Probing gluonic structure in diffractive J/ψ production

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Outline

- Exclusive VM production in DIS- lessons from HERA

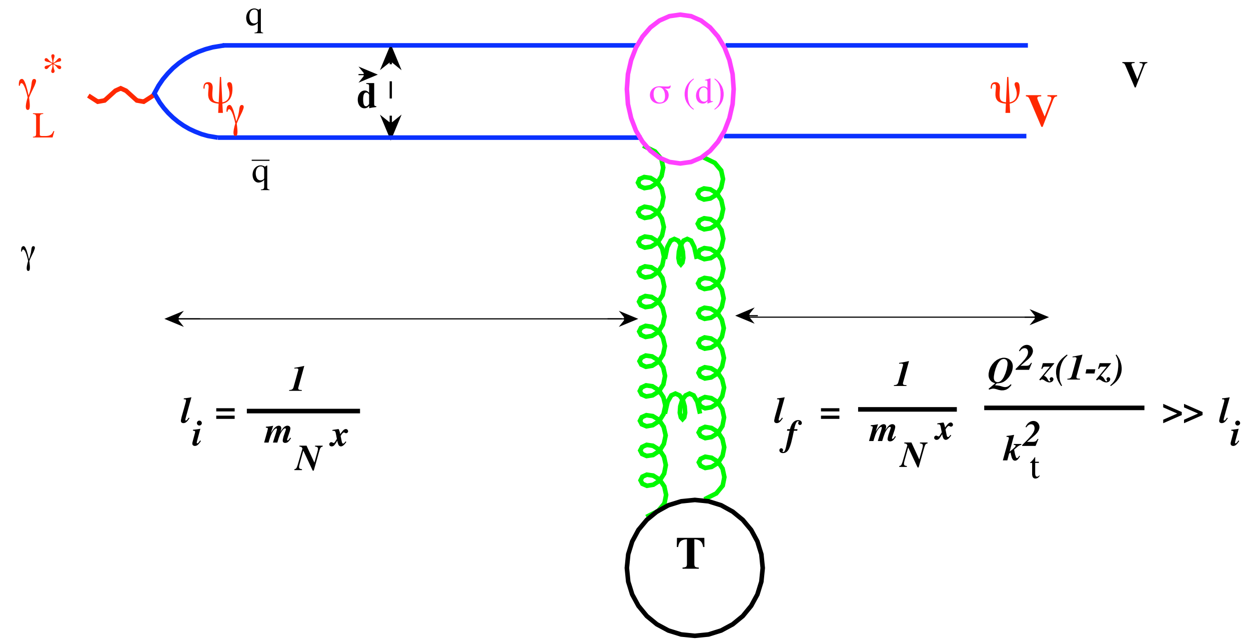
- Theory of the Leading twist shadowing

- Coherent J/ψ production off heavy and light nuclei

- Remarks on incoherent diffraction

Vector meson diffractive production: Theory and HERA data

Space-time picture of Vector meson production at small x in the target rest frame



$\Rightarrow$ *Similar to the* $\pi + T \to 2jets + T$ *process,* $A(\gamma^*_L + p \to V + p)$ *at* $p_t = 0$ *is a convolution of the light-cone wave function of the photon* $\Psi_{\gamma^* \to |q\bar{q}\rangle}$*, the amplitude of elastic* $q\bar{q}$ *- target scattering,* $A(q\bar{q}T)$*, and the wave function of vector meson,* ψ_V*:* $A = \int d^2 d \psi^L_{\gamma *}(z,d)\sigma(d,s)\psi^{q\bar{q}}_V(z,d)$.

The leading twist parameter free answer is BFGMS94

$$\left.\frac{d\sigma^L_{\gamma^* N\to VN}}{dt}\right|_{t=0} =$$

$$\frac{12\pi^3\Gamma_{V\to e^+e^-} M_V \alpha_s^2(Q)\eta_V^2 \left|\left(1 + i\frac{\pi}{2}\frac{d}{d\ln x}\right) xG_T(x,Q^2)\right|^2}{\alpha_{EM} Q^6 N_c^2}$$

. *Here,* $\Gamma_{V\to e^+e^-}$ *is the decay width of* $V \to e^+e^-$;

$$\eta_V \equiv \frac{1}{2}\frac{\int \frac{dz\, d^2k_t}{z(1-z)}\,\Phi_V(z,k_t)}{\int dz\, d^2k_t\,\Phi_V(z,k_t)} \to 3 \;|_{Q^2\to\infty}$$

Note: In the leading twist d=0 in $\psi_V(z,d)$. *Finite b effects in the meson wave function is one of the major sources of the higher twist effects.*

energy denominator $\frac{1}{Q^2 + \frac{m^2+k_t^2}{z(1-z)}}$ **operator of interaction** → $\left(\frac{1}{Q^2 + \frac{m^2+k_t^2}{z(1-z)}}\right)^4$

m- quark mass

→ $$\frac{Q^2}{(\mu^2+Q^2)^4} \to \frac{1}{Q^6}$$

$$\mu^2 \geq m_V^2$$

A QCD dipole model of J/Ψ production - aims to account more accurately for geometry

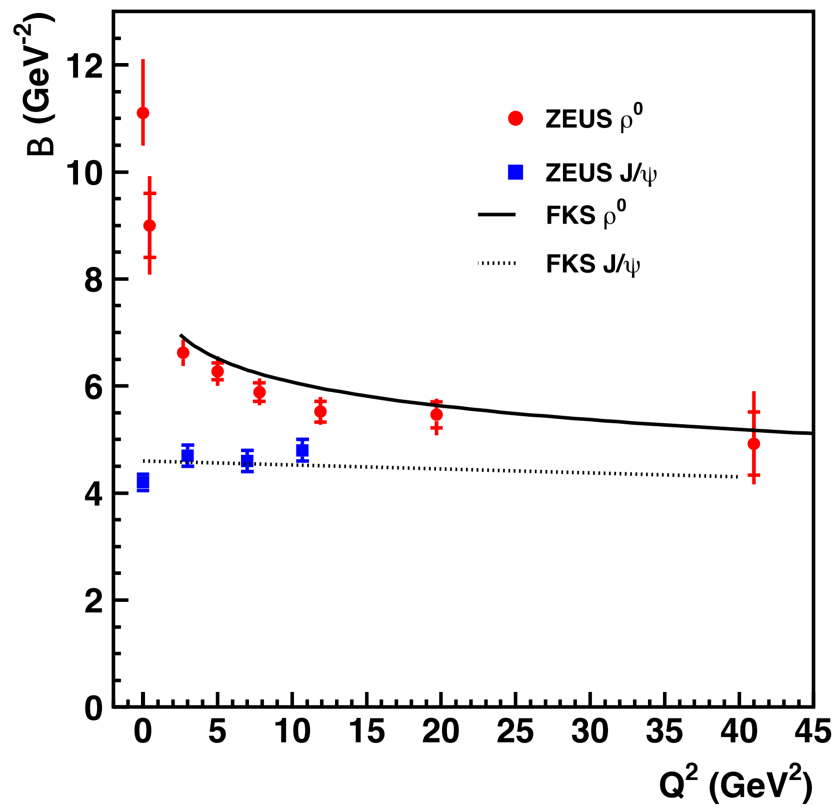
$$A(\gamma + p \to J/\psi + p) = \int d^2 d\psi_{\gamma \to c\bar{c}}(z,d)\sigma_{tot}(c\bar{c},p)\psi_{J/\psi}(z,d)$$

