A Large Ion Collider Experiment

European Organisation for Nuclear Research

UNIVERSITY of HOUSTON

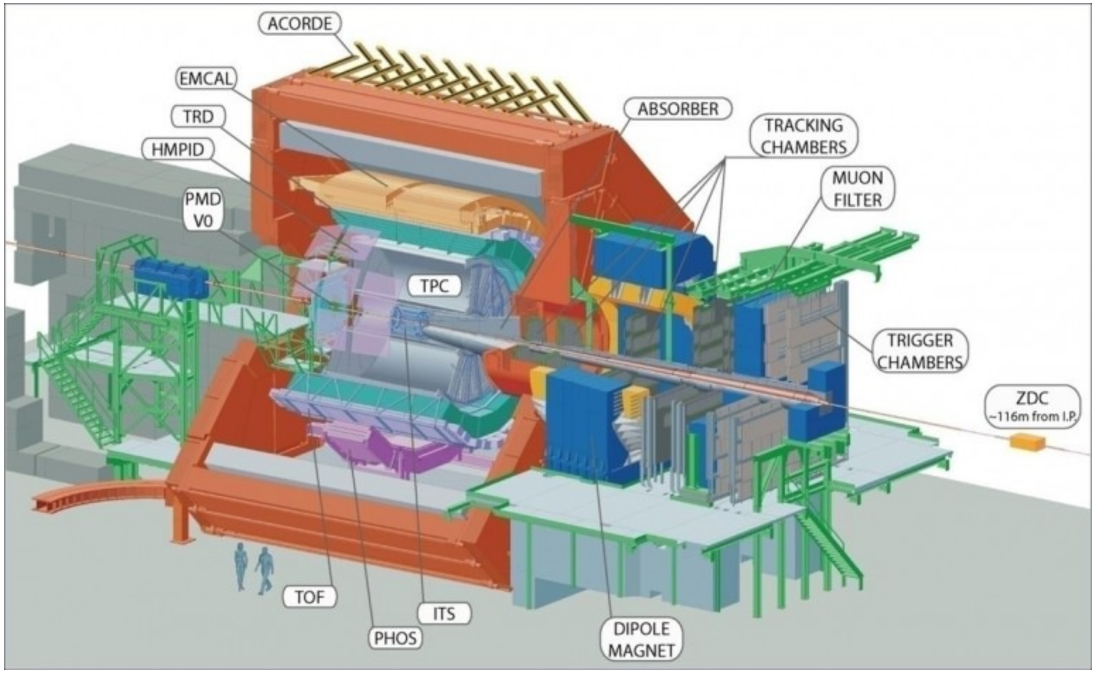
Results on flow from ALICE

Anthony Timmins for the ALICE Collaboration

IS2014

Overview

1. Papers published/submitted over the year
2. Flow fluctuations
3. Identified particle flow
4. Searches for strong parity violation
5. Papers in progress



ALICE Experiment

Papers submitted/published over the year

1. Elliptic flow of identified hadrons in Pb-Pb collisions at 2.76 TeV
   - ✓ Submitted to PLB (arXiv:1405.4632)

2. Multi-particle azimuthal correlations in p-Pb and Pb-Pb collisions at the CERN Large Hadron Collider
   - ✓ Phys. Rev. C 90 (2014) 054901

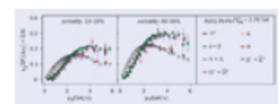
3. Directed Flow of Charged Particles at Mid-rapidity Relative to the Spectator Plane in Pb-Pb Collisions at 2.76 TeV
   - ✓ Phys. Rev. Lett. 111 (2013) 232302

CERN COURIER

Jul 23, 2014

ALICE and the flowing particle zoo

Relativistic heavy-ion collisions produce large numbers of particles that do not move individually, but rather as an organized group, with a collective motion known as flow. Flow studies at Brookhaven's Relativistic Heavy-Ion Collider (RHIC) contributed to the surprising realization that the hot and dense matter created in the collisions behaves like a perfect liquid and not as a hadron gas. Now, the ALICE collaboration at the LHC has looked further into how these effects vary for different particle species.


The p_T-differential v_2

In relativistic heavy-ion collisions the collective motion, or flow, is governed by the spatial anisotropy of the almond-shaped overlap region of the colliding nuclei and the initial density inhomogeneities of the fireball. These features are transformed, through interactions between the produced particles, into an anisotropy in momentum space. The degree of this transformation depends on the ratio of shear viscosity to entropy, η/s, which quantifies the friction of the created matter. This resulting anisotropy in particle production can be quantified by a Fourier analysis of the azimuthal distribution relative to the system's symmetry plane, characterized by Fourier coefficients, v_n. The second harmonic, v_2, is known as the elliptic-flow coefficient.

http://cerncourier.com/cws/article/cern/57840

Flow fluctuations

- Usually characterized from measurements of v_n moments and/or cumulants.

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

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

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

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$\longrightarrow$

- Flow coefficients formed from cumulants

$$v_n\{2\} = \sqrt{c_n\{2\}}$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$
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- Methods have different sensitivity to flow fluctuations

$$v_n\{2\} \approx \langle v_n\rangle + \sigma_n^2/(2\langle v_n\rangle)$$
$$v_n\{4,6\} \approx \langle v_n\rangle - \sigma_n^2/(2\langle v_n\rangle)$$

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$$v_n\{4,6\} \approx \langle v_n\rangle - \sigma_n^2/(2\langle v_n\rangle)$$

