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Q_T RESUMMATION IN TRANSVERSELY POLARIZED DRELL-YAN PROCESS *

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We calculate QCD corrections to transversely polarized Drell-Yan process at a measured Q_T of the produced lepton pair in the dimensional regularization scheme. The Q_T distribution is discussed resumming soft gluon effects relevant for small Q_T .

Keywords: Q_T resummation, Transversity, Drell-Yan process

Hard processes with polarized nucleon beams enable us to study spin-dependent dynamics of QCD and the spin structure of nucleon. The helicity distribution $\Delta q(x)$ of quarks within nucleon has been measured in polarized DIS experiments, and $\Delta G(x)$ of gluons has also been estimated from the scaling violations of them. On the other hand, the transversity distribution $\delta q(x)$, i.e. the distribution of transversely polarized quarks inside transversely polarized nucleon, can not be measured in inclusive DIS due to its chiral-odd nature,¹ and remains as the last unknown distribution at the leading twist. Transversely polarized Drell-Yan (tDY) process is one of the processes where the transversity distribution can be measured, and has been undertaken at RHIC-Spin experiment.

We compute the 1-loop QCD corrections to tDY at a measured Q_T and azimuthal angle ϕ of the produced lepton in the dimensional regularization scheme. For this purpose, the phase space integration in D -dimension, separating out the relevant transverse degrees of freedom, is required to extract the $\propto \cos(2\phi)$ part of the cross section characteristic of the spin asymmetry of tDY.¹ The calculation is rather cumbersome compared with the corresponding calculation in unpolarized and longitudinally polarized cases, and has not been performed so far. We obtain the NLO

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$\mathcal{O}(\alpha_s)$ corrections to the tDY cross section in the $\overline{\text{MS}}$ scheme. We also include soft gluon effects by all-order resummation of logarithmically enhanced contributions at small Q_T (“edge regions of the phase space”) up to next-to-leading logarithmic (NLL) accuracy, and obtain the first complete result of the Q_T distribution for all regions of Q_T at NLL level.

We first consider the NLO $\mathcal{O}(\alpha_s)$ corrections to tDY: $h_1(P_1, s_1) + h_2(P_2, s_2) \rightarrow l(k_1) + \bar{l}(k_2) + X$, where h_1, h_2 denote nucleons with momentum P_1, P_2 and transverse spin s_1, s_2 , and $Q = k_1 + k_2$ is the 4-momentum of DY pair. The spin dependent cross section $\Delta_T d\sigma \equiv (d\sigma(s_1, s_2) - d\sigma(s_1, -s_2))/2$ is given as a convolution

$$\Delta_T d\sigma = \int dx_1 dx_2 \delta H(x_1, x_2; \mu_F) \Delta_T d\hat{\sigma}(s_1, s_2; \mu_F), \quad (1)$$

where μ_F is the factorization scale, and

$$\delta H(x_1, x_2; \mu_F) = \sum_i e_i^2 [\delta q_i(x_1; \mu_F) \delta \bar{q}_i(x_2; \mu_F) + \delta \bar{q}_i(x_1; \mu_F) \delta q_i(x_2; \mu_F)] \quad (2)$$

is the product of transversity distributions of the two nucleons, and $\Delta_T d\hat{\sigma}$ is the corresponding partonic cross section. Note that, at the leading twist level, the gluon does not contribute to the transversely polarized process due to its chiral odd nature. We compute the one-loop corrections to $\Delta_T d\hat{\sigma}$, which involve the virtual gluon corrections and the real gluon emission contributions, e.g., $q(p_1, s_1) + \bar{q}(p_2, s_2) \rightarrow l(k_1) + \bar{l}(k_2) + g$, with $p_i = x_i P_i$. We regularize the infrared divergence in $D = 4 - 2\epsilon$ dimension, and employ naive anticommuting γ_5 which is a usual prescription in the transverse spin channel.⁴ In the $\overline{\text{MS}}$ scheme, we eventually get,^{6,7} to NLO accuracy,

$$\frac{\Delta_T d\sigma}{dQ^2 dQ_T^2 dy d\phi} = N \cos(2\phi) [X(Q_T^2, Q^2, y) + Y(Q_T^2, Q^2, y)], \quad (3)$$

