Search for additional Higgs Bosons and BSM Higgs decays (E)

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Discovery...

$H \rightarrow ZZ \rightarrow 4\ell$

$H \rightarrow \gamma\gamma$

4th July 2012
Higgs Boson mass

- ATLAS+CMS LHC run-1 combination:

\[ 125.06 \pm 0.21 \text{ (stat.)} \pm 0.19 \text{ (syst.) GeV} \]
Higgs Boson couplings

\( f^{\text{obs}}_{H \rightarrow ff} = \kappa_f \cdot f^{\text{SM}}_{H \rightarrow ff} \)

\( \sqrt{\frac{f^{\text{obs}}_{H \rightarrow VV}}{2v}} = \sqrt{\kappa_V} \cdot \sqrt{\frac{f^{\text{SM}}_{H \rightarrow VV}}{2v}} = \sqrt{\kappa_V} \cdot \frac{mv}{v} \quad V = W, Z \)

\( \text{Within measurement accuracy unique scaling as expected within the SM.} \)
Why the Higgs boson still is not THE Higgs boson\(^{(1)}\)

- Gravity is not included in the SM.
- The SM suffers from the hierarchy problem.
- Dark matter is not included in the SM.
- Neutrino masses are not included in the SM.
- There are known deviations from the SM expectation in \(a_\mu \equiv \frac{g_\mu - 2}{2}\) (3.6\(\sigma\) unresolved).

\((1)\) Arguments taken from S. Heinemeyer (HH Higgs workshop 2014)

There must be physics beyond the SM!

At what scale does it set in?

(How) Does it influence the Higgs sector?
Higgs sector in the light of (tree-level) unitarity

- Unitarity problem demonstrated for $W^+W^+ \rightarrow W^+W^+$ scattering:

\[ \mathcal{M}_{\text{gauge}} = -g^2 \frac{s}{4m_W^2} + \mathcal{O}(s^0) \]

constraint

\[ \mathcal{M}_H = g_{HWW}^2 \frac{s}{m_W^4} + \mathcal{O}(s^0) \]

Exact cancellation of **divergent behavior** only if scalar exchange particle has coupling of type $\propto m_W^2$.

- Any additional contribution to this process should preserve this cancellation.

\[ g_{HWW} = \frac{2m_W^2}{v} = g \cdot m_W \]

with: $v = \frac{2m_W}{g}$
Space left for new physics in the Higgs sector

Two signatures of new physics in the Higgs sector:

- Find signal of new Higgs bosons directly.
- Presence of new Higgs bosons usually leads to modifications of $h(125)$ couplings.

$\kappa_\tau = 0.87^{+0.12}_{-0.11}$

$\kappa_W = 0.90 \pm 0.09$

Space left: 20% @ the two sigma level.
Direct searches for $H \rightarrow \text{invisible}$

$BR(H \rightarrow \text{inv}) \leq 0.24(0.23) \ @ \ 95\% \ CL$
Higgs mediated DM

Reminder:
$10^{-46} \text{ cm}^2 = 10^{-10} \text{ pb}$

→ Pushing limits for direct DM searches.
Extensions of the Higgs sector

Additional $SU(2)_L$ singlets.

- Just one more Higgs boson.
- Mostly searched for in $WW/ZZ$ final states.

Additional $SU(2)_L$ doublets.

- 5 additional Higgs bosons ($\rightarrow H^{+/−}, A, H, h$).
- 2HDM of four types (a priori 14 unconstrained parameters).

Additional $SU(2)_L$ triplets.

- Georgi-Machacek model (preserves custodial sym. of SM):
  \[
  \Phi = \begin{pmatrix}
  \phi^0 & \phi^+ \\
  -\phi^{++} & \phi^0
  \end{pmatrix}
  \]
  \[
  X = \begin{pmatrix}
  \chi^{0*} & \xi^+ & \chi^{++} \\
  -\chi^{++*} & \xi^0 & \chi^{+*} \\
  \chi^{++*} & -\xi^{0*} & \chi^{0*}
  \end{pmatrix}
  \]
  under global $SU(2)_L \times SU(2)_R$

- Two custodial singlets ($m_h, m_H$), one doublet ($m_3$), one fiveplet ($m_5$).

NMSSM (singlet + doublet)

MSSM

All what is theoretically thinkable hosted/sorted by LHC HXSWG-3 (LHC HXSWG authority of CERN YR’s).
Higgs Bosons in the 2HDM

• Any 2 Higgs Doublet Model (2HDM) predicts five Higgs bosons: \(^{(1)}\)

\[
\begin{align*}
\phi_u &= \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \\ \phi_u^- \end{pmatrix}, & Y_{\phi_u} &= +1, & v_u : \text{VEV}_u \\
\phi_d &= \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}, & Y_{\phi_d} &= -1, & v_d : \text{VEV}_d
\end{align*}
\]

\[N_{\text{ndof}} = 8 - 3 = 5\]

\[\{W, Z\} \cup \{H^\pm, H, h, A\}\]

