Higgs couplings and mass measurements in the ZZ and WW decay channels with ATLAS and CMS

Will Leight
for the ATLAS and CMS Collaborations
H→ZZ*→4l Decay Channel

- Low BR of ~0.01%, but high purity with S/B~2 in the mass peak
- Useful for many Higgs boson properties measurements
- ATLAS and CMS both have ~200 signal events with the full Run-2 sample

Dominant background from SM ZZ* production is estimated using MC in CMS; normalization constrained in sidebands in ATLAS

Background from ttV, ttt, ttVV can be constrained in sidebands or taken from MC; VVV from MC
Higgs Boson Mass

ATLAS-CONF-2020-005
• First mass measurement with full Run-2 dataset
• Recover FSR, constrain $m_{12}$ to $m_Z$ (15% resolution gain)
• Parametrize $m_{4l}$ distribution as double-sided Crystal Ball function
  ▶ Analysis categories based on final state (resolution) and BDT (for better S/B)
  ▶ Background shapes from smoothed MC, $ZZ^*$ norm floats

• Not a test of the Standard Model
  ▶ $m_H$ is a free parameter
• Important ingredient in SM predictions
• Best measured in clean channels like $H \rightarrow ZZ^* \rightarrow 4l$

![Graph showing Higgs Boson mass distribution](image)

![Histogram showing $m_{4l}$ distribution](image)
Higgs Boson Mass

**ATLAS-CONF-2020-005**

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**ATLAS Preliminary**

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

- $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
- $115 < m_{4l} < 130$ GeV

**ATLAS Preliminary**

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

- $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

- Low stats → gain from using per-event $m_{4l}$ resolution
  - ~2% better resolution, more robust to fluctuations
- Lepton momentum resolution is non-Gaussian → hard to calculate $m_{4l}$ resolution from lepton resolutions
  - Constraint on $m_{12}$ introduces correlations between leading leptons
- Train a NN to predict $m_{4l}$ resolution using lepton and event-level information
Higgs Boson Mass

**ATLAS-CONF-2020-005**

- First mass measurement with full Run-2 dataset
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- Parametrize m_{4l} distribution as double-sided Crystal Ball function
  - Analysis categories based on final state (resolution) and BDT (for better S/B)
  - Background shapes from smoothed MC, ZZ^* norm floats

- Final result: m_H = 124.92±0.21 GeV
  - Compare previous CMS 4l result 125.26±0.21 GeV
- 20% improvement on previous ATLAS result
- Still stat-dominated: leading systematic is muon momentum scale

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Impact (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon momentum scale</td>
<td>+0.08, −0.06</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>±0.02</td>
</tr>
<tr>
<td>Muon momentum resolution</td>
<td>±0.01</td>
</tr>
<tr>
<td>Muon sagitta bias correction</td>
<td>±0.01</td>
</tr>
</tbody>
</table>
Simplified Template Cross Sections

- Target specific phase space regions within production modes
  - Using SM as a kinematic template
- Attempt to maximize experimental sensitivity and minimize dependence on theoretical uncertainties

**Schematic overview of the simplified template cross sections**

1. **σ(ggF)**
   - ≥ 0-jet
   - ≥ 1-jet
   - ≥ 2-jet VBF cuts

2. **σ(VBF)**
   - Rest
   - ≥ 2-jet VBF cuts
   - high-$$q^2$$ BSM
   - ≥ 3-jet

3. **σ(VH)**
   - low $$p_T^V$$
   - high $$p_T^V$$
   - very high $$p_T^V$$

4. **σ(ttH)**, **σ(bbH)**, **σ(tH)**
Reconstructed categories are defined to target STXS bins

- Both experiments use STXS Stage 1 with some bins merged
  - ATLAS: Reduced Stage 1.1; CMS: Stage 1.1

- Extract cross-sections in each bin from fit to values in categories
Kinematic Discriminants

All plots in the signal region $118 < m_{4\ell} < 130$

$D_{2\text{jet}} = \left[ 1 + \frac{\mathcal{P}_{HJJ}(\bar{\Omega}^{H+JJ}|m_{4\ell})}{\mathcal{P}_{VBF}(\bar{\Omega}^{2H+JJ}|m_{4\ell})} \right]^{-1}$

