PROCEEDINGS OF SCIENCE

Di-vector Boson Production with Jets at the LHC

Fernando Febres Cordero*, **Harald Ita**
Physikalisches Institut, Albert-Ludwigs-Universität, Freiburg
D-79104 Freibug, Germany
E-mail: ffebres@physik.uni-freiburg.de

In this talk we present the first calculation of next-to-leading-order QCD corrections for the production of W^+W^- pairs in association with three jets at the LHC. We show the observed improvement in the dependence of total and differential cross sections on the unphysical renormalization and factorization scales. We study the radiation pattern for configurations associated to vector-boson fusion and the impact that the QCD corrections have on them.

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1. Introduction

Signatures of di-vector boson production in association with jets are associated to very rich phenomenology. They are key to understanding the electroweak gauge structure, as they can be used to measure trilinear and quartic gauge couplings and to put constraints on anomalous gauge couplings. They appear naturally in top physics, since final-state configurations in $t\bar{t}$ production contain a W^+W^- pair and two or more jets. The Higgs boson can decay into a vector-bosons pair, for example W^+W^-, ZZ, $\gamma\gamma$ and $Z\gamma$, and is accompanied by jets in its production through vector boson fusion. Also in many models beyond the Standard Model (SM) decay chains started by pairs of heavy colored particles lead to the associated production of several leptons and jets, for which the SM production of two weak bosons and jets are main backgrounds.

In this talk we present details of our next-to-leading-order (NLO) QCD study [1] of the production of a W^+W^- pair in association with up to three jets at the LHC. Related calculations have been published before, starting with studies of the inclusive W^+W^- rates at leading order (LO) [2], NLO [3] and reaching up to next-to-next-to-leading (NNLO) order in QCD [4]. The case of W^+W^- hadro production in association with one jet was studied at NLO QCD in ref. [5] and with two jets in ref. [6, 7, 8]. Studies of same-sign W pair production with two jets were presented in ref. [9]. Our calculation for W^+W^-+3 jets is a state-of-the-art large-multiplicity NLO QCD calculation at hadron colliders which presently reach five [10, 11, 12] or six [13] objects in the final state.

At the LHC experiments many studies of inclusive di-vector boson production have been performed, mainly motivated by their importance for Higgs phenomenology. Dedicated studies of di-vector bosons measured in bins of jet multiplicity, however, are scarce. This is due to constraints from dataset sizes as well as the intrinsic difficulties of measuring multi-lepton multi-jet signatures. Nevertheless, recently the CDF collaboration has measured W^+W^- plus multi-jet production at the Tevatron [14] and the ATLAS collaboration WZ plus many jets at the LHC [15]. In Figure 1 we collected results of these two analyses. The impressive advances by ATLAS, showing results with up to 5 jets in the final state, is compared to LO (SHERPA) and NLO predictions (POWHEG and MC@NLO) combined with parton showers. The Sherpa predictions include matrix elements with the vector-boson pair and up to three hard partons. In contrast, the POWHEG and MC@NLO predictions include hard scattering matrix elements of a vector-boson pair with at most one associated jet. Such differences explain the deviations of the theory predictions and motivate further theoretical work for this signature. Presently, inclusive fixed-order predictions beyond two associated jets are not available for the WZ final state. We hope to make this next level of predictions, i.e. VV+3-jet results at NLO QCD, available in the near future. Here we focus on the related signature of W^+W^- production in association with up to three jets.

2. The Calculation

We employ the BLACKHAT library [16], based on unitarity and on-shell techniques for the computation of the one-loop matrix elements. This library has been used for many NLO QCD studies in pure-jet production, single-vector-boson-production plus jets and di-photon plus jets (see for example [10, 11, 13] and references therein). New additions to the library include: on-shell recursion relations for tree amplitudes with quarks, gluons and several vector bosons; the

