INSTITUTE OF SPACE SCIENCE
A subsidiary of INFLPR

ALICE

Recent results from the ALICE experiment at the LHC

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for the ALICE Collaboration

Institute of Space Science - INFLPR Subsidiary (RO)

ALICE in Run 3

Large LS2 upgrade: continuous readout at high rate

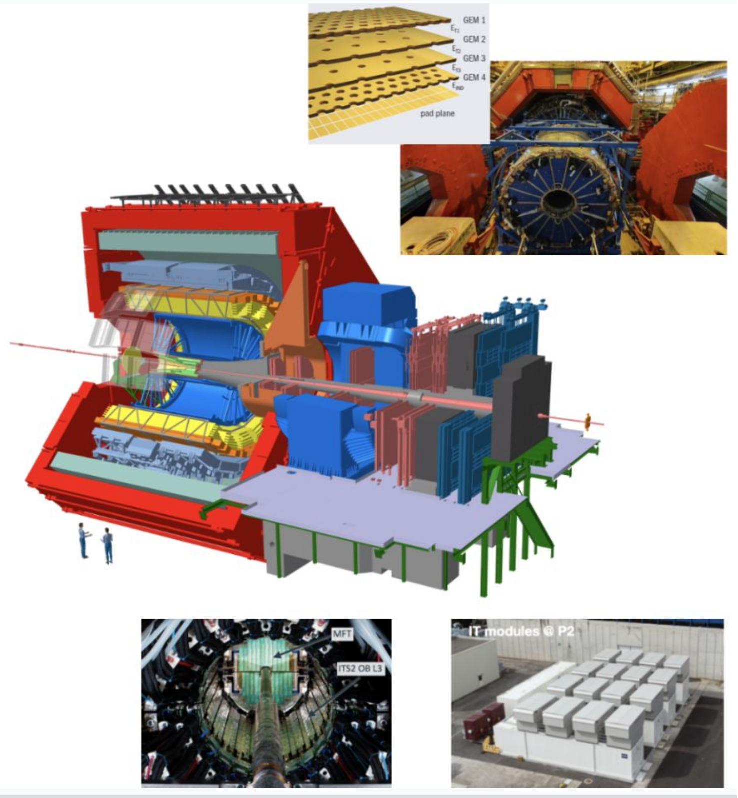
- Inner Tracking System (ITS) - full pixel layers
- Time Projection Chamber (TPC) - GEM redout
- New Forward Interaction Trigger, new Muon Forward Tracking
- New event processing farm
- Upgraded readout for most detectors
- New software - O2, O2Physics, new AF - Hyperloop

pp data taking at 500 kHz

- Intermediate storage on disk buffer
- Asynchronous offline trigger

Pb-Pb data taking at 50 kHz

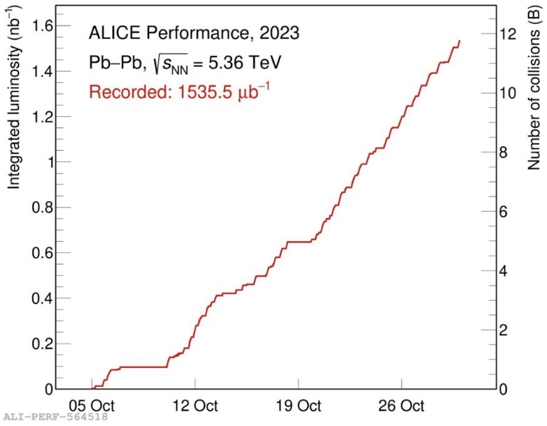
- All compressed time frame data stored on tapes

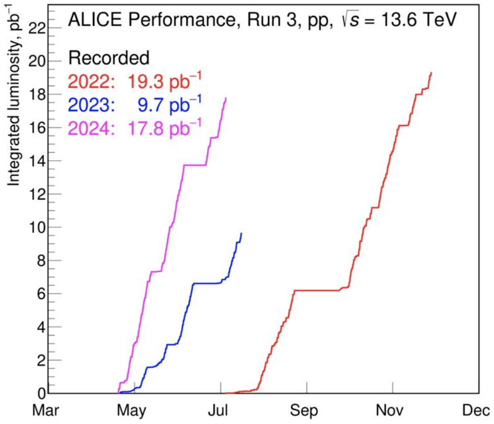


ALICE 2024 JINST 19 P05062

ALICE in Run 3 and Run 1, 2

Type	System	pp	p–Pb / Pb–p	Xe–Xe	Pb–Pb
Energy	(TeV)	0.9, 2.76, 7, 8, 5.02, 13/13.6	5.02, 8.16	5.44	2.76, 5.02/5.36
Run 1+2	L_{int}	200μb^{-1}, 100nb^{-1}, 1.5pb^{-1}, 2.5pb^{-1}, 1.3pb^{-1}, 25pb^{-1}	18 nb^{-1}, 25 nb^{-1}	30 μb^{-1}	75 μb^{-1}, 250 μb^{-1}
Run 3	L_{int}	~50pb^{-1}			1.6nb^{-1}

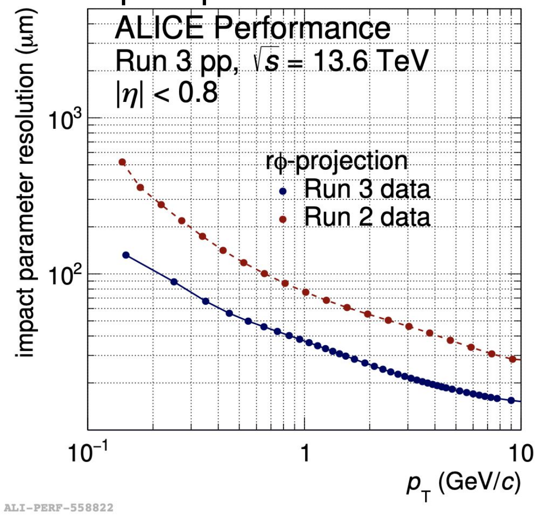




- Successful 2023 heavy-ion run
  - Collected 1.6nb^{-1} (approx 11.5 G minimum bias events)
- pp 2024: on track to record ~50pb^{-1} by the end of the year
  - ALICE operational efficiency: 95%
  - Run 3 = 1000 x Run 2 statistics

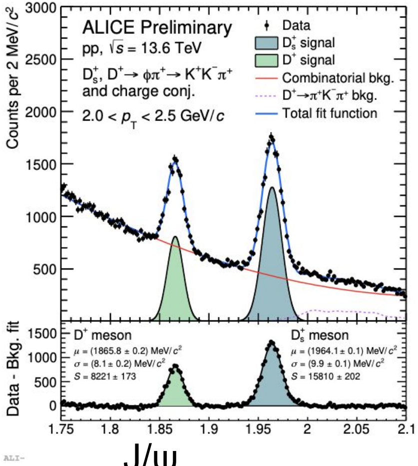
Run 3 physics performance - few examples

