From soft to hard diffraction in ultraperipheral collisions at the LHC

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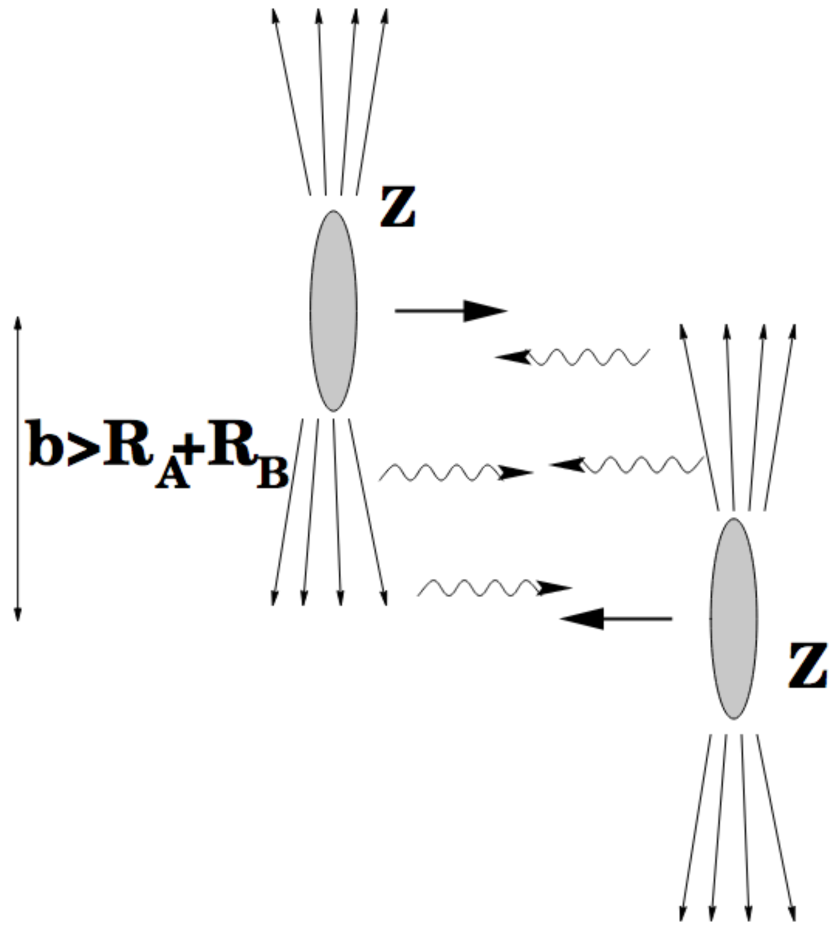
based on papers with L. Frankfurt, V,Guzey, M.Zhalov, E.Krushin

Low x, Ela, September 29, 2021

Next 10 -15 years - the only reasonably direct way to probe small x and moderate virtualities are different ultraperipheral collisions



Schematic diagram of an ultraperipheral collision of two ions. The impact parameter, b, is larger than the sum of the two radii, R_A+R_B.

Depending on the channel $W_{\gamma N}$ up to 1 TeV can be reached. Hardness of the process can be regulated using different final states.

for moderate virtualities (J/psi), $x=10^{-3}$ was reached - much smaller x in the future.

I will review comparison of the vector meson theory predictions and comparison with the LHC data results and some directions for further studies

Basic guiding features of QCD relevant for diffraction in QCD

a) cross section of a small dipole off a proton/ nucleus interaction is small, proportional t to area of dipole occupied by color, and to gluon density of target and hence grows with decrease of x.

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

—> factorization theorem for exclusive meson production (Collins, Frankfurt and MS 1997)

b) Diffraction in DIS is the leading twist effect - (formal proof Collins 1998)

- rescatterings of a small dipole off several nucleons are not suppressed by power of r^2_{tr}

- qualitative difference from eikonal: n-th rescaattering is suppressed by Q^{2n}

theory of leading twist parton shadowing (Frankfurt, Guzey, MS)

Fundamental feature of QCD: ratio $\dfrac{\sigma_{inel\,diff}}{\sigma_{el}}$

is small and decreasing with energy for soft interactions (pp)

large (> 1) ($\propto Q^2/Q_0^2$) and increasing with energy for small dipoles interactions (DIS)

Space - time picture of high energy pA collisions

Fluctuations of overall strength of high energy NN interaction

High energy projectile stays in a frozen configuration distances l_{coh} =cΔt

$$\Delta t \sim 1/\Delta E \sim \frac{2p_h}{m^2_{int} - m^2_h}$$

At LHC for pp $m^2_{int} - m^2_h \sim 1\mathrm{GeV}^2$ $l_{coh} \sim 10^7$ fm>> $2R_A$>> $2r_N$

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

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

For γN (ultraperipheral collisions in pA & AA) $l_{coh} \sim 10^5$ fm

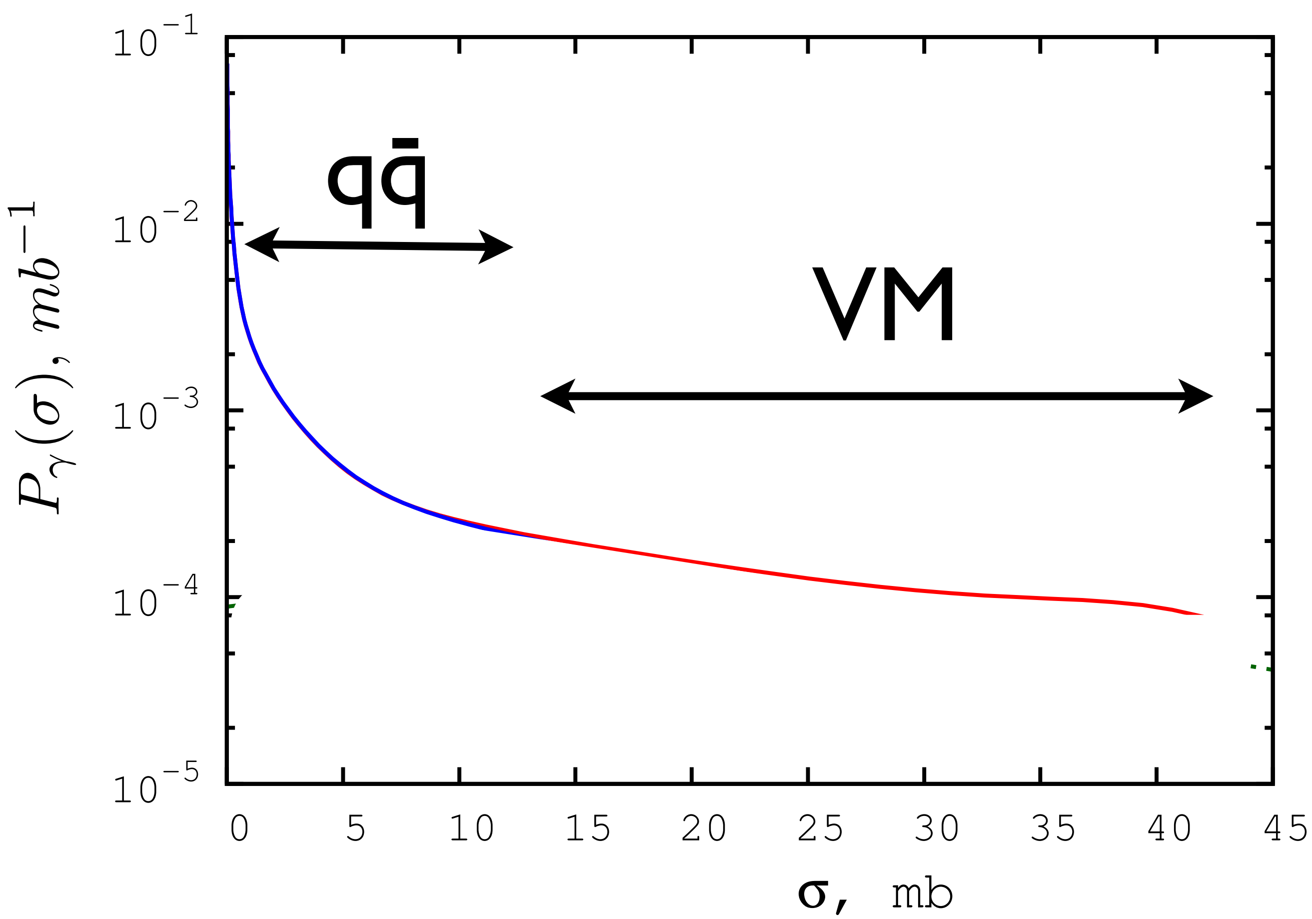
Parton structure of photon - Color fluctuations in γA collisions

Photon is a multi scale 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 (vector meson (VM) like) - color fluctuations (CF). *Unique opportunity to compare soft and hard interactions*

