Color transparency in $\bar{p}A$ reactions

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The Future of Color Transparency and Hadronization Studies at Jefferson Lab and Beyond, 08.06.2021

Plan

1. Introduction: PANDA program with nuclear targets

2. Charmonium production $\bar{p}\, d \to \psi\, n_{sp}$, $\psi = J/\psi,\ \psi'(2s)$

3. Large-angle process $\bar{p}\, d \to \pi^{-}\, \pi^{0}\, p_{sp}$

4. Photon transparency

5. Conclusions and outlook

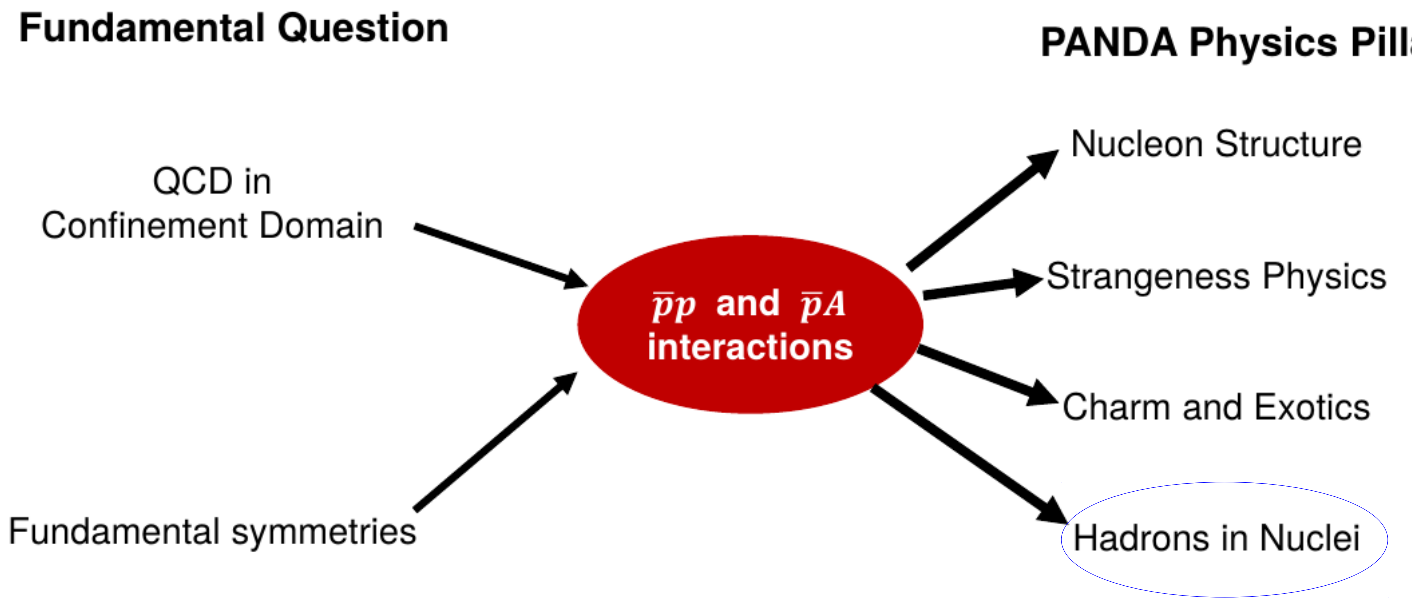


Figure from
G. Barucca et al.,
arXiv:2101.11877

Beam momentum 1.5-15 GeV/c

- Hadron modifications in nuclear medium (slow hadrons, soft processes): antibaryon potentials, new decay channels due to in-medium thresholds (e.g. $\psi' \rightarrow D\bar{D}$), partial restoration of chiral symmetry at finite ρ_B .

- Hadron interactions with nuclear medium (fast hadrons, hard processes): ***color transparency***, SRCs in nuclei.

Exclusive charmonium production in $\bar{p}A$ interactions:

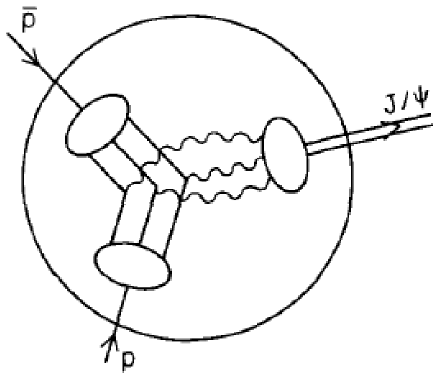


Fig. 2. The dominant mechanism for $p\bar{p}$ exclusive annihilation into J/ψ.

Figure from *S.J. Brodsky and A.H. Mueller, PLB 206, 685 (1988)*

- **Charmonium formed in $\bar{p}p$ annihilation is slow ($p_{J/\psi} \approx 4$ GeV/c)**

- **Short coherence length:**

$$l_{J/\psi} = \frac{1}{E_{\psi'} - E_{J/\psi}} \simeq \frac{2p_{J/\psi}}{m^2_{\psi'} - m^2_{J/\psi}} \simeq 0.1 \text{ fm} \frac{p_{J/\psi}}{\text{GeV}}$$

G.R. Farrar, H. Liu, L.L. Frankfurt, M.I. Strikman, PRL 61, 686 (1988).

- **$c\bar{c}$ PLC is formed due to hard scale $M_{c\bar{c}}$, but it expands before reaching the neighbouring nucleon since $l_{J/\psi}$ is smaller than the internucleon distance (≈ 2 fm). No CT effects.**

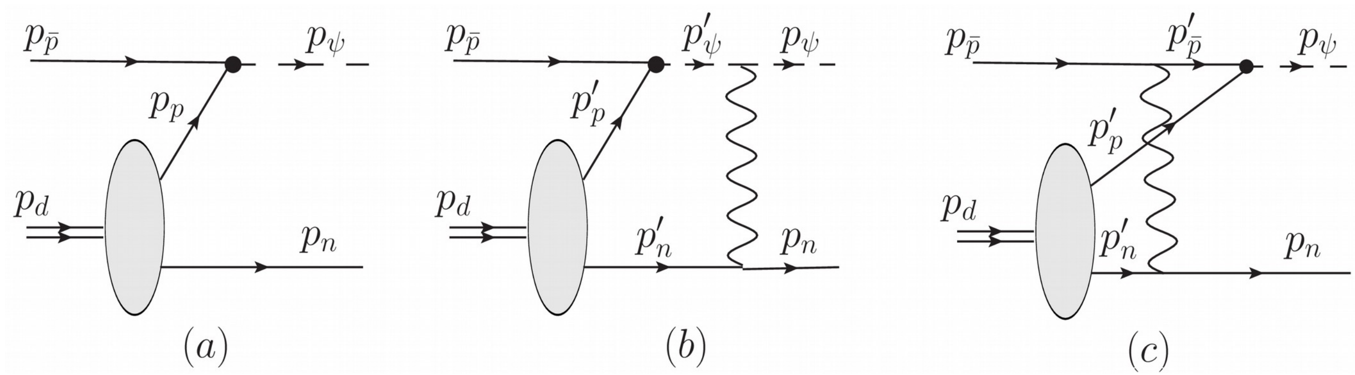
- **The best known opportunity to study the genuine charmonium-nucleon cross section. (At threshold $\gamma p \to J/\psi + p$, $p_{J/\psi}$=6.3 GeV/c and $pp \to p+p+J/\psi$, $p_{J/\psi}$= 7.6 GeV/c.)**

- **But for $\bar{p}$ the coherence length may be larger, CT is expected :**

$$l_{\bar{p}} = \frac{2p_{\bar{p}}}{\Delta M^2} = 0.4 - 0.6 \text{ fm} \frac{p_{\bar{p}}}{\text{GeV}} \; ,$$

$$\Delta M^2 \simeq 0.7 - 1.1 \text{ GeV}^2$$ **(from pionic transparency studies at JLab)**

$\bar{p}\, d \to J/\psi\, n$



Impulse approximation (IA):

$$M^{(a)} = M_{\psi;\bar{p}p}(p_\psi, p_{\bar{p}}) \frac{i\Gamma_{d\to pn}(p_d, p_n)}{p_p^2 - m_N^2 + i\epsilon} = M_{\psi;\bar{p}p}(p_\psi, p_{\bar{p}}) \left(\frac{2E_n m_d}{E_p}\right)^{1/2} (2\pi)^{3/2} \phi(\mathbf{p}_p) \, .$$

DWF (Paris model)

Quasifree process: $|p_\psi^z - p_{\rm lab}| \ll p_{\rm lab}$

Charmonium rescattering (neutron pole):

$$M^{(b)} = -\frac{M_{\psi;\bar{p}p}(p_\psi, p_{\bar{p}})}{m_N^{1/2}} \int \frac{d^3 p'_n}{(2\pi)^{3/2}} \frac{M_{\psi n}(t) \phi(\mathbf{p}'_p)}{p'^2_\psi - m_\psi^2 + i\epsilon} \, ,$$

$t = k^2, \quad k = p_n - p'_n$

four-momentum transfer to the spectator neutron.

Antiproton rescattering (proton pole):

$$M^{(c)} = -\frac{M_{\psi;\bar{p}p}(p_\psi, p_{\bar{p}})}{m_N^{1/2}} \int \frac{d^3 p'_n}{(2\pi)^{3/2}} \frac{M_{\bar{p}n}(t) \phi(\mathbf{p}'_p)}{p'^2_{\bar{p}} - m_N^2 + i\epsilon} \, ,$$

$\mathbf{p}'_p = -\mathbf{p}'_n$ - three-momentum of the struck proton.