Impact parameter resolution

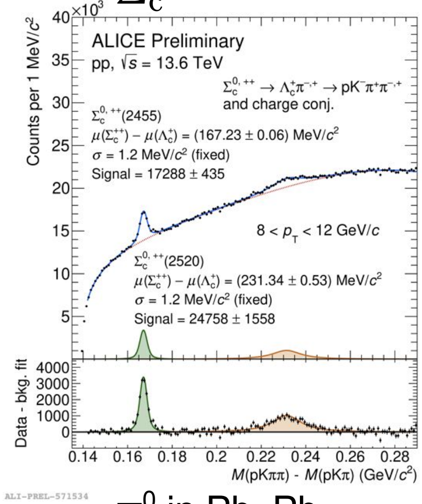


Alignment and calibrations ready for physics analysis

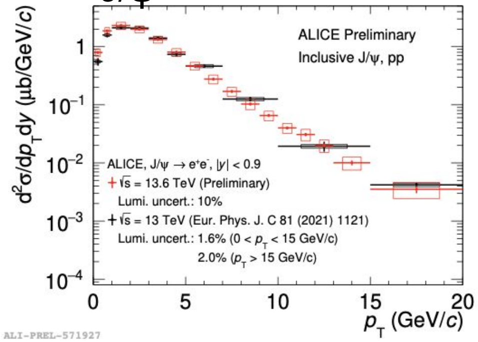
D mesons



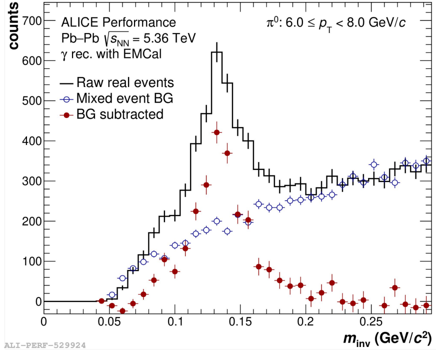
$\Sigma_c^{0,++}$



J/ψ

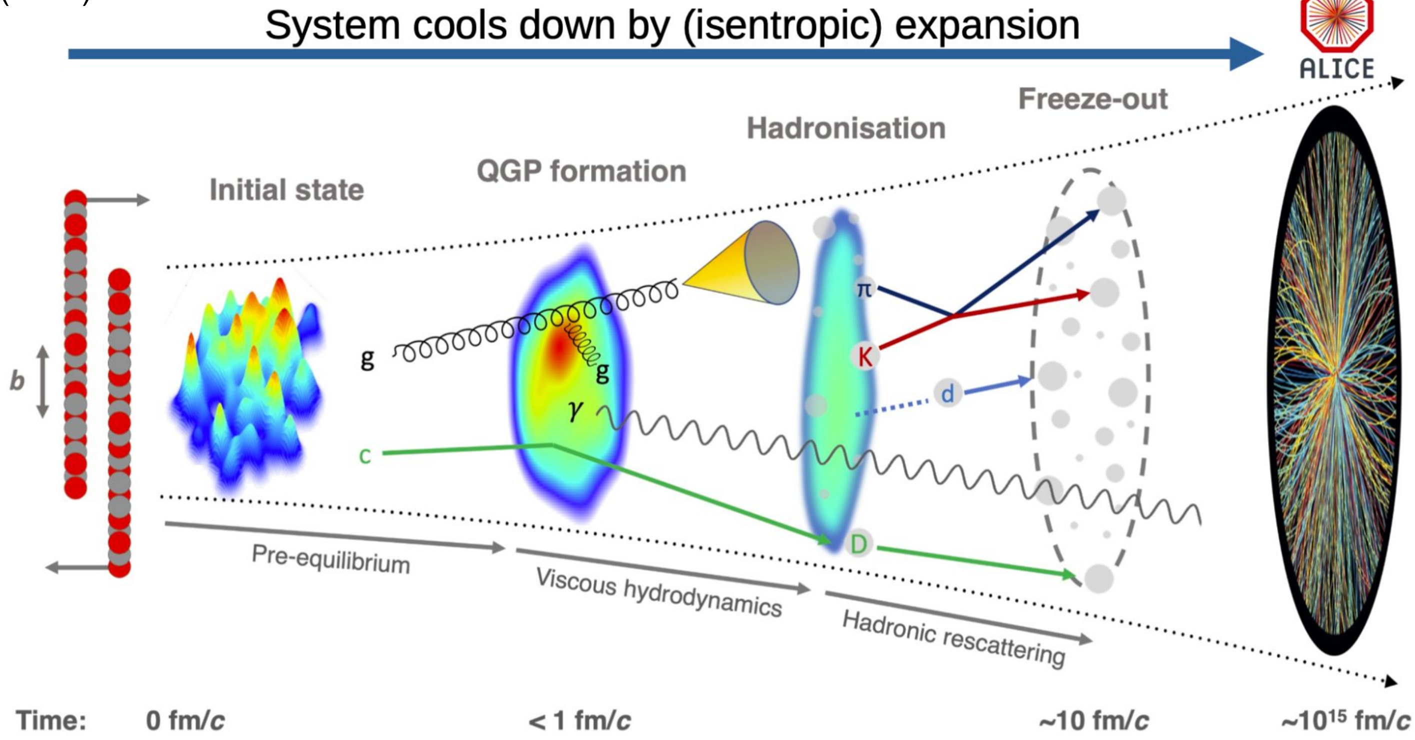


π^0 in Pb–Pb

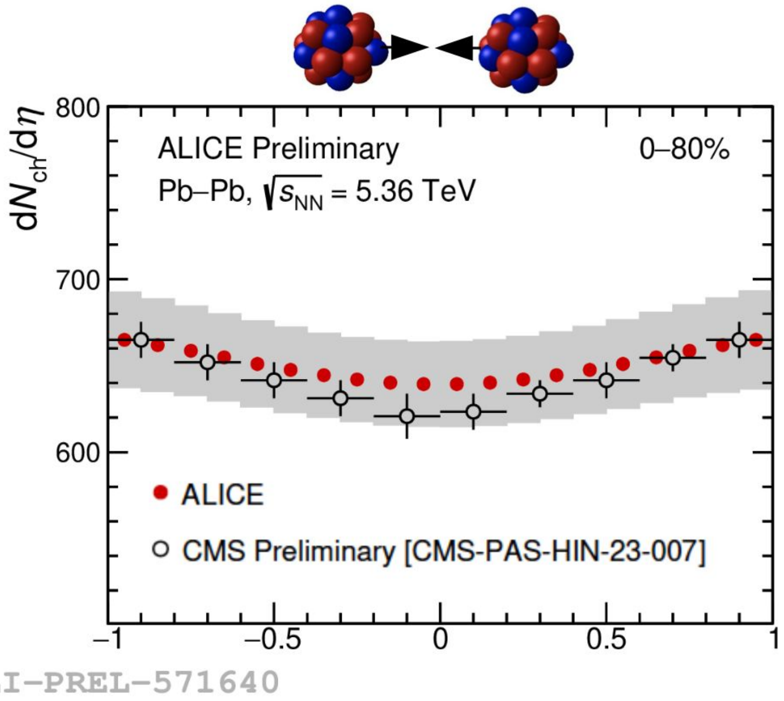


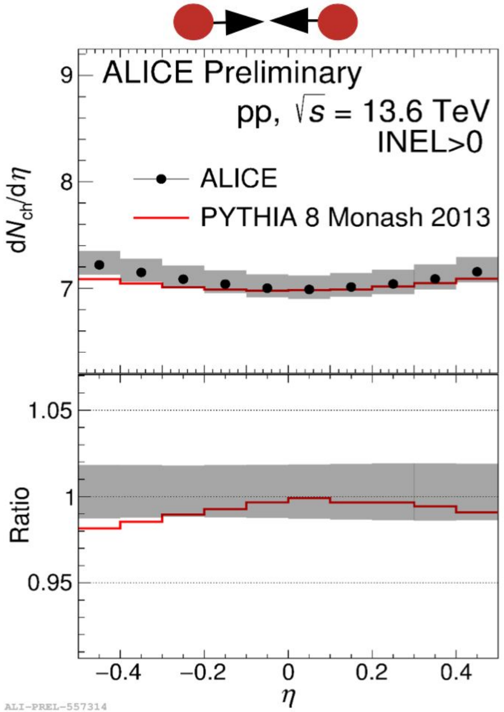
Heavy-ion collisions: quark–gluon plasma (QGP)

ALICE, EPJC 84 (2024) 813



dN_{ch}/dη in Run 3



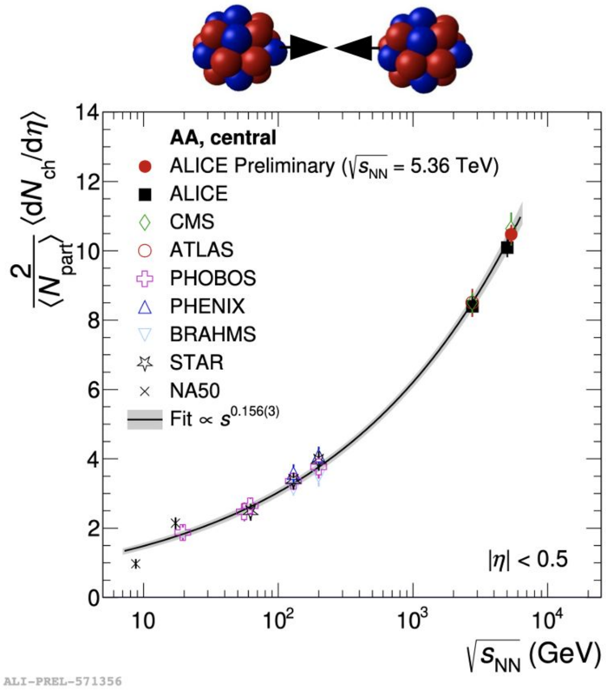


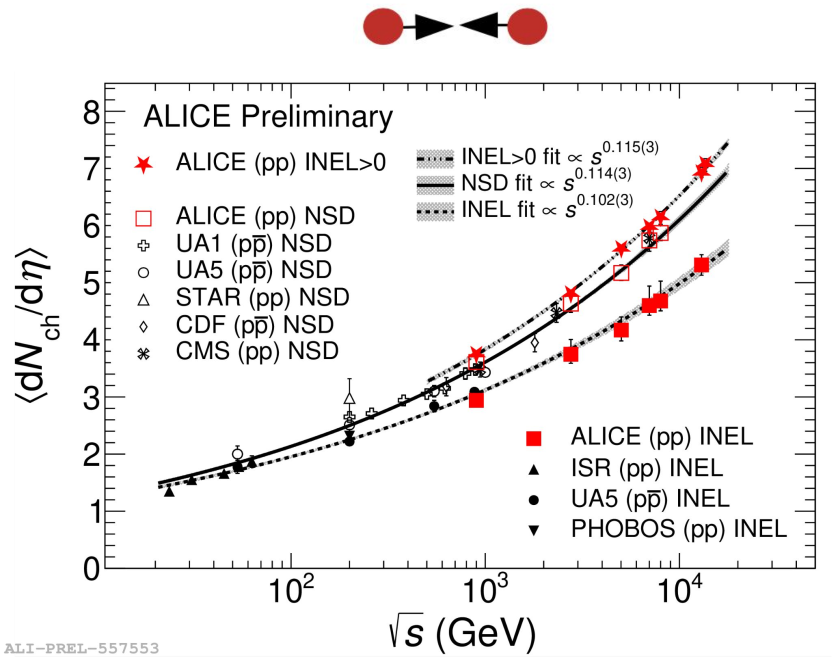
Constrain initial conditions and evolution of AA collisions

Constrain gluon saturation effects and nuclear shadowing

- dN_{ch}/dη measured at highest energy in Pb–Pb and pp collisions
- Magnitude and shape not fully described by MC calculations