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

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

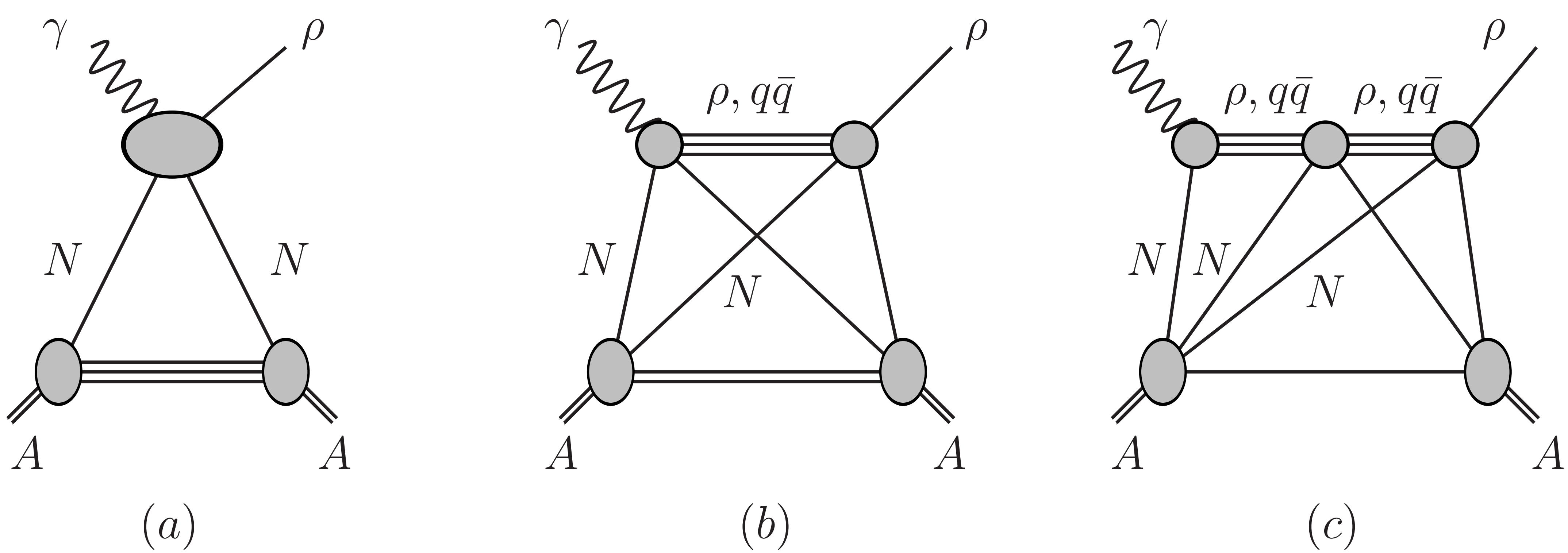


Alvioli et al 2017

Soft diffraction - ρ-meson production

only ρ= Glauber + vector dominance for γ-ρ coupling

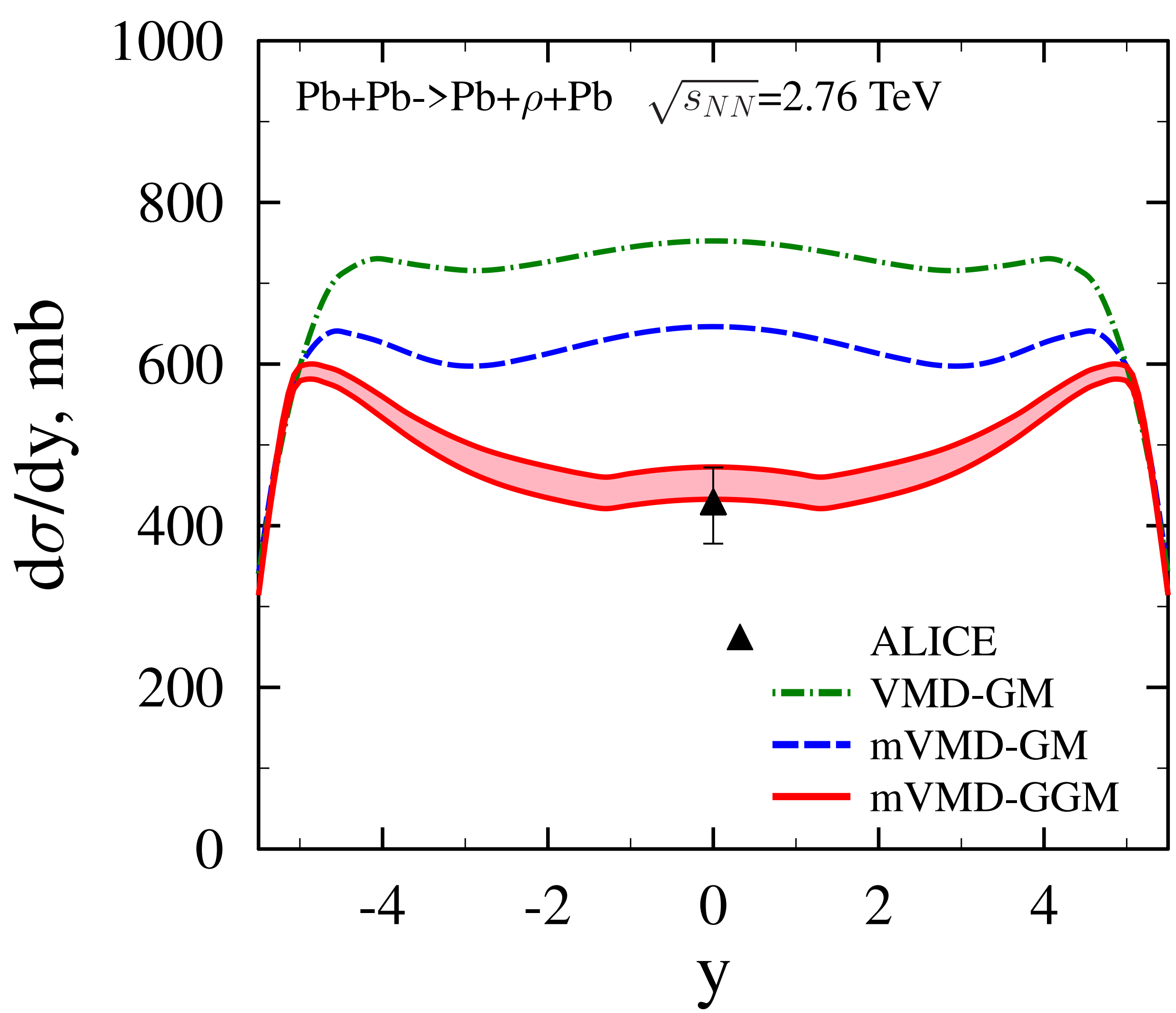
ρ + ρ’ +q\bar q,…= Gribov -Glauber + vector dominance



Need to model fluctuations of the strength of interaction, P(σ)

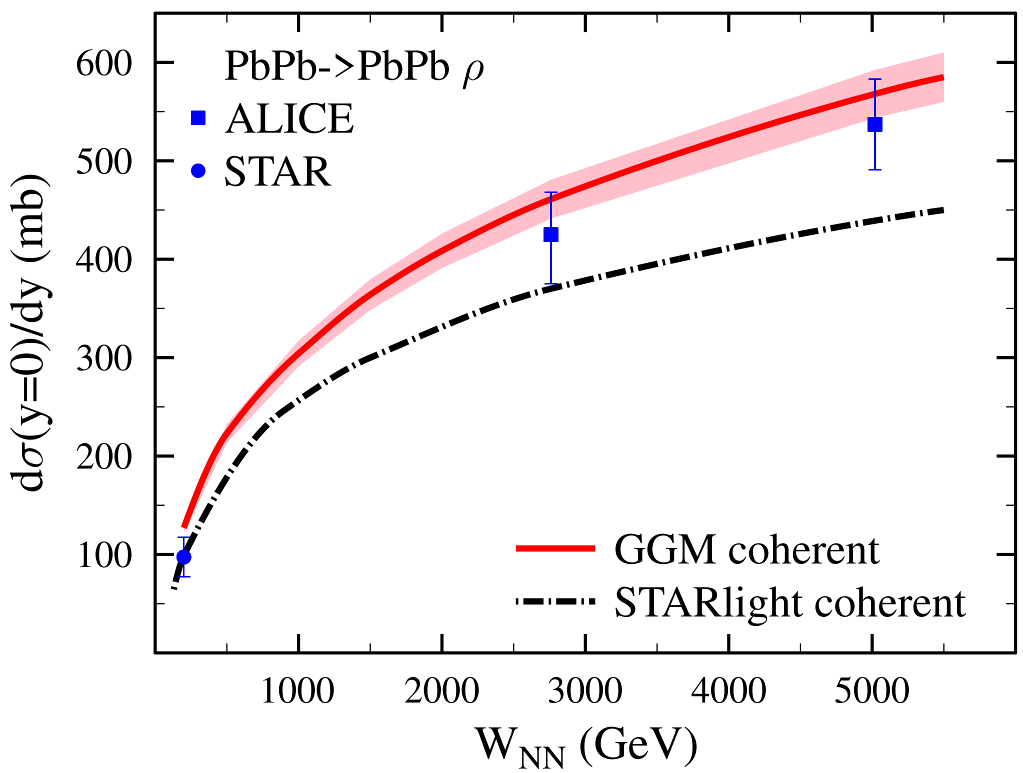
$$\sigma_{\gamma A\to\rho A} = \left(\frac{e}{f_\rho}\right)^2 \int d^2\mathbf{b} \left| \int d\sigma P_\rho(\sigma) \left(1 - e^{-\frac{1}{2}\sigma T_A(b)}\right) \right|^2$$

