Color fields at medium energy: color transparency, nuclear shadowing and diffraction

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Outline:

- High-energy scattering in the target rest frame: cross section (color) fluctuations, color transparency, and nuclear shadowing

- Nuclear shadowing in the leading twist approach: predictions for inclusive, diffractive and exclusive processes

- Gluon shadowing: exclusive J/ψ photoproduction in Pb-Pb UPCs at the LHC; EIC potential

- Conclusions

High-energy scattering in target rest frame

- Soft hadron-hadron scattering: a fast projectile (pion, proton, photon) fluctuates into configurations with different cross sections.

Feinberg and Pomeranchuk (1956)
Good and Walker (1960)

- The lifetime of these fluctuations can be larger than the target size:

$$l_c = \frac{1}{\Delta E} = \left(\sqrt{M^{*2} + p_{\rm lab}^2} - \sqrt{m^2 + p_{\rm lab}^2}\right)^{-1} = \frac{2p_{\rm lab}}{M^{*2} - m^2} > 2R_T$$

- This leads to the concept of cross section fluctuations:

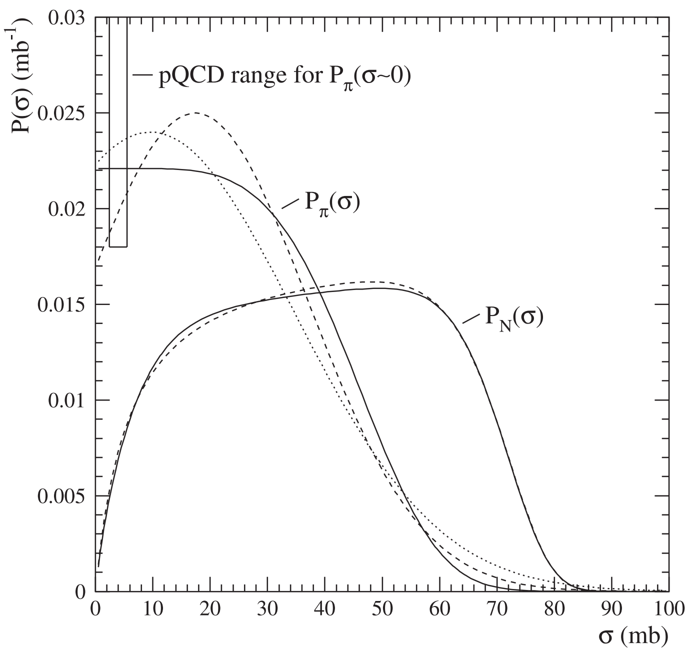
Frankfurt, Miller, Strikman (1994)
Blattel et al. (1993, 1996)

$$|\Psi\rangle = \sum_k c_k |\Psi_k\rangle$$

$$\Im m\, T|\Psi_k\rangle = \sigma_k |\Psi_k\rangle$$

$$P(\sigma) = \sum_k |c_k|^2 \delta(\sigma - \sigma_k)$$

distribution over σ



- Cross section fluctuations lead to:
  - diffractive dissociation of beam particles
  - Glauber shadowing correction

High-energy scattering in target rest frame (2)

- DIS: a fast virtual photon fluctuates into quark-gluon configurations (dipoles)

$|\gamma^*(Q^2)\rangle = |q\bar{q}\rangle + |q\bar{q}g\rangle \ldots$ with the lifetime $l_c = \frac{1}{\Delta E} = \frac{2q}{\langle M_X^2\rangle + Q^2} \approx \frac{1}{2m_N x}$

- These dipoles can be roughly of two types:
  - asymmetric in photons's momentum sharing (pre-QCD align jet model): Bjorken (1971)
    large transverse size $d_t^2 \approx 1/[Q^2 z(1-z)]$ and small probability ~$1/Q^2$
  - symmetric in photons's momentum sharing (pQCD) → small transverse size and small cross section:

$$\sigma(d_t, x) = \frac{\pi^2}{3}\alpha_s(Q^2_{\text{eff}}) d_t^2 xG(x, Q^2_{\text{eff}})$$

F. Low (1975)
Nikolaev, Zakharov (1991)
Blattel et al. (1993)

$$Q^2_{\text{eff}} = \lambda/d_t^2$$

- The presence of small-size weakly interacting dipoles is an example of color transparency (CT).

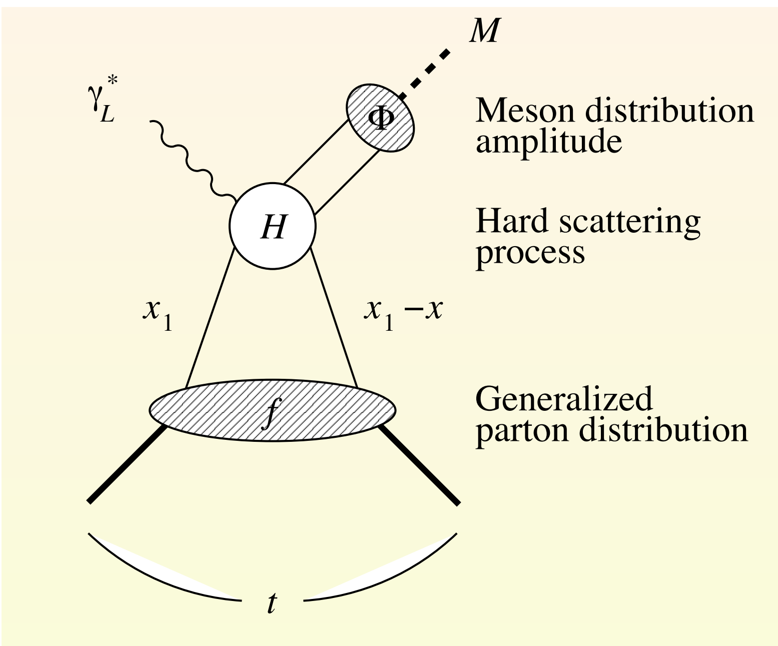
- In DIS, CT is needed for scaling of the total cross section.

Color transparency

• CT is a dynamical QCD phenomenon of absence of initial/final state interactions of small-size quark-gluon configurations.

• CT has been observed experimentally (Fermilab, HERA, BNL, JLab) and will be studied in the future (JLab12, COMPASS, FAIR). Dutta, Hafidi, Strikman (2012)

• CT plays multiple roles:
- probes dynamics and space-time evolution of the strong interaction
- probes the minimal Fock components of hadrons
- used in proofs of factorization for exclusive processes



Brodsky et al. (1994)
Collins, Frankfurt, Strikman (1997)

Tests of CT is a crucial element of studies of 3D structure at EIC.

