Nuclear shadowing in photoproduction of light and heavy vector mesons in ultraperipheral collisions of heavy ions at the LHC

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Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290
Guzey, Zhalov, JHEP 10 (2013) 207; JHEP 02 (2014) 046
Guzey, Strikman, Zhalov, EPJ C (2014) 74: 2942
Guzey, Zhalov, arXiv:1404.6101; 1405.7529
Frankfurt, Guzey, Strikman, Zhalov, PLB 732 (2016) 51
Guzey, Kryshen, Zhalov, PRC 93 (2016) 055206

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Outline:

- Nuclear shadowing and ultraperipheral collisions (UPCs)

- Soft inelastic nuclear shadowing in coherent photoproduction of ρ mesons on nuclei in UPCs at the LHC

- Hard inelastic nuclear shadowing in coherent photoproduction of J/ψ and ψ' mesons on nuclei in UPCs at the LHC and nuclear gluon density $g_A(x,\mu^2)$ at small x

- Conclusions

Nuclear shadowing

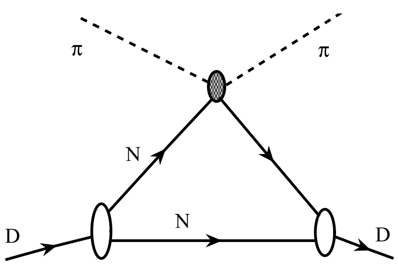
• Nuclear shadowing = suppression of cross section on a nucleus compared to sum of cross sections on individual nucleons: $\sigma_A < A\, \sigma_N$.

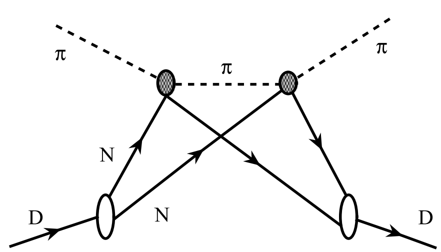
• Observed for beams of nucleons, pions, real and virtual photons, neutrinos, other hard probes of large energies (> 1 GeV)

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

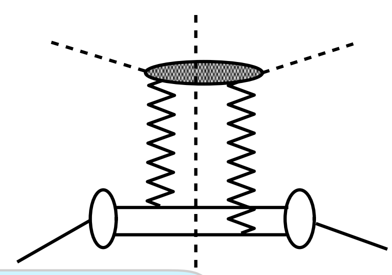
• Classic example: Pion-deuteron scattering. 2 contributions to shadowing:

- elastic intermediate state, Glauber 1955





- inelastic intermediate state, Gribov 1969



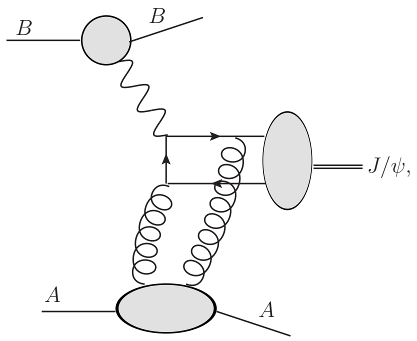
$$\sigma_{\rm tot}^{\pi D} = 2\sigma_{\rm tot}^{\pi N} - 2\int d\vec{k}^2 \rho(4k^2) \frac{d\sigma_{\rm diff}^{\pi N}(\vec{k})}{d\vec{k}^2}$$

deuteron form factor

diffractive cross section

Ultraperipheral collisions (UPCs)

• Ions can interact at large impact parameters $b > R_A + R_B = 10\text{-}20$ fm → ultraperipheral collisions (UPCs) → strong interaction suppressed → interaction via quasi-real photons, Fermi (1924), von Weizsäcker; Williams (1934)



- For studied vector meson production, UPCs correspond to empty detector with only two lepton (pion) tracks
- Nuclear coherence by veto on neutron production by Zero Degree Calorimeters (ZDCs) and selection on events with small (pt < 200 MeV/c) momentum transfer to the nucleus

• 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

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 using the vector meson dominance (VMD) model for $\gamma \to \rho$ transition and Glauber model for shadowing in ρA scattering:

Frankfurt, Strikman, Zhalov, 2002

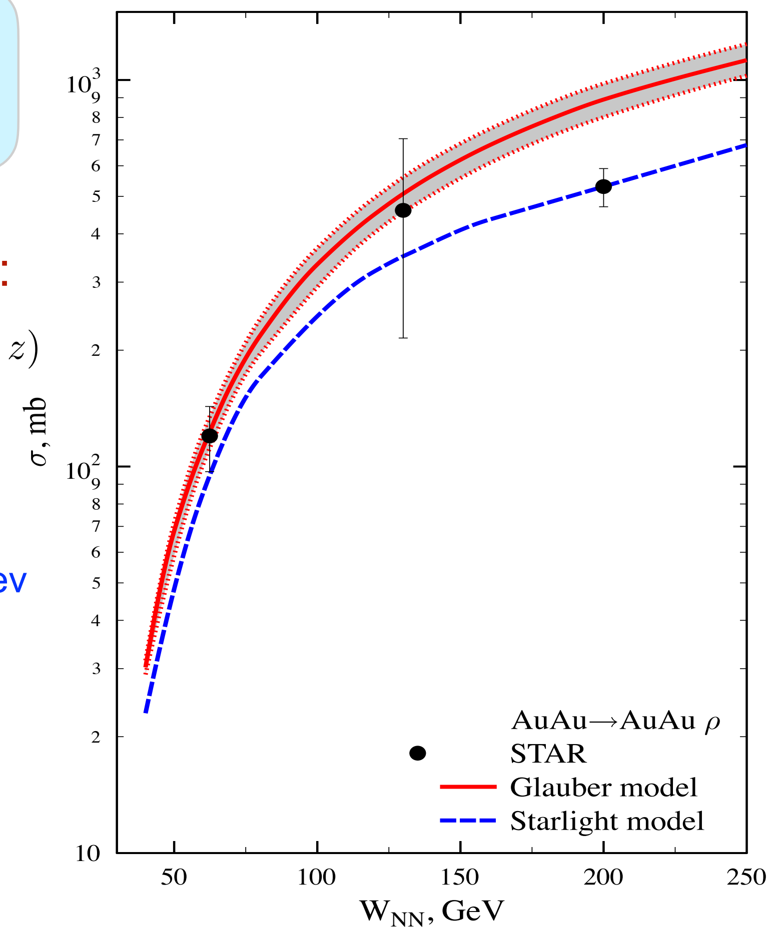
$$\sigma^{VMD}_{\gamma A \to \rho A} = \left(\frac{e}{f_\rho}\right)^2 \int d^2 b \left|1 - e^{-\frac{1}{2}\sigma_{\rho N} T_A(b)}\right|^2$$

f_ρ from e^+e^- decay

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

Optical density:

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



• This approach fails to describe large-W RHIC (STAR Coll.), 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 LHC data, Adam et al (ALICE), JHEP 1509 (2015) 095

• What is missing? Inelastic nuclear shadowing.

