ALICE Physics Analysis – Results and Future Prospects

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ALICE

Outline

- ALICE in Run 3 and beyond.

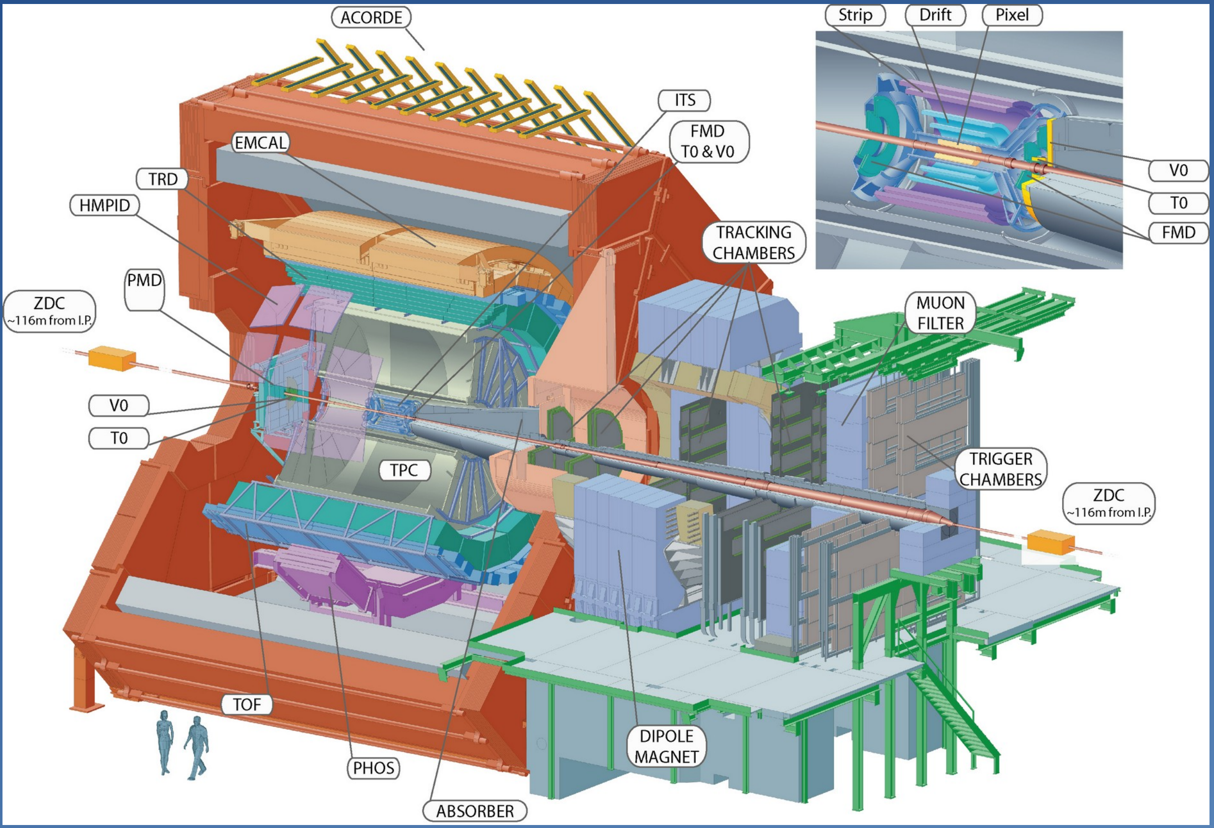
- Some standard heavy-ion variables (R_{AA} and v_2).

- Open charm and charmonium production in ALICE; first results from Run 3.

- Ultra-peripheral collisions in ALICE in Run 3.

- Outlook for the next 20 years.

The ALICE Experiment Run 1 and 2



A central tracking system with particle identification.

Acceptance |η| ≤ 0.9, p_T > 100 MeV/c.

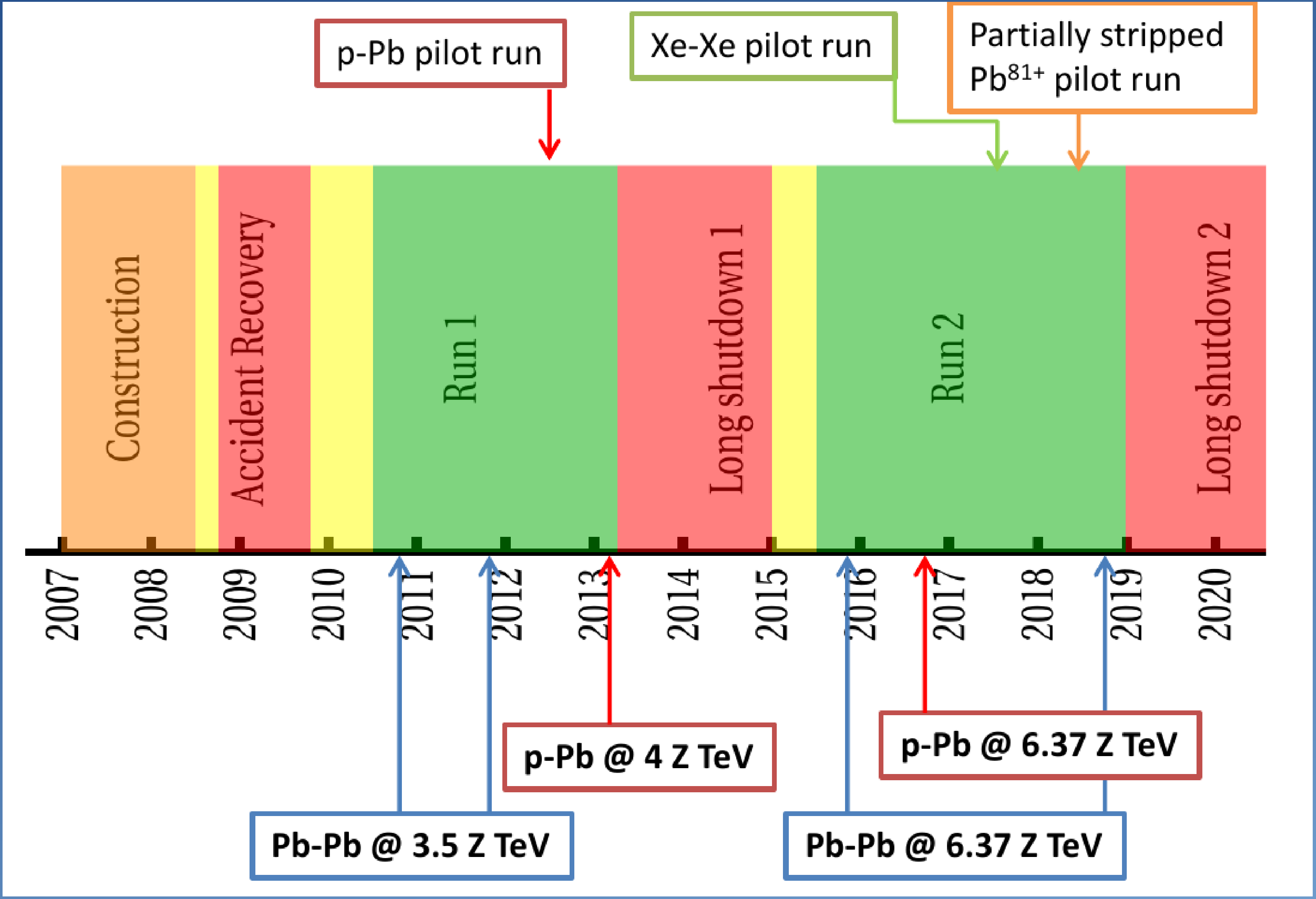
Trigger from SPD and TOF.

- A muon arm at forward rapidities -4.0 < η < -2.5. Triggering, tracking and identification of muons.