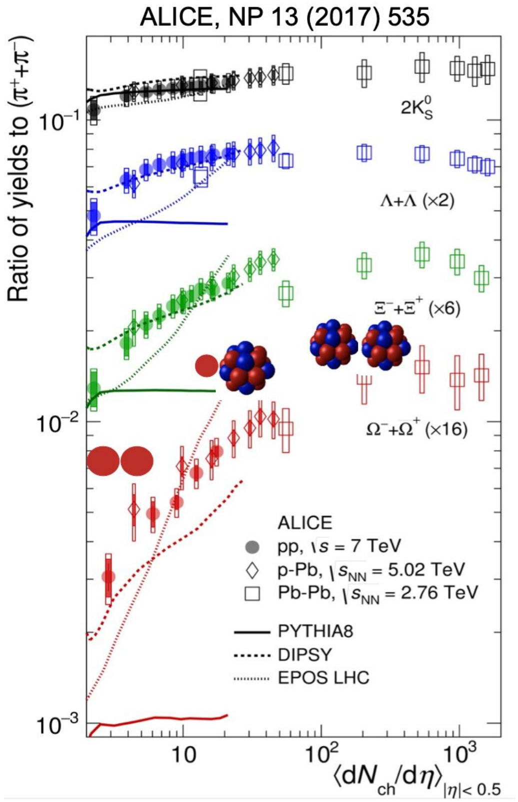
dN_{ch}/dη in Run 3

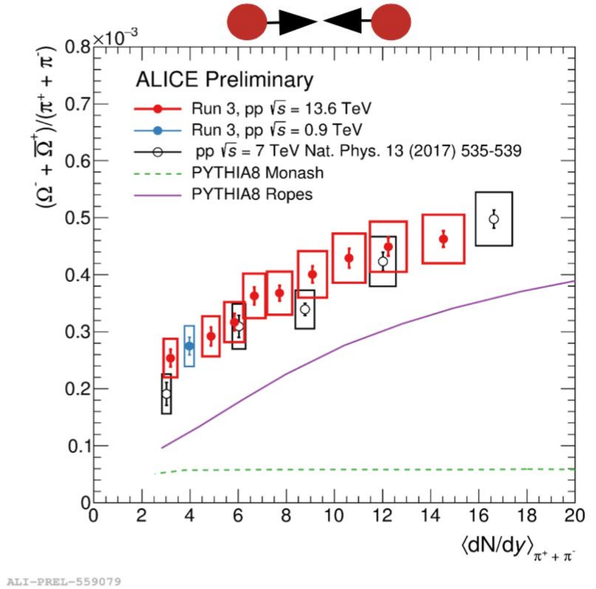




- $\sqrt{s_{NN}}$ dependence consistent with power law from lower energies
  - Grows faster in AA than in pp collisions

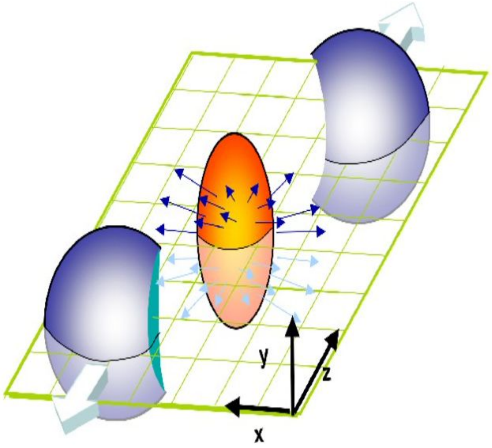
Strangeness enhancement



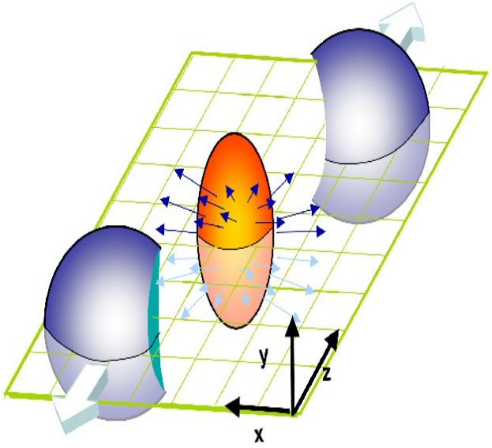


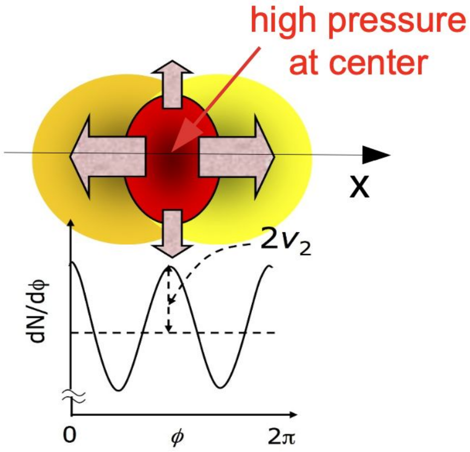
- Strangeness increases with multiplicity
  - Hierarchy with strangeness content
- More differential measurements in Run 3 → better constraints
  - pQCD-inspired models need extra mechanisms

Anisotropic flow



Anisotropic flow

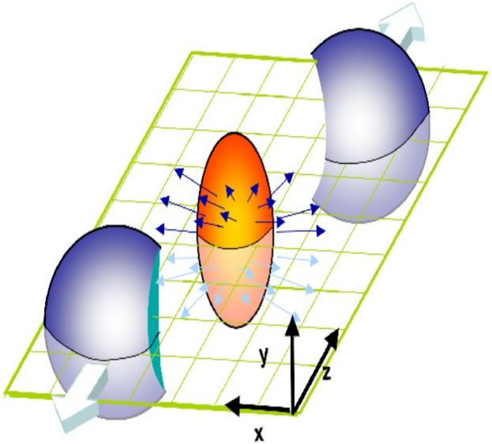


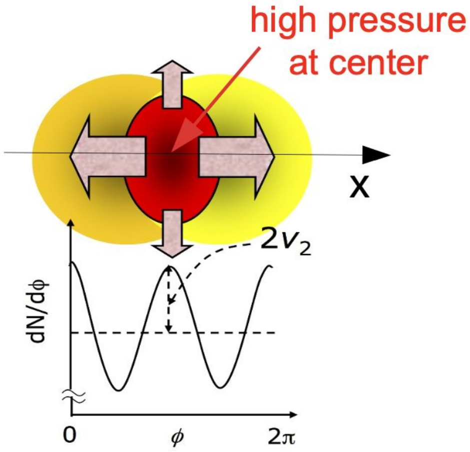


Pressure gradients (larger in the x direction) push bulk “out” → “flow”

More particles seen in the x-direction

Anisotropic flow





$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos(n(\varphi-\Psi_n))\right)$$

- Anisotropic flow: initial spatial anisotropy → final momentum anisotropy via collective interactions

Pressure gradients (larger in the x direction) push bulk “out” → “flow”

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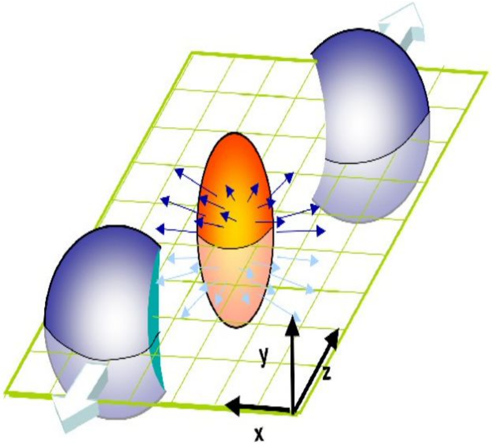
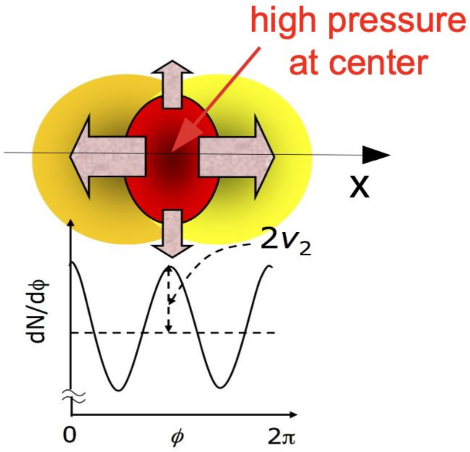
Anisotropic flow





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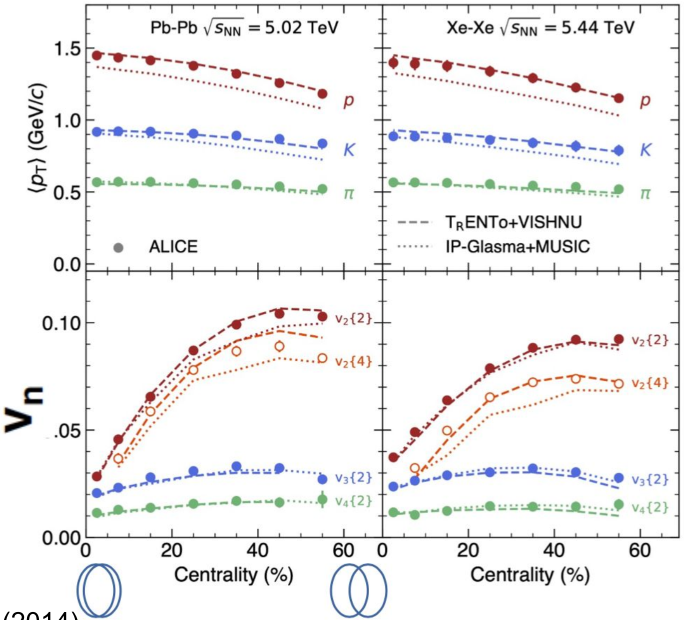
ALICE, EPJC 84 (2024) 813



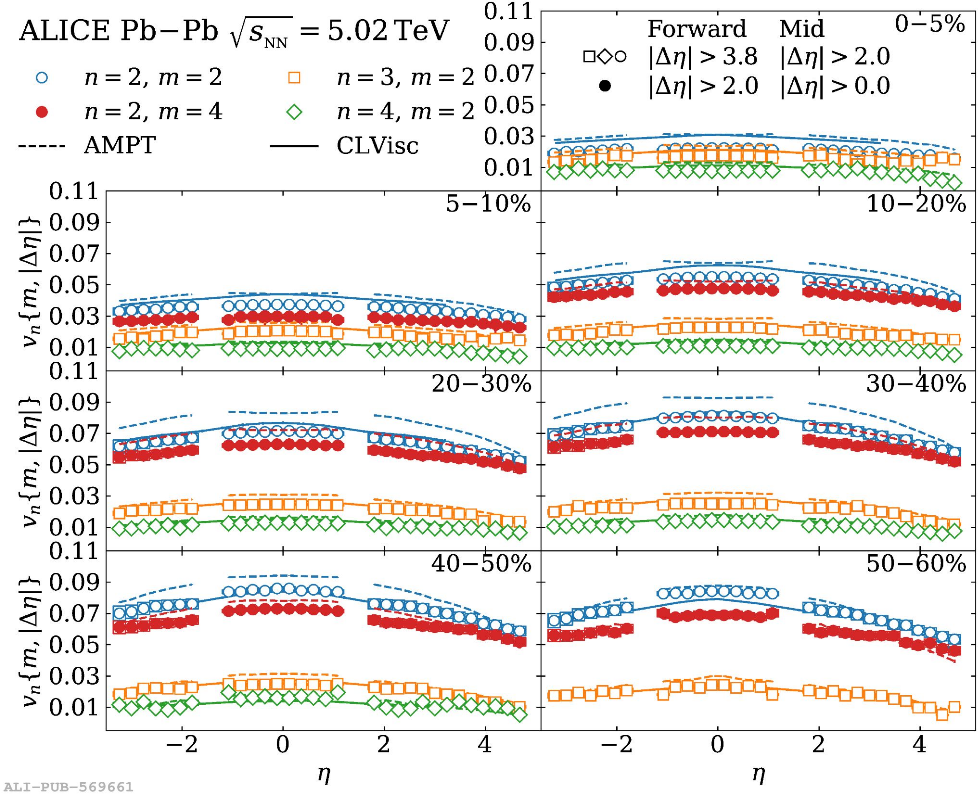
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+\sum_{n=1}^{\infty} 2v_n\cos\left(n\left(\varphi-\Psi_n\right)\right)\right)$$

