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Higher-order QCD corrections to vector boson production at hadron colliders.

Giancarlo Ferrera
Dipartimento di Fisica, Università di Firenze & INFN Sez. di Firenze, I-50019 Sesto Fiorentino, Florence, Italy
E-mail: ferrera@fi.infn.it

We present two recent results on higher-order QCD corrections to the production of vector bosons in hadron collisions.
We discuss the resummation of logarithmic-enhanced QCD corrections at small values of q_T and the matching procedure to consistently combine resummation with the fixed-order perturbative result at intermediate and large q_T. We study the perturbative uncertainty of the results and we compare our prediction with Tevatron data for Z bosons production.
Moreover we discuss a fully exclusive calculation up to next-to-next-to-leading order (NNLO) in QCD perturbation theory. The calculation is implemented in a parton level Monte Carlo program which allows the user to apply arbitrary kinematical cuts on the final-states and to compute the corresponding distributions in the form of bin histograms.

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1. Transverse-momentum resummation

We are interested in the high-energy collisions of the hadrons h_1 and h_2 which produce a vector boson V (which decays into the lepton pair l_1, l_2) plus an arbitrary and undetected final state X

$$h_1 + h_2 \rightarrow V(M, q_T) + X \rightarrow l_1 + l_2 + X \,, \tag{1.1}$$

where q_T and M are respectively the transverse momentum and the invariant mass of the vector boson.

We consider the transverse-momentum distribution and we identify two different kinematical regions. In the region where $q_T \sim m_V$, m_V being the mass of the vector boson ($m_V = m_W, m_Z$), the QCD perturbative series is controlled by a small expansion parameter, $\alpha_S(m_V)$. In this region the fixed-order QCD calculations, known up to next-to-leading order (i.e. $\mathscr{O}(\alpha_S^2)$) [1], are theoretically justified. In the small-q_T region ($q_T \ll m_V$), the convergence of the fixed-order perturbative expansion is spoiled by the presence of powers of large logarithmic terms, $\alpha_S^n \ln^m(m_V^2/q_T^2)$. In order to obtain reliable predictions in such region an all order resummation of these terms is mandatory.

The q_T resummation is performed at the level of the partonic cross section, which is decomposed in two terms: $d\hat{\sigma}^V/dq_T^2 = d\hat{\sigma}^{V\,(\text{res.})}/dq_T^2 + d\hat{\sigma}^{V\,(\text{fin.})}/dq_T^2$ [2, 3]. The term $d\hat{\sigma}^{V\,(\text{res.})}$ contains all the logarithmically enhanced contributions (at small q_T) we have to resum while the term $d\hat{\sigma}^{V\,(\text{fin.})}$ is free of such contributions and can be evaluated at fixed order in perturbation theory.

The resummation procedure is performed in the impact-parameter space through a Fourier-Bessel transform

$$\frac{d\hat{\sigma}^{V\,(\text{res.})}}{dq_T^2}(q_T, M, \hat{s}, \alpha_S) = \hat{\sigma}^V_{LO}(M)\,\frac{M^2}{\hat{s}}\,\int_0^\infty db\,\frac{b}{2}\,J_0(bq_T)\,\mathscr{W}^V(b, M, \hat{s}, \alpha_S)\,, \tag{1.2}$$

where the impact parameter b is the conjugate variable with respect to q_T, $J_0(x)$ is the 0-order Bessel function and $\hat{\sigma}^V_{LO}$ is the Born partonic cross section. We can now write the partonic resummed component $\mathscr{W}^V(b, M, \hat{s}, \alpha_S)$ in the exponential form by considering its N-moments with respect to the variable $z = M^2/\hat{s}$ at fixed M

$$\mathscr{W}_N^V(b, M, \alpha_S) = \mathscr{H}_N^V(\alpha_S) \times \exp\{\mathscr{G}_N(\alpha_S, L)\}\,, \ \text{ with } \ L = \ln(Q^2 b^2/b_0^2), \ \ b_0 = 2e^{-\gamma_E}\,. \tag{1.3}$$

We have introduced in the above formula the scale $Q \sim M \sim m_V$, the so called resummation scale, which has a role analogous to the factorization and renormalization scales: variations of Q around m_V can be used to estimate the size of higher-order logarithmic contributions that are not explicitly resummed in a given calculation.

