Constraints on the Higgs boson width from off-shell production and decay to $ZZ \rightarrow 4l$ or $2l2\nu$

Jian Wang (Universite Libre de Bruxelles)
On behalf of the CMS collaboration

CERN LHC seminar
April 15, 2014
After discovery

- Great progress since Higgs boson discovery
  - Observation in boson channels
  - Evidence in fermion channels
  - Mass measurements
    - CMS $H \rightarrow ZZ \rightarrow 4l$ measurement
      $125.6 \pm 0.4\text{(stat.)} \pm 0.2\text{(syst.)}\text{GeV}$
  - Spin/parity studies

Looks more and more like the SM Higgs boson
"Signal strength" $\mu = \sigma / \sigma_{SM}$

Narrow width approximation

$$\sigma_{on-peak}^{\gamma gH\rightarrow ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}$$

Define

$$r = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

$$\kappa_g = \frac{g_{ggH}}{g_{ggH}^{SM}} \quad \kappa_Z = \frac{g_{HZZ}}{g_{HZZ}^{SM}}.$$ 

$$\sigma_{on-peak}^{\gamma gH\rightarrow ZZ} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot \mathcal{B})_{SM} \equiv \mu (\sigma \cdot \mathcal{B})_{SM}.$$ 

The $\mu$ unchanged if the numerator and denominator are scaled by a common factor.
SM Higgs total width $\sim 4$ MeV @125GeV

Property measurements - width

$\Gamma_H < 3.4$ GeV

H$\rightarrow$γγ results $\Gamma_H < 6.9$ GeV (CMS-HIG-13-016)

Direct measurements are limited by experimental resolutions
SM Higgs total width $\sim 4$ MeV @125GeV

Property measurements - width

$\Gamma_H < 3.4$ GeV

$H \rightarrow \gamma \gamma$ results $\Gamma_H < 6.9$ GeV (CMS-HIG-13-016)

Experimental resolutions

Waiting for a lepton collider...
Higgs off-shell production and decay

Off-shell production cross section has been shown to be sizable at high $VV$ invariant mass

A mixed effect of production and decay: enhancement at $2m_V$ and $2m_t$ thresholds

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ [pb] $M_{ZZ} &gt; 2M_Z$ [pb]</th>
<th>$R$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \to H \to all$</td>
<td>19.146</td>
<td>0.1525</td>
</tr>
<tr>
<td>$gg \to H \to ZZ$</td>
<td>0.5462</td>
<td>0.0416</td>
</tr>
</tbody>
</table>

With current experimental cuts in $H \to ZZ \to 4l$ analysis, this ratio is further enhanced

Constraining the Higgs boson width

J. Campbell et al. (arXiv:1311.3589)

The production cross section as a function of $m_{ZZ}$

\[
\frac{d\sigma_{gg\rightarrow H\rightarrow ZZ}}{dm_{ZZ}^2} \propto g_{ggH}^2 g_{HZZ}^2 \frac{F(m_{ZZ})}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}
\]

**On-shell vs. off-shell**

\[
\sigma_{on-peak}^ {gg\rightarrow H\rightarrow ZZ} \propto g_{ggH}^2 g_{HZZ}^2, \quad \sigma_{off-peak}^{gg\rightarrow H\rightarrow ZZ} \propto \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}
\]

Away from the resonance, the cross section is independent of the width. The ratio of off-shell and on-shell production leads to a direct constraint of $\Gamma_H$

Assuming the coupling constants remain invariant at the low and high mass region.
Data and MC samples

- 2012 data, 8 TeV, corresponding to $L = 19.7 \text{ fb}^{-1}$
- $gg \rightarrow ZZ \rightarrow 4l/2l2\nu$ events are generated at LO using $gg2VV3.1.5$ and/or MCFM6.7
  - Generations include Higgs boson signal, continuum background and their interference
  - Higgs boson mass set to 125.6 GeV (corresponding SM width 4.15 MeV)
  - The renormalization and factorization scales are set to $m_{ZZ}/2$ (running scales)
  - NNLO K factors applied as a function of $m_{ZZ}$; same K factors applied to continuum backgrounds (M. Bonvini et al. (Phys. Rev. D88 (2013) 034032))

Higgs signal interferes with continuum background

G. Passarino (arXiv:1312.2397)
MC samples

- **Vector Boson Fusion (VBF)** Higgs production mode is expected to also produce an off-shell tail, and could be as large as 10% in the high mass region, compared to gg fusion mode. \( qq' \rightarrow ZZ + qq' \rightarrow 4l/2l2\nu + qq' \) events are generated using PHANTOM, including the signal, background and their interference.

