Leading twist nuclear shadowing: theory and applications to coherent charmonium photoproduction on nuclei at the LHC

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Outline:

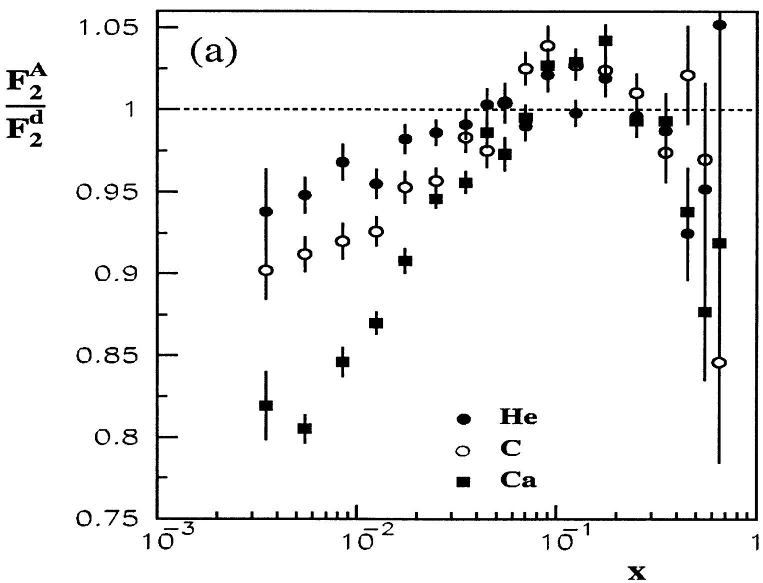
- Basics of nuclear shadowing
- Leading twist nuclear shadowing model, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255
- Gluon shadowing from charmonium photoproduction at the LHC
- Conclusions

Workshop "Proton and photon-induced nuclear collisions at the LHC"
CERN, July 6-8, 2016

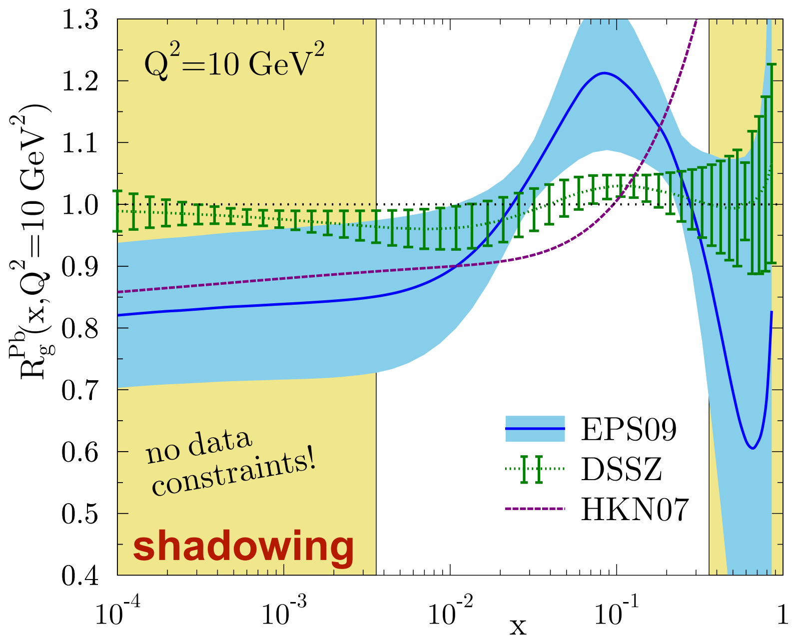
Nuclear shadowing: data and global fits

- Nuclear shadowing = high-energy (small x) coherent nuclear effect that $F_{2A}(x,Q^2) < A\, F_{2N}(x,Q^2) \rightarrow g_A(x,Q^2) < A\, g_N(x,Q^2)$

Piller, Weise (2000)



H. Pauukunen, NPA 926 (2014) 24



- For heavy nuclei, shadowing as large as 20% for $Q^2 > 1$ GeV^2 and $x > 0.005$.
- The nuclear gluon distribution $g_A(x,\mu^2)$ is known with large uncertainties.
- pA@LHC data can help mostly in antishadowing region, Armesto et al, arXiv:1512.01528; Eskola et al, JHEP 1310 (2013) 213
- Future options: Electron-Ion Collider in the US, Accardi et al, ArXiv:1212.1701; LHeC@CERN, LHEC Study Group, J. Phys. G39 (2012) 075001
- Option right now: Charmonium photoproduction in Pb-Pb UPCs@LHC

Nuclear shadowing: Gribov-Glauber model

- At high-energies, probe interacts *coherently (simultaneously)* with all nucleons of the nucleus target.
- Nuclear shadowing is a result of destructive interference among the amplitudes for the interaction with 1, 2, 3, etc. nucleons of the target.
- Classic example: Total pion-deuteron cross section

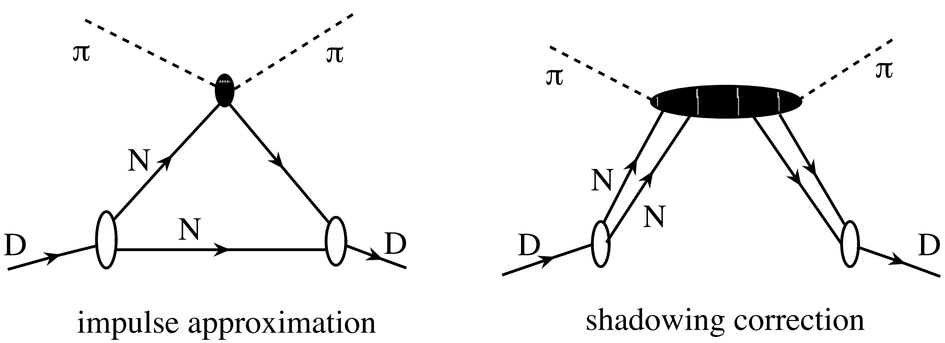
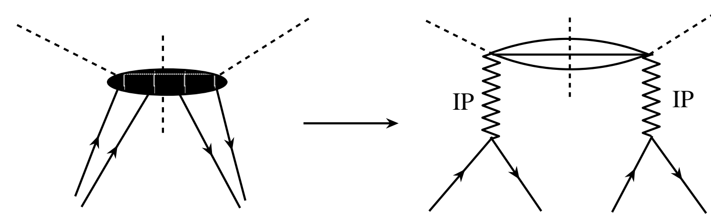


Figure 2: Graphs for pion-deuteron scattering.



If interaction is given by Pomeron exchange, the shadowing term can be expressed in terms of pion-proton diffractive cross section

$$\sigma_{\text{tot}}^{\pi D} = 2\sigma_{\text{tot}}^{\pi N} - 2\int d\vec{k}^2 \rho_D(4\vec{k}^2)\frac{d\sigma_{\text{diff}}^{\pi N}(k)}{d\vec{k}^2}$$

Glauber (1955); Gribov (1969)

Deuteron form factor

Pion-nucleon diffr. diss. cross section

- For nucleon beams, diffractive dissociation is dominated by elastic scattering → Glauber model for total, elastic, inelastic pA and nA cross sections with % accuracy.

Gribov-Glauber model for γA and γ^*A scattering

- For γ (γ^*), diffraction into large masses is 40% (~100%) of diffr. dissociation cross section → interaction with 2 nucleons is determined by $\sigma_{\rm eff}$:

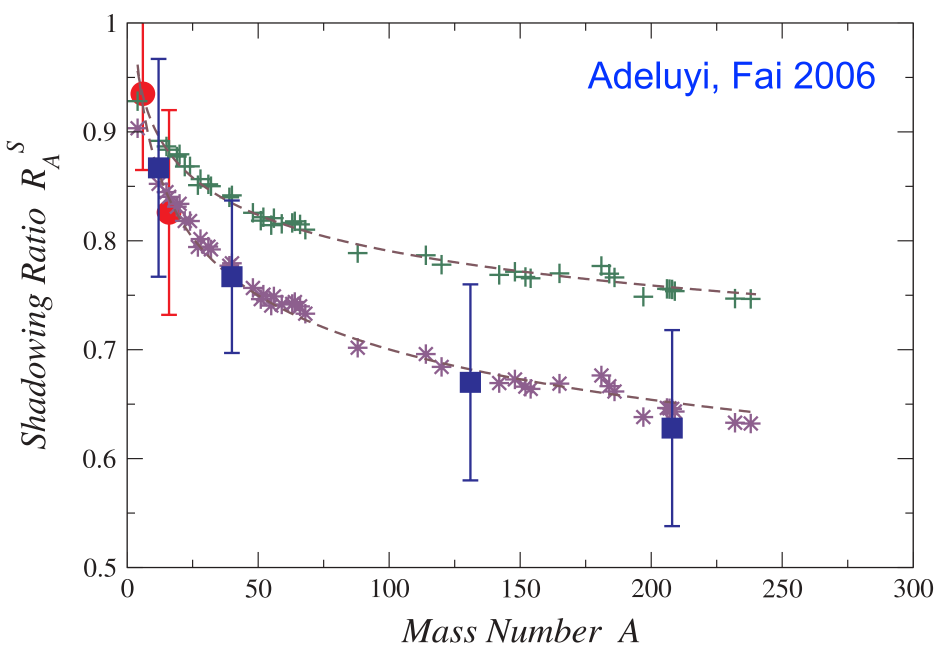
$$\sigma_{\rm eff} = \frac{16\pi}{\sigma_{\gamma^* N}} \int dM_X^2 \frac{d\sigma^{\rm diff}_{\gamma^* N}(t=0)}{dM_X^2 dt}$$

