Charmonium production
in antiproton-induced reactions on nuclei

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Outline

- Motivation
- Glauber model
- Results for J/Ψ and Ψ´ production
- Color filtering and polarized χ_{c1}, χ_{c2} production
- Summary and outlook

Exclusive charmonium production (formation):

$$\bar{p}p \longrightarrow J/\Psi$$

$$p \simeq 4 \text{ GeV/c}$$
$$l_f \simeq \frac{2p}{m^2_{\Psi'} - m^2_{J/\Psi}} \simeq 0.4 \text{ fm}$$

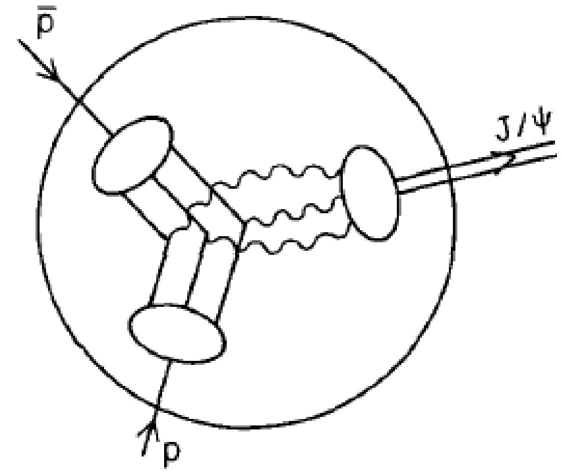


Fig. 2. The dominant mechanism for pp̄ exclusive annihilation into J/ψ.

J/Ψ is formed inside the nucleus

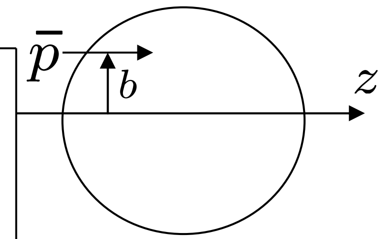
Genuine J/Ψ N dissociation cross section can be studied !

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

— Important for understanding J/Ψ production in heavy-ion collisions at SPS, RHIC and LHC: ***is QGP formed or not ?***

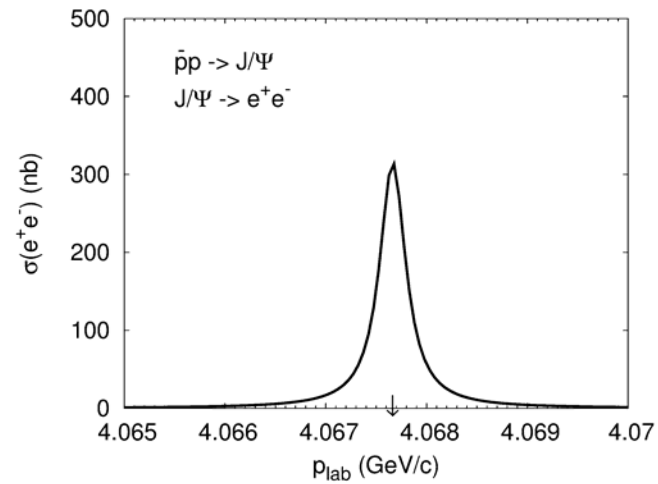
— Propagation of ***the polarized charmonia*** χ_{c1}, χ_{c2} **(1P states) in nuclear medium.**

— Planning for the PANDA experiment at FAIR



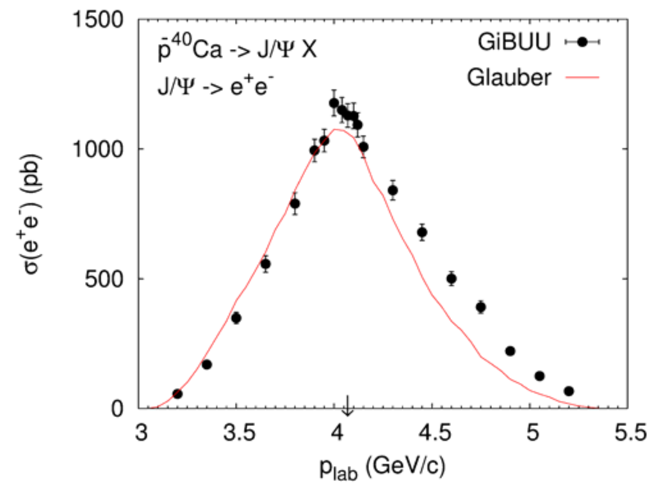
G.R. Farrar, L.L. Frankfurt, M.I. Strikman, and H. Liu, NPB 345, 125 (1990)

Fermi motion by Monte-Carlo:
„looking for a needle in a haystack“



Due to Fermi motion
cross section drops
by a factor of ~10^{-3} at the peak

Good agreement between GiBUU
and Glauber calculations



Partial width:

$$p_{\text{lab}} = m_R\sqrt{m_R^2/4m_N^2 - 1} \quad (\text{for } \bar{p}p \to R_{\text{on-shell}}):$$

$$\Gamma_{\bar{p}\to R} = \int \frac{2d^3p}{(2\pi)^3} v_{\bar{p}p}\sigma_{\bar{p}p\to R}(\sqrt{s}) f_p(\mathbf{p}) \simeq \frac{3m_R\Gamma_{R\to\bar{p}p}p_{F,p}^2}{8E_{\bar{p}}q_R^2} \propto \rho_p^{2/3}$$

$$E_{\bar{p}} = \sqrt{p_{\text{lab}}^2 + m_N^2},\ q_R = \sqrt{m_R^2/4 - m_N^2},\ f_p(\mathbf{p}) = \Theta(p_{F,p} - |\mathbf{p}|).$$

$$\frac{\Gamma_{\bar{p}\to R}}{v_{\bar{p}}\sigma_{\bar{p}p\to R}(m_R)\rho_p} = \frac{3\pi\Gamma_R m_R}{8p_{F,p}E_{\bar{p}}} \sim 10^{-3}$$

(for $m_{J/\Psi} = 3.097$ GeV, $\Gamma_{J/\Psi} = 93$ keV,
$p_{F,p} \simeq 0.3$ GeV/c, $p_{\text{lab}} = 4.07$ GeV/c)

Strong reduction of charmonium production due to Fermi motion

Density profiles:

For light nuclei (A ≤ 20) — harmonic oscillator model:

$$\rho_q(r) = \rho_q^0 \left[1 + a_q \left(\frac{r}{R_q}\right)^2\right] \exp\{-(r/R_q)^2\}\ , \quad q = p, n\ .$$

For heavy nuclei (A > 20) — two-parameter Fermi distribution:

$$\rho_q(r) = \frac{\rho_q^0}{\exp\left(\frac{r-R_q}{a_q}\right) + 1}\ , \ q = p, n$$

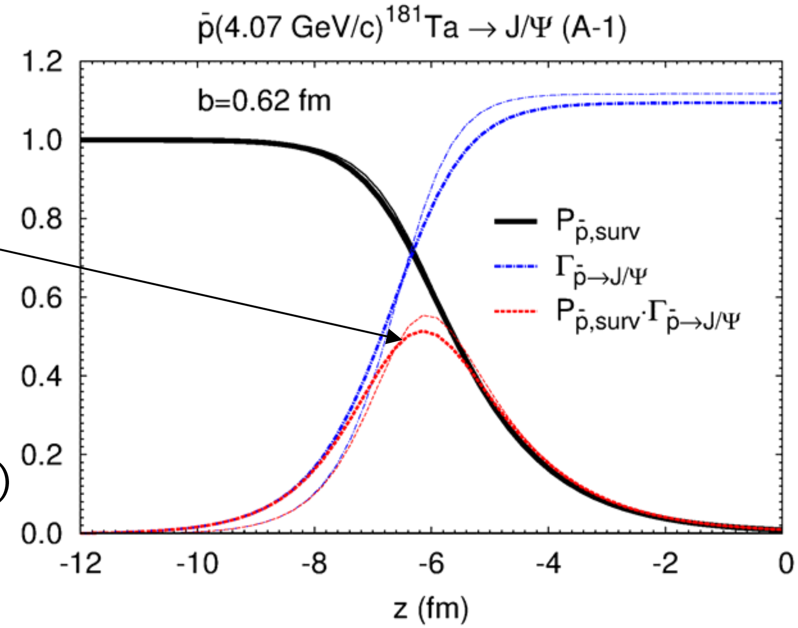
Charge density parameters: **C. De Jager et al., Atom. Data Nucl. Data Tabl. 14, 479 (1974).**

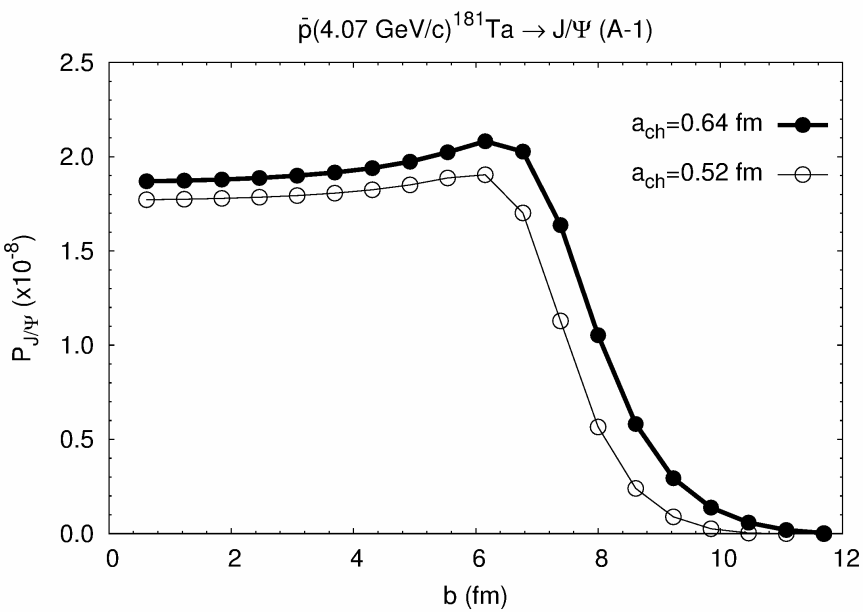
Neutron density parameters: **J. Nieves et al., NPA 554, 509 (1993); V. Koptev et al., Yad. Fiz. 31, 1501 (1980); R. Schmidt et al., PRC 67, 044308 (2003).**

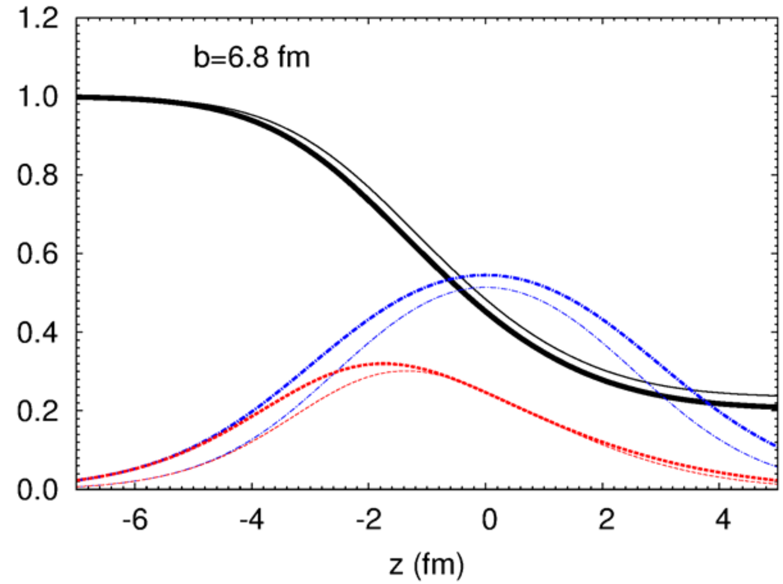
Charmonium production is localized in the diffuse surface zone

