Цветовая прозрачность в жестких протон-ядерных столкновениях

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Outline:

- Introduction: phenomenon of color transparency (CT) and its search at intermediate energies (BNL, JLab)

- The process d(p,2p)n at large momentum transfer: generalized eikonal approximation (GEA), quantum diffusion model of CT, separation of the hard (quark counting) and soft (Landshoff) amplitudes

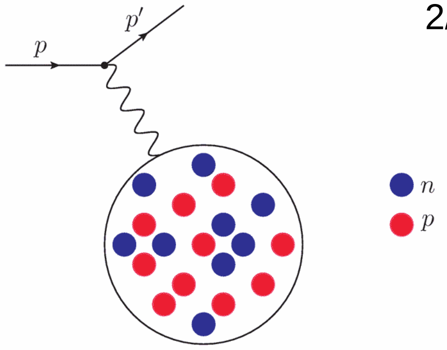
- Nuclear transparency, analyzing powers

- Summary

Based on PRC 107, 014605 (2023) [arXiv:2208.08832];
Phys. Part. Nucl. 56, 381 (2025) [arXiv:2409.07845];
EPJA 61, 160 (2025) [arXiv:2409.10260];
and work in progress

„Физика Частиц при Средних и Высоких Энергиях"
ИВФЭ, Протвино, 04.06.2026

Introduction



Hadron- or electron- nucleus interaction

Four momentum transfer squared: $Q^2 = -t = -(p - p')^2$

Hard processes: $Q^2 \gg 1 \text{ GeV}^2$

- *Quark-gluon degrees of freedom*
- *Point-like $q\bar{q}$ and qqq configurations (PLCs):* $r_\perp \sim 1/Q$

Color dipole – proton cross section in the pQCD limit $(r_\perp \to 0)$: $\sigma_{q\bar{q}} \propto r_\perp^2 \sim 1/Q^2$

L. Frankfurt, G.A. Miller, M. Strikman, PLB 304, 1 (1993)

Color transparency (CT): quark configurations in final or initial state of a high momentum transfer exclusive process interact with nucleons with a reduced cross section.

Originally predicted for the binary semi-exclusive processes with large momentum transfer

$$h + A \to h + p + (A-1)^*$$

S.J. Brodsky, 1982; A.H. Mueller, 1982

Reviews of CT:

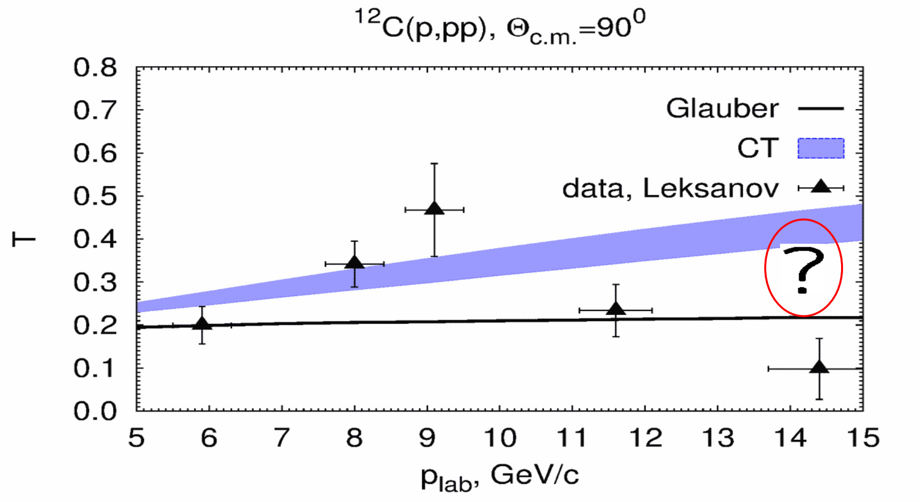
L. Frankfurt, G.A. Miller, M. Strikman, Annu. Rev. Nucl. Part. Sci. 44, 501 (1994);
P. Jain, B. Pire, J.P. Ralston, Phys. Rept. 271, 67 (1996);
D. Dutta, K. Hafidi, M. Strikman, Prog. Part. Nucl. Phys. 69, 1 (2013)

Nuclear target needed.

Observable – nuclear transparency:

$$T = \frac{\sigma}{\sigma_{\rm IA}} \;, \qquad \sigma_{\rm IA} \simeq Z\sigma_p$$

Neglecting Fermi motion



Decrease of T at high p_{lab} is not understood yet:

- could be due to stronger absorption of the large-size quark configurations produced by Landshoff mechanism, J.P. Ralston, B. Pire, PRL 61, 1823 (1988);

- or due to intermediate (very broad, Γ~ 1 GeV) 6$qc\bar{c}$ resonance formation with mass ~ 5 GeV, S.J. Brodsky, G.F. de Teramond, PRL 60, 1924 (1988).

Data: EVA@AGS, A. Leksanov et al., PRL 87, 212301 (2001).

Exclusive meson electroproduction at JLab:

$A(e,e'\pi^+)$ for ^{2}H, ^{12}C, ^{27}Al, ^{63}Cu, and ^{197}Au at $Q^2 = 1.1 - 4.7$ GeV^2, $E_{beam} = 4.0 - 5.8$ GeV

B. Clasie et al., PRL 99, 242502 (2007)

$A(e,e'\rho^0)$ for ^{12}C and ^{56}Fe at $Q^2 = 1 - 2.2$ GeV^2, $E_{beam} = 5$ GeV

L. El Fassi et al., PLB 712, 326 (2012)

- Clear indications for the enhanced nuclear transparency due to CT effect

Quasielastic electron scattering at JLab:

$A(e,e'p)$ for ^{2}H, ^{12}C,^{56}Fe at $Q^2 = 3.3 - 8.1$ GeV^2, $E_{\rm beam} = 3.1 - 5.6$ GeV

K. Garrow et al., PRC 66, 044613 (2002)

$^{12}C(e,e'p)$ at $Q^2 = 8 - 14.2$ GeV^2, $E_{\rm beam} = 6.4, 10.6$ GeV

D. Bhetuwal et al., PRL 126, 083301 (2021)

- No CT signal

Deuteron target:

- ISI and FSI are small, however, the PLCs will likely not expand too much on the length scale < 1.5 fm (internucleon distances in the deuteron contributing to the rescattering amplitides) for momenta above several GeV/c, i.e. they are likely to be frozen.

