Photoproduction of ρ mesons on nuclei in ultraperipheral nuclear collisions at the LHC

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Outline:

- Heavy-ion ultraperipheral collisions (UPCs) at the LHC
- Nuclear shadowing in coherent photoproduction of ρ mesons on nuclei and comparison to ALICE Pb-Pb data
- Incoherent photoproduction of ρ mesons in Pb-Pb UPCs

Based on Frankfurt, Guzey, Strikman, Zhalov, Phys. Lett. B 752 (2016) 51;
Guzey, Kryshen, Zhalov, Phys. Rev C 102 (2020) 1, 015208

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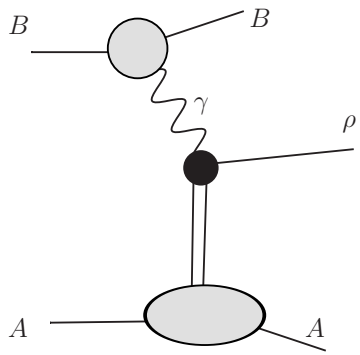
Ultraperipheral collisions (UPCs)

• In ion-ion collisions, nuclei can interact at large impact parameters $b >> R_A+R_B$ → ultraperipheral collisions (UPCs) → strong interaction suppressed → in equivalent photon approximation, interaction via quasi-real photons, Budnev, Ginzburg, Meledin, Serbo, Phys. Rept. 15 (1975) 181 → photon-proton and **photon-nucleus** scattering at unprecedentedly high energies, Baltz et al, Phys. Rept. 480 (2008) 1



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

• Coherent and incoherent (target nucleus breaks up) photoproduction of vector mesons in UPCs:

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

Photon flux from QED+ suppression of strong interactions at small b:
- high intensity ~ Z^2
- high photon energy ~ γ_L

Photoproduction cross section

y = rapidity of ρ

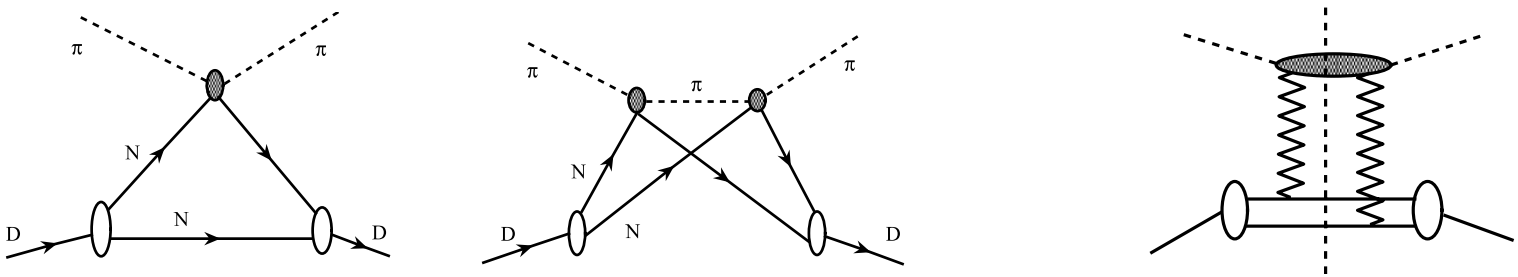
Nuclear shadowing

- 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
  - test of VMD model and role of inelastic (Gribov) shadowing

- 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@RHIC (W < 12 GeV), and Pb-Pb UPCs@LHC at 2.76 TeV (W=46 GeV) and 5.02 TeV (W=62 GeV)

