Interaction of high-energy hadrons with nuclei and nuclear shadowing

Vadim Guzey

Petersburg Nuclear Physics Institute (PNPI),
National Research Center "Kurchatov Institute",
Gatchina, Russia

Outline:

- Glauber theory of nuclear shadowing, R.J. Glauber, Phys. Rev. 100 (1955) 242
- Gribov-Glauber theory of nuclear shadowing, V.N. Gribov, Sov. Phys. JETP 29 (1969) 483
- Leading twist theory of nuclear shadowing, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255
- Gluon nuclear shadowing from coherent J/Ψ photoproduction on nuclei in heavy ion collisions at the LHC, Guzey, Kryshen, Strikman, Zhalov, Phys. Lett. B726 (2013) 290

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Glauber theory of nuclear shadowing

R.J. Glauber, 2005 Nobel Prize in Physics
for “quantum theory of optical coherence”

• Applies to high-energy scattering at small angles

• Nuclear shadowing is the result of quantum-mechanical interference among scattering amplitudes for the interaction with 1, 2, …, A nucleons of the nuclear target.

• At high energies the amplitudes are predominantly imaginary (recall Ch. 8 of Gribov’s book) → this interference is destructive → $\sigma_A < A\,\sigma_N$

Glauber theory of nuclear shadowing

• I explained in my seminar 1 that at high energies, one recovers the approximation of geometrical optics: particles move essentially along straight trajectories acquiring only an additional phase:

$$f(\vec{k}',\vec{k}) = \frac{ik}{2\pi}\int d^2\vec{b}\, e^{i\vec{q}\vec{b}}\left[1 - e^{-\frac{i}{\hbar v}\int_{-\infty}^{\infty} dz' V(\vec{b},z')}\right] = \frac{ik}{2\pi}\int d^2\vec{b}\, e^{i\vec{q}\vec{b}}\left[1 - e^{i\chi(b)}\right]$$

scattering amplitude

accumulated phase

scattering amplitude in impact parameter space = profile Γ(b)

• This representation is useful not only in non-relativistic quantum mechanics, but also in field theory:

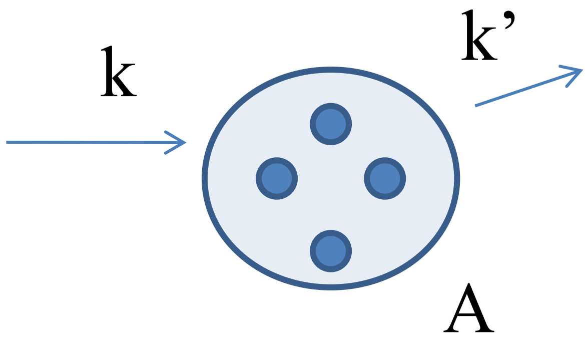
$$\sigma_{\mathrm{tot}} = \frac{4\pi}{k} Im f(\vec{k},\vec{k}) = 2\Re e \int d^2\vec{b}\,(1 - e^{i\chi(b)})$$

$$\sigma_{\mathrm{elastic}} = \int d\Omega |f(\vec{k}',\vec{k})|^2 = \int d^2\vec{b}\,|1 - e^{i\chi(b)}|^2$$

Glauber theory of nuclear shadowing

- Specifically, for a nucleus target:

  - the nuclear potential changes slowly during the interaction time → nucleons can be considered “frozen” in their positions (recall seminar 1, when it was formally derived)



Scattering amplitude on “frozen” nucleons, which depends on nucleon coordinates:

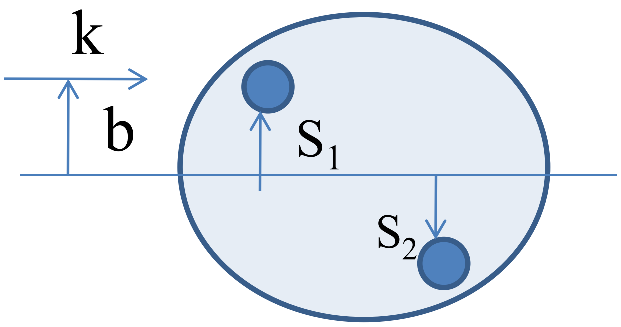
$$f_A(\vec{k}', \vec{k}, \vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \frac{ik}{2\pi} \int d^2\vec{b}\, e^{i\vec{q}\vec{b}} (1 - e^{i\chi_A}) = \frac{ik}{2\pi} \int d^2\vec{b}\, e^{i\vec{q}\vec{b}}\, \Gamma_A(\vec{b}, \vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A)$$

Integration over nucleon positions with nuclear wave function:

$$f_A(\vec{k}', \vec{k}) = \int \prod_{i=1}^{A} d^3\vec{r}_i |\Psi_A^*(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A)|^2 f_A(\vec{k}', \vec{k}, \vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A)$$

Glauber theory of nuclear shadowing

- Specifically, for a nucleus target:
  - pair-wise nuclear forces → total phase on nucleus is sum of phases on individual nucleons



$$\chi_A(b, \vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \sum_{i=1}^{A} \chi(\vec{b} - \vec{s}_i)$$

- Nuclear scattering amplitude in impact parameter space (profile) in terms of nucleon amplitudes:

$$\Gamma_A(\vec{b}, \vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = 1 - \prod_{i=1}^{A}(1 - \Gamma_i) = \sum_i^A \Gamma_i - \sum_{i,j} \Gamma_i \Gamma_j + \ldots$$

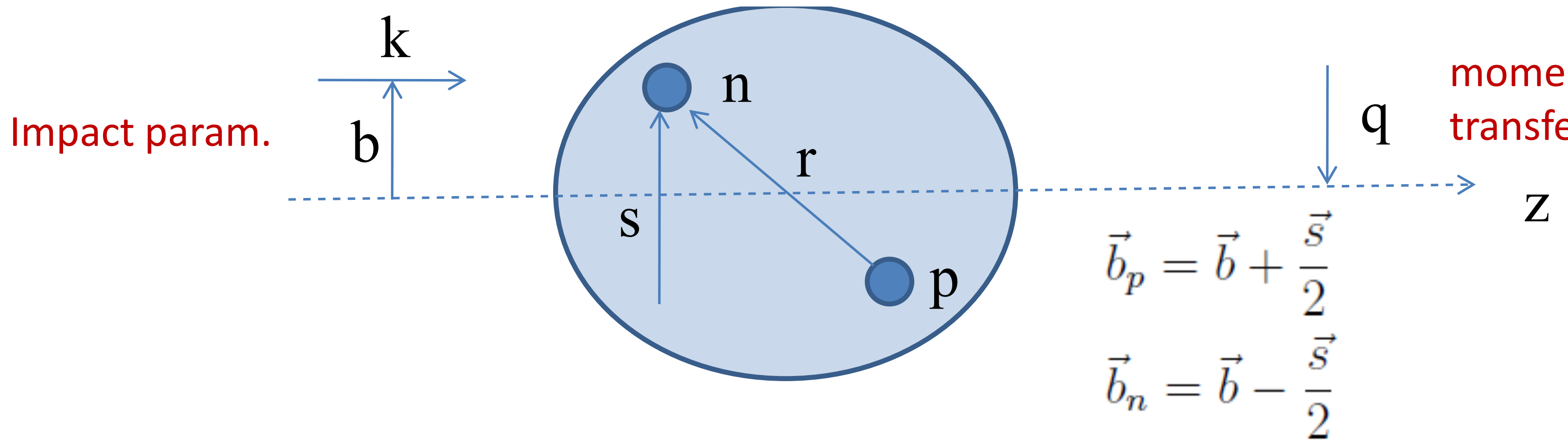
- Averaging over the nuclear wave function squared → Glauber series for nuclear cross section, where each term corresponds to interaction with 1, 2, .. A nucleons:

$$\sigma_{\mathrm{tot}}^A = \sum_{i=1}^{A} \sigma_{\mathrm{tot}}^N - \frac{c_2}{R_A^2} \sum_{i,j} (\sigma_{\mathrm{tot}}^N)^2 + \ldots$$

Born (impulse) approximation

shadowing correction

Glauber theory: pion-deuteron scattering



- Nuclear profile function:

$$\Gamma_A(\vec{b}, \vec{r}_p, \vec{r}_n) = \Gamma_p(\vec{b} + \frac{\vec{s}}{2}) + \Gamma_n(\vec{b} - \frac{\vec{s}}{2}) - \Gamma_p(\vec{b} + \frac{\vec{s}}{2})\Gamma_n(\vec{b} - \frac{\vec{s}}{2})$$

- Scattering amplitude on deuteron:

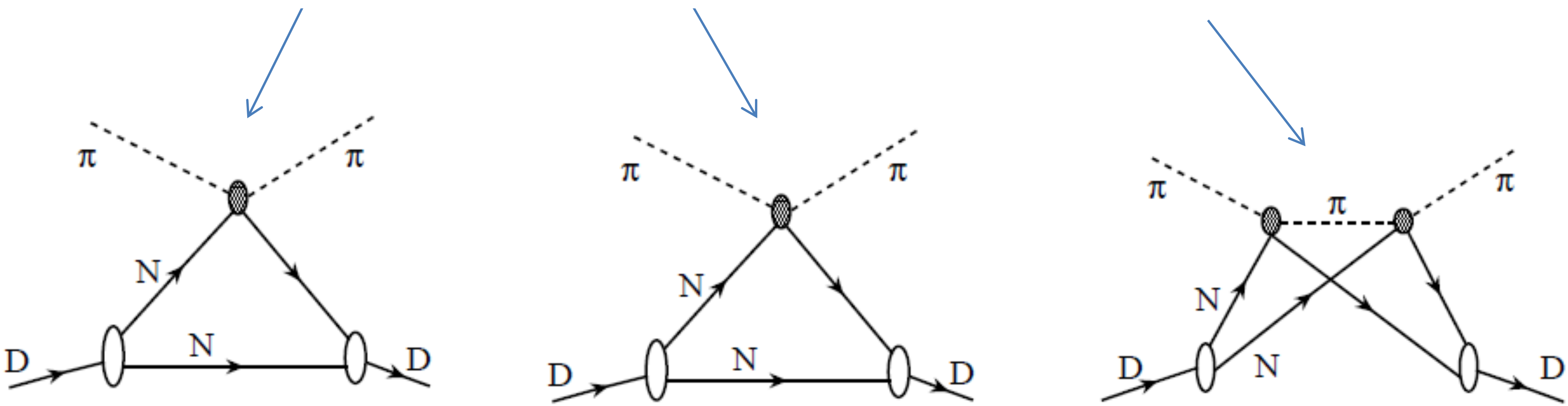
$$f_A(\vec{k'}, \vec{k}) = \int d^3\vec{r}\, |\Phi_D(\vec{r})|^2 \frac{ik}{2\pi} \int d^2\vec{b}\, e^{i\vec{q}\vec{b}}\, \Gamma_A(\vec{b}, \vec{r}_p, \vec{r}_n)$$

deuteron wave function

Glauber theory: pion-deuteron scattering

- Substitute $\Gamma_{p,n}(\vec{b}) = \frac{1}{2\pi i k} \int d^2\vec{q}\, e^{-i\vec{q}\vec{b}} f_{p,n}(\vec{q})$ and do integrals over r:

$$f_A(\vec{k'},\vec{k}) = G_D(-\frac{q}{2}) f_p(\vec{q}) + G_D(\frac{q}{2}) f_n(\vec{q}) - \frac{1}{2\pi i k}\int d^2\vec{q'}\, G_D(\vec{q'}) f_p(\frac{\vec{q}}{2}+q') f_n(\frac{\vec{q}}{2}-q')$$



effective Feynman diagrams from seminar 1

- $G_D(q)$ is the deuteron form factor: $G_D(\vec{q}) \equiv \int d^3\vec{r}\, e^{i\vec{q}\vec{r}} |\Phi_D(\vec{r})|^2$

Glauber theory: pion-deuteron scattering

- Optical theorem:

$$\sigma_D = \sigma_p + \sigma_n - \frac{1}{8\pi^2}\sigma_p\sigma_n \int d^2\vec{q}'\, G_D(\vec{q}') = \sigma_p + \sigma_n - \frac{1}{4\pi}\sigma_p\sigma_n \langle \frac{1}{r^2} \rangle_D$$

characterizes p-n overlap in D

- Physics of shadowing: incoming particle scatters on first nucleon, gets absorbed and, thus, cannot interact with the second nucleon. The effect depends on the geometric overlap of the two nucleons — hence, the term "shadowing".

- Magnitude of the shadowing effect: $\sigma_{p,n}$=70 mb (Tevatron), $<1/r^2>_D$=0.05 mb^{-1}:

$$\sigma_D = 140 - \frac{70 \times 70}{4\pi} 0.05 = 140 - 20 = 120 \text{ mbarn}$$

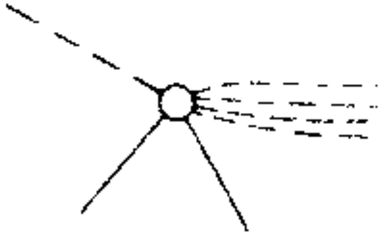
Nuclear shadowing is ~15% effect at Tevatron energies.

Gribov theory of nuclear shadowing

- Glauber: non-rel. QM, successive interactions, elastic intermediate states
- Gribov: QFT, coherent interactions, inelastic intermediate states
- Based on Gribov's picture of the strong interaction at high energies, seminar 1
- Fast hadrons are superpositions of fluctuations with long lifetime:

$$l_c \propto \frac{p}{\mu^2} \geq \text{target size}$$

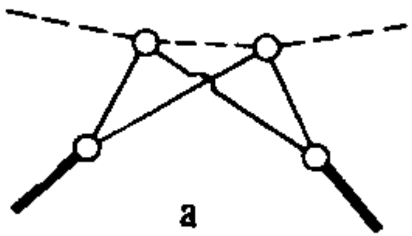
- These fluctuations describe diffractive production, Good, Walker, 1960; the momentum transfer to nucleon is small.