$$\Gamma_{\bar{p}\to R} \propto \rho_p^{2/3}$$

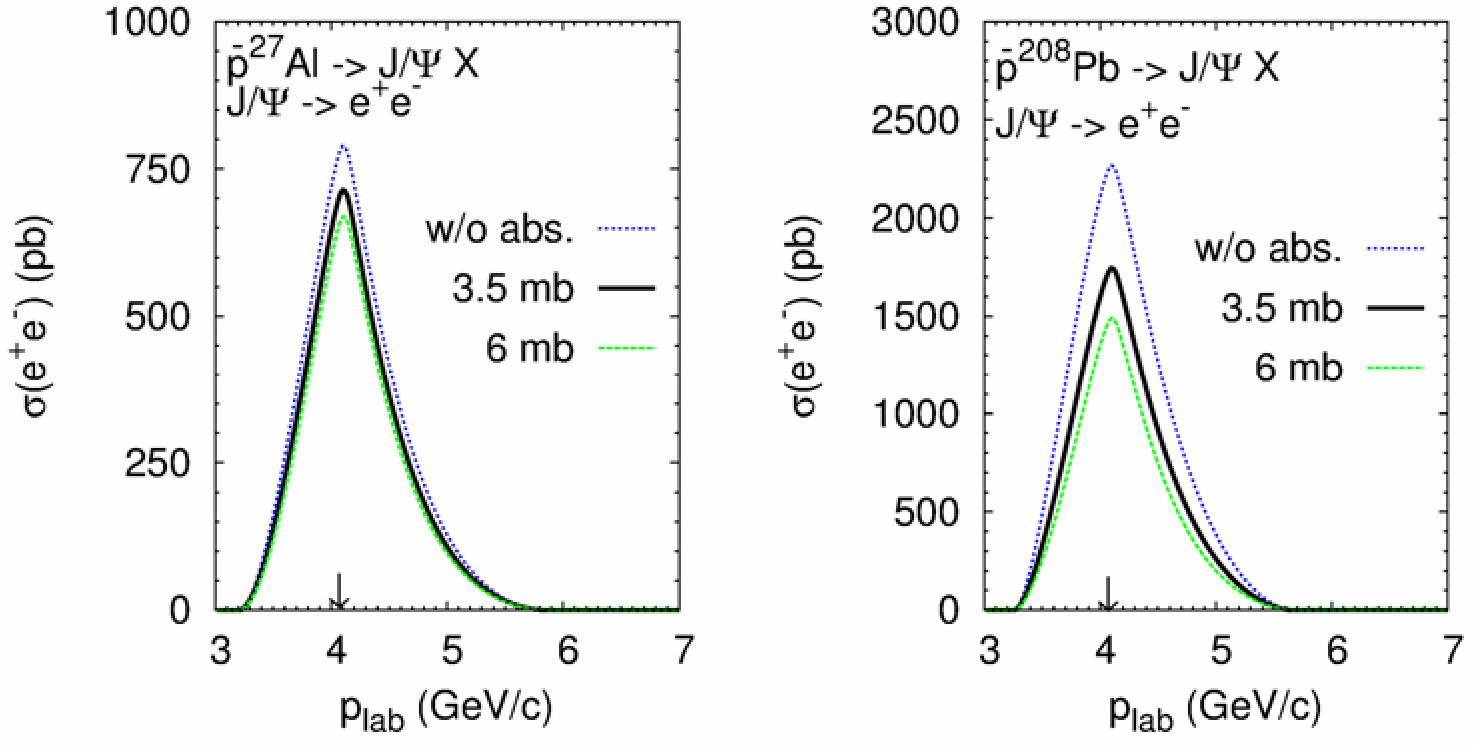
$$P_{\mathrm{J}/\Psi}(b) = v_{\bar{p}}^{-1} \int\limits_{-\infty}^{\infty} dz \mathcal{P}_{\bar{p},\mathrm{surv}}(z,b)\Gamma_{\bar{p}\to \mathrm{J}/\Psi}(z,b)$$



