"*Leading twist nuclear shadowing and color fluctuations in photons and nucleons*"

Mark Strikman, PSU

Outline

- Intro: Color fluctuations in hadrons - new pattern of high energy hadron - nucleus scattering - going beyond single parton structure of nucleon.
- Calculating leading twist shadowing and antishadowing
- A new frontier : probing color fluctuations in photon in γA collisions starting with UPC data from LHC (pre-sequel of EIC & LHeC studies)
- Evidence for x -dependent color fluctuations in nucleons -nucleon squeezing

Fluctuations of overall strength of high energy (γ)hN interaction*

High energy projectile stays in a frozen configuration distances $l_{coh} = c\Delta t$

$$\Delta t \sim 1/\Delta E \sim \frac{2p_h}{m_{int}^2 - m_h^2} \qquad \Delta t \sim \frac{1}{2xm_N} \quad \textbf{DIS}$$

At LHC for $m_{int}^2 - m_h^2 \sim 1\mathrm{GeV}^2$ $l_{coh} \sim 10^7$ fm>> $2R_A$>> $2r_N$

coherence up to $m_{int}^2 \sim 10^6 \mathrm{GeV}^2$

Hence system of quarks and gluons passes through the nucleus interacting essentially with the same strength but changes from one event to another different strength

r

Strength of interaction of white small system is proportional to the area occupies by color.

QCD factorization theorem for the <u>interaction of small size color singlet wave package of quarks and gluons.</u>

For small quark - antiquark dipole

$$\sigma(q\bar{q}T) = \frac{\pi^2}{3}\alpha_s(Q^2) r_{tr}^2 x g_T(x, Q^2 = \lambda r_{tr}^2)$$

small but rapidly growing with energy.

In case T= nucleus, LT interactions with 2,3… nucleons are hidden in $g_T(x,Q)$

For small 3 quark tripole

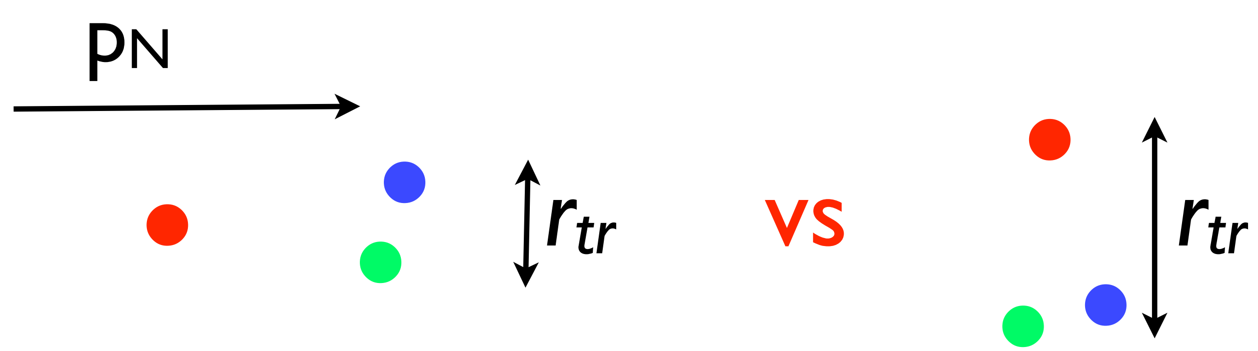
$$r_{tr}^2 \rightarrow (r_1 - (r_2 + r_3)/2)^2 + (r_2 - (r_1 + r_3)/2)^2 + (r_3 - (r_1 + r_2)/2)^2$$

dependence of $\sigma_{tot}(hN)$ on size holds in the nonperturbative regime

$$\sigma_{tot}(KN) < \sigma_{tot}(\pi N)$$

Global fluctuations of the strength of interaction of a fast nucleon/pion/photon, can originate from fluctuations of the overall size /shape, number of constituents.

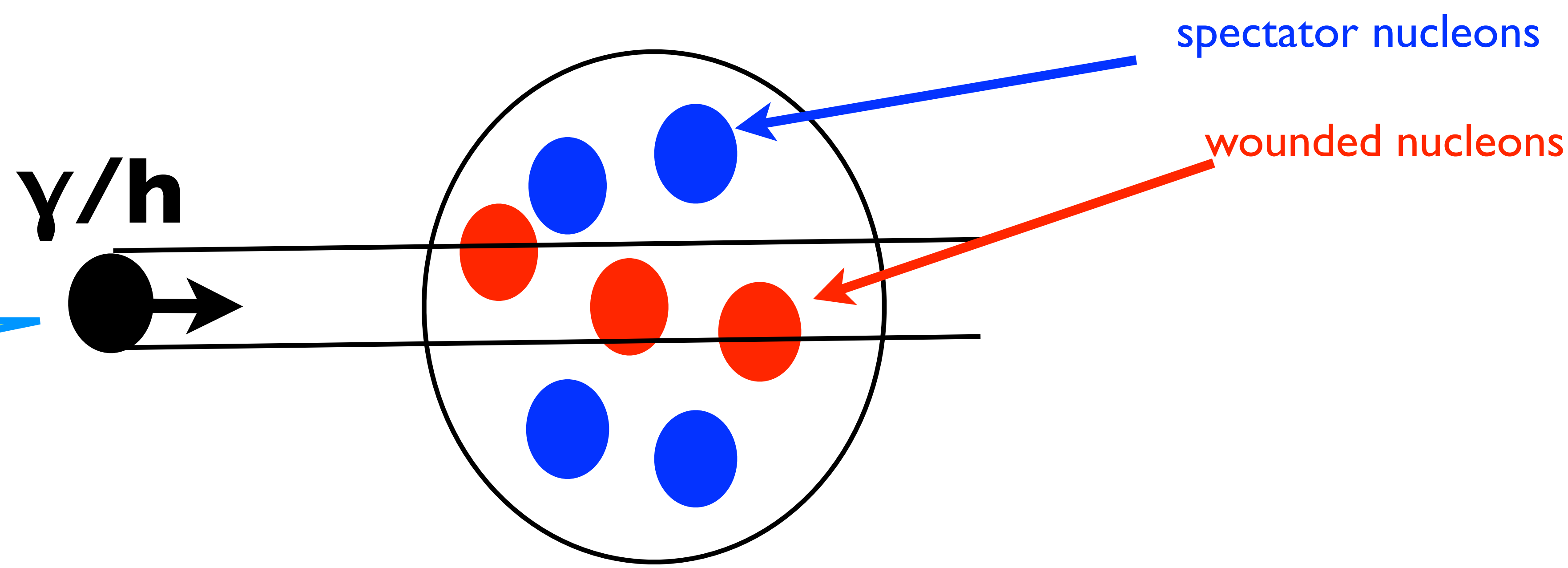
Example: quark -diquark model of nucleon



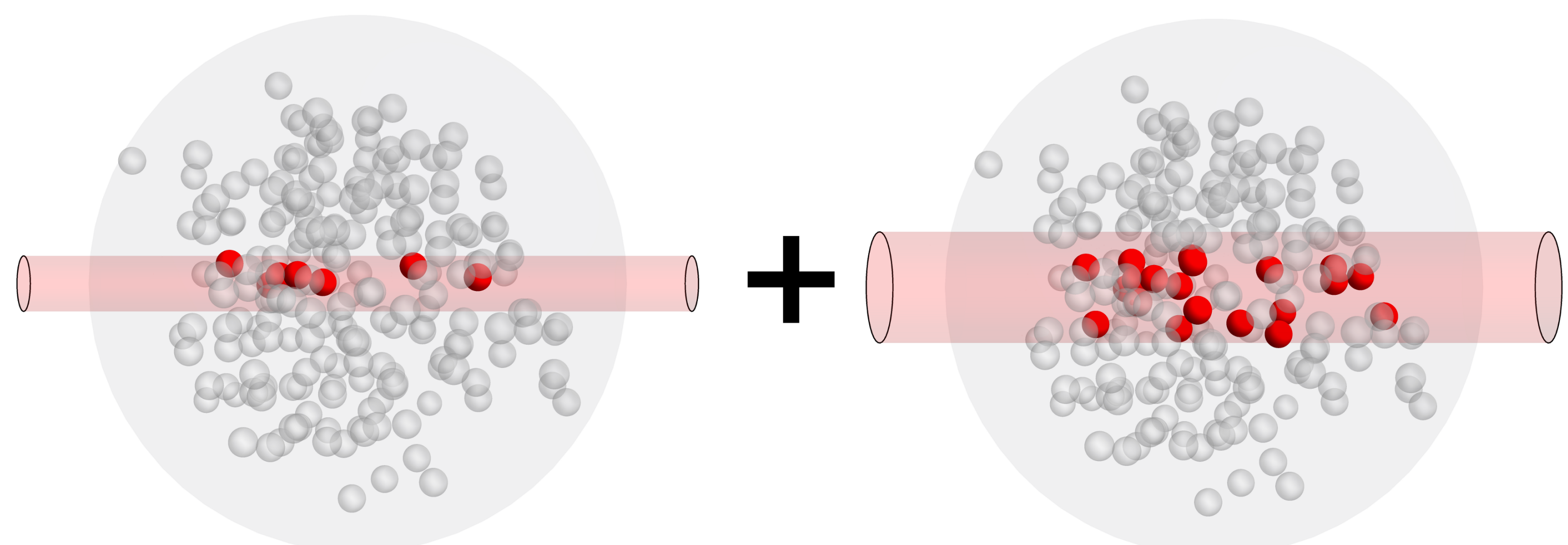
We will refer fluctuations of the strength of interaction of nucleon, photon,.. as color fluctuations of interaction strength - studying them allows to go beyond single parton 3-D mapping of the nucleon

Constructive way to account for coherence of the high-energy dynamics is Fluctuations of interaction = cross section fluctuation formalism. Analogy: consider throwing a stick through a forest - with random orientation relative to the direction of motion. (No rotation while passing through the forest - large l_{coh}.) Different absorption for different orientations.

Classical low energy picture of inelastic h A collisions implemented in Glauber model based Monte Carlos



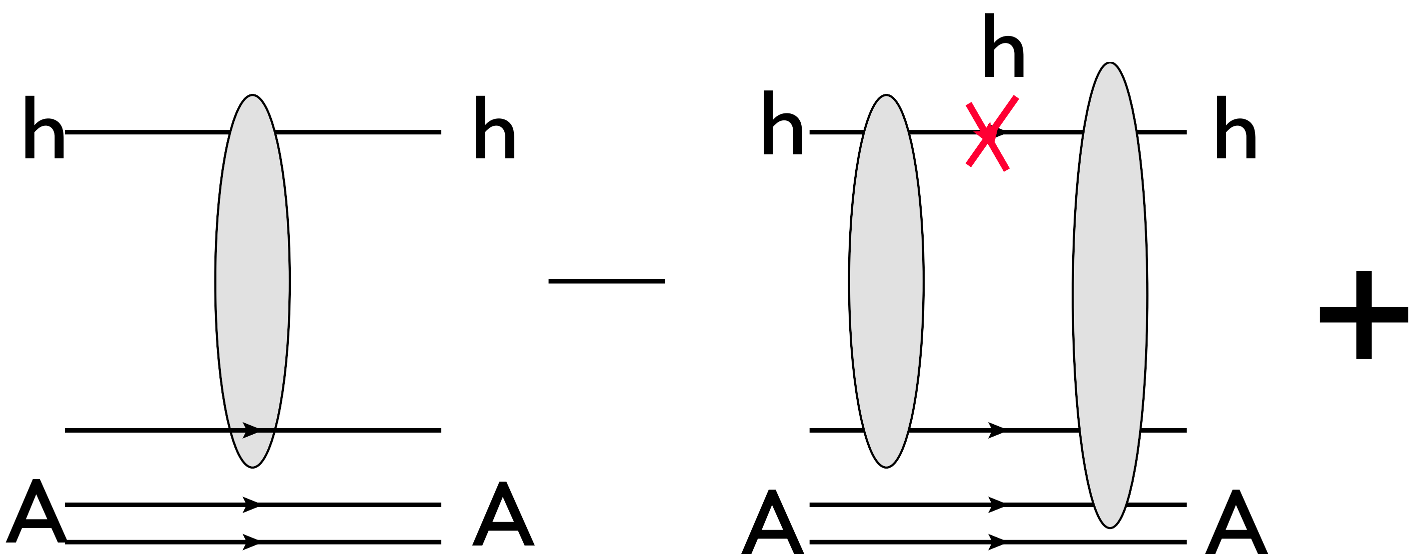
High energy picture of inelastic h A collisions consistent with the Gribov - Glauber model - interaction of frozen configurations



Expect effects similar positronium example = correlation between size and number of wounded nucleons

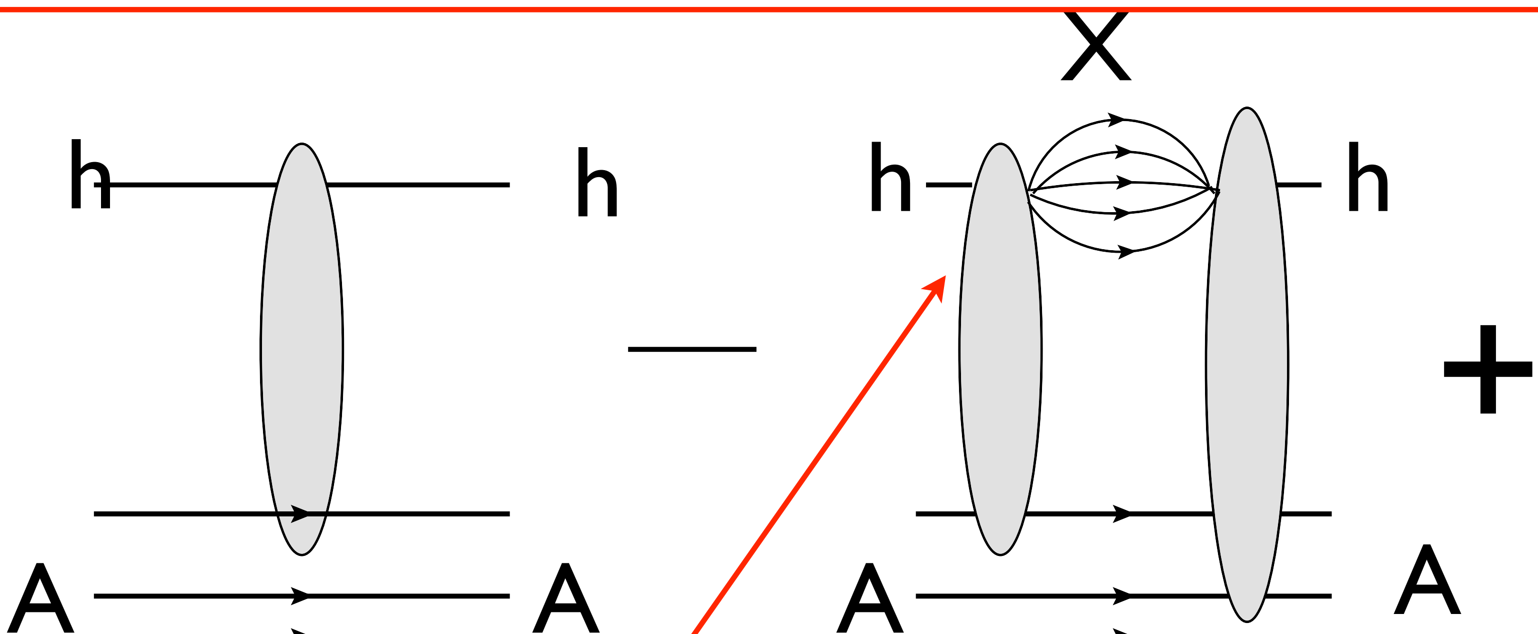
Comment. Though inelastic shadowing effects result in a rather small correction for the total pA cross section - presence of the fluctuations of the strength of NN interaction leads to significant fluctuations in inelastic pA, AA collisions (Baym, LF, MS,.. 92) - recently several attempts to take these effects into account in MC generators.

Formal account of large l_{coh} ➟ different set of diagrams describing p A scattering:



Glauber model

in rescattering diagrams proton propagates in intermediate state - zero at high energy - cancelation of planar diagrams (Mandelstam & Gribov)- no time for projectile to come back between interactions.



$$\sigma_2 \propto \int dt F_A^2(t) \frac{d\sigma(p+p \to p + X(p+\ inel\ diff))}{dt}$$

High energies = Gribov -Glauber model

X= set of frozen intermediate states the same as in hN diffraction

deviations from Glauber are small for E_{inc} < 10 GeV as inelastic diffraction is still small.

Comment : Good Walker picture. h decomposed into scattering eigenstates

$$|h\rangle = \sum a_i \, |\sigma_i\rangle$$

$$\sigma_{shad} \propto \sum_i |a_i|^2 \sigma_i^2 \quad \propto \frac{d\sigma_{diff}^{hN \to XN}(t=0)}{dt}$$

reproduces Gribov result in the limit $R_A >> r_N$

No matching away from t=0 as no universal basis of scattering eigenstates exists in finite t. Not important for A > 4 where essential t are very small.

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Leading twist nuclear shadowing phenomena in hard processes with nuclei

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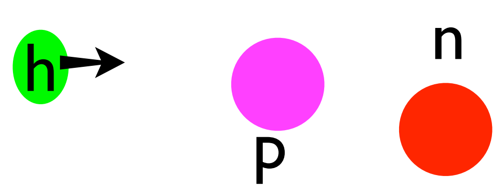
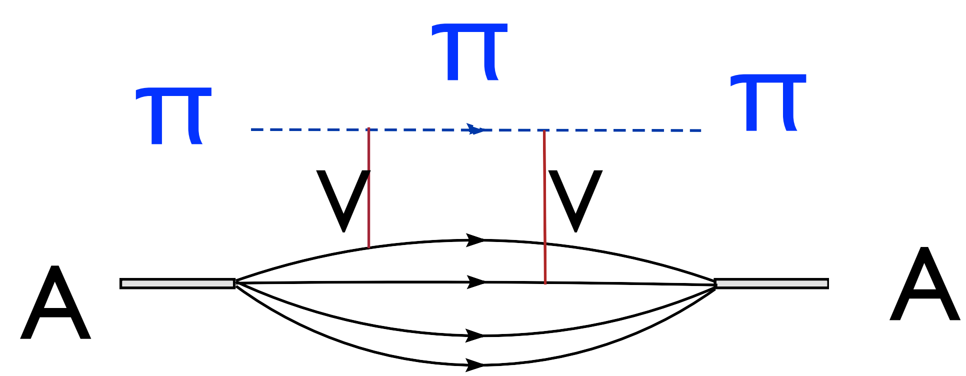
Nuclear shadowing in DIS - is this obvious?



$\Rightarrow$ $\sigma_{h^2H} < \sigma_{hp} + \sigma_{hn}$

$\sigma_{e^2H}(x,Q^2) < \sigma_{ep}(x,Q^2) + \sigma_{en}(x,Q^2)$ in DIS???

Glauber model: interaction of the projectile with nucleons via potential

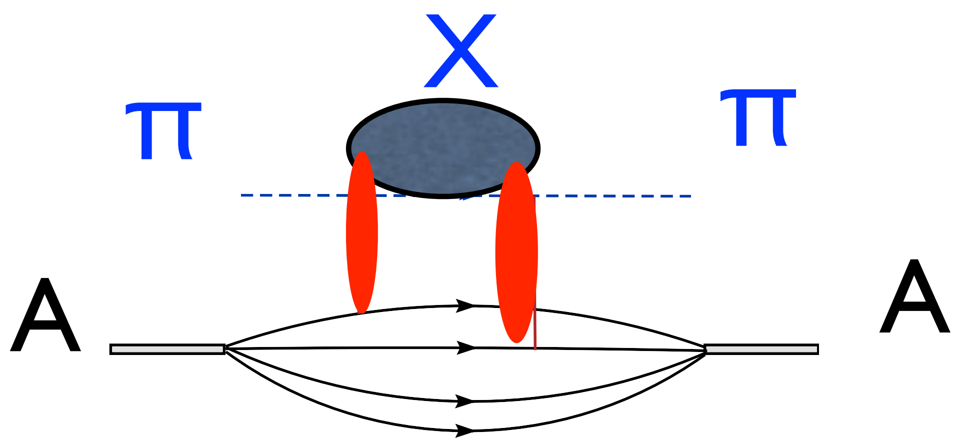


The diagrams consider by Glauber in QM treatment of hA scattering are exactly zero at $E_h >> m_h$ (Mandelstam & Gribov proof of the cancelation of planar (AFS) diagrams).

Physics: no time for pion to go back to pion during a short time between the interactions.

Natural explanation in the Gribov space-time picture of high energy scattering:

photon/ hadron fluctuates into different configurations, **x**, long before the collisions.

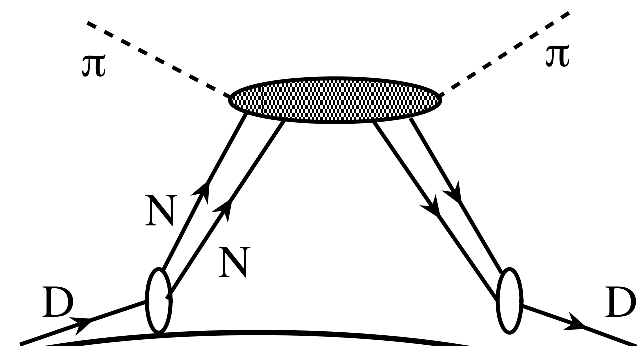


These configurations are frozen during the collision.
Sum over these configurations = elastic + inelastic diffraction.

Nuclear shadowing in high energy hadron - nucleus scattering (Gribov 68)

Though the diagrams consider by Glauber are exactly zero at $E_h >> m_h$, the answer for double scattering

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



shadowing correction

ρ(4t) is the deuteron form factor

is expressed through the diffractive cross section (elastic + inelastic) at t~0. For triple,... rescatterings (A>2) the answer is related to the low t diffraction but cannot be obtained in a model independent way

Theoretical accuracy of the approach - nonnucleonic degrees of freedom - pions, off-mass-shell effects. Empirically Glauber model for E_p=1 GeV, Gribov-Glauber model for $E_p \leq$ 500 GeV work with accuracy of better than 5% **including photon - nucleus scattering**.

