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New target transverse spin dependent azimuthal asymmetries from COMPASS experiment

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Abstract. In general, eight target transverse spin-dependent azimuthal modulations are allowed in semi inclusive deep inelastic scattering of polarized leptons on a transversely polarized target. In the QCD parton model four of these asymmetries can be interpreted within the leading order approach. Two of them, namely Collins and Sivers effects were already measured by HERMES and COMPASS experiments. Other two leading twist and remaining four azimuthal asymmetries which can be interpreted as twist-three contributions have been measured for the first time in COMPASS using a 160 GeV/c longitudinally polarized ($P_{beam} \simeq -0.8$) muon beam and a transversely polarized ^6LiD target. We present here the preliminary results from the 2002-2004 data.

PACS. 13.88.+e Polarization in interactions and scattering – 13.60.-r Photon and charged-lepton interactions with hadrons – 13.87.Fh Fragmentation into hadrons – 13.85.Ni Inclusive production with identified hadrons

1 Introduction

Transverse spin effects in Semi Inclusive Deep Inelastic Scattering (SIDIS) of polarized leptons on a transversely polarized target have become an interesting issue in the past years.

The first two of the eight target transverse spin asymmetries which are allowed in the general expression of the SIDIS cross-section [1] and have been measured by HERMES and COMPASS experiments [2,3,4] were the Collins and the Sivers effects. Measurements done by these collaborations together with the BELLE [5] data allowed for example, a first extraction of the transversity and Sivers Transverse Momentum Dependent (TMD) distribution functions (DFs) and Collins fragmentation function (FF) [6],[7]. Here we present preliminary results on the six remaining transverse spin asymmetries first extracted by COMPASS from the 2002-2004 data.

2 Definition of the asymmetries

Based on the general principles of quantum field theory it can be shown in a model independent way that in the one photon exchange approximation the cross-section of lepton-hadron SIDIS processes include 18 structure functions [1], [8]:

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\times \\
&\times\Bigg\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+P_{beam}\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&+P_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&+P_L P_{beam}\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&+|\mathbf{P}_T|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
&+|\mathbf{P}_T|P_{beam}\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}
\end{aligned}
$$

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$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}, \quad (1)$$

where the standard SIDIS notations are used, and the ratio ε of longitudinal and transverse photon fluxes is given by

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}, \quad (2)$$

where $\gamma = \frac{2Mx}{Q}$. The notations for the structure functions F_{sub}^{sup} which on the r.h.s. depend on x, Q^2, z and P_T^h have the following meaning: the superscript corresponds to the azimuthal asymmetry described by the given structure function, whereas the first and second subscripts indicate the respective (”U”-unpolarized,”L”-longitudinal and ”T”-transverse) polarization of beam and target and the third one specifies the polarization of the virtual photon. Integrating these structure functions over the produced hadron momentum and summing over all hadrons in the final state one can find relations between the polarized SIDIS structure functions and ordinary DIS structure functions. For more details see [1], [8].

Azimuthal angles have the following notations: ϕ_h is the azimuthal angle of the produced hadron, ϕ_S of the nucleon spin and ψ is the laboratory azimuthal angle of the scattered lepton, and in DIS kinematics $d\psi \approx d\phi_S$.

As one can see from expression Eq.(1), there are only eight target transverse polarization dependent azimuthal modulations:

$$\begin{aligned} &w_1(\phi_h,\phi_s) = \sin(\phi_h-\phi_s),\ w_2(\phi_h,\phi_s) = \sin(\phi_h+\phi_s),\\ &w_3(\phi_h,\phi_s) = \sin(3\phi_h-\phi_s),\ w_4(\phi_h,\phi_s) = \sin(\phi_s),\\ &w_5(\phi_h,\phi_s) = \sin(2\phi_h-\phi_s),\ w_6(\phi_h,\phi_s) = \cos(\phi_h-\phi_s),\\ &w_7(\phi_h,\phi_s) = \cos(\phi_s),\ w_8(\phi_h,\phi_s) = \cos(2\phi_h-\phi_s) \end{aligned} \quad (3)$$

Five of them are single target spin dependent and three are double beam-target spin dependent asymmetries. The first two modulations $w_1(\phi_h,\phi_s)$ and $w_2(\phi_h,\phi_s)$ correspond to the Sivers and Collins effects.

