Constraint on Higgs boson total width using off-shell production in the ZZ decay

Ian Anderson (Johns Hopkins University)
on behalf of the CMS Collaboration

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Outline

• Prior Status
• Theoretical Background
• Statistical approach
• $H \rightarrow ZZ \rightarrow 4l$ analysis and results
• $H \rightarrow ZZ \rightarrow 2l2\nu$ analysis and results
• Combination results
• Conclusion
Prior Status of $\Gamma_H$

- Current limit in $4l$ on total width of Higgs is $\leq 3.4$ GeV $\approx 800 \times \Gamma_{SM}$ ($\Gamma_{SM} = 4.25$ MeV)

- At LHC, resolution limits direct measurement to $O(1)$ GeV

- We can use off-shell production to make a stricter limit on total width of Higgs
Theoretical Background

• Well known that the Zero Width Approximation is poor approximation far from Higgs mass

• Competing effects from BW in high mass region and $\Gamma_{H \rightarrow 4l}$ cause plateau in region above $2m_Z$

• $\sim 8\%$ of total $H \rightarrow ZZ$ cross section found in $m_{ZZ} > 2m_Z$ region

\[1\] Kauer, Passarino (JHEP 08 (2012))
Theoretical Background

• As suggested in a recent paper\(^2\), we can make a \textit{model-independent} measurement of the Higgs width

\[
\sigma_{gg \to ZZ}^{\text{on-peak}} \propto g_{ggH}^2 g_{HZZ}^2 \Gamma \\
\sigma_{gg \to ZZ}^{\text{off-peak}} \propto g_{ggH}^2 g_{HZZ}^2
\]

• \(m_{ZZ}\) distribution can be used alone, but kinematic discriminants can improve sensitivity

• Interference is significant at high masses, accounted for in analysis of off-shell signal

\(^2\text{Caola, Melnikov (Phys Rev D 88 (2013) 054024)}\)
Monte Carlo Simulation

- Gluon-gluon Fusion (gg2VV, MCFM)
  - NNLO/LO K-factors for signal are $m_{ZZ}$ dependent\(^3\)
  - Use same k-factor for signal and background, shown to be true for WW\(^4\) expect to be identical for ZZ

- Vector Boson Fusion (PHANTOM)
  - Contributes only $\sim 7\%$ at peak, grows to $\sim 10\%$ in high mass region
  - VH and ttH do not contribute in the high mass region

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\(^3\) Passarino (arXiv:1312.2397)  \(^4\) Bonvini et al. (Phys Rev D 88 (2013) 034032)
Statistical Approach

• Perform a maximum likelihood fit in CMS Higgs combination tool using selected event candidates, split into the final states

• Each event has an associated likelihood describing the probability it belongs to signal, background, or interference:

\[
\mathcal{L}_i = N_{gg\to ZZ} \left[ \mu \Gamma \times P_{\text{sig}}^{gg} + \sqrt{\mu \Gamma} \times P_{\text{int}}^{gg} + P_{\text{bkg}}^{gg} \right] + \\
N_{VBF} \left[ \mu \Gamma \times P_{\text{sig}}^{VBF} + \sqrt{\mu \Gamma} \times P_{\text{int}}^{VBF} + P_{\text{bkg}}^{VBF} \right] + N_{q\bar{q}ZZ} P_{\text{bkg}}^{q\bar{q}} + N_{ZX} P_{\text{bkg}}^{ZX}
\]

where \( P \) is the normalized probability distribution for each process

• Total \( gg/VV\to ZZ \) process (above in brackets) normalized together; \( P_{\text{int}} \) may have both positive and negative values but \( P_{\text{tot}} \) is positive-definite

• For self-contained analysis, use observed signal strength from 4l Legacy results, \( \mu = 0.93^{+0.26}_{-0.24} \).
H → ZZ → 4l
4l Analysis

• Selection is consistent with Legacy paper (arXiv:1312.5353)
• Designed discriminant for gg→ZZ production using matrix element likelihood approach (MELA)
  • Optimal for separation of gg→ZZ from q̅q→ZZ, where gg→ZZ includes signal, continuum background, and their interference with any relative signal strength
    \[ D_{gg,a} = \frac{P_{gg,a}}{P_{gg,a} + P_{qq}} \]
• Construct two probabilities to make a discriminant
  • Built with 7 variables that completely describe decay kinematics (m_{Z1}, m_{Z2}, five angles)
  • P_{gg(qq)} are joint probabilities for gg→ZZ signal + background + interference (q̅q→ZZ background) from MCFM matrix elements
**m_{4l} & D_{gg} Distributions/Yields**

