Nuclear gluon distributions at small-x from charmonium and dijet photoproduction on nuclei at the LHC

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Outline:

- Gluon nuclear shadowing
- Leading twist nuclear shadowing model
- Gluon nuclear shadowing from J/ψ photoproduction on nuclei at the LHC
- Nuclear diffractive PDFs from diffractive dijet photoproduction in UPCs@LHC

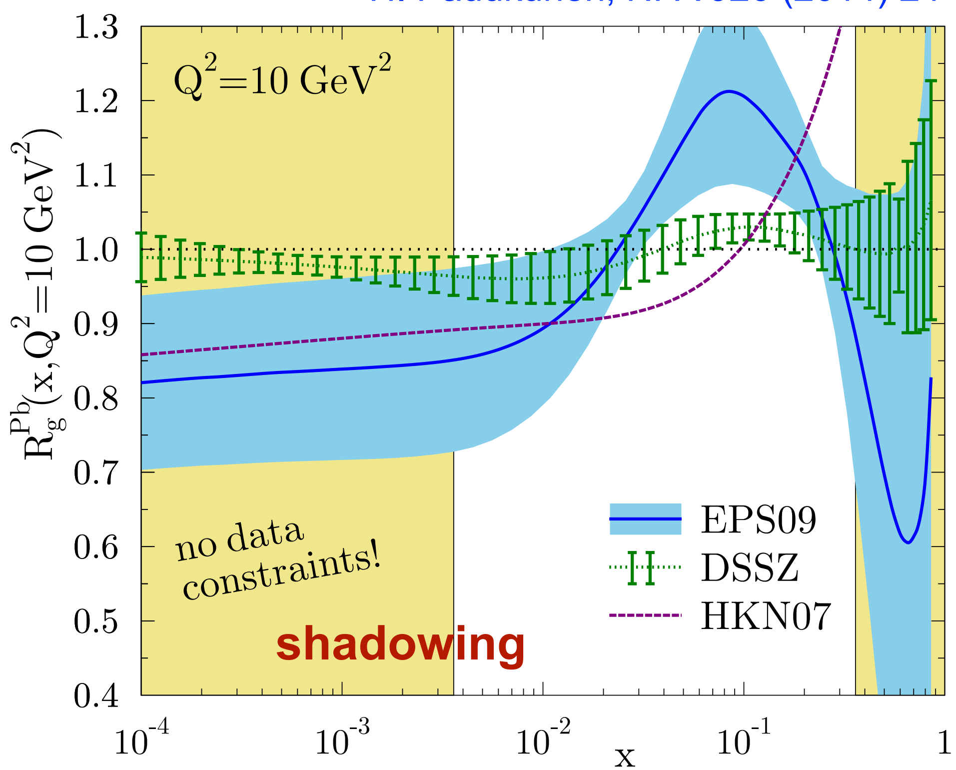
RIKEN BNL Research Center workshop “Synergies of pp and pA Collisions with an Electron-Ion Collider”, June 26-28, 2017

Gluon nuclear shadowing

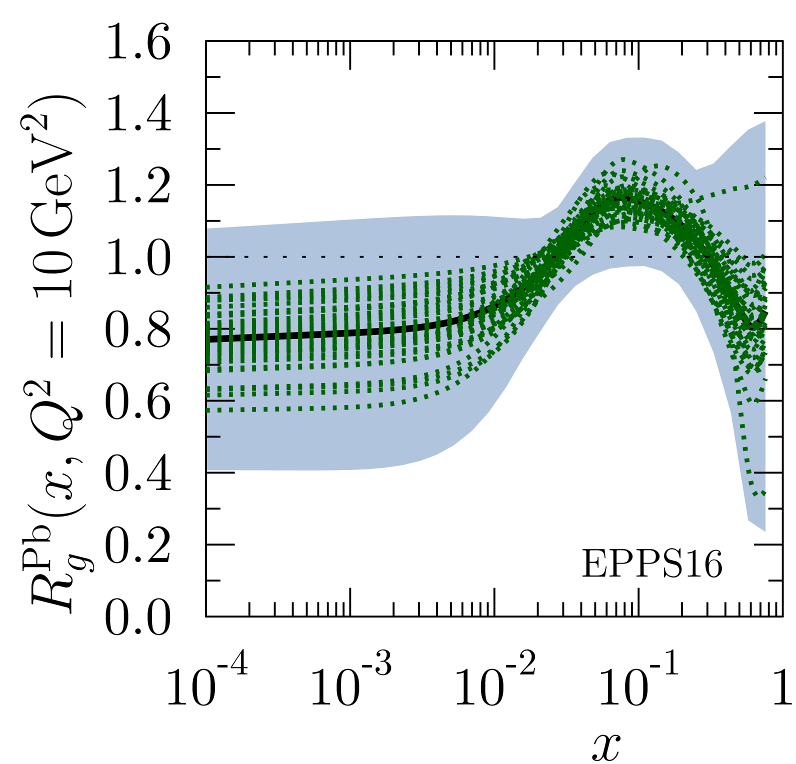
- Gluon nuclear shadowing: $g_A(x,\mu^2) < A\, g_N(x,\mu^2)$ for small $x < 0.005$.
- Important for QCD phenomenology of hard processes with nuclei: cold nuclear matter effects (RHIC, LHC), gluon saturation (RHIC, LHC, EIC)
- $g_A(x,\mu^2)$ is determined from global QCD fits to data on fixed-target DIS, hard processes in dA (RHIC) and pA (LHC) $\rightarrow g_A(x,\mu^2)$ with large uncertainties