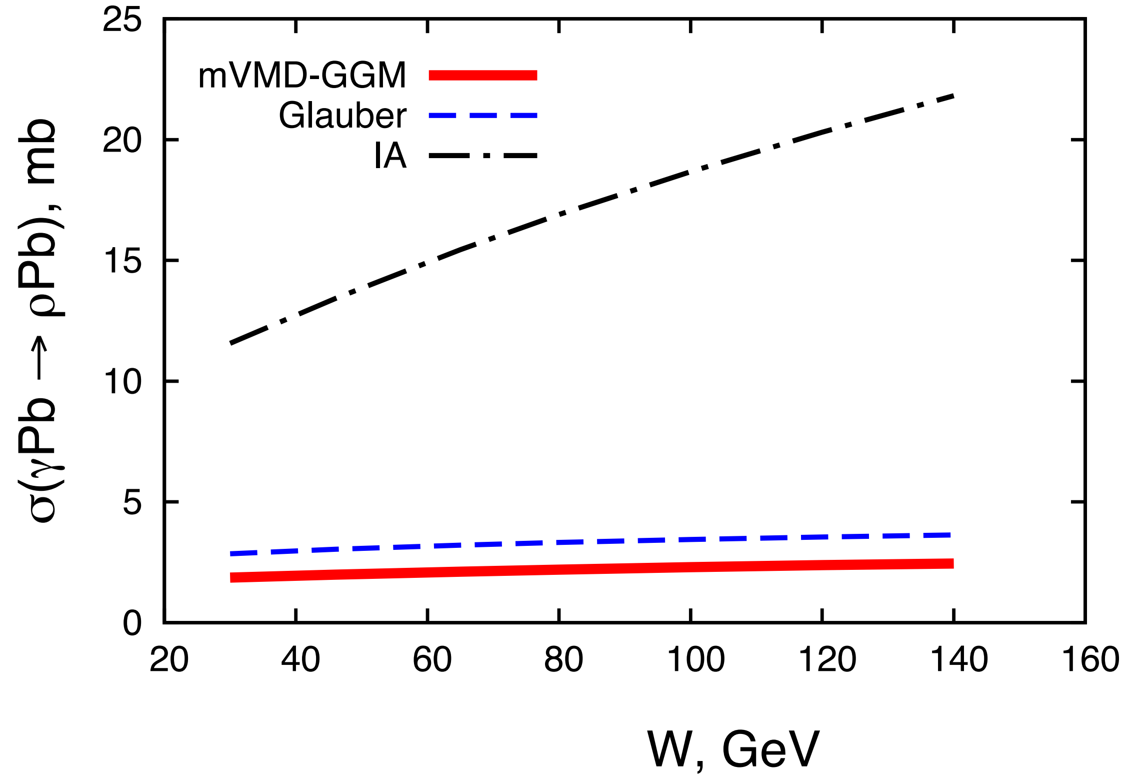
where $f_\rho^2/(4\pi) = 2.01 \pm 0.1$ is determined from the $\rho \to e^+e^-$ decay

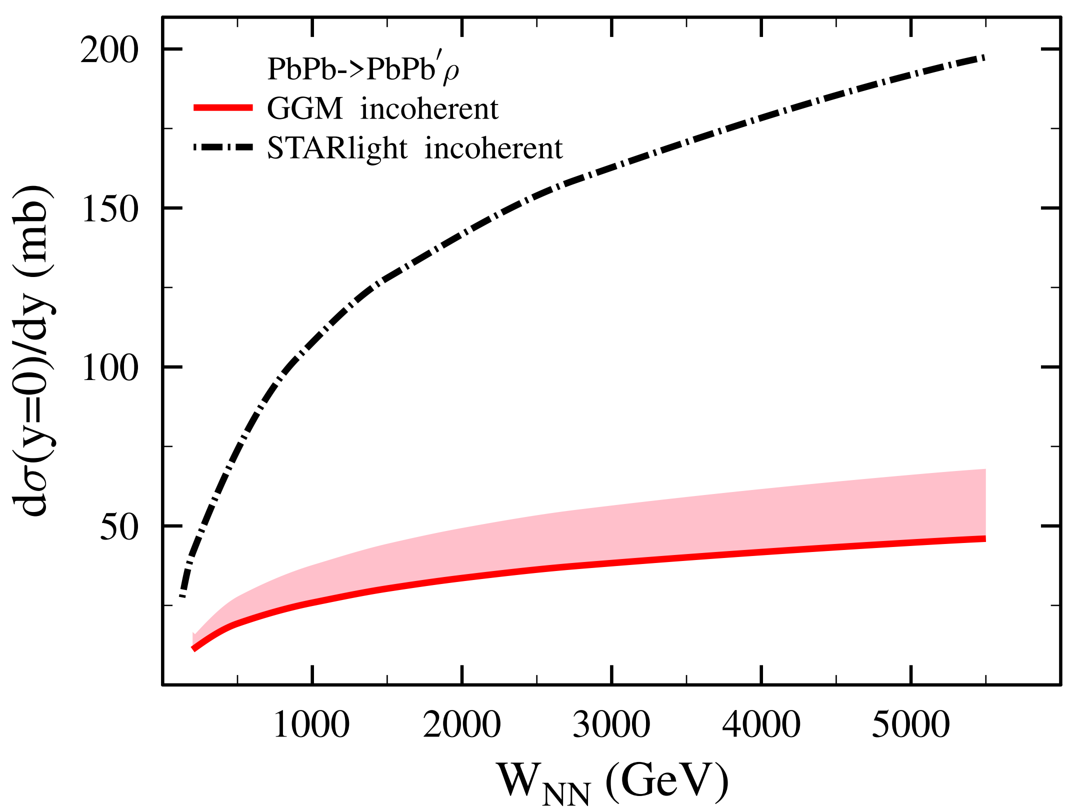


The cross section of coherent ρ photoproduction in Pb-Pb UPCs at $\sqrt{s_{NN}}$ = 2.76 TeV as a function of the rapidity y: predictions of the Gribov–Glauber model (red solid curves) and the Glauber model (blue dashed and green dot-dashed curves) are compared to the ALICE

Coherent scattering is dominated by smaller photon energy contribution away from y=0. Gribov - Glauber and classical mechanics (STARlight) differ relatively little

