Theory overview of vector meson photoproduction on nuclei in UPCs at the LHC

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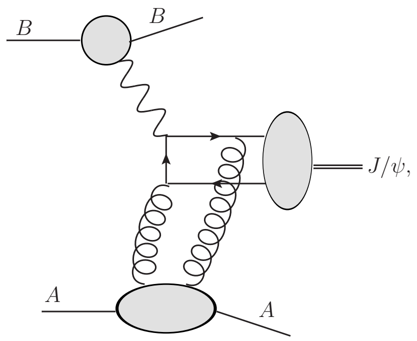
Outline:

- Introduction: UPCs and nuclear shadowing
- Inelastic nuclear shadowing and coherent ρ photoproduction on nuclei
- Gluon nuclear shadowing from J/ψ photoproduction on nuclei at the LHC
- Open questions, topics for discussion, outlook and summary

Workshop INT-17-65W "Probing QCD in Photon-Nucleus Interactions at RHIC and LHC: the Path to EIC", INT, Seattle, Feb 13-17, 2017

Ultraperipheral collisions (UPCs)

• Ions can interact at large impact parameters $b >> R_A+R_B$ → ultraperipheral collisions (UPCs) → strong interaction suppressed → interaction via quasi-real photons, Fermi (1924), von Weizsäcker; Williams (1934)



- UPCs correspond to empty detector with only two lepton/pion tracks
- Nuclear coherence by veto on neutron production by Zero Degree Calorimeters and selection of small pt

• Coherent photoproduction of vector mesons in UPCs:

$$\frac{d\sigma_{AA\to AAJ/\psi}(y)}{dy} = N_{\gamma/A}(y)\sigma_{\gamma A\to AJ/\psi}(y) + N_{\gamma/A}(-y)\sigma_{\gamma A\to AJ/\psi}(-y)$$

Photon flux: Photoproduction cross section

$y = \ln[W^2/(2\gamma_L m_N M_V)]$ = J/ψ rapidity

• Photon flux from QED:

- high intensity ~ Z^2
- large photon energies $\zeta = k(2R_A/\gamma_L)$

$$N_{\gamma/Z}(k) = \frac{2Z^2\alpha_{\rm em}}{\pi}[\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}(K_1^2(\zeta) - K_0^2(\zeta))]$$

UPCs = γp and γA interactions at unprecedentedly large energies,
Baltz *et al.*, The Physics of Ultraperipheral Collisions at the LHC, Phys. Rept. 480 (2008) 1

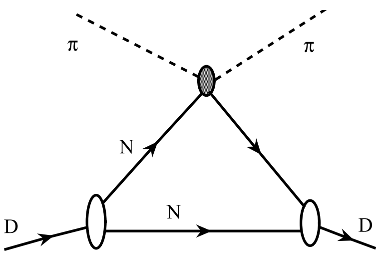
Nuclear shadowing

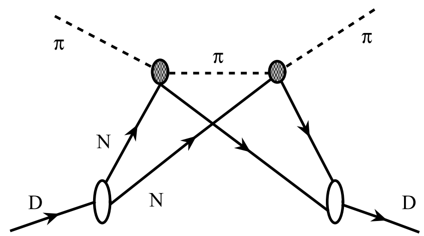
- Nuclear shadowing (NS) = suppression of cross section on a nucleus compared to sum of cross sections on individual nucleons: $\sigma_A < A\, \sigma_N$.

- Observed for various beams (p, π, γ, γ^*, ν) of large energies (> 1 GeV)

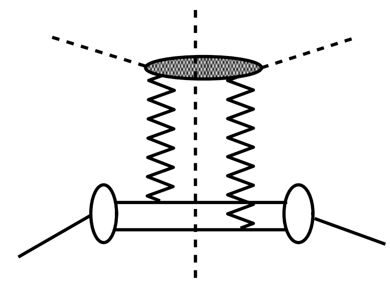
- Explained by simultaneous interaction of projectile with target nucleons → destructive interference among amplitudes for interaction with 1, 2, …nucleons → nucleons in rear of the nucleus "see" smaller (shadowed) flux: $\sigma_A \sim A^{2/3}$.

elastic intermediate state, Glauber 1955





inelastic intermediate state, Gribov 1969



- NS in photoproduction of light vector mesons ρ, ω, ϕ:
  - dynamics of soft γp and γA interaction at high energies
  - validity of VMD model and role of inelastic (Gribov) shadowing
  - constraints on color dipole approach

- NS in photoproduction of heavy vector mesons J/ψ, ψ(2S), Υ:
  - mechanism of nuclear shadowing; leading twist vs. HT vs. saturation
  - new constraints on nuclear gluon distribution $g_A(x,\mu^2)$ at small x

Coherent photoproduction of ρ on nuclei

• Measured with fixed targets (SLAC, W < 6 GeV), in Au-Au UPCs at RHIC (W < 12 ГэВ), and Pb-Pb UPCs at the LHC@2.76 TeV (W=46 GeV).

• For W < 10 GeV, explained by the vector meson dominance (VMD) model for $\gamma \to \rho$ transition and Glauber model for shadowing in ρA scattering:

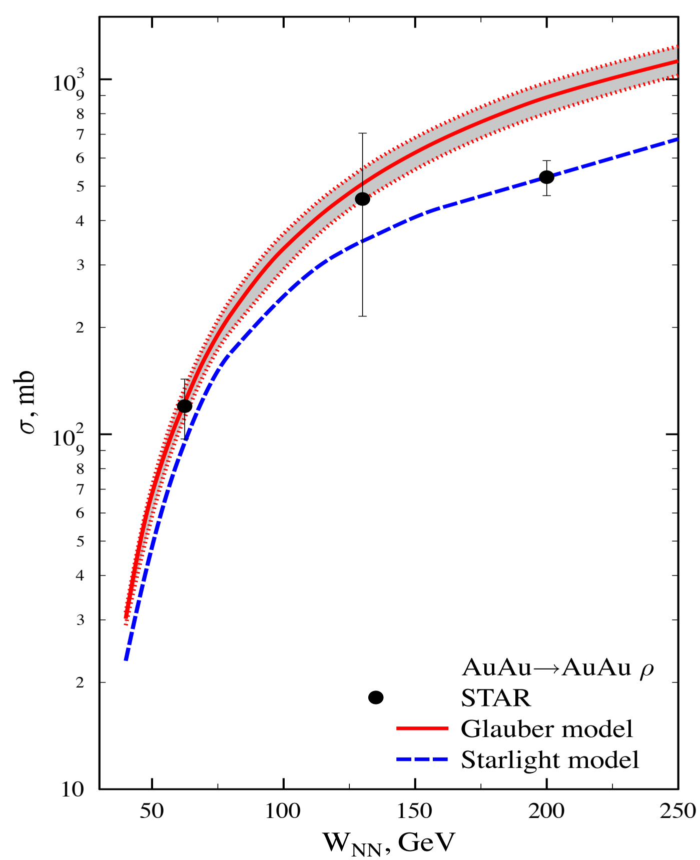
$$\sigma^{VMD}_{\gamma A \to \rho A} = \left(\frac{e}{f_\rho}\right)^2 \int d^2 b \left| 1 - e^{-\frac{1}{2}\sigma_{\rho N} T_A(b)} \right|^2$$

$\sigma_{\rho N}$ from constituent quark model/data:

Optical density:

$$T_A(b) = \int dz \rho_A(b,z)$$

Frankfurt, Strikman, Zhalov, 2002



• …but fails to describe large-W RHIC (STAR), Adler, et al, Phys. Rev. Lett. 89 (2002) 272302; Abelev et al., Phys. Rev. C 77 (2008) 034910; Agakishiev, et al., Phys. Rev. C 85 (2012) 014910 and ALICE data by factor **~1.5**, Adam et al (ALICE), JHEP 1509 (2015) 095

• Dipole models describe data better, but strongly model-dependent, Goncalves, Machado, PRC 84 (2011) 011902

• Best description by STARlight despite approximate treatment of Glauber model, Klein and Nystrand, PRC60 (1999) 014903.

Modified vector meson dominance (mVMD) model

- At large beam energies E_γ, the photon can be viewed as superposition of long-lived ($l_c \sim E_\gamma$) fluctuations interacting with hadrons with different cross sections, Gribov, Ioffe, Pomeranchuk 1965; Good, Walker, 1960

- Convenient to realize introducing the probability distribution $P(\sigma)$, Blattel et al, 1993

