First study of the initial gluonic fluctuations using UPCs with ALICE

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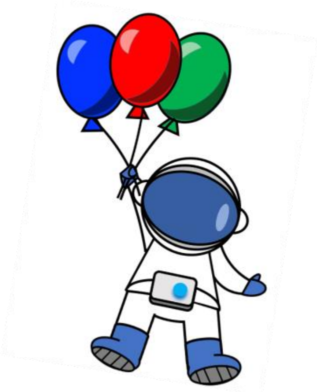
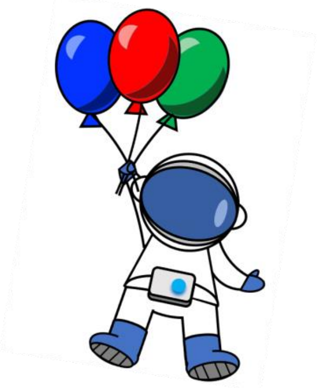




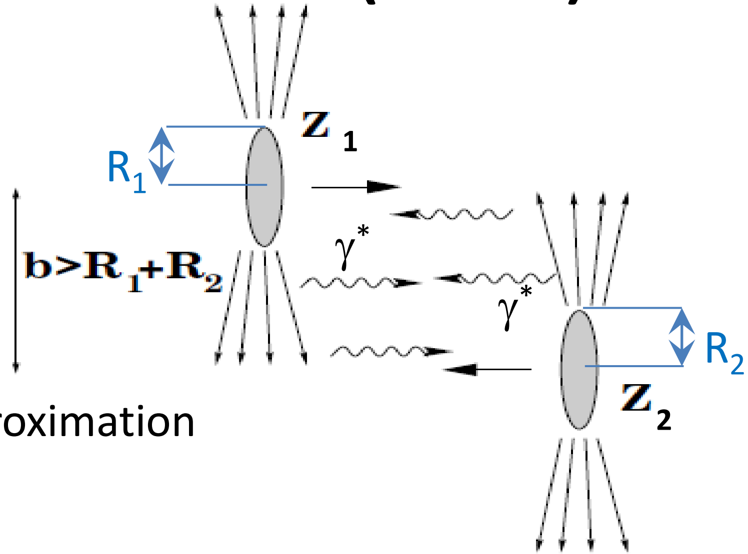
Quark Matter 2023
XXXth International Conference
on Ultra-relativistic Nucleus-Nucleus Collisions

Sep. 5, 2023, Houston, TX, USA

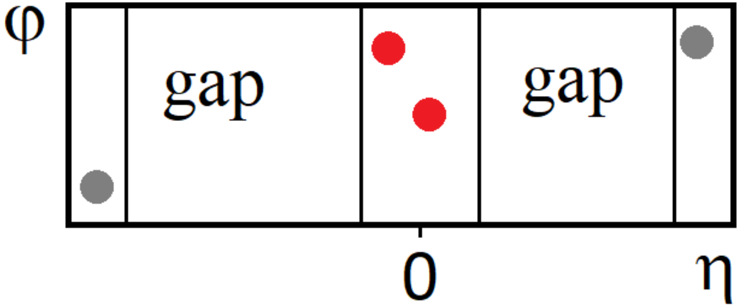
Outline

- Introduction to UPC
- Motivation for *t*-dependent measurements
- Experimental apparatus
- Results:
  - Dissociative J/ψ photoproduction in p-Pb
  - Coherent J/ψ photoproduction in Pb-Pb
  - Incoherent J/ψ photoproduction in Pb-Pb
- Summary

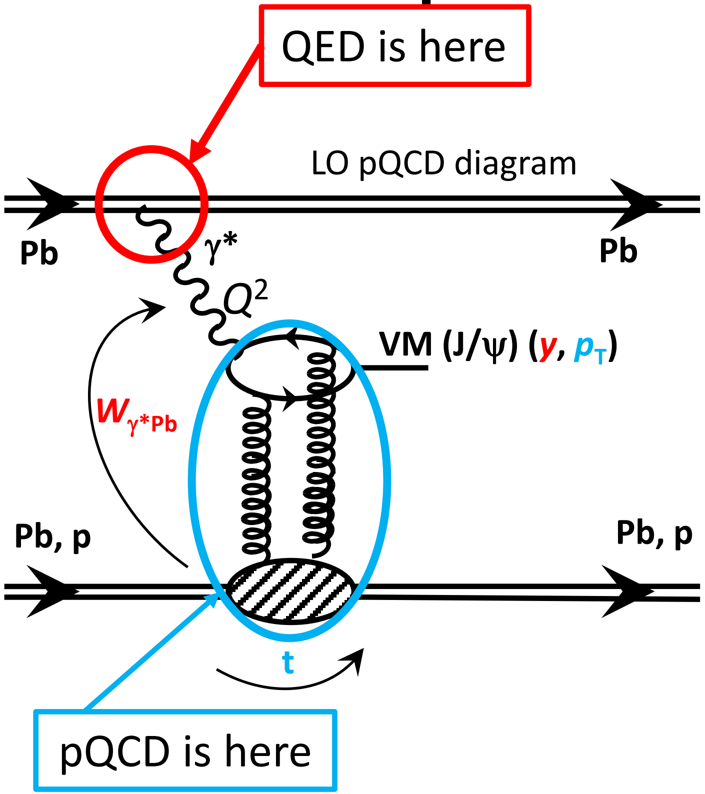
Ultra-peripheral collisions (UPC)



