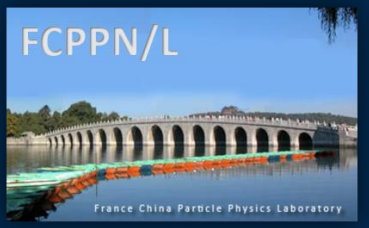
# ALICE highlights

**Nicole BASTID**
**Laboratoire de Physique Clermont Auvergne, IN2P3-CNRS, UCA, France**

- Disclaimer: only a selection can be presented (time constraint)
- Main focus:
  - Bulk properties
  - Light flavours
  - Open heavy flavours and quarkonia
  - Jets (see Y. Mao) & photons (see G. Conesa-Balbastre)

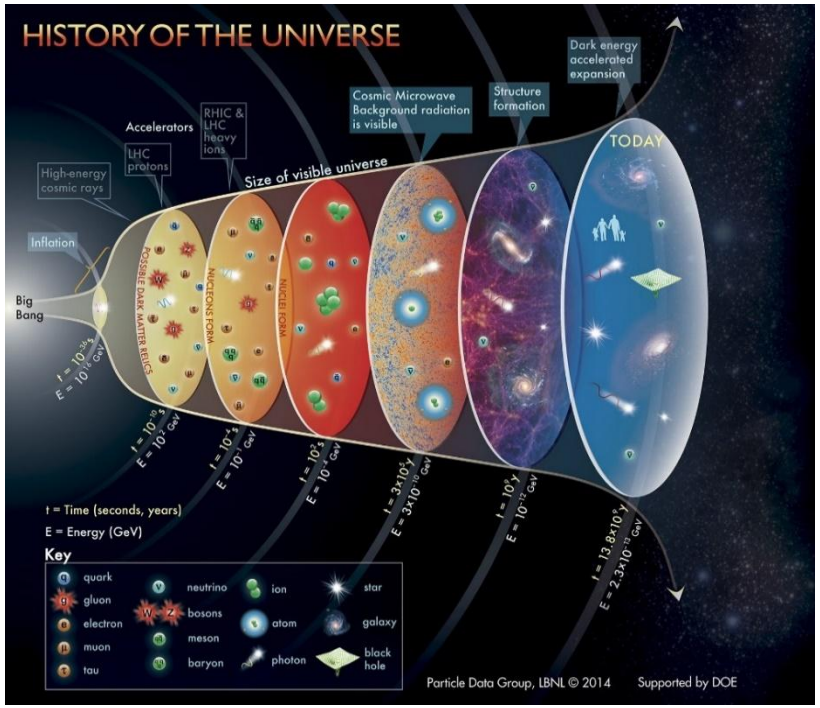


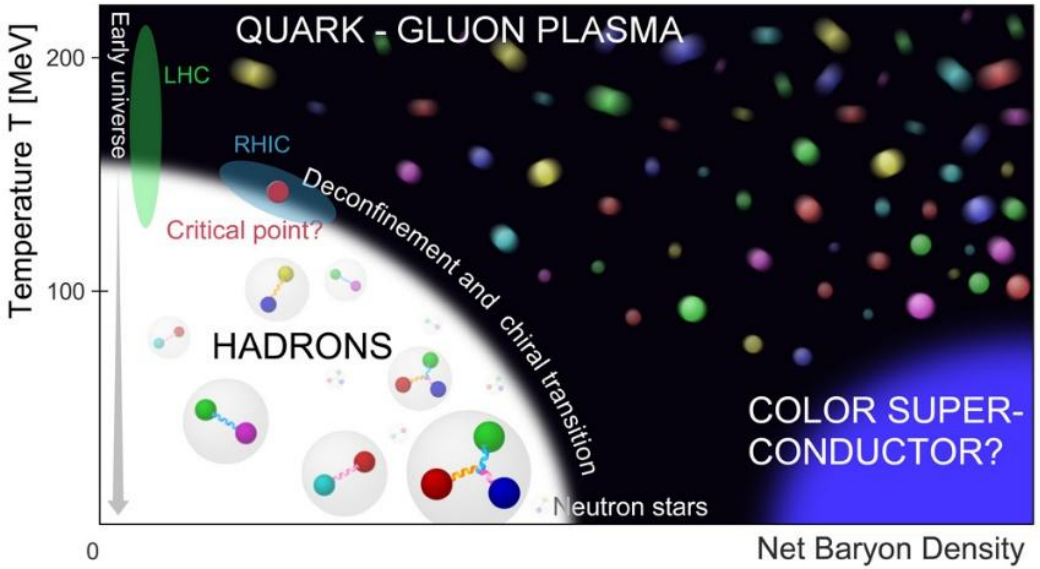
# Scientific context: the quark-gluon plasma (QGP)

Quark-Gluon Plasma (QGP):

- State of strongly-interacting matter at extreme conditions in which quarks and gluons are no more confined into hadrons
- Predicted by QCD: $T_c$ ~ 155 MeV, $\varepsilon_c$ ~ 0.5 GeV/fm$^3$

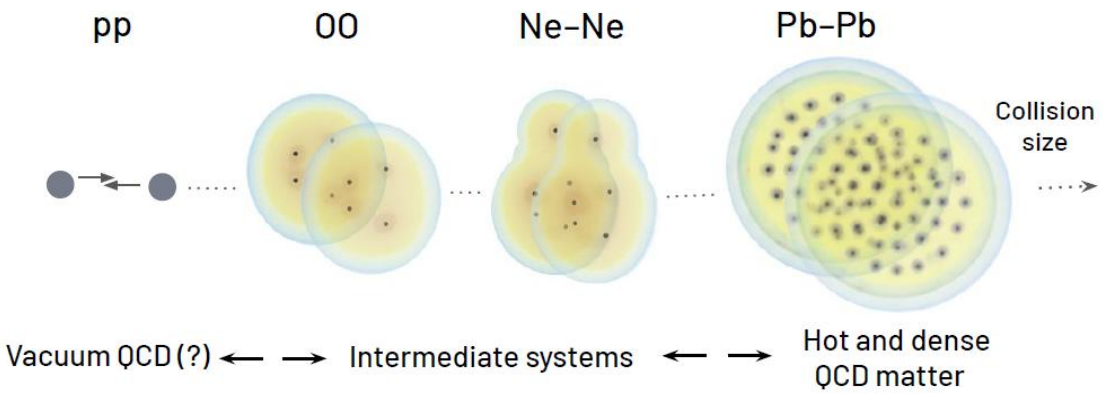
- A QGP state can be created using ultrarelativistic heavy-ion collisions
- Studied at the LHC with **ALICE**, the dedicated experiment for heavy-ion physics



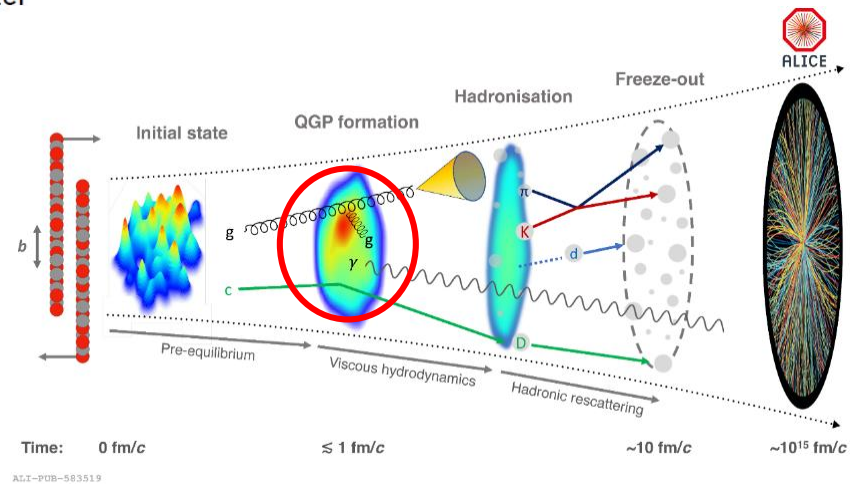




*Eur. Phys. J. C 84 (2024) 813*

# Motivations




- **Heavy-ion collisions**: study the various phases of heavy-ion collisions & QGP properties
  - ✓ Bulk properties
  - ✓ Medium response & transport properties, hadronisation
  - ✓ Collective effects



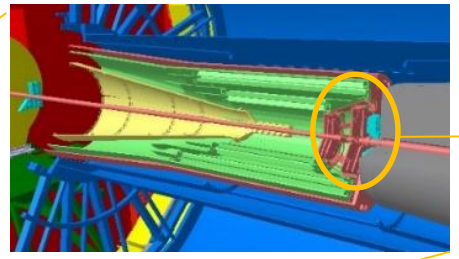

- **Light-ion collisions (NEW in Run 3)**:
  - ✓ Does the evolution of a heavy-ion collision hold for light ions?
  - ✓ Unique opportunity to investigate the onset of QGP

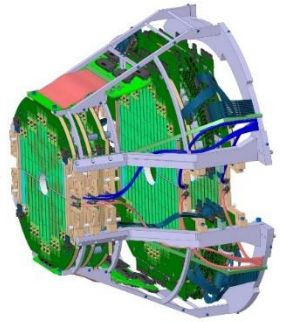
- **Small collision systems**:
  - ✓ Reference
  - ✓ Disentangle initial-state effects & final-state effects (pA)
  - ✓ Probe collective-like effects

# ALICE setup during the Run 3

- Major upgrades during LS2
- Taking data in Run 3: mid 2022-June 2026

**Inner Tracking System ($ITS_2$)**
Improved pointing resolution at midrapidity



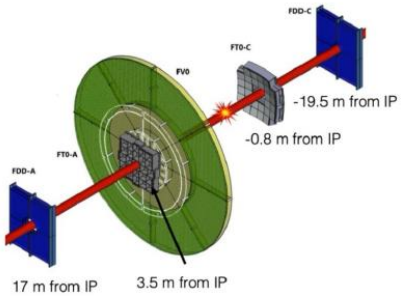


**New Muon Forward Tracker (MFT)**
Vertexing at forward rapidity

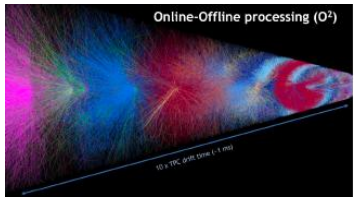
**New GEM-based TPC**

**Upgraded readout for most subdetectors**

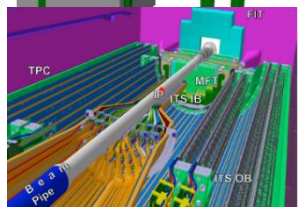





**Fast Integration Trigger**




**Integrated Online-Offline system ($O^2$)**

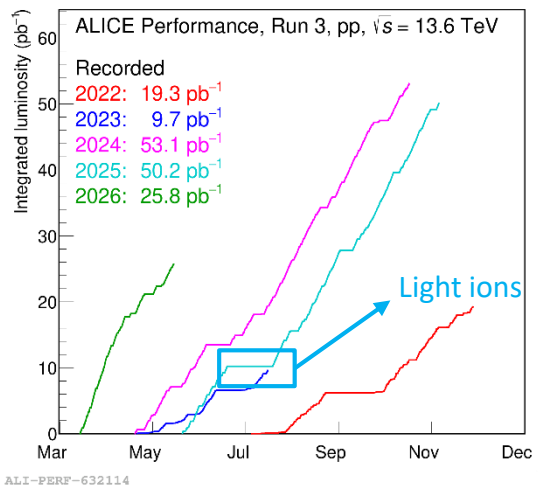



**New beam pipe**

*JINST 19 (2024) 222303*

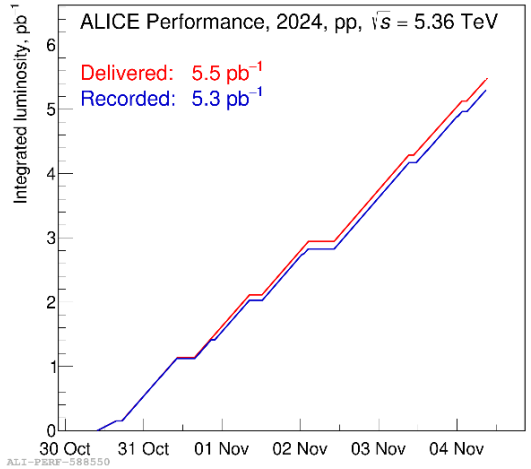
# ALICE data taking in Run 3

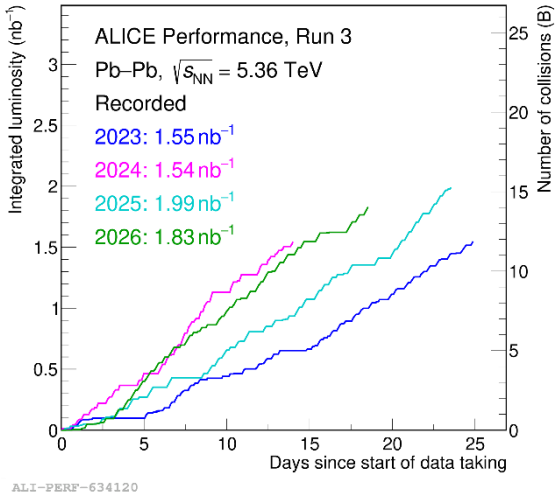
- Large interaction rates: up to 750 kHz in pp & up to 50 kHz in Pb-Pb
- Continuous readout mode
  - Dedicated software triggers in pp collisions




