Probing the nucleus and nucleons with vector mesons in ultra-peripheral collisions in ALICE

Minjung Kim[1,2,3] on behalf of the ALICE Collaboration

[1]LBNL, [2]UC Berkeley, [3]CFNS (Stony Brook U.)

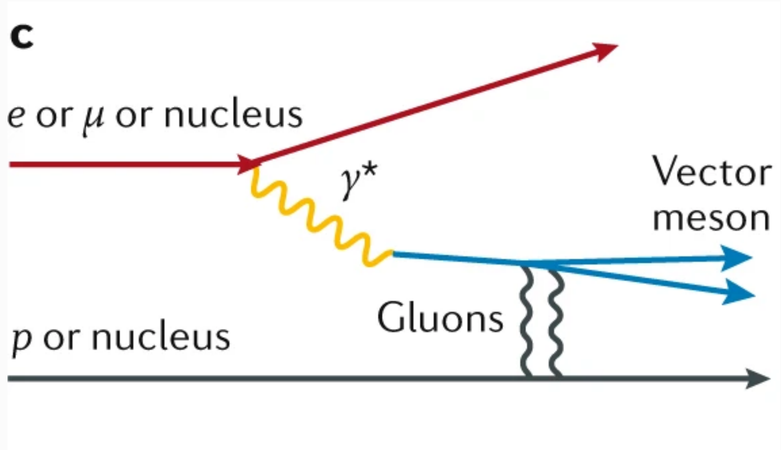
12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
(Hard Probes 2024)
22. Sep. 2024 - 27. Sep. 2024
Nagasaki, Japan

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: must proceed via the exchange of at least two gluons

➡ Sensitive to **gluon density** of the target

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



Exclusive vector meson photoproduction

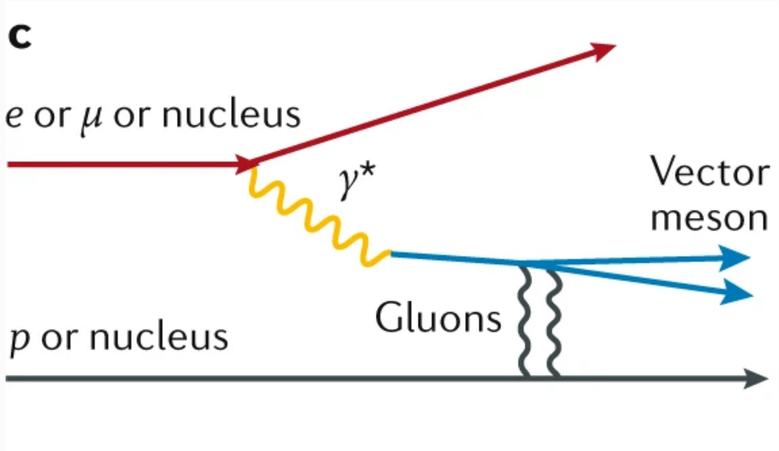
- **Vector meson photoproduction:** photon fluctuates to a dipole which then elastically scatters off the nucleus, emerging as vector meson
- Cannot involve color exchange: must proceed via the exchange of at least two gluons

➡ Sensitive to **gluon density** of the target

- **Exclusivity:** Physics variables accessible with final state mass and rapidity

$$x = \frac{M_{\mathrm{VM}}}{\sqrt{s_{\mathrm{NN}}}} e^{\pm y} \text{ and } Q^2 \sim (\frac{M_{\mathrm{VM}}}{2})^2$$

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



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: must proceed via the exchange of at least two gluons

➡ Sensitive to **gluon density** of the target

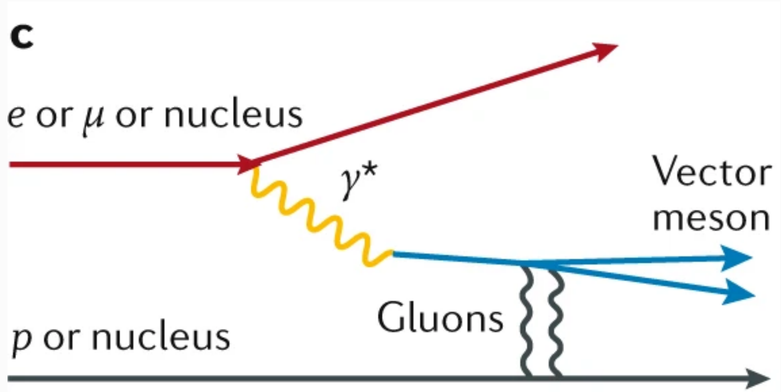
- **Exclusivity:** Physics variables accessible with final state mass and rapidity

$$x = \frac{M_{\mathrm{VM}}}{\sqrt{s_{\mathrm{NN}}}} e^{\pm y} \text{ and } Q^2 \sim (\frac{M_{\mathrm{VM}}}{2})^2$$

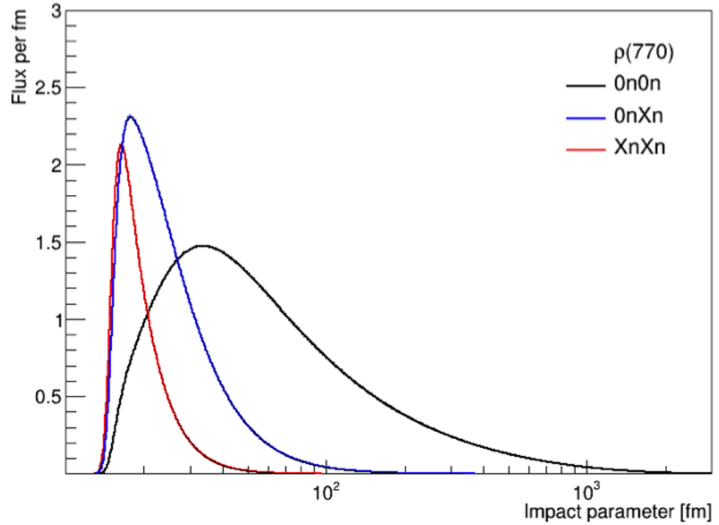
- High probability of additional low-energy photon exchanges leads to ion dissociation and **neutron emission in the forward direction**

➡**ZDC** measurements, with factorized photon emission probability, provide **impact parameter information**

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

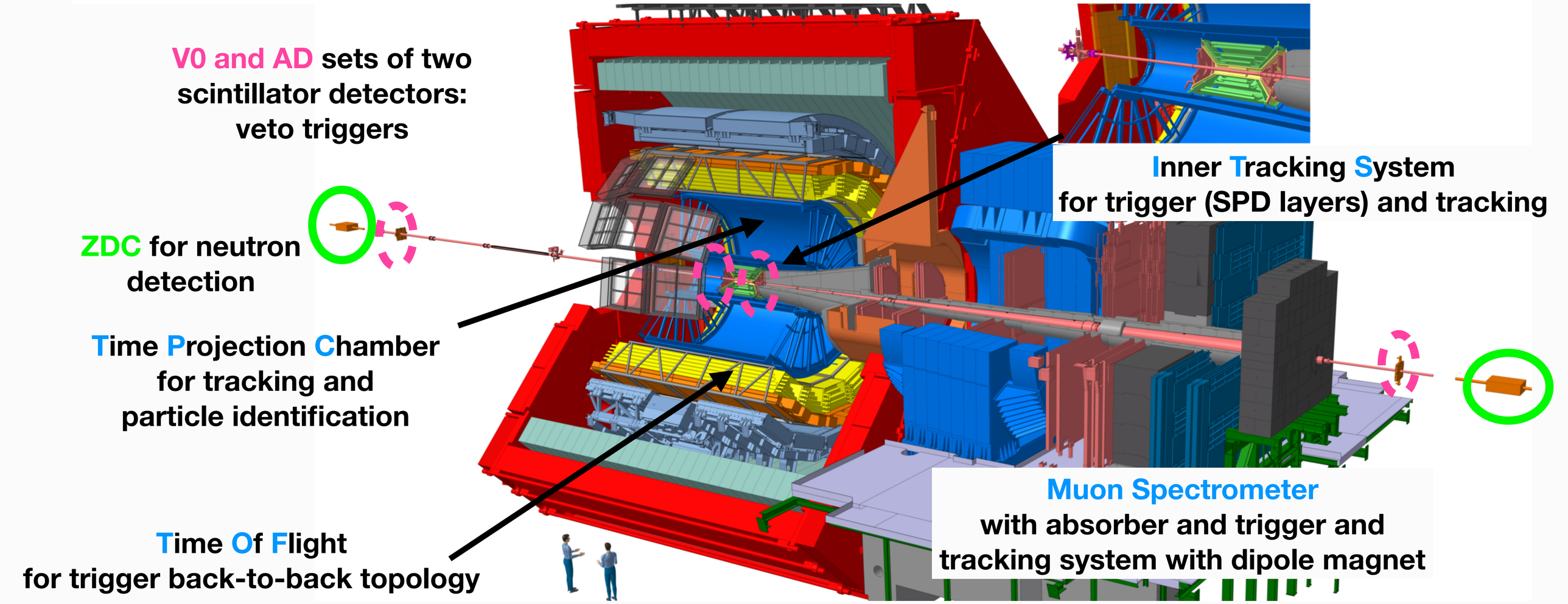


M. Broz et. al., Computer Physics Communications Volume 253, August 2020, 107181



ALICE as photon-hadron collider experiment

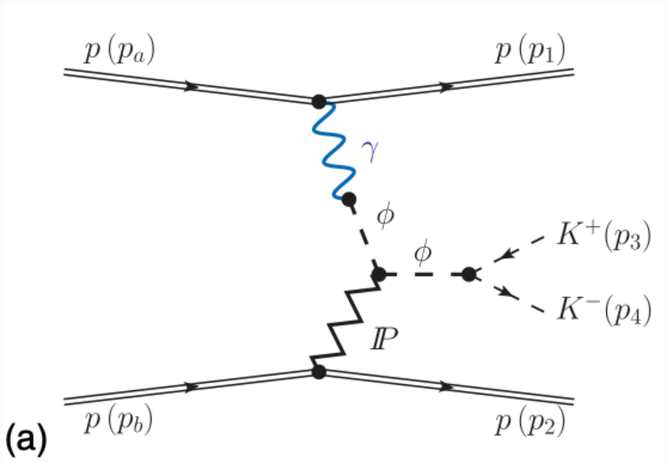
- Photon energy frontier: up to ~ 500 TeV in target frame at the LHC energies
- Run 2 (2015 - 2018): Trigger events having two back-to-back tracks in the transverse plane



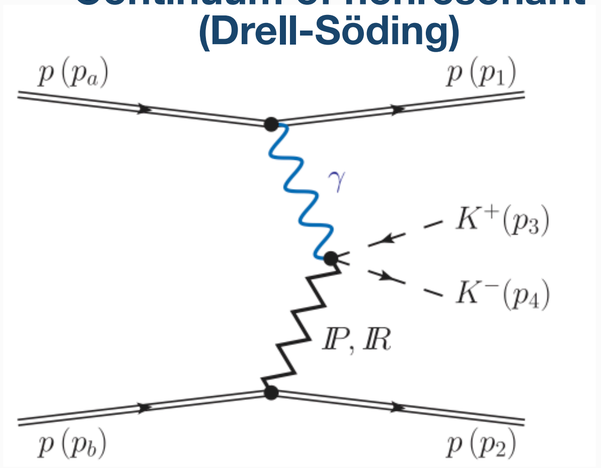
Exclusive $\pi^+\pi^-$ and K^+K^- photoproduction

- Final state K^+K^- ($\pi^+\pi^-$): Different physics processes are involved, which cannot be distinguished from and interfere
- Large cross section of light vector mesons ($\rho(770)$, $\phi(1020)$, …..): sensitive tool to the black-disc limit approach of QCD at a semi-hard scale
- Useful tool to access couplings of a vector meson and meson pair ($\pi^+\pi^-$, K^+K^-) with a photon and a nucleus at extremely high energies
- First time study both $\pi^+\pi^-$ and K^+K^- photoproduction, as two parallel systems

$\phi(1020)$ photoproduction



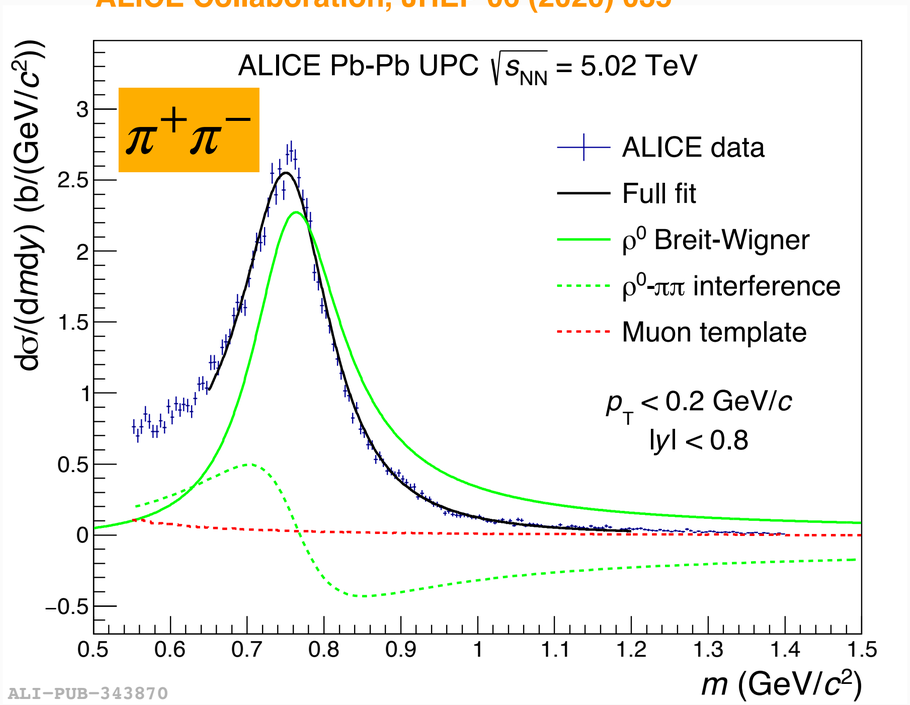
Continuum of nonresonant (Drell-Söding)



