# JET AND INCLUSIVE PARTICLE PRODUCTION IN PHOTON INDUCED COLLISIONS*

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Recent progress in application of higher order QCD calculations to jet and inclusive particle production in photon induced collisions is reviewed. Attention is paid to theoretical uncertainties of such calculations, particularly those coming from the choice of renormalization and factorization scales.

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## 1. Introduction

From the variety of hard processes involving initial state photon I will discuss jet and inclusive particle production in $\gamma p$ and $\gamma\gamma$ collisions with emphasis on recent phenomenological applications. I will concentrate on the discussion of theoretical uncertainties because they are often bigger than experimental errors thereby complicating the interpretation of data.

Let me start with brief recollection of basic facts concerning the structure and hard collisions of protons and photons. For details see [1]. Parton distribution functions (PDF) of the photon depend on the factorization scale, denoted below by $M$, and satisfy the system of evolution equations

$$\frac{d\Sigma(x,M)}{d\ln M^2} = \delta_\Sigma k_q + P_{qq}\otimes\Sigma + P_{qG}\otimes G, \tag{1}$$

$$\frac{dG(x,M)}{d\ln M^2} = k_G + P_{Gq}\otimes\Sigma + P_{GG}\otimes G, \tag{2}$$

$$\frac{dq_{\rm NS}(x,M)}{d\ln M^2} = \delta_{\rm NS} k_q + P_{\rm NS}\otimes q_{\rm NS}, \tag{3}$$

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where $\Sigma(x,M)$, $q_{\rm NS}$ and $G(x,M)$ stand for standard singlet, nonsinglet and gluon distribution functions and the splitting functions $P_{ij}$ and $k_i$ are given as power expansions in $\alpha_{\rm s}(M)$. For the proton the inhomogeneous splitting functions $k_q$ and $k_G$ are absent.

General solution of the evolution equations (1)–(3) can be written as the sum of a particular solution of the full inhomogeneous equations and the general solution of the corresponding homogeneous ones. For instance, the solution of (3) including only the lowest order terms $k_q^{(0)}$ and $P_{qq}^{(0)}$ and vanishing at some factorization scale $M_0$, is given in momentum space as

$$q_{\rm NS}^{\rm PL}(n,M_0,M)=\frac{4\pi}{\alpha_{\rm s}(M)}\left[1-\left(\frac{\alpha_{\rm s}(M)}{\alpha_{\rm s}(M_0)}\right)^{1-2P_{qq}^{(0)}(n)/\beta_0}\right]a_{\rm NS}(n), \quad (4)$$

$$a_{\rm NS}(n)\equiv\frac{\alpha}{2\pi\beta_0}\frac{k_{\rm NS}^{(0)}(n)}{1-2P_{qq}^{(0)}(n)/\beta_0}. \quad (5)$$

It is often claimed that because of the presence of $\alpha_{\rm s}$ in the denominator of (4) quark distribution functions of the photon behave as $\alpha/\alpha_{\rm s}$. As argued in [2] this is misleading and PDF of the photon actually start at the order $\alpha$. The standard assignment of the order of PDF of the photon has important implications for the definition of finite order approximations, but in this talk I will not pursue this point further.

The cross section of inclusive hadron $h$ production in $\gamma p$ or $\gamma\gamma$ collisions has the generic form

$$\sigma(\gamma B\rightarrow hX)\propto\sum_{a,b,c}D_{a/\gamma}(M_\gamma)\otimes D_{b/B}(M_B)\otimes\sigma(ab\rightarrow cX)\otimes D_c^h(M_h)\,, \quad (6)$$

where the sum runs over quarks, gluons and photons (in the direct photon channels) in the photon or proton. The hard partonic cross sections can be expanded in powers of $\alpha_{\rm s}$ as follows

$$\sigma(ab\rightarrow cX)=\alpha_{\rm s}^k(\mu)\sigma^{\rm LO}(ab\rightarrow cX)+\alpha_{\rm s}^{k+1}(\mu)\sigma^{\rm NLO}(ab\rightarrow cX)+\cdots \quad (7)$$

with $k=1$ for direct photon processes and $k=2$ for resolved ones. For jet production fragmentation functions are replaced by some jet algorithm.