~$8 \cdot 10^{12}$ MB → **~150 pb$^{-1}$**

x **1000 more MB** than Runs 1+2

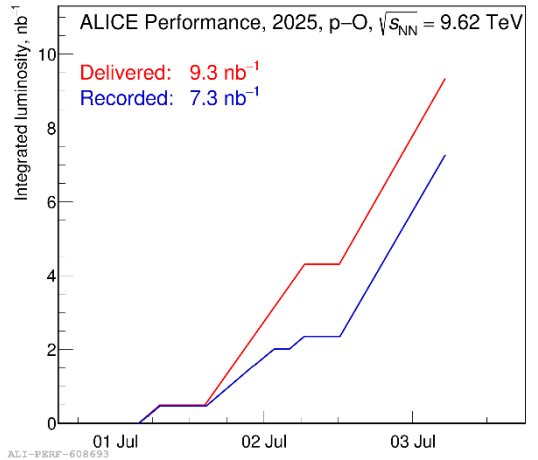


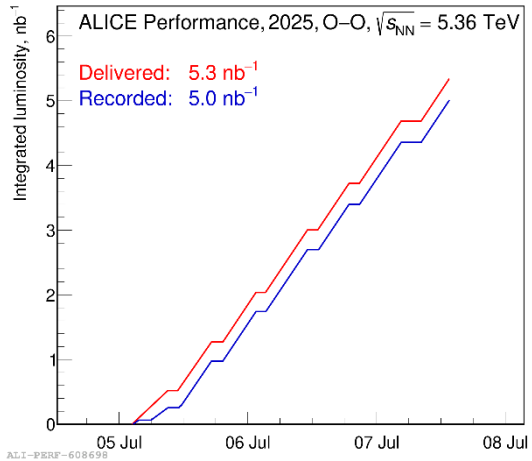




~$53 \cdot 10^{9}$ MB → ~ 7 nb$^{-1}$

x **160 more MB** than Runs 1+2

x **27 more central** than Runs 1+2



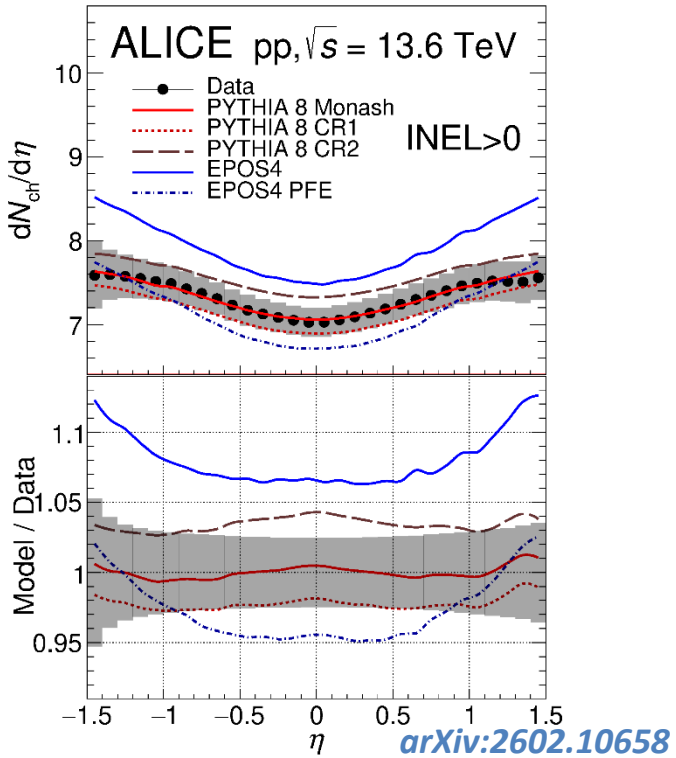




+ Ne-Ne at $\sqrt{s_{NN}}$ = 5.36 TeV
0.87 pb$^{-1}$

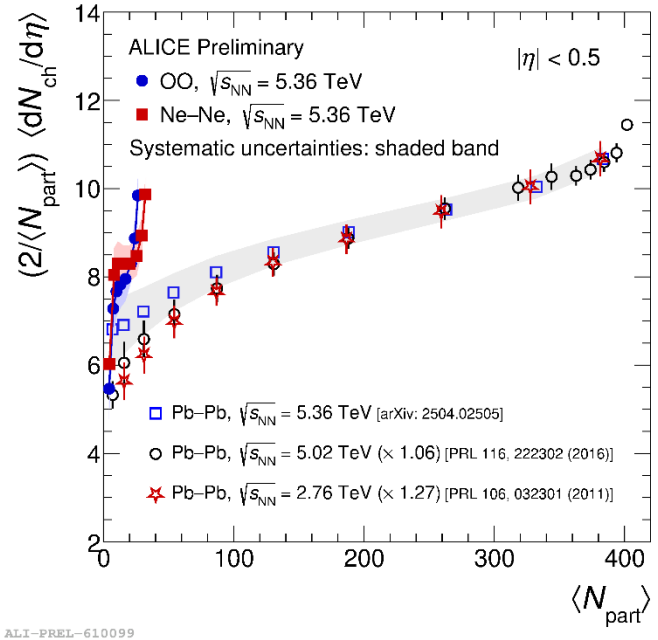
# Charged-particle density from small to large systems (II)

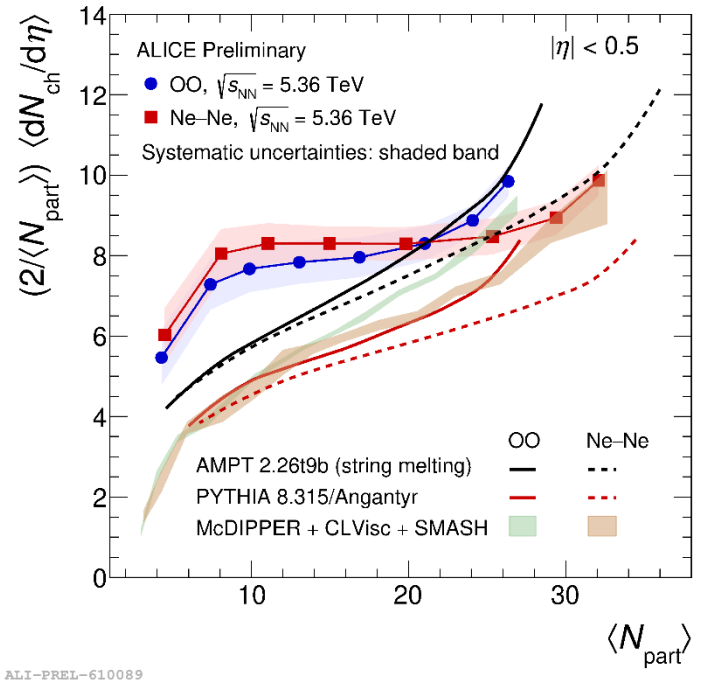
Important observable for

- Understanding of the particle production mechanisms
- Constraining model calculation parameters
- Providing important information of the initial-state energy density and collision centrality




arXiv:2602.10658



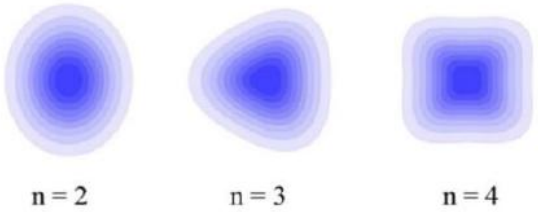



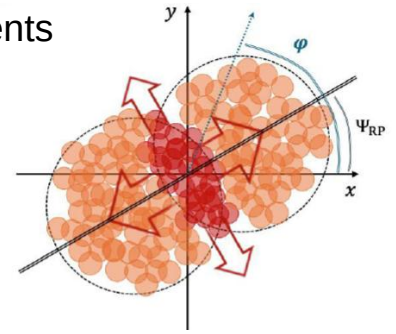

- Charged-particle pseudorapidity density in pp collisions: described by PYTHIA8 Monash, significant deviations with EPOS4
- Charged-particle density per participating nucleon pairs in OO & Ne-Ne:
  - Faster increase with $\langle N_{part}\rangle$ than in PbPb
- Charged-particle density can constrain model calculations

# Anisotropic flow in heavy-ion collisions

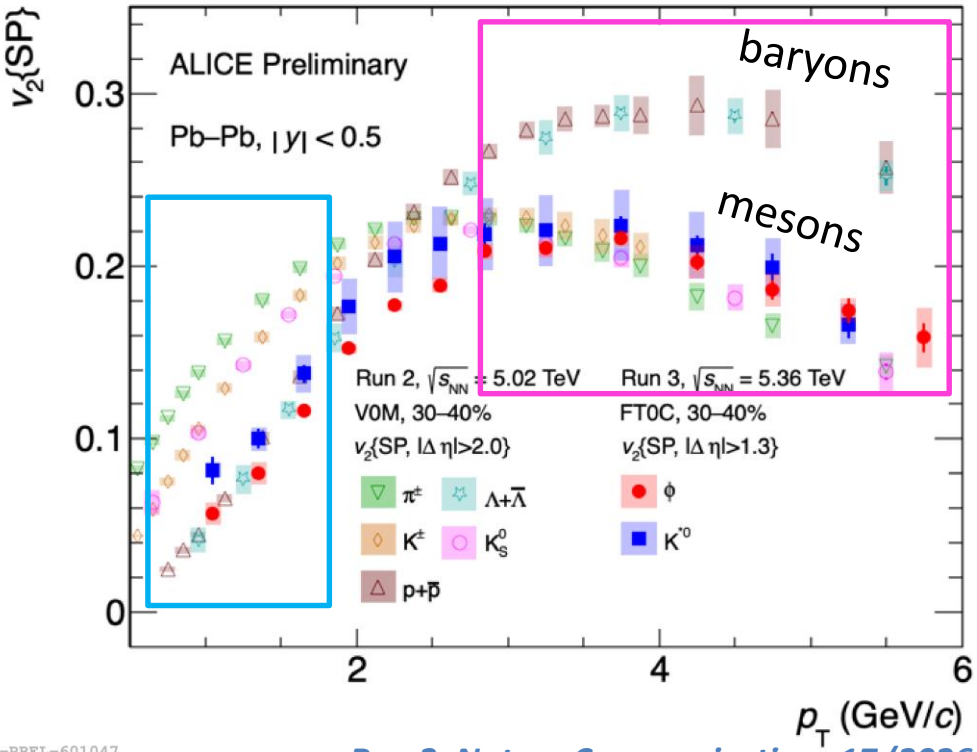
- Initial spatial anisotropy → momentum anisotropy of final-state particles in non-central collisions through pressure gradients
  - Quantified via Fourier series decomposition

$$\frac{2\pi}{N}\frac{\mathrm{d}N}{\mathrm{d}\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)]$$




*n = 2:* $v_2$, elliptic flow, sensitive to QGP
*n = 3:* $v_3$, triangular flow, event by event fluctuations
*n = 4*: $v_4$, quadrangular flow



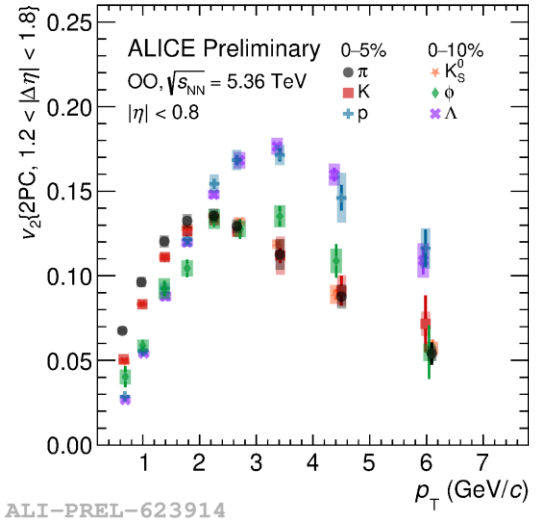

ALI-PREL-601047

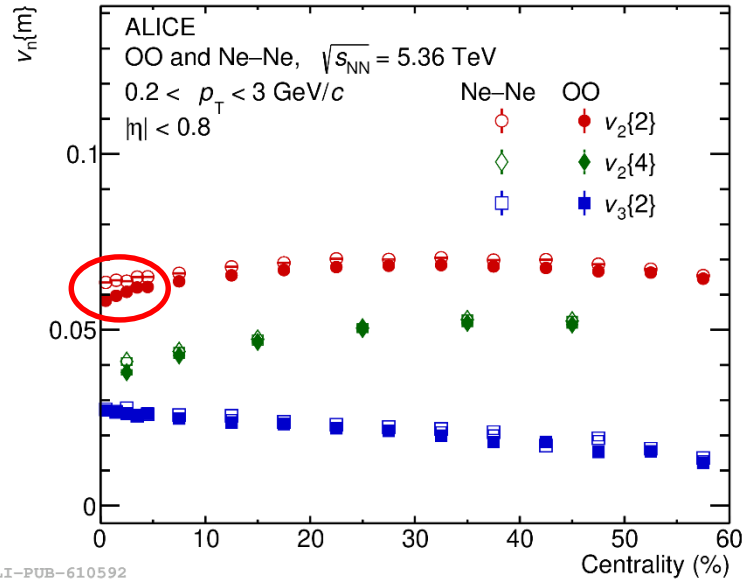
*Run 2: Nature Communications 17 (2026) 2585*

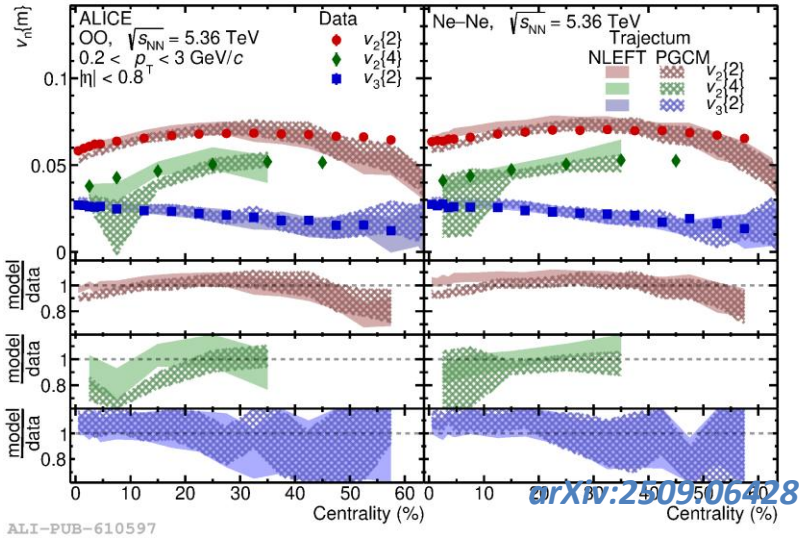
- Low $p_T$:
  - Particle mass ordering → hydrodynamics
- Intermediate $p_T$:
  - Baryon-meson grouping → splitting driven by quark constituents
  - Φ follows same trends as mesons despite similar mass as p & Λ
  → supports hadronisation via quark recombination

→ Evidence of partonic flow in Pb-Pb collisions

# Emergence of collectivity in light-ion collisions?


*arXiv:2509.06428*

- $v_2$ in OO: similar particle-mass grouping & baryon-meson splitting as in Pb-Pb collisions → evidence of partonic collective effects
- Charged particles: $v_2 > v_3$ & $v_2\{2\} > v_2\{4\}$ in both OO & Ne-Ne → expected ordering from collective expansion
- $v_2$ (Ne-Ne) > $v_2$ (OO) in central collisions, in particular → deformation of Ne nucleus
- Trajectum model with realistic nuclear structure describes the charged-particle $v_2$ and $v_3$ within uncertainties
  → Signature of collectivity in light-ion collisions

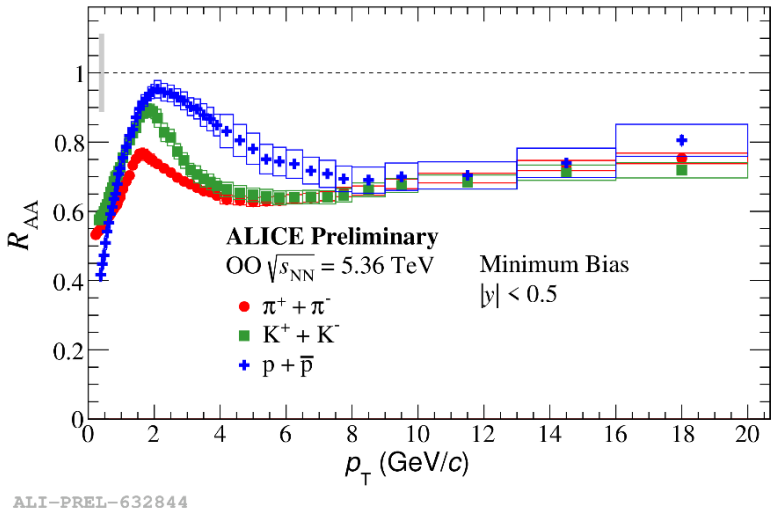
# In-medium parton energy loss light-ion in collisions?

