Quantum Interference at the Femtometer Scale

Measurement of the impact-parameter dependent azimuthal anisotropy in coherent ρ^0 photoproduction in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (ALICE, arXiv:2405.14525 [nucl-ex], accepted by PLB)

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Outline

Introduction: UPCs and photon-nuclear interactions

Coherent ρ^0 photoproduction: experimental aspects and previous measurements

Interference and polarization in vector meson photoproduction

Anisotropy from quantum interference and photon polarization

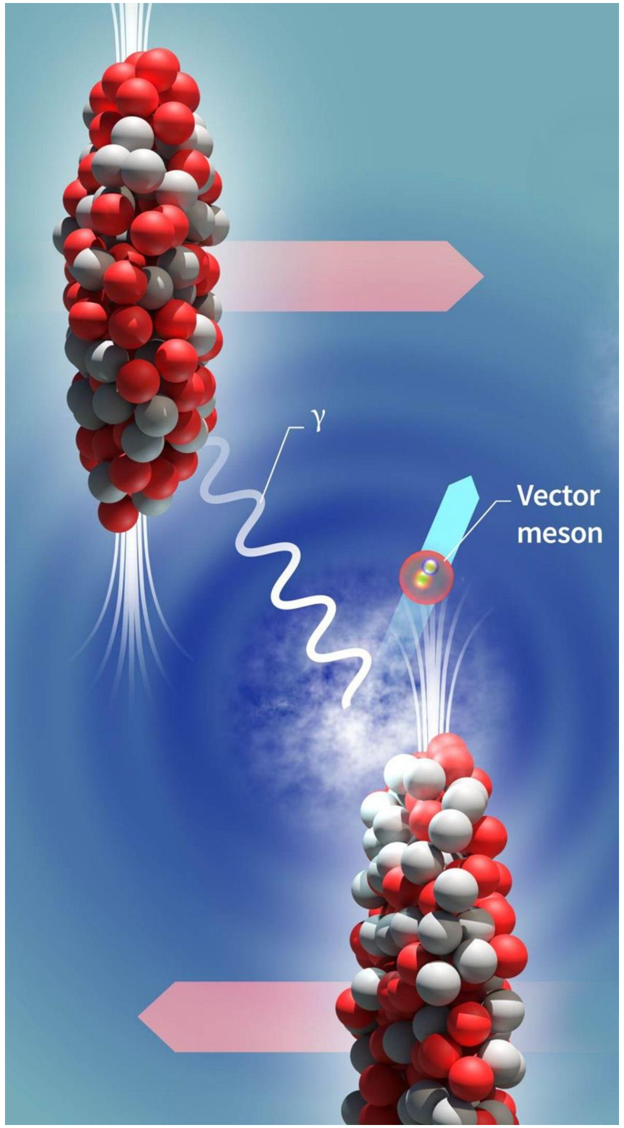
Analysis and results on the impact-parameter dependence of the anisotropy

Conclusions and outlook

Introduction

Ultra-peripheral collisions and vector meson photoproduction

Ultra-peripheral collisions



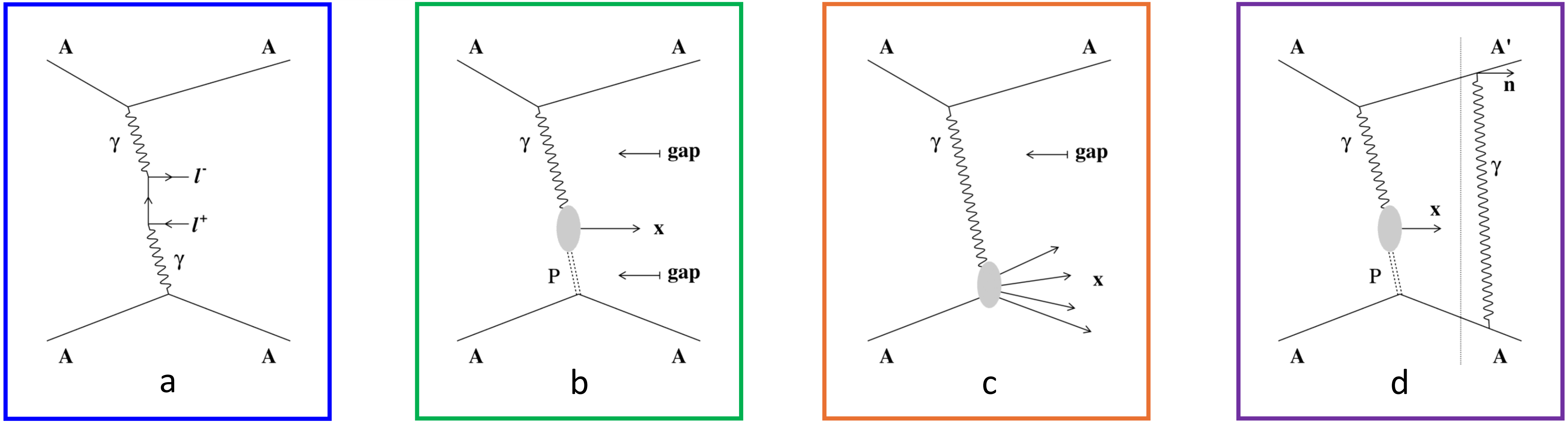
- **UPCs** = ultra-peripheral collisions
→ impact parameter b **greater than the sum of the radii of the colliding nuclei**

- Heavy nuclei have a strong electromagnetic (**EM**) **field** that can be **described as** a **flux of photons**

- Heavy-ion collisions: intense ($\sim Z^2$), energetic, and low-virtuality photon fluxes
→ electromagnetic dissociation cross section $\sim$ 30 times greater than hadronic cross section in Pb-Pb

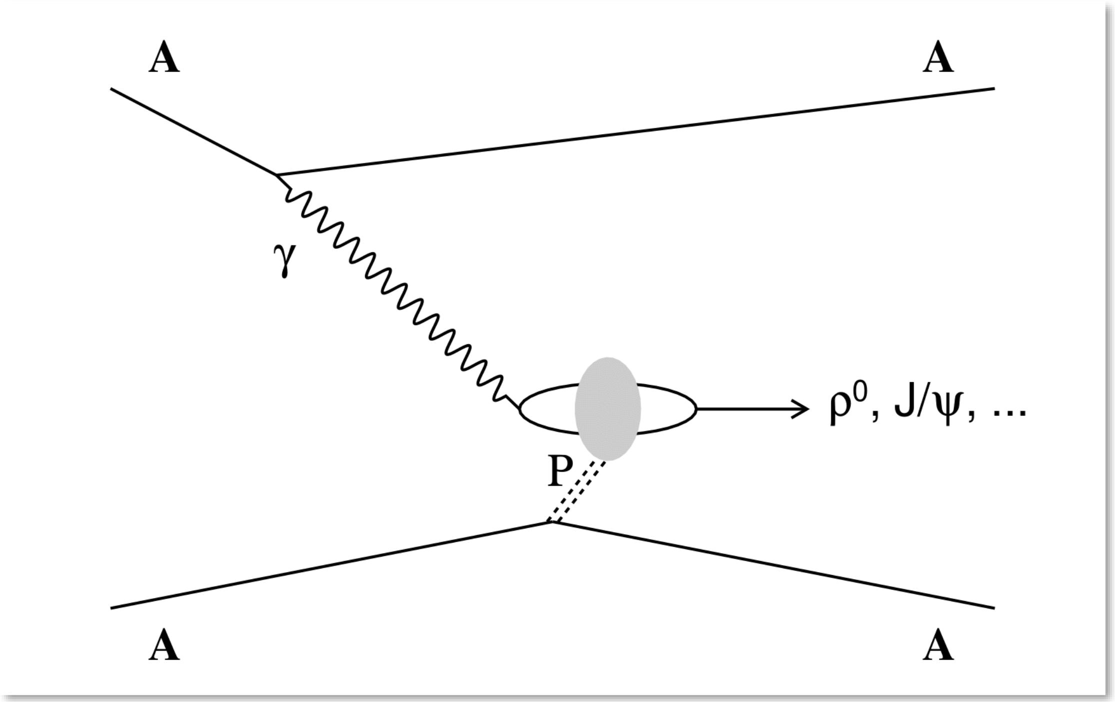
- **Hadronic interactions** are short range: highly **suppressed** in UPCs
→ UPCs allow for the **study of photon-induced reactions**, such as purely EM processes, but also photon-nuclear reactions

Processes in UPCs



- Photon-induced reactions: pure EM processes, such as $\gamma\gamma \rightarrow l^{+}l^{-}$ (a), or γ-nucleus reactions
- γ-nucleus reactions:
  - Diffractive (b): interaction without color exchange → 2 rapidity gaps
  - Inelastic (c): color exchange → rapidity gap only in the photon side
- Due to the very intense EM field it is possible to have multi-photon exchange, that may lead to electromagnetic dissociation (EMD) processes that cause neutron emission at beam rapidity (d)

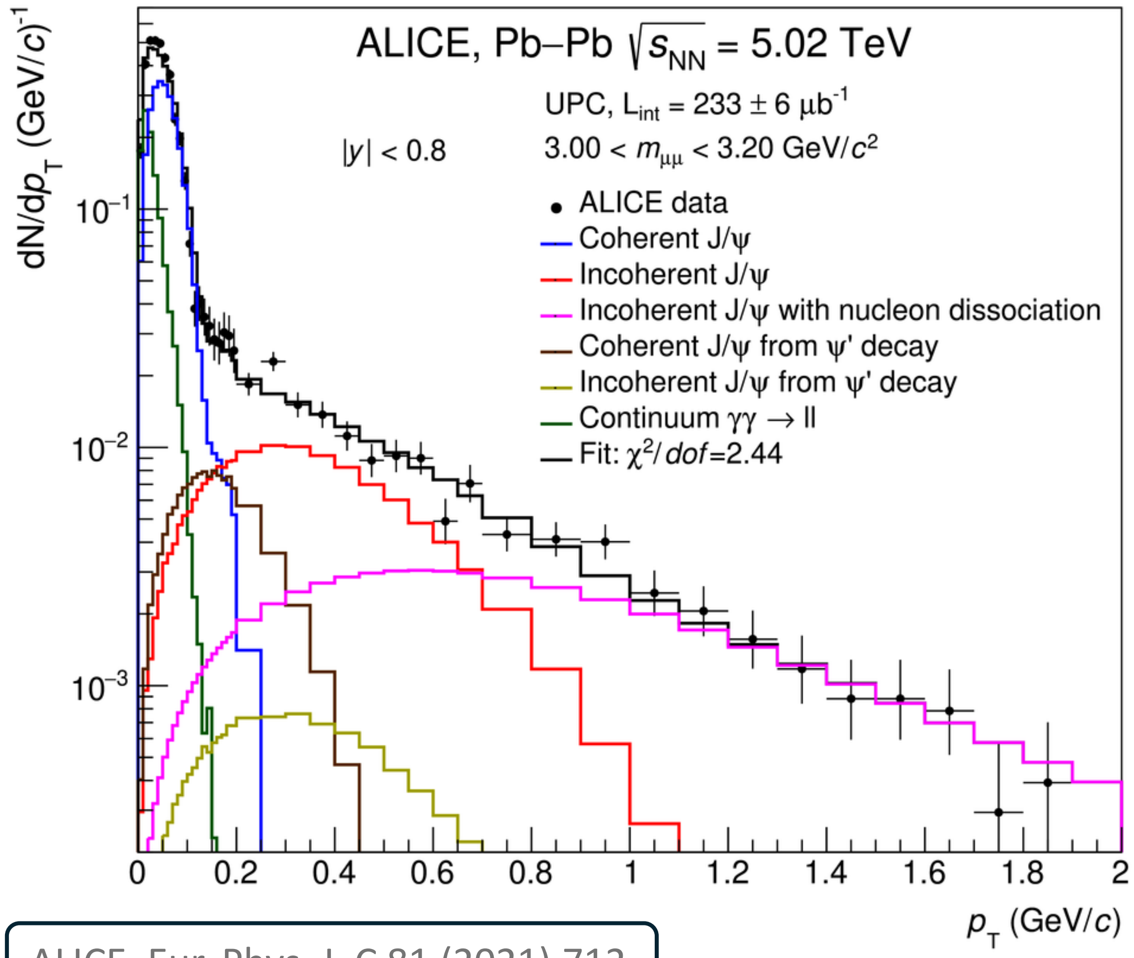
Diffractive vector meson photoproduction



How does the process work?

1. One of the **nuclei emits a quasi-real photon**
2. The exchanged photon splits into a virtual **quark-antiquark pair** that **interacts strongly with the nucleus** via Pomeron exchange
3. The interaction brings the quark-antiquark pair on its mass-shell and a real particle is produced
   → due to the spin J = 1 of the photon the interaction is very likely to **produce a vector meson** (VM)

Coherent and incoherent photoproduction



ALICE, Eur. Phys. J. C 81 (2021) 712

VM photoproduction can be:

Coherent:

- the photon interacts with the nucleus as a whole
- the nucleus remains intact

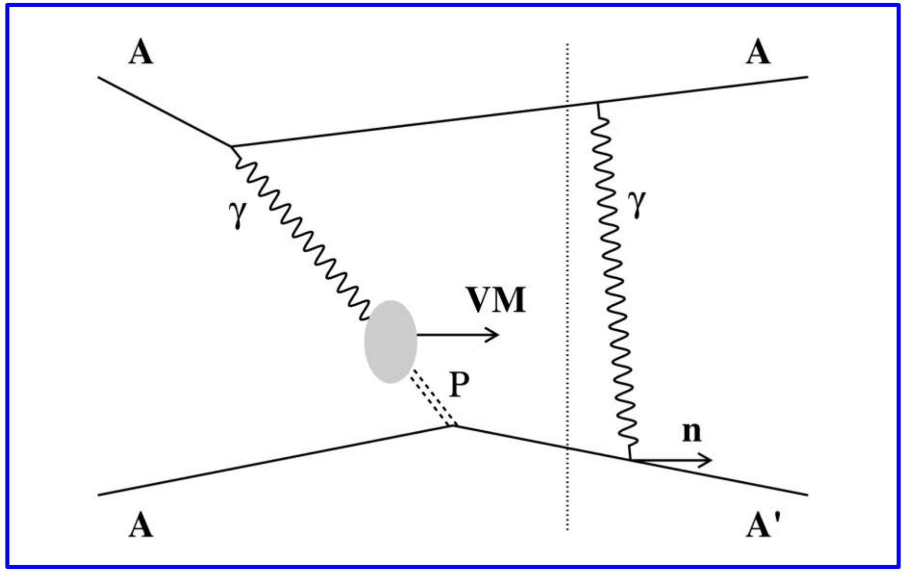
Incoherent:

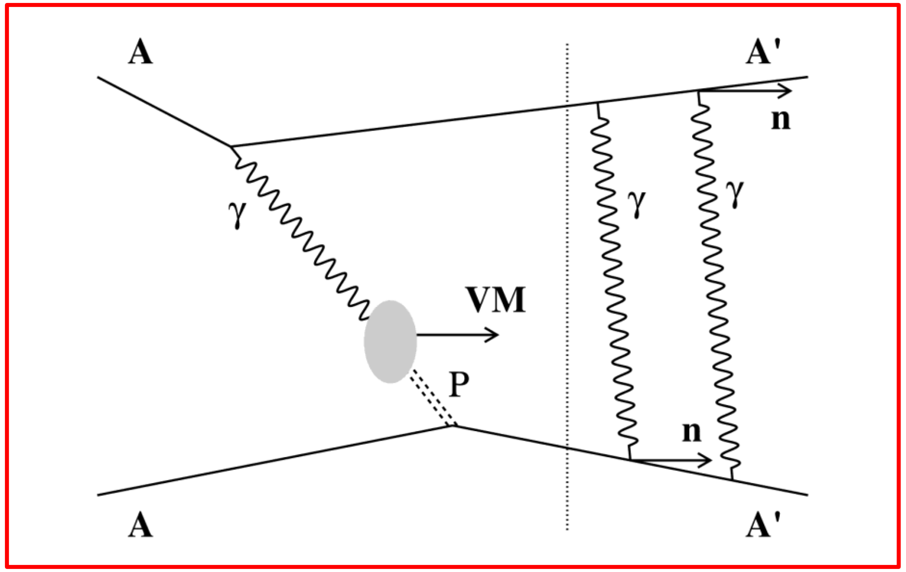
- the photon interacts with only one nucleon
- the nucleus usually breaks up

