Interpretation of ATLAS and CMS Higgs measurements in STXS and EFT

Nikita Belyaev
on Behalf of the ATLAS and CMS Collaborations
Introduction: STXS

- The Simplified Template Cross-Section (STXS) measurements, which are the most common type of the results in ATLAS and CMS, are often used to probe the Higgs boson couplings.

- The advantage of STXS measurements are the following:
  - Maximizing experimental sensitivity
  - Minimizing the theoretical uncertainties
  - Isolation of possible BSM effects
  - Suitable for global combinations
  - Not fully fiducial
  - No Higgs decay information
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  + Suitable for global combinations
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  - The Stage 1 brings additional bins based on kinematics.

- The goal is that the full granularity should become accessible in the combination of all decay channels.

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STXS measurements: an example

- The 4l CMS STXS measurements with the full Run II dataset are done in 7 Stage 0 and 22 Stage 1 bins.
- Expected fraction of signal events is estimated per production mode in the different categories.
- Cross sections in each bin are extracted from the fits in categories.

More details about the STXS measurements for presented EFT results can be found at W. Leight and S. Jiggins talks (ZZ/WW and bb/ττ modes, respectively).
Effective field theory approach

• After Run 1 discovery of the Higgs boson, the increased number of Higgs decays allows improved precision in the couplings and cross section measurements to test the compatibility of the SM predictions and search for possible deviations.

• One of the most promising tools in this field is the Effective Field Theory (EFT) approach, in which the SM Lagrangian is supplemented by new operators with canonical dimensions $D$ larger than 4:

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3} \mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \ldots \]

where $c_i$ are so-called Wilson coefficients and $\mathcal{O}_i^{(D)}$ are the operators of dimension $D$.

• This framework can be used to interpret the STXS results (but also applicable for the interpretation of differential cross sections and kinematic measurements):

➢ The Higgs boson production cross-section in STXS region $p$ can be expressed as:

\[ \sigma_p = \sigma_{p,\text{SM}} + \sigma_{p,\text{int}} + \sigma_{p,\text{BSM}} \]

➢ Its ratio to the SM can be then parameterized as follows:

\[ \frac{\sigma_p}{\sigma_{p,\text{SM}}} = 1 + \sum_i A_i^{\sigma_p} c_i + \sum_{ij} B_{ij}^{\sigma_p} c_i c_j \]

where $A_i^{\sigma_p}$ and $B_{ij}^{\sigma_p}$ are coefficients independent of the $c_i$ and determined from simulation.

• Main simulation tool: SMEFTsim model for the MadGraph5_aMC@NLO Monte Carlo generator.

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EFT bases

• A complete and non-redundant set of higher-dimensional operators forms so-called EFT basis.
• For each specific type of interaction, EFT bases can be constructed in several different ways, but all of them are equivalent in terms of physics effects.
• For example, CP-violating operators of the Higgs Effective Lagrangian (HEL) model in the gauge eigenbasis can be written as:

\[
\mathcal{L}_{CP} = \frac{ig}{m_W^2} c_{\mu\nu} D^\mu \Phi \Phi^\dagger B_{\mu\nu} + \frac{ig'}{m_W^2} D^\mu \Phi \Phi^\dagger D^\nu \Phi B_{\mu\nu} + \frac{g'}{m_W^2} \tilde{c}_\gamma \Phi \Phi^\dagger B_{\mu\nu} \tilde{B}^{\mu\nu} \\
+ \frac{g_s^2}{m_W^2} \tilde{c}_g \Phi \Phi G_{\mu\nu}^a \tilde{G}_a^{\mu\nu} + \frac{g_s^3}{m_W^2} \tilde{c}_{3W} \epsilon_{ijk} W_{\mu\nu}^i W_{\rho\kappa}^j \tilde{W}_{\rho\kappa}^{\mu\nu} + \frac{g_s^3}{m_W^2} \tilde{c}_{3G} \epsilon_{abc} G_{\mu\nu}^a G_{\rho\kappa}^{\nu b} \tilde{G}_{\rho\kappa}^{\mu\nu}
\]

• There are many different bases describing the BSM Higgs boson interactions: Warsaw (SMEFT) basis, SILH basis, Higgs basis and others.
• But sometimes it is reasonable to work only with a small subset of new operators, not with the whole basis.

➢ Example: an effective amplitude of the HVV interaction can be written as follows:

\[
A(HVV) \sim \left[ a_1^{VV} + \frac{\kappa_{11}^{VV} q_1^2 + \kappa_{22}^{VV} q_2^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_\mu^{(1)} f_\nu^{* (2)} + a_3^{VV} f_\mu^{(1)} f_\nu^{* (2)} f_\nu^{* (2)}
\]
EFT measurements in the $bb$ channel (ATLAS)

- The STXS measurements and their EFT interpretation were done with the $H \rightarrow bb$ decay channel for the $W/ZH$ production.
- Cross-sections are measured as a function of the gauge boson transverse momentum in kinematic fiducial volumes.
- One-dimensional limits on four linear combinations of the Wilson coefficients in the SILH basis have been set.

All measurements are found to be in agreement with the Standard Model predictions.

### Table

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{c}_{HW}$</td>
<td>$i (D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$</td>
</tr>
<tr>
<td>$\tilde{c}_{HB}$</td>
<td>$i (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$</td>
</tr>
<tr>
<td>$\tilde{c}_W$</td>
<td>$\frac{i}{2} \left( H^\dagger \sigma^a D^\mu H \right) D^\nu W^a_{\mu\nu}$</td>
</tr>
<tr>
<td>$\tilde{c}_B$</td>
<td>$\frac{i}{2} \left( H^\dagger D^\mu H \right) \partial^\nu B_{\mu\nu}$</td>
</tr>
<tr>
<td>$\tilde{c}_d$</td>
<td>$y_d</td>
</tr>
</tbody>
</table>

### ATLAS VH, $H \rightarrow bb$, $V \rightarrow$ leptons cross-sections:

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Expected interval</th>
<th>Observed interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{c}_{HW}$</td>
<td>$[-0.003, 0.002]$</td>
<td>$[-0.001, 0.004]$</td>
</tr>
<tr>
<td>(interference only)</td>
<td>$[-0.002, 0.003]$</td>
<td>$[-0.001, 0.005]$</td>
</tr>
<tr>
<td>$\tilde{c}_{HB}$</td>
<td>$[-0.066, 0.013]$</td>
<td>$[-0.078, -0.055]$ (\cup) [0.005, 0.019]</td>
</tr>
<tr>
<td>(interference only)</td>
<td>$[-0.016, 0.016]$</td>
<td>$[-0.005, 0.030]$</td>
</tr>
<tr>
<td>$\tilde{c}_W - \tilde{c}_B$</td>
<td>$[-0.006, 0.005]$</td>
<td>$[-0.002, 0.007]$</td>
</tr>
<tr>
<td>(interference only)</td>
<td>$[-0.005, 0.005]$</td>
<td>$[-0.002, 0.008]$</td>
</tr>
<tr>
<td>$\tilde{c}_d$</td>
<td>$[-1.5, 0.3]$</td>
<td>$[-1.6, -0.9]$ (\cup) $[-1.3, 0.4]$</td>
</tr>
<tr>
<td>(interference only)</td>
<td>$[-0.4, 0.4]$</td>
<td>$[-0.2, 0.7]$</td>
</tr>
</tbody>
</table>

