Exploring light hadrons in ultra-peripheral Pb-Pb collisions with ALICE

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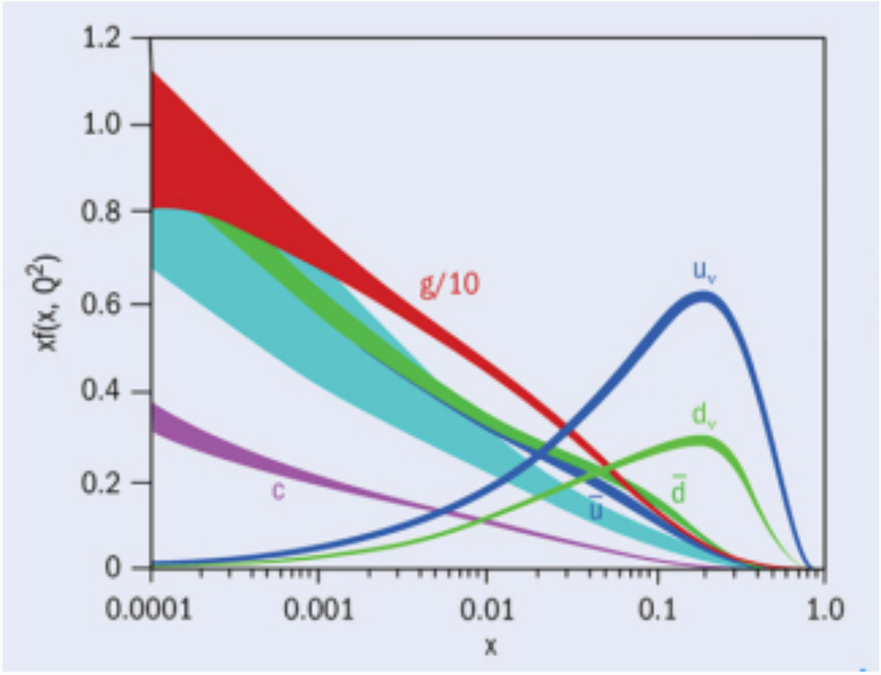
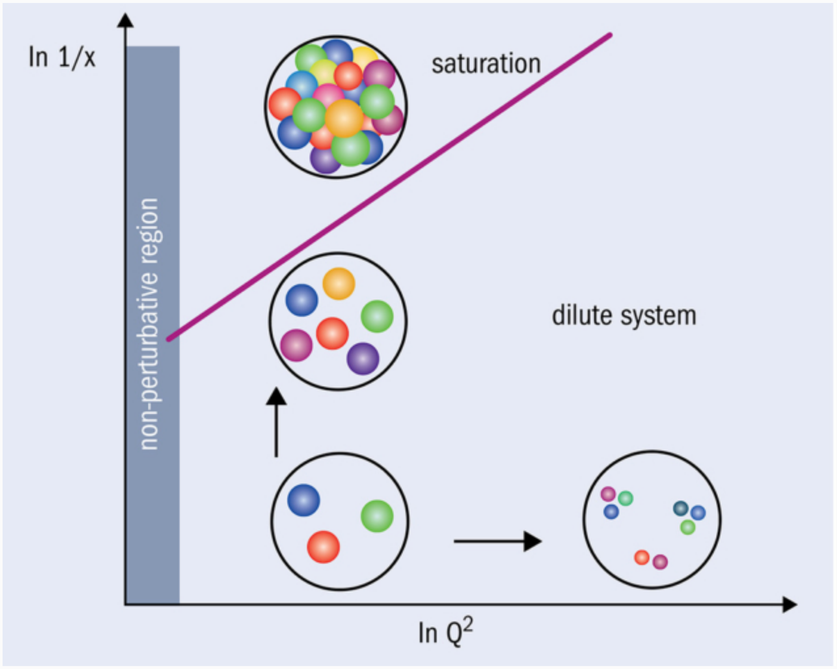
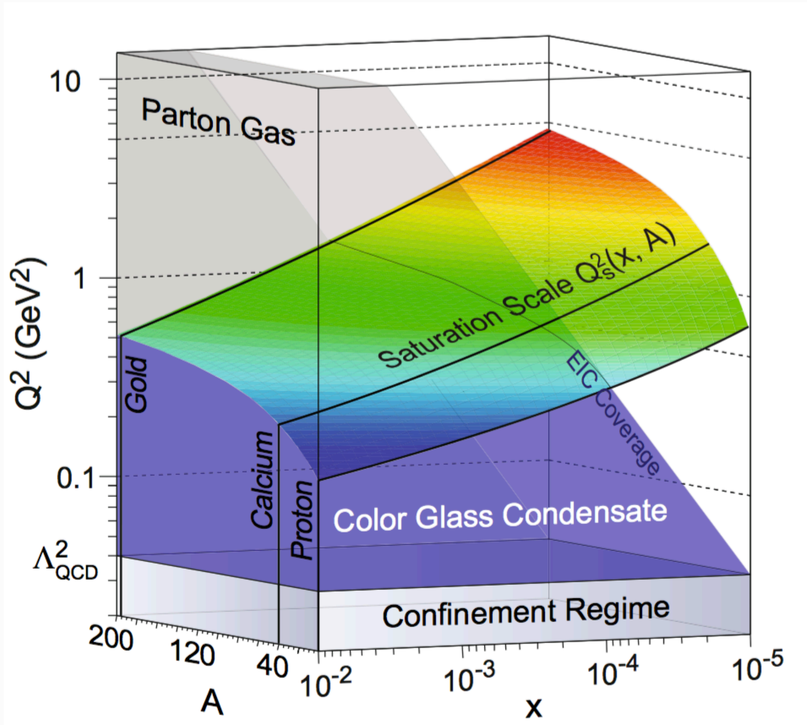
ECT* Workshop: Diffraction and gluon saturation at the LHC and the EIC
10. Jun. 2024 - 14. Jun. 2024
Trento, Italy

Probing gluons in nuclei

Accardi et. al, EPJA 52 (2016) 268







- Nucleus gluon field is not simple superposition of A nucleon fields
- More general question: Where and how does the transition from a dilute parton system to a dense gluon regime state occur?
- Saturation is expected to set at higher x in heavy nuclei

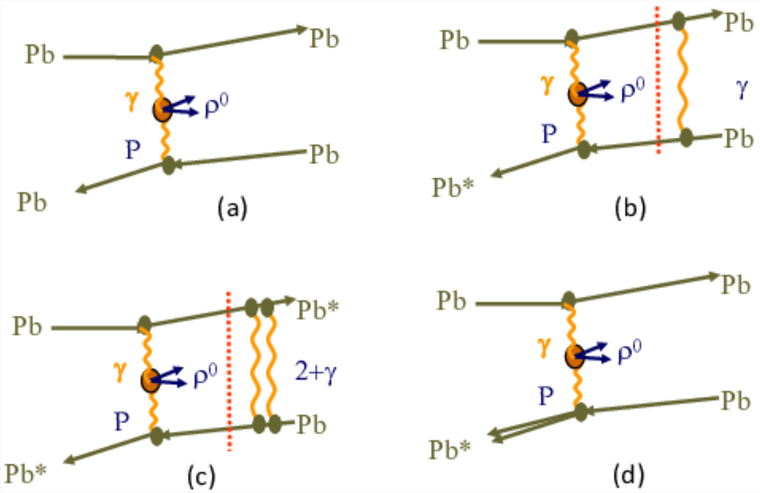
Ultra-peripheral heavy-ion collisions at the LHC

- EM field from ultra-relativistic ions: **a beam of quasi real photons** (intensity ≈ Z^2)

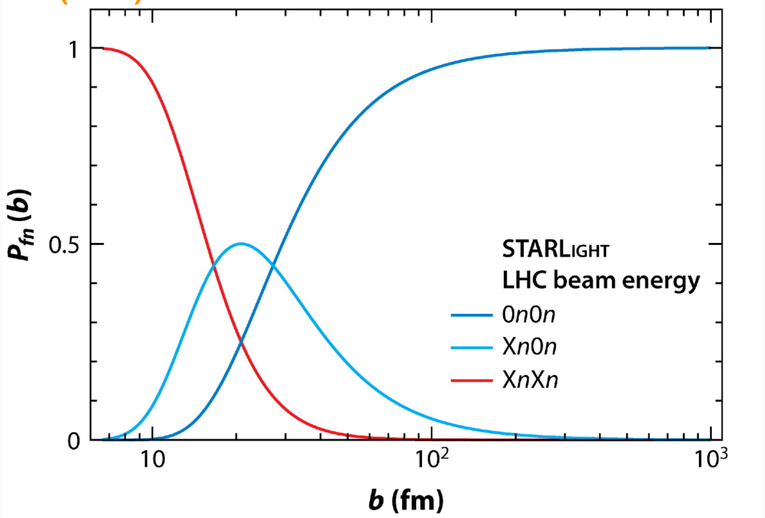
➡ Photon energy frontier: up to ~ 500 TeV in target frame at the LHC energies

- **Photo-nuclear interaction in ultra-peripheral collisions (UPC):** collisions with an impact parameter greater than the sum of the radii of the colliding nuclei, in which hadronic interactions are strongly suppressed
- High intensity photon flux allows more than one photon exchange between the same nuclei →accompanying neutrons emitted due to the electromagnetic dissociation
- Probability to emit additional photons is assumed to factorize in impact parameter space→provide impact parameter information for photon flux estimation