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(σ), Blattel et al, 1993

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

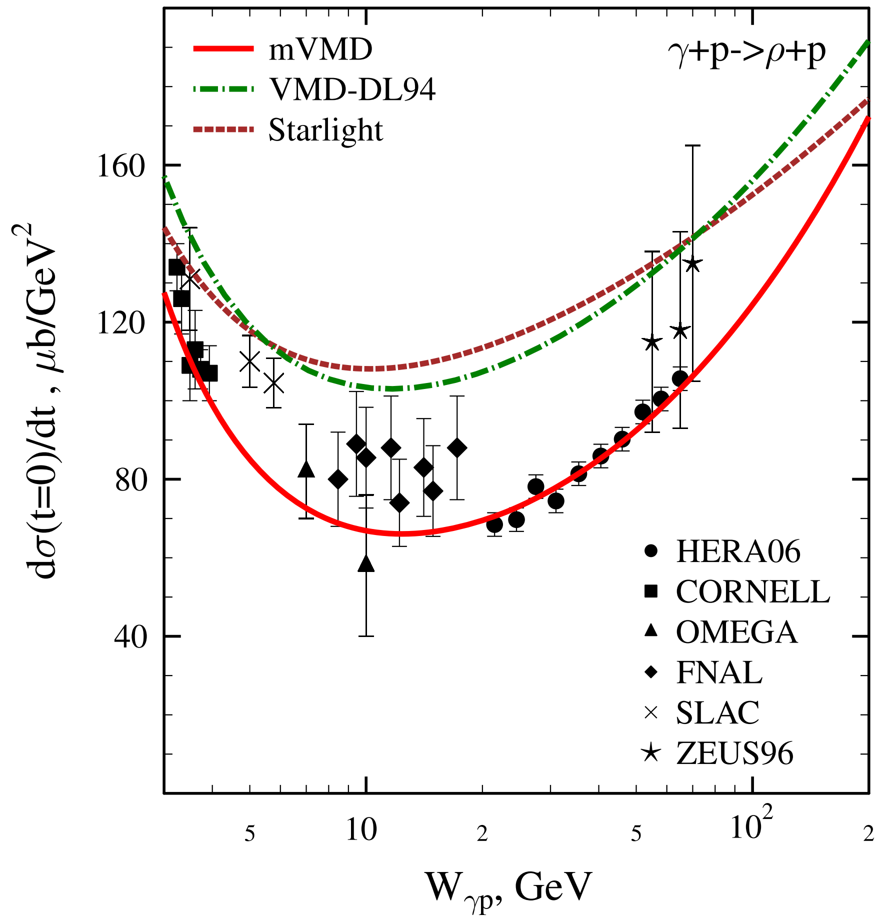
$$\int d\sigma\, P(\sigma)\sigma = \langle\sigma\rangle\,, \quad \rightarrow \text{ from } \quad d\sigma(\gamma p \rightarrow \rho p)/dt$$

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

→ 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 $\sigma_{\pi N}$ →

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



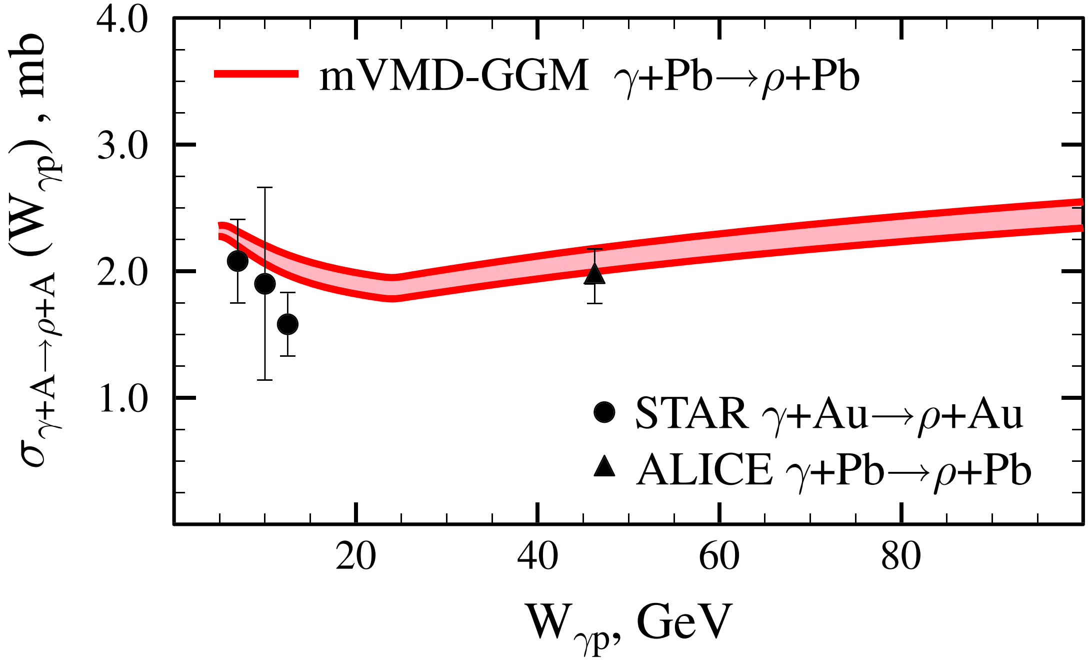
Photoproduction of ρ on Pb in mVMD+Gribov-Glauber model

