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Letter

Combined effective field theory interpretation of measurements sensitive to quartic gauge boson couplings in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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ABSTRACT

A combination of measurements sensitive to anomalous quartic electroweak gauge boson couplings is presented using proton–proton collision data collected by the ATLAS detector at $\sqrt{s} = 13$ TeV at the LHC. Contributing analyses include measurements of vector-boson scattering in numerous final states as well as a tri-boson measurement. The combined measurement is used to constrain anomalous electroweak boson quartic self-couplings that result from dimension-8 operators in the Éboli model using an effective field theory. Results are presented as 68% and 95% confidence level intervals parameterised by one or two Wilson coefficients, both with and without unitarity constraints applied. Theoretical bounds from unitarity and positivity are overlaid where relevant. Confidence intervals obtained from simultaneous profiled fits to all Wilson coefficients are also presented.

1. Introduction

The Large Hadron Collider (LHC) has enabled a rigorous study of the Standard Model (SM) up to the electroweak scale and beyond. Numerous dedicated analyses searching for new TeV-scale particles have been conducted by both the ATLAS and CMS collaborations, see for example Ref. [1,2], without finding any significant excess above the SM background prediction. In the absence of direct evidence of new physics, a complementary program is to search for small deviations from SM predictions that can arise from new physics with energy scales beyond that of direct production at the LHC. The SM effective field theory (EFT) [3] is a theoretical framework that describes potential new physics at or above a scale Λ in terms of SM gauge invariant operators of dimension-d, which are suppressed by the scale $\frac{E^{d-4}}{\Lambda^{d-4}}$, where E is the energy scale of the process. Wilson coefficients, denoted f_i, parameterise the size of each potential operator contribution.

Constraints on dimension-6 operators were extracted from combinations of results from Higgs boson, electroweak, top-quark, and jet related measurements using 13 TeV LHC data from both the ATLAS and CMS collaborations [4,5], and electroweak precision observables at the Z mass performed at LEP and SLC [6]. Such results are truncated at dimension-6 since these are the leading-order new-physics contributions to most processes, excluding odd-dimension operators that violate baryon and lepton number conservation. Many potential beyond the SM scenarios predict direct anomalous Quartic-Gauge Couplings (aQGCs) [7,8]. Others predict resonant new physics beyond the TeV scale that could be experimentally observed at current collider experiments as aQGCs, for example composite Higgs boson models [9], warped extra-dimension models [10], gravitons [11], two-Higgs-doublet models [12] and unified models [13]. While dimension-6 operators can indirectly affect processes sensitive to aQGCs through diagrams with triple-gauge boson vertices, operators affecting only quartic-gauge couplings begin to appear at dimension-8. Thus, such models are potentially not well constrained by dimension-6 results.

At dimension-8 there are tens of thousands of new operators along with multiple insertions of dimension-6 operators, making probing all operators experimentally impractical. The effects of dimension-8 operators that give rise to aQGCs are most experimentally prevalent in the vector-boson-scattering (VBS) process and tri-boson production. Representative Feynman diagrams for the VBS and tri-boson processes are shown in Fig. 1. The results presented here use the Éboli model [8] as the basis for the dimension-8 operators that predict aQGCs. The dimension-6 operators that cause anomalous triple gauge couplings that would contribute to the analyzed VBS and tri-boson channels (Fig. 1(a) and (c)) are assumed to be sufficiently well constrained by dedicated searches such that their contributions are negligible.

Measurements of VBS production have been reported by the ATLAS and CMS collaborations using the full Run 2 13 TeV data in

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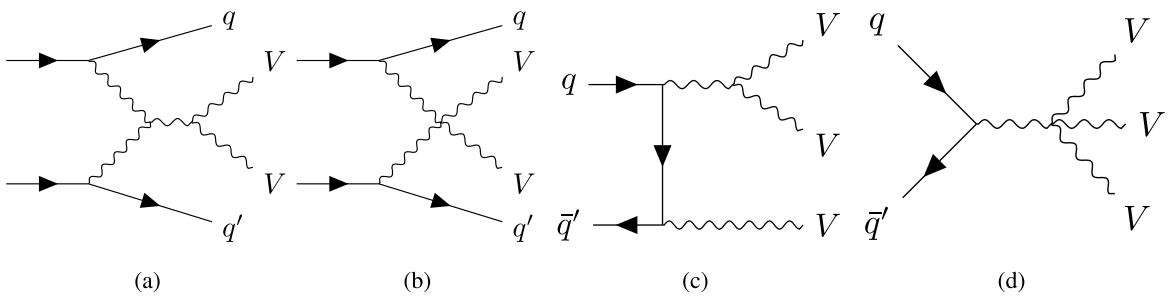

Fig. 1. Representative Feynman diagrams for a) vector-boson scattering with triple-gauge vertices, b) vector-boson scattering with quartic-gauge vertices, c) tri-boson production with triple-gauge vertices, and d) tri-boson production with quartic-gauge vertices. The aQGCs act only on diagrams b) and d) through anomalous values or vertices forbidden in the SM.

numerous experimental channels [14–28]. Similarly, tri-boson production has been measured in several experimental channels by the ATLAS [29–31] and CMS [32–35] collaborations.

This Letter presents a combination of measurements from seven VBS analyses [14,18,20,22,24,25,27] and one tri-boson analysis [29], each performed using 140 fb^{-1} of pp collision data recorded by the ATLAS detector during Run 2 of the LHC. A combined likelihood is built from the likelihoods of the input measurements and a likelihood fit is performed to extract constraints on dimension-8 Wilson coefficients. Constraints on the Wilson coefficients of 17 of the Éboli basis operators are presented when considering one or two operators at a time, with and without unitarity constraints. Profiled confidence intervals obtained from simultaneous fits to the 17 operators are also presented.