AL, A. Gillitzer, M. Strikman, EPJA 55, 154 (2019)

Generalized Eikonal Approximation (GEA):

L. Frankfurt, M. Sargsian, M. Strikman, PRC 56, 1124 (1997);
M. Sargsian, Int. J. Mod. Phys. E 10, 405 (2001).

- Express inverse propagators of fast intermediate particles as functions of the longitudinal momentum transfer to the spectator neutron:

$$p'^2_\psi - m^2_\psi + i\epsilon = 2p_{\rm lab}(p'^z_n - p^z_n + \Delta^0_\psi + i\epsilon) \ , \qquad \Delta^0_\psi = \frac{(E_{\bar p} + m_d)(E_n - E'_n)}{p_{\rm lab}} \simeq \frac{(E_{\bar p} + m_d)(E_n - m_N)}{p_{\rm lab}} \ ,$$

$$p'^2_{\bar p} - m^2_N + i\epsilon = 2p_{\rm lab}(p^z_n - p'^z_n - \Delta^0_{\bar p} + i\epsilon) \ , \qquad \Delta^0_{\bar p} = \frac{E_{\bar p}(E_n - E'_n)}{p_{\rm lab}} - \frac{(p'_n - p_n)^2}{2p_{\rm lab}} \simeq \frac{(E_{\bar p} + m_N)(E_n - m_N)}{p_{\rm lab}} \ .$$

neglect neutron Fermi motion

valid for quasifree production, i.e. if $|p^z_\psi - p_{\rm lab}| \ll p_{\rm lab}$

Integration over longitidinal momentum of the intermediate neutron in the rescattering amplitudes can be performed analytically which gives:

$$M^{(b)} = \frac{iM_{\psi;\bar p p}(p_\psi, p_{\bar p})}{2p_{\rm lab} m_N^{1/2}} \int d^3r \phi(\mathbf{r}) \Theta(-z) {\rm e}^{i\mathbf{p}_n\mathbf{r} - i\Delta^0_\psi z} \int \frac{d^2k_t}{(2\pi)^2} M_{\psi n}(t) {\rm e}^{-i\mathbf{k}_t\mathbf{b}} \ , \quad t = (E_n - m_N)^2 - k_t^2 - (\Delta^0_\psi)^2 \ ,$$

$$M^{(c)} = \frac{iM_{\psi;\bar p p}(p_\psi, p_{\bar p})}{2p_{\rm lab} m_N^{1/2}} \int d^3r \phi(\mathbf{r}) \Theta(z) {\rm e}^{i\mathbf{p}_n\mathbf{r} - i\Delta^0_{\bar p} z} \int \frac{d^2k_t}{(2\pi)^2} M_{\bar p n}(t) {\rm e}^{-i\mathbf{k}_t\mathbf{b}} \ , \quad t = (E_n - m_N)^2 - k_t^2 - (\Delta^0_{\bar p})^2 \ .$$

$$\phi(\mathbf{r}) = \int \frac{d^3p}{(2\pi)^{3/2}} {\rm e}^{i\mathbf{p}\mathbf{r}} \phi(\mathbf{p}) \ , \quad \mathbf{r} = \mathbf{r}_p - \mathbf{r}_n \ .$$

(The sums over spin projections of the intermediate particles are implicitly assumed.)

$\bar{p}p \to J/\Psi$:

Effective Lagrangian with Dirac (γ_μ) and Pauli $(\sigma_{\mu\nu})$ couplings

T. Barnes, X. Li, W. Roberts, PRD 77, 056001 (2008)

$$\mathcal{L}_{\psi NN} = -g\bar{N}(\gamma_\mu - \frac{\kappa}{2m_N}\sigma_{\mu\nu}\partial^\nu_\psi)N\psi^\mu \ ,$$

$$M_{\psi;\bar{p}p}(q,p_{\bar{p}}) = -g\bar{u}(-p_{\bar{p}},-\lambda_{\bar{p}})(\gamma_\mu - \frac{i\kappa}{2m_N}\sigma_{\mu\nu}q^\nu)u(p_p,\lambda_p)\varepsilon^{(\lambda)\mu *} \ , \qquad q = p_{\bar{p}} + p_p$$

Parameters:

$\kappa = -0.089$ from angular distribution of the $e^+e^- \to J/\psi \to p\bar{p}$ scattering

$$\frac{d\sigma}{d\cos(\Theta_{c.m.})} \propto 1 + \alpha\cos^2(\Theta_{c.m.}) \ , \quad \alpha = 0.595 \pm 0.012 \pm 0.015$$

M. Ablikim et al. (BESIII), PRD 86, 032014 (2012).

$g = 1.79 \cdot 10^{-3}$ from partial width $\Gamma_{J/\psi\to\bar{p}p} = \Gamma_{J/\psi} B(J/\psi \to \bar{p}p)$

$\Gamma_{J/\psi} = 92.9 \pm 2.8$ keV - total width,

$B(J/\psi \to \bar{p}p) = (2.121 \pm 0.029) \cdot 10^{-3}$

M. Tanabashi et al. (PDG), PRD 98, 030001 (2018).

J/Ψ n → J/Ψ n: $M_{\psi n}(t) = 2ip_{\rm lab} m_N \sigma_{\psi n}^{\rm tot}(1 - i\rho_{\psi n}) {\rm e}^{B_{\psi n} t/2}$, $\rho_{\psi n} = \frac{{\rm Re} M_{\psi n}(0)}{{\rm Im} M_{\psi n}(0)}$

$\sigma_{\psi n}^{\rm tot} = 3.5 - 6$ mb (used 4 mb in calculations)

Upper limit (6 mb) – from pA and noncentral AA collisions at SPS $(\sqrt{s} = 17.3 \text{ GeV})$.

In a simple Glauber model, this is consistent with world data on J/Ψ transparency ratios from $\gamma-, \pi-$ and $\bar{p}-$induced reactions on nuclei (except SLAC data set at E_γ=20 GeV)

C. Gerschel, J. Hüfner, ZPC 56, 171 (1992);
D. Kharzeev, C. Lourenco, M. Nardi, H. Satz, ZPC 74, 307 (1997)

Lower limit (3.5 mb) – from the SLAC data set at E_γ=20 GeV

R.L. Anderson et al., PRL 38, 263 (1977)

Consistent with noncentral AA collisions at SPS
if corrections due to $\chi_c \to \gamma J/\psi$ and $\psi' \to J/\psi + \text{anything}$ are included

L. Gerland, L. Frankfurt, M. Strikman, H. Stöcker, W. Greiner, PRL 81, 762 (1998)

$B_{\psi n} \sim 3 \text{ GeV}^{-2}$ - from two-gluon exchange calculations

L. Gerland, L. Frankfurt, M. Strikman, PLB 619, 95 (2005)

$\rho_{\psi n} = 0.15 - 0.30$ (used 0.2 in calculations)

soft Pomeron exchange (→ 0.15) pQCD (→ 0.30)

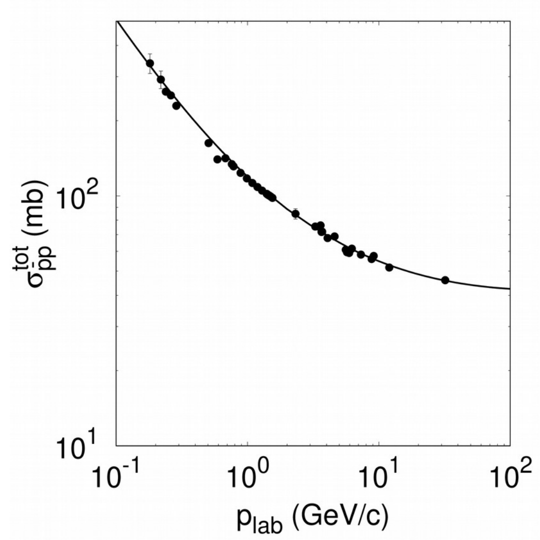
A.L., M. Strikman, M. Bleicher, PRC 89, 014621 (2014)

$\bar{p}n \to \bar{p}n$: $M_{\bar{p}n}(t) = 2ip_{\rm lab}m_N\sigma^{\rm tot}_{\bar{p}n}(1-i\rho_{\bar{p}n}){\rm e}^{B_{\bar{p}n}t/2}$, use $\bar{p}p$ parameters

$$\sigma^{\rm tot}_{\bar{p}p}(p_{\rm lab}) = \begin{cases} \exp\{4.5485\exp[-0.0601\ln(T_{\rm lab})]\} & \text{for } p_{\rm lab} < 5.92 \text{ GeV/c} \\ 38.4 + 77.6p_{\rm lab}^{-0.64} + 0.26\ln^2(p_{\rm lab}) - 1.2\ln(p_{\rm lab}) & \text{for } p_{\rm lab} \geq 5.92 \text{ GeV/c} \end{cases}$$

in mb

$$T_{\rm lab} = \sqrt{p_{\rm lab}^2 + m_N^2} - m_N$$



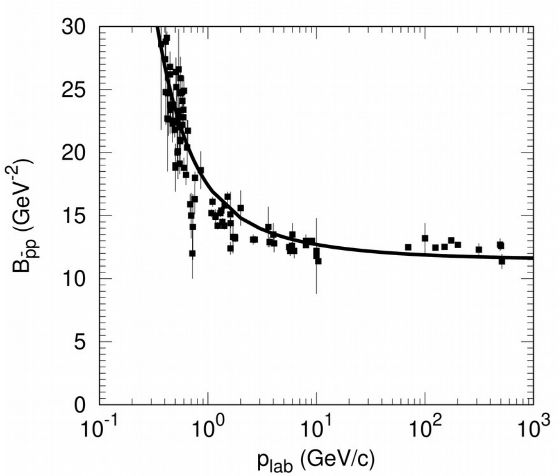
At lower $p_{\rm lab}$: ***M.R. Clover et al., PRC 26, 2138 (1982).***
At higher $p_{\rm lab}$: ***L. Montanet et al. (PDG), PRD 50, 1173 (1994).***

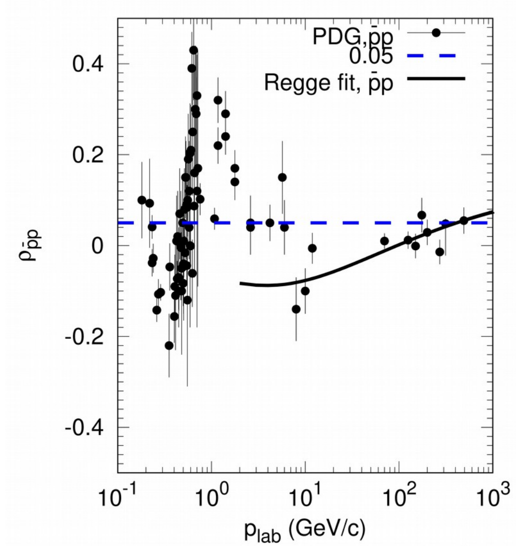
$$B_{\bar{p}p} = (0.67 + 0.35/k_{\bar{p}p})^2 \; ,$$

in fm^2

L.A. Kondratyuk, M.G. Sapozhnikov, Sov. J. Nucl. Phys. 46, 56 (1987)

$k_{\bar{p}p} = \sqrt{m_N T_{\rm lab}/2}$ – c.m. momentum (fm^{-1})





$$\rho_{\bar{p}p} = \frac{{\rm Re}M_{\bar{p}p}(0)}{{\rm Im}M_{\bar{p}p}(0)} \simeq 0.05$$

CT effects

Quantum diffusion model (QDM) ***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).***

Without CT :

$$\begin{cases} M_{\bar{p}n}(t) = 2ip_{\rm lab}m_N\sigma^{\rm tot}_{\bar{p}n}(1-i\rho_{\bar{p}n})\mathrm{e}^{B_{\bar{p}n}t/2} \ , \\ M_{\psi n}(t) = 2ip_{\rm lab}m_N\sigma^{\rm tot}_{\psi n}(1-i\rho_{\psi n})\mathrm{e}^{B_{\psi n}t/2} \ . \end{cases}$$