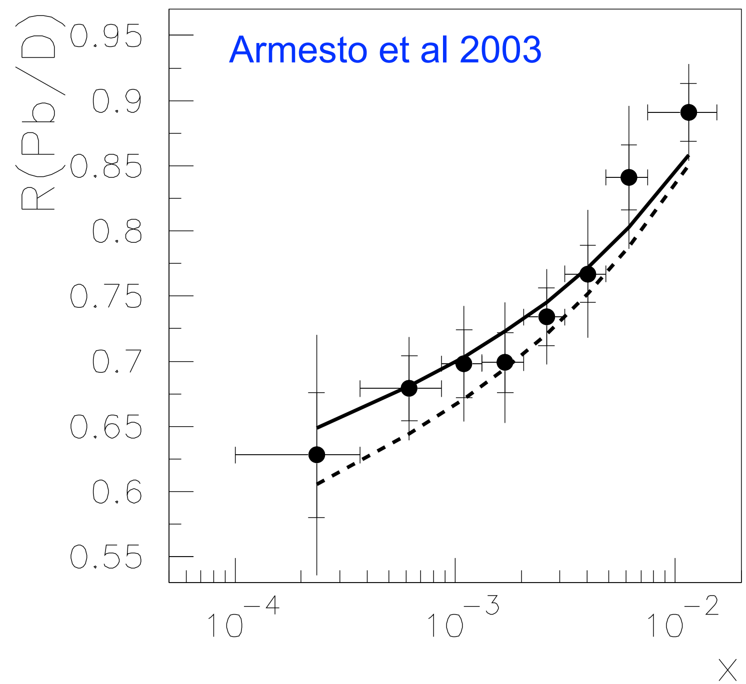
- Interaction with N ≥ 3 nucleons of nuclear target is model-dependent:
  - eikonal approximation, Frankfurt, Strikman (1999); Adeluyi, Fai (2006)
  - Schwimmer model, Capella et al (1997); Armesto et al (2003); Tywoniuk et al (2006)

- Eikonal approx. in high-energy limit:

$$\sigma_{\gamma^* A} = \frac{2\sigma_{\gamma^* N}}{\sigma_{\rm eff}} \int d^2b \left(1 - e^{-\frac{1}{2}\sigma_{\rm eff} \underbrace{T_A(b)}_{\text{Nuclear optical density}}}\right)$$

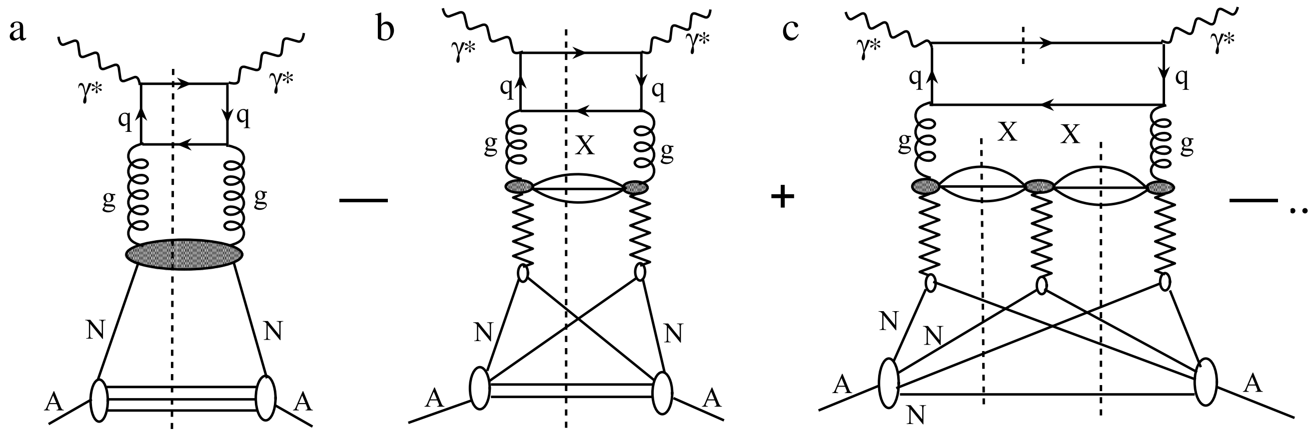
- Good description of total γA and γ^*A cross sections:





Leading twist nuclear shadowing model

- For γ^*, one can combine Gribov-Glauber model with QCD factorization theorems for inclusive and diffractive DIS → shadowing for individual partons j, Frankfurt, Strikman (1999)



- Interaction with 2 nucleons: model-indep via diffractive PDFs: $$\sigma_2^j(x) = \frac{16\pi}{x f_{j/N}(x,\mu^2)} \int_x^{0.1} dx_P \beta f_{j/N}^{D(4)}(x,\mu^2,x_P,t=0)$$

- Interaction with ≥ 3 nucleons: via soft hadronic fluctuations of γ^* $$\sigma_{\text{soft}}(x) = \frac{\int d\sigma P_\gamma(\sigma)\sigma^3}{\int d\sigma P_\gamma(\sigma)\sigma^2}$$ P(σ) probability to interact with cs σ

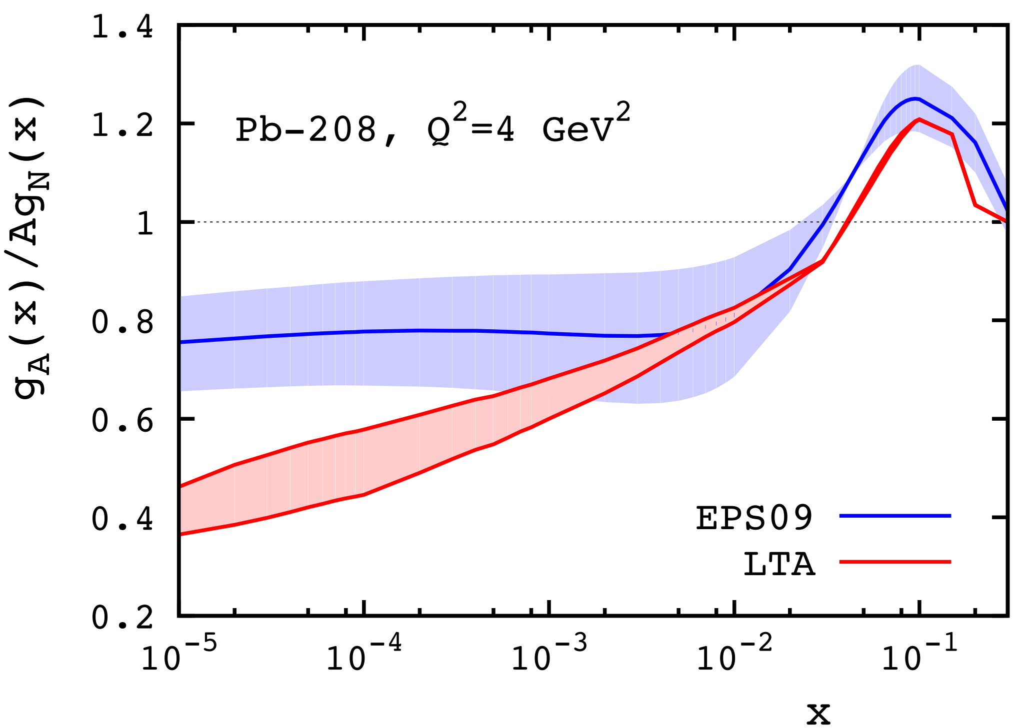
- In quasi-eikonal approximation in low-x limit, Frankfurt, Guzey, Strikman 2012:

$$x f_{j/A}(x,\mu^2) = A f_{j/N}(x,\mu^2) - \frac{2\sigma_2^j f_{j/N}(x,\mu^2)}{[\sigma_{\text{soft}}^j(x)]^2} \int d^2b \left(e^{-\frac{1}{2}\sigma_{\text{soft}}^j(x) T_A(b)} - 1 + \frac{\sigma_{\text{soft}}^j(x)}{2} T_A(b) \right)$$

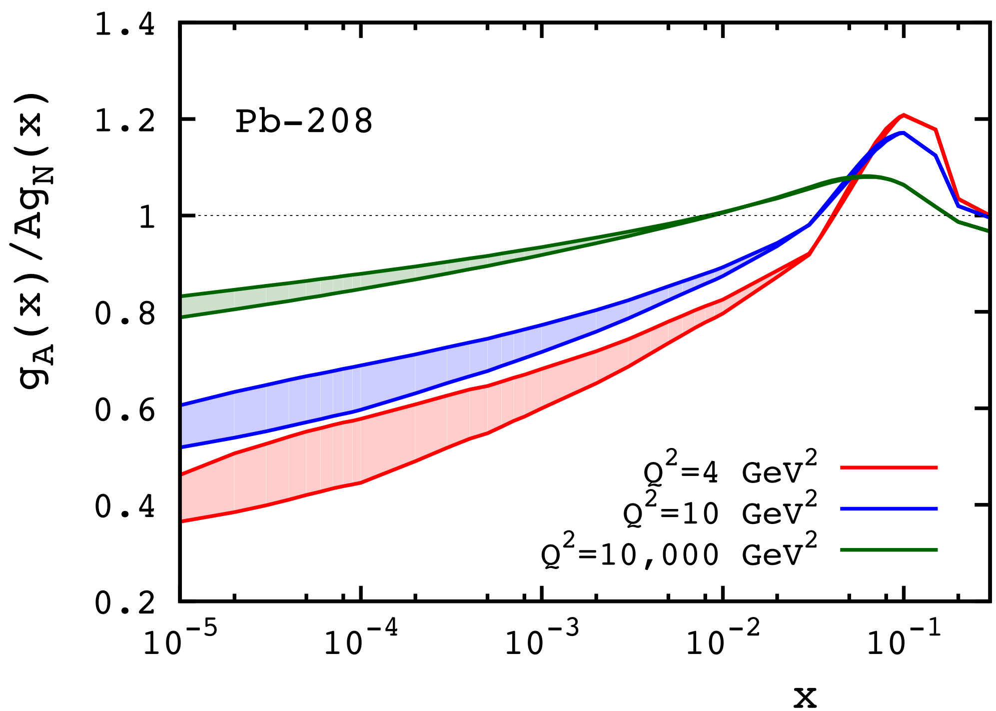
Leading twist nuclear shadowing model (2)

