Exploring the scattering of vector bosons at LHCb

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In this letter, I propose a strategy to measure vector-boson scattering (VBS) at the LHCb experiment. The typical VBS topology features two energetic back-to-back jets with large rapidities and two gauge bosons produced centrally. Such a topology is well suited to the LHCb-detector characteristics. In particular, tagging only one of the two jets in combination with two same-sign leptons allows for a measurement with upcoming luminosities. In this article, I present an illustrative event selection where cross sections and differential distributions are computed for VBS and its irreducible background.

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Introduction

The electroweak sector is a fascinating part of the Standard Model (SM) of particle physics. It is imprinted by the underlying symmetries governing the SM and in particular the electroweak symmetry breaking mechanism, making it a possible access point to new physics mechanisms. One of the most exciting processes to study this is vector-boson scattering (VBS). Due to the presence of triple and quartic gauge couplings as well as unitary cancellation, it constitutes a perfect candidate for witnessing deviations from SM expectations.

It is therefore paramount to measure it as precisely as possible and in all possible manners. The present letter follows the latter path by devising a strategy to measure VBS at the LHCb experiment. To my knowledge, this idea has never been promoted before and is thus completely original. It therefore opens new opportunities for exploring scattering processes at hadron colliders and a challenging physics programme for the LHCb collaboration.

At hadron colliders, the scattering of vector bosons happens after being radiated off two quark lines. An exemplary Feynman diagram contributing to the process is shown in Fig. 1. This particular color structure leads to a very particular topology where the two jets are preferably produced back-to-back with a large rapidity separation while the gauge bosons are produced centrally. This feature is exploited by the ATLAS and CMS collaboration for their measurements. In particular, the invariant mass and the rapidity separation between the two tagging jets provide good leverage to distinguish it from its irreducible background. At the ATLAS and CMS experiments, the golden channel is the same-sign W scattering due to its large cross section in combination with very low irreducible background. It is followed by the WZ and ZZ channels which have lower cross sections and signal-over-background ratios but better reconstruction power.

The main challenge at LHCb is the asymmetry of the detector and thus the impossibility to reconstruct the full event. In addition, the luminosity at LHCb is greatly reduced with respect to the ones delivered to the ATLAS and CMS experiments. Despite these challenges, I show in this letter that it is actually possible to measure VBS at the LHCb experiment in its future operations. Here, I focus on the signature with one jet and two anti-muons as a prime example for the measurement.

In the first part, I motivate the event selection and strategy proposed. I then briefly list the input parameters used for the predictions as well as the tools used. In the third part, the cross sections and differential distributions are presented and discussed. To conclude, I expose the main findings of this letter and ways to go beyond.

Measurement strategy

Typical VBS measurements rely on the fact that all final state particles are measured (the neutrinos through the missing transverse momentum). At the LHCb experiment, the detector is only covering one part of the phase space and is asymmetric. It implies that either the whole system has to be boosted to be detected as for the W+jet and Z+jet measurements or only parts of the full process is detected. In this letter, the latter avenue is followed.
As mentioned previously, the golden channel for measurement of the electroweak (EW) component of order $\mathcal{O}(\alpha^6)$ is the same-sign W channel (with $\ell^+\mu\ell'^+\nu\ell''\bar{j}$ final state) due to its unique signature in the SM. Its irreducible background of order $\mathcal{O}(\alpha^4\alpha_s^2)$ is rather suppressed, at the level of 10% while its interference of order $\mathcal{O}(\alpha^5\alpha_s)$ is at the per-cent level [8]. Therefore, it is natural to focus on measuring two same-sign leptons while tagging only one of the quark-jets. Figure 2 represents how such an event would be measured at the LHCb experiment. The leptonic system is slightly boosted in order to measure the two same-sign leptons along with one of the two jets. The second jet is not tagged as it is likely to be on the other side of the detector due kinematic constraints.

At ATLAS or CMS, one can unambiguously distinguish between the same-sign WW (ss WW), WZ, and ZZ channel as all the final-state particles are measured. At LHCb, requiring same sign leptons is not sufficient to isolate the same-sign WW and all other leptonic channels have to be included. Indeed, one (for WZ) or two (for ZZ) leptons could be undetected and still lead to the signature $\ell^\pm j^\pm j$.

Including the WZ and ZZ channels has the drawback of lowering the signal over background ratio with respect to same-sign WW. In order to diminish the effect of such channels, a veto whenever additional leptons are detected can be introduced. From a theoretical point of view, it also has the advantage to cut away singular contributions of the type $\gamma^* \rightarrow \ell^+\ell^-$ with low virtuality for the photon.

In principal, the final state $\ell^\pm j^\pm j$ with all flavour combinations $\ell, \ell' = \mu, e$ should be considered. As the present study is mainly illustrative, only the case $\mu^+\mu^+ j$ is examined here. It is justified by the fact that the negative signature is only about one third of positive one due to a different parton distribution function (PDF) [9].

