BEH Boson (CMS)

From Discovery to precision measurements

Outline

- 'Ἐν ἀρχῇ ἦν ὁ ...., a bit of history: ..
- Higgs properties after Run I
- First results at 13 TeV
- Implications
- Future perspectives
History: a long hunt since 1969

The legacy of LEP, SLC, Tevatron, first LHC searches on SM BEH state

Fits to SM precision measurements prefer a low mass value and exclusion regions are compatible with the fit
Higgs properties after RUN I

The expectations at LHC

- **gluonFusion**
- **Vector Boson Fusion**
- **VH (Higgs-strahlung)**
- **ttH**

**Production**

**Decay**

SM predictions of production/decay properties depend on the mass
Higgs properties after RUN I

The mass

Two final states with peaks: the same channels relevant for the discovery are giving a precise measurement of the mass.

\[ H \rightarrow \gamma\gamma \rightarrow \] EPCJ 74 (2014) 3076

\[ H \rightarrow ZZ^* \rightarrow 4l: \] PRD 89 (2014) 092007

124.70\pm0.31\text{(stat)}\pm0.15\text{(syst)} \text{ GeV}

125.6\pm0.4\text{(stat)}\pm0.2\text{(syst)} \text{ GeV}

\begin{align*}
125.02 &\pm0.26 \text{ (stat)} \pm0.14 \text{ (syst)} \text{ GeV} \\
\end{align*}

NB1: dominated by stat. errors; systematic from detector calibr. (Energy/momentum scale)

NB2: difference within \(\sim 1.6 \sigma\)

NB3: evaluations from other channels (less precise) compatible with this result.

NB4: ATLAS+CMS PRL 114 191803 (2015) \(m_H=125.09\pm0.24 \pm 0.21\pm0.11\)
Higgs properties after RUN I

The mass

Once mass is known SM predicts all production/decay properties
Higgs properties after RUN I

Spin-parity

Crucial to determine the nature of the particle: it is a BEH boson if it is a scalar: is $J^P=0^+$ hypothesis the most probable?

Variables used to discriminate: $\Phi \theta_1 \theta_2$

Combining all the discriminant observables, define the signal plus background likelihood functions $L_{J^P}$ for a given $J^P$ hypothesis.

Test statistics to compare that hypothesis with the SM one ($0^+$) is $q = -\ln \left( \frac{L_{J^P}}{L_{0^+}} \right)$

The expected distributions of $q$ for both hypotheses are obtained with Monte Carlo pseudo-experiments.

From the ratio of cumulative probabilities $P_{J^P} = P(q > q_{obs} | J^P)$

the hypothesis $0^+$ is excluded at the 99.9% C. L.
Higgs properties after RUN I

Other Boson channel: WW

For \( m_h = 125 \text{ GeV} \): WW 2\textsuperscript{nd} largest SM Branching Ratio

Due to background \( \Rightarrow \) only \( H \rightarrow WW \rightarrow l^+ l^- \) (no invariant mass): \( m_{ll} \)

\[
m_T = \sqrt{2 p_T^{ll} E_T^{\text{miss}} (1 - \cos \Delta \phi_{ll}, E_T^{\text{miss}})}
\]

Observed (expected) Significance w.r.t. bckg only hypothesis:

\( 4.3 \sigma \) (5.8) @ 125.6

Relevant to study VBF and VH production
Higgs properties after RUN I

The fermionic channels: $H \rightarrow \tau\tau$

Yukawa coupling with fermions proportional to their mass

$\Rightarrow$ for leptonic decay only $H \rightarrow \tau\tau$ is visible at present

neutrino’s in the final state:
peak reconstruction problematic
(with a much larger peak from $Z \rightarrow \tau\tau$)

Significance w.r.t. bckg only hyp.: $3.2 \sigma$ (3.7)

** only limits for $H \rightarrow \mu\mu$ (end ee)

Evidence: no flavor universality for leptons in the BEH decay
Higgs properties after RUN I

The fermionic channels: $H \rightarrow b\bar{b}$

The most copious decay channel is embedded in a huge QCD $b\bar{b}$ background.