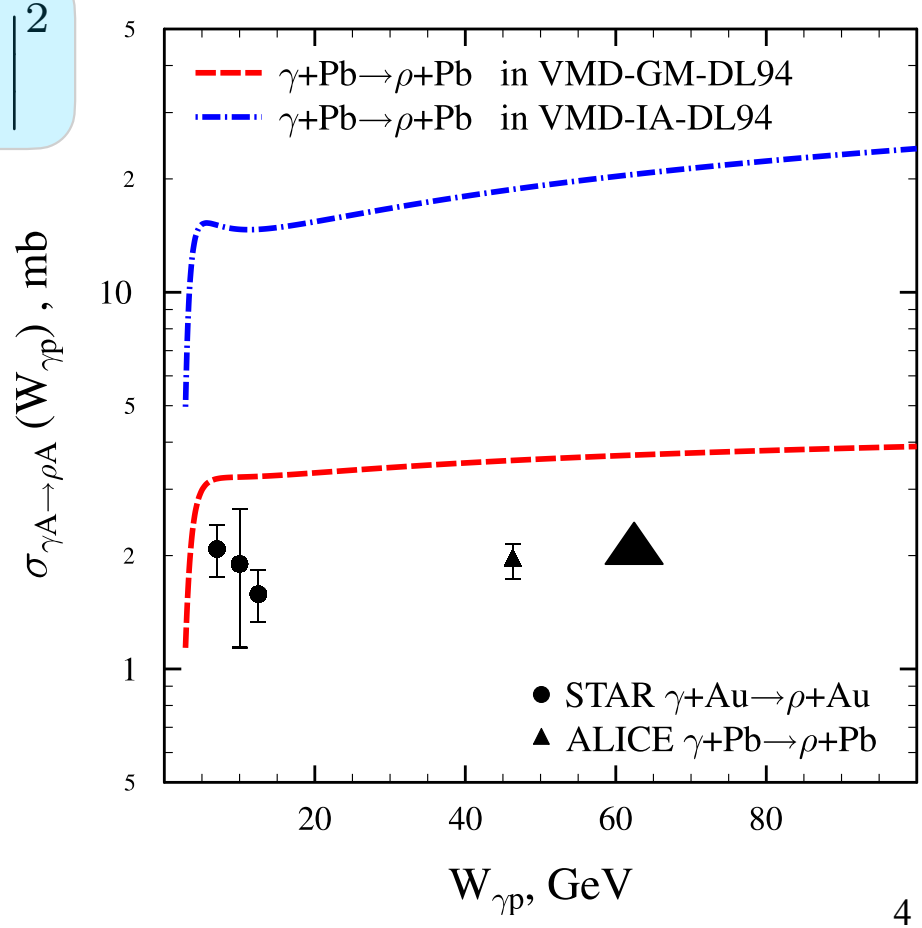
- The method based on the vector meson dominance (VMD) model for $\gamma \to \rho$ transition and Glauber model for shadowing in ρA scattering fails to describe the data.

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

$\sigma_{\rho N}$=ρ-nucleon total cross section from VMD and constituent quark counting

nuclear optical density:

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



- The disagreement is by factor ~1.5 for 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, Adam et al (ALICE), JHEP 1509 (2015) 095; Acharya et al, JHEP 06 (2020) 035.
- → modified model is required.

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, Good, Walker, Phys. Rev. 120 (1960) 1857

- It can be realized by introducing the probability distribution $P(\sigma)$, Blattel et al, Phys. Rev. D 47 (1993) 2761

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

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

$$\int d\sigma\, P(\sigma)\sigma^2 = \langle\sigma\rangle^2(1+\omega_\sigma) \rightarrow \text{ from measured } \gamma$$