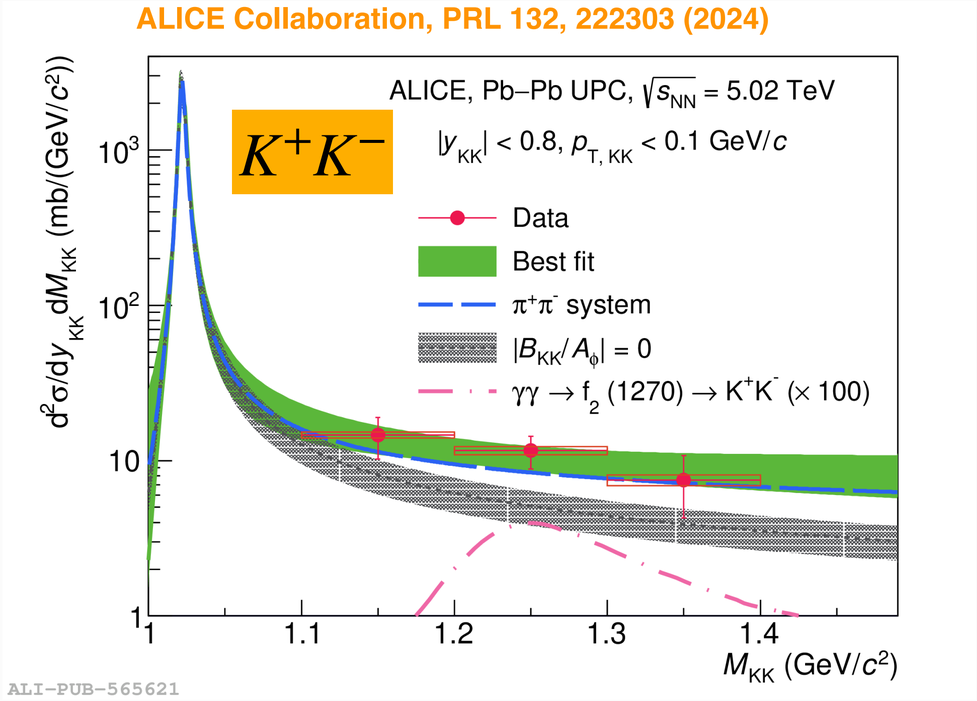
Diagrams from O. Nachtmann et. al., PRD 98, 014001 (2018)

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

ALICE Collaboration, JHEP 06 (2020) 035



ALICE Collaboration, PRL 132, 222303 (2024)



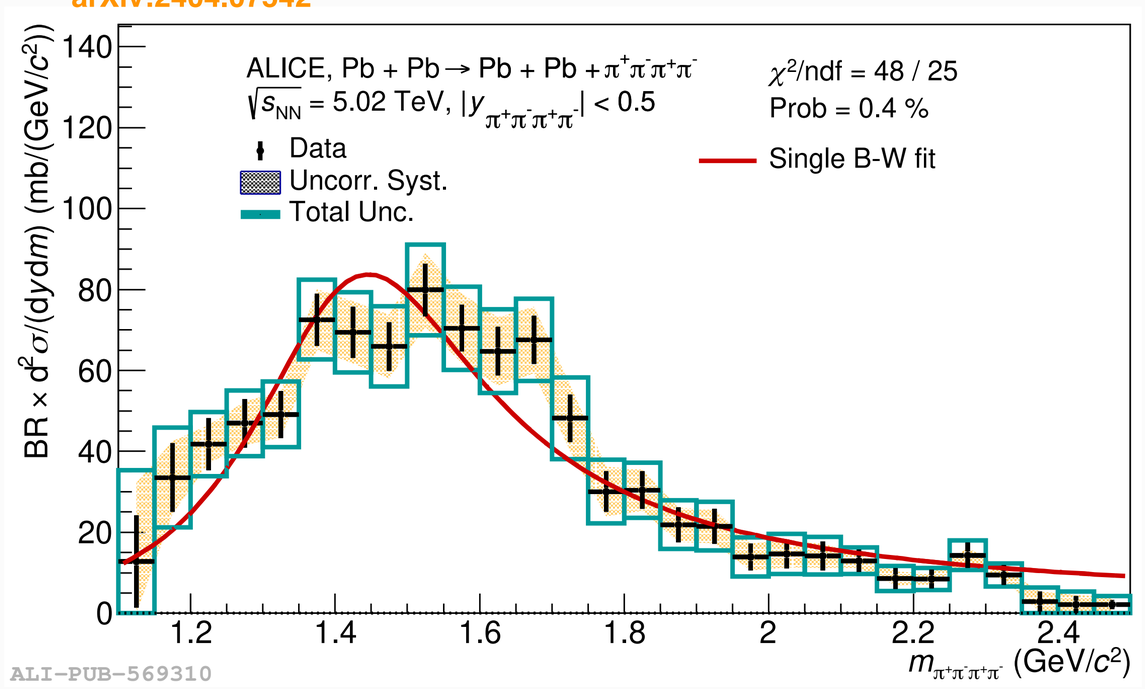
- Cross section of exclusive K^+K^- ($\pi^+\pi^-$) photoproduction described by the Söding formula

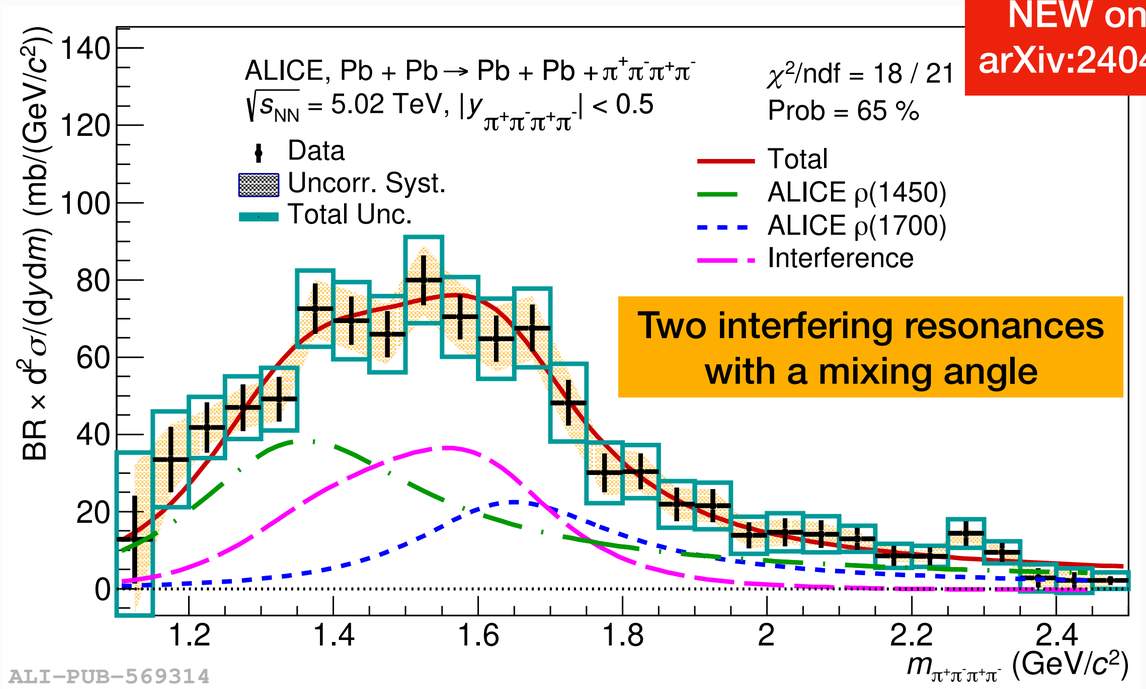
$$\frac{d\sigma}{dM_{KK}} = \left| A_\phi \frac{\sqrt{M_{KK} M_\phi \Gamma_\phi}}{M_{KK}^2 - M_\phi^2 + i M_\phi \Gamma_\phi} + B_{KK} \right|^2 \qquad \Gamma_\phi = \Gamma_0 \frac{M_K}{M_{KK}} \left(\frac{M_{KK}^2 - 4M_K^2}{M_\phi^2 - 4M_K^2} \right)^{3/2}$$

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

Exclusive four pion photoproduction

arXiv:2404.07542



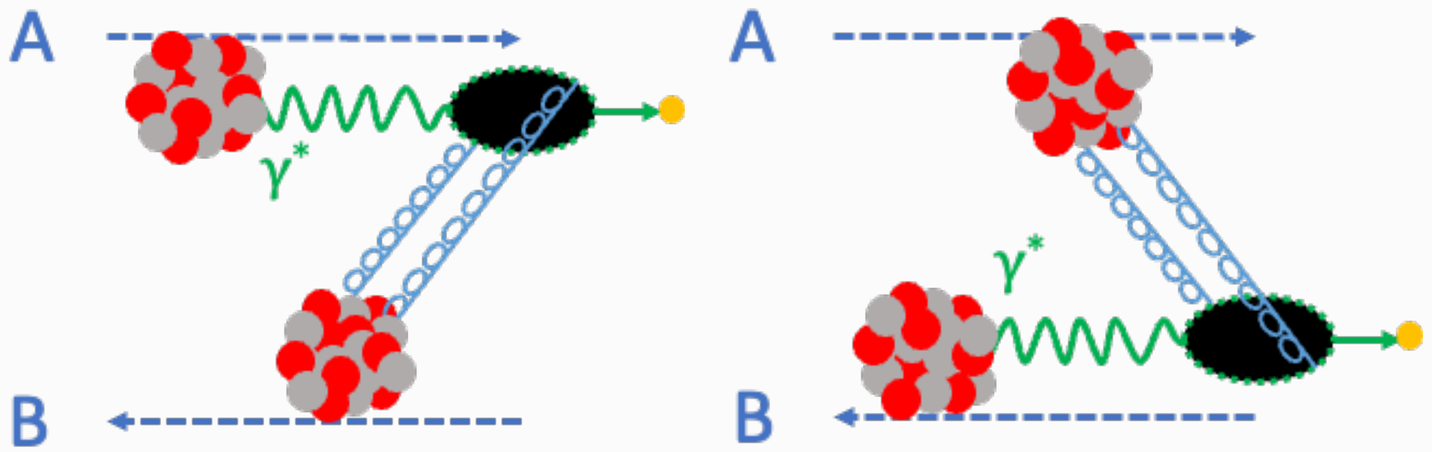


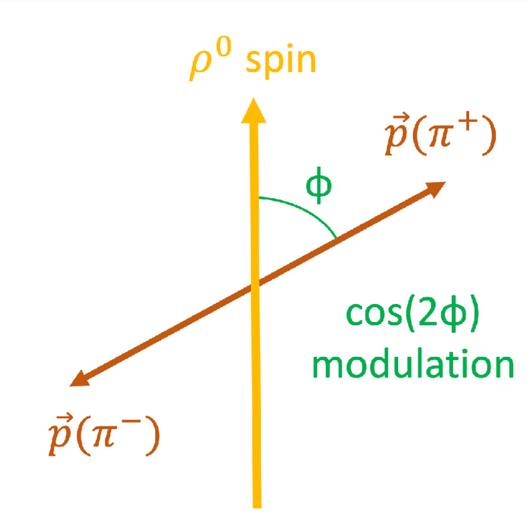
NEW on arXiv
arXiv:2404.07542

- Fully corrected invariant mass distribution of coherently produced four pions fits to two different scenarios:
  - Single Breit-Wigner resonance
  - **Two interfering resonances with a mixing angle favored**