$$R_g(x,Q^2) = \frac{g_A(x,Q^2)}{A g_p(x,Q^2)}$$

H. Pauukunen, NPA 926 (2014) 24

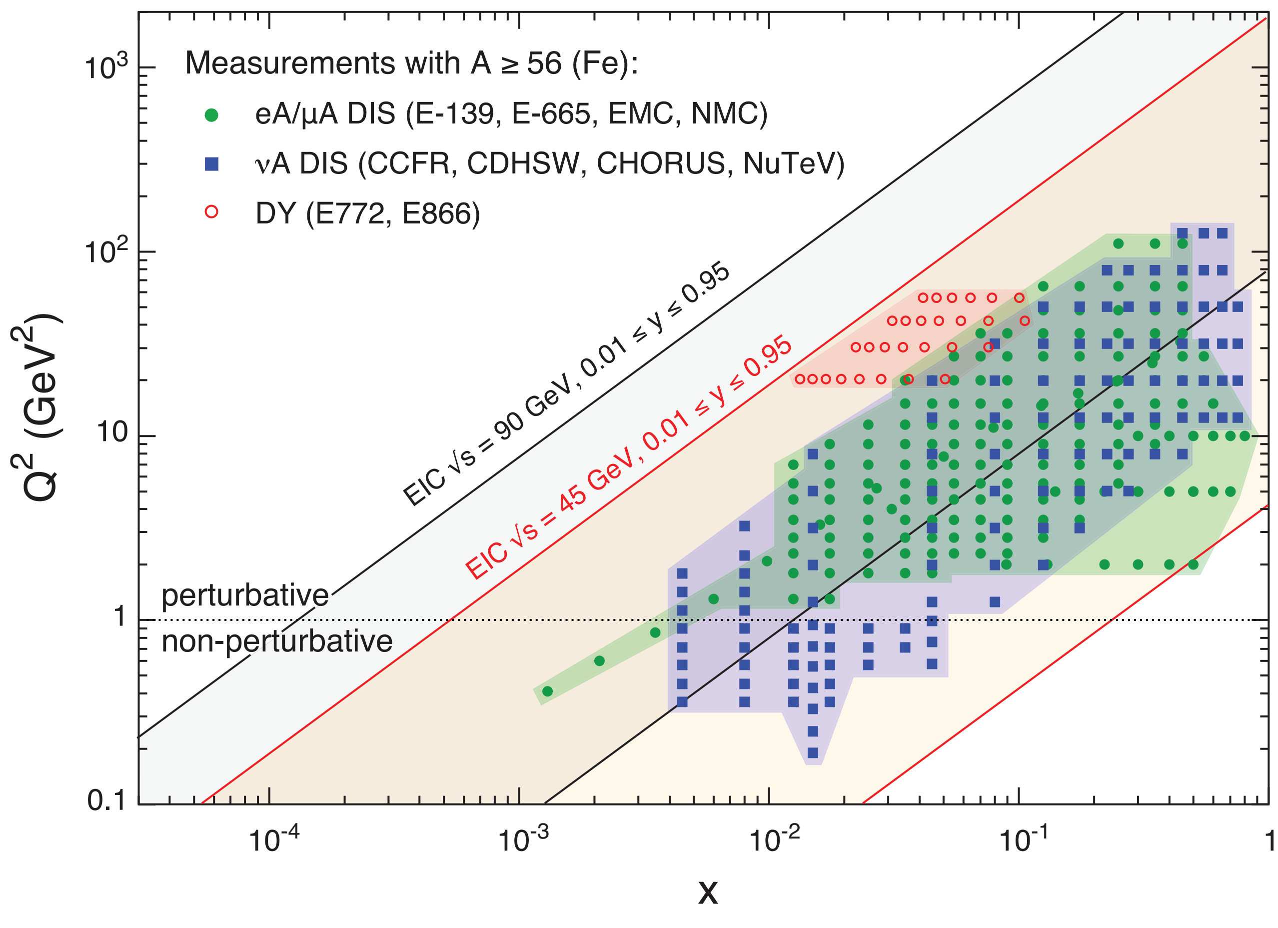


- pA@LHC data can help little, EPPS16, Eskola et al, EPJ C77 (2017) 163

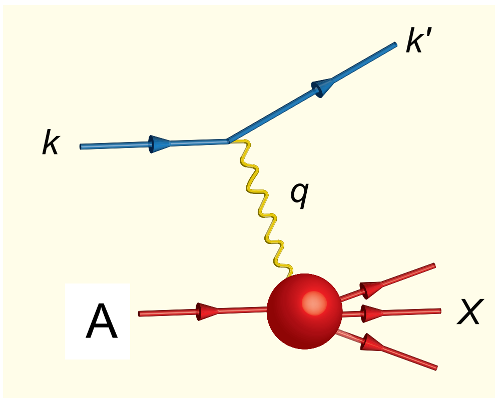


Gluon nuclear shadowing at EIC

• In the future, gluon nuclear shadowing will be constrained at EIC, Accardi et al, EPJ A52 (2016) no.9, 268; LHeC@CERN, LHEC Study Group, J. Phys. G39 (2012) 075001 due to wide Q^2-x kinematic coverage and $F_L^A(x,Q^2)$ measurements:



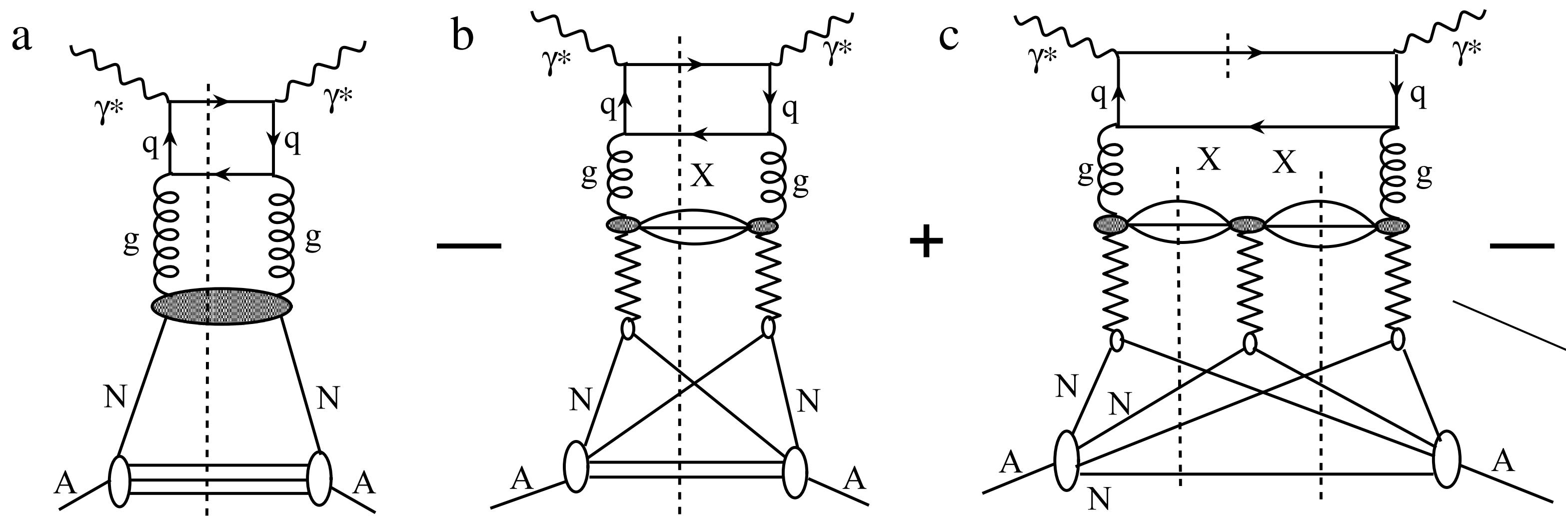
See also talks on plans for nPDFs:
- STAR (E. Aschenauer),
- sPHENIX (N. Feege)
- pA@ALICE (T. Chujo)
- global QCD fits (P. Zurita)



• Option right now: Charmonium and jet photoproduction in Pb-Pb UPCs@LHC

Leading twist nuclear shadowing model

- Combination of Gribov-Glauber nuclear shadowing model with QCD factorization theorems for inclusive and diffractive DIS → shadowing is driven by diffraction for individual partons j, Frankfurt, Strikman (1999); Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255



diffractive exchange

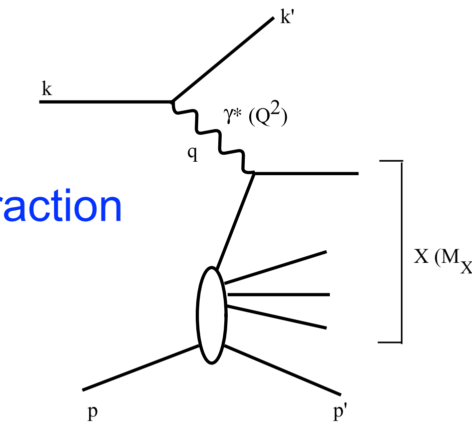
$$xf_{j/A}(x,Q_0^2) = Axf_{j/N}(x,Q_0^2) - 8\pi A(A-1)\,\Re e\frac{(1-i\eta)^2}{1+\eta^2}B_{\rm diff}\int_x^{0.1} dx_{\mathbb{P}}\,\beta f_j^{D(3)}(\beta,Q_0^2,x_{\mathbb{P}})$$

$$\times \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2\,\rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2)e^{i(z_1-z_2)x_{\mathbb{P}}m_N}\,e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm soft}^j(x,Q_0^2)\int_{z_1}^{z_2}dz'\rho_A(\vec{b},z')}$$

proton diffractive PDFs

effective cross section

Leading twist nuclear shadowing model



- Main input: diffractive parton distributions $f_j^{D(3)}$ measured in diffractive DIS on proton at HERA, H1, ZEUS

See talk on diffraction (A. Stasto)