Limit the analysis to associated production (VH)

Significance w.r.t. bckg only hyp.: $2.1 \, \sigma$ (2.1)

NB combined with $\tau\tau$ $3.8 \, \sigma$: evidence for fermionic coupling

And VBF

Significance w.r.t. bckg only hyp.: $2.2 \, \sigma$ (0.8)
Higgs properties after RUN I

**ttH production**

Several categories depending on H decay (3: bb, γγ, multiLeptons) and t decay (3: sl, dl, h)

Significance w.r.t. bckg only hyp.: 3.4 σ (1.2)

Higher than expected:
if SM signal is considered excess of ~2 σ

New: Matrix Element Method to improve signal/ background separation: each event is assigned a p.d.f. based on theoretical differential cross section

Single lepton and double lepton for t only H → bb

Limit: <4.2 σ_{SM} (3.3)
(4.1 with H SM)
Couplings

Some formalism

A direct comparison with SM expectation is convenient:

$$g_{HVV} = \frac{2m_V^2}{v}$$

$$g_{Hff} = \frac{m_f}{v}$$

SM coupling to V bosons:  

<table>
<thead>
<tr>
<th>Name</th>
<th>Meaning</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal strength</td>
<td>$\frac{\sigma(BR)}{\sigma^{SM}(BR^{SM})}$</td>
<td>$\mu$</td>
</tr>
<tr>
<td>Coupling modifiers</td>
<td>$\frac{g_{HXX}}{g^{SM}_{HXX}}$</td>
<td>$\kappa_X$</td>
</tr>
<tr>
<td>Total width modifier</td>
<td>$\frac{\Gamma_{tot}}{\Gamma^{SM}_{tot}}$</td>
<td>$\kappa_H^2$</td>
</tr>
<tr>
<td>Ratio of coupling modifiers</td>
<td>$\frac{\kappa_X}{\kappa_Y}$</td>
<td>$\lambda_{XY}$</td>
</tr>
</tbody>
</table>

When the coupling is not direct (e.g. in gluon fusion production or $\gamma\gamma$ decay) : calculated in terms of direct parameters:  

$$\kappa_g = \kappa_g(\kappa_b, \kappa_t, m_H)$$  

$$\kappa_\gamma = \kappa_\gamma(\kappa_b, \kappa_t, \kappa_W, m_H)$$

arXiv:1307.1347
Couplings

\[
\mu(\sigma/\sigma_{SM}) = 1.00 \pm 0.14
\]

Production

Decay

Custodial symmetry: equal coupling modifiers for W and Z: \( \lambda_{WZ} = \kappa_W / \kappa_Z = 1 \)

Since

\[
\lambda_{WZ} = \frac{0.92 \pm 0.14}{-0.12}
\]

Assumed to be valid: \( \kappa_W = \kappa_Z \equiv \kappa_V \)
Couplings

Compatible with SM
(also the combination ATLAS-CMS)

\[ \kappa_V = 1.01^{+0.07}_{-0.07} \]
\[ \kappa_f = 0.87^{+0.14}_{-0.13} \]

**several assumptions**

\[ \lambda_f \sim \kappa_f m_f / \nu \]
\[ \left[ g_{V}/(2\nu) \right]^{1/2} \sim (\kappa_V)^{1/2} \quad m_V / \nu \]

\[ \nu = \text{VEV} \approx 246 \text{ GeV} \]
First Results at 13 TeV*

\( H \rightarrow ZZ^* \rightarrow 4l: \)

HIG-15-004

Significance w.r.t. bckg only hyp.: 
\[ 2.5 \sigma \ (3.4) \]

\[ \mu = \sigma / \sigma_{SM} = 0.82^{+0.57}_{-0.43} \]

Fiducial cross section compared with results at 7 and 8 TeV

*Only 2015 data
First Results at 13 TeV

H → γγ

Several categories
Significance w.r.t. bckg only hyp.: 1.7 σ (2.7)

$\mu = \frac{\sigma}{\sigma_{SM}} = 0.69^{+0.47}_{-0.42}$
First Results at 13 TeV

H→WW

WW→eμ 0/1 jet

Signal/bckg as function of \(m_{ll}\) and \(m_H^T\)

events divided in 4 categories: \(μe, eμ\) (leading \(p_T\))

0j , 1j

Two dimensional plot (\(m_{ll}, m_T^H\))

Significance w.r.t. bckg only

hyp.: 0.7 \(σ\) (2.0)
First Results at 13 TeV

VBF H→bb

VBF: events in 4 jets
1 or 2 b tag and BDT categorization

HIG-16-003

No evidence yet @ 13 TeV

Combined with RUN I:

significance w.r.t. bckg only hyp.: 1.2 σ

\( \mu = \sigma / \sigma_{SM} = 1.3^{+1.2}_{-1.1} \)
First Results at 13 TeV

**ttH(bb)**

HIG-16-004

**ttH(\gamma\gamma)**

HIG-15-005

**ttH multileptons**

HIG-15-008

dileptons and l+j

\geq 2 \ b \ tag \ and \ other \ categorizations

Leptonic or hadronic \ tt

\geq 2 \ j \ \geq 5 \ j

\geq 1 \ b \ tag

and other \ \gamma\gamma \ BDT \ cat.

ss \ dileptons \ or \ \geq 3 \ l

\geq 4 \ j \ \geq 5 \ j

\geq 1 \ b \ tag

and other \ cat.

