Recent EFT measurements from ATLAS

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on behalf of the ATLAS Collaboration

LHC EFT Working Group
3rd General Meeting

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Overview

- Growing effort in recent years to have EFT interpretation of ATLAS measurements across different sectors

- Many preliminary ATLAS EFT results across different sectors since last LHCEFTWG General Meeting
**SMEFT framework**

\[
\mathcal{L} = \frac{1}{\Lambda^0} \mathcal{L}_{SM}^{(d=4)} + \frac{1}{\Lambda} \mathcal{L}^{(d=5)} + \frac{1}{\Lambda^2} \mathcal{L}^{(d=6)} + \ldots = \mathcal{L}_{NP}
\]

Lagrangian with new particles at \( \Lambda \)

- All results are based on **Warsaw basis** definitions with \( m_w, m_z, \alpha_s \) input parameter scheme
- \( \mathcal{L}^{(d)} = \sum_i c_i \mathcal{O}_i^{(d)} \) all possible local interactions allowed by symmetries, \( c_i \rightarrow \) free parameters of model
- 2499 operators at \( d=6 \) with \( \Delta L = \Delta B = 0 \), smaller set considered with flavour assumptions
- SMEFT dependence can be parameterised as polynomials in wilson coefficients,

\[
\sigma_{SMEFT} \xrightarrow{\text{SM}} 2 + \frac{2c}{\Lambda^2} \text{Re} \begin{pmatrix} \ldots \end{pmatrix} X + \frac{c^2}{\Lambda^4} \xrightarrow{\text{Quadratic : } (d=6)^2, \text{ missing SM x } d=8 \text{ interference}}
\]

\[
= \sigma_{SM} \left( 1 + \sum_i \alpha_i c_i + \sum_{ij} \beta_{ij} c_i c_j \right), \quad \alpha_i, \beta_{ij} \text{ are numerical factors}
\]

**SM prediction from SMEFT re-scaled to best known SM prediction**
Measurements to Wilson coefficients

Wide variety of experimental observables analysed consistently in a physics framework

- Reconstructed distributions
  - Invariant mass, angles, asymmetries, transverse momenta & more

- Unfolded distributions
  - Differential cross-sections, fiducial cross-sections

- Physics Parameters
  \[ L_{\text{SMFT}} = L_{\text{SM}} + \sum_{i,d > 4} \frac{c^i_d}{\text{uni}} \]

- Experimental acceptance on EFT contribution can be considerable for some cases
- When all wilson coefficients cannot be measured, analysis sensitivity used to measure sensitive EFT parameters
- Top processes sensitive to unique parameter set, different kinematic information crucial
- All systematic effects from experimental and theory sources included for EFT results

[ATLAS-CONF-2021-031]
Higgs
- VHbb resolved + boosted combination
- Higgs combination

Top
- Energy asymmetry in t\bar{t} production
- Boosted t\bar{t} production
- Angular observables
- Top EFT Summary plots

EW
- WW, WZ, 4l, & Z+2jets combination
(VH) $H \rightarrow b\bar{b}$ resolved + boosted

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**EFT Impact on STXS bins**

- **ATLAS Preliminary**
  - $\sigma bH \times B_{B}^{V} \times B_{H}^{V}$
  - $V = W$
  - $V = Z$

- **ATLAS Simulation Preliminary**
  - 7 STXS bins
  - 5 STXS bins

- **ATLAS-CONF-2021-051**

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- **EFT parameterisation derived using SMEFTsim3.0 $U(3)$**
- Combination of boosted with resolved analysis gives access to high $p_T^V$ tail, going ahead EFT theory uncertainties crucial in such regimes
- Serves as key input to measuring $p_T^V$ distribution kinematic VH production in Higgs combination

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Higgs Combination

- Combined Higgs results are based on a likelihood level combination built as product of individual analyses likelihood

- Negligible overlap in event selections of input analyses

- Signal modelling and related uncertainties are treated coherently across input analyses

- Nuisance Parameters: Try to fully correlate between analyses where possible, if not left decorrelated, O(2000) systematic sources of uncertainties