S. Klein arXiv: 2112.07827



S.Klein, P. Steinberg Annu. Rev. Nucl. Part. Sci, 70 (2020)-323-54



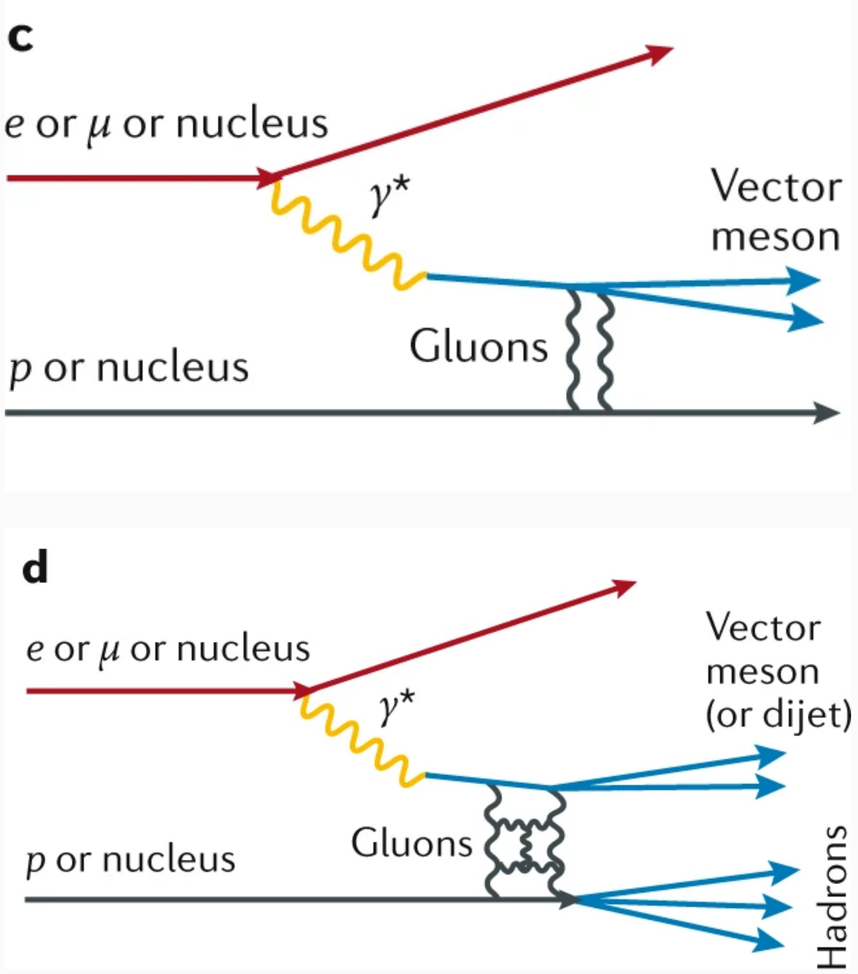
Exclusive vector meson photoproduction

- **Vector meson photoproduction:** photon fluctuates to a dipole which then elastically scatters off the nucleus, emerging as vector meson
- Cannot involve color exchange: so it must proceed via the exchange of at least two gluons→sensitive to gluon density of the target

➡ Dipole size inversely related to the photon Q^2 and the final state mass, probing shadowing at different length scales

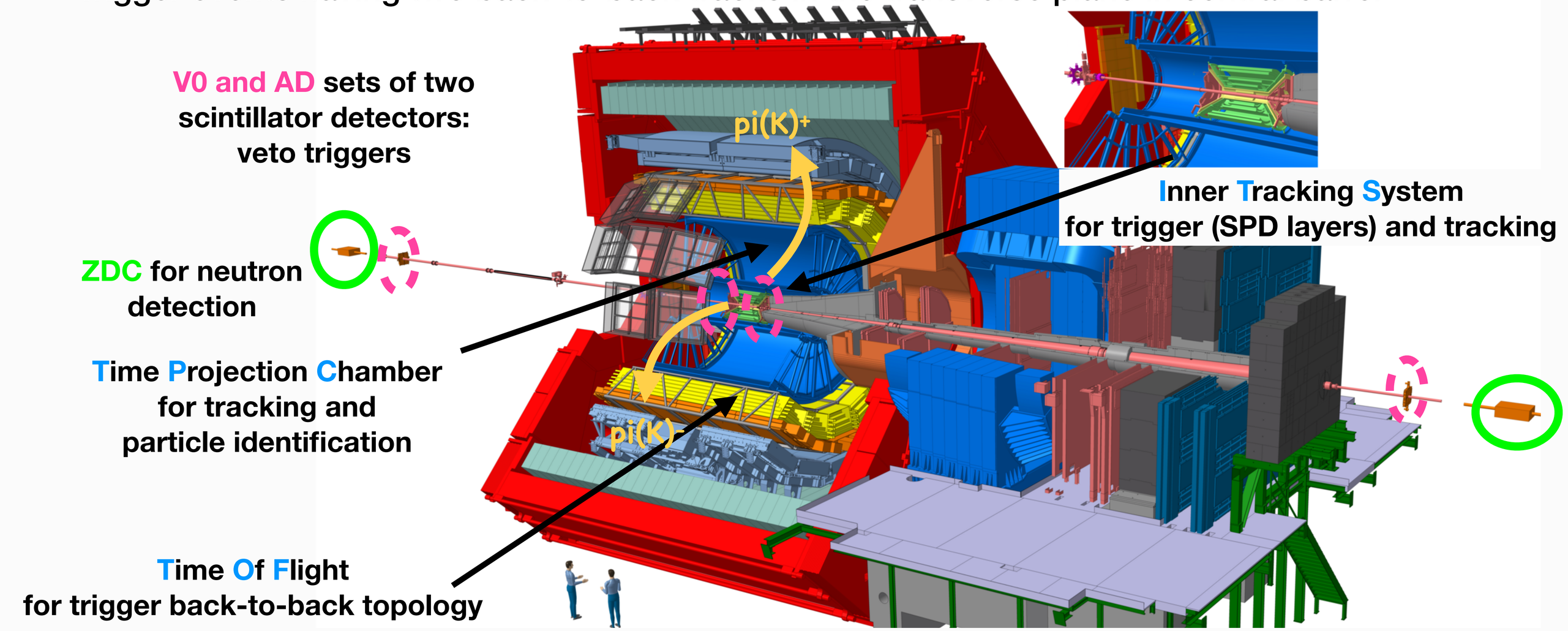
- **Light vector meson photoproduction:** Sensitive to nuclear shadowing effects and to the black-disc limit approach of QCD at a semi-hard scale

S. Klein, H. Mäntysaari, Nature Reviews Physics 1, 662–674 (2019)



ALICE as photon-hadron collider experiment

- Run 2 (2015 - 2018):
  Trigger events having two back-to-back tracks in the transverse plane in central barrel



Exclusive K^+K^- and $\pi^+\pi^-$ photoproduction

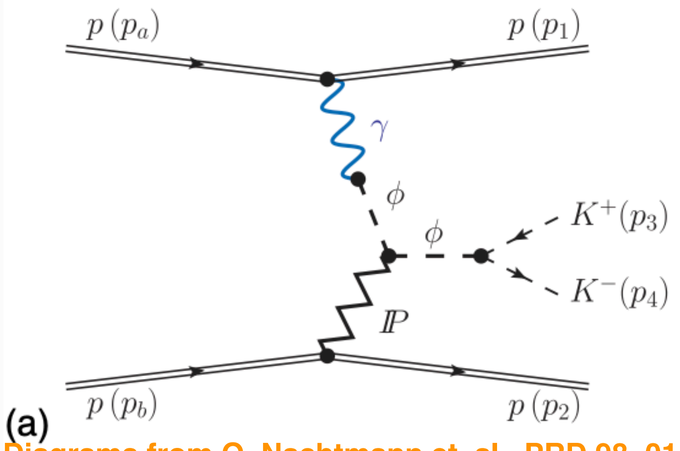
- Different physics processes are involved, which cannot be distinguished from and interfere;
  $\phi(1020) \to K^+K^-$ (B.R. $\sim 49.2\%$) & $\rho(770) \to \pi^+\pi^-$ (B.R. $\sim 100\%$)
- Cross section of exclusive K^+K^- ($\pi^+\pi^-$) photoproduction described by the Söding formula

$$\frac{d\sigma}{dM_{KK}} = \left| A_\phi \frac{\sqrt{M_{KK} M_\phi \Gamma_\phi}}{M_{KK}^2 - M_\phi^2 + i M_\phi \Gamma_\phi} + B_{KK} \right|^2 \quad \text{where} \quad \Gamma_\phi = \Gamma_0 \frac{M_K}{M_{KK}} \left(\frac{M_{KK}^2 - 4M_K^2}{M_\phi^2 - 4M_K^2} \right)^{3/2}$$

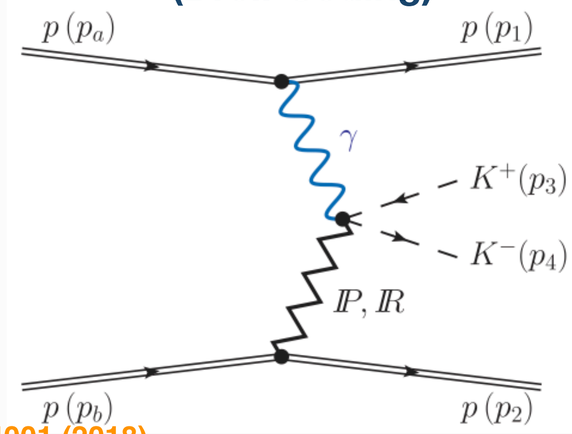
  mass dependent width and M_K is the kaon mass, while A_ϕ and B_{KK} are the amplitudes for $\phi(1020) \to K^+K^-$ and direct K^+K^- production