The process dependent function $\mathscr{H}_N^V$ includes all the perturbative terms that behave as constants as $q_T \to 0$. It can thus be expanded in powers of $\alpha_S = \alpha_S(\mu_R^2)$:

$$\mathscr{H}_N^V(\alpha_S) = \left[1 + \frac{\alpha_S}{\pi}\,\mathscr{H}_N^{V\,(1)}\left(\frac{\alpha_S}{\pi}\right)^2\,\mathscr{H}_N^{V\,(2)} + \ldots\right]. \tag{1.4}$$

The universal exponent $\mathscr{G}_N$ resums all the terms that order-by-order in α_S are logarithmically divergent.

Finally the finite component has to be evaluated starting from the usual fixed-order perturbative truncation of the partonic cross section and subtracting the expansion of the resummed part at the same perturbative order: $[d\hat{\sigma}^{V\,(\mathrm{fin.})}/dq_T^2]_{f.o.} = [d\hat{\sigma}^{V}/dq_T^2]_{f.o.} - [d\hat{\sigma}^{V\,(\mathrm{res.})}/dq_T^2]_{f.o.}$. This matching procedure is important to achieve uniform theoretical accuracy over the entire range of transverse momenta.

To perform a resummation at next-to-next-to-leading logarithmic order, the knowledge of the coefficient $\mathscr{H}_N^{V(2)}$ is necessary. Since this coefficient has been computed only recently [4], here we limit ourselves to presenting results up to next-to-leading logarithmic accuracy matched with the leading fixed-order result (NLL+LO).

In Fig. 1 we compare our NLL+LO resummed spectrum [3] (with different values of the factorization, renormalization and resummation scale) with the Tevatron D0 Run II data [5]. We find that the scale uncertainty is about $\pm 12-15\%$ from the region of the peak up to the intermediate q_T region ($q_T \sim 20$ GeV), and it is dominated by the resummation-scale uncertainty. Taking into account the scale uncertainty, we see that the resummed curve agrees reasonably well with the experimental points [1]. We expect a sensible reduction of the scale dependence once the complete NNLL+NLO calculation is available.

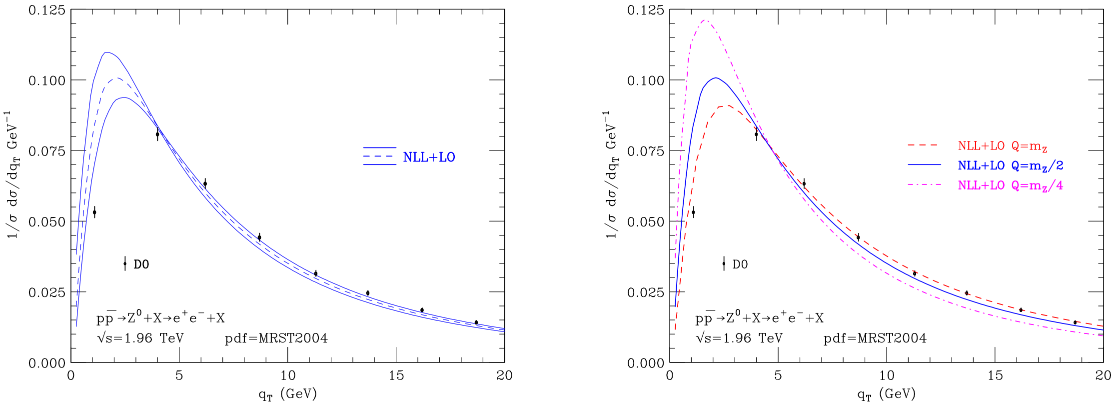

Figure 1: The q_T-spectrum of the Drell-Yan e^+e^- pairs produced in $p\bar{p}$ collisions at the Tevatron Run II [5]. Theoretical results are shown at NLL+LO, including scale variations. Left side: $m_Z/2 \leq \mu_F, \mu_R \leq 2\,m_Z$, with the constraint $1/2 \leq \mu_F/\mu_R \leq 2$. Right side: $m_Z/4 \leq Q \leq m_Z$

2. Fully exclusive NNLO calculation

We now consider a generic observable $d\hat{\sigma}^V$ for the process in Eq. 1.1. We present a computation of the next-to-next-to-leading order (NNLO) QCD radiative corrections for such observable with arbitrary (though infrared safe) kinematical cuts on the final-state [4]. Provided the observable is sufficiently inclusive over the small-q_T region, resummation is not necessary and fixed-order perturbation theory can be used.

