Z. Phys. C – Particles and Fields 48, 467–470 (1990)

Zeitschrift für Physik C Particles and Fields

Photon-gluon fusion at HERA: measurement of the fractional momentum of the gluon in low Q^2 events

G. D'Agostini and D. Monaldi

Università "La Sapienza" and INFN, I-00185 Roma, Italy

Received 14 February 1990

Abstract. We have performed a Monte Carlo study of photon–gluon interactions at the *ep* collider HERA. We show that it is possible to determine the fractional momentum carried by the gluon (x_g) from hadronic informations alone. In particular, in the photoproduction region, where the x and Q^2 are badly measured, this could be the only global physical variable of interest, together with the hadronic invariant mass. The study of these quantities would allow a direct measurement of the gluon density of the proton in the range $x_g = 2.5 \times 10^{-3} \div 5 \times 10^{-1}$.

Introduction

The collider HERA, presently in an advanced status of construction at DESY, will provide collisions of 30 GeV electrons against 820 GeV protons. One of the main issues of the HERA physics program will be the determination of the parton densities inside the proton, as a continuation at higher Q^2 and lower x of the deep inelastic scattering (DIS) experiments. This information will be very precious both for comparison with theoretical predictions based on QCD calculations and to give an empirical description of the proton, essential to understand the parton beams in the supercolliders of the next generation, like LHC or SSC. In particular, we think that HERA will provide a unique opportunity to study the gluon density in a more direct way than that presently followed [1] through the Q^2 evolution of the structure functions. By *direct* we refer to methods where one is able to identify the events in which the gluons play a primary role, while in *indirect* methods no detailed information of the scattered partons is used and one limits oneself to a study of the absorption probability of a virtual boson of a given energy and invariant mass. We find that the importance of using direct methods has become particularly important, since a recent study [2] has shown that, of all the various structure functions entering in the charged and neutral current cross section, only F_2^{em} could be measured with the needed precision to make quantitative tests of QCD. Moreover, since at high x the Q^2 dependence of F_2^{em} is small, while at small x the QCD interpretation of the data is not straightforward, the determination of the gluon density at HERA from standard structure function analysis could be really challenging. An alternative indirect method is the study of the longitudinal structure function F_L [3], strongly related to the gluon density of the proton, but its measurement implies several experimental problems, like that of running HERA at different energies and so it will be of practical interest only after several years of running the experiments.

The first direct method proposed to study the gluon density $g(x_g, \hat{Q}^2)$ is based on the inclusive J/Ψ production from γg fusion. Its cross section is directly related to $g(x_g, \hat{Q}^2)$ at $\hat{Q}^2 = M^2_{J/\Psi}$ and $x_g = 3.4 M^2_{J/\Psi}/s_{\gamma g}$, where $s_{\gamma g}$ is the γg invariant mass squared and can be measured by detecting the electron scattered at very small angles*. A detailed study of this process [4], including detector simulation, has shown that the effective cross section, taking into account the probability of the reconstruction of the J/Ψ through the muon decay, is of the order of 10 pb. The second method [5] is based on the isolation of the high p_T events coming from the open $Q\bar{Q}$ production in the photon gluon fusion process. Its advantages, with respect to the previous one, are the expected higher cross section, which could make this subject one of the most interesting physics items for the first years of HERA, and the wider range of x_g and $\hat{Q}^2$. It has been shown that, in a large kinematical region, selection criteria based on a detailed study of topological variables or on a more simple muon tagging are rather efficient against background from DIS with QCD final state correction at the lowest order, and that it could be possible, even if with large errors, to reconstruct the gluon momentum fraction x_g. A case study, based on the use of an unfolding technique, has also shown encouraging results for the determination of the gluon density.