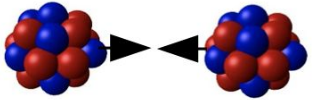
- Anisotropic flow: initial spatial anisotropy → final momentum anisotropy via collective interactions
  - v_n quantify the event anisotropy

TRENTo PRC 92 (2015) 011901
IP-Glasma PLB 772, 681 (2017), PRC 89, 024901 (2014)

Pseudorapidity dependence of anisotropic flow

ALICE, PLB 850 (2024) 138477





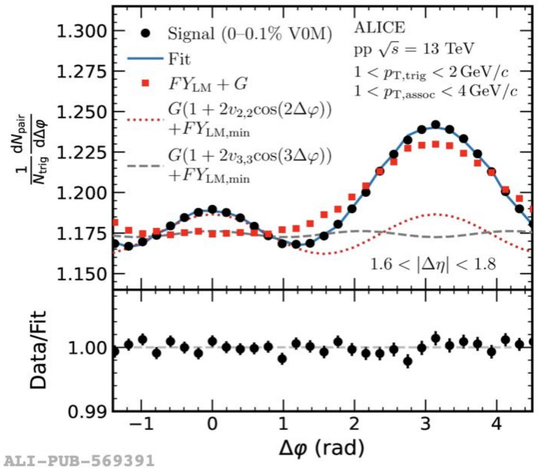
- Measurements of v_2, v_3, and v_4 coefficients are extended at large η
  - Hit-based analysis
- v_2 shows strong centrality dependence
- v_3 and v_4 reveal a modest centrality dependence
- Models overestimate the measured v_n coefficients
  - Constrain initial conditions

$$\frac{dN}{d\varphi} \sim 1 + \sum_{n=1}^{\infty} 2 v_n \cos(n(\varphi - \Psi_n))$$

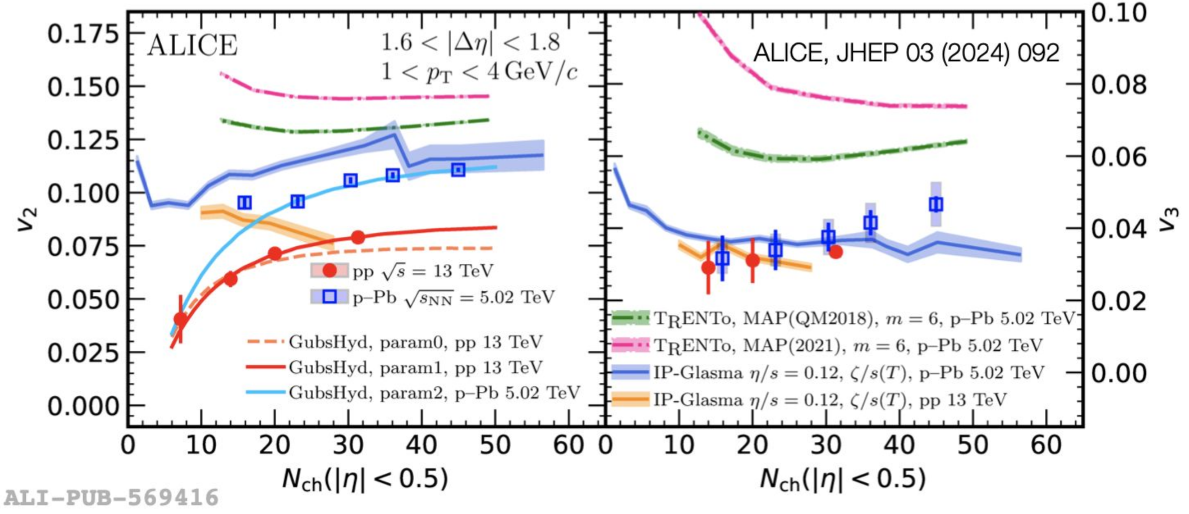
AMPT PRC 72 (2005) 064901, CLVisc PRC 98 (2018) 024913

Azimuthal anisotropy (flow) in pp and p–Pb collisions

Template fit $|\Delta\eta| > 1.6$



v_2 and v_3 vs multiplicity



Use $|\Delta\eta|$ gap and template fit to remove jet-signal

Both v_2 and v_3 persist down to small multiplicity

Gubs Hyd PRD 82 (2010) 085027, Nucl. Phys. B 846 (2011) 469

Azimuthal anisotropy (flow) in pp and p–Pb collisions

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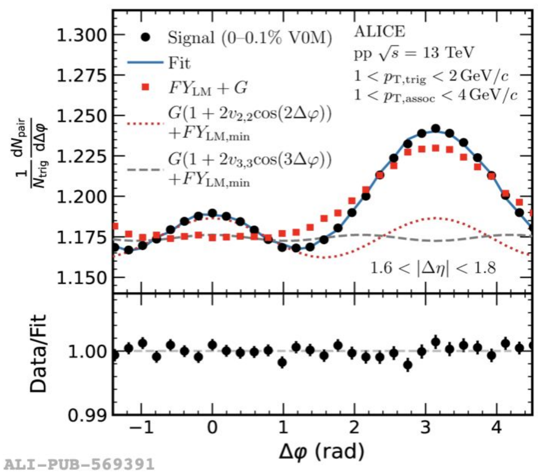
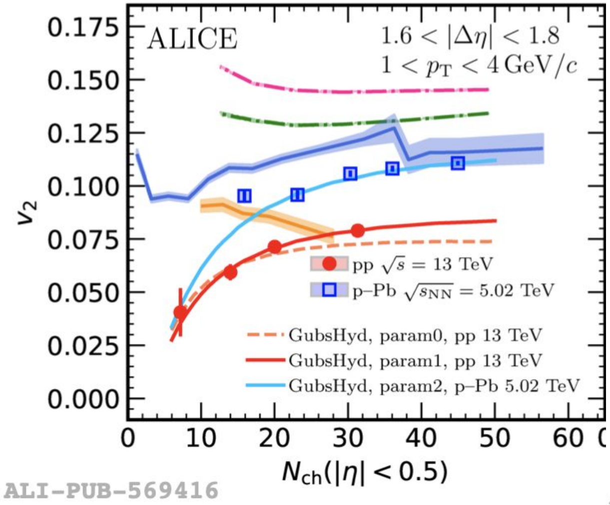
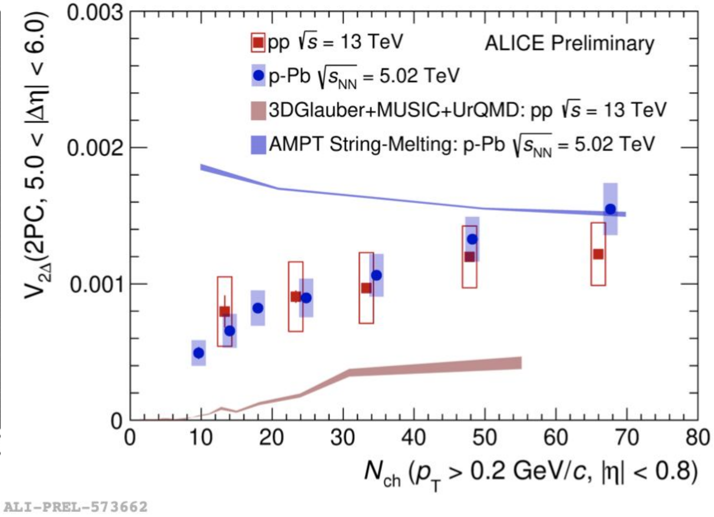


v_2 and v_3 vs



Large rapidity gap



Use $|\Delta\eta|$ gap and template fit to remove jet-signal

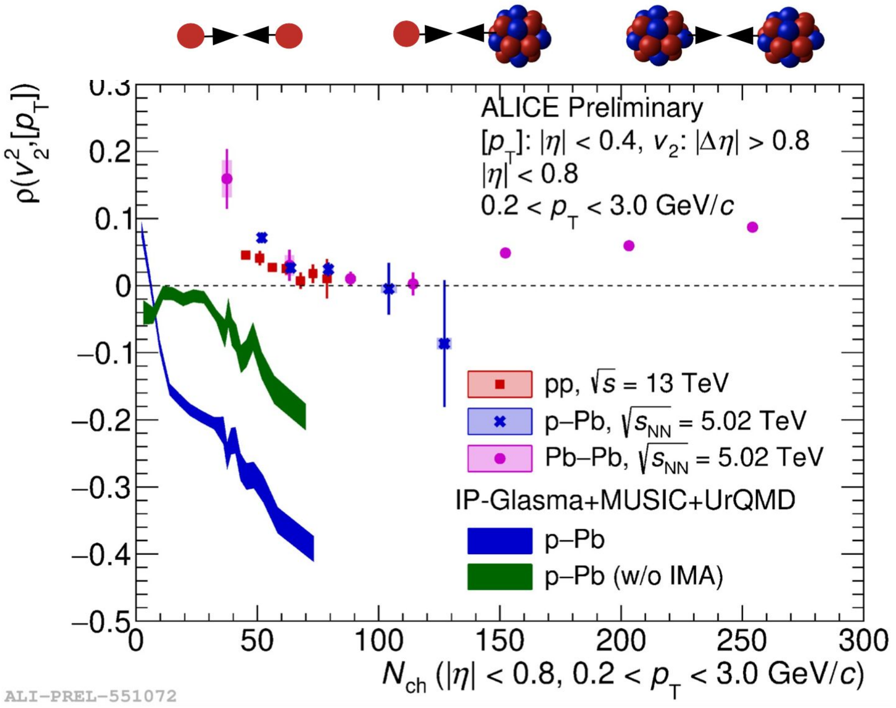
Both v_2 and v_3 persist down to small multiplicity

