Flow Measurements in Heavy-ion Collisions at LHCb

Zhengchen Lian

Tsinghua University & INFN Firenze

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Content

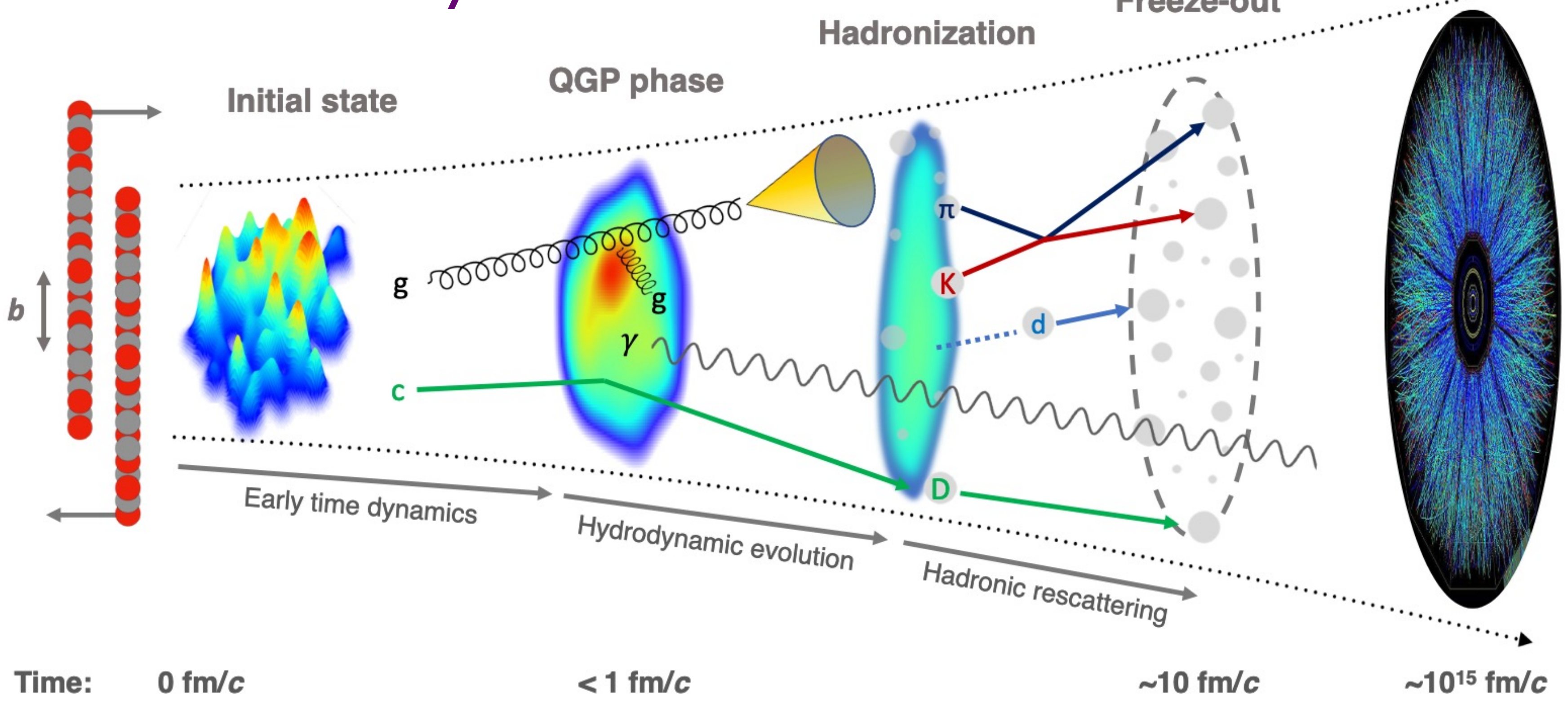
- Introduction of collective flow in heavy-ion collisions
- Flow as a probe of quark–gluon plasma(QGP)
- Flow as a probe of nuclear structure
- Summary

Introduction of collective flow in heavy-ion collisions

- The evolution of a heavy-ion collision
- Collective flow: an observable of QGP phase

The evolution of a heavy-ion collision

illustration from
arXiv:2303.17254



- Initial Overlap & Pre-equilibrium
- QGP Formation & Hydrodynamic Expansion
- Hadronization & Freeze-out
- Final State & Detection

- Strongly coupled Quark-Gluon Plasma (QGP)
- Hot, dense, and nearly perfect fluid
- Pressure gradients hydrodynamic expansion

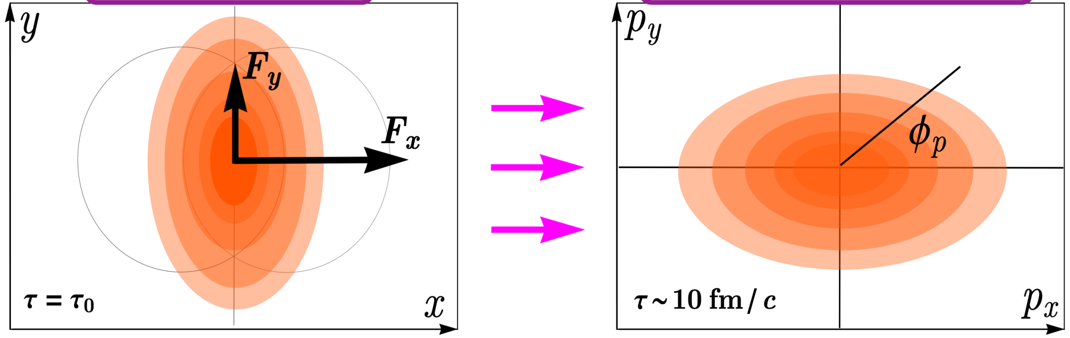
Collective flow: An observable of QGP phase

- Hydro expansion controlled by QCD Equation of State($P = \frac{1}{3}\epsilon$, i.e.)

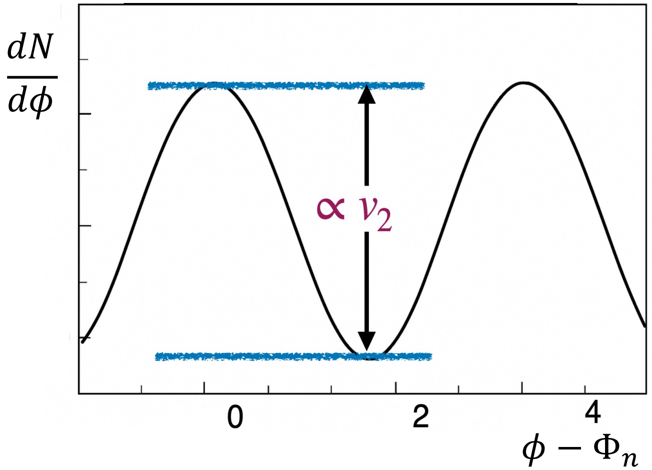
Energy density

Momentum anisotropy

G.Giacalone, arXiv: 2101.00168



Particle distribution in x-y plane



Signature of Fluid

- Observables: anisotropic flow coefficients

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n=1} v_n \cos[n \cdot (\phi - \Phi_n)]\right]$$

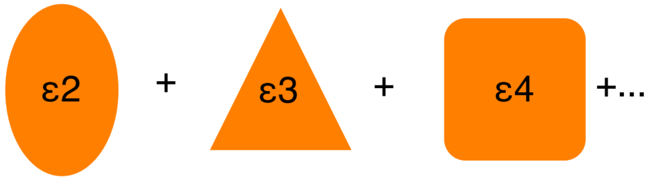
ϕ: Azimuthal angle

Φ_n: Reaction plane

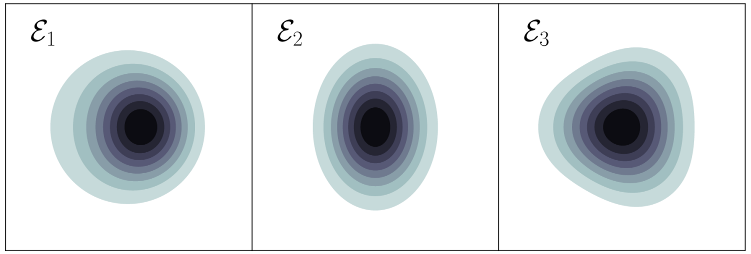
v_n: Flow coefficients

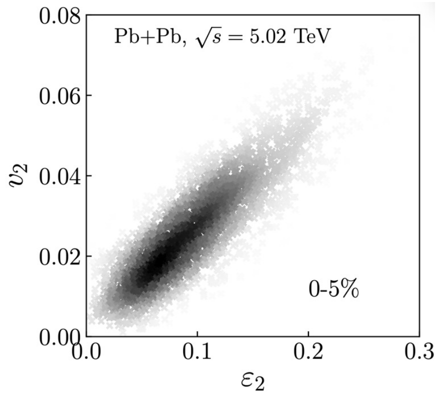
- Collective flow reflects both initial geometry and medium's hydro response

Hydro prediction: $v_n \propto \varepsilon_n$



$$\varepsilon_2 = \frac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle}$$

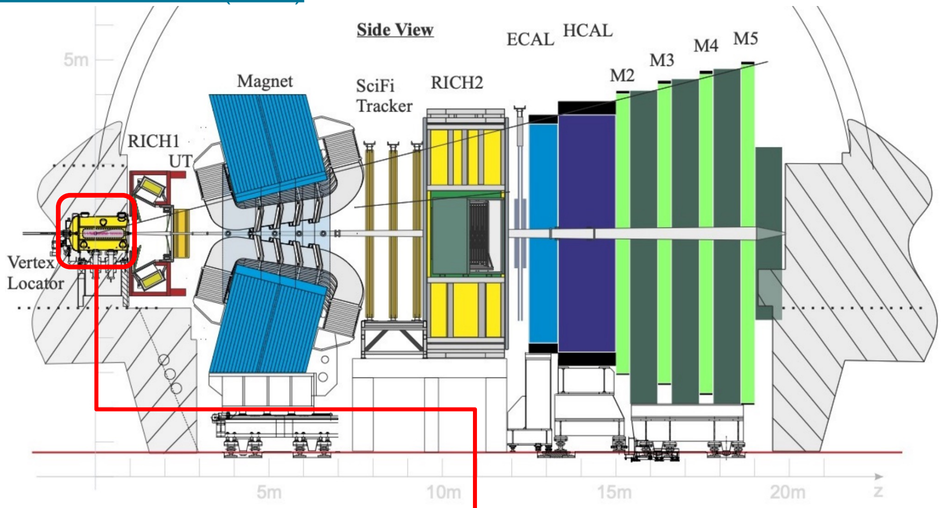




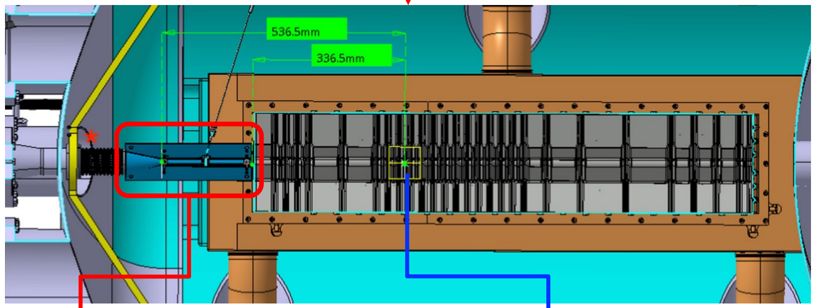
G.Giacalone, arXiv: 2101.00168

The LHCb experiment

Int.J.Mod.Phys.A30 (2015) 1530022
JINST 19 P05065 (2024)



Phys. Rev. Accel. Beams 27 111001



SMOG2 Storage cell
20 cm

Nominal beam-beam
collision point

- LHCb is a general purpose experiment in the forward direction
  - Single-arm forward spectrometer: $2 < \eta < 5$
  - Maintain excellent tracking and particle identification capabilities under a luminosity roughly X5 than Run2: $\mathcal{L} \sim 2 \times 10^{33} cm^{-2} s^{-1}$
  - Collect data in both colliding and fixed-target mode

- SMOG2: The updated *System for Measuring Overlap with Gas*
  - A high density storage cell placed in the LHC primary vacuum
  - Wide choice of injectable gases: He, Ne, Ar, H_2, D_2, …
  - Unique physics opportunities at intermediate energies: $\sqrt{s_{NN}} \in [30, 115]$ GeV

Flow as a probe of quark–gluon plasma(QGP)

- Two particle correlations: Flow measurements on LHCb
- Multi-particle correlations: Cumulant method

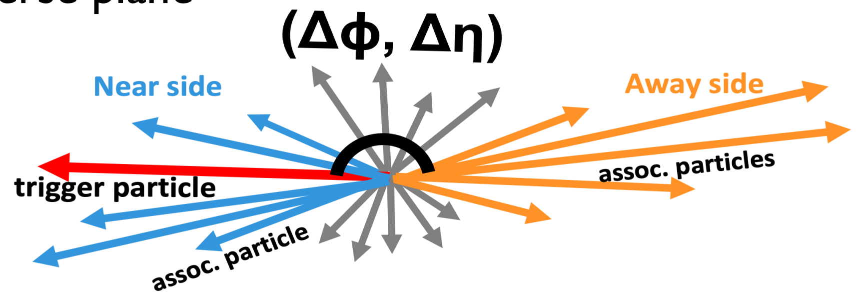
Collective flow: How to measure on LHCb

Definitions?

