Exclusive four pion photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at ALICE

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On behalf of the ALICE Collaboration

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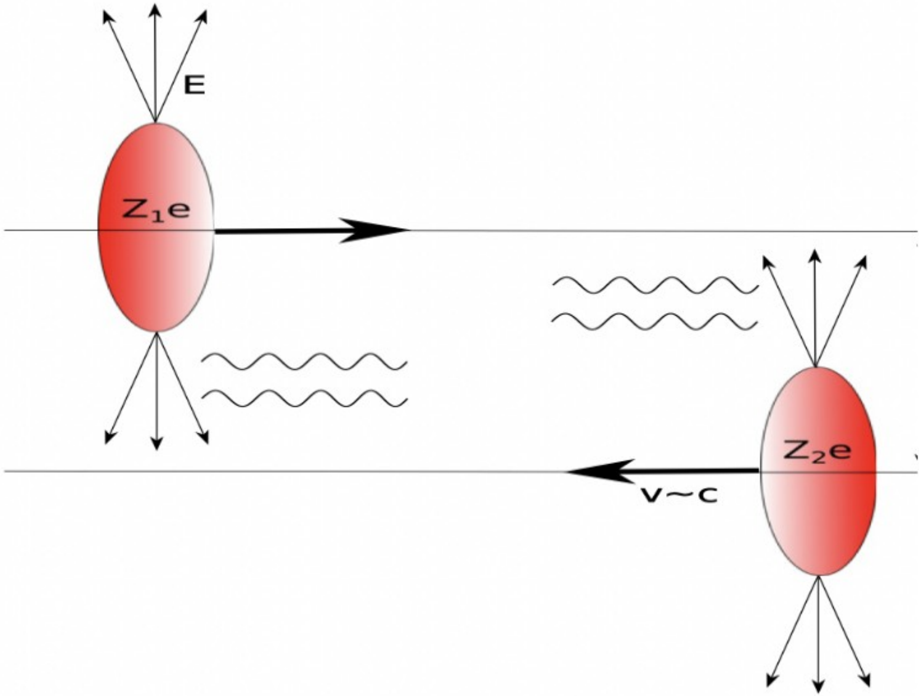
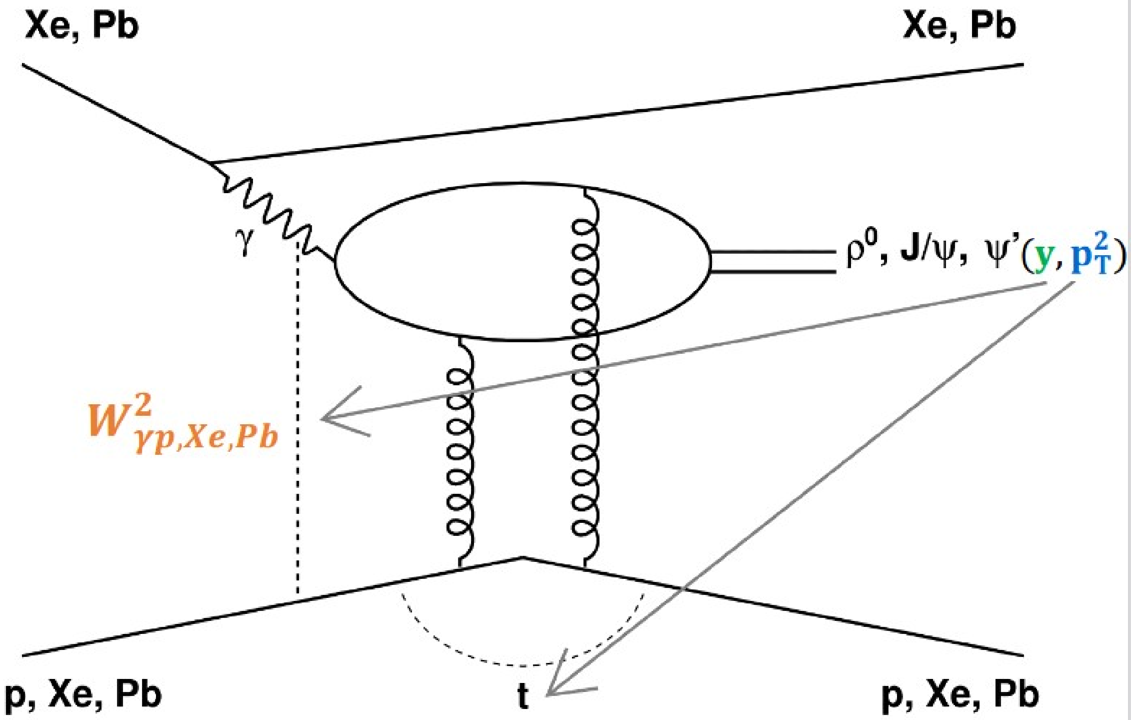
Outline

- Motivation
- ALICE detector
- Exclusive four-pion production
  - Breit-Wigner fits to the invariant mass distribution
  - Cross section extraction
- Summary

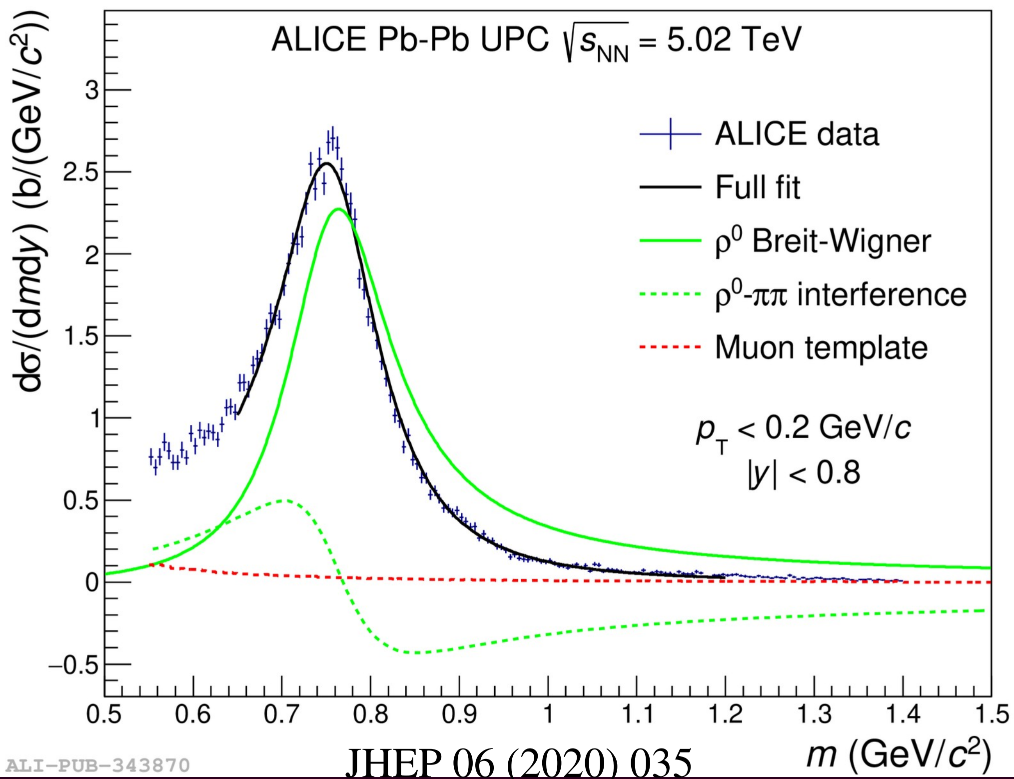
Photon induced processes in heavy ion collisions