2. Theoretical framework

The SM Effective Field Theory provides a model-independent description of effects beyond the SM that introduce new particles at a mass scale Λ, which is large in comparison to the electroweak scale. At energies significantly below the scale Λ, the effect of new physics can be described by additional operators $\mathcal{O}_i^{(d)}$ of energy dimension $d > 4$ that extend the SM Lagrangian in orders of E/Λ, where E is the energy exchanged in the process. These operators are built from combinations of SM fields that obey the symmetries of the SM such as gauge invariance. Ignoring odd-dimensional operators, which introduce lepton and baryon number violation, and dimension-6 terms, which are highly constrained by existing results, the leading terms in this effective Lagrangian become

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}}^{(4)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} \tag{1}$$

where $\mathcal{L}_{SM}^{(4)}$ is the SM Lagrangian, which contains dimension-2 and dimension-4 operators. The remaining terms $\mathcal{O}_i^{(8)}$ denote the new dimension-8 operators, and $f_i^{(8)}$ are the corresponding dimensionless Wilson coefficients.

With the Lagrangian given in Eq. (1), scattering cross-sections can be approximated as

$$\sigma = |\mathcal{M}_{\text{SM}}|^2 + \sum_i \frac{f_i^{(8)}}{\Lambda^4} 2\text{Re}\left(\mathcal{M}_i^{(8)} \mathcal{M}_{\text{SM}}^*\right) + \sum_i \frac{\left(f_i^{(8)}\right)^2}{\Lambda^8} |\mathcal{M}_i^{(8)}|^2 + \sum_{i<j} \frac{f_i^{(8)} f_j^{(8)}}{\Lambda^8} 2\text{Re}\left(\mathcal{M}_i^{(8)} \mathcal{M}_j^{(8)*}\right) \tag{2}$$

where $\mathcal{M}_{\text{SM}}$ is the matrix element as it occurs in the SM, and $\mathcal{M}_i^{(8)}$ are the new matrix elements calculated from the operators $\mathcal{O}_i^{(8)}$. The first and third terms refer to the SM and the dimension-8 squared amplitude contributions to the cross-section, respectively. The second term, which is of order Λ^{-4}, is the interference between the SM and the dimension-8 operators. Due to the scaling behavior of the SM-interference and the dimension-8 squared amplitude contributions to the cross-section relative to the Wilson coefficients, the second and third terms are referred to as the linear and quadratic contributions of the expansion, respectively. The last term represents the interference of dimension-8 operators with one another, and is referred to as the cross-term.

In this work, confidence intervals on dimension-8 operator couplings are set using the Éboli model [8], which provides a subset of the total dimension-8 operators satisfying the SM $SU(2)_L \times U(1)_Y$ symmetry and specifically producing aQGCs. In this model, the 21 new C-even P-even dimension-8 operators can be categorized into: scalar-types that only contain derivatives of the scalar Higgs field (O_{S0}, O_{S1}, O_{S2}), tensor-types that only contain electroweak boson field strengths (O_{T0}, …, O_{T9}), and mixed-type operators (O_{M0}, …, O_{M7}). The O_{M6} term was found to be redundant in Ref. [36] and is not considered in this work. Similarly, the O_{T3} and O_{T4} operators are excluded due to the fact this MadGraph5_aMC@NLO simulation implementation was not available in many of the individual analysis publications. Following Ref. [14,18,27] the operators O_{S0} and O_{S2} are varied simultaneously with equal coefficient values f_{S02}. This leaves 17 independent Wilson coefficients, all of which are considered in this work. It is worth noting that due to the helicity structure of the Éboli operators, the SM-interference term in Eq. (2) is highly suppressed in the Éboli basis.

Theoretical constraints limit the regime of validity of the EFT operator expansion, and are considered in the result. Operators with mass dimension greater than four can lead to interaction probabilities that increase until unitarity is violated. Theoretical bounds are thus obtained by requiring that perturbative partial-wave unitarity is satisfied as derived in Ref. [37,38]. In addition, assuming the new high-energy physics obeys the low-scale principles of unitarity, locality, and causality, cross-sections on the helicity-amplitude must be positive definite at all scales. Positivity bounds are computed for the Éboli dimension-8 basis in Ref. [39].

Simulated samples of VBS and tri-boson production under the effect of the Éboli model were simulated using MadGraph5_aMC@NLO (v3.5.5) [40] at leading-order in quantum chromo-dynamcis (QCD) with the NNPDF30_nlo_as_0119 parton distribution function set [41]. Decays of the vector bosons were handled with MadSpin [42]. Parton showering, hadronisation, and underlying event modeling were performed using Pythia 8 with the dipole recoil scheme enabled [43]. The total cross-section in Eq. (2) was decomposed, with the linear, quadratic, and cross-term EFT contributions simulated separately. The SM component of the expansion uses the original simulated samples from the individual analyses that may be at higher-orders in QCD. The total process including the EFT effects for a given Wilson coefficient value is then reproduced by adding the EFT contributions, scaled appropriately by the Wilson coefficients, to the predicted SM contribution.

Table 1
Summary of input analyses in the combination. Full, Partial, and None refer to whether all relevant operators, a subset of them, or no dedicated interpretation were explored in the original publication.