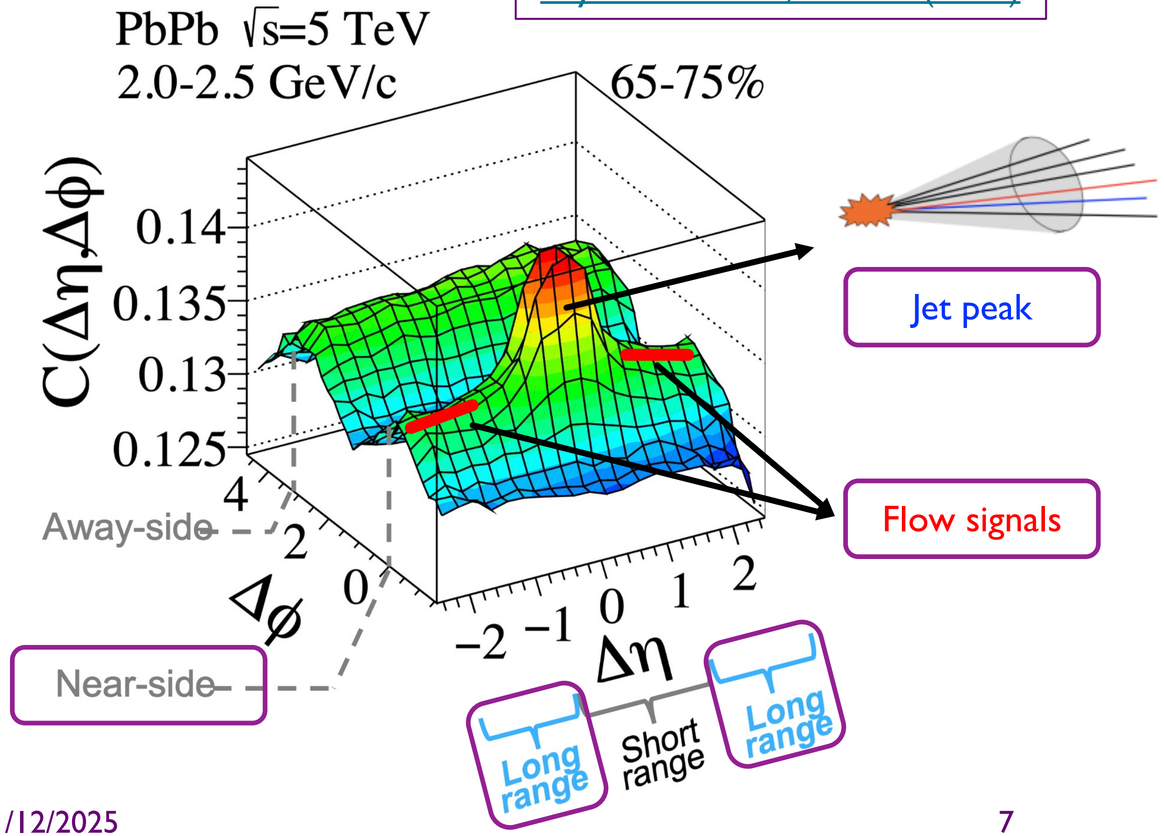
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n=1} v_n \cos[n \cdot (\phi - \Phi_n)]\right]$$

- Challenge: random reation plane(Φ_n) event-by-event
- Particle pair distribution: $$\frac{dN_{pair}}{d\Delta\phi} = \frac{N_{pair}}{2\pi}\left[1 + 2\sum_{n=1} V_{n\Delta,ab}\cos(n \cdot \Delta\phi)\right]$$ $\Delta\phi = \phi_a - \phi_b$
  $V_{n\Delta,ab} = v_{n,a} v_{n,a}$ when $\Phi_{n,a} = \Phi_{n,b}$
- Two particle correlation method:

Transverse plane



Phys. Rev. C 109, 054908 (2024)



- Significant background: Jets(non-flow correlations)
- 2D angular correlation function $C(\Delta\eta, \Delta\phi)$
  (details in backup)
  - Long-range near-side ridge: sign of collectivity
    $|\Delta\eta| > 1 \qquad \Delta\phi \approx 0$

Collective flow: How to measure on LHCb

Definitions?

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n=1} v_n \cos[n\cdot(\phi - \Phi_n)]\right]$$

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- Two particle correlation method:

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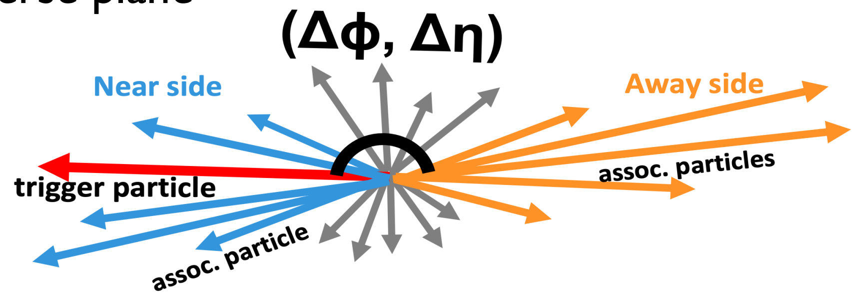

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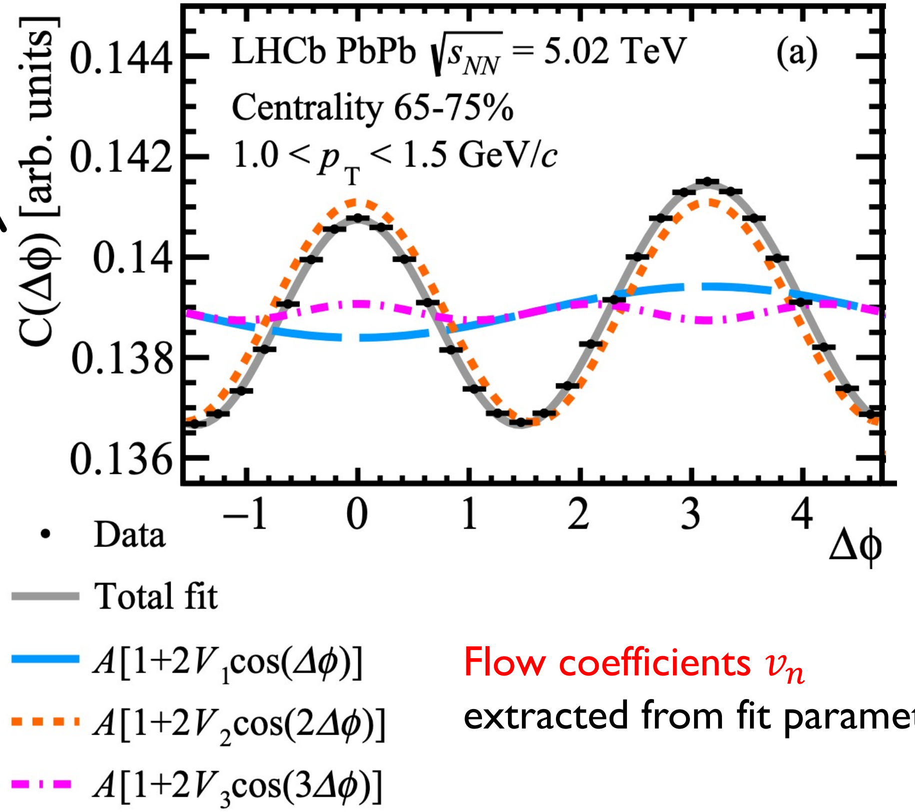


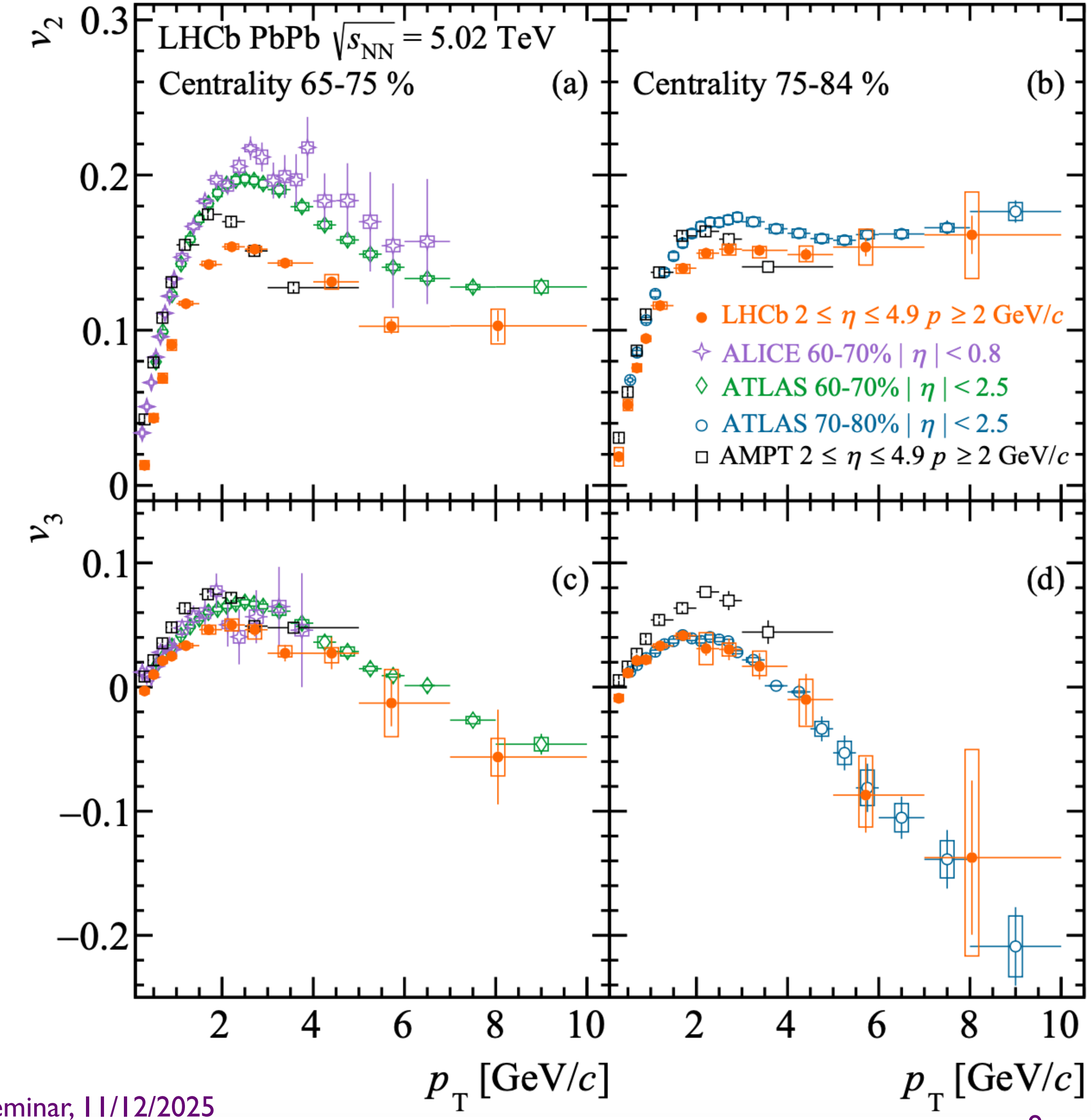
Flow coefficients v_n extracted from fit parameters

- Significant background: Jets(non-flow correlations)
- 1D azimuthal correlation function $C(\Delta\phi)$
  - Projection onto the $\Delta\phi$ axis in long-range($|\Delta\eta| > 1$)
  - A Fourier series fit on $C(\Delta\phi)$

LHCb measurement: Forward charged hadron flow in peripheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

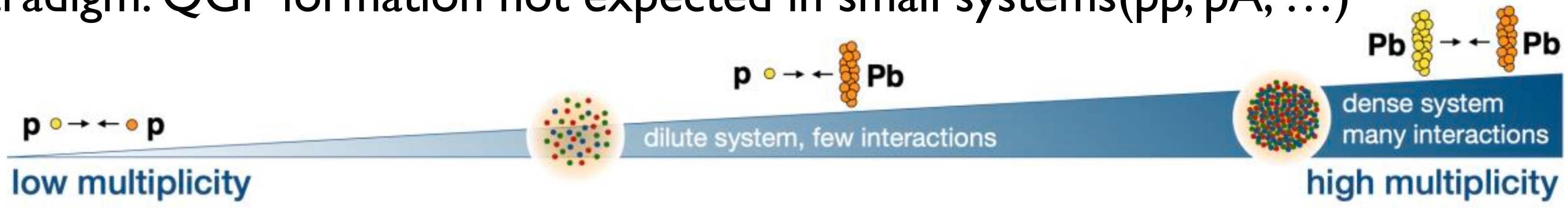
Phys. Rev. C 109, 054908 (2024)

- First result of charged hadron $v_n(p_T)$ at LHCb
- LHCb results in the forward region are complementary to other LHC measurements at midrapidity
- Weaker v_n observed compared with ALICE and ATLAS results
- Hadronic viscosity becomes increasingly dominant in the forward region
- AMPT model overestimated v_n, and LHCb data can be used to constrain model in the forward region.