diffract. dissociation into large masses, Chapin 1985

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

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

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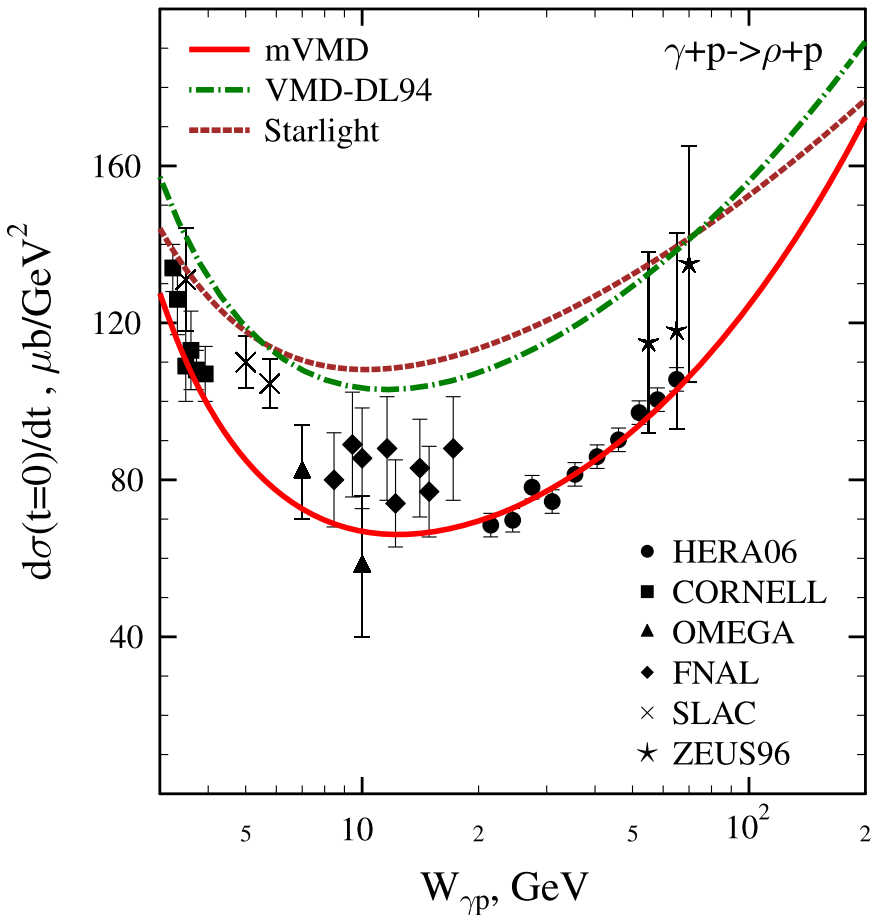


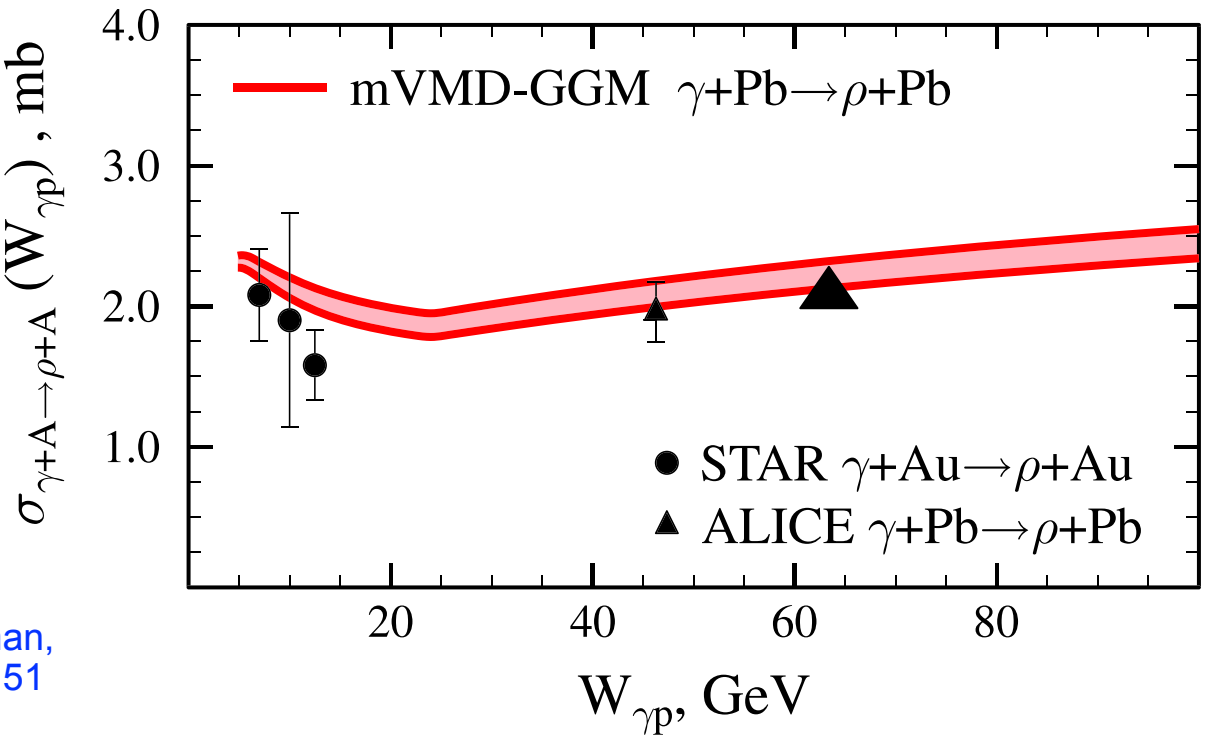
Photoproduction of ρ on Pb in modified VMD with Gribov-Glauber model of shadowing

