Measurement of cross sections and properties of the Higgs boson in decays to bosons using the ATLAS detector

Monica Trovatelli
University of Victoria (Canada)

DIS2018, Kobe 16-20 Apr 2018
Outline

• Higgs physics in diboson final states
  • Overview of the (so far) ATLAS Run-2 measurements in WW*/ZZ*/γγ decay channels

• Higgs boson cross-sections, which?
  • Fiducial inclusive and Differential
  • Total (full phase-space)
  • Production-mode cross-section

• Other properties measurements:
  • Couplings
  • Mass
  • Width and Spin/Parity

• Remarks and Conclusions
Higgs boson measurements in diboson final states

- Despite the low branching fraction of $H \rightarrow WW^* (\rightarrow l\ell l\ell)/ZZ^*/\gamma\gamma$, these decays channels have a clean signature and constitute a powerful tool for many Higgs boson properties measurements.

Plenty of new ATLAS results already published:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>JHEP10(2017)132</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>arXiv:1802.04146</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined(*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ATLAS-CONF-2017-047</td>
</tr>
</tbody>
</table>

M. Trovatelli

DIS2018, Kobe 16-20 Apr 2018

(*) currently combining only 4l and $\gamma\gamma$ channels
Higgs boson cross-section measurements

In Run-2 different Higgs boson cross-section measurements considered:

- **Inclusive fiducial and differential cross-section**

  - **Measured in fiducial volume**
    - Avoid model-dependent extrapolations → only correct for inefficiencies & reconstruction effects
    
    \[
    \sigma_{i,fid} = \frac{N_{i,fit}}{L \times C_i}, \quad C_i = \frac{N_{i,reco}}{N_{i,part}}
    \]
    
    - Preserve measured results over years to allow comparison to future new theories

  - **Inclusive**: No attempt to separate Higgs production/decay modes → compare with best available predictions in the detector phase space

  - **Differential**: test Higgs boson kinematics and modelling with $p_T^H$, $|y_H|$, $p_{Tj1}$, $N_{jet}$,…
    
    also sensitive to BSM physics

- **Total cross-section**: extrapolate to full phase space and combine channels to improve precision

- **Production mode cross-section** (Simplified Template cross section framework* (STXS)):

  - *simple fiducial region definitions* matching specific experimental categories (ggF 0jets, etc..)
  
  - reduce theoretical uncertainties

(*) LHC Higgs X-Sec WG: 4 [arXiv:1610.07922]
Analysis strategy in brief

• **Signature**: two prompt isolated leptons and missing momentum

• **Events split in 3 major Signal Regions** on Njets(\(^\star\)):
  - Njet = 0 and Njet = 1 (ggF dominated)
    - \(m_T\) used as discriminant
  - Njet \(\geq 2\) (VBF dominated)
    - BDT used as discriminant

  \{ b-jet veto in all categories to reduce ttbar (\(\sigma_{13\ TeV}/\sigma_{8\ TeV} \approx 3.3\)) \}

• Irreducible backgrounds normalised to data via CRs
  - non-resonant WW, ttbar and \(Z\rightarrow\tau\tau\)
  - Mis-identified leptons (~10% of total bkg) fully data-driven

(*) complete event selection table in backup

• **Simultaneous SRs and CR max likelihood fit**
  - **16 fits regions defined for Njet \(\leq 1\)**:
    - Different bkg composition
    - Enhance sensitivity

\[
[2 \times m_{\ell\ell}] \cdot [2 \times p_T^{\text{sub-leading}}] \cdot [e\mu / \mu e]
\]

• **4 BDT bins for VBF enriched category**
  - S(VBF)/B \(\sim 0.6\) in the last bin

\(\Rightarrow\) extract both ggF and VBF cross-sections

• Other production/decays modes fixed to SM
**H → WW* → eνμν - Results**

**Signal strength and cross-section results:**

<table>
<thead>
<tr>
<th></th>
<th>Run-2</th>
<th>Run-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$μ_{ggF}$</td>
<td>$1.21^{+0.12}<em>{-0.11}$ (stat.) $^{+0.18}</em>{-0.17}$ (sys.)</td>
<td>$1.21^{+0.22}_{-0.21}$</td>
</tr>
<tr>
<td>$μ_{VBF}$</td>
<td>$0.62^{+0.30}<em>{-0.28}$ (stat.) $^{+0.37}</em>{-0.36}$ (sys.)</td>
<td>$1.27^{+0.53}_{-0.45}$</td>
</tr>
</tbody>
</table>

$ggF$: Precision improved by 36%  
$VBF$: Limited due higher pile-up ⇒ higher bkg

\[
\begin{align*}
\sigma_{ggF} \cdot B_{H → WW^*} & = 12.6^{+1.3}_{-1.2} \text{(stat.)} ^{+1.9}_{-1.8} \text{(sys.) pb} = 12.6^{+2.3}_{-2.1} \text{ pb} \\
\sigma_{VBF} \cdot B_{H → WW^*} & = 0.50^{+0.24}_{-0.23} \text{(stat.)} ^{+0.30}_{-0.29} \text{(sys.) pb} = 0.50^{+0.30}_{-0.29} \text{ pb}.
\end{align*}
\]

**Uncertainties on the cross-sections measurement:**

**Significant uncertainties from Theory:**
- ~5% on $σ_{(ggF)}$ due to WW background modelling
- 15% on $σ_{(VBF)}$ due to QCD scale on ggF in VBF phase space

**Limited MC statistics important especially in VBF**

$σ_{(ggF)}$ dominated by systematics (exp~theo)

---

M. Trovatelli  

**DIS2018, Kobe 16-20 Apr 2018**
Fit m4l for each decay channel (right) or differential distributions (below) to extract N_{Signal}

p+H→ test perturbative QCD

l+4l→ test gluon PDFs

Combined inclusive fiducial xsec:

\[ \sigma_{\text{fid, comb}} = 3.62 \pm 0.50 \text{(stat)}^{+0.25}_{-0.20} \text{(sys)} \text{ fb} \]

\[ \sigma_{\text{fid, SM}} = 2.91 \pm 0.13 \text{ fb} \]

\~15% precision

Good agreement with LHCxSWG prediction

(1.3σ difference in mixed channels)

N_{jets}→ test modelling of radiations at high p_T, sensitive to prod modes

Overall good theoretical description of data. Precision statistically limited

M. Trovatelli

DIS2018, Kobe 16-20 Apr 2018
$H \rightarrow \gamma\gamma$ inclusive and differential cross-section