- Linear Parameterisation derived for all contributing operators with U(3)^5 symmetry,
  - SMEFTsim 3.0 for EFT insertions for tree-level SM process
  - SMEFTatNLO to resolve loop contributions to ggH, ggZH
  - analytical prediction for NLO-QED in Hγγ from Phys. Rev. D 98, 095005

- Acceptance effect on EFT parameterisation relevant for 4-body Higgs decay, estimated using selections used in H → ZZ* and H → WW* analyses

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Target Production Modes</th>
<th>( L ) [fb⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \to \gamma\gamma )</td>
<td>ggF, VBF, WH, ZH, ( t\bar{t}H, tH )</td>
<td>139</td>
</tr>
<tr>
<td>( H \to ZZ^* )</td>
<td>ggF, VBF, WH, ZH, ( t\bar{t}H(4\ell) )</td>
<td>139</td>
</tr>
<tr>
<td>( H \to WW^* )</td>
<td>ggF, VBF</td>
<td>139</td>
</tr>
<tr>
<td>( H \to W^+W^- )</td>
<td>( t\bar{t}H )</td>
<td>36.1</td>
</tr>
<tr>
<td>( H \to \tau\tau )</td>
<td>ggF, VBF, WH, ZH, ( t\bar{t}H(\tau_{had}\tau_{had}) )</td>
<td>139</td>
</tr>
<tr>
<td>( H \to bb )</td>
<td>WH, ZH</td>
<td>139</td>
</tr>
<tr>
<td>( H \to \mu\mu )</td>
<td>VBF</td>
<td>126</td>
</tr>
<tr>
<td>( H \to Z\gamma )</td>
<td>VBF</td>
<td>139</td>
</tr>
<tr>
<td>( H \to inv )</td>
<td>( t\bar{t}H )</td>
<td>139</td>
</tr>
</tbody>
</table>

- Updated since last round [ATLAS-CONF-2020-053]
- Not included for STXS & EFT
**Simplified template cross-sections**

- STXS regions defined to measure kinematic properties across decay channels while minimising statistical uncertainties and theory-dependence
- Kinematic regions help isolate BSM effects (typically tails of distributions)
- Measure 37 kinematic bins across 5 production modes, Probe Higgs cross-sections ranging across 4 orders of magnitude!
- Access to additional kinematic information thanks to inclusion of new analyses,
  - $qq\rightarrow Hqq$ access to higher end of $m_{jj}$ spectrum thanks to inclusion of HWW analysis
  - With inclusion of boosted $VHbb$ additional split at high-$p_{TW}$, $p_{TZ}$ ($p_{TV} = 400$ GeV)
  - $ttHbb$ analysis give access to tail of $ttH$ pT spectrum
EFT Impact on kinematics

Relative EFT impact wrt SM

Uncertainty on measurements across production modes

STXS bins
EFT Impact on kinematics

Uncertainty on measurements across production modes

Relative EFT impact wrt SM

H → γγ

STXS bins
EFT Impact on kinematics

Relative EFT impact wrt SM

Increasing impact with $p_T(V)$

Uncertainty on measurements across production modes

$\{O_{Hq}^{(3)}, O_{Hd}, O_{Hu}, O_{Hq}^{(1)}\}$

$H \rightarrow WW \rightarrow \gamma \gamma \rightarrow H \gg H \tau \rightarrow H \tau \rightarrow H \gg$

STXS bins
EFT Impact on kinematics

Relative EFT impact wrt SM

Uncertainty on measurements across production modes

$H \rightarrow ZZ$

$H \rightarrow \tau\tau$

$H \rightarrow bb$

STXS bins

ATLAS Preliminary

$\sigma_{ggH}$

$\sigma_{VBF}$

$\sigma_{VH}$

$\sigma_{WH}$

$\sigma_{ZH}$

$\sigma_{ttH}$

Multiple production modes

Uncertainty on measurements across production modes

$\{O_{dH}, O_{eH}\}$

$\{O_{Hl}^{(1)}, O_{He}\}$

$O_{dH}$

$O_{eH}$

$H \rightarrow ZZ$

$H \rightarrow \tau\tau$

$H \rightarrow bb$
EFT Impact on kinematics

Relative EFT impact wrt SM

Constant across production modes

Uncertainty on measurements across production modes

extracted value of the Fermi constant in the general SMEFT is

\[ \frac{-4 G_F}{\sqrt{2}} = \frac{2}{\alpha_s^2} \left( C_{\pi^{23}} + C_{\pi^{24}} \right) - 2 \left( C_{\pi^{25}} + C_{\pi^{26}} \right) \]

