Interpretation of the Higgs signal
and possible phenomenology of
additional Higgs states

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Based on collaboration with:
P. Bechtle, F. Domingo, E. Fuchs, S. Heinemeyer, O. Stål, T. Stefaniak
Introduction

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

• Extended Higgs sectors: where are the additional Higgses and how can we find them?

• Composite Higgs: resonances, composite top partners, ... ?

• ...

• ...
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

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

⇒ 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, NMSSM, ...?
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, ...
  - $M_h = 125$ GeV in MSSM $\Rightarrow M_A > 200$ GeV: decoupling limit
  $\Rightarrow$ Only small deviations in the couplings expected

- detection of additional Higgses: $H, A \rightarrow \tau\tau, H \rightarrow hh, H, A \rightarrow \chi\chi, ...$
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”:

$$\sum_i g_{H_iVV}^2 = (g_{HVVV}^{SM})^2$$

- The SM coupling strength is “shared” between the Higgses of an extended Higgs sector, $\kappa_V \leq 1$
- 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
- Searches for additional Higgs bosons need to test compatibility with the observed signal at 125 GeV!
Small modification of well-known $m_h^{\text{max}}$ 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 $\text{BR}(H \rightarrow hh)$, up to 30%, for relatively small $\tan\beta$ possible.
Incorporation of cross section limits and properties of the signal at 125 GeV: *HiggsBounds* and *HiggsSignals*

- Programs that use the experimental information on cross section limits (*HiggsBounds*) and observed signal strengths (*HiggsSignals*) for testing theory predictions [*P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, K. Williams ’08, ’12, ’13*]


  - Test of Higgs sector predictions in arbitrary models against measured signal rates and masses

  - Systematic uncertainties and correlations of signal rates, luminosity and Higgs mass predictions taken into account
Heavy non-standard Higgses: application of CMS result in $\tau\tau$ channel and impact of interference contributions

- CMS has published likelihood information for searches for a narrow Higgs resonance in $\tau\tau$ channel as function of the two production channels gluon fusion and $b$ associated production [CMS Collaboration ’14]

- Simple algorithm for mapping arbitrary models with several Higgses to narrow resonance model, incorporation into HiggsBounds

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Validation: comparison with exclusion limit from dedicated CMS analysis in $m_h^{\text{max}}$ benchmark scen.

[Bechtle, Heinemeyer, Stål, Stefaniak, Weiglein '15]

Likelihood distribution and excl. limits:

Good agreement with dedicated CMS analysis in the benchmark scenario (proper combination of channels possible)
Application to the $m_h^{alt}$ benchmark scenario: "alignment without decoupling"

Alignment without decoupling: $h$ in the MSSM behaves SM-like even for small values of $M_A$, $m_h^{alt}$ scen. [M. Carena, H. Haber, I. Low, N. Shah, C. Wagner’15]

Likelihood distribution from $H, A \rightarrow \tau\tau$: Likelihood from Higgs signal rates:

![Graphs showing likelihood distributions and constraints from Higgs searches.](image)

Likelihood distribution from $H, A \rightarrow \tau\tau$: Likelihood from Higgs signal rates:

![Graphs showing likelihood distributions and constraints from Higgs searches.](image)

In order to illustrate the complementarity between the constraints from the CMS $\tau\tau$ search and the constraints obtained from the signal rate measurements of the discovered Higgs boson, we show in Fig. 5(b) the likelihood distribution, $\Delta\chi^2_{HS}$, obtained from a test of the light Higgs boson signal rates against a combination of the latest rate measurements from the LHC [65–73] and the Tevatron [74, 75], using the public computer code HiggsSignals-1.3.0 [8] (see also Refs. [14, 76]). The 95% CL preferred region lies within the orange contours in Fig. 5(b). It is given by the difference with respect to the minimal $\Delta\chi^2$ value (located in the alignment region and indicated as the gray asterisk).
Combination of likelihood information from the Higgs signal rates and the search for heavy Higgses

[Public tools] HiggsBounds and HiggsSignals

⇒ Large impact on parameter space of the model
Lower limit on $M_A$ from searches for heavy Higgses!
Search for heavy Higgs bosons at the LHC: impact of interference effects

Exclusion limits from neutral Higgs searches in the MSSM with and without interference effects:

CP-violating case, \( \phi_{At} = \pi / 4 \)

H, A are nearly mass degenerate: large mixing possible in CP-violating case!