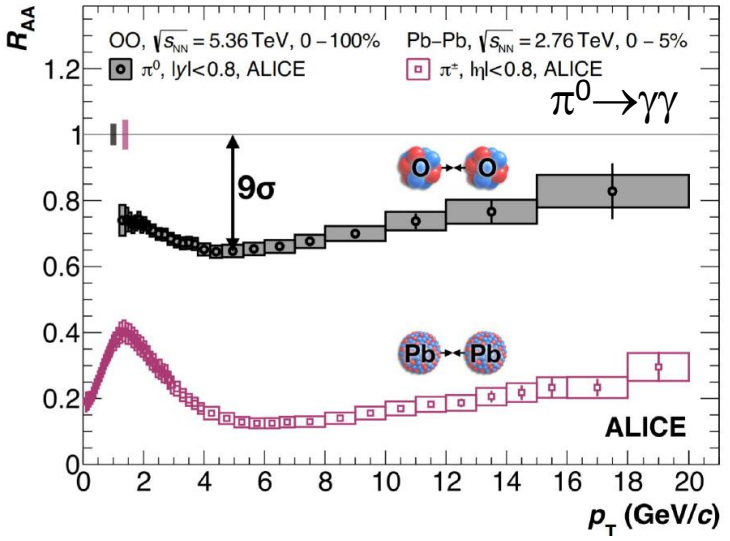
$$R_{AA}(p_T) = 1/< N_{coll} > \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

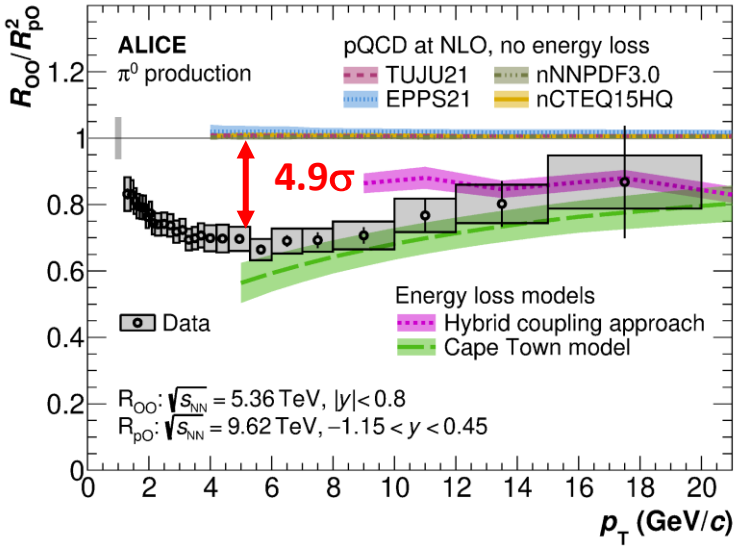
$R_{AA}$ = 1: no modification
$R_{AA} \neq 1$: nuclear effects

$$R_{OO} = \frac{1}{O^2} \times \sigma_{OO}/\sigma_{pp}$$

$$R_{pO} = \frac{1}{O} \times \sigma_{pO}/\sigma_{pp}$$



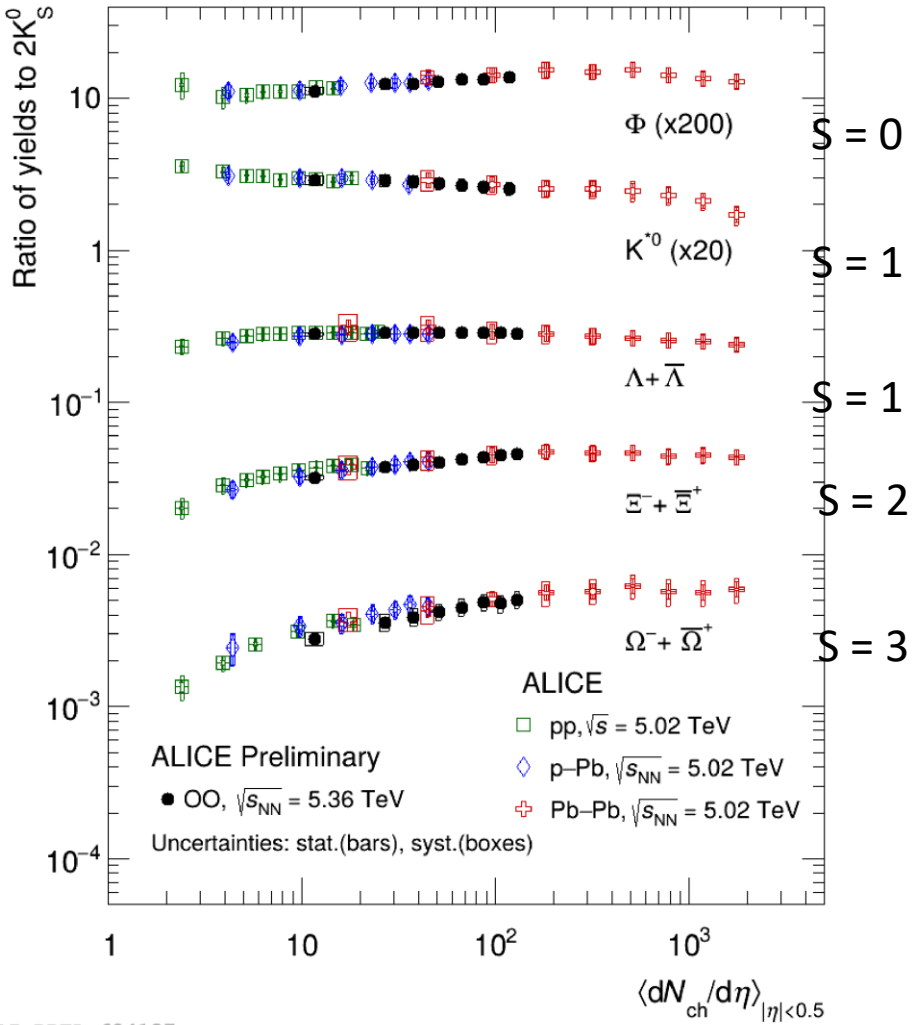

- Significant suppression measured in the light-flavour sector
- Significant suppression of $\pi^0$ production in MB OO collisions at intermediate/high $p_T$, with similar shape as in central Pb-Pb
- $R_{OO}/(R_{pO})^2$: no cold nuclear matter effects → direct probe for energy loss effects
  - Evidence for in-medium parton energy loss with a 4.9σ significance at intermediate $p_T$

*arXiv:2606.19967*

# Strangeness production in OO collisions

- Bridge the gap between small and large collision systems
- First measurement of strange and multi-strange particles in OO collisions
  - Particle yield ratios in OO collisions in agreement with the common smooth increase as a function of charged-particle multiplicity
  - Stronger enhancement for higher strangeness content
- First measurement of resonances ($\Phi$, K*$^0$) in OO collisions
  - **Short-lived K*0** resonances (~4 fm/*c*), suppressed due to rescattering during the hadronic phase
  - **Longer-lived $\Phi$** resonances (~46 fm/*c*) unaffected by the hadronic phase

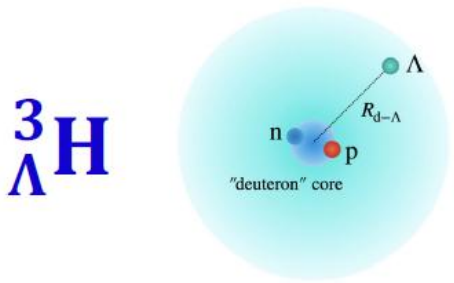
    → Influence of the hadronic phase



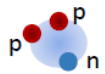
# Hypertriton and $^3$He elliptic flow in Pb-Pb

Insights into particle production mechanisms & constraints on hadronisation models

Lightest known hypernucleus
Loosely bound object

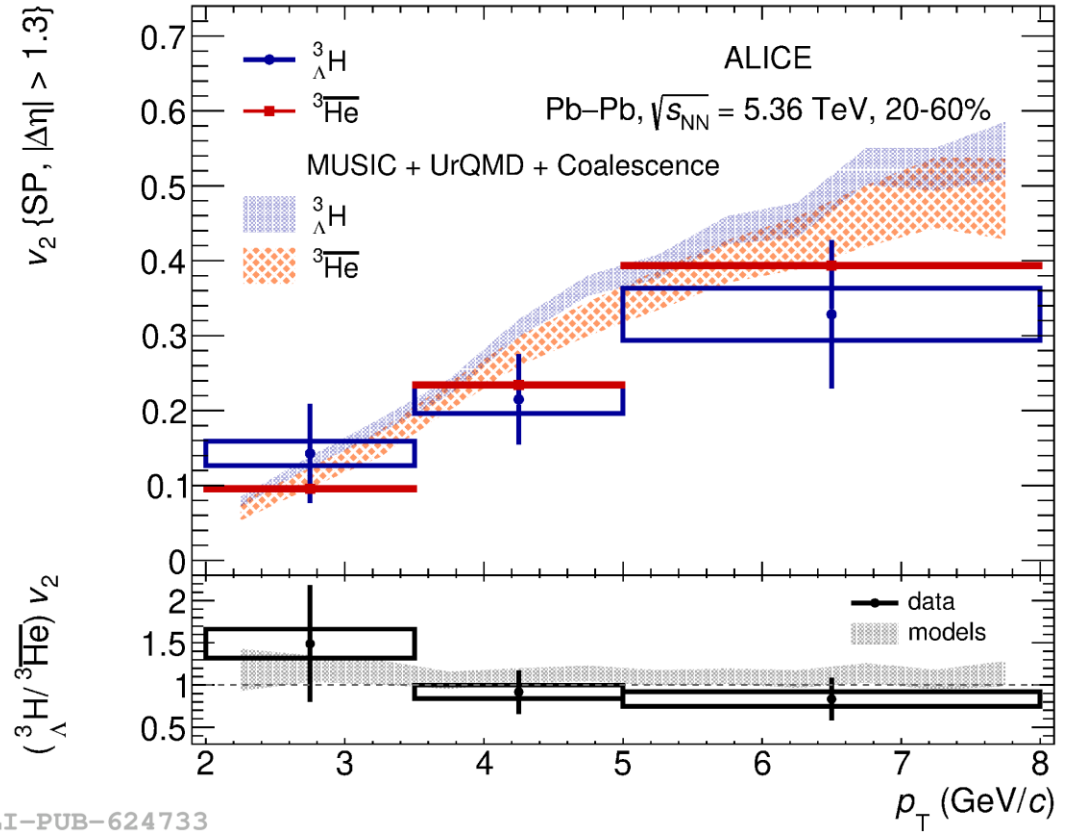



$^3$He




$m$ = 2.991 GeV/$c^2$
$R$ = 10 fm
$c\tau$ = 7.1 cm

m= 2.809 GeV/$c^2$
$R$ = 1.8 fm




ALI-PUB-624733

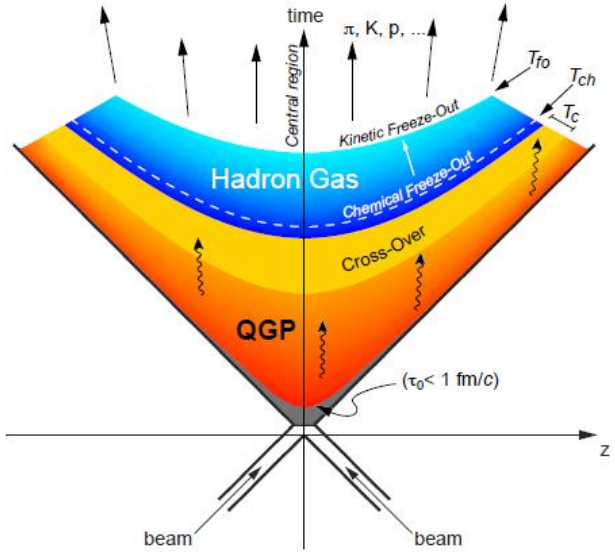
*arXiv:2603.19398*

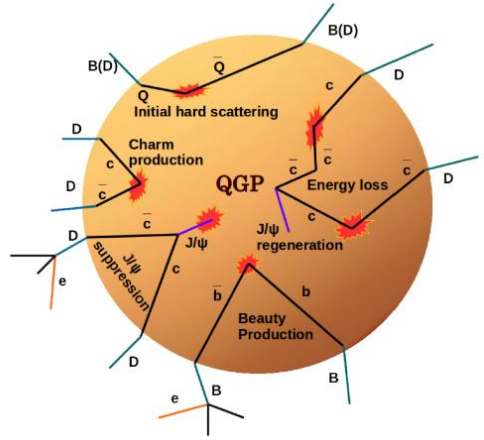
- First measurement of the elliptic flow of hypertriton at the LHC
- Comparable $v_2 > 0$ for hypertritons and $^3$He due to similar masses
- Hydrodynamics model with coalescence in agreement with the measurement within uncertainties

# Open and hidden heavy flavours

AA collisions (Pb-Pb & Xe-Xe collisions):

- Charm and beauty quarks produced in initial hard scatterings, prior to the formation of the quark-gluon plasma (QGP)
  - $\tau_{b,c}$ ~ 0.1-0.4 fm/$c$ < $\tau_{QGP}$ (~1 fm/$c$)
    - Experience the full collision history
- Interact with medium constituents
  - Parton energy loss, collective motion & thermalisation
  - Suppression (colour screening) & regeneration of quarkonia
- Sensitive to modified hadronisation in the medium
- Excellent probes to characterise the QGP



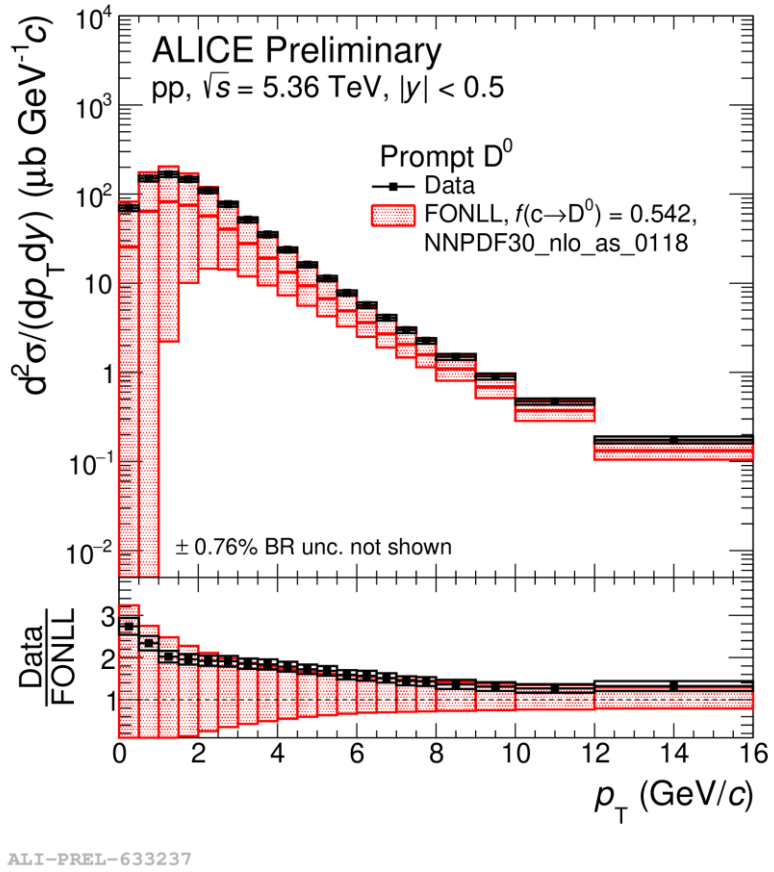

Intermediate systems (OO, Ne-Ne)