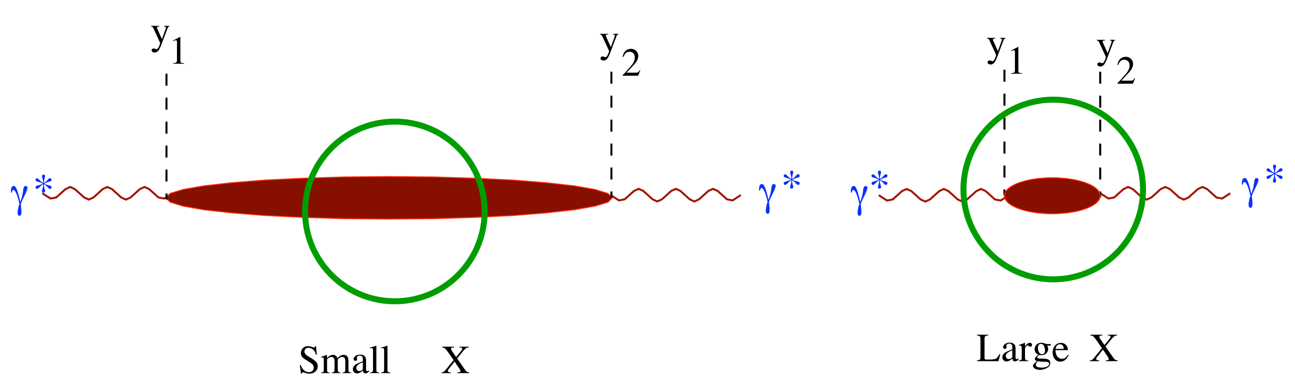
Small x DIS in the target rest frame: Large longitudinal distance dominate

Gribov, Ioffe, Pomeranchuk 65, Ioffe 68, Gribov 69

Follows from the analysis of the representation of the forward Compton scattering amplitude expressed as a Fourier transform of the matrix element of the commutator of two electromagnetic (weak) current operators:

$$ImA_{\mu\nu}^{\gamma^* N}(q^2, 2qp) = \frac{1}{\pi}\int \exp^{iq(y_2-y_1)} \langle p| \left[j_\mu(y_2), j_\nu(y_1)\right] |p\rangle \, d^4(y_2-y_1)$$

y_1 and y_2 are the points where γ^* is absorbed and emitted.



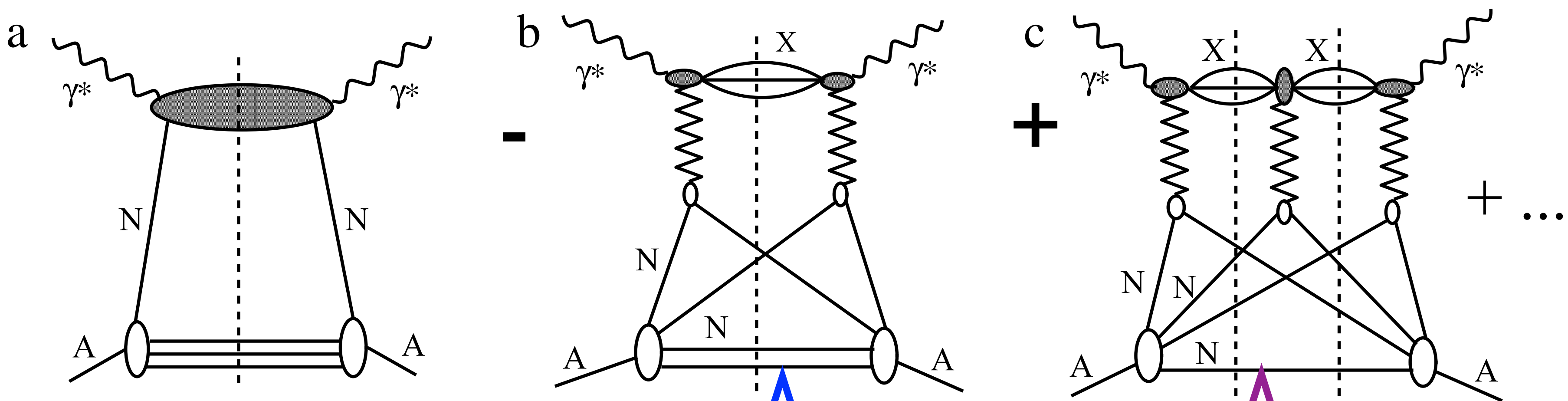
full shadowing

In the nucleus rest frame the z component of y_2-y_1 $\langle z \rangle \sim \dfrac{1}{2m_N x}$ >> 2 R_A

Scaling violation for small x ⇒z= λ_s /2mNx, with λ_s << 1 at large Q^2

Kovchegov & MS, Blok & Frankfurt

The Gribov theory of nuclear shadowing relates shadowing in γ^* A and diffraction in the elementary process: $\gamma^* + N \rightarrow X + N$.

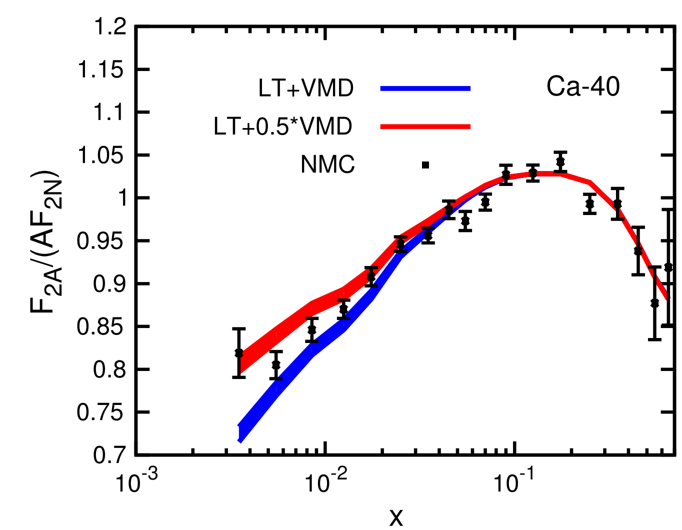


model independent

model dependent but universal (~ same for different A)

four fold rescattering a small correction for $x > 10^{-3}$

Before HERA one had to model ep diffraction to calculate shadowing for $\sigma_{\gamma^* A}$ (FS88-89, Kwiecinski89, Brodsky & Liu 90, Nikolaev & Zakharov 91). Several groups (Capella et al) used the HERA diffractive data as input to obtain a reasonable description of the NMC data. Also the diffractive data were used to describe shadowing in γ A scattering without free parameters.



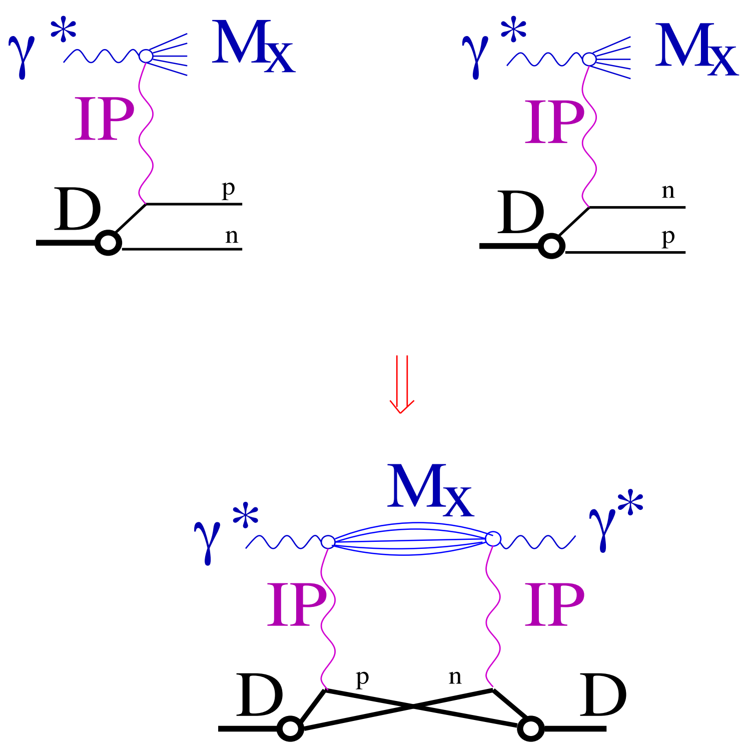
However, this approach does not allow to calculate gluon pdfs and hence quark pdfs

Connection between nuclear shadowing and diffraction - nuclear rest frame

Qualitatively, the connection is due to a possibility of scattering with small momentum transfer (t) to the nucleon at small x: $-t_{min} = x^2 m_N^2 (1 + M_{dif}^2/Q^2)^2$

If $\sqrt{t} \leq$ "average momentum of nucleon in the nucleus"
→ large shadowing /interference

Deuteron example -amplitudes of diffractive scattering off proton and off neutron interfere



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

$\boxed{\text{AGK cutting rules}}$

$$\sigma_{eD} = \sigma_{imp} - \sigma_{double}, \sigma_{diff} = \sigma_{double},$$

$$\sigma_{single\ N} = \sigma_{imp} - 4\sigma_{double}; \sigma_{two\ N} = 2\sigma_{double}$$

→ Number of wounded nucleons is very sensitive to shadowing effects

Summary of studies of the measurement of diffractive pdf's

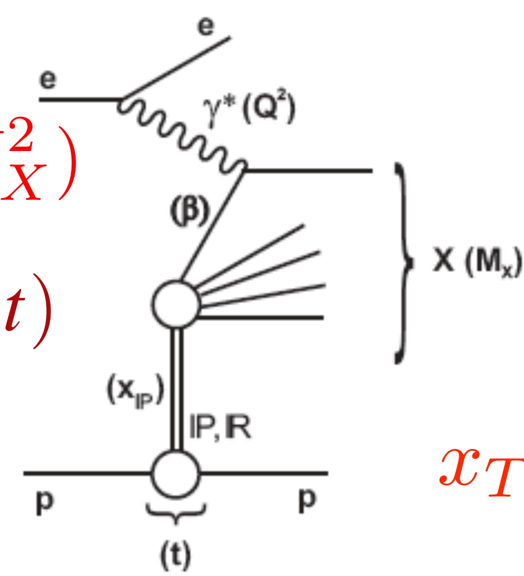
Collins factorization theorem: consider hard processes like

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

one can define fracture (Trentadue &Veneziano) parton distributions

$$\beta \equiv x/x_{I\!P} = Q^2/(Q^2 + M_X^2)$$

$$f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$$



$$x_{T_f} = 1 - x_{I\!P}$$

For fixed $x_{I\!P}$,t universal fracture pdf + the evolution is the same as for normal pdf's.

General QCD feature - smaller the elementary cross section, larger is the ratio $\sigma_{diff}/\sigma_{el.}$ (>> for small dipoles)

*Theorem is violated in dipole model of γ*N diffraction in several ways*

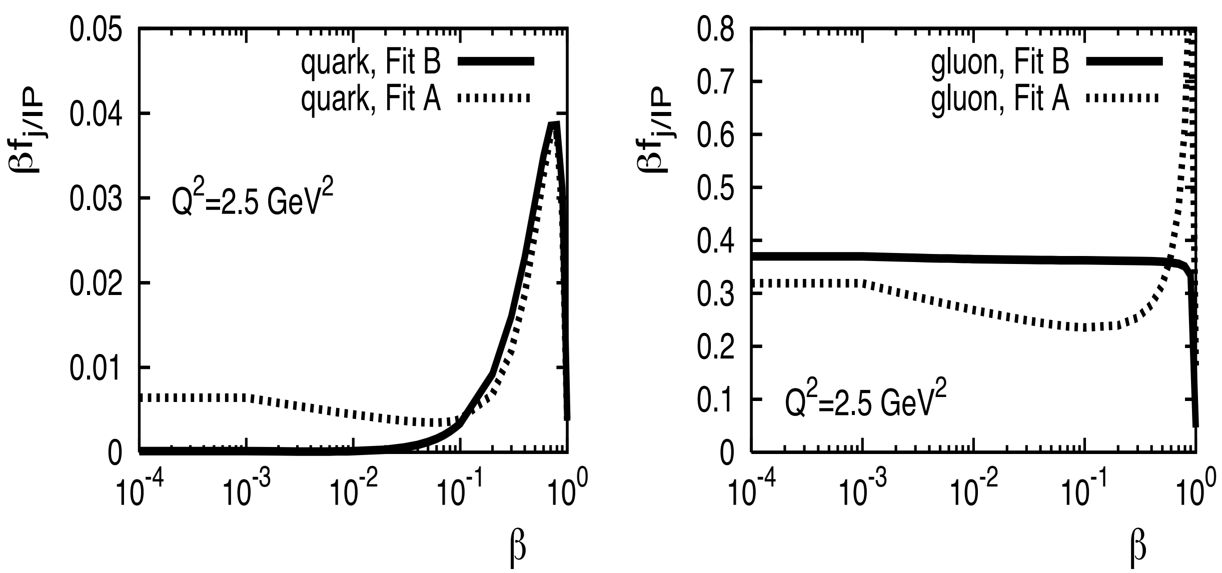
HERA: Good consistency between H1 and ZEUS three sets of measurements

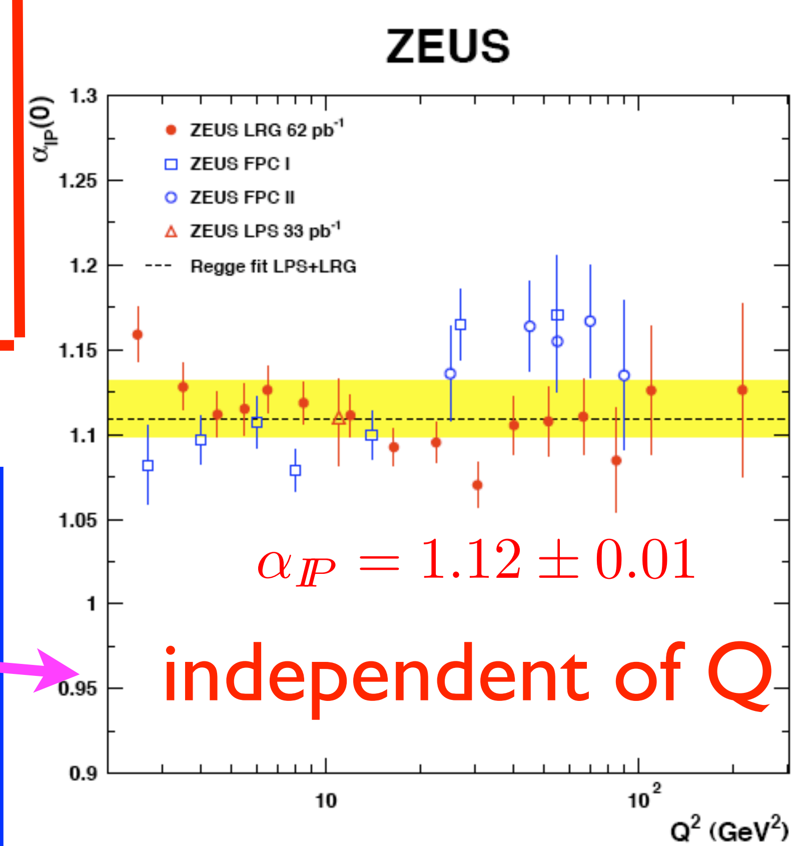
- *Measurements of $F_2^{D(4)}$*
- *Measurements of dijet production*
- *Diffractive charm production*

DGLAP describes totality of the data well several crosschecks - Collins factorization theorem valid for discussed Q^2,x range

gluon dPDF >> quark dPDF

The quark and gluon diffractive PDFs at Q^2 =2.5 GeV^2 as a function of β





$\alpha_{I\!P} = 1.12 \pm 0.01$

independent of Q

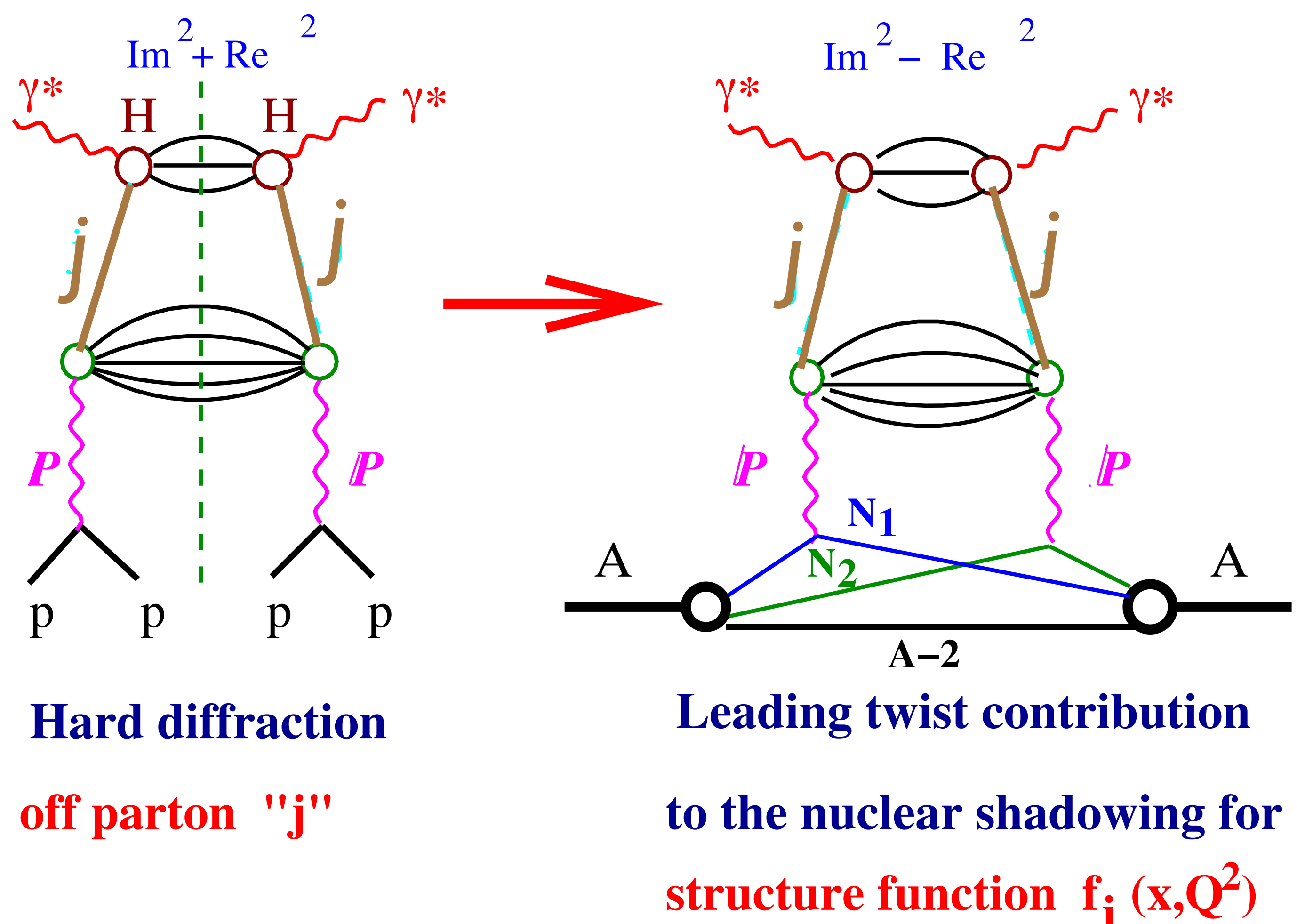
Current fits to soft hadron - hadron interactions find $\alpha_{IP}(0)$=1.09 - 1.10

Diffraction at HERA is mostly due to the interaction of hadron size components of γ^* not small dipoles. Confirms QCD aligned jet logic for x > 10^{-4}

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) Detailed study FS + Guzey Phys.Rep. 2012

Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the nucleon diffractive parton densitie $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$:



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

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

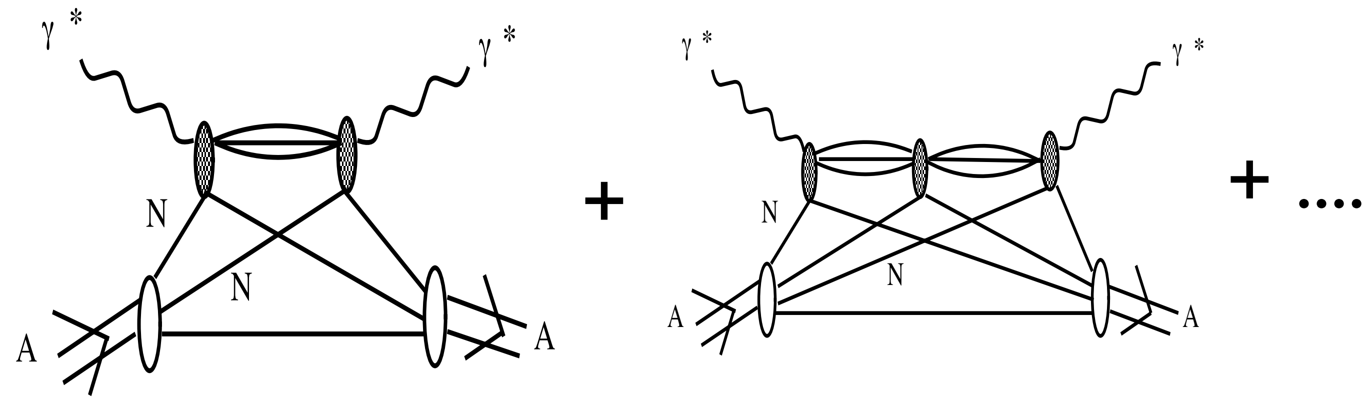
$$\cdot f^{D}_{j/N}\left(\beta,Q^2,x_{I\!P},t\right)\Big|_{k_t^2=0} \rho_A(b,z_1)\ \rho_A(b,z_2)\mathrm{Re}\left[(1-i\eta)^2\exp(ix_{I\!P}m_N(z_1-z_2))\right],$$

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

$\eta = ReA^{diff}/ImA^{diff} \approx 0.174,\ \rho_A(r)$ nuclear matter density.