$D_{\text{VH}} = \max\left( \left[ 1 + \frac{\mathcal{P}_{HJJ}(\bar{\Omega}^{H+JJ}|m_{4\ell})}{\mathcal{P}_{WH}(\bar{\Omega}^{H+JJ}|m_{4\ell})} \right]^{-1}, \left[ 1 + \frac{\mathcal{P}_{HJJ}(\bar{\Omega}^{H+JJ}|m_{4\ell})}{\mathcal{P}_{ZH}(\bar{\Omega}^{H+JJ}|m_{4\ell})} \right]^{-1} \right)$

$D_{1\text{jet}} = \left[ 1 + \frac{\mathcal{P}_{HJ}(\bar{\Omega}^{H+}|m_{4\ell})}{\int d\eta J \mathcal{P}_{VBF}(\bar{\Omega}^{H+JJ}|m_{4\ell})} \right]^{-1}$
• ATLAS approach uses fewer categories to reduce migrations
• To maintain sensitivity, train NNs to optimize signal efficiency
  ▶ These are also used to define some category boundaries
• Final fits use NN distributions inside categories
• Results obtained for (Reduced) STXS stage 1.1
  ▶ Different bin mergings used by the 2 experiments
  ▶ Note that ggZH is included in the ATLAS gg2H categories so the correspondence is not exact
• Good agreement with the SM observed in all cases
H → WW → llνν Decay Channel

H → WW* → eνμν candidate and no jets

Longitudinal view

Transverse view

Run 302300, Ev. no. 4386907856
Jun. 18, 2016, 13:09:05 CEST
H$\rightarrow$WW$\rightarrow$llvv Decay Channel

**WW** background constrained by CR (ATLAS) or as part of the final fit (CMS)

Top quark and Drell-Yan backgrounds constrained by CR’s

- Much higher BR than H$\rightarrow$ZZ$^*$→4l, ~1%
- More backgrounds, final state not fully reconstructed
- STXS stage 1 difficult but stage 0 (production modes) possible

Non-WW diboson backgrounds constrained by CRs or taken from MC

Misidentified lepton backgrounds estimated from data

\(\tilde{\gamma}_s = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}\)
VH → WW: WH

min(ΔRll) between the oppositely charged leptons

**OSSF pair**: less pure, WZ background dominates

**SSSF pair**: higher purity, leading background is top/nonprompt

BDTs for S/B rejection (separate in each category)
VH→WW: ZH, VH(had)

- ZH is fairly pure but low stats
- Split on # of SFOS lepton pairs
- Counting only

- V→2j has higher BR but much more background
- Dominantly from tW and ttbar
- Require central jets for b-tagging
- m_\ell_\ell as variable
Couplings Measurements

- Measure cross section in production modes
- Mostly good agreement with the SM observed
Summary

• Higgs decays to all-leptonic diboson final states provide valuable probes of its properties
• $H \rightarrow ZZ^* \rightarrow 4l$ can be used for precision measurements of the Higgs mass
• Both channels are used for couplings measurements in the STXS framework
• Final $H \rightarrow ZZ^* \rightarrow 4l$ results using Run-2 data are here
  ‣ Though still room for more interpretations
• $H \rightarrow WW \rightarrow ll\nu\nu$ not yet exploiting the full dataset
• Stay tuned for more results!
Backup
Expected vs. Measured $m_H$ Uncertainty

$\sqrt{s} = 13$ TeV, $139$ fb$^{-1}$

1-sided p-value of 0.17

$\text{ATLAS Preliminary}$

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

$P(m_d) \text{ Expected: } 0.20 \text{ GeV}$

$P(m_d) \text{ Observed: } 0.22 \text{ GeV}$

$P(m_d \mid \sigma) \text{ Expected: } 0.19 \text{ GeV}$

$P(m_d \mid \sigma) \text{ Observed: } 0.21 \text{ GeV}$
• 3D likelihood includes mass, mass resolution, kinematic discriminant
  ▶ Discriminant to separate signal and background
  ▶ Final result uses mass and resolution with Z-mass constraint applied to leading lepton pair
### STXS Correlation Matrices