Fit to $m_{\gamma\gamma}$ distribution to extract $N_{\text{Signal}}$: 1) **inclusively** in production mode 2) in each **production mode-enhanced region** or differential distribution

**Inclusive fiducial xsec:**

\[
\sigma_{\text{fid.,comb}} = 55 \pm 9\text{ (stat)} \pm 4\text{ (exp)} \pm 0.1\text{ (theo)}\text{ fb} \\
\sigma_{\text{fid.,SM}} = 64 \pm 2\text{ fb}
\]

\~18% precision

Overall good theoretical description of data. 
Precision statistically limited

Differential and double differential measurements

M. Trovatelli

DIS2018, Kobe 16-20 Apr 2018
Total Higgs boson cross-section: H4l, Hγγ combination

- Combining H→4l and H→γγ measurements to improve precision on Higgs boson cross-section(*)
- Combination is done in total phase space
  - more model-dependent

\[ \sigma_i = \frac{N_i^{sig}}{L B_F A_i C_i} \]

- assumed SM branching fractions: \( B_F(H\rightarrow\gamma\gamma) = 0.23\% \), \( B_F(H\rightarrow ZZ^*\rightarrow 4l) = 0.013\% \)

Acceptance correction
fiducial total phase space from MC:

\( A(H\rightarrow\gamma\gamma) \sim 50\% \), \( A(H\rightarrow 4l) \sim 42\% \)

Combined measurement in agreement with SM prediction

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Total cross section ((pp \rightarrow H+X))</th>
<th>( \sqrt{s} = 7) TeV</th>
<th>( \sqrt{s} = 8) TeV</th>
<th>( \sqrt{s} = 13) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow \gamma\gamma )</td>
<td>( 35^{+13}_{-12} ) pb</td>
<td>( 30.5^{+7.3}_{-7.0} ) pb</td>
<td>( 47.9^{+9.1}_{-8.6} ) pb</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow ZZ^* \rightarrow 4l )</td>
<td>( 33^{+21}_{-16} ) pb</td>
<td>( 37^{+9}_{-8} ) pb</td>
<td>( 68.0^{+11.4}_{-10.4} ) pb</td>
<td></td>
</tr>
<tr>
<td>Combination</td>
<td>( 34 \pm 10 ) (stat.) ( +4_{-2} ) (syst.) pb</td>
<td>( 33.3^{+5.5}<em>{-5.3} ) (stat.) ( +1.7</em>{-1.3} ) (syst.) pb</td>
<td>( 57.0^{+6.0}<em>{-5.9} ) (stat.) ( +4.0</em>{-3.3} ) (syst.) pb</td>
<td></td>
</tr>
<tr>
<td>SM prediction [8]</td>
<td>( 19.2 \pm 0.9 ) pb</td>
<td>( 24.5 \pm 1.1 ) pb</td>
<td>( 55.6^{+2.4}_{-3.4} ) pb</td>
<td></td>
</tr>
</tbody>
</table>

M. Trovatelli

DIS2018, Kobe 16-20 Apr 2018

(*)H→WW will be added in a later step
Total Higgs boson cross-section: H4l, Hγγ combination

**Differential distributions: Higgs observables**

**Differential distributions: Jets observables**

**Total and differential measurements limited by statistics**

More data and channels will further improve!

Statistical precision: 20-30% (improved combining)
Systematics uncertainties: ~10% (larger for Njets ≥ 2)

Single channel and combination compared with several theory predictions(\(^\ast\)):

<table>
<thead>
<tr>
<th>p-values [%]</th>
<th>( p_T^H )</th>
<th>( \gamma^H )</th>
<th>( N_{jets} )</th>
<th>( p_T^{1l} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NNLOPS (@N^3LO)</td>
<td>29</td>
<td>92</td>
<td>45</td>
<td>5</td>
</tr>
<tr>
<td>HRes</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Radish + NNLOjet</td>
<td>29</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>SCETlib</td>
<td>–</td>
<td>91</td>
<td>–</td>
<td>21</td>
</tr>
<tr>
<td>Madgraph5_aMC@NLO (@N^3LO)</td>
<td>–</td>
<td>–</td>
<td>57</td>
<td>–</td>
</tr>
</tbody>
</table>

(\(^\ast\)) - NNLOPS normalised to N3LO cross section, nominal sample
- HRes (NNLO+NNLL)
- Radish (NNLL)+NNLOjet
- SCETlib+MCMF8 (NNLO+NNLL')
- MG5_aMC@NLO (@N3LO), NLO for 0,1,2 additional jets
Production mode cross-sections in kinematic bins

1. Combined $H \rightarrow 4l$ and $H \rightarrow \gamma \gamma$ for $|y(H)| < 2.5$ in **Higgs boson production categories**: ggF, VBF, VH and ttH. bbH included in ggF while tHX in ttH

2. Provided **cross-sections and BF ratios** => common systematic uncertainties cancel

3. Reduce model dependance by defining **exclusive kinematic regions** targeting specific production modes:
   - categories based on Higgs and associated particles kinematic (bins of Njets, $p_{T H/jet}$,..)

   **Best precisions ~20%**


---

**Figure 4**: Correlation matrix for the measured values of the production cross sections shown in Table 1.

**Figure 7**: Cross sections for ggF, VBF, VH and ttH Production mode cross-sections in kinematic bins → targeting specific production modes:

- for $|y(H)| < 2.5$ in $\gamma\gamma$
- Best precisions ~20%

---

**Figure 3**: Simplified template cross section measurements.

**Figure 5**: ATLAS Preliminary $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$ $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^{*} \rightarrow 4l$

- $m_{H} = 125.09$ GeV, $|y_{H}| < 2.5$
- 2.2 deviation in VBF

**Figure 6**: Categories in $H \rightarrow \gamma \gamma$ with high-purity

**Figure 8**: ATLAS Simulation $H \rightarrow \gamma \gamma$, $m_{H} = 125.09$ GeV

- Categories for VH and top merging needed
Higgs boson couplings measurement

Cross-sections results can be interpreted in the contest of the couplings framework:

$$\sigma_i \cdot B_f^f = \frac{\sigma_i(k)}{\Gamma_H}$$

Couplings modifiers

No significant deviation from SM prediction observed

Coupling modifiers to vector bosons and fermions ($k_V$, $k_f$) or to loop contributions ($k_g$, $k_V$)