Flow-like behavior in small systems

- Pre-LHC paradigm: QGP formation not expected in small systems(pp, pA, …)

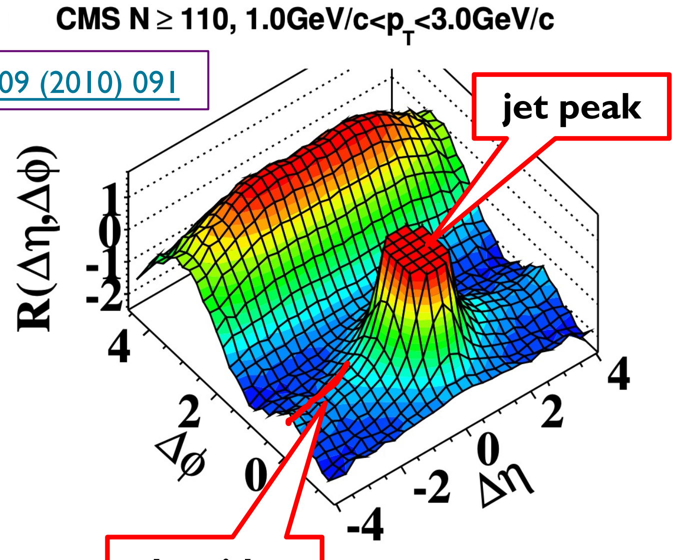


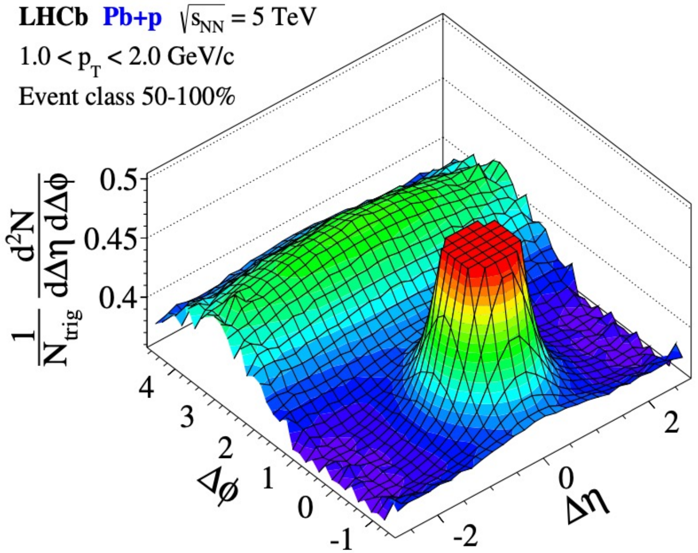
- Emergence in small system: collectivity discovered in pp and pPb collisions at LHC

- Long-range near-side angular correlations in very high multiplicity 7 TeV pp collisions
- Long-range near-side angular correlations in very high multiplicity 5 TeV pPb collisions

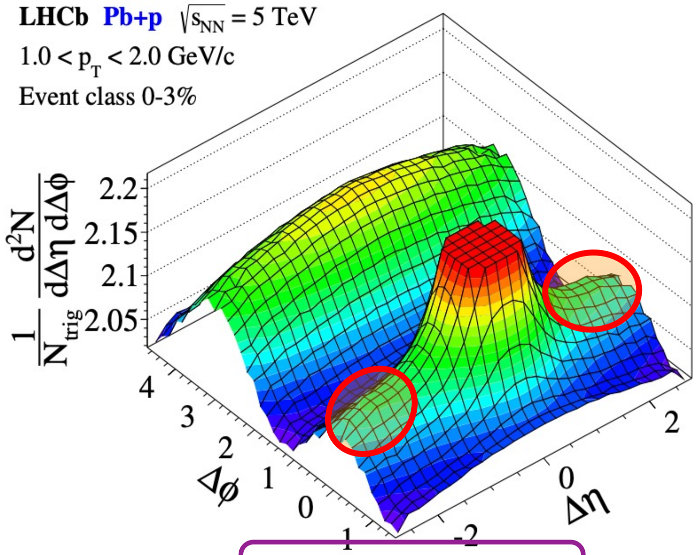
LHCb, Phys. Lett. B762 (2016) 473

CMS , JHEP 09 (2010) 091





low multiplicity

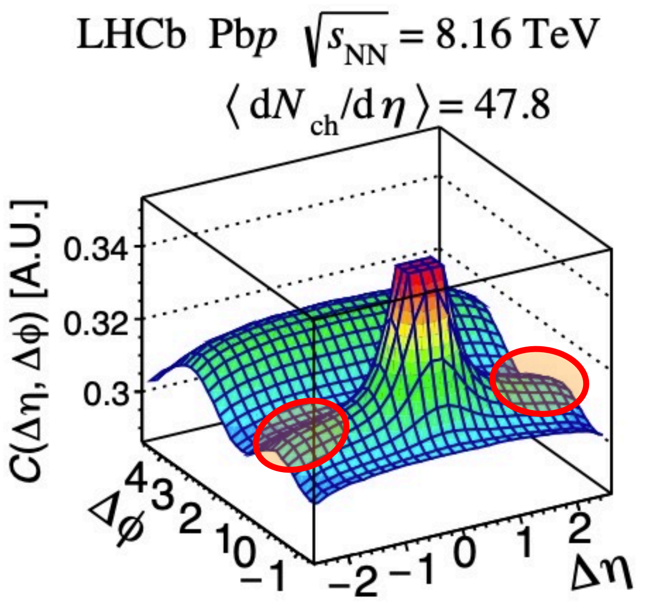


high multiplicity

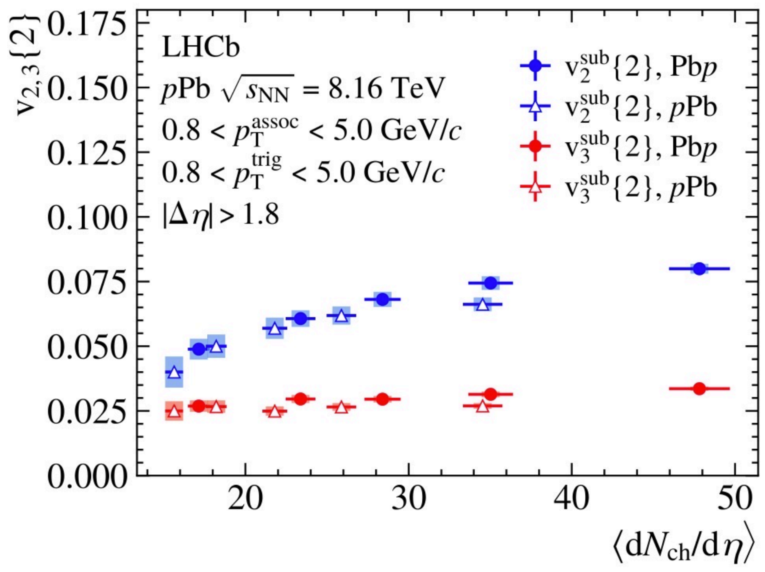
LHCb measurement: Charged particle flow in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

JHEP 10 (2025) 124

- First $v_n\{2\}$ results in pPb & Pbp collisions at LHCb
  - Clear long-range near-side ridge observed in high multiplicity events, consistent with previous 5TeV results
  - $v_2\{2\}$ increases with charged particle density
  - $v_3\{2\}$ remains constant across multiplicities
  - No significant difference between pPb and Pbp



- Help to understand the origin of particle correlations in small systems
- Provide experimental inputs to theoretical models that include longitudinal dynamics



Multi-particle correlations: Cumulant method

A. Bilandzic, R. Snellings, and S. Voloshin, Phys. Rev. C 83, 044913 (2011)

- Multi-particle distribution $\frac{dN_1}{d\phi_1}\dots\frac{dN_m}{d\phi_m} \Longrightarrow v_{n_1}v_{n_2}\dots v_{n_m}\cos(n_1\phi_1+n_2\phi_2+\cdots+n_m\phi_m)$

- Flow measurement with cumulants

$$\langle\langle m\rangle\rangle_{n_1,n_2,\dots,n_m} = \left\langle\left\langle e^{i(n_1\phi_1+n_2\phi_2+\cdots+n_m\phi_m)}\right\rangle\right\rangle$$

$$v_2\{2\} = \sqrt{c_2\{2\}}$$

$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$

  - Going through all m-particle combinations event-by-event $c_n\{m\} = \langle\langle m\rangle\rangle - \cdots$
  - Q-vectors help to avoid computing all combinations by the property of polynomial expansion

polynomial expansion

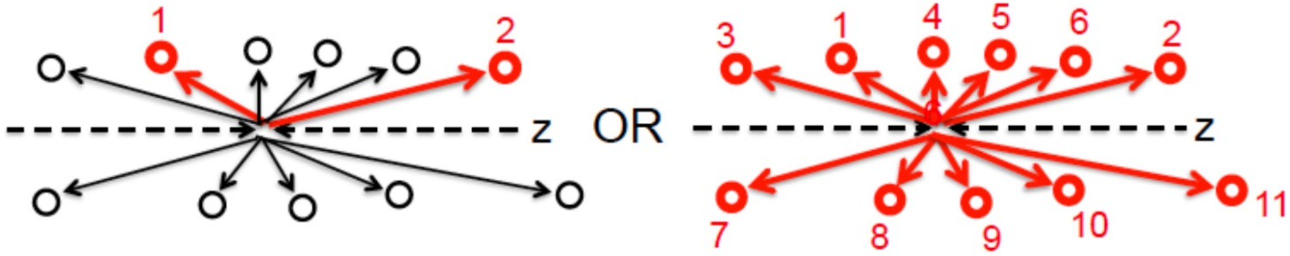
$$Q_n = \sum_{k=1}^{M} e^{in\phi_k}$$

Single particle loop

$$\langle 2\rangle_n = \left\langle e^{in(\phi_1+\phi_2)}\right\rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$\langle 4\rangle_n = \left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 + \cdots}{M(M-1)(M-2)(M-3)}$$

- Advantages
  - Results directly come from the event-by-event measurement
  - Lower nonflow contribution with more particles correlated

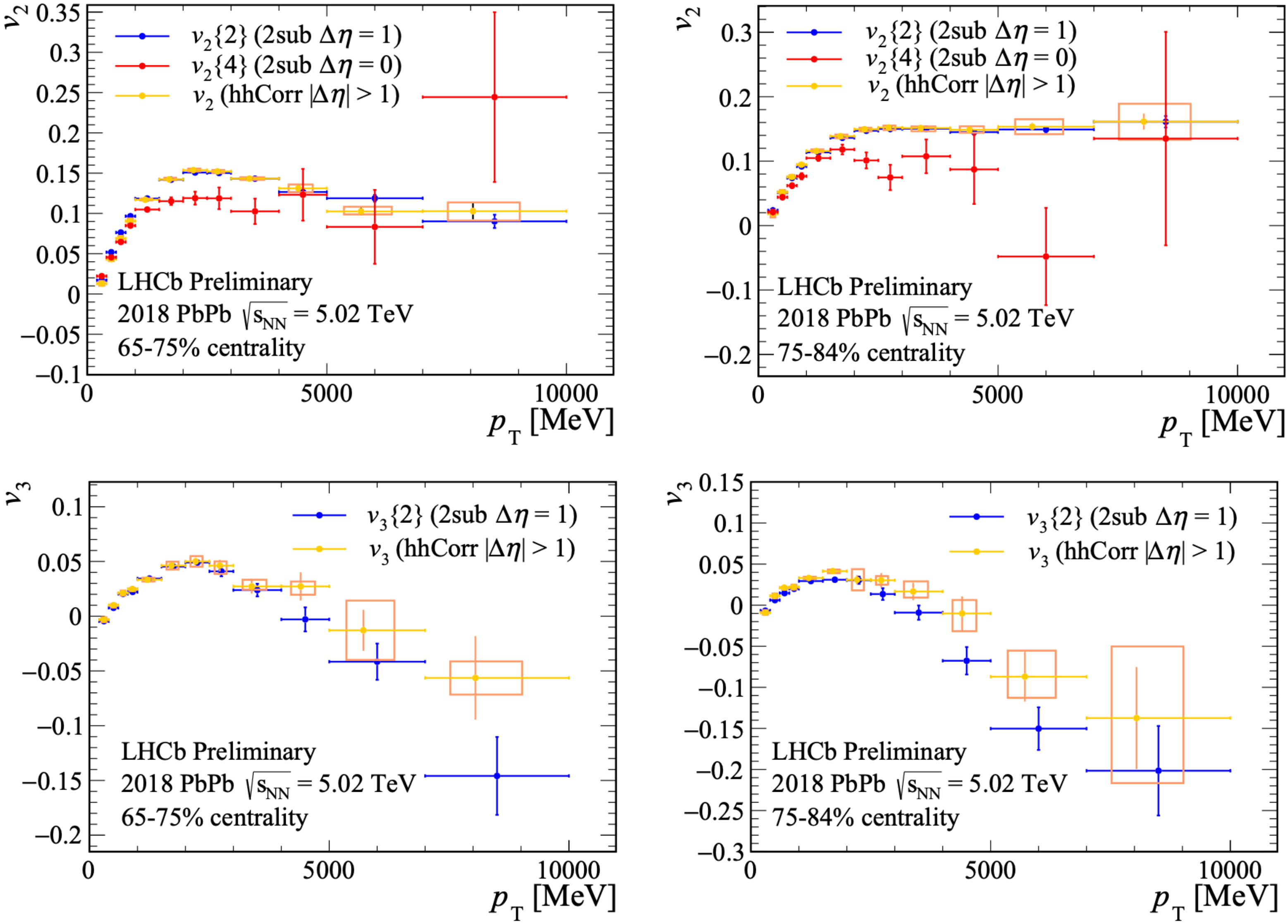


Two-particle correlations Multi-particle correlations

Preliminary results with cumulant method to PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV on LHCb

