The process $pp \rightarrow W^+W^+jj$ gives rise to an exotic Standard Model signature at the LHC, involving high-$p_T$ like-sign leptons, missing energy and jets. In this brief article the motivation for study, along with selected results from the computation of NLO QCD corrections to the QCD-mediated part of this process are presented. It is shown that the corrections reduce the dependence of the cross-section on renormalisation and factorisation scales, and produce a relatively hard third jet in a significant fraction of events.

1 Introduction

The process $pp \rightarrow W^+W^+jj$ is a quirky one, both theoretically and experimentally. At a particle collider, the signature involves like-sign leptons, jets and missing energy – an exotic signal from the Standard Model! The mechanisms by which two positively charged $W$ bosons can be created are rather restricted and this leads to the theoretical quirkiness. Figure 1 shows a typical Feynman diagram for this process (even though in our calculation we do not compute a single one). Charge conservation requires that the $W$ bosons be emitted from separate quark lines. Because a massive particle is always produced on each fermion line, the cross-section for the process $pp \rightarrow W^+W^+jj$ remains finite even if the requirement that two jets are observed is lifted. This rather unusual feature is seldom present in NLO QCD calculations.

At $\sqrt{s} = 14$ TeV, the cross-section for this process is about 1 pb (40% of this for $W^-W^-jj$) and therefore accessible. When the $W$ bosons decay leptonically, the two positively charged isolated leptons and missing energy give rise to a nearly background-free signature. The observation of this process is interesting in its own right, but there are other reasons to study it. Of particular importance are various physics cases for which $pp \rightarrow W^+W^+jj$ is a background process. Interestingly, such cases can be found both within and beyond the Standard Model. For example, it is possible to use same-sign lepton pairs to study double parton scattering at the LHC in which case the single scattering process $pp \rightarrow W^+W^+jj$ is the background. Events with same-sign leptons, missing energy and two jets can also appear due to resonant slepton production which may occur in $R$-parity violating SUSY models or in the case of diquark production with subsequent decay of the diquark to e.g. pairs of top quarks. Similarly, one of the possible production mechanisms of the double-charged Higgs boson at the LHC has a signature of two same-sign leptons, missing energy and two jets. A final reason is that the diagrams which contribute are a subset of the diagrams for $pp \rightarrow W^+W^-jj$, an important background to Higgs boson production in weak boson fusion. This calculation can be seen as a theoretical stepping stone leading to the recently computed NLO corrections to $pp \rightarrow W^+W^-jj$. 
Figure 1: A typical Feynman diagram which contributes to the process $pp \rightarrow W^+W^+jj$.

Full details of the calculation can be found in Ref. [1], but it is worth pointing out that because $pp \rightarrow W^+W^+jj$ is a $2 \rightarrow 4$ process, one-loop six-point tensor integrals of relatively high rank need to be dealt with. It is only very recently that theoretical methods for one-loop calculations have become adequate to handle computations of such a complexity. We use the framework of generalized $D$-dimensional unitarity [7,8], closely following and extending the implementation described in Ref. [9], and demonstrating the ability of this method to deal with complicated final states involving two colourless particles. This process has since been implemented in the POWHEG BOX [10], and is the first $2 \rightarrow 4$ NLO process to be matched with a parton shower.

2 Results

We consider proton-proton collisions at a center-of-mass energy $\sqrt{s} = 14$ TeV. We require leptonic decays of the $W$-bosons and consider the final state $e^+\mu^+\nu_e\nu_{\mu}$. The $W$-bosons are on the mass-shell and we neglect quark flavour mixing. We impose standard cuts on lepton transverse momenta $p_{t,l} > 20$ GeV, missing transverse momentum $p_{t,\text{miss}} > 30$ GeV and charged lepton rapidity $|\eta_l| < 2.4$. We define jets using anti-$k_T$ algorithm [11], with $\Delta R_{j_1, j_2} = 0.4$ and, unless otherwise specified, with a transverse momentum cut $p_{t,j} = 30$ GeV on the two jets. The mass of the $W$-boson is taken to be $m_W = 80.419$ GeV, the width $\Gamma_W = 2.140$ GeV. $W$ couplings to fermions are obtained from $\alpha_{\text{QED}}(m_Z) = 1/128.802$ and $\sin^2 \theta_W = 0.2222$. We use MSTW08LO parton distribution functions for leading order and MSTW08NLO for next-to-leading order computations, corresponding to $\alpha_s(M_Z) = 0.13939$ and $\alpha_s(M_Z) = 0.12018$ respectively [12]. We do not impose lepton isolation cuts. All results discussed below apply to the QCD production $pp \rightarrow W^+W^+jj$; the electroweak contribution to this process is ignored.