- Two contributions to nuclear shadowing, Gribov, Sov. Phys. JETP 29 (1969) 483:

Gribov theory of nuclear shadowing

• At high energies, graph "a" for elastic intermediate state → 0



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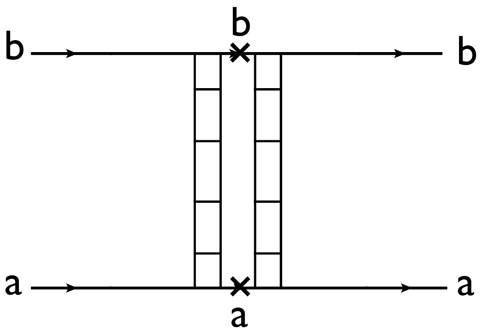


as a result of cancellation of the planar (AFS) diagram, Amati, Fubini, Stanghellini; Mandelstam 1963; Frankfurt, Strikman, arXiv:1304.4308; **Gribov's book, chapter 12**

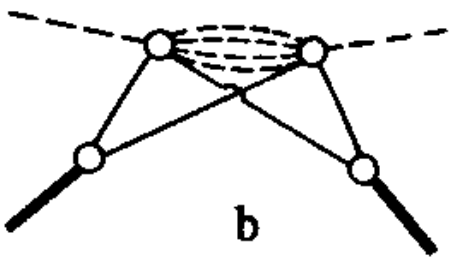
• In physics terms, configurations of the projective do not have time to recombine in the elastic state (pion) between two successive interactions.

• At high energies (BDL), elastic scattering = diffractive scattering → diffractive intermediate state.

• At high energies, elastic cross section → 0 due to shrinkage of diffractive cone, recall our discussion of BDL, when l_{max}~b_{max} ~ ln(s).

Gribov theory of nuclear shadowing

- Thus, shadowing correction is given by the non-planar ladder diagram, which does not vanish as s → ∞



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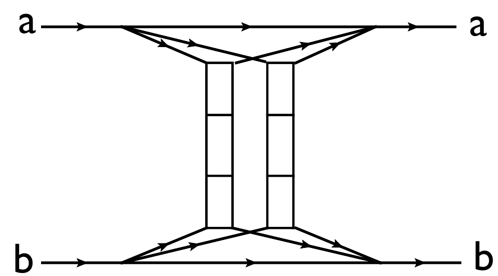
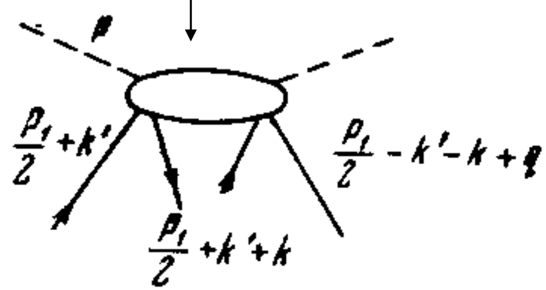


- The corresponding expression, Gribov, Sov. Phys. JETP 29 (1969) 483 (recall also derivation using effective Feynman diagrams of seminar 1)

$$F_D^{\text{shad}}(s) = \frac{2}{M}\int \frac{d\vec{k}^2}{4\pi^2}\,\rho\left(4\vec{k}^2\right)\int_0^{2|\vec{p}||\vec{k}|+\mu^2}\frac{ds'}{2|\vec{p}|}f\left(s_1,\vec{k}^2,s'\right)$$

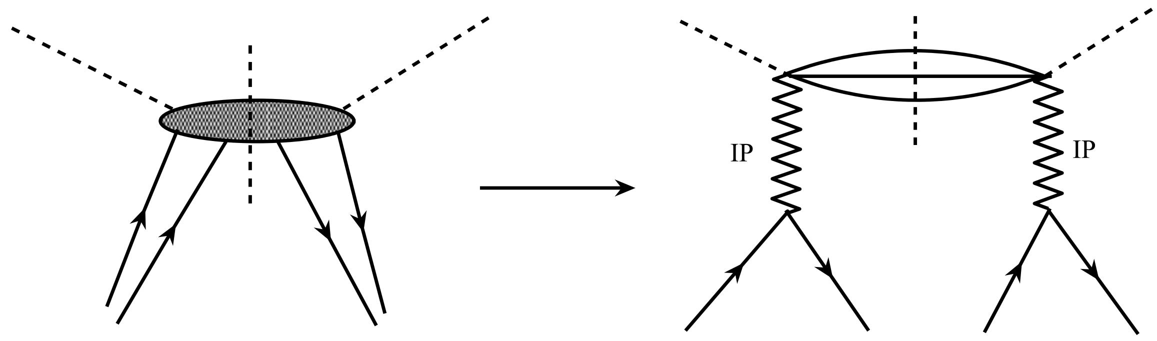
deuteron form factor

double scattering

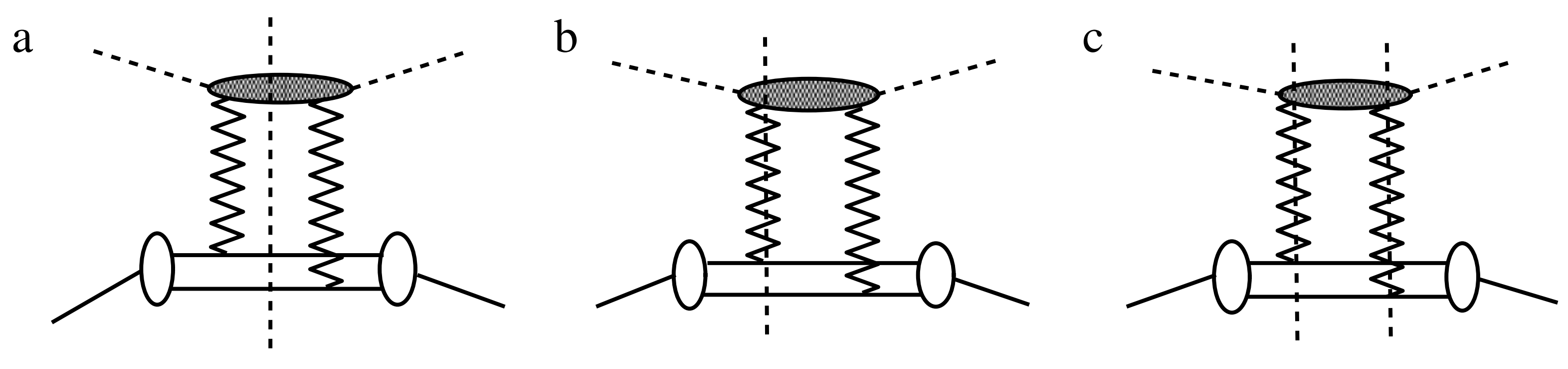


Gribov theory of nuclear shadowing

• Assume that the asymptotic behavior is determined by a Pomeranchuk pole (Pomeron) and the cuts connected with it:



• Abramovsky-Gribov-Kacheli (AGK) cutting rules, **Chapter 15 of Gribov's book** → shadowing is given by the *diffractive cut*, which enters with minus sign:



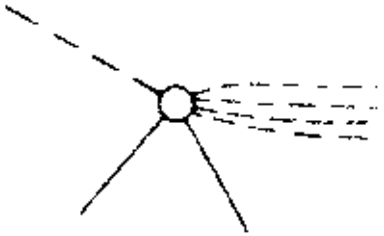
diffractive cut　　single-multiplicity cut　　double-multiplicity cut

Gribov theory of nuclear shadowing

- Total pion-deuteron cross section:

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

- Main result: shadowing correction for nucleus is given by diffractive cross section on nucleon.



