Color transparency effects on the deuteron spin observables in the hard $pd \to ppn$ reaction

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The pionless breakup of a deuteron induced by 15 GeV/c beam proton is considered theoretically in the kinematics where both outgoing protons are fast and the neutron is slow in the rest frame of the deuteron. Significant influence of color transparency on the deuteron vector and tensor analyzing powers is expected.

1. INTRODUCTION

The color transparency (CT) effect is known as the reduction of the interaction with the surrounding nuclear medium for point-like color-singlet (anti)quark configurations in the initial or final state of a hard two-particle collision. CT has been predicted for binary semi-exclusive processes with large momentum transfer $h + A \to p + (A-1)^*$ [1, 2]. The reviews on CT can be found in Refs. [3–5]. So far the experimental search for CT was mostly focused on the intermediate energy region where BNL and JLab operate. CT was observed at AGS@BNL in the $^{12}C(p,pp)$ reaction at $p_{\rm lab} = 5.9 - 14.5$ GeV/c [6], and also at JLab in the $A(e,e'\pi^+)$ reaction at $E_{beam} = 4.0 - 5.8$ GeV [7] and in the $A(e,e'\rho^0)$ reaction at $E_{beam} = 5$ GeV [8] for several nuclear targets. In all existing experimental studies, the observable sensitive to the CT effect was nuclear transparency, $T = \sigma/\sigma_{\rm IA}$, where σ is the measured cross section of the studied process and $\sigma_{\rm IA}$ is the same cross section, but calculated in the impulse approximation (IA). Thus, enhanced T above predictions of the Glauber model points to the presence of the CT effect. The hardness of the underlying elementary reactions was reached by setting $Q^2 > 1$ GeV^2. On the other hand, recent JLab data for $^{12}C(e,e'p)$ at $Q^2 = 8 - 14.2$ GeV^2, $E_{\rm beam} = 6.4, 10.6$ GeV [9] do not indicate CT. This controversary situation calls for new theoretical and experimental studies of CT. One

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idea is to use deuteron target, where the uncertainties of the wave function are minimal and the processes $d(e, e'pn)$ [10–12] or $d(p, ppn)$ [13, 14] can be studied fully exclusively. In particular, it was shown in Refs. [11, 14] that the nuclear transparency and deuteron tensor analyzing power (DTAP) are sensitive to the presence of CT. The consideration was, however, limited to the component A_{zz} with z-axis along the proton (in Ref. [11] - virtual photon) momentum. The purpose of this work is to extend the calculations of Ref. [14] of hard $pd \to ppn$ process to other components of the DTAP and also to study the deuteron vector analyzing power (DVAP).

The paper is structured as follows. Sec. 2 contains a short description of theoretical model. Numerical results of calculations of the DTAP and DVAP are given in sec. 3. The summary and experimental opportunities are included in sec. 4.

2. THE MODEL

The calculations were based on the generalized eikonal approximation (GEA) method developed in Refs. [13–16]. The starting point was Feynman diagrams describing one-, two-, and three-step scattering processes. In the simplest one-step, i.e. IA, diagram the incoming proton experiences hard elastic scattering on the proton of the deuteron without any distortion from initial- and final state interactions (ISI/FSI). The two- and three-step diagrams include soft elastic scattering amplitudes of the incoming and outgoing protons on the spectator neutron. These diagrams were calculated by factorizing the hard amplitude $M_{\rm hard}(s_{\rm hard}, t_{\rm hard})$ out of the momentum integrals that were taken in the pole approximation, i.e. putting the intermediate spectator neutron on the mass shell. In the present calculations, the latest model version [16] was used that includes more accurate three-step amplitudes with soft rescattering of both outgoing protons, taking into account the renormalization due to the infinite sequence of subsequent rescattering, as well as improved Δ's, which are included in the phases of the integrals in coordinate space in partial two- and three-step amplitudes.

