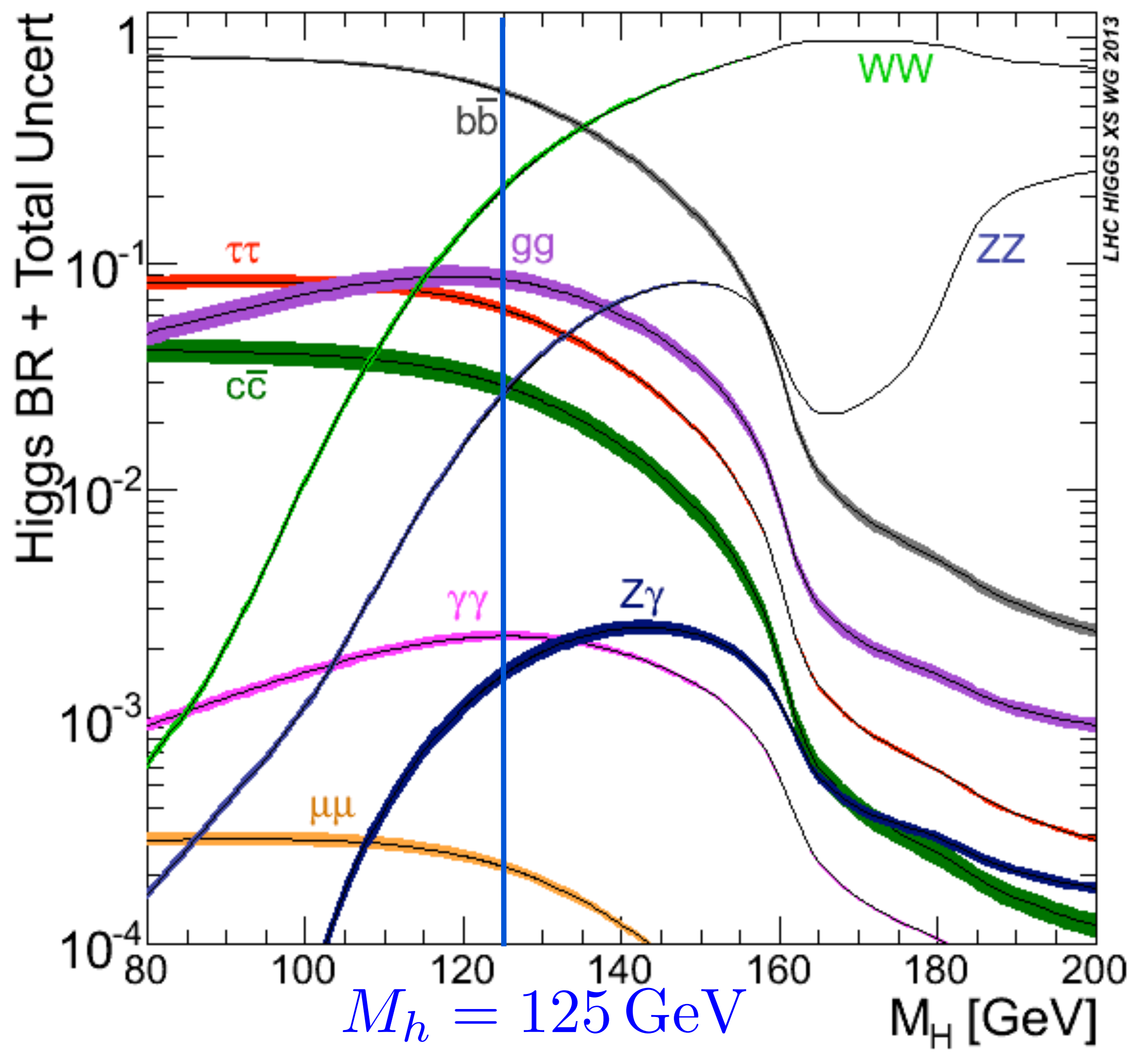
Can the implementation of experimental results be made more systematic / standardised?

Can we do better?

Additional source of information: off-shell effects

Reason for importance of off-shell effects (and high sensitivity to Higgs mass value) for BR($H \to ZZ^*$), BR($H \to WW^*$):

SM Higgs branching fractions:



[LHC Higgs XS WG '14]

For a 125 GeV Higgs boson the branching ratios into BR($H \to ZZ^*$), BR($H \to WW^*$) are far below threshold

⇒ Strong phase-space suppression, steep rise with M_H

Total Higgs width: recent analyses from CMS and ATLAS

- Exploit different dependence of on-peak and off-peak contributions on the total width in Higgs decays to $ZZ^{(*)}$

- CMS quote an upper bound of $\Gamma/\Gamma_{\mathrm{SM}} < 5.4$ at 95% C.L., where 8.0 was expected, ATLAS: $\Gamma/\Gamma_{\mathrm{SM}} < 5.7$ at 95% C.L., 8.5 expect.
  [CMS Collaboration '14] *[ATLAS Collaboration '14]*

- Problem: equality of on-shell and far off-shell couplings assumed; relation can be severely affected by new physics contributions, in particular via threshold effects (note: effects of this kind may be needed to give rise to a Higgs-boson width that differs from the SM one by the currently probed amount)
  [C. Englert, M. Spannowsky '14]

$\Rightarrow$ SM consistency test rather than model-independent bound

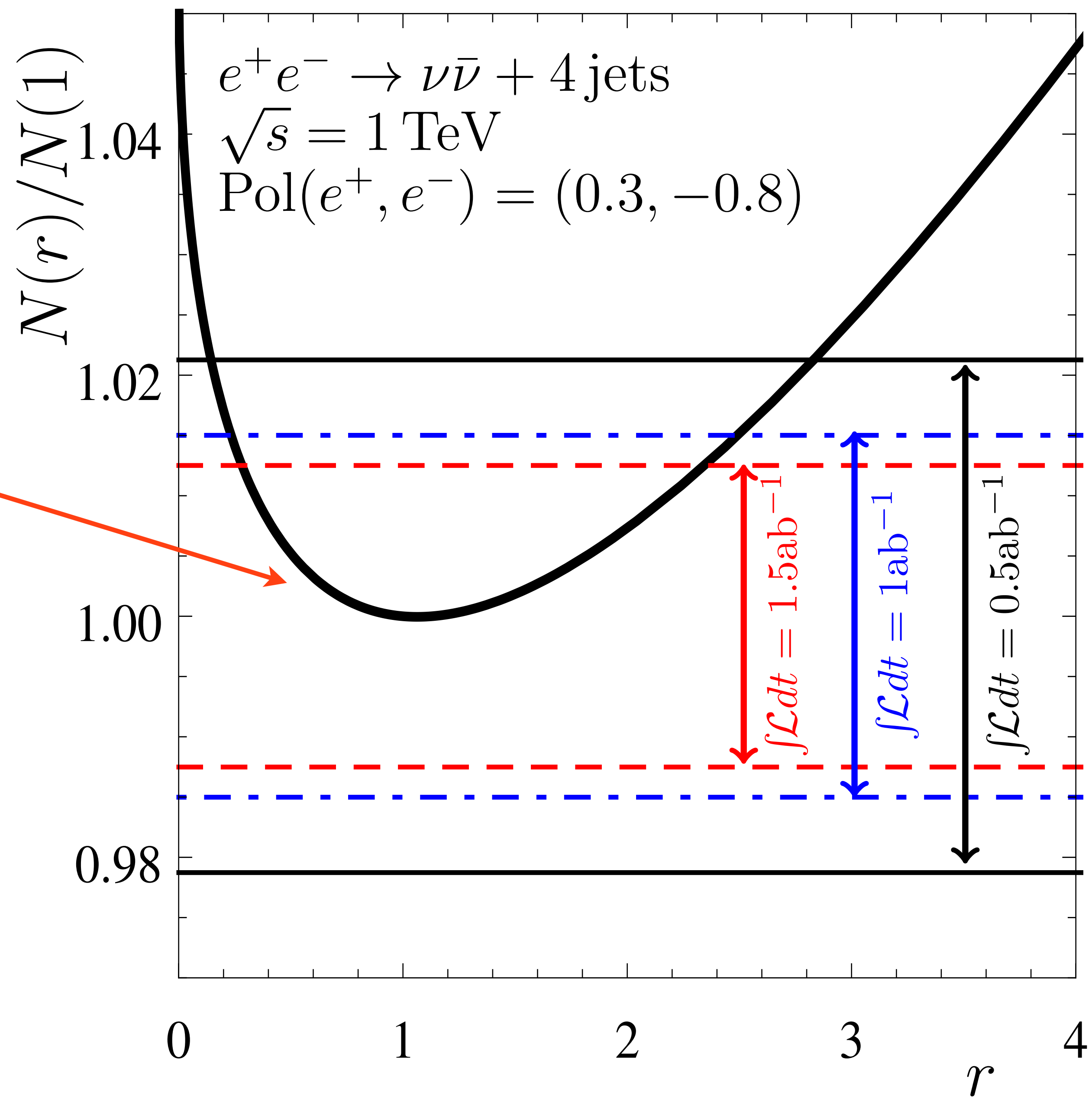
Destructive interference between Higgs- and gauge-boson contributions (unitarity cancellations) $\Rightarrow$ difficult to reach $\Gamma/\Gamma_{\mathrm{SM}} \approx 1$ even for high statistics

