Virtual Photon Structure from Jet Production at HERA

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[*] Supported by grants No. A1010619 and A1010602 of the GA of the Academy of Sciences of CR

Abstract: The feasibility of measuring parton distribution functions of of virtual photons via the jet production at HERA is investigated.

Production of jets in ep collisions at HERA offers one of the ways of studying the structure of the virtual photon. Due to the fact that this structure needs time to develop, parton distribution functions (PDF) $f_i(x,P^2,Q^2)$ of the virtual photon, probed at the hard scattering scale Q, are expected to be decreasing functions of the magnitude P^2 of its virtuality. As P^2 approaches Q^2 from below $f_q(x,P^2,Q^2)$ should approach parton model formula

$$f_i^{\rm PM}(x,P^2,Q^2) \equiv \frac{3\alpha}{2\pi}\left[x^2+(1-x)^2\right]\ln\frac{Q^2}{P^2}. \tag{1}$$

The transition of the quark distribution functions of the real photon to the form (1) is so far not calculable but there are models which interpolate between $f_q^{\rm real}$ and (1). Measurement of the PDF of the virtual photon would provide valuable new information on the properties of parton interactions at short distances. In ref. [3] this transition is parametrized as follows

$$f_q(x,Q^2,P^2) = f_q^{\rm real}(x,Q^2)L(Q^2,P^2,\omega), \quad L \equiv \frac{[\ln(Q^2+\omega^2)/(P^2+\omega^2)]}{[\ln(Q^2+\omega^2)/(\omega^2)]}, \tag{2}$$

while in analogous relation for the gluon L is replaced by L^2. The parameter ω determines the value of P^2 above which the suppression factor L becomes significant. Small ω means strong suppression already for weekly off–mass shell photons, while $\omega\to\infty$ corresponds to no suppression at all. The suppression formula (2) is implemented, for instance, in the recent versions of HERWIG MC generator. Because of a different x behaviour of PDF of the real photon and parton model formula (1), ω must in general be a function of x. As, however, in our simulations $P^2 \ll Q^2 \approx 4(p_T^{\rm jet})^2 \geq 100$ GeV^2 we considered ω as x independent.

Jet production at HERA for general values of P^2 and $p_T^{\rm jet}$ is a two–scale problem, where it is thus not obvious what to take for the relevant har–scattering scale Q^2 in $f_i(x,P^2,Q^2)$: P^2 or p_T^2 of the produced jets, or some combinations thereof? In this study we stayed in the region $\Lambda_{\rm QCD} \ll P^2 \ll p_T^2$ and therefore assumed $Q^2=\kappa p_T^2$ with the proportionality factor of the order of unity. To make the experimental procedure of jet finding well–defined and ensure the applicability of perturbative QCD, we furthemore required $p_T^{\rm jet} \geq p_T^{\rm min} = 5$ GeV, $P^2 \leq 10$ GeV^2. As in this region dynamics of the jet production is close to that of the real photoproduction, all our further considerations were carried out in the γ^*p CMS. To study the P^2 dependence we split the region $P^2 \leq 10$ GeV^2 into eight intervals: $(0, 0.1)$ ("photoproduction"), $(0.1, 0.2)$, $(0.2, 0.5)$, $(0.5, 1)$, $(1, 2)$, $(2, 5)$, $(5, 10)$ GeV^2, each with roughly the same number of events. To guarantee good electron identification, the cut on $0.2 \leq y \leq 0.7$ was imposed in all simulations.

Our simulations were guided by recent preliminary H1 and ZEUS data on virtual photon structure [1, 2]. The results presented here are based on HERWIG 5.8d MC generator and standard cone jet finder with $R = 1$. To estimate the dependence of the results on the strength of the virtual photon suppression factor the simulations were performed for three values of $\omega = 0.1, 1.0, 3.0$. We addressed the following questions:

a) How to isolate the contribution of the resolved photon, which depend on $f_i(x, P^2, Q^2)$ and thus in principle allow its measurement, from direct photon one?

b) What are the ensuing requirements on the detector and experimental procedure?

c) What is the required luminosity upgrade to get a reasonable statistics?