## 2. Remarks on phenomenology

In (6)–(7) I have distinguished the factorization scales of the beam particles from the fragmentation scale $M_h$ and the renormalization scale $\mu$. The latter appears only in perturbative expansion of the partonic hard scattering cross sections (7). There is *no theoretical reason* to identify any two or more of these four scales as they come from the treatment of different singularities. Unfortunately, in most phenomenological analyses all the four scales are set equal and identified with some "natural physical scale" Q: $\mu = M_\gamma = M_p = M_h = M = Q$. However, choosing the renormalization scale does not fix $\alpha_{\rm s}$ because $\alpha_{\rm s}(\mu)$ depends beside the renormalization scale also on the renormalization scheme (RS). Consequently, the same choice of the renormalization scale gives different results in different RS! The choice of the RS is in fact as important as that of renormalization scale $\mu$, but there is no "natural" RS! The conventional procedure of working in $\overline{\rm MS}$ RS is entirely *ad hoc.* Choosing the scales and schemes should be based on the investigation of the dependence of finite order approximants on renormalization and factorization scales as independent parameters and should reflect the possible existence of regions of local stability.

In comparing data with theoretical calculations the latter are quoted with estimates of their "theoretical uncertainty". This quantity usually comprises several components: dependence on PDF and FF, hadronization effects and scale and scheme variation. Hadronization corrections are usually claimed to be small, but as we shall see in the case of jet and inclusive particle production in $\gamma\gamma$ collisions it does not have to be always the case and further investigation of this point is certainly worth the efforts.

Whereas the uncertainty reflecting the dependence on PDF, FF and hadronization is reasonable well-defined, the conventional way of estimating the uncertainty due to the freedom of choice of scales and scheme is definitely not. Identifying all scales with some "natural scale" $Q$ and varying this common scale $M$ typically in the interval $Q/2 \leq M \leq 2Q$ makes little sense. First, the results still depend on the selected renormalization scheme, and, second, the chosen range of multiplicative factor $(1/2, 2)$ is again entirely arbitrary.

Another important aspect of the comparisons of theory with data concerns the relation between LO MC event generators, like HERWIG, RAPGAP and PYTHIA, and NLO parton level calculations. Some of the features of full NLO QCD effects are mimicked within LO MC event generators by means of parton showers and noncollinear kinematics of initial state parton emissions. Moreover, LO MC use different input (PDF, FF and $\alpha_{\rm s}$) which were extracted in LO global analysis from data, and so have a chance to describe also other data.

## 3. Jet production in $\gamma p$ and $\gamma^* p$ collisions

Theory and phenomenology of jet production in (quasi)real $\gamma p$ collisions has recently been reviewed in [3]. Extensive application to HERA data has lead to a good agreement, except for some IR sensitive quantities, but suffers from non-negligible scale dependence of existing QCD calculations.

In this talk I will concentrate on the phenomenological application of QCD calculations to HERA data in the kinematic region of moderate $Q^2$, where the transition region between photoproduction and deep inelastic scattering takes place. This region is of particular interest because of the expected manifestation of effects due to BFKL dynamics. Unfortunately, it is also the region, where playing with scales does wonders and may easily mask the presence of new phenomena. Although in this region the concept in resolved (virtual) photon does not have to be introduced it turns out to be very useful phenomenologically.

From the NLO parton level Monte Carlo codes appropriate for this kinematic region three are most frequently used in phenomenological applications: DISENT [4], NLOJET [5] and JETVIP [6]. From them only JETVIP includes the contribution of resolved virtual photon and only NLOJET offers the option of calculating three jet production at the NLO.

Out of many interesting analyses of jet production I will briefly mention two. The series of investigations of dijet production in the region $Q^2 \ll E_{\mathrm{T}}^2$ has shown convincingly the importance of the contributions of resolved virtual photon for the description of HERA data [7]. The relevance of the concept of resolved virtual photon as an approximate method for including higher order direct photon contributions has been studied in [8] using NLOJET in the three jet mode. These studies have also demonstrated the importance of the contributions of the longitudinal virtual photon.

