Measurement of the Angular Coefficients of Drell-Yan e^+e^- pairs in the Z Mass Region from $p\bar{p}$ Collisions at $\sqrt{s}$=1.96 TeV

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Abstract. We report on the first measurement of the angular distributions of final state electrons in $p\bar{p} \rightarrow \gamma^*/Z \rightarrow e^+e^- + X$ events produced in the Z boson mass region at $\sqrt{s} = 1.96$ TeV. The data sample collected by the CDF II detector for this result corresponds to 2.1 fb^{-1} of integrated luminosity. The angular distributions are studied as a function of the transverse momentum of the electron-positron pair and show good agreement with the Lam-Tung relation, consistent with a spin-1 description of the gluon, and demonstrate that at high values of the transverse momentum, Z bosons are produced via quark anti-quark annihilation and quark-gluon Compton processes.

Keywords: Z bosons, gluon spin, Lam Tung
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INTRODUCTION

We report on the CDF study[1] of the angular distributions of final state electrons in $p\bar{p} \rightarrow \gamma^*/Z \rightarrow e^+e^- + X$ Drell-Yan events ($66 < M_{e^+e^-} < 116$ GeV/c^2) to probe Z-boson production mechanisms. In general the γ^*/Z is produced with sizeable transverse momentum($p_T = p_T(\gamma^*/Z) = p_T(e^+e^-)$). In Quantum Chromodynamics (QCD) at leading order (LO) this occurs either through the annihilation process with a gluon (G) in the final state ($q\bar{q} \rightarrow \gamma^*/Z\ G$), or via the Compton process with a quark in the final state ($qG \rightarrow \gamma^*/Z\ q$) (as shown in Fig. 1)

The general expression for the angular distribution is described by the polar (θ) and azimuthal (ϕ) angles of the decay-electron in the Collins-Soper (CS) frame. When integrated over $\cos\theta$ or ϕ, respectively, the decay-electron angular distribution is described by:

$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta; \tag{1}$$

$$\frac{d\sigma}{d\phi} \propto 1 + \beta_3\cos\phi + \beta_2\cos 2\phi + \beta_7\sin\phi + \beta_5\sin 2\phi \tag{2}$$

$$(\beta_3 = \frac{3\pi A_3}{16},\ \ \beta_2 = \frac{A_2}{4}, \beta_7 = \frac{3\pi A_7}{16},\ \ \beta_5 = \frac{A_5}{4}).$$

A_0 and A_4 can be extracted from Eq. 2, and A_2 and A_3 can be extracted from Eq. 2, while A_5 and A_7 are expected to be zero.

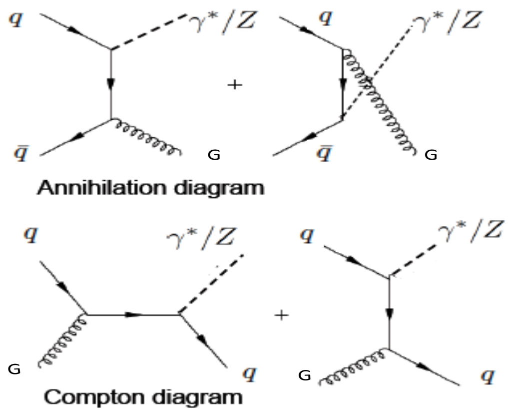

FIGURE 1. Annihilation and Compton diagrams for the production of Drell-Yan events with P_T

Perturbative QCD (pQCD) makes definite predictions for the angular coefficients $A_{0,2,3,4}$ (A_0 and A_2 are the same for γ^* or Z exchange, and A_3 and A_4 originate from the γ^*/Z interference). For the $q\ \bar{q} \ \to \gamma^*/Z\ G$ annihilation process pQCD at LO predicts that the angular coefficients A_0 and A_2 are equal and can be analytically described by $A_0^{q\bar{q}} = A_2^{q\bar{q}} = \frac{p_T^2}{M_{e^+e^-}^2 + p_T^2}$ (Eq. 3).

At higher order, there are small deviations from the above expression (Eq. 3) which depend on PDFs and dilepton rapidity(y).

For the $qG \to \gamma^*/Z\ q$ Compton process, A_0 and A_2 depend on parton distribution functions (PDFs) and y. However, in pQCD at LO, when averaged over y, A_0 and A_2 are approximately described [3] by $A_0^{qG} = A_2^{qG} \approx \frac{5p_T^2}{M_{e^+e^-}^2 + 5p_T^2}$ (Eq. 4).