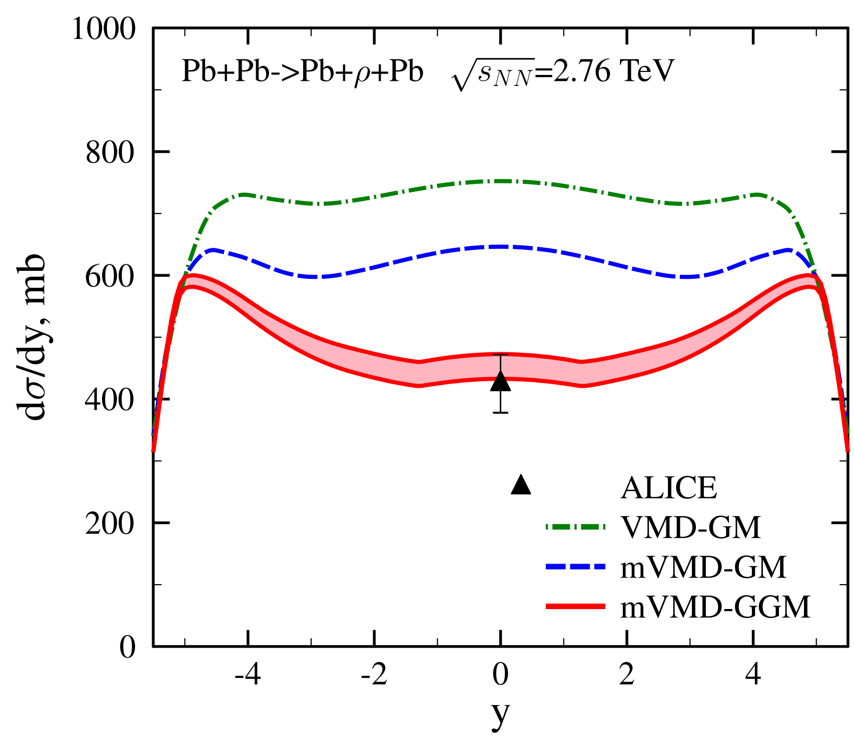
• With cross section fluctuations:

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

• “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



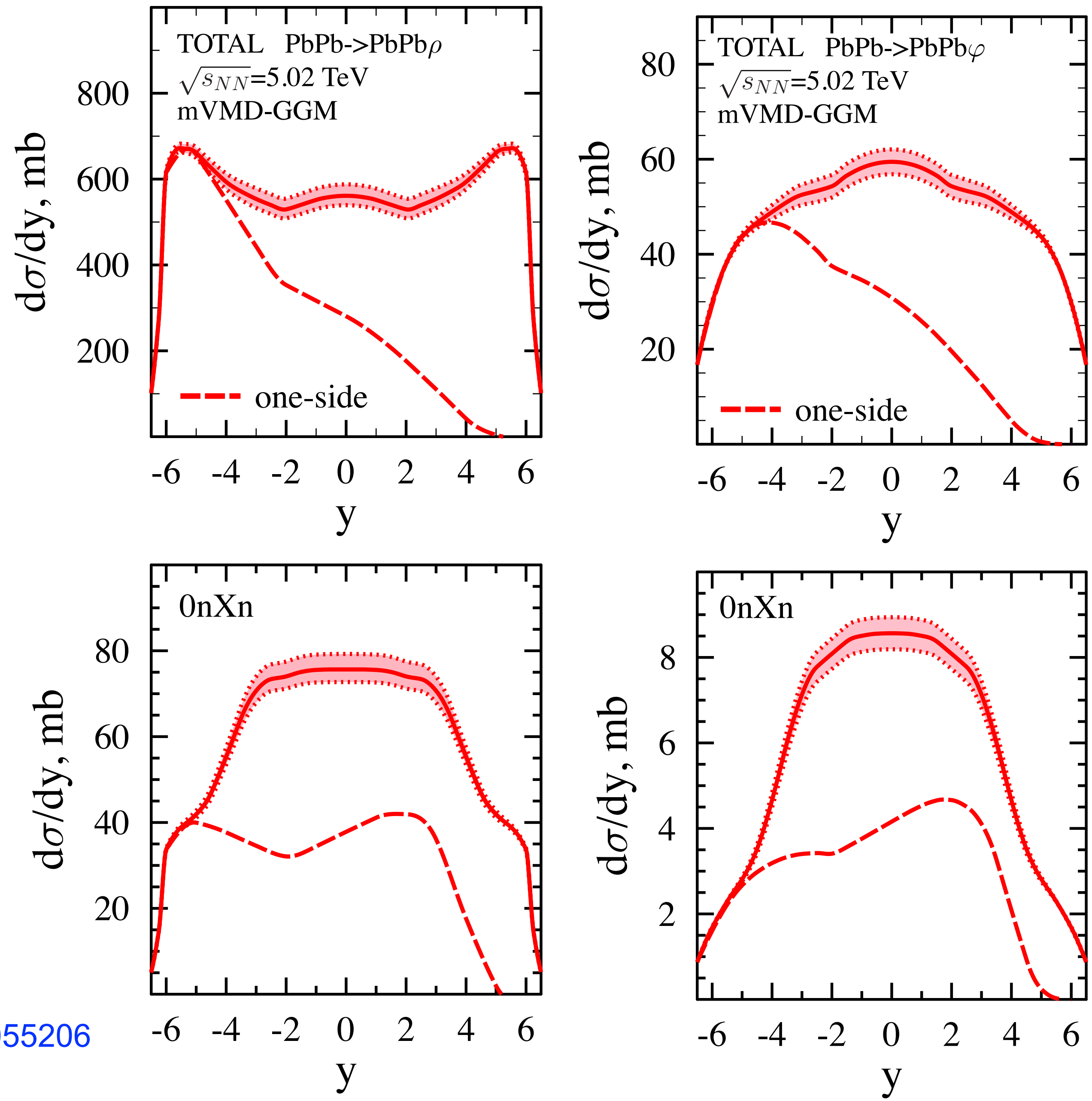


Predictions for Run 2@LHC: ρ and ϕ mesons

- 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

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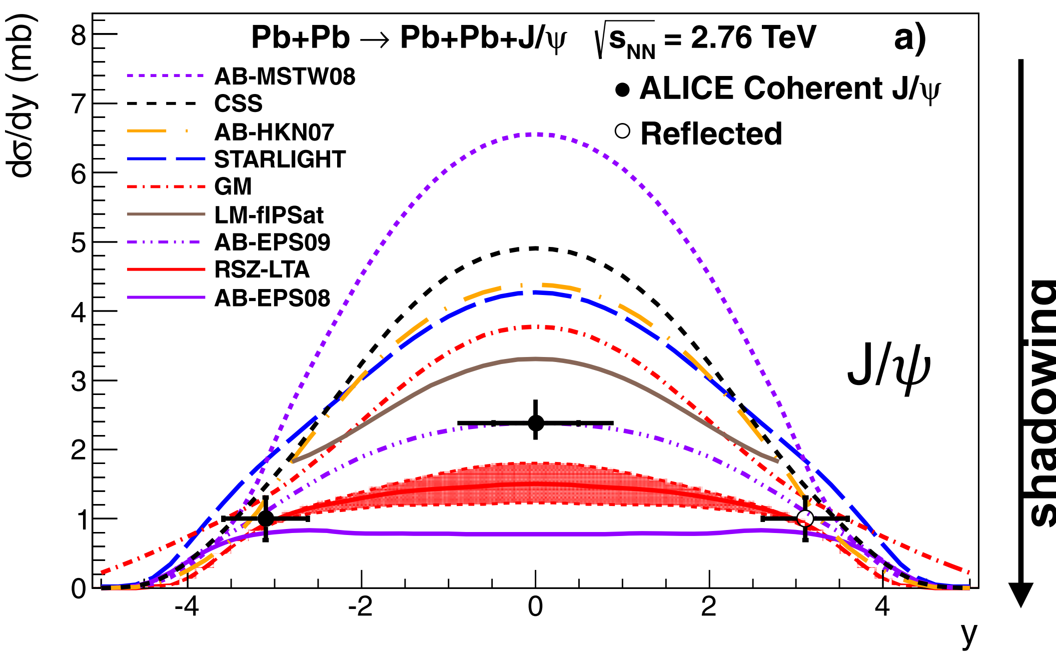
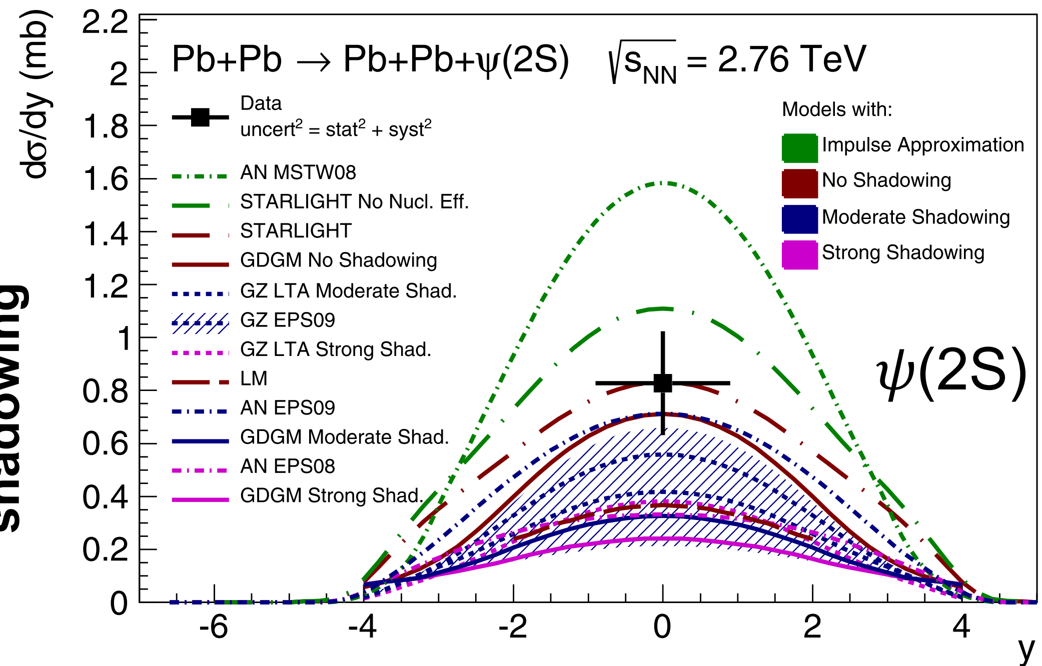
Coherent charmonium photoproduction@LHC

- ALICE measured photoproduction of J/ψ, ψ' in Pb-Pb UPCs at $\sqrt{s_{NN}}$=2.76 TeV

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

Adam *et al*. [ALICE], PLB751 (2015) 358





- “Consistent with models incorporating moderate nuclear gluon shadowing at x ≈10^{-3}”
- “Disfavors models implementing strong nuclear gluon shadowing”

Nuclear shadowing in nuclear gluon distribution

- Nuclear gluon distribution $g_A(x,\mu^2)$ = probability (at LO) to find gluon in nucleus with momentum fraction x at resolution scale μ^2.

- Important element of QCD phenomenology of hard processes with nuclei: cold nuclear matter effects (RHIC, LHC), gluon saturation (RHIC, LHC, EIC)

- $g_A(x,\mu^2)$ determined from global QCD fits to fixed-target DIS and dA data (RHIC)

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

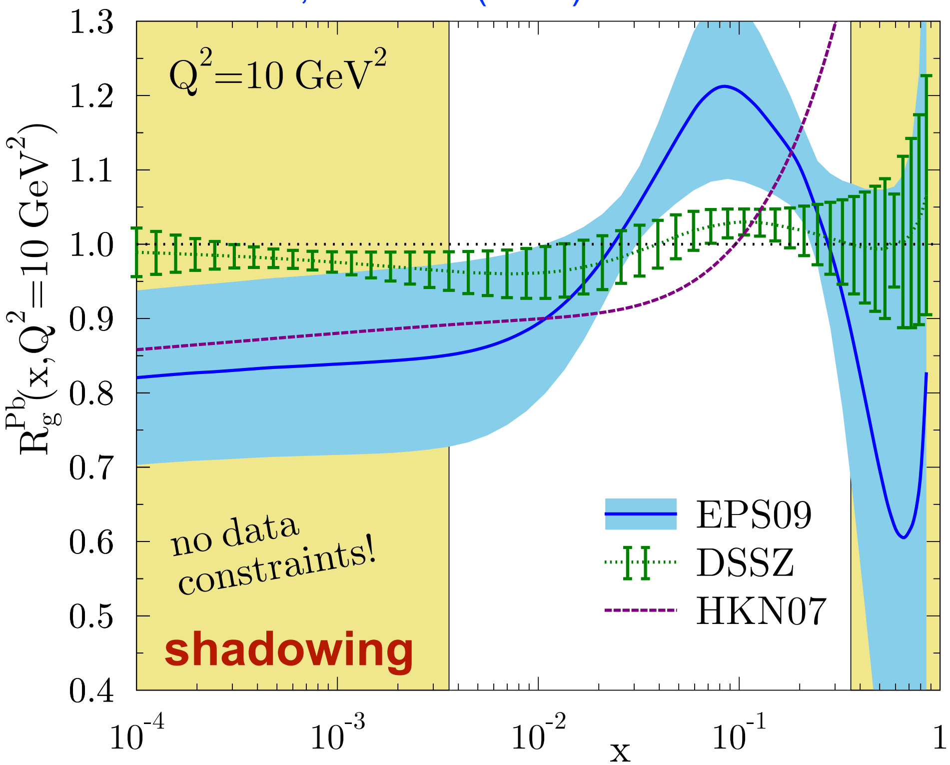
- At small x < 0.005, $g_A < Ag_N$ → shadowing: $g_A(x,\mu^2)$ is known with large uncertainties →

