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First 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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We report on the first measurement of the angular distributions of final state electrons in $p\bar{p} \to \gamma^*/Z \to e^+e^- + X$ 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.

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We report on a study of the angular distributions of final state electrons in $p\bar{p} \to \gamma^*/Z \to e^+e^- + X$ Drell-

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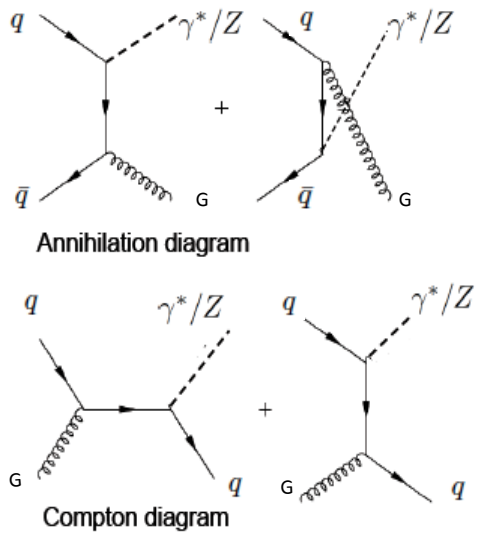

FIG. 1: Leading order annihilation ($q\bar{q} \rightarrow \gamma^*/Z\ G$) and Compton ($qG \rightarrow \gamma^*/Z\ q$) diagrams for the production of γ^*/Z bosons with transverse momentum.

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[1] ($p_T = p_T(\gamma^*/Z) = p_T(e^+e^-)$). 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 [2] is described by the polar (θ) and azimuthal (ϕ) angles of the decay-electron in the Collins-Soper (CS) frame [3]. When integrated over $\cos\theta$ or ϕ, respectively, the decay-electron angular distribution is described by:

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

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

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

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 [2].

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 $q\ \bar{q} \rightarrow \gamma^*/Z\ G$ annihilation process pQCD at LO predicts that the angular coefficients A_0 and A_2 are equal [4–7] and can be analytically described by $A_0^{q\bar{q}} = A_2^{q\bar{q}} = \frac{p_T^2}{M^2_{e^+e^-}+p_T^2}$ (Eq. 3). At higher order, there are small deviations from the above expression (Eq. 3) which depend on PDFs and dilepton rapidity [1] (y).

For the $qG \rightarrow \gamma^*/Z\ q$ 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 [8, 9] by $A_0^{qG} = A_2^{qG} \approx \frac{5p_T^2}{M^2_{e^+e^-}+5p_T^2}$ (Eq. 4).

At LO, the Lam-Tung relation ($A_2 = A_0$) [10] is valid for both $q\bar{q}$ and qG processes [5]. Fixed-order pQCD calculations at next-to-leading order (NLO) [2], as well as QCD resummation calculations to all orders [6], 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 [11]. 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 ($e^+e^- \rightarrow q\bar{q}\ G$) in e^+e^- annihilation[12].

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 [13, 14]. Some experiments report large violations [8, 14–16], and one experiment [17] is consistent with the Lam-Tung relation. Here we report on 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 [2] and Monte Carlo (MC) simulations at next-to-leading order (NLO) (e.g. DYRAD [18] and MADGRAPH [19], and PYTHIA in Z+1jet mode [20]) indicate that there is a significant contribution of the Compton process to the production of γ^*/Z bosons with large transverse momentum at the Tevatron. Therefore, as shown in Fig. 3, 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 [21], a NLO MC with additional parton showering, and FEWZ [22] which is a next-to-next-to-leading order (NNLO) QCD calculation.

In contrast, the default, LO version of PYTHIA [23], and VBP [24] (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 [25] 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 Fig. 3. Therefore, measurements of A_0 and A_2 as a function of p_T elucidate the relative contributions between the annihilation and Compton processes.

