FORWARD GAUGE BOSON PRODUCTION IN pp COLLISIONS

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1. INTRODUCTION

The particle production at forward rapidities in hadronic collisions is one of the most promising processes to probe the QCD dynamics at small - x as well as to observe the breakdown of the collinear and k_T factorization theorems, predicted to occur to high partonic densities. In this process, one has the interaction between projectile partons with large cone momentum fractions and target partons carrying a very small momentum fraction. Thus, the projectile parton scatter off a dense gluonic system in the target. In this contribution, we investigate the case where one of the particles in the final state is an electroweak gauge boson (G = $W^{\pm}$, Z^0, γ) and present the differential cross-section for the isolated gauge boson produciton in pp collisions at forward rapidities as a function of the dipole - proton cross-section or the unintegrated gluon distribution as presented in our paper (BANDEIRA; GONCALVES; SCHÄFER, 2024).

Moreover, we also present the associated electroweak gauge boson production. These new formalism can be used to estimate the impact of the saturation effects in the gauge boson production at the LHC and future colliders. Moreover, we demonstrate that our general parton-level cross-section reduces to expressions previously used in the literature for the description of the real photon production and Drell - Yan process at forward rapidities in some particular limits.

2. METODOLOGY

The master formula for the dijet production in the color - dipole S - matrix framework is given by (NIKOLAEV et al., 2003)

$$\begin{aligned}\frac{d\sigma(a\to b(p_b)c(p_c))}{dz\,d^2\boldsymbol{p}_b d^2\boldsymbol{p}_c} &= \frac{1}{(2\pi)^4}\int d^2\boldsymbol{b}_b d^2\boldsymbol{b}_c d^2\boldsymbol{b}'_b d^2\boldsymbol{b}'_c \exp[i\boldsymbol{p}_b\cdot(\boldsymbol{b}_b-\boldsymbol{b}'_b)+i\boldsymbol{p}_c\cdot(\boldsymbol{b}_c-\boldsymbol{b}'_c)]\\ &\times \Psi(z,\boldsymbol{b}_b-\boldsymbol{b}_c)\Psi^*(z,\boldsymbol{b}'_b-\boldsymbol{b}'_c)\\ &\times \Big\{S^{(4)}_{\bar{b}\bar{c}cb}(\boldsymbol{b}'_b,\boldsymbol{b}'_c,\boldsymbol{b}_b,\boldsymbol{b}_c)+S^{(2)}_{\bar{a}a}(\boldsymbol{b}',\boldsymbol{b})-S^{(3)}_{\bar{b}\bar{c}a}(\boldsymbol{b},\boldsymbol{b}'_b,\boldsymbol{b}'_c)-S^{(3)}_{\bar{a}bc}(\boldsymbol{b}',\boldsymbol{b}_b,\boldsymbol{b}_c)\Big\}\end{aligned} \quad (1)$$

where we have defined the quantities

$$\begin{aligned}
S^{(2)}_{a\bar{a}}(\boldsymbol{b}', \boldsymbol{b}) &= S^{\dagger}_{a}(\boldsymbol{b}')S_a(\boldsymbol{b}) \ , && (2)\\
S^{(3)}_{\bar{a}bc}(\boldsymbol{b}', \boldsymbol{b}_b, \boldsymbol{b}_c) &= S^{\dagger}_{a}(\boldsymbol{b}')S_b(\boldsymbol{b}_b)S_c(\boldsymbol{b}_c) \ , && (3)\\
S^{(3)}_{\bar{b}\bar{c}a}(\boldsymbol{b}, \boldsymbol{b}'_b, \boldsymbol{b}'_c) &= S^{\dagger}_{b}(\boldsymbol{b}'_b)S^{\dagger}_{c}(\boldsymbol{b}'_c)S_a(\boldsymbol{b}) \ , && (4)\\
S^{(4)}_{\bar{b}\bar{c}cb}(\boldsymbol{b}'_b, \boldsymbol{b}'_c, \boldsymbol{b}_b, \boldsymbol{b}_c) &= S^{\dagger}_{b}(\boldsymbol{b}'_b)S^{\dagger}_{c}(\boldsymbol{b}'_c)S_c(\boldsymbol{b}_c)S_b(\boldsymbol{b}_b) \ . && (5)
\end{aligned}$$

As the hermitian conjugate $S^{\dagger}$ can be viewed as the S matrix for an antiparticle, one has that $S_{a\bar{a}}(\boldsymbol{b}',\boldsymbol{b})$ represents the S matrix for the interaction of the $a\bar{a}$ state with the target, with $\bar{a}$ propagating at the impact parameter $\boldsymbol{b}'$. The averaging over the color states of the beam parton a implies that one has a color - singlet $a\bar{a}$ state. Similarly, $S_{\bar{a}bc}$ and $S_{\bar{b}\bar{c}cb}$ can be associated with the interaction of the color - singlet $\bar{a}bc$ and $\bar{b}\bar{c}cb$ systems, respectively. A detailed discussion about how to calculate these quantities in the general case was presented in a series of publications (NIKOLAEV et al., 2003, 2005; NIKOLAEV; SCHAFER; ZAKHAROV, 2005), which we refer for the interested reader. In what follows, we will focus on the $a \rightarrow Gc$ process, with G an electroweak gauge boson, which was not discussed in these previous studies.

