The VII-th International Conference on the **Initial Stages** of High-Energy Nuclear Collisions (IS2023), Copenhagen.

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### **Experimental overview on UPC**

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- > Physics of ultra-peripheral collisions (UPC) has advanced significantly over recent years since the LHC start
  - Boosted nuclei and strong EM fields: source of quasi-real photons
    - ►  $E_{\text{max}} \leq \gamma/R \sim 80 \text{ GeV}$  at LHC ( ~ 3 GeV at RHIC)
  - >  $Z^2$ ( $\approx 6.7 \times 10^3$ ) enhancement of cross sections for A wrt p beams
  - Precision tool to study photon fluxes and QED
  - > Handle on nuclear gluonic structure and nuclear modifications to **PDFs**
  - Instrumentation in the forward region (ZDCs) offers control over backgrounds and impact-parameter dependence
  - > Large integrated luminosities give access to rare processes

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 Complementary tool to search for beyond Standard Model (BSM) physics

### Also interplay with hadronic collisions





# **EXPERIMENTAL CONSIDERATIONS**

- Coherent and incoherent vector meson photo-production
  - ► Coherent: photon couples coherently to all nucleons (whole nucleus), scale:  $p_{\rm T}^{\rm VM} \sim 1/R_{\rm Pb} = 50$  MeV, target ion intact
  - ► Incoherent: photon couples to a single nucleon  $p_{\rm T}^{\rm VM} \sim 1/R_{\rm p} = 400$  MeV, target ion breaks, usually neutron emission
- Neutron emission (forward activity) measured in Zero Degree Calorimeters (ZDC)





**OnOn**: no activity in either ZDC arm **XnOn**: activity in one ZDC arm **XnXn**: activity in both ZDC arms



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# INITIAL STATE





# COHERENT $J/\psi$ Photo-Production IN A+A



- ► Probes poorly known nuclear gluonic structure and dynamics at  $10^{-5} < x < 10^{-2}$
- ► Novel approach for resolving the photon-emitter ambiguity using forward neutrons in ZDC by **CMS**
- ► Cross section raises rapidly in  $15 < W_{\gamma N}^{Pb} < 40 \text{ GeV}$ , and flattens out for  $W_{\gamma N}^{Pb} > 40 \text{ GeV}$ 
  - Onset of nuclear shadowing/saturation
  - ► None of the theoretical models are consistent with the data
    - ► For theory models see Vadim Guzey, Tue 9:00
- ► The observed behaviour is also expected when approaching the **black disk limit** 
  - $\blacktriangleright$  Large scattering probability in the presence of dense gluons at small x
- ► See talk by Jiazhao Lin, Tue 16:30
- ► See also results by ALICE [EPJC 81 (2021) 712] and LHCb [arXiv:2206.08221]







• Coherent  $J/\psi$  photo-production in Pb+Pb accompanied by nuclear EM dissociation measured by forward-neutron activity by **ALICE** 

► Sensitivity to  $1.1 \cdot 10^{-5} < x < 3.3 \cdot 10^{-1}$  and  $17 < W_{\gamma Pb,n} < 920 \text{ GeV}$ 

- IA and STARlight predictions are disfavoured at low x, while models that include either shadowing or gluon saturation give an equally good description of the data in that region
- ► See talk by Joakim Nystrand, Tue 16:50

# $J/\psi \text{AND} \psi(2S) \text{ PRODUCTION IN PB+PB}$



- ► Incoherent  $J/\psi$  by ALICE and coherent  $J/\psi$  and  $\psi(2S)$  photo-production by LHCb in UPC Pb+Pb
  - ► Correspond to small Bjorken x from  $(0.3 1.4) \times 10^{-3}$  (ALICE) and  $10^{-5} 10^{-2}$  (LHCb)
- ► Models which include **quantum fluctuations** of the **gluon density** in the colliding hadron provide a better description
- New or improved theoretical models are needed to describe simultaneously energy and Itl-dependence of both coherent and incoherent processes
  - See poster by David Grund
- ► Excellent agreement between data and various predictions in  $\sigma_{\psi(2S)}/\sigma_{J/\psi}$  in LHCb
- See also older results from CMS: Υ [PJC 79 (2019) 277], ρ [EPJC 79 (2019) 702] in p+Pb and ALICE: coherent J/ψ [PLB 817 (2021) 136280]

