# Dijet Production at Low $\mathbf{Q^2}$

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Triple differential dijet cross-sections in $e^{\pm}p$ interactions measured with the H1 detector at HERA are presented. The data are compared to Monte Carlo simulations based on the DGLAP and CCFM parton evolution schemes. Effects of longitudinally polarized virtual photons are investigated.

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## 1. Dijet Production at HERA

The production of dijet events at HERA is dominated by processes in which a virtual photon, coupling to the electron, interacts with a parton in the proton. In the region of photon virtuality $Q^2 \gg \Lambda^2_{QCD}$, hard collisions of the photons do not necessitate the introduction of the concept of the resolved photon (as for the real photon) and the process can in principle be described by the direct photon contribution alone.

The analysis presented here explores the region $\Lambda^2_{QCD} \ll Q^2 \lesssim E_t^2$, where different theoretical approaches can be used to take into account higher order corrections – either next-to-leading order (NLO) calculations, $k_t$ unordered initial QCD cascades, or additional interactions with resolved photons. Comparisons with NLO predictions are likely to become possible in the future. In more detail, the present measurements are compared with the following models:

**a) LO direct and resolved interactions** based on the DGLAP evolution equations and parton showers. The effects of transversally ($\gamma_T^*$) and also longitudinally ($\gamma_L^*$) polarized resolved photon interactions are included [1, 2, 3]. The cross section for longitudinal photons vanishes for $Q^2 = 0$ due to gauge invariance. On the other hand, the concept of a resolved photon breaks down for $Q^2 > E_t^2$. Therefore the most promising region in which to search for the $\gamma_L^*$ resolved processes is $\Lambda^2_{QCD} < Q^2 \ll E_t^2$, which is often the case of the present analysis. The main difference between $\gamma_L^*$ and $\gamma_T^*$ induced interactions arises from the $y$ dependence of the respective fluxes:

$$f_{\gamma^T/e}(y,Q^2) = \frac{\alpha}{2\pi}\left[\frac{2(1-y)+y^2}{y}\frac{1}{Q^2} - \frac{2m_e^2 y}{Q^4}\right] \tag{1}$$

$$f_{\gamma^L/e}(y,Q^2) = \frac{\alpha}{2\pi}\left[\frac{2(1-y)}{y}\frac{1}{Q^2}\right] \tag{2}$$

While for $y \to 0$, both transverse and longitudinal fluxes are approximately same, the longitudinal flux vanishes for $y \to 1$. Also the dependence of the point-like [1] (i.e. perturbatively calculable) parts of the photon parton distribution functions (PDF) on $Q^2$ and $E_t^2$ differs – while the $\gamma_T^*$ PDF are proportional to $\ln(E_t^2/Q^2)$, the $\gamma_L^*$ PDF do not, in the first approximation, depend on either $E_t^2$ or $Q^2$ [2].

**b) k$_t$ unordered initial QCD cascades** accompanying the hard process are present for example in BFKL or CCFM evolution. These evolution schemes can lead to final states in which the partons with the largest $k_t$ may come from the cascade, and not, as in DGLAP evolution, from the hard subprocess. Such events may have a similar topology to that for the resolved interactions in the DGLAP approximation. This possibility is investigated using the CASCADE generator [5, 6, 7] based on the CCFM evolution equations.

## 2. Measurement of Dijet Cross-Section

The measurement was done with 16.3 pb$^{-1}$ of data collected in 1999, when the electron-proton center-of-mass energy $\sqrt{s}$ reached 318 GeV. The analysis was performed in $\gamma^*$-proton center-of-mass system and jets were found using the $k_t$ longitudinally invariant jet algorithm. The phase space is defined by the photon virtuality: 2 GeV$^2 < Q^2 <$ 80 GeV$^2$, the electron inelasticity: $0.1 < y < 0.85$, the transverse energy of two leading jets: $E_t^{jet\,1,2} > 5$ GeV, $\overline{E}_t = (E_t^{jet\,1} + E_t^{jet\,2})/2 > 6$ GeV and the pseudorapidity of the two leading jets: $-2.5 < \eta^{jet\,1,2} < 0$.

The measured data are corrected for detector effects using the Bayesian unfolding method. The largest source of systematic errors arises from the model dependence of the detector correction, and from the main calorimeter calibration uncertainty.

