Dynamic mechanisms for shadowing

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AoF CoE in
Quark Matter

ERC adG YoctoLHC

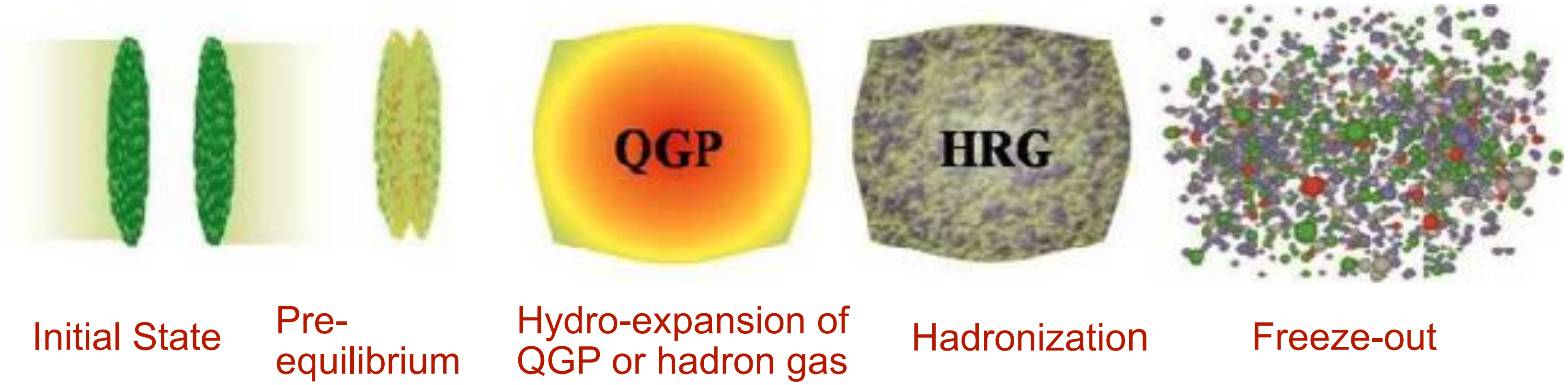
Outline:

- Nuclear shadowing in scattering with nuclei
- Leading twist approximation for nuclear shadowing
- Nuclear shadowing in dipole picture
- Nuclear shadowing and saturation
- Summary and outlook

Nuclear shadowing in AA scattering

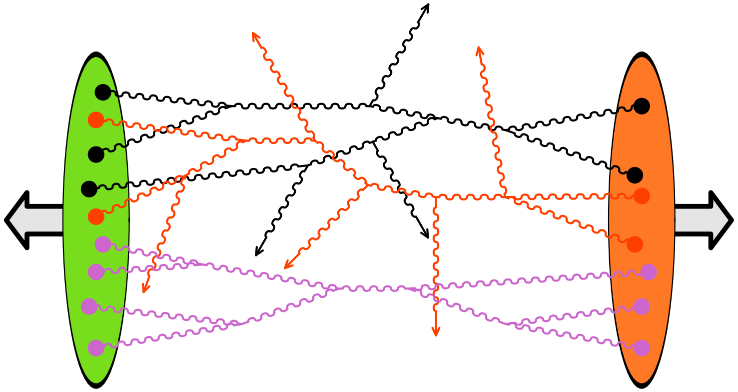
• Nuclear shadowing (NS) is general phenomenon of high-energy scattering → nuclear cross section < sum of nucleon cross sections → nuclear parton distributions (nPDFs) < sum of nucleon PDFs at small x.

• In context of nucleus-nucleus (AA) scattering → NS defines initial conditions (cold nuclear matter effects).



S. Bass, Duke Univ.

• Fundamental in its own right (e.g. nPDFs) and also for description of onset of new states of matter → color glass condensate (CGC) and quark-gluon plasma (QGP).

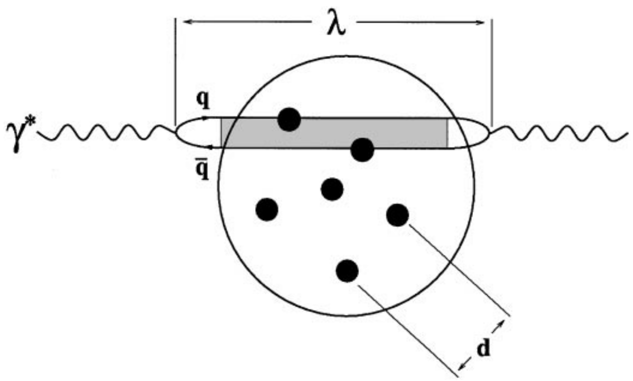


F. Gelis, 1412.0471 [hep-ph]

Nuclear shadowing in $\gamma^{(*)}$A scattering

• Cleanest way to probe NS is using photons: real photons in UPCs at RHIC and LHC and virtual photons eA DIS with fixed targets and at EIC.

• In target rest frame, NS is due to multiple interactions of long-lived fluctuations of $\gamma^{(*)}$ with target nucleons → destructive interference of amplitudes with N=1,2,..A nucleons → nucleons geometrically shadow each other → Gribov-Glauber (GG) theory of NS, 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.

