Color transparency in hard proton-deuteron interactions

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Outline:

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

- 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, tensor analyzing power, event rate estimate at NICA-SPD

- Summary

Based on PRC 107, 014605 (2023) [arXiv:2208.08832];
Phys. Part. Nucl. 56, 381 (2025) [arXiv:2409.07845]

SPD 1st phase meeting
06.05.2025

Introduction

Hard processes (e.g. exclusive meson electroproduction): $Q^2 \gg 1\ \mathrm{GeV}^2$

- ***Quark-gluon d.o.f.***
- ***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.

CT is a necessary condition for the factorization in exclusive hard processes.

Factorization is only possible when the multiple soft gluon exchanges before and after hard scattering are suppressed. This suppression may only take place if PLCs are formed in the hard scattering (similar to the EM interactions of a dipole).
In the case of nuclear target this leads to CT.

For review of CT see

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***: $T = \frac{\sigma}{\sigma_{\rm IA}}$, $\sigma_{\rm IA} \simeq Z\sigma_p$

Neglecting Fermi motion

Exclusive meson electroproduction experiments 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)

Theoretical analyses: ***A. Larson, G. Miller, M. Strikman, PRC 74, 018201 (2006); W. Cosyn, M.C. Martinez, J. Ryckebusch, PRC 77, 034602 (2008); M. Kaskulov, K. Gallmeister, U.Mosel, PRC 79, 015207 (2009); AL, M. Strikman, M. Bleicher, PRC 93, 034618 (2016)***

$A(e,e'\rho^0)$ 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)

Theory predictions: ***L. Frankfurt, G.A. Miller, M. Strikman, PRC 78, 015208 (2008); M. Kaskulov, K. Gallmeister, U.Mosel, PRC 83, 015201 (2011)***

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

Coherence length

- transversely squeezed qqq or $q\bar{q}$ PLC can be decomposed into hadronic basis:

$$|\Psi_{PLC}(t)>=\sum_{i=1}^{+\infty} a_i e^{-iE_i t}|\Psi_i>= e^{-iE_1 t}\sum_{i=1}^{+\infty} a_i e^{i(E_1-E_i)t}|\Psi_i>, \quad E_i=\sqrt{p^2+m_i^2}$$

- the configuration expands to the normal hadronic size on the space (or time) scale of the coherence loss between the lowest and first radially-excited state:

$$l_h \sim t_{\rm coh} = \frac{1}{\sqrt{m_2^2+p^2}-\sqrt{m_1^2+p^2}} \simeq \frac{2p}{m_2^2-m_1^2} \equiv \frac{2p}{\Delta M^2}\ , \quad p \gg m_1, m_2$$

Estimates:

Nucleon: $\Delta M^2 \simeq m^2_{N^*(1440)} - m^2_N \simeq 1.2\ \mathrm{GeV}^2$

Pion: $\Delta M^2 \simeq m^2_{\pi(1300)} - m^2_\pi \simeq 1.7\ \mathrm{GeV}^2$

Empirical values from pion transparency studies at JLab :

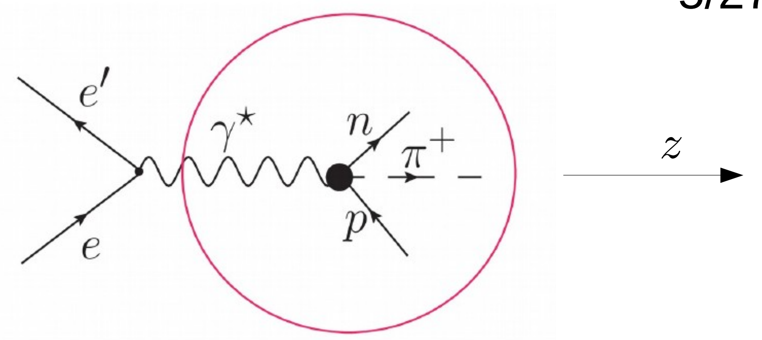
$$\Delta M^2 \simeq 0.7 - 1.1\ \mathrm{GeV}^2$$

$$l_h = 0.4 - 0.6\ \mathrm{fm}\frac{p}{\mathrm{GeV}}\ .$$

Pion electroproduction at JLab:

$$A(e, e'\pi^+)$$

- collinear kinematics: $\mathbf{p}_\pi \parallel \mathbf{q} = \mathbf{p}_e - \mathbf{p}_{e'}$



Transparency:

$$T = \frac{d\sigma_{eA\to e'\pi^+}/d^3p_{e'}d\Omega_{\pi^+}}{Zd\sigma_{ep\to e'\pi^+n}/d^3p_{e'}d\Omega_{\pi^+}} = \frac{1}{Z}\int d^3r\rho_p(\mathbf{r})\,\mathrm{e}^{-\int\limits_z^\infty dz'\sigma_{\pi N}^{\mathrm{eff}}(p_\pi,z'-z)\rho(\mathbf{b},z')}$$

CT effects in a quantum diffusion model
G.R. Farrar, H. Liu, L.L. Frankfurt, M.I. Strikman, PRL 1988:

$$\sigma_{\pi N}^{\mathrm{eff}}(p_\pi, z) = \sigma_{\pi N}(p_\pi)\left(\left[\frac{z}{l_\pi} + \frac{< n^2k_t^2 >}{Q^2}\left(1 - \frac{z}{l_\pi}\right)\right]\Theta(l_\pi - z) + \Theta(z - l_\pi)\right)\ , \quad Q^2 = -(p_e - p_e')^2$$

Scale of shrinkage of pion (transverse size)²

$n = 2$ **- number of valence quarks and antiquarks,**

$< k_t^2 >^{1/2} \simeq 0.35\ \mathrm{GeV/c}$ **- average transverse momentum of a quark in a hadron.**

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

$$p_\pi = 2.8 \div 4.4 \text{ GeV/c}$$

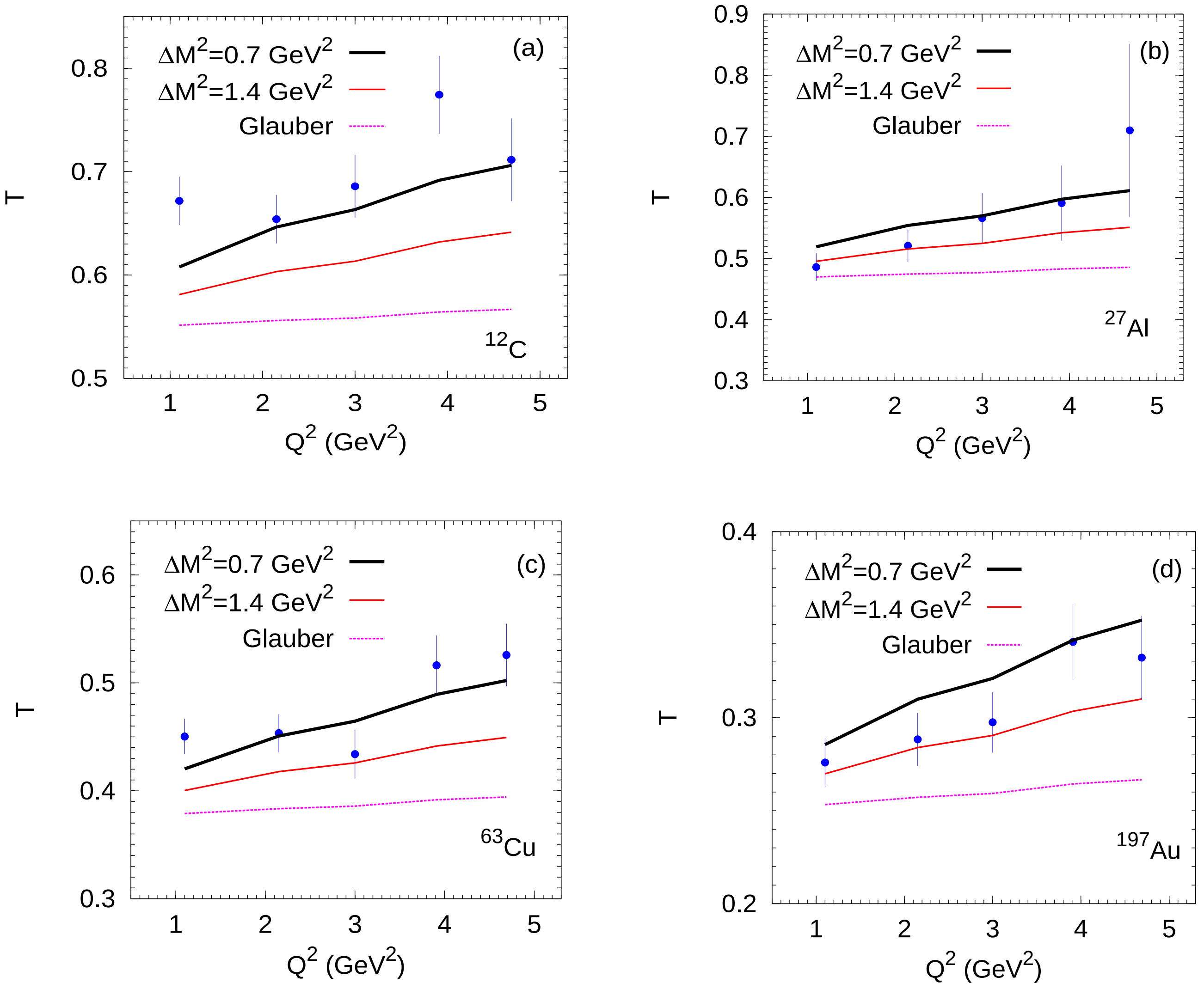
Large coherence length:

$$l_\pi = 1.6 \div 2.5 \text{ fm}$$

$$l_\pi \sim < r^2 >^{1/2}_{^{12}\mathrm{C}} = 2.46 \text{ fm}$$

- Significant CT effect;