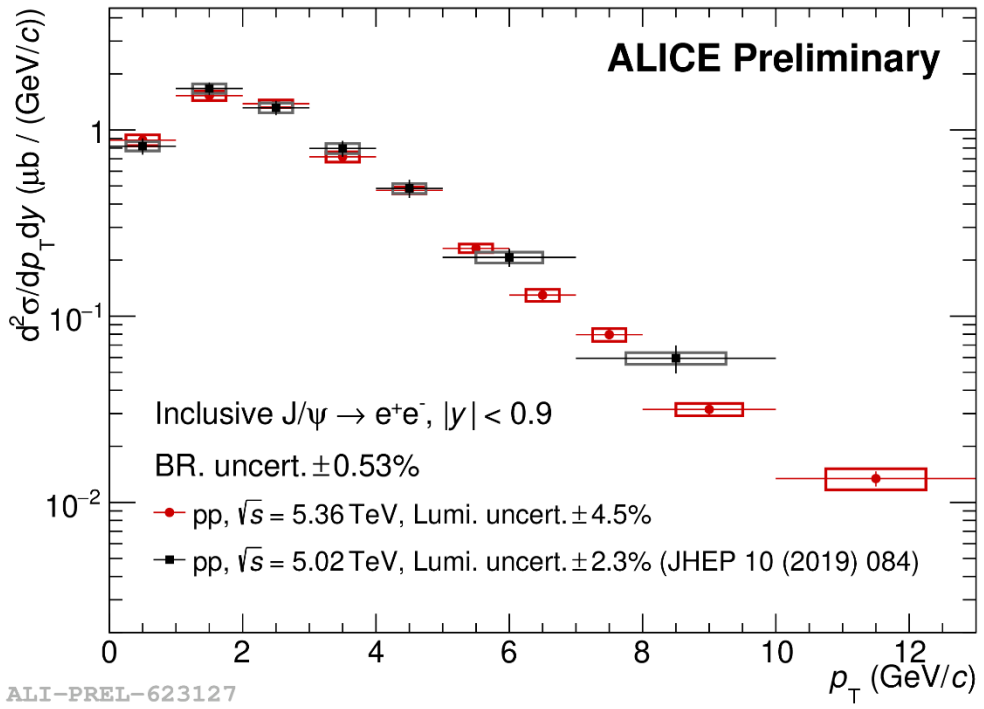
- Unique opportunity to investigate the onset of QGP
  - Energy loss, collectivity, suppression of quarkonium production?

Small systems (pp & pA collisions)

- Baseline for heavy-ion measurements
- Test of perturbative QCD & production mechanisms
- Insights into heavy-flavour hadronisation
- Probe modification of parton distribution functions in nuclei

# Open and hidden charm production in pp

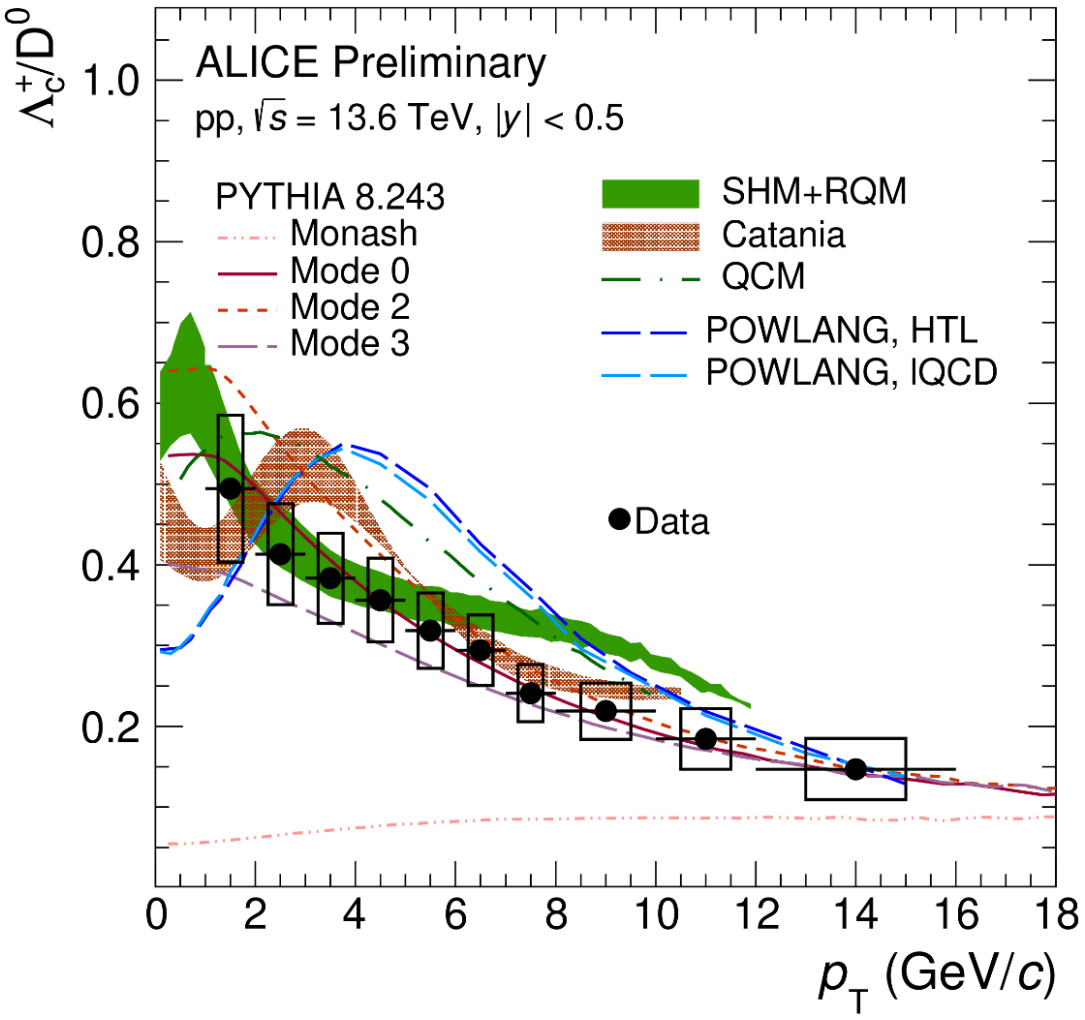



- High-precision measurement of the $p_T$-differential production cross section of prompt D$^0$ and inclusive J/ψ at midrapidity in Run 3 over a wide $p_T$ range and down to $p_T$ = 0
- Prompt-D$^0$ well described by FONLL, data at the upper limit of model calculations
  - Experimental uncertainties smaller than theoretical uncertainties → constraints on model calculations

# Charm baryon-to-meson production ratio in pp

- Observable for providing insights on hadronisation mechanisms and probing fragmentation functions



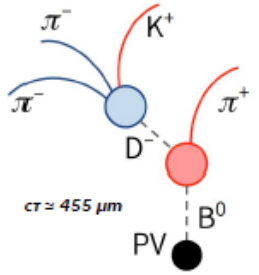

- Strong enhancement at low $p_T$ of the $\Lambda_c^+/D^0$ ratio in pp collisions compared to $e^+e^-$ collisions
  - LEP: 0.113 + 0.013 + 0.006
- PYTHIA 8 Monash with fragmentation functions tuned on $e^+e^-$ results underestimates the measurement
  - Evidence of breaking of universality of charm fragmentation functions
- Shape qualitatively reproduced by:
  - Excited baryon states (SHM+RQM)
  - Colour reconnection beyond leading colour approximation (PYTHIA 8 Mode 0, 2, 3)
  - Coalescence (Catania, QCM, POWLAND)

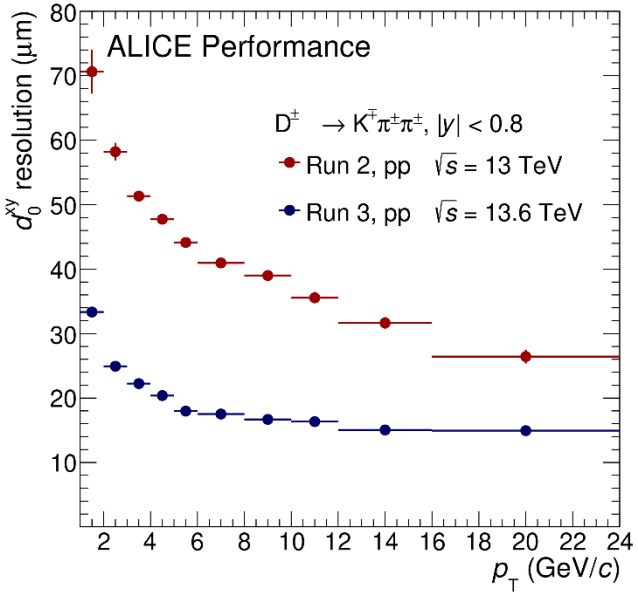
ALI-PREL-623568

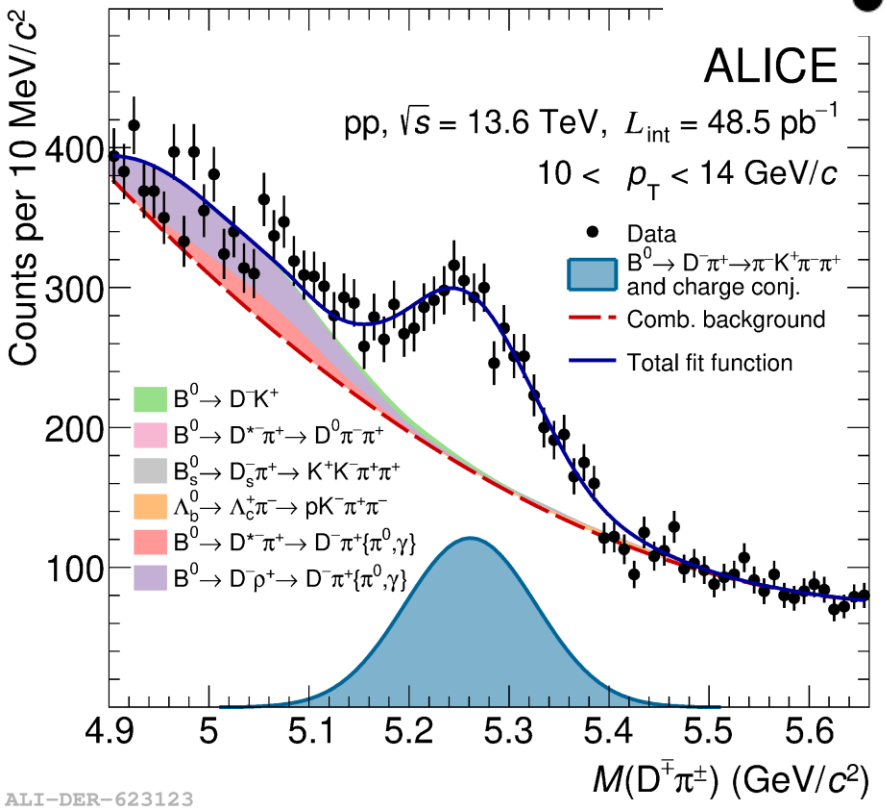
# Open beauty production in pp

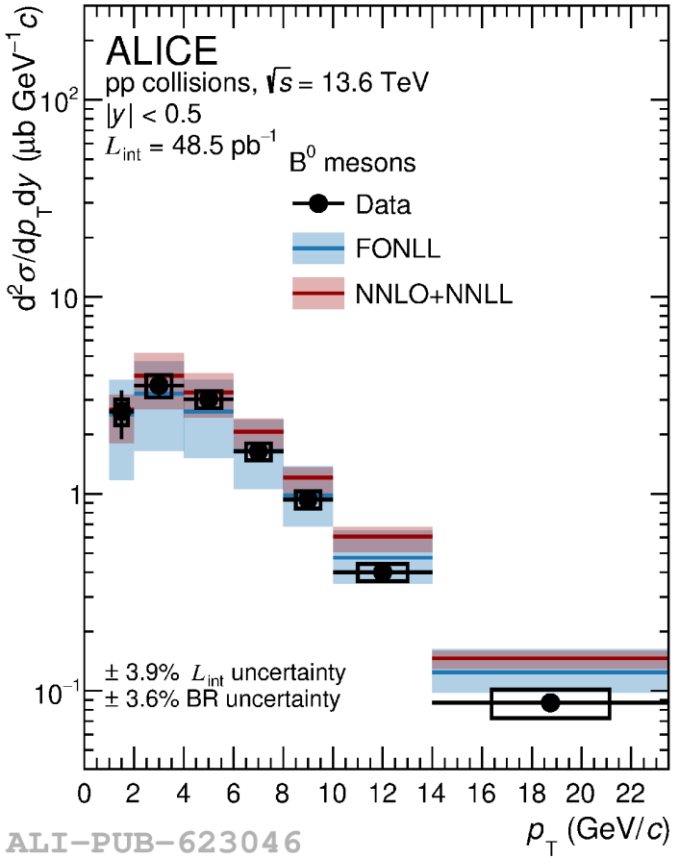
M. Zhang
30 June, 9:00

- First exclusive reconstruction of beauty hadrons with ALICE



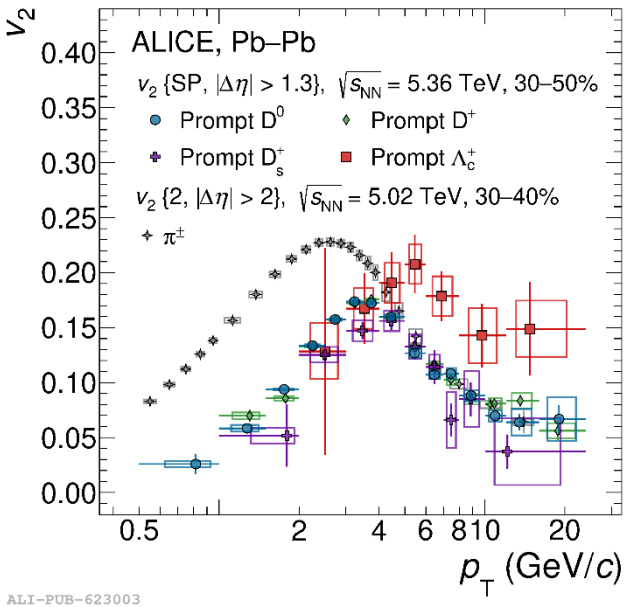



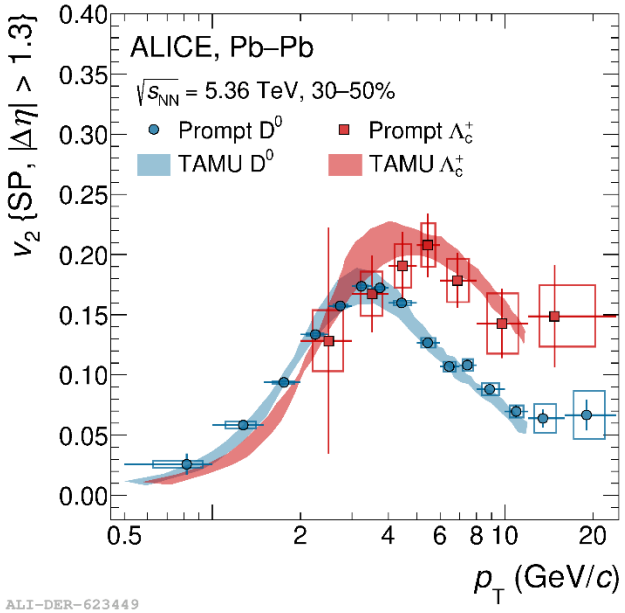




*arXiv:2603.18904*

- Raw yields down to $p_T$ = 1 GeV/$c$ extracted from unbinned maximum likelihood fit
- $B^0$ production cross section described by FONLL & NNLO +NNLL pQCD predictions within uncertainties