- pA@LHC data can help in antishadowing region, Armesto et al, arXiv: 1512.01528; Eskola et al, JHEP 1310 (2013) 213

- Best future option: Electron-Ion Collider in the US, Accardi et al, ArXiv:1212.1701

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

H. Pauukunen, NPA 926 (2014) 24

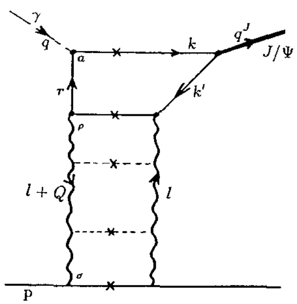


Exclusive charmonium photoproduction

- In leading logarithmic approximation of perturbative QCD and non-relativistic approximation for charmonium wave function (J/ψ, ψ(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(μ^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 $\kappa_{A/N} \approx 0.95$ — 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

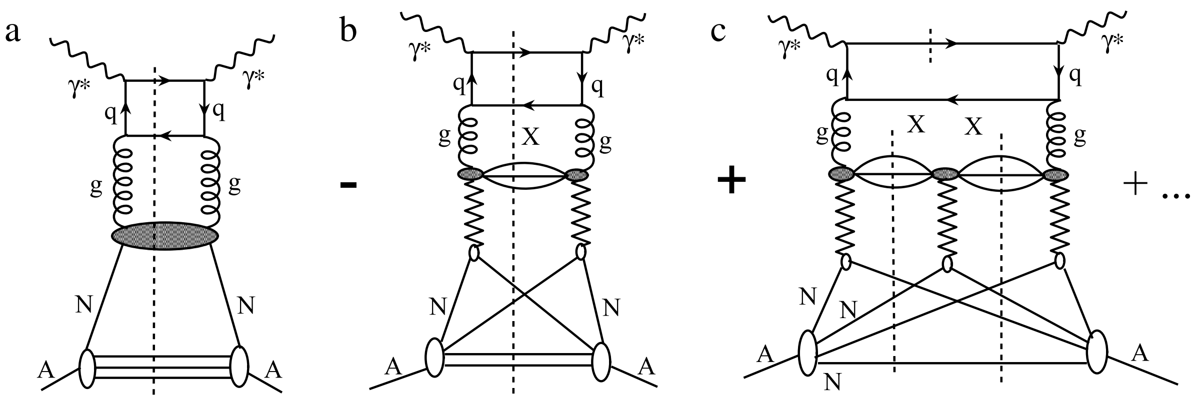
$$S(W_{\gamma p}) = \left[\frac{\sigma_{\gamma Pb\to J/\psi Pb}}{\sigma^{\mathrm{IA}}_{\gamma Pb\to J/\psi Pb}}\right]^{1/2} = \kappa_{A/N}\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)} = \kappa_{A/N}R_g$$

Impulse Approximation

Leading twist nuclear shadowing model

- Based on generalization of Gribov-Glauber model and QCD factorization,

Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

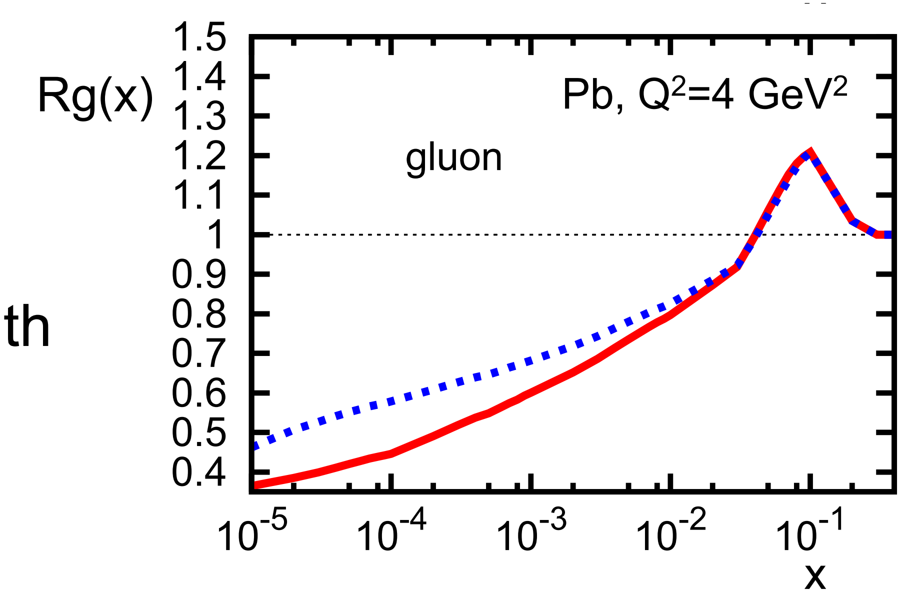


Inelastic shadowing dominates → given by diffraction in ep DIS

$$x f_{j/A}(x,Q_0^2) = A x f_{j/N}(x,Q_0^2) - 8\pi A(A-1)\,\Re e \frac{(1-i\eta)^2}{1+\eta^2} B_{\rm diff} \int_x^{0.1} dx_P\, \beta f_j^{D(3)}(\beta, Q_0^2, x_P)$$