Color transparency and nuclear shadowing

- Factorization theorem for high-energy exclusive meson production (CT) for nuclear targets probes nuclear GPDs modified by nuclear shadowing:

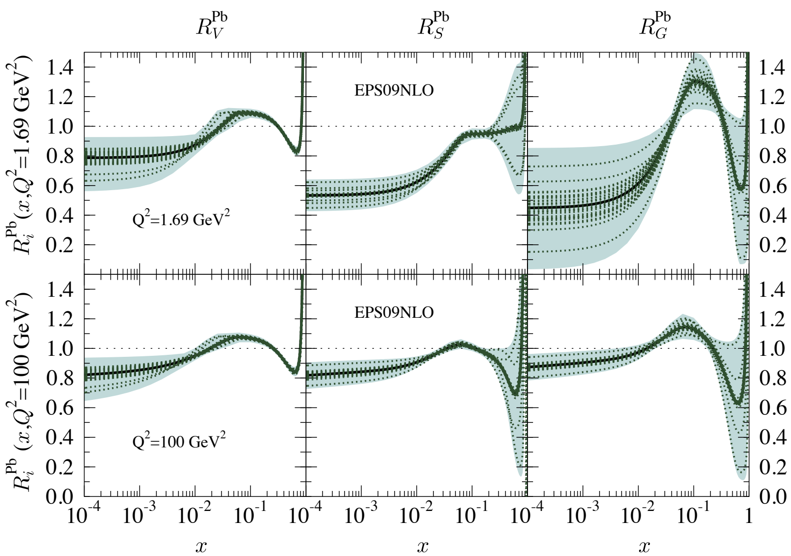
Frankfurt, Strikman, Koepf (1996)

$$\sigma_{\gamma A\to VA} = \frac{d\sigma_{\gamma N\to VN}(t_{\min})}{dt}\left[\frac{G_A(x_1,x_2,Q^2_{\text{eff}},t=0)}{AG_N(x_1,x_2,Q^2_{\text{eff}},t=0)}\right]^2 \int_{\infty}^{t_{\min}} dt|F_A(t)|^2$$

$$x_1 - x_2 = x = M_V^2/W_{\gamma p}^2$$

- Good approx.: $\dfrac{G_A(x_1,x_2,Q^2_{\text{eff}},t=0)}{AG_N(x_1,x_2,Q^2_{\text{eff}},t=0)} \approx R_g \dfrac{G_A(x,Q^2_{\text{eff}})}{AG_N(x,Q^2_{\text{eff}})}$

- The gluon distribution in nuclei at small x is suppressed -- nuclear shadowing



R=$f_{j/A}(x,Q^2)/[Af_{j/N}(x,Q^2)]$

see talk by H. Paukkunen

- Nuclear PDFs have large uncertainties:
  - limited kinematics
  - indirect extraction of gluons via Q^2 evolution
  - assumptions about the initial shape
  - different choice/treatment of data used in fits

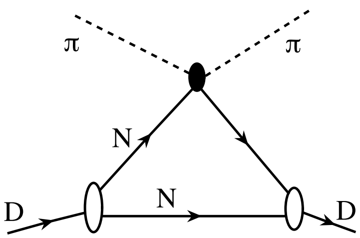
→ determination of nuclear PDFs and discrimination between different approaches to small-x parton dynamics is one of key goals of EIC

Connection of shadowing and diffraction

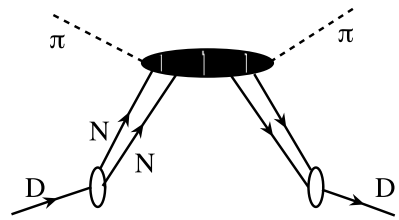
• At high energies, incoming hadron interact with all nucleons of the target via its fluctuations with $l_c \propto p_{\text{beam}} \propto 1/x$

Feinberg, Pomeranchuk (1956)
Gribov, Ioffe, Pomeranchuk (1965)
Good, Walker (1960)

• Pion-deuteron forward amplitude:



impulse approximation



shadowing correction

• The second graph gives the shadowing correction expressed in terms of the elem. pion-nucleon diffractive cross section ➞ Gribov-Glauber theory of nuclear shadowing

$$\sigma_{\text{tot}}^{\pi D} = 2\sigma_{\text{tot}}^{\pi N} - 2\left(\frac{d\sigma_{\text{diff}}}{dt}\right)_{t=0} \int dt S(t) = 2\sigma_{\text{tot}}^{\pi N} - \frac{1}{8\pi}\langle\sigma^2\rangle \int dt S(t)$$

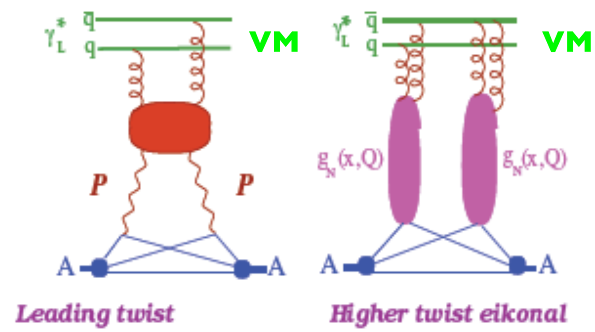
V. Gribov (1969)

deuteron form factor

moment of P(σ) from slide 3

• When generalized to hard processes with nuclei, Gribov's theory leads to leading twist shadowing.

Compare to the picture of successive interactions leading to higher twist shadowing ➞



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Leading twist theory of nuclear shadowing

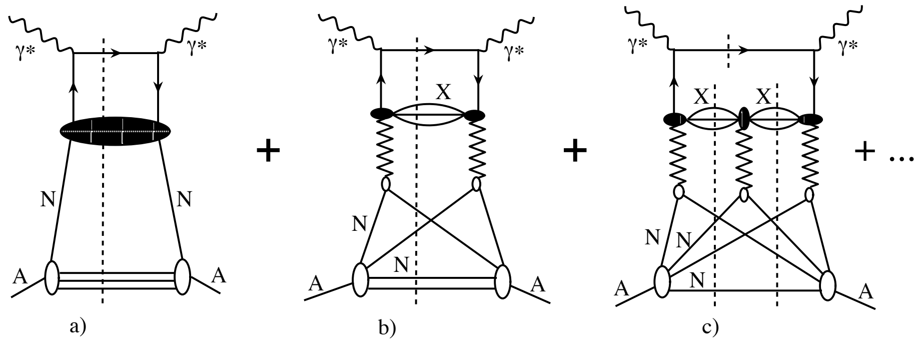
A method to evaluate parton (sea quark and gluon) distributions in nuclei for small *x* as a function of *x* and impact parameter *b* at certain input scale Q_0. Further Q^2 dependence given by DGLAP.

