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Transverse Momentum Resummation for Z boson Plus Jet Production at the LHC

Peng Sun[1,⋆], *Bin* Yan[2,3,⋆⋆], *C.-P.* Yan[3,⋆⋆⋆], and *Feng* Yuan[4,⋆⋆⋆⋆]

[1] *Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing, Jiangsu, 210023, China*
[2] *Theoretical Division, Group T-2, MS B283, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA*
[3] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[4] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Abstract. We study the transverse momentum resummation effects for the Z boson plus jet associated production at the LHC within the transverse momentum dependent (TMD) factorization formalism. The large logarithm $\ln(Q^2/q_\perp^2)$ with $Q \gg q_\perp$ has been resummed to Next-to-Leading Logarithm (NLL) accuracy. We compare our numerical results to the CMS data by reweighting method. It shows that our prediction agree with the data very well.

1 Introduction

Precisely study the Z boson and jet associated production at the Large Hadron Collider (LHC) is important for us to test the standard model (SM) and search the possible new physics effects. In order to give a robust prediction and compare it to the experimental data, the higher order QCD correction is necessary. The next-to-next-to-leading order (NNLO) QCD correction has been finished in Refs. [1–3] and it shows that the theoretical uncertainties could be reduced to percent-level. However, for the observables which are sensitive to the soft and collinear radiations (e.g. the total transverse momentum of Z boson and leading jet system), we should use the resummation technique to improve the theoretical prediction, not by the fixed-order calculation. Here, we use the transverse momentum dependent (TMD) factorization formalism to discuss the kinematical distributions of Z boson plus one jet [4]. A similar work based on the soft-collinear effective theory can be found in Ref. [5].

2 TMD resummation

TMD resummation formula can be written as [6]:

$$\frac{d^5\sigma}{dy_Z dy_J dP_{J\perp}^2 d^2\vec{q}_\perp} = \sum_{ab}\left[\int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp\cdot\vec{b}_\perp} W_{ab\to ZJ}(x_1, x_2, b_\perp) + Y_{ab\to ZJ}\right], \tag{1}$$

⋆e-mail: pengsun@msu.edu
⋆⋆e-mail: binyan@lanl.gov
⋆⋆⋆e-mail: yuan@pa.msu.edu
⋆⋆⋆⋆e-mail: fyuan@lbl.gov

where y_Z and y_J denote the rapidity of the Z boson and the leading jet; $P_{J\perp}(P_{Z\perp})$ and $\vec{q}_\perp = \vec{P}_{Z\perp} + \vec{P}_{J\perp}$ are the leading jet (Z boson) transverse momentum and the imbalance transverse momentum of the Z boson and the jet system. The all order resummation effects have included in $W_{ab\to ZJ}$. $Y_{ab\to ZJ}$ is the remainder function between fixed order and asymptotic result. x_1 and x_2 are the momentum fractions of the incoming hadrons carried by the two incoming partons,

$$x_{1,2} = \frac{\sqrt{m_Z^2 + P_{Z\perp}^2}e^{\pm y_Z} + \sqrt{P_{J\perp}^2}e^{\pm y_J}}{\sqrt{S}}. \tag{2}$$

The $W_{ab\to ZJ}$ can be further written as,

$$\begin{aligned} W_{ab\to ZJ}(x_1, x_2, b) = & \, x_1 f_a(x_1, \mu_F = b_0/b_\perp) x_2 f_b(x_2, \mu_F = b_0/b_\perp) \\ & \times H_{ab\to ZJ}(s, \mu_{\rm res}, \mu_R) e^{-S_{\rm Sud}(s,\mu_{\rm res},b_\perp)} e^{-\mathcal{F}_{NP}}, \end{aligned} \tag{3}$$

Here μ_F, μ_R and $\mu_{\rm res}$ are the factorization, renormalization and resummation scales.

The Sudakov form factor can be expressed as,

$$S_{\rm Sud} = \int_{b_0^2/b_\perp^2}^{\mu_{\rm res}^2} \frac{d\mu^2}{\mu^2} \left[\ln\left(\frac{s}{\mu^2}\right) A + B_1 + B_2 + D \ln\frac{1}{R^2} \right], \tag{4}$$

where R is the jet cone size. The coefficients $A, B_{1,2}$ and D can be expanded perturbatively in α_s. The NLO results have show in Ref. [4]. Factor $\mathcal{F}_{NP}$ denotes the contribution from non-perturbative effects [7]. The hard function $H_{ab\to ZJ}$ is depending on the initial state and the full NLO results can be found in Ref. [4].