Results at 68% confidence level

### ATLAS $V = W$

- $\sigma \times B^{H \rightarrow bb} \times B_V^{\ell \ell}$ [fb]

### ATLAS $V = Z$

- $\sigma \times B^{H \rightarrow bb} \times B_V^{\ell \ell}$ [fb]

### ATLAS VH, $H \rightarrow bb$, $V \rightarrow$ leptons cross-sections:

- Results at 95% confidence level

- All measurements are found to be in agreement with the Standard Model predictions.
EFT measurements in the $bb$ channel (ATLAS)

- The same measurements as in the previous analysis, but with the whole Run II dataset.
- The key improvement compared to the previous analysis is the addition of a reconstructed-event category with $p_T > 250$ GeV.
- The STXS measurements are now used to constrain the coefficients of the operators in the Warsaw basis.

The obtained results are all consistent with the Standard Model expectations.

The results will be published shortly (HIGG-2018-51)
More EFT measurements in the $bb$ channel (ATLAS)

- The STXS measurements and their EFT interpretation were also done in the boosted $VH/H \rightarrow bb$ channel.
- The high-$p_T$ measurements are particularly interesting due to their sensitivity to BSM physics.
- The STXS measurements are used to constrain the coefficients of the operators in the Warsaw basis.

The results will be published shortly (HIGG-2018-52)
EFT measurements in the 4l channel (ATLAS)

- The EFT operators in the SMEFT formalism probed in this analysis:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Structure</th>
<th>Coeff.</th>
<th>Operator</th>
<th>Structure</th>
<th>Coeff.</th>
<th>Impact on production</th>
<th>decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{uH}$</td>
<td>$H H^\dagger \tilde{q}_\mu u, \tilde{H}$</td>
<td>$c_{uH}$</td>
<td>$O_{uH}$</td>
<td>$H H^{\dagger} \tilde{q}_\mu u, \tilde{H}$</td>
<td>$c_{uH}$</td>
<td>$t t H$</td>
<td>-</td>
</tr>
<tr>
<td>$O_{HG}$</td>
<td>$H H^\dagger G_{\mu\nu}^\mu G_{\mu\nu}^A$</td>
<td>$c_{HG}$</td>
<td>$O_{HG}$</td>
<td>$H H^{\dagger} G_{\mu\nu}^\mu G_{\mu\nu}^A$</td>
<td>$c_{HG}$</td>
<td>$g g F$</td>
<td>Yes</td>
</tr>
<tr>
<td>$O_{HW}$</td>
<td>$H H^\dagger W_{\mu\nu}^H W_{\mu\nu}$</td>
<td>$c_{HW}$</td>
<td>$O_{HW}$</td>
<td>$H H^{\dagger} W_{\mu\nu}^H W_{\mu\nu}$</td>
<td>$c_{HW}$</td>
<td>$V B F, V H$</td>
<td>Yes</td>
</tr>
<tr>
<td>$O_{HB}$</td>
<td>$H H^\dagger B_{\mu\nu} B_{\mu\nu}$</td>
<td>$c_{HB}$</td>
<td>$O_{HB}$</td>
<td>$H H^{\dagger} B_{\mu\nu} B_{\mu\nu}$</td>
<td>$c_{HB}$</td>
<td>$V B F, V H$</td>
<td>Yes</td>
</tr>
<tr>
<td>$O_{HWB}$</td>
<td>$H H^\dagger \tau_l^l W_{\mu\nu}^H B_{\mu\nu}$</td>
<td>$c_{HWB}$</td>
<td>$O_{HWB}$</td>
<td>$H H^{\dagger} \tau_l^l W_{\mu\nu}^H B_{\mu\nu}$</td>
<td>$c_{HWB}$</td>
<td>$V B F, V H$</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- 1D and 2D scans over the SMEFT Wilson coefficients were produced (one or two non-zero coefficients).

- Quadratic terms are taken into account in addition to the linear ones, due to their significant contribution.

- The test statistic is used to perform the measurements:

$$q(\hat{\sigma}) = -2 \ln \frac{\mathcal{L}(\hat{\sigma}, \hat{\theta}(\hat{\sigma}))}{\mathcal{L}(\hat{\sigma}, \hat{\theta})} = -2 \ln \lambda(\hat{\sigma})$$

- The acceptance correction is also considered.

- The constraints on the Wilson coefficients are obtained.

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HIGG-2018-28
EFT measurements in the $4\ell$ channel (ATLAS)

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HIGG-2018-28
EFT measurements in the $4l$ channel (ATLAS)

### CP-even couplings

<table>
<thead>
<tr>
<th>BSM coupling parameter</th>
<th>Observed best fit</th>
<th>Best-fit $p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{HW}, c_{HB}$</td>
<td>$\hat{c}_{HW} = 0.57$</td>
<td>$\hat{c}_{HB} = 0.05$</td>
</tr>
<tr>
<td>$c_{HG}, c_{HB}$</td>
<td>$\hat{c}_{HG} = -0.001$</td>
<td>$\hat{c}_{HB} = -0.04$</td>
</tr>
<tr>
<td>$c_{HG}, c_{uH}$</td>
<td>$\hat{c}_{HG} = -0.001$</td>
<td>$\hat{c}_{uH} = -5.7, 17.7$</td>
</tr>
<tr>
<td>$c_{HW}, c_{HB}$</td>
<td>$\hat{c}_{HW} = \pm 1.12$</td>
<td>$\hat{c}_{HB} = \pm 0.21$</td>
</tr>
<tr>
<td>$c_{HG}, c_{HB}$</td>
<td>$\hat{c}_{HG} = 0.00$</td>
<td>$\hat{c}_{uH} = 0.00$</td>
</tr>
<tr>
<td>$c_{HG}, c_{uH}$</td>
<td>$\hat{c}_{HG} = 0.000$</td>
<td>$\hat{c}_{uH} = \pm 21$</td>
</tr>
</tbody>
</table>

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The constraints are placed on possible CP-even and CP-odd BSM interactions.

As a result, the data are found to be consistent with the SM hypothesis.
Combined CMS EFT measurements

- Combined measurements of the production and decay rates of the Higgs boson and its couplings to vector bosons and fermions, and interpretations in the EFT framework were performed.

- The acceptance is assumed to be the same as that predicted in the SM.

- The signal strength values are parameterized in terms of EFT.