With CT :

$$\begin{cases} M_{\bar{p}n}(t,z) = 2ip_{\rm lab}m_N\sigma^{\rm eff}_{\bar{p}n}(p_{\bar{p}},|z|)(1-i\rho_{\bar{p}n})\mathrm{e}^{B_{\bar{p}n}t/2}\,\dfrac{G_N\left(t\cdot\frac{\sigma^{\rm eff}_{\bar{p}n}(p_{\bar{p}},|z|)}{\sigma^{\rm tot}_{\bar{p}n}}\right)}{G_N(t)} \ , \\ M_{\psi n}(t,z) = 2ip_{\rm lab}m_N\sigma^{\rm eff}_{\psi N}(p_{\psi},|z|)(1-i\rho_{\psi n})\mathrm{e}^{B_{\psi n}t/2} \ , \quad z = z_p - z_n \ , \end{cases}$$

$$\sigma^{\rm eff}_{\bar{p}n}(p_{\bar{p}},|z|) = \sigma^{\rm tot}_{\bar{p}n}\left(\left[\frac{|z|}{l_{\bar{p}}} + \frac{\langle n^2_{\bar{p}}k^2_{\bar{p}t}\rangle}{m^2_{\psi}}\left(1-\frac{|z|}{l_{\bar{p}}}\right)\right]\Theta(l_{\bar{p}}-|z|) + \Theta(z-l_{\bar{p}})\right) \ , \quad \sqrt{\langle k^2_{\bar{p}t}\rangle} = 0.35\ \mathrm{GeV/c}\ , \quad n_{\bar{p}} = 3\ ,$$

$$G_N(t) = \frac{1}{(1-t/0.71\ \mathrm{GeV}^2)^2}$$ - Sachs electric formfactor of the proton,

$$\sigma^{\rm eff}_{\psi N}(p_{\psi},|z|) = \sigma^{\rm tot}_{\psi N}\left(\left[\frac{|z|}{l_{\psi}} + \frac{\langle n^2_{\psi}k^2_{\psi t}\rangle}{m^2_{\psi}}\left(1-\frac{|z|}{l_{\psi}}\right)\right]\Theta(l_{\psi}-|z|) + \Theta(|z|-l_{\psi})\right) \ ,$$

$$\sqrt{\langle k^2_{J/\psi t}\rangle} = 0.8\ \mathrm{GeV/c}\ , \quad \sqrt{\langle k^2_{\psi' t}\rangle} = 0.4\ \mathrm{GeV/c}\ , \quad n_{\psi} = 2\ .$$

IA, $\bar{\text{p}}$ resc., J/Ψ resc.

$$\frac{d^2\sigma_{\bar{p}d\to\psi n}}{d^2p_{\psi t}} = \frac{|M^{(a)} + M^{(b)} + M^{(c)}|^2}{|p^z_\psi(E_{\bar{p}} + m_d) - p_{\rm lab}E_\psi|64\pi^2 p_{\rm lab} m_d}$$

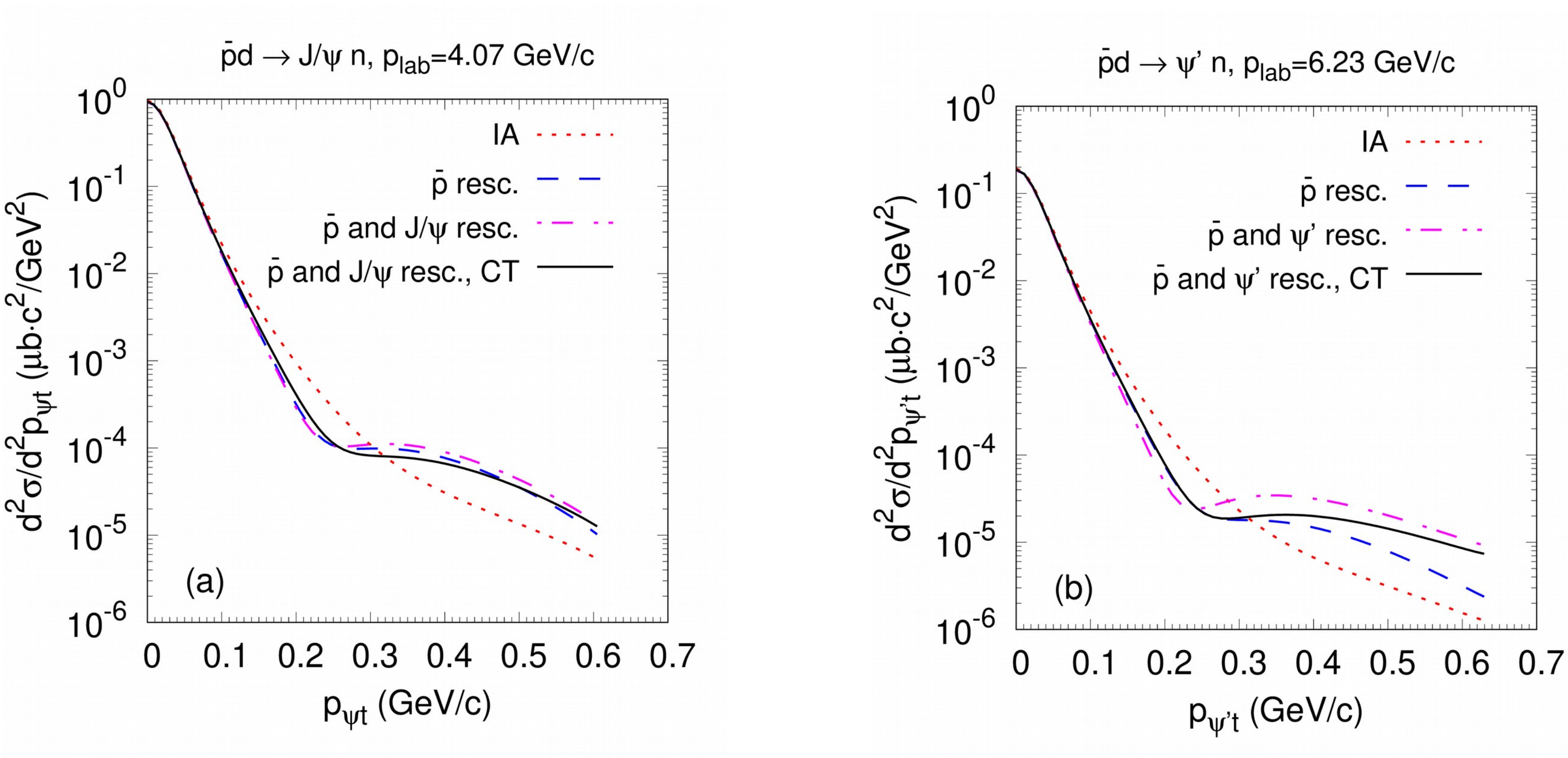
Used values:

$\sigma^{\rm tot}_{J/\Psi n} = 4$ mb

$\sigma^{\rm tot}_{\Psi' n} = 20$ mb

$l_{J/\psi} = 0.1 \text{ fm } \frac{p_{J/\psi}}{\rm GeV}$

$l_{\psi'} = 0.2 \text{ fm } \frac{p_{\psi'}}{\rm GeV}$



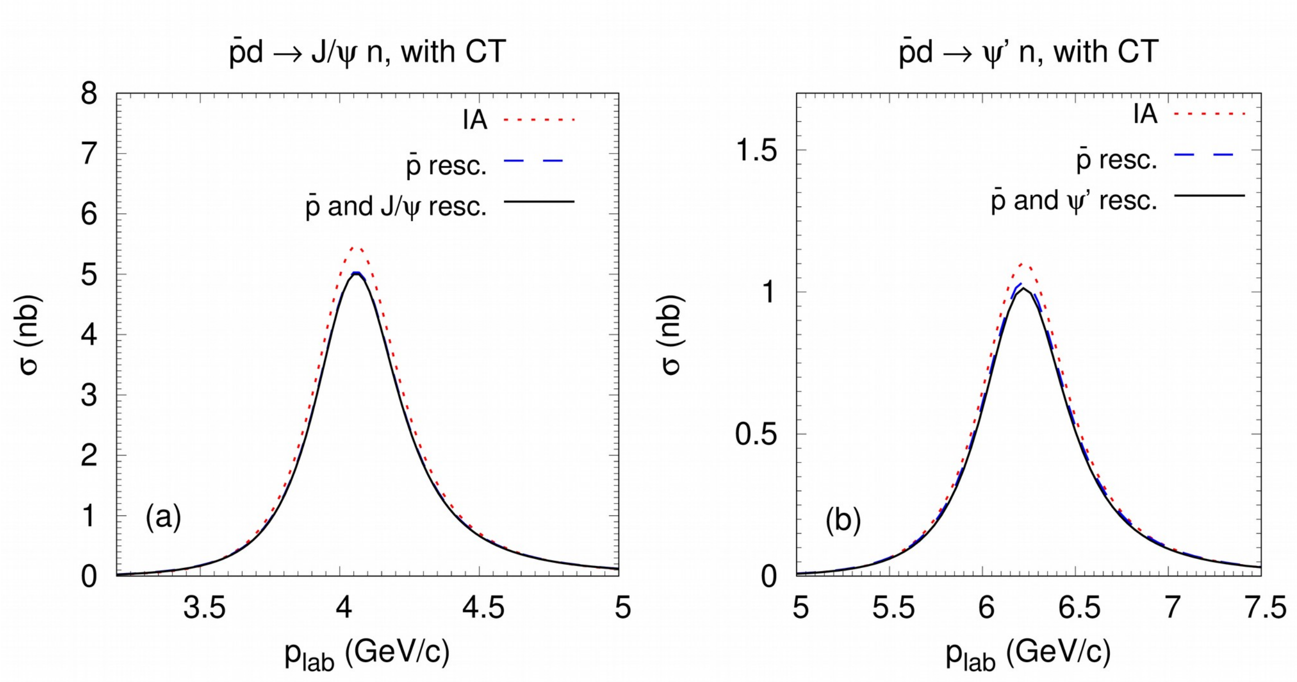
- ***Antiproton rescattering depletes the spectrum at low $p_{\psi t}$ (absorption) and enhances the spectrum at high $p_{\psi t}$.***
- ***Antiproton CT is important both at low and high $p_{\psi t}$.***
- ***Charmonium rescattering is a subtle effect.***