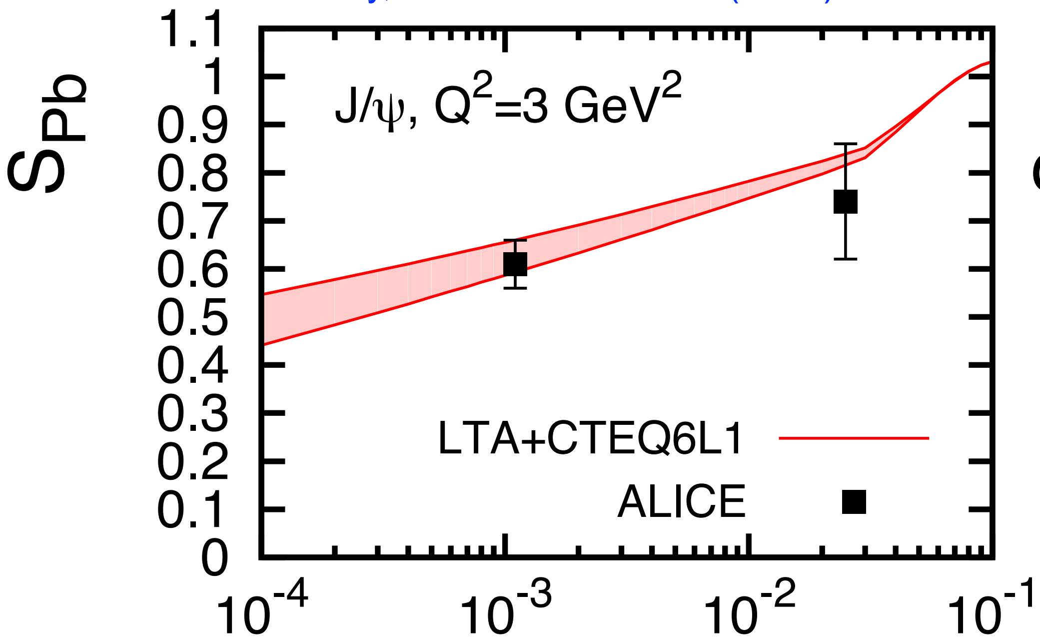
$$\times \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2) e^{i(z_1-z_2)x_P m_N} e^{-\frac{A}{2}(1-i\eta)\sigma^j_{\rm soft}(x,Q_0^2)\int_{z_1}^{z_2} dz' \rho_A(\vec{b},z')}$$

- Diffractive structure functions (dPDFs) measured at HERA are large and scale with Q^2 → large gluon shadowing predicted →



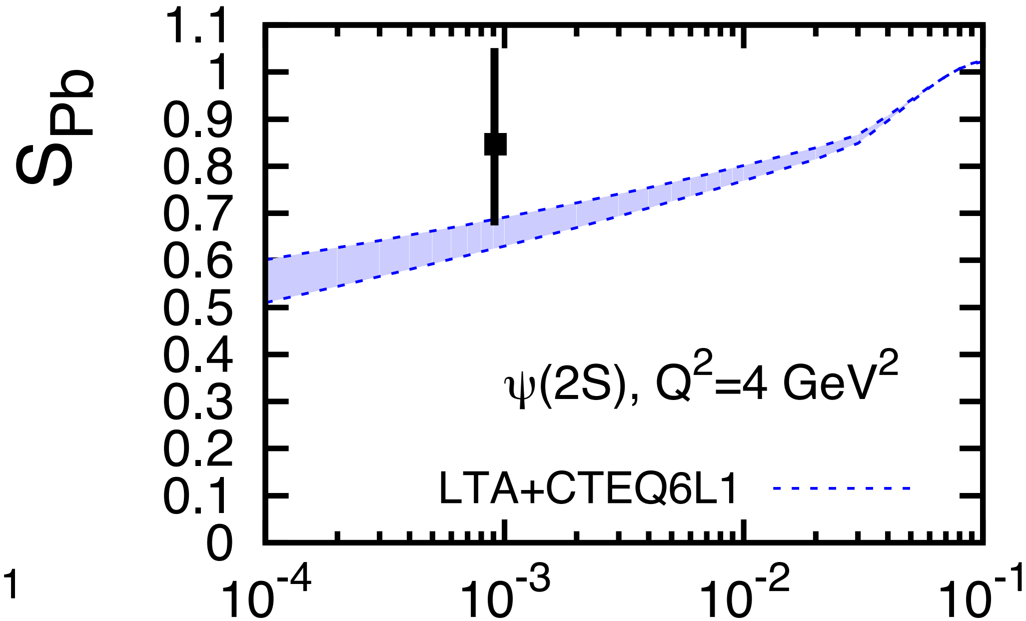
Comparison to S_{Pb} from ALICE UPC data

Guzey, Zhalov JHEP 1310 (2013) 207



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

Guzey, Zhalov, arXiv:1404.6101

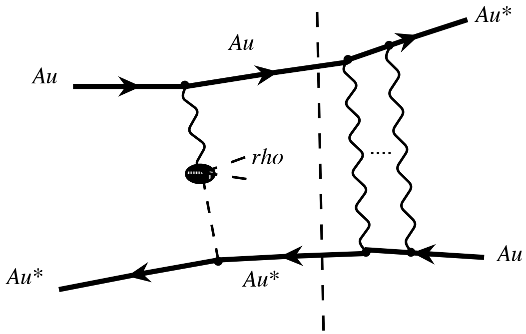


Adam *et al*. [ALICE], PLB751 (2015) 358

- Good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs@2.76 TeV → first direct evidence of large gluon nuclear shadowing at x=0.001.