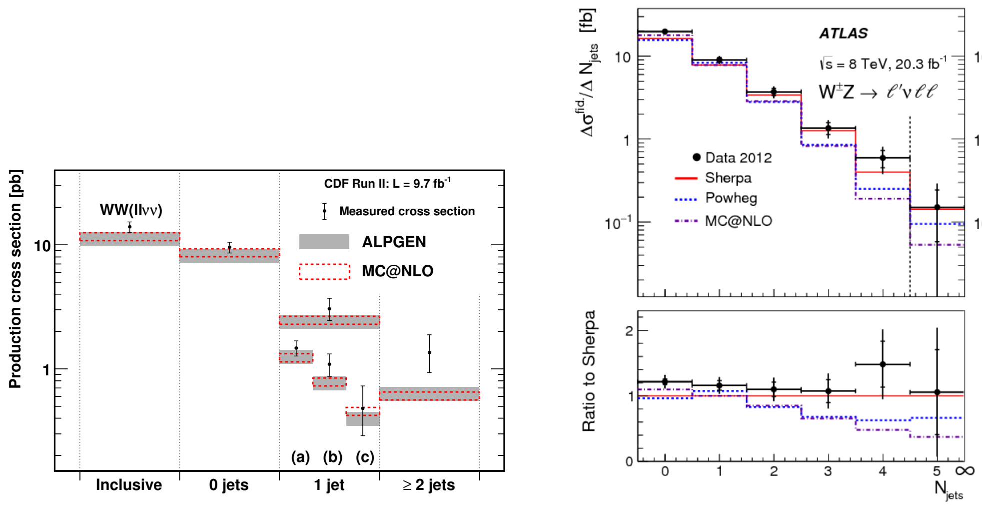

Figure 1: Experimental measurements of di-vector boson production in association with many jets. On the left CDF's measurement [14] of W^+W^- production in bins of jet multiplicity, including an inset for the E_T distribution of the leading jet in inclusive W^+W^-+1-jet production at the Tevatron. On the right the ATLAS collaboration show their measurement [15] for $W+Z$ jet production in bins of jet multiplicity at the LHC, including up to the case of $WZ+5$ jets.

implementation of off-shell tree-level recursions as a cross check; extensions of the unitarity engine to handle these trees and the assemblies of loop and tree-level helicity amplitudes into squared matrix elements. We employ the SHERPA library [17] to compute real-radiation corrections, to integrate over phase space and to produce *ntuple* files [18], which are used to compute general infrared-safe observables.

We use a leading-color approximation only for the one-loop matrix elements in W^+W^-+3-jet production. By explicit comparison to lower-point results ($W^+W^-+\leq 2$ jets) we expect this approximation to be reliable at the percent level. We have dropped all contributions from closed massive-quark loops and we work with a diagonal CKM matrix. We decay the W bosons into distinct massless lepton flavors ($W^+\to\mu^++\nu_\mu$ and $W^-\to e^-+\bar{\nu}_e$).

All results shown have been produced for the LHC with $\sqrt{s}=13$ TeV, employing the MSTW2008 set of PDFs [19]. We take the strong coupling α_s provided by the PDF sets consistently at each order of the perturbative expansion. To set the renormalization (μ_r) and factorization (μ_f) scales, we use a dynamical scale $\mu=\mu_r=\mu_f=\hat{H}_\mathrm{T}/2$, which is half the scalar sum of the transverse momentum of the partons and leptons in the final state. The W and Z boson mass and width are given respectively by $\Gamma_W=2.085$ GeV, $M_W=80.399$ GeV and $\Gamma_Z=2.4952$ GeV, $M_Z=91.188$ GeV.

For the lepton sector we impose the following kinematical cuts:

$$\begin{aligned} &p_\mathrm{T}^{e,\mu}>20\ \mathrm{GeV}\,, && |\eta^{e,\mu}|<2.4\,, && \not{E}_\mathrm{T}>30\ \mathrm{GeV}\,,\\ &p_\mathrm{T}^{e\mu}>30\ \mathrm{GeV}\,, && m^{e\mu}>10\ \mathrm{GeV}\,, && \end{aligned} \tag{2.1}$$

where $p_T^{e\mu}$ and $m^{e\mu}$ represent the transverse momentum and mass of the electron-muon system

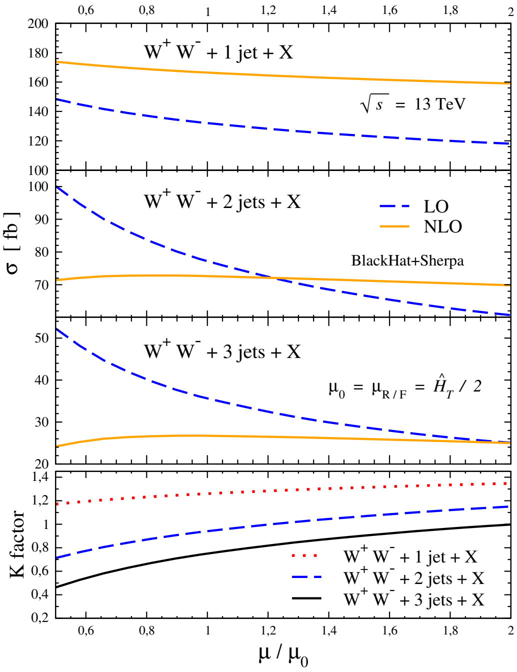

Figure 2: Scale dependence for total cross sections in W^+W^-+1,2,3 jets at the LHC. LO results are shown with the solid (orange) lines and NLO with the dashed (blue) lines. The bottom panel shows the ratio NLO to LO, so called K factor, for all multiplicities.

respectively. For defining jets we employ the anti-k_{T} algorithm together with the following cuts:

$$p_{\mathrm{T}}^{jet} > 30 \text{ GeV}, \qquad |\eta^{jet}| < 4.5, \qquad R = 0.4\,. \tag{2.2}$$

3. Total and Differential Rates

In Figure 2 we show the dependence of the total inclusive cross sections on the unphysical renormalization and factorization scales for W^+W^- production in association with one, two and three jets. The bottom panel of the figure shows the ratio of NLO cross sections to LO cross sections, the so called K factors. It can be seen that for all multiplicities a marked reduction in the spurious scale dependence is achieved. Even more, these improvements become all the more relevant for larger multiplicities.