Most of the current attempts at separating resolved from direct photon contributions to jet cross–sections are based on the fact that for the latter the distribution of the variable

$$x_\gamma \equiv \frac{E_T^{(1)} \exp(-\eta^{(1)}) + E_T^{(2)} \exp(-\eta^{(2)})}{2E_\gamma}, \tag{3}$$

where $\eta^{(j)}$ and $E_T^{(j)}$ correspond to two jets with highest transverse energies, peaks at a value close to unity, while for the resolved component the spectrum peaks at low x and drops rapidly as $x_\gamma \to 1$. In parton model x_γ is interpreted as a fraction of the photon momentum carried by the parton or photon participating in the hard collision with a parton from the proton. In the direct channel and for two final state massless partons $x_\gamma = 1$ identically. Taking into account nonzero P^2 leads to slightly modified formula for x_γ but we sticked to (3) as in realistic QCD–based MC simulations there are other, more important, effects that lead to the smearing of the x_γ distribution. To see which of them is most important we compared, in both direct and resolved channels, our MC results for a) two final massless partons with no parton showers, b) two final partons after they acquire nonzero virtuality, c) jets formed out of final state on mass–shell partons and finally d) realistic hadron jets. It turns out that the most dramatic effect of the smearing, due mainly to hadronization, occurs for the x_γ distribution: instead of a pronounced peak for $x_\gamma = 1$ we get much wider and less pronounced structure peaked at about $x_\gamma = 0.85$, as shown in Fig.1a. Its position and shape is essentially independent of P^2.

To measure the parton structure of the virtual photon requires a suitable signature to separate resolved and direct components. The best candidate remains, even after the smearing shown in Fig. 1a, the x_γ distribution. The resolved component can be enhanced by imposing cuts on other variables. The most effective would be a cut on the pseudorapidity $\eta > 0$, illustrated in Fig. 1b. Unfortunately, in this region there are problems with the separation of hard jets from the proton remnant one. Both experiments [1, 2] therefore restrict their jets to the region $\eta < -0.5$. Another, but less effective way of enhancing the resolved component exploits the fact that the $\mid \Delta\eta \mid$ distribution is broader for the resolved component. In some simulations we therefore imposed also the cut $\mid \Delta\eta \mid > 1$.

To assess the feasibility of measuring PDF of the virtual photon at HERA and to get some idea of what the theoretical predictions look like, we show in Fig.2 for three values of the suppression parameter $\omega = 0.1, 1, 3$ our MC results for the x_γ distribution. We see that the direct component of the virtual photon gives rise to a peak at about $x_\gamma = 0.85$, while the resolved one, wherefrom the virtual photon PDF would be determined, is dominant below

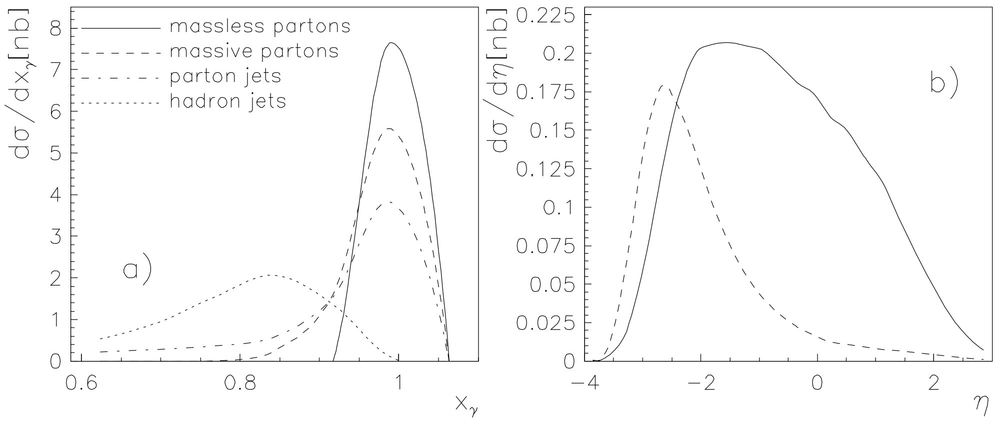

Figure 1: a) Distributions of x_γ in direct channel for $2 < P^2 < 5$ GeV^2, taking into account various smearing effects. b) The η distributions of jets with $E_T > 5$ GeV in direct (dashed curve) and resolved (solid curve) channels.

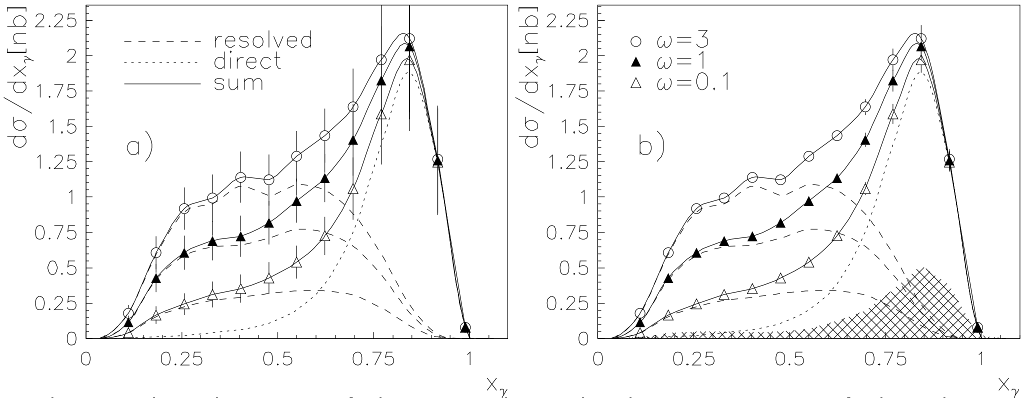

Figure 2: The x_γ distributions of direct and resolved components of the photon and their sum for three values of ω and jets with $\eta < -0.5$. Superimposed are present (a) as well as anticipated future (b) statistical error bars. The hatched in b) area shows systematic error due to 3% uncertainty in jet energy measurement.