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

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

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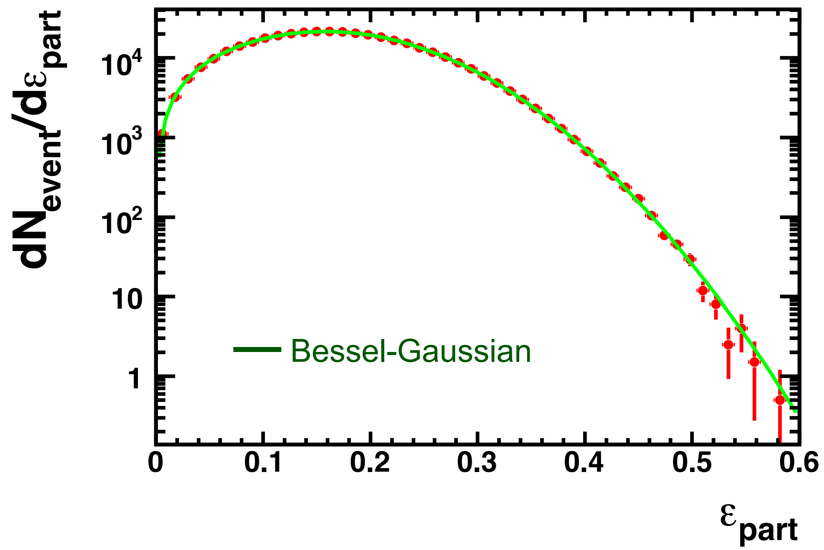
Flow fluctuations

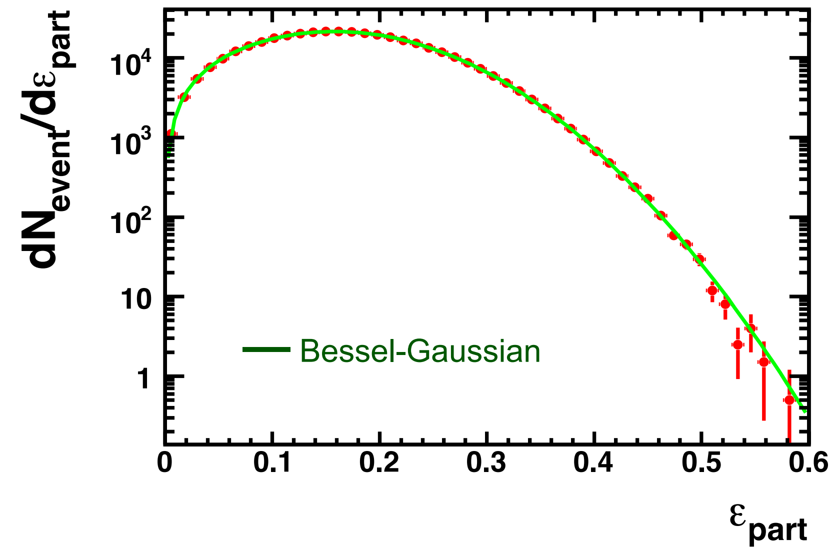
Phys. Lett. B 659 (2008) 537-541



- If $v_n \propto \varepsilon_n$
  - ✓ Originally proposed distribution of ε_n and v_n Bessel Gaussian
- Bessel-Gaussian assumes:
  - ✓ Large number of sources form eccentricity
  - ✓ 1D projection of Gaussian ε_x and ε_y distributions

Flow fluctuations

Phys. Lett. B 659 (2008) 537-541



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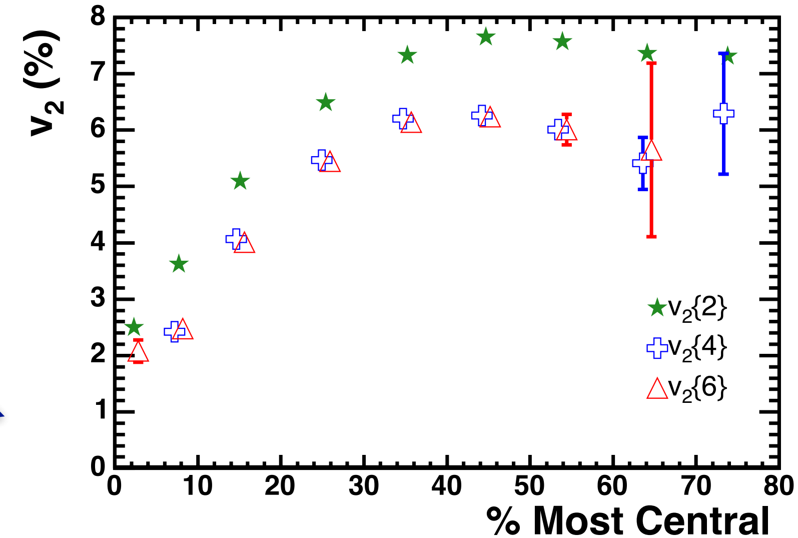
  - ✓ Originally proposed distribution of ε_n and v_n Bessel Gaussian
- Bessel-Gaussian assumes:
  - ✓ Large number of sources form eccentricity
  - ✓ 1D projection of Gaussian ε_x and ε_y distributions
- Consequence: $v_2\{4\}=v_2\{6\}$
  - ✓ First observed by NA49
  - ✓ Then by STAR with better precision