**CMS Preliminary**

<table>
<thead>
<tr>
<th>Category</th>
<th>Correlation Matrix</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH-0j/pT[0,10]</td>
<td></td>
<td>1.00</td>
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<tr>
<td>ggH-0j/pT[10-200]</td>
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<td>0.12</td>
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<tr>
<td>ggH-1j/pT[0-60]</td>
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<tr>
<td>ggH-1j/pT[60-120]</td>
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<tr>
<td>ggH-1j/pT[120-200]</td>
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<tr>
<td>ggH-2j/pT[0-60]</td>
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<tr>
<td>ggH-2j/pT[60-120]</td>
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<td>-0.02</td>
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<tr>
<td>ggH-2j/pT[120-200]</td>
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<td>-0.04</td>
</tr>
<tr>
<td>ggH/pT&gt;200</td>
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<tr>
<td>ggH-2j/mJJ&gt;350</td>
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<td>ggH-2j/mJJ[350,700]</td>
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<tr>
<td>qqH restless</td>
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<td>qqH-2j/pT&gt;200</td>
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<td>tH,tH</td>
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<td>ttH</td>
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<td>ZZ-0j</td>
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<tr>
<td>tXX</td>
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**ATLAS**

<table>
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<tr>
<th>Category</th>
<th>Correlation Matrix</th>
<th>Value</th>
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<td>gg2H-0j-(p_T^{H})_{\text{Low}}</td>
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<tr>
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<td>gg2H-2j</td>
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<td>gg2H-p_{T}^{H}_High</td>
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<td>qq2Hqq-VH</td>
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<td>qq2Hqq-VBF</td>
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<td>tXX</td>
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</table>

137.1 fb\(^{-1}\) (13 TeV)
ATLAS H→WW Measurements
Effective Field Theory Interpretations

\[ \mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{c_i}{\Lambda^2} O^{d=6}_i + (\text{dim} > 6) \]

- Add new physics to the Lagrangian without committing to specific model
- Wilson coefficients for generic interactions

\[ O_{HG} \sim c_{HG} H H^\dagger G^A_\mu \nu G^{\mu \nu A}_\perp \]

CP-even interaction between Higgs and gluons

**ATLAS**

H → ZZ^* → 4l

\[ \sqrt{s} = 13 \text{ TeV, } 139 \text{ fb}^{-1} \]

Reduced Stage 1.1 - |y_H| < 2.5

| gg2H-0/-p^+|Low | gg2H-0/-p^+|High |
| gg2H-1/-p^-|Low | gg2H-1/-p^-|Med |
| gg2H-1/-p^-|High | gg2H-2/ | |
| gg2H-3/-p^+|High | qq2Hq-VH |
| qq2Hqq-VBF | qq2Hqq-BSM |
| VH-Lep | lH |

\[ \sigma B(\text{fb}) \]

- Observed: Stat-Sys
- Observed: Stat-Only
- p-value = 77%

- SM Prediction

\[ \sigma B(\text{SM})_{\text{SM}}(\text{fb}) \]

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4</td>
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<td>6</td>
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<tr>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

\[ \frac{\sigma B}{(\sigma B)_{SM}} \]

\[ \sigma B/((\sigma B)_{SM}) \]

ggH STXS: split by \text{Njets} and \text{pT}^H
Effective Field Theory Interpretations

\[ \mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{d=6} + (\text{dim} > 6) \]

\[ O_{HG} \sim c_{HG} HH^{\dagger} G^{A}_{\mu\nu} G^{H^{\mu\nu}A} \]

- Add new physics to the Lagrangian without committing to a specific model
- Wilson coefficients for generic interactions
- Parametrize predictions in STXS bins
  - Include effects on cross sections, branching fractions, in some cases acceptances
Effective Field Theory Interpretations

\[ \mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{d=6} + (\text{dim} > 6) \]

\[ O_{HG} \sim c_{HG} H H^{\dagger} G^A_{\mu
u} G^{\mu\nu} \]

CP-even interaction between Higgs and gluons

- Fit to STXS results to constrain values of Wilson coefficients
- Best-fit values are all consistent with 0
CP-Odd Wilson Coefficients

\[ \text{ATLAS} \]
\[ H \rightarrow ZZ^* \rightarrow 4l \]
\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]
\[ \text{SMEFT} \]

- \( c_{\tilde{H}W} \pm 0.6 \) \([-2.4, 2.4]\)
- \( c_{\tilde{H}B} = 0.0 \) \([-0.56, 0.56]\)
- \( c_{\tilde{H}WB} = 0.0 \) \([-1.0, 1.0]\)
- \( c_{\tilde{H}G} = 10^2 \) \([-0.029, 0.029]\)
- \( c_{uH} = 5 \times 10^{-2} \pm 21 \) \([-50, 50]\)