- Theory suggestions to study CT in several large-angle processes:

d(e,e'p)n – *V.V. Anisovich, L.G. Dakhno, M.M. Giannini, PRC 49, 3275 (1994);*
L.L. Frankfurt, W.R. Greenberg, G.A. Miller, M.M. Sargsian, M.I. Strikman, Z. Phys. A352, 97 (1995)

Recent proposal at JLab: S. Li et al, MDPI Physics 4, 1426 (2022) [arXiv:2209.14400]

d(p,2p)n - *L.L. Frankfurt, E. Piasetzky, M.M. Sargsian, M.I. Strikman, PRC 56, 2752 (1997);*
AL PRC 107, 014605 (2023)

- Can be measured at NICA SPD

d($\bar{p}$,$\pi^-\pi^0$)p – *AL, M.I. Strikman, EPJA 56, 21 (2020)*

- Can be measured at PANDA

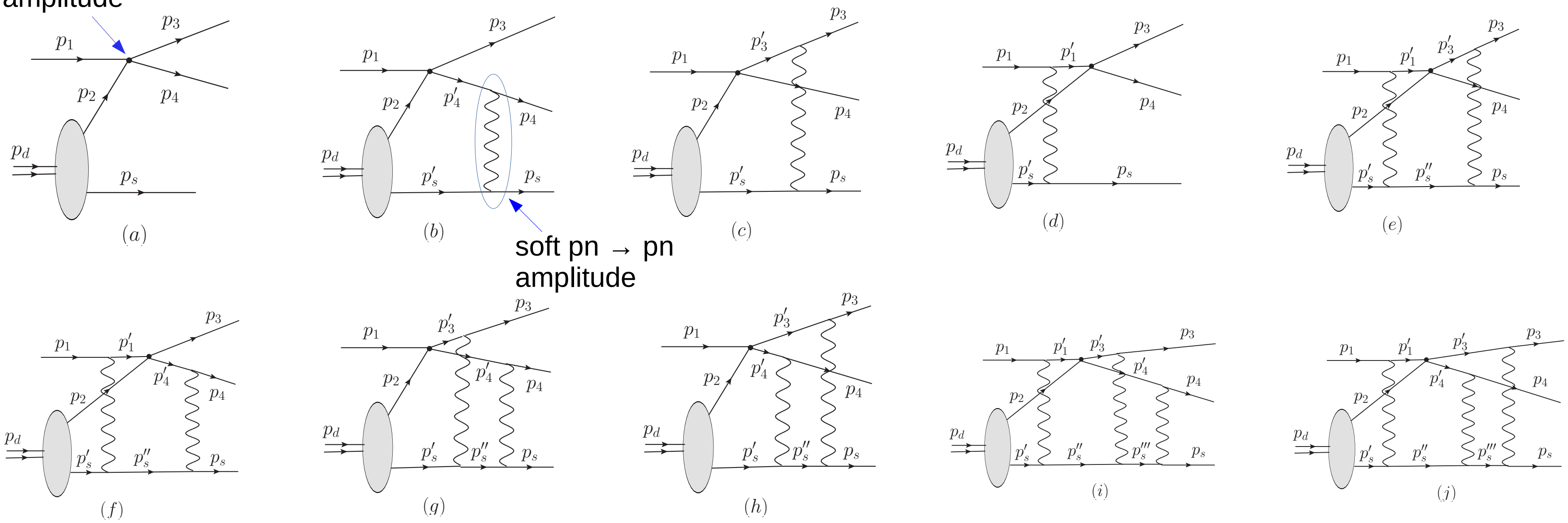
Hard d(p,2p)n process

$$s_{hard} = (p_3 + p_4)^2,\ t_{hard} = (p_1 - p_3)^2,\ u_{hard} = (p_1 - p_4)^2$$

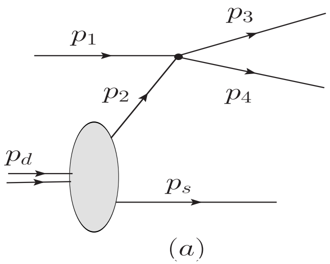
$$Q^2 = \min(-t_{\text{hard}}, -u_{\text{hard}}) \gg 1\ \text{GeV}^2$$ ***- hard scale***

Partial amplitudes:

hard pp → pp amplitude



Impulse approximation (IA) amplitude:



$$M^{(a)} = M_{\rm hard}(s_{\rm hard}, t_{\rm hard}) \frac{i\Gamma_{d\to pn}(p_d, p_s)}{(p_2)^2 - m^2 + i\epsilon} \ ,$$

Non-relativistic treatment of the deuteron wave function (DWF)
in the deuteron rest frame for the on-shell spectator neutron:

$$\frac{i\Gamma_{d\to pn}(p_d, p_s)}{(p_2)^2 - m^2 + i\epsilon} = \left(\frac{2E_s m_d}{p_2^0}\right)^{1/2} (2\pi)^{3/2} \phi^{\lambda_d}(\boldsymbol{p}_2, \lambda_2, \lambda_s) \ , \quad \boldsymbol{p}_2 = -\boldsymbol{p}_s \ , \quad E_s \equiv (m^2 + \boldsymbol{p}_s^2)^{1/2} \ , \quad p_2^0 = m_d - E_s$$

DWF:

$$\phi^{\lambda_d}(\boldsymbol{p}_2, \lambda_2, \lambda_s) = \frac{1}{\sqrt{4\pi}} \left[u(p_2) + \frac{w(p_2)}{\sqrt{8}} S(\boldsymbol{p_2}) \right] \chi^{\lambda_d} \ ,$$

$$S(\boldsymbol{p}) = \frac{3(\boldsymbol{\sigma}_{\lambda_2\lambda_p}\boldsymbol{p})(\boldsymbol{\sigma}_{\lambda_s\lambda_n}\boldsymbol{p})}{p^2} - \boldsymbol{\sigma}_{\lambda_2\lambda_p}\boldsymbol{\sigma}_{\lambda_s\lambda_n}$$

- spin tensor operator

$$\chi^{\pm 1} = \delta_{\pm 1/2, \lambda_p} \delta_{\pm 1/2, \lambda_n}$$

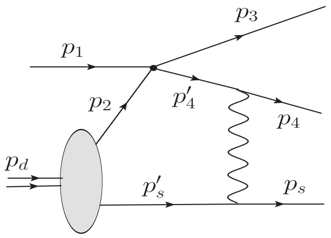
$$\chi^0 = \frac{1}{\sqrt{2}} (\delta_{1/2,\lambda_p}\delta_{-1/2,\lambda_n} + \delta_{-1/2,\lambda_p}\delta_{1/2,\lambda_n})$$

$$\int d^3p \sum_{\lambda_2, \lambda_s} |\phi^{\lambda_d}(\boldsymbol{p}, \lambda_2, \lambda_s)|^2 = 1 \ .$$

$$M^{(a)} \simeq 2m^{1/2} M_{\rm hard}(s_{\rm hard}, t_{\rm hard}) (2\pi)^{3/2} \phi(-\boldsymbol{p}_s) = 2m^{1/2} M_{\rm hard}(s_{\rm hard}, t_{\rm hard}) \int d^3r\, {\rm e}^{i\boldsymbol{p}_s\boldsymbol{r}} \phi(\boldsymbol{r}) \ , \quad \boldsymbol{r} = \boldsymbol{r}_2 - \boldsymbol{r}_s$$

nucleon mass

Amplitude with rescattering of an outgoing proton:



(b)

- momentum transfer in soft rescattering is small, $M_{\rm hard}$ can be factorized out of the four momentum integral

$$M^{(b)} = M_{\rm hard}(s_{\rm hard}, t_{\rm hard}) \int \frac{d^4 p_s'}{(2\pi)^4} \frac{\Gamma_{d\to pn}(p_d, p_s') M_{\rm el}(p_4, p_s, p_4')}{((p_2)^2 - m^2 + i\epsilon)((p_4')^2 - m^2 + i\epsilon)((p_s')^2 - m^2 + i\epsilon)} ,$$

- static neutron approximation: neglect the dependence of the soft rescattering amplitude $M_{\rm el}$ on the energy $p_s'^0$ of intermediate neutron

- perform contour integration over $p_s'^0$ (pole approximation, $(p_s')^2 = m^2$)

$$M^{(b)} = -\frac{M_{\rm hard}(s_{\rm hard}, t_{\rm hard})}{m^{1/2}} \int \frac{d^3 k}{(2\pi)^3} \frac{(2\pi)^{3/2} \phi(-\boldsymbol{p}_s') M_{\rm el}(|\boldsymbol{p}_4|, t)}{(p_4')^2 - m^2 + i\epsilon} ,$$

$$k = p_s - p_s',\ \boldsymbol{k}_t = \boldsymbol{k} - (\boldsymbol{k}\boldsymbol{p}_4)\boldsymbol{p}_4/|\boldsymbol{p}_4|^2, \quad t = k^2 \simeq -k_t^2$$

- express the propagator of the fast proton in the eikonal form:

$$(p_4')^2 - m^2 + i\epsilon = (p_4 + p_s - p_s')^2 - m^2 + i\epsilon = 2p_4(p_s - p_s') + (p_s - p_s')^2 + i\epsilon = 2|\boldsymbol{p}_4|(p_s'^{z_4} - p_s^{z_4} + \Delta_4 + i\epsilon) , \quad \boldsymbol{e}_{z_4} \upuparrows \boldsymbol{p}_4 ,$$

$$\Delta_4 \equiv \frac{E_4(E_s - E_s')}{|\boldsymbol{p}_4|} + \frac{(p_s - p_s')^2}{2|\boldsymbol{p}_4|} \simeq \frac{(E_4 - m)(E_s - m)}{|\boldsymbol{p}_4|}$$

neglecting Fermi motion in the deuteron (GEA)

Use identity: $$\frac{i}{p + i\epsilon} = \int dz^0 \Theta(z^0) \mathrm{e}^{ipz^0}$$

$$M^{(b)} = -2m^{1/2} M_{\rm hard}(s_{\rm hard}, t_{\rm hard}) \int d^3 r \Theta(-z_4) \phi(\boldsymbol{r}) \mathrm{e}^{i\boldsymbol{p}_s\boldsymbol{r} - i\Delta_4 z_4} \Gamma_4(b_4) ,\ \Gamma_4(b_4) = -\frac{i}{4|\boldsymbol{p}_4|m} \int \frac{d^2 k_t}{(2\pi)^2} \mathrm{e}^{-i\boldsymbol{k}_t\boldsymbol{b}_4} M_{\rm el}(|\boldsymbol{p}_4|, -k_t^2)$$

$$z_4 = \boldsymbol{r}\boldsymbol{p}_4/|\boldsymbol{p}_4|,\ \ \boldsymbol{b}_4 = \boldsymbol{r} - (\boldsymbol{r}\boldsymbol{p}_4)\boldsymbol{p}_4/|\boldsymbol{p}_4|^2$$

- profile function

Color transparency in the pn soft elastic rescattering amplitudes:

Without CT (GEA): $$M_{\rm el}(|\boldsymbol{p}_j|,t) = 2|\boldsymbol{p}_j| m\sigma^{\rm tot}_{pn}(i+\rho_{\rm pn}){\rm e}^{B_{\rm pn}t/2}$$

With CT: $$M_{\rm el}(|\boldsymbol{p}_j|,t,l) = 2|\boldsymbol{p}_j| m\,\sigma^{\rm eff}_{pn}(l)\,(i+\rho_{\rm pn}){\rm e}^{B_{\rm pn}t/2}\,\frac{G(t\cdot\frac{\sigma^{\rm eff}_{pn}(l)}{\sigma^{\rm tot}_{pn}})}{G(t)}\;,\quad l=|\boldsymbol{r}\hat{\boldsymbol{p}}_j|$$

$$\sigma^{\rm eff}_{pn}(l) = \sigma^{\rm tot}_{pn}\left(\left[\frac{l}{l_c}+\frac{Q_0^2}{Q^2}\left(1-\frac{l}{l_c}\right)\right]\Theta(l_c-l)+\Theta(l-l_c)\right)\;,\qquad Q_0\simeq 1\ {\rm GeV}$$

$Q^2=\min(-t_{\rm hard},-u_{\rm hard})$ - hard scale

$l_c = \frac{2|\boldsymbol{p}_j|}{\Delta M^2}$ - coherence length

$\Delta M^2 \simeq 1\ {\rm GeV}^2$ - from pion transparency studies at JLab

$\Delta M^2 \simeq 2-3\ {\rm GeV}^2$ - from recent JLab ^{12}C(e,e'p) data analysis, S. Li et al., MDPI Physics 4, 1426 (2022) [arXiv:2209.14400]

$G(t) = \frac{1}{(1-t/0.71\ {\rm GeV}^2)^2}$ - electric formfactor of the proton

Quantum diffusion model of CT: ***G.R. Farrar, H. Liu, L.L. Frankfurt, M.I. Strikman, PRL 61, 686 (1988); L.L. Frankfurt, W.R. Greenberg, G.A. Miller, M.M. Sargsian, M.I. Strikman, ZPA 352, 97 (1995)***

Hard pp → pp scattering amplitude

J.P. Ralston, B. Pire, PRL 61, 1823 (1988)

$$M_{\rm hard} = M_{\rm QC} + M_{\rm L} = M_{\rm QC}(1 + R(s))$$

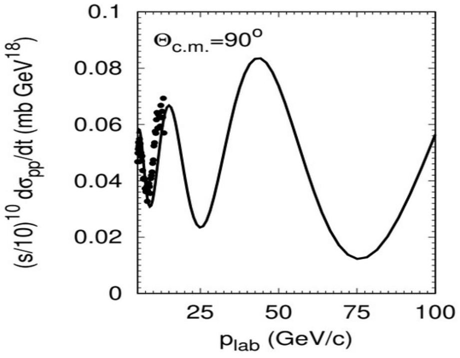
quark counting component ~ s^{-4}
minimally connected graphs,
small-size configurations (PLCs)
affected by CT