where $N = \alpha^2/(3 N_c S Q^2)$ with $S = (P_1 + P_2)^2$, y is the rapidity of virtual photon, and ϕ is the azimuthal angle of one of the leptons with respect to the initial spin axis. For later convenience, we have decomposed the cross section into the two parts: the function X contains all terms that are singular as $Q_T \rightarrow 0$, while Y is of $\mathcal{O}(\alpha_s)$ and finite at $Q_T = 0$. Writing $X = X^{(0)} + X^{(1)}$ as the sum of the LO and NLO contributions, we have^{6,7} $X^{(0)} = \delta H(x_1^0, x_2^0; \mu_F) \delta(Q_T^2)$, and

$$X^{(1)} = \frac{\alpha_s}{2\pi} C_F \left\{ \delta H(x_1^0, x_2^0; \mu_F) \left[2 \left(\frac{\ln Q^2/Q_T^2}{Q_T^2} \right)_+ - \frac{3}{(Q_T^2)_+} + (-8 + \pi^2) \delta(Q_T^2) \right] \right. \\ \left. + \left(\frac{1}{(Q_T^2)_+} + \delta(Q_T^2) \ln \frac{Q^2}{\mu_F^2} \right) \left[\int_{x_1^0}^1 \frac{dz}{z} \delta P_{qq}^{(0)}(z) \delta H \left(\frac{x_1^0}{z}, x_2^0; \mu_F \right) + (x_1^0 \leftrightarrow x_2^0) \right] \right\} \quad (4)$$

where $x_1^0 = \sqrt{\tau} e^y, x_2^0 = \sqrt{\tau} e^{-y}$ are the relevant scaling variables with $\tau = Q^2/S$, and $\delta P_{qq}^{(0)}(z) = 2z/(1-z)_+ + (3/2) \delta(1-z)$ is the LO transverse splitting function.⁵ In (4), the terms involving $\delta(Q_T^2)$ come from the virtual gluon corrections, while the other terms represent the recoil effects due to the real gluon emissions. For the analytic expression of Y , see Ref.⁷. Eq. (3) gives the first NLO result in the $\overline{\text{MS}}$

scheme. We note that there has been a similar NLO calculation of tDY cross section in massive gluon scheme.² We also note that, integrating (3) over Q_T , our result coincides with the corresponding Q_T -integrated cross sections obtained in previous works employing massive gluon scheme² and dimensional reduction scheme,³ via the scheme transformation relation.⁴

The cross section (3) becomes very large when $Q_T \ll Q$, due to the terms behaving $\sim \alpha_s \ln(Q^2/Q_T^2)/Q_T^2$ and $\sim \alpha_s/Q_T^2$ in the singular part X . It is well-known that, in unpolarized and longitudinally polarized DY, large “recoil logs” of similar nature appear in each order of perturbation theory as $\alpha_s^n \ln^{2n-1}(Q^2/Q_T^2)/Q_T^2$, $\alpha_s^n \ln^{2n-2}(Q^2/Q_T^2)/Q_T^2$, and so on, corresponding to LL, NLL, and higher contributions, respectively, and that the resummation of those “double logarithms” to all orders is necessary to obtain a well-defined, finite prediction of the cross section.⁹ Because the LL and NLL contributions are universal,¹¹ we can work out the all-order resummation of the corresponding logarithmically enhanced contributions in (3) up to the NLL accuracy, based on the general formulation⁹ of the Q_T resummation. This can be conveniently carried out in the impact parameter b space, conjugate to the Q_T space. As a result, the singular part X of (3) is modified into the corresponding resummed part, which is expressed as the Fourier transform,

$$X \rightarrow \sum_i e_i^2 \int_0^\infty db \frac{b}{2} J_0(bQ_T) e^{S(b,Q)} (C_{qq} \otimes \delta q_i) \left(x_1^0, \frac{b_0^2}{b^2} \right) (C_{\bar{q}\bar{q}} \otimes \delta \bar{q}_i) \left(x_2^0, \frac{b_0^2}{b^2} \right) + (x_1^0 \leftrightarrow x_2^0). \quad (5)$$

