Study of color dynamics in photoproduction at HERA

Juan Terrón (on behalf of the ZEUS Collaboration)

Universidad Autónoma de Madrid, Spain

Abstract. Measurements of normalised differential cross sections for the photoproduction of three-jet events are presented as functions of jet angular variables to highlight the contributions from the different color configurations. Fixed-order calculations were compared to the results and used to study the underlying gauge-group symmetry.

Keywords: QCD
PACS: 12.38.Qk

INTRODUCTION

The gauge theory of the strong interactions, Quantum chromodynamics (QCD), is based on the non-abelian group SU(3). In general, the physical manifestation of the underlying group structure is encapsulated in the color factors C_F, C_A and T_F. In strong interactions, they represent the relative strengths of the processes $q \to qg$, $g \to gg$ and $g \to q\bar{q}$, respectively. Investigations of the color factors have been carried out at LEP using angular correlations in four-jet events from Z° hadronic decays.

At HERA, the effects of the different color configurations arising from the underlying gauge-group structure should manifest themselves in three-jet events in photoproduction. Photoproduction at HERA is studied by means of ep scattering at low four-momentum transfers ($Q^2 \approx 0$, where Q^2 is the virtuality of the exchanged photon). In photon-proton reactions, two types of QCD processes contribute to jet production at leading order (LO): either the photon interacts directly with a parton in the proton (the direct process) or the photon acts as a source of partons which scatter off those in the proton (the resolved process). Direct-photon events provide a clean way to study the effects of the different color configurations. An illustrative diagram for each color configuration is shown in Fig. 1: (A) double-gluon bremsstrahlung from a quark line (C_F^2), (B) the splitting of a virtual gluon into a pair of final-state gluons ($C_F C_A$), (C) the production of a $q\bar{q}$ pair through the exchange of a virtual gluon emitted by an incoming quark ($C_F T_F$) and (D) the production of a $q\bar{q}$ pair through the exchange of a virtual gluon arising from the splitting of an incoming gluon ($T_F C_A$). The variables that have been devised to highlight the contributions from the different color configurations are based on the angular correlations between the final-state jets and the beam and make use of the three jets with highest transverse energy ($E_T^{\rm jet}$) in an event:

- θ_H, the angle between the plane determined by the highest-$E_T^{\rm jet}$ jet and the beam and the plane determined by the two lowest-$E_T^{\rm jet}$ jets [1];

- α_{23}, which is inspired by the variable $\alpha_{34}^{e^+e^-}$ [2] for $e^+e^- \to 4$ jets, is defined as the angle between the two lowest-$E_T^{\rm jet}$ jets;
- $\beta_{\rm KSW}$, which is inspired by the Körner-Schierholz-Willrodt angle $\Phi_{\rm KSW}^{e^+e^-}$ [3] for $e^+e^- \to 4$ jets, is defined as $\cos(\beta_{\rm KSW}) = \cos\left[\frac{1}{2}\left(\angle[(\vec{p}_1 \times \vec{p}_3),(\vec{p}_2 \times \vec{p}_B)] + \angle[(\vec{p}_1 \times \vec{p}_B),(\vec{p}_2 \times \vec{p}_3)]\right)\right]$, where $\vec{p}_i$, $i = 1,...,3$ is the momentum of jet i and $\vec{p}_B$ is a unit vector in the direction of the beam; the jets are ordered according to decreasing transverse energy.

In this contribution, measurements of angular distributions [4] in photoproduced three-jet events are presented and compared to fixed-order $O(\alpha\alpha_s^2)$ perturbative calculations [5].

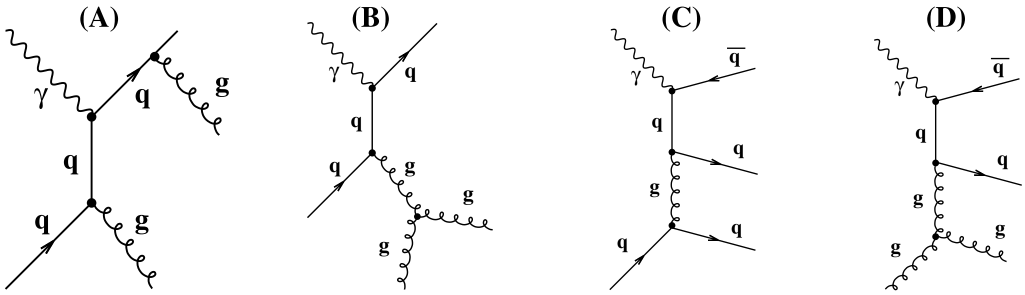

FIGURE 1. Examples of diagrams for the photoproduction of three-jet events through direct-photon processes in each color configuration: (A) C_F^2; (B) $C_F C_A$; (C) $C_F T_F$; (D) $T_F C_A$.

