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Study of the impact of unitarity bounds on analysis of Vector Boson Scattering with same-sign W processes at LHC

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Summary. — Effective Field Theories (EFT) are a powerful tool for exploring the effect of physics Beyond Standard Model (BSM) in a model independent approach. However, the introduction of EFT contributions could lead to an unphysical growth of scattering amplitudes and a violation of unitarity in the high-energy region. To validate the EFT approach, it is necessary to implement unitarity constraints. We present a preliminary study of the impact of unitarity bounds on experimental sensitivity to Vector Boson Scattering processes in proton-proton collisions at LHC, considering dimension-six EFT operators. The analysis is performed at the generator level on Monte Carlo samples at $\sqrt{s} = 13\,\text{TeV}$ and integrated luminosity of 100 fb^{-1}.

1. – Introduction

Vector Boson Scattering (VBS) processes are an important probe for exploring possible new physics at high energy scales: divergences from Standard Model (SM) predictions within VBS may suggest the existence of novel particles or interactions beyond the scope of the SM. VBS has garnered interest in experimental investigations due to its sensitivity to deviations in both triple and quartic gauge couplings [1]. VBS processes are also essential to probe the validity of the electroweak symmetry breaking mechanism as formulated in SM. In VBS, the unphysical growth of the scattering amplitude in high-energy regions is exactly compensated by the Higgs boson-mediated channels [2]. The presence of new interactions related to the Higgs sector could break this balance, so the growing behavior of the scattering amplitude could be a sign of new physics effects, which can be well parameterized by an EFT.

In this work, we consider the scattering between two W bosons with the same charge, denoted as VBS same-sign WW (VBS ssWW). The outgoing W bosons in the scattering process can undergo various decay channels, with this study focusing on the fully leptonic final state. This specific process is the so-called "golden channel" for VBS studies since

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background contributions from QCD-induced WW production are small, ensuring high sensitivity in LHC experiments. The process signature includes two jets exhibiting large angular separation and large invariant mass. The entire process is represented as $qq' \rightarrow W^{\pm}W^{\pm}jj \rightarrow \ell\nu_{\ell}\ell'\nu_{\ell'}jj$, where ℓ, ℓ' and $\nu_{\ell}, \nu_{\ell'}$ refer to charged leptons $(e^{\pm}, \mu^{\pm}, \tau^{\pm})$ and neutral leptons $(\nu_e, \nu_{\mu}, \nu_{\tau})$, respectively.

2. – SM effective field theory

A minimal and non-redundant set of dimension 6 operators is given by the Warsaw basis [3] inside SMEFT [4], which should obey SM gauge symmetries. The SMEFT Lagrangian can be written as follows:

$$\mathcal{L}_{\mathcal{SMEFT}} = \mathcal{L}_{\mathcal{SM}} + \sum_{d>4} \sum_{i} \frac{c_i}{\Lambda^{d-4}} Q_i^{(d)}. \tag{1}$$

In this expression, the Wilson coefficients c_i are the EFT couplings associated with $Q_i^{(d)}$ operators of mass dimension d. To reduce the number of independent input parameters of the theory we chose the flavor symmetry $U(3)^5$ and $\{m_W, m_Z, G_F\}$ input parameter scheme. We used the SMEFTsim_U35_MwScheme model [5] to include 5 CP-conserving bosonic operators of the Warsaw basis that can affect VBS ssWW processes,

$$\begin{aligned} &Q_W = \epsilon^{ijk} W_{\mu}^{\nu i} W_{\nu}^{\rho j} W_{\rho}^{\mu k}, \quad Q_{\varphi\Box} = (\varphi^{\dagger}\varphi)\Box(\varphi^{\dagger}\varphi), \quad Q_{\varphi W} = \varphi^{\dagger}\varphi W_{\mu\nu}^{i} W^{\mu\nu i}, \\ &Q_{\varphi D} = (\varphi^{\dagger} D^{\mu}\varphi)^{*}(\varphi^{\dagger} D_{\mu}\varphi), \quad Q_{\varphi WB} = \varphi^{\dagger}\tau^{i}\varphi W_{\mu\nu}^{i} B^{\mu\nu}. \end{aligned} \tag{2}$$

The notation of these operators is generalized: φ represents the Higgs scalar field, $W_{\mu\nu}^{i}$, $B_{\mu\nu}$ the field strength tensors and indices are summed over.

3. – Unitarity bounds for dim-6 EFT operators in VBS

Given the scattering matrix S of a certain process, the conservation of probability translates into the request of the unitarity of S-matrix, *i.e.*, $S^{\dagger}S = 1$. One of the most relevant consequences of this assumption is the optical theorem, which relates the forward scattering amplitude to the total cross-section of the process. An important implication of the optical theorem is that scattering amplitudes cannot be arbitrarily large. Roughly speaking, the optical theorem states that $\Im[\mathcal{M}] \leq |\mathcal{M}|^2$, which implies that $|\mathcal{M}| < 1$. One of the ways to make these constraints operational is to exploit the partial wave expansion of the scattering amplitude

$$\mathcal{M}_{\lambda_1\lambda_2\lambda_3\lambda_4}(\theta) = 16\pi \sum_{j=0}^{\infty} a^{j}_{\lambda_1\lambda_2\lambda_3\lambda_4}(2j+1)P_j(\cos\theta). \tag{3}$$

$\mathcal{M}_{\lambda_1\lambda_2\lambda_3\lambda_4}$ is the helicity amplitude, j is the total angular momentum of the WW system and $P_j(\cos\theta)$ are Legendre polynomials, where θ is the scattering angle.