(10.10)

arXiv:1709.06492
EFT Impact on kinematics

Relative EFT impact wrt SM

Increasing impact with $p_T(H)$

Uncertainty on measurements across production modes

STXS bins

Relative EFT impact wrt SM
EFT Impact on kinematics

**Groups of parameters that:**
- mainly sensitive in inclusive observable
- appear as overall normalisation
- similar shape dependence across bins

Insufficient information in data to measure EFT parameters simultaneously!

Fit only sensitive directions within parameter groups using STXS covariance matrix

**Principle Component Analysis of**

\[
C^{-1}_{EFT} = P^T C^{-1}_{STXS \times BR} P
\]

where

- \( C \) → covariance matrix,
- \( P \) → EFT parameterisation matrix
Fit basis defined to capture maximum experimental sensitivity across Higgs measurements, can probe 13 parameters with reasonable sensitivity ($\sigma_{unc} \sim 2$) with manageable correlations. Large overlap of operators that also affect top and EW sectors, combination will help improve sensitivity and relax flat directions.
EFT fit results

- Only linear EFT parameterisation considered.
- With these 13 EFT parameters, 3 new parameters than last round (Hyy, H4l, VHbb combination).
- Up to 70% improvement in limits compared to last round due to interplay of EFT effects across different physics process.
- Residual correlations as PCA performed only with groups of operator to preserve interpretability of fit directions.

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**ATLAS** Preliminary $m_H = 125.09$ GeV, $|y_{tH}| < 2.5$

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

**SMEFT $\lambda = 1$ TeV**

$\rho_{tot} = 59\%$
Energy asymmetry in $t\bar{t}$ production
boosted $t\bar{t}$ production
angular observables
Top EFT Summary plots

Higgs combination
VHbb resolved + boosted combination

Top

EW
WW, WZ, 4l, & Z+2jets combination
Considering one unfolded differential cross-section distribution from individual analysis of each process with consistent modelling of measurements: correlated treatment of important systematic sources and SM theory uncertainties.

SMEFTsim 3.0 used to generate linear & quadratic EFT parameterisation in topU3l symmetry.
Sensitive directions

ATLAS Preliminary
\( \sqrt{s} = 13 \) TeV, 36-139 fb\(^{-1} \)

Relative Effect of Wilson Coefficient, for \( \Lambda = 1 \) TeV

- Linear Effect of Wilson Coefficient
- Lin+Quad Effect of Wilson Coefficient
- Experimental Uncertainty

unique impact on WW, WZ and Z+jet

unique impact on WW, WZ

Fit directions determined with PCA

ATLAS Preliminary \( \sqrt{s} = 13 \) TeV, 36-139 fb\(^{-1} \)

Fit directions

Warshaw basis coefficients

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ATLAS PHYS-PUB-2021-021

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Sensitive directions

Fit directions determined with PCA

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

Linear Effect of Wilson Coefficient
Lin+Quad Effect of Wilson Coefficient
Experimental Uncertainty

4q operators mainly affect $\Delta \phi_{ij}$ in Z+2]

Warsaw basis coefficients

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**Sensitive directions**

**ATLAS Preliminary**  
\( \bar{\tau} = 13 \text{ TeV}, 36-139 \text{ fb}^{-1} \)

Relative Effect of Wilson Coefficient, for \( \Lambda = 1 \text{ TeV} \)

2q2l operators mainly affect 4l for \( m_{d_1} > 2m_2 \)

some 2q2l operators also affect high \( p_T^{10} \) WW

**Fit directions**

**Extended Higgs sector**

\( c_{W} = 0.46 \)

\( c_{W} = 0.27 \)

\( c_{W} = 0.57 \)

\( c_{W} = 2.2 \)

\( c_{W} = 0.069 \)

\( c_{W} = 0.16 \)

**Linear Effect of Wilson Coefficient**

**Lin+Quad Effect of Wilson Coefficient**

**Experimental Uncertainty**

**Fit directions determined with PCA**

**ATLAS Preliminary**  
\( \bar{\tau} = 13 \text{ TeV}, 36-139 \text{ fb}^{-1} \)

−0.16

\( \Delta \phi \)