- Relative effect of CT is stronger for heavy nuclei due to larger density



Glauber and quantum diffusion model calculations:
AL, M. Strikman, M. Bleicher, PRC 93, 034618 (2016)

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

K. Garrow et al., PRC 66, 044613 (2002) E_{beam}=3.1-5.6 GeV

$^{12}C(e, e'p)$ at $Q^2 = 8 - 14.2$ GeV^2

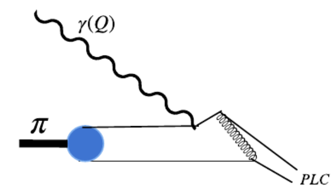
D. Bhetuwal et al., PRL 126, 083301 (2021) E_{beam}=6.4,10.6 GeV

- No CT signal

Possible explanations:

- squeezing proton may need larger Q^2 than for meson (dependence on hadron's twist, i.e. the number of constituents) **S.J. Brodsky, G.F. de Teramond, MDPI Physics 4, 633 (2022) [arXiv:2202.13283]**

- Feynman mechanism without squeezing may dominate for x_B=1:



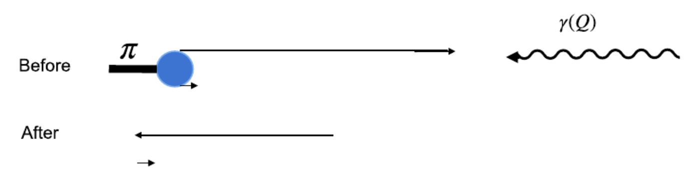


FIG. 1. High-momentum transfer reaction mechanisms. Top picture: A pQCD mechanism. Middle picture: Initial state in the Feynman mechanism. Bottom picture: Final state in the Feynman mechanism. The final state overlaps well with the turned around version of the initial state.

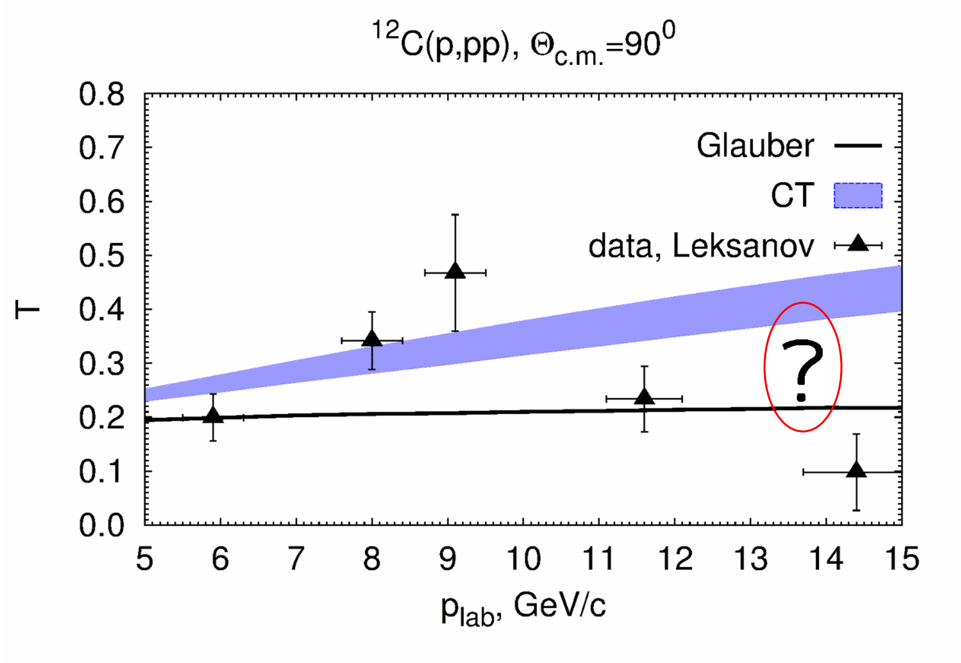
Figure from **O. Caplow-Munro, G.A. Miller, PRC 104, L012201 (2021) [arXiv:2104.11168]**

- Three-layer structure of the nucleon (external pion cloud, intermediate layer with broken chiral symmetry, internal pQCD core) may lead to a quasi-Feynman mechanism when CT appears only at very large Q^2 due to Sudakov form-factors **L. Frankfurt, M. Strikman, MDPI Physics 4, 774 (2022) [arXiv:2210.11569]**

CT has been 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



$$T = \frac{\sigma}{\sigma^{\mathrm{IA}}}$$

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

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

- 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) 6q$c\bar{c}$ resonance formation with mass ~ 5 GeV, S.J. Brodsky, G.F. de Teramond, PRL 60, 1924 (1988).

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

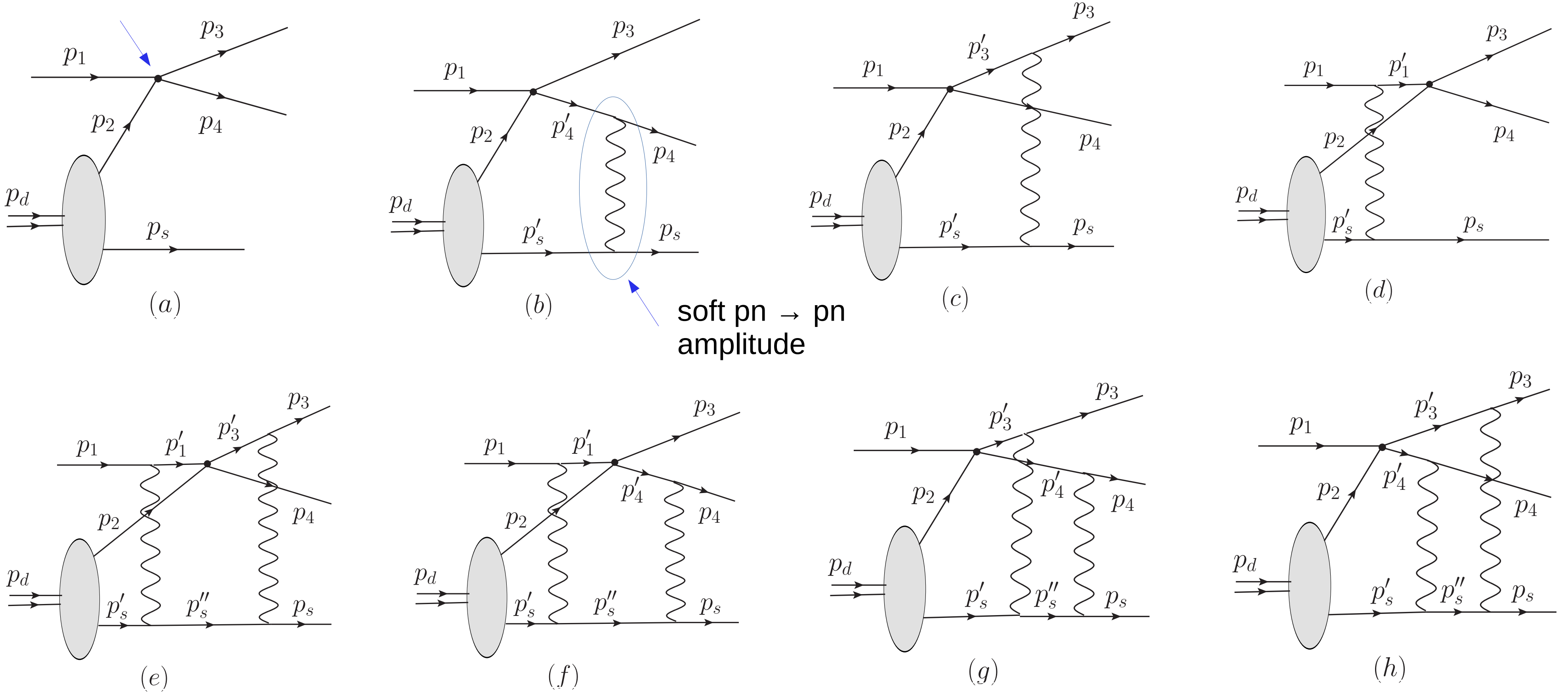
d(p,2p)n large-angle process

Partial amplitudes:

hard pp → pp amplitude

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

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

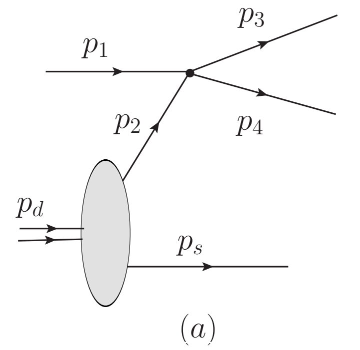


- The amplitudes with soft rescattering are evaluated in the generalized eikonal approximation (GEA)

