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Interpretation of angular distributions of Z-boson production at colliders

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ABSTRACT

High precision data of dilepton angular distributions in γ^*/Z production were reported recently by the CMS Collaboration covering a broad range of the dilepton transverse momentum, q_T, up to ~ 300 GeV. Pronounced q_T dependencies of the λ and ν parameters, characterizing the $\cos^2\theta$ and $\cos 2\phi$ angular distributions, were found. Violation of the Lam–Tung relation was also clearly observed. We show that the q_T dependence of λ allows a determination of the relative contributions of the $q\bar{q}$ annihilation versus the qG Compton process. The violation of the Lam–Tung relation is attributed to the presence of a non-zero component of the $q-\bar{q}$ axis in the direction normal to the "hadron plane" formed by the colliding hadrons. The magnitude of the violation of the Lam–Tung relation is shown to reflect the amount of this 'non-coplanarity'. The observed q_T dependencies of λ and ν from the CMS and the earlier CDF data can be well described using this approach.

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The Drell–Yan process [1], in which a lepton pair is produced in a hadron–hadron collision, is one of the most extensively studied reactions. This process together with Deep Inelastic Scattering (DIS) are the main tools for extracting the parton distributions in hadrons [2]. However, some characteristics of the lepton decay angular distributions in the Drell–Yan process are still not well understood. In particular, the Lam–Tung relation [3], which is expected to be largely valid in the presence of QCD corrections, was found to be significantly violated in pion-induced Drell–Yan data collected at CERN [4] and Fermilab [5]. Very recently, the CMS Collaboration reported a precision measurement of angular distribution in Z production at $\sqrt{s}=8$ TeV, again showing a significant violation of the Lam–Tung relation [6].

A general expression for the Drell–Yan angular distribution is [3]

$$\frac{d\sigma}{d\Omega} \propto 1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi, \qquad (1)$$

where θ and ϕ denote the polar and azimuthal angle, respectively, of the l^- in the dilepton rest frame. In the "naive" Drell–Yan model, where the transverse momenta of the partons and QCD processes involving gluons are ignored, $\lambda=1$ and $\mu=\nu=0$. When QCD effects [7] and intrinsic transverse momentum [8] are included, $\lambda\neq 1$ and $\mu,\nu\neq 0$ are allowed. Nevertheless, λ and ν are expected to largely satisfy the Lam–Tung relation [3], $1-\lambda=2\nu$. This relation, obtained as a result of the spin-1/2 nature of the quarks, is analogous to the Callan–Gross relation [9] in DIS. However, unlike the Callan–Gross relation, the Lam–Tung relation is predicted to be insensitive to QCD corrections [10].

The Drell–Yan angular distributions were first measured in fixed-target experiments with pion beams by the CERN NA10 [4] and the Fermilab E615 Collaborations [5]. A sizable ν, increasing with the dilepton transverse momentum q_T was observed by NA10 and E615. Perturbative QCD calculations predict much smaller values of ν [7]. A large violation of the Lam–Tung relation was also found in the E615 data [5], suggesting the presence of effects other than perturbative QCD. Several non-perturbative effects [11–14] were suggested to explain the data. Boer suggested [15] that the observed behavior of ν can be explained by the existence of a transverse-momentum dependent function [16]. This interpretation was later shown to be consistent with a fixed-target Drell–Yan experiment using a proton beam [17,18].

