Latest ALICE results from angular correlations studies in UPCs

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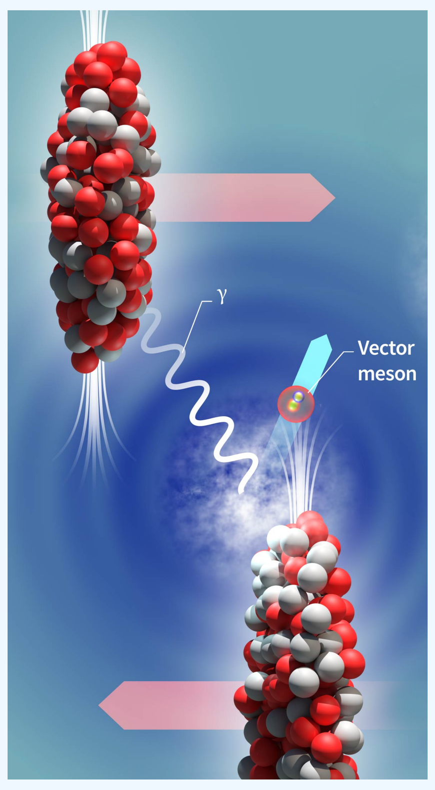
Introduction

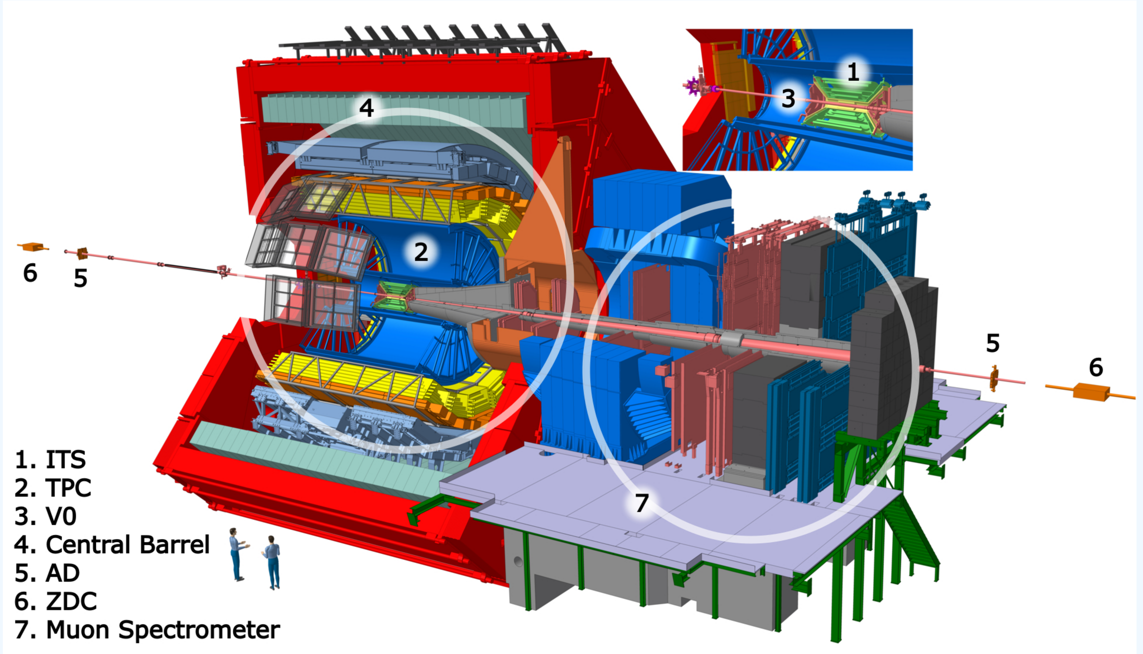


- Ultraperipheral collisions (UPCs): impact parameter b greater than the sum of the radii of the colliding nuclei
- Purely hadronic interactions highly suppressed → UPCs allow us to study photon induced reactions
- γ-nucleus interactions: **coherent** if the **interaction** is **with the whole nucleus**, or incoherent if the interaction is with one nucleon
- **vector meson (VM) photoproduction**: the exchanged γ^* fluctuates into a $q\bar{q}$ pair → interacts strongly with the nucleus
- EM fields of the nuclei highly Lorentz contracted → quasi-real **photons linearly polarized along the impact parameter direction**
- UPCs can be accompanied by independent electromagnetic dissociation → nuclear break-up with emission of forward neutrons

