Semi–inclusive Asymmetries with Polarized Proton Beams at HERA

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Abstract

The prospects of semi-inclusive measurements with polarized proton beams at HERA are discussed. Detailed simulations show that one can disentangle the valence-quark and sea-quark contribution to the polarized structure function $g_1(x)$ in the small x-domain, if the equivalent of 1000 pb^{-1} of data are collected. It is also shown how semi-inclusive charged-current events can provide information on the relative importance of the spin contribution of the anti-s and anti-d sea quarks. Moreover, various methods to determine the fragmentation functions in this kinematical domain are presented.

1 Introduction

While inclusive measurements are only sensitive to the sum of all quark flavors weighted by the square of their charge, semi-inclusive measurements allow to disentangle the valence-quark and sea-quark contributions to structure functions [1]. Moreover they allow for the measurement of fragmentation functions, which are sensitive to the nature of final state interactions.

Fragmentation functions and parton distributions cannot be determined at the same time, as there are too many unknowns in the cross section. But one can make important cross checks by fixing the parton distributions by common parameterizations and determining subsequently the fragmentation functions.
We compare three different methods of extracting fragmentation functions in section 2 and show to which extend these methods allow to disentangle the flavor structure of the nucleon. In section 3 semi-inclusive measurements of pure γ-exchange events at small x and Q^2 are discussed. We show that with polarized proton beams at HERA interesting information on the ratio of valence- and sea-quark distributions can be obtained. In the last section charged current (CC) events at high Q^2 are discussed, where semi-inclusive measurements might give some very useful signature in case the strange- or the down-sea should be unexpectedly large.

2 Fragmentation functions

The primary goal of semi-inclusive measurements is to identify those particles (leading particles) which contain a quark which has been struck by the incoming photon or weak gauge boson. Generally, for the semi-inclusive cross section the following decomposition is chosen which defines the fragmentation functions D_q^h:

$$\begin{aligned} \frac{d\sigma_{\text{unpol.}}}{dxdQ^2dz} &= \frac{2\pi\alpha_{\text{em}}^2}{Q^4}\sum_f e_f^2(1+(1-y)^2)q_f(x)D_q^h(z) \\ \frac{d\sigma_{\text{pol.}}}{dxdQ^2dz} &= \frac{2\pi\alpha_{\text{em}}^2}{Q^4}\sum_f e_f^2(1-(1-y)^2)\Delta q_f(x)D_q^h(z) \quad , \end{aligned} \tag{1}$$

where the unpolarized and polarized fragmentation functions are supposed to be equal. (Note that this assumption is certainly violated at some level. The size of such violations can be determined experimentally by e.g. analyzing the x-dependences for fixed target experiments.) x is the usual Bjorken-x, $y = P\cdot q/(P\cdot k)$, $z = P\cdot P_h/(P\cdot q)$ with P being the momentum of the incoming nucleon, k of the incoming lepton, q of the exchanged photon, and P_h of the measured hadron h. $q_f, \Delta q_f$ denote the unpolarized and polarized parton densities with flavor f. $Q^2 = -q^2$.

In general for extracting parton distributions from semi-inclusive measurements one normally identifies the favored and unfavored fragmentation functions:

$$\begin{aligned} D_u^{\pi+}(z) = D_{\bar{d}}^{\pi+}(z) &= D_{\bar{u}}^{\pi-}(z) = D_d^{\pi-}(z) \quad \text{(favored)} \\ D_u^{\pi-}(z) = D_{\bar{d}}^{\pi-}(z) &= D_{\bar{u}}^{\pi+}(z) = D_d^{\pi+}(z) \\ = D_s^{\pi+}(z) = D_{\bar{s}}^{\pi+}(z) &= D_{\bar{s}}^{\pi-}(z) = D_s^{\pi-}(z) \quad \text{(unfavored)} \quad . \end{aligned} \tag{2}$$

The form of the fragmentation function depends on the way the hadron h is measured. Therefore in principle no normalization independent of the extraction procedure is possible. Usually, the normalization is fixed by the second moment $\int_0^1 zD(z)dz$. As we will discuss three completely different ways of isolating leading particles, we base our normalization simply on the cross section formula, this is reasonable because one of the discussed extraction procedures allows for more than one 'leading particle' per event, while the two others do not. The following three extraction methods are regarded:

- **Inclusive method:** All final state particles are taken into account.
- **Pion/kaon method:** The leading particle is the charged pion or kaon with the maximum z of all charged pions or kaons.
- **Maximum method:** The leading particle is the final state particle which carries the maximum z of all final state particles (including photons and baryons).