<table>
<thead>
<tr>
<th>(a)</th>
<th>gg + VBF → 4\ell (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)</th>
<th>2.22 ±0.15</th>
<th>1.20 ±0.08</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>gg + VBF → 4\ell (background)</td>
<td>31.1 ±3.1</td>
<td>2.12 ±0.21</td>
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<td>gg + VBF → 4\ell (total, $\Gamma_H/\Gamma_H^{SM} = 1$)</td>
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<td>51.8 ±5.0</td>
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<td>(b)</td>
<td>$q\bar{q} → 4\ell$</td>
<td>154.7 ±7.4</td>
<td>8.6 ±0.4</td>
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<tr>
<td>(c)</td>
<td>Reducible background</td>
<td>3.7 ±0.6</td>
<td>0.44 ±0.08</td>
</tr>
<tr>
<td>(a+b+c)</td>
<td>Total expected ($\Gamma_H/\Gamma_H^{SM} = 1$)</td>
<td>188.0 ±7.9</td>
<td>10.8 ±0.4</td>
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<tr>
<td>Observed</td>
<td></td>
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m_{4l} & D_{gg} Distributions/Yields

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4l Limits

- Small deficit of signal events in high mass region
- Observed (Expected) $\Gamma \leq 27.4$ (47.7) MeV at 95% CL
- Best fit at $\Gamma = 2.0^{+9.6}_{-2.0}$ MeV
H → ZZ → 2ℓ2ν
2l2v Analysis

- Selection identical to PAS-HIG-13-014
  - See backup for explicit details
- Split events into three categories by number of selected jets ($p_T > 30$ GeV and $|\eta| < 4.7$)
  - VBF-like: two jets with $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 4$
  - $>=1$ jets: excluding events in VBF-like category
  - 0 jets
- Data-driven estimate of reducible backgrounds (double and single top, WW, W+jets, Z +jets), $q\bar{q}\rightarrow ZZ/WZ$ from MC
- Fit the distribution of transverse mass for 0 and 1-jet categories:
  $$m_T^2 = \left[ \sqrt{p_{T,2l}^2 + m_{2l}^2} + \sqrt{E_T^{miss}^2 + m_{2l}^2} \right]^2 - \left[ \vec{p}_{T,2l} - \vec{E}_{T}^{miss} \right]^2$$
- Fit MET for VBF category
$m_T$/MET Distributions

CMS preliminary, $\sqrt{s}=8.0$ TeV, $\mathcal{L}=19.7$ fb$^{-1}$

Transverse mass [GeV]

Events/bin

ee, $=0$ jets
- Data
- $qq\rightarrow ZZ\rightarrow 2\ell2\nu$
- $WZ\rightarrow 3\ell\nu$
- Top/W/WW
- $Z+jets$
- $SBI_{gg}(r=10)$
- $SBI_{qq}(r=10)$

ee, $\geq 1$ jets

Transverse mass [GeV]

Events/bin

ee, VBF

Missing transverse energy [GeV]

Transverse mass [GeV]

Events/bin

$\mu\mu$, $=0$ jets

Transverse mass [GeV]

Events/bin

$\mu\mu$, $\geq 1$ jets

Transverse mass [GeV]