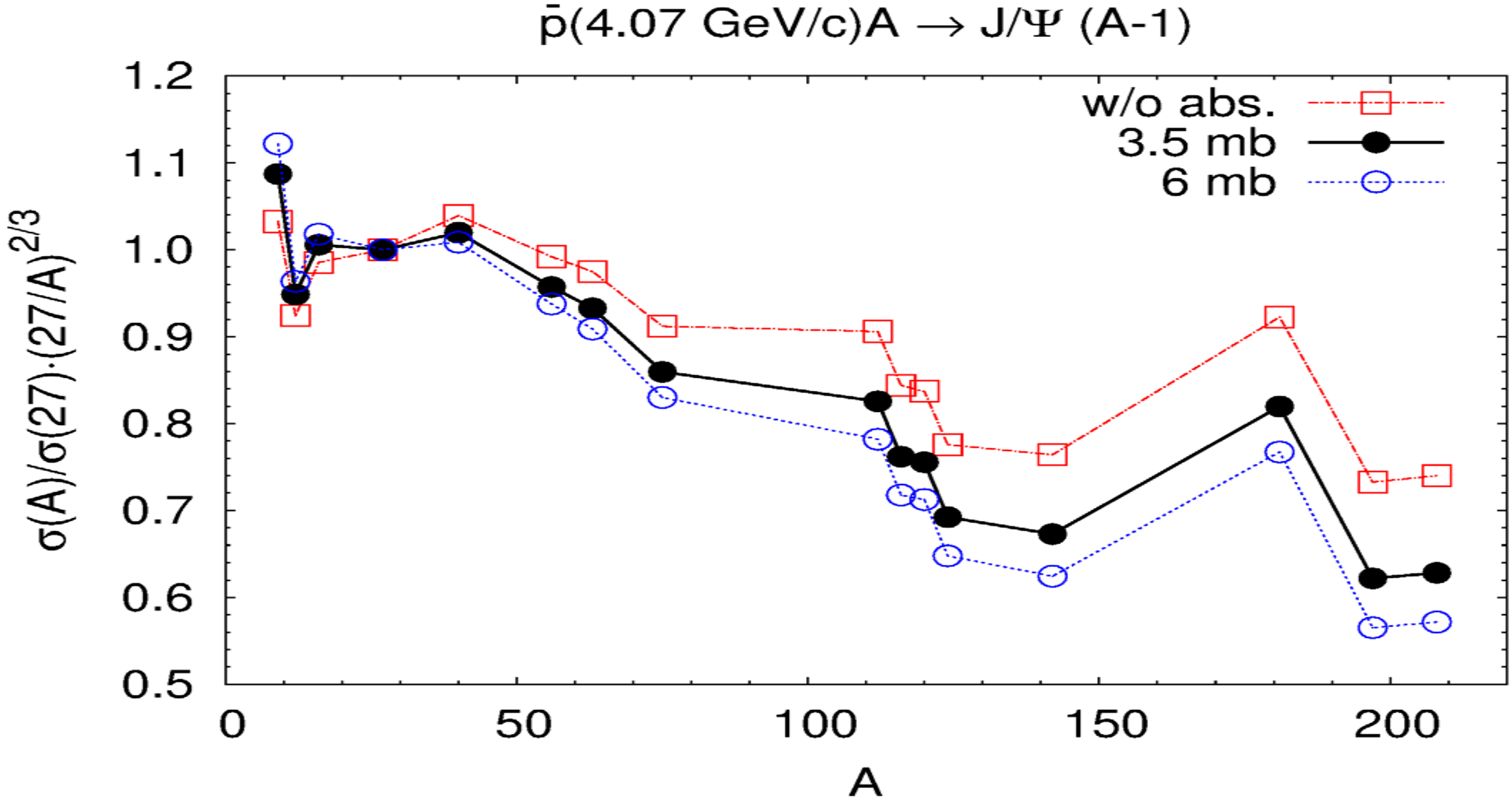




Sensitivity to the J/Ψ N dissociation cross section:



$$\textbf{Transparency ratio} =: \frac{\sigma_{\bar{p}A \to J/\Psi(A-1)}}{\sigma_{\bar{p}^{27}\mathrm{Al}} \to J/\Psi(26)} \left(\frac{27}{A}\right)^{2/3}$$

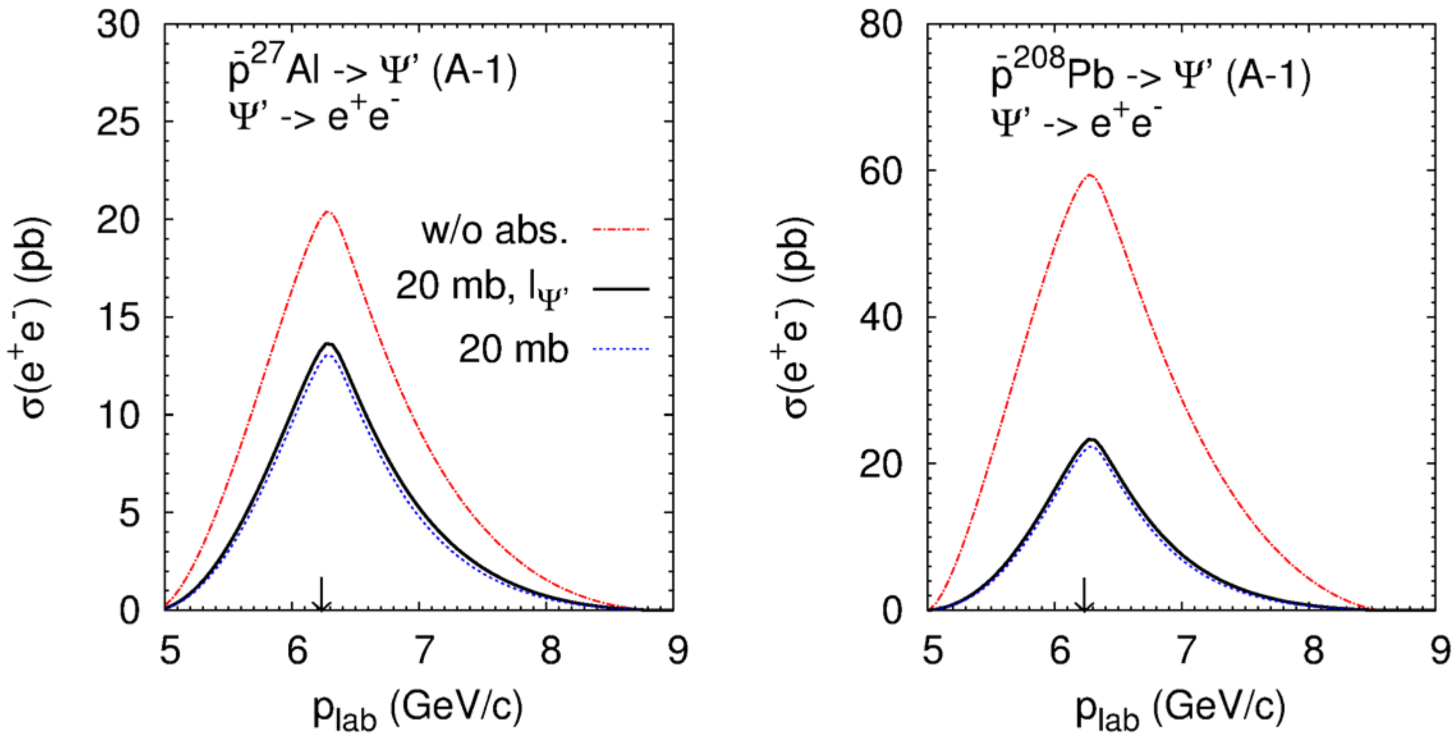


^{9}Be ^{16}O ^{40}Ca ^{56}Fe ^{75}As ^{112,116,120,124}Sn ^{181}Ta ^{197}Au ^{208}Pb