The pion/kaon method is inspired by the fact that leading particles are mostly mesons. For our Monte-Carlo simulations we use the program LEPTO-6.5 [2] for event generation together with JETSET-7.4 [3] for hadronization.

In Fig. 1 the three methods of extraction are compared with each other in a 4π simulation without detector acceptances in order to concentrate on the energy dependence. For $z > 0.5$ all

methods result in the same values as to be expected by energy conservation, but the inclusive method has by far the largest multiplicity, while the maximum method gives no particles for $z < 0.2$ for HERMES and $z < 0.1$ for H1 energies.
Fig. 2 shows in an ideal 4π simulation how well the assumed combined isospin and charge conjugation (IC) symmetry, i.e $D_u^{\pi^+} = D_{\bar{d}}^{\pi^+}$ in the favored case and $D_{\bar{u}}^{\pi^+} = D_{\bar{d}}^{\pi^+}$ in the unfavored case, is fulfilled. Within the Lund string fragmentation model with its standard settings we observe deviations from this IC-symmetry assumption only in the small z region for HERMES energies which might be a hint that the identification of favored and unfavored fragmentation functions is for HERA-energies even better justified than for experiments with lower energies.

Another very essential question is to ask whether an extracted particle is really a leading particle, i.e that it contains a struck quark or at least a quark which has the same flavor as the quark hit by the incoming photon. For this purpose we regard the ratio of the favored fragmentation functions of a hadron h to all fragmentation functions of the same hadron and define this quantity as purity P_h

$$P_h = \frac{\sum_{q \in \text{favored}} D_q^h}{\sum_q D_q^h} \quad . \tag{3}$$

There exist deviating definitions of purity [4], but all agree in so far as for purity of 1 all fragmentation processes are favored ones. The smaller the purity, the less reliable is the identification of leading particles. In Fig. 3 we plot the purity for HERMES and H1 energies again in an ideal 4π simulation for charged pions and kaons. For pions the purity for small z is nearly independent of the energy. For large z it reaches up to 90% for H1 energies, but only up to 70% for lower energies. For the kaonic purities for the HERMES energies a charge conjugated anomaly is visible which changes its sign from $K^+ \longrightarrow K^-$.

In summary we find that with the H1 energies deviations from IC symmetry are negligible and that the identification in favored and unfavored fragmentation functions is better fulfilled than for lower energies.

3 Semi-inclusive asymmetries for γ-exchange at small x

At small x, in the unpolarized case, the sea is dominating over the valence quarks. Polarized proton beams at HERA would allow to determine additional combinations of valence and sea quark distributions. The following two asymmetry combinations are of interest:

$$\begin{aligned}
\Delta\sigma/\sigma(\pi, val) &:= \frac{\Delta N(\pi^+) - \Delta N(\pi^-)}{\Sigma N(\pi^+) + \Sigma N(\pi^-)} = \mathcal{D}\frac{(4\Delta u_v - \Delta d_v)(D - \overline{D})}{(4u_{\text{tot}} + d_{\text{tot}})(D + \overline{D}) + 2s\overline{D}} \ , \\
\Delta\sigma/\sigma(\pi, tot) &:= \frac{\Delta N(\pi^+) + \Delta N(\pi^-)}{\Sigma N(\pi^+) + \Sigma N(\pi^-)} = \mathcal{D}\frac{(4\Delta u_{\text{tot}} + \Delta d_{\text{tot}})(D + \overline{D}) + 2\Delta s\overline{D}}{(4u_{\text{tot}} + d_{\text{tot}})(D + \overline{D}) + 2s\overline{D}} \ .
\end{aligned}$$

