Study of VBF/VBS in the LHC at 13 TeV, the EFT Approach.

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We review the current status of vector boson fusion and vector boson scattering studies in the frame of Run-2 of LHC. These processes are equally interesting and challenging, and new ideas have to be applied for their experimental analysis. These channels are optimal for the search of new physics, and therefore we discuss two promising techniques for this purpose: standard model effective field theory and pseudo observables. Regarding their implementation in the analyses, we also discuss briefly how these techniques should be included in the Monte Carlo generators.

1 Introduction: Why Study VBF/VBS at LHC

Vector Boson Fusion (VBF) is the subleading channel for Higgs production at LHC. More concretely we call VBF to the production of a Higgs boson, in association with two hard jets, in the forward and backward regions of the detector. However, this process can only be understood in the frame of the vector boson scattering (VBS), which involves other Higgs production channels (VH associated production) and processes with no Higgs bosons (VV → VV).

Historically, the family of VBS processes has illustrated a paradigmatic problem in theoretical particle physics: violation of unitarity. If there is something that we know for sure in quantum field theory is that unitarity, representing probability, has to be conserved. Without the Higgs boson, the cross section for vector boson scattering would grow proportionally with the center of mass energy

$$\sigma_{V_L V_L \rightarrow V_L V_L} \propto \begin{bmatrix} -s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2} \end{bmatrix}$$ (1)

There is a subtlety here to be noted: although the Higgs ensures the convergence of the cross section when $s \rightarrow \infty$, we still have very little information about the behaviour in the intermediate energy regime, where phenomena like delayed unitarity could possibly hide the portals to new physics.
From the experimental perspective, all VBS processes have a very clean signature. There are two very energetic forward jets, which can be tagged, and the products of the decay lay in the central region of the detector, well separated from the jets. However a challenge still exists, on separating the Higgs signal from the background, since they both share these particular characteristics. This is one of the tasks to be addressed on the LHC run-2 dataset, possibly using a MELA\textsuperscript{a} approach. A further difficulty for the experimental analysis is the fact that the final decays can be of the type $ZZ \rightarrow 4\ell$, $ZZ \rightarrow 2\ell2\nu$ or $W^\pm W^\pm \rightarrow \ell\nu\ell\nu$. These processes are quite similar from the theory point of view and in fact interdependent, since all are needed to satisfy gauge invariance, but completely different for the experimental reconstruction and analysis.

2 The Importance of NLO EW corrections

When we talk about NLO corrections in LHC we are often only including QCD ones. However there is evidence that electroweak corrections should not be neglected at the current precision. The VBF total cross section is:

$$\sigma_{\text{VBF}} = \sigma_{\text{DIS}}^{\text{NNLOQCD}} (1 + \delta_{\text{EW}}) + \sigma_\gamma = \frac{1241.4 \text{ fb}^{-1}}{4277.7 \text{ fb}^{-1}} \pm \Delta$$

were $\delta_{\text{EW}}$ has been calculated\textsuperscript{b} to be $-4.4\%$ (7 TeV) and $-5.4\%$ (14 TeV), and reaching $-6.9\%$ if we restrict to the fiducial cross section.

2.1 Collier and Recola

At the computational level, two very promising pieces of software were released recently, namely RECOLA\textsuperscript{3} which is able to produce matrix elements for NLO EW corrections, and COLLIER\textsuperscript{2} which can perform the phase space integration of such elements. These two projects open the door to the implementation of NLO EW corrections in the event generators used for the experimental analyses\textsuperscript{b}.

3 Effective Field Theory

In order to look for small deviations from the SM\textsuperscript{f} but keeping the quantum field theory behind consistent (with the assumption that QFT must be the underlying theory governing new physics), the most reasonable path to follow is that of effective field theory (EFT).

