COMBINATION OF RESULTS ON THE HIGGS BOSON & MEASUREMENT OF ITS PROPERTIES AT CMS

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on behalf of the CMS collaboration
Higgs signatures explored at CMS

- CMS explored a large set of accessible signatures
  - Strong evidence in bosonic & fermionic channels!
  - Details on individual bosonic and fermionic decays in talks by X. Janssen & J. Konigsberg (Higgs I)
    Higgs overview talk by M. Klute (SM Higgs plenary)

- Significant set of explored signatures used for combined measurements

<table>
<thead>
<tr>
<th>Channels explored by CMS, subset used for combined results</th>
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<tbody>
<tr>
<td>inclusive (ggH)</td>
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<tr>
<td>-----------------</td>
</tr>
<tr>
<td>VBF tag</td>
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<td>VH tag</td>
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<td>ttH tag</td>
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- ✔  : combined properties measurement: mass, spin-parity
- ✔✔  : used for combination results: deviations of couplings (CMS-HIG-13-005)

<table>
<thead>
<tr>
<th>Signal significance</th>
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<tbody>
<tr>
<td>Decay</td>
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<tr>
<td>Expected [σ]</td>
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<tr>
<td>Observed [σ]</td>
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Note: Expected [σ] and Observed [σ] values for various decays.
Mass of the new boson

• Mass measurement using high resolution channels:
  \( H \rightarrow ZZ \rightarrow 4l \)
  • Very good control of the leptons scale and resolution, exploits per-event mass uncertainties

\( H \rightarrow \gamma\gamma \)
• Good resolution, systematics on the extrapolation from the \( Z \rightarrow ee \) to \( H \rightarrow \gamma\gamma \)

• Combined mass measurement (2013)
  • individual signal strengths independently profiled

\[ m_H = 125.7 \pm 0.3_{\text{STAT}} \pm 0.3_{\text{Syst}} \text{ GeV} \]

• Latest measurement in \( H \rightarrow ZZ \rightarrow 4l \) (2014)
  • public results: CMS-HIG-13-002

\[ m_H = 125.6 \pm 0.4_{\text{STAT}} \pm 0.2_{\text{Syst}} \text{ GeV} \]

See talk by X. Janssen for details on individual channels
Alternative $J^P$ hypotheses

- Tested the compatibility of the new boson with alternative $J^P$ hypotheses
- exploit shapes of kinematic observables (angles, inv. masses)
  $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow 2l2\nu$, $H \rightarrow \gamma\gamma$
- HWW tested spin-2 hypotheses ($2m^+$) for diff. prod. mechanisms
- Many hypotheses excluded using the $HZZ$ channel @99%C.L.

- Combined test for hypothesis $gg \rightarrow 2m^+$ (HWW & HZZ, 2013)
  - Hypothesis $gg \rightarrow 2m^+$ is excluded at 99% CL

$J^P = 0^+$ strongly favoured by measurements
CP-odd contribution in $H \rightarrow ZZ \rightarrow 4l$ decays

• Probe for fractional presence of the CP-odd contribution ($0^-$) in the scalar decays:

$$A(X \rightarrow VV) = v^{-1} \varepsilon_1^\ast \varepsilon_2^\ast (a_1 g_{\mu\nu} m_H^2 + a_2 q_{\mu\nu} + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta) = A_1 + A_2 + A_3$$

$A_2$ contribution assumed to be 0

• $0^+_m / 0^-$ decays governed by the $A_1 / A_3$ amplitudes (total x-sections $\sigma_{0^+_m} / \sigma_{0^-}$),

• Explore it using $H \rightarrow ZZ \rightarrow 4l$ decay channel

• Total cross-section insensitive to interference between the CP-odd and CP-even components

• Use shapes of kinematic observables for SM Higgs ($0^+_m$) and $0^-$ states and fit the data for their relative presence (the total event yield is taken from data)

$$f_{a3} = \frac{\sigma_{0^-}}{\sigma_{0^+_m} + \sigma_{0^-}}$$

defined for $2e2\mu$ final state

Upper limit on the fractional x-section $f_{a3}$ in data:

$$f_{a3} < 0.51 \text{ (@95%CL)}$$
Search for deviations - Production modes

- Signal strength ($\mu$) results explored for various decay and production modes
  - Results from individual modes compatible to SM Higgs predictions!
  - probe the couplings by expanding around that reference point!

