Leading twist shadowing and black disk limit phenomena at LHC energies

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Outline

1. Leading twist shadowing is unambiguous consequence of QCD factorization theorem for hard diffraction.

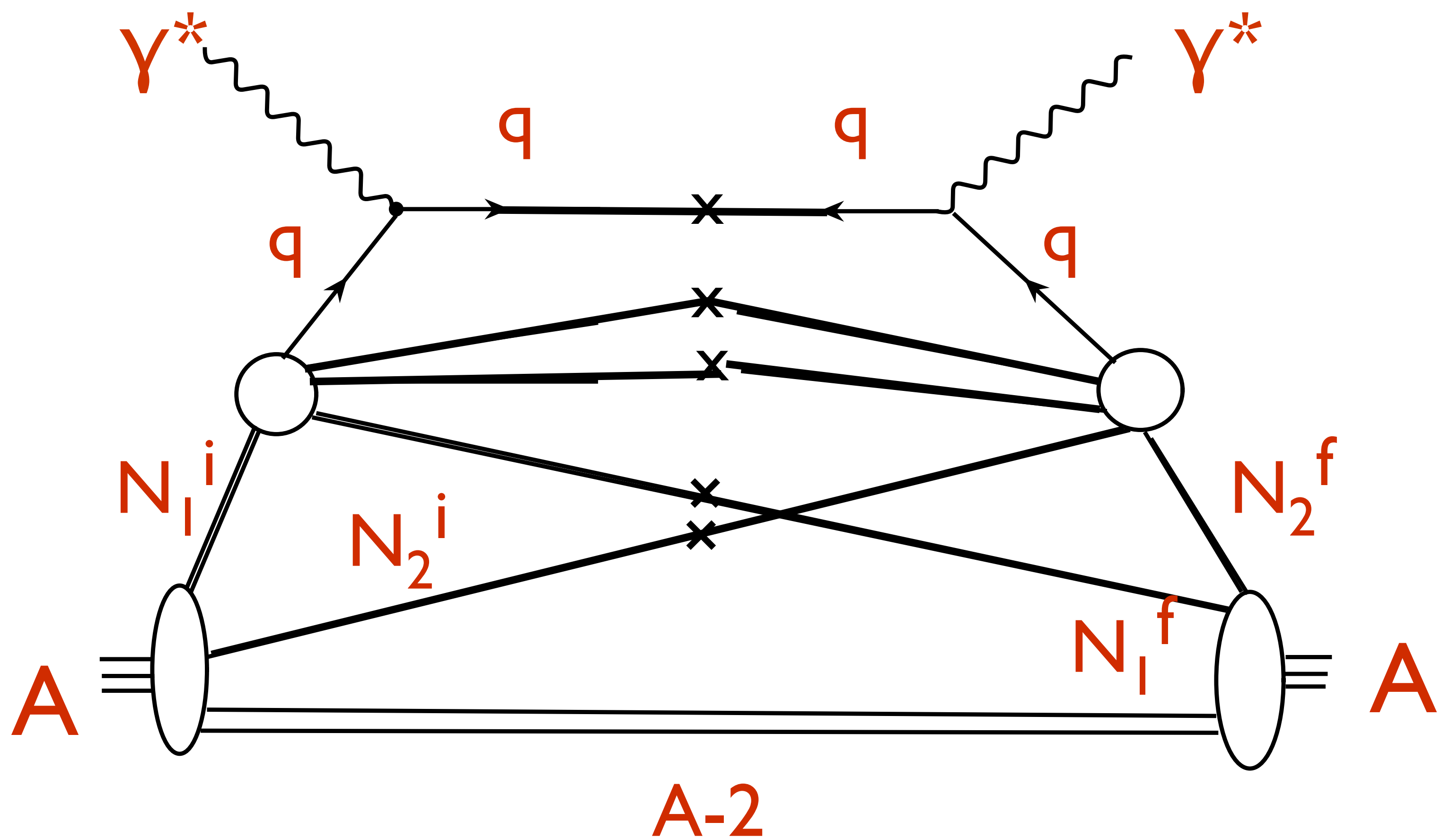
2. Numerical estimates for large virtualities.

3. Black disk limit for parton interactions - numerical estimates and way to observe it.

Nuclear shadowing and diffraction

Usually one starts from an impulse approximation form for the scattering of a hard probe (γ^*,W) off a nucleus. In the parton language - QCD factorization. Can we trust impulse approximation form in the hadronic basis for the nucleus wave function?

Consider interference between scattering off two different nucleons



Introduce nucleon light-cone fractions, α. Free nucleon $\alpha=1$, $\alpha_f \leq 1-x$

For nucleus to have significant overlap of |in> and <out| states

$$\alpha_{N_1^f} \leq \alpha_{N_1^i} - x \sim 1,\ \alpha_{N_2^i} \leq \alpha_{N_2^f} - x \sim 1$$

⟹ Interference is very small for $x > 0.1$ and impossible for $x > 0.3$.

