# High–$p_T$ Particles in the Forward Region at HERA

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**Abstract:** In order to probe the dynamics of parton evolution in deep inelastic scattering at small $x$ , high–$p_T$ particles produced centrally in pseudorapidity are studied. In the BFKL mechanism gluon radiation is expected to be more abundant than for DGLAP evolution with strong ordering of the gluon transverse momenta, leading to harder $p_T$ spectra. The proposed measurements require charged particle tracking capability as much forward as possible in the HERA laboratory frame, for example with a Very Forward Silicon Tracker, and high luminosity for detailed studies.

HERA allows the study of a new kinematical regime in deep inelastic scattering, reaching very small values of Bjorken-$x$ ($\approx 10^{-5}$) with $Q^2$ still a few GeV$^2$ , such that perturbation theory can be applied. It is an open theoretical question whether HERA data can still be described with the conventional DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) parton evolution equations [1] which are derived for not too small $x$ and correspond to a resummation of terms proportional to $(\alpha_s \ln(Q^2/Q_0^2))$, or whether terms proportional to $(\alpha_s \ln 1/x)^n$ become important, which are treated in the BFKL (Balitsky-Fadin-Kuraev-Lipatov) equation [2][1]. The two approximations lead to different constraints for the gluons which can be emitted in the parton evolution chain (Fig. 1a). The leading log DGLAP evolution corresponds to a strong ordering of the transverse momenta $k_T$ (with respect to the proton beam) in the parton cascade ($Q_0^2 \ll k_T{}_1^2 \ll ...k_T{}_i^2 \ll ...Q^2$ ), while in the BFKL evolution arbitrary $k_T$ are possible [4]. It appears that the structure function measurements are too inclusive to distinguish the different evolutions [5]. The hadronic final state emerging from the cascade may be more sensitive to the new type of evolution (see e.g. [6]). However, hadronization effects screen to some extent the parton dynamics from direct observation [7].

QCD predictions for the hadronic final state are extracted from Monte Carlo models, which incorporate the QCD evolution in different approximations and utilize phenomenological models for the non-perturbative hadronization phase. The MEPS (Matrix Element plus Parton Shower) [8] and the HERWIG [11] models invoke leading log DGLAP parton showers with strong $k_T$ ordering. In the colour dipole model (CDM) [9], an unordered parton emission scenario is realized, and in that respect it is similar to the BFKL evolution [12]. Gluon radiation in MEPS and HERWIG is suppressed w.r.t. CDM without the $k_T$ ordering constraint (see Fig. 1b)[2]. However, all models give a satisfactory overall description of current HERA final state data [13].

[1]More recently, in the CCFM approach [3] an equation for both small and large $x$ has been provided.

[2]All distributions shown are in the hadronic centre of mass system (CMS), and are normalized to the number of events $N$ which enter the distribution. The pseudorapidity $\eta$ in the CMS is defined as $\eta = -\ln \tan\theta/2$, with $\theta$ measured with respect to the virtual photon direction.

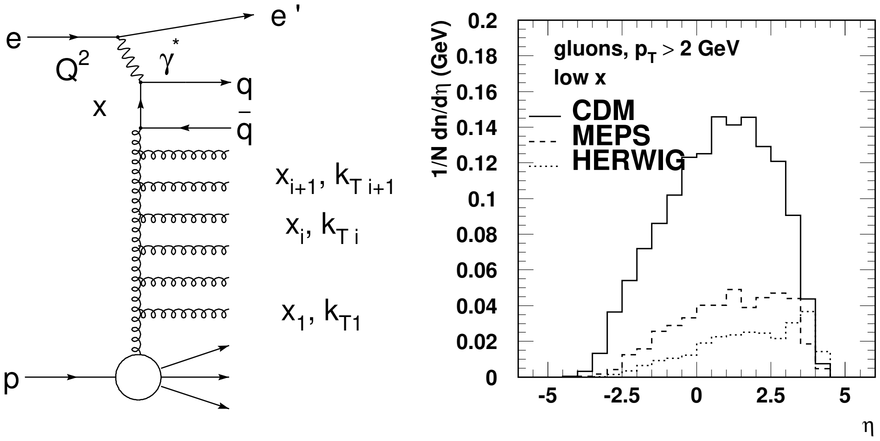


Figure 1: **a)** *Parton evolution cascade.* **b)** *The multiplicity of hard gluons with* $p_T > 2$ GeV *as a function of* $\eta$ *for events at small* $x$, $\langle x \rangle$*=0.00037 at* $\langle Q^2 \rangle \approx 14$ GeV$^2$ *. The proton remnant direction is to the left.*

During the HERA workshop it was found that inclusive charged particle transverse momentum ($p_T$) spectra offer a handle to disentangle hard perturbative from soft hadronization effects [14]. The hard tail of the $p_T$ spectra (see Fig. 2a) is sensitive to parton radiation from the cascade. The CDM generates a harder tail than LEPTO and HERWIG with suppressed gluon radiation. One can thus hope to study the parton evolution dynamics with high–$p_T$ particles, and discriminate between the different scenarios. Here the implications for the future experimentation at HERA will be investigated.

