Higgs/Top/EWK and Global EFT results at ATLAS

Eleonora Rossi

LHCP2023
22/05/2023
**Latest results**

- **$t\bar{t}$ charge (rapidity) asymmetry:**
  

- 4 top observation
  

- **WW VBS**
  

- **4l VBS measurements**
  

- ** electroweak $Z(\nu\nu)\gamma jj$**
  

- **$Z\gamma$ production**
  

- **4 top observation**
  

**First ATLAS Global combination (Higgs+EW+EWPO):**


  - (SMEFTsim + SMEFT@NLO)
• Measurement of the **fiducial cross section** for EWK $Z(\nu\overline{\nu})\gamma j j$ in the region of $E_T^* > 150$ GeV - first evidence!!!

• BSM physics could induce anomalous QGCs, enhancing the **cross section** and modifying the **kinematic distributions** of the final-state bosons.

• The effect of new physics introduced by aQGCs can be realised using an EFT linearly parameterised by an effective Lagrangian.

• A clipping technique is introduced to preserve unitarity at very high parton centre-of-mass energies: the anomalous signal contribution is set to zero for $m_{Z_f} > E_c$.

**Constraints on EFT coefficients** are either competitive with or more stringent than those previously published by CMS.

The constraints on $f_{T5}/\Lambda^4, f_{T8}/\Lambda^4$ and $f_{T9}/\Lambda^4$ are significantly stronger than results previously published by ATLAS and CMS.
- Production of a $Z$ boson in association with two photons in a phase-space region dominated by the ISR production of photons.

- **Integrated and differential cross-sections** measured (first time - differential).

- Sensitive to transverse operators involving neutral aQGCs.

- $p_T^{\ell\ell}$ **unfolded cross-section** used to set limits on dim8 WCs in EFT framework as it is the most sensitive to NP effects.

- The constraints on four of the eight operators considered are tightened by up to two orders of magnitude with respect to previous ATLAS analyses using 8 TeV data.
• Fiducial and differential cross sections for the electroweak and inclusive production of a same-sign W boson pair in association with two jets ($W\pm W\pm j j$) - (analysis details in Alessandro’s talk).

• Differential $m_\ell$ distribution with optimised binning used to set limits on EFT dim8 operator coefficients $f_{S02}/\Lambda^4, f_{S1}/\Lambda^4, f_{M0}/\Lambda^4, f_{M1}/\Lambda^4, f_{M7}/\Lambda^4, f_{T0}/\Lambda^4, f_{T1}/\Lambda^4$, and $f_{T2}/\Lambda^4$.

• Results using EFT unitarisation cut-off also provided.

• Constraints competitive with those previously published by CMS.

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• Differential cross-sections \((m_{4\ell} \text{ and } m_{jj})\) measured for the production of four charged leptons in association with two jets (analysis details in Chilufya's talk).

• Unfolded cross sections used to search for signatures of anomalous weak-boson self-interactions using the framework of dim8 EFT.

\[
\mathcal{O}_{T0}, \mathcal{O}_{T1}, \mathcal{O}_{T2}, \mathcal{O}_{T5}, \mathcal{O}_{T6}, \mathcal{O}_{T7}, \mathcal{O}_{T8}, \mathcal{O}_{T9}
\]

• The WCs associated with the \(\mathcal{O}_{T0}\) and \(\mathcal{O}_{T1}\) operators are the most tightly constrained.

• Constraints with the pure dim8 contribution are more stringent than interference-only constraints.

• Constraints are placed on each WC after restricting the interference- and pure dimension-eight contributions to have \(m_{4\ell} < E_c\)

• The 95% confidence intervals degrade by a factor of 4-5 (\(E_c = \infty\) to \(E_c = 1\) TeV).
Evidence for the charge asymmetry in $pp \rightarrow t\bar{t}$

**arXiv:2208.12095**

- Inclusive and differential measurement of $t\bar{t}$ and leptonic charge asymmetry $A_{c}^{t\bar{t}}$ & $A_{c}^{\ell\bar{\ell}}$ with full Run2 dataset.

- Differential measurements provided for invariant mass, transverse momentum and longitudinal boost of the $t\bar{t}$ system.

- $A_{c}^{t\bar{t}}$ results are interpreted in the SMEFT framework (SMEFT@NLO).

- 14 four-fermion operators + 1 operator for top–gluon interaction.

- Large improvement w.r.t LHC 8 TeV/Tevatron results.

- Interplay between EFT sensitivity (increases for higher $m_{t\bar{t}}$) and statistical uncertainty (0.2% – 0.3% to 2.9%).

- Tightest limit obtained for the linear EFT approximation in the mass bin from 1 to 1.5 TeV.

- Constraint from the differential $A_{c}^{t\bar{t}}$ measurement more than a factor 2 stronger than inclusive measurement.

The combined inclusive charge asymmetry is measured to be $A_{c}^{t\bar{t}} = 0.0068 \pm 0.0015$, which differs from zero by **4.7 standard deviations**.
Evidence for the charge asymmetry in $pp \rightarrow t\bar{t}$

- The obtained EFT bounds (from charge asymmetry) are compared to those from energy asymmetry measurement in $t\bar{t}j$ production.