- 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 additional effects compared to standard methods: correct description of the $\gamma p \to \rho p$ cross section and inclusion of inelastic Gribov shadowing in $\sigma_{\gamma A\to\rho A}$

- → good description of normalization and W-dependence of $\sigma_{\gamma A\to\rho A}$



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Photoproduction of ρ in Pb-Pb UPCs at LHC

- This translates into good description of RHIC and LHC (Run 1 and 2) data on cross section of coherent photoproduction of ρ mesons dσ(AA→ρAA)/dy at y=0
- Left panel: Rapidity y dependence within Glauber (GM) and Gribov-Glauber (GGM) approaches to shadowing
- Right panel: Invariant energy $W_{NN}=\sqrt{s_{NN}}$ dependence

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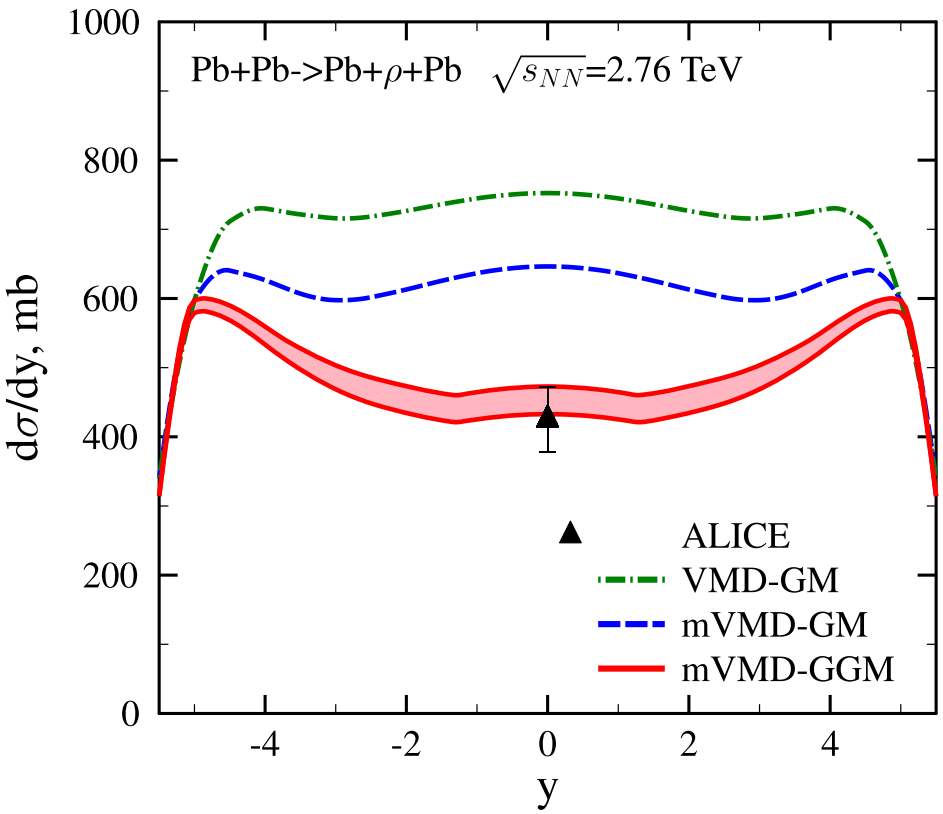