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#### STAR [PRL 128 (2022) 122303]



- ► First measurement of  $J/\psi$  in d+Au collisions at  $\sqrt{s_{\rm NN}} = 200$  GeV by STAR
- ► Probes the **gluon density** of the deuteron
  - > With  $x \sim 0.01$  very small gluon saturation or the nuclear shadowing effects are expected
- ► Neutron-tagging technique in ZDC explored for the first time
  - ► Serves as an experimental baseline for the EIC
- Theoretical predictions based on the Colour Glass Condensate saturation model and the Leading Twist Approximation
  - ► A better agreement with the saturation model is observed

# PHOTO-NUCLEAR JETS IN PB+PB



- Photo-nuclear production of dijets in UPC Pb+Pb by ATLAS
- One nuclei intact and a rapidity gap in the γ-going direction
- Triple-differential cross-sections measured as a function of
  - ►  $x_A$ : Bjorken-x in nucleus
  - >  $z_{\gamma}$ : photon or resolved  $\gamma$  momentum fractions
  - ►  $H_{\rm T}$ : total transverse momentum of jet
- Sensitive to nuclear modifications of PDFs in the colliding nuclei
- Ongoing work on further reduction of systematics and modelling of nuclear breakup probabilities
  - ► See talk by Ricardo Longo, Tue 16:10





# EXCLUSIVE DIMUONS IN PB+PB

#### ATLAS [PRC 104 (2021) 024906]



- ► Exclusive  $\gamma \gamma \rightarrow \mu^+ \mu^-$  production for  $m_{\mu\mu} > 10$  GeV in Pb+Pb collisions by **ATLAS**
- Precision test of initial photon fluxes and QED calculations
- > Differential cross sections studied in  $m_{\mu\mu}$ ,  $|y_{\mu\mu}|$ ,  $|\cos \theta^*|$ ,  $k_{\min}$ ,  $k_{\max}$ ,  $\alpha$
- Significant differences wrt pure STARlight calculations for large acoplanarity α (missing FSR)



# FORWARD ACTIVITY IN A+A

 Excitation of one or both ions via photon absorption into giant dipole resonances or higher excited states may occur in γγ interactions 11

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- ► ATLAS and CMS measured activity in ZDC in events with  $\gamma\gamma \rightarrow \mu^+\mu^-$ 
  - Constraints on impact-parameter dependence of Pb+Pb collisions
  - ► **Baseline** to search for possible final-state effects on  $\gamma\gamma \rightarrow \mu^+\mu^-$  by traversing the QGP in hadronic HI collisions (non-UPC studies)



# EXCLUSIVE DIELECTRONS IN A+A



- ► Breit-Wheeler  $\gamma \gamma \rightarrow e^+e^-$  process for  $m_{ee} > 5$  GeV in Pb+Pb by ATLAS and  $0.4 < m_{ee} < 2.6$  GeV in Au+Au by STAR
  - ► Inclusive and OnOn category differential cross sections
  - Comparisons to STARlight and SuperChic reveal systematic differences in normalisation
  - STAR demonstrates colliding photons are linearly polarised
- > See also the first polarisation measurement of coherent  $J/\psi$  in Pb+Pb by ALICE [arXiv:2304.10928]



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## **EXCLUSIVE DITAUS IN PB+PB**





► Event candidate for  $\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow e^+\nu_e\nu_\tau\mu^-\nu_\mu\nu_\tau$ 

# **EXCLUSIVE DITAUS IN PB+PB**



- > First observation of exclusive  $\gamma\gamma \rightarrow \tau^+\tau^-$  production in the hadron colliders by ATLAS and CMS
- ► Use  $\mu$ +3prong (**CMS**) and  $\mu$ +1prong and  $\mu$ +3prong (**ATLAS**)
- ► CMS: fiducial cross section with 16% precision in 2015 data
- ► ATLAS: signal strength  $\mu_{\tau\tau} = N_{\gamma\gamma \to \tau\tau}^{\text{meas}} / N_{\gamma\gamma \to \tau\tau}^{\text{SM,pred}}$  with 5% precision in 2018 data
- ► Results **compatible** with **SM**
- Potential for improvements based on full Run-2 Pb+Pb data

