Neutron production in the acceptance of ZDC as a probe of the dynamics of hard gamma A interactions

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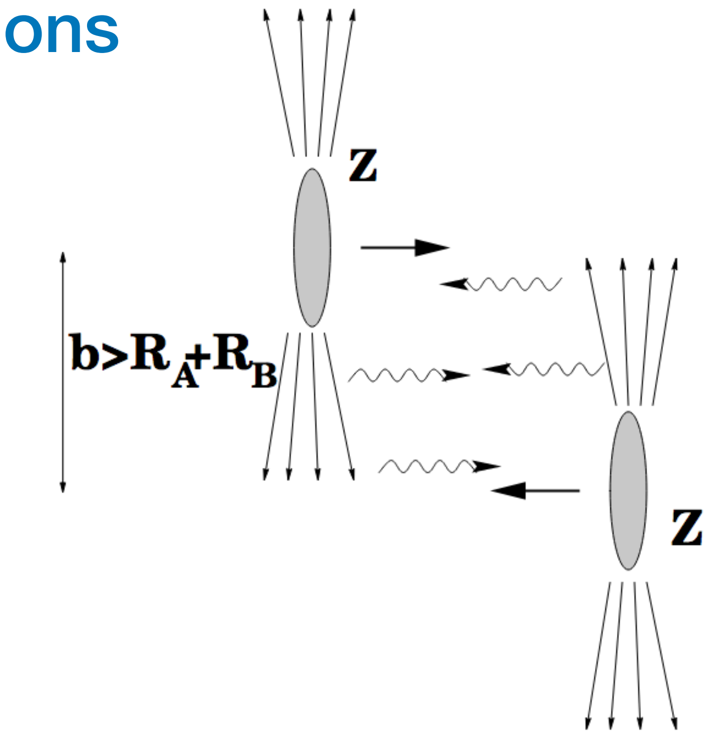
based on papers with L. Frankfurt, V,Guzey, M.Zhalov, E.Krushin, A.Larionov

MPI12, Lisbon,, 2021

Next 10 -15 years - the only reasonably direct way to probe small x domain for moderate virtualities is via 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//ψ), $x=10^{-3}$ was reached - much smaller x in the near future

UPC

allows to reach to a factor 10 — 100 smaller x

EIC

Much higher effective Lumi

Cleaner environment

LHC problem - lack of instrumentation in the proton/ nucleus fragmentation region. But for many processes one can use ZDC - zero degree calorimeter to detect practically all neutrons from decay of the nucleus

Few examples

- **Hard diffraction - J/ψ meson production**

  exclusive production: $\gamma + p\ (A) \to J/\psi + p\ (A)$

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

  most popular now

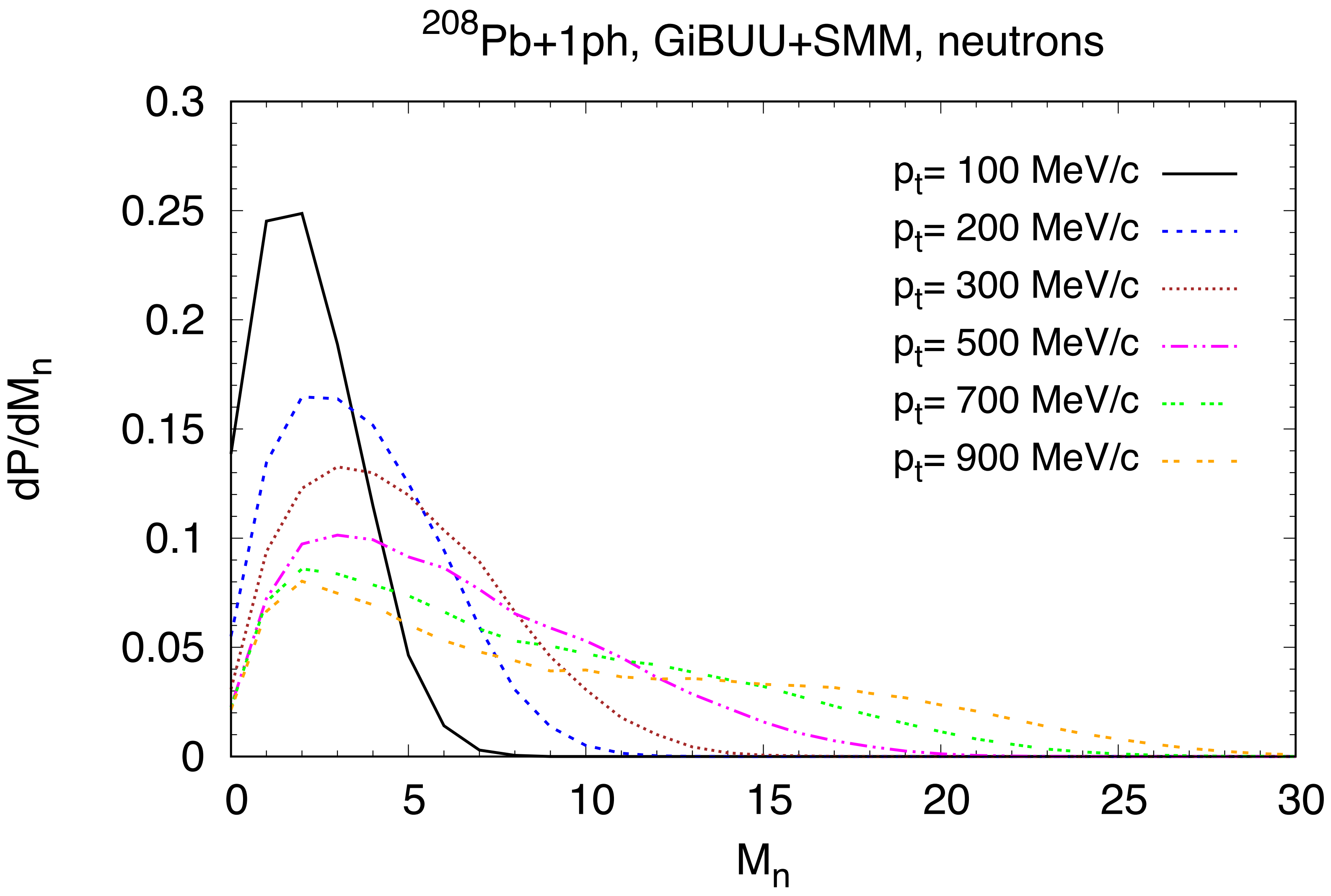
- **quasielastic** **$\gamma + p\ (A) \to J/\psi + Y$ at $t=0$**