$D, \overline{D}$ are the favored and unfavored fragmentation functions as defined in Eq. 2. $\mathcal{D}$ is the depolarization factor, $\Delta N(\pi^+), \Sigma N(\pi^+)$ the difference and the sum, respectively, of the π^+ multiplicities for the two different spin configurations. In the numerator we consider the sum and the difference of the polarized multiplicities $\Delta N(\pi^+)$ and $\Delta N(\pi^-)$. The sum of both contains contributions from the valence and the sea quarks, while the difference is only sensitive to the valence-quark distributions. For the unpolarized parton distributions at small x, the valence contribution is

small, namely on the percent level. Consequently, in the denominators of Eq. 4 only sea-quark parton distributions contribute effectively.

For pions we choose in order to maximize the luminosity the inclusive extraction method, but require $z > 0.2$. We make no further restrictions than those which are given by the limitations of the H1 detector and the HERA itself ($E_p = 820$ GeV, $E_e = 27.5$ GeV) :

$$\begin{aligned} 0.01 < \quad & y & < 0.9 \\ 0.0001 < \quad & x & < 0.01 \\ 177 \text{ deg} < \quad & \Theta_e^{(\text{scat})} & \\ 5 \text{ GeV} < \quad & E_e^{(\text{scat})} & \\ 0.15 \text{ GeV/c} < \quad & p_{\perp\pi,K}^{\text{track,lab}} & \\ 20 \text{ deg.} < \quad & \Theta_{\pi,K}^{\text{track,lab}} & < 150 \text{ deg.} \quad . \end{aligned} \tag{4}$$

For our polarized MC simulations we use a new version of PEPSI [5]. Presently one can only speculate about the behavior of g_1 at small x. Gehrmann/Stirling LO Gluon A (GSA) [6] for example, assumes g_1 for H1 energies to be positive, i.e a positive sea-quark polarization at small x, while the opposite assumption (negative g_1 at small x) is made by GSRV LO STD [7]. Both parameterizations use the LO set [8] for the unpolarized parton distributions. This behavior is well reflected in the semi-inclusive asymmetry $\Delta\sigma/\sigma(\pi, tot)$ in Fig. 4, where at $x < 10^{-3.5}$ the simulation for the GRSV LO STD shows a negative value while the corresponding MC-values for the Gehrmann/Stirling set still remain positive. It would be interesting to check experimentally how the sea and valence distributions behave separately. This can be determined experimentally by measuring the valence asymmetry $\Delta\sigma/\sigma(\pi, val)$ (see Fig. 5). For both sets the valence contribution is of the same size within the error bars. It becomes small for decreasing x and points to a dominant sea at small x. If, e.g., the valence asymmetries would show nearly the same behavior as the total asymmetries $\Delta\sigma/\sigma(\pi, tot)$ then the polarized valence contribution would be dominant.

In this way semi-inclusive measurements provide an important tool to disentangle at small x the valence and the sea contributions. These measurements can only be done in the foreseeable future with polarized proton beams at HERA.

4 Semi-inclusive measurements for W^- exchange

While semi-inclusive pionic asymmetries allow to separate the valence and the sea contributions to structure functions, one can distinguish positively from negatively charged flavors via $W^\pm$ exchange. At $Q^2 > 600$ GeV^2 those events are a frequent subprocess in DIS. They can be identified by the missing momentum. In the semi-inclusive case we deal with asymmetries of the form

$$\mathcal{A}(W^-, h) \;=\; \frac{1}{P_e P_p} \frac{\Delta\sigma^h}{\sigma^h}\bigg|_{W^-} = \frac{\Delta u D_u^{h,W} - (y-1)^2(\Delta\bar{s} D_{\bar{s}}^{h,W} + \Delta\bar{d} D_{\bar{d}}^{h,W})}{u D_u^{h,W} + (y-1)^2(\bar{s} D_{\bar{s}}^{h,W} + \bar{d} D_{\bar{d}}^{h,W})} \quad , \tag{5}$$

where h is an outgoing hadron. $D_q^{h,W}$ describes the charged current fragmentation function. As opposed to the neutral current exchange, the struck quark changes its flavor to a flavor

with opposite isospin within the same generation, except for flavor mixing. The identification $D_{\bar{s}}^{h,W} \equiv D_{\bar{c}}^{h}$ is plausible, but may be wrong because of kinematic differences.

