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*SB/F/378-10*

# Jet and $W/Z$ Production at Hadron Colliders

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The start of the physics program at the LHC has added great impetus in the development of powerful theoretical tools to meet the many challenges that this collider brings. The production of jets and weak vector bosons is at the center of most analyses, from machine performance to new physics searches. In this talk we review some recent advances in the study of jets, in the computation of quantum corrections to processes with large jet multiplicity and their impact in $W/Z+$jets and $W/Z+b-$jets production at the Tevatron and the LHC.

*XXth Hadron Collider Physics Symposium*
*November 16 – 20, 2009*
*Evian, France*

[*] Speaker.

## 1. Introduction

Our understanding of the behavior of fundamental particles will be newly tested with the start of the LHC. With every step into higher energies we will be able to keep exploring the validity of the Standard Model (SM), and especially of its mechanism for Electroweak Symmetry Breaking, as well as testing possible scenarios of physics beyond the SM (BSM). In these tasks studying the production of weak vector bosons and jets is fundamental, given that they are our basic tools to extract information from hard interactions. Understanding Drell-Yan (DY) production is for example highly beneficial because of the close connection that these processes have to the determination of important quantities like luminosity and parton distribution functions.

As the strong coupling constant is relatively large at the scales of interest, the inclusion of perturbative QCD corrections to differential cross sections is necessary in order to successfully describe hadron collider data (see e.g. Ref. [1, 2]). For instance, it is well known that DY processes receive large next-to-leading order (NLO) QCD corrections, in some cases up to factors of two or more. In part this is also understood due to the strong kinematical constraints for leading order (LO) production and to the opening of new production channels at NLO. Nevertheless, one then has to show the validity of the perturbative expansion. Currently next-to-next-to-leading order (NNLO) QCD corrections to DY processes are available, and at this level it is shown that the perturbative expansion stabilizes. Programs like `Vrap` [3] and `FEWZ` [4] (see also Ref. [5]) compute related observables at NNLO precision.

Having tools that would allow for computations of NLO QCD corrections for a large variety of processes of interest is then highly desirable, especially for processes with large jet multiplicity which suffer from large uncertainties in normalization and shape of distributions [6].

In the following we will review central topics that have seen considerable progress over the last years to improve our theoretical control over the production of jets and weak vector bosons, in particular as the number of jets increases.

## 2. IR Safe Jet Algorithms (Fast!)

Except for a handful of examples, all studies including jets that have been performed by the Tevatron experiments, CDF and D0, have used cone like jet algorithms which are known to suffer from infrared unsafety. From a theoretical point of view, the use of an infrared unsafe algorithm in a perturbative computation spoils the order by order cancellation of infrared (soft and/or collinear) divergences. This turns even LO computations meaningless, for sufficiently large multiplicities, as the effective expansion parameter of the perturbative series becomes of $O(1)$ (for a nice review, see Ref. [7]). But technical constraints kept the experimental collaborations from using existing IR safe algorithms, like $k_T$ or seedless cone jet algorithms. Basically the computational need for clustering of those algorithms grew too quickly with the number of input towers (or particles) $N$: past implementations of the $k_T$ and seedless cone jet algorithms had a $N^3$ and exponential time scaling respectively. But with the help of sequential recombination algorithms and computational geometry techniques, $N\ln(N)$ implementations of the $k_T$ algorithm (and of related sequential jet algorithms) [8, 9], as well as a $N^2\ln(N)$ implementation of a seedless cone algorithm (SISCone) [10] became available.

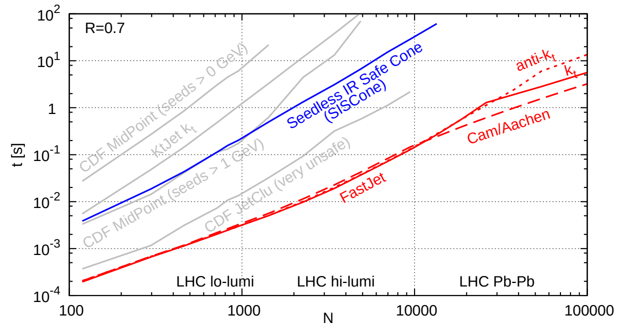


**Figure 1:** Clustering time as a function of the number of input momenta for several jet algorithms. IR safe algorithms are shown in dark colors (read and blue), and IR unsafe algorithms in light grey. Taken from Ref. [7].

As Fig. 1 shows, new implementations of IR safe jet algorithms perform similarly or better than commonly used IR unsafe cone algorithms. These then allow the ATLAS and CMS collaborations to use IR safe jet algorithms, even as their default jet algorithm. Indeed, a large amount of fast IR safe jet algorithms are now on the market, and with them a lot of new ideas have appeared (like pruning, filtering, variable-R algorithms, etc.) that should allow for optimizations in jet definitions for specific studies (see for example the review Ref. [7]).