Phys. Rev. C72 (2005) 014904



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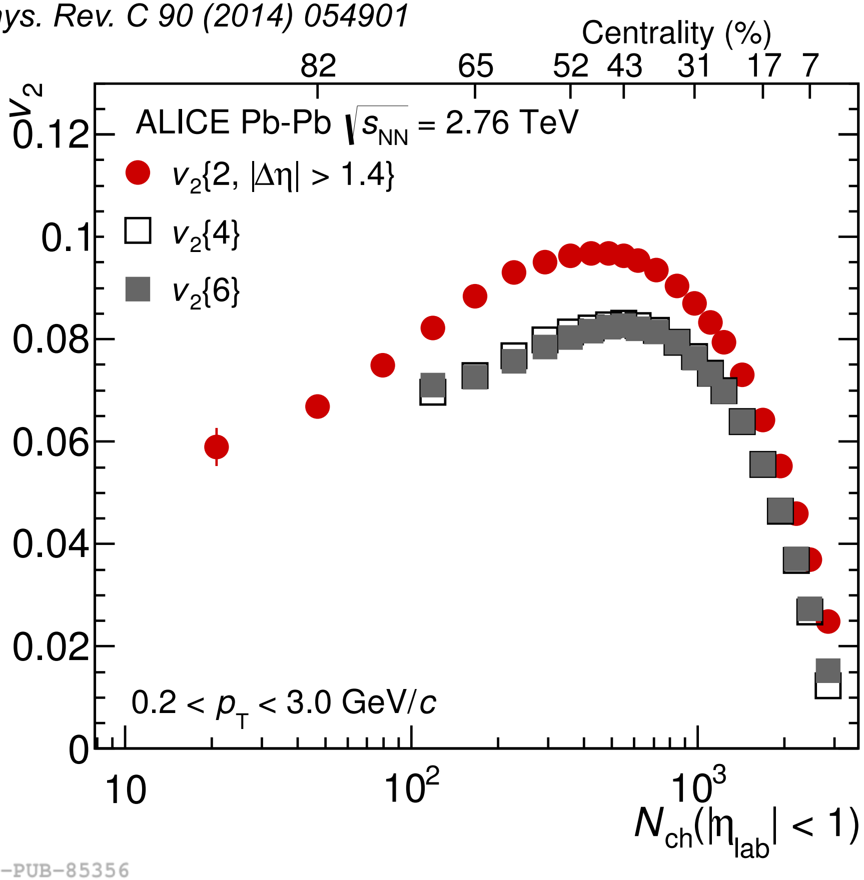
Flow fluctuations