Constraints on the total width via off-shell effects

[S. Liebler, G. Moortgat-Pick, G. W. '15]

Large negative signal - background interference

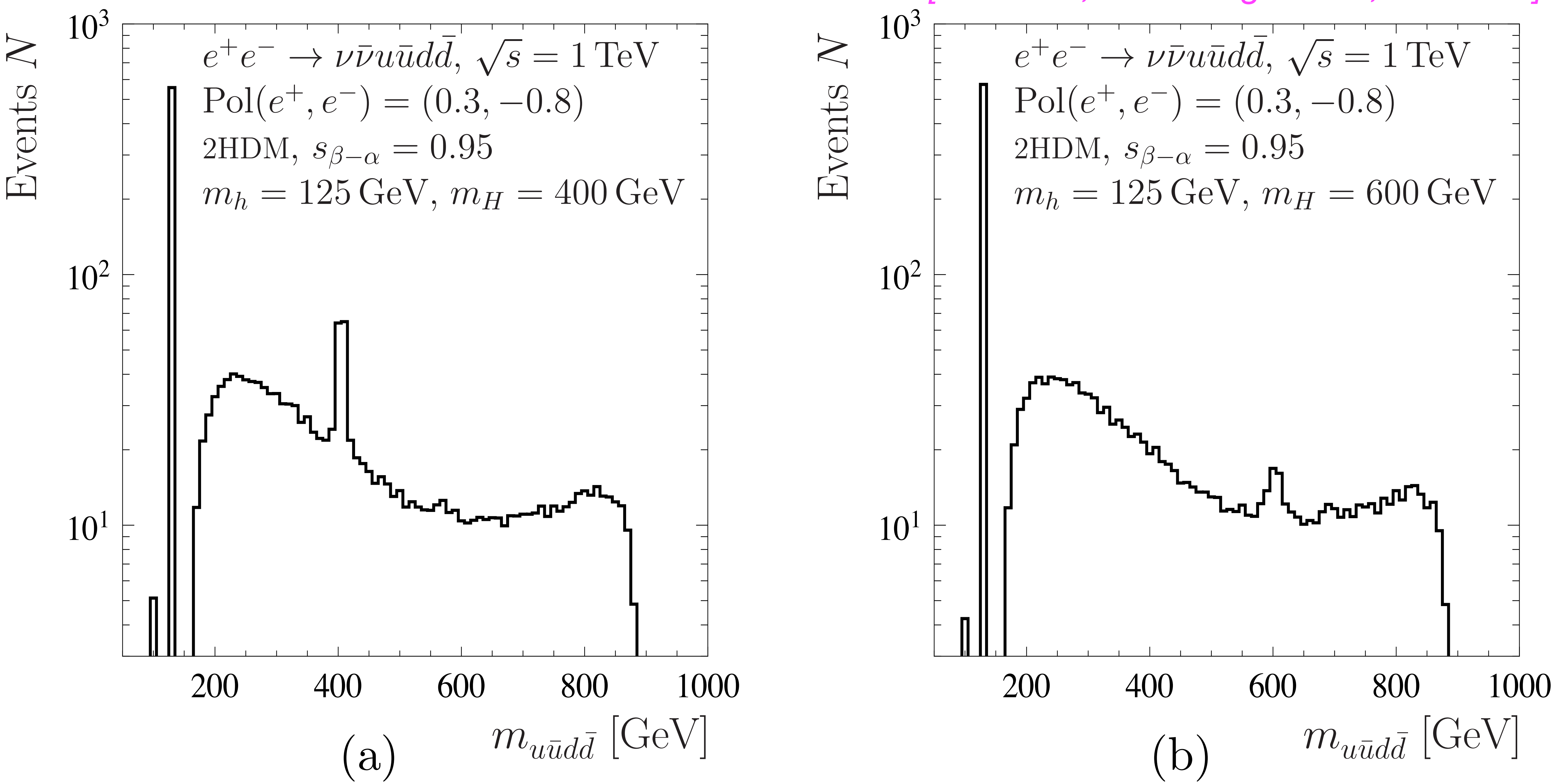
$$N(r) = N_0(1 + R_1\sqrt{r} + R_2 r)$$



⇒ Limited sensitivity even with high integrated luminosity

Sensitivity to a small signal via signal - background interference; example: heavy Higgs at ILC

[S. Liebler, G. Moortgat-Pick, G. W. '15]



$\Rightarrow$ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

Search for additional Higgs bosons

In a large variety of models with extended Higgs sectors the squared couplings to gauge bosons fulfill a ``sum rule”:

$$\sum_i g^2_{H_i VV} = \left(g^{\rm SM}_{HVV}\right)^2$$

$\Rightarrow$ •The SM coupling strength is ``shared” between the Higgses of an extended Higgs sector

•$\varkappa_V \leqq 1$

•The more SM-like the couplings of the state at 125 GeV turn out to be, the more suppressed are the couplings of the other Higgses to gauge bosons

•Heavy Higgses have a much smaller width than a SM-like Higgs of the same mass

Search for non-standard heavy Higgses

"Typical" features of extended Higgs sectors:

- A light Higgs with SM-like properties, couples with about SM-strength to gauge bosons
- Heavy Higgs states that decouple from the gauge bosons

⇒ • A signal could show up in $H \to ZZ \to 4\,l$ as a small bump, very far below the expectation for a SM-like Higgs (and with a much smaller width)