Construct ratios to probe simultaneously $k_V$, $k_f$, $k_g$, $k_f$ and the Higgs boson width $\Gamma_H$

$$k_{gV} = k_g k_V / k_H, \quad \lambda_{Vg} = k_V / k_g, \quad \lambda_{fV} = k_f / k_V, \quad \lambda_{fg} = k_f / k_g$$
Higgs boson mass measurement

- Higgs boson mass measured in \( H \to ZZ^* \to 4\ell/h \to \gamma \gamma \) channels, profiting from the fully reconstructed narrow peak over a smooth background:
  
  - \( H \to 4\ell \) per-event measurement with fit in BDT bins to further distinguish signal against \( ZZ^* \). Statistically limited channel
  
  - \( H \to \gamma \gamma \) fit to \( m_{\gamma \gamma} \) distribution modelled with a double-sided Crystal-ball function
  
  - Same categories as in cross-section measurement
  
  - Channel dominated by systematic uncertainty on photon energy scale

**Combined mass result**

<table>
<thead>
<tr>
<th>Channel</th>
<th>ATLAS Preliminary ( \sqrt{s} = 13 ) TeV, 36.1 ( fb^{-1} )</th>
<th>Total</th>
<th>Stat.</th>
<th>Syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \to ZZ^* \to 4\ell )</td>
<td>( 125.09 \pm 0.24 (\pm 0.21 \pm 0.11) ) GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H \to \gamma \gamma )</td>
<td>( 124.88 \pm 0.37 (\pm 0.37 \pm 0.05) ) GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>( 125.11 \pm 0.42 (\pm 0.21 \pm 0.36) ) GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( 124.98 \pm 0.28 (\pm 0.19 \pm 0.21) ) GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In agreement and with a similar precision to the ATLAS+CMS Run-I combination:

\( m_H = 125.09 \pm 0.24 \) GeV
Other Higgs boson properties

**Width**
- SM predicts $\Gamma_H \sim 4\text{ MeV} \rightarrow$ too low to be measured at LHC (resolution $\sim 1\text{-}2\text{ GeV}$)
- **Indirect constraint on $\Gamma_H$ by studying off-shell Higgs boson production** in diboson final states:
  - when $m_{VV} \gg m_H$, the cross-section doesn’t depend on $\Gamma_H$
  - by assuming same on-shell and off-shell couplings:
    \[ \mu_{\text{off-shell}} = \mu_{\text{on-shell}} \frac{\Gamma_H}{\Gamma_{H,\text{SM}}} \]
    \[
    \Gamma_H < 22.7\text{ MeV} \quad @\quad 95\%\text{CL} \\
    (<33\text{ MeV exp.})
    \]

**Spin/CP**
- Spin and Parity of the Higgs boson measured in $WW^*/ZZ^*$ final states using Run-I 7 TeV and 8 TeV data ($\sim 25\text{ fb}^{-1}$). SM Higgs boson hypothesis, $J^P = 0^+$, tested against alternative spin scenarios, which were excluded at 99.9% CL.
- In Run-II Higgs boson spin-CP tested, e.g. in $\gamma\gamma$ decays, with angle distributions of photons and jets sensitive to these properties

All measurements compatible with a SM Higgs boson

M. Trovatelli

DIS2018, Kobe 16-20 Apr 2018
Remarks and Conclusions

✦ A summary of the first set of ATLAS Run-II Higgs boson properties measurements has been presented
✦ Precision of cross-section measurements ~2 times better than with Run-I dataset
✦ Overall, a remarkable good agreement with SM predictions observed

✦ Most of the measurements limited by statistics:
✦ So far analysed ~36 fb^{-1} →~45 fb^{-1} still in the pipeline ready to be used
✦ And more data expected in the last year of LHC Run-2 data-taking

Stay tuned for the sequel of the Higgs characterisation saga!
Backup
**Analysis strategy**

- **Signature**: two prompt isolated leptons and missing momentum

- **Events split in 3 Signal Regions** on Njets(*):
  - Njet = 0 and Njet = 1 (ggF dominated)
    - Spin 0 Higgs → leptons close together $\Delta\phi_{\ell\ell} < 1.8$ and $m_{\ell\ell} < 55$ GeV
    - $m_T$ used as discriminant
  - Njet ≥ 2 (VBF dominated)
    - BDT used as discriminant
      - $m_{jj}$ and $\Delta\gamma_{jj}$ highest ranking (2 recoiling, well-separated jets)
  - b-jet veto in all categories to reduce ttbar ($\sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}} \approx 3.3$)

**Backgrounds estimation**

- **Irreducible background** normalised from Data control samples:
  - non-resonant WW (from Njets ≤1 high $m_{\ell\ell}$ events)
  - ttbar (b-tag requirement)
  - $Z\rightarrow\tau\tau$ ($m_\tau\tau$ or $\Delta\phi_{\ell\ell}$ inverted)

- **Mis-identified leptons from data** with lepton failing ID/isolation
  - large uncertainties but on a ~10% background

- Other minor backgrounds from simulation

(*) complete event selection table in backup

M. Trovatelli

DIS2018, Kobe 16-20 Apr 2018  Signal fraction at best 14%
H→WW*→eνμν - Results

- Simultaneous SRs and CR max likelihood fit
  - 16 fits regions defined for Njets = 0/1:
    
    \[ [2 \times m_{\ell\ell}] \times [2 \times p_T^{\text{sub-leading}}] \times [e\mu / \mu e] \]