Much attention has recently been paid to forward jet production at HERA in the kinematic region where $Q^2/E_{\mathrm{T}}^2$ is around unity. This region has been suggested [9] as suitable place to look for manifestations of BFKL dynamics. However, identification of these effects has turned out to be complicated by the contributions of the resolved virtual photon, as well as by large scale uncertainties of QCD calculations.

The ZEUS [10] and H1 data [11] of forward jet production in the kinematic region $0.5 \leq E_{\mathrm{T}}^2/Q^2 \leq 2$, $E_{\mathrm{T}} \geq 5$ GeV and $p_z/E_p \geq 0,05$ have been analysed in NLO QCD using JETVIP and including the resolved virtual photon contribution [12]. The common scale $M$ was set to $M = \sqrt{Q^2+E_{\mathrm{T}}^2}$ and allowed to vary between $M = \sqrt{Q^2+E_{\mathrm{T}}^2/3}$ and $M = \sqrt{Q^2+3E_{\mathrm{T}}^2}$.

The results, presented in Fig. 1 show that the direct photon contribution alone undershoots data significantly, but the inclusion of NLO resolved photon contribution leads to nice agreement! However, as shown by the dotted and dashed curves, this agreement relies crucially on the chosen scale.

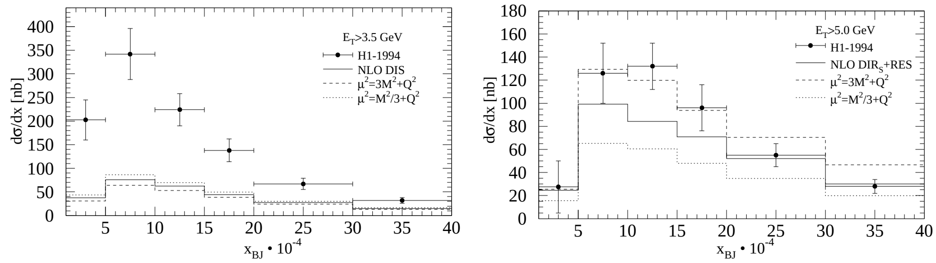


Fig. 1. Comparison of H1 data [11] on forward jet production with NLO QCD calculation of [12].

## 4. Inclusive particle production in $\gamma^* p$ collisions

Similarly as for jets the interest in this process is motivated primarily by search for BFKL effects. In [13] the recent H1 data on large $p_{\rm T}$ forward $\pi^0$ production [14] in the region of moderate $Q^2$ were compared to QCD calculations including only the direct photon contribution. Setting the common scale $\mu = M = \sqrt{(Q^2+E_{\rm T}^2)/2}$ the authors found a nice description of the H1 data for broad range of values of $Q^2$ (see left part of Fig. 2). However, they noted strong dependence of their results on $M$. Varying their preferred value of $M$ by factor of mere $\sqrt{2}$ their results change by a factor of more than 2! This significant scale dependence in their view "suggests the presence of non-negligible NNLO effects" and together with large $K$-factors