VM p_T is related to the target size in the transverse plane by Fourier transform

- coherent → $< p_T > \sim$ 50 MeV
- inchoerent → $< p_T > \sim$ 500 MeV

Electromagnetic dissociation (EMD)





- **Vector meson photoproduction** can occur **with independent EMD processes** (process d in slide 5)

- EMD needs the exchange of energetic photons
→ the probability of finding energetic photons decreases as the impact parameter increases

- **EMD processes can be used to select different impact parameter ranges in UPCs**

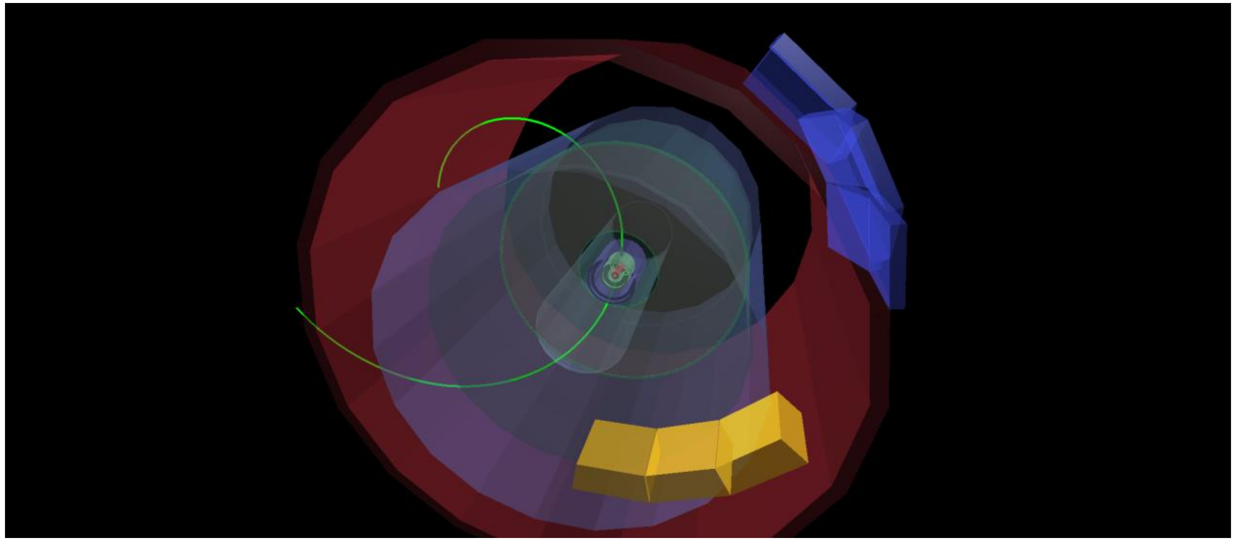
- EMD classes from large to small b:
0n0n: no EMD,
Xn0n: EMD of one of the nuclei,
XnXn: both nuclei undergo EMD

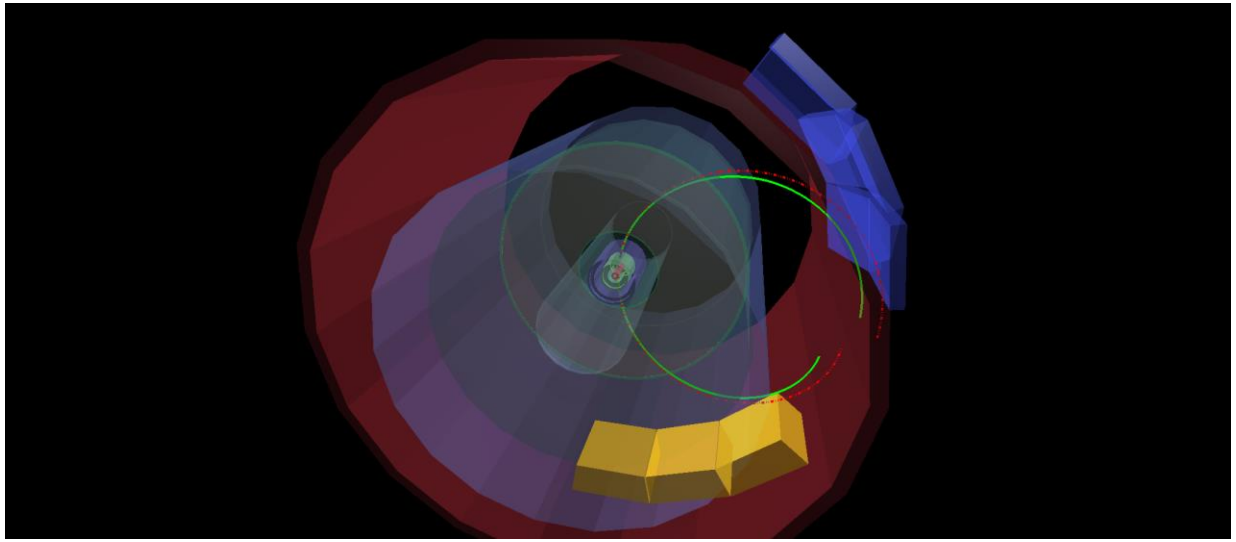
Coherent ρ^0 photoproduction in ALICE

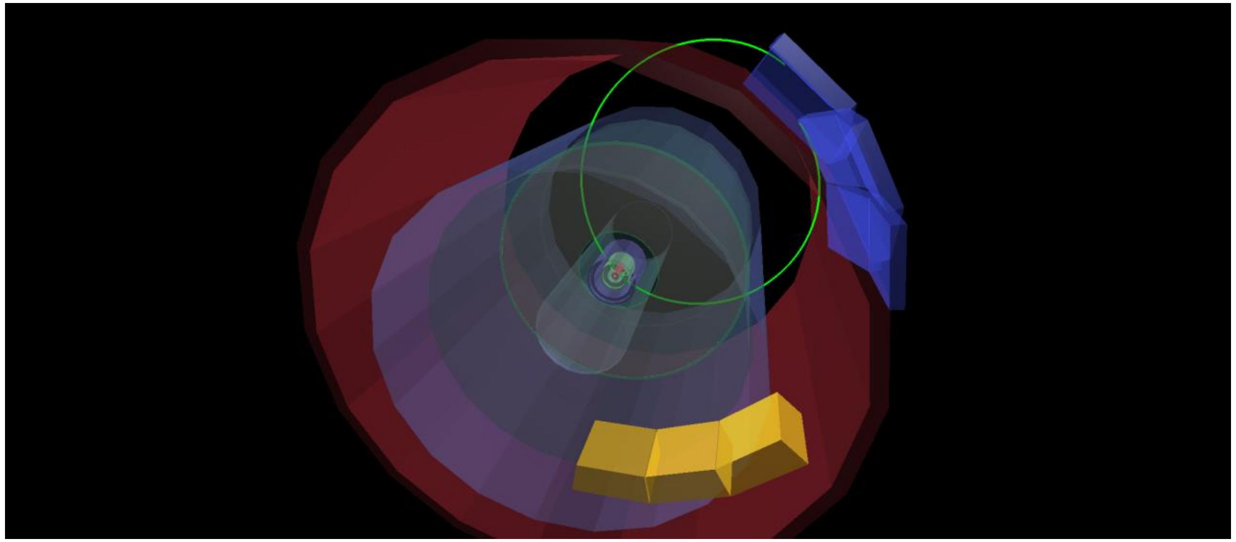
We are interested in coherent ρ^0 photoproduction

ALICE detects the ρ^0 at midrapidity, using the $\rho^0 \rightarrow \pi^+\pi^-$ decay channel (BR~100%)

Very clear signal: two tracks in an otherwise empty detector







ALICE results on coherent ρ^0 photoproduction

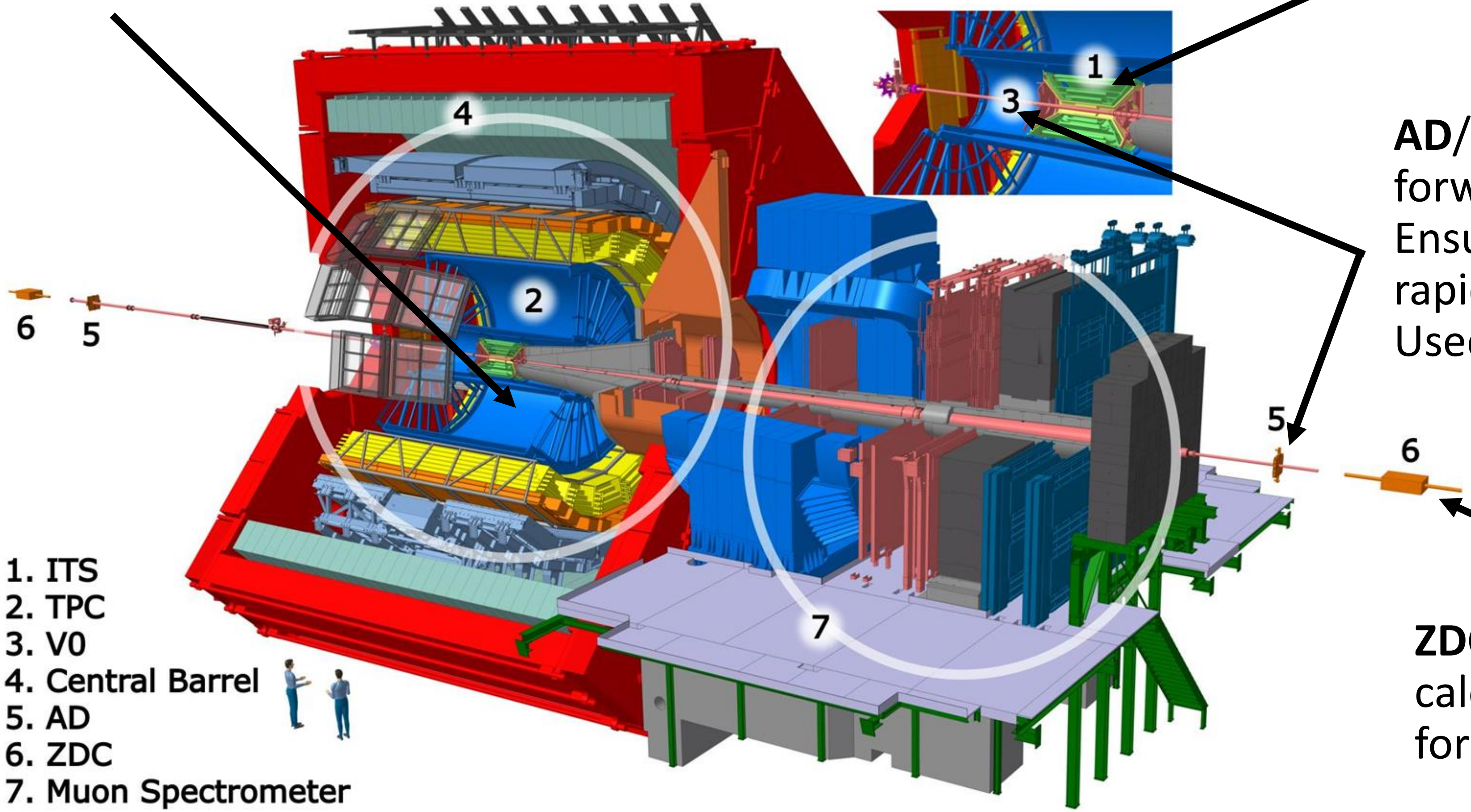
ALICE detector and Run 2 results on coherent ρ^0 photoproduction using different colliding systems

ALICE in Run 2

TPC: large gaseous detector. Main tracker, used also for PID via specific energy loss dE/dx

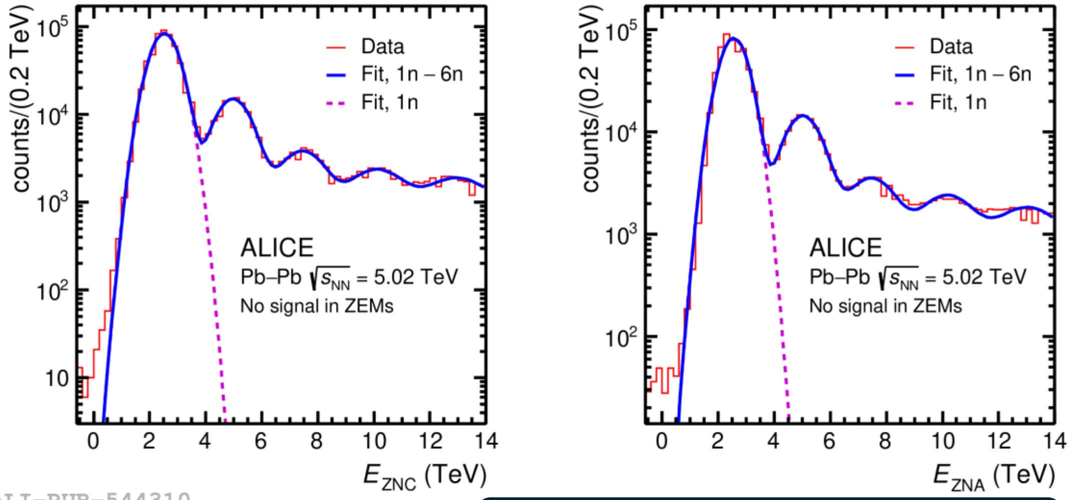
ITS: 6 layers of silicon trackers. The 2 innermost layers are also used for triggering

AD/V0: arrays of scintillators at forward rapidity.
Ensure the presence of large rapidity gaps
Used for triggering.