- Background samples are generated from POWHEG or MADGRAPH, and normalized to NLO cross sections where available.

- **GEANT4** based CMS detector simulation.
Analysis strategy

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

Once the \( \mu \) taken from a measurement or calculation, the off-shell cross section gives direct constraint on \( r = \Gamma / \Gamma_{SM} \)

\( \mu \) from CMS on-peak 4l measurement is used (with its stat. uncertainty)

\[ \mu(\text{obs}) = 0.93^{+0.26}_{-0.24} \]
\[ \mu(\text{exp}) = 1.00^{+0.27}_{-0.24} \]

\[ \mathcal{L}_i = N_{gg\rightarrow ZZ} \left[ \mu r \times \mathcal{P}_{\text{sig}}^{gg} + \sqrt{\mu r} \times \mathcal{P}_{\text{int}}^{gg} + \mathcal{P}_{\text{bkg}}^{gg} \right] \]
\[ + N_{\text{VBF}} \left[ \mu r \times \mathcal{P}_{\text{sig}}^{\text{VBF}} + \sqrt{\mu r} \times \mathcal{P}_{\text{int}}^{\text{VBF}} + \mathcal{P}_{\text{bkg}}^{\text{VBF}} \right] + N_{q\bar{q}\rightarrow ZZ} \mathcal{P}_{\text{bkg}}^{qq} + \ldots \]

The parameterization of \( gg\rightarrow ZZ \) and VBF processes includes three correlated distributions for signal, background and their interference;
Assuming \( \mu_{ggF} = \mu_{\text{VBF}} \)
$H \rightarrow ZZ \rightarrow 2\ell 2\ell'$

4-lepton Mass : 126.9 GeV

$\mu^+(Z_1) \ p_T : 43 \text{ GeV}$

$\mu^- (Z_1) \ p_T : 24 \text{ GeV}$

$e^- (Z_2) \ p_T : 10 \text{ GeV}$

$e^+ (Z_2) \ p_T : 21 \text{ GeV}$
4l analysis - overview

• Same event reconstruction and selection as those used in the previous measurement of Higgs boson properties (arXiv: 1312.5353)

• Event selections:
  • Two pairs of leptons (electrons or muons), isolated, of opposite sign and same flavor; $Z_1$: closest to the Z boson mass; $Z_2$: the remaining with highest scalar sum of $p_T$
  • At least one lepton has $p_T > 20$ GeV, and another has $p_T > 10$ GeV
  • $40 < m_{Z_1} < 120$ GeV; $12 < m_{Z_2} < 120$ GeV
  • Off-shell analysis region: $220 < m_{4l} < 1600$ GeV

• Background:
  • Irreducible background is $qq \rightarrow ZZ$, modeled from MC
  • Reducible background (much smaller) is $Z+X$ ($Z$ and $WZ$, at least one lepton is non-prompt), evaluated using a “fake rate” method, with control regions in data
4l analysis - MELA $D_{gg}$

**Matrix element likelihood approach (MELA)**

A kinematic discriminant to separate $gg \rightarrow ZZ$ from $qq \rightarrow ZZ$

Characterize event topology in ZZ center-of-mass frame, with 7 variables completely describing kinematics ($m_{Z1}$, $m_{Z2}$, five angles)

\[
D_{gg} \equiv \frac{P_{gg}}{P_{gg} + P_{qg}} = \left[ 1 + \frac{P_{qq}^{\text{bkg}}}{a \times P_{\text{sig}}^{gg} + \sqrt{a} \times P_{\text{int}}^{gg} + P_{\text{bkg}}^{gg}} \right]^{-1}
\]