New results with $|\Delta\eta| > 5$ gap show significant v_2: long-range correlations

Gubs Hyd PRD 82 (2010) 085027, Nucl. Phys. B 846 (2011) 469

$$V_{2\Delta} \propto v_2^2$$

v_2^2-$[p_T]$ correlations



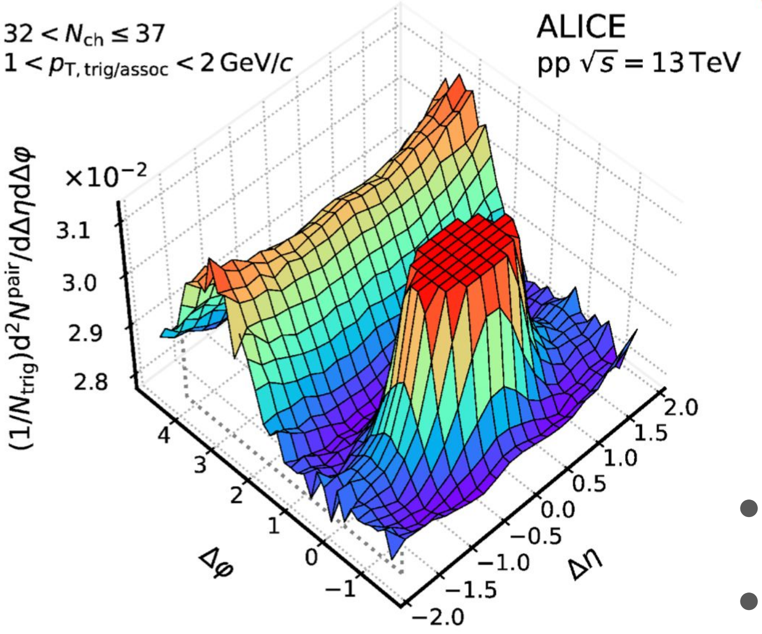
- Probe the initial stage
  - $\rho < 0$: geometric response
  - $\rho > 0$: Color Glass Condensate (CGC)
- Decreasing trend with increasing multiplicity in pp and p–Pb collisions
  - Not explained by simple geometry picture
  - Not described by a CGC-based hybrid model (w/wo initial momentum anisotropy)

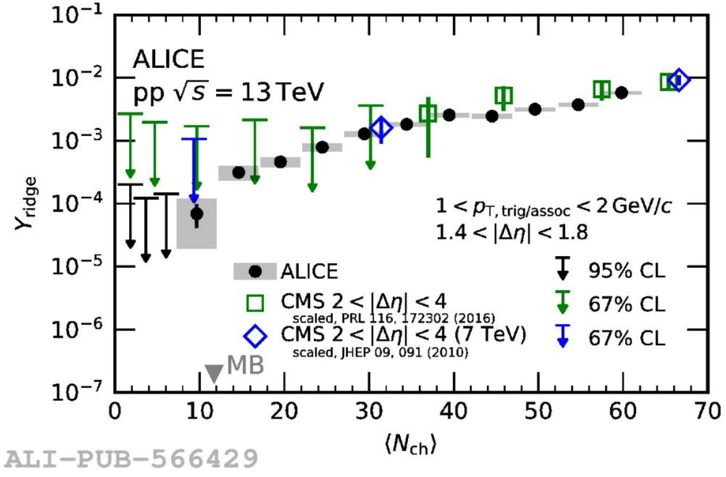
Pearson corr. coeff.

$$\rho(v_n^2, [p_T]) = \frac{\mathrm{Cov}(v_n^2, [p_T])}{\sqrt{\mathrm{Var}(v_n^2)}\sqrt{c_k}}$$

Ridge yields

ALICE, PRL 132 (2024) 172302

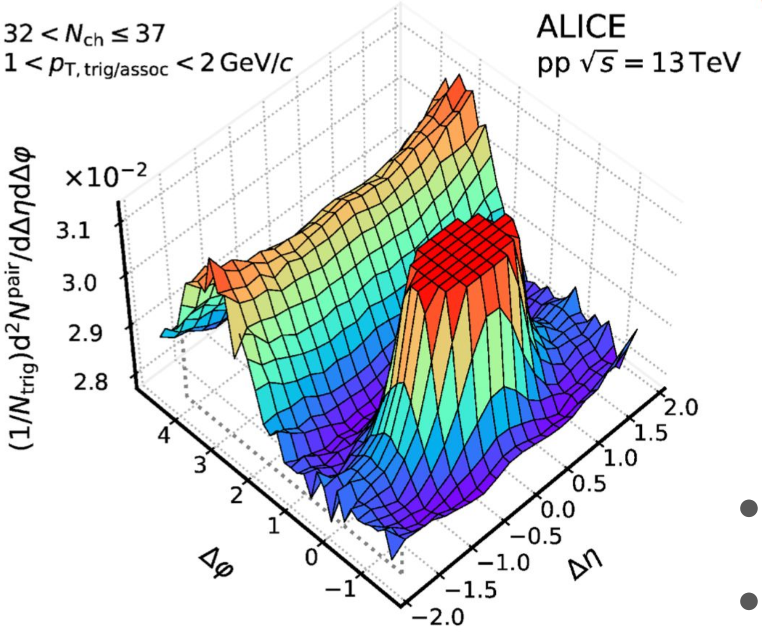


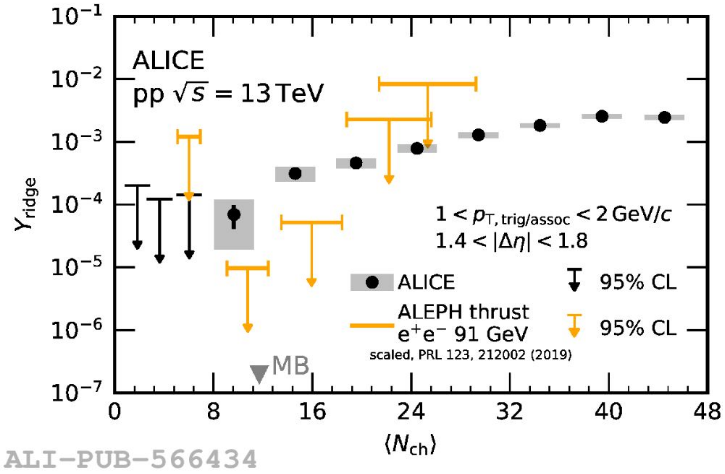


- Ridge yields to study collective effects down to low multiplicities
- Strong multiplicity dependence
  - Good agreement with CMS results

Ridge yields

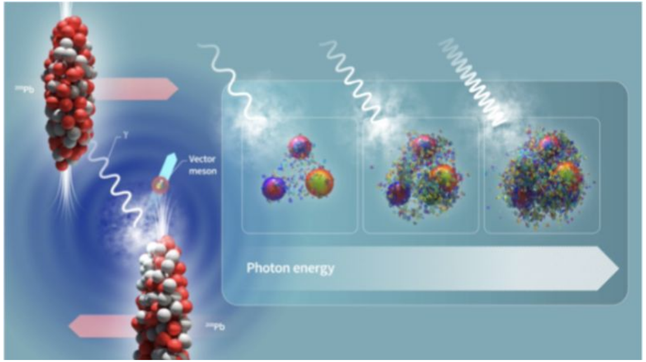
ALICE, PRL 132 (2024) 172302

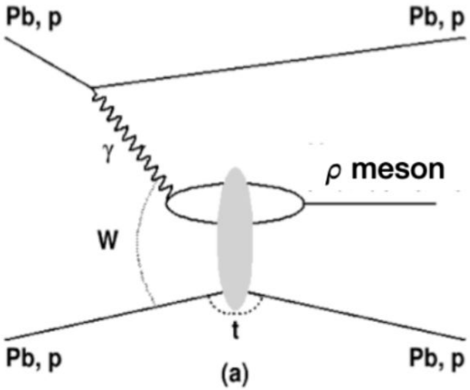




- Ridge yields to study collective effects down to low multiplicities
- Strong multiplicity dependence
  - Overlap with e^+e^- results from ALEPH at $\sqrt{s}$ = 91 GeV → Large differences between pp and e^+e^- results for $N_{ch} < 18$