- Useful tool to access couplings of a vector mesons ($\phi(1020)$, $\rho(770)$) and meson pairs (K^+K^-, $\pi^+\pi^-$) with a photon and a nucleus at extremely high energies

$\phi(1020)$ photoproduction



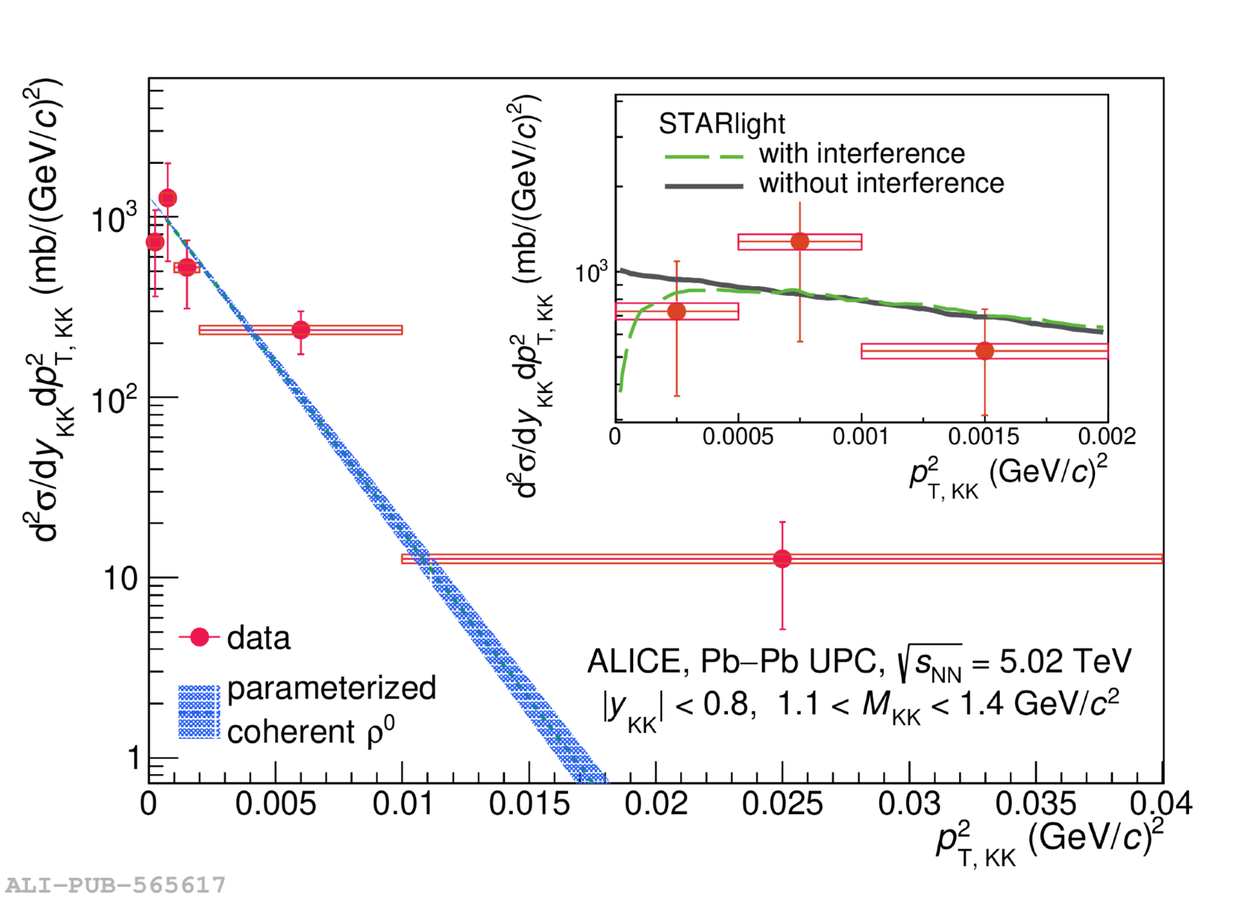
Continuum of nonresonant (Drell-Söding)



Diagrams from O. Nachtmann et. al., PRD 98, 014001 (2018)

Exclusive K^+K^- photoproduction

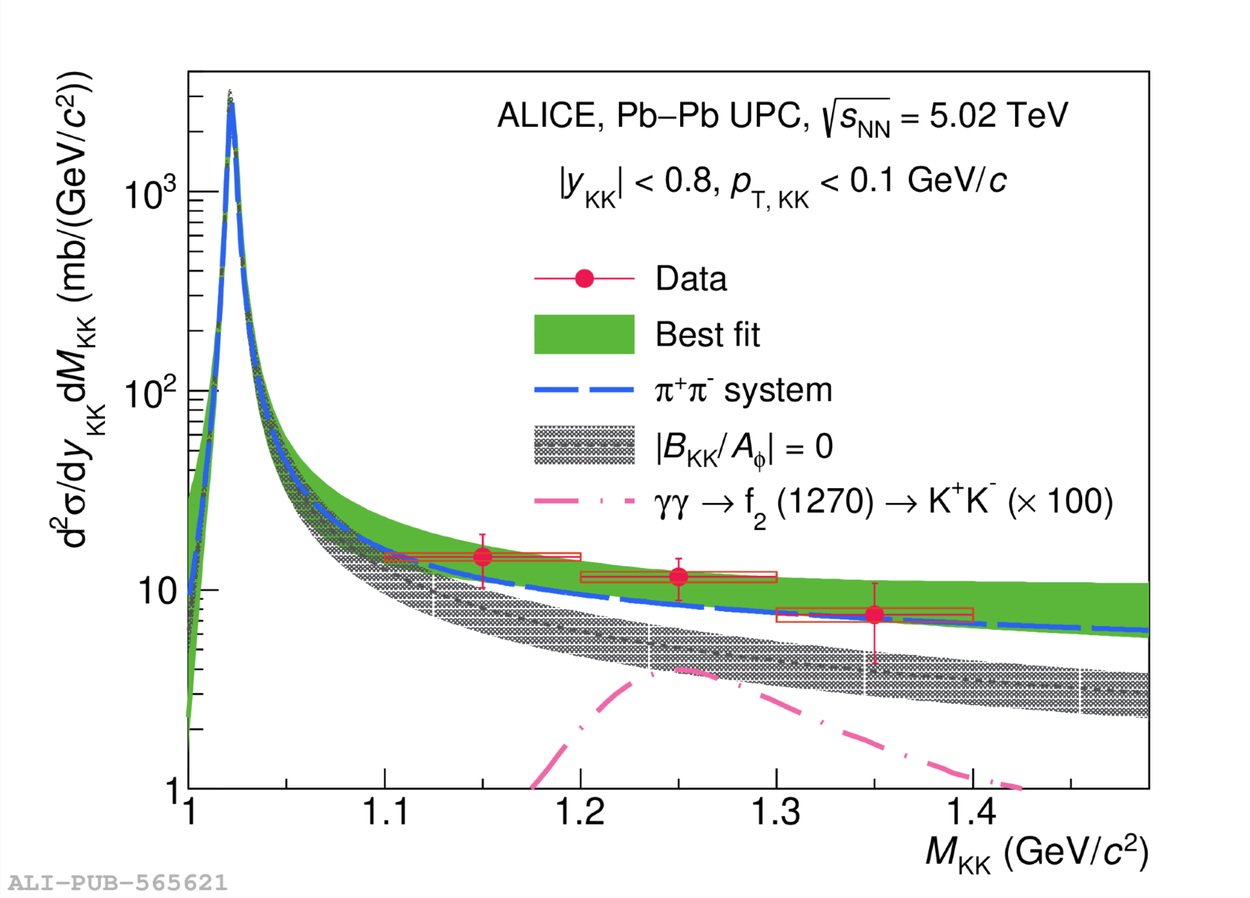
ALICE Collaboration, PRL 132, 222303 (2024)



- First measurement of **photoproduction of K⁺K⁻ pairs** in ultra-peripheral heavy-ion collisions
- Exclusive K⁺K⁻ photoproduction as a function of $p_{\mathrm{T}}^2 \approx |t|$
- Exponential function: $ae^{-b \times p_{\mathrm{T}}^2}$ with slope parameter b = 428±6 (stat.)±15 (syst.) GeV^{-2} taken from ALICE $\rho(770) \rightarrow \pi^+\pi^-$ measurement fairly well describes the data
- The cross section at low p_{T}^2 is in favor of photoproduction with destructive interference (as both nuclei can be either the photon source or scattering target)

Invariant mass distribution of coherent K^+K^- photoproduction

ALICE Collaboration, PRL 132, 222303 (2024)