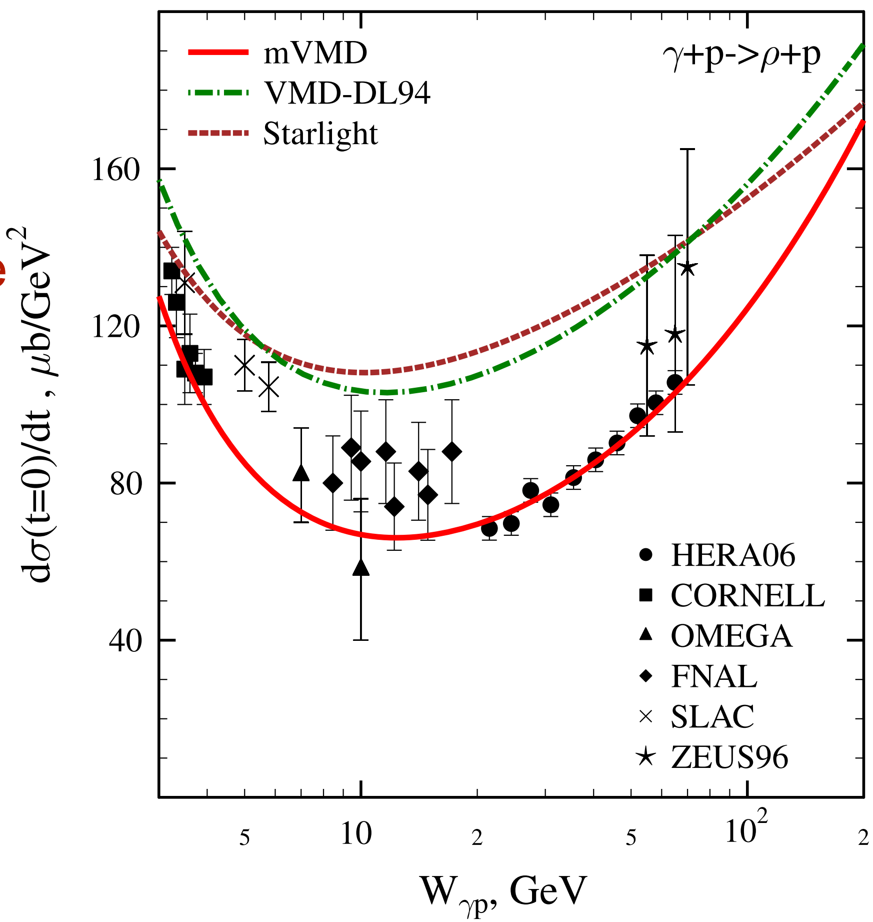
→ talk by **L. Frankfurt**

$$\int d\sigma\, P(\sigma) = 1\,,$$

$$\int d\sigma\, P(\sigma)\sigma = \langle\sigma\rangle\,, \quad \rightarrow \text{ from } \quad d\sigma(\gamma p \rightarrow \rho p)/dt$$

$$\int d\sigma\, P(\sigma)\sigma^2 = \langle\sigma\rangle^2(1+\omega_\sigma)$$

→ from measured γ diffract. dissociation into large masses, Chapin 1985



- Shape like for pion, Blattel et al, 1993 + small-σ enhancement to take into account smaller size of ρ in $\gamma p \rightarrow \rho p$ than in $\sigma_{\pi N}$ →

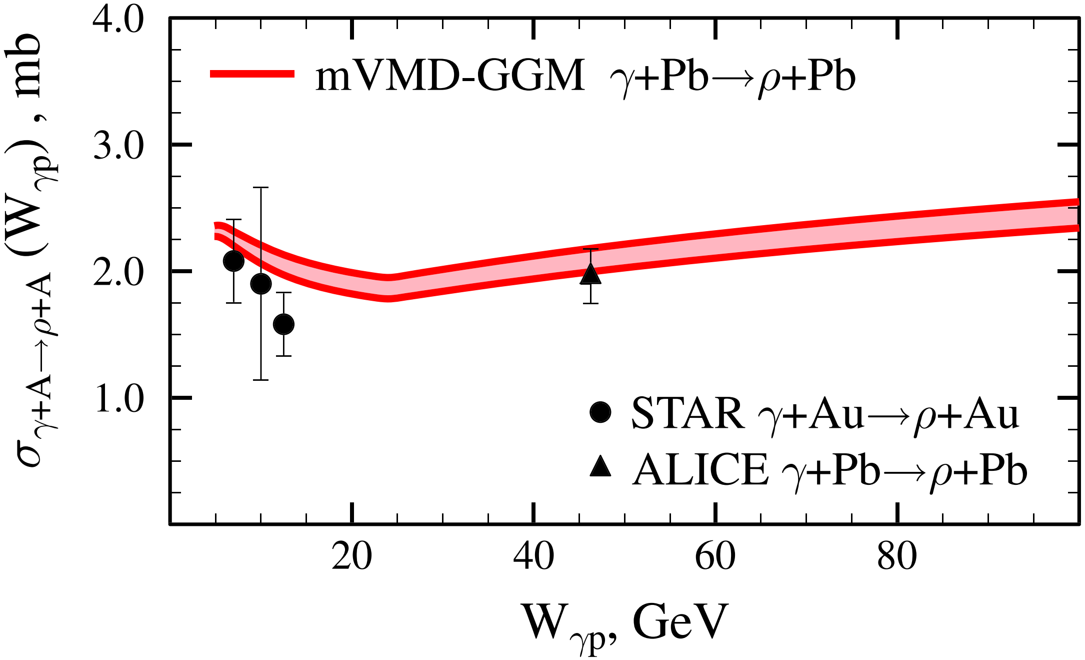
$$P(\sigma) = C\frac{1}{1+(\sigma/\sigma_0)^2}e^{-(\sigma/\sigma_0-1)^2/\Omega^2}$$

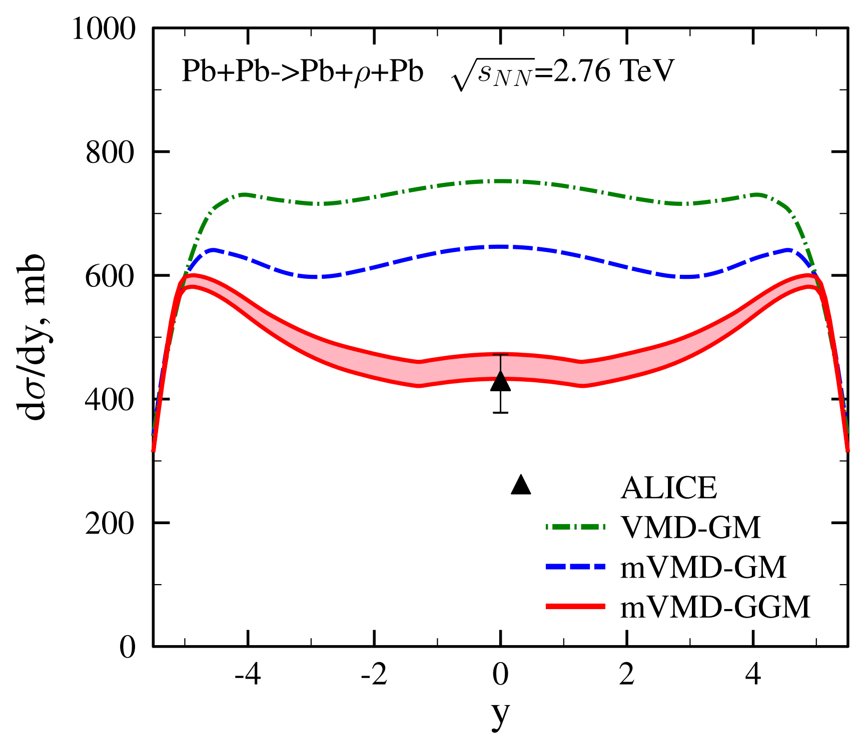
Photoproduction of ρ on Pb in mVMD+Gribov-Glauber model

- With cross section fluctuations: $\sigma_{\gamma A\to\rho A}^{\text{mVMD-GGM}} = \left(\frac{e}{f_\rho}\right)^2 \int d^2\vec{b} \left| \int d\sigma\, P(\sigma) \left(1 - e^{-\frac{\sigma}{2} T_A(b)}\right) \right|^2$

- "Two birds with one stone": we describe correctly the elementary $\gamma p\to\rho p$ cross section and include inelastic Gribov shadowing in $\sigma_{\gamma A\to\rho A}$

- → describe well normalization and W-dependence $\sigma_{\gamma A\to\rho A}$, Frankfurt, Guzey, Strikman, Zhalov, PLB 732 (2016) 51





Predictions for Run 2@LHC: ρ and ϕ mesons

- Combination of mVMD and Gribov-Glauber models:

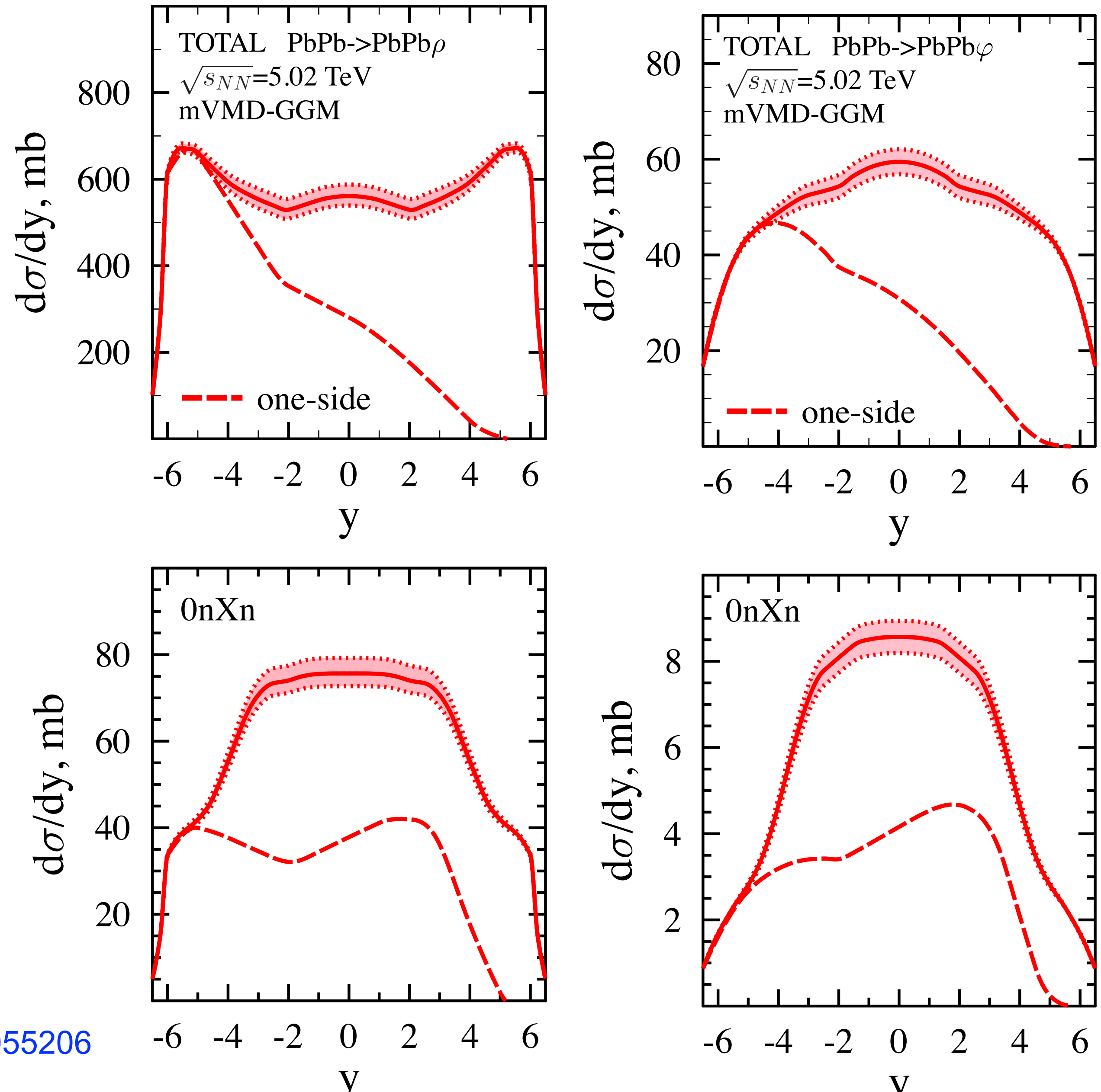
- ρ: P(σ) from data
- ϕ: P(σ) from $\sigma_{\phi N}$
(Donnachie, Landshoff, 1995) +
constituent quark $\omega_\sigma^\phi = \frac{\sigma_{NN}}{\sigma_{\phi N}} \omega_\sigma^\phi$

- “Ears” for ρ: effect of Reggeon in $\sigma_{\rho N}$

- Change of shape for 0nXn-channel due to large $W_{\gamma p}$ enhancement of photon flux

0nXn-channel: e.m. excitation of either of nuclei with forward emission > 1 neutron in ZDC

Guzey, Kryshen, Zhalov, PRC 93 (2016) 055206



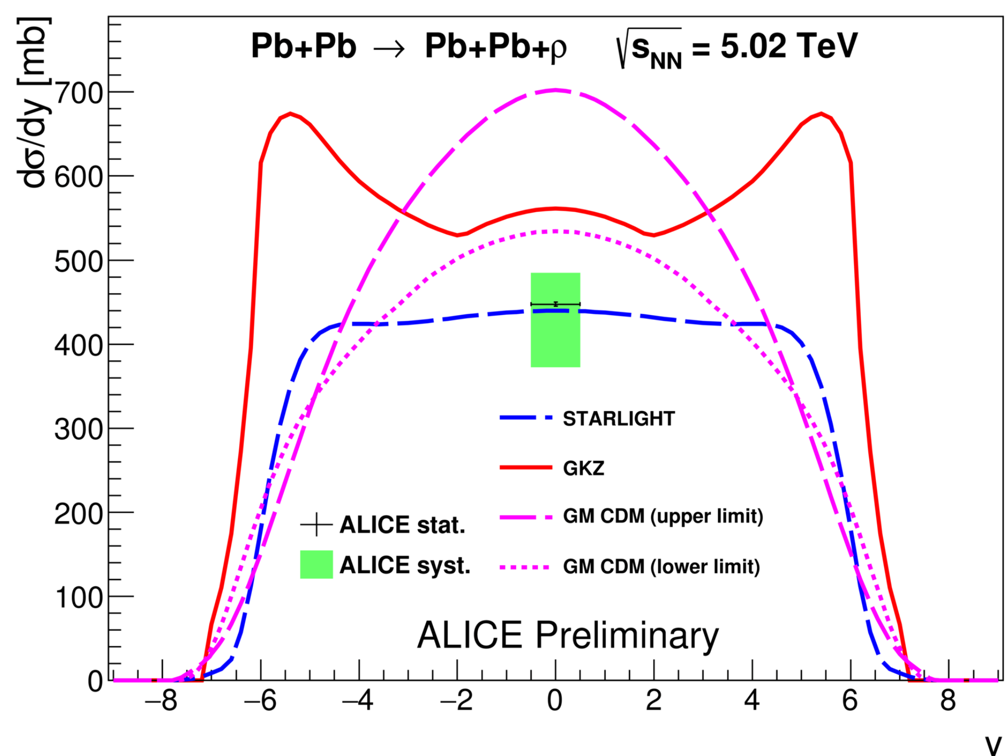
News from QM2017 on ρ photoproduction on nuclei in Pb-Pb UPCs in Run 2

- Preliminary ALICE result on Pb-Pb UPCs at $\sqrt{s_{NN}}$=5.02 TeV: cross section is almost the same as in Run 1
- Cannot be described by our mVMD-GG approach and color dipole models
- Excellent description by STARlight

Different theoretical approaches predicts very different shapes of rapidity dependence.

D. Horak (ALICE), poster at conference “Quark Matter 2017”, Feb 6-11, 2017

- $d\sigma/dy = (448 \pm 2(\text{stat})^{+38}_{-75}(\text{syst}))$ [mb]
- Predictions by **STARLIGHT** [2], Gonçalves and Machado using Color Dipole Model (**CDM**) [3,4] and Guzey, Kryshen Zhalov (**GKZ**) [5] reported
- Result compatible with STARLIGHT model



Nuclear shadowing in nuclear gluon distribution

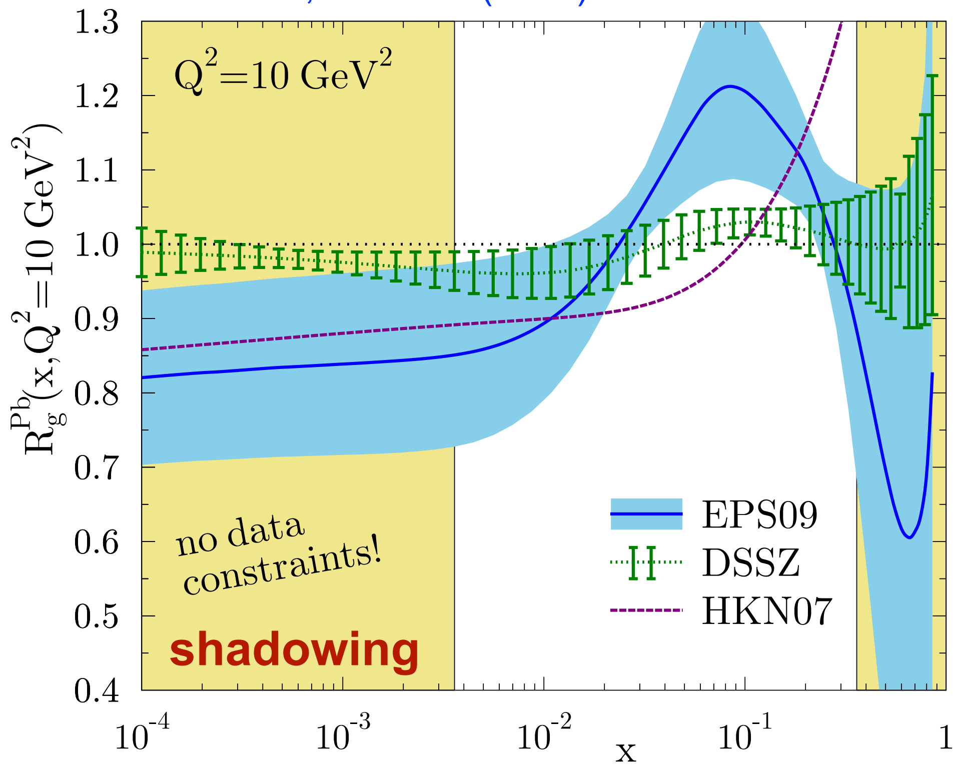
- Gluon nuclear shadowing: $g_A(x,\mu^2) < A\, g_N(x,\mu^2)$ for small $x < 0.005$.
- Important for QCD phenomenology of hard processes with nuclei: cold nuclear matter effects (RHIC, LHC), gluon saturation (RHIC, LHC, EIC)
- $g_A(x,\mu^2)$ is determined from global QCD fits to data on fixed-target DIS, hard processes in dA (RHIC) and pA (LHC) → talks by **R. Vogt, F. Olness, S. Kumano**

- At small x, $g_A(x,\mu^2)$ is known with large uncertainties →
- pA@LHC data can help little, Armesto et al, arXiv:1512.01528; Eskola et al, JHEP 1310 (2013) 213, Eskola et al, arXiv:1612.075 (EPPS16 nPDFs)
- Future: Electron-Ion Collider in the US, Accardi et al, ArXiv:1212.1701; LHeC@CERN, LHEC Study Group, J. Phys. G39 (2012) 075001 → talks by **E. Aschenauer, C. Weiss**

- Option right now: Charmonium photoproduction in Pb-Pb UPCs@LHC

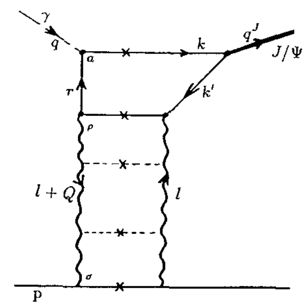
$$R_g(x,Q^2) = \frac{g_A(x,Q^2)}{A g_p(x,Q^2)}$$

