Color coherence effects at SPD-NICA

Alexei Larionov

Joint Institute for Nuclear Research, BLTP, Dubna, Moscow reg., 141980 Russia

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 arXiv:2208.08832

SPD Collaboration meeting
VBLHEP, JINR, Dubna,
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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 $(r_\perp \to 0)$**:** $\sigma_{q\bar{q}} \propto r_\perp^2 \sim 1/Q^2$

Color transparency (CT): the quark configuration produced in high momentum transfer exclusive process interacts with nucleons with reduced cross section.

CT in a nutshell - "squeeze and freeze":

``Squeezing'' - the preferential selection of the color singlet, small transverse size configurations (PLCs) in exclusive processes on a nucleus at high momentum transfer.
"Freezing" - the PLC should not expand to the normal hadronic size while
 it traverses the nucleus. The coherence length should be larger or equal to the nuclear size.

(cf. ***D. Dutta, K. Hafidi, M. Strikman, Prog. Part. Nucl. Phys. 69, 1 (2013)***).

Nuclear target needed.
Observable – nuclear transparency:

$$T = \frac{\sigma_A}{\sigma_{\rm PWIA}} \simeq \frac{\sigma_A}{A\sigma_p}$$

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

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

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

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

$A(e,e'p)$ for ^{2}H, ^{12}C, and ^{56}Fe at $Q^2 = 3.3 - 8.1$ GeV^2

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

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

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

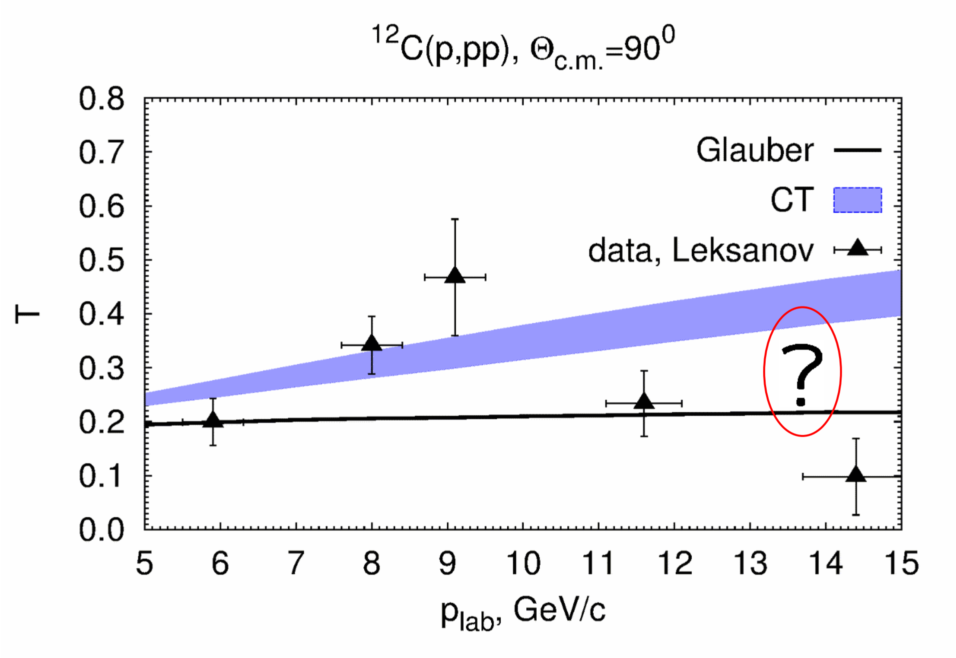
- No CT signal

➡ Possible explanations:
- squeezing proton needs larger Q^2 than for meson,
- Feynman mechanism without squeezing may dominate for x_B=1

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) 6qc$\bar{c}$ 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.

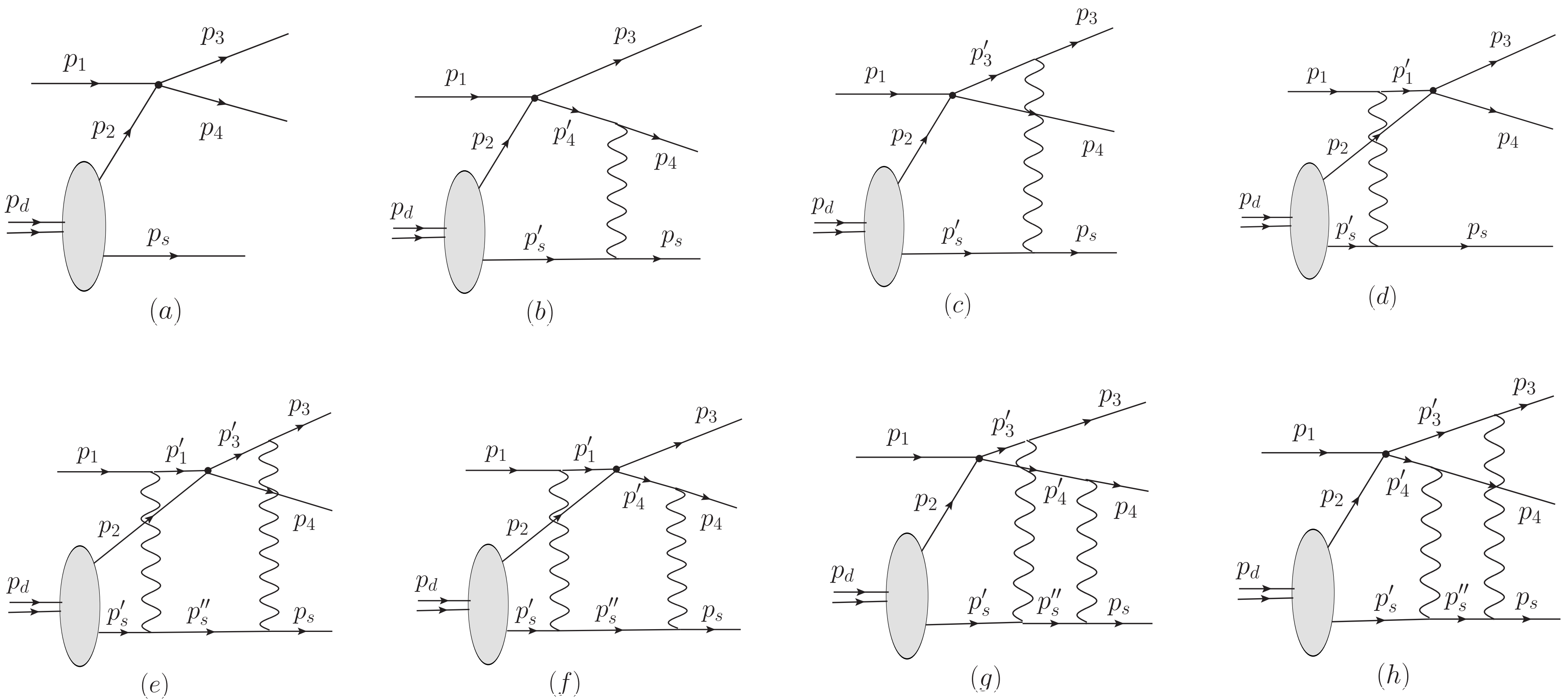
- suggested to study CT in several large-angle processes:

