

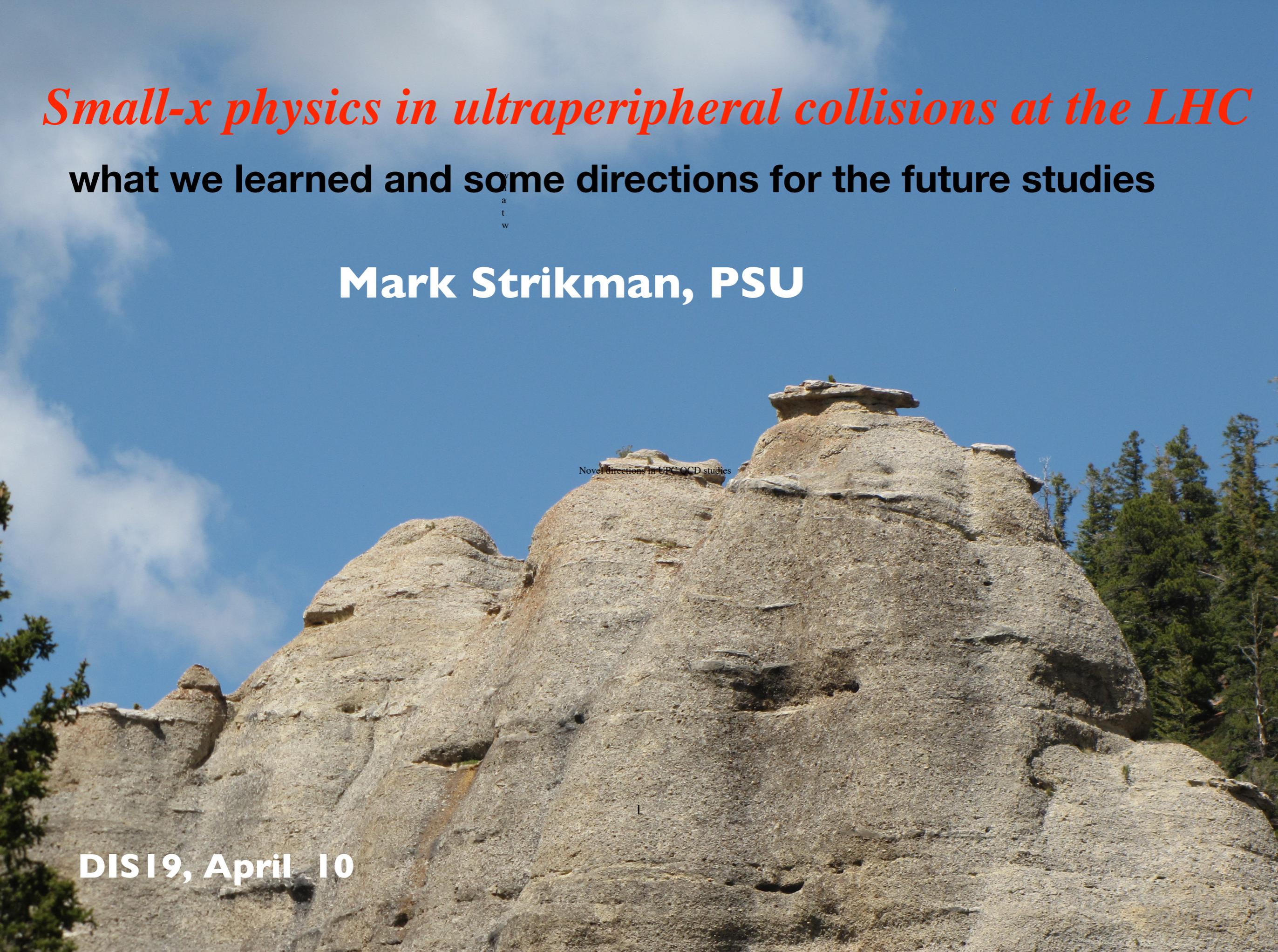
Small- x physics in ultraperipheral collisions at the LHC

what we learned and some directions for the future studies

Mark Strikman, PSU

Novel directions in UPC QCD studies

DIS19, April 10



Why ultraperipheral (UPC) - photon - nucleus & nucleon interactions are interesting:

Wide range of W in the same setting (Bonus for studying HE dynamics)

Forward physics at central rapidities - small x at smaller virtualities

Color fluctuations in photon - nucleus collisions

Photon is a multiscale state:

Presence in the photon of soft “vector meson like” and hard

$q\bar{q}, c\bar{c}$ components - relative contribution of soft and hard components

can be regulated by selecting different final states

will try to minimize overlap with three previous talks on UPC processes

UPC provided unique information about interaction of both small dipoles like and hadron like configurations with nuclei.

Roadmap of the talk:

Small dipoles interactions with several nucleons is much larger than in the eikonal approximation - leading twist nuclear shadowing for J/psi coherent scattering

Shadowing for hadron (ρ -meson) - nucleus interaction is much larger than in the Glauber model - expected in the Gribov picture of hA high energy interactions

Expectations of large color fluctuations (fluctuations of the strength of interaction) inelastic photon nucleus interactions

Inelastic diffraction - large t (rapidity gaps) & small t (gluon fluctuations)



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

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

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 $g_T(x,Q)$

Theory of the leading twist nuclear shadowing for pdfs is based on

AGK cutting rules

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

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

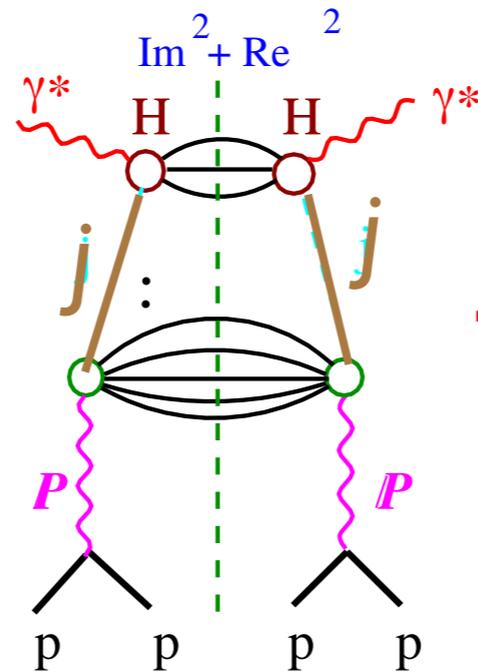
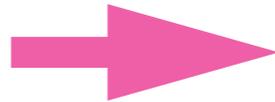
Collins factorization theorem

for hard diffractive processes

tested at HERA for $Q^2 > \text{few GeV}^2$ - *larger probability of diffraction for gluon induced diffraction*

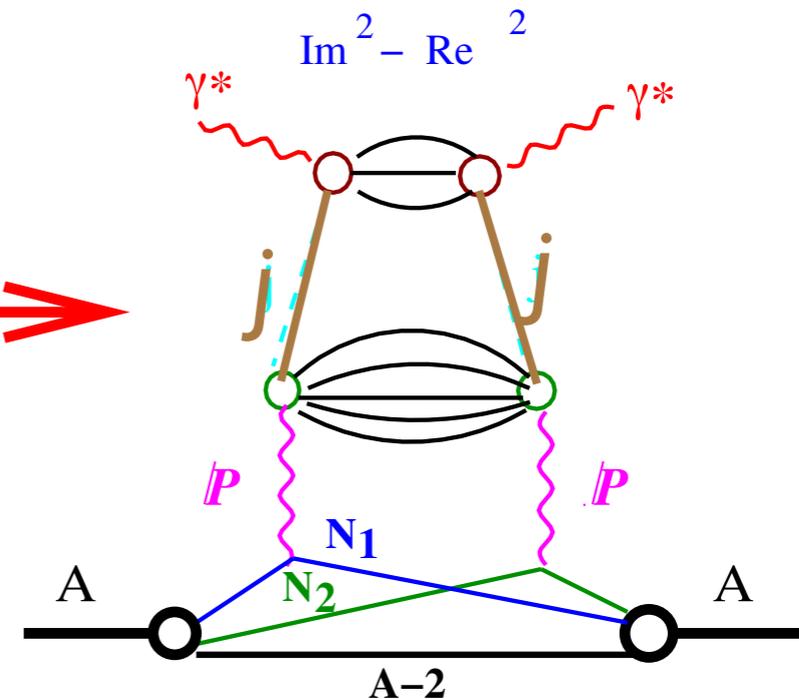
$$f_j^D\left(\frac{x}{x_{IP}}, Q^2, x_{IP}, t\right)$$

nucleon diffractive parton densities ($j=\bar{q},g$)