- The STXS interpretation was done within the Higgs Effective Lagrangian (HEL) model.

- The HEL Lagrangian adds 39 flavor independent dimension-6 operators:
  \[ \mathcal{L}_{\text{HEL}} = \mathcal{L}_{\text{SM}} + \sum_j \mathcal{O}_j f_j / \Lambda^2 \]

- New physics \( \sim f_j / \Lambda^2 \).
Combined CMS EFT measurements

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- The acceptance is assumed to be the same as that predicted in the SM.
- The signal strength values are parameterized in terms of EFT.
- The STXS interpretation was done within the Higgs Effective Lagrangian (HEL) model.

The HEL Lagrangian adds 39 flavor independent dimension-6 operators:

$$\tilde{\mathcal{O}}_{ij}^f = \frac{\mu_{ij}^f}{\Lambda^2}$$
Combined CMS EFT measurements

- Signal strength measurements were interpreted in terms of HEL EFT framework.
- Only leading CP-even terms were considered, which are not tightly constrained by other data.
- CP-odd parameters are neglected – not present at the leading order in $1/\Lambda^2$. The CP-even quadratic terms are also assumed to be small.

**HEL Parameters**

<table>
<thead>
<tr>
<th>HEL Parameters</th>
<th>Definition</th>
<th>Others profiled</th>
<th>Fix others to SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_A \times 10^4$</td>
<td>$c_A = \frac{m_W^2 f_A}{\Lambda^2}$</td>
<td>$-1.03 \pm 1.53$</td>
<td>$-0.78 \pm 1.11$</td>
</tr>
<tr>
<td>$c_G \times 10^5$</td>
<td>$c_G = \frac{m_W^2 f_G}{\Lambda^2}$</td>
<td>$1.43 \pm 3.20$</td>
<td>$0.27 \pm 1.05$</td>
</tr>
<tr>
<td>$c_u \times 10$</td>
<td>$c_u = -\bar{v}^2 \frac{f_u}{\Lambda^2}$</td>
<td>$0.68 \pm 0.82$</td>
<td>$0.43 \pm 0.69$</td>
</tr>
<tr>
<td>$c_d \times 10$</td>
<td>$c_d = -\bar{v}^2 \frac{f_d}{\Lambda^2}$</td>
<td>$0.59 \pm 1.03$</td>
<td>$-0.01 \pm 0.31$</td>
</tr>
<tr>
<td>$c_\ell \times 10$</td>
<td>$c_\ell = -\bar{v}^2 \frac{f_\ell}{\Lambda^2}$</td>
<td>$-0.57 \pm 0.74$</td>
<td>$-0.75 \pm 0.60$</td>
</tr>
<tr>
<td>$c_{HW} \times 10^2$</td>
<td>$c_{HW} = \frac{m_W^2 f_{HW}}{2g^2 \Lambda^2}$</td>
<td>$-1.45 \pm 4.72$</td>
<td>$0.77 \pm 0.84$</td>
</tr>
<tr>
<td>$(c_{WW} - c_B) \times 10^2$</td>
<td>$c_{WW} = \frac{m_W^2 f_{WW}}{g^2 \Lambda^2}$, $c_B = \frac{2m_W^2 f_B}{g^2 \Lambda^2}$</td>
<td>$2.16 \pm 2.84$</td>
<td>$0.62 \pm 1.06$</td>
</tr>
</tbody>
</table>

- All results are found to be compatible with the standard model expectation within the current uncertainties.

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EFT measurements in the $\gamma\gamma$ channel (ATLAS)

- Measurements of the fiducial integrated and differential cross sections for the $\gamma\gamma$ mode.

<table>
<thead>
<tr>
<th>Objects</th>
<th>Fiducial 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, $</td>
</tr>
<tr>
<td>Diphoton</td>
<td>$N_\gamma \geq 2$, $105$ GeV $&lt; m_{\gamma\gamma} &lt; 160$ GeV, $p_T^{1\gamma}/m_{\gamma\gamma} &gt; 0.35$, $p_T^{2\gamma}/m_{\gamma\gamma} &gt; 0.25$</td>
</tr>
</tbody>
</table>

- EFT interpretation of differential cross sections with CP-even and CP-odd interactions.

- Effective Lagrangian - SILH formulation:
  \[
  \mathcal{L}^{SILH}_{\text{eff}} \supset \bar{c}_g O_g + \bar{c}_\gamma O_\gamma + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} \\
  + \bar{c}_g \tilde{O}_g + \bar{c}_\gamma \tilde{O}_\gamma + \bar{c}_{HW} \tilde{O}_{HW} + \bar{c}_{HB} \tilde{O}_{HB}
  \]

- Effective Lagrangian - SMEFT formulation:
  \[
  \mathcal{L}^{SMEFT}_{\text{eff}} \supset \bar{C}_{HG} O_g' + \bar{C}_{HW} O_{HW}' + \bar{C}_{HB} O_{HB}' + \bar{C}_{HWB} O_{HWB}' \\
  + \bar{C}_{HG} \tilde{O}_g' + \bar{C}_{HW} \tilde{O}_{HW}' + \bar{C}_{HB} \tilde{O}_{HB}' + \bar{C}_{HWB} \tilde{O}_{HWB}'
  \]

  ➢ CP-conserving: $\bar{C}_{HG}, \bar{C}_{HW}, \bar{C}_{HB}$ and $\bar{C}_{HWB}$.
  ➢ CP-violating: $\tilde{C}_{HG}, \tilde{C}_{HW}, \tilde{C}_{HB}$ and $\tilde{C}_{HWB}$.
EFT measurements in the $\gamma\gamma$ channel (ATLAS)

**ATLAS Preliminary**

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

- Data, tot. unc.  syst. unc.

- $gg \rightarrow H$ default MC + $XH$
- NLO@NFC SCET NNLO + $XH$
- $XH = VBF+VH+tH+bbH$

**ATLAS Preliminary**

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

- Data, tot. unc.  syst. unc.

- $gg \rightarrow H$ default MC + $XH$
- $gg \rightarrow H$ NNLO@NFC SCET $+ XH$
- $gg \rightarrow H$ SCETlib $+ XH$
- $XH = VBF+VH+tH+bbH$
- anti $k_t, R = 0.4, N_{jets} = 0$

**ATLAS Preliminary**

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

- Data, tot. unc.  syst. unc.

- $gg \rightarrow H$ default MC + $XH$
- $gg \rightarrow H$ Sherpa $+ XH$
- $gg \rightarrow H$ GoSam+Sherpa $+ XH$
- $XH = VBF+VH+tH+bbH$
- anti $k_t, R = 0.4, p_T > 30$ GeV

**ATLAS Preliminary**

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

- Data, tot. unc.  syst. unc.