Events/bin

$\mu\mu$, VBF

Missing transverse energy [GeV]
2l2v Limits

• As with 4l, small deficit of signal events in high mass region

• Observed (Expected) $\Gamma \leq 26.6 \ (44.4) \text{ MeV at 95\% CL}$

• Best fit at $\Gamma = 0.8^{+9.1}_{-0.8} \text{ MeV}$

<table>
<thead>
<tr>
<th>Source</th>
<th>ee</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) gg + VBF (signal, $\Gamma_H/\Gamma^{SM}_H = 1$)</td>
<td>2.30±0.03</td>
<td>2.72±0.03</td>
</tr>
<tr>
<td>gg + VBF (background)</td>
<td>5.4±0.2</td>
<td>6.5±0.2</td>
</tr>
<tr>
<td>gg + VBF (total, $\Gamma_H/\Gamma^{SM}_H = 1$)</td>
<td>4.8±0.1</td>
<td>5.7±0.3</td>
</tr>
<tr>
<td>gg + VBF (total, $\Gamma_H/\Gamma^{SM}_H = 10$)</td>
<td>19.2±0.6</td>
<td>22.6±1.2</td>
</tr>
<tr>
<td>(b) $q\bar{q} \to ZZ$</td>
<td>25.0±0.5</td>
<td>29.4±0.5</td>
</tr>
<tr>
<td>WZ</td>
<td>11.6±0.4</td>
<td>13.5±0.4</td>
</tr>
<tr>
<td>$t\bar{t}/tW/WW$</td>
<td>3.3±1.1</td>
<td>4.2±1.4</td>
</tr>
<tr>
<td>Z + jets</td>
<td>1.5±0.9</td>
<td>2.4±1.4</td>
</tr>
<tr>
<td>(a+b) Total expected ($\Gamma_H/\Gamma^{SM}_H = 1$)</td>
<td>46.2±1.6</td>
<td>55.3±2.1</td>
</tr>
<tr>
<td>Observed</td>
<td>39</td>
<td>52</td>
</tr>
</tbody>
</table>
Combination Results

- Observed (Expected) $\Gamma \leq 17.4$ (35.3) MeV at 95% CL

- Best fit at $\Gamma = 1.4_{-1.4}^{+6.1}$ MeV

- Primary Systematic Uncertainties:
  - QCD scale and PDF for both $qqZZ$ and $ggZZ$
  - $\mu$ uncertainties from $4l$ Legacy results
  - $k$-factor for $ggZZ$ background
  - Experimental uncertainties (trigger/reconstruction efficiencies, etc)

<table>
<thead>
<tr>
<th>Expected 95% CL limit, $r$</th>
<th>4$\ell$</th>
<th>2$\ell$2$\nu$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed 95% CL limit, $r$</td>
<td>11.5</td>
<td>10.7</td>
<td>8.5</td>
</tr>
<tr>
<td>Observed 95% CL limit, $\Gamma_H$ (MeV)</td>
<td>6.6</td>
<td>6.4</td>
<td>4.2</td>
</tr>
<tr>
<td>27.4</td>
<td>26.6</td>
<td>17.4</td>
<td></td>
</tr>
<tr>
<td>Observed best fit, $r$</td>
<td>0.5$^{+2.3}_{-0.5}$</td>
<td>0.2$^{+2.2}_{-0.2}$</td>
<td>0.3$^{+1.5}_{-0.3}$</td>
</tr>
<tr>
<td>Observed best fit, $\Gamma_H$ (MeV)</td>
<td>2.0$^{+9.6}_{-2.0}$</td>
<td>0.8$^{+9.1}_{-0.8}$</td>
<td>1.4$^{+6.1}_{-1.4}$</td>
</tr>
</tbody>
</table>
Conclusions

• First experimental limit on total Higgs width using off-shell $H \rightarrow ZZ$ events

  • Both channels see small deficit of signal in high mass region

  • Combined results: Observed (Expected) $\Gamma \leq 17.4 (35.3)$ MeV at 95% CL with best fit at $\Gamma = 1.4^{+6.1}_{-1.4}$ MeV

• Very little model dependence

  • Off-shell enhancement only dependent on Higgs propagator structure

    • No enhancement from heavy fermions; Higgs has scalar spin-parity

  • Assume no BSM enhancements to $q\bar{q} \rightarrow ZZ$ background or overall $ZZ$ yields in high mass region

• Could be further combined with $H \rightarrow WW$
Citations


BACKUP
Legacy Results

- Observation of a Higgs boson candidate
  - Narrow resonance with local significance of 6.8$\sigma$, signal strength in agreement with SM
  - Resonance has mass of $125.6 \pm 0.4$ (stat.) $\pm 0.2$ (sys.) GeV
  - $\Gamma_{\text{tot}} \leq 3.4$ GeV

Primarily ggF production

Higgs in agreement with scalar particle

MC Samples

- Use gg2VV and MCFM to generate ggF samples (includes signal\(m_{H}=125.6\) GeV, background, and interference terms)
  - LO in QCD, running QCD scale used \((m_{4l}/2)\) with scale and PDF
- Settings and cuts:
  - CTEQ6L LO PDF
  - \(m_{H} = 125.6\) GeV, \(\Gamma_{H} = 4.15\) MeV - matching values from Legacy
  - Running scale for renormalization & factorization of \(m_{4l}/2\) for MCFM (generation and hadronization), fixed scale of \(m_{H}/2\) for GG2VV (reweighting applied)
  - \(m_{ll} > 4\) GeV (OSSF), \(m_{4l} > 95\) GeV, \(p_{T}(\text{lepton}) > 3\) GeV, \(|\eta(\text{lepton})| < 2.7\)
  - \(p_{T}(\text{lepton pair}) > 0.1\) GeV for MCFM samples, \(>1\) GeV (\(>2\) GeV) for different (same) flavor lepton pairs in GG2VV
- All cuts are looser than analysis or have \(<1\%\) impact
MC Samples