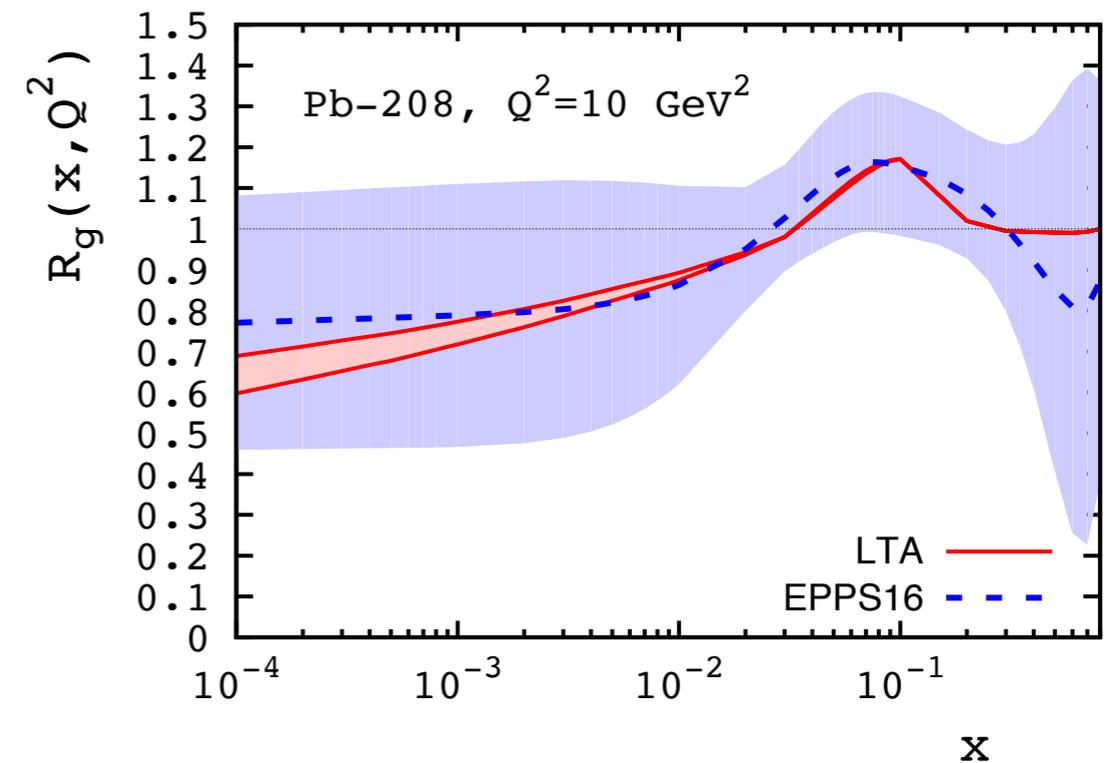
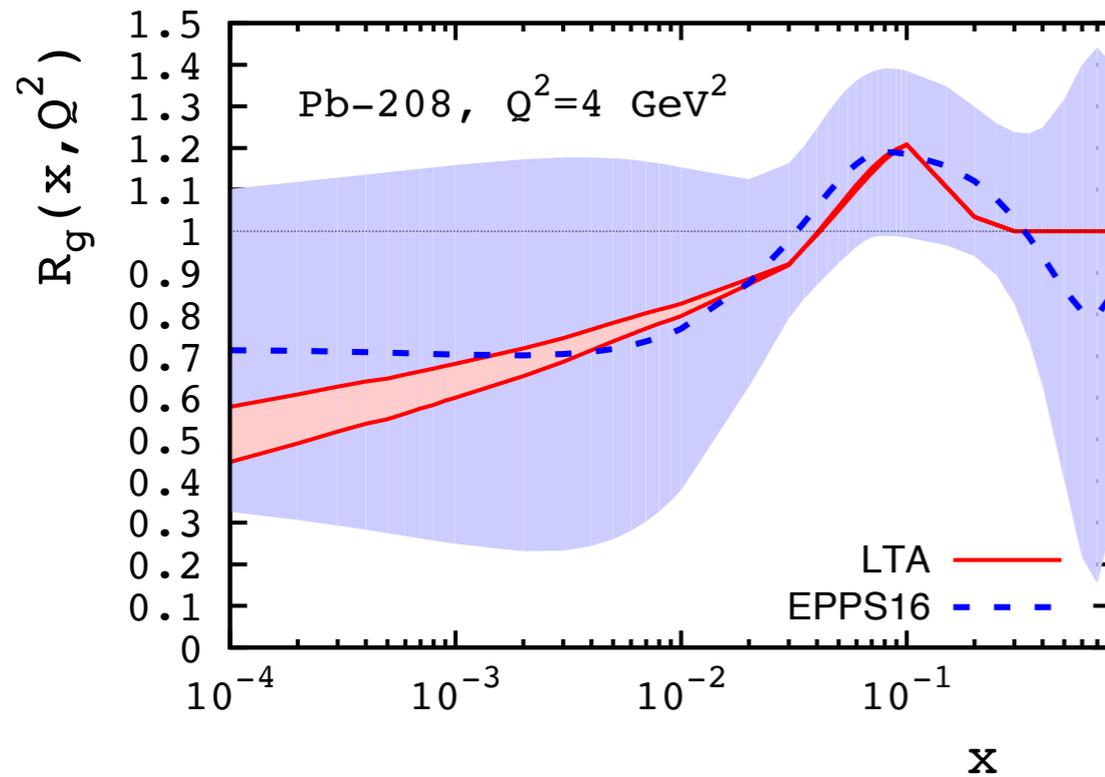
Hard diffraction

off parton "j"



Leading twist contribution

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



Comparison of predictions of FGS 10 and EPPS16 at $Q^2= 4, 10 \text{ GeV}^2$

EPPS16 includes dijet LHC pA data - since pt are large - shadowing is small and backward evolution is not stable

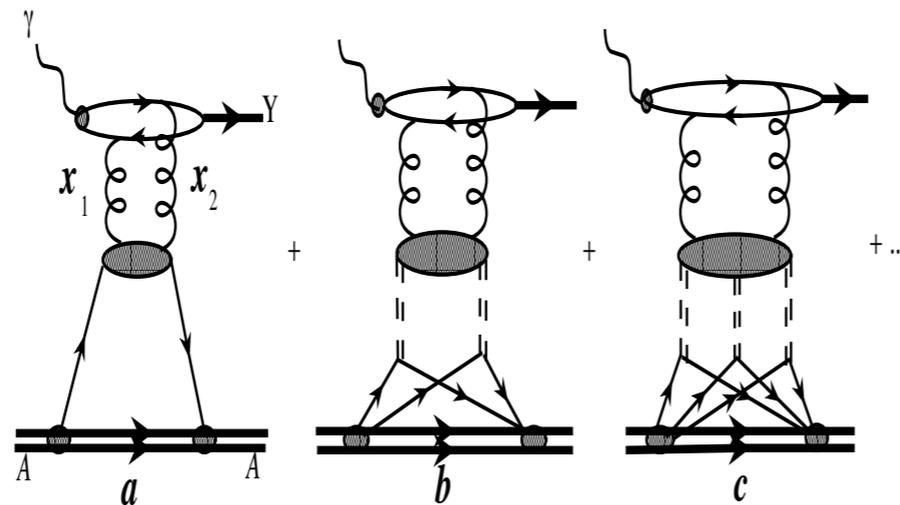
Exclusive vector meson production in DIS (onium in photoproduction)

–sensitive test of nuclear shadowing dynamics

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

$$\sigma_{\gamma A \rightarrow VA}(s) = \frac{d\sigma_{\gamma N \rightarrow VN}(s, t_{min})}{dt} \left[\frac{G_A(x_1, x_2, Q_{eff}^2, t=0)}{AG_N(x_1, x_2, Q_{eff}^2, t=0)} \right]^2 \int_{-\infty}^{t_{min}} dt \left| \int d^2b dz e^{i\vec{q}_t \cdot \vec{b}} e^{iq_1 z} \rho(\vec{b}, z) \right|^2.$$

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



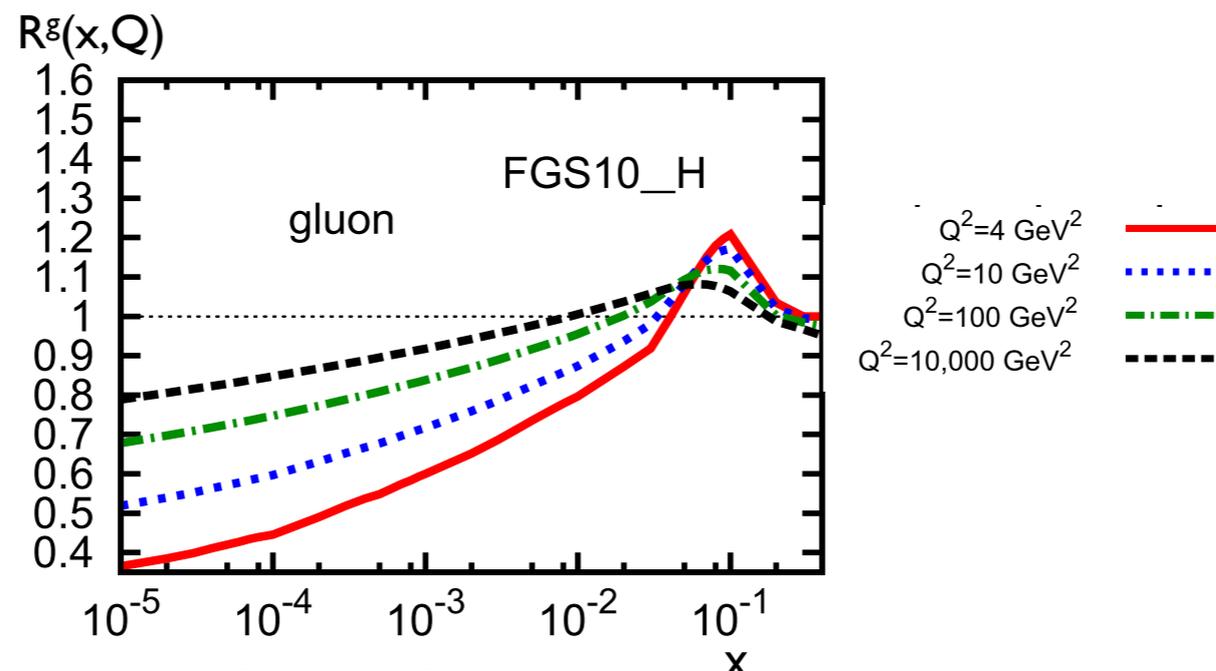
: High energy quarkonium photoproduction in the leading twist approximation.

