Effective Field Theory interpretations of Standard Model and Higgs measurements the ATLAS experiment

Bryan Kortman on behalf of the ATLAS collaboration

Higgs 2022 Conference, 7-11 November
Introduction

- **Observation** of the Higgs boson production in **Run 1**
- The experimental profile of the Higgs boson is becoming less blurry
  - Excellent **precision measurements** performed in **Run 2**
- **Run 3** ongoing! → exciting times and results ahead

- Combine results of seemingly very different analyses and slight deviations from the SM in a near-model independent way

- (selection) recent (combined) EFT interpretations of
  - Higgs boson pair searches in $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ (**ATL-PHYS-PUB-2022-019**)
  - Combination of EW $Z(\nu\bar{\nu})\gamma jj$ production, limits on anomalous quartic gauge couplings (**arXiv:2208.12741**)
  - Flavour-changing neutral current (FCNC) $tqH(q = u, c), H \rightarrow \tau^+\tau^-$ (**arXiv:2208.11415**)

- **Featured** in this talk
  - EFT interpretation of HWW and SMWW measurement (**ATL-PHYS-PUB-202-010**)
  - EFT interpretation of combined single Higgs measurement (**ATLAS-CONF-2021-053**)
  - differential cross-sections of WW, WZ, 4l, and Z+2j production (**ATL-PHYS-PUB-2021-022**)
  - EFT interpretation of Higgs, EW and LEP data (**ATL-PHYS-PUB-2022-037**)

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**Table:**

<table>
<thead>
<tr>
<th>ATLAS Preliminary</th>
<th>Higgs (\rightarrow WW^* \rightarrow e\mu\nu) p-value = 52%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>Statistical Unc.</td>
</tr>
<tr>
<td></td>
<td>(Stat. Syst.)</td>
</tr>
<tr>
<td>1.20</td>
<td>-0.16 (0.09)</td>
</tr>
<tr>
<td>0.85</td>
<td>-0.08 (0.02)</td>
</tr>
<tr>
<td>0.73</td>
<td>-0.05 (0.12)</td>
</tr>
<tr>
<td>1.64</td>
<td>-0.17 (0.16)</td>
</tr>
<tr>
<td>1.52</td>
<td>-0.22 (0.47)</td>
</tr>
<tr>
<td>2.17</td>
<td>-0.74 (0.25)</td>
</tr>
<tr>
<td>-0.22</td>
<td>0.13 (0.26)</td>
</tr>
<tr>
<td>0.50</td>
<td>-0.50 (0.26)</td>
</tr>
<tr>
<td>1.07</td>
<td>0.47 (0.23)</td>
</tr>
<tr>
<td>0.96</td>
<td>-0.54 (0.34)</td>
</tr>
<tr>
<td>1.13</td>
<td>-0.67 (0.54)</td>
</tr>
</tbody>
</table>

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Precision is key

- Precision measurements may hold the key for observing physics beyond the SM

- When interpreting them the SM may written down as a low-energy approximation or EFT to an UV complete theory

\[ \mathcal{L}_{SMEFT} = \mathcal{L}_4^S + \sum_i \frac{c_i^{(5)}}{\Lambda} \Phi_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \Phi_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3} \Phi_i^{(7)} + \Phi(8) + \ldots = \mathcal{L}_{BSM} \]

- Deviations from the SM interpreted through:
  
  - Higher dimension orthogonal operators \( \Phi_i^{(d)} \), suppressed by \( \Lambda^{(d-4)} \)
  
  - Scaled by Wilson coefficients \( c_i^{(d)} \)

- All new operators respect symmetries of the SM

- BSM scenarios show up as a combination of operators

\( \Lambda \sim O(TeV) \)

new physics scale

BSM (EFT) - valid
\( E < \Lambda \)

