

# Recent ALICE results on photon-induced interactions

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### LHC as a $\gamma p$ and $\gamma Pb$ collider





#### Ultra-peripheral (UPC) collisions: b > R<sub>1</sub>+R<sub>2</sub>

 $\rightarrow$  hadronic interactions strongly suppressed

#### High photon flux

- $\rightarrow$  well described in Weizsäcker-Williams
  - approximation (quasi-real photons)
- $\rightarrow$  flux proportional to Z<sup>2</sup>
- $\rightarrow$  high cross section for  $\gamma$ -induced reactions

### Pb-Pb UPC at LHC can be used to study $\gamma\gamma$ , $\gamma$ -p and $\gamma$ -Pb interactions at higher center-of-mass energies than ever before

Recent reviews on UPC physics: A.J. Baltz et al, Phys. Rept. 458 (2008) 1 J.G. Contreras, J.D. Tapia Takaki. Int.J.Mod.Phys. A30 (2015) 1542012 S.Klein and P. Steinberg, Ann. Rev. Nuclear Part. Sci. 70 (2020) 323

#### From typical hadronic interaction...







#### to ultra-peripheral collisions

- Experimental signature: few signal tracks in an otherwise empty detector •
  - Wide acceptance coverage is important to ensure event emptiness

#### Looking for two tracks in an otherwise empty detector...





### Vector meson photoproduction in UPC





Exclusive vector meson production in UPC can be factorized in two parts:

- QED: photon flux
- QCD: vector meson photoproduction: σ(W<sub>νp</sub>)

#### Heavy vector meson photoproduction



 LO pQCD: exclusive photoproduction cross section is proportional to the square of the gluon density in the proton target:

$$\left. \frac{d\sigma_{\gamma A \to J/\psi A}}{dt} \right|_{t=0} = \frac{M_{J/\psi}^3 \Gamma_{ee} \pi^3 \alpha_s^2(Q^2)}{48\alpha_{\rm em} Q^8} \Big[ xg_A(Q^2) \Big]_{t=0} + \frac{M_{J/\psi}^3 \Gamma_{ee} \pi^3 \alpha_s^2(Q^2)}{48\alpha_{\rm em} Q^8} \Big]_{t=0} + \frac{M_{J/\psi}$$

• J/ $\psi$  mass serves as a hard scale:

$$Q^2 \sim \frac{M_{J/\psi}^2}{4} \sim 2.5 \text{ GeV}^2$$

• Bjorken  $x \approx 10^{-2} - 10^{-5}$  accessible at LHC:

$$x = \frac{M_{J/\psi}^2}{W_{\gamma p}^2} = \frac{M_{J/\psi}}{2E_p} \exp(\pm y)$$

Vector meson photoproduction in UPC allows one to probe poorly known **gluon distributions at low** *x* and search for **saturation effects** 



Ryskin: Z. Phys. C 57, 89 (1993)



Figure courtesy of Voica Radescu, DESY

## Exclusive J/ $\psi$ photoproduction







- Energy dependence well described with a power law fit
- Nice agreement between HERA in ep, LHCb in pp and ALICE in p-Pb
- Caveat: saturation models (CGC) are also consistent with data at these energies

## Dissociative J/ $\psi$ photoproduction





- Dissociative cross section is sensitive to quantum fluctuations of the proton structure
- Expect reduced fluctuations in saturation regime

   → Reduced dissociative cross section at high energy
   could serve as a sign of saturation!
- To be tested in Run 3





#### $J/\psi$ photoproduction on Pb target



## $J/\psi$ photoproduction on Pb target



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LO pQCD: Coherent J/ $\psi$  photoproduction cross section is proportional to the square of the gluon density in nuclei:

$$\frac{d\sigma_{\gamma A \to J/\psi A}}{dt}\Big|_{t=0} = \frac{M_{J/\psi}^3 \Gamma_{ee} \pi^3 \alpha_s^2(Q^2)}{48\alpha_{\rm em} Q^8} \Big[xg_A(x,Q^2)\Big]^2$$





$$R_g^A(x,Q^2) = \frac{g_A(x,Q^2)}{Ag_p(x,Q^2)} \quad - \text{gluon shadowing factor}$$