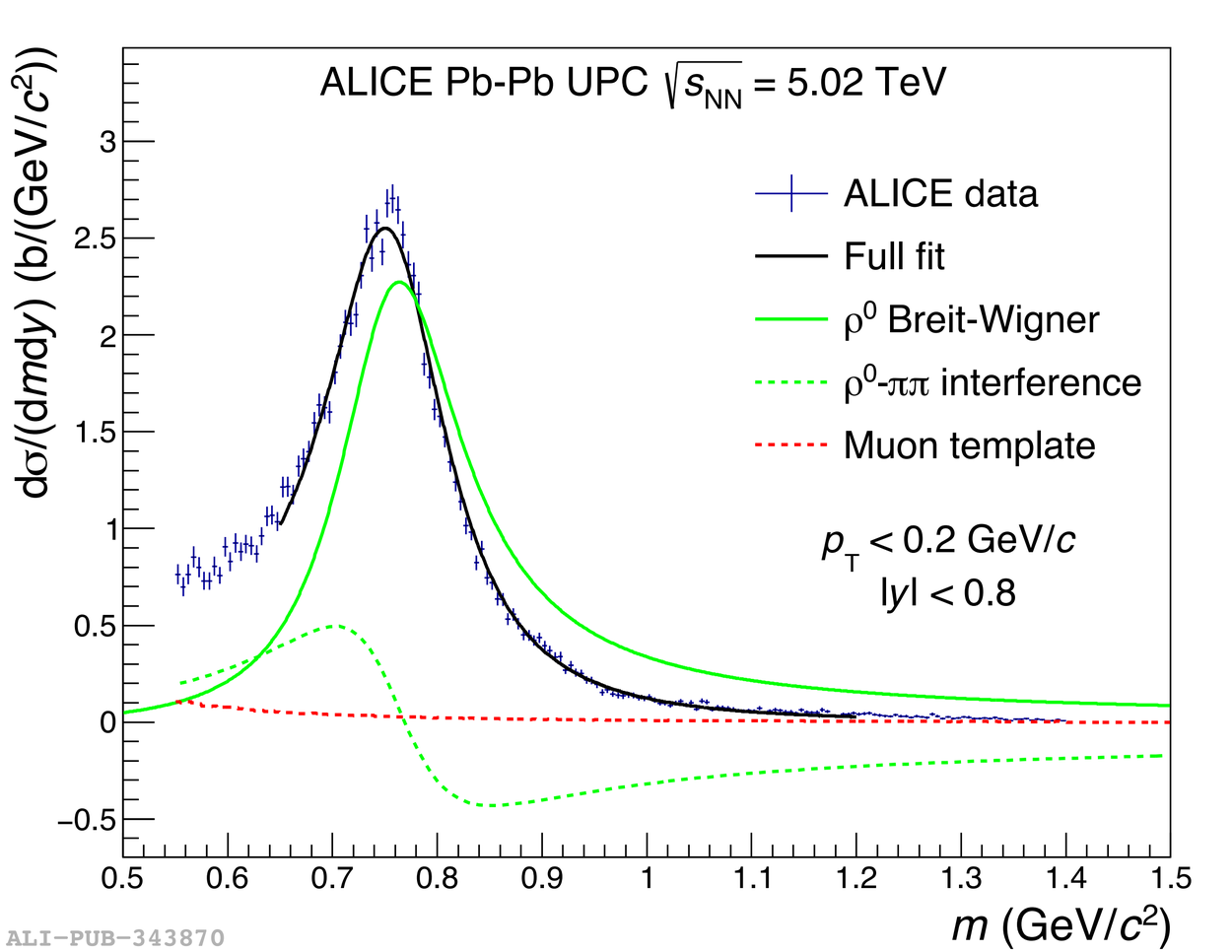
- Possible physics background of $\gamma\gamma \rightarrow X \rightarrow K^+K^-$ seems small: signal is likely the composition of $\phi(1020) \rightarrow K^+K^-$ and direct K^+K^-
- Söding formula with $|B/A| = 0$ hypothesis is more than 2 sigma away from the measurements → suggesting non-negligible non-resonant contribution
- Cross section ratio ($|B/A|$) and relative phase angle (Φ) between $\phi(1020) \rightarrow K^+K^-$ and direct K^+K^- determined with Söding formula

  R. M. Egloff et al., PRL 43 (1979) 657, ZEUS Collaboration PLB 377 (1996) 259

  ✓ ϕ meson cross section fixed with **fixed target experiments** + HERA measurement + Glauber model
- Set of parameters from $\pi^+\pi^-$ system describes the measurement; lower edge of best-fit result

Exclusive $\pi^+\pi^-$ photoproduction

ALICE Collaboration, JHEP 06 (2020) 035

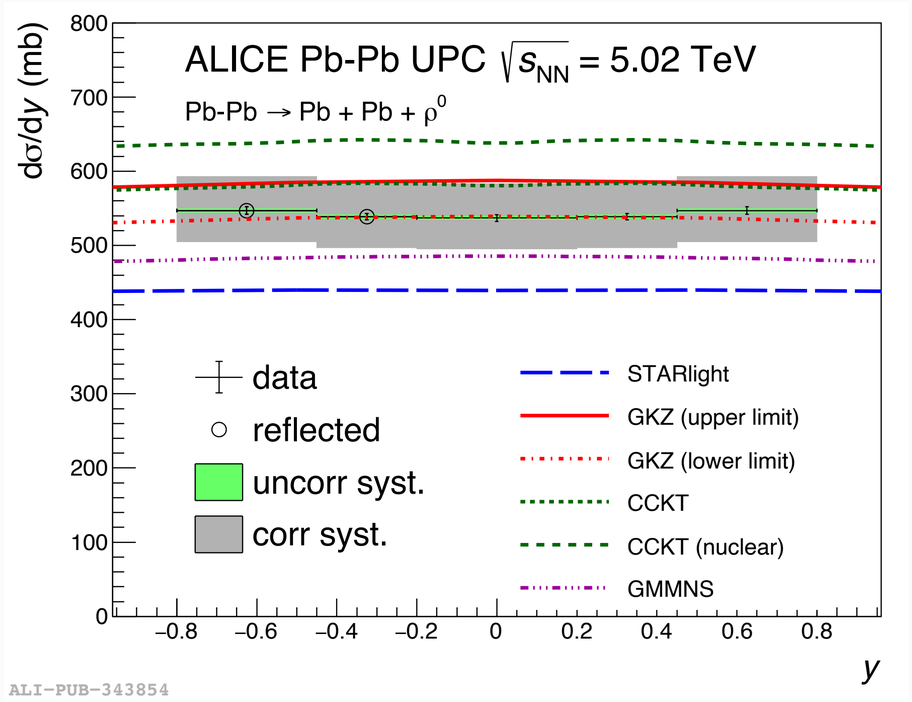


- Multiple measurements from LHC and RHIC in UPCs showing interference of $\rho(770) \rightarrow \pi\pi$ and continuum of direct $\pi\pi$
- Contribution from continuum, |*B*/*A*|:
  - constant as a function of rapidity, collision energy (vs. 2.76 TeV) and different neutron classes in current precision
    ALICE Collaboration, JHEP 09 (2015) 095
    STAR Collaboration, PRC 96 054904 (2017)
  - Larger contribution of continuum in AuAu collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV

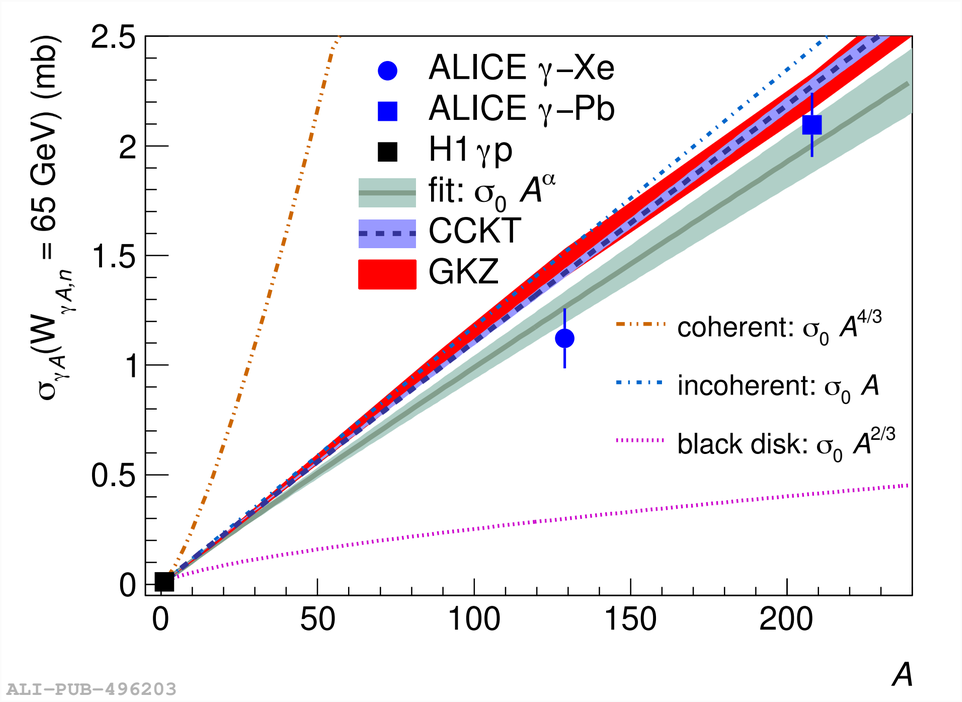
    → sensitive to the kinematics of interaction or type of target?