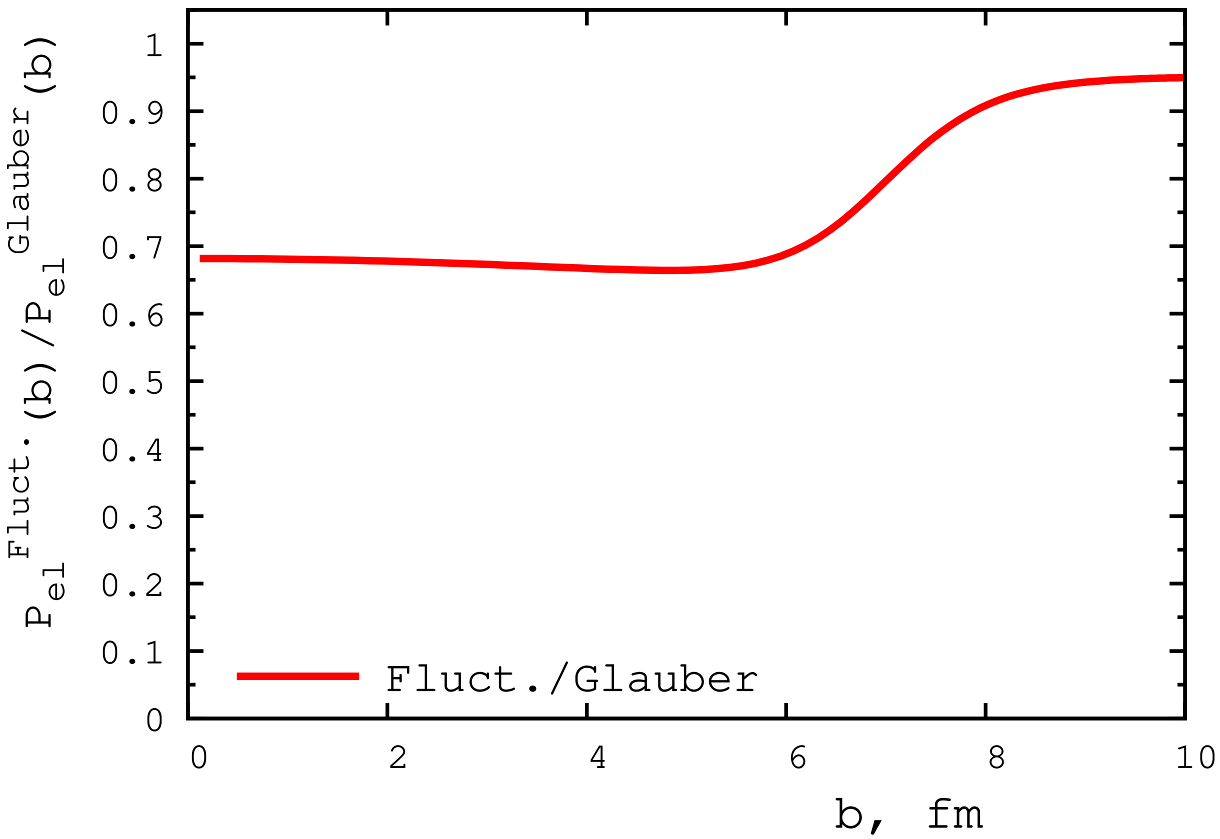


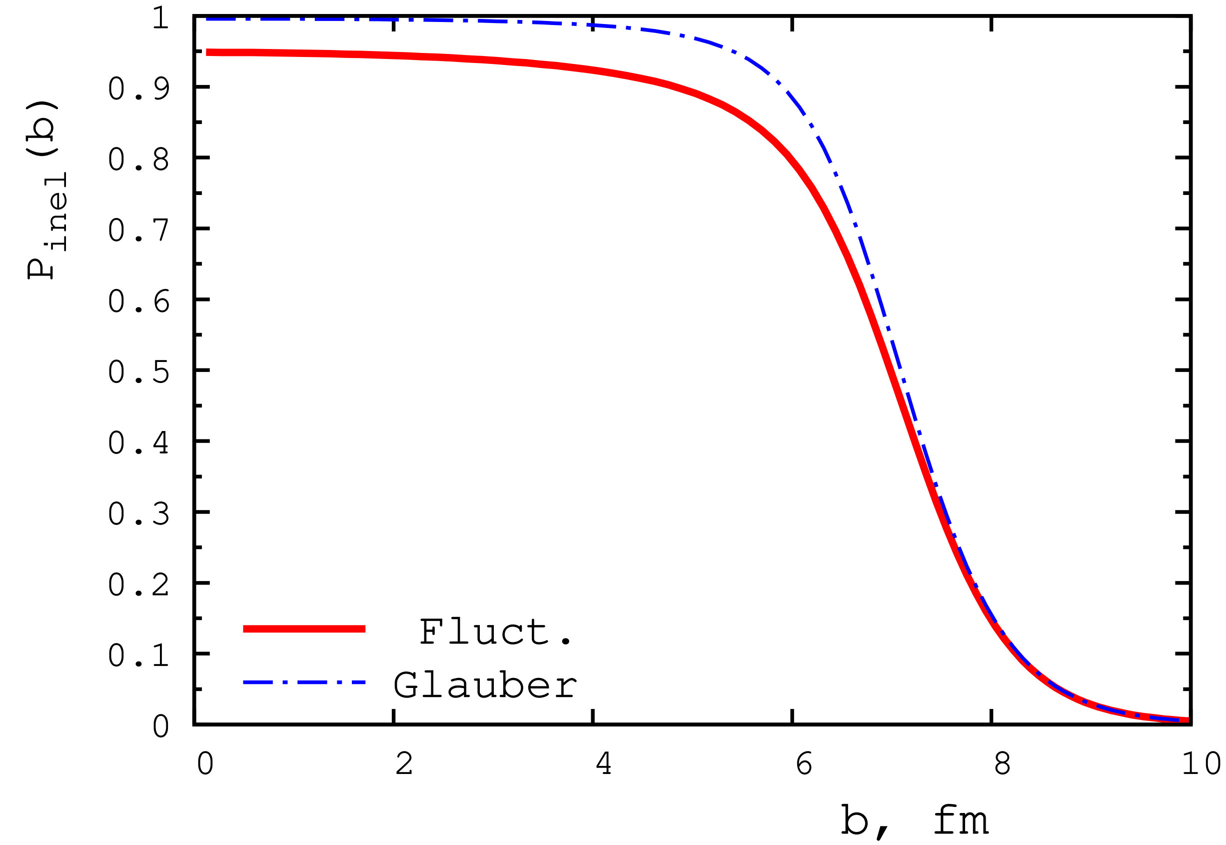




Gross difference for incoherent diffraction — measurements could be pushed to higher W.

P=1 = black limit





The ratio of the nuclear profile functions squared with and without cross section fluctuations (left) and the probability of inelastic interactions as a function of |b| at W = 100 GeV. From comparison a) and b) - diffraction is much more sensitive to onset of black disk limit

$$P_{\rm inel}^{\rm Fluct.}(b) = 1 - \int d\sigma P_\rho(\sigma) \left(1 - \Gamma_A(b,\sigma)\right)^2$$

$$P_{\rm inel}^{\rm Glauber}(b) = 1 - \left(1 - \Gamma_A(b,\sigma_{\rho N})\right)^2 \,,$$

$$\Gamma_A(b,\sigma) = 1 - \exp[-\sigma T_A(b)/2]$$

Hard diffraction - J/ψ meson production

- **exclusive production: γ +p (A)→ J/ψ +p (A)**

  Issues: gluon pdfs and gpd's, gluon shadowing)

  most popular now

- **quasielastic γ +p (A)→ J/ψ + Y at t=0**

Issues: color fluctuations in nucleons and nuclei; gluon shadowing

- **γ +p (A)→ J/ψ(large t) + rapidity gap + Y**

  Issues: **BFKL at $-t > 1$ GeV^2**

- **γ +p (A)→ J/ψ($x_F < 0.8$) + X**

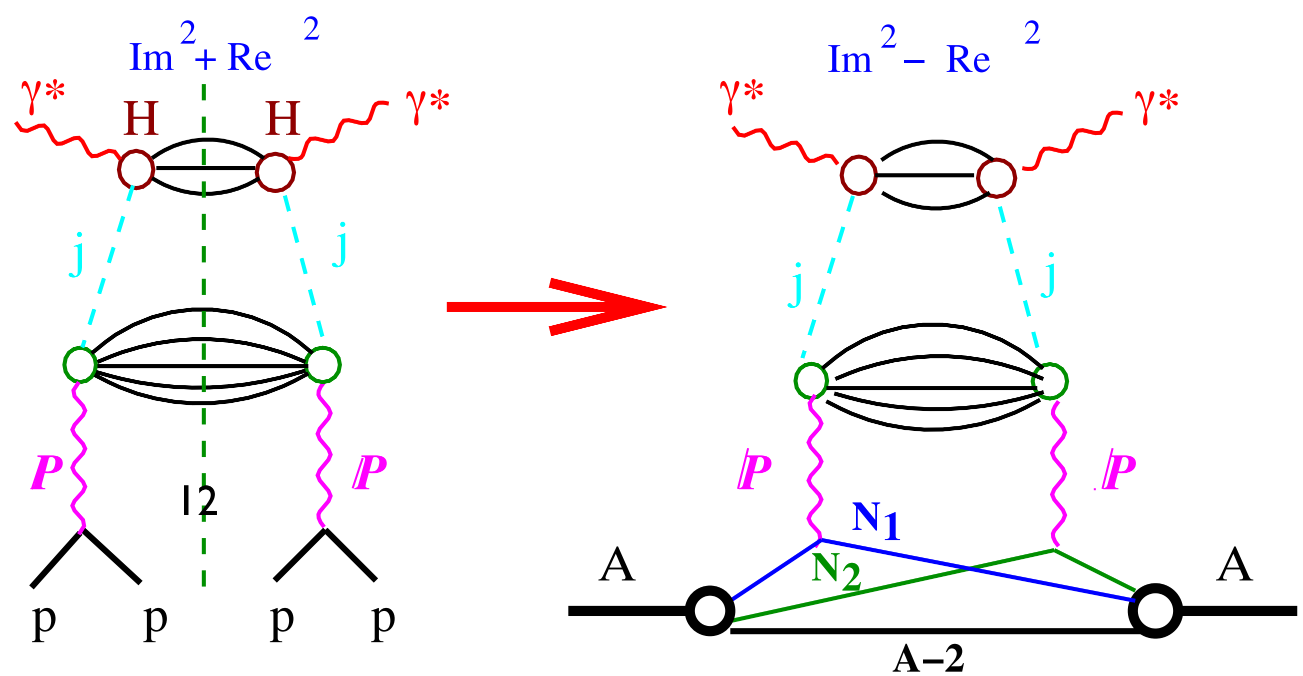
  for p —- neutrons in proton fragmentation region, ZDC signal forA decay

QCD factorization for fragmentation of nucleon, multinucleon inelastic interactions, small x gluon densities in p &A

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



Hard diffraction off parton "j"

Leading twist contribution to the nuclear shadowing for structure function $f_j\,(x,Q^2)$

Coherent J/ψ production - update (Guzey, Kryshen, Zhalov, MS 2020)

Theory (Frankfurt, Guzey, MS): Leading twist theory of nuclear shadowing expressing shadowing through LT diffractive PDFs. Alternative - fitting small x data - very limited sample

Predicted correctly shadowing for J/ψ in UPS. Use new LHC data to go below y=0, $x=m_{J/\psi}/E_N$

