Beam spin asymmetry in deeply virtual $\pi$ production

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Abstract. An interpretation of the beam spin azimuthal asymmetries measured at JLAB in deep exclusive electroproduction of charged and neutral pions is presented. The model combines a Regge pole approach with the effect of nucleon resonances. The $s$- and $u$-channel contributions are described using a dual Bloom-Gilman connection between the exclusive form factors and inclusive deep inelastic structure functions. The results are in agreement with data provided the excitations of nucleon resonances are taken into account.

1. Introduction
Electroproduction of mesons in the deep inelastic scattering (DIS), $\sqrt{s} > 2$ GeV and $Q^2 > 1$ GeV$^2$, is a modern tool which permits to study the structure of the nucleon on the partonic level. Exclusive channels in DIS are of particular importance. In this kind of hard processes one may learn about the off-forward parton distributions that parameterize an intrinsic nonperturbative pattern of the nucleon, see Ref. [1] and references therein. Much work have been done to understand the production of pions in exclusive kinematics. For instance, in QCD at large values of $(\sqrt{s}, Q^2)$ and finite value of Bjorken $x_B$ the description of $N(e,e'\pi)N'$ relies on the dominance of the longitudinal cross section $\sigma_L$ [2]. The transverse part $\sigma_T$ is predicted to be suppressed by power of $\sim 1/Q^2$. However, being a leading twist prediction the kinematic domain where this power suppresion dominates is not yet known for $\pi$ production. A somewhat different concept is used in Regge pole models which rely on effective hadronic degrees of freedom. Here the exclusive $(\gamma^*, \pi)$ forward production mechanism is peripheral, that is a sum of all possible $t$-channel meson-exchange processes. Although both partonic and Regge descriptions are presumably dual the exclusive reactions have a potential to discriminate between different models. Related studies have been carried out at JLAB [3, 4] and at DESY [5]. A dedicated program on exclusive production of pions is planned in the future at the JLAB upgrade.

On the experimental side, it is tempting to see an onset of $\sigma_L/\sigma_T \propto Q^2$ scaling at presently available energies. However, the high $Q^2$ data from JLAB and single spin asymmetries measured in true DIS events at HERMES [6] show clearly nonvanishing transverse components in $p(\gamma^*, \pi^+)n$. At JLAB [3, 7, 8, 9], DESY [10, 11, 12], Cornell [13, 14, 15] and CEA [16] the high $Q^2$ region is dominated by the conversion of transverse photons in $\sigma_T$. For instance, the $Q^2$ dependence of the partial $\sigma_L$ and $\sigma_T$ cross sections in the $\pi^+$ electroproduction above $\sqrt{s} > 2$ GeV has been studied in [3]. In the charged pion case the longitudinal cross section $\sigma_L$ at forward angles is well described by the quasi-elastic $\pi$ knockout mechanism [17, 18]. It is driven by the pion charge form factor [19, 20] both at JLAB and HERMES. On the contrary, the $(\sqrt{s}, Q^2)$ behavior of $\sigma_T$ remains to be puzzling. The data demonstrate that $\sigma_T$ is large and tends to increase relative to $\sigma_L$ as a function of $Q^2$. Interestingly, the $(\sqrt{s}, Q^2)$ dependence of
exclusive $\sigma_T$ exhibits features similar to that in $p(e,e'\pi^+)X$ semi-inclusive cross sections in DIS in the limit $z \to 1$ [21, 22]. This kind of an exclusive-inclusive connection [23] has been also observed in exclusive $(\gamma^*,\rho^0)$ production [24]. On the theoretical side, hadronic models based on the meson-exchange scenario alone largely underestimate the measured $\sigma_T$ in electroproduction, see Ref. [9] for further discussions and references therein.