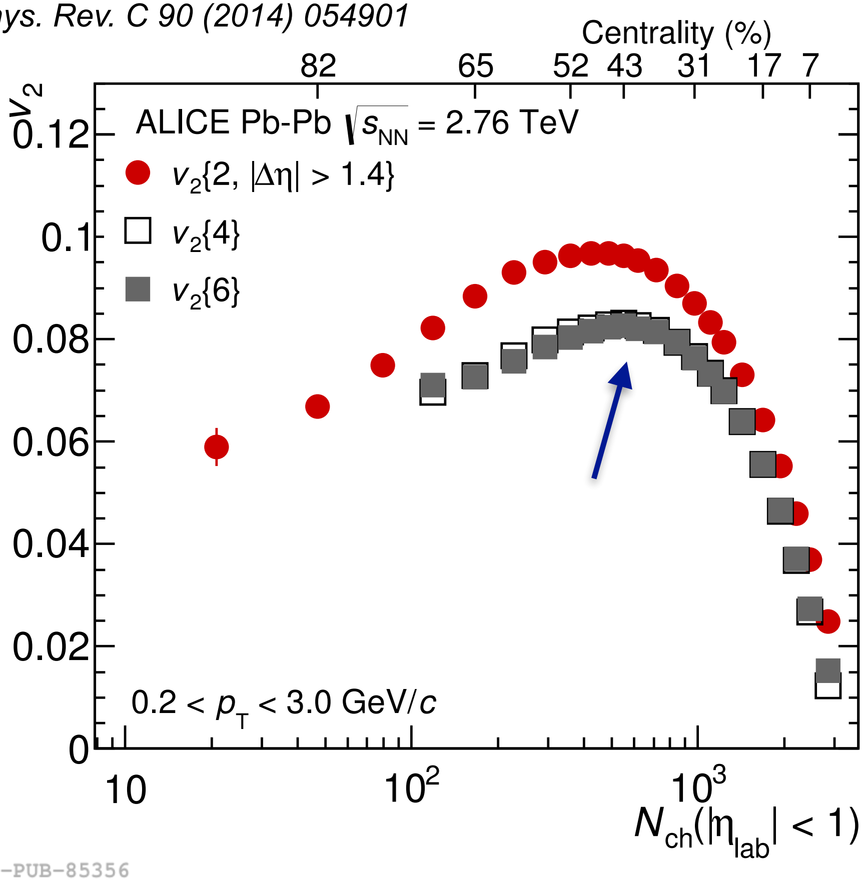
Phys. Rev. C 90 (2014) 054901

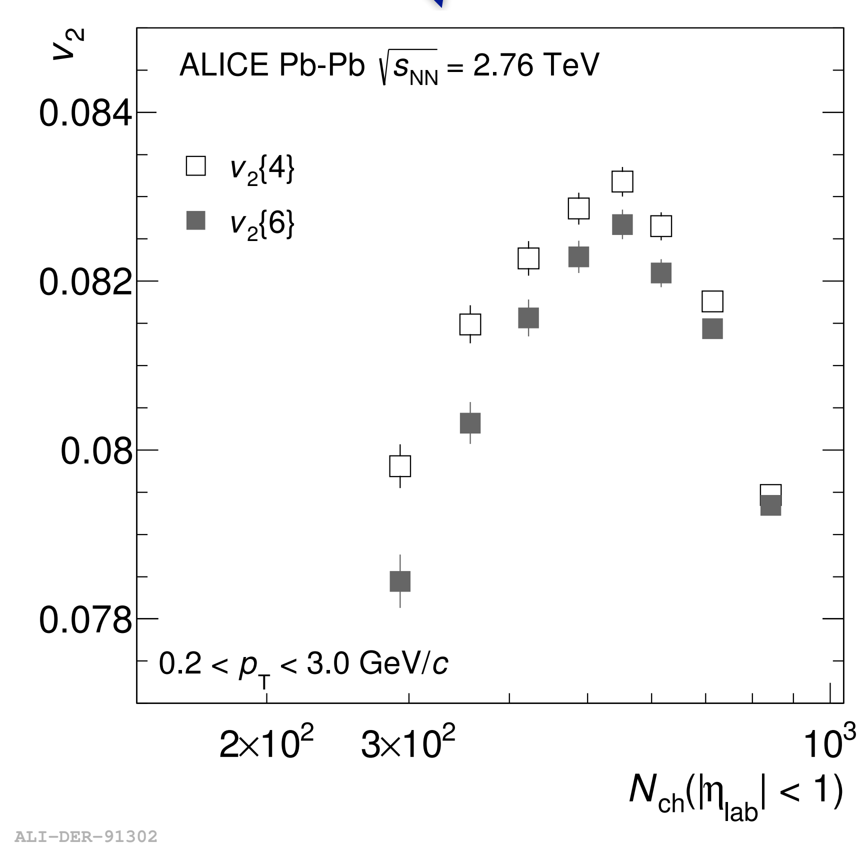


Flow fluctuations

Zoom in

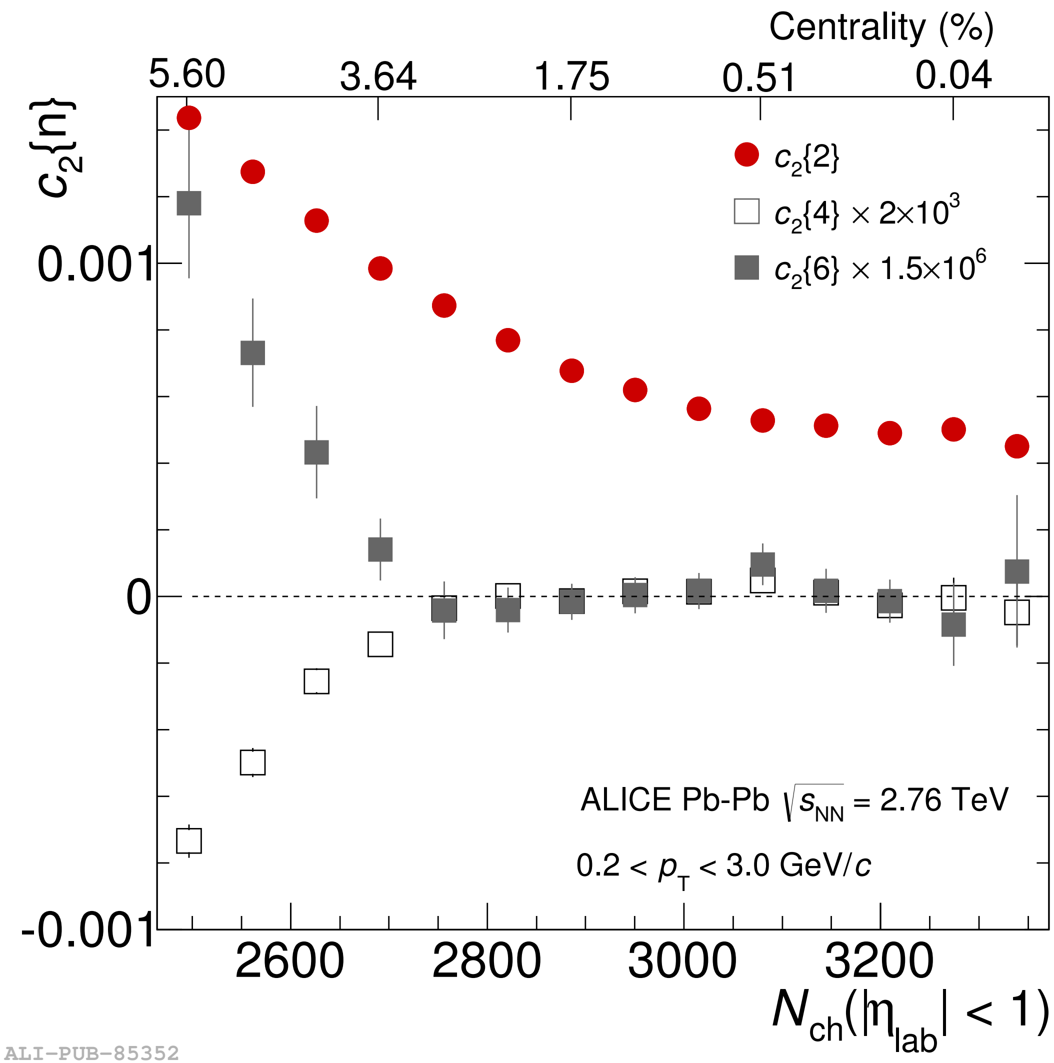
Phys. Rev. C 90 (2014) 054901





- $v_2\{4\}$ not exactly equal to $v_2\{6\}$ at the LHC
  - ✓ Evidence of “Elliptic Power” fluctuations
  - ✓ See talks by Jean-Yves and Art
  - ✓ Will be investigated further in run 2

Flow fluctuations



- Very central Pb-Pb collisions have higher order cumulants of zero.
- Multi-particle flow correlations gone??
  - ✓ No!
- v_2 fluctuations likely follow:

$$f(v_2) = \frac{v_2}{\sigma_{v_2}^2} \exp\left[\frac{-v_2^2}{\sigma_{v_2}^2}\right]$$

- Valid for large numbers of sources and b~0 fm.

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Phys. Rev. C 90 (2014) 054901

