Higgs boson Couplings and Properties with CMS

Linda Finco
INFN and University of Torino

On behalf of the CMS Collaboration

XXII International Workshop on Deep-Inelastic Scattering and Related Subjects
Outline

- Higgs production and decay modes
- Properties
  - Mass measurement
  - Spin-parity measurements
  - Width measurement
- Couplings
  - Production and decay mechanisms
  - Tests of the Standard Model
- Conclusions
Production and Decay Modes

4 production mechanisms

5 decay modes exploited (WW, ZZ, γγ, bb and ττ)
Channel features

- Modest branching fraction
- Clear signature
  - 2 isolated and energetic $\gamma$
- Large background from QCD
- Excellent mass resolution

Analysis strategy

- Event categorization on photon resolution and kinematic properties
- Additional event classes according to production mechanism
- Signal extracted from background by fitting the observed diphoton mass distributions in each class
H→ZZ→4l Decay Channel

Channel features
• Very small branching fraction
• Very clean signature
  • 2 pairs of high $p_T$ and isolated $\mu$ or $e$
  • full reconstructed event topology
• Small background contribution
• Excellent mass resolution

Analysis strategy
• Event categorization according to lepton flavor
• Mass measurement performed using 3D fit with $(m_{4l}, \delta m_{4l}, D_{bkg}^{\text{kin}})$

$$D_{bkg}^{\text{kin}} = \frac{P_{\text{kin}}^{\text{sig}}}{P_{\text{kin}}^{\text{sig}} + P_{\text{kin}}^{\text{bkg}}}$$
Combination

Combination of the results obtained from $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ \rightarrow 4l$ measurements, thanks to their excellent resolution

$$m_H = 125.7 \pm 0.3\,\text{(stat.)} \pm 0.3\,\text{(syst.)} \text{ GeV}$$
SPIN and PARITY
Channel features
• Distinct signature
  • 2 isolated and high $p_T$ leptons
  • small opening angle
  • missing transverse energy
• Very poor mass resolution
• Large background

Analysis strategy
• Different-flavor 0-jet and 1-jet categories used to distinguish between $0^+$ and $2^+_m (gg \rightarrow X, qq \rightarrow X)$ or $0^- (gg \rightarrow X)$ hypotheses
• Discriminating variables: $m_T$ and $m_{ll}$

Data favor the SM hypothesis
H→ZZ→4l Decay Channel

- 2D fit using $D_{\text{bkg}}$ and $D_{\text{JP}}$ kinematic discriminants based on angular information

$D_{\text{bkg}}$ separates SM Higgs from background

$D_{\text{JP}}$ discriminates alternative $J^p$ hypothesis from SM Higgs

- Twelve models tested

$CL_S = 0.09\%$

$0^+ \text{ vs } 0^-$

$0^+$ hypothesis highly favored
WIDTH
Width Measurement

- Standard Model prediction at $m_H = 125.7$ GeV is $\Gamma \sim 4$ MeV
- Direct measurement strongly limited by experimental resolution
- Current upper limit of 3.4 (6.9) GeV at 95% C.L. in the $H \rightarrow ZZ \rightarrow 4l$ ($H \rightarrow \gamma\gamma$) channel

**Sensitivity at the resonance peak far beyond the expected width**
**Goal**: to constrain the Higgs boson width using the Higgs boson production and decay away from the resonance

**Channels**: $H \rightarrow ZZ$ decay in $4l$ and $2l2\nu$ final states

\[
\sigma_{\text{on-peak}}^{gg \rightarrow H \rightarrow ZZ} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot B)_{\text{SM}} \equiv \mu (\sigma \cdot B)_{\text{SM}}
\]

\[
\frac{d\sigma_{\text{off-peak}}^{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}} = \kappa_g^2 \kappa_Z^2 \cdot \frac{d\sigma_{\text{off-peak,SM}}^{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}} = \mu r \frac{d\sigma_{\text{off-peak,SM}}^{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}}
\]

- Signal strength $\mu$ provided by the measurement of the on-shell production
- $r$ value (and $\Gamma_H$) can be obtained by measuring the ratio of the production in the off-shell and on-shell region

**Warning**: the destructive interference with continuum $gg \rightarrow ZZ$ is not negligible at high $m_{ZZ}$
To describe all the different contributions to the final state, a likelihood is defined, depending on:

- **4ℓ final state**: $m_{4\ell}$ and a kinematic discriminant $D_{gg}$, to separate $gg\rightarrow ZZ$ and $qq\rightarrow ZZ$ processes
- **2ℓ2ν final state**: $m_T$ and $E_T^{\text{miss}}$

\[
\begin{align*}
\Gamma_H/\Gamma^\text{SM}_H &< 6.6 \ (11.5) \\
\Gamma_H/\Gamma^\text{SM}_H &< 6.4 \ (10.7) \\
\Gamma_H &< 4.2 \ (8.5) \\
\Gamma_H &< 17.4 \text{ MeV}
\end{align*}
\]
COUPLINGS
The Couplings

\[ \sigma \times BR(ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H} \]

- \(\sigma_{ii}\) and \(\Gamma_{ff}\) are proportional to the square of effective Higgs boson couplings to the corresponding particle \((\sigma_{ii} \sim g_i^2, \Gamma_{ff} \sim g_f^2)\).
- To test SM deviations, modified couplings are defined, denoted by scale factors \(k_i\).

Example: \(gg \rightarrow H \rightarrow \gamma\gamma\)

\[ \sigma \cdot BR(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \cdot BR_{SM}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2} \]

Significant deviations of any \(k\) from 1 would imply physics beyond the SM.
Production Mechanisms

**VH**
Leptons, missing $E_T$ or low-mass dijets from $W$ or $Z$ decays

**VBF**
Two high $p_T$ jets with high-mass and large pseudorapidity separation

**ttH**
Two top quarks: leptons, missing $E_T$, multijets or $b$-tagged jets

**ggF**
The rest

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L. Finco

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CMS Preliminary $m_H = 125.7$ GeV

$$\mu = 0.80 \pm 0.14$$

$$\mu = 0.78 \pm 0.16$$

$$\mu = 1.02 \pm 0.34$$

$$\mu = 1.02 \pm 0.49$$

$$\mu = -0.15 \pm 2.86$$

$$\mu = 0.52$$
Vector Boson and Fermion Couplings

- At L.O. all partial widths scale either as $k_V^2$ or $k_f^2$, except for $\Gamma_{\gamma\gamma}$ that scales as $|\alpha k_V + \beta k_f|^2$

  $\gamma\gamma$ channel is sensitive to the relative sign of $k_V$ and $k_f$

Anomalous $k_f < 0$ disfavored at $\sim 2.7\sigma$

Data are consistent with the expectation
Search for New Physics

- Processes induced by loop diagrams ($H \rightarrow \gamma\gamma$ and $gg \rightarrow H$) are particularly sensitive to new physics

Data fitted for $k_\gamma$ and $k_g$

$k_\gamma \in [0.59, 1.30]$

$k_g \in [0.63, 1.05]$

at 95% C.L.

- Higgs could decay into invisible particles or not detectable at LHC

Modified total Higgs width, left free to float in the fit

Results are compatible with the expectation

$\Gamma_{BSM} < 0.52$ at 95% C.L.
Conclusions

• The mass of the analyzed resonance is measured with high precision
• The particle is compatible within uncertainties with a SM Higgs boson and alternative spin-parity hypotheses are disfavored by the data
• The experimental constraint on Higgs total width is determined using off-shell production and decay, improving by more than two orders of magnitude the previous experimental result
• A comprehensive set of Higgs coupling fits is reported and no significant deviation from SM predictions is observed within the uncertainties
Backup
Bosonic Decay Modes
Kinematic Discriminant

Signal/background kinematic discriminant defined using matrix element techniques

\[ \mathcal{D}_{\text{bkg}}^{\text{kin}} = \frac{\mathcal{P}_{\text{sig}}^{\text{kin}}}{\mathcal{P}_{\text{sig}}^{\text{kin}} + \mathcal{P}_{\text{bkg}}^{\text{kin}}} \]

121.5 < \( m_{4l} \) < 130.5 GeV

H(126) 2D PDF
## Mass Systematic Uncertainties

### $H \rightarrow ZZ \rightarrow 4l$

<table>
<thead>
<tr>
<th>source</th>
<th>systematic uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon momentum scale uncertainty</td>
<td>± 0.1% (4μ)</td>
</tr>
<tr>
<td>Electron energy uncertainty</td>
<td>± 0.3% (4e)</td>
</tr>
</tbody>
</table>

### $H \rightarrow \gamma\gamma$

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>non linearity when extrapolating from Z</td>
<td>± 0.4%</td>
</tr>
<tr>
<td>upstream material simulation</td>
<td>± 0.25%</td>
</tr>
</tbody>
</table>
$H \rightarrow \gamma \gamma$ Decay Channel

- $2^+_{m}$ hypothesis tested (direct decay of a spin-1 particle into $\gamma \gamma$ forbidden by the Landau-Yang theorem)
- Discriminating variable: $\cos(\theta^*)$
  - photons from a spin-0 particle are isotropic
- Event categorization according to photon resolution and $\cos(\theta^*)$