( Depends on parameter $a$ (relative weight of signal in the likelihood ratio). Since the expected exclusion is $r \sim 10$, use $a = 10$)
4l analysis - inputs to $D_{gg}$

Tuesday, April 15, 2014
4l analysis - $m_{4l}$ and $D_{gg}$ distributions

<table>
<thead>
<tr>
<th>Category</th>
<th>Full region</th>
<th>Signal-enriched region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg + VBF \rightarrow 4\ell$ (signal, $\Gamma_H/\Gamma_{H}^{SM} = 1$)</td>
<td>2.22 $^{+0.15}_{-0.17}$</td>
<td>1.20 $^{+0.08}_{-0.09}$</td>
</tr>
<tr>
<td>$gg + VBF \rightarrow 4\ell$ (background)</td>
<td>31.1 $^{+3.0}_{-3.1}$</td>
<td>2.12 $^{+0.21}_{-0.2}$</td>
</tr>
<tr>
<td>(a) $gg + VBF \rightarrow 4\ell$ (total, $\Gamma_H/\Gamma_{H}^{SM} = 1$)</td>
<td>29.6 $^{+2.8}_{-2.9}$</td>
<td>1.73 $^{+0.16}_{-0.17}$</td>
</tr>
<tr>
<td>$gg + VBF \rightarrow 4\ell$ (total, $\Gamma_H/\Gamma_{H}^{SM} = 15$)</td>
<td>51.8 $^{+4.9}_{-5.0}$</td>
<td>13.1 $^{+1.1}_{-1.2}$</td>
</tr>
<tr>
<td>(b) $q\bar{q} \rightarrow 4\ell$</td>
<td>154.7 $^{+7.4}_{-7.0}$</td>
<td>8.6 $^{+0.4}_{-0.4}$</td>
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<tr>
<td>(c) Reducible background</td>
<td>3.7 $^{+0.6}_{-0.6}$</td>
<td>0.44 $^{+0.08}_{-0.08}$</td>
</tr>
<tr>
<td>(a+b+c) Total expected ($\Gamma_H/\Gamma_{H}^{SM} = 1$)</td>
<td>188.0 $^{+7.9}_{-7.9}$</td>
<td>10.8 $^{+0.4}_{-0.4}$</td>
</tr>
</tbody>
</table>

Observed

<p>| | |</p>
<table>
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<tr>
<th></th>
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<tr>
<td></td>
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Tuesday, April 15, 2014
4l analysis - $m_{4l}$ and $D_{gg}$ distributions

![Graph showing $m_{4l}$ (GeV) and $D_{gg}$ distributions with data points and histograms for different processes.]

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$H \rightarrow ZZ \rightarrow 2l2\nu$
$H \rightarrow ZZ \rightarrow 2\ell 2\nu$
2l2ν analysis - overview

- 6 times higher branching ratio compared to 4l final state
  - Branching ratio matters in high mass region where cross section is low
- No access to Higgs on-shell production
  - Z+jets background is several orders of magnitude higher (fake $E_T^{\text{miss}}$ due to hadronic energy mis-measurement)
- Other backgrounds
  - Irreducible: ZZ, WZ
  - Non-resonant (not involving a Z boson): top, WW

Transverse mass

$$m_T^2 = \left[ \sqrt{p_{T,ee}^2 + m_{ee}^2} + \sqrt{E_T^{\text{miss}}^2 + m_{ee}^2} \right]^2 - \left[ \vec{p}_{T,ee} + \vec{E}_{T}^{\text{miss}} \right]^2$$
2l2v analysis - event selection

• Z+large $E_T^{miss}$ signature

  • To select a $Z \rightarrow ll$: a pair of electrons or muons, isolated, $p_T > 20$ GeV, $|m(ll) - 91| < 15$ GeV
  
  • To reject $WZ$: veto 3rd lepton ($p_T > 10$ GeV)
  
  • To reject top processes: veto b-tagged jet; veto soft-muon ($p_T > 3$ GeV)
  