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)

d(p,2p)n - **L.L. Frankfurt, E. Piasetzky, M.M. Sargsian, M.I. Strikman, PRC 56, 2752 (1997);**
AL arXiv:2208.08832

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

Partial amplitudes:



Calculations are done in the deuteron rest frame

Impulse approximation (IA) amplitude:

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

nucleon mass

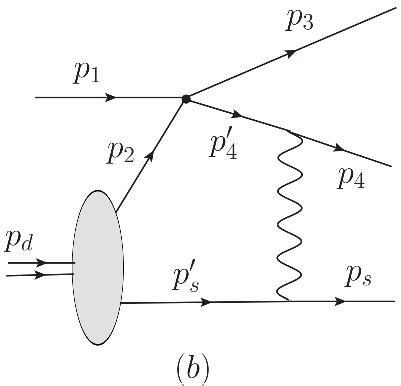
pp→ pp hard scattering amplitude

deuteron wave function

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

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

Amplitude with rescattering of outgoing proton



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

- 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, $(p_s')^2 = m^2$) and on the longitudinal momentum transfer (along $\boldsymbol{p}_4$)

$$M^{(b)} = \frac{M_{\rm hard}(s_{\rm hard}, t_{\rm hard})}{2p_4 m^{1/2}} \int d^3r \Theta(-\tilde{z}) \phi(\boldsymbol{r}) {\rm e}^{i\boldsymbol{p}_s\boldsymbol{r} - i\Delta_4\tilde{z}} \int \frac{d^2k_t}{(2\pi)^2} {\rm e}^{-i\boldsymbol{k}_t\tilde{\boldsymbol{b}}} iM_{\rm el}(p_4, t)\ , \quad t = -k_t^2$$

$$\tilde{z} = \boldsymbol{r}\boldsymbol{p}_4/p_4 \qquad \tilde{\boldsymbol{b}} = \boldsymbol{r} - (\boldsymbol{r}\boldsymbol{p}_4)\boldsymbol{p}_4/|\boldsymbol{p}_4|^2$$

$$\Delta_4 \simeq (E_4 - m)(E_s - m)/p_4$$

Without CT (GEA): $$M_{\rm el}(p_4, t) = 2p_4 m \sigma_{pn}^{\rm tot}(i + \rho_{\rm pn}){\rm e}^{B_{\rm pn}t/2}$$

With CT: $$M_{\rm el}(p_4, t, l) = 2p_4 m\, \sigma_{pn}^{\rm eff}(l)\, (i + \rho_{\rm pn}){\rm e}^{B_{\rm pn}t/2} \frac{G\left(t \cdot \frac{\sigma_{pn}^{\rm eff}(l)}{\sigma_{pn}^{\rm tot}}\right)}{G(t)}\ , \quad l = |\boldsymbol{r}\boldsymbol{p}_4|/p_4$$

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

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

$l_c = \frac{2p_4}{\Delta M^2}$ - coherence length $\Delta M^2 \simeq 0.7 - 1.1\ {\rm GeV}^2$ - from pion transparency studies at JLab

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

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

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

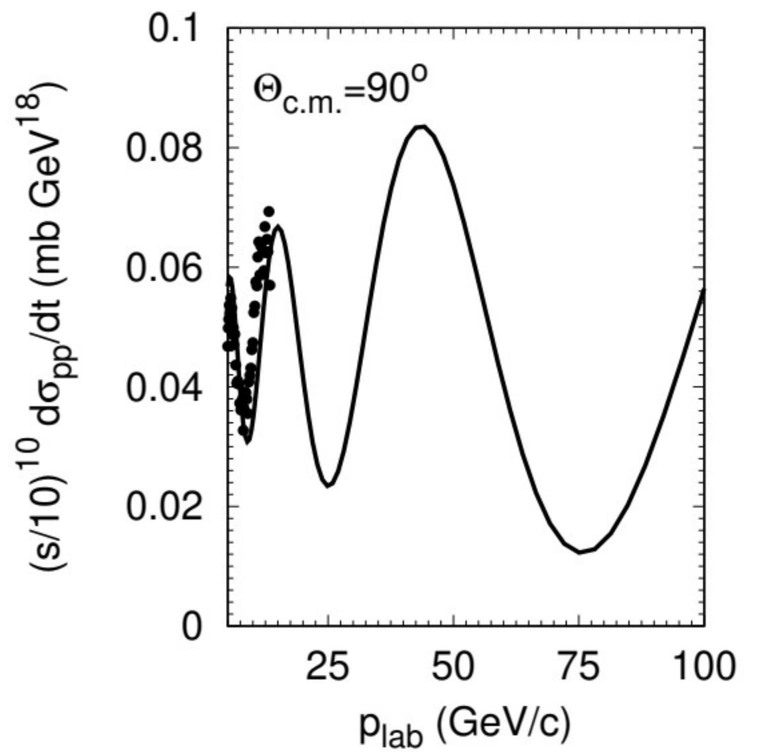
Cross section parameterization
L. Frankfurt, E. Piasetsky,
M. Sargsian, M. Strikman,
PRC 51, 890 (1995)