For given parton distributions, one can analyze these asymmetries with regard to quark flavor:

- W^- triggers only on positively charged flavors.
- $\mathcal{A}(W^-, \pi^+)$, $\mathcal{A}(W^-, \pi^-)$ differ only with respect to the anti-strange quark contribution.
- $\mathcal{A}(W^-, K^+)$, $\mathcal{A}(W^-, K^-)$ differ only with respect to the anti-down quark contribution.

The pionic and kaonic asymmetries are given in Fig. 6. The same machine parameters are used as in the previous section (see Eq. 4). The corresponding asymmetries for the W^+ case are unfortunately much smaller. The error bars are given for a luminosity of 200 pb^{-1} per relative polarization and polarization degree of 70% for the electron and the proton beam each. As the $\bar{s}$ and $\bar{d}$ contributions are small compared to the u-quark distribution, in our simulation the pionic and kaonic asymmetries are nearly equal. But if $\bar{s}$ and $\bar{d}$ would be much larger than assumed in the parameterization of GRSV 96 STD LO, one would recognize significant deviations.

5 Conclusions

Semi-inclusive measurements at an upgraded HERA with polarized proton beams and a luminosity of 1000 pb^{-1} can provide a key for understanding the valence and sea behavior at small x. Important cross checks for the u-quark dominance over $\bar{s}$ and $\bar{d}$ distributions can be done with polarized CC experiments. Moreover, polarized proton beams at HERA will offer the possibility to test several assumptions and models of fragmentation functions.

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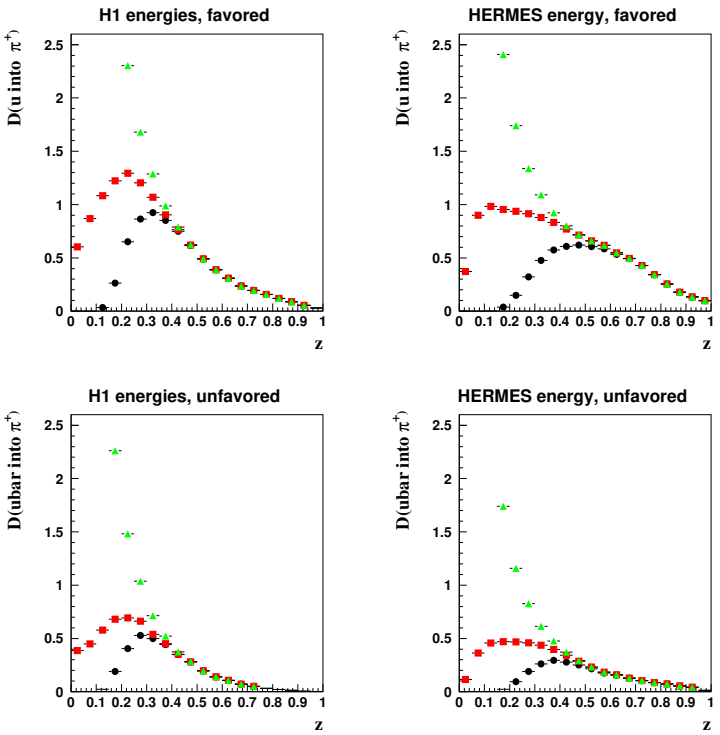

Figure 1: Comparison of the three different extraction methods: triangles - inclusive method, squares - pion/kaon method, circles - maximum method. Ideal 4π simulation.