3 Phenomenology

We apply the resummation formula in Eq. 1 to calculate the $q_\perp$ spectrum and ϕ angle distribution between Z boson and leading jet. The anti-k_t jet algorithm with cone size $R = 0.4$ is used in our numerical calculation. In order to compare our theoretical prediction to data, we apply a reweighting procedure to estimate the effect from imposing kinematic cuts on the leptons from Z boson decay. The differential cross section after we including the kinematic cuts can be written as,

$$\left.\frac{d\sigma}{dq_\perp}\right|_{\rm decay} = \left.\frac{d\sigma}{dq_\perp}\right|_{\rm stable,Z} \times \kappa(m_{\ell^+\ell^-}, y_{\ell^+\ell^-}, p_T^{\ell^+\ell^-}), \tag{5}$$

where $\kappa(m_{\ell^+\ell^-}, p_T^{\ell^+\ell^-}, y_{\ell^+\ell^-})$ is the reweighting factor which depends on lepton pair invariant mass ($m_{\ell^+\ell^-}$), transverse momentum ($p_T^{\ell^+\ell^-}$) and rapidity ($y_{\ell^+\ell^-}$). We find that the reweighting factor could approximate as a constant when $|y_Z| < 1.5$. Therefore, we have,

$$\left.\frac{d\sigma}{\sigma dq_\perp}\right|_{\rm decay} \simeq \left(\left.\frac{d\sigma}{\sigma dq_\perp}\right|_{\rm stable,Z}\right), \text{ for } |{\rm y}_{\ell^+\ell^-}| < 1.5. \tag{6}$$

We calculate the normalized $q_\perp$ distribution of Z boson plus one jet production at the $\sqrt{s} = 13$ TeV with CT14NNLO PDF [8] in Fig. 1. The ϕ angle distribution at the $\sqrt{s} = 8$ TeV is shown in Fig. 2. The blue and red bands represent the experimental and scale uncertainty respectively. It is clear that our theoretical prediction agree well with the experimental data.

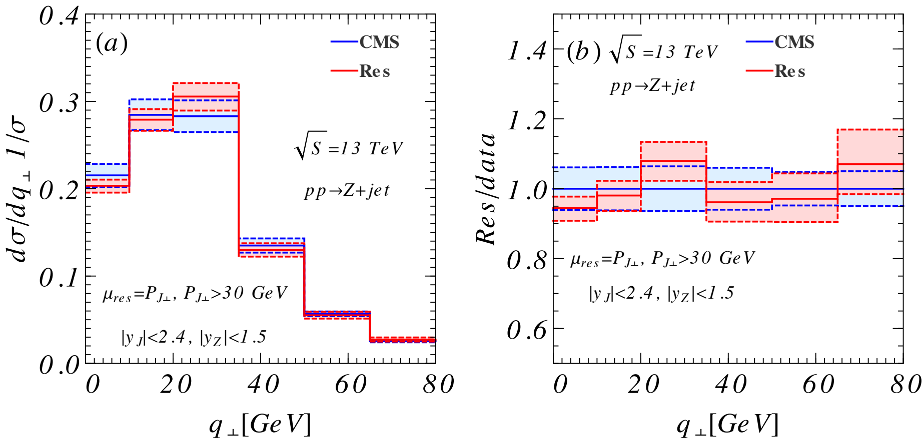

Figure 1. (a) The normalized $q_\perp$ distribution of the Z boson plus one jet system, produced at the $\sqrt{S}$ = 13 TeV LHC with $|y_J| < 2.4$ and $P_{J\perp} > 30$ GeV. The blue and red bands represent the CMS experimental uncertainty [9] and the resummation calculation (Res) scale uncertainty, respectively. (b) The ratio of resummation prediction to CMS data as a function of $q_\perp$.