We also explore the impact of the quantum corrections over phase space. In Figure 3 we show the jet p_{T} spectra for $W^+W^- + 3$-jet production. The softer the jet the more steeply their p_{T} distribution falls. This is very relevant for quantifying the large impact of jet-energy-scale uncertainties on measuring large-jet multiplicity processes. A good feature of our dynamical scale choice is that the NLO QCD correction do not significantly affect the shape of the p_{T} distribution of the softest jet. This feature is very similar to what has been observed in studies of single-vector-boson production and jets (see for example [13]). But not all features of the quantum corrections can be accounted for by a single scale choice. This is clear for example by looking at the first and

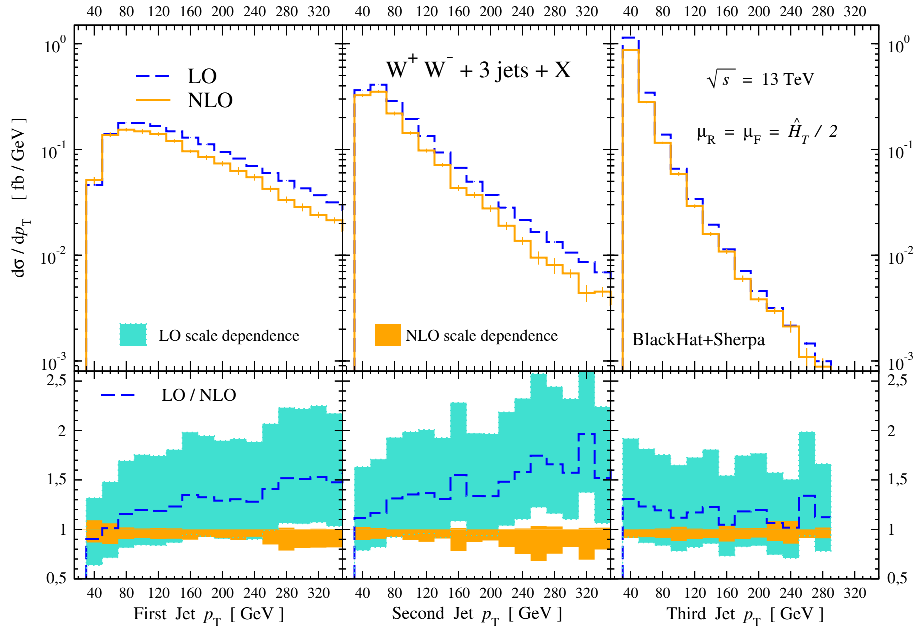

Figure 3: A comparison of the p_T distributions of the leading three jets in $W^+W^- + 3$-jet production at the LHC at $\sqrt{s} = 13$ TeV. In the upper panels the NLO distribution is the solid (orange) histogram and the LO predictions are shown as dashed (blue) lines. The thin vertical line in the center of each bin (where visible) gives its numerical (Monte Carlo) integration error. The lower panels show the LO distribution and the scale-dependence bands normalized to the central NLO prediction. The bands are shaded (orange) for NLO and light-shaded (cyan) for LO.

second jet $p_{\rm T}$ distributions. Notice in general the large reduction of scale dependence at NLO in the bottom panels.

In Figure 4 we show the distribution of the $p_{\rm T}$ of the neutrino-pair system. As neutrinos escape the detector leaving no traces, they are a source for missing transverse energy. This is a key observable for the process type that we study. NLO corrections for $W^+W^- + 3$-jet production for this observable appear stable, particularly for large transverse momentum; they show only a minor change in the shape of the distribution and LO and NLO scale dependence bands overlap.

4. Radiation Gap

Vector-boson scattering events, $VV \to VV$, typically produce two energetic jets (*tagging* jets) in the forward and backward parts of the detectors. These jets are associated to incoming quarks which emit the scattering vector bosons. Since the exchange between the interacting quarks is colorless, the resulting events tend to suppress hard radiation between the tagging jets. QCD background processes, however, tend to radiate into the gap, which is exploited in order to disentangle signal from background events.