BSM (UV complete)
\( E > E_{LHC} \)
SMEFT interpretations of ATLAS measurements

- A popular EFT model for interpretations is the SMEFT.
- Multiple orthogonal basis available for interpretation e.g. the SILH or the Warsaw basis.
- EFT operators affect:
  - Input parameters: \( \Delta G_F, c_{Hd}, \Delta m^2_{H}, c_{HWB} \)
  - CP-Even/Odd Interactions

\[ Q_{H}^{(1)} = (iH^{*}D_{u}^{H}) (i\mu_{l}) \]
\[ Q_{He} = (iH^{*}D_{e}^{H}) (i\mu_{e}) \]
\[ Q_{Hq}^{(1)} = (iH^{*}D_{t}^{H}) (i\mu_{q}) \]
\[ Q_{Hq}^{(3)} = (iH^{*}D_{t}^{H}) (i\mu_{q}) \]
\[ Q_{Hu} = (iH^{*}D_{u}^{H}) (i\mu_{u}) \]
\[ Q_{Hd} = (iH^{*}D_{d}^{H}) (i\mu_{d}) \]

- Necessary to retain all relevant operators in interpretations.
- No single measurement can constrain all operators simultaneously.
  - A Global fit is required.

\[ Z, W \text{ couplings} \]
\[ Bhabha scattering \]

\[ Q_{Hbox} = (H^{*} H) \]
\[ Q_{HG} = (H^{*} H) G_{\mu \nu}^{a} G_{\mu \nu}^{a} \]
\[ Q_{HB} = (H^{*} H) B_{\mu \nu} B_{\mu \nu} \]
\[ Q_{Hw} = (H^{*} H) W_{\mu \nu}^{\alpha} W_{\mu \nu}^{\alpha} \]
\[ Q_{uH} = (H^{*} H) (\bar{q} H) \]
\[ Q_{dH} = (H^{*} H) (\bar{q} H) \]
\[ Q_{He} = (H^{*} H) (\bar{q} H) \]
\[ Q_{G} = \varepsilon_{abmu} G_{\mu}^{a} G_{\mu}^{b} G_{\mu}^{c} \]
\[ Q_{ug} = (\bar{q} H) T_{a} H_{\mu \nu} G_{\mu \nu}^{a} \]

\[ Q_{W} = \varepsilon_{ijk} W_{\mu \nu}^{ij} W_{\nu \rho}^{jk} \]

illegal Brivio

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SMEFT interpretation of SM WW + $H \rightarrow WW$ *

- First ATLAS Run 2 combination of Higgs and EW measurements (using $36.1\, fb^{-1}$)
- Developed methodology for EW+Higgs combinations
- Orthogonality ensured via opposite $m_{e\mu}$ selection at 55 GeV, any overlap in data removed during combination
- Ensured consistent statistical treatment of EFT effects in signal and background (WW)

\[ H \rightarrow WW \text{ measurement} \]

\[ pp \rightarrow WW \text{ measurement} \]
PCA of SM $WW + H \rightarrow WW^*$ combination

- Extracting eigenvectors (EV's) from **principal component analysis** (PCA), using Fischer info. Matrix

- **Linear** comb. of Wilson coefficients, along sensitive directions of parameter space
  - Grouping operators in terms of **impact** and physics motivation
  - Eliminating flat directions in the fit
  - **Fitted simultaneously** and can be translated back into Wilson coefficients

- $\Sigma_{\Sigma S M E F T} = P^T_{\mu \rightarrow c_i} V^{-1}_{\text{meas}} P_{\mu \rightarrow c_i}$

  - $V^{-1}_{\text{SMEFT}}$: measurement info. Matrix (Gaussian approx.)
  - $P_{\mu \rightarrow c_i}$: SMEFT parameterisation Matrix
SMEFT interpretation of SM WW + $H \rightarrow WW^*$

- Perform fits for all 20 $c_i^{(6)}$ coefficients **one-at-a-time** with others fixed to SM ($c_i^{(6)}=0$)
- Compare 3 different combinations ($HWW$, $SMWW$, $HWW+SMWW$)
- **Flat** directions (EV’s) set **constant** in the fit
- **Simultaneous** fit with 8 sensitive EV directions, 1 being a direct Wilson coefficient ($c_W$)
SMEFT interpretations of combined single Higgs measurements