• Particularly important search channel: $H, A \to \tau\tau$

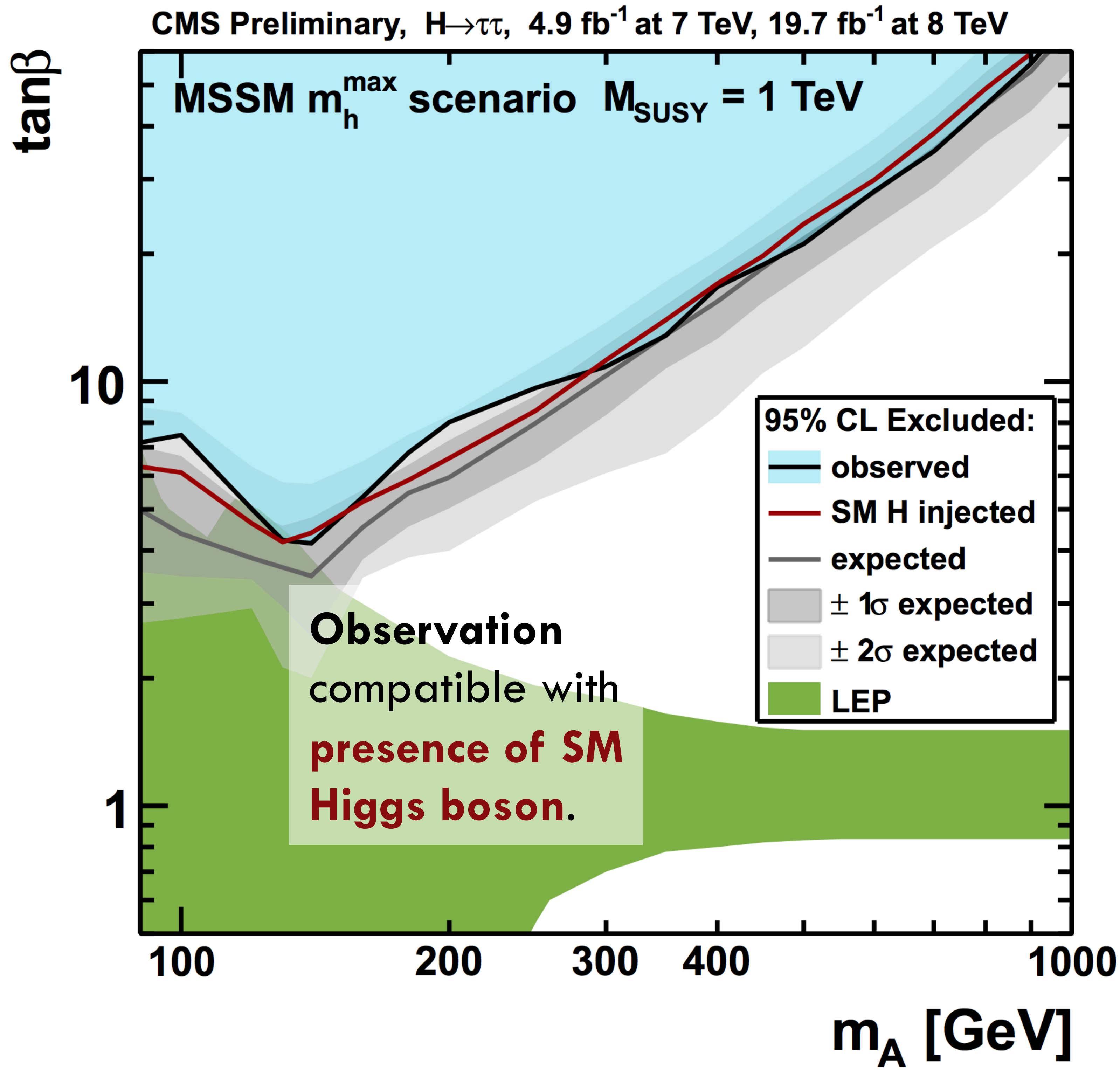
• Non-standard search channels can play an important role: $H \to hh$, $H, A \to \chi\chi$, ...

CMS result for h, H, A → $\tau\tau$ search

[CMS Collaboration '14]

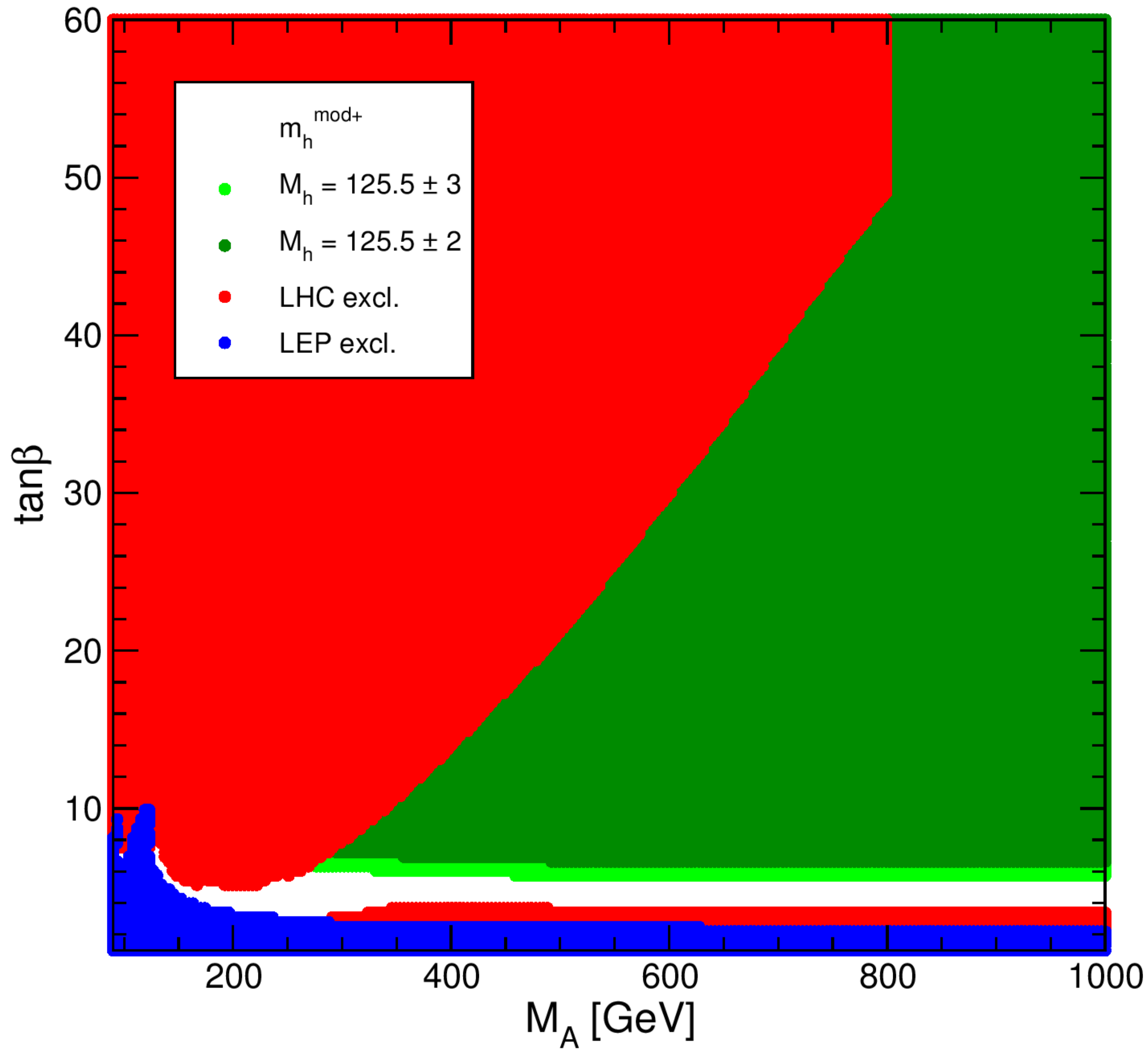
Analysis starts to become sensitive to the presence of the signal at 125 GeV