Issues: *color fluctuations in nucleons and nuclei; gluon shadowing*

- **$\gamma + p\ (A) \to J/\psi(\text{large } t)$ + rapidity gap + Y**

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

Larionov and MS (Phys.Rev.C 101 (2020)) - extended transport model GiBUU to include emission of neutrons



$$\gamma + Pb \rightarrow J/\psi(p_T) + M\ neutrons + A^*$$

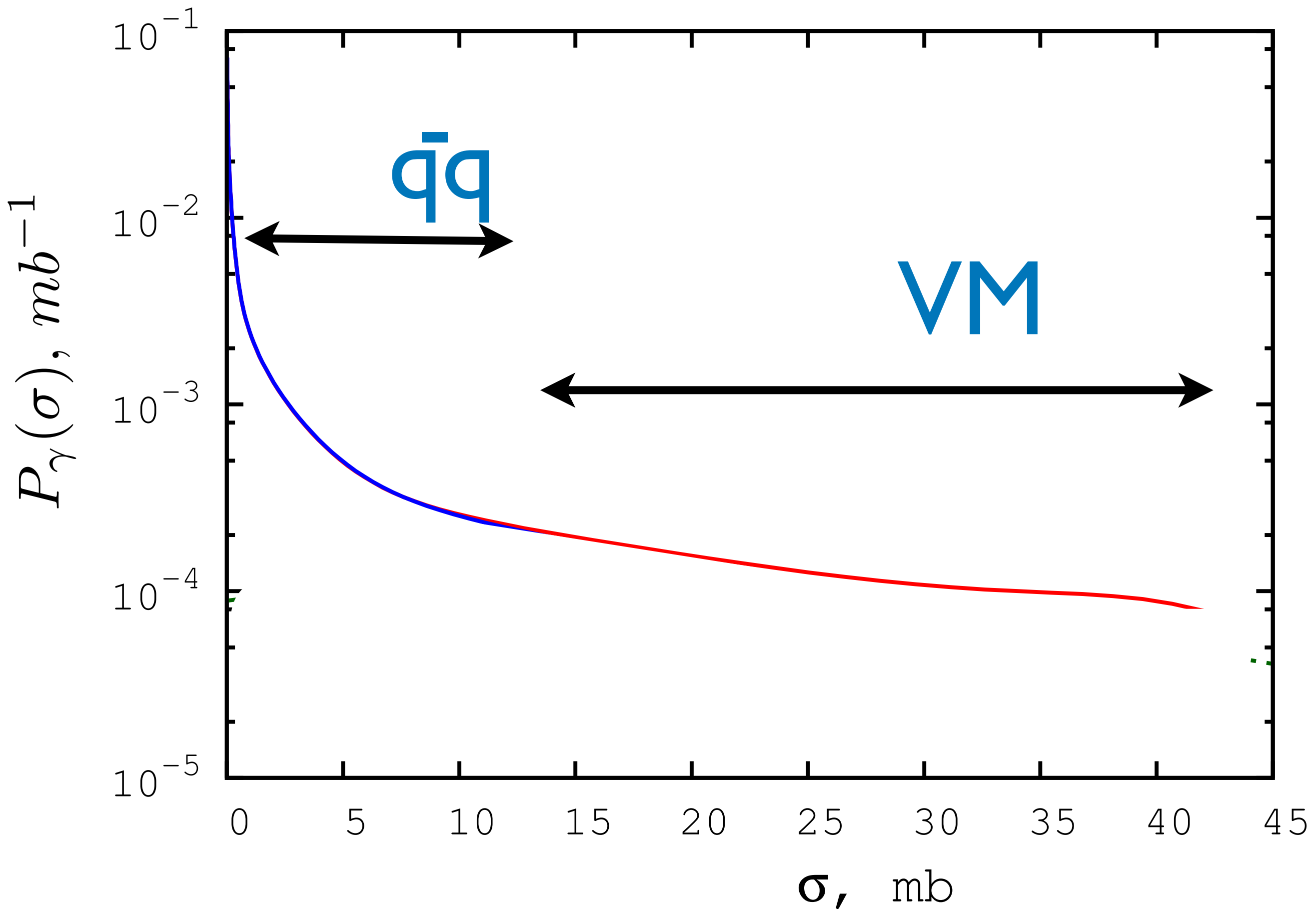
Parton structure of photon - Color fluctuations in γA collisions