AL, A. Gillitzer, M. Strikman, EPJA 55 (2019) 154

Integrated cross sections

- very small effects of ISI and FSI with deuteron target

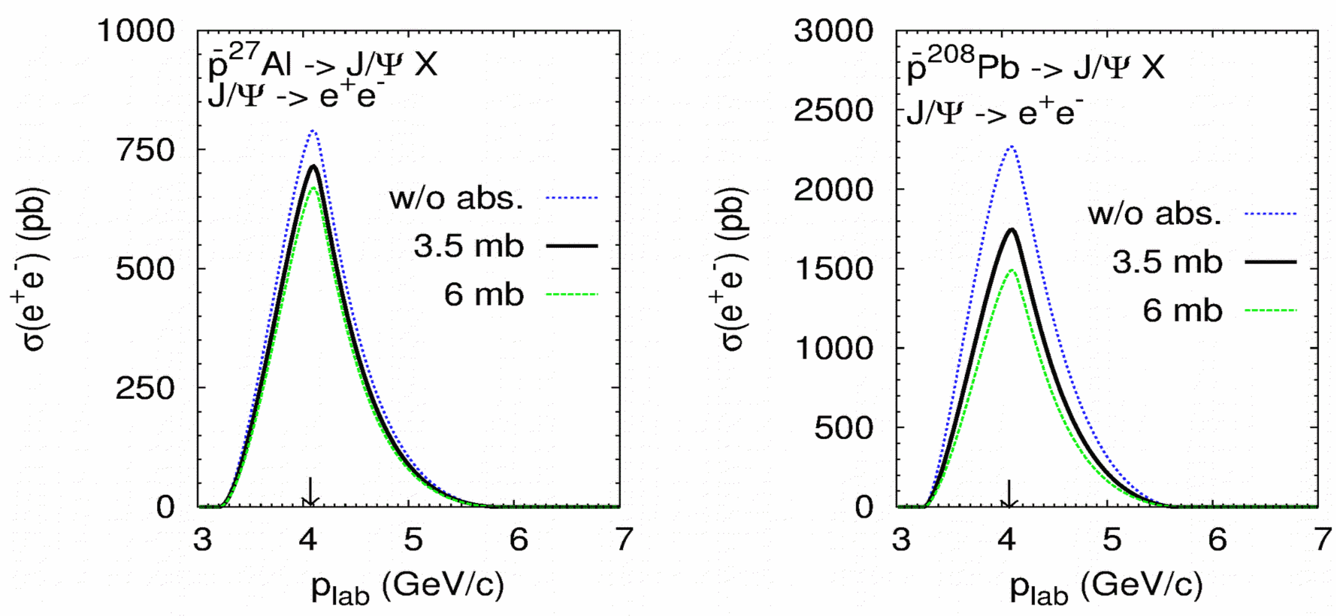
AL, A. Gillitzer, M. Strikman, EPJA 55 (2019) 154



- for heavy targets charmonium absorption is more pronounced (due to the interference of IA and rescattering amplitudes)

Glauber+quantum diffusion model calculations:

AL, M. Bleicher, A. Gillitzer, M. Strikman, PRC 87, 054608 (2013)

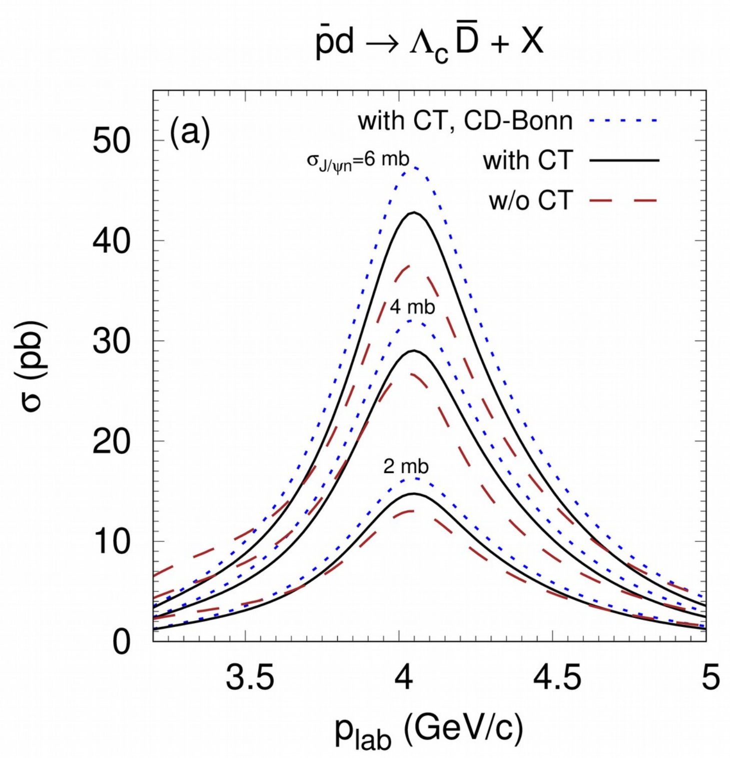


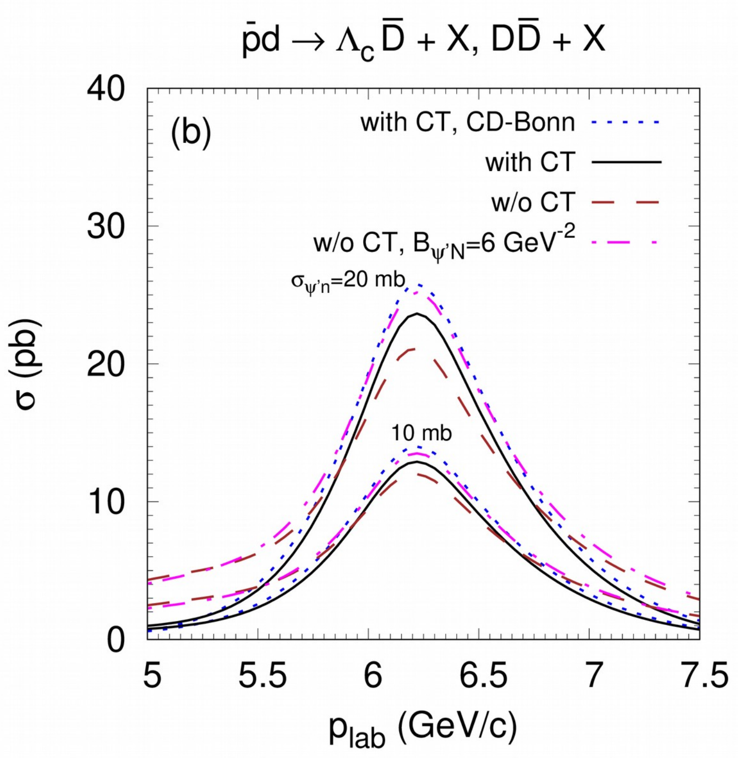
In GEA, charmonium absorption is due to the interference between IA amplitude and charmonium rescattering amplitude. Near the quasifree peaks of charmonium production, it is possible to calculate the open charm production cross sections:

$$\sigma_{\bar{p}d\to\Lambda_c\bar{D}+X} = \sigma^{w/o\,J/\psi\,resc.}_{\bar{p}d\to J/\psi\,n} - \sigma_{\bar{p}d\to J/\psi\,n} \;,$$

$$\sigma_{\bar{p}d\to\Lambda_c\bar{D}+X} + \sigma_{\bar{p}d\to D\bar{D}+X} = \sigma^{w/o\,\psi'\,resc.}_{\bar{p}d\to\psi'\,n} - \sigma_{\bar{p}d\to\psi'\,n} \;.$$

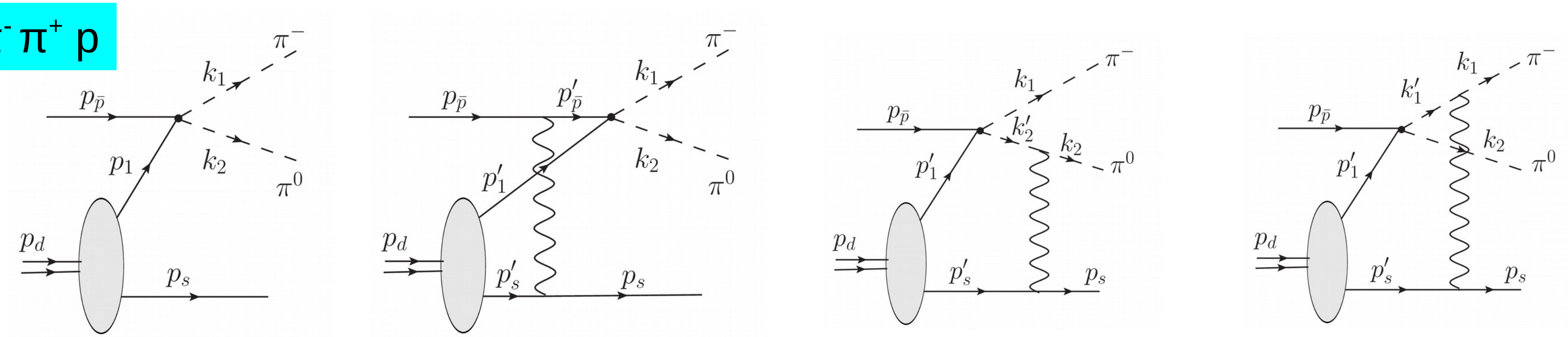
These cross sections are strongly sensitive to the charmonium-nucleon total cross section:





AL, A. Gillitzer, M. Strikman, EPJA 55 (2019) 154

$\bar{p}\, d \to \pi^- \pi^+ p$



(a) (b) (c) (d)

Impulse approximation:

$$M^{(a)} = M_{\rm ann}(k_1, k_2, p_{\bar{p}}) 2 m_N^{1/2} (2\pi)^{3/2} \phi(-\mathbf{p}_s) \ ,$$

Antiproton rescattering:

$$M^{(b)} = -m_N^{-1/2} \int \frac{d^3 p'_s}{(2\pi)^{3/2}} \phi(-\mathbf{p}'_s) \frac{M_{\bar{p}p}(t) M_{\rm ann}(k_1, k_2, p'_{\bar{p}})}{p'^2_{\bar{p}} - m_N^2 + i\epsilon} \ ,$$

π^0 rescattering:

$$M^{(c)} = -m_N^{-1/2} \int \frac{d^3 p'_s}{(2\pi)^{3/2}} \phi(-\mathbf{p}'_s) \frac{M_{\pi^0 p}(t) M_{\rm ann}(k_1, k'_2, p_{\bar{p}})}{k'^2_2 - m_\pi^2 + i\epsilon} \ ,$$

π^- rescattering:

$$M^{(d)} = -m_N^{-1/2} \int \frac{d^3 p'_s}{(2\pi)^{3/2}} \phi(-\mathbf{p}'_s) \frac{M_{\pi^- p}(t) M_{\rm ann}(k'_1, k_2, p_{\bar{p}})}{k'^2_1 - m_\pi^2 + i\epsilon} \ .$$

Double rescattering neglected: reasonable assumption at $p_{st} \lesssim 0.4$ GeV/c .

L.L. Frankfurt, E. Piasetzky, M.M. Sargsian, M.I. Strikman, PRC 56, 2752 (1997)

Eikonal forms of the inversed propagators of fast particles (GEA):

z-axis along $\mathbf{p}_{\bar{p}}$: $p_{\bar{p}}'^2 - m_N^2 + i\epsilon = 2|\mathbf{p}_{\bar{p}}|(p_s^z - p_s'^z - \Delta_{\bar{p}}^0 + i\epsilon)$,

$$\Delta_{\bar{p}}^0 = |\mathbf{p}_{\bar{p}}|^{-1}[E_{\bar{p}}(E_s - E_s') - (p_s' - p_s)^2/2] \simeq |\mathbf{p}_{\bar{p}}|^{-1}(E_{\bar{p}} + m_N)(E_s - m_N) \ .$$

z-axis along $\mathbf{k}_2$: $k_2'^2 - m_\pi^2 + i\epsilon = 2|\mathbf{k}_2|(p_s'^z - p_s^z + \Delta_2^0 + i\epsilon)$,

$$\Delta_2^0 = |\mathbf{k}_2|^{-1}[\omega_2(E_s - E_s') + (p_s - p_s')^2/2] \simeq |\mathbf{k}_2|^{-1}(\omega_2 - m_N)(E_s - m_N) \ .$$

(similar for $k_1'^2 - m_\pi^2 + i\epsilon$)

Put intermediate particles on mass shell, i.e. set $k^z \equiv p_s^z - p_s'^z = \Delta_{\bar{p},1,2}^0$ in the elastic scattering amplitudes.