Quantum interference of coherent photoproduction

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

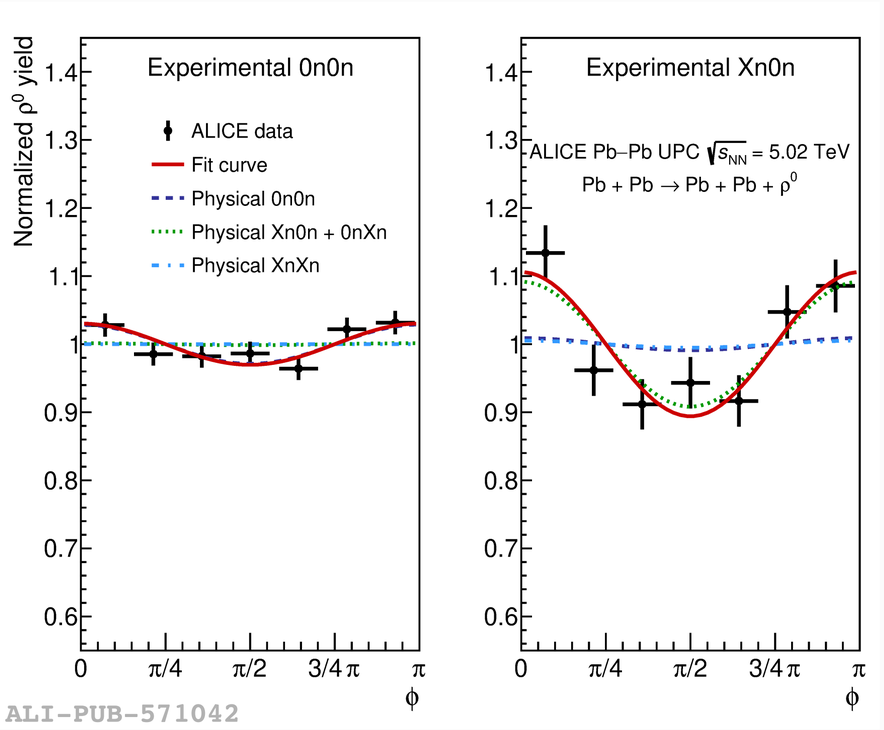


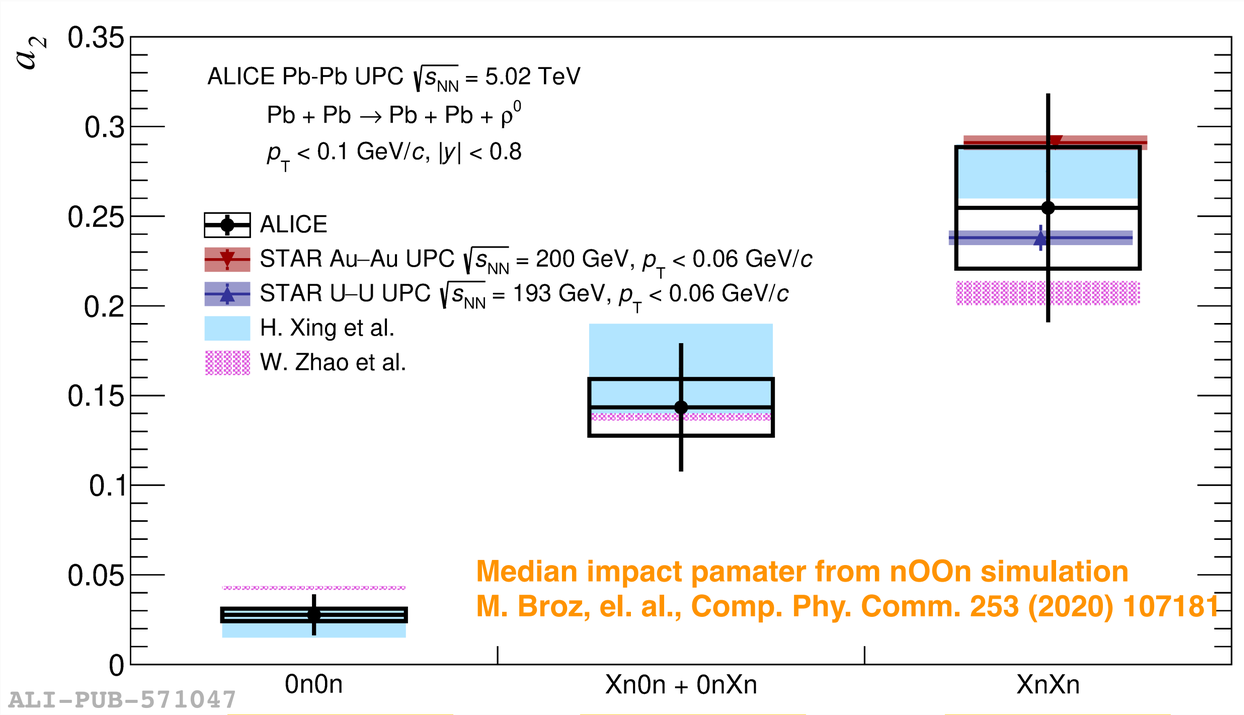


- Photons from Lorentz boosted nuclei are fully linearly polarized along the impact parameter
  - ➡ Polarization transferred to ρ^0
  - ➡ Azimuthal cos(2ϕ) modulation of decay products in the momentum distribution w.r.t. the polarization direction (orbital angular momentum conservation)
- Interference 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

Impact parameter dependent angular anisotropy of $\rho(770) \rightarrow \pi^+\pi^-$

arXiv:2405.14525 (accepted by PLB)



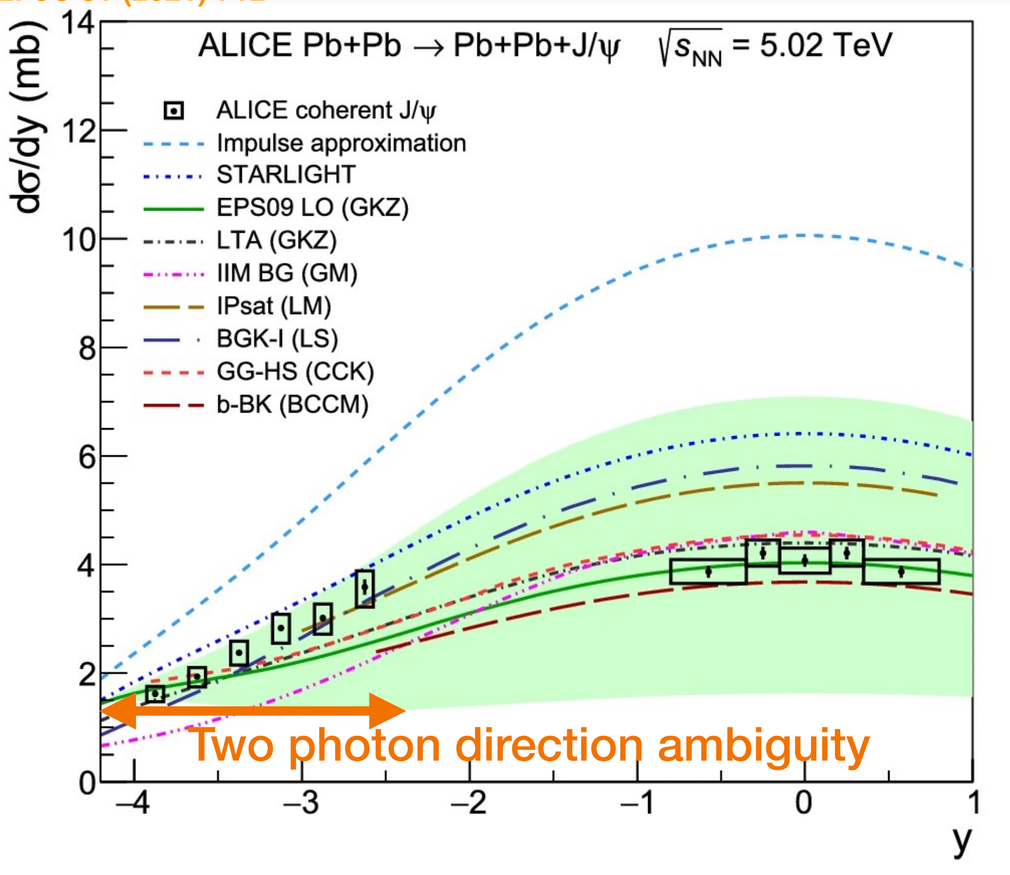


b **~ 49 fm** | ***b*** **~ 23 fm** | ***b*** **~ 19 fm**

- 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

J/ψ photoproduction in ALICE: region of moderate shadowing

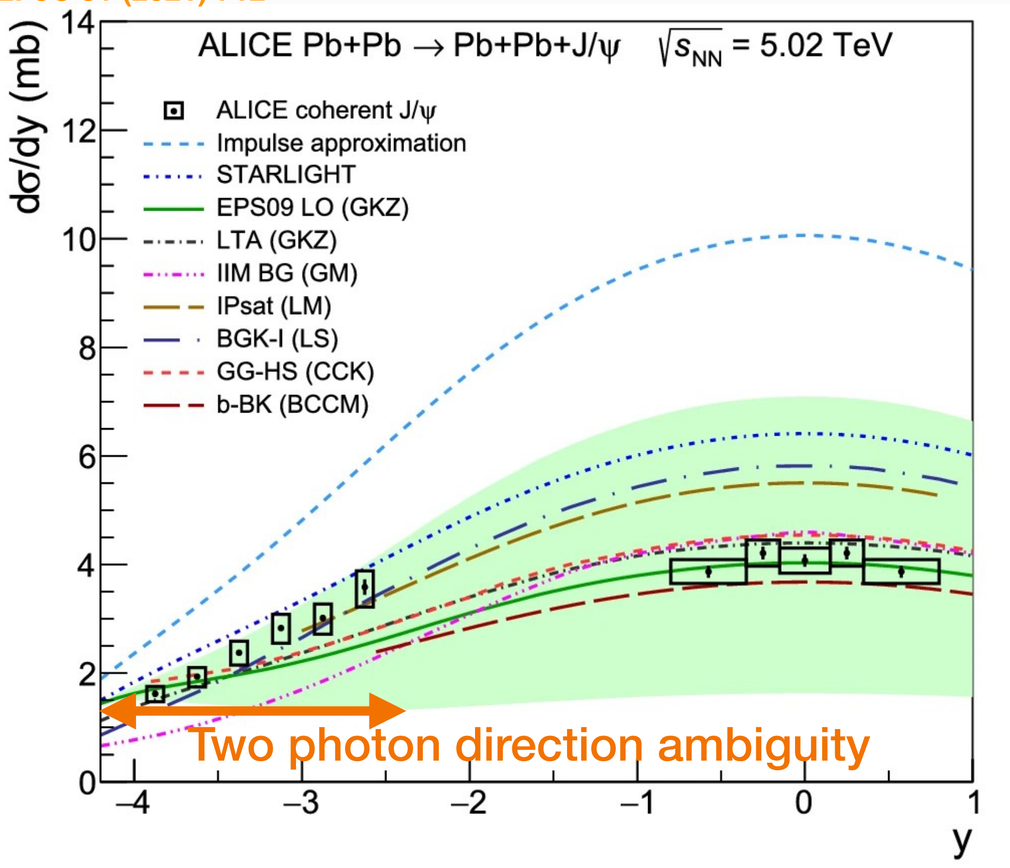
EPJC 81 (2021) 712



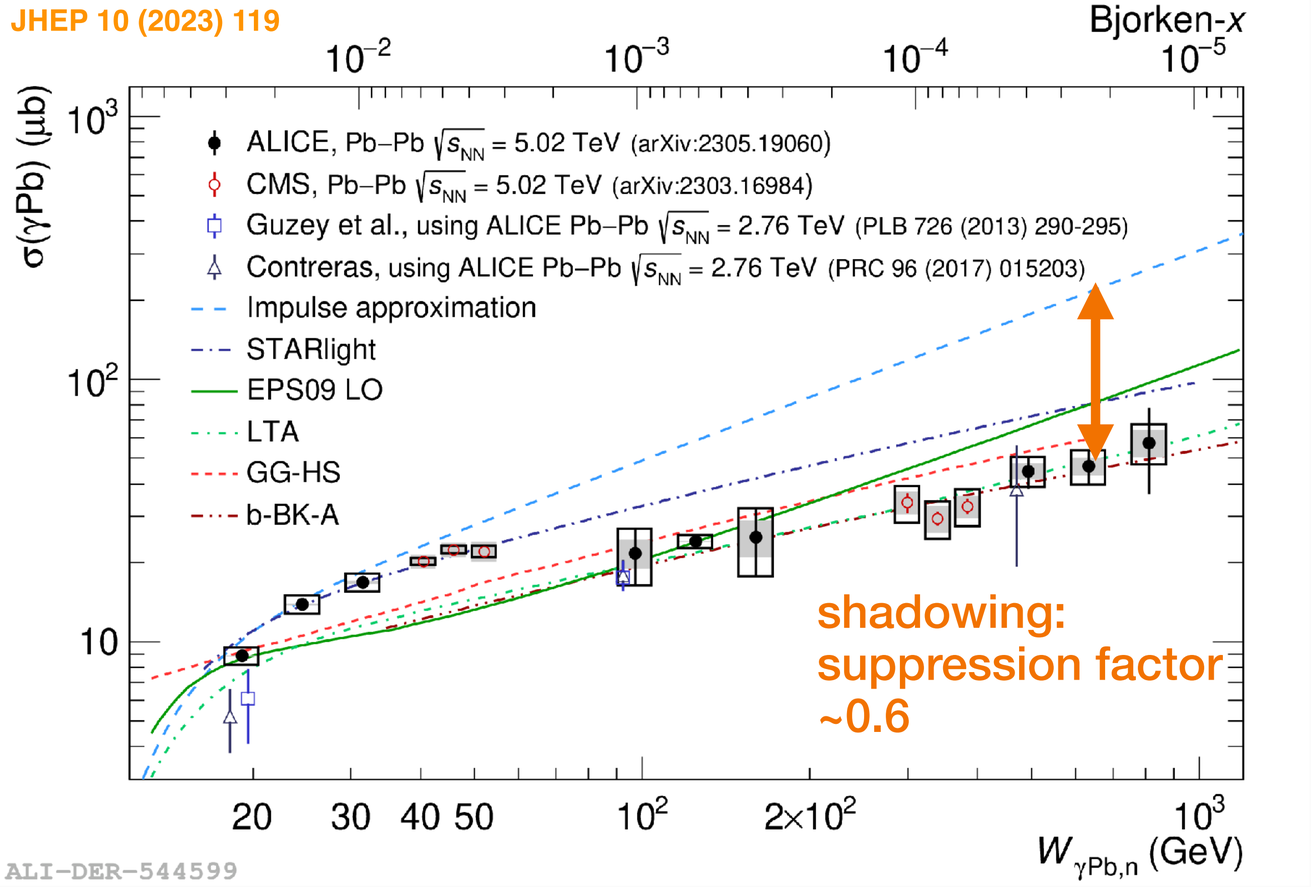
- Midrapidity: $x \in (0.3, 1.4) \times 10^{-3}$, compatible with models predicting moderate shadowing

