PROCEEDINGS OF SCIENCE

EFT interpretation of off-shell Higgs boson to $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ decay channels at ATLAS

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This proceeding reports on the effective field theory (EFT) interpretation of the measurement of off-shell Higgs boson production using 139 fb^{-1} of proton-proton collision data at a centre-of-mass energy of 13 TeV, collected by the ATLAS detector at the Large Hadron Collider. Higgs boson decays to $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ final states, with $\ell = e$ or μ, are considered. Off-shell Higgs boson events with masses of the order of 1 TeV are sensitive to phenomena beyond the Standard Model. Furthermore, the Higgs boson coupling to the top quark and its effective coupling to the gluon are degenerate in the inclusive on-shell measurements while the off-shell events can break the degeneracy. EFT operators affecting these couplings are studied and their associated Wilson coefficients are observed (expected) to be [-9, 18] ([-9, 17]) for $c_{t\varphi}$ (Higgs-top coupling modifier) and [-0.04, 0.03] ([-0.04, 0.03]) for $c_{\varphi G}$ (Higgs-gluon coupling modifier) at the 95 confidence level with new physics energy scale $\Lambda = 1$ TeV, in agreement with the SM prediction.

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1. Introduction

The Higgs boson provides a pivotal window for searching for possible beyond the Standard Model (BSM) physics. Off-shell Higgs boson events offer the opportunity to probe a higher energy scale, where BSM physics may emerge. Furthermore, the ATLAS and CMS experiments [1]) have shown that the Higgs-top and effective Higgs-gluon couplings in the gluon-gluon fusion (ggF) Higgs production mode cannot be measured independently using the on-shell inclusive measurements, while the off-shell Higgs boson offers a means to decouple them [2]. This proceeding focuses on the ggF production mode in the Effective Field Theory (EFT) framework to search for BSM physics using off-shell Higgs boson events in 4ℓ and $2\ell 2\nu$ final states, with the full ATLAS Run-2 dataset.

2. Theoretical frameworks and motivation

The results in this proceeding are provided in the Warsaw basis of the Standard Model Effective Field Theory (SMEFT) framework [3], where the Lagrangian of the SMEFT is expanded as:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{\forall i, \forall d>4} \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} \tag{1}$$

Here, Λ is the scale at which new physics is expected to appear and d refers to the dimensionality of the operators in the effective Lagrangian. It can be associated with a possible UV-complete BSM model that contributes to the EFT operators. $C_i^{(d)}$ are the Wilson coefficients that encode information about the couplings associated with the possible UV-complete model.

Among many dimension-six operators, only Higgs-gluon and Higgs-top related operators in the $gg \to ZZ$ channel are considered. The corresponding leading-order Feynman diagrams are depicted in Figure 1. In the SM, $c_{\varphi G} = 0$ and $c_{t\varphi} = 0$.

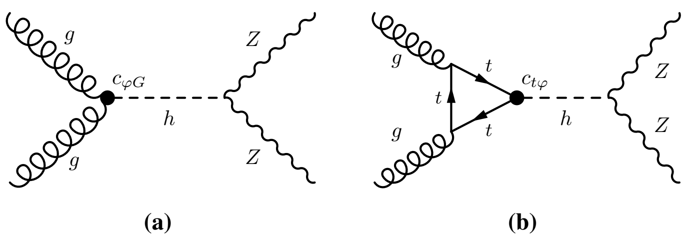

Figure 1: The representative leading-order diagrams in $gg \to ZZ$, showing where (a) the effective Higgs-gluon coupling and (b) the top-Higgs coupling are modified by the corresponding Warsaw operators.

3. Analysis

The analysis strategies are the same as that in Ref [4], and are only briefly summarized here.

3.1 $ZZ \to 4\ell$ analysis

In the $ZZ \to 4\ell$ decay channel, two on-shell Z bosons are required and the mass of the lepton pairs is compatible with m_Z. Control regions (CR) are defined in the background-enriched 180

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GeV < $m_{4\ell}$ < 220 GeV region, with the signal regions being in the $m_{4\ell}$ > 220 GeV range. The SRs are defined based on the number of jets to separate ggF and electroweak (EW) Higgs boson production. The jet multiplicity is also introduced in the CRs to better mimic the background in SRs. A deep neural network (NN), implemented using Keras [5] with TensorFlow [6] as the back-end, is trained with the SM samples for Higgs signal (S), interfering background (B) ($gg \to ZZ$) and non-interfering background (NI) ($qq \to ZZ$). The network output is the probability of a given event falling into each of the input categories. The final observable is constructed as follows, with P representing the corresponding probability:

$$O_{\rm NN} = \log_{10} \frac{P_{\rm S}}{P_{\rm B} + P_{\rm NI}} \tag{2}$$

The NN inputs include matrix elements, the transverse momenta of the two Z bosons, the invariant mass $m_{4\ell}$, and other kinematic variables.

3.2 $ZZ \to 2\ell2\nu$ analysis

The final state in the $ZZ \to 2\ell2\nu$ channel consists of a pair of isolated leptons (e or μ) and large $E_{\rm T}^{\rm miss}$ from undetectable neutrinos. Compared with the 4l channel, the branching ratio of the $2\ell2\nu$ channel is much larger but it suffers a larger background contamination as well. The main backgrounds include $q\bar{q} \to ZZ$, WZ, non-resonant-$\ell\ell$ (originating from $qq \to WW$, $t\bar{t}$ and single-top production), and Z + jets. The $q\bar{q} \to ZZ$ background is estimated from the CRs in the 4ℓ channel while others are extracted from dedicated CRs defined for the $2\ell2\nu$ channel only. There are three SRs, i.e., ggF SR, mixed SR and EW SR, as in the 4ℓ channel 3.1.

