The profile of the h(125) from Run 1

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on behalf of ATLAS and CMS collaborations

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Introduction

- After the discovery in July 2012, the emphasis shifted towards measurements to characterise the h(125) boson
  - mass
  - couplings
  - differential x-sections
  - spin/parity and CP invariance test
  - width
  - non-SM decays
    - LFV decays
    - invisible decays
    - h->aa decays
- In this talk will review the latest run 1 ATLAS and CMS results (20+5 fb⁻¹ at 8 and 7 TeV)
Spin and Parity

- Run 1 data provide evidence for the spin-0 nature of the found Higgs particle with a strong preference for positive parity.

- SM hypothesis tested w.r.t. non-SM spin-0, spin-1 and spin-2 with universal and non-universal couplings to vector bosons
  - independent of the assumptions on the coupling strengths to the SM particles
  - analysis based mainly on angular information
Spin and Parity

- studies mostly in di-boson events up to now
- all pure alternatives tested against 0+ strongly rejected
**Tensor Structure**

- BSM theories predict anomalous contributions and/or CP-violation in the Higgs sector
- 2HDM predicts a scalar (H) and a pseudo-scalar (A) spin-0 particle
  - the observed boson (mass eigenstate) is a mixture of the CP eigenstates (H+A)
- model independent approach: measure the coupling structure and compare to the SM prediction

\[
\text{SM Higgs: } \frac{\bar{\kappa}_{HVV}}{\kappa_{SM}} = 0, \\
\text{BSM CP-even: } \frac{\bar{\kappa}_{HVV}}{\kappa_{SM}} = 1
\]

\[
\text{SM Higgs: } \frac{\bar{\kappa}_{AVV}}{\kappa_{SM}} \tan \alpha = 0, \\
\text{BSM CP-odd: } \frac{\bar{\kappa}_{AVV}}{\kappa_{SM}} \tan \alpha = 1
\]

\[f_{a_3} = \text{effective pseudoscalar } \chi\text{-section fraction}\]

scalar Higgs: \(f_{a_3} = 0\)
pseudoscalar Higgs: \(f_{a_3} = 1\)

- \(18.9 \text{ fb}^{-1} (8 \text{ TeV})\)
- \(f_{a_3} < 0.0034 @ 95\% \text{ CL}\)
• **test CP invariance** in the Higgs boson coupling to vector bosons using VBF production and H→ττ decays

• **model-independent** by measuring the mean value of a CP-odd observable

  - CP invariance = mean value equal to zero

• using an optimal observable: combines information of high-dimensional phase space in a single variable
Width

- SM width $\sim 4$ MeV $\rightarrow$ the precision of direct width measurements at LHC is limited by the instrumental resolution
  - **direct upper limit** from mass distribution: $\Gamma < 1.7$ GeV
  - **direct lower limit** from lifetime in 4l:
    \[ \tau_{\text{Higgs}} < 190 \text{ fs} \Rightarrow \Gamma_{\text{Higgs}} > 3.5 \times 10^{-9} \text{ MeV} \]
  - **indirect constraint** through the **on-shell/off-shell ratio** of $gg\rightarrow H\rightarrow VV$
- Analysis strategy:
  - measure on-shell Higgs x-section: $\sigma \sim 1/\Gamma \ast$ couplings
  - measure off-shell Higgs x-section: $\sigma \sim$ couplings
  - ratio $\sim \Gamma$
- ATLAS and CMS combined ZZ and WW channels
  - interference $gg\rightarrow VV$ is taken into account (largest systematic uncertainty)
• **observed** (expected) results:
  • $\Gamma < 22.7 \ (33) \ \text{MeV (ATLAS)}$
  • $\Gamma < 13 \ (26) \ \text{MeV (CMS)}$

![Graph showing width limits and observed results](image-url)
Non-SM Decays: Lepton Flavour Violation

- lepton flavour violation in decays to pairs of leptons with different flavours
  - test models with more than one Higgs doublet, composite Higgs models, models with flavour symmetries, Randall-Sundrum models, …
  - relatively large $Br(H \rightarrow \mu \tau)$ can be achieved without any particular tuning of the effective couplings
  - large $Br(H \rightarrow e \tau)$ possible only at the cost of some fine-tuning of the corresponding couplings
  - search performed in $(e,\mu) \tau_{\text{had}}$, $(e,\mu) \tau_{\text{lep}}$

\[
Br(H \rightarrow e \tau) = 1.04(0.70)\%, \quad Br(H \rightarrow \mu \tau) = 1.43(1.51)\% \text{ ATLAS(CMS)}
\]

- a similar study in $Z \rightarrow \mu \tau_{\text{had}}$
  - $Br(Z \rightarrow \mu \tau) < 1.69 \times 10^{-5}$
Non-SM Decays: Invisible or partially invisible

