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Azimuthal correlations in photoproduction and deep inelastic ep scattering at HERA

P. J. Bussey*

On behalf of the ZEUS Collaboration.
SUPA, School of Physics and Astronomy, University of Glasgow,
Glasgow G12 8QQ, United Kingdom

E-mail: peter.bussey@glasgow.ac.uk

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Recent results from the ZEUS Collaboration are presented on the features of multiparticle correlations in photoproduction in ep collisions at HERA. They are compared to correlations observed in deep inelastic ep scattering and to earlier results in heavy-ion collisions at the LHC. No evidence for quark-gluon plasma formation is seen at HERA. Detailed correlation coefficients are compared to various models, and it is concluded that multiparton collisions form an important part of the photoproduction process.

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*Speaker

1. "Ridge" plots

When two heavy ions collide at high energies, some of their constituent partons may temporarily escape from hadronic confinement to form a central dense, hot mixture of partons. Often referred to as a quark-gluon plasma, this material can be described in terms of hydrodynamic models. It quickly decays into a multihadronic final state, which retains a memory of its origins in terms of correlations between the emerging hadrons.

These correlations can be measured, and in particular, the two-dimensional plot of the particle separation in pseudorapidity (η) and azimuth (ϕ) shows some interesting features. A strong enhancement of particle pairs with small separation in both variables signifies the familiar formation of a jet. Given the presence of a jet and a recoil jet, there is a tendency for pairs of particles to emerge in opposite azimuthal directions. A jet and a recoil jet are not strongly correlated in pseudorapidity, however, and so the opposite-azimuth particle pairs form a "ridge" in pseudorapidity difference $\Delta\eta$, rather than a peak around zero.

Perhaps surprisingly, heavy-ion collisions also show a significant ridge-like component in $\Delta\eta$ in particle pairs with small azimuthal separation [1]. This is attributable to quark-gluon plasma formation and to a lesser extent it is also evident in proton-ion and even proton-proton collisions [2, 3], indicating that even the partons in the proton have a capability of forming a quark-gluon plasma when in collision with those in other hadrons. This effect is naturally absent in electron-positron collisions, and so it is of interest to observe whether it is present in electron-proton collisions, where "electrons" also implies positrons.

The ZEUS collaboration at HERA, where 27.5 GeV electrons collided with 920 GeV protons, has measured these processes both in deep inelastic scattering (DIS) [4] and in scattering processes with low virtuality of the exchanged virtual photon, referred to as photoproduction [5]. It is the exchanged virtual photon that interacts with the incoming proton, and at high values of virtuality Q^2 this exchanged object is not regarded as containing partons. No quark-gluon plasma is therefore expected to be formed, and in practice no near-side ridge is seen. A certain fraction of photoproduction processes likewise occur by "direct" interactions in which the exchanged photon interacts non-hadronically. However a majority of such collisions are "resolved" processes in which the photon fluctuates through a partonic intermediate state. One asks, therefore, whether the virtual partons in such a virtual photon can be instrumental in generating a quark-gluon plasma, which

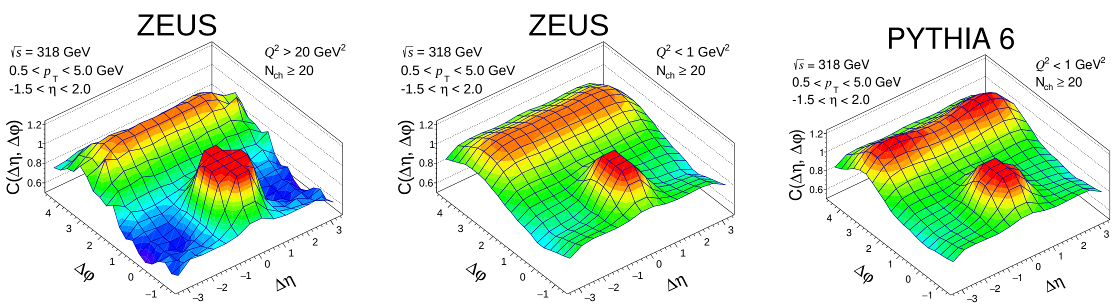

Figure 1: "Ridge" plots showing the correlation between azimuth and pseudorapidity for pairs of produced particles: (left) DIS data, (centre) photoproduction data, (right) photoproduction simulation by PYTHIA.