J/ψ photoproduction in ALICE: region of moderate shadowing

EPJC 81 (2021) 712

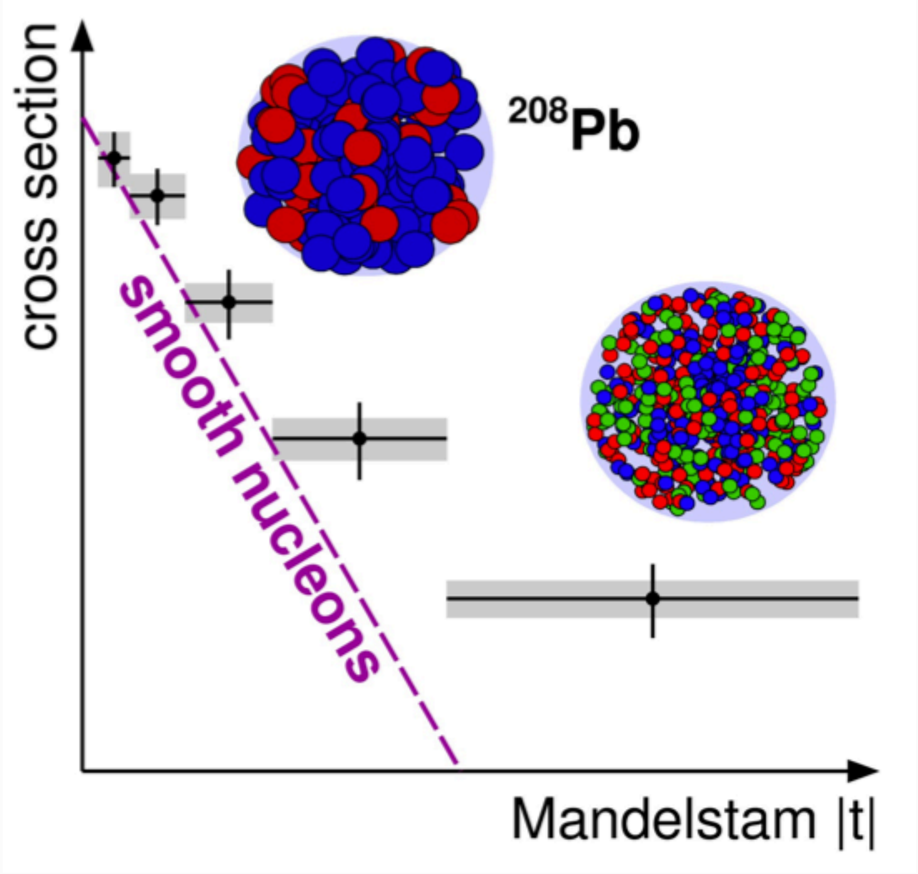


JHEP 10 (2023) 119

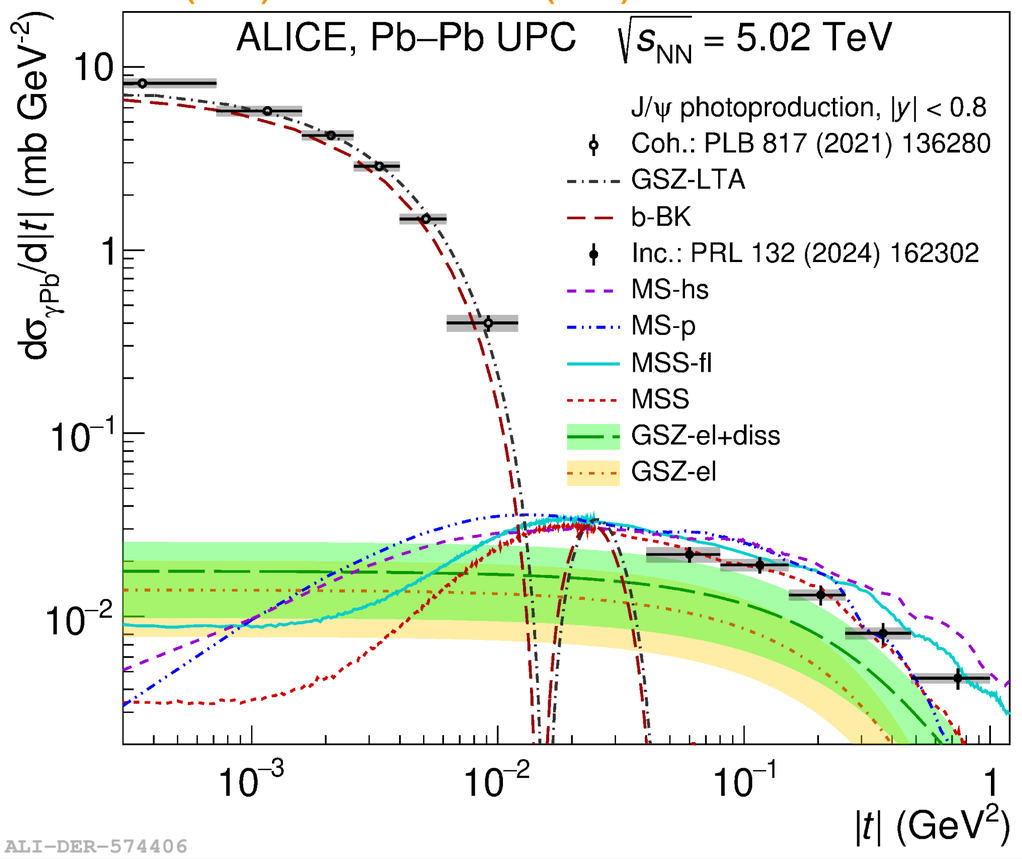


- Midrapidity: $x \in (0.3, 1.4) \times 10^{-3}$, compatible with models predicting moderate shadowing
- No single model describes measured cross section in full range of center of mass energy (Bjorken x)
- Lower-x better described with models including saturation while Glauber calculation works better in higher-x

Imaging the nucleus with photoproduced J/ψ

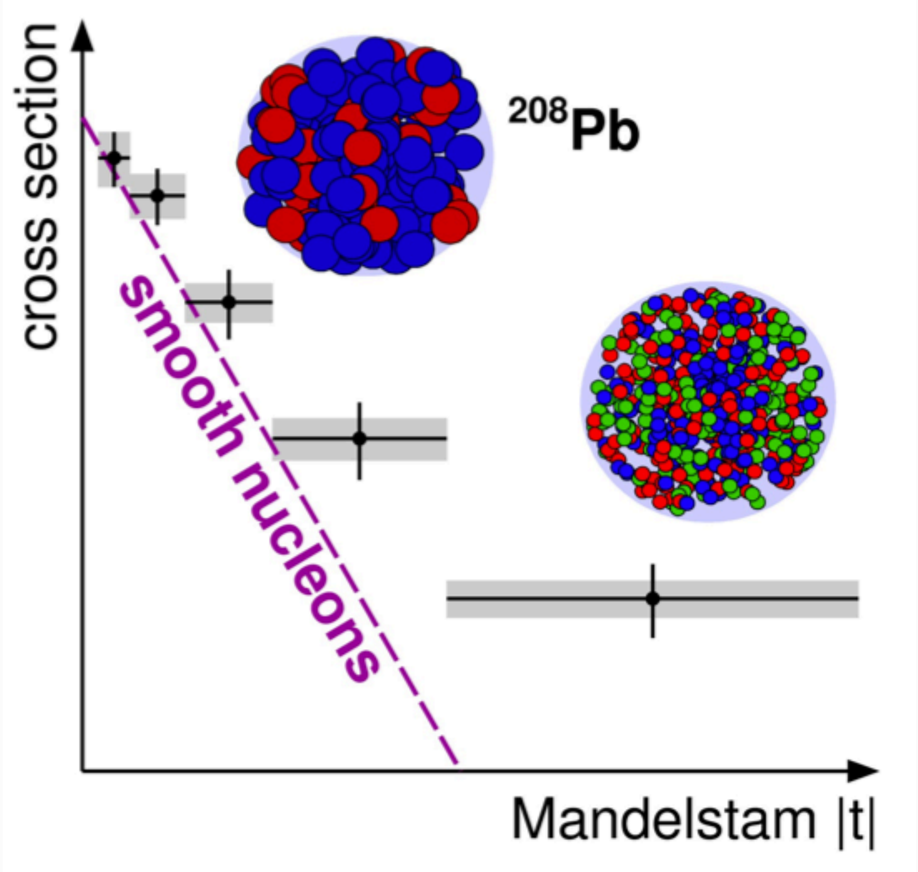


PLB 817 (2021) 136280 PRL 132 (2024) 162302

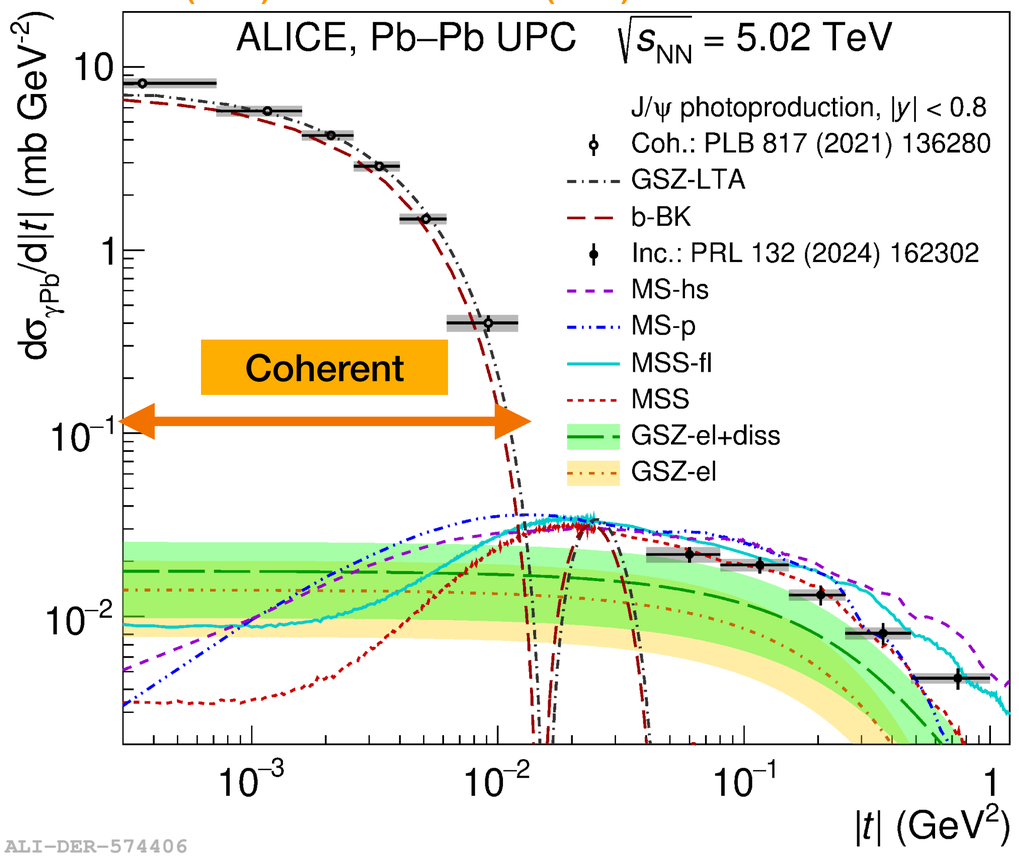


- Impact parameter *b* and the p_T of VM are Fourier conjugates
  → $\mathrm{d}\sigma/\mathrm{d}\,|\,t\,|$ probes transverse interaction density F(*b*)
- $|\mathrm{d}\sigma/\mathrm{d}\,|\,t\,|$ is sensitive to various scales of the nuclear structure, depending on the |*t*| range.

Imaging the nucleus with photoproduced J/ψ

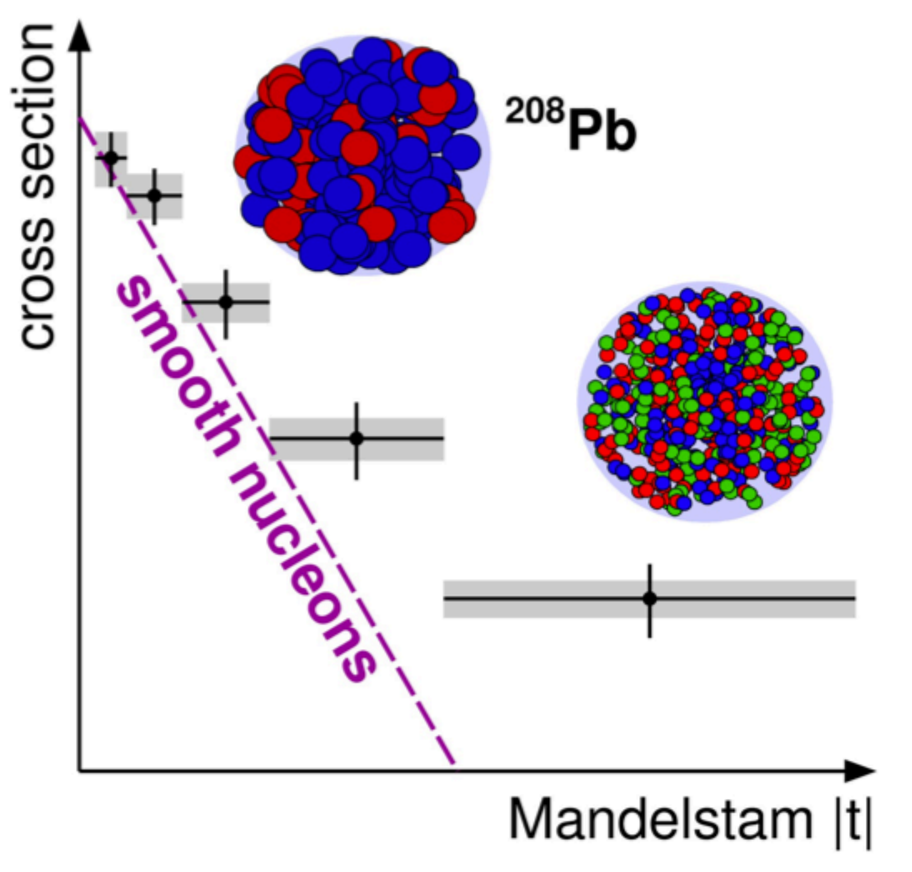


PLB 817 (2021) 136280 PRL 132 (2024) 162302

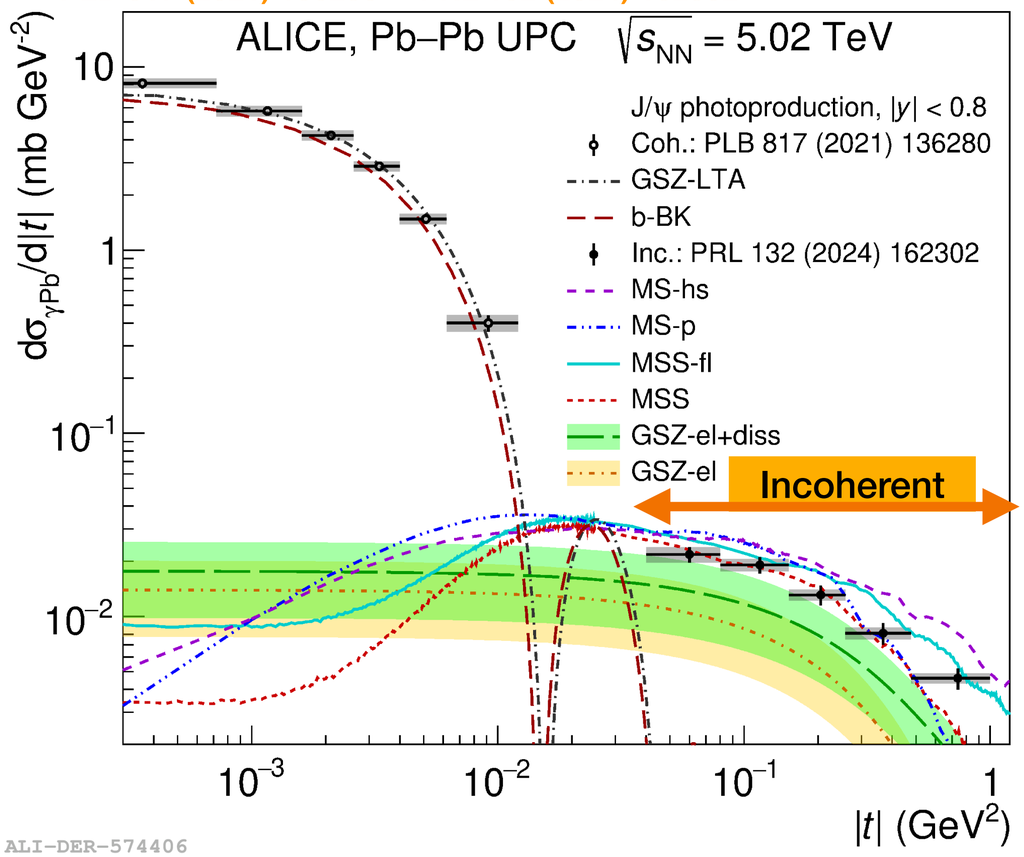


- **Small-|t| coherent production: photon interacts with the whole nucleus sensitive to the average of the gluon spatial distribution in the transverse plane**
- **Slope and magnitude better described by models including QCD dynamical effects in the form of shadowing (LTA) or saturation (b-BK) than Pb nuclear form factor**