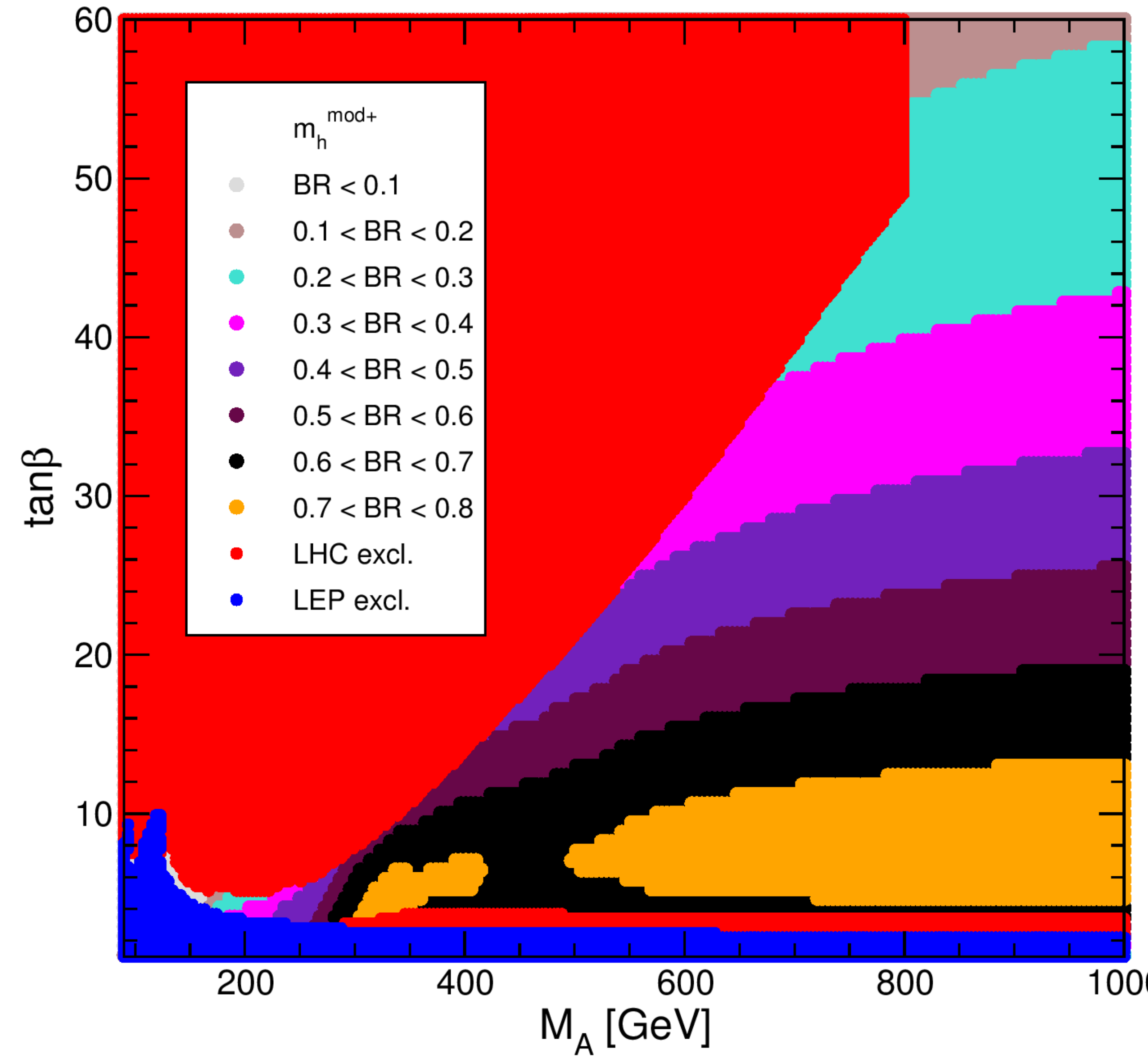
⇒ Searches for Higgs bosons of an extended Higgs sector need to test compatibility with the signal at 125 GeV (→ appropriate benchmark scenarios) and search for additional states



m_h^{mod} benchmark scenario

[M. Carena, S. Heinemeyer, O. Stål, C. Wagner, G. W. '14]





Small modification of well-known m_h^{max} scenario where the light Higgs h can be interpreted as the signal at 125 GeV over a wide range of the parameter space

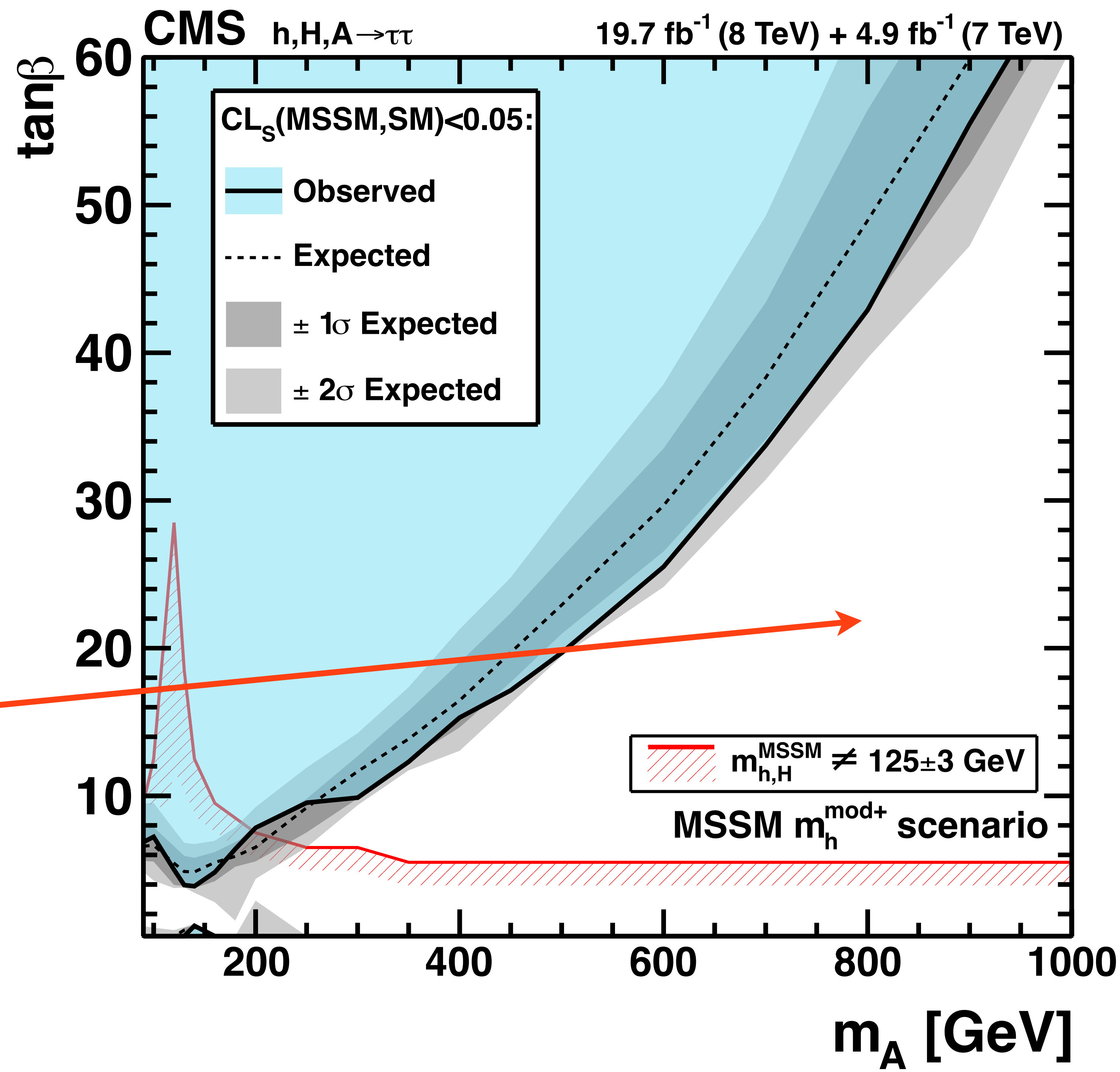
Large branching ratios into SUSY particles (right plot) and sizable BR(H → hh), up to 30%, for rel. small tanβ possible

CMS result for h, H, A → ττ search

[CMS Collaboration ’14]

m_h^{mod} benchmark scenario

Test of compatibility of the data to the signal of h, H, A (MSSM) compared to SM Higgs boson hypothesis



⇒ ``Wedge region”, where only h(125) can be detected; difficult to cover also with more luminosity

Interpretation of the signal in extended Higgs sectors (SUSY), case II: signal interpreted as next-to-lightest state H