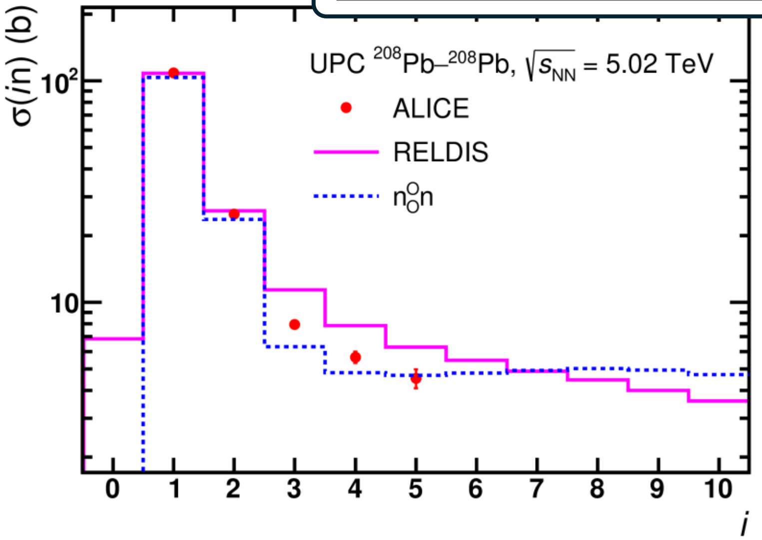
ZDC: sampling spaghetti calorimeters. Used to detect forward neutrons and protons

Neutron emission in EMD



ALI-PUB-544310

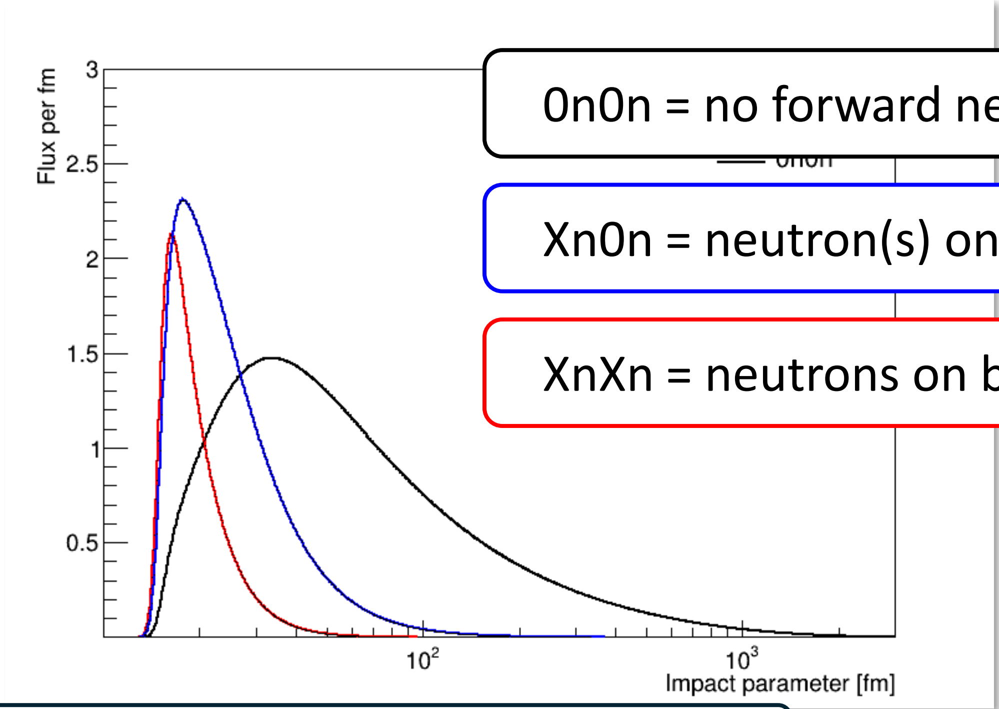
ALICE, PRC 107, 064902 (2023)



ALI-PUB-544313

- EMD processes may lead to emission of neutron at beam rapidity and with energy ~ beam energy
- Neutrons are detected using ZDCs
→ energy distribution in ZDCs clearly shows the peaks correspondent to different number of emitted neutrons
- ALICE measured the cross section for neutron emission at beam rapidity in Pb-Pb UPCs
- $\mathbf{n_0^0n}$ Broz et al., Comput. Phys. Comm. (2020) 107181
and RELDIS MC Pshenichnov et al., PRC 60, 044901
well reproduce the data, especially for low neutron multiplicities
→ **neutron emission in EMD processes is well understood**

Using EMD to select impact parameter ranges

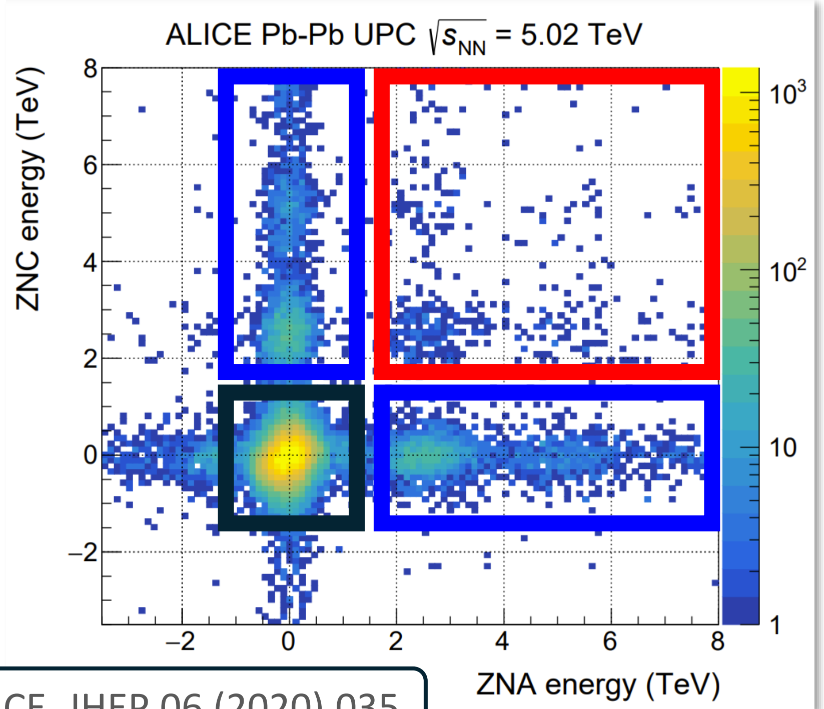


0n0n = no forward neutron

Xn0n = neutron(s) on one side of the IP

XnXn = neutrons on both sides of the IP

Broz et al., Comput. Phys. Comm. (2020) 107181



ALICE, JHEP 06 (2020) 035

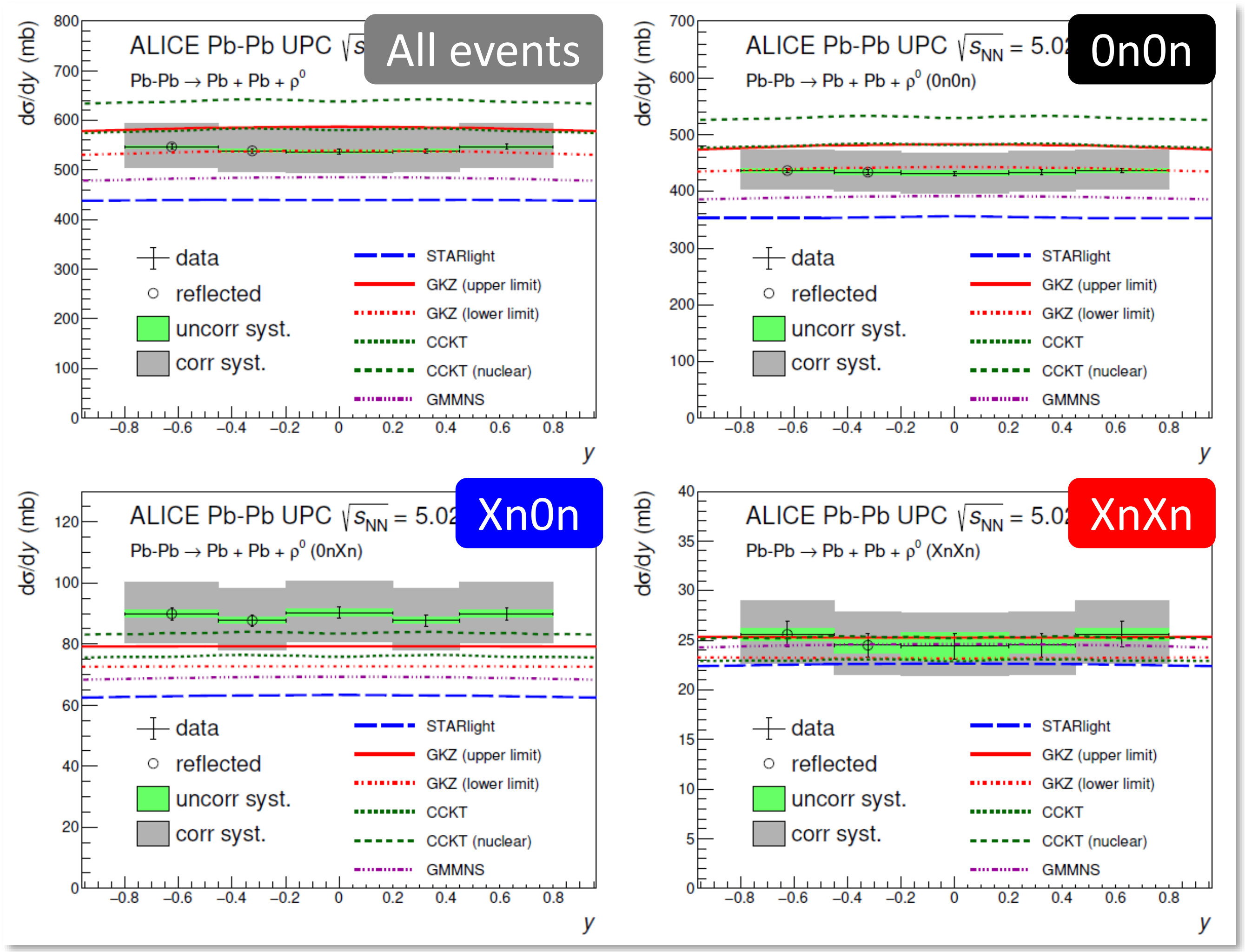
We classify events in different EMD classes using neutron detection in the ZDCs

Left figure: impact parameter distributions in different EMD classes in coherent ρ^0 photoproduction, according to the $\mathbf{n_0^0n}$ MC

(similar results obtained earlier in Baltz et al., PRL 89 (2002) 012301)

EMD class	Median b from $\mathbf{n_0^0n}$
0n0n	49 fm
Xn0n	23 fm
XnXn	18 fm

ρ^0 photoproduction cross section (Pb-Pb)



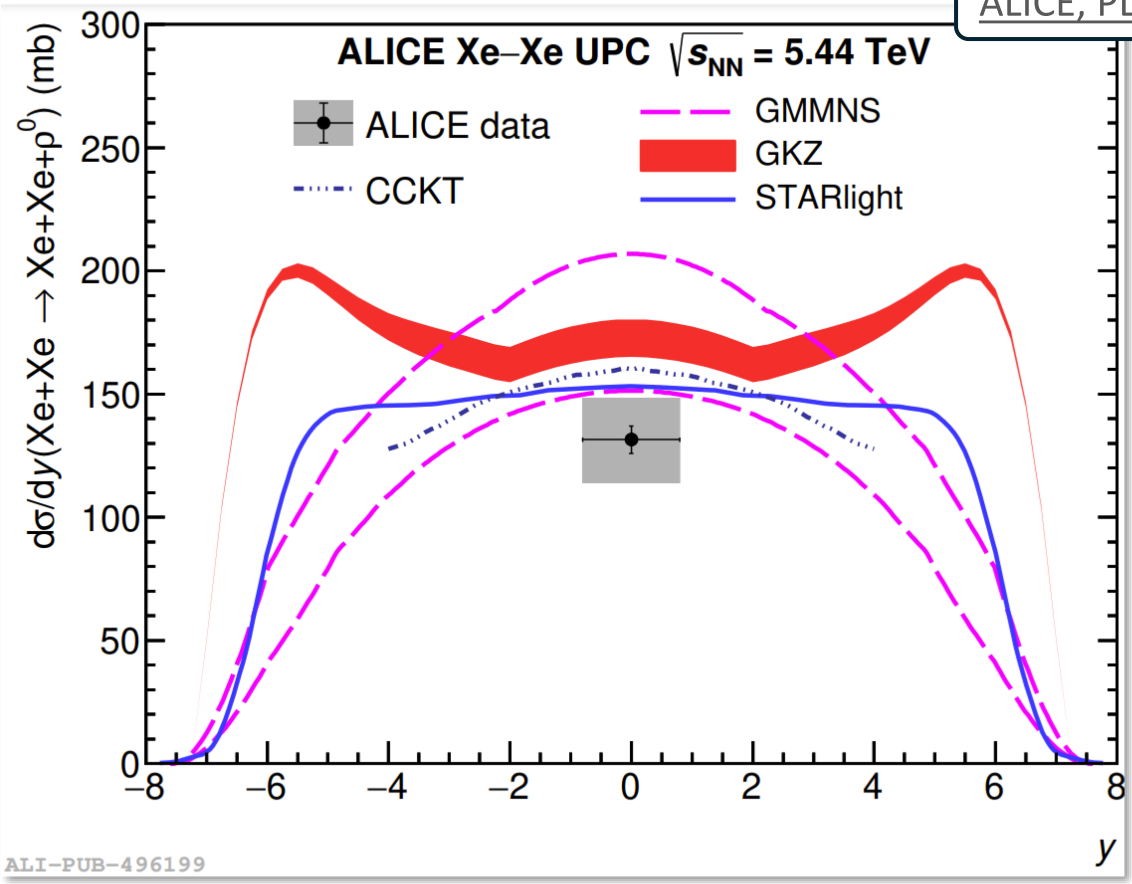
ALICE, JHEP 06 (2020) 035

- ALICE measured the coherent ρ^0 photoproduction cross section in Pb-Pb collision
- Measurement done in different EMD classes (0n0n, Xn0n, XnXn)
- Xn0n and XnXn cross section are $\sim$ 17 % and $\sim$ 4.5 % of total cross section → **cross section dominated by events without EMD**
- **Relative yields in EMD classes in fair agreement with prediction** from the STARlight
  Klein et al., Comput. Phys. Comm. 212 (2017) 258268
  and $\mathbf{n_0^0n}$ MCs
  Broz et al., Comput. Phys. Comm. (2020) 107181

ρ^0 photoproduction cross section (Xe-Xe)

ALICE

ALICE, PLB 820 (2021) 136481

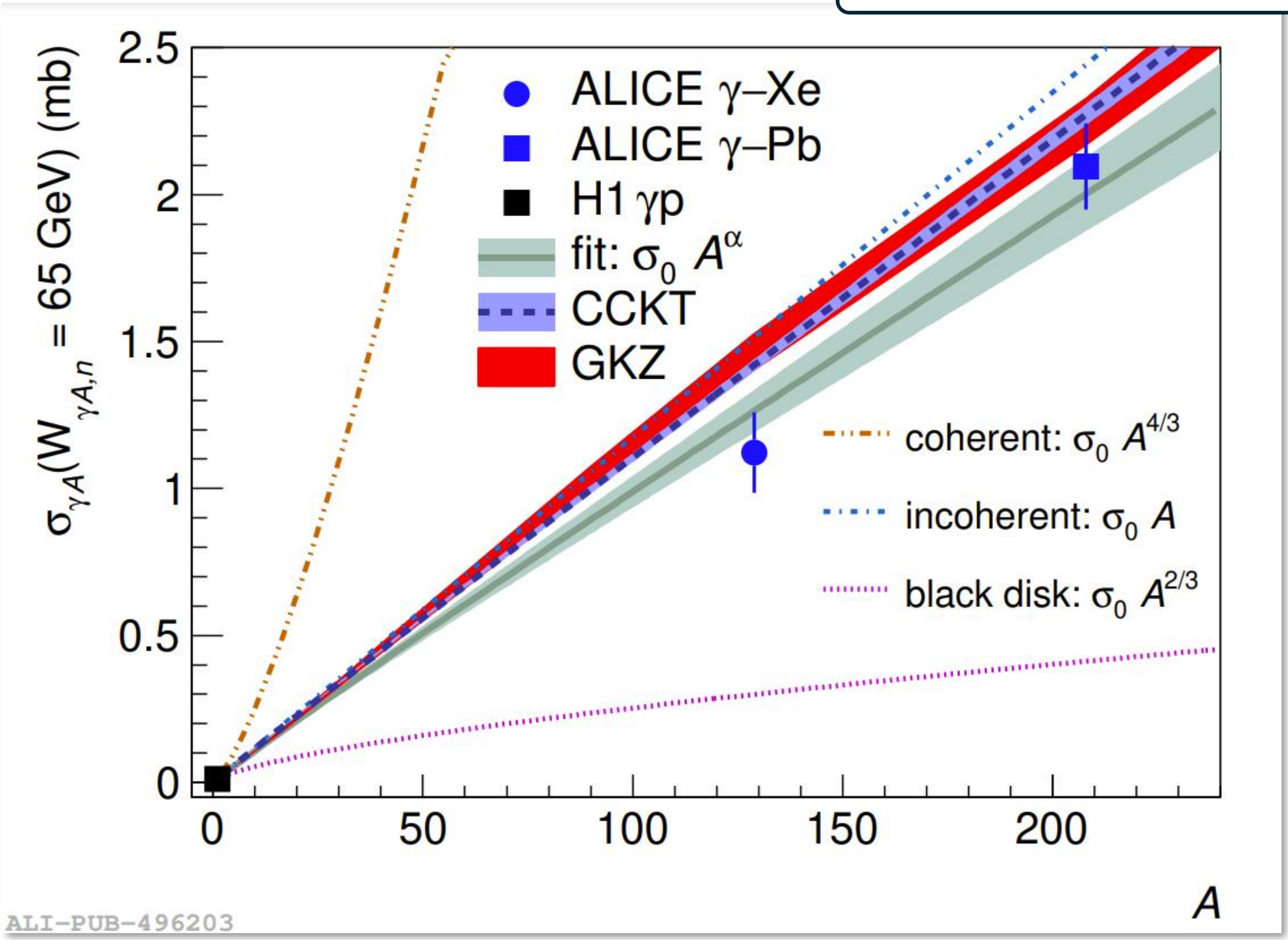


Class	Measured fraction	n^0_0n prediction
0n0n	$(90.46 \pm 0.70 \pm 0.17 \mp 0.68)\%$	92.4%
0nXn+Xn0n	$(8.48 \pm 0.66 \mp 0.13 \pm 0.64)\%$	6.9%
XnXn	$(1.07 \pm 0.25 \mp 0.04 \pm 0.07)\%$	0.7%

