TRANSVERSE-MOMENTUM RESUMMATION: VECTOR BOSON PRODUCTION AND DECAY AT HADRON COLLIDERS

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We consider the W and Z/γ^* bosons transverse-momentum (q_T) distribution at hadron colliders. We include the leptonic decay of vector bosons with the corresponding spin correlations, the finite width effects and the fully-differential dependence on leptonic variables. At small values of q_T, we resum to all-orders the logarithmically-enhanced perturbative QCD contributions up to next-to-next-to-leading logarithmic accuracy. Resummed results are consistently combined with the next-to-leading fixed-order result at intermediate and large values of q_T. We present a preliminary comparison with some of the available LHC data.

1 Introduction

The Drell-Yan (DY) mechanism, i.e. the hadroproduction of vector bosons which decay in lepton pairs, plays a crucial role in physics studies at hadron colliders. It is thus a major task to provide accurate theoretical predictions to the DY cross section and the related kinematical distributions. This requires, in particular, the computation of perturbative QCD corrections[1,2,3,4].

A particularly relevant observable is the transverse-momentum (q_T) distribution of the vector boson. In the large-q_T region ($q_T \sim m_V$), where the transverse momentum is of the order of the vector boson mass m_V, QCD corrections are known up to the next-to-leading order (NLO) [5,6]. However the bulk of the vector boson events is produced in the small-q_T region ($q_T \ll m_V$), where the reliability of the fixed-order expansion is spoiled by the presence of large logarithmic corrections of infrared and collinear origin of the form $\alpha_S^n\, m_V^2/q_T^2 \ln^m(m_V^2/q_T^2)$ (with $1 \leq m \leq 2n-1$). In order to obtain reliable predictions, these logarithmically-enhanced terms have to be systematically resummed to all orders in perturbation theory [7]. The resummed and fixed-order approaches have to be be consistently matched at intermediate values of q_T to achieve a uniform theoretical accuracy for the entire range of transverse momenta. Experiments can directly measure only the decay products of vector bosons, in finite kinematical regions, it is thus important to include in the theoretical calculations the vector boson leptonic decay.

In this paper we show some preliminary results on DY q_T resummation, based on Refs. [8], taking into account the full dependence on the lepton decay variables with the corresponding spin correlations. This allows us to include the typical kinematical cuts on the final state leptons applied in the actual experimental analyses. We combine the most advanced perturbative information that is available at present: next-to-next-to-leading logarithmic (NNLL) resummation at small q_T and the NLO calculation at large q_T. Our results contain all the $\mathcal{O}(\alpha_S^2)$ corrections in the entire q_T range and implements a unitarity constraint that guarantees to reproduce the exact value of the corresponding fixed order cross section after integration over the q_T variable. Other phenomenological studies of DY q_T distribution can be found in Refs. [9].

2 Transverse-momentum resummation

We follow the transverse-momentum resummation formalism proposed and discussed in detail in Refs.[10]. Weconsider the production of a vector boson V ($V = W^+, W^-, Z/\gamma^*$) that subsequently decays in a lepton pair

$$h_1(p_1) + h_2(p_2) \to V(\boldsymbol{q_T}, M, y) + X \to l_1 l_2(\boldsymbol{q_T}, M, y, \theta, \phi) + X, \tag{1}$$

where h_1 and h_2 are the colliding hadrons (with momenta p_1 and p_2), V is the vector boson, $l_1 l_2$ is the lepton pair and X is an arbitrary and undetected final state. The kinematical variables we use to give a complete description of the leptons in the final state are the two-dimension transverse-momentum vector $\boldsymbol{q_T}$, the invariant mass M and the rapidity y of the vector boson (dilepton system) and the polar θ and azimuthal ϕ lepton angular variables[a].