$x_0(quarks) \sim 0.1,\ x_0(gluons) \sim 0.03$ **a cutoff absent when antishadowing is included**

Including higher order terms



Color fluctuation approximation: Amplitude to interact with j nucleons $\sim\sigma^j$

$$
\begin{aligned}
xf_{j/A}(x,Q^2) &= \frac{xf_{j/N}(x,Q^2)}{\langle\sigma\rangle_j} 2\,\Re e \int d^2b \left\langle \left(1 - e^{-\frac{A}{2}(1-i\eta)\sigma T_A(b)}\right)\right\rangle_j \\
&= Axf_{j/N}(x,Q^2) - xf_{j/N}(x,Q^2)\frac{A^2\langle\sigma^2\rangle_j}{4\langle\sigma\rangle_j}\Re e(1-i\eta)^2 \int d^2b\, T_A^2(b) \\
&- xf_{j/N}(x,Q^2) 2\Re e \int d^2b \frac{\sum_{k=3}^{\infty}(-\frac{A}{2}(1-i\eta)T_A(b))^k \langle\sigma^k\rangle_j}{k!\,\langle\sigma\rangle_j},
\end{aligned}
$$

does not depend on f_j

$\langle\cdots\rangle_j$ integral over σ with weight $P_j(\sigma)$ - probability for the probe to be in configuration which interacts with cross section σ;

$$\left\langle\sigma^k\right\rangle_j = \int_0^\infty d\sigma P_j(\sigma)\sigma^k$$

For intermediate x one needs also to keep finite coherence length factor $e^{i(z_1-z_2)m_N x_{I\!P}}$

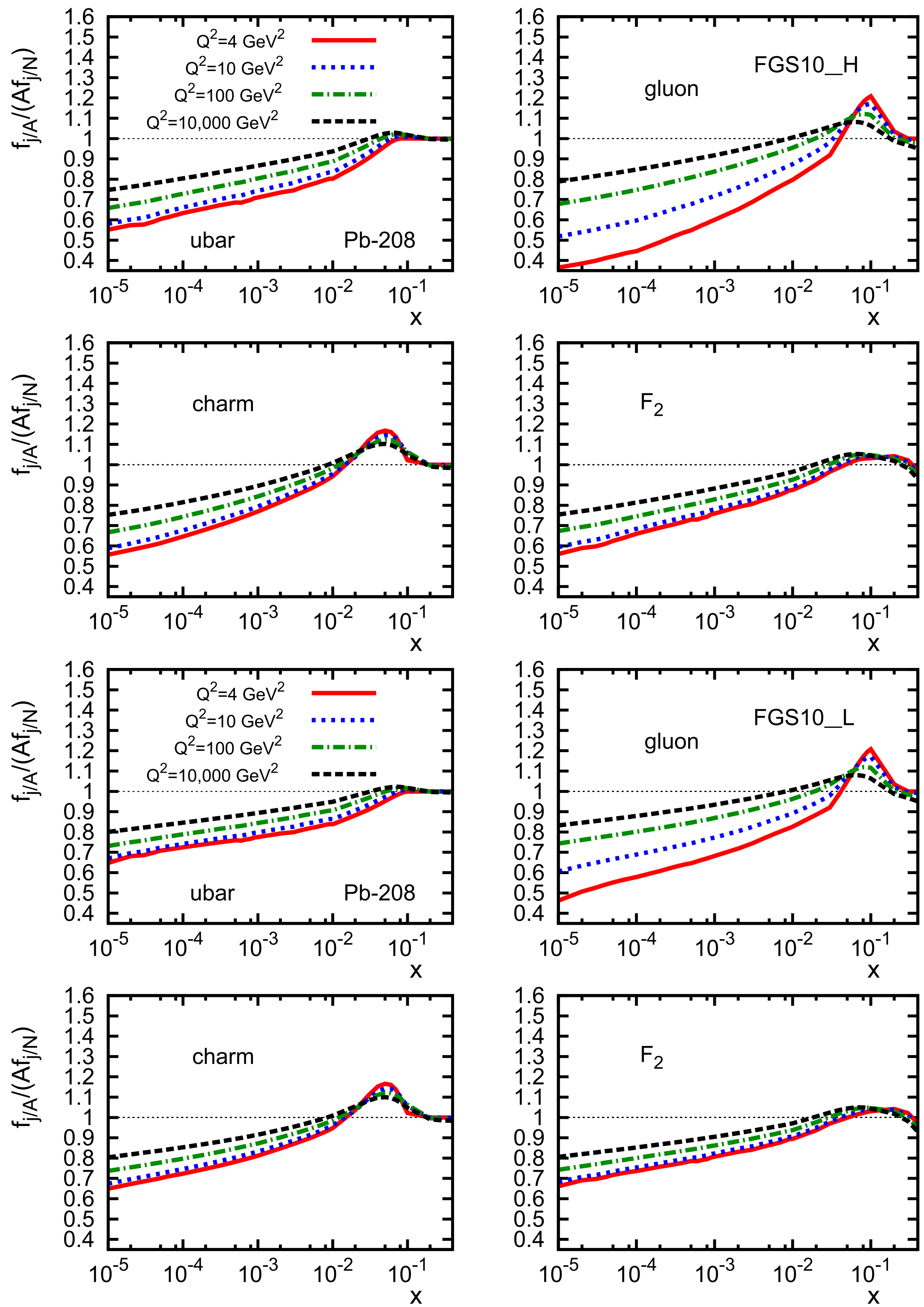
Main theoretical unknown - what fraction of hard scattering does not lead to diffraction. Hidden in $$\frac{\langle \sigma_j^2 \rangle}{\langle \sigma_j^1 \rangle}$$ known from DIS diffraction

$\Longrightarrow$ uncertainties in $$\frac{\langle \sigma_j^3 \rangle}{\langle \sigma_j^2 \rangle}$$ FGS10 H &L (High & Low)

one parameter is known not sufficiently well and which can be fixed from 4He, DIS, diffraction,…

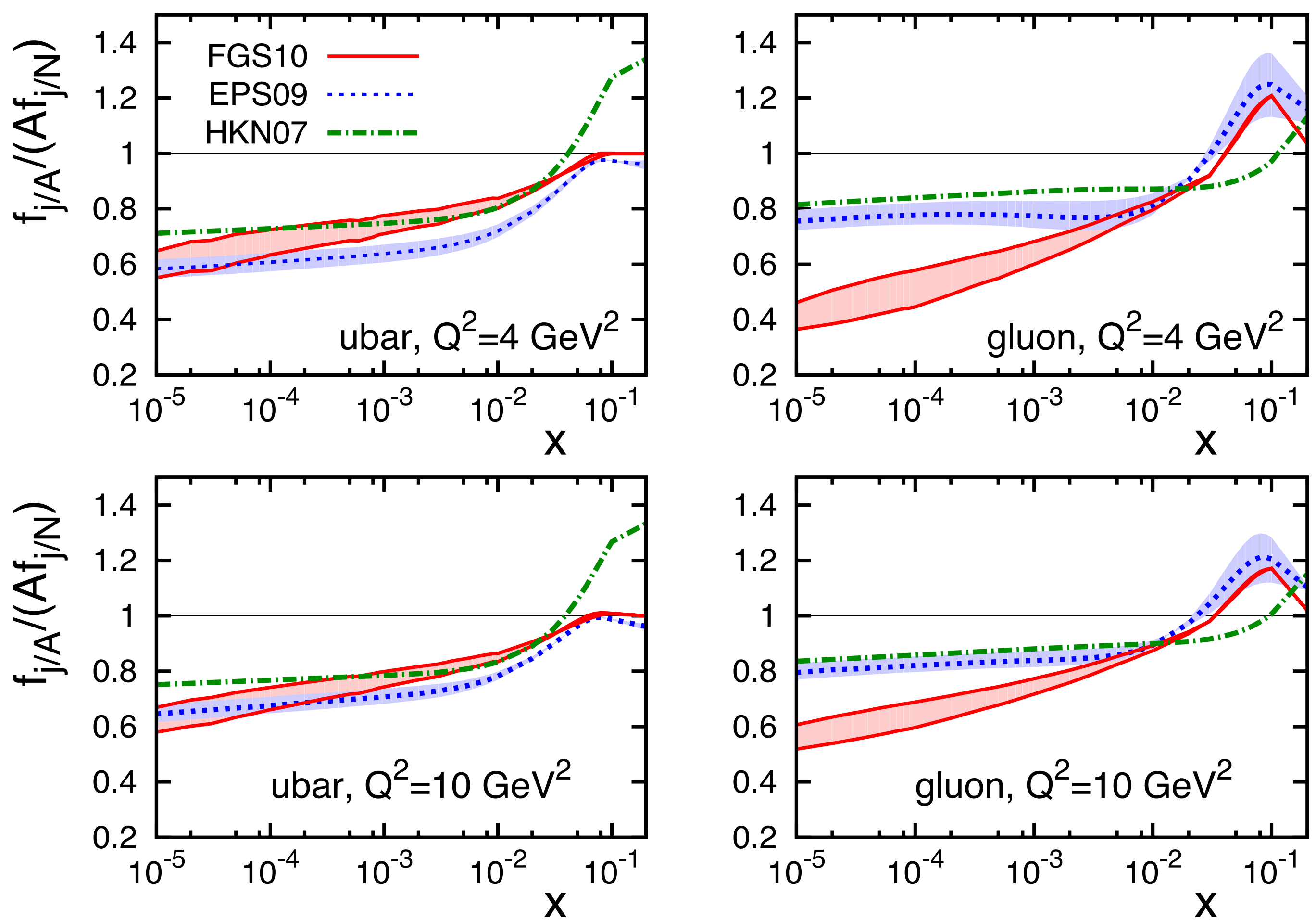
High moments are dominated by soft contributions , so approximately

$$\frac{\langle \sigma_j^{k+1} \rangle}{\langle \sigma_j^k \rangle} = \left[\frac{\langle \sigma_j^3 \rangle}{\langle \sigma_j^2 \rangle} \right]^{k-1}$$ for k ≥ 2



Q^2 dependence of shadowing

- Decrease is stronger for gluons due to a faster DGLAP evolution in this channel -- "arrival" of gluons from larger x. Still shadowing is not negligible for Q^2=10,000 GeV^2.
- "Mixing" of small and large x is a major effect - neglected in CGC models.
- Shadowing is continuing to increase with decrease of x below 10^{-3} - qualitative difference from the assumption of EKS09 (next slide)

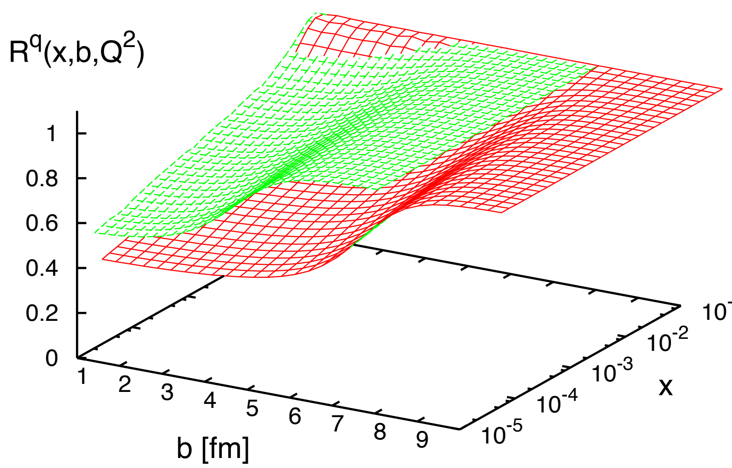


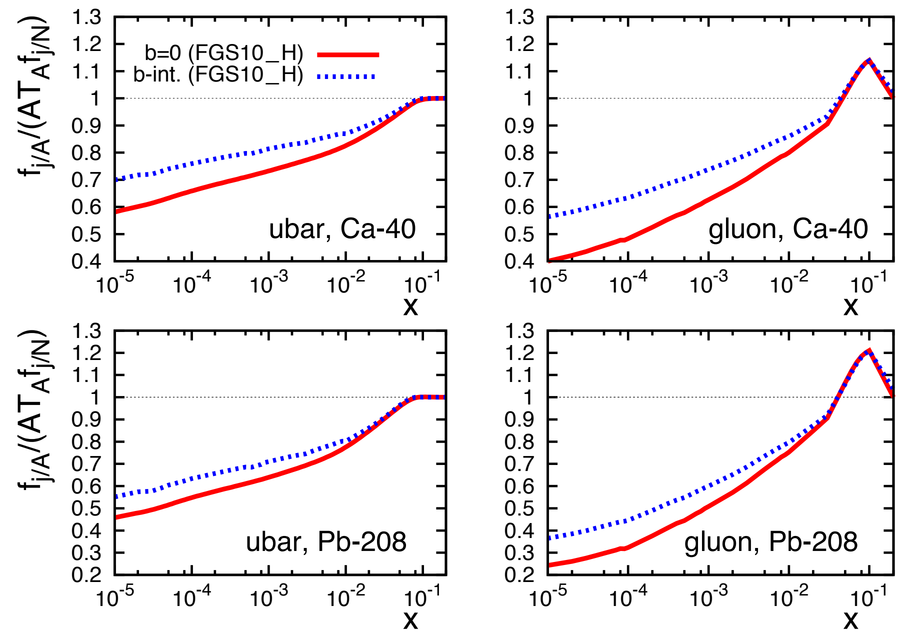
Comparison of predictions of the leading twist theory of nuclear shadowing [the area bound by the two solid curves corresponding to models FGS10 H (lower boundary) and FGS10 L (upper boundary)], the EPS09 fit (dotted curves and the corresponding shaded error bands), and the HKN07 fit (dot-dashed curves). The NLO $f_{j/A}(x, Q^2)/[Af_{j/N}(x, Q^2)]$ ratios for the $\bar{u}$-quark and gluon distributions in ^{208}Pb are plotted as functions of x at $Q^2 = 4$ GeV^2 (upper panels) and $Q^2 = 10$ GeV^2 (lower panels).

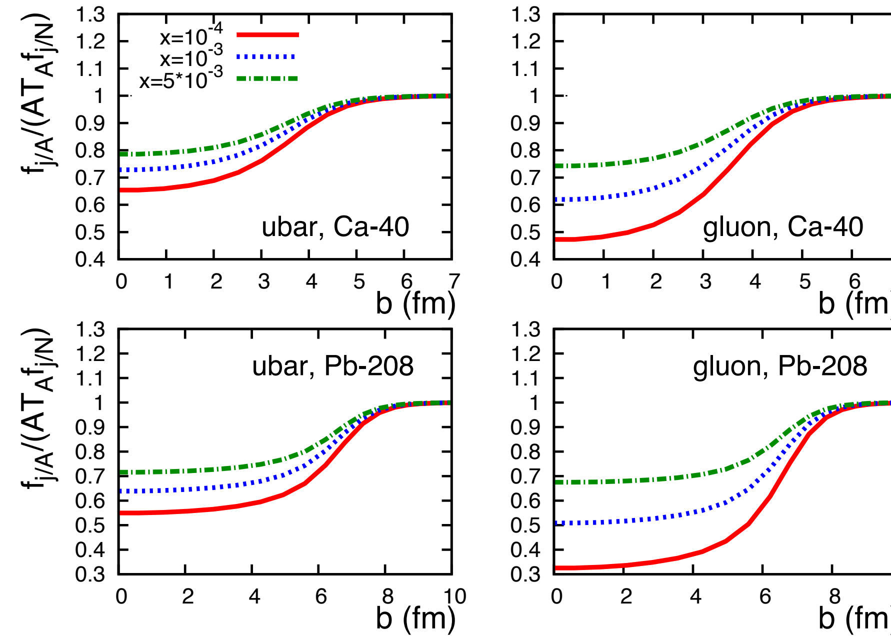
Nuclear diagonal generalized parton distributions.

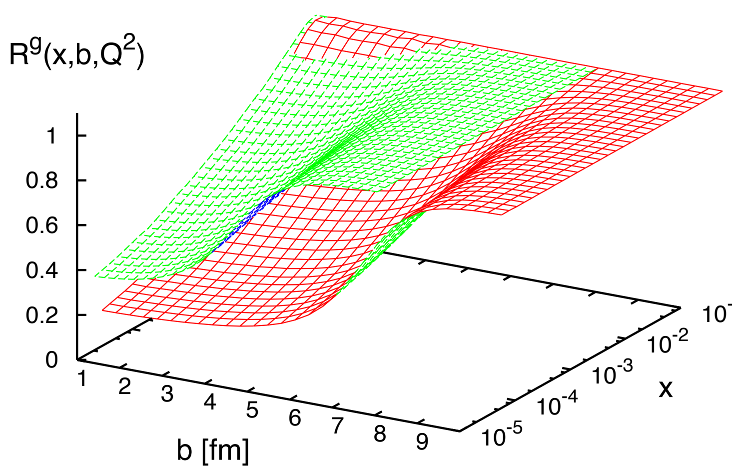
Shadowing strongly depends on the impact parameter, b, - one can formally introduce nuclear diagonal generalized parton distributions. In LT theory to calculate them one just needs to remove integral over b.

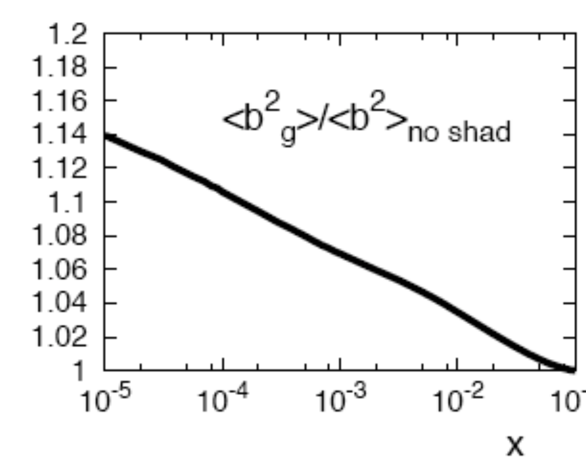
Important for modeling centrality dependence of hard processes in pA, AA









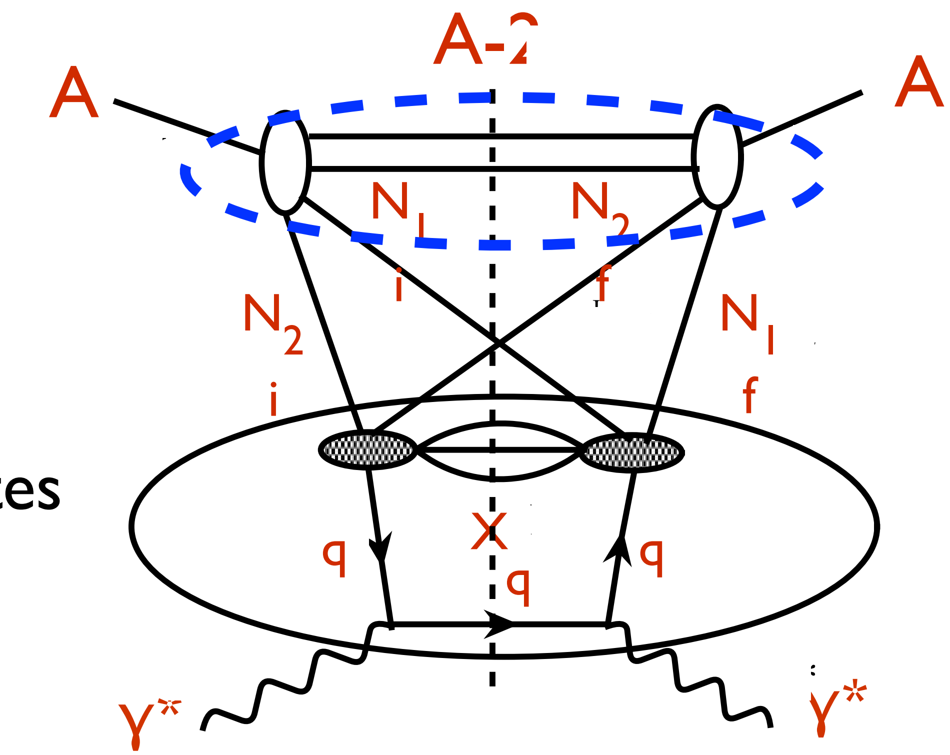


Impact parameter dependence of nuclear shadowing for ^{40}Ca (upper green surfaces) and ^{208}Pb (lower red surfaces). The graphs show the ratio $R_j(x,b,Q^2)$ as a function of x and the impact parameter |b| at $Q^2 = 4$ GeV^2. The top panel corresponds to ū-quarks; the bottom panel corresponds to gluons. For the evaluation of nuclear shadowing, model FGS10 H was used.

Connection between nuclear shadowing and diffraction - nucleus fast frame

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

Consider interference between γ^* ("Higgs") *scattering off two different nucleons*



Introduce light cone fraction α for nucleon

Free nucleon $\alpha=1$, $\alpha_f \leq 1-x$

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

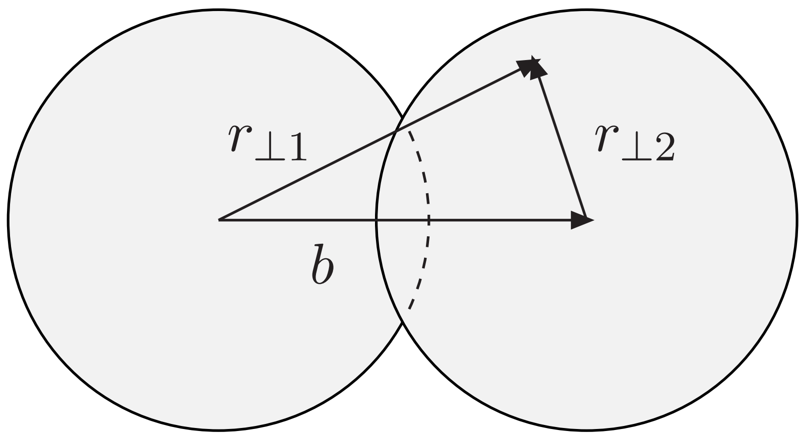
$$\alpha_{N_1^f} \leq \alpha_{N_1^i} - x \sim 1,\ \alpha_{N_2^i} \leq \alpha_{N_2^f} - x \sim 1$$

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

$\Longrightarrow$ Large interference for $x < 0.01$ due to the final states where small light cone fraction is transferred from one nucleon to another nucleon≡ **possible only in diffraction**. It results in the leading twist shadowing.

One obtains essentially the same expression as we obtained in the nucleus rest frame + small relativistic corrections. The nuclear blob is the same in the Glauber theory and hence for given diffractive input expected accuracy of the calculation of the nuclear effects is similar - few %

Key element of the logic - nucleus is a system of color singlet clusters - nucleons which are weakly deformed in nuclei - checked by success of the Gribov-Glauber theory of soft hA interactions - σ_{tot} (hA) to few %.



. Geometry of the parton overlap in the transverse plane.

A transverse slice of the wave function of a heavy nucleus for $x \sim 5 \times 10^{-3}$ looks like a system of colorless (white) clusters with some clusters ($\sim$ 30%) built of two rather than of one nucleon, with a gradual increase of the number of two-nucleon, three-nucleon, etc. clusters with decreasing x.

In our derivations, the global and local color neutrality are satisfied at every step. Not trivial to implement in some other approaches.

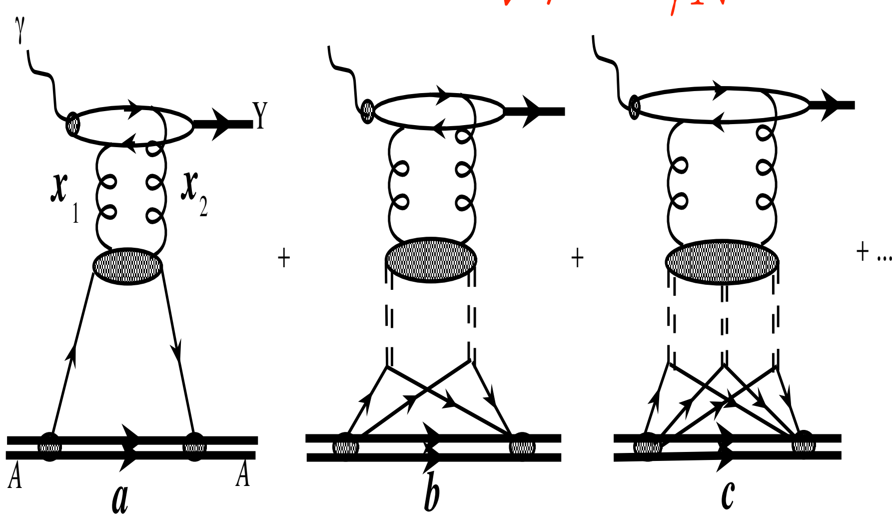
Exclusive vector meson production in DIS (onium in photoproduction)

--sensitive test of nuclear shadowing dynamics

The leading twist prediction (neglecting small t dependence of shadowing)

$$\sigma_{\gamma A\to VA}(s) = \frac{d\sigma_{\gamma N\to VN}(s,t_{min})}{dt}\left[\frac{G_A(x_1,x_2,Q^2_{eff},t=0)}{AG_N(x_x,x_2,Q^2_{eff},t=0)}\right]^2 \int_{-\infty}^{t_{min}} dt \left|\int d^2b dz e^{i\vec{q}_t\cdot\vec{b}} e^{iq_l z}\rho(\vec{b},z)\right|^2.$$

$$where\ x = x_1 - x_2 = m_V^2/W_{\gamma N}^2$$



: High energy quarkonium photoproduction in the leading twist approximation.