UPCs can be used to **study the angular distribution of coherently produced VMs and their decay products to get information of the process and on the nucleus**:

- **polarization of photoproduced** J/ψ [1]: quasi-real photons interact with a simple object → s-channel helicity conservation (SCHC) suggests transverse polarization for the VM
- **azimuthal anisotropy in the** ρ^0 **photoproduction**: linearly polarized photon + quantum interference at amplitude level = azimuthal anisotropy. The asymmetry depends on the QCD structure of the nuclei → test quantum interference and high-energy QCD

The ALICE detector



- **AD** and **V0** → scintillators used to veto purely hadronic interactions
- **ITS** → silicon tracker, here used also for triggering on 2-track events
- **TPC** → main tracker of the central barrel, used also to identify pions
- **ZDCs** → used to detect neutrons at forward rapidity
- **Forward Muon Spectrometer** → used to identify and track muons at forward rapidity

Coherent VM photoproduction has large cross section and a very clear signature in the detector: 2 unlike sign tracks in an otherwise empty detector

J/ψ **at forward rapidity**: $J/\psi \to \mu^+\mu^-$ ⇒ two tracks in the muon spectrometer

ρ^0 **at mid-rapidity**: $\rho^0 \to \pi^+\pi^-$ ⇒ two tracks in the central barrel (ITS + TPC)

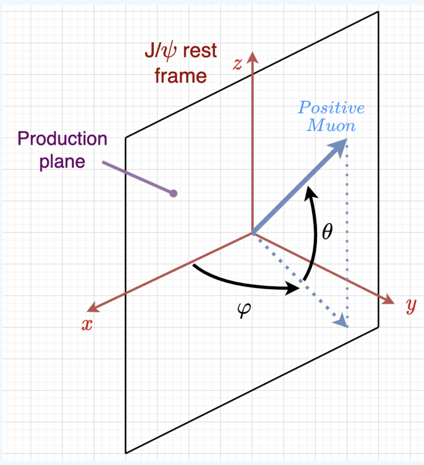
Analysis strategy: J/ψ polarization

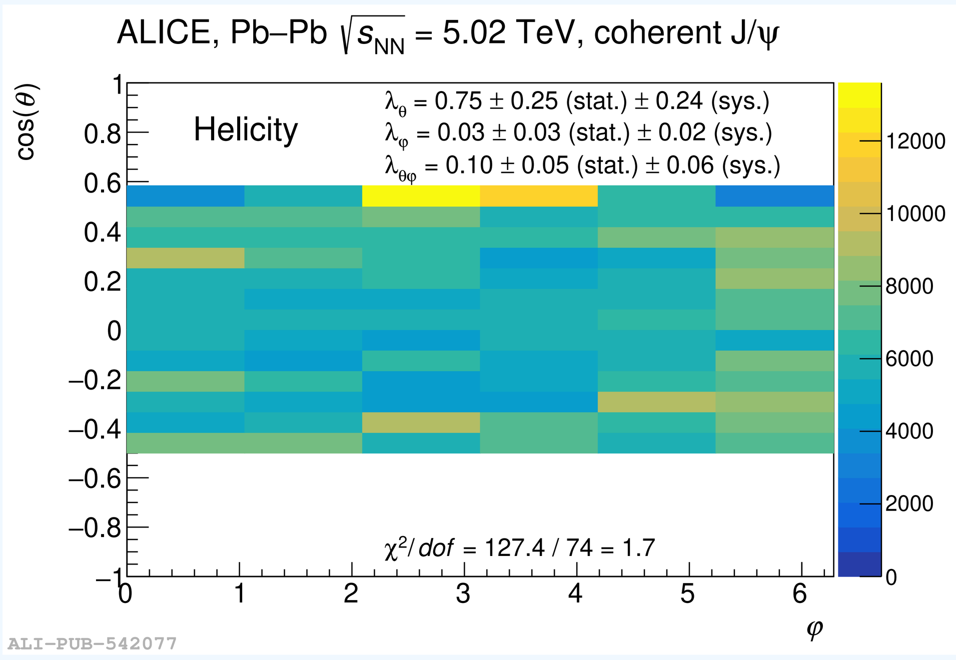
The **polarization of the** J/ψ can be **studied through the angular distribution of the decay muons**, written in terms of the polarization parameters λ_θ, λ_φ and $\lambda_{\theta\varphi}$