H. Pauukunen, NPA 926 (2014) 24



Coherent charmonium photoproduction

• In leading logarithmic approximation of perturbative QCD and non-relativistic approximation for charmonium wave function (J/ψ, $\psi(2S)$):



$$\frac{d\sigma_{\gamma T\to J/\psi T}(W,t=0)}{dt} = C(\mu^2)\left[xG_T(x,\mu^2)\right]^2$$

M. Ryskin (1993)

$$x=\frac{M^2_{J/\psi}}{W^2}, \qquad \mu^2 = M^2_{J/\psi}/4 = 2.4\ \mathrm{GeV}^2 \quad C(\mu^2) = M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s(\mu^2)/(48\alpha_{em}\mu^8)$$

• Corrections on quark and gluon k_T, non-forward kinematics, real part of amplitude → corrections to $C(\mu^2)$ and μ^2, Ryskin, Roberts, Martin, Levin, Z. Phys. (1997); Frankfurt, Koepf, Strikman (1997)

• Application to nuclear targets:

$$\sigma_{\gamma A\to J/\psi A}(W_{\gamma p}) = \frac{(1+\eta_A^2)R^2_{g,A}}{(1+\eta^2)R_g^2}\frac{d\sigma_{\gamma p\to J/\psi p}(W_{\gamma p},t=0)}{dt}\left[\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)}\right]^2\Phi_A(t_{\min})$$

Small correction $\kappa_{A/N} \approx$ 0.0.90-95

From HERA and LHCb

Gluon shadow. Rg

From nuclear form factor

$$\Phi_A(t_{\min}) = \int_{-\infty}^{t_{\min}} dt|F_A(t)|^2$$

• Nuclear suppression factor S → direct access to Rg

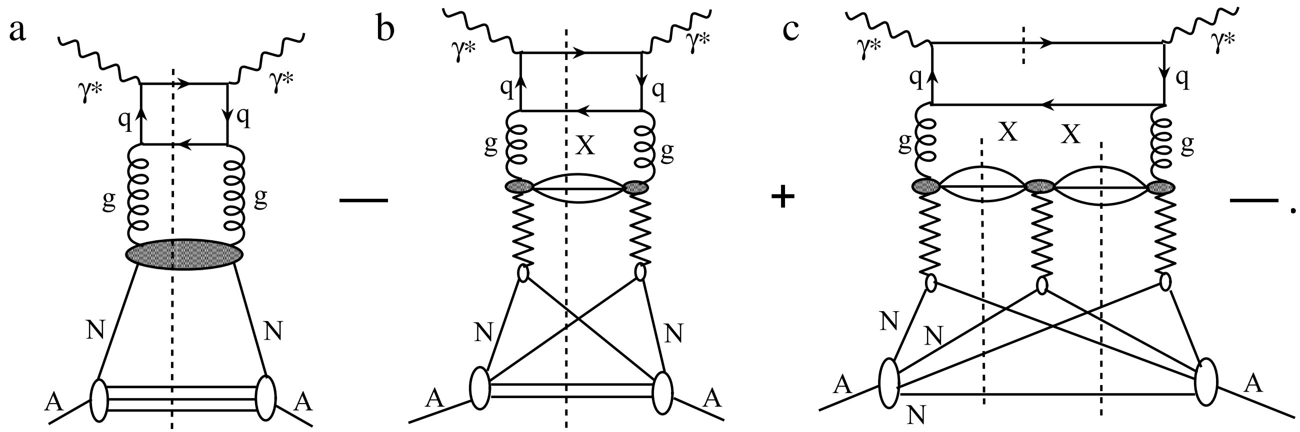
$$S(W_{\gamma p}) = \left[\frac{\sigma_{\gamma Pb\to J/\psi Pb}}{\sigma^{\mathrm{IA}}_{\gamma Pb\to J/\psi Pb}}\right]^{1/2} = \kappa_{A/N}\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)} = \kappa_{A/N}R_g$$

Impulse approx.

Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290

Leading twist nuclear shadowing model

- Combination of Gribov-Glauber NS model with QCD factorization theorems for inclusive and diffractive DIS → shadowing for individual partons j, Frankfurt, Strikman (1999)



- Interaction with 2 nucleons: model-indep via diffractive PDFs: $$\sigma_2^j(x) = \frac{16\pi}{x f_{j/N}(x,\mu^2)} \int_x^{0.1} dx_P \beta f_{j/N}^{D(4)}(x,\mu^2,x_P,t=0)$$

- Interaction with ≥ 3 nucleons: via soft hadronic fluctuations of γ^*: $$\sigma_{\text{soft}}(x) = \frac{\int d\sigma P_\gamma(\sigma)\sigma^3}{\int d\sigma P_\gamma(\sigma)\sigma^2}$$

P(σ) probability to interact with cross section σ

- In quasi-eikonal approximation in low-x limit, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

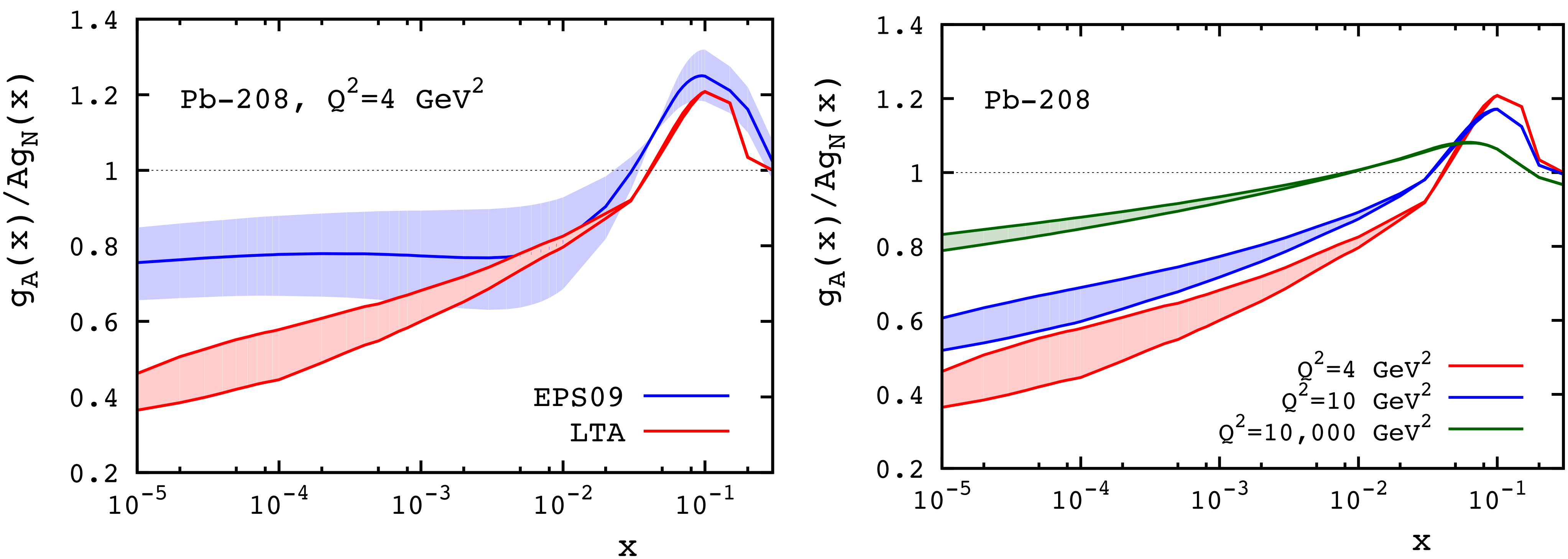
$$x f_{j/A}(x,\mu^2) = A f_{j/N}(x,\mu^2) - \frac{2\sigma_2^j f_{j/N}(x,\mu^2)}{[\sigma_{\text{soft}}^j(x)]^2} \int d^2b \left(e^{-\frac{1}{2}\sigma_{\text{soft}}^j(x) T_A(b)} - 1 + \frac{\sigma_{\text{soft}}^j(x)}{2} T_A(b) \right)$$

Leading twist nuclear shadowing model (2)

- Model gives nuclear PDFs at μ^2=3-4 GeV^2 for subsequent DGLAP evolution.
- Name "leading twist" since diffractive structure functions/PDFs measured at HERA scale with Q^2.
- Gluon diffractive PDFs are large, ZEUS, H1 2006 → predict large shadowing for $g_A(x,\mu^2)$, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