The approach is based on: L. Frankfurt, VG, M. Strikman, Phys. Rept. 512 (2012) 255

- The picture of the strong interactions at high energies in the laboratory frame, Gribov-Glauber shadowing theory and its extension to eA DIS → expression for $F_{2A}(x,Q^2)$
- Collinear factorization for total and diffractive DIS cross sections → from $F_{2A}(x,Q^2)$ to individual nuclear parton distributions $f_{j/A}(x,Q^2)$
- Diffractive parton distributions in the proton (HERA) → input for predictions

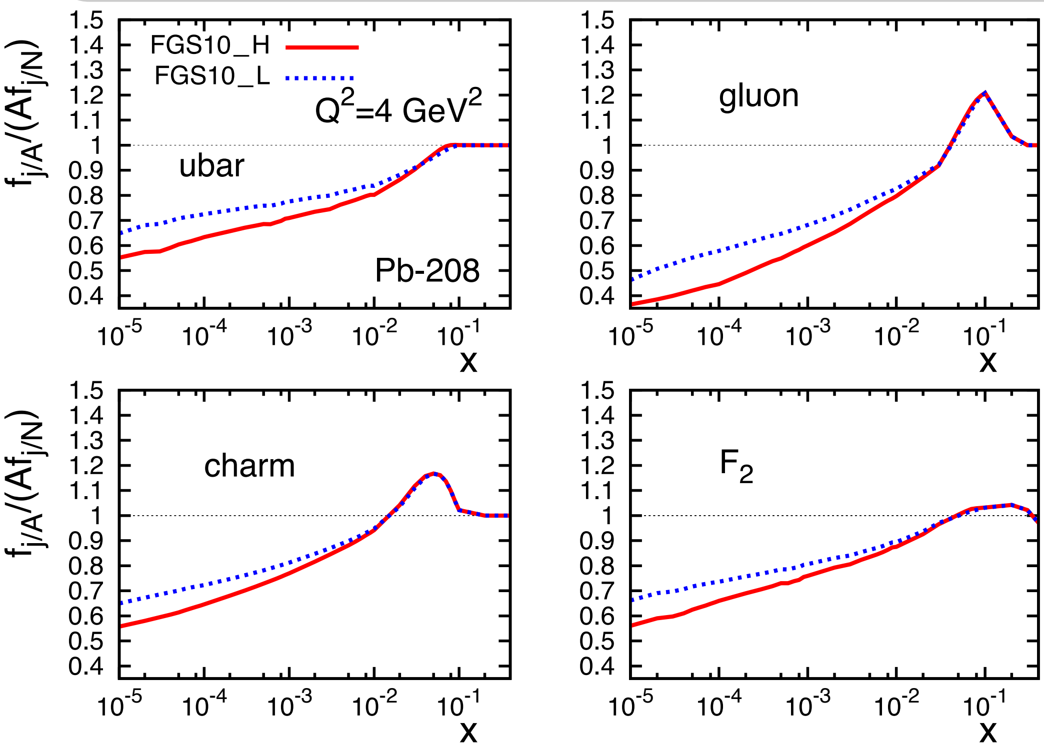
Terminology "leading twist":
Shadowing is expressed via elementary diffraction → diffraction is a leading-twist phenomenon (HERA) → the approach describes *the leading twist component of nuclear shadowing* (modulo modeling of N >2 contribution)

Leading twist theory of nuclear shadowing (2)



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

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



- Two curves correspond to uncertainty due to multiple scatterings ➞ can be reduced by varying A

- Antishadowing is modeled using momentum sum rule

- Gluon shadowing > quark shadowing ➞ large shadowing for $F_L^A(x,Q^2)$

EIC and LHeC are ideal places to test these predictions!

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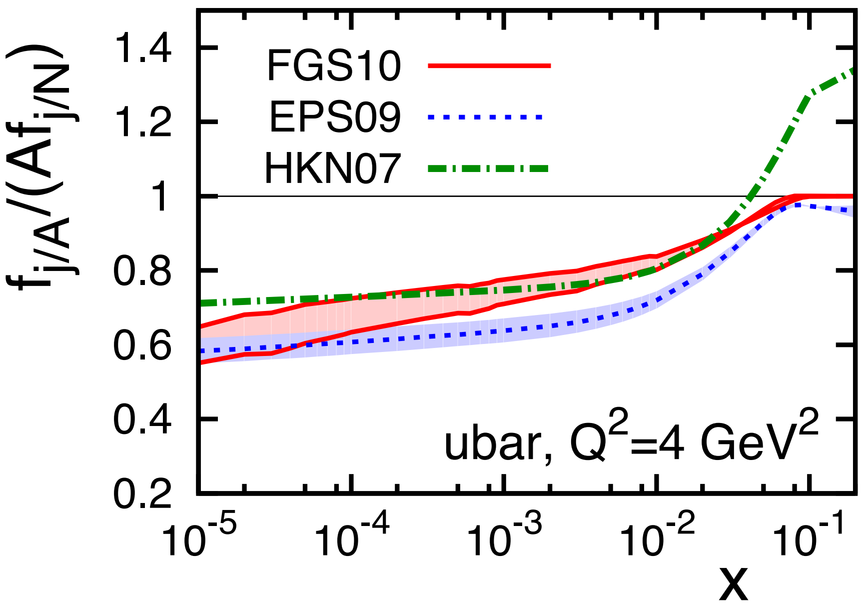
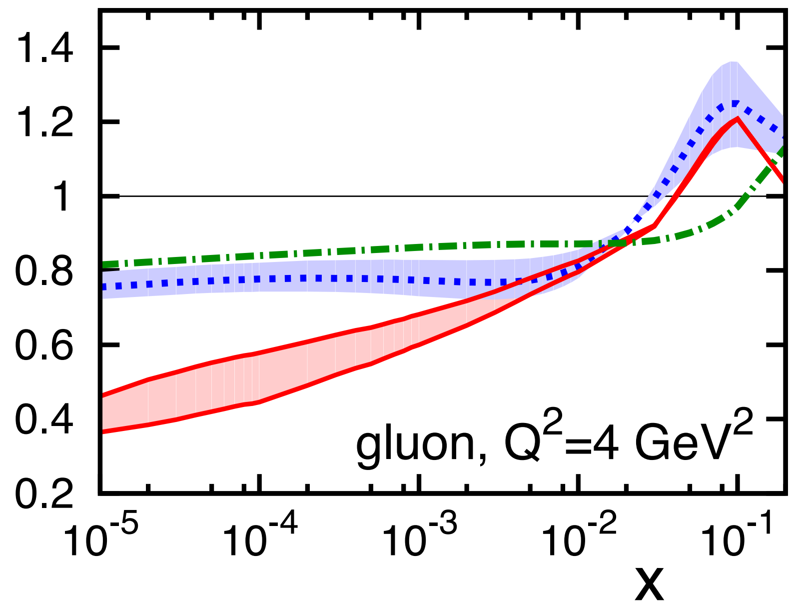
Comparison to the results of global fits

