Higgs boson mass and width
Atlas and CMS

Fabrice Couderc
on behalf of the Atlas and CMS collaborations

Higgs couplings 2016, SLAC
Introduction

• Mass measurement: rely on precise mass resolution channels
  ✓ $H \rightarrow \gamma \gamma, H \rightarrow ZZ^* \rightarrow 4\ell$

• Width measurements
  ✓ Direct constraints from mass spectra
    ✦ $H \rightarrow \gamma \gamma, H \rightarrow ZZ^* \rightarrow 4\ell$
  ✓ Direct constraints from off-shell production
    ✦ $H \rightarrow ZZ^* \rightarrow 4\ell, H \rightarrow ZZ \rightarrow 2\ell2\nu, H \rightarrow WW \rightarrow e\mu2\nu$
  ✓ Indirect constraints from couplings study
    ✦ All final states

• Dataset
  ✓ LHC Run1: 5/fb (7TeV) + 20/fb (8TeV)
  ✓ LHC Run2: 12.9/fb (13TeV)

• Strategy
  ✓ Event selection as signal strength measurements + minor optimisation
  ✓ Minimise a profiled likelihood $L(\alpha, \hat{\theta}(\alpha))$

\(\alpha\) = parameter of interest ($m_H, \Gamma_H$)
\(L\) = likelihood of relevant discriminant variables
  (mass spectra …)
\(\theta\) = nuisance parameters (systematic)

Likelihood scan example

\(\hat{m}_H = 124.70 \pm 0.34 \text{ GeV}\)
\(124.70 \pm 0.31 \text{ (stat)} \pm 0.15 \text{ (syst)} \text{ GeV}\)

Floating $\mu_{VBF, VH}$ and $\mu_{95\% c.l.}$

Total uncertainty

Statistical only

95% 68%
• 2D Likelihood
  ✓ m_4\mu, kinematic BDT (sig vs bkg discrimination)

• Energy measurement
  ✓ includes FSR recovery, Ecal-tracker combination for e^\pm
  ✓ Z-mass constraint to improve mass resolution
  ✓ Energy scale linearity: Z, \psi, \Upsilon's

• Inclusive mass resolution \sigma_{4\mu} = 1.6 \text{ GeV}
• 3D Likelihood
  ✔ $m_4\ell$, matrix-element discriminant (sig vs bkg), per-event mass resolution

• Energy measurement
  ✔ includes FSR recovery, Ecal-tracker combination for $e^\pm$
  ✔ Energy scale linearity: $Z$, $\psi$, $\Upsilon$’s

• Inclusive mass resolution $\sigma_{4\mu} = 1.7$ GeV
• 1D likelihood
  ✓ $m_{\gamma\gamma}$ + event categorisation
• Dedicated event categorisation to be more sensitive to the mass
  ✓ 10 categories based on diphoton $p_T$, converted/unconverted, central Ecal
• Experimental scale assessed from $Z \rightarrow ee$
  ✓ checked with $Z \rightarrow ll\gamma$
• Inclusive mass resolution $\sigma_{\gamma\gamma} = 1.7$ GeV
• ID likelihood
  ✓ $m_{\gamma\gamma}$ + event categorisation
• Experimental scale assessed from $Z \to ee$
  ✓ also checked with $E/p$
• Inclusive mass resolution $\sigma_{\gamma\gamma} = 1.8$ GeV
• Overall 300 nuisance parameters
• Model independence: profiled 3 signal strengths:
  ✓ $\mu[ggH+ttH]$, $\mu[VBF+VH]$, $\mu[4\ell]$

Several compatibility check performed
$\Delta m[\text{Atlas-CMS}]_{\gamma\gamma} = 1.3 \pm 0.6 \text{ GeV (2.1}\sigma)$
$\Delta m[\text{Atlas-CMS}]_{4\ell} = -0.9 \pm 0.7 \text{ GeV (1.3}\sigma)$
**ATLAS and CMS LHC Run 1**

Uncertainty in ATLAS combined result

- ATLAS ECAL non-linearity / CMS photon non-linearity
- Material in front of ECAL
- ECAL longitudinal response
- ECAL lateral shower shape
- Photon energy resolution
- ATLAS $H \rightarrow \gamma \gamma$ vertex & conversion reconstruction
- $Z \rightarrow ee$ calibration
- CMS electron energy scale & resolution
- Muon momentum scale & resolution
- ATLAS $H \rightarrow \gamma \gamma$ background modeling
- Integrated luminosity
- Additional experimental systematic uncertainties
- Theory uncertainties