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

≈ 1 for s > 15 GeV^2
(p_{lab} > 7 GeV/c)

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

$\gamma = 1.6$



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

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

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

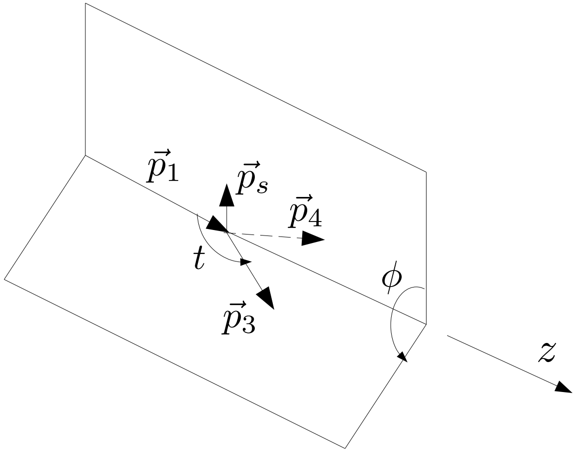
Kinematic variables

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

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

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



The deuteron rest frame

Default choice: $\alpha_s = 1$ - transverse kinematics which minimizes relativistic corrections to the DWF, see **L.L. Frankfurt et al, PRC 56, 2752 (1997)**

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

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

Nuclear transparency vs transverse momentum of spectator neutron

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

- ***absorptive ISI/FSI at small p_{st} due the interference between the IA and single-rescattering amplitudes***

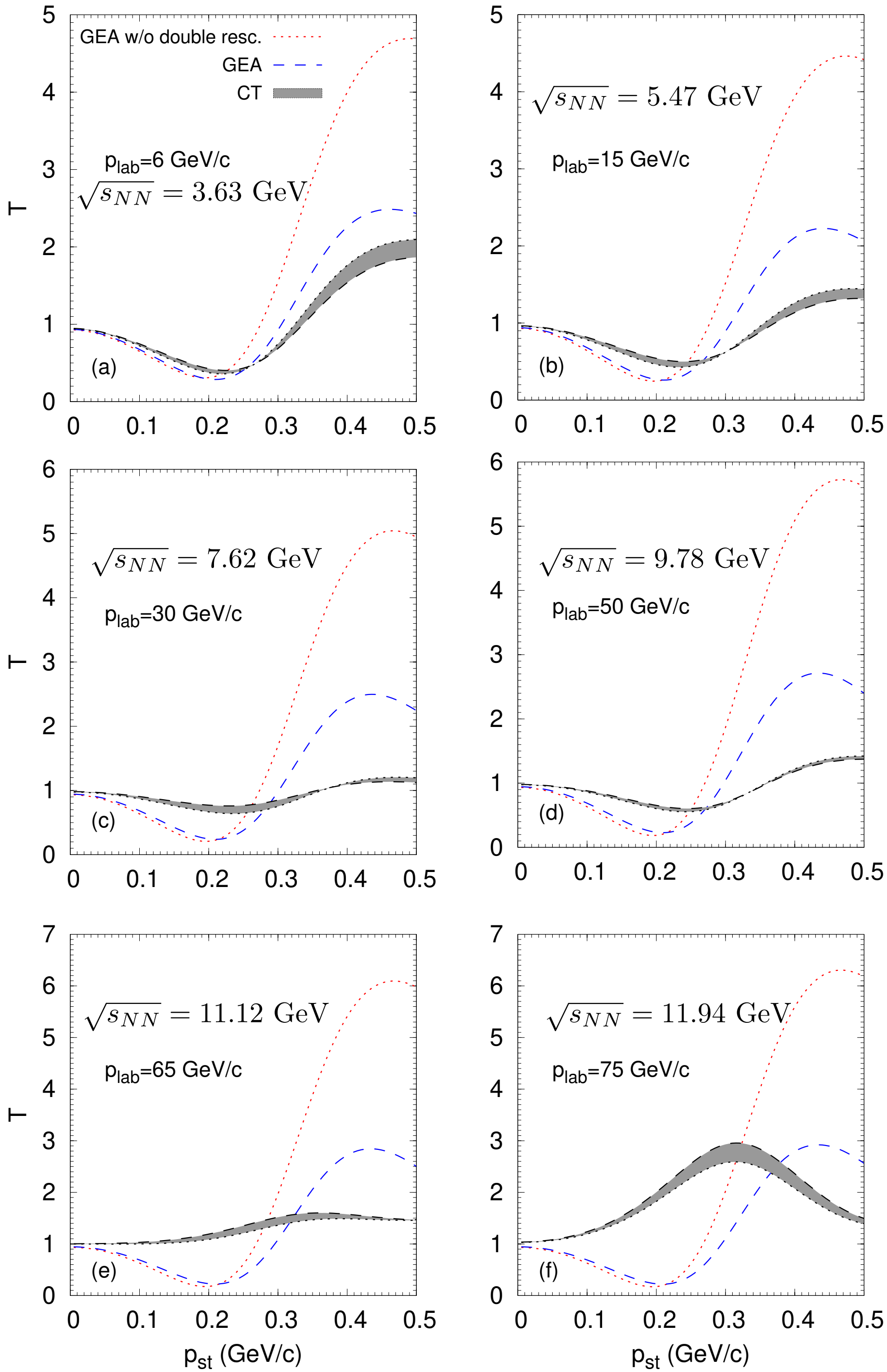
- ***enhancement at large p_{st} due to the single-rescattering amplitudes squared***