The relation proposed in [5] to infer the gluon

* Hereafter we use Q^2 for the DIS scattering variable and $\hat{Q}^2$ for the scale entering in the structure functions and in the QCD coupling constant

momentum fraction x_g from the measurable quantities is

$$x_g = x\left(1 + \frac{M_{q\bar{q}}^2}{Q^2}\right) \tag{1}$$

where $x = Q^2/2Pq$ is the Bjorken variable of the DIS and $M_{q\bar{q}}$ is the invariant mass of the quark pair produced in the reaction, estimated through the transverse mass of the hadronic system. In this paper we would like to extend the study of the measurability of x_g in the very low Q^2 region, where the events of interest are supposed to dominate.

x_g determination at low Q^2

Figure 1 shows the Feynman diagram leading to the high p_T γg events. In this process a photon radiated from the incident electron interacts with a gluon to produce a $q\bar{q}$ pair. All quark–antiquark pairs can be produced in the interaction, with rates proportional to the square of the electric charge and threshold factors depending on the quark mass and the γg invariant mass. The simulation of this process has been performed with a preliminary version of the AROMA Monte Carlo program [6], including gluon radiation from the $q\bar{q}$ pair and using the Lund program [7] for the fragmentation of the produced partons. In this study we have considered only $\gamma g \to c\bar{c}$ production. In fact the charm pair events can be tagged easily by demanding one or more energetic muons in the final state, and this gives little background from light quark production, as for example shown in [5]. The $b\bar{b}$ contribution can be included easily in a more complete analysis due to the fact that, in the kinematical region taken into account in the present work, the threshold factor can be ignored (apart for very low x_g) and the event topology looks very similar to that of the $c\bar{c}$, the only appreciable difference being the higher efficiency of muon tagging*. Following the suggestion of [5] also the light quark signal could be used if one could control the severe QCD background of the other processes which yield only light quarks and gluons in the final state, the main one being the so called QCD Compton scattering $\gamma q \to qg$. We have not taken into account detector effects, apart for the dominating one caused by the loss of two cones of 4° around the beam pipe. We do not consider this simplification to be an important limitation of this work.

In [5] it was proposed to measure the x and Q^2 variables entering in (1) from the electron measurement and form its combination with the hadron informations. This cannnot be done in the photoproduction region. In fact the electron is lost most of the times, and the x and Q^2 determination from the hadrons through the Jacquet–Blondel method [10] is rather poor [11], so that (1)

* The process $\gamma g \to Q\bar{Q}(g)$ is presently estimated to be the dominant but not the unique source of $c\bar{c}$ and $b\bar{b}$ events at HERA [8]. The other processes, in order of importance, at high p_T are: $\gamma q \to QQq$, $q\bar{q} \to Q\bar{Q}$ and $gg \to Q\bar{Q}$. The first background can be reduced (at expenses of $\gamma g \to Q\bar{Q}g$) by the demand of planar events, while for the other two we have studied a way to tag with high efficiency the high p_T processes involving the anomalous structure function of the photon [9]

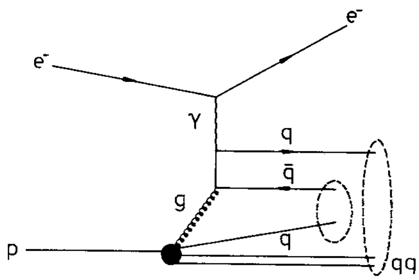

Fig. 1. Feynman diagram describing the photon gluon fusion $\gamma g \to q\bar{q}$. The colour singlets are recombined by the Monte Carlo in the way shown in the figure

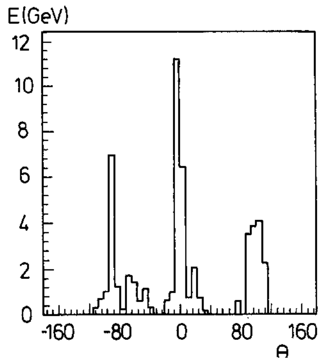

Fig. 2. Energy flow, with respect to the incoming proton direction, in the event plane for a typical high $p_T \gamma g \to c\bar{c}$ process. Only particles with a polar angle respect to the beam axis greater than 4° have been included in the analysis. The peak around zero comes from particles passing this cut, but having a small projected angle in the plane of the event

become useless. However, analysing the Jacquet–Blondel relations to obtain the DIS variables and only depending on the hadronic energy (E^h), longitudinal momentum (P_L^h) and incoming electron energy (E_e), one observes that $y = \sum_h (E^h - p_L^h)/2E_e$ can be measured well in events characterized by high p_T jets accompanied by the proton remnants in the very forward region. We can then rewrite, making use of $xy = Q^2/s$, (1) as $x_g = (Q^2 + M_{q\bar{q}}^2)/sy$. Taking for y the Jacquet–Blondel relation and neglecting $Q^2 \sim 0$, we obtain

$$x_g = \frac{2E_e}{s} \frac{M_{q\bar{q}}^2}{\sum_h (E^h - p_L^h)} \tag{2}$$

that depends only on the hadronic final state. Also the energy of the photon interacting with the gluon can be measured from the hadronic information alone:

$$E_\gamma = \frac{M_{q\bar{q}}^2}{4E_p x_g} = \frac{s \sum_h (E^h - p_L^h)}{8E_p E_e} \tag{3}$$