  - Different bkg composition
  - Enhance sensitivity

- 4 BDT bins for VBF enriched category
  - S(VBF)/B ~0.6 in the last bin

⇒ extract both ggF and VBF cross-sections

- Other production/decays modes fixed to SM

\[ m_T [\text{GeV}] \]

\[ \text{Events /} \text{10 GeV} \]

\[ \text{16 fits regions defined for Njets = 0/1:} \]

\[ [2 \times m_{\ell\ell}] \times [2 \times p_T^{\text{sub-leading}}] \times [e\mu / \mu e] \]

\[ \text{Different bkg composition} \]

\[ \text{Enhance sensitivity} \]

\[ \text{4 BDT bins for VBF enriched category} \]

\[ \text{S(VBF)/B} \sim 0.6 \text{ in the last bin} \]

\[ \Rightarrow \text{extract both ggF and VBF cross-sections} \]

\[ \text{Other production/decays modes fixed to SM} \]

\[ (*) \text{ all plots are post-fit} \]

\[ ggF: 6.3\sigma \text{ (exp. 5.2\sigma)} \]

\[ VBF: 1.9\sigma \text{ (exp. 2.7\sigma)} \]
**H→WW*→eνμν - Results**

**Signal strength and cross-section results:**

<table>
<thead>
<tr>
<th>Run-2</th>
<th>Run-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{ggF}$ = $1.21^{+0.12}_{-0.11}^{(stat.)} + 0.18^{(sys.)}$</td>
<td>$\mu_{ggF} = 1.02^{+0.29}_{-0.26}$</td>
</tr>
<tr>
<td>$\mu_{VBF} = 0.62^{+0.30}_{-0.28}^{(stat.)} \pm 0.22^{(sys.)}$</td>
<td>$\mu_{VBF} = 1.27^{+0.53}_{-0.45}$</td>
</tr>
</tbody>
</table>

**ggF:** Precision improved by 36%

**VBF:** Limited due higher pile-up ⇒ higher bkg

\[
\begin{align*}
\sigma_{ggF} \cdot B_{H→WW^*} &= 12.6^{+1.3}_{-1.2}^{(stat.)} + 1.9^{(sys.)} \text{ pb} = 12.6^{+2.3}_{-2.1} \text{ pb} \\
\sigma_{VBF} \cdot B_{H→WW^*} &= 0.50^{+0.24}_{-0.23}^{(stat.)} \pm 0.18^{(sys.)} \text{ pb} = 0.50^{+0.30}_{-0.29} \text{ pb}.
\end{align*}
\]

**Uncertainties on the cross-sections measurement:**

**Significant uncertainties from Theory:**
- ~5% on $\sigma_{(ggF)}$ due to WW background modelling
- 15% on $\sigma_{(VBF)}$ due to QCD scale on ggF in VBF phase space

**Limited MC statistics important especially in VBF**

$\sigma_{(ggF)}$ dominated by systematics (exp~theo)
## Systematic uncertainties on $WW^* \rightarrow e\nu\mu\nu$ result

<table>
<thead>
<tr>
<th>Source</th>
<th>$\frac{\Delta \sigma_{ggF}}{\sigma_{ggF}}$ [%]</th>
<th>$\frac{\Delta \sigma_{VBF}}{\sigma_{VBF}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data statistics</td>
<td>$\pm 8$</td>
<td>$\pm 46$</td>
</tr>
<tr>
<td>CR statistics</td>
<td>$\pm 8$</td>
<td>$\pm 9$</td>
</tr>
<tr>
<td>MC statistics</td>
<td>$\pm 5$</td>
<td>$\pm 23$</td>
</tr>
<tr>
<td>Theoretical uncertainties</td>
<td>$\pm 8$</td>
<td>$\pm 21$</td>
</tr>
<tr>
<td>ggF signal</td>
<td>$\pm 5$</td>
<td>$\pm 15$</td>
</tr>
<tr>
<td>VBF signal</td>
<td>$&lt; 1$</td>
<td>$\pm 15$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$\pm 5$</td>
<td>$\pm 12$</td>
</tr>
<tr>
<td>Top-quark</td>
<td>$\pm 4$</td>
<td>$\pm 4$</td>
</tr>
<tr>
<td>Experimental uncertainties</td>
<td>$\pm 9$</td>
<td>$\pm 8$</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>$\pm 5$</td>
<td>$\pm 6$</td>
</tr>
<tr>
<td>Pile-up</td>
<td>$\pm 5$</td>
<td>$\pm 2$</td>
</tr>
<tr>
<td>Jet</td>
<td>$\pm 3$</td>
<td>$\pm 4$</td>
</tr>
<tr>
<td>Electron</td>
<td>$\pm 3$</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>Misidentified leptons</td>
<td>$\pm 5$</td>
<td>$\pm 9$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\pm 2$</td>
<td>$\pm 3$</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$\pm 17$</td>
<td>$\pm 59$</td>
</tr>
</tbody>
</table>
Run1/Run2 comparison for $WW^* \rightarrow e\nu\mu\nu$ result

<table>
<thead>
<tr>
<th></th>
<th>$\mu_{ggF}$</th>
<th>stat.</th>
<th>syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, 13 TeV, 36.1 fb$^{-1}$</td>
<td>$1.21^{+0.22}_{-0.21}$</td>
<td>10%</td>
<td>15%</td>
</tr>
<tr>
<td>ATLAS, 7+8 TeV, 24.8 fb$^{-1}$</td>
<td>$1.02^{+0.29}_{-0.26}$</td>
<td>19%</td>
<td>20%</td>
</tr>
<tr>
<td>CMS, 13 TeV, 35.9 fb$^{-1}$</td>
<td>$1.38^{+0.21}_{-0.24}$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\mu_{VBF}$</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, 13 TeV, 36.1 fb$^{-1}$</td>
<td>$0.62^{+0.37}_{-0.36}$</td>
<td>59%</td>
</tr>
<tr>
<td>ATLAS, 7+8 TeV, 24.8 fb$^{-1}$</td>
<td>$1.27^{+0.53}_{-0.45}$</td>
<td>+41% $-$35%</td>
</tr>
<tr>
<td>CMS, 13 TeV, 35.9 fb$^{-1}$</td>
<td>$0.29^{+0.66}_{-0.29}$</td>
<td>+228% $-$100%</td>
</tr>
</tbody>
</table>

CMS also gives results for VH. Theory ggF cross section prediction improved in Run 2 w.r.t. Run 1. $\mu$ of Run 2 uses different cross section prediction than in Run 1.