## 3. NLO QCD corrections to $W/Z+n$ jets ($n=1,2,3$) at Hadron Colliders

In 2009 the first full NLO QCD corrections to hadron collider processes with four particles in the final state became available, including $t\bar{t}b\bar{b}$ production [11], $W+3$ jets production [12, 13] and $Z+3$ jets production [14]. A good part of the progress has been due to the use of new on-shell techniques (for a recent review see Ref. [15]).

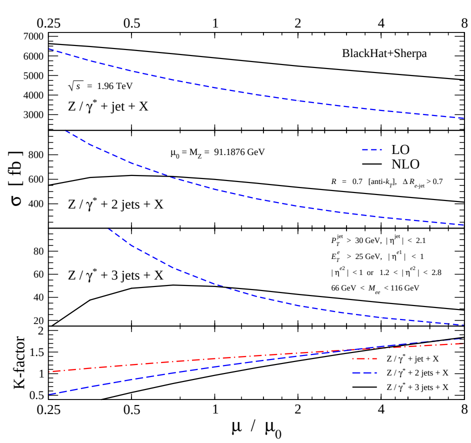


**Figure 2:** Total cross section dependence on renormalization and factorization scales ($\mu_r = \mu_f = \mu$) at LO (dashed-blue) and NLO (solid-black) for $Z/\gamma^* + n$ jets ($n = 1,2,3$) production at the Tevatron. Bottom panel shows K-factors for each jet multiplicity. Taken from Ref. [14].

Understanding $W/Z+$ jet production is especially important given that it leads to signals of missing energy plus jets, in itself a typical signature associated to physics BSM (see for example Refs. [16]). To disentangle signal and backgrounds, NLO predictions are needed especially for high jet multiplicity processes, given the large theoretical uncertainty associated to LO based predictions. This is explicitly shown in Fig. 2, where we see how the dependence on factorization and renormalization scales of the K-factor for the total cross sections for $Z/\gamma^* + n$ jets ($n = 1, 2, 3$) production at the Tevatron increases with the numbers of jets.

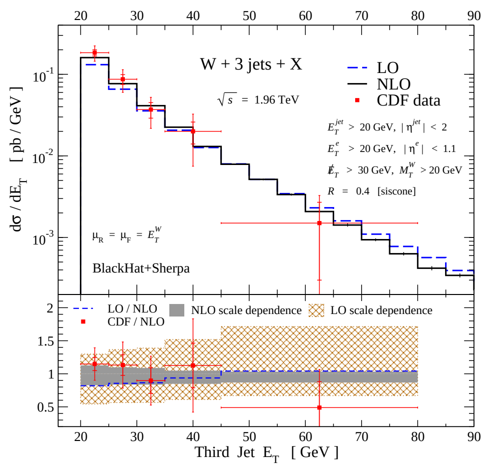


**Figure 3:** NLO QCD corrections to third jet $E_T$ distributions in $W + jets$ production compared to CDF data [2]. Taken from Ref. [12].

NLO corrections give then the first quantitatively reliable prediction of total rates, and even more, their reduced sensibility to unphysical scales implies improved predictions for the shape of distributions as well. In Fig. 3 we see for example how NLO predictions fit well CDF's data [2] for the $E_T$ distribution of the third jet in inclusive $W+$ jets production. In part the LO difference in shape with CDF's data, is mostly due to a poor choice of dynamical scale, namely $E_T^W$. This choice can be shown, armed with NLO predictions, to be even worse for the LHC, as it will sample a larger dynamical range. For example, the left panel of Fig. 4 shows a large shape change from LO to NLO, and more troublesome it shows the NLO prediction turning negative at large second jet $E_T$! This as a consequence of having introduced large logs in the computation, due to poor choice of dynamical scales [12]. In the right panel we show similar results with the dynamical scale set to $\hat{H}_T$, which behave much better. Indeed such choice leads to fairly flat bin-by-bin K-factors over full phase space (a nice feature when NLO effects are introduced in Monte Carlo programs via a global K-factor rescaling).