Slow onset of the LT for cross section both for light and heavy mesons

Slow squeezing of dipole size for light mesons, but early dominance of small dipoles for J/ψ

- Universal t-slope: process is dominated by the scattering of quark-antiquark pair in a small size configuration - t-dependence is predominantly due to the transverse spread of the gluons in the nucleon - two gluon nucleon form factor/ diagonal gluon GPD $F_g(x,t).\ d\sigma/dt \propto F_g^2(x,t).$ Onset of universal regime FKS[Frankfurt,Koepf, MS,97] early for J/ψ late for ρ

$$r_T \propto \frac{1}{Q}\left(\frac{1}{m_c}\right) \ll r_N$$



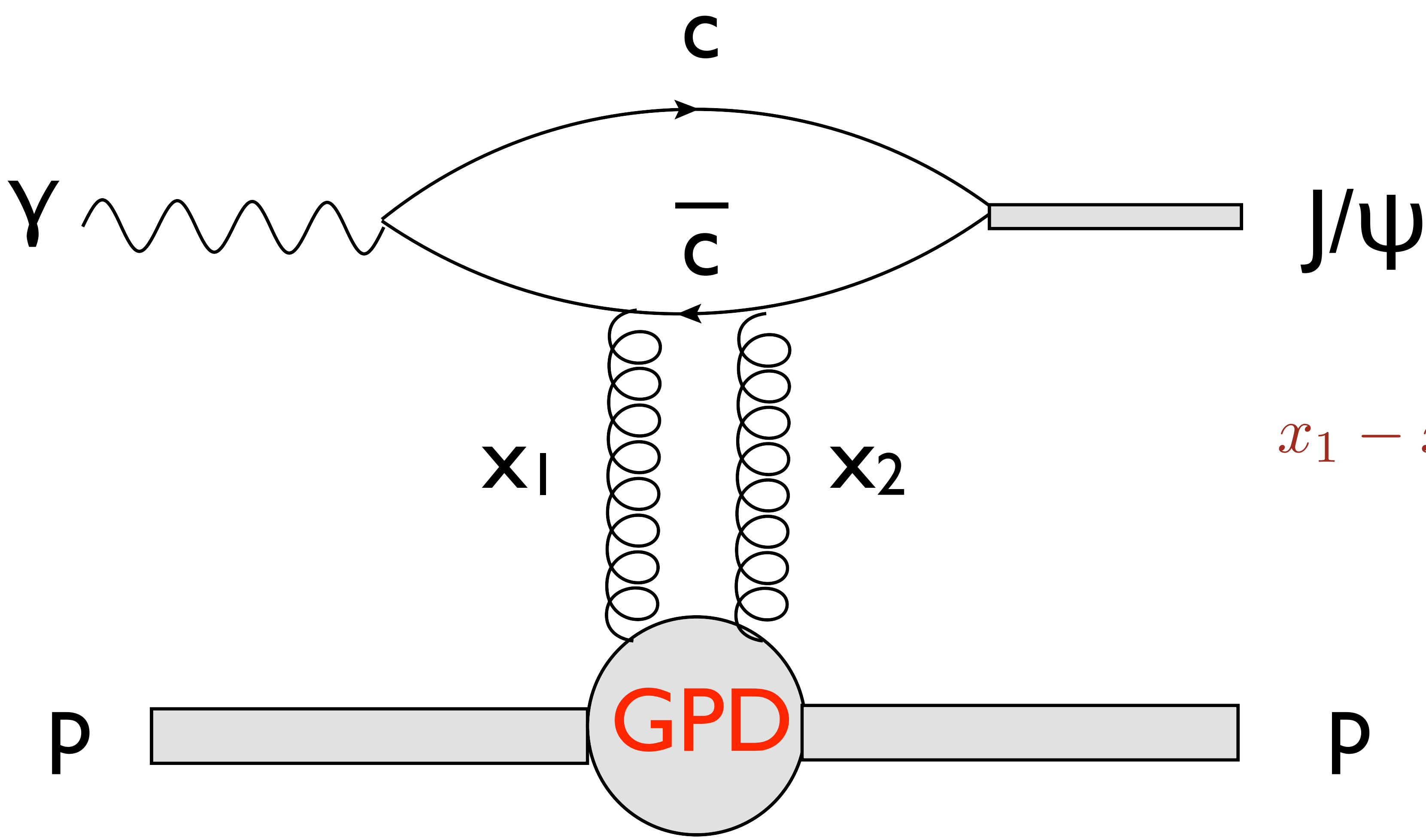
Convergence of the t-slopes, B - $\frac{d\sigma}{dt} = A\exp(Bt)$ of ρ-meson electroproduction to the slope of J/ψ photo(electro)production.

⇒ Transverse distribution of gluons GPD) can be extracted from $\gamma + p \to J/\psi + N$

Correction for finite J/ψ size is ~ 10%.

Reminder: transverse spread of gluons enters into description of jet production in pp collisions at the LHC energies

Caviate: experimentally one can measure only nondiagonal GPD



$$x_1 - x_2 = x \approx \frac{Q^2 + m^2_{J/\psi}}{W^2}$$

Analysis of the overlapping integral including Fermi motion of quarks in J /ψ (Koepf et al)

