Forward $z^0 \to \mu^+\mu^-$ production in pp collisions using the CDSM framework

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I. INTRODUCTION

In series of Refs. [1–3], we lay groundwork to perform a series of phenomenological work. Thus, in this document we will perform the evaluation of inclusive Z^0 production in pp collision decaying into dimuon $\mu^+\mu^-$ pair. Moreover, we will compare the numerical results with the DATA present in Ref. [4] by the LHCb collaboration.

In Ref. [4], the production cross-section was measured in the following pseudorapidity region $2.0 < \eta < 4.5$ and transverse momentum $p_T > 20$ GeV/c for both muons and dimuon invariant mass $60 < M_{\mu\mu} < 120$ GeV/c^2 at $\sqrt{s} = 13$TeV.

This document has the following structure, in the next section we will approach the full process differential cross-section i.e. $pp \to (Z^0 \to \mu^+\mu^-)X$. In the third section, we will discuss only the Z^0 electroweak gauge boson production cross-section which relates with the prescription present in Refs. [1, 2] by us.

II. FULL DIFFERENTIAL CROSS-SECTION

In this section, we will discuss the forward dimuon cross-section. At forward rapidities, one expects the collinear factorization. Thus, in this scenario a hybrid factorization scheme must be used, in particular we will use the color – dipole S–matrix framework. In the hybrid factorization scheme, the lepton pair produciton is described by (in what follows $M \equiv M_{\mu\mu}$)

$$\frac{\mathrm{d}\sigma(pp \to [Z^0 \to \mu^+\mu^-]X)}{\mathrm{d}^2 p_T \mathrm{d}M^2 \mathrm{d}\eta} = \mathcal{F}_{Z^0\to\mu^+\mu^-}(M)\frac{\mathrm{d}\sigma(pp \to Z^0 X)}{\mathrm{d}^2 p_T \mathrm{d}\eta} \tag{1}$$

where

$$\mathcal{F}_{Z^0\to\mu^+\mu^-}(M) = \mathrm{Br}(Z^0 \to \mu^+\mu^-)\rho_Z(M)\,. \tag{2}$$

Here, the branching ration $\mathrm{Br}(Z^0 \to \mu^+\mu^-) \simeq 3.3662\%$, and $\rho_Z(M)$ is the invariant mass distribution of the Z^0 boson in the narrow width approximation

$$\rho_Z(M) = \frac{1}{\pi}\frac{M\Gamma_Z(M)}{(M^2 - m_Z^2)^2 + (M\Gamma(M))^2} \tag{3}$$

for

$$\frac{\Gamma_Z(M)}{M} \ll 1\,, \tag{4}$$

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in terms of the on-shell Z^0 boson mass, $m_Z \simeq 91.2$ GeV, and the generalized total Z^0 decay width

$$\Gamma_Z(M) \;=\; \frac{\alpha_{\rm em} M}{6\sin^2 2\theta_W}\left(\frac{160}{3}\sin^4\theta_W - 40\sin^2\theta_W + 21\right) . \tag{5}$$

III. Z^0 PRODUCTION DIFFERENTIAL CROSS-SECTION

In eq. (1) r.h.s, $\mathrm{d}\sigma(pp \to Z^0 X)$ is the inclusive Z^0 gauge boson production with invariant mass M and transverse momentum p_T in terms of the quark (antiquark) densities q_f ($\bar{q}_f$) at momentum fraction $x_q = x_1/z$ which is given by

$$\frac{\mathrm{d}\sigma(pp \to Z^0 X)}{\mathrm{d}^2 p_T \mathrm{d}\eta} \;=\; J(\eta, p_T)\frac{x_1}{x_1+x_2}\sum_f \sum_{L,T}\int_{x_1}^{1}\frac{\mathrm{d}z}{z^2}\left[q_f(x_1/z,\mu_F^2) + \bar{q}_f(x_1/z,\mu_F^2)\right]\frac{\mathrm{d}\sigma(qp \to Z^0 X)}{\mathrm{d}\ln z\,\mathrm{d}^2 p_T} \tag{6}$$

where

$$J(\eta, p_T) \equiv \frac{\mathrm{d}x_F}{\mathrm{d}\eta} = \frac{2}{\sqrt{s}}\sqrt{M^2 + p_T^2}\cosh\eta\,, \tag{7}$$

is the Jaccobian of transformation between Faynman variable $x_F = x_1 - x_2$ and pseudorapidity η of the virtual gauge boson, Z^0. The differential cross-section in the r.h.s of eq. (6) is the parton–target cross section which describe the in interaction between the projectile quark with the proton target producing a Z^0 gauge boson. This parton–target cross-section is derived in details in Ref. [1] which has the following form:

$$\left.\frac{\mathrm{d}\sigma_T\,(q \to qZ)}{\mathrm{d}\ln z\,\mathrm{d}p_T}\right|_V \;=\; \frac{\left(C_f^G\right)^2 (g_{V,f})^2}{2\pi^2}\int \mathrm{d}k\,k\,f(x,k)\left\{z^4 m_f^2 \mathcal{E}_1(z,p,k,\epsilon) + \left[1 + (1-z)^2\right]\mathcal{E}_2(z,p,k,\epsilon)\right\} \tag{8}$$

$$\left.\frac{\mathrm{d}\sigma_T\,(q \to qZ)}{\mathrm{d}\ln z\,\mathrm{d}p_T}\right|_A \;=\; \frac{\left(C_f^G\right)^2 (g_{A,f})^2}{2\pi^2}\int \mathrm{d}k\,k\,f(x,k)\left\{z^2 m_f^2\,(2-z)^2\,\mathcal{E}_1(z,p,k,\epsilon)\right.$$
$$\left. + \left[1 + (1-z)^2\right]\mathcal{E}_2(z,p,k,\epsilon)\right\} \tag{9}$$