- ***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***

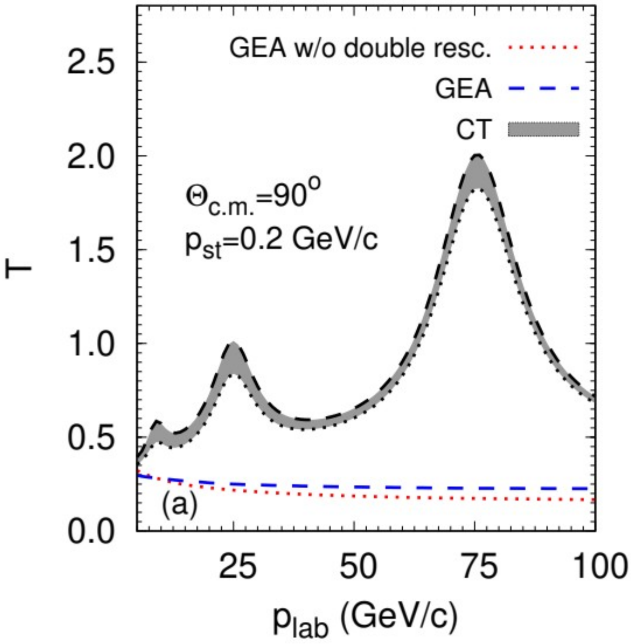


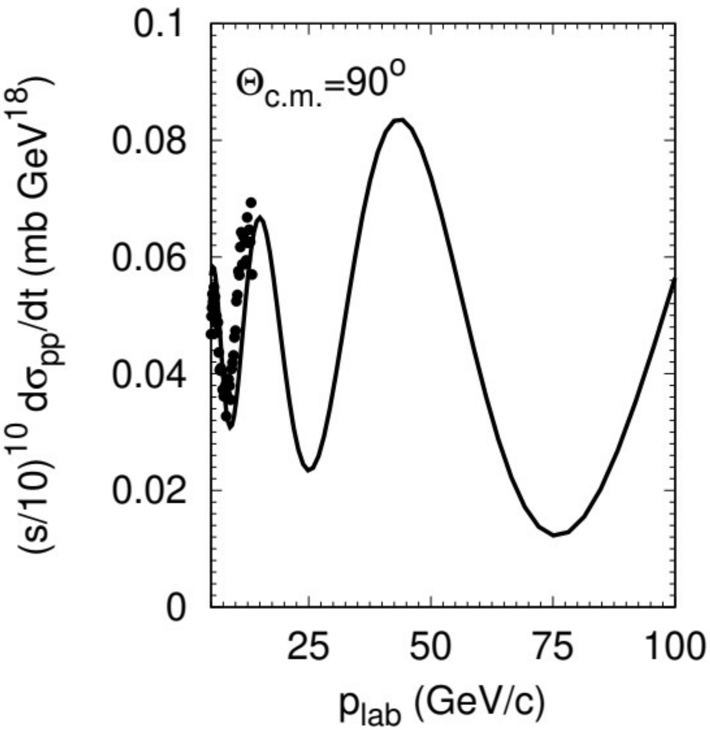
Nuclear transparency vs proton beam momentum

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

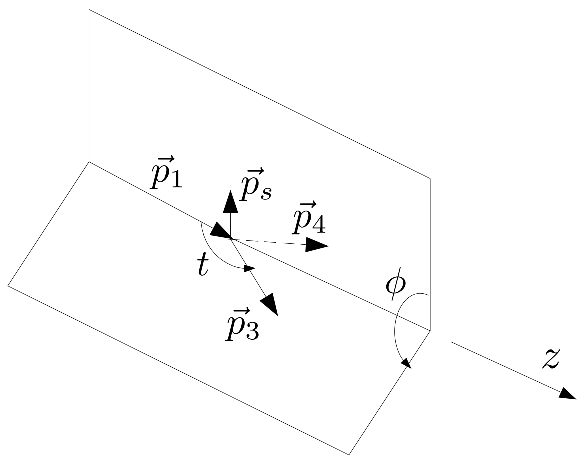
- very similar to the nuclear filtering of the Landshoff component for heavy nuclei
J.P. Ralston, B. Pire, PRL 61, 1823 (1988)

