Elliptic flow coefficients of identified hadrons in p-Pb and pp collisions

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on behalf of the ALICE Collaboration
Flow $v_n$ coefficients & identified hadrons

- Constraining medium properties & testing initial conditions

Initial geometry & event-by-event fluctuations cause azimuthal anisotropy wrt. common symmetry plane

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

[ ALICE, JHEP 09 (2017) 032 ]

Pb-Pb $s_{NN} = 2.76$ TeV
Centrality: 20-30% $|n| < 0.8$

ALICE
- $v_2(2,|n|<0.8)$
- $v_3(2,|n|<0.8)$

Hydrodynamics
- $v_2(2)$, MC-KLN & $\eta/s=0.20$
- $v_2(2)$, MC-Gib & $\eta/s=0.08$
- $v_2(2)$, Trento & $\eta/s(T)$
- $v_2(2)$, AMPT & $\eta/s=0.08$

ALICE-DER-139356
Flow $v_n$ coefficients & identified hadrons

- Constraining medium properties & testing initial conditions
- Studying the particle production in different $p_T$ regions
  - **Mass ordering** (hydrodynamic flow, hadron re-scattering)
  - **Baryon/meson grouping** (recombination/coalescence)

Initial geometry & event-by-event fluctuations cause azimuthal anisotropy wrt. common symmetry plane

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

[ ALICE, JHEP 09 (2017) 032 ]

ALICE Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV $|y| < 0.5$, 10-20%

[ arXiv:1805.04390 ]

Mass ordering

Baryon/meson grouping
What about small systems?

**Pb-Pb collisions**

**Mass ordering & baryon/meson grouping**

**v2, v3, v4 signal**

**Medium induced collectivity**

Initial geometry, hydro evolution, E/e fluctuations

**ALICE Pb–Pb** $\sqrt{s_{NN}} = 5.02$ TeV

$|y| < 0.5, 10\text{-}20\%$

[ arXiv:1805.04390 ]
What about small systems?

**Pb-Pb collisions**

**Medium induced collectivity**
- Initial geometry, hydro evolution, EbE fluctuations
- Mass ordering & baryon/meson grouping

**v₂, v₃, v₄ signal**

**Flow-like signatures**
- Mass ordering? (What about grouping?)
- Small droplet(s) of QCD medium?
- No clear picture

**ALICE Pb–Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)**
- \(|y| < 0.5, 10-20\%\)

**Flow-like signatures**

[arXiv:1805.04390]

Mass ordering

- Mass ordering described by 3+1D viscous hydrodynamics with different initial conditions
- Parton based Gribov-Regge multiple scattering (flux tubes)
- MC Glauber initial conditions

Higher precision results needed to validate and distinguish theoretical models
Collectivity in small systems
What is the origin? Initial or final state effects?
A Large Ion Collider Experiment

Multi-purpose detector at the LHC with unique particle identification capabilities and tracking down to very low momenta

- **Inner Tracking System (ITS)**
  - Tracking
  - Triggering

- **Time-Projection Chamber (TPC)**
  - Tracking
  - Particle identification

- **Time-of-flight detector (TOF)**
  - Particle identification

- **V0 detector**
  - $2.8 < \eta < 5.1$ (V0A : Pb-going)
  - $-3.7 < \eta < -1.7$ (V0C : p-going)
  - Triggering
  - Event multiplicity determination

Minimum-bias data from LHC Run II
- 5.02 TeV p-Pb & 13 TeV pp
Particle identification & reconstruction

A. Identification of $\pi^{\pm}$, $K^{\pm}$, and $p(\bar{p})$

- Utilising combined TPC & TOF detector response
- Track-by-track basis with purity > 80%

B. Reconstruction of $\phi$, $K^0_S$, and $\Lambda(\bar{\Lambda})$

- Short-lived & no charge - cannot be measured directly
- Reconstruction via decay products on statistical basis
  - Particle identification of products
  - Constraining decay topology