Flow fluctuations

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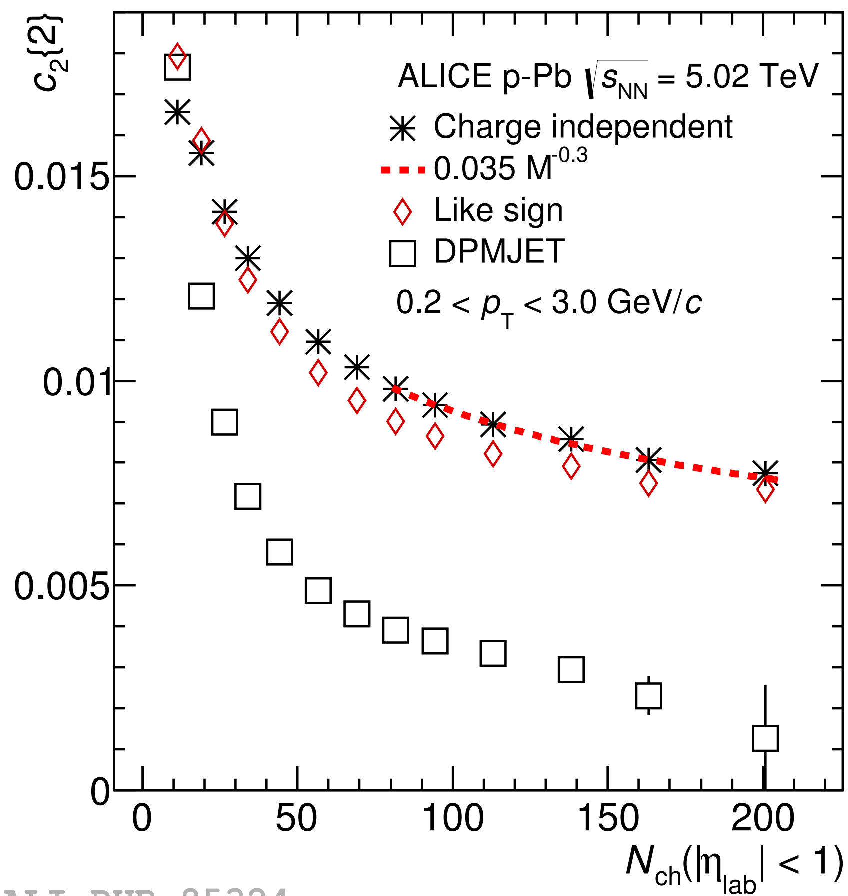

ALI−PUB−85324

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

- Two particle correlations the good probe for global correlations
  - ✓ Decrease when non-flow dominates

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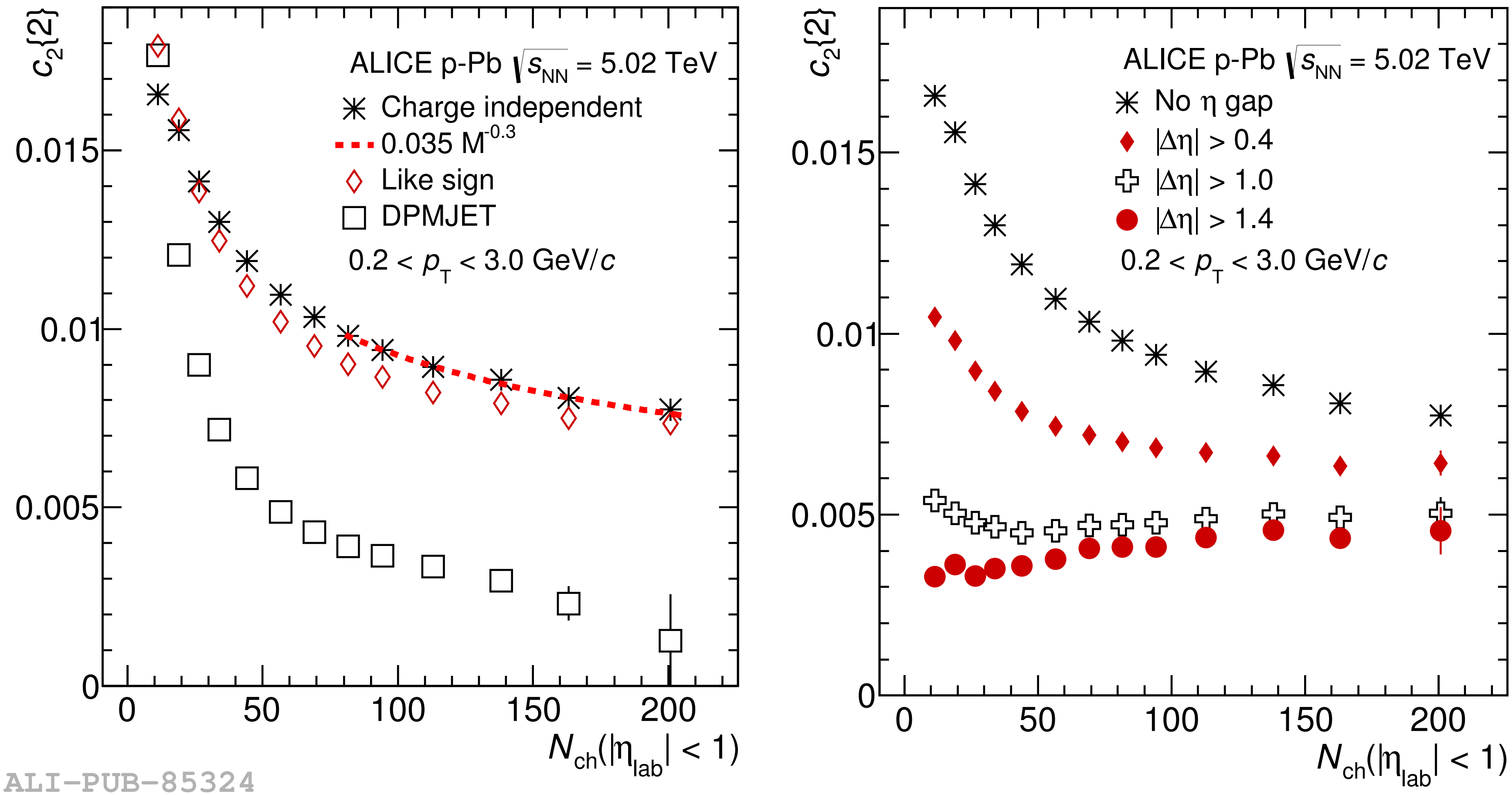
Flow fluctuations

Phys. Rev. C 90 (2014) 054901



- Two particle correlations the good probe for global correlations
  - ✓ Decrease when non-flow dominates
  - ✓ Increase can only be explained by emergence of global correlations