Analysis	Input type	Éboli operator results	Luminosity [fb^{-1}]	Reference
$VVjj \to (\ell\ell jj/\ell\nu jj/\nu\nu jj)jj$	Reco-level Differential	Full	140	[27]
$WZjj \to l^+l^-l^\pm\nu jj$	Reco-level Differential	Partial	140	[18]
$W^\pm W^\pm jj \to l^\pm\nu l^\pm\nu jj$	Reco-level Differential	Full	139	[14]
$ZZjj \to l^+l^-l^+l^-jj$	Unfolded Differential	None	140	[20]
$W\gamma jj \to l^\pm\nu\gamma jj$	Unfolded Differential	Full	140	[22]
$Z\gamma jj \to \nu\bar{\nu}\gamma jj$	Reco-level Inclusive	Partial	139	[24]
$Z\gamma jj \to l^+l^-\gamma jj$	Unfolded Differential	None	140	[25]
$W\gamma\gamma \to l^\pm\nu\gamma\gamma$	Reco-level Differential	None	140	[29]

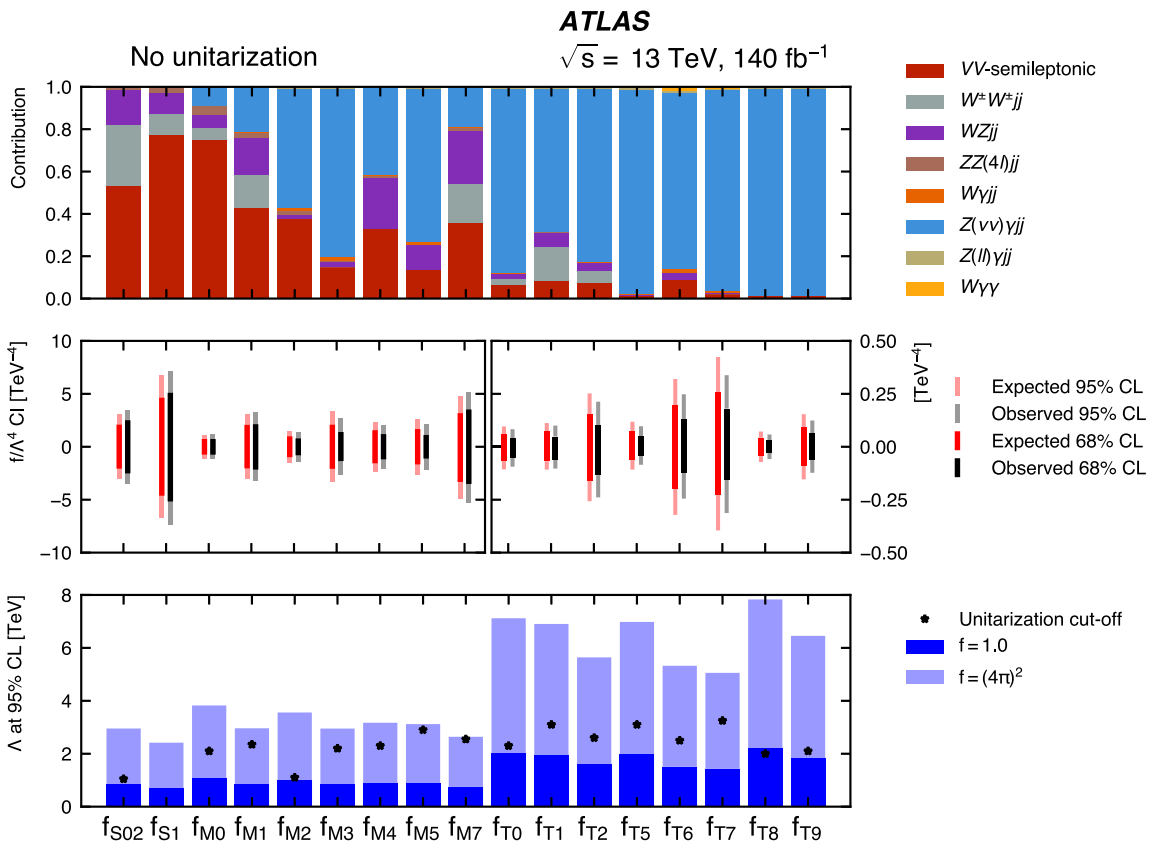

Fig. 2. Contributions of the individual channels to the combination (top), expected and observed 68% and 95% confidence level intervals from the combined fit (middle) and the probed energy scale for two illustrative values of the Wilson coefficients (bottom). No constraints from unitarity bounds are applied. The energy scale of the observed unitarization cut-off as evaluated through a clipping procedure is overlaid on the bottom panel. No unitarization cut-off is found for the f_{S1} operator where the experimental interval is always weaker than the unitarity constraint.

3. Input measurements

All measurements included in the combination were performed using 140 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data recorded with the ATLAS detector at the LHC. The input measurements used to constrain aQGC parameters are summarized in Table 1. The individual measurements provide either reconstruction-level (reco-level) results in a differential distribution, unfolded results of a differential distribution, or a reconstruction-level inclusive cross-section. Several analyses were published with an earlier measured integrated luminosity value of 139 fb^{-1} with a larger uncertainty. For this result, these inputs were adjusted to reflect the more precise, updated measured values.

To facilitate the statistical interpretation, it is preferable that each included analysis region has no statistical overlap so that each data event is only counted once in the combined result. There is a non-negligible overlap found between the control region of the $W^\pm W^\pm jj$ measurement that is used to determine the shape of the $WZjj$ background, and the signal region of the $WZjj$ measurement. This overlapping control region is dropped from the combination to avoid double counting events. This choice has a negligible effect on the results. The overlap between analyses is at the sub-percent level in all other cases.