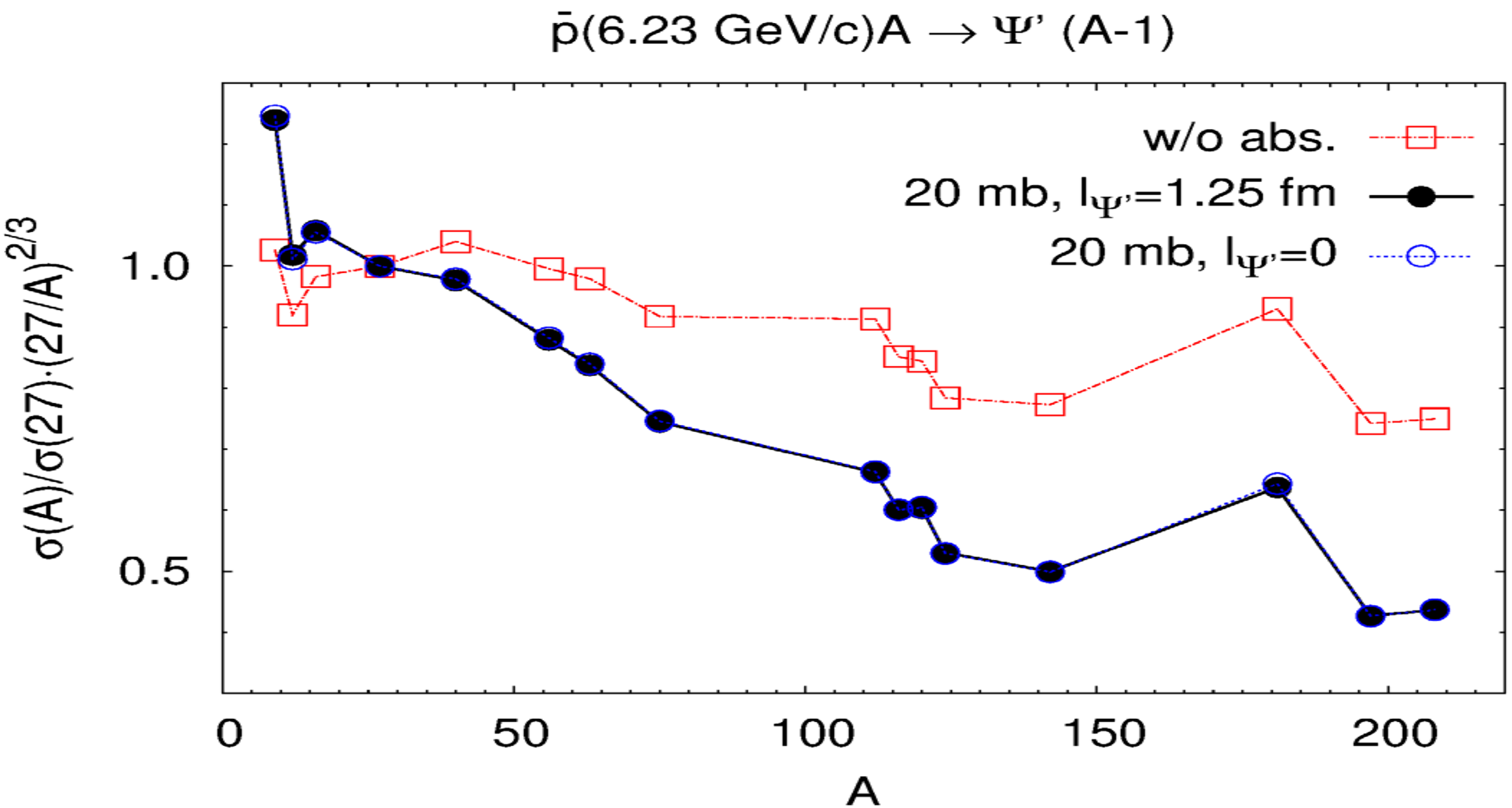
^{12}C ^{27}Al ^{63}Cu ^{142}Ce

For Ψ´ the expected cross section is 20 mb

L. Gerland et al, PRL 81, 762 (1998)



Transparency ratio $=: \frac{\sigma_{\bar{p}A\to\Psi'(A-1)}}{\sigma_{\bar{p}^{27}\mathrm{Al}} \to \Psi'(26)}\left(\frac{27}{A}\right)^{2/3}$



^{9}Be ^{16}O ^{40}Ca ^{56}Fe ^{75}As ^{112,116,120,124}Sn ^{181}Ta ^{197}Au ^{208}Pb

^{12}C ^{27}Al ^{63}Cu ^{142}Ce

X_{c1} and X_{c2} polarization

Wave function of $\chi_{cJ},\ J=0,1,2$
(neglecting spin-orbit interaction):

$$|JJ_z\rangle = \sum_{L_z,S_z} |LL_z;SS_z\rangle\langle LL_z;SS_z|JJ_z\rangle$$

$$L=1, S=1$$

$$|LL_z>=:\psi(\vec{r})$$ **— relative coordinate wave function**

$$\psi(\vec{r}) = \frac{\chi(r)}{r} Y_{LL_z}(\Theta,\phi)$$

$$\left(-\frac{1}{2\mu}\frac{d^2}{dr^2}+\frac{L(L+1)}{2\mu r^2}+U(r)\right)\chi(r) = E\chi(r)$$

$$\mu = m_c/2,\ m_c \simeq 1.8\,\mathrm{GeV}$$

$$U(r) = \boxed{-\frac{\kappa}{r}+\frac{r}{a^2}} - \frac{4e^2/9}{r}$$

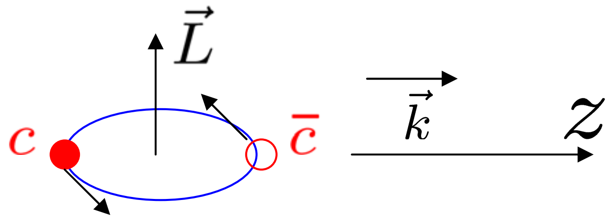
Cornell potential **(E. Eichten et al., PRD 21, 203 (1980))**

Charmonium-nucleon total cross section (QCD factorization theorem):

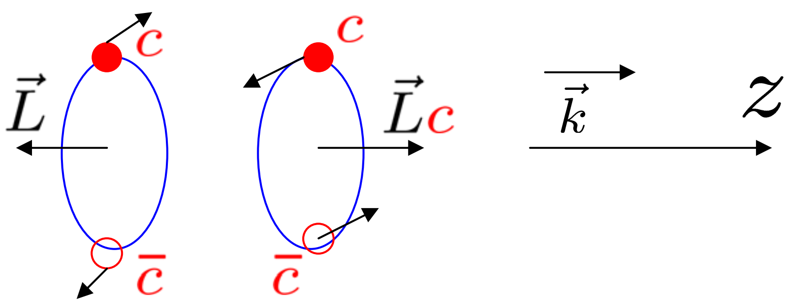
$$\sigma_{XN} = \int \sigma(b)|\psi(\vec{r})|^2 d^3r$$

b — **transverse distance between** c **and** $\bar{c}$ **,**

$\sigma(b)$ — **PQCD cross section**
replaced by the nonperturbative evaluation
L. Gerland et al, PRL 81, 762 (1998)