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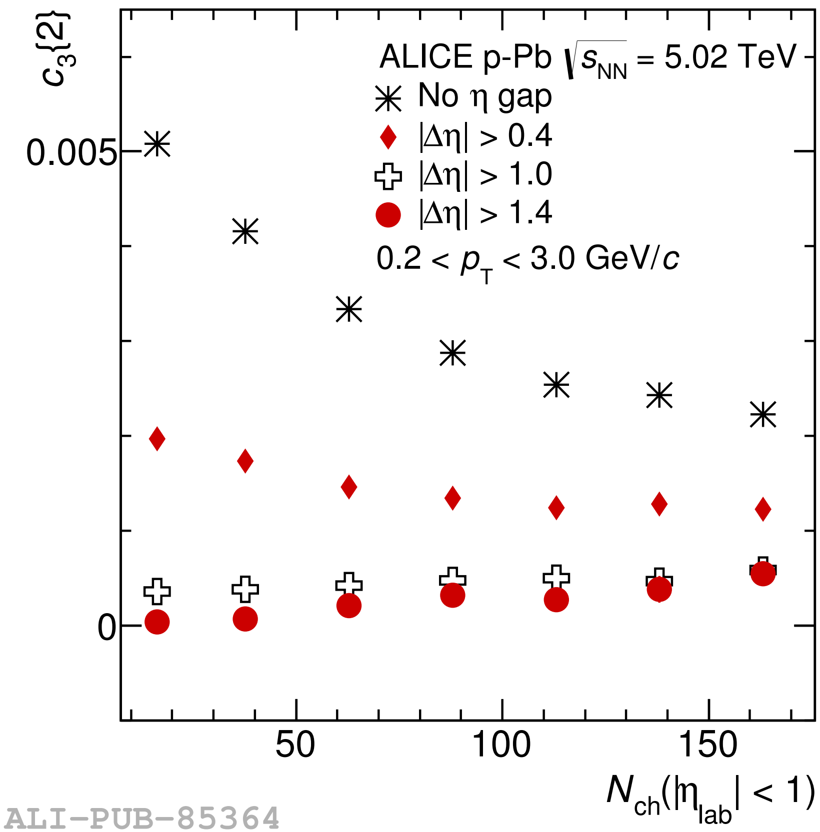
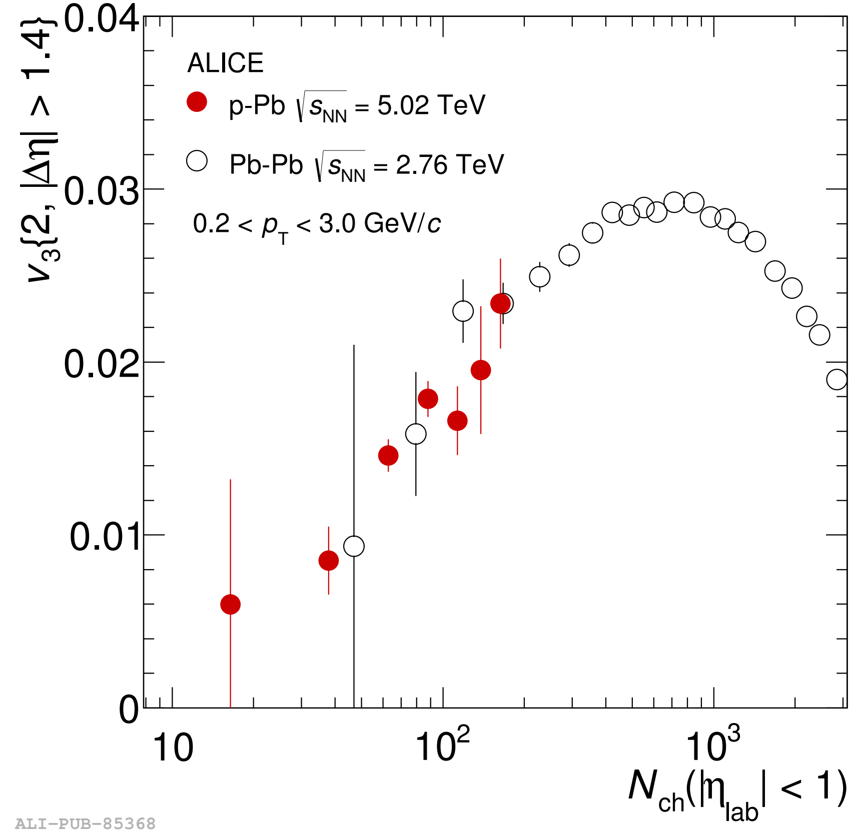
Flow fluctuations

Phys. Rev. C 90 (2014) 054901





- Large dependence on $\Delta\eta$ gap for $c_3\{2\}$. Increases with N_{ch} for large $\Delta\eta$
- $v_3\{2\}$ consistent with Pb-Pb at same N_{ch}
  - ✓ $\varepsilon_3(\text{p-Pb})_{RMS} \sim \varepsilon_3(\text{Pb-Pb})_{RMS}$ and driven by fluctuations?

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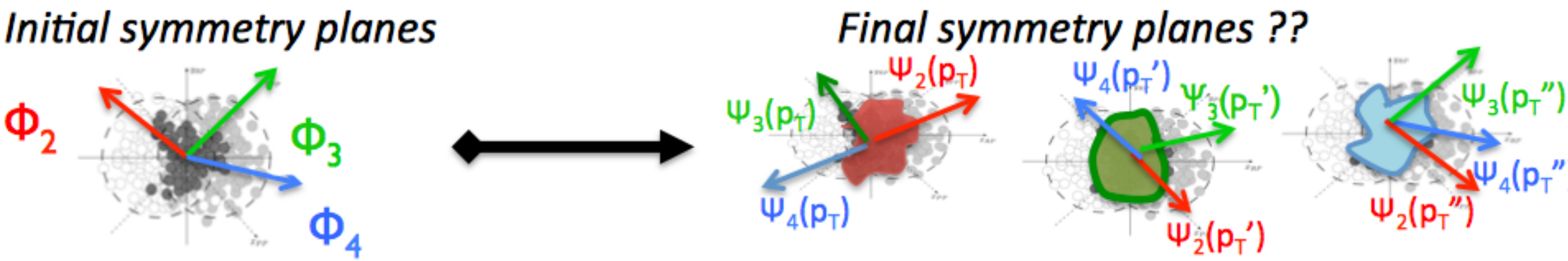
Flow fluctuations