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

MOST POPULAR UPC REACTION IS

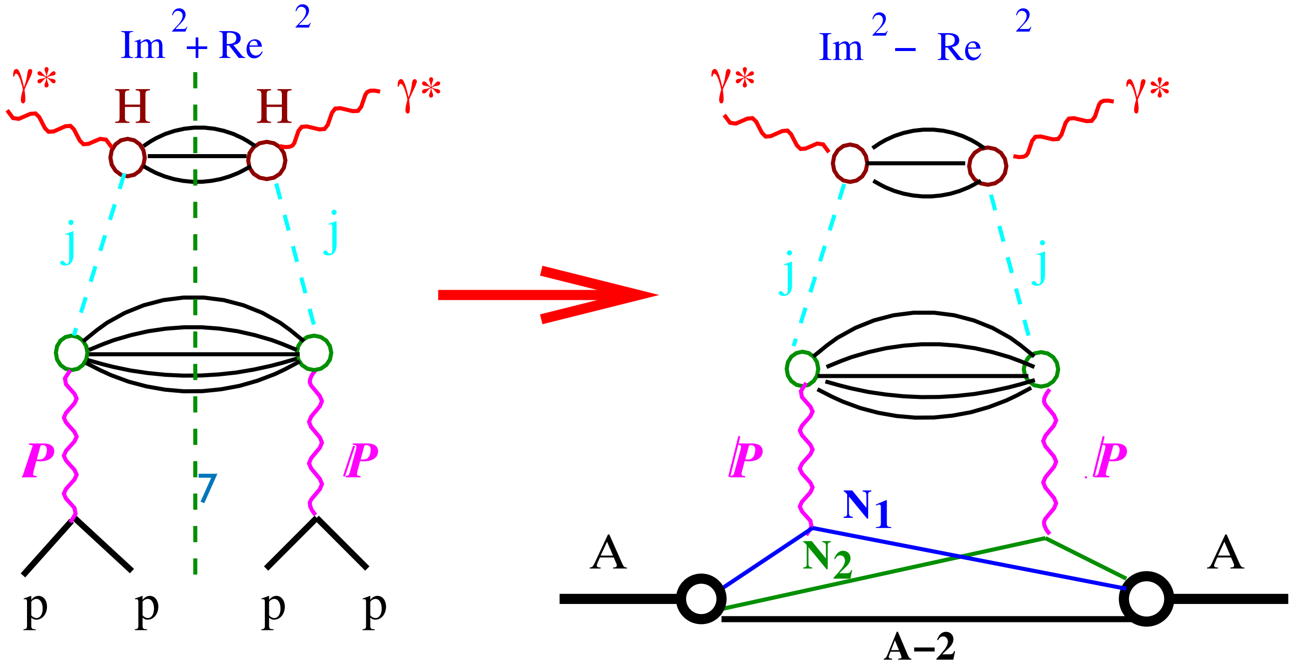
$\gamma + A \rightarrow J/\psi + A$

MEASURES GLUON SHADOWING AT SMALL X

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 $f_j(x,Q^2)$

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

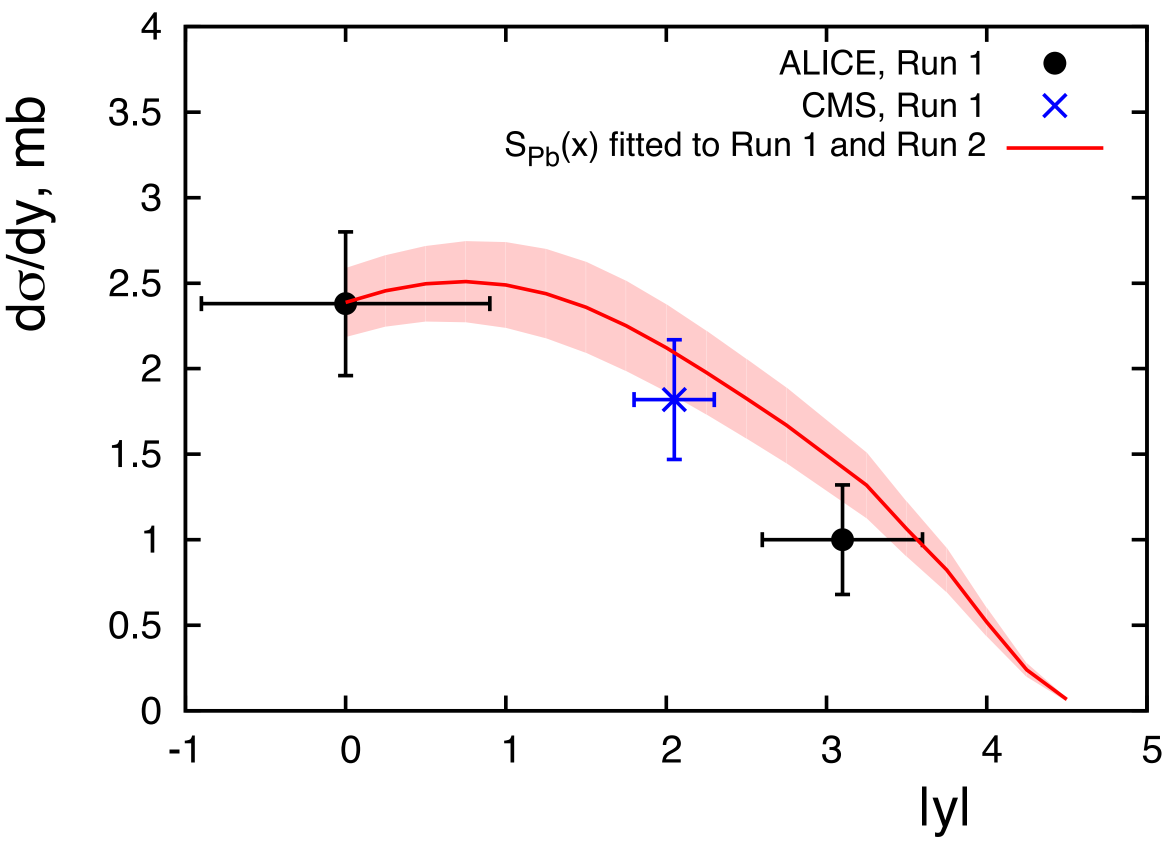
Predicted correctly shadowing for J/ψ in UPS. Use new LHC data to go below y=0, $x=m_{J/\psi}/2E_N$