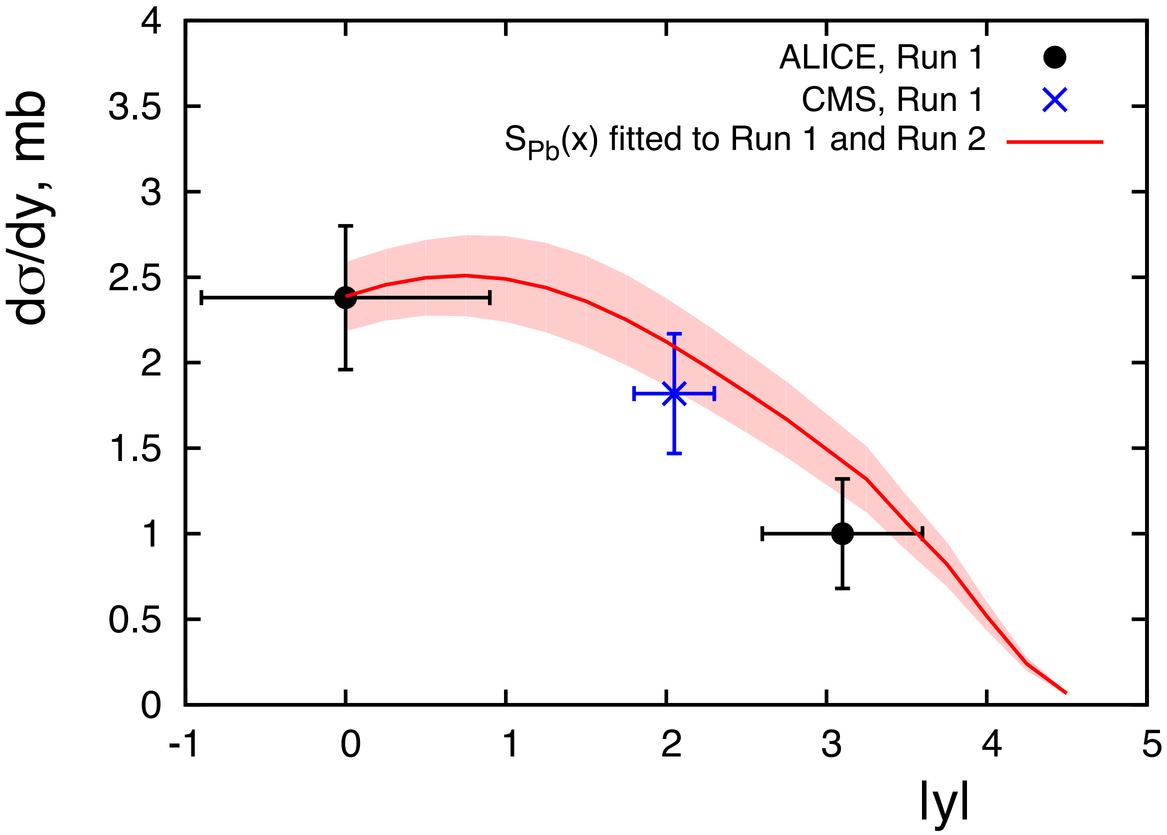
$$S_{Pb}(x) = \sqrt{\frac{\sigma_{\gamma A\to J/\psi A}(W_{\gamma p})}{\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W_{\gamma p})}}$$

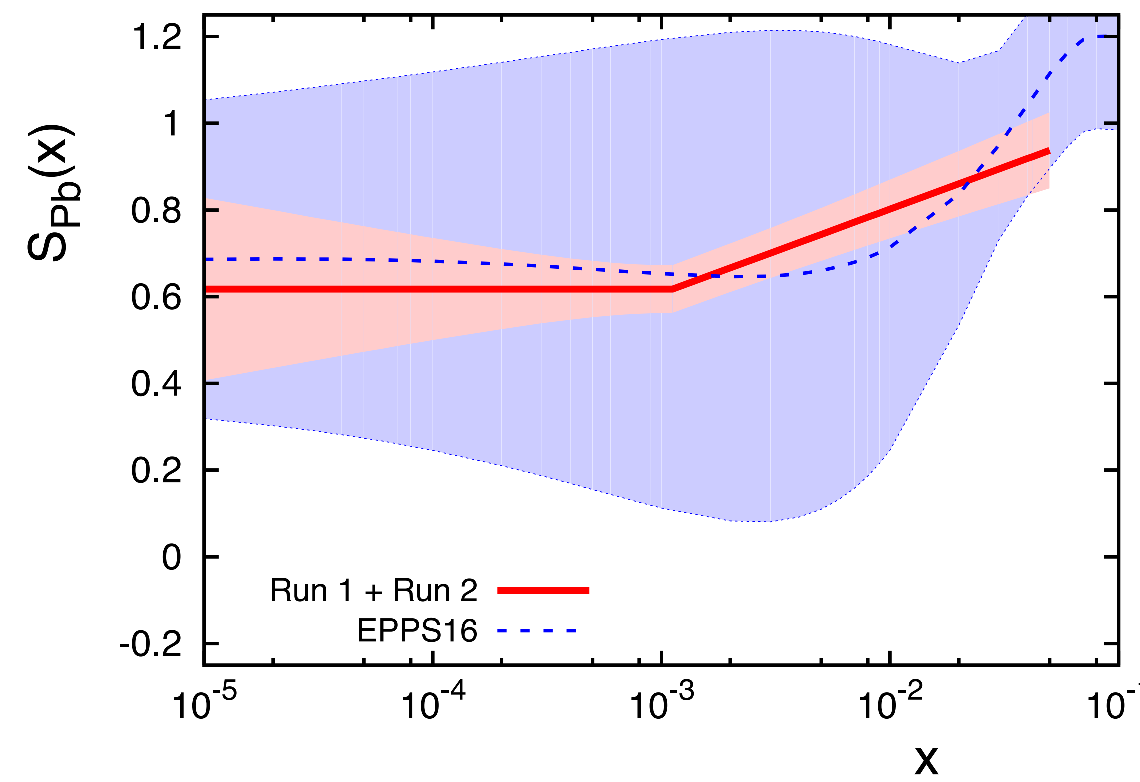
= $g_A(x, \mu)/g_p(x, \mu)$

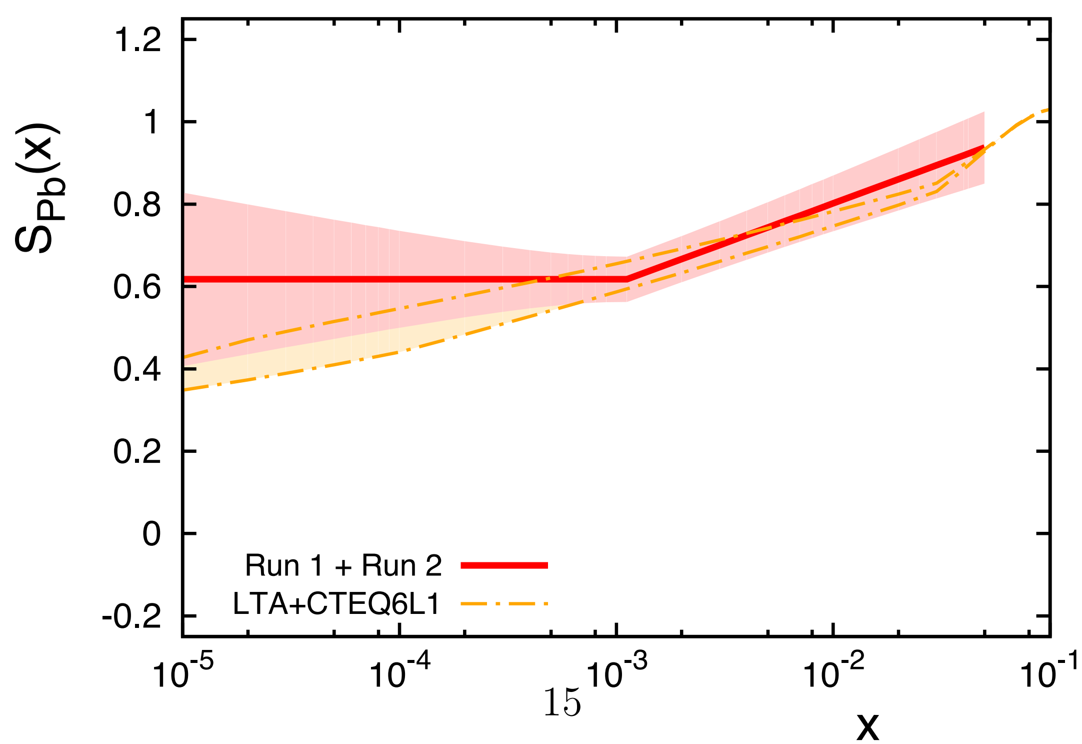
$$\left(\frac{d\sigma_{AA\to J/\psi AA}(\sqrt{s_{NN}}, y)/dy}{d\sigma^{\rm IA}_{AA\to J/\psi AA}(\sqrt{s_{NN}}, y)/dy}\right)^{1/2}$$

$$= \left(\frac{N_{\gamma/A}(W^+_{\gamma p})S^2_{Pb}(x_+)\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W^+_{\gamma p}) + N_{\gamma/A}(W^-_{\gamma p})S^2_{Pb}(x_-)\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W^-_{\gamma p})}{N_{\gamma/A}(W^+_{\gamma p})\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W^+_{\gamma p}) + N_{\gamma/A}(W^-_{\gamma p})\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W^-_{\gamma p})}\right)^{1/2}$$