Uncertainty in CMS combined result

- Observed
- Expected

Uncertainty in LHC combined result

- Observed
- Expected

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**statistical uncertainty**

0.22

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Higgs couplings 2016
Higgs boson width $\Gamma_H$

- $\Gamma_H^{\text{SM}} \approx 4.1$ MeV

- LHC: Higgs boson production inversely prop to $\Gamma_H$
  - ✓ No inclusive Higgs sample at LHC, only “known” final states are recorded!
  - ✓ $\Gamma_H$ difficult measurement at LHC

- Direct measurement @ LHC from the mass shape
  - ✓ Measure width of the on-shell mass peak
    - ✦ experimental mass resolution $\approx 1500$ MeV
  - ✓ Assess $\Gamma_H$ from off-shell to on-shell production
    - ✦ some model-dependent assumptions
    - ✦ best proxy to-date

- Indirect measurement @ LHC from couplings
  - ✓ $\kappa$-framework!
  - ✓ model dependence

- Direct measurement @ LHC from life time!

- In this talk a brief overview of the three
• Overall mass peak width convolution of $\Gamma_H$ (4.1 MeV) and experimental mass resolution (1500 MeV)

✓ require excellent mass resolution: $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$

<table>
<thead>
<tr>
<th>channel</th>
<th>obs(exp) in GeV @95%CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas $\gamma\gamma$ [1]</td>
<td>5.0 (6.2)</td>
</tr>
<tr>
<td>Atlas $4\ell$ [1]</td>
<td>2.6 (6.2)</td>
</tr>
<tr>
<td>CMS $\gamma\gamma + 4\ell$ [6]</td>
<td>1.7 (2.3)</td>
</tr>
</tbody>
</table>
• Direct measurement limited
  ✓ detector resolution ≈ 1500 MeV while $\Gamma_H^{\text{SM}} \approx 4$ MeV

• Off-shell Higgs boson production offers a proxy

  on-shell
  $\sigma_{\text{on-shell}}^{gg \to H \to ZZ} \sim \frac{g_{ggH}g_{HZZ}^2}{m_H \Gamma_H}$

  off-shell
  $\sigma_{\text{off-shell}}^{gg \to H^* \to ZZ} \sim \frac{g_{ggH}g_{HZZ}^2}{(2m_Z)^2}$.

• Not that simple: interference with non resonant background
  ✓ interfere with non resonant bkg
  $gg \to ZZ + gg \to H^* \to ZZ$
  ✓ massive $qq \to ZZ$
  ✓ Some model dependence.
  Assumptions:
  ✦ same productions as SM
  ✦ SM off to on-shell couplings ratios

\[ \frac{d\sigma_{gg \to H \to ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}. \]
**Γ_H from off-shell production**

- Off-shell production accessible for 3 channels
  - ✓ H → ZZ → 4ℓ / 2ℓ2ν ; H → WW → eνμν
- Off-shell signal to background enhanced with a multivariate discriminants, e.g.
  - ✓ H → 4ℓ : likelihood 5 angles, mZ₁, mZ₂
  - ✓ Atlas H → WW → eνμν: R₈

\[
R₈ = \sqrt{m_{e\ell}² + (a \cdot m_W^{WW})²}.
\]

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**CMS**

\[19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV})\]

- Data
- All contributions (Γ₇ = 10×Γ^{SM}_H, μ = 1)
- q̅q → ZZ (Γ₇ = Γ^{SM}_H, μ = 1)
- m_{qℓ} > 330 GeV

**ATLAS**

\[[7]\]

\[[8]\]

**H → 4ℓ**

**H → eμ2ν**

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Combination done forcing $\mu_{VBF} / \mu_{GF}$ to be identical for ZZ and WW

$\Gamma_H < 13 \ (26) \text{ MeV}$

@ 95% C.L.
NNLO/LO K-factor $gg \rightarrow VV$ poorly known and assumed to be similar to $gg \rightarrow H^* \rightarrow VV$

$$R^{B}_{H^*} = \frac{K(gg \rightarrow VV)}{K(gg \rightarrow H^* \rightarrow VV)} = \frac{K^B(m_{VV})}{K_{gg}^H(m_{VV})}$$