\sigma/\sigma_{SM} < 2.6 \ (3.6)

\mu = \sigma/\sigma_{SM} = -2.0 \pm 1.8

\mu = \sigma/\sigma_{SM} = 3.8^{+4.5}_{-3.6}

Combined \ \mu = 0.15^{+0.95}_{-0.81} \ (1.00^{+0.96}_{-0.85}) \ @ \ 13 \ TeV
Implications

• The 125 GeV particle is in the range of fits to SM precision measurements
• It is a SCALAR so it is a BEH-like boson
• at that mass several accessible final states according to SM
• coupled to bosons and fermions
• all the measured production/decay products compatible with SM @that mass
• couplings do not show deviations from SM predictions
• no other states from additional H doublets have been found despite…
  • No other signals of new physics discovered (yet)

The above does not prove this is the SM BEH boson:
Lightest states of more complex H sectors may have similar properties

The value $m_H=125$ GeV is within the SUSY-accepted range

More precise measures are necessary
Perspectives

Short time scale

• The 2016 LHC run is going to confirm (or exceed?) the expectations
• CMS is taking data with a good efficiency
• ggF production increased by ~2.2 @ 13 TeV w.r.t. 8 TeV (but ~ 3.9 for ttH)
• “rediscovery” with the same RUN I accuracy possible with half lumi

• results coming soon
• likely at the end of 2016 a relevant improvement on the measured values
• A factor 2 reduction on uncertainties (?)
Perspectives

middle time scale

- Following plans LHC should deliver **300-350 /fb (@ 13 and/or 14 TeV)**

**Expected CMS precisions with integrated lumi of 300/fb @ 14 TeV**

\[
\begin{align*}
\kappa_\gamma & \quad \kappa_W & \quad \kappa_Z & \quad \kappa_g & \quad \kappa_b & \quad \kappa_t & \quad \kappa_\tau & \quad \kappa_{Z\gamma} & \quad \kappa_\mu \\
[5, 7] & \quad [4, 6] & \quad [4, 6] & \quad [6, 8] & \quad [10, 13] & \quad [14, 15] & \quad [6, 8] & \quad [41, 41] & \quad [23, 23] \quad (\Delta \kappa/\kappa \%) 
\end{align*}
\]

- Theory uncertainties begin to play a role

The increase in E and Lumi gives **an opportunity to observe heavy H states** as foreseen by MSSM or to extend the excluded region in \(m_A\)-\(\tan\beta\) plane.

If the discovered particle is the lightest CP-even state \(h\), \(m_A<230-260\) excluded for all \(\tan\beta\) values.
Perspectives

long time scale

• HL LHC recently officially approved! 3000/fb (@ 14 TeV)

theory uncertainties play a crucial role

rare signals as ....

pair production

to measure the self coupling parameter

.... H→μμ
The discovery of the BEH particle has been not only one of the most important results in particle Physics but also one of the most relevant scientific achievements. The discovery requires several further actions that will engage the HEP community for several years. In particular, try to give an answer to:

- Is the new particle really the SM BEH Boson?
- Is it an elementary particle? Or...
- Is it a composite particle?
- Is it natural?
- Are there other Higgs fields?
- Is it really responsible for the mass of all elementary particles?

And also:

- Is it at the origin of the matter-antimatter asymmetry?
- Does it have a role in the inflationary expansion of the Universe?

More and more precise measures are necessary.
ευχαριστώ
MORE Slides
Higgs properties after RUN I

Spin-parity

Crucial to determine the nature of the particle:

- it is a BEH boson if it is a scalar: is \( J^p = 0^+ \) hypothesis the most probable?

- Spin 1 ~ ruled out by the two photon final state (..and by measurements)
- Several models for spin-2 are disfavored or excluded by kinematic properties of final states
- Can we distinguish between \( 0^+ \) and \( 0^- \)?

Yes:

Mainly from \( H \rightarrow ZZ^* \rightarrow 4 l \)

as in the past the parity of \( \pi^0 \) was determined from \( \pi^0 \rightarrow \gamma^* \gamma^* \rightarrow e^+e^-e^+e^- \):


The width

The expected width @ 125 GeV is ~4 MeV.
Too large…. and too narrow…. to be measured.