The CT effects were included within the quantum diffusion model [11, 17] by using position-dependent soft pn-scattering amplitudes

$$M_{\rm el}(|\boldsymbol{p}_j|, t, l) = 2|\boldsymbol{p}_j| m\, \sigma_{pn}^{\rm eff}(l)\, (i + \rho_{\rm pn}) {\rm e}^{B_{\rm pn} t/2}\, \frac{G(t \cdot \frac{\sigma_{pn}^{\rm eff}(l)}{\sigma_{pn}^{\rm tot}})}{G(t)}\ , \tag{1}$$

where $\boldsymbol{p}_j$ is the momentum of the incoming ($j = 1$) or outgoing ($j = 3, 4$) proton in the deuteron rest frame (r.f.), $\rho_{\rm pn} = {\rm Re}M_{\rm el}(t=0)/{\rm Im}M_{\rm el}(t=0)$ is the ratio of the real part of the forward pn scattering amplitude to the imaginary one, and $B_{\rm pn}$ is the slope of the dependence on the transverse momentum transfer, m is the nucleon mass.

$$\sigma^{\rm eff}_{pn}(l) = \sigma^{\rm tot}_{pn}\left(\left[\frac{l}{l_c} + \frac{\langle n^2 k_t^2\rangle}{Q^2}\left(1-\frac{l}{l_c}\right)\right]\Theta(l_c - l) + \Theta(l - l_c)\right) \tag{2}$$

is the effective pn cross section that depends on the distance $l = |(\boldsymbol{r}_2 - \boldsymbol{r}_s)\boldsymbol{p}_j|/|\boldsymbol{p}_j|$ traveled by the incoming or outgoing proton between its hard interaction with a proton of the deuteron with position $\boldsymbol{r}_2$ and soft rescattering on the neutron of the deuteron with position $\boldsymbol{r}_s$.

$$l_c = \frac{2p_j}{\Delta M^2}\ , \tag{3}$$

is the coherence length with parameter $\Delta M^2 \simeq 1$ GeV^2 as determined from pion transparency studies [7] and $\Delta M^2 \simeq 2-3$ GeV^2 as determined in Ref. [12] that accommodates the proton transparency data [9]. $Q^2 = -t_{\rm hard}$ is the hard scale, $\sqrt{\langle k_t^2\rangle} = 0.35$ GeV/c is the average transverse momentum of a quark in a proton, $n=3$ is the number of valence quarks in the proton.

$$G(t) = \frac{1}{(1 - t/0.71\ {\rm GeV}^2)^2}\ , \tag{4}$$

is the Sachs electric form factor of a proton. One sees from Eq.(2) that at $l < l_c$ the effective cross section is smaller than phenomenological total pn cross section $\sigma^{\rm tot}_{pn}$ due to CT, while at $l \geq l_c$ CT effects disappear and $\sigma^{\rm eff}_{pn}(l) = \sigma^{\rm tot}_{pn}$.

3. RESULTS

The DVAP and DTAP are defined, respectively, as (c.f. Refs. [18, 19])

$$A_\alpha = \frac{{\rm Sp}(MS_\alpha M^\dagger)}{{\rm Sp}(MM^\dagger)}\ , \quad \alpha = x,y,z\ , \tag{5}$$

$$A_{\alpha\beta} = \frac{{\rm Sp}(MS_{\alpha\beta} M^\dagger)}{{\rm Sp}(MM^\dagger)}\ , \quad \alpha,\beta = x,y,z\ , \tag{6}$$

where M is the invariant matrix element of the studied reaction process (in the present case $pd \to ppn$), S_α are the deuteron spin matrices and $S_{\alpha\beta} = \frac{3}{2}(S_\alpha S_\beta + S_\beta S_\alpha) - 2\delta_{\alpha\beta}$ is the spin-quadrupole operator. The DTAP satisfies the condition $\sum_\alpha A_{\alpha\alpha} = 0$.