Hadronic decays

$\phi \rightarrow K^+ + K^-$

$K^0_S \rightarrow \pi^+ + \pi^-$

$\Lambda \rightarrow p + \pi^-$

$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$
\( v_n \) vs. invariant mass method

- \( v_n \) extracted from 2-particle Q-cumulants using Generic Framework (GF) implementation
  
  \[ v_n \{2\}(p_T) = \frac{d_n \{2\}(p_T)}{\sqrt{c_n \{2\}}} = \frac{\langle v_n(p_T) \cdot v_n \rangle}{\sqrt{\langle v_n \cdot v_n \rangle}} \quad (h^\pm, \pi^\pm, K^\pm, p(\bar{p})) \]

- Particles selected in \(|\eta| < 0.8\) (\& RPF in \(0.3 < p_T < 3\ \text{GeV/c}\))

- Reconstructed candidates consisting of signal particles & combinatorial background
  
  \[ v_n^{\text{tot}} \{2\}(p_T, m_{\text{inv}}) = \frac{d_n \{2\}(p_T, m_{\text{inv}})}{\sqrt{c_n \{2\}}} \quad (K_S^0, \Lambda(\bar{\Lambda}), \phi) \]

- \( v_n \) coefficient of signal particles extracted using \( v_n \) vs. inv. mass method
  
  - Based on additivity of \( v_n \) coefficients weighted by their fractions
  
  \[ v_n^{\text{tot}}(m_{\text{inv}}) = N_{\text{sig}}^{\text{tot}}(m_{\text{inv}}) \cdot v_n^{\text{sig}} + N_{\text{bg}}^{\text{tot}}(m_{\text{inv}}) \cdot v_n^{\text{bg}}(m_{\text{inv}}) \]
Non-flow suppression

- Non-flow consisting of correlation not related to common symmetry plane
- Resonance decays, jets, ...
- Pseudorapidity separation partially suppresses short-range correlations

\[ |\Delta \eta| > 0.4 \]

- Additional non-flow subtraction performed on cumulants using MB pp collisions

\[
v_2^{pPb,\text{sub}}(p_T) = \frac{d_2^{pPb} \{2\} - k \cdot d_2^{pPb} \{2\}}{\sqrt{c_2^{pPb} \{2\} - k \cdot c_2^{pPb} \{2\}}}\]

- Contribution of non-flow scaled by mean event multiplicities

  - Based on assumption for non-flow \[ [\text{Voloshin et al., arXiv:0809.2949}] \]

\[
\delta_n \propto \frac{1}{M} \quad \Rightarrow \quad k = \frac{\langle M \rangle^{pPb}}{\langle M \rangle^{pPb}}
\]
$v_2(p_T)$ coefficients of identified hadrons in 5.02 TeV p-Pb collisions
Non-flow subtracted $v_2(p_T)$ of identified hadrons

- $v_2(p_T)$ of identified hadrons in 5.02 TeV p-Pb using Run II data
- Non-flow subtracted results using MB 13 TeV pp collisions
- First ALICE measurement of $K^0_S$, $\Lambda(\Lambda)$ and $\phi$ $v_2$ in small systems
- Similar features as Pb-Pb measurements
  - Clear mass ordering (low $p_T$ region)
    - Qualitatively predicted by hydrodynamic models
    - Indication of baryon/meson grouping (intermediate $p_T$)
Multiplicity class evolution

Mass ordering and baryon/meson grouping persists but slowly vanishes towards low multiplicity events
Examination of NCQ scaling

- Test of number of constituent quarks (NCQ) scaling properties originally investigated by RHIC experiments

Only approximate NCQ (and $KE_T$) scaling similar to previously reported results in Pb-Pb collisions

$$KE_T = m_T - m_0 = \sqrt{p_T^2 - m_0^2} - m_0$$
Multiplicity evolution of NCQ scaling

Approximate NCQ-scaling holds across all multiplicity classes.
Conclusion

- Results of $p_T$-differential $v_2\{2\}$ of identified hadrons in 5.02 TeV $p$-Pb collisions in LHC Run II
  - First ALICE measurement of $K^0_S$, $\Lambda(\bar{\Lambda})$ and $\phi$ meson $v_2(p_T)$ in small systems
  - Precision measurement of $\pi^\pm$, $K^\pm$ and $p(\bar{p})$ $v_2$ in p-Pb collisions
  - Non-flow subtraction using minimum-bias 13 TeV pp collision