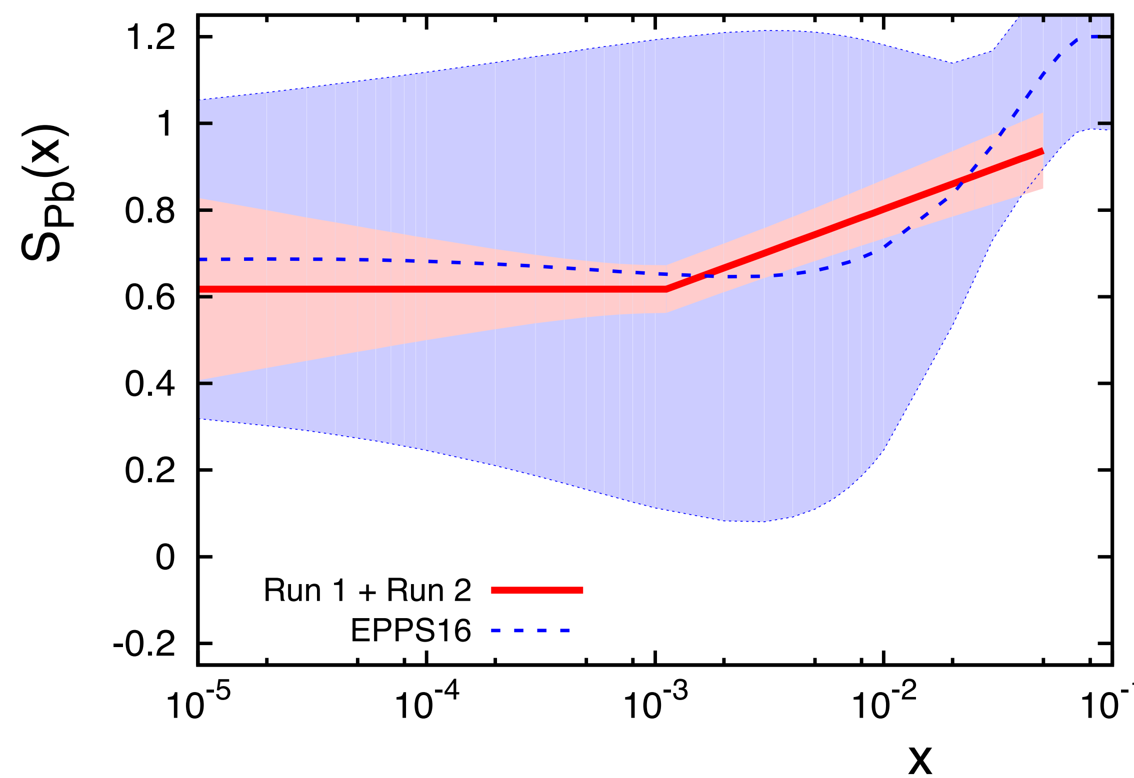
$$S_{Pb}(x) = \sqrt{\frac{\sigma_{\gamma A\to J/\psi A}(W_{\gamma p})}{\sigma^{\rm IA}_{\gamma A\to J/\psi A}(W_{\gamma p})}} \quad = g_A(x,\mu)/g_p(x,\mu)$$

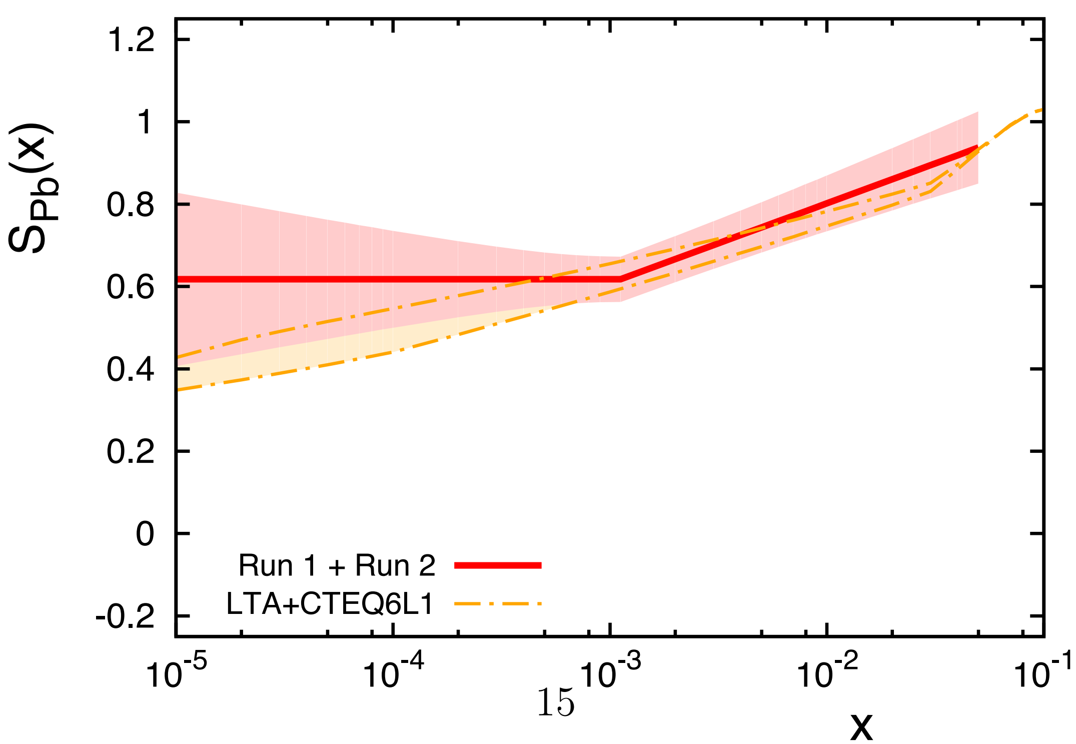
$$\left(\frac{d\sigma_{AA\to J/\psi AA}(\sqrt{s_{NN}},y)/dy}{d\sigma^{\rm IA}_{AA\to J/\psi AA}(\sqrt{s_{NN}},y)/dy}\right)^{1/2}$$