Ultra-peripheral heavy-ion collisions at the LHC





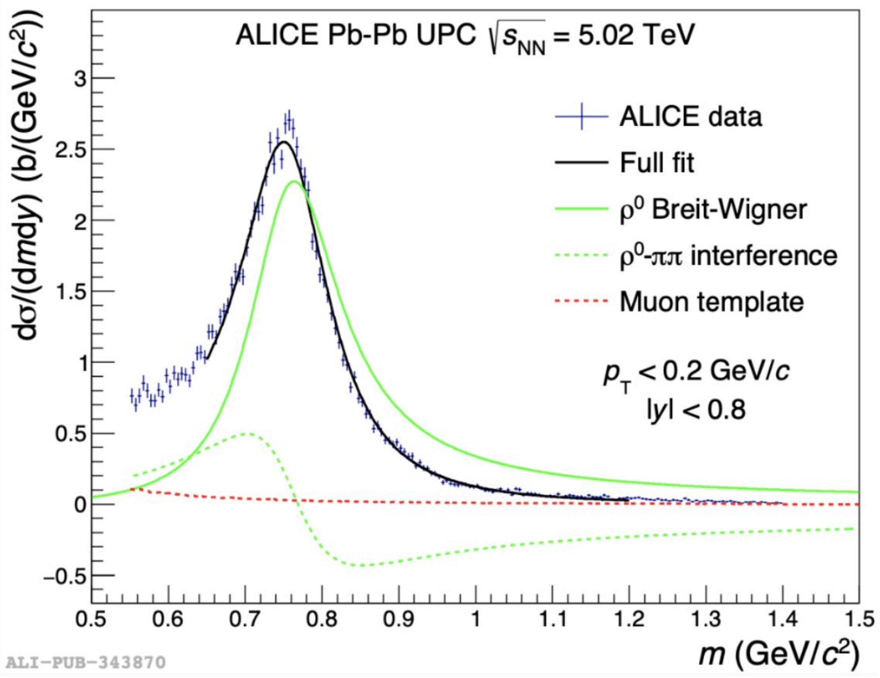
EM field from ultra-relativistic ions: **a beam of quasi real photons** (intensity ≈ Z^2)

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

Vector meson photoproduction: photon fluctuates to a dipole which then elastically scatters off the nucleus, emerging as vector meson

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

ALICE, JHEP 06 (2020) 035

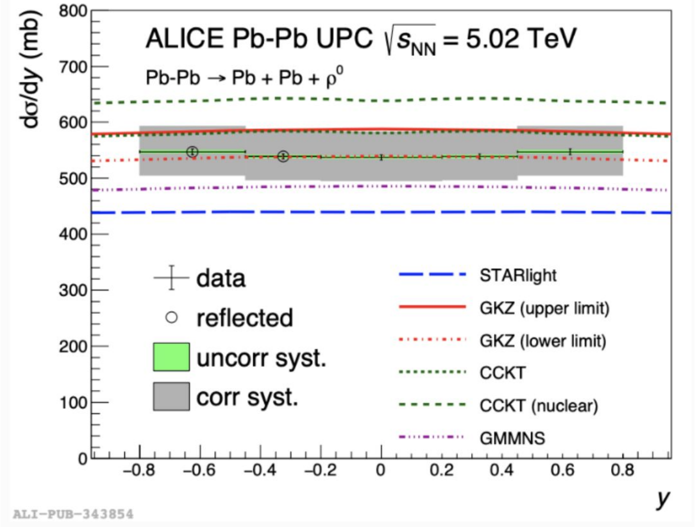


- Interference of $\rho^0(770) \rightarrow \pi\pi$ and continuum of direct $\pi\pi$
- Clear signal for the ρ^0 vector meson
- Small contribution from the $\gamma\gamma \rightarrow \mu^+\mu^-$ process
- Not included production of ω vector mesons

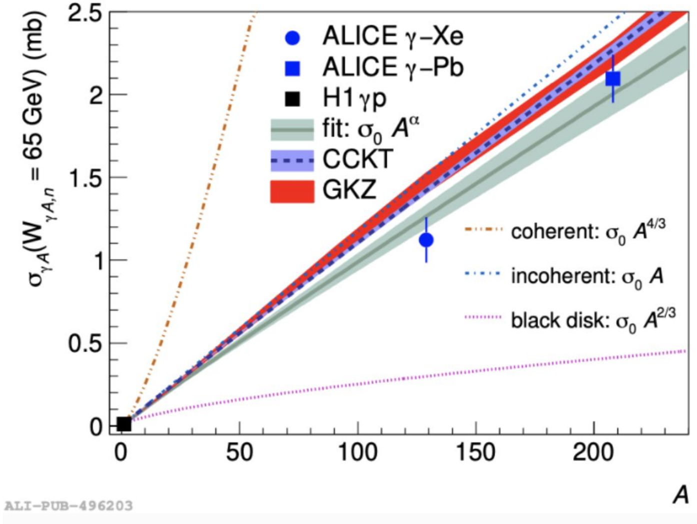
m = 769.5±1.2 (stat.) ± 2.0 (syst.) MeV/c^2
Γ = 156±2 (stat.) ± 3 (syst.) MeV/c^2

Coherent $\rho^0(770)$ photoproduction

ALICE, JHEP 06 (2020) 035



ALICE, PLB 820 (2021) 136481

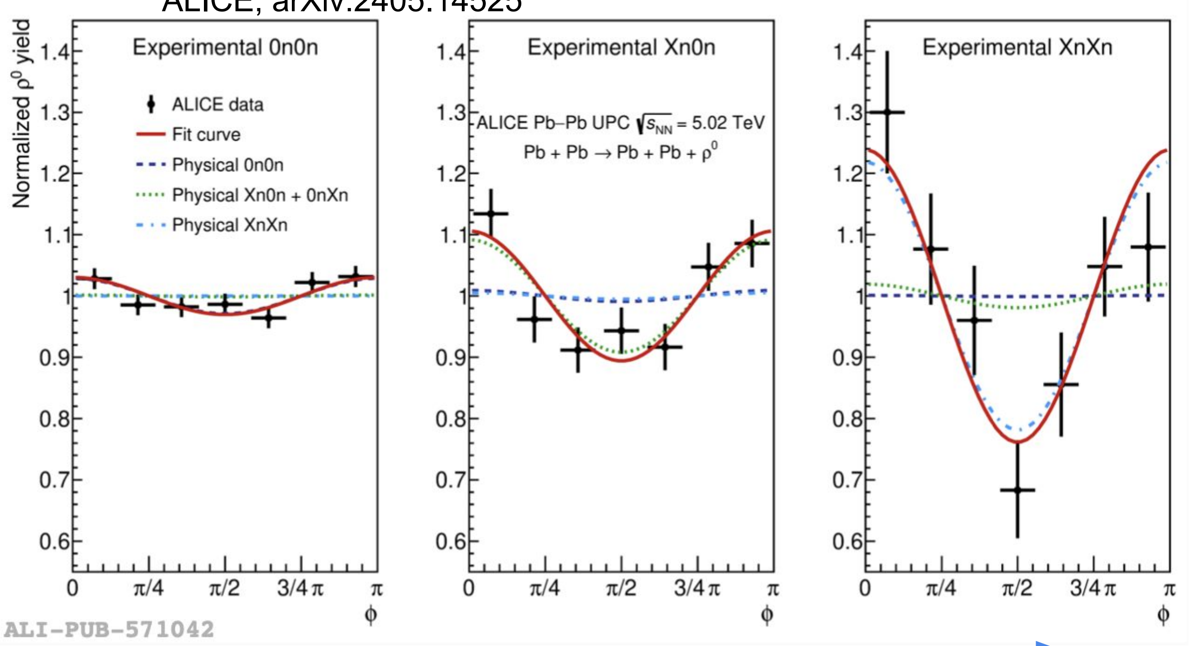


- Measured cross section of coherent photoproduction shows good agreement with model predictions
- Xe measurement: models slightly overestimate the measurement
- Atomic number (A) dependent γA cross section, $\sigma(\gamma A \rightarrow \rho^0 A) \propto A^\alpha$ with $\alpha = 0.96 \pm 0.02$
  - **substantial nuclear effects**

CCKT PLB 766 (2017) 186–191, Nucl. Phys. B 934 (2018) 330–340
GKZ PLB 782 (2018) 251–255
GMMNS PRD 96 (2017) 094027

Angular anisotropy in ρ(770) → $\pi^+\pi^-$ in different neutron emission classes

ALICE, arXiv:2405.14525

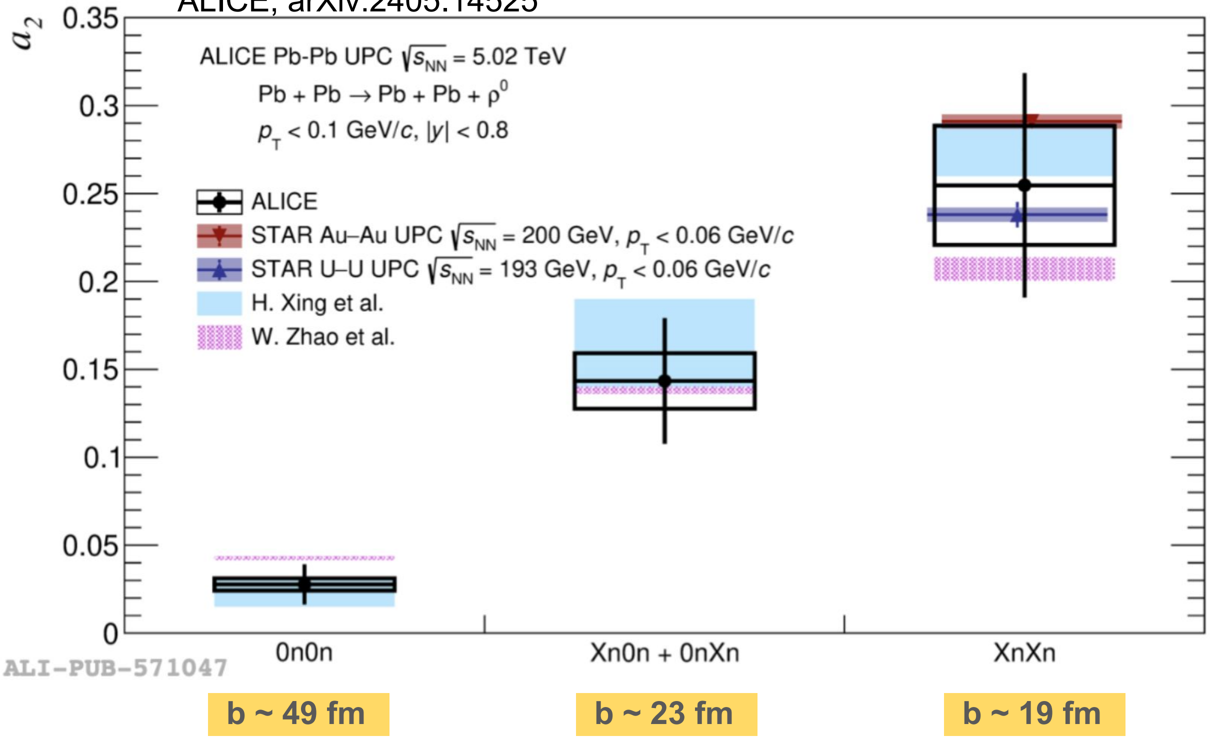


More neutrons ⇒ smaller impact parameter

- Azimuthal asymmetry due to interference and polarization effects increases with decreasing impact parameter