- CT effect is included via position-dependent soft pn→ pn amplitude in the quantum diffusion model

L.L. Frankfurt, E. Piasetzky, M.M. Sargsian, M.I. Strikman, PRC 56, 2752 (1997);
AL, PRC 107, 014605 (2023)

Impulse approximation (IA) amplitude:



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

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

$$t_{\rm hard} \simeq u_{\rm hard} \simeq -s_{\rm hard}/2 \qquad \Theta_{c.m.} \simeq 90^\circ$$

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

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

DWF:

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

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

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

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

- spin tensor operator

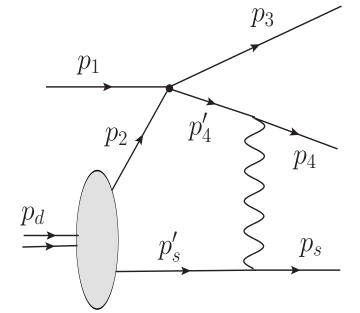
$$\int d^3p \sum_{\lambda_2, \lambda_s} |\phi^{\lambda_d}(\boldsymbol{p}, \lambda_2, \lambda_s)|^2 = 1 .$$

$\Rightarrow$

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

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 neutron

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

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

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

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

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

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

neglect Fermi motion in the deuteron (GEA)

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

$$\tilde z = \boldsymbol{r}\boldsymbol{p}_4/|\boldsymbol{p}_4| \qquad \tilde{\boldsymbol{b}} = \boldsymbol{r} - (\boldsymbol{r}\boldsymbol{p}_4)\boldsymbol{p}_4/|\boldsymbol{p}_4|^2$$

Color transparency in the pn elastic scattering amplitude:

Without CT (GEA): $M_{\rm el}(|\boldsymbol{p}_4|,t) = 2|\boldsymbol{p}_4| m \sigma_{pn}^{\rm tot}(i+\rho_{\rm pn}) {\rm e}^{B_{\rm pn}t/2}$

With CT: $M_{\rm el}(|\boldsymbol{p}_4|,t,l) = 2|\boldsymbol{p}_4| m\, \sigma_{pn}^{\rm eff}(l)\, (i+\rho_{\rm pn}) {\rm e}^{B_{\rm pn}t/2} \frac{G(t\cdot \frac{\sigma_{pn}^{\rm eff}(l)}{\sigma_{pn}^{\rm tot}})}{G(t)}\,, \quad l = |\boldsymbol{r}\boldsymbol{p}_4|/|\boldsymbol{p}_4|$

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

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

$l_c = \frac{2|\boldsymbol{p}_4|}{\Delta M^2}$ - 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)

Landshoff component – independent qq scattering,
disconnected graphs, **large-size configurations**

Only a part of rescattering amplitudes $\propto \mathrm{M_{QC}}$ is influenced by CT !

chromo-Coulomb phase shift

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

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

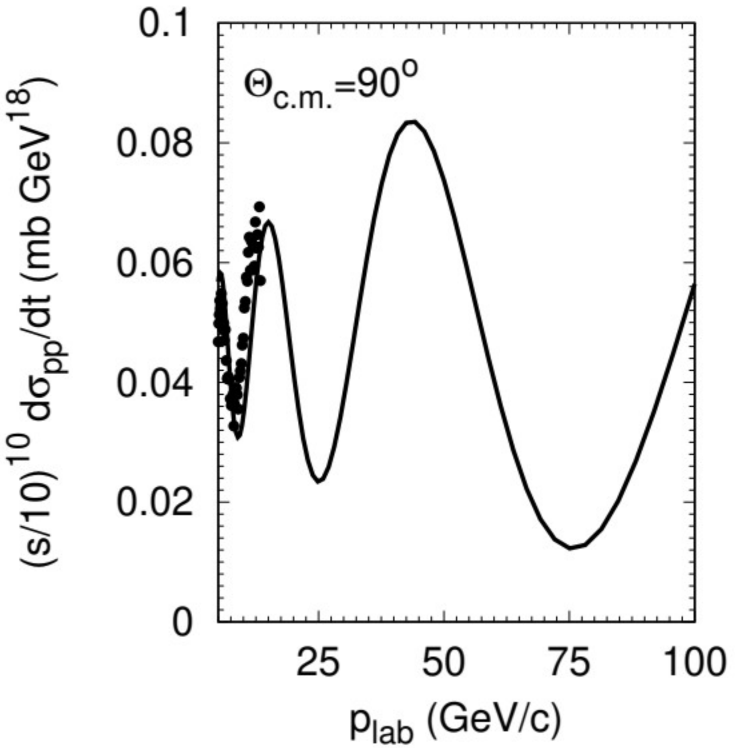
Cross section parameterization
L. Frankfurt, E. Piasetsky,
M. Sargsian, M. Strikman,
PRC 51, 890 (1995)

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

$F(s,\Theta_{c.m.}) \approx 1$ for $s > 15~\mathrm{GeV}^2$ ($p_{lab} > 7$ GeV/c)

$$\frac{d\sigma^{\rm QC}_{pp}}{dt} = 45\frac{\mu{\rm b}}{{\rm GeV}^2}\left(\frac{10~{\rm GeV}^2}{s}\right)^{10}\left(\frac{4m^2-s}{2t}\right)^{4\gamma}$$

$$\gamma = 1.6$$



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

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

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

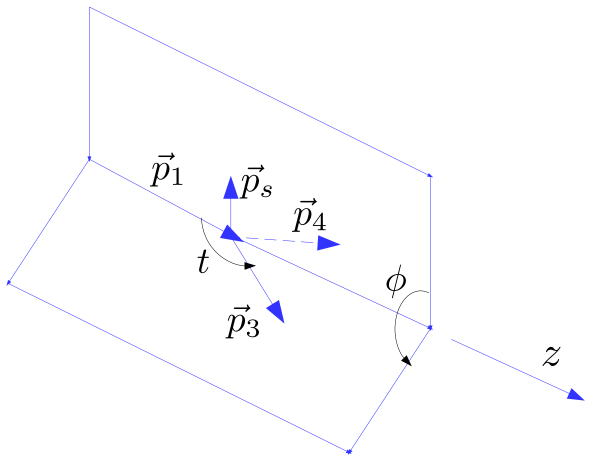
Kinematic variables

$\alpha_s = \frac{2(E_s - p_s^z)}{m_d}$ - the light cone variable (α_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} - the transverse momentum of the spectator neutron

$\phi = \phi_3 - \phi_s$ - the 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

Default choice: $\alpha_s = 1$ - transverse kinematics which minimizes relativistic corrections to the deuteron wave function and maximizes ISI/FSI, see **L.L. Frankfurt et al, PRC 56, 2752 (1997)**