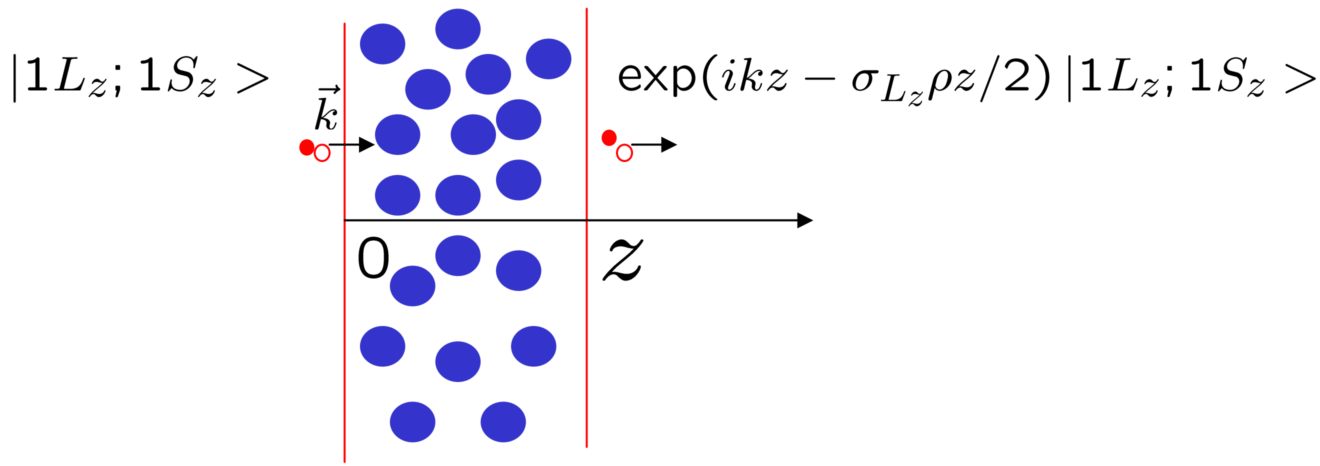


$L_z = 0: \quad \sigma_{\chi_c N} = 6.8$ mb



$L_z = \pm 1: \quad \sigma_{\chi_c N} = 15.9$ mb

Assumption: intrinsic charmonium time scale is longer than the passage time through the nuclear medium



Transition probability:

$$W_{J'J'_z;JJ_z}=|\sum_{L_z,S_z}\langle J'J'_z|1L_z;1S_z\rangle\exp(-\sigma_{L_z}\rho z/2)\langle 1L_z;1S_z|JJ_z\rangle|^2$$

L_z-dependent absorption leads to the production of another states

(similar to the diffractive dissociation mechanism M.L. Good, W.D. Walker, PRD 120, 1857 (1960))

Cross section of χ_{cJ} production with helicity J_z on a nucleus :

$$\sigma_{\bar{p}A\to JJ_z(A-1)} = 2\pi \int\limits_0^\infty db\, b \int\limits_{-\infty}^{\infty} \frac{dz}{v_{\bar{p}}} \mathcal{P}_{\bar{p},\mathrm{surv}}(z,b) \sum_{J'} \Gamma_{\bar{p},J'J_z}(z,b) W_{JJ_z;J'J_z}(z,b)$$

$$\Gamma_{\bar{p},J'J_z}(z,b) = \int \frac{2d^3p}{(2\pi)^3} v_{\bar{p}p}\, \sigma_{\bar{p}p,J'J_z}(\sqrt{s})\, \Theta[p_{F,p}(z,b) - |\mathbf{p}|]$$

$$\sigma_{\bar{p}p,J'J_z}(\sqrt{s}) = \frac{\pi}{q^2} \frac{s\Gamma_{\chi_{cJ'}\to\bar{p}p}\Gamma_{\chi_{cJ'}}}{(s - m^2_{\chi_{cJ'}})^2 + s\Gamma^2_{\chi_{cJ'}}}$$

$$W_{JJ_z;J'J_z}(z,b) = |\sum_{L_z,S_z} \langle JJ_z|1L_z;1S_z\rangle \exp(-\sigma_{L_z} T(z,b)/2) \langle 1L_z;1S_z|J'J_z\rangle|^2$$

$$T(z,b) = \int\limits_z^{+\infty} dz' \rho(z',b)$$

Transition amplitude:

$$\langle JJ_z|\widehat{A}|J'J_z\rangle = \sum_{L_z,S_z} \langle JJ_z|1L_z;1S_z\rangle A_{L_z}\langle 1L_z;1S_z|J'J_z\rangle$$

$$A_{L_z} = \exp(-\sigma_{L_z}T(z,b)/2)$$

J	J_z	J'	$\langle JJ_z\|\widehat{A}\|J'J_z\rangle$
0	0	0	$(2A_1 + A_0)/3$
0	0	1	$-$
0	0	2	$\sqrt{2}(A_1 - A_0)/3$
1	0	1	A_1
1	0	2	$-$
1	1	1	$(A_1 + A_0)/2$
1	1	2	$(A_1 - A_0)/2$
2	0	2	$(A_1 + 2A_0)/3$
2	1	2	$(A_1 + A_0)/2$
2	2	2	A_1