- QCD structure of the energy asymmetry is different due to the extra jet in $t\bar{t}j$ production.
  - The two asymmetries probe different directions in chiral and colour space.

- Different shapes of the bounds for colour-octet operators with the same chirality scenarios:
  - charge asymmetry (dashed/solid red lines) leaves a blind direction broken by the energy asymmetry (dashed/solid blue lines) due to operator interference with the QCD amplitude.

**ATLAS**

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

- Energy Asymmetry
  - $A_E$ 68% CL
  - $A_E$ 95% CL

- Charge Asymmetry
  - $A_C$ 68% CL
  - $A_C$ 95% CL

Bounds on color-octet operators

- $C_{Oq}^B$ (TeV/Λ)$^2$
- $C_{Oq}^B$ (TeV/Λ)$^2$
4 top observation

- The $t\bar{t}t\bar{t}$ process (observed with a significance of $6.1 \sigma$) is sensitive to 4 heavy-flavour fermion operators, $O_{tt}^1, O_{QQ}^1, O_{Qt}^1, O_{Qt}^8$ -> BSM models that enhance interactions between the third-generation quarks (Johnny’s talk).

- Limits on EFT parameters extracted parameterising the $t\bar{t}t\bar{t}$ yield in each bin of the multivariate discriminant score distribution (used to separate signal and background).

<table>
<thead>
<tr>
<th>Operators</th>
<th>Expected $C_i/\Lambda^2$ [TeV$^{-2}$]</th>
<th>Observed $C_i/\Lambda^2$ [TeV$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{QQ}^1$</td>
<td>[-2.4, 3.0]</td>
<td>[-3.5, 4.1]</td>
</tr>
<tr>
<td>$O_{Qt}^1$</td>
<td>[-2.5, 2.0]</td>
<td>[-3.5, 3.0]</td>
</tr>
<tr>
<td>$O_{tt}^1$</td>
<td>[-1.1, 1.3]</td>
<td>[-1.7, 1.9]</td>
</tr>
<tr>
<td>$O_{Qt}^8$</td>
<td>[-4.2, 4.8]</td>
<td>[-6.2, 6.9]</td>
</tr>
</tbody>
</table>

- Limits on the Higgs oblique parameter, $\hat{H}$, defined as the Wilson coefficient of the sole dim6 operator that affects the off-shell Higgs interaction ($t\bar{t}t\bar{t}$ cross section + $t\bar{t}H$ background production), are set.

- Observed upper limit at 95% CL on $\hat{H}$=0.20:
  - coincides with the largest value that still preserves unitarity.

arXiv:2303.15061
Accepted for journal publication
**HH → b¯b b¯b SMEFT**

- Non-resonant HH ggF production - 4b decay channel (126 fb⁻¹).
- Analysis categorisations to improve sensitivity to BSM physics.

- The interpretations are performed with two EFT frameworks, Higgs Effective Field Theory (HEFT) and SM Effective Field Theory (SMEFT) - first LHC SMEFT interpretation for HH.
- The different BSM scenarios are considered re-weighting the SM non-resonant HH ggF sample.

- 1D and 2D limits for the 5 Wilson coefficients: $c_H, c_{H\Box}, c_{tH}, c_{tG}, c_{tHG}$. SMEFT@NLO

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected Constraint</th>
<th>Observed Constraint</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>$c_H$</td>
<td>-20</td>
<td>11</td>
</tr>
<tr>
<td>$c_{HG}$</td>
<td>-0.056</td>
<td>0.049</td>
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<tr>
<td>$c_{H\Box}$</td>
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<td>$c_{tG}$</td>
<td>-0.97</td>
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ATLAS
\[ \sqrt{s} = 13 \text{ TeV}, 126 \text{ fb}^{-1} \]
\[ c_H = 0.0, c_{HG} = 0.0, c_{H\Box} = 0.0 \]

* Observed Limit (95% CL)
* Expected Limit ±1σ
* Expected Limit ±2σ

SM Prediction

Other 2D scans in backup
• 7 HEFT benchmark models for $c_{HHH}$, $c_{tHH}$, $c_{ttHH}$, $c_{ggH}$ and $c_{ggHH}$ to probe a wide variety of characteristic shapes of the $m_{HH}$ spectrum.

• Advantage of HEFT: anomalous single-Higgs-boson and HH couplings defined separately.

• The spread of sensitivity between the seven benchmark models reflects the different shapes of the signal $m_{HH}$ distributions.

• BM3, BM5 and BM7 are observed to be excluded with more than 95% confidence.

Limits competitive with ATLAS $b\bar{b}\tau\tau + b\bar{b}\gamma\gamma$ standalone limits $\rightarrow$ improvement when included in the combination

$HH \rightarrow b\bar{b}b\bar{b}$

$\begin{align*}
c_{gghh} : & \left[ -0.36, 0.78 \right] \left[ -0.42, 0.75 \right] \\
c_{ttHH} : & \left[ -0.55, 0.51 \right] \left[ -0.46, 0.40 \right]
\end{align*}$

$HH \rightarrow b\bar{b}\tau\tau + b\bar{b}\gamma\gamma$

The different variation between observed and expected limits is linked to a slight excess observed in the low $m_{HH}$ region.
A combined SMEFT interpretation of these measurements has already been performed in Ref. 