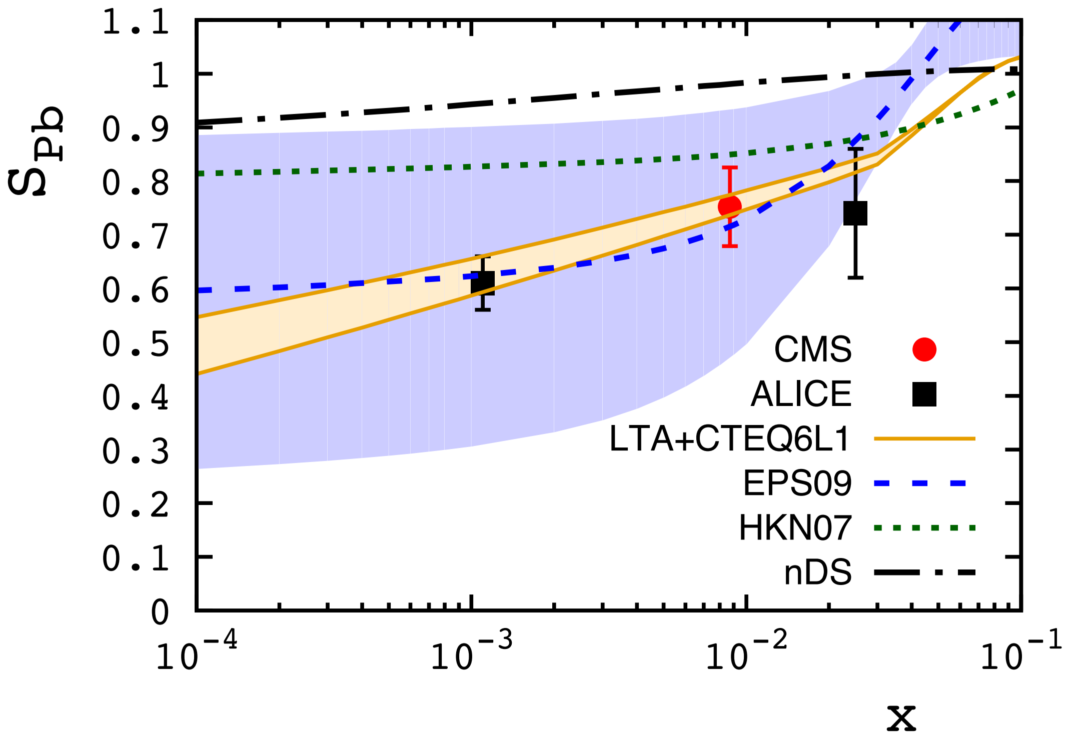
Input: Leading twist (LTA) vs. EPS09

Results of DGLAP evolution: from Q^2=4 GeV^2 to Q^2=10 and 10,000 GeV^2



For quarks, the agreement between LTA and EPS09 is much better.

Comparison to S_{Pb} from ALICE and CMS UPC data



LTA: Guzey, Zhalov JHEP 1310 (2013) 207
EPS09: Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065
HKN07: Hirai, Kumano, Nagai, PRC 76 (2007) 065207
nDS: de Florian, Sassot, PRD 69 (2004) 074028

Abelev *et al*. [ALICE], PLB718 (2013) 1273;
Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617;
CMS Collab., arXiv:1605.06966

- Good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs@2.76 TeV → first direct evidence of large gluon NS, Rg(x=0.001) ≈ 0.6.
- Similarly good description using central value of EPS09+CTEQ6L, large uncertainty.
- Qualitatively similar large nuclear suppression is predicted in kT-factorization approach, Cisek, Schafer, Szczurek, PRC86 (2012) 014905.
- Dipole model cannot (Goncalves, Machado PRC84 (2011) 011902; Lappi, Mantysaari, PRC 87 (2013) 032201), but sometimes can (Goncalves, Moreira, Navarra, PRC90(2014) 015203; G. Chen et al, arXiv:1610.04945) describe the data → talks by **G. Chen, W. Schaefer, B. Gay Ducati, H. Mantysaari**

3D nuclear gluon distribution

- Large LT nuclear shadowing does not only suppress $\gamma A \rightarrow J/\psi A$ cross section, but also shifts its t-dependence towards smaller |t| → access to impact parameter dependent nPDF $g_A(x,b,Q^2)$

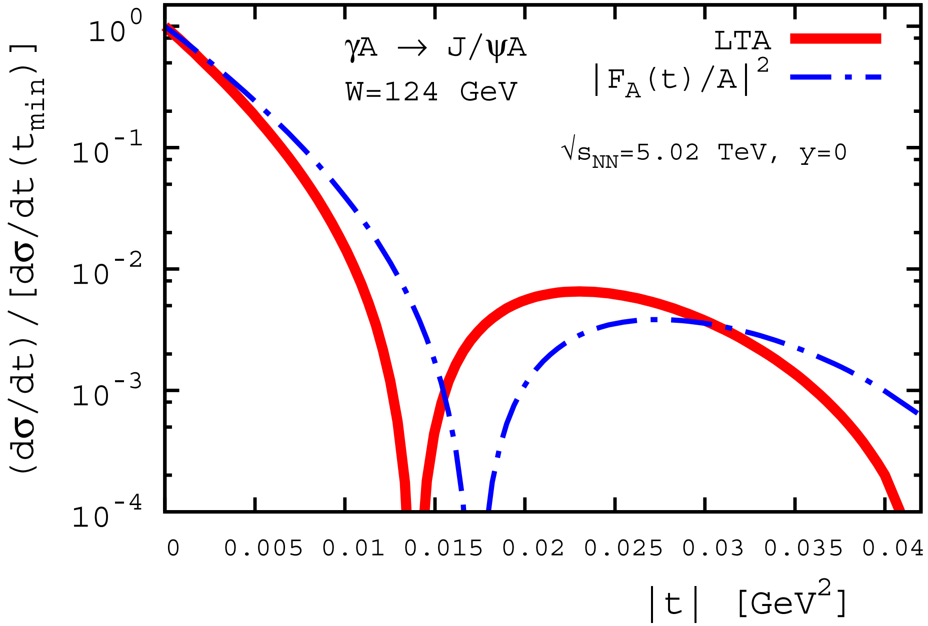
$$\frac{d\sigma_{\gamma A \to J/\psi A}}{dt} = \frac{d\sigma_{\gamma p \to J/\psi p}(t=0)}{dt} \left(\frac{R_{g,A}}{R_{g,p}}\right)^2 \left[\frac{\int d^2b\, e^{i\vec{q}_\perp \vec{b}} g_A(x,b,\mu^2)}{A g_p(x,\mu^2)}\right]^2$$

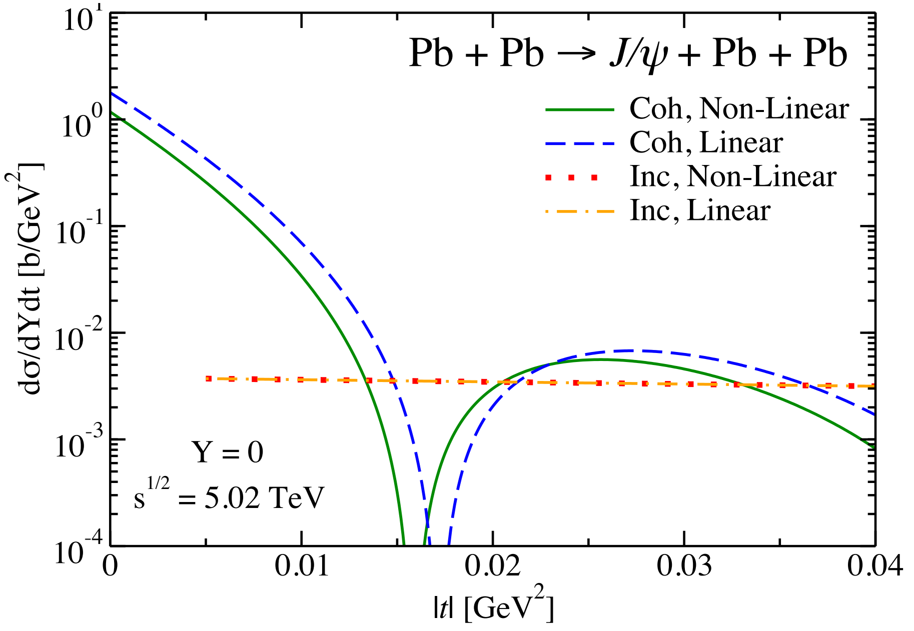
predicted by LT shadowing model

extracted/guessed in EPS09s, Helenius et al, JHEP 1207 (2012) 073

- Resulting shift can be interpreted as **5-11% broadening** in impact parameter space of gluon nPDF, Guzey, Strikman, Zhalov, arXiv:1611.05471 (accepted to PRC)

- Similar effect is predicted to be caused by saturation, but magnitude is smaller, Cisek, Schafer, Szczurek, PRC86 (2012) 014905; Lappi, Mantysaari, PRC 87 (2013) 032201; Toll, Ullrich, PRC87 (2013) 024913; Goncalves, Navarra, Spiering, arXiv:1701.04340





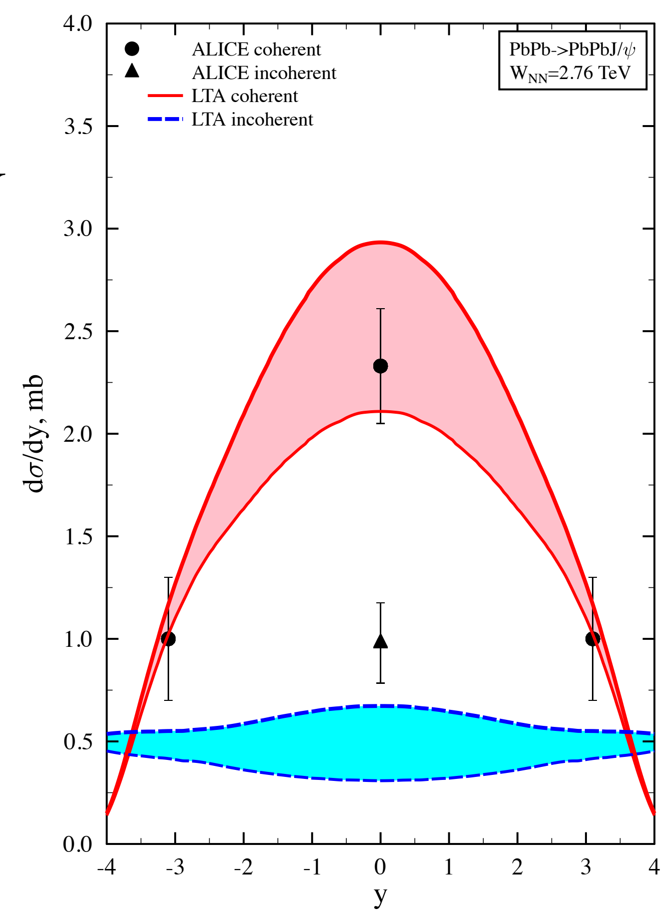
Q1: Incoherent J/ψ photoproduction in Pb-Pb UPCs@LHC