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>95% CL lim. $(CL_s)$ on $\mu_{off-shell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference $gg \rightarrow (H^* \rightarrow)VV$</td>
<td>7.2</td>
</tr>
<tr>
<td>QCD scale $K^{H^*}<em>{VV}(m</em>{VV})$ (correlated component)</td>
<td>7.1</td>
</tr>
<tr>
<td>PDF $q\bar{q} \rightarrow VV$ and $gg \rightarrow (H^* \rightarrow)VV$</td>
<td>6.7</td>
</tr>
<tr>
<td>QCD scale $q\bar{q} \rightarrow VV$</td>
<td>6.7</td>
</tr>
<tr>
<td>Luminosity</td>
<td>6.6</td>
</tr>
<tr>
<td>Drell–Yan background</td>
<td>6.6</td>
</tr>
<tr>
<td>QCD scale $K^{H^*}<em>{gg}(m</em>{VV})$ (uncorrelated component)</td>
<td>6.5</td>
</tr>
<tr>
<td>Remaining systematic uncertainties</td>
<td>6.5</td>
</tr>
<tr>
<td>All systematic uncertainties</td>
<td>8.1</td>
</tr>
<tr>
<td>No systematic uncertainties</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Dominant sources of systematics (off-shell rate measurement)
• Coupling analysis framework
  \[ \Gamma_i = \Gamma_i^{\text{SM}} \times \kappa_i^2 \quad \Rightarrow \quad \Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{\text{SM}}}{1 - B_{\text{BSM}}} \]

• Two relevant frameworks
  \[ B_{\text{BSM}} > 0 : |\kappa_V| < 1 \text{ (same sign for } \kappa_Z \text{ and } \kappa_W) \]
  \[ B_{\text{BSM}} = 0 \]

<table>
<thead>
<tr>
<th>Production</th>
<th>loops</th>
<th>interference</th>
<th>effective scaling factor</th>
<th>resolved scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma^{ZZ} )</td>
<td>-</td>
<td>-</td>
<td>( \kappa_Z^2 )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma^{WW} )</td>
<td>-</td>
<td>-</td>
<td>( \kappa_W^2 )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma^\gamma\gamma )</td>
<td>( \checkmark )</td>
<td>( t-W )</td>
<td>( \kappa_\gamma^2 )</td>
<td>( 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_\gamma^2 - 0.66 \cdot \kappa_\gamma \kappa_W )</td>
</tr>
<tr>
<td>( \Gamma^{tt} )</td>
<td>-</td>
<td>-</td>
<td>( \kappa_t^2 )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma^{bb} )</td>
<td>-</td>
<td>-</td>
<td>( \kappa_b^2 )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma^{\mu\mu} )</td>
<td>-</td>
<td>-</td>
<td>( \kappa_\mu^2 )</td>
<td></td>
</tr>
</tbody>
</table>

Total width (\( B_{\text{BSM}} = 0 \))

\[ \Gamma_H \quad \checkmark \quad - \quad \kappa_H^2 \]

\[ 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_\gamma^2 + 0.06 \cdot \kappa_t^2 + 0.03 \cdot \kappa_\gamma^2 + 0.03 \cdot \kappa_\gamma^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_\gamma^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2 \]
• $\Gamma_H = h \tau_H \Rightarrow c\tau_H = 48\text{ fm}$

✓ typical track IP resolution = 10$\mu$m

• Measure Higgs boson lifetime

$$\Delta t = \frac{m_{4\ell}}{p_T} (\Delta r_T \cdot \hat{p}_T)$$

$\Delta r_T = 4\ell$ vertex distance to PV

• relaxed lepton IP cuts

$\Delta c\tau_H < 57\ (56)\ \mu$m ($= 10^9\text{ fm}$!)