In this Letter, we report on the first measurement of the angular coefficients A_0, A_2, A_3 and A_4, for $p\bar{p} \rightarrow \gamma^*/Z \rightarrow e^+e^- + X$ 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 corresponds to an integrated luminosity of 2.1 fb^{-1} collected by the CDF II Detector at Fermilab [26] during 2004-2007. Charged particle directions and momenta are measured by an open-cell drift chamber (COT), a silicon vertex detector (SVX), and an intermediate silicon layer in a 1.4 T magnetic field. Projective-tower-geometry calorimeters and outer muon detectors enclose the magnetic tracking volume. The coverage of COT tracking in pseudorapidity is $|\eta| < 1.2$ [1]. Reconstructed tracks are used to determine the $p\bar{p}$ collision point along the beam line (z_{vertex}), which is required to be within $z = \pm 60$ cm of the center of the detector. The energies and directions [1] of electrons, photons, and jets are measured by two separate calorimeters: central ($|\eta| < 1.1$) and plug ($1.1 < |\eta| < 3.6$). Each calorimeter has an electromagnetic compartment with a shower maximum detector followed by a hadronic compartment. Three topologies of e^+e^- pairs are considered: two central electrons (CC), one central and one plug electron (CP), and two plug electrons (PP). Events with at least one electron with high E_T are selected online. Off-line refined selection requires the electron to have $E_T > 25$ GeV for CC and PP events, and $E_T > 20$ GeV for CP events. in the central ($|\eta_e| < 1.1$) and plug ($1.2 < |\eta_e| < 2.8$) fiducial regions of the calorimeters. To minimize background, the second electron candidate is required to have $E_T > 15$ GeV for CC, $E_T > 25$ GeV for PP, and $E_T > 20$ GeV for CP events. The selection criteria listed above are the same as in a related previous publication [27] of the Z rapidity distribution, but are augmented in this analysis with the additional requirement that both electrons have an associated track in the SVX. The data sample consists of about 140 000 events. The fractional contribution of the total QCD background (2-jet events misidentified as a Drell-Yan pairs) to the number of selected events is 0.3%. This is determined by studying the distribution of transverse energy in a cone surrounding the center of the electromagnetic cluster in the calorimeter. The total background from electroweak (WW, WZ, W+jets, and $Z \to \tau^+\tau^-$) and $t\bar{t}$ processes is estimated from simulation to be 0.2%. Figure 2 shows the di-electron P_T spectrum for data, the default PYTHIAprediction, and the backgrounds. There is good agreement he default PYTHIAprediction.

The effect of the acceptance on the angular distributions is modeled using the default PYTHIAMC generator [23] combined with a GEANT [28] simulation of the CDF detector. The default PYTHIAgenerator includes a LO QCD interaction ($q\bar{q} \to \gamma^*/Z$), initial state QCD radiation, parton shower fragmentation, the $\gamma^*/Z \to e^+e^-$ decay, and photon radiation from the final state. The version of default PYTHIAused at CDF has additional ad-hoc tuning [23] in order to accurately represent the γ^*/Z boson transverse momentum distribution measured in data. Further tuning was introduced in order to ensure that the MC simulation correctly described the rapidity, as well as the correlations between rapidity and transverse momentum that are observed in the data. To reconstruct the simulated events in the same way as data, the calorimeter energy scale, resolutions, and selection efficiencies used in the detector simulation are tuned using data. Details are given in reference [27].

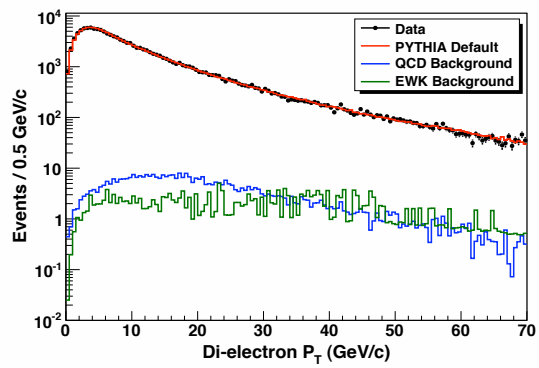

FIG. 2: Di-electron P_T spectrum of data, default PYTHIAprediction, and backgrounds (QCD and electroweak process). The mass range corresponds to $66 < M_{ee} < 116$ GeV/c^2.