Coherent $\rho^0(770)$ photoproduction

ALICE Collaboration, JHEP 06 (2020) 035



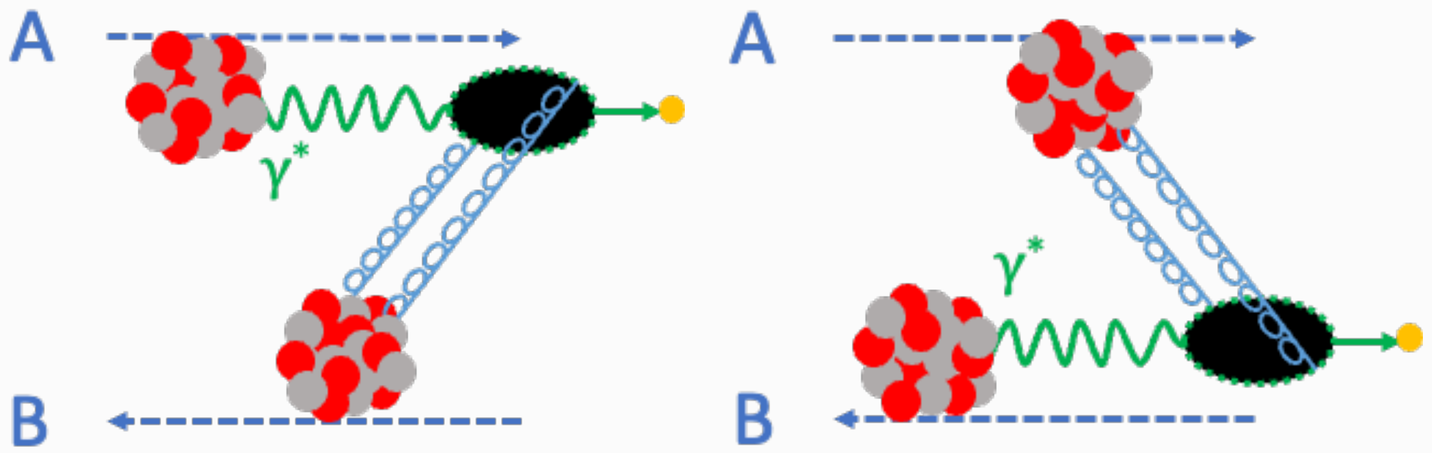
ALICE Collaboration, PLB 820 (2021) 136481



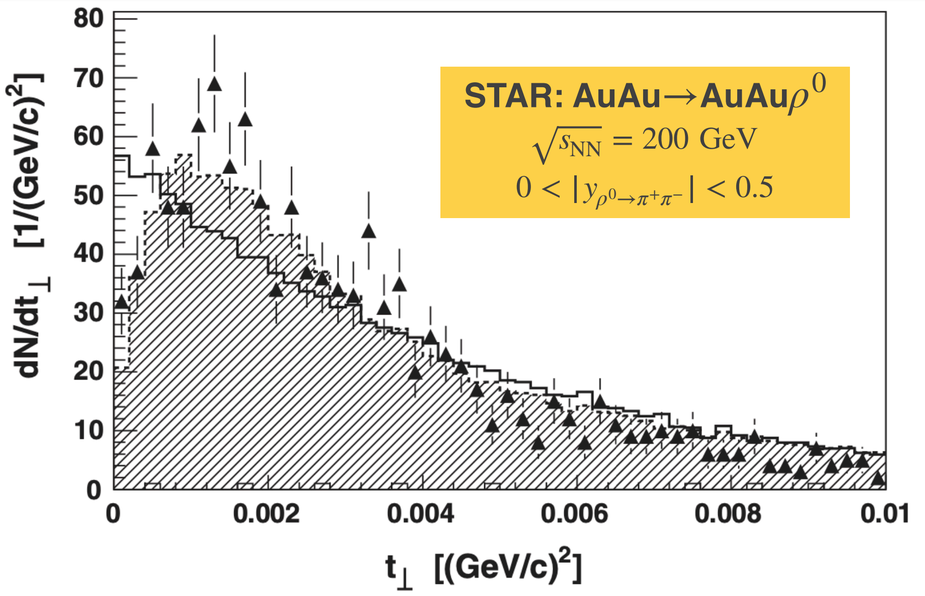
- Measured cross section of coherent photoproduction shows good agreement with model predictions for different neutron emission classes → similarly favored in colour-dipole approach with gluon saturation/hot spots or Gribov-Glauber shadowing approach
- Atomic number (*A*) dependent *γA* cross section, $\sigma(\gamma A \rightarrow \rho^0 A) \propto A^{\alpha}$ with *α* = 0.96 ± 0.02
  - **substantial nuclear effects, yet considerably above black-disk limit**

Quantum interference of coherent photoproduction

S. Klein, J. Nystrand, PRL 84, 2330 (2000) & Phys. Lett. A308, 323 (2003)



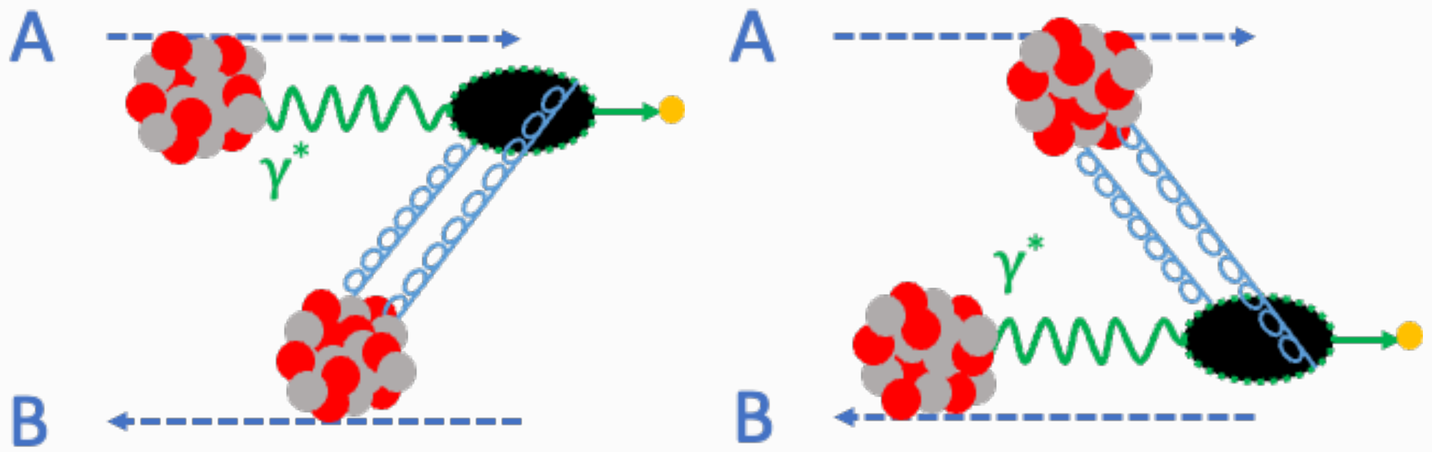
STAR Collaboration, PRL 102, 112301 (2009)

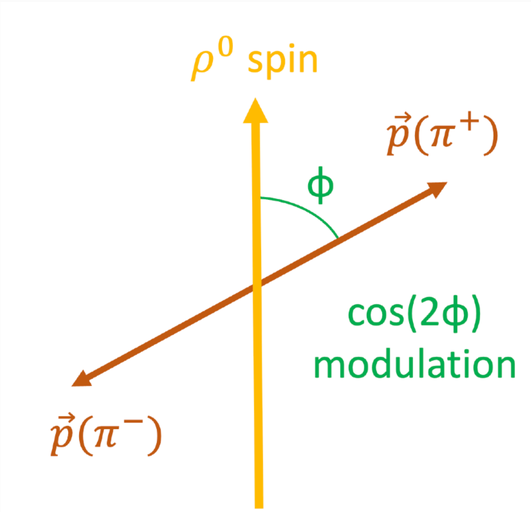


- Indistinguishable source(γ^*) and target of produced VM related by parity transformation
- Negative parity of VM → opposite sign of amplitude
  - ➡ $\sigma \propto |1 - e^{i\vec{p}\cdot\vec{b}/\hbar}|^2$
  - ➡ Destructive interference at $p_{\mathrm{T}} < \hbar/b$
  - ➡ Reducing production cross section at small p_{T}