- VZERO counters for triggering; used here as veto detectors to define rapidity gaps (-3.7 < η < -1.7) and (2.8 < η < 5.1)

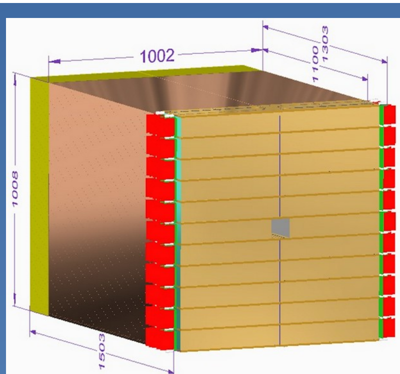
- Zero Degree Calorimeters (ZDC) – detects neutrons from nuclear breakup.

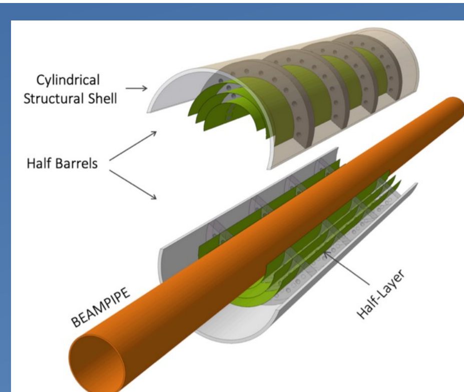
History of LHC Heavy-Ion Runs so far

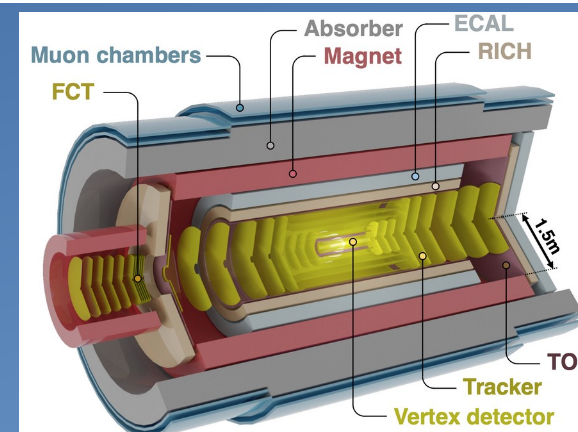


The ALICE Experiment Run 3 and beyond

Major upgrades in Run 3:
- Upgraded Inner Tracking System (ITS2).
- Continuous TPC read-out.
- Muon Forward Tracker.



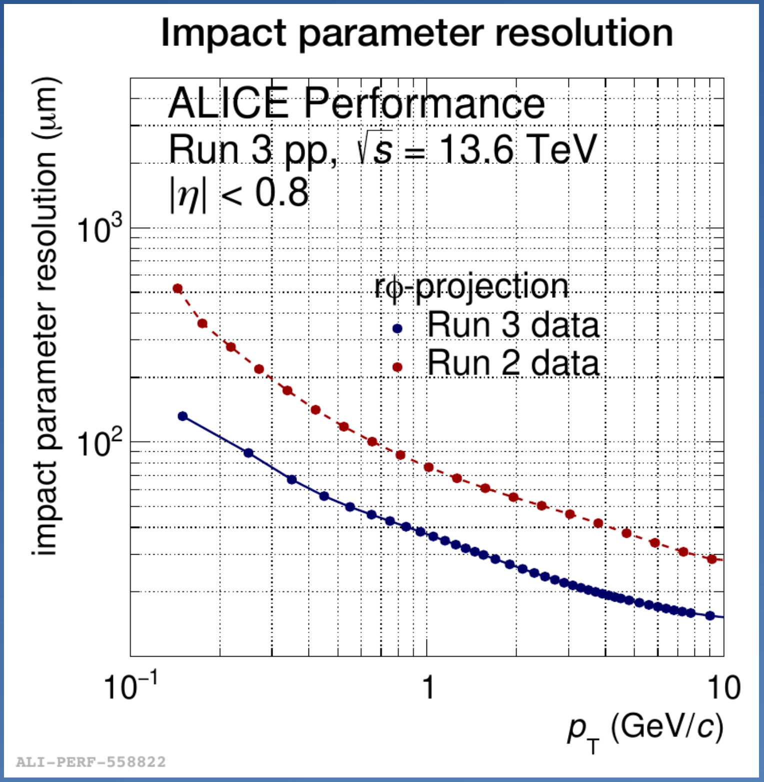


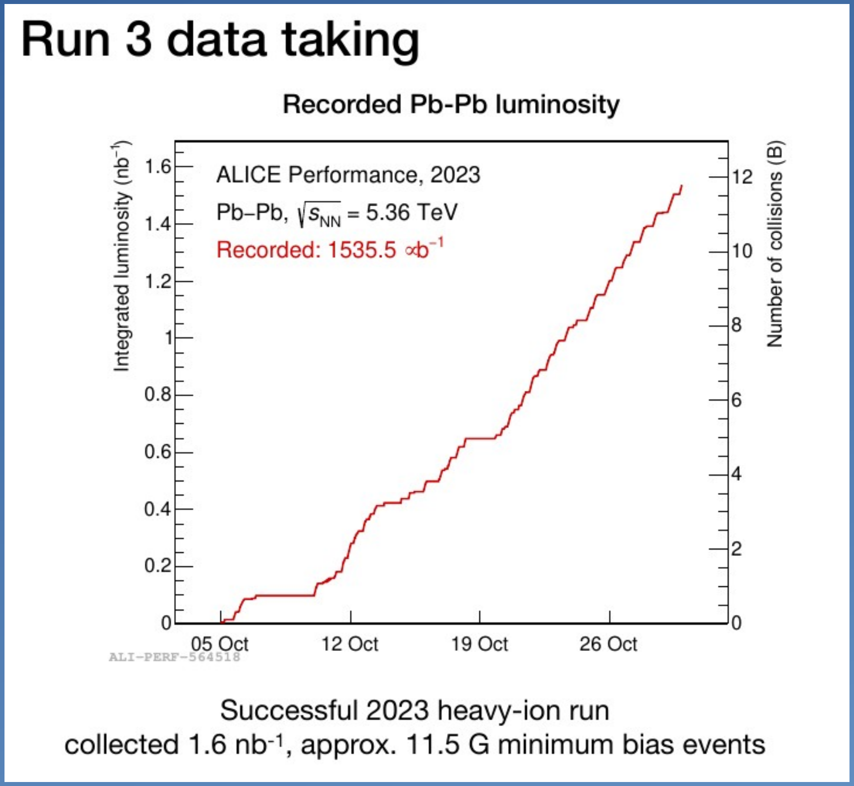


Upgrades in the future LS3:
- Upgrade of the Inner Tracking System (ITS3).
- Installation of the Forward Calorimeter (FoCal).

ALICE 3 in LS4.

The ALICE Experiment in Run 3





- Improved impact parameter resolution .
- Improved luminosity, already a factor of ∼6 larger than Run 2.

The ALICE Experiment in Run 3 and 4

Taking data at 500 kHz (pp) and 50 kHz (PbPb).

Pb-Pb:

- Goal to collect 13 nb^{-1}. 1.6 nb^{-1} achieved in 2023.
- PbPb runs also in 2024 and 2025.

