Coherent J/ψ production on light nuclei

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Based on V. Guzey, M. Rinaldi, S. Scopetta, M. Strikman, M. Viviani, PRL 129 (2022) 242503

Outline:

- Nuclear shadowing
- Coherent J/ψ production in eA scattering on He-4 and He-3
- Summary and Outlook

1st International Workshop on a 2nd Detector for the Electron-Ion Collider, Temple University, USA, May 17-19, 2023

Nuclear shadowing

• Nuclear shadowing is general phenomenon of high-energy scattering → nuclear cross section < sum of nucleon cross sections.

• Present in soft hadron-nucleus scattering, Bauer, Spital, Yennie, Pipkin, Rev. Mod. Phys. 50 (1978) 261 and hard processes with nuclei, H. Paukkunen, talk this morning.

• In the target rest frame, understood as multiple interactions of projectile with target nucleons → destructive interference of amplitudes with N=1,2,..A nucleons → Gribov-Glauber theory of shadowing, Glauber, PRD 50 (1955) 242; Gribov, Sov. Phys. JETP 29 (1969) 483; Frankfurt, Strikman, Phys. Rept. 160 (1988) 235; Piller, Weise, Phys. Rept. 330 (2000) 1; Armesto, J. Phys. G 32 (2006) R367.

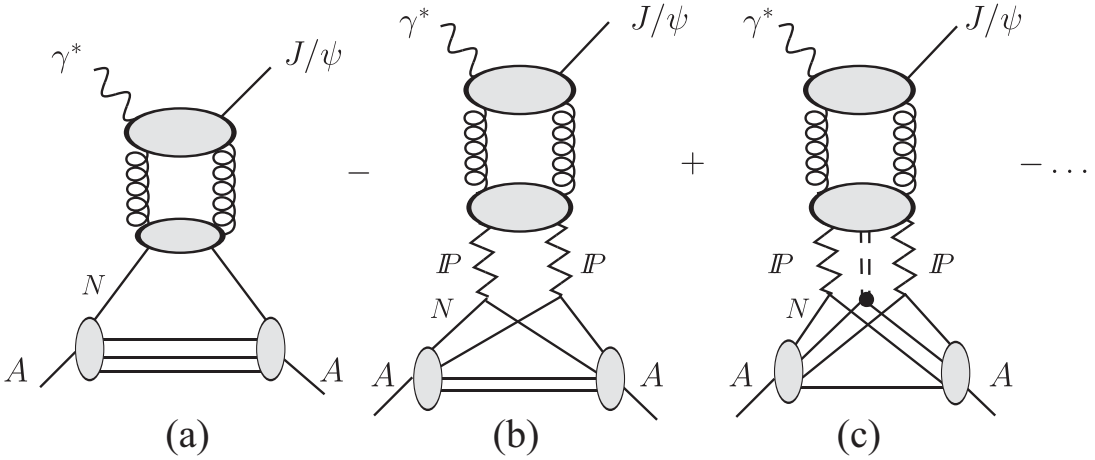
• For hard processes, QCD factorization theorem for N=2 term to relate shadowing to diffraction on nucleon at the level of parton distributions, Frankfurt, Strikman, EPJA 5 (1999) 293

• Interactions with 3≤N≤A modeled using soft physics → predictions for nuclear parton distributions (nPDFs) at small x (leading twist model of nuclear shadowing), Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255.

• Alternative, complementary point of view: shadowing is mixture of leading and higher twist effects in dipole picture with saturation, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303, or a purely HT effect, Qiu, Vitev, PRL 93 (2004) 262301.