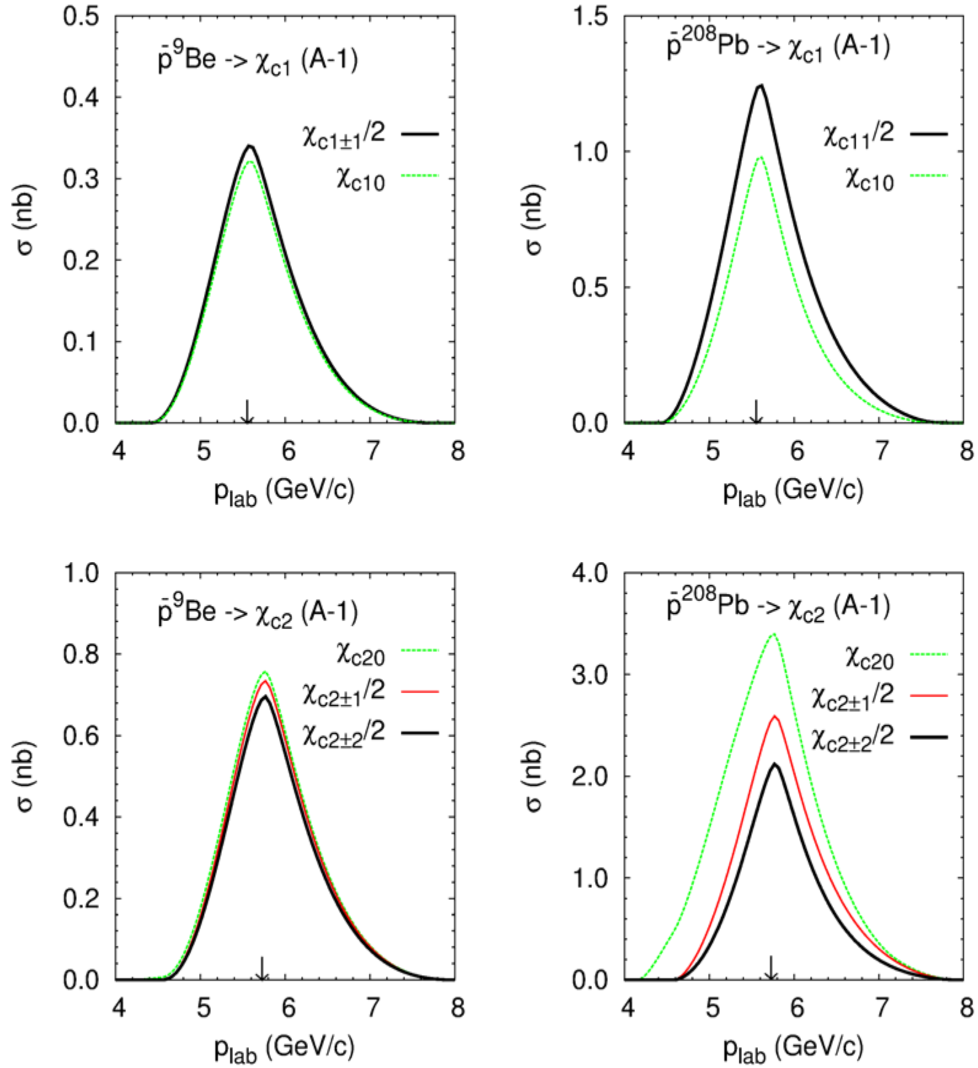
$$A_1 < A_0$$

Polarization-dependent transition probabilities:

$$W_{10;10} < W_{11;11}$$

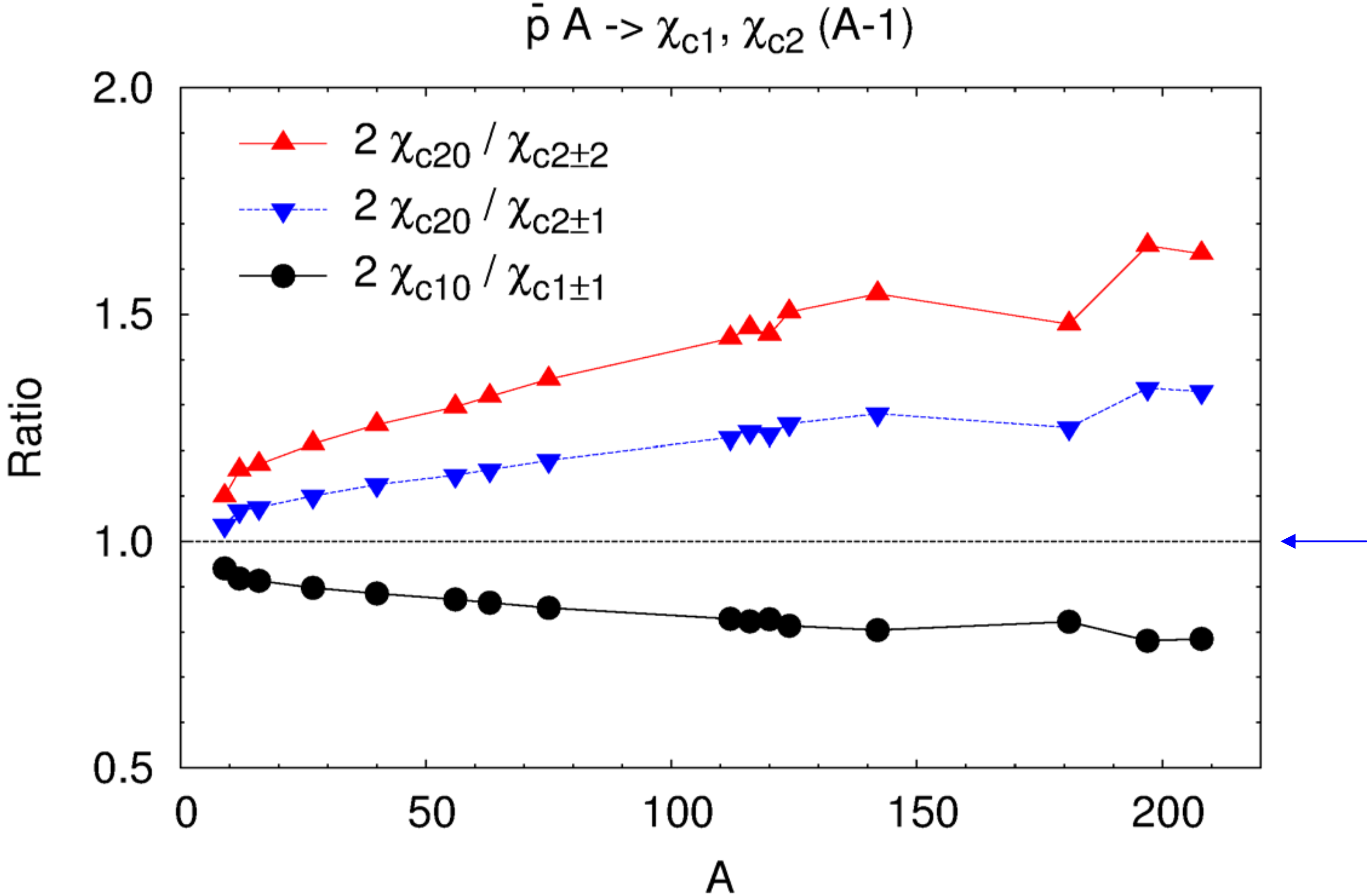
$$W_{20;20} > W_{21;21} > W_{22;22}$$

Due to color filtering χ_{cJJ_z} states with different J_z are absorbed differently



Deviations from pure statistical populations of the different helicity states

Mass dependence of the helicity ratios:



No absorption

Summary

— **Strong sensitivity of J/Ψ(Ψ´) production in antiproton-induced reactions to the *genuine* J/Ψ N (Ψ´N) dissociation cross section**

— **For the quantitative determination of J/Ψ N (Ψ´N) cross sections the density profiles are important**

— **Polarization effects for the χ_{c1} and χ_{c2} production due to color filtering**

Possible observables for the planned PANDA experiment at FAIR

Further steps

— **Influence of the realistic nucleon spectral function**

— **Sensitivity of the charmonium p_t-spectra to the angular-differential cross section J/Ψ N → J/Ψ N (within GiBUU)**

Thank you for your attention !