- Good compatibility between Run 1 and Run 2, as well as ATLAS and CMS
- ggF: Precision improved by 36% with respect to Run 1.
  - Systematic uncertainties reduced by 25%.
- VBF signal strength low in Run 2
  - Expected significance is 2.7$\sigma$ for the Run 1 and the Run 2 measurements

New measurements in $H \rightarrow WW^*$ will contribute to combined Higgs results.
**H→ZZ*→4ℓ inclusive and differential cross-section**

- Experimental and particle level selection as similar as possible to minimise theory uncertainties

---

### Fiducial phase space definition

<table>
<thead>
<tr>
<th>Leptons and jets</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Muons:</strong></td>
<td>$p_T &gt; 5$ GeV, $</td>
</tr>
<tr>
<td><strong>Electrons:</strong></td>
<td>$p_T &gt; 7$ GeV, $</td>
</tr>
<tr>
<td><strong>Jets:</strong></td>
<td>$p_T &gt; 30$ GeV, $</td>
</tr>
<tr>
<td><strong>Jet-lepton overlap removal:</strong></td>
<td>$\Delta R(\text{jet}, \ell) &gt; 0.1 (0.2)$ for muons (electrons)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lepton selection and pairing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lepton kinematics:</strong></td>
<td>$p_T &gt; 20, 15, 10$ GeV</td>
</tr>
<tr>
<td><strong>Leading pair ($m_{12}$):</strong></td>
<td>SFOS lepton pair with smallest $</td>
</tr>
<tr>
<td><strong>Subleading pair ($m_{34}$):</strong></td>
<td>remaining SFOS lepton pair with smallest $</td>
</tr>
</tbody>
</table>

**Event selection (at most one quadruplet per channel)**

| Mass requirements: | $50 < m_{12} < 106$ GeV and $12 < m_{34} < 115$ GeV |
| Lepton separation: | $\Delta R(\ell_i, \ell_j) > 0.1 (0.2)$ for same- (different-) flavour leptons |
| $J/\psi$ veto:     | $m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs |
| Mass window:       | $115$ GeV $< m_{4\ell} < 130$ GeV |

Fiducial xsections are defined at the particle level

$\Rightarrow$ correct the number of reconstructed events by the difference in acceptance between detector-level and particle level
Higgs boson signal xsections normalised at LHCXS WG predictions:
- for ggF, N3LO in QCD and NLO EW corrections applied
- VBF is fully NLO (approximate NNLO QCD corrections applied)

H → ZZ* → 4ℓ inclusive and differential cross-section

<table>
<thead>
<tr>
<th>Final state</th>
<th>SM Higgs</th>
<th>ZZ*</th>
<th>Z + jets, t̄t</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4μ</td>
<td>20.1 ± 2.1</td>
<td>9.8 ± 0.5</td>
<td>1.3 ± 0.3</td>
<td>31.2 ± 2.2</td>
<td>33</td>
</tr>
<tr>
<td>4e</td>
<td>10.6 ± 1.2</td>
<td>4.4 ± 0.4</td>
<td>1.3 ± 0.2</td>
<td>16.3 ± 1.3</td>
<td>16</td>
</tr>
<tr>
<td>2e2μ</td>
<td>14.2 ± 1.4</td>
<td>7.1 ± 0.4</td>
<td>1.0 ± 0.2</td>
<td>22.3 ± 1.5</td>
<td>32</td>
</tr>
<tr>
<td>2μ2e</td>
<td>10.8 ± 1.2</td>
<td>4.6 ± 0.4</td>
<td>1.4 ± 0.2</td>
<td>16.8 ± 1.3</td>
<td>21</td>
</tr>
<tr>
<td>Total</td>
<td>56 ± 6</td>
<td>25.9 ± 1.5</td>
<td>5.0 ± 0.6</td>
<td>87 ± 6</td>
<td>102</td>
</tr>
</tbody>
</table>

**Exclusive, Inclusive and Total cross-section**

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Data (± (stat) ± (sys))</th>
<th>LHCXSWG prediction</th>
<th>p-value [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ_{4μ} [fb]</td>
<td>0.92 ±0.23 ±0.07</td>
<td>0.880 ± 0.039</td>
<td>88</td>
</tr>
<tr>
<td>σ_{4e} [fb]</td>
<td>0.67 ±0.28 ±0.08</td>
<td>0.688 ± 0.031</td>
<td>96</td>
</tr>
<tr>
<td>σ_{2μ2e} [fb]</td>
<td>0.84 ±0.24 ±0.06</td>
<td>0.625 ± 0.028</td>
<td>39</td>
</tr>
<tr>
<td>σ_{2e2μ} [fb]</td>
<td>1.18 ±0.26 ±0.05</td>
<td>0.717 ± 0.032</td>
<td>7</td>
</tr>
<tr>
<td>σ_{4μ+4e} [fb]</td>
<td>1.59 ±0.37 ±0.12</td>
<td>1.57 ± 0.07</td>
<td>65</td>
</tr>
<tr>
<td>σ_{2μ2e+2e2μ} [fb]</td>
<td>2.02 ±0.36 ±0.11</td>
<td>1.34 ± 0.06</td>
<td>6</td>
</tr>
<tr>
<td>σ_{sum} [fb]</td>
<td>3.61 ±0.54 ±0.26</td>
<td>2.91 ± 0.13</td>
<td>19</td>
</tr>
<tr>
<td>σ_{comb} [fb]</td>
<td>3.62 ±0.53 ±0.25</td>
<td>2.91 ± 0.13</td>
<td>18</td>
</tr>
<tr>
<td>σ_{tot} [pb]</td>
<td>69 ±10 ±5</td>
<td>55.6 ± 2.5</td>
<td>19</td>
</tr>
</tbody>
</table>

**Uncertainties breakdown**

<table>
<thead>
<tr>
<th>Observable</th>
<th>Stat unc. [%]</th>
<th>Systematic unc. [%]</th>
<th>Dominant systematic components [%]</th>
<th>Model</th>
<th>Z + jets + t̄t</th>
<th>Lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ_{comb}</td>
<td>14</td>
<td>7</td>
<td>3 &lt; 0.5</td>
<td>3</td>
<td>2</td>
<td>42</td>
</tr>
<tr>
<td>dσ/dp_{T,4μ}</td>
<td>30 ± 150</td>
<td>3 ± 11</td>
<td>2 ± 0.5</td>
<td>1</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dp_{T,4e}</td>
<td>31 ± 52</td>
<td>10 ± 18</td>
<td>2 ± 0.5</td>
<td>2</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dp_{T,2μ2e}(μ)</td>
<td>35 ± 15</td>
<td>6 ± 30</td>
<td>2 ± 0.5</td>
<td>3</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dp_{T,2e2μ}(μ)</td>
<td>30 ± 41</td>
<td>5 ± 21</td>
<td>2 ± 0.5</td>
<td>4</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dδμ</td>
<td>29 ± 120</td>
<td>5 ± 8</td>
<td>2 ± 0.5</td>
<td>1</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dδcosθ⁺</td>
<td>31 ± 100</td>
<td>5 ± 8</td>
<td>2 ± 0.5</td>
<td>2</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dN_{jets}</td>
<td>26 ± 53</td>
<td>4 ± 13</td>
<td>2 ± 0.5</td>
<td>3</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dm_{jj}</td>
<td>21 ± 40</td>
<td>4 ± 12</td>
<td>2 ± 0.5</td>
<td>4</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dN_{jets}</td>
<td>22 ± 44</td>
<td>6 ± 31</td>
<td>1 ± 0.5</td>
<td>5</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dp_{T,jet}</td>
<td>30 ± 53</td>
<td>5 ± 18</td>
<td>1 ± 0.5</td>
<td>6</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dΔφj</td>
<td>29 ± 43</td>
<td>9 ± 17</td>
<td>1 ± 0.5</td>
<td>7</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>dσ/dm_{jj}</td>
<td>23 ± 100</td>
<td>9 ± 27</td>
<td>1 ± 0.5</td>
<td>8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

