ANGULAR DISTRIBUTION OF DRELL YAN PAIRS IN p+A AT LHC

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Abstract
We discuss the angular distribution of dilepton pairs in p+A collisions at LHC at low momentum transfer and transverse momentum. This includes helicity amplitudes and angular coefficients as well as a look at the Lam-Tung sum rule. We use leading twist NLO calculations and higher twist corrections by double scattering in large nuclei.

1. INTRODUCTION
The Drell Yan cross section can be described by a contraction of the lepton and hadron tensors

$$\frac{d\sigma}{dQ^2 dq^2_\perp dy d\Omega} = \frac{\alpha^2}{64\pi^3 S Q^4} L_{\mu\nu} W^{\mu\nu}. \quad (1)$$

Here we parametrize the lepton pair by the invariant mass $Q$ of the virtual photon and its transverse momentum $q_\perp$ and rapidity $y$ in the center of mass frame of the colliding hadrons. In addition we give the direction of one of the leptons, say the positively charged one, in a photon rest frame using polar and azimuthal angles $\phi$ and $\theta$:

$$d\Omega = d\phi d\cos\theta. \quad (2)$$

These are defined as contractions $W_{\sigma,\sigma'} = \epsilon_\mu(\sigma) W^{\mu\nu} \epsilon^{\nu}_{\sigma'}(\sigma')$ of the hadron tensor with polarization vectors of the virtual photon for polarizations $\sigma = 0, \pm 1$. Only four out of all possible contractions are independent, the others can be related by symmetries of the hadron tensor. The usual choice is to pick the longitudinal $W_L = W_{0,0}$, the helicity flip $W_\Delta = (W_{1,0} + W_{0,1})/\sqrt{2}$ and the double helicity flip amplitude $W_{\Delta\Delta} = W_{1,-1}$ together with the trace $W_{TL} = W_T + W_L/2 = -W^\mu_{\mu}/2$ as a basis. Note that integration over the angles $\theta$ and $\phi$ leaves only contributions from the trace

$$\frac{d\sigma}{dQ^2 dq^2_\perp dy d\Omega} = \frac{\alpha^2}{64\pi^3 S Q^4} \left[ W_{TL}(1 + \cos^2 \theta) + W_L(1/2 - 3/2 \cos^2 \theta) \right.$$  \left. + W_\Delta \sin 2\theta \cos \phi + W_{\Delta\Delta} \sin^2 \theta \cos 2\phi \right]. \quad (3)$$

On the other hand, if we are only interested in relative angular distributions — i.e. in the ratio

$$\frac{16\pi}{3} \frac{d\sigma}{dQ^2 dq^2_\perp dy d\Omega} / \left( \frac{d\sigma}{dQ^2 dq^2_\perp dy d\Omega} \right) \quad (4)$$

— we can make use of angular coefficients. Two different sets can be found in the literature [4]. One set consists of the coefficients

$$A_0 = \frac{W_L}{W_{TL}}, \quad A_1 = \frac{W_\Delta}{W_{TL}}, \quad A_2 = \frac{2W_{\Delta\Delta}}{W_{TL}}. \quad (5)$$

the other one is defined by

$$\lambda = \frac{2 - 3 A_0}{2 + A_0}, \quad \mu = \frac{2 A_1}{2 + A_0}, \quad \nu = \frac{2 A_2}{2 + A_0}. \quad (6)$$
The helicity amplitudes are frame dependent. In principle we allow all frames where the photon is at rest, i.e. $q^\mu = (Q, 0, 0, 0)$. However there are some frames with particular properties studied in [3]. Here we only use the Collins-Soper (CS) frame. It is characterized by two properties. First the $y$-axis is perpendicular to the plane spanned by the two hadron momenta $P_1$ and $P_2$ (which are no longer collinear in a photon rest frame as long as $q_\perp \neq 0$, what is true in our kinematic domain) and second the $z$-axis cuts the angle between $P_1$ and $-P_2$ into two equal halves, see Fig. 1.