The DVAP and diagonal DTAP can be expressed in terms of the reaction cross section $\sigma_\alpha(\lambda)$ for the deuteron spin projection λ on the axis α:

$$A_\alpha = \frac{\sigma_\alpha(+1) - \sigma_\alpha(-1)}{\sigma_\alpha(+1) + \sigma_\alpha(-1) + \sigma_\alpha(0)} , \tag{7}$$

$$A_{\alpha\alpha} = \frac{\sigma_\alpha(+1) + \sigma_\alpha(-1) - 2\sigma_\alpha(0)}{\sigma_\alpha(+1) + \sigma_\alpha(-1) + \sigma_\alpha(0)} . \tag{8}$$

Being, respectively, a pseudo-vector and a tensor, the DVAP and DTAP can be generally represented as

$$\boldsymbol{A} = \sum_{i,j} f_{ij}[\boldsymbol{p}_i \times \boldsymbol{p}_j] , \tag{9}$$

$$A_{\alpha\beta} = \sum_{i,j} g_{ij} \left(3p_{i,\alpha}p_{j,\beta} - \boldsymbol{p}_i\boldsymbol{p}_j\delta_{\alpha\beta}\right) , \tag{10}$$

where the sums run over all pairs of particles i, j involved in the reaction and the coefficients f_{ij}, g_{ij} depend on the scalar products of the momenta of particles.

In the IA, for a spin-independent hard pp amplitude, the DVAP disappears, while the DTAP is fully determined by the deuteron wave function:

$$A^{\rm IA}_{\alpha\beta} = \frac{(3p_{s,\alpha}p_{s,\beta}/p_s^2 - \delta_{\alpha\beta})(\sqrt{2}u(p_s)w(p_s) - w^2(p_s)/2)}{u^2(p_s) + w^2(p_s)} , \tag{11}$$

where $\boldsymbol{p}_s$ is the momentum of spectator neutron in the deuteron r.f., $u(p_s)$ and $w(p_s)$ are, respectively, the S- and D-wave components of the deuteron wave function.

The final state of the reaction $pd \to ppn$ is characterized in the deuteron r.f. by the light cone variable $\alpha_s = 2(E_s - p_s^z)/m_d$, the transverse momentum p_{st} of the spectator neutron, the Mandelstam variable $t = (p_1 - p_3)^2$, and the relative azimuthal angle $\phi = \phi_3 - \phi_s$ between the scattered proton and the spectator neutron. Here, $E_s = \sqrt{\boldsymbol{p}_s^2 + m^2}$ and m_d are, respectively, the energy of the spectator neutron and the deuteron mass. The neutron is supposed to move in the (x, z) plane, i.e. $\phi_s = 0$. The calculations were performed for a beam momentum $p_{\rm lab} = 15$ GeV/c at $t = (2m^2 - s/2)(1 - \cos\Theta_{c.m.})$ with a fixed center-of-mass scattering angle $\Theta_{c.m.} = 53$ deg.. Here, $s = (E_1 + m_d - E_s)^2 - p_{st}^2 - (p_{\rm lab} - p_s^z)^2$ where $E_1 = \sqrt{p_{\rm lab}^2 + m^2}$ is the energy of the incoming proton. This corresponds to $Q^2 \sim 5.2$ GeV^2. The transverse kinematics of the neutron was considered by requiring $\alpha_s = 1$.

Fig. 1 shows the components $A_y, A_{xx}, A_{yy}, A_{zz}$ and A_{xz} as functions of the transverse momentum of spectator neutron at $\phi = 180$ deg. Since all particles move in the (x, z) plane, $A_x = A_z = A_{xy} = A_{yz} = 0$, as follows from Eqs.(9),(10). The component A_y becomes finite