[1] The perturbatively non-calculable hadron-like part of the photon PDF becomes negligible in our kinematical region with respect to the point-like one, as has been demonstrated in [4].

## 3. Results and Discussion

The corrected triple-differential dijet cross-section measured as a function of $Q^2$ , $\overline{E}_t^2$ and $x_\gamma$ is shown in Fig. 1(a). A prediction of HERWIG [8] with the SaS1D parameterization of the $\gamma_T^*$ PDF, as well as the pure direct contribution is compared to the data.

In general, HERWIG and RAPGAP [9] tend to underestimate the measured cross-section. The decrease of the resolved contribution at high $\overline{E}_t^2$ is of kinematic origin, due to the limited phase space at low $x_\gamma$ . The direct contributions almost describe the data in the highest $Q^2$ bin, while a clear need for resolved processes is observed for $Q^2 \ll \overline{E}_t^2$.

In the highest $Q^2$ range ($25 < Q^2 < 80$ GeV$^2$) and $x_\gamma < 0.75$, the HERWIG direct contribution almost describes the data in the lowest $\overline{E}_t^2$ bin, but is significantly below it in the highest $\overline{E}_t^2$ bin. This indicates that the relevance of the resolved photon contribution is governed by the ratio $\overline{E}_t^2/Q^2$, rather than by $Q^2$ itself.

Standard HERWIG with direct and $\gamma_T^*$ resolved contributions underestimates the data. The description is improved by adding $\gamma_L^*$ resolved photon interactions, which is done using a slightly modified version of HERWIG with the longitudinal photon flux according to eq. (2) and a recent $\gamma_L^*$ PDF parameterization [3]. As demonstrated in Fig. 1(a), the $\gamma_L^*$ resolved contribution is significant, and brings HERWIG closer to the measurement.

On the other hand, a simple enhancement of the PDF of the $\gamma_T^*$ in the resolved contribution could lead to a similar prediction as the introduction of resolved $\gamma_L^*$. To distinguish between a non-optimal choice of $\gamma_T^*$ PDF and the need for resolved $\gamma_L^*$ , the dijet cross-section has also been studied as a function of $Q^2$ , $x_\gamma$ and $y$, which is shown in Fig. 1(b). HERWIG is below the data. The discrepancy becomes smaller if the resolved $\gamma_L^*$ is added. According to eq. (1-2), the slope of inelasticity $y$ of the HERWIG prediction in the region of $x_\gamma < 0.75$, depends significantly on whether $\gamma_L^*$ processes are included or not. Unlike a pure enhancement of $\gamma_T^*$ PDF, which would not change the slope of the $y$ distribution, addition of $\gamma_L^*$ brings the $y$ dependence of HERWIG much closer to the measurement.

As motivated in Section 1, the measured cross-sections are also compared to a prediction of the CASCADE MC program based on the CCFM evolution scheme. This theoretical approach does not involve the concept of virtual photon structure and employs much fewer parameters for tuning than the usual DGLAP-based MC programs. CASCADE describes the data reasonably but not perfectly. In particular, the $Q^2$ dependence at low $x_\gamma$ is poorly described.

As indicated by Fig. 1(b), the $y$ dependence of the dijet cross-section is better described by CASCADE than by HERWIG without the $\gamma_L^*$ resolved process, since photon polarization states are correctly treated in CASCADE for all virtualities (only direct photon interactions are considered).

## 4. Conclusions

The importance of $\gamma_T^*$ resolved photon interactions within the DGLAP evolution scheme at leading order is clearly demonstrated in the region where $\overline{E}_t^2 > Q^2$, even at rather high $Q^2$. Additional $\gamma_L^*$ resolved photon contributions further improve the agreement of HERWIG with the measured data.

Exploring the CCFM approach, the MC program CASCADE does not reproduce the data perfectly, the main discrepancy is observed in the $Q^2$ dependence at low $x_\gamma$ . On the other hand, the $x_\gamma$ dependence in CASCADE is comparable to the sum of the direct and resolved contributions in DGLAP-based MC programs, showing that non $k_t$ ordered parton cascades can successfully produce the same observables as resolved virtual photons in the LO DGLAP evolution scheme.

## Acknowledgments

I am grateful to J. Cvach, J. Chýla, H. Jung, P.R. Newman, M. Taševský and A. Valkárová for many valuable discussions and careful reading of the manuscript.