- Ultrarelativistic moving nuclei produce strong electromagnetic fields that can be treated as a quasi-real photon flux

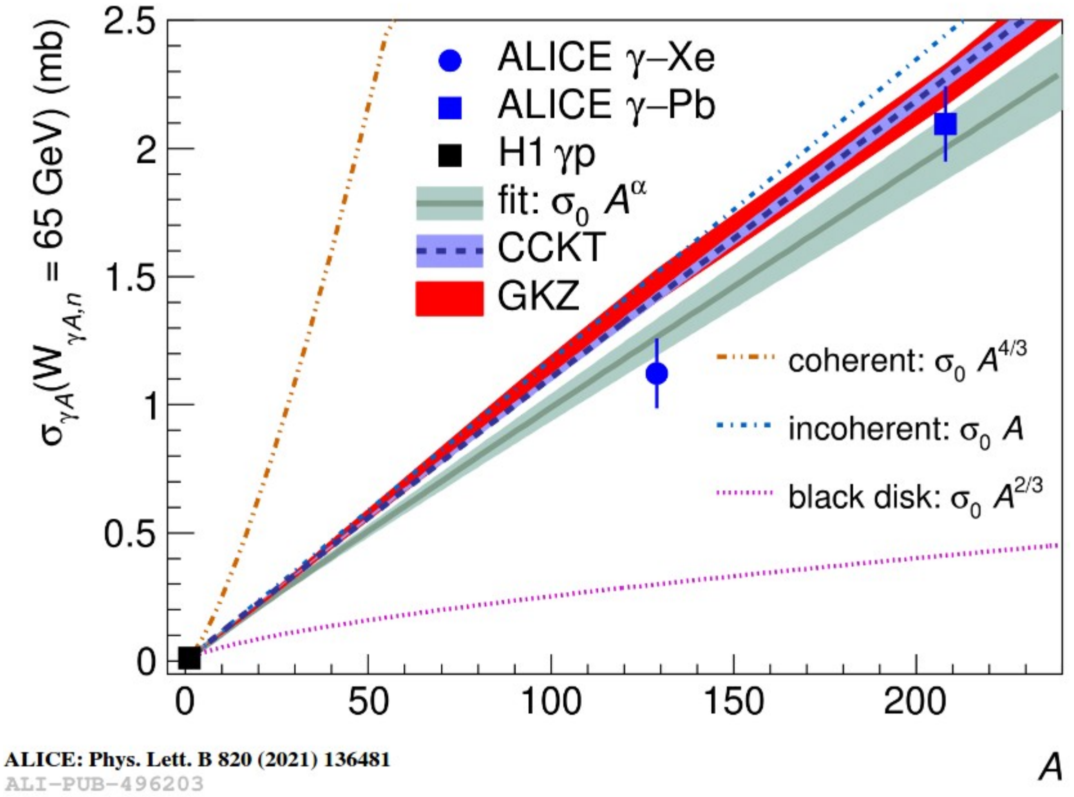




Coherent $\rho^0(770)$ photoproduction in Pb–Pb and Xe–Xe



JHEP 06 (2020) 035

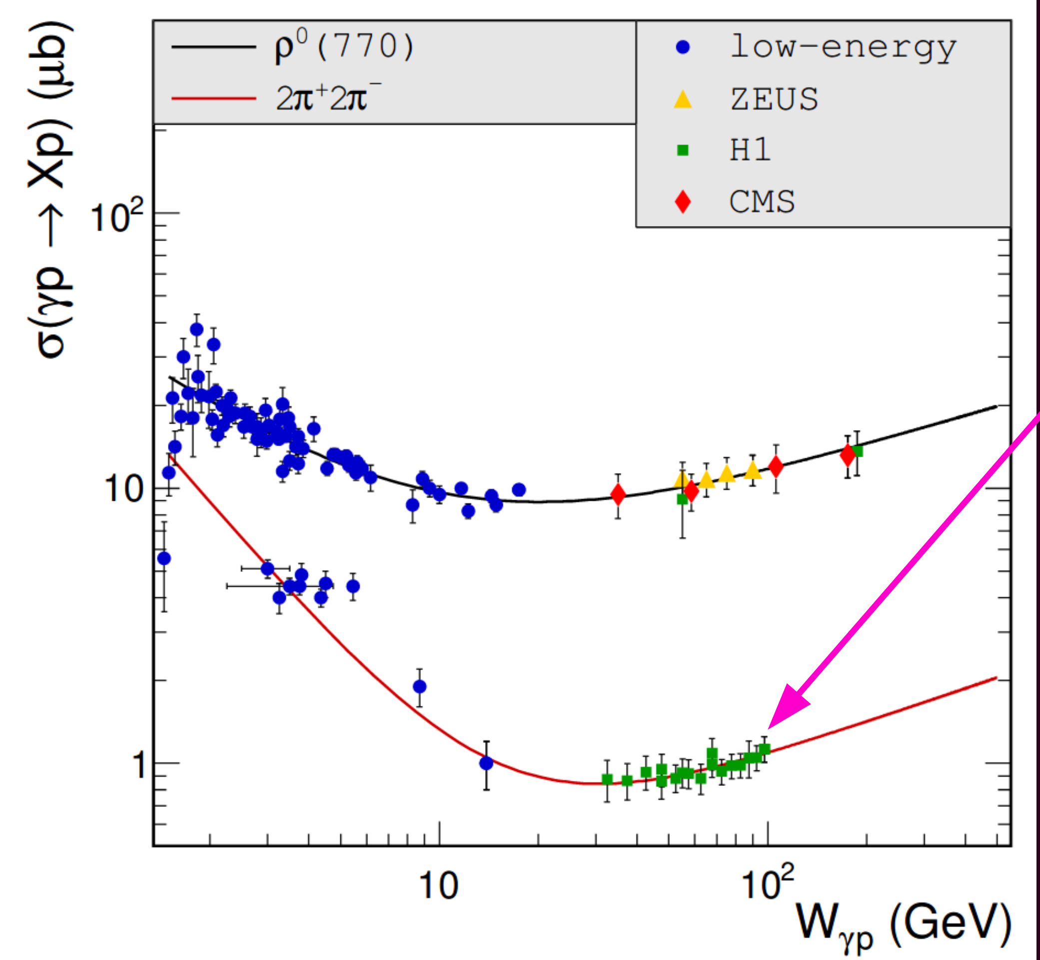


ALICE: Phys. Lett. B 820 (2021) 136481

$\rho^0(770)$ is a great tool to study the nuclear structure!