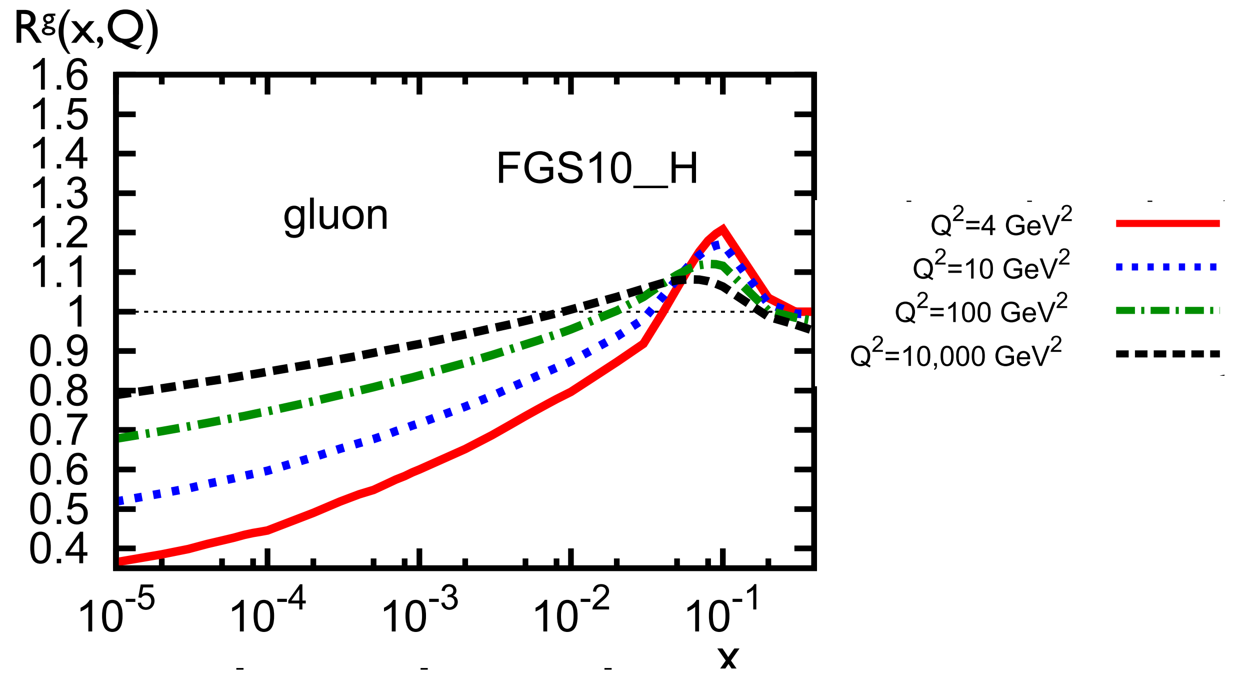
$$\Downarrow$$

$$\frac{G_A(x_1,x_2,Q^2_{eff},t=0)}{G_N(x_1,x_2,Q^2_{eff},t=0)} \approx \frac{G_A((x_1+x_2)/2,Q^2_{eff},t=0)}{G_N((x_1+x_2)/2,Q^2_{eff},t=0)}$$

For small sizes, d, dipoles - LT leads to much larger screening than eikonal models since in LT screening is proportional to $G_A(x, Q^2 \sim 1/d^2) / G_N(x, Q^2 \sim 1/d^2)$ while in the eikonal shadowing term is a higher twist - much smaller suppression.

$$\sigma_{dipole-A}/\sigma_{dipole-N} = 1 - cd^2$$

In LT approximation interaction of small dipoles with multiple nucleons are not suppressed by d² factor (LT DGLAP evolution)



Why eikonal works reasonably well for soft processes and not for small dipoles ?

for small dipoles: σ(inel diffraction)/σ(elast.) at t=0 >> 1

in soft physics: σ(inel diffraction)/σ(elast.) at t=0 << 1

Test: J/ψ-meson production: γ+A → J/ψ +A

Small dipoles ➟ QCD factorization theorem

$$S_{Pb} = \left[\frac{\sigma(\gamma A \to J/\psi + A)}{\sigma_{imp.approx.}(\gamma A \to J/\psi + A)}\right]^{1/2} = \frac{g_A(x, Q^2)}{g_N(x, Q^2)}$$

Much larger shadowing than in the eikonal dipole models

Technical remarks:

a) elementary amplitudes are expressed through non-diagonal GPD . However in J/ψ case light-cone fractions of gluons attached to $c\bar{c}$ -- x_1 and x_2 are comparable x_1=1.5 x , & x_2 = 0.5 → $(x_1+ x_2)/2$ =x

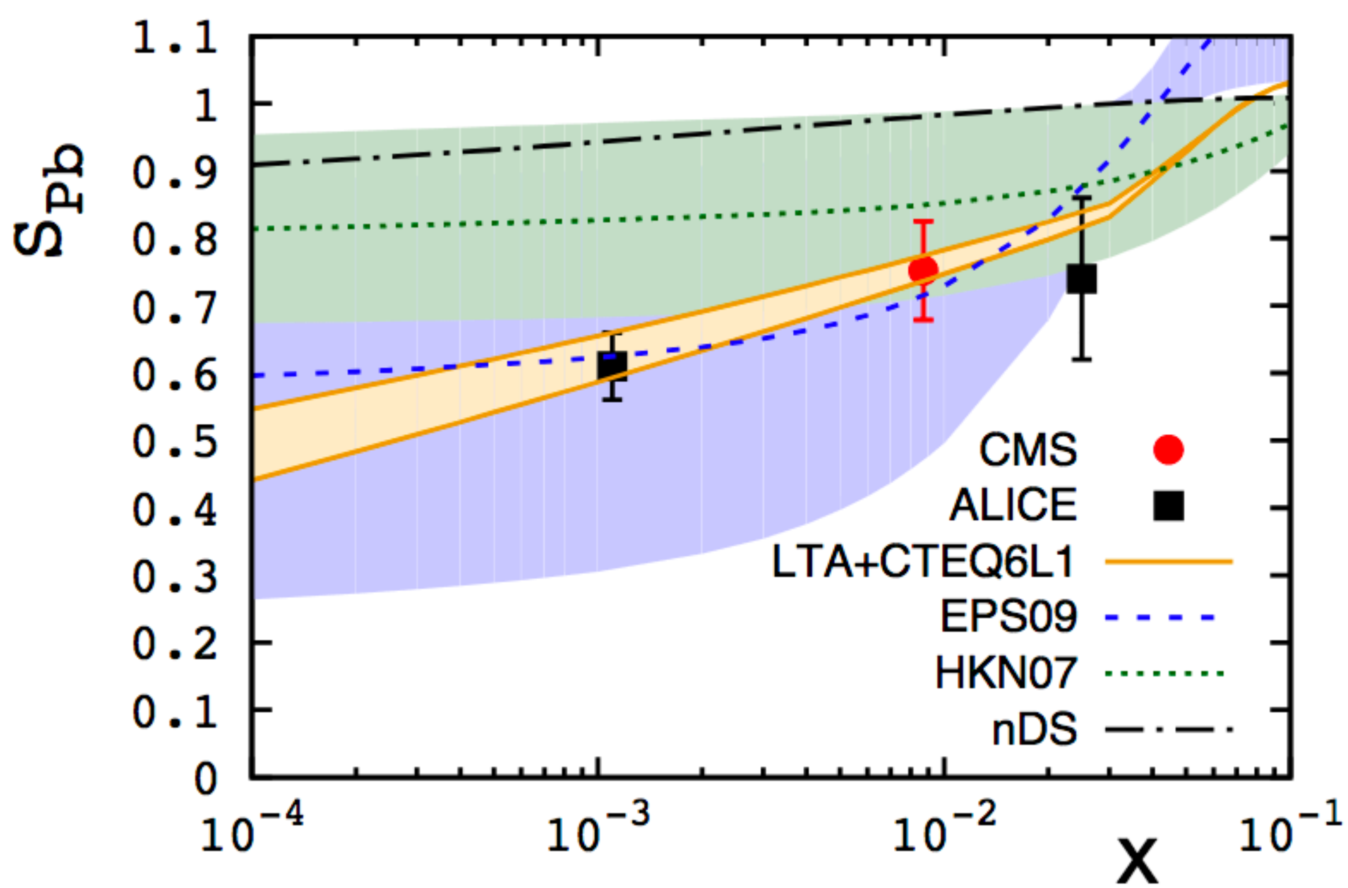
$$\frac{(x_1+x_2)_{J/\psi}}{2} \approx x; \quad \frac{(x_1+x_2)_{\Upsilon}}{2} \approx x/2$$

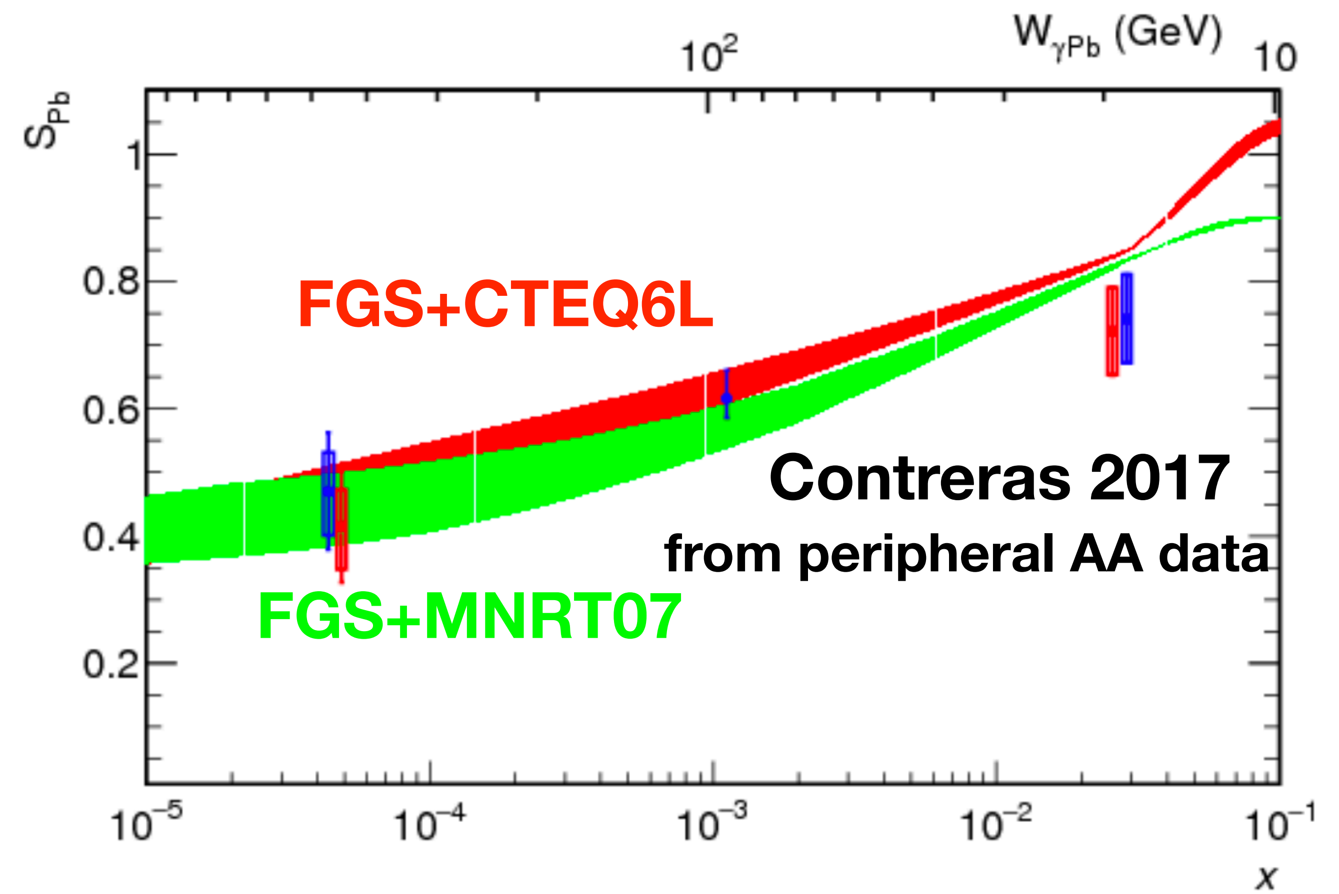
So non-diagonality effect is very small for J/ψ case.

b) High energy factorization → HT effects are large mostly cancel in the ratio of nuclear and elementary cross sections at t=0.

Strong suppression of coherent J/ψ production observed by ALICE confirms our prediction of significant gluon shadowing on the $Q^2 \sim 3$ GeV^2 . Dipole models predict very small shadowing (S_{Pb}> 0.9).

$$S_{Pb} = \left[\frac{\sigma(\gamma A \to J/\psi + A)}{\sigma_{imp.approx.}(\gamma A \to J/\psi + A)}\right]^{1/2} = \frac{g_A(x, Q^2)}{g_N(x, Q^2)}$$





Large gluon shadowing consistent with the leading twist theory prediction of FGS2012

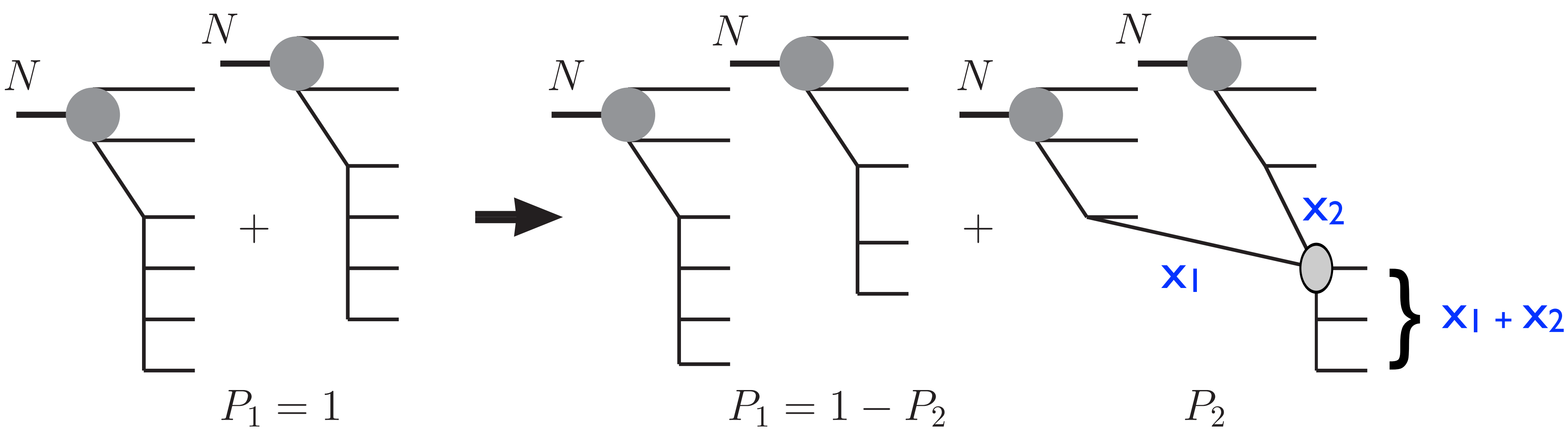
Models based on fitting the data have large uncertainties as no data constrain $g_A(x \sim 10^{-3})$

$S_{Pb}(x)$ is extracted from the data by Guzey, Zhalov & MS 2014-2017

Dynamical model of antishadowing

Guzey et al 16

At a soft scale one can consider small x infinite momentum frame nucleon wave function as a soft ladder - consistent with HERA observation of α_{IP}(diff) =1.12 -soft. In the diffusion ladders belonging to two nucleons can overlap and merge into one ladder.

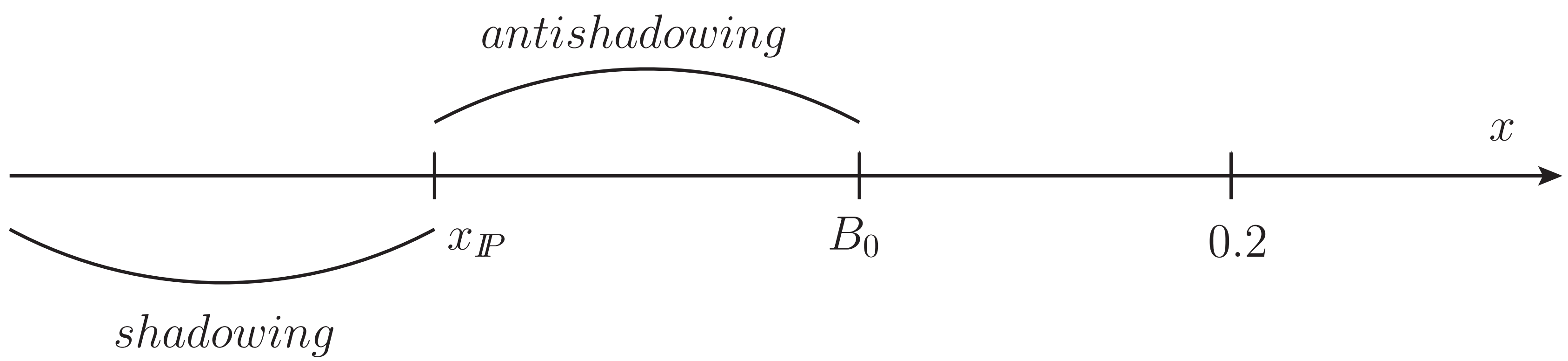


Merging of two ladders coupled to two different nucleons in the 2IP → IP process in the nucleus infinite momentum frame. This process corresponds both to

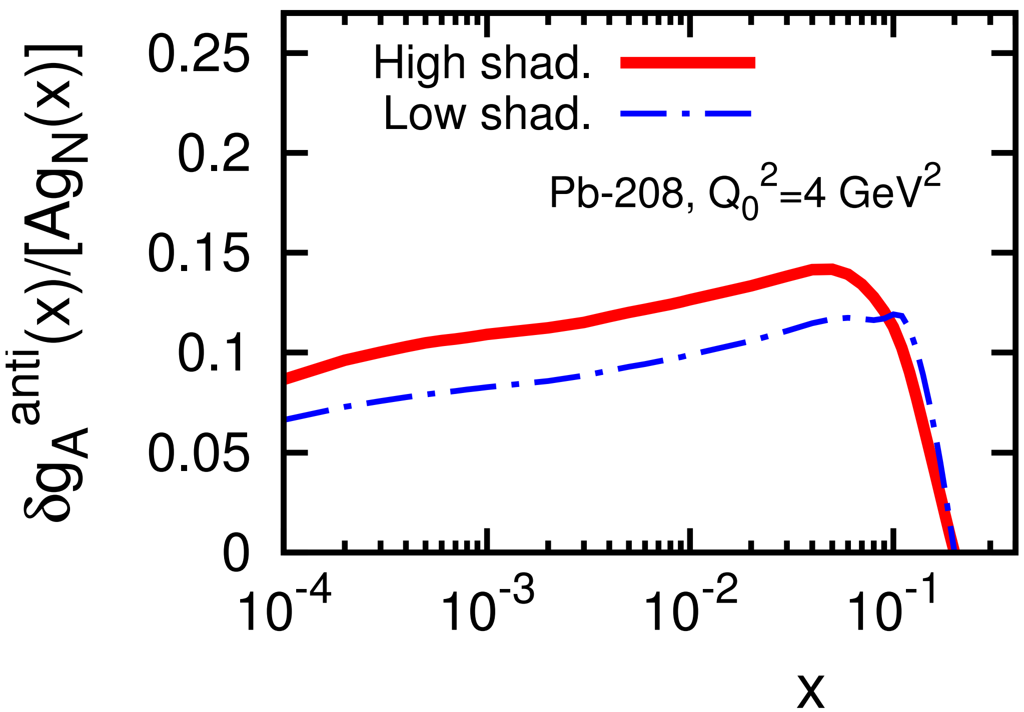
- *nuclear shadowing: fewer partons at small x by factor 2- P_2*
- *antishadowing: more partons at $x \sim x_1 + x_2$*

Total light cone momentum carried in the merged configuration is the same as for two free nucleons, hence the momentum sum rule is automatically concerned

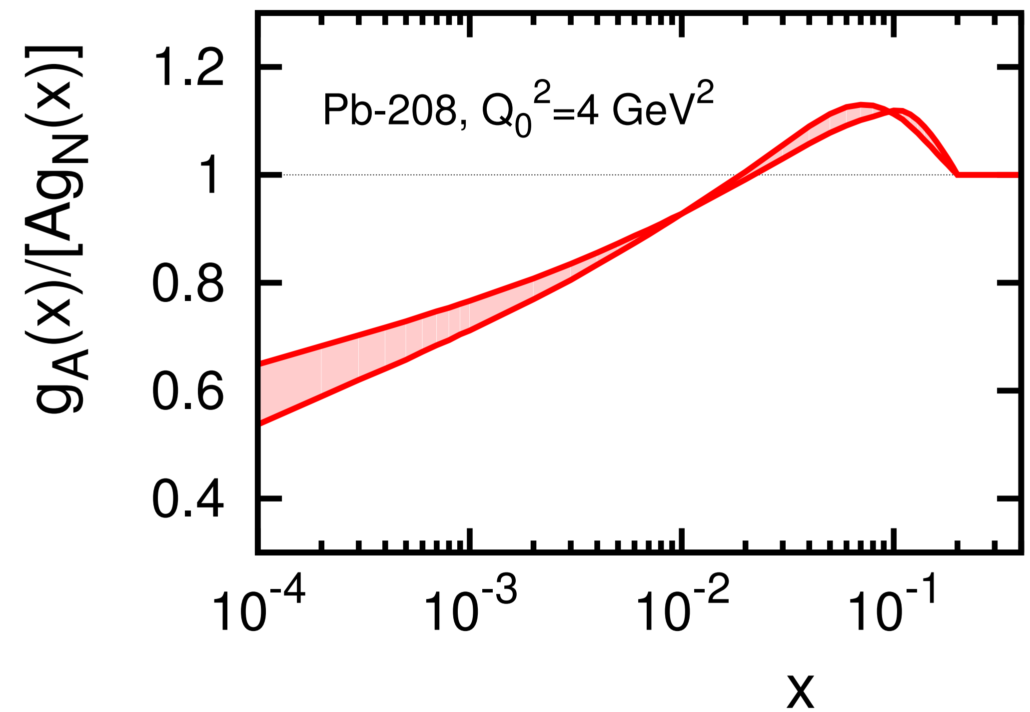
Soft process ⇒ for a merger leading to shadowing at given x the compensating antishadowing should occur at nearby rapidities: $\Delta y \leq 1$ $\rightarrow B_0/x_{I\!P} \sim 3$