Extended Higgs sector where the second-lightest (or higher) Higgs has SM-like couplings to gauge bosons

Lightest neutral Higgs with heavily suppressed couplings to gauge bosons, may have a mass below the LEP limit of 114.4 GeV for a SM-like Higgs (in agreement with LEP bounds)

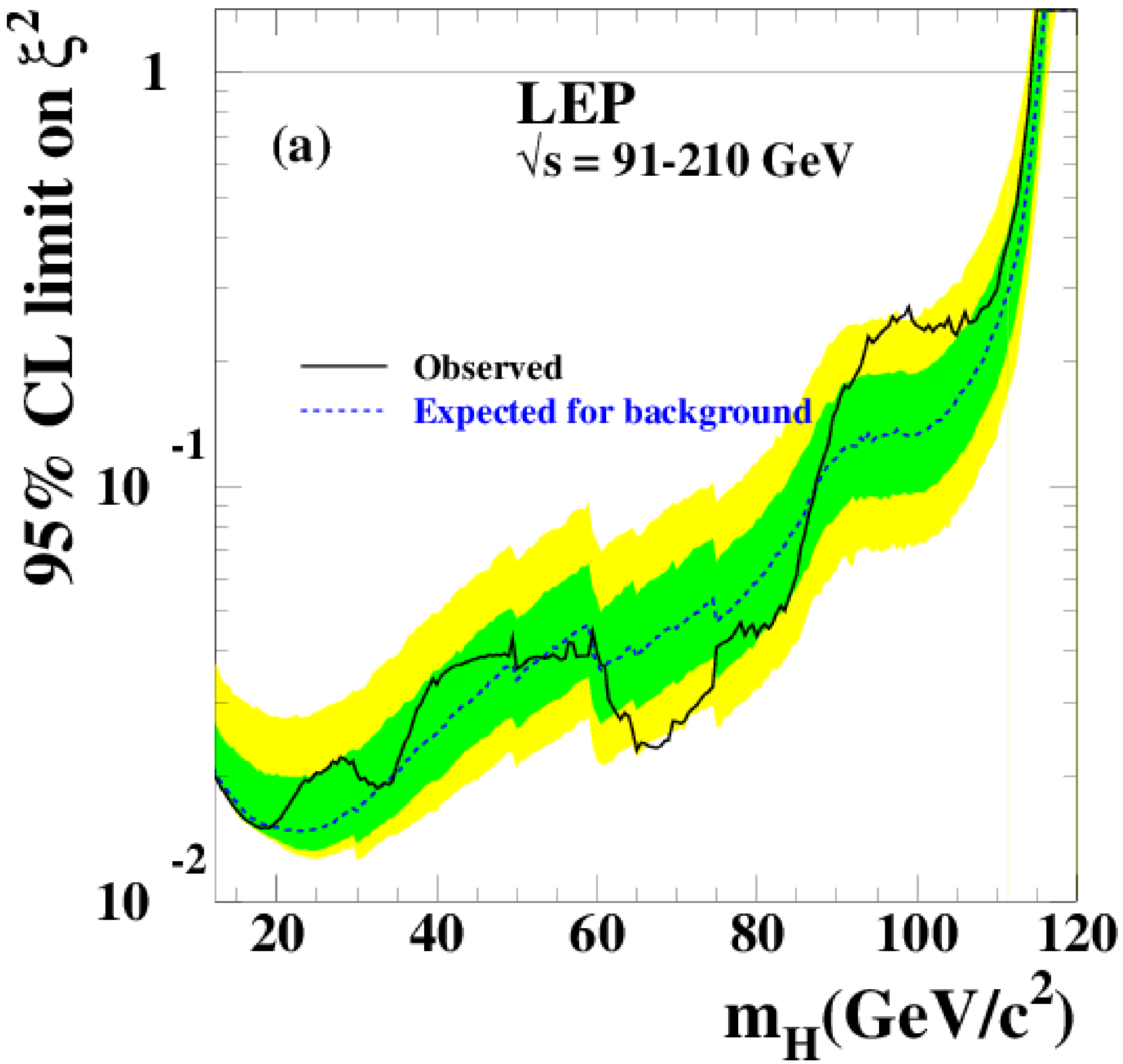
Possible realisations: 2HDM, MSSM, NMSSM, ...

A light neutral Higgs in the mass range of about 60-100 GeV (above the threshold for the decay of the state at 125 GeV into hh) is a generic feature of this kind of scenario. The search for Higgses in this mass range has only recently been started at the LHC. Such a state could copiously be produced in SUSY cascades.