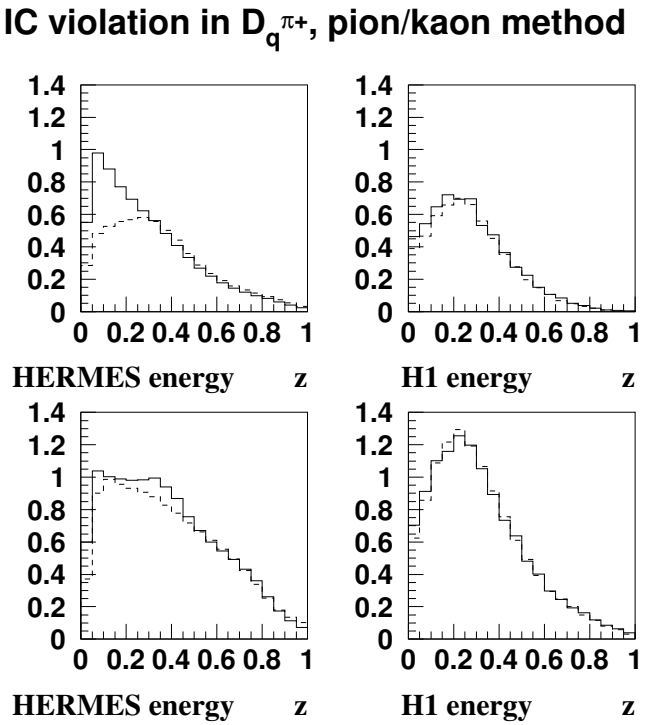

Figure 2: Energy dependence of the IC-violation with respect to HERMES energies and H1 energies. Ideal 4π simulation. Above: solid line $D_d^{\pi+}$, dashed line $D_{\bar{u}}^{\pi+}$; below: solid line $D_{\bar{d}}^{\pi+}$, dashed line $D_u^{\pi+}$.

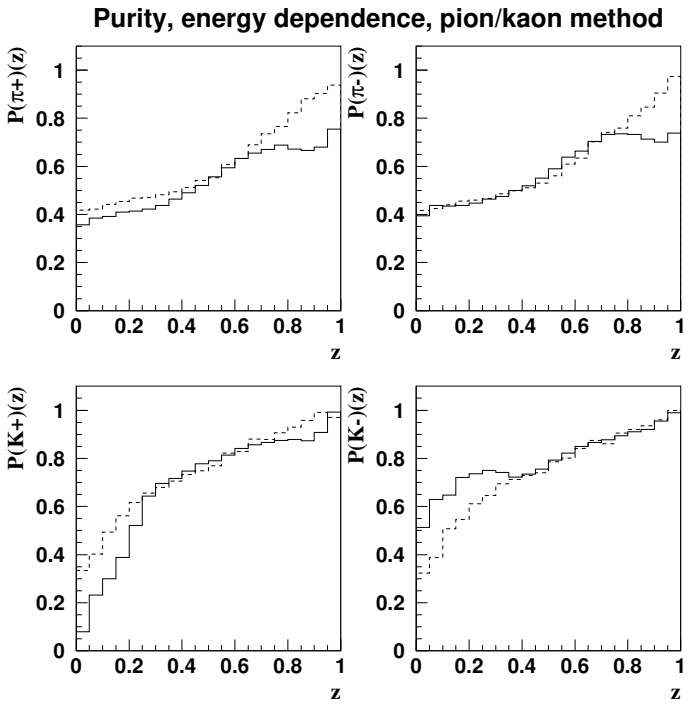

Figure 3: Energy dependence of the purity for HERMES energies (solid line) and H1 energies (dashed line). Ideal 4π simulation.