  • To reject $Z+jets$: $E_T^{miss} > 80$ GeV; Azimuthal angle of $E_T^{miss}$ and the closest jet: $\Delta \phi > 0.5$

• To improve sensitivity, selected events are categorized according to number and topology of jet ($p_T > 30$ GeV)

  • VBF, 0 jet, $\geq$1 jet(non-VBF)

  • VBF is defined as $m(jj) > 500$ GeV and $\Delta \eta(jj) > 4$
**2l2ν analysis - background estimations**

- $qq \rightarrow ZZ, WZ$ estimated from MC

- Non-resonant background ($tt, tW, WW$)
  - Estimated from data using *lepton flavor symmetry*: compute the $ee/e\mu$ and $\mu\mu/e\mu$ ratios in sideband, and apply the ratios to $e\mu$ events in signal region

\[
\alpha_\mu = \frac{N_{\mu\mu}^{SB}}{N_{e\mu}^{SB}}, \quad \alpha_e = \frac{N_{ee}^{SB}}{N_{e\mu}^{SB}}.
\]

\[
N_{\mu\mu} = \alpha_\mu \times N_{e\mu}, \quad N_{ee} = \alpha_e \times N_{e\mu}.
\]

- $Z$+jets background
  - Modeled by *photon+jets events in data*: reweight photon $p_T$ spectrum to match that of dilepton in data, and model $E_T^{miss}$ with photon sample
2l2ν analysis - $m_T$ and $E_T^{\text{miss}}$ distributions

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

- $ee$, =0 jets
- $ee$, ≥1 jets
- $ee$, VBF

- $\mu\mu$, =0 jets
- $\mu\mu$, ≥1 jets
- $\mu\mu$, VBF
**2l2v analysis - event yields**

**Signal enriched region:** $E_T^{\text{miss}} > 100$ GeV and $m_T > 350$ GeV

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg + VBF$ (signal, $\Gamma_H/\Gamma_H^{\text{SM}} = 1$)</td>
<td>2.3±0.5</td>
<td>2.7±0.6</td>
</tr>
<tr>
<td>$gg + VBF$ (background)</td>
<td>5.4±1.2</td>
<td>6.5±1.4</td>
</tr>
<tr>
<td>$gg + VBF$ (total, $\Gamma_H/\Gamma_H^{\text{SM}} = 1$)</td>
<td>4.8±1.1</td>
<td>5.7±1.3</td>
</tr>
<tr>
<td>$gg + VBF$ (total, $\Gamma_H/\Gamma_H^{\text{SM}} = 10$)</td>
<td>19.2±5.5</td>
<td>22.6±6.7</td>
</tr>
<tr>
<td>$q\bar{q} \to ZZ$</td>
<td>25.0±2.1</td>
<td>29.4±2.5</td>
</tr>
<tr>
<td>$WZ$</td>
<td>11.6±1.2</td>
<td>13.5±1.4</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>$Z + \text{jets}$</td>
<td>1.5±0.9</td>
<td>2.4±1.4</td>
</tr>
<tr>
<td>(a+b) Total expected ($\Gamma_H/\Gamma_H^{\text{SM}} = 1$)</td>
<td>46.2±3.0</td>
<td>55.3±3.7</td>
</tr>
<tr>
<td>Observed</td>
<td>39</td>
<td>52</td>
</tr>
</tbody>
</table>
Systematic uncertainties

- Theoretical uncertainties
  - $gg \to ZZ$ processes: QCD renormalization and factorization scales varied by a factor of two both up and down, and applied corresponding NNLO $K$ factors; PDF variations by using CT10, MSTW2008 and NNPDF2.1
  - Additional 10% on continuum $gg \to ZZ$ background, accounting for limited knowledge on its NNLO cross section
  - QCD scales and PDF uncertainties on $qq \to ZZ$ and $WZ$ backgrounds
  - In the 4l analysis, uncertainty of VBF shapes to account for approximate simulation
  - In the 2l2ν analysis, theoretical uncertainties on jet-binning
Systematic uncertainties