Several adjustments are made to the input results to facilitate full coverage of the operator parameter space across experimental channels. In the $Z(\nu\nu)\gamma jj$ aQGC results, only a single overflow bin in leading photon p_T was used in the original EFT interpretation, with a threshold value varying as function of the operator and of the clipping value. For this analysis the full leading photon p_T distribution is used in eight bins, as it facilitates the combination with the other analyses and allows probing

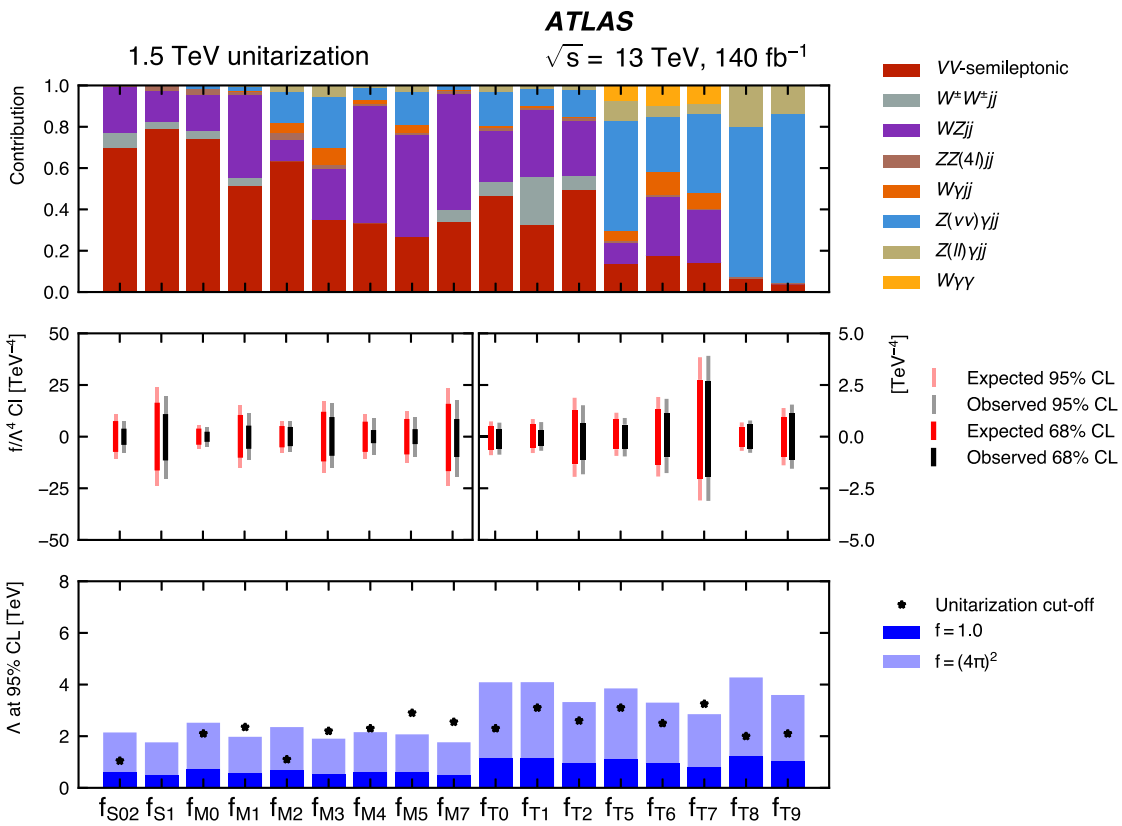

Fig. 3. Contributions of the individual channels to the combination (top), expected and observed 68% and 95% confidence level intervals from the combined fit (middle) and the probed energy scale for two illustrative values of the Wilson coefficients (bottom). Unitarity is preserved by setting higher dimension operator contributions to zero above a clipping threshold of 1.5 TeV. The energy scale of the observed unitarization cut-off as evaluated through a clipping procedure is overlaid on the bottom panel. No unitarization cut-off is found for the f_{S1} coefficient where the experimental interval is always weaker than the unitarity constraint.

several operators at the same time. This change improves the confidence intervals by 1%. For $W\gamma\gamma$, the reco-level result was used, splitting the final observable of leading photon p_{T} into three bins $[25, 45, 80, \infty]$ GeV, as opposed to the single-bin result used in the publication. The data-driven background estimation procedure was reproduced and validated, as was done in the original publication, with this finer binning. This finer binning improves the constraints by up to 40%. In its original publication, the $W\gamma jj$ result used a different kinematic observable for each operator under consideration. For simplicity in this combination, the unfolded p_{T} of the leading lepton distribution is used as the final observable, which at most degrades the confidence intervals on a subset of operators by 20%.

In several of the individual measurement publications, either none or only a subset of the operators were probed. For completeness, this result considers the potential impact of all operators in all channels. The published $Z(\ell\ell)\gamma jj$, $ZZ(4\ell)jj$ and $W\gamma\gamma$ measurements do not provide a dedicated Éboli model result, and so in this Letter a dedicated interpretation is conducted for each of these analyses. For the $Z(\ell\ell)\gamma jj$ ($ZZ(4\ell)jj$) result, the publicly available one(two)-dimensional unfolded distribution of the p_{T} of the $Z\gamma$ system (invariant masses of the ZZ and dijet systems), are reinterpreted in this context. For the $W\gamma\gamma$ analysis, the full reconstruction level template was generated for all samples, and is used for reinterpretation. In the initial publication of $Z(\nu\nu)\gamma jj$ and $WZjj$, which used reco-level results, only a subset of operators was probed, so a template replacement procedure is developed to derive the kinematic shapes of the missing operators. In this procedure, the histogram template of the differential yields of the missing operator in the observable of interest is approximated using the reco-level template of an existing operator that has the lowest χ^2 difference between corresponding templates at particle-level. Differences between cross-sections are accounted for in the replacement procedure. Dedicated non-closure studies on this procedure are conducted by applying the replacement in situations where the original templates exist. The difference in the confidence intervals obtained from the two templates is found to be at the percent level in all cases, except for the $Z(\nu\nu)\gamma jj$ analysis that found an impact of 9% on the intervals for the f_{M1} and f_{T9} coefficients. A residual closure study is performed adding a conservative 30% difference directly as an additional source of uncertainty in the $Z(\nu\nu)\gamma jj$ analysis for all operators, with the corresponding confidence intervals widened by at most 4%, and usually at the sub-percent level. Due to the negligible effect of the residual non-closure uncertainty on the replacement procedure, it is not included for the complete set of final results presented here.