Since the cross section remains finite even if the requirement that two jets are observed is lifted, we can consider the production of same-sign gauge bosons in association with $n$ jets $pp \rightarrow W^+W^++n$ jets, where $n = 0, 1, 2$ or $n \geq 2$. Fig. 2 shows the dependence of the production cross-sections for $pp \rightarrow e^+\mu^+\nu_e\nu_{\mu}+n$ jets on the renormalisation and factorisation scales, which we set equal to each other.

Considering the range of scales $50$ GeV $\leq \mu \leq 400$ GeV, we find the two-jet inclusive cross-section to be $\sigma^{\text{LO}} = 2.7 \pm 1.0$ fb at leading order and $\sigma^{\text{NLO}} = 2.44 \pm 0.18$ fb at next-to-leading order. The forty percent scale uncertainty at leading order is reduced to less than ten percent at NLO. We observe similar stabilization of the scale dependence for the 0- and 1-jet exclusive multiplicities. Combining these cross-sections we obtain a total NLO cross-section of about 2.90 fb for $pp \rightarrow e^+\mu^+\nu_e\nu_{\mu}$ inclusive production. This implies about 60 $e^+\mu^+ + e^+e^+ + \mu^+\mu^+$ events per year at the LHC with 10 fb$^{-1}$ annual luminosity. While this is not a gigantic number, such events will have a very distinct signature, so they will definitely be seen and it will be possible to study them.

The dramatic change in the two-jet exclusive cross-section apparent from Fig. 2 is discussed
Figure 2: The dependence on factorisation and renormalisation scales of cross-sections for $pp \rightarrow e^+\mu^+\nu_e\nu_\mu+n$ jets, $n = 0, 1, 2$ at leading and next-to-leading order in perturbative QCD. Here $\mu_F = \mu_R = \mu$.

and investigated in Ref.\[1\]. We find that the feature observed here, that the two-jet exclusive is significantly smaller than the two-jet inclusive, remains present when we increase the jet cut and so allow for greater perturbative convergence of the exclusive cross section. This smallness implies that quite a large fraction of events in $pp \rightarrow e^+\mu^+\nu_e\nu_\mu+\geq 2$ jets have a relatively hard third jet. This feature may be useful for rejecting contributions of $pp \rightarrow W^+W^+jj$ when looking for multiple parton scattering.

Selected kinematic distributions are shown in Fig. 3. It is clear that jets in $pp \rightarrow W^+W^+jj$ are hard; a typical transverse momentum of the hardest jet is close to 100 GeV and the transverse momentum of the next-to-hardest jet is close to 40 GeV. The NLO distributions show a characteristic depletion at large values of $p_T$. One reason this change occurs is because a constant, rather than a dynamical, renormalisation scale is used in our leading order calculation. Scale dependencies of the distributions are reduced dramatically. The angular distance $\Delta R_{lj}$ between a charged lepton of fixed flavor ($e^+$ or $\mu^+$) and the next-to-hardest jet is displayed, as well as the distribution of the relative azimuthal angle of the two charged leptons. Although the distribution of angular distance between leptons and the next-to-hardest jet is broad, it peaks at $\Delta R_{lj} \approx 3$. NLO QCD effects do not change this conclusion but, interestingly, they make the angular distance between next-to-hardest jet and the charged lepton somewhat larger. The distribution of the relative azimuthal angle of the two charged leptons becomes less peaked at $\Delta \phi_{l,l'} = \pi$, although the two leptons still prefer to be back to back. It is interesting to remark that, if the two same sign leptons are produced through a double-parton scattering mechanism, their directions are not correlated. Hence, yet another possibility to reduce the single-scattering-background is to cut on the relative azimuthal angle between the two leptons.

To conclude, selected results from the calculation of NLO QCD corrections to the QCD-mediated process $pp \rightarrow W^+W^+jj$ have been presented. Methods developed very recently for computing one-loop amplitudes allowed for relatively straightforward calculation of this $2 \rightarrow 4$ process. The detector signature is an exotic one, and is exciting to study at the LHC.
Figure 3: Distributions of the transverse momentum of the two hardest jets and angular distributions in the process $pp \rightarrow e^+ \mu^+ \nu_e \nu_\mu + 2$ jets at leading and next-to-leading order in perturbative QCD for inclusive two-jet events. The bands show renormalisation and factorisation scale uncertainty, for $50 \text{ GeV} \leq \mu \leq 400 \text{ GeV}$. Solid lines show leading and next-to-leading order predictions for $\mu = 150 \text{ GeV}$.

Acknowledgments

I wish to thank the organisers of the Moriond QCD session for providing both financial support and a fantastic conference. This write-up is based on work done in collaboration with Kirill Melnikov, Raoul Röntsch and Giulia Zanderighi and closely follows Ref. 1, and the research is supported by the British Science and Technology Facilities Council.

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