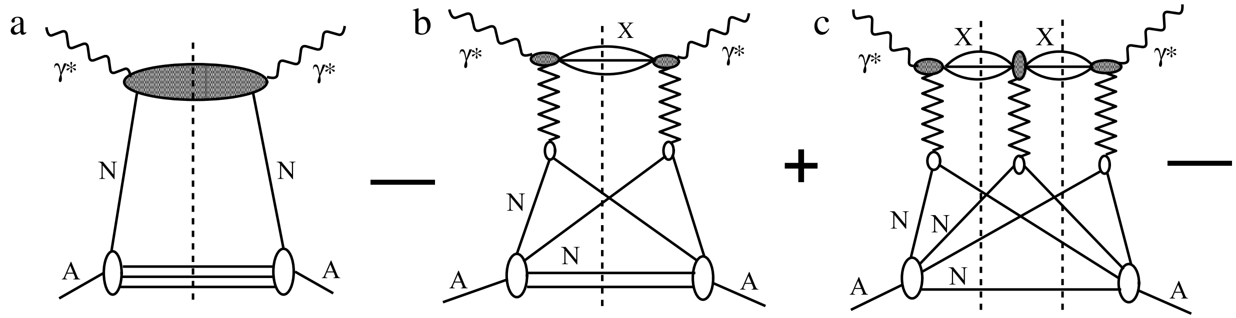


• Soft processes: fluctuations are vector mesons (VMD model), Bauer, Spital, Yennie, Pipkin, Rev. Mod. Phys. 50 (1978) 261 or generic hadronic states in Good-Walker picture, Good, Walker, PR 120 (1960) 1857; Blättet, Baym, Frankfurt, Heiselberg, Strikman, PRD 47 (1992) 2761.

• Hard processes: fluctuations are $q\bar{q}$, $q\bar{q}g$,… QCD states (dipoles), Nikolaev, Zakharov, Z. Phys. C 49 (1991) 607; Mueller, NPB 415 (1994) 373.

Gribov-Glauber theory of nuclear shadowing

- Interactions with N=1,2,3,..A target nucleons:

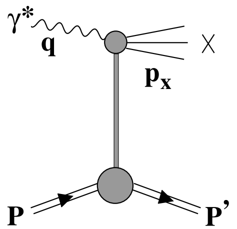


- Shadowing correction to total $\gamma^{(*)}$A cross section, Karmanov, Kondratyuk, JETP Lett. 18 (1973) 266; Kaidalov et al, EPJ C 5 (1998) 111; Piller, Weise, Phys. Rept. 330 (2000) 1

$$\delta\sigma_{\gamma^* A} = -8\pi \int d^2b \int_{-\infty}^{+\infty} dz_1 \int_{z_1}^{+\infty} dz_2\, \rho_A(\boldsymbol{b}, z_1)\, \rho_A(\boldsymbol{b}, z_2)$$
$$\times \int_{4m_\pi^2}^{W^2} dM_X^2 \cos[(z_2 - z_1)/\lambda] \frac{d^2\sigma_{\gamma^* N}^{\rm diff}}{dM_X^2\, dt}\bigg|_{t\approx 0} \exp\left[-\frac{\sigma_{XN}}{2}\int_{z_1}^{z_2} dz\, \rho_A(\boldsymbol{b}, z)\right]$$

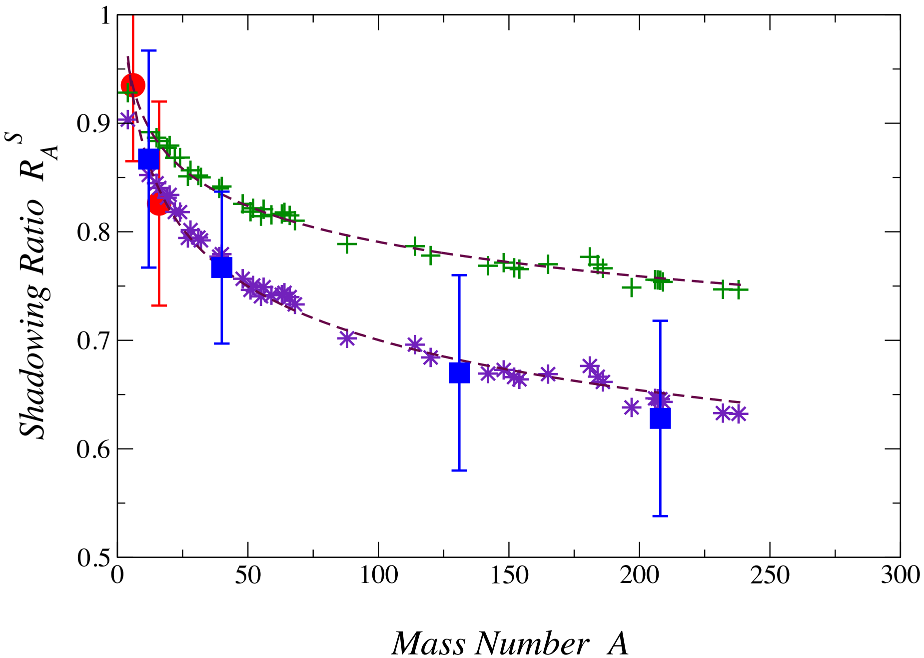
- Main feature: N=2 contribution to NS in terms of diffraction on proton → consequence of unitarity (AGK cutting rules), Abramovsky, Gribov, Kancheli, Sov. J. Nucl. Phys. 18 (1974) 308 → elastic and inelastic intermediate states.

$$\sigma_{\rm eff} = \frac{16\pi}{\sigma_{\gamma N}(1+\eta^2)} \int_{4m_\pi^2}^{W^2} dM_X^2 \, \frac{d^2\sigma_{\gamma^* N}^{\rm diff}}{dM_X^2 dt}\bigg|_{t\approx 0}$$