At LO, the Lam-Tung [2] relation ($A_2 = A_0$) [2] is valid for both $q\bar{q}$ and qG processes. Fixed-order pQCD calculations at next-to-leading order (NLO), as well as QCD resummation calculations to all orders, indicate that violations of the Lam-Tung relation are small. The Lam-Tung relation is only valid for vector (spin-1) gluons. It is badly broken for scalar (spin-0) gluons [4]. Therefore, confirmation of the Lam-Tung relation is a fundamental test of the vector gluon nature of QCD and is equivalent to a measurement of the spin of the gluon. A previous determination of the gluon spin was made from a study of 3-jet events ($e^+e^- \to q\bar{q}\ G$) in e^+e^- annihilation[5].

To date, the Lam-Tung relation has been tested only at fixed-target experiments using samples of low mass Drell-Yan dilepton pairs at relatively low transverse momentum. In this region, non-perturbative higher-twist effects can be significant. Some experiments report large violations and one experiment is consistent with the Lam-Tung relation.

CDF has performed the first measurement of the angular coefficients in the production of Drell-Yan events and the first test of the Lam-Tung relation at large dilepton mass and high transverse momentum, where non-perturbative higher-twist effects are expected to be negligible.

Fixed order pQCD calculations and Monte Carlo (MC) simulations at next-to-leading order (NLO) (e.g. DYRAD and MADGRAPH and PYTHIA in Z+1jet mode indicate that there is a significant contribution of the Compton process to the production of