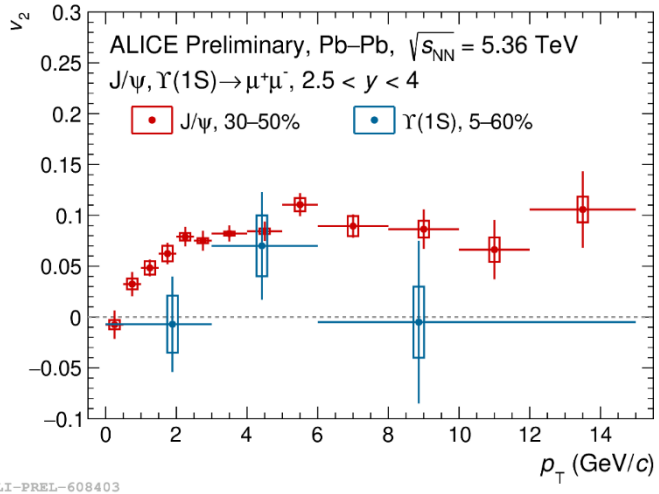
# Charm-hadron elliptic flow in Pb-Pb




- Precise measurement of D-meson $v_2$ in a wide $p_T$ interval
- $v_2(\pi) > v_2(D)$: mass-grouping at low $p_T$ as observed in the light-flavor sector
- $v_2$ (D) > 0 at low $p_T$: participation of charm quarks to the collective expansion of the system
- First $\Lambda_c^+$ $v_2$ measurement:
  - Larger than $v_2$ ($D^0$) for $p_T > 4$ GeV/$c$
  - Evidence of charm baryon-meson splitting
    → Charm hadronisation by coalescence and partonic origin of charm-hadron flow

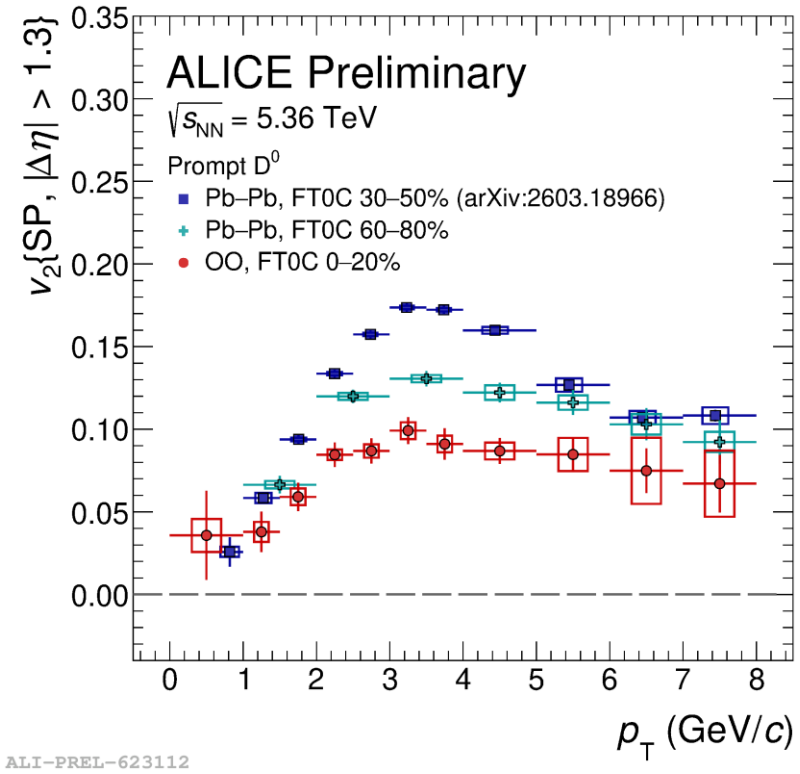
X. Bai
30 June, 9:20

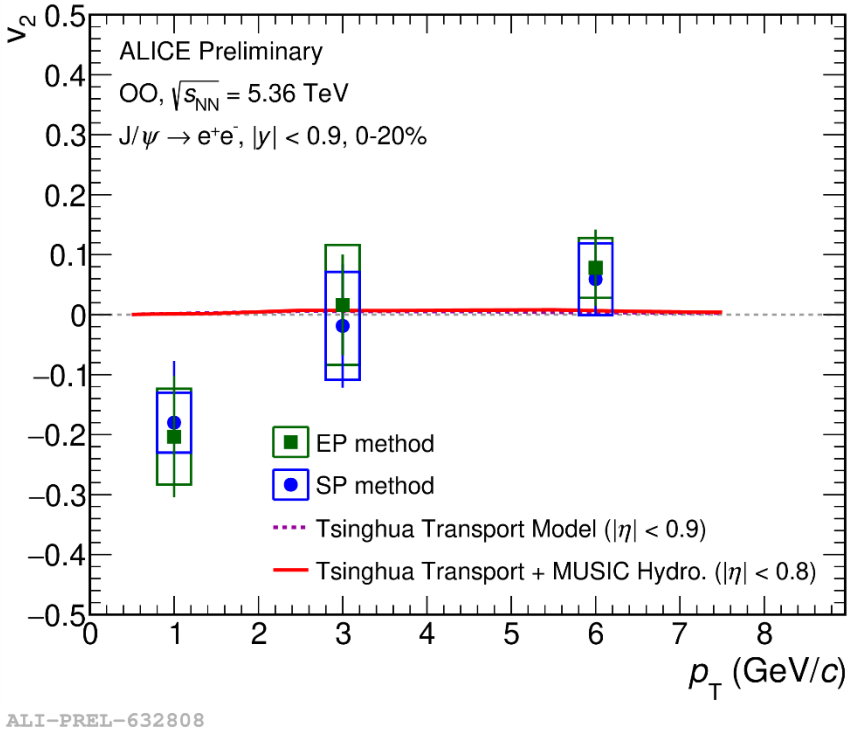



- Significant J/ψ $v_2$ while ϒ(1S) $v_2$ compatible with 0 within uncertainties
  - Bottomonia not affected by collectivity, longer relaxation time, negligible regeneration?

→ Analysis of full statistics collected in the Run 3 needed

# Collectivity in the heavy-flavour sector in OO: charm $v_2$




X. Bai
30 June, 9:20

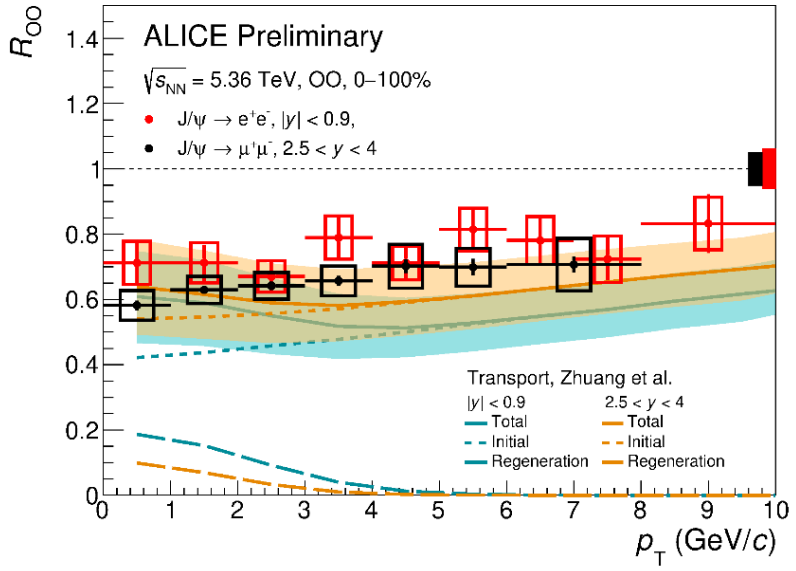
- Significant positive v2 for $D^0$ mesons
- Smaller $D^0$-meson $v_2$ in central OO compared to peripheral Pb-Pb, with similar shape
  - Similar d$N$/d$y$ in central OO & peripheral Pb-Pb, smaller eccentricity
- …but $J/\psi$ $v_2$ at midrapidity consistent with zero within uncertainties
  - Transport models predict a very small $v_2$ in agreement with the measurement within uncertainties

→ Are charm quark flowing?
→ Better precision needed to conclude

# Energy loss in the heavy-flavor sector in OO: J/ψ $R_{OO}$

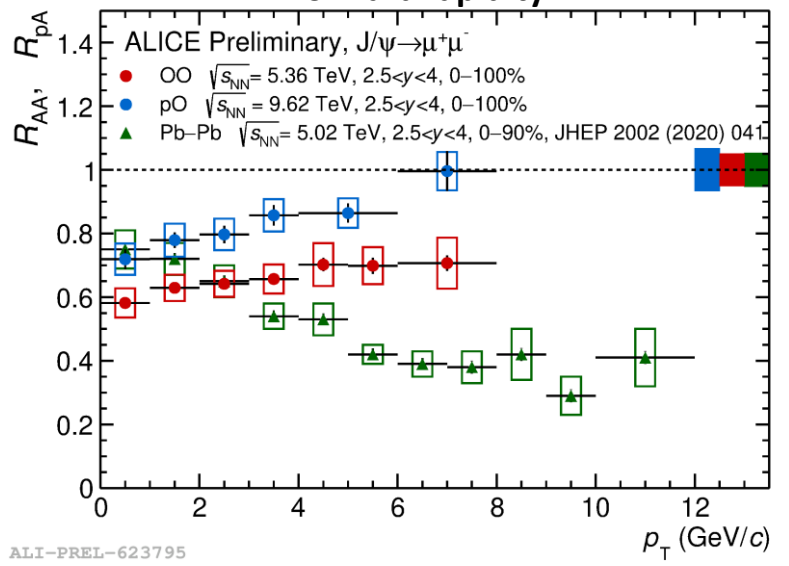
X. Bai
30 June, 9:20

**midrapidity vs. forward rapidity**




ALI-PREL-633552

**forward rapidity**




ALI-PREL-623795

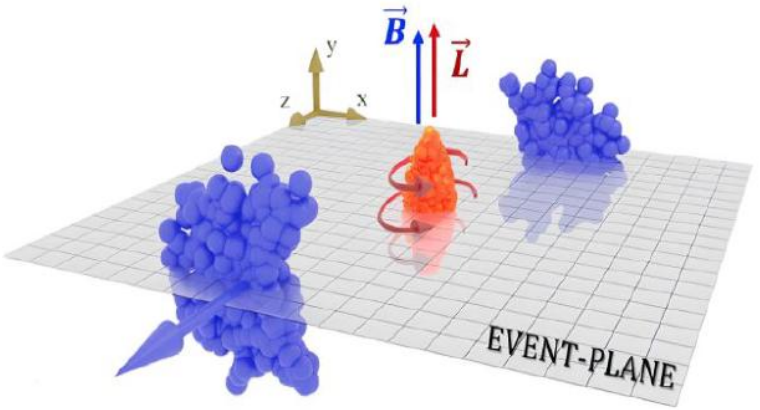
- Similar $R_{OO}$ at forward rapidity and midrapidity within uncertainties
- $R_{OO}$ smaller than unity → indication of suppression
- Transport model describes the measured $R_{OO}$ at forward rapidity and slightly underestimates the midrapidity $R_{OO}$

- $R_{OO}$ < $R_{pO}$:indication of hot-medium effects
- Stronger $p_T$ dependence and suppression in Pb-Pb than in OO, enhancement at low $p_T$ in Pb-Pb mainly due to regeneration
- No clear indication of regeneration at forward rapidity

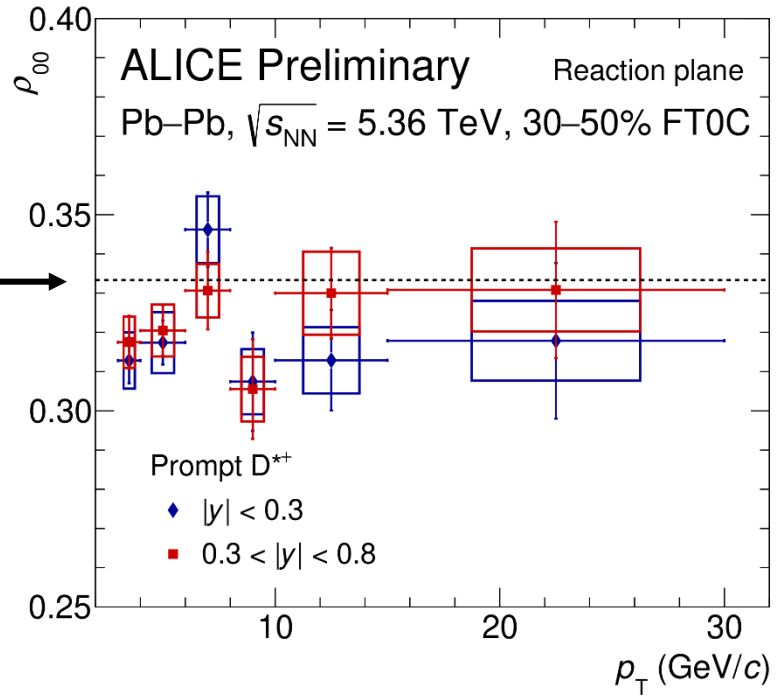
# Spin alignment in Pb-Pb

- Large angular momentum $\vec{L}$ due to medium rotation
- Huge transient magnetic field $\vec{B}$ (~$10^{16}$ T) with lifetime expected to increase with rapidity

- Heavy quarks produced before the QGP formation
  - → Sensitive to vorticity and magnetic field
  - → Spin polarisation transferred to vector mesons during hadronisation