 $J/\psi$  photoproduction in Pb-Pb UPC (lead target) provides information on gluon shadowing in nuclei

## **Coherent and incoherent photoproduction**







Two types of photoproduction processes:

- Coherent:
  - photon couples coherently to all nucleons
  - $-\langle p_{\rm T} \rangle \simeq 1/R_{\rm Pb} \simeq 60$  MeV/c
- Incoherent:
  - photon couples to a single nucleon
  - $\langle p_{\rm T} \rangle \sim 1/R_{\rm p} \sim 450 \,{\rm MeV/c}$
  - usually accompanied by neutron emission

## Coherent J/ $\psi$ cross section





ALI-PUB-499958

- Strong suppression wrt impulse approximation
- No models describing all data

- Impulse approximation: no nuclear effects
- STARLIGHT: VDM + Glauber, Klein, Nystrand et al: Comput. Phys. Commun. 212 (2017) 258
- EPS09 L0 (GKZ): EPS09 shadowing Guzey, Kryshen, Zhalov, PRC93 (2016) 055206
- LTA (GKZ): Leading Twist Approximation Guzey, Kryshen, Zhalov, PRC93 (2016) 055206
- GM: Color dipole model + IIM CGC Goncalves, Machado et al.: PRC 90 (2014) 015203, JPG 42 (2015) 105001
- LM IPSat: Color dipole model + IPSat CGC
   T. Lappi, H. Mäntysaari, PRC 83 (2011) 065202; 87 (2013) 032201
- CCK: hot-spot model + Glauber-Gribov: Cepila, Contreras, Krelina, PRC97 (2018) 024901
- LS: Color dipole model + BGK-I CGC: Luszczak, Schafer: PRC 99, 044905 (2019)

#### Gluon shadowing from $J/\psi$ photoproduction data





Guzey, EK, Strikman, Zhalov. Phys. Lett. B726 (2013) 290 Guzey, EK, Strikman, Zhalov. Phys.Lett. B816 (2021) 136202 **Experimental cross section in Pb-Pb UPC** divided by the photon flux

**Impulse approximation:** 

forward photoproduction cross section off proton times integral over squared Pb form-factor

- Nuclear suppression factor S gives direct access to gluon shadowing factor  $R_g(x,\mu)$
- Direct evidence of large gluon shadowing effects:  $R_g(x \sim 10^{-3}, \mu \sim 2.4 \text{ GeV}) \sim 0.65$
- Coherent J/ $\psi$  measurements can be used to reduce uncertainties of shadowing parameterizations
- Caveat: significant contribution from quarks at NLO? See: Eskola et al. PRC 106 (2022), 035202

## Coherent J/ $\psi$ cross section: *t*-dependence



t-dependence of the coherent J/ $\psi$  cross section is expected to probe shadowing effects in the transverse plane



Guzey, Strikman, Zhalov PRC95 (2017) 025204

t-dependence measured by ALICE shows clear deviation from a simple form-factor-driven model





#### Photon-induced processes in hadronic Pb-Pb collisions



#### Coherent J/ $\psi$ in peripheral collisions?



- Data shows an excess of  $J/\psi$  at low  $p_T < 200 \text{ MeV/c}$
- Possible interpretation: coherent photoproduction on nuclear fragments
- Many open questions:
  - How can the coherence condition survive when both nuclei are broken by hadronic interaction?
  - Do only spectator nucleons participate in the coherence?