$$\text{where } x_\pm = M^2_{J/\psi}/W^{\pm 2}_{\gamma p}$$

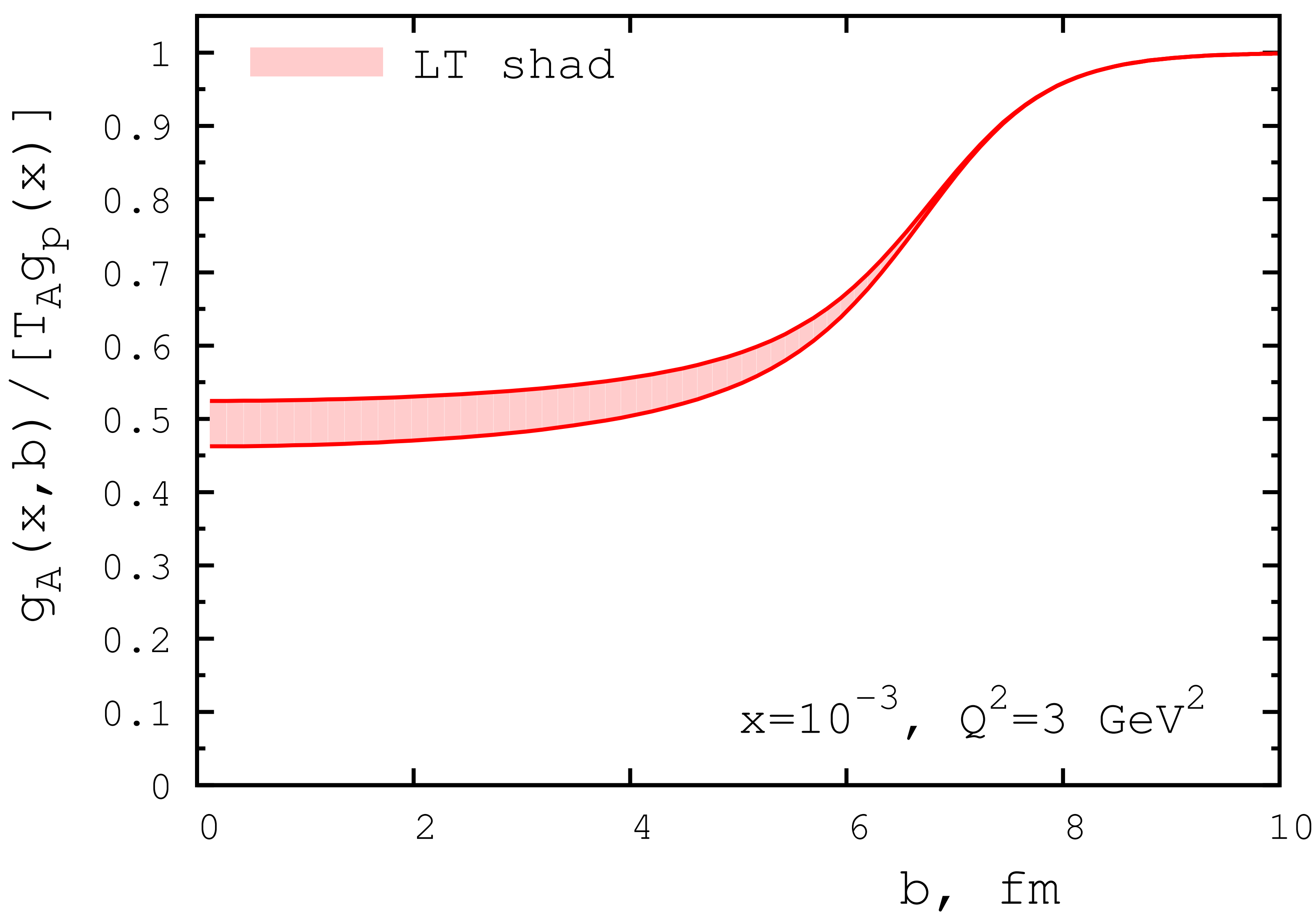




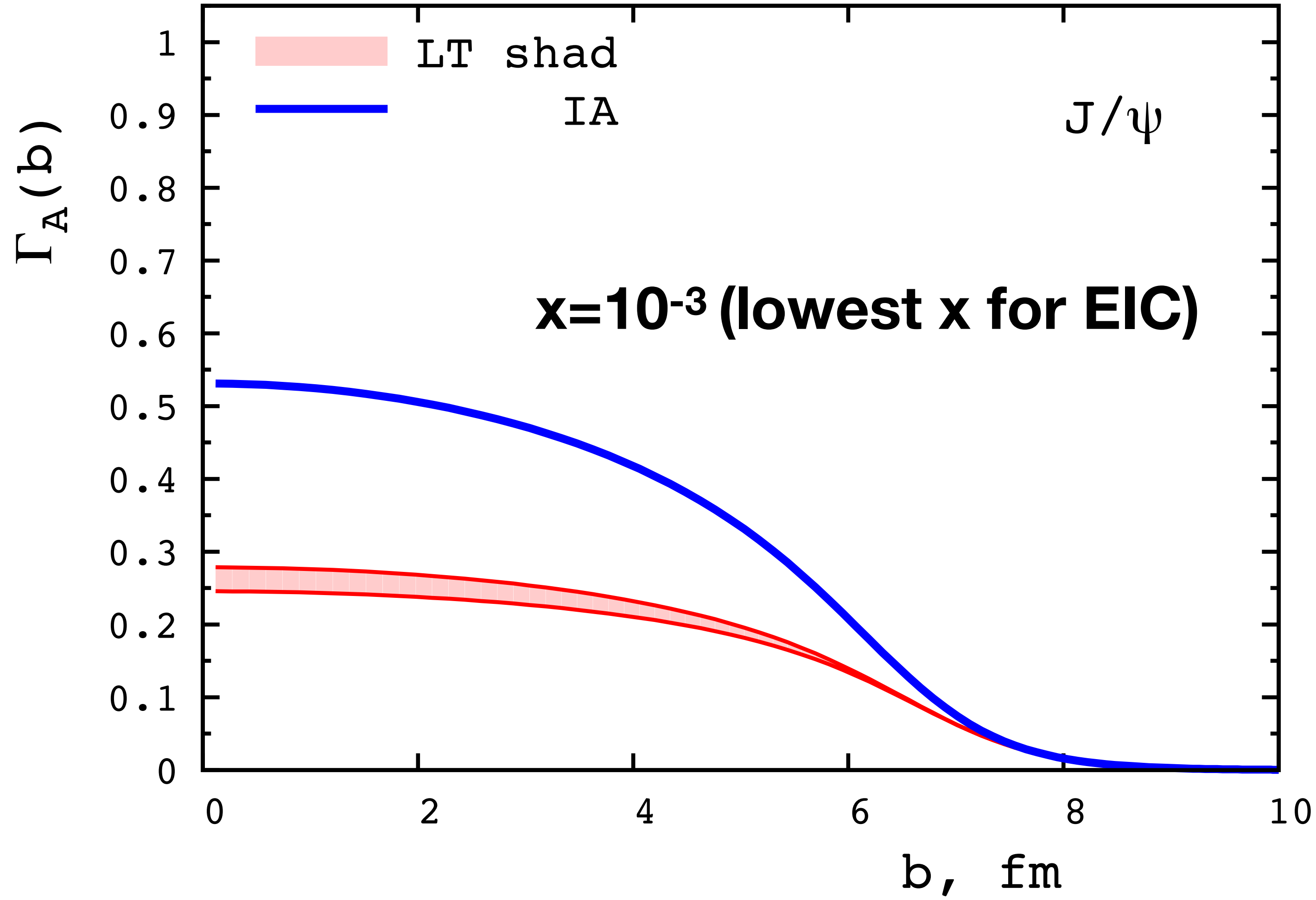


Our prediction for $x=10^{-4}$ is bit below the range. Necessary to figure out the reasons for discrepancy between LHCb and ALICE. & study impact parameter dependence of the J/ψ yield

we also predicted increase of t -dependence of coherent J/ψ production as compared to impulse approximation



Leading twist gluon shadowing in impact parameter space for coherent J/ψ photoproduction on Pb as a function of $|\vec{b}|$.



The scattering amplitude in impact parameter space $\Gamma_A(b)$ for coherent J/ψ photoproduction on Pb as a function of $|\vec{b}|$.

Gluon shadowing changes regime of interaction for $x \sim 10^{-3}$ and small b from close to black (probability to interact inelastically) $1-(1-\Gamma)^2 = 0.77$ to gray $1-(1-\Gamma)^2 = 0.45$

To reach the black limit $x \sim 10^{-5}$ is necessary

why heavy nucleus did not help significantly?