- $gg \rightarrow H$ default MC + $XH$
- N$^3$LO $+ XH$
- $N^3$LO+JVE $+ XH$
- STWZ, BLPTW $+ XH$
- MG5 aMC@NLO $+ XH$
- $XH = VBF+VH+tH+bbH$
EFT measurements in the $\gamma\gamma$ channel (ATLAS)

- Limits on Wilson coefficients are set with the differential cross sections:

$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k |C|}} \exp \left( -\frac{1}{2} (\hat{\sigma}_{\text{data}} - \hat{\sigma}_{\text{pred}})^T C^{-1} (\hat{\sigma}_{\text{data}} - \hat{\sigma}_{\text{pred}}) \right)$$

- Fitting one Wilson coefficient at a time.

- Five analyzed observables: $p_T^{\gamma\gamma}$, $p_T^1$, $N_{jets}$, $m_{jj}$ and $\Delta\phi_{jj}$.

- Results have improved by a factor of two in comparison to the previous measurement.

**SILH basis:**

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Observed 95% CL limit</th>
<th>Expected 95% CL limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{c}_g$</td>
<td>$[0.26, 0.26] \times 10^{-4}$</td>
<td>$[-0.25, 0.25] \cup [-4.7, -4.3] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\bar{c}_g$</td>
<td>$[-1.3, 1.1] \times 10^{-4}$</td>
<td>$[-1.1, 1.1] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\bar{c}_{HW}$</td>
<td>$[-2.5, 2.2] \times 10^{-2}$</td>
<td>$[-3.0, 3.0] \times 10^{-2}$</td>
</tr>
<tr>
<td>$\bar{c}_{HW}$</td>
<td>$[-6.5, 6.3] \times 10^{-2}$</td>
<td>$[-7.0, 7.0] \times 10^{-2}$</td>
</tr>
<tr>
<td>$\bar{c}_\gamma$</td>
<td>$[-1.1, 1.1] \times 10^{-4}$</td>
<td>$[-1.0, 1.2] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\bar{c}_\gamma$</td>
<td>$[-2.8, 4.3] \times 10^{-4}$</td>
<td>$[-2.9, 3.8] \times 10^{-4}$</td>
</tr>
</tbody>
</table>

**SMEFT basis:**

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>95% CL, interference-only terms</th>
<th>95% CL, interference and quadratic terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{C}_{HG}$</td>
<td>$[-4.2, 4.8] \times 10^{-4}$</td>
<td>$[-6.1, 4.7] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\bar{C}_{HG}$</td>
<td>$[-2.1, 1.6] \times 10^{-2}$</td>
<td>$[-1.5, 1.4] \times 10^{-3}$</td>
</tr>
<tr>
<td>$\bar{C}_{HW}$</td>
<td>$[-8.2, 7.4] \times 10^{-4}$</td>
<td>$[-8.3, 8.3] \times 10^{-4}$</td>
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<td>$\bar{C}_{HW}$</td>
<td>$[-0.26, 0.33]$</td>
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<tr>
<td>$\bar{C}_{HB}$</td>
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<td>$[-2.4, 2.4] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\bar{C}_{HB}$</td>
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<td>$[-1.2, 1.1] \times 10^{-3}$</td>
</tr>
<tr>
<td>$\bar{C}_{HWB}$</td>
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<td>$[-4.2, 4.2] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\bar{C}_{HWB}$</td>
<td>$[-11.1, 6.5]$</td>
<td>$[-2.0, 2.0] \times 10^{-3}$</td>
</tr>
</tbody>
</table>

- The measurements are found to be in good agreement with the Standard Model predictions.

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ATLAS-CONF-2019-029
A study of anomalous HVV interactions was performed.

Production: ggF and VBF.

Decay: \( \tau\tau \).

Combination with \( H \rightarrow 4l \) analysis.

Anomalous interactions are parametrized by a scattering amplitude:

\[
A(HVV) \sim \left[ a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} \right] m_{V_1}^2 e_{V_1} e_{V_2}^* + a_2^{VV} f_{\mu\nu}^{(1)} f^{*\mu\nu} + a_3^{VV} f_{\mu\nu}^{(1)} f^{*\mu\nu}
\]

The results are consistent with the standard model expectations.
Conclusion

- There are 8 years passed since the Higgs boson discovery, but many questions are still requiring answers.

- The Effective Field Theory approach allows to test various BSM hypotheses in different production and decay channels of the Higgs boson.

- Series of STXS and EFT ATLAS and CMS analyses were performed in order to find possible traces of BSM physics.

- As for now, no significant deviations from the Standard Model were observed.

- New, more strict limits were placed on the EFT parameters.
Thank You
Backup
SILH basis and Higgs Effective Lagrangian (HEL)

- CP-conserving operators (SILH basis - the main part of HEL):

\[ \mathcal{L}_{\text{SILH}} = \frac{\bar{c}_H}{2v^2} \partial^\mu [\Phi^\dagger \Phi] \partial_\mu [\Phi^\dagger \Phi] + \frac{\bar{c}_T}{2v^2} [\Phi^\dagger \overleftrightarrow{D}^\mu \Phi] [\Phi^\dagger \overleftrightarrow{D}_\mu \Phi] - \frac{\bar{c}_6 \lambda}{v^2} [\Phi^\dagger \Phi]^3 
\]

\[- \left( \frac{\bar{c}_u}{v^2} y_u \Phi^\dagger \Phi \Phi^\dagger \cdot \overline{Q}_L u_R + \frac{\bar{c}_d}{v^2} y_d \Phi^\dagger \Phi \Phi \overline{Q}_L d_R + \frac{\bar{c}_l}{v^2} y_\ell \Phi^\dagger \Phi \Phi \overline{L}_L e_R + \text{h.c.} \right) \]

\[ + \frac{ig}{m_W^2} [\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi] D^\nu W^k_{\mu\nu} + \frac{ig'}{2m_W^2} [\Phi^\dagger \overleftrightarrow{D}^\mu \Phi] \partial^\nu B_{\mu\nu} \]

\[ + \frac{2ig}{m_W^2} [D^\mu \Phi^\dagger T_{2k} D^\nu \Phi] W^k_{\mu\nu} + \frac{ig'}{m_W^2} [D^\mu \Phi^\dagger D^\nu \Phi] B_{\mu\nu} \]

\[ + \frac{g'^2}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} + g_s^2 \frac{\bar{c}_g}{m_W^2} \Phi^\dagger \Phi G_\mu^a G_\nu^a , \]

- CP-violating operators (additional part of HEL):

\[ \mathcal{L}_{\text{CP}} = \frac{ig}{m_W^2} D^\mu \Phi^\dagger T_{2k} D^\nu \Phi \widetilde{W}^k_{\mu\nu} + \frac{ig'}{m_W^2} D^\mu \Phi^\dagger D^\nu \Phi \widetilde{B}_{\mu\nu} + \frac{g'^2}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} \widetilde{B}^{\mu\nu} \]

\[ + g_s^2 \frac{\bar{c}_g}{m_W^2} \Phi^\dagger \Phi G_\mu^a G_\nu^a + g_s^3 \frac{\bar{c}_3}{m_W^2} \epsilon_{ijk} W^i_{\mu\nu} W^j_{\rho\sigma} \mu_k + \frac{g_s^3}{m_W^2} f_{abc} G_\mu^a G_\nu^b G_\rho^c \]

- Higgs Effective Lagrangian:

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum \bar{c}_i \mathcal{O}_i = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{SILH}} + \mathcal{L}_{\text{CP}} + \mathcal{L}_{F1} + \mathcal{L}_{F2} + \mathcal{L}_{G} \]
STXS measurements in the $4l$ channel (CMS)

- The dominant experimental sources of systematics: lepton identification efficiencies and luminosity measurement.
- The dominant theoretical source of systematics: the category migration for the ggH process.