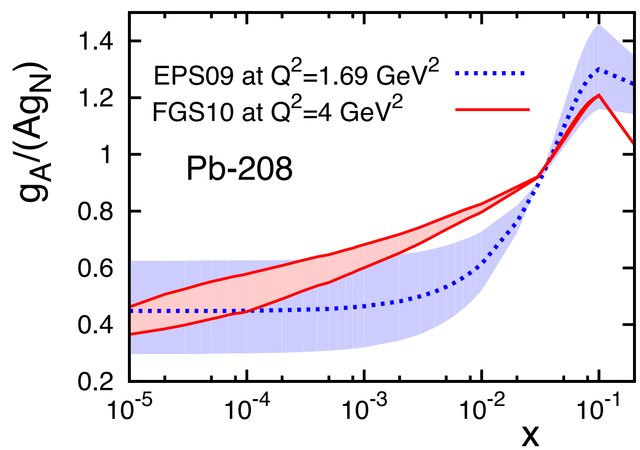
Pb-208





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

- For quarks: shadowing is similar
- For gluons: our shadowing is the largest at Q^2=4 GeV^2



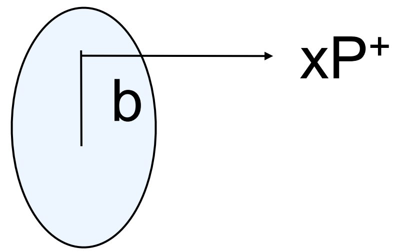
Dependence on the impact parameter

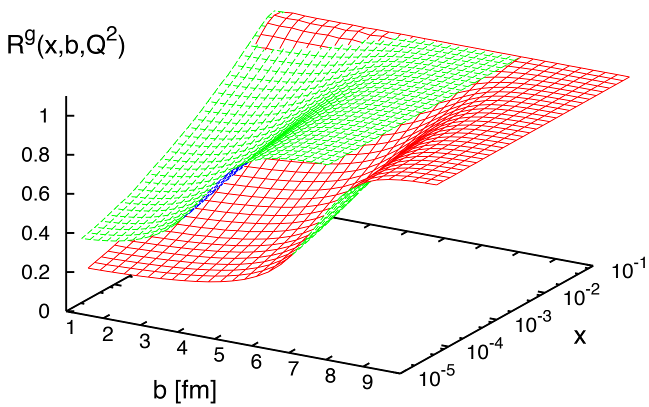
- The leading twist theory of nuclear shadowing *naturally* predicts the dependence of nuclear PDFs on the impact parameter *b*:

nuclear density

$$x f_{j/A}(x,Q_0^2,b) = A\,T_A(b)\,x f_{j/N}(x,Q_0^2) - \pi A(A-1) B_{\text{diff}}\, \Re e \frac{(1-i\eta)^2}{1+\eta^2} \int_x^{0.1} dx_P\, \beta f_j^{D(3)}(\beta,Q_0^2,x_P)$$
$$\times \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2\, \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2)\, e^{i(z_1-z_2)x_P m_N}\, e^{-\frac{A}{2}(1-i\eta)\sigma^j_{\text{soft}}(x,Q_0^2)\int_{z_1}^{z_2} dz'\,\rho_A(\vec{b},z')}$$

Probability to find a parton with given *x and b*



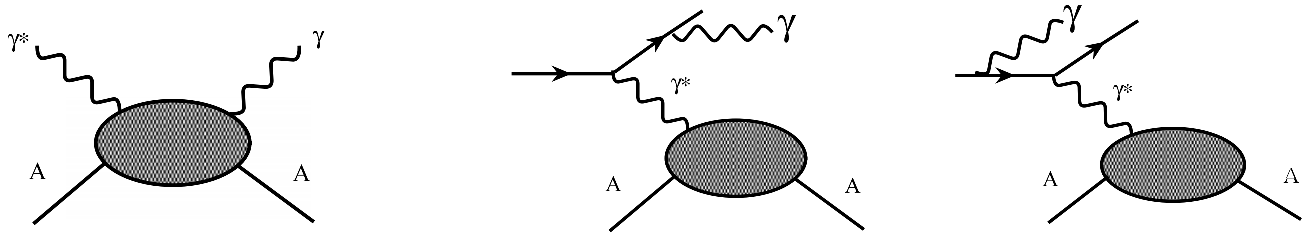


$$R^j(x,b,Q^2) = \frac{f_{j/A}(x,Q^2,b)}{A\,T_A(b)\,f_{j/N}(x,Q^2)}$$

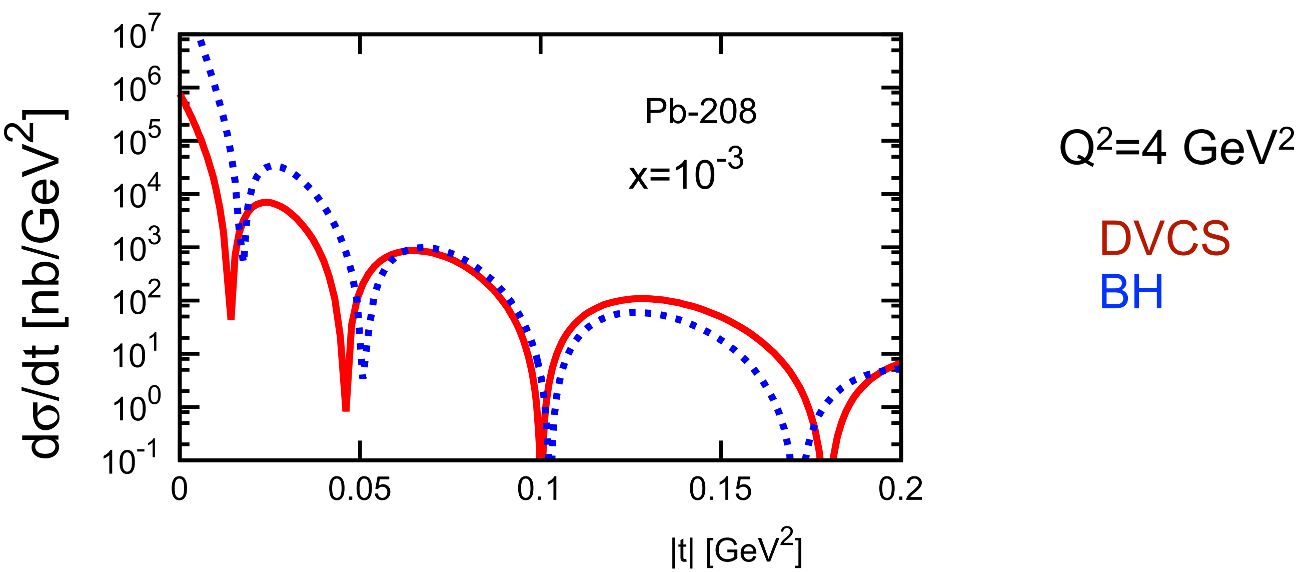
- Until recently, unique feature of our approach ➞ spatial image of shadowing
- Recent global QCD fit analysis finds similar results, I. Helenus *et al*, ArXiv:1205.5359
- Impact-parameter dependent PDFs=nuclear GPDs in the special limit of xi=0 ➞ *essential ingredient for calculation of hard exclusive processes with nuclei (DVCS, electroproduction of VM, etc.)!*