EFT comes in two possible flavors, the top-down approach which is strictly model dependent. And the relatively model independent bottom-up approach. In the top-down approach we start by an ultraviolet (UV) theory, find its low-energy behaviour, and try to match it to the SM in that regime. This is a quite straightforward technique, and it can provide with tests and predictions for concrete BSM models. First applying the path integral formalism and the covariant derivative expansion\textsuperscript{4} and then using the renormalization group equations, one can match the Wilson coefficients of the UV theory with those of the SM. This procedure has to be applied carefully though, since one might be neglecting mixing terms\textsuperscript{5,6} between light and heavy particles if we try to apply the procedure in a generalized way. Alternatively, the bottom-up approach starts from the SM and tries to build a bridge towards the UV regime. This is, it does not provide with concrete predictions for BSM scenarios but rather with a framework for the study of new physics in the regime accesible from the SM. We will address this approach in detail in the following.

\textsuperscript{a}Matrix Element Likelihood Approach

\textsuperscript{b}Note that such corrections are already included in the Monte Carlo generators that theorists use privately.

\textsuperscript{f}In the energy regime accessible to us, there are enough hints to assume such deviations will be small.
An EFT for the standard model can be parametrized as:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_n \frac{c_n}{\Lambda^d} \mathcal{O}_n^{(d)} = \mathcal{L}_{SM} + \sum_n \frac{c_n}{\Lambda^2} \mathcal{O}_n^{(6)} + \sum_m \frac{c_m}{\Lambda^4} \mathcal{O}_m^{(8)} + \ldots$$

(3)

where $\mathcal{O}_n^{(d)}$ are operators of dimension $d > 4$, representing new interactions but built completely from standard model fields and $\Lambda$ is a scale of new physics up to which the EFT is valid. Observe that $\Lambda$ is not necessarily the Planck scale, it might be that on top of the EFT we need another EFT, or a series of them, to extend its regime of validity.

This Lagrangian is renormalizable, order by order in $\Lambda$ and in fact it has to be renormalized in order to make accurate predictions, since the self energies, tadpoles and counterterms will be modified with respect to the standard model ones. In particular, for the search for deviations of the SM in the energy regime accessible from LHC, it is enough to implement and renormalize dimension 6 operators. The full set of gauge-invariant, independent, dimension-6 operators can be parametrized in the so called Warsaw basis. Analogously to the Lagrangian, the amplitude squared can be expanded as:

$$|A|^2 = \left| A_{SM} + A_{6}^{(6)} + A_{8}^{(8)} \right|^2 = A_{SM}^2 + 2 \frac{A_{SM} A_{6}^{(6)}}{\Lambda^2} \Re(A_{SM} A_{6}^{(6)}) + \mathcal{O}(\Lambda^{-4})$$

(4)

In terms of Feynman diagrams this means that, to be consistent, we should only consider those diagrams with only Standard Model vertices ($A_{SM}$) and those diagrams with one dimension 6 insertion ($A_{SM} A_{6}^{(6)}$). For terms with two dimension 6 insertions to be considered, we should as well include those with one dim 8 insertion (i.e. order $\Lambda^{-4}$ in $|A|^2$). Nevertheless the former should be calculated as an estimate for the theoretical uncertainty.

### 3.1 Predictions within EFT

After the framework has been designed, we have to figure out which are the most interesting or urgent applications. The goal of LHC in the long term is to find new physics and answer the open questions in high energy physics, however in the short term, the paths towards these goals are several.

The EFT at dimension 6 naturally adds 59 new operators to the SM Lagrangian, and therefore, 59 new Wilson coefficients that have to be fitted. The main open question right now is if it makes sense to try and fit these coefficients independently, this is, varying them one by one and seeing if they hint at some deviation from the SM, or alternatively, if we should try to do a global fit. The latter option is more reasonable since the coefficients are correlated in non obvious ways, but it is also harder to implement. We can go one step further and discuss if it makes sense to look at Wilson coefficients at all, since they are not observable, nor independent and, when compared to other quantities like scattering amplitudes, they seem less natural.