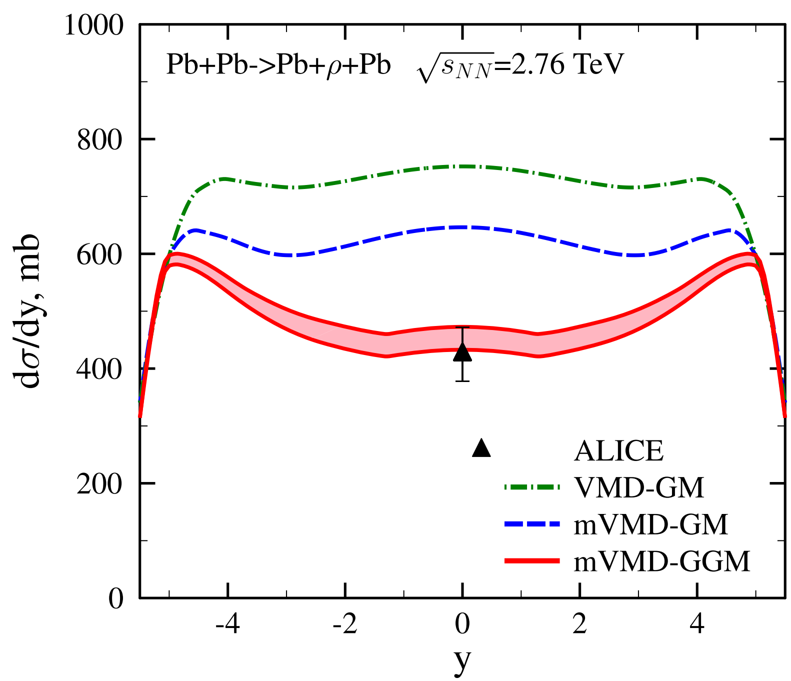


GG shadowing in soft γA scattering

• Using data on diffraction of real photons to low and high diffractive masses $M_X \rightarrow$ good description of total γA cross section, Adeluyi, Fai, PRC 74 (2006) 054904



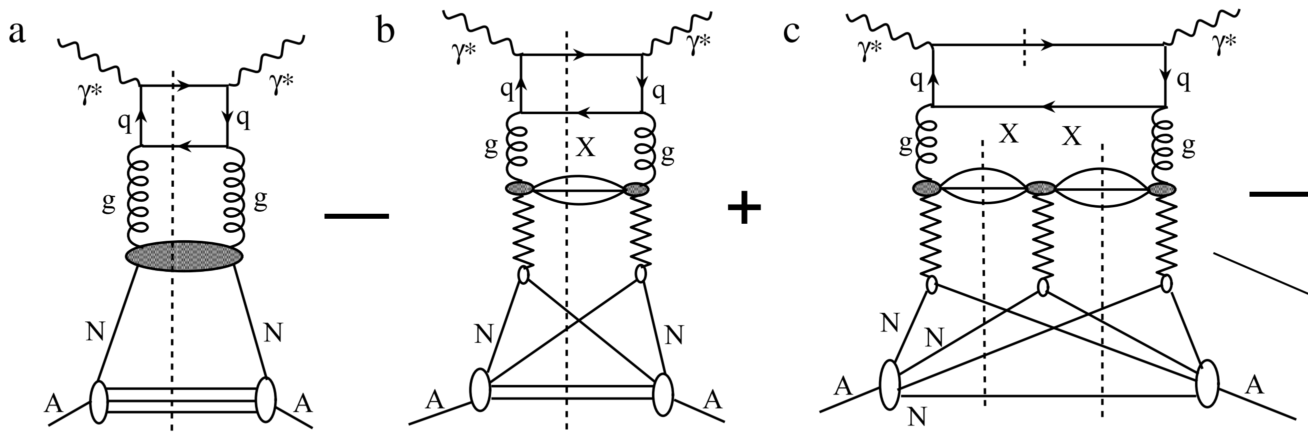
• Account of hadronic fluctuations of real photons $\rightarrow$ elastic (ρ) and inelastic intermediate states $\rightarrow$ good description of Run 1,2 data on coherent ρ photoproduction in Pb-Pb UPCs@LHC, Frankfurt, Guzey, Strikman, Zhalov, PLB 752 (2016) 51; Guzey, Kryshen, Zhalov, PRC 102 (2020) 1, 015208



• Gribov (inelastic) shadowing correction is small for pA, noticeable for γA, and dominant (leading twist) for γ^*A.

Leading twist model of nuclear shadowing

- Combination of Gribov-Glauber theory with QCD factorization theorems for inclusive and diffractive DIS → prediction for small-x nPDFs at input scale Q_0,
  Frankfurt, Strikman, EPJ A5 (1999) 293; Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255



diffractive exchange

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

j=q or g

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

nuclear density

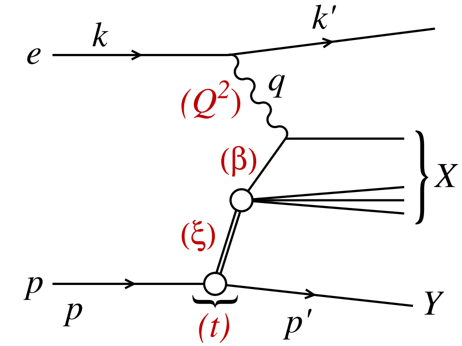
N=2 term: proton diffractive PDFs from HERA

N ≥ 3 terms: model-dependent effective cross section

- Alternative to extraction of nPDFs using global QCD fits, Plenary talk on nPDFs, 23.06.