- Ratio of $\mu$s in production modes with fermionic and bosonic couplings: $\mu_{VBF,VH}/\mu_{ggH,ttH}$
  - Best-fit $\mu_{VBF,VH}/\mu_{ggH,ttH} = 1.538^{+1.16}_{-0.743}$ (3.2$\sigma$ against a zero ratio)

  
  "evidence for vector-boson induced production!"
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Most of the updated results ready: New CMS Higgs combination coming soon...

NEW: April 2014
**Search for deviations - Couplings**

- **Search for deviations from SM in the scalar couplings (LHC XS WG benchmarks)**

- **Assumptions:**
  - Observed signals originate from a single narrow resonance
  - Parametrise deviations only with couplings strengths modifiers \{κ_x\}

- **Procedure:**
  - Scale SM x-sections & SM partial widths as function of parameters \{κ_x\}.

\[
(\sigma \cdot BR)(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}
\]

- In cases of loop processes, κ_x can be expressed as a function of more fundamental κ_y
  - If BSM decays are allowed - scale down all SM decays uniformly

- **Scenarios:**
  - Fermion vs. vector boson couplings and asymmetries in couplings
  - Searches for new physics in loops and decays
  - Simultaneous fit of coupling modifiers

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Asymmetries in couplings

• Test universality between couplings/modifiers to vector bosons and fermions 
  \((k_Z = k_W = k_V \text{ and } k_t = k_b = k_\tau = k_f)\)

• In \(H \rightarrow \gamma\gamma\) loop we are sensitive to sign of \(k_f k_V\) through interference (choose \(k_V > 0\))

\[
\begin{align*}
  k_Z &= k_W = k_V \\
  k_t &= k_b = k_\tau = k_f
\end{align*}
\]

compatible with SM (\(k_f = k_V\)), clear preference for \(k_f > 0\)

• Also tested (HIG-13-005): Custodial symmetry, lepton-quark and up-down universality

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New physics in loops and decays

- Probe for new physics in loops - allow general $\kappa_g$ & $\kappa_\gamma$ modifiers of $ggH$ and $H\gamma\gamma$
  - Assume no additional new physics in Higgs width, all other SM tree-level couplings
- Probe new physics in loops & decays - allow $\kappa_g$ & $\kappa_\gamma$ modifiers with $BR_{BSM} > 0$
  - Constrain total width from observed $\sigma \cdot BR$'s assuming SM tree-level couplings

Effective couplings to gluons and photons in agreement with SM

$BR_{BSM} < 0.52$ @ 95%C.L.
Simultaneous fit of coupling modifiers

• Probe for 6 couplings simultaneously: $\kappa_V, \kappa_t, \kappa_b, \kappa_T, \kappa_g, \kappa_\gamma$

  • assume custodial and up-down fermion symmetry:
    $\kappa_W = \kappa_Z = \kappa_V$ & $\kappa_u = \kappa_c = \kappa_t$ & $\kappa_d = \kappa_s = \kappa_b$ & $\kappa_e = \kappa_\mu = \kappa_T$

• No BSM decays: $BR_{BSM} = 0$

• In addition allow $BR_{BSM} > 0$, by adding requirement $\kappa_V \leq 1$ (common in EWSB)

All effective couplings in good agreement with SM
Searches for H→invisible

• Performed search using the VBF and associated ZH production modes

• Sensitive to non-SM invisible decays of the observed Higgs boson,
  • also sensitive to additional bosons with similar production and large invisible BR