DATA SELECTION AND JET SEARCH

The data sample was collected with the ZEUS detector at HERA and corresponds to an integrated luminosity of 45.0 ± 0.7 (65.5 ± 1.5) pb^{-1} for e^+p collisions taken during 1995-97 (1999-2000) and 16.7 ± 0.3 pb^{-1} for e^-p collisions taken during 1998-99. During 1995-97 (1998-2000), HERA operated with protons of energy $E_p = 820$ GeV (920 GeV) and positrons or electrons of energy $E_e = 27.5$ GeV, yielding a centre-of-mass energy of $\sqrt{s} = 300$ GeV (318 GeV).

Events from collisions between protons and quasi-real photons were selected offline using similar criteria as reported in a previous publication [6].

The k_T cluster algorithm [7] was used in the longitudinally invariant inclusive mode [8] to reconstruct jets in the hadronic final state. The axis of the jet was defined according to the Snowmass convention, where $\eta^{\rm jet}$ ($\varphi^{\rm jet}$) is the transverse energy-weighted mean pseudorapidity (azimuth) of all the particles belonging to that jet. Events with at least three jets of $E_T^{\rm jet} > 14$ GeV and $-1 < \eta^{\rm jet} < 2.5$ were retained. Direct-photon events were selected by requiring $x_\gamma^{\rm obs} > 0.7$, where $x_\gamma^{\rm obs}$, the fraction of the photon momentum participating in the production of the three jets with highest $E_T^{\rm jet}$, is defined as $x_\gamma^{\rm obs} = \sum_{i=1}^{3}(E_T^{\rm jet,i} e^{-\eta^{\rm jet,i}})/(2yE_e)$, where y is the inelasticity variable. The remaining contribution from resolved-photon events was estimated by Monte Carlo techniques to be $\approx 34\%$. It was checked that the angular distributions of the events from resolved processes with $x_\gamma^{\rm obs} > 0.7$ were similar to those from direct processes and, therefore, no subtraction was performed when comparing to the fixed-order calculations described in the next Section. The selected sample consisted of events from ep interactions with $Q^2 < 1$ GeV^2 and a median of $Q^2 \approx 10^{-3}$ GeV^2. The event sample was restricted to the kinematic range $0.2 < y < 0.85$. There remained 2233 events after all selection criteria were applied.

FIXED-ORDER CALCULATIONS

The calculations of direct-photon processes used in this analysis are based on the program by Klasen, Kleinwort and Kramer [5]. The MRST99 [9] parameterisations of the parton distribution functions (PDFs) of the proton were used as defaults for the comparisons with the measured cross sections. These calculations are $\mathrm{O}(\alpha\alpha_s^2)$ and represent the lowest-order contribution to three-jet photoproduction. The LO calculation of three-jet cross sections for direct-photon processes can be expressed in terms of the color factors C_A, C_F and T_F as follows [10]: $\sigma_{ep\to 3\text{jets}} = C_F^2 \cdot \sigma_A + C_F C_A \cdot \sigma_B + C_F T_F \cdot \sigma_C + T_F C_A \cdot \sigma_D$, where $\sigma_A, \ldots, \sigma_D$ are the cross sections for the different contributions (see Fig. 1). The component which contains the contribution from the triple-gluon vertex in quark-induced processes, σ_B, has a very different shape than the other components for the three angular variables considered here (not shown here, see [4]). The other components are best separated by the distribution of $\cos\alpha_{23}$. Thus, these variables are sensitive to the different color configurations. The predicted relative contributions in QCD (i.e. SU(3)) are A: 13%, B: 10%, C: 45% and D: 32%. The full prediction for a given gauge group was obtained by adding up σ_i ($i = A, \ldots, D$) weighted with the corresponding color factors.

RESULTS

Using the selected data sample, normalised three-jet differential cross sections were measured for $Q^2 < 1$ GeV^2, $0.2 < y < 0.85$ and $x_\gamma^{\text{obs}} > 0.7$. The cross sections were determined for jets of $E_T^{\text{jet}} > 14$ GeV and $-1 < \eta^{\text{jet}} < 2.5$. The normalised cross-sections $(1/\sigma)(d\sigma/d\theta_H)$, $(1/\sigma)(d\sigma/d\cos\alpha_{23})$ and $(1/\sigma)(d\sigma/d\cos\beta_{\text{KSW}})$ are presented in Fig. 2. The experimental systematic uncertainties were added in quadrature to the statistical uncertainty (thin error bars) of the data and are shown as thick error bars in the figure. The calculations based on SU(3), shown in Fig. 2, give a good description of the data for $\theta_H > 35°$, $\cos\alpha_{23} > -0.6$ and $-0.8 < \cos\beta_{\text{KSW}} < 0.6$.

To illustrate the sensitivity of the measurements to the color factors, calculations based on different symmetry groups are also compared to the data in Fig. 2. In this figure, the color components have been combined in such a way as to reproduce the color structure of a theory based on the non-abelian group SU(N) in the limit of large N ($C_F = (N^2-1)/2N, T_F = 1/2, C_A = N$), the abelian group U(1)^3 ($C_F = 1, T_F = 3, C_A = 0$) and, as an extreme choice, a calculation with $C_F = 0$. The shapes of the distributions predicted by U(1)^3 are very similar to those by SU(3) due to the smallness of the component σ_B and the difficulty to distinguish the component σ_D. The data clearly disfavour a theory in which $T_F/C_F \approx 0$ such as predicted by SU(N) in the limit of large N or $C_F = 0$.