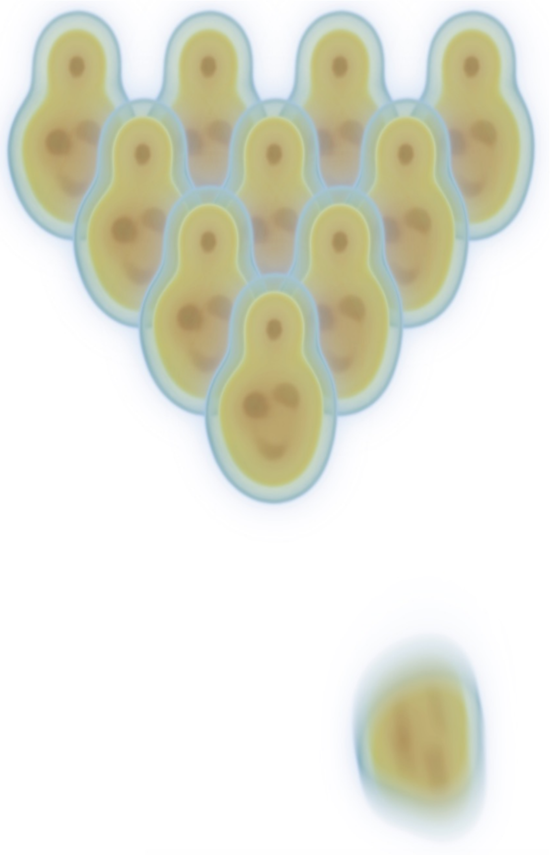
[LHCb-CONF-2025-001]

- $v_n(p_T)$ in peripheral PbPb collisions for two centrality classes
- Comparison between two method with same data sample and condition
- Published results via two-particle correlations
- Two-particle cumulants: consistent with previous results
- Four-particle cumulants: lower values (as expected), larger uncertainties



Cumulant method is successfully validated!

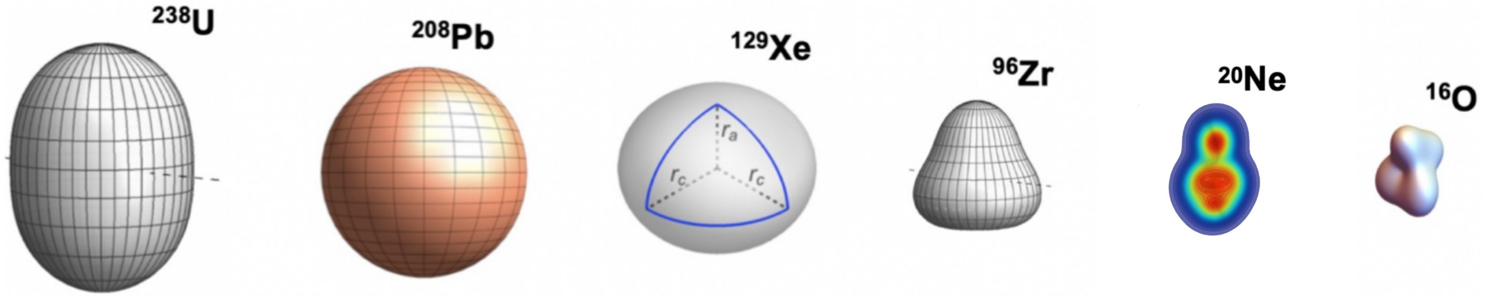
Flow as a probe of nuclear structure



- Imaging the nuclear structure in nuclear collisions
- Unique geometry of light nuclei: α-cluster
- LHCb SMOG2 Pb + X collisions

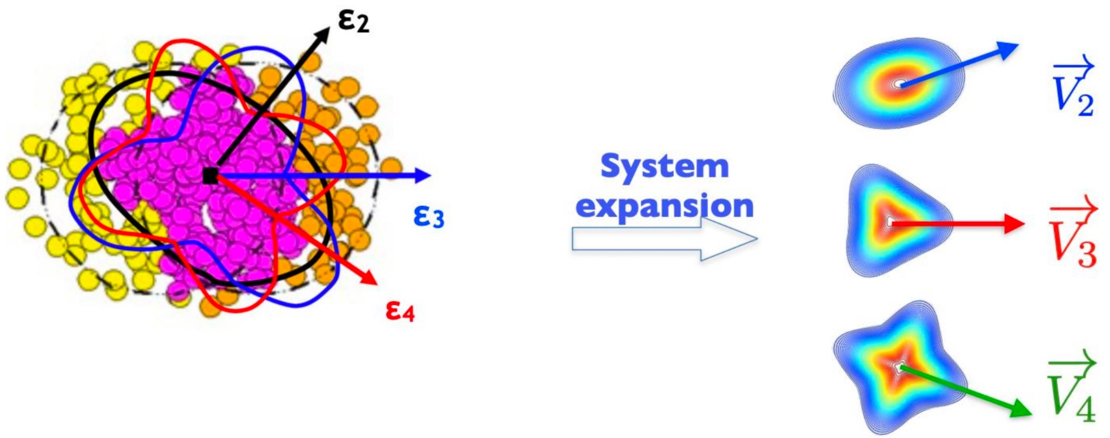
Imaging the nuclear structure in nuclear collisions

- Nuclei are not necessarily spherical
  - Described by many theories: Woods-Saxon density profile, ab initio calculation(NLEFT, PGCM, …)
  - Not directly observed at low energy experiments



- "Imaging-by-smashing" technique
  - Collective motion converts initial geometry into momentum space anisotropy

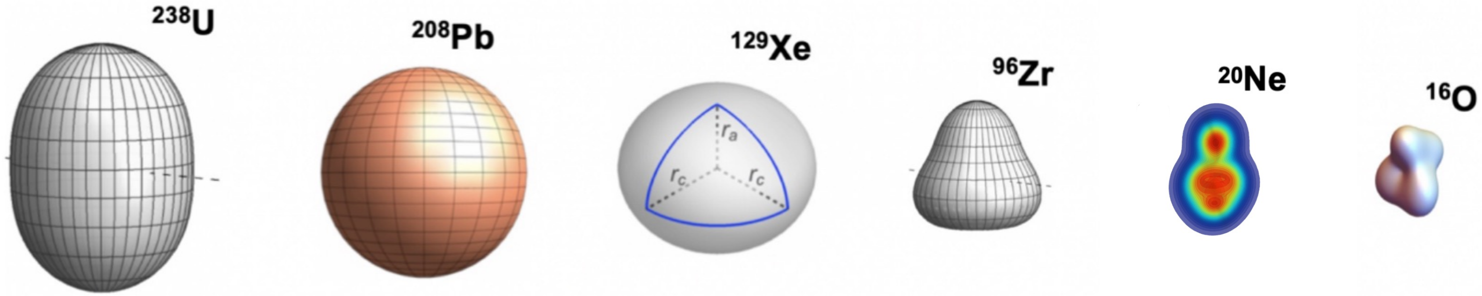
Initial state
anisotropic spatial distribution



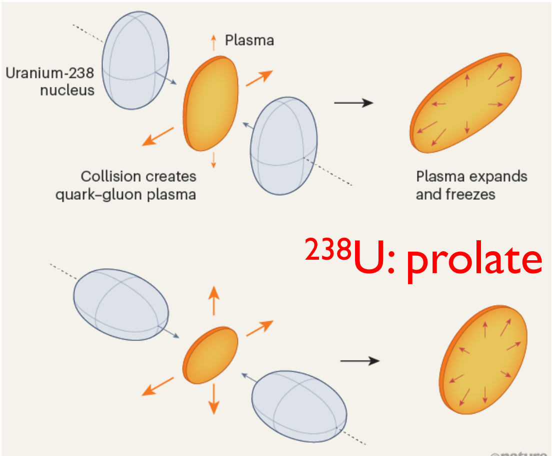
Final state
anisotropic momentum distribution

Imaging the nuclear structure in nuclear collisions

- Nuclei are not necessarily spherical
  - Described by many theories: Woods-Saxon density profile, ab initio calculation(NLEFT, PGCM, …)
  - Not directly observed at low energy experiments



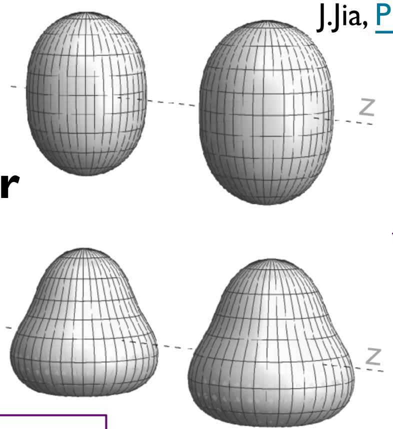
- "Imaging-by-smashing" technique
  - Collective motion converts initial geometry into momentum space anisotropy
  - Reverse engineering



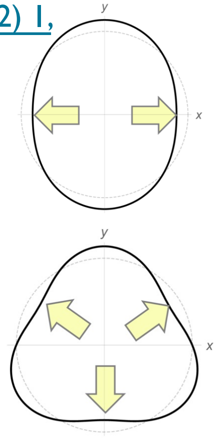
^{238}U: prolate shape

STAR Collaboration
Nature 635, 67–72 (2024)

Nuclear shape



J.Jia, PRC 105 (2022) 1, 014905



Large ε_2

Initial geometry

Large ε_3

Hydro response
$v_n \propto \varepsilon_n$

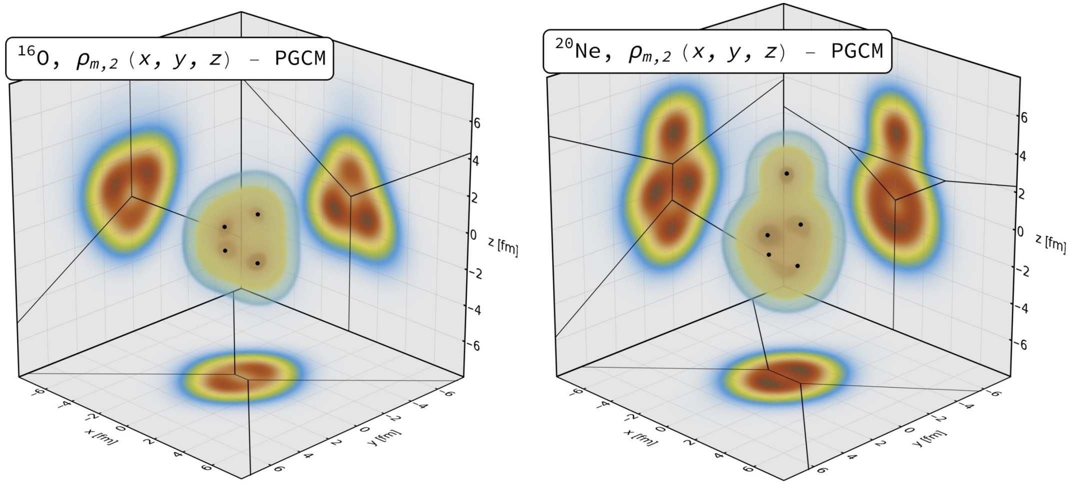
Large v_2

Flow observables

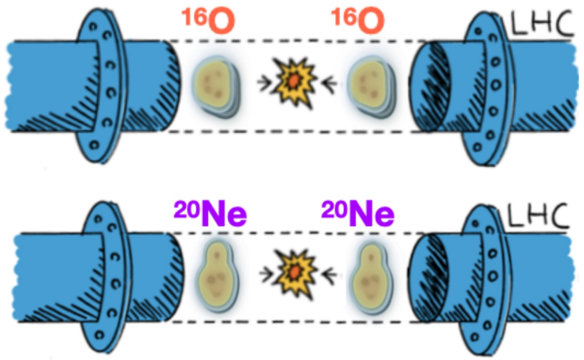
Large v_3

Unique geometry of light nuclei: α-cluster

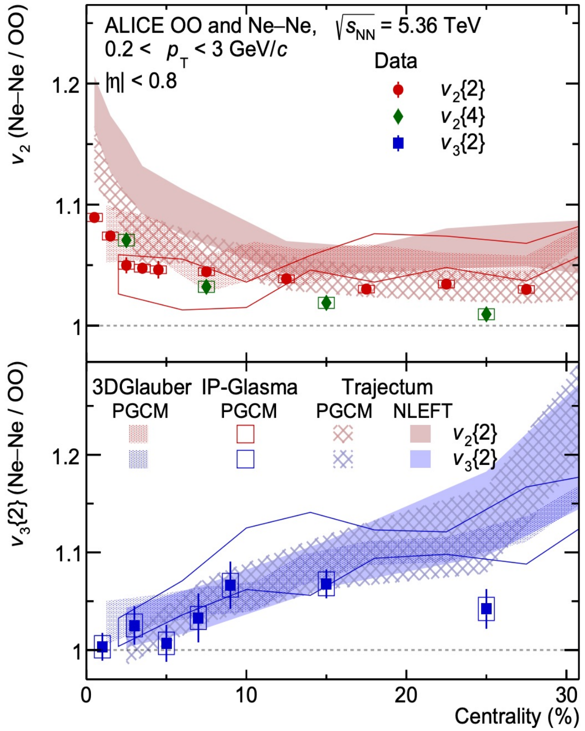
[Phys. Rev. Lett. 135, 012302]