A combined measurement of Higgs boson production process in several Higgs decay channels allows the results used for the interpretation in this note are based on Table 1, 

more restricted flavour symmetry and considering only SMEFT e 

input analysis entering the combined Higgs boson measurement are shown in Table 

A more optimal analysis of the Higgs boson mass regions is more important than the relatively weak 

the normalization of the signal from the 

region used to constrain the continuum 

mass of 

topologies. The inclusive 

experimental value, the third to the theory prediction in the 

` 

35 

1992 the SLD 

Table 2 

Electroweak precision observables included in the analysis. The second column corresponds to the 

Observable Measurement Prediction Ratio 

\( \Gamma_Z \) [MeV] 
2495.2 ± 2.3 
2495.7 ± 1 
0.9998 ± 0.0010 

\( R_0^0 \) 
20.767 ± 0.025 
20.758 ± 0.008 
1.0004 ± 0.0013 

\( R_0^0 \) 
0.1721 ± 0.0030 
0.17223 ± 0.00003 
0.999 ± 0.017 

\( R_0^0 \) 
0.21629 ± 0.00066 
0.21586 ± 0.00003 
1.0020 ± 0.0031 

\( A_{F_B}^{0,\ell} \) 
0.0171 ± 0.0010 
0.01718 ± 0.00037 
0.995 ± 0.062 

\( A_{F_B}^{0,\ell} \) 
0.0707 ± 0.0035 
0.0758 ± 0.0012 
0.932 ± 0.048 

\( A_{F_B}^{0,\ell} \) 
0.0992 ± 0.0016 
0.1062 ± 0.0016 
0.935 ± 0.021 

\( \sigma_{\text{had}}^0 \) [pb] 
41488 ± 6 
41489 ± 5 
0.99998 ± 0.00019
**ATLAS Global combination**

**HIGGS+EW** (lin+quad results)

- Principal component analysis to identify sensitive directions -> a modified basis of linear combinations of WCs is defined.

- The fit uses sensitivity eigenvectors instead of original Wilson Coefficient.

- Constraining 7 individual and 17 linear combinations of Wilson coefficients.

- Data overlap across datasets checked -> remove from the combination whenever relevant.

![Diagram showing Higgs and EW contributions](image)

*Most stringent constraints*

Constrained by both diboson and VH measurements

Weakly constrained fit directions -> quadratic contributions are large; validity of the constraints - neglected higher order contributions

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**LHCP2023 - 22/05/2023**

Eleonora Rossi
4th General Meeting of the LHC EFT Working Group

HIGGS + EW + EWPO

- Constraining 6 individual and 22 linear combinations of Wilson coefficients.
- Several constraints driven by both ATLAS and LEP/SLD.
- Complementary information.
- Linear fits agree with the SM expectation for most fitted parameters, except for:
  - $c^{[4]}_{HVV,Vff}$ → excess driven by a well-known discrepancy in $A^{0,b}_{FB}$ from the SM expectation.

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

• Increasing number of analyses in SM, Top and Higgs sectors providing interesting EFT interpretations (additional ATLAS EFT interpretations in Chilufya’s, Bo’s and Adrian’s talks).

• First Global ATLAS EFT interpretation available (also simplified likelihood model for re-interpretation):
  • well established framework used to perform the ATLAS Global combination;
  • combination with additional Top + EW analyses ongoing-> provide complementary sensitivity.

• ATLAS + CMS: ongoing exercise to include few published input measurements and test the combination using consistent parameterisations and assumptions.

for many interesting results to come!!
- Fiducial and differential cross sections for the electroweak and inclusive production of a same-sign $W$ boson pair in association with two jets ($W^±W^±jj$) - (analysis details in Alessandro’s talk).

- Differential $m_{\ell\ell}$ distribution with optimised binning used to set limits on EFT dim8 operator coefficients $f_{S02}/\Lambda^4, f_{S1}/\Lambda^4, f_{M0}/\Lambda^4, f_{M1}/\Lambda^4, f_{M7}/\Lambda^4, f_{T0}/\Lambda^4, f_{T1}/\Lambda^4$ and $f_{T2}/\Lambda^4$.

- Results using EFT unitarisation cut-off also provided.

- These constraints are competitive with those previously published by the CMS Collaboration.

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2D limits at 95% CL obtained with a unitarisation cut-off scale of 1.5 TeV.

Evolution of the limits as a function of the cut-off scale of the unitarisation procedure.
4l VBS measurements

- Differential cross-sections ($m_{4\ell}$ and $m_{jj}$) measured for the production of four charged leptons in association with two jets (analysis details in Chilufya’s talk).

- Unfolded cross sections used to search for signatures of anomalous weak-boson self-interactions using the framework of dim6 and dim8 EFT.

$$\mathcal{O}_{T0}, \mathcal{O}_{T1}, \mathcal{O}_{T2}, \mathcal{O}_{T5}, \mathcal{O}_{T6}, \mathcal{O}_{T7}, \mathcal{O}_{T8}, \mathcal{O}_{T9}$$

- The WCs associated with the $\mathcal{O}_{T0}$ and $\mathcal{O}_{T1}$ operators are the most tightly constrained.