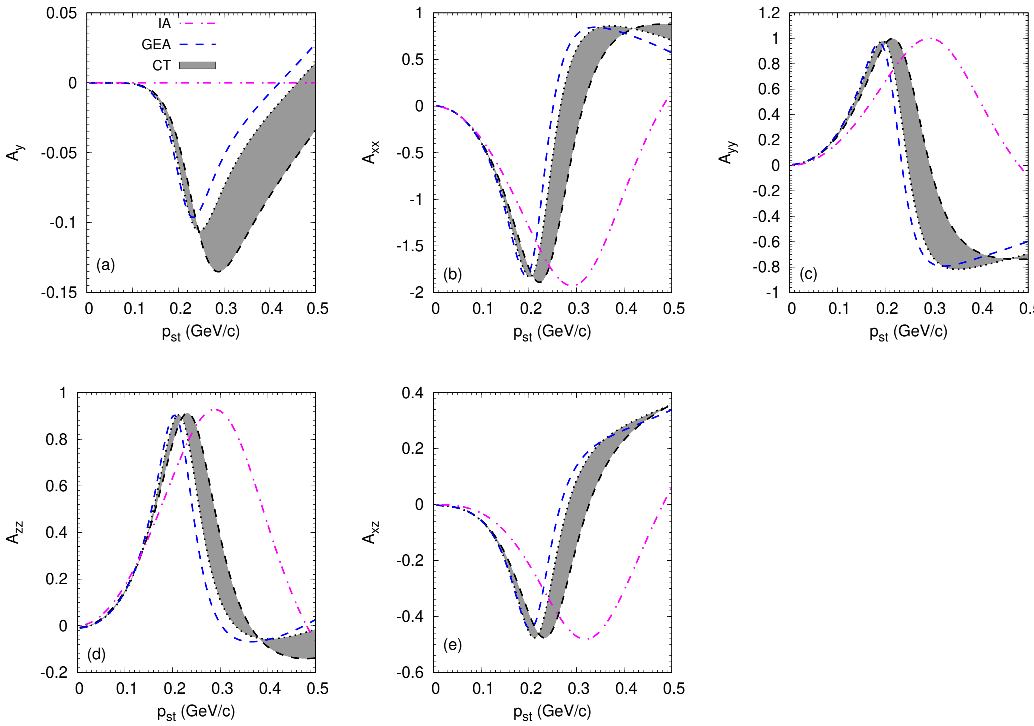

Figure 1. DVAP and DTAP vs transverse momentum of spectator neutron for fixed relative azimuthal angle $\phi = 180$ deg.. Magenta dash-dotted line – IA calculation. Blue dashed line – GEA calculation. The gray band with borders given by the mass denominator of the coherence length, $\Delta M^2 = 0.7$ GeV^2 (black dashed line) and 3 GeV^2 (black dotted line) – the calculation with CT effects.

when ISI/FSI are taken into account. At $p_{st} = 0$ all components disappear which is the consequence of the D-wave dominance. The extrema of the tensor components experience a shift from $p_{st} \simeq 0.3$ GeV/c to $p_{st} \simeq 0.2$ GeV/c due to ISI/FSI in the GEA calculations while the width of the p_{st}-dependence becomes smaller. CT effects grow with p_{st} and become most pronounced at $p_{st} \simeq 0.3$ GeV/c.

Fig. 2 presents the azimuthal dependence of the DVAP. In line with Eq.(9), the components A_x and A_z are antisymmetric with respect to reflection in the (x, z) plane while the component A_y is symmetric. The components of DVAP do not exceed 0.15 by absolute value. However, they exhibit quite significant CT effects, in-particular, A_y at large transverse momenta.

The azimuthal dependence of diagonal and non-diagonal DTAP is shown in Fig. 3 and Fig. 4, respectively. In accord with Eq.(10), the diagonal components as well as the A_{xz}

component are symmetric while A_{xy} and A_{yz} are antisymmetric with respect to reflection in the (x, z) plane. Since the spectator neutron moves almost along the positive x-direction, the A_{xx} component is out of phase with A_{yy} and A_{zz} ones. The components A_{xx}, A_{yy}, A_{zz} and A_{xz} are large and show pronounced variation with an angle ϕ due to the ISI/FSI effects. The influence of CT on these components is strongest for in-plane kinematics, i.e. for $\phi = 0$ and 180 deg.

4. SUMMARY

Calculations for the $d(p, 2p)n$ hard deuteron breakup at $p_{\rm lab} = 15$ GeV/c ($\sqrt{s_{NN}} = 5.5$ GeV) were performed on the basis of the GEA that includes ISI/FSI effects in the form of multi-step amplitudes with soft rescattering of the incoming and outgoing protons on the spectator neutron. The focus was on the deuteron polarization observables. The effects of CT were included within the quantum diffusion model taking into account the interference of the small- and large-size qqq configurations.