The analysis is performed in five bins of transverse momentum as shown in Table I. For each transverse momentum range, data and MC simulated events are binned in $\cos\theta$. The MC events are re-weighted to generate the expected angular distributions for a range of values of A_0 and A_4. A maximum likelihood comparison of the data and MC distributions in $\cos\theta$ is used to extract the best values of the angular coefficients A_0 and A_4 that describe the data. Similarly, for each transverse momentum range, data and MC simulated events are also binned in ϕ. A maximum likelihood comparison of the data and MC distributions in ϕ is used to extract the best values of the angular coefficients A_2 and A_3 that describe the data. The results are shown in Table I and Fig. 3, where statistical and systematic uncertainties have been added in quadrature. (The correlation between extracted values of A_0 A_2, A_3 and A_4 is negligible). A study of all of the systematic uncertainties discussed in reference [27] (originating from backgrounds, electron identification efficiency, SVX tracking efficiency, boson P_T and rapidity modeling, and modeling of detector material) shows that the uncertainties on the extracted angular coefficients are dominated by the statistical uncertainties.

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 uncertain-

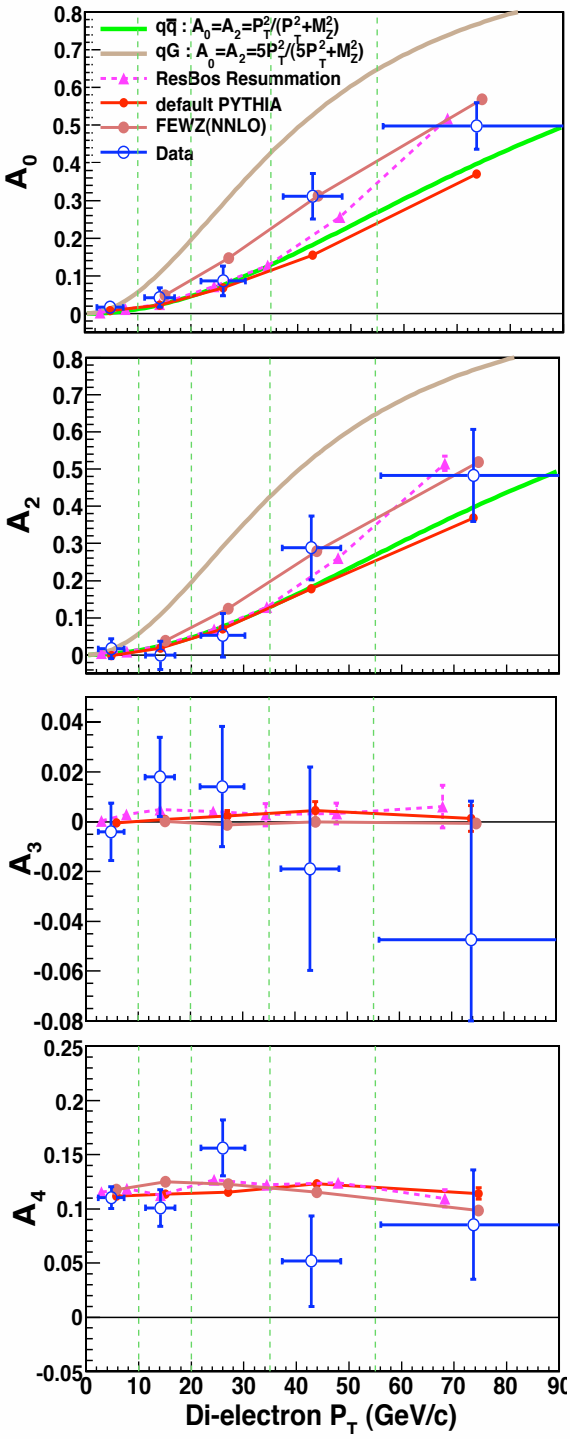

FIG. 3: Comparison of the measured values of A_0, A_2, A_3 and A_4 (for $66 < M_{ee} < 116$ GeV/c^2), shown with statistical and systematic uncertainties combined, to theory predictions. The data points are plotted at the mean p_T of the events for each bin. The horizontal uncertainty is the standard deviation of the transverse momenta of events in each bin. Agreement [29] is found with the predictions of FEWZ, and also with DYRAD, MADGRAPH, POWHEG, and PYTHIA Z +1-jet MC (not shown). The data do not favor [29] the predictions of default PYTHIA, and VBP. Also shown are the pure $q\bar{q} \to \gamma^*/Z\ G$ annihilation diagram prediction (Eq. 3), and the $qG \to \gamma^*/Z\ q$ Compton process prediction as approximated by Eq. 4.

ties 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 [29]. Our results are in agreement[29] with fixed-order perturbation theory calculations including DYRAD [18], MADGRAPH [19], PYTHIA Z+1 jet [20], POWHEG [21], and FEWZ [22] (all of these give similar predictions). We find that the values of A_3 and A_4 are in agreement with the predictions of all models (A_4 is calculated with $\sin^2\theta_W = 0.232$).