2. LEADING TWIST

The hadron tensor for the Drell Yan process in a leading twist (twist-2) calculation is given by the well known factorization formula as a convolution of two parton distributions with a perturbative parton cross section. We are interested here in the kinematic region characterized by intermediate photon mass $Q$ and intermediate transverse momentum $q_\perp \sim Q$ of a few GeV. For these values the dominant contribution to twist-2 is given by the next-to-leading order (NLO) perturbative diagrams like the one in Fig. 2 (left) and we can safely omit logarithmic corrections of type $\ln^2 Q^2 / q_\perp^2$. It has been shown that a leading twist calculation up to NLO respects the so called Lam Tung sum rule $W_L = 2W_{\Delta\Delta}$ [5]. In terms of angular coefficients this can be rewritten as $A_0 = A_2$ or $2\nu = 1 - \lambda$. Furthermore the spin flip amplitude $W_\Delta$ has to vanish for a symmetric colliding system like $p + p$. For $p + A$ we expect small contributions for $W_\Delta$ due to lost isospin symmetry and nuclear corrections to the parton distributions. Results for $p + p$ at $\sqrt{S} = 5.5$ TeV have already been presented elsewhere [6].

3. NUCLEAR ENHANCED TWIST-4

For large nuclei corrections to the leading twist calculation, induced by multiple scattering, play an important role. The formalism how to take into account these nuclear enhanced higher twist contributions was worked out by Luo, Qiu and Sterman [7, 8, 9]. The leading nuclear corrections (twist-4 or double

Fig. 2: Examples for diagrams contributing to the dilepton production in hadron (h) nucleus (A) scattering at twist-2 (left) and twist-4 (right) level
scattering) have already been calculated for some observables. For Drell Yan this was first done by Guo [10] and later generalized to the Drell Yan angular distribution [4, 11].

Fig. 3 (right) shows an example for a diagram contributing at twist-4 level. Now two partons, \( a \) and \( b \) from the nucleus and one (\( c \)) from the single hadron are involved. As long as \( q_\perp \sim Q \) twist-4 is dominated by two different contributions. The double hard (DH) process where each parton from the nucleus has a finite momentum fraction and the soft hard (SH) process where one parton has vanishing momentum fraction. The factorization formulas are given by

\[
W^{\mu\nu} = \sum_{a,b,c} \int \frac{dx_c}{x_c} T^{DH}_{ab}(x_a, x_b) H^{\mu\nu}_{ab+c}(q, x_a, x_b, x_c) f_c(x_c),
\]

(7)

\[
W^{\mu\nu} = \sum_{a,b,c} \int \frac{dx_c}{x_c} D_{x_a.x_b}(q, x_c) T^{SH}_{ab}(x_a) H^{\mu\nu}_{ab+c}(q, x_a, x_b = 0, x_c) f_c(x_c)
\]

(8)

for double hard and soft hard scattering respectively [4, 10, 11]. \( D_{x_a.x_b}(q, x_c) \) is a second order differential operator in \( x_a \) and \( x_b \). \( T^{DH}_{ab} \) and \( T^{SH}_{ab} \) are new matrix elements of twist-4 which encode non perturbative correlations between the partons \( a \) and \( b \). Since we are still missing solid experimental information about these new quantities, they are usually modeled in a simple way through parton distributions. We use \( T^{DH}_{ab}(x_a, x_b) = CA^{1/3} f_a(x_a)f_b(x_b) \) and \( T^{SH}_{ab}(x_a) = \lambda^2 A^{1/3} f_a(x_a) \) where \( C \) and \( \lambda^2 \) are normalization constants. The key feature, their nuclear enhancement, is their scaling with the nuclear size.