O-O:

- Short run in July 2025. Goal ~0.5 nb^{-1}.

p-Pb:

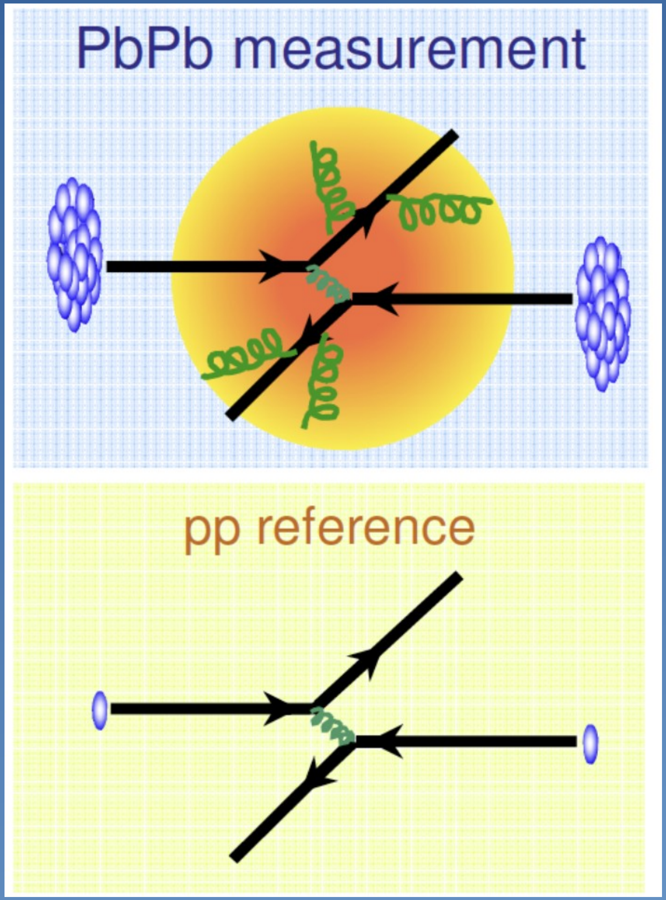
- Will be done in Run 4.

“Standard observable”: R_{AA}.

Separate the nuclear effects from a simple scaling of pp data.

$$R_{AA} = \frac{1}{N_{coll}} \frac{Y_{AA}}{Y_{pp}} = \frac{QCD\ Medium}{QCD\ vacuum}$$

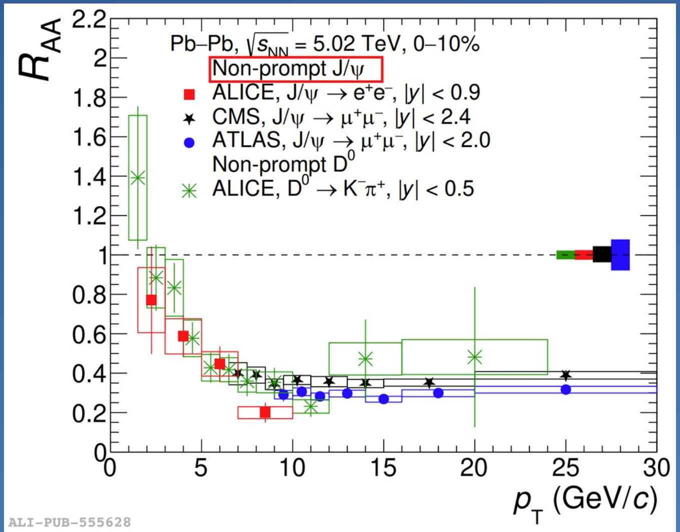
- No nuclear effects: $R_{AA} = 1$
- Hot or cold nuclear effects: $R_{AA} \neq 1$



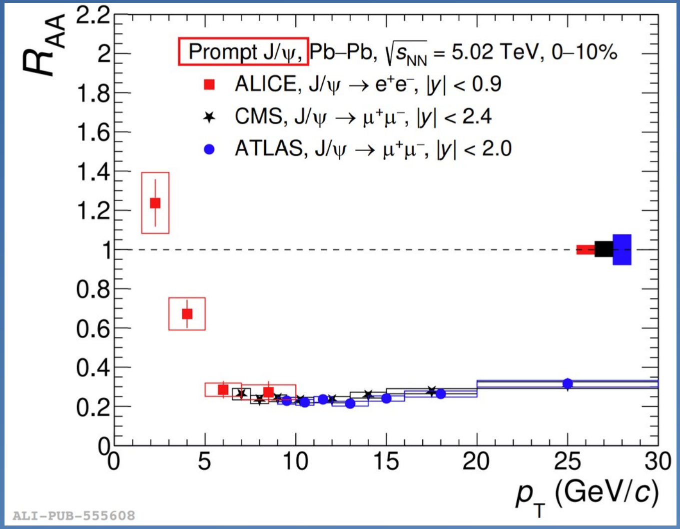
"Standard observable": R_{AA}.

Scaling of J/ψ as a function of p_T.

Non-prompt



Prompt

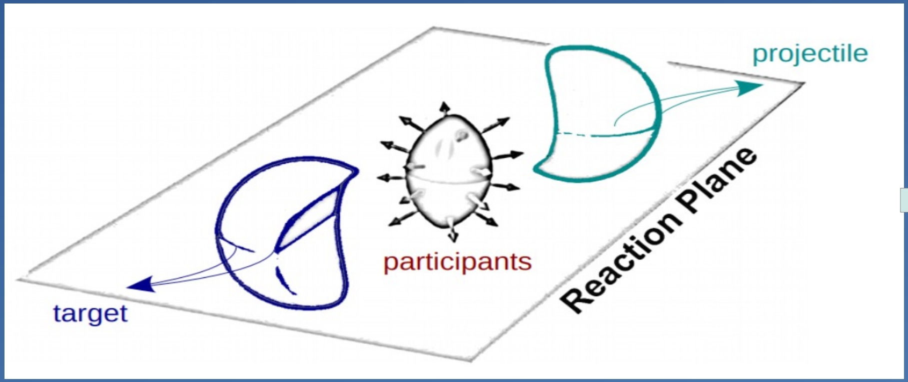


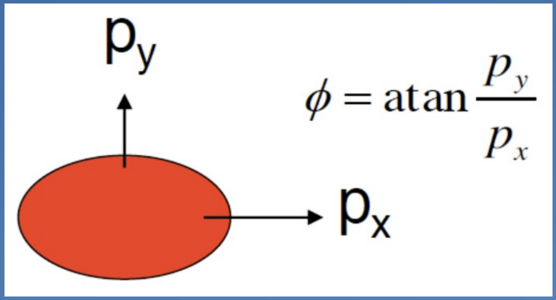
Low-p_T: moderate suppression or enhancement

High-p_T: Strong suppression

“Standard observable”: v_2 (collective flow).

The initial spatial asymmetry is converted to an asymmetry in momentum space by the hydrodynamical pressure.



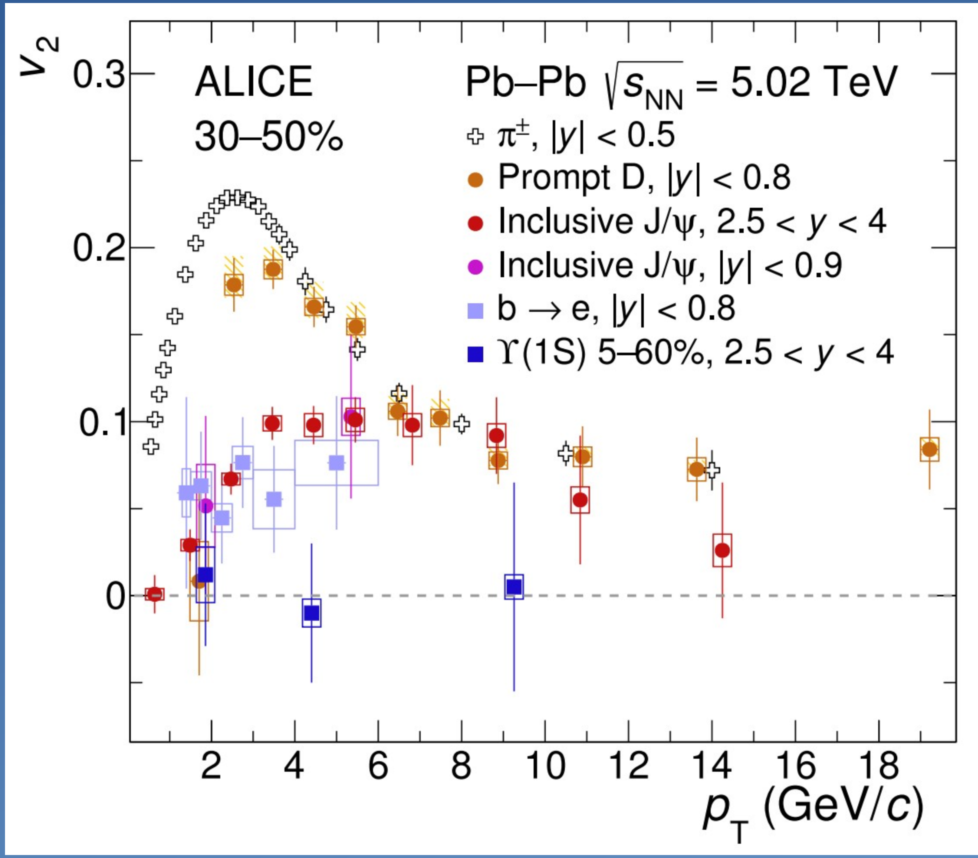


- Typically quantified via a Fourier expansion wrt reaction plane Ψ:

- Dominated by the elliptic flow coefficient: v_2

“Standard observable”: v_2 (collective flow).