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

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 d^2 factor (LT DGLAP evolution)



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

for small dipoles: $\sigma(\text{inel diffraction}) / \sigma(\text{elast.})$ at $t=0 \gg 1$

in soft physics: $\sigma(\text{inel diffraction}) / \sigma(\text{elast.})$ at $t=0 \ll 1$

Test: J/ψ-meson production: $\gamma+A \rightarrow J/\psi +A$

Small dipoles \Rightarrow QCD factorization theorem

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

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 $x_1=1.5 x$, & $x_2 = 0.5 \rightarrow (x_1 + x_2)/2 =x$

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

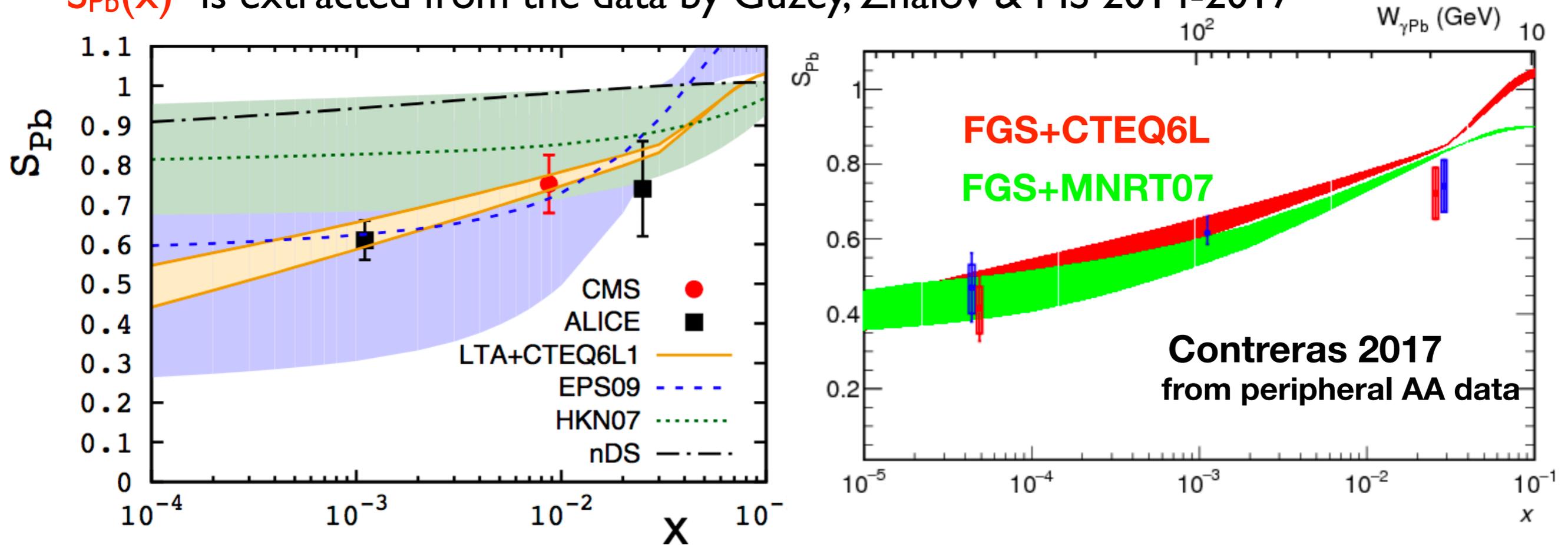
So non-diagonality effect is small for J/ψ case.

b) High energy factorization \rightarrow HT effects are large but mostly cancel in the ratio of nuclear and elementary cross sections at $t=0$. However NLO effects require further studies.

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

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

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



Large gluon shadowing consistent with the leading twist theory prediction of FGS2012. LHCb data consistent with ALICE and CMS data.

No other data significantly constrain $g_A(x \sim 10^{-3})$ at relevant Q^2 scale

$S = 0.6 - 0.4$ strongly reduces difference between proton and nuclear GPDs at small impact parameters b .

Testing the dynamics of interaction with nuclei for large configurations

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

Expectations:

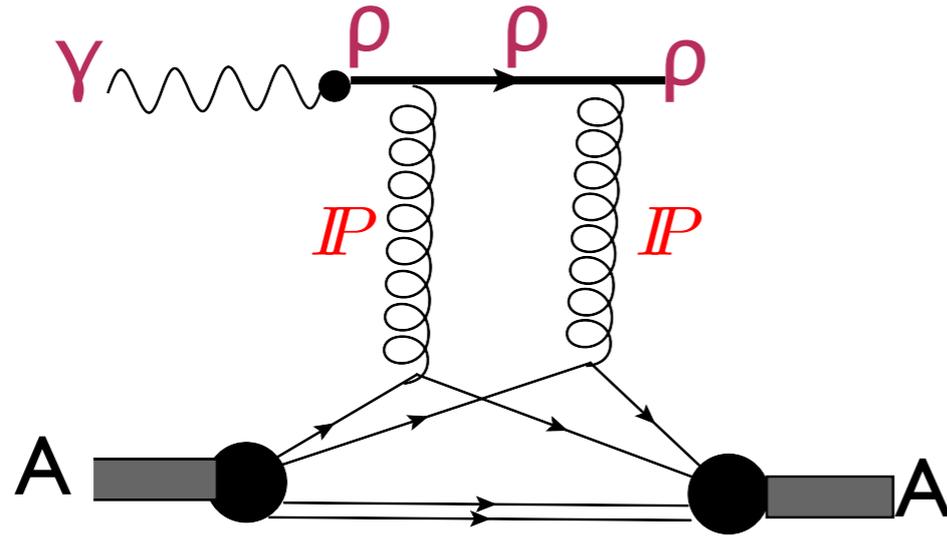
❖ *vector dominance model for scattering off proton*

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

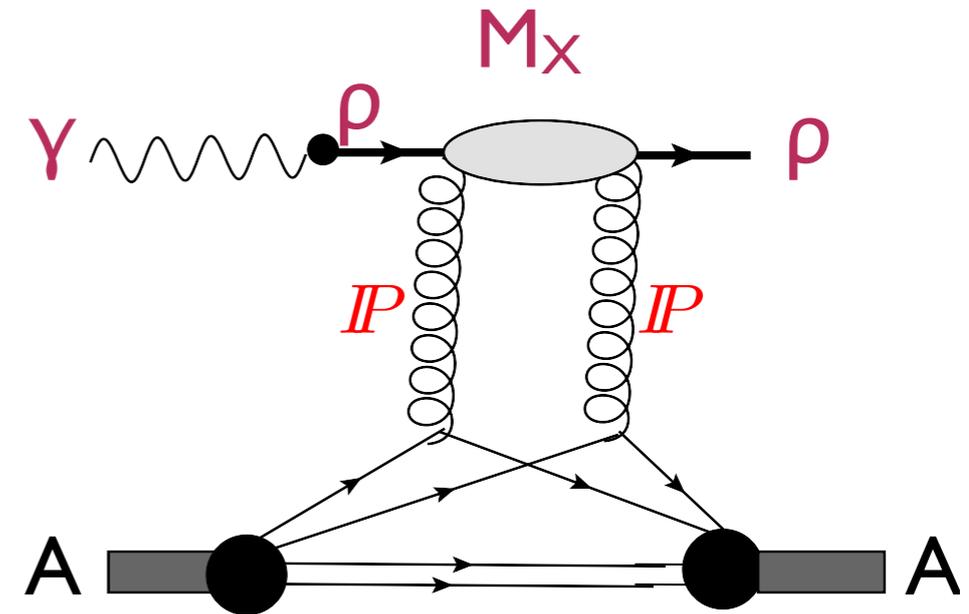
since overlapping integral between γ and ρ is suppressed as compared to $\rho \rightarrow \rho$ case

