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

Quit 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 $NLO$ calculations for the production of the electroweak 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 $D0$, $CDF$, $CMS$ and $ATLAS$ collaborations. In the present work, we intend to follow the same $NLO$ 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.

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I. 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, to count a few see 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 $\sqrt{s} = 13\text{TeV}$, 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, 15]), 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

$$P_1 + P_2 \rightarrow W^\pm/Z^0 + X.$$  \hspace{1cm} (1)

In order to increase the precision of the calculations, we have used a complete set of $2 \rightarrow 3$ NLO partonic sub-processes, i.e.

$$g^*(k_1) + g^*(k_2) \rightarrow V(p) + g(p_1) + q'(p_2),$$

$$g^*(k_1) + q^*(k_2) \rightarrow V(p) + g(p_1) + q'(p_2),$$

$$q^*(k_1) + q^*(k_2) \rightarrow V(p) + g(p_1) + g(p_2),$$  \hspace{1cm} (2)

where $V$ represents the produced gauge vector boson. $k_i$ and $p_i$, $i = 1, 2$ are the 4-momenta of the incoming and the out-going partons. 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 D0, CDF, ATLAS and CMS collaborations [8, 10, 16, 22]. 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, 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.

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, [36]. In the following section, the reader will be presented with a brief introduction to the NLO $\otimes$ LO framework (i.e. NLO QCD matrix elements and LO UPDF) that is utilized to perform these computations. The section II also includes the main description of the KMR formalism in the $k_t$-factorization procedure. Finally, the section III is devoted to results, discussions and a thoroughgoing conclusion.

II. NLO $\otimes$ LO FRAMEWORK, KMR UPDF AND NUMERICAL ANALYSIS

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

$$\sigma_{\text{Hadron-Hadron}} = \sum_{a_1,a_2=q,g} \int_{0}^{1} \frac{dx_1}{x_1} \int_{0}^{1} \frac{dx_2}{x_2} \int_{0}^{\infty} \frac{dk_{1,t}^2}{k_{1,t}^2} \int_{0}^{\infty} \frac{dk_{2,t}^2}{k_{2,t}^2} \hat{\sigma}_{a_1a_2}(x_1,k_{1,t}^2,\mu_1^2;x_2,k_{2,t}^2,\mu_2^2) \times f_{a_1}(x_1,k_{1,t}^2,\mu_1^2) f_{a_2}(x_2,k_{2,t}^2,\mu_2^2). \quad (3)$$

In the equation $\hat{3}$, $x_i$ and $k_{i,t}$ respectfully 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, \( \mu_i \), 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 \[13\])

\[
\sigma(P + \bar{P} \to Z^0 + X) = \sum_{a_i,b_i=q,g} \int \frac{dk_{a_1,t}^2}{k_{a_1,t}^2} \frac{dk_{a_2,t}^2}{k_{a_2,t}^2} dp_{1,t}^2 dp_{2,t}^2 dy_1 dy_2 dy_{W/Z} \times
\]

\[
\frac{d\varphi_{a_1} d\varphi_{a_2} d\varphi_{b_1} d\varphi_{b_2}}{2\pi 2\pi 2\pi 2\pi} \times
\frac{|\mathcal{M}(a_1 + a_2 \to Z^0 + b_1 + b_2)|^2}{256\pi^3 (x_1 x_2 s)^2} \times
\]

\[
f_{a_1}(x_1, k_{a_1,t}^2, \mu^2) f_{a_2}(x_2, k_{a_2,t}^2, \mu^2).
\]

(4)

\( y_i \) are the rapidities of the produced particles (since \( y_i \simeq \eta_i \) in the infinite momentum frame, i.e. \( p_i^2 \gg m_i^2 \)). \( \varphi_i \) 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 \[13, 37–40\]. \( s \) 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:

\[
P_1 = \frac{\sqrt{s}}{2} (1, 0, 0, 1), \quad P_2 = \frac{\sqrt{s}}{2} (1, 0, 0, -1),
\]

\[
k_i = x_i P_i + k_{i,\perp}, \quad k_{i,\perp}^2 = -k_{i,t}^2, \quad i = 1, 2. \quad (5)
\]