• LT nuclear shadowing model makes predictions for incoherent J/ψ photoproduct. on nuclei without additional parameters, Guzey, Strikman, Zhalov, EPJ C 74 (2014) 2942

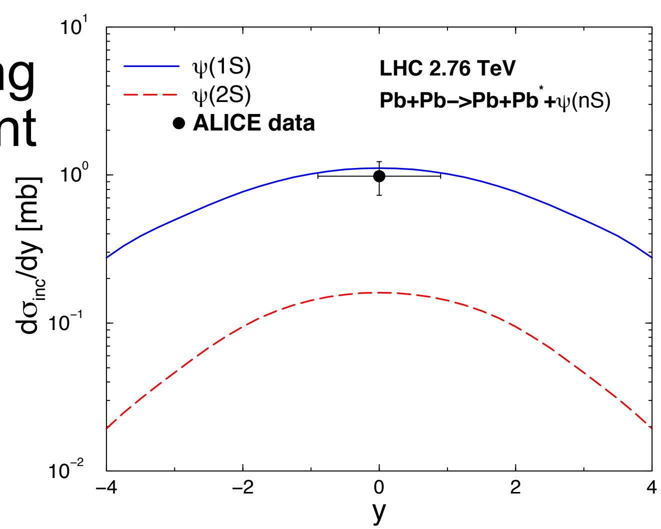
$$S_{\rm incoh}(W_{\gamma p}) \equiv \frac{d\sigma^{\rm pQCD}_{\gamma A\to J/\psi A'}(W_{\gamma p})/dt}{A d\sigma^{\rm pQCD}_{\gamma p\to J/\psi p}(W_{\gamma p})/dt} = \frac{1}{A}\int d^2\vec{b}\, T_A(b)\left[1-\frac{\sigma_2}{\sigma_3}+\frac{\sigma_2}{\sigma_3}e^{-\sigma_3/2 T_A(b)}\right]^2$$

• ... and predicts too much shadowing

• One possible source of discrepancy: contribution of nucleon dissociation $\gamma + N \to J/\psi + Y$
→ singled out by different t-dep.



• Dipole models with typically weaker shadowing are closer to the incoherent data, Lappi, Mantysaari, PRC 87 (2013) 032201; Gay Ducati, Griep, Machado, PRC88 (2013) 014910

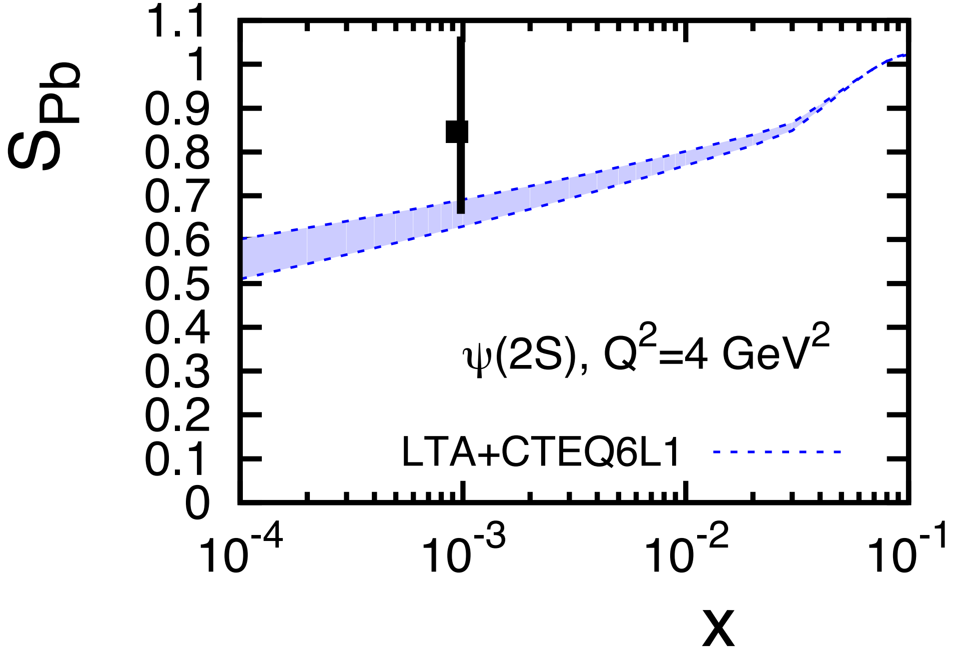


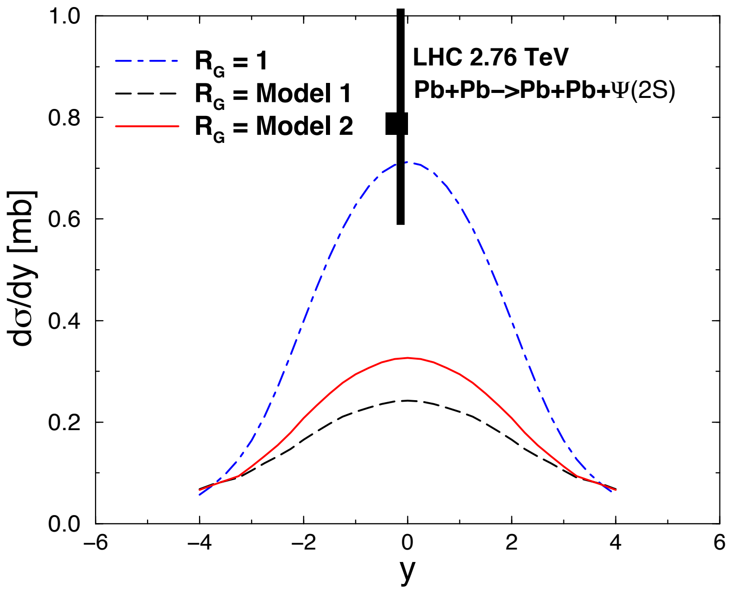
Q2: ψ(2S) photoproduction in Pb-Pb UPCs@LHC

• Our LTA approach naturally predicts similar suppression for J/ψ and ψ(2S) → tension with ALICE data on ψ(2S) photoproduction in Pb-Pb UPCs at y=0 indicating less shadowing, Adam *et al*. [ALICE], PLB751 (2015) 358

• The versions of the dipole model, which do not describe coherent J/ψ data, work reasonable well for coherent ψ(2S), Gay Ducati, Griep, Machado, PRC88 (2013) 014910.

LTA: Guzey, Zhalov, arXiv:1404.6101





→ challenge to reconcile theoretical description of data on coherent and incoherent J/ψ and coherent ψ(2S) photoproduction in Pb-Pb UPCs.

Q3: Impact on global QCD fits of nPDFs

- In our approach, we use

$$\frac{d\sigma_{\gamma T\to J/\psi T}(W,t=0)}{dt} = C(\mu^2)\left[xG_T(x,\mu^2)\right]^2$$

- We fix μ^2 and $C(\mu^2)$ using W-dependence of cross section on proton measured at HERA:

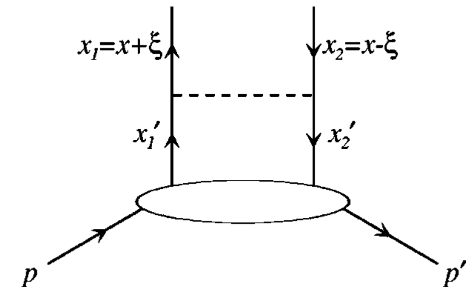
- $\mu^2 \approx 3$ GeV^2 for J/ψ, Guzey, Zhalov JHEP 1310 (2013) 207
- $\mu^2 \approx 4$ GeV^2 for $\psi(2S)$, Guzey, Zhalov, arXiv:1405.7529

- In LO of collinear factorization for exclusive processes and NR expansion for J/ψ distribution amplitude (wave function), cross section is in terms of gluon GPD:

$$\frac{d\sigma_{\gamma T\to J/\psi T}(W,t=0)}{dt} = \frac{16\pi^3\Gamma_{ee}}{3\alpha_{\mathrm{e.m.}}M_V^5}\left[\alpha_S(\mu^2)H^g(\xi,\xi,t=0,\mu^2)\right]^2$$

- At high energies (small ξ) and LO, GPDs can be connected to PDFs in a weakly model-dependent way:

  - At low μ_0, $x_{1,2} \gg \xi \rightarrow$ skewness can be neglected
  - All skewness at $\mu > \mu_0$ due to evolution, Frankfurt, Freund, Guzey, Strikman, PLB 418 (1998) 345; Shuvaev et al., RPD 60 (1999) 014015