Leading twist model of nuclear shadowing (2)

- Essential input: universal, leading twist (LT) diffractive PDFs of proton, Collins, PRD 57, 3051 (1998); PRD 61, 019902 (2000)

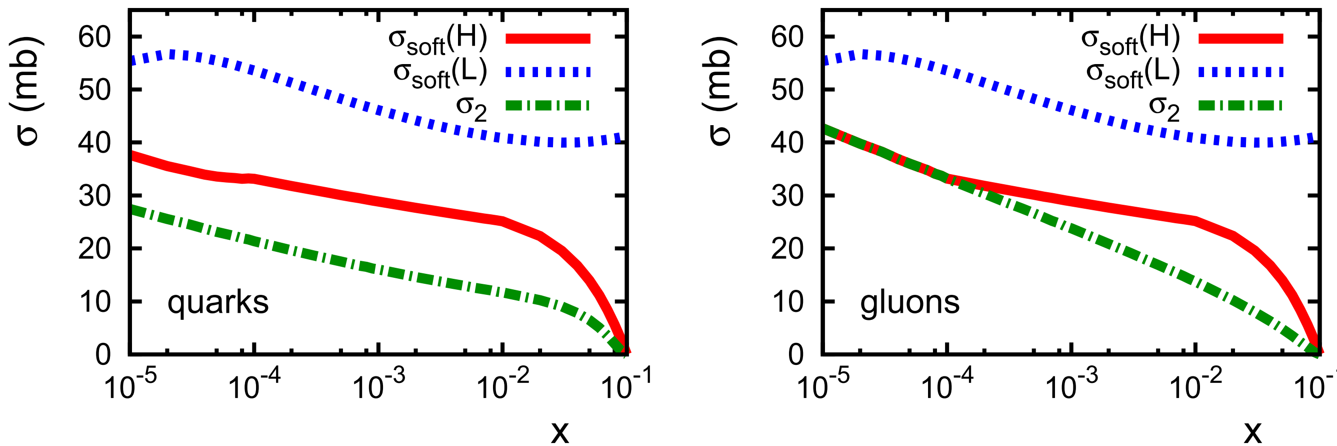


- Extracted from HERA data on diffraction in ep DIS, Aktas et al [H1], EPJ C48, 715 (2006), EPJC 48, 749 (2006); Chekanov et al [ZEUS], NPB 831, 1 (2010)

- Interaction with 2 nucleons model-independently in terms of diffractive (Pomeron) PDFs:

$$\sigma_2^j(x,Q^2) = \frac{16\pi}{(1+\eta^2) x f_{j/N}(x,Q^2)} \int_x^{0.1} dx_{\mathbb{P}} \beta f_j^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t_{\min}).$$

- Interaction with N ≥ 3 nucleons modeled using hadronic fluctuations of photon

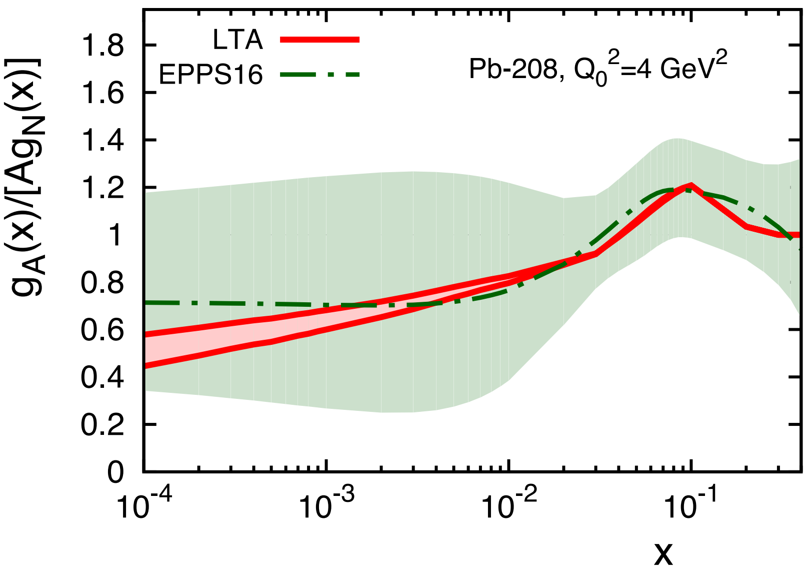


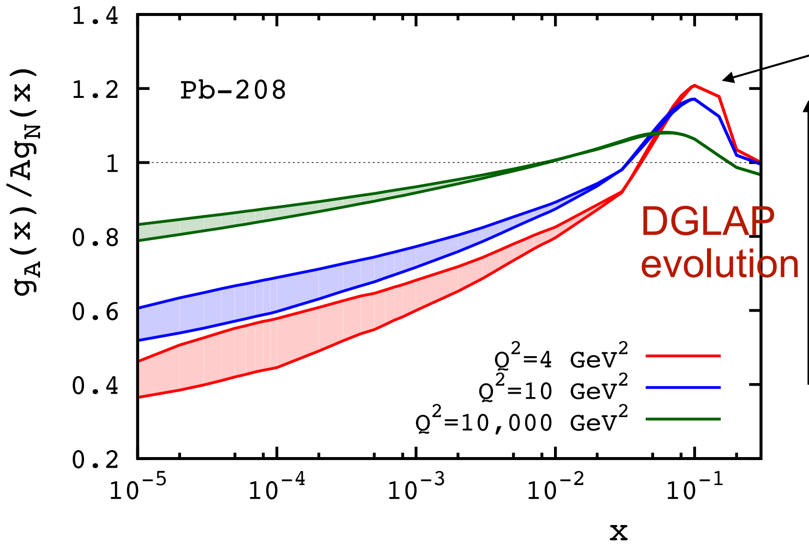
Spread in σ_{soft} → uncertainty of LTA predictions