Imaging the nucleus with photoproduced J/ψ

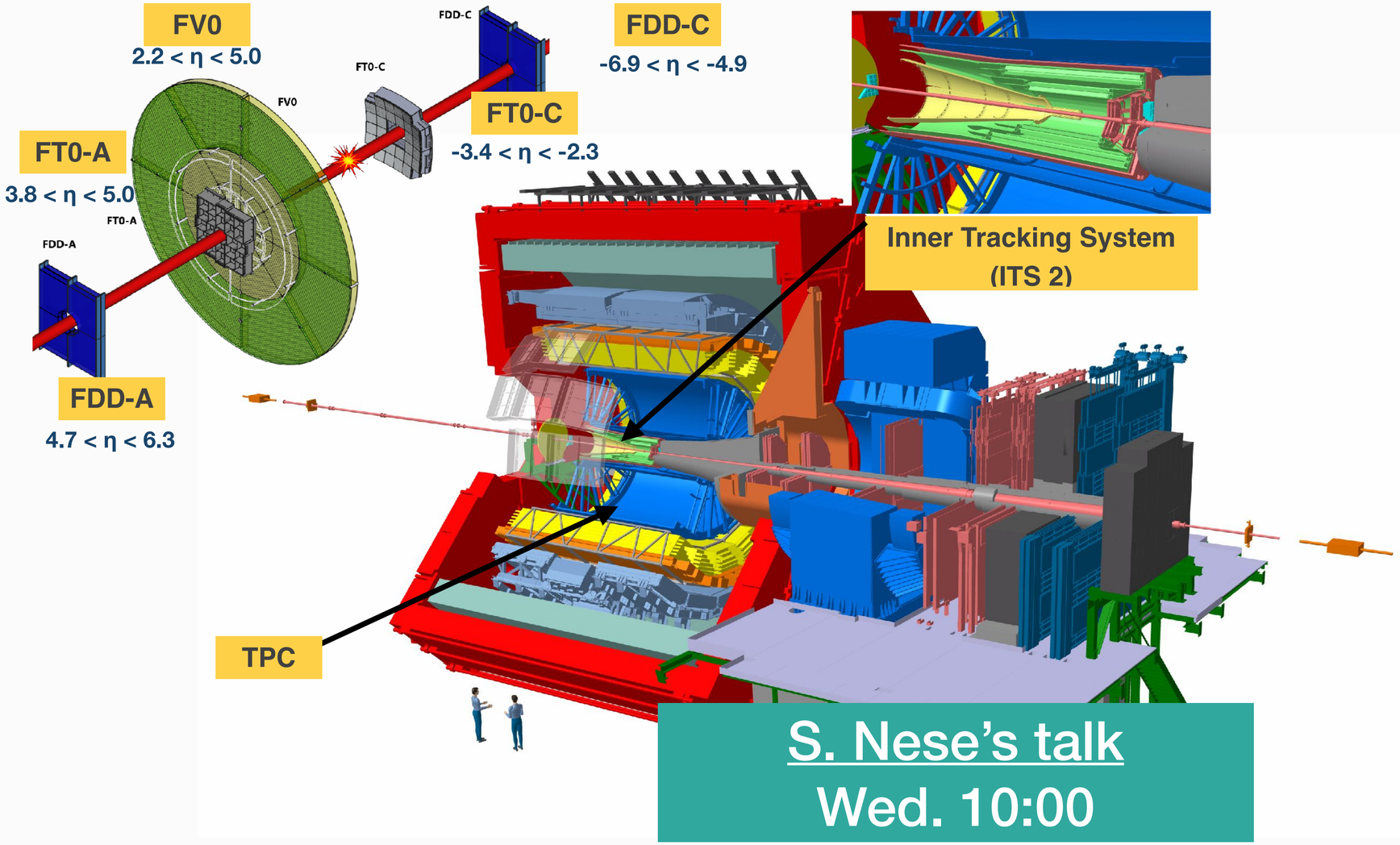


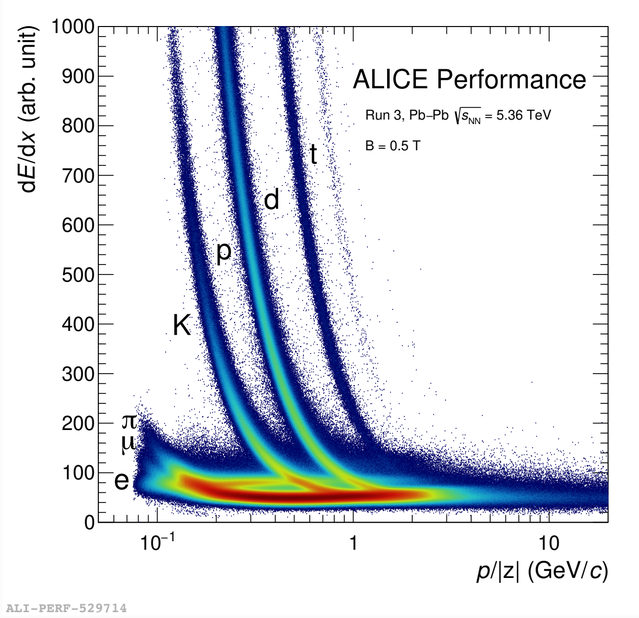
PLB 817 (2021) 136280 PRL 132 (2024) 162302

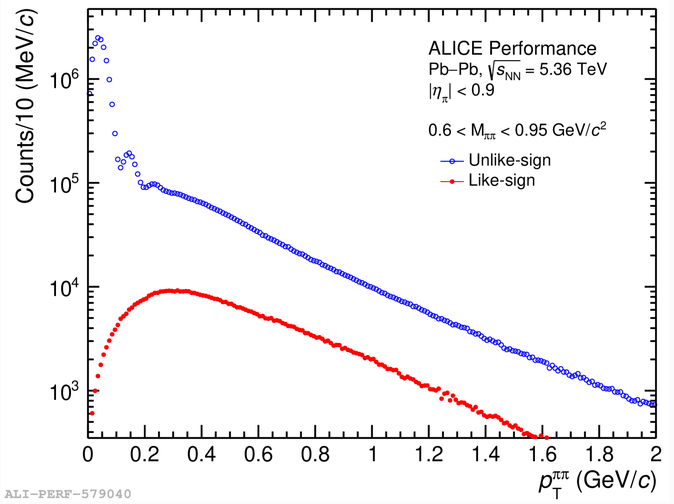


- **Large-|t| Incoherent production: photon interacts with single nucleon/subnucleonic structure**
- **Slope better described by models including subnucleonic degree of freedom; target likely to be lumpy structure than smooth nucleons**

ALICE as photon-hadron collider experiment in Run 3



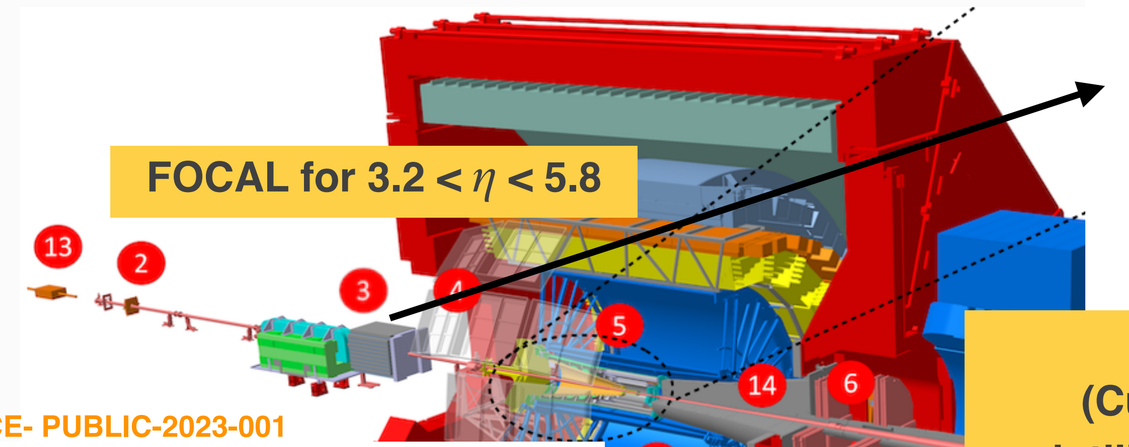


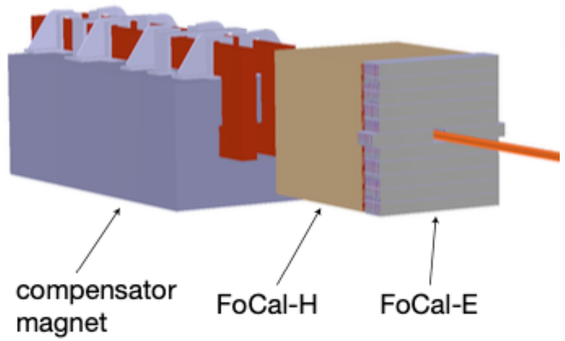


S. Nese's talk
Wed. 10:00

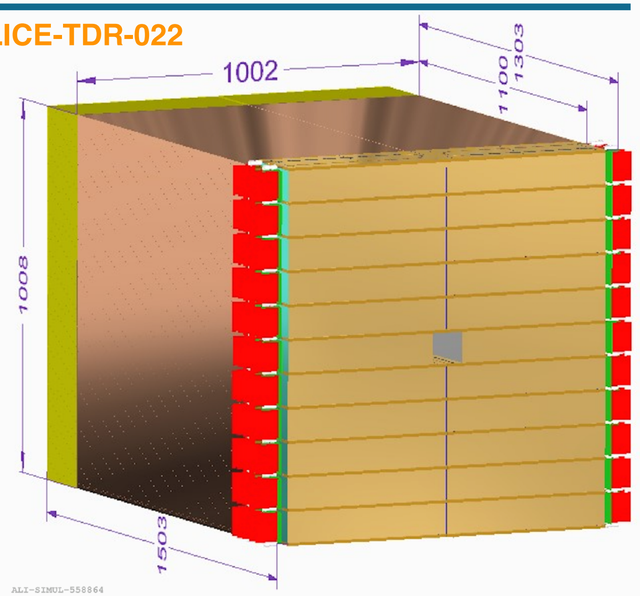
ALICE as photon-hadron collider experiment in Run 4

FOCAL for $3.2 < \eta < 5.8$



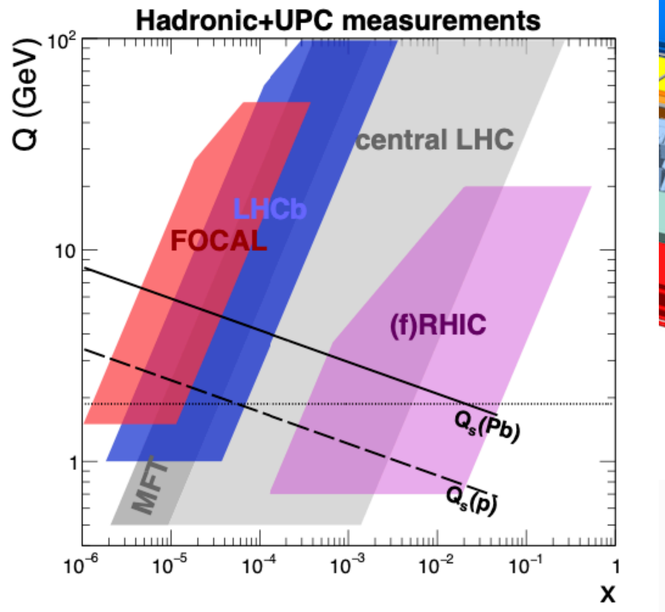


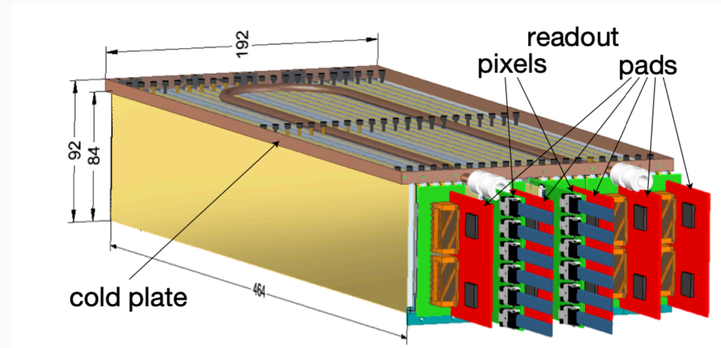
ALICE-TDR-022



FOCAL-H
(Cu capillary tubes filled with scintillating fibers w/ SiPMs readout)