Landshoff component – independent qq scattering,
disconnected graphs, large-size configurations
not affected by CT

chromo-Coulomb phase shift

$$R(s) = M_{\rm L}/M_{\rm QC} = \frac{\rho_1\sqrt{s}}{2} {\rm e}^{\pm i(\phi(s)+\delta_1)}, \quad \rho_1 = 0.08~{\rm GeV}^{-1}, \quad \delta_1 = -2$$

$$\phi(s) = \frac{\pi}{0.06}\log\left[\log\left(\frac{s}{\Lambda^2_{\rm QCD}}\right)\right], \quad \Lambda_{\rm QCD} = 0.1~{\rm GeV}$$

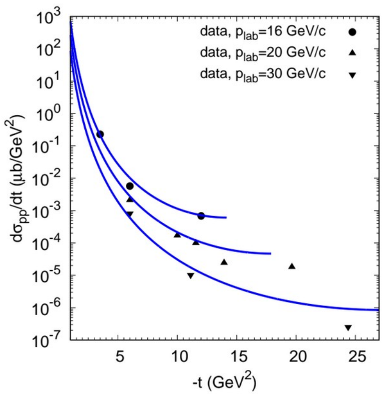


Data: **C.W. Akerlof et al., Phys. Rev. 159, 1138 (1967)**

Cross section parameterization **L. Frankfurt, E. Piasetsky, M. Sargsian, M. Strikman, PRC 51, 890 (1995); P.V. Landshoff, J.C. Polkinghorne PL 44B, 293 (1973)**

$$\frac{d\sigma_{pp}}{dt} = \frac{d\sigma^{\rm QC}_{pp}}{dt}|1 + R(s)|^2 ,$$

$$\frac{d\sigma^{\rm QC}_{pp}}{dt} = 45\frac{\mu{\rm b}}{{\rm GeV}^2}\left(\frac{10\,{\rm GeV}^2}{s}\right)^{10}(\sin\Theta_{c.m.})^{-14}$$

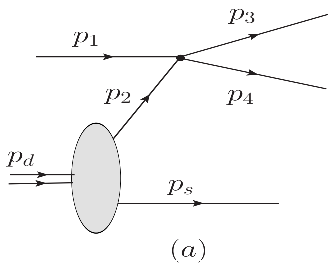


Data: **G. Cocconi et al., Phys. Rev. 138, B165 (1965)**

Assume spin-independent hard amplitude, non-polarized proton beam:

$$\Rightarrow \quad M_{\rm hard} = \left(16\pi(s - 4m^2)s\frac{d\sigma^{\rm QC}_{pp}}{dt}\right)^{1/2}[1 + R(s)]\,\delta_{\lambda_1\lambda_3}\delta_{\lambda_2\lambda_4}$$

Kinematic variables

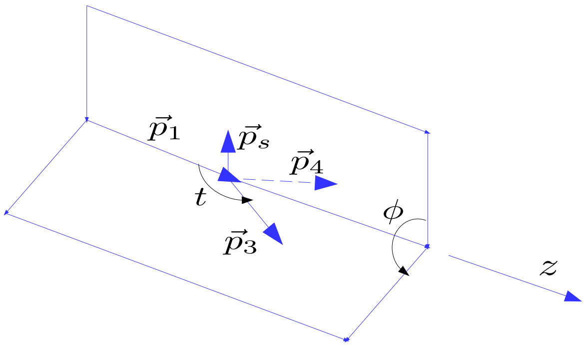


$\alpha_s = \frac{2(E_s - p_s^z)}{m_d}$ - light cone variable: $\alpha_s/2$ = momentum fraction of the deuteron carried by the spectator neutron in the infinite momentum frame where the deuteron moves fast backward

p_{st} - transverse momentum of the spectator neutron

$\phi = \phi_3 - \phi_s$ - relative azimuthal angle between the scattered proton and spectator neutron

$t = (p_1 - p_3)^2 \equiv t_{\text{hard}}$ - Mandelstam variable



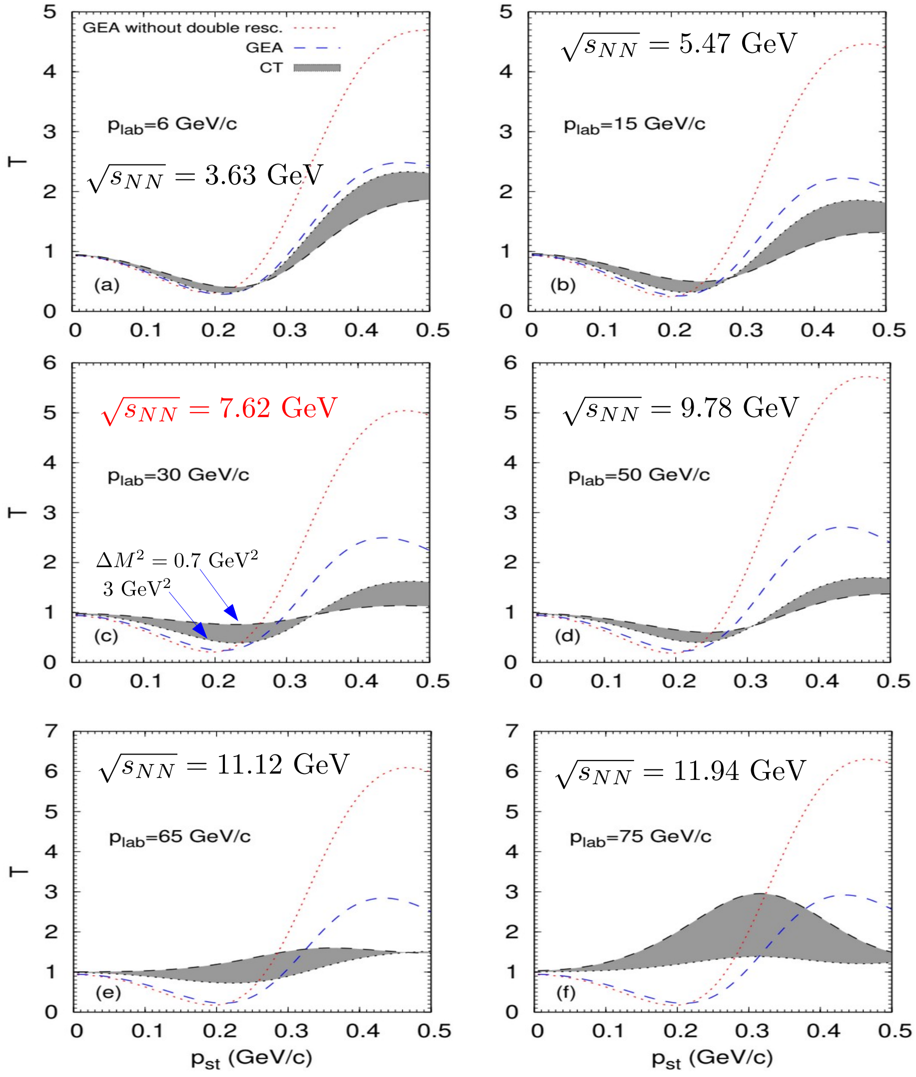
The deuteron rest frame

Nuclear transparency vs transverse momentum of spectator neutron (α_s=1, φ=180 deg., $\Theta_{c.m.}$=90 deg.)