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# INTERPLAY WITH QUARK-GLUON PLASMA



# **NON-UPC DIELECTRONS AND** $J/\psi$ **IN PB+PB**



- ► Measurement of  $e^+e^-$  pairs with  $0.4 \le m_{ee} < 2.7$  GeV in **peripheral** and **semi-peripheral** Pb+Pb collisions by **ALICE** and  $J/\psi \rightarrow \mu^+\mu^-$  production in 2.0 < y < 4.5 in **peripheral Pb+Pb** events with  $\langle N_{part} \rangle$ =19.7 by **LHCb** 
  - ► Excess consistent with  $\gamma\gamma \rightarrow e^+e^-$  and coherent  $J/\psi$  photo-production
- ► In 70–90% centralities, **about 50%** of  $e^+e^-$  pairs are produced inside the nuclei
- ► Yields for  $p_{T,ee} > 0.1$  GeV can be explained by hadronic cocktail, low  $p_{T,ee}$  region is dominated by  $\gamma\gamma \rightarrow e^+e^-$  with the impact-parameter dependent  $k_T$  distribution
- Shapes of measured distributions are qualitatively described by theoretical predictions, although a normalisation discrepancy is observed

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- Isobar collisions of <sup>96</sup><sub>44</sub>Ru and <sup>96</sup><sub>40</sub>Zr provide a unique opportunity to test EM field dependence by STAR
- ► At very low  $p_T (p_T < 0.15 \text{ GeV})$  photon-induced processes ( $\gamma \gamma \rightarrow e^+ e^-$  and  $\gamma A \rightarrow J/\psi$ ) dominate over hadronic collisions in 40-80% centrality
  - ► Hadronic contributions are similar in Ru+Ru and Zr+Zr
  - ► Ratio is consistent with  $(\frac{Z_{\text{Ru}}}{Z_{\text{Zr}}})^4 = (\frac{44}{40})^4$  for  $e^+e^-$  or  $(\frac{Z_{\text{Ru}}}{Z_{\text{Zr}}})^2 = (\frac{44}{40})^2$  for  $J/\psi$
  - ► Initial EM fields are different in Ru+Ru versus Zr+Zr by  $\sim 3\sigma$  in  $e^+e^-$  and by  $\sim 1.7\sigma$  in  $J/\psi$

## NON-UPC DIMUONS IN PB+PB



- ► Measurement of  $\gamma \gamma \rightarrow \mu^+ \mu^-$  in non-UPC events by **ATLAS**
- ► Centrality-dependent **broadening** of acoplanarity  $\alpha$  and  $k_{\perp} = \frac{1}{2}(p_{T1}^{\mu} + p_{T2}^{\mu})(\pi |\phi_1^{\mu} \phi_2^{\mu}|)$  is confirmed
  - Significant increase in the mean and RMS values is observed as one goes from UPC to higher centralities
  - Standard deviation shows a much slower increase
  - Initial state PWF [PRD 102 (2020) 094013] and QED [PLB 800 (2020) 135089] predictions reproduce many of the trends, but the mean and RMS values lie systematically below the data
- > Predicted trends associated with impact of **magnetic fields** on dimuons are not observed
- ► See talk by Peter Steinberg, Wed 14:20







> Measurement of flow in photo-nuclear  $\gamma A$  events in Pb+Pb collisions by ATLAS

- Dedicated high-multiplicity trigger
- Significant non-zero values of the second- and third-order flow coefficients are observed
- $\blacktriangleright$  v<sub>2</sub> values are smaller than those in pp and p+Pb systems
- > Input to a discussion about the origin of flow in small systems