- "LT" in the name comes from HERA analysis, but higher twist effects in diffraction at low Q_0 could be significant, Motyka, Sadzikowski, Slominski, PRD 86 (2012) 111501; Maktoubian, Mehraban, Khanpour, Goharipour, PRD 100 (2019) 054020.

LTA predictions for nPDFs

- HERA analysis: perturbative Pomeron is made mostly of gluons → LTA model naturally predicts large gluon nuclear shadowing, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255





Antishadowing from momentum sum rule.

Alternative: dynamic model, Frankfurt, Guzey, Strikman, PRC 95 (2017) 1, 055208

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

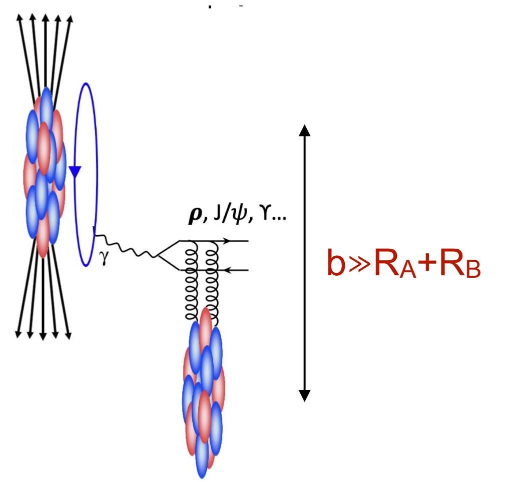
- Electron-Ion Collider has potential to discriminate models of NS due to:

- wide x-Q^2 coverage
- measurements of the longitudinal structure function $F_L^A(x,Q^2)$ sensitive to gluons
- measurements of diffraction in eA DIS

Plenary talks on EIC, 23.06.

Nuclear shadowing in UPC at LHC

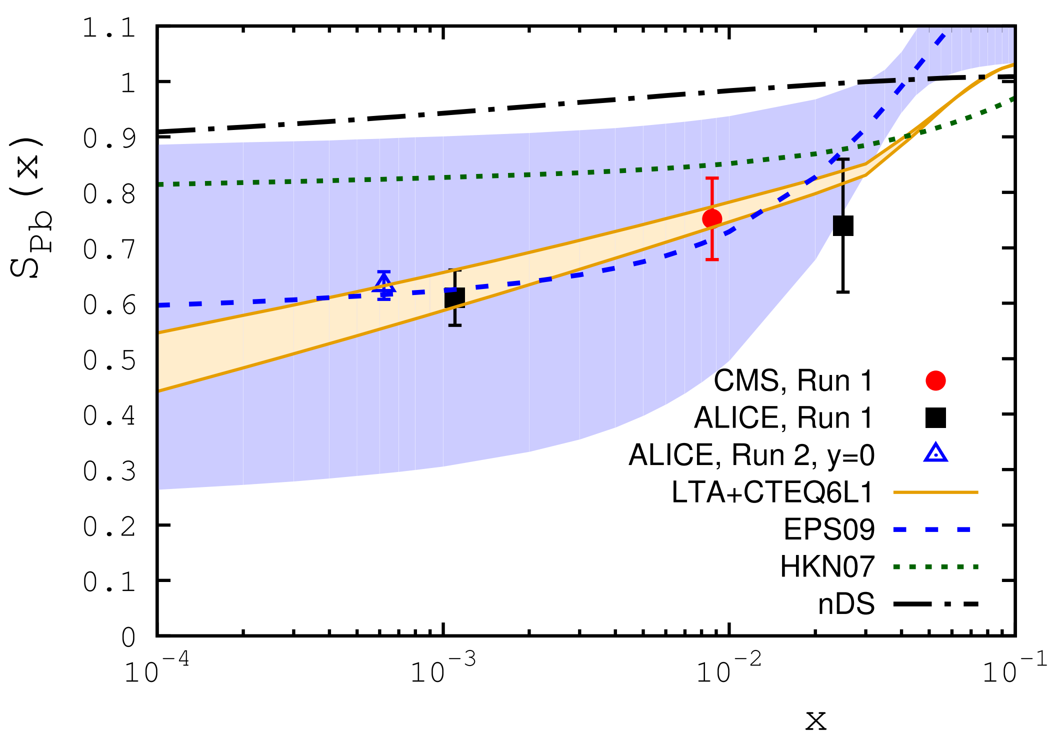
• Before EIC, models of NS can be tested in ultraperipheral collisions (UPCs) of heavy ions at LHC and RHIC, Plenary talks on UPCs, 21.06; Nystrand, 20.06