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, \( f_a(x, k_{i,t}^2, \mu^2) \) (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 \( \mu \)) can be defined in the framework of \( k_t \)-factorization, through the \( KMR \) formalism:

\[
f_a(x, k_{i,t}^2, \mu^2) = T_a(k_{i,t}^2, \mu^2) \sum_{b=q,g} \left[ \frac{\alpha_s(k_{i,t}^2)}{2\pi} \int_x^{1-\Delta} dz P_{ab}^{(LO)}(z) \frac{b(x, z, k_{i,t}^2)}{z} \right], \quad (7)
\]
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:

\[
T_a(k_t^2, \mu^2) = \exp \left( - \int_{k_t^2}^{\mu^2} \frac{\alpha_S(k^2)}{2\pi} \frac{dk^2}{k^2} \sum_{b=q,g} \int_{0}^{1-\Delta} dz' P_{ab}^{(LO)}(z') \right),
\]

with \( T_a(\mu^2, \mu^2) = 1 \). \( \alpha_S \) 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 momentum fraction \( x \) to be emitted form a parent parton with the fraction \( x' \), while \( z = x/x' \), see the references \[15, 41\]. The infrared cutoff parameter, \( \Delta \), is a visualization of the angular ordering constraint \( (AOC) \), as a consequence of the color coherence effect of successive gluonic emissions \[35\], defined as \( \Delta = k_t/(\mu + k_t) \). Limiting the upper boundary on \( z \) integration by \( \Delta \), excludes \( z = 1 \) from the integral equation and automatically prevents facing the soft gluon singularities, \[13\]. Additionally, the \( b(x, k_t^2) \) are the single-scaled parton distribution functions \( (PDF) \), i.e. the solutions of the LO DGLAP evolution equation. The required \( PDF \) for solving the equation \[7\] are provided in the form of phenomenological libraries, e.g. the \( MMHT2014 \) libraries, the reference \[36\], where the calculation of the single-scaled functions have been carried out using the deep inelastic scattering data on the \( F_2 \) structure function of the proton.

Now, one can carry out the numerical calculation of the equation \[4\] using the \textsc{Vegas} algorithm in the Monte-Carlo integration, \[42\]. To do this, we have chosen the hard-scale of the \textsc{Updf} as:

\[
\mu = (m_{W/Z}^2 + p_{W/Z,t}^2)^{\frac{1}{2}},
\]

and set the upper bound on the transverse momentum integrations of the equation \[4\] to be \( k_{i,\text{max}} = p_{i,\text{max}} = 4\mu_{\text{max}} \), with

\[
\mu_{\text{max}} = (m_{W/Z}^2 + p_{t,\text{max}}^2)^{\frac{1}{2}}.
\]

One can easily confirm that since the \textsc{Updf} of \( KMR \) quickly vanish in the \( k_t \gg \mu \) domain, further domain have no contribution into our results. Also we limit the rapidity integrations to \([-8, 8]\), since \( 0 \leq x \leq 1 \) and according to the equation \[6\], further domain has no contribution into our results. The choice of above hard scale is reasonable for the production of the Z bosons, as has been discussed in the reference \[40\].
Finally, we choose
\[ f_{a_i}(x_i, k_{a_i,t}^2 < \mu_0^2, \mu^2) = \frac{k_{a_i,t}^2}{\mu_0^2} a_i(x_i, \mu_0^2) T_{a_i}(\mu_0^2, \mu^2), \tag{9} \]
to define the density of the incoming partons in the non-perturbative region, i.e. \( k_t < \mu_0 \) with \( \mu_0 = 1 \) GeV. This appears to be a natural choice, since (see the references \[13, 43\])
\[
\lim_{k_{a_i,t}^2 \to 0} f_{a_i}(x_i, k_{a_i,t}^2, \mu^2) \sim k_{a_i,t}^2.
\]