M. Trovatelli

DIS2018, Kobe 16-20 Apr 2018

23
H→ZZ*→4\ell inclusive and differential cross-section

Bin-by-bin correction factors for detector inefficiencies and reconstruction

- For ggF, NNLOPS sample used to derived the correction factor
- Correction factors agree within 15% for all production modes except for ttH, due to the missing isolation requirement needed to identify leptons from hadronic jets at particle level
- Large uncertainty on the last bin of Njets due to exp jet reconstruction uncertainty mainly
H→ZZ*→4ℓ inclusive and differential cross-section

More differential distributions…

different ggF predictions but normalised to N3LO with the corresponding k-factors

XH processes have been added

M. Trovatelli

DIS2018, Kobe 16-20 Apr 2018
H→ZZ*→4ℓ inclusive and differential cross-section

Run-I/Run-II comparison

More bins at high-pt and gain in statistical precision.
Not enough sensitivity to different generators (yet)
**H→γγ inclusive and differential cross-section**

Table 14: Summary of the particle-level definitions of the five fiducial integrated regions described in the text. The photon isolation $p_{T}^{iso,0.2}$ is defined analogously to the reconstructed-level track isolation as the transverse momentum of the system of charged particles within $ΔR < 0.2$ of the photon.

<table>
<thead>
<tr>
<th>Objects</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>$</td>
</tr>
<tr>
<td>Jets</td>
<td>anti-$k_t$, $R = 0.4$, $p_T &gt; 30$ GeV, $</td>
</tr>
<tr>
<td>Leptons, $ℓ$</td>
<td>$e$ or $μ$, $p_T &gt; 15$ GeV, $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diphoton fiducial</td>
<td>$N_γ ≥ 2$, $p_T^{γ1} &gt; 0.35 m_{γγ} = 43.8$ GeV, $p_T^{γ2} &gt; 0.25 m_{γγ} = 31.3$ GeV</td>
</tr>
<tr>
<td>VBF-enhanced</td>
<td>Diphoton fiducial, $N_j ≥ 2$ with $p_T^{jet} &gt; 25$ GeV, $m_{jj} &gt; 400$ GeV, $</td>
</tr>
<tr>
<td>$N_{lepton} ≥ 1$</td>
<td>Diphoton fiducial, $N_ℓ ≥ 1$</td>
</tr>
<tr>
<td>High $E_T^{miss}$</td>
<td>Diphoton fiducial, $E_T^{miss} &gt; 80$ GeV, $p_T^{γγ} &gt; 80$ GeV</td>
</tr>
<tr>
<td>$t{t}H$-enhanced</td>
<td>Diphoton fiducial, $(N_j ≥ 4, N_{b-jets} ≥ 1)$ or $(N_j ≥ 3, N_{b-jets} ≥ 1, N_ℓ ≥ 1)$</td>
</tr>
</tbody>
</table>

**Measured fiducial cross-sections**

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Measured cross section</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diphoton fiducial</td>
<td>$55 ± 9$ (stat.) ± 4 (exp.) ± 0.1 (theo.) fb</td>
<td>$64 ± 2$ fb, $[N^3LO + XH]$</td>
</tr>
<tr>
<td>VBF-enhanced</td>
<td>$3.7 ± 0.8$ (stat.) ± 0.5 (exp.) ± 0.2 (theo.) fb</td>
<td>$2.3 ± 0.1$ fb, [default MC + $XH$]</td>
</tr>
<tr>
<td>$N_{lepton} ≥ 1$</td>
<td>$≤ 1.39$ fb 95% CL</td>
<td>$0.57 ± 0.03$ fb, [default MC + $XH$]</td>
</tr>
<tr>
<td>High $E_T^{miss}$</td>
<td>$≤ 1.00$ fb 95% CL</td>
<td>$0.30 ± 0.02$ fb, [default MC + $XH$]</td>
</tr>
<tr>
<td>$t{t}H$-enhanced</td>
<td>$≤ 1.27$ fb 95% CL</td>
<td>$0.55 ± 0.06$ fb, [default MC + $XH$]</td>
</tr>
</tbody>
</table>
More differential distributions…

H→γγ inclusive and differential cross-section

Figure 29: The differential cross sections for H→γγ, \( \sqrt{s} = 13 \) TeV, 36.1 fb\(^{-1}\). In addition, the anti-distributions are shown for all event topologies. The predictions are shown for all event topologies.
Total cross section - Channels combination

Acceptance factors

ATLAS Preliminary
Simulation
13 TeV

$H \rightarrow \gamma\gamma$
$H \rightarrow ZZ^* \rightarrow 4l$

$\rho_T^H$ [GeV]

$|\eta^H|$
Both $H \rightarrow \gamma \gamma$ and $H \rightarrow 4l$ observe an anti-correlation between ggF and VBF measurements.

| Process ($|y_H| < 2.5$) | Result [pb] | Uncertainty [pb] | SM prediction [pb] |
|------------------------|-------------|------------------|--------------------|
| ggF                    | 43.9        | Total Stat. Exp. Th. | $44.5 \pm 2.0$ |
| VBF                    | 7.9         | +2.1 -1.8 (+1.7 -1.6) +0.8 -0.6 +1.0 -0.7 | $3.52 \pm 0.08$ |
Table 4: Leading uncertainties on the global signal strength. Signed impacts on \( \mu \) are shown for a 1\( \sigma \) upward or downward shift on the uncertainty source, except in the cases of PDFs and branching fractions. The PDF uncertainty is dominated by PDF4LHC eigenvector 5, which decreases the signal strength by 0.018 due to a relative increase in the gluon distribution of 1.5\% for a momentum fraction of \( x = 0.01 \) [68].