Moreover, for the fraction of events where the scattered electron is well measured [4], Eq. (3) may be used to determine x_g with only the uncertainty on the $q\bar{q}$ invariant mass: $x_g = M_{q\bar{q}}^2/4E_p(E_e - E_{e'})$.

The main difficulty in measuring the invariant mass of the outgoing quark pair produced in the photon-gluon interaction comes from the fact that it is not possible, not even in principle, to have a perfect separation of the hadronization products of these quarks from those of all other partons. In fact, since the photon gluon system is not a colour singlet, the fragmentation of the quark pair has also to involve the spectator quarks. In practice this is done, in the Lund scheme used in the present work, by connecting with colour strings the quarks of the pair with the rest of the proton, which is considered as a spectator diquark plus the quark which radiated the gluon, as shown in Fig. 1. The result of these colour strings is that the particles are not only produced within a narrow cone along the parton directions, as it would be in case of independent fragmentation, but also between the partons, as experimentally observed in the three jet analysis of e^+e^- events [12]. However, the most energetic particles, and hence the hadron jets, will still go close to the parton directions. Then, for high p_T events, there is a substancial separation between the jets which follow the directions of the quark originated from the photon gluon fusion and those following the proton remnants, as shown in the example of Fig. 2, where the energy flow in the event plane is given for *a* $\gamma g \to c\bar{c}$ event.

Results of a Monte Carlo study

We have tried several techniques to find a good estimation of the quark pair invariant mass $M_{q\bar{q}}$ that enters in (2). We present here the results obtained using the transverse energy $E_T = \sum_h p_T^h$ as estimate of $M_{q\bar{q}}$ (also other algorithms have been tried, including some based on cluster reconstruction; the search of the best one is however outside the aims of the present work). Equation (2) is then replaced by the experimentally measurable quantity:

$$X_g = \frac{E_T^2}{2E_p \sum_h (E^h - p_L^h)} \tag{4}$$

where E_p is the energy of the incoming proton. The variable E_T reconstructs exactly $M_{q\bar{q}}$ only when the $q\bar{q}$ are produced, in the γg rest frame, orthogonally to the beam axis, and the influence of the spectator quarks and the loss of particles in the beam pipe are negligible. It has been found that the combined effect of the spectator quarks and the particle loss is minimized if one demands a large transverse energy in the central region of the detector. We have then required $E_T > 15\,\text{GeV}$ in the angular region $37° < \theta < 129°$, corresponding to the barrel calorimeter acceptance of the ZEUS detector [13]. This cut is also very efficient against DIS events if it is accompanied by the requirement that Q^2, as calculated with the Jacquet–Blondel relations, is below a few GeV^2, and the cut still leaves a cross section for the charm pairs of $\sim 1.2 \times 10^3$ pb. Since the numerator and the denominator of (4) depend in a similar way on the acceptance, we have observed a certain degree of compensation and the final uncertainty of X_g is inferior that expected from the propagation of the errors of $M_{q\bar{q}}$ and y. Figure 2 shows the energy flow, with respect to the incoming proton direction, in the plane of the event as determined

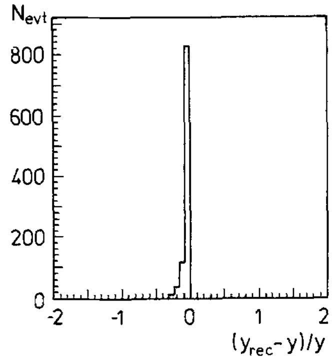

Fig. 3. Distribution of the reconstructed y through the Jaquet–Blondel method for the events having $E_T(37° < \theta < 129°) > 15\,\text{GeV}$

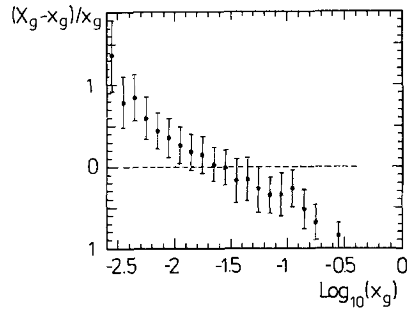

Fig. 4. Relative difference between the reconstructed gluon fractional momentum (X_g) and the Monte Carlo one (x_g) as function of x_g. The error bars indicate the standard deviation of the single event distribution.