ALICE- PUBLIC-2023-001





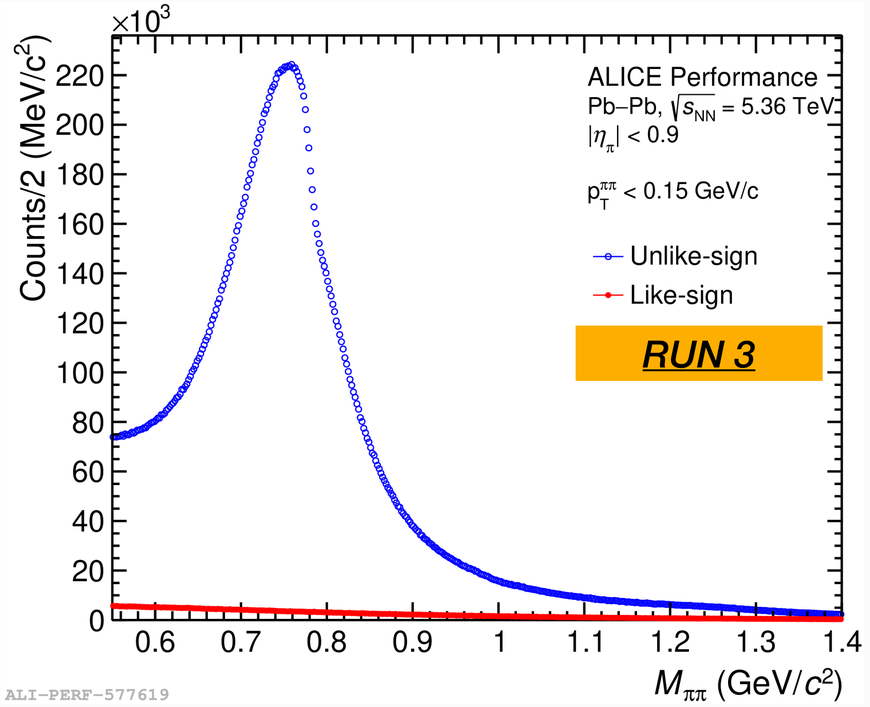
FOCAL-E modules
(Si-W EM calorimeter with hybrid Si readout technologies of pads and pixels)

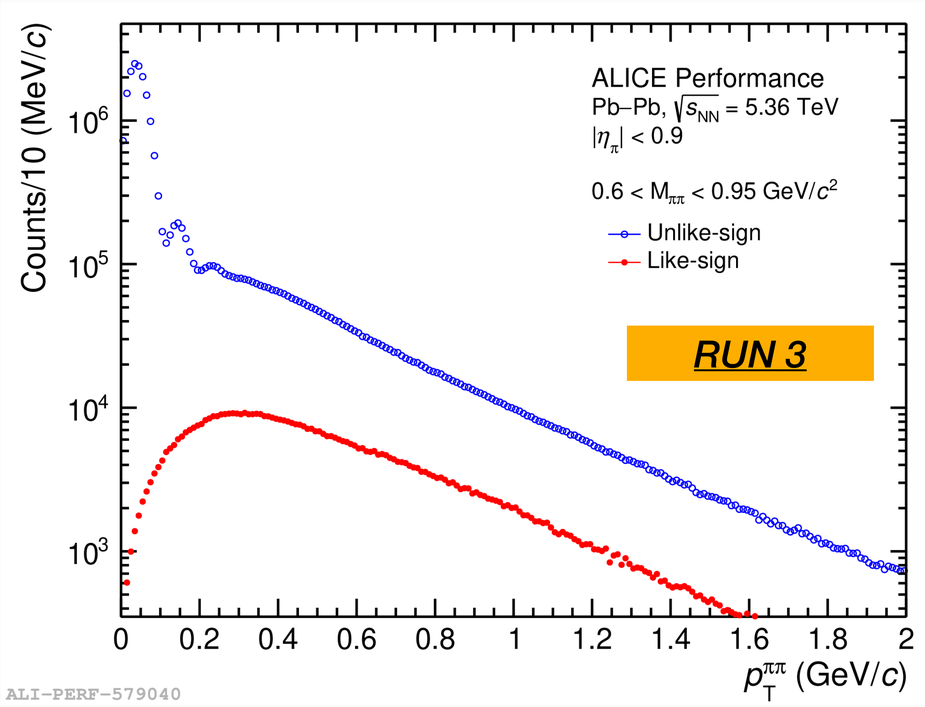
J. Otwinowski's talk: Tue. 16:15

Summary

- Various observables of vector meson 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
- ALICE is collecting **large data sample with upgraded detectors over LHC Run 3 campaign** and extend kinematic coverage **down to lower *x* is foreseen in Run 4** with ALICE FoCAL

STAY TUNED!!

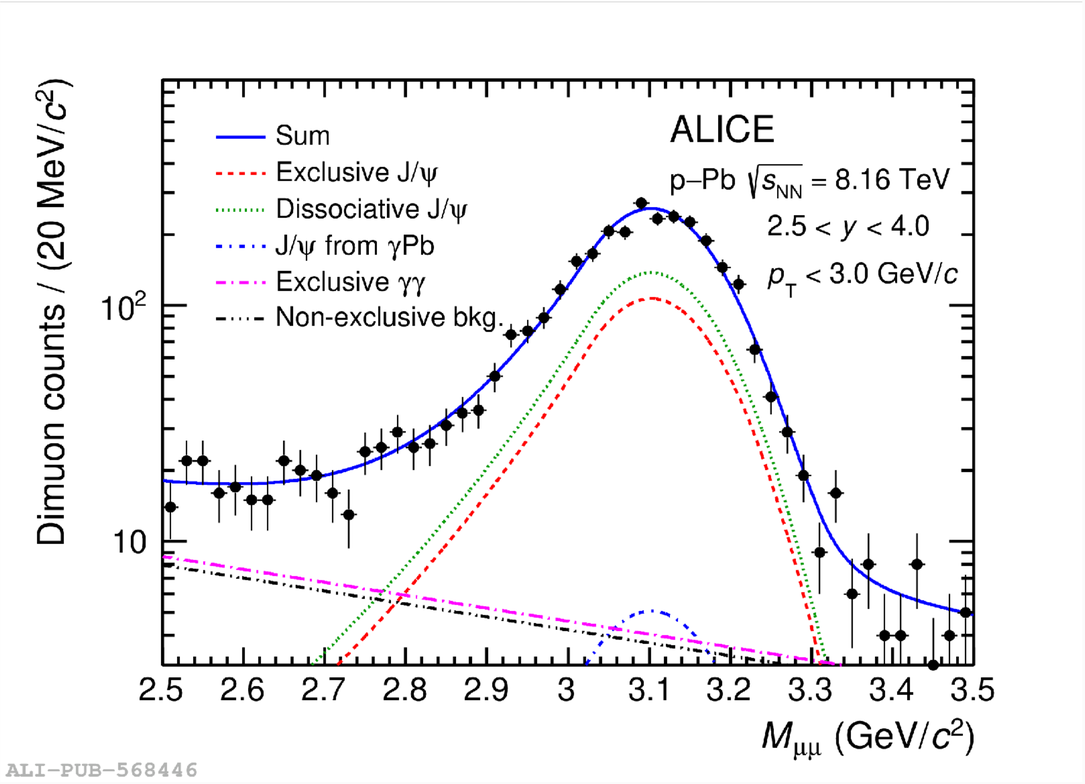


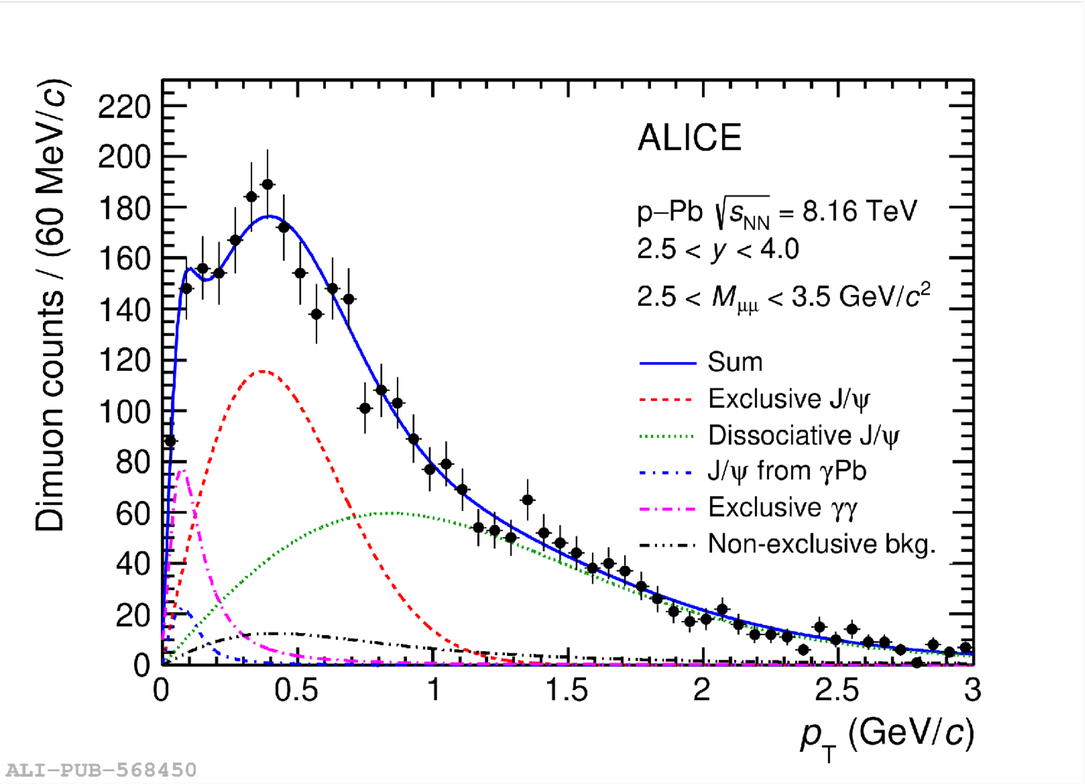


Backup

γp interaction with p-Pb collisions

ALICE Collaboration, PRD 108 (2023) 11, 112004

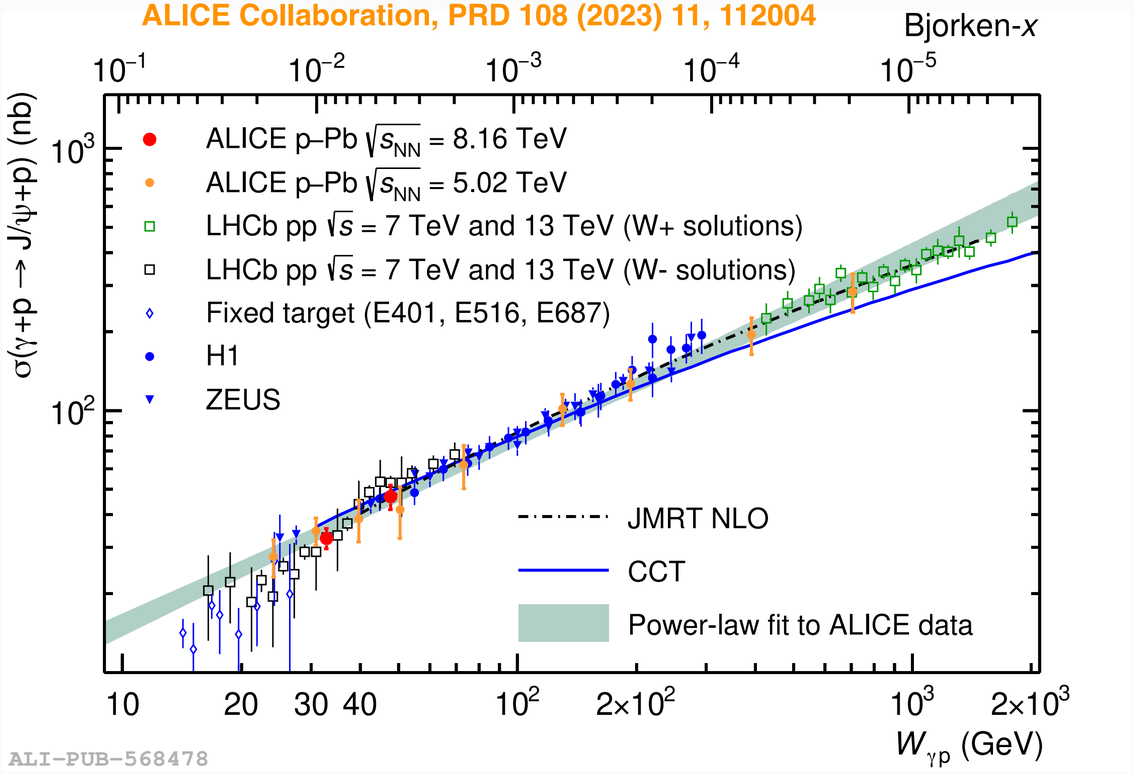


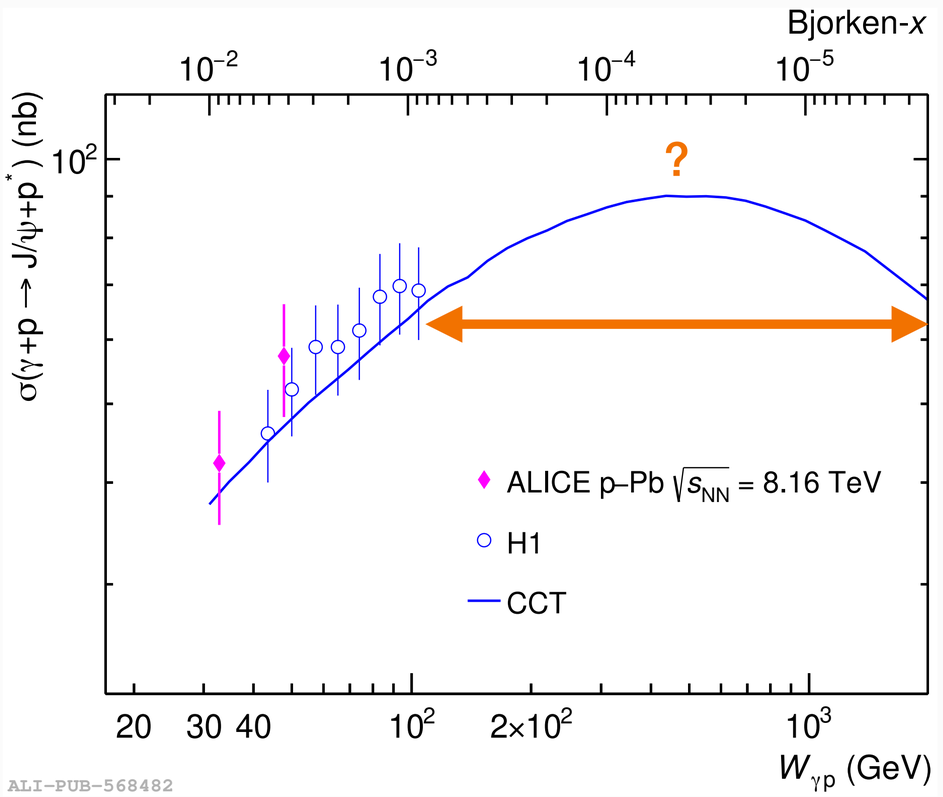


- Photon flux grows with the square of the charge, Z^2 → Pb-ion is photon-emitter in p-Pb collisions
- 2-D loglikelihood fit of mass and p_T to extract exclusive and dissociative (production with proton break up) contributions simultaneously