### 3.2 A complement to EFT: Pseudo Observables

A natural bridge between EFT and experimental data is the pseudo observable (PO) approach. POs are strictly related to EFT parameters, but they are not the same thing. They are universal quantities, defined from a theoretical perspective, but with a well defined experimental meaning. We can divide them into two big groups: effective on-shell couplings (equivalent to the $\kappa$ framework, and restricted to lowest order) and ideal observables, such as partial decay widths, electroweak precision data, and differential cross-sections.

POs are extracted from a decomposition of the scattering amplitude, followed by a momentum expansion (therefore assuming there are no new light particles). Using analyticity, unitarity

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4Think for instance on Fermi’s operator, representing a direct interaction between four fermions without Gauge bosons mediating.
and crossing symmetry arguments, one can define these quantities to be the coefficients of such a
decomposition. The crossing symmetry argument is particularly interesting, since it relates the
POs from the production and decay modes, lowering the theoretical uncertainty (and amount
of work) when we carry the analysis for a complete $pp \rightarrow H \rightarrow X$ process.

4 Implementing NLO EFT corrections in the Monte Carlo generators

As we addressed in the introduction, the set of VBS Feynman diagrams only respect gauge
invariance if they are considered together. And this as well is the main feature we have to
take into account when implementing NLO EW corrections and NLO EFT in the Monte Carlo
generators.

The algorithms for the inclusion of QCD NLO corrections in these generators are such that
each Feynman diagram is computed and integrated over the phase space independently, and the
different contributions are summed up in the end. However this method is not the best one to
use in the case of electroweak processes.

Firstly, electroweak vertices (and EFT-EW ones) are of a much more complicated nature.
Due to the presence of masses in the propagators, the loop integrals are more time- and resource-
consuming, and these are the main variables that one needs to optimize when designing a MC
generator. Secondly, and more important, there is the question of being rigorous: since we know
from the SM that gauge cancellations have to happen, it does not look right to calculate the con-
tributions of different non-gauge invariant diagrams separately using numerical techniques, and
then sum them up hoping that those cancellations calculated numerically will cancel, specially
given the fact that these spurious contributions are relatively large in the EW case.

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References

1. Chang-rim Ahn, Michael E. Peskin, B. W. Lynn, and Stephen B. Selipsky. Delayed
   Unitarity Cancellation and Heavy Particle Effects in $e^+e^- \rightarrow W^+W^-$. Nucl. Phys.,
   B309:221–258, 1988.
2. Ansgar Denner, Stefan Dittmaier, and Lars Hofer. Collier: a fortran-based Complex
   One-Loop Library in Extended Regularizations. 2016.
3. Stefano Actis, Ansgar Denner, Lars Hofer, Jean-Nicolas Lang, Andreas Scharf, and Sandro
   Uccirati. RECOLA: REcursive Computation of One-Loop Amplitudes. 2016.
4. Brian Henning, Xiaochuan Lu, and Hitoshi Murayama. How to use the Standard Model
   effective field theory. JHEP, 01:023, 2016.
5. Francisco del Aguila, Zoltan Kunszt, and Jose Santiago. One-loop effective lagrangians
   after matching. Eur. Phys. J., C76(5):244, 2016.
6. Michele Boggia, Raquel Gomez-Ambrosio, and Giampiero Passarino. Low energy be-
   haviour of standard model extensions. JHEP, 05:162, 2016.
7. Margherita Ghezzi, Raquel Gomez-Ambrosio, Giampiero Passarino, and Sandro Uccirati.
   NLO Higgs effective field theory and -framework. JHEP, 07:175, 2015.
8. B. Grzadkowski, M. Iskrzyzinski, M. Misiak, and J. Rosiek. Dimension-Six Terms in the
   Standard Model Lagrangian. JHEP, 10:085, 2010.
9. Admir Greljo, Gino Isidori, Jonas M. Lindert, and David Marzocca. Pseudo-observables
   in electroweak Higgs production. Eur. Phys. J., C76(3):158, 2016.