LEP limits on low-mass Higgs bosons

Limits from the LEP Higgs searches: $e^+e^- \to ZH, H \to b\bar{b}$

$$\left(\frac{g_{\mathrm{HZZ}}}{g_{\mathrm{HZZ}}^{\mathrm{SM}}}\right)^2$$

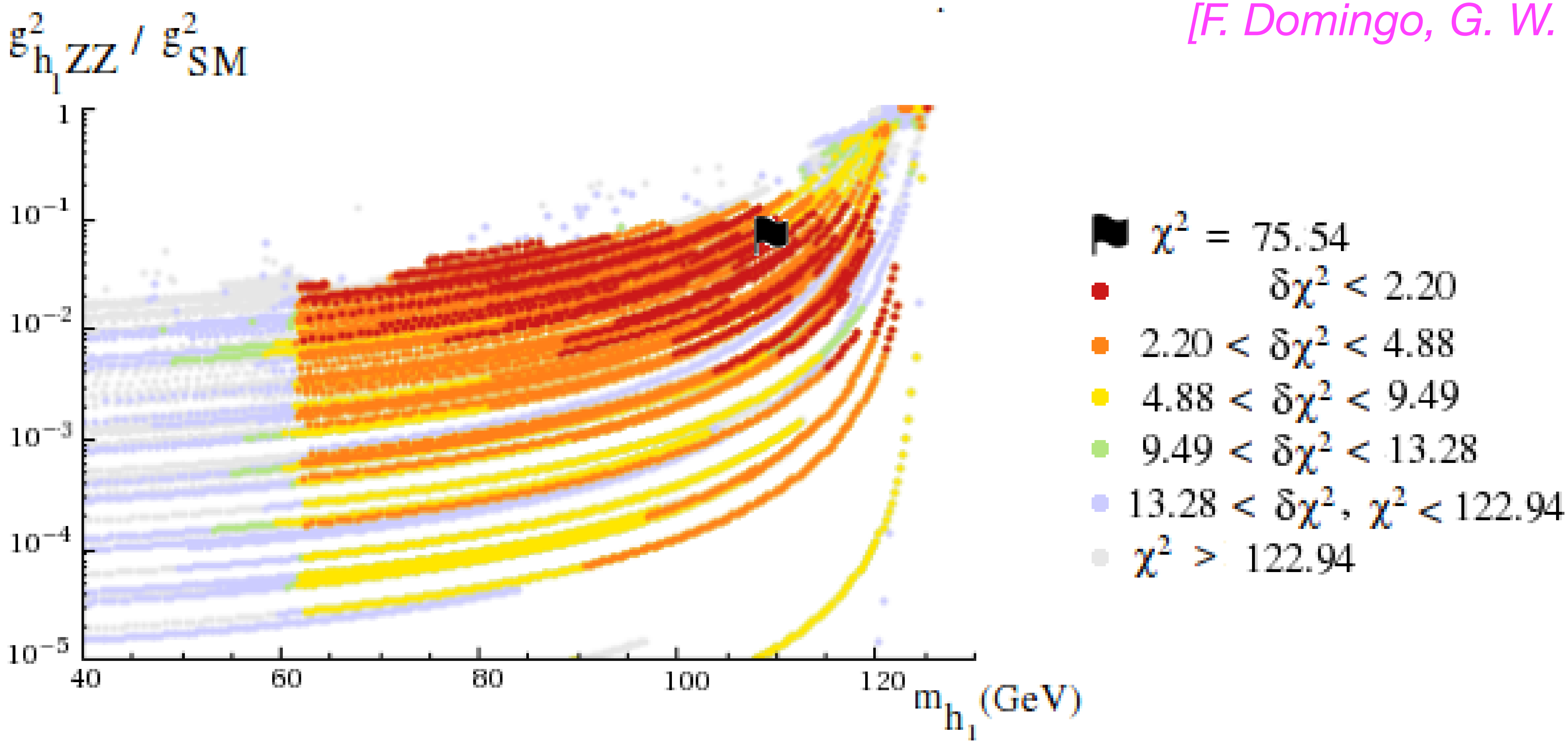


⇒ Limit for SM Higgs (ξ = 1): M_H > 114.4 GeV at 95% CL

No limit if the HZZ coupling is below 10% of the SM value

In the NMSSM such a situation arises generically if the Higgs singlet is light

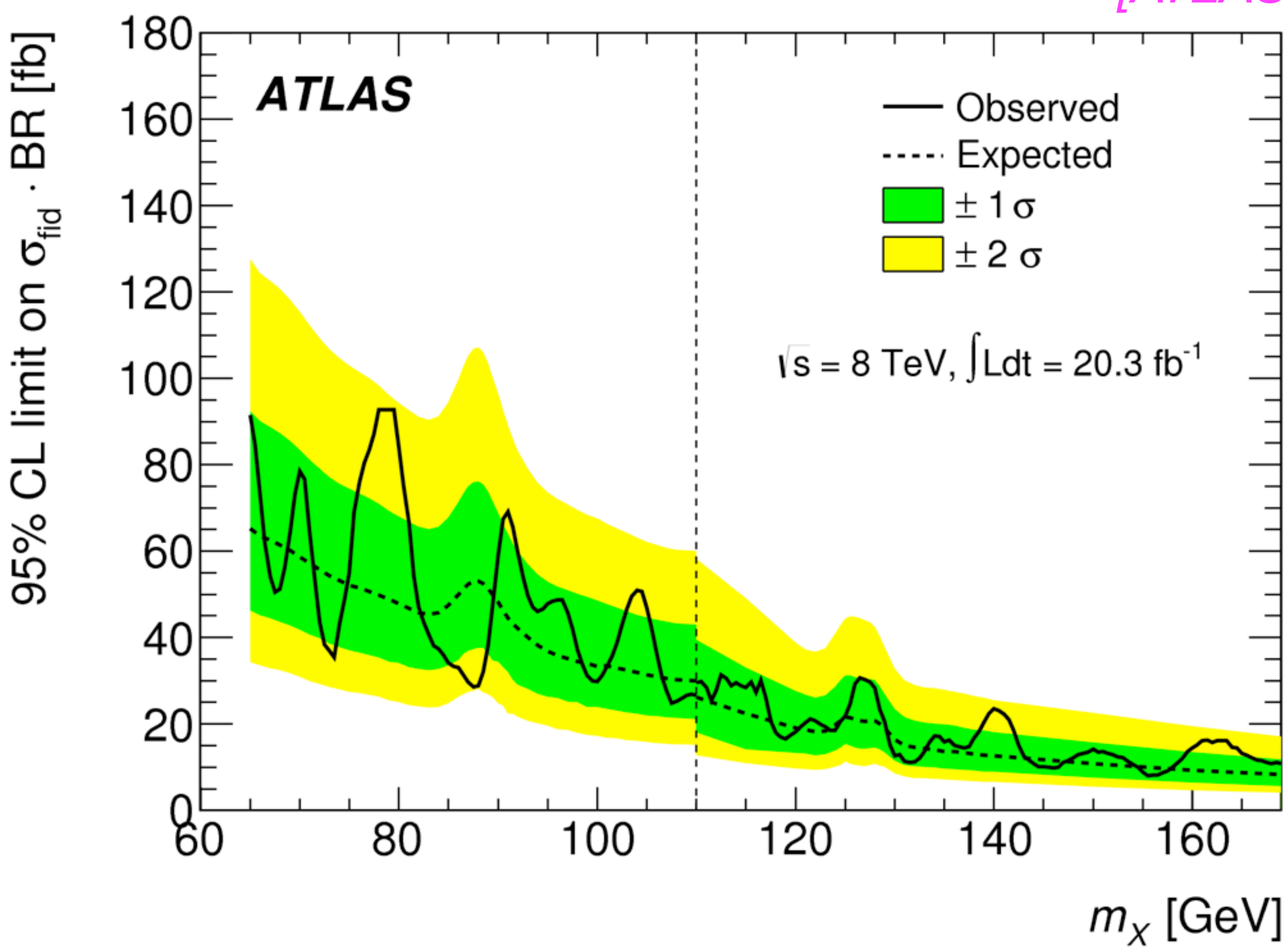
[F. Domingo, G. W. '15]



⇒ SM-like Higgs at 125 GeV + singlet-like Higgs at lower mass
Large singlet component leads to strong suppression of the coupling to gauge bosons

Are LHC searches sensitive to a low-mass Higgs with suppressed couplings to gauge bosons?

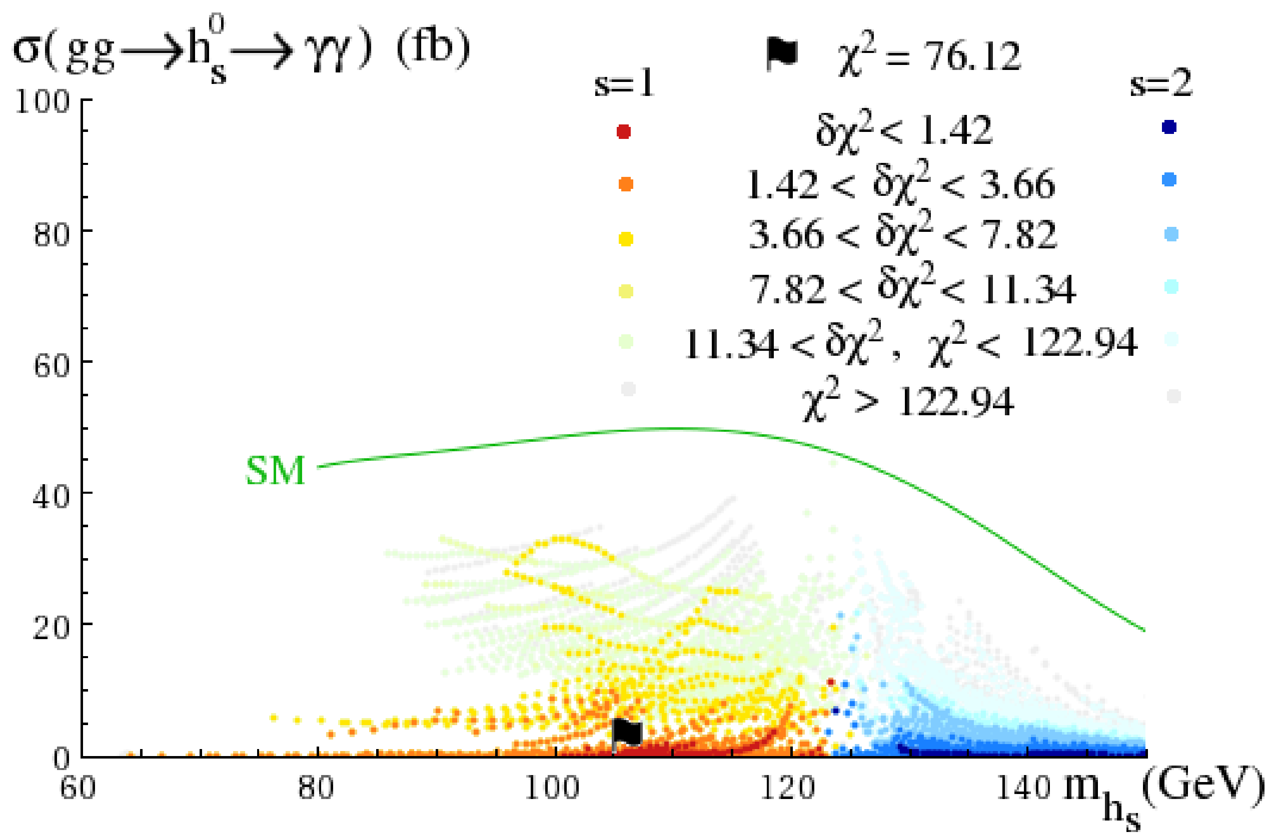
ATLAS h → $\gamma\gamma$ searches in the low-mass region: *[ATLAS Collaboration '14]*