A measurement of the angular distributions of electrons in the $p\bar{p}\to e^+e^-+X$ reaction at $\sqrt{s}=1.96$ TeV in the Z mass region ($66<M_{ee}<116$ GeV/c^2) with q_T up to 90 GeV was reported by the CDF Collaboration [19]. The CDF data were found to be in good

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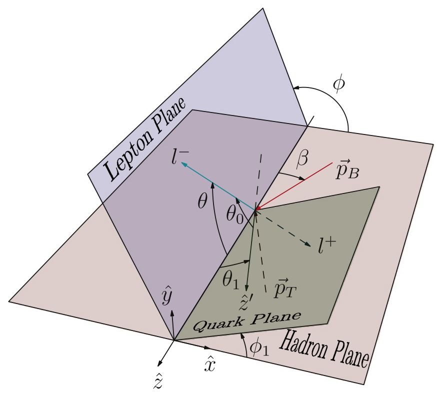

Fig. 1. Definition of the Collins–Soper coordinates, the hadron plane, the lepton plane, the quark plane, and the various angles discussed in the text.

agreement with the Lam–Tung relation, in contrast to the findings in fixed-target experiments. Very recently, the CMS Collaboration reported a high-statistics measurement [6] of angular distributions of γ^*/Z production in $p+p$ collisions at $\sqrt{s}=8$ TeV with q_T up to 300 GeV, clearly observing the violation of the Lam–Tung relation [6]. The different conclusions reached by the CDF and the CMS Collaborations regarding the Lam–Tung relation in γ^*/Z production are surprising and require further study. Moreover, the much larger values of q_T covered by the CDF and CMS experiments imply that the cross sections are dominated by QCD processes involving hard gluon emissions [20]. This is different from the fixed-target Drell–Yan experiments at low q_T, where the leading-order $q-\bar{q}$ annihilation and non-perturbative effects dominate. The collider data could offer important insights on the impact of perturbative QCD effects on the validity of the Lam–Tung relation.

In this paper, we present an intuitive interpretation for the CMS and CDF results on the q_T dependencies of λ and ν, as well as the origin for the violation of the Lam–Tung relation. We show that the emission of more than one gluon in higher-order ($\geq \alpha_s^2$) QCD processes would lead to a non-coplanarity between the $q-\bar{q}$ axis and the beam/target hadron plane in the γ^*/Z rest frame, resulting in a violation of the Lam–Tung relation. Using this geometric picture, the pronounced q_T dependencies of λ and ν observed by the CMS and CDF Collaborations can be well described.

The angular distributions of the leptons are typically expressed in the rest frame of γ^*/Z, where the l^- and l^+ have equal momenta with opposite directions. Clearly, the q and $\bar{q}$ forming the γ^*/Z are also co-linear in the rest frame. Various choices of the coordinate system in the rest frame have been considered. In the Collins–Soper frame [21], the $\hat{x}$ and $\hat{z}$ axes lie in the hadron plane formed by the two colliding hadrons and the $\hat{z}$ axis bisects the momentum vectors of the two hadrons (see Fig. 1). We define the momentum unit vector of the quark as $\hat{z}'$, which has polar and azimuthal angles θ_1 and ϕ_1, as shown in Fig. 1. The corresponding angles of the lepton l^- (e^- or μ^-) from the γ^*/Z decay are labeled as θ and ϕ, as in Eq. (1). Note that for any given values of θ and ϕ, θ_1 and ϕ_1 can vary over a range of values.

In the dilepton rest frame the angular distribution of l^- must be azimuthally symmetric with respect to the $\hat{z}'$ axis with the following polar angular dependence [22]

$$\frac{d\sigma}{d\Omega} \propto 1 + a\cos\theta_0 + \cos^2\theta_0. \tag{2}$$

The forward–backward asymmetry coefficient, a, comes from the parity-violating coupling to the Z boson, and θ_0 is the angle between the l^- momentum vector and $\hat{z}'$. One must convert Eq. (2) into an expression in terms of the physically measurable quantities θ and ϕ. The expression given by CMS is

$$\begin{aligned}\frac{d\sigma}{d\Omega} \propto\ & (1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi \\ & + \frac{A_2}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta \\ & + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi \\ & + A_7\sin\theta\sin\phi. \end{aligned} \tag{3}$$

To go from Eq. (2) to Eq. (3), we note that $\cos\theta_0$ satisfies the following relation:

$$\cos\theta_0 = \cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos(\phi-\phi_1). \tag{4}$$