@ 95% C.L.
Run 2 preliminary results
- Dataset 12.9/fb (13TeV 2016)
- 3 channels: 4µ, 2e2µ, 4e
  - ✓ electrons pT > 7GeV |η| < 2.5
  - ✓ muons pT > 5GeV ; |η| < 2.4
- 6 categories based on topology
- Strategy
  - ✓ $D_{\text{kin}}$: matrix element based signal vs background discrimination
  - ✓ $D_{\text{mass}}$: per-event mass resolution gives more weight to best measured event
    - ✦ tune on Z
    - ✦ improves mass determination

\[ D_{\text{mass}} \approx 10\% \text{ improvement} \]
Run2 mass measurement

$118 < m_{4\ell} < 130 \text{ GeV}$

<table>
<thead>
<tr>
<th>Channel</th>
<th>$4e$</th>
<th>$4\mu$</th>
<th>$2e2\mu$</th>
<th>$4\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \rightarrow ZZ$</td>
<td>$1.37^{+0.16}_{-0.15}$</td>
<td>$3.09^{+0.27}_{-0.27}$</td>
<td>$3.90^{+0.46}_{-0.43}$</td>
<td>$8.36^{+0.81}_{-0.79}$</td>
</tr>
<tr>
<td>$gg \rightarrow ZZ$</td>
<td>$0.16^{+0.03}_{-0.03}$</td>
<td>$0.32^{+0.05}_{-0.05}$</td>
<td>$0.30^{+0.05}_{-0.05}$</td>
<td>$0.77^{+0.12}_{-0.12}$</td>
</tr>
<tr>
<td>$Z + X$</td>
<td>$0.90^{+0.38}_{-0.37}$</td>
<td>$1.40^{+0.52}_{-0.51}$</td>
<td>$2.34^{+0.91}_{-0.89}$</td>
<td>$4.64^{+1.11}_{-1.09}$</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$2.42^{+0.32}_{-0.40}$</td>
<td>$4.81^{+0.59}_{-0.39}$</td>
<td>$6.54^{+1.33}_{-1.00}$</td>
<td>$13.77^{+1.41}_{-1.38}$</td>
</tr>
<tr>
<td>Signal ($m_H = 125\text{ GeV}$)</td>
<td>$3.90^{+0.33}_{-0.54}$</td>
<td>$7.92^{+0.88}_{-0.93}$</td>
<td>$9.80^{+1.34}_{-1.36}$</td>
<td>$21.61^{+2.53}_{-2.71}$</td>
</tr>
<tr>
<td>Total expected</td>
<td>$6.32^{+0.78}_{-0.76}$</td>
<td>$12.73^{+1.21}_{-1.24}$</td>
<td>$16.34^{+1.92}_{-1.90}$</td>
<td>$35.38^{+3.43}_{-3.45}$</td>
</tr>
<tr>
<td>Observed</td>
<td>5</td>
<td>12</td>
<td>16</td>
<td>33</td>
</tr>
</tbody>
</table>

$N_{4\ell}^{\text{run1}} \approx 17$

$N_{\text{obs}}^{\text{run1}} = 25$

$m_H = 124.50^{+0.47}_{-0.45} \text{(stat.)}^{+0.13}_{-0.11} \text{(sys.)} \text{ GeV}$
Extract signal with 1D fit to $m_{4\ell}$, 2 mass ranges used:
- $105 < m_{4\ell} < 1600$ GeV (similar to run 1)
- $105 < m_{4\ell} < 140$ GeV lower sensitivity but smaller theoretical assumptions
Conclusions

- Presented selected measurements on the Higgs boson mass and natural width measurement
  - $m_H = 125.09 \pm 0.24$ GeV
- LHC Run 1 dataset was great for Higgs physics
  - well understood dataset
  - great details in systematic effect for mass measurement
  - fancy analysis techniques
  - still statistically limited
- LHC Run2 measurements starting
  - statistical power is already larger than Run1
  - will require some time to get to the same level of understanding
  - stay tuned…
References

[12] CMS-PAS-HIG-16-033
Mass shift $\approx -35$ MeV
ATLAS Simulation

\[ \frac{1}{N} \frac{dN}{dm_{4\mu}} / 0.5 \text{ GeV} \]

- \( m_H = 125 \text{ GeV} \)
- Gaussian fit

**H\to ZZ^*\to4\mu**

- \( \sqrt{s} = 8 \text{ TeV} \)
- \( m = 124.92 \pm 0.01 \text{ GeV} \)
- \( \sigma = 1.60 \pm 0.01 \text{ GeV} \)
- Fraction outside \( \pm 2\sigma \): 17%

With Z mass constraint

\[ m_{4\mu} \text{ [GeV]} \]

ATLAS Simulation

\[ \frac{1}{N} \frac{dN}{dm_{2\mu e/2e 2\mu}} / 0.5 \text{ GeV} \]