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

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

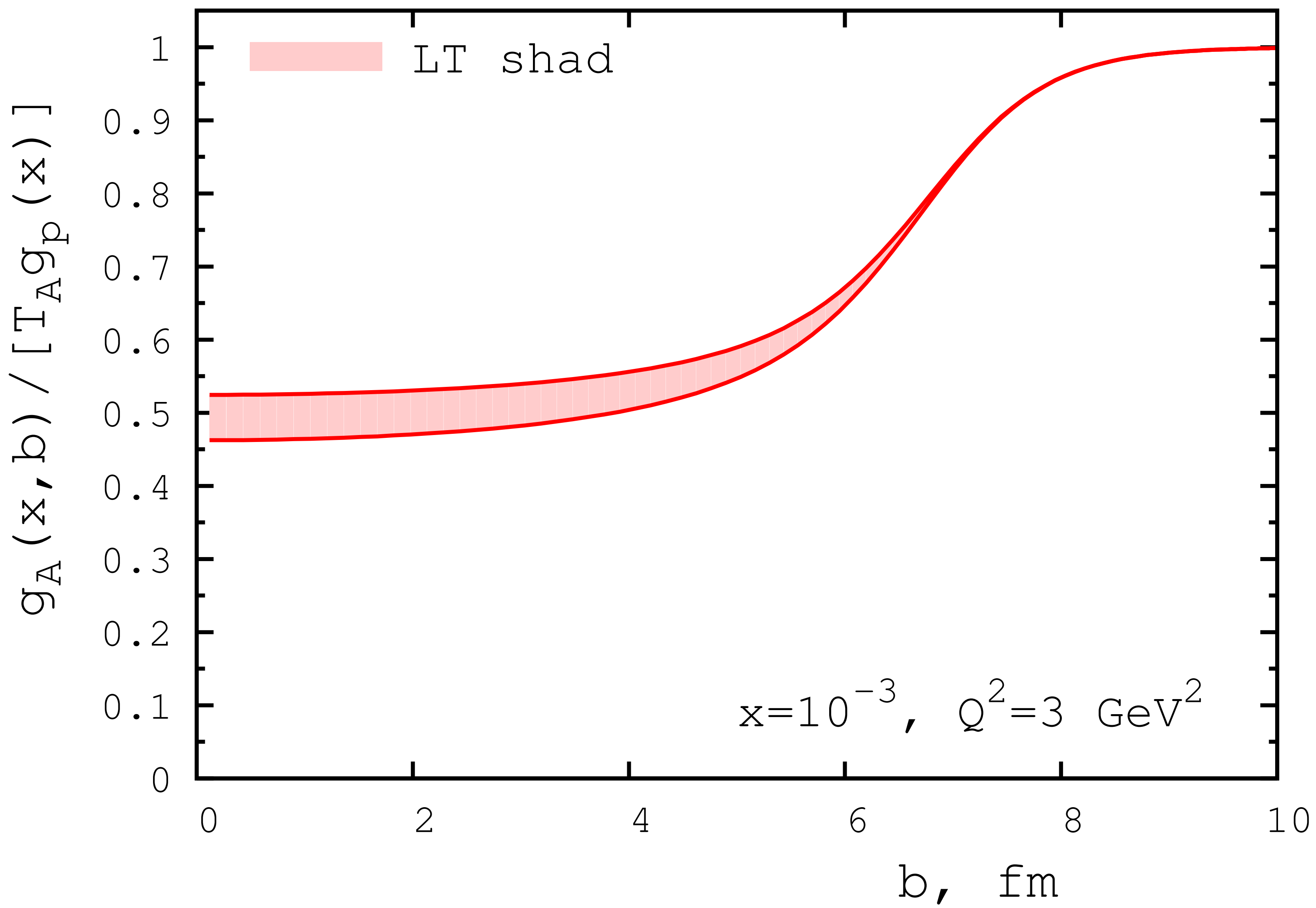




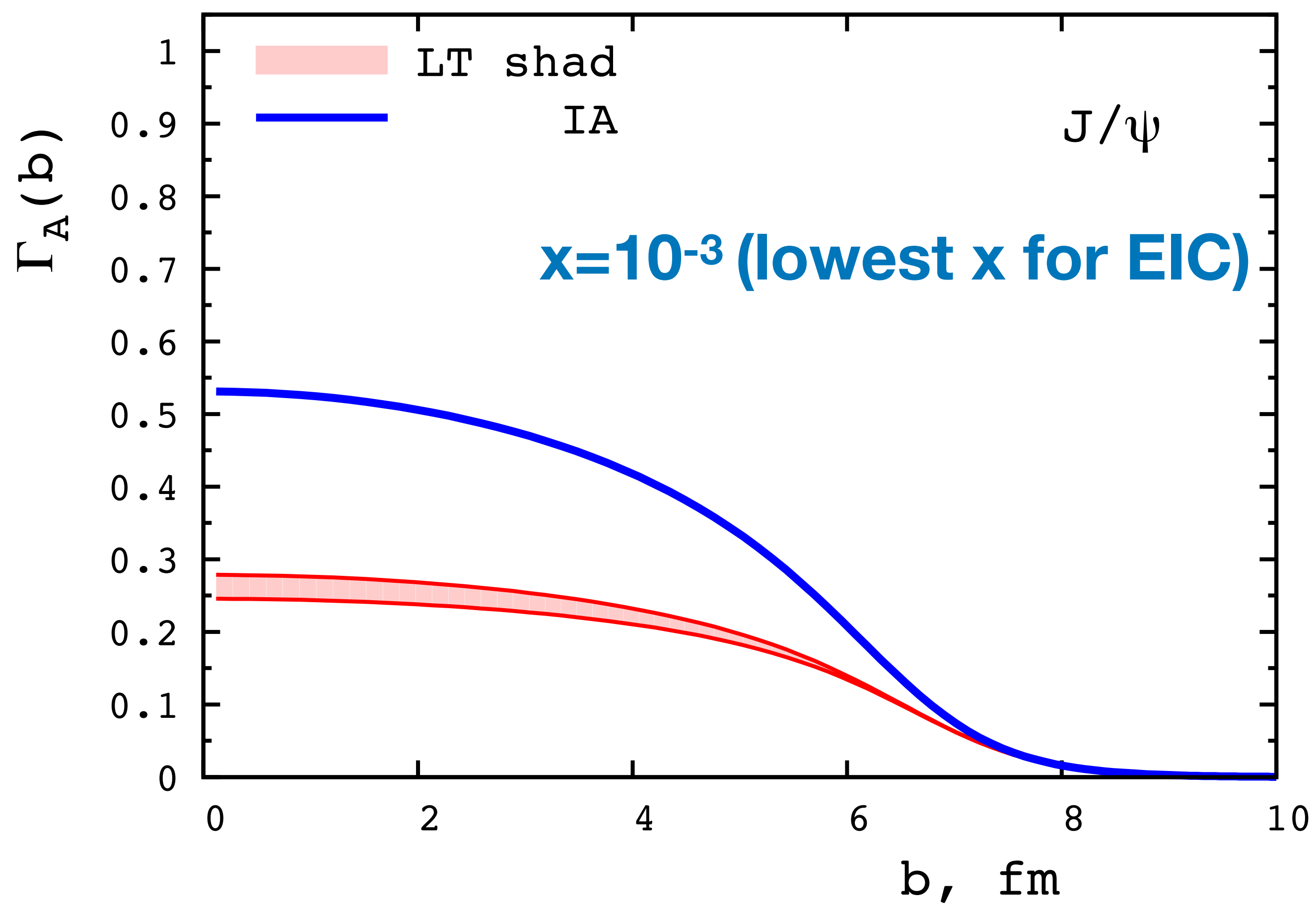


Our prediction for $x=10^{-4}$ is bit below the range. Necessary to figure out the reasons