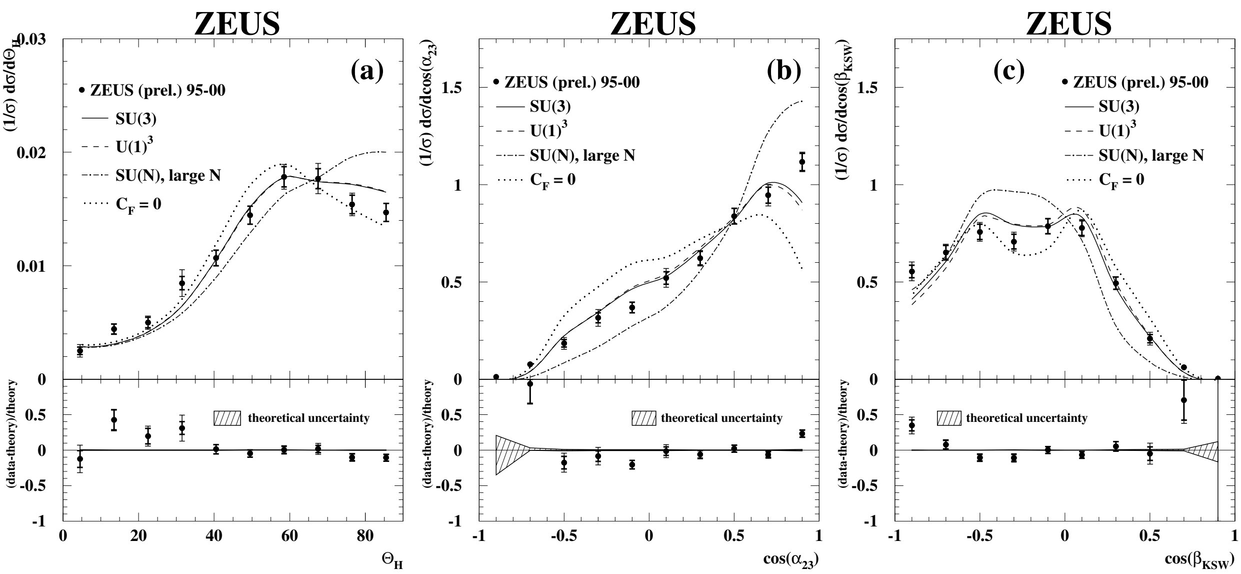

FIGURE 2. (a) Normalised differential *ep* cross sections for three-jet photoproduction as functions of (a) θ_H, (b) $\cos\alpha_{23}$ and (c) $\cos\beta_{\rm KSW}$. For comparison, the $O(\alpha\alpha_s^2)$ calculations for direct-photon processes based on SU(3) (solid lines), $U(1)^3$ (dashed lines), SU(N) in the limit of large N (dot-dashed lines) and $C_F = 0$ (dotted lines) are included. The lower part of the figures displays the fractional difference between the measured normalised cross section and the calculation based on SU(3).

SUMMARY

Measurements of angular correlations in three-jet photoproduction have been made in *ep* collisions using 127 pb^{-1} of data collected with the ZEUS detector at HERA. Normalised differential cross sections were measured as functions of θ_H, $\cos\alpha_{23}$ and $\cos\beta_{\rm KSW}$. Fixed-order ($O(\alpha\alpha_s^2)$) calculations for three-jet photoproduction through direct-photon processes separated according to the color configurations were used to study the sensitivity of the angular distributions to the underlying gauge-group structure. The measurements are found to be consistent with the admixture of color configurations as predicted by SU(3). The data clearly disfavour a theory in which $T_F/C_F \approx 0$, as predicted by SU(N) in the limit of large N, or $C_F = 0$.

REFERENCES

1. R. Muñoz-Tapia and W.J. Stirling, *Phys. Rev.* **D** 52 (1995) 3894.
2. DELPHI Coll., P. Abreu et al., *Phys. Lett.* **B** 255 (1991) 466.
3. J.G. Körner, G. Schierholz and J. Willrodt, *Nucl. Phys.* **B** 185 (1981) 365.
4. ZEUS Coll., contributed paper 5-0271, 32nd International Conference on HEP, Beijing, China, 2004.
5. M. Klasen, T. Kleinwort and G. Kramer, *Eur. Phys. Jour. direct* **C** 1 (1998) 1.
6. ZEUS Coll., S. Chekanov et al., *Phys. Lett.* **B** 560 (2003) 7.
7. S. Catani et al., *Nucl. Phys.* **B** 406 (1993) 187.
8. S.D. Ellis and D.E. Soper, *Phys. Rev.* **D** 48 (1993) 3160.
9. A.D. Martin et al., *Eur. Phys. Jour.* **C** 4 (1998) 463 and *Eur. Phys. Jour.* **C** 14 (2000) 133.
10. P. Aurenche et al., *Nucl. Phys.* **B** 286 (1987) 553.