Phenomenological solutions of the $\sigma_T$ problem already exist in the literature [21, 25]. The description of charged pion production proposed in Ref. [25] relies on the residual contribution of the nucleon resonances. It is supposed that the excitations of nucleon resonances dominate in electroproduction. The resonances are dual to the direct partonic interactions due to the Bloom-Gilman duality connection and, correspondingly, their form factors are determined by parton distribution functions. The $s(u)$-channel resonances supplement the Reggeon exchanges in the $t$-channel. Therefore, we distinguish peripheral $t$-channel meson-exchange processes and the $s(u)$-channel resonance/partonic contributions. In this way all the data collected so far in the charged pion electoproduction $(e,e'\pi^\pm)$ at JLAB, DESY, Cornell and CEA can be well described [25]. As an example, in Fig. 1 we show our results for the $-t + t_{\text{min}}$ dependence of the differential cross section $d\sigma_U/dt = d\sigma_T/dt + c d\sigma_L/dt$ in exclusive reaction $p(\gamma^*,\pi^+)n$ at HERMES.

2. Beam single spin asymmetry (SSA)
In this talk we consider the electroproduction reaction

$$\bar{e} + N \to e' + \pi + N$$

Here we assume that the target nucleon is unpolarized, whereas we allow arbitrary polarization for the incoming electron. With a polarized beam $\bar{e}$ and with an unpolarized target there is an additional component $\sigma_{UL}'$ [25] in the $(e,e'\pi)$ cross section which is proportional to the imaginary part of an interference between the L/T photons and therefore sensitive to the relative phases of amplitudes.
Using the polarized electron beam, the longitudinal beam single-spin asymmetry (SSA) in $N(\vec{e}, e'\pi)N'$ scattering is defined so that

$$A_{LU}(\phi) \equiv \frac{d\sigma^\rightarrow(\phi) - d\sigma^\leftarrow(\phi)}{d\sigma^\rightarrow(\phi) + d\sigma^\leftarrow(\phi)},$$

where $d\sigma^\rightarrow$ refers to positive helicity $h = +1$ of the incoming electron. The azimuthal moment associated with the beam SSA is given by

$$A_{LU}^{\sin(\phi)} = \sqrt{2\varepsilon(1-\varepsilon)}d\sigma_{LT}' + \varepsilon d\sigma_{LT} + \varepsilon d\sigma_{LT}.$$  \hspace{1cm} (3)

In general, a nonzero $\sigma_{LT}'$ or the corresponding beam SSA $A_{LU}(\phi)$, Eq. (2), demands interference between single helicity flip and nonflip or double helicity flip amplitudes. In Regge models the asymmetry may result from Regge cut corrections to single reggeon exchange. This way the amplitudes in the product acquire different phases and therefore relative imaginary parts. A nonzero beam SSA can be also generated by the interference pattern of amplitudes where particles with opposite parities are exchanged.

3. Beam SSA in charged pion production

In the left panel of Fig. (2) we plot the CLAS data [26] for the azimuthal moment $A_{LU}^{\sin(\phi)}$ associated with the beam SSA, Eq. (3), in the reaction $p(\vec{e}, e'\pi^+)n$. These data have been collected in hard scattering kinematics $E_e = 5.77$ GeV, $W > 2$ GeV and $Q^2 > 1.5$ GeV$^2$. The experiment shows a sizable and positive beam SSA.

In the left and right panels of Fig. (2) we present our results for the azimuthal moments $A_{LU}^{\sin(\phi)}$ in the reactions $p(\vec{e}, e'\pi^+)n$ and $n(\vec{e}, e'\pi^-)p$, respectively.

Figure 2. Left panel: The beam spin azimuthal moment $A_{LU}^{\sin(\phi)}$ in exclusive reaction $p(\gamma^*, \pi^+)n$ as a function of $-t$. The CLAS/JLAB data are from [26]. The dashed curves describe the results (the asymmetry is zero) without the resonance contributions and neglecting the exchange of unnatural parity $a_1(1260)$ Regge trajectory. The dash-dotted curves correspond to the addition of the axial-vector $a_1(1260)$-reggeon exchange. The solid curves are the model results and account for the resonance/partonic effects. Right panel: The beam spin azimuthal moment $A_{LU}^{\sin(\phi)}$ in exclusive reaction $n(\gamma^*, \pi^-)p$.