- Model gives nuclear PDFs at μ^2=4 GeV^2 for subsequent DGLAP evolution.
- Name "leading twist" since diffractive structure functions/PDFs measured at HERA scale with Q^2.
- Gluon diffractive PDFs are large, ZEUS, H1 2006 → predict large shadowing for $g_A(x,\mu^2)$,
  Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

Input: Leading twist (LTA) vs. EPS09



Results of DGLAP evolution: from Q^2=4 GeV^2 to Q^2=10 and 10,000 GeV^2

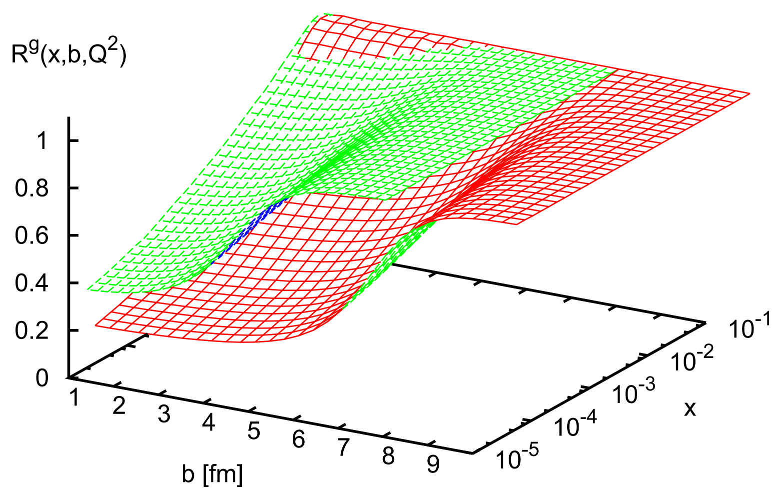


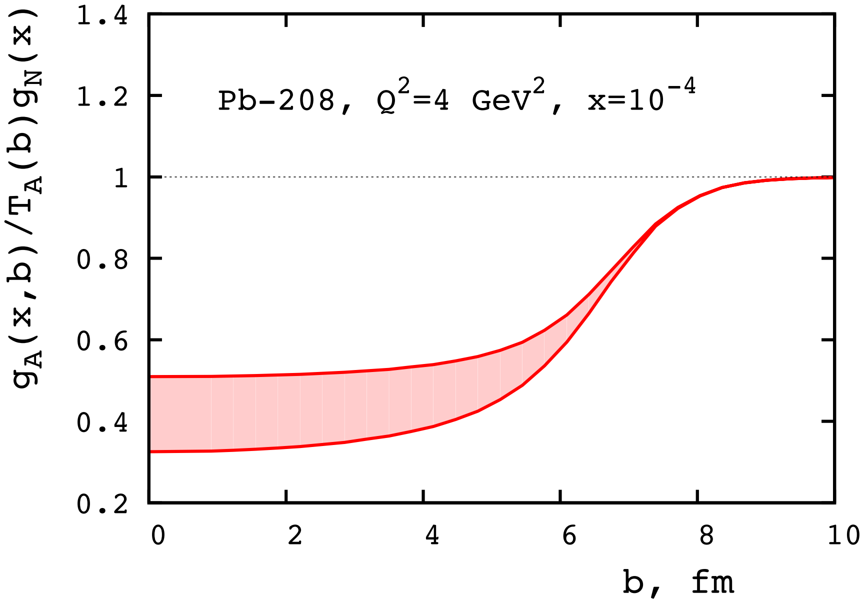
For quarks, the agreement between LTA and EPS09 is much better.

LT shadowing: Impact parameter dependence

- Shadowing arises from rescattering on target nucleons at given impact parameter b.
- Removing integral over b → impact-parameter-dependent nuclear PDFs:

$$x f_{j/A}(x,b,\mu^2) = T_A(b) x f_{j/N}(x) - \frac{2\sigma_2^j f_{j/N}(x,\mu^2)}{[\sigma_{\text{soft}}^j(x)]^2}\left(e^{-\frac{1}{2}\sigma_{\text{soft}}^j(x)T_A(b)} - 1 + \frac{\sigma_{\text{soft}}^j(x)}{2}T_A(b)\right)$$

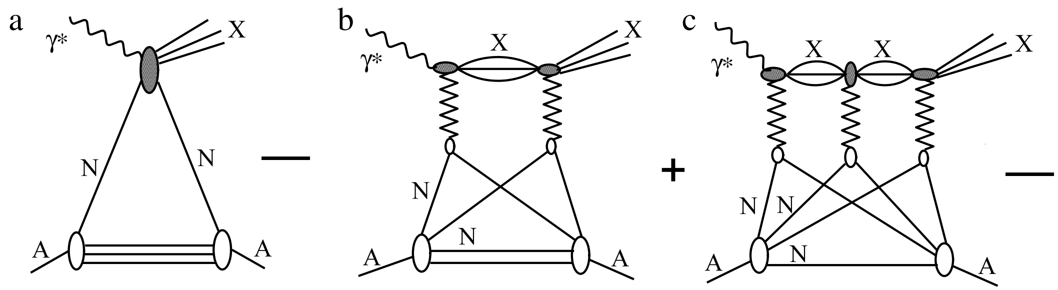




- Can be only indirectly determined using global QCD fits, EPS09s nPDFs, Helenius et al (2012)
- Can be probed and tested in:
  - centrality dependence of hard pA/AA processes, Helenius et al (2012)
  - *t* dependence of exclusive γ^*A processes, e.g., beam-spin asymmetry of nuclear DVCS at LHeC/EIC, Frankfurt, Guzey, Strikman 2012

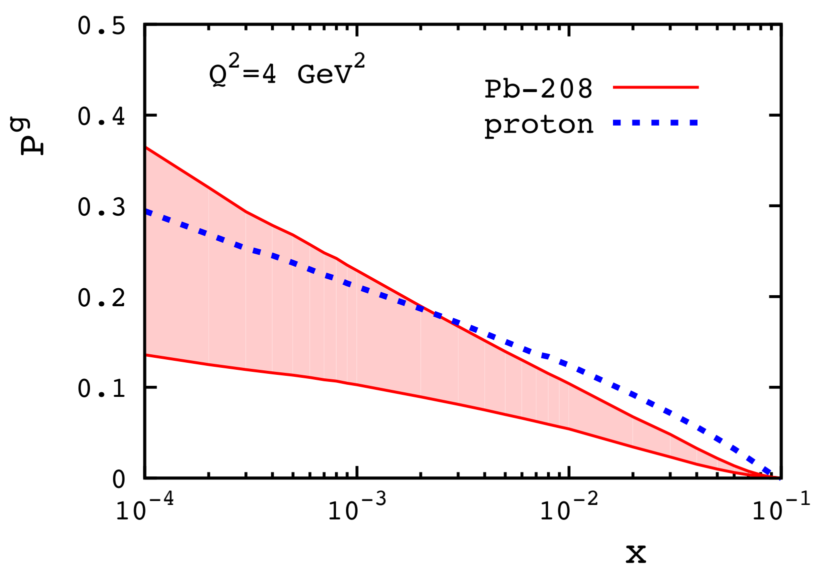
Nuclear diffractive parton distributions

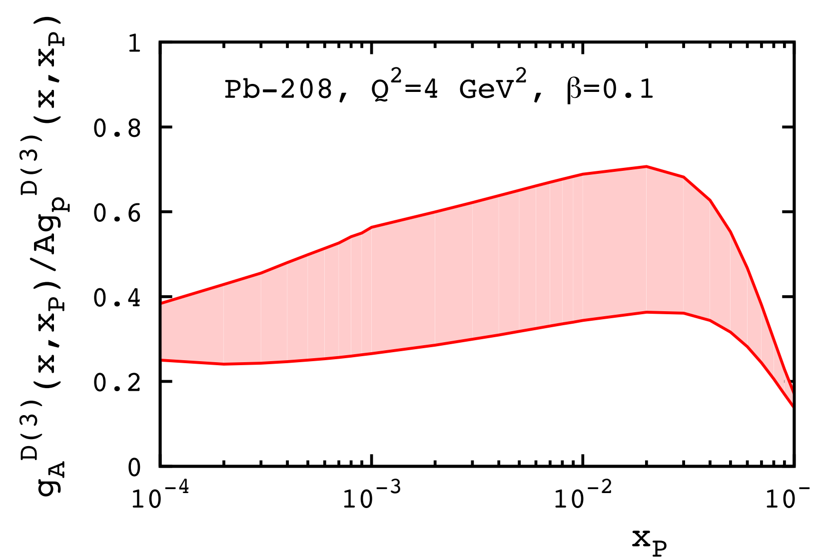
- Leading twist nuclear shadowing model can be applied to inclusive diffraction in γ^*A:



$$\beta f_{j/A}^{D(3)}(x,\mu^2,x_P) = 16\pi f_{j/N}^{D(4)}(x,\mu^2,x_P,t=0)\int d^2b \left(\frac{1-e^{-\frac{1}{2}\sigma^j_{\mathrm{soft}}(x)T_A(b)}}{\sigma^j_{\mathrm{soft}}(x)}\right)^2$$