To close this section, we mention an interesting feature found for the QCD production of $W+$ jets [12]. At the LHC the production of $W+$ jets shows both $W^+$ and $W^-$ being produced with left-handed polarization for large $P_T^W$. This effect is fairly independent of the number of jets considered, and is found both at LO and NLO. In Fig. 5 we show how this effect results in an asymmetry in the $E_T$ distributions of the decay leptons in $W^+$ and $W^-$ production. We notice that this feature does not appear for example when the leptons and jets come from top production or other BSM signals, where $W^+$ tends to be left-handed while $W^-$ tends to be right-handed for large $P_T^W$, and giving then

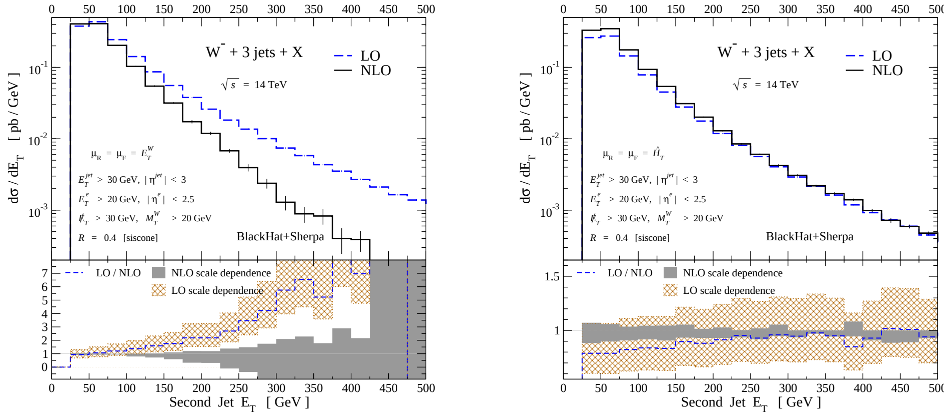


**Figure 4:** Second Jet $E_T$ distribution for $W+3$ jets production at the LHC, computed with a dynamical scale set to $E_T^W$ (left) and $\hat{H}_T$ (right). The latter clearly gives more stable results both at LO and NLO. Taken from Ref. [12].

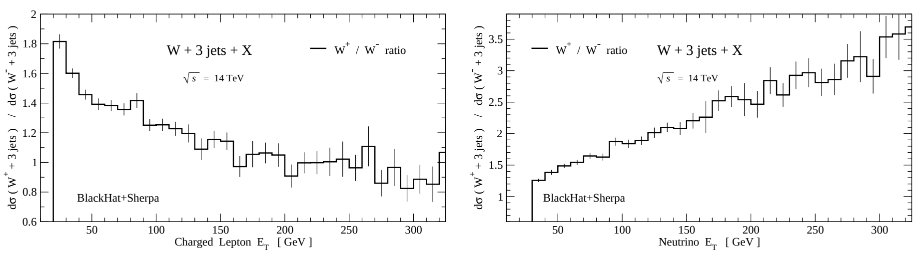


**Figure 5:** Charged lepton (left) and neutrino (right) $E_T$ distributions for the ratio ($W^+ + 3$ jets)/($W^- + 3$ jets) at the LHC. Large asymmetries are found due to left-handed polarization of the parents $W^+$ and $W^-$. Taken from Ref. [12].

no asymmetries as the ones in Fig. 5.

## 4. $W$ Associate Production to $b$-jets

A recent measurement of the cross section of $W$ boson production in association with one or two $b$-jets by the CDF collaboration at the Tevatron finds [17]

$$\sigma_{b-\text{jets}} \times \mathscr{B}(W \to \ell\nu)(\text{CDF}) = 2.74 \pm 0.27(\text{stat.}) \pm 0.42(\text{syst.}) \text{ pb} . \tag{4.1}$$

This $b$-jet cross section includes $Wb\bar{b}$ and $W+1b$-jet contributions, and the NLO QCD predictions for both signatures have to be considered. The NLO QCD prediction for $Wb\bar{b}$ production is based on Refs. [18] and the one for $W+1b$-jet production on Ref. [19], where in both cases events with a non-$b$-jet that result in a three-jet event are discarded. Combining the results of predictions for $Wb\bar{b}$ and $W+1b$-jet production, yields the following NLO QCD predictions (with $\mu_r = \mu_f = M_W$) [19]:

$$\sigma_{b-\text{jets}} \times \mathscr{B}(W \to \ell\nu)(\text{NLO QCD}) = 1.22 \pm 0.14 \text{ pb} . \tag{4.2}$$

Together with the LO prediction of $0.91^{+0.29}_{-0.20}$ pb (including scale uncertainties) this results in a moderate K-factor of about 1.35. There is then a clear discrepancy between theory and experiment, even when comparing to shower montecarlo results [17]. The origin of the discrepancy is still an open problem [1].

## Acknowledgments

We would like to thank the organizers of the HCP2009 Symposium for their kind invitation and their work to prepare such wonderful conference. We thank too C.F. Berger, Z. Bern, J. Campbell, L. Dixon, K. Ellis, D. Forde, T. Gleisberg, H. Ita, D. Kosower, D. Maître, F. Maltoni, L. Reina, D. Wackeroth and S. Willenbrock for collaboration in several of the topics presented in this talk.

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