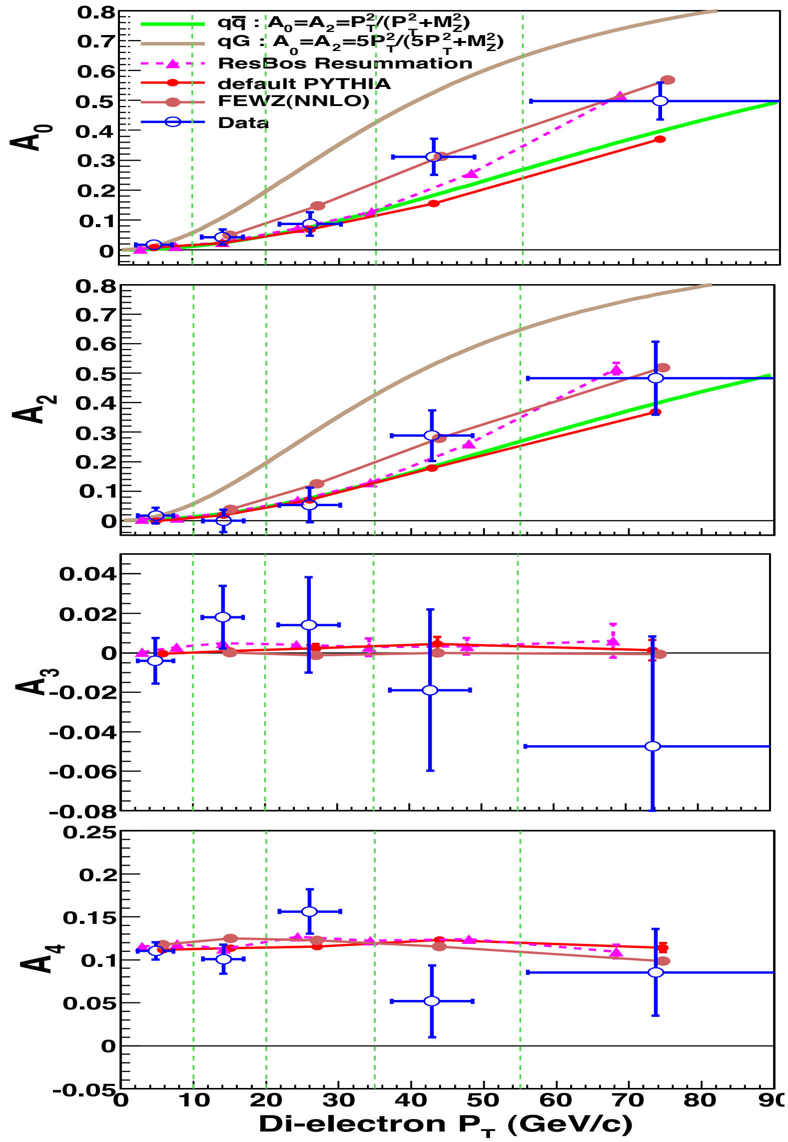

FIGURE 2. A0, A2, A3 and A4 versus P_T

γ^*/Z bosons with large transverse momentum at the Tevatron. Therefore, as shown in Fig. 2 , these calculations yield values of A_0 and A_2 which are larger than the pure annihilation process prediction (Eq. 3). Similar results are predicted by POWHEG, a NLO MC with additional parton showering, and FEWZ which is a next-to-next-to-leading order (NNLO) QCD calculation. In contrast, the default, LO version of PYTHIA, and VBP (an MC generator based on QCD resummation) predict values of A_0 and A_2 which are close to Eq. 3 (this is only correct if the $q\bar{q}$ process is dominant). The RESBOS MC generator, which is also based on QCD resummation, predicts values of A_0 and A_2 close to Eq. 3 at low p_T, and larger values (close to the predictions of fixed order pQCD) at high p_T, as shown in Figures 1 and 2. Therefore, measurements of A_0 and A_2 as a function of p_T elucidate the relative contributions between the annihilation and Compton processes.

Here, we report on the CDF measurement of the angular coefficients A_0, A_2, A_3 and A_4, for $p\bar{p} \to \gamma^*/Z \to e^+e^- + X$ events in the Z boson mass region ($66 < M_{ee} <$ 116 GeV/c^2) produced at $\sqrt{s} = 1.96$ TeV. We also report on the first test of the Lam-Tung relation at high transverse momentum.

The sample used consist of about 140,00 e^+e^- events (for an integrated luminosity of 2.1 fb^{-1}) collected by the CDF II Detector at Fermilab during 2004-2007. The analysis is performed in five bins of transverse momentum. For each transverse momentum the angular coefficients are extracted from the angular distributions in $\cos\theta$ and ϕ. The results for A_0 and A_2 as function of P_T are shown in Fig. 2, and Table 1 respectively, where statistical and systematic uncertainties have been added in quadrature.

The data are in good agreement with the Lam-Tung relation $A_0 - A_2 = 0$, which is expected in QCD with vector gluons. The values of $A_0 - A_2$ for the five p_T bins are 0.00 ± 0.03, 0.04 ± 0.05, 0.03 ± 0.07, 0.02 ± 0.11, and 0.01 ± 0.14 (statistical and systematic uncertainties combined), which average to $\langle A_0 - A_2 \rangle$=$0.02 \pm 0.02$. At low p_T the measured values of A_0 and A_2 are well described by the $q\bar{q} \to \gamma^*/Z\,G$ annihilation function (Eq. 3). At high p_T the larger values show that both the annihilation and Compton processes contribute to the cross section [6]. Our results are in agreement with fixed-order perturbation theory calculations including DYRAD, MADGRAPH, PYTHIA Z+1 jet, POWHEG, and FEWZ (all of these give similar predictions). The data do not favor the predictions of VBP or the default PYTHIA (which does not include all of the Compton diagrams). We find that the values of A_3 and A_4 are in agreement with the predictions of all models. Additional details are given in Ref.[1]

TABLE 1. The measured angular coefficients (statistical and systematic uncertainties are added in quadrature).

P_T bin (GeV/c)	A_0 ($\times 10^{-1}$)	A_2 ($\times 10^{-1}$)	A_3 ($\times 10^{-1}$)	A_4 ($\times 10^{-1}$)
0–10	0.17 ± 0.16	0.16 ± 0.27	-0.04 ± 0.12	1.10 ± 0.10
10–20	0.42 ± 0.26	-0.01 ± 0.38	0.18 ± 0.16	1.01 ± 0.17
20–35	0.86 ± 0.40	0.52 ± 0.59	0.14 ± 0.24	1.56 ± 0.26
35–55	3.11 ± 0.60	2.88 ± 0.86	-0.19 ± 0.41	0.52 ± 0.42
> 55	4.97 ± 0.62	4.83 ± 1.24	-0.47 ± 0.56	0.85 ± 0.51

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6. For the four highest p_T bins the χ^2 values for A_0 are 11.7, 9.4, 5.6 and 3.7 for default PYTHIA, VBP, RESBOS, and FEWZ, respectively.