$$T \equiv \frac{\sigma}{\sigma_{\rm IA}} = \frac{\overline{|M^{(a)} + M^{(b)} + M^{(c)} + \ldots|^2}}{\overline{|M^{(a)}|^2}}$$

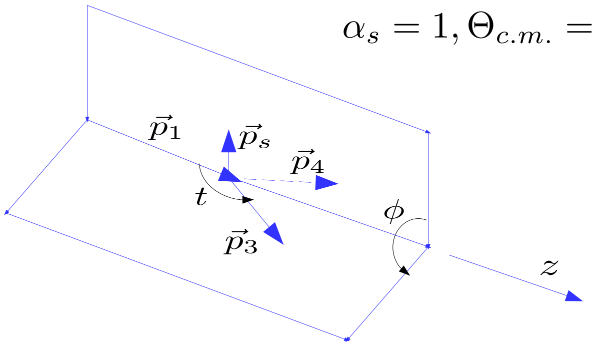
- *Absorption at small p_{st} due to the interference between the IA and single-rescattering amplitudes. Enhancement at large p_{st} due to the single-rescattering amplitudes squared.*

- *CT-transparencies tend to unity (IA-limit) with increasing p_{lab} up to p_{lab}≈30 GeV/c and then start to deviate from unity again. This is due to the fact that CT influences only the QC part of the amplitude and not the Landshoff part.*



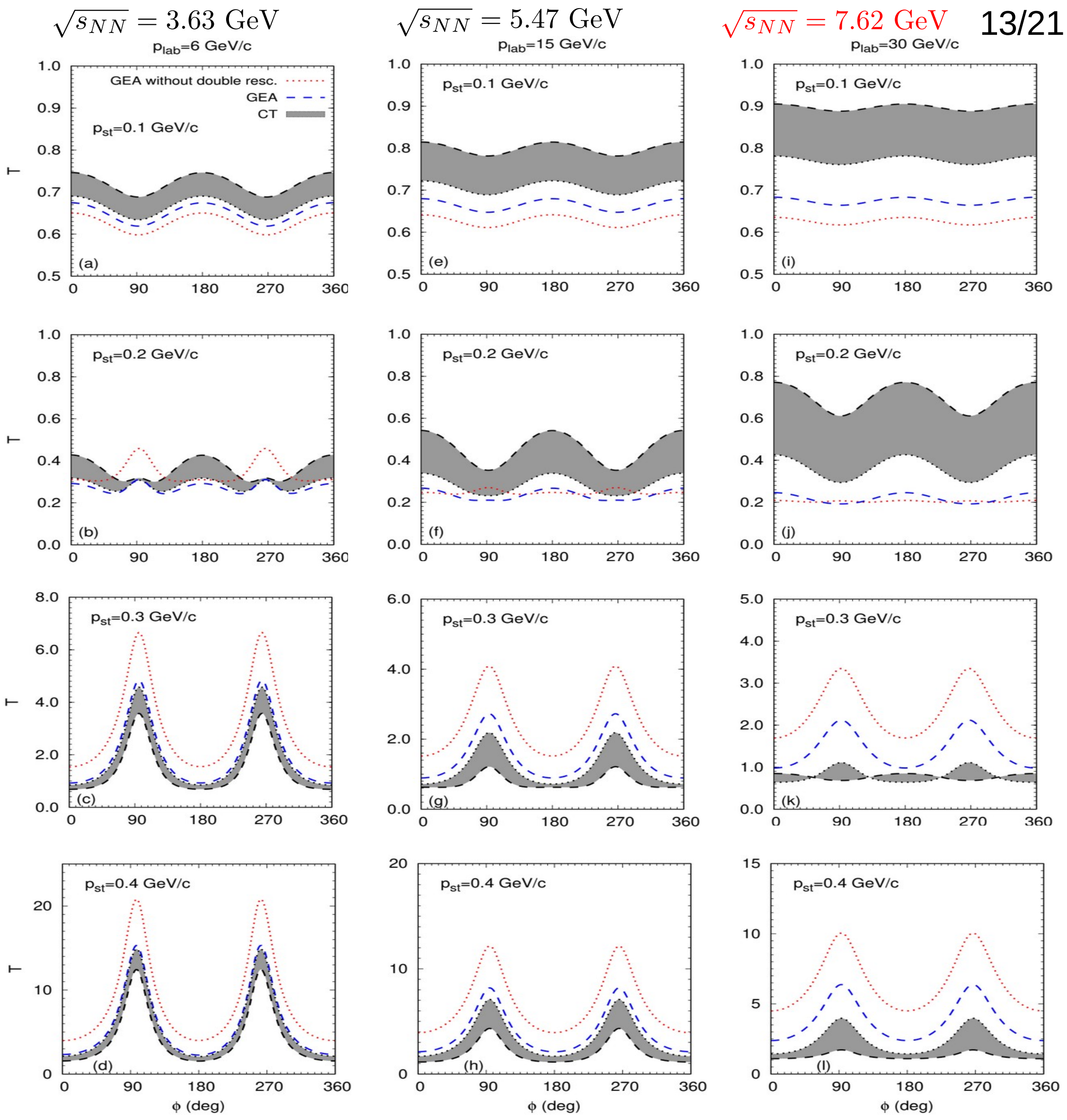
Dependence of the **transparency** on the azimuthal angle between the scattered proton and spectator neutron

$\alpha_s = 1, \Theta_{c.m.} = 90$ deg.