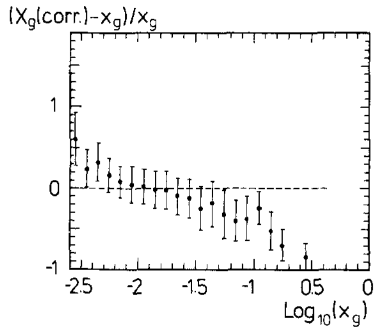

Fig. 5. Same as Fig. 4, but with X_g corrected for the average angle of the high p_T hadrons

with a modified version of the sphericity analysis where the condition is imposed that the reconstructed plane must contain the beam axis. Although only particles outside the acceptance hole are considered, a residual peak around zero degrees remains, due to the proton fragments. The reconstruction quality of y for events passing the transverse energy cut described before is shown in Fig. 3.

Figure 4 gives the average of $(X_g - x_g)/x_g$ and an error bar, meant as standard deviation of the single event distribution, as a function of x_g. Some of the residual systematic difference between the generated x_g and the reconstructed X_g, which depends on the angle of production of the quark and the antiquark, has been empirically corrected in a simple way by studying the dependence of the relative difference $(X_g - x_g)/x_g$ as a function of the average production angle of the high p_T hadrons in the laboratory frame. The same quantities of Fig. 4 are shown in Fig. 5 for X_g(corr). The correction takes the form of $X_g(\text{corr}) = X_g/(1+\alpha+\beta\bar{\Theta}_h)$, where α and β are determined from Monte Carlo events and $\bar{\Theta}_h$ is the average, weighted with the momentum, of the modulus of the hadron angles calculated in the event plane with respect to the proton direction. To reduce the effect of the proton fragments in the forward region, $\bar{\Theta}_h$ has been calculated in a recursive way, skipping in the second evaluation all particles with $\Theta < 2/3\bar{\Theta}_{h_1}$, where $\bar{\Theta}_{h_1}$ is the average obtained in the first iteration. The result of Fig. 5 is that, already with this simple correction, a resolution of 25% (on the single event distribution) can be achieved in the range $2.5 \times 10^{-3} < x_g < 0.5$ and with a systematic shift smaller than $\pm 50\%$*. We did not try to perform a more sophisticated correction to reduce further the bias of the x_g measurement, since this depends on the details of the apparatus. On the other hand, it is interesting to note that this systematic shift does not depend on the input function for the gluon density. In fact, for a given x_g the topology of the final state hadrons, responsible for the measured X_g, depends on the calculable photon spectrum $P_{\gamma/e}(k)$ and on the fragmentation.

We would like to point out that the transverse energy E_T could also represent a reasonable choice for the scale entering in the gluon structure function, as well as for the scale of the strong coupling constant of the $gq\bar{q}$ vertex. Then the study of $f(X_g, E_T^2)$ could be the right tool to determine the parton gluon density $g(x_g, \hat{Q}^2)$ over a large range of x_g and scale $\hat{Q}^2$. The range of E_T^2 is limited firstly by the minimum transverse energy required by the selection criteria, put by us at 15 GeV but that perhaps could be lowered in a particular experiment, and secondly by twice the maximum p_T of the $Q\bar{Q}$ pair for which there is still a significant event statistics**.

One should note that, even if in the kinematical region considered in this analysis x is very small (since $x < x_g$ from (1)) and $Q^2 \sim 0$, there is no contradiction with the results of [11] about the kinematical region of measurability at HERA, since those results are only valid for deep inelastic scattering at the Born term (eventually with QCD corrections in the final state). For example, one of the limiting cuts of [11] is set by the requirement of the experimental trigger that the hadron p_T should be larger than 15 GeV. In the DIS at the Born term the transverse hadron energy is essentially due to the current jet p_T related to the scaling variables through $p_T = \sqrt{(1-y)Q^2}$. In γg collisions with high p_T jets it is however still possible to have large transverse energy even at $Q^2 = 0$, and y and E_T, used in this work, are better measured than x and Q^2. Moreover, also the amount of calorimetric energy required for the trigger can be safely lowered if one also demands a certain p_T balancing, typical of the kind of events of interest.