- Predicted large probability of hard diffraction on nuclei and nuclear diffractive PDFs:





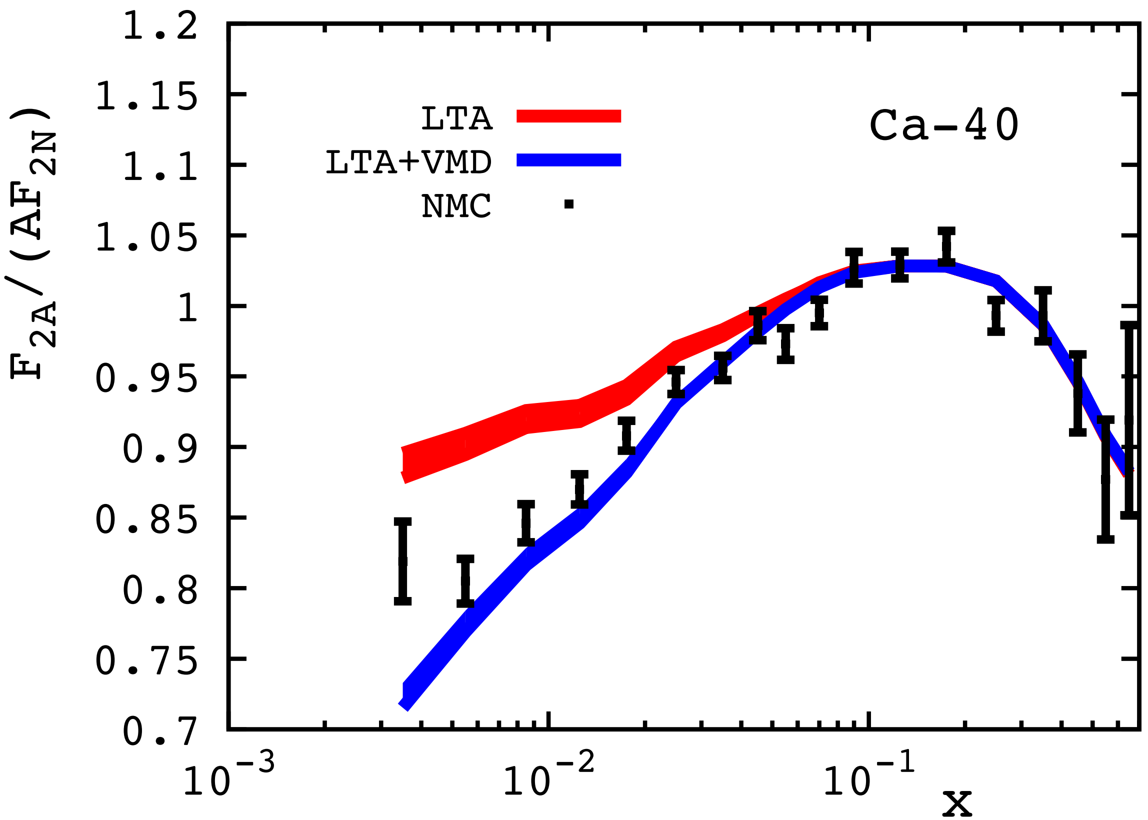
- Can be measured in inclusive γ^*A diffraction at LHeC/EIC and hard diffraction in γA, e.g., diffractive photoproduction of dijets in UPCs@LHC, Guzey, Klasen 2016

Leading twist vs. all-twist shadowing

- In our leading twist shadowing model, we take $\mu^2=4$ GeV^2 to minimize (i) HT effects in diffractive PDFs, H1, ZEUS, 2006, (ii) cross section fluctuation in γ^*

- We underestimate shadowing at fixed-target energies → HT effects contaminate global QCD fits of nuclear PDFs.

Comparison of theoretical predictions: Leading twist model (LTA) and LT+HT (ρ, ω, and ϕ vector mesons) to NMC 1995 fixed-target data.

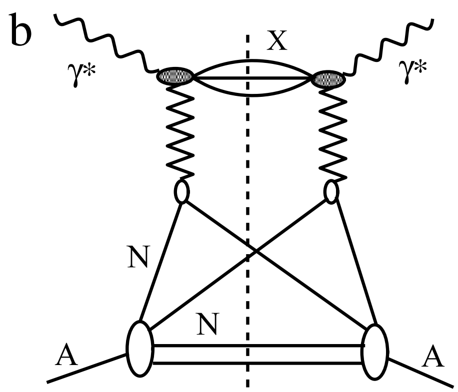


Leading twist vs. higher-twist shadowing

- Principal difference between our LTA and all-twist approaches, e.g. dipole model:

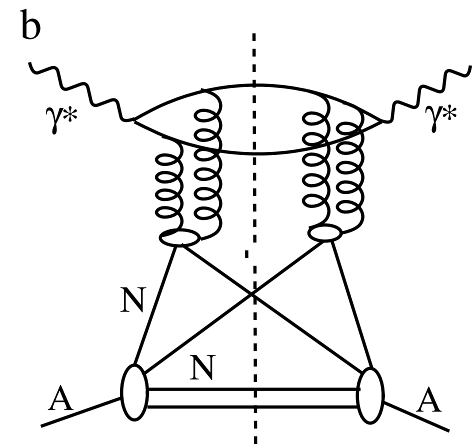
Frankfurt, Guzey, McDermott, Strikman 2002

Triple-Pomeron coupling to 2 nucleons



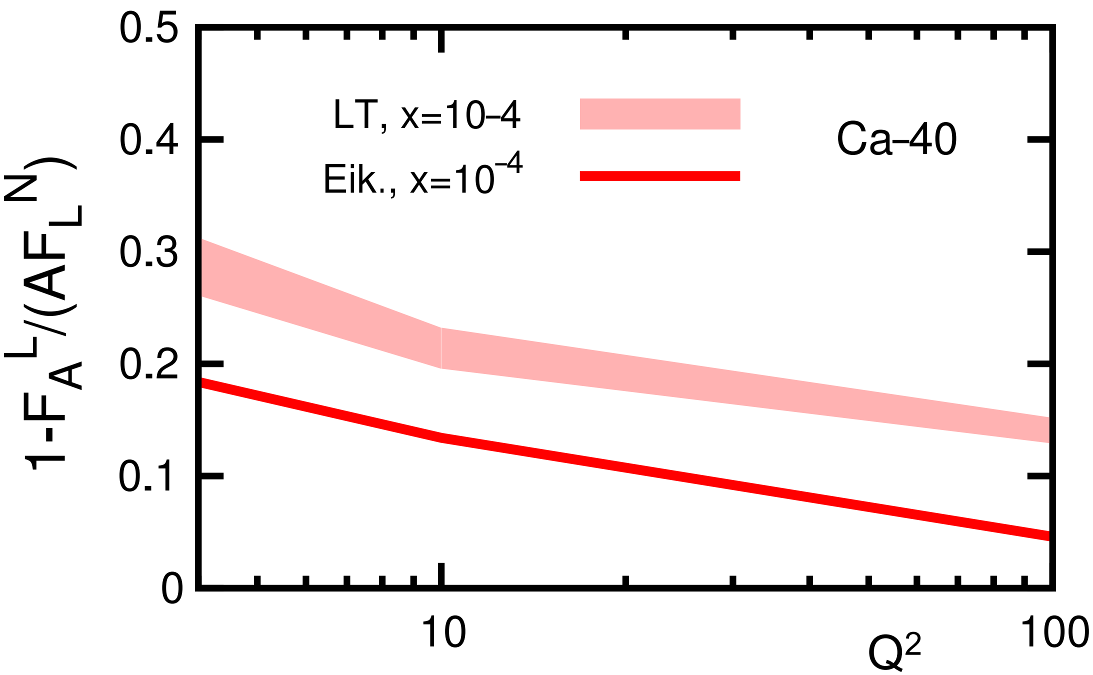
vs.

