PROCEEDINGS OF SCIENCE

Experimental Effective Field Theory Results

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The framework of Effective Field Theory (EFT) Lagrangians is an effective and systematic way to search for physics beyond the Standard Model at the LHC using distributions of events in many topologies. A large number of measurements performed by ATLAS and CMS experiments in the top-quark, Higgs and electroweak sectors of the Standard Model include EFT interpretations. They provide complementary constraints, although with various choices of bases and interpretation frameworks. No significant deviations from the Standard Model predictions have been observed so far.

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1. Introduction

Physics beyond the Standard Model (BSM) has been searched for extensively in the past ten years at the LHC, without any evidence so far. In order to complement the direct searches for BSM signatures, precision measurements of Standard Model (SM) processes can be used to look for deviations from the predictions. As deviations could appear with many different patterns, a framework is required to parameterise them in a systematic way. Effective Field Theory (EFT) Lagrangians provide such a framework, where additional operators of dimension greater than four suppressed by powers of a cut-off energy Λ (usually chosen to be $O(1\ \text{TeV})$) are added to the SM Lagrangian. Constraints are then set on the corresponding Wilson Coefficients (WCs).

In the Standard Model EFT (SMEFT), after rejecting operators of dimension 5 and 7, as they violate baryon- and lepton-number conservation, a large number of operators are allowed at dimension 6 or 8, which can be strongly reduced using additional assumptions such as flavour-universal scenarios. The squaring of the Lagrangian then yields linear (from the interference between SM and BSM amplitudes) and quadratic terms in the dimension 6 WCs as lowest order terms in the cross-sections.

While each single measured observable is usually affected by several operators, the accumulation of measurements performed can help disentangle their effects. In particular there is a good interplay between measurements in the top-quark, Higgs and electroweak sectors to probe the SMEFT. As a result, more than 20 measurements performed by the ATLAS [1] and CMS [2] experiments in the past year contain SMEFT interpretations. The most significant are highlighted in this mini-review.

2. Constraints in the top-quark sector

The ATLAS experiment has recently measured the top quark and antiquark polarization in t-channel, using the unfolded distributions of the lepton decay angles in a top-quark reference frame [3]. In this frame, the normalized distributions of $\cos\theta_{\ell x'}$ and $\cos\theta_{\ell y'}$ are sensitive to the real and imaginary coefficients c_{tW} and c_{itW} in the Warsaw basis, while being insensitive to other SMEFT operators. As the corresponding operators appear in both production and decay, terms in the expansion up to the quartic terms are affected, although the linear term dominates the sensitivity. The measurements are compatible with the SM within 2σ.

Differential cross-sections of $t\bar{t}+\gamma$ events have been measured by CMS [4]. The unfolded distribution of $p_{\mathrm{T}}(\gamma)$ in single-lepton events is used to constrain the c_{tZ} and c_{tZ}^{J} operators of SMEFT, which are sensitive to an anomalous $t\gamma$ vertex inducing top-quark electroweak dipole moments. The results are consistent with the SM within 2σ.

The topologies with top quarks and additional leptons have been studied by CMS [5] to probe the $t\bar{t}H$, $t\bar{t}\ell\bar{\ell}$, $t\bar{t}\ell\nu$, $t\ell\bar{\ell}q$ and tHq topologies. A direct SMEFT fit to event yields in 35 signal regions is performed to allow for a simultaneous measurement of 16 WCs. The results are consistent with the SM within 2σ.

A recent analysis of the associated production $t\bar{t}+Z$ and tZ has been performed by CMS [6]. It is dedicated to the constraint of five EFT coefficients, and uses multiclass neural network classifiers in signal regions with 3 or 4 leptons to enhance the sensitivity to either one operator at a time, or to the five operators simultaneously, with an improvement of up to 75% compared to a counting experiment. The constraints on c_{tZ} and c_{tW} are limited by statistical uncertainties, while those on $c^3_{\phi Q}$, $c^-_{\phi Q}$ and $c_{\phi t}$ are limited by systematic uncertainties.

3. Constraints in the Higgs boson sector

In the Higgs boson sector, SMEFT interpretations are included in the publications of many analysis channels. While such interpretations are possible from unfolded cross-section measurements [7], ATLAS uses mainly the measurements performed in the Higgs Simplified Template Cross-Sections (STXS) framework [8–10]. The production cross-sections and branching fractions are parameterised as functions of the WCs, and acceptance effects are included on top when significant. The highest sensitivity is achieved in the interpretation of a combined fit to the $H \to \gamma\gamma$, $H \to 4\ell$, and VH, $H \to b\bar{b}$ channels [11]. As the measurements are impacted by 32 operators that cannot be measured at the same time, a rotation into a basis of physics-guided eigenvectors allows to find 10 sensitive directions that can be probed simultaneously, while all the other WCs are set to 0 without any loss of generality. Results are well compatible with the SM predictions.