The expression for the cross section can be represented in terms of the asymmetries:

$$\begin{aligned} &d\sigma(\ \phi_h,\phi_s,...) \propto \quad (4)\\ &(1+|\mathbf{S}_T|\sum_{i=1}^{5} D^{w_i(\phi_h,\phi_s)}A_{UT}^{w_i(\phi_h,\phi_s)}w_i(\phi_h,\phi_s)\\ &+\ P_{beam}|\mathbf{S}_T|\sum_{i=6}^{8} D^{w_i(\phi_h,\phi_s)}A_{LT}^{w_i(\phi_h,\phi_s)}w_i(\phi_h,\phi_s)+...), \end{aligned}$$

where $\mathbf{S}_T$ is the target transverse polarization. The depolarization factors $D^{w_i(\phi_h,\phi_s)}$, have been factored out, and the asymmetries have been defined as the ratios of corresponding structure functions to the unpolarized one:

$$A_{BT}^{w_i(\phi_h,\phi_s)} \equiv \frac{F_{BT}^{w_i(\phi_h,\phi_s)}}{F_{UU,T}}, \quad (5)$$

where $B = L$ or $B = U$ indicates the beam polarization.

The depolarization factors entering in Eq. (4) depend only on y and are given as

$$\begin{aligned} &D^{\sin(\phi_h-\phi_s)}(y) = 1,\ \ D^{\cos(\phi_h-\phi_s)}(y) = \frac{y(2-y)}{1+(1-y)^2},\\ &D^{\sin(\phi_h+\phi_s)}(y) = D^{\sin(3\phi_h+\phi_s)}(y) = \frac{2(1-y)}{1+(1-y)^2},\\ &D^{\sin(2\phi_h-\phi_s)}(y) = D^{\sin(\phi_s)}(y) = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}, \quad (6)\\ &D^{\cos(2\phi_h-\phi_s)}(y) = D^{\cos(\phi_s)}(y) = \frac{2y\sqrt{1-y}}{1+(1-y)^2}. \end{aligned}$$

The asymmetries extracted from the data as the amplitudes of the corresponding azimuthal modulations (raw asymmetries) are then given by

$$A_{UT,\,raw}^{w_i(\phi_h,\phi_s)} = D^{w_i(\phi_h,\phi_s)}(y)f|S_T|A_{UT}^{w_i(\phi_h,\phi_s)}, \quad (7)$$
$$(i=1,5),$$
$$A_{LT,\,raw}^{w_i(\phi_h,\phi_s)} = D^{w_i(\phi_h,\phi_s)}(y)fP_{beam}|S_T|A_{LT}^{w_i(\phi_h,\phi_s)}, \quad (8)$$
$$(i=6,8)$$

where f is the target polarization dilution factor.

In the QCD parton model four of the eight transverse asymmetries are given by the ratio of convolutions of spin-dependent to spin-independent twist two DFs and FFs:

$$\begin{aligned} &A_{UT}^{\sin(\phi_h-\phi_s)} \propto \frac{f_{1T}^{\perp q}\otimes D_{1q}^h}{f_1^q\otimes D_{1q}^h},\ A_{UT}^{\sin(\phi_h+\phi_s)} \propto \frac{h_1^q\otimes H_{1q}^{\perp h}}{f_1^q\otimes D_{1q}^h},\\ &A_{LT}^{\cos(\phi_h-\phi_s)} \propto \frac{g_{1T}^q\otimes D_{1q}^h}{f_1^q\otimes D_{1q}^h},\ A_{UT}^{\sin(3\phi_h-\phi_s)} \propto \frac{h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}}{f_1^q\otimes D_{1q}^h} \end{aligned} \quad (9)$$

As an example, the $A_{LT}^{\cos(\phi_h-\phi_s)}$ and $A_{UT}^{\sin(3\phi_h-\phi_s)}$ leading-twist asymmetries can be used for extraction of DFs g_{1T}^q and $h_{1T}^{\perp q}$ describing the quark longitudinal and transverse (along the quark transverse momentum) polarization in the transversely polarized nucleon. The other four asymmetries can be interpreted as Cahn kinematic corrections to spin effects on the transversely polarized nucleon [1]:

$$\begin{aligned} &A_{LT}^{\cos(\phi_s)} \propto \frac{M}{Q}\frac{g_{1T}^q\otimes D_{1q}^h}{f_1^q\otimes D_{1q}^h},\ A_{LT}^{\cos(2\phi_h-\phi_s)} \propto \frac{M}{Q}\frac{g_{1T}^q\otimes D_{1q}^h}{f_1^q\otimes D_{1q}^h},\\ &A_{UT}^{\sin(\phi_s)} \propto \frac{M}{Q}\frac{h_1^q\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^h}{f_1^q\otimes D_{1q}^h},\\ &A_{UT}^{\sin(2\phi_h-\phi_s)} \propto \frac{M}{Q}\frac{h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^h}{f_1^q\otimes D_{1q}^h}. \end{aligned} \quad (10)$$