$$\left.\frac{\mathrm{d}\sigma_L\,(q \to qZ)}{\mathrm{d}\ln z\,\mathrm{d}p_T}\right|_V \;=\; \frac{\left(C_f^G\right)^2 (g_{V,f})^2}{4\pi^2}\int \mathrm{d}k\,k\,f(x,k) 4\,(1-z)^2\,M^2 \mathcal{E}_1(z,p,k,\epsilon) \tag{10}$$

$$\left.\frac{\mathrm{d}\sigma_L\,(q \to qZ)}{\mathrm{d}\ln z\,\mathrm{d}p_T}\right|_A \;=\; \frac{\left(C_f^G\right)^2 (g_{A,f})^2}{4\pi^2}\int \mathrm{d}k\,k\,f(x,k)\left\{4\frac{\left(z^2 m_f^2 + (1-z)M^2\right)^2}{M^2}\mathcal{E}_1(z,p,k,\epsilon)\right.$$
$$\left. + 4\frac{z^2 m_f^2}{M^2}\mathcal{E}_2(z,p,k,\epsilon)\right\} \tag{11}$$

these four expression are the four possible polarization combination. Where $f(x,k)$ is the Unintegrated Gluon Distribution (UGD) and $\epsilon^2 = (1-z)M^2 + z^2 m_f^2$. Moreover,

$$\mathcal{E}_1(z,p,\epsilon) = \frac{1}{2}\int_0^{2\pi} \mathrm{d}\theta \left\{ \frac{1}{[\tau^2+\epsilon^2]^2} - \frac{2}{(p^2+\epsilon^2)[\tau^2+\epsilon^2]} + \frac{1}{(p^2+\epsilon^2)} \right\}, \tag{12}$$

$$\mathcal{E}_2(z,p,\epsilon) = \frac{1}{2}\int_0^{2\pi} \mathrm{d}\theta \left\{ \frac{\tau^2}{[\tau^2+\epsilon^2]^2} - \frac{2\eta}{(p^2+\epsilon^2)[\tau^2+\epsilon^2]} + \frac{p^2}{(p^2+\epsilon^2)^2} \right\}. \tag{13}$$

for

$$\tau^2 = (\boldsymbol{p} - z\boldsymbol{k})^2 = p^2 + z^2k^2 - 2zpk\cos\theta. \tag{14}$$

$$\eta = \boldsymbol{p}\cdot(\boldsymbol{p} - z\boldsymbol{k}) = p^2 - zpk\cos\theta \tag{15}$$

One can simplify the parton–target cross-section only in terms of transverse and longitudinal ones as: $(C_f^Z = \frac{\sqrt{\alpha_{\mathrm{em}}}}{\sin 2\theta_W})$

$$\frac{\mathrm{d}\sigma_T\,(q\to qZ)}{\mathrm{d}\ln z \mathrm{d}p_T} = \frac{\sqrt{\alpha_{\mathrm{em}}}}{2\pi^2 \sin 2\theta_W}\int \mathrm{d}k\,k\,f(x,k)\Bigg\{\Big[(g_{V,f})^2 z^4 m_f^2 + (g_{A,f})^2 z^2 m_f^2 (2-z)^2\Big]\mathcal{E}_1(z,p,k,\epsilon) + \Big[1+(1-z)^2\Big]\Big((g_{V,f})^2 + (g_{A,f})^2\Big)\mathcal{E}_2(z,p,k,\epsilon)\Bigg\} \tag{16}$$

and

$$\frac{\mathrm{d}\sigma_L\,(q\to qZ)}{\mathrm{d}\ln z \mathrm{d}p_T} = \frac{\sqrt{\alpha_{\mathrm{em}}}}{\pi^2 \sin 2\theta_W}\int \mathrm{d}k\,k\,f(x,k)\Bigg\{(g_{A,f})^2\frac{z^2m_f^2}{M^2}\mathcal{E}_2(z,p,k,\epsilon) + \left[(g_{V,f})^2(1-z)^2M^2 + (g_{A,f})^2\frac{\Big(z^2m_f^2+(1-z)M^2\Big)^2}{M^2}\right]\mathcal{E}_1(z,p,k,\epsilon)\Bigg\} \tag{17}$$

defining:

$$\Gamma_T = (g_{V,f})^2 z^4 m_f^2 + (g_{A,f})^2 z^2 m_f^2 (2-z)^2 \tag{18}$$

$$\Gamma_L = (g_{V,f})^2(1-z)^2M^2 + (g_{A,f})^2\frac{\Big(z^2m_f^2+(1-z)M^2\Big)^2}{M^2} \tag{19}$$

$$\Lambda_T = \Big[1+(1-z)^2\Big]\Big((g_{V,f})^2 + (g_{A,f})^2\Big) \tag{20}$$

$$\Lambda_L = (g_{A,f})^2\frac{z^2m_f^2}{M^2} \tag{21}$$

Thus, the parton–target cross-section can be reduce to one expression:

$$\frac{\mathrm{d}\sigma\,(q\to qZ)}{\mathrm{d}\ln z\mathrm{d}p_T} = \frac{\sqrt{\alpha_{\rm em}}}{2\pi^2\sin 2\theta_W}\int \mathrm{d}k\,k\,f(x,k)\Bigg\{\Big(\Gamma_T+2\Gamma_L\Big)\mathcal{E}_1(z,p,k,\epsilon)+\Big(\Lambda_T+2\Lambda_L\Big)\mathcal{E}_2(z,p,k,\epsilon)\Bigg\} \tag{22}$$

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