Factorize-out hard annihilation amplitudes with quasifree struck neutron momentum.

Integrate over $p_s'^z$ ➡

$$M^{(b)} = \frac{iM_{\rm ann}(k_1,k_2,p_{\bar{p}})}{2|\mathbf{p}_{\bar{p}}|m_N^{1/2}} \int d^3r \phi(\mathbf{r}) \Theta(z) {\rm e}^{i\mathbf{p}_s\mathbf{r} - i\Delta_{\bar{p}}^0 z} \int \frac{d^2k_t}{(2\pi)^2} {\rm e}^{-i\mathbf{k}_t\mathbf{b}} M_{\bar{p}p}(t) \ , \qquad \mathbf{r} = \mathbf{r}_n - \mathbf{r}_p,$$

$$t = (E_s - m_N)^2 - (\Delta_{\bar{p}}^0)^2 - k_t^2, \ \ \mathbf{k}_t\mathbf{p}_{\bar{p}} = 0,$$

$$M^{(c)} = \frac{iM_{\rm ann}(k_1,k_2,p_{\bar{p}})}{2|\mathbf{k}_2|m_N^{1/2}} \int d^3r \phi(\mathbf{r}) \Theta(-\mathbf{r}\cdot\hat{\mathbf{k}}_2) {\rm e}^{i\mathbf{p}_s\mathbf{r} - i\Delta_2^0 \mathbf{r}\cdot\hat{\mathbf{k}}_2} \int \frac{d^2k_t}{(2\pi)^2} {\rm e}^{-i\mathbf{k}_t[\mathbf{r} - \hat{\mathbf{k}}_2(\mathbf{r}\cdot\hat{\mathbf{k}}_2)]} M_{\pi^0 p}(t) \ ,$$

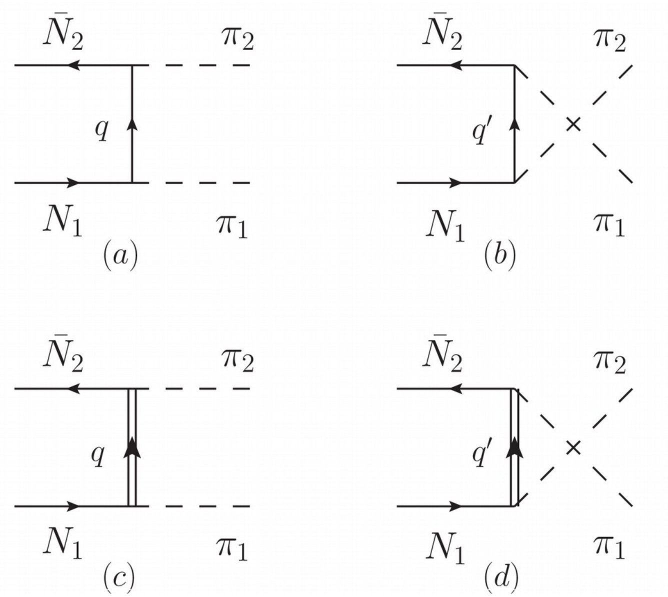
$$\hat{\mathbf{k}}_2 = \mathbf{k}_2/|\mathbf{k}_2|, \quad t = (E_s - m_N)^2 - (\Delta_2^0)^2 - k_t^2, \ \ \mathbf{k}_t\mathbf{k}_2 = 0,$$

$$M^{(d)} = \frac{iM_{\rm ann}(k_1,k_2,p_{\bar{p}})}{2|\mathbf{k}_1|m_N^{1/2}} \int d^3r \phi(\mathbf{r}) \Theta(-\mathbf{r}\cdot\hat{\mathbf{k}}_1) {\rm e}^{i\mathbf{p}_s\mathbf{r} - i\Delta_1^0 \mathbf{r}\cdot\hat{\mathbf{k}}_1} \int \frac{d^2k_t}{(2\pi)^2} {\rm e}^{-i\mathbf{k}_t[\mathbf{r} - \hat{\mathbf{k}}_1(\mathbf{r}\cdot\hat{\mathbf{k}}_1)]} M_{\pi^- p}(t) \ ,$$

$$\hat{\mathbf{k}}_1 = \mathbf{k}_1/|\mathbf{k}_1|, \quad t = (E_s - m_N)^2 - (\Delta_1^0)^2 - k_t^2, \ \ \mathbf{k}_t\mathbf{k}_1 = 0.$$

Antiproton annihilation into two pions - N and Δ exchange model:

AL, A. Gillitzer, J. Haidenbauer, M. Strikman, PRC 98, 054611 (2018)



$$\mathcal{L}_{\pi NN} = \frac{f_{\pi NN}}{m_\pi}\bar{\psi}\gamma^\mu\gamma^5\boldsymbol{\tau}\psi\partial_\mu\boldsymbol{\pi} \ ,$$
$$\mathcal{L}_{\pi N\Delta} = \frac{f_{\pi N\Delta}}{m_\pi}\bar{\psi}^\mu\boldsymbol{T}\psi\partial_\mu\boldsymbol{\pi} + h.c. \ ,$$
$$F_{\pi NN}(t) = \left(\frac{\Lambda^2_{\pi NN} - m_N^2}{\Lambda^2_{\pi NN} - t}\right)^2 ,$$
$$F_{\pi N\Delta}(t) = \left(\frac{\Lambda^2_{\pi N\Delta} - m_\Delta^2}{\Lambda^2_{\pi N\Delta} - t}\right)^{5/2} ,$$

$$f_{\pi NN} = 1.008,\ f_{\pi N\Delta} = 2.202,\ \Lambda_{\pi NN} = 2.0\ \text{GeV},\ \Lambda_{\pi N\Delta} = 1.8\ \text{GeV}.$$

Powers of vertex form factors motivated by dimensional counting at large |t| and |u|:

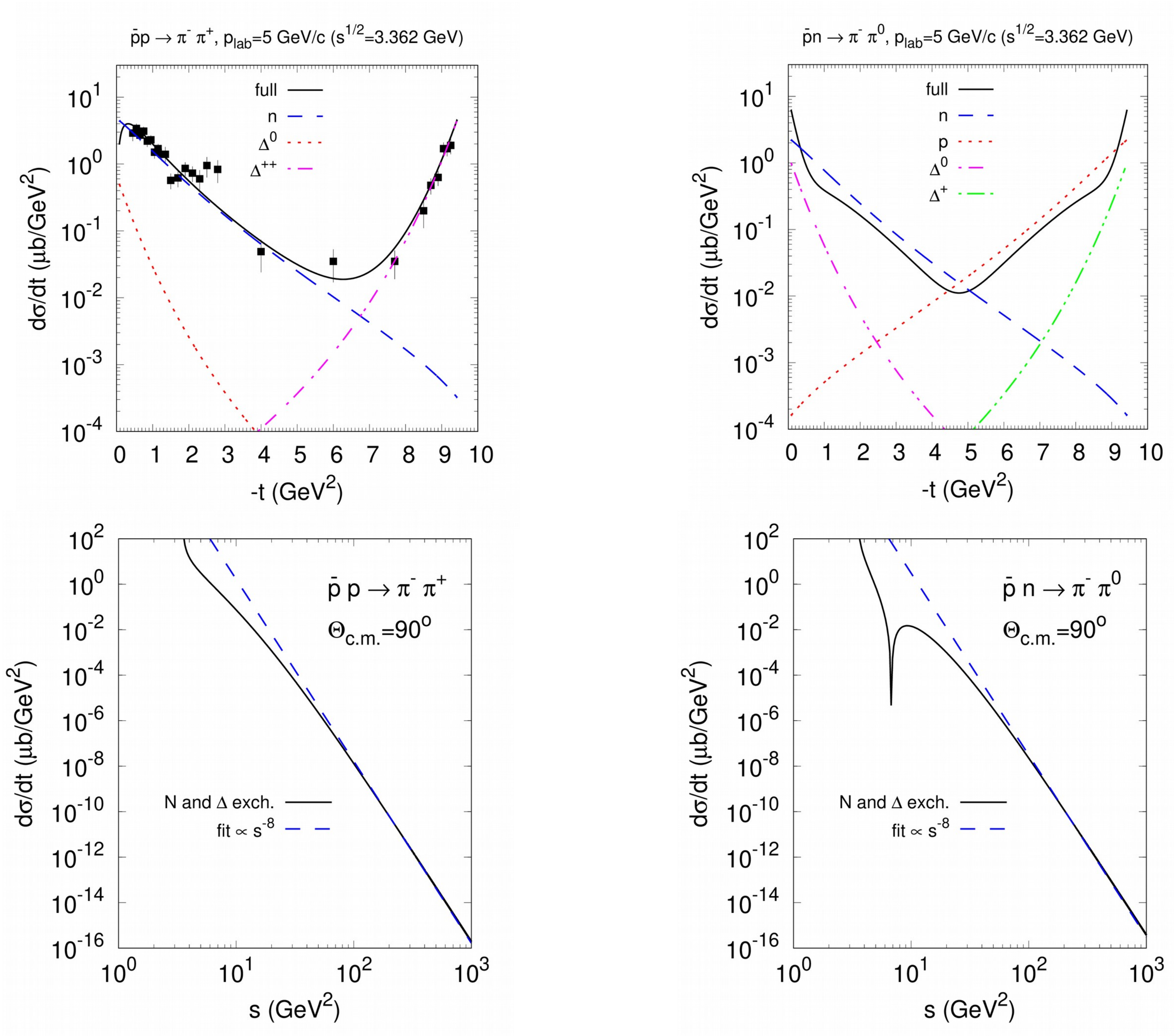
S.J. Brodsky, G.R. Farrar,
PRL 31, 1153 (1973);
V.A. Matveev, R.M. Muradian,
A.N. Tavkhelidze,
Lett. Nuovo Cimento 7, 719 (1973)

$$\frac{d\sigma}{dt} = \frac{f(t/s)}{s^{n-2}} \ , \quad n = \sum n_i \ ,$$

n_i – the number of the constituents
$(n_B = 3, n_M = 2)$

Corrections due to absorptive ISI of the $\bar{\text{N}}$ are taken into account by including the scaling factor of the amplitude: $\sqrt{\Omega}$, $\Omega = 0.008$.