Higgs STXS measurements

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Production modes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>ggF, VBF, VH, ttH+tH</td>
<td>[1]</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>ggF, VBF, VH, ttH+tH</td>
<td>[2]</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow \ell\ell\nu\nu$</td>
<td>ggF, VBF</td>
<td>[3]</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>VBF, VH, ttH+tH</td>
<td>[4, 5, 6, 7]</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>ggF, VBF, VH, ttH+tH</td>
<td>[8]</td>
</tr>
</tbody>
</table>

Most important changes w.r.t previous combination

- Adding more measurements improves sensitivity
- Allows for de-correlating of Wilson coefficients
**SMEFT interpretations of combined single Higgs measurements**

### Decay Channel vs. Production modes vs. Reference

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Production modes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$g\gamma F$, VBF, VH, thH+tH</td>
<td>[1]</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>$g\gamma F$, VBF, VH, thH+tH</td>
<td>[2]</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow ll\nu\nu$</td>
<td>$g\gamma F$, VBF</td>
<td>[3]</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>VBF, VH, thH+tH</td>
<td>[4],[5],[6],[7]</td>
</tr>
<tr>
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<td>$g\gamma F$, VBF, VH, thH+tH</td>
<td>[8]</td>
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### Wilson Coefficients

<table>
<thead>
<tr>
<th>Wilson coefficient</th>
<th>Operator</th>
<th>Wilson coefficient</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{HH}$</td>
<td>$(H^H)(H^H)$</td>
<td>$c_{GG}$</td>
<td>$(g_{\rho}\gamma\rho T^a_{\mu\nu} u^\mu v^\nu)$, $H G^a_{\mu\nu}$</td>
</tr>
<tr>
<td>$c_{DD}$</td>
<td>$(H^D)(H^D)$, $(H^F)(H^F)$</td>
<td>$c_{GW}$</td>
<td>$(g_{\rho}\gamma\rho T^a_{\mu\nu} u^\mu)$, $H W^a_{\mu\nu}$</td>
</tr>
<tr>
<td>$c_{HG}$</td>
<td>$H^H G^a_{\mu\nu}$, $G^a_{\mu\nu}$</td>
<td>$c_{GB}$</td>
<td>$(g_{\rho}\gamma\rho T^a_{\mu\nu} u^\mu)$, $H B^a_{\mu\nu}$</td>
</tr>
<tr>
<td>$c_{HB}$</td>
<td>$H^H B^a_{\mu\nu}$, $B^a_{\mu\nu}$</td>
<td>$c_{GW}$</td>
<td>$(g_{\rho}\gamma\rho T^a_{\mu\nu} u^\mu) Q^a_{q\gamma}$, $(g_{\rho}\gamma\rho T^a_{\mu\nu} u^\mu) Q^a_{l\gamma}$</td>
</tr>
<tr>
<td>$c_{HW}$</td>
<td>$H^H W^a_{\mu\nu}$, $W^a_{\mu\nu}$</td>
<td>$c_{GW}$</td>
<td>$(g_{\rho}\gamma\rho T^a_{\mu\nu} u^\mu) Q^a_{q\gamma}$, $(g_{\rho}\gamma\rho T^a_{\mu\nu} u^\mu) Q^a_{l\gamma}$</td>
</tr>
<tr>
<td>$c_{HW}$</td>
<td>$H^H W^a_{\mu\nu}$, $W^a_{\mu\nu}$</td>
<td>$c_{GW}$</td>
<td>$(g_{\rho}\gamma\rho T^a_{\mu\nu} u^\mu) Q^a_{q\gamma}$, $(g_{\rho}\gamma\rho T^a_{\mu\nu} u^\mu) Q^a_{l\gamma}$</td>
</tr>
</tbody>
</table>

- Assuming $U(3)^3 = U(3)_q \times U(3)_d \times U(3)_l \times U(3)_e$

### Diagram: Higgs STXS measurements

- **Weak+Higgs boson interactions**
- **Boson ($\gamma/V/H$) Couplings to fermions**
- **4-fermion interactions**
SMEFT interpretations of combined single Higgs measurements