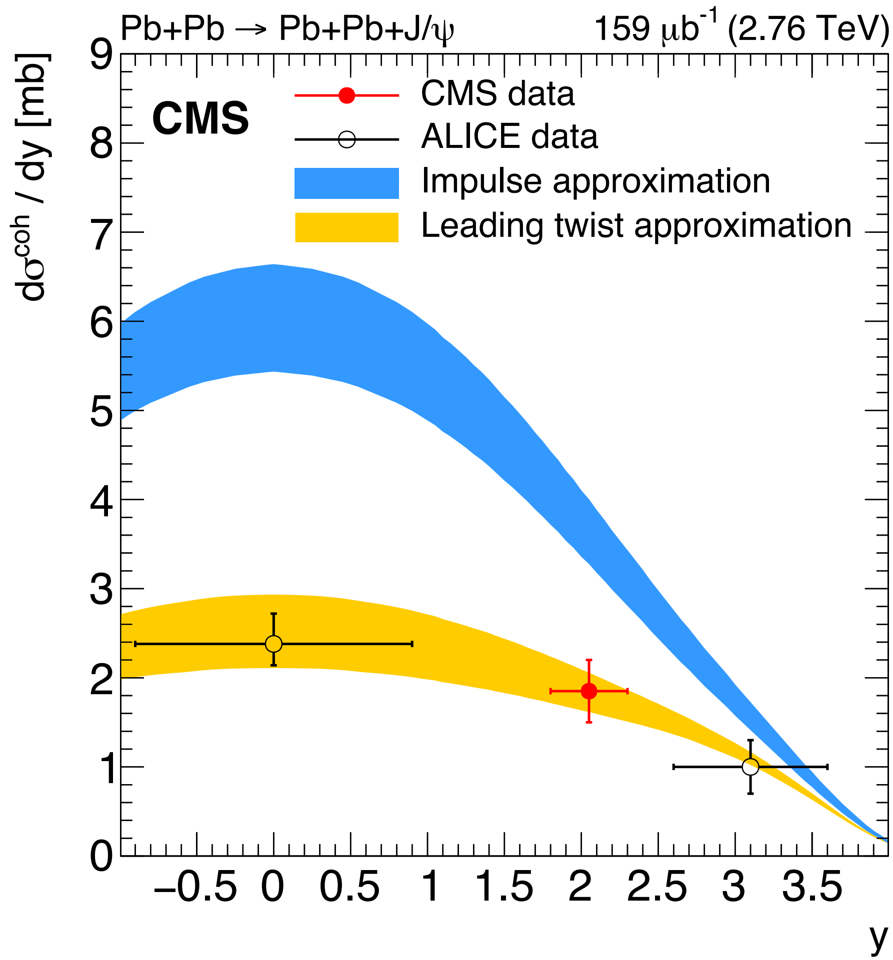
- We predict similar suppression J/ψ и ψ(2S) → tension with ALICE data on ψ(2S) photoproduction in Pb-Pb UPCs at y=0 → maybe resolved in Run 2.

Coherent J/ψ photoproduction in Pb-Pb UPCs with forward neutron emission



• UPCs can be accompanied by e.m. excitation of colliding ions followed by forward neutron emission, Baltz, Klein, Nystrand, PRL 89 (2002) 012301

• CMS data in 0nXn-channel* agrees very well with our predictions of large gluon shadowing, CMS, arXiv:1605.06966



Predictions for Run 2: J/ψ and ψ' mesons

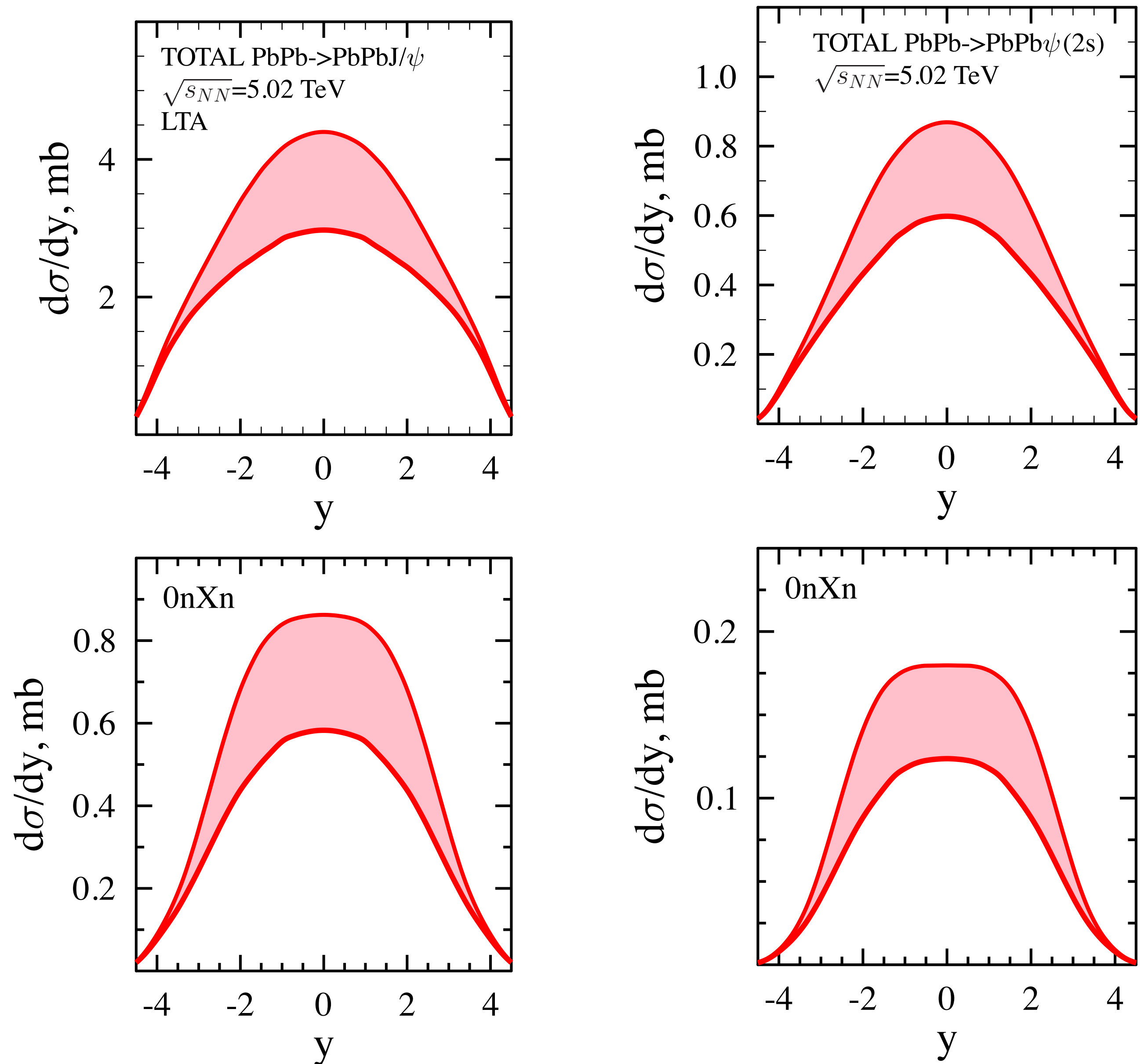
- Combination of LO pQCD and leading twist nuclear shadowing model:

- Measurement in two channels $\rightarrow$ separation of contributions of small and large $W_{\gamma p} \rightarrow g_A(x,\mu^2)$ at smaller x.