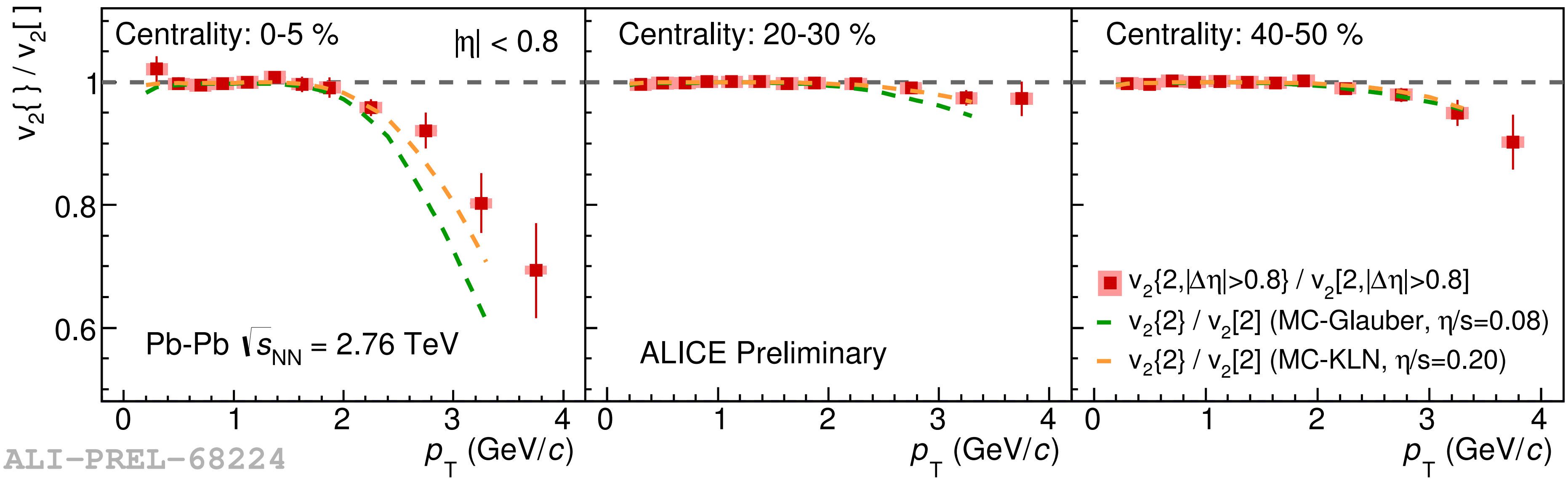


- Do the symmetry planes depend on p_T?
  - ✓ If so, leads to a breakdown in factorization.

- Tested by comparing $v_n\{2\}$ and $v_n[2]$ vs. p_T
  - ✓ $\{2\}$ all particles used as reference flow
  - ✓ $[2]$ p_T subset used as reference flow

- $v_n\{2\}/v_n[2] = 1$ if factorization holds

Flow fluctuations



- Deviations observed at higher p_T
  - ✓ Currently investigating dependence of non-flow

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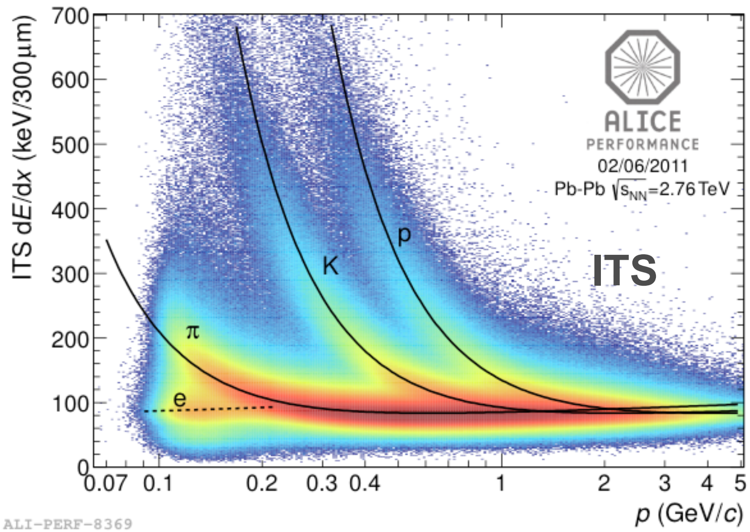
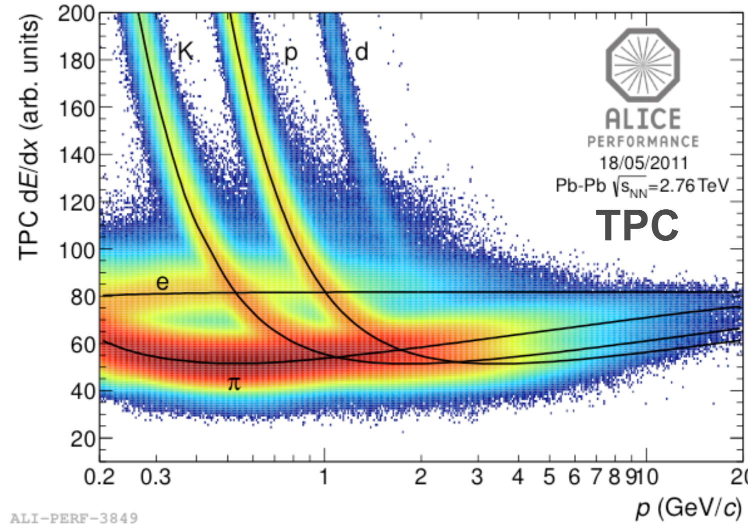
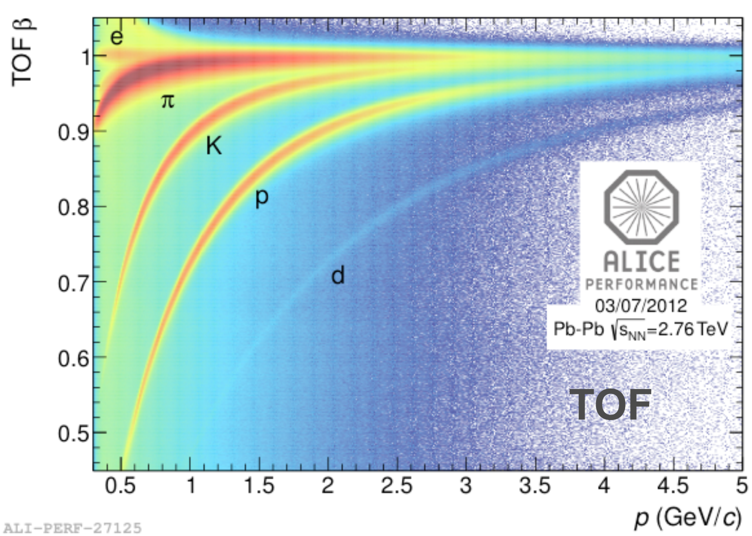
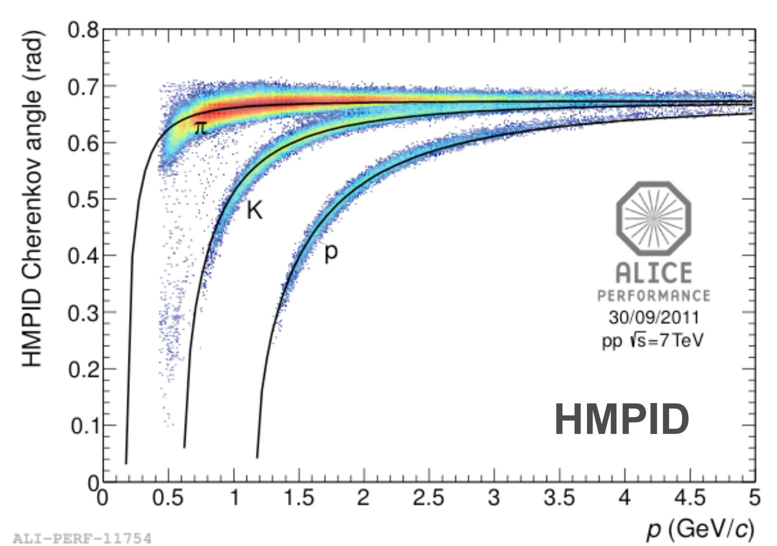
Identified particle flow