To be more concrete, the event selection reads as follows: the final state is $\mu^+\mu^+ j$ and the requirements on these objects are

\begin{align}
\text{\textbf{Beam axis}} & \quad \nu_{\mu} \\
\text{LHCb detector} & \quad \mu^+ \\
W & \quad \nu_{\mu} \\
W & \quad \mu^+ \\
\end{align}

FIG. 2: Schematic representation of a typical VBS event to be measured at the LHCb experiment. The blue objects are the ones that are actually detected.

\begin{align}
\quad p_{T,j} & > 20 \text{ GeV}, \quad 2.2 < \eta_j < 4.2, \\
\quad p_{T,\mu^+} & > 20 \text{ GeV}, \quad 2.0 < y_{\mu^+} < 4.5, \\
\Delta R_{\mu^+} & > 0.5.
\end{align}

In addition, a veto is applied to all events featuring extra lepton(s) of different charge or flavour in the detector

\begin{align}
2.0 < \eta_\ell < 4.5,
\end{align}

with $\ell = \mu^-, e^+, e^-$. 

Details of the calculation

Given that all channels contribute to the final state $\mu^+\mu^+ j$, the following hadronic processes have been simulated:

\begin{align}
\mu^+\nu_\mu\mu^+\nu_\mu j & \quad \text{ss WW}, \quad (5) \\
\mu^+\nu_\mu\mu^+\mu^- j & \quad \text{WZ}, \quad (6) \\
\mu^+\mu^-\mu^+\mu^- j & \quad \text{ZZ}, \quad (7)
\end{align}

at orders $\mathcal{O}(\alpha^6)$ (denoted by EW). These are the signal processes containing VBS contributions. The dominant irreducible QCD backgrounds (denoted by QCD) for these processes are:

\begin{align}
\mu^+\nu_\mu\mu^+\nu_\mu j & \quad (8) \\
\mu^+\nu_\mu\mu^+\mu^- j & \quad (9) \\
\mu^+\mu^-\mu^+\mu^- j & \quad (10)
\end{align}

at orders $\mathcal{O}(\alpha^4\alpha_s^2)$ and $\mathcal{O}(\alpha^4\alpha_s)$ (for the last two).

Note that for the EW contributions, singular contributions can also arise from $\gamma^* \rightarrow q\bar{q}$ subprocesses in the WZ and ZZ channels. In the simulations, these have been regulated by technical cuts as their effects are small [10,11]. Nonetheless, for completeness, they should be dealt with using the method proposed in Ref. [11].

Also, the interference contribution of order $\mathcal{O}(\alpha^5\alpha_s)$ has been left out in this study as it usually amounts to few per cent [8,10]. All predictions are done at leading order (LO). Nonetheless, to obtain the subleading QCD contributions at order $\mathcal{O}(\alpha^4\alpha_s^2)$ in the channels WZ and ZZ, the next-to-leading order (NLO) QCD corrections should be computed. For V+ j, in a similar set-up, they have been found to be about +30% [12].

For all predictions, the resonant particles are treated within the complex-mass scheme [13,14], ensuring gauge invariance. To evaluate all tree amplitudes in the 5-/6-body phase space, the computer code RECOLA [15,16] is employed. The integration is performed with the code MoCaNLO which has been already used in NLO computations for VBS [8,10,17,18].
TABLE I: Cross sections for processes contributing to pp → µ⁺µ⁻j + X at 13 TeV at LHCb. The cross sections are expressed in femtobarn for the orders $\mathcal{O}(\alpha^6)$ (EW) and $\mathcal{O}(\alpha^4\alpha_s^2)$ or $\mathcal{O}(\alpha^4\alpha_s)$ (QCD). The digit in parenthesis indicates the integration error.

| Channel | $\sigma_{\text{EW}}$ [fb] | $\sigma_{\text{QCD}}$ [fb] | $\sigma_{\text{EW}}/\sigma_{\text{QCD}}$ |
|---------|-----------------|-----------------|-----------------|
| ss WW   | 0.0185(1)       | 0.0104(1)       | 1.78            |
| WZ      | 0.0071(1)       | 0.2952(4)       | 0.02            |
| ZZ      | 0.0003(1)       | 0.0161(1)       | 0.02            |
| Sum     | 0.0258(1)       | 0.3217(4)       | 0.08            |

Theoretical predictions are presented for pp collisions at a center-of-mass energy of 13 TeV. The on-shell values for the masses and widths of the gauge bosons read

$$M_W^\text{os} = 80.379 \text{ GeV}, \quad \Gamma_W^\text{os} = 2.085 \text{ GeV},$$
$$M_Z^\text{os} = 91.1876 \text{ GeV}, \quad \Gamma_Z^\text{os} = 2.4952 \text{ GeV} \quad (11)$$

and are converted into pole masses according to

$$M_V = M_V^\text{os}/c_V, \quad \Gamma_V = \Gamma_V^\text{os}/c_V,$$
$$c_V = \sqrt{1 + (\Gamma_V^\text{os}/M_V^\text{os})^2}, \quad V = W, Z. \quad (12)$$

The Higgs-boson and top-quark masses and widths are fixed to

$$M_H = 125 \text{ GeV}, \quad \Gamma_H = 4.07 \times 10^{-3} \text{ GeV},$$
$$m_t = 173 \text{ GeV}, \quad \Gamma_t = 0 \text{ GeV}.$$  

The top-quark width has been set to zero as no resonant top quarks appear at tree level when no external bottom quarks are considered.