- Sensitivity to 3 Wilson coefficients directly \((c^{(3)}_{Hq}, c_{dH}, c_{eH})\) and 10 linear combinations of other coefficients
  - \(c_{eH}, c_{dH}, c_{top}^{[1]}\) now \textit{disentangled} from other parameters due to new inputs from \(H \rightarrow \tau\tau, VBF H \rightarrow bb\) and \(ttH H \rightarrow bb\)
  - Limits improve by up to 70% compared to the previous combination.
  - **Correlations** in general significantly reduced.
EFT interpretation of differential cross-sections of WW, WZ, 4l, and Z+2j production

- **EW differential distributions**

<table>
<thead>
<tr>
<th>Process</th>
<th>Phase space req</th>
<th>Observable</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow e^{\pm} \nu e^{\mp} \nu$</td>
<td>$m_{ll} &gt; 55 \text{ GeV}, p_T^{\text{jet}} &lt; 35 \text{ GeV}$</td>
<td>$p_T^{\text{lead,lep}}$</td>
<td>[1]</td>
</tr>
<tr>
<td>$pp \rightarrow l^{\pm} \nu l^{\mp} l^{\pm}$</td>
<td>$m_{ll} \in (81,101) \text{ GeV}$</td>
<td>$m_{T}^{WZ}$</td>
<td>[2]</td>
</tr>
<tr>
<td>$pp \rightarrow l^{+} l^{-} l^{+} l^{-}$</td>
<td>$m_{ll} &gt; 180 \text{ GeV}$</td>
<td>$m_{Z2}$</td>
<td>[3]</td>
</tr>
<tr>
<td>$pp \rightarrow l^{+} l^{-} j j$</td>
<td>$m_{ll} &gt; 1000 \text{ GeV}, m_{ll} \in (81,101) \text{ GeV}$</td>
<td>$\Delta \phi_{jj}$</td>
<td>[4]</td>
</tr>
</tbody>
</table>

- Combination performed of 4 unfolded differential cross section measurements

- Fit performed after PCA assuming *top U*(3)l flavour symmetry
  - 33 operators included in 15 sensitive directions, 2 direct operators
  - Basis ready for including top measurements

- **CP-even** operators (sensitive to CP-odd only in $\Delta \phi_{jj}$)
  - Including all $1/\Lambda^2$ terms, some $1/\Lambda^4$ terms
SMEFT interpretation of Higgs, EW + electroweak precision observables

**ATL-PHYS-PUB-2022-037**

- **LEP/SLD EWPO**
  - $\Gamma_Z, \left( R_1^0, R_2^0 \right), A_{FB}^{0,1}, A_{FB}^{0,c}, A_{FB}^{0,b}, \sigma_{had}^0$

- **Measurement**
  - **Type**
  - **Ref.**
  - ATLAS Higgs boson Simplified Template Cross section (STXS) [1]
  - ATLAS electroweak Differential cross section [2]
  - Electroweak precision Electroweak precision variables (EWPO) [3]

- Included results from **LEP**
  - Observables describing **physics at the Z-pole**

- First **global** EFT interpretation in ATLAS
  - *top U(3)_l* flavour symmetry

- **Tight limits** provided by LEP
  - Only sensitive to a **limited** number of parameters

- **Higgs STXS measurements**

- **EW differential distributions**
  - WW ($p_T^{l_1}$), WZ($m_{WZ}$), 4l ($m_{ZZ}$) and VBF Z ($\Delta \phi_{jj}$)
SMEFT interpretation of Higgs, EW and decay + electroweak precision observables

- **Higgs STXS measurements**
- **EW differential distributions**
  \[ WW (p_T^{W1}), WZ(m_{WZ}), 4l (m_{Z2}) \] and VBF Z (\(\Delta \phi_{jj}\))
- **LEP/SLD EWPO**
  \[ \Gamma_Z, R_l^0, R_b^0, A_{FB}^{0,l}, A_{FB}^{0,c}, A_{FB}^{0,b}, \sigma_{had}^0 \]

- Constraining 22 linear combinations and 6 individual Wilson coeff.
- Several constraints driven by either EW, Higgs, or LEP
  - Example: \(c_2^{[1]}\), \(c_tG\), \(c_{HVV, Vff}^{[1]}\)
- Clearly shows the complementarity of each measurement
- **Simplified likelihood model** available for re-interpreations!
Summary

- Many Higgs and EW measurements being interpreted in terms of Effective Field Theories.