⟹ Large interference for $x < 0.01$ due to the final states where small light cone fraction is transfered to the nucleon ≡ diffraction. It results in the leading twist shadowing as well as higher twist shadowing.

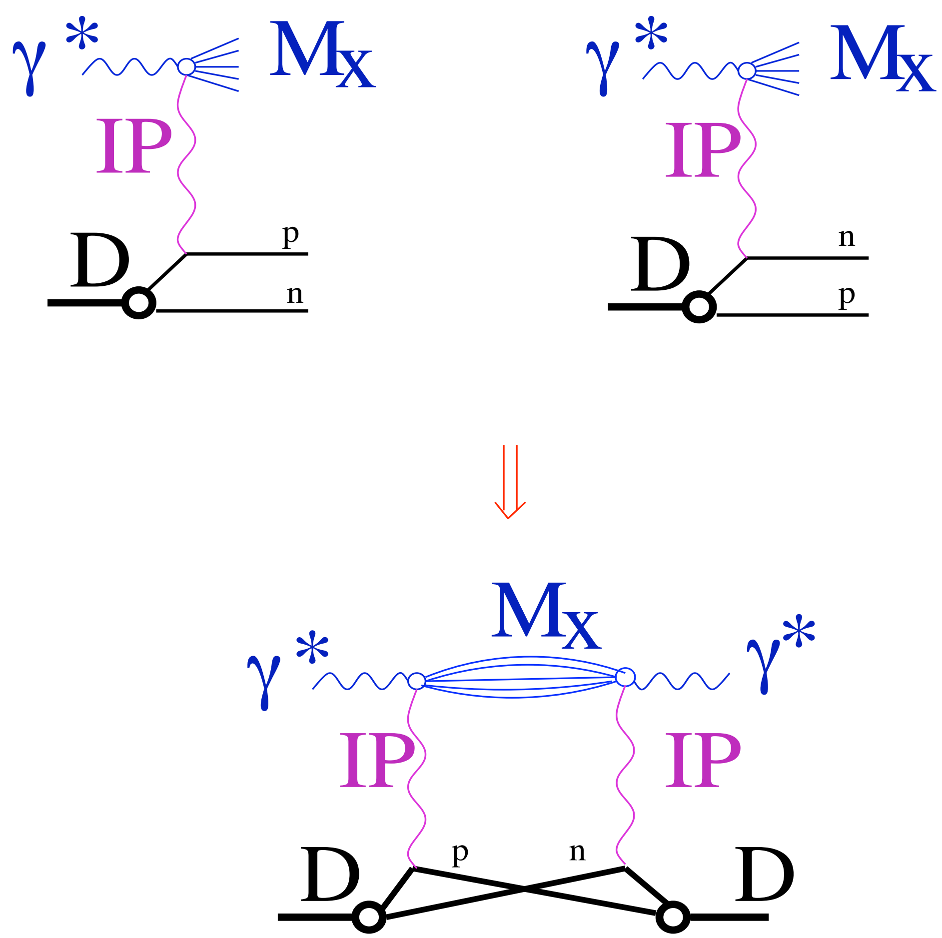
How big is HT shadowing is an open question. Issue of duality.

Deep connection between phenomenon of diffraction and nuclear shadowing - Gribov 1968 - relates cross section of diffraction in elementary reaction $\gamma^* + N \rightarrow X + N$ and deviation of cross section of scattering off nuclei from additivity.

Qualitatively, the connection is due to a possibility of small momentum transfer to the nucleon at small x, where

$$If\ \sqrt{-t} \leq \text{"}average\ momentum\ in\ nucleon(nucleus)$$

amplitudes of diffractive scattering off proton and off neutron interfere



Double scattering diagram for the $\gamma^* D$ scattering

$$\frac{d\sigma^{\gamma^*+D \to M_X + (pn)}}{dt\, dM_X^2} = \frac{d\sigma^{\gamma^*+N \to M_X + (pn)}}{dt\, dM_X^2} (2+2F_D(4t))$$

Here $F_D(t)$ is the deuteron form factor. For $t=0$ - 100% constructive interference - (pn) system is D. Coherence dies out at large t.

Integrate over t, M_X ➡ positive correction to the impulse approximation. Coincides with the Gribov shadowing correction to the total cross section (up to small corrections due to the real part of the amplitude). However the sign is opposite !!!

Explanation is unitarity - Abramovskii, Gribov, Kancheli cutting rules (AGK)

which relate different cuts of a particular diagram. In particular contribution to the total cross section (screening) is equal with opposite sign to that of diffraction. ➡Using AGK we rederived original Gribov result extending it to include the real part effects. This approach does not require separation of diffraction into leading twist and higher twist parts.