$x_\gamma \approx 0.5$. The cross–over point, where the two contributions are equal depends on ω and P^2 but lies around $x_\gamma^{cr} = 0.75$. The peak of the direct photon contribution at $x_\gamma = 0.85$ is reflected in the η distribution (not shown) as the dominance of the direct component in the low η region around $\eta \approx -3$. The error bars superimposed in Fig. 2a on the MC results characterize the present statistical errors, while those in Fig. 2b indicate the effect of increasing the present luminosity by a factor of 50 to 50 pb^{-1}. This increase would allow rather detailed study of P^2 dependence of overall suppression factor. To measure the x_γ dependence of the virtual photon PDF would, however, require still significantly higher luminosity.

The crudest measure of the resolved photon contribution to jet cross–sections is the ratio $R \equiv \sigma^{\mathrm{resolved}}/\sigma^{\mathrm{direct}}$. It depends, beside ω, sensitively on p_T^{min} and also on cuts on η. We consider $p_T^{\mathrm{min}} = 5$ GeV as is the minimal reasonable lower cut–off on p_T^{jet}. Increasing p_T^{min} would significantly improve the possibility of separating direct and resolved components but, on the other hand, lower the statistics. In Fig. 3 we plot the ratio R as a function of P^2 for three

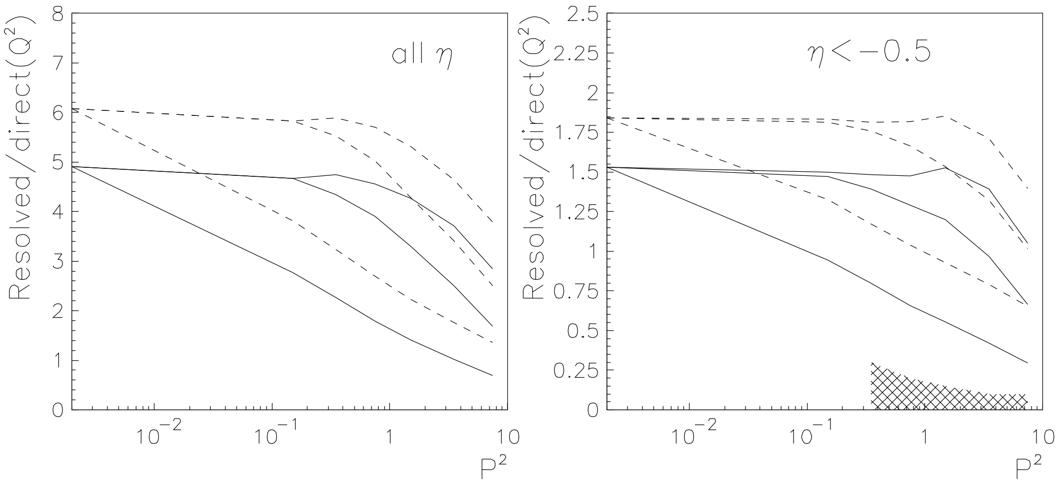

Figure 3: P^2 dependence of the ratio $R \equiv \sigma^{\text{resolved}}/\sigma^{\text{direct}}$. The hatched area shows the systematic error due to 3% uncertainty in jet energy measurement. Solid lines correspond to R as given by generator, the dashed ones to the method based on the x_{cr} cut–off described in the text. The triplets of solid and dashed curves correspond from above to $\omega = 3, 1, 0.1$.

values of ω. The solid curves correspond to R evaluated from the knowledge, available in MC generators, of separate contributions of direct and resolved channels. In real experiments at HERA we may attempt to separate them using the cut on x_γ, defining the resolved contribution by the condition $x_\gamma \leq x_\gamma^{\text{crit}} = 0.75$ and complementarily for the direct one. The corresponding results for R are shown as dashed curves in Fig. 3.

Conclusions:

- Higher luminosity is clearly a precondition to serious studies of virtual photon structure.
- Kinematical region of positive η in hadronic CMS and large $\mid \Delta\eta \mid$ can further enhance the contribution of the resolved component.
- Direct photon component should be observable at about $x_\gamma \doteq 0.85$.
- Generator dependence should be investigated.

References

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