Separate Pomeron couplings to 2 nucleons
→ higher twist (HT) for small dipoles



- The difference should manifest itself in observables dominated by small-size dipoles:

- nuclear longitudinal structure function $F_L^A(x,Q^2)$ at LHeC/EIC
- cross section of J/ψ photoproduction on nuclei in UPCs@LHC

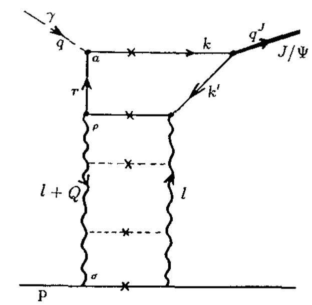


Exclusive charmonium photoproduction

- In leading logarithmic approximation of perturbative QCD and non-relativistic approximation for charmonium wave function (J/ψ, ψ(2S)):

$$\frac{d\sigma_{\gamma T \to J/\psi T}(W, t=0)}{dt} = C(\mu^2)\left[xG_T(x,\mu^2)\right]^2$$

M. Ryskin (1993)



$$x = \frac{M^2_{J/\psi}}{W^2}, \qquad \mu^2 = M^2_{J/\psi}/4 = 2.4\ \mathrm{GeV}^2 \quad C(\mu^2) = M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s(\mu^2)/(48\alpha_{em}\mu^8)$$

- Corrections on quark and gluon k_T, non-forward kinematics, real part of amplitude → corrections to C(μ^2) and μ^2, Ryskin, Roberts, Martin, Levin, Z. Phys. (1997); Frankfurt, Koepf, Strikman (1997)

- Application to nuclear targets:

$$\sigma_{\gamma A \to J/\psi A}(W_{\gamma p}) = \frac{(1+\eta_A^2)R^2_{g,A}}{(1+\eta^2)R^2_g}\frac{d\sigma_{\gamma p \to J/\psi p}(W_{\gamma p}, t=0)}{dt}\left[\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)}\right]^2 \Phi_A(t_{\min})$$

Small correction $\kappa_{A/N} \approx 0.95$

From HERA and LHCb

Gluon shadow. Rg

From nuclear form factor

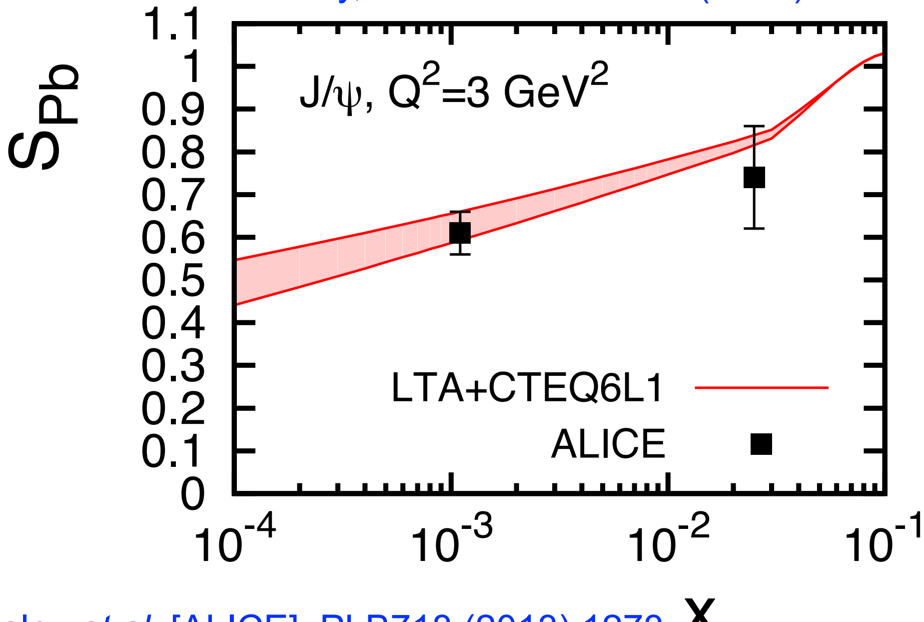
$$\Phi_A(t_{\min}) = \int_{-\infty}^{t_{\min}} dt |F_A(t)|^2$$

- Nuclear suppression factor S → direct access to Rg

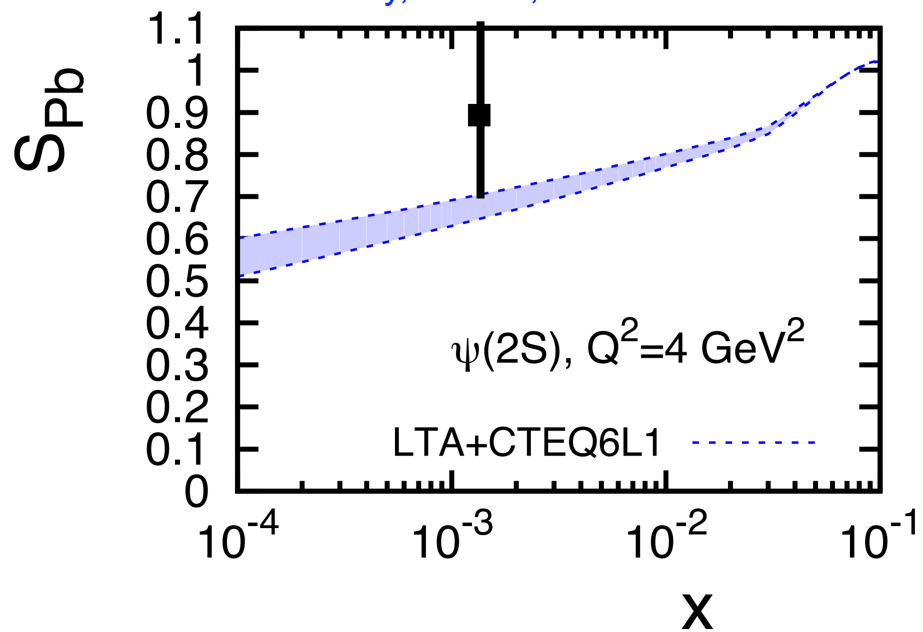
$$S(W_{\gamma p}) = \left[\frac{\sigma_{\gamma Pb \to J/\psi Pb}}{\sigma^{\mathrm{IA}}_{\gamma Pb \to J/\psi Pb}}\right]^{1/2} = \kappa_{A/N}\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)} = \kappa_{A/N}R_g$$

Impulse Approximation

Comparison to S_{Pb} from ALICE UPC data



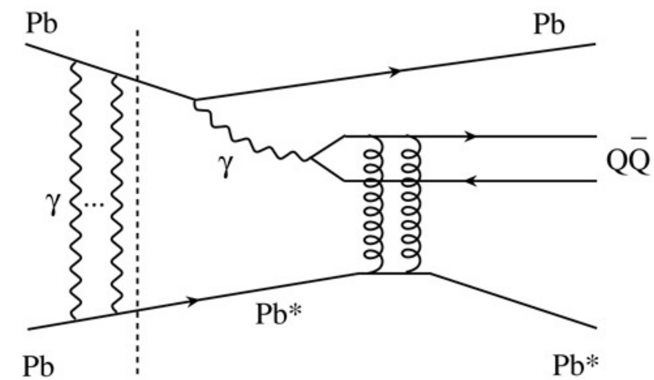
Abelev *et al*. [ALICE], PLB718 (2013) 1273;
Abbas *et al*. [ALICE], EPJ C 73 (2013) 2617



Adam *et al*. [ALICE], PLB751 (2015) 358

- Good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs@2.76 TeV → first direct evidence of large gluon nuclear shadowing at x=0.001.
- Similarly good description using EPS09+CTEQ6L.
- Cannot be described by simple versions of the dipole model, Lappi, Mantysaari 2013
- We predict similar suppression for J/ψ and ψ(2S) → tension with ALICE data on ψ(2S) photoproduction in Pb-Pb UPCs at y=0 → need to wait for better precision Run 2 data.

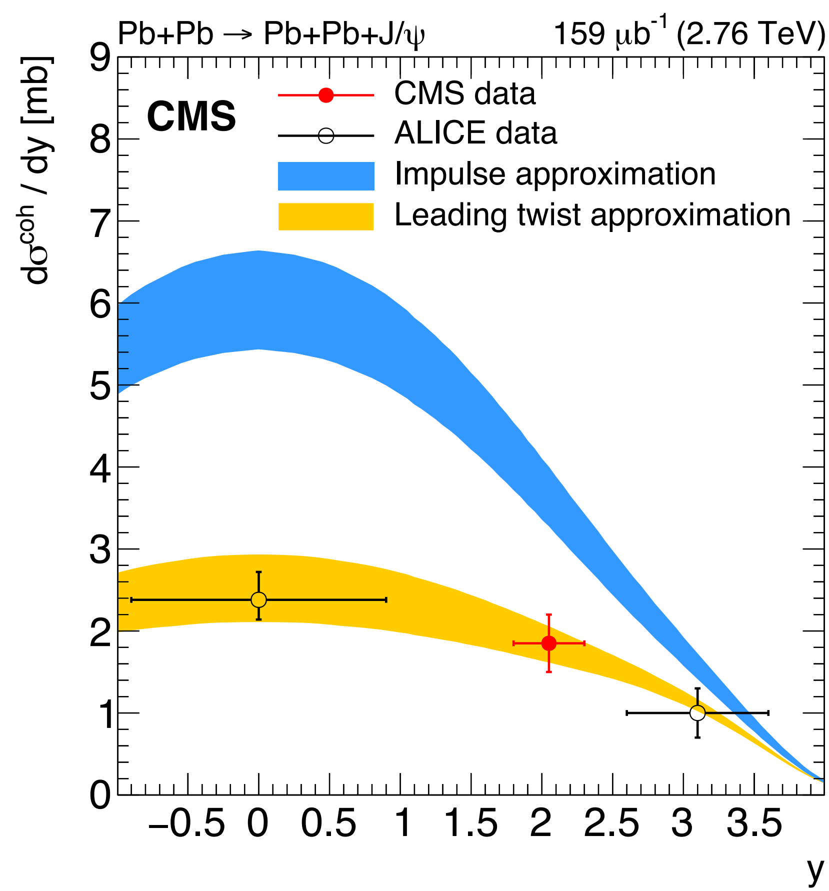
Coherent J/ψ photoproduction in Pb-Pb UPCs with forward neutron emission



- UPCs can be accompanied by e.m. excitation of colliding ions followed by forward neutron emission,

Baltz, Klein, Nystrand, PRL 89 (2002) 012301

- CMS data in 0nXn-channel converted to the total coherent cross section agrees very well with our predictions of large gluon shadowing, CMS Collab., arXiv:1605.06966



Conclusions

• Leading twist nuclear shadowing model is a dynamical approach to nuclear PDFs and nuclear diffractive PDFs at small x, whose phenomenology requires only a few weakly-constrained parameters.