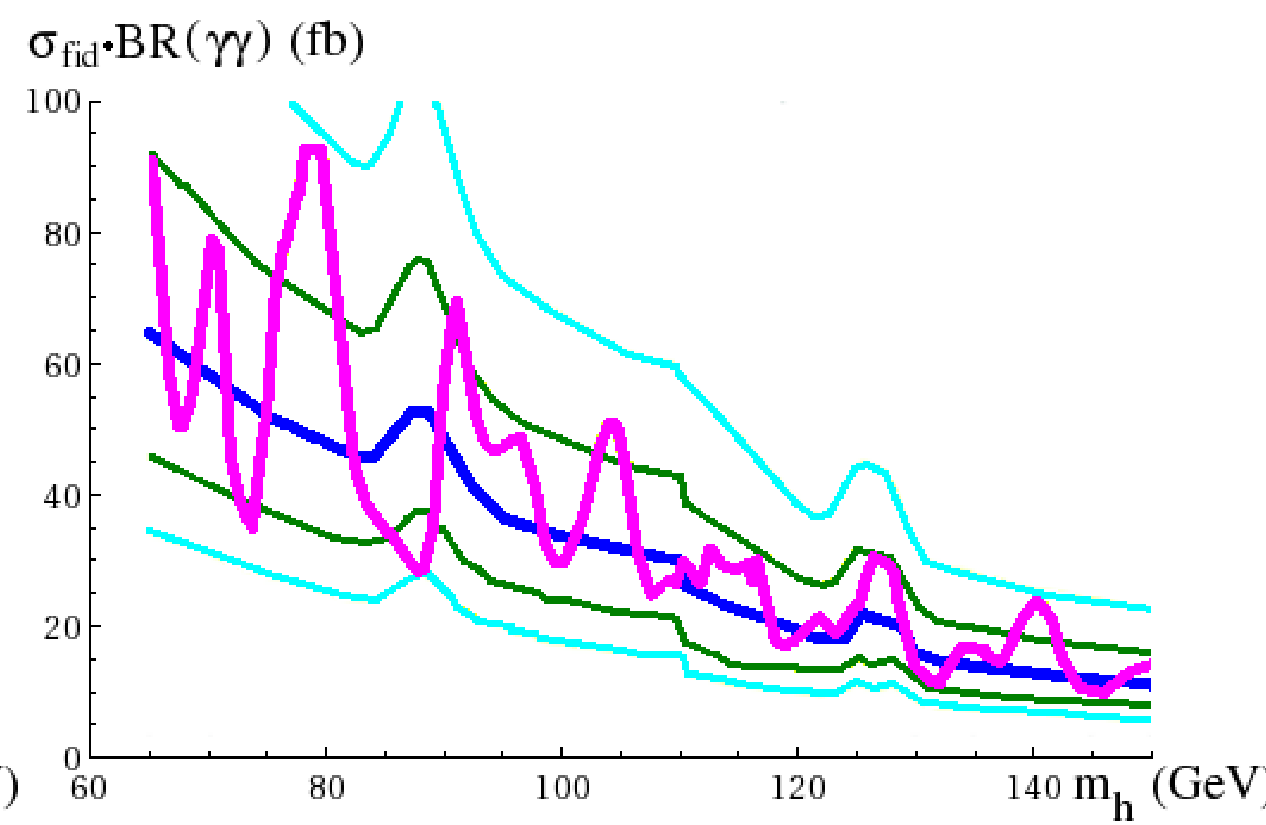


Example: MSSM, H(125) case: BR($h_1 \to \gamma\gamma$) = 8.5 10^{-7}, three orders of magnitude below BR for a SM-like Higgs of this mass (65 GeV)

Light NMSSM Higgs: comparison of $gg \to h_1 \to \gamma\gamma$ with the SM case and the ATLAS limit on fiducial σ

[F. Domingo, G. W. '15]





⇒ Limit starts to probe the NMSSM parameter space

But: best fit region is far below the present sensitivity

Are LHC searches sensitive to such a low-mass Higgs with suppressed couplings to gauge bosons?

⇒ Limited sensitivity from h → $\gamma\gamma$ searches for scenarios of this kind

For very light Higgses: constraints on H(125) → h_1 h_1 decays

Such a light Higgs could be produced in a SUSY cascade, e.g.
$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ [O. Stål, G. W. '11] [CMS Collaboration '15]

⇒ Could get a signal of SUSY + BSM Higgs at the same time!

Conclusions

Discovered signal is so far compatible with a SM-like Higgs, but variety of interpretations possible ⇔ very different underlying physics

WP1: We need high-precision measurements of the properties of the detected particle + precise theory predictions to reveal the nature of electroweak symmetry breaking!

The best way to experimentally prove that the observed state at 125 GeV is not the SM Higgs would be to find in addition (at least one) non-SM like Higgs, which could be heavier but also lighter than the signal at 125 GeV!

⇒ Exciting prospects for Run 2 of the LHC and beyond in the quest for identifying the nature of Higgs physics and electroweak symmetry breaking!

Backup

Higgs mass measurement: the need for high precision

Measuring the mass of the discovered signal with high precision is of interest in its own right

But a high-precision measurement has also direct implications for probing Higgs physics

M_H: crucial input parameter for Higgs physics

BR($H \to ZZ^*$), BR($H \to WW^*$): highly sensitive to precise numerical value of M_H

A change in M_H of 0.2 GeV shifts BR($H \to ZZ^*$) by 2.5%!

$\Rightarrow$ Need high-precision determination of M_H to exploit the sensitivity of BR($H \to ZZ^*$), ... for testing BSM physics

CP properties

$\mathcal{CP}$ properties: more difficult than spin, observed state can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables mainly used for investigaton of $\mathcal{CP}$-properties ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

General structure of HVV coupling (from Lorentz invariance):

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

SM, 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 many models (example: SUSY, 2HDM, ...) a_3 is loop-induced and heavily suppressed

CP properties

⇒ Observables involving the *HVV* coupling provide only limited sensitivity to effects of a CP-odd component, even a rather large CP-admixture would not lead to detectable effects in the angular distributions of $H \to ZZ^* \to 4\,l$, etc. because of the smallness of a_3

Hypothesis of a pure CP-odd state is experimentally disfavoured

However, there are only very weak bounds so far on an admixture of CP-even and CP-odd components

Channels involving only Higgs couplings to fermions could provide much higher sensitivity