- Invisible Higgs boson decay direct search using “tagged” production modes
  - most sensitive channel is VBF production

Higgs boson decay to one or two photons + invisible particles (inspired by neutrino to graviton + photon)

\[ \sigma \text{BR}_{\text{inv}} < 0.25 \text{ @ 95\% CL} \]

\[ \sigma \text{BR}_{\text{inv}} < 0.36 \text{ @ 95\% CL} \]
Constraints on new Phenomena

WIMP

• Higgs portal model of dark matter introduce an additional weakly interacting massive particle (WIMP) as a dark matter candidate

• assumption: resulting Higgs boson decays to WIMP pairs account entirely for BR to invisible particles
  • observed upper limit BR to invisible < 0.22 at 90% CL

• translated to the couplings of the WIMP to the Higgs boson as a function of its mass
Non-SM Decays: h→aa

- inspired by NMSSM: can have pseudo scalar state “a” much lighter than h(125)
  - h(125)→aa → 4µ, 2τ2µ, 4τ, 2b2µ, ...
- no excess found, limits on BR

\[ \text{BR}(H \rightarrow \mu^+ \mu^- b\bar{b}) < 9 \times 10^{-4} \]
Summary

- From run 1 data, properties of h(125) are consistent with SM predictions
  - spin and parity
  - width
  - couplings (not discussed in this talk), typical accuracy ~ 10-20% on coupling measurements depending on assumptions
    - could be enough room for BSM contributions
  - no BSM decays observed, small excess in LFV channel

- 2015 data does not have the sensitivity of run 1 data for h(125)
- 2016 data should improve significantly sensitivity over run 1
BACKUP
Direct Measurements of Spin

- measure differential x-sections to test **directly** the compatibility of data with the spin-0 hypothesis
- as a function of the production angle $|\cos \theta^*|$
- spin-sensitive: **isotropic** for spin-0, polynomial for other spin values
Effective Field Theory Approach

- effective Lagrangian to describe the interaction of a spin-0 particle with vector bosons

\[ \mathcal{L}_0^W = \left\{ \cos \alpha \kappa_{\text{SM}} \left[ \frac{1}{2} g_{\text{HW}W_\mu W^{-\mu}} \right] - \frac{1}{2} \frac{1}{\Lambda} \left[ \cos \alpha \kappa_{\text{HW}W_\mu W^{-\mu}} + \sin \alpha \kappa_{\text{AW}W_\mu W^{-\mu}} \right] \right\} X_0 \]

- \( k = \) dimensionless coupling parameters (real) and \( \alpha \) is the mixing angle
  - SM case: \( \cos \alpha = 1 \) and \( k_{\text{SM}} = 1 \), CP-odd case: \( \cos \alpha = 0 \) and \( k_{\text{AVV}} \neq 0 \)
  - mixed state: \( 0 < \cos \alpha < 1 \) and \( k_i \neq 0 \)

- CP-odd scan: \( \frac{\tilde{\kappa}_{\text{AVV}}}{\kappa_{\text{SM}}} \tan \alpha \)
- CP-even scan: \( \frac{\tilde{\kappa}_{\text{HVV}}}{\kappa_{\text{SM}}} \)
### Spin and Parity