Here $b_0 = 2e^{-\gamma_E}$, and the large logarithmic corrections are resummed into the Sudakov factor $e^{S(b,Q)}$ with $S(b,Q) = -\int_{b_0^2/b^2}^{Q^2} (d\kappa^2/\kappa^2) \{(\ln \frac{Q^2}{\kappa^2}) A_q(\alpha_s(\kappa)) + B_q(\alpha_s(\kappa))\}$. The functions A_q , B_q as well as the coefficient functions C_{qq} , $C_{\bar{q}\bar{q}}$ are calculable in perturbation theory, and at the present accuracy of NLL, we get:^{6,7} $A_q(\alpha_s) = (\alpha_s/\pi) C_F + (\alpha_s/2\pi)^2 2C_F \{(67/18 - \pi^2/6) C_G - 5N_f/9\}$, $B_q(\alpha_s) = -3C_F(\alpha_s/2\pi)$, $C_{qq}(z, \alpha_s) = C_{\bar{q}\bar{q}}(z, \alpha_s) = \delta(1-z) \{1 + (\alpha_s/4\pi) C_F(\pi^2 - 8)\}$. We have utilized a relation¹⁰ between A_q and the DGLAP kernels in order to obtain the two-loop term of A_q . The other contributions have been determined so that the expansion of the above formula (5) in powers of $\alpha_s(\mu_F)$ reproduces X of (3), (4) to the NLO accuracy. Eq. (3) with (5) presents the first result of the NLL Q_T resummation formula for tDY. The NLO parton distributions in the $\overline{\text{MS}}$ scheme have to be used.

One more step is necessary to make the QCD prediction of tDY. Similarly to other all-order resummation formula, our result (5) is suffered from the IR renormalons due to the Landau pole at $b = (b_0/Q) e^{(1/2\beta_0\alpha_s(Q))}$ in the Sudakov factor, and it is necessary to specify a prescription to avoid this singularity. Here we deform the integration contour in (5) in the complex b space, following the method introduced in the joint resummation.¹² Obviously prescription to define the b integration is not unique reflecting IR renormalon ambiguity, e.g., “ b_* prescription” to “freeze” effectively the b integration along the real axis is frequently used.⁹ The

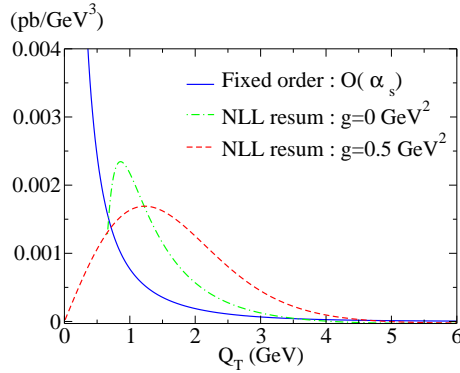


Fig. 1. Q_T distribution $\Delta_T d\sigma/dQ^2 dQ_T dy d\phi$ at $\sqrt{S} = 100$ GeV, $Q = 10$ GeV, $y = \phi = 0$.

renormalon ambiguity should be eventually compensated in the physical quantity by the power corrections $\sim (b\Lambda_{\text{QCD}})^n$ ($n = 2, 3, \dots$) due to non-perturbative effects. Correspondingly, we make the replacement $e^{S(b,Q)} \rightarrow e^{S(b,Q)} F^{NP}(b)$ in (5) with the “minimal” ansatz for non-perturbative effects,^{9,12} $F^{NP}(b) = \exp(-gb^2)$ with a non-perturbative parameter g . Fig.1 shows the Q_T distribution of tDY at $\sqrt{S} = 100$ GeV, $Q = 10$ GeV, $y = \phi = 0$, and with a model for the transversity $\delta q(x)$ that saturates the Soffer’s inequality at a low scale.¹³ Solid line shows the NLO result using (3), and the dashed and dot-dashed lines show the NLL result using (3), (5), $F^{NP}(b) = \exp(-gb^2)$, with $g = 0.5$ GeV² and $g = 0$, respectively.

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