It has been also extensively studied in p–Pb UPCs by CMS and in ep by H1 and ZEUS.

Excited ρ photoproduction



ρ^0(770) photoproduction has been studied in p–Pb UPCs by CMS, in ep by H1 and ZEUS, in Pb–Pb and Xe-Xe UPCs by ALICE and in Au–Au UPCs by STAR.

As for other VMs one can expect that an excited state of the ρ^0 should also exist.

However, the mass and the width of this resonance are rather poorly measured.

Theory curve for excited ρ from M. Klusek and D. Tapia Takaki Acta Phys. Polon. B 51 (2020) 6, 1393

Excited ρ states: High-mass two-pion final state

Not much is known about excited ρ:

- PDG lists ρ(1450), ρ(1700), ρ_3(1690)
- All of them can decay into 2 or 4 pions.

ALICE and STAR searched for it in 2-pion decay channel:

ρ(1450) $I^G(J^{PC}) = 1^+(1^{--})$

See the review on "Spectroscopy of Light Meson Resonances."

Mass $m = 1465 \pm 25$ MeV [i]

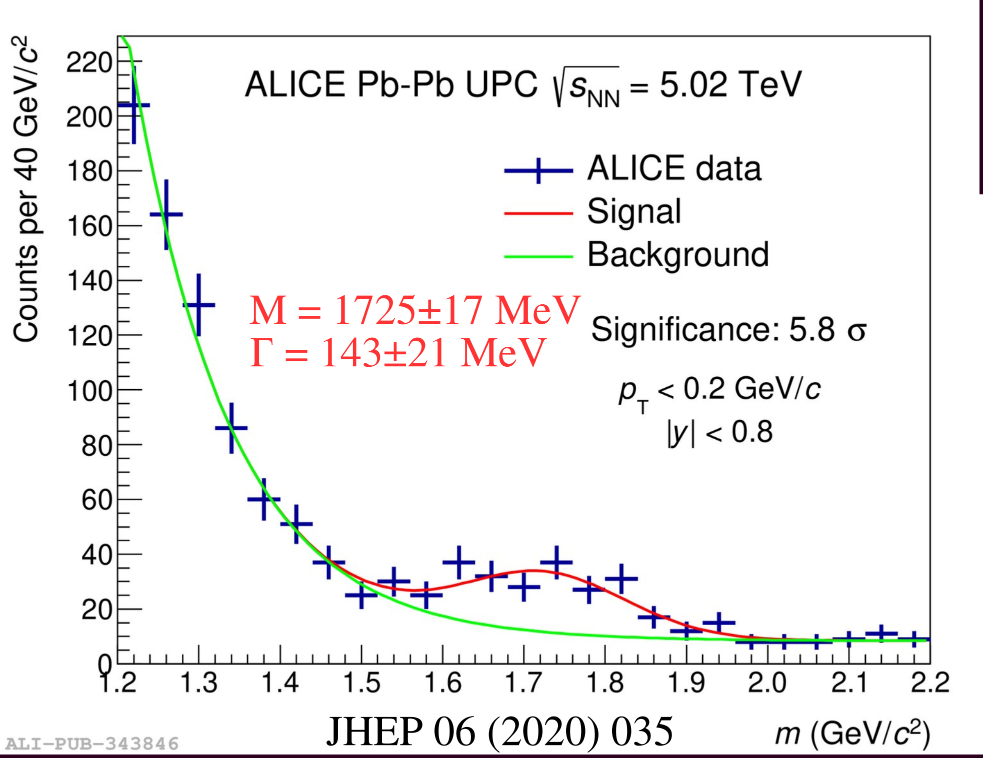
Full width $\Gamma = 400 \pm 60$ MeV [i]

ρ(1700) $I^G(J^{PC}) = 1^+(1^{--})$

See the review on "Spectroscopy of Light Meson Resonances."

Mass $m = 1720 \pm 20$ MeV [i] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)

Full width $\Gamma = 250 \pm 100$ MeV [i] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)