\(^{(1)}\) here shown for type-II.
Higgs Bosons in the MSSM

- Any 2 Higgs Doublet Model (2HDM) predicts five Higgs bosons:
  \[ \phi_u = \begin{pmatrix} \phi^+_u \\ \phi^0_u \end{pmatrix}, \quad Y_{\phi_u} = +1, \quad v_u : \text{VEV}_u \]
  \[ \phi_d = \begin{pmatrix} \phi^0_d \\ \phi^-_d \end{pmatrix}, \quad Y_{\phi_d} = -1, \quad v_d : \text{VEV}_d \]

  \[ N_{\text{ndof}} = 8 - 3 = 5 \]

  \( W, Z, H^\pm, H, h, A \)

- Strict mass requirements at tree level:
  two free parameters: \( m_A, \tan \beta = \frac{v_u}{v_d} \)

  \[ m^2_{H^\pm} = m^2_A + m^2_W \]
  \[ m^2_{H, h} = \frac{1}{2} \left( m^2_A + m^2_Z \pm \sqrt{(m^2_A + m^2_Z)^2 - 4m^2_A m^2_Z \cos^2 2\beta} \right) \]
  \[ \tan \alpha = \frac{-\left( m^2_A + m^2_Z \right) \sin 2\beta}{\left( m^2_Z - m^2_A \right) \cos 2\beta + \sqrt{\left( m^2_A + m^2_Z \right)^2 - 4m^2_A m^2_Z \cos^2 2\beta}} \]

Large values of \( \tan \beta \) of interest.
The role of down-type fermions

<table>
<thead>
<tr>
<th></th>
<th>$g^{VV}/g^{SM}_{\nu V}$</th>
<th>$g^{uu}/g^{SM}_{\nu u}$</th>
<th>$g^{dd}/g^{SM}_{\nu d}$</th>
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</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$-$</td>
<td>$\gamma_5 \cot \beta$</td>
<td>$\gamma_5 \tan \beta$</td>
</tr>
<tr>
<td>$H$</td>
<td>$\cos(\beta - \alpha) \rightarrow 0$</td>
<td>$\sin \alpha / \sin \beta \rightarrow \cot \beta$</td>
<td>$\cos \alpha / \cos \beta \rightarrow \tan \beta$</td>
</tr>
<tr>
<td>$h$</td>
<td>$\sin(\beta - \alpha) \rightarrow 1$</td>
<td>$\cos \alpha / \sin \beta \rightarrow 1$</td>
<td>$- \sin \alpha / \cos \beta \rightarrow 1$</td>
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For $m_A \gg m_Z : \alpha \rightarrow \beta - \pi/2$ (coupling to down-type fermions enhanced by $\tan \beta$).

Interesting production modes:

$gg \rightarrow \phi$ ("gg\phi")

$gg \rightarrow \phi b\bar{b}$ ("b\bar{b}\phi")

Interesting decay channels:

![Graph showing BR(A -> XX) vs tan beta](image-url)
Upshot of LHC run-1:

Similar results (only not in single plots) from ATLAS.
**LHC run-1 → run-2**

<table>
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<tr>
<th>Process</th>
<th>$\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$</th>
<th>$\delta X / \delta h(125)$</th>
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<td>$t\bar{t}$</td>
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<td>0.87</td>
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**H1 and ZEUS HERA I+II PDF Fit**

$Q^2 = (100 \text{ GeV})^2$

- HERAPDF1.5 NNLO (prel.)
- exp. uncert.
- model uncert.
- parametization uncert.

$\langle x \rangle_{8 \text{ TeV}} = \sqrt{\frac{125 \text{ GeV}}{8 \text{ TeV}}} \approx 0.125$

$\langle x \rangle_{13 \text{ TeV}} = \sqrt{\frac{125 \text{ GeV}}{13 \text{ TeV}}} \approx 0.100$

**Graphs:**
- Graph showing the ratios of LHC parton luminosities for 13 TeV vs 8 TeV.
- Graph depicting the H1 and ZEUS HERA I+II PDF fit with $Q^2 = (100 \text{ GeV})^2$.
LHC run-1 → run-2

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Results end of 2015:

Results for ICHEP 2016:

$13.2/fb$ (ATLAS)
$12.9/fb$ (CMS)

Results end of 2015:

$3.2/fb$ (ATLAS)
$2.3/fb$ (CMS)
$H \rightarrow \tau\tau$ decay channel

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<th>Decay Mode</th>
<th>BR [%]</th>
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<td>$e\nu_e\nu_\tau$</td>
<td>17.83</td>
</tr>
<tr>
<td>$\mu\nu_\mu\nu_\tau$</td>
<td>17.41</td>
</tr>
<tr>
<td>1-prong $\nu_\tau$</td>
<td>37.10</td>
</tr>
<tr>
<td>3-prong $\nu_\tau$</td>
<td>15.20</td>
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- Search for 2 isolated high $p_T$ leptons ($e$, $\mu$, $\tau_h$).
- Reduce obvious backgrounds (e.g. use $E_T'$) & reconstruct $m_{\tau\tau}$.

- Inputs: visible leptons, x-, y-component of $E_T'$.
- Free parameters: $\varphi$, $\theta^*$, ($m_{\nu\nu}$) per $\tau$.
Search

- Search for peak(s) e.g. in (transverse) $m_{\tau\tau}$ distribution.

