Study of Higgs production in bosonic decay channels at CMS

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on behalf of the CMS collaboration

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Introduction

Higgs boson production:
- All production modes accessible at LHC

1. Gluon–gluon fusion
2. In associated with $Qar{Q}$
3. Higgs–strahlung
4. Vector boson fusion

Higgs decays:
- Given the Higgs mass at 125 GeV, the branching ratios are determined from theory:

Higgs-$\rightarrow$ff (fermions):
- $H \rightarrow bb$, $H \rightarrow \tau\tau$ : [ jets/MET ] “low mass resolution”
- $H \rightarrow \mu\mu$ : small BR

Higgs-$\rightarrow$VV (bosons):
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ \rightarrow 4\ell$ “high mass resolution”
- $H \rightarrow WW$ : large x-sec
- $H \rightarrow \gamma\gamma$; rare
Overview of CMS searches

CMS Run1 (2011-2012):
\[ \sqrt{s} = 7 \text{ TeV}, \ L \sim 5.1 \text{ fb}^{-1} \text{ and } \sqrt{s} = 8 \text{ TeV}, \ L \sim 19.6 \text{ fb}^{-1}. \]

\[ H \rightarrow \gamma\gamma, \ H \rightarrow ZZ \text{ and } H \rightarrow WW \text{ channels} \]
- Higgs discovery and measurements of its properties
- Higgs mass and width
- signal strength measurements in event categories
- production and decay: couplings / cross-section / spin and parity measurements
- BSM searches: additional Higgs partners, (non-)resonant HH

CMS Run2 (2015):
\[ \sqrt{s} = 13 \text{ TeV}, \ L \sim 2.9 \text{ fb}^{-1}. \]
- Towards Higgs re-discovery: \( H \rightarrow \gamma\gamma, \ H \rightarrow ZZ \rightarrow 4\ell \text{ and properties} \)
- Searches for high mass resonances in \( \gamma\gamma / Z\gamma \) and \( ZZ \rightarrow (4\ell, 2\ell2\nu, 2\ell2q) \) final states
- HH resonant: e.g. \( H(bb)H(WW) \) etc
Observation of Higgs in the di-photon decay channel

- Small BR~0.2% but good S/B and high mass resolution.
- Backgrounds from irreducible SM $\gamma\gamma$ production and $\gamma$-jet reducible sources.

Event categorization according to photon quality (MVA), kinematics and presence of objects to probe different production modes

- $ttH$, VBF [dijet0,1], VH [MET, dijet], Untagged 0,1,2,3

$m_H = 124.70 \pm 0.34$ GeV = 124.70 $0.31$ (stat) $0.15$ (syst) GeV

Local significance: $5.7\sigma$ (obs) vs $5.2\sigma$ expected
Observation of Higgs as a narrow resonance in the 4-lepton invariant Mass

- Backgrounds: ZZ and $Z\gamma^*$ estimate from simulation; reducible Zbb, tt and instr. Z+X from control regions in data.
- Excellent mass resolution; relies on calibration of the lepton $p_T$ scale and resolution / lepton selection efficiencies.

Events split in categories to allow sensitivity to diff production mechanisms:

- **Cat. I**: < 2jets; 4-lep $p_T/m_4\ell$ discriminates VBF and VH from gluon fusion
- **Cat. II**: >= 2jets; VBF-like variables $\Delta\eta_{jj}$ and $M_{jj}$

$m_H = 125.80 \pm 0.5$ (stat) $\pm 0.2$ (syst) GeV

**Observation of Higgs as a narrow resonance in the 4-lepton invariant Mass**

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$m_H = 125.80 \pm 0.5$ (stat) $\pm 0.2$ (syst) GeV

**local significance**: 6.7σ (obs) vs 7.2σ expected

$\mu = 0.91^{+0.30}_{-0.24}$
Higgs mass: combination

A combined ATLAS and CMS mass measurement with \( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ \rightarrow 4\ell \) channels

- Simultaneous fit to the inv. Mass peaks in the two channels for ATLAS and CMS

Dominant systematic uncertainties:

- experimental: photon, electron/muon \( p_T \) scale and resolution
- theory: Higgs x-sections and BRs, SM backgrounds normalization etc

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Higgs production and decay

Compatibility tests with SM expectations:

\[ \mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \]

**Production modes**

<table>
<thead>
<tr>
<th>ATLAS and CMS LHC Run 1</th>
<th>ATLAS+CMS</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_{ggF} )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
</tr>
<tr>
<td>( \mu_{VBF} )</td>
<td>( \pm 2\sigma )</td>
<td>( \pm 2\sigma )</td>
<td>( \pm 2\sigma )</td>
</tr>
<tr>
<td>( \mu_{WH} )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
</tr>
<tr>
<td>( \mu_{ZH} )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
</tr>
<tr>
<td>( \mu_{ttH} )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
</tr>
</tbody>
</table>

- \( \mu_{i} \) observed
- \( \mu_{VH} \), \( \sigma_{comb} = 3.5 (4.2) \)
- \( \mu_{ttH} \), \( \sigma_{comb} = 4.4 (2.0) \)

**Decay channels**

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</thead>
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<tr>
<td>( \mu_{\gamma\gamma} )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
</tr>
<tr>
<td>( \mu_{ZZ} )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
</tr>
<tr>
<td>( \mu_{WW} )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
</tr>
<tr>
<td>( \mu_{t\bar{t}t} )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
</tr>
<tr>
<td>( \mu_{bb} )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
<td>( \pm 1\sigma )</td>
</tr>
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</table>

- \( \mu_{i} \) clearly observed
- \( \sigma_{comb} = 5.5 (5.0) \)
- \( \sigma_{comb} = 2.6 (3.7) \)

Constraints on the couplings:

\[ \mu^{f} = \frac{BR^{f}}{(BR^{f})_{SM}} \]

<table>
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<th>Hff vs HVV</th>
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Global signal strength \( \mu \) compatible with SM within 1\( \sigma \); dominant systematic term from theory unc. on ggF
Spin and parity

Studied using the $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow WW \rightarrow \ell\nu\ell\nu$, and $H \rightarrow \gamma\gamma$ decay modes.