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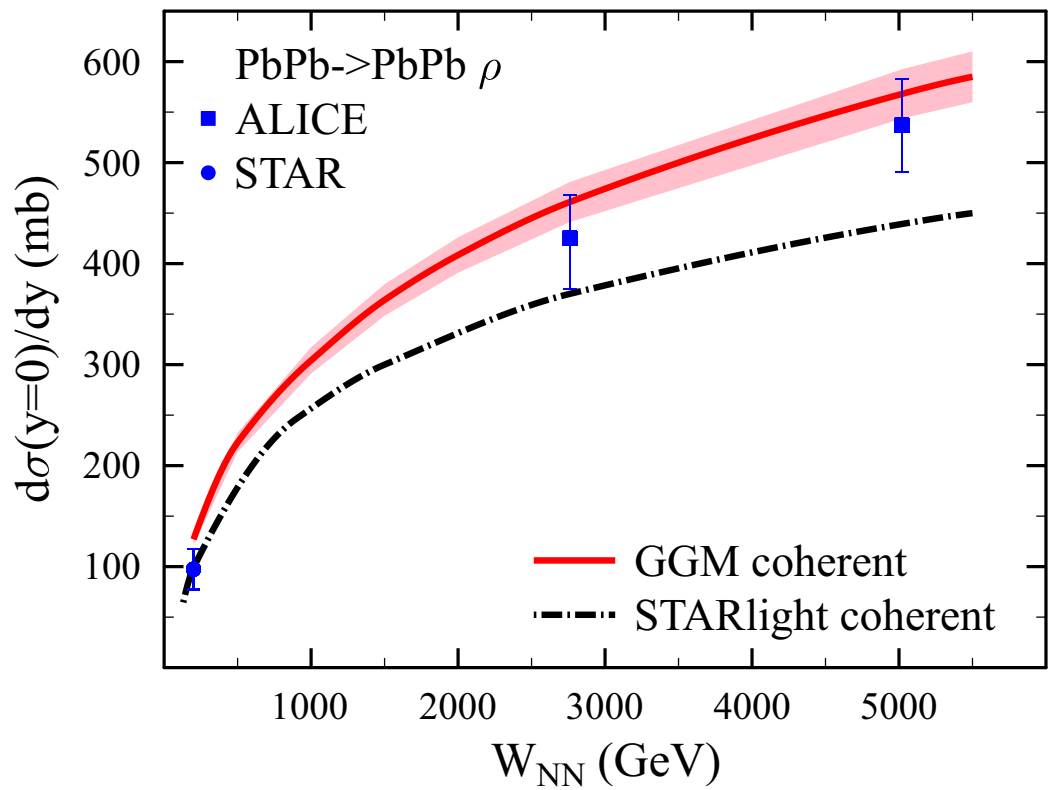


Incoherent photoproduction of ρ on nuclei

• The discussed framework can be generalized to incoherent ρ meson photoproduction on nuclei using completeness of intermediate nuclear states:

$$\sigma^{\rm GG}_{\gamma A\to\rho A'} = \left(\frac{e}{f_\rho}\right)^2 \int d^2\vec{b} \int d\sigma P(\sigma) \int d\sigma' P(\sigma') \frac{\sigma\sigma'}{16\pi B} T_A(b) \exp\left[-\frac{\sigma+\sigma'}{2} T_A(b) + \frac{\sigma\sigma'}{16\pi B} T_A(b)\right]$$
$$= \left(\frac{e}{f_\rho}\right)^2 \int d^2\vec{b}\, T_A(b) \left(\int d\sigma P(\sigma) \frac{\sigma}{\sqrt{16\pi B}} \exp\left[-\frac{\sigma^{\rm in}}{2} T_A(b)\right]\right)^2 .$$