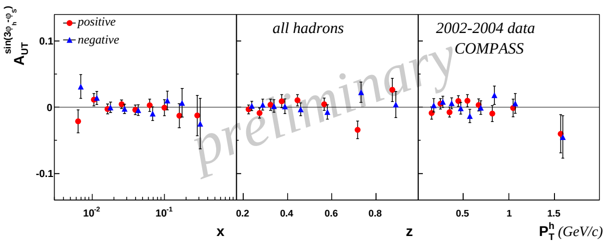

Fig. 1. $A_{UT}^{sin(3\phi_h-\phi_s)}$ asymmetry for positive (red circles) and negative (blue triangles) hadrons vs. x, z and p_t.

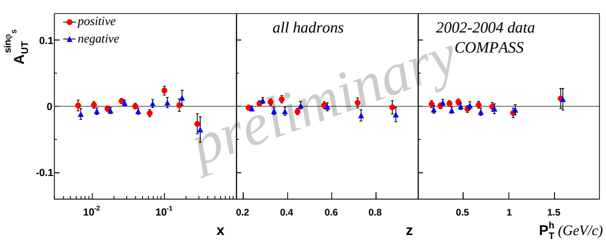

Fig. 2. $A_{UT}^{sin\phi_s}$ asymmetry for positive (red circles) and negative (blue triangles) hadrons vs. x, z and p_t.

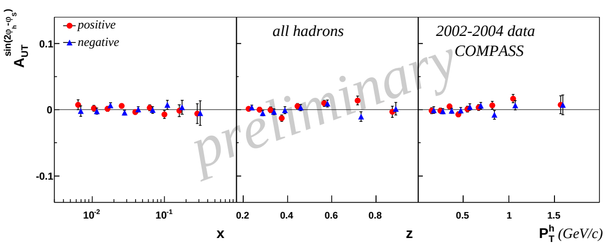

Fig. 3. $A_{UT}^{sin(2\phi_h-\phi_s)}$ asymmetry for positive (red circles) and negative (blue triangles) hadrons vs. x, z and p_t.

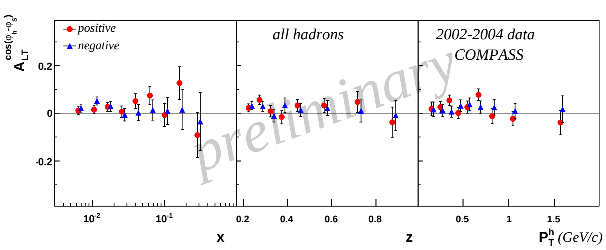

Fig. 4. $A_{LT}^{cos(\phi_h-\phi_s)}$ asymmetry for positive (red circles) and negative (blue triangles) hadrons vs. x, z and p_t.

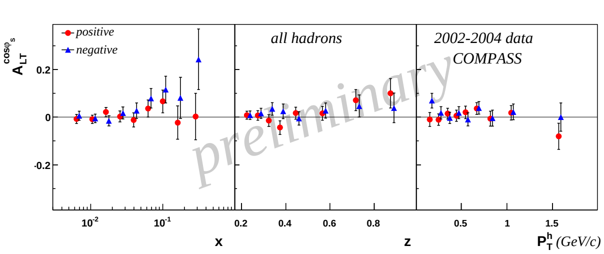

Fig. 5. $A_{LT}^{cos\phi_s}$ asymmetry for positive (red circles) and negative (blue triangles) hadrons vs. x, z and p_t.

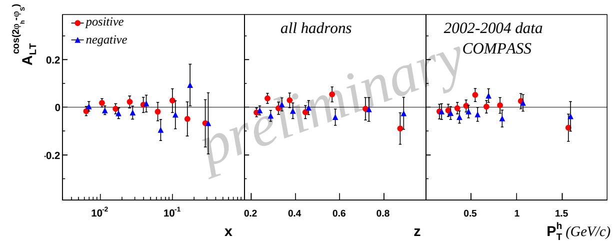

Fig. 6. $A_{LT}^{cos(2\phi_h-\phi_s)}$ asymmetry for positive (red circles) and negative (blue triangles) hadrons vs. x, z and p_t.