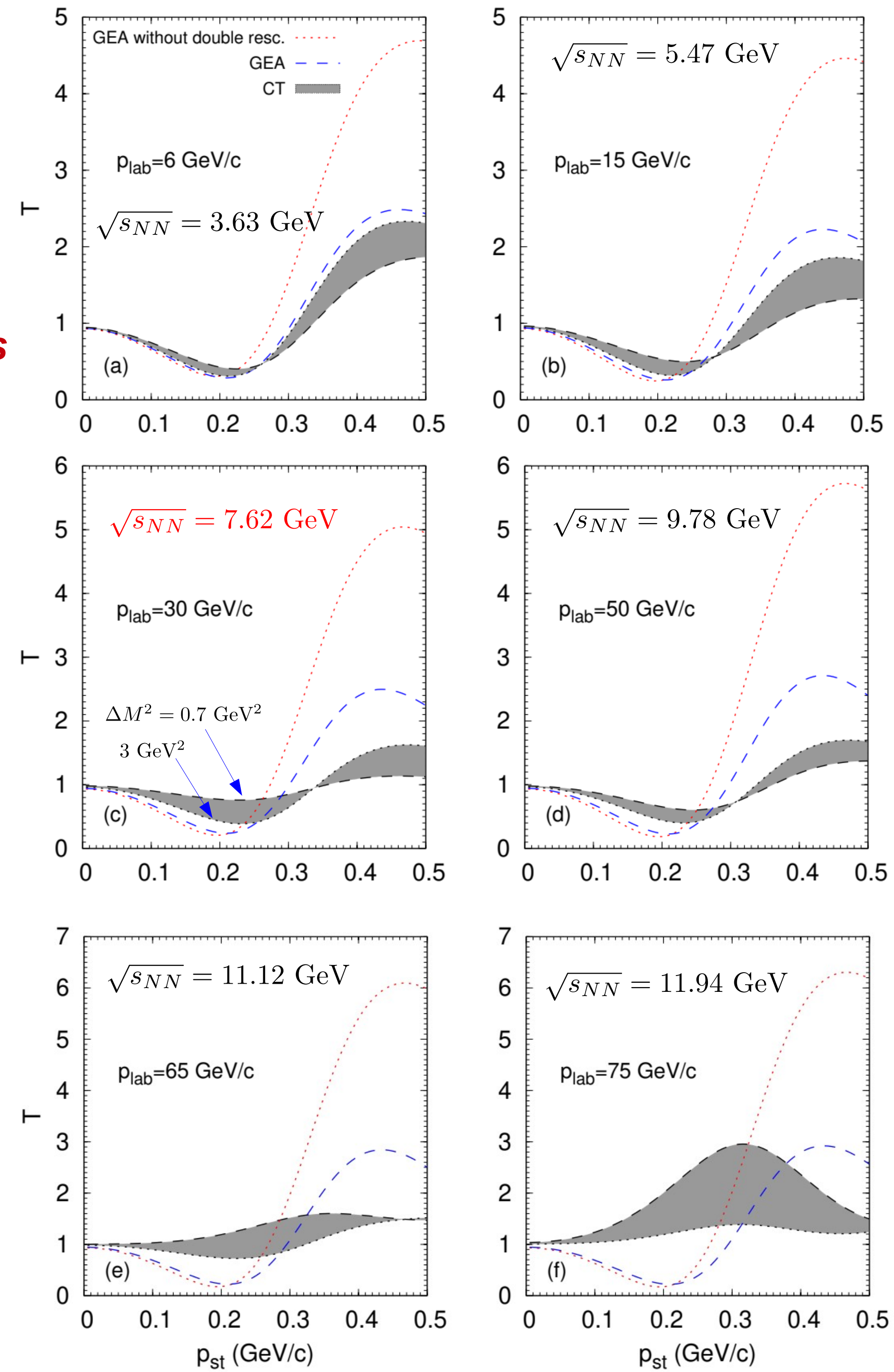
$t = (4m^2 - s)/2,\ s = (p_3 + p_4)^2 \equiv s_{\text{hard}}$
- corresponds to $\Theta_{c.m.} = 90^\circ$

$\phi = 180^\circ$ - in-plane kinematics

Nuclear transparency vs transverse momentum of spectator neutron

$$T = \frac{\sigma}{\sigma_{\rm IA}}$$

- *absorptive ISI/FSI at small p_{st} due the interference between the IA and single-rescattering amplitudes*
- *enhancement at large p_{st} due to the single-rescattering amplitudes squared*
- *destructive interference of the single- and double-rescattering amplitudes, important at large p_{st}*
- *GEA-transparencies do not much depend on p_{lab} (parameters of soft NN scattering amplitude are rather weakly p_{lab}-dependent)*
- *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 "anomaly" is due to the fact that CT influences only the QC part of the amplitude and not the Landshoff part*



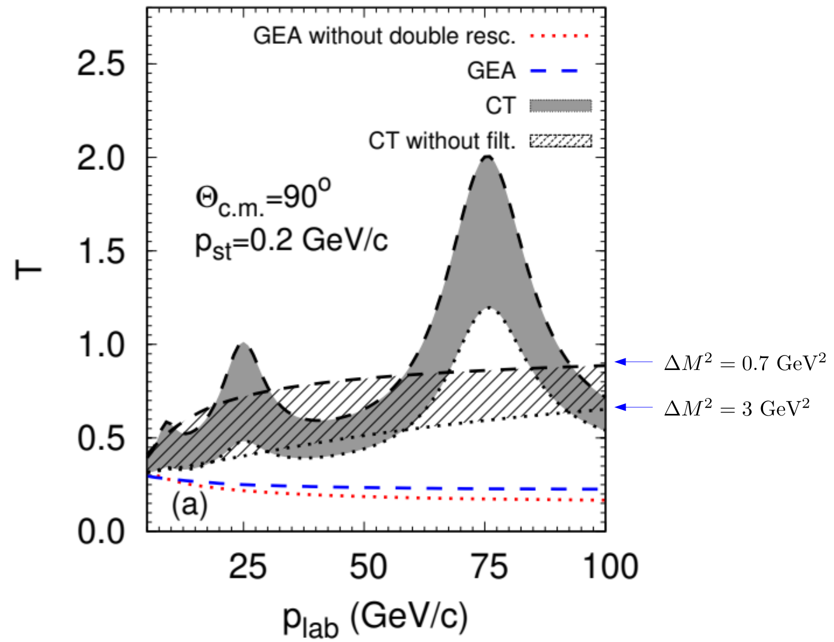
Nuclear transparency vs proton beam momentum

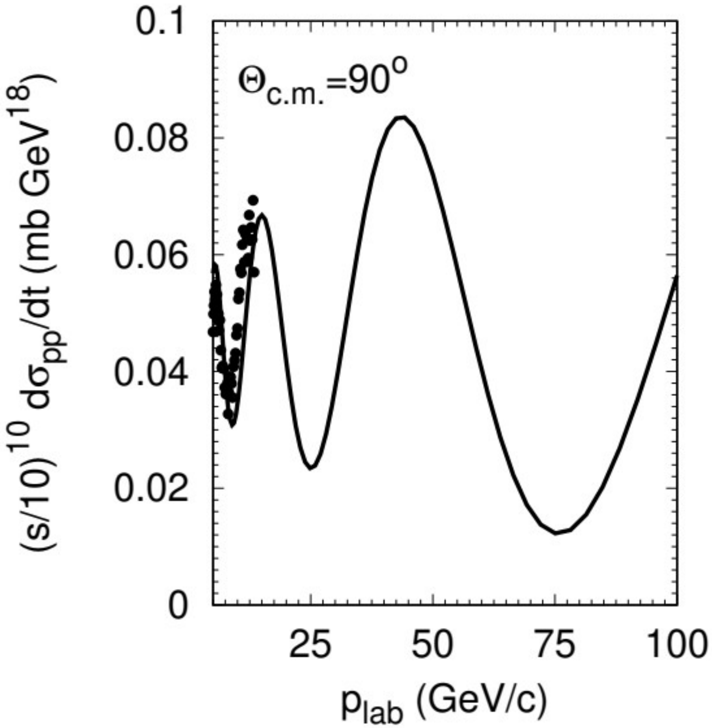
- out-of-phase oscillations relative to the elementary cross section due to σ_{IA} in the denominator

- very similar to the nuclear filtering of the Landshoff component for heavy nuclei
J.P. Ralston, B. Pire, PRL 61, 1823 (1988)

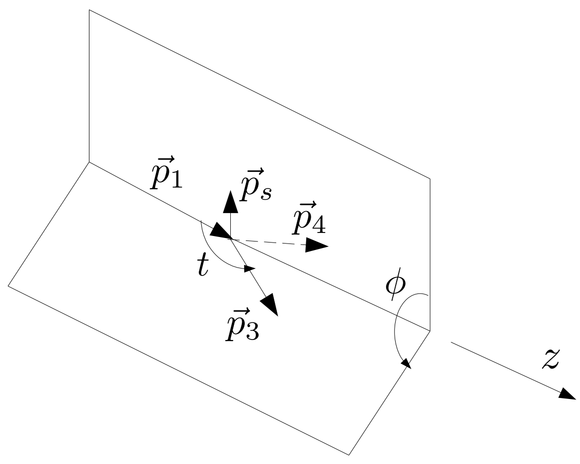
- "antiabsorptive" behavior (i.e. T > 1) at p_{lab}≈75 GeV/c due to the constructive interference of the IA amplitude and the Landshoff part of the single-rescattering amplitudes

- monotonic increase w/o nuclear filtering (i.e. when CT affects both the Landshoff and QC parts of hard scattering amplitude)