• Use PHANTOM to generate at same settings
  
  • LO generation
    
    • NNLO/LO k-factor is 6% and independent on $m_{ZZ}$ (YR3)
    
    • Do not apply explicitly, normalize cross-section at the peak relatively to ggF
  
  • Central scale $m_{ZZ}/\sqrt{2}$
    
    • Same scale and PDF variations as ggF, effect much smaller (1-2%)
    
    • Signal, background, interference not available separately. Generate total amplitudes with $r = 1, 10, 25$ (and equal coupling scalings) and extract the 3 components from:

\[
\begin{pmatrix}
  p_1 \\
  p_{10} \\
  p_{25}
\end{pmatrix}
= \begin{pmatrix}
  1 & 1 & 1 \\
  10 & \sqrt{10} & 1 \\
  25 & 5 & 1
\end{pmatrix}
\begin{pmatrix}
  S \\
  I \\
  B
\end{pmatrix}
\]
Discriminant

\[ \mathcal{P}_{gg,a}(\tilde{\Omega}, m_1, m_2|m_{4\ell}, m_H) = a \times \mathcal{P}_{gg}^{\text{sig}} + \sqrt{a} \times \mathcal{P}_{\text{int}}^{gg} + \mathcal{P}_{\text{bkg}}^{gg} \]

\[ \mathcal{P}_{q\bar{q}}(\tilde{\Omega}, m_1, m_2|m_{4\ell}) = \mathcal{P}_{bkg}^{q\bar{q}} \]

\[ \mathcal{D}_{gg,a} = \frac{\mathcal{P}_{gg,a}}{\mathcal{P}_{gg,a} + \mathcal{P}_{q\bar{q}}} = \left[ 1 + \frac{\mathcal{P}_{bkg}^{q\bar{q}}}{a \times \mathcal{P}_{\text{sig}}^{gg} + \sqrt{a} \times \mathcal{P}_{\text{int}}^{gg} + \mathcal{P}_{bkg}^{gg}} \right]^{-1} \]

- Note that \( \mathcal{D}_{gg,a} \) requires choice of signal strength, studies show \( \frac{\Gamma}{\Gamma_{SM}} \approx 10 \) in analysis of Run1 data, use \( a=10 \)
Discriminant Inputs

\[ \theta \cos^{-1} (-0.5) = 0 \]

Events / 0.1

Data = 1, SM \[ \Gamma \times = 25 \Gamma_{ZZ} \rightarrow gg+VV \]

\[ Z+X > 220 \text{ GeV} \]

4l m

Events / 0.314

Data = 1, SM \[ \Gamma \times = 25 \Gamma_{ZZ} \rightarrow gg+VV \]

\[ Z+X > 220 \text{ GeV} \]

CMS Preliminary
$m_{4l}$ & $D_{gg}$ Distributions/Yields

CMS preliminary

$\sqrt{s} = 8$ TeV, $L = 19.7$ fb$^{-1}$

Events/10GeV

- Data
- $gg+VV \rightarrow ZZ$ ($\Gamma = 25 \times \Gamma_{SM}$, $t = 1$)
- $gg+VV \rightarrow ZZ$ (SM)
- $qq \rightarrow ZZ$
- $Z+X$

MELA $D_{gg} < 0.5$

Events/0.05

- Data
- $gg+VV \rightarrow ZZ$ ($\Gamma = 25 \times \Gamma_{SM}$, $t = 1$)
- $gg+VV \rightarrow ZZ$ (SM)
- $qq \rightarrow ZZ$
- $Z+X$

$m_{4l} < 330$ GeV

I Anderson 26
2D Templates

CMS Preliminary

$\sqrt{s}=8$ TeV, $L=19.7$ fb$^{-1}$
CMS Preliminary \[ \sqrt{s} = 8 \text{ TeV}, L = 19.7 \text{ fb}^{-1} \]