Cross-terms were not considered in the original publications except for the $WZjj$ and $W^{\pm}W^{\pm}jj$ analyses in several specific cases. As such, cross-term effects at reco-level are simulated through the same replacement procedure.

4. Statistical model

The combination of the individual channels proceeds via a joint simultaneous likelihood model of the discriminating variables across all

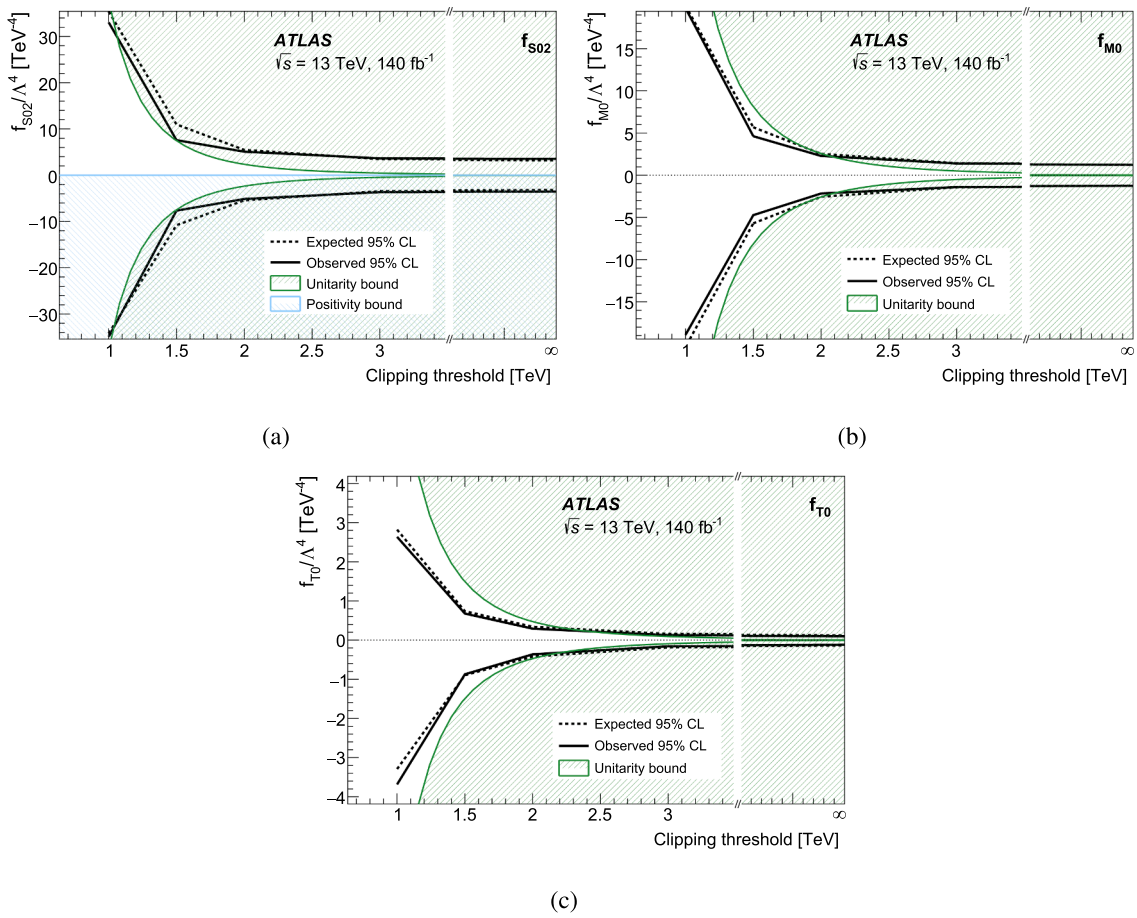

Fig. 4. Expected and observed 95% confidence level confidence intervals on the a) f_{S02}, b) f_{M0} and c) f_{T0} Wilson coefficients as a function of clipping threshold. Unitarity and positivity bounds are shown in green and blue respectively. Unitarized intervals are taken to be the intersection between the interpolated confidence intervals and the unitarity bound.

of the channels. The Wilson coefficients f_i are treated as parameters of interest of the fit model. Systematic uncertainties are treated as nuisance parameters, denoted by $\boldsymbol{\theta}$. A likelihood ratio test statistic λ, is built from the likelihood to evaluate 68% and 95% confidence level intervals for the Wilson coefficients:

$$\lambda = -2\log\frac{L(\boldsymbol{\mu_i}, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\boldsymbol{\mu}}_{\boldsymbol{i}}, \hat{\boldsymbol{\theta}})} \tag{3}$$

where $\mu_i = f_i/\Lambda$, $L(\boldsymbol{\mu_i}, \hat{\hat{\boldsymbol{\theta}}})$ is the maximum of the likelihood for a given μ_i, and $L(\hat{\boldsymbol{\mu}}_{\boldsymbol{i}}, \hat{\boldsymbol{\theta}})$ is the absolute maximum of the likelihood. The total likelihood is the product of the individual likelihoods from the individual channels, which have not been changed relative to the original publications except for details mentioned earlier in this Letter. For each given set of Wilson coefficients, a maximum-likelihood fit is performed by setting other coefficients to zero and maximizing the likelihood relative to the nuisance parameters. Confidence intervals are derived using Wilks' theorem, assuming that the profile likelihood test statistic is χ^2-distributed [44] with degrees of freedom matching the number of fitted Wilson coefficients. The validity of Wilks' theorem, which holds asymptotically in the large sample limit, is tested against a full pseudo-experiment procedure in several cases, and the reported 68/95% confidence level intervals are validated within 5%. Expected confidence intervals are computed from synthetic data constructed such that the estimators of all parameters match the true parameters of the SM-only hypothesis [44].