Detour: Diffractive phenomena - inclusive diffraction and measurement of diffractive pdf's

Collins factorization theorem: consider hard processes like

$$\gamma^* + T \to X + T(T'), \;\; \gamma + T \to \; jet_1 \; + \; jet_2 + X + T$$

one can define conditional (fractional) parton distributions

$$f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t) \qquad \text{where} \qquad x_{I\!P} \equiv 1 - x_{T_f}$$

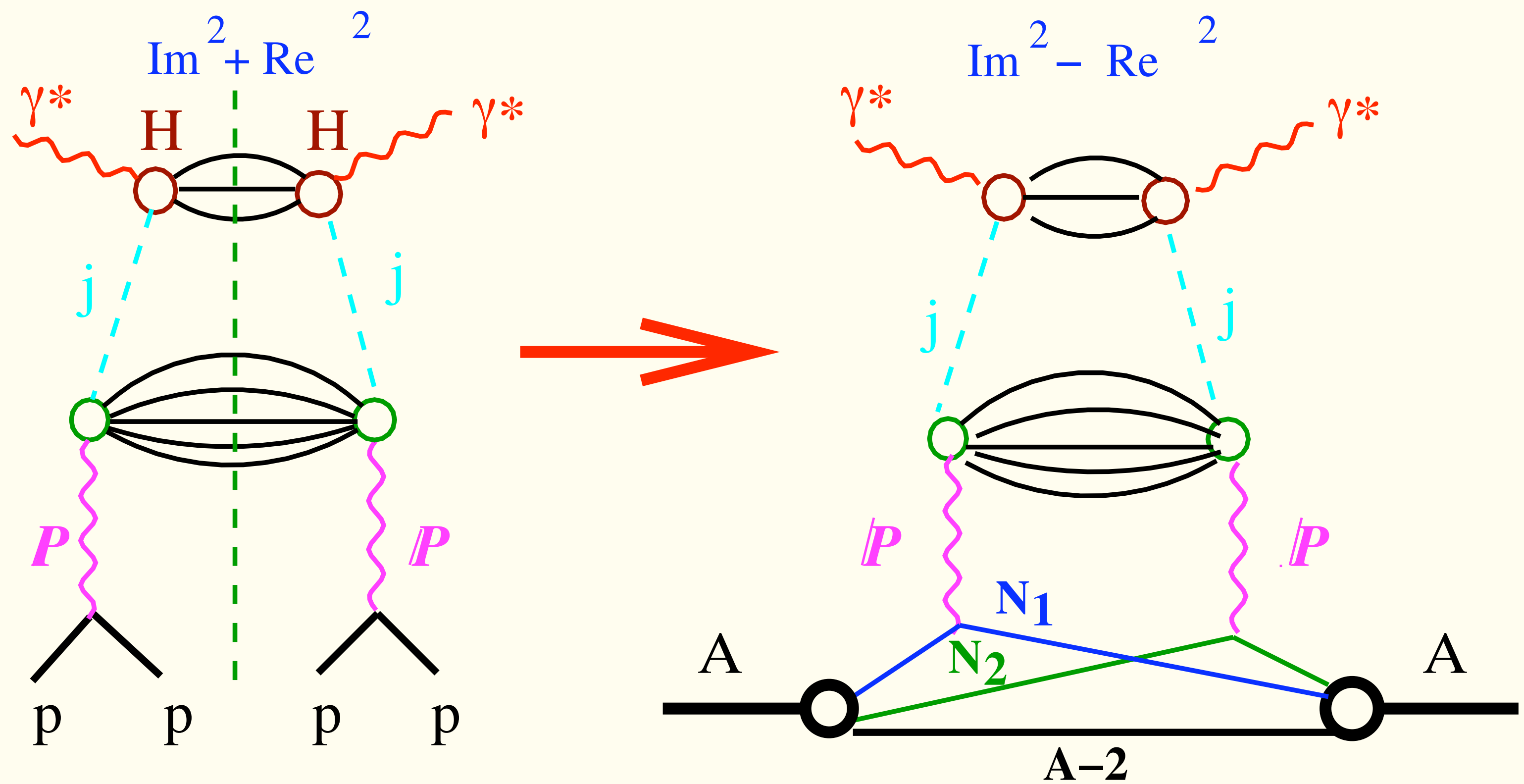
Theorem: for fixed $x_{I\!P},\ t$ the same Q evolution for diffractive pdf's as for normal pdf's.