Using the integral version of this distribution in $\cos\theta$ and in φ:

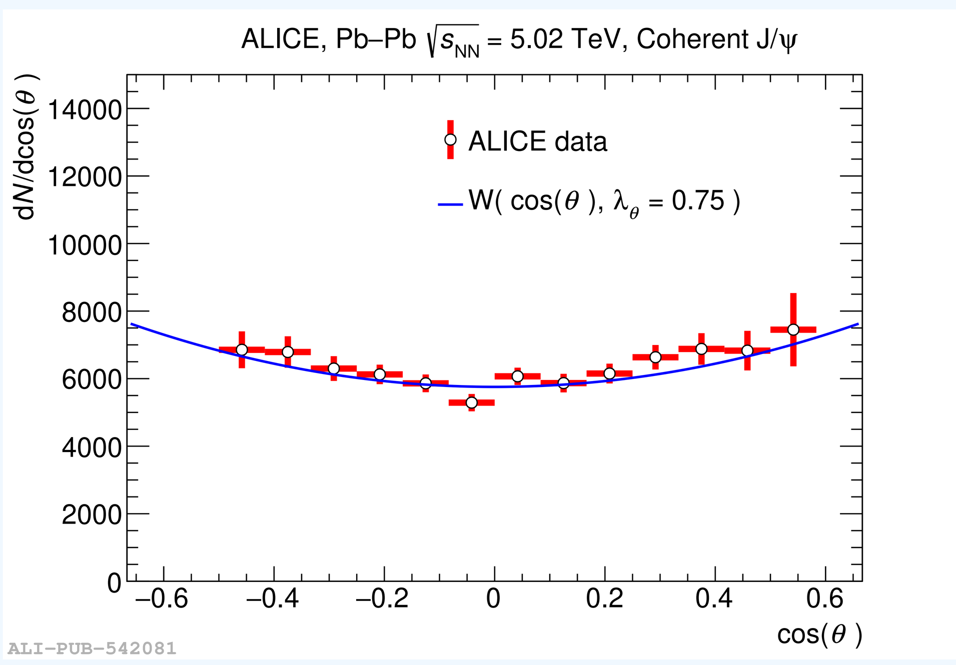
$$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta}\left[1+\lambda_\theta\cos^2\theta\right] \quad (1)$$

$$W(\varphi) \propto 1 + \frac{2\lambda_\varphi}{3+\lambda_\theta}\cos 2\varphi \quad (2)$$





- Data binned in 24 $\cos\theta$ and 6 φ ranges
- Unfolding of the data in φ and correction for acceptance × efficiency ($A\times\epsilon$) of the detector
- Fit to the corrected muon pair invariant mass spectrum, using a Crystal Ball function → extraction of the coherent J/ψ yield in each bin
- Construction of the 2D map of the J/ψ yield vs φ and $\cos\theta$



- Fit to the 2D map using Eq. (1) and Eq. (2) to extract the polarization parameters
- Systematic uncertainties: $\cos\theta$ fit range + signal extraction + unfolding + response matrix + trigger
- **Spin-density matrix elements** extracted from polarization parameters

$$r^{04}_{00} = \frac{1-\lambda_\theta}{3+\lambda_\theta}$$
$$r^{04}_{1,-1} = \frac{\lambda_\varphi}{2}(1+r^{04}_{00}) \quad (3)$$

Analysis strategy: ρ^0 azimuthal anisotropy

H. Xing *et al.* model [4], based on the $q\bar{q}$ color model, predicts that the anisotropy manifests in a $\cos(2\phi)$ **modulation of the** ρ^0 **yield**, with an amplitude that varies as a function of b.