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

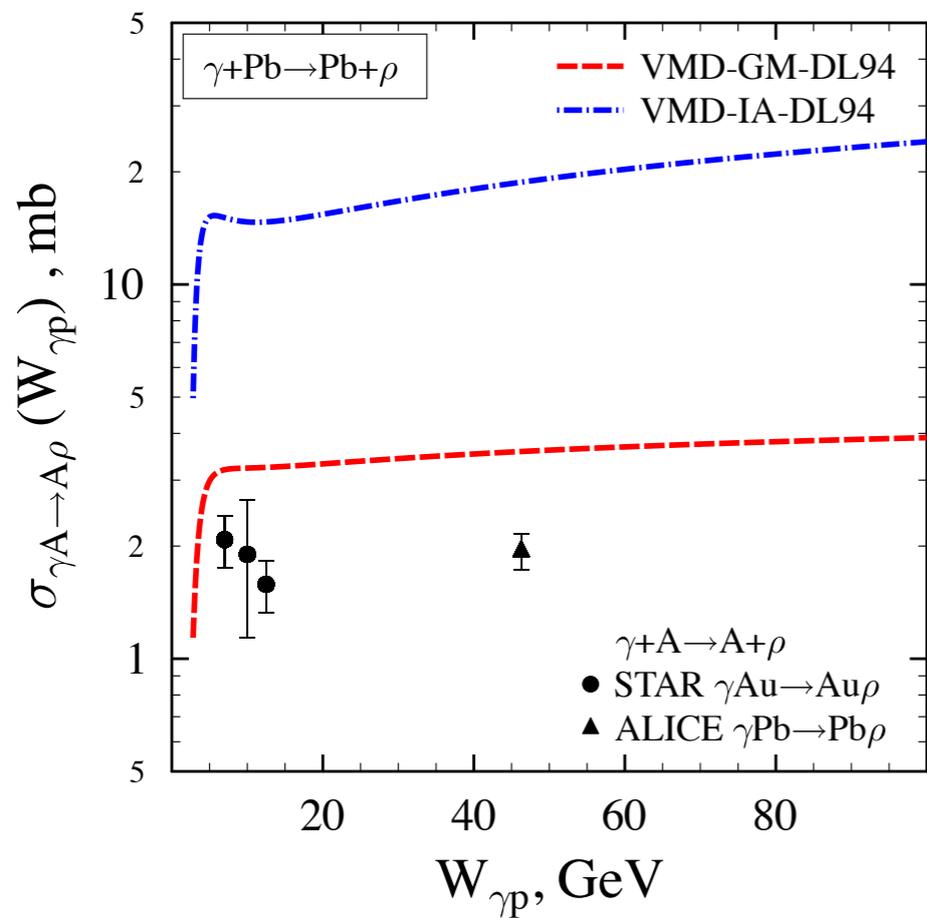


Gribov inelastic shadowing

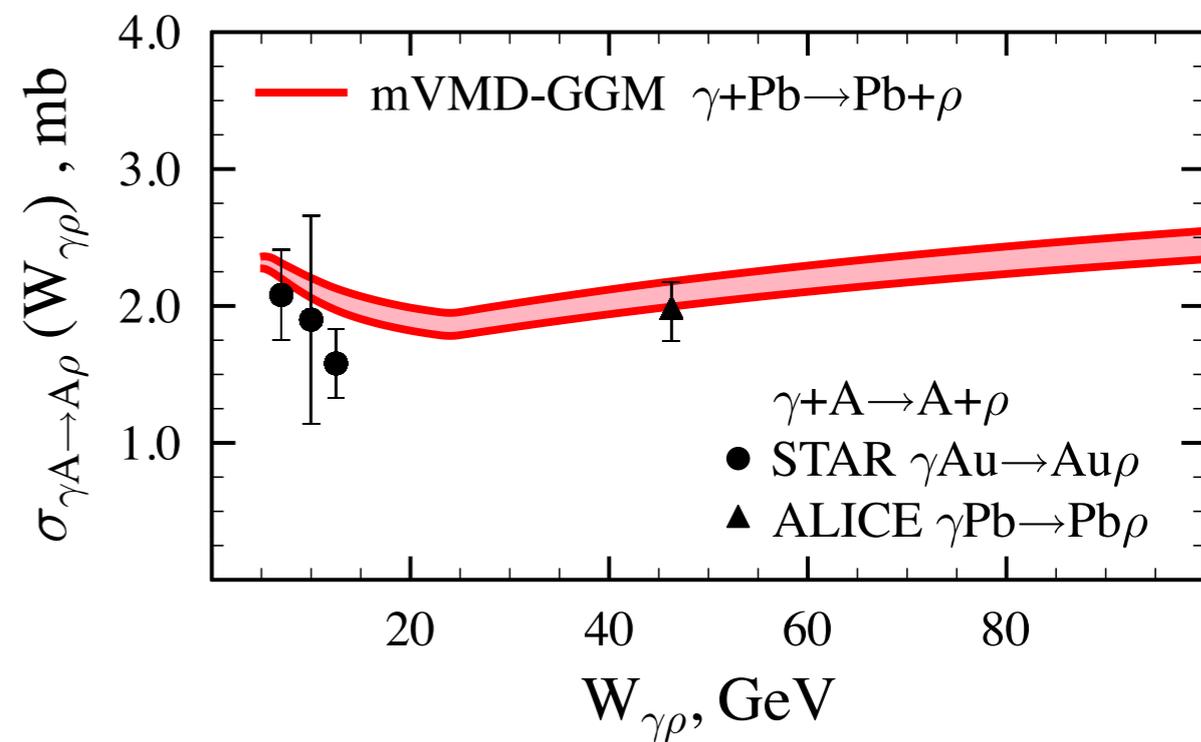
❖ Gribov type inelastic shadowing is enhanced in discussed process - fluctuations grow with decrease of projectile - nucleon cross section. We estimate variance, $\omega_{Y \rightarrow \rho} \sim 0.5$ of $P_{Y \rightarrow \rho}(\sigma)$ - distribution of configurations in transition over σ and model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

Next we use $P_{Y \rightarrow \rho}(\sigma)$ 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 predicts large shadowing, still **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 $P_\gamma(\sigma)$ modeling color fluctuations in photon

For

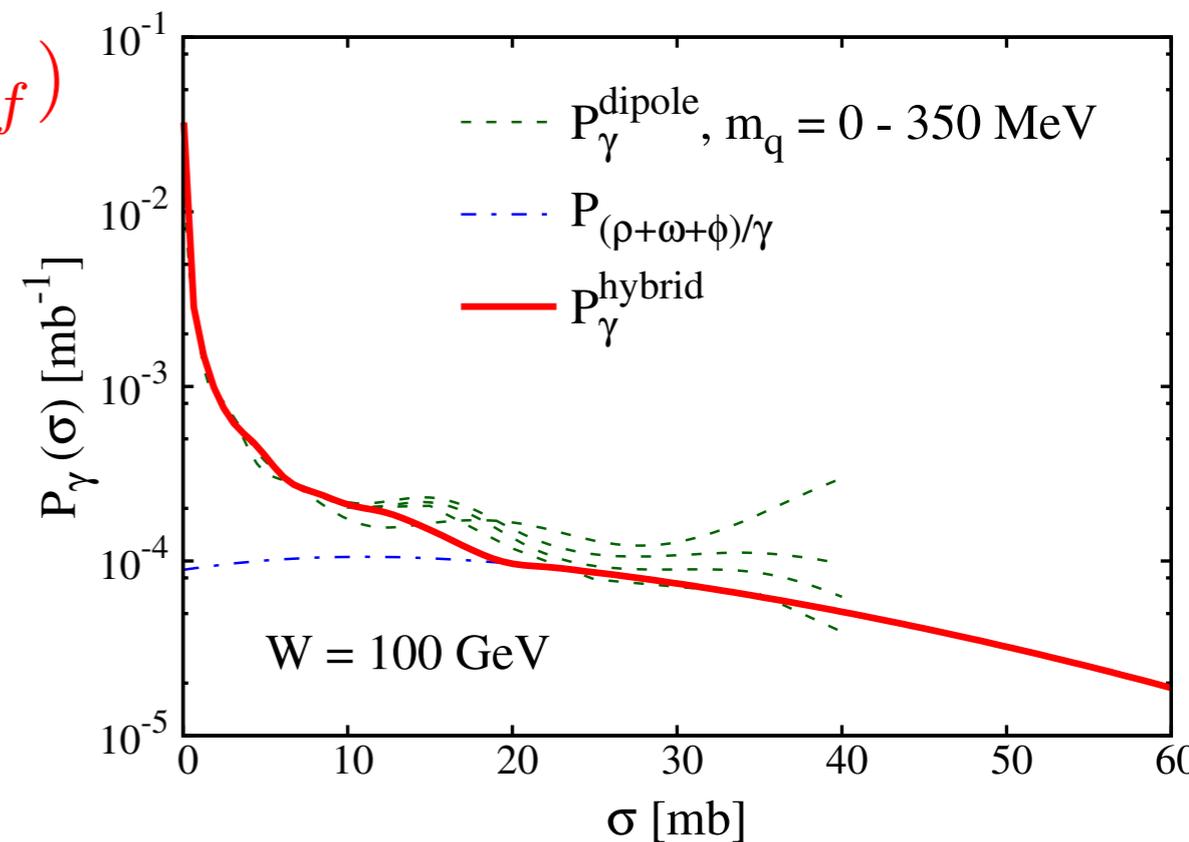
$$\sigma > \sigma(\pi N), P_\gamma(\sigma) = P_{\gamma \rightarrow \rho}(\sigma) + P_{\gamma \rightarrow \omega}(\sigma) + P_{\gamma \rightarrow \phi}(\sigma)$$

