It is reported on an analysis of $-\pi$ meson electroproduction at small Bjorken-$x$ within the handbag approach. The amplitudes factorize into generalized parton distributions (GPDs) and a partonic subprocess, electroward production off gluons. Cross sections and spin density matrix elements (SDMEs) are evaluated for $-\pi$ meson electroproduction and found to be in fair agreement with recent HERA data.

It has been shown that, at large photon virtuality $Q^2$, meson electroproduction factorizes into a partonic subprocess, electroward production of gluons or quarks, $g(q)$! $M g(q)$, and GPDs, representing soft proton matrix elements (see Fig.1). At small $x_{Bj}$ and in particular for $-\pi$ meson production the quark subprocesses can be ignored and only the gluonic subprocess, $g!g$, contributes. In the following I am going to report on an analysis of $-\pi$ meson electroproduction within this handbag approach carried through in the kinematical regime of large $Q^2$ and large energy $W$ in the photon-proton c.m.s., but small $x_{Bj}$ and Mandelstam $t$.

The structure of the proton is rather complex. In correspondence to its four form factors there are four gluon GPDs $h^g, E^g, f^g$ and $E^g$ and four for each quark flavour. All GPDs are functions of three variables, $t$, skewness, and the average momentum fraction $x$, the latter two are defined by (see Fig.1)

$$x = k^+ = \frac{p^+}{(p + p^0)^+}; \quad k = (p - p^0)^+,$$

(1)

The skewness is kinematically fixed to $x_{Bj} = 2$ in a small $x_{Bj}$ approximations and in the p.c.m.s. This is to be contrasted with the frequently used leading log $l = x_{Bj}$ approximation.
where \( x = x_{B,j} \) is assumed and the GPD replaced by the usual gluon distribution \( g(x) \).

The handbag approach leads to the following proton helicity non-\( \bar{p} \) amplitude

\[
M_{0+;+} = \frac{e^{2}}{6} \int \frac{dx}{x} \frac{g_{+}(x)}{x} H_{0+;+}^{0+} + H_{0+;+}^{1} \quad (0,1,2) \quad (2n+2) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2n+1) \quad (2
Higher order terms in this expansion are not shown. Gausians for the meson wavefunctions, $\psi(x)$, are used which may depend on the polarization of the vector meson. The first term in (5) dominates for $L$ while it is approximately zero for transversely polarized vector mesons ($T$). The second term dominates in this case. The soft physics parameter $M$ in the second term of Eq. (5) is of order of the vector meson mass $m$. As can be seen from Eq. (5) the $L! L$ transition is dominant while the $T! T$ one is of relative order $k^2_i i^2=Q$ and the $T! T$ one of order $k^2_i i^2=Q$. The latter amplitude is tiny and only noticeable in some of the SDMEs. All other transitions are negligible.

Before comparing the results to experiment a comment is in order on the large dependence of the amplitudes. Exponentials in $t$ are assumed with slopes $B_{LL} (TT)$ taken from experiment. In combination with the calculated forward amplitudes one can thus evaluate the integrated cross sections and the SDME for small $t$. From (5) one sees that the size of the $T! T$ amplitude is controlled by the following product of parameters ($f_T$ denotes the corresponding decay constant)

$$M_{TT} / f_T ^{1/2} \frac{1}{B_{TT}}$$

Since the available data do practically not allow for an independent determination of the slope $B_{TT}$, only this product is probed. Only the SDMEs are slightly sensitive to the value of $B_{TT}$. All values of this slope lying in the range from about $B_{LL}=2$ up to about $B_{LL}$ lead to fair agreement with the present data.

In Fig. 2, a selection of SDMEs is shown and the results obtained in Ref. 3 are compared to experiment $t=0$. Results for the integrated cross section $L$ are displayed and compared to data in Fig. 3. The GPD approach as detailed in Ref. 2, can in principle also be applied to electroproduction of mesons for COMPASS kinematics where $W$ is much smaller than at HERA. Contributions from the quark GPDs are expected to be very small due to the smallness of the and proton valence quarks. Even for HERMES kinematics the quark contribution is likely tiny. As an example the initial state helicity correlation $A_{LL}$ is shown in Fig. 2 which measures an interference term between the contribution from the GPD $H^g$ (see Eq. (5)) and a similar one from the GPD $H^g$. The latter contribution is negligible in the cross sections and SDMEs, the relative size of $H^g$ and $H^g$ is approximately given by the ratio of the polarized and unpolarized gluon distributions. The smallness of this ratio leads to small values of the helicity correlation. A detailed investigation of electroproduction in the GPD framework for COMPASS and HERMES kinematics is in progress.

The approach discussed here applies also to electroproduction for HERA kinematics. Indeed results for this process are given in Ref. 2. The analysis of electroproduction of mesons at
Figure 3: Left: The integrated cross section for $p!p$ versus $Q^2$ at $W' = 75$ GeV. Data taken from $H1$ (filled squares) and $ZEUS$ (open symbols). The solid line represents the result obtained in Ref. Right: Predictions for the helicity correlation $A_{LL}$ for electroweak versus $Q^2$ at $W = 5$ GeV (solid line) and $W = 10$ GeV (dashed line), $t' = 0$ and $y' = 0$. The shaded bands reflect the uncertainties due to the errors of the gluon distributions.

COMPASS and HERMES kinematics de nately requires the inclusion of the quark contributions.

I summarize: meson electroproduction on unpolarized protons at small $x_B$ and small $t$ probes the GPD $H^g$. Calculating the partonic subprocess within the modified perturbative approach (using gaussian wavefunctions), one achieves fair agreement with HERA data on the integrated cross sections for longitudinally and transversally polarized virtual photons and the SDMEs for electroproduction of mesons. It is to be stressed that only the forward amplitudes are calculated within the GPD approach as yet. Their $t$ dependencies are assumed to be exponentials with slopes taken from experiment. The present data do, however, not x the slope of the $T!T$ amplitude precisely. This treatment of the $t$ dependence is unsatisfactory and improvements are required. In principle the GPD approach has the potential to do better but the GPDs as a function of $t$ are needed for that. Some results on production for COMPASS kinematics are already presented in Ref.

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