What is ϕ?

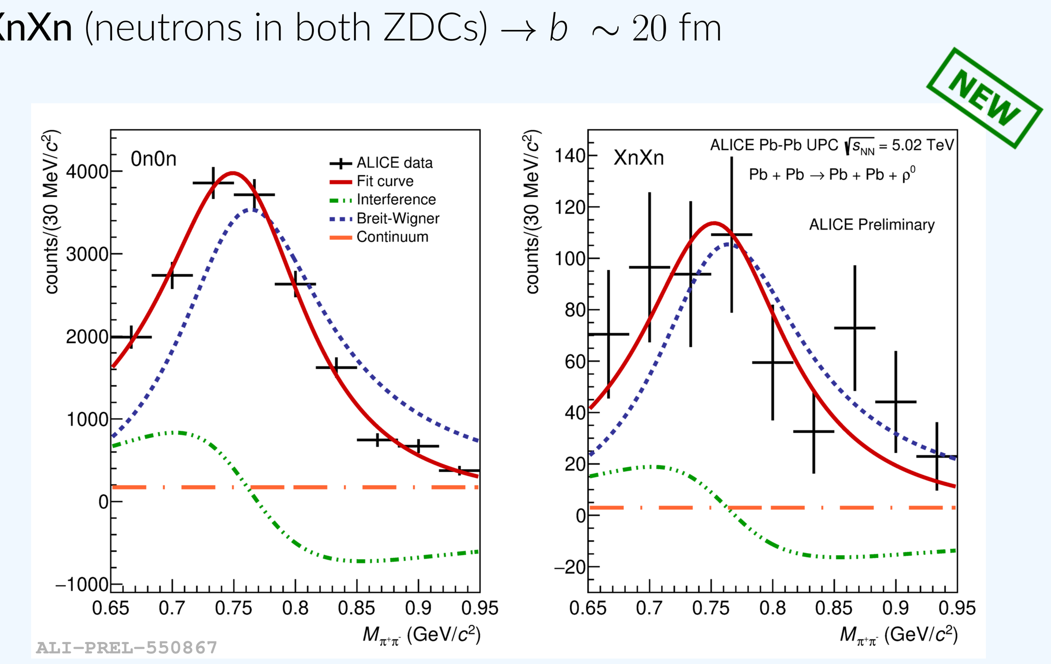
$\phi =$ **azimuth angle between** p_+ **and** p_-

$p_\pm = \pi_1 \pm \pi_2$, π_j = 4-momentum of jth track, randomly assigned to the positive or negative track

How to select different impact-parameter ranges?

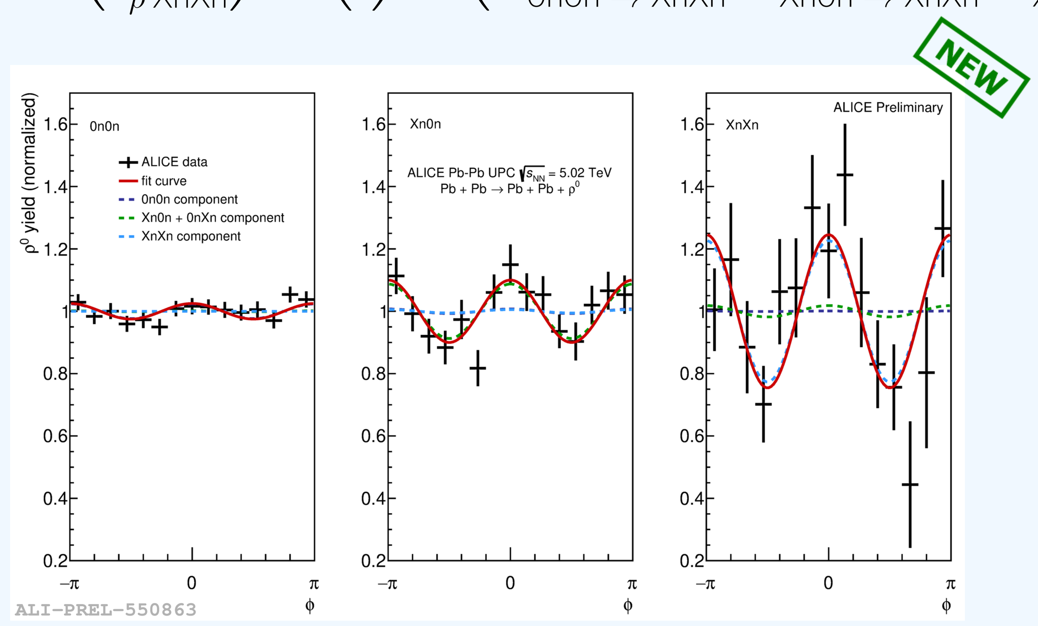
Neutron emission probability from EMD depends on b → different neutron emission classes correspond to different average values of b