- Experimental uncertainties
  - Lepton trigger, identification, isolation
  - In the 2l2ν analysis, uncertainties on lepton momentum scale and jet energy scale are propagated to $E_T^{\text{miss}}$, b-tagging efficiency
  - Background estimations from data
  - Integrated luminosity of data
  - Limited statistics in MC or data control samples
- For systematics affect both normalization and shape, variations of shape are taken into account
Results in 4l analysis

2D fit using $m_{4l}$ and $D_{gg}$

- **Observed (expected) 95% CL limit:** 
  - $r < 6.6$ (11.5)

- **Best fit value:** 
  - $r = 0.5^{+2.3}_{-0.5}$

- **Equivalent to** 
  - $\Gamma < 27.4$ MeV 
  - $\Gamma = 2.0^{+9.6}_{-2.0}$ MeV

1D fit on $m_{4l}$: $r < 26.3$ (17.0 expected)

1D fit on $D_{gg}$: $r < 7.1$ (12.7 expected)
Results in 2l2ν analysis

**1D fit using m_T or E_T^{\text{miss}}**

Observed (expected) 95% CL limit:
\[ r < 6.4 \ (10.7) \]

Best fit value:
\[ r = 0.2^{+2.2}_{-0.2} \]

Equivalent to
\[ \Gamma < 26.6 \ \text{MeV} \]
\[ \Gamma = 0.8^{+9.1}_{-0.8} \ \text{MeV} \]

ee-only : \( r < 6.9 \) (14.3 expected)
\mu\mu-only : \( r < 14.0 \) (13.7 expected)
Counting analysis in “signal enriched region”:
\[ r < 12.4 \] (16.4 expected)
Combined results

**Observed (expected)**
95% CL limit:
r < 4.2 (8.5)
p-value = 0.02

Best fit value:
r = 0.3$^{+1.5}_{-0.3}$

Equivalent to
$\Gamma < 17.4$ (35.3) MeV
$\Gamma = 1.4^{+6.1}_{-1.4}$ MeV

<table>
<thead>
<tr>
<th></th>
<th>$4\ell$</th>
<th>$2\ell2\nu$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected 95% CL limit, $r$</td>
<td>11.5</td>
<td>10.7</td>
<td>8.5</td>
</tr>
<tr>
<td>Observed 95% CL limit, $r$</td>
<td>6.6</td>
<td>6.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Observed 95% CL limit, $\Gamma_H$ (MeV)</td>
<td>27.4</td>
<td>26.6</td>
<td>17.4</td>
</tr>
<tr>
<td>Observed best fit, $r$</td>
<td>$0.5^{+2.3}_{-0.5}$</td>
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Summary

• First experimental constraint on the Higgs boson width from off-shell production has been presented

• Analysis performed in 4l and 2l2ν final states
  • 4l analysis uses invariant mass and kinematic discriminant
  • 2l2ν analysis relies on transverse mass and missing transverse energy
  • Small deficits in signal regions observed in both channels

• Combined results
  • \( \Gamma / \Gamma_{SM} < 4.2 \) (8.5 expected) @ 95% CL, equivalent to \( \Gamma < 17.4 \) (35.3 expected) MeV
  • Improve by more than two orders of magnitude over the on-peak measurement

• A good example of interaction between theorists and experimentalists. We welcome new ideas to dig deeper in the data
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Thank you!
Back up
4l mass

- Data
- $gg+VV \rightarrow ZZ$ ($\Gamma = 25\times\Gamma_{\text{SM}}^2$, $\mu = 1$)
- $gg+VV \rightarrow ZZ$ (SM)
- $qq \rightarrow ZZ$
- $Z+X$

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

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

$m_{4l} < 330 \text{ GeV}$

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

$MELA D_{gg} < 0.5$
Input to MELA
Limits

\[ \frac{-2 \Delta \ln L}{1} \]

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

\[ H \rightarrow ZZ \rightarrow 4l \]

- Expected $\mu = 1$ (observed)
- Expected $\mu = 2\mu$
- Expected $\mu = 4\mu$
- Expected $\mu = 4e$
- Expected $\mu = 4\mu$

\[ \frac{\Gamma}{\Gamma_{\text{SM}}} \]

\[ 0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30 \]