$$x_1/x_2 \sim 2 \div 3$$

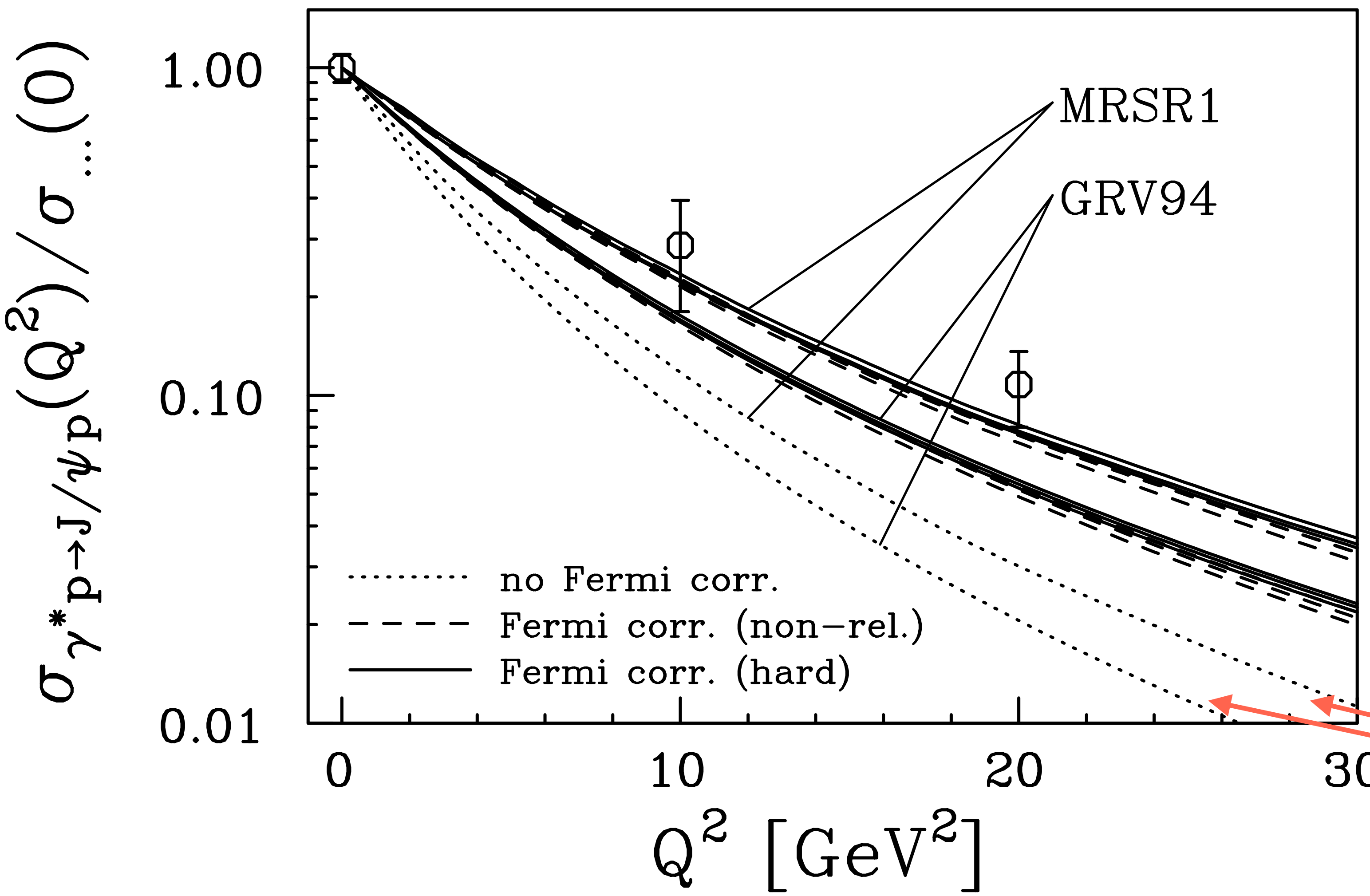
$$x_{eff} = (x_1 + x_2)/2 \sim x$$

In many models Fermi motion is neglected and x_2 is assumed to be 0.

Open questions in exclusive J/psi production

a) How safe it is to neglect Fermi motion of quarks

- Confirmation of the presence of the Fermi suppression factor $T(Q^2)$ in Q^2 dependence of J/ψ production:



KFS97 = large suppression for

Ryskin model

b) Relation between NR and LC wave functions LC wave function of quarkonium

Normalization of light cone wave function through f_V does not contain, αS Brodsky & Lepage), while in nonrelativistic model there is a Barbiery factor

$$1 - 16\alpha_s/3\pi \sim 0.5$$

suggests presence of large $c\bar{c}g$ component in charmonia

c) what is the value of m_c and how it evolves with resolution?

Charmonium models: $m_c > m_{J/\psi}/2$; pQCD < $m_{J/\psi}/2$

→ **These processes cannot be used so far for extraction of the absolute value of gluon density. However since J/ψ is a compact probe, ratios for different targets are mostly unaffected.**

Hard diffraction - J/ψ meson production

- **exclusive production: $\gamma + p\ (A) \rightarrow J/\psi + p\ (A)$**

  Issues: gluon pdfs and gpd's, gluon shadowing)

  most popular now (will focus on this process)

- **quasielastic $\gamma + p\ (A) \rightarrow J/\psi + Y$ at $t=0$**

Issues: color fluctuations in nucleons and nuclei; gluon shadowing

- **$\gamma + p\ (A) \rightarrow J/\psi$ (large t) + rapidity gap + Y**

  Issues: **BFKL at $-t > 1\ GeV^2$**

- **$\gamma + p\ (A) \rightarrow J/\psi(x_F < 0.8) + X$**

  for p —- neutrons in proton fragmentation region, ZDC signal forA decay

exclusive production: $\gamma\ (\gamma^*) + A \rightarrow J/\psi + A$

In the leading twist (LT) approximation for t=0

$$\left.\frac{\sigma\,(\gamma + A \rightarrow J/\psi + A)}{\sigma\,(\gamma + p \rightarrow J/\psi + p)}\right|_{t=0} = [g_A(x,\mu^2)/g_p(x,\mu^2)]^2$$

EIC: detailed studies using a range of nuclei, $x \geq 0.5\ 10^{-3}$

LHC: ultraperipheral heavy ion collisions using Pb nuclei, So far the best measurements are for $x > 0.5\ 10^{-3}$.
In the future $x \sim 10^{-5}$ can be probed.

Run 3: y=0 -> x= $0.5\ 10^{-3}$

Basic guiding features of QCD relevant for diffraction in QCD

a) cross section of a small dipole off a proton/ nucleus interaction is small, proportional to area of dipole occupied by color, and to gluon density of target and hence grows with decrease of x.

$$\sigma(q\bar{q}T) = \frac{\pi^2}{3} r_{tr}^2 x g_T(x, Q^2 = \lambda / r_t^2) \alpha_s(Q^2)$$

—> factorization theorem for exclusive meson production (Collins, Frankfurt and MS 1997)

b) Diffraction in DIS is the leading twist effect - (formal proof Collins 1998)

➡ rescatterings of a small dipole off several nucleons are not suppressed by power of r^2_t

➡ qualitative difference from eikonal: n-th rescattering is suppressed by Q^{2n}

theory of leading twist parton shadowing (Frankfurt, Guzey, MS - 1989 - 1998- 2012)

Note that discussion is simple in the nucleus rest frame but possible also in the fast/ nucleus reference frame