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

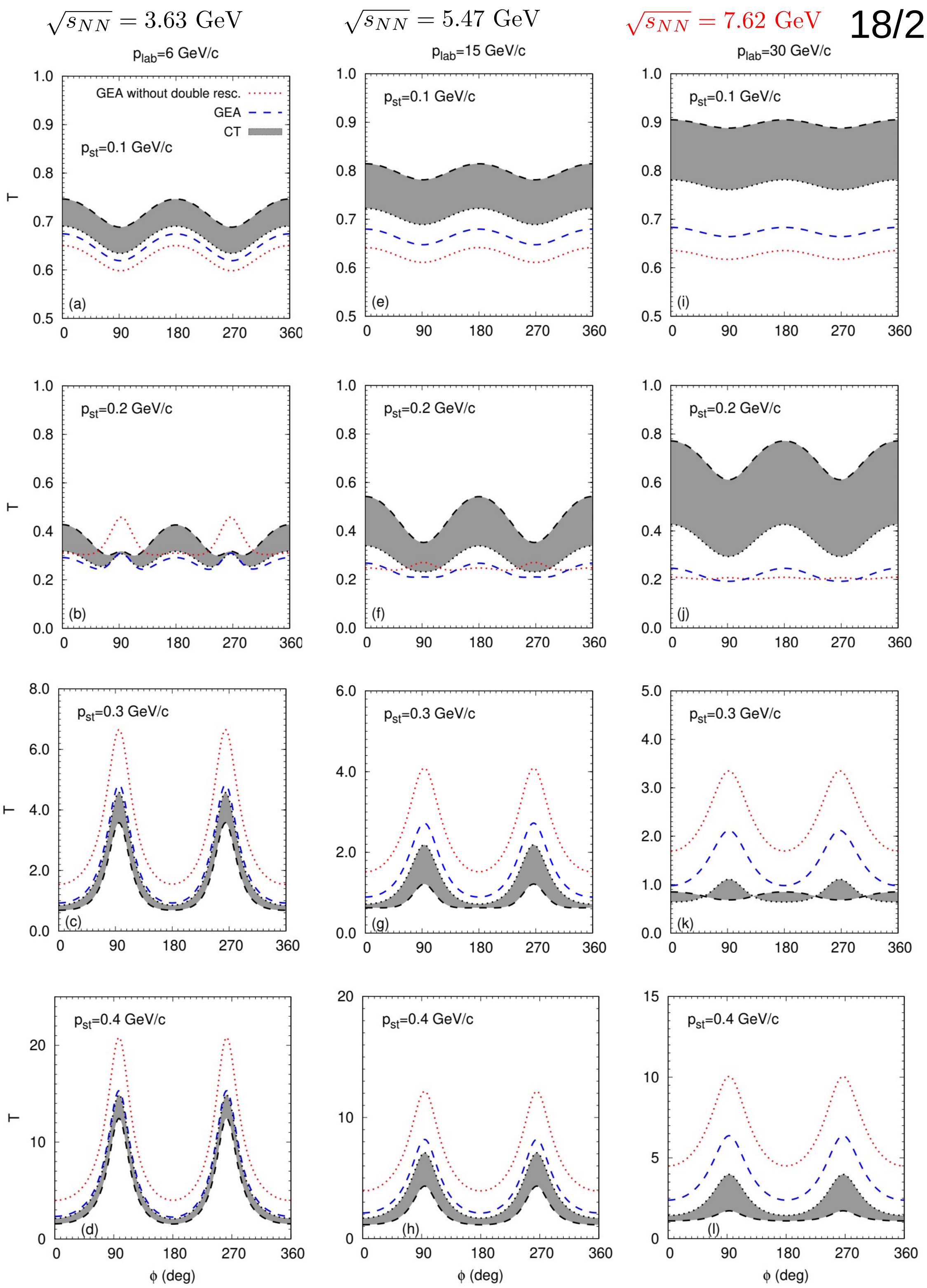


- ***enhanced single-rescattering amplitudes for outgoing protons (3 and 4) for φ=90° and 270° when $\vec{p}_s \simeq \vec{k}_t$***

- ***at small p_{st} this leads to the increased absorption while at large p_{st} – to the increased yield at φ=90° and 270°***

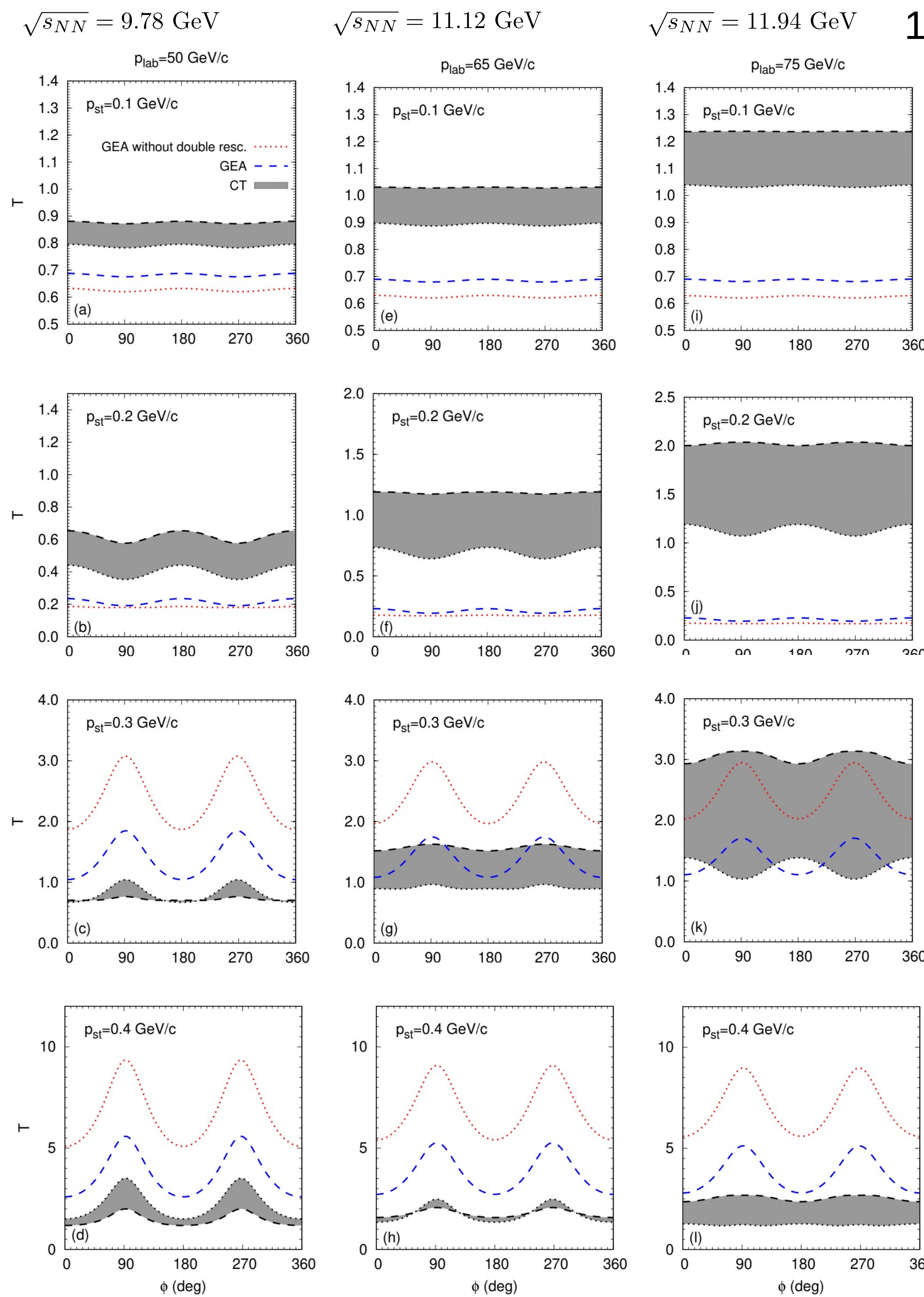
- ***CT effects grow with p_{lab} and become strongest at p_{lab}≈30 GeV/c***

- ***reasonable agreement with*** **L.L. Frankfurt et al, PRC 56, 2752 (1997)** ***at p_{lab}=6 and 15 GeV/c***



- ***between p_{lab}=30 and 50 GeV/c***
  the transparency changes quite weakly

- ***a tendency to isotropy at higher p_{lab}***
  in the calculations with CT



Deuteron tensor analyzing powers: $A_{\alpha\beta} = \dfrac{\mathrm{Sp}(M S_{\alpha\beta} M^\dagger)}{\mathrm{Sp}(M M^\dagger)}$, $\alpha, \beta = x, y, z$