Since each analysis is statistically limited, the choice of correlation scheme between nuisance parameters of the input analysis has negligible impact on the final result, with the total confidence intervals changing by less than one percent in the extreme case where all systematic effects are removed. None the less, all systematic uncertainties are treated as correlated across analyses if they originate from the same source. Thus all experimental uncertainties in the reconstruction and identification of final state jets, electrons, photons, muons, and missing transverse momentum, and the luminosity and pile-up uncertainties, are treated as fully correlated across all analyses. There is an exception for jet-based systematic uncertainties in the $Z(\nu\nu)\gamma jj$ analysis that are uncorrelated from the other analyses as a different jet definition is used. Similarly heavy-flavor identification uncertainties are only correlated across analysis using the same algorithm definition and identification working point and uncorrelated otherwise. Modeling uncertainties on the various background processes of each analysis are treated as uncorrelated due to the specific phase space of each analysis. On the other hand, modeling uncertainties on the signal EFT processes, originating from QCD scale and parton distribution functions, are treated as correlated across all VBS analyses, with the $W\gamma\gamma$ process left uncorrelated due to the different initial parton contributions and relevant energy scales. For the $Z(\nu\nu)\gamma jj$ and $W\gamma\gamma$ analyses, all systematic uncertainties were re-evaluated using the finer discriminant binning explored in this work.

Several fits are performed for different interpretations of the data. One-dimensional fits are performed for each operator allowing only its matching Wilson coefficient to vary in the fit, while the remaining are set to zero. Two-dimensional confidence intervals are presented for pairs of operators using a similar fit model where only the respective Wilson coefficients are non-zero and allowed to vary. Profiled likelihood confidence intervals are also presented where all Wilson coefficients are allowed to float simultaneously. Profiled results enable the interpretation

Table 2
Expected and observed 95% confidence level intervals from the combined fit within the constraints of unitarity for each Wilson coefficient considered. Unitarity is preserved using the clipping procedure where the abscissa and ordinate of the intersection point of the unitarity bound and the confidence intervals as a function of clipping threshold is taken as the unitarization cut-off and interval respectively. No unitarized confidence interval is found for the f_{S1} coefficient where the experimental interval is always weaker than the unitarity constraint.

Coefficient	Expected		Observed	
	Confidence interval [TeV^{-4}]	Unitarization cut-off [TeV]	Confidence Intervals [TeV^{-4}]	Unitarization cut-off [TeV]
f_{S02}/Λ^4	[-32.3, 34.2]	1.0	[-33.2, 30.1]	1.0, 1.1
f_{S1}/Λ^4	–	–	–	–
f_{M0}/Λ^4	[-2.55, 2.52]	2.0	[-2.08, 2.22]	2.1
f_{M1}/Λ^4	[-5.72, 5.78]	2.3	[-5.44, 5.18]	2.3, 2.4
f_{M2}/Λ^4	[-15.8, 15.7]	1.2	[-23.7, 22.8]	1.1
f_{M3}/Λ^4	[-8.49, 8.49]	2.0	[-6.56, 6.63]	2.2
f_{M4}/Λ^4	[-4.78, 4.76]	2.1	[-3.59, 3.63]	2.3
f_{M5}/Λ^4	[-4.79, 4.79]	2.5	[-3.04, 3.10]	2.9
f_{M7}/Λ^4	[-8.50, 8.04]	2.5	[-7.90, 7.65]	2.5, 2.6
f_{T0}/Λ^4	[-0.40, 0.30]	2.1, 2.3	[-0.32, 0.22]	2.2, 2.4
f_{T1}/Λ^4	[-0.18, 0.18]	3.0	[-0.16, 0.16]	3.1
f_{T2}/Λ^4	[-0.71, 0.67]	2.4	[-0.61, 0.42]	2.5, 2.7
f_{T5}/Λ^4	[-0.26, 0.39]	2.5, 2.7	[-0.15, 0.17]	3.0, 3.2
f_{T6}/Λ^4	[-0.87, 0.85]	2.2	[-0.55, 0.57]	2.5
f_{T7}/Λ^4	[-0.69, 1.05]	2.7, 3.0	[-0.52, 0.56]	3.2, 3.3
f_{T8}/Λ^4	[-0.50, 0.50]	1.8	[-0.28, 0.28]	2.0
f_{T9}/Λ^4	[-0.65, 0.65]	2.0	[-0.53, 0.53]	2.1

of the results with phenomenological models that predict simultaneous changes to multiple Wilson coefficients.

5. Results

The 68% and 95% confidence level intervals for each Wilson coefficient are shown in Fig. 2 (middle panel), which are obtained from fits where all but the relevant coefficient are fixed to zero. The contribution of each input channel on the combined confidence intervals is shown in Fig. 2 (top-panel) and is calculated as in Eq. (4), where σ_i is the 68% confidence level intervals obtained in channel i for a given Wilson coefficient:

$$\text{Contribution(chan.)} = \frac{\frac{1}{\sigma^2_{\text{chan.}}}}{\sum_i^{N_{\text{chan.}}} \frac{1}{\sigma_i^2}} \tag{4}$$

The sensitivity reach in terms of the new physics scale Λ for each Wilson coefficient is shown at the 95% confidence level intervals in Fig. 2 (bottom-panel) and compared to bounds set by unitarity constraints. The best individual constraint on the f_{S02}, f_{S1}, f_{M0}, f_{M1}, and f_{M7} Wilson coefficients originate from the $VV-$semileptonic analyses, while the best individual result on the f_{M2}, f_{M3}, f_{M4}, f_{M5}, and all tensor-type Wilson coefficients come from the $Z(\nu\nu)\gamma jj$ channel. The intervals on the scalar and mixed-type operators are tightened by up to 20% in the combined fit relative to those derived using individual channels. Due to the dominant sensitivity in the $Z(\nu\nu)\gamma jj$ analysis, the tensor-type operator constraints are negligibly improved in the combined fit.