- Suppression due to nuclear shadowing same for J/ψ and ψ':

$$\frac{d\sigma_{\psi'}/dy}{d\sigma_{J/\psi}/dy} = 0.17 - 0.20$$

at y=0.



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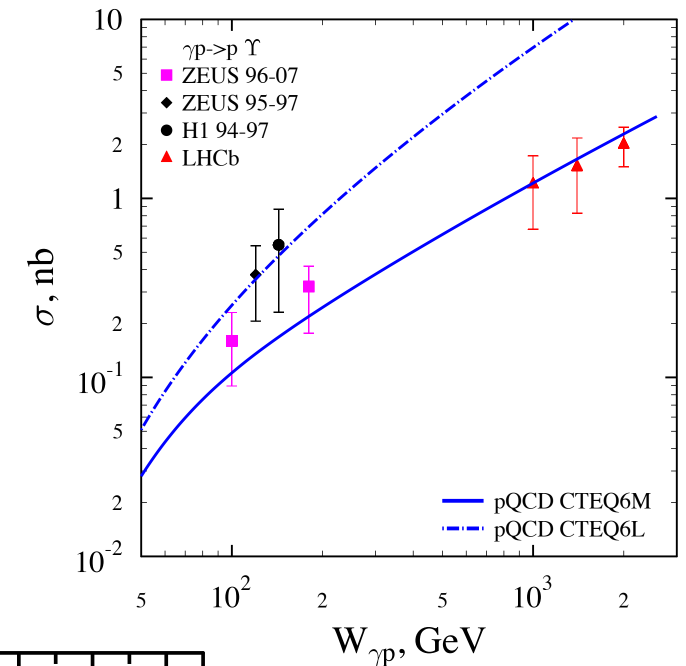
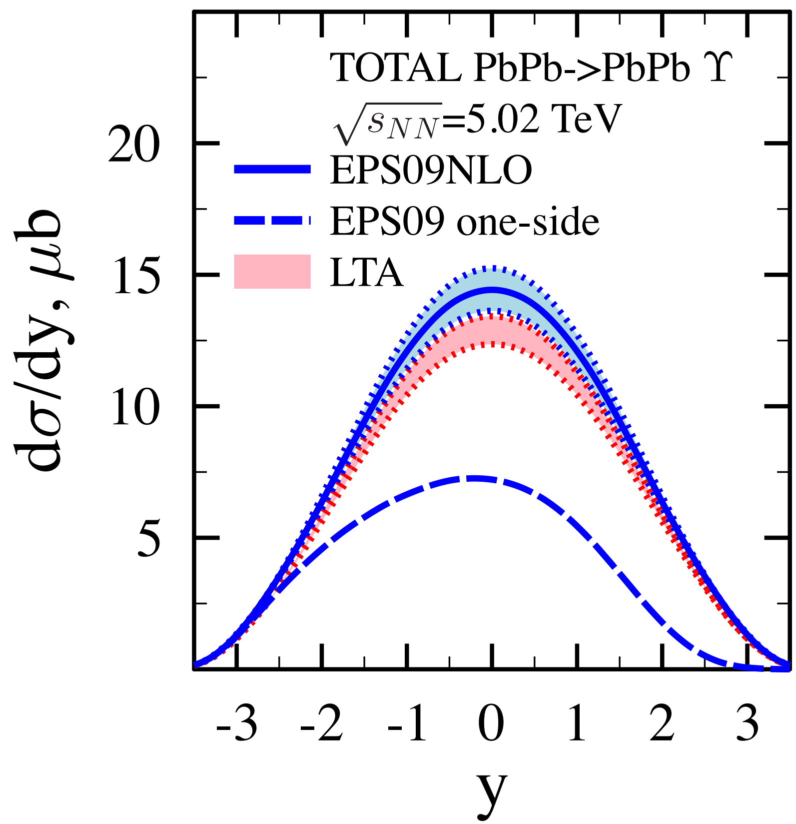
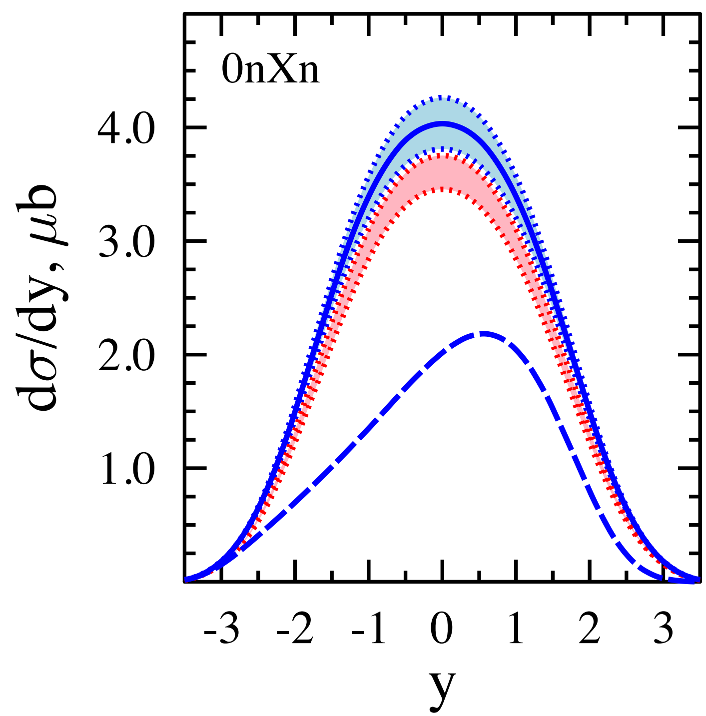
Predictions for Run 2: Υ meson

- In case of Υ-meson (b-bar), LO pQCD predicts too fast a W dependence of $\sigma_{\gamma p \to \Upsilon p}(W_{\gamma p})$ but NLO pQCD works well →



- Combination of NLO pQCD with LT shadowing:





→ possibility to determine $g_A(x,\mu^2)$ at smaller x.

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Conclusions

• 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.

• Two problems with pQCD description of UPCs data:

- large gluon shadowing leads to tension with ALICE data on $\psi(2S)$ photoproduction in Pb-Pb UPCs@ 2.76 TeV → expecting Run 2 results

- predicted cross section of incoherent J/ψ photoproduction in Pb-Pb UPCs@2.76 TeV ~50% smaller than the experimental one

• UPC measurements in pp, pA и AA collisions will continue in Run 2@LHC.