- "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





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

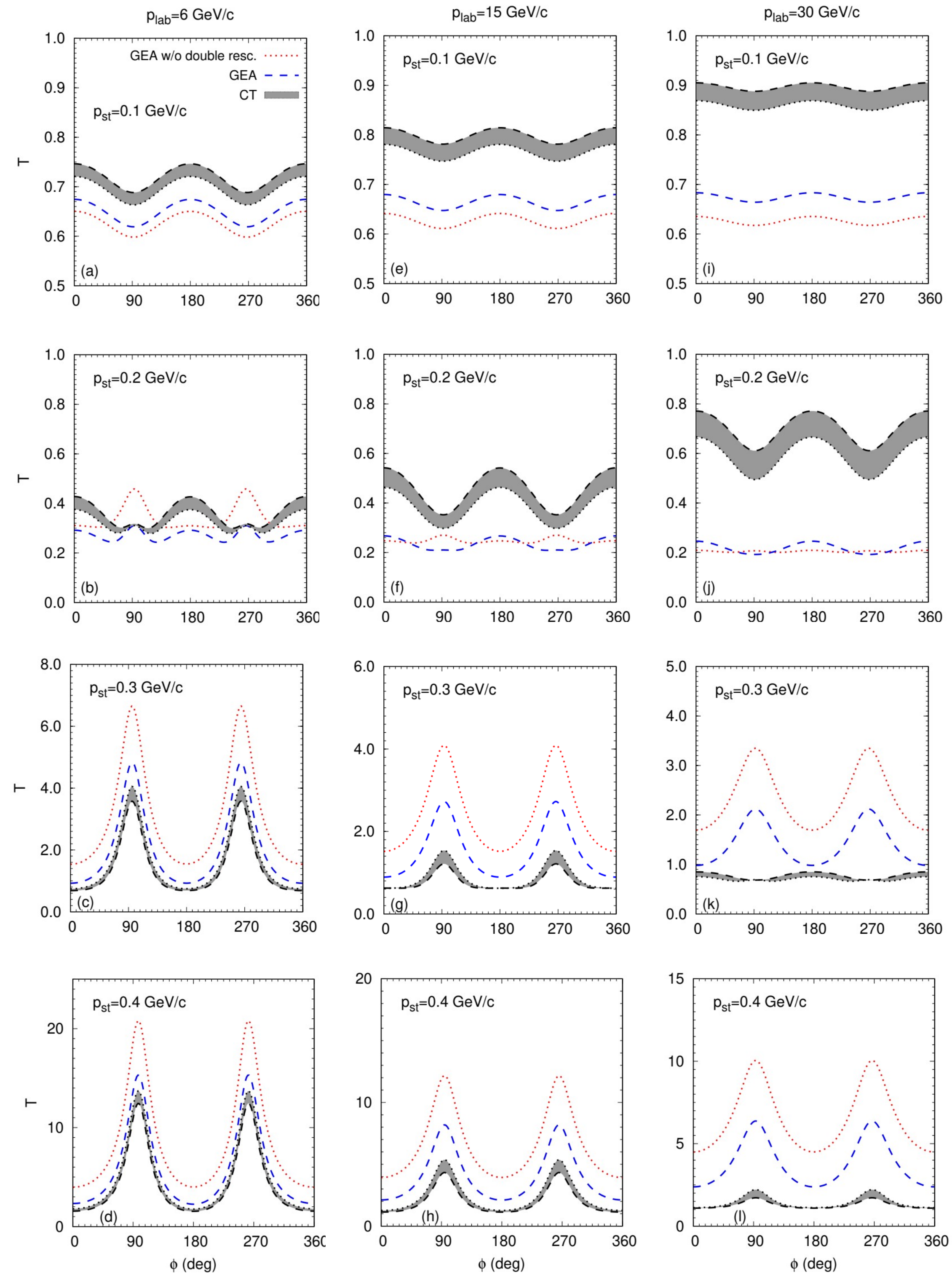


- enhanced single-rescattering amplitudes for outgoing protons (3 and 4) for φ=90º and 270º when $\vec{p}_s \simeq \vec{k}_t$

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

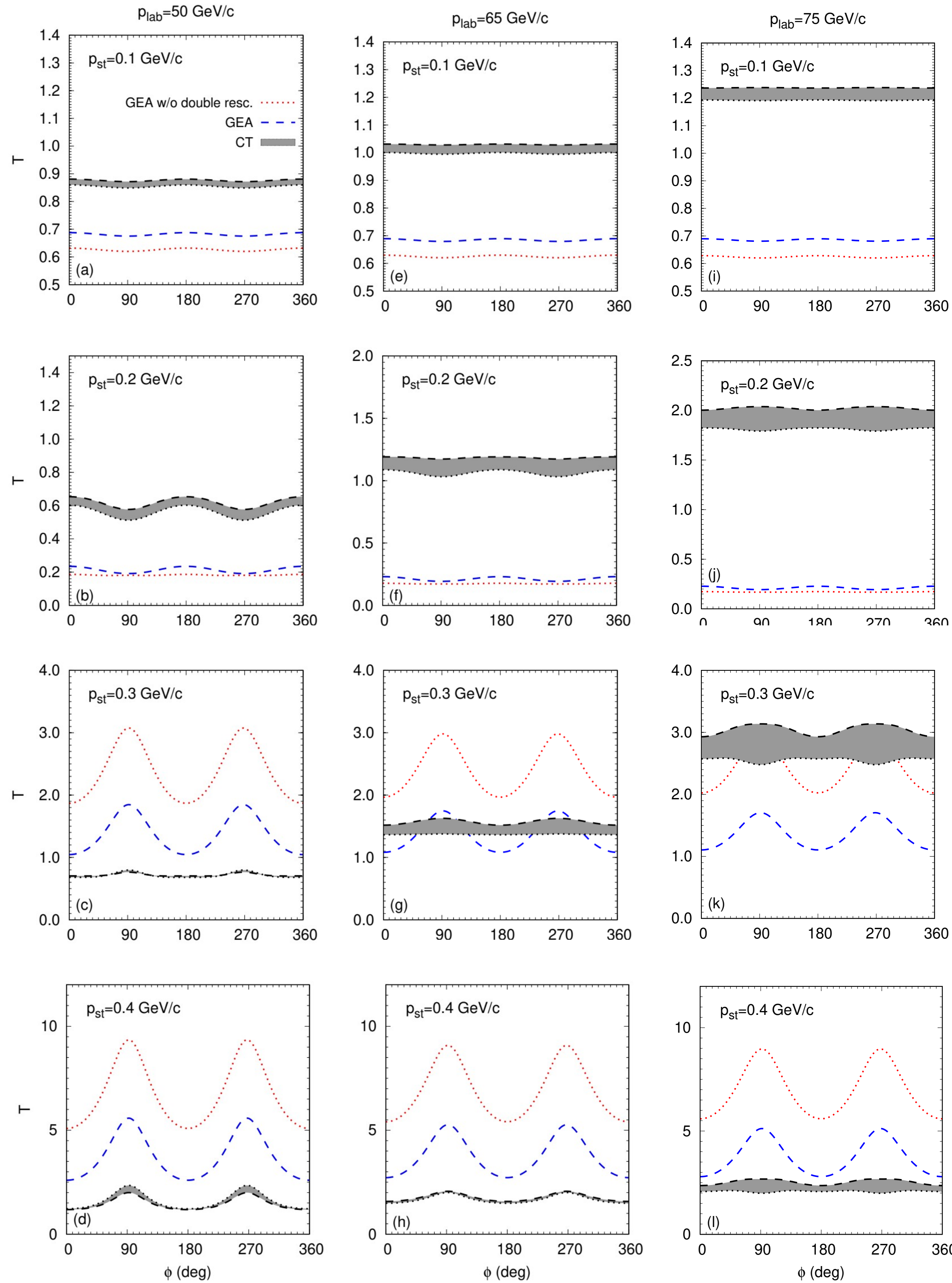
- CT effects grow with p_{lab} ***and become strongest at*** p_{lab}***≈30 GeV/c***