• Measured cross section converted nuclear suppression factor S_{Pb}, Abelev *et al.* [ALICE], PLB718 (2013) 1273; Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; [CMS] PLB 772 (2017) 489; Acharya et al [ALICE], EPJC 81 (2021) 8, 712

$$S_{Pb}(W) = \left[\frac{\sigma^{\gamma A\to J/\psi A}(W)}{\sigma_{\rm IA}^{\gamma A\to J/\psi A}(W)}\right]^{1/2} = \frac{g_A(x,\mu^2)}{A g_p(x,\mu^2)}$$

A. Stahl, LPCC CERN Seminar, 6.12.2022



• Direct evidence of large gluon shadowing, $R_g(x=6\times10^{-4} - 0.001) \approx 0.6$ in agreement with LTA model and EPS09/ EPPS16 nPDFs, Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290, Guzey, Zhalov, JHEP 1310 (2013) 207

• NLO pQCD challenges this interpretation due strong cancellation between LO and NLO gluon terms, Eskola, plenary talk on 21.06.

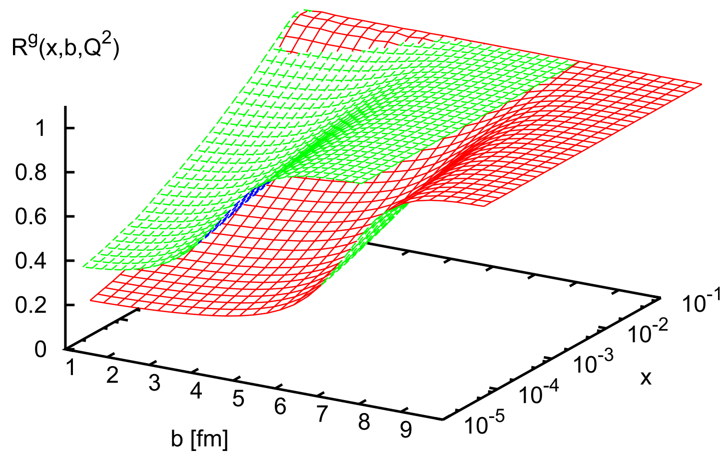
Impact parameter dependence of NS

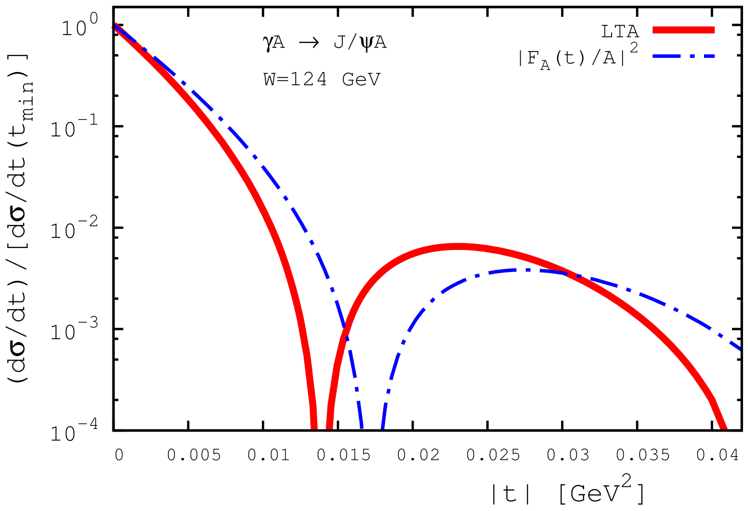
- Leading twist models predicts dependence of nPDFs on the impact parameter b (transverse position of partons in nucleus):

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

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

- Shadowing is stronger at small b → broadening of nPDFs in b-space → shift of t-dependence of $\gamma A \to J/\psi A$ cross section, Guzey, Strikman, Zhalov, PRC 95 (2017) 2, 025204 → confirmed by ALICE, Acharya et al., PLB 817 (2021) 1, 136280





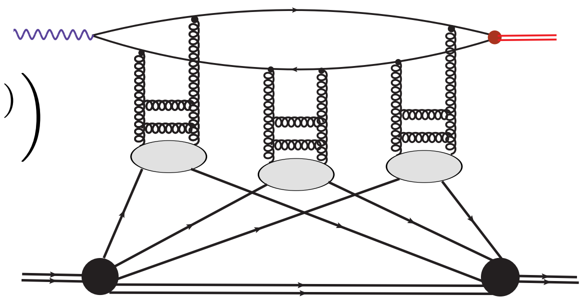
- Similar effect is caused by saturation in dipole picture, Bendova, Cepila, Contreras, Matas, PLB 817 (2021) 136306
- With additional assumptions, b-dependence of nPDFs can be extracted from data using global QCD fits, EPS09s, Helenius, Eskola, Honkanen, Salgado, JHEP 07 (2012) 073.

Nuclear shadowing in dipole picture

• Space-time picture of strong interaction at high energies in target rest frame → photon is a superposition of long-lived q$\bar{q}$, q$\bar{q}$g,… dipoles.