Fundamental feature of QCD: ratio $\frac{\sigma_{inel\,diff}}{\sigma_{el}}$

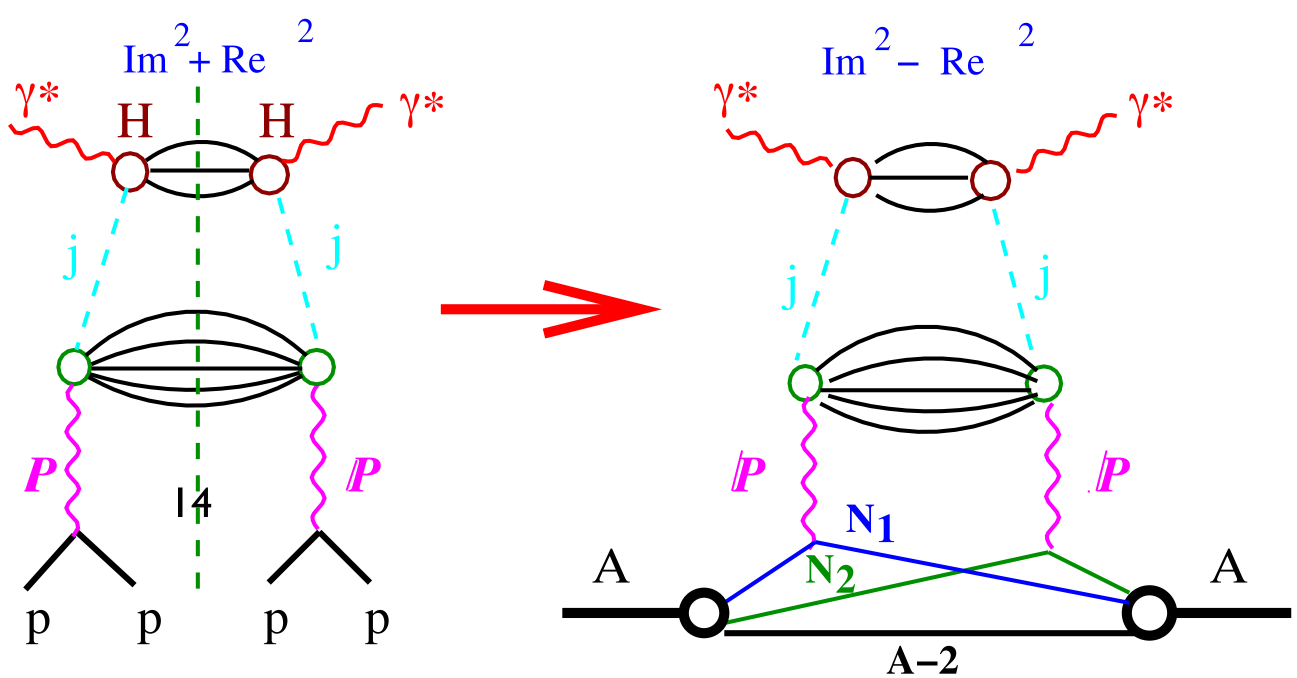
is small and decreasing with energy for soft interactions (pp)

large (> 1) ($\propto Q^2/Q_0^2$) and increasing with energy for small dipoles interactions (DIS)

Theoretical expectations for shadowing in the LT limit

Combining Gribov theory of shadowing and pQCD factorization theorem for diffraction in DIS allows to calculate LT shadowing for all parton densities (FS98)
(instead of calculating F_{2A} only)

Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the nucleon diffractive parton densities $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$:



Hard diffraction off parton "j"

Leading twist contribution to the nuclear shadowing for structure function $f_j(x,Q^2)$

Coherent J/ψ production - update (Guzey, Kryshen, Zhalov, MS 2020)

Theory (Frankfurt, Guzey, MS): Leading twist theory of nuclear shadowing expressing shadowing through LT diffractive PDFs. Alternative - fitting small x data - very limited sample

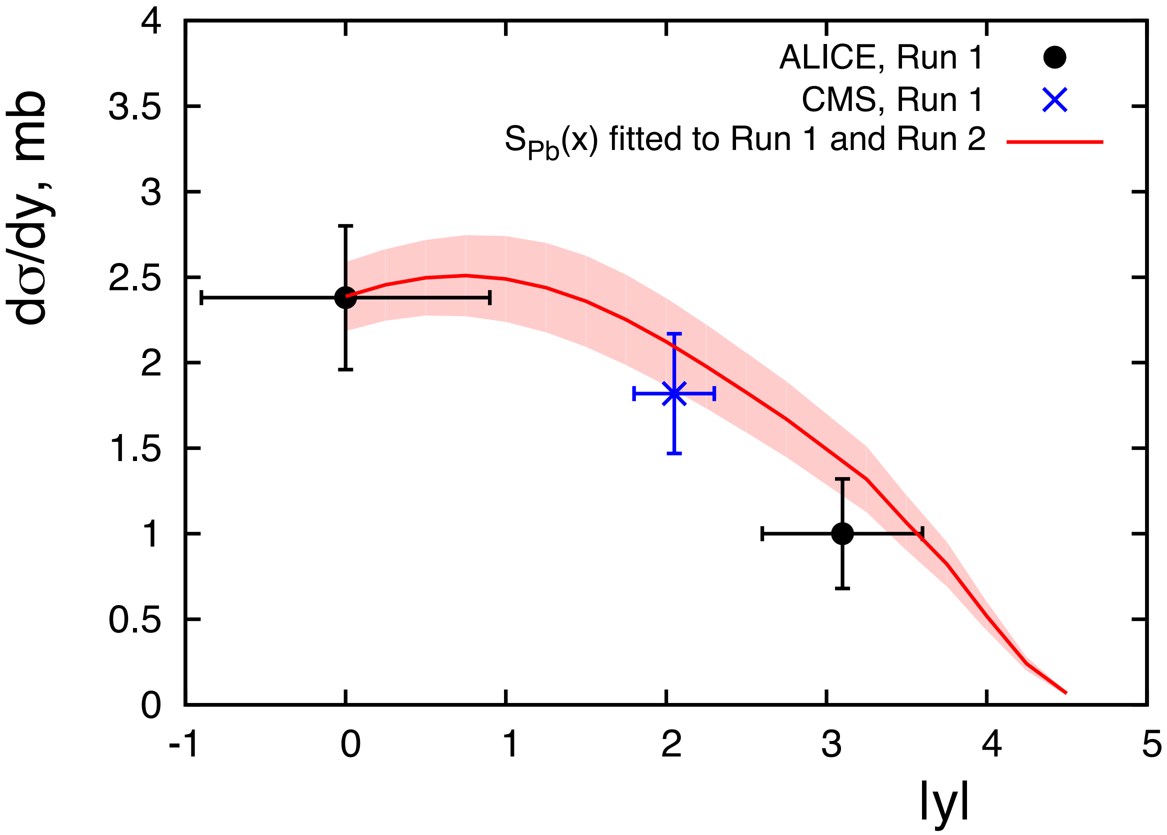
Predicted correctly shadowing for J/ψ in UPC. Use new LHC data to go below
y=0, $x=m_{J/\psi}/2E_N$