γp interaction with p-Pb collisions: Exclusive and dissociative J/ψ photoproduction

ALICE Collaboration, PRD 108 (2023) 11, 112004

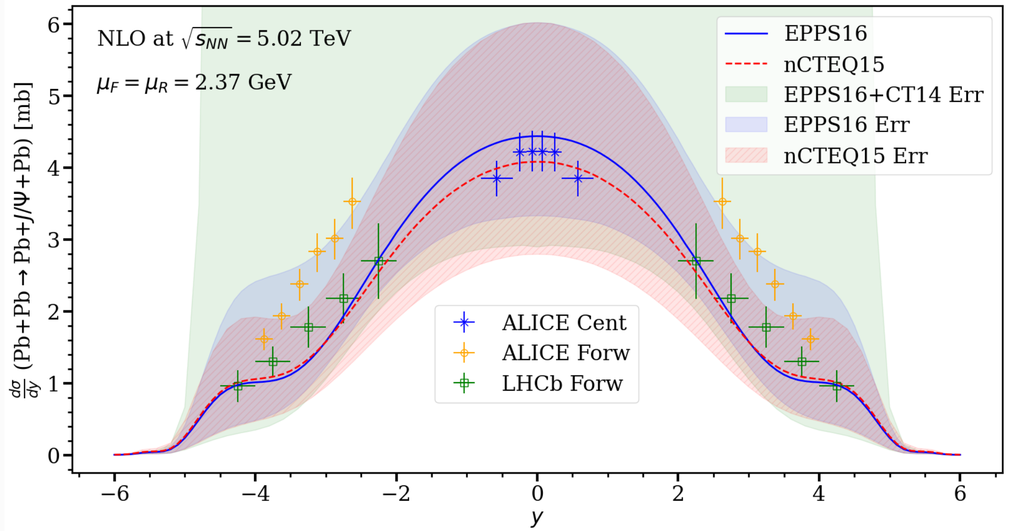


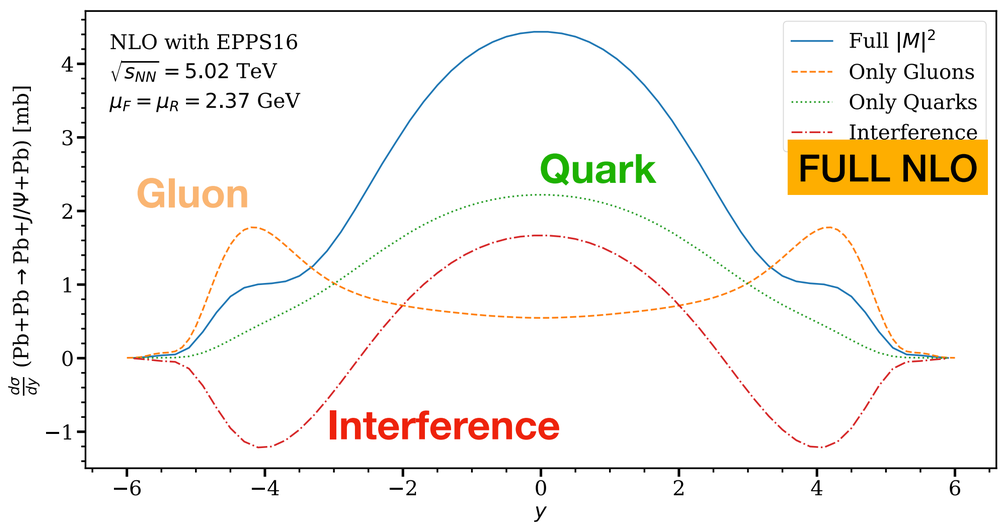


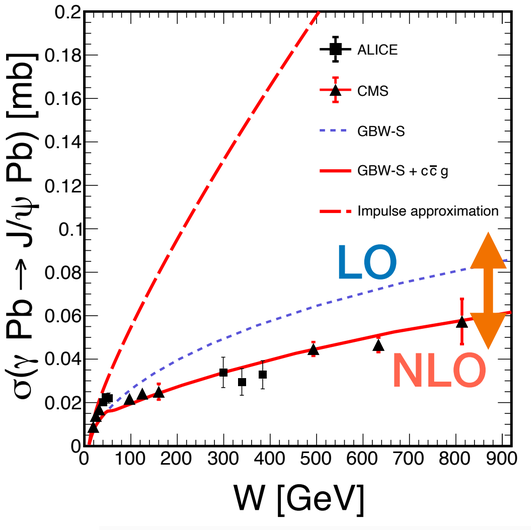
- Exclusive production cross section shows good agreement measurements from different experiments
- Cross section described by power-law mimicking the evolution of the gluon density
  → still far from the onset of saturation?
- First measurement of the dissociative cross section at the LHC, compatible with HERA measurements
- Models considering fluctuation of the subnucleonic structure in protons → homework for RUN 3 and Run 4

Do we understand all about J/ψ photoproduction?

K. J. Eskola et. al.,PRC 106 (2022) 035202







H. Mäntysaari, J. Penttala, PLB 823 (2021) 136723

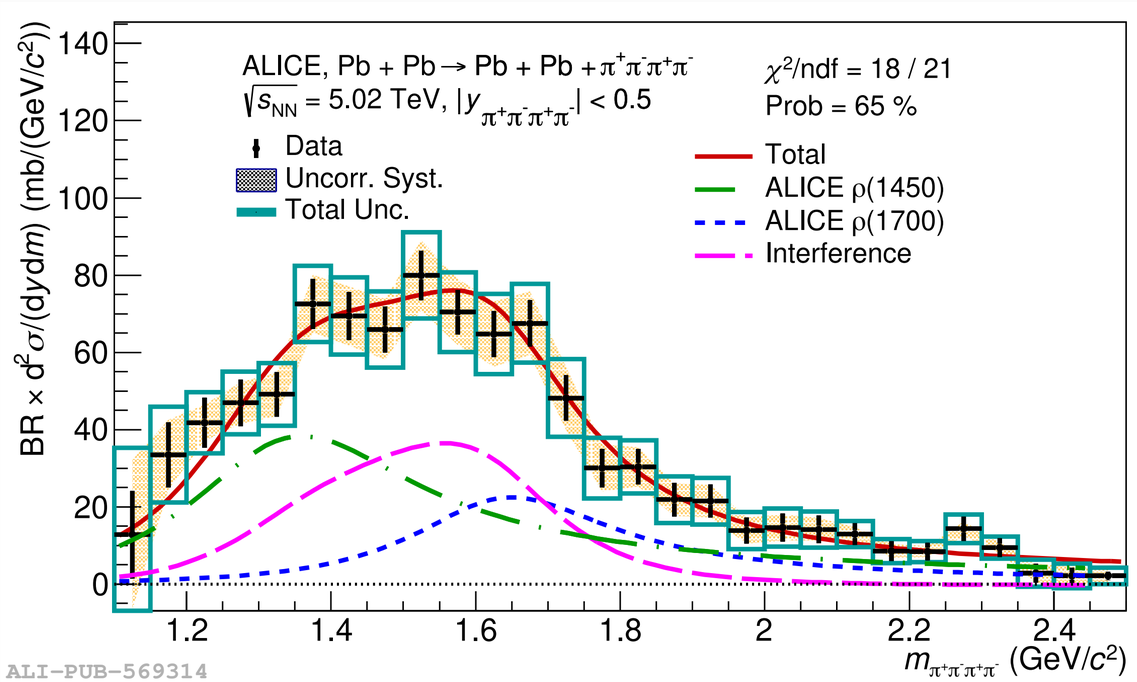
A. Łuszczak, W. Schäfer, PLB 856 (2024) 138917

- Tension between measurements and NLO pQCD calculation
- LO and NLO gluon amplitudes dominate over the NLO quark contribution, yet LO and NLO gluon amplitudes cancel to a large degree different quark/gluon density sensitivity than LO
- Sizable impact of NLO contribution in dipole picture, better describes the measurements

➡ Precision measurements from experiments + Theoretical developments required!