At first, we consider $A_{LU}^{\sin(\phi)}$ generated by the exchange of Regge trajectories. In Fig. (2) the dashed curves describe the model results without the effects of resonances and neglecting the exchange of the axial-vector $a_1(1260)$ Regge trajectory. This model results in a zero $A_{LU}^{\sin(\phi)}$ and therefore a zero beam SSA. The addition of the unnatural parity $a_1(1260)$-exchange generates by the interference with the natural parity $\rho(770)$ exchange a sizable $A_{LU}^{\sin(\phi)}$ in both channels. This result corresponds to the dash-dotted curves in Fig. (2). In the rest of unpolarized observables...
the effect of the axial-vector $a_1(1260)$ is small. However, as one can see, the contribution of $a_1(1260)$ is important in the polarization observables. For instance, a strong interference pattern of the $a_1(1260)$-reggeon exchange makes the polarization observables, like the beam SSA, very sensitive to the different scenarios describing the structure and behavior of $a_1(1260)$ in high-$Q^2$ processes. In the last step we account for the resonance contributions. The latter strongly influence the asymmetry parameter $A_{LU}^{\sin(\phi)}$. The model results (solid curves) are in agreement with the positive $A_{LU}^{\sin(\phi)}$ in the $\pi^+$ channel and predict much smaller $A_{LU}^{\sin(\phi)}$ in the $\pi^-$ channel.

A sizable and positive $A_{LU}^{\sin(\phi)}$ has been also observed at HERMES in $\pi^+$ SIDIS close to the exclusive limit $z \to 1$ [27].

**Figure 3.** The beam spin azimuthal moment $A_{LU}^{\sin(\phi)}$ in exclusive reaction $p(\gamma^*, \pi^0)p$ as a function of $-t$ for different $(Q^2, x_B)$ bins. The solid curves are the model results and account for the residual effect of nucleon resonances. The experimental data are from [28].

### 4. Beam SSA in neutral pion production

As in deep exclusive $\pi^+$ electroproduction a sizeable and positive beam SSA has recently been measured at CLAS/JLAB also in the exclusive reaction $p(e^-, e'\pi^0)p$ [28]. It was shown that the simple Regge model used in [28] fails to explain the measured kinematic ($\sqrt{s}, Q^2$) dependencies. We have, therefore, extended our calculation of Ref. [25] to the neutral pion channel. In the
Regge exchange contributions the vector $\omega(782)$, $\rho(770)$ and axial-vector $b_1(1235)$ and $h_1(1170)$ trajectories are taken into account. We find that at high values of $Q^2$ the dominant contribution to the beam SSA again comes from the residual excitation of nucleon resonances. Our results are shown in Fig. 3 and describe the JLAB data very well.

5. Summary
In summary, a description of exclusive pion electroproduction ($e, e'\pi$) off nucleons at high energies is proposed. Following the two-component hadron-parton picture of Refs. [21, 22] the model of Ref. [25] combines a Regge pole approach with residual effects of nucleon resonances. The contribution of nucleon resonances has been assumed to be dual to direct partonic interaction and therefore describes the hard part of the model cross sections.

In this talk we presented the results for the cross sections with longitudinally polarized electron beam. We have shown that the resonance/partonic mechanism is responsible for the positive azimuthal beam SSA observed in exclusive reactions $p(\vec{e}, e'\pi^+)n$ and $p(\vec{e}, e'\pi^0)p$. On the contrary, the beam SSA in deep exclusive $\pi^-$ production off the neutrons is predicted to be much smaller in magnitude and very sensitive to the different scenarios concerning the structure of the $a_1(1260)$ axial-vector meson.

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