for discrepancy between LHCb and ALICE & study impact parameter dependence of the J/ψ yield

we also correctly 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 $1-(1-\Gamma)^2= 0.45$

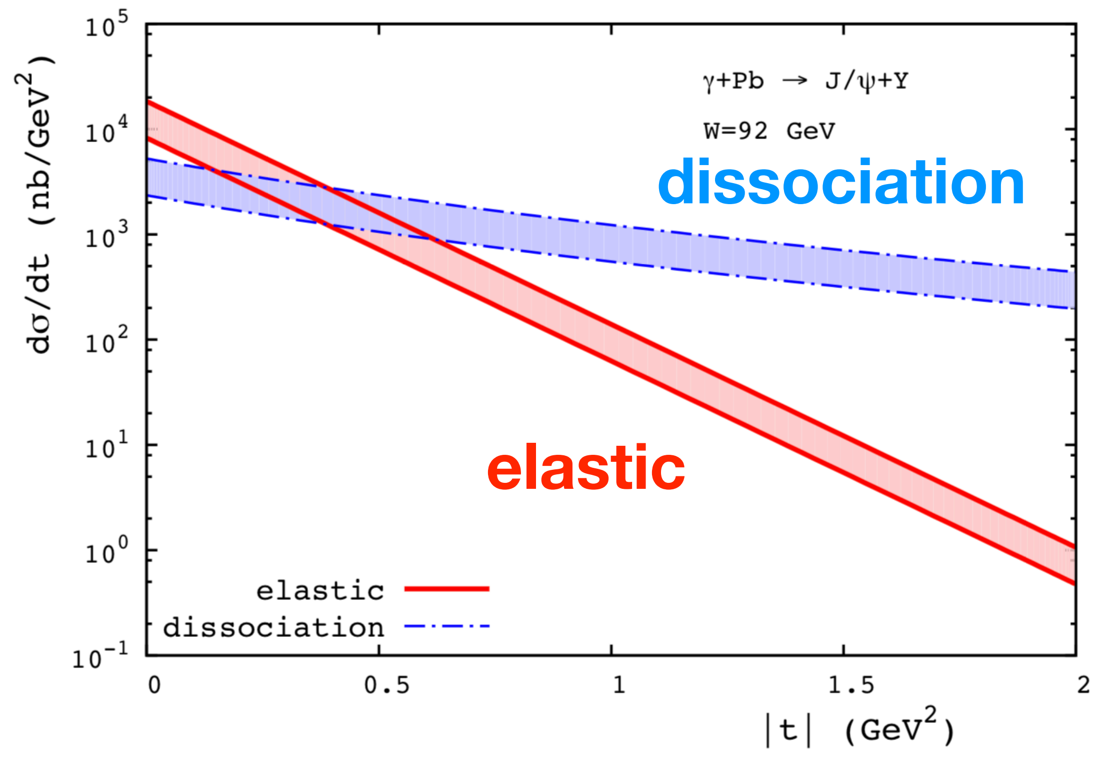
To reach the black disk limit $x\sim 10^{-5}$ is necessary