III. RESULTS, DISCUSSIONS AND CONCLUSIONS

Using the theory and the notions of the previous sections, one can calculate the production rate of the \( Z^0 \) gauge vector boson for the center-of-mass energy of 13 TeV. The PDF of Martin et al \[36\], \( MMHT2014 - LO \), are used as the input functions to feed the equations \[7\]. The results are the double-scale UPDF of the KMR schemes. These UPDF are in turn substituted into the equation \[4\] to construct the \( Z \) cross-sections in the framework of \( k_t \)-factorization. One must note that the experimental data of the \( LHCb \) collaboration, \[11\], and the preliminary data of the \( CMS \) collaboration, \[12\], are produced in different dynamical setups; the \( LHCb \) data are in the forward rapidity region, \( 2 < |y_Z| < 4.5 \), while \( CMS \) data are in a central rapidity sector, i.e. \( 0 < |y_Z| < 2.4 \). We have imposed the same restrictions in our calculations.

Thus, in the figure \[1\] we present the reader with a comparison between the different contributions into the differential cross-sections of the production of \( Z^0 \), \( (d\sigma_Z/dp_t) \), as a function of the transverse momentum \( (p_t) \) of the produced particles, in the KMR scheme. One readily notices that the contributions from the \( g^* + g^* \to Z^0 + q + \bar{q} \) (the so-called gluon-gluon fusion process) dominate the the production. The share of other production vertices is small (but not entirely negligible) compared to these main contributions. This is to extent different from our observations in the smaller center-of-mass energies (see the section V of the reference \[13\]). Also, differential cross-sections are considerably larger at the central rapidity region compared to the results in the forward sector.

The total differential cross-section of the production of \( Z^0 \) vector boson is calculated within the figure \[2\] as the sum of the constituting partonic sub-processes (see the relation \[2\]). The calculations are carried out for the center-of-mass energy \( E_{CM} = 13 \) TeV and plotted as a function of the transverse momentum of the produced particle. In the panels
(a) and (c), the contributions from the individual sub-processes have been compared to each other. The results in these panels respectfully correspond to the forward rapidity region, $2 < |y_Z| < 4.5$ (with the addition of $p_t^{\mu\bar{\mu}} > 20 \text{ GeV}$ and $60 < m^{\mu\bar{\mu}} < 120 \text{ GeV}$ constraints, corresponding for the experimental measurements of the LHCb collaboration, the reference [11]) and to the central rapidity region, $0 < |y_Z| < 2.4$ (with the addition of $p_t^{\mu\bar{\mu}} > 25 \text{ GeV}$ and $60 < m^{\mu\bar{\mu}} < 120 \text{ GeV}$ constraints, corresponding for the preliminary measurements of the CMS collaboration, the reference [12]). The calculations have been performed, using the KMR UPDF and the PDF of MMHT2014. The panels (b) and (d) illustrate our results in their corresponding uncertainty bounds, compared to the data of the LHCb and the CMS collaborations. The uncertainty bounds have been calculated, by means of manipulating the hard-scale, $\mu$, of the UPDF by a factor of 2, since this is the only free parameter in our framework. Also, as expected for the both regions, the contributions from the $g^* + g^* \rightarrow Z^0 + q + \bar{q}$ sub-process dominate,

$$\hat{\sigma}(g^* + g^* \rightarrow Z^0 + q + \bar{q}) \gg \hat{\sigma}(q^* + \bar{q}^* \rightarrow Z^0 + g + g) > \hat{\sigma}(g^* + q^* \rightarrow Z^0 + g + q). \quad (10)$$

The figure 3 presents the differential cross-section of the production of $Z^0$ vector boson, $d\sigma_{Z}/dy_Z$, as a function of the rapidity of the produced boson ($y_Z$) at the center-of-mass energy of $E_{CM} = 13 \text{ TeV}$ in the KMR formalism. The notion of the figure is similar to that of the figure 2. The panels (a) and (c) illustrate the contributions of each of the sub-processes into the total production rate, while the total results have been subjected to comparison with the experimental data of the LHCb and the CMS collaborations (the references [11] [12]), within their corresponding uncertainty bounds, in the panels (b) and (d). One finds that our calculations are in general agreement with the experimental measurements.