Exclusive four pion photoproduction

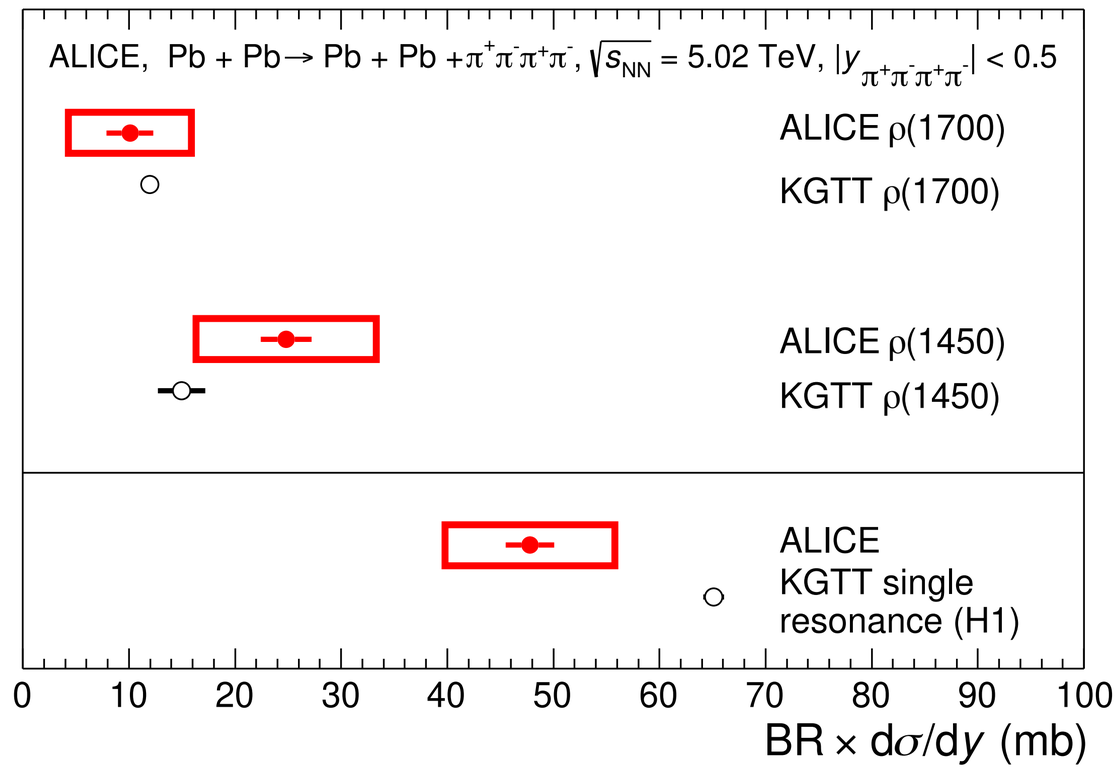
arXiv:2404.07542



	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



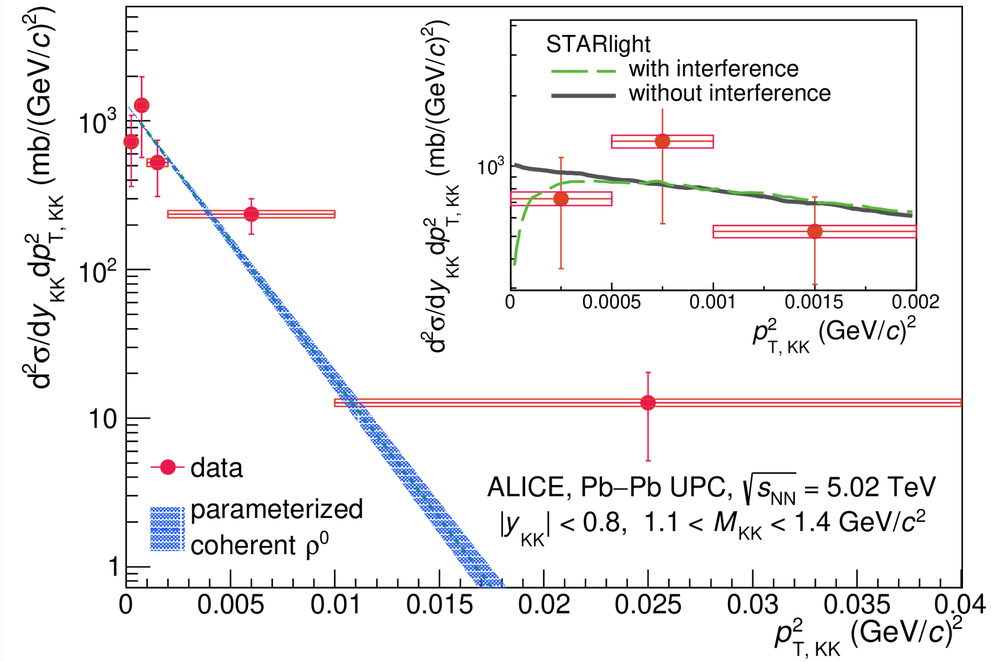
ALI-PUB-569269

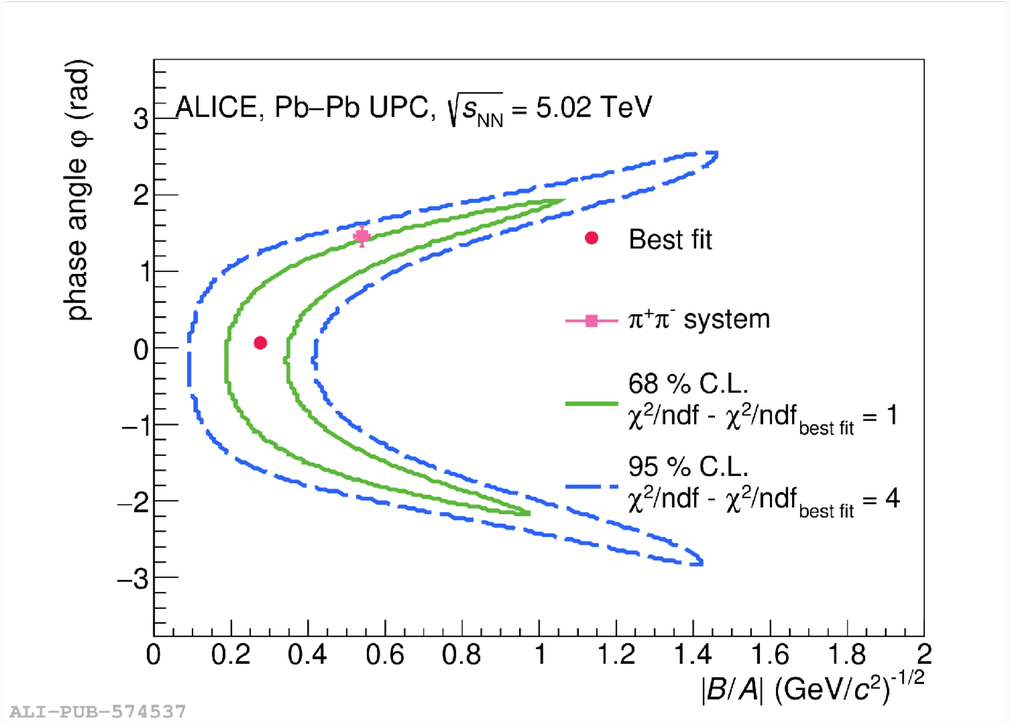
- The total cross section based on single resonance scenario, as well as two interfering $\rho(1450)$ and $\rho(1700)$ obtained
- Due to the large interference component, the sum of $\rho(1450)$ and $\rho(1700)$ cross sections is smaller than the total cross section
- The cross sections for $\rho(1450)$ 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

First access of K^+K^- photoproduction in UPCs

ALICE Collaboration, PRL 132, 222303 (2024)

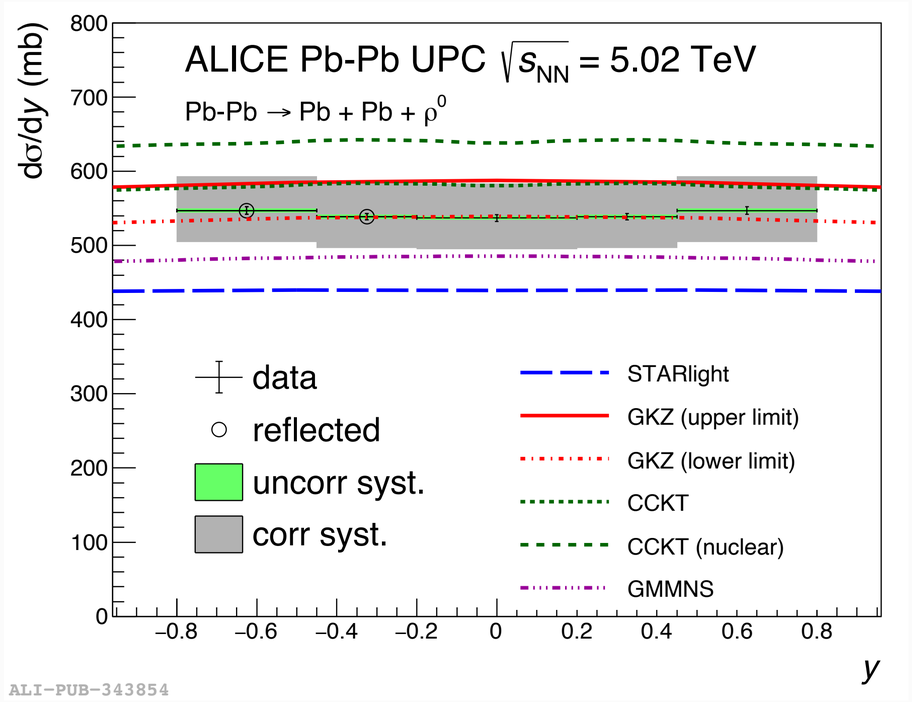




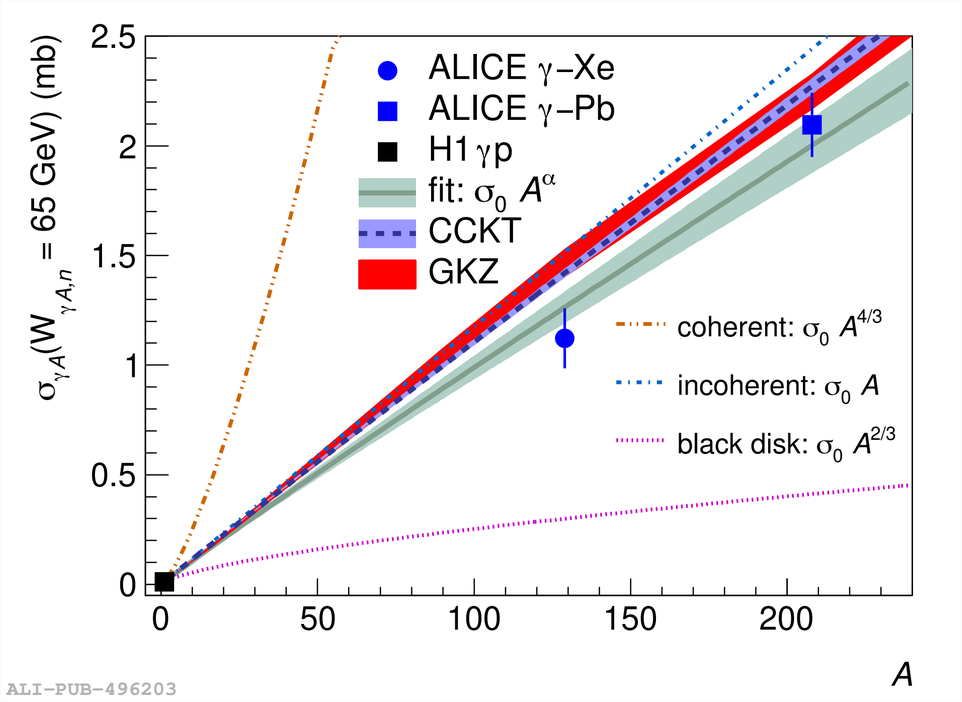
- Exclusive K^+K^- photoproduction as a function of $p_{\mathrm{T}}^2 \approx |t|$ fairly well described by $ae^{-b \times p_{\mathrm{T}}^2}$ with slope parameter b = 428±6 (stat.)±15 (syst.) GeV^{-2} taken from ALICE $\rho(770) \rightarrow \pi^+\pi^-$ results
- Cross section ratio ($|B/A|$) and relative phase angle (Φ) between $\phi(1020) \rightarrow K^+K^-$ and direct K^+K^- determined with Söding formula similar → non-resonant contribution to $\pi^+\pi^-$ system

Coherent $\rho^0(770)$ photoproduction

ALICE Collaboration, JHEP 06 (2020) 035



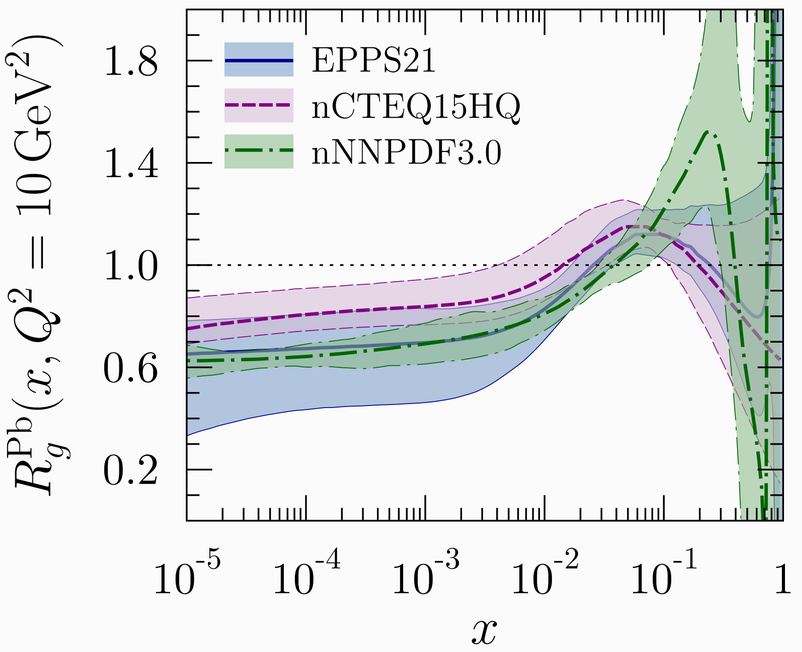
ALICE Collaboration, PLB 820 (2021) 136481



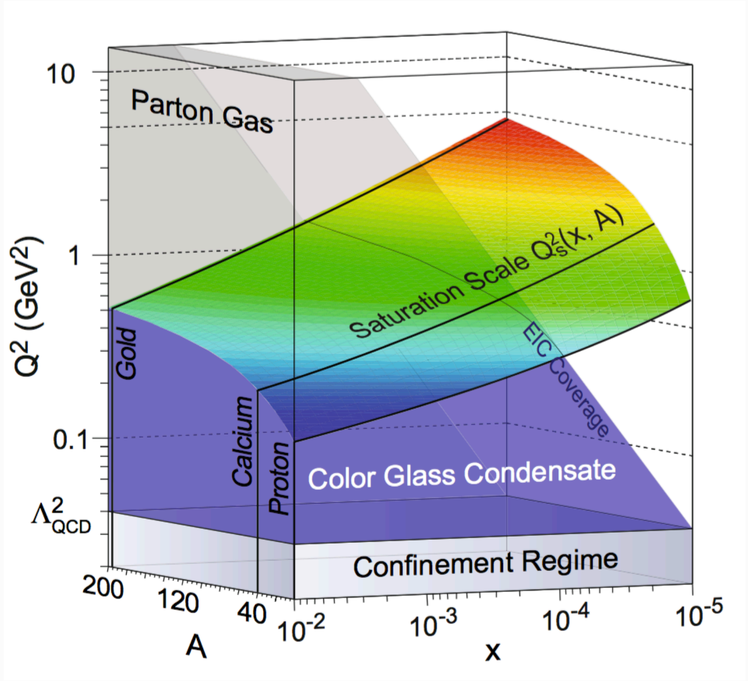
- Measured cross section of coherent photoproduction shows good agreement with model predictions for different neutron emission classes → similarly favored in colour-dipole approach with gluon saturation/hot spots or Gribov-Glauber shadowing approach
- Atomic number (*A*) dependent *γA* cross section,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

Probing the nucleus and nucleons

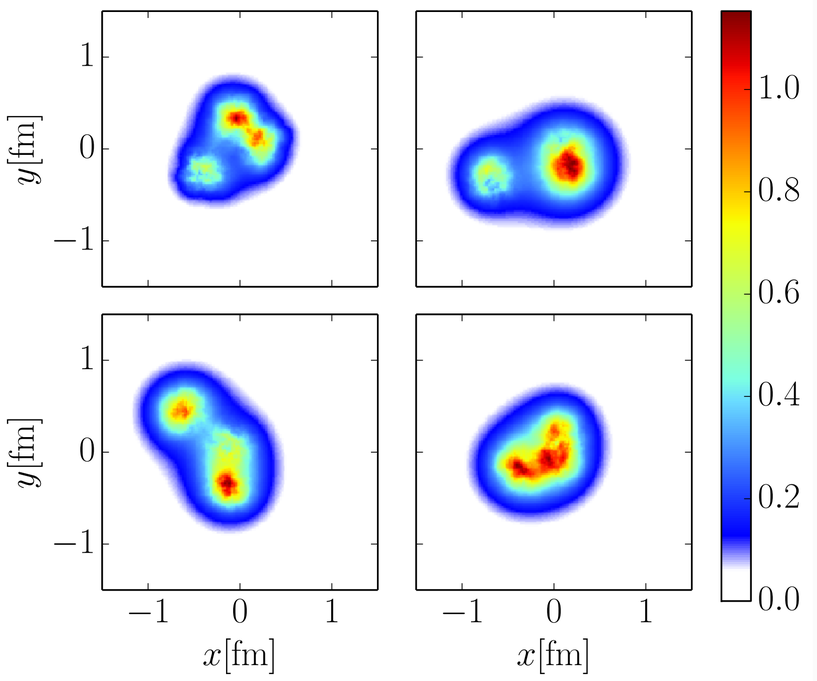
M. Klasen, H. Paukkunen
Ann. Rev. Nucl. Part. Sci. 102122-022747



Accardi et. al, EPJA 52 (2016) 268



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



- Nucleus gluon field is not simple superposition of A nucleon fields
- More fundamental questions:
  - Where and how does the transition from a dilute parton system to a dense gluon regime state occur?
  - How nucleus and nucleons fluctuate and what would be the impact?