Where is $A^{1/3}$ factor?

nucleus is much more delta than proton + gluon shadowing

$$\frac{Q^2_{sA}}{Q^2_{sN}} = A\,\frac{R^2_{gN}}{R^2_A}\,\frac{g_A(x,Q^2)}{Ag_N(x,Q^2)}$$

$$R^2_{gN}(x=10^{-3}) = 0.6\,\mathrm{fm}^2$$

$$Q^2_{sA}(b=0)/Q^2_{sN} = T_A(b=0)\cdot S_A(x,b=0)\cdot 2R^2_{gN} = 1.2$$

A~200

Next step - study of other nuclear shadowing effects - testing value of $R_A(x, \mu) = g_A(x, \mu)/g_p(x, \mu)$ at small $x \sim 10^{-3}$

pushing to $x \sim 10^{-5}$ using neutron information

$\gamma + p\ (A) \rightarrow J/\psi(x_F < 0.8) + X$

$\gamma + p\ (A) \rightarrow$ leading dijet (charm) + X

$R_A(x=10^{-3}, \mu) \sim 0.6$ → average number of wounded nucleons $\nu = 1/R_A$

enhanced hadron production for $y_{UPC}=0$

neutrons in ZDC

Inelastic diffraction in γ +p (A)→ J/ψ (leading dijet) + gap + Y

Three regimes

- t=0 - color fluctuations in nucleons variance of

$$\sigma_{diff}/\sigma_{el} =$$ variance of gluon density at given x (color fluctuations)

Frankfurt et al

- $-t>0.3 \div 0.5$ GeV^2 elastic scattering of a small dipole of gluons & quarks

next slide

for smaller t this mechanism is suppressed by factor

$$R = 1 - \left(\frac{1}{1-t/M^2}\right)^4$$

M^2= 1 GeV^2

- 0.1 < $-t<0.3 \div 0.5$ GeV^2 interplay of these two mechanisms

Perturbative Pomeron: what is energy dependence cross section in vacuum channel ?

Problem for the study - two large parameters ln Q^2, and ln 1/x.

DIS - both parameters enter (DGLAP); BGKL - only ln 1/x (scattering of two small dipoles)

BFKL elastic amplitude $f(s)= (s/s_0)^{1+\omega}$

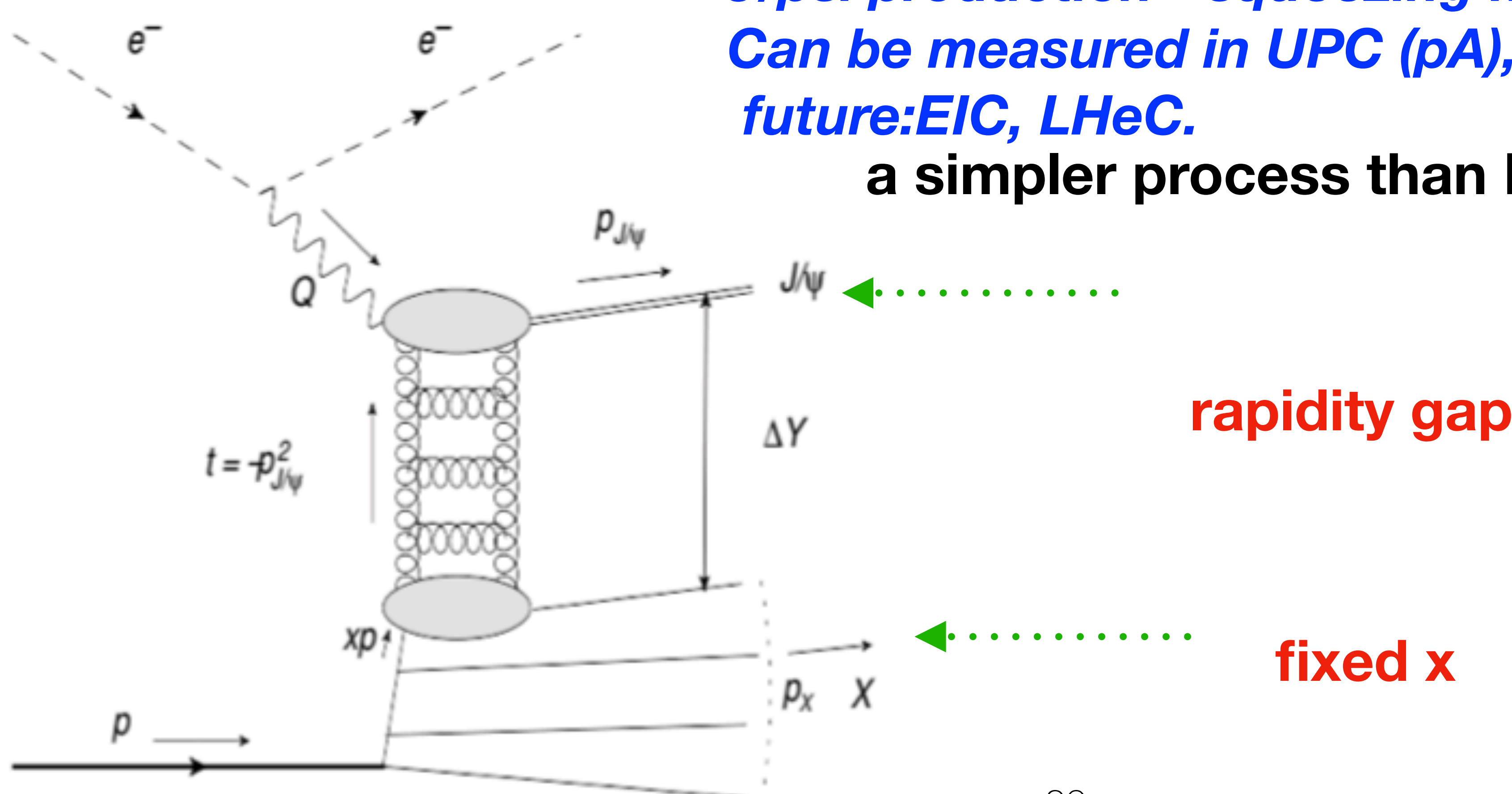
$$\omega_{/P} = a_1\alpha_S - a_2\alpha_S^2 + \dots$$

leading log $\omega_{/P}$ ~ 0.5 ÷ 0.8 , NLO ~ 0.1, resummation ~0.25

Main reason for small values of $\omega_{/P}$ - energy conservation

Promising direction: Rapidity gaps at large t for J/psi production - squeezing from both ends. Can be measured in UPC (pA), future:EIC, LHeC.

a simpler process than Mueller and Tung dijet



The choice of large t ensures several important simplifications:

✳ *the parton ladder mediating quasielastic scattering is attached to the projectile via two gluons*.

✳✳ *attachment of the ladder to two partons of the target is strongly suppressed*.

✳✳✳ *small transverse size* $d_{q\bar{q}} \propto 1/\sqrt{-t} \sim 0.15\text{fm for} J/\psi \text{ for } -t \sim m^2_{J/\psi}$

$$\frac{d\sigma_{\gamma+p\to V+X}}{dtd\tilde{x}} =$$

$$= \frac{d\sigma_{\gamma+quark\to V+quark}}{dt}\left[\frac{81}{16}g_p(x,t) + \sum_i (q^i_p(x,t) + \bar{q}^i_p(x,t))\right]$$

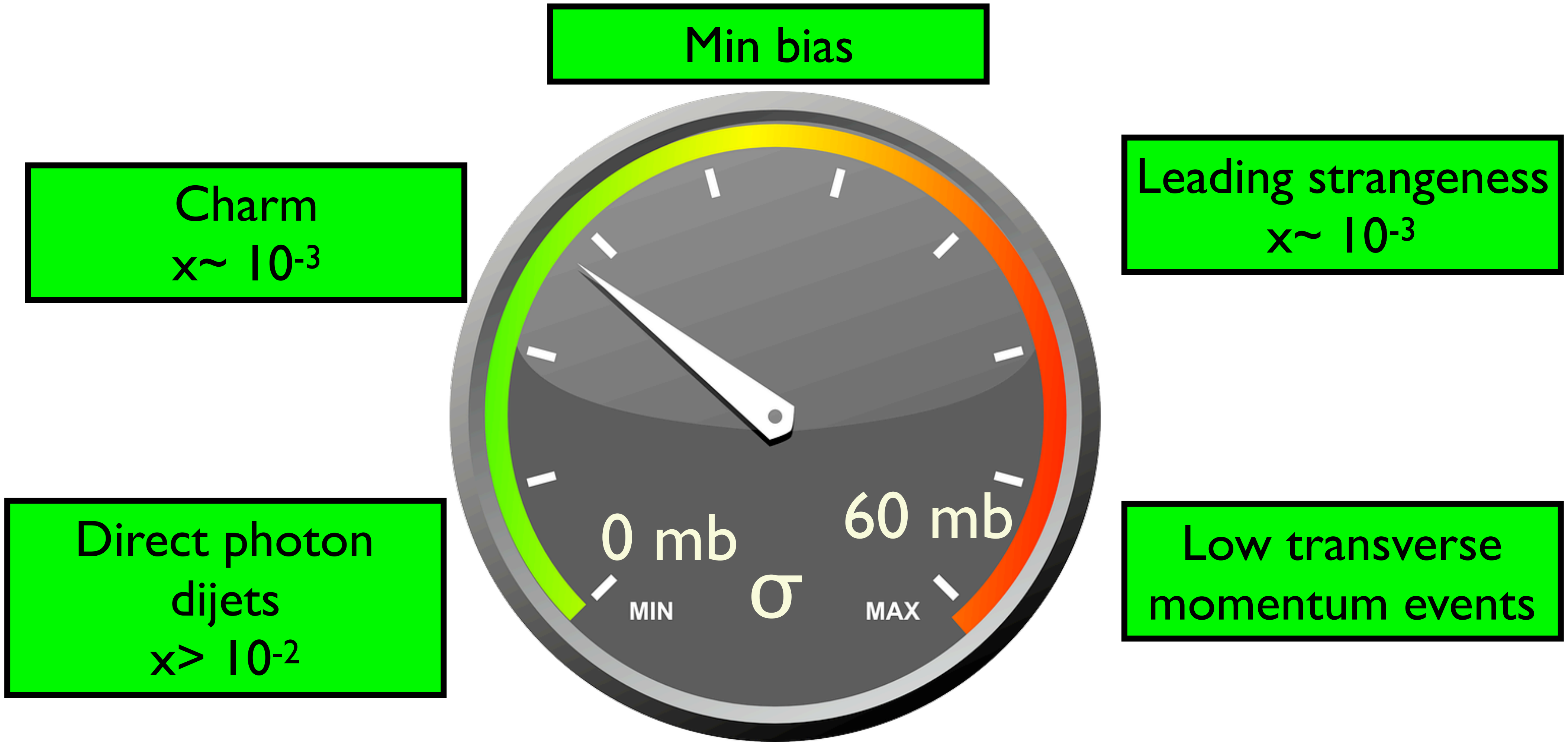
$\exp(2\omega_{I\!P}\, \Delta Y)$

resummation predicts a huge effect - between ΔY =2 and ΔY =4 σ is expected to increase by a factor of 3 !!!