\( \alpha \)

\( \chi^2 \)

\( \bar{\tau} \)

2q2l : 4 fermion

4q : 4 fermion

Probed separately

Warsaw basis coefficients

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Sensitivity directions

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 36-139 \text{ fb}^{-1} \)

Relative Effect of Wilson Coefficient, for \( \Lambda = 1 \) TeV

- \( c_{W} = 0.44 \)
- \( c_{W} = 0.21 \)
- \( c_{W} = 0.4 \)
- \( c_{W} = 0.4 \)
- \( c_{W} = 0.54 \)
- \( c_{W} = 0.99 \)
- \( c_{W} = 2.0 \)
- \( c_{W} = 5.1 \)
- \( c_{W} = 6.1 \)

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 36-139 \text{ fb}^{-1} \)

Fit directions determined with PCA

- \( \text{VFF vertex: 9 operators with correlated impacts} \)
- \( \text{Higgs-EW (quarks/leptons), G_F shift} \)
- \( \text{2q2l: 4 fermion} \)
- \( \text{4q: 4 fermion} \)

Warsaw basis coefficients
Results for sensitive parameters

- Measure 15 EFT parameters simultaneously with combination of four EW analyses
- Results derived for both profiled and one-at-a-time, differences indicative of correlation of parameter
  - Linear, profiled
  - Linear+quadratic, profiled

- Probe coefficients from to ~5 to ~0.1 corresponding to energy scale \( \frac{\Lambda}{\sqrt{c}} \) of ~0.45 TeV to ~3 TeV

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Energy asymmetry in $t\bar{t}$ production
boosted $t\bar{t}$ production
angular observables
Top EFT Summary plots

Higgs
VHbb resolved + boosted combination
Higgs combination

EW
WW, WZ, 4l, & Z+2jets combination

Top
boosted $t\bar{t}$ production

Differential cross-section measured as a function of $p_{T}^{t,1}$ most sensitive to EFT effects, used for reinterpretation

- boosted topologies to access top quarks with high $p_{T}^{t}$
- One-at-a-time limits for several 4-fermion (2-light-quark 2-heavy quark) operators
- Constraints are also placed for two parameters simultaneously, $(c_{tG}, c_{tq}^{3,8}), (c_{tq}^{1,8}, c_{Qq}^{3,8}), (c_{Qq}^{1,8}, c_{tq}^{8})$
First ATLAS measurement of top - anti top-quark energy asymmetry!

- reconstruct boosted hadronic top decay to single lepton+jets
- Sensitive operators: \( LL, RR = \{ c_{Qq11}, c_{Qq18}, c_{tq8}, c_{tu1} \} \), \( RL = \{ c_{tq8}, c_{tu1} \} \)
- One-at-a-time and two-at-time limit for these four fermion operators

Highly polarised top quarks due to V-A nature, decay preserve spin information!

- Polarisation in t-channel single top production
- Unfolded differential distribution of \( \cos \theta_{lx} \) & \( \cos \theta_{ly} \) correlation estimated using statistical bootstrap
- Sensitive to \( c_{tW} \) and \( c_{itW} \) respectively
Summary plots showing sensitivity of different top measurements (t\bar{t}, t\bar{t} + X, single top) to Wilson coefficients

- Linear term negligible for FCNC, constraints reported for d=6 operators contributions at O(Λ⁻⁴)
- Single top polarisation probes c_{\text{tW}} and c_{\text{B}} simultaneously, rest of the limits are obtained for one-at-a-time where all other parameters are set to SM
Conclusions

- SMEFT interpretations across different sectors and processes with ATLAS data evolving well!

- Top processes uniquely sensitive to a large set of operators, can be probed by using different kinematic measurements.

- Full power of SMEFT captured by combining different processes!
  - Higgs (13 parameters)
  - EW (15 parameters)

- Moving towards a harmonised SMEFT framework to interpret different measurements in global fit.

- Theory and experimental considerations evolving for a lot of items,
  - (d=8 operators, EFT uncertainties, EFT validity, matching to UV models, ...)

Exciting Times Ahead!