The ISI/FSI effects lead to highly non-trivial behavior of the DVAP and DTAP as functions of the transverse momentum of spectator neutron and relative azimuthal angle between the scattered proton and the spectator neutron. These dependencies are sensitive to the CT effects. Experimental determination of the DVAP and DTAP provides an excellent opportunity for both GEA testing and CT identification in hard pd collisions. Such measurements can be performed on the first stage of SPD NICA operation by using dd collisions where one of the colliding deuterons serves as a source of the quasi-free proton that experiences a hard collision with another deuteron, see Refs. [20–22]. Furthermore, the ISI/FSI and possibly the onset of CT could be studied at lower energies at the JINR nuclotron using a deuteron beam interacting with a proton target.

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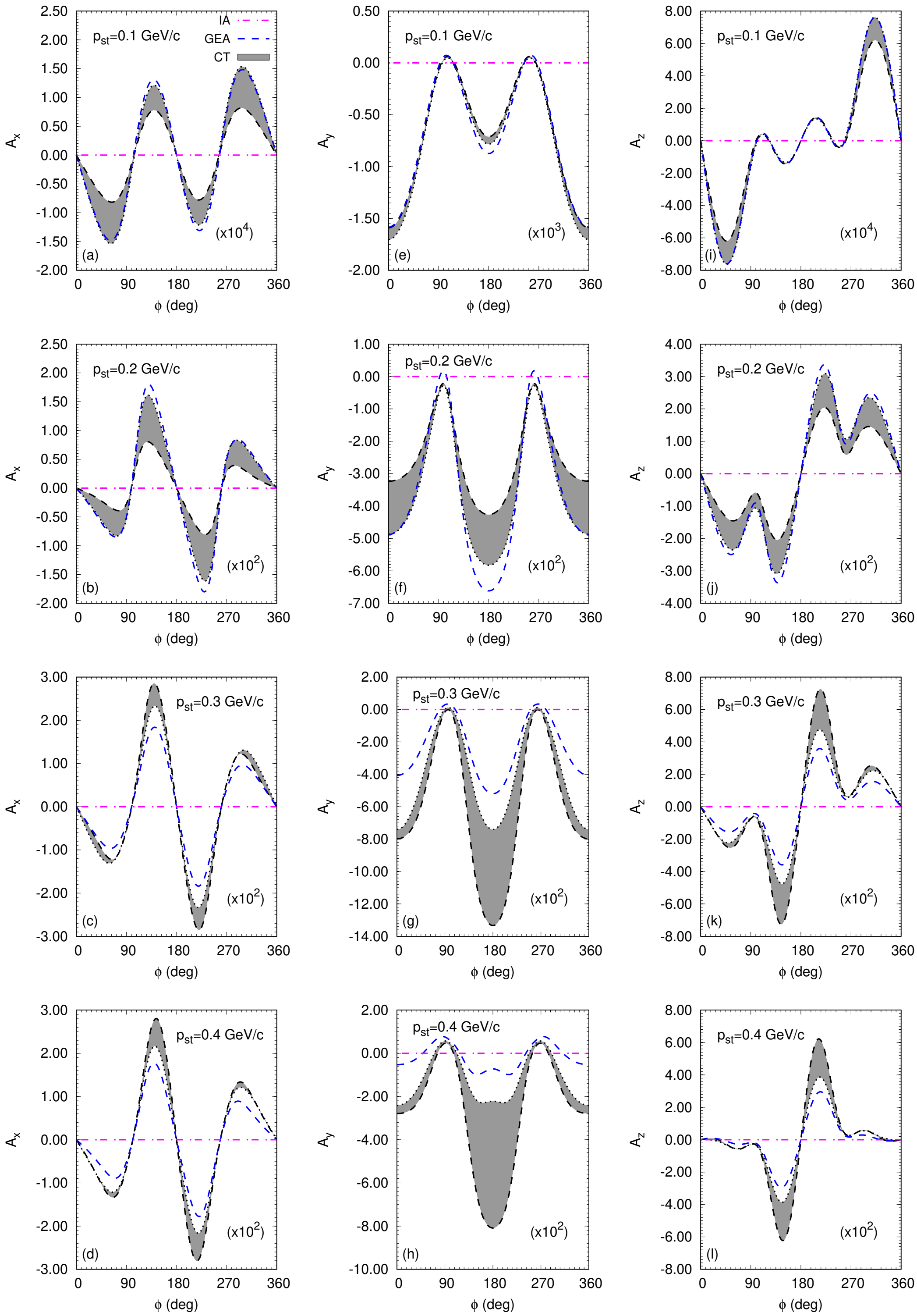

Figure 2. DVAP as a function of relative azimuthal angle ϕ between scattered proton and spectator neutron at different transverse momenta of spectator neutron. Plotted results are multiplied by the factors given in parentheses. Line notation is the same as in Fig. 1.