Neutron classes: **0n0n** (no neutrons) → $b \sim 98$ fm; **Xn0n** (neutrons only in one ZDC) → $b \sim 27$ fm; **XnXn** (neutrons in both ZDCs) → $b \sim 20$ fm



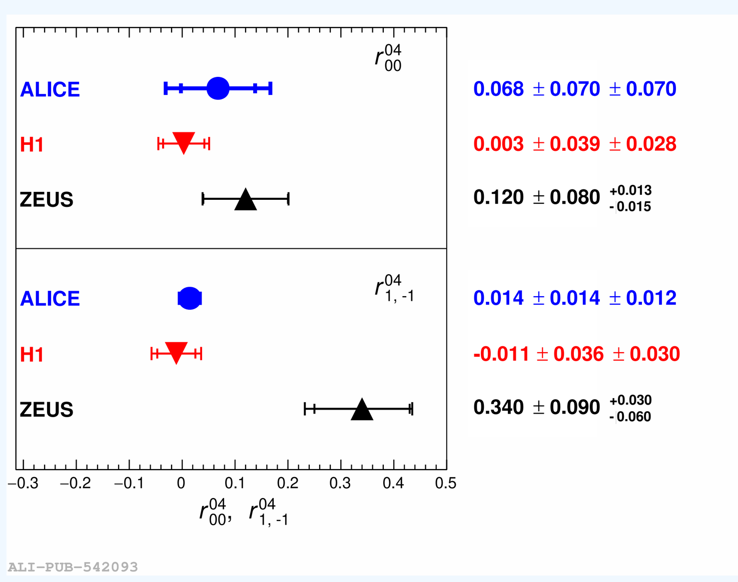
- Data binned in 15 ϕ ranges and in 3 independent neutron class
- Reweighting of the MC to match the p_T distribution of data
- Fit to the $A\times\epsilon$ corrected invariant mass spectrum using the Söding model → extraction of the ρ^0 yield as a function of ϕ in each neutron class

$$\begin{pmatrix} n_{\rho\,0n0n} \\ n_{\rho\,Xn0n} \\ n_{\rho\,XnXn} \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} + \begin{pmatrix} w_{0n0n\to0n0n} & w_{Xn0n\to0n0n} & w_{XnXn\to0n0n} \\ w_{0n0n\to Xn0n} & w_{Xn0n\to Xn0n} & w_{XnXn\to Xn0n} \\ w_{0n0n\to XnXn} & w_{Xn0n\to XnXn} & w_{XnXn\to XnXn} \end{pmatrix} \begin{pmatrix} a_{2\,0n0n} \\ a_{2\,Xn0n} \\ a_{2\,XnXn} \end{pmatrix} \cos(2\phi), \quad (4)$$



- Simultaneous fits of the yields in different neutron classes to extract the amplitudes of the ρ^0 yield vs ϕ using Eq.(4), to consider migrations across neutron classes
- Systematic uncertainties: signal extraction + $A\times\epsilon$