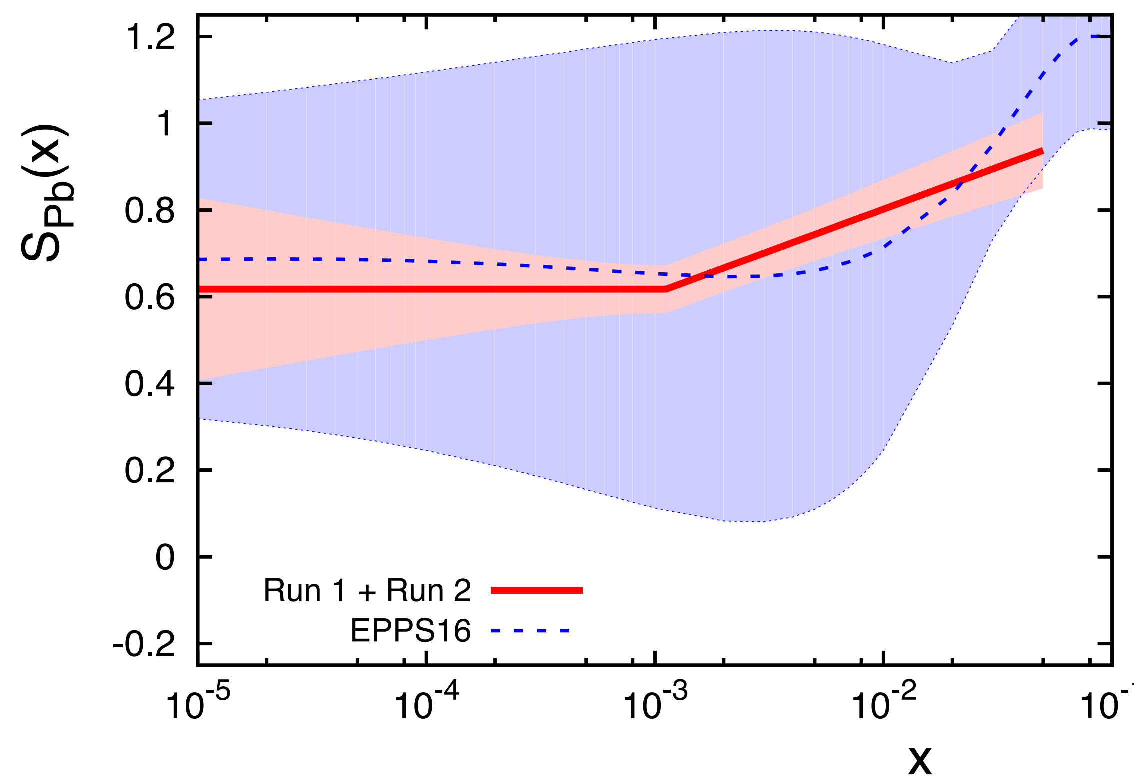
$$S_{Pb}(x) = \sqrt{\frac{\sigma_{\gamma A\to J/\psi A}(W_{\gamma p})}{\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W_{\gamma p})}} \quad = g_A(x,\mu)/g_p(x,\mu)$$

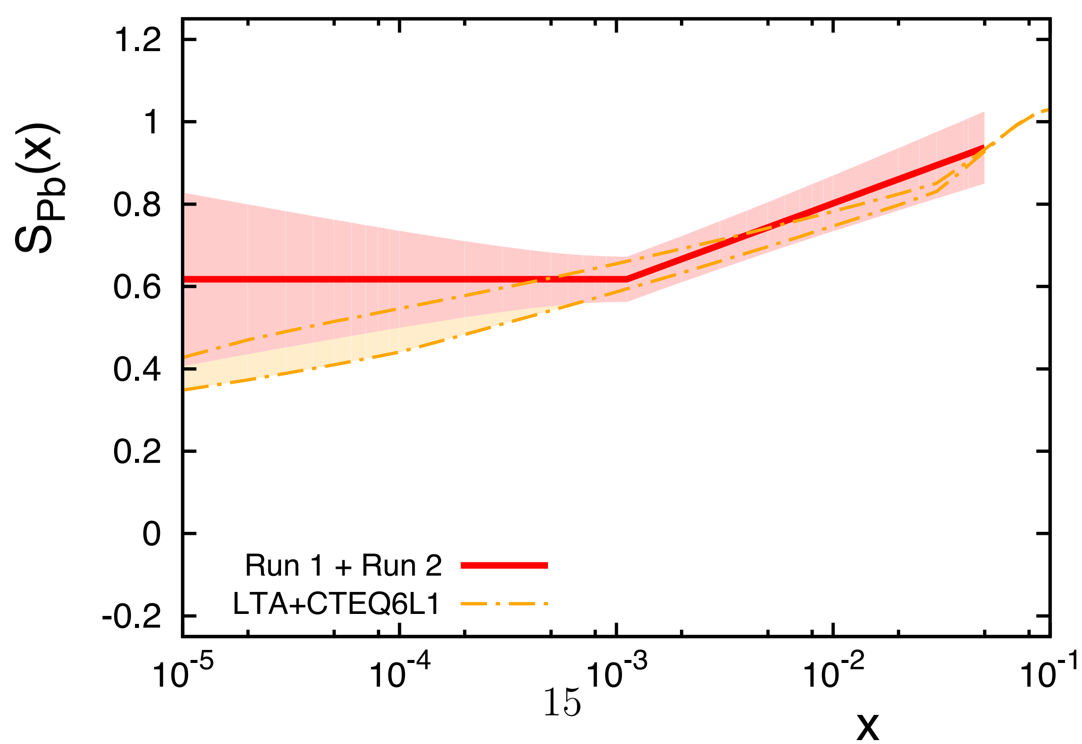
$$\left(\frac{d\sigma_{AA\to J/\psi AA}(\sqrt{s_{NN}},y)/dy}{d\sigma^{\rm IA}_{AA\to J/\psi AA}(\sqrt{s_{NN}},y)/dy}\right)^{1/2}$$

$$= \left(\frac{N_{\gamma/A}(W^+_{\gamma p})S^2_{Pb}(x_+)\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W^+_{\gamma p}) + N_{\gamma/A}(W^-_{\gamma p})S^2_{Pb}(x_-)\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W^-_{\gamma p})}{N_{\gamma/A}(W^+_{\gamma p})\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W^+_{\gamma p}) + N_{\gamma/A}(W^-_{\gamma p})\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W^-_{\gamma p})}\right)^{1/2}$$