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

S_α - deuteron spin matrices

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

$\sigma(\lambda_d)$ - differential cross section for the fixed projection λ_d of deuteron spin on z-axis (along the proton beam)

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

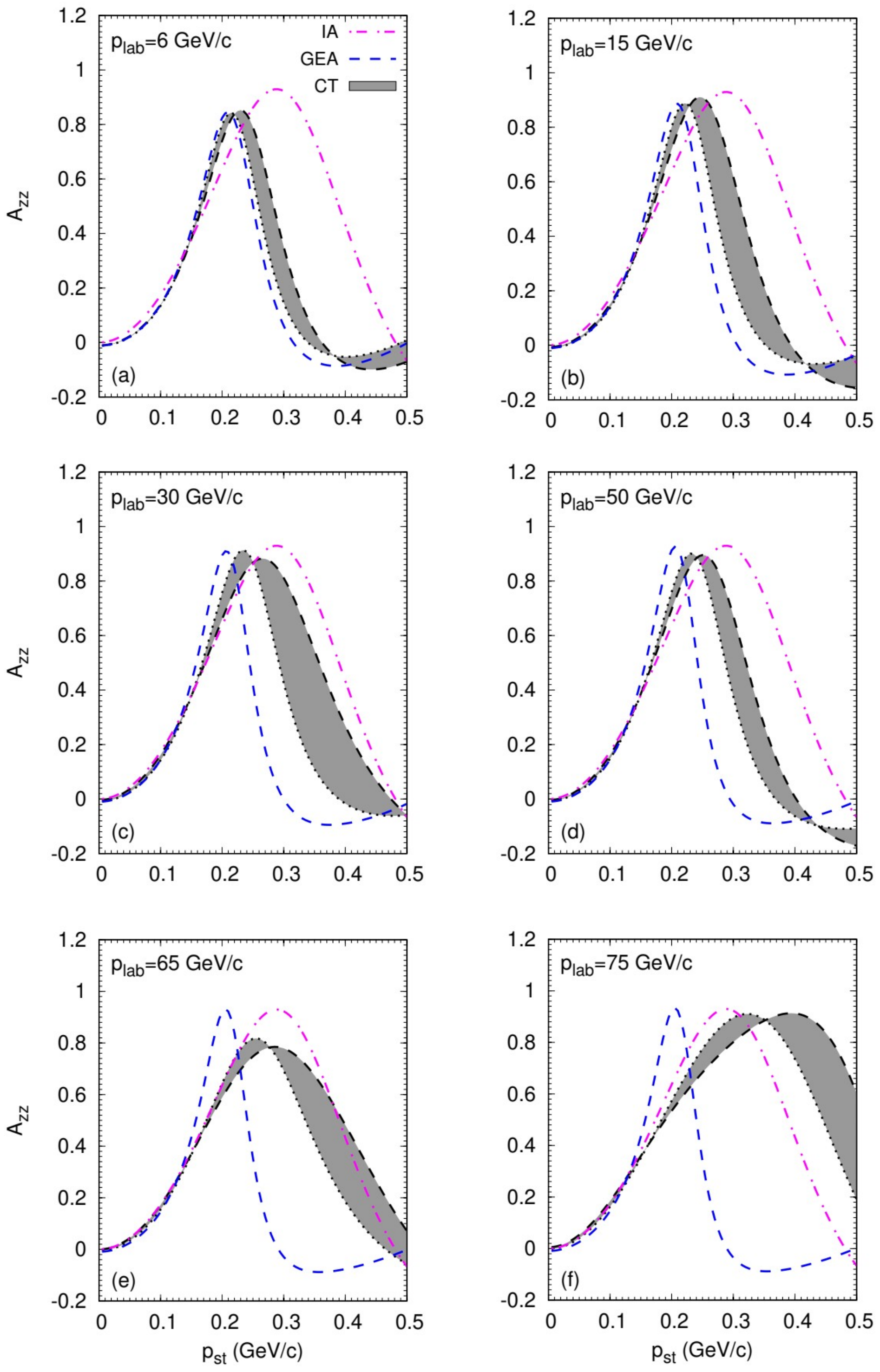
$$A_{zz}^{IA} = \frac{|\phi^{+1}(-\boldsymbol{p}_s))|^2 + |\phi^{-1}(-\boldsymbol{p}_s))|^2 - 2|\phi^{0}(-\boldsymbol{p}_s))|^2}{|\phi^{+1}(-\boldsymbol{p}_s))|^2 + |\phi^{-1}(-\boldsymbol{p}_s))|^2 + |\phi^{0}(-\boldsymbol{p}_s))|^2}$$
$$= \frac{(3(p_s^z/p_s)^2 - 1)(\sqrt{2}u(p_s)w(p_s) - w^2(p_s)/2)}{u^2(p_s) + w^2(p_s)} \propto w(p_s)$$

➡ A_{zz} is governed by the D-state component of the DWF.

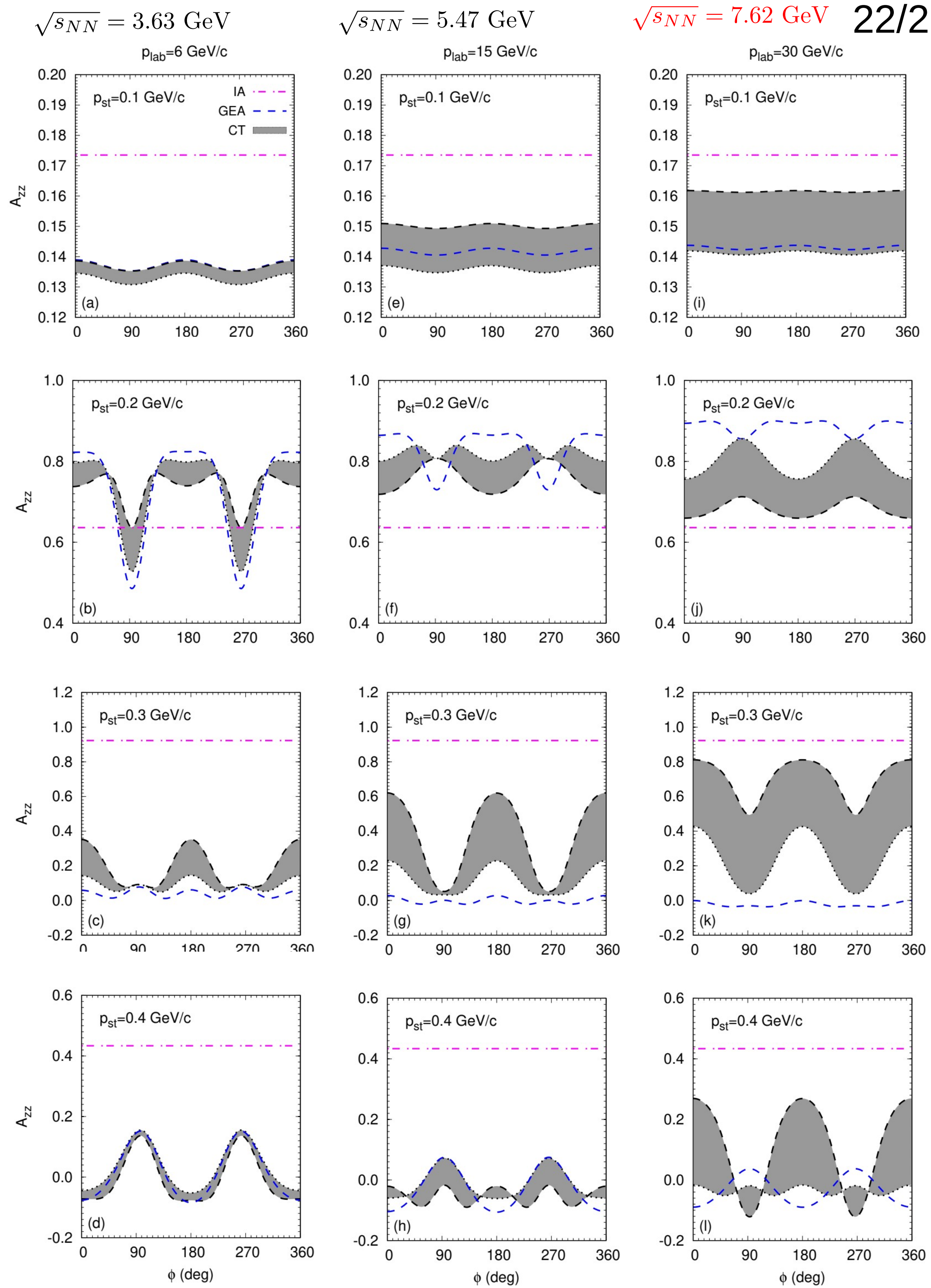
Dependence of the **tensor analyzing power** on the transverse momentum of the spectator neutron