In summary, we present the first measurement of the angular coefficients in the production of γ^*/Z bosons at large transverse momenta, and the first test of the Lam-Tung relation at high transverse momentum. We find good agreement with the predictions of QCD fixed-order perturbation theory, and with the Lam-Tung relation $A_0 = A_2$. The measurements presented here are statistically limited. An analysis with larger samples in both muon and electron channels is currently under way. A comparison of these results with future measurements at the LHC would provide additional tests of production mechanisms since the contribution of the Compton process ($qG \to \gamma^*/Z\ q$) at the LHC is expected to be larger.

TABLE I: The measured angular coefficients (statistical and systematic uncertainties are added in quadrature). For A_0 and A_2, the systematic uncertainty is $\sim 56\%$ of the statistical uncertainty at low P_T ($P_T < 35$ GeV) and $\sim 17\%$ at high P_T. The systematic uncertainties in A_3 and A_4 are less than 10% of the statistical uncertainty for all P_T bins. The mean p_T of the events in the five bins are 4.8, 14.1, 26.0, 42.9 and 73.7 GeV/c, respectively.

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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de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

[1] In the CDF detector frame, the positive z axis is define by the proton beam direction. The pseudorapidity is $\eta = -\ln\tan(\theta/2)$. For an e^+e^- pair $P_T = P\sin\theta$, $E_T = E\sin\theta$, where θ is the polar angle between the particle direction and the z axis. For an e^+e^- pair, $y = \frac{1}{2}\ln\frac{E+P_z}{E-P_z}$, where P and P_z are the magnitude and z-component of the momentum, and E and $M_{e^+e^-}$ are the energy and mass.

[2] E. Mirkes and J. Ohnemus, Phys. Rev. D **50**, 5692 (1994); Phys. Rev. D **51**, 4891 (1995).

[3] J. C. Collins and D. E. Soper, Phys. Rev. D **16**, 2219 (1977). The CS frame is the center of mass of the γ^*/Z, where the z axis is defined as the bisector of the p and $\bar{p}$ beams. The polar angle is defined as the angle of the positive lepton with respect to the proton direction.

[4] J. C. Collins, Phys. Rev. Lett. **42**, 291 (1979).

[5] D. Boer and W. Vogelsang, Phys.Rev. D **74**, 014004 (2006).

[6] Edmond L. Berger, Jian-Wei Qiu, and Ricardo A. Rodriguez-Pedraza, Phys.Lett. B **656**, 74 (2007).