$\rho_{00}$ = 1/3
no spin
alignment



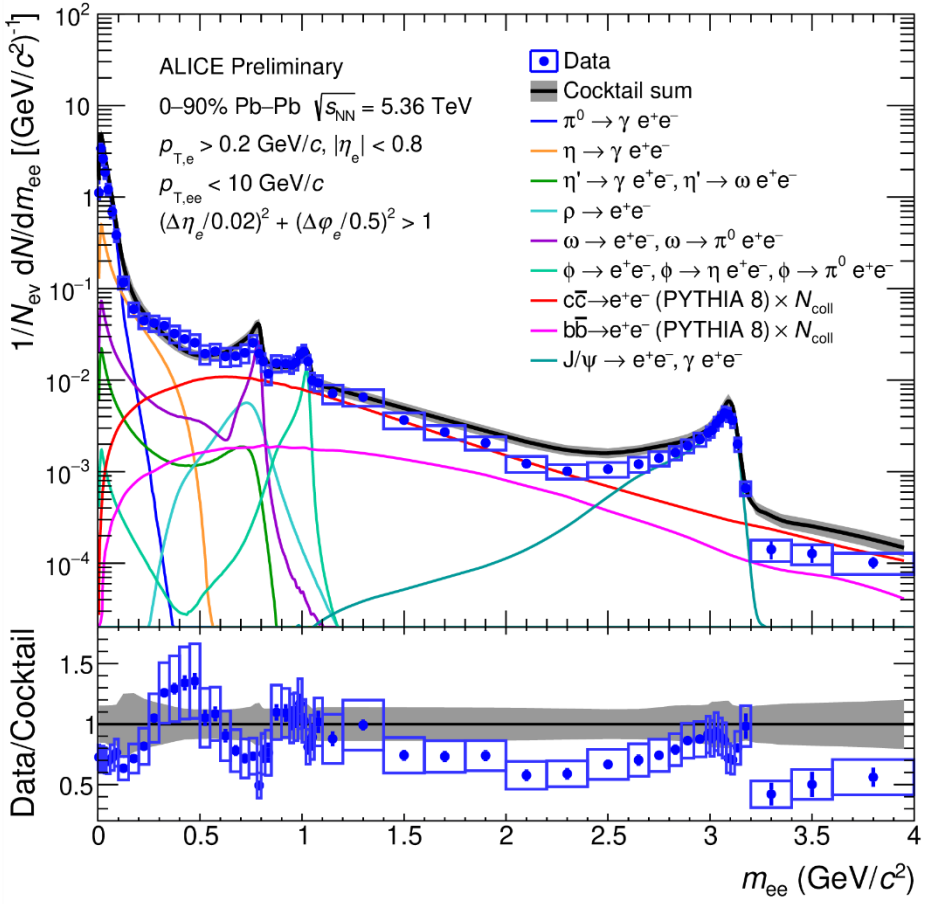

ALI-PREL-633288

- Prompt D*+: no evidence of spin alignment within uncertainties and no dependence on the rapidity selection

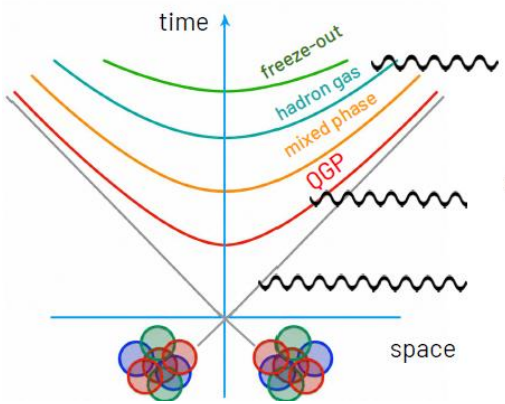
- Full Pb-Pb sample needed to perform multi-differential measurements as a function of centrality and rapidity

# Dilepton production in Pb-Pb

- Dileptons produced in all stages of heavy-collisions & do not interact strongly with the medium
  - Sensitive to the QGP temperature
  - Chiral-symmetry restoration




ALI-PREL-633063




| γ origin | $M_{inv}(e^+e^-)$ regions |
|---|---|
| Hadronic thermal ($\omega$, $\phi$, $\rho$, ...) | Low mass |
| Early QGP - thermal HF decays | Intermediate mass (IMR) $1.2 < m_{ee} < 2.6$ GeV $c^{-2}$ |
| Drell-Yan, quarkonium | High mass |

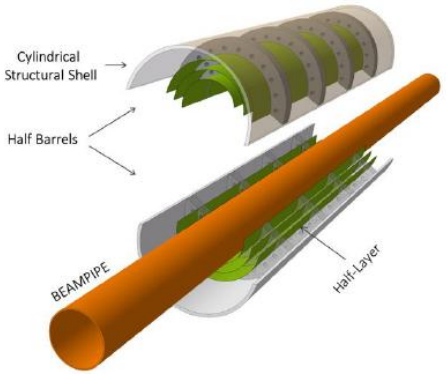
- First corrected invariant mass distribution of dielectrons compared with a cocktail of hadronic sources
  - Consistent with an excess at low $m_{ee}$
    - Expected from $\rho$ mesons produced thermally in the medium
  - Indication of heavy-flavour suppression at intermediate $m_{ee}$

# The future of ALICE

A. Uras
29 June, 18:10


## ITS3

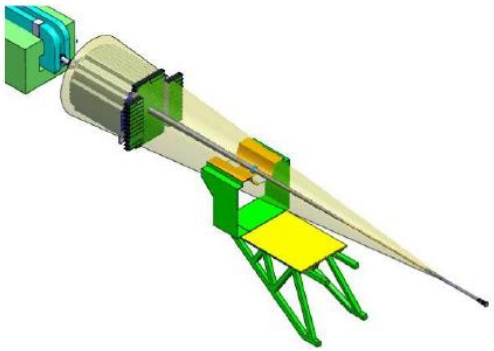
TDR: CERN-LHCC-2024-003




New Inner Tracking System
3 cylindrical layers of CMOS MAPS
x2 pointing resolution & x3 less material

## FoCal

TDR: CERN-LHCC-2024-004

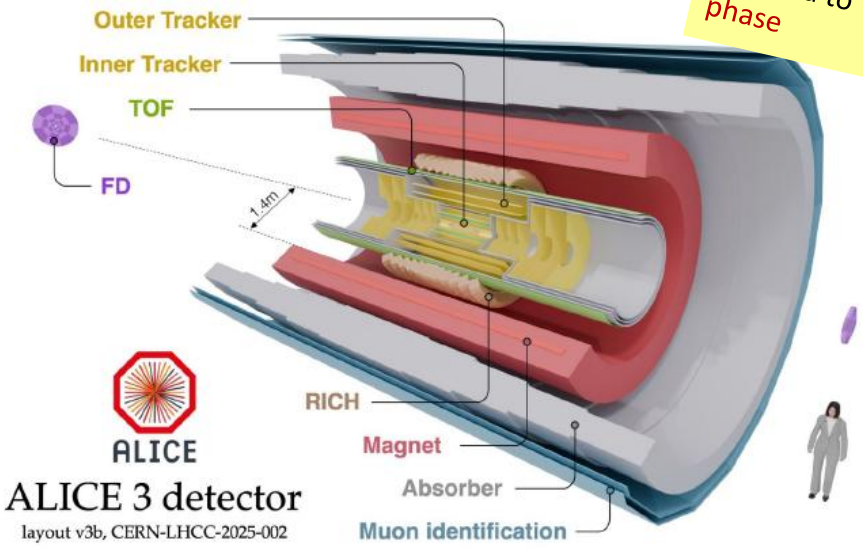


New Forward Calorimetry
$3.4 < \eta < 5.8$
Focal-E: high-granularity Si + W EM calorimeter
FoCal-H: hadronic calorimeter

## ALICE 3

LoI: CERN-LHCC-2022-009
Scoping document: CERN-LHCC-2025-002

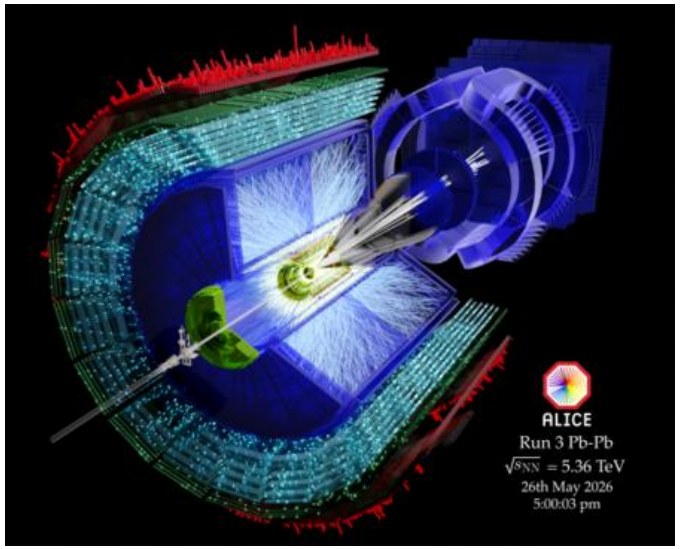
**Fresh news:** Approved by CERN Reseach Board to proceed to TDR phase



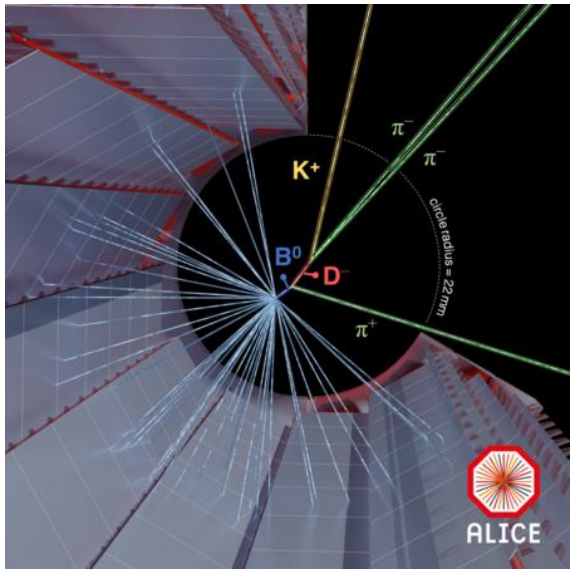

Completely new detector
Compact all silicon detector
Retractable iris vertexer, 5mm from interaction point
Large acceptance for tracking &PID
~3 μm pointing resolution for $p_T > 1$GeV/$c$

# Conclusion

ALICE explores QCD across collision systems and scales from vacuum to strong interacting matter




- Impressive amount of new exciting results have been obtained by ALICE with the LHC Run 3 data
  - 11 papers recently submitted in arXiv, 24 papers in preparation, 32 new preliminary results for last approval campaign
- New insights into the characterization of the hot QCD medium from light flavours, open and hidden heavy flavours, electromagnetic probes
- Results from light-ion systems bring information on the conditions of emergence of QGP-like effects
- ALICE is extending its heavy-flavor program to the beauty sector via the exclusive beauty-meson reconstruction down to low $p_T$
- Full exploitation of Run 3 data is at the beginning

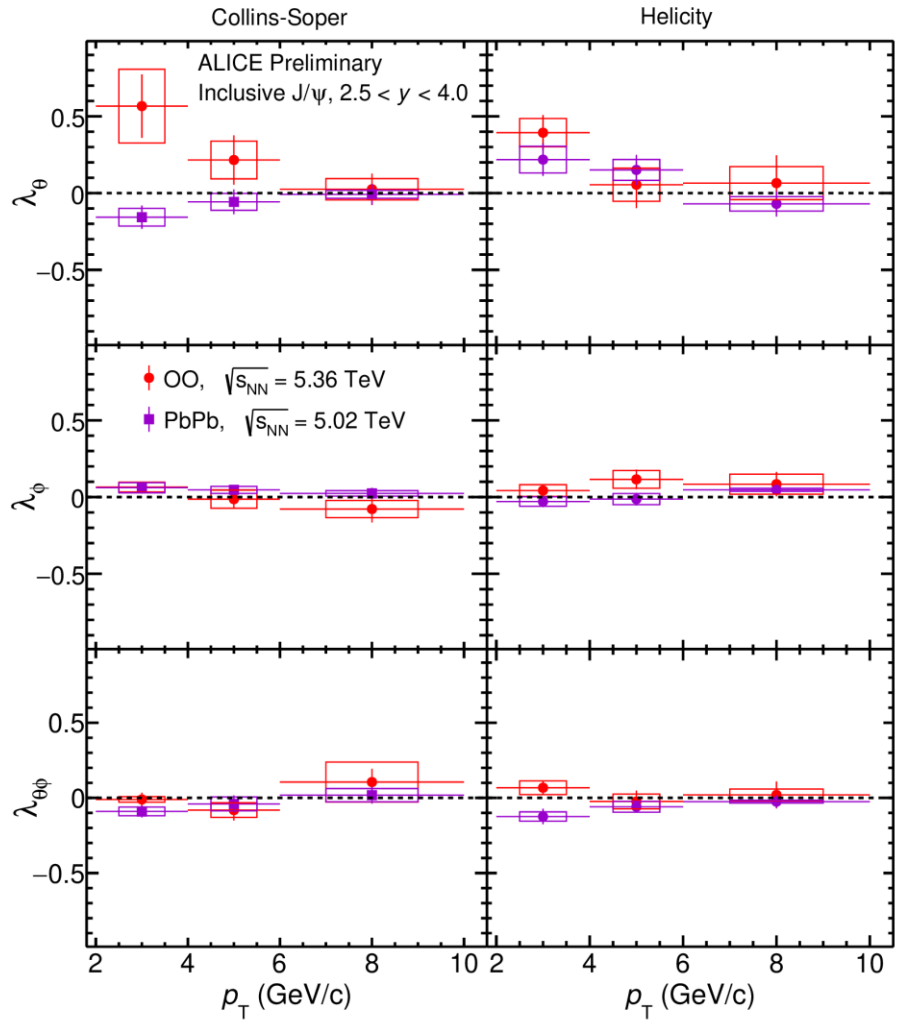



More to come soon using full Run 3 and
from exciting upgrade programs for Run 4 and Run 5
→ Stay tunned!