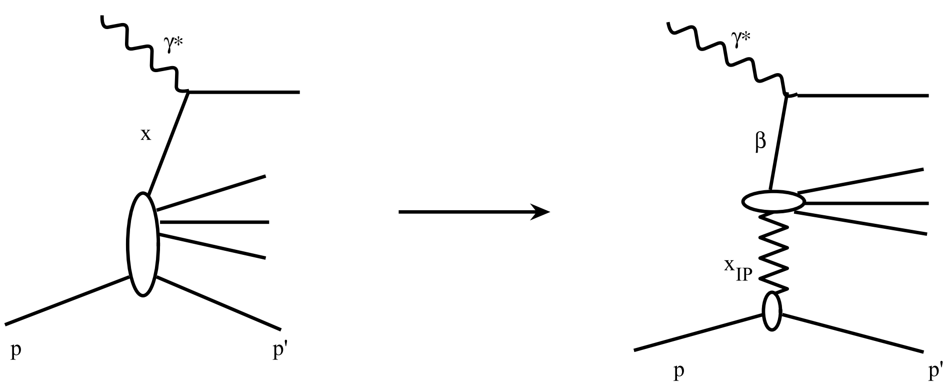
$$F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t) = \beta \sum_{j=q,\bar{q},g} \int_{\beta}^{1} \frac{dy}{y} C_j\left(\frac{\beta}{y}, Q^2\right) f_j^{D(4)}(y, Q^2, x_{\mathbb{P}}, t)$$

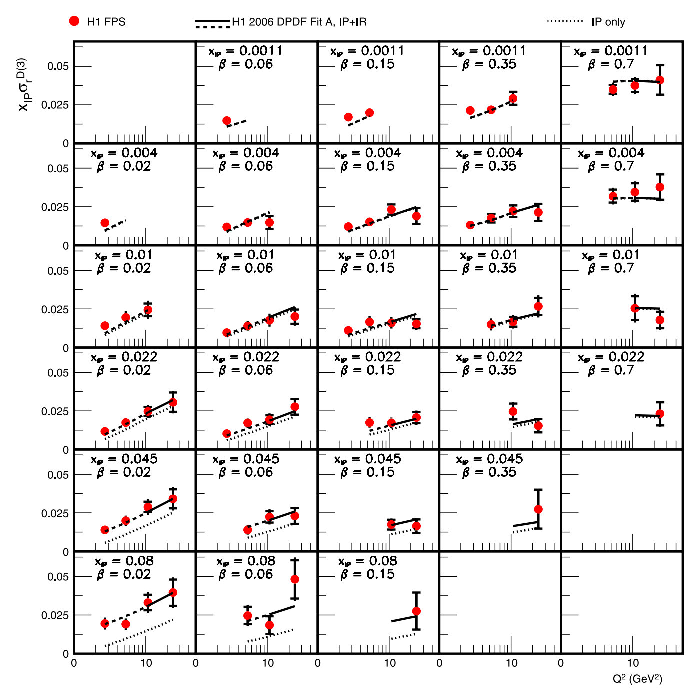
$$t = (p' - p)^2,$$

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

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

- Diffractive parton distribution $f_j^{D(3)}$ = conditional probability to find parton with momentum fraction β provided the proton does not break





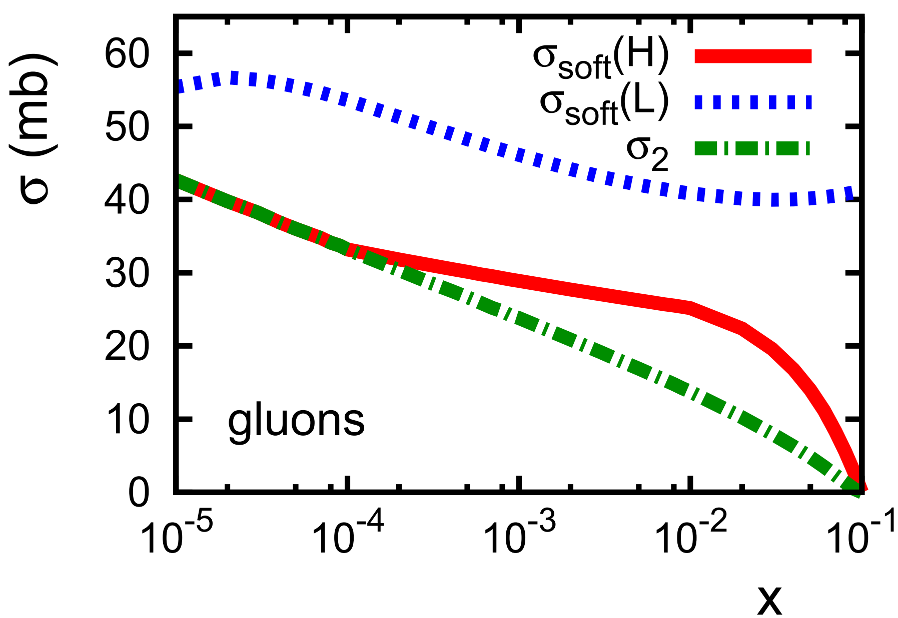
- One of main HERA results: diffraction in DIS is leading twist → hence the name "leading twist shadowing"

Leading twist nuclear shadowing model

- Predicts nuclear PDFs at μ^2=3-4 GeV^2 → input for DGLAP evolution.
- Magnitude of shadowing is determined by proton diffractive PDFs, ZEUS, H1 2006 → naturally predicts large shadowing for $g_A(x,\mu^2)$.
- Presents alternative to small-x extrapolation of nPDFs from global fits.

- One free parameter: $\sigma_{\rm soft}(x) = \dfrac{\int d\sigma P_\gamma(\sigma)\sigma^3}{\int d\sigma P_\gamma(\sigma)\sigma^2}$

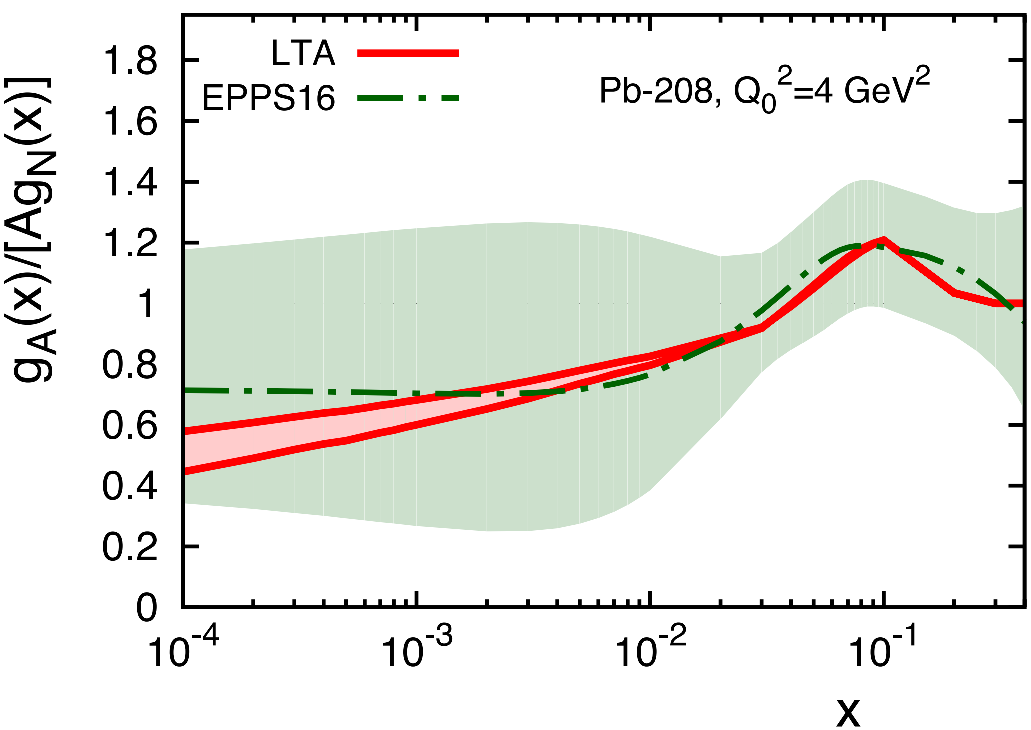
- Estimated two plausible models of photon hadronic fluctuations:
  - like in the pion, Blattel et al, 1993
  - like in the dipole model, McDermott, Frankfurt, Guzey, Strikman, 2000