- \( m_H = 125 \text{ GeV} \)
- Gaussian fit

**H\to ZZ^*\to2\mu2e/2e2\mu**

- \( \sqrt{s} = 8 \text{ TeV} \)
- \( m = 124.78 \pm 0.01 \text{ GeV} \)
- \( \sigma = 1.77 \pm 0.01 \text{ GeV} \)
- Fraction outside \( \pm 2\sigma \): 20%

With Z mass constraint

\[ m_{2\mu e/2e 2\mu} \text{ [GeV]} \]

ATLAS Simulation

\[ \frac{1}{N} \frac{dN}{dm_{e e}} / 0.5 \text{ GeV} \]

- \( m_H = 125 \text{ GeV} \)
- Gaussian fit

**H\to ZZ^*\to4e**

- \( \sqrt{s} = 8 \text{ TeV} \)
- \( m = 124.51 \pm 0.02 \text{ GeV} \)
- \( \sigma = 2.18 \pm 0.02 \text{ GeV} \)
- Fraction outside \( \pm 2\sigma \): 19%

With Z mass constraint

\[ m_{e e} \text{ [GeV]} \]
CMS ZZ* resolution

CMS Simulation

H → ZZ → 4μ

$\sqrt{s} = 8$ TeV

$H \rightarrow ZZ \rightarrow 4\mu$

$m_H = 126$ GeV

$\sigma_{dCB} = 1.2$ GeV

$\sigma_{eff} = 1.7$ GeV

Simulation

Parametric Model

CMS Simulation

H → ZZ → 2e2μ

$\sqrt{s} = 8$ TeV

$H \rightarrow ZZ \rightarrow 2e2\mu$

$m_H = 126$ GeV

$\sigma_{dCB} = 1.6$ GeV

$\sigma_{eff} = 2.3$ GeV

Simulation

Parametric Model
CMS Simulation
\[ s = 8 \text{ TeV} \]

\[ \sigma_{\text{eff}} / \rho \]

- ECAL barrel

- \( E_{\text{regr.}} - \rho \) comb.
- \( \text{ECAL}_{\text{std}} \)
- Tracker \( \rho \)

Electron \( \rho \) (GeV)
## Event Yield ($120 < m_{4l} < 130$ GeV)