Having precise predictions for $W^+W^- + 3$-jet production allows to study the structure of the radiation into the gap for the main irreducible background to $W^+W^- \to W^+W^-$ scattering. The

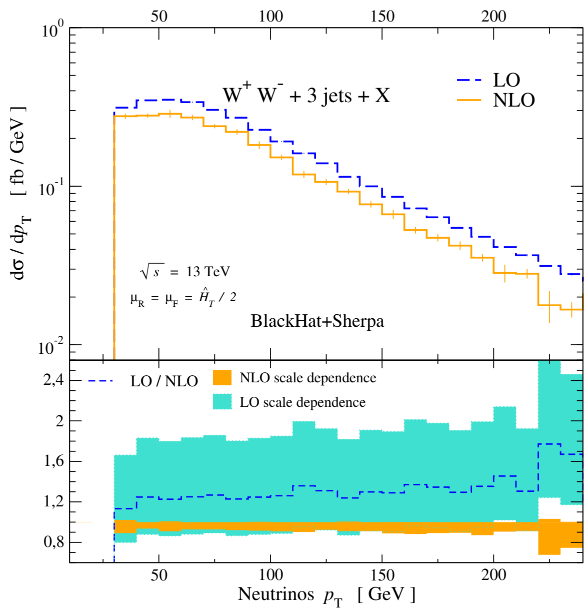

Figure 4: The missing p_T distribution for W^+W^-+3-jet production. This observable is associated to the p_T of the ν_μ-$\bar{\nu}_e$ neutrino-pair system. Format as in Figure 3.

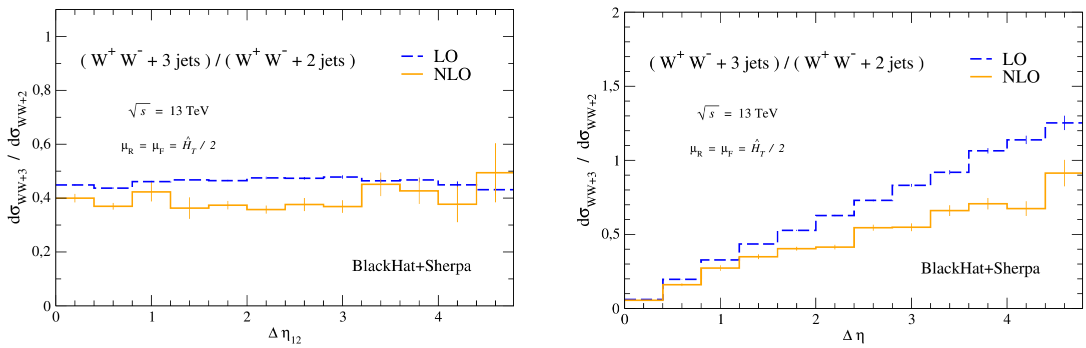

Figure 5: Probability of emission of an extra jet in W^+W^-+2-jet production at the LHC. On the left the tagging jets are chosen by their p_T, on right the most-forward and most-backward jets are chosen.

idea is that the ratio of W^+W^-+3-jet to W^+W^-+2-jet rates gives the probability of finding an extra jet in an inclusive sample for W^+W^-+2-jet production.

In Figure 5 we present this observable as a function of pseudo-rapidity separation between two tagging jets. Two different configurations are shown: *i)* on the left the tagging jets are selected as the two leading jets organized in p_T. *ii)* on the right, the tagging jets are actually taken as the most-forward and most-backward jets in the event. Interesting patterns of radiation emerge. When the jets are organized in p_T we find a flat radiation pattern as a function of the jet-pseudo-rapidity separation $\Delta\eta_{12}$. This behaviour is to be expected and accounts for democratic radiation in all directions. In this case quantum corrections only very mildly reduce radiation probability and no change in the shape of the distribution is observed. The case of radiation into the rapidity gap has more structure. Phase-space effects suppress the emission probability in the regime with $\Delta\eta \to 0$. On the other hand, the emission probability increases rapidly for larger values of the rapidity separation $\Delta\eta$. A marked change in the radiation pattern is induced by the NLO QCD corrections and it is important to take into account these effects in experimental studies. We note that the patterns presented are actually very similar to a related measurement performed by the D0 collaboration [20] for the case of a W boson produced in association with jets.

5. Conclusions

We have presented NLO QCD results for the production of a W^+W^- pair in association with three jets at the LHC. We also computed the cases with zero, one and two jets which were already given in the literature. We have shown the considerable reduction in spurious scale sensitivity that is achieved by including NLO QCD corrections both at the level of total cross sections and for differential distributions. Having precise $W^+W^- + 3$-jet predictions, and also for $W^+W^- + 2$-jet, allows to study radiation patterns into the gap. This is of key importance for studies of di-vector boson scattering. We hope to extend the calculations to other combinations of di-vector bosons, such as WZ+jet production in the future.

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