Direct measurement of peak width dominated by experimental resolution $\Theta$(GeV)

But * for VV final states the off-shell contribution is relevant:

$$\sigma_{\text{on-shell}} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{\Gamma_H m_H}$$
$$\sigma_{\text{off-shell}} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(2m_Z)^2}$$

Positive off-shell signal compared to on-shell prop to $\Gamma_H/\Gamma_H^{SM}$, considering negative interference with $gg\rightarrow ZZ$ bckg ($\sqrt{\Gamma_H/\Gamma_H^{SM}}$)

Including information from WW final state and VBF process  

$$\Gamma_H < 13 \ (26) \ \text{MeV} @ 95\% \ \text{CL}$$

N. Kauer, G. Passarino
arXiv:1605.02329
Higgs properties after RUN I

Observed and expected excesses at 125 GeV  

<table>
<thead>
<tr>
<th>Channel grouping</th>
<th>Significance (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>H → ZZ tagged</td>
<td>6.5</td>
</tr>
<tr>
<td>H → γγ tagged</td>
<td>5.6</td>
</tr>
<tr>
<td>H → WW tagged</td>
<td>4.7</td>
</tr>
<tr>
<td><em>Grouped as in Ref.</em></td>
<td>4.3</td>
</tr>
<tr>
<td>H → ττ tagged</td>
<td>3.8</td>
</tr>
<tr>
<td><em>Grouped as in Ref.</em></td>
<td>3.9</td>
</tr>
<tr>
<td>H → bb tagged</td>
<td>2.0</td>
</tr>
<tr>
<td><em>Grouped as in Ref.</em></td>
<td>2.1</td>
</tr>
<tr>
<td>H → μμ tagged</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

*References:
JHEP 01 (2014) 096
JHEP 05 (2014) 104
Phys. Rev. D 89 (2014) 012003*
Couplings

Fit assumptions

• the signals on different channels are supposed to come from the same resonance with a well defined mass
• the width is supposed to be narrow so that the zero-width approximation can be used
• SM tensor structure of the Lagrangian is assumed while the couplings are free to vary

\[ \kappa_W = \kappa_Z = \kappa_V \]

\[ \kappa_t = \kappa_b = \kappa_\tau = \kappa_g = \kappa_f \]