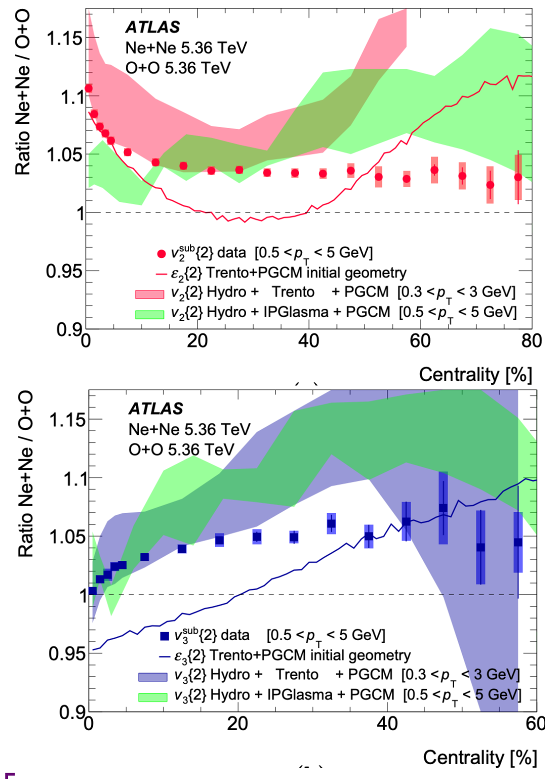
- State-of-the-art ab initio prediction
  - $^{16}\mathrm{O}$ consists of 4 α-clusters, close to spherical
  - $^{20}\mathrm{Ne}$ is similar, with an extra α-cluster on top, bowling pin shape
- LHC OO/NeNe Run: $\sqrt{s_{\mathrm{NN}}} = 5.36\mathrm{TeV}$, July 2025



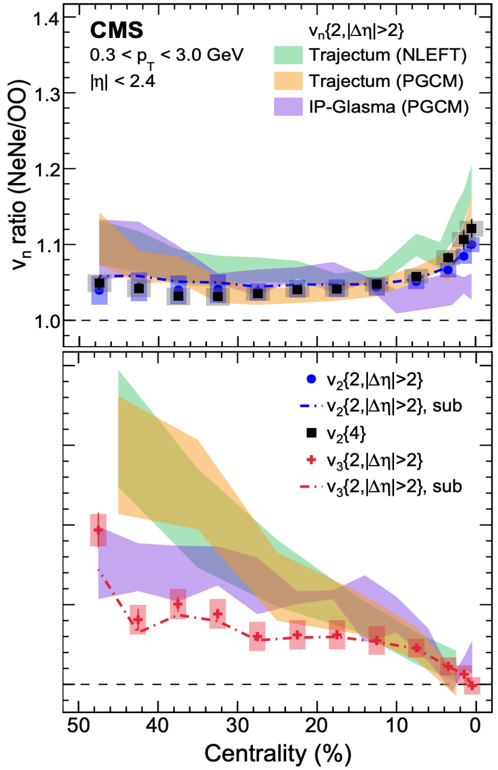
- Test both hydrodynamic and nuclear structure theories by flow measurements



[ALICE: arXiv:2509.06428]



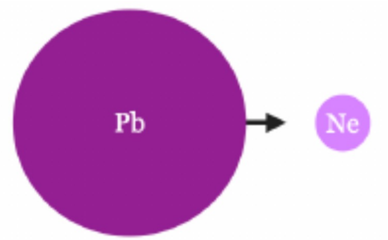
[ATLAS: arXiv:2509.05171]

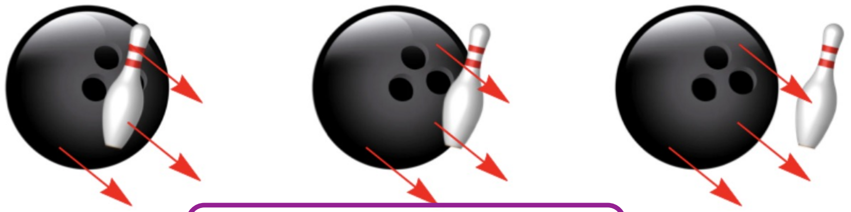


[CMS: arXiv:2510.02580]

LHCb SMOG2 Pb + X collisions

- By injecting Ne gas in SMOG2, LHCb provide a unique opportunity to study neon nucleus structure
- Pb + X collisions: A bowling alley at high energy

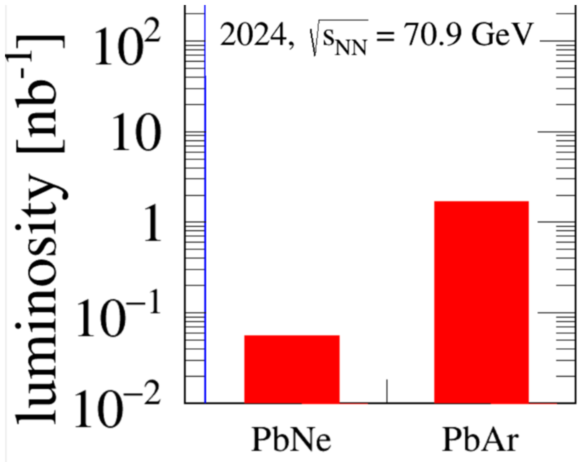


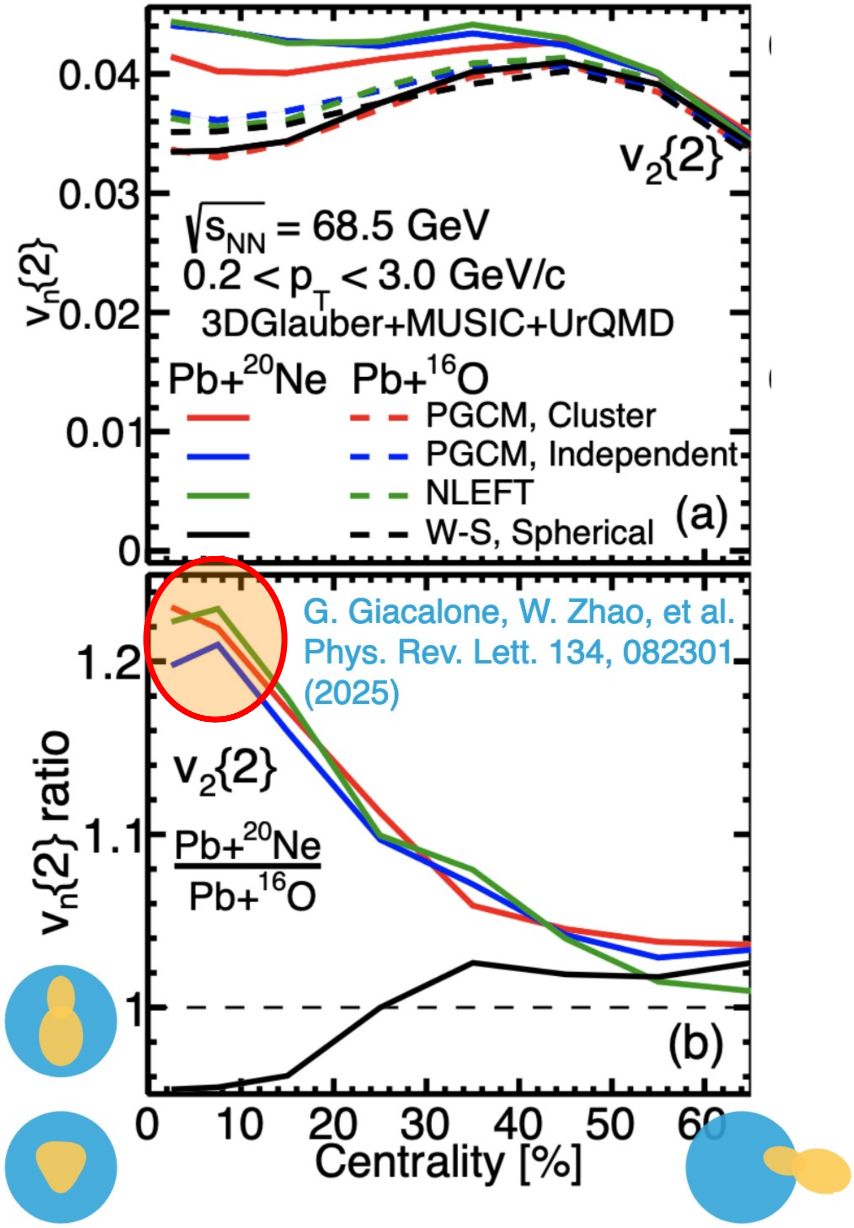


Snapshot as overlap

- Pb+Ne/Pb+O v_2 ratio
  - Central collisions: a large signal is predicted by multiple models
- Challenges from experiment
  - Injecting O was not approved.
  - Solution: Pb+Ar as reference