- 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***



The tensor analyzing power (spin asymmetry)

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

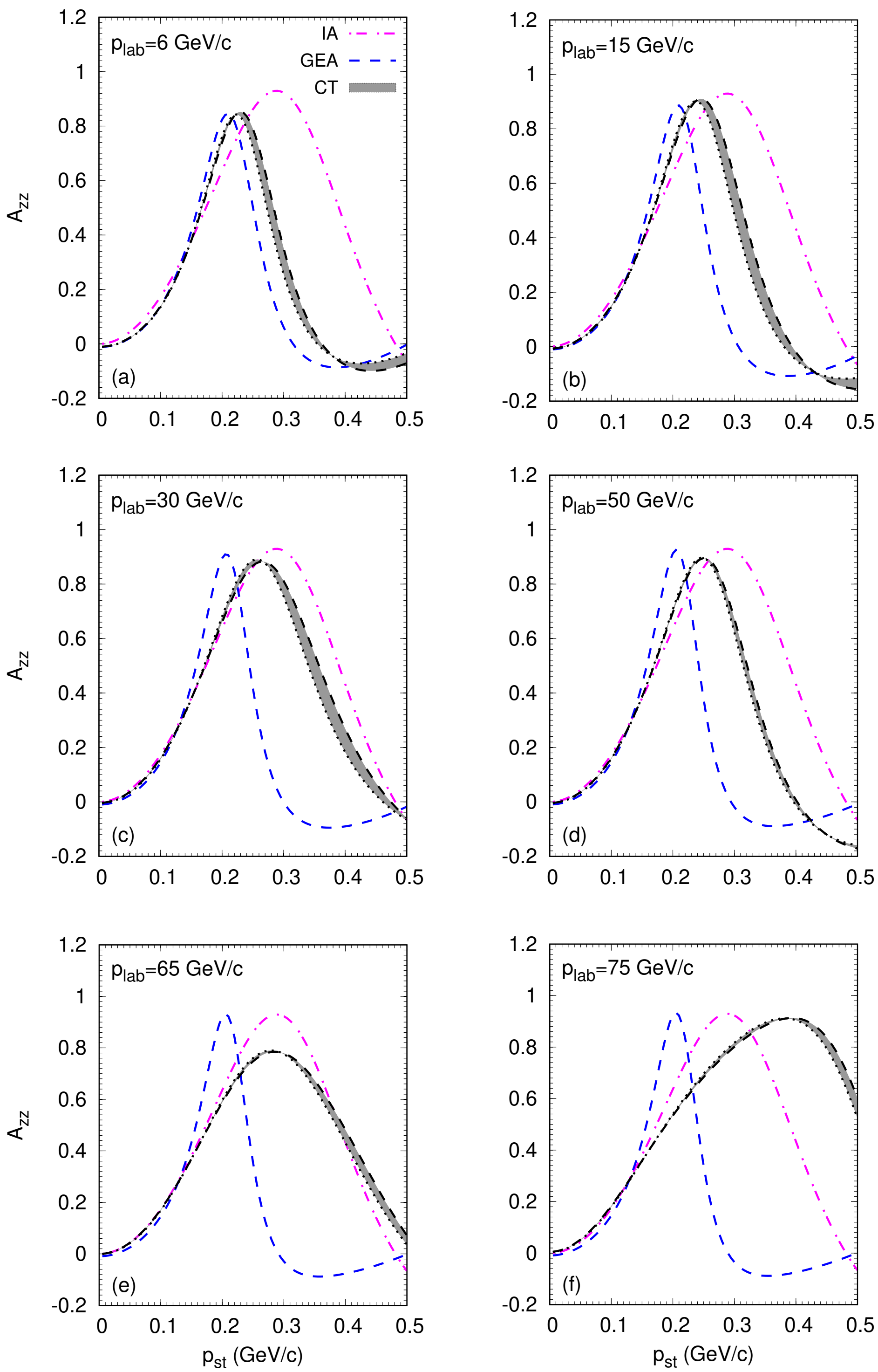
$\sigma(\lambda_d)$ - differential cross section for the fixed projection λ_d of deuteron spin on z-axis (along the proton beam)

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

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

Thus, it probes the D-state component of the DWF.