<table>
<thead>
<tr>
<th>Final state</th>
<th>Signal</th>
<th>$ZZ^*$</th>
<th>$Z + \text{jets, } t\bar{t}$</th>
<th>$s/b$</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>$1.00 \pm 0.10$</td>
<td>$0.91 \pm 0.09$</td>
<td>$0.46 \pm 0.02$</td>
<td>$0.10 \pm 0.04$</td>
<td>$1.7$</td>
<td>$1.47 \pm 0.10$</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$0.66 \pm 0.06$</td>
<td>$0.58 \pm 0.06$</td>
<td>$0.32 \pm 0.02$</td>
<td>$0.09 \pm 0.03$</td>
<td>$1.5$</td>
<td>$0.99 \pm 0.07$</td>
</tr>
<tr>
<td>$2\mu2e$</td>
<td>$0.50 \pm 0.05$</td>
<td>$0.44 \pm 0.04$</td>
<td>$0.21 \pm 0.01$</td>
<td>$0.36 \pm 0.08$</td>
<td>$0.8$</td>
<td>$1.01 \pm 0.09$</td>
</tr>
<tr>
<td>$4e$</td>
<td>$0.46 \pm 0.05$</td>
<td>$0.39 \pm 0.04$</td>
<td>$0.19 \pm 0.01$</td>
<td>$0.40 \pm 0.09$</td>
<td>$0.7$</td>
<td>$0.98 \pm 0.10$</td>
</tr>
<tr>
<td>Total</td>
<td>$2.62 \pm 0.26$</td>
<td>$2.32 \pm 0.23$</td>
<td>$1.17 \pm 0.06$</td>
<td>$0.96 \pm 0.18$</td>
<td>$1.1$</td>
<td>$4.45 \pm 0.30$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Final state</th>
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<th>$s/b$</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>$5.80 \pm 0.57$</td>
<td>$5.28 \pm 0.52$</td>
<td>$2.36 \pm 0.12$</td>
<td>$0.69 \pm 0.13$</td>
<td>$1.7$</td>
<td>$8.33 \pm 0.6$</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$3.92 \pm 0.39$</td>
<td>$3.45 \pm 0.34$</td>
<td>$1.67 \pm 0.08$</td>
<td>$0.60 \pm 0.10$</td>
<td>$1.5$</td>
<td>$5.72 \pm 0.37$</td>
</tr>
<tr>
<td>$2\mu2e$</td>
<td>$3.06 \pm 0.31$</td>
<td>$2.71 \pm 0.28$</td>
<td>$1.17 \pm 0.07$</td>
<td>$0.36 \pm 0.08$</td>
<td>$1.8$</td>
<td>$4.23 \pm 0.30$</td>
</tr>
<tr>
<td>$4e$</td>
<td>$2.79 \pm 0.29$</td>
<td>$2.38 \pm 0.25$</td>
<td>$1.03 \pm 0.07$</td>
<td>$0.35 \pm 0.07$</td>
<td>$1.7$</td>
<td>$3.77 \pm 0.27$</td>
</tr>
<tr>
<td>Total</td>
<td>$15.6 \pm 1.6$</td>
<td>$13.8 \pm 1.4$</td>
<td>$6.24 \pm 0.34$</td>
<td>$2.00 \pm 0.28$</td>
<td>$1.7$</td>
<td>$22.1 \pm 1.5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Final state</th>
<th>Signal</th>
<th>$ZZ^*$</th>
<th>$Z + \text{jets, } t\bar{t}$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>$6.80 \pm 0.67$</td>
<td>$6.20 \pm 0.61$</td>
<td>$2.82 \pm 0.14$</td>
<td>$0.79 \pm 0.13$</td>
<td>$1.7$</td>
<td>$9.81 \pm 0.64$</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$4.58 \pm 0.45$</td>
<td>$4.04 \pm 0.40$</td>
<td>$1.99 \pm 0.10$</td>
<td>$0.69 \pm 0.11$</td>
<td>$1.5$</td>
<td>$6.72 \pm 0.42$</td>
</tr>
<tr>
<td>$2\mu2e$</td>
<td>$3.56 \pm 0.36$</td>
<td>$3.15 \pm 0.32$</td>
<td>$1.38 \pm 0.08$</td>
<td>$0.72 \pm 0.12$</td>
<td>$1.5$</td>
<td>$5.24 \pm 0.35$</td>
</tr>
<tr>
<td>$4e$</td>
<td>$3.25 \pm 0.34$</td>
<td>$2.77 \pm 0.29$</td>
<td>$1.22 \pm 0.08$</td>
<td>$0.76 \pm 0.11$</td>
<td>$1.4$</td>
<td>$4.75 \pm 0.32$</td>
</tr>
<tr>
<td>Total</td>
<td>$18.2 \pm 1.8$</td>
<td>$16.2 \pm 1.6$</td>
<td>$7.41 \pm 0.40$</td>
<td>$2.95 \pm 0.33$</td>
<td>$1.6$</td>
<td>$26.5 \pm 1.7$</td>
</tr>
<tr>
<td>Source</td>
<td>Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>--------------------------------</td>
<td>-----------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow WW$</td>
<td>8–18% (0,1-jet)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}, tW$</td>
<td>$\sim$10% (0,1-jet); $\sim$30% (2-jet)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau^-\tau^+$</td>
<td>$\sim$10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W + \text{jet, QCD multijet}$</td>
<td>$\sim$40%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W\gamma/\gamma^*$</td>
<td>20–30%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Experimental uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.2% at 7 TeV 2.5% at 8 TeV</td>
</tr>
<tr>
<td>Lepton reconstruction and identification</td>
<td>3–4%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>10%</td>
</tr>
</tbody>
</table>

**Theoretical uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \rightarrow WW$</td>
<td>20% (2-jet)</td>
</tr>
<tr>
<td>$WZ, ZZ, VVV$</td>
<td>$\sim$4%</td>
</tr>
<tr>
<td>QCD scale uncertainties:</td>
<td></td>
</tr>
<tr>
<td>On-shell signal</td>
<td>20% (GF); 2% (VBF)</td>
</tr>
<tr>
<td>Off-shell signal</td>
<td>25% (GF); 2% (VBF)</td>
</tr>
<tr>
<td>Bkg. and sig. + bkg. interf.</td>
<td>35% (GF); 2% (VBF)</td>
</tr>
<tr>
<td>Exclusive jet bin fractions</td>
<td>30–50% (GF); 3–11% (VBF)</td>
</tr>
<tr>
<td>PDFs</td>
<td>3–8%</td>
</tr>
<tr>
<td>Underlying event and parton shower</td>
<td>20% (GF); 10% (VBF)</td>
</tr>
</tbody>
</table>
• on-shell analysis: $H \rightarrow 4\ell$
  ✓ extraction 3D fit ($m_{4\ell}, D_{\text{bkg}}^{\text{kin}}, p_T^{4\ell}$ or $D_{\text{jet}}$)