A different strategy was chosen by CMS in the $H \to 4\ell$ channel, where a dedicated EFT measurement is performed with an analysis optimised in each category using a matrix element method. The production and decay amplitudes are parameterised including the anomalous effects [12]. This framework is closely related to SMEFT in the Higgs basis. Four coefficients affecting the HVV couplings are probed, including the CP-odd term $\tilde{c}_{ZZ}$. The Hgg and Htt couplings are studied in combination with the $t\bar{t}H$, $H \to \gamma\gamma$ results, as it provides complementary information on κ_t, c_{gg} and their CP-odd counterparts.

4. Constraints from electroweak processes

Many electroweak processes provide interesting EFT constraints, where the sensitivity comes mostly from the high-energy tails of distributions. All results are compatible with the SM predictions.

In the $W\gamma$ final state, constraints can be obtained using the differential cross-section $p_{\mathrm{T}}(\gamma)$ [13] or a 2D differential cross-section in $p_{\mathrm{T}}(\gamma)$ and in the azimuthal angle of the lepton in a center-of-mass frame of the $W\gamma$ system (ϕ_f) [14]. The latter significantly enhances the constraint on the linear term of the O_{WWW} operator of the HISZ basis by overcoming its helicity suppression, as shown in Fig. 1.

Double differential cross-sections in the 4 leptons final state (probing $Z \to 4\ell$, $H \to 4\ell$ and $ZZ \to 4\ell$) are used by ATLAS to set individual constraints on 22 WCs in the Warsaw basis [15]. In the WZ final state, the m_{WZ} distribution is fitted by CMS to simultaneously constrain the CP-even WCs c_W, c_{WWW} and c_b or the CP-odd $\tilde{c}_W$ and $\tilde{c}_{WWW}$ [16]. Constraints on the same operators are also set in the WW final state from the $m_{e\mu}$ distribution [17]. The $WW+\geq 1$ jet topology is studied by ATLAS, as the hard jet requirement reduces the helicity suppression of the linear term involving the c_W coefficient, although the quadratic term still dominates the sensitivity.

A combined fit of unfolded $p_{\mathrm{T}}^{\mathrm{lep}}$ cross-sections in WW events and of the ggH and VBF signal strengths in the $H \to WW^*$ final state has been performed by ATLAS [18]. A rotation from

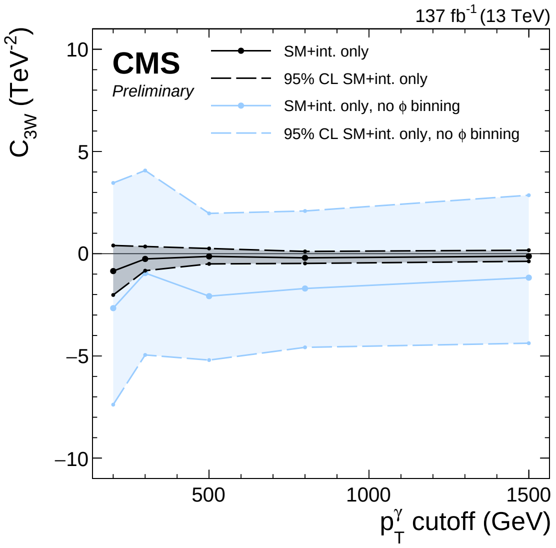

Figure 1: Best-fit values of c_{WWW} and corresponding 95% CL confidence intervals as a function of the maximum p_T^{γ} bin included in the fit of the double differential $W\gamma$ analysis [14]. The limits using the linear terms are shown with and without the binning in $|\phi_f|$, with black and blue lines respectively.

the Warsaw basis into a physics-guided eigenbasis is used to probe 8 sensitive directions. This combination of analyses that used different methodologies is the first of its kind and represents a stepping stone for more global EFT combinations.

The electroweak production of dibosons in association with dijets is sensitive to anomalous quartic gauge couplings (aQGC). Such final states are used by CMS to probe dimension-8 operators involving the Higgs and the gauge fields (Sx, Tx and Mx): $WZjj$ and $WWjj$ [19], $W\gamma jj$ [20], $ZZjj$ [21] and $Z\gamma jj$ [22]. Fits are performed to m_{VV} distributions, with or without a cut-off at the unitary limit of 1.5 TeV. The $p_T^{\gamma\gamma}$ distributions in triple gauge boson processes $W\gamma\gamma$ and $Z\gamma\gamma$ provide complementary information on the same aQGC operators [23]. All results are consistent with the SM.

5. Conclusions

Interpretations of measurements in the SMEFT framework are included in many results in the top-quark, Higgs and electroweak sectors by ATLAS and CMS, as they provide complementary information to probe subtle effects in higher-energy BSM physics. While all individual results have not shown any significant deviation from the SM predictions so far, a more complete picture could be obtained by means of a simultaneous interpretation of all measurements. Such a momentous task would require a much higher degree of harmonization (given the diversity of interpretation frameworks, of EFT bases and of methodologies) and better prescriptions for the treatment of higher-order effects. All these topics are in the mandate of the LHC EFT Working Group [24].

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