Searches for azimuthal flow in pp, p-Pb and Pb-Pb collisions

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Motivation

- Double ridge observed in p-Pb collisions
  - Few or many particle correlations?

- Flow cumulants sensitive to multi-particle correlations
  - How do they compare to Pb-Pb at same multiplicity?

- Mass dependence of $v_2$ observed in Pb-Pb collisions
  - Interplay of radial and elliptic flow
  - What happens in pp and p-Pb collisions?

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ALICE PID flow paper just submitted to arivx
p-Pb and Pb-Pb results to be submitted this week
Experimental details

- Minbias triggering based on V0s (forward detectors), High multiplicity on SPD (Silicon Pixel Detector)

- Tracking uses TPC and SPD

- Integrated $h^\pm v_n$
  - $0.2 < p_T < 3$ GeV/$c$
  - $|\eta_{lab}| < 1$
  - $N_{ch}$ uses same cuts, corrected for efficiency

- Differential PID $v_2(p_T)$
  - TPC $dE/dx$ and TOF for PID
  - $|\Delta \eta| > 0.8$ for non-flow suppression, $|\eta_{lab}| < 0.8$

### System | Collision energy
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pp | $\sqrt{s} = 7$ TeV
p-Pb | $\sqrt{s_{NN}} = 5.02$ TeV
Pb-Pb | $\sqrt{s_{NN}} = 2.76$ TeV
Flow cumulants and coefficients

- Cumulants formed from $v_n$ moments. Moments from multi-particle correlations ($n=$flow harmonic, $<v_n^m>=<m>$).

$$c_n\{2\} = \langle\langle 2\rangle\rangle$$
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2$$
$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\langle\langle 2\rangle\rangle^3$$

- Methods have different sensitivity to flow fluctuations and non-flow

- If non-flow dominates, naively expected to scale with Multiplicity (M) as:

$$c_n\{m\} \propto \frac{1}{M^{m-1}}$$

- Flow coefficients formed from cumulants

$$v_n\{2\} = \sqrt{c_n\{2\}}$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$
$$v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$$
\( c_2 \{2\} \) in p-Pb and Pb-Pb

\[ v_2 \{2\} = \sqrt{c_2 \{2\}} \]

- p-Pb \( c_2 \{2\} \) rises for large \( \Delta \eta \) gap. Inconsistent with naïve expectations of non-flow

- Pb-Pb \( c_2 \{2\} \) values bigger at same \( N_{ch} \).
  - \( \varepsilon_2 \) (Pb-Pb) \( _{RMS} \) driven by geometry & fluctuations.
  - \( \varepsilon_2 \) (p-Pb) \( _{RMS} \) by just fluctuations?
$c_2\{4\}$ in p-Pb and Pb-Pb

\[ v_2\{4\} = \frac{4}{c_2\{4\}} \]

- p-Pb $c_2\{4\}$ switches from pos. to neg. at high $N_{ch}$ ($v_2\{4\}$ becomes real).

- Pb-Pb $c_2\{4\}$ values more neg. at same $N_{ch}$ after $N_{ch} > 100$
Hints of non-zero $c_2\{6\}$ at $N_{ch} \sim 60$ for p-Pb.

$v_2\{6\}$ consistent with $v_2\{4\}$ at large p-Pb $N_{ch}$

Pb-Pb clearly higher than p-Pb at same $N_{ch}$

$$v_2\{6\} = \sqrt[6]{\frac{1}{4} c_2\{6\}}$$
\( v_2\{2\} \) and \( v_2\{4\} \) in p-Pb

- \( v_2\{2\} > v_2\{4\} \) in p-Pb -> Indicative of flow fluctuations? Contributions from non-flow?
- \( R_2 \) approximates \( \sigma_{v_2}/\langle v_2 \rangle \). Fluctuations larger in p-Pb compared to Pb-Pb.
Third harmonic in p-Pb and Pb-Pb collisions

- Large dependence on Δη gap for $c_3\{2\}$. Increases with $N_{ch}$ for large Δη
- $v_3\{2\}$ consistent with Pb-Pb at same $N_{ch}$
  - $\varepsilon_3(p-Pb)_{RMS} \sim \varepsilon_3(Pb-Pb)_{RMS}$ and driven by fluctuations?
$v_2\{\text{SP}\}$ in minbias pp collisions

- $v_2\{\text{SP}\}$ equivalent to $v_2\{2\}$
- Non-flow dominates measurement
  - No ridge observed
- Ordering
  - $v_2(\pi) > v_2(p)$
  - $v_2(p) \sim v_2(K)$
  - No cross over for $v_2(\pi)$ & $v_2(p)$

$v_2\{\text{SP}\}$ and $v_2\{\text{2PC}\}$ in p-Pb

- Both $v_2\{\text{SP}\}$ and $v_2\{\text{2PC}\}$ equivalent for current $p_T$ selections
- “Centrality” characterized via multiplicity in V0 (Pb side)
- Mass ordering at high multiplicity:
  - Different to pp
  - $v_2(p) < v_2(K)$
  - $v_2(\pi) \approx v_2(K)$
  - Hint of cross over in high mult. classes

$2\text{PC} = \text{di-hadron correlations}$
$v_2\{2PC, \text{ sub}\}$ in p-Pb

- $v_2\{2PC, \text{ sub}\}$: Obtained via central yields – peripheral associated yields
  - Aims to subtract non-flow
  - Mass dependence more pronounced.
  - Cross over of $v_2(\pi)$ & $v_2(p)$

- Qualitatively more similar to Pb-Pb.

See ALICE talks by Alex Dobrin and Leonardo Milano for more details.
Summary

- Experimental observations **highly suggestive of collective effects in high mult. p-Pb collisions**

- Integrated $h^\pm v_n$ measurements
  - $c_2\{2\}$ rises in p-Pb with $N_{ch}$ for large $|\Delta \eta|$. Naively inconsistent with non-flow.
  - $c_2\{4\}$ in p-Pb transitions from pos. to neg. values. $v_2\{4\}$ becomes real.
  - $c_2\{m\}$ higher in Pb-Pb compared to p-Pb at same $N_{ch}$.
  - $v_3\{2\}$ in p-Pb and Pb-Pb similar at same $N_{ch}$.

- Differential PID $v_2$ measurements
  - Different mass ordering in minbias pp and high mult. p-Pb.
  - Mass ordering in high mult. p-Pb more pronounced after non-flow subtraction.
  - Qualitative similar features to Pb-Pb collisions.
Back-up