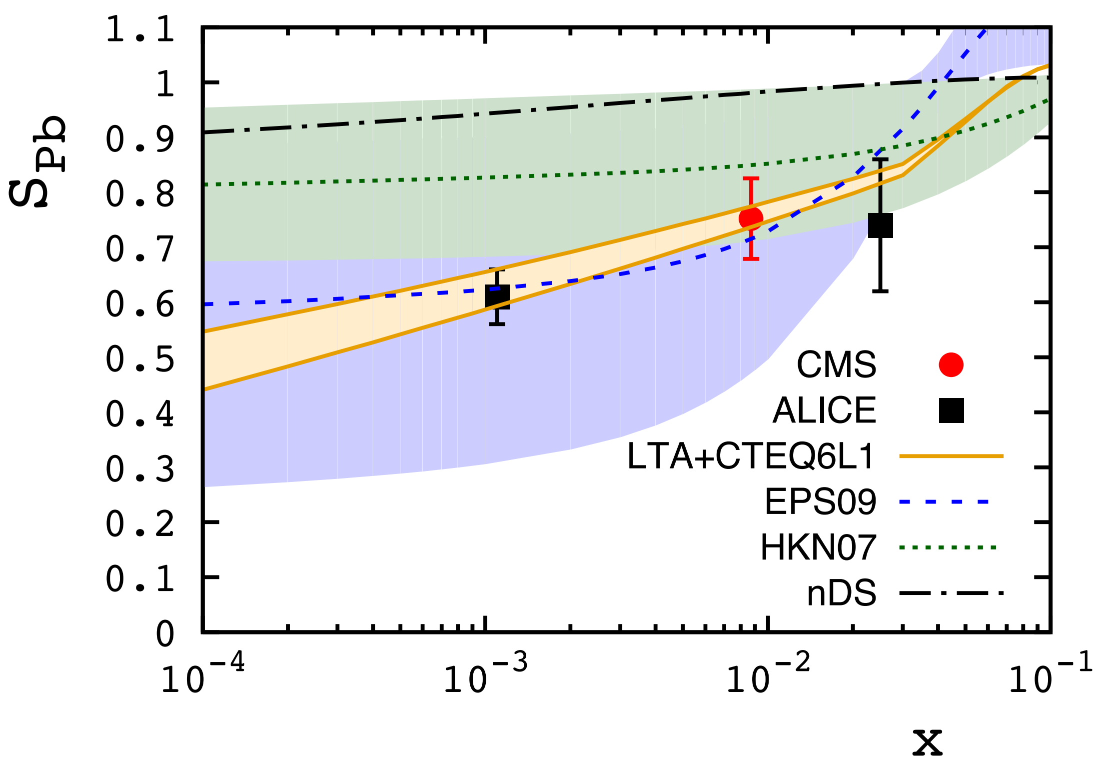
$$H^g(\xi,\xi,t=0,\mu^2) = R_g xg(x_B,\mu^2)$$

$$R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}}\frac{\Gamma(\lambda+5/2)}{\Gamma(4+\lambda)} \approx 1.2, \quad \text{for } xg \sim 1/x^\lambda \text{ with } \lambda \approx 0.2$$

Q3: Impact on global QCD fits of nPDFs (2)

• NLO corrections are very large, Ivanov, Schafer, Szymanowski, Krasninov, EPJ C 75 (2015) 2, 75; Jones, Martin, Ryskin, Teubner, J. Phys. G43 (2015) 035002, but can be tamed by choice of factorization scale $\mu=m_c$ and other tricks, Jones et al, Eur.Phys.J. C76 (2016) 633.

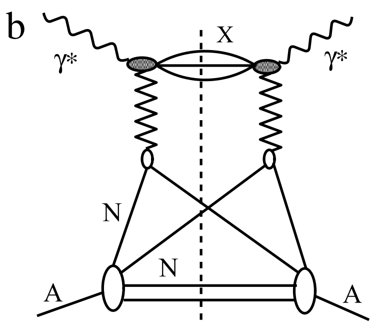
• However, in the nuclear suppression factor S_{Pb} many complications (skewness, NLO and higher-twist corrections) are likely minimized → use S_{Pb} in global QCD fits of nPDFs.



Q4: Leading twist vs. dipole model vs. saturation

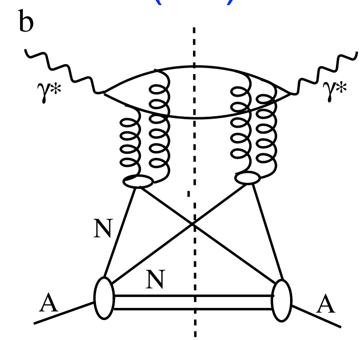
- Principal difference between our LTA and dipole model: Frankfurt, Guzey, McDermott, Strikman 2002

Triple-Pomeron coupling to 2 nucleons



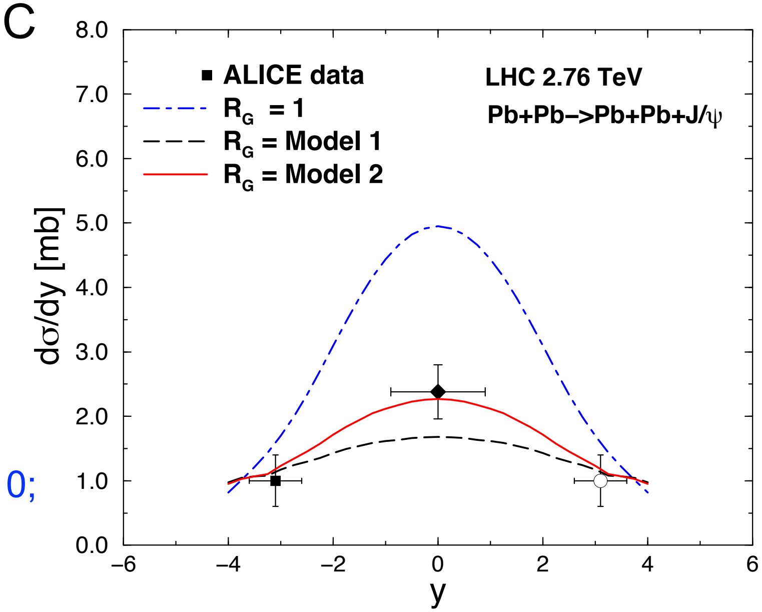
vs.

Separate Pomeron couplings to 2 nucleons → higher twist (HT) for small dipoles



- The difference should manifest itself in observables dominated by small-size dipoles:

- nuclear longitudinal structure function $F_L^A(x,Q^2)$ at LHeC/EIC
- cross section of J/ψ photoproduction on nuclei in UPCs@LHC



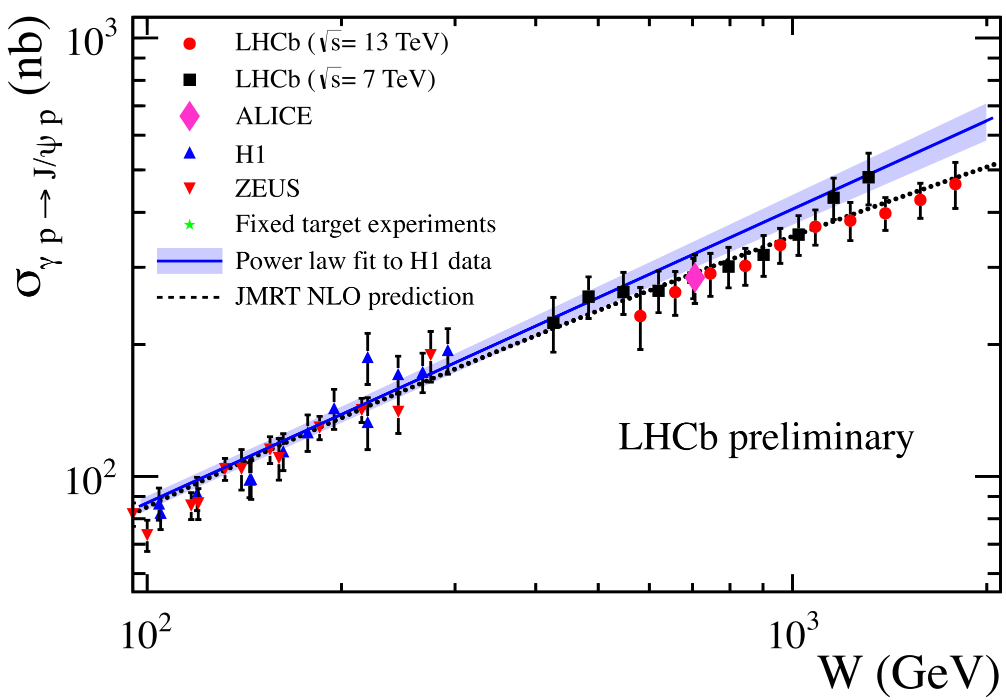
- As soon as dipole model includes q-qbar-g, q-qbar-2g, etc. dipoles → correctly models diffraction → reproduces large inelastic Gribov shadowing.