Overall, it appears that our NLO $\otimes$ LO framework is generally successful in describing the corresponding experimental measurements in the explored energy range. This success if by part owed to the UPDF of KMR, which as an effective model, has been very successful in producing a realistic theory in order to describe the experiment, see the references [13] [27] [34]. One however should note that having a semi-successful prediction from the framework of $k_t$-factorization by itself is a success, since our calculations utilizing these UPDF have inherently a considerably larger error compared to those from the NNLO QCD or even the NLO QCD, presented here by the relatively large uncertainty region. This is because we are incorporating the single-scaled PDF (with their already included uncertainties) to
form double-scaled \textit{UPDF} with additional approximations and further uncertainties. Being able to provide predictions with a desirable accuracy would require a thorough universal fit for these frameworks, see the reference [43]. Nevertheless, the $k_t$-factorization framework, despite its simplicity and its computational advantages, see the reference [34, 43], can provide us with a valuable insight regarding the transverse momentum dependency of various high-energy QCD events.

In summary, throughout the present work, we have calculated the production rate of the $Z^0$ gauge vector boson in the framework of $k_t$-factorization, using a NLO $\otimes$ LO framework and the \textit{UPDF} of the KMR formalism. The calculations have been compared with the experimental data of the \textit{LHCb} and the \textit{CMS} collaborations. Our calculation, within its uncertainty bounds, are in good agreement with the experimental measurements. We also reconfirm that the KMR prescription, despite its theoretical disadvantages and its simplistic computational approach, has a remarkable behavior toward describing the experiment.

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FIG. 1: Contributions of the individual quark flavors into the differential cross-section of the production of $Z^0$ boson in an inelastic collision at $E_{\text{CM}} = 13\,\text{TeV}$, plotted as a function of the transverse momentum of the produced particle. The panels (a), (b) and (c) illustrate our calculations for the forward rapidity region, $2 < |\eta_Z| < 4.5$ (with the addition of $p_\mu \bar{\mu}^t > 20\,\text{GeV}$ and $60 < m_{\mu\bar{\mu}} < 120\,\text{GeV}$ constraints, corresponding to the experimental measurements of the LHCb collaboration, the reference [11]). The panels (d), (e) and (f) are our results in the central rapidity region, $0 < |\eta_Z| < 2.4$ (with the addition of $p_\mu \bar{\mu}^t > 25\,\text{GeV}$ and $60 < m_{\mu\bar{\mu}} < 120\,\text{GeV}$ constraints, corresponding to the preliminary measurements of the CMS collaboration, the reference [12]). The calculations are performed, using the KMR UPDF and the PDF of MMHT 2014.
FIG. 2: Differential cross-section of the production of $Z^{0}$ boson as a function of the transverse momentum of the produced boson at $E_{\text{CM}} = 13$ TeV. Panels (a) and (c) illustrate the contributions from the individual sub-processes have been compared to each other in the respective rapidity regions. The panels (b) and (d) illustrate our results in their corresponding uncertainty bounds, compared to the data of the LHCb and the CMS collaborations, the references [11, 12]. The uncertainty bounds have been calculated, by manipulating the hard-scale of the UPDF by a factor of 2.
FIG. 3: Differential cross-section of the production of $Z_0$ boson as a function of the rapidity of the produced boson at $E_{CM} = 13$ TeV. The notions of the diagrams are the same as in the figure 2.