Collective flow for open charm/beauty and charmonium/bottonium.



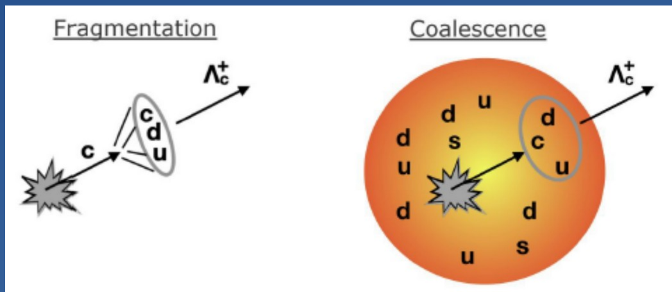
Quark mass hierarchy seen in the flow measurements

Open and hidden charm: strong flow

Open beauty: possible flow

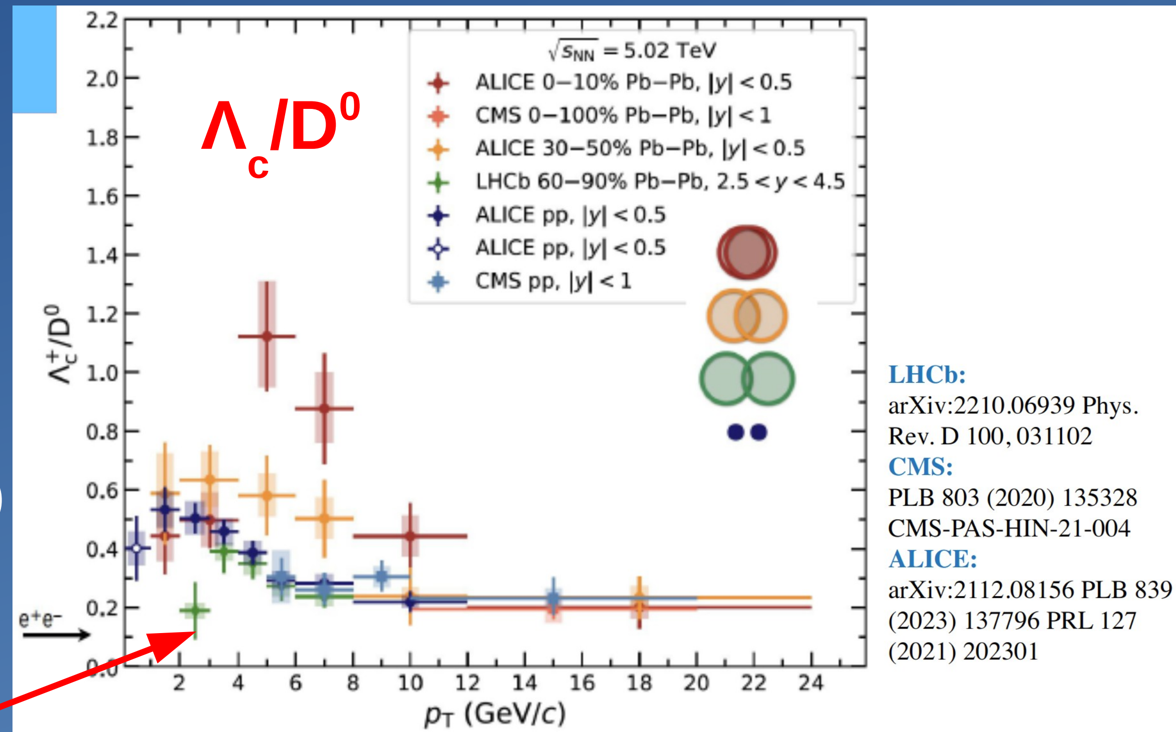
Bottomonia: compatible with no flow

Charm fragmentation



Fragmentation: break-up of charm quark as in e^+e^- collisions (expected also in pp)

Coalescence: combination of quarks close in phase space



Largely enhanced charm baryon to meson ratios in pp collisions wrt e^+e^- at intermediate p_T.

Baryon/meson ratios larger in Pb-Pb than pp.

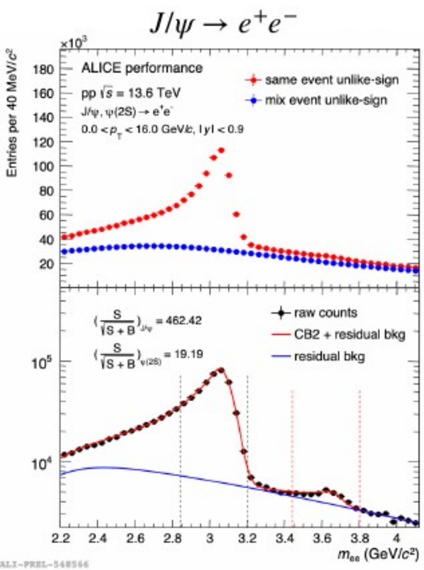
One of the first physics results from Run 3