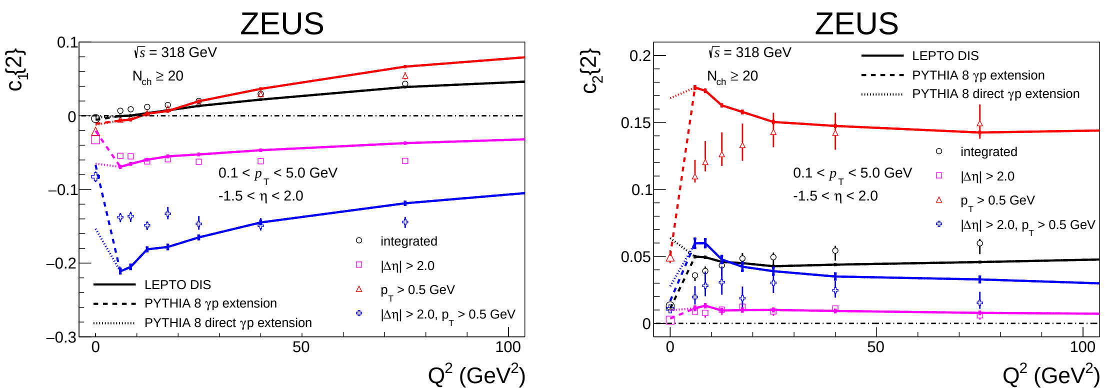

Figure 2: Correlation parameters $c_1\{2\}$ and $c_2\{2\}$ versus Q^2. The photoproduction result (at a single point) and values obtained over higher Q^2 values are compared to models.

could manifest itself in terms of a near-side ridge analogous to that seen in hadron-hadron collisions.

The results from ZEUS, shown in Figure 1, indicate that this is not the case. Events with at least 20 final-state tracks are selected. The DIS events exhibit a strong jet peak at zero two-particle separation in pseudorapdity and azimuth, together with the expected far-side ridge. No near-side ridge is present. Exactly the same features are seen in photoproduction events, defined as those with $Q^2 < 1$ GeV^2. A simulation of the photoproduction process using PYTHIA closely resembles the data; these simulated events include colour strings but no quark-gluon plasma. The conclusion is that the virtual partons in a virtual photon, unlike the partons in a proton, are not efficient in the production of a quark-gluon plasma, at least under the conditions presented at HERA.

2. Correlation coefficients

A further tool for studying the properties of multiparticle final states consists of correlaton coefficients (cumulants) that describe the azimuthal structure of events by considering sets of even numbers of particles with different Fourier components in ϕ. These coefficients are defined for particle pairs in terms of

$$c_n\{2\} = \langle\langle \cos n(\phi_i - \phi_j)\rangle\rangle,$$

where n denotes the degree of the correlation and a suitable weighted average is performed over the particles. Corresponding but more complex definitions are available for higher numbers of particles. For pairs of particles, n=1 describes the degree of asymmetric directedness in one dimension exhibited by the particles in an event, $n = 2$ describes the degree of elongation or ellipticity of the event structure, and higher values of n relate to more complex azimuthal structures.

Figure 2 shows the experimental results for $c_1\{2\}$ and $c_2\{2\}$ from ZEUS for photoproduction events and DIS events covering a range of Q^2 values. The PYTHIA and LEPTO models give reasonable descriptions of the results, but fit less well in the marked transition between the photoproduction result, plotted at Q^2=0, and the DIS results. A purely direct-photon description of the photoproduction results fails, as expected, since a large majority of these events are resolved; this marks a key difference between the physics of photoproduction and DIS.

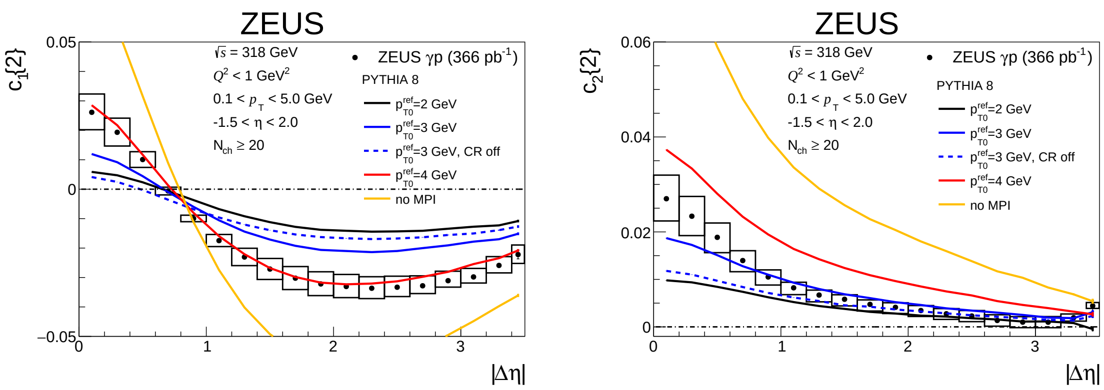

Figure 3: Correlation parameters $c_1\{2\}$ and $c_2\{2\}$ versus $\Delta\eta$ for photoproduction data, showing the effects of varying the multiparton interaction parameter in PYTHIA.