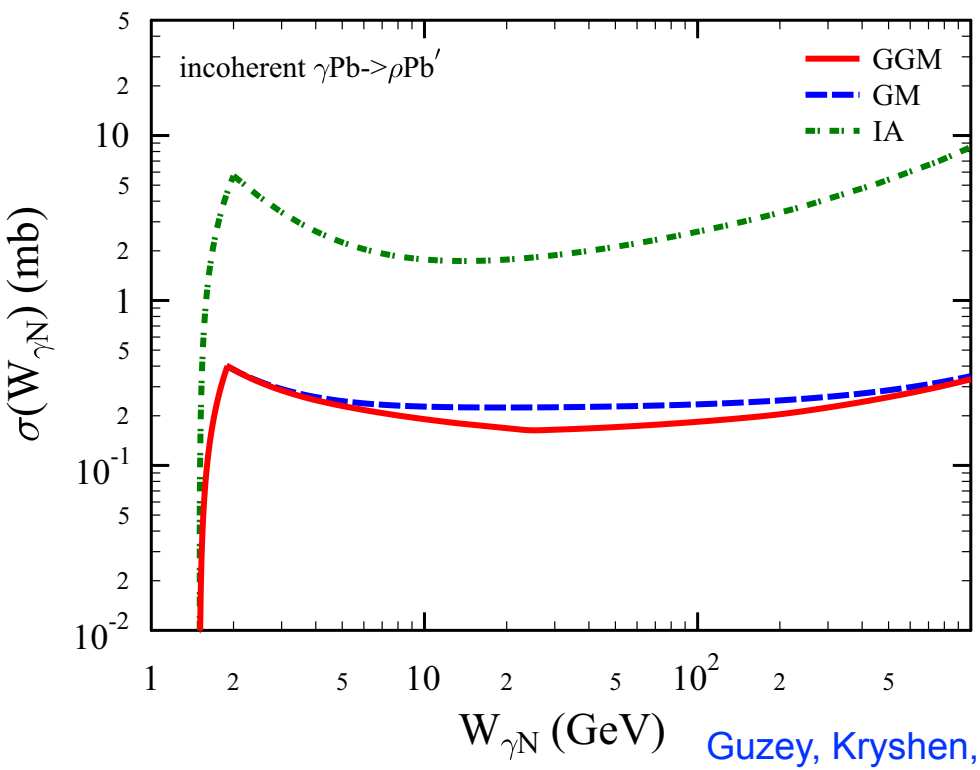
• In the absence of cross section fluctuations $P(\sigma)=\delta(\sigma-\sigma_{\rho N})$ → reproduced standard Glauber model formula:

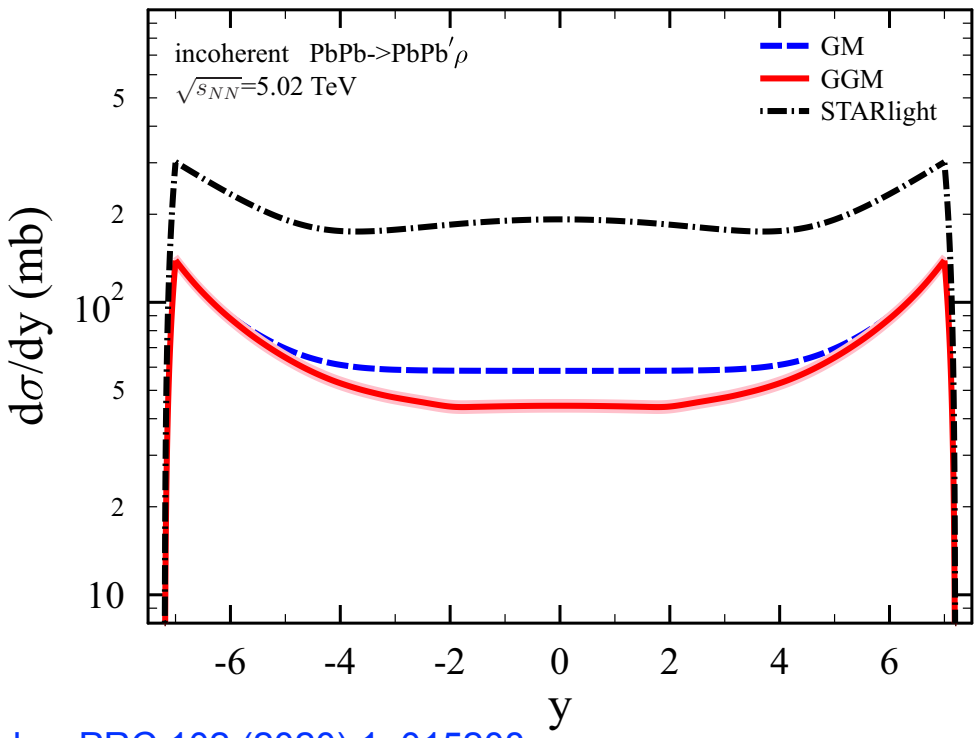
$$\sigma^{\rm Glauber}_{\gamma A\to\rho A'} = \left(\frac{e}{f_\rho}\right)^2 \frac{\sigma^2_{\rho N}}{16\pi B} \int d^2\vec{b}\, T_A(b) e^{-\sigma^{\rm in}_{\rho N} T_A(b)} = \sigma_{\gamma p\to\rho p} \int d^2\vec{b}\, T_A(b) e^{-\sigma^{\rm in}_{\rho N} T_A(b)}$$

• Like in the coherent case, cross section fluctuations increase nuclear shadowing → decrease nuclear cross section.