Neutron information is critical to separate low energy and high energy photon contributions and reach $x << 10^{-2}$

next steps:

- pushing to $x \sim 10^{-5}$ using neutron information
- shadowing for quasielastic and inelastic diffraction:: separating
  J/ψ +A* and J/ψ +Y + A* using ZDC information

critical tests of the theory of LT shadowing



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

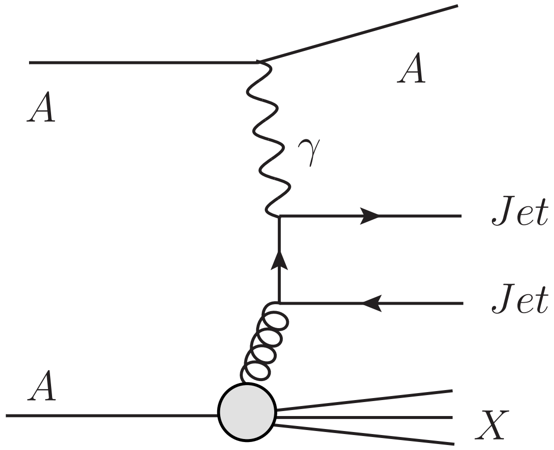
$\gamma + p\,(A) \rightarrow$ leading dijet (charm) + X

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

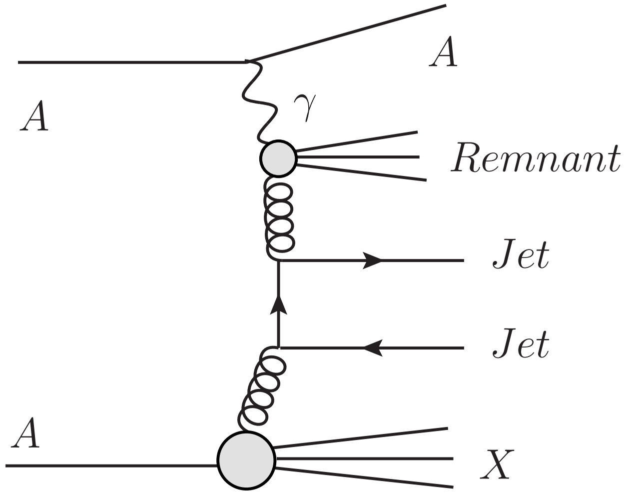
enhanced hadron production for $y_{UPC}=0$

more neutrons in ZDC

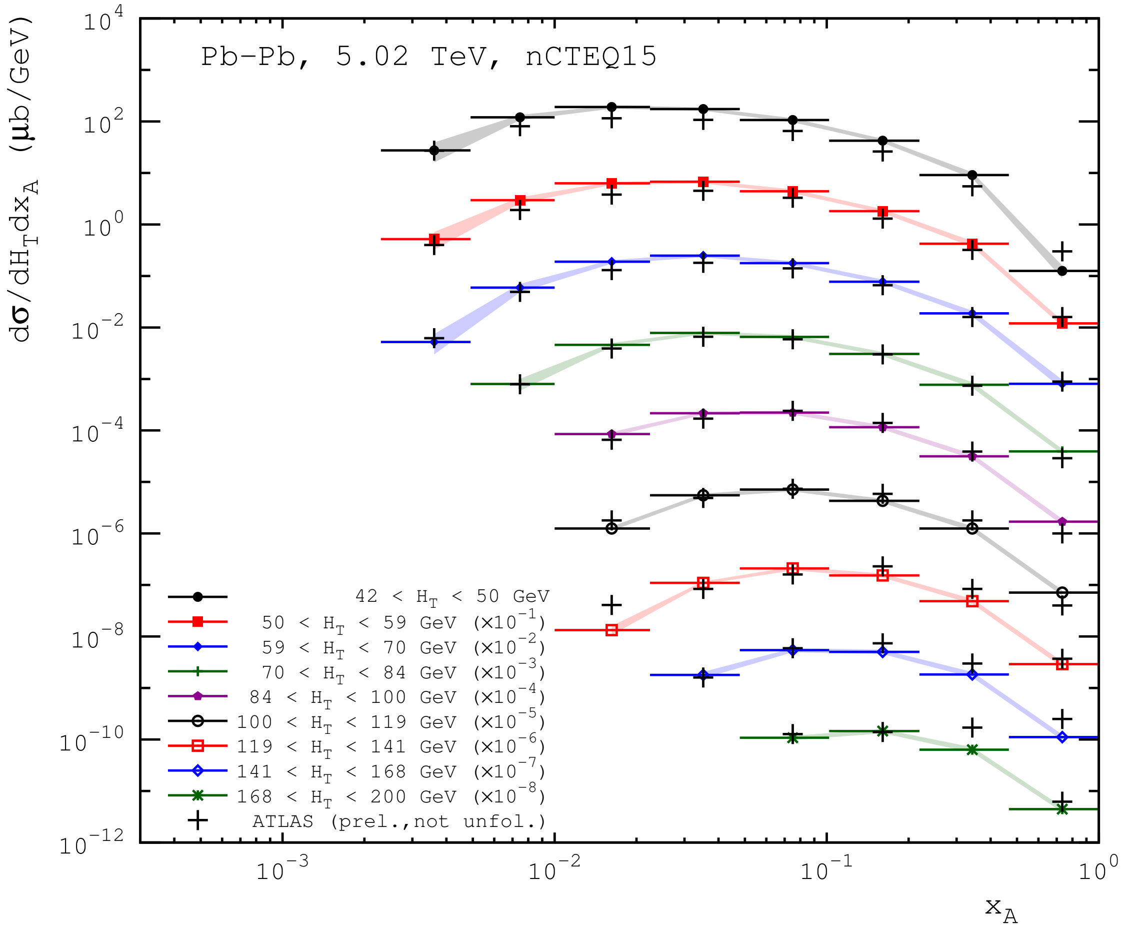
Other promising directions: Study of small x interactions for direct photon and transverse structure of resolved photon



direct



resolved



Guzey & Klasen 2021

NLO QCD results for the cross section of dijet photoproduction in Pb-Pb UPCs at W_{NN} = 5.02 TeV as a function of x_A for different bins of p_{T1}+ p_{T2}. The crosses are the ATLAS data points