- Impact parameter $b > R_1 + R_2$
  - Hadronic interactions suppressed
- Photon induced reactions:
  - Well described in Weizsäcker-Williams approximation
  - Photon flux $\sim Z^2$ ($Z_{Pb} = 82$)
  - Large γ-induced interaction cross section
- Clear signature:
  - Low detector activity
  - Rapidity gap(s)



Photoproduction and main variables



- Momentum scale $Q^2 \sim M_{VM}{}^2 / 4$
  - Hard scale assured by high mass of J/ψ meson
- Vector Meson (VM) quantum numbers:
  - $J^{PC} = 1^{--}$
- Bjorken-*x:* fraction of longitudinal momentum of proton

$$x_B = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\pm y}$$

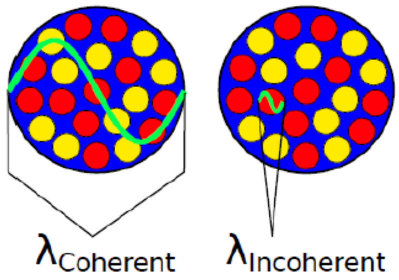
  - ➢ Photoproduction is sensitive to gluon density evolution at low x_B at LO (more complex at NLO)
- Photon-target center-of-mass energy

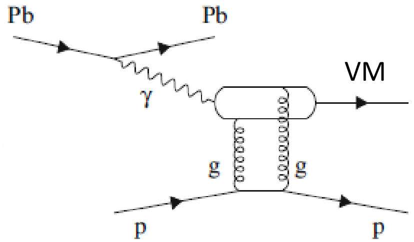
$$W^2_{\gamma^* Pb} = 2E_{Pb} M_{VM} e^{\mp y}$$

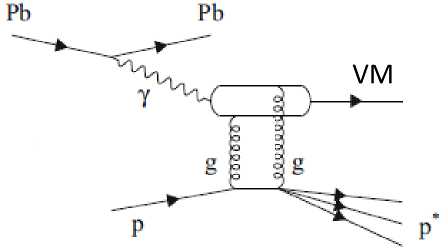
- 4-momentum transfer *t* = Mandelstam *t*
  - Gluon distribution in the transverse plane $|t| \sim p_T{}^2$

Photoproduction types

- **Coherent** Vector Meson (VM) photoproduction:
  - Photon couples coherently to all nucleons (whole nucleus)
  - $\langle p_T^{VM} \rangle \sim 1/R_{Pb} \sim 60$ MeV/c
- **Incoherent** VM photoproduction:
  - Photon couples to a single nucleon
  - $\langle p_T^{VM} \rangle \sim 1/R_p \sim 500$ MeV/c
- **Exclusive** VM photoproduction on target proton (in p-Pb case):
  - Photon couples to a single proton
  - $\langle p_T^{VM} \rangle \sim 1/R_p \sim 500$ MeV/c
  - Similar to coherent VM photoproduction
- **Dissociative** (or semiexclusive) VM photoproduction:
  - Photon interacts with a single nucleon and excites it
  - $\langle p_T^{VM} \rangle \sim 1$ GeV/c
  - Target nucleon and ion break (in heavy ion collision)
  - Target proton breaks (in p-Pb)