- Constraints with the pure dim8 contribution are more stringent than interference-only constraints

- Constraints are placed on each WC after restricting the interference- and pure dimension-eight contributions to have $m_{4\ell} < E_c$

- The 95% confidence intervals degrade by a factor of 4-5 when the energy scale cut off is reduced from $E_c = \infty$ to $E_c = 1$ TeV.

### Table: Wilson coefficient $\mathcal{M}_{48}$

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<td>$[-0.98, 0.93]$</td>
<td>$[-1.0, 0.97]$</td>
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<td>$[-220, 220]$</td>
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<td>$[-2.2, 2.2]$</td>
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<tr>
<td>$f_{T,9}/\Lambda^4$</td>
<td>$[-7.5, 5.5] \times 10^4$</td>
<td>$[-6.4, 6.3] \times 10^4$</td>
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The WCs associated with the $\mathcal{O}_{T0}$ and $\mathcal{O}_{T1}$ operators are the most tightly constrained.
Evidence for the charge asymmetry in $pp \rightarrow t\bar{t}$

- Inclusive and differential full Run2 measurements of the top–antitop ($t\bar{t}$) charge asymmetry $A^t_\ell$ and the leptonic asymmetry $A^{\ell\bar{\ell}}_c$
- Differential measurements are performed as a function of the invariant mass, transverse momentum and longitudinal boost of the $t\bar{t}$ system.
- Combined results are interpreted in the SMEFT framework.
- **14 four-fermion operators** + 1 operator for top–gluon interaction.

The combined inclusive charge asymmetry is measured to be $A^t_\ell = 0.0068 \pm 0.0015$, which differs from zero by **4.7 standard deviations**.
Evidence for the charge asymmetry in $pp \rightarrow t\bar{t}$

- Inclusive and differential full Run2 (139 fb$^{-1}$) measurements of $t\bar{t}$ and leptonic charge asymmetry $A^t_c & A^\ell_c$.
- Differential measurements provided for invariant mass, transverse momentum and longitudinal boost of the $t\bar{t}$ system.
- Combined results are interpreted in the SMEFT framework.
- **14 four-fermion operators** + 1 operator for top–gluon interaction.
- Large improvement w.r.t LHC 8TeV/Tevatron results.
- Interplay between sensitivity (increases for higher $m_{t\bar{t}}$) and uncertainty (0.2% – 0.3% to 2.9%).
- Tightest linear limit obtained in the mass bin from 1 to 1.5 TeV.
- Constraint from the differential $m_{t\bar{t}}$ measurement more than a factor 2 stronger than inclusive measurement.

The combined inclusive charge asymmetry is measured to be $A^t_c = 0.0068 \pm 0.0015$, which differs from zero by **4.7 standard deviations**.
Evidence for the charge asymmetry in $pp \rightarrow t\bar{t}$

- QCD structure of the energy asymmetry not the same as for the charge asymmetry in $t\bar{t}$ production due to the extra jet in $t\bar{t}j$ production.
  - the two asymmetries probe different directions in chiral and colour space.
- For colour-singlet operators with different quark chiralities (top row), the two asymmetries probe similar areas in the parameter space.

[Graphs showing data from ATLAS with $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$]
Evidence for the charge asymmetry in $pp \to t\bar{t}$

- QCD structure of the energy asymmetry not the same as for the charge asymmetry in $t\bar{t}$ production due to the extra jet in $t\bar{t}j$ production.
  - the two asymmetries probe different directions in chiral and colour space.
- Different shapes of the bounds are due to the different colour-singlet and colour-octet contributions to $t\bar{t}$ and $t\bar{t}j$ production, which is probed with high sensitivity by the asymmetries.

![Graph](image)

colour-singlet versus colour-octet operators with the same quark chiralities
• Search for charged-lepton-flavour violating $\mu\tau q t$ interaction in top-quark production and decay.

• The analysis sensitivity is dominated by the cLFV production process; decay process improves the observed limits by 2.7%.

• EFT interpretation: dedicated samples to set limits on EFT operators describing contact interactions between two leptons and two quarks permitting cLFV interactions (dim6-top).

• Cross section of the cLFV process: dependence on the square of the value of WC.

<table>
<thead>
<tr>
<th>$95%$ CL upper limits on Wilson coefficients</th>
<th>$c/\Lambda^2$ [TeV$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{lq}^{(ijk3)}$</td>
<td>$c_{eq}^{(ijk3)}$</td>
</tr>
<tr>
<td>Previous (u) [22]</td>
<td>12</td>
</tr>
<tr>
<td>Expected (u)</td>
<td>0.47</td>
</tr>
<tr>
<td>Observed (u)</td>
<td>0.49</td>
</tr>
<tr>
<td>Previous (c) [22]</td>
<td>14</td>
</tr>
<tr>
<td>Expected (c)</td>
<td>1.6</td>
</tr>
<tr>
<td>Observed (c)</td>
<td>1.7</td>
</tr>
</tbody>
</table>

The limits obtained on the Wilson coefficients improve upon the previous results from a re-interpretation of an ATLAS FCNC $tZq$ analysis (from a factor of 8 to 51) - JHEP 04 (2019) 014.