As discussed in Section 2, operators with mass dimension greater than four can lead to interaction probabilities that increase until unitarity is violated. Following Ref. [45], the confidence intervals are recalculated for cases where the EFT contributions are zeroed for energy scales above a selected value, known as the clipping threshold. This method provides an easily reproducible result, and provides a conservative limit as any deviations above the energy-scale are not considered consistent with the EFT. The energy scale is given by the diboson invariant mass for VBS analyses and by the largest of the three possible diboson invariant masses for the tri-boson analysis. The confidence intervals are recalculated for clipping thresholds of 0.7, 1, 1.5, 2 and 3 TeV, with the results for the 1.5 TeV clipping threshold shown in Fig. 3. It can be seen that the combined intervals on the Wilson coefficients at the 1.5 TeV clipping threshold are approximately an order of magnitude wider than the non-unitarized intervals. The input channels most sensitive to the clipping threshold are the $VV-$semileptonic and $Z(\nu\nu)\gamma jj$ channels, where the fitted observables have a large reach in energy. Consequently, it can be seen at the 1.5 TeV clipping threshold that the contribution to the interval of some coefficients is more distributed across the input channels, with the $WZjj$ channel providing a similar contribution to previously-dominant $VV-$semileptonic and $Z(\nu\nu)\gamma jj$ channels.

Unitarized confidence intervals are chosen as the intersection between the interpolated confidence intervals as a function of clipping threshold and the theoretical unitarity bounds provided in Ref. [37, 38]. The clipping threshold at the unitarized point is designated as the unitarization cut-off. Examples of the confidence intervals scans across clipping thresholds for the combined fit on the f_{S02}, f_{M0}, and f_{T0} Wilson coefficients are shown in Fig. 4. Where applicable, positivity bounds from Ref. [39] are shown. A unitarization cut-off is found in all cases except for the f_{S1} coefficient, where the theory bound is tighter than the derived experimental interval at all clipping thresholds.

The combined expected and observed unitarized confidence intervals, along with the energy threshold that maintains unitarity, are displayed in Table 2. These combined results improve upon the previous published confidence intervals on these Wilson coefficients by 17–96% depending on the coefficient. The improvements in the unitarized results are larger than for the results without unitarity, due to steep trend in the theoretical unitarity bounds as a function of clipping threshold seen in Fig. 4, which favors sensitivity at low clipping threshold. In this regime more analyses have a non-negligible contribution to the combined results, which illustrates the merit of such a combination. The confidence intervals are competitive with existing results from CMS [21,26,33,45–47].

Results were investigated for pairs of Wilson coefficients that have an appreciable cross-term, while keeping the others set to zero. The size of cross-terms is highly correlated with the structure of the Éboli operator basis, with high-suppression between scalar, mixed, and tensor type families, and block-structure within each. For instance, the operators associated with the f_{M0}, f_{M1}, and f_{M7} coefficients form a mostly orthogonal subset relative to the f_{M2}, f_{M3}, f_{M4} and f_{M5} in the mixed-type family. Two dimension exclusion contours at 68% and 95% confidence level for the f_{M2}, f_{M3}, f_{M4}, and f_{M5} pairings can be seen in Fig. 5, without clipping, alongside with the individual negative-log likelihood scans projections along each coefficient direction in the fit. Two