Predictions for DVCS observables

The strong amplitude of deeply virtual Compton scattering (DVCS) competes with the electromagnetic Bethe-Heitler (BH) amplitude:



$$d\sigma_{\mathrm{DVCS}}/dt \sim 1/Q^4$$
$$d\sigma_{\mathrm{BH}}/dt \sim 1/(tQ^2)$$



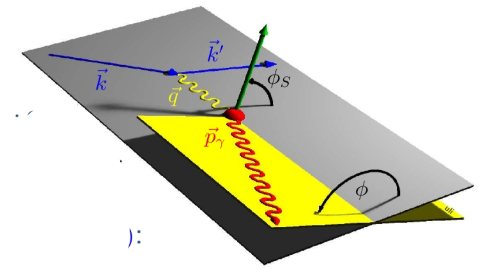
- The shift is the measure of nuclear shadowing for sea quarks which increases the size of the transverse distribution of quarks in nuclei <b^2>.
- Similar shape for the gluon channel (coherent electroproduction of J/ψ)

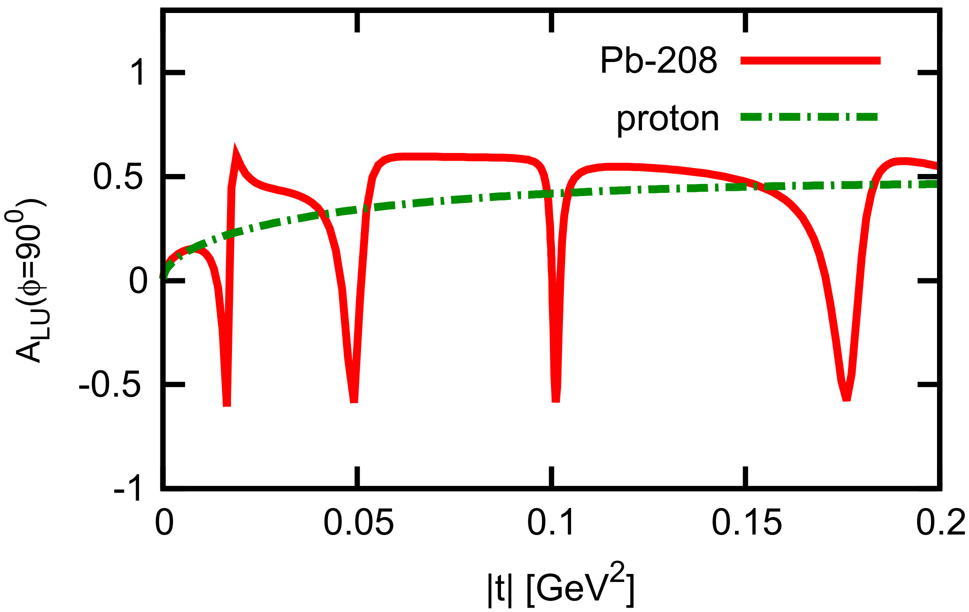
Predictions for DVCS observables (2)

- One can extract separately the imaginary and real parts of the DVCS amplitude through interference with the BH amplitude.

- Beam-spin asymmetry=polarized lepton beam, unpolarized target

$$A_{\mathrm{LU}}(\phi) = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \propto \sin\phi \frac{H_A(\xi, \xi, t)}{F_A(t)}$$

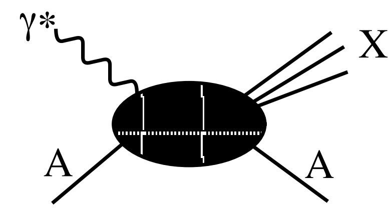




The oscillations are due to nuclear shadowing.

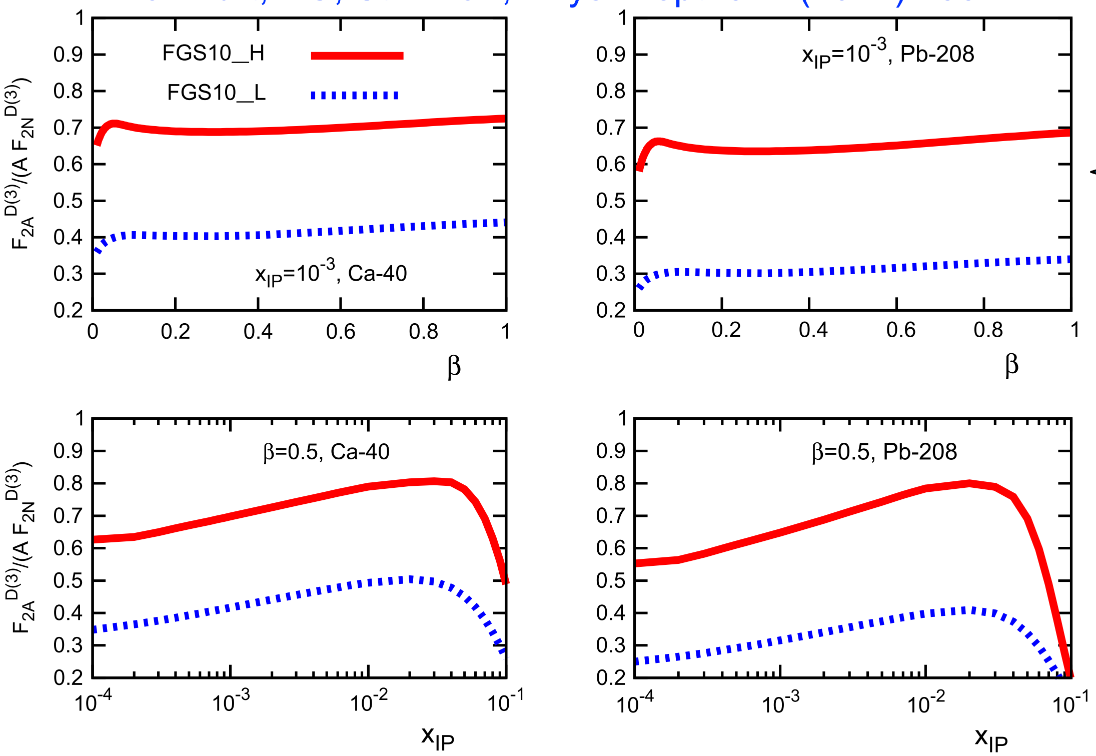
Nuclear diffractive structure functions

The leading twist theory of nuclear shadowing also predicts shadowing for nuclear diffractive structure functions:

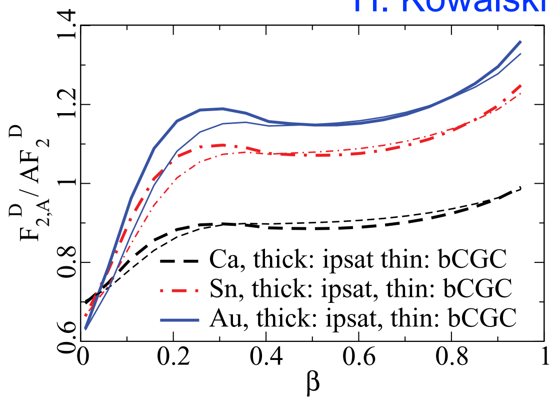


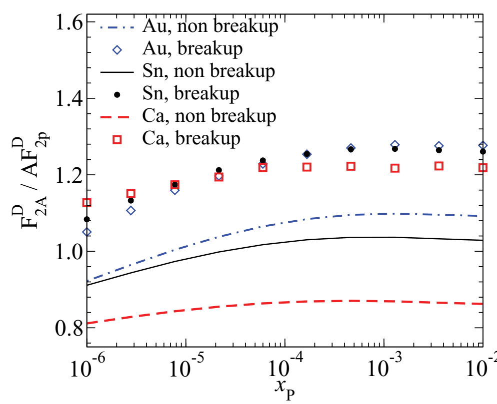
$$F_{2A}^{D(3)}(\beta, Q^2, x_P) = 4\pi A^2 F_{2N}^{D(4)}(\beta, Q^2, x_P, t_{\min}) \int d^2b \left| \int_{-\infty}^{\infty} dz e^{ix_P m_N z} e^{-\frac{A}{2}(1-i\eta)\sigma_{\mathrm{soft}}^{j}(x,Q^2)\int_z^{\infty} dz' \rho_A(b,z')} \rho_A(b,z) \right|^2$$

Frankfurt, VG, Strikman, Phys. Rept. 512 (2012) 255



H. Kowalski et al (2008)

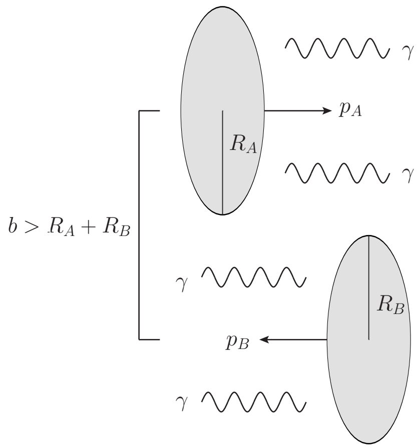




Predictions are similar in shape and for some cases in magnitude → not the best diffractive observable to distinguish between non-saturation and saturation!

Ultraperipheral pp, pA and AA collisions at the LHC

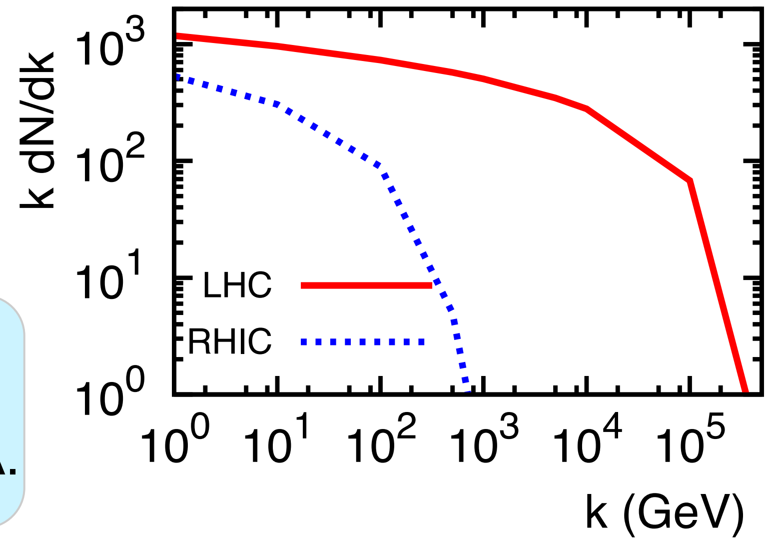
In pp, pA and AA collisions, nuclei can scatter at large impact parameters $b > R_A + R_B$ — ultraperipheral collisions (UPCs).



In UPCs, ions interact *electromagnetically* via quasi-real photons (the method of equivalent photons) ,
E. Fermi (1924)

The photon energy in target rest frame is HUGE

Spectrum of equivalent photons of Pb



☞ UPCs allow one to study γA collisions at photon energies **10 times** larger than at HERA.

A. Baltz et al., The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1

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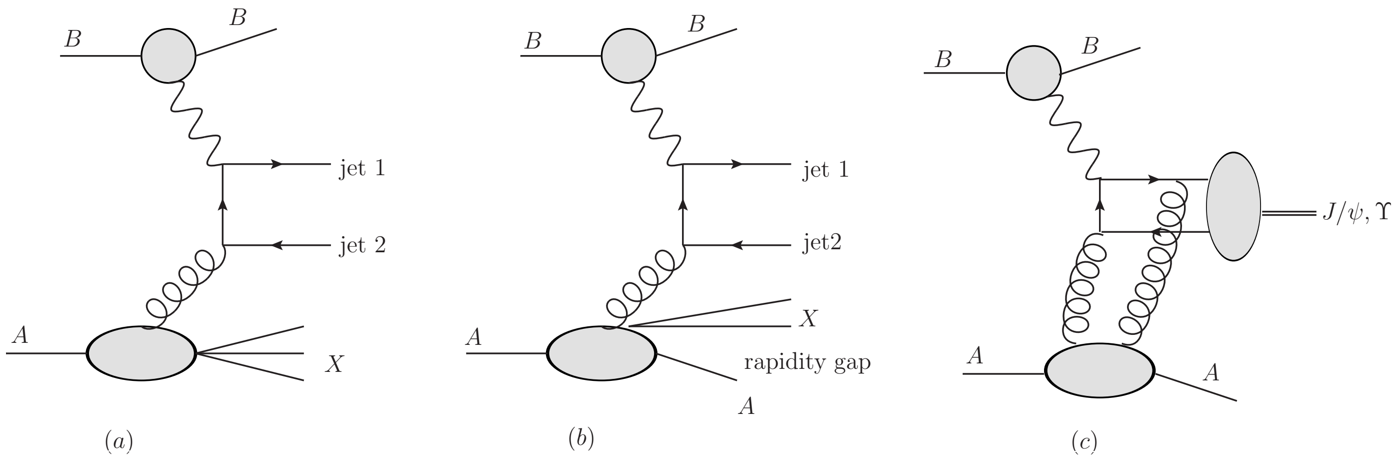
Ultraperipheral pp, pA and AA collisions at the LHC (2)

Hard real photon-nucleus processes can be used to study various gluon distributions in nuclei:



Inclusive photoproduction of jets (large pT or HQ jets): usual gluon distribution.

Diffractive photoproduction of jets (large pT or HQ jets): diffractive gluon distribution.