All results are found to be compatible with the SM predictions, within the measurements precision.
STXS measurements in the $bb$ channel (CMS)

• An inclusive search for the SM Higgs boson produced with large $p_T$ and decaying to a $bb$ pair was performed.

• With respect to the previous CMS result, the relative precision of the Higgs boson signal strength measurement improves by approximately a factor of two.

• The measured signal strength is $\mu_H = 3.68 \pm 1.20\,(stat) \pm 0.63\,(syst) \pm 0.81\,(theo)$.

For a Higgs boson mass of 125 GeV, an excess of events above the expected background is observed with a local significance of 2.54 standard deviations, where the expectation is 0.71.

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STXS measurements in the $bb$ channel (ATLAS)

- The same measurements were performed with the whole Run II dataset.

- Results of the STXS measurements were already published, but their EFT interpretation is still under the ATLAS collaboration’s approval.

- The total uncertainties vary from 30% in the high gauge boson transverse momentum regions to 85% in the low regions.

- The cross-section measurements are all consistent with the Standard Model expectations.

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ATLAS-CONF-2020-006
STXS measurements in the $4l$ channel (ATLAS)

- Cross-sections times branching ratio are measured for the main Higgs boson production modes in several exclusive phase-space regions with full Run II dataset.
- The dominant Stage 0 experimental systematic uncertainty: lepton efficiency and integrated luminosity measurements. The dominant theoretical uncertainty: parton shower modelling.
- The SM Higgs boson signal is assumed to have a mass $m_H = 125$ GeV.
STXS measurements in the $4l$ channel (ATLAS)

- The dominant Stage 1.1 cross section uncertainties are the jet energy scale and resolution, and parton shower uncertainties.

- By using obtained STXS measurements, exclusion limits are set on the CP-even and CP-odd ‘beyond the Standard Model’ EFT couplings.

- The measured cross section are in a good agreement with the SM predictions.

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### ATLAS $4l$ selection criteria

#### Trigger
Combination of single-lepton, dilepton and trilepton triggers

#### Leptons and Jets
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrons</strong></td>
<td>$E_T &gt; 7$ GeV and $</td>
</tr>
<tr>
<td><strong>Muons</strong></td>
<td>$p_T &gt; 5$ GeV and $</td>
</tr>
<tr>
<td><strong>Jets</strong></td>
<td>$p_T &gt; 30$ GeV and $</td>
</tr>
</tbody>
</table>

#### Quadruplets
All combinations of two same-flavour and opposite-charge lepton pairs
- Leading lepton pair: lepton pair with invariant mass $m_{12}$ closest to the $Z$ boson mass $m_Z$
- Subleading lepton pair: lepton pair with invariant mass $m_{34}$ second closest to the $Z$ boson mass $m_Z$

Classification according to the decay final state: $4\mu$, $2e2\mu$, $2\mu2e$, $4e$

#### Requirements on each quadruplet
| **Lepton Reconstruction** | - Three highest-$p_T$ leptons must have $p_T$ greater than 20, 15 and 10 GeV |
| **Lepton Pairs**          | - At most one calorimeter-tagged or stand-alone muon |
| - Leading lepton pair: $50 < m_{12} < 106$ GeV |
| - Subleading lepton pair: $m_{\text{min}} < m_{34} < 115$ GeV |
| - Alternative same-flavour opposite-charge lepton pair: $m_{\ell\ell} > 5$ GeV |
| - $\Delta R(\ell, \ell') > 0.10$ for all lepton pairs |
| **Lepton Isolation**      | - The amount of isolation $E_T$ after summing the track-based and 40% of the calorimeter-based contribution must be smaller than 16% of the lepton $p_T$ |
| **Impact Parameter Significance** | - Electrons: $|d_0|/\sigma(d_0) < 5$ |
| - Muons: $|d_0|/\sigma(d_0) < 3$ |
| **Common Vertex**         | - $\chi^2$-requirement on the fit of the four lepton tracks to their common vertex |

#### Selection of the best quadruplet
- Select quadruplet with $m_{12}$ closest to $m_Z$ from one decay final state in decreasing order of priority: $4\mu$, $2e2\mu$, $2\mu2e$ and $4e$
- If at least one additional (fifth) lepton with $p_T > 12$ GeV meets the isolation, impact parameter and angular separation criteria, select the quadruplet with the highest matrix-element value

#### Higgs boson mass window
- Correction of the four-lepton invariant mass due to the FSR photons in $Z$ boson decays
- Four-lepton invariant mass window in the signal region: $115 < m_{4\ell} < 130$ GeV
- Four-lepton invariant mass window in the sideband region:
  - $105 < m_{4\ell} < 115$ GeV or $130 < m_{4\ell} < 160$ (350) GeV
ATLAS 4l STXS scheme

Production Mode

- ggF
  - $p_T < 200$ GeV
  - 0-jet
  - $p_T > 10$ GeV
  - gg2H-0j-$p_T^{4l}$-Low
  - gg2H-0j-$p_T^{4l}$-High
- gg2H-1j-$p_T^{4l}$-Low
- gg2H-1j-$p_T^{4l}$-Med
- gg2H-1j-$p_T^{4l}$-High
- gg2H-2j
- VBF
  - $60 < m_T < 120$ GeV
  - $m_T < 60$ GeV or $m_T > 350$ GeV
  - qq2Hqq-VF
  - qq2Hqq-VBF
  - qq2Hqq-BSM
- VH
  - Leptonic V decay
  - VHLep
- ttH
  - ttH

STXS Reduced Stage 1.1

Signal Region

- $N_{sv} = 0$
- $p_T^4 < 10$ GeV
- $0$-$p_T^{4l}$-Low
- $0$-$p_T^{4l}$-Medium
- $1$-$p_T^{4l}$-Low
- $1$-$p_T^{4l}$-Medium
- $1$-$p_T^{4l}$-High
- $2$-$p_T^{4l}$-BSM-like
- $2$-$p_T^{4l}$-Low
- $2$-$p_T^{4l}$-High
- $N_{sv} = 1$
- $p_T^4 > 200$ GeV
- $SB$ - 0j
- $SB$ - 1j
- $SB$ - 2j

