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NLO QCD Predictions for $W + 3$ jets

Daniel Maître**Department of Physics, University of Durham, DH1 3LE, UK**E-mail: daniel.maitre@durham.ac.uk***Carola F. Berger***Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA**E-mail: cfberger@mit.edu***Zvi Bern, Fernando Febres Cordero, Harald Ita***Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095-1547, USA**E-mail: bern@physics.ucla.edu, ffebres@physics.ucla.edu, ita@physics.ucla.edu***Lance J. Dixon, Darren Forde, Tanju Gleisberg***SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309, USA**E-mail: lance@slac.stanford.edu, dforde@slac.stanford.edu, tanju@slac.stanford.edu***David Kosower***Institut de Physique Théorique, CEA-Saclay, F-91191 Gif-sur-Yvette cedex, France**E-mail: david.kosower@cea.fr*

In this contribution we present results from the NLO computation of the production of a W boson in association with three jets in hadronic collisions. The results are obtained by combining two programs: BlackHat for the virtual one-loop matrix elements and Sherpa for the real-emission contributions. We present results for the Tevatron and the LHC, and address the issue of the choice of a common factorization and renormalization scale for this process.

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1. Introduction

The production of a W boson in association with jets forms a key set of processes at hadron colliders. These processes are not just important benchmarks in understanding the Standard Model at colliders; they also constitute important backgrounds to top-quark production and to new physics signals. In addition, inclusive W production is a means for determining the (partonic) luminosity at the LHC. An important aspect of such studies is to have good theoretical control over Standard Model predictions. Precise predictions are first obtained at next to leading order (NLO) in the QCD coupling. In contrast, leading-order (LO) computations usually suffer from large renormalization and factorization scale uncertainties. More importantly, shapes of distributions can be altered by higher-order corrections.

NLO predictions have been available for processes involving a W boson and up to two jets [1]. The bottleneck for the inclusion of a third jet had been the computation of the virtual matrix elements. Recently, significant progress has been made on this problem [2, 3]. In these proceedings, we summarize results from the first complete NLO calculation of $W + 3$ jets [3].

NLO results are obtained by combining the Born-level matrix elements with two additional contributions, the virtual one-loop amplitude interfered with the tree-level amplitude, and the squared real-emission matrix elements. These two additional contributions are provided by two different programs, `BlackHat` for the one-loop matrix elements and `Sherpa` for the real-emission contribution.

`Sherpa` [4] is a Monte Carlo event generator framework written in C++. The automatic generation of the real-emission matrix elements, along with a suitable set of Catani-Seymour [5] subtraction terms, have been implemented [6] in its framework. All the phase-space integrations for the results presented below have been performed using `Sherpa`'s efficient multi-channel phase-space integration.

`BlackHat` [7] is a C++ library aimed at automating the computation of one-loop matrix elements, and based on the modern unitarity method [8, 9]. In general, one-loop matrix elements can be decomposed into two terms. The first term, called the “cut part”, contains all the functions that have branch cuts. The second “rational part” only contains rational functions of spinor products. The cut part itself can be decomposed at one loop into a sum of coefficients multiplying scalar one-loop scalar integrals. The coefficients of these integrals can be determined purely numerically at the integrand level [10, 11, 12] in a way that meshes well with the unitarity method. In `BlackHat`, a numerical version of Forde's analytic approach [10, 13] accomplishes this. The rational part is computed in `BlackHat` using either on-shell recursion [14, 7] or a variant of D -dimensional unitarity [15] along the lines of ref. [16].

2. Tevatron Results

The left panel of Figure 1 gives the E_T distribution of the third jet, and the right panel the dijet mass distributions, for $W + 3$ -jet production at the Tevatron. The former results agree well with data from CDF [17]. The lower panels show the LO and NLO scale variation bands, and the data, normalized by the central NLO result, in order to illustrate the shape difference between LO and NLO. As expected, the NLO scale variation, represented by the shaded grey band, is much smaller

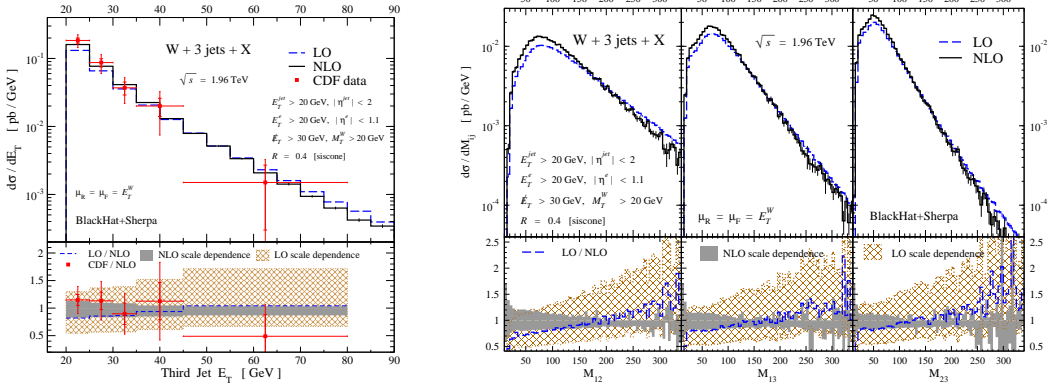


Figure 1: Left panel: E_T distribution of the third jet at the Tevatron. Right panel: dijet mass distributions. In both plots the LO and NLO results are represented by the blue and black lines, respectively. The (red) data points in the left panel show the E_T distribution measured by CDF [17], including experimental errors. The lower panels show the data and the LO results normalized by the NLO result.