3 Analysis method and results

In this section we will briefly review the analysis method used in COMPASS for the extraction of transverse spin asymmetries. The event selection procedure and the analysis method are the same as the one applied for already published Collins and Sivers asymmetries, and a detailed description can be found in [4].

In our analysis we used the COMPASS data collected in years 2002-2004 with the 160 GeV/c longitudinally polarized ($P_{beam} \simeq -0.8$) muon beam and a transversely polarized ^6LiD target. The COMPASS target consists of two oppositely polarized target cells with the dilution factor $\simeq 0.38$ and average polarization $\simeq 50\%$. Once per week the polarization was reversed in both cells. Such a configuration of the target serves to reduce the systematic effects arising due to the difference in acceptance of the target cells.

The following kinematic cuts were imposed in the analysis: $Q^2 > 1$ (GeV/c)^2, $W > 5$ GeV, $0.1 < y < 0.9$, $P_T^h > 0.1$ GeV/c and $z > 0.2$.

One can see that eight transverse spin modulations are based on five combinations of azimuthal hadron (ϕ_h) and spin (ϕ_s) angles which are: $\Phi_1 = \phi_h - \phi_s$, $\Phi_2 = \phi_h + \phi_s$, $\Phi_3 = 3\phi_h - \phi_s$, $\Phi_4 = \phi_s$, $\Phi_5 = 2\phi_h - \phi_s$.Therefore, we can define the following five Φ_j dependent modulations:

$$\begin{aligned}
W_1(\Phi_1) &= A_{raw}^{w_1(\phi_h,\phi_s)} \sin(\Phi_1) + A_{raw}^{w_6(\phi_h,\phi_s)} \cos(\Phi_1) \\
W_2(\Phi_2) &= A_{raw}^{w_2(\phi_h,\phi_s)} \sin(\Phi_2) \qquad (11) \\
W_3(\Phi_3) &= A_{raw}^{w_3(\phi_h,\phi_s)} \sin(\Phi_3) \\
W_4(\Phi_4) &= A_{raw}^{w_4(\phi_h,\phi_s)} \sin(\Phi_4) + A_{raw}^{w_7(\phi_h,\phi_s)} \cos(\Phi_4) \\
W_5(\Phi_5) &= A_{raw}^{w_5(\phi_h,\phi_s)} \sin(\Phi_5) + A_{raw}^{w_8(\phi_h,\phi_s)} \cos(\Phi_5)
\end{aligned}$$

For each subperiod of our measurement and each target cell, we can now describe the counting rate dependence on Φ_j by

$$N_{u/d}^{\pm}(\Phi_j) = F_{u/d}^{\pm} n_{u/d}^{\pm} a_{u/d}^{\pm}(\Phi_j) \sigma (1 \pm W_j(\Phi_j)) \qquad (12)$$

where +(-) indicates up (down) target polarization and u(d) the upstream and downstream target cells, σ is the unpolarized cross-section, $F_{u/d}^{\pm}$ is the flux and $n_{u/d}^{\pm}$ the target density. Finally, $a_{u/d}^{\pm}(\Phi_j)$ is the Φ_j dependent acceptance for the corresponding cell and polarization state.

We used for one measurement period (i.e. two subperiods with opposite spin direction) the information of both target cells (u, d) and both sub-periods simultaneously by constructing the estimator:

$$F(\Phi_j) = \frac{N_u^+(\Phi_j)N_d^+(\Phi_j)}{N_u^-(\Phi_j)N_d^-(\Phi_j)}, \tag{13}$$

It can be shown, that under a reasonable assumption on the ratio of acceptances of the upstream and downstream cells to be constant after the spin reversal $a_u^+(\Phi_j)/a_d^-(\Phi_j)$ $= a_u^-(\Phi_j)/a_d^+(\Phi_j)$, the acceptance differences in two cells cancel out, so finally one can obtain:

$$F(\Phi_j) = const(1 + 4W_j(\Phi_j)) \tag{14}$$

and the asymmetries can be extracted by fitting the $F(\Phi_j)$ with the appropriate function. In Figs. 1 - 6 we present six target transverse spin dependent asymmetries extracted for the first time from COMPASS 2002–2004 data collected on a deuterium target.