- $H \rightarrow \gamma\gamma$ (sensitive to spin-2\(^{+}\), excludes spin-1)
- $H \rightarrow ZZ \rightarrow 4\ell$ (sensitive to all spin-parity)
- $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ (sensitive to spin-1 and spin-2)

H$\rightarrow$VV$\rightarrow$4\ell:

All consistent with the expectations for the standard model Higgs boson quantum numbers $J^{PC} = 0^{++}$. 
Higgs boson re-discovery in $\gamma\gamma$ and $ZZ \rightarrow 4l$ final states; mass is fixed to 125.09 GeV

- Event categorization similar to Run1 (except where low statistics are expected)

- Not yet as competitive as in Run1

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Cross sections: $H \rightarrow ZZ$

Differential cross-sections in terms of quantities like $p_T(H)$, $|\eta(H)|$ and Njet multiplicity

- Statistical uncertainties (23% - 75%) dominate all differential distributions

7 TeV: $\sigma_{fid} = 0.56^{+0.67}_{-0.44}$(stat) $+0.21_{-0.06}$(syst) fb
8 TeV: $\sigma_{fid} = 1.11^{+0.41}_{-0.35}$(stat) $+0.14_{-0.10}$(syst) fb

Compatible with SM estimates up to NNLO accuracy

13 TeV: $\sigma_{fid} = 2.48^{+1.48}_{-1.14}$(stat $\oplus$ syst) $+0.01_{-0.04}$(model dep.) fb.
Cross-sections: $H \rightarrow WW$

Fiducial cross-section measurement in the Higgs transverse momentum distribution

- Allows to test possible deviations from the SM predictions.

$H \rightarrow WW \rightarrow 2\ell 2\nu$ fiducial selection:

- Inclusive in $N_{\text{jet}}$ to reduce syst. from theory modeling of $H + \text{jets}$ associated production.
More from run2

Search for ttH (multi-leptons) in ZZ*, WW* and ττ decay channels
- 2 same-sign leptons or
- >= 3 leptons + b jets

Resonant H(bb)H(WW) search:
- spin-0/2 resonance X decay to H boson pairs:
  - For \( m_X = [500, 900] \) GeV, set limits on cross-section x branching ratio of a spin-0 particle from 174 to 101 (exp. 135 to 75.8) fb
High mass resonances in $H \rightarrow \gamma\gamma / Z\gamma$

$\gamma\gamma$ final states:
- spin-0/ -2 resonances for $m_X$: [0.5, 4] TeV and width $\Gamma_X/m_X$: [1.4x10^{-4}, 5.6x10^{-2}]

$Z\gamma$ final states:
- $A \rightarrow Z\gamma \rightarrow \ell\ell\gamma$
- For $m_A$: [200,1200] GeV, set upper limits on $\sigma \times BR$: [0.15, 3.8] fb

For $m_X \sim 750$ GeV, $\Gamma_X/m_X = 1.4 \times 10^{-4}$: sign. of 3.4$\sigma$ [8 TeV + 13 TeV]

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High mass resonances in $H \rightarrow ZZ$

Limits on additional resonance $H (m_X, \Gamma_X)$ for masses up to $\sim 1$ TeV:

- Limits for a heavy Higgs-like particle
- EWS, 2HDM interpretations

$H \rightarrow ZZ \rightarrow 4\ell$:
- Fit in the $m(4\ell)$ distribution:

$H \rightarrow ZZ \rightarrow 2\ell 2\nu$:
- Event categorization in 0/1-jet, VBF; use MET (>125 GeV) and $M_T$ variables:

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Run1: very important measurements of the Higgs sector from the bosonic channels:
- $H \rightarrow ZZ, Z\gamma^* \rightarrow 4\ell$, $H \rightarrow WW \rightarrow \ell\nu\ell\nu$, and $H \rightarrow \gamma\gamma$
- Higgs discovery and measurement of its properties: Mass, width, spin, $\sigma$, $d\sigma/dX$, signal strength (production and decay), couplings =>
- Higgs profile fully consistent with the SM expectations

Run2: 2015 was a commissioning phase in the Higgs sector; not yet as competitive

Bosonic channels offer important tool in searches for New Physics:
- High mass resonances, HH resonances etc
Back-ups: $H \rightarrow WW$ (run2)

$H \rightarrow WW \rightarrow e\mu + \nu\nu$: opposite-charge $e\mu$ in association with large MET for up to 1-jet.

For $m_H=125\text{ GeV}$, obs. significance is $0.7\sigma$ ($2.0\sigma$ expected); best fit signal strength $\frac{\sigma}{\sigma_{SM}} = 0.3 \pm 0.5$