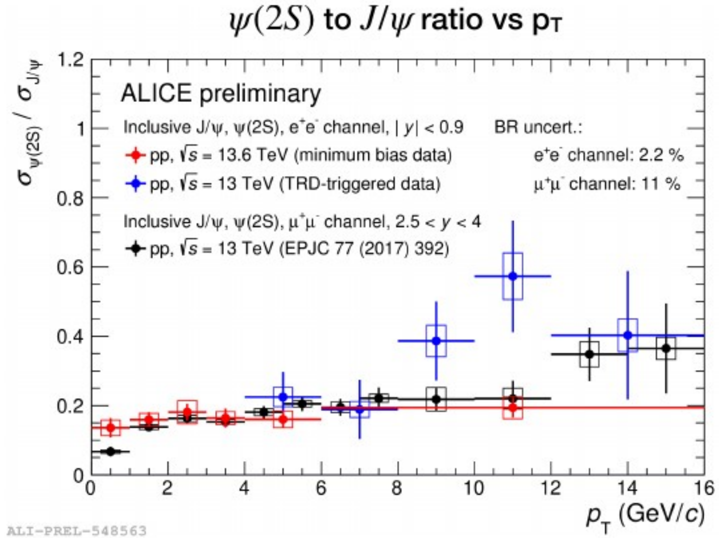
A Large Ion Collider Experiment

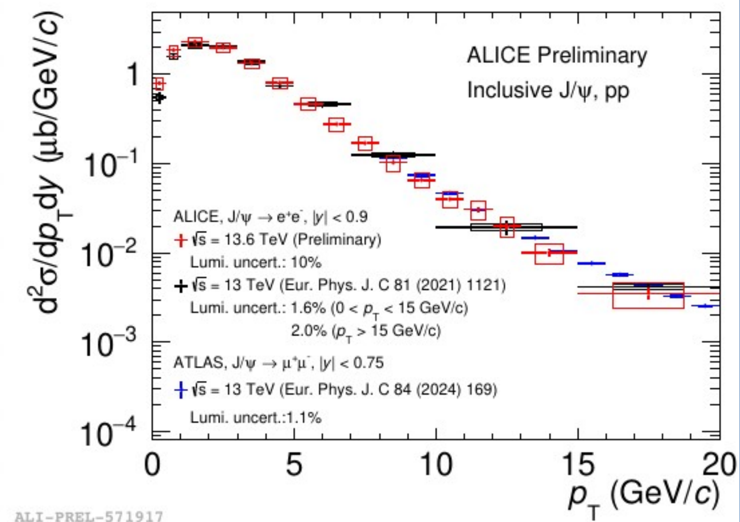
J/ψ and ψ(2s) to J/ψ ratio

New run 3 results

ALICE







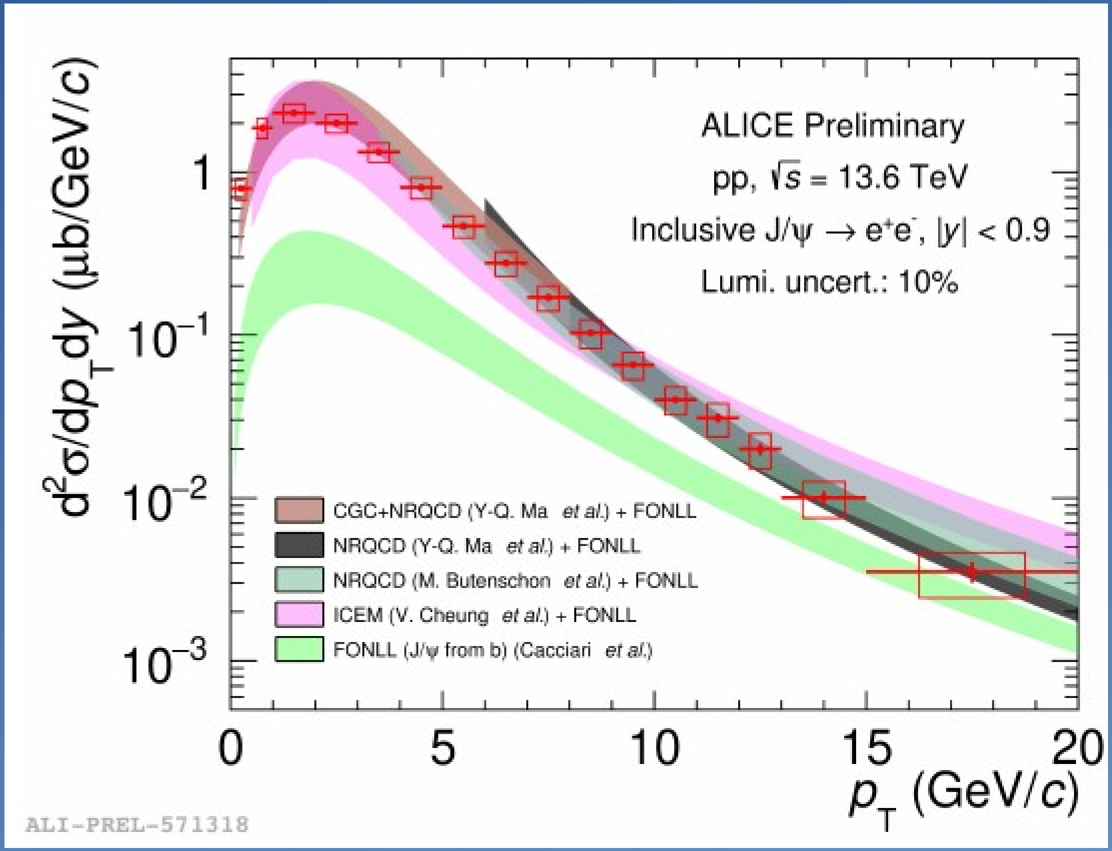
New measurements of J/ψ and $\psi(2S)$

e^+e^- decays cover down to $p_T = 0$ with excellent precision

Important input to quarkonia production models

One of the first physics results from Run 3

p_T spectrum of J/ψ at midrapidity

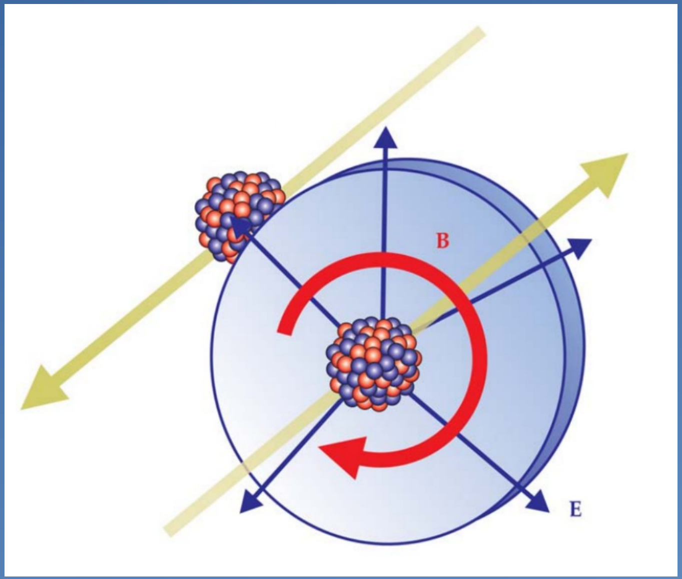


Constrains models on charmonium production.

Another aspect of heavy-ion collisions - ultra-peripheral collisions

Collisions between nuclei and protons with impact parameters larger than the sum of the radii.

Strong interactions suppressed. Interactions instead mediated by the electromagnetic field.



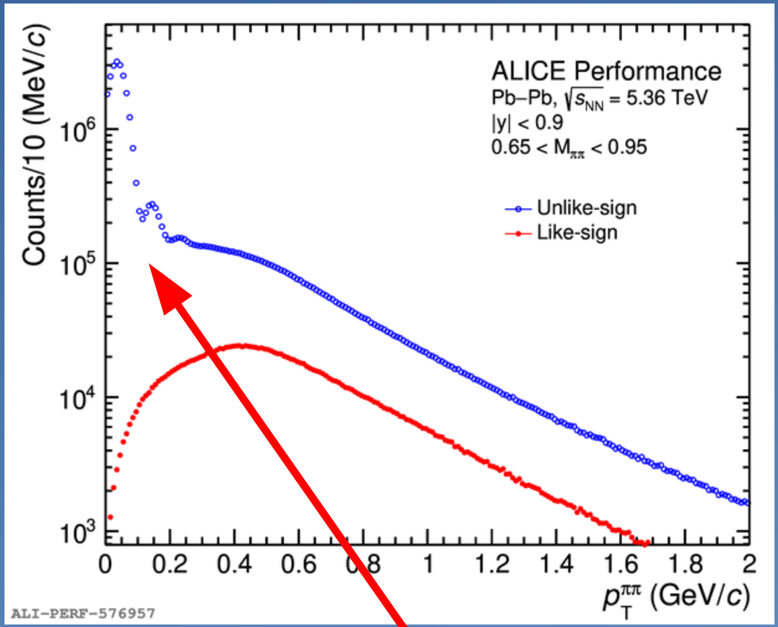
The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

UPCs represent the energy frontier for electromagnetic and electroweak interactions.

Continuous read-out has some surprising consequences

Cross section for exclusive ρ^0 photoproduction Pb+Pb→ Pb+Pb+ρ^0 is huge, about 5 b. (Total hadronic PbPb cross section 7 b.)

-Now we collect everything so we get everything!



Should have a sample of $75 \cdot 10^6$ photoproduced ρ^0 already from Run 3.

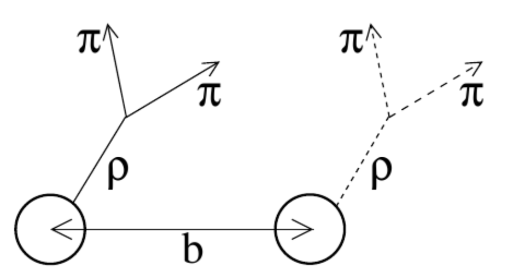
More than an order of magnitude larger than in any previous experiment!