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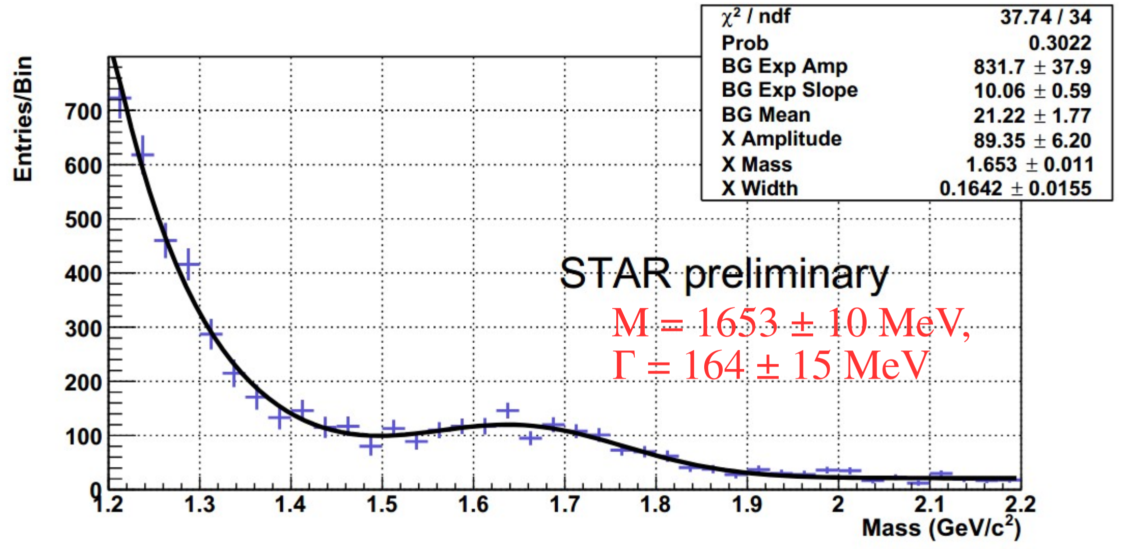
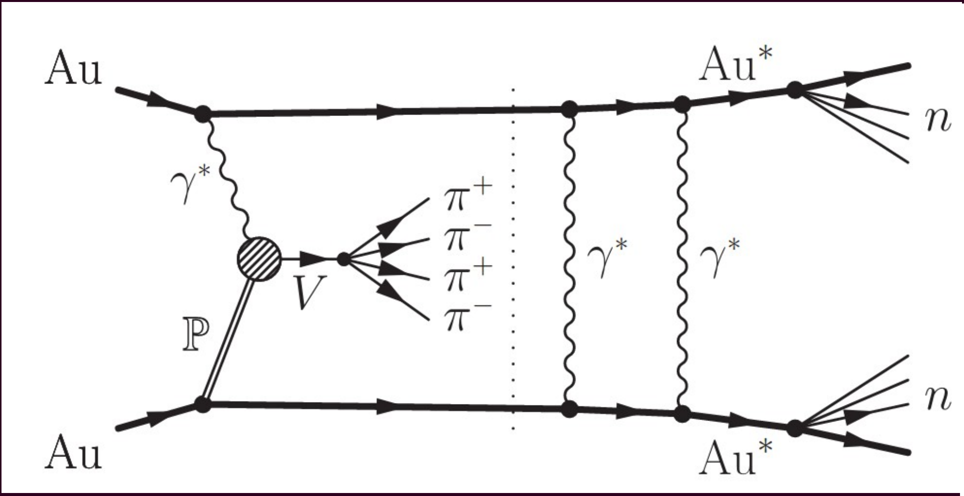
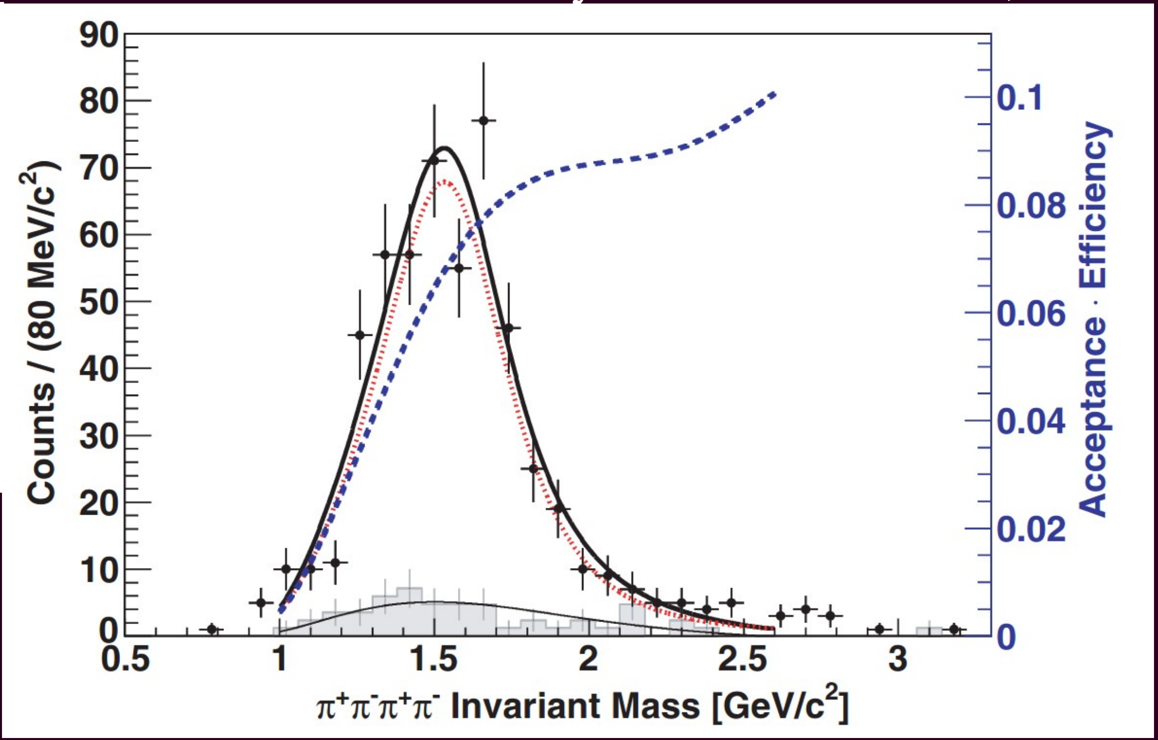


Exclusive four pion in UPCs

STAR Collaboration: Phys Rev C 81 044901, 2010





M = 1540±40 MeV, Γ = 570±60 MeV

In agreement with the data for **ρ(1700)**.

"One resonance does not describe the peak shape well. However, the low statistics of the data does not allow for the extraction of the resonance and mixing parameters for a two-resonance scenario."

Never studied in UPCs at LHC yet!