• off-shell analysis: $H \rightarrow 2\ell 2\nu + H \rightarrow 4\ell$
  ✓ $m_{4\ell} > 220\text{GeV}, m_T[2\ell 2\nu] > 180\text{ GeV}$
  ✓ off-shell discriminant $D_{gg}$ (LL based 5 angles, $m_{Z1}, m_{Z2}$)
  ✓ extraction 2D fit ($m_{4\ell}, D_{gg}$)
Run1 CMS $H \rightarrow WW^*$

- Final state $H \rightarrow 2\ell 2\nu$
  - ✓ poor mass resolution but larger branching ratio than $4\ell + W$ less virtual
- Same analysis strategy as standard couplings
  - ✓ 0 / 1 / 2 jets categories
- Width measurement specific
  - ✓ on/off shell region based on 3 variables
  - ✓ discriminant for off shell signal vs background (7 variables)
- extraction via a 2D fit

<table>
<thead>
<tr>
<th></th>
<th>On-shell (7, 8 TeV: all-jet)</th>
<th>Off-shell (8 TeV: 0,1-jet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\ell\ell}$</td>
<td>$&lt; 70$ GeV</td>
<td>$&gt; 70$ GeV</td>
</tr>
<tr>
<td>$p_T^{\ell\ell}$</td>
<td>$&gt; 30$ GeV</td>
<td>$&gt; 45$ GeV</td>
</tr>
<tr>
<td>$p_T^{T2}$</td>
<td>$&gt; 10$ GeV</td>
<td>$&gt; 20$ GeV</td>
</tr>
<tr>
<td>fit Var.</td>
<td>$m_{\ell\ell}, m_T^H$</td>
<td>$m_{\ell\ell},$ MVA</td>
</tr>
</tbody>
</table>
Combination done assuming custodial symmetry

\[ \mu_{\text{GF}}^{\text{off-shell}} / \mu_{\text{GF}}^{\text{WW}} = \mu_{\text{VBF}}^{\text{ZZ}} / \mu_{\text{VBF}}^{\text{WW}} = \Lambda_{WZ} = 1 \]

\[ \mu_{\text{GF}}^{\text{off-shell}} < 2.4 \ (4.6) \]
@ 95% C.L.

\[ \mu_{\text{VBF}}^{\text{off-shell}} < 19.3 \ (34.4) \]
@ 95% C.L.

Fabrice Couderc

Higgs couplings 2016
• off-shell analysis
  ✓ $m[4\ell] > 220\text{GeV}$
  ✓ $m_{T}[2\ell 2\nu] > 380\text{ GeV} + E_{T}^{\text{miss}}[2\ell 2\nu] > 180\text{ GeV}$
• Analysis inclusive in jet (QCD corrections for signal) but similar to standard analysis
• $4\ell$ matrix element discriminant based on 8 variables