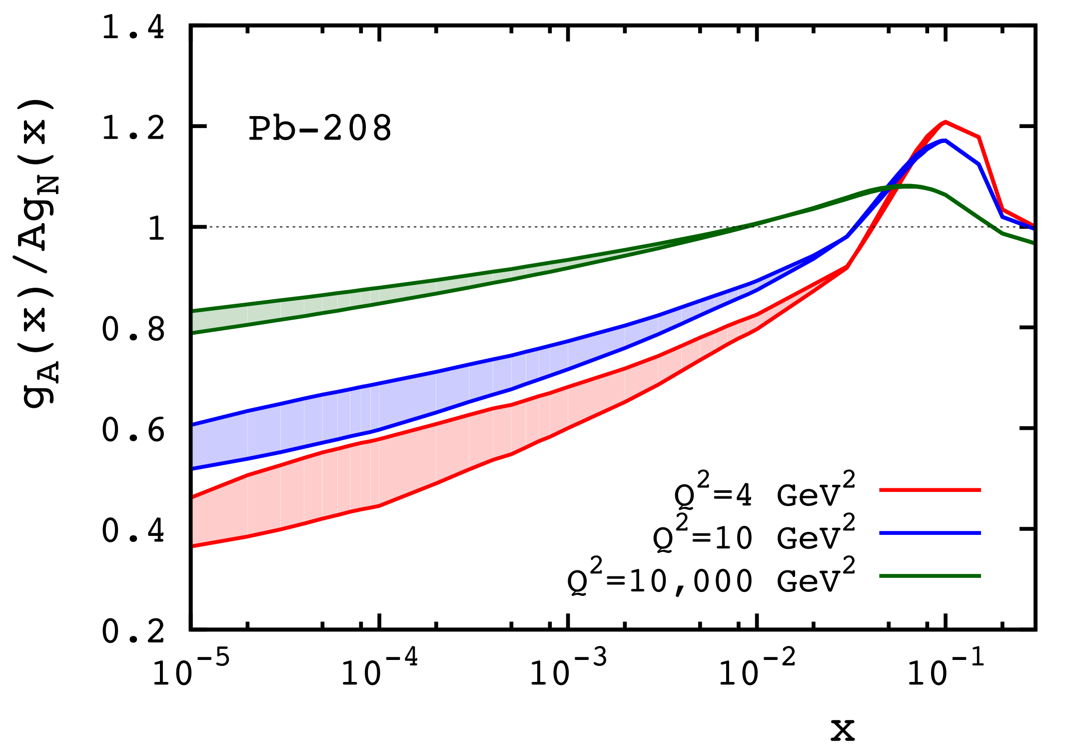
- Model also predicts impact parameter dependent nuclear PDFs $g_A(x,b,Q^2)$ →
  - shift of t-dependence of $\gamma A \to J/\psi A$ cross section in UPCs;
  - oscillations of beam-spin nuclear DVCS asymmetry at EIC.

Leading twist nuclear shadowing model

Leading twist (LTA) vs. EPPS16



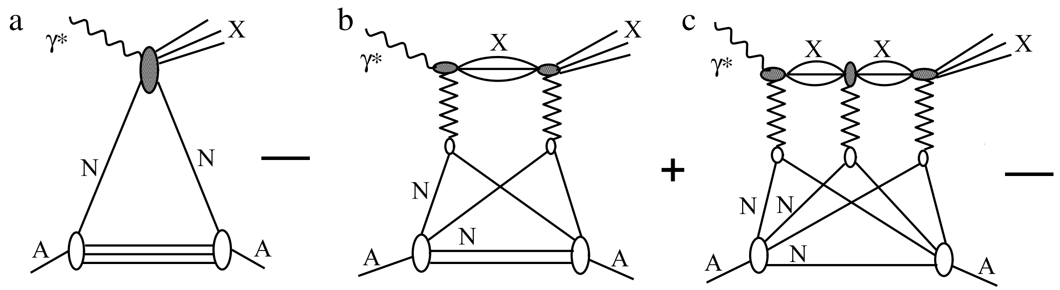
Results of DGLAP evolution: from Q^2=4 GeV^2 to Q^2=10 and 10,000 GeV^2



For quarks, the agreement between LTA and EPS09 and EPPS16 is much better.

Nuclear diffractive parton distributions

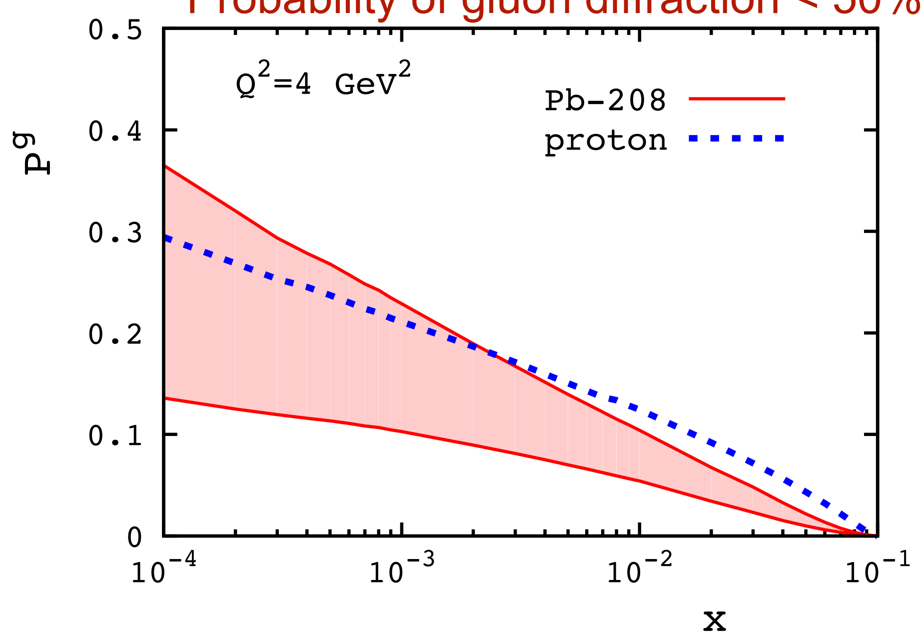
- Leading twist nuclear shadowing model for inclusive diffraction in γ^*A:



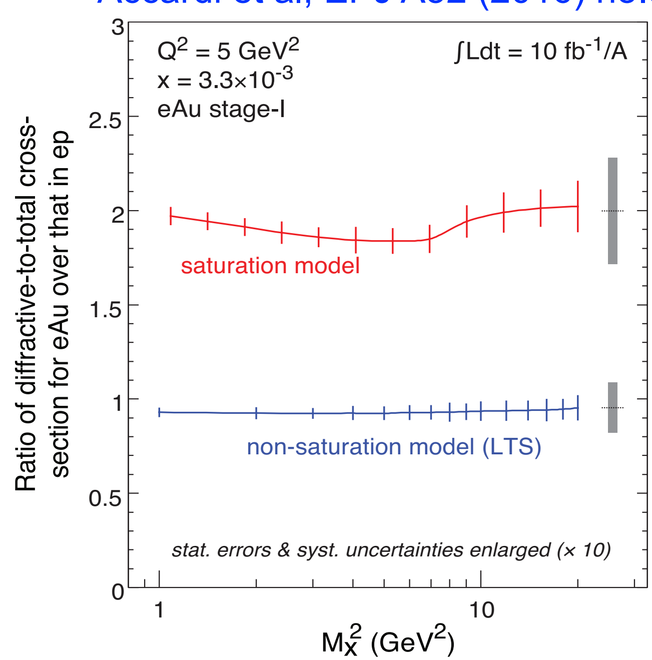
$$\beta f_{j/A}^{D(3)}(x,\mu^2,x_P) = 16\pi f_{j/N}^{D(4)}(x,\mu^2,x_P,t=0)\int d^2b\left(\frac{1-e^{-\frac{1}{2}\sigma_{\rm soft}^j(x)T_A(b)}}{\sigma_{\rm soft}^j(x)}\right)^2$$

- LT shadowing suppresses diffraction on nuclei → slows down approach to saturation :

Probability of gluon diffraction < 50%

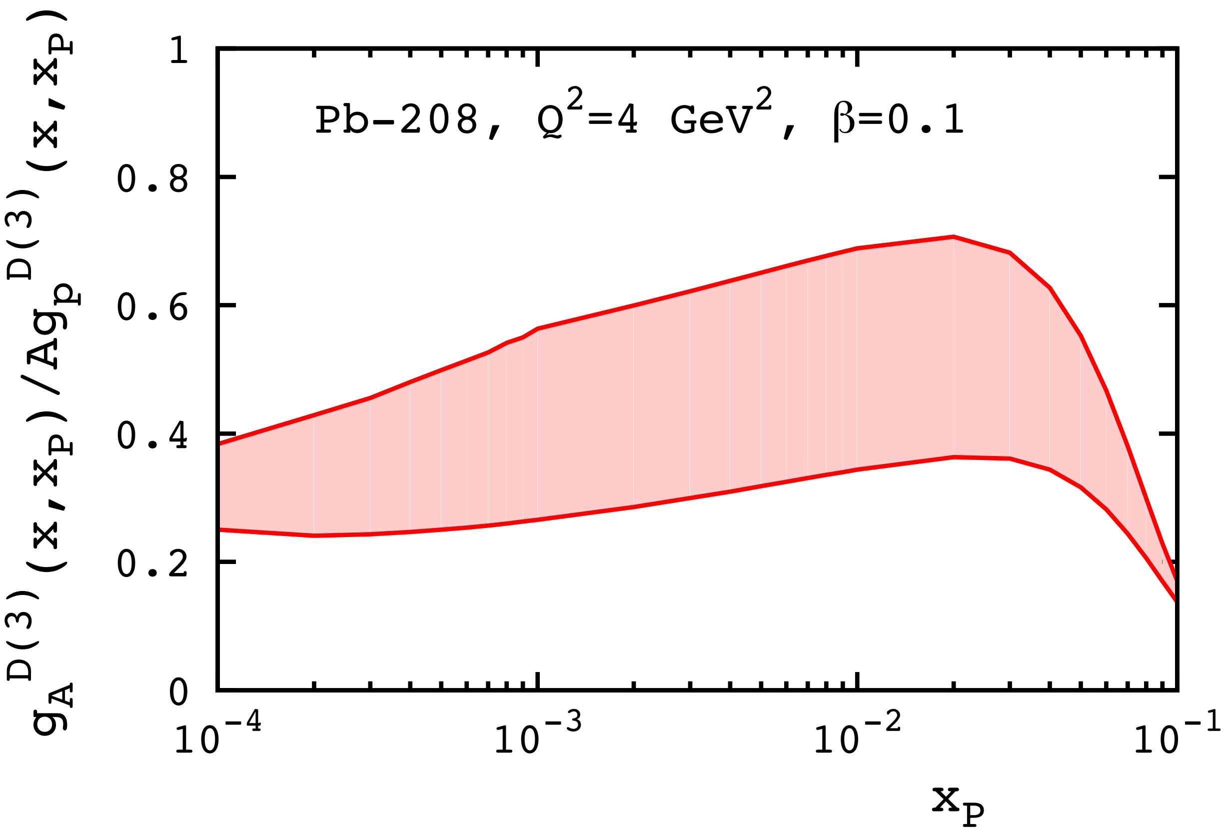


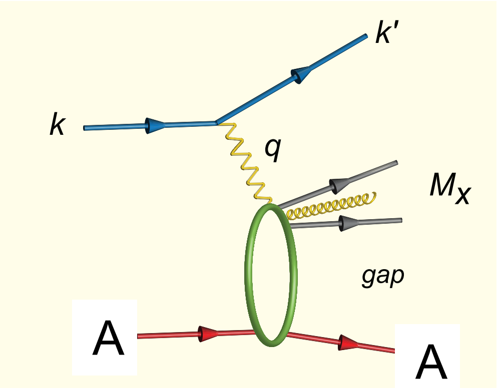
Accardi et al, EPJ A52 (2016) no.9, 268



Nuclear diffractive parton distributions

- LT nuclear shadowing model predicts nuclear diffractive PDFs:

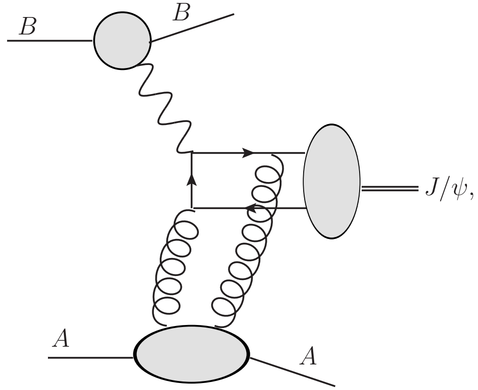




- Can be measured in inclusive γ^*A diffraction at LHeC/EIC and hard diffraction in γA, e.g., diffractive photoproduction of dijets in UPCs@LHC, Guzey, Klasen 2016

Ultraperipheral collisions

• Ions can interact at large impact parameters $b \gg R_A+R_B$ → ultraperipheral collisions (UPCs) → strong interaction suppressed → interaction via quasi-real photons, Fermi (1924), von Weizsäcker; Williams (1934)



- UPCs correspond to empty detector with only two lepton/pion tracks
- Nuclear coherence by veto on neutron production by Zero Degree Calorimeters and selection of small pt

• Coherent photoproduction of vector mesons in UPCs:

$$\frac{d\sigma_{AA\to AAJ/\psi}(y)}{dy} = N_{\gamma/A}(y)\sigma_{\gamma A\to AJ/\psi}(y) + N_{\gamma/A}(-y)\sigma_{\gamma A\to AJ/\psi}(-y)$$

Photon flux from QED:
- high intensity ~ Z^2
- high photon energy ~ γ_L

Photoproduction cross section

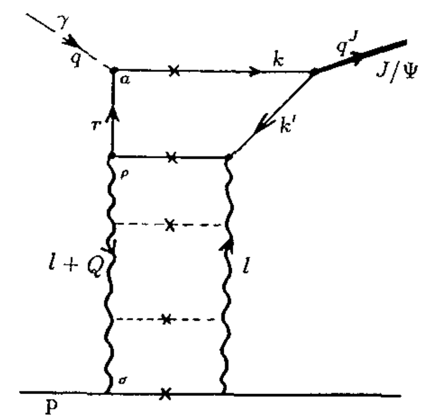
$y = \ln[W^2/(2\gamma_L m_N M_V)]$

= J/ψ rapidity

UPCs@LHC = γp and γA interactions at unprecedentedly large energies, Baltz *et al.*, The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1

Coherent charmonium photoproduction

• In leading logarithmic approximation of pQCD 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)