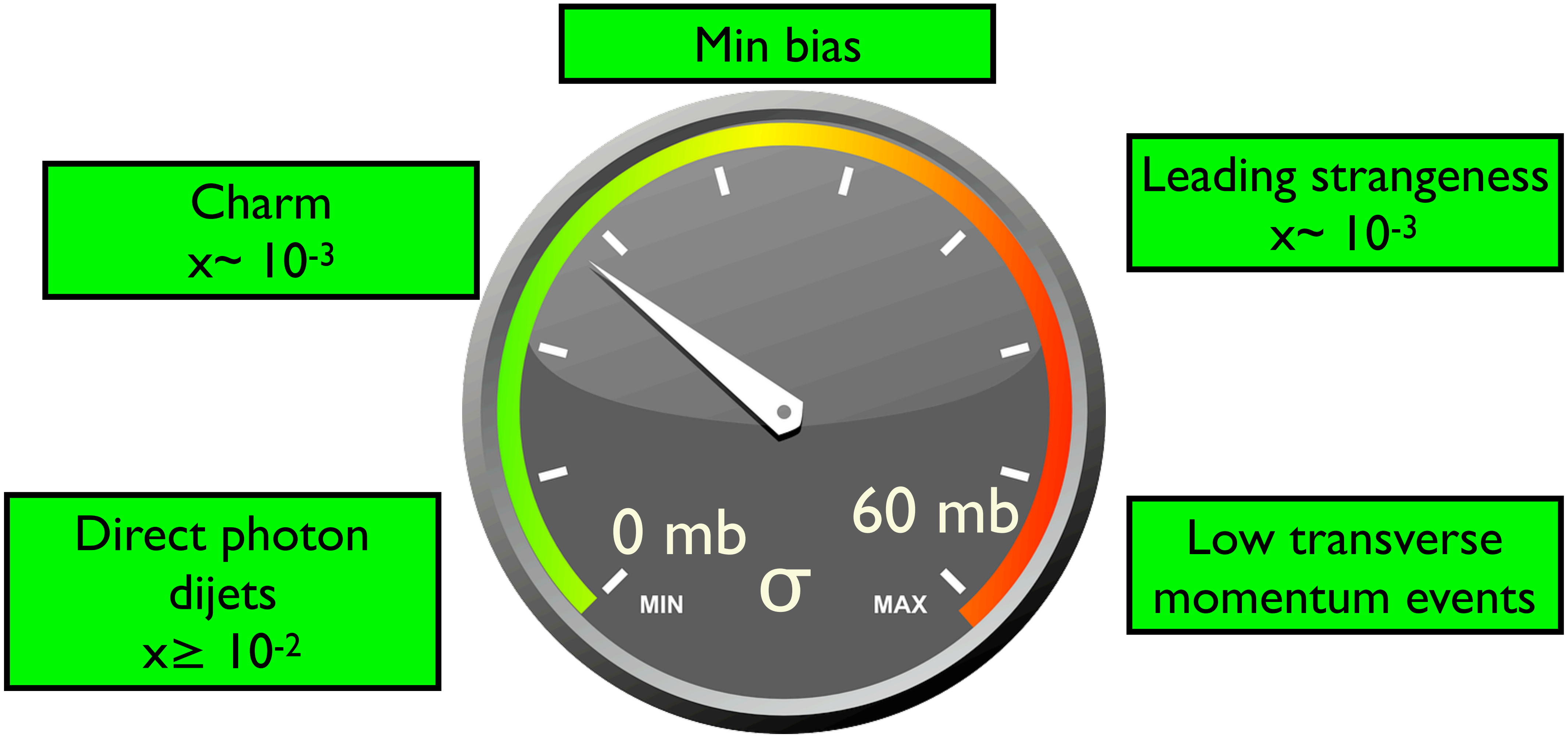
direct photons: Shadowing at x< 10^{-2} should result in an increase of the neutron yield in ZDC. Should be possible to observe at rather small p_T of jets.

Resolved photons: neutron yield should strongly depend on x_γ : *increase of* ν *with decrease of* x_γ *and* x_A

mapping of the transverse structure of photon.

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

allow to tune strength of interaction of configurations in photons and testing it among other options by detecting neutron production



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*

Supplementary slides

Space - time dynamics of parton interaction in the nucleus fragmentation region in DIS

Question: what is formation time of hadrons produced in the nucleus fragmentation region?

Puzzle in nuclear fragmentation: a factor > 2 fewer slow neutrons are produced in the DIS process

μ +Pb → μ + n +X **E665, 1995**

than according to cascade models

Zhalov, Tverskoi, MS 96 - confirmed by Larionov &MS 2019 and M.Baker group 2020

Option 1:Pythia not modeling well fragmentation of nucleons in DIS (not very likely such a gross effect)

Option 2: novel coherence effect - perhaps related to ability of DIS in which a small x parton is removed to break effectively a nucleon (no time to discuss).

Test in UPC (both LHC and RHIC) by looking at neutrons in ZDC

γPb → dijet (direct photon) + X+ neutrons in ZDC

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