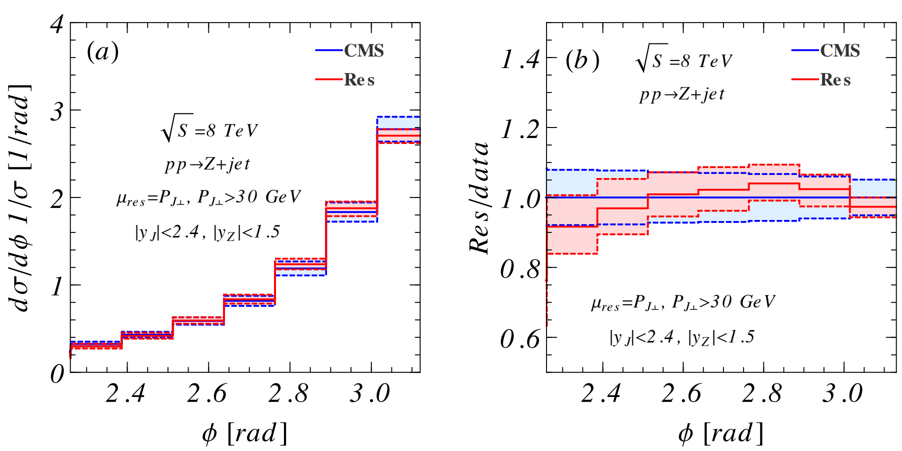

Figure 2. The normalized distribution of ϕ, the azimuthal angle between the final state jet and Z boson measured in the laboratory frame, for $pp \to Z + jet$ production at the $\sqrt{S}$ = 8 TeV LHC with $|y_J| < 2.4$, $|y_Z| < 1.5$ and $P_{J\perp} > 30$ GeV. The blue and red bands represent the CMS experimental error [10] and resummation scale uncertainty respectively.

4 Summary

In this work, we discuss the transverse momentum resummation effects for the Z boson and jet associated production. The large logarithms of $\ln(Q^2/q_\perp^2)$ has be resuumed to NLL accuracy. In order to compare to data directly, the reweighting method is used in our analysis. It shows that our resummation calculation can describe well the CMS data, both the transverse momentum distribution and azimuthal angle of Z boson plus jet system.
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References

[1] R. Boughezal, J. M. Campbell, R. K. Ellis, C. Focke, W. T. Giele, X. Liu and F. Petriello, Phys. Rev. Lett. **116**, no. 15, 152001 (2016) doi:10.1103/PhysRevLett.116.152001 [arXiv:1512.01291 [hep-ph]].

[2] A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, A. Huss and T. A. Morgan, Phys. Rev. Lett. **117**, no. 2, 022001 (2016) doi:10.1103/PhysRevLett.117.022001 [arXiv:1507.02850 [hep-ph]].

[3] R. Boughezal, X. Liu and F. Petriello, Phys. Rev. D **94**, no. 7, 074015 (2016) doi:10.1103/PhysRevD.94.074015 [arXiv:1602.08140 [hep-ph]].

[4] P. Sun, B. Yan, C.-P. Yuan and F. Yuan, Phys. Rev. D **100**, no. 5, 054032 (2019) doi:10.1103/PhysRevD.100.054032 [arXiv:1810.03804 [hep-ph]].

[5] Y. T. Chien, D. Y. Shao and B. Wu, JHEP **1911**, 025 (2019) doi:10.1007/JHEP11(2019)025 [arXiv:1905.01335 [hep-ph]].

[6] P. Sun, C.-P. Yuan and F. Yuan, Phys. Rev. Lett. **114**, no. 20, 202001 (2015) doi:10.1103/PhysRevLett.114.202001 [arXiv:1409.4121 [hep-ph]].

[7] P. Sun, J. Isaacson, C.-P. Yuan and F. Yuan, Int. J. Mod. Phys. A **33**, no. 11, 1841006 (2018) doi:10.1142/S0217751X18410063 [arXiv:1406.3073 [hep-ph]].

[8] S. Dulat *et al.*, Phys. Rev. D **93**, no. 3, 033006 (2016) doi:10.1103/PhysRevD.93.033006 [arXiv:1506.07443 [hep-ph]].

[9] A. M. Sirunyan *et al.* [CMS Collaboration], Eur. Phys. J. C **78**, no. 11, 965 (2018) doi:10.1140/epjc/s10052-018-6373-0 [arXiv:1804.05252 [hep-ex]].

[10] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1704**, 022 (2017) doi:10.1007/JHEP04(2017)022 [arXiv:1611.03844 [hep-ex]].