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

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

+ smooth interpolation in between

Smooth matching for $m_q \sim 300 \text{ MeV}$





Calculation of distribution over the number of wounded nucleons

(a) Color fluctuation model

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

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

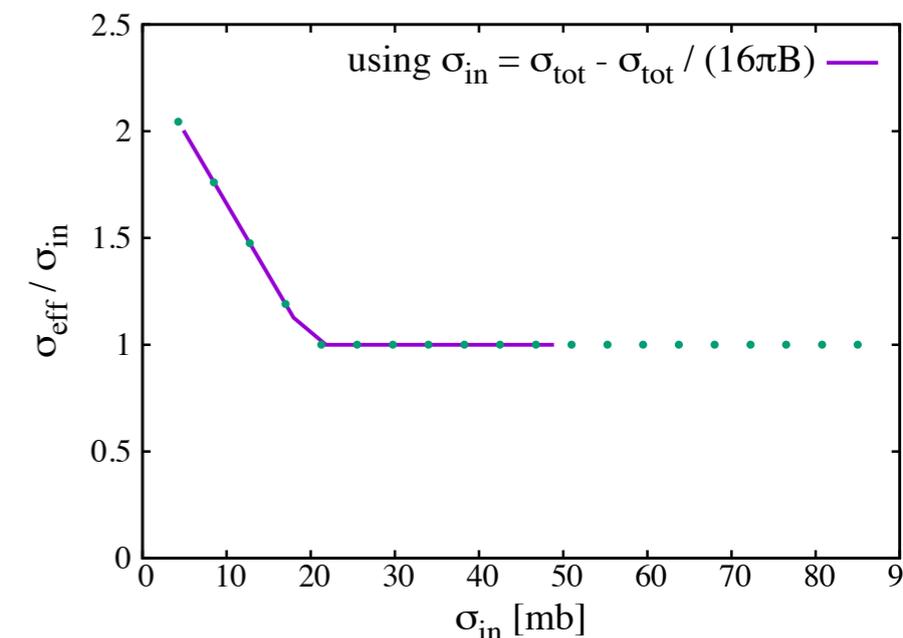
(b) Generalized Color fluctuation model (includes LT shadowing for small σ)

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

evidence from J/psi production - next slide

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

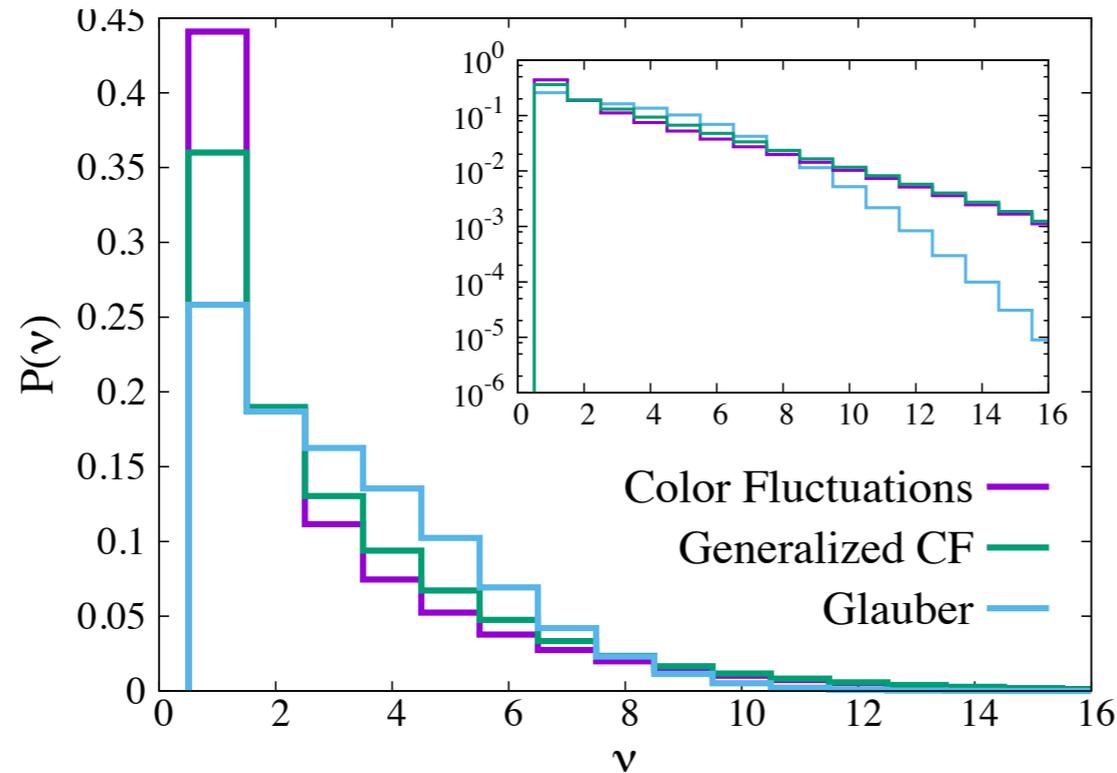
σ_{eff}/σ calculated in the LT nuclear shadowing theory for small σ



consistent with shadowing for J/psi coherent production

Ultrapерipheral 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



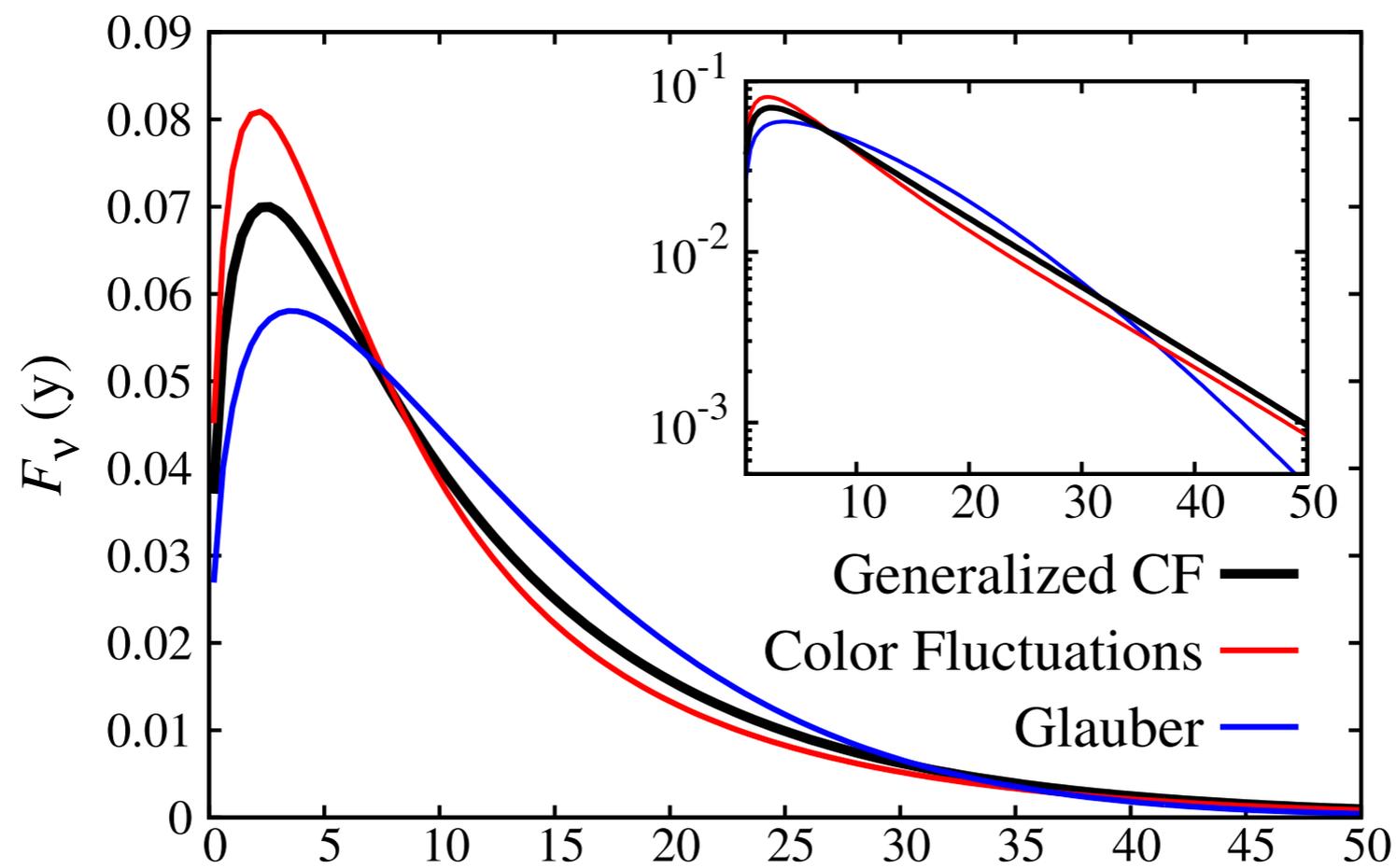
distribution over the number of wounded nucleons in γA scattering, $W \sim 70$ GeV

Alvioli, Guzey, Zhalov, LF, MS

Phys.Lett. B767 (2017) 450-457

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 $\sigma \sim 40$ 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 γ A collisions for same v .

Using forward detector (CASTOR?) for centrality via measurement of “ y ” advantageous : larger rapidity interval - smaller kinematical/ energy conservation correlations. For using ΣE_T for centrality determination one needs $\Delta y > 4$. Interesting alternative is to use information from ZDC.

$$\gamma A \rightarrow \text{jets} + X$$

Observables which are easier to measure than shadowing for total cross sections (neutrons, ΣE_T)

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

Color change propagation through matter.