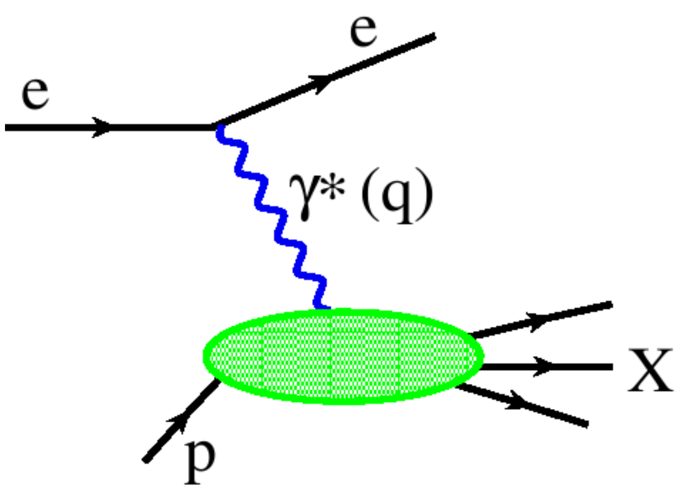
- While space-time pictures in Glauber and Gribov approaches are very different, Gribov's result *superficially* looks like a generalization of Glauber formula:

  - assume elastic intermediate state
  - relate coordinate and momentum deuteron wf

$$\sigma_{\text{tot}}^{\pi D} \approx 2\sigma_{\text{tot}}^{\pi N} - \left.\frac{d\sigma_{\text{el}}^{\pi N}(\vec{k})}{d\vec{k}^2}\right|_{|\vec{k}|^2=0} 2\int d\vec{k}^2 \rho\left(4\vec{k}^2\right) \Rightarrow \left.\frac{d\sigma_{\text{el}}^{\pi N}(\vec{k})}{d\vec{k}^2}\right|_{|\vec{k}|^2=0} = \frac{\left(\sigma_{\text{tot}}^{\pi N}\right)^2}{16\pi} \Rightarrow \sigma_{\text{tot}}^{\pi D} = 2\sigma_{\text{tot}}^{\pi N} - \frac{\left(\sigma_{\text{tot}}^{\pi N}\right)^2}{4\pi}\left\langle\frac{1}{r^2}\right\rangle_D$$

- Resulting approach is called Gribov-Glauber theory of nuclear shadowing.

Deep inelastic scattering



$$\left.\begin{array}{l} \left.\begin{array}{l} q^2 = -Q^2 \\ W^2 = (p+q)^2 \end{array}\right\} \text{ large} \\ x_B = \dfrac{Q^2}{2p\cdot q} \quad \text{fixed} \end{array}\right\} \text{Bjorken limit}$$

Terms "*deep inelastic*" or "*hard*" denote Processes with large $Q^2 \geq 1$ GeV^2

$$\frac{d^2\sigma}{dx\, dQ^2} = \frac{4\pi\alpha_{\rm em}^2}{xQ^4}\left[(1-y)F_2(x,Q^2) + y^2 x\, F_1(x,Q^2)\right]$$

Unpolarized structure functions

Evolution of our understanding of sf's:

- theoretically predicted to scale, i.e. depend only on x by J. Bjorken
- confirmed by experiments at SLAC
- explained in the parton model by R. Feynman
- parton model is improved by QCD: scaling is only approximate, structure functions depend logarithmically on Q^2 due to parton emission

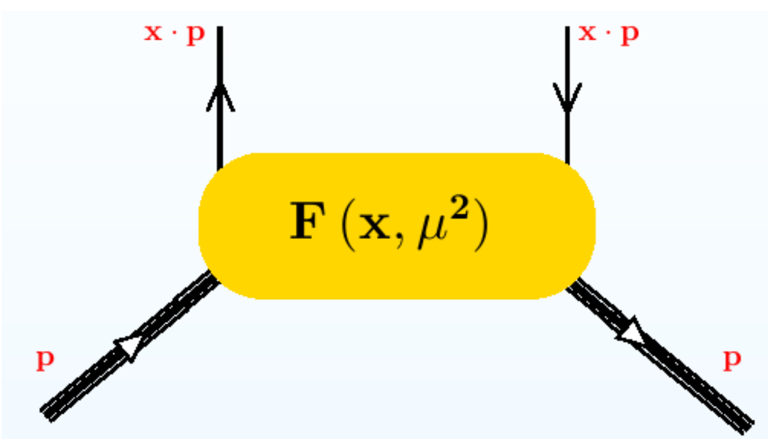
QCD factorization

In the Bjorken limit, $\alpha_s(Q^2)$ is small (asymptotic freedom) and one can use the perturbation theory to prove the *factorization theorem*:

$$F_2(x,Q^2) = \sum_{i=q,\bar{q},g} \int_0^1 \frac{dz}{z} C^i\left(\frac{x}{z}, \frac{Q^2}{\mu^2}\right) \phi_i(z,\mu^2)$$

Perturbative coefficient function

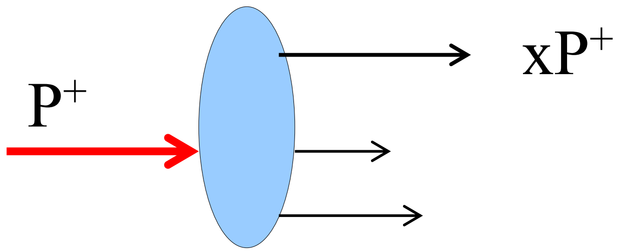
Non-perturbative parton distribution functions (PDFs) defined via matrix elements of parton operators between nucleon states with equal momenta



p -- nucleon momentum
x -- longit. momentum fraction
μ^2 -- factorization scale

Parton distributions

Interpretation is simplest in the infinite momentum frame:



Fast moving nucleon with $P^+ = E + p_z$ very large

Parton distributions are probabilities* to find a parton with the light-cone fraction x of the nucleon P^+ momentum.