Impact parameter dependent angular anisotropy

ALICE, arXiv:2405.14525



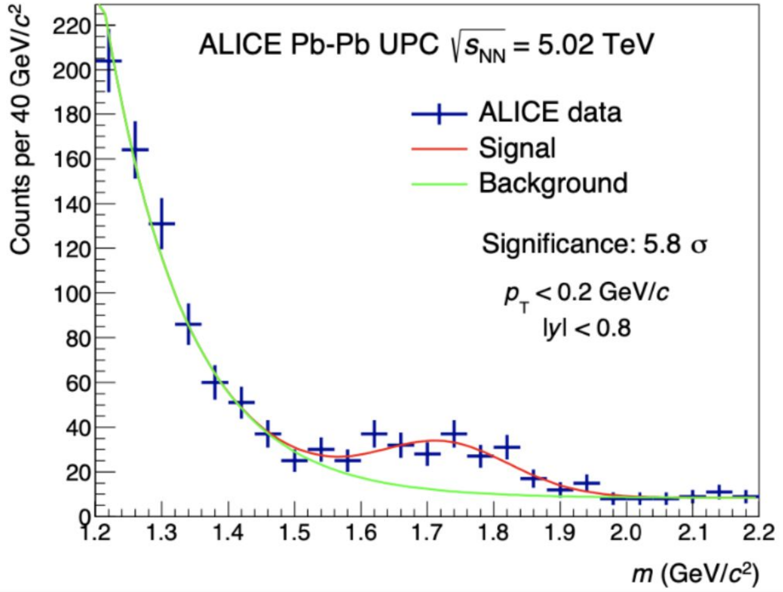
First time measurement of the angular anisotropy in photoproduced $\rho(770) \rightarrow \pi^+\pi^-$ as a function of the impact parameter (***b***)

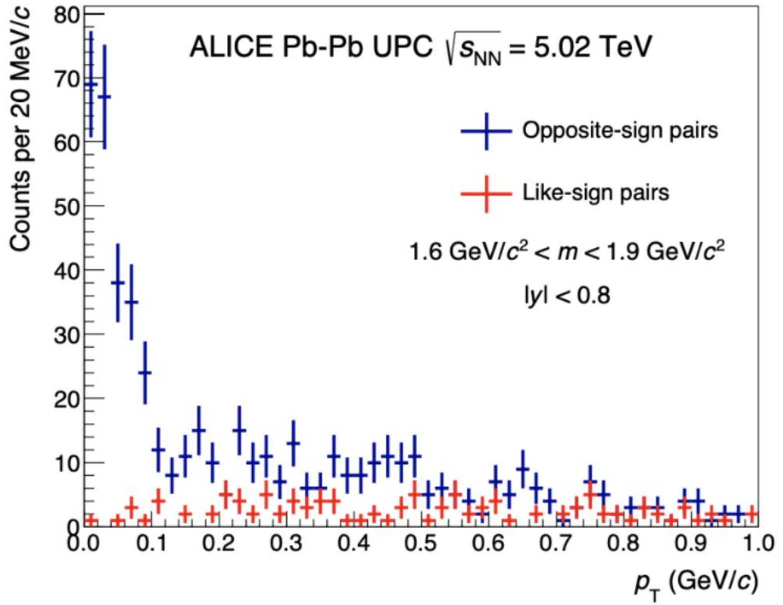
The strength of modulation increases by about one order of magnitude from large to small ***b***

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, PLB 820 (2021) 136481

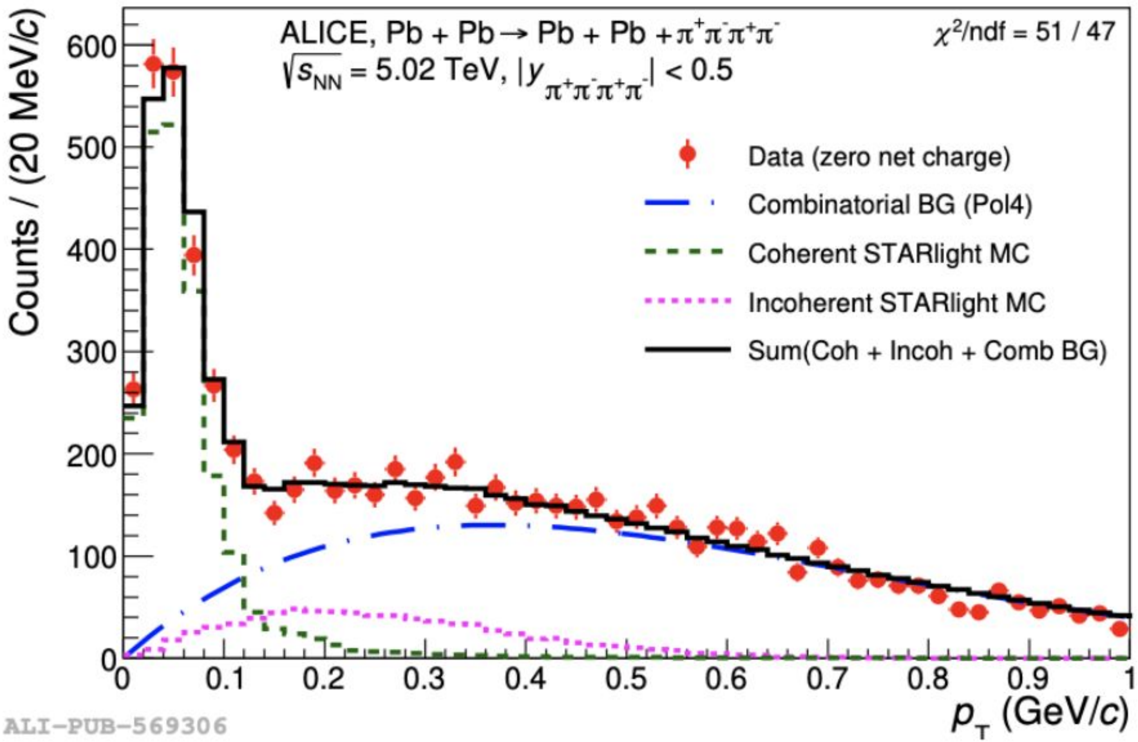




- Resonance-like structure observed in $\pi^+\pi^-$ invariant mass distribution → likely to be from coherent photoproduction
- Known excited states in PDG: ρ(1450), ρ(1700), ρ_3(1690)

Exclusive four pion photoproduction

ALICE, arXiv:2404.07542



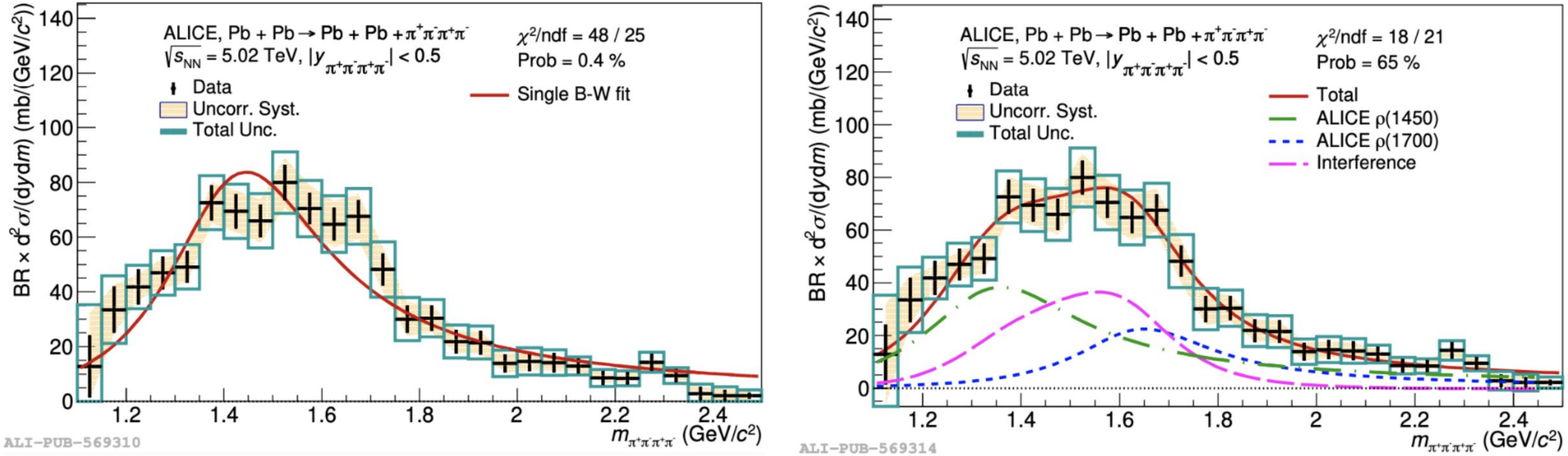
STARlight Comput. Phys. Commun. 212, 258 (2017)