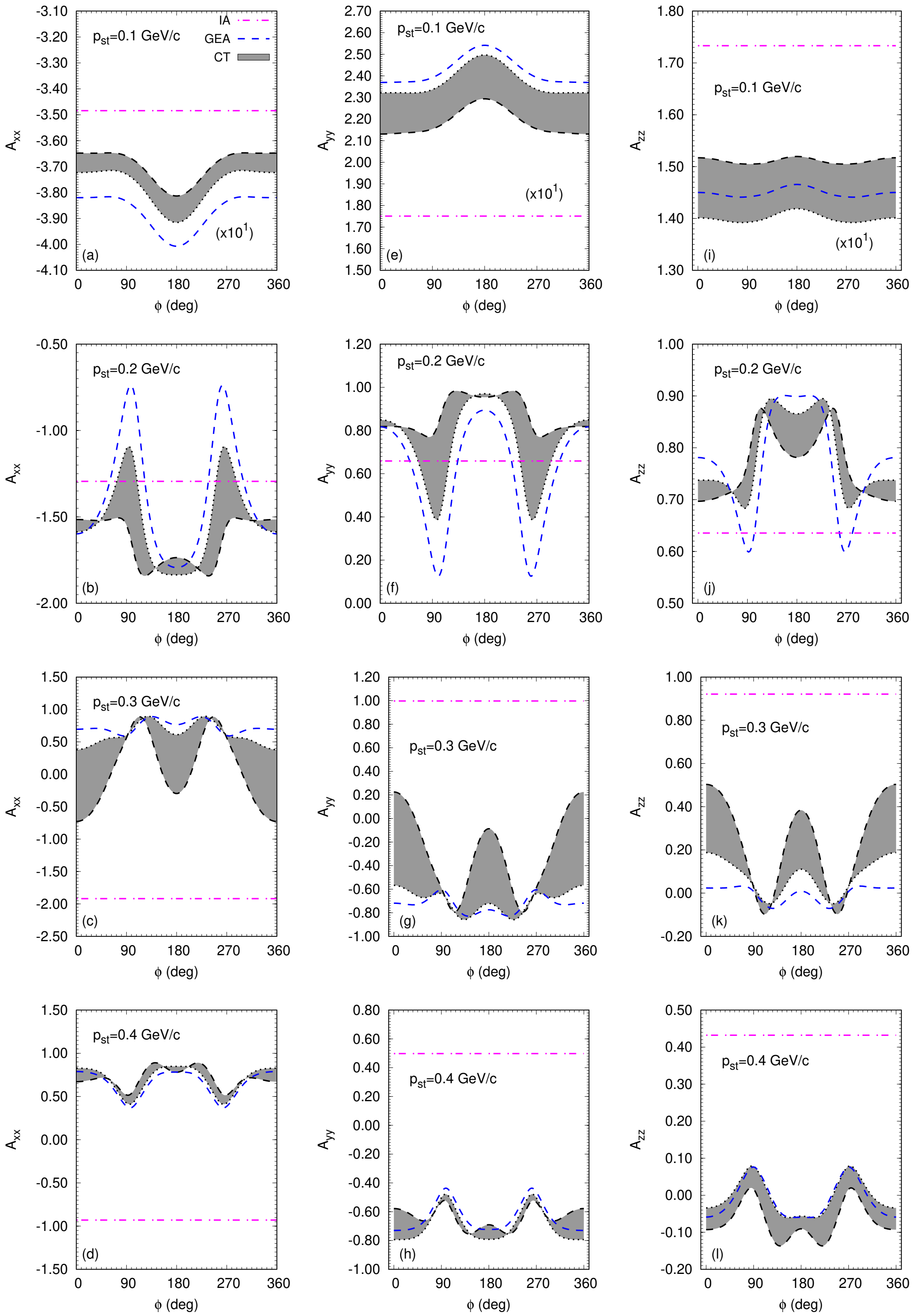

Figure 3. Same as Fig. 2, but for diagonal DTAP.