Consistent with the HERA studies of hard diffraction

Theoretical expectations for shadowing in the LT limit

Combining Gribov theory of shadowing and pQCD factorization theorem for diffraction in DIS allows to calculate LT shadowing for all parton densities (FS98) (instead of calculating F_{2A} only)

Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the nucleon diffractive pdf's: $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$



Hard diffraction

off parton "j"

Leading twist contribution

to the nuclear shadowing for

structure function $f_j\,(x,Q^2)$

Theorem: in the low thickness limit (or for x>0.005)

$$f_{j/A}(x,Q^2)/A = f_{j/N}(x,Q^2) - \frac{1}{2+2\eta^2}\int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{x_0} dx_{I\!P} \cdot$$

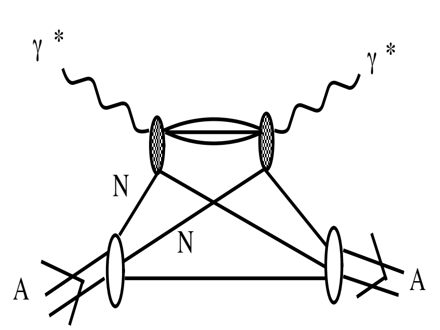
$$\cdot f_{j/N}^D(\beta, Q^2, x_{I\!P}, t)\rho_A(b,z_1)\ \rho_A(b,z_2)\ \mathrm{Re}\left[(1-i\eta)^2 \exp(i x_{I\!P} m_N(z_1-z_2))\right],$$

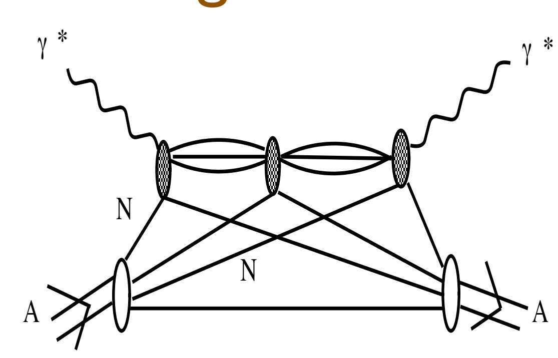
where $f_{j/A}(x,Q^2), f_{j/N}(x,Q^2)$ are nucleus(nucleon) pdf's,

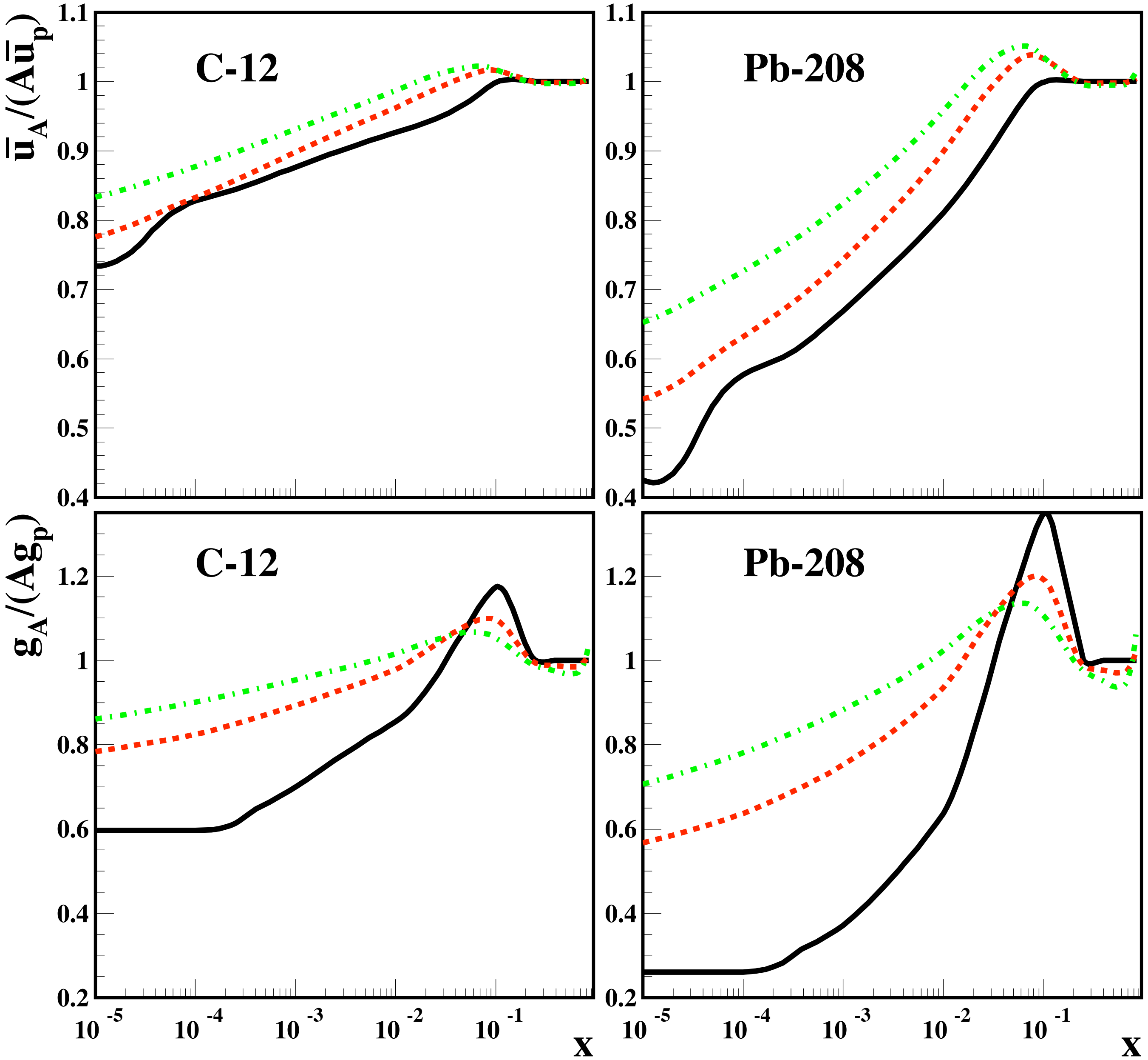
$\eta = ReA^{diff}/ImA^{diff} \approx 0.3,\ \rho_A(r)$ nuclear matter density.