[7] A. Bodek, Eur. Phys. J. C **67**, 321 (2010).

[8] S. Falciano *et al.* (NA10 Collaboration) Z. Phys. C **31**, 513 (1986).

[9] J. Lindfors, Physica Scripta **20**, 19 (1979).

[10] C. S. Lam and W. K. Tung, Phys. Lett. B **80**, 228 (1979).

[11] $A0 - A2 \approx 2$ in the Gottfried-Jackson frame, see N. Arteaga-Romero, N. Niclaidis, and J. Silva, Phys. Rev. Lett. **52**, 172 (1984).

[12] R. Brandelik *et al.* (TASSO Collaboration) Phys. Lett. B **97**, 453 (1980) (their data was consistent with spin 1 gluons, but 3.8 standard deviations from the prediction for spin 0 gluons).

[13] D. Boer, Phys. Rev. D **60**, 014012 (1999).

[14] J. S. Conway *et al.* (E615 Collaboration), Phys. Rev. D **39**, 92 (1989).

[15] M. Guanziroli *et al.* (NA10 Collaboration) Z. Phys. C **37**, 545 (1988).

[16] J. G. Heinrich *et al.*(E615 Collaboration), Phys. Rev. D **44**, 1909 (1991).

[17] L. Y. Zhu *et al.* (FNAL-E866/NuSea Collaboration), Phys. Rev. Lett. **99**, 082301 (2007).

[18] W.T. Giele, E.W.N. Glover, and D. A. Kosower, Nucl. Phys. **B403**, 633 (1993).

[19] F. Maltoni and T. Stelzer, J. High Energy Phys. **302**, 27(2003). We use CTEQ6.6 PDFs for MADGRAPH.

[20] T. Sjöstrand *et al.*, J. High Energy Phys. **05**, 26 (2006) We use PYTHIA6.4 $Z + 1$ jet matrix element event generator (MSEL = 13) without any parton showering (MSTP(61) = 0 and MSTJ(41) = 0) and CTEQ5L PDFs.

[21] We have used the most recent version of POWHEG. See Simone Alioli , Paolo Nason, Carlo Oleari, and Emanuele Re, arXiv:1009.5594v1 (2010), with CTEQ6.6 PDFs.

[22] K. Melnikov and F. Petriello, Phys. Rev. Lett. **96** 231803 (2006); Phys. Rev. D **74** 114017 (2006), with MSTW2008 NNLO PDFs.

[23] Default PYTHIA: T. Sjøstrand *et al.*, J. High Energy Phys. **05**, 26 (2006) We use the default (MSEL=11) LO matrix element (Z + 0 jet) with CTEQ5L PDFs. The parton showering produces the boson p_T. The CDF EWK/TOP standard W/Z p_T tuning parameters are: MSTP(91)=1, PARP(91)=2.10, PARP(93)=15 for the low p_T Gaussian smearing, with PART(62)=1.25 and PARP(62)=0.2 for the p_T evolution in 7-25 GeV region. The underlying event is included as Tune A. The QED parton showering uses the same machinery as QCD parton showering aside from coupling differences.

[24] R. K. Ellis and S. Veseli, Nucl. Phys. B **511**, 649 (1998); We use CTEQ6.6 PDFs with VBP.

[25] F. Landry, R. Brock, P.M. Nadolsky, and C.-P. Yuan, Phys. Rev. D **67** 073016 (2003). We use CTEQ6.6 PDFs with RESBOS.

[26] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).

[27] T. Aaltonen *et al.* (CDF Collaboration) Phys, Lett. **B692**, 232 (2010); Jiyeon Han, Ph.D. Thesis, University of Rochester, FERMILAB-THESIS-2008-65.

[28] GEANT: CERN Program Library Long Writeup W5013.

[29] 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 PYTHIA($q\bar{q}$ only), VBP, RESBOS, and FEWZ($q\bar{q}$+qG), respectively.