• The approach makes definite predictions for x, Q2 and b dependence of nPDFs in the collider kinematics of LHC, LHeC and EIC, where results of global QCD fits are an extrapolation.

• Predicted large nuclear gluon shadowing is confirmed by ALICE and CMS measurements of coherent J/ψ photoproduction on Pb in UPCs@LHC.

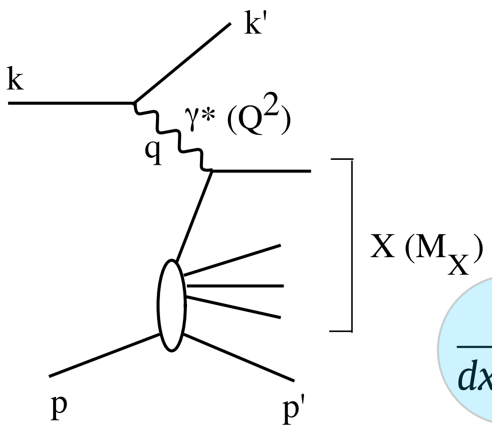
• Predictions of the LT shadowing model can be further tested in pA and γA scattering at the LHC in Run 2: photoproduction of charmonia (J/ψ,ψ') and bottomia (Y), inclusive and diffractive photoproduction of dijets.

Additional Slides

Diffraction in ep DIS at HERA

- One of main HERA results is the discovery of large fraction of diffractive events (~10%) ➞ diffraction is a leading twist phenomenon (H1 and ZEUS, 1994-2006)

$$e + p \to e' + X + p'$$



$$t = (p' - p)^2 ,$$

$$x_{I\!P} = \frac{q \cdot (p - p')}{q \cdot p} \approx \frac{M_X^2 + Q^2}{W^2 + Q^2} ,$$

$$\beta = \frac{Q^2}{2q \cdot (p - p')} = \frac{x}{x_{I\!P}} \approx \frac{Q^2}{Q^2 + M_X^2}$$

$$\frac{d^4\sigma_{ep}^D}{dx_{\mathbb{P}}\, dt\, dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\left(1 + (1-y)^2\right) F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t) - y^2 F_L^{D(4)}(x, Q^2, x_{\mathbb{P}}, t)\right]$$

- Collinear factorization (Collins '97) ➞ diffractive parton distributions

$$F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t) = \beta \sum_{j=q,\bar{q},g} \int_\beta^1 \frac{dy}{y} C_j\left(\frac{\beta}{y}, Q^2\right) f_j^{D(4)}(y, Q^2, x_{\mathbb{P}}, t)$$

- Measurement of the t-dependence of diffractive cross section: $B_{diff} = 6\ \text{GeV}^{-2} \pm 15\%$

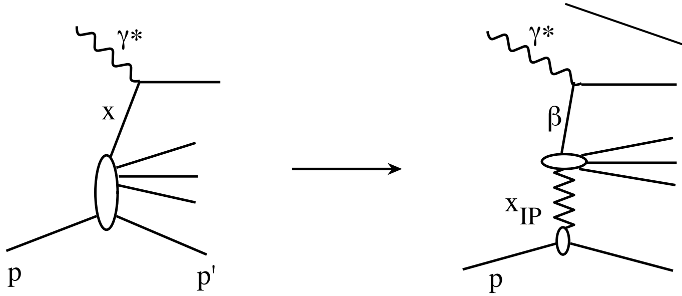
$$F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t) = e^{B_{\text{diff}}(t - t_{\text{min}})} F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t_{\text{min}})$$

$$F_2^{D(3)}(x, Q^2, x_{\mathbb{P}}) = \int_{-1\,\text{GeV}^2}^{t_{\text{min}}} dt F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t)$$

Diffraction in ep DIS at HERA (2)

- It is convenient to use (supported by data):

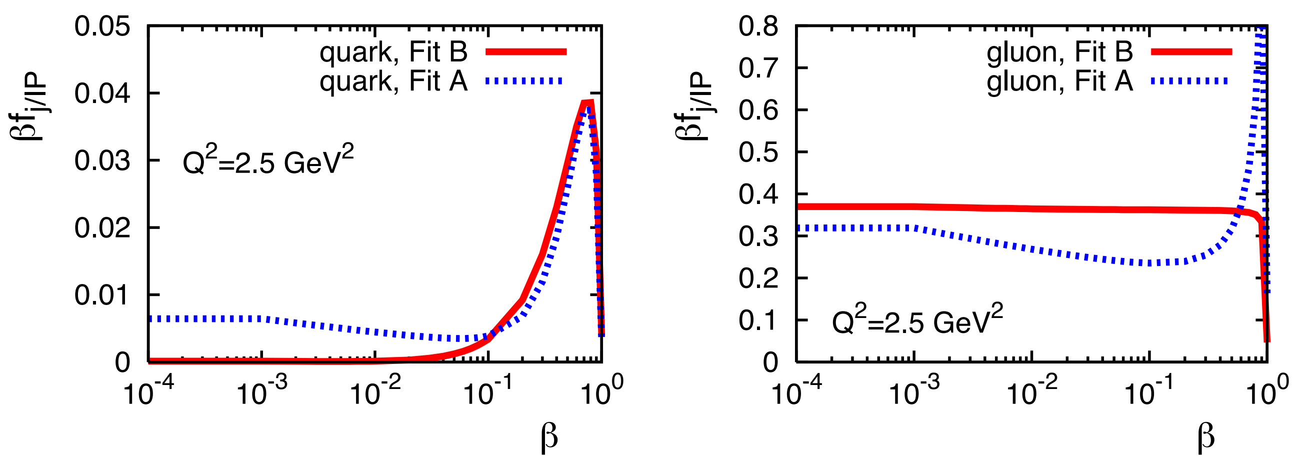
$$f_j^{D(3)}(\beta, Q^2, x_{I\!P}) = f_{I\!P/p}(x_{I\!P}) f_{j/I\!P}(\beta, Q^2) + n_{I\!R} f_{I\!R/p}(x_{I\!P}) f_{j/I\!R}(\beta, Q^2)$$



“Pomeron” flux

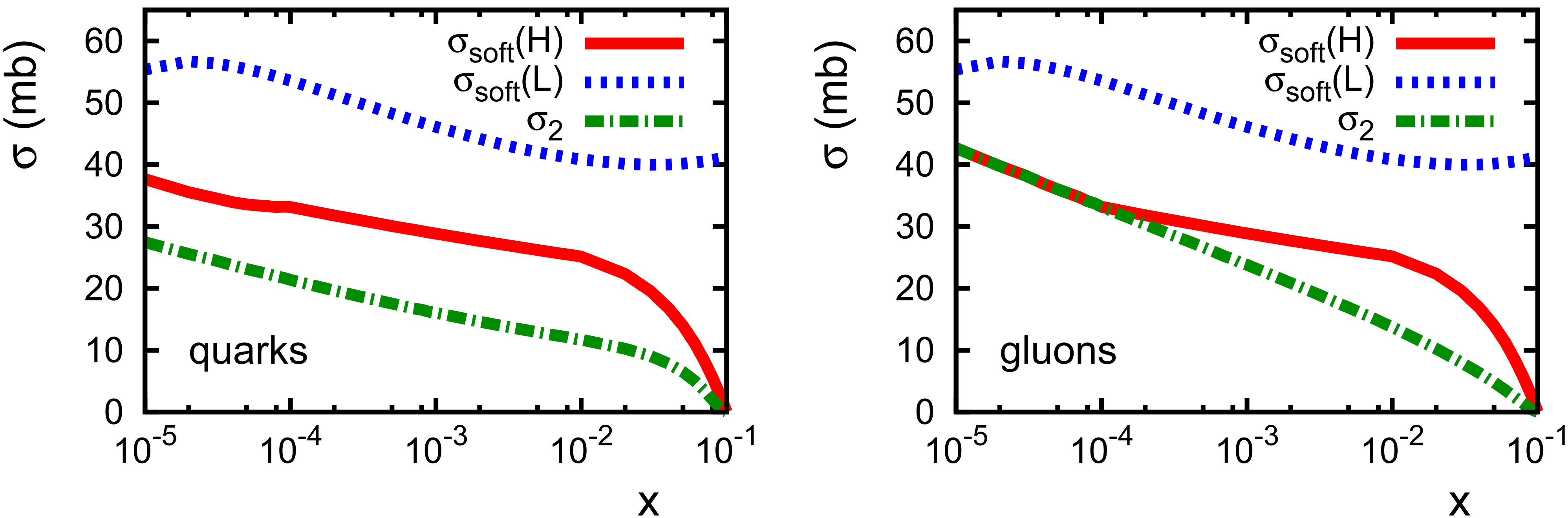
“Pomeron” PDFs

- H1 and ZEUS determined “Pomeron” PDFs:

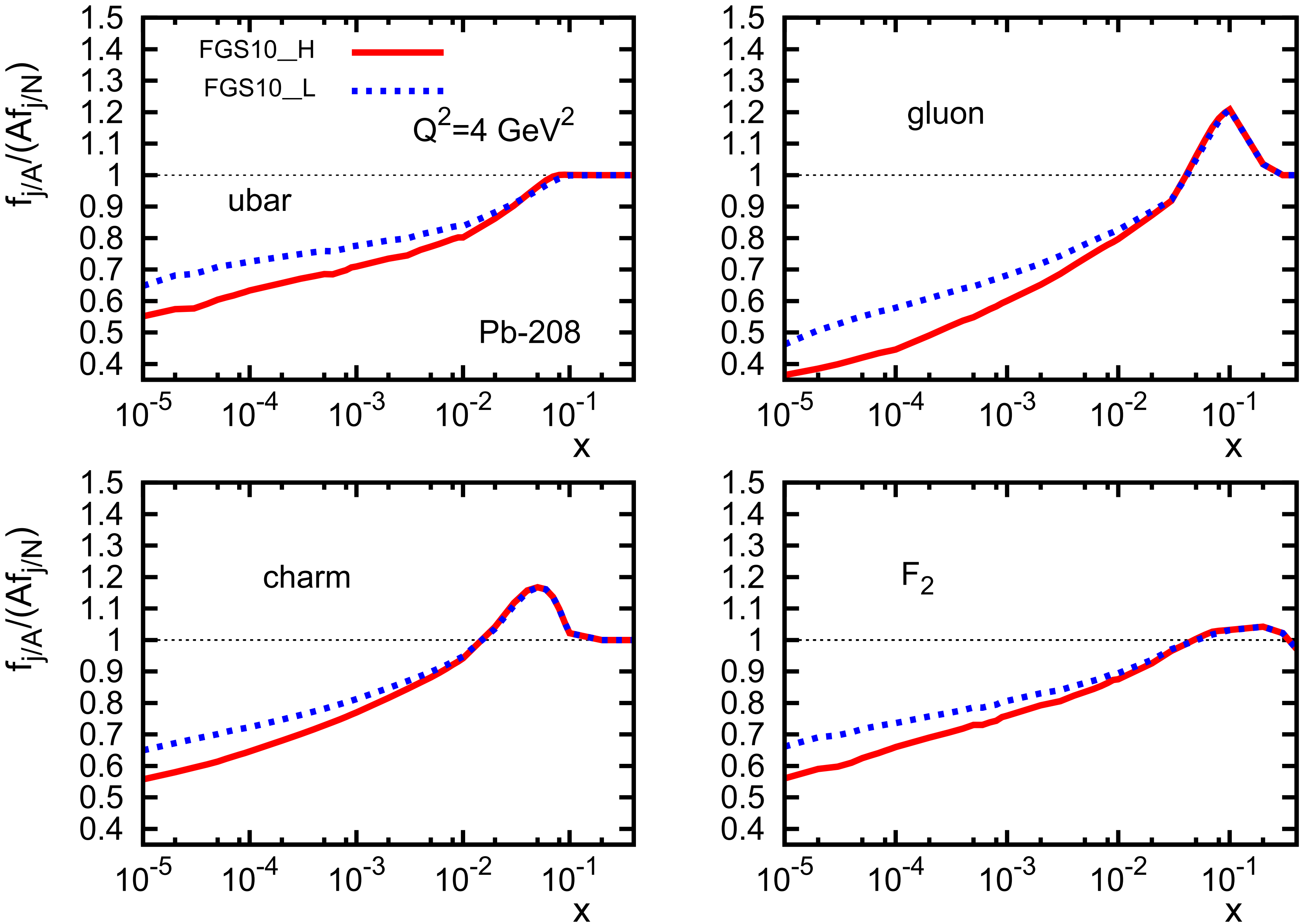


- Necessary information for numerical prections.
  Important that $g_P >> q_P$.

Effective cross sections σ_2 and σ_{soft}

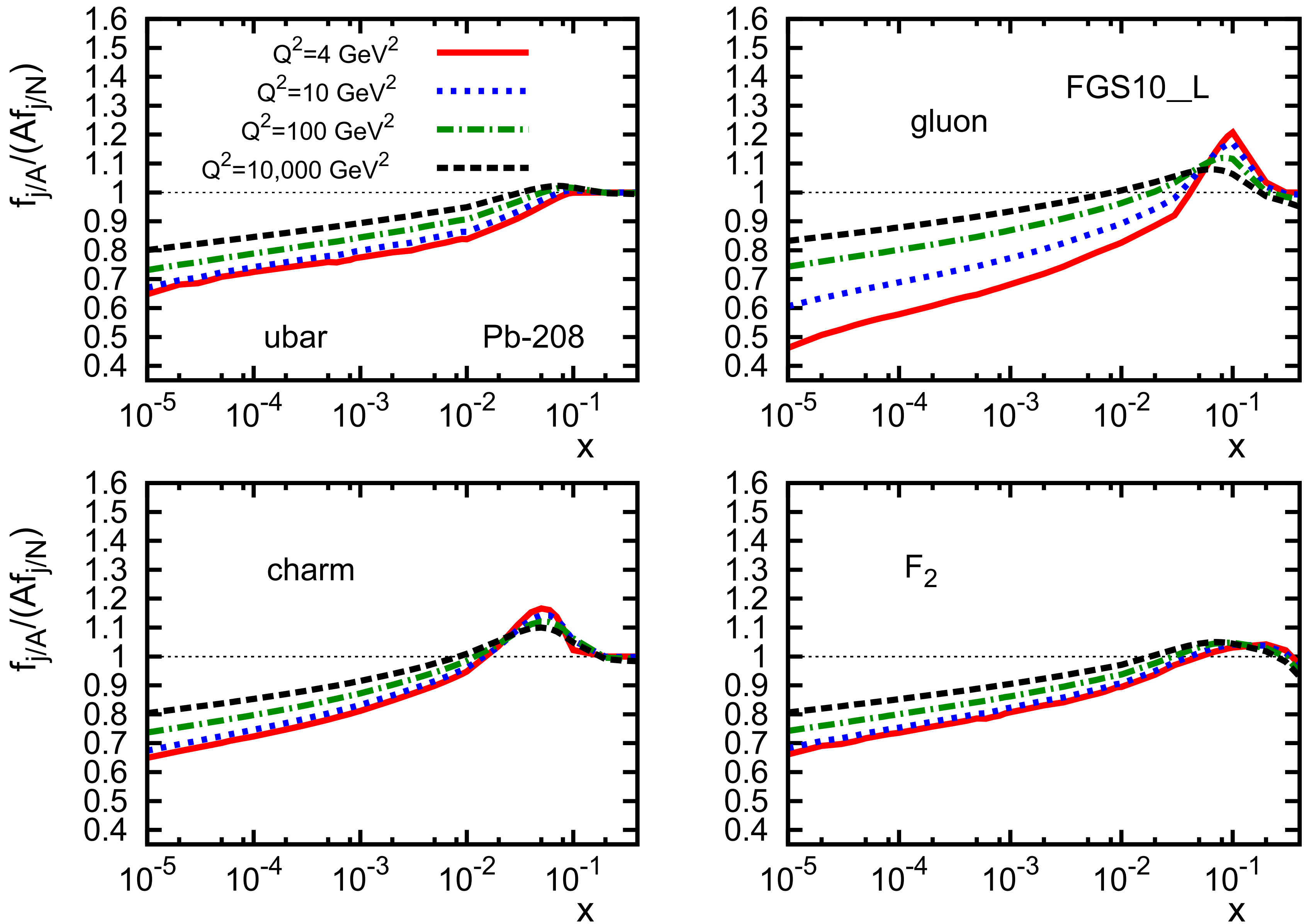


LT nuclear shadowing predictions: Input



- Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

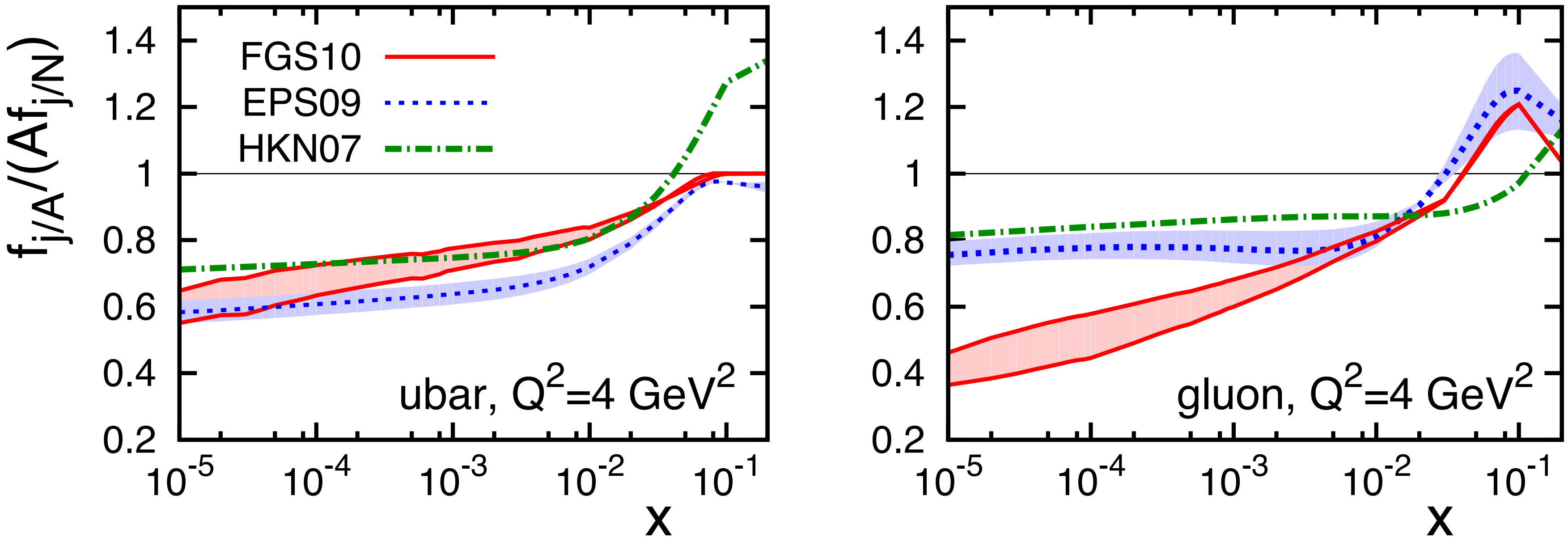
LT nuclear shadowing predictions: Q2 evolution



- Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

Comparison to results of global fits

Pb-208



EPS09 = Eskola, Puukkunen, Salgado, JHEP 04 (2009) 065
HKN07 = Hirai, Kumano, Nakano, PRC 76(2007) 065207

- In the quark channel, shadowing is similar
- In the gluon channel, we predict much larger shadowing → seems to be supported by the fit that used RHIC dAu data

Predictions for Run 2: J/ψ and ψ' mesons

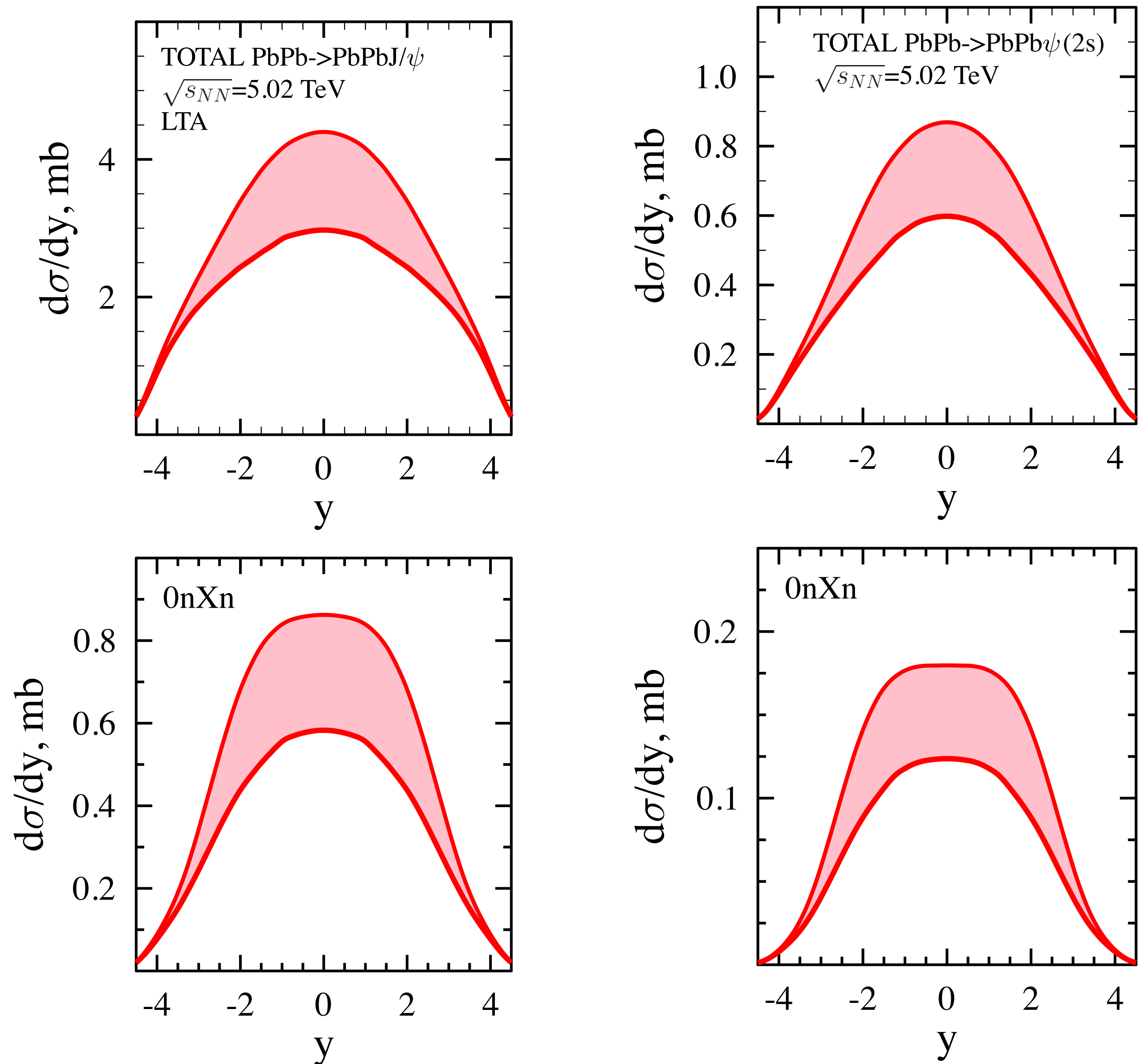
- Combination of LO pQCD and leading twist nuclear shadowing model:

- Measurement in two channels $\rightarrow$ separation of contributions of small and large $W_{\gamma p} \rightarrow g_A(x,\mu^2)$ at smaller x.

- Suppression due to nuclear shadowing same for J/ψ and ψ':

$$\frac{d\sigma_{\psi'}/dy}{d\sigma_{J/\psi}/dy} = 0.17 - 0.20$$

at y=0.



Guzey, Kryshen, Zhalov, PRC 93 (2016) 055206

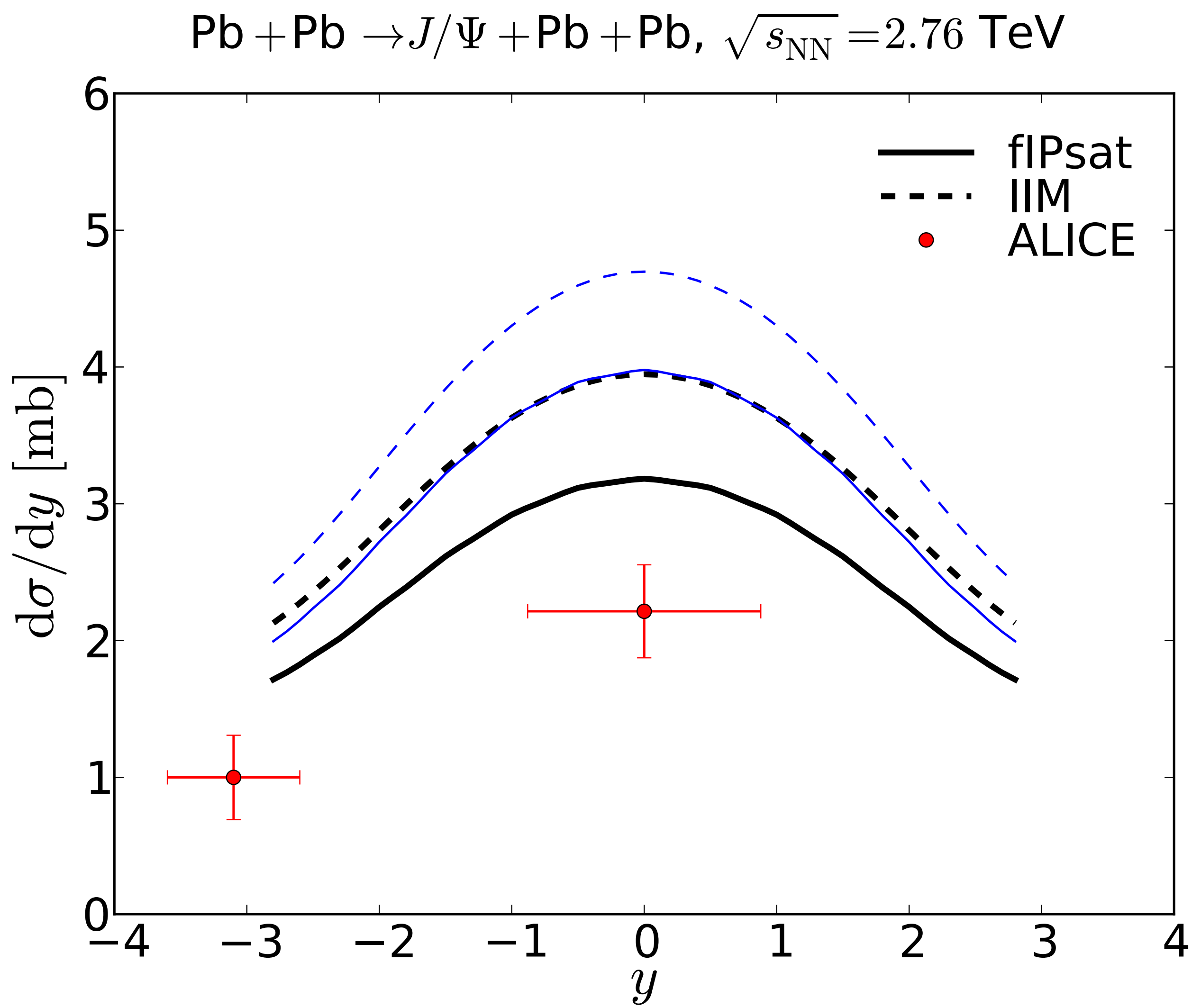


FIG. 1: The coherent diffractive J/Ψ photoproduction ($Q^2 = 0$ GeV^2) cross section in lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV computed using fIPsat and IIM parametrizations and Boosted Gaussian (thin blue lines) and Gaus-LC (thick black lines) wavefunctions compared with the ALICE data [8, 24].