**H → ZZ → 4l 1D(m_{4l})**

- **Observed**
- **Expected \( \mu = \mu_{\text{obs}} \)**
- **Expected \( \mu = 1 \)**

- **68% CL**
- **95% CL**

**H → ZZ → 4l 1D(D_{gg})**

- **Observed**
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- **68% CL**
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Limits by Channel

CMS Preliminary

\[ \sqrt{s} = 8 \text{ TeV}, L = 19.7 \text{ fb}^{-1} \]

\( H \rightarrow ZZ \rightarrow 4l \)

-2\( \Delta \ln L \)

-2\( \Delta \ln L \) vs. \( \Gamma / \Gamma_{\text{SM}} \)

Observed \( \mu = \mu_{\text{obs}} \)

Expected \( \mu = \mu_{\text{obs}} \)

\( 4l \)

\( 2e2\mu \)

\( 4e \)

\( 4\mu \)
Legacy Leptons/Jets

- Trigger specifics: Dilepton (first $p_T \geq 17$ GeV, second $\geq 8$ GeV), Trielectron ($\geq 15$ GeV, $\geq 8$ GeV, $\geq 5$ GeV)

- Good leptons must pass certain cuts:
  - Geometric: $|\eta| < 2.5$ for electrons, $< 2.4$ for muons
  - Momentum: $p_T > 7$ GeV for electrons, $> 5$ GeV for muons
  - Isolation: $p_T$ from charged hadrons, neutral hadrons, and photons (not FSR) from primary vertex must be less than 40% of total $p_T$ in cone about lepton track
  - Originate from primary vertex: Significance of impact parameter $< 4$

- Good Jets must have $|\eta| < 4.7$, $E_T > 30$ GeV, isolated from leptons and FSR photons
• Once we have at least four good leptons, we attempt to create two Z bosons

• Take pairs of same flavor and opposite charge leptons, assemble invariant mass with any FSR photons (photons $|\eta| < 2.4$, $p_T > 2$ GeV and found within $\Delta R$ cone of 0.07 or $p_T > 4$ GeV and found at $0.07 < \Delta R < 0.5$ around lepton)

• Pair with invariant mass closest to $m_Z$ ($40$ GeV < $m_{ll}$ < $120$ GeV) is called $Z_1$

• Remaining leptons must make a second pair that can be off-shell ($12$ GeV < $m_{ll}$ < $120$ GeV) - if more than one, choose pair with highest sum of $p_T$

• At least one lepton with $p_T > 20$ GeV and a second with $p_T > 10$ GeV

• Any opposite charge pairs must have $m_{ll} > 4$ GeV to eliminate selecting possible jet fragments

• $m_{4l} > 100$ GeV to be considered a possible Higgs candidate
2l2nu Event selection/categorization

- **Selection** :
  - dilepton+single lepton triggers
  - Two isolated leptons $p_T > 20$ GeV (medium/tight ID for e/µ)
  - $|M-91| < 15$ GeV and $p_T(Z) > 50$ GeV
  - Veto: $3^{rd}$ lepton ($p_T > 10$ GeV) and Btag (CSVL)
  - Raw PF $E_T^{miss} > 80$ GeV and $\Delta \phi(jet, E_T^{miss}) > 0.5$
  - Transverse Mass for shape analysis : $m_T^2 = \left[ \sqrt{p_{T,2l}^2 + m_{2l}^2} + \sqrt{E_T^{miss}^2 + m_{2l}^2} \right]^2 - \left[ \vec{p}_{T,2l} - \vec{E}_T^{miss} \right]^2$

- **Event categorization based on Jets** :
  - $p_T > 30$ GeV $|\eta| < 4.7$, loose PF+PU id
    - **VBF category**
      - $M_{jj} > 500$ GeV, $|\Delta \eta| > 4$
      - Central jet veto
    - $\geq 0$, $\geq 1$ jets categories
      - Fall-back for non-VBF tagged events
      - Count number of selected jets
2l2nu Yield Variation

CMS simulation, $\sqrt{s}=8$ TeV, $\mathcal{L}=19.7$ fb$^{-1}$

$H \rightarrow ZZ \rightarrow 2l2\nu$

- total
- signal only
- interference
- background only

$Z_{gg}$

$r=\Gamma/\Gamma_{SM}$
2l2nu breakdown

- ee deficit drives strong limit
- 0 jet category drives sensitivity of the analysis