Color exchanges ? \Rightarrow nucleus excitations, ZDC & CASTOR

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

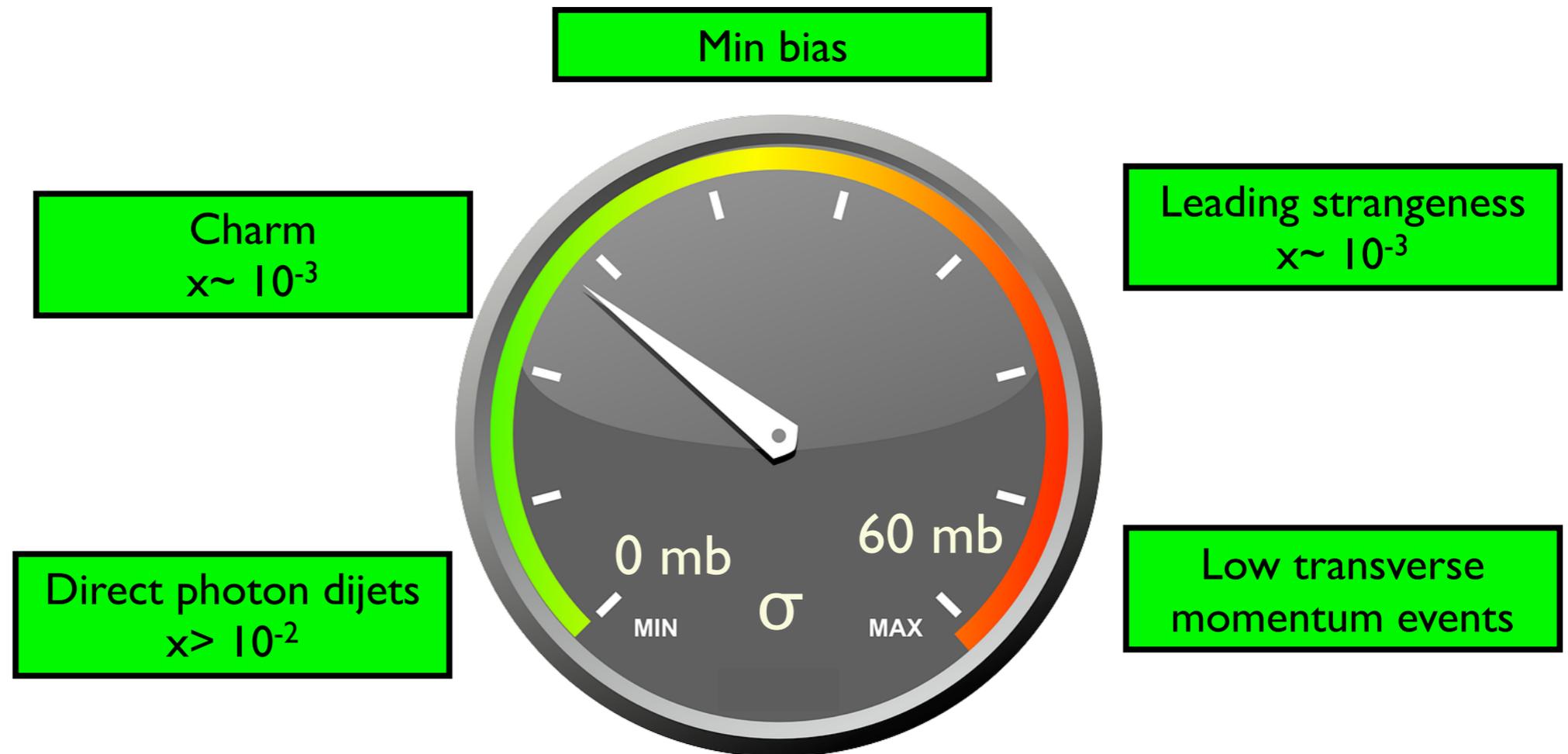
3) *Resolved photon - increase of ν with*

decrease of x_γ and x_A \mathbb{W} dependence of distribution over ν

Centrality dependence of the forward spectrum in $\gamma A \rightarrow h + X$

— 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

Opportunities for studying small x dynamics in

UPC rapidity gap processes

$$\gamma(\gamma^*) + p(A) \rightarrow \text{''vector meson''} + \text{rapidity gap} + X$$

➡ *Probing BFKL dynamics in $\gamma p, \gamma A$ scattering
in large t “diffractive” rapidity gap processes*

➡ *Color fluctuations in nucleons from hard diffraction at $t=0$*

only $-t \lesssim 0.2 \text{ GeV}^2$

Rapidity gaps in UPC pA/AA at the LHC

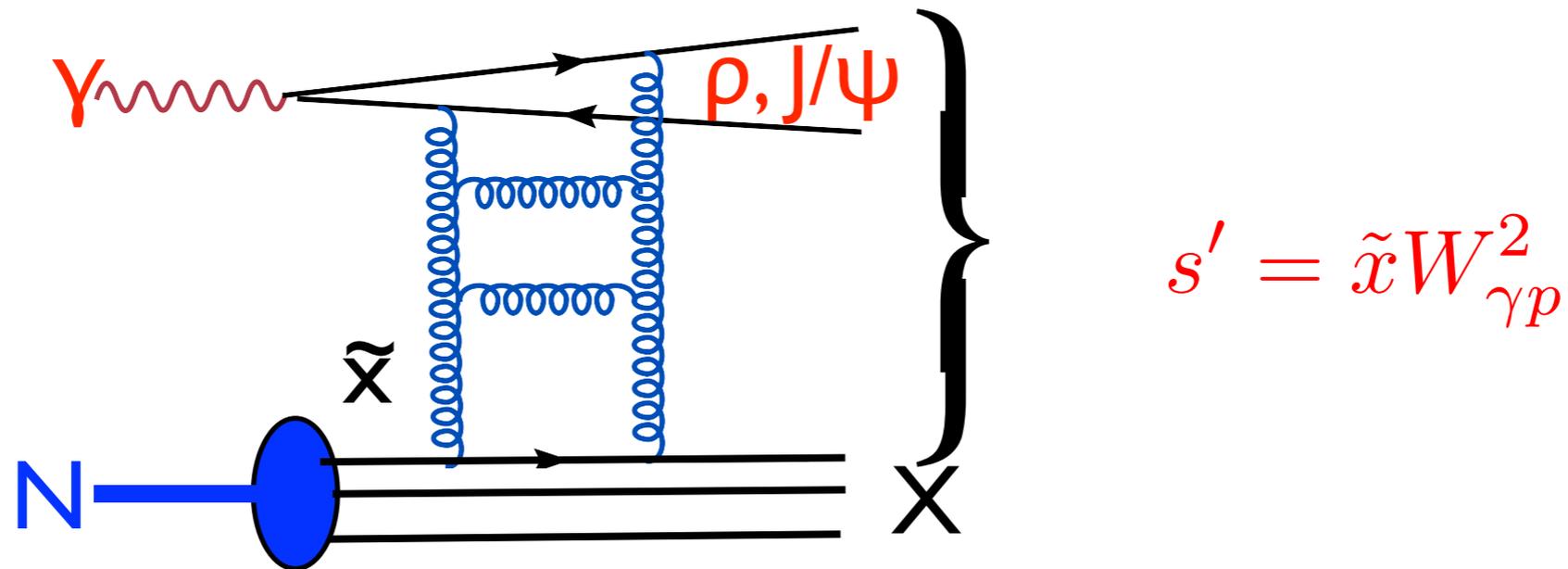
$$\gamma(\gamma^* EIC) + p(A) \rightarrow \text{''vector meson''} + \text{rapidity gap} + Y$$

important - in UPC with hadron production no ambiguity with the source of photons (not the case for coherent J/ψ production) - higher W can be probed

Will focus on three questions which could be studied in process

- * What is asymptotic behavior of the amplitude of the elastic scattering of small dipoles in QCD at large t ? At what energies BFKL approximation works?*
- * gluon field strength fluctuations from low t kinematics*
- * How small dipoles interact with nuclear media?*

These questions can be addressed by studying rapidity gap processes at large $t=(p_\rho-p_\gamma)^2$ which were first studied at HERA - best combining γN and γA



Elementary reaction - scattering of a hadron (γ, γ^*) off a parton of the target at large $t=(p_\gamma-p_V)^2$

FS 89 (large t $pp \rightarrow p + \text{gap} + \text{jet}$),

Mueller & Tung 91

FS95

Forshaw & Ryskin 95

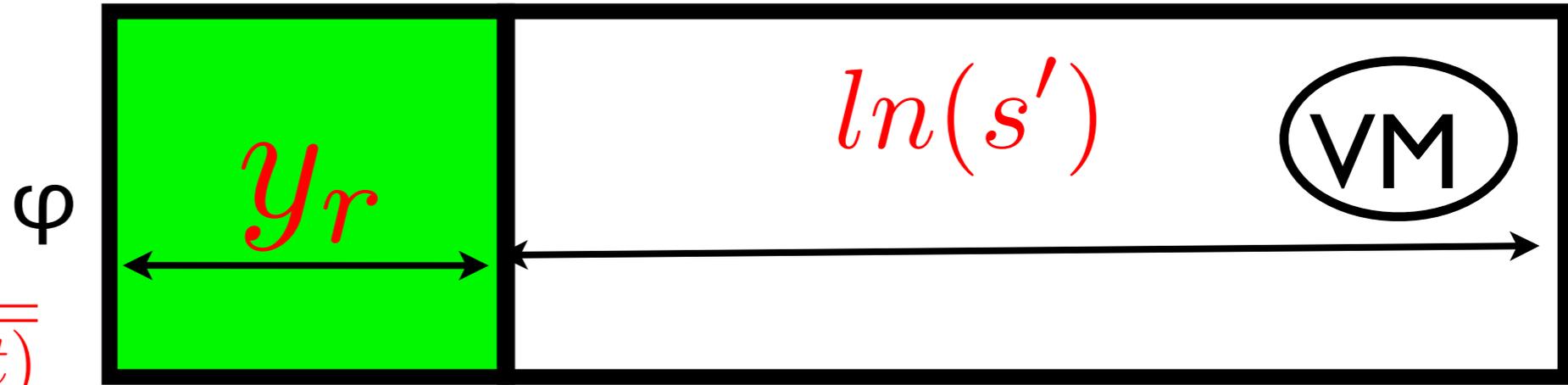
$$\tilde{x} = \frac{-t}{(-t + M_X^2 - m_N^2)}$$

Remark: low $-t$ (small \tilde{x}) are also interesting

- check dynamics of the leading twist nuclear shadowing

The rapidity gap between the produced vector meson and knocked out parton (roughly corresponding to the leading edge of the rapidity range filled by the hadronic system X) is related to $W_{\gamma p}$ and t (for large t , $W_{\gamma p}$) as

$$y_r = \ln \frac{\tilde{x} W_{\gamma p}^2}{\sqrt{(-t)(m_V^2 - t)}}$$



Advantage of CASTOR (other detectors capable to fix the rapidity range with no hadron activity over - large rapidity gaps), can use central detector to select events with ρ^0 -meson with $p_t > 2$ GeV over 4 units of rapidity (change of s' by a factor ~ 50). In particular CASTOR can be used for defining a gap or be used in combination with ZDC for looking at even larger gaps.