<table>
<thead>
<tr>
<th>Source</th>
<th>Up</th>
<th>Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \sigma_{ggF}^{SM} ) (perturbative)</td>
<td>-0.045</td>
<td>+0.044</td>
</tr>
<tr>
<td>PDFs</td>
<td>±0.018</td>
<td></td>
</tr>
<tr>
<td>Branching fractions</td>
<td>±0.014</td>
<td></td>
</tr>
<tr>
<td>( \alpha_S )</td>
<td>-0.011</td>
<td>+0.012</td>
</tr>
<tr>
<td>Experimental</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>-0.037</td>
<td>+0.038</td>
</tr>
<tr>
<td>Energy resolution ( (e, \gamma) )</td>
<td>+0.021</td>
<td>-0.019</td>
</tr>
<tr>
<td>Pileup</td>
<td>+0.014</td>
<td>-0.015</td>
</tr>
</tbody>
</table>
Production cross-sections in 4l channel

σ×B measured in several dedicated mutually exclusive regions of the phase space based on the production process. Production bins are chosen in such a way that the measurement precision is maximised and at the same time possible BSM contributions can be isolated.

- **simple fiducial region definitions for each Higgs production mode** based on Higgs kinematics and associated particles → match experimental categories

Advantage: cross-sections can be interpreted in terms of Higgs boson couplings, and theory uncertainties enter only at that stage

Two sets of production bins considered:
- Stage 0 (more inclusive ==> smaller statistical uncertainty)
- Reduced Stage 1(*) (smaller theoretical uncertainties)

- e.g. exclusive jet bins and $p_T^H$

(*) too fine granularity for precise measurements in all STXS Stage-1 bins => merge some categories
H→4l  Stage-0 production cross-section measurements

Combination of Stage-0 production cross-section measurements:
Correlation matrix

ggF and VBF anti-correlated since VBF category has large contribution from ggF production
Towards Stage-1 Template XS measurement:
9 categories

**Stage-1 and bins merging for intermediate Stage-1 ATLAS measurements**

- $gg \rightarrow H$ (0-jet)
- $gg \rightarrow H$ (1-jet, $p_T^H < 60$ GeV)
- $gg \rightarrow H$ (1-jet, $60 \leq p_T^H < 120$ GeV)
- $gg \rightarrow H$ (1-jet, $120 \leq p_T^H < 200$ GeV)
- $gg \rightarrow H$ ($\geq$ 2-jet, $p_T^H < 200$ GeV or VBF-like)
- $gg \rightarrow H$ ($\geq$ 1-jet, $p_T^H > 200$ GeV) + $qq \rightarrow Hqq (p_T^H > 200$ GeV)
- $qq \rightarrow Hqq (p_T^H < 200$ GeV)
- $gg/qq \rightarrow Hll/Hlv$
- $gg/qq \rightarrow ttH$
Production cross-sections in $\gamma\gamma$ channel

The events satisfying the diphoton selection classified into 31 exclusive categories that are optimized for the best separation of the Higgs boson production processes and for the maximum sensitivity to the phase space regions defined by the stage 1 of the simplified template cross-section framework. A combined fit to the event reconstruction categories is then performed to determine nine simplified template cross sections (with $|y_H| < 2.5$).

No sensitivity to all the 31 categories $\implies$ merge categories and fit in only 10/31 final categories.
Production cross-sections in γγ channel

ATLAS

$\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$

$H \rightarrow \gamma\gamma$, $m_H=125.09$ GeV

In general, all main production modes can be probed in diboson decays

Measurements agree with SM predictions within 2σ

68% and 95% CL 2D counters VBF vs ggF top and VH profiled in the fit
Higgs boson couplings

The Higgs boson couplings to heavy SM vector bosons ($W$ and $Z$) and gluons are studied by measuring the cross sections for different production modes. The reconstructed Higgs boson candidate events are classified into different categories. The categories are defined to be sensitive to different Higgs boson production modes, which in turn also provides sensitivity to the BSM contributions.

$$\sigma(i \to H \to f) = k_i^2 \sigma_i^{SM} \frac{k_f^2 \Gamma_f^{SM}}{k_H^2 \Gamma_H^{SM}}$$

Fermion vs vector boson couplings:
- $ggF \sim \kappa_f^2$, $VBF \sim \kappa_V^2$
- $B_{4l} \sim \kappa_V^2$
- $B_{\gamma\gamma} \sim f(\kappa_f^2, \kappa_f^2, \kappa_f \times \kappa_V)$ from loops
- Assume $\Gamma_{BSM}^H = 0$ and only $\kappa_f$ and $\kappa_V \approx 1$

$\kappa_f$ and $\kappa_V$ are effective loop couplings for $ggF$ and $H \to \gamma\gamma$
BMS searches

The differential fiducial cross sections can be interpreted in the context of searches for physics beyond the SM. Limits are set on modified Higgs boson interactions within the framework of pseudo-observables. The couplings related to the contact interaction of the Higgs boson decay are considered, $\varepsilon_L, \varepsilon_R$, which modify, in a flavour-universal way, the contact terms between the Higgs boson, the Z boson, and left- or right-handed leptons. These contact terms only affect the dilepton invariant mass (not the lepton angular distribution) $\Rightarrow$ The difference in $\chi^2$ between the measured and predicted cross sections in the $m_{12}$ vs $m_{34}$ observable plane is therefore used to constrain the possible contributions from contact interactions.
Higgs boson mass - 4l channel

Measured signal distribution as a convolution of the BW and a **response function F**

From simulation, using the lepton energy response functions (electron/muon and per detector region)

Depends on the lepton kinematics

==> the response functions combination for the 4l mass vary event-by-event

<table>
<thead>
<tr>
<th>Final state</th>
<th>Signal (125 GeV)</th>
<th>ZZ^*</th>
<th>Z + jets, tt, WZ, ttV, VV</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4µ</td>
<td>20.6 ± 1.7</td>
<td>15.9 ± 1.2</td>
<td>2.0 ± 0.4</td>
<td>38.5 ± 2.1</td>
<td>38</td>
</tr>
<tr>
<td>2e2µ</td>
<td>14.6 ± 1.1</td>
<td>11.2 ± 0.8</td>
<td>1.6 ± 0.4</td>
<td>27.5 ± 1.4</td>
<td>34</td>
</tr>
<tr>
<td>2µ2e</td>
<td>11.2 ± 1.0</td>
<td>7.4 ± 0.7</td>
<td>2.2 ± 0.4</td>
<td>20.8 ± 1.3</td>
<td>26</td>
</tr>
<tr>
<td>4e</td>
<td>11.1 ± 1.1</td>
<td>7.1 ± 0.7</td>
<td>2.1 ± 0.4</td>
<td>20.3 ± 1.3</td>
<td>24</td>
</tr>
<tr>
<td>Total</td>
<td>57 ± 5</td>
<td>41.6 ± 3.2</td>
<td>8.0 ± 1.0</td>
<td>107 ± 6</td>
<td>122</td>
</tr>
</tbody>
</table>