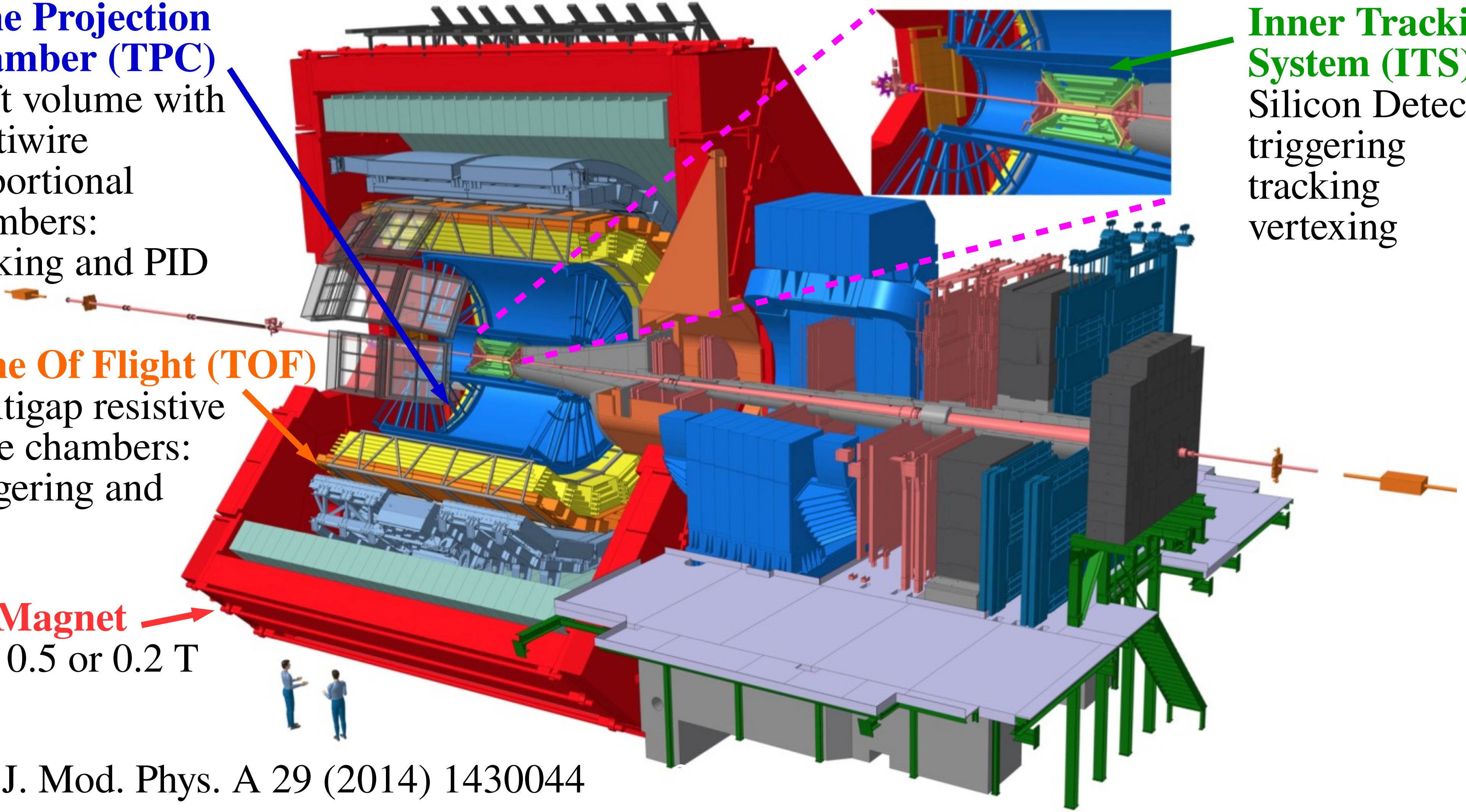
Analysis goals

- Search for the excited ρ resonance in the four-pion decay channel for the first time in UPCs at the LHC.
- Measure its mass and width.
- Measure its cross section × branching ratio and compare it to the available theoretical calculations.
  - Can we observe two resonances?

ALICE detector (Run 2): central trackers

Time Projection Chamber (TPC)
Drift volume with multiwire proportional chambers: tracking and PID

Inner Tracking System (ITS)
Silicon Detector: triggering tracking vertexing



Time Of Flight (TOF)
Multigap resistive plate chambers: triggering and PID

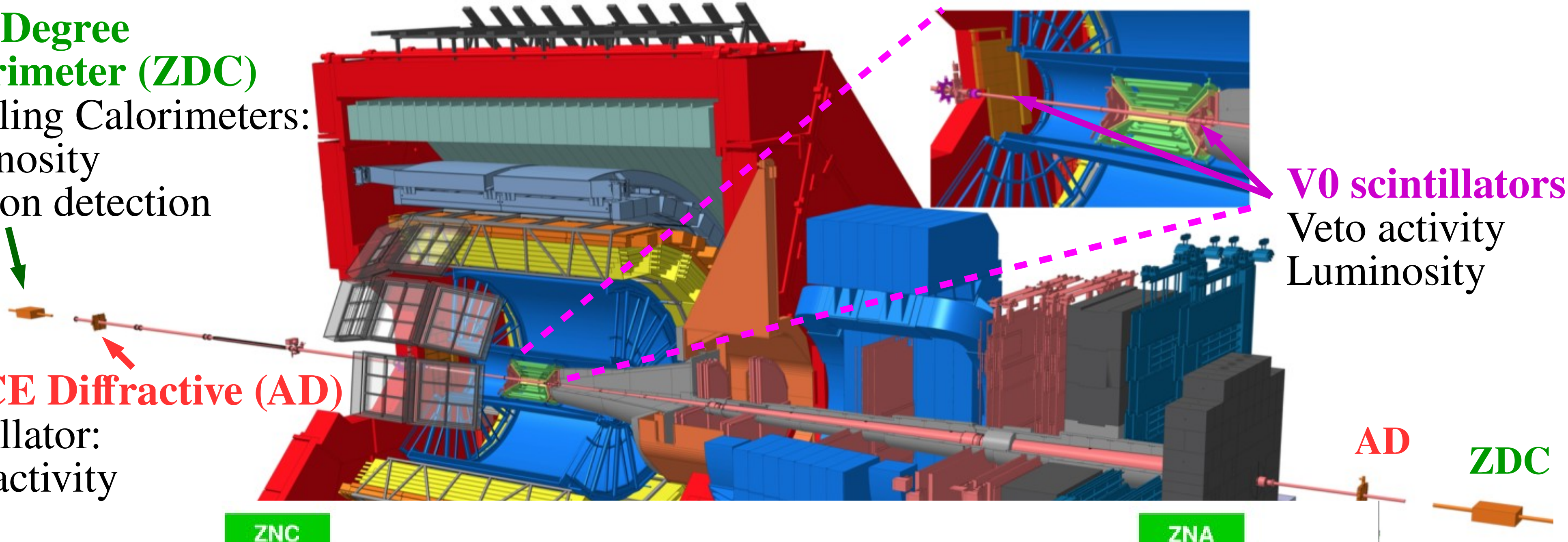
L3 Magnet
B = 0.5 or 0.2 T

Int. J. Mod. Phys. A 29 (2014) 1430044

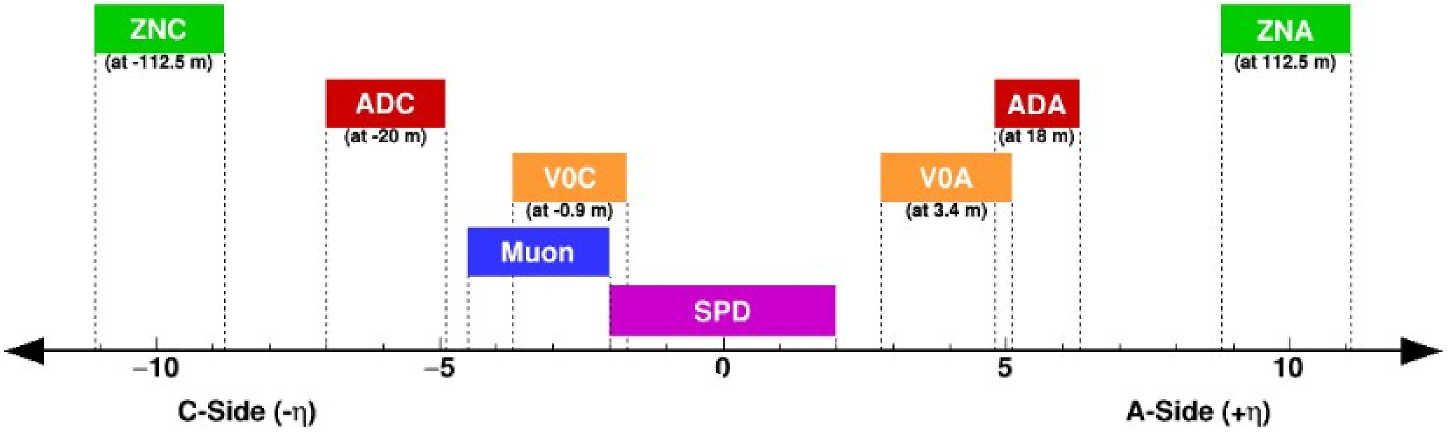
ALICE detector: exclusivity condition

Zero Degree Calorimeter (ZDC)
Sampling Calorimeters:
Luminosity
Neutron detection