Δ Y up to 4 maybe possible at EIC, and Δ Y up to 8 at LHC in pA

Ultraperipheral collisions at LHC ($W_{\gamma N}$< 500 GeV)

Tuning strength of interaction of configurations in photon



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

Novel way to study dynamics of γ &γ interactions*

Conclusions

UPC already contributed in a unique way into studies of QCD eluding J/psi production at very small x and off nuclei.

Fresh look at directions of study of UPC is necessary reflecting new theoretical issues as well as new detector capabilities (acceptance, effective lumi) - 14 years from the Phys.Rep. UPC 2007 study (cited ~500 times, but not probably read at depth).

UPC - FORERUNNER OF EIC

Supplementary slides

Hard regime: $\gamma A \to$ jets + X

1) *Direct photon & $x_A > 0.01$, $\nu = 1$?* ν *- number of wounded nucleons*

Color charge propagation through matter.
Color exchanges ? ➠ nucleus excitations, ZDC & very forward detectors

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

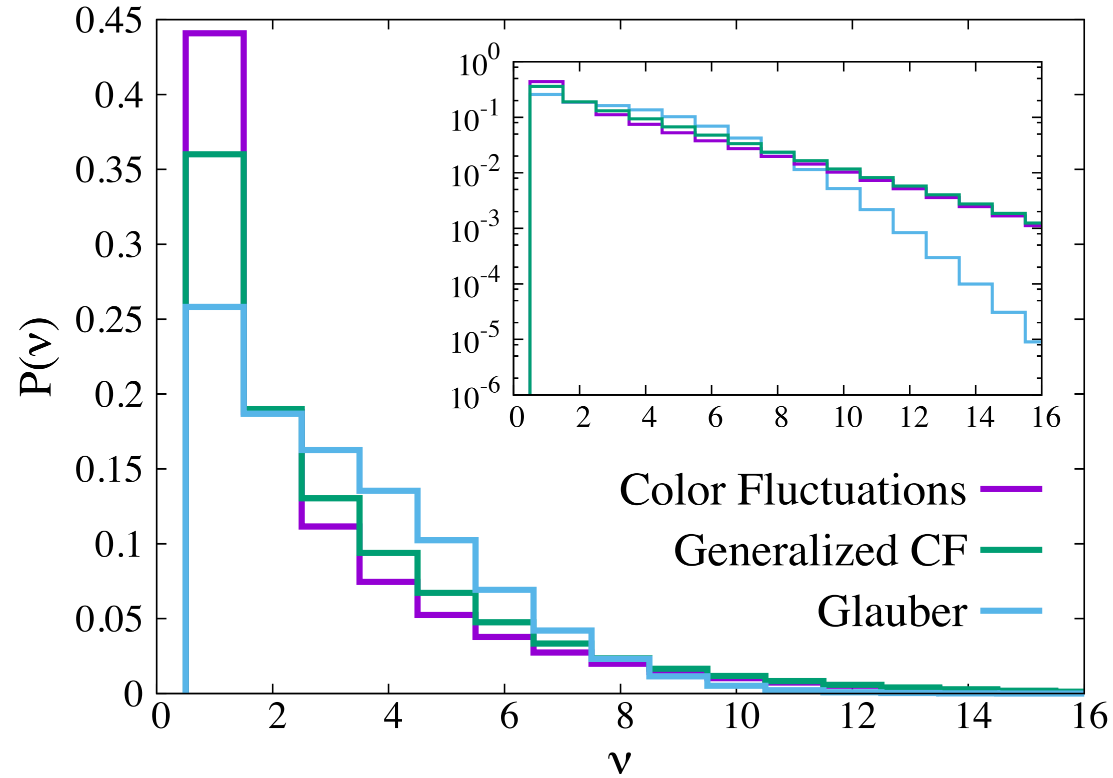
3) *Resolved photon - increase of ν with decrease of x_γ and x_A*

W dependence

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

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

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



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

Alvioli, Guzey, Zhalov, LF, MS

Phys.Lett. B767 (2017) 450-457

CFs 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.

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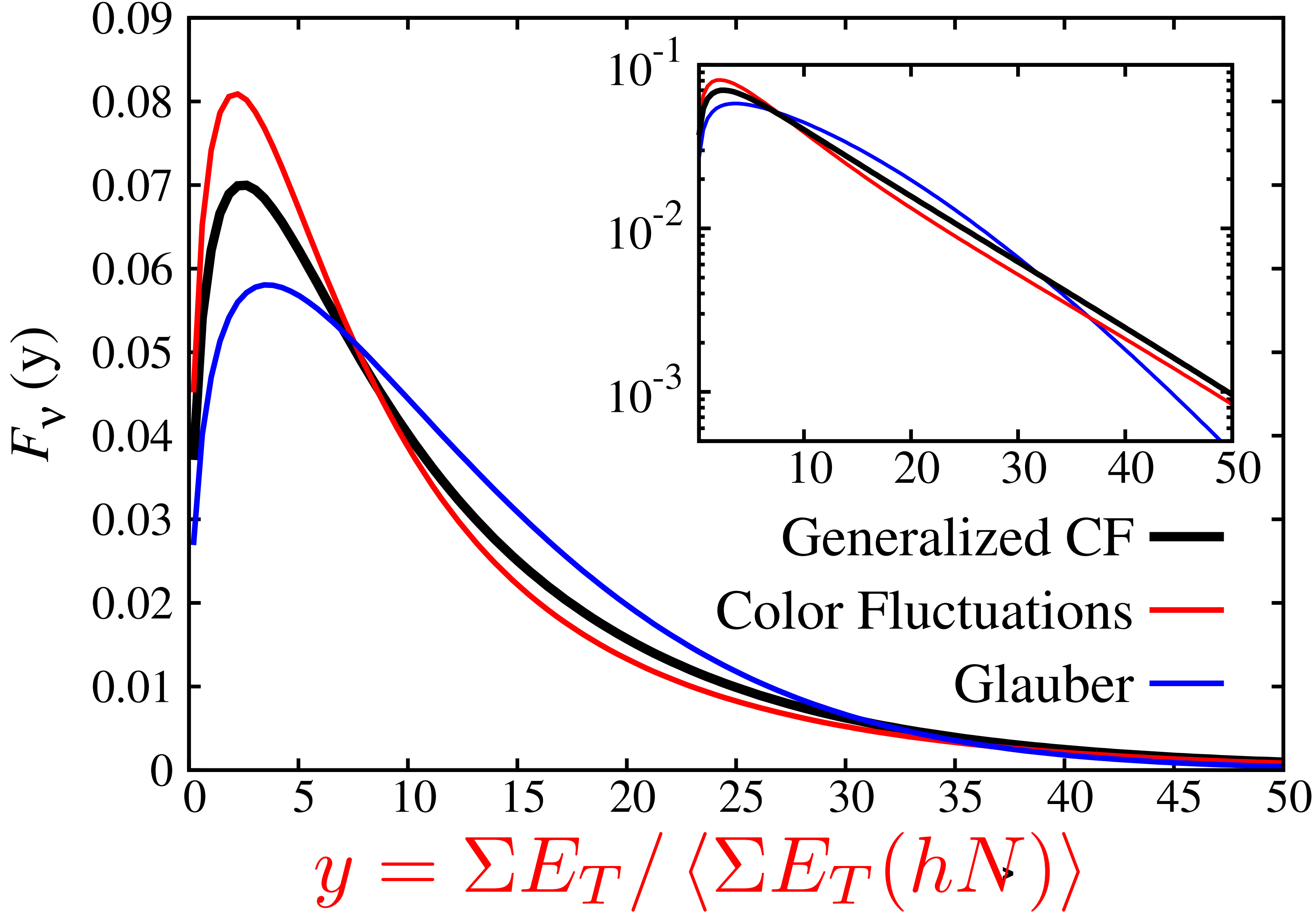

The probability distributions over the transverse energy in the Generalized Color Fluctuations (GCF) model assuming distribution over E_T is the same for pA and γA collisions for same ν.

Using forward detector for centrality via measurement of "y" advantageous: larger rapidity interval - smaller kinematical/ energy conservation correlations. For using ΣE_T for centrality determination one needs $\Delta y > 4$.