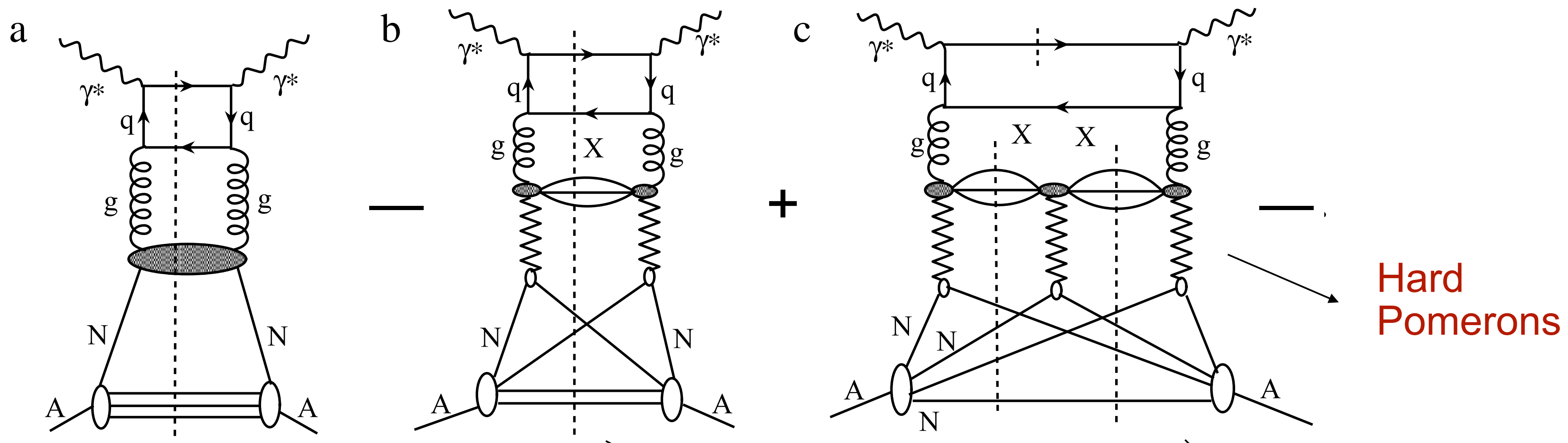
Q^2 is the resolution of the "microscope"

Information about the transverse position of the parton is integrated out.

*This is true only at leading order in $\alpha_s(Q^2)$

Leading twist nuclear shadowing model

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

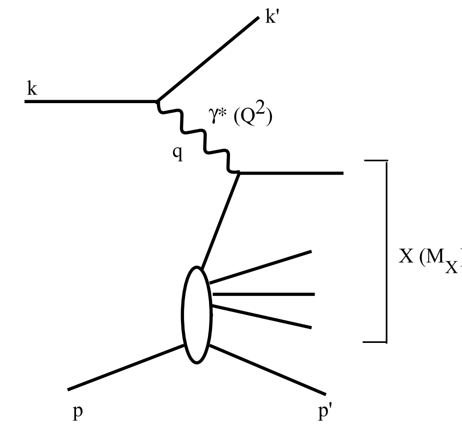


$$xf_{j/A}(x,Q_0^2) = Axf_{j/N}(x,Q_0^2) - 8\pi A(A-1)\,\Re e\frac{(1-i\eta)^2}{1+\eta^2}B_{\text{diff}}\int_x^{0.1} dx_{\mathbb{P}}\,\beta f_j^{D(3)}(\beta,Q_0^2,x_{\mathbb{P}})$$

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

Seminar 1: all nucleons at same impact parameter, eikonal phase

Leading twist nuclear shadowing model



- Main input: diffractive parton distributions $f_j^{D(3)}$ measured in diffractive deep inelastic scattering on proton at Hadron Electron Ring Accelerator, H1, ZEUS

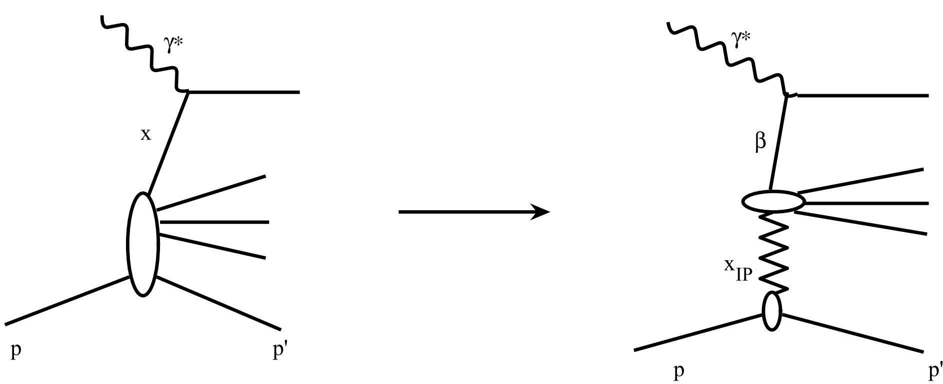
$$F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t) = \beta \sum_{j=q,\bar{q},g} \int_{\beta}^{1} \frac{dy}{y} C_j\left(\frac{\beta}{y}, Q^2\right) f_j^{D(4)}(y, Q^2, x_{\mathbb{P}}, t)$$