^{40}Ar: nearly spherical shape

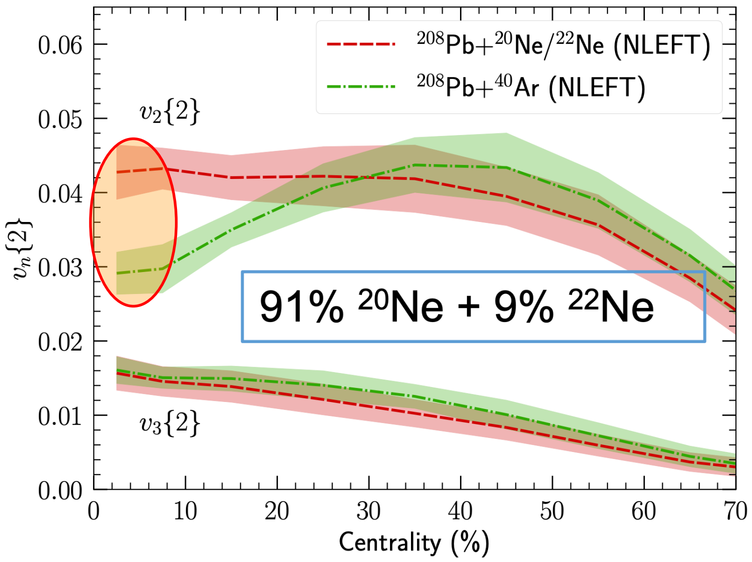


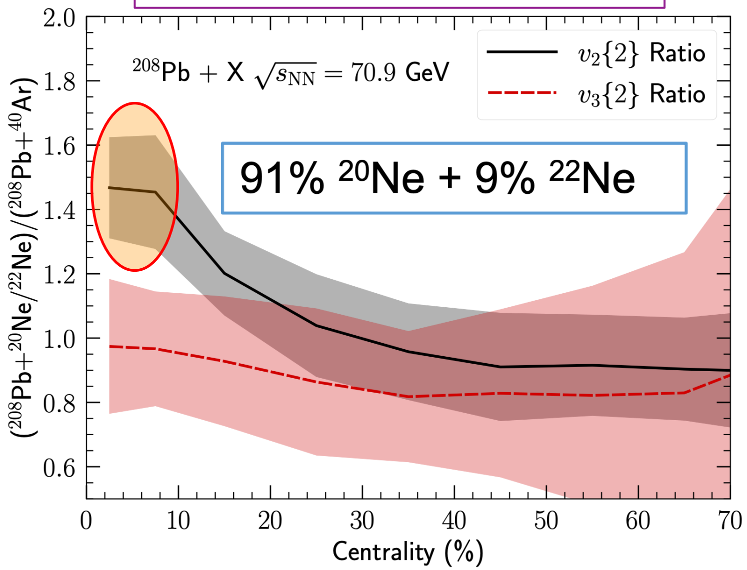


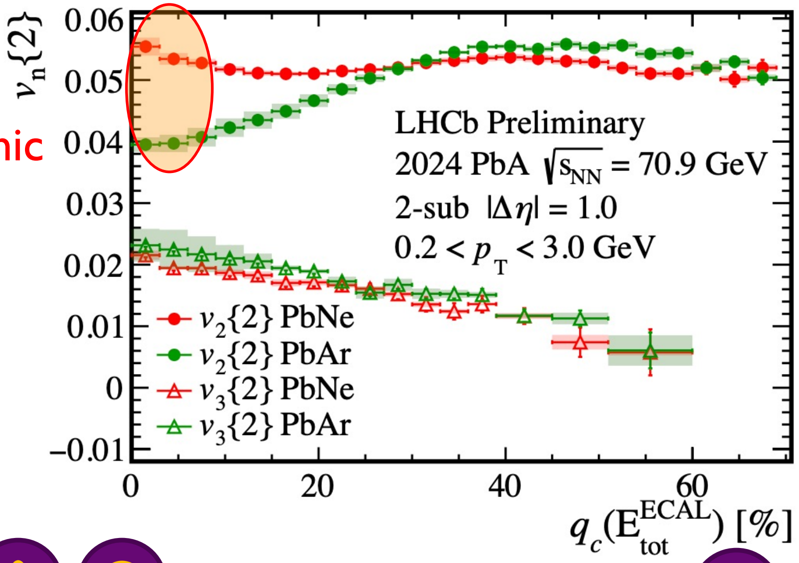
LHCb measurement: Charged particle flow in PbNe and PbAr collisions at $\sqrt{s_{NN}} = 70.9$ GeV

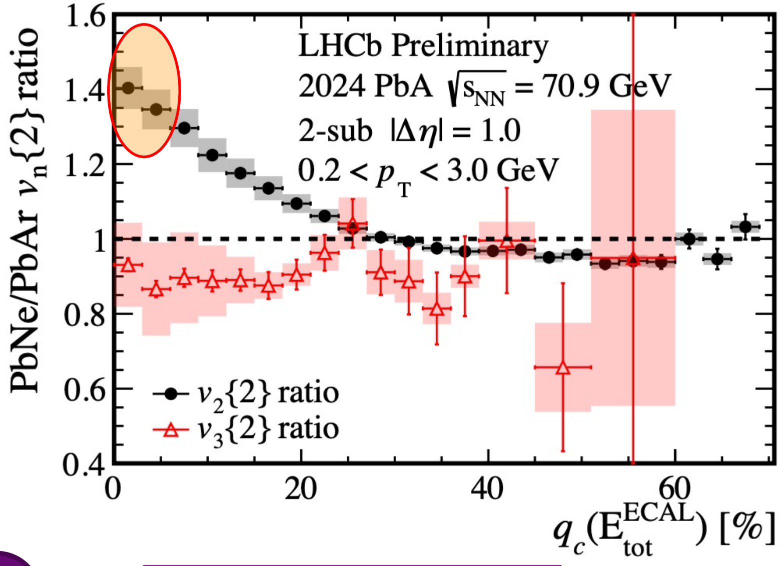
Wenbin Zhao @ Implication25

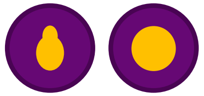
- 3+1D hydro prediction with ab-initio nuclear-structure (NLEFT)
- Evidently flatter $v_2\{2\}$ values for PbNe than PbAr and a similar decreasing $v_3\{2\}$
- LHCb observed a significant Pb+Ne/Pb+Ar $v_2\{2\}$ ratio greater than unity in central collisions, qualitatively consistent with predictions
- Suggest the elongated nuclear shape of neon and the validity of the hydrodynamic description in these collisions
- Final results will require MC-Glauber based centrality calibration

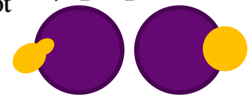












LHCb-CONF-2025-001

Summary

- Collective flow is a probe of QGP phase of heavy-ion collisions
  - Long-range near-side ridge measured in PbPb and pPb via two-particle correlations
  - Cumulants: direct measurement with multi-particle correlations
  - Understand the evolution and transport properties of QGP in forward rapidity

Phys. Rev. C 109, 054908 (2024)
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PbPb in preparation

- Imaging the nuclear structure through flow tools
  - State-of-the-art ab-initio prediction : α-cluster in ^{16}O and ^{20}Ne
  - First observation of Ne deformation on SMOG2 : unique capability to image nuclei
  - Demonstrated LHCb Upgrade I detector's capabilities for physics in high-occupancy collisions (central PbAr)

Yet to be verified by flow measurements

PbNe/PbAr
LHCb-CONF-2025-001

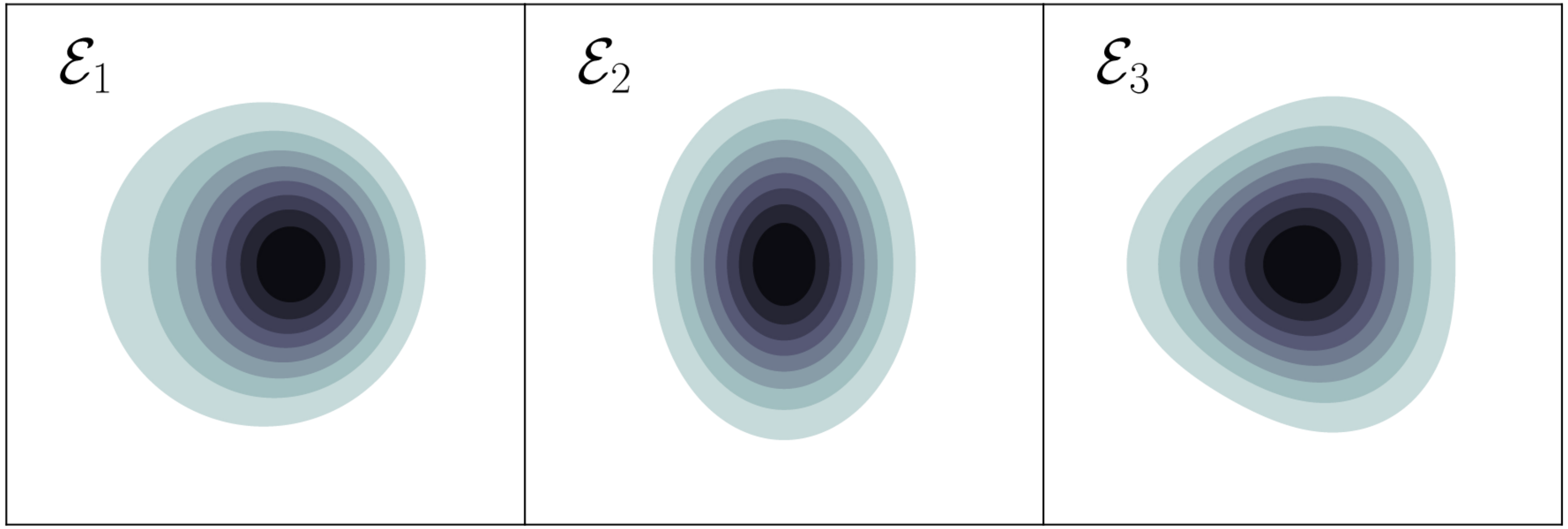
- Future opportunities:
  - Colliding mode: heavy flavor flow, special ^{16}O+^{16}O & ^{20}Ne+^{20}Ne collisions
  - Fixed target: Pb+^{16}O, Pb+^{20}Ne

Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

Tsinghua University

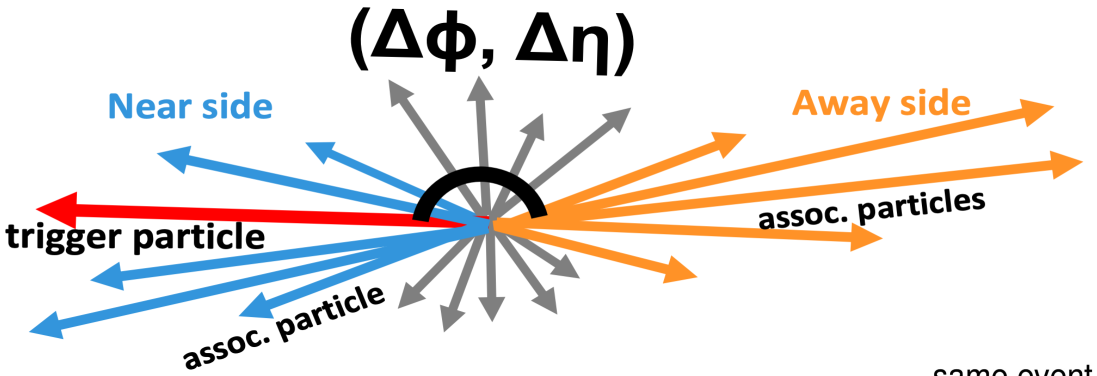
Thanks for attention!

Initial Geometry

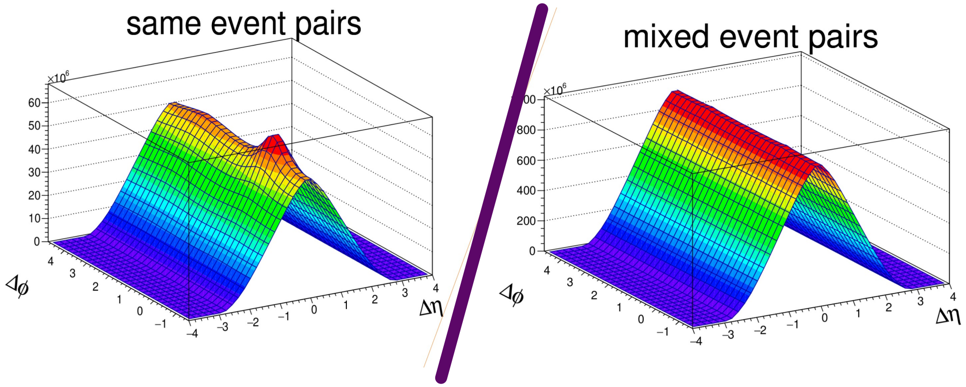


$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

Analysis strategy: 2D angular correlation with mixed-event correction

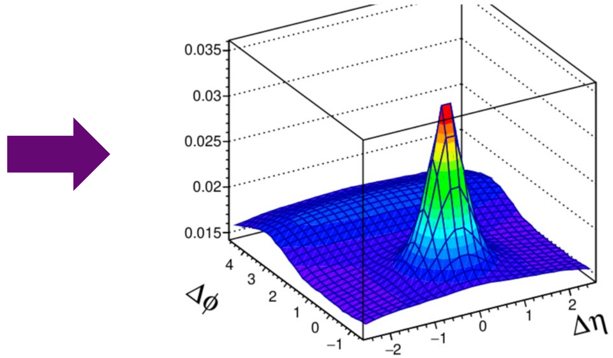


[Phys. Rev. C 109, 054908 (2024)]



- A pair of charged hadrons: trigger + partner (associated)
- $\Delta\eta = \eta^{trig} - \eta^{assoc}$, $\Delta\phi = \phi^{trig} - \phi^{assoc}$
- Same event pairs: two hadrons from the same event
- Mixed event pairs: two hadrons from different events
- Correlation function = same event pairs / mixed event pairs

$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$



LHCb measurement: forward charged hadron flow in peripheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Phys. Rev. C 109, 054908 (2024)

- 1D two-particle azimuthal ($\Delta\phi$) correlation
  - Remove $|\Delta\eta| \leq 1$ region to reduce short-range nonflow contributions

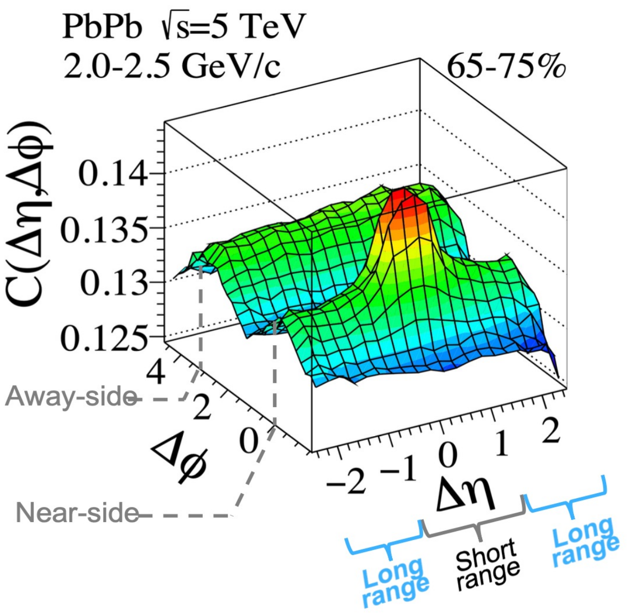
$$C(\Delta\phi) = \frac{\int_1^{2.9} S(|\Delta\eta|, \Delta\phi)\, d(|\Delta\eta|)}{\int_1^{2.9} B(|\Delta\eta|, \Delta\phi)\, d(|\Delta\eta|)}$$