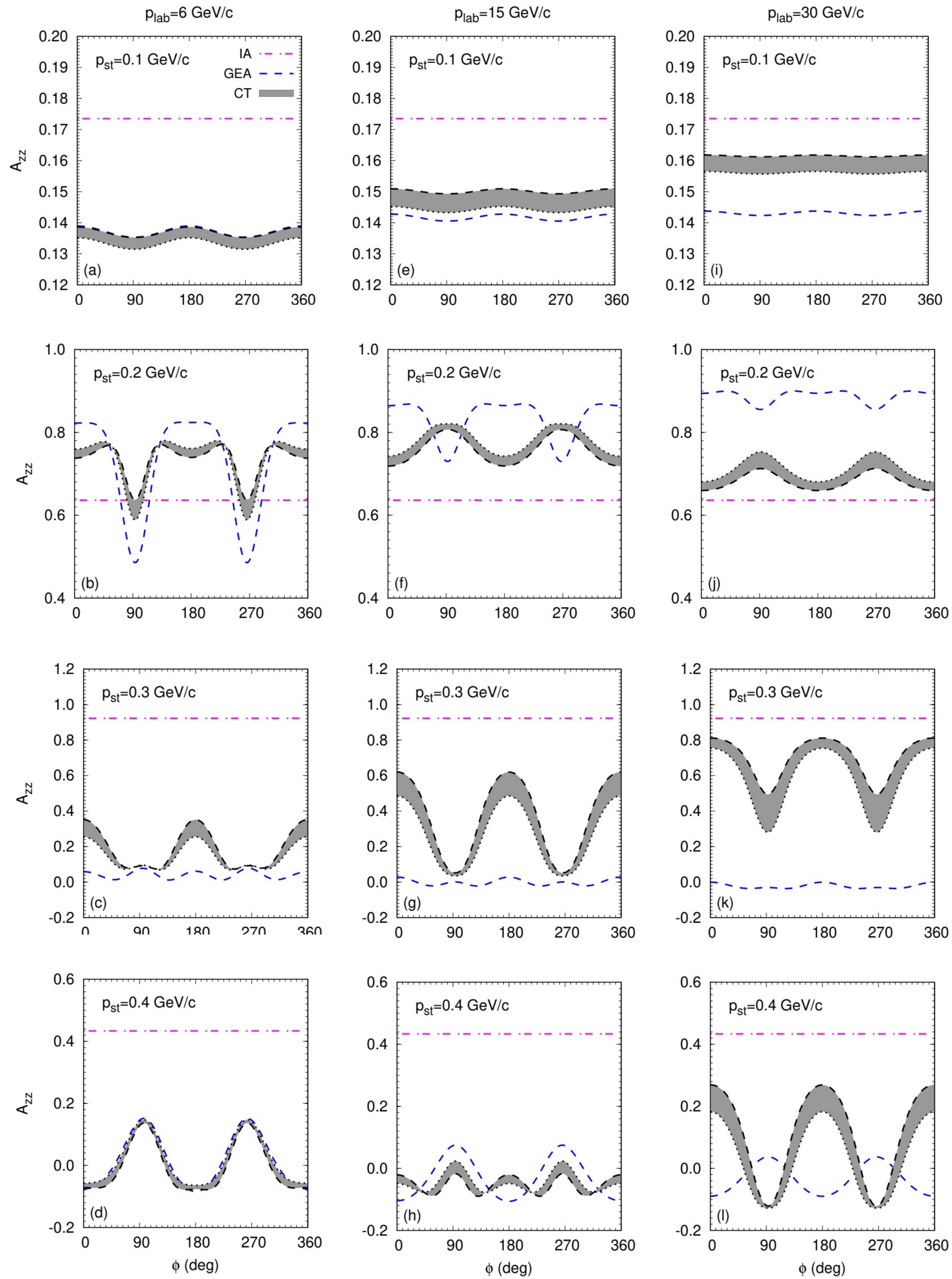
Dependence of the **tensor analyzing power** on the transverse momentum of the spectator neutron



- 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)

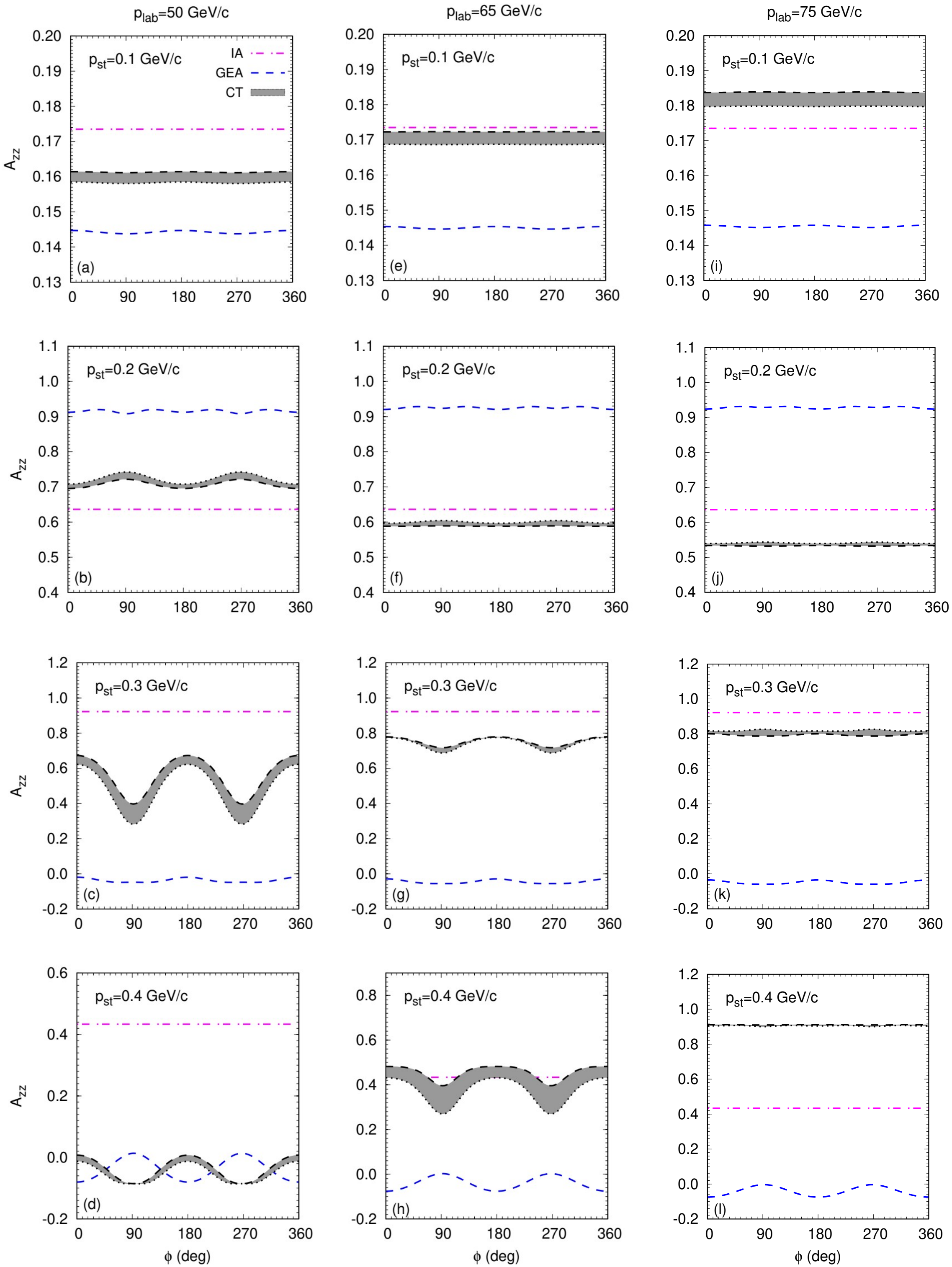
Dependence of the **tensor analyzing power** on the azimuthal angle between the scattered proton and spectator neutron