Low p_T selects coherent production

UPC events provide a clean laboratory for vector meson spectroscopy

Exclusive four pion photoproduction

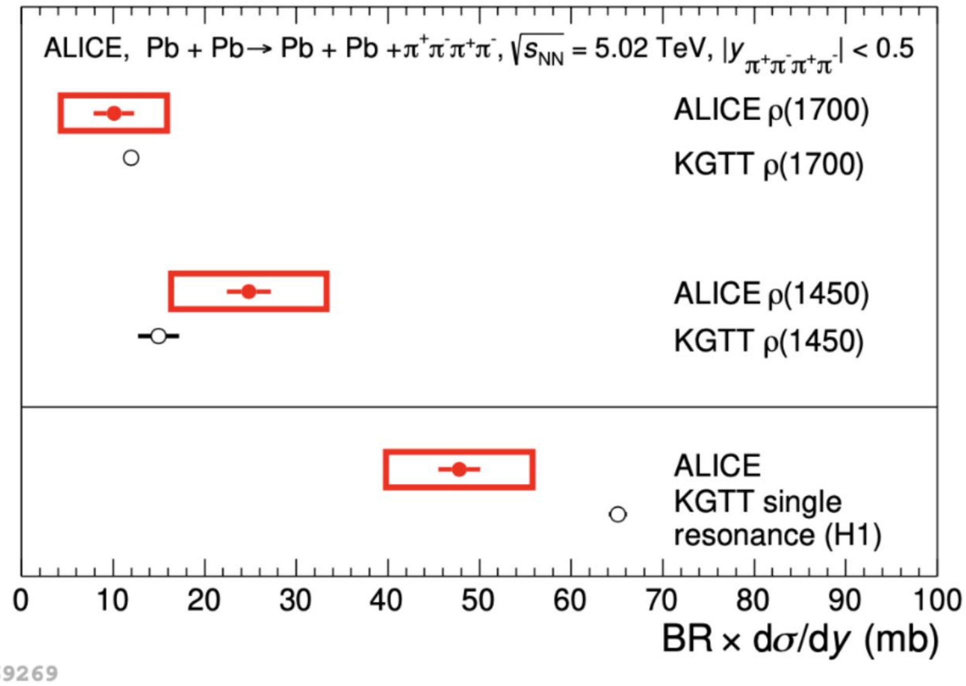
ALICE, arXiv:2404.07542



- 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 ρ(1450)
- Two interfering resonances with a mixing angle: compatible with PDG ρ(1450) and ρ(1700); hypothesis is favored by the measurement

Total cross-section for resonance(s)

ALICE, arXiv:2404.07542



The total cross section based on single resonance scenario, as well as two interfering ρ(1450) and ρ(1700) obtained

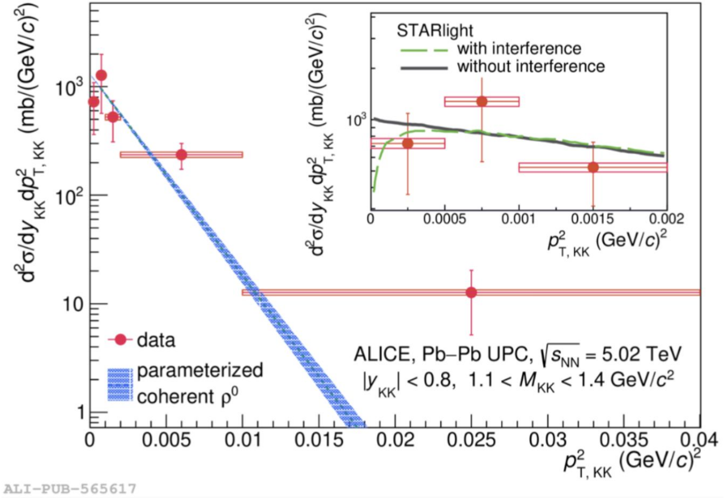
Due to the large interference component, the sum of ρ(1450) and ρ(1700) cross sections is smaller than the total cross section

The cross sections for ρ(1450) and ρ(1700) give better agreement with theoretical calculations KGTT

KGTT Acta Phys. Polon. B 51 (2020) 1393

Exclusive K^+K^- photoproduction

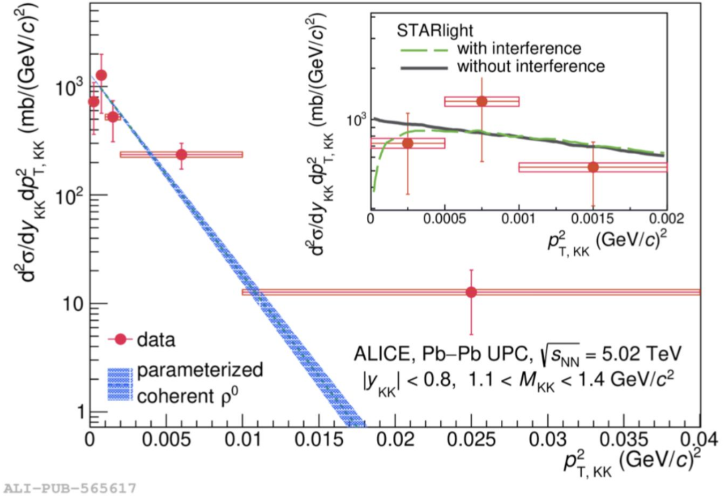
ALICE, PRL 132, 222303 (2024)

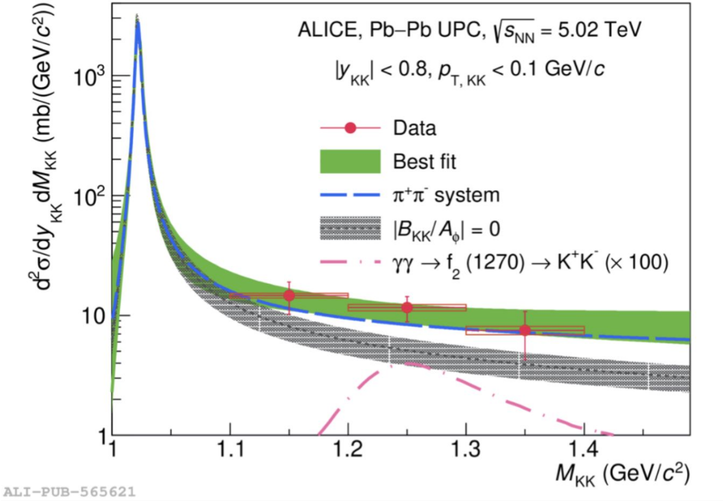


- First measurement of photoproduction of K^+K^- pairs in UPC
- Significant K^+K^- production at low $p_T \rightarrow$ coherent photoproduction on Pb-target

Exclusive K^+K^- photoproduction

ALICE, PRL 132, 222303 (2024)

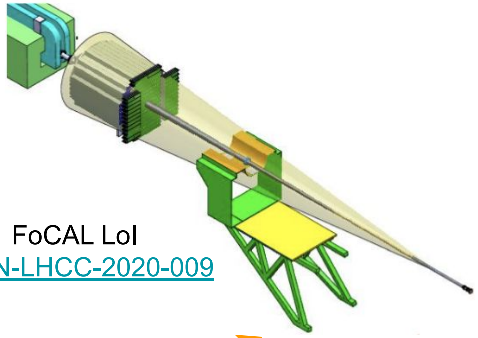




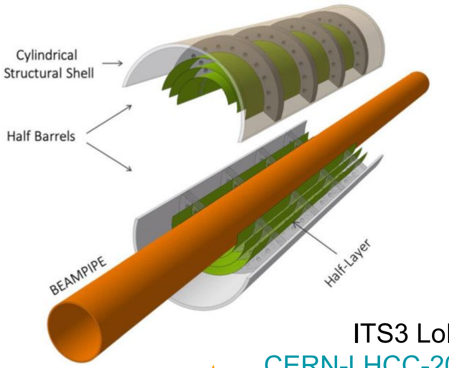
- First measurement of photoproduction of K^+K^- pairs in UPC
- Significant K^+K^- production at low p_T → coherent photoproduction on Pb-target

- Larger cross-section than expected for φ(1020) photoproduction alone → mixture of φ(1020) and direct K^+K^- production

Upgrade projects



FoCAL LoI
CERN-LHCC-2020-009



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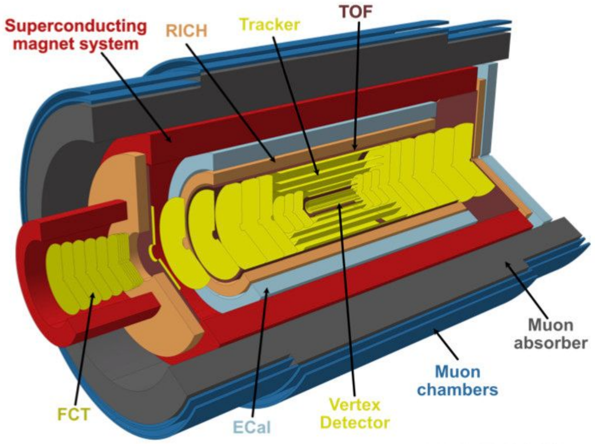
CERN-LHCC-2019-018



ALICE3 LoI
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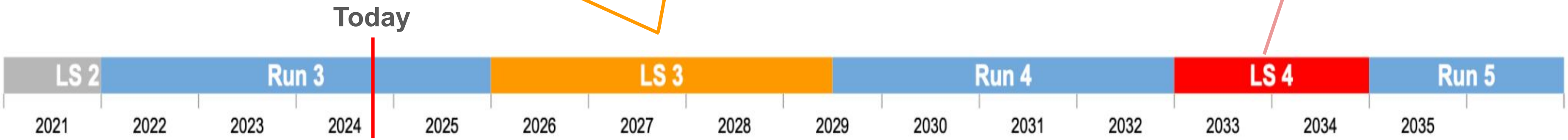

Summary

- LS2 upgrades functioning very well — high data taking efficiency in 2024

- Collectivity and strangeness enhancement in small systems
  - Develop new techniques and more differential measurements
    - Pushing the limits to understand the responsible mechanism(s)

- UPC events ~ clean laboratory for vector meson spectroscopy
  - ρ(770) and resonances photoproduction
  - First investigations of direct K^+K^- photoproduction in heavy-ion collisions