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KMR k_t-factorization procedure for the description of the *LHCb* forward hadron–hadron Z^0 production at $\sqrt{s} = 13$ TeV

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ABSTRACT

Quite recently, two sets of new experimental data from the *LHCb* and the *CMS* Collaborations have been published, concerning the production of the Z^0 vector boson in hadron–hadron collisions with the center-of-mass energy $E_{CM} = \sqrt{s} = 13$ TeV. On the other hand, in our recent work, we have conducted a set of semi-*NLO* calculations for the production of the electro-weak gauge vector bosons, utilizing the unintegrated parton distribution functions (*UPDF*) in the frameworks of *Kimber–Martin–Ryskin* (*KMR*) or *Martin–Ryskin–Watt* (*MRW*) and the k_t-factorization formalism, concluding that the results of the *KMR* scheme are arguably better in describing the existing experimental data, coming from *D*0, *CDF*, *CMS* and *ATLAS* Collaborations. In the present work, we intend to follow the same semi-*NLO* formalism and calculate the rate of the production of the Z^0 vector boson, utilizing the *UPDF* of *KMR* within the dynamics of the recent data. It will be shown that our results are in good agreement with the new measurements of the *LHCb* and the *CMS* Collaborations.

1. Introduction

Traditionally, the production of the electroweak gauge vector bosons is considered as a benchmark for understanding the dynamics of the strong and the electroweak interactions in the Standard Model. It is also an important test to assess the validity of collider data. Many collaborations have reported numerous sets of measurements, probing different events in variant dynamical regions, in direct or indirect relation with such processes, for example the references [1–10]. Among the most recent of these reports are the measurements of the production of Z^0 bosons at the *LHCb* and *CMS* Collaborations, for proton–proton collisions at the *LHC* for $\sqrt{s} = 13$ TeV, with different kinematical regions [11,12]. The *LHCb* data are in the forward pseudorapidity region ($2 < |\eta| < 4.5$) while the *CMS* measurements are in the central domain ($0 < |\eta| < 2.4$).

In our previous work [13], we have successfully utilized the transverse momentum dependent (*TMD*) unintegrated parton distribution functions (*UPDF*) of the k_t-factorization (the references [14–16]), namely the *Kimber–Martin–Ryskin* (*KMR*) and *Martin–Ryskin–Watt* (*MRW*) formalisms in the leading order (*LO*) and the next-to-leading order (*NLO*) to calculate the inclusive production of the $W^\pm$ and the Z^0 gauge vector bosons, in the proton–proton and the proton–antiproton inelastic collisions

$$P_1 + P_2 \to W^\pm/Z^0 + X. \quad (1)$$

In order to have the total production rate of Z^0 boson in the calculations, we have used a complete set of $2 \to 3$ partonic sub-processes, i.e.

$$g^*(\mathbf{k}_1) + g^*(\mathbf{k}_2) \to V(\mathbf{p}) + q(\mathbf{p}_1) + \bar{q}'(\mathbf{p}_2),$$
$$g^*(\mathbf{k}_1) + q^*(\mathbf{k}_2) \to V(\mathbf{p}) + g(\mathbf{p}_1) + q'(\mathbf{p}_2),$$
$$q^*(\mathbf{k}_1) + \bar{q}'^*(\mathbf{k}_2) \to V(\mathbf{p}) + g(\mathbf{p}_1) + g(\mathbf{p}_2), \quad (2)$$

where V represents the produced gauge vector boson. $\mathbf{k}_i$ and $\mathbf{p}_i$, $i = 1, 2$ are the 4-momenta of the incoming and the out-going partons. These calculations tend to include some missing contributions from the total production rate of Z^0 boson via extending the *LO* $2 \to 1$ diagrams to $2 \to 3$ diagrams by the means of including the semi-hard step on the processes into the matrix elements. In this way, it has been shown (in Fig. 4 of the manuscript and in