$$\text{where } x_\pm = M^2_{J/\psi}/W^{\pm 2}_{\gamma p}$$

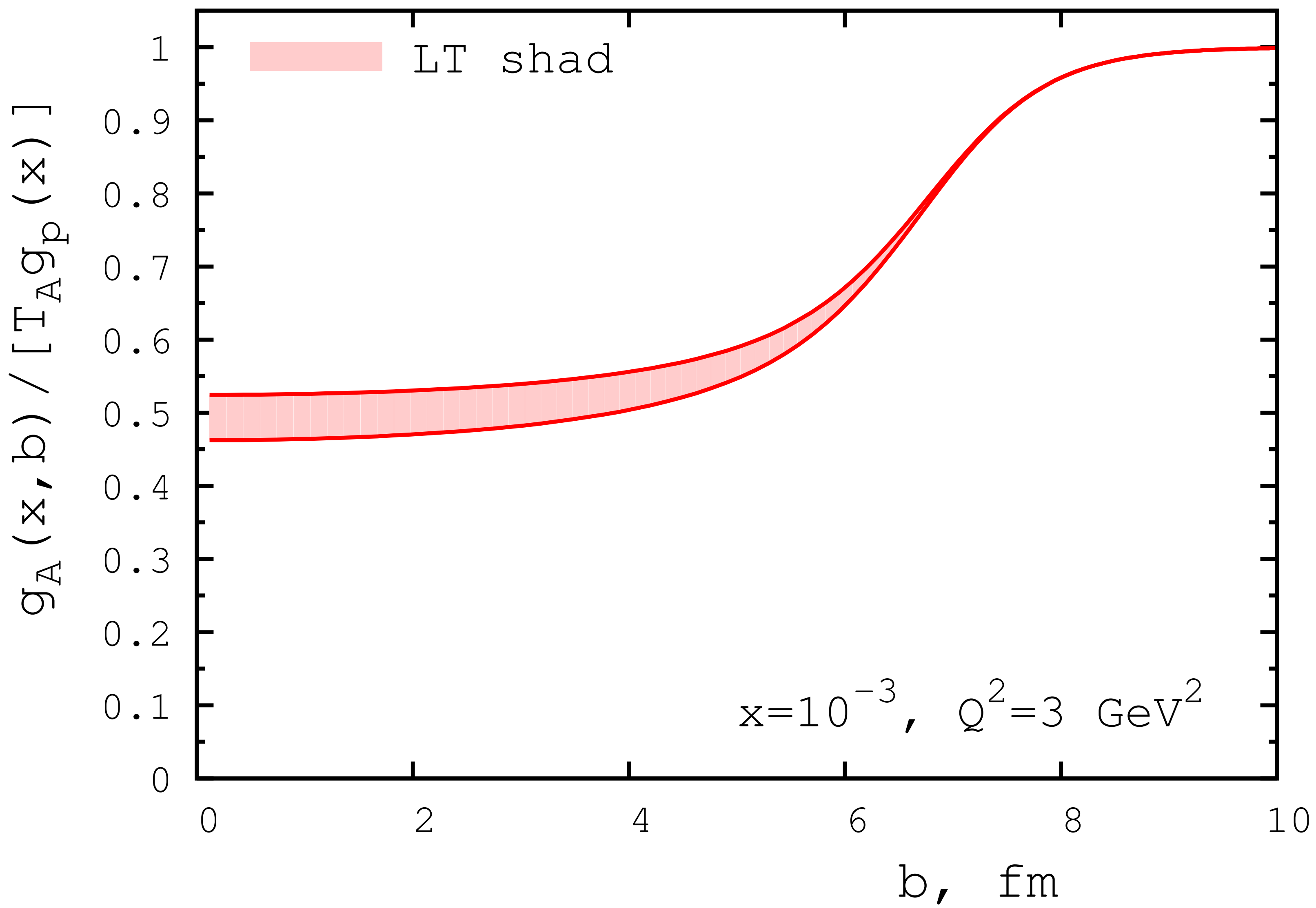




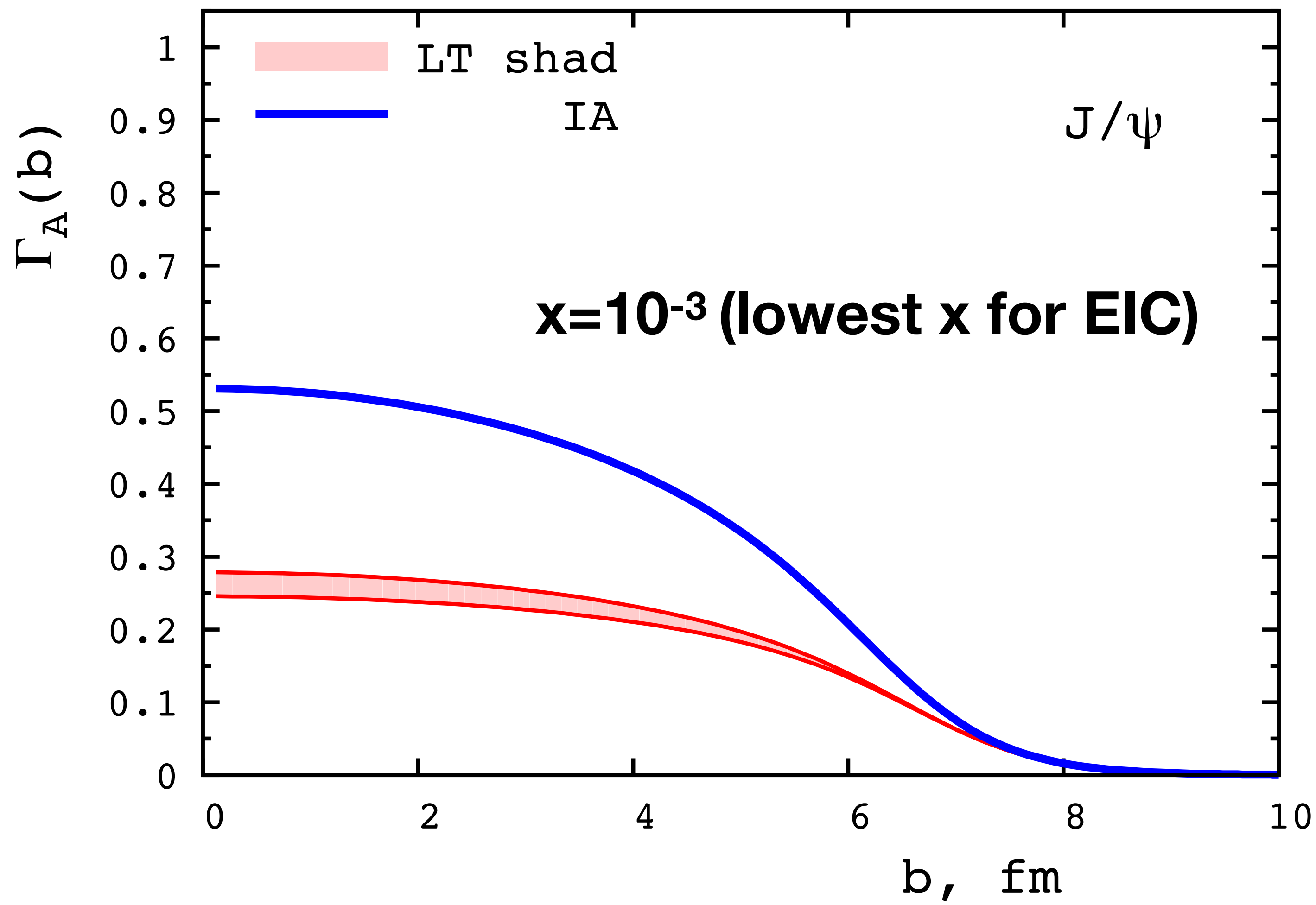


Our prediction (orange dashed dot) for $x=10^{-4}$ is bit below the range. Necessary to figure out the reasons for discrepancy between LHCb and ALICE & study impact parameter dependence of the J/ψ yield

we also predicted increase of t -dependence of coherent J/ψ production as compared to impulse approximation



Leading twist gluon shadowing in impact parameter space for coherent J/ψ photoproduction on Pb as a function of $|\vec{b}|$.



The scattering amplitude in impact parameter space $\Gamma_A(b)$ for coherent J/ψ photoproduction on Pb as a function of $|\vec{b}|$.