Backup

Effective charmonium-nucleon cross section:

$$\sigma_{RN}^{\text{eff}}(p_R, z) = \sigma_{RN}(p_R)$$
$$\times \left(\left[\left(\frac{z}{l_R} \right)^{\tau} + \frac{< n^2 k_t^2 >}{m_R^2} \left(1 - \left(\frac{z}{l_R} \right)^{\tau} \right) \right] \Theta(l_R - z) + \Theta(z - l_R) \right) \ ,$$
$$\tau = 1 \ .$$

$< k_t^2 >^{1/2} \simeq 0.35 \ \text{GeV/c}$ **— average quark transverse momentum in a hadron**

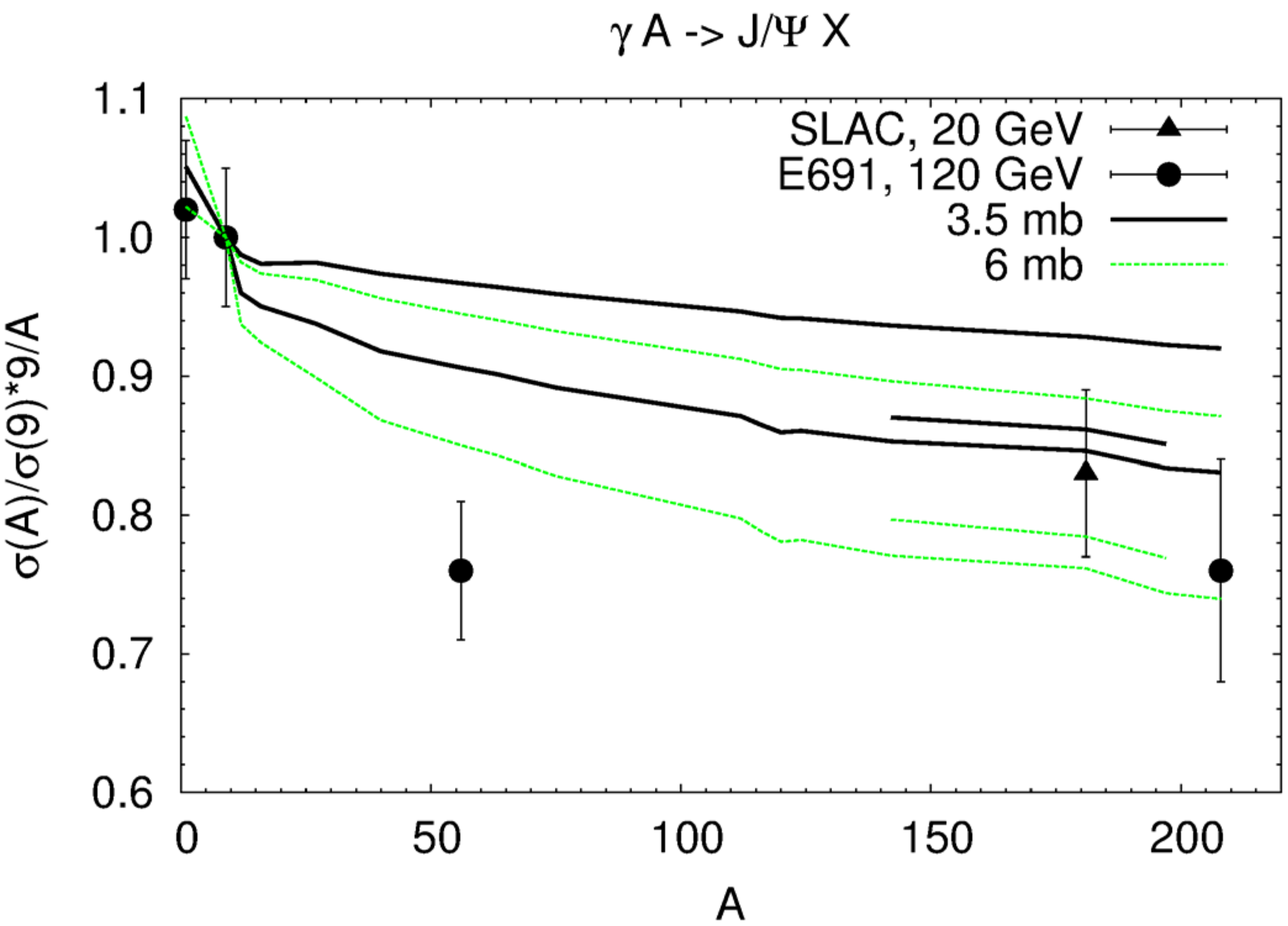
$n = 3$ **— number of intermediate gluons**

$$l_{J/\Psi} \simeq \frac{2p_{J/\Psi}}{m_{\Psi'}^2 - m_{J/\Psi}^2} \simeq 3\text{fm}\frac{p_{J/\Psi}}{30\text{GeV}} \ ,$$
$$l_{\Psi'} \simeq 6\text{fm}\frac{p_{\Psi'}}{30\text{GeV}} \ ,$$
$$l_{\chi_c} \simeq 3\text{fm}\frac{p_{\chi_c}}{30\text{GeV}} \ .$$

— formation lengths

L. Gerland et al, PRL 81, 762 (1998)

Photon-induced reactions: influence of formation length



Cross sections for different helicity states (with separate contributions of the diagonal and nondiagonal transitions):