  - Perform a Fourier series fit to this function including the the first three harmonic terms

$$C(\Delta\phi) = A\left[1 + 2\sum_{n=1}^{3} V_n(p_{T_a}, p_{T_b}) \cos(n \cdot \Delta\phi)\right]$$

  - Extract the n^{th} flow harmonic coefficient of particle as a function of transverse momentum $v_n(p_T)$

$$V_n(p_{T_a}, p_{T_b}) = v_n^a(p_{T_a}) \cdot v_n^b(p_{T_b})$$



LHCb measurement: charged particle flow in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

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- Extract flow with 2D angular correlation method as previous
- Significant contributions from other Non-flow effect: resonances and minijets
- Non-flow subtraction method:

$$V_{n\Delta} = c_n + d_n$$

Non-flow contribution (d_n)

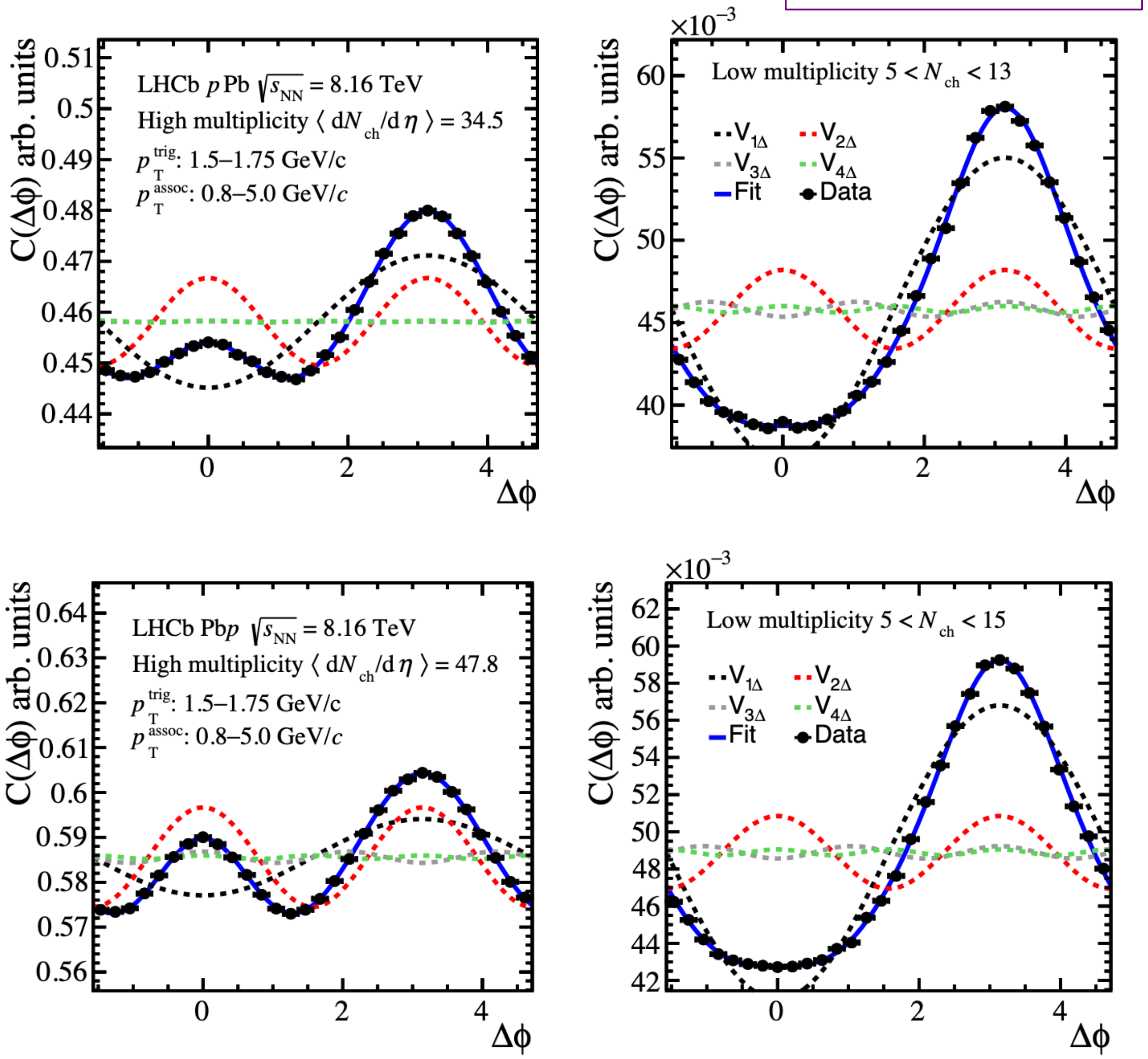
- In low-multiplicity events where collective flow is negligible:

$$d_n^{LM} \approx V_{n\Delta}^{LM}$$

- In high-multiplicity events:

$$d_n^{\mathrm{HM}} = J_{\mathrm{LM}}^{\mathrm{HM}} d_n^{\mathrm{LM}}$$

$$c_n = V_{n\Delta}^{HM} - d_n^{HM}$$



Cumulants

A. Bilandzic, R. Snellings, and S. Voloshin, Phys. Rev. C **83**, 044913 (2011)

- Multi-particle distribution

$$\frac{dN_1}{d\phi_1} \dots \frac{dN_m}{d\phi_m} \Longrightarrow v_{n_1} v_{n_2} \dots v_{n_m} \cos(n_1\phi_1 + n_2\phi_2 + \cdots + n_m\phi_m)$$

- Calculate $v_n\{m\}$ with m-particle correlation

$$\langle\langle m \rangle\rangle_{n_1,n_2,\dots,n_m} = \left\langle\left\langle e^{i(n_1\phi_1 + n_2\phi_2 + \cdots + n_m\phi_m)} \right\rangle\right\rangle$$

$$c_n\{m\} = \langle\langle m \rangle\rangle - \cdots$$

  - Inner ⟨ ⟩: average of all m-particle combinations in single event
  - Outer ⟨ ⟩: average of all events
  - For $n_1 = n_2 = \dots = n_m = 2$
    - m = 2

$$c_2\{2\} = \langle\langle 2 \rangle\rangle$$

$$v_2\{2\} = \sqrt{c_2\{2\}}$$

m = 4

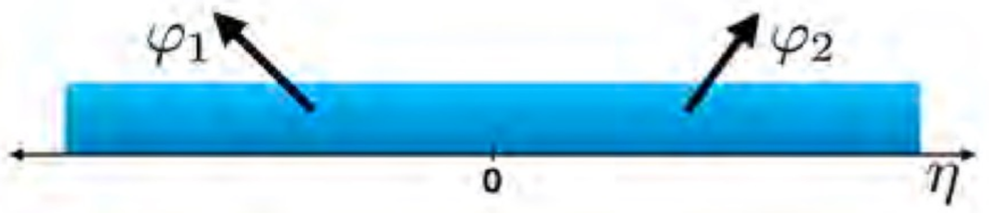
$$c_2\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2$$

$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$

Sub-event method

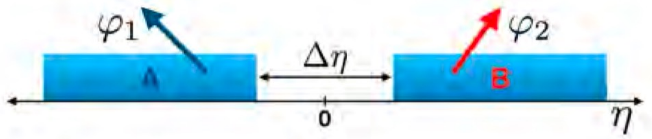
K. Gajdosova, PhD thesis, University of Copenhagen, 2018.

- Particles close to each other might originate from the same source and contribute non-flow effect.



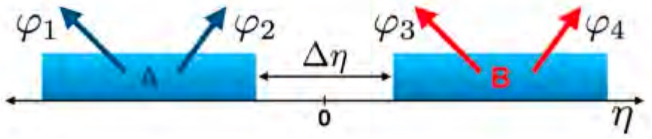
- We can split the η range into two subevents A, B.

- 2-particle cumulant:



$$\langle\langle 2\rangle\rangle_{n,2-\mathrm{sub}} = \langle\langle e^{in(\varphi_1-\varphi_2)}\rangle\rangle$$

- 4-particle cumulant:



$$\langle\langle 4\rangle\rangle_{n,2-\mathrm{sub}} = \langle\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\rangle\rangle$$

Corrections for detector acceptance

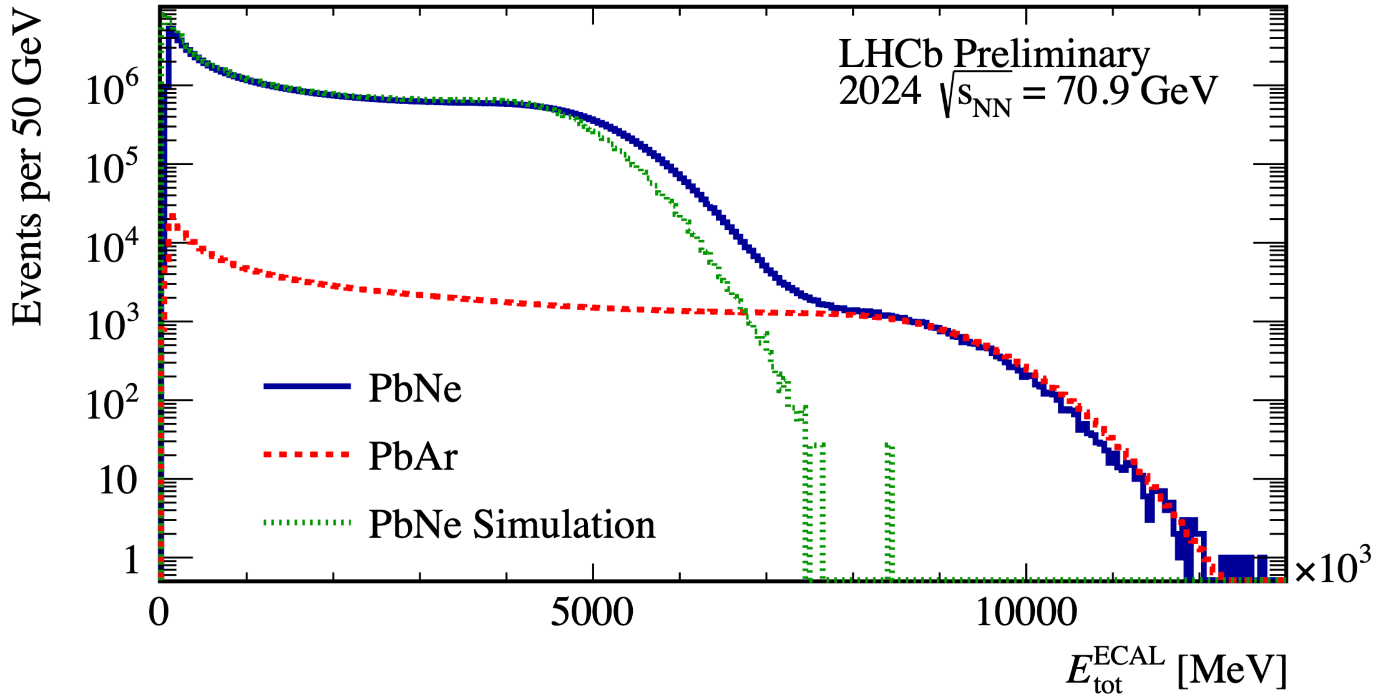
- Tracks are weighted as a function of kinematics $(\phi, \eta, p_{\mathrm{T}})$ and detector occupancy $(N_{\mathrm{VP}}^{\mathrm{Clusters}})$:
  - Number of intervals for $(\phi, \eta, p_{\mathrm{T}}, N_{\mathrm{VP}}^{\mathrm{Clusters}})$: $(100,10,10,100)$

$$w_{\phi}(\phi, \eta, p_{\mathrm{T}}, N_{\mathrm{VP}}^{\mathrm{Clusters}}) = \frac{\langle N(\delta\eta, \delta p_{\mathrm{T}}, \delta N_{\mathrm{VP}}^{\mathrm{Clusters}})\rangle}{N(\delta\phi, \delta\eta, \delta p_{\mathrm{T}}, \delta N_{\mathrm{VP}}^{\mathrm{Clusters}})} \cdot \frac{\rho_{\mathrm{Sim}}(\eta, p_{\mathrm{T}}, N_{\mathrm{VP}}^{\mathrm{Clusters}})}{\epsilon_{\mathrm{Sim}}(\eta, p_{\mathrm{T}}, N_{\mathrm{VP}}^{\mathrm{Clusters}})}$$