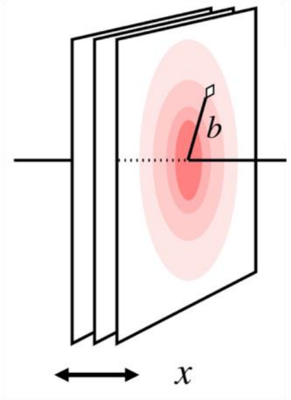


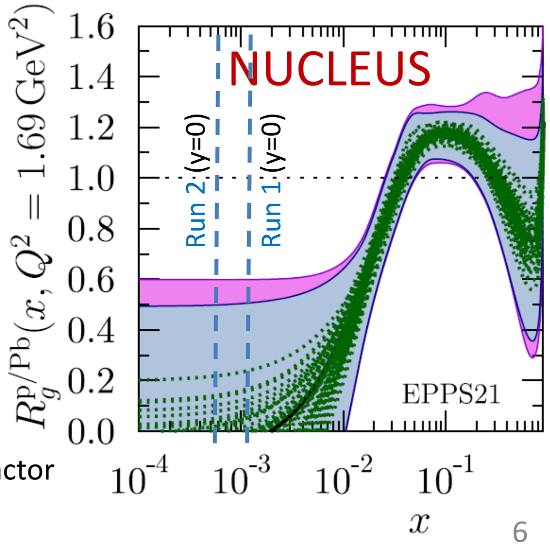


Motivation for *t*-dependent measurements

- Gluon density is impact parameter *b* dependent at given Bjorken-*x* and Q^2
- *b* and p_T are Fourier conjugates
- $p_T{}^2 \approx |t|$ - dependence of the cross section helps to constrain **transverse gluonic structure** at low x_B
- In Good – Walker approach
  - Coherent photoproduction tells about transverse dependence of the gluon shadowing
    - Saturation may contribute to nuclear shadowing
  - Incoherent photoproduction is sensitive to the variance of the spatial gluon distribution (subnucleonic fluctuations)

$$\frac{d\sigma^{inc}}{dt} = \frac{R_g{}^2}{16\pi}\left(\langle|A(x,Q^2,\vec{\Delta})|^2\rangle - |\langle A(x,Q^2,\vec{\Delta})\rangle|^2\right)$$



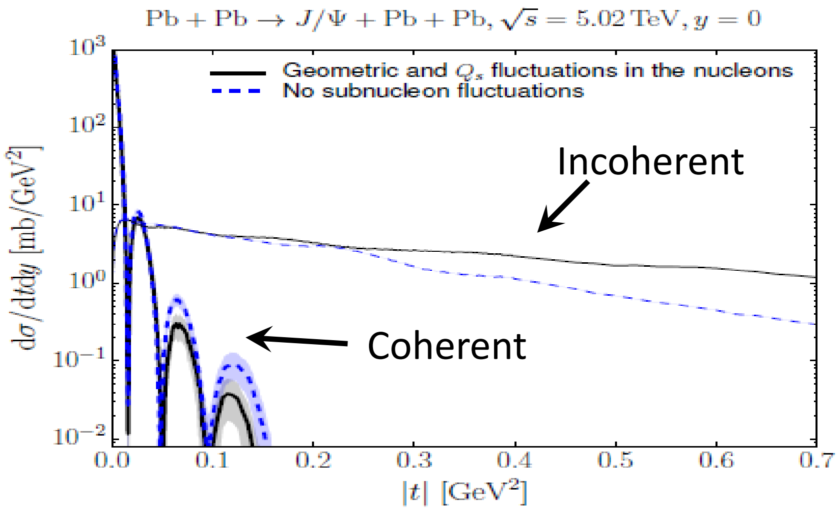


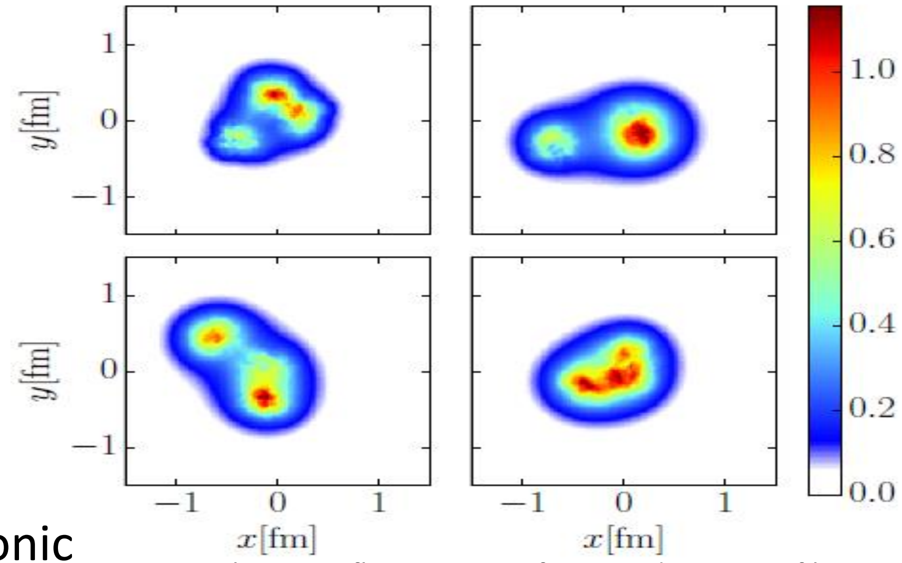
Nuclear gluon shadowing factor

Eskola et al.: Eur. Phys. J. C 82 (2022) 413

Motivation – cont.