What to do with it?

Clear coherent peak with 3 diffractive minima.

Interferometry at femtometer scales

A vector meson can be produced on either nucleus in an exclusive process A+A → A+A+V.



The cross section is the sum of the two possibilities

$$\frac{d\sigma}{dy\,dp_T} = \int_{b>2R} k_1 \frac{dN}{dk_1 d^2b}\, \sigma(\gamma A_2)\, f_{1,2}(p_T) \;+\; k_2 \frac{dN}{dk_2 d^2b}\, \sigma(\gamma A_1)\, f_{2,1}(p_T)\; d^2\vec{b}\,.$$

This can be written as the sum of two amplitudes squared

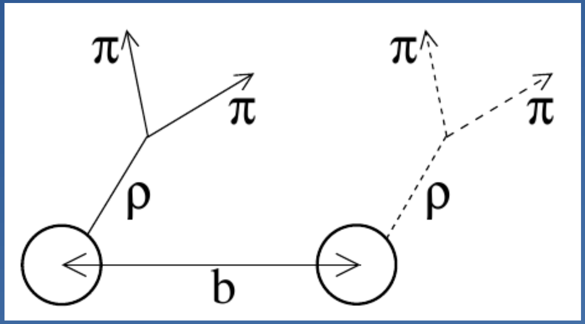
$$\frac{d\sigma}{dy\,dp_T} = \int_{b>2R} \left(|A_1|^2 + |A_2|^2\right) d^2\vec{b}\,,$$

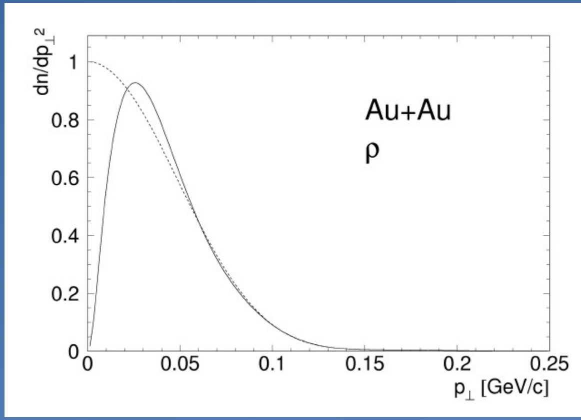
But when p_T << 1/b, interference becomes important and one must add the amplitudes:

$$\frac{d\sigma}{dy\,dp_T} = \int_{b>2R} |A_1 + A_2|^2\, d^2\vec{b}\,.$$

Interferometry at femtometer scales

A vector meson can be produced on either nucleus in A+A $\rightarrow$ A+A+V reactions.





S.R. Klein, J. Nystrand, Phys. Rev. Lett. 84 (2000) 2330;
K. Hencken, G. Baur,
D. Trautmann, PRL 97 (2006) 012303.

Median separation between nuclei for light vector meson production typically $\approx$ 50 fm at RHIC.

For $p_T < \approx 1/50$ fm $\approx$ 5 MeV/c, the interference will suppress the yield and modify the p_T spectrum.

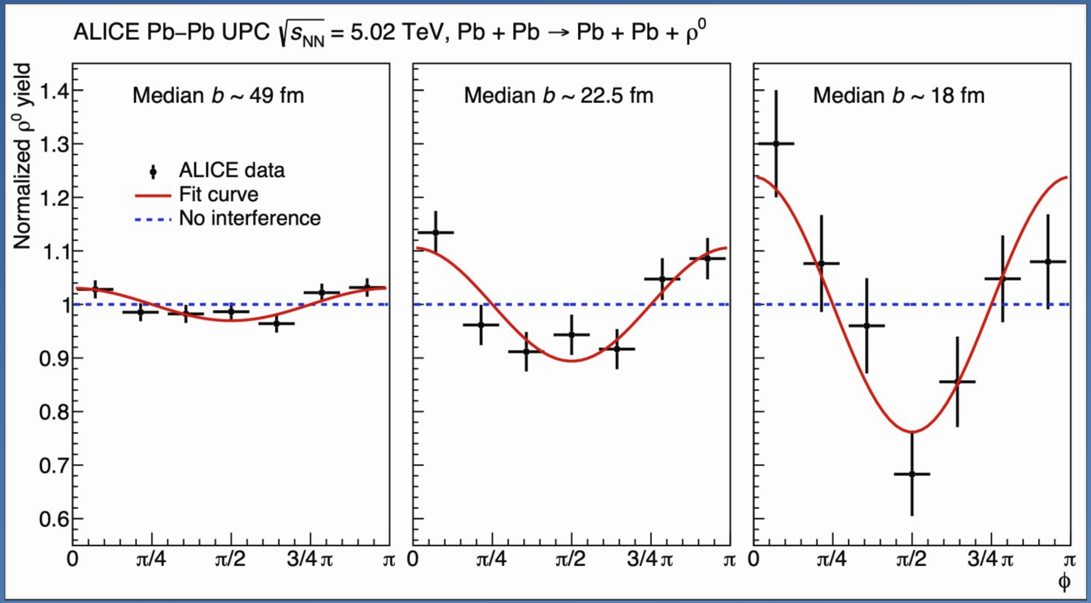
This modification was observed by STAR at RHIC (PRL 102 (2009) 112301).

Works as a double-slit interference experiment but at the femtometer rather than nanometer scale!

A handle on the impact parameter/distance between the slits through exchange of multiple photons followed by neutron emission.

Interferometry at femtometer scales

The interference also reveals itself in angular correlations between the ρ^0 and its decay products (H. Xing, C. Zhang, J. Zhou, and Y.-J. Zhou, JHEP 10 (2020) 064; H. Mäntysaari, F. Salazar, B. Schenke, C. Shen, and W. Zhao, Phys. Rev. C 109 (2024) 024908.).



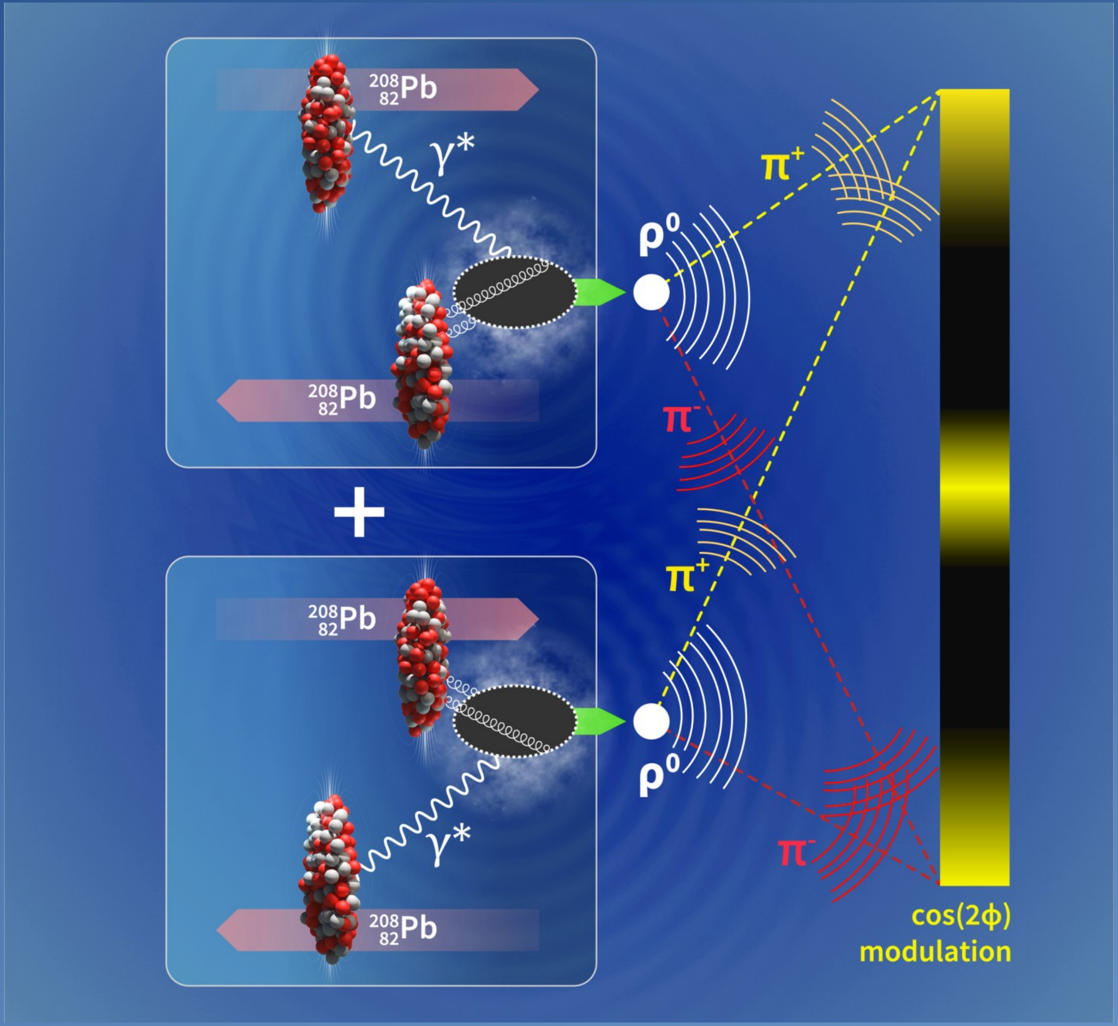
ALICE arXiv:2405.14525.