Constraints on scattering amplitude can be translated into a constraint on the coefficients of expansion given in eq. (3), namely $|a^{j}_{\lambda_1\lambda_2\lambda_3\lambda_4}| \leq 1$. In the EFT context, these coefficients are functions of $\hat{s}$, the center of mass energy of the system. Consequently, the optical theorem provides a limit on $\hat{s}$, denoted with $\sqrt{\hat{s}_u}$: above this energy, the unitarity

TABLE I. – *The table shows the threshold of unitarity violation as a function of $|c_i|$ and Λ and its value for $c_i = 1$ and $\Lambda = 1$ TeV.*

Operator	$\sqrt{\hat{s}_u}(\lvert c_i\rvert)$	Bound on $\sqrt{\hat{s}}$ ($c_i = 1, \Lambda = 1$ TeV)
Q_W	$2\left(\frac{\Lambda^2\pi}{3\bar{g}}\right)^{1/2}\frac{1}{\lvert c_W\rvert^{1/2}}$	≤ 2.53 TeV
$Q_{\varphi W}$	$4\left(\Lambda^2\pi\right)^{1/2}\frac{1}{\lvert c_{\varphi W}\rvert^{1/2}}$	≤ 7.1 TeV
$Q_{\varphi WB}$	–	–
$Q_{\varphi\Box}$	$2\left(2\Lambda^2\pi\right)^{1/2}\frac{1}{\lvert c_{\varphi\Box}\rvert^{1/2}}$	≤ 5.01 TeV
$Q_{\varphi D}$	$4\left(\Lambda^2\pi\right)^{1/2}\frac{1}{\lvert c_{\varphi D}\rvert^{1/2}}$	≤ 7.1 TeV

is violated. Unitarity bounds extracted using the partial wave expansion of scattering amplitudes are called perturbative unitarity bounds.

For amplitudes calculation, specific tools of Mathematica have been used: FeynRules [6] for the generation of models including dimension-6 EFT operators, FeynArts [7] for the definition of the process and the generation of associated Feynman diagrams and FormCalc [8] for the computation of helicity amplitudes.

Partial wave expansion has been carried out for each independent amplitude. Once the coefficients $a^j_{\lambda_1\lambda_2\lambda_3\lambda_4}$ were obtained, the condition given by the optical theorem was applied to derive the behavior of $\sqrt{\hat{s}_u}$ as a function of the EFT parameters (c_i, Λ). Results are summarized in table I for the chosen working point of $c_i = 1$ and $\Lambda = 1$ TeV.

4. – Analysis at generator level

We studied the impact of the unitarity constraints on the theoretical limits of the Wilson coefficients. The analysis was performed at the generator level, *i.e.*, using event samples generated using MadGraph_aMC@NLO v.2.7 [9]. We examined EFT operator's impact individually by generating two distinct event samples: a first sample including only the contribution from the linear term of the amplitude (SM · EFT), corresponding to terms of Λ^{-2} order in the EFT expansion; a second sample exclusively containing the contribution from the quadratic term of the scattering amplitude (EFT^2), representing terms of order Λ^{-4} and excluding those describing mutual interference between the operators. Additionally, a sample corresponding to SM processes was generated.

Theoretical limits on the Wilson coefficients have been quantified via a likelihood-based approach using Combine [10], a set of statistical analysis tools developed by the CMS Collaboration. The kinematic distributions of several variables were studied. The extracted limit takes into account the most sensitive variable to the specific EFT contribution, which has been found to be transverse mass of lepton system and missing energy for all operators. Results are summarized in table II.

The unitarity bounds were applied by making a preliminary selection to the simulated samples [11]: the energy of the center of mass of the two W system was reconstructed

TABLE II. – *This table shows the theoretical limits for the Wilson coefficients before and after the application of the unitarity constraints.*

WC	Rejected events (%)	68% CL limit (w/o bounds)	95% CL limit (w/o bounds)	68% CL limit (w/ bounds)	95% CL limit (w/ bounds)	Impact (%)
c_W	0.053	[–0.042,0.040]	[–0.065,0.078]	[–0.038,0.039]	[–0.065,0.080]	1.4
$c_{\varphi W}$	0.0	[–0.62,0.64]	[–1.04,1.21]	[–0.62,0.64]	[–1.04,1.21]	0.0
$c_{\varphi WB}$	0.0	[–1.60,1.68]	[–3.08,3.50]	[–1.60,1.68]	[–3.08,3.50]	0.0
$c_{\varphi\Box}$	0.0	[–3.15,2.61]	[–5.73,4.52]	[–3.15,2.61]	[–5.73,4.52]	0.0
$c_{\varphi D}$	0.0	[–1.72,1.83]	[–3.18,3.88]	[–1.72,1.83]	[–3.18,3.88]	0.0

event by event, and the events beyond the EFT validity region were rejected. Again, from table II it is possible to see that the percentage of events rejected is zero or, in the case of c_W, almost zero. This means that the implementation of unitarity constraints does not impact the confidence intervals we can derive for the Wilson coefficients.

5. – Summary

The study discussed showed that in a 6-dimensional EFT the energy scale at which unitarity is violated is higher than the energy currently accessible at LHC, ensuring that no EFT MC event is rejected. Consequently, it is possible to conduct analyses in the EFT context without the need to apply approaches that restore the physical sense of the theory. This aspect may change if strongly coupled theories are considered since the unitarity bounds become more stringent. Given the generality of theoretical results, this work represents a good basis for investigating the impact of unitarity constraints in other experimental contexts where we expect to have higher statistics in high-energy regions. These results can also be used as benchmark for analyzes that include higher-dimensional operators. Work in this direction is in progress.

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