Results: J/ψ polarization

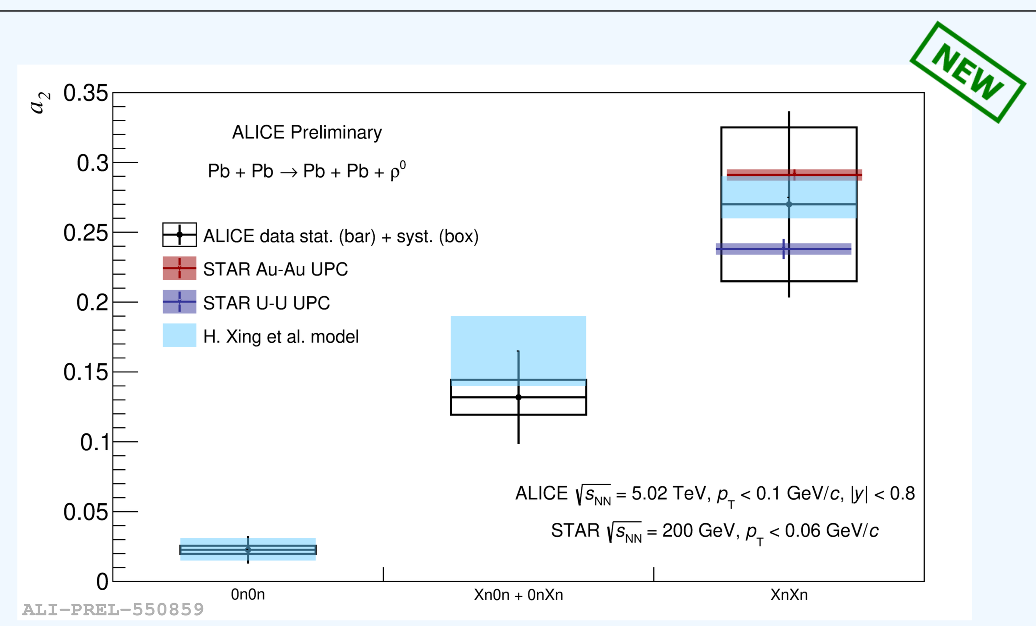


- The polarization parameters are extracted

$$\lambda_\theta = 0.75 \pm 0.25\text{ (stat.)} \pm 0.24\text{ (syst.)}$$
$$\lambda_\varphi = 0.03 \pm 0.03\text{ (stat.)} \pm 0.02\text{ (syst.)}$$
$$\lambda_{\theta\varphi} = 0.10 \pm 0.05\text{ (stat.)} \pm 0.06\text{ (syst.)}$$

- Parameters compatible with $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (1, 0, 0)$ → indicates **transverse** J/ψ **polarization**
- Spin-density matrix elements compared with the results from H1 [2] and ZEUS [3] → **compatible with H1**, which explores similar photon virtualities

Results: ρ^0 azimuthal anisotropy



- First measurement of the impact-parameter dependent modulation of the ρ^0 yield vs ϕ
- The **modulation strength strongly increases as** b **decreases**
- H. Xing *et al.* **predictions reproduce the data**
- XnXn amplitude **in agreement with** STAR results [5]

Conclusions and Outlook

Results compatible with transverse J/ψ polarization → **corroborates SCHC hypothesis!**

The measured **azimuthal anisotropy in** ρ^0 **photoproduction is compatible with the predictions**; current uncertainties do not allow the measurement to constrain the models → possible with Run 3 data!

The anisotropy measurement can be seen as a **double-slit experiment at fm scale** → **QM valid here!**

References

[1] ALICE Collaboration, *arXiv:2304.10928 [nucl-ex]*, 2023.

[2] H1 Collaboration, *The European Physical Journal C*, vol. 46, apr 2006.

[3] ZEUS Collaboration, *Nuclear Physics B*, vol. 695, no. 1-2, 2004.

[4] H. Xing *et al. J. High Energ. Phys.*, vol. 10, no. 64, 2020.

[5] STAR Collaboration, *Science Advances*, vol. 9, no. 1, 2023.

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