3. Multiparton interactions

It is possible to vary a parameter p_{T0} in PYTHIA that, while nominally a lower cut-off on parton momenta, has the effect of varying the mean numbers of multiparton interactions that PYTHIA generates in its events. This has been studied with the aim of demonstrating a possible sensitivity to physics of this kind in photoproduction, seeing that the formation of a quark-gluon plasma appears to be disfavoured.

Figure 3 illustrates the results obtained. Values of the first and second order correlation coefficients for two particles are plotted as a function of the azimuthal separation of the two particles. If multiparton interactions are turned off in PYTHIA, the match to the data is bad. As the minimum momentum parameter p_{T0} is decreased from large values, the match improves, but becomes poor again for the lowest value considered. Although this approach does not give a well-defined optimum value for the parameter, a situation that could be attributed to inadequacies in the PYTHIA modelling at this level, it suggests strongly that multiparticle correlations are occurring and are influencing

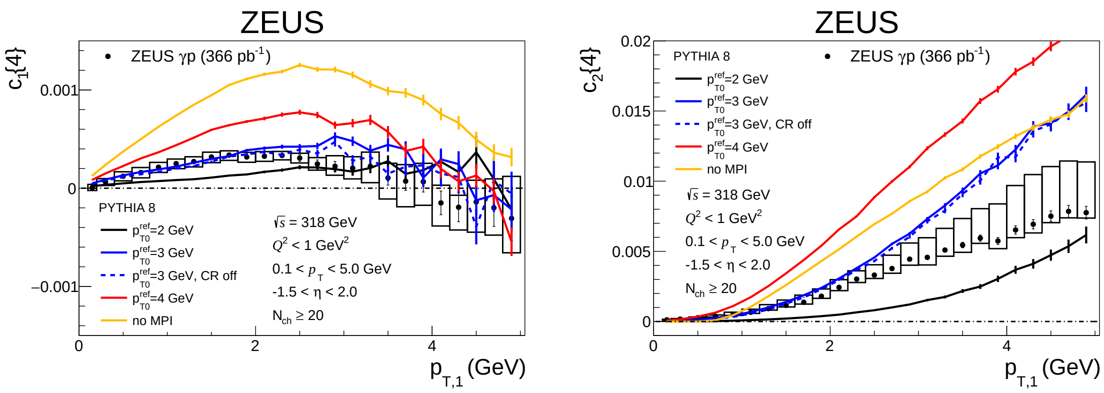

Figure 4: Correlation parameters $c_1\{4\}$ and $c_2\{4\}$ versus p_T of the leading particle for photoproduction data, showing effect of varying the multiparton interaction parameter in PYTHIA.

the shape of the events. A similar conclusion can be drawn from the four-particle correlation coefficients, plotted as a function of the momentum of the leading outgoing particle in Figure 4. An optimum value of p_{T0} of approximately 3 ± 1 GeV is suggested, implying the presence of multiparton interactions in the range 2 to 8 per event in the PYTHIA model used.

4. Summary and comments

Two- and four-particle azimuthal correlations have been studied using high-multiplicity data from the ZEUS collaboration at HERA. When the azimuthal and pseudorapidity correlations are combined in a two-dimensional distribution, the events show no evidence for the double-ridge structure that is present in hadron-hadron collisions, most notably in heavy-ion collisions. There is thus no evidence for effects of a hydrodynamic type in the HERA collisions that would arise from quark-gluon plasma formation, as observed at the LHC. Instead, the data can be modelled reasonably well by PYTHIA and imply the presence of multiparton interactions. It should be borne in mind, however, that LHC collisions are at higher energies than were available at HERA, and higher track multiplicities are also measurable at the LHC.

References

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[2] CMS Collaboration, Phys. Lett. B 718 (2013) 795

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[4] ZEUS Collaboration, JHEP 04 (2020) 070

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