- Features observed in p-Pb collisions similar to previously reported Pb-Pb measurements
  - Low $p_T$ region, clear mass ordering - predicted by hydrodynamic models
  - Intermediate $p_T$, indication of baryon/meson grouping
  - Approximate NCQ & KE$_T$ scaling holds

- Collective phenomena present in small systems. Initial and final state effects?
  - Current results present tighter constrain for future comparisons of theoretical models
    - Will help to disentangle the origin of the observed collectivity

--- Thank you for your attention! ---
— Back-up —
Two-particle Q-cumulants

- Flow coefficients $v_n$ extracted from $\{2\}$-particle Q-cumulants using Generic Framework (GF) implementation
- Construction of (single event) flow vectors from selected particles in $|\eta| < 0.8$
  
  **A. Reference particles (RFP)**
  - Un-identified charged hadrons in $0.3 < p_T < 5$ GeV/c
  - $Q_n = \sum_{i \in \text{RFP}} w_i \exp(in\varphi_i)$, $W_i = \sum_{i \in \text{RFP}} w_i$

  **B. Particles of interest (POI)**
  - Differential measurement (wrt. pt range, species, …)
  - Per-particle weights $w_k = w_k(\eta, \varphi)$ for correction

2-particle correlations $\to$ 2-particle cumulants $\to$ $v_n$ coefficients

- $\langle 2 \rangle_n = \langle \cos n(\varphi_i - \varphi_j) \rangle = \frac{Q_n Q_n^*}{W_i^2}$
  - $c_n\{2\} = \langle \langle 2 \rangle \rangle_n = \langle v_n^2 \rangle$
  - $v_n\{2\}(p_T) = \frac{d_n\{2\}(p_T)}{\sqrt{c_n\{2\}}}$

- $\langle 2' \rangle_n = \langle \cos n(\psi_j - \varphi_i) \rangle = \frac{p_n Q_n^*}{W_j W_i}$
  - $d_n\{2\}(p_T) = \langle \langle 2' \rangle \rangle_n = \langle v_n(p_T) \cdot v_n \rangle$

\[ \langle \ldots \rangle \ldots \text{averaged over all particles in single event} \quad \langle \langle \ldots \rangle \rangle \ldots \text{averaged over all particles AND all events} \]
Multiplicity class dependence

ALICE Preliminary
$p-Pb \mid S_{NN} = 5.02$ TeV
$|\eta| < 0.8$

$V_2^{q\phi}$ (2, $|\Delta\eta| > 0.4$)

$p_T$ (GeV/c)

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Examination of KEₜ scaling

\[ KEₜ = mₜ - m₀ = \sqrt{pₜ^2 - m₀^2} - m₀ \]

As for NCQ, KEₜ scaling holds in central collisions and slowly vanishes in low multiplicity events.
NCQ scaling in Pb-Pb at 5.02 TeV

[ arXiv:1805.04390 ]

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Comparison to published results

Comparison to CMS results form [PLB 724 (2013) 213-240]

- Differences in methodology
  - $v_2$ extraction (2PC vs Q-Cumulants)
  - Event classification (selection)
  - Pseudo-rapidity regions

- Similar non-flow subtraction prescription …

\[
V_{n\Delta} = V_{n\Delta} - V_{n\Delta}(N_{\text{trk}}^{\text{offline}} < 20) \times \frac{N_{\text{assoc}}(N_{\text{trk}}^{\text{offline}} < 20)}{N_{\text{trk}}^{\text{offline}}} \times \frac{Y_{\text{jet}}(N_{\text{trk}}^{\text{offline}} < 20)}{Y_{\text{jet}}}. \tag{9}
\]

- … but additional scaling factor (enhancement of near-side jet)

Only qualitative comparison - differences expected