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Figs. 13 and 14 of [13]) that the predictions that are derived from this particular framework can (up to a better approximation) describe the behavior of the related experimental data. Please bear in mind that the uncertainty bound are intentionally chosen by manipulating the hard scale μ by a factor of 2. We believe that this factor can be chosen (somehow, according to the specifications of the experimental measurements) to have some smaller value. Hence, the width of the uncertainty bounds cannot fully pin point an increase or decrease in the precision of the calculations. The results underwent comprehensive and rather lengthy comparisons and it was concluded that the calculations in the *KMR* formalism are more successful in describing the existing experimental data (with the center-of-mass energies of 1.8 and 8 TeV) from the *D*0, *CDF*, *ATLAS* and *CMS* Collaborations [8,10,17–23]. The success of the *KMR* scheme (despite being of the *LO* and suffering from some misalignment with its theory of origin, i.e. the *Dokshitzer–Gribov–Lipatov–Altarelli–Parisi* (*DGLAP*) evolution equations, [24–27]) can be traced back to the particular physical constraints that rule its kinematics. To find extensive discussions regarding the structure and the applications of the *UPDF* of k_t-factorization, the reader may refer to the references [28–35].

Meanwhile, arriving the new data from the *LHCb* and *CMS* Collaborations, the references [11,12], gives rise to the necessity of repeating our calculations at the $E_{CM} = 13$ TeV. This is in part due to the very interesting rapidity domain of the *LHCb* measurements, since in the forward rapidity sector ($2 < |\eta_f| < 4.5$), one can effectively probe very small values of the Bjorken variable x (x being the fraction of the longitudinal momentum of the parent hadron, carried by the parton at the top of the partonic evolution ladder), where the gluonic distributions dominate and hence the transverse momentum dependency of the particles involving in the partonic sub-processes becomes important.

In the present work, we intend to calculate the transverse momentum and the rapidity distributions of the cross-section of production of the Z^0 boson using our *NLO* level diagrams (from the reference [13]) and the *UPDF* of the *KMR* formalism. The *UPDF* will be prepared using the *PDF* of *MMHT2014 − LO* [37]. In the following section, the reader will be presented with a brief introduction to the semi-*NLO* framework (i.e. some *NLO QCD* matrix elements and *LO UPDF*) that is utilized to perform these computations. Since we are using *LO* k_t-factorization plus the terms that contributing in the collinear *QCD* factorization at the *NLO* and *NNLO* levels, therefore we will call our procedure the semi-*NLO* approach (see Fig. 4 and related discussion in the section 3 in which $\bar{q} + q \to Z^0$ processes are dominant). The section 2 also includes the main description of the *KMR* formalism in the k_t-factorization procedure. Finally, the section 3 is devoted to results, discussions and a thoroughgoing conclusion.

2. Semi-*NLO* framework, *KMR UPDF* and numerical analysis

Generally speaking, the total cross-section for an inelastic collision between two hadrons ($\sigma_{Hadron-Hadron}$) can be expressed as a sum over all possible partonic cross-sections in every possible momentum configuration:

$$\sigma_{Hadron-Hadron} = \sum_{a_1,a_2=q,g} \int_0^1 \frac{dx_1}{x_1} \int_0^1 \frac{dx_2}{x_2} \int_0^\infty \frac{dk_{1,t}^2}{k_{1,t}^2} \int_0^\infty \frac{dk_{2,t}^2}{k_{2,t}^2} \times f_{a_1}(x_1, k_{1,t}^2, \mu_1^2) f_{a_2}(x_2, k_{2,t}^2, \mu_2^2) \times \hat{\sigma}_{a_1a_2}(x_1, k_{1,t}^2, \mu_1^2; x_2, k_{2,t}^2, \mu_2^2). \quad (3)$$