- ALICE measured coherent ρ^0 photoproduction cross section in Xe-Xe collision
- Measurement done in different EMD classes (0n0n, Xn0n, XnXn)
- Predictions slightly overestimate the total cross section
- The **predicted relative yields in different EMD classes agree with data** at one sigma level
- **Coherent ρ^0 photoproduction accompanied by EMD is understood at the LHC**

A-dependence of $\gamma A \to \rho^0 A$ cross section

ALICE, PLB 820 (2021) 136481

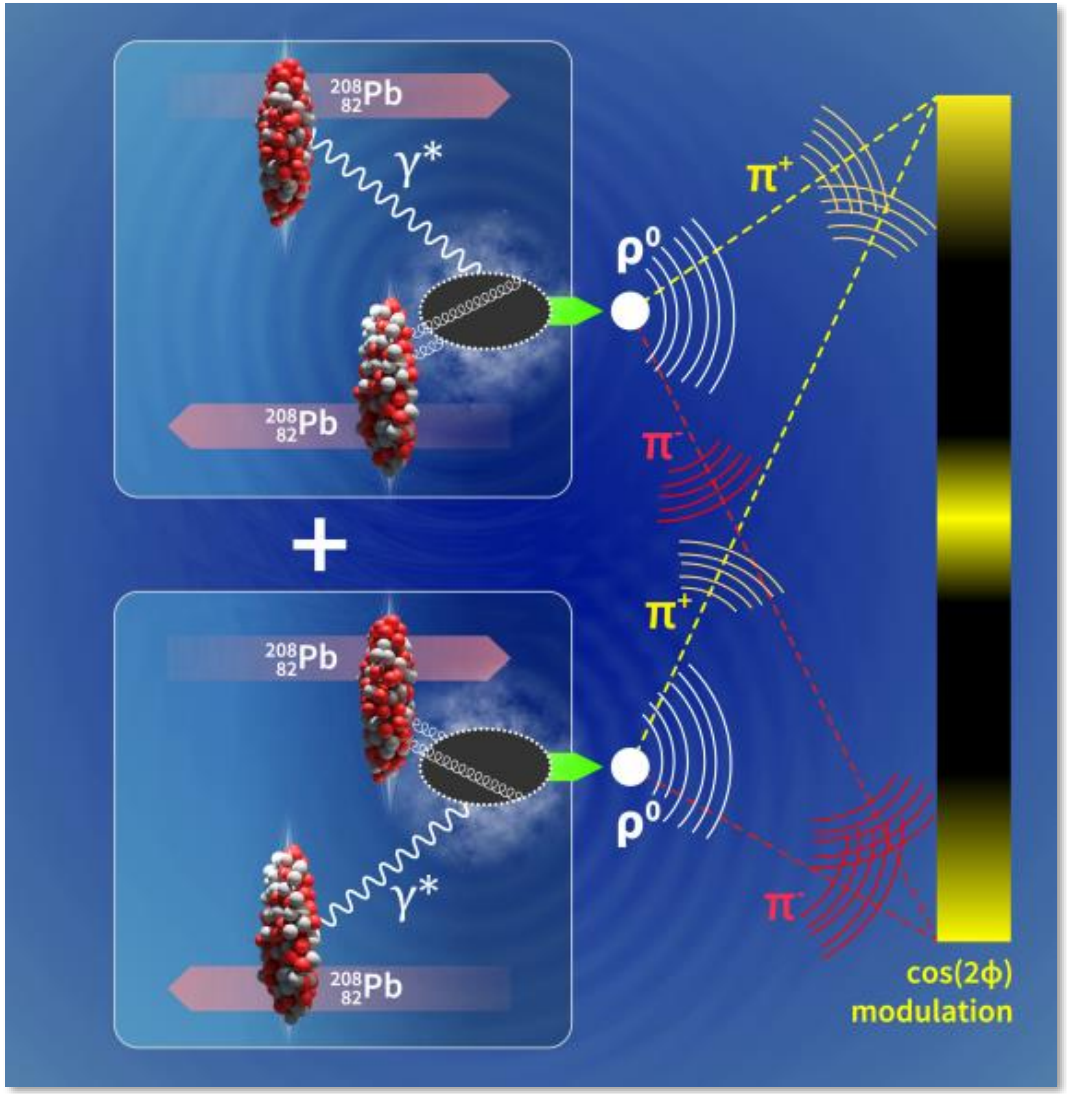


- ALICE measured the A-dependence of the γA cross section in coherent ρ^0 photoproduction ($\gamma A \to \rho^0 A$)
- **Fair description of Pb-Pb and Xe-Xe data** using models based on hadronic (GZK) or partonic (CCKT) degrees of freedom
  GZK: Guzey et al., PRC 93 (2016) 055206
  CCKT: Krelina et al., Nucl. Phys. A 989 (2019)187-200
- The A dependence is a strong indicator that **QCD effects are important and well understood**

Interference and polarization

Effects of the quantum interference and of the photon polarization in photon-induced processes

Interference in coherent VM photoproduction

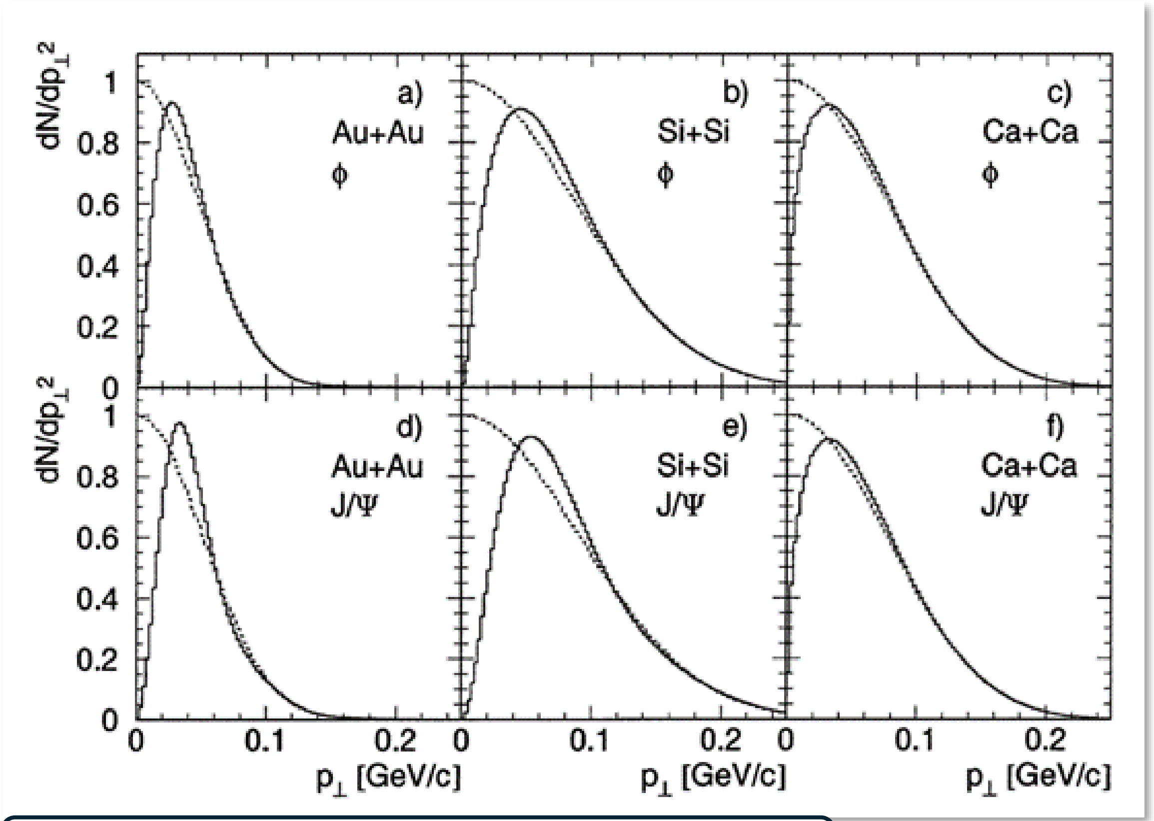


- Each nucleus can act as the source of the photon or as the target in the interaction
  → **two indistinguishable amplitudes** contribute to the cross section
- The two **contributions** to the cross section need to be **summed at** the **amplitude level**
- Amplitude related by parity exchange
  → amplitudes need to be subtracted due to the negative parity of the VM
- At midrapidity the cross section (in natural units) reads:

$$\sigma(p_T, b, y = 0) = \left| A(p_T, b) - A(p_T, b)\, e^{i\vec{p}\cdot\vec{b}} \right|^2$$

Klein and Nystrand, PRL 84 (2000) 2330-2333

Effect of the interference



Klein and Nystrand, PRL 84 (2000) 2330-2333

- The cross section oscillates and for $\vec{p}\cdot\vec{b} \ll 1$ the **interference is destructive**

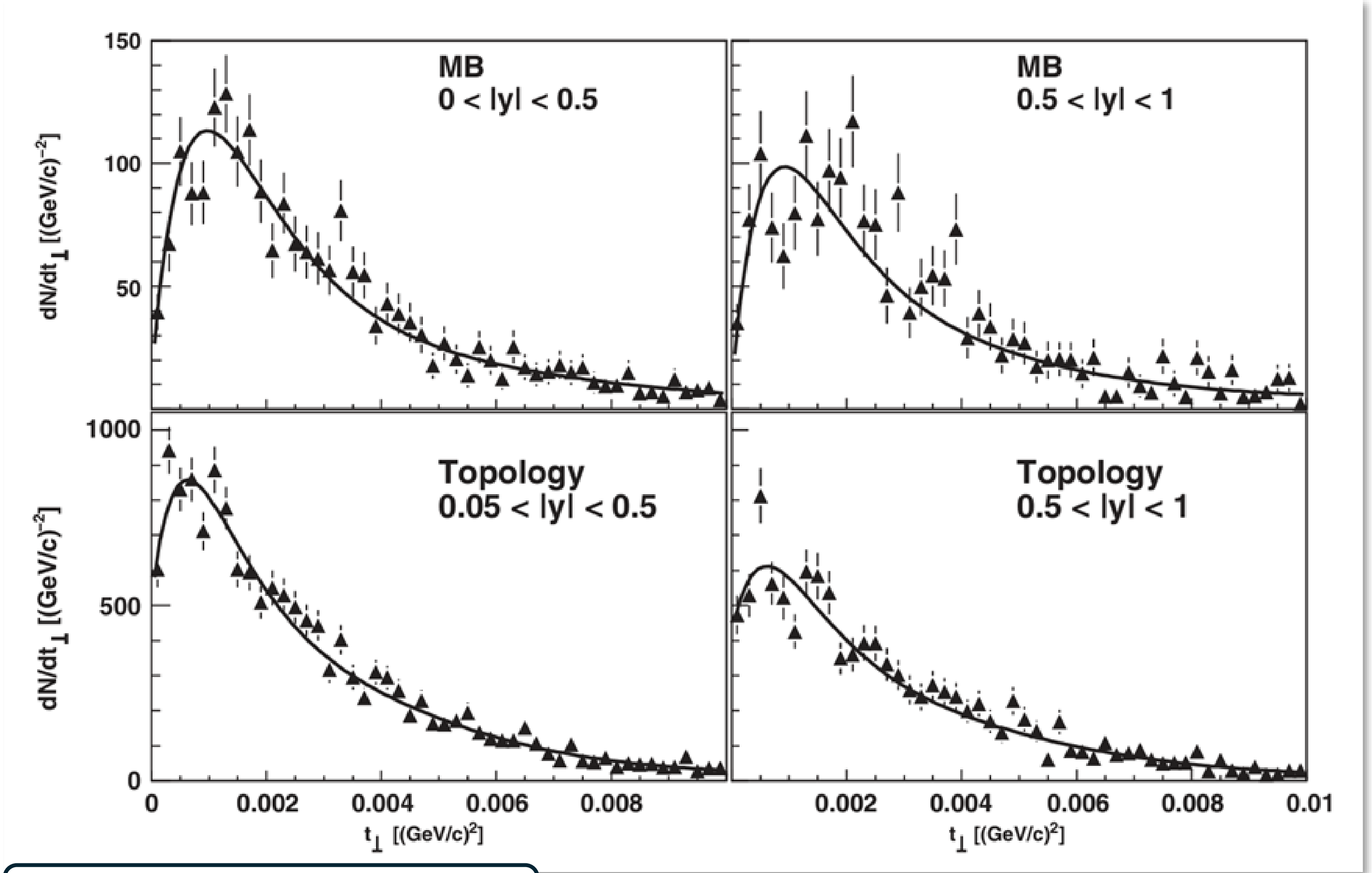
$$\sigma(p_T, b, y=0) = \left|A(p_T, b) - A(p_T, b)\, e^{i\vec{p}\cdot\vec{b}}\right|^2$$

- The first observable proposed to study the interference is the **drop of the p_T distribution of the vector meson at small p_T**

- Predictions for J/ψ and Φ at midrapidity in Au-Au and Si-Si collisions at RHIC and Ca-Ca collisions at LHC → solid histograms include interference, dashed lines do not

- The interference effects are predicted to be greater:
  - at midrapidity, where the amplitudes are equal
  - at small impact parameter