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

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

• Our phenomenological approach: μ^2 and C(μ^2) from W-dependence of γp →J/ψp measured at HERA:

- $\mu^2 \approx 3$ GeV^2 for J/ψ, Guzey, Zhalov JHEP 1310 (2013) 207
- $\mu^2 \approx 4$ GeV^2 for ψ(2S), Guzey, Zhalov, arXiv:1405.7529

Coherent charmonium photoproduction

- Application to nuclear targets:

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

Small correction $k_{A/N} \approx 0.90$-95

From HERA and LHCb

Nucleus/proton gluon ratio Rg

From nuclear form factor

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

- Well-defined impulse approximation (IA):

$$\sigma^{\mathrm{IA}}_{\gamma A\to J/\psi A}(W_{\gamma p}) = \frac{d\sigma_{\gamma p\to J/\psi p}(W_{\gamma p}, t=0)}{dt} \Phi_A(t_{\min})$$

- Nuclear suppression factor S $\rightarrow$ direct access to R_g

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

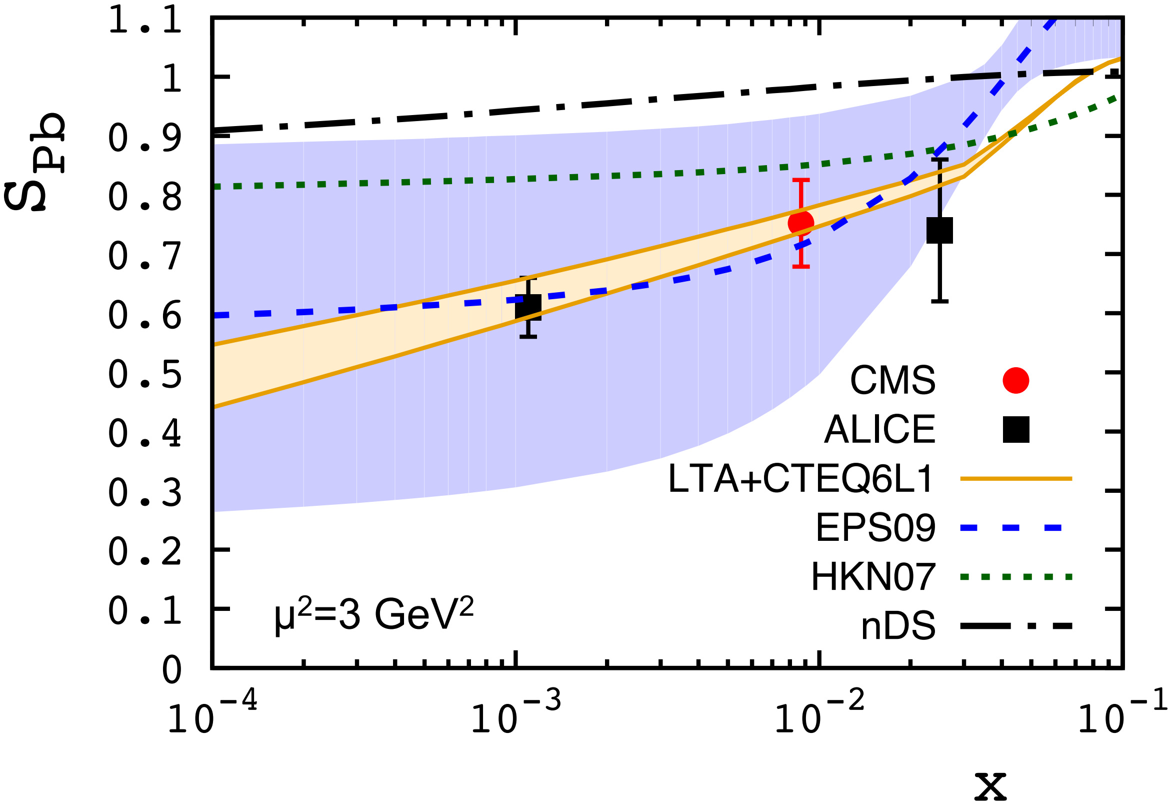
Model-independently from data on UPC@LHC (ALICE, CMS) and HERA

From global QCD fits of nPDFs or leading twist nuclear shadowing model

Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290

Comparison to S_{Pb} from ALICE and CMS UPC data

- J/ψ photoproduction in Pb-Pb UPCs at LHC, Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; CMS Collab., arXiv:1605.06966 → suppression factor S

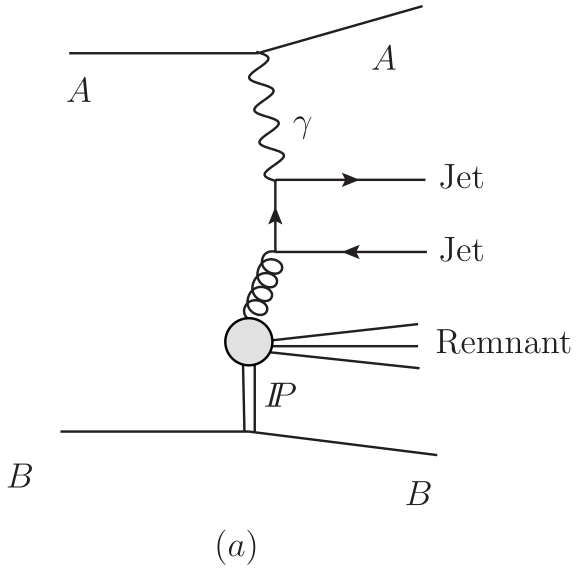


LTA: Guzey, Zhalov JHEP 1310 (2013) 207
EPS09: Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065
HKN07: Hirai, Kumano, Nagai, PRC 76 (2007) 065207
nDS: de Florian, Sassot, PRD 69 (2004) 074028

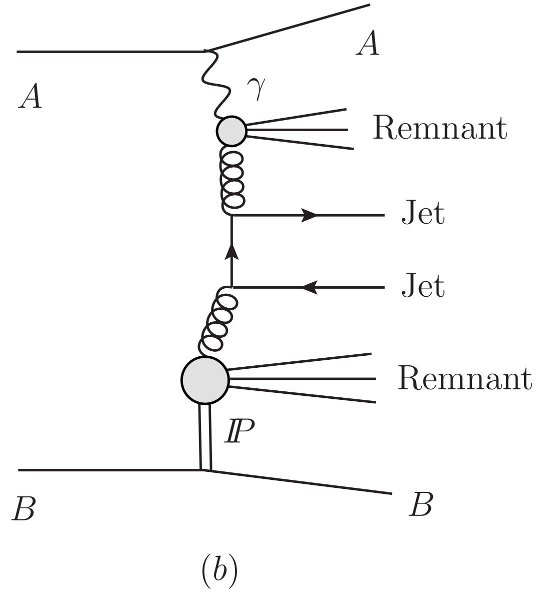
- Good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs@2.76 TeV → first direct evidence of large gluon NS, $R_g(x=0.001) \approx 0.6$.
- Also good description using central value of EPS09 and EPPS16, large uncertainty.
- Color dipole models generally fail to reproduce suppression, Goncalves, Machado (2011); Lappi, Mantysaari, 2013, but proton shape fluctuations help, see talk B. Schenke

Diffractive dijet photoproduction in UPCs

- Run 1 UPC program focused on photoproduction of light (ρ) and heavy (J/ψ, ψ(2S), Υ) vector mesons, see talk by D. Tapia Takaki
- First Run 2 results on inclusive jet photoproduction in UPCs, see talk by B. Cole
- We propose: diffractive dijet photoproduction, Guzey, Klasen, JHEP 2016 (2013) 290



direct photon



resolved photon

These events are characterized by:
- no hadronic activity along beam directions (rapidity gaps)
- two jets with large pt
- remnants from Pomeron and γ

- Studies of this process in UPCs at the LHC may allow to:

- improve understanding of QCD factorization breaking in diffraction
- for the first time determine nuclear diffractive PDFs
- improve determination of proton diffractive PDFs

Diffractive dijet photoproduction in UPC

- In direct analogy with NLO pQCD calculations for the ep case, Klasen, Kramer 2010
  - photon flux from electron → photon flux from proton/nucleus
  - proton diffractive PDFs → nuclear diffractive PDFs
  - model for factorization breaking for resolved photon for nuclear case

- Two contributions for right/left moving ions:

$$d\sigma(AA \to A + 2\text{jets} + X' + A) = d\sigma(AA \to A + 2\text{jets} + X' + A)^{(+)} + d\sigma(AA \to A + 2\text{jets} + X' + A)^{(-)}$$

- Cross section of dijet photoproduction in UPCs:

$$d\sigma(AA \to A + 2\text{jets} + X' + A)^{(+)} = \sum_{a,b} \int_{t_{\text{cut}}}^{t_{\text{min}}} dt \int_{x_P^{\text{min}}}^{x_P^{\text{max}}} dx_P \int_0^1 dz_P \int_{y_{\text{min}}}^{y_{\text{max}}} dy \int_0^1 dx_\gamma$$
$$\times \quad f_{\gamma/A}(y) f_{a/\gamma}(x_\gamma, \mu^2) f_{b/A}^{D(4)}(x_P, z_P, t, \mu^2) d\hat{\sigma}_{ab\to\text{jets}}^{(n)}$$

photon flux (including suppression of strong interaction at small b)

PDF of the photon (includes direct component and effect of factorization breaking)

nuclear diffractive PDF (including the effect of nuclear shadowing)

elementary parton cros section

Factorization breaking for resolved photon

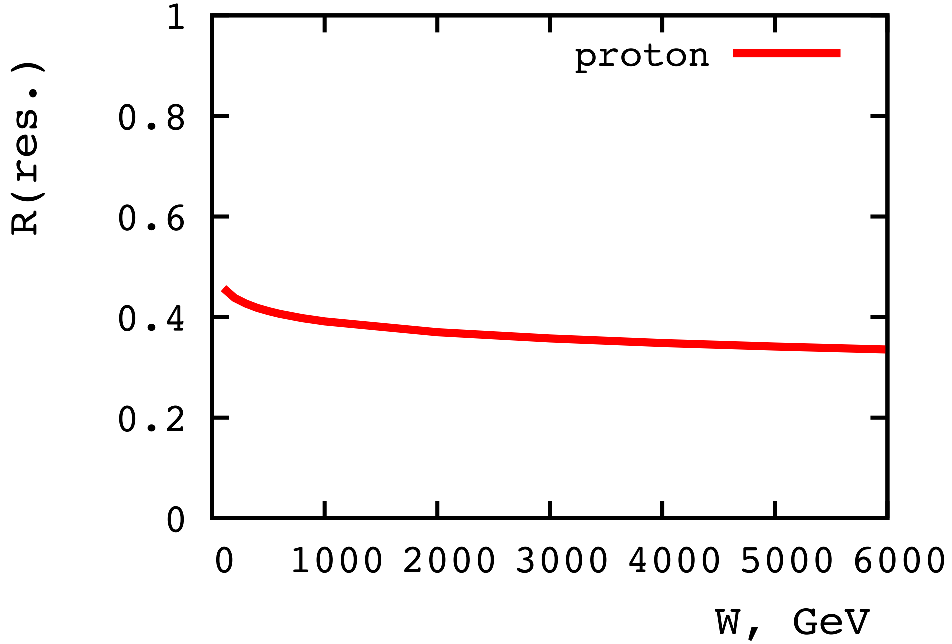
- Suppression factor for resolved component for γA case:

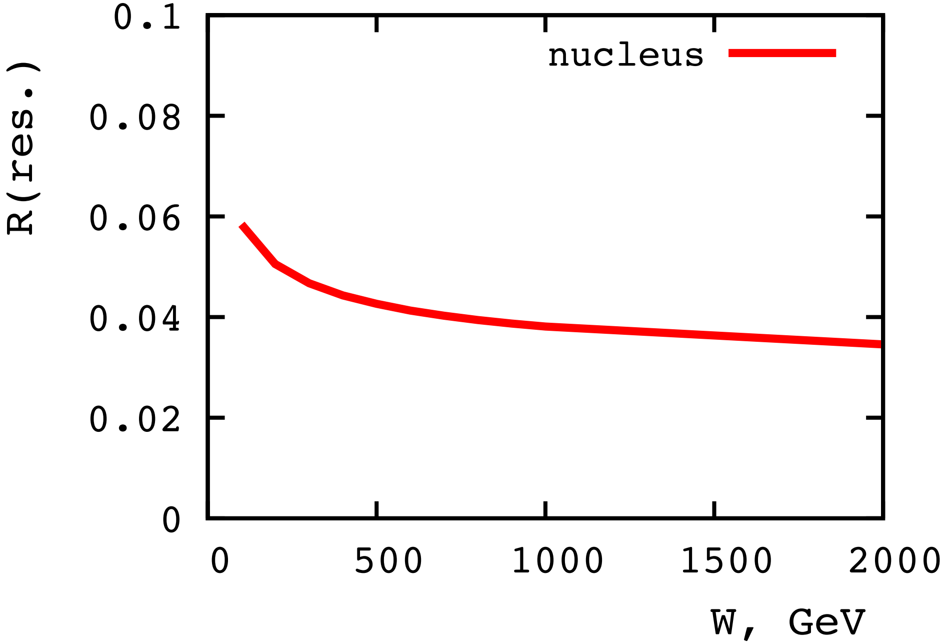
$$R(\text{res.}) = \frac{\int d^2b \, |1 - e^{-\sigma_{\rho N}/2 T_A(b)}|^2 e^{-\sigma_{\rho N} T_A(b)}}{\int d^2b \, |1 - e^{-\sigma_{\rho N}/2 T_A(b)}|^2}$$

Nuclear optical density

Probability of coherent ρ photoproduction

Probability not to have inelastic interactions

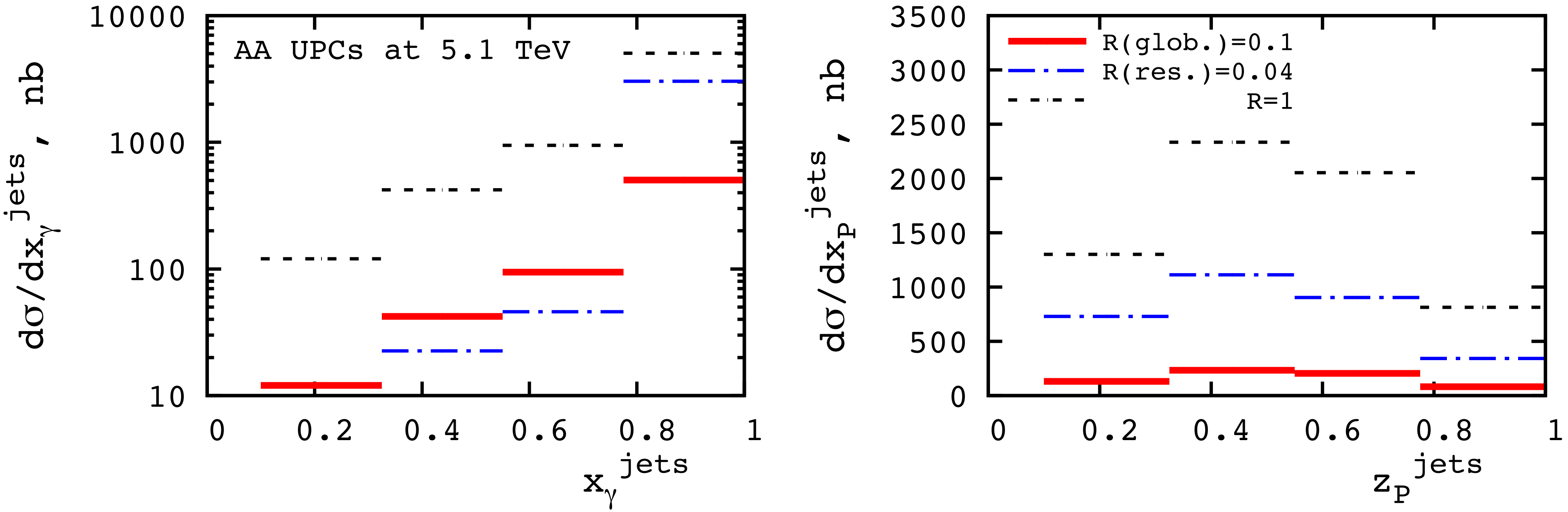




R(res) ≈ 0.4 agrees with analysis of HERA data, Klasen, Kramer (2010). Follows Kaidalov, Khoze, Martin, Ryskin,PLB 567 (2003) 61