• Dipoles successively, elastically scatter on target nucleons → high-energy factorization for, e.g., γ+A→J/ψ+A amplitude:

$$\mathcal{M}^{\gamma A\to J/\psi A} = \int d^2\mathbf{r}_T \int \frac{dz}{4\pi} \int d^2\mathbf{b}_T [\Psi^*_{J/\psi}\Phi_\gamma] 2\left(1 - e^{-\frac{1}{2}\sigma_{\rm dip}(\mathbf{r}_T)T_A(\mathbf{b}_T)}\right)$$



Overlap of photon (QED) and J/ψ (model) wf's

Dipole cross section from fits to HERA

Nuclear density

• Describes data on $F_{2A}(x,Q^2)$ in eA DIS, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303

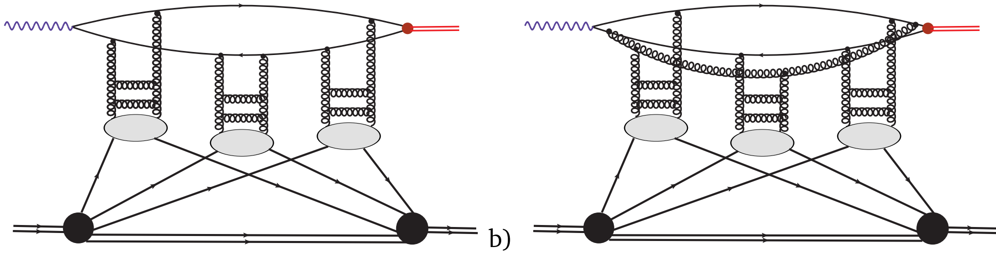
• But overestimates coherent J/ψ photoproduction in Pb-Pb UPCs, Lappi, Mäntysaari, PRC 87 (2013) 3, 032201; Luszczak, Schäfer, PRC 99 (2019) 4, 044905

• Weak shadowing is general property of eikonal scattering of small-size dipoles, e.g. longitudinal structure function $F_L^A(x,Q^2)$, Frankfurt, Guzey, McDermott, Strikman, JHEP 02 (2002) 027

• Need to include higher q$\bar{q}$g Fock states (dipoles) to better describe diffraction on proton driving NS, Buchmüller, McDermott, Hebeker, NPB 487 (1997) 283; Kowalski, Lappi, Marquet, Venugopalan, PRC 78 (2008) 045201; Golek-Biernat, Luszczak, PRD 79 (2009) 114010

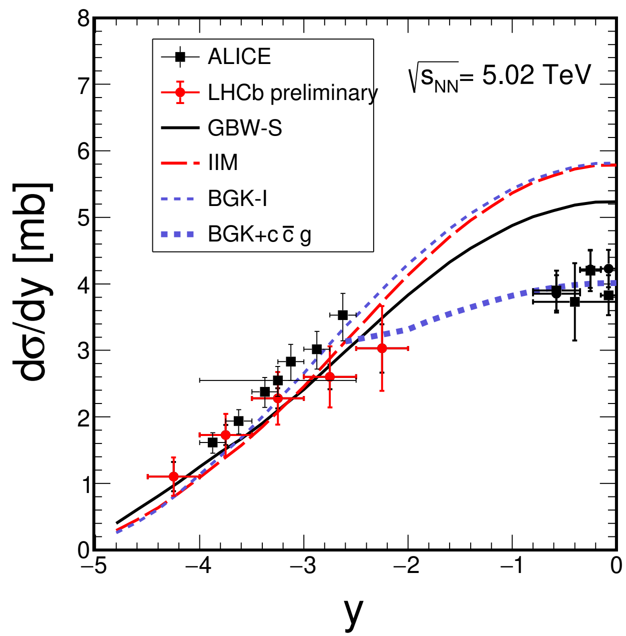
Dipole picture: role of $q\bar{q}g$ dipoles

- Higher $q\bar{q}g$ Fock states contribute to inelastic shadowing → bridge gap between dipole picture and LT model.

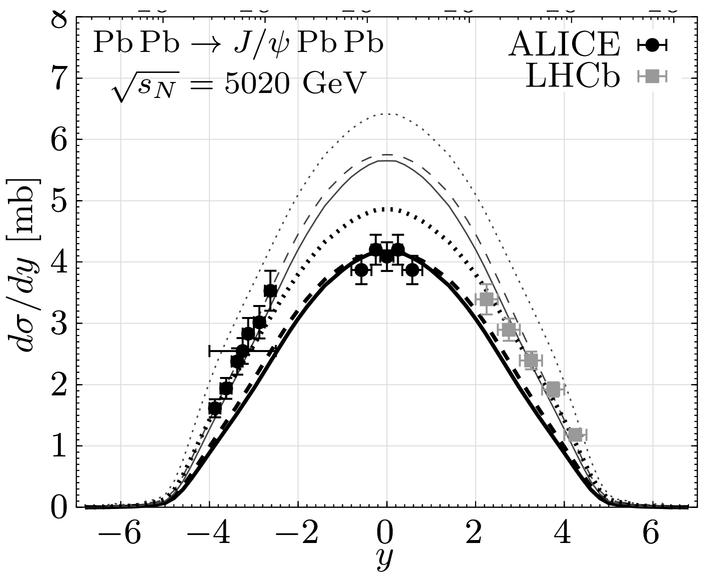


- Provide good description of coherent J/ψ photoproduction in Pb-Pb UPCs

Luszczak, Schäfer, SciPost Phys.Proc. 8 (2022) 109, arXiv:2108.06788 [hep-ph]