The observable used in the $ZZ \to 2\ell2\nu$ analysis is the transverse mass of the two Z bosons,

$$m_{\rm T}^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_{\rm T}^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_{\rm T}^{\rm miss})^2}\right]^2 - \left|\vec{p}_{\rm T}^{\,\ell\ell} + \vec{E}_{\rm T}^{\rm miss}\right|^2} \tag{3}$$

where m_Z is the PDG Z boson mass [7], $p_{\rm T}^{\ell\ell}$ is the transverse momentum of the lepton pair and $E_{\rm T}^{\rm miss}$ is the missing transverse energy.

4. Results

To probe the impact of EFT operators on Higgs boson couplings in the off-shell region in the $ZZ \to 4\ell$ and $ZZ \to 2\ell2\nu$ decay channels, the profile likelihood technique [8] is employed.

A binned likelihood function is then constructed as a product of Poisson probability terms over all bins and fitted to the observed data or the expected SM prediction in all the SRs and CRs simultaneously. The likelihood depends on the parameters of interest, $c_{\varphi G}$ and $c_{t\varphi}$, and a set of nuisance parameters $\boldsymbol{\theta}$.

The observed and expected results based on the profile likelihood ratios (denoted by $-2\ln(\lambda)$) are presented in Figure 2. The observed (expected) result of $c_{t\varphi}$ in the linear and quadratic fit is $-1^{+19}_{-8}(0^{+17}_{-9})$ at the 95% confidence level, which is comparable to the result from the boosted $t\bar{t}H$ analysis by CMS [9]. Figure 3 shows 2D contour projections of $-2\ln(\lambda)$ on the Wilson coefficient plane.

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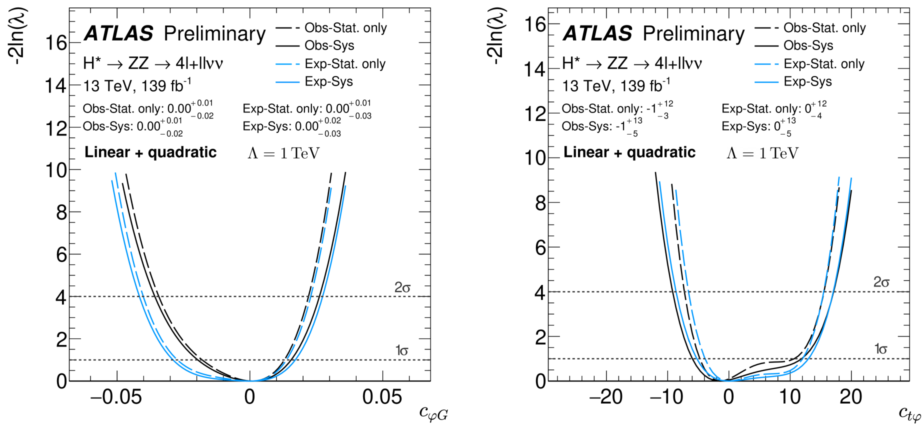

(a) **(b)**

Figure 2: Negative log-likelihood, $-2\ln(\lambda)$, as a function of dimension-six EFT coefficients 2a $c_{\varphi G}$, and 2b $c_{t\varphi}$ for the combined 4ℓ and $2\ell2\nu$ channels. Only one coefficient is fit while the other is set to 0.

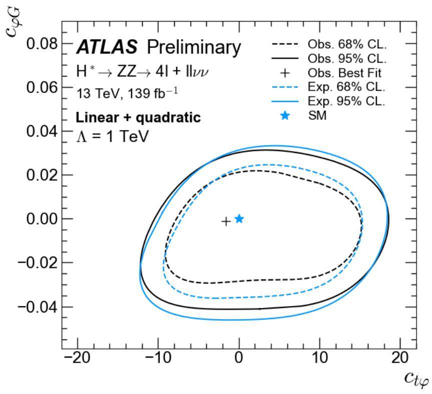

Figure 3: Projection of negative log-likelihood, $-2\ln(\lambda)$, on the plane of the dimension-six EFT coefficients $c_{\varphi G}$ (Higgs-gluon) and $c_{t\varphi}$ (Higgs-top modifier) in the combined analysis of the 4ℓ and $2\ell2\nu$ channels.

5. Conclusion

Off-shell Higgs boson production with a high invariant mass at the TeV level is potentially sensitive to new physics beyond the Standard Model. Additionally, the degeneracy of the Higgs-top quark and effective Higgs-gluon couplings is broken in the off-shell region, enabling separate measurements of the coupling modifiers.

This proceeding presents the EFT interpretation of off-shell Higgs boson production measured in the $ZZ \to 4\ell$ and $ZZ \to 2\ell2\nu$ decay channels to constrain BSM phenomena, using ATLAS full Run-2 dataset. The Wilson coefficients associated with the couplings are observed (expected) as $-1^{+19}_{-8}(0^{+17}_{-9})$ for $c_{t\varphi}$ (Higgs-top coupling modifier) and $0.00^{+0.03}_{-0.04}(0.00^{+0.03}_{-0.04})$ for $c_{\varphi G}$ (Higgs-gluon coupling modifier) at the 95% confidence level. This proceeding gives the observed event yields in each region for both $ZZ \to 4\ell$ and $ZZ \to 2\ell2\nu$ decay channels and the fitted dimension-six cross-section distributions. No significant deviation from the SM is observed.

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