R_A(res) ≈ 0.1 R_p(res) since it is much easier to break up nuclei.

Predictions for AA UPCs



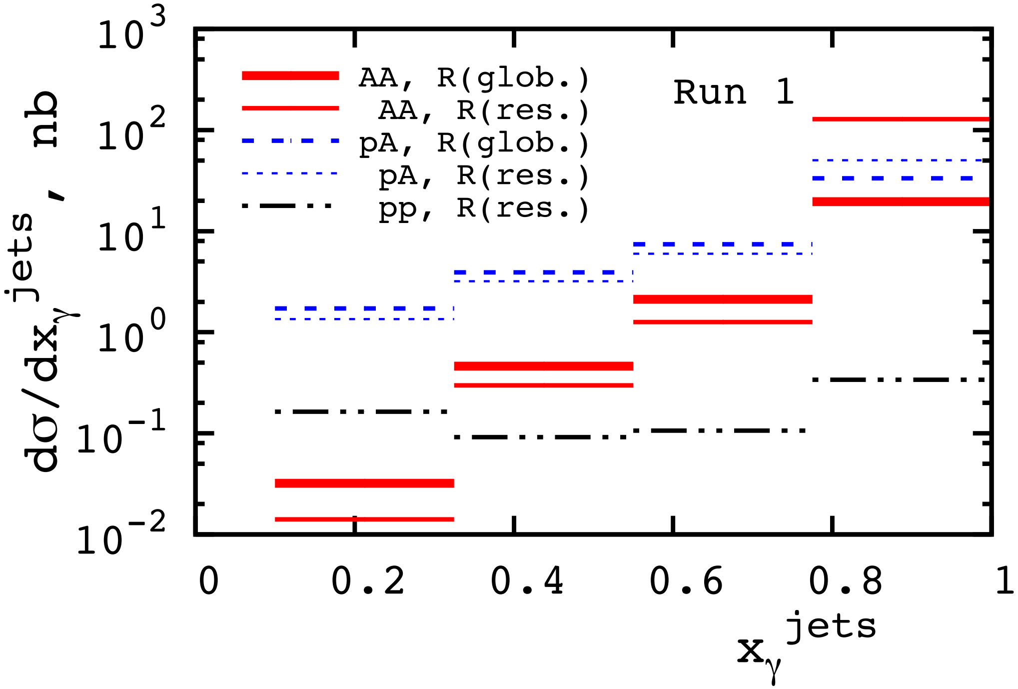
- Cross sections are enhanced by $Z^2 \approx 7000$ due to photon flux and $A^{4/3} \approx 1200$ due to nuclear diffractive PDFs → large: O(microbarns)

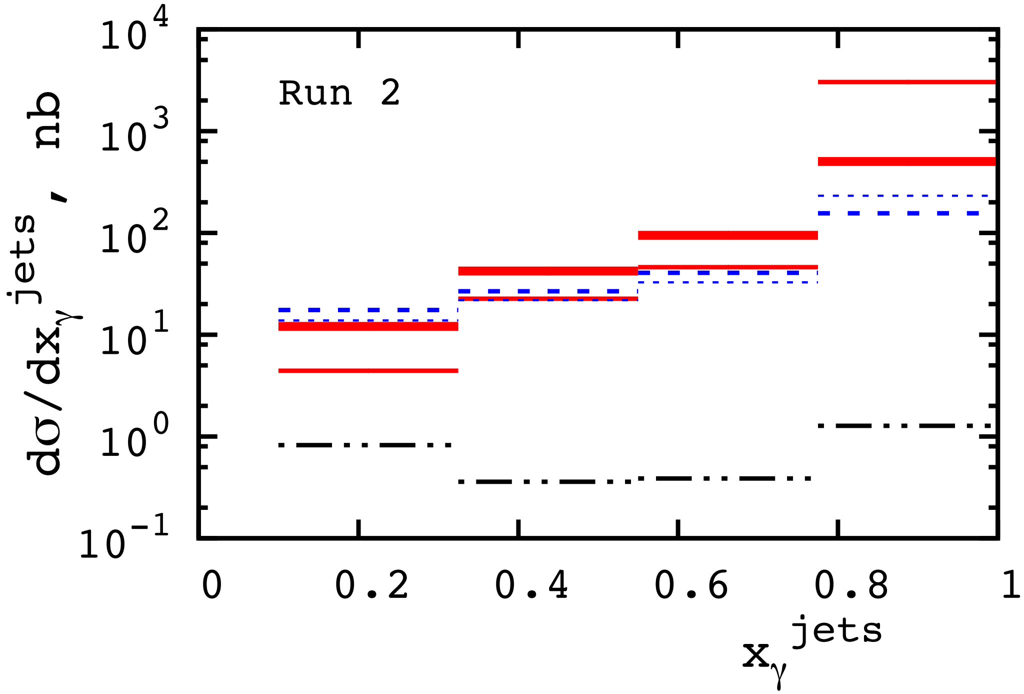
- Without LT nuclear shadowing → cross section increases by factor **7**

- Large sensitivity to scheme of factorization breaking: red and blue lines cross over!

x_γ-dependence of factorization breaking

- x_γ is most sensitive observable to scenario of factorization breaking.
- UPCs with nuclei give a principle possibility to distinguish the global suppression and resolved-only suppression scenarios.





Summary

- Small-x nPDFs — especially gluon nPDFs — are poorly constrained. Small-x predictions of global QCD fits of nPDFs are extrapolations.
- An alternative is leading twist nuclear shadowing model, which connects shadowing and diffraction and predicts large gluon shadowing.
- Photoproduction of J/ψ in Pb-Pb UPCs at the LHC gives direct evidence of large gluon nuclear shadowing $R_g(x=0.001, \mu^2 \approx 3\ \mathrm{GeV}^2) = 0.6$.
- Diffractive dijet photoproduction on nuclei in UPCs probes nuclear diffractive PDFs and is sensitive to the mechanism of QCD factorization breaking in diffraction. The key observable is dependence on photon momentum fraction x_γ.
- New STAR data on J/ψ photoproduction in Au-Au UPCs at 200 GeV: $x_A=0.015$ at $y=0$, see talk by E. Aschenauer.
- Theoretical challenge: include UPC data in global QCD fits for nPDFs.
- UPCs@LHC = forerunner of measurements of $g_A(x,\mu^2)$ at an EIC.
- Recent workshop on UPC physics: INT workshop “Probing QCD in Photon-Nucleus Interactions at RHIC and LHC: the Path to EIC”, Feb 13-17, 2017: http://www.int.washington.edu/talks/WorkShops/int_17_65W/, see talk by D. Tapia Takaki.