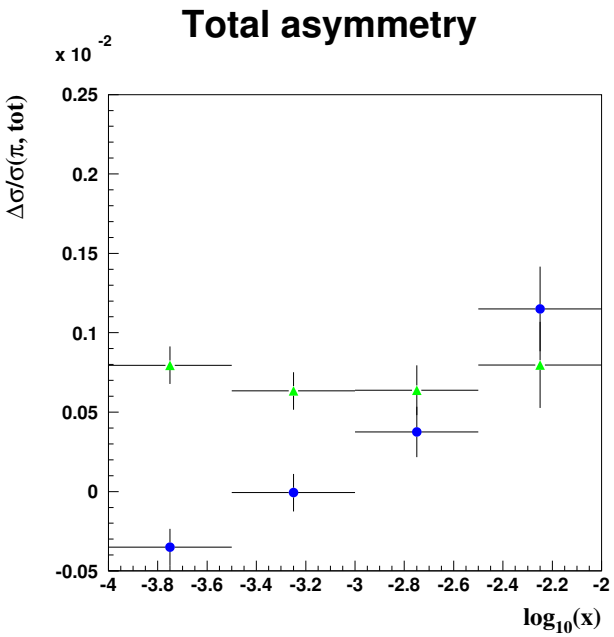

Figure 4: Total pionic asymmetry $\frac{1}{P_e P_p}\frac{\Delta\sigma^{\pi+}+\Delta\sigma^{\pi-}}{\sigma^{\pi+}+\sigma^{\pi-}}$ for 500 pb^{-1} per relative polarization and polarization degree $P_e = P_p = 0.7$. Triangles GSA, circles GRSV LO STD. Simulation done with PEPSI.

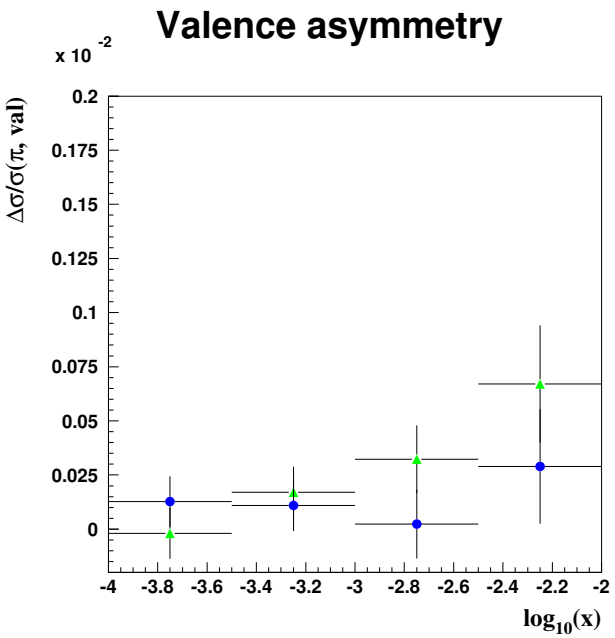

Figure 5: Valence sensitive pionic asymmetry $\frac{1}{P_e P_p}\frac{\Delta\sigma^{\pi+}-\Delta\sigma^{\pi-}}{\sigma^{\pi+}+\sigma^{\pi-}}$ for 500 pb^{-1} per relative polarization and polarization degree $P_e = P_p = 0.7$. Triangles GSA, circles GRSV LO STD. Simulation done with PEPSI.

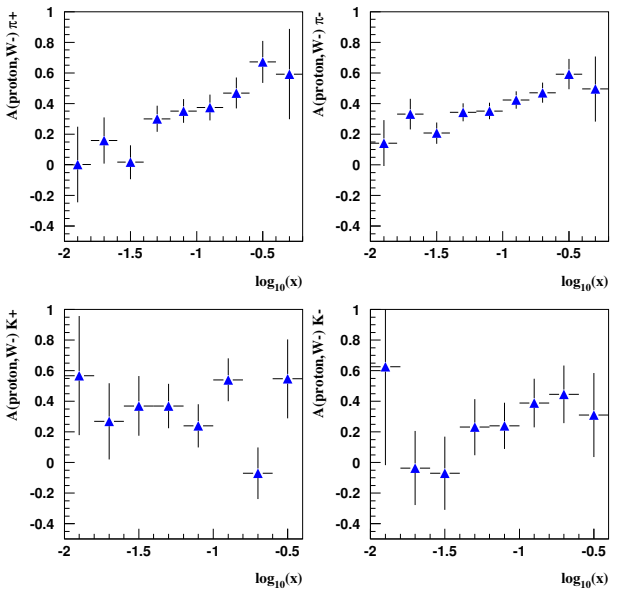

Figure 6: Semi-inclusive asymmetries $\frac{1}{P_e P_p}\frac{\Delta\sigma^H}{\sigma^H}, H = \pi^+, \pi^-, K^+, K^-$ for W^- exchange, for 200 pb^{-1} per relative polarization and polarization degree $P_e = P_p = 0.7$. Parton distribution set GRSV LO STD. Simulation done with PEPSI.