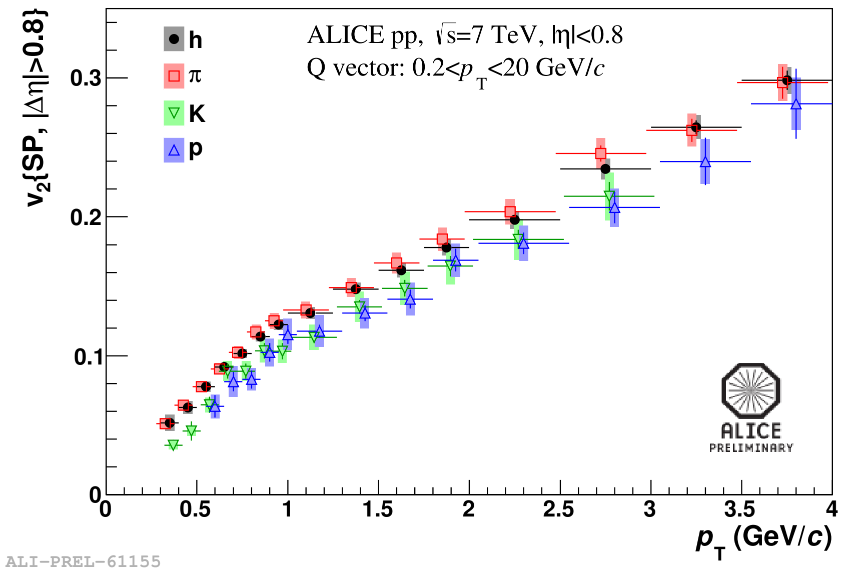






- Suite of detectors available, ALICE optimised for PID

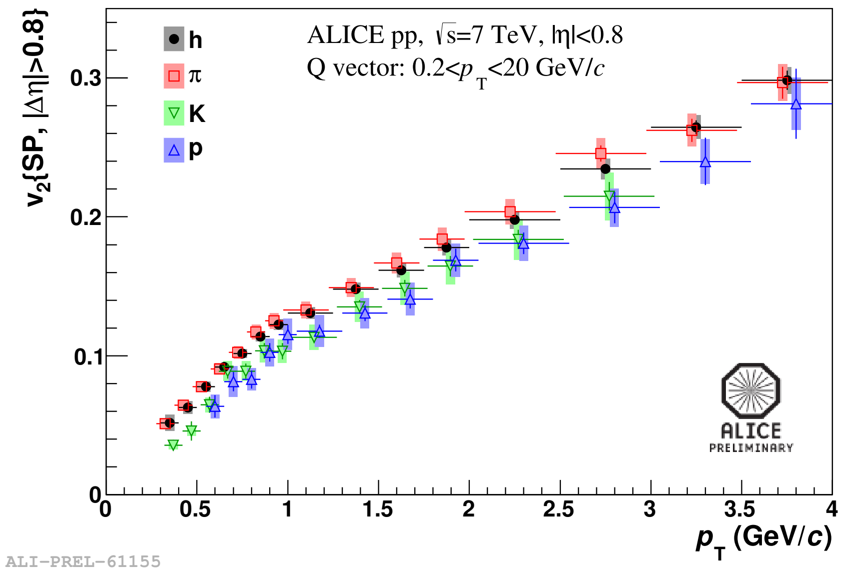
Identified particle flow