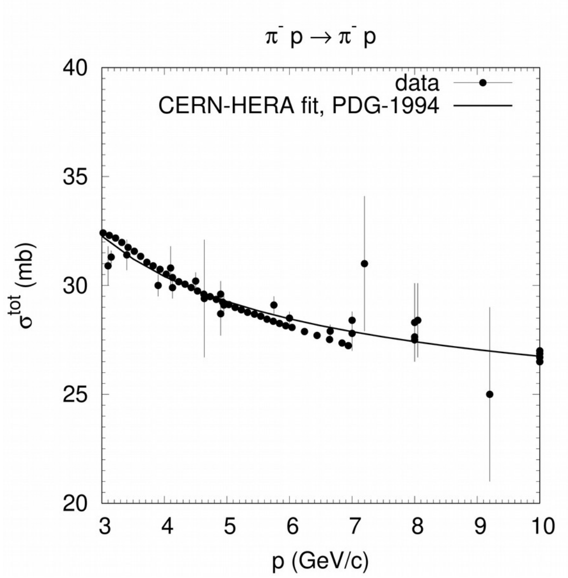
Data: ***A. Eide et al., NPB 60, 173 (1973)***

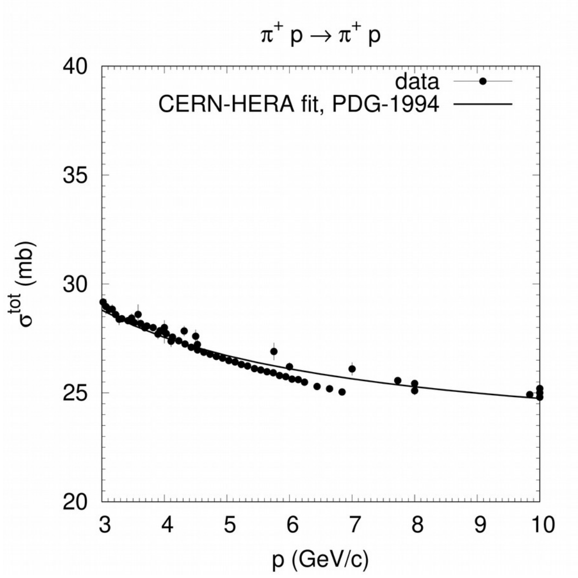


Local minimum at p_{lab}=2.5 GeV/c ($s^{1/2}$=2.6 GeV/c) due to destructive interference of n and p exchanges.

π p → π p (EL): $$M_{\pi^\pm p}(t) = 2ip_\pi m_N \sigma^{\rm tot}_{\pi^\pm p}(1 - i\rho_{\pi^\pm p}) e^{B_{\pi^\pm p} t/2} \ ,$$

$$M_{\pi^0 p}(t) = \frac{1}{2}(M_{\pi^- p}(t) + M_{\pi^+ p}(t))$$ (isospin conservation).





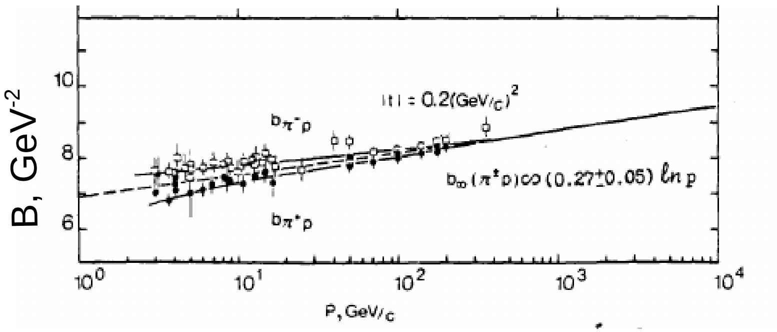
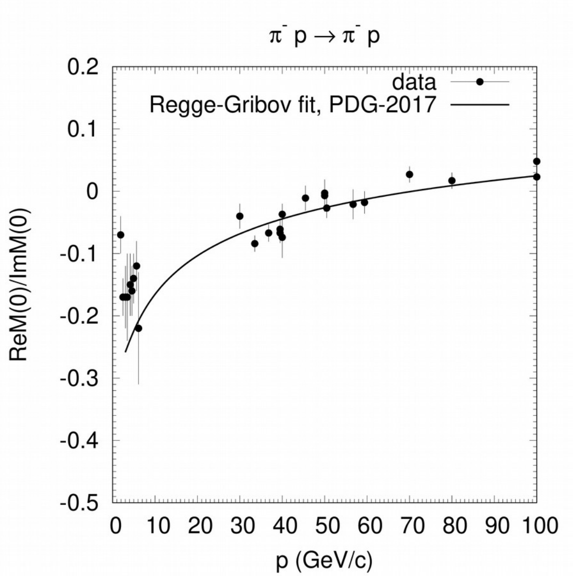
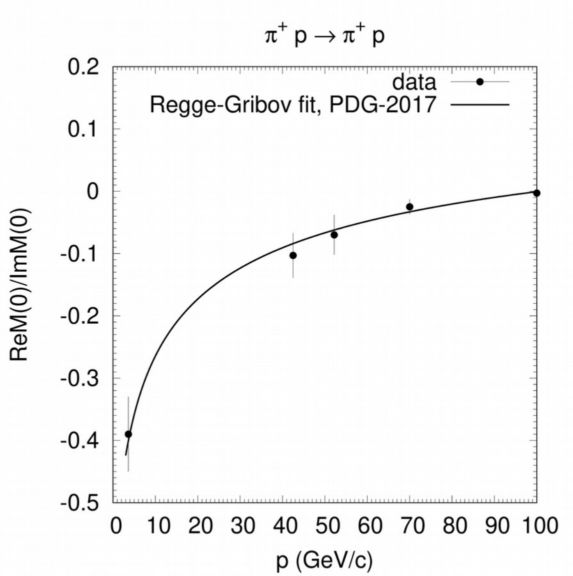


Figure from
J.P. Burq et al., NPB 217, 285 (1983)





CT effects:

Quantum diffusion model (QDM) **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)**

Without CT : $M_{hp}(t) = 2ip_h m_N \sigma_{hp}^{\rm tot}(1 - i\rho_{hp})\mathrm{e}^{B_{hp}t/2}\ , \quad h = \bar{p}, \pi$

With CT : $M_{hp}(t,z) = 2ip_h m_N \sigma_{hp}^{\rm eff}(p_h,|z|)(1 - i\rho_{hp})\mathrm{e}^{B_{hp}t/2}\dfrac{G_h(t \cdot \frac{\sigma_{hp}^{\rm eff}(p_h,|z|)}{\sigma_{hp}^{\rm tot}})}{G_h(t)}\ , \quad z = (\mathbf{r}_n - \mathbf{r}_p)\cdot\mathbf{p}_h$

$$\sigma_{hp}^{\rm eff}(p_h,|z|) = \sigma_{hp}^{\rm tot}\left(\left[\frac{|z|}{l_h} + \frac{\langle n_h^2 k_t^2\rangle}{Q^2}\left(1 - \frac{|z|}{l_h}\right)\right]\Theta(l_h - |z|) + \Theta(|z| - l_h)\right)\ ,$$

$$\sqrt{\langle k_t^2\rangle} = 0.35\ \mathrm{GeV/c}\ , \quad n_{\bar{p}} = 3\ , \quad n_\pi = 2\ ,$$

$Q^2 = \min(-t_{\rm hard}, -u_{\rm hard})$ - hard scale, $t_{\rm hard} = (p_{\bar{p}} - p_{\pi^-})^2, \quad u_{\rm hard} = (p_{\bar{p}} - p_{\pi^0})^2.$

$G_{\bar{p}}(t) = \dfrac{1}{(1 - t/0.71\ \mathrm{GeV}^2)^2}$ - Sachs electric formfactor of the proton.

$G_\pi(t) = \dfrac{1}{1 - \langle r_\pi^2\rangle t/6}$ - pion EM formfactor, $\langle r_\pi^2\rangle = 0.439 \pm 0.008\ \mathrm{fm}^2.$

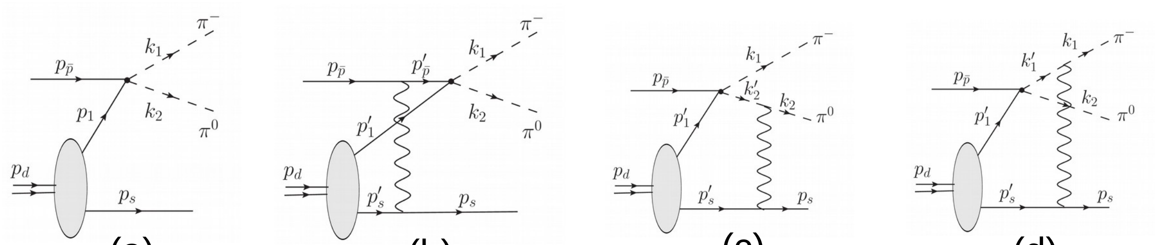
S.R. Amendolia et al., NPB 277, 168 (1986)

Observables

averaging over initial and sum over final spins

$$d\sigma_{\bar{p}d\to\pi_1^-\pi_2^0 p} = (2\pi)^4\delta^{(4)}(p_{\bar{p}}+p_d-k_1-k_2-p_s)\frac{\overline{|M|^2}}{4p_{\rm lab}m_d}\frac{d^3k_1}{(2\pi)^3 2\omega_1}\frac{d^3k_2}{(2\pi)^3 2\omega_2}\frac{d^3p_s}{(2\pi)^3 2E_s}\,,$$

$$M = M^{(a)} + M^{(b)} + M^{(c)} + M^{(d)}$$

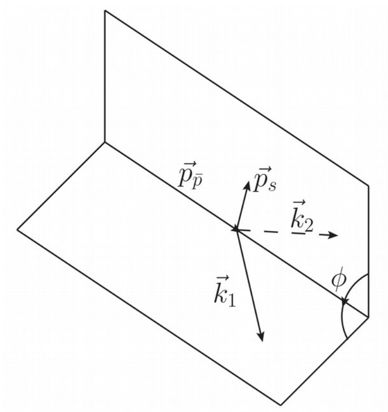


Four-fold differential cross section: $$\alpha_s\beta\frac{d^4\sigma}{d\alpha_s\, d\beta\, d\phi\, p_{st}dp_{st}} = \frac{\overline{|M|^2}k_{1t}}{16(2\pi)^4 p_{\rm lab}m_d\kappa_t}\,, \quad \kappa_t = 2\left|\frac{2k_{1t}}{\beta} + p_{st}\cos\phi\right|\,,$$

$$\alpha_s = \frac{2(E_s - p_s^z)}{m_d}$$ - light cone (LC) momentum fraction of the spectator proton,

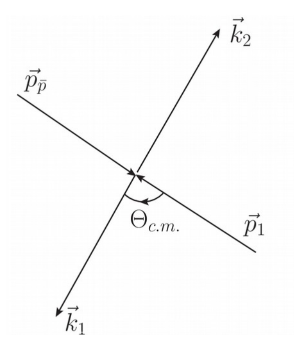
$$\beta = \frac{2(\omega_1 + k_1^z)}{E_{\bar{p}} + m_d - E_s + p_{\rm lab} - p_s^z} \simeq 1 + \cos\Theta_{c.m.}$$ - LC momentum fraction of π⁻,

lab. frame:

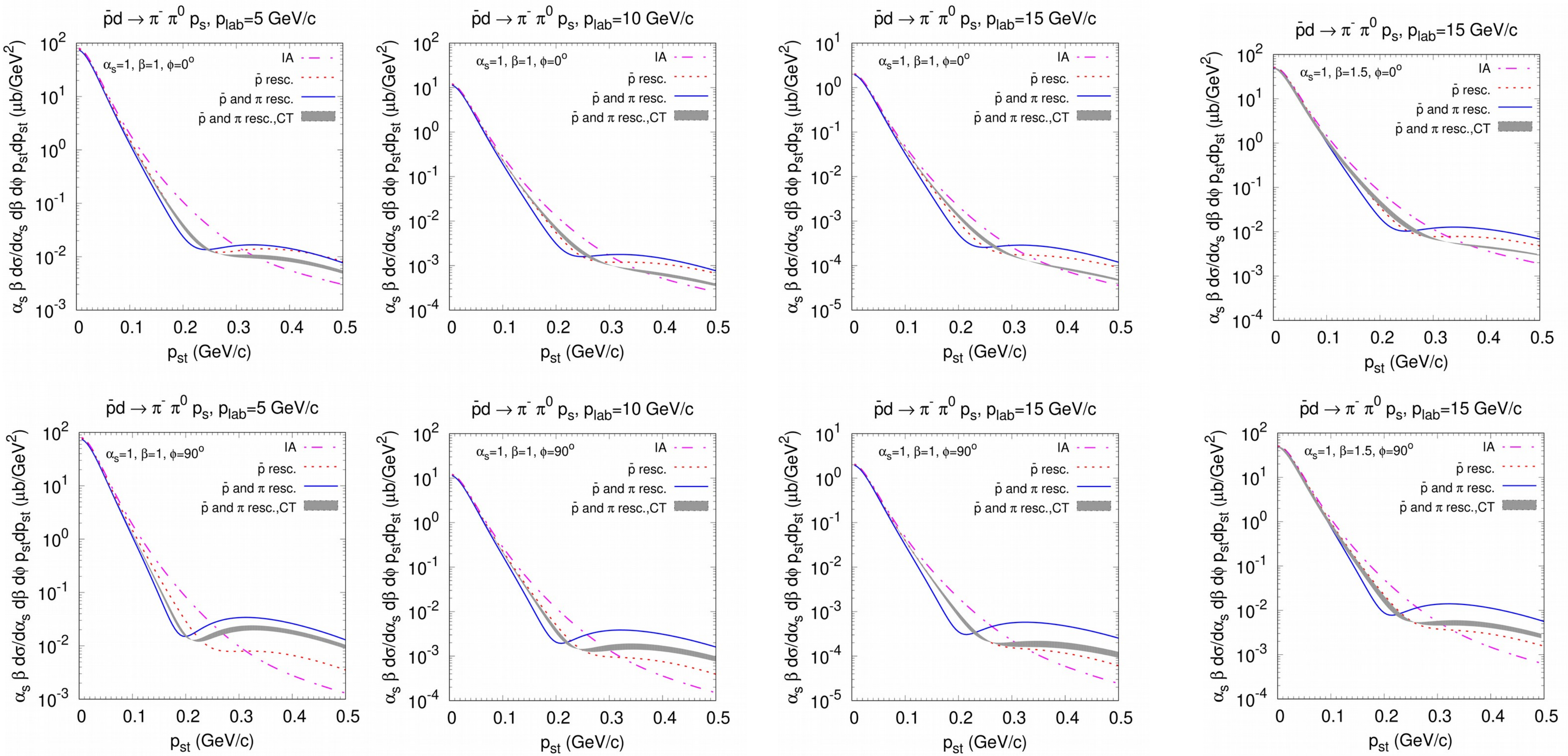


boost

c.m. frame of $\bar{\rm p}$ and struck neutron:



Bands – uncertainty due to variation of the coherence length, $l_h=2p/\Delta M^2$, $\Delta M^2=0.7\text{-}1.1\ \mathrm{GeV}^2$.



- Rescattering leads to strong deviations from IA: depletion at low and enhancement at high spectator transverse momenta.

- Pion rescattering is significant, especially at $\varphi=90^o$.

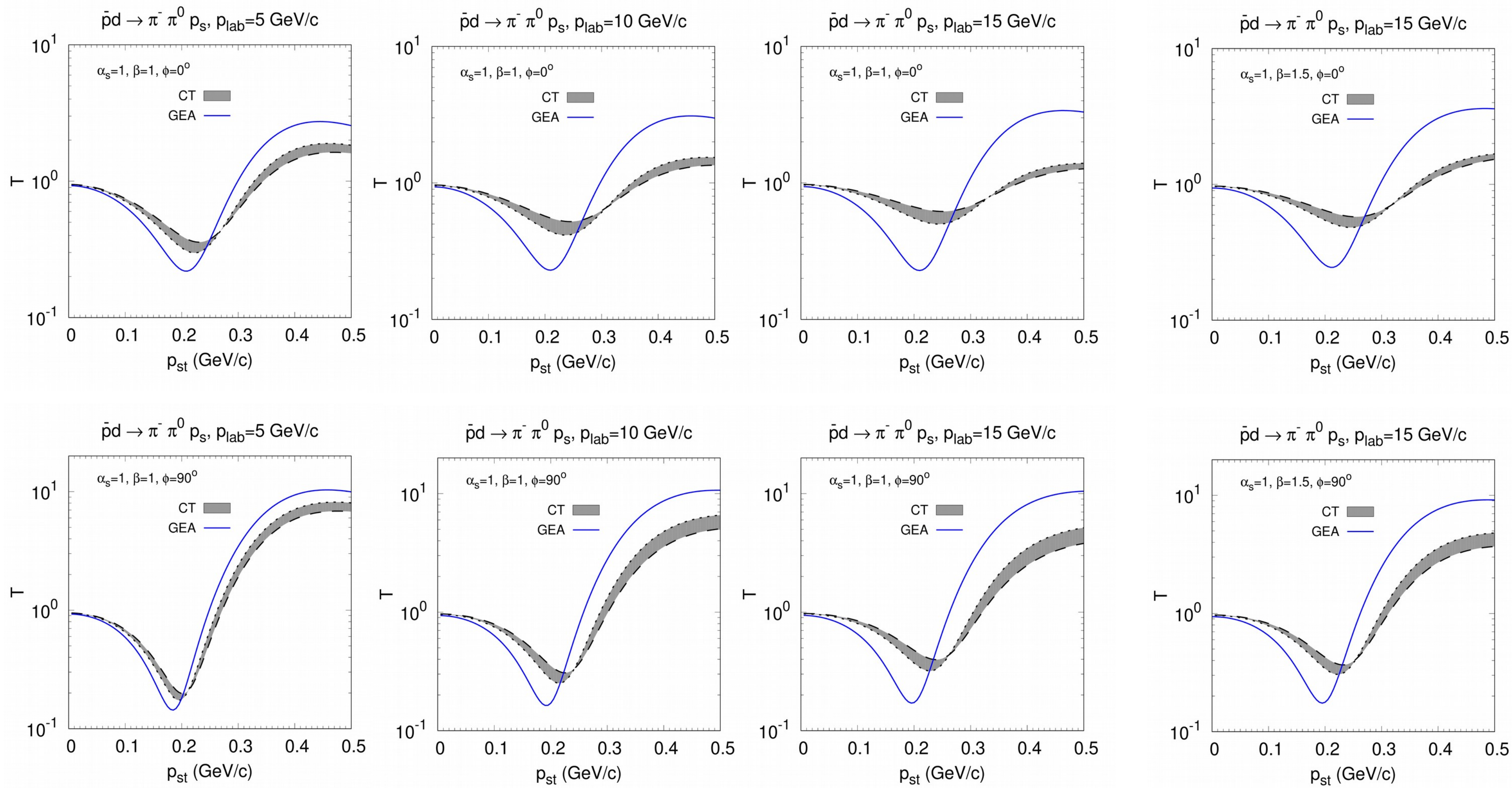
- ***Large difference between CT and GEA***, effect grows with p_{lab}, but the cross section drops for fixed $\beta = 1\ (\Theta_{c.m.} = 90^o)$.

- By choosing $\beta = 1.5\ (\Theta_{c.m.} = 60^o)$ it is possible to increase the cross section at p_{lab} =15 GeV/c by an order of magnitude, while the strong CT effect still persists.

Transparency ratio (definition adopted from studies of A(e,e'p) and d(p,2p)n reactions, see ***L.L. Frankfurt et al., ZPA 352, 97 (1995); PRC 56, 2752 (1997)*** and refs.therein):

$$T \equiv \frac{\sigma^{\mathrm{DWIA}}}{\sigma^{\mathrm{IA}}} = \frac{\overline{|M^{(a)} + M^{(b)} + M^{(c)} + M^{(d)}|^2}}{\overline{|M^{(a)}|^2}}$$

In the experiment, σ^{DWIA} should be replaced by the measured cross section.



Bands – uncertainty due to variation of the coherence length.
Dashed lines - ΔM^2=0.7 GeV^2. Dotted lines - ΔM^2=1.1 GeV^2.

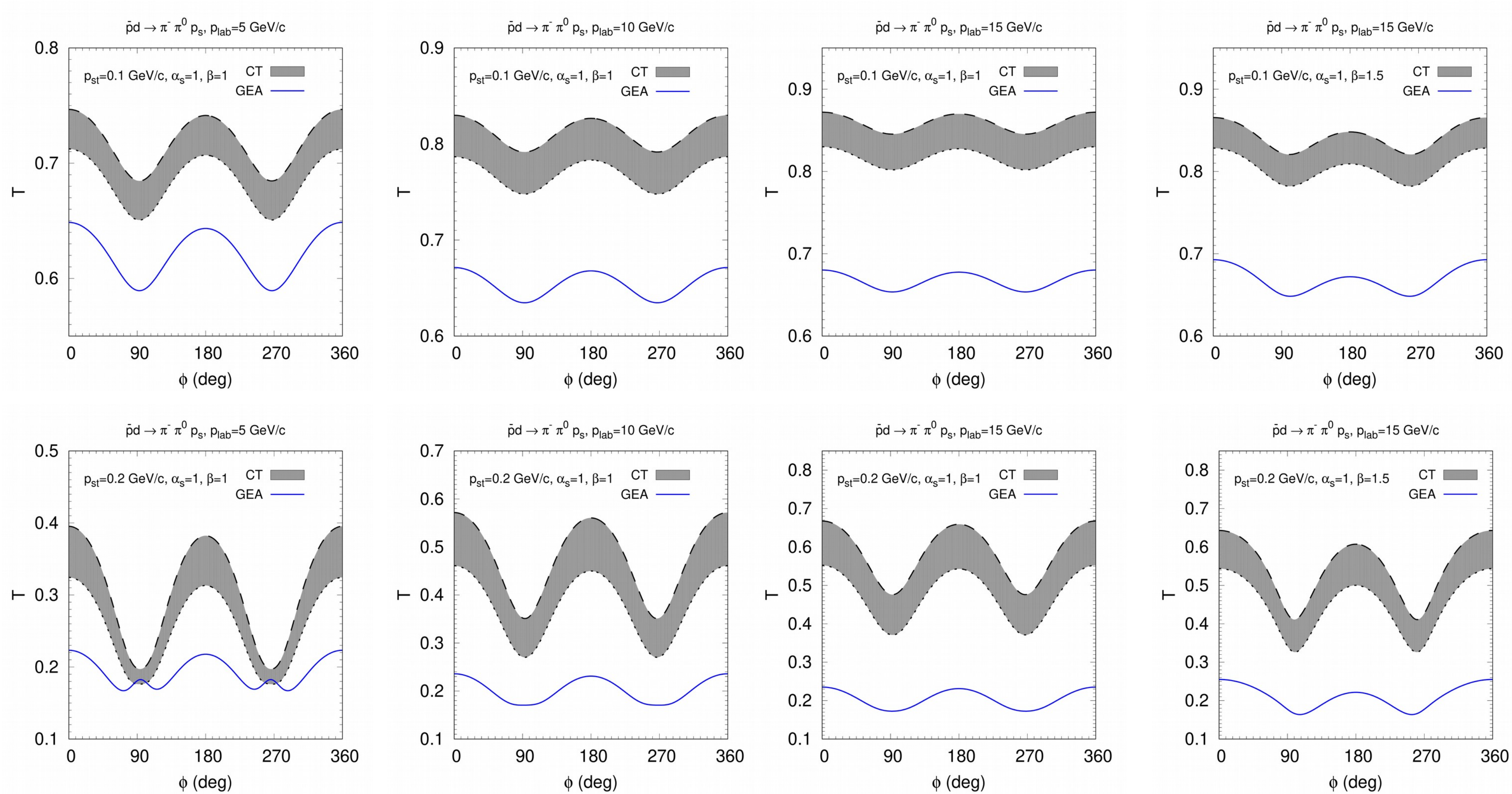
- In QF kinematics $(p_{st} = 0)$ absorption is very weak, $\lesssim 10\%$.