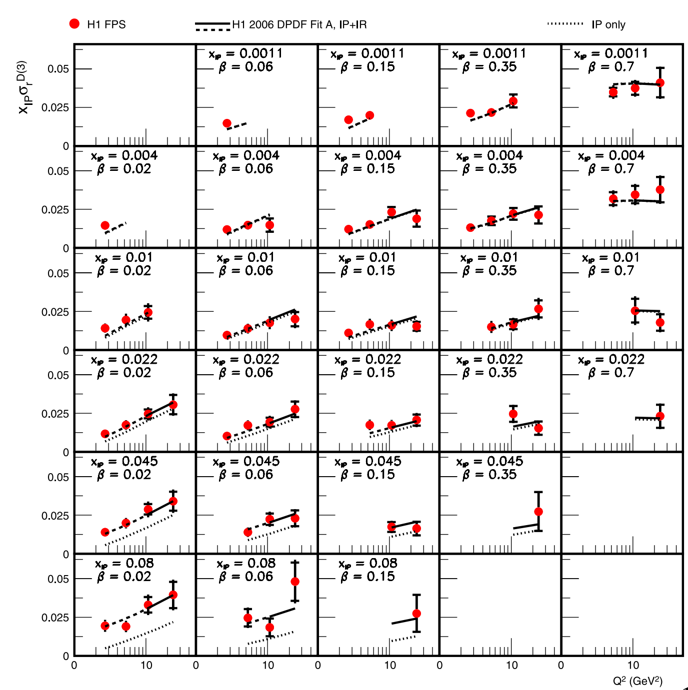
$$t = (p' - p)^2,$$

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

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

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



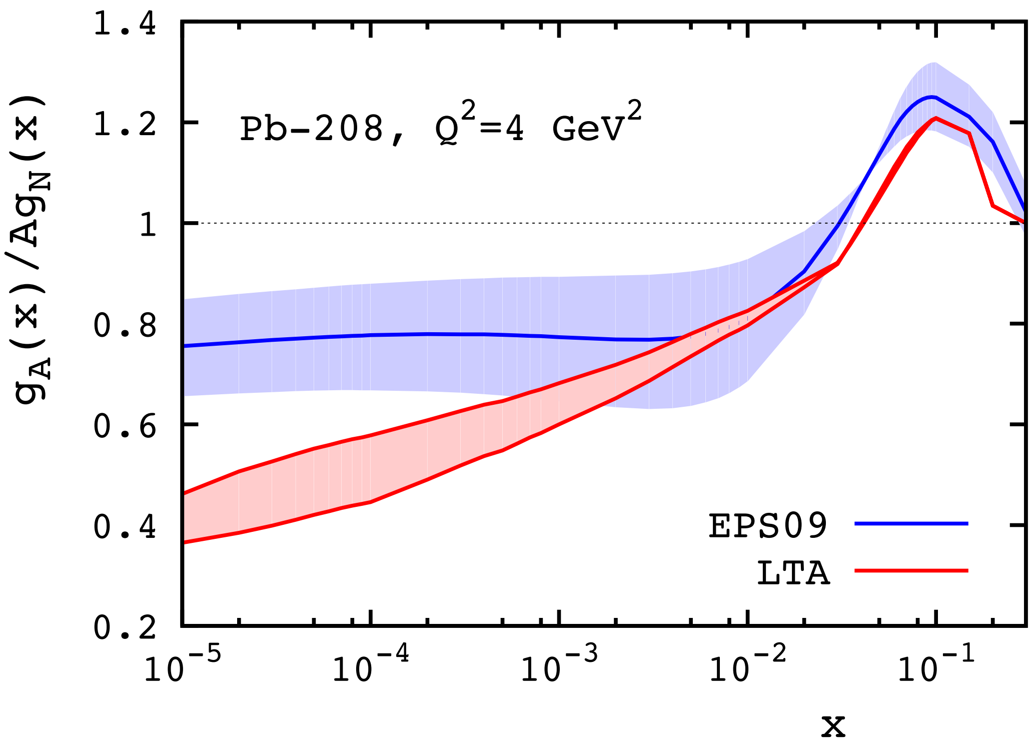


- One of main HERA results: diffraction in DIS can be described by pQCD, leading twist → hence the name "leading twist shadowing"

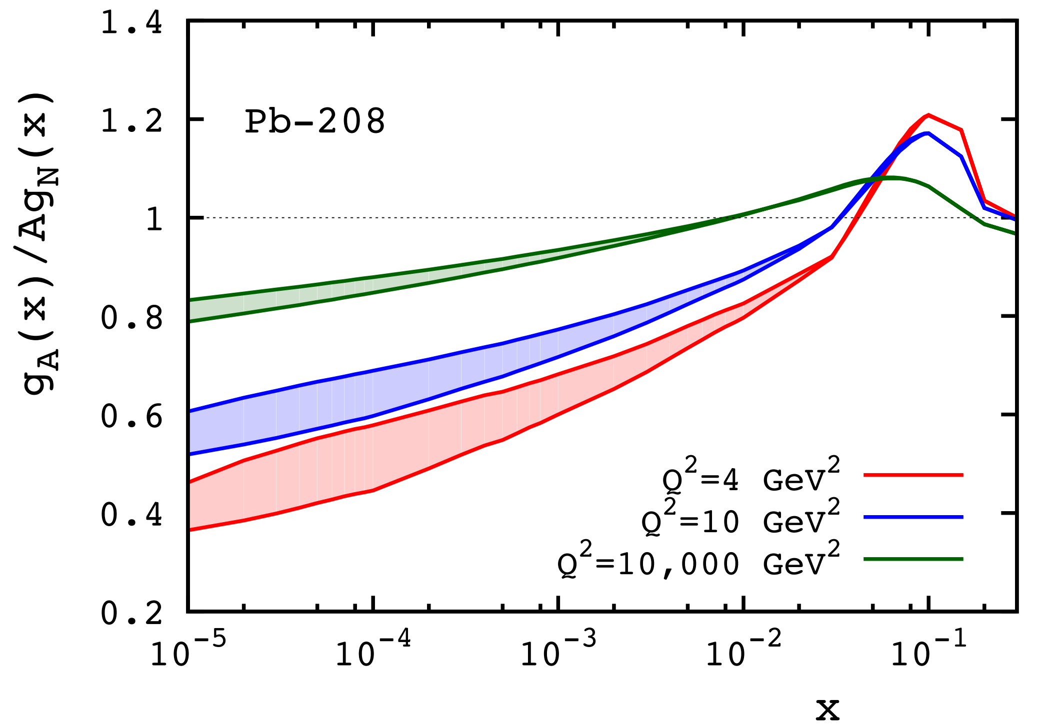
Leading twist nuclear shadowing model

- Allows to calculate small-x sea quark and gluon distributions in nuclei at certain scale $Q_0 \rightarrow$ can be used as input for DGLAP evolution to higher Q^2
- Main feature: large gluon shadowing (suppression) because the hard Pomeron is mostly made of gluons (recall the discussion of gluon ladders).

Leading twist (LTA) vs. global QCD fit EPS09



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



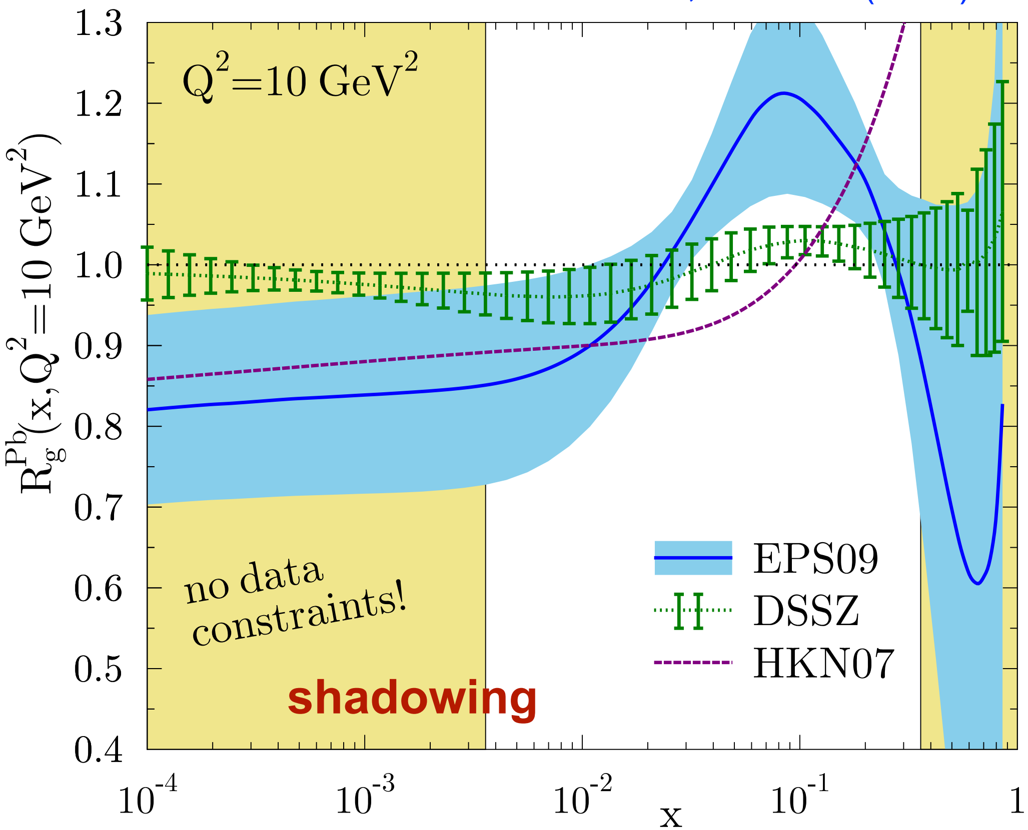
- LT model offers alternative to *small-x extrapolation* of global QCD fits.