$b$-tag category:
- $N(b\text{-tag}) \geq 1$
- $N(\text{Jet}) \leq 1$

No $b$-tag category:
- $N(b\text{-tag}) = 0$
Both collaborations present their results also in form of maximally model independent limits on $\sigma \times BR$ or $\Delta NLL$ values.

With slightly different event categories & different final discriminator.

Exclusion
Both collaborations present their results also in form of maximally model independent limits on $\sigma \times BR$ or $\Delta NLL$ values.

With slightly different event categories & different final discriminator.
$H \rightarrow \mu \tau$ LFV Higgs couplings

- SM forbids LFV couplings at tree level.
- LVF could take place in Higgs sector.

**LHC run-1 legacy:**

No excess, but also not same sensitivity reached, yet, as for LHC run-1.

- $H \rightarrow \mu \tau_h / \mu \tau_e$ with two specialties:
  - $p_T(\mu)$ harder ($\rightarrow$ less $\nu'$s in decay).
  - $\nu$ more collinear.
Charged Higgs

- Expect signal in top sector:
- Most sensitive channels: $H^+ \rightarrow \tau \nu$, $H^+ \rightarrow tb$.

In decay ($m_{H^+} < m_t$):

In production ($m_t < m_{H^+}$):

- Heavy flavors preferred
- Flavor democratic
- Additional $b$ jets

\[ \int L dt = 19.5 \text{ fb}^{-1} \]
\[ s=8 \text{ TeV} \]
\[ \text{Data 2012} \]
\[ \text{MSSM } m_{\tilde{t}} \text{ mod scenario} \]
Charged Higgs

- Expect signal in top sector:

  \[ m_{H^+} < m_t \]

- Most sensitive channels:

  In decay (\( m_{H^+} < m_t \)):
  
  - \( \text{flavor democratic heavy flavors preferred} \)
  
  In production (\( m_t < m_{H^+} \)):
  
  - Most sensitive channels: stuff, stuff.
**Charged Higgs** \( (H^+ \rightarrow \tau \nu) \)

- Usually restrict to \( \tau_h \) (1-prong), use \( m_T(\tau_h, MET) \) as discriminating variable.
Exclusion

- Chapter of low mass region already closed by LHC run-1 results.
- About to surpass LHC run-1 sensitivity in high mass regime.
Charged Higgs ($H^+ \rightarrow tb$)

Select one leptonic and one hadronic $W$ decay.

Gain sensitivity to low $\tan \beta$!
$X \rightarrow h(125)h(125)$

- In principle sensitive to $f_{h \rightarrow hh}$ (search (non-)resonant).
- Plenty of constraints due to “cascade”:

In the end one has only two degrees of freedom left: $\tau$ and $b$-Jet, transverse momentum!!

Kinematic Fit to reconstruct the Heavy Higgs mass!

**Kinematic Fit: minimize the $\chi^2$ function:**

$$\chi^2_{\text{reco}} = (P_{T,\text{measured}} - P_{T,\text{reco}}) \cdot \text{COV}^{-1} \cdot (P_{T,\text{measured}} - P_{T,\text{reco}})$$

Collinear approximation for tau decays

- Kinematic Fit: $m_{h} = 125$ GeV
- Heavy Higgs momentum balance with (hadronic) recoil.
- b-Jet angular uncertainties are negligible

Example: $H \rightarrow h(125)(\tau\tau)h(125)(bb)$
\[ X \to h(125)h(125) \]

- Search channels according to \( h(125) \) couplings:
\( X \rightarrow h(125) h(125) \)
Conclusions

● Very rich LHC run-2 BSM Higgs program of both ATLAS & CMS.

● Impossible to cover all (even in 50min) → personal selection.

● Higgs physics requires high statistics → also and esp. in BSM Higgs the most interesting results are still to come.

● Looking forward to full “LHC 2016” and “LHC 2017” datasets!
How can $SU(2)_L$ symmetry be the source of weak interactions while at the same time all interacting particles with $m \neq 0$ explicitly break this symmetry?!?

Spontaneous symmetry breaking:

- Symmetry inherent to the system but not to its energy ground state ($\rightarrow$ quantum vacuum).
- Excitation of vacuum ground state leads to existence of a new particle, characterized by very peculiar coupling structure, needed to preserve the symmetry of the system:

\[
\begin{align*}
\mathcal{L}_{\text{Higgs}} &= \partial_{\mu} \phi^\dagger \partial^{\mu} \phi - V(\phi) \\
V(\phi) &= -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2
\end{align*}
\]

Postulate new field $\phi$ with symmetry breaking vacuum:

\[
\begin{align*}
\mathcal{L}_{\text{Higgs}} &= \partial_{\mu} \phi^\dagger \partial^{\mu} \phi - V(\phi) \\
V(\phi) &= -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2
\end{align*}
\]

Particle masses created dynamically by coupling to non-zero vacuum.

\[
y_e \left( v + \frac{H}{\sqrt{2}} \right) \bar{e} e \quad m_e = y_e \cdot v
\]