excluded at more than 99.9% CL

<table>
<thead>
<tr>
<th>Tested Hypothesis</th>
<th>$p^\text{alt}_{\text{exp},\mu=1}$</th>
<th>$p^\text{alt}_{\text{exp},\mu=\mu}$</th>
<th>$P^\text{SM}$</th>
<th>$P^\text{alt}_\text{obs}$</th>
<th>Obs. CLs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+_h$</td>
<td>$2.5 \times 10^{-2}$</td>
<td>$4.7 \times 10^{-3}$</td>
<td>0.85</td>
<td>$7.1 \times 10^{-5}$</td>
<td>$4.7 \times 10^{-2}$</td>
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<tr>
<td>$0^-$</td>
<td>$1.8 \times 10^{-3}$</td>
<td>$1.3 \times 10^{-4}$</td>
<td>0.88</td>
<td>$&lt; 3.1 \times 10^{-5}$</td>
<td>$&lt; 2.6 \times 10^{-2}$</td>
</tr>
<tr>
<td>$2^+(\kappa_q = \kappa_g)$</td>
<td>$4.3 \times 10^{-3}$</td>
<td>$2.9 \times 10^{-4}$</td>
<td>0.61</td>
<td>$4.3 \times 10^{-5}$</td>
<td>$1.1 \times 10^{-2}$</td>
</tr>
<tr>
<td>$2^+(\kappa_q = 0; p_T &lt; 300GeV)$</td>
<td>$&lt; 3.1 \times 10^{-5}$</td>
<td>$&lt; 3.1 \times 10^{-5}$</td>
<td>0.52</td>
<td>$&lt; 3.1 \times 10^{-5}$</td>
<td>$&lt; 6.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$2^+(\kappa_q = 0; p_T &lt; 125GeV)$</td>
<td>$3.4 \times 10^{-3}$</td>
<td>$3.9 \times 10^{-4}$</td>
<td>0.71</td>
<td>$4.3 \times 10^{-5}$</td>
<td>$1.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>$2^+(\kappa_q = 2\kappa_g; p_T &lt; 300GeV)$</td>
<td>$&lt; 3.1 \times 10^{-5}$</td>
<td>$&lt; 3.1 \times 10^{-5}$</td>
<td>0.28</td>
<td>$&lt; 3.1 \times 10^{-5}$</td>
<td>$&lt; 4.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$2^+(\kappa_q = 2\kappa_g; p_T &lt; 125GeV)$</td>
<td>$7.8 \times 10^{-3}$</td>
<td>$1.2 \times 10^{-3}$</td>
<td>0.80</td>
<td>$7.3 \times 10^{-5}$</td>
<td>$3.7 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coupling ratio</th>
<th>Best-fit value</th>
<th>95% CL Exclusion Regions</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\kappa}<em>{HVV}/\kappa</em>{SM}$</td>
<td>$-0.48$</td>
<td>$(-\infty, -0.55] \cup {4.80, \infty)$</td>
<td>$(-\infty, -0.73] \cup {0.63, \infty)$</td>
<td></td>
</tr>
<tr>
<td>$(\tilde{\kappa}<em>{AVV}/\kappa</em>{SM}) \cdot \tan \alpha$</td>
<td>$-0.68$</td>
<td>$(-\infty, -2.33] \cup {2.30, \infty)$</td>
<td>$(-\infty, -2.18] \cup {0.83, \infty)$</td>
<td></td>
</tr>
</tbody>
</table>

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**Observed 95% CL limits**

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$

- $f_{g_2} < 0.053$ for $\phi_{g_2} = 0$
- $f_{g_2} < 0.20$ for $\phi_{g_2} = \pi$
- $f_{g_4} < 0.78$ for $\phi_{g_4} = 0$
- $f_{g_4} < 0.84$ for $\phi_{g_4} = \pi$

$H \rightarrow ZZ^* \rightarrow 4\ell$

- $f_{g_2} < 0.68$ for $\phi_{g_2} = 0$
- $f_{g_2} < 0.16$ for $\phi_{g_2} = \pi$
- $f_{g_4} < 0.11$ for $\phi_{g_4} = 0$
- $f_{g_4} < 0.54$ for $\phi_{g_4} = \pi$

Combination of $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

- $f_{g_2} < 0.12$ for $\phi_{g_2} = 0$
- $f_{g_2} < 0.16$ for $\phi_{g_2} = \pi$
- $f_{g_4} < 0.090$ for $\phi_{g_4} = 0$
- $f_{g_4} < 0.41$ for $\phi_{g_4} = \pi$
"Tensor Structure H to $\gamma\gamma$"

- Test strength and tensor structure of the Higgs boson’s interactions using an effective Lagrangian, which introduces additional CP-even and CP-odd interactions.

- The parameters of the effective Lagrangian are probed using a fit to differential cross sections:

\[-0.08 < \tilde{\kappa}_{HV} / \kappa_{SM} < 0.09\]
\[-0.22 < \tan(\alpha) \cdot \tilde{\kappa}_{AV} / \kappa_{SM} < 0.2\]

- Limits are approximately 7 times stronger than those from an angular analysis in the ZZ and WW channels due to increased sensitivity to the different Higgs boson production channels arising from the inclusion of rate and jet kinematic information in the signal hypothesis.
Lepton Flavour Violation

\[
\text{Br}(Z \to \mu\tau)[10^{-5}] \\
\begin{array}{ccc}
\text{Expected limit} & 2.6^{+1.1}_{-0.7} & 6.4^{-1.8}_{+2.8} & 2.6^{+1.1}_{-0.7} \\
\text{Observed limit} & 1.5 & 7.9 & 1.7 \\
\text{Best fit} & -2.1^{+1.2}_{-1.3} & 2.6^{+2.9}_{-2.6} & -1.6^{+1.3}_{-1.4}
\end{array}
\]
Lepton Flavour Violation: $Z$ to $\mu\tau$

- search performed in the final state with hadronic decaying tau

![Graphs showing $m_{\mu\tau}^{MMC}$ distribution for ATLAS events SR1 and SR2.](image_url)