$x_0(quarks) \sim 0.1,\ x_0(gluons) \sim 0.03$

Next step: use the HERA measurements of diffractive quark and gluon PDFs which indicate dominance of the gluon induced diffraction to calculate gluon and quark shadowing. Detailed analysis in Guzey, FS & McDermott + further studies in Guzey et al 04. Numerical studies include higher order rescattering terms and HERA measurements of diffractive quark and gluon PDFs which indicate dominance of the gluon-induced diffraction to calculate gluon and quark shadowing. Higher order terms are a small correction for x> 0.003 - so in this region predictions for sufficiently high Q are not sensitive to higher twist effects due to nonlinearities at low Q as one uses HERA diffractive pdfs which are fitted to data at large virtualities.



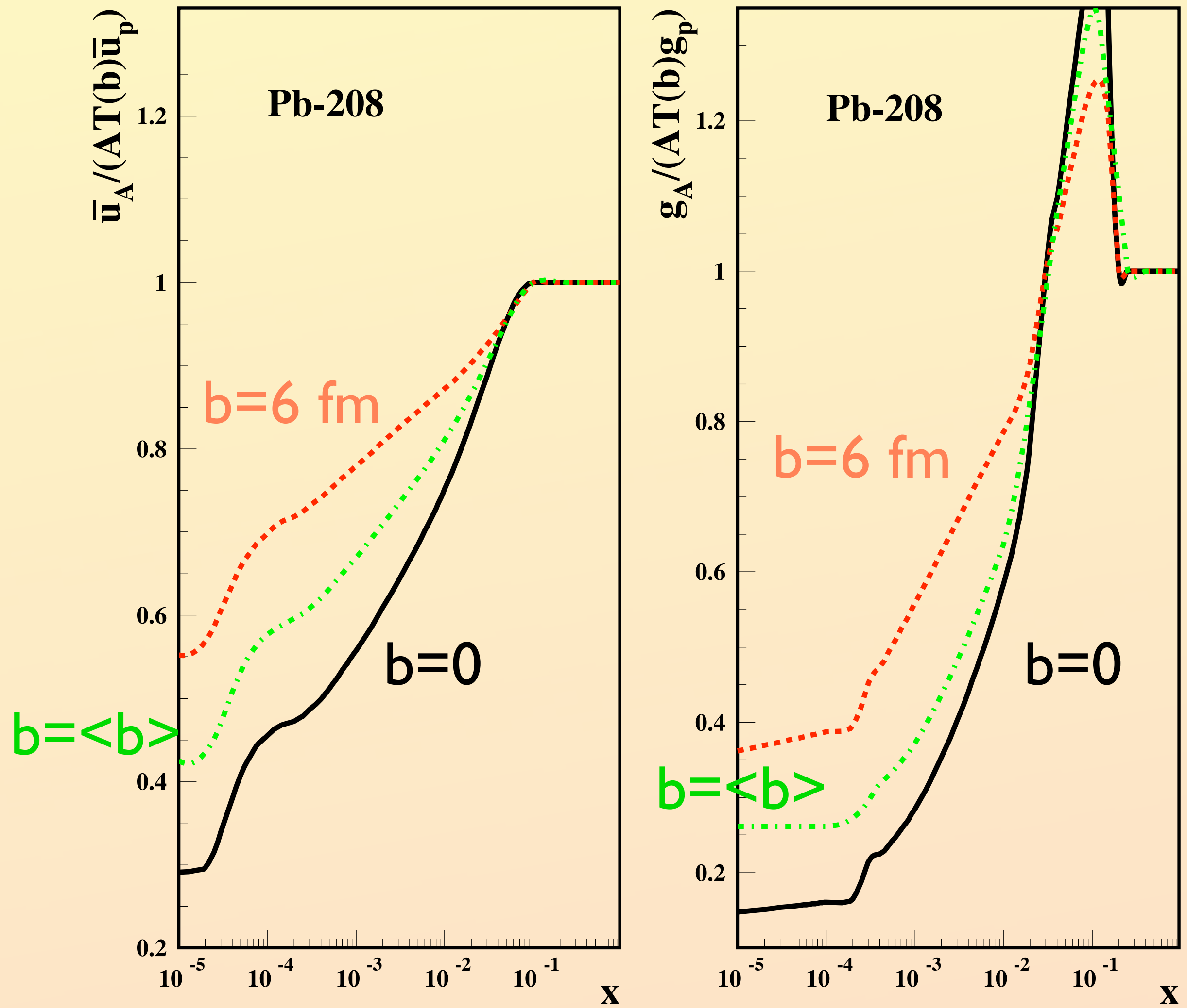




Dependence of G_A/AG_N and $\bar{q}_A/A\bar{q}_N$ on x for Q=2 (solid), 10 (dashed), 100 GeV (dot-dashed) curves calculated using diffractive parton densities extracted from the HERA data, the quasieikonal model for $N \geq 3$, and assuming validity of the DGLAP evolution.