### $J/\psi$ photoproduction in semicentral Pb-Pb collisions





- J/ $\psi$  photoproduction measured up to 10-30% centralities
- Several models reproduce the data fairly well:
  - VDM: photons in the spectator region, unmodified γPb cross section
  - IIM/GBW S3: modified γPb cross section (overlap region excluded)





#### UPC in Run 3 and 4



#### ALICE in Run 3 and Run 4





- All-pixel Inner Tracking System
- **GEM-based TPC readout**
- Pixel Muon Forward Tracker
- Fast Interaction trigger
- New Online-Offline system
- Readout upgrade of all detectors
- Forward calorimeter (FoCal) in Run 4

• Collect 13/nb in Run 3 and 4 (x100 larger minimum bias statistics)

6.3

**FDDA** 

Improve tracking precision by a factor 3-6

## Vector meson photoproduction in Pb-Pb UPC



#### Yellow report on Run3-4: 1812.06772



$$R_{\rm Pb}(x) = \left(\frac{\sigma_{\gamma \rm Pb}(x)}{\sigma_{\rm IA}(x)}\right)^{1/2}, \qquad x = \frac{m_V}{\sqrt{s_{NN}}} \exp(-y)$$

#### Expected statistics in Run 3-4 (13 /nb):

PbPb, $13 \text{ nb}^{-1}$				
Meson	$\sigma$	Total	$ \eta  < 0.9$	$-4 < \eta < -2.5$
$\rho \to \pi^+ \pi^-$	$5.2\mathrm{b}$	68 B	$5.5 \mathrm{B}$	4.9 B
$\rho' \to \pi^+ \pi^- \pi^+ \pi^-$	$730 \mathrm{~mb}$	$9.5 \mathrm{B}$	$210 { m M}$	$190 { m M}$
$\phi \to \mathrm{K^+K^-}$	0.22b	$2.9 \mathrm{B}$	$82 \mathrm{M}$	$15 \mathrm{M}$
$J/\psi \to \mu^+\mu^-$	$1.0 {\rm ~mb}$	$14 \mathrm{M}$	$1.1 \ \mathrm{M}$	$600 \mathrm{K}$
$\psi(2S) \rightarrow \mu^+ \mu^-$	$30~\mu{ m b}$	$400 \mathrm{K}$	$35~{ m K}$	$19~\mathrm{K}$
$\Upsilon(1S) \to \mu^+ \mu^-$	$2.0~\mu{ m b}$	$26 \mathrm{K}$	$2.8~{ m K}$	880

#### Main goals for Run3-4:

- access to gluon shadowing at low x
- study scale dependence of gluon shadowing with different meson species
- probe gluon distribution in **transverse plane**
- Explore UPC physics with FoCal

## Prospects for $a_{\tau}$ measurements in Run 3





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Burmasov et al. Comput.Phys.Commun. 277 (2022) 108388

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 $m_{\tau\tau}$  [GeV/ $c^2$ ]

14

8

6

## Summary and outlook



- Shedding light on the partonic structure of protons and nuclei with UPCs:
  - Exclusive J/ $\psi$  photoproduction keeps rising as a power law with energy well beyond HERA energies (down to x ~ 10<sup>-5</sup>)
  - Dissociative J/ $\psi$  photoproduction promising for saturation searches
  - New results on coherent J/ $\psi$  photoproduction cross section provide constraints on gluon shadowing in nuclei
  - t-dependence of coherent J/ $\psi$  photoproduction promising tool to probe gluon shadowing in the transverse plane
- Exciting results on  $J/\psi$  photoproduction in hadronic collisions
- Looking forward for high-precision measurements in Run 3-4



#### BACKUP

#### Ultimate goal: access gluon shadowing at x~10<sup>-5</sup>





• Two terms in vector meson photoproduction cross section in UPC:

$$\sigma(y) = n(+y)\sigma_{\gamma \mathrm{Pb}}(+y) + n(-y)\sigma_{\gamma \mathrm{Pb}}(-y)$$

$$\uparrow \qquad \uparrow \qquad \uparrow \qquad \uparrow$$

$$\stackrel{\text{high-energy}}{\stackrel{\text{photons}}{}} \stackrel{\text{low-x}}{\stackrel{\text{gluons}}{}} \stackrel{\text{low energy}}{\stackrel{\text{photons}}{}} \stackrel{\text{high-x}}{\stackrel{\text{gluons}}{}}$$

- Effective flux is modified in presence of additional photon exchange
- Neutron-differential cross sections may help to decouple low-x and high-x cross sections:

#### Low-x gluons with coherent J/ $\psi$ in hadronic collisions?