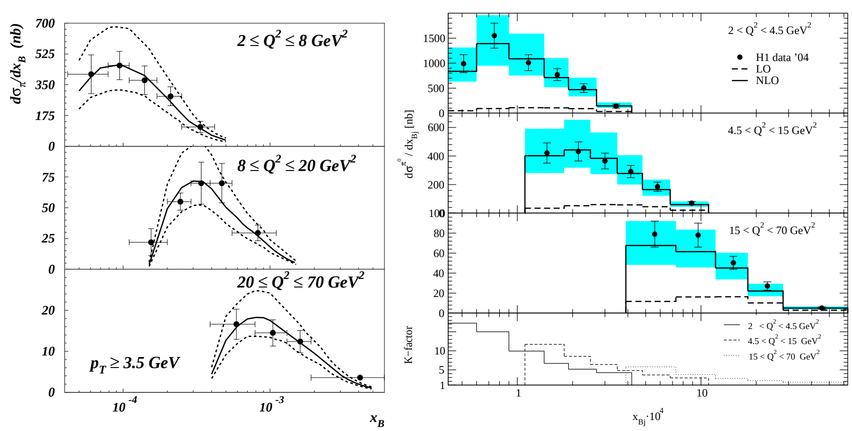


Fig. 2. The H1 data on forward $\pi^0$ production [14] compared to calculations of [13] (left) and [15] (right), which include only direct photon contributions. The band between two dashed curves in the left part and the shaded bands at right correspond to the variation of the common scale in the interval $\sqrt{(Q^2+E_{\rm T}^2)/4} \leq M \leq \sqrt{Q^2+E_{\rm T}^2}$.

"restraining, for the moment, any empirical suggestion of dynamics different to plain DGLAP evolution". I share their reservations.

The same H1 data on forward $\pi^0$ have been analyzed also in [15] using the same input and identical choice of scales as in [13]. Not surprisingly they have also found a good agreement with H1 data (see right plot of Fig. 2) and factor of 2 difference between their results corresponding to $M \equiv \sqrt{(Q^2+E_{\rm T}^2)/4}$ and $M \equiv \sqrt{Q^2+E_{\rm T}^2}$. Compared to [13] the authors of [15] are more optimistic and claim that their "default predictions, endowed with theoretical uncertainties estimated by moderate unphysical scale variations led to a satisfactory description of the HERA data in the preponderant part of the accessed phase space". In view of the arbitrariness of the standard choice of the common scale I consider their conclusion difficult to justify.

This is illustrated by the most recent analysis of the same H1 data performed in [16] taking into account the contribution of the resolved virtual photon. This paper includes the most detailed analysis of the dependence on different scales, finding very different dependence on the renormalization, factorization and fragmentation scales. In particular "large instability is observed when varying independently the renormalization and fragmentation scales". Default calculations (see Fig. 3) have been performed for the common scale set to $M \equiv \sqrt{Q^2+E_{\rm T}^2}$. Compared to [13] and [15] their common scale is bigger by a factor $\sqrt{2}$ and thus their NLO direct contribution substantially smaller with the resolved photon contribution filling the gap! However, again large scale sensitivity "prevents a really quantitative prediction for the single pion inclusive distribution in the forward region."

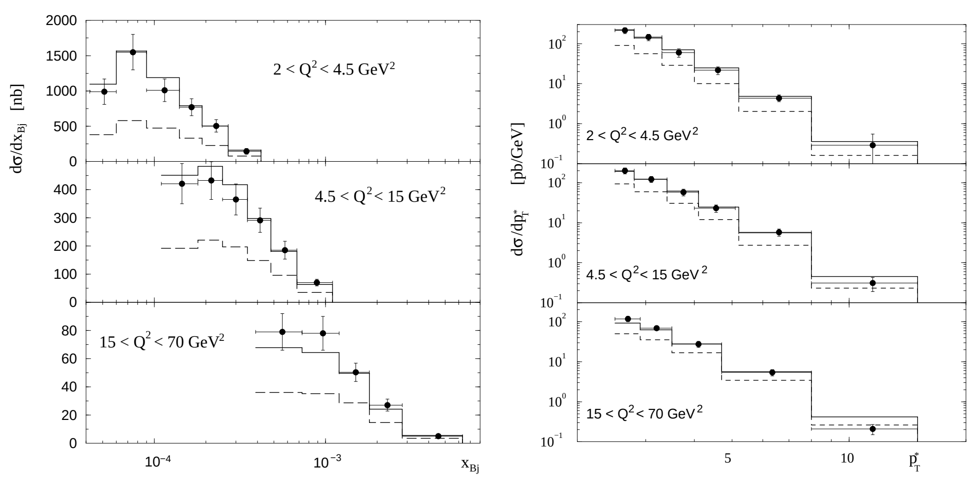


Fig. 3. The H1 data on forward $\pi^0$ as a function of $x_{\rm Bj}$ for $p_{\rm T} > 2.5$ GeV (left) and of $p_{\rm T}$ for three different intervals in $Q^2$ compared to calculations of [16] with (solid curves) and without (dashed curves) the resolved photon contribution.