Gluon nuclear shadowing

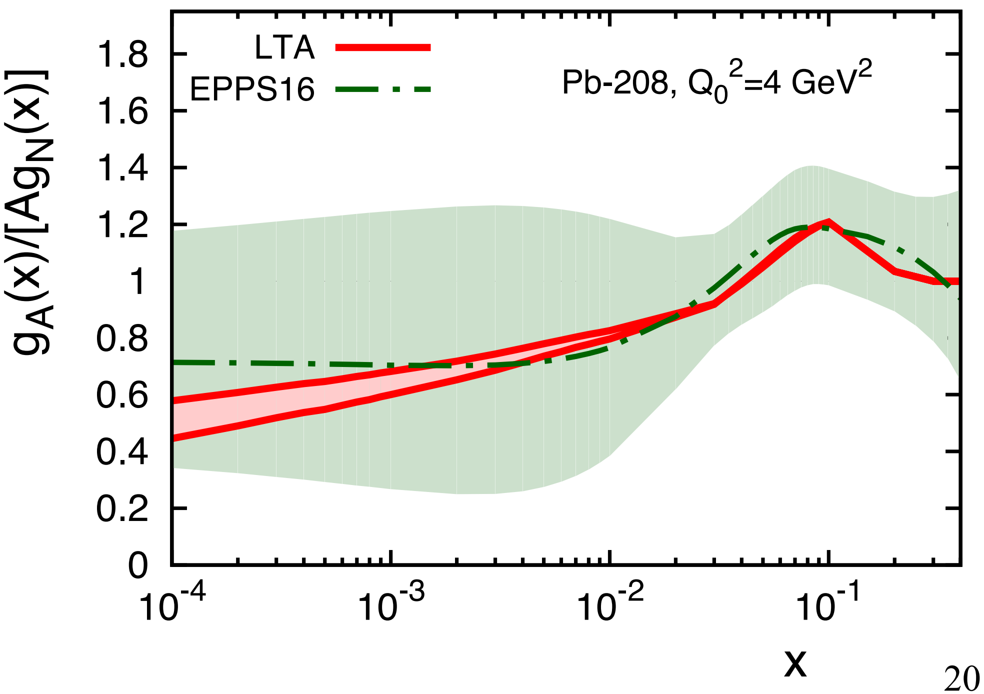
- Gluon nuclear shadowing: $g_A(x,\mu^2) < A\, g_N(x,\mu^2)$ for small $x < 0.005$.
- Important for QCD phenomenology of hard processes with nuclei: cold nuclear matter effects (RHIC, LHC), gluon saturation (RHIC, LHC, EIC)
- $g_A(x,\mu^2)$ is determined from global QCD fits using data on fixed-target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