35

Tuesday, April 15, 2014
Yields vs width (loose Missing ET cut)

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

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

$r = \Gamma / \Gamma_{\text{SM}}$
## Event yields

<table>
<thead>
<tr>
<th>Channel</th>
<th>$qq \rightarrow ZZ \rightarrow 2\ell 2\nu$</th>
<th>$WZ \rightarrow 3\ell\nu$</th>
<th>Top/WW/W</th>
<th>$Z \rightarrow \ell\ell$</th>
<th>total expected</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee $\geq 1$ jets</td>
<td>33.9 ± 0.5</td>
<td>41.2 ± 0.7</td>
<td>93 ± 8 ± 23</td>
<td>0.3 ± 0.3 ± 0.1</td>
<td>169 ± 8 ± 23</td>
<td>186</td>
</tr>
<tr>
<td>ee VBF</td>
<td>0.15 ± 0.04</td>
<td>0.23 ± 0.05</td>
<td>1.4 ± 0.4 ± 0.4</td>
<td>1.2 ± 0.7 ± 0.3</td>
<td>3.0 ± 0.9 ± 0.5</td>
<td>3</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>83.8 ± 0.8</td>
<td>42.8 ± 0.7</td>
<td>57 ± 7 ± 14</td>
<td>7.0 ± 4.6 ± 2</td>
<td>190 ± 8 ± 14</td>
<td>175</td>
</tr>
<tr>
<td>$\mu\mu$ $\geq 1$ jets</td>
<td>43.1 ± 0.6</td>
<td>48.2 ± 0.7</td>
<td>121 ± 10 ± 30</td>
<td>0.9 ± 0.8 ± 0.2</td>
<td>213 ± 10 ± 30</td>
<td>219</td>
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<tr>
<td>$\mu\mu$ VBF</td>
<td>0.22 ± 0.04</td>
<td>0.17 ± 0.04</td>
<td>1.8 ± 0.3 ± 0.5</td>
<td>1.5 ± 1.1 ± 0.4</td>
<td>3.7 ± 1.1 ± 0.6</td>
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<table>
<thead>
<tr>
<th>Channel</th>
<th>$gg \rightarrow 2\ell 2\nu$</th>
<th>$qq \rightarrow qq2\ell 2\nu$</th>
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<tr>
<td>$b$</td>
<td>SBI</td>
<td>SBI</td>
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<tr>
<td>$=0$ jets</td>
<td>10.7 ± 0.2</td>
<td>0.034 ± 0.006</td>
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<td>ee $\geq 1$ jets</td>
<td>7.8 ± 0.2</td>
<td>0.99 ± 0.03</td>
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<tr>
<td>ee VBF</td>
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<td>0.18 ± 0.01</td>
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<td>$\mu\mu$ $=0$ jets</td>
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<td>0.048 ± 0.007</td>
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<td>$\mu\mu$ $\geq 1$ jets</td>
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<td>1.14 ± 0.03</td>
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<tr>
<td>$\mu\mu$ VBF</td>
<td>0.27 ± 0.04</td>
<td>0.21 ± 0.01</td>
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## Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
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<tr>
<td><strong>Experimental uncertainties</strong></td>
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<tr>
<td>Luminosity</td>
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<td>Anti b-tagging</td>
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<td>Lepton ID+Isolation</td>
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<td>Lepton momentum scale</td>
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<td>Jet energy scale</td>
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<td>PU effects, $uE_T^{miss}$</td>
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<td>Trigger</td>
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<td>15+shape</td>
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<td>Z+jets estimation from data</td>
<td>25+shape</td>
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<td><strong>Theory uncertainties</strong></td>
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<td>pdf, gluon-gluon initial state</td>
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<tr>
<td>pdf, quark-quark initial state</td>
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<td>$gg \rightarrow ZZ$ k-factor uncertainty</td>
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<td>Exclusive jet binning for $gg \rightarrow ZZ$</td>
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<tr>
<td>Underlying event and parton shower</td>
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Limits per jet bin