Quantum interference of coherent photoproduction

H. Xing, C. Zhang, J. Zhou and Y.-J, Zhou JHEP10 (2020) 064

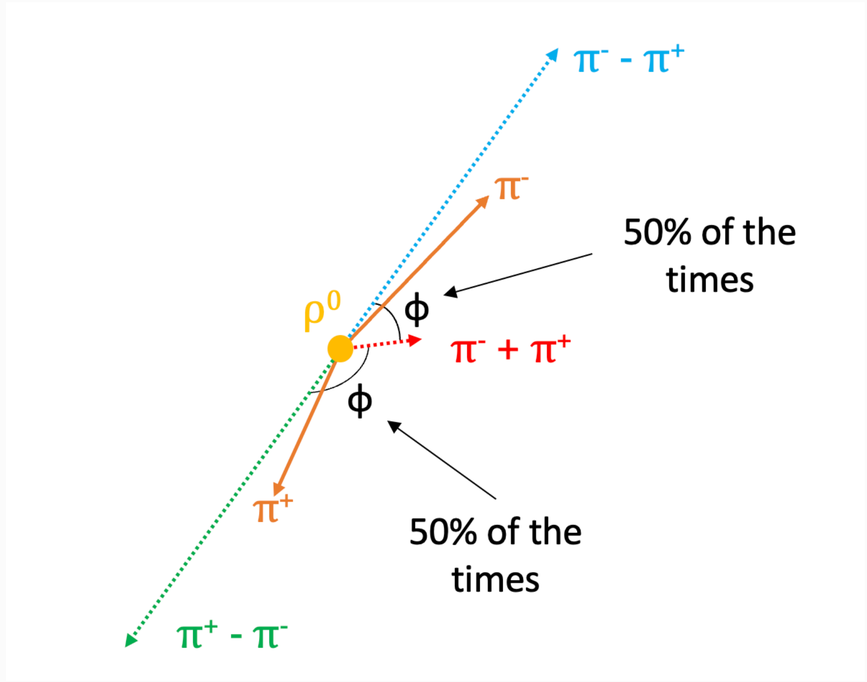




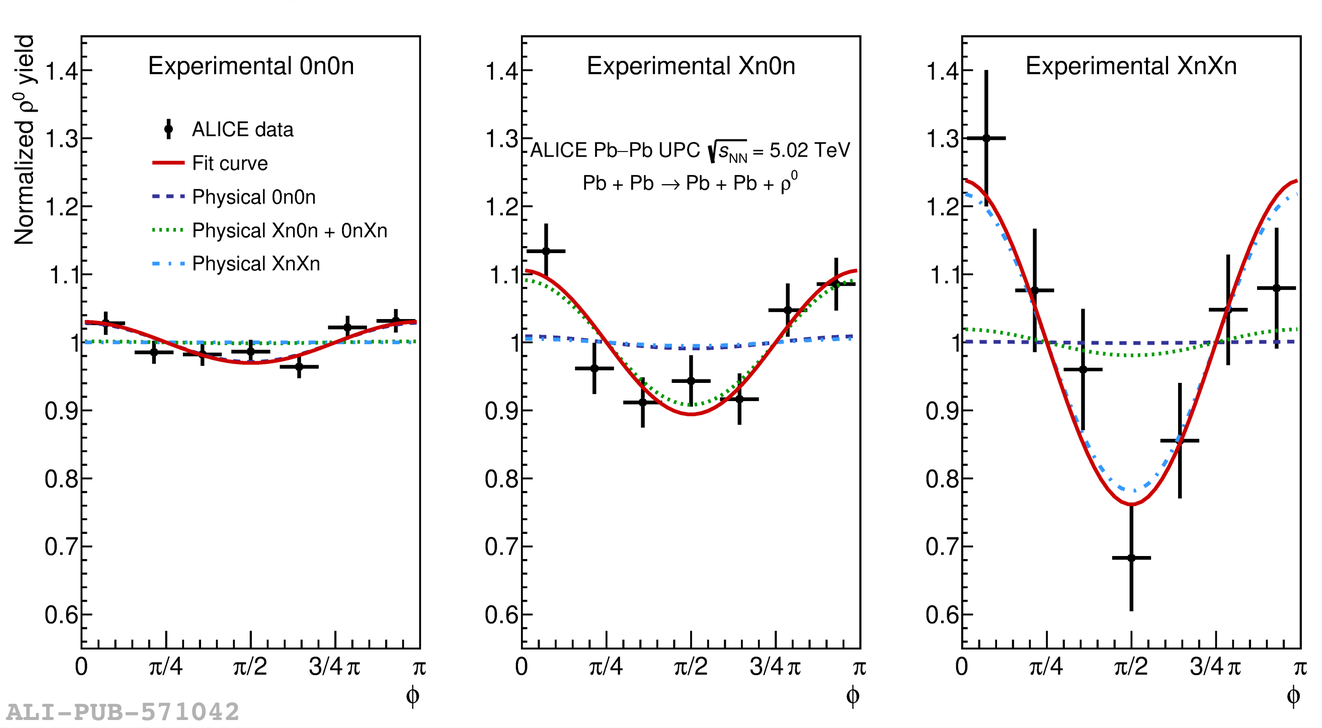
- Photons from Lorentz boosted nuclei are fully linearly polarized along the impact parameter
  - ➡ Polarization transferred to ρ^0
  - ➡ Azimuthal cos(2ϕ) modulation of decay products in the momentum distribution w.r.t. the polarization direction (orbital angular momentum conservation)
- Interference effect (correlation between ρ^0 momentum and polarization along $\vec{b}$) preserves the anisotropy, enables to access spin information (otherwise cancelled due to the randomly distributed ***b***)
- Angular correlations is a new measure of the interference effect

Angular anisotropy in $\rho(770) \rightarrow \pi^+\pi^-$ in different neuron emission classes

A. Riffero, Private discussion



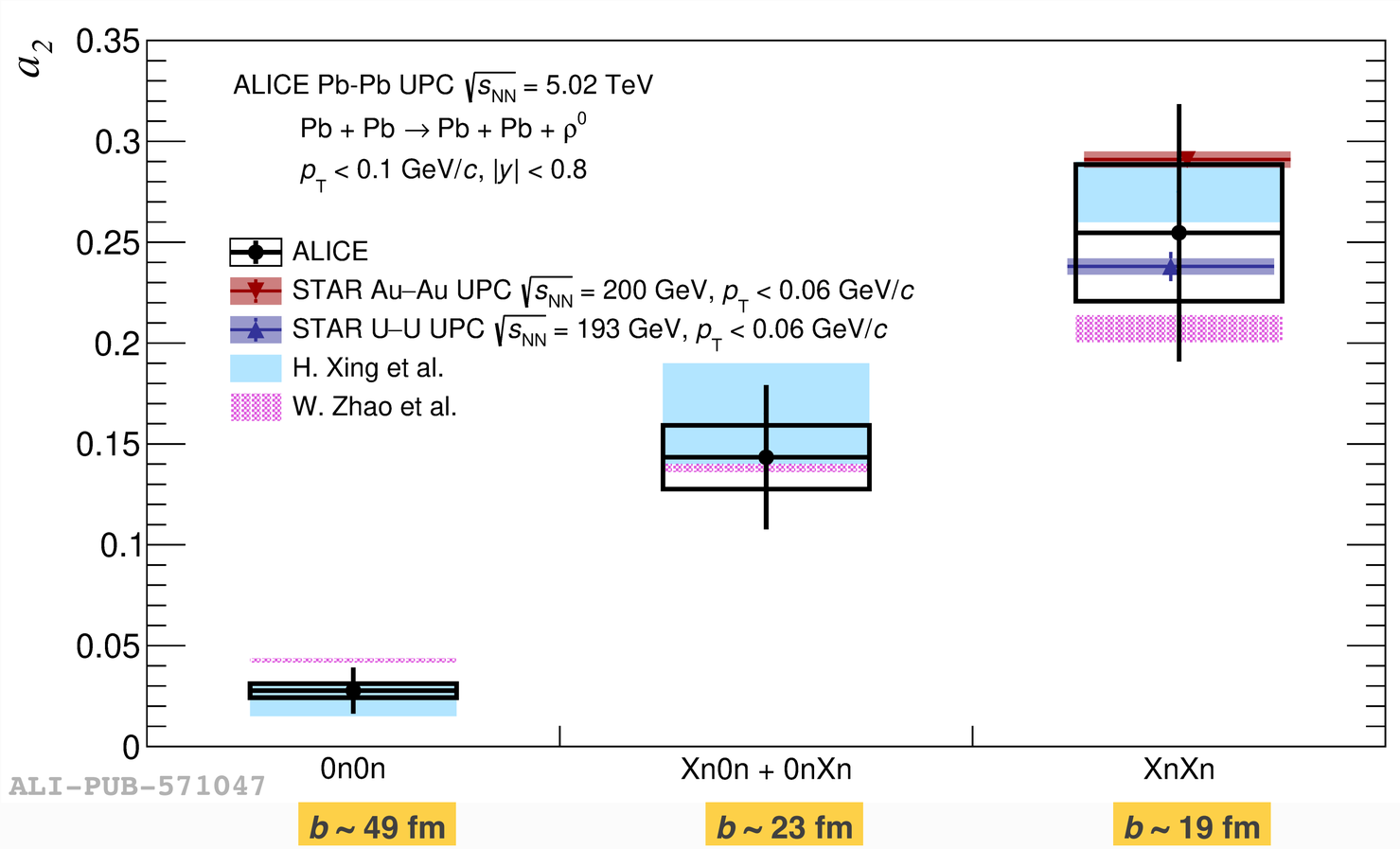
ALICE Collaboration, arXiv:2405.14525



- ϕ: angle between the transverse components of $\vec{p}_+$ and $\vec{p}_-$ where $\vec{p}_\pm = \vec{\pi}_1 \pm \vec{\pi}_2$ (randomly assign track1 and track2, not upon charge)
- Obtain $\rho(770) \rightarrow \pi^+\pi^-$ yield from invariant mass distribution as a function of ϕ in each neutron emission class
- Measured yield migrations across neutron classes (due to ZN efficiency and pile-up) corrected for comparison with theoretical predictions