• This result complements searches for cLFV in $\mu\tau q t$ interactions by the CMS Collaboration.
EFT interpretation: use dedicated samples to set limits on EFT operators describing contact interactions between two leptons and two quarks permitting cLFV interactions (dim6top model).

The cross section of the cLFV process depends on the square of the value of the relevant Wilson coefficient for a given value of the scale of new physics.

$$\Gamma(t \rightarrow \ell_i^+ \ell_j^- q_k) = \frac{m_t}{6144\pi^3} \left(\frac{m_t}{\Lambda}\right)^4 \left\{ 4|c_{lq}^{-(ijk3)}|^2 + 4|c_{eq}^{(ijk3)}|^2 + 4|c_{lu}^{(ijk3)}|^2 + 4|c_{eu}^{(ijk3)}|^2 + 4|c_{lequ}^{1(ijk3)}|^2 + 4|c_{lequ}^{1(ij3k)}|^2 \right. $$

$$+ |c_{lequ}^{1(ijk3)}|^2 + |c_{lequ}^{1(ij3k)}|^2 + 48|c_{lequ}^{3(ijk3)}|^2 + 48|c_{lequ}^{3(ij3k)}|^2 \right\}$$

### 95\% CL upper limits on BR($t \rightarrow \mu \tau q$) ($\times 10^{-7}$)

<table>
<thead>
<tr>
<th>Operator</th>
<th>Lorentz Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{(ijkl)}^{1}$</td>
<td>$(\bar{\ell}_i \gamma \mu \ell_j)(\bar{q}_k \gamma \mu q_l)$ Vector</td>
</tr>
<tr>
<td>$O_{(ijkl)}^{2}$</td>
<td>$(\bar{\ell}_i \gamma \mu \sigma \ell_j)(\bar{q}_k \gamma \sigma \mu q_l)$ Vector</td>
</tr>
<tr>
<td>$O_{(ijkl)}^{3}$</td>
<td>$(\bar{\ell}_i \gamma \mu e_j)(\bar{q}_k \gamma \mu q_l)$ Vector</td>
</tr>
<tr>
<td>$O_{(ijkl)}^{4}$</td>
<td>$(\bar{\ell}_i \gamma \mu e_j)(\bar{q}_k \gamma \mu q_l)$ Vector</td>
</tr>
<tr>
<td>$O_{(ijkl)}^{5}$</td>
<td>$(\bar{\ell}_i \gamma e_j)(\bar{q}_k \gamma \mu q_l)$ Vector</td>
</tr>
<tr>
<td>$O_{(ijkl)}^{6}$</td>
<td>$(\bar{\ell}_i \gamma e_j)(\bar{q}_k \gamma \mu q_l)$ Vector</td>
</tr>
<tr>
<td>$O_{(ijkl)}^{7}$</td>
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</tr>
<tr>
<td>$O_{(ijkl)}^{8}$</td>
<td>$(\bar{\ell}_i \gamma \mu \sigma \ell_j)(\bar{q}_k \gamma \sigma \mu q_l)$ Vector</td>
</tr>
<tr>
<td>$O_{(ijkl)}^{9}$</td>
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<tr>
<td>$O_{(ijkl)}^{10}$</td>
<td>$(\bar{\ell}_i \gamma \mu \sigma \ell_j)(\bar{q}_k \gamma \sigma \mu q_l)$ Vector</td>
</tr>
<tr>
<td>$O_{(ijkl)}^{11}$</td>
<td>$(\bar{\ell}_i \gamma \mu \sigma \ell_j)(\bar{q}_k \gamma \sigma \mu q_l)$ Vector</td>
</tr>
<tr>
<td>$O_{(ijkl)}^{12}$</td>
<td>$(\bar{\ell}_i \gamma \mu \sigma \ell_j)(\bar{q}_k \gamma \sigma \mu q_l)$ Vector</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expected (u)</th>
<th>4.6</th>
<th>4.2</th>
<th>4.0</th>
<th>4.5</th>
<th>2.5</th>
<th>2.5</th>
<th>5.8</th>
<th>5.8</th>
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<tbody>
<tr>
<td>Observed (u)</td>
<td>5.1</td>
<td>4.6</td>
<td>4.4</td>
<td>5.0</td>
<td>2.8</td>
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<td>Expected (c)</td>
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<td>51</td>
<td>52</td>
<td>35</td>
<td>35</td>
<td>61</td>
<td>61</td>
</tr>
<tr>
<td>Observed (c)</td>
<td>60</td>
<td>56</td>
<td>56</td>
<td>57</td>
<td>38</td>
<td>38</td>
<td>68</td>
<td>68</td>
</tr>
</tbody>
</table>
**VBF HWW**

- Integrated and differential fiducial (first in VBF) cross-section measurements for VBF in the $HWW$ $e\nu\mu\nu$ channel.

- Differential cross-sections used to constrain extensions to the SM using an EFT approach:

\[
\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}, \quad \text{for} \ d > 4.
\]

- The WCs are constrained one at a time using the differential distribution that is most sensitive to the corresponding operator ($\Delta \phi_{jj}$- CP-odd, leading jet pT - CP-even)

- More stringent constraints for all WCs when the quadratic term is added to the parameterization.