Predictions for incoherent ρ photoproduction in Pb-Pb UPCs at LHC at 5.02 TeV

- Left: W dependence of σ(γA→ρA') using 3 different approaches to nuclear shadowing: no shadowing (IA), Glauber (GM) and Gribov-Glauber models (GGM)
- Right panel: Rapidity y dependence of UPC cross section dσ(AA→ρAA')/dy
- If no special data selection is made, these predictions can be increased by 50% by the contribution of nucleon dissociation γN → ρY (next slide)





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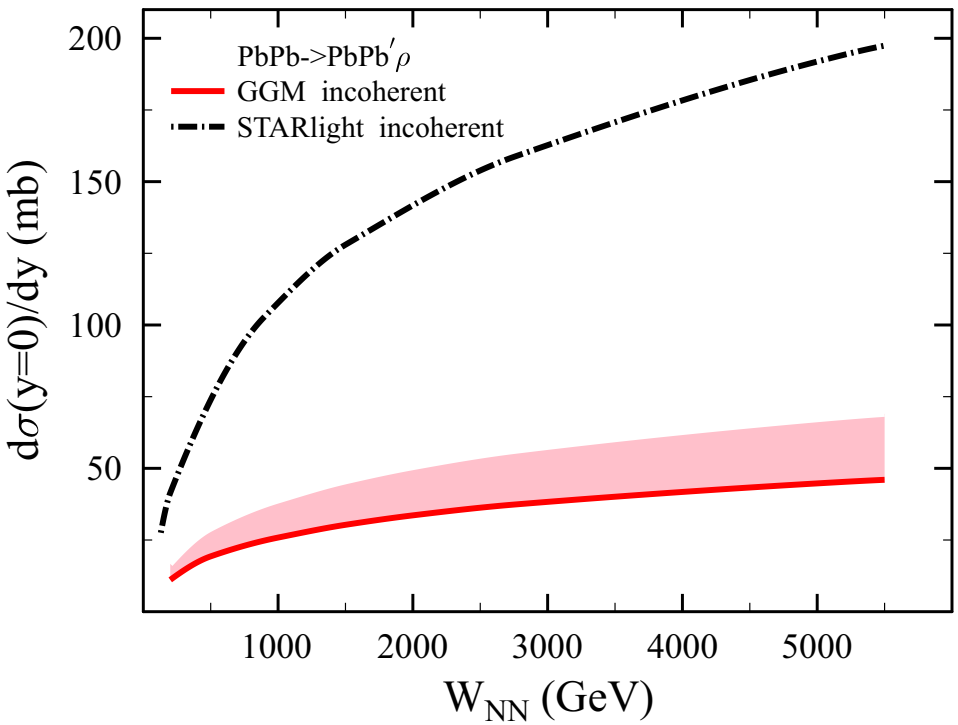
Comparison to STARlight MC

- Our predictions significantly differ from those of STARlight Monte Carlo both in coherent and incoherent cases.

- STARlight is the main MC generator used in data analysis of UPCs at RHIC and LHC, Klein at al, Comput. Phys. Commun. 212 (2017) 258

- STARlight incoherent cross section:

$$\sigma^{\text{STARlight}}_{\gamma A\to\rho A'} = \frac{\sigma_{\gamma p\to\rho p}}{\sigma^{\text{in}}_{\rho N}}\sigma^{\text{in}}_{\rho A} = \left(\frac{e}{f_\rho}\right)^2 \frac{\sigma^{\text{el}}_{\rho N}}{\sigma^{\text{in}}_{\rho N}} \int d^2\vec{b}(1-e^{-\sigma_{\rho N}T_A(b)})$$



	GM	GGM	STARlight
Incoherent, mb	58	44	192
Coherent, mb	840	570	440

Summary

• Coherent and incoherent photoproduction of ρ mesons in Pb-Pb UPCs at the LHC allows one to study nuclear shadowing and hadronic fluctuations of the photon at unprecedentedly high energies.

• Inelastic (Gribov) nuclear shadowing is essential for describing the normalization and energy dependence of the Run 1 and 2 ALICE data.

• Presented framework allowed us to make predictions for incoherent photoproduction of ρ mesons in Pb-Pb UPCs at the LHC, which are very different from frequently used STARlight MC.