Substituting Eq. (4) into Eq. (2), we obtain

$$\begin{aligned}\frac{d\sigma}{d\Omega} \propto\ & (1+\cos^2\theta) + \frac{\sin^2\theta_1}{2}(1-3\cos^2\theta) \\ & + (\frac{1}{2}\sin 2\theta_1\cos\phi_1)\sin 2\theta\cos\phi \\ & + (\frac{1}{2}\sin^2\theta_1\cos 2\phi_1)\sin^2\theta\cos 2\phi \\ & + (a\sin\theta_1\cos\phi_1)\sin\theta\cos\phi + (a\cos\theta_1)\cos\theta \\ & + (\frac{1}{2}\sin^2\theta_1\sin 2\phi_1)\sin^2\theta\sin 2\phi \\ & + (\frac{1}{2}\sin 2\theta_1\sin\phi_1)\sin 2\theta\sin\phi \\ & + (a\sin\theta_1\sin\phi_1)\sin\theta\sin\phi. \end{aligned} \tag{5}$$

From Eq. (3) and Eq. (5) one can express A_0 to A_7 in terms of θ_1, ϕ_1 and a as follows:

$$\begin{aligned} & A_0 = \langle\sin^2\theta_1\rangle && A_1 = \frac{1}{2}\langle\sin 2\theta_1\cos\phi_1\rangle \\ & A_2 = \langle\sin^2\theta_1\cos 2\phi_1\rangle && A_3 = a\langle\sin\theta_1\cos\phi_1\rangle \\ & A_4 = a\langle\cos\theta_1\rangle && A_5 = \frac{1}{2}\langle\sin^2\theta_1\sin 2\phi_1\rangle \\ & A_6 = \frac{1}{2}\langle\sin 2\theta_1\sin\phi_1\rangle && A_7 = a\langle\sin\theta_1\sin\phi_1\rangle. \end{aligned} \tag{6}$$

Equation (6) is a generalization of an earlier work [23] which considered the special case of $\phi_1 = 0$ and $a = 0$. The $\langle\cdot\cdot\rangle$ in Eq. (6) is a reminder that the measured values of A_n are averaged over the event sample. A comparison of Eq. (1) and Eq. (3) gives

$$\lambda = \frac{2-3A_0}{2+A_0};\quad \mu = \frac{2A_1}{2+A_0};\quad \nu = \frac{2A_2}{2+A_0}. \tag{7}$$

Equation (7) shows that the Lam–Tung relation, $1-\lambda = 2\nu$, becomes $A_0 = A_2$.

From Eq. (6) and Eq. (7) several remarks regarding the nature of the γ^*/Z decay angular distribution can be made:

a) In the "naive" Drell–Yan the $q-\bar{q}$ axis coincides with the $\hat{z}$ axis of the Collins–Soper frame, hence $\theta_1 = 0$ and $\lambda = 1$. The deviation of λ from the "naive" Drell–Yan prediction of unity is due to non-zero θ_1, which reflects the mis-alignment between the $q-\bar{q}$ axis and the $\hat{z}$ axis of the Collins–Soper frame [23,22]. It is important to note that λ (or A_0) does not depend on ϕ_1, which is a measure of the non-coplanarity between the $q-\bar{q}$ axis and the hadron plane. In contrast, μ and ν (or A_1 and A_2) depend on both θ_1 and ϕ_1.
b) Eq. (6) also shows that the Lam–Tung relation, $A_0 = A_2$, is valid when $\phi_1 = 0$, i.e., for the co-planar case. Violation of the Lam–Tung relation is caused by the presence of the $\cos 2\phi_1$ term in A_2 (or ν), and not due to the A_0 (or λ) term. Moreover, the non-coplanarity factor, $\cos 2\phi_1$, ensures that $A_0 \geq A_2$, or $1-\lambda-2\nu \geq 0$.

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