Measurement of low-p_T suppression

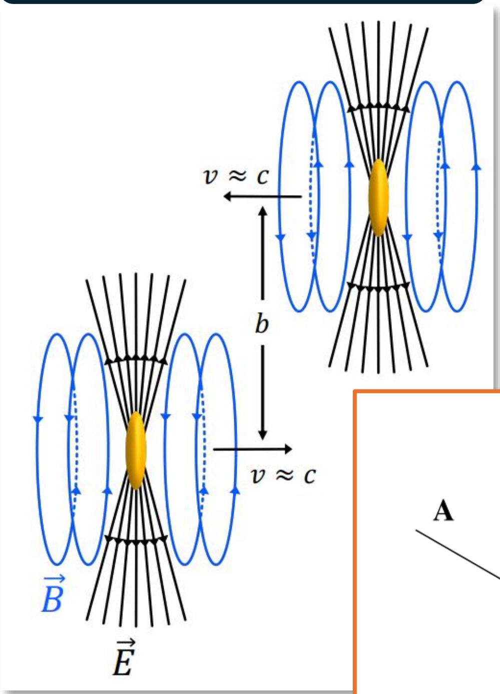


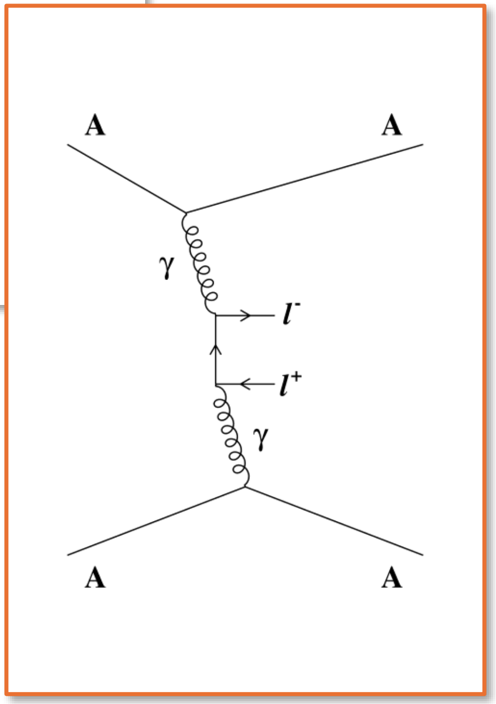
STAR, PRL 102 (2009) 112301

- **STAR measured the suppression at low p_T** from quantum interference in the photoproduction reaction Au Au → Au Au ρ^0
- Figure: measurement of $t_\perp \simeq p_\mathrm{T}^2$ spectra in two samples:
  - MB = ρ^0 accompanied by mutual Coulomb dissociation (XnXn)
  - Topology = two pions back-to-back
- As predicted**, greater interference effects**:
  - In MB sample, where the impact parameter is lower
  - In left plots, that are more at mid rapidity

Photons in UPC are linearly polarized

Fig. from D. Brandenburg





- EM field of the nuclei highly Lorentz-contracted
  → **exchanged photons fully linearly polarized along $\boldsymbol{b}$**

Li et al., PLB 795 (2019) 576-580

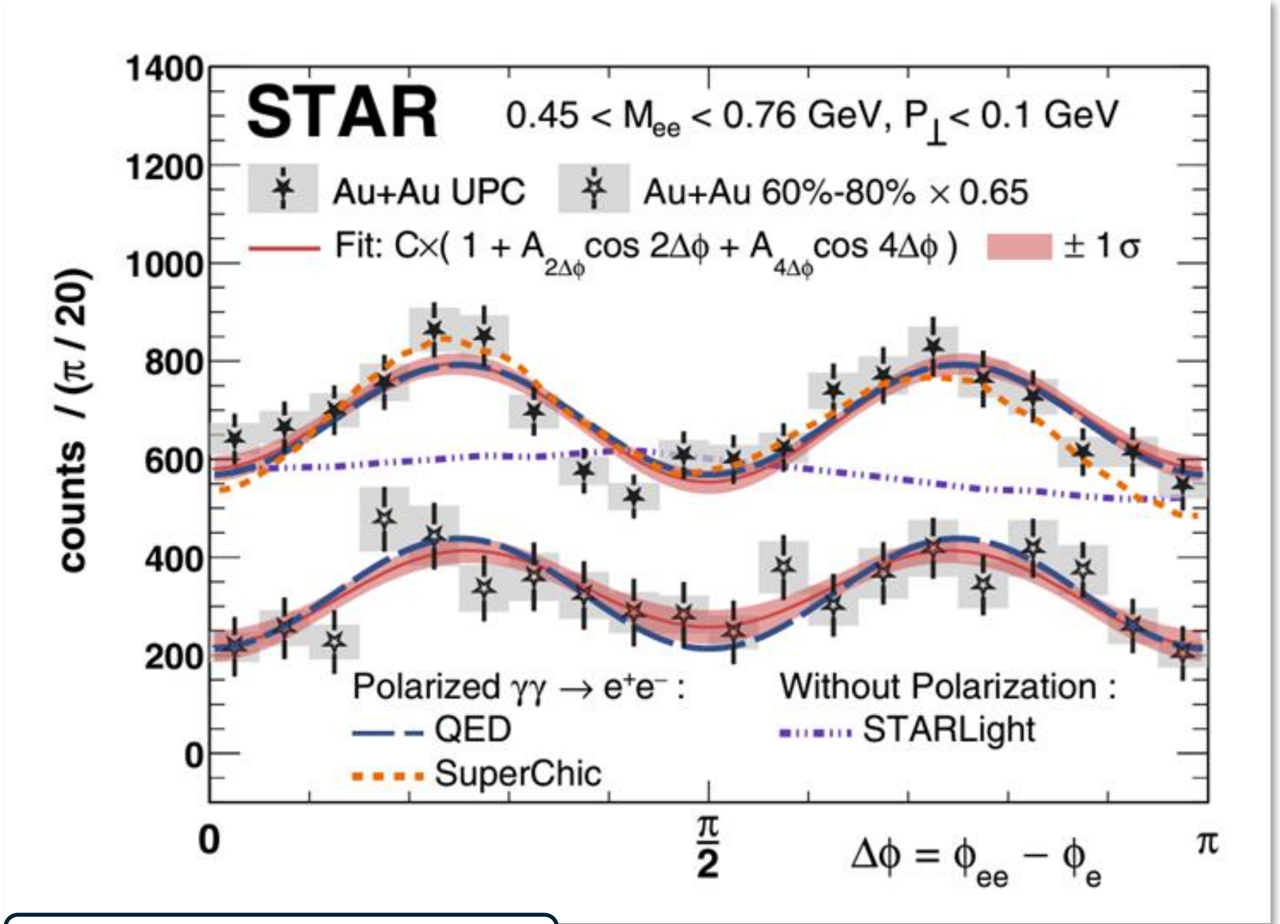
Experimental signature for this process?

- We can use the Breit-Wheeler process: $\gamma\gamma \rightarrow l^{+}l^{-}$
  → the total spin of the two-photon state must be encoded (also) into the orbital angular momentum of the leptons

- QED predicts **$\cos(2\Delta\phi)$ and $\cos(4\Delta\phi)$ modulation in di-lepton production**

- $\Delta\phi$ ~ angle between the momentum of the lepton pair and the momentum of one of the leptons

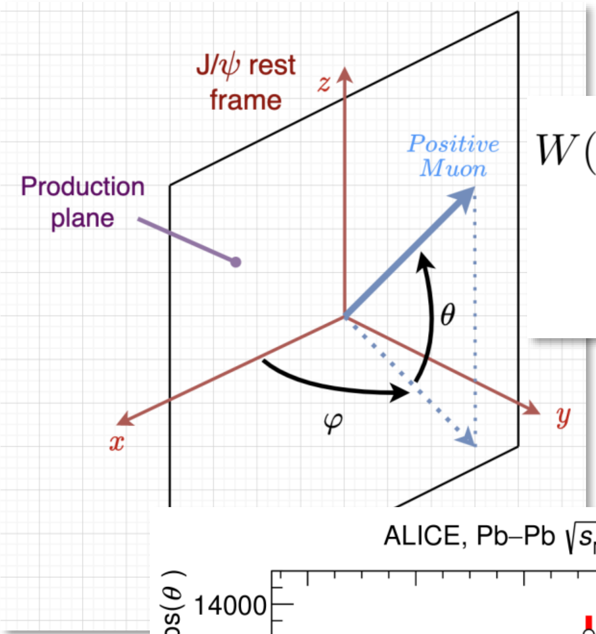
Breit-Wheeler measurement



STAR, PRL 127 (2021) 052302

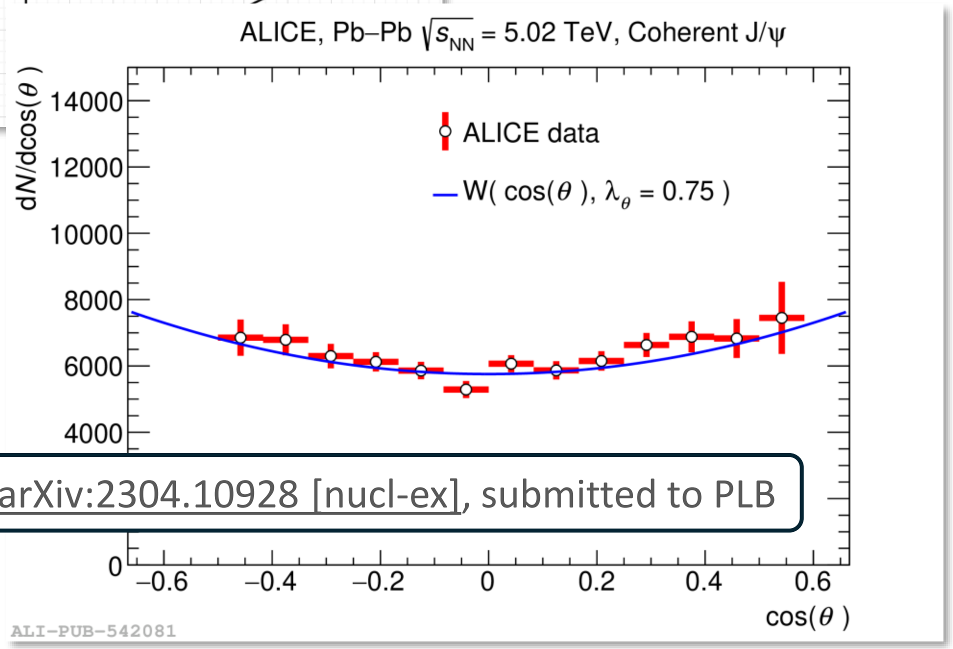
- STAR studied the Breit-Weeler process
- They **measured** the predicted $\cos(4\Delta\phi)$ **modulation** of the production of e^+e^- pair from real photon fusion
  → the $\cos(2\Delta\phi)$ modulation depends on the lepton mass and it is not sizeable for electrons
- Good agreement with predictions from QED Li et al., PLB 795 (2019) 576-580 and SuperChic Haraland-Lang et al., EPJC 79, 39 (2019)
- The measurement **demonstrates** that the **photons** exchanged in UPCs are transverse **linearly polarized**
  → STARlight: no photon polarization, predicts no anisotropy

s-channel helicity conservation



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

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



ALICE, arXiv:2304.10928 [nucl-ex], submitted to PLB

- A similar anisotropy could appear in vector meson photoproduction if the **spin of the photon is transferred to the vector meson without helicity flip**
- This is known as s-channel helicity conservation (SCHC)
- ALICE tested it, measuring the polarization of coherently photoproduced J/ψ at forward rapidity decaying into a muon pair
- The polarization is measured by investigating the angular distribution of the muons $W(\cos\theta), W(\varphi)$ that can be written in terms of polarization parameters $\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}$
- **Photoproduced J/ψ** have been measured to be **transverse linearly polarized**:
  $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi})$ compatible with $(1, 0, 0)$
  → **compatible with SCHC** hypothesis

Anisotropy in ρ^0 photoproduction

- Strong hints that:
  - exchanged **photons** in UPCs are linearly **polarized along *b***
  - the **polarization** is **transferred to the $\boldsymbol{\rho^0}$**

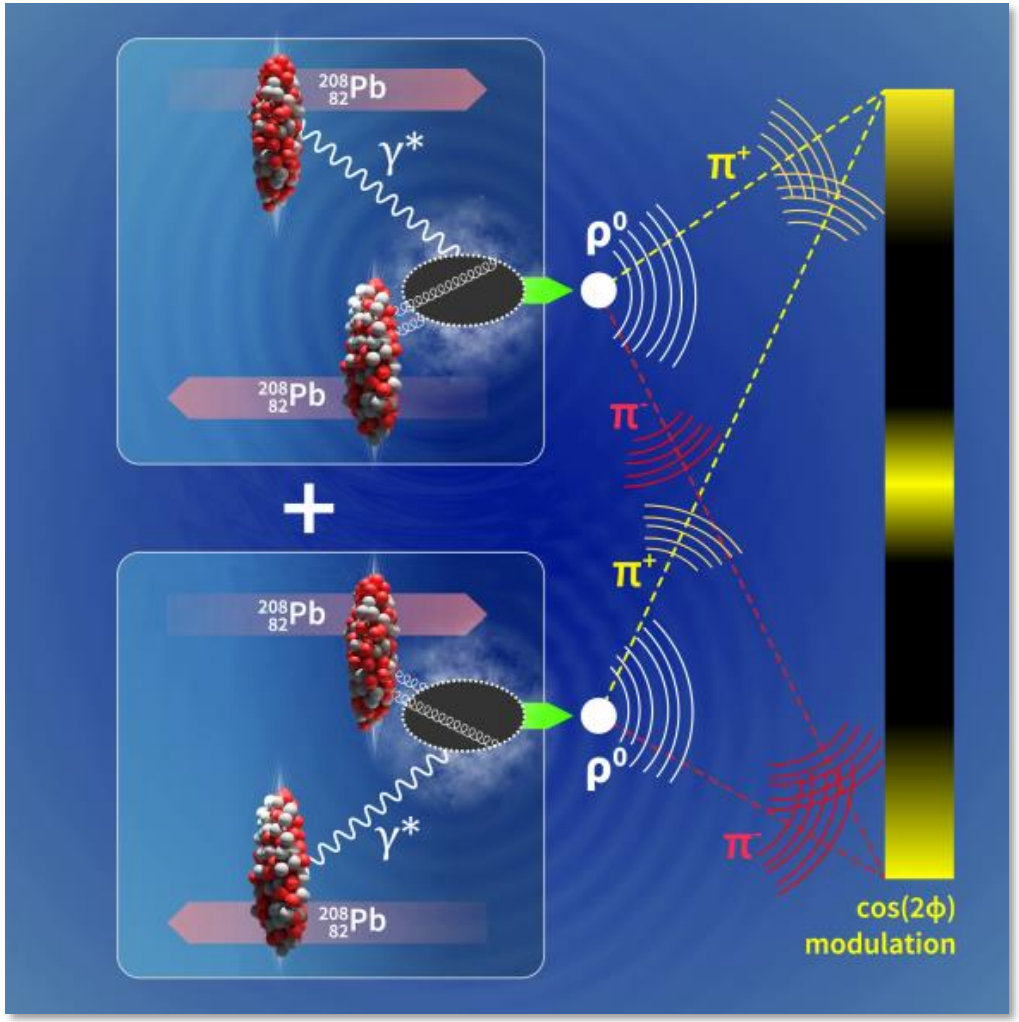
- Now we have something like $\gamma\gamma \to e^+e^-$, with two differences:
  - the $\boldsymbol{\rho^0}$ inherits the **spin $\boldsymbol{J = 1}$** of the photon
  - the ρ^0 decay products (pions) are spin-less, so the **polarization** is **totally transferred to the orbital angular momentum**

- This results in an **azimuthal modulation in the momentum direction wrt the polarization direction**

- <u>Important note</u>: the impact parameter is randomly distributed event-by-event (also true for $\gamma\gamma \to e^+e^-$)
  → **the anisotropy should vanish when averaging over all the events**