• Combined all search VBF/ZH channels

Upper limit on the invisible BR, m_H=125GeV

\[ \text{BR}_{\text{invisible}} < 0.58 \text{ @ 95% C.L.} \]

• Results also interpreted in terms of a Higgs-portal model of DM interactions.
  • DM interaction with nucleons through Higgs exchange diagram
  • reported limits for DM candidate as scalar, vector, or Majorana fermion (CMS-HIG-13-030)
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Summary

• CMS has analysed a comprehensive set of production and decay channels
  • Measured properties combining information from different channels:
    mass: \( m_H = 125.7 \pm 0.3^{\text{STAT}} \pm 0.3^{\text{SYST}} \) GeV
    spin-parity: compatible with \( J^P = 0^+ \)
    total width: \( \Gamma < 22 \) MeV @ 95% C.L.

• A wide range of Higgs coupling tests is performed
  • No significant deviation from SM predictions observed within the uncertainties

• Combined results for \( H \rightarrow \text{invisible} \)

• Next combination of CMS results expected soon

• All measurements show: the new boson is compatible with the SM Higgs boson!
Backup slides
Compact Muon Solenoid

**Superconducting Coil**
- Silicon Microstrips
- Pixels

**Tracker**
- Drift Tube Chambers (DT)
- Resistive Plate Chambers (RPC)
- Cathode Strip Chambers (CSC)

**Calorimeters**
- ECAL: Scintillating PbWO4 crystals
- HCAL: Plastic scintillator/brass sandwich

**Iron Yoke**
- Muon Endcaps

**Total Weight**: 12,500 t
**Overall Diameter**: 15 m
**Overall Length**: 21.6 m
**Magnetic Field**: 4 Tesla
Higgs production and decay modes

Production

Decay modes and branching ratios

Main contributions:

Low mass: \( H \rightarrow \gamma \gamma, \ H \rightarrow ZZ \) (also \( H \rightarrow WW \))

Intermediate/high mass: \( H \rightarrow WW, \ H \rightarrow ZZ \)

LHC Higgs XS WG:

arXiv:1101.0593,
arXiv:1201.3084,
arXiv:1209.0040

common inputs to experiments
Constraint on Higgs boson width

- Experimental resolution strongly limits direct width ($\Gamma_H$) measurement to $\sim 1$ GeV
  - SM Higgs decay width is 4.15 MeV at $m_H = 125.6$ GeV

- Important theoretical advances [*]:
  made possible to constrain the Higgs boson width using its off-shell production & decay away from the peak.

\[ \sigma_{on-peak}^{gg \rightarrow ZZ} \propto \frac{g_{gH}^2 g_{HZZ}^2}{\Gamma} \]
\[ \sigma_{off-peak}^{gg \rightarrow ZZ} \propto g_{gH}^2 g_{HZZ}^2 \]

experimental constraints on the width $\Gamma_H$ with mild model-dependence

- Channels $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow ZZ \rightarrow 2l2\nu$
  $m_{ZZ}$ distribution can be used alone, but kinematic observables improve sensitivity (sig-bkg interference significant, accounted properly)

$\Gamma_H < 22$ MeV at 95% C.L.,
$\Gamma_H < 5.4 \times \Gamma_H, \text{SM}$

[*] JHEP 08 (2012), Phys Rev D 88 (2013) 054024, see also talk by X. Janssen for details
Mass measurement validation with $Z \to 4l$

- Perform the mass measurement of the near-by $Z \to 4l$ resonance
  - identical procedure as for the new boson mass measurement (without $\delta m_{4l}$ and $KD$),
  - relaxed phase space due to the limited statistics ($m_{Z2} > 4$ GeV)

### Fit for $Z$ mass/width in $Z \to 4l$ events

- $M_Z = 91.17 \pm 0.23 - 0.22$ GeV
- $\Gamma_Z = 2.86 \pm 0.51 - 0.47$ GeV

### Likelihood scans for $4e, 4\mu, 2e2\mu$

- Assumed $Z$ width 2.50 GeV

Compatible with the PDG values within uncertainties.