In the equation (3), x_i and $k_{i,t}$ respectively represent the longitudinal fraction and the transverse momentum of the parton i, while $f_{a_i}(x_i, k_{i,t}^2, \mu_i^2)$ are the density functions of the i-th parton. The second scale, μ_i, are the ultra-violet cutoffs related to the virtuality of the exchanged particle (or particles) during the inelastic scattering. $\hat{\sigma}_{a_1a_2}$ are the partonic cross-sections of the given particles. For the production of the Z^0 boson, the equation (3) comes down to (for a detailed description see the reference [13])

$$\sigma(P + \bar{P} \to Z^0 + X) = \sum_{a_i,b_i=q,g} \int \frac{dk_{a_1,t}^2}{k_{a_1,t}^2} \frac{dk_{a_2,t}^2}{k_{a_2,t}^2} dp_{b_1,t}^2 \, dp_{b_2,t}^2 \, dy_1 \, dy_2 \, dy_Z \times \frac{d\varphi_{a_1}}{2\pi} \frac{d\varphi_{a_2}}{2\pi} \frac{d\varphi_{b_1}}{2\pi} \frac{d\varphi_{b_2}}{2\pi} \times \frac{|\mathcal{M}(a_1 + a_2 \to Z^0 + b_1 + b_2)|^2}{256\pi^3 (x_1x_2s)^2} \times f_{a_1}(x_1, k_{a_1,t}^2, \mu^2) \, f_{a_2}(x_2, k_{a_2,t}^2, \mu^2). \quad (4)$$

y_i are the rapidities of the produced particles (since $y_i \simeq \eta_i$ in the infinite momentum frame, i.e. $p_i^2 \gg m_i^2$). φ_i are the azimuthal angles of the incoming and the out-going partons at the partonic cross-sections. $|\mathcal{M}|^2$ represent the matrix elements of the partonic sub-processes in the given configurations. The reader can find a number of comprehensive discussions over the means and the methods of deriving analytical prescriptions of these quantities in the references [13,38–41]. s is the center of mass energy squared. Additionally, in the proton–proton center of mass frame, one can utilize the following definitions for the kinematic variables:

$$P_1 = \frac{\sqrt{s}}{2}(1, 0, 0, 1), \quad P_2 = \frac{\sqrt{s}}{2}(1, 0, 0, -1),$$
$$\mathbf{k}_i = x_i \mathbf{P}_i + \mathbf{k}_{i,\perp}, \quad k_{i,\perp}^2 = -k_{i,t}^2, \quad i = 1, 2\,. \quad (5)$$

Defining the transverse mass of the produced particles, $m_{i,t} = \sqrt{m_i^2 + p_i^2}$, we can write

$$x_1 = \frac{1}{\sqrt{s}}\left(m_{1,t}e^{+y_1} + m_{2,t}e^{+y_2} + m_{Z,t}e^{+y_Z}\right),$$
$$x_2 = \frac{1}{\sqrt{s}}\left(m_{1,t}e^{-y_1} + m_{2,t}e^{-y_2} + m_{Z,t}e^{-y_Z}\right). \quad (6)$$

Furthermore, the density functions of the incoming partons, $f_a(x, k_t^2, \mu^2)$ (which represent the probability of finding a parton at the semi-hard process of the partonic scattering, with the longitudinal fraction x of the parent hadron, the transverse momentum k_t and the hard-scale μ) can be defined in the framework of k_t-factorization, through the *KMR* formalism:

$$f_a(x, k_t^2, \mu^2) = T_a(k_t^2, \mu^2) \sum_{b=q,g} \left[\frac{\alpha_S(k_t^2)}{2\pi} \int_x^{1-\Delta} dz P_{ab}^{(LO)}(z) \frac{x}{z} b\left(\frac{x}{z}, k_t^2\right) \right]. \quad (7)$$

The *Sudakov* form factor, $T_a(k_t^2, \mu^2)$, factors over the virtual contributions from the *LO DGLAP* equations, by defining a virtual (loop) contributions as:

$$T_a(k_t^2, \mu^2) = exp\left(-\int_{k_t^2}^{\mu^2} \frac{\alpha_S(k^2)}{2\pi} \frac{dk^2}{k^2} \sum_{b=q,g} \int_0^{1-\Delta} dz' P_{ab}^{(LO)}(z') \right), \quad (8)$$

with $T_a(\mu^2, \mu^2) = 1$. α_S is the *LO QCD* running coupling constant, $P_{ab}^{(LO)}(z)$ are the so-called splitting functions in the *LO*, parameterizing the probability of finding a parton with the longitudinal