ALICE Diffractive (AD)
Scintillator:
Veto activity



V0 scintillators:
Veto activity
Luminosity



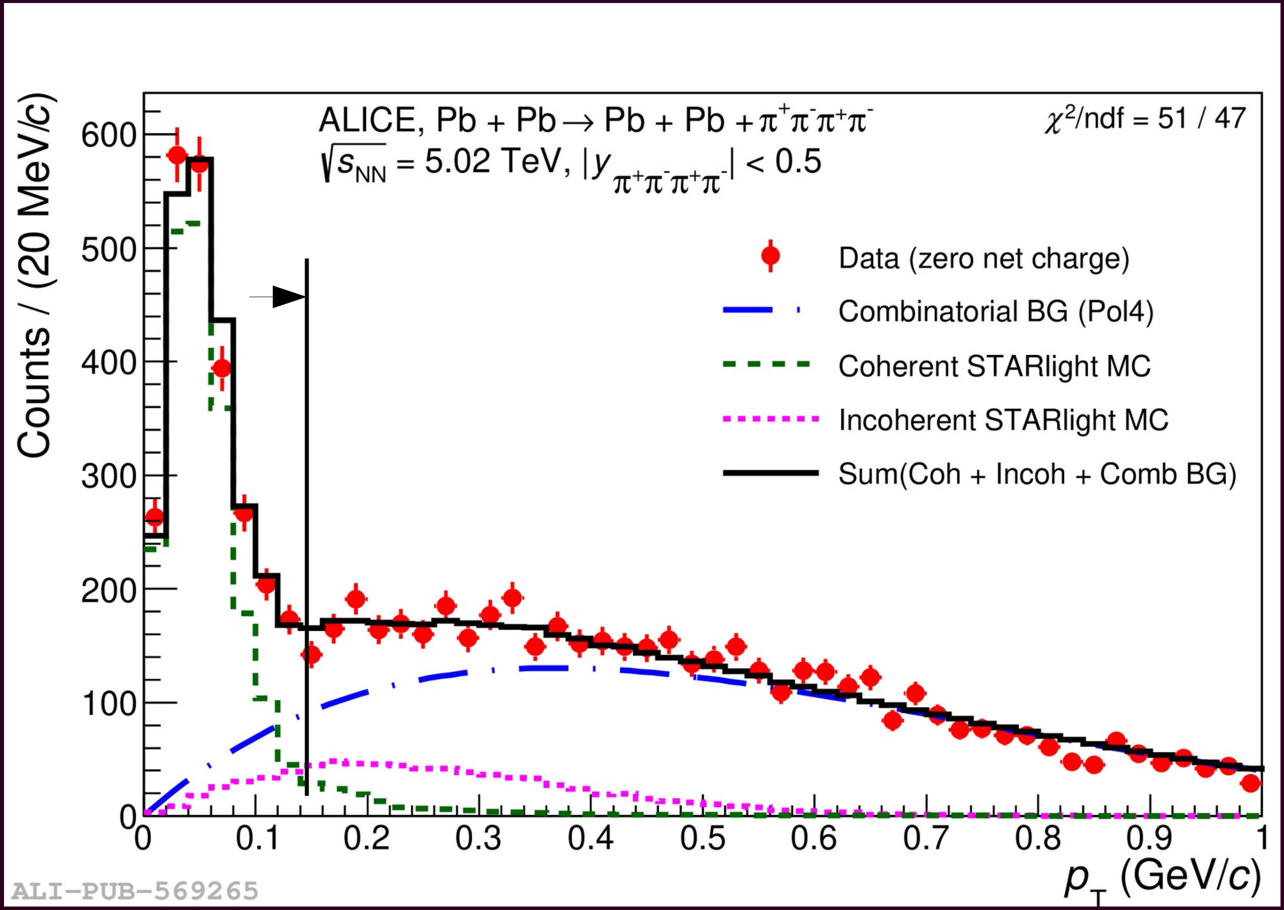
Main selections

- Data sample: 2015 PbPb collisions
- Trigger: Veto in V0 and AD detectors, two back-to-back tracklets
- Events: Exactly 4 good tracks with net charge equal to zero

Background estimation

- Template fit

CERN-EP-2024-104
https://cds.cern.ch/record/2894890



Three contributions:
- Signal <100 MeV
  STARlight MC (reweighted)
- Incoherent production <1 GeV
  STARlight MC
- Combinatorial background
  Non-zero net charge events

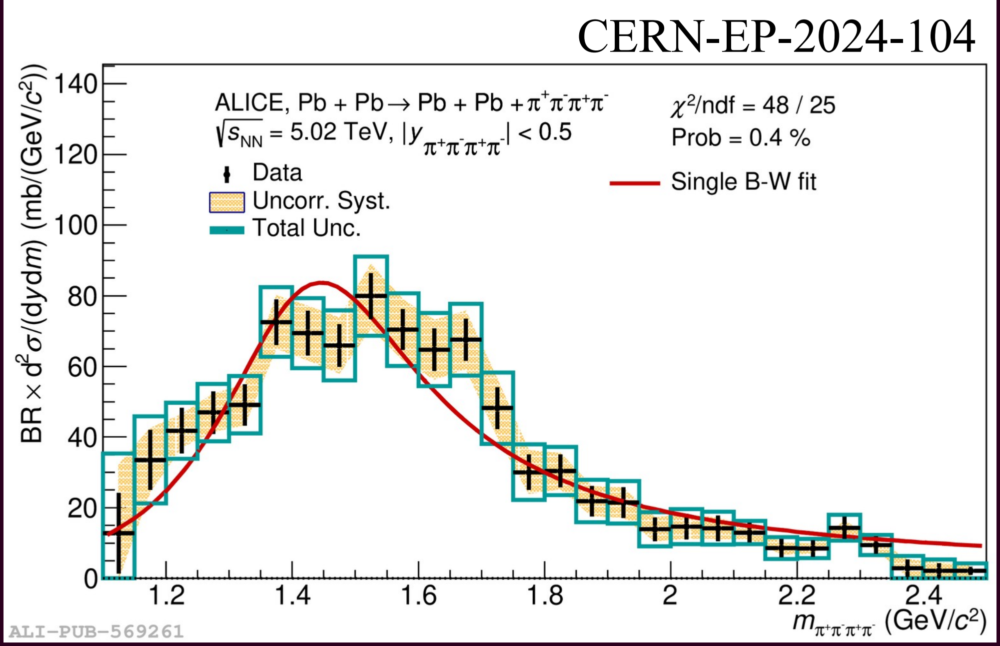
Most backgrounds are rejected by the requirement: event p_T < 150 MeV.
The template fit is needed to estimate the remaining contributions.