Mantysaari, Schenke, PLB 772 (2017) 832





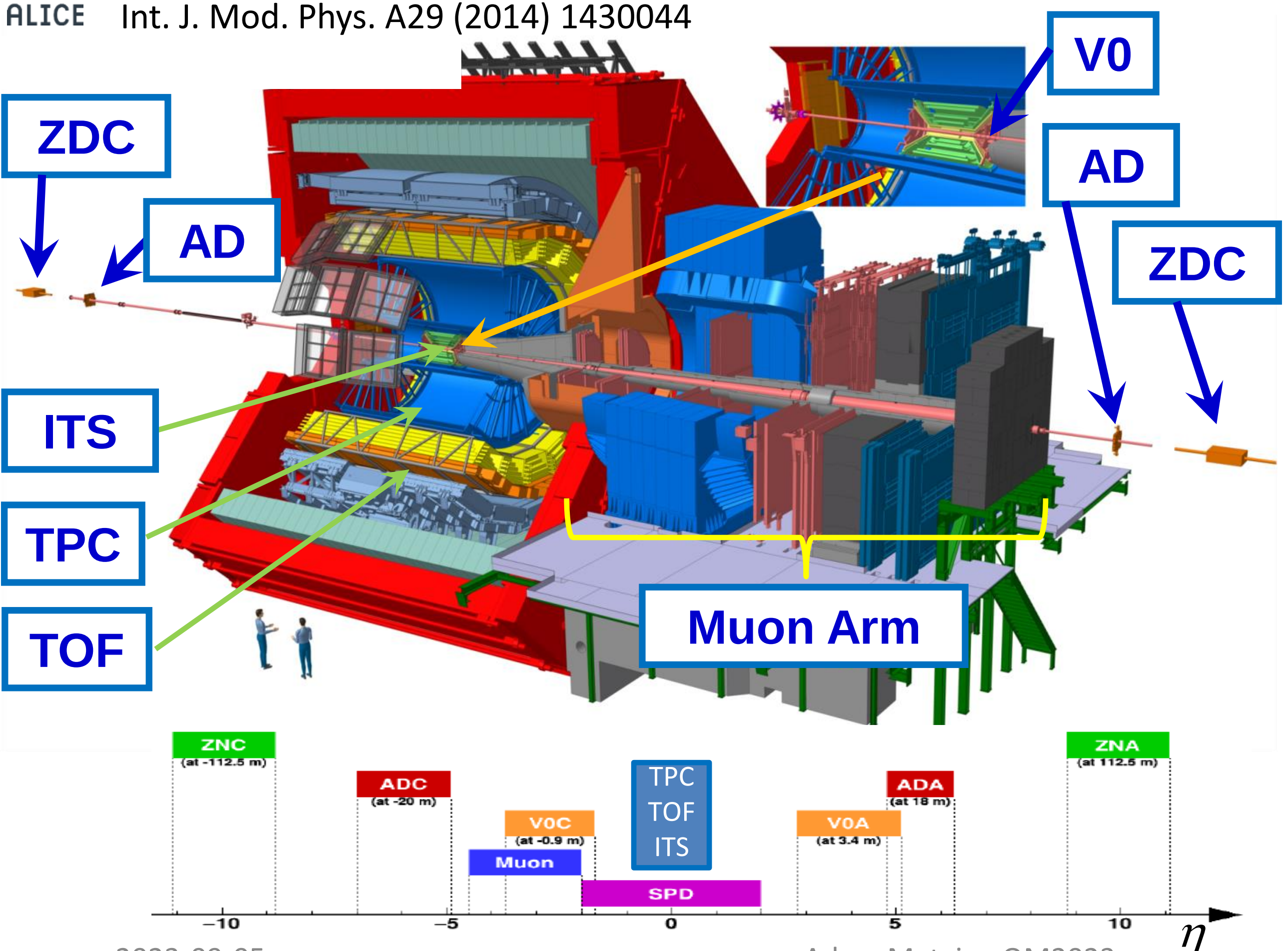
Event by event fluctuations of proton density profile

H. Mantysaari, B. Schenke, PRD 94 (2016) 034042,
J. Cepila, et al., PLB 766, 186 (2017),
S. R. Klein, PRC 107, 055203 (2023).