Sideband Region

- $N_{sv} = 2$
- $m_T < 120$ GeV or $p_T^4 < 200$ GeV
- $m_T > 120$ GeV or $p_T^4 > 200$ GeV
- $N_{sv} = 3$
- $m_T = [105, 115] \text{ GeV}$
- $m_T = [115, 130] \text{ GeV}$
- $m_T = [130, 160] \text{ GeV}$
- $m_T = [160, 350] \text{ GeV}$
- $ttH$ Hadronic
- $ttH$ Leptonic
- $m_T = [105, 115] \text{ GeV}$
- $m_T = [130, 350] \text{ GeV}$

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Alternative ATLAS 4l STXS scheme

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Acceptance in the 4\(l\) channel (ATLAS)

- The acceptance correction relative to the SM prediction is described by a three-dimensional Lorentzian function with free acceptance parameters \(\tilde{\alpha}, \tilde{\beta}\) and \(\tilde{\delta}\):

\[
\frac{A(\vec{c})}{A_{SM}} = \alpha_0 + (\alpha_1)^2 \cdot \left[ \alpha_2 + \sum_i \delta_i \cdot (c_i + \beta_i)^2 + \sum_{i \neq j} \delta_{i,j} \cdot c_i c_j + \delta_{i,j,k} \cdot c_i c_j c_k \right]^{-1},
\]

where indices \(i, j\) and \(k\) run over \((HW, HB, HWB)\) in case of the acceptance correction for the set of CP-even parameters and over \((H\tilde{W}, H\tilde{B}, H\tilde{WB})\) in case of the CP-odd parameters.
STXS measurements in the $4l$ channel (CMS)

- Properties of the Higgs boson were measured in the $H \rightarrow ZZ^* \rightarrow 4l$ ($l = e, \mu$) decay channel.
- The STXS measurements were performed for ggF, VBF, VH and ttH Higgs boson production channels and for different phase space sub-categories.
- The cross section values were obtained assuming the Higgs mass $m_H = 125.1$ GeV (best fit mass value).
## CMS 4\(l\) event yields

<table>
<thead>
<tr>
<th>Event category</th>
<th>ggH</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>ttH</th>
<th>bbH</th>
<th>tqH</th>
<th>Total signal</th>
<th>Background gg \to ZZ</th>
<th>Total expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH-0j/pT[0,10]</td>
<td>25.3</td>
<td>0.08</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.14</td>
<td>0.00</td>
<td>25.6</td>
<td>26.5</td>
<td>54.2</td>
<td>61</td>
</tr>
<tr>
<td>ggH-0j/pT[10-200]</td>
<td>86.8</td>
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<td>0.54</td>
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<td>0.00</td>
<td>90.8</td>
<td>35.4</td>
<td>145</td>
<td>153</td>
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<tr>
<td>ggH-1j/pT[0-60]</td>
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<td>0.50</td>
<td>0.45</td>
<td>0.01</td>
<td>0.43</td>
<td>0.01</td>
<td>29.1</td>
<td>10.3</td>
<td>54.6</td>
<td>40</td>
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<tr>
<td>ggH-1j/pT[60-120]</td>
<td>12.4</td>
<td>1.24</td>
<td>0.45</td>
<td>0.47</td>
<td>0.01</td>
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<td>0.01</td>
<td>14.6</td>
<td>2.76</td>
<td>20.8</td>
<td>17</td>
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<tr>
<td>ggH-1j/pT[120-200]</td>
<td>3.31</td>
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<td>0.17</td>
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<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
<td>4.38</td>
<td>0.38</td>
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<td>6</td>
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<tr>
<td>ggH-2j/pT[0-60]</td>
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<td>0.02</td>
<td>4.42</td>
<td>0.97</td>
<td>7.60</td>
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<td>ggH-2j/pT[60-120]</td>
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<td>0.22</td>
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<td>0.02</td>
<td>6.30</td>
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<td>0.17</td>
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<td>0.01</td>
<td>0.02</td>
<td>3.71</td>
<td>0.26</td>
<td>4.37</td>
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<tr>
<td>ggH/pT&gt;200</td>
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<td>0.06</td>
<td>0.01</td>
<td>0.02</td>
<td>3.91</td>
<td>0.16</td>
<td>4.28</td>
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<tr>
<td>ggH/pT&gt;350</td>
<td>0.82</td>
<td>0.17</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
<td>0.01</td>
<td>0.01</td>
<td>1.16</td>
<td>0.16</td>
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<td>0.18</td>
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<td>0.12</td>
<td>0.01</td>
<td>17.6</td>
<td>2.37</td>
<td>21.5</td>
<td>20</td>
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<tr>
<td>VBF-2j/mjj[350,700]</td>
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<td>1.11</td>
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<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>1.95</td>
<td>0.08</td>
<td>2.09</td>
<td>2</td>
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<tr>
<td>VBF-2j/mjj&gt;700</td>
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<td>1.80</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.25</td>
<td>0.02</td>
<td>2.31</td>
<td>2</td>
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<tr>
<td>VBF-3j/mjj&gt;350</td>
<td>2.43</td>
<td>2.15</td>
<td>0.06</td>
<td>0.07</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
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<tr>
<td>VBF-2j/pT&gt;200</td>
<td>0.42</td>
<td>0.76</td>
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<td>0.01</td>
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<td>0.00</td>
<td>0.01</td>
<td>1.22</td>
<td>0.01</td>
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<td>VBF-rest</td>
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<td>0.87</td>
<td>0.11</td>
<td>0.10</td>
<td>0.03</td>
<td>0.04</td>
<td>0.01</td>
<td>3.56</td>
<td>0.34</td>
<td>4.70</td>
<td>2</td>
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<tr>
<td>VH-lep/pTV[0-150]</td>
<td>0.24</td>
<td>0.04</td>
<td>0.71</td>
<td>0.25</td>
<td>0.08</td>
<td>0.02</td>
<td>0.02</td>
<td>1.37</td>
<td>0.82</td>
<td>2.72</td>
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</tr>
<tr>
<td>VH-lep/pTV&gt;150</td>
<td>0.02</td>
<td>0.01</td>
<td>0.21</td>
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<td>0.04</td>
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<tr>
<td>VH-had/mjj[60-120]</td>
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<tr>
<td>VH-rest</td>
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<td>0.08</td>
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<td>ttH-had</td>
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<tr>
<td>ttH-lep</td>
<td>0.02</td>
<td>0.00</td>
<td>0.02</td>
<td>0.02</td>
<td>0.60</td>
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<td>0.03</td>
<td>0.70</td>
<td>0.03</td>
<td>0.85</td>
<td>0</td>
</tr>
</tbody>
</table>
Measurements in the $\tau\tau$ channel (ATLAS)

- A test of CP invariance in VBF Higgs boson production was performed in $\tau\tau$ channel with the Optimal Observable method.