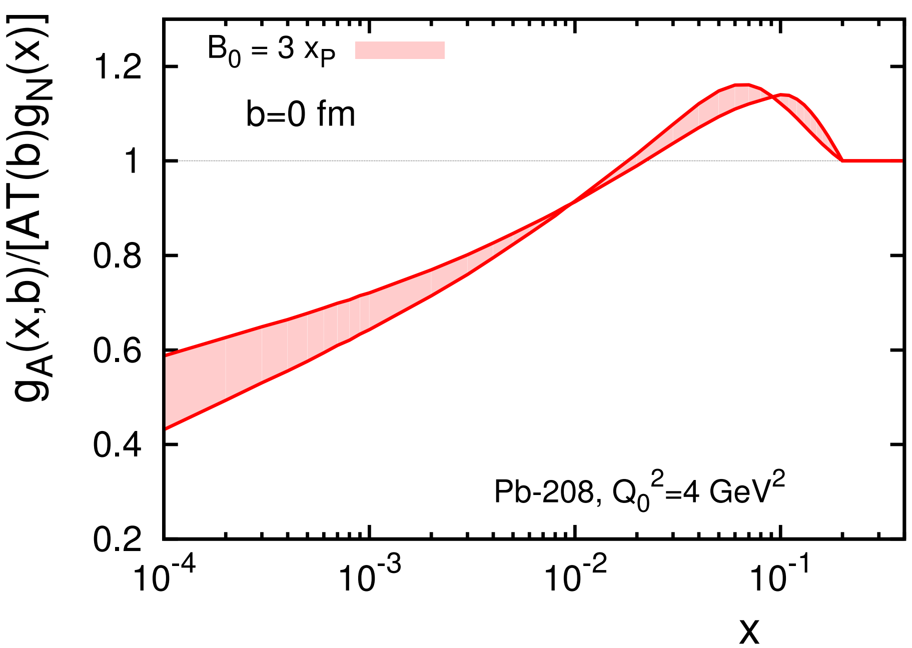
I do not have time to discuss details of modeling which includes accurate definition of x for the nucleus and account for a small fraction of the momentum carried by coherent photons (0.8% for Pb)



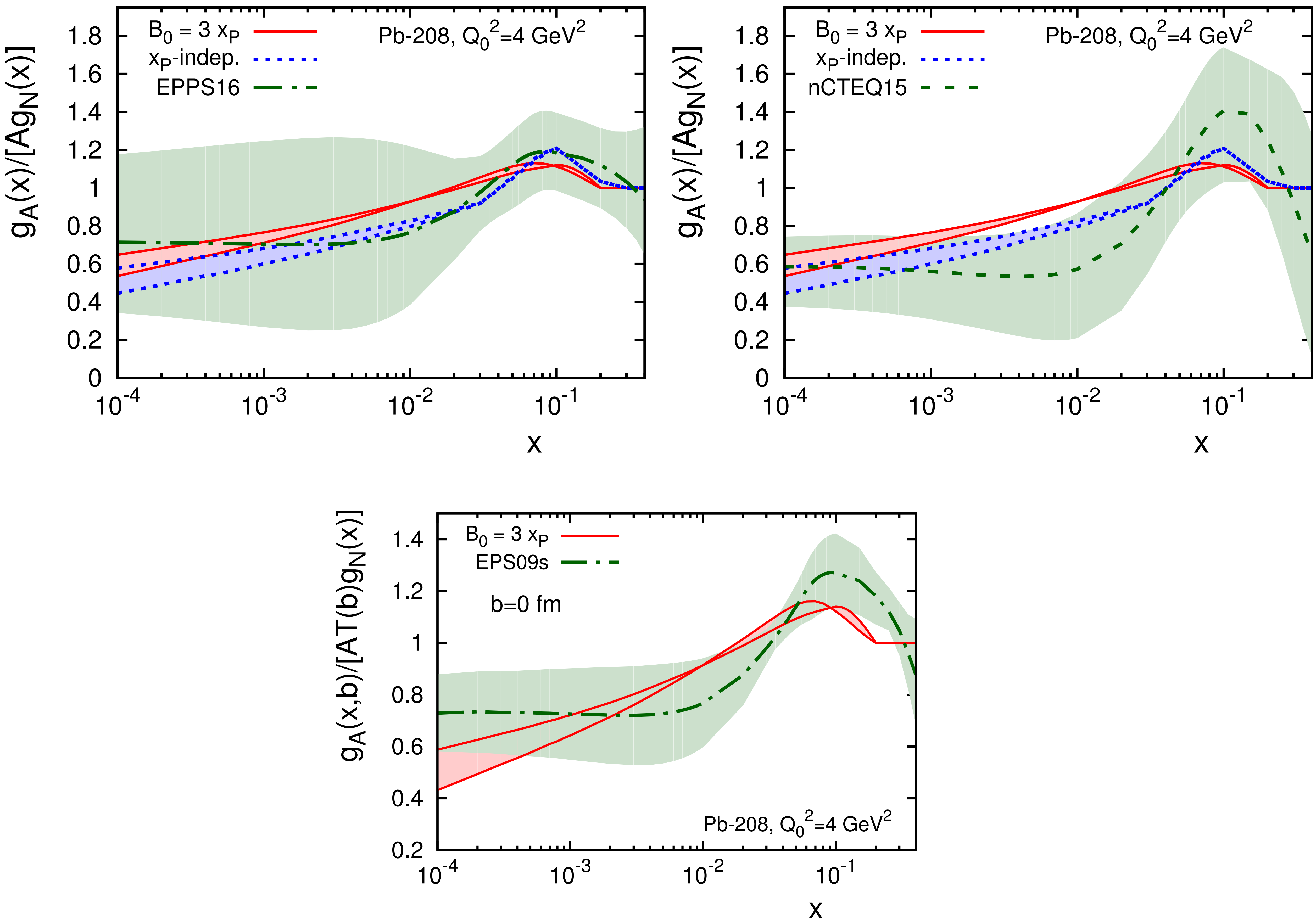
High shad.
Low shad.
Pb-208, Q_0^2=4 GeV^2
$\delta g_A^{anti}(x)/[Ag_N(x)]$
x



Pb-208, Q_0^2=4 GeV^2
$g_A(x)/[Ag_N(x)]$
x



B_0 = 3 x_P
b=0 fm
Pb-208, Q_0^2=4 GeV^2
$g_A(x,b)/[AT(b)g_N(x)]$
x



$g_A(x)/[Ag_N(x)]$
$B_0 = 3\ x_P$
x_P-indep.
EPPS16
Pb-208, Q_0^2=4 GeV^2
x
$g_A(x)/[Ag_N(x)]$
$B_0 = 3\ x_P$
x_P-indep.
nCTEQ15
Pb-208, Q_0^2=4 GeV^2
x
$g_A(x,b)/[AT(b)g_N(x)]$
$B_0 = 3\ x_P$
EPS09s
b=0 fm
Pb-208, Q_0^2=4 GeV^2
x

Color fluctuations in protons

Convenient quantity - $P(\sigma)$ -probability that hadron/photon interacts with cross section σ with the target. $\int P(\sigma) d\sigma = 1$, $\int \sigma P(\sigma) d\sigma = \sigma_{tot}$,

cf $P_{MCGlauber}(\sigma) = \delta(\sigma - \sigma_{tot})$

$$\left.\frac{\frac{d\sigma(pp\to X+p)}{dt}}{\frac{d\sigma(pp\to p+p)}{dt}}\right|_{t=0} = \frac{\int(\sigma-\sigma_{tot})^2 P(\sigma)d\sigma}{\sigma_{tot}^2} \equiv \omega_\sigma$$

variance

Pumplin &Miettinen

$\int (\sigma - \sigma_{tot})^3 P(\sigma) d\sigma = 0$,

Baym et al from pD diffraction

$P(\sigma)_{|\sigma\to 0} \propto \sigma^{n_q - 2}$

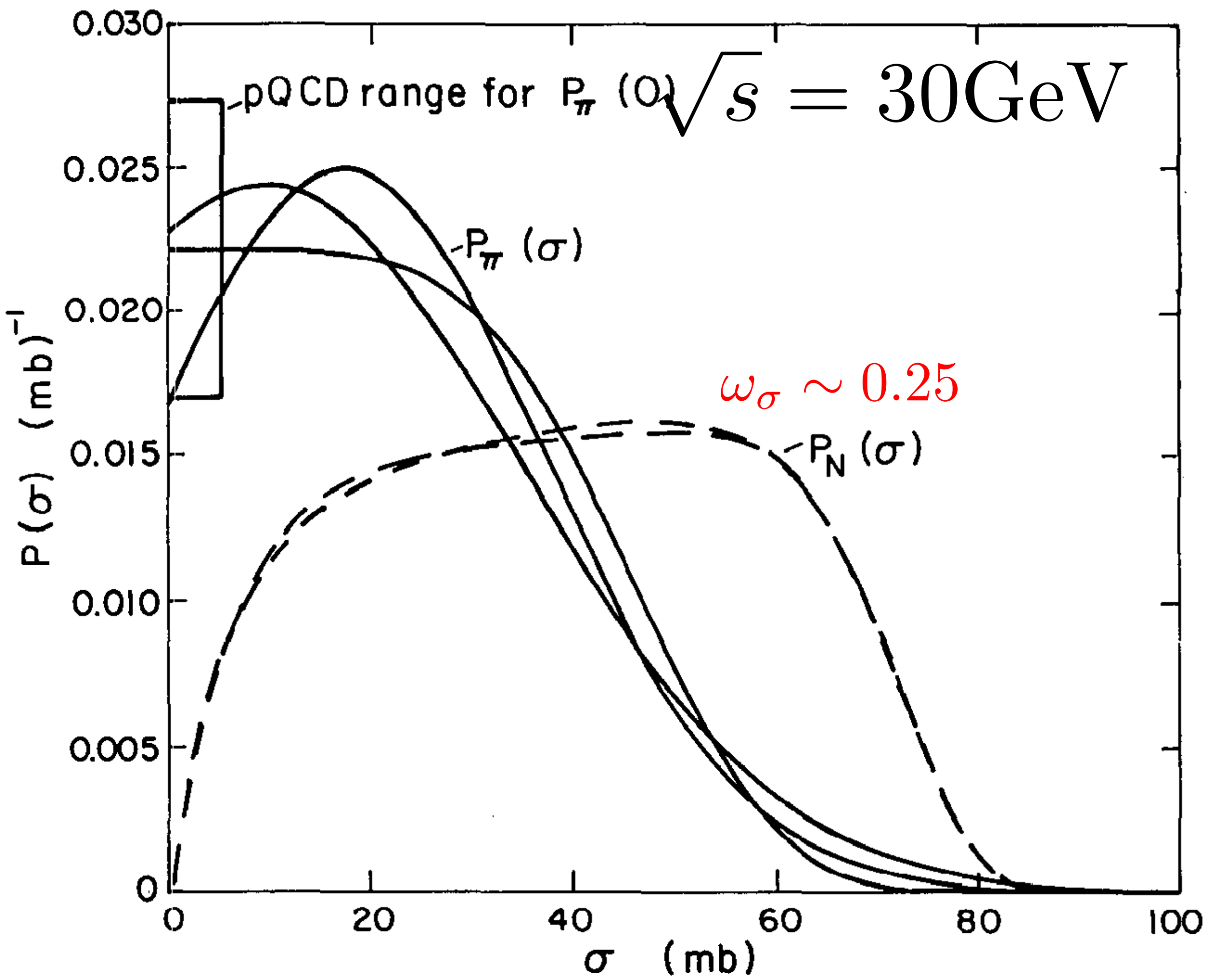
Baym et al 1993 - analog of QCD counting rules probability for all constituents to be in a small transverse area

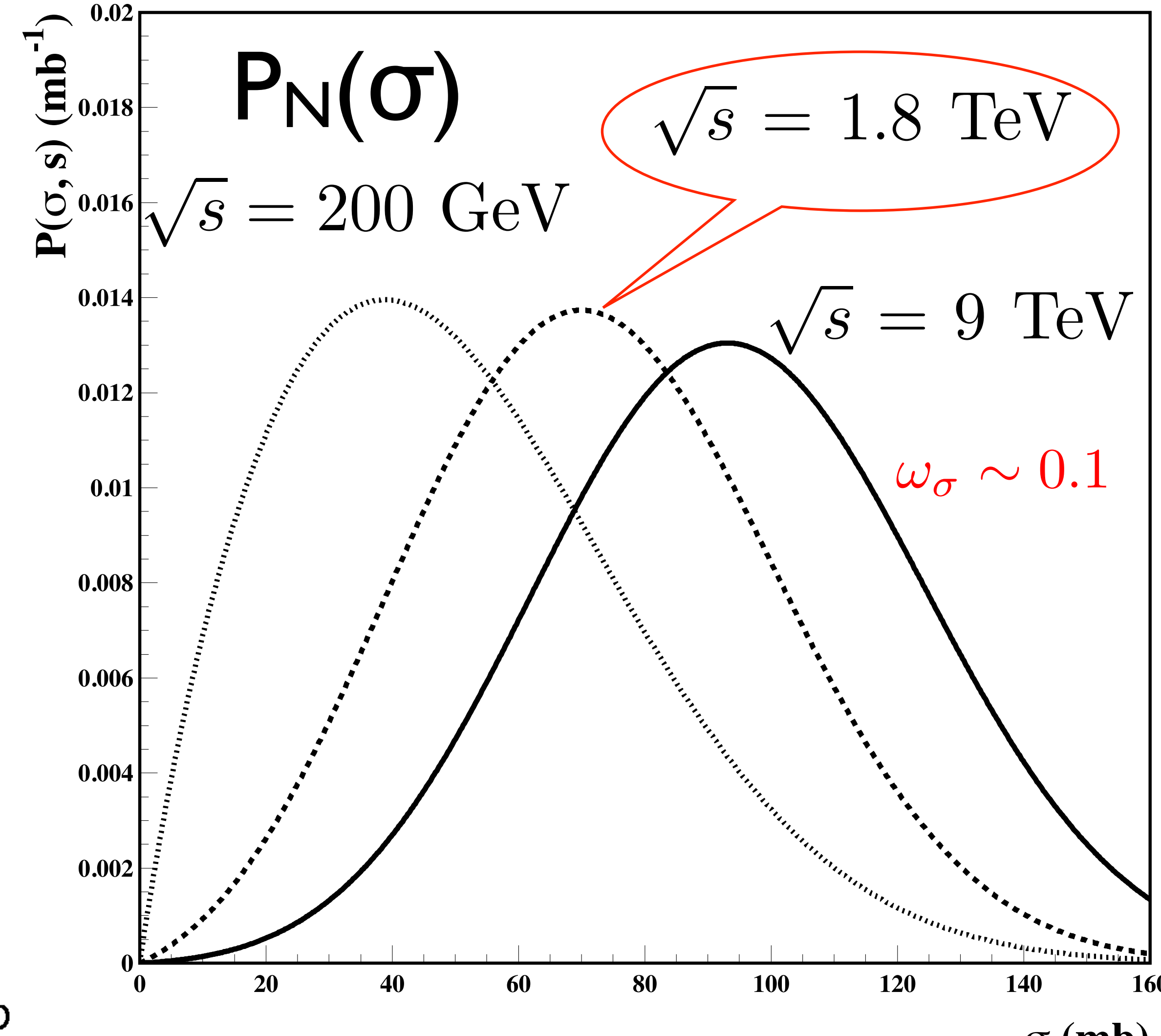
+ additional consideration that *for a many body system fluctuations near average value should be Gaussian*

$$P_N(\sigma_{tot}) = r\frac{\sigma_{tot}}{\sigma_{tot}+\sigma_0} exp\{-\frac{(\sigma_{tot}/\sigma_0 - 1)^2}{\Omega^2}\}$$

$P_\gamma(\sigma)_{|\sigma\to 0} \propto \sigma^{-1}$ γ =mix of small $q\bar{q}$ and mesonic configurations

Test: calculation of coherent diffraction off nuclei: $\pi A \to XA$, $p A \to XA$ through $P_h(\sigma)$





Extrapolation of Guzey & MS before the LHC data

$P_N(\sigma)$ extracted from pp,pd diffraction and $P_\pi(\sigma)$; Baym et al 93

Variance drops with increase of energy, overall shift of distribution to larger σ

Flat $P_N(\sigma)$ in a wide range of σ - can suggests few effective constituents at this energy scale like in quark - diquark model.

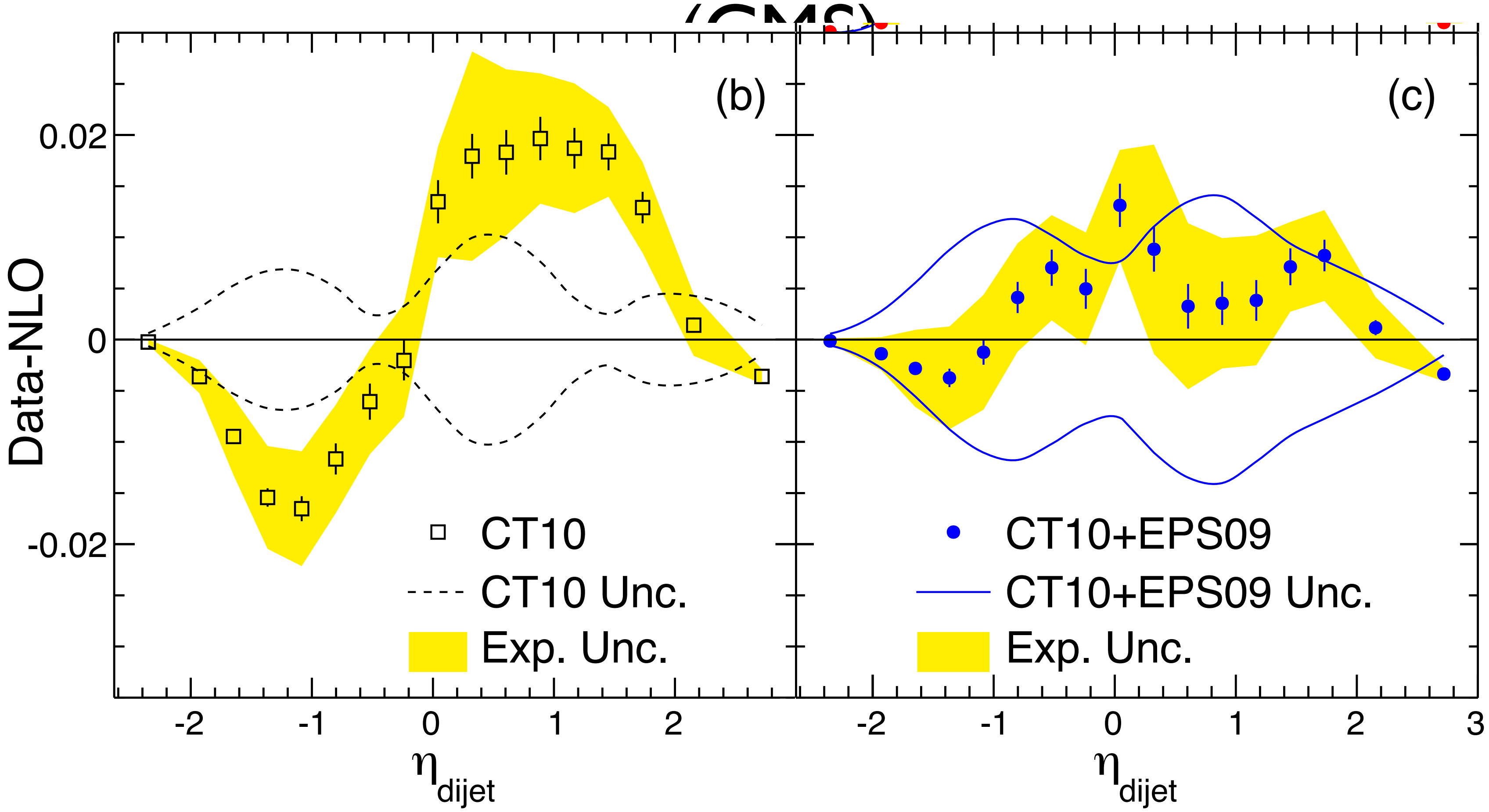
Fast drop of $P_N(\sigma)$ at small σ, with increase of energypQCD?