Incoherent sum is not sufficient!

\( \Rightarrow \) Large CP-violating interference effects between H, A possible
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.
In the NMSSM such a situation arises generically if the Higgs singlet is light

⇒ SM-like Higgs at 125 GeV + singlet-like Higgs at lower mass
The case where the signal at 125 GeV is not the lightest Higgs arises generically if the Higgs singlet is light
⇒ Strong suppression of the coupling to gauge bosons

Coupling of the lightest Higgs to gauge bosons:

[F. Domingo, G. W. ’15]
Are LHC searches sensitive to a low-mass Higgs with suppressed couplings to gauge bosons?

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

Example: MSSM, $H(125)$ case: $\text{BR}(h_1 \rightarrow \gamma\gamma) = 8.5 \times 10^{-7}$, three orders of magnitude below $\text{BR}$ for a SM-like Higgs of this mass (65 GeV)
Light NMSSM Higgs: comparison of $gg \rightarrow h_1 \rightarrow \gamma\gamma$
with the SM case and the ATLAS limit on fiducial $\sigma$

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

\[ \sigma(\text{gg} \rightarrow h_s^0 \rightarrow \gamma\gamma) \text{ (fb)} \]

\[ \sigma_{\text{fid}} \cdot \text{BR}(\gamma\gamma) \text{ (fb)} \]

$\Rightarrow$ Limit starts to probe the NMSSM parameter space
But: best fit region is far below the present sensitivity

Such a light Higgs could be produced in a SUSY cascade, e.g.
$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$

$[O. \ Stål, \ G. \ W. \ '11] \quad [\text{CMS Collaboration '15}]$

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Conclusions

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

Extended Higgs sectors of SUSY-type: h(125), lightest Higgs state
MSSM: $M_h = 125$ GeV implies $M_A \gg M_Z$: decoupling region, SM-like

Heavy Higgs searches: new result from CMS allows to combine likelihood information from the Higgs signal with the one from the $H, A \rightarrow \tau\tau$, searches (and from the LEP searches)
Large interference effects between heavy Higgs contributions possible in the CP-violating case

Extended Higgs sector where second-lightest Higgs is identified with signal at 125 GeV: additional light Higgs with suppressed couplings to gauge bosons; can be realised generically in the NMSSM: NMSSM fit prefers singlet-like light Higgs
Backup
Possibility of a sizable deviation even if the couplings to gauge bosons and SM fermions are very close to the SM case

- If dark matter consists of one or more particles with a mass below about 63 GeV, then the decay of the state at 125 GeV into a pair of dark matter particles is kinematically open.

- The detection of an invisible decay mode of the state at 125 GeV could be a manifestation of BSM physics.

  - Direct search for $H \to \text{invisible}$

  - Suppression of all other branching ratios
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 $H \rightarrow ZZ \rightarrow 4 \ell$ as a small bump, very far below the expectation for a SM-like Higgs (and with a much smaller width)

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

• Non-standard search channels can play an important role:
  $H \rightarrow hh, H, A \rightarrow \chi\chi, \ldots$
LEP limits on low-mass Higgs bosons

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

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

$95\%$ CL limit on $\xi^2$

(a) LEP $\sqrt{s} = 91$-210 GeV

$\Rightarrow$ Limit for SM Higgs ($\xi = 1$): $M_H > 114.4$ GeV at $95\%$ CL

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