- *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*



An estimate of event rate at SPD-NICA

$p_{\rm lab} = 30$ GeV/c ($\sqrt{s_{NN}} = 7.6$ GeV)

For $\Theta_{c.m.} = 90^\circ$ and $p_{st} = 0.2$ GeV/c

$$\alpha_s \frac{d^4\sigma}{d\alpha_s\, dt\, d\phi\, p_{st} dp_{st}} \simeq 10^{-6} \mu\text{b}/\text{GeV}^4$$

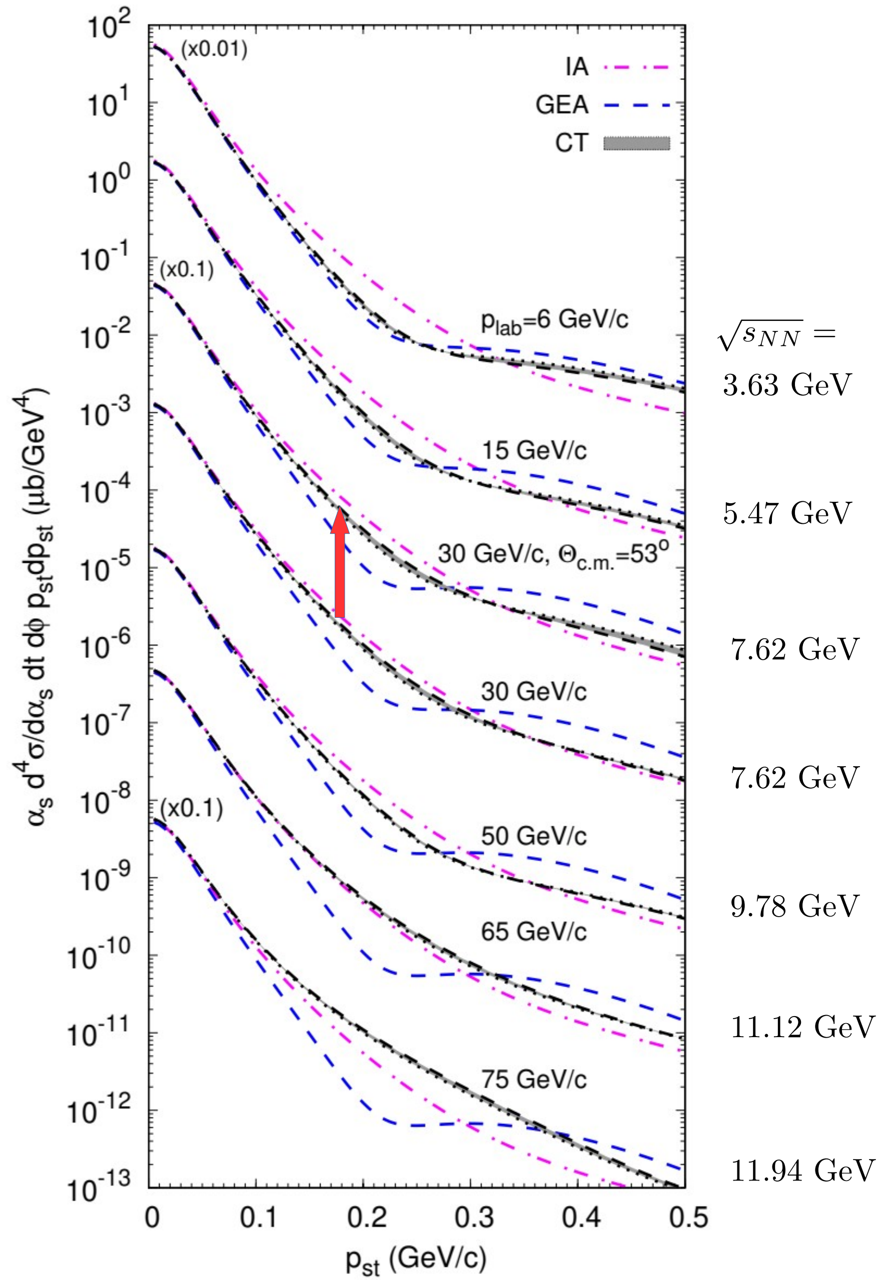
$\sigma \simeq 5$ fb in the ranges $\Delta\alpha_s = 0.2$, $\Delta t = 3$ GeV^2, $\Delta\phi = \pi/3$, $\Delta p_{st} = 0.04$ GeV/c.

3 events/year for $L = 2 \cdot 10^{31}$ cm^{-2} s^{-1}

Too low because $d\sigma_{pp}^{\rm QC}/dt$ quickly drops with |t|.
Smaller |t| needed.

→ Several events/day

for $\Theta_{c.m.} = 53^\circ$, i.e. for $t = 0.4(4m^2 - s)/2$



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 included within the quantum diffusion model, including the interference of the small- and large-size qqq configurations.

- At p_{lab}=6 and 15 GeV/c the calculated nuclear transparency agrees with earlier results by L. Frankfurt et al (1997) reasonably well. Some differences are presumably due to different parameters of the soft NN rescattering amplitude.

- Similar to the case of heavier nuclear targets, the Landshoff component of the hard pp→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.

- Extremely low reaction rates for $\Theta_{c.m.}=90^o$. The effects of CT remain almost unchanged if one reduces $\Theta_{c.m.}$ from 90^o to $\sim 50^o$ that increases the event rate by 2-3 orders of magnitude to the level of several events per day.