Kopeliovich, Krelina, Nemchik, Potashnikova, PRD 107 (2023) 5, 054005



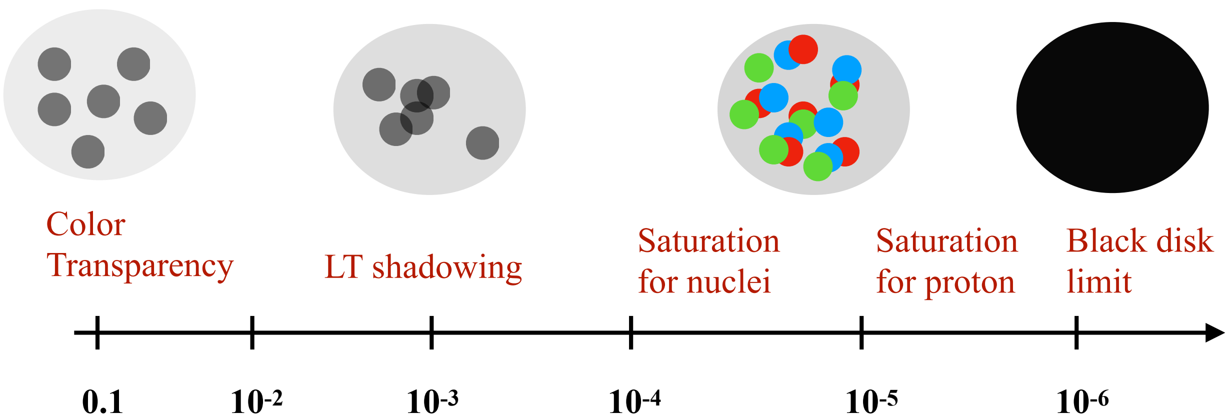
- Depends on details of dipole cross section and photon and J/ψ wave functions.
- Alternatively, good description using BK equations with nuclear geometry,

Bendova, Cepila, Contreras, Matas, PLB 817 (2021) 136306

Nuclear shadowing and saturation

- Many questions on connection between shadowing and saturation:
  - ⋆ Are they the same thing or capture the same physics?
  - ⋆ If not, how should one combine them together?
  - ⋆ What are their distinctive signatures?
  - ⋆ …

- Possible stages of high-energy scattering off nuclei :



- LT shadowing is linear regime, not the same as non-linear saturation, but it lowers saturation scale Q_s, Frankfurt, Guzey, Stasto, Strikman, Rept. Prog. Phys. 85 (2022) 12, 126301

- Q_s controls onset of non-linear parton recombination, Gribov, Levin, Ryskin, Phys. Rep. 100 (1983) 1; Muller, Qiu, NPB 268 (1986) 427 ⟶ delayed by NS and dilute nuclear density:

$$Q_s^2 \sim \frac{\alpha_s(Q_s^2)}{\pi R_{gN}^2}\, xg(x, Q_s^2) \;\Rightarrow\; \frac{Q_{sA}^2}{Q_{sN}^2} = A\,\frac{R_{gN}^2}{R_A^2}\,\frac{g_A(x,Q^2)}{A g_N(x,Q^2)} \;\Rightarrow\; \frac{Q_{sA}^2}{Q_{sN}^2} = 0.3A^{1/3} \approx 1.75$$

Nuclear shadowing and black disk limit (BDL)

- LT approximation breaks down at sufficiently low x.
- Estimated using BDL limit $\sigma_{diff}/\sigma_{tot} \leq 1/2 \to \sigma_2 \leq 8\pi B_{2g} \approx 50$ mb at $x \sim 10^{-5} \to$ lower limit on NS $g_A(x,Q^2)/Ag_p(x,Q^2) \geq 0.3 \to$ compare to Kopeliovich, et al PRC79 (2009) 064906
- In BDL, photon fluctuations interact with maximal cross section $2\pi R^2$, but their masses grow $\to$ Bjorken scaling of DIS structure functions violated, Gribov, Sov. Phys. JETP 30 (1970) 709; McDermott, Frankfurt, Guzey, Strikman, EPJC 16 (2000) 641

$$F_2^A(x,Q^2) = \sum_i e_i^2 Q^2 \frac{2\pi R_A^2}{12\pi^3} \ln 1/4m_N R_A x$$

$$F_2^p(x,Q^2) \propto \sum_i e_i^2 Q^2 \frac{2\pi R_N^2}{12\pi^3} (1 + \frac{4c_N^2}{R_N^2} \ln^2 x_0/x) \ln 1/x$$

additional logs from interaction range

- Shadowing continues to decrease:

$$\frac{F_2^A(x,Q^2)}{AF_2^N(x,Q^2)} \propto \frac{R_A^2}{AR_N^2} \frac{1}{1+4c_N^2 R_A^2 \ln^2 1/x}$$

- Signals of saturation/BDL more pronounced in diffractive final states: vector mesons, Frankfurt, Guzey, McDermott, Strikman, PRL 87 (2001) 192301, structure functions, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303, dijets, E. Iancu, parallel session talk, 20.06.

Summary and Outlook

- Leading twist model and dipole picture are two competing dynamic mechanisms for nuclear shadowing.

- They are best discriminated by nuclear longitudinal F_L^A and diffractive F_{2A}^D structure functions in the EIC kinematics.

- Real photon-nucleus scattering in UPCs at the LHC and RHIC has provided new information on dynamics of nuclear shadowing in small-x QCD.

- The UPC data at the LHC — including the recent measurements of energy dependence of NS — challenge both LT and dipole models.

- The LT model would benefit from better treatment of antishadowing and a possible symbiosis with nPDFs from global QCD fits.

- Important to apply recent progress in NLO calculations in the dipole model to UPC phenomenology.

- LT shadowing ≠ saturation, but slows down its onset.

- Nuclear shadowing does not saturate even in BDL.

- I didn't have time to discuss large LT shadowing in incoherent scattering.