It has been shown in [4, 11] that the DH process shows a trivial angular pattern in the sense that it is similar to the lowest order simple annihilation of on shell quarks with the only difference that one of the quarks now carries finite transverse momentum \( q_\perp \). In this spirit it is no surprise that the DH contribution respects the Lam Tung relation. On the other hand SH scattering is more complicated and violates the Lam Tung sum rule. Also we expect that the spin flip amplitude \( W_\Delta \) can receive large contributions from the twist-4 calculation.

4. NUMERICAL RESULTS

In this section we present some numerical results obtained for proton lead collisions at the LHC energy \( \sqrt{S} = 8.8 \text{ TeV} \). Results for RHIC energies can be found elsewhere [4]. We use CTEQ5L parton distributions [12] combined with EKS98 [13] nuclear nuclear modifications both for the nuclear parton distributions and for the models of the twist-4 matrix elements. In some plots we also give results for double hard contributions where the nuclear modification was omitted. Since we do not know any-

Fig. 3: Rapidity dependence of \( N_\sigma W_{TL} \) (left) and \( N_\sigma W_\Delta \) (right) for \( p+Pb \) at \( \sqrt{S} = 8.8 \text{ TeV} \), \( Q = 5 \text{ GeV} \) and \( q_\perp = 4 \text{ GeV} \): twist-2 NLO (short dashed), double hard with EKS98 modifications (long dashed), soft hard (dash dotted, scaled up by a factor of 10) and the sum of all contributions (bold solid line). The double hard contribution calculated without EKS98 modifications is also shown (dotted line). Note that the incoming nucleus has positive rapidity.
Fig. 4: The angular coefficients $\lambda$ (long dashed), $\mu$ (short dashed) and $\nu$ (dot dashed) for $p + Pb$ at $\sqrt{S} = 8.8$ TeV and $Q = 5$ GeV as functions of rapidity (left, at $q_\perp = 4$ GeV) and transverse momentum (right, at $y = 0$). Thin lines represent pure twist-2 calculations, thick lines show the results including twist-4. The solid line gives the violation of the Lam Tung relation $2\nu - (1 - \lambda)$ scaled up by a factor of 10.

thing about the correct $x$-dependence of the higher twist matrix elements this gives an impression about the error we may at least assume for the higher twist calculation. The normalization constants for the twist-4 matrix elements are chosen to be $\lambda^2 = 0.01 \text{ GeV}^2$ and $C = 0.005 \text{ GeV}^2$. In order to enable convenient comparison with cross sections we show all helicity amplitudes multiplied with the prefactor $N_\sigma = \alpha^2/(64\pi^3 SQ^2)$ from Eq. (2).

In Fig. 3 we give results for the helicity amplitudes $W_{TL}$ and $W_\Delta$ as functions of rapidity. We observe that DH scattering gives a large contribution at negative rapidities (the direction of the proton) which can easily balance the suppression of the twist-2 contribution by shadowing. Soft hard scattering is strongly suppressed at these energies. $W_L$ (not shown) qualitatively has the same behavior as $W_{TL}$. The helicity flip amplitude $W_\Delta$ picks up only a small contribution from twist-2 and is entirely dominated by double hard scattering as already expected. This would be a good observable to pin down nuclear effects in $p + A$ collision. Fig. 4 gives the full set of angular coefficients $\lambda$, $\mu$ and $\nu$ as functions of $y$ and $q_\perp$. Both the twist-2 results and the modifications by twist-4 are given. The violation of the Lam Tung sum rule is numerically almost negligible since the soft hard contribution is so small. Note here that earlier experiments have discovered a large violation of the Lam Tung relation in $\pi + A$ collisions \cite{15}. This issue is still not fully resolved.

$p + A$ collisions offer the unique opportunity to study nuclear effects directly via the rapidity dependence of observables. Helicity amplitudes and angular coefficients can help to pin down the role of nuclear enhanced higher twist. Particularly promising are the helicity flip amplitude $W_\Delta$ and the coefficient $\mu$ which both vanish for $p + p$. The usage of several different species of nuclei is advisable in order to address the important question of $A$ scaling.

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