The measurement of the hard tail of the $p_T$ spectrum shown in Fig. 2a would pose a challenge to QCD (in fact, a QCD calculation for the rate of high $p_T$ forward pions, based upon the BFKL equation, has just become available [15]), and it has been investigated what experimental precision can be achieved. In Fig. 2b the luminosity needed is shown to reduce the statistical error for a given $p_T$ bin to the same level as the expected systematic error [16] for that bin. The luminosity estimate is based upon the CDM. The binning was chosen such that the systematic error is constant ($\approx 5\%$) for all bins. In order to measure the $p_T$ spectrum at $p_T = 12$ GeV with a precision of 5% for both statistical and systematic error an integrated luminosity of 300 pb$^{-1}$ would be needed. The quest for a measurement at large $p_T$ (and large luminosity) is also motivated by the expectation that perturbative QCD will be more reliable there.

As a measure of the rate of hard particles as a function of pseudorapidity, the multiplicity flow of charged particles with $p_T > 2$ GeV is shown vs. $\eta$ in Fig. 3. Events from two kinematic bins, one at "large $x$ " ($\langle$x$\rangle$=0.0023) and one at "small $x$" ($\langle$x$\rangle$=0.00037) are compared, with $\langle Q^2 \rangle \approx 14$ GeV$^2$ approximately constant. At high $x$ the differences between the model predictions are not very big, but at small $x$ the models deviate by a large amount. The CDM produces much more particles with $p_T > 2$ GeV than MEPS and HERWIG, and the discrepancy increases with the distance from the current system. That difference has its origin in the very different gluon emission pattern, see Fig. 1b.

The sensitivity to this effect with typical (here H1 [17]) HERA tracking devices is indicated. It is clear that such a measurement requires charged particle tracking capability as far "forward" (into the remnant direction) as possible. The so called "forward" region of the HERA detectors corresponds to the central region in the hadronic CMS. Rather than measuring with

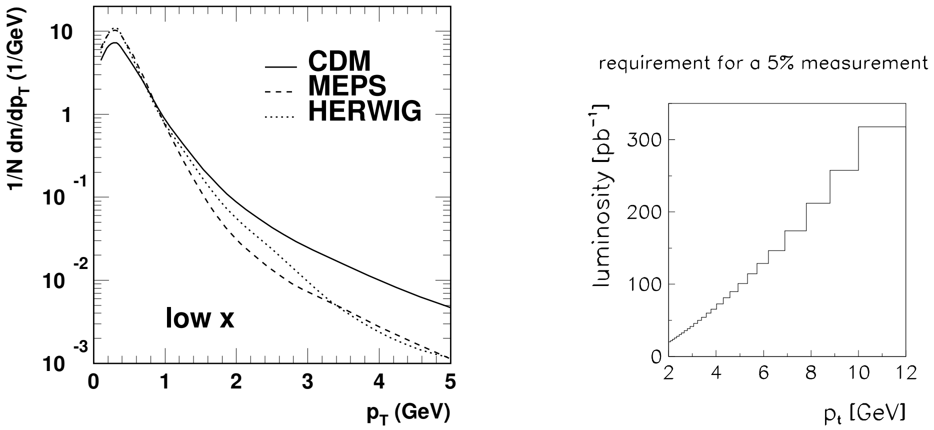


Figure 2: **a)** *The $p_T$ spectra for charged hadrons from $0 < \eta < 2$ at $\langle x \rangle$=0.00037 and $\langle Q^2 \rangle \approx$* 14 GeV$^2$ *.* **b)** *The luminosity needed for a statistical precision of 5% for a given bin in $p_T$.*