Exclusive VM production: generalized gluon distribution (impact parameter dependent)

Before EIC и LHeC (and analysis of pA data at the LHC)
UPCs is the only place where the nuclear gluon distribution can be constrained in the near future.

Exclusive J/ψ photoproduction in Pb-Pb UPCs at LHC

The recent ALICE measurement of exclusive J/ψ photoproduction in Pb-Pb UPCs gives a *first direct evidence* of large gluon shadowing at $x=10^{-3}$.

VG, E. Kryshen, M. Strikman, M. Zhalov, PLB (2013)

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

Photon flux of Pb
(well-known)

$y = \ln(2\omega/M_{J/\psi}) = \ln(W_{\gamma p}^2/(2\gamma_L m_N M_{J/\psi}))$ is the J/ψ rapidity

- Using the experimental $d\sigma_{PbPb\to PbPbJ/\psi}/dy$ and calculated $N_{\gamma/A}(y)$, we obtain:

E. Abbas *et al.* [ALICE Collaboration], arXiv:1305.1467
B.Abelev *et al*. [ALICE Collaboration], arXiv:1209.3715

$$\sigma_{\gamma Pb\to J/\psi Pb}(W_{\gamma p} = 92.4\,\mathrm{GeV}) = 17.6^{+2.7}_{-2.0}\ \mu\mathrm{b}\,,$$
$$\sigma_{\gamma Pb\to J/\psi Pb}(W_{\gamma p} = 19.6\,\mathrm{GeV}) = 6.1^{+1.8}_{-2.0}\ \mu\mathrm{b}$$

- These values can be converted into the nuclear suppression factor *S*:

$$S(W_{\gamma p}) \equiv \left[\frac{\sigma^{\mathrm{exp}}_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})}{\sigma^{\mathrm{IA}}_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})}\right]^{1/2}$$

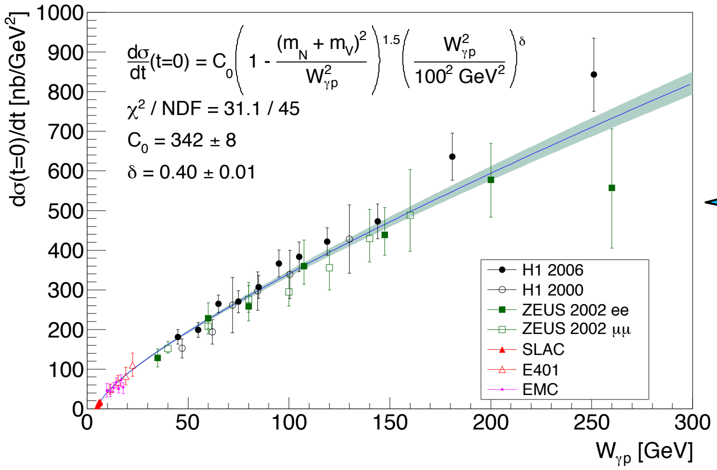
Exclusive J/ψ photoproduction in Pb-Pb UPCs at LHC (2)

- The denominator is the $\gamma Pb \to J/\psi Pb$ cross section in the impulse approximation:

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

Known from HERA and LHCb

Calculated using nuclear form factor



Btw, the data shows no signs of saturation (slowing down of W-dependence)!

- Model-independent determination of *S*:

VG, E. Kryshen, M. Strikman, M. Zhalov, PLB (2013)

$$S(W_{\gamma p} = 92.4\,\mathrm{GeV}) = 0.61^{+0.05}_{-0.04}$$

$$S(W_{\gamma p} = 19.6\,\mathrm{GeV}) = 0.74^{+0.11}_{-0.12}$$

- Modulo fine details, *S* is equal to the suppression due to the nuclear gluon shadowing.

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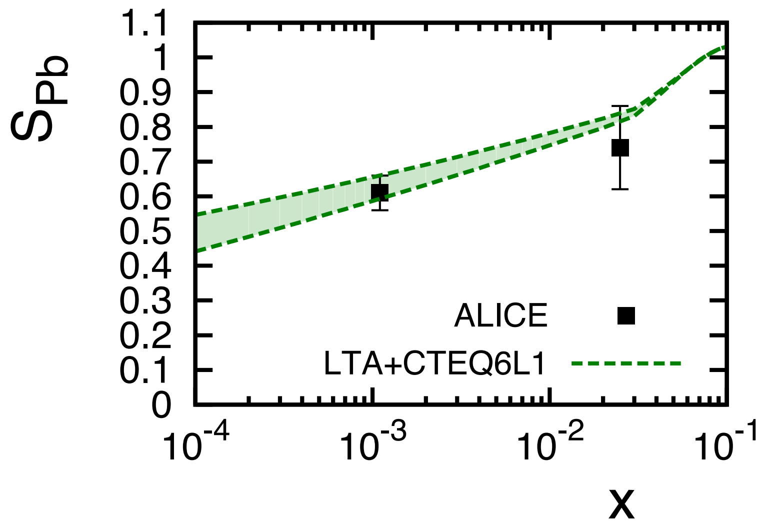
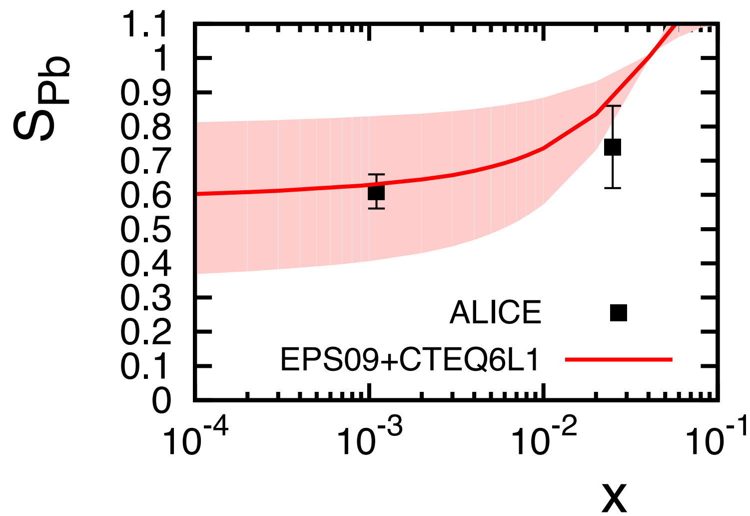
Exclusive J/ψ photoproduction in Pb-Pb UPCs at LHC (3)

- Large gluon shadowing in the leading twist approach agrees with large suppression factor *S*:

$$\frac{d\sigma_{\gamma A\to J/\psi A}(W_{\gamma p}, t=0)}{dt} = C(\mu^2)\left[xG_A(x,\mu^2)\right]^2 \quad \to \quad S(W) = \frac{G_A(x,Q^2)}{AG_N(x,Q^2)}$$