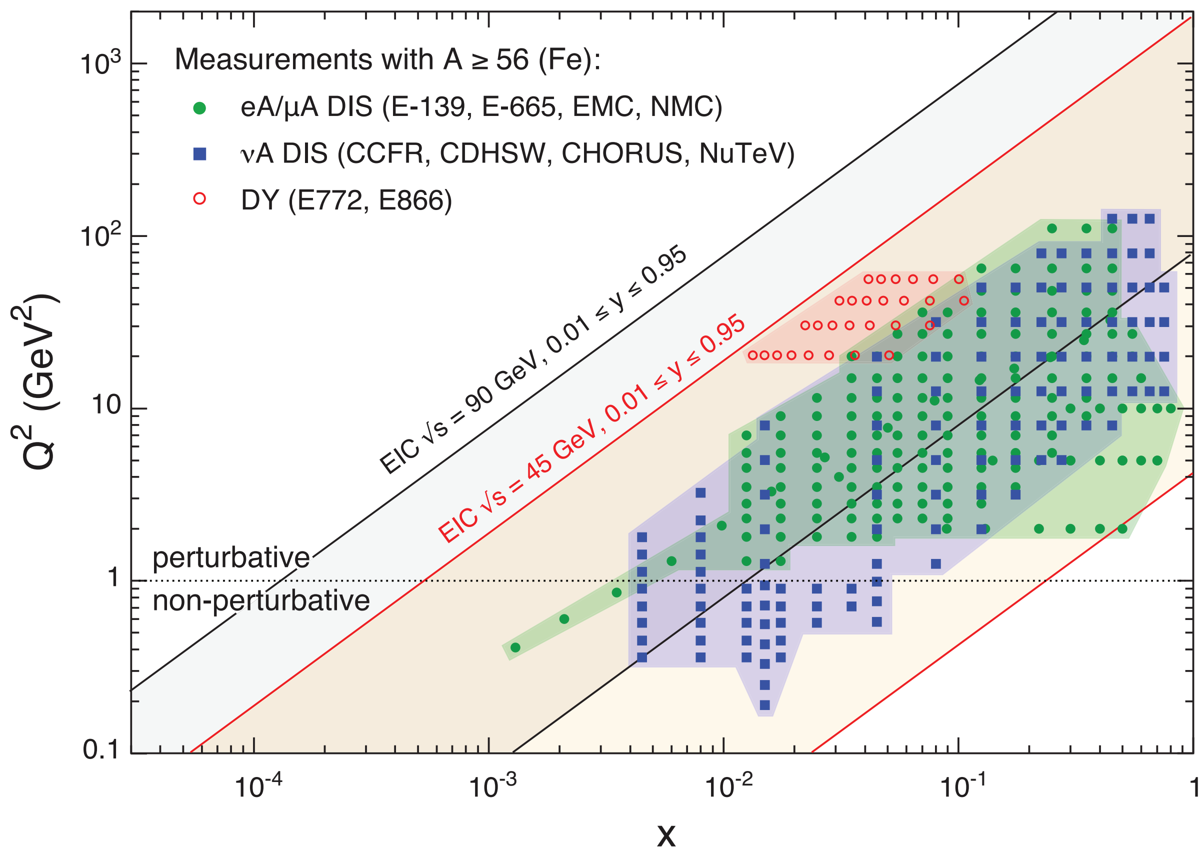


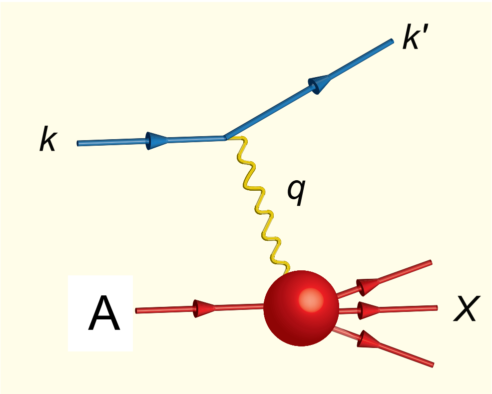
- pA@LHC data can help little, Armesto et al, arXiv:1512.01528; Eskola et al, JHEP 1310 (2013) 213, Eskola et al, EPJC 77 (2017) 163 (EPPS16 nPDFs)



Gluon nuclear shadowing

• In the future, gluon nuclear shadowing will be constrained at Electron-Ion Collider in the US, Accardi et al, EPJ A52 (2016) no.9, 268; LHeC@CERN, LHEC Study Group, J. Phys. G39 (2012) 075001

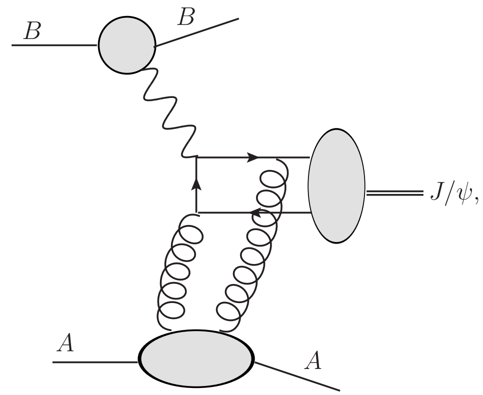




• Option right now: Charmonium photoproduction in Pb-Pb UPCs@LHC

Ultraperipheral collisions (UPCs)

• 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

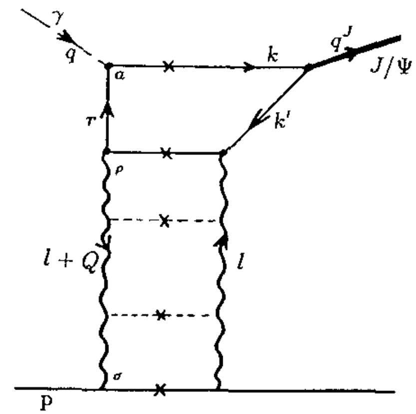
$y = \ln[W^2/(2\gamma_L m_N M_V)]$

= 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 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 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 cross section on proton 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 Rg

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

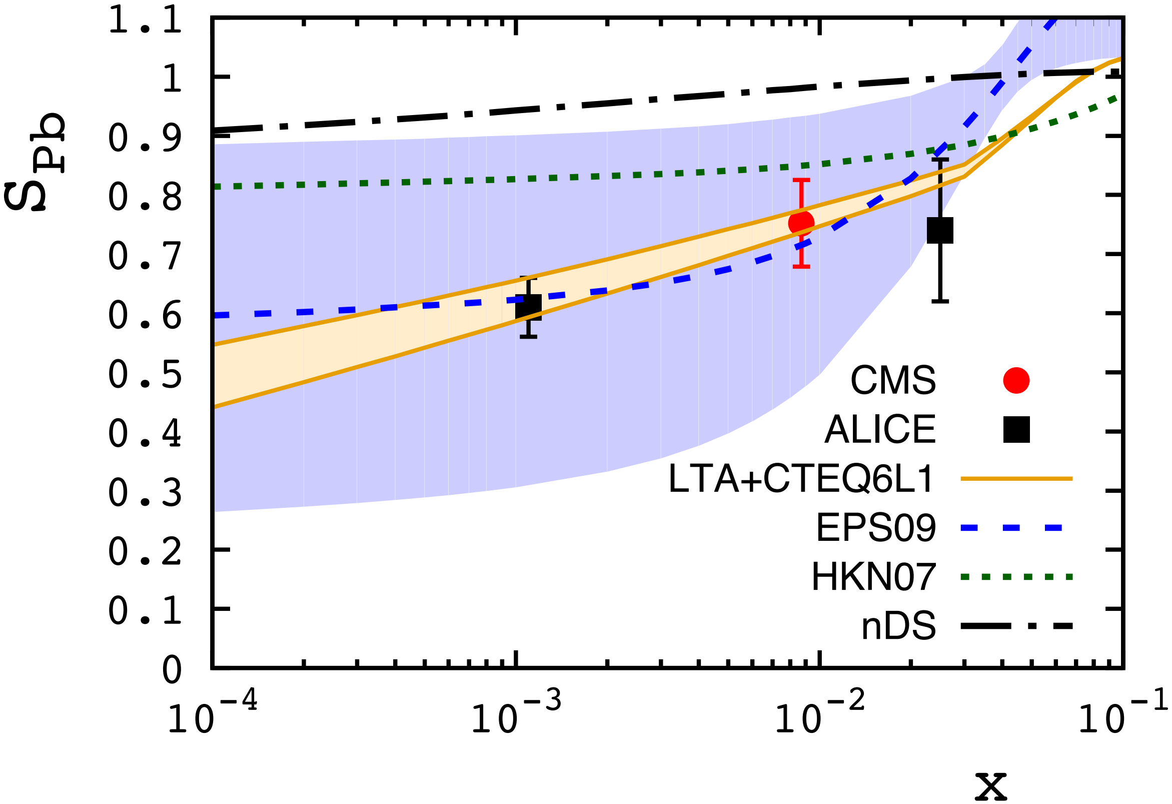
Model-independently from data on UPC@LHC (ALICE, CMS) and HERA

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

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, $R_g(x=0.001) \approx 0.6$.

- Similarly good description using central value of EPS09+CTEQ6L, large uncertainty.

- Color dipole models generally fail to reproduce suppression, Goncalves, Machado PRC84 (2011) 011902; Lappi, Mantysaari, PRC 87 (2013) 032201

Summary

• Using the space-time picture of strong interaction, Gribov developed theory of nuclear shadowing for soft hadron-nucleus scattering, where shadowing on nucleus is expressed in terms of diffraction.

• It uses methods of quantum field theory and supersedes Glauber theory → Gribov-Glauber theory of nuclear shadowing.

• Using QCD factorizations theorems for DIS, Gribov theory can be generalized to calculate shadowing in nuclear parton distributions at small x.

• Hard diffraction (hard Pomeron) is dominated by gluons → the model naturally predicts large nuclear gluon shadowing → important prediction for Electron-Ion Collider.

• Nicely confirmed by J/ψ photoproduction in Pb-Pb UPCs at the LHC.