with the further assumption that \( \kappa_g \) depends only on the fermion contribution without additional contributions
<table>
<thead>
<tr>
<th>Model parameters</th>
<th>Table in Ref. [171]</th>
<th>Parameter</th>
<th>Best-fit result</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_Z, \lambda_{WZ}$ ($\kappa_T = 1$)</td>
<td>–</td>
<td>$\lambda_{WZ}$</td>
<td>$0.94_{-0.18}^{+0.22}$</td>
<td>$\lambda_{WZ} = \kappa_W/\kappa_Z$ from ZZ and 0/1-jet WW channels</td>
</tr>
<tr>
<td>$\kappa_Z, \lambda_{WZ}, \kappa_T$</td>
<td>44 (top)</td>
<td>$\lambda_{WZ}$</td>
<td>$0.92_{-0.12}^{+0.14}$</td>
<td>$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination</td>
</tr>
<tr>
<td>$\kappa_V, \kappa_T$</td>
<td>43 (top)</td>
<td>$\kappa_V$</td>
<td>$1.01_{-0.07}^{+0.07}$</td>
<td>$\kappa_V$ scales couplings to $W$ and $Z$ bosons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_T$</td>
<td>$0.87_{-0.13}^{+0.14}$</td>
<td>$\kappa_T$ scales couplings to all fermions</td>
</tr>
<tr>
<td>$\kappa_V, \lambda_{d_{u}}, \kappa_U$</td>
<td>46 (top)</td>
<td>$\lambda_{d_{u}}$</td>
<td>$0.99_{-0.18}^{+0.10}$</td>
<td>$\lambda_{d_{u}} = \kappa_u/\kappa_d$, relates up-type and down-type fermions</td>
</tr>
<tr>
<td>$\kappa_V, \lambda_{e_{q}}, \kappa_q$</td>
<td>47 (top)</td>
<td>$\lambda_{e_{q}}$</td>
<td>$1.03_{-0.21}^{+0.23}$</td>
<td>$\lambda_{e_{q}} = \kappa_{e_q}/\kappa_q$, relates leptons and quarks</td>
</tr>
<tr>
<td>$\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_T, \kappa_{\mu}$</td>
<td>Extends 51</td>
<td>$\kappa_W$</td>
<td>$0.95_{-0.13}^{+0.14}$</td>
<td>$\kappa_T = \sqrt{m_{W}^{2}/M^{2} + \mu_{W}}$ and $\kappa_V = \sqrt{m_{Z}^{2}/M^{2} + \mu_{Z}}$ (Sect. 7.4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_Z$</td>
<td>$1.05_{-0.16}^{+0.16}$</td>
<td>$\kappa_t$ scales the coupling to tau leptons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_t$</td>
<td>$0.81_{-0.15}^{+0.10}$</td>
<td>$\kappa_b$ scales the coupling to muons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_b$</td>
<td>$0.74_{-0.29}^{+0.33}$</td>
<td>$\kappa_b$ scales the coupling to up-type fermions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_T$</td>
<td>$0.84_{-0.18}^{+0.19}$</td>
<td>$\kappa_{\mu}$ scales the coupling to muons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_{\mu}$</td>
<td>$0.49_{-0.49}^{+0.38}$</td>
<td></td>
</tr>
<tr>
<td>$M, \epsilon$</td>
<td>Ref. [206]</td>
<td>$M$ (GeV)</td>
<td>$245 \pm 15$</td>
<td>$\epsilon = 0.014_{-0.036}^{+0.041}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$[-0.054, 0.100]$</td>
</tr>
<tr>
<td>$\kappa_g, \kappa_{\gamma}$</td>
<td>48 (top)</td>
<td>$\kappa_g$</td>
<td>$0.89_{-0.10}^{+0.11}$</td>
<td>Effective couplings to gluons ($g$) and photons ($\gamma$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_{\gamma}$</td>
<td>$1.14_{-0.13}^{+0.12}$</td>
<td></td>
</tr>
<tr>
<td>$\kappa_g, \kappa_{\gamma}, \text{BR}_{\text{BSM}}$</td>
<td>48 (middle)</td>
<td>$\text{BR}_{\text{BSM}}$</td>
<td>$\leq 0.14$</td>
<td>$[0.00, 0.32]$</td>
</tr>
<tr>
<td>With $H(\text{inv})$ searches</td>
<td>–</td>
<td>$\text{BR}_{\text{inv}}$</td>
<td>$0.03_{-0.03}^{+0.15}$</td>
<td>$H(\text{inv})$ use implies $\text{BR}_{\text{undet}} = 0$</td>
</tr>
<tr>
<td>With $H(\text{inv})$ and $\kappa_t = 1$</td>
<td>–</td>
<td>$\text{BR}_{\text{inv}}$</td>
<td>$0.06_{-0.06}^{+0.11}$</td>
<td>Assumes $\kappa_t = 1$ and uses $H(\text{inv})$</td>
</tr>
<tr>
<td>$\kappa_{e_{g}}, \lambda_{WZ}, \lambda_{Zg}, \lambda_{Zc}, \lambda_{YZ}, \lambda_{TZ}, \lambda_{t_{g}}$</td>
<td>50 (bottom)</td>
<td>$\kappa_{e_{g}}$</td>
<td>$0.98_{-0.13}^{+0.14}$</td>
<td>$\kappa_{e_{g}} = \kappa_g/\kappa_H$, i.e. floating $\kappa_H$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda_{WZ}$</td>
<td>$0.87_{-0.13}^{+0.15}$</td>
<td>$\lambda_{WZ} = \kappa_W/\kappa_Z$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda_{Zg}$</td>
<td>$1.39_{-0.28}^{+0.36}$</td>
<td>$\lambda_{Zg} = \kappa_Z/\kappa_g$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda_{bZ}$</td>
<td>$0.59_{-0.23}^{+0.22}$</td>
<td>$\leq 1.07$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda_{YZ}$</td>
<td>$0.93_{-0.14}^{+0.17}$</td>
<td>$\lambda_{YZ} = \kappa_{\gamma}/\kappa_Z$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda_{TZ}$</td>
<td>$0.79_{-0.17}^{+0.10}$</td>
<td>$\lambda_{TZ} = \kappa_{\gamma}/\kappa_Z$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda_{t_{g}}$</td>
<td>$2.18_{-0.46}^{+0.54}$</td>
<td>$\lambda_{t_{g}} = \kappa_t/\kappa_{e_{g}}$</td>
</tr>
</tbody>
</table>
First Results at 13 TeV

**H → WW**   **WW → eμ 0/1 jet**

Significance w.r.t. bckg only: 0.7 σ (2.0)
First Results at 13 TeV

Paolo Checchia for CMS collaboration