- The Optimal Observable (OO) is defined as follows:

$$M = M_{SM} + \tilde{d} \cdot M_{CP-odd} \quad O_{opt} = \frac{2 \text{Re}(M^e_{SM} M_{CP-odd})}{|M_{SM}|^2}$$

$$2 \text{Re}(M^e_{SM} M_{CP-odd}) = \sum_{i,j,k,l} f_i(x_1)f_j(x_2)2 \text{Re}((M_{SM}^{ij\rightarrow kIH})^* M_{CP-odd}^{kj\rightarrow lIH})$$

$$|M_{SM}|^2 = \sum_{i,j,k,l} f_i(x_1)f_j(x_2)|M_{SM}^{ij\rightarrow kIH}|^2.$$
Measurements in the $\tau\tau$ channel (ATLAS)

- A test of CP invariance in VBF Higgs boson production was performed in $\tau\tau$ channel with the Optimal Observable method.
- The Optimal Observable (OO) is defined as follows:

\[
\mathcal{M} = \mathcal{M}_{SM} + \tilde{d} \cdot \mathcal{M}_{CP-odd} \\
\mathcal{O}_{opt} = \frac{2 \text{ Re}(\mathcal{M}_{SM}^* \mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2} \\
2 \text{ Re}(\mathcal{M}_{SM}^* \mathcal{M}_{CP-odd}) = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) 2 \text{ Re}((\mathcal{M}_{SM}^{ij \rightarrow kH})^* \mathcal{M}_{CP-odd}^{ij \rightarrow kH}) \\
|\mathcal{M}_{SM}|^2 = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) |\mathcal{M}_{SM}^{ij \rightarrow kH}|^2.
\]

N. Belyaev, 8th annual conference on Large Hadron Collider Physics
Measurements in the $\tau\tau$ channel (ATLAS)

- A test of CP invariance in VBF Higgs boson production was performed in $\tau\tau$ channel with the Optimal Observable method.
- The Optimal Observable (OO) is defined as follows:

$$M = M_{SM} + \tilde{d} \cdot M_{CP-odd}$$

$$O_{opt} = \frac{2 \text{Re}(M_{SM}^* M_{CP-odd})}{|M_{SM}|^2}$$

$$2 \text{Re}(M_{SM}^* M_{CP-odd}) = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) 2 \text{Re}((M_{SM}^{ij-kH})^* M_{CP-odd}^{ij-kH})$$

$$|M_{SM}|^2 = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) |M_{SM}^{ij-kH}|^2.$$
Measurements in the $\tau\tau$ channel (ATLAS)

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- The Optimal Observable (OO) is defined as follows:

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \bar{d} \cdot \mathcal{M}_{\text{CP-odd}}$$

$$O_{\text{opt}} = \frac{2 \text{Re}(\mathcal{M}_{\text{SM}}^\ast \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$

$$2 \text{Re}(\mathcal{M}_{\text{SM}}^\ast \mathcal{M}_{\text{CP-odd}}) = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) 2 \text{Re}(\mathcal{M}_{\text{SM}}^{ij \rightarrow kH} \ast \mathcal{M}_{\text{CP-odd}}^{ij \rightarrow kIH})$$

$$|\mathcal{M}_{\text{SM}}|^2 = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) |\mathcal{M}_{\text{SM}}^{ij \rightarrow kIH}|^2.$$
Measurements in the $\tau\tau$ channel (ATLAS)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\tau_{lep}\tau_{lep}$ SF</th>
<th>$\tau_{lep}\tau_{lep}$ DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>26</td>
<td>30</td>
</tr>
<tr>
<td>VBF $H \rightarrow \tau\tau/WW$ ($\mu = 0.73, \tilde{d} = -0.01$)</td>
<td>$3.3 \pm 2.1$</td>
<td>$5.1 \pm 3.1$</td>
</tr>
<tr>
<td>VBF $H \rightarrow \tau\tau/WW$ ($\mu = 1, \tilde{d} = 0$)</td>
<td>$4.5 \pm 2.9$</td>
<td>$6.9 \pm 4.4$</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>$6.6 \pm 3.7$</td>
<td>$8.2 \pm 3.8$</td>
</tr>
<tr>
<td>Fake lepton</td>
<td>$0.02 \pm 0.20$</td>
<td>$2.3 \pm 0.7$</td>
</tr>
<tr>
<td>$t\bar{t} + $ single top</td>
<td>$3.8 \pm 2.3$</td>
<td>$10.6 \pm 5.5$</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>$11 \pm 18$</td>
<td>$1.8 \pm 1.1$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$0.70 \pm 0.59$</td>
<td>$1.8 \pm 1.1$</td>
</tr>
<tr>
<td>ggF $H / VH / t\bar{t}H, H \rightarrow \tau\tau/WW$</td>
<td>$0.49 \pm 0.48$</td>
<td>$0.70 \pm 0.30$</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$23 \pm 17$</td>
<td>$23.6 \pm 6.1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>$\tau_{lep}\tau_{had}$</th>
<th>$\tau_{had}\tau_{had}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>30</td>
<td>37</td>
</tr>
<tr>
<td>VBF $H \rightarrow \tau\tau$ ($\mu = 0.73, \tilde{d} = -0.01$)</td>
<td>$11.8 \pm 7.4$</td>
<td>$8.9 \pm 5.6$</td>
</tr>
<tr>
<td>VBF $H \rightarrow \tau\tau$ ($\mu = 1, \tilde{d} = 0$)</td>
<td>$16 \pm 10$</td>
<td>$12.3 \pm 7.7$</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>$7.8 \pm 3.5$</td>
<td>$15.5 \pm 5.2$</td>
</tr>
<tr>
<td>Fake lepton/\tau</td>
<td>$6.2 \pm 1.0$</td>
<td>$5.4 \pm 2.7$</td>
</tr>
<tr>
<td>ggF $H / VH / t\bar{t}H, H \rightarrow \tau\tau$</td>
<td>$2.1 \pm 1.5$</td>
<td>$2.8 \pm 1.4$</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>$2.8 \pm 3.1$</td>
<td>$2.3 \pm 0.8$</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$19.0 \pm 5.5$</td>
<td>$26.0 \pm 6.6$</td>
</tr>
</tbody>
</table>

- No sign of CP violation is observed in the distributions of the Optimal Observable.
Measurements in the $\tau\tau$ channel (ATLAS)