- Rescattering effects for outgoing protons are strongest for φ=90° and 270° when $\vec{p}_s \simeq \vec{k}_t$

- CT effects grow with p_{lab} and become strongest at p_{lab}≈30 GeV/c



Deuteron vector analyzing powers:

$$A^d_\alpha = \frac{\mathrm{Sp}(MS_\alpha M^\dagger)}{\mathrm{Sp}(MM^\dagger)}\ , \qquad \alpha = x, y, z$$

S_α - deuteron spin matrices

$$A^d_\alpha = \frac{\sigma_\alpha(+1) - \sigma_\alpha(-1)}{\sigma_\alpha(+1) + \sigma_\alpha(-1) + \sigma_\alpha(0)}$$

$\sigma_\alpha(\lambda_d)$ - differential cross section for the projection λ_d of deuteron spin on the axis α

In the IA for a spin-independent hard pp amplitude, the deuteron vector analyzing powers disappear:

$$A^{d,IA}_\alpha = \frac{|\phi^{+1}(-\boldsymbol{p}_s))|^2 - |\phi^{-1}(-\boldsymbol{p}_s))|^2}{|\phi^{+1}(-\boldsymbol{p}_s))|^2 + |\phi^{-1}(-\boldsymbol{p}_s))|^2 + |\phi^{0}(-\boldsymbol{p}_s))|^2} = 0$$

Deuteron tensor analyzing powers:

$$A_{\alpha\beta} = \frac{\mathrm{Sp}(MS_{\alpha\beta}M^\dagger)}{\mathrm{Sp}(MM^\dagger)}\ , \qquad \alpha,\beta = x,y,z$$

$$S_{\alpha\beta} = \frac{3}{2}(S_\alpha S_\beta + S_\beta S_\alpha) - 2\delta_{\alpha\beta}$$ - spin-quadrupole operator,

$$A_{\alpha\alpha} = \frac{\sigma_\alpha(+1) + \sigma_\alpha(-1) - 2\sigma_\alpha(0)}{\sigma_\alpha(+1) + \sigma_\alpha(-1) + \sigma_\alpha(0)}$$ (spin asymmetry)

$$\sum_\alpha A_{\alpha\alpha} = 0$$

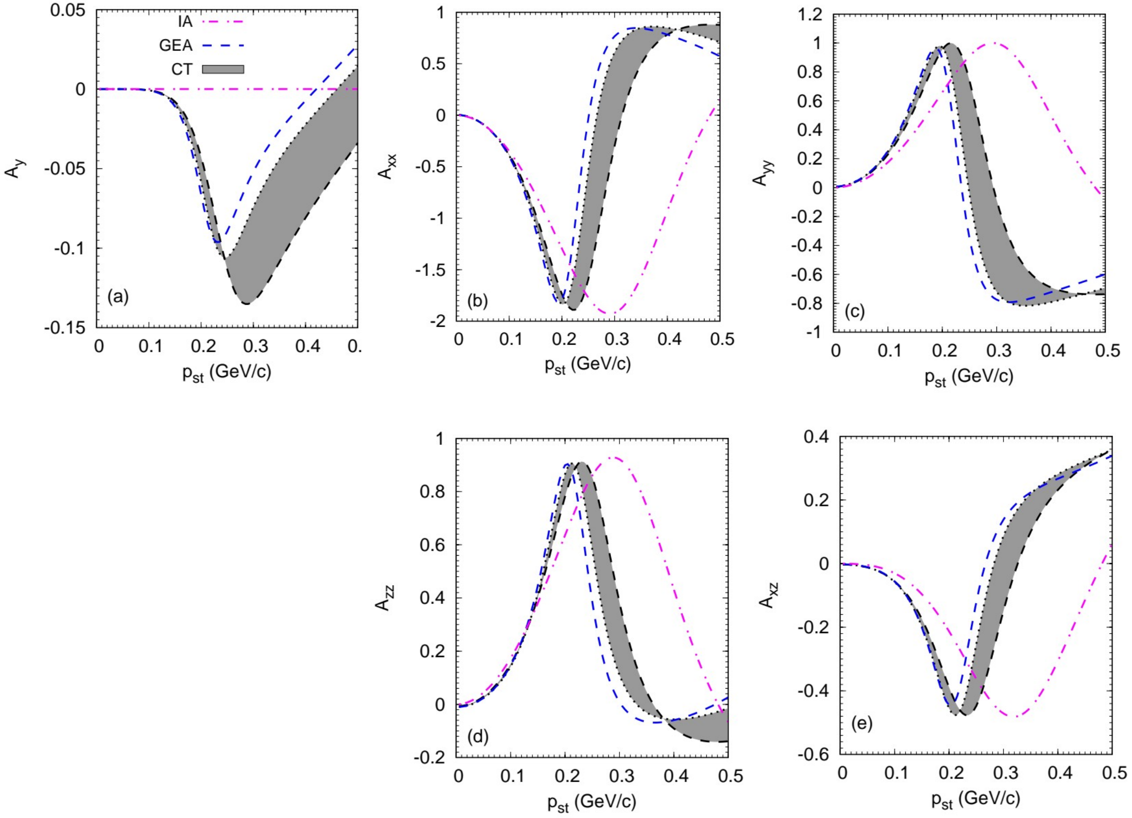
In the IA for a spin-independent hard pp amplitude, the tensor analyzing power is fully determined by the DWF:

$$A^{IA}_{\alpha\beta} = \frac{(3\hat{p}_{s,\alpha}\hat{p}_{s,\beta} - \delta_{\alpha\beta})(\sqrt{2}u(p_s)w(p_s) - w^2(p_s)/2)}{u^2(p_s) + w^2(p_s)}\ , \quad \hat{\boldsymbol{p}}_s = \boldsymbol{p}_s/|\boldsymbol{p}_s|$$

⇒ $A_{\alpha\beta}$ is governed by the D-wave component of the DWF.

Dependence of the vector and tensor analyzing powers on the transverse momentum of the spectator neutron

$p_{\rm lab} = 15$ GeV/c, $\alpha_s = 1$, $\Theta_{c.m.} = 53$ deg., $\phi = 180$ deg.



– all particles move in the (x,z) plane, thus, $A_x=A_z=A_{xy}=A_{yz}=0$

- finite A_y is entirely due to ISI/FSI

- D-wave dominance: $A_{\alpha\beta}=0$ at $p_{st}=0$

- shift of the extremum from $p_{st} \approx 0.3$ GeV/c to $p_{st} \approx 0.2$ GeV/c and reduced width due to ISI/FSI in the GEA calculations

- pronounced CT effects due to the D-wave dominance in $A_{\alpha\beta}$ (favors shorter distances in the deuteron)

Dependence of vector analyzing powers on the azimuthal angle between the scattered proton and spectator neutron

$$p_{\text{lab}} = 15 \text{ GeV/c}, \, \alpha_s = 1, \, \Theta_{c.m.} = 53 \text{ deg.}$$

- vector analyzing power is a pseudovector:

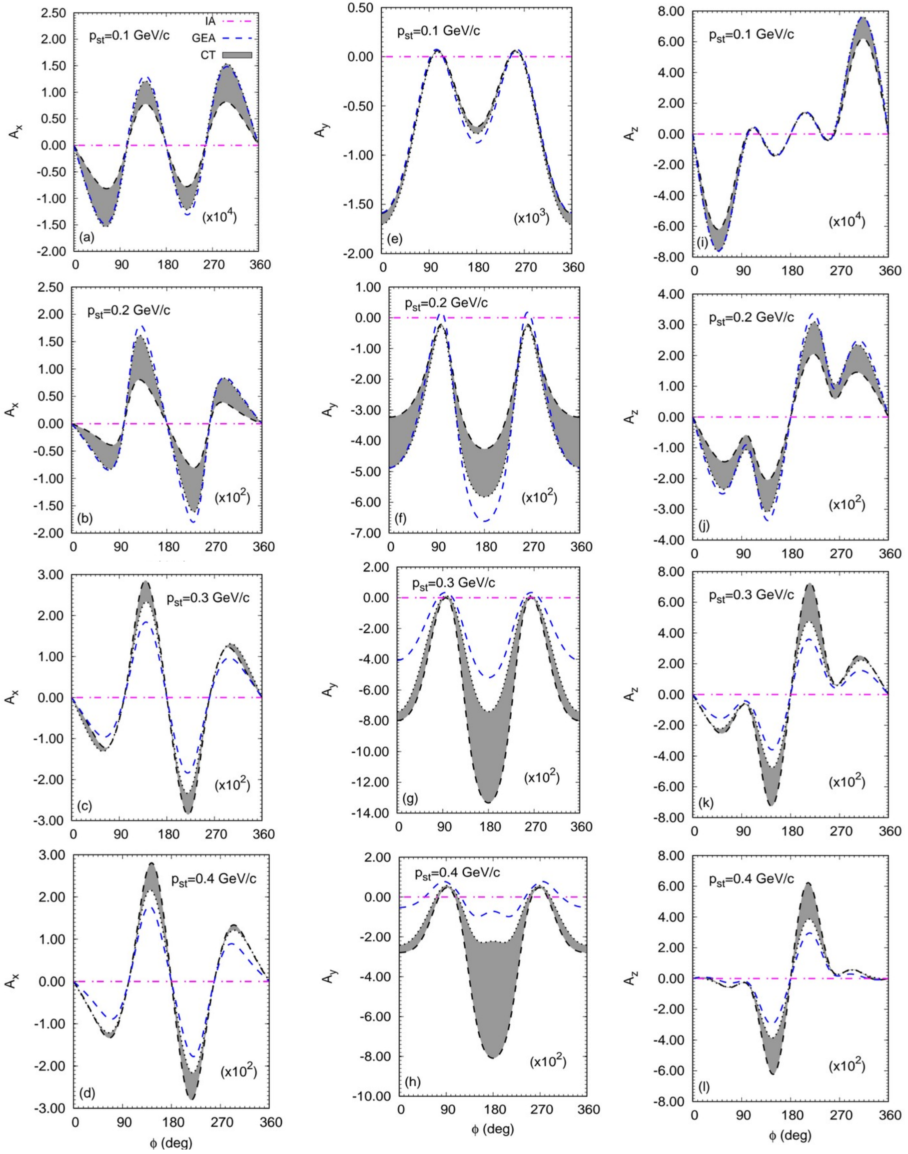
$$\boldsymbol{A} = \sum_{i,j} f_{i,j} [\boldsymbol{p}_i \times \boldsymbol{p}_j]$$

- (anti)symmetry with respect to reflection in the (x,z) plane:

$$A_x(360^\circ - \phi) = -A_x(\phi) \; ,$$
$$A_y(360^\circ - \phi) = A_y(\phi) \; ,$$
$$A_z(360^\circ - \phi) = -A_z(\phi)$$

- vector analyzing powers are small and, perhaps, hard to be observed

- still, significant CT effects, especially for A_y



Dependence of tensor analyzing powers on the azimuthal angle between the scattered proton and spectator neutron

$$p_{\rm lab} = 15\ {\rm GeV/c},\ \alpha_s = 1,\ \Theta_{c.m.} = 53\ {\rm deg.}$$

$$A_{\alpha\beta} = g\delta_{\alpha\beta} + \sum_{i,j} f_{i,j}\, p_{i,\alpha} p_{j,\beta}$$