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

- pronounced CT effects due to the D-state dominance in A_{zz} (favors shorter distances in the deuteron)



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



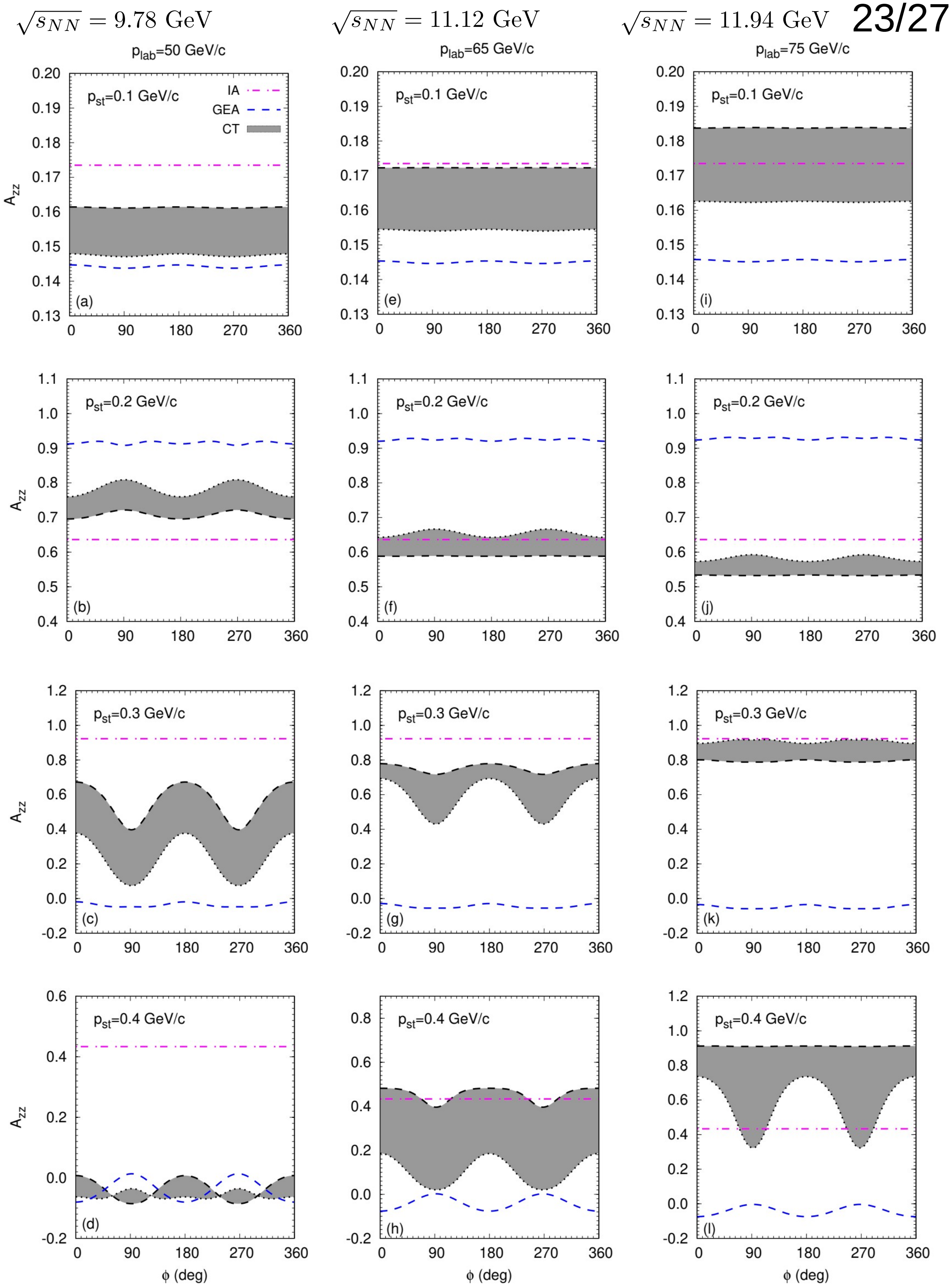
- in the GEA, A_{zz} behaves similar to T as a function of φ both at small and large p_{st}

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

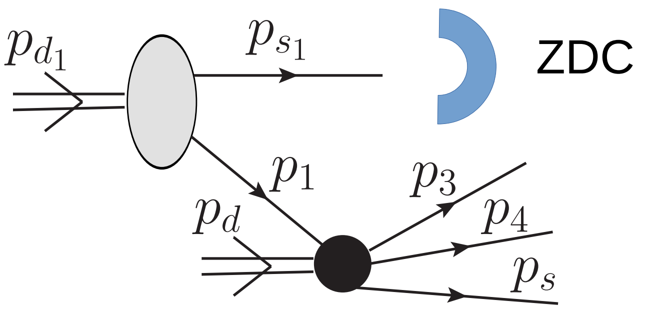
- p_{lab} = 15-30 GeV/c seems to be optimal for the studies of CT effects

- *at higher beam momenta, the GEA gives a saturation of φ-dependence of A_{zz}*

- *in calculations with CT A_{zz} tends to isotropy in φ*



Using dd interactions for the study of hard pd collisions:



in the rest frame of d_1

$$M_{dd} = 2m^{1/2}(2\pi)^{3/2}\phi^{\lambda_1}(-\boldsymbol{p}^r_{s_1})M_{pd}(p_3, p_4, p_s; p_1) \ ,$$

$$\overline{|M_{dd}|^2} = 4m(2\pi)^3\overline{|\phi(-\boldsymbol{p}^r_{s_1})|^2}\,\overline{|M_{pd}|^2} \ ,$$

$$\overline{|\phi(\boldsymbol{p})|^2} = \frac{1}{3}\sum_{\lambda_1}|\phi^{\lambda_1}(\boldsymbol{p})|^2 = \frac{u^2(p)+w^2(p)}{4\pi} \ , \qquad \int dpp^2(u^2(p)+w^2(p)) = 1 \ .$$

$$d\sigma = (2\pi)^4\delta^{(4)}(p_{s_1}+p_3+p_4+p_s-p_{d_1}-p_d)\frac{\overline{|M_{dd}|^2}}{4I_{dd}}\frac{d^3p_{s_1}}{(2\pi)^3 2E_{s_1}}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}\frac{d^3p_s}{(2\pi)^3 2E_s} \ ,$$

$$I_{dd} = [(p_{d_1}p_d)^2 - m_d^4]^{1/2}.$$

For $p_1 \approx p_{d1}/2$ (quasifree kinematics) : $\quad d\sigma \simeq \overline{|\phi(-\boldsymbol{p}^r_{s_1})|^2}\, d^3p^r_{s_1}\, d\sigma_{1d\to 34s} \ ,$

$$d\sigma_{1d\to 34s} = (2\pi)^4\delta^{(4)}(p_3+p_4+p_s-p_1-p_d)\frac{\overline{|M_{pd}|^2}}{4I_{pd}}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}\frac{d^3p_s}{(2\pi)^3 2E_s} \ ,$$