Gluon shadowing changes regime of interaction for $x \sim 10^{-3}$ and small b from close to black (probability to interact inelastically)

$1-(1-\Gamma)^2 = 0.77$ to gray $1-(1-\Gamma)^2 = 0.45$

To reach the black limit $x \sim 10^{-5}$ is necessary

why heavy nucleus did not help significantly?

Where is $A^{1/3}$ factor?

nucleus is much more dilute than proton + gluon shadowing

$$\frac{Q^2_{sA}}{Q^2_{sN}} = A\,\frac{R^2_{gN}}{R^2_A}\,\frac{g_A(x,Q^2)}{A g_N(x,Q^2)}$$

$$R^2_{gN}(x=10^{-3}) = 0.6\,\mathrm{fm}^2$$

$$Q^2_{sA}(b=0)/Q^2_{sN} = T_A(b=0)\cdot S_A(x,b=0)\cdot 2R^2_{gN} = 1.2$$

A~200

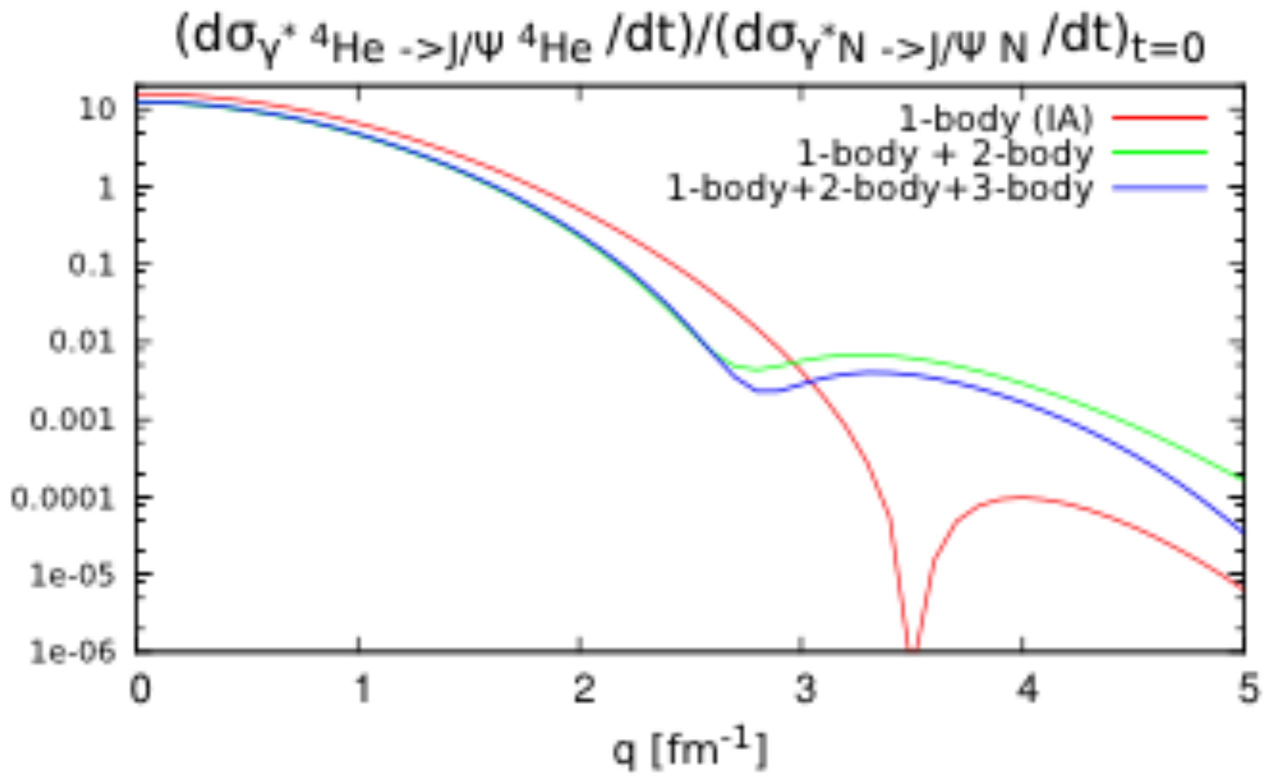
compare: Q^2_{sat}= 1 GeV^2 for proton at $x=10^{-4}$ (Jamal Jalilian-Marian 2021)

New opportunity at EIC - light nuclei. Allows to measure interaction with exactly 2, 3 nucleons

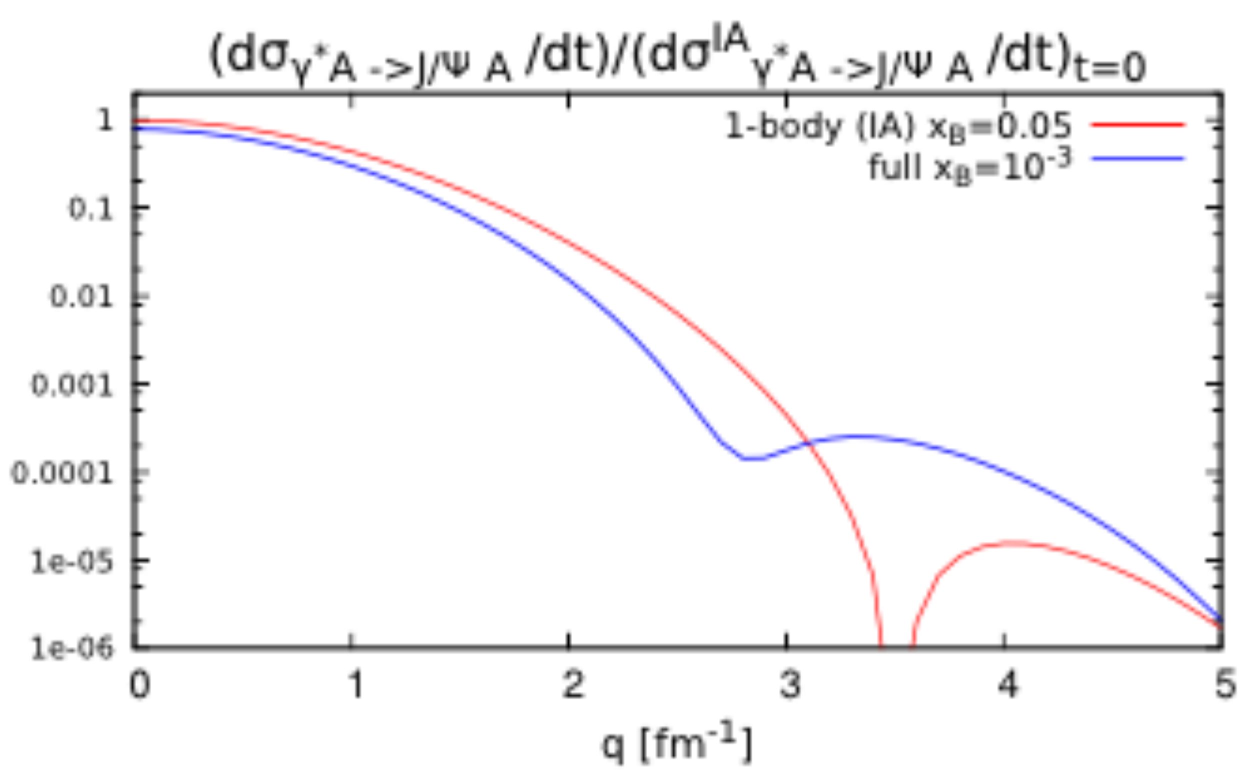
Shadowing for heavy nuclei involves interactions with 2, 3,4,… nucleons with individual terms canceling each other. Difficult to separate interactions with2,3 nucleons and perform critical tests of the models. For the lightest nuclei (4He, 3He) only interactions with 1 & 2 & 3 nucleons contribute.