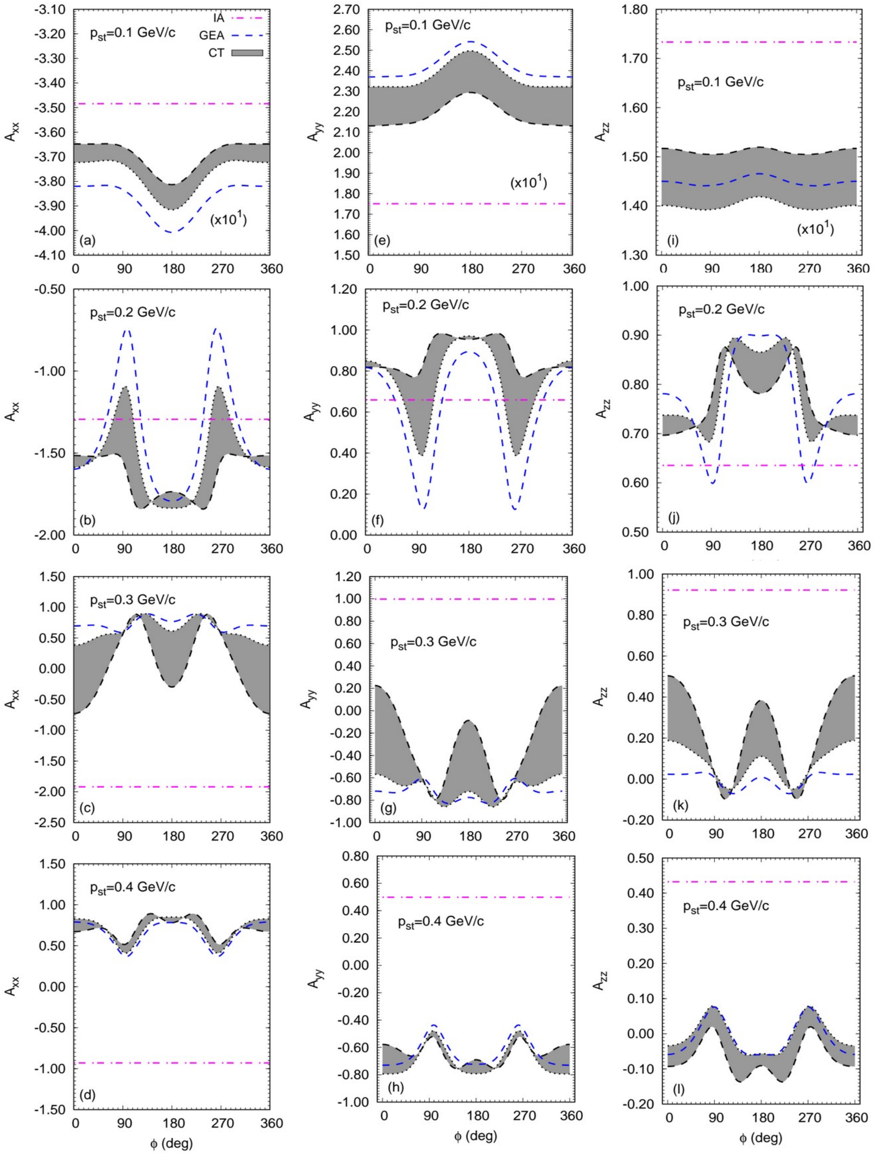
→

$$A_{xx}(360^\circ - \phi) = A_{xx}(\phi)\ ,$$
$$A_{yy}(360^\circ - \phi) = A_{yy}(\phi)\ ,$$
$$A_{zz}(360^\circ - \phi) = A_{zz}(\phi)\ ,$$
$$A_{xy}(360^\circ - \phi) = -A_{xy}(\phi)\ ,$$
$$A_{xz}(360^\circ - \phi) = A_{xz}(\phi)\ ,$$
$$A_{yz}(360^\circ - \phi) = -A_{yz}(\phi)$$

- diagonal components are large

- strong variation with φ due to ISI/FSI

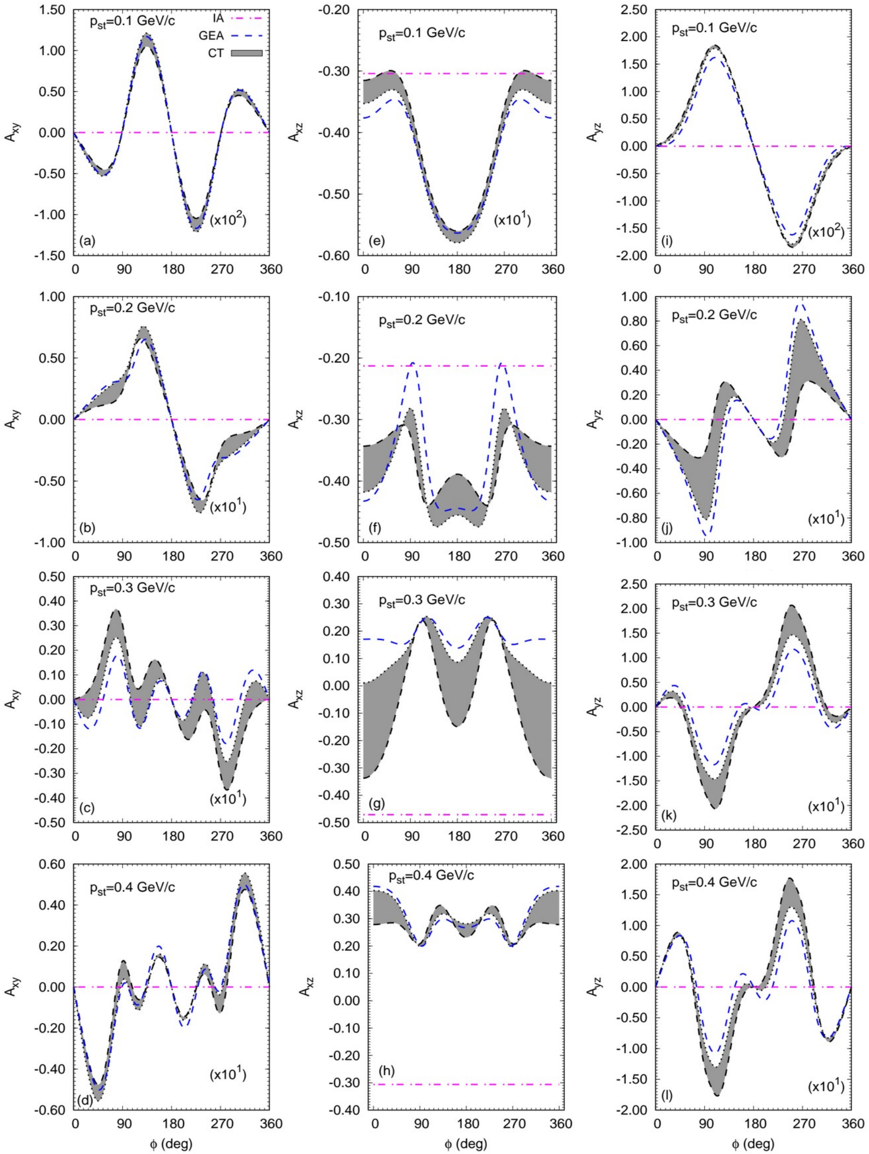
- the influence of CT is strongest at $p_{st} \approx 0.3$ GeV/c



- ***components A_{xy} and A_{yz} are small, but A_{xz} is large: recall that neutron-spectator moves in the (x,z) plane.***

- ***strong variation with φ due to ISI/FSI***

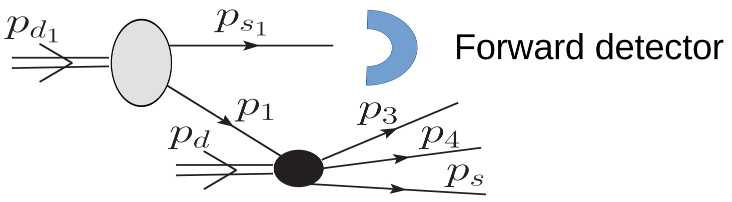
- ***the influence of CT is strongest at p_{st}≈0.3 GeV/c***



Using dd interactions at NICA SPD for the study of hard pd collisions

For $p_1 \approx p_{d1}/2$ (quasifree kinematics) :

$$d\sigma \simeq \underbrace{\overline{|\phi(-\boldsymbol{p}^r_{s_1})|^2}\, d^3p^r_{s_1}}_{\text{in the r. f. of } d_1}\, d\sigma_{1d\to 34s}$$



A hard pd collision can be selected in the dd interaction by registering one neutron with transverse momentum < 0.1 GeV/c in forward detector. This cut includes 80% of the deuteron internal momentum distribution and suppresses rescattering of this neutron.

Summary

- Calculations for the d(p,2p)n large-angle breakup process at p_{lab}=6-75 GeV/c ($\sqrt{s_{NN}}$=3.6-12 GeV) are performed on the basis of the generalized eikonal approximation. The effects of CT are included within the quantum diffusion model taking into account the interference of the small- and large-size qqq configurations.

- ISI/FSI lead to highly non-trivial behavior of the nuclear transparency, vector and tensor analyzing powers as functions of transverse momentum of spectator neutron and relative azimuthal angle between scattered proton and spectator neutron. These dependencies are sensitive to the CT effects.

Next steps

- Feasibility study for CT in dd collisions at the 1st stage of NICA SPD
in collaboration with *Iulia Skorodumina*

- Heavier nuclear targets (CT effects should be more pronounced)

Thank you for your attention !