Impact parameter dependent angular anisotropy

ALICE Collaboration, arXiv:2405.14525



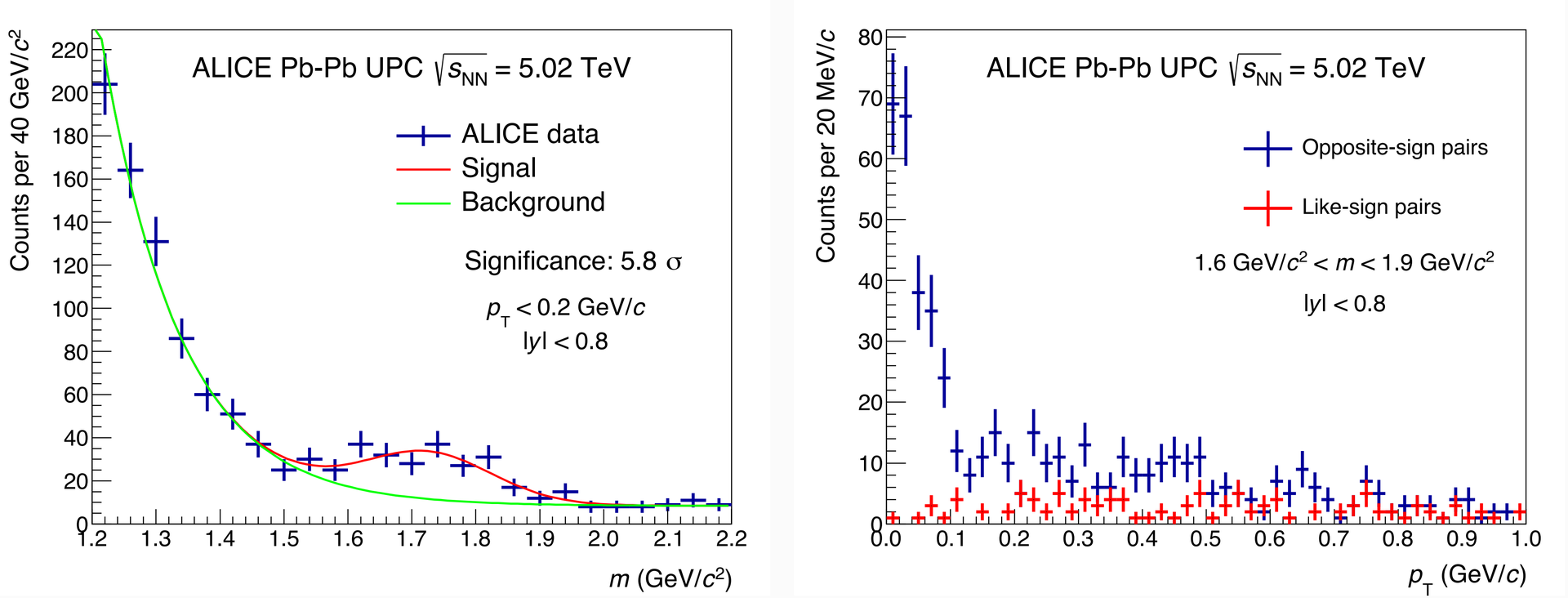
b ~ 49 fm | ***b*** ~ 23 fm | ***b*** ~ 19 fm

Median impact pamater from nOOn simulation
M. Broz, J.G. Contreras, J.D. Takaki, Comp. Phy. Comm. 253 (2020) 107181

- First time measurement of the angular anisotropy in photoproduced $\rho(770) \rightarrow \pi^+\pi^-$ as a function of the impact parameter (***b***)
- The strength of modulation increases by about one order of magnitude from large to small ***b***
- Theoretical calculations based on the picture of anisotropy from linearly polarized photon with quantum interference effect describe the measurements

Photoproduction of excited ρ-meson states

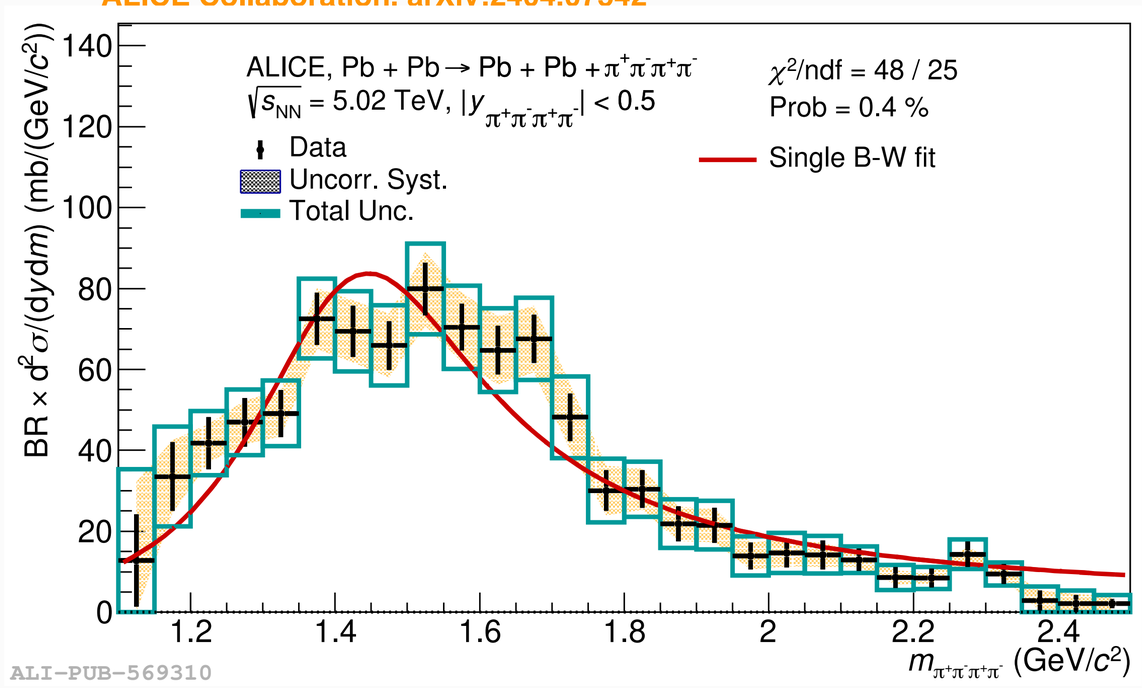
ALICE Collaboration, JHEP 06 (2020) 035

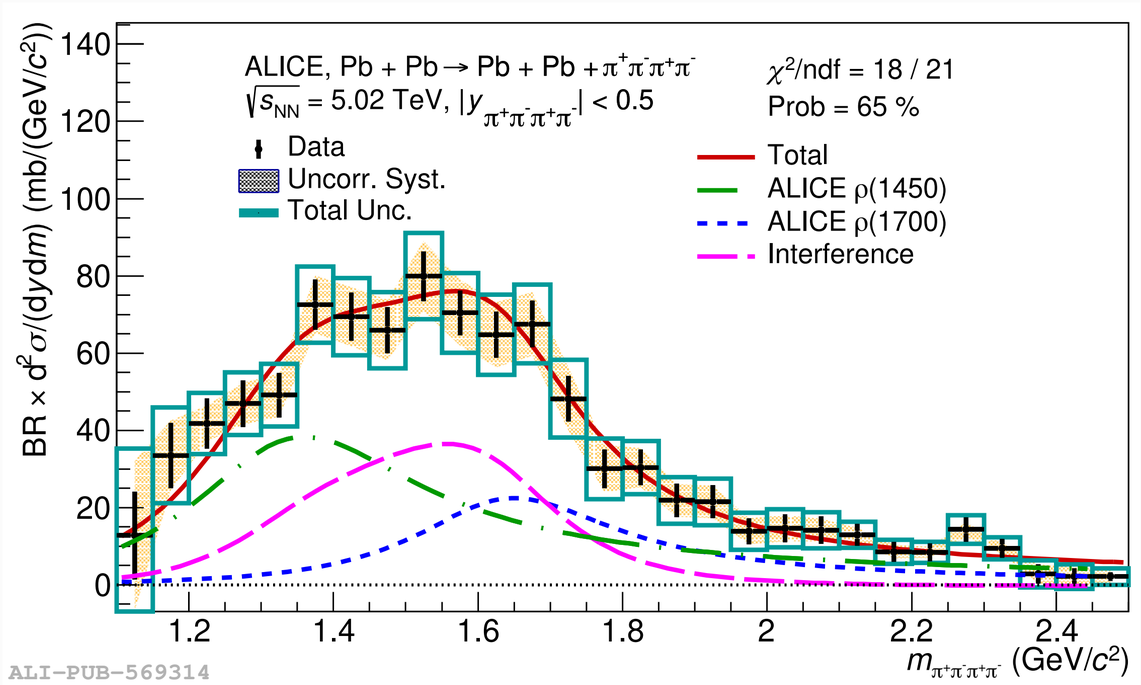


- Resonance-like structure observed in $\pi^+\pi^-$ invariant mass distribution, also seen in STAR preliminary → likely to be from coherent photoproduction
- Known excited states in PDG: $\rho(1450)$, $\rho(1700)$, $\rho_3(1690)$

Exclusive four pion photoproduction

ALICE Collaboration. arXiv:2404.07542



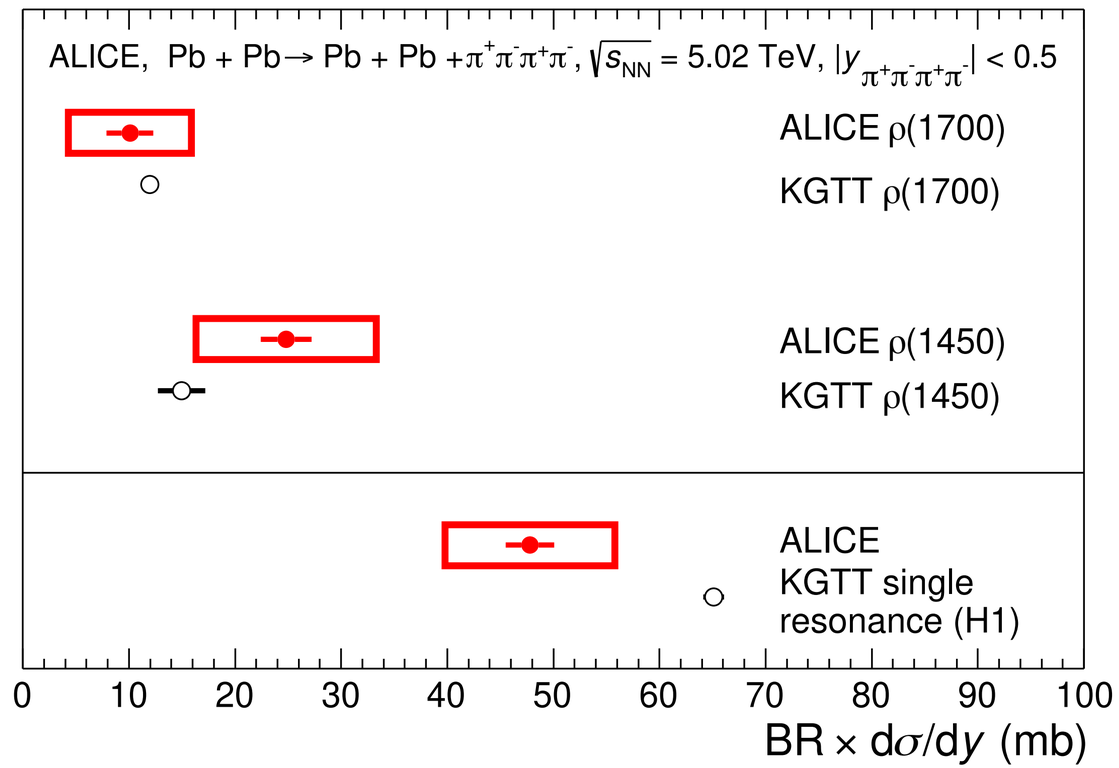


- Fully corrected invariant mass distribution of coherently produced four pions fits to two different scenarios:
  - Single Breit-Wigner resonance: not describing data well (Prob = 0.4%), though compatible with PDG $\rho(1450)$, but lower than STAR
  - Two interfering resonances with a mixing angle: compatible with PDG $\rho(1450)$ and $\rho(1700)$; hypothesis is favored by the measurement