**off-shell yields**

<table>
<thead>
<tr>
<th>Process</th>
<th>$ZZ \rightarrow 4\ell$</th>
<th>$ZZ \rightarrow 2\ell 2\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H^{*} \rightarrow VV$ (S)</td>
<td>$1.1 \pm 0.3$</td>
<td>$3.2 \pm 1.0$</td>
</tr>
<tr>
<td>$gg \rightarrow VV (B)$</td>
<td>$2.8 \pm 0.8$</td>
<td>$5.3 \pm 1.6$</td>
</tr>
<tr>
<td>$gg \rightarrow (H^{*} \rightarrow)VV$</td>
<td>$2.4 \pm 0.7$</td>
<td>$3.9 \pm 1.2$</td>
</tr>
<tr>
<td>$gg \rightarrow (H^{*} \rightarrow)VV (\mu_{\text{off-shell}} = 10)$</td>
<td>$9.2 \pm 2.5$</td>
<td>$24.0 \pm 7.3$</td>
</tr>
<tr>
<td>$VBF H^{*} \rightarrow VV$ (S)</td>
<td>$0.12 \pm 0.01$</td>
<td>$0.48 \pm 0.04$</td>
</tr>
<tr>
<td>$VBF VV (B)$</td>
<td>$0.71 \pm 0.04$</td>
<td>$1.2 \pm 0.2$</td>
</tr>
<tr>
<td>$VBF (H^{*} \rightarrow)VV$</td>
<td>$0.59 \pm 0.03$</td>
<td>$0.7 \pm 0.1$</td>
</tr>
<tr>
<td>$VBF (H^{*} \rightarrow)VV (\mu_{\text{off-shell}} = 10)$</td>
<td>$1.17 \pm 0.06$</td>
<td>$2.9 \pm 0.2$</td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow ZZ$</td>
<td>$21.3 \pm 2.1$</td>
<td>$31.5 \pm 3.5$</td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow WZ$</td>
<td>-</td>
<td>$10.6 \pm 1.4$</td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow WW$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$t\bar{t}, Wt,$ and $tb/\bar{t}qb$</td>
<td>-</td>
<td>$0.4 \pm 0.2$</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$Z \rightarrow ee, \mu\mu$</td>
<td>-</td>
<td>$3.5 \pm 3.0$</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>-</td>
<td>$0.8 \pm 0.2$</td>
</tr>
<tr>
<td>Total Expected (SM)</td>
<td>24.4 ± 2.2</td>
<td>51 ± 6</td>
</tr>
<tr>
<td>Observed</td>
<td>18</td>
<td>48</td>
</tr>
</tbody>
</table>
• Final state $H \rightarrow e\mu\nu\nu$
  ✓ poor mass resolution but larger branching ratio than
  $4\ell + W$ less virtual

• Same analysis selection as standard couplings
  analysis

• Width measurement specific
  ✓ new variable introduced $R_8$
  ✓ $R_8 > 450$ GeV

$$R_8 = \sqrt{m_{ee}^2 + (a \cdot m_{WW}^2)^2}.$$
- NNLO/LO K-factor $gg\rightarrow VV$ poorly known and assumed to be similar to $gg\rightarrow H^* \rightarrow VV$
- Results shown vs $R_{H^*}$

$$R^B_{H^*} = \frac{K(gg \rightarrow VV)}{K(gg \rightarrow H^* \rightarrow VV)} = \frac{K^B(m_{VV})}{K^H_{gg}(m_{VV})}$$
### Summary of relative systematic uncertainties

<table>
<thead>
<tr>
<th>Category</th>
<th>Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common experimental uncertainties</strong></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>6.2 %</td>
</tr>
<tr>
<td>Lepton identification/reconstruction efficiencies</td>
<td>6 – 11 %</td>
</tr>
<tr>
<td><strong>Background related uncertainties</strong></td>
<td></td>
</tr>
<tr>
<td>QCD scale (q̄q → ZZ, gg → ZZ)</td>
<td>3 – 10 %</td>
</tr>
<tr>
<td>PDF set (q̄q → ZZ, gg → ZZ)</td>
<td>3 – 5 %</td>
</tr>
<tr>
<td>Electroweak corrections (q̄q → ZZ)</td>
<td>1 – 15 %</td>
</tr>
<tr>
<td>gg → ZZ K factor</td>
<td>10 %</td>
</tr>
<tr>
<td>Reducible background (Z+X)</td>
<td>40 – 55 %</td>
</tr>
<tr>
<td>Event categorization (experimental)</td>
<td>2 – 18 %</td>
</tr>
<tr>
<td>Event categorization (theoretical)</td>
<td>3 – 20 %</td>
</tr>
<tr>
<td><strong>Signal related uncertainties</strong></td>
<td></td>
</tr>
<tr>
<td>QCD scale (q̄q → VBF/VH, gg → H/ttH)</td>
<td>3 – 10 %</td>
</tr>
<tr>
<td>PDF set (q̄q → VBF/VH, gg → H/ttH)</td>
<td>3 – 4 %</td>
</tr>
<tr>
<td>BR(H → ZZ → 4ℓ)</td>
<td>2 %</td>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>0.04 – 0.3 %</td>
</tr>
<tr>
<td>Lepton energy resolution</td>
<td>20 %</td>
</tr>
<tr>
<td>Event categorization (experimental)</td>
<td>2 – 15 %</td>
</tr>
<tr>
<td>Event categorization (theoretical)</td>
<td>8 – 20 %</td>
</tr>
</tbody>
</table>