LT shadowing in coherent J/ψ production

- Amplitude of coherent J/ψ production on nucleus as a series of interactions with N=1, 2, 3, … nucleons:



- The lower part is the gluon density in the leading twist model of shadowing:

$$xf_{j/A}(x,Q_0^2) = Axf_{j/N}(x,Q_0^2) - 8\pi A(A-1)\,\Re e\frac{(1-i\eta)^2}{1+\eta^2}B_{\rm diff}\int_x^{0.1} dx_{I\!P}\,\beta f_j^{D(3)}(\beta,Q_0^2,x_{I\!P}) \times \int d^2b\int_{-\infty}^{\infty}dz_1\int_{z_1}^{\infty}dz_2\,\rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2)e^{i(z_1-z_2)x_{I\!P}m_N}e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm soft}^{j}(x,Q_0^2)\int_{z_1}^{z_2}dz'\rho_A(\vec{b},z')}$$

Proton diffractive PDFs

Impulse approximation term (a)

Woods-Saxon nuclear density

Model-dependent soft cross section, $\sigma_{\rm soft}$~25-50 mb

Coherent J/ψ photoproduction in UPCs@LHC

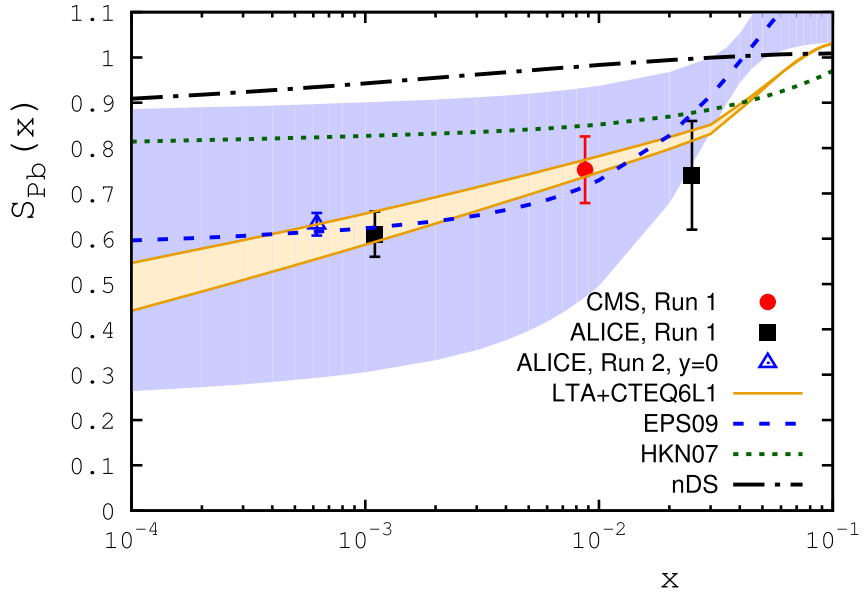
• Predictions of LT model nicely agree with LHC data on coherent J/ψ photoproduction on heavy nuclei in Pb-Pb ultraperipheral collisions (UPCs).

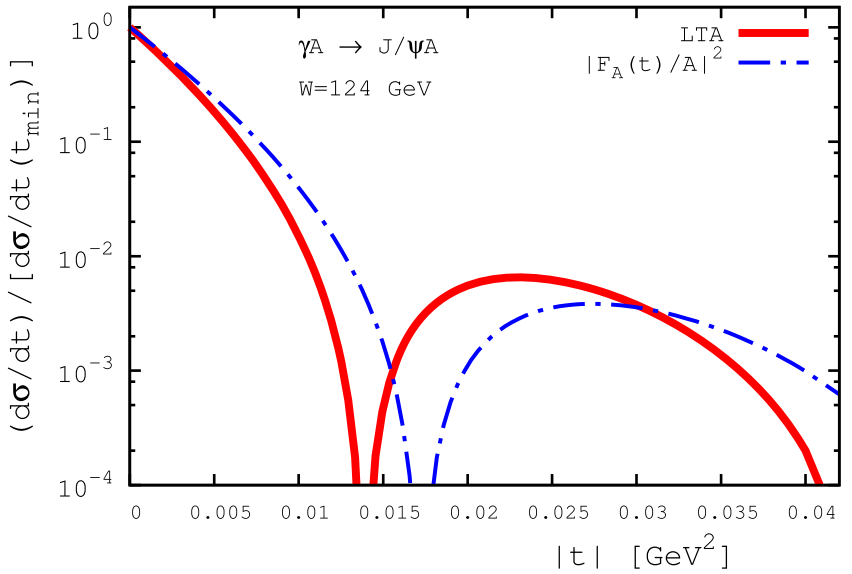
• Measured cross section converted to nuclear suppression factor