	m (MeV/c^2)	Γ (MeV/c^2)
PDG $\rho(1450)$	1465 ± 25	400 ± 60
PDG $\rho(1700)$	1720 ± 20	250 ± 100
STAR Au–Au	1540 ± 40	570 ± 60
ALICE Pb–Pb single resonance	$1463 \pm 2 \pm 15$	$448 \pm 6 \pm 14$
ALICE Pb–Pb $\rho(1450)$	$1385 \pm 14 \pm 36$	$431 \pm 36 \pm 82$
ALICE Pb–Pb $\rho(1700)$	$1663 \pm 13 \pm 22$	$357 \pm 31 \pm 49$
Mixing angle	$1.52 \pm 0.16 \pm 0.19$ (rad)	

Total coherent cross section for resonance(s)

ALICE Collaboration, arXiv:2404.07542

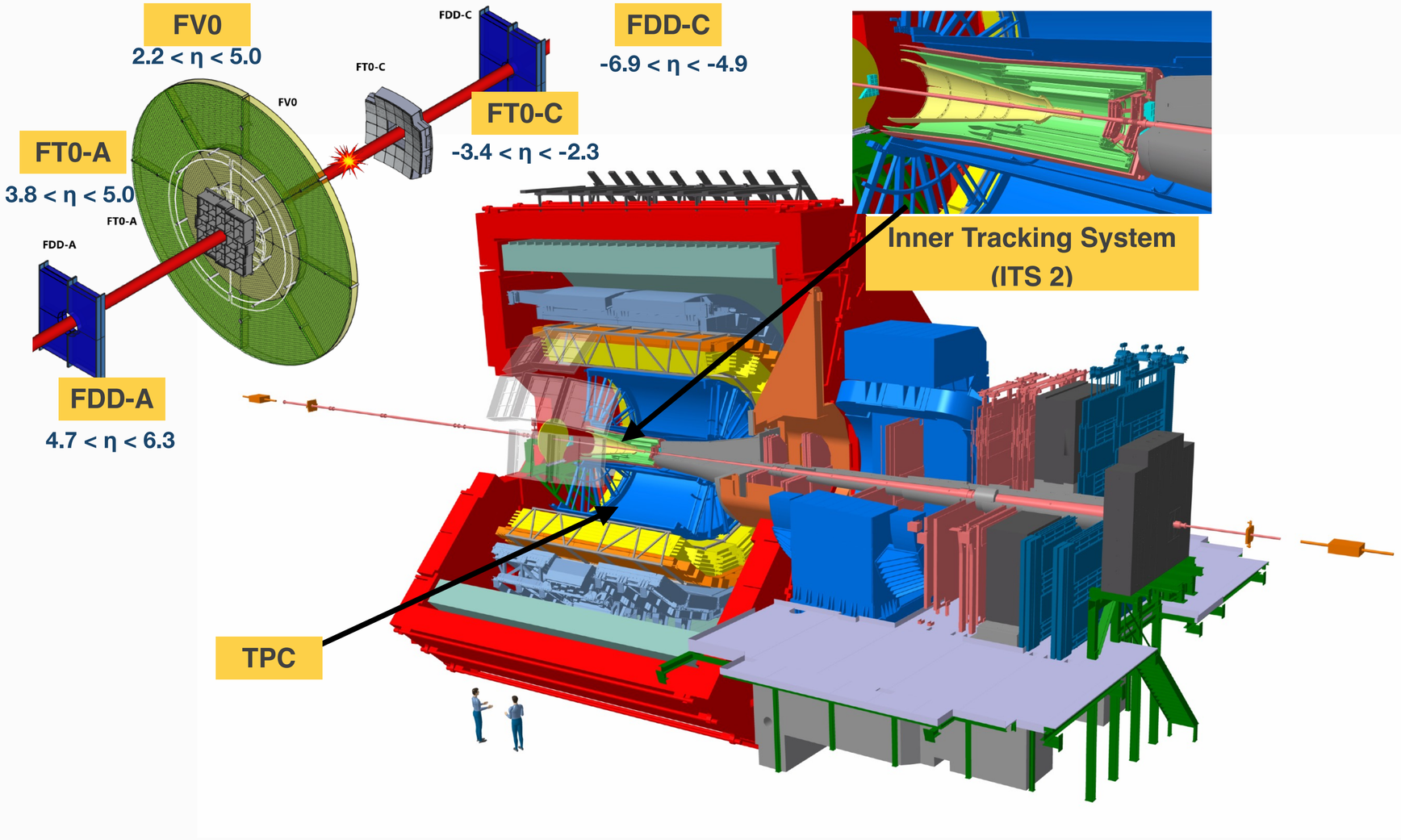


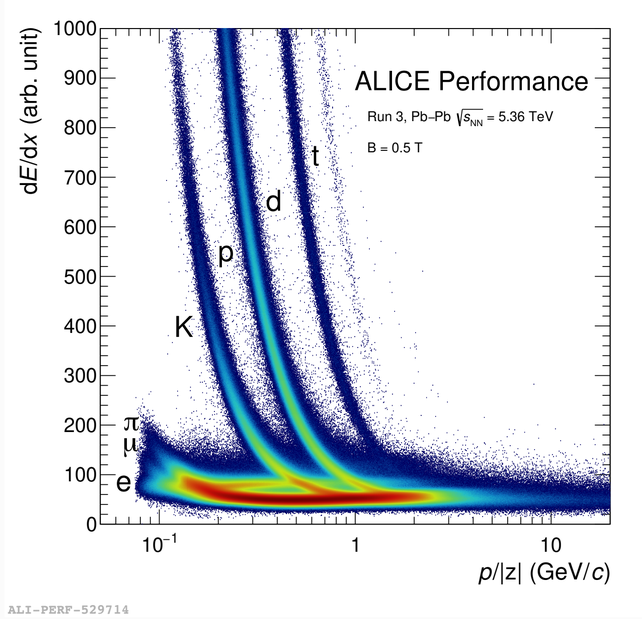
ALI-PUB-569269

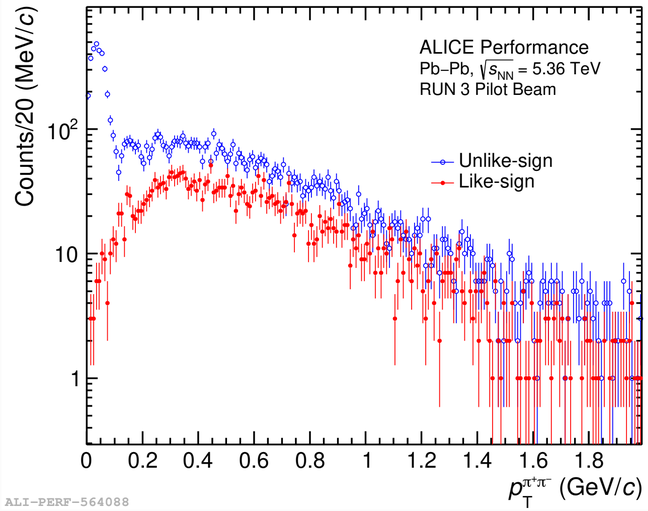
- The total cross section based on single resonance scenario, as well as two interfering $\rho(1450)$ and $\rho(1700)$ obtained
- Due to the large interference component, the sum of $\rho(1450)$ and $\rho(1700)$ cross sections is smaller than the total cross section
- The cross sections for $\rho(1450)$ and $\rho(1700)$ give better agreement with theoretical calculations (KGTT) based on VDM-Regge model than single resonance case

M. Klusek-Gawenda, J. D. T. Takaki, Acta Phys. Polon. B 51 (2020) 1393

ALICE as photon-hadron collider experiment in Run 3







Summary

- Various observables of photoproduction have been explored in ultra-peripheral Pb-Pb collisions with ALICE, providing valuable inputs for studying the nuclear structure at high energies (small Bjorken-*x*), dense gluon system
- In addition, measurements of photoproduced light hadrons could be used as tools for other physics aspects:
  - Couplings of vector mesons ($\phi(1020)$, $\rho(770)$) and meson pairs (K^+K^-, $\pi^+\pi^-$) with a photon and a nucleus at extremely high energies
  - Quantum interference effect in femtometer scale
  - Search for new resonances
- ALICE is collecting large data sample with upgraded detectors over LHC Run 3 campaign and extend kinematic coverage down to smaller x is foreseen in Run 4 with ALICE FoCAL

N. Strangmann's talk

STAY TUNED!!