- Variations in nucleon positions and/or gluonic hot spots $\to$ **quantum fluctuations**
- Larger $|t|$ range $\to$ scatter of smaller object
- Coherent vs. Incoherent vs. Dissociative J/ψ
  - Access to **different scales**: nucleus, nucleon, hot spots

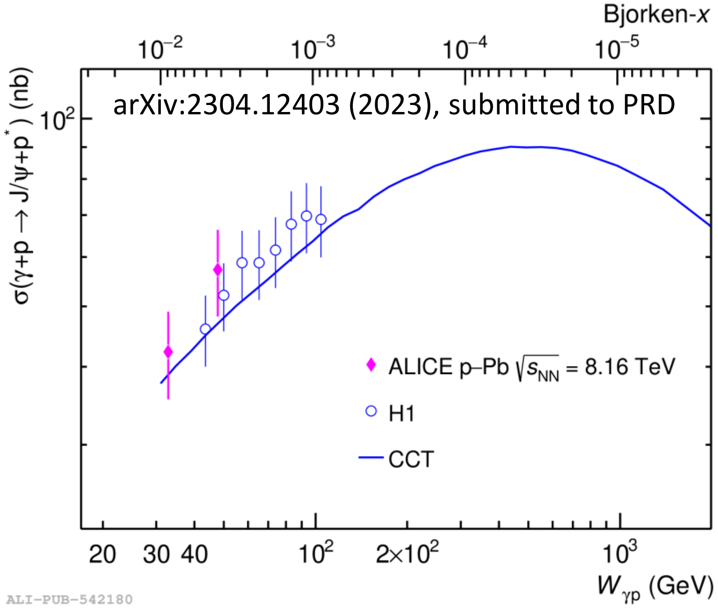
ALICE detector

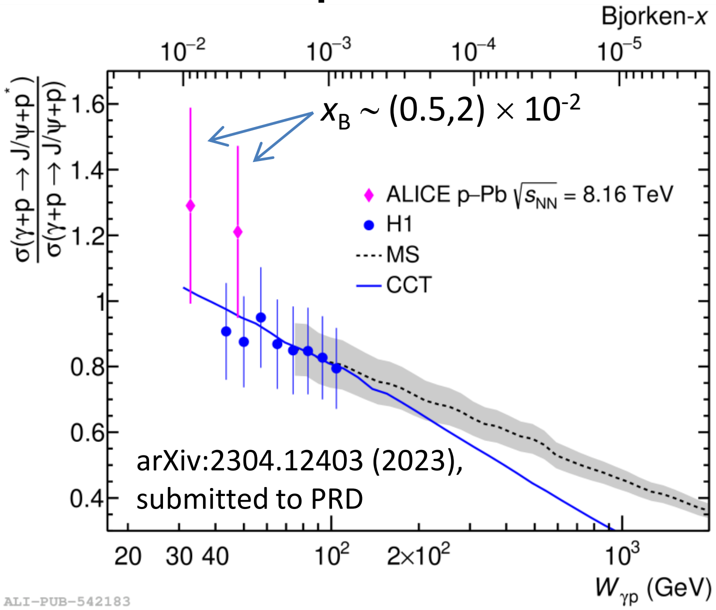
ALICE: 2008 *JINST* **3** S08002;
Int. J. Mod. Phys. A29 (2014) 1430044



- **Central Barrel tracking ($\mu^{\pm}$, $e^{\pm}$, $h^{\pm}$)**
  - $|\eta| < 0.9$, $0 < \varphi < 2\pi$
  - ITS - silicon detector
  - TPC - gas drift detector
  - TOF - resistive plate chambers
- **Forward tracking ($\mu^{\pm}$)**
  - $-4 < \eta < -2.5$
  - Absorber
  - Muon tracker
  - Muon trigger
  - Dipole magnet
- **Diffractive detectors**
  - AD - scintillator counter
  - V0 - scintillator counter
  - ZDC – sampling calorimeter
- **Trigger**
  - Topology in SPD, TOF
  - Veto in AD, V0
  - Muon

Dissociative J/ψ in p-Pb





H1: EPJ C73 (2013) 2466.
CCT: PLB 766 (2017) 186;
- colour dipole + energy dependent hot spot model.

MS: PRD 98 (2018) 034013;
- perturbative JIMWLK + constrains from fits to H1 data.

- **First measurement** of the energy dependent **dissociative J/ψ cross section** at the LHC
- Agreement with HERA results
- CCT model with saturation agrees with data
  - Predicted maximum at $W_{\gamma p}$ ~ 500 GeV to be studied in Run 3
- MS model with saturation to be studied in Run 3