- Neglected contributions of higher-dimensional operators in the EFT expansion.

- Correlations obtained between central values of EFT operators using the bootstrapping technique. (backup)
• Integrated and differential fiducial (first in VBF) cross-section measurements for VBF in the $HWW$ $e\nu\mu\nu$ channel (139 fb$^{-1}$).

• Differential cross-sections used to constrain extensions to the SM using an EFT approach:

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}, \text{ for } d > 4.$$ 

SMEFTsim

• The WCs are constrained one at a time using the differential distribution that is most sensitive to the corresponding operator ($\Delta \phi_{jj}$- CP-odd, leading jet pT - CP-even)

• Correlations obtained between central values of EFT operators using the bootstrapping technique.

• Pairs of measurements can be used to set constraints on new and different models of physics beyond the SM, for example in future global fits
HH(4b) SMEFT

- Non-resonant HH production ggF production mode - 4b decay channel (126 fb⁻¹).
- Analysis categorisations to improve sensitivity to BSM physics.
- The interpretations are performed with two EFT frameworks, Higgs Effective Field Theory (HEFT) and SM Effective Field Theory (SMEFT).
  - first LHC SMEFT interpretation for HH.
- The different BSM scenarios are considered re-weighting the SM non-resonant HH ggF sample.

1D and 2D limits for the 5 Wilson coefficients: $c_H, c_{H\Box}, c_{tH}, c_{tG}, c_{tG}$. SMEFT@NLO

### Linear+quadratic results, one WC at a time

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected Constraint</th>
<th>Observed Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>$c_H$</td>
<td>$-20$</td>
<td>11</td>
</tr>
<tr>
<td>$c_{HG}$</td>
<td>$-0.056$</td>
<td>0.049</td>
</tr>
<tr>
<td>$c_{H\Box}$</td>
<td>$-9.3$</td>
<td>13.9</td>
</tr>
<tr>
<td>$c_{tH}$</td>
<td>$-10.0$</td>
<td>6.4</td>
</tr>
<tr>
<td>$c_{tG}$</td>
<td>$-0.97$</td>
<td>0.94</td>
</tr>
</tbody>
</table>

ATLAS

- $\sqrt{s} = 13$ TeV, 126 fb⁻¹
- $c_{tH}, c_{tG}, c_{H\Box}$
- Observed limits (95% CL)
- Expected limit (95% CL)
- SM Prediction

- $\mathcal{O}_{c_{tH}}, \mathcal{O}_{c_{tG}}, \mathcal{O}_{c_{H\Box}}$
7 HEFT benchmark models for $c_{HHH} c_{tth} , c_{ttHH} c_{ggH}$ and $c_{ggHH}$ to probe a wide variety of characteristic shapes of the $m_{HH}$ spectrum.

Advantage of HEFT: anomalous single-Higgs-boson and HH couplings defined separately.

The spread of sensitivity between the seven benchmark models reflects the different shapes of the signal $m_{HH}$ distributions.

- Limits competitive with ATLAS $b\bar{b}\tau\tau + b\bar{b}\gamma\gamma$ standalone limits -> improvement when included in the combination

$$HH \rightarrow 4b$$

\[
c_{gghh} : [-0.36, 0.78] [-0.42, 0.75]
\]

\[
c_{tthH} : [-0.55, 0.51] [-0.46, 0.40]
\]

The different variation between observed and expected limits is linked to a slight excess observed in the low $m_{HH}$ region.
• 7 HEFT benchmark models for $c_{HHH}, c_{ttH}, c_{ggH}$ and $c_{ggHH}$ to probe a wide variety of characteristic shapes of the $m_{HH}$ spectrum.

• Advantage of HEFT: anomalous single-Higgs-boson and HH couplings defined separately.

• The spread of sensitivity between the seven benchmark models reflects the different shapes of the signal $m_{HH}$ distributions.

The different variation between observed and expected limits is linked to a slight excess observed in the low $m_{HH}$ region.
Global combination: SMEFT parameterisation

- Warsaw basis, assuming $\Lambda = 1$ TeV.
- SMEFTsim + SMEFT@NLO + TopFCNC.
- Results are usually provided for linear model (+ linear-quadratic models).
- SMEFTsim: different flavour symmetries used to reduce the number of Wilson coefficients.

"$U(3)^5$ flavour symmetry", "topU3I"

$U(3)^5$ flavour symmetry

- All quark generations treated similarly
- Relax $t,b$

topU3I flavour symmetry

- First two quark generations treated similarly
- All lepton generations treated similarly
- Relax leptons

Top flavour symmetry

- First two quark generations treated similarly
- All lepton generations treated similarly

### Global combination: SMEFT parameterisation

- $\sigma_{\text{SMEFT}} \sim |\langle \sigma \rangle_{\text{STXS}}^S|^2$

### Linear model

- $\text{SM}$

### Linear-quadratic models

- $\text{SM} / \text{dim-6 interference}$

### Linear-quadratic models

- $\text{dim-6 squared}$
Global combination: SMEFT parameterisation

The impact of dim-6 CP-even operators is estimated using both MC truth and analytical predictions for all the Wilson coefficients that have numerically relevant contributions (62).