- We already saw that the anisotropy in $\gamma\gamma \to e^+e^-$ does not vanish
  → an ingredient is missing

Interference in ρ^0 photoproduction



- We already saw that the two amplitudes interfere due to photon emission ambiguity

- Due to the interference the cross section contains the term:

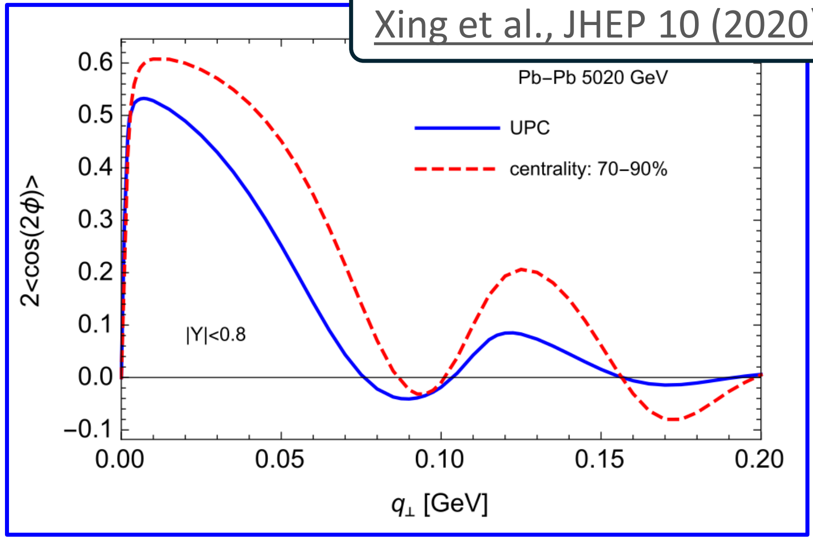
$$exp(i\,\vec{p}\cdot\vec{b})$$

  it **correlates the momentum and the polarization** (along the impact parameter) of the ρ^0
  → **preserves the anisotropy!**

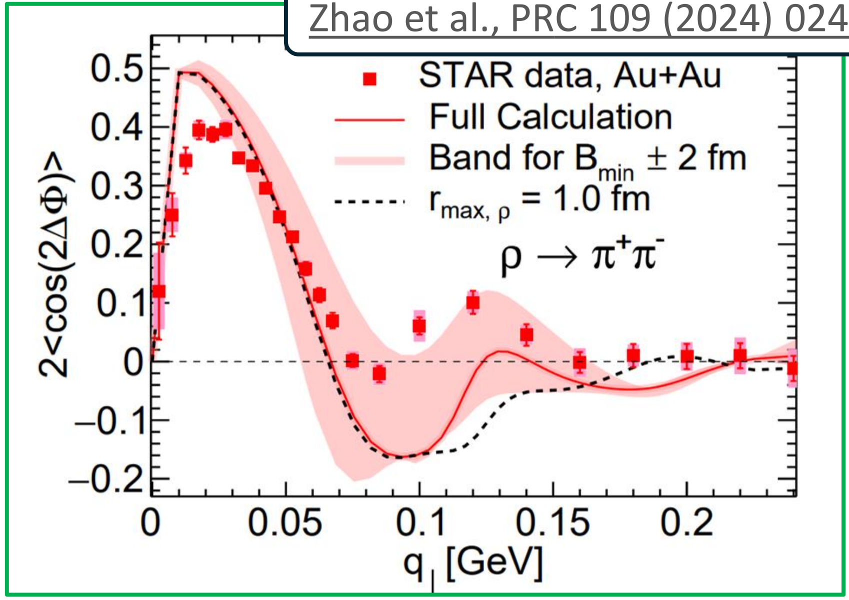
- The lifetime of the ρ^0 is very short: $c\tau \ll b$
  → **the $\boldsymbol{\rho^0}$ decays before the amplitudes can overlap**
  - the decay products are emitted in an entangled state, and the interference depends on observing the complete final state Klein and Nystrand, PRL 84 (2000) 2330-2333
  - the decay does not make the wave function to collapse Klein and Nystrand, PLA 308 (2003) 323–328

Theoretical models

Xing et al., JHEP 10 (2020) 064

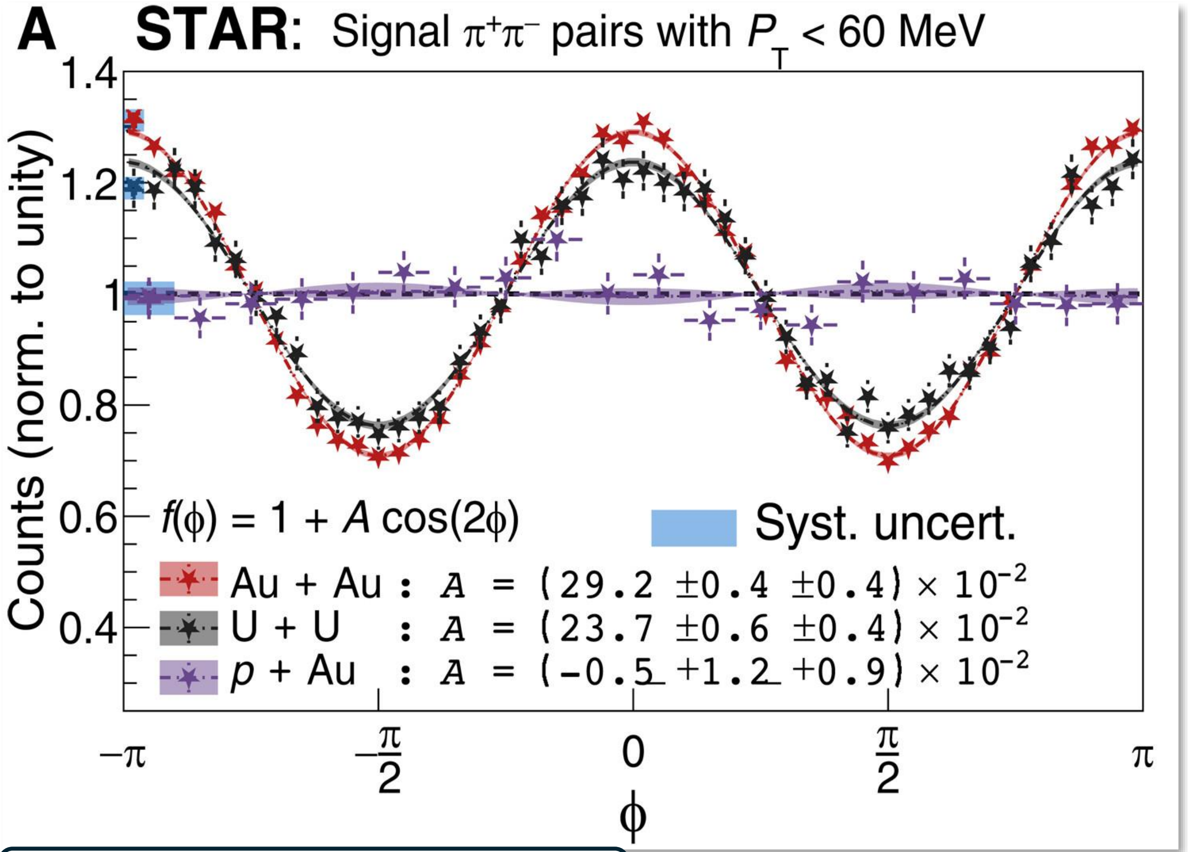


Zhao et al., PRC 109 (2024) 024908



- Theoretical models available:
  - H. Xing *et al.*: color-dipole model + scattering with gluons from color glass condensate inside nuclei
  - W. Zhao *et al.*: same formalism as Xing et al. but:
    1) interaction dipole/target → Wilson lines
    2) event-by-event variation of Wilson lines
    → account for different color charge configurations
- Both models:
  - implement a **correlation between the incoming photon's spin and momentum**
  - **predict a $\cos(2\phi)$ modulation of the ρ^0 yield**, with an amplitude that depends on p_T and b

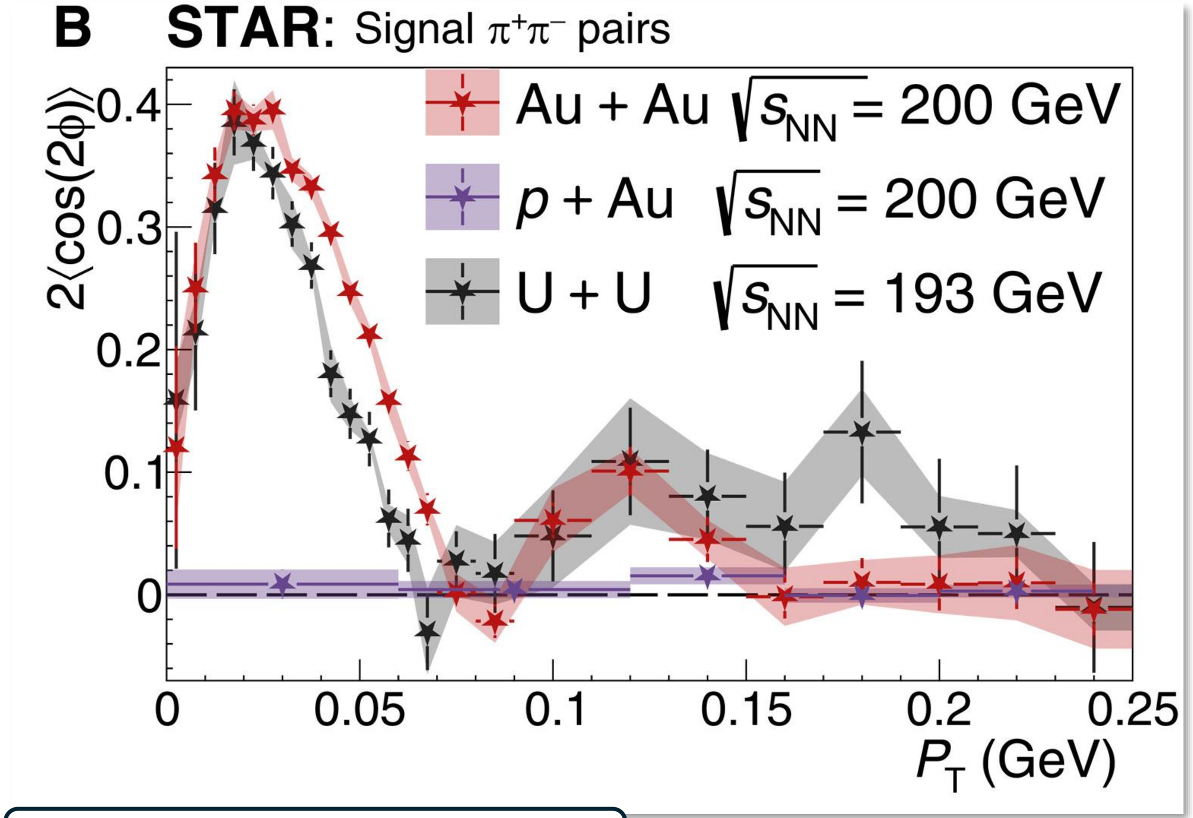
STAR measured the anisotropy in XnXn



STAR, Sci.Adv. 9 (2023) eabq3903

- The anisotropy is measured as a function of ϕ
  → $\phi \sim$ angle between the transverse momenta of the ρ^0 and of one the pions
- STAR measured the anisotropy for AA and pA collisions:
  the **interference is present only in AA collisions** since the photon emission amplitudes are very different in pA collisions
- The anisotropy is different for Au-Au and U-U collisions
  → **sensitive to the nuclear structure and gluon distribution** inside nuclei

p_T dependence of the anisotropy in XnXn

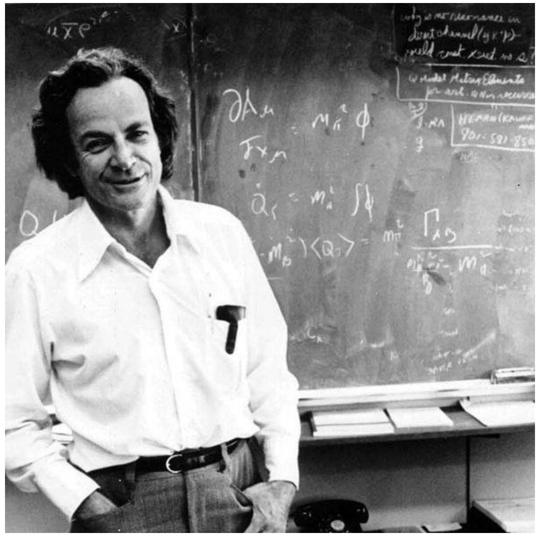


STAR, Sci.Adv. 9 (2023) eabq3903

- The structure of the **anisotropy as a function of p_T** resembles the shape of the differential cross section $d\sigma/p_T$, that shows **diffractive peaks**
- The amplitude of the **modulation** is consistent with **zero at high p_T** ($p_T > 0.2$ GeV/c), where the incoherent contribution is dominant
- In pA collisions, where there is no interference, the anisotropy shows no structure and it is always compatible with zero

A double-slit experiment at fm scale

ALICE performed the first measurement of the impact parameter dependence of the anisotropy
→ why is this interesting?

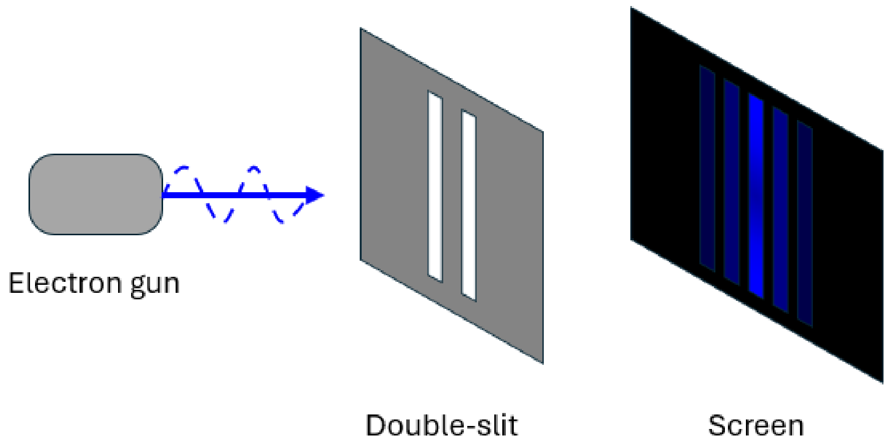


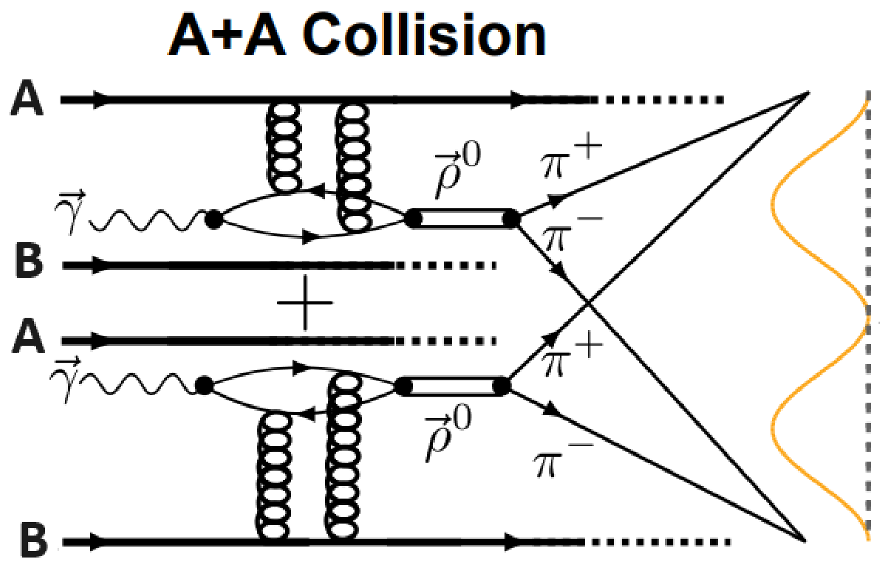
I will take just this one experiment, which has been designed to contain all of the mystery of quantum mechanics, to put you up against the paradoxes and mysteries and peculiarities of nature one hundred per cent. Any other situation in quantum mechanics, it turns out, can always be explained by saying, ***'You remember the case of the experiment with the two holes? It's the same thing'****.*