Large gluon shadowing at x~ 0.003 agrees semi quantitatively with dA RHIC data: PHENIX data on J/ψ production.

Shadowing strongly depends on the impact parameter. Dependence of parton densities on impact parameter in the quasieikonal model (GFS -03) at Q=2 GeV.



b-dependence can be studied experimentally by comparing the rapidity dependence of the hard processes in peripheral and central collisions

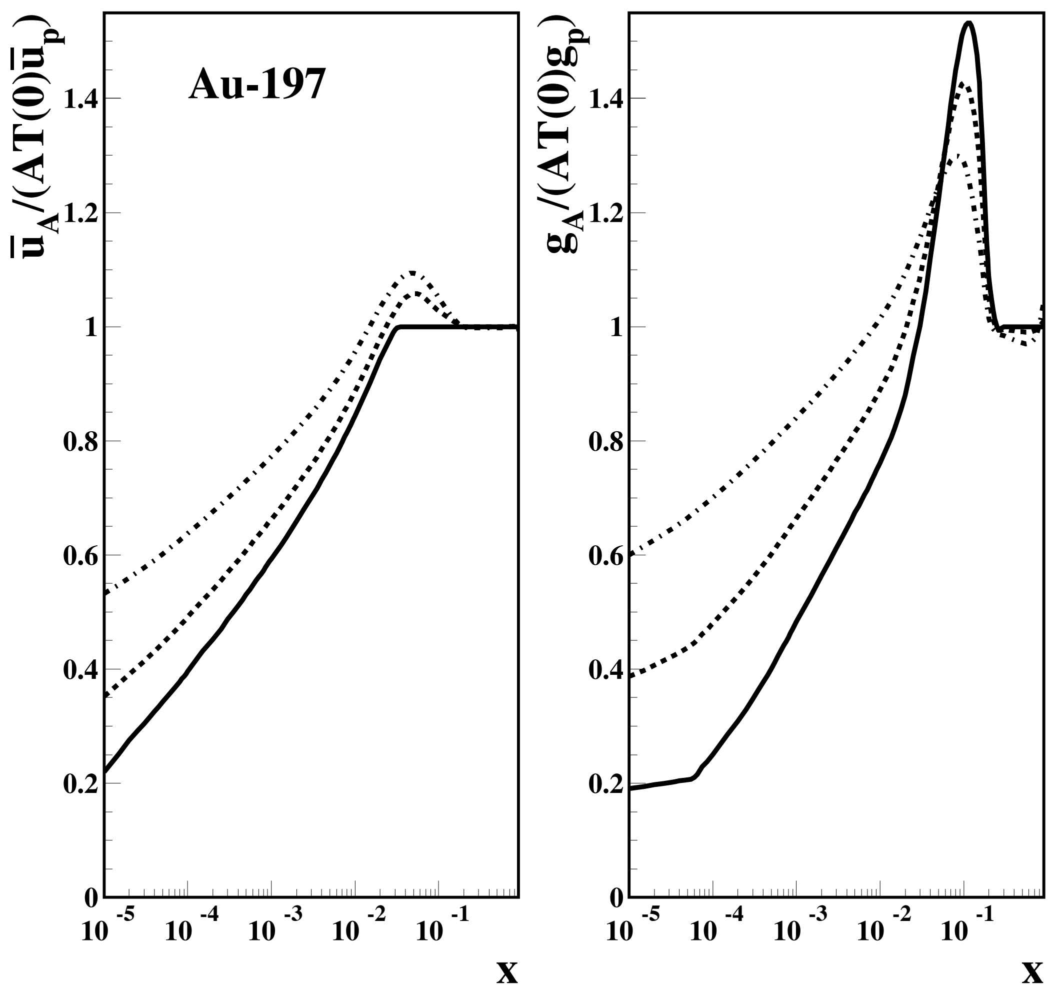
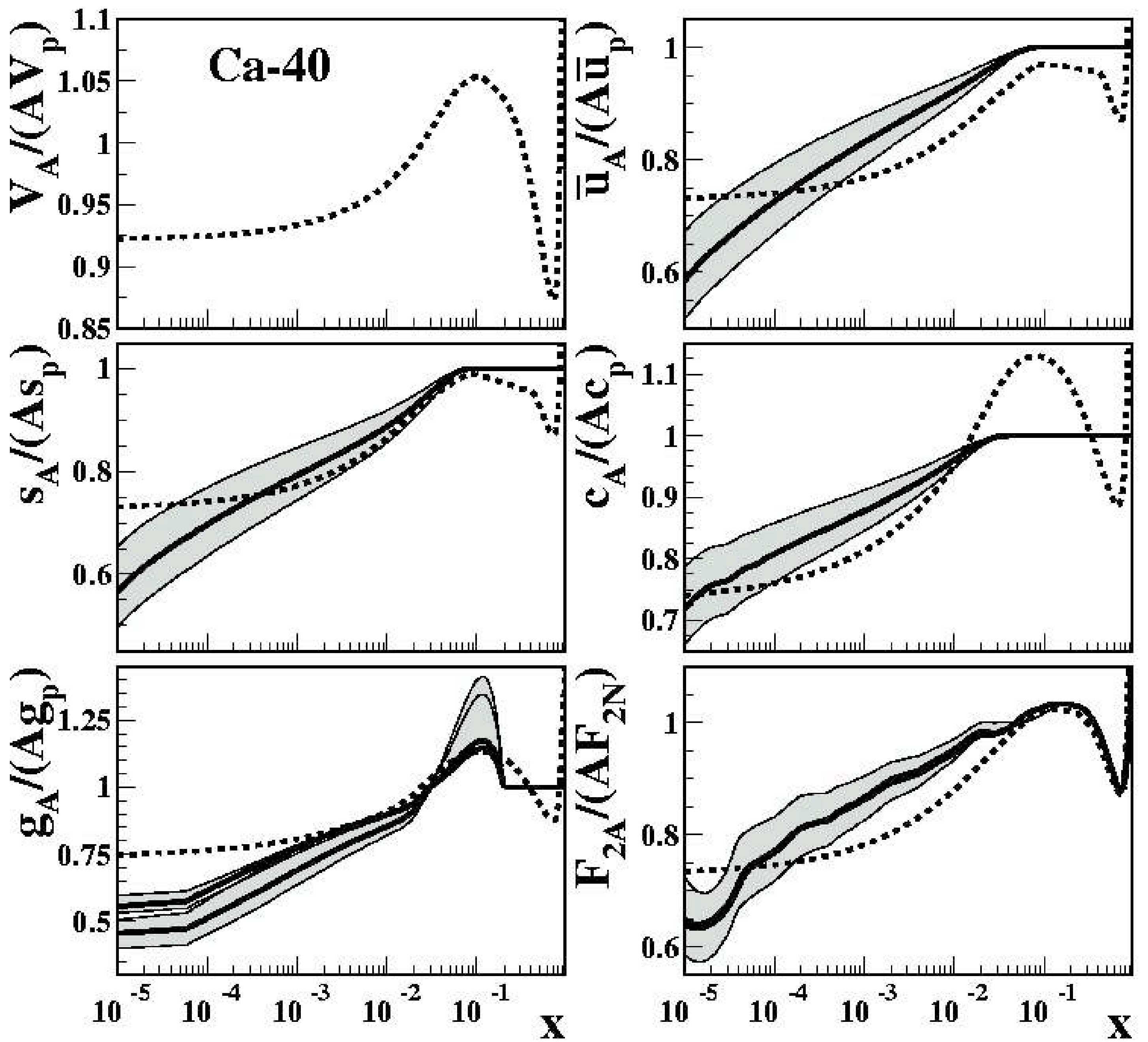