M. Ryskin (1993); S. Brodsky et al (1994)

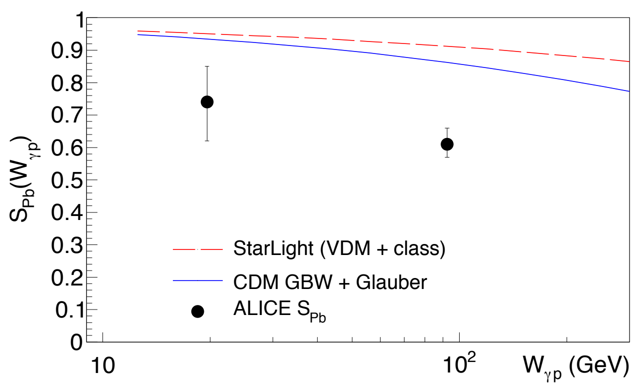




VG, M. Zhalov, arXiv:1307.4526 (accepted to JHEP)

$$x = M^2_{J/\psi}/W^2_{\gamma p}$$

- StarLight MC and dipole model overestimate *S:*

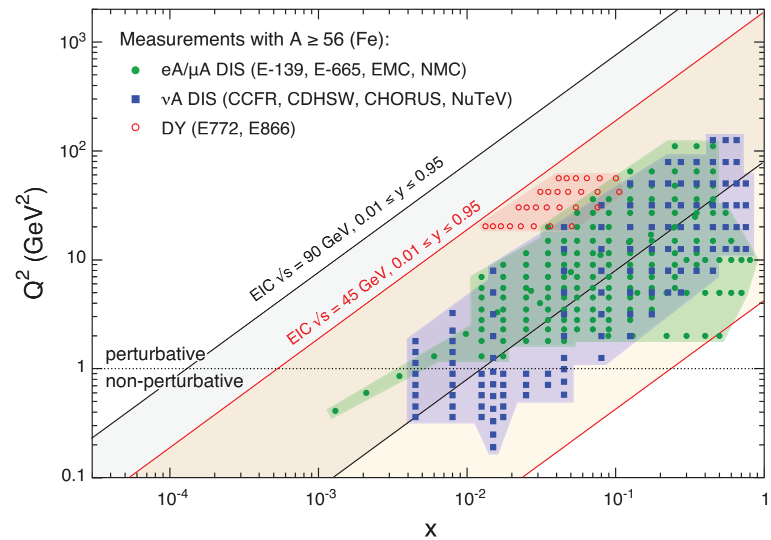


$$\sigma_{VA}(W_{\gamma p}) = 2\int d^2\vec{b}\left[1-\exp\left\{-\frac{\sigma(W_{\gamma p})}{2}T_A(\vec{b})\right\}\right]$$

Similar conclusion in:
T. Lappi and H. Mäntysaari, arXiv:1301.4095

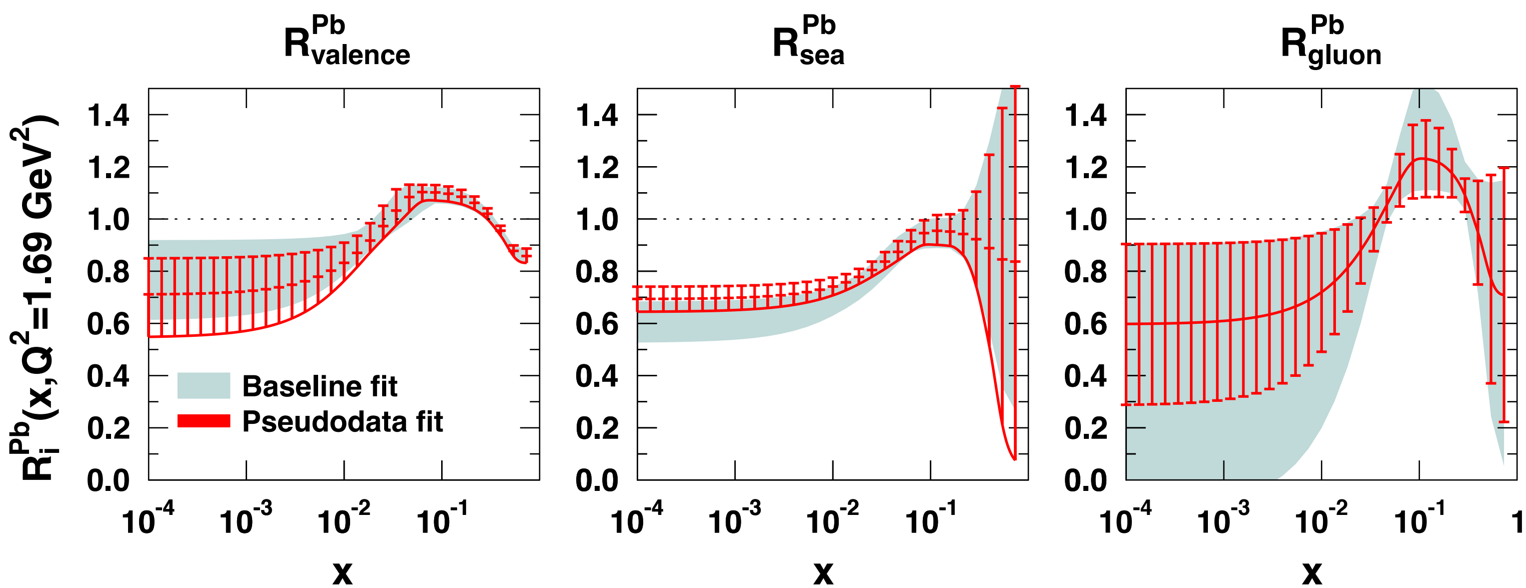
Nuclear gluon distribution at EIC

- Main goals:
  - determine gluon distributions in nuclei as a function of *x* and *b*
  - onset of high density regime
- Methods:
  - wide kinematic x-Q^2 coverage
  - measurement of $F_L(x,Q^2)$ и $F_2^c(x,Q^2)$
  - measurement of jets



A. Accardi *et al*., "Electron-Ion Collider: The Next QCD Frontier" , arXiv: 1212.1701

- Example of inclusion of EIC pseudo-data in global fits:



M. Lamont, POETIC IV, Jyvaskyla, Sep. 2-5, 2013

POETIC IV - Finland 2013: macl@bnl.gov 17

Conclusions

- The picture of high-energy scattering in the target rest frame allows for intuitive explanations of such phenomena as color transparency, inelastic diffraction and nuclear shadowing.

- The phenomenon of nuclear shadowing in the sea quark and gluon parton distributions plays major role in various reactions (inclusive, diffractive, exclusive) to be studied in collider kinematics at EIC.

- The leading twist theory of nuclear shadowing makes definite predictions for various (usual, diffractive, impact parameter dependent) nuclear PDFs and predicts large gluon shadowing.

- The first direct evidence of large nuclear gluon shadowing can be deduced from the recent ALICE measurement of exclusive J/ψ photoproduction in Pb-Pb UPCs.