Evidence for x -dependent color fluctuations in nucleons -nucleon squeezing

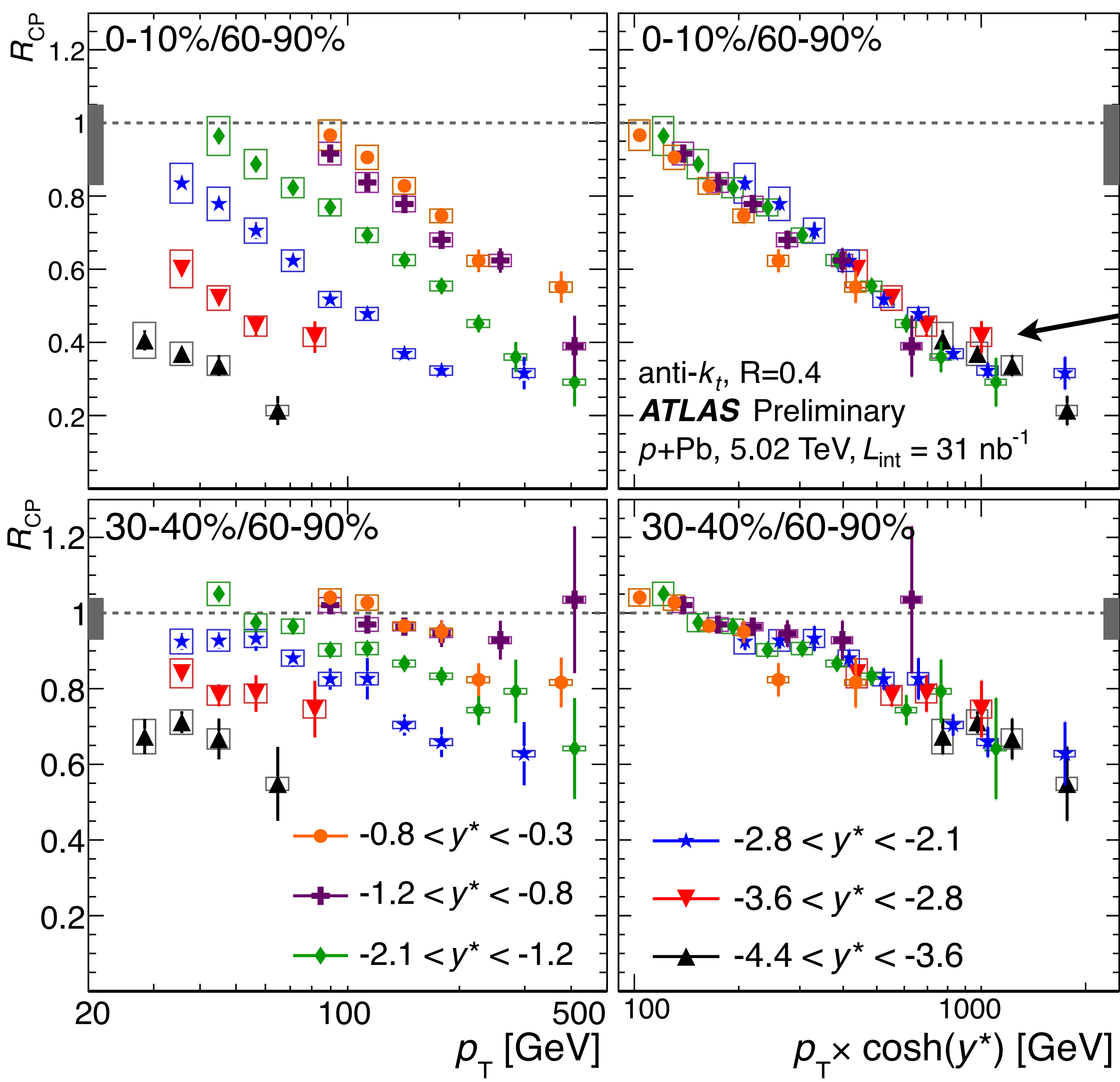
Jet production in pA collisions - possible evidence for x -dependent color fluctuations

Summary of some of the relevant experimental observations of CMS & ATLAS

- Inclusive jet production is consistent with pQCD expectations (CMS)



ATLAS and CMS studied dijet production in pA at the LHC. Both observed very small nuclear effects for inclusive dijet production which rules out energy loss interpretation. However nuclear effects are strong function of ν which was estimated using negative rapidities. Forward jet production in central collisions is strongly suppressed - suppression is mainly function of x_p. and not p_t of the jet. Consistent with expectation that configurations in protons with large x -belong to configurations which are smaller and interact with $\sigma < \sigma_{tot.}$

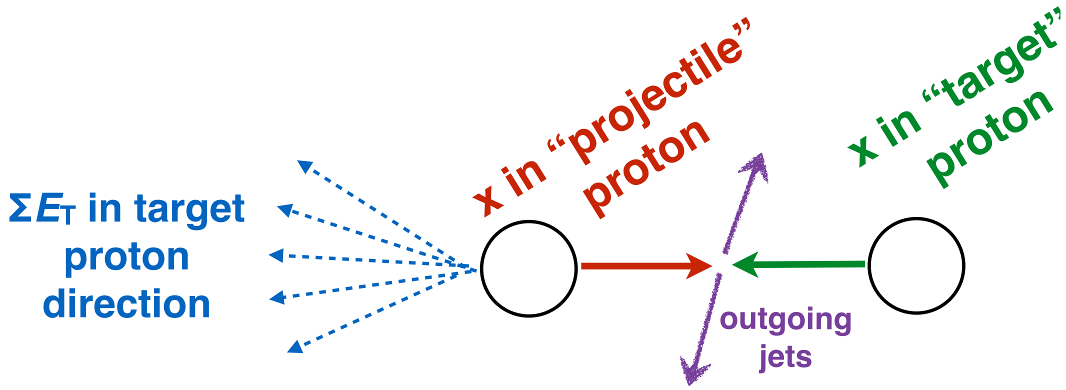


$x_p \sim 0.5$

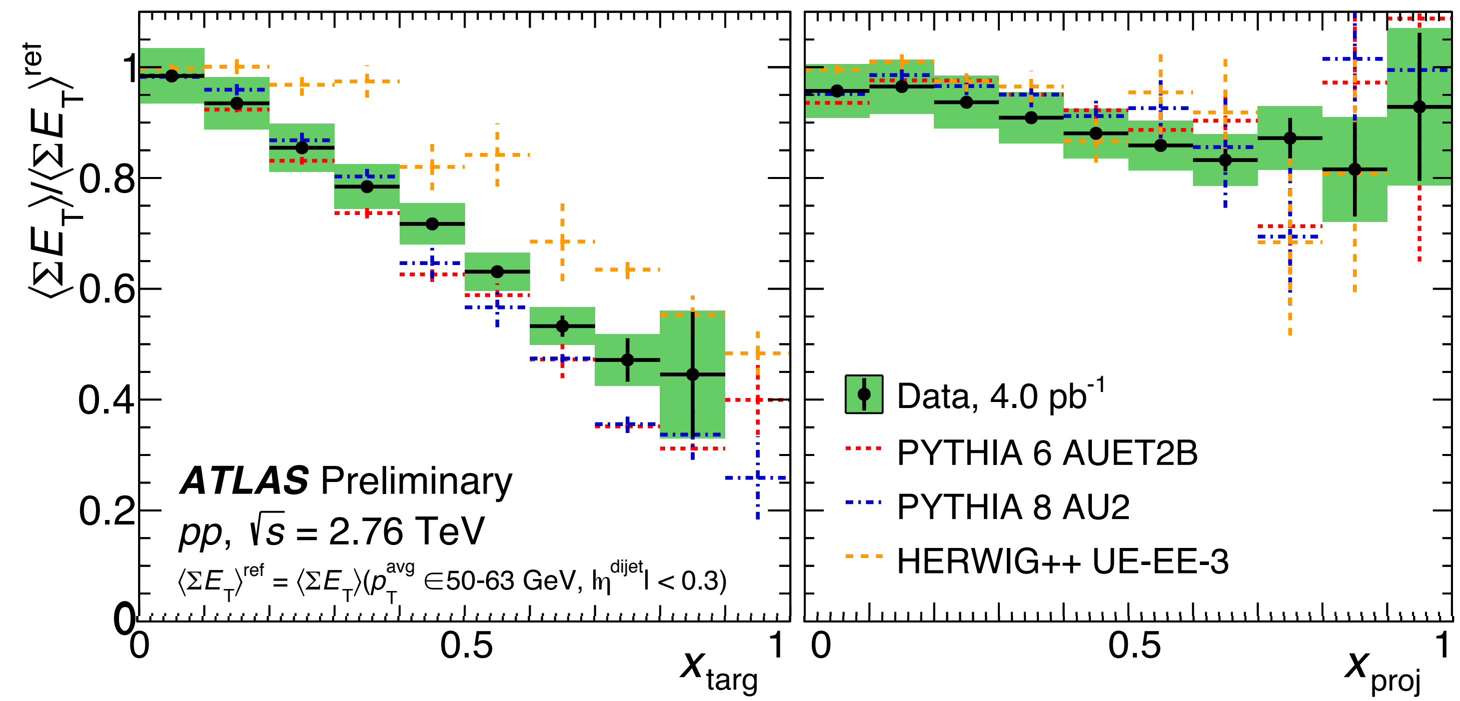
R_{CP}, is a function of x of the quark. No p_T dependence for fixed $x_p = E_{jet}/E_{proton}$

In order to compare with the data we need to use a model for the distribution in E_T^{Pb} as a function of ν. We use the analysis of ATLAS . Note that E_T^{Pb} was measured at large negative rapidities which minimizes the effects of energy conservation (production of jets with large x_p) suggested as an explanation of centrality dependence

ATLAS-CONF-2015-019 analysis of pp data confirms this expectation



Measure ΣE_T at large pseudorapidity vs.
x in the **projectile** proton (moving away)
x in the **target** proton (moving towards)



Dependence on x_{proj} and x_{targ}

M.Alvioli, L.Frankfurt, V.Guzey and M.Strikm
``Revealing nucleon and nucleus flickering in pA collisions at the LHC,' arXiv:1402.2868

DISTRIBUTION OVER THE NUMBER OF COLLISIONS FOR PROCESSES WITH A HARD TRIGGER

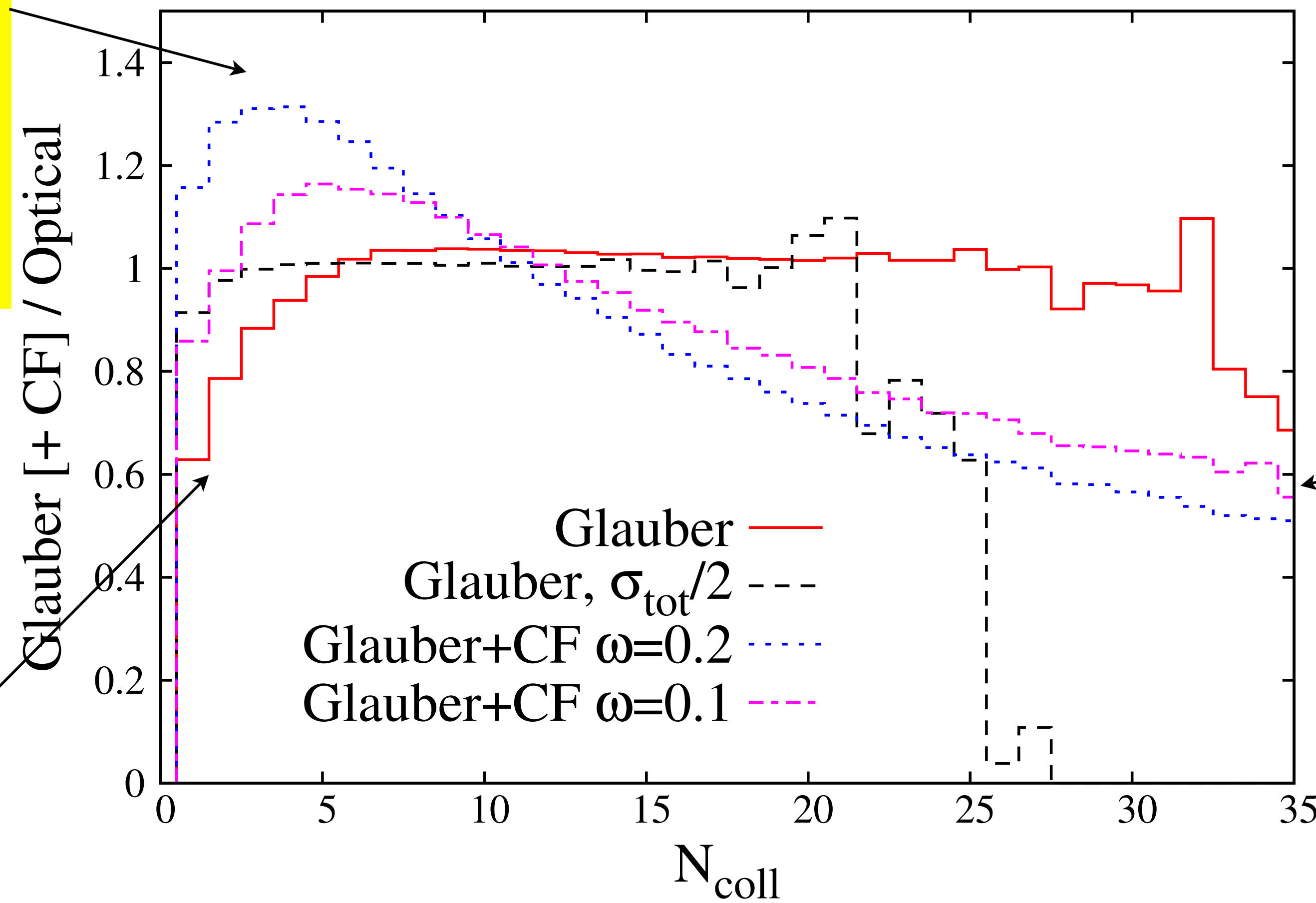
Consider multiplicity of hard events $Mult_{pA}(HT) = \sigma_{pA}(HT + X)/\sigma_{pA}(in)$ as a function of N_{coll}

If the radius of strong interaction is small and hard interactions have the same distribution over impact parameters as soft interactions multiplicity of hard events:

$$R_{HT}(N_{coll}) \equiv \frac{Mult_{pA}(HT)}{Mult_{pN}(HT)N_{coll}} = 1$$

Accuracy?

Two effects: Two scale dynamics of pp interaction at the LHC, large radius of NN interaction increase due to more central interactions of configurations with $\sigma < \sigma_{tot}$

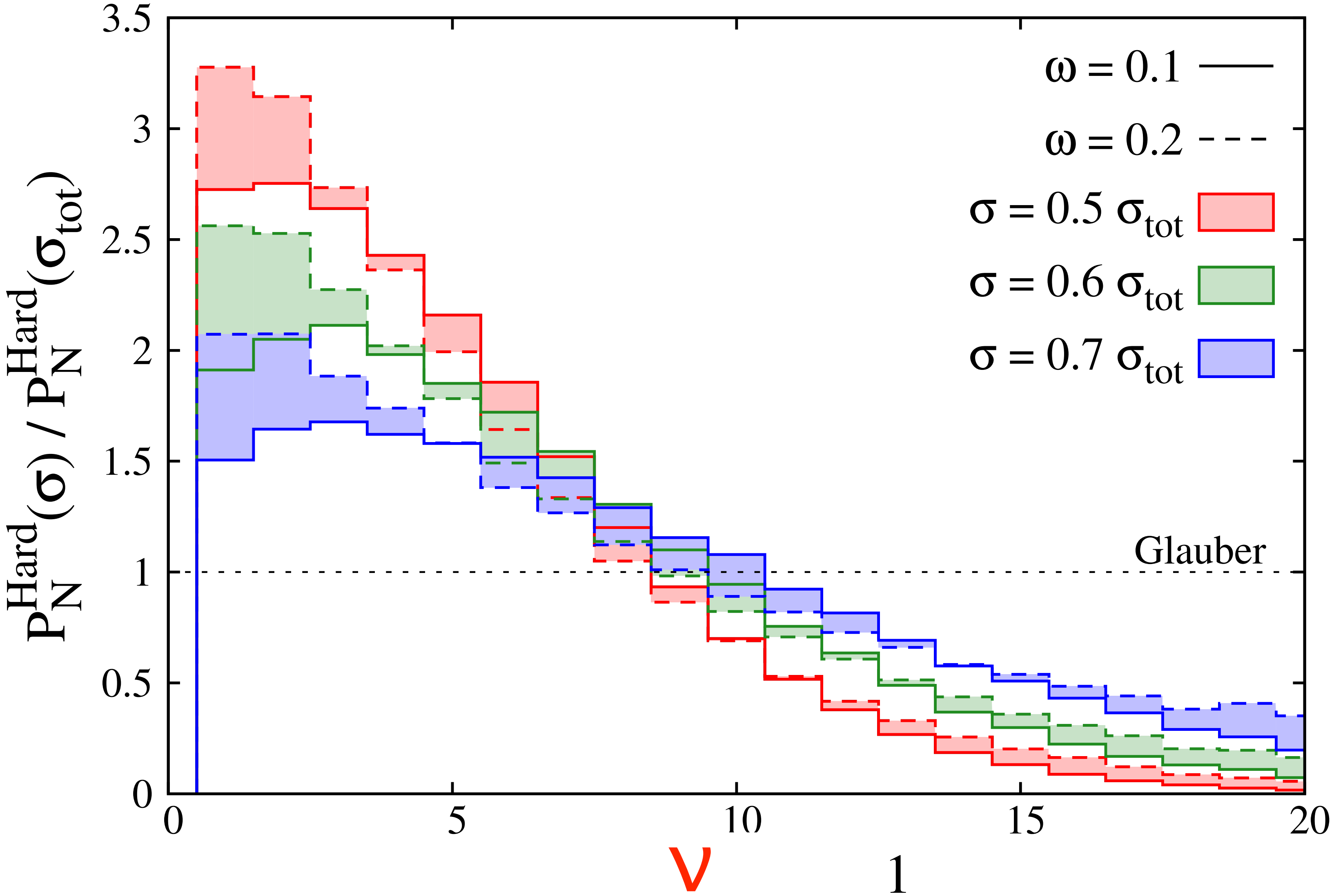


drop due increased role of configurations with $\sigma > \sigma_{tot}$ the cylinder in which interaction occur is larger but local density does not go up as fast in Glauber

Deviation of $R_{HT}(\nu = N_{coll})$ from 1

drop due to more localized hard interactions

Fluctuations for configurations with small σ maybe different than for average one so we considered both $\omega_\sigma(x\sim0.5)$ =0.1 & 0.2

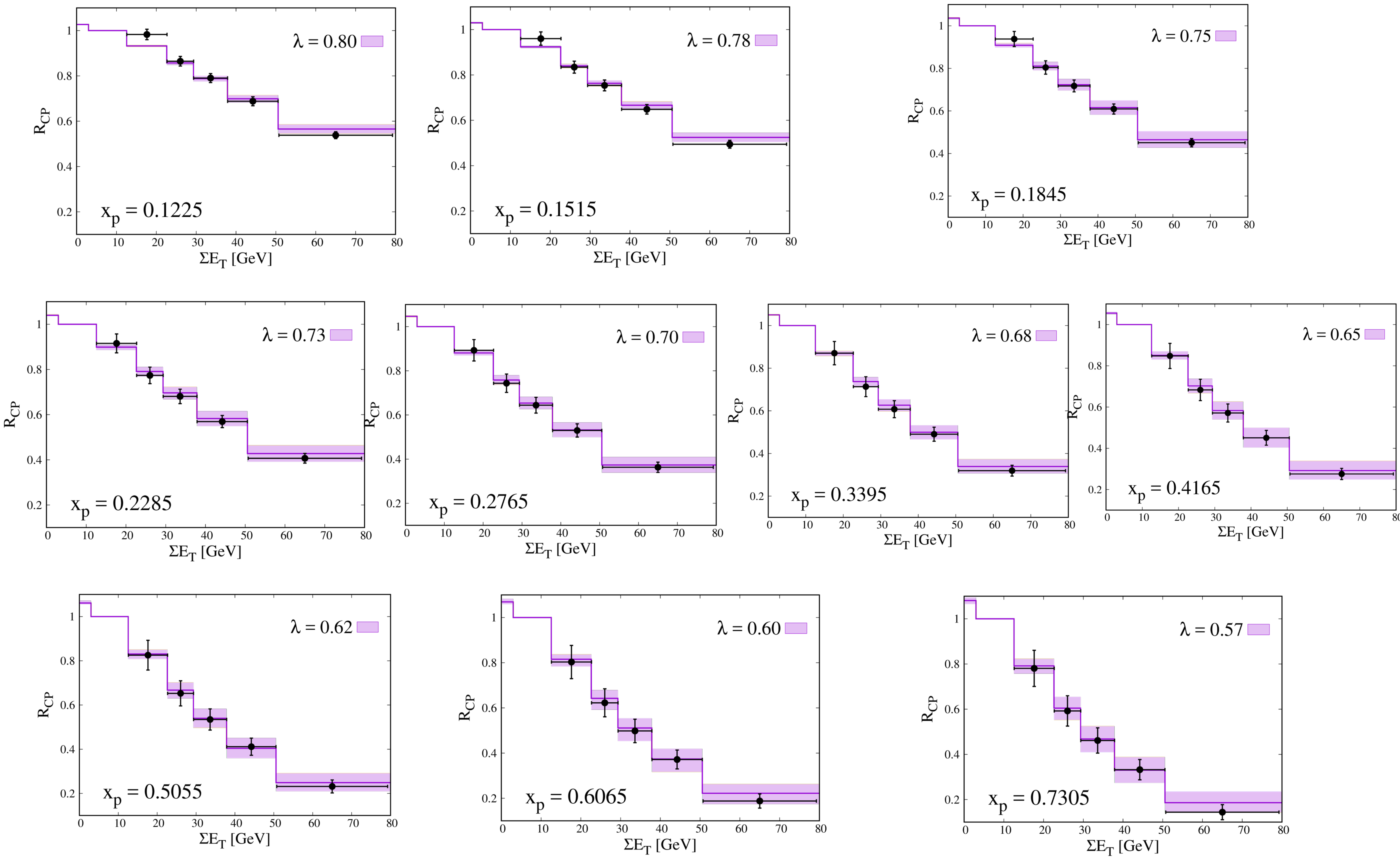


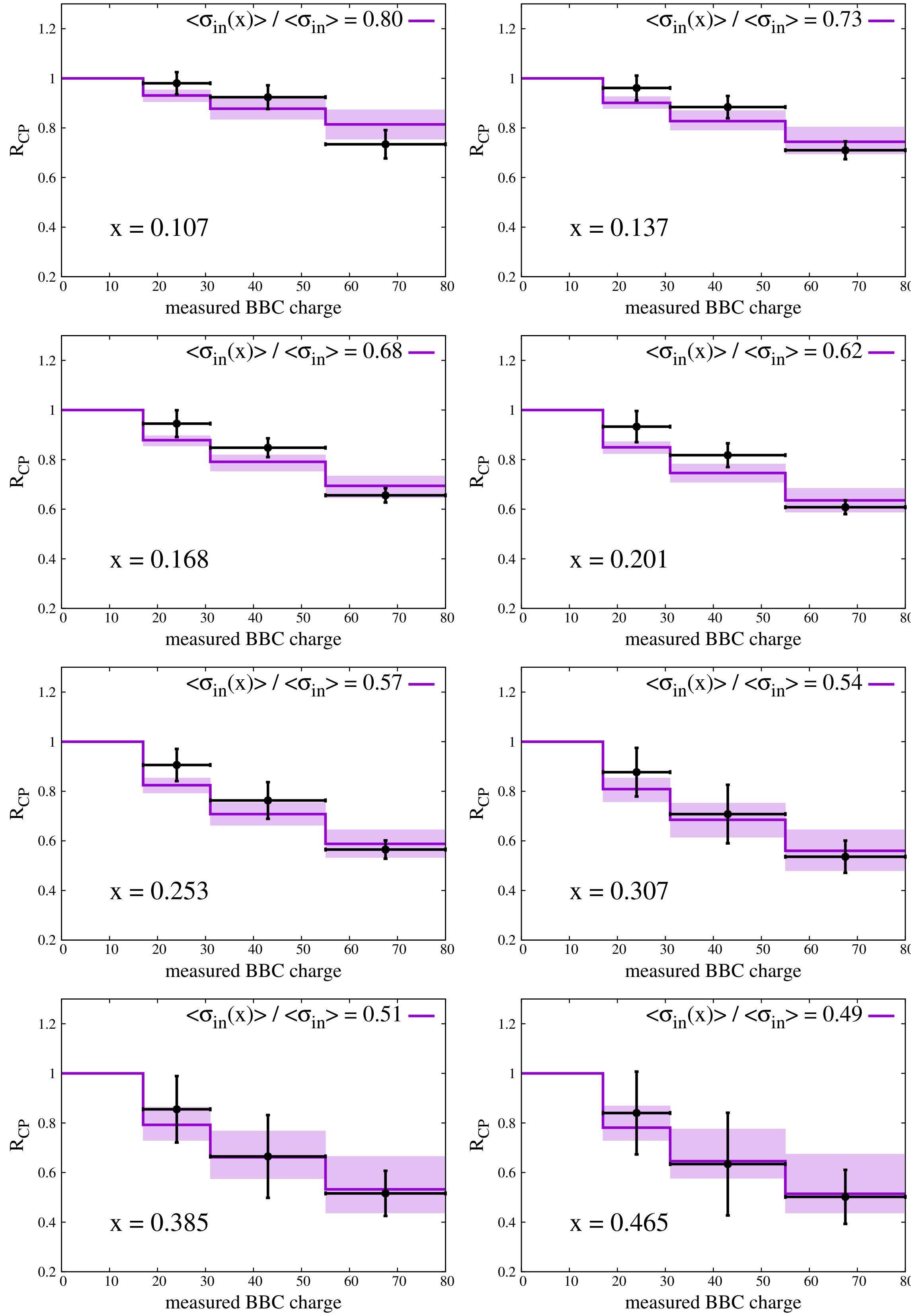
Sensitivity to ω_σ is small, so we use ω_σ =0.1 for following comparisons