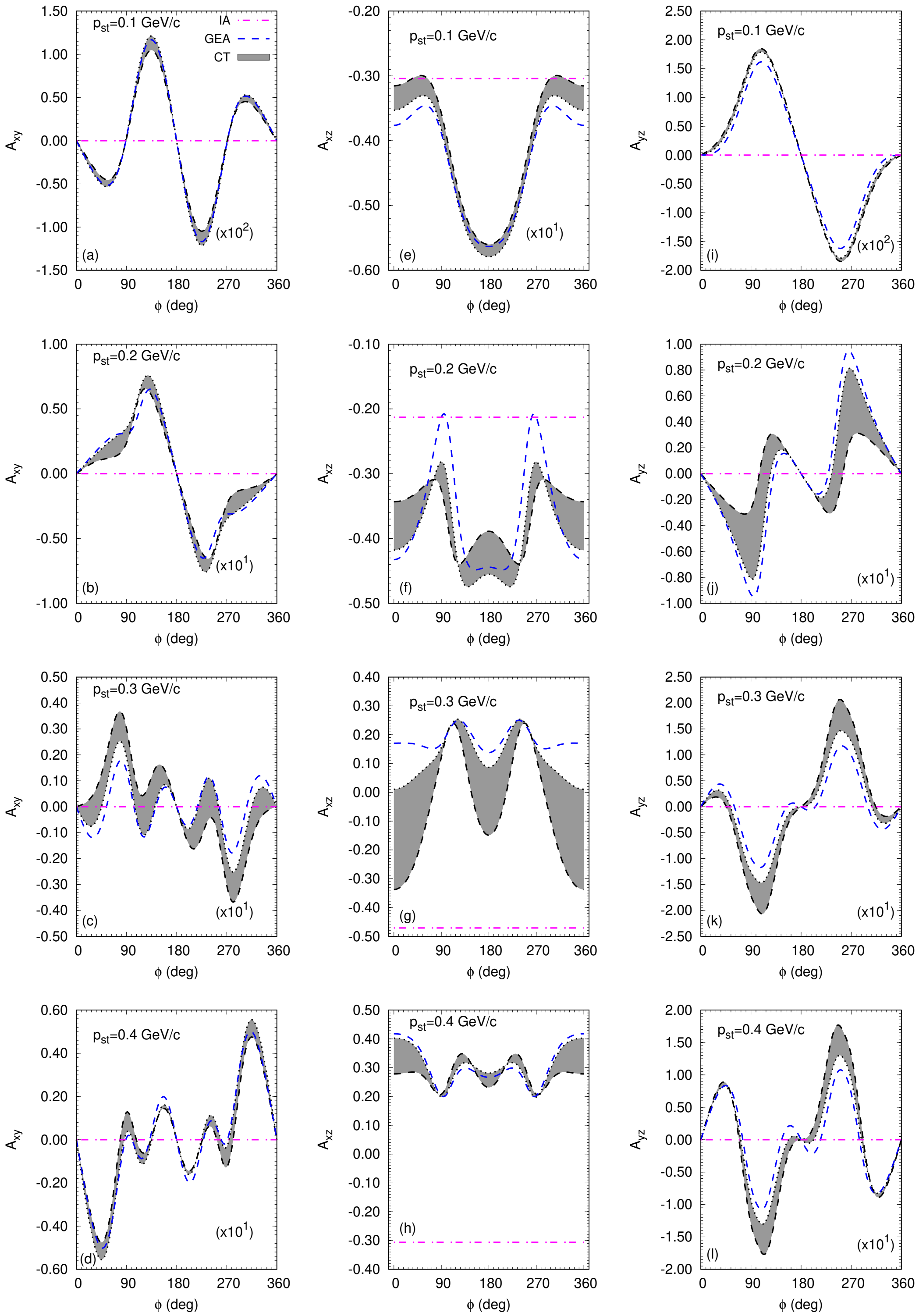

Figure 4. Same as Fig. 2, but for non-diagonal DTAP.