Richard Feynman *in "The Character of Physical Law, chapter 6"*

The short-range strong interaction ensures that the ρ^0 production happens within the target nucleus
→ **measurement analogous to a double slit experiment at fm scale**, where b acts as the distance between the openings

About the double-slit experiment analogy





STAR, Sci.Adv. 9 (2023) eabq3903

Differences wrt the double-slit experiment with electrons:

- **Interference**
  Classical experiment: one source → interference given by the ambiguity of the slit used to go through
  Our analysis: two independent sources → interference given by the ambiguity on the ρ^0 source
- **Length scale**
  Classical experiment: min distance between the slits ~ nm
  Our analysis: min distance down to ~ fm → probe quantum mechanics at the fm scale

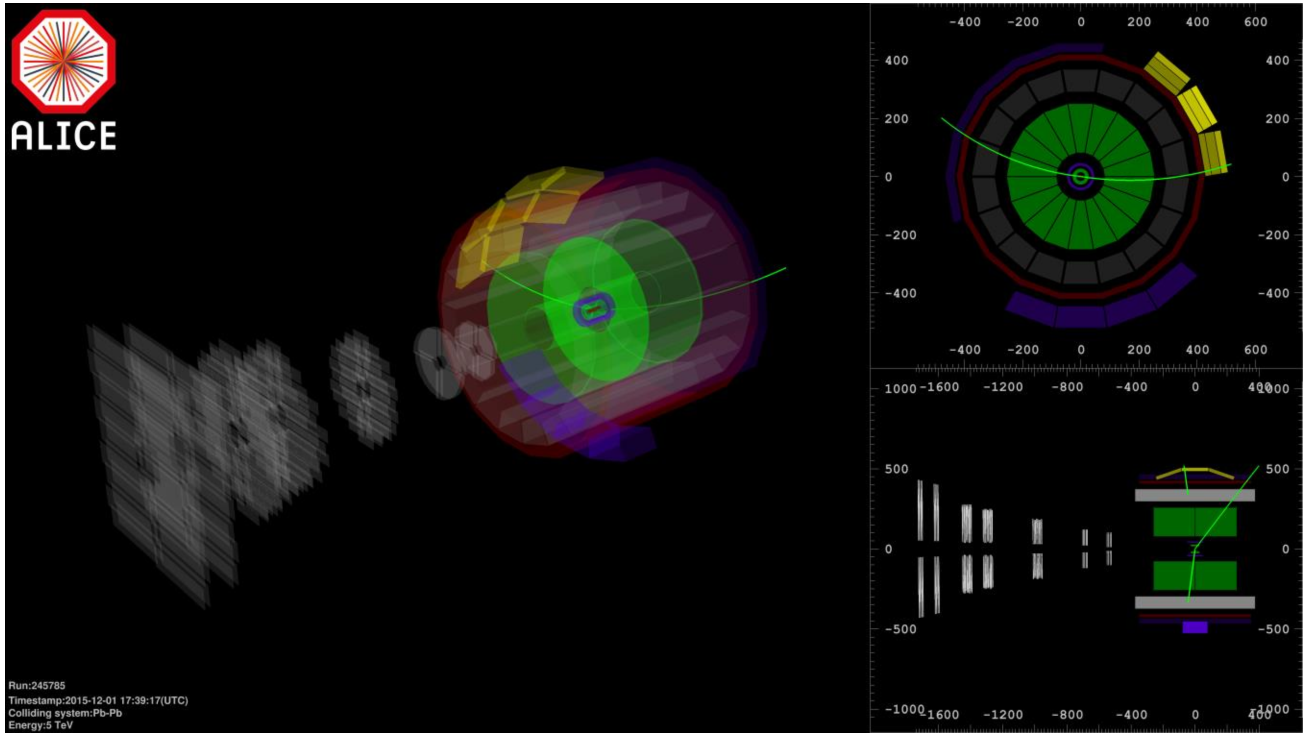
Data analysis

Measurement of the impact-parameter dependent azimuthal anisotropy in coherent ρ^0 photoproduction

Analysis strategy

1. Collect and select the data
2. Define the observable ϕ
3. Divide the data in ϕ ranges and EMD classes
4. Correct the mass spectra for acceptance x efficiency
5. Extract the ρ^0 signal as a function of ϕ
6. Extract the amplitude of the $\cos(2\phi)$ anisotropy

Data sample

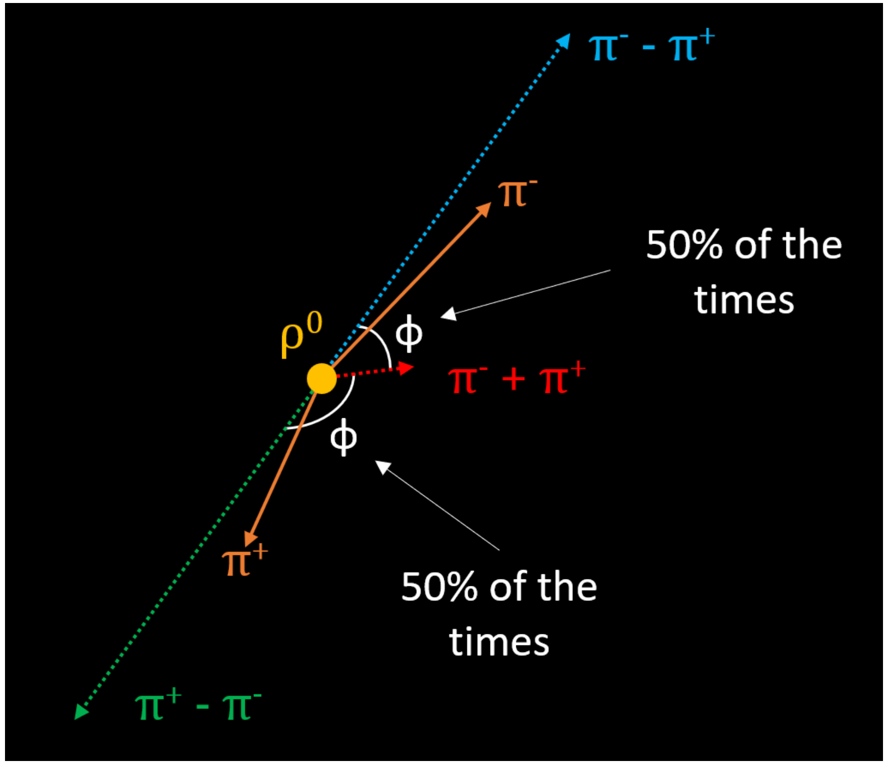


Data from Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Trigger:

- Coherently photoproduced ρ^0 have very low p_{T} → pions emitted almost back-to-back in the transverse plane
- AD and V0 used as veto → suppression of purely hadronic interactions
- Topological trigger: events with at least two track segments in the ITS SPD with an opening angle θ>153°

ϕ definition



Sketch of the ϕ *average* definition

$\boldsymbol{\phi}$ = angle between $\vec{\boldsymbol{p}}_+$ and $\vec{\boldsymbol{p}}_-$

There are two possible definitions, equivalent in terms of the predicted $\cos(2\phi)$ modulation

Average: $\vec{p}_\pm = \vec{p}_{\mathrm{T},1} \pm \vec{p}_{\mathrm{T},2}$

where $\vec{p}_{\mathrm{T},1}(\vec{p}_{\mathrm{T},2}) =$ transverse momentum of the track 1 (2), randomly assigned to the positive and negative tracks

Charge: $\vec{p}_\pm = \vec{p}_{\mathrm{T},+} \pm \vec{p}_{\mathrm{T},-}$

The *average* definition does not allow for a possible $\cos\phi$ component
→ used as default

In principle, ϕ is defined in the region $-\pi < \phi < \pi$
→ since $\cos(2\phi)$ is even, negative ϕ values are re-mapped in $0 < \phi < \pi$ by flipping the sign

Acceptance and efficiency correction

Data (invariant mass distributions) need to be corrected for acceptance and efficiency

Use STARlight MC (ρ^0 + continuum pion pair production) Klein et al., Comput. Phys. Comm. 212 (2017) 258268

p_T distribution of the ρ^0 not perfectly reproduced
→ re-weighting needed!

Re-weighting procedure:

1. Fit the MC generated ${p_T}^2$ distribution using the square of the nuclear form factor (1) to extract a_{Pb} and R_{Pb}
2. Compute the weights using (2), where R_X is chosen to minimize discrepancies between data and reconstructed MC p_T distributions
3. Build the MC mass distributions by weighting each event with $\mathrm{w}(p_T)$ evaluated at the generated p_T

$$\frac{\mathrm{d}N}{\mathrm{d}p_\mathrm{T}^2} = c \mid F(t, a_\mathrm{Pb}, R_\mathrm{Pb}) \mid^2 \quad (1)$$

$$\mathrm{w}(p_\mathrm{T}) = \frac{\mid F(\mid t \mid, a_\mathrm{Pb}, R_\mathrm{X}) \mid^2}{\mid F(\mid t \mid, a_\mathrm{Pb}, R_\mathrm{Pb}) \mid^2} \quad (2)$$

Signal extraction

The corrected mass spectra in each neutron emission class and ϕ range are fitted using two different models

Söding model: the invariant mass has a contribution from the ρ^0 (resonant pion pair production), the continuum, and the interference between the two

$$\frac{d\sigma}{dm_{\pi\pi}} = \left|A\, BW_\rho + B\right|^2 + M(m_{\pi\pi})$$

Ross-Stodolsky model: parametrization in terms of *f* and *k* free parameters

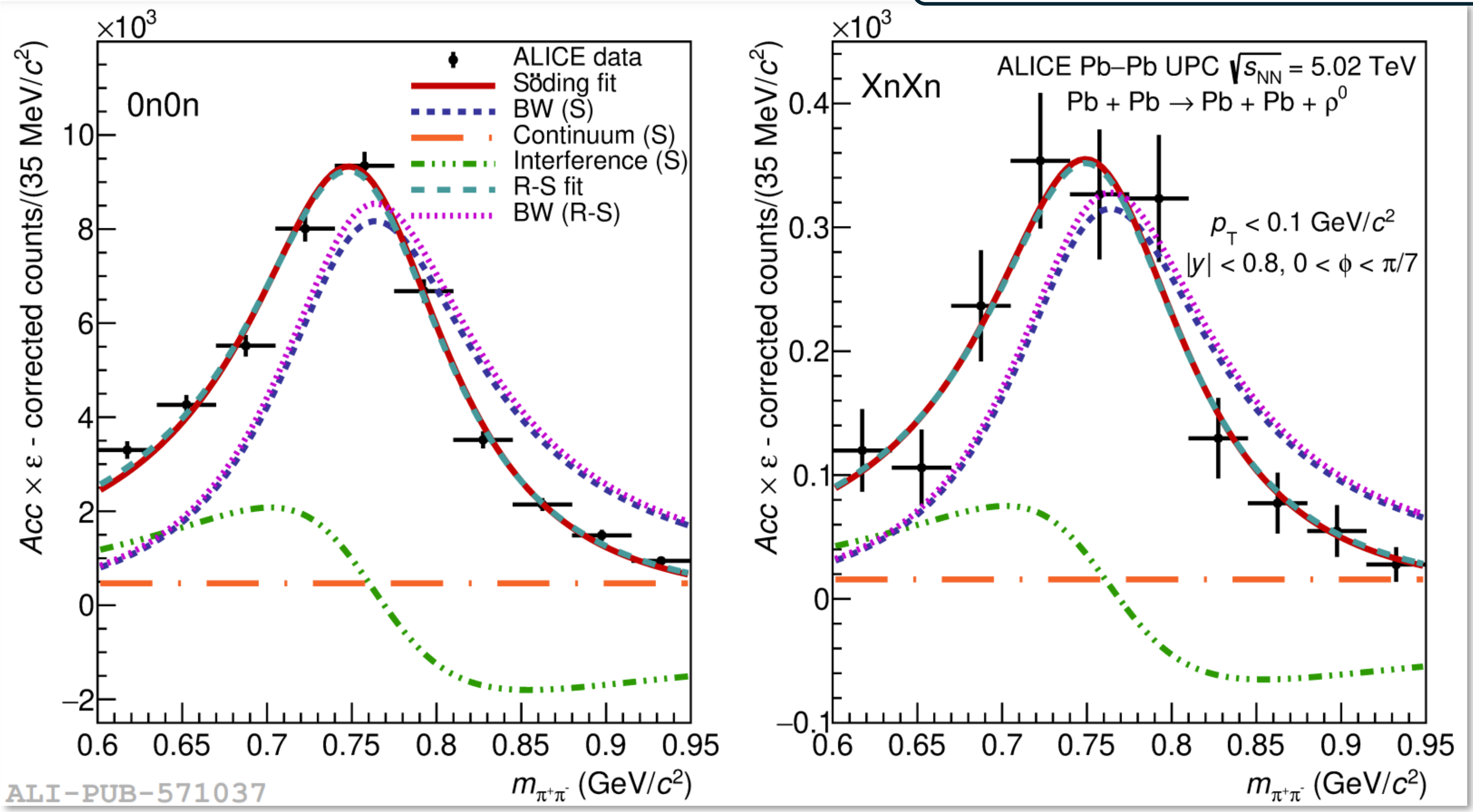
$$\frac{d\sigma}{dm_{\pi\pi}} = \left|f\, BW_\rho\right|^2 \left(\frac{m_\rho}{m_{\pi\pi}}\right)^k + M(m_{\pi\pi})$$

In both models the ρ^0 is modelled with a relativistic Breit-Wigner distribution.

The term $M(m_{\pi\pi})$ represents the background, that originates from muons mis-identified as pions.
It is very small: compatible with zero in most ϕ ranges.

Signal extraction

ALICE, arXiv:2405.14525 [nucl-ex], accepted by PLB



- Example of the **fit to the** invariant **mass distribution** in a specific ϕ range for 0n0n (left) and XnXn (right) neutron class
- The two fit models (Söding and Ross-Stodolsky) give compatible results
- After the fit the **signal** part (the BW) is **integrated** in the range $0.6 < m_{\pi\pi}(\mathrm{GeV}/c^2) < 0.95$ **to obtain the ρ^0 yield**

Accounting for migration across EMD classes

- To extract the amplitude of the **anisotropy** we need to **fit the distribution of the normalized ρ^0 yields as a function of ϕ** in each neutron emission class.