- ϕ flattening procedure:
  - Particles averaged over many events follow a uniform ϕ distribution
  - N: the number of selected tracks in each 4-D interval
  - $\langle N \rangle$: average over the ϕ variable
- Predicted correction from simulation
  - Estimation fully from simulated sample by counting the number of reconstructed and generated tracks
  - ϵ_{Sim}: track efficiency
  - ρ_{Sim}: purity

Preliminary selections for the proper PbA collisions

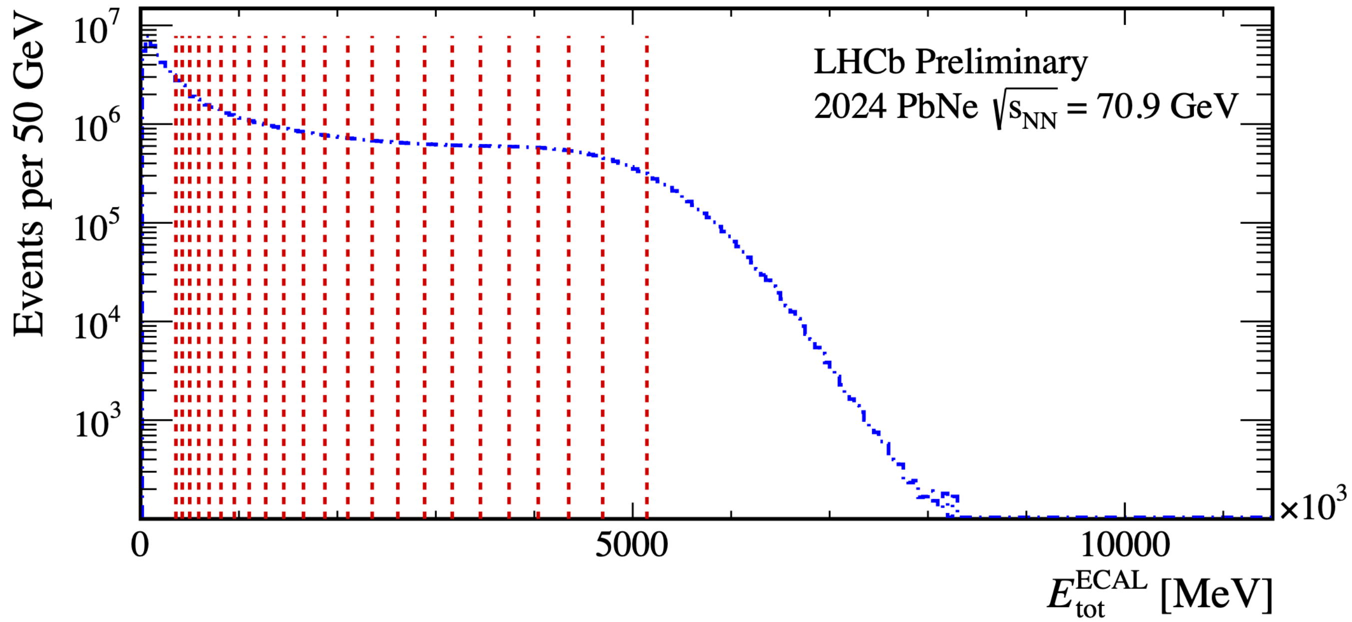
- Collisions outside the SMOG2 cell and ultraperipheral events are suppressed:
  - Requirements on the correlation between ECAL total energy ($E_{\text{tot}}^{\text{ECAL}}$) and detector occupancy ($N_{\text{VP}}^{\text{Clusters}}$)
- Argon contamination in PbNe collisions:
  - A small amount of argon persists in the beam pipe after the purging of the SMOG2, showing a clear dependence on the time elapsed since the most recent argon injection.
  - Estimated from the high-energy tail in the $E_{\text{tot}}^{\text{ECAL}}$ distribution, < 0.5% overall contamination, dominated by PbAr in high-energy tail, excluded

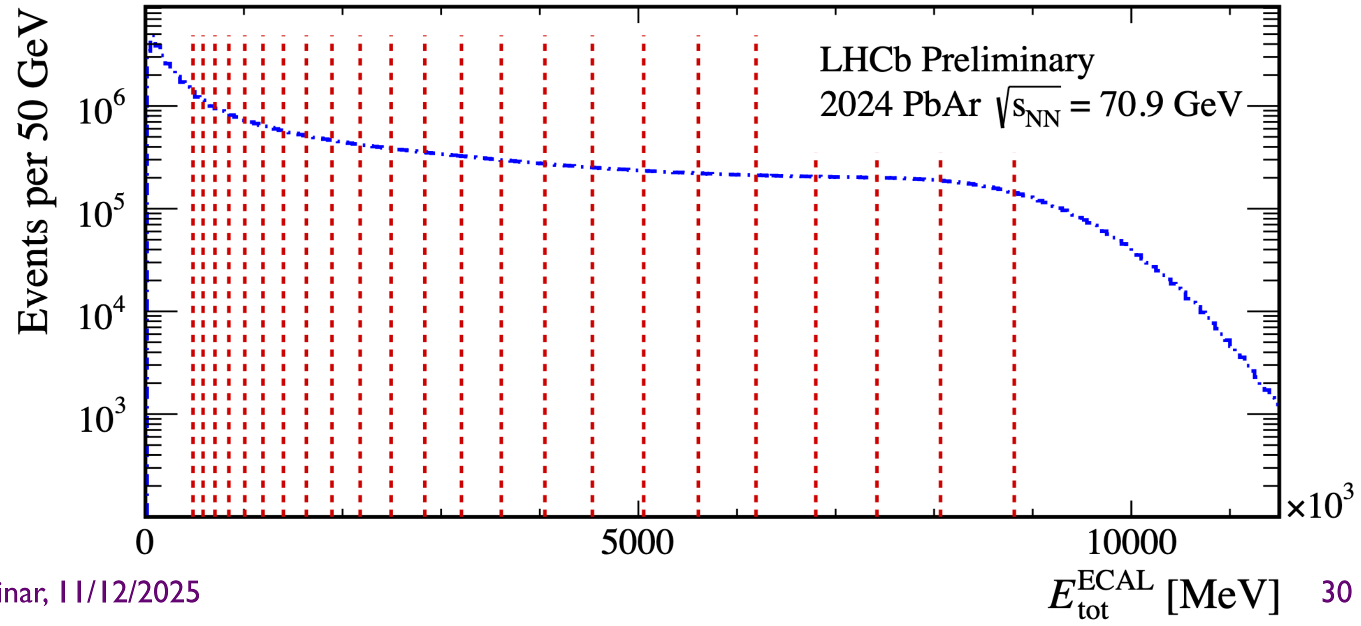


- Track selection
  - Prompt particles produced in a single collision are selected by track quality requirements from the detector acceptance phase space

A preliminary estimator of the centrality

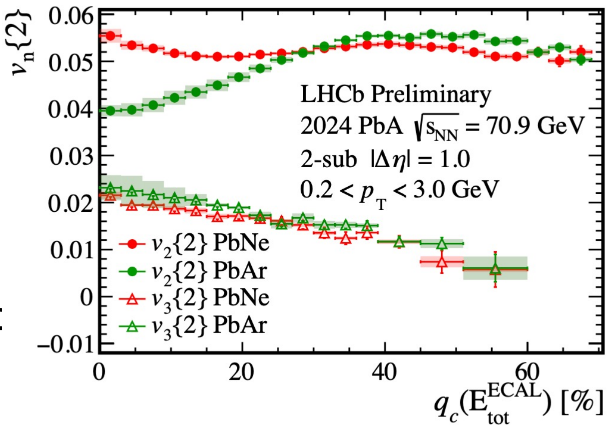
- Complementary quantile of $E_{\text{tot}}^{\text{ECAL}}$ distribution:
  - $q_c(E_{\text{tot}}^{\text{ECAL}}) \equiv 1 - q(E_{\text{tot}}^{\text{ECAL}})$
- $E_{\text{tot}}^{\text{ECAL}}$ distributions after correction agree with Glauber-based EPOS simulation
- The most peripheral events at $E_{\text{tot}}^{\text{ECAL}} <$ 500 GeV are corrected using normalized simulated distributions
- The cumulants are calculated for $q_c(E_{\text{tot}}^{\text{ECAL}})$ from 0 to 69% in steps of 3%

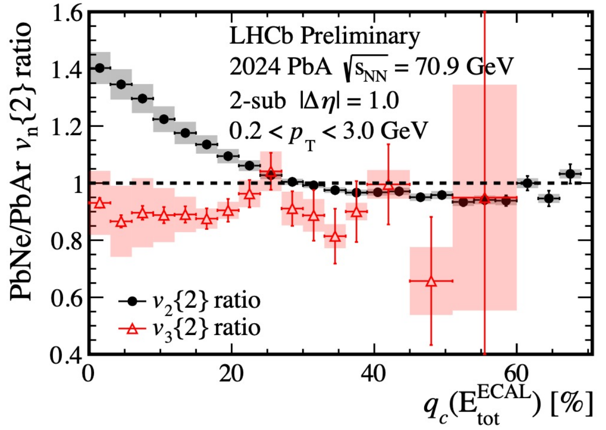


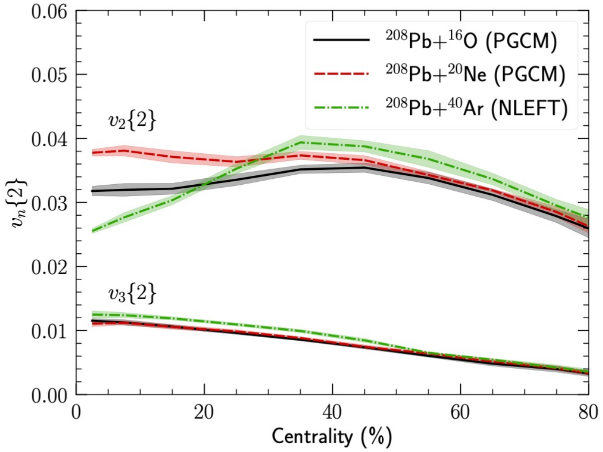


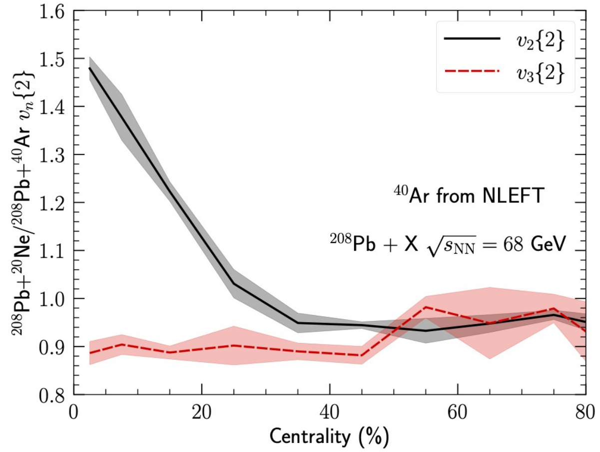
Data vs Model

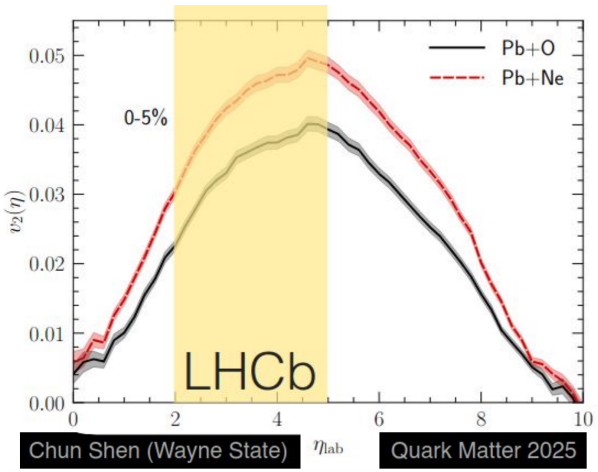
- Data collision energy in the nucleon-nucleon frame is 70.9 GeV, while 68 GeV (the Run2 one) is here considered
- Data refer to natural Ne injection (90.48% ^{20}Ne, 9.25% ^{22}Ne, 0.27% ^{21}Ne), while contamination is not accountec for in the projections
- Centrality proxy to be calibrated
- Predictions referred to $2 < \eta < 5$, phase-space considered for data is $2.4 < \eta < 3.5 + 4.5 < \eta < 5.0$. Elliptic flow largely dependent on pseudorapidity.











Chasing signatures of α-cluster

$$\rho(v_n^2, \langle p_T \rangle) = \frac{\langle \hat{\delta} v_n^2 \hat{\delta} \langle p_T \rangle \rangle}{\sqrt{\langle (\hat{\delta} v_n^2)^2 \rangle \langle (\hat{\delta} \langle p_T \rangle)^2 \rangle}}$$

- The ratios of $v_2 - p_T$ correlation show sensitivity to nuclear configurations from different low-energy nuclear theory calculations

G. Giacalone, W. Zhao, B. Schenke, C. Shen, et al., in preparation