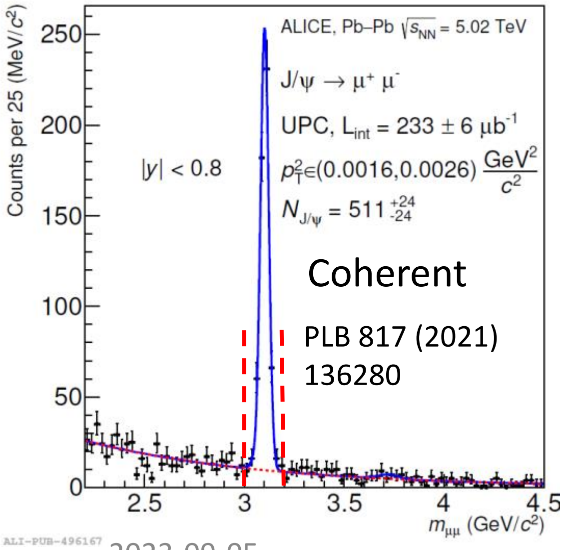
J/ψ in UPC Pb-Pb

- Central rapidity region $|y^{J/\psi}| < 0.8$ which corresponds to $x_B \sim 10^{-3}$
- Very clear $J/\psi \to \mu^+\mu^-$ signal
- Corrections from p_T distribution
- Bayesian (and SVD) unfolding in coherent analysis
  - To account for p_T migrations
  - To transform $p_T^2 \to |t|$
- Transition from UPC to photonuclear cross section

What we want to extract

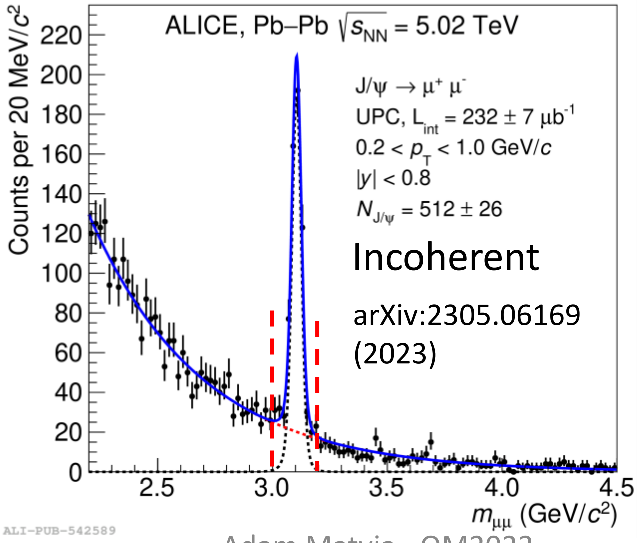
Photon flux

$$\left.\frac{d^2\sigma_{J/\psi}^{coh/incoh}}{dy\,dp_T^2}\right|_{y=0} = \boxed{2n_{\gamma Pb}(y=0)}\,\boxed{\frac{d\sigma_{\gamma Pb}}{d|t|}}$$