This work has been supported in part by the Ministry of Education of the Czech Republic under the project LN00A006.

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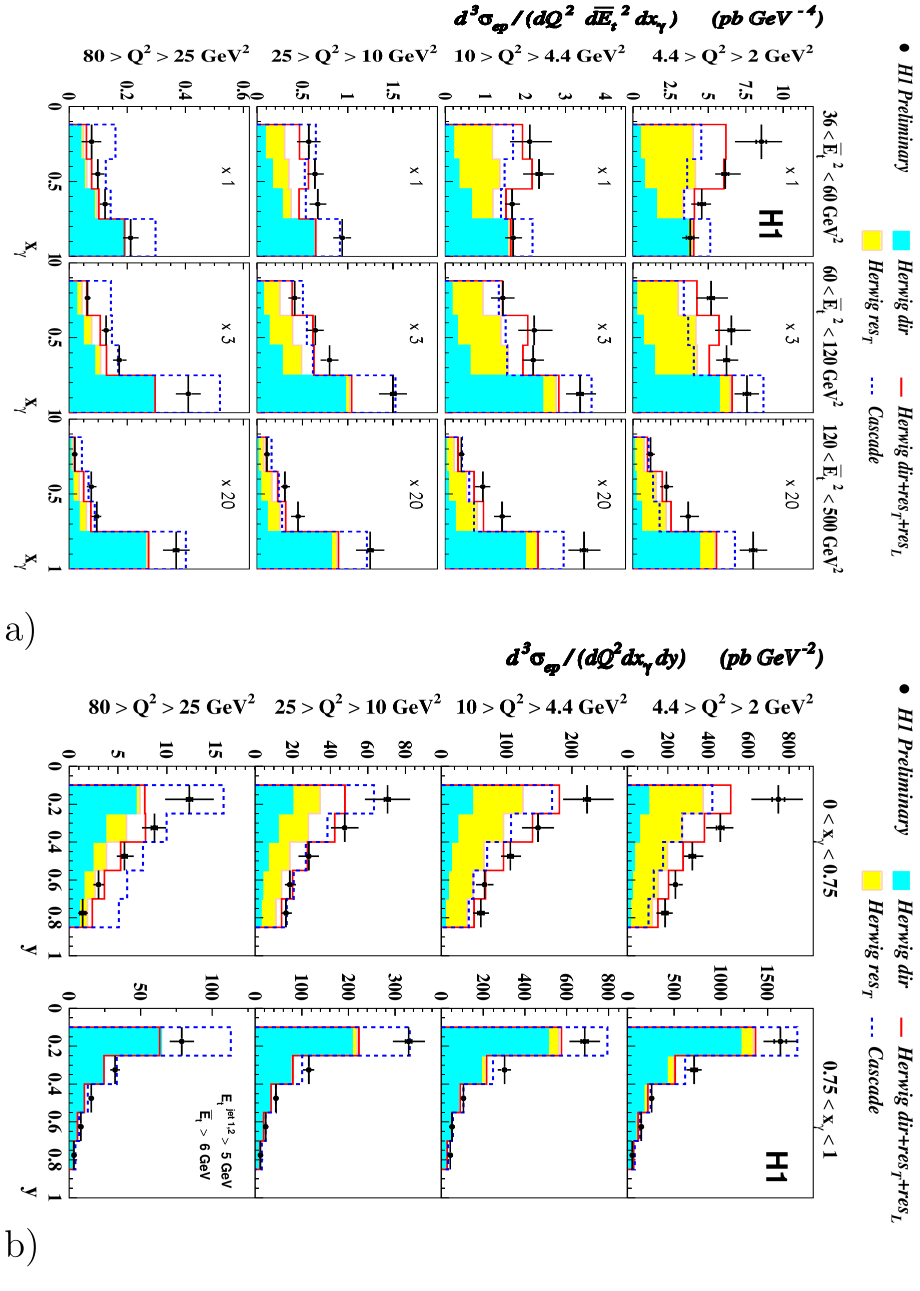


Fig. 1. (a) Triple differential dijet cross-section $d^3\sigma_{ep}/dQ^2 d\overline{E}_t^2 dx_\gamma$ for the H1 data depicted by points is compared to predictions of the HERWIG and CASCADE MC programs. (b) Triple differential dijet cross-section $d^3\sigma_{ep}/dQ^2 dx_\gamma dy$.