Decreasing impact parameter ⇒

Without interference these distributions would be flat.

Interferometry at femtometer scales

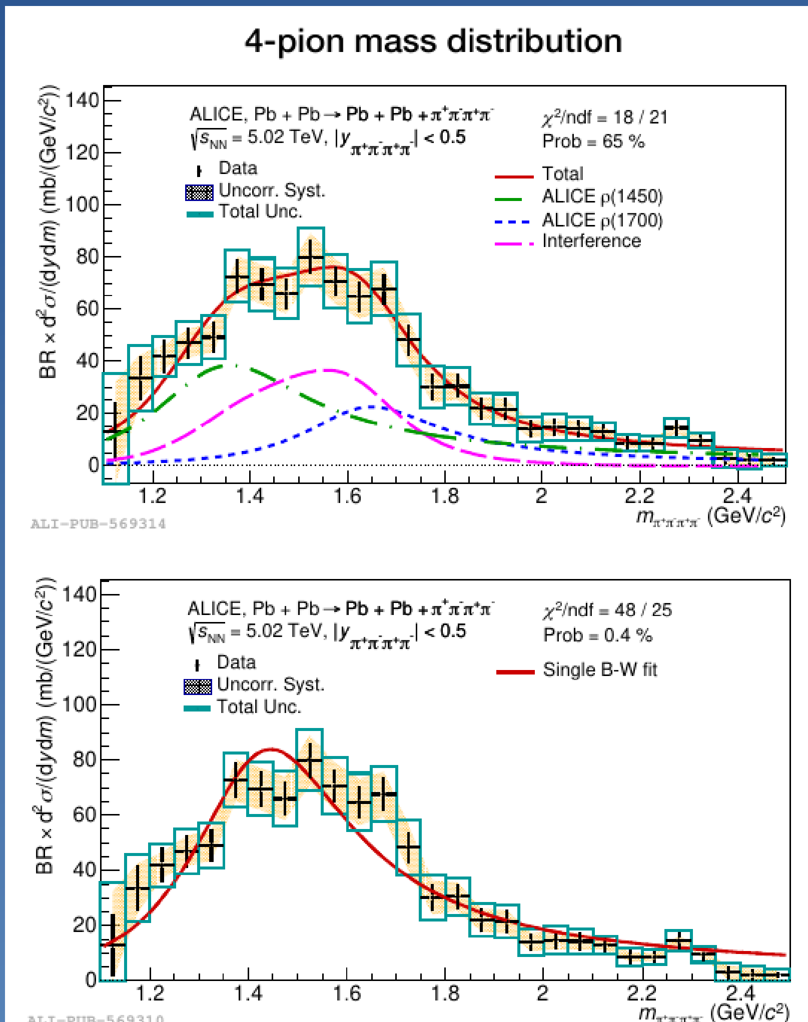
Recently high lighted in CERN News and CERN Courier.



https://home.cern/news/news/physics/alice-does-double-slit

Meson spectroscopy

Photoproduction of excited ρ'. PDG lists at least two candidates.



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)

ALICE result inconsistent with only a single ρ'.

Note: some of the excited ρ's are candidates to be hybrid states ($q\bar{q}g$).

ALICE arXiv:2404.07542

General photonuclear interactions

- A photon from the EM field of one of the nuclei hits the other nucleus.

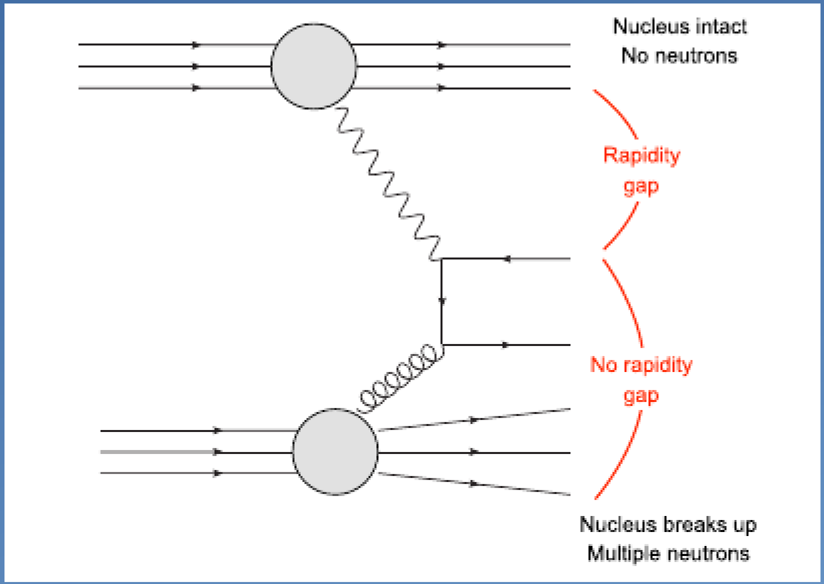
- The photon-emitting nucleus remains intact

- The photons have an energy spectrum, but the photon energy is always much lower than that of the target nucleus.

Two consequences:

1) There is a rapidity gap, void of particles, on the side of the photon-emitting nucleus. This is the main experimental signature.

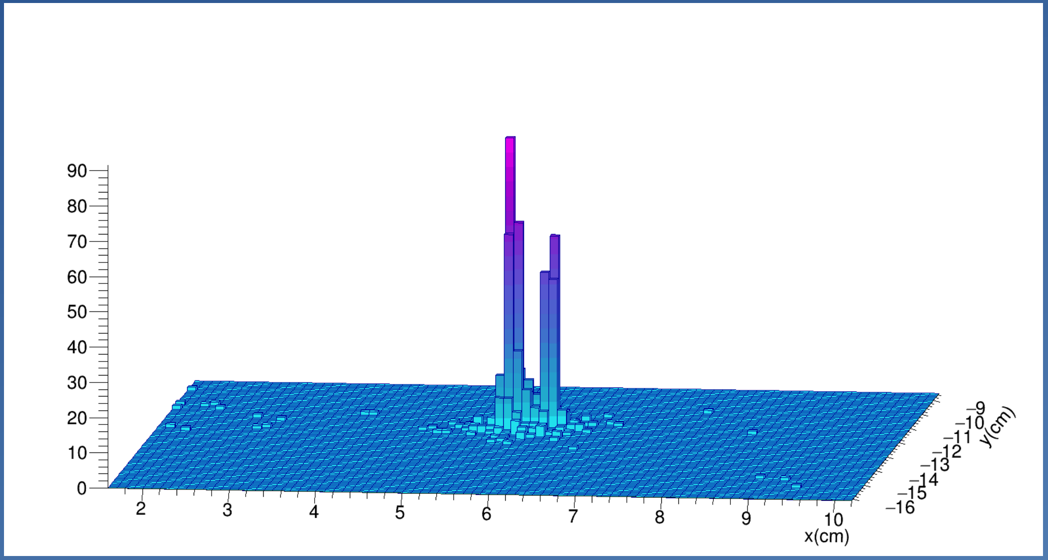
2) The particle production is not centered at mid-rapidity but shifted to the side of the target nucleus.