* The interval of measurability of the fractional momentum of the gluon is limited at large values by the statistics of events, and at low values by the kinematical limit given by

$$x_g = \frac{\hat{s}}{sy} > \frac{\hat{s}_{\min}}{sy_{\max}} = \frac{4(m_c^2 + p_{T_{\min}}^2)}{s}. \tag{5}$$

** For example, the cross section of $ep \to c\bar{c} + X$ with $p_T > 20$ GeV is 70 pb, falling to ~ 10 pb for $p_T > 30$ GeV and to ~ 1.5 pb for $p_T > 40$ GeV [6]. Then the upper E_T^2 limit will range from $\sim 2000\,\text{GeV}^2$ to $\sim 6000\,\text{GeV}^2$ depending on the available luminosity

Conclusions

We propose a parametrization of the final state hadron momenta of the electron-proton collisions at HERA, which allows the reconstruction of the fractional momentum of the gluon interacting with a quasi real photon. This method is particularly promising with charm and bottom production, where the high expected rate and the muon tagging possibility yields an almost background free sample of γg collision events. The result is that the proton gluon density $g(x_g, \hat{Q}^2)$ could be directly measured in the range of fractional momentum $2.5 \times 10^{-3} < x_g < 0.5$, and in the range of the $\hat{Q}^2$ scale, estimated via transverse energy of the high p_T hadrons, $200 < \hat{Q}^2 < 6000\,\text{GeV}^2$.

Acknowledgements. We would like to thank G. Ingelman and G. Schuler for having allowed us to use a preliminary version of the leptoproduction Monte Carlo AROMA; W. de Boer, P. Lipari and L. Stanco for comments on the manuscript. A special thank, in particular by D.M. who had a summer student position in 1988, to the DESY directorate for the kind hospitality during the initial stage of this work.

References

1. See e.g. M. Diemoz, F. Ferroni, E. Longo, G. Martinelli: Z. Phys. C – Particles and Fields 39 (1988) 21 and references therein
2. J. Blümlein, M. Klein, G. Ingelman, R. Rückl: Z. Phys. C – Particles and Fields, 45 (1990) 501; to relate the experimental error of Λ_{QCD} to the uncertainty on $g(x_g, \hat{Q}^2)$ see J. Blümlein, M. Klein, Th. Naumann, T. Rienmann: Proc. of the DESY Workshop "Physics at HERA", Hamburg, 1987, R. Peccei, (ed.) DESY, p. 67, 1988
3. A.M. Cooper-Sarkar et al.: Proc. of the DESY Workshop "Physics at HERA", Hamburg, 1987, R. Peccei, (ed.) p. 231. DESY, 1988
4. S.M. Tkaczyk, W.J. Stirling, D.H. Saxon: Proc. of the DESY Workshop "Physics at HERA", Hamburg, 1987, R. Peccei, (ed.) p. 265. DESY, 1988
5. G. Barbagli, G. D'Agostini: Proc. of the DESY Workshop "Physics at HERA", Hamburg, 1987, R. Peccei, (ed.) DESY, p.135, 1988
6. G. Ingelman, G. Schuler: The AROMA Monte Carlo Program DESY preprint in preparation; G. Ingelman, G. Schuler; Z. Phys. C – Particles and Fields 40 (1988) 229
7. T. Sjöstrand: JETSET6.3, Comp. Phys. Commun. 39 (1986) 347
8. R. K. Ellis, Z. Kunszt: Nucl. Phys. B303 (1988) 653
9. G. D'Agostini, D. Monaldi: ZEUS Note 90-015, DESY, 1990, to be published
10. See Proc. of "Study of an e-p facility for Europe", U. Amaldi, (ed.) DESY 79/48 (1979) p. 391–394
11. J. Feltesse: Proc. of the DESY Workshop "Physics at HERA", Hamburg, 1987, R. Peccei, (ed.) p. 33. DESY, 1988
12. JADE Coll. F. Ould Saada et al.: Z. Phys. C – Particles and Fields 39 (1988) 1 and references therein
13. ZEUS Collaboration: "The ZEUS Detector", Technical Proposal, DESY, 1986