Fits to the invariant mass distributions

Background subtracted, corrected by acceptance and efficiency

$$BW_{part} = \left| \frac{\sqrt{m_{part} \cdot m_{event} \cdot \Gamma_{event}}}{m_{event}^2 - m_{part}^2 + i \cdot m_{part} \cdot \Gamma_{event}} \right|^2$$

$$\Gamma_{\text{event}} = \Gamma_{\text{part}} \cdot \frac{m_{\text{part}}}{m_{\text{event}}} \cdot \left(\frac{m_{\text{event}}^2 - k \cdot m_\pi^2}{m_{\text{part}}^2 - k \cdot m_\pi^2} \right)^{3/2}$$



M = 1463 ± 2 (stat.) ± 15 (syst.) MeV,
Γ = 448 ± 6 (stat.) ± 14 (syst.) MeV

ρ(1450) $I^G(J^{PC}) = 1^+(1^{--})$

See the review on "Spectroscopy of Light Meson Resonances."
Mass $m = 1465 \pm 25$ MeV [i]
Full width $\Gamma = 400 \pm 60$ MeV [i]

ρ(1700) $I^G(J^{PC}) = 1^+(1^{--})$

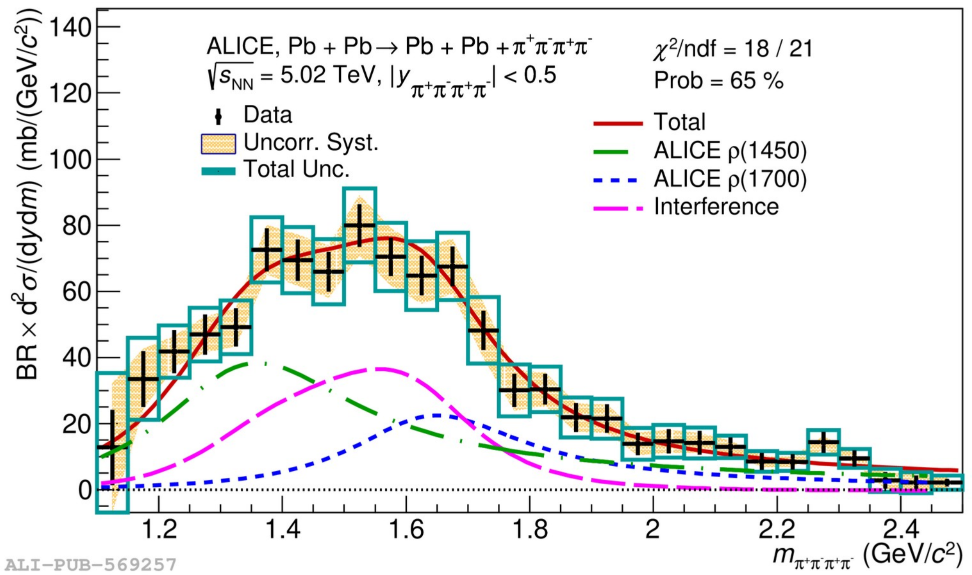
See the review on "Spectroscopy of Light Meson Resonances."
Mass $m = 1720 \pm 20$ MeV [i] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)
Full width $\Gamma = 250 \pm 100$ MeV [i] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)

The extracted mass and width are in agreement with the the PDG values fot the ρ(1450) resonance. However two resonances are also expected.

Two resonances with interference

$$\frac{d\sigma}{dm_{\pi\pi\pi\pi}} = |A \cdot \sqrt{BW_1} + e^{-i\phi} \cdot B \cdot \sqrt{BW_2}|^2;$$

CERN-EP-2024-104



M_1 = 1385 ± 14 (stat.) ± 36 (syst.) MeV,
Γ_1 = 431 ± 36 (stat.) ± 82 (syst.) MeV,
M_2 = 1663 ± 13 (stat.) ± 22 (syst.) MeV,
Γ_2 = 357 ± 31 (stat.) ± 49 (syst.) MeV

ρ(1450) $I^G(J^{PC}) = 1^+(1^{--})$

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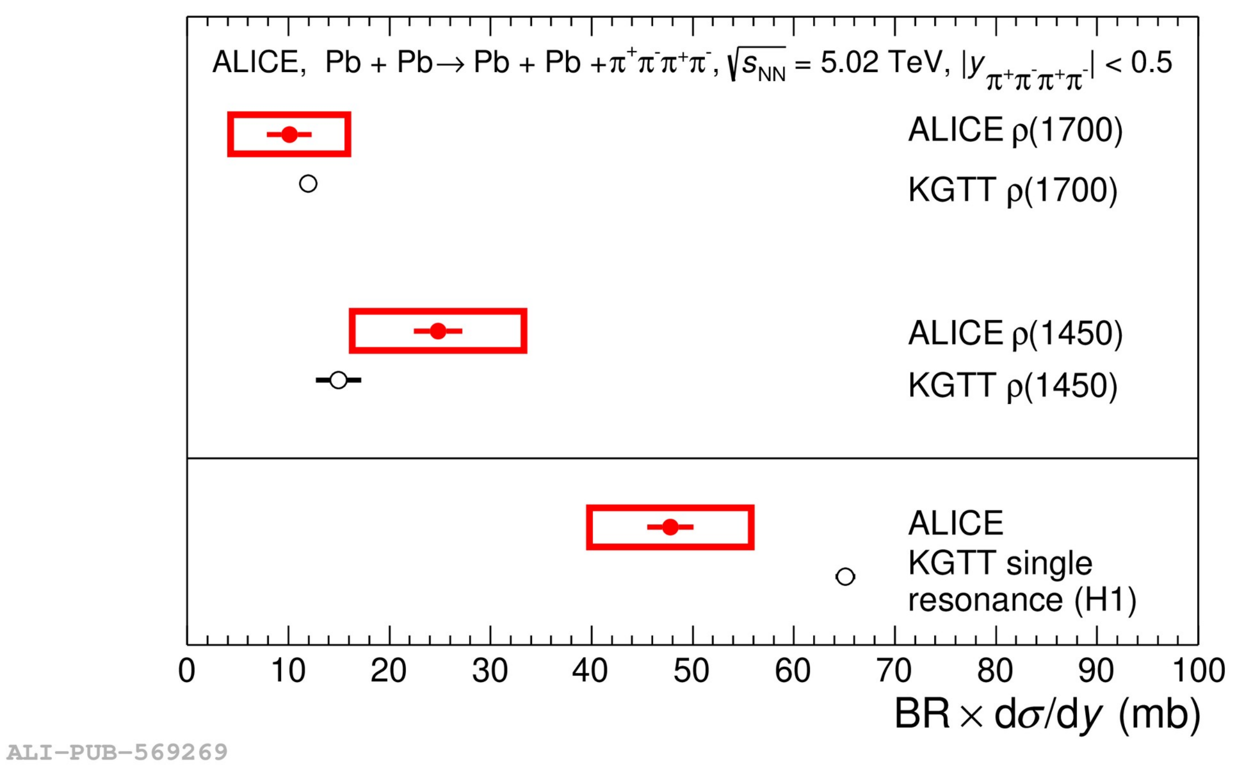
Full width $\Gamma = 250 \pm 100$ MeV [i] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)

Better data description w.r.t. single resonance scenario: χ^2/ndf = 18/21 vs 48/25.