We extended our 2015 analysis of ATLAS data and extracted $R_{CP}(x)$

$\lambda(x)= \sigma(x)/<\sigma>$

Alvioli, Frankfurt, Perepelitsa, MS



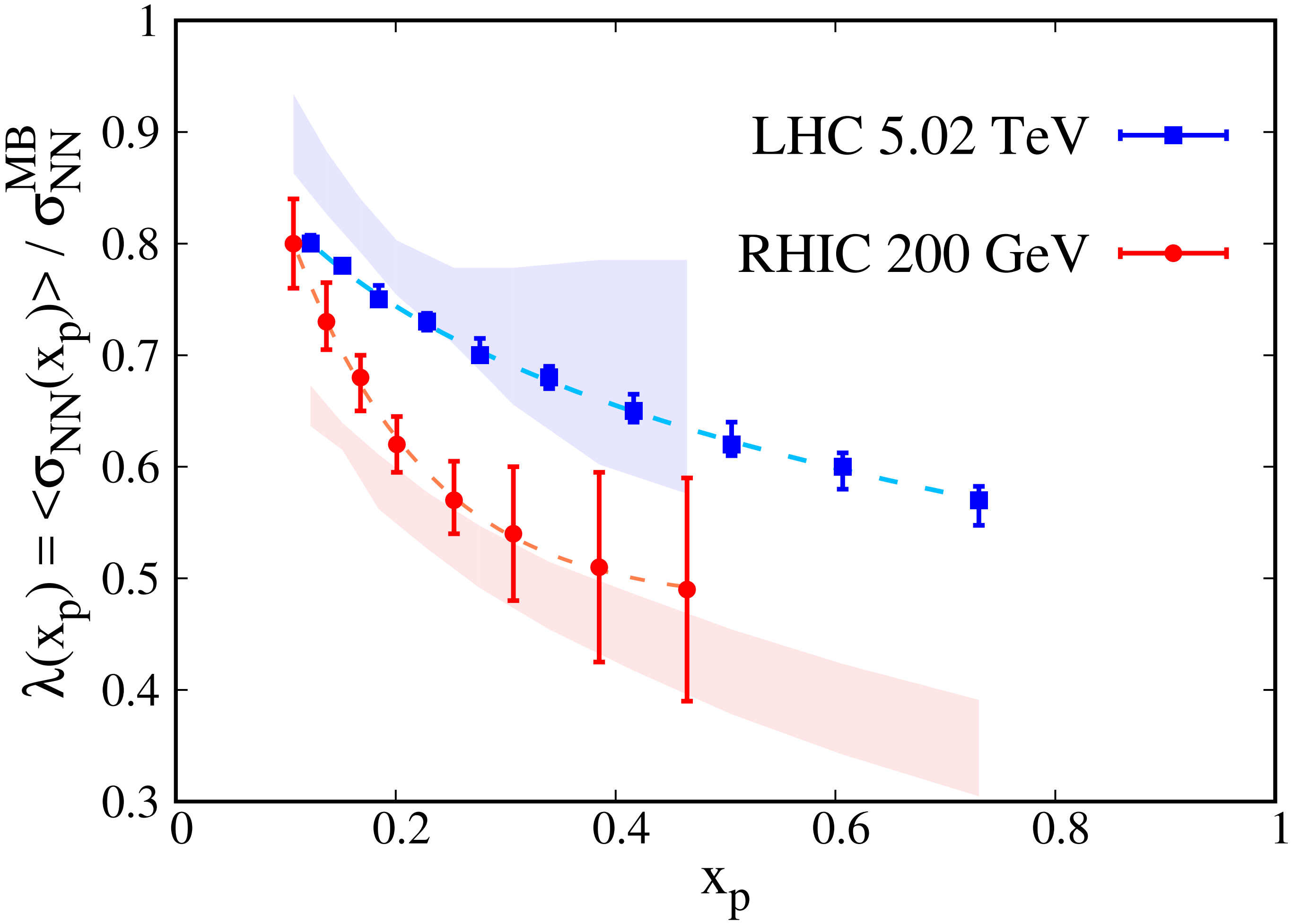


DAu PHENIX data at y=0 and large transverse momenta of the jets, R_{CP}, $\lambda(x)= \sigma(x)/\langle\sigma\rangle$ .Very different kinematics from the one studied at the LHC

Implicit eqn. for relation of $\lambda(x_p, s_1)$ and $\lambda(x_p, s_2)$

$$\int_0^{\lambda(x_p;\sqrt{s_1})\sigma_{tot}(\sqrt{s_1})} d\sigma\, P_N(\sigma;\sqrt{s_1}) = \int_0^{\lambda(x_p;\sqrt{s_2})\sigma_{tot}(\sqrt{s_2})} d\sigma\, P_N(\sigma;\sqrt{s_2})$$

Eq. (*)



$\lambda(x_p, s)$ grows with s since cross section at higher virtualities of the projectile grows faster with s

Highly nontrivial consistency check of interpretation of data at different energies and in different kinematics

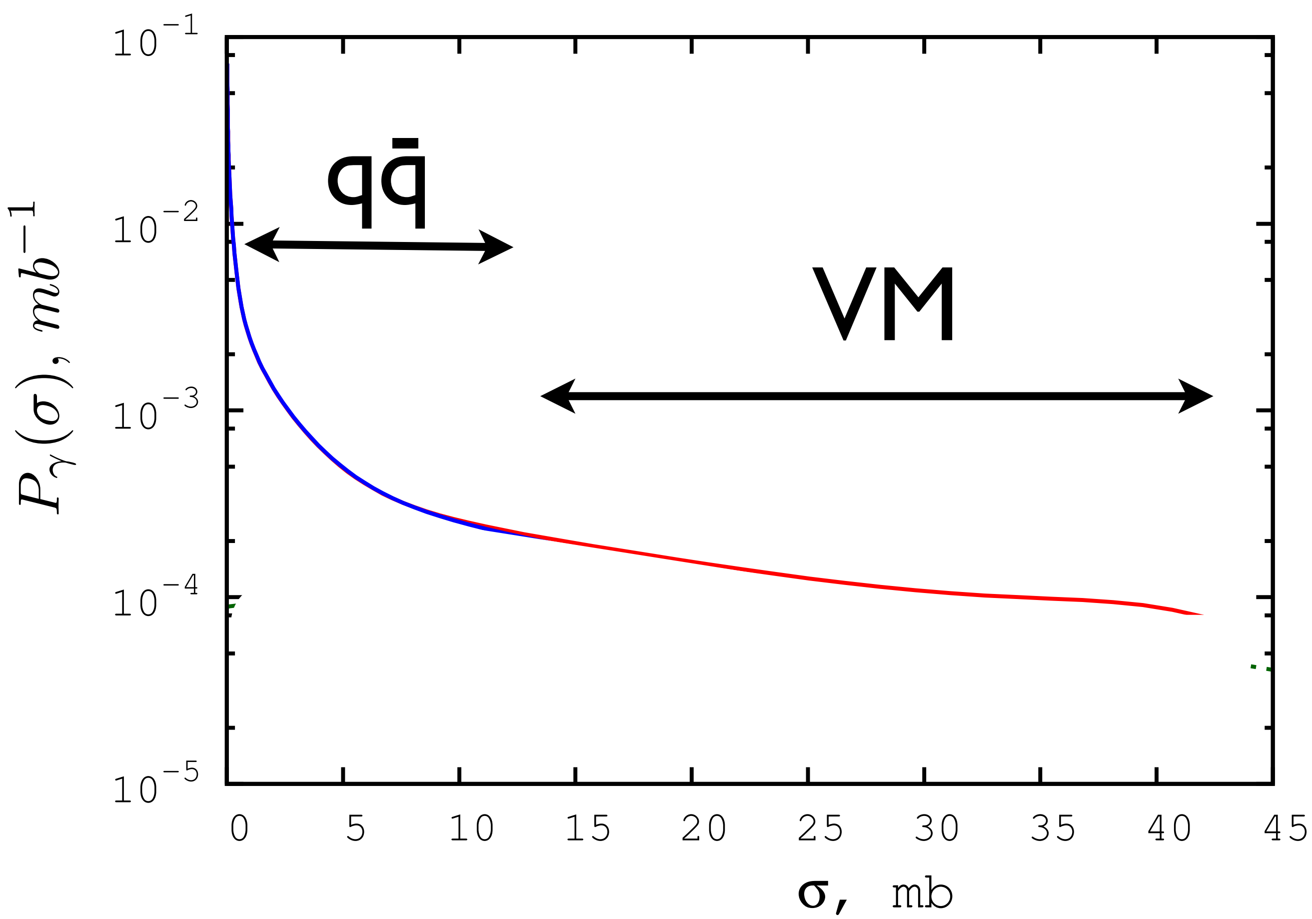
Eq.(*) suggests $\lambda(x_p=0.5$, low energy) ~1/4. Such a strong suppression results in the EMC effect of reasonable magnitude due to suppression of small size configurations in bound nucleons (Frankfurt & MS83)

Color fluctuations in photon - nucleus collisions

Photon is a multiscale state:

Probability, $P_\gamma(\sigma)$ for a photon to interact with nucleon with cross section σ, gets contribution from point - like configurations and soft configurations (VM like)

$P_\gamma(\sigma) \propto 1/\sigma \text{ for } \sigma \ll \sigma(\pi N)$ $P_\gamma(\sigma) \propto P_\pi(\sigma) \text{ for } \sigma > \sigma(\pi N)$



Exclusive processes of vector meson production off nuclei at LHC in ultraperipheral collisions allow to test theoretical expectations for small and large σ. $P_\gamma(\sigma)$ *for small σ from photon wave function and dipole DGLAP formula. Need model for large enough* σ *. Build a realistic model f and check in*

ρ-meson production: $\gamma + A \to \rho + A$

Expectations:

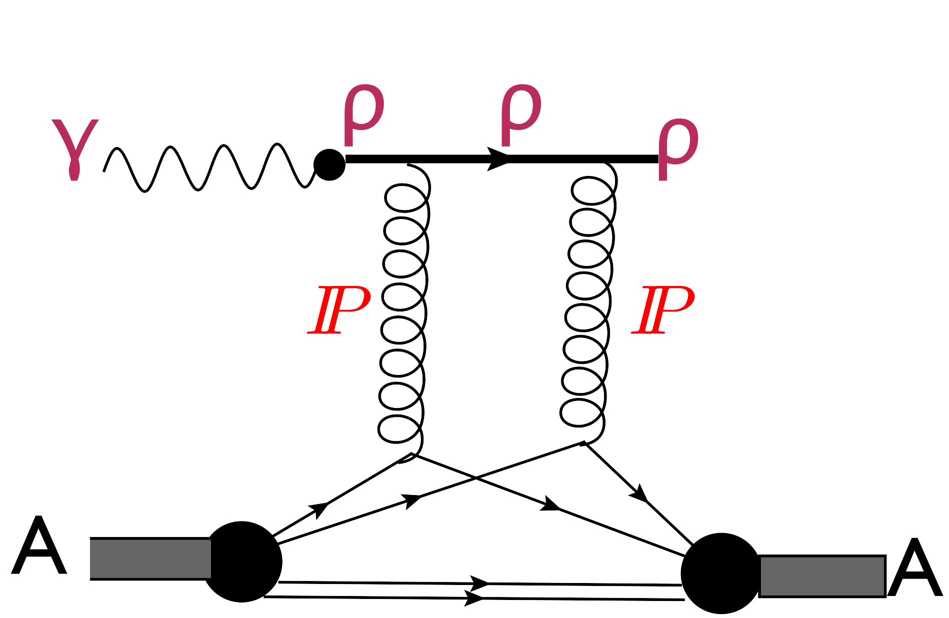
- *vector dominance model for scattering off proton*

$$\sigma(\rho N) < \sigma(\pi N)$$

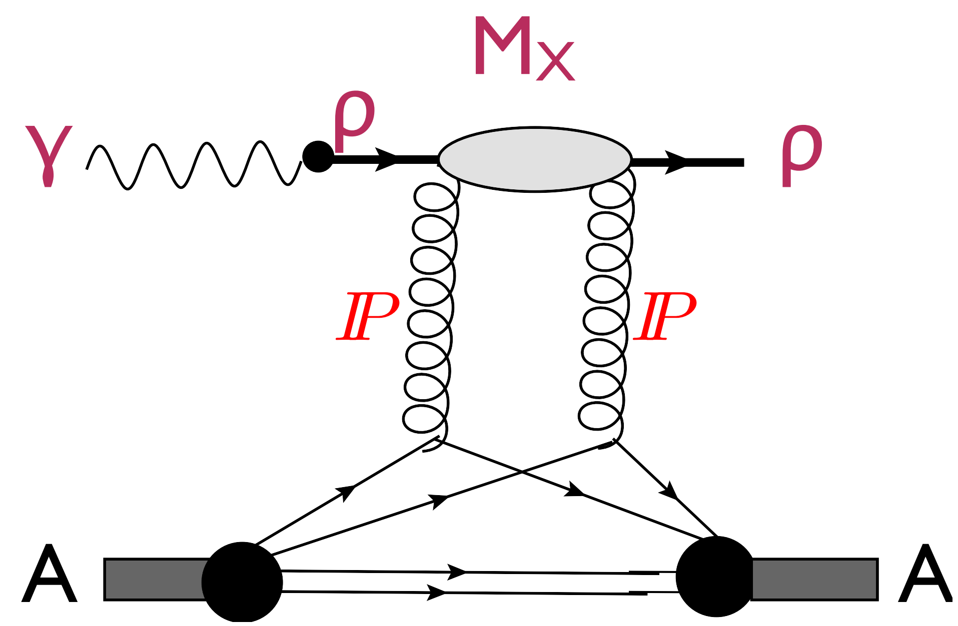
since overlapping integral between γ and ρ is suppressed as compared to $\rho \to \rho$ case

observed at HERA but ignored before our analysis: $\sigma(\rho N)/\sigma(\pi N) \approx 0.85$

Analysis of Guzey, Frankfurt, MS, Zhalov 2015 (1506.07150)



Glauber double scattering

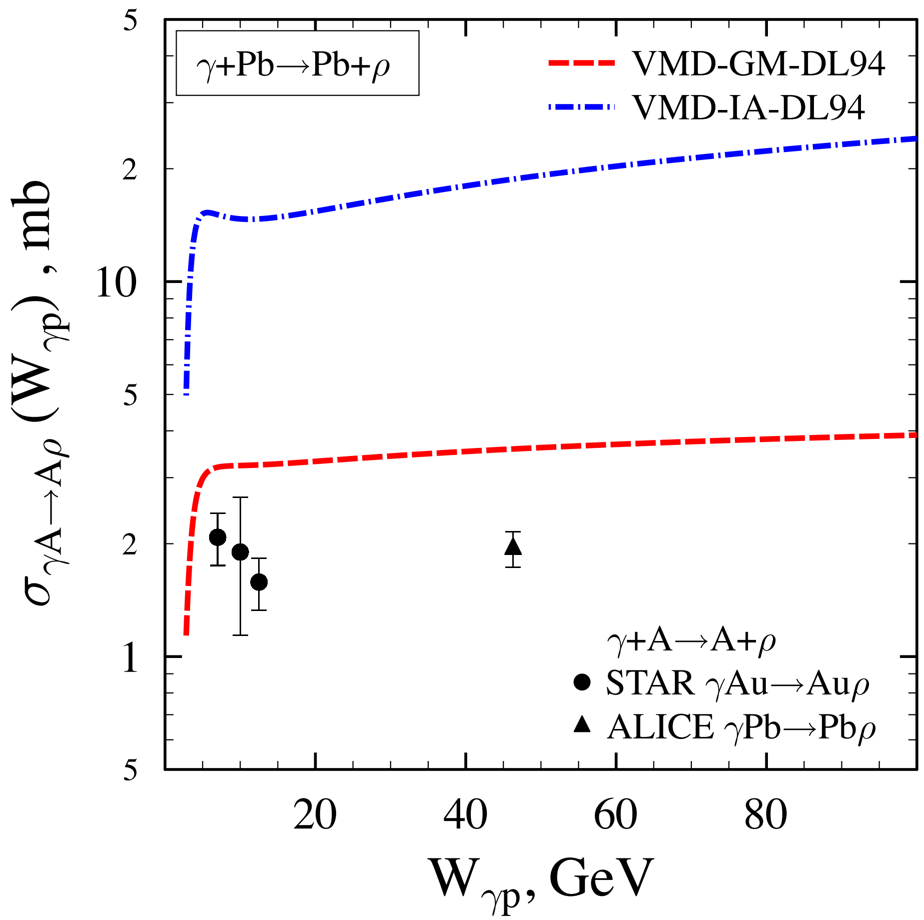


Gribov inelastic shadowing

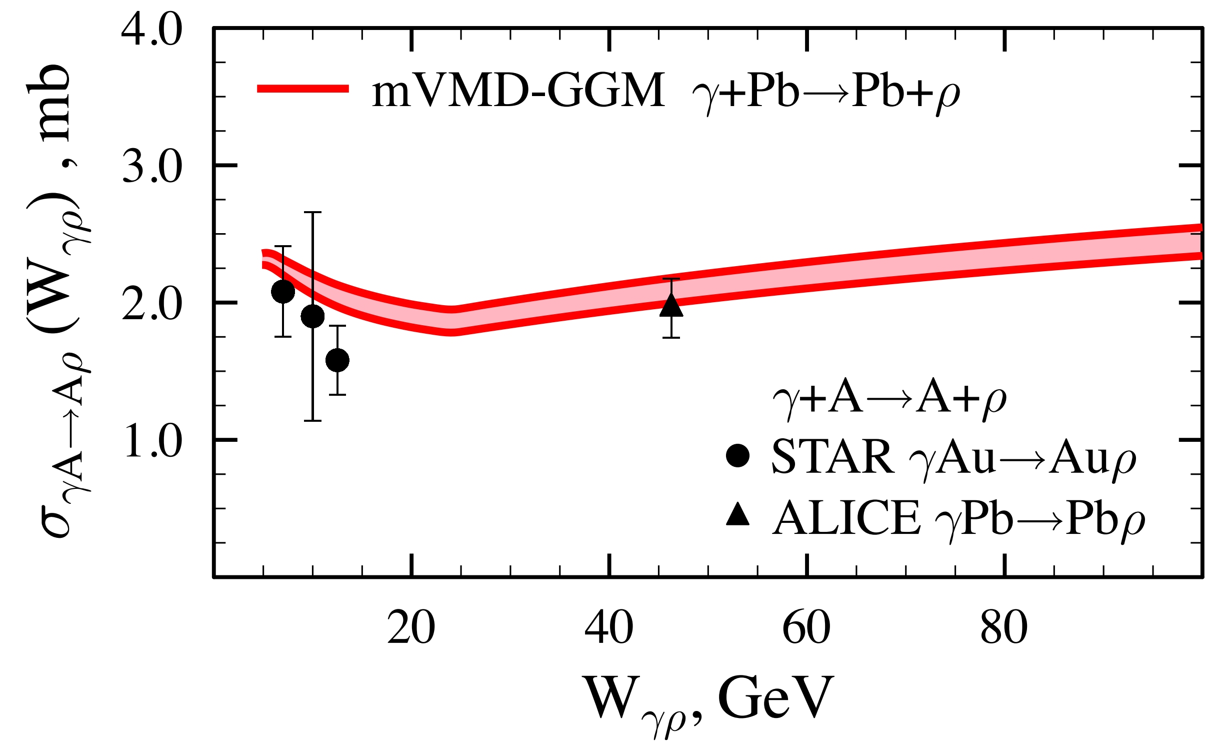
❖ Gribov type inelastic shadowing is enhanced in discussed process - fluctuations grow with decrease of projectile - nucleon cross section. We estimate $\omega_{\gamma\to\rho} \sim 0.5$ and model $P_{\gamma\to\rho}(\sigma)$ - distribution of configurations in transition over σ

Next we use $P_{\gamma\to\rho}(\sigma)$ to calculate coherent ρ production. Several effects contribute to suppression a) large fluctuations, b) enhancement of inelastic shadowing is larger for smaller σ_{tot}. for the same W, c) effect for coherent cross section is square of that for σ_{tot}.