V.Guzey, M. Renaldi, S.Scopetta, MS, M. Viviani

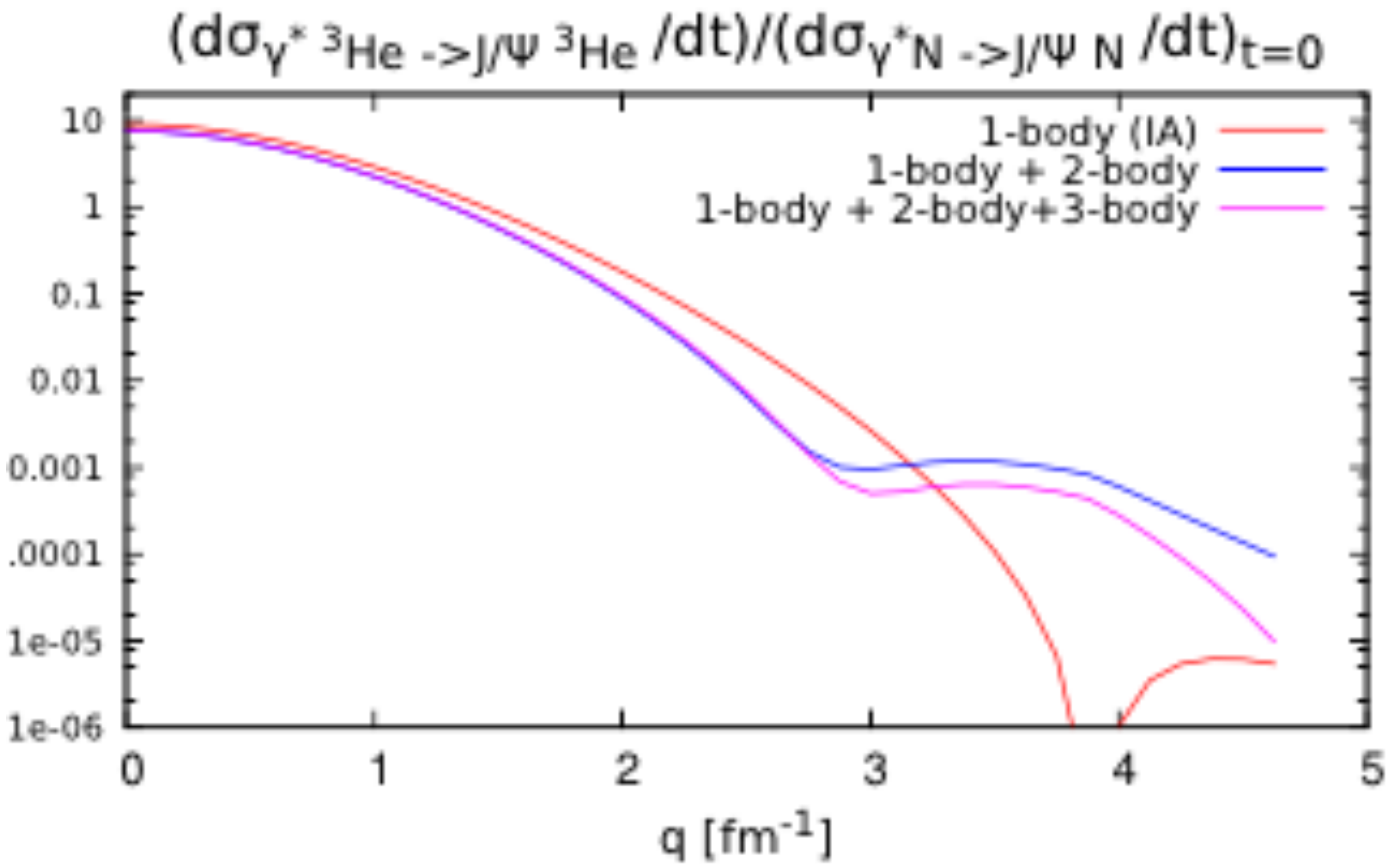
Naively — impulse approximation masks 2 & 3 scattering term. However there is a special feature for A=3, 4. One body term which is proportional to form factor goes through zero at moderate t providing window to 2 & 3 contribution. Challenge: calculation of 2, 3,4 body form factors with realistic 4He wave functions.



Ratio of the differential cross section for J/Ψ coherent production on ^{4}He to the same quantity for the nucleon target at t=0, x=10^{-3}.



Prediction: Strong x - dependence of the ratio of the differential cross section for J/Ψ coherent production on ^{4}He to the same quantity for the nucleon target at t=0, x=10^{-3} & x=.05



Ratio of the differential cross section for J/Ψ coherent production on ^{3}He to the same quantity for the nucleon target at t=0, x=10^{-3}

Other directions

- **quasielastic** **γ +p (A)→ J/ψ + Y at t=0**

inelastic diffraction at t=0 measures color fluctuations in nucleons

$$\frac{\langle g_N^2(x) \rangle}{g_N^2(x)} - 1$$

Frankfurt, MS, Treleani, Weiss

for heavy nuclei details of gluon shadowing dynamics

For -t>1 GeV2 - dynamics of parton (gluon) knock out
(minor sensitivity to color fluctuations)

- **γ +p (A)→ J/ψ(large t) + rapidity gap + Y**

Issues: **BFKL at -t > 1 GeV^2, propagation of small dipole through nuclear media**

Conclusions

- J/ψ coherent and quasielastic production provide unique probes of the gluon dynamics at in nucleons and nuclei.

- Complementarity of EIC and UPC at the LHC

- Detector challenges: Low t resolution, separation of inelastic and elastic channels, detection of light nuclei.

Supplementary slide

Perturbative Pomeron: what is energy dependence cross section in vacuum channel ?

Problem for the study - two large parameters ln Q^2, and ln 1/x.

DIS - both parameters enter (DGLAP); BGKL - only ln 1/x (scattering of two small dipoles)

BFKL elastic amplitude $f(s)= (s/s_0)^{1+\omega}$

$$\omega_{/P} = a_1\alpha_S - a_2\alpha_S^2 + \ldots$$

leading log $\omega_{/P}$ ~ 0.5 ÷ 0.8 , NLO ~ 0.1, resummation ~0.25

Main reason for small values of $\omega_{/P}$ - energy conservation

Promising direction: Rapidity gaps at large t for J/psi production - squeezing from both ends. Can be measured in UPC (pA), future:EIC, LHeC.

a simpler process than Mueller and Tung dijet