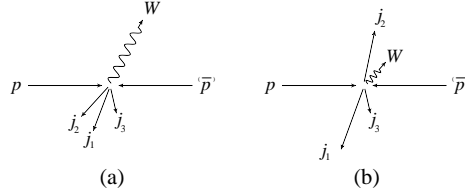


Figure 2: Different kinematic configurations for $W + 3$ jets: in (a) the W boson recoils against the three jets; in (b) the W is relatively soft compared to the jets.

than the LO one, represented by the brown hatched bands. We use the CTEQ6 [18] PDF sets. The Tevatron data in the plots have been obtained using the infrared-unsafe JETCLU jet algorithm [19]. We cannot use this algorithm in our NLO analysis, so we use the SISCONe [20] algorithm instead.

3. Scale choices

We choose the (common) factorization and renormalization scale dynamically, on an event-by-event basis. The wide range of scales available at the LHC makes choosing a reasonable scale more important than at the Tevatron. In multijet processes, typically more than one scale is involved, which no single scale choice can fully model. A bad choice of scale can manifest itself as a strong dependence of the ratio of NLO to LO cross sections, or K factor, as a function of the observable considered. A poorly chosen scale can even turn the NLO differential cross section negative in the tails of distributions, because of uncancelled large logarithms between the chosen scale and the typical scale in the process [3].

In particular, consider the two configurations shown in Figure 2 for the case of $W + 3$ jets. In case (a), the three jets recoil against the W boson, whereas in case (b) most of the energy is taken by the jets and the W boson is soft. Choosing the transverse energy of the W , E_T^W , as the scale is a good choice for case (a) but rather poor for case (b), since it does not capture the larger energy scale of the jets. On the other hand, choosing the total transverse energy, H_T (the scalar sum of the

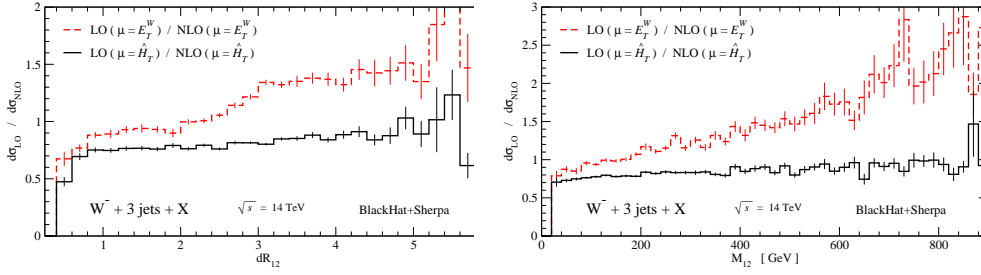


Figure 3: Comparison between two scale choices for the jet angular separation ΔR_{12} (left) and dijet mass M_{12} (right) for the two hardest jets. The red line represents the choice $\mu = M_W^T$ and the black line $\mu = \hat{H}_T$.

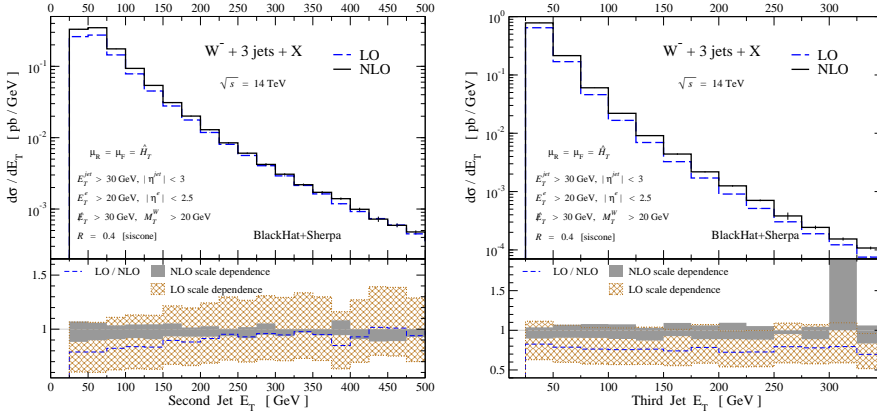


Figure 4: The left panel shows the E_T distribution of the second hardest jet at the LHC, while the right panel shows the third jet E_T . In both graphs, the LO and NLO results are represented by the blue (dashed) and black lines respectively. The lower panel shows the LO and NLO scale variation bands, normalized by the central NLO result.

jet, electron and neutrino E_T s), as the scale interpolates better between cases (a) and (b). In light of this, our default scale choice for the LHC is a partonic version of the total transverse energy, \hat{H}_T .

In order to assess the given scale choice, we plot in Figure 3 the ratio of LO to NLO for the jet angular separation ΔR_{12} and dijet mass M_{12} distributions for the two highest- E_T jets in the event, for both the E_T^W and \hat{H}_T scale choices. The curve corresponding to the scale \hat{H}_T is much flatter, indicating that this choice is better. A systematic discussion of scale choices, and their pitfalls, may be found in ref. [3].

4. LHC results

Figure 4 shows the second and third jet E_T distribution in $W^- + 3$ -jet production at the LHC. The lower panels show the reduced scale dependency of the NLO result as compared to the LO one.

5. Conclusion

In these proceedings we outlined some sample results from a full NLO calculation of $W + 3$ -jet production at the Tevatron and the LHC. We also summarized the suitability of the total transverse

energy H_T (or a fixed fraction of it) as a suitable scale choice for observables involving a W boson in conjunction with many jets. A more detailed discussion, including many more distributions, may be found in ref. [3].

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