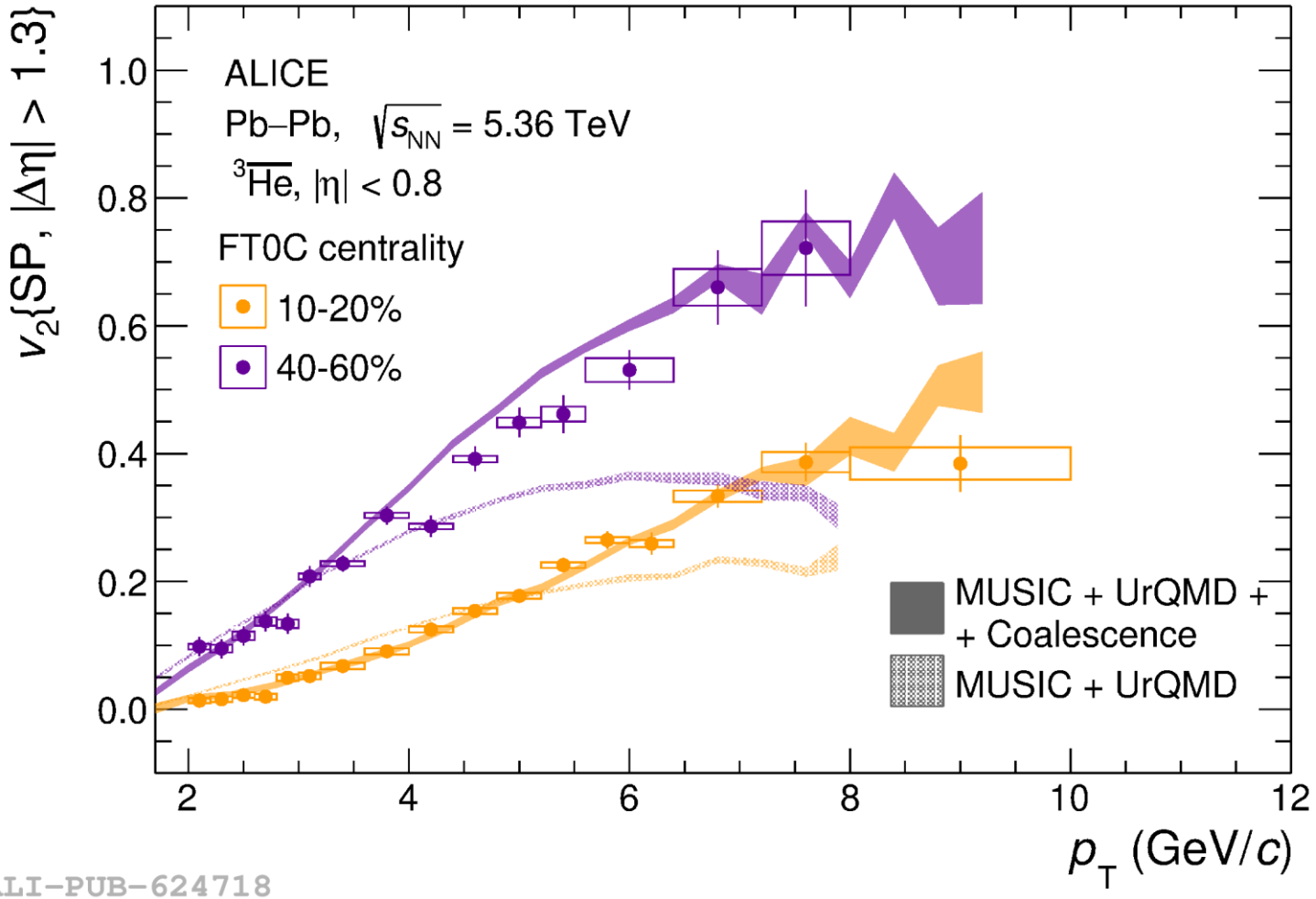

感谢您的聆听
Merci pour votre attention

# Backup

# Polarisation



# $^3$He elliptic flow

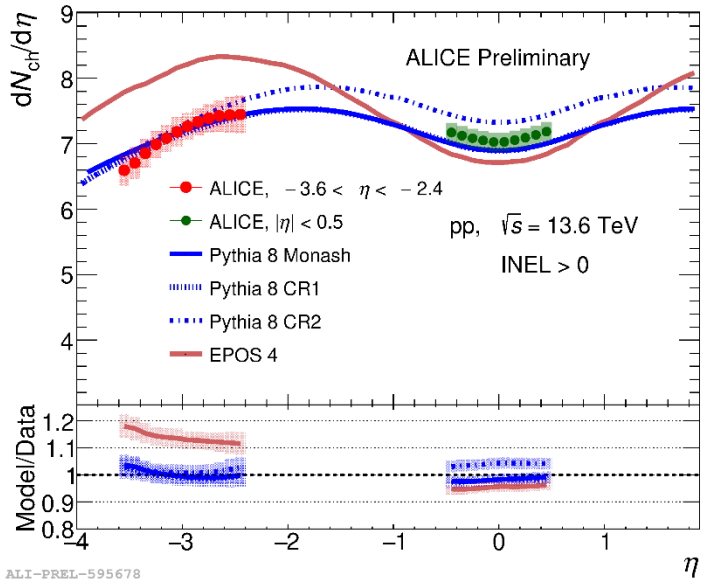


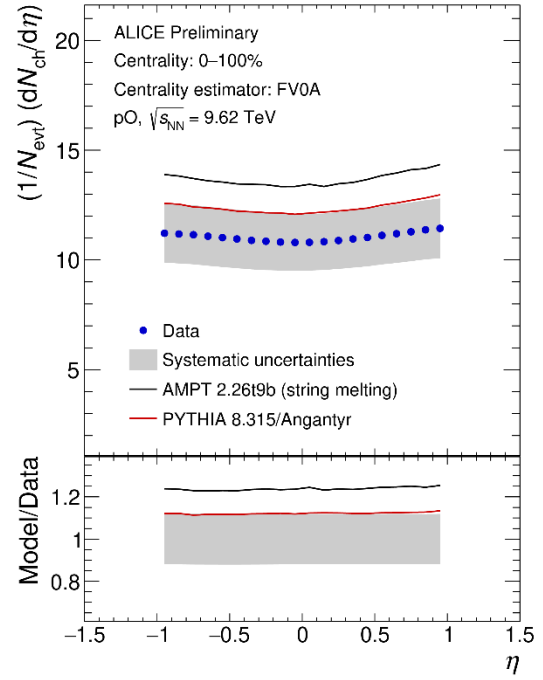

ALI-PUB-624718

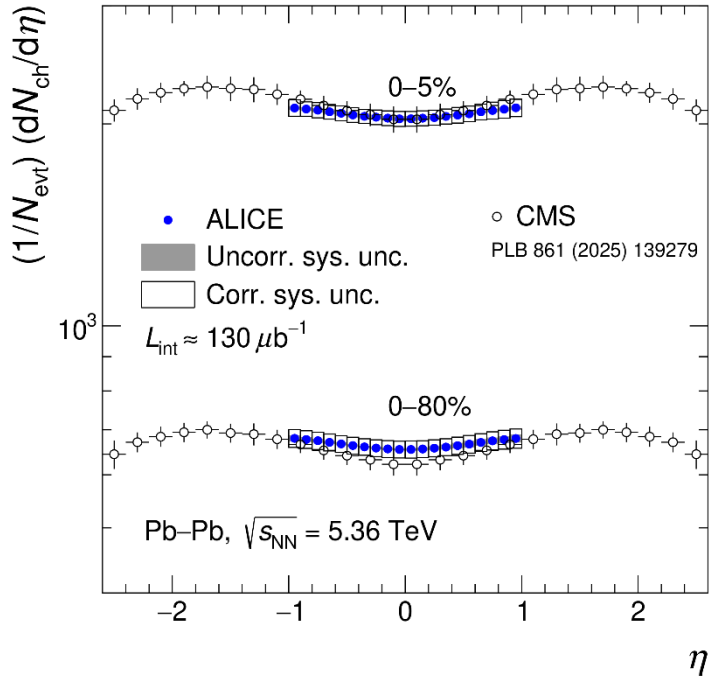
# Charged-particle density from small to large systems (I)

Fundamental observable for

- Understanding of the particle production mechanisms
- Constraining model calculation parameters
- Providing important information of the initial-state energy density and collision centrality



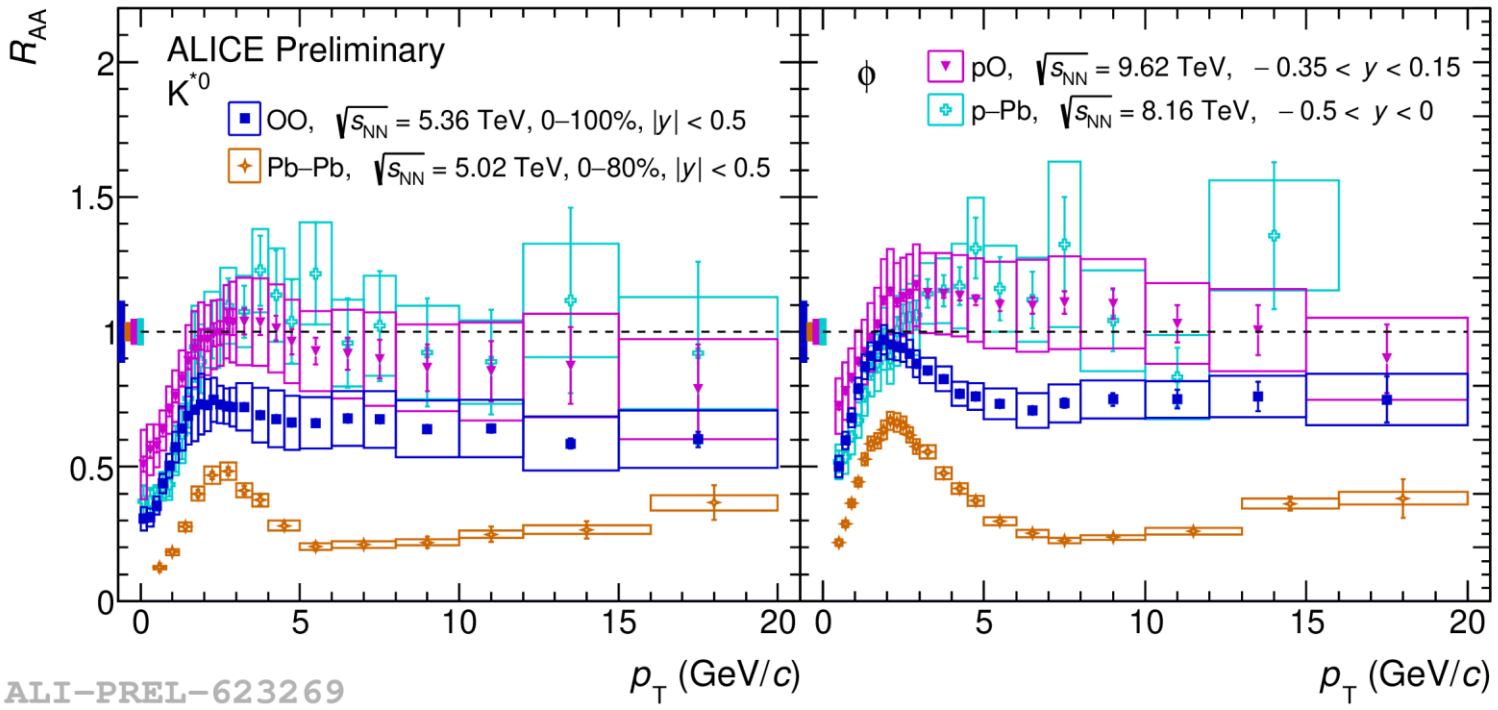



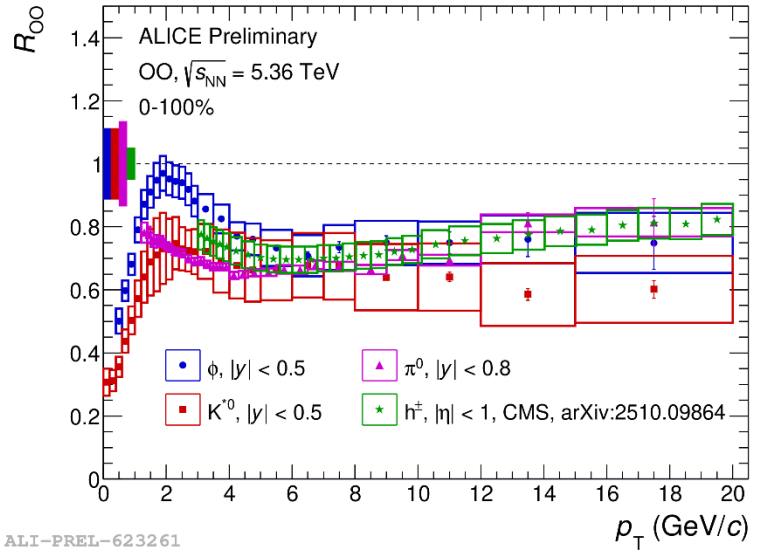



# In-medium energy loss light-ion collisions

$$R_{AA}(p_T) = 1/< T_{AA} > \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

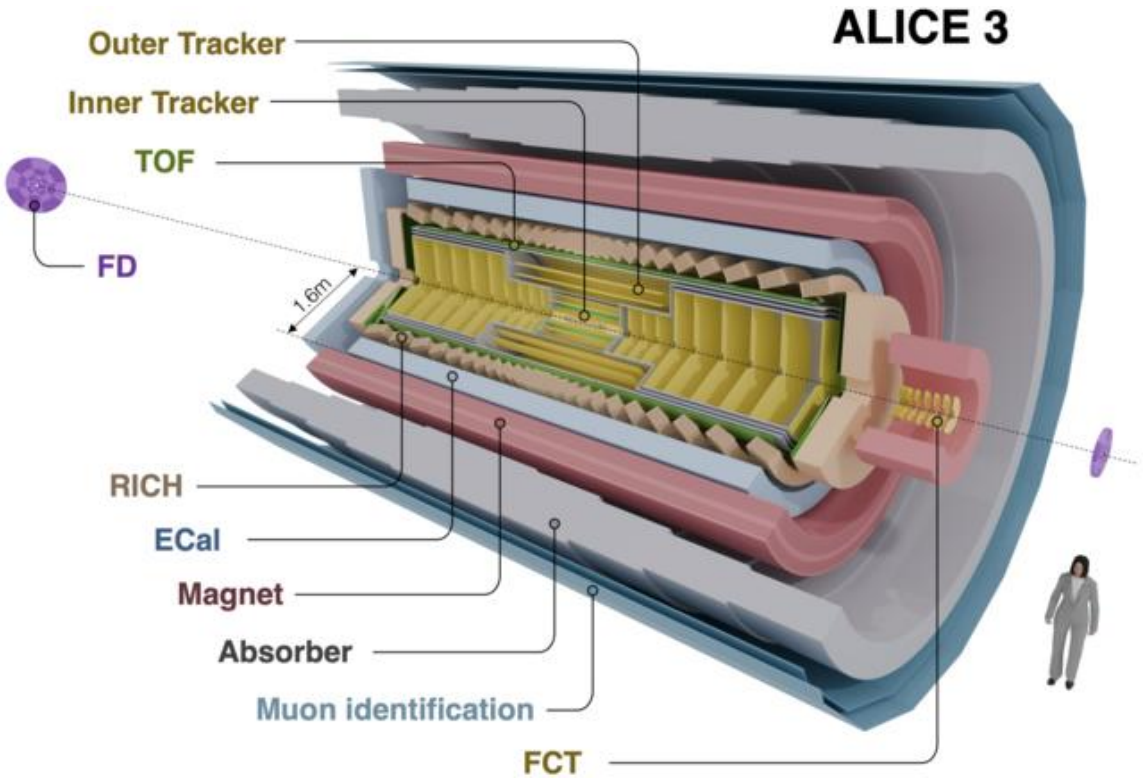
$R_{AA}$ = 1: no modification
$R_{AA} \neq 1$: nuclear effect