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.

*** the transverse size $d_{q\bar{q}} \propto 1/\sqrt{-t} \sim 0.15\text{fm}$ for J/ψ for $-t \sim m_{J/\psi}^2$

$$\frac{d\sigma_{\gamma+p \rightarrow V+X}}{dt d\tilde{x}} =$$

$$= \frac{d\sigma_{\gamma+quark \rightarrow V+quark}}{dt} \left[\frac{81}{16} g_p^{24}(\tilde{x}, t) + \sum_i (q_p^i(\tilde{x}, t) + \bar{q}_p^i(\tilde{x}, t)) \right]$$

gluon density fluctuations do not enter in this limit

t-range for sufficient squeezing $-t \sim \text{few GeV}^2$, For J/ψ $-t \sim 4 - 10 \text{ GeV}^2$,

Note - t-dependence is weak

$$\frac{d\sigma}{dt} \propto \frac{1}{(t + t_0)} \frac{1}{(-t + m_{J/\psi}^2)^3}$$



Large rates up to large t

LF & MS & Zhalov 2008

HERA --Analyses with z cut, $M_{\chi}^2/s < \text{const}$ cuts are good for study of the dominance of the mechanism of scattering off single partons. However they correspond to rapidity interval between VM and jet which are typically of the order $\Delta y = 2 - 3$.

Optimal way to study BFKL dynamics is different: keep M_{χ}^2 (in practice $y_r < \text{const}$) and study W-dependence.

Was difficult but not impossible at HERA, natural at LHC

At LHC one can study energy dependence of elastic $q \bar{q}$ - parton scattering at $W' = 20 \text{ GeV} - 400 \text{ GeV}$ (higher lumi now - need new estimates)

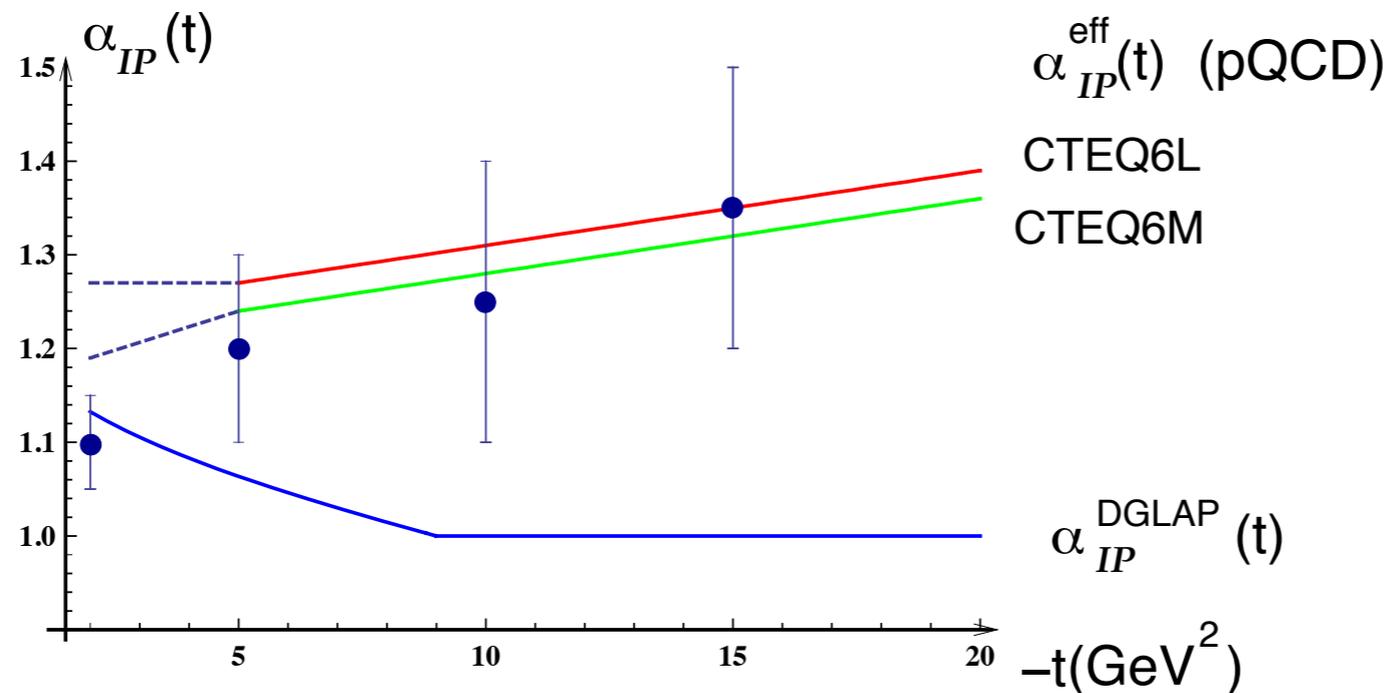
$$\sigma_{el}(q\bar{q} - q(g))(W' = 400 \text{ GeV}) / \sigma_{el}(q\bar{q} - q(g))(W' = 20 \text{ GeV}) \sim 10 !!!$$

if $\Delta = 0.2$ -- NLO BFKL

$$W'^2 \equiv W^2(q\bar{q} - \text{parton}) = \tilde{x} W^2$$

better rapidity coverage of detector larger W' range

● -- J/ψ data from HERA



Large experimental value of $\alpha_{IP}^{eff}(t)$ is due to the dependence chosen kinematics - bins did not correspond to fixed \tilde{x}

DGLAPS with $\alpha_{IP}^{eff}(-t \gg \text{few GeV}^2) = 1$ gives a good description of the data.

Blok, Frankfurt, MS, Phys.Lett. B690 (2010) 159-163

W' is too small?

At low t the approximation breaks down -

additional overall factor $1 - F_N^2(x, t)$ in basic formula



suppression at $-t < 0.2 \text{ GeV}^2$ and ultimate disappearance of incoherent distribution at $-t = 0$.

Transition to gluon fluctuation mechanism at $t \sim 0$.

Strength of the gluon field should depend on the size of the quark configurations - for small configurations the field is strongly screened - gluon density much smaller than average.

we know a little bit about such fluctuations - MS + LF + C.Weiss, D.Treliani PRL 08

Consider $\gamma_L^* + p \rightarrow V + X$ for $Q^2 > \text{few GeV}^2$

In this limit the QCD factorization theorem (BFGMS03, CFS07) for these processes is applicable

Expand initial proton state in a set of partonic states characterized by the number of partons and their transverse positions, summarily labeled as $|n\rangle$

$$|p\rangle = \sum_n a_n |n\rangle$$

Each configuration n has a definite gluon density $G(x, Q^2 | n)$ given by the expectation value of the twist--2 gluon operator in the state $|n\rangle$

$$G(x, Q^2) = \sum_n |a_n|^2 G(x, Q^2 | n) \equiv \langle G \rangle$$

Making use of the completeness of partonic states, we find that the elastic ($X = p$) and total diffractive (X arbitrary) cross sections are proportional to

$$(d\sigma_{\text{el}}/dt)_{t=0} \propto \left[\sum_n |a_n|^2 G(x, Q^2 | n) \right]^2 \equiv \langle G \rangle^2,$$

$$(d\sigma_{\text{diff}}/dt)_{t=0} \propto \sum_n |a_n|^2 [G(x, Q^2 | n)]^2 \equiv \langle G^2 \rangle.$$

Hence cross section of inelastic diffraction is

$$\sigma_{\text{inel}} = \sigma_{\text{diff}} - \sigma_{\text{el}}$$

\Rightarrow

$$\omega_g \equiv \frac{\langle G^2 \rangle - \langle G \rangle^2}{\langle G \rangle^2} = \frac{d\sigma_{\gamma^*+p \rightarrow VM+Y}}{dt} \bigg/ \frac{d\sigma_{\gamma^*+p \rightarrow VM+p}}{dt} \bigg|_{t=0}.$$

For sufficient Q^2 we expect inelastic/elastic ratio should be the same for $\rho, \phi, J/\psi$ production. Agrees with the HERA data

$$\omega_g \sim 0.15 \div 0.2.$$

further analyses of the HERA data are necessary for different channels and same Y cuts.