$$S_{\rm Pb}(x) = \sqrt{\frac{\sigma_{\gamma A\to J/\psi A}(W_{\gamma p})}{\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W_{\gamma p})}} = \kappa_{A/\rm N}\frac{x g_A(x,\mu^2)}{A x g_{\rm N}(x,\mu^2)}$$

• → direct evidence of large gluon shadowing, Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290, Guzey, Zhalov, JHEP 1310 (2013) 207

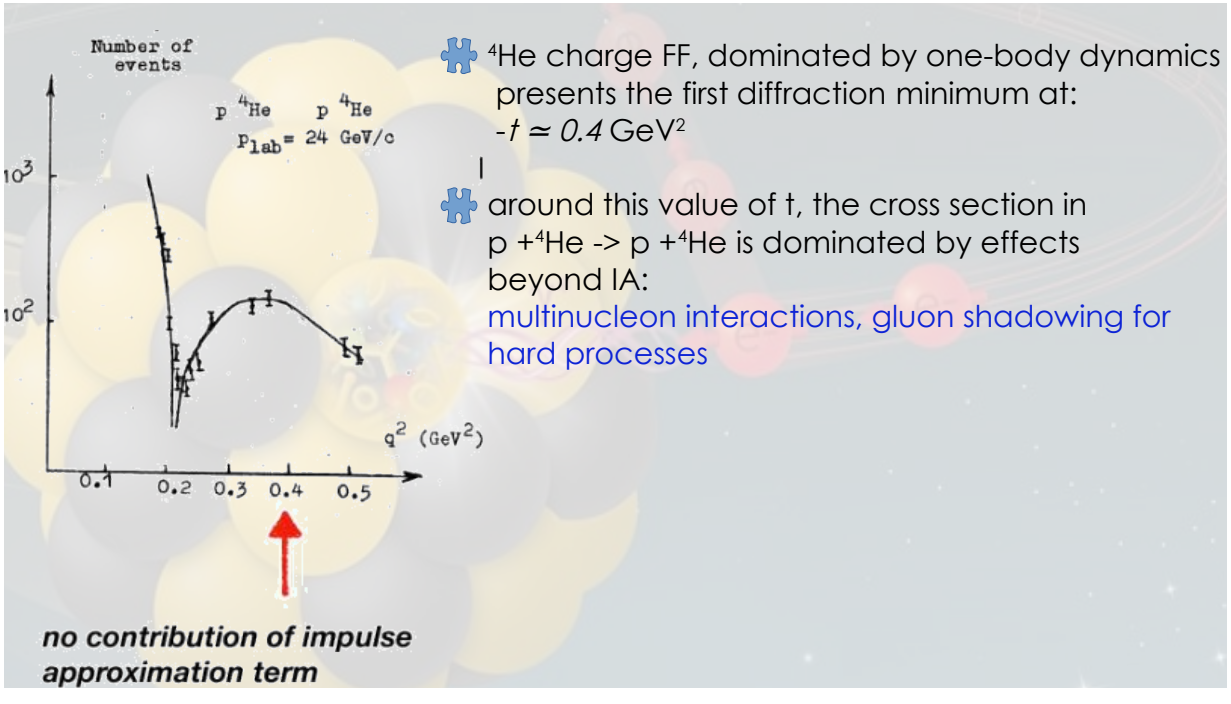
• LT nuclear shadowing depends on impact parameter b → broadening of gluon distribution in b-space → shifts t-dependence of coherent cross section, Guzey, Strikman, Zhalov, PRC 95 (2017) 2, 025204 → confirmed by ALICE, Acharya et al., PLB 817 (2021) 1, 136280