Systematic effect | Uncertainty on $m_{ZZ^*}$ [MeV]
---|-------------------|
Muon momentum scale | 40
Electron energy scale | 20
Background modelling | 10
Simulation statistics | 8

σ(mass) ~ resolution

==> Z1 (leading pair) mass constraint

==> +15% improvement on m4l resolution
Higgs boson mass - $\gamma\gamma$ channel

Systematic uncertainties breakdown

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty on $m_H$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAr cell non-linearity</td>
<td>$\pm$ 200</td>
</tr>
<tr>
<td>LAr layer calibration</td>
<td>$\pm$ 190</td>
</tr>
<tr>
<td>Non-ID material</td>
<td>$\pm$ 120</td>
</tr>
<tr>
<td>Lateral shower shape</td>
<td>$\pm$ 110</td>
</tr>
<tr>
<td>ID material</td>
<td>$\pm$ 110</td>
</tr>
<tr>
<td>Conversion reconstruction</td>
<td>$\pm$ 50</td>
</tr>
<tr>
<td>$Z \rightarrow ee$ calibration</td>
<td>$\pm$ 50</td>
</tr>
<tr>
<td>Background model</td>
<td>$\pm$ 50</td>
</tr>
<tr>
<td>Primary vertex effect on mass scale</td>
<td>$\pm$ 40</td>
</tr>
<tr>
<td>Resolution</td>
<td>$\pm$ 20 $+$ 30</td>
</tr>
<tr>
<td>Signal model</td>
<td>$\pm$ 20</td>
</tr>
</tbody>
</table>
Anomalous couplings in EFT approach

The tensor structure of the Higgs boson couplings is studied, probing for admixtures of CP-even and CP-odd interactions in theories beyond the SM (BSM). Use Effective Field Theory to search for deviations in the Higgs Lagrangian:

\[ L_{EFT} = L_{SM} + \sum_i \frac{f_i}{\Lambda^2} O_i \]

EFT assume BSM particles above the cut-off \( \Lambda (=1\text{TeV}) \).

Introduce additional operators to the lagrangian

The CP-even and CP-odd BSM couplings to heavy vector bosons are also probed simultaneously

Figure 10: Observed (black) and SM expected (blue) contours of the two-dimensional negative log-likelihood at 95% CL for the \( \kappa_{HVV} \) and \( \kappa_{AVV} \) coupling parameters with 36.1 fb\(^{-1}\) of data at \( \sqrt{s} = 13\text{ TeV} \). The coupling \( \kappa_{Hgg} \) is fixed to the SM value of one in the fit. The coupling \( \kappa_{SM} \) is (a) fixed to the SM value of one or (b) left as a free parameter of the fit (b).
Spin/CP testing in $\gamma\gamma$ decays

The differential cross sections for $pp \to H \to \gamma\gamma$ as a function of $|\cos \theta^*|$ and $\Delta \phi_{jj}$ are shown in Figure 28. For a scalar particle $|\cos \theta^*|$, shows a strong drop around 0.6 due to the fiducial requirement on the photon system, whereas for a spin-2 particle, an enhancement would be present in precisely this region. The charge conjugation and parity properties of the Higgs boson are encoded in the azimuthal angle between the jets: For example, in gluon–gluon fusion, its distribution for a CP-even coupling has a dip at $\pm \frac{\pi}{2}$ and present peaks at 0 and $\pm \pi$, whereas for a purely CP-odd coupling it would present as peaks at $\pm \frac{\pi}{2}$ and dips at 0 and $\pm \pi$. For VBF the SM prediction for $\Delta \phi_{jj}$ is approximately constant with a slight rise towards $\Delta \phi_{jj} = \pm \pi$. Any additional anomalous CP-even or CP-odd contribution to the interaction between the Higgs boson and weak bosons would manifest itself as an additional oscillatory component, and any interference between the SM and anomalous couplings can produce distributions peaked at either $\Delta \phi_{jj} = 0$ or $\Delta \phi_{jj} = \pm \pi$ [138, 140, 141]. The shape of the distribution is therefore sensitive to the relative contribution of gluon–gluon fusion and vector-boson fusion, as well as to the tensor structure of the interactions between the Higgs boson and gluons or weak bosons. This is exploited in Section 9.5.8 to set limits on new physics contributions. To quantify the structure of the azimuthal angle between the two jets, a ratio is defined as

$$A_{|\Delta \phi_{jj}|} = \frac{\sigma(|\Delta \phi_{jj}| < \frac{\pi}{3}) - \sigma(\frac{\pi}{3} < |\Delta \phi_{jj}| < \frac{2\pi}{3}) + \sigma(|\Delta \phi_{jj}| > \frac{2\pi}{3})}{\sigma(|\Delta \phi_{jj}| < \frac{\pi}{3}) + \sigma(\frac{\pi}{3} < |\Delta \phi_{jj}| < \frac{2\pi}{3}) + \sigma(|\Delta \phi_{jj}| > \frac{2\pi}{3})},$$

which is motivated by a similar ratio presented in Ref. [140]. The measured ratio in data as determined by measuring $|\Delta \phi_{jj}|$ in three bins is

$$A_{|\Delta \phi_{jj}|}^{\text{meas}} = 0.45^{+0.10}_{-0.11} \text{ (stat.)}^{+0.10}_{-0.11} \text{ (syst.)}.$$  

This value can be compared to the SM prediction from the default MC simulation. The predicted value is $A_{|\Delta \phi_{jj}|}^{\text{SM}} = 0.44 \pm 0.01$, consistent with the measured ratio.

In summary, the measured $|\cos \theta^*|$ and $\Delta \phi_{jj}$ distributions are consistent with Standard Model predictions for a CP-even scalar particle.