In this case, $2^+_{m}$ spin hypothesis can not be excluded

$0^+ \text{ vs } 2^+_{m}$

$CL_S = 60.1\%$

$CL_S = 17.4\%$
Discriminating Variable Distributions

4l final state

\[ \mathcal{L}_i = N_{gg \to ZZ} \left[ \mu r \times \mathcal{P}^{gg}_{\text{sig}} + \sqrt{\mu r} \times \mathcal{P}^{gg}_{\text{int}} + \mathcal{P}^{gg}_{\text{bkg}} \right] + \ldots \]
Discriminating Variable Distributions

2l2ν final state

CMS preliminary, √s=8.0 TeV, |L|=19.7 fb⁻¹
Signal Strength

\[ \sqrt{s} = 7 \text{ TeV}, L \leq 5.1 \text{ fb}^{-1} \quad \sqrt{s} = 8 \text{ TeV}, L \leq 19.6 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Process</th>
<th>CMS Preliminary</th>
<th>( m_H = 125.7 \text{ GeV} )</th>
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<tbody>
<tr>
<td>Combined</td>
<td>( \mu = 0.80 \pm 0.14 )</td>
<td>( p_{SM} = 0.94 )</td>
</tr>
<tr>
<td>( H \to bb ) (VH tag)</td>
<td></td>
<td></td>
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<tr>
<td>( H \to bb ) (ttH tag)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H \to \gamma\gamma ) (untagged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H \to \gamma\gamma ) (VBF tag)</td>
<td></td>
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<td>( H \to \gamma\gamma ) (VH tag)</td>
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</tr>
<tr>
<td>( H \to WW ) (0/1 jet)</td>
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<td>( H \to \tau\tau ) (0/1 jet)</td>
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<tr>
<td>( H \to ZZ ) (2 jets)</td>
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\[ \sqrt{s} = 7 \text{ TeV}, L \leq 5.1 \text{ fb}^{-1} \quad \sqrt{s} = 8 \text{ TeV}, L \leq 19.6 \text{ fb}^{-1} \]

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<tr>
<td>Combined</td>
<td>( \mu = 0.60 \pm 0.14 )</td>
<td>( p_{SM} = 0.85 )</td>
</tr>
<tr>
<td>( H \to bb )</td>
<td>( \mu = 1.15 \pm 0.62 )</td>
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</tr>
<tr>
<td>( H \to \tau\tau )</td>
<td>( \mu = 1.10 \pm 0.41 )</td>
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</tr>
<tr>
<td>( H \to \gamma\gamma )</td>
<td>( \mu = 0.77 \pm 0.27 )</td>
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</tr>
<tr>
<td>( H \to WW )</td>
<td>( \mu = 0.88 \pm 0.20 )</td>
<td></td>
</tr>
<tr>
<td>( H \to ZZ )</td>
<td>( \mu = 0.92 \pm 0.28 )</td>
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Signal Strength

CMS Preliminary \( \sqrt{s} = 7 \text{ TeV}, L \leq 5.1 \text{ fb}^{-1} \), \( \sqrt{s} = 8 \text{ TeV}, L \leq 19.6 \text{ fb}^{-1} \)

- \( H \rightarrow \tau \tau \)
- \( H \rightarrow WW \)
- \( H \rightarrow ZZ \)
- \( H \rightarrow bb \)
- \( H \rightarrow \gamma \gamma \)
**H→ZZ→4l Decay Channel**

**Channel features**

- Very small branching fraction
- Very clean signature
  - 2 pairs of high $p_T$ and isolated $\mu$ or $e$
  - full reconstructed event topology
- Small background contribution
- Excellent mass resolution

**Analysis strategy**

- Event categorization according to lepton flavor
- Mass measurement performed using 3D fit with $(m_{4l}, \delta m_{4l}, D_{\text{kin}})$
- 8% improvement using per-event mass errors
- Main systematic uncertainties due to lepton scale and resolution
Asymmetries in Fermion Couplings

• Modifications to the fermion couplings may arise from theories beyond the SM

→ Study of $\lambda_{lq} = k_l/k_q$ and $\lambda_{du} = k_d/k_u$ ratios (constrained to be positive)

$\lambda_{lq} \in [0.57, 2.05]$  
$\lambda_{du} \in [0.74, 1.95]$ at 95% C.L.

Data are consistent with the expectation
Fit six Couplings at once

Assumptions

- Custodial symmetry \( k_W = k_Z = k_V \)
- Scale factors for couplings to 1\(^{st}\) and 2\(^{nd}\) generation fermions are equal to the 3\(^{rd}\) ones
- No beyond SM decays \( \Gamma_{\text{BSM}} = 0 \)

Data are consistent with the SM