Coherent J/ψ production on light nuclei

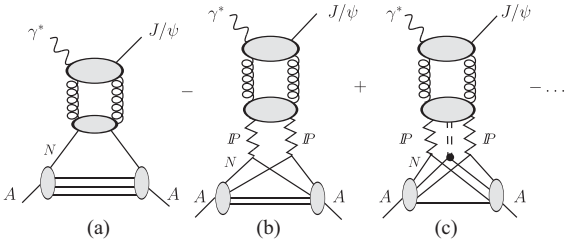
- Systematics of A dependence of nuclear shadowing and nPDFs
- Theoretically clean since modeling of interactions with N≥3 nucleons is numerically small
- Possibility to single out N =2,3 terms by studying t-dependence.
In particular, nuclear shadowing shifts t-dependence of coherent cross section, Levin, Strikman, Sov. J. Nucl. Phys. 23 (1976) 216.
- State-of-the-art calculations of nuclear structure.
- No excited nuclear states → easy to select coherent events.



M. Rinaldi, EICUG Theory WG Meeting, Feb 27, 2023

Coherent J/ψ production on light nuclei

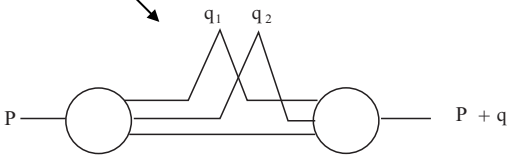
- Amplitude as a series of interactions with k=1, 2, 3,… nucleons:



$$\frac{d\sigma_{\gamma^* A\to J/\psi A}}{dt}(t) = \frac{d\sigma_{\gamma^* N\to J/\psi N}}{dt}(t=0)\left| A\Phi_1(t)e^{(B_0(x)/2)t} + \sum_{k=2}^{A} F_k(t)\right|^2$$

1-body form factor

slope of J/ψ cross section, B_0=4.5 GeV^{-2}



2-body form factor

- Factors for k=2, 3,… nucleons:

$$F_k(t) = \left(-\frac{1}{8\pi^2}\right)^{k-1}\binom{A}{k}\frac{\langle\sigma^k\rangle}{\langle\sigma\rangle}\frac{(1-i\eta)^k}{1-i\eta_0}\int\prod_{l=1}^{k} d^2\vec{q}_l f(q_l)\,\Phi_k(\vec{q},\vec{q}_l)\,\delta^2\left(\sum_{l=1}^{k}\vec{q}_l - \vec{q}\right)$$

Input of LT model of shadowing:

$$\frac{\langle\sigma^2\rangle}{\langle\sigma\rangle} = \sigma_2(x), \qquad \frac{\langle\sigma^3\rangle}{\langle\sigma\rangle} = \sigma_3(x)\sigma_2(x)$$