According to the QCD factorization theorem the multi-differential cross section $d\sigma^V$ can be written as

$$\begin{aligned} \frac{d\sigma^V}{d^2\boldsymbol{q_T} dM^2\, dy\, d\cos\theta\, d\phi}(\boldsymbol{q_T}, M, y, \theta, \phi, s) &= \sum_{a_1,a_2} \int_0^1 dx_1 \int_0^1 dx_2\, f_{a_1/h_1}(x_1, \mu_F^2)\, f_{a_2/h_2}(x_2, \mu_F^2) \\ &\times \frac{d\hat{\sigma}^V_{a_1 a_2}}{d^2\boldsymbol{q_T}\, dM^2\, d\hat{y}\, d\cos\theta\, d\phi}(\boldsymbol{q_T}, M, \hat{y}, \theta, \phi, \hat{s}; \alpha_S, \mu_R^2, \mu_F^2) \end{aligned} \tag{2}$$

where $f_{a/h}(x, \mu_F^2)$ are the parton densities of the colliding hadrons at the factorization scale μ_F^2, $d\hat{\sigma}^V_{a_1 a_2}/dq_T^2$ are the perturbative QCD computable partonic cross sections, s ($\hat{s} = x_1 x_2 s$) is the hadronic (partonic) centre-of-mass energy, $\hat{y} = y - \ln\sqrt{x_1/x_2}$ is the partonic rapidity and μ_R^2 is the renormalization scale.

The resummation is performed at the level of the partonic cross section, which is decomposed as

$$d\hat{\sigma}^V_{a_1 a_2} = d\hat{\sigma}^{V\,(\text{res.})}_{a_1 a_2} + d\hat{\sigma}^{V\,(\text{fin.})}_{a_1 a_2}. \tag{3}$$

The first term on the right hand side, the *resummed* component, contains all the logarithmically enhanced contributions (at small q_T) which have to be resummed to all orders in α_S, while the second term, the *finite* component, is free of such contributions and can thus be evaluated at fixed order in perturbation theory.

Resummation holds in the impact parameter space (Fourier conjugated to $\boldsymbol{q_T}$), where the resummed component can be expressed in an exponential form collecting the large logarithmic contributions at leading (LL), next-to-leading (NLL), next-to-next-to-leading accuracy (NNLL) and so forth[10].

We evaluated the finite component 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:

$$\left[d\hat{\sigma}^{V\,(\text{fin.})}_{a_1 a_2}\right]_{f.o.} = \left[d\hat{\sigma}^{V}_{a_1 a_2}\right]_{f.o.} - \left[d\hat{\sigma}^{V\,(\text{res.})}_{a_1 a_2}\right]_{f.o.}. \tag{4}$$

In the case of $q\bar{q}$ initiated process, as the DY process, the resummed component depends on $q_T \equiv |\boldsymbol{q_T}|$ and it does not contain any dependence on the azimuthal angle $\phi_{\boldsymbol{q_T}}$. The azimuthal correlations are contained in the standard fixed-order component (and thus also the finite component).

[a]The angles θ and ϕ are referred to the lepton l_1, with respect to the direction of the hadron h_1, in the rest of frame of the dilepton system.

3 Numerical results

In this section we present selected numerical results for Z/γ^* and W production at NNLL+NLO accuracy and we compare them with some of the available LHC data. We compute the hadronic cross sections using the NNLO MSTW2008 parton distributions[11], with α_S evaluated at 3-loop order.

Our calculation implements the leptonic decays $Z/\gamma^* \to l^+l^-$ and $W \to l\nu_l$ with the corresponding spin correlations and the full dependence on the final state leptons variables. This allows us take into account the typical kinematical cuts on final state leptons considered in the experimental analyses. Moreover, we include the effects of the $\gamma^* Z$ interference and of the W and Z finite-width effects.