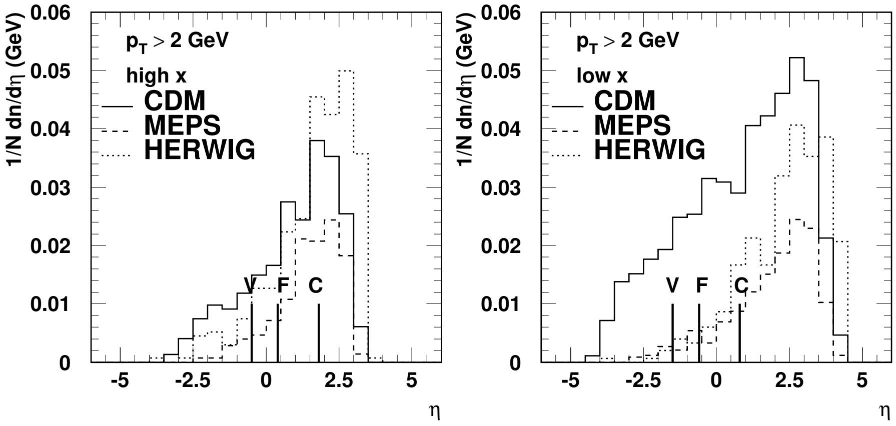


Figure 3: *Multiplicity flow vs. $\eta$ for charged hadrons with $p_T > 2$ GeV at* **a)** *"high" $x$ and* **b)** *"low" $x$ . The current direction is to the right. Indicated are the acceptance limits of the H1 central tracking system (C, $\theta_{\rm lab} > 20^\circ$), the forward tracking system (F, $\theta_{\rm lab} > 7^\circ$), and a hypothetical very forward tracking system (V, $\theta_{\rm lab} > 3^\circ$). Here $\theta_{\rm lab}$ is measured in the laboratory system w.r.t. the proton direction.*

high precision a relatively small effect, which may be masked by hadronization and other uncertainties, it is preferable to measure a large effect with moderate precision. Therefore a "Very Forward Tracker" is proposed which covers angles down to $\theta_{\rm lab} = 3^\circ$.

Here a feasibility study for the case of H1 is presented. A silicon tracker similar to the H1 Backward Silicon Tracker (BST), but with radial ("$\phi$") readout strips to measure curvature, could be positioned suitably in the forward region [18]. It would consist of four to eight disks mounted perpendicular to the beam line, and sit in between the central drift chamber and the beam pipe. There is space available between $z \approx 40 - 120$ cm, with $z$ being the longitudinal distance from the interaction point. Radially, the sensitivity would extend from 6 to 12 cm. Angular coverage from $\theta_{\rm lab} = 3^\circ$ to $8^\circ$ would be possible, matching with the end of the H1 forward tracker acceptance at $\theta_{\rm lab} = 7^\circ$. With four readout planes, spaced 0.1 m apart, and with a pitch of 50 $\mu$m, a momentum resolution of $\delta p_T / p_T \approx 10\% \cdot p_T$ can be achieved. It can be improved by a vertex constraint. Since the effective HERA beam width is 70 $\mu$m (vertical) by 330 $\mu$m (horizontal), the event vertex needs to be defined by tracks measured in the existing central silicon tracker [18] (impact parameter resolution 60 $\mu$m), reducing it to roughly 50 $\mu$m by 50 $\mu$m. When such a vertex constraint is applied, the momentum resolution could be improved to $\delta p_T / p_T \approx 2-3\% \cdot p_T$. That is certainly sufficient for the simple measurement of the $p_T$ spectra discussed here. More detailed studies and simulations would be neccessary to study the occupancy in the detector and questions of pattern recognition. The detector would cost 250k-500k DM (estimate based upon the BST costs), depending on the number of silicon planes.

The HERA luminosity upgrade would have an impact on the VFT. When dipoles are inserted into the H1 detector, perhaps up to the faces of the central drift chamber, that would require a larger diameter beam pipe to let out the produced synchrotron radiation. The existing BST could no longer be used, and the VFT would need to be redesigned according to the larger diameter beam pipe. Of course other options could also be explored. For example, H1 is building a Very Low Q-square (VLQ) tracker for the backward region based upon GaAs technology. Again, this device would not fit on a larger diameter beam pipe. However, it may be possible to save on the new detector by re-using the existing electronics.

Initially, for a minimal meaningful measurement a moderate integrated luminosity of 10 pb$^{-1}$ would already be sufficient. For that purpose, one could even think of a short dedicated HERA run with minimal, but optimized instrumentation, including only the trackers and backward electron detection devices.

In this study, however, only the sensitivity of charged particle spectra[3] to suppressed or abundant gluon radiation scenarios has been exploited. It should be possible to construct variables based on correlations between high–$p_T$ particles which probe the gluon dynamics, for example $k_T$ ordering or recombination effects, more directly and locally. Considering the rate of such particles (Fig. 3), high luminosity would be needed to have enough events with pairs of high–$p_T$ particles. Again, a large forward acceptance would increase the evolution length that can be probed, as well as the statistics of high–$p_T$ particle pairs for correlation studies.

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