Following Ref. [6], we observe that, at LO, the transverse momentum q_T of V is exactly zero. This means that if $q_T \neq 0$ the (N)NLO contributions is given by the (N)LO contribution to the final state $V + jet(s)$: $d\hat{\sigma}^V_{(N)NLO}|_{q_T \neq 0} = d\hat{\sigma}^{V+\mathrm{jets}}_{(N)LO}$. We compute $d\hat{\sigma}^{V+\mathrm{jets}}_{NLO}$ by using the subtraction

[1] We note that in Fig. 1 the theoretical results are obtained in a pure perturbative framework, without introducing any models of non-perturbative contributions. These contributions can be relevant in the q_T region below the peak.

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method at NLO and we treat the remaining NNLO singularities at $q_T = 0$ by the additional subtraction of a counter-term constructed by exploiting the universality of the logarithmically-enhanced contributions to the q_T distribution (see Eq. 1.3)

$$d\hat{\sigma}^{V}_{(N)NLO} = \mathscr{H}^{V}_{(N)NLO} \otimes d\hat{\sigma}^{V}_{LO} + \left[d\hat{\sigma}^{V+\text{jets}}_{(N)LO} - d\hat{\sigma}^{CT}_{(N)LO} \right] \quad , \tag{2.1}$$

where $\mathscr{H}^{V}_{(N)NLO}$ is the process dependent coefficient function of Eq. 1.4.

We have encoded our NNLO computation in a parton level Monte Carlo event generator. The calculation includes finite-width effects, the $\gamma - Z$ interference, the leptonic decay of the vector bosons and the corresponding spin correlations [2]. Our numerical code is particularly suitable for the computation of distributions in the form of bin histograms, as shown the illustrative numerical results presented in Fig. 2.

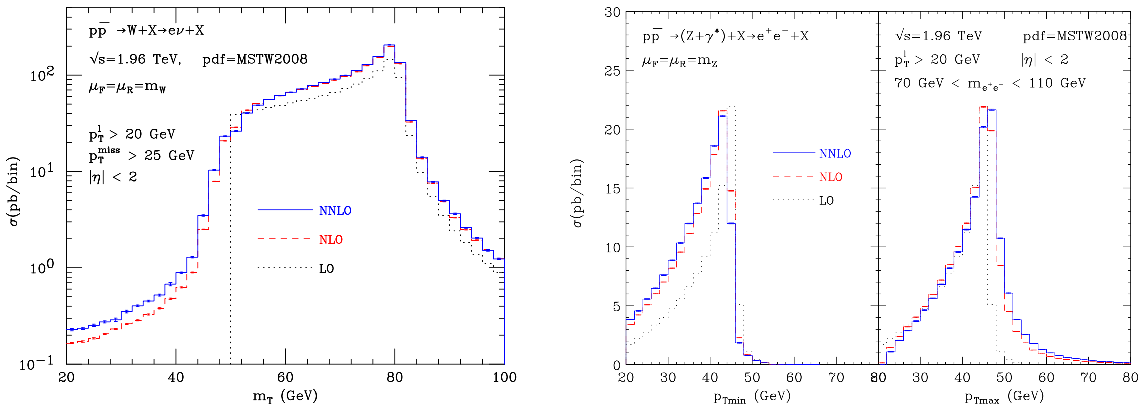

Figure 2: Left side: transverse mass distribution for W production at the Tevatron. Right side: distributions in $p_{T\,min}$ and $p_{T\,max}$ for the Z signal at the Tevatron.

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[2] In the quantitative studies that we have carried out, our computation gives results in numerical agreement with the calculation, performed with a different method, presented in Ref. [7].