$$I_{pd} = [(p_1p_d)^2 - m^2m_d^2]^{1/2}.$$

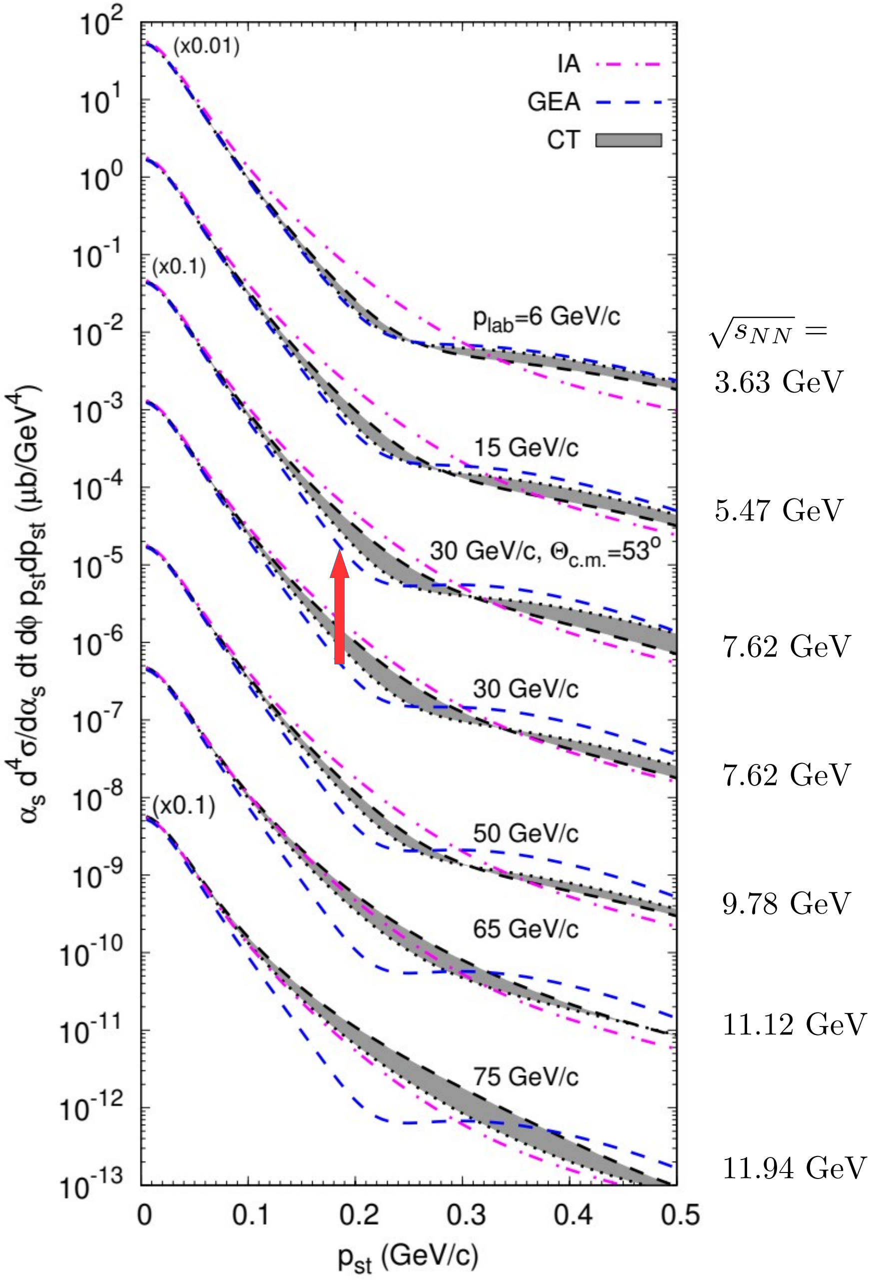
A hard pd collision can be selected in dd interaction by requiring one neutron with transverse momentum < 0.1 GeV/c in a zero-degree calorimeter. This cut includes 80% of the deuteron internal momentum distribution and almost excludes rescattering of this neutron.

- Cross section quickly drops with s_{NN}

- But CT effects grow with s_{NN}

- Taking c.m. scattering angle $\Theta_{c.m.}$ < 90 deg. for hard pp→ pp would increase event rate

- Optimization needed



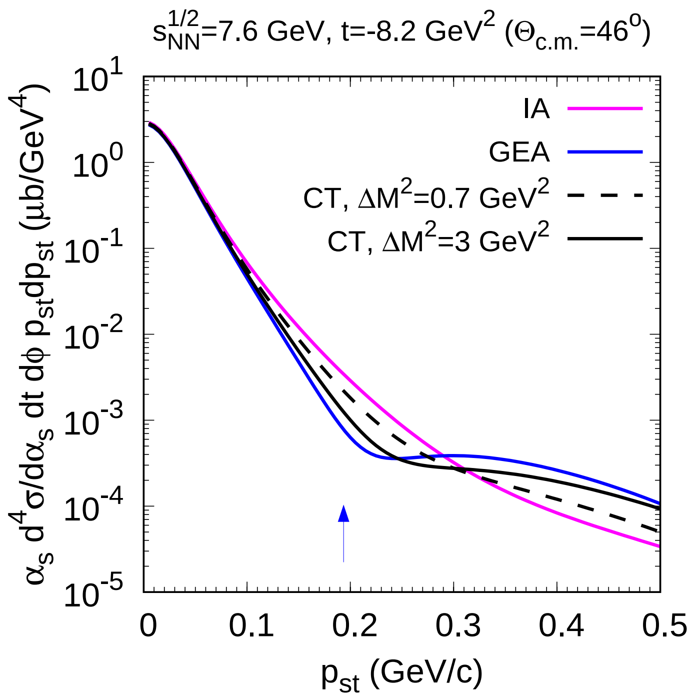
$\sigma_{GEA} \simeq 2.5 \cdot 10^3$ fb for $\alpha_s = 1 \pm 0.1$, $t = -8.2 \pm 1.25$ GeV^2, $\phi = \pi \pm \pi/6$, $p_{st} = 0.2 \pm 0.02$ GeV/c.

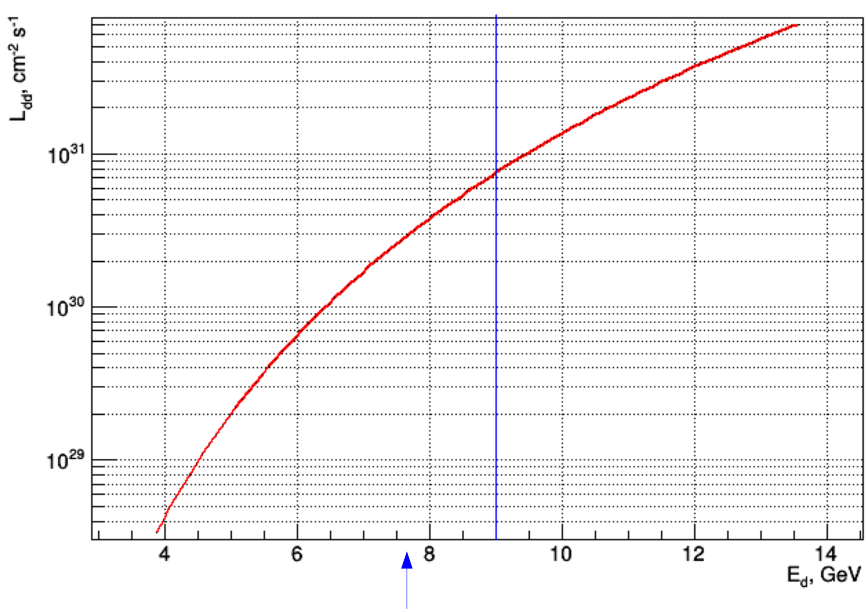
$$\simeq 200 \textbf{ events/year for } L_{dd} = 2.7 \cdot 10^{30} \textbf{ cm}^{-2} \textbf{ s}^{-1}$$

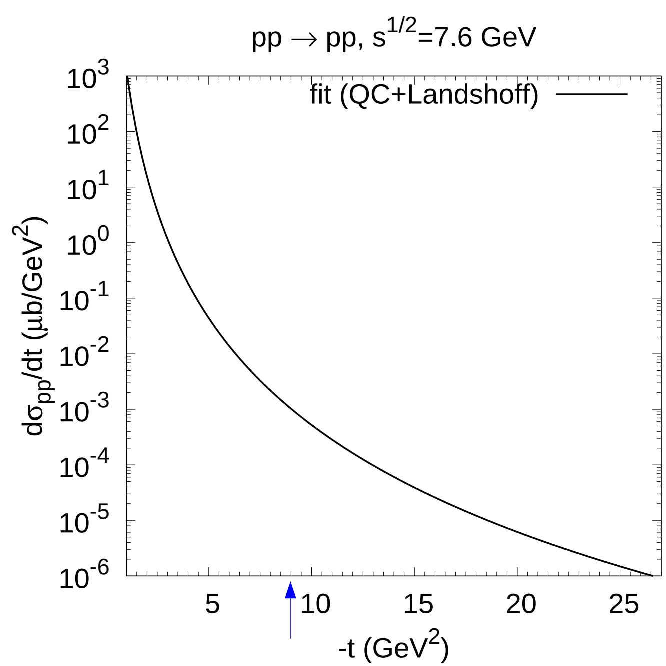
6 weeks needed to get statistical error of 20% of difference between CT with ΔM^2=3 GeV^2 and GEA (assuming that all spectator neutrons are in ZDC)

$$\sigma_{pp} = 4.6 \cdot 10^{-3} \mu\text{b for } t = -8.2 \pm 1.25 \text{ GeV}^2$$

45000 dd→ ppnn events with hard pp→ pp and one neutron in ZDC







Summary

- Calculations for the d(p,2p)n large-angle 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 described within the quantum diffusion model. The interference of the small- and large-size qqq configurations is included.

- Similar to the case of heavier nuclear targets, the Landshoff component of the hard $pp \to pp$ amplitude is effectively filtered-out that leads to the oscillation pattern of the nuclear transparency as a function of p_{lab} at small transverse momentum of the spectator neutron.

- The azimuthal dependence of the nuclear transparency and of the tensor analyzing power are especially sensitive to the CT effects.

- Measurements at the 1st stage of NICA-SPD seem feasible. Detailed MC simulation with detector efficiency and acceptance needed.

Thank you for your attention !