Gay Ducati, Griep, Machado, PRC88 (2013) 014910;
Cisek, Schafer, Szczurek, PRC86 (2012) 014905

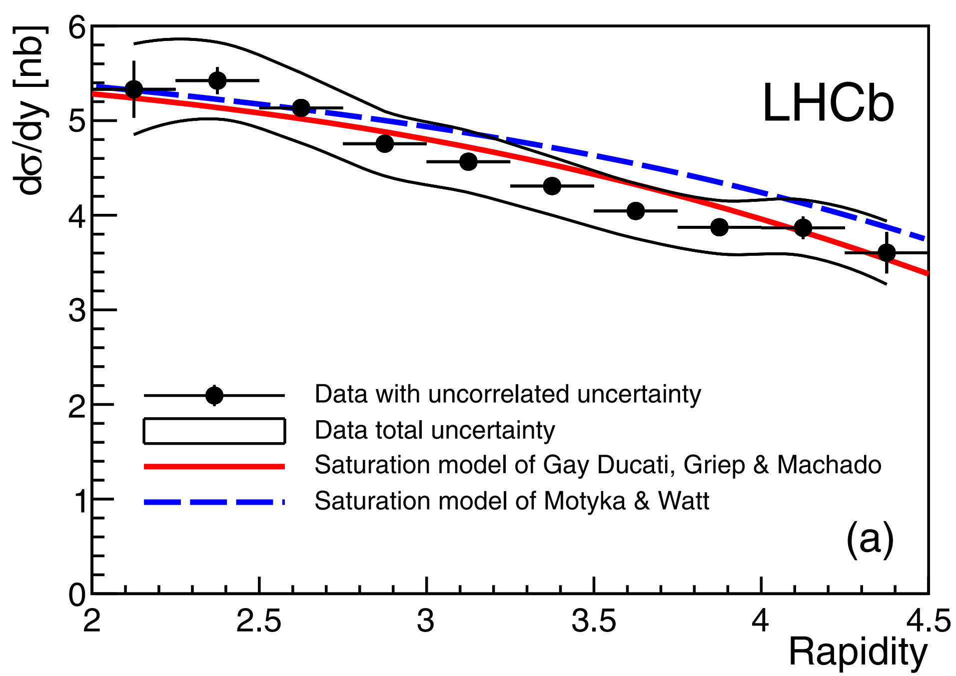
Q4: Leading twist vs. dipole model vs. saturation (2)

- Saturation of dipole cross section is part of dynamics of color dipole models.
- Since dipoles models have large theoretical uncertainties and non-perturbative contributions, *in my opinion*, LHC data on vector meson photoproduction in UPCs has not allowed so far to unambiguously establish necessity of saturation.
- All the data can also be described in collinear factorization and kt-factorization frameworks.
- Example: J/ψ photoproduction in pp UPCs measured by LHCb in Run 1 and 2:

LHCb-CONF-2016-007



LHCb, J. Phys. G 41 (2014) 055002

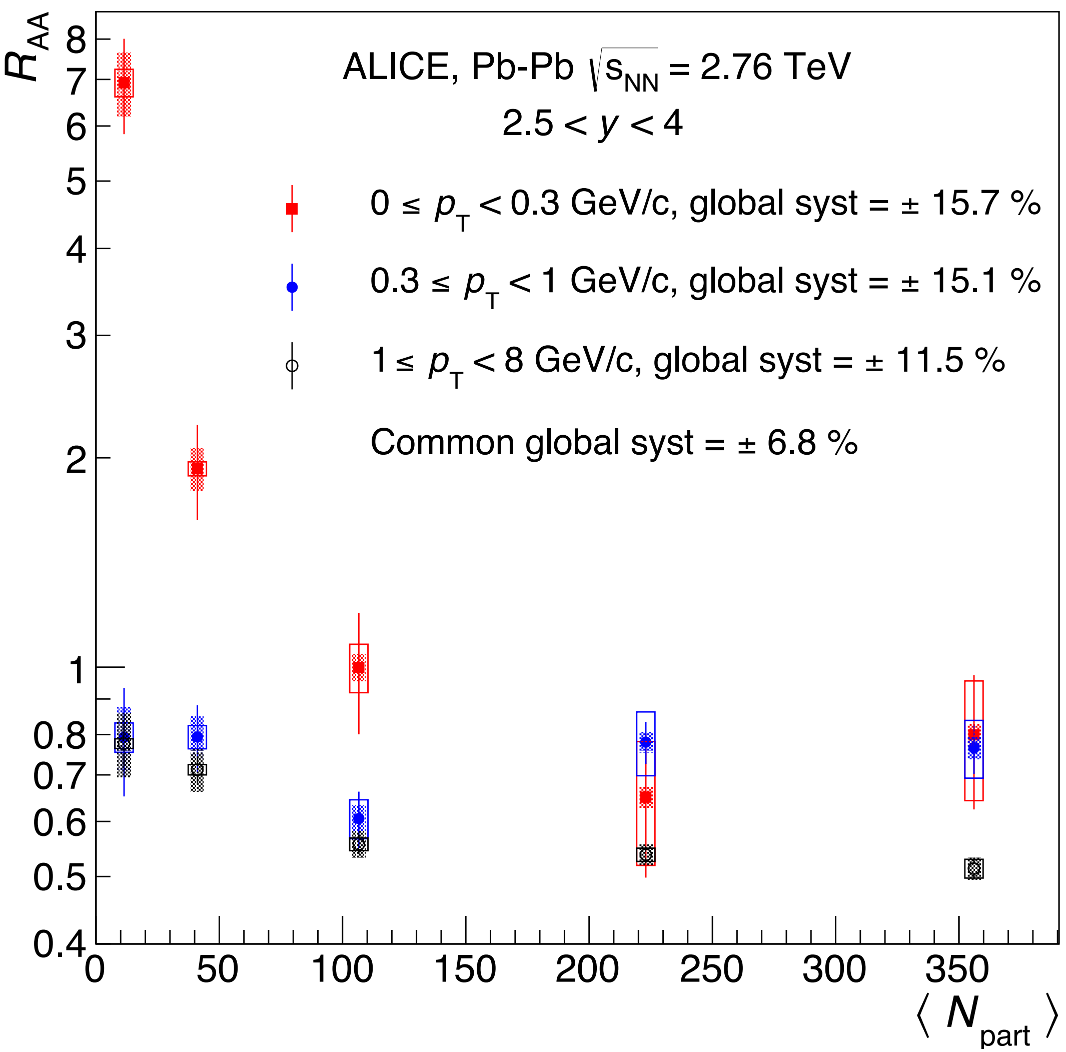


Q5: Peripheral production of J/ψ in Pb-Pb collisions

- Very interesting recent data: enhanced J/ψ yield in AA *peripheral* collisions at small pT.

J. Adam et al [ALICE], PRL 116 (2016) 222301

Possible interpretation: coherent photoproduction on nucleus fragment(s).



Outlook: other UPC processes

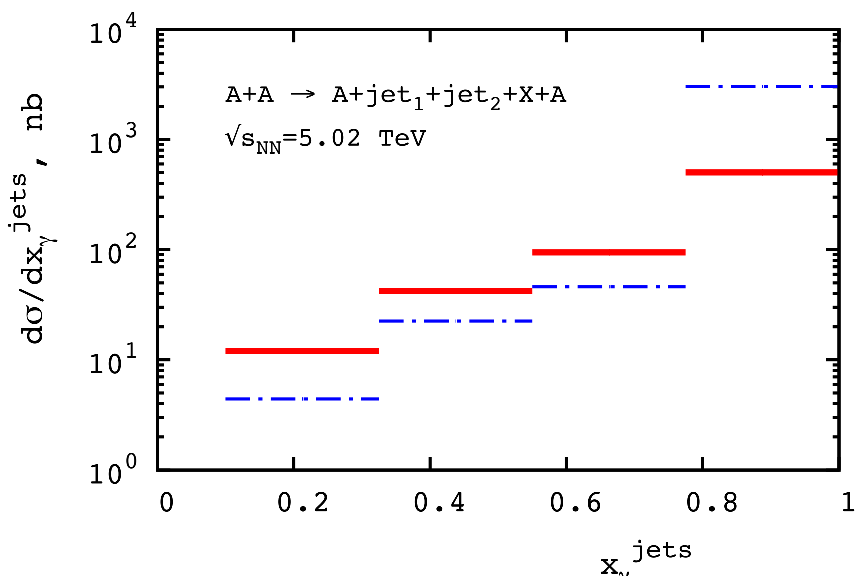
- Photoproduction of Υ:
  - will allows one to study μ^2 dependence of shadowing suppression and $g_A(x,\mu^2)$ at small x
  - NLO and HT corrections are smaller, Ivanov, Schafer, Szymanowski, Krasninov, EPJ C 75 (2015) 2, 75; Jones, Martin, Ryskin, Teubner, J. Phys. G43 (2015) 035002
  - Dipole models have still large uncertainty, Goncalves, Moreira, Navarra, arXiv:1408.1344.

- UPCs accompanied by forward neutron emission: possibility to probe smaller x, Guzey, Strikman, Zhalov, EPJ C (2014) 74: 2942

- Photoproduction of dijets in AA UPCs: complimentary probe of $g_A(x,\mu^2)$ at small x and large μ^2, Strikman, Vogt, White, PRL 96 (2006) 082001 ⟶ **talks by A. Angerami, P. Kotko**

- *Diffractive* photoproduction of dijets in UPCs, Guzey, Klasen JHEP 1604 (2016) 158:

  - access to nuclear diffractive PDFs at small x
  - probe of mechanism of QCD factorization breaking: global suppression vs. resolved-only suppression ⟶



Summary

• Coherent photoproduction of vector mesons on nuclei in UPCs@LHC allows one to study nuclear shadowing in soft and hard processes at unprecedentedly high energies.

• Photoproduction of ρ and ϕ on nuclei tests the roles of hadronic fluctuations of the photon and inelastic nuclear shadowing.

• Photoproduction of J/ψ, ψ' and Y on nuclei gives direct access to the nuclear gluon distribution $g_A(x,\mu^2)$ down to $x \approx 10^{-3}$ (5×10^{-4}) at $\mu^2 \approx$ 3-4 GeV^2 and allows one to study its μ^2 dependence; direct evidence of large gluon nuclear shadowing Rg(x=0.001) =0.6.

• Apart from several mentioned problem, the available UPC data can be described by competing theoretical approaches — collinear factorization, kt-factorization, dipole models with/out saturation.

• Hopefully, new Run 2 UPC data on photoproduction of VM and jets will help to clarify the situation.