FIG. 9: Nuclear shadowing at zero impact parameter: The ratios $\bar{u}_A(x,Q^2,0)/(AT(0)\bar{u}_N(x,Q^2,0))$ and $g_A(x,Q^2,0)/(AT(0)g_N(x,Q^2,0))$ for ^{197}Au at $Q^2 = 4$ GeV^2 (solid), $Q^2 = 10$ GeV^2 (dashed) and $Q^2 = 100$ GeV^2 (dot-dashed).



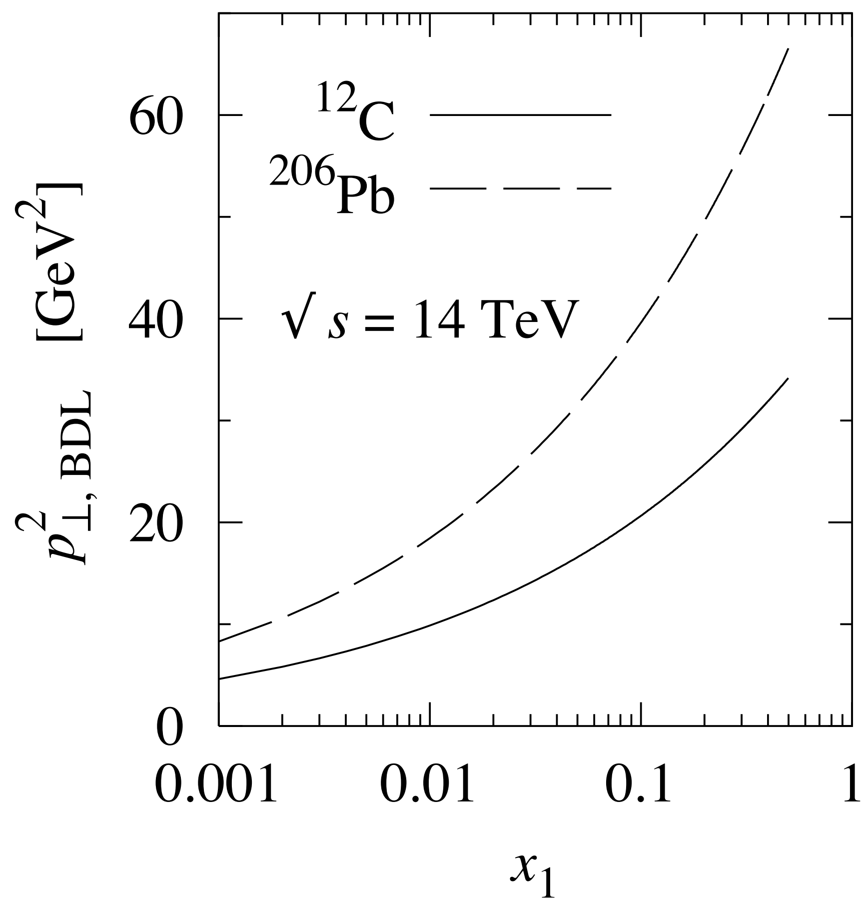
Main differences with EKS

- EKS =LO fit to the data assuming no higher twist effects for $Q^2 > 1 GeV^2$ - a dangerous assumption - Qiu & Vitev, FGS
- Ad hoc extrapolation to small where no data are available assuming that for small x shadowing is x independent.

The range of input nuclear pdf's allowed by the HERA diffraction data for Q=2 GeV vs EKS98 fit (dashed curves)

We expect large effects at LHC due the breakdown of the QCD factorization due to proximity to the black disk limit in which the strength of parton interaction is close to maximal

The average p^2_T for a parton passing through the nuclear media at small impact parameter can be estimated using unitarity considerations for the scattering of a small color dipole (Frankfurt, Weiss, MS)



Average p^2_T (gluon) for b=0 - for quarks p^2_T is a factor of 2 smaller

New NLO approach for getting a lower limit on p_T (Frankfurt, Vogelsang, MS) leads to

p_T (gluon)> 4 GeV/c for x> 0.1

p_T (quark)> 2.5 GeV/c for x> 0.1

Ways to study nuclear shadowing at LHC

- Ultraperipheral AA collisions: dijet production: study of gluon pdfs down to $x \sim 4 \cdot 10^{-5}$ and $p_T > 6$ GeV/c + ratio of diffractive and inclusive pdf's which will allow to study proximity to BDL

A process

- Hard pA processes - DY (backgrounds except very forward), QQ, jets, Z - most of the problems are affected by fsi. Z-boson transverse distribution is very sensitive for $p_t < 2$ GeV/c to BDL effect - additional suppression of this region.

A^{-} process

$$\frac{d\sigma(p + A \rightarrow \mu^+\mu^- + X)}{dx_A dx_p} = \frac{4\pi\alpha^2}{9}\frac{K(x_A, x_p, M^2)}{M^2} F_{2p}(x_p, Q^2) \cdot \frac{1}{6\pi^2} M^2 \cdot 2\pi R_A^2 \ln(x_0/x_A).$$

BDL - very weak dependence of the cross section on M^2

- AA collisions - ***effects of shadowing are large*** for example for production of jets at $y\sim0$ and intermediate $p_T < 10$ GeV/c. - a factor of the order 4 for $p_T \sim 5$ GeV/c (at larger for central collisions), small effect for $p_T > 20$ GeV/c, $y=0$. However chances to measure directly shadowing are slim - too many extra effects like fsi.

  One of the very few exceptions is Z-boson production - at $|y|<2$ suppression is of the order 0.65 - 0.7. Could be inferred from a comparison of peripheral and central collisions.

B^+ process

- Probing onset of Black Disk Dynamics:

  - UPC - Diffraction/Total, shadowing for J/ψ production

  - pA/AA - Testing transverse momentum broadening of partons propagating through nuclear media:

    - Suppression of the forward hadron production combined with transverse momentum broadening of the spectrum

    - Transverse momentum broadening for channels with minimal fsi - Z-boson, photon,...

Conclusions

- Leading shadowing effects effects are large for generic central collisions
- Challenge - to measure shadowing in the relevant kinematics - UPC seems the best bet.
- Partons with tranverse momenta less than few GeV will interact with maximal strength (black disk limit) in a wide range of rapidites