- The Combined interpretation of Higgs STXS and EW measurements has made big steps in the last few years.
  - SMWW+HWW, 7 EV’s and 1 Wilson coeff. measured
  - EW combination, 13 EV’s and 2 Wilson coeff. measured
  - Higgs STXS, 13 EV’s and 3 Wilson coeff. measured
  - Higgs+EW+LEP, 22 EV’s and 6 Wilson coeff. measured

- First global ATLAS EFT interpretation available, also providing a simplified likelihood model for re-interpretation

- Next up: including Top analyses in the global fit, treatment of truncation, Higher-order uncertainties, etc.
Combined EFT interpretations of SM and Higgs measurements at the ATLAS experiment
Backup
SMEFT interpretation of SM $WW + H \rightarrow WW^*$

- Observed one-at-a-time fit parameter limits
- Split for $HWW$, $SMWW$, $HWW+SMWW$

![SMEFT parameter sensitivity gain by combination](image)
SMEFT interpretation of Higgs, EW + electroweak precision observables

- Acceptance parametrisation applied for $H \rightarrow 4l$ decay rate.
SMEFT interpretation of Higgs, EW and decay + electroweak precision observables

- Fitted EigenVectors after PCA
Combined EFT interpretations of SM and Higgs measurements at the ATLAS experiment

- Correlation matrix of the fitted Eigenvectors

\( \sqrt{s} = 13 \text{ TeV}, 36.1-139 \text{ fb}^{-1} \)
\( m_h = 125.09 \text{ GeV}, |y_h| < 2.5 \)
SMEFT interpretation of Higgs, EW and decay + electroweak precision observables

- Constraints on Wilson coefficients from the combined ATLAS-only analysis
SMEFT interpretation of Higgs, EW and decay + electroweak precision observables

- Constraints on Wilson coefficients from Full likelihood model compared to the simplified likelihood model
- Using a Gaussian approximation of the likelihood
- Using $n_\mu = 128$ in a Multivariate Gaussian

$$\Delta \mu = \mu - \hat{\mu}$$

$$L(\mu) = \frac{1}{\sqrt{(2\pi)^{n_\mu} \det(V_\mu)}} \exp\left(-\frac{1}{2} \Delta \mu^\top V_\mu^{-1} \Delta \mu\right)$$

\[\mu = 128\]
EFT interpretation of differential cross-sections of WW, WZ, 4l, and Z+2j production

- Fitted EigenVectors after PCA
EFT interpretation of differential cross-sections of WW, WZ, 4l, and Z+2j production

- Impact plot of $c_W$, $c_H^{(3)}$, $c_{Vff}^{[0]}$, $c_{Vff}^{[1]}$, $c_{Vff}^{[2]}$, $c_{Vff}^{[3]}$, $c_{2q2l}$, $c_{4q}$

### ATLAS Preliminary

* $\sqrt{s} = 13$ TeV, 36-139 fb$^{-1}$

<table>
<thead>
<tr>
<th>Relative Effect of Wilson Coefficient, for $\Lambda = 1$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_W=0.29$</td>
</tr>
<tr>
<td>$c_{Hq}=0.11$</td>
</tr>
<tr>
<td>$c_{Vff}^{[0]}=0.17$</td>
</tr>
<tr>
<td>$c_{Vff}^{[1]}=0.3$</td>
</tr>
<tr>
<td>$c_{Vff}^{[2]}=0.8$</td>
</tr>
<tr>
<td>$c_{Vff}^{[3]}=0.061$</td>
</tr>
<tr>
<td>$c_{2q2l}=0.12$</td>
</tr>
</tbody>
</table>

**Figure Description:**
- The plot shows the relative effect of Wilson coefficients on various event kinematic variables.
- The impact of each coefficient is color-coded and plotted against different kinematic variables such as $p_T$, $m_{WW}$, $m_{ZZ}$, and $\Delta \phi$.
- The plot includes lines for the linear effect of Wilson coefficients and the linear plus quadratic effect, along with experimental uncertainty bands.