These are two rather wide resonances close to each other, so the obtained parameter values have large uncertainties. We still can obtain the mixing angle: Φ = 1.52 ± 0.16 (stat.) ± 0.19 (syst.)

Cross section extraction



*times branching ratio

CERN-EP-2024-104
https://cds.cern.ch/record/2894890

Theory calculation from
M. Klusek and D. Tapia Takaki
Acta Phys. Polon. B 51 (2020) 6, 1393

The extracted cross sections are

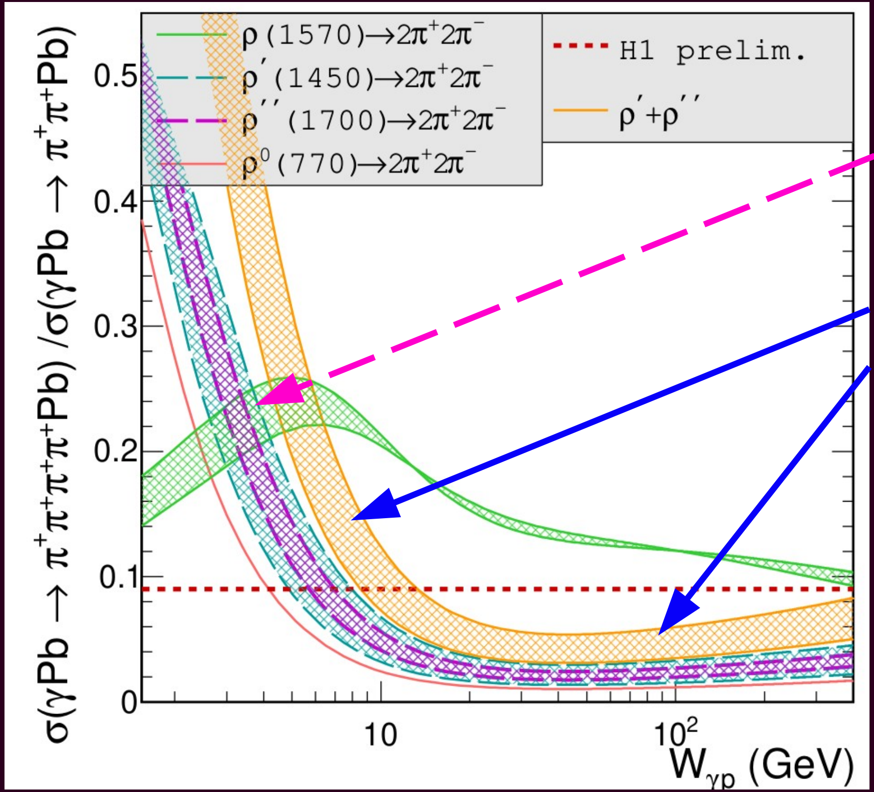
One B-W	47.8 ± 2.3 (stat.) ± 7.7 (syst.) mb
ρ(1450) Two B-W with interference	24.8 ± 2.5 (stat.) ± 8.1 (syst.) mb
ρ(1700) Two B-W with interference	10.1 ± 2.3 (stat.) ± 5.3 (syst.) mb

The total cross section is below the calculation assuming one wide resonance.

Cross section ratio

$$(\rho \to \pi^+\pi^-\pi^+\pi^-)/(\rho^0 \to \pi^+\pi^-)$$

Theory calculation from
M. Klusek and D. Tapia Takaki Acta Phys. Polon. B 51 (2020) 6, 1393



Rapid reduction of Reggeon exchange for excited ρ at low center-of-mass energies.

		√sNN	Ratio
STAR	Au–Au	200 GeV	(13.4 ± 0.8 ± 4.4) %
ALICE	Pb–Pb	5.02 TeV	(7.3 ± 0.4 ± 1.2) %

STAR Collaboration performed the measurement for the events with mutual nuclear excitation.

Theoretical calculation is performed as a function of $W_{\gamma p}$, so no direct comparison is possible, but a qualitative agreement is observed.

Summary

- Exclusive four pion photoproduction in ultra-peripheral Pb–Pb collisions is measured for the first time at the LHC.
- New inputs to the PDG values (mass and width). The invariant mass distribution is best described by a fit to two resonances, $\rho(1450)$ and $\rho(1700)$, with an interference term.
- The extracted cross section is compared to the theoretical predictions. It is in agreement with the case of two resonances.
- The reduction in $(\rho \rightarrow \pi^{+}\pi^{-}\pi^{+}\pi^{-}) / (\rho^{0} \rightarrow \pi^{+}\pi^{-})$ ratio can be attributed to a more rapid reduction of Reggeon exchange contributions in excited ρ compared to ρ^{0} photoproduction.

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Zheleznogorsk, Kurskaya obl., Russia – Saint-Genis-Pouilly, France

Joint Institute of Nuclear Research, Dubna, Russia

1987 – 2010, DELPHI (LEP)

Studies of two-photon interactions

2010 – 2015, ATLAS

Heavy-ion UPCs

2015 – 2024, ALICE

Heavy-ion UPCs:

- Coherent $\rho^0(770)$ photoproduction in PbPb Collisions
- ***Exclusive four-pion photoproduction in PbPb Collisions***

Backup

Cross section systematics

Source	Uncertainty
Background Subtraction	±3.5%
Acceptance and efficiency	±12%
Variations to the fit procedure[1]	±1.7%
Track selection	±1.5%
Track matching	±4%
Incoherent contribution	±1.0%
Trigger efficiency	±1.0%
Pile-up	±3.8%
Luminosity	±2.6%
Total correlated	±6.7 %

Uncorrelated systematics:
Influence both the extracted parameters and the cross section
→ considered in invariant mass fits

Correlated systematics:
→ considered in cross section calculations

The largest uncertainty comes from the difference in AxE due to the angular distribution in the final state.

[1] Uncertainty on the total number of events extracted from the fit with one B-W resonance.