From diffraction@HERA

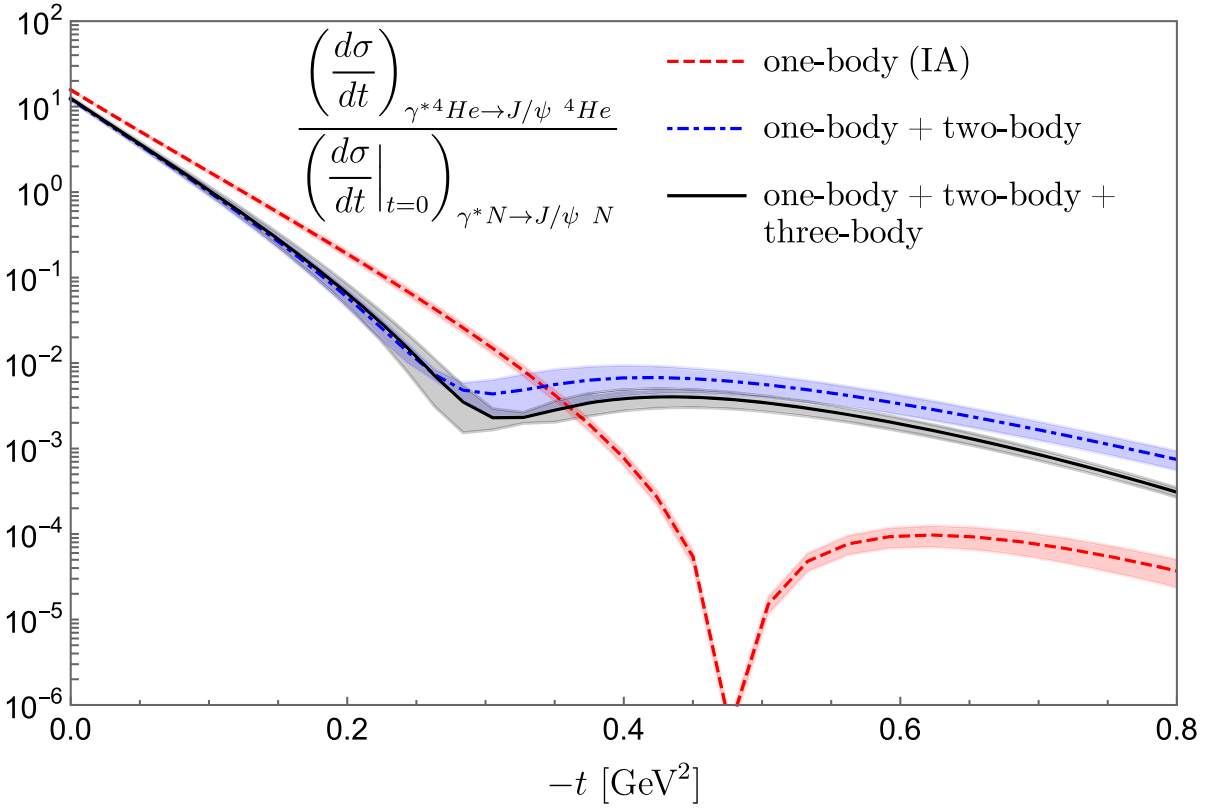
From soft models

k-body form factor as overlap of nuclear wave functions

t-dependence of soft amplitude with slope B=6 GeV^{-2}

Coherent J/ψ production in eA on He-4

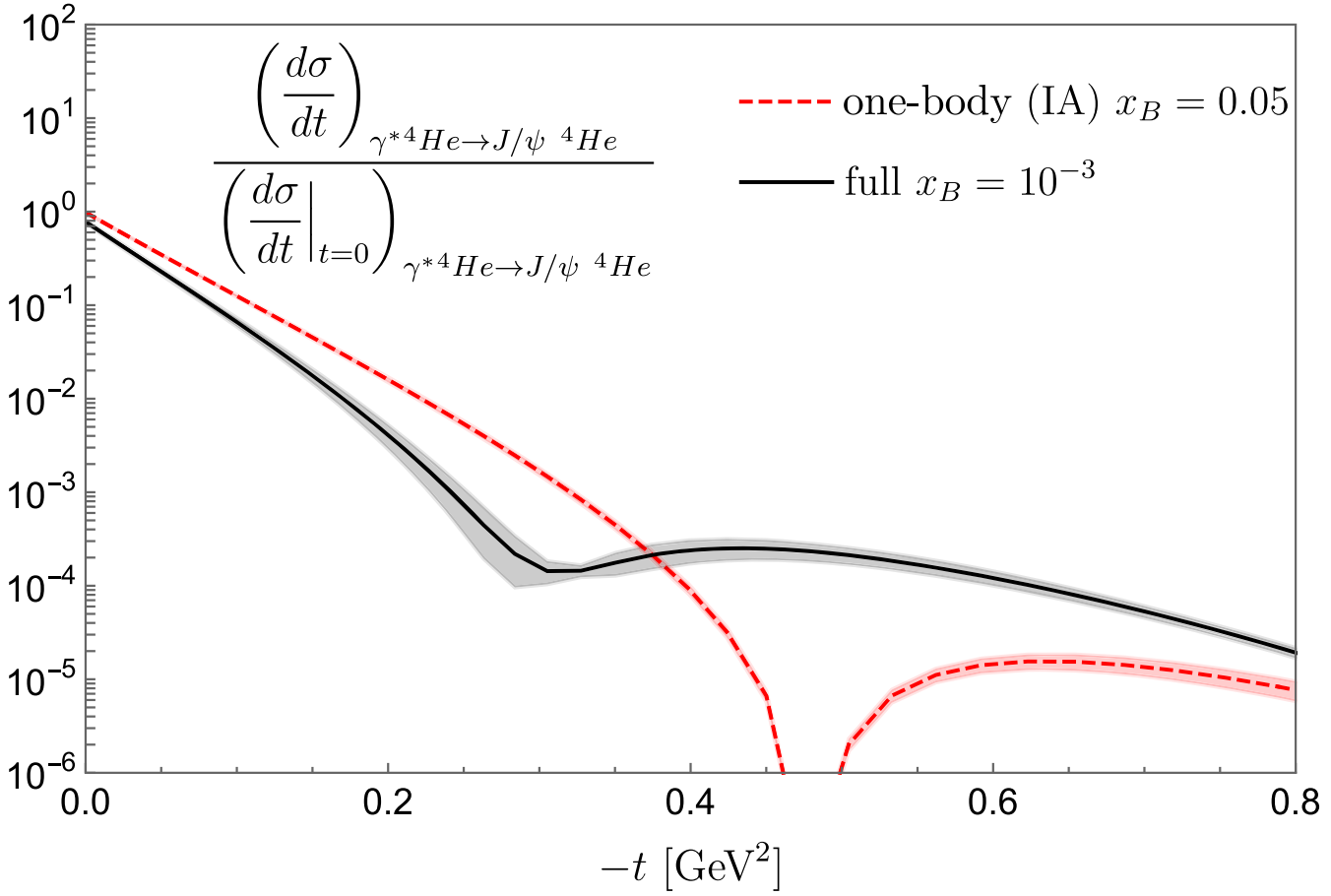
- Normalized differential γ^* + ^{4}He $\rightarrow$ J/ψ + ^{4}He cross section at $x_B=10^{-3}$ as function of t with σ_2=25±15% mb, σ_3=30-50 mb, and $\Phi_{2,3}$ using realistic nuclear wave function with N^{4}LO chiral potential, Marcucci, Dohet-Eraly, Girlanda, Gnech, Kievsky, Viviani, Front. Phys. 8 (2020) 69; Entem, Machleidt, Nosyk, PRC 96 (2017) 2, 024004



- 2-body contribution (shadowing) shifts minimum |t|=0.45 GeV^2 $\rightarrow$ |t|=0.27 GeV^2
- The minimum is filled due to real part of scattering amplitudes $\eta_0 \neq \eta \neq 0$.

Coherent J/ψ production in eA on He-4

- Comparison of calculations at $x_B=10^{-3}$ and $x_B=0.05$:

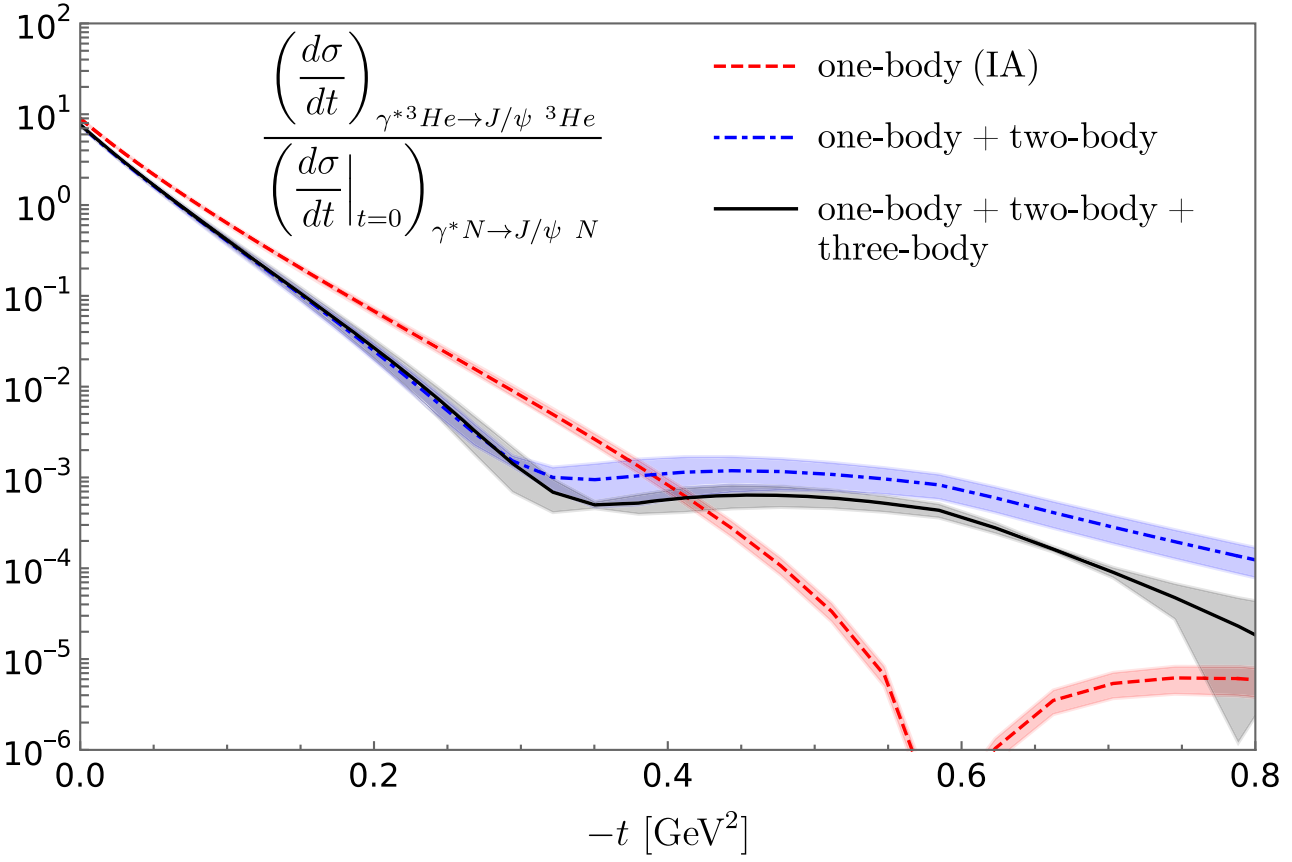


- At $x_B=0.05$, nuclear shadowing negligibly small → 1-body (IA) gives full result.

Coherent J/ψ production in eA on He-3

- Repeated calculations for He-3 using realistic nuclear wf with AV18 potential, Marcucci, Dohet-Eraly, Girlanda, Gnech, Kievsky, Viviani, Front. Phys. 8 (2020) 69; Wiringa, Stoks, Schiavilla, PRC 51 (1995) 38 and 3-body forces, Pudliner, Pandharipande, Carlson, Wiringa, PRL 74 (1995) 4396

- Normalized differential $\gamma^* + {}^3He \rightarrow J/\psi + {}^3He$ cross section at $x_B=10^{-3}$ vs. t



- Pattern similar to He-4.

Summary and Outlook:

- Measurements of coherent J/ψ production on light nuclei at finite t complement UPCs of heavy ions at the LHC.

- Light nuclei enable one to probe nuclear shadowing one nucleon at a time with good theoretical control of nuclear structure.

- Dominant effect by model-independent 2-nucleon contribution → test of nuclear shadowing models.

- LT model of nuclear shadowing predicts shift of the t-dependence of coherent J/ψ production to smaller |t| → broadening of the gluon distribution in impact parameter space.

- Formalism can be readily applied to estimate coherent DVCS on light nuclei.