- Glauber model grossly overestimates the cross section (at LHC factor ~2)



- Gribov - Glauber model with cross section fluctuations



Outline of calculation of inelastic γA scattering - distribution over number of wounded nucleons ν

- Modeling $P_\gamma(\sigma)$

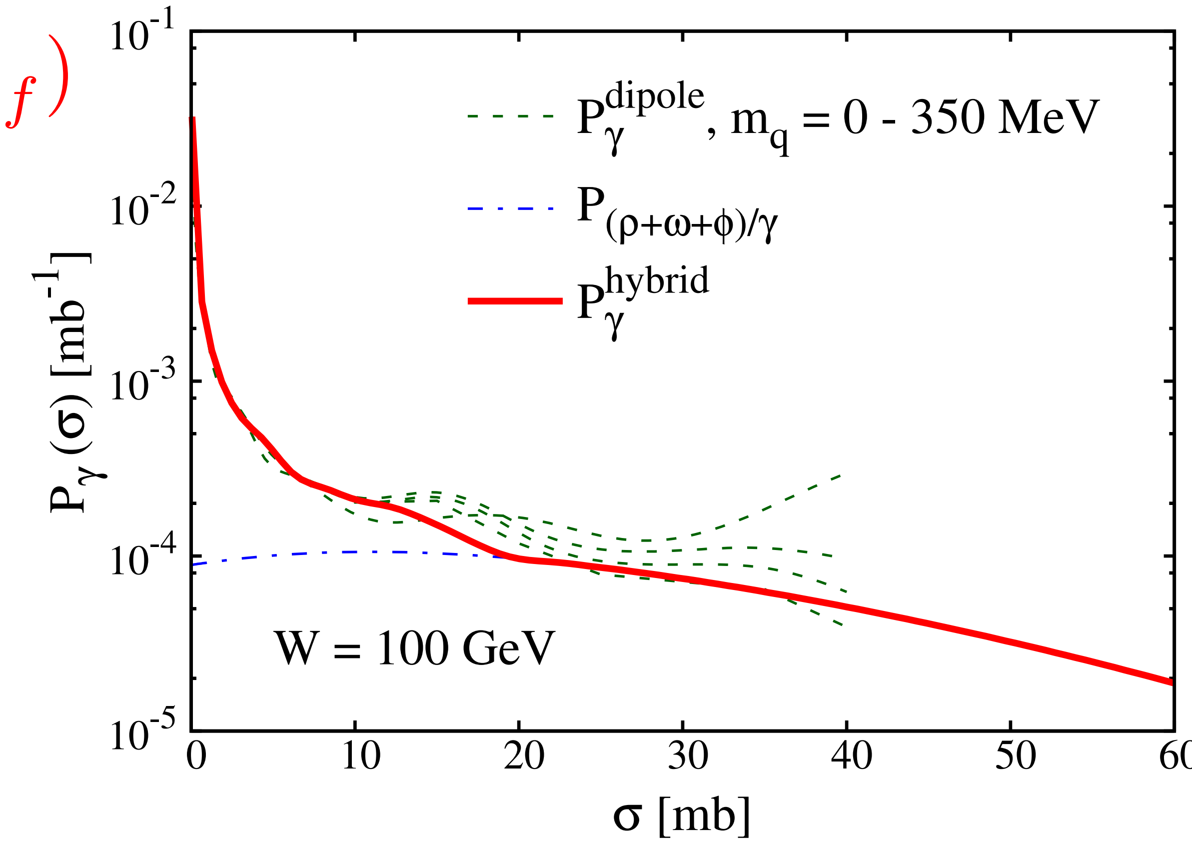
For

$$\sigma > \sigma(\pi N), P_\gamma(\sigma) = P_{\gamma\to\rho}(\sigma) + P_{\gamma\to\omega}(\sigma) + P_{\gamma\to\phi}(\sigma)$$

For $\sigma \leq 10mb$ (cross section for a J/ψ -dipole) use pQCD for $\psi_\gamma(q\bar{q})$

$$\sigma(d,x) = \frac{\pi^2}{3}\alpha_s(Q^2_{eff})d^2 x G_N(x, Q^2_{eff})$$

+ smooth interpolation in between



Smooth matching for m_q~ 300 MeV

Calculation of distribution over the number of wounded nucleons

(a) Color fluctuation model

$$\sigma_\nu = \int d\sigma P_\gamma(\sigma) \begin{pmatrix} A \\ \nu \end{pmatrix} \times \int d\vec{b} \left[\frac{\sigma_{in}(\sigma)T(b)}{A}\right]^\nu \left[1 - \frac{\sigma_{in}(\sigma)T(b)}{A}\right]^{A-\nu}$$

$$p(\nu) = \frac{\sigma_\nu}{\sum_1^\infty \sigma_\nu}.$$

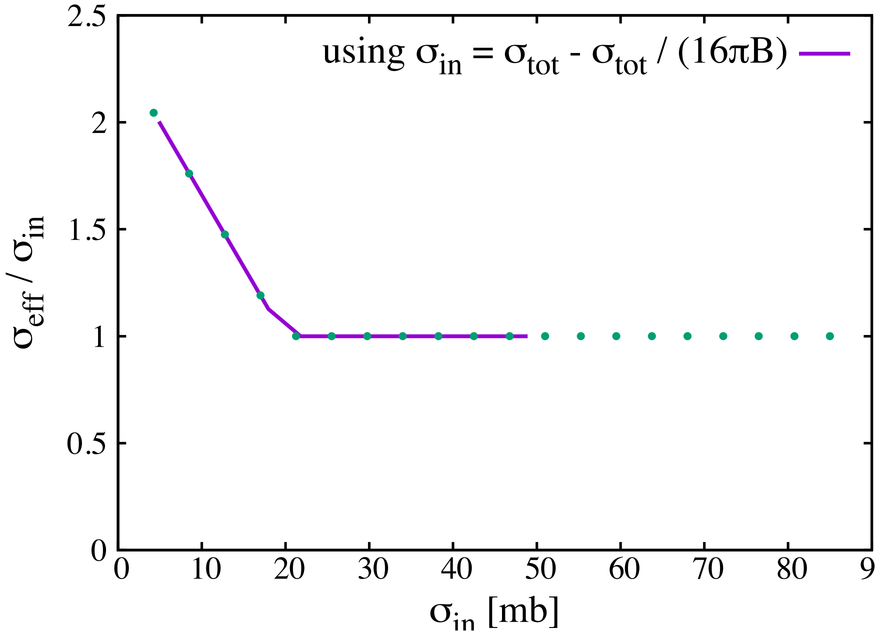
(b) Generalized Color fluctuation model (includes LT shadowing for small σ)

interaction of small dipoles is screened much stronger than in the eikonal model

evidence from J/psi production - next slide

$$P_\gamma(\sigma) \begin{pmatrix} A \\ \nu \end{pmatrix} \times \frac{\sigma^{in}}{\sigma^{in}_{eff}} \int d\vec{b} \left[\frac{\sigma_{eff}T(b)}{A}\right]^\nu \left[1 - \frac{\sigma_{eff}T(b)}{A}\right]^{A-\nu}$$

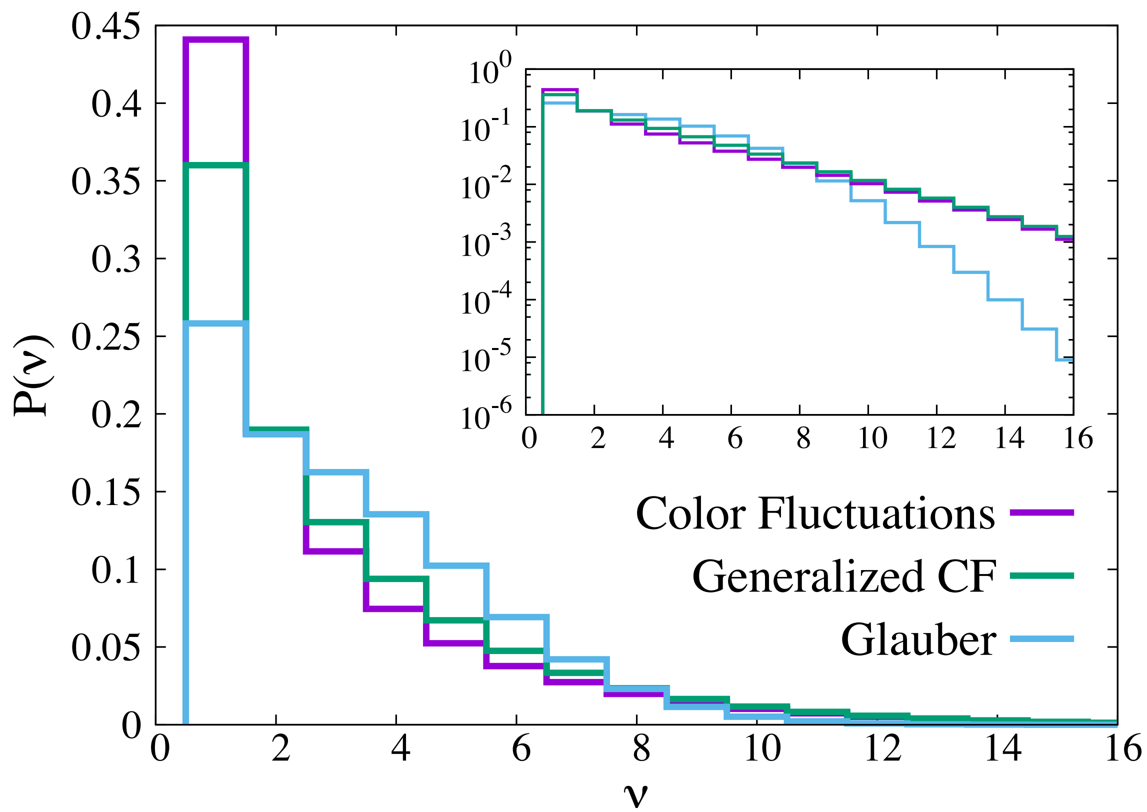
σ_{eff}/σ calculated in the LT nuclear shadowing theory for small σ



consistent with shadowing for J/ψ coherent production

Ultraperipheral minimum bias γA at the LHC ($W_{\gamma N}$ < 0.5 TeV)

Huge fluctuations of the number of wounded nucleons, ν, in interaction with both small and large dipoles

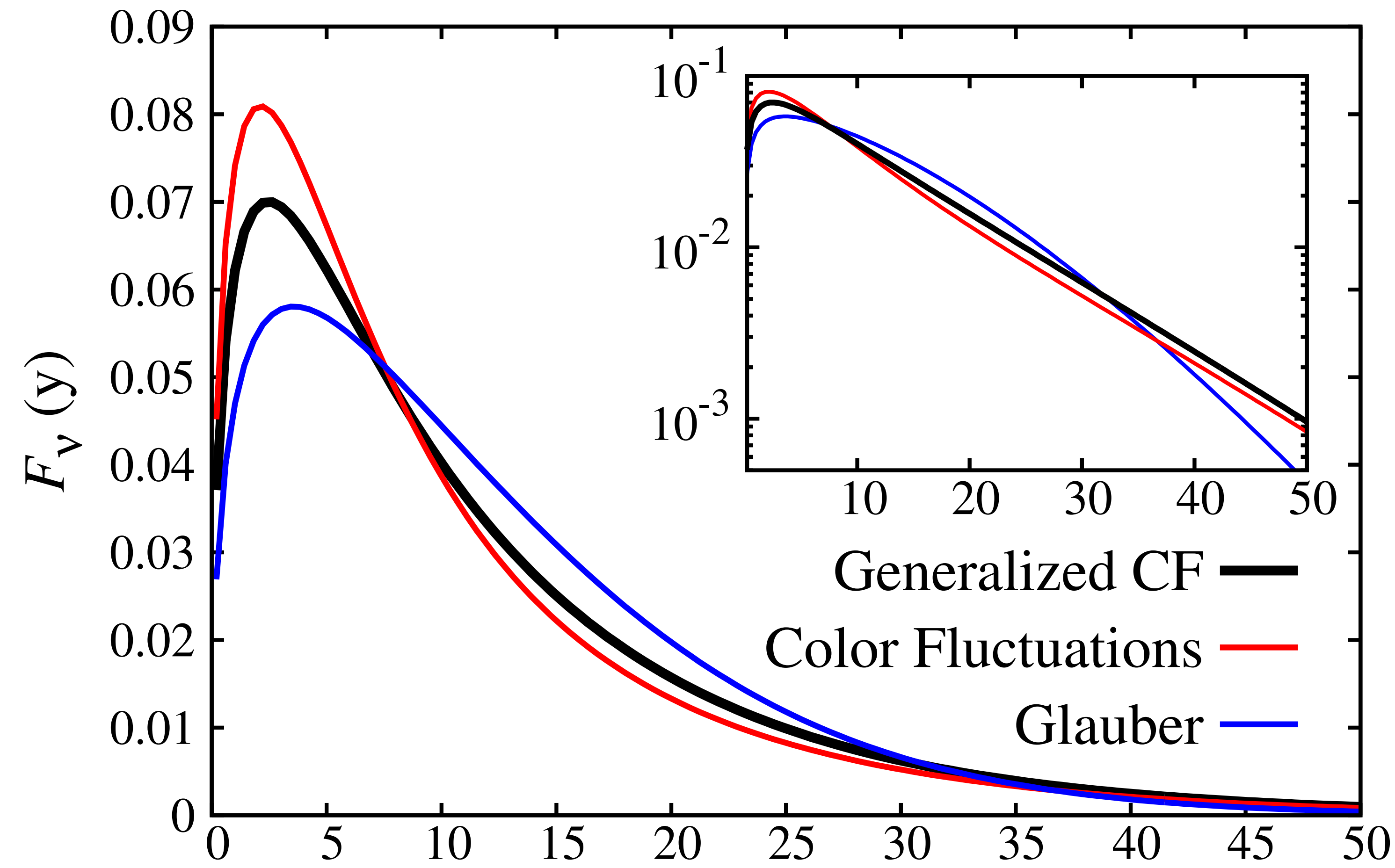


Alvioli, Guzey, Zhalov, LF, MS

Phys.Lett. B767 (2017) 450-457

distribution over the number of wounded nucleons in γA scattering, W ~ 70 GeV

CF broaden very significantly distribution over ν.
"pA ATLAS/CMS like analysis" using energy flow at large rapidities would test both presence of configurations with large σ ~40 mb, and weakly interacting configurations.



$$y = \Sigma E_T / \langle \Sigma E_T(hN) \rangle$$

The probability distributions over the transverse energy in the Generalized Color Fluctuations (GCF) model assuming distribution over y is the same for pA and γA collisions for same ν.

Using CASTOR for centrality via measurement of "y" advantageous : larger rapidity interval - smaller kinematical/ energy conservation correlations. For using ΣET for centrality determination one needs Δy > 4

$\gamma A \to$ jets + X

1) *Direct photon & $x_A > 0.01$, $\nu = 1$?*

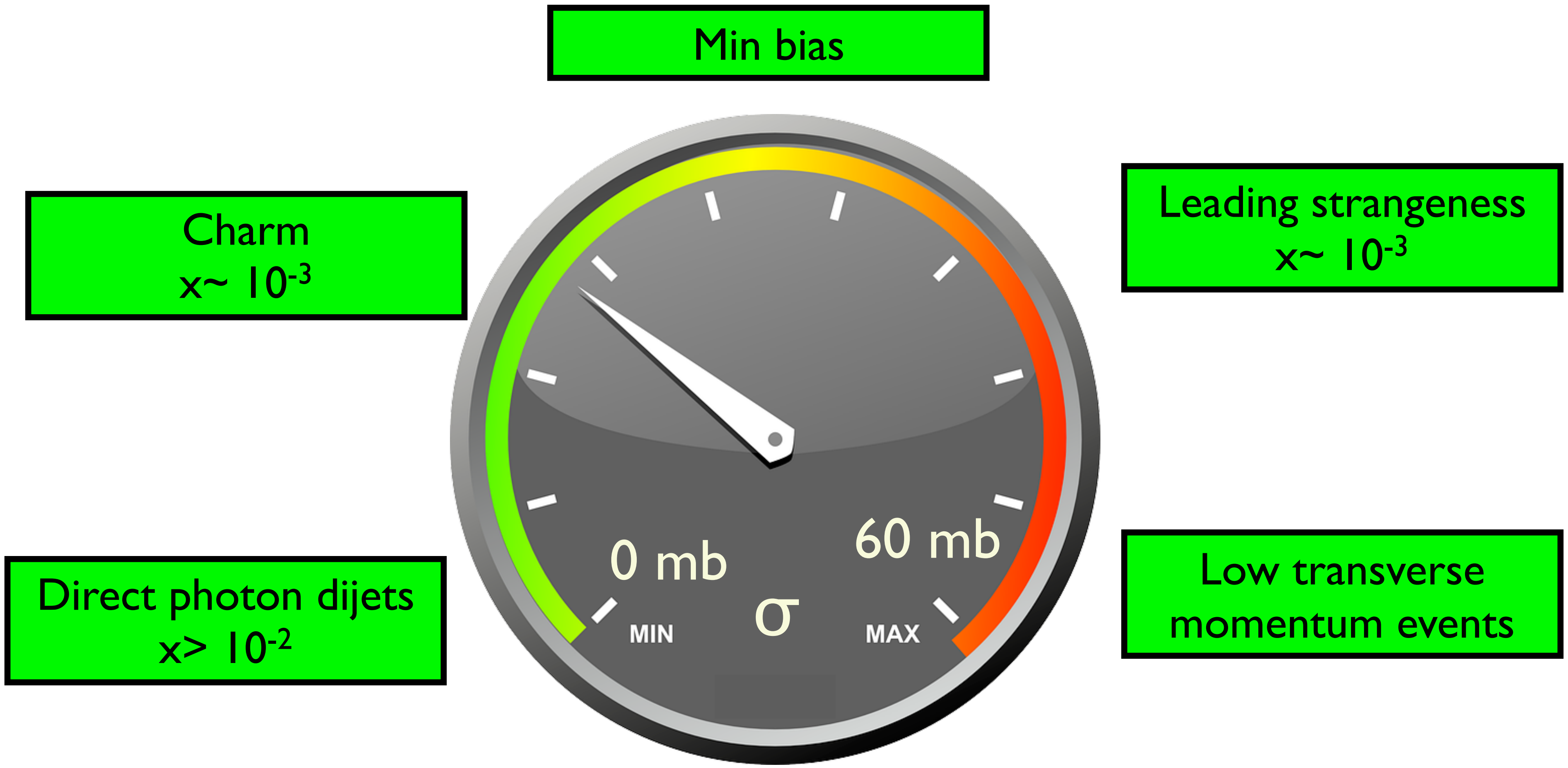
Color change propagation through matter.
Color exchanges ? ➠ nucleus excitations, ZDC & CASTOR

2) *Direct photon & $x_A < 0.005$ - nuclear shadowing increase of ν*

3) *Resolved photon - increase of ν with decrease of x_γ and x_A* W dependence

Centrality dependence of the forward spectrum in $\gamma A \to h + X$
— connection to modeling cosmic rays cascades in the atmosphere

Tuning strength of interaction of configurations in photon using forward (along γ information) . Novel way to study dynamics of γ &γ interactions with nuclei*



"2D strengthonometer" - EIC & LHeC - Q^2 dependence - decrease of role of "fat" configurations, multinucleon interactions due to LT nuclear shadowing

Comment: Forward γA & γp physics at the LHC mostly within acceptance of central ATLAS, CMS detectors

Summary

- Color fluctuations are a regular feature of of DIS at small x, high energy nucleon, photon collisions... Effects in very central AA collisions are present.

- **LT DGLAP framework for calculation of nuclear pdfs; etc passed the J/psi coherent production test.**

- Gross violation of the Glauber approximation for photoproduction of vector mesons due to CFs. CF are much stronger in photons than in nucleons. and can be regulated using different triggers (charm, jets,…). EIC will allow to study CF in photons at different Q,W - novel tests of interplay of soft and hard physics in γ^* interactions. UPC = forerunner at the LHC.

- Jet production at RHIC and LHC produced first glimpse of the global quark - gluon structure of nucleons as a function of x. Nucleon becomes much smaller at large x. Interact weaker than in average, but grows faster with energy. Need to separate gluons and quarks in hard processes at x ~0.1. Critical test pA at RHIC.

supplementary slides

Where DGLAP approximation breaks & non-linear(black disk?) regime (BDR) of strong absorption for configurations for small size configurations sets in? To determine proximity to BDR - calculate impact factor Γ(b) for "qq-dipole"- p (Pb) scattering

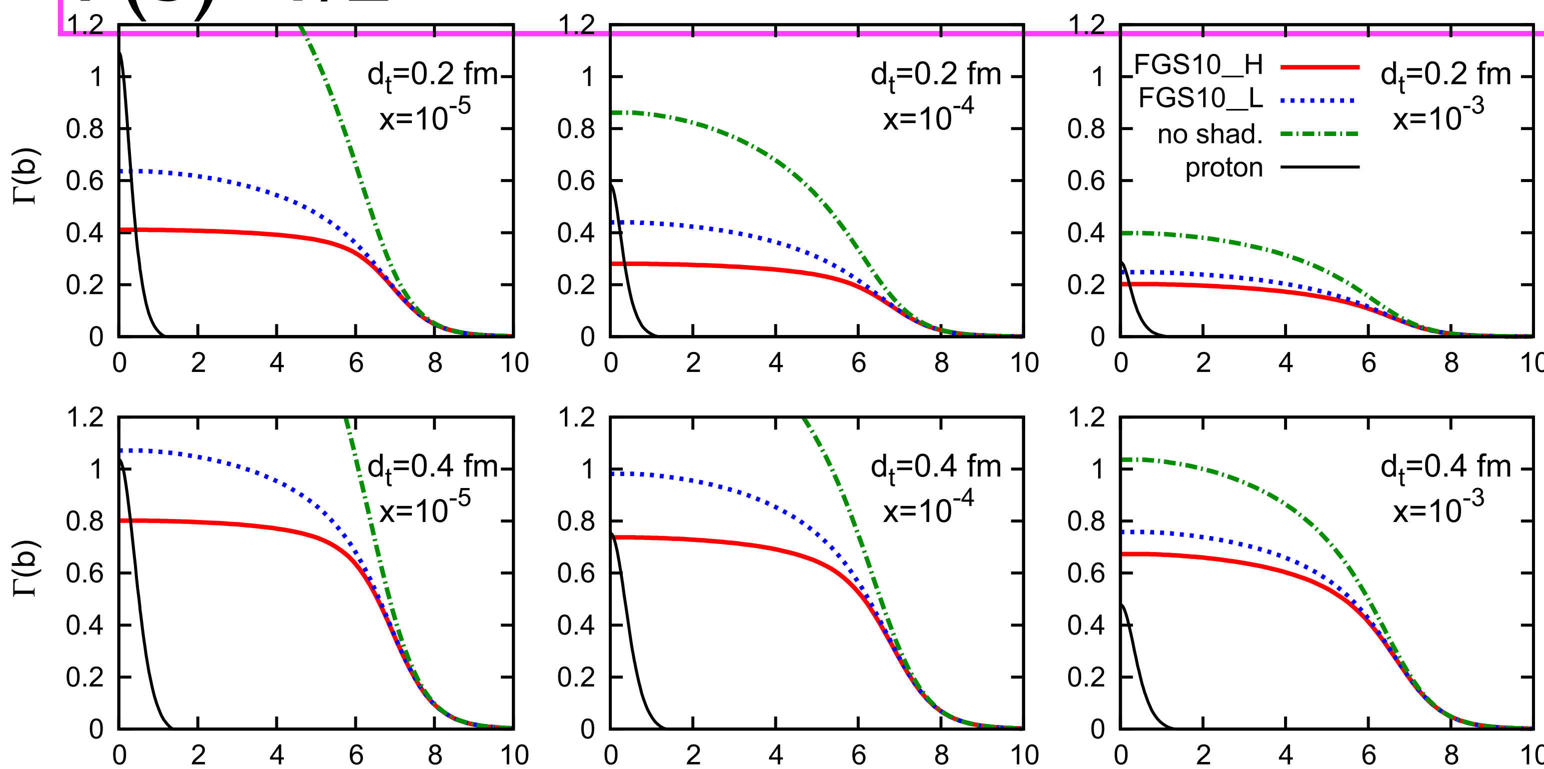
For nucleus in pQCD regime for the case of dipole of size $d_\perp$ impact factor for the scattering off nucleus is given by

$$2\Gamma_A(x, b d_\perp)_{pQCD} = \frac{\pi^2 F^2}{4} d_\perp^2 \alpha_S(Q^2_{eff}) x' g_A(x', Q^2_{eff}, b)$$

$$\frac{F^2(gg)}{F^2(q\bar{q})} = \frac{9}{4}$$

Earlier onset of BDR for interaction of gluo

Probability of inelastic interaction is $P_{in} = |1-\Gamma(b)|^2 \rightarrow P_{in}=3/4$ for $\Gamma(b)=1/2$



$"q\bar{q}" - N(Pb)$

Gluon densities in nuclei and proton at b=0 are rather similar. Difference at <b> is ~30% larger

J/ψ for x ~ 10^{-4} should be close to BDR.