For the electromagnetic coupling $\alpha$, the $G_\mu$ scheme is used where $\alpha$ is obtained from the Fermi constant,

$$\alpha_{G_\mu} = \sqrt{2}G_\mu M_W^2 (1 - M_W^2/M_H^2) / \pi, \quad (13)$$

with

$$G_\mu = 1.16638 \times 10^{-5} \text{ GeV}^{-2}. \quad (14)$$

The PDF set NNPDF31_lo_as_0118 [10] has been used everywhere. The scale $\mu$ is set to the pole mass of the W boson, $\mu = M_W$. Quarks and gluons are clustered using the anti-$k_T$ algorithm [20] with jet-resolution parameter $R = 0.4$.

Numerical results

First, the cross sections for the processes [5]-[10] in the set-up of Eqs. (1)-(4) are given in Table I in femtobarn. In addition, the ratios $\sigma_{\text{EW}}/\sigma_{\text{QCD}}$ are also given.

As expected, for the EW component, the cross sections are larger for processes with W instead of Z couplings. As for the ATLAS and CMS measurements, the same-sign WW channel is clearly the golden channel to measure VBS in terms of cross section and background. Finally, the last line where the sum over all channels is performed is the physical cross section that would be measured in the experiment when looking at the $\mu^+\mu^-j$ final state. It amounts to about 0.35 fb and is the combined cross section of the the EW (8%) and QCD (82%) contributions.

In order to measure only the EW component, it would be desirable to use improved event selections to reduce the WZ and ZZ QCD contributions. Also, ways to increase the measured cross section should be explored based on the detailed knowledge of the LHCb detector [21].

For illustrative purpose, only the case $\mu^+\mu^+$ has been considered here. In the limit of massless leptons, $\sigma_{\mu^+\mu^+} = \sigma_{e^+e^+}$. In addition, given that interference contributions are negligible [9], $\sigma_{\mu^+\mu^+} \simeq \sigma_{e^+e^+}$. This implies that the total combined cross section (QCD+EW) is about

$$\sigma_{\ell^+\ell'^+} \simeq 1.3 \text{ fb}, \quad (15)$$

with $\ell, \ell' = \mu, e$. From these, 6% i.e. about 0.1 fb is due to the EW production. In addition, the cross section with negatively charged leptons can also be considered using the same principle. Even if it represents only a fraction of the ‘++’ signature due to PDF contributions [9], it has the same diagrammatic contributions and thus is equally interesting. With an expected luminosity of 50 fb$^{-1}$ or even 300 fb$^{-1}$ for future operations of LHCb, it is thus possible to measure both the combined QCD and EW contributions as well as the EW component on its own. To that end, a combined measurement which is tested against a hypothesis with and without an EW component is preferred over a measurement where the QCD component is subtracted from the data based on Monte Carlo simulations. Indeed, as pointed out in Ref. [8], the notion of EW signal and QCD background is ill defined at NLO from a theoretical point of view due to interferences.

Finally, two differential distributions are also shown in Figs. [3] and [4]. In the upper plot, the absolute predictions for the EW and QCD components as well as their sum is shown for all channels together. The lower plot shows the contributions of the EW and QCD components with respect to the combined process.

Both distributions show that the composition of the combined process is not uniform over the kinematic range displayed. Figure 3 shows that the EW contribution steadily increases toward high transverse momentum of the hardest jet to reach about 20% at 300 GeV. On the other hand, for the rapidity of the hardest anti-muon (Fig. 4), the maximal EW composition is reached for the minimum rapidity (here 2.0 due to the detector limitations). While these distributions are here mainly illustrative, they suggest ways to improve the signal over back-
ground ratio in certain phase-space regions for a realistic measurement.

**Discussion**

In this article, I have presented a proof-of-concept for an original strategy to measure VBS processes at the LHCb experiment. In particular, an event selection has been designed to deal with the peculiarities of the LHCb detector. The key point is that not all final states are required to be tagged as opposed to what is traditionally done at ATLAS or CMS. Based on this set-up, simulations have been performed. The results show that a combined measurement of the QCD and EW components and even of the EW contribution on its own is in reach.

The asymmetric nature of the LHCb detector and the low luminosity available constitute the main challenges to overcome. Still, this measurement would open up the possibility to test the SM even further and explore its possible connexions with new mechanisms. In particular, the LHCb detector allows for measurements in the forward region particularly sensitive to VBS. Performed in a unique environment, such an independent measurements would hence complement very well the pre-existing ones.

While the present study provides the main information and theoretical inputs for such a measurement, it can be extended in several ways. First, NLO QCD and EW corrections should be computed for both the signal and the background along the lines of Refs. [8, 10]. Second, a more thorough analysis of the experimental capabilities should be performed. It would be interesting to optimise the event selection depending on whether a combined measurement or the measurement of the EW component only is targeted. In particular, exploring the possibilities for the different flavour and charge combinations as well as a detailed estimation of the experimental systematic error should be done [21].

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