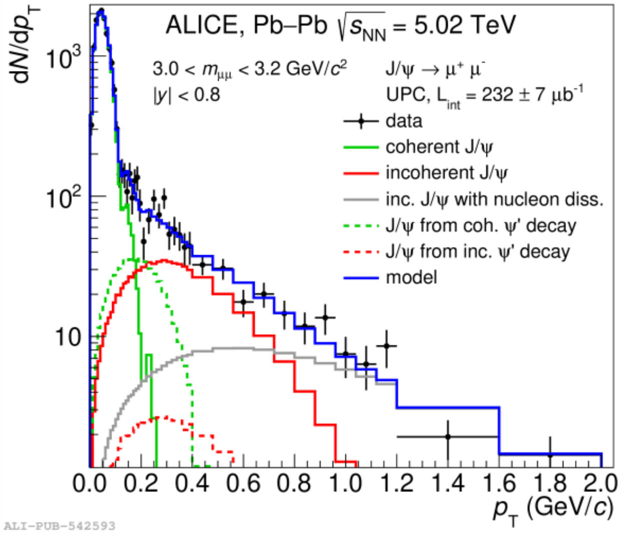
Coherent

PLB 817 (2021) 136280



Incoherent

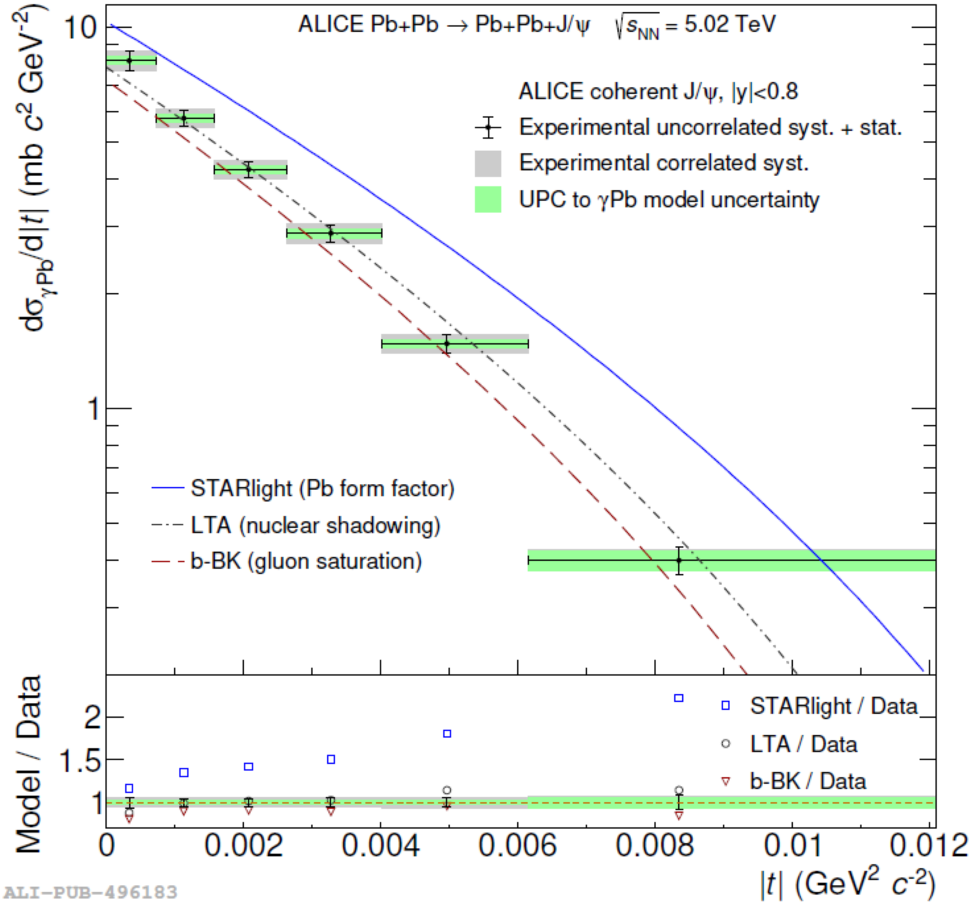
arXiv:2305.06169 (2023)



Coherent J/ψ

PLB 817 (2021) 136280

- **|*t*|dependence** of coherent J/ψ photoproduction is sensitive to the gluon distribution in the transverse plane
- HERA-like precision achieved
- Comparison to models:
  - STARlight does not have shadowing, so does not describe shape nor magnitude
  - LTA contains nuclear shadowing – agrees with data
  - b-BK based on gluon saturation – agrees with data



LTA (shadowing): PRC 95 (2) (2017) 025204;
- vector dominance model (VDM) based on perturbative Leading Twist Approximation (LTA) of nuclear shadowing.

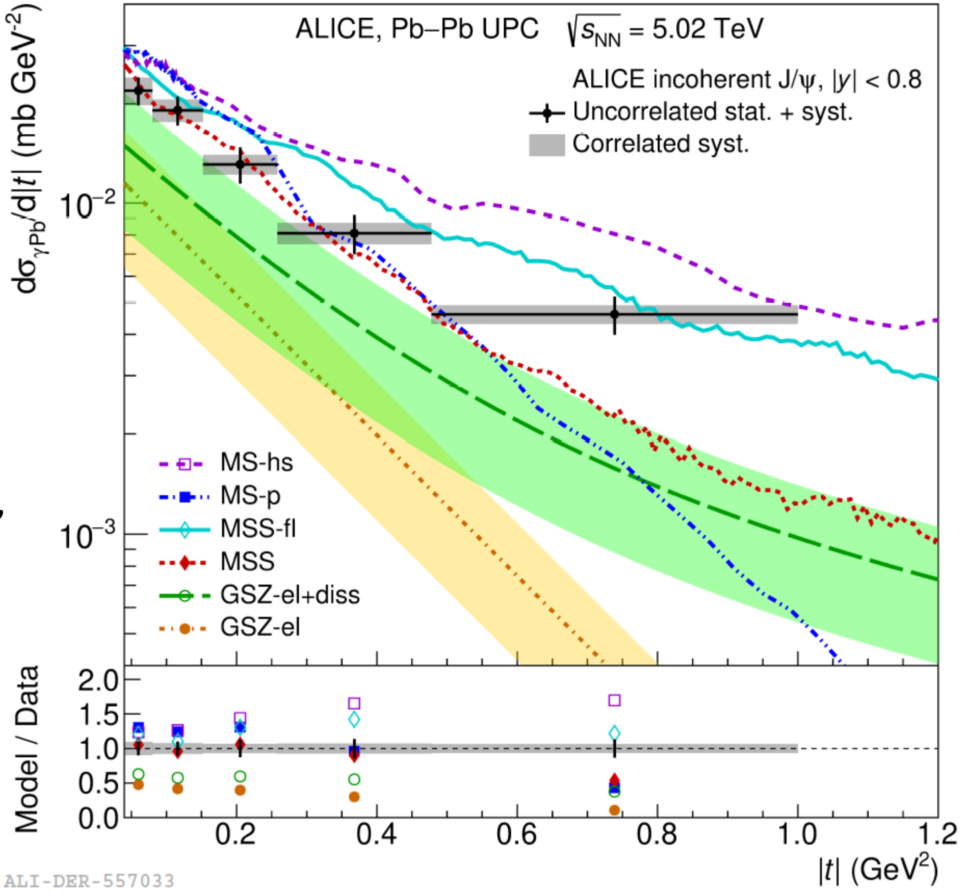
b-BK (saturation): arXiv:2006.12980 [hep-ph];
- impact parameter dependent BK computation.