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

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\tau_{lep}\tau_{lep}$ SF</th>
<th>$\tau_{lep}\tau_{lep}$ DF</th>
<th>$\tau_{lep}\tau_{had}$</th>
<th>$\tau_{had}\tau_{had}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>Two isolated $\tau$-lepton decay candidates with opposite electric charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$p_T^{\tau_1} &gt; 19^{+15}_{-15}$ GeV ($\mu/e$)</td>
<td>$p_T^{\tau_2} &gt; 18$ GeV</td>
<td>$p_T^{\tau_{had}} &gt; 30$ GeV</td>
<td>$p_T^{\tau_{had}} &gt; 40$ GeV</td>
</tr>
<tr>
<td></td>
<td>$p_T^{\tau_2} &gt; 10^{+15}_{-15}$ GeV ($\mu/e$)</td>
<td>$p_T^{\tau_1} &gt; 14$ GeV</td>
<td>$p_T^{\tau_{had}} &gt; 21$ GeV</td>
<td>$p_T^{\tau_{had}} &gt; 30$ GeV</td>
</tr>
<tr>
<td></td>
<td>$m_{\tau\tau} &gt; m_Z - 25$ GeV</td>
<td></td>
<td>$m_T &lt; 70$ GeV</td>
<td>$0.8 &lt; \Delta R_{\tau\tau} &lt; 2.5$</td>
</tr>
<tr>
<td></td>
<td>$30 &lt; m_{\ell\ell} &lt; 75$ GeV</td>
<td>$30 &lt; m_{\ell\ell} &lt; 100$ GeV</td>
<td>$</td>
<td>\Delta \eta_{\tau\tau}</td>
</tr>
<tr>
<td></td>
<td>$E_{Tmiss} &gt; 55$ GeV</td>
<td>$E_{Tmiss} &gt; 20$ GeV</td>
<td>$E_{Tmiss} &gt; 20$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$E_{Tmiss, hard} &gt; 55$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$N_{b,jets} = 0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF topology</td>
<td>$N_{jets} \geq 2$, $p_T^{\ell_1} &gt; 30$ GeV, $m_{jj} &gt; 300$ GeV, $</td>
<td>\Delta \eta_{jj}</td>
<td>&gt; 3$</td>
<td>$p_T^{\ell_1} &gt; 40$ GeV</td>
</tr>
<tr>
<td>BDT input variables</td>
<td>$m_{T\tau\tau}$, $m_{T\tau\tau}^{MHC}$, $m_{jj}$, $\Delta R_{\tau\tau}$, $C_{jj}(\tau_1)$, $C_{jj}(\tau_2)$, $p_T^{\ell_1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$m_{\tau\tau}^{vis}$, $m_{\tau\tau}^{vis}$, $p_T^{\ell_1}$, $E_{Tmiss}^{\tau_1}$, $E_{Tmiss}^{\tau_2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Delta \phi_{\tau\tau}$, $E_{Tmiss}/p_T^{\tau_1}$, $E_{Tmiss}/p_T^{\tau_2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal region</td>
<td>BDT$_{score} &gt; 0.78$</td>
<td>BDT$_{score} &gt; 0.86$</td>
<td>BDT$_{score} &gt; 0.87$</td>
<td></td>
</tr>
</tbody>
</table>
Measurements in the $4l$ channel (CMS)

- Properties of the Higgs boson were measured in the $H \rightarrow ZZ^* \rightarrow 4l \ (l = e, \mu)$ decay channel.
- The STXS measurements were performed for different Higgs boson production channels.

<table>
<thead>
<tr>
<th>Requirements for the $H \rightarrow 4\ell$ fiducial phase space</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lepton kinematics and isolation</strong></td>
</tr>
<tr>
<td>Leading lepton $p_T$</td>
</tr>
<tr>
<td>Next-to-leading lepton $p_T$</td>
</tr>
<tr>
<td>Additional electrons (muons) $p_T$</td>
</tr>
<tr>
<td>Pseudorapidity of electrons (muons)</td>
</tr>
<tr>
<td>Sum of scalar $p_T$ of all stable particles within $\Delta R &lt; 0.3$ from lepton</td>
</tr>
<tr>
<td><strong>Event topology</strong></td>
</tr>
<tr>
<td>Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above</td>
</tr>
<tr>
<td>Inv. mass of the $Z_1$ candidate</td>
</tr>
<tr>
<td>Inv. mass of the $Z_2$ candidate</td>
</tr>
<tr>
<td>Distance between selected four leptons</td>
</tr>
<tr>
<td>Inv. mass of any opposite sign lepton pair</td>
</tr>
<tr>
<td>Inv. mass of the selected four leptons</td>
</tr>
</tbody>
</table>

<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>$333^{+57}_{-55}$</td>
<td>$622^{+31}_{-44}$</td>
<td>$815 \pm 73$</td>
<td>$1770^{+98}_{-101}$</td>
</tr>
<tr>
<td>$gg \rightarrow ZZ$</td>
<td>$75.1^{+14.3}_{-13.5}$</td>
<td>$116.6^{+12.8}_{-11.7}$</td>
<td>$176.9 \pm 23.0$</td>
<td>$368.5^{+29.5}_{-29.6}$</td>
</tr>
<tr>
<td>$Z + X$</td>
<td>$19.3 \pm 7.2$</td>
<td>$50.8 \pm 15.2$</td>
<td>$64.6 \pm 15.6$</td>
<td>$134.7 \pm 22.9$</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$428^{+59.2}_{-55.2}$</td>
<td>$790^{+36.4}_{-48.3}$</td>
<td>$1057 \pm 78.1$</td>
<td>$2274^{+104.9}_{-107.7}$</td>
</tr>
<tr>
<td>Signal ($m_H = 125$ GeV)</td>
<td>$19.6^{+3.3}_{-3.1}$</td>
<td>$40.8^{+2.5}_{-2.9}$</td>
<td>$50.7 \pm 5.6$</td>
<td>$111.1^{+6.9}_{-7.0}$</td>
</tr>
<tr>
<td>Total expected</td>
<td>$447^{+99.3}_{-55.2}$</td>
<td>$830^{+36.5}_{-48.4}$</td>
<td>$1108 \pm 78.3$</td>
<td>$2385^{+105.1}_{-107.9}$</td>
</tr>
<tr>
<td>Observed</td>
<td>$462$</td>
<td>$850$</td>
<td>$1130$</td>
<td>$2442$</td>
</tr>
</tbody>
</table>

\[
N_{\text{obs}}^{m_4\ell} = N_{\text{fid}}^{m_4\ell} + N_{\text{nonfid}}^{m_4\ell} + N_{\text{nonres}}^{m_4\ell} + N_{\text{bkg}}^{m_4\ell}
\]

\[
= e_{ij} \cdot (1 + f_{\text{nonfid}}^{ij}) \cdot \sigma_{\text{fid}}^{ij} \cdot \mathcal{L} \cdot P_{\text{res}}(m_4\ell)
+ N_{\text{nonres}}^{ij} \cdot P_{\text{nonres}}(m_4\ell) + N_{\text{bkg}}^{ij} \cdot P_{\text{bkg}}(m_4\ell)
\]
Measurements in the $\tau\tau$ and $4\ell$ channels (CMS)

N. Belyaev, 8th annual conference on Large Hadron Collider Physics

HIG-17-034