- We are looking for a $\cos(2\phi)$ modulation with b-dependent amplitude, and $b \leftrightarrow$ neutron emission classes

- We need to **account for migrations across neutron classes**, due to ZDC efficiency for neutrons and pile-up

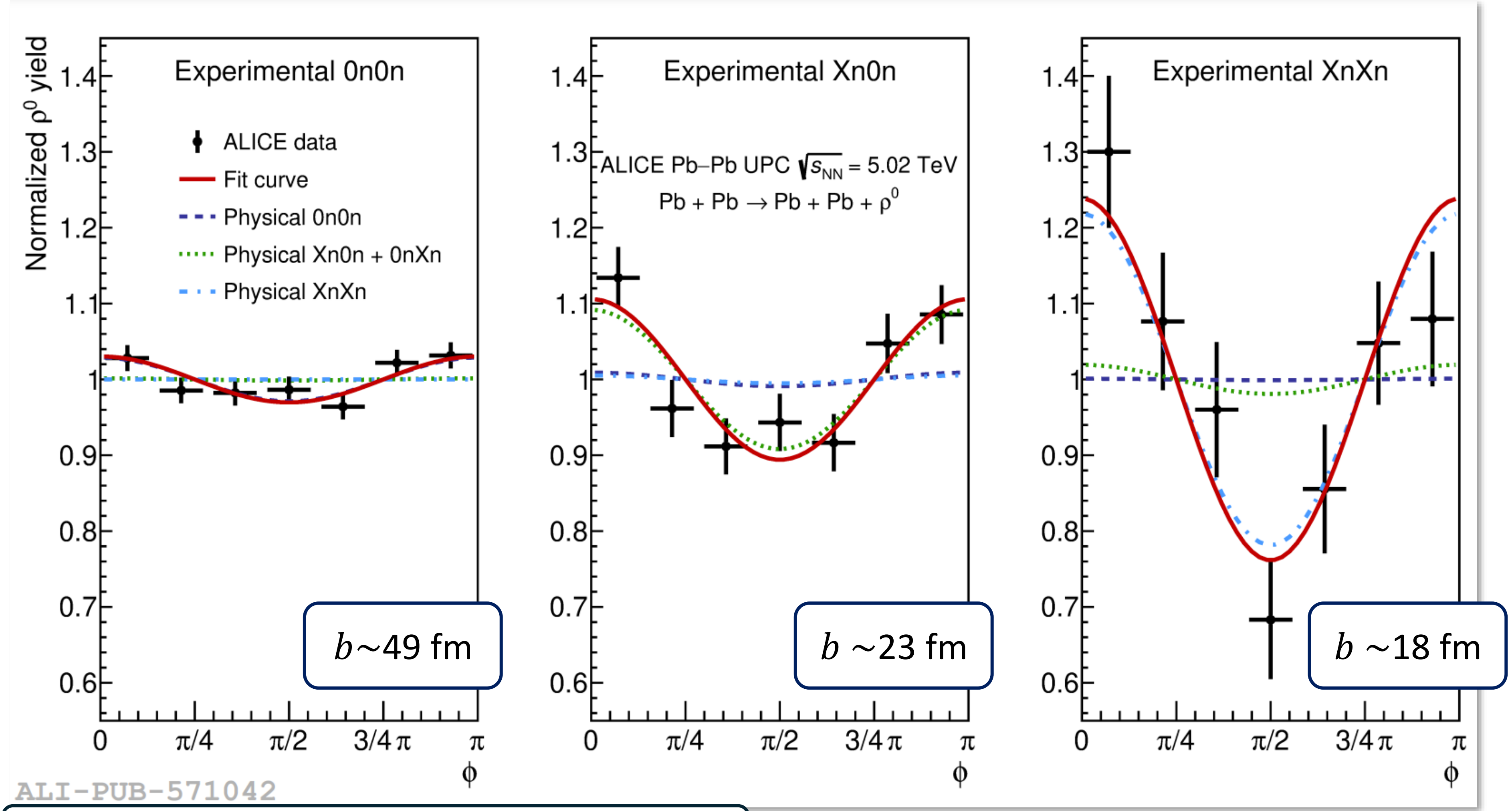
$$\begin{pmatrix} n_{\rho\,\mathrm{0n0n}} \\ n_{\rho\,\mathrm{Xn0n}} \\ n_{\rho\,\mathrm{XnXn}} \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} + \begin{pmatrix} w_{\mathrm{0n0n}\to\mathrm{0n0n}} & w_{\mathrm{Xn0n}\to\mathrm{0n0n}} & w_{\mathrm{XnXn}\to\mathrm{0n0n}} \\ w_{\mathrm{0n0n}\to\mathrm{Xn0n}}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

Normalized ρ^0 yield

$w_{Y\to Z}$ = contribution of the yield in the physical class Y to the yield in the experimental class Z. Computed from measured cross-section ratios and migration probabilities.

a_2 = true amplitudes of the modulation

Asymmetry extraction



ALICE, arXiv:2405.14525 [nucl-ex], accepted by PLB

- Example of one of the fits to extract the amplitude of the modulation
- The different components of the modulation in each class due to migrations are shown
- The **modulation strongly increases as *b* decreases**

Central values and statistical uncertainty

Each **invariant mass spectra is fitted using different strategies**:

- 2 fitting models
- including or not the background
- different binning and fit ranges

In total 48 different configurations are used
→ **every condition brings a set of ρ^0 yield vs ϕ in all neutron classes**

In each neutron class

- amplitude = weighted average of the amplitudes from each strategy
- statistical uncertainty = uncertainty on the weighted average, multiplied by $\sqrt{48}$, to account from fully correlated stat. uncertainty of different fit configurations

Systematic uncertainties

Source	Uncertainty (%) 0n0n	Xn0n + 0nXn	XnXn
Signal extraction	12	9.1	13
ϕ definition	3.6	5.7	3.3
Acc $\times$ ε	2.9	0.8	0.9
ZN pile-up	0.1	2.3	0.9
ZN efficiency	0.7	0.1	0.1
Total	12.6	11.0	13.3

ALICE, arXiv:2405.14525 [nucl-ex], accepted by PLB

The main systematic uncertainties are

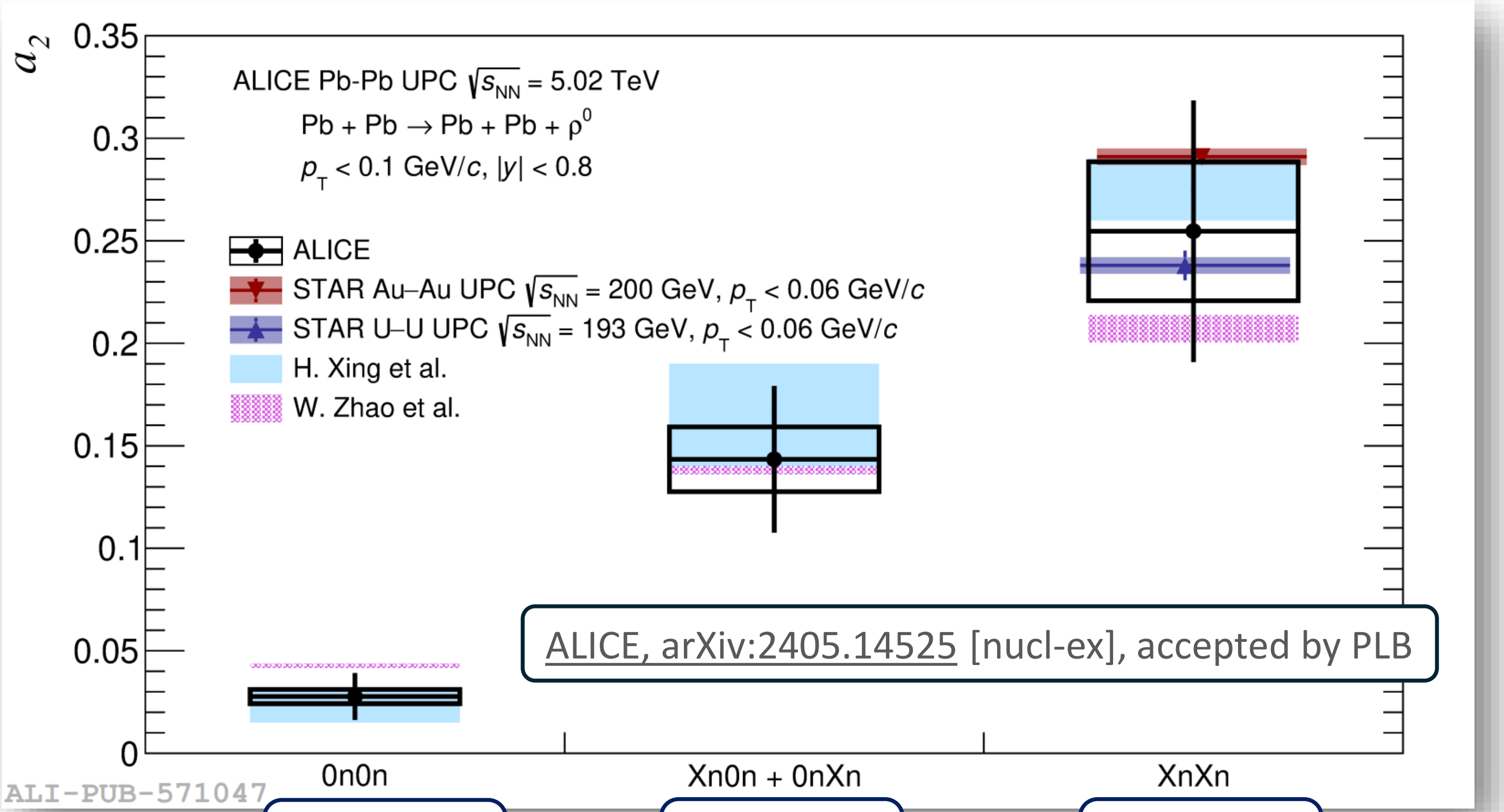
- **Signal extraction**: includes the effect of the different fitting strategies used to fit the invariant mass spectra
  → **dominant contribution**
- Definition of the ϕ angle: obtained using the difference between *average* and *charge* definition
- Acceptance x efficiency: mainly due to the re-weighting, evaluated propagating the uncertainty on the weights
- ZDC efficiency and pile-up probability: obtained propagating these uncertainties

Results, take home & outlook

What we have found and what can be done in the future

Results

First measurement of the impact-parameter dependent angular anisotropy in the decay of coherently photoproduced ρ^0



b~49 fm | b ~23 fm | b ~18 fm

- In each physical neutron class the anisotropy is
$$dn/d\phi = 1 + a_2 \cos 2\phi$$
- The **amplitude** (a_2) of the modulation **increases of ~ one order of magnitude as b decreases**
→ compatible with expectations from interference
- Compatible with predictions from both theoretical models
Xing et al., JHEP 10 (2020) 064
Zhao et al., PRC 109 (2024) 024908
- XnXn amplitude compatible with STAR results for Au-Au and U-U collisions at lower energy Sci.Adv. 9 (2023) eabq3903

Take home messages

- We **measured** for the first time the angular **anisotropy** in the decay of coherently photoproduced $\boldsymbol{\rho^0}$ **as a function of the impact parameter**
- The anisotropy needs **two ingredients**:
    - **linearly polarized photons**
    - quantum **interference** between the two possible photoproduction amplitudes
- This **experiment can be seen as a double slit experiment at fm scale**, with b acting as the distance between the openings
- The strength of the anisotropy varies by one order of magnitude from the largest to the smallest impact-parameter event class
- Results compatible with available theoretical predictions and with STAR for the same neutron emission requirement
- The measurement proves the **validity of quantum mechanics at the fm scale**

What to expect in the near future?

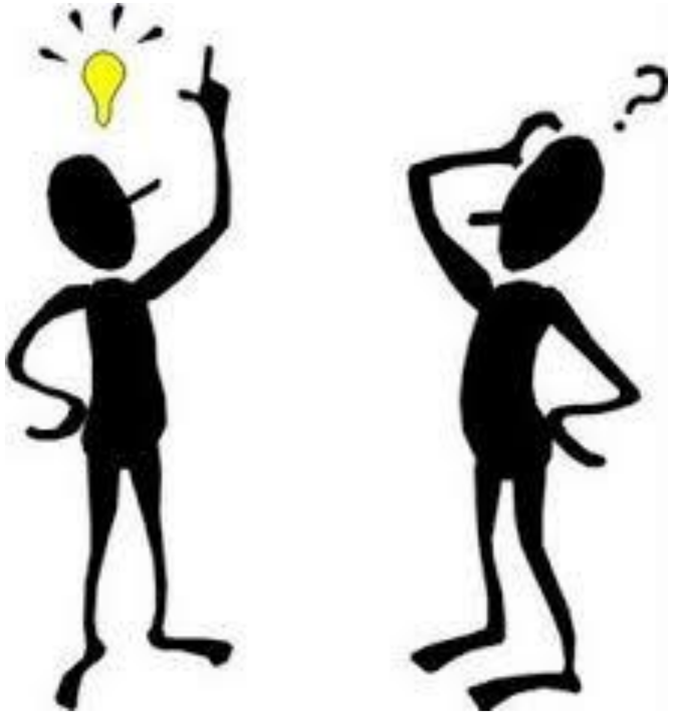
- ALICE undergone major hardware and software upgrades
  → allow to **collect huge amount of data in Run 3 and Run 4**

- **Constrain models** and perform **more differential studies** to study the interference at fm level with great detail

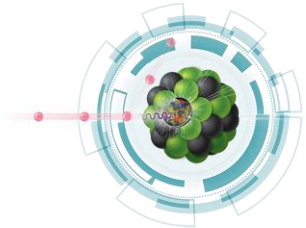
- The effect depends on the nuclear structure
  → useful to repeat the **analysis for other colliding systems** (e.g. OO at the LHC)

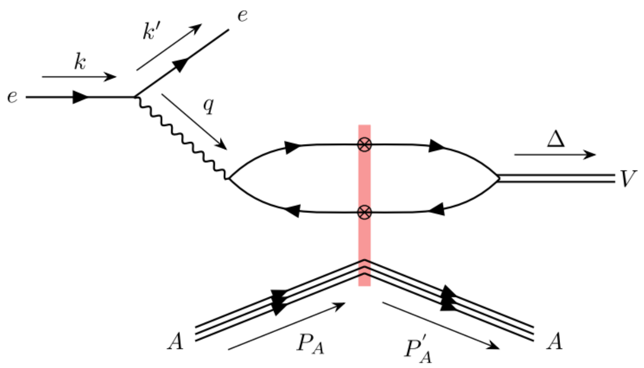
- The **same effect can be studied with other particles** (e.g. J/ψ) where the model predictions are expected to be more precise, and the spin of the decay particle can influence the anisotropy (Brandenburg et al., PRD 106 (2022) 074008)

- **Other interference processes** may lead to **other anisotropies**:
  - $\cos(\phi)$ and $\cos(3\phi)$ modulations from the interference of the ρ^0 with QED processes (Hagiwara et al., PRD 103 (2021) 074013)
  - $\cos(4\phi)$ modulation from the interference of resonant and open pion pair production (Hagiwara et al., PRD 104 (2021) 094021)



What about the EIC?





The ep and eA collisions are not symmetric (like pA collisions)
→ no interference :(

At the EIC we can study the electroproduction of a vector particle V, e.g.:

- Deeply Virtual Compton Scattering (DVCS), where V is a photon
- J/ψ production

The study of azimuthal correlations between V and the scattered electron e is sensitive to the gluon structure of the target Mäntysaari et al., PRD 103 094026 (2021)
→ the cross section has modulations in the azimuth angle $\phi_{k\Delta}$ between V and e

Main modulations: $\cos\phi_{k\Delta}$ and $\cos 2\phi_{k\Delta}$
→ $\cos 2\phi_{k\Delta}$ is a probe of spatial angular correlations in the gluon distribution

Sizable anisotropies both in $e\gamma$ and eJ/ψ systems are predicted in ep collisions, in DVCS they are ~ 1 order of magnitude greater than in J/ψ production

Modulations in e-Au collisions are predicted to be significantly smaller

Thank you for your attention!

Questions? Comments?