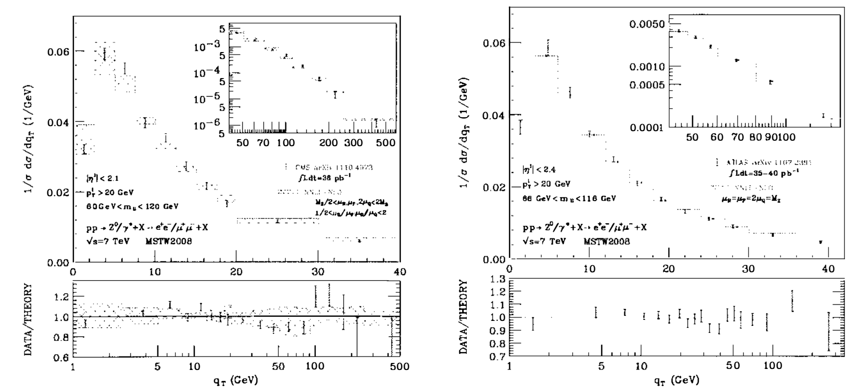

Figure 1: CMS data (left) and ATLAS data (right) for the Z/γ^* q_T spectrum compared with NNLL+NLO result.

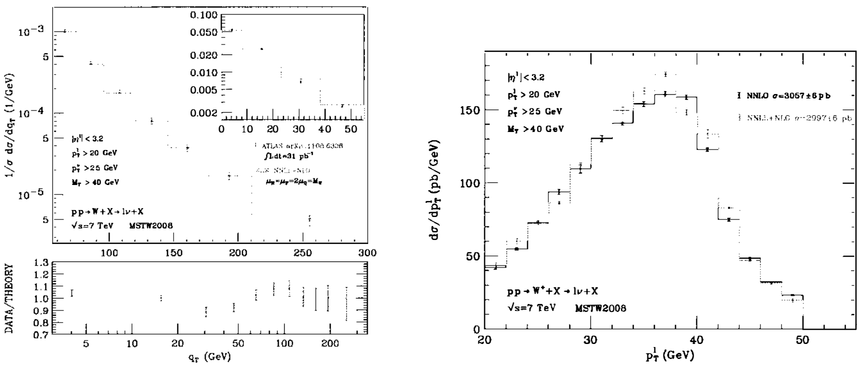

Figure 2: ATLAS data for W q_T spectrum compared with the NNLL+NLO result (left) and NNLL+NLO result compared with the NNLO result for the lepton p_T spectrum from W^+ decay (right).

In Fig. 1 we show the NNLL+NLO q_T spectrum for Z/γ^* production at the LHC[12,13]. The kinematical cuts on the final state leptons are reported in the plots. In the left panel of Fig. 1 we also give an estimate of the perturbative uncertainty considering the independent variation of the factorization, renormalization and resummation (Q) scale by a factor two around their central values, $\mu_F = \mu_R = 2Q = m_Z$, with the constraints [8]: $1/2 \leq \{\mu_F/\mu_R, Q/\mu_R\} \leq 2$. The perturbative uncertainty is roughly around ±5% for $5 \lesssim q_T \lesssim 30$GeV, while it reaches ±10% for $q_T \lesssim 5$GeV and $q_T \gtrsim 30$GeV.

In the left panel of Fig. 2 we show the NNLL+NLO q_T spectrum for W production at the LHC [14]. The kinematical cuts on the final state leptons are reported in the plots.

In the case of the W production, because of the neutrino in the final state, the q_T of the vector boson can only be reconstructed through a measure of the hadronic recoil. In this case it is thus specially relevant the transverse-momentum distribution of the final state charged lepton. In the right panel of Fig. 2 we show the resummed and fixed-order predictions for the lepton transverse-momentum distribution from W decay: the difference between the NNLL+NLO and the next-to-next-to-leading order (NNLO) distribution can reach the 10% level.

In summary we observe an overall good agreement of the NNLL+NLO results with the LHC data for the W/Z q_T distribution without the inclusion of any model for non-perturbative effects and we find a moderate effect of the q_T-resummation on the lepton p_T distribution from W decay.

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