Constructing the same estimator in two dimensional φ_h, φ_S space all the eight transverse spin asymmetries can be extracted simultaneously by using the two-dimensional fitting procedure. In addition this method reveal possible correlations between the asymmetries. Corresponding checks have shown only negligible or small correlations, as an example we present in Fig. 7 the correlation coefficients with absolute values larger than 0.1 versus x, and it can be clearly seen that even at maximum they remains smaller than 0.4. Various systematic checks have been applied for the analysis. Finally the estimated systematic errors are smaller than statistical ones.

All the six newly measured asymmetries are compatible with zero within statistical errors. This, in fact, can be explained by different models predicting cancelation between the contributions of the proton and the neutron to the asymmetry in the deuteron target. As an example, our results for the $A_{LT}^{cos(\phi_h-\phi_s)}$ asymmetry have been compared with the predictions presented in [9]. The authors performed calculations for the $A_{LT}^{cos(\phi_h-\phi_s)}$ asymmetry by using some models for the otherwise unknown g_{1T}^q function and expressing it through the well known integrated helicity distributions. In Fig. 7 we compare the curves plotting the calculated in [9] x-dependence of the $A_{LT}^{cos(\phi_h-\phi_s)}$ asymmetry in the COMPASS kinematical region, with our experimental measurements. The blue line corresponds to the asymmetry calculated for the proton target and the red dashed line is for the deuteron target. Experimental observations do not contradict the predictions, and the theoretical curve lies within experimental error bands. The asymmetry is predicted to be roughly twice larger at high x for COMPASS and even larger for HERMES and JLab kinematics. It would be very interesting to perform such measurements.

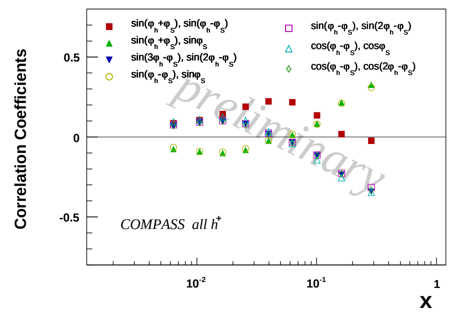

Fig. 7. Correlation coefficients with the absolute value > 0.1 vs. x.

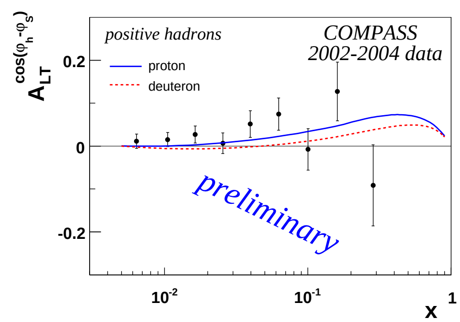

Fig. 8. $A_{LT}^{cos(\phi_h-\phi_s)}$ asymmetry, positive hadrons vs. x.

4 Conclusions

We have presented six new target transverse spin dependent asymmetries extracted from COMPASS 2002–2004 data collected on a deuterium target. The estimated systematic errors are smaller than the statistical ones. All six newly measured asymmetries are compatible with zero within statistical errors. COMPASS has already started data taking with the proton target, and the transverse spin effects, in this case, are expected to be more significant.

References

1. A. Kotzinian, Nucl. Phys. B **441**, 234 (1995) [arXiv:hep-ph/9412283].
2. A. Airapetian *et al.* [HERMES Collaboration], Phys. Rev. Lett. **94** (2005) 012002 [arXiv:hep-ex/0408013].
3. V. Y. Alexakhin *et al.* [COMPASS Collaboration], Phys. Rev. Lett. **94**, 202002 (2005) [arXiv:hep-ex/0503002].
4. E. S. Ageev *et al.* [COMPASS Collaboration], Nucl. Phys. B **765**, 31 (2007) [arXiv:hep-ex/0610068];
5. R. Seidl *et al.* [Belle Collaboration], Phys. Rev. Lett. **96**, 232002 (2006) [arXiv:hep-ex/0507063].
6. M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia and A. Prokudin, Phys. Rev. D **72** (2005) 094007 [Erratum-ibid. D **72** (2005) 099903] [arXiv:hep-ph/0507181].
7. M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, A. Prokudin and C. Turk, Phys. Rev. D **75** (2007) 054032 [arXiv:hep-ph/0701006].
8. A. Bacchetta, M. Diehl, K. Goeke, A. Metz, P. Mulders and M. Schlegel, JHEP **0702**, 093 (2007) [arXiv:hep-ph/0611265].
9. A. Kotzinian, B. Parsamyan and A. Prokudin, Phys. Rev. D **73** (2006) 114017 [arXiv:hep-ph/0603194].