Add def raa ,
Sensitivity to medium effects

# Upgrade for Run 5: ALICE 3




Detector

- Compact and low mass all-silicon tracker
- Retractable vertex detector
- Large acceptance $|\eta| < 4$
- PID (TOF, RICH, MID, Ecal) over a wide $p_T$ range
- Excellent pointing precision: ~3μm at $p_T > 3$ GeV/$c$

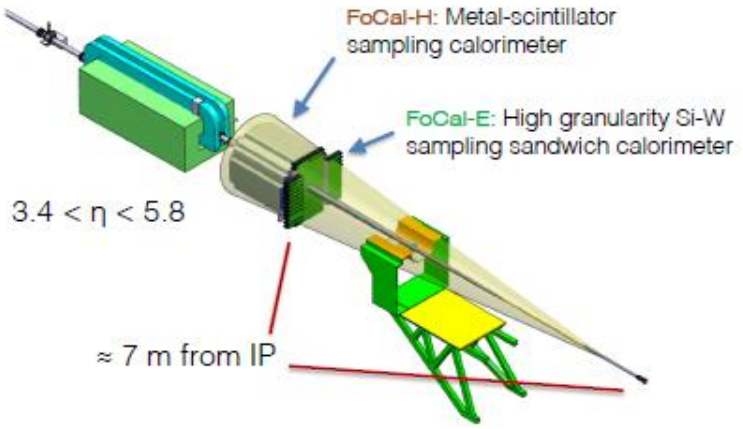
Key physics motivations

- Early stage temperature with dielectrons
- Properties and hadronisation of the QGP with (multi) heavy-flavour hadrons
- Fundamental aspects of QCD phase transition

*LoI: CERN-LHCC-2022-009*
*Scoping Doc.: CERN-LHCC-2025-002*

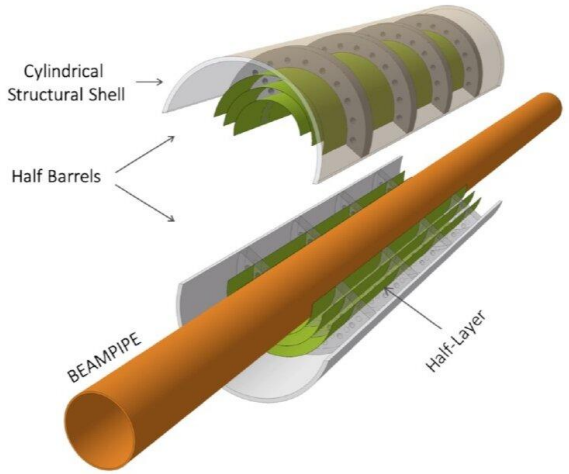
# ALICE upgrades


## FOCAL

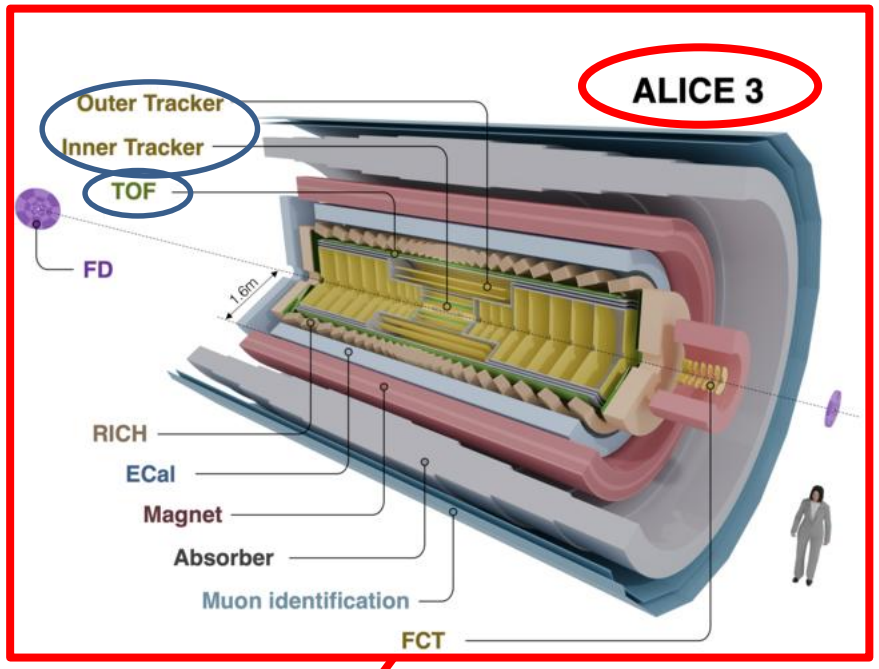



*TDR: CERN-LHCC-2024-004*

## ITS 3




*TDR: CERN-LHCC-2024-003*




*LoI: CERN-LHCC-2022-009*
*Scoping Doc.: CERN-LHCC-2025-002*

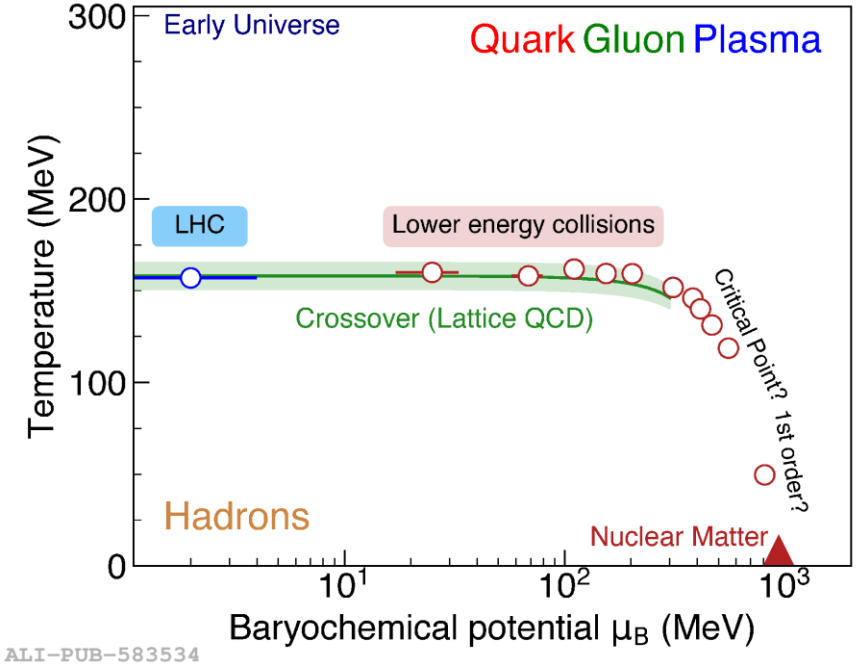
FCPPN/L ALICE: interest for ALICE 3*

*in discussion for ALICE 3 in both institutes from China & France

Zhongbao Yin, Friday, July 25th, 9:00-9:25
Antonio Uras, Friday , July 25th, 9:25-9:45

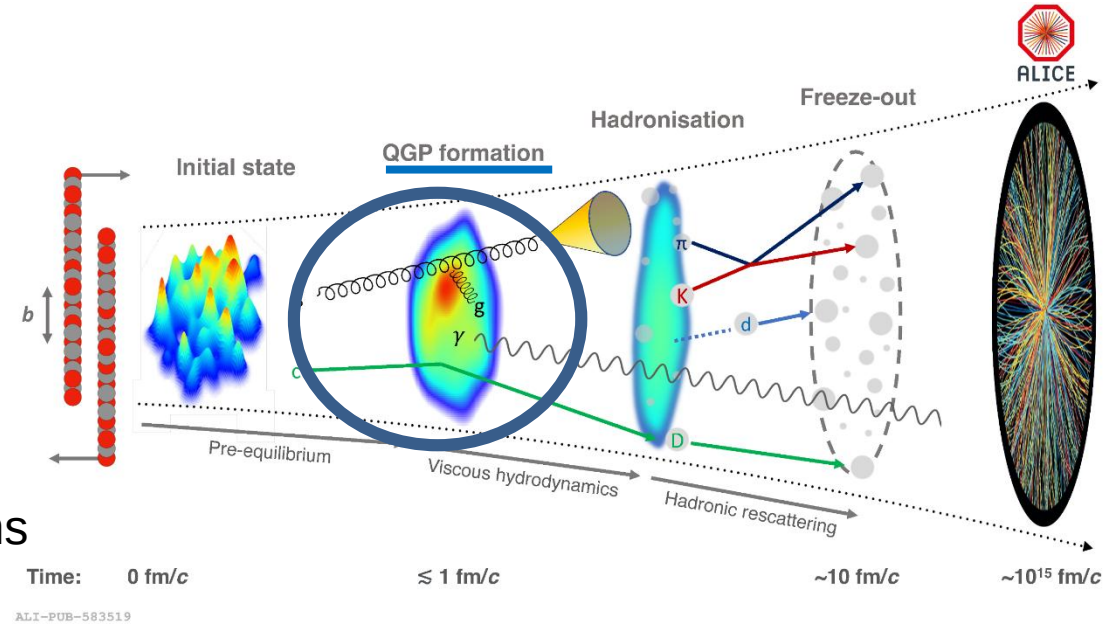
# Scientific context: the quark-gluon plasma (QGP)

Quark-Gluon Plasma: state of strongly-interacting matter in which quarks and gluons are no more confined into hadrons



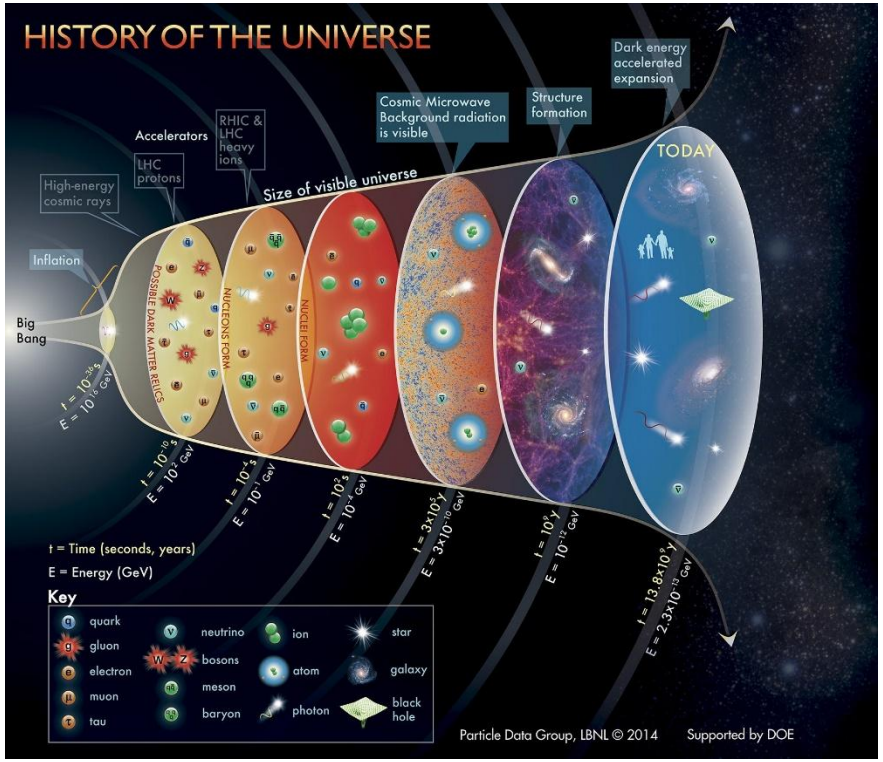

- QCD phase diagram: shows the phase transition via temperature vs. baryochemical potential
- Predicted by QCD, from Lattice QCD calculations:
  - Critical temperature: $T_c$ ~ 155 MeV
  - Critical energy density: $\varepsilon_c$ ~ 0.5 GeV/fm$^3$

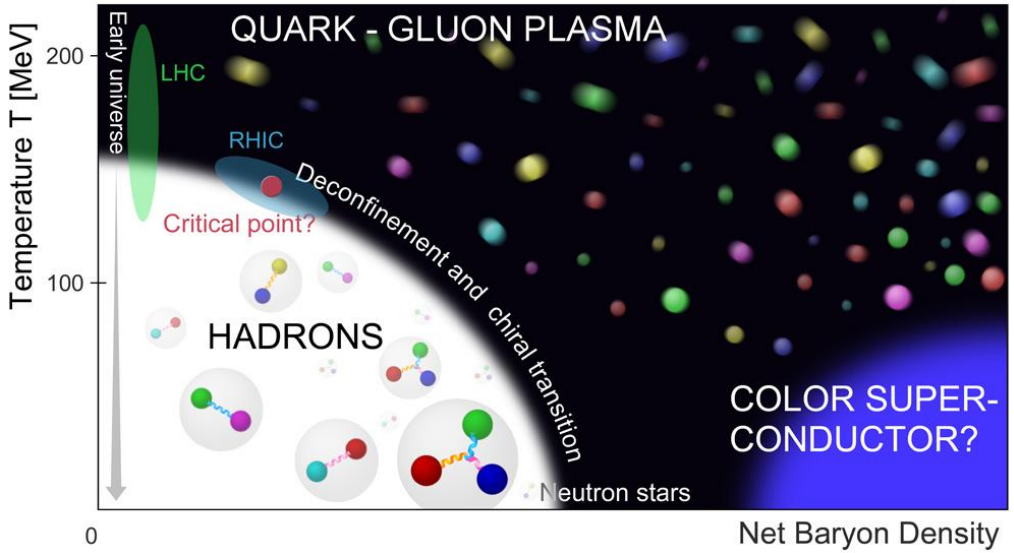
- A QGP state can be created using ultrarelativistic heavy-ion collisions
- ALICE at the LHC:
  - Dedicated experiment for heavy-ion physics
  - Also, important physics program with small collision systems




*Eur. Phys. J. C 84 (2024) 813*

# Scientific context: the quark-gluon plasma (QGP)




- Study the properties of nuclear matter at extreme conditions of temperature and energy density
  - Deconfined state of matter: quark-gluon plasma (QGP)
  - Predicted by QCD: $T_c$ ~ 155 MeV, $\varepsilon_c$ ~ 0.5 GeV/fm$^3$

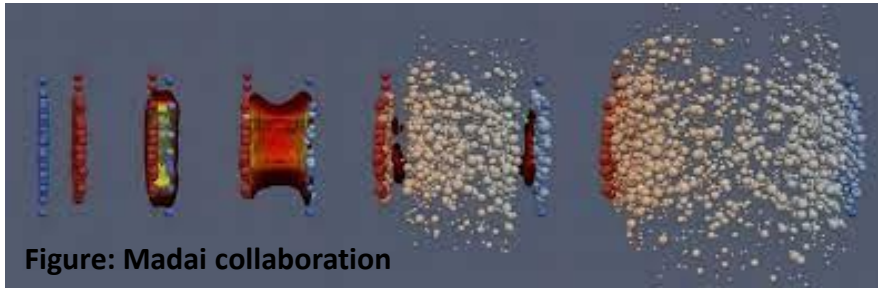


Figure: Madai collaboration

- A QGP state can be created using ultrarelativistic heavy-ion collisions
- ALICE at the LHC: dedicated experiment for heavy-ion physics