General case with non-zero CP violation

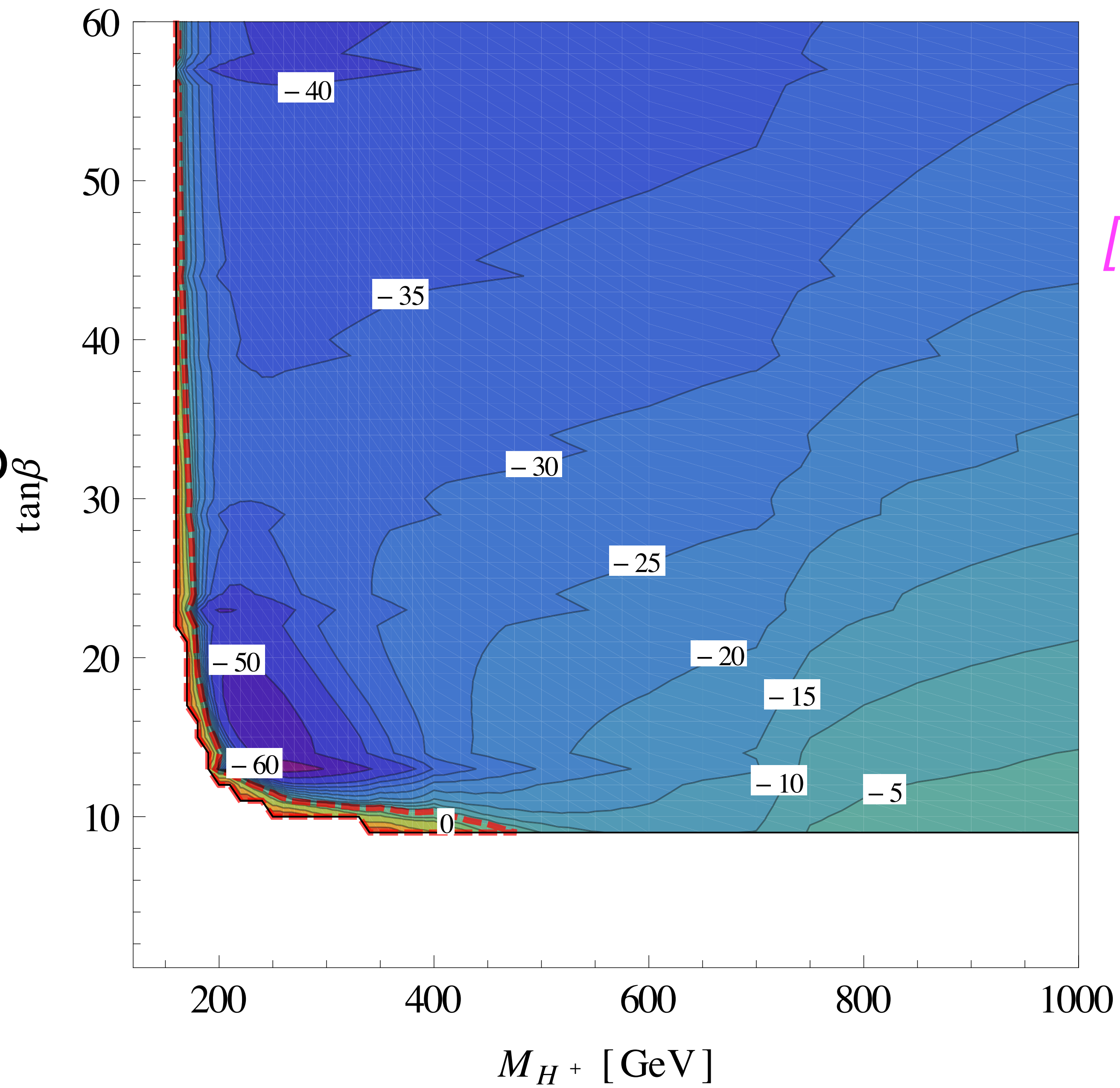
Mixing of the three neutral Higgs states: h, H, A → h_1, h_2, h_3
Heavy Higgs search: h_2, h_3, are nearly mass-degenerate, large mixing possible [A. Fowler, G. W. '10]

⇒ Large interference effects (constructive / destructive) possible

Effect of non-zero phase ϕ_{A_t}:
$\delta = (\sigma_\phi - \sigma_0)/\sigma_0$

m_h^{mod+} scenario

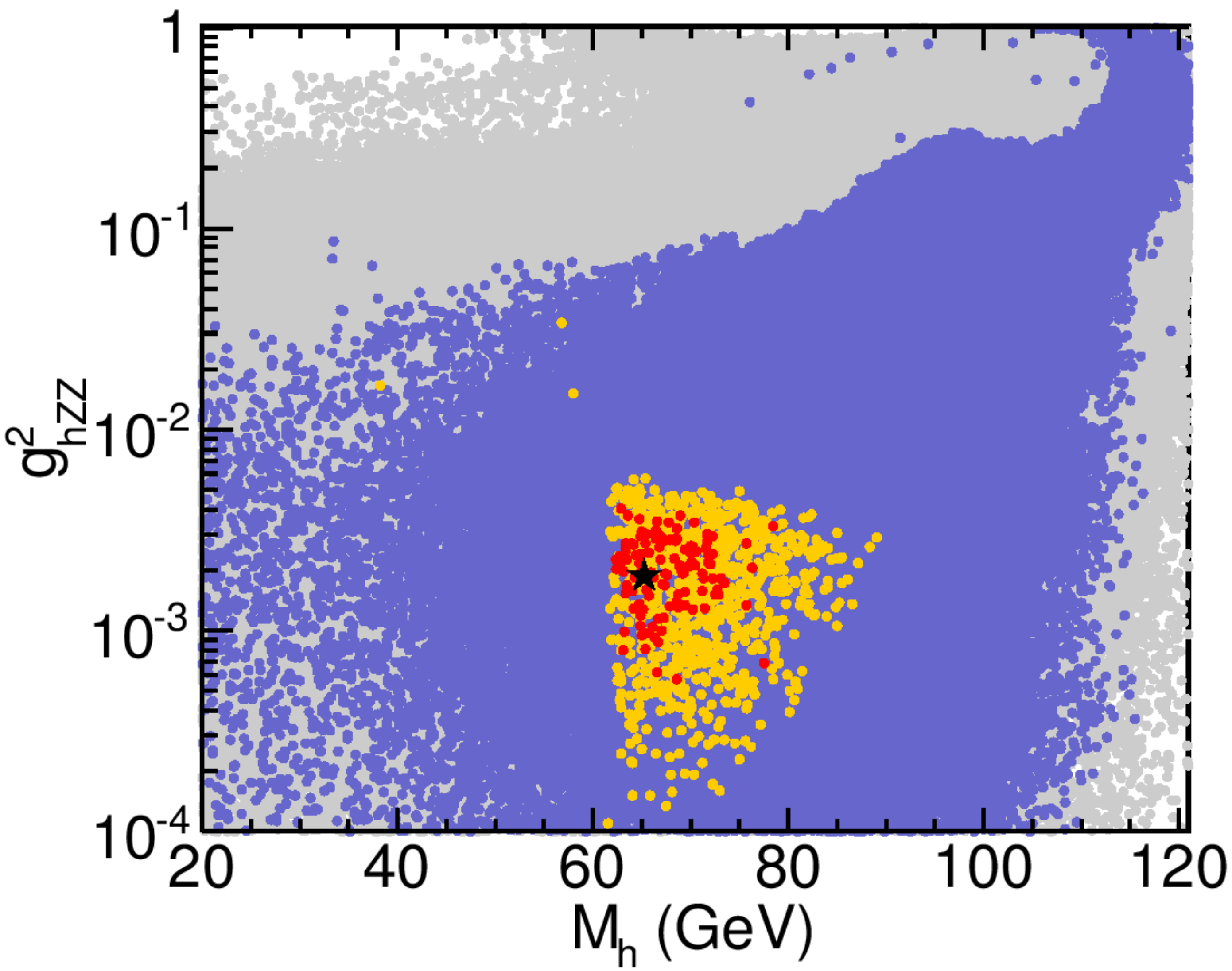
μ = +500 GeV



[E. Fuchs, G. W. '14]

MSSM realisation: very exotic scenario, where all five Higgs states are light, h, H(125), A, H^{+-}

Lightest Higgs: mass and couplings to gauge bosons (blue: *HiggsBounds*-allowed)
[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12*]



$\Rightarrow$ Light Higgs with $M_{\rm h} \approx 70$ GeV, in agreement with LEP limits

Before charged Higgs results from ATLAS: global fit yielded acceptable fit probability