Incoherent J/ψ

NEW RESULT!

arXiv:2305.06169 (2023), submited to PRL

- **|*t*| dependence** of the incoherent J/ψ photoproduction is sensitive to the variance of the gluon distribution in the transverse plane
- First measurement which probes **fluctuations** of the gluonic „hot spots" in Pb
- Models fail to predict the normalisation
- Normalization is linked to the scaling from proton to nuclear targets
- (Slope of) data favor models with gluonic subnucleon fluctuations (hot spots in MS-hs, fluctuations MSS-fl and dissociation in GSZ el+dis)



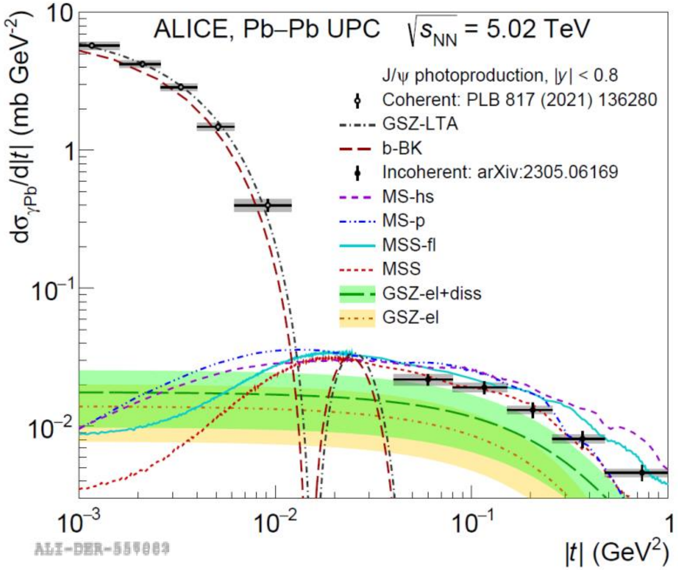
MS (saturation): PLB 772 (2017) 832;
- Based on IPsat model.

GSZ (shadowing): PRC 99 (2019) 015201;
- VDM based on LTA shadowing including elasic and/or dissociative part

MSS (saturation): PRD 106, 7 (2022) 074019
- Based on JIMWLK equations.

Summary

- First measurement of dissociative J/ψ photoproduction in p-Pb
  - Sensitive to gluon density fluctuations in proton
- Measurement of coherent J/ψ photoproduction in Pb-Pb in 6|t| bins
  - Measurements signal large nuclear gluon shadowing effects at $x_B \sim 10^{-3}$
  - Models with shadowing or saturation describe data best at low x_B
- First measurement of incoherent J/ψ photoproduction in Pb-Pb in 5|t| bins
  - **Subnucleon fluctuations are important**
- ALICE data strongly challenge to describe both coherent and incoherent regime



Look into other ALICE UPC contributions

- First global study of super dense gluonic matter with UPCs by ALICE – Simone Ragoni – talk at the UPC session
- Physics prospects of central exclusive production in pp collisions with ALICE Run 3 data – Minjung Kim – poster
- Exploring light hadrons in UPCs with ALICE – Alexander Bylinkin – poster
- Studying the nucleus via angular correlations in UPCs with ALICE – Andrea Giovanni Riffero – poster

Backup

Systematic uncertainties

Source	Uncertainty (%)	
	Coherent	Incoherent
Signal extraction	(0.7, 2.2)	(1.0, 2.9)
Z vertex selection	-	(0, 2.9)
f_D – feed down from ψ(2S)	(0.1, 0.5)	(0.2, 6.5)
f_I – feed down from incoherent	(1.1, 2.3)	-
f_C – feed down from coherent	-	(0, 0.4)
Luminisoty	2.7	2.9
Veto inefficiency due to pile-up	3	
Veto inefficiency due to dissociation	2	3.8
ITS-TPC tracking	2.8	
Trigger efficiency	1.3	
Branching ratio	0.5	0.6
Photon flux	2	
p_T^2 migration unfolding	(0.6, 2.3)	-
p_T^2 -> $\|t\|$ unfolding	(0.1, 5.7)	-
Interference strength	(0.3, 1.2)	-

Different z-vertex selection

important only at low p_T