- Less absorpion at small and less rescattering at large spectator transverse momenta due to CT.

- More pronounced effect of CT for in-plane kinematics (φ=0°).

Relative azimuthal angle dependense of transparency

1) Small transverse momenta of the spectator:



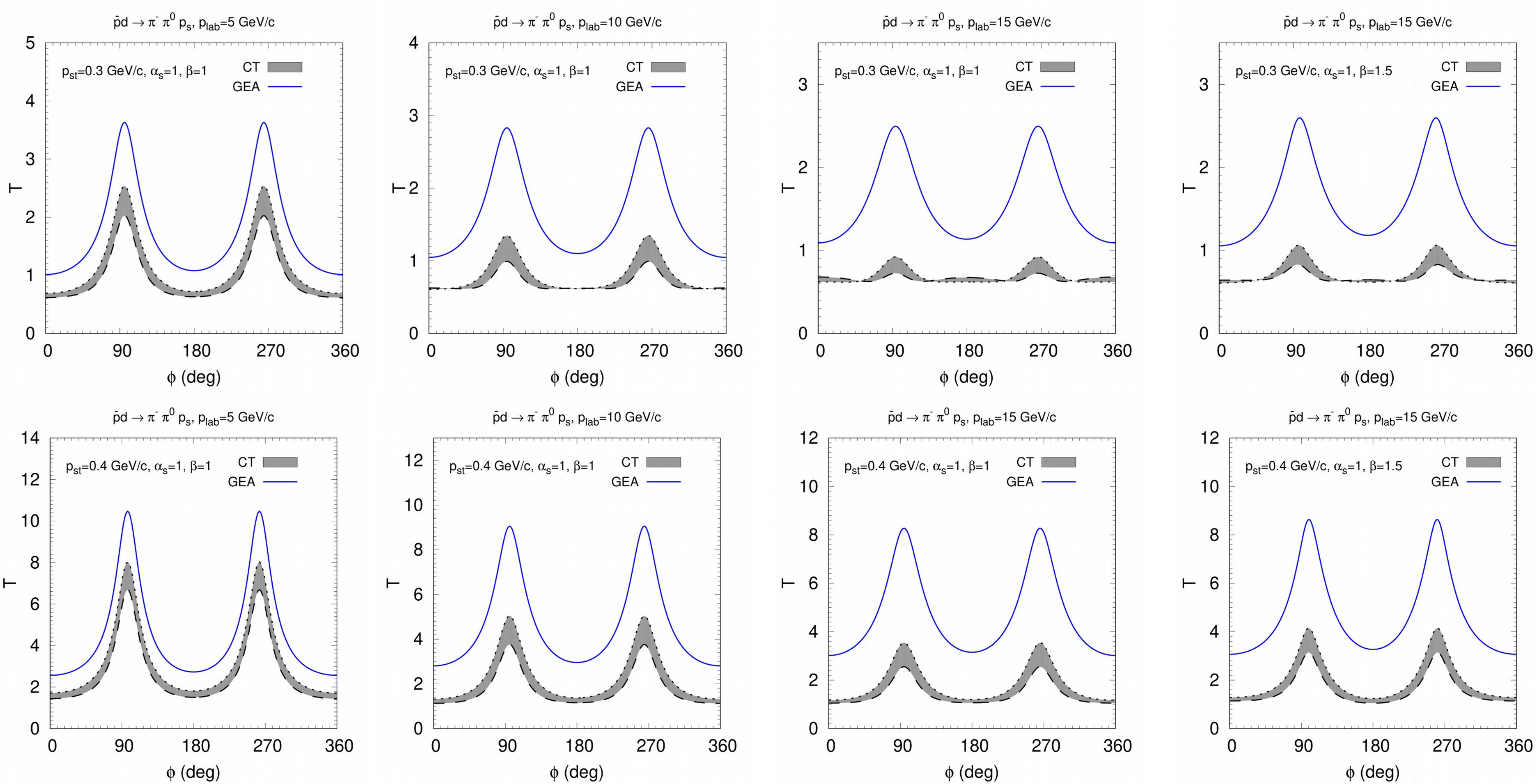
- Absorption grows with p_{st}.

- Stronger absorption for out-of-plane kinematics ($\varphi=90^o$ and $\varphi=270^o$).

- CT effects are strong at $p_{st} \approx 0.2$ GeV/c

Relative azimuthal angle dependense of transparency

2) Large transverse momenta of the spectator:



- Rescattering grows with p_{st}.
- Stronger rescattering for out-of-plane kinematics ($\varphi=90^o$ and $\varphi=270^o$).

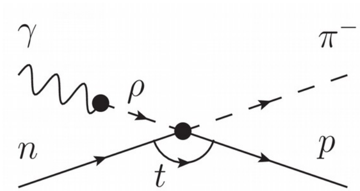
The maxima at 90^o and 270^o correspond to almost pure transverse momentum transfer from pions to the spectator.
In agreement with the study of the d(p,2p)n reaction
L.L. Frankfurt, E. Piasetzky, M.M. Sargsian, M.I. Strikman, PRC 56, 2752 (1997).

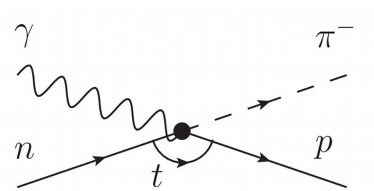
Photon transparency

$s \to \infty,\ t/s = \text{const}$ asymptotic scaling law

$$\frac{d\sigma}{dt} = \frac{f(t/s)}{s^{n-2}}\,, \qquad n-2=7$$

- unresolved photon regime





Small |t|
- resolved photon (RP),

more absorption.

Large |t|
- unresolved photon (UP),

less absorption.

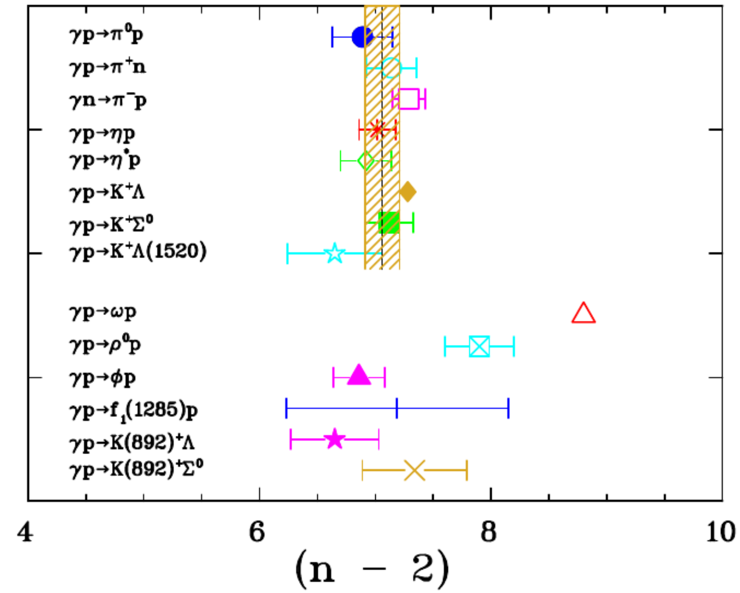


FIG. 2. Power factor $(n-2)$ in Eq. (1) for light-meson photoproduction off the nucleon from the CLAS Collaboration. The black solid vertical line shows the average value for pseudoscalar mesons $\langle(n-2)\rangle = 7.06 \pm 0.15$. The yellow band represents its uncertainty. In the case of the ω, the result corresponds to the higher energy range, $s = 5$–$8.1\ \text{GeV}^2$. The notation for the different reactions is the same as in Fig. 1.

At which |t| the transition RP to UP occurs ?
Will this interfere with CT ?

Figure from ***M. J. Amaryan et al., PRC 103, 055203 (2021)***

At JLab can be studied from nuclear transparency ratio for $A(\gamma, \text{Meson} + \text{Baryon})$

AL, M. Strikman, PLB 760, 753 (2016)

At PANDA one can study nuclear transparency for $A(\bar{p}, \gamma + \text{Meson})$.

Conclusions

- Exclusive $\bar{p}\, d \to J/\Psi\, n$, $\Psi'\, n$ channels are influenced by $\bar{p}\, n$ elastic rescattering. Semiexclusive channel $\bar{p}\, d \to \Lambda_c\, \bar{D} + X$ can be better used to test $J/\Psi\, n$ dissociation cross section. CT effect is small (for $\bar{p}$ rescattering mostly).

- The process $\bar{p}\, d \to \pi^- \pi^0 p_s$ at p_{lab}=5-10 GeV/c for large momentum transfer in the annihilation $\bar{p}\, n \to \pi^- \pi^0$ is well suited for the studies of CT, in qualitative agreement with previous studies of the channel $p\, d \to p\, p\, n_s$ in transverse kinematics (α_s=1) ***L.L. Frankfurt, E. Piasetzky, M.M. Sargsian, M.I. Strikman, PRC 56, 2752 (1997)***

Outlook

- CT is expected to significantly reduce absorption in semiexclusive two-meson channels with heavy targets

$$A(\bar{p}, \mathrm{Meson} + \mathrm{Meson})(A-1)^*$$

- Nuclear transparency in the quasi-elastic scattering channel

$$A(\bar{p}, \bar{p}p)(A-1)^*$$

In $\bar{p}\, p \to \bar{p}\, p$ only gluon exchange or $\bar{q}q$ annihilation is possible (no quark exchange). Thus, squeezing to PLC might not present, in contrast to $p\, p \to p\, p$.