Tracking Fast Small Color Dipoles through Strong Gluon Fields at the LHC **at large t**

L. Frankfurt,¹ M. Strikman,² and M. Zhalov³

$$\gamma + A \rightarrow J/\psi(\rho, 2\pi) + \text{"gap"} + X$$

Complementary to $\gamma + A \rightarrow J/\psi + A$ and has several advantages:

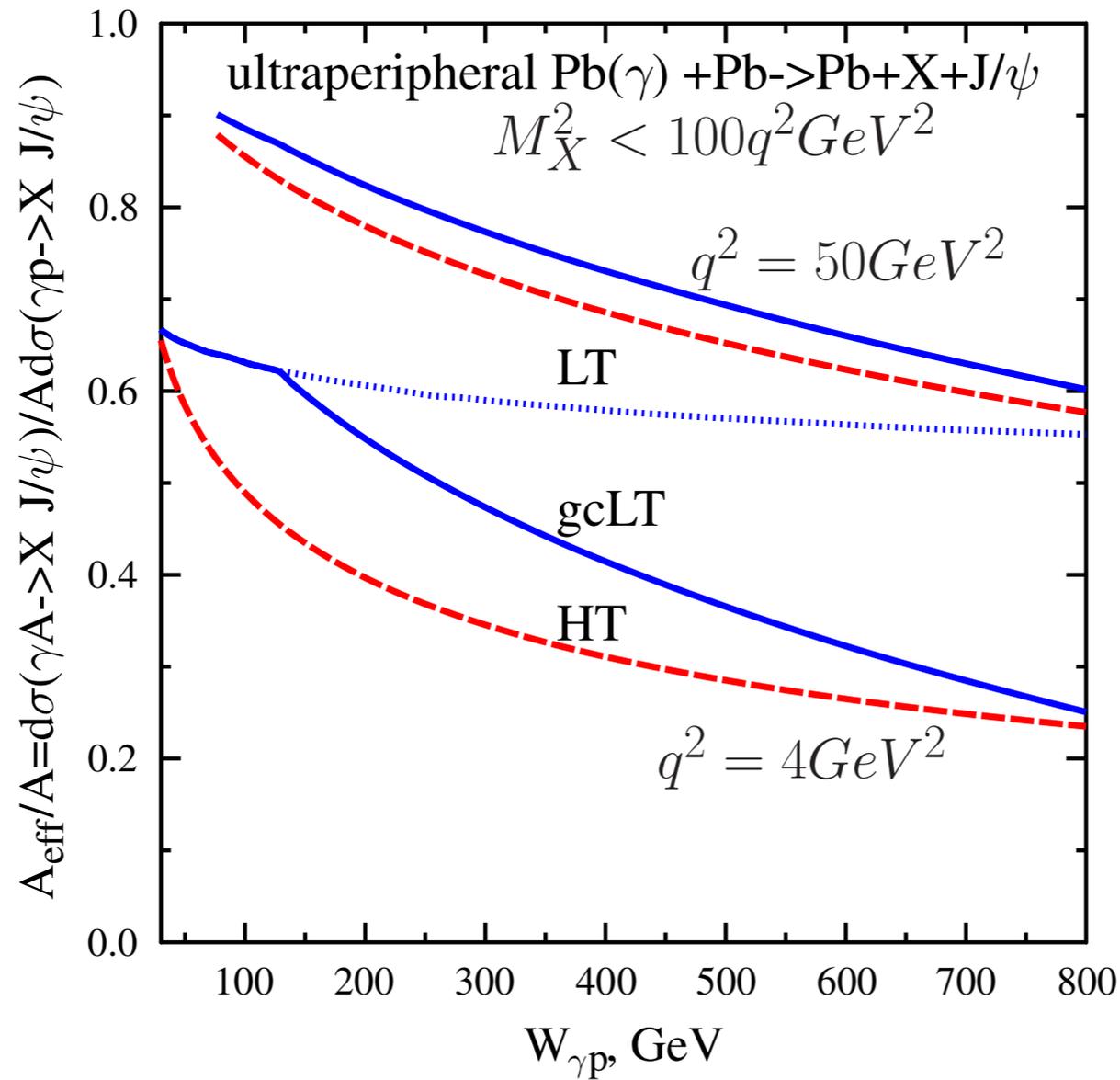
- (i) larger W range for UPC (due to ability to determine which of nuclei generated photon)
- (ii) Regulating of \tilde{x} for the parton in nucleus - shadowing vs linear regime for $G_A(x, Q)$
- (iii) More central collisions - larger local gluon density

Qualitative Predictions:

- * A_{eff}/A should increase with t at fixed W - smaller dipoles
- * A_{eff}/A should decrease with increase of W at fixed t - onset of black disk regime. Larger shadowing for small x (regulated by the rapidity covered by X -system)

$$P_A^{\text{gap}} = \frac{1}{A} \int d^2b T(\vec{b}) \left[1 - \sigma_{\text{dip-N}}(x, d) \frac{g_A(x, Q^2, \vec{b})}{g_N(x, Q^2)} \right],$$

$$q^2 \equiv -t = Q^2$$



The rapidity survival probability for the J/ ψ photoproduction as a function of W

Summary

- ◆ **LT DGLAP framework for calculation of nuclear pdfs; etc passed the J/psi coherent production test. Possible onset of black regime pushed to much smaller x .**
- ◆ 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.*
- ◆ Rapidity gap processes for fixed produced mass Y - clean probe of high energy hard Pomeron

supplemental slides

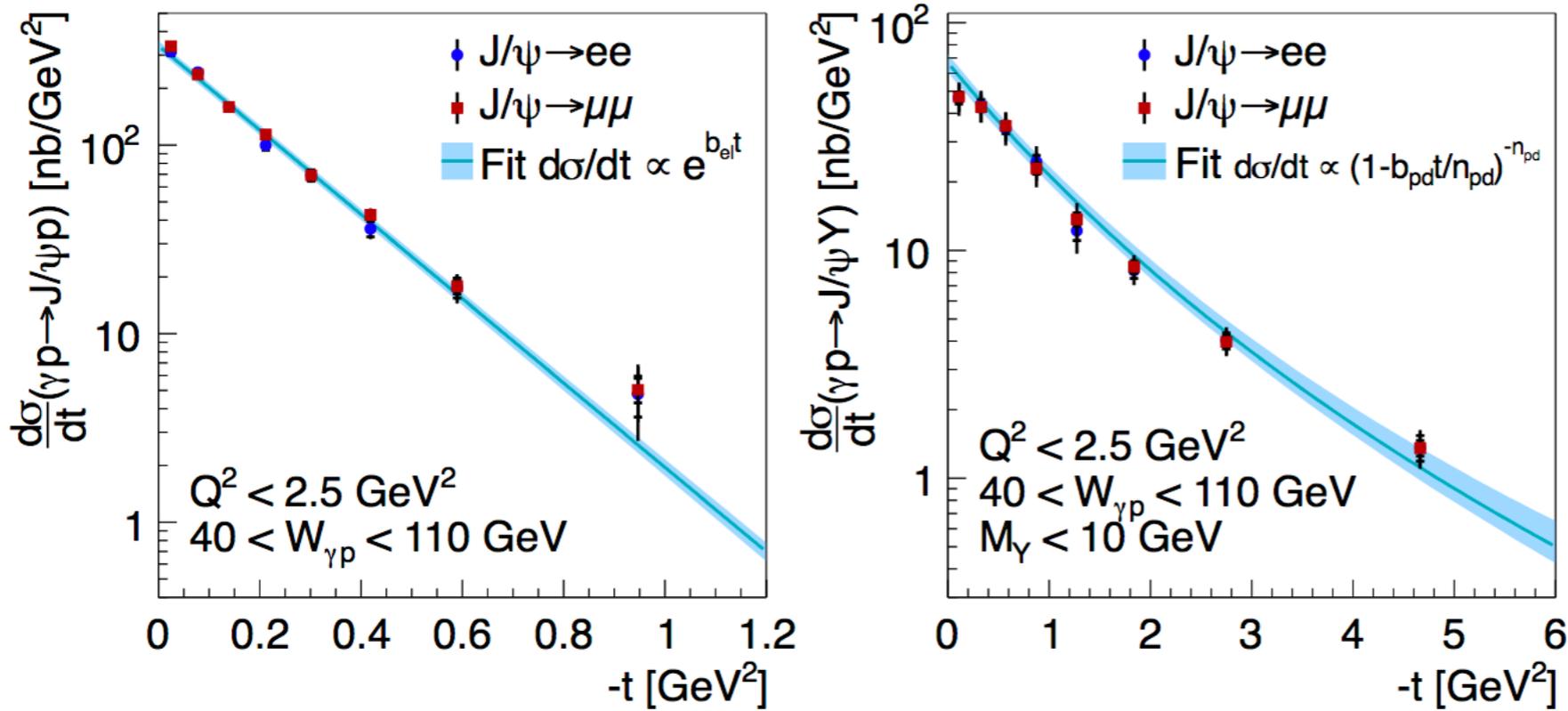


Figure 10.1: Differential cross section as function of $-t$ for elastic $\gamma p \rightarrow J/\psi p$ (left) and proton dissociative $\gamma p \rightarrow J/\psi Y$ (right) process for the high energy data period obtained at a centre of mass energy of 318 GeV. The red circles and blue squares represent the cross sections measured in the decay channels $J/\psi \rightarrow ee$ and $J/\psi \rightarrow \mu\mu$, respectively. The turquoise solid line represents the combined fits to both data sets. The inner and outer error bars reflect the square root of the diagonal elements in the covariance matrix $\sqrt{V_{ii}}$ for only statistical and statistical plus systematic uncertainties. The normalisation uncertainties as given in Table 9.1 are not included in the systematic uncertainty representation of the data points.