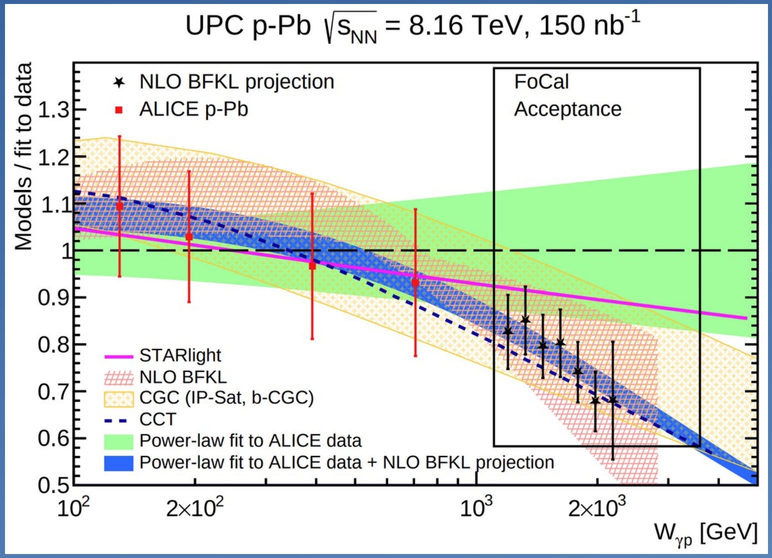
A novel aspect of UPCs.
ALICE in Run 1 and 2 hampered by the lack of a trigger ==>
Continuous read-out in Run 3.
Should have results on open charm and strangeness photoproduction.

Some physics goal of FoCal

Two peaks from $\pi^0 \rightarrow \gamma\gamma$ resolved.



J/ψ photoproduction ($x \sim 2 \cdot 10^{-6}$).



A.Bylinkin, J.Nystrand, D.T.Takaki, arxiv:2211.16107

- Forward production of quarkonia and neutral pions.
- Exploration of non-linear evolution of gluon PDFs.

  Direct photons, photoproduction of charmonium and di-jets in UPCs

What can we answer in the next ≈20 years?

Properties of the Quark-Gluon Plasma (QGP):
Main focus will be on heavy flavour and jet measurements, well aligned with the ALICE upgrades for Run 4 and with our detector R&D involvement.

Non-linear evolution of gluon content in nuclei:
Probed by UPCs (charmonium and open charm photoproduction) and p-Pb collisions. Forward rapidities most sensitive (FoCal). Higher energy scale and earlier time scale than EIC (Electron-Ion Collider).

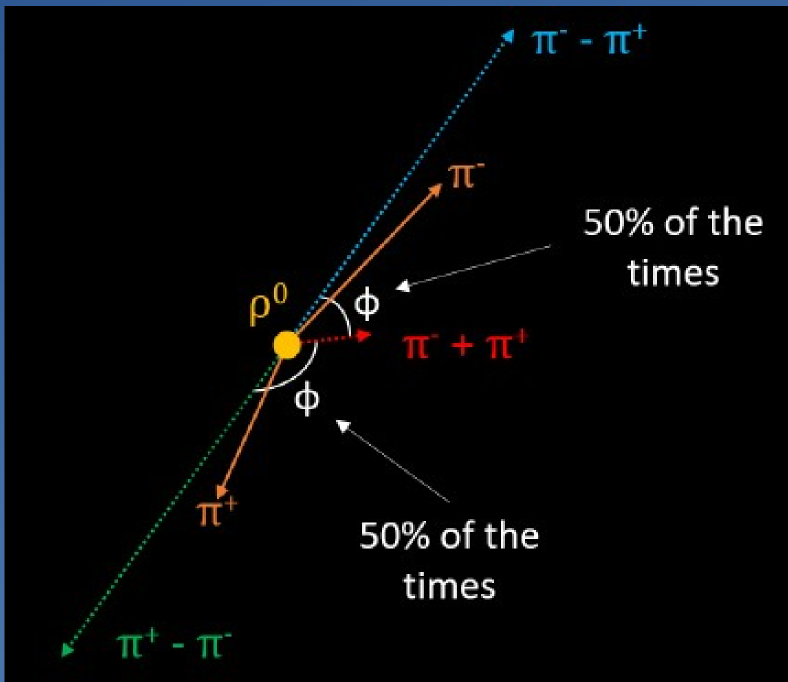
QCD studies in small systems:
Can be studied in high multiplicity pp collisions, and photonuclear interactions in UPC.

Miscellaneous:
- Quantum interference at a new length scale.
- Hadron spectroscopy.

Backup slides

Azimuthal angular correlations in ρ^0 photoproduction

A consequence of the interference and polarization is that one expects angular correlations between the p_T of the VM and the p_T of the decay products, $\rho^0 \to \pi^+ + \pi^-$.



Andrea Riffero, DIS 2024

$$\frac{dn}{d\phi} = 1 + a_2 \cos(2\phi)$$

where φ is the angle between the $\mathbf{p}_T$ of the ρ^0 ($\mathbf{p}_+$)

$$\mathbf{p}_+ = \mathbf{p}_T^{\rho} = \mathbf{p}_T^{\pi+} + \mathbf{p}_T^{\pi-}$$

and the difference between p_T of the decay products ($\mathbf{p}_-$)

$$\mathbf{p}_- = \mathbf{p}_T^{\pi+} - \mathbf{p}_T^{\pi-}$$

H. Xing, C.Zhang, J. Zhou, Y.J. Zhou, JHEP 10 (2020) 064; W.Zha, J.D. Brandenburg, L. Ruan, Z. Tang, PRD 103 (2021) 033007; H. Mäntysaari et al. arXiv:2310.15300.

$$|A_1 + A_2|^2 = 2A_0^2 \left(1 - \cos(\vec{p} \cdot \vec{b})\right)$$

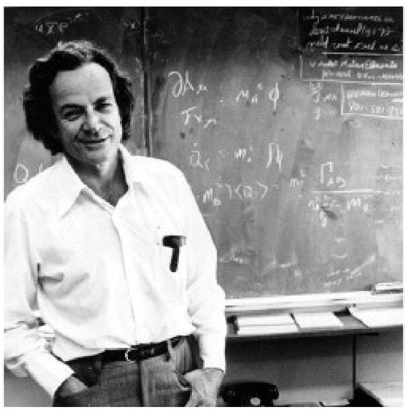
$\mathbf{p}_T$ of the ρ^0

direction of **b** correlated with the angular distribution of the decay products.

A double-slit experiment at fm scale

ALICE

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

Exclusive vector meson production

PHYSICAL REVIEW C, VOLUME 60, 014903

Exclusive vector meson production in relativistic heavy ion collisions

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Lawrence Berkeley National Laboratory, Berkeley, California 94720
(Received 8 February 1999; published 16 June 1999)

The production rates are large enough that heavy ion colliders could be used as vector meson factories. The ϕ and J/ψ production rates at LHC are comparable to those at existing or planned meson factories based on e^+e^- annihilation.

A series of workshops on UPCs has started

Second edition will be in Finland (Saariselkä, Northern Lapland) 9-13 June 2025.

https://indico.cern.ch/event/1378275/overview