#### CMS [arXiv:2204.13486]



- > Search for azimuthal correlations in  $\gamma p$  interactions in p+Pb collisions at  $\sqrt{s_{\rm NN}} = 8.16$  TeV by CMS
- ➤ Unique initial conditions with N<sub>trk</sub> lower than in p+Pb collisions but comparable to recent e<sup>+</sup>e<sup>-</sup> and e<sup>±</sup>p<sup>+</sup> data
- ► Results can be described by models which do not include collective effects
- > Data suggests **the absence of collectivity** in the  $\gamma p$  system over  $N_{trk}$  explored



# **RARE PROCESSES**



# LIGHT-BY-LIGHT SCATTERING IN PB+PB



- Light-by-light (LbyL) scattering is a rare fundamental QED process
  - ► Observed in a direct way at the LHC for the first time [PRL 123 (2019) 052001]
  - About 100 event candidates in full Run-2 UPC Pb+Pb data
- ► Both ATLAS (full Run 2) and CMS (only 2015 data set) measure LbyL scattering
  - ► First differential cross sections in  $m_{\gamma\gamma}$ ,  $|y_{\gamma\gamma}|$ ,  $|\cos\theta^*|$  and  $(p_T^{\gamma 1} + p_T^{\gamma 2})/2$  provided by **ATLAS**
  - Good agreement in shape, 50% differences in the normalisation to SuperChic v3.0 [EPJ C 79 (2019) 39]

# FIRST HI COMBINATION AT THE LHC



G. Krintiras et al [Acta Phys.Polon.Supp. 16 (2023) 1, 123]



- ► Combination of integrated fiducial cross sections for LbyL scattering from ATLAS and CMS
  - ► Part of the <u>HonexComb</u> group activities STRGNG-2...20
  - ► ATLAS: 2015+2018 Pb+Pb data (2.2 nb<sup>-1</sup>)
  - ► CMS: 2015 Pb+Pb data (0.39 nb<sup>-1</sup>)
- ► 10% improvement in the precision
- Pave the way for future cross-experimental combinations
- ► For theory see talk by Mariola Kłusek-Gawenda, Wed 11:30



# SEARCH FOR NEW PHYSICS





## ANOMALOUS MAGNETIC MOMENT OF TAU IN PB+PB

#### ATLAS [arXiv:2204.13478]

CMS [arXiv: 2206.05192]



- ► Measurement of  $\gamma \gamma \rightarrow \tau^+ \tau^-$  in Pb+Pb provides access to **anomalous magnetic moment** of tau lepton  $a_{\tau} = \frac{g-2}{2}$ 
  - Poorly constrained experimentally, sensitive to BSM physics
- Both CMS and ATLAS provide constraints on a<sub>τ</sub> using theory predictions by L.Beresford et al. [PRD 102 (2020) 113008] and M.Dyndal et al. [PLB 809 (2020) 135682], respectively
  - ► First constraints on  $a_{\tau}$  from hadron colliders
- ► Constraints from ATLAS similar in precision to those observed by DELPHI

# SEARCH FOR ALP IN PB+PB



- > Distribution of  $m_{\gamma\gamma}$  from light-by-light measurement in Pb+Pb used to search for axion-like particles (ALP) by CMS and ATLAS
  - ► Signal:  $\gamma \gamma \rightarrow a \rightarrow \gamma \gamma$ , BR( $a \rightarrow \gamma \gamma$ )=100%
- ▶ 95% CL limits on  $\sigma$  and coupling  $1/\Lambda_{\rm a}$ 
  - ► The most stringent limit established for ALP masses  $5 < m_{\gamma\gamma} < 100 \text{ GeV}$
- See poster by Melike Akbiyik



# SUMMARY AND OUTLOOK



- ► A lot of progress in the UPC physics programme across all experiments
- Large integrated luminosities at the LHC and photon fluxes (Z<sup>2</sup> per beam) give access to precision information on initial state
  - Models which include nuclear shadowing/gluon saturation better describe the data but still more work is needed for interpretation
  - Experiments make use of information on forward-neutron emission in ZDC
- Thanks to these conditions new rare processes can be studied for the first time
- UPC data seems to provide the most stringent constraints for BSM physics searches with ALPs and anomalous magnetic moment of tau in the hadron colliders
- Looking forward to new measurements from future data taking at the LHC and RHIC