## 5. Jets and inclusive particle production in $\gamma\gamma$ collisions

Inclusive particle production in $\gamma\gamma$ collisions has been a challenge for perturbative QCD already at PETRA and has become so even more at LEP2. The recent L3 data on charged particle production in $\gamma\gamma$ collisions [17], shown in Fig. 4, are far above the NLO QCD predictions [18] in the range of transverse momenta, where the direct–direct contribution dominates and where there is thus little chance that higher order QCD corrections could make any difference. There is, however, one aspect of the L3 analysis which

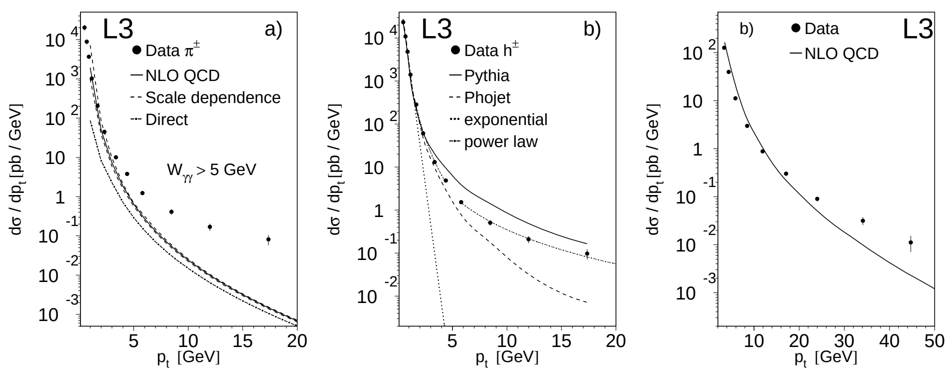


Fig. 4. Left: the comparison of L3 data on inclusive charged particle production in $\gamma\gamma$ collisions [17] with the NLO parton level calculation of [18]. Middle: the same data compared to the predictions of PYTHIA and PHOJET LO event generators. Right: L3 data on jet production compared to NLO QCD calculations of [20].

deserves closer attention. As shown in the middle plot of Fig. 4, precisely in the region where data exceed by more than order of magnitude NLO QCD prediction there is a huge difference between two LO MC event generators, PYTHIA and PHOJET, the former even exceeding the data! Both these MC use the same LO cross sections, which dominate the large $p_{\mathrm{T}}$ region, but nevertheless lead to vastly different shape of the distribution. This represents a warning that the effects beyond purely perturbative stage of the process and where the MC do differ, may play a crucial role for the tail of distributions like that in Fig. 4.

The disagreement between L3 data and QCD calculations extends, as shown in the right plot of Fig. 4, also to jet production. Note that for jets both the shape and magnitude of L3 jet data [19] and NLO QCD predictions of [20] are significantly different. However, also in this case PYTHIA lies above and PHOJET below the L3 data. The puzzle is still there.

### 6. Summary and conclusions

Jet and inclusive hadron production in $\gamma p$, $\gamma^* p$ and $\gamma\gamma$ collisions has provided wealth of new data for the comparison with higher order QCD calculations. Unfortunately, in the most interesting processes, like forward jet and hadron production at HERA, where signals of new physics are expected, theoretical predictions are burdened with large uncertainties stemming primarily from strong dependence on renormalization, factorization and fragmentation scales. The standard procedure of identifying all these scales and setting them equal to some physical scale characteristic for the process lacks theoretical justification and, moreover, is ambiguous as it implicitly assumes working in *ad hoc* chosen $\overline{\mathrm{MS}}$ RS. Systematic investigation of scale dependence of QCD calculations should be performed with the aim of formulating better justified procedure for choosing the various scales.

In theoretically seemingly clean case of jet and inclusive hadron production in $\gamma\gamma$ collisions perturbative QCD faces serious challenge to explain recent L3 data.

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