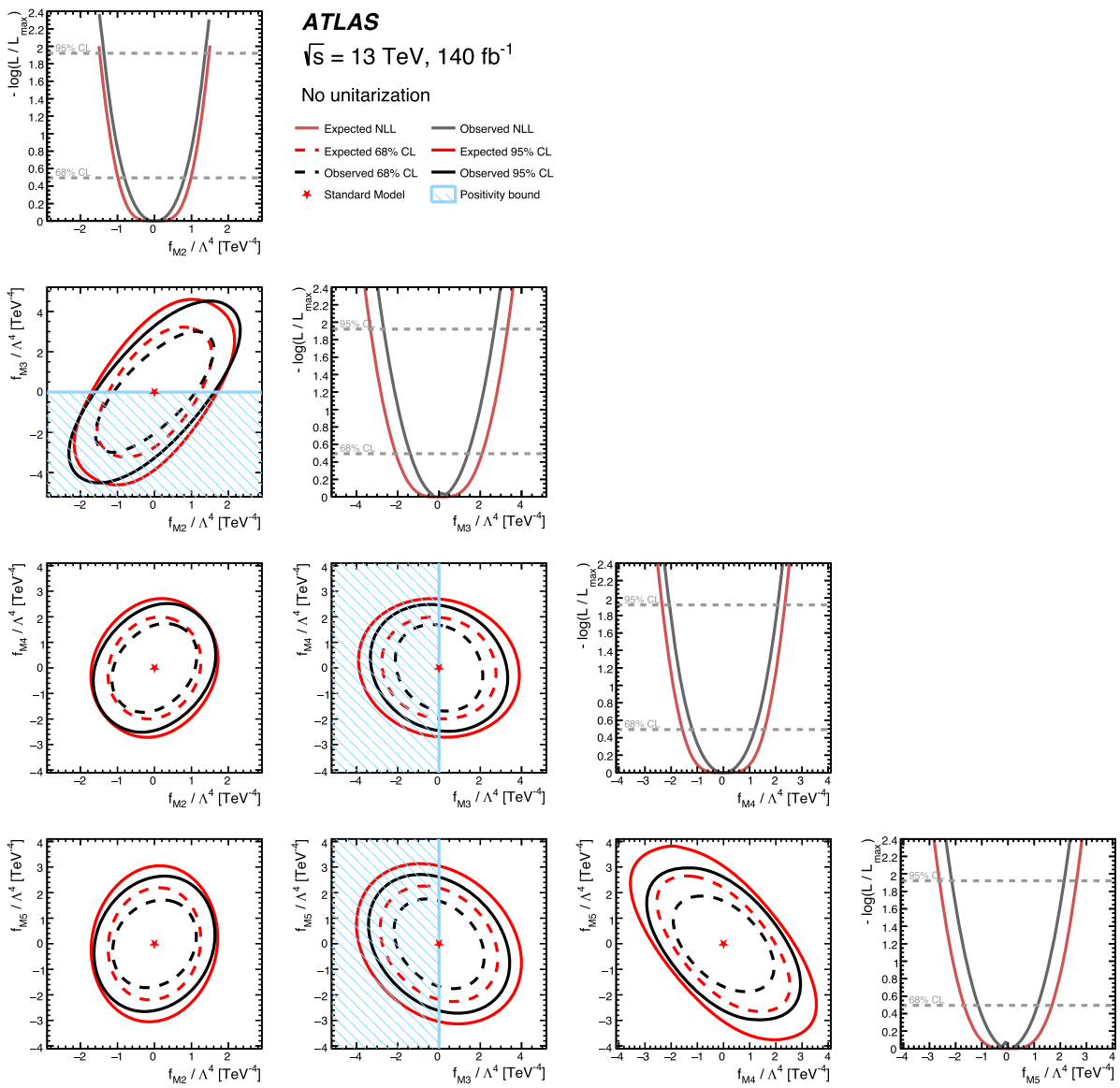

Fig. 5. Expected (red) and observed (black) 68% (dashed) and 95% (solid) confidence level contours when considering two of the f_{M2}, f_{M3}, f_{M4}, and f_{M5} coefficients simultaneously alongside the relevant cross-term. The expected (greyed-red) and observed (grey) negative log-likelihood (NLL) curve for each of the operators when considering just one coefficient at a time is also shown. Unitarity constraints are not visible and positivity bounds are overlaid as a blue filled region.

Table 3
Expected and observed 95% confidence level intervals allowing all Wilson coefficients to be fitted simultaneously.

Coefficient	Profiled expected confidence intervals [TeV^{-4}]	Profiled observed confidence intervals [TeV^{-4}]
f_{S02}/Λ^4	[-4.06, 4.08]	[-4.87, 4.88]
f_{S1}/Λ^4	[-8.72, 8.73]	[-9.82, 9.82]
f_{M0}/Λ^4	[-1.67, 1.68]	[-1.68, 1.65]
f_{M1}/Λ^4	[-8.13, 7.52]	[-9.05, 8.58]
f_{M2}/Λ^4	[-1.91, 1.91]	[-1.97, 1.99]
f_{M3}/Λ^4	[-4.16, 4.16]	[-3.89, 3.92]
f_{M4}/Λ^4	[-3.15, 3.15]	[-2.55, 2.56]
f_{M5}/Λ^4	[-3.48, 3.49]	[-2.77, 2.77]
f_{M7}/Λ^4	[-16.6, 15.7]	[-12.4, 12.9]
f_{T0}/Λ^4	[-0.33, 0.24]	[-0.34, 0.22]
f_{T1}/Λ^4	[-0.199, 0.211]	[-0.254, 0.283]
f_{T2}/Λ^4	[-0.578, 0.639]	[-0.665, 0.599]
f_{T5}/Λ^4	[-0.405, 0.384]	[-0.319, 0.289]
f_{T6}/Λ^4	[-0.658, 0.642]	[-0.490, 0.370]
f_{T7}/Λ^4	[-1.51, 1.58]	[-1.17, 1.13]
f_{T8}/Λ^4	[-0.196, 0.181]	[-0.163, 0.147]
f_{T9}/Λ^4	[-0.360, 0.384]	[-0.281, 0.280]

dimensional results are obtained for each clipping threshold. Positivity bounds are shown where applicable, and reduce the constrained phase space drastically in such cases.

Fits are also performed allowing all Wilson coefficients to float in the fit. Cross-term contributions are relevant in this fit, which, as explained above, are highly suppressed between operators of different scalar/mixed/tensor type, but can be sizeable within the types. The expected and observed 95% confidence level intervals from these profiled fits with no clipping applied are shown in Table 3. For coefficients without sizeable cross-term pairs, the profiled results differ by only a few percent relative to those obtained with the individual Wilson coefficient fits presented earlier. More significant changes can be seen for f_{M7}, f_{T0}, f_{T1}, f_{T5}, f_{T6}, f_{T7}, f_{T8}, and f_{T9} that have non-negligible cross terms with other operators.

6. Conclusions

This Letter details a combination of VBS and tri-boson measurements performed using pp collision data collected by the ATLAS detector at $\sqrt{s} = 13$ TeV at the LHC to optimally constrain dimension-8 effective field theory operators producing aQGCs. This is the most comprehensive set of aQGC EFT results to date and the confidence intervals are competitive with similar results from CMS.

Results are presented in the form of 68% and 95% confidence level intervals, from fits to single Wilson coefficients with others set to zero, and from two dimensional fits for operator pairs with non-negligible cross terms. It is found that the 68% and 95% confidence level intervals on the coefficients without unitarization applied are mainly driven by the $Z\gamma jj \to \nu\bar{\nu}\gamma jj$ and $VVjj \to (\ell\ell jj/\ell\nu jj/\nu\nu jj)jj$ channels, depending on the operator, with the combination bringing up to a 20% improvement on individual results. Results respecting unitarity constraints are presented following the clipping method. At a clipped energy threshold of 1.5 TeV the relative contributions of each input analysis are more even, and the combined bounds are found to improve the published results by up to 96%. Confidence intervals are also presented from profiled fits where all Wilson coefficients are free to vary simultaneously.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The ATLAS Collaboration's Athena software, including the configuration of event generators, is open source. The public release of data supporting this article will follow the CERN Open Data Policy.

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