3. RESULTS AND DISCUSSION

At (BANDEIRA; GONCALVES; SCHÄFER, 2024), we present for the first time the light front wave function (LFWF) for all electroweak gauge boson in the light front gauge. Consequently, once we got the LFWF, we were able to presented the differential spectrum for both impact parameter space and momentum space. Furthermore, we are expanding our approach for the associated production of a gauge boson and a jet which is part of a paper in progress, where we obtained the full differential spectrum, which is given by

$$
\begin{aligned}
\left.\frac{\mathrm{d}\sigma_T}{\mathrm{d}z\,\mathrm{d}^2\boldsymbol{p}\,\mathrm{d}^2\boldsymbol{\Delta}}\right|_V &= \frac{1}{2}\frac{(C_f^G)^2(g_{V,f})^2}{2\pi^2} f(x,\boldsymbol{\Delta})\left\{\frac{1+(1-z)^2}{z}\mathcal{E}_1(\boldsymbol{p},\boldsymbol{\Delta},z,\epsilon)\right.\\
&+ \left. z\left[(m_b-m_a)+zm_a\right]^2\mathcal{E}_2(\boldsymbol{p},\boldsymbol{\Delta},z,\epsilon)\right\} \qquad (8)\\
\left.\frac{\mathrm{d}\sigma_T}{\mathrm{d}z\,\mathrm{d}^2\boldsymbol{p}\,\mathrm{d}^2\boldsymbol{\Delta}}\right|_A &= \frac{1}{2}\frac{(C_f^G)^2(g_{A,f})^2}{2\pi^2} f(x,\boldsymbol{\Delta})\left\{\frac{1+(1-z)^2}{z}\mathcal{E}_1(\boldsymbol{p},\boldsymbol{\Delta},z,\epsilon)\right.\\
&+ \left. z\left[(m_b-m_a)+zm_a\right]^2\mathcal{E}_2(\boldsymbol{p},\boldsymbol{\Delta},z,\epsilon)\right\} \qquad (9)\\
\left.\frac{\mathrm{d}\sigma_L}{\mathrm{d}z\,\mathrm{d}^2\boldsymbol{p}\,\mathrm{d}^2\boldsymbol{\Delta}}\right|_V &= \frac{1}{2}\frac{(C_f^G)^2(g_{f,V}^G)^2}{4\pi^2} f(x,\boldsymbol{\Delta})\left\{\frac{z(m_b-m_a)^2}{M_G^2}\mathcal{E}_1(\boldsymbol{p},\boldsymbol{\Delta},z,\epsilon)\right.\\
&+ \left.\frac{\left[z^2m_a(m_b-m_a)-z(m_b^2-m_a^2)-2(1-z)M_G^2\right]^2}{zM_G^2}\mathcal{E}_2(\boldsymbol{p},\boldsymbol{\Delta},z,\epsilon)\right\} \qquad (10)\\
\left.\frac{\mathrm{d}\sigma_L}{\mathrm{d}z\,\mathrm{d}^2\boldsymbol{p}\,\mathrm{d}^2\boldsymbol{\Delta}}\right|_A &= \frac{1}{2}\frac{(C_f^G)^2(g_{f,A}^G)^2}{4\pi^2} f(x,\boldsymbol{\Delta})\left\{\frac{z(m_b-m_a)^2}{M_G^2}\mathcal{E}_1(\boldsymbol{p},\boldsymbol{\Delta},z,\epsilon)\right.\\
&+ \left.\frac{\left[z^2m_a(m_b-m_a)-z(m_b^2-m_a^2)-2(1-z)M_G^2\right]^2}{zM_G^2}\mathcal{E}_2(\boldsymbol{p},\boldsymbol{\Delta},z,\epsilon)\right\} \qquad (11)
\end{aligned}
$$

Therefore, we creat a complete description for both isolated and associated production for all electroweak gauge boson which is a novelty in the literature. Also, we presented in the literature, for the first time, the LFWF for the W ± boson together with Z 0 and γ. Beyond our general differential cross-sections expressions be a novelty by the description of W ± production, our results reduce to expressions previously used in the literature for the description of the real photon production and Drell - Yan process at forward rapidities in some particular limits, e.g., in Refs. (SCHÄFER; SZCZUREK, 2016; BASSO et al., 2016; LIMA; GIANNINI; GONCALVES, 2024).

4. FINAL CONSIDERATIONS

The description of the particle production at forward rapidites in proton – proton and proton – nucleus collisions at high energies is still one of the main challenges of the strong interactions theory. In this kinematical region, are expected that non linear effects in the QCD dynamics contribute and, therefore, the usual calculation of cross sections in terms of the collinear factorization formalism breakdown. In general, the final formulas for the cross-sections associated with the production of two parton/hadrons involve new quantities, which are non-trivial to estimate. In this work, we addressed a simpler process, where one of the particles in the final state is an electroweak gauge boson *G*. As we have demonstrated, for this case, the differential cross-section for the associated production of the gauge boson with a quark can be fully expressed in terms of the squared light cone wave function (LCWF) for the $q_f \rightarrow Gq_k$ transition, and the usual dipole-proton cross-section, which can be constrained by the HERA data. In the current study, we have derived, for the first time, the generic expressions for the LCWF's. Moreover, we have estimated the vector and axial contributions for the description of the longitudinal and transverse spectra associated with the isolated gauge boson production in the impact parameter and transverse momentum spaces. In addition, our results reduce to expressions previously used in the literature for the description of the real photon production and Drell – Yan process at forward rapidities in some particular limits.

5. REFERENCES

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