- Dimension-six operator effects are calculated:
  - at tree level using SMEFTsim 3.0.
  - for processes that are loop-induced in the SM, thus ggH and ggZH production, Higgs boson decays into gluons -> SMEFTatNLO.
  - Analytic formulas for $H \rightarrow \gamma\gamma$ including NLO EW corrections and LEP observables.

- Theory uncertainties on SM predictions, no additional uncertainties on SMEFT.

- Acceptance corrections to account for kinematic differences between SM and SMEFT in Higgs boson decays on both linear and linear+quadratic terms.

- Effects of width changes of intermediate particles (“propagator corrections”) included.
A combined SMEFT interpretation of these measurements has already been performed in Ref. [12].

The results used for the interpretation in this note are based on Table 1, as a function of Wilson coefficients. Measurements of differential cross-sections of weak boson production and decay, referred to as electroweak STXS production cross-sections as well as Higgs boson branching ratios are reparametrized in terms of Wilson coefficients.

2.2 Combined analysis of differential cross-section measurements of Higgs boson production for each production mode. For the associated production of a Higgs boson and a top quark, the small contribution is measured in combination with ATLAS Higgs boson data (2021 combination).

Higgs boson production and decay combined measurements in STXS bins

SMEFTsim: “topU3l” flavour symmetry

- ATLAS Higgs boson data (2021 combination)
- Higgs boson production and decay combined measurements in STXS bins
\[ L(x|c, \theta) = \frac{1}{\sqrt{2\pi}^{n_{\text{theo}}} \det(V)} \exp\left(-\frac{1}{2} \Delta x^\top (c, \theta) V^{-1} \Delta x (c, \theta) \right) \times \prod_i f_i (\theta_{\text{theo syst,}i}) \times \prod_i f_i (\theta_{\text{exp syst,}i}). \]
\[ \Delta x_b (c, \theta) = x_{b, \text{meas}} (\theta) - x_{b, \text{pred}} (c, \theta). \]

### Multivariate gaussian

<table>
<thead>
<tr>
<th>Process</th>
<th>Important phase space requirements</th>
<th>Observable</th>
<th>( L ) [fb(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pp \rightarrow e^+\nu\mu^-\bar{\nu} )</td>
<td>( m_{\ell\ell} &gt; 55 \text{ GeV}, p_T^{\text{jet}} &lt; 35 \text{ GeV} )</td>
<td>( p_T^{\text{lead. lep.}} )</td>
<td>36</td>
</tr>
<tr>
<td>( pp \rightarrow e^+\nu\mu^-\bar{\nu} )</td>
<td>( m_{\ell\ell} \in (81, 101) \text{ GeV} )</td>
<td>( m_W )</td>
<td>36</td>
</tr>
<tr>
<td>( pp \rightarrow \ell^+\ell^-\ell^+\ell^- )</td>
<td>( m_{\ell\ell} &gt; 180 \text{ GeV} )</td>
<td>( m_T )</td>
<td>139</td>
</tr>
<tr>
<td>( pp \rightarrow \ell^+\ell^- jj )</td>
<td>( m_{jj} &gt; 1000 \text{ GeV}, m_{\ell\ell} \in (81, 101) \text{ GeV} )</td>
<td>( \Delta \phi_{jj} )</td>
<td>139</td>
</tr>
</tbody>
</table>

- ATLAS electroweak data
- Differential cross-section measurements for diboson and Z production via VBF

SMEFTsim: “topU3l” flavour symmetry
A more optimal analysis of the Higgs boson mass regions is more important than the relatively weak
The 0-jet control region of the signal region of the inclusive mass of topologies. The inclusive constraints provided by the low-mass region of the inclusive

Electroweak precision observables included in the analysis. The second column corresponds to the measurement but excludes analysis regions of the inclusive

The signal region targeting VBF production and the invariance mass target gluon fusion Higgs boson production are orthogonal, as the former analysis requires the dilepton

The likelihood is modelled as a multivariate Gaussian, both theoretical and experimental uncertainties are included in the covariance matrix.

<table>
<thead>
<tr>
<th>Observable</th>
<th>Measurement</th>
<th>Prediction</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_Z$ [MeV]</td>
<td>$2495.2 \pm 2.3$</td>
<td>$2495.7 \pm 1$</td>
<td>$0.9998 \pm 0.0010$</td>
</tr>
<tr>
<td>$R_\ell^0$</td>
<td>$20.767 \pm 0.025$</td>
<td>$20.758 \pm 0.008$</td>
<td>$1.0004 \pm 0.0013$</td>
</tr>
<tr>
<td>$R_c^0$</td>
<td>$0.1721 \pm 0.0030$</td>
<td>$0.17223 \pm 0.00003$</td>
<td>$0.999 \pm 0.017$</td>
</tr>
<tr>
<td>$R_b^0$</td>
<td>$0.21629 \pm 0.00066$</td>
<td>$0.21586 \pm 0.00003$</td>
<td>$1.0020 \pm 0.0031$</td>
</tr>
<tr>
<td>$A_{FB}^{0,\ell}$</td>
<td>$0.0171 \pm 0.0010$</td>
<td>$0.01718 \pm 0.000037$</td>
<td>$0.995 \pm 0.062$</td>
</tr>
<tr>
<td>$A_{FB}^{0,c}$</td>
<td>$0.0707 \pm 0.0035$</td>
<td>$0.0758 \pm 0.00012$</td>
<td>$0.932 \pm 0.048$</td>
</tr>
<tr>
<td>$A_{FB}^{0,t}$</td>
<td>$0.0992 \pm 0.0016$</td>
<td>$0.1062 \pm 0.0016$</td>
<td>$0.935 \pm 0.021$</td>
</tr>
<tr>
<td>$\sigma_{had}^0$ [pb]</td>
<td>$41488 \pm 6$</td>
<td>$41489 \pm 5$</td>
<td>$0.99998 \pm 0.00019$</td>
</tr>
</tbody>
</table>

**EWPD in the SMEFT to dimension eight**

- Electroweak precision observables measured at LEP and SLC
- Eight pseudo observables describing the physics at the $Z$-pole are interpreted.
- Measurement probed with high sensitivity $O(1 - 0.01 \%)$
One parameter at a time scans to compare sensitivity to an operator across the 3 measurement groups;

- all remaining Wilson coefficients fixed to zero;
- correlations between operators are neglected.
Impact of linear SMEFT parameterisation shown for bins along with corresponding measurement uncertainty.

- Relative impact of linear SMEFT terms with Wilson coefficients $c_{HG}$, $c_W$, $c_{1G}$, $c_bH$, $c_tH$, and $c_{eH}$ on the Higgs STXS cross sections and branching ratios.

The corresponding selected values of Wilson coefficients are shown.

Operators affecting HVV, Vff
Additional sensitivity coming from EW measurements and EWPO, e.g. cW that cannot be disentangled using just $H \to \gamma\gamma$ decay.

**ATLAS Global combination**

**operators affecting HVV,Vff**
Impact of linear SMEFT parameterisation shown for bins along with corresponding measurement uncertainty.

mostly affecting the $H \to \gamma\gamma$ branching ratio

overall normalisation, modifications to Fermi constant (cH13, cH11)

---

**ATLAS** Global combination

LHCP2023 - 22/05/2023  Eleonora Rossi
- SMEFT impact on measurements shown in Warsaw basis and fit basis-> allows to understand the impact of the different fit directions on measurements.
Overlapping categories:
- regions of the inclusive $4\ell$ analysis that target $m_{4\ell} < 180$ GeV are excluded (small impact on SMEFT).
- the 0-jet $WW$ control region from HWW is excluded; $WW$ normalisation is correlated with $WW$ signal normalisation.

A multivariate Gaussian model is used for the interpretation of both LHC EW measurements and EWPO.

Systematic uncertainties modelled with common nuisance parameter:
- for unfolded SM measurements: experimental nuisance parameter shift unfolded results;
- same nuisance parameter shift reco-level prediction for Higgs measurements.

For EWPO the model contains no nuisance parameters and both theoretical and experimental uncertainties are included in the covariance matrix.

Limits on WCs extracted using combined likelihood (product of individual likelihood).

<table>
<thead>
<tr>
<th>Correlated Uncertainty Source</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (correlated part)</td>
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<tr>
<td>Luminosity 2015/16</td>
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<td>Luminosity 2017/18</td>
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<td>Pile-up modelling</td>
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<td>Pile-up jet suppression</td>
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<td>Jet energy scale (pile-up modelling)</td>
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<td>Jet energy scale $\eta$-inter-calibration</td>
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<tr>
<td>Jet energy resolution</td>
<td>12</td>
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<tr>
<td>B-tagging efficiency ($WW$ and $H \rightarrow WW^*$)</td>
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<tr>
<td>$WW$ modelling ($WW$ and $H \rightarrow WW^*$)</td>
<td>2</td>
</tr>
</tbody>
</table>
ATLAS Global combination: sensitivity studies

- PCA considering all operators: directions ordered by increasing uncertainties, keeping σ < 5;
- Wilson coefficients expected to be at most order 1, new physics scale Λ expected to be at least 1 TeV -> directions with σ > 5 have very little impact on the measurement.

Eigenvectors from PCA, corresponding eigenvalues
**ATLAS Global combination: sensitivity studies**

- PCA considering all operators: directions ordered by increasing uncertainties, keeping $\sigma < 5$;
- Fit basis defined by grouping operators of similar physics impact together.

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**Warsaw Basis, Wilson coefficients**

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**LHCP2023 - 22/05/2023**
**ATLAS Global combination: simplified likelihood**

- Simplified likelihood model:
  - format to deliver results for re-interpretation;
  - signal strength modifier + correlation matrix.

- Results from the full likelihood fit compared to those using a simplified likelihood following a multi-variate Gaussian approach:
  - minimal differences between the two methods;
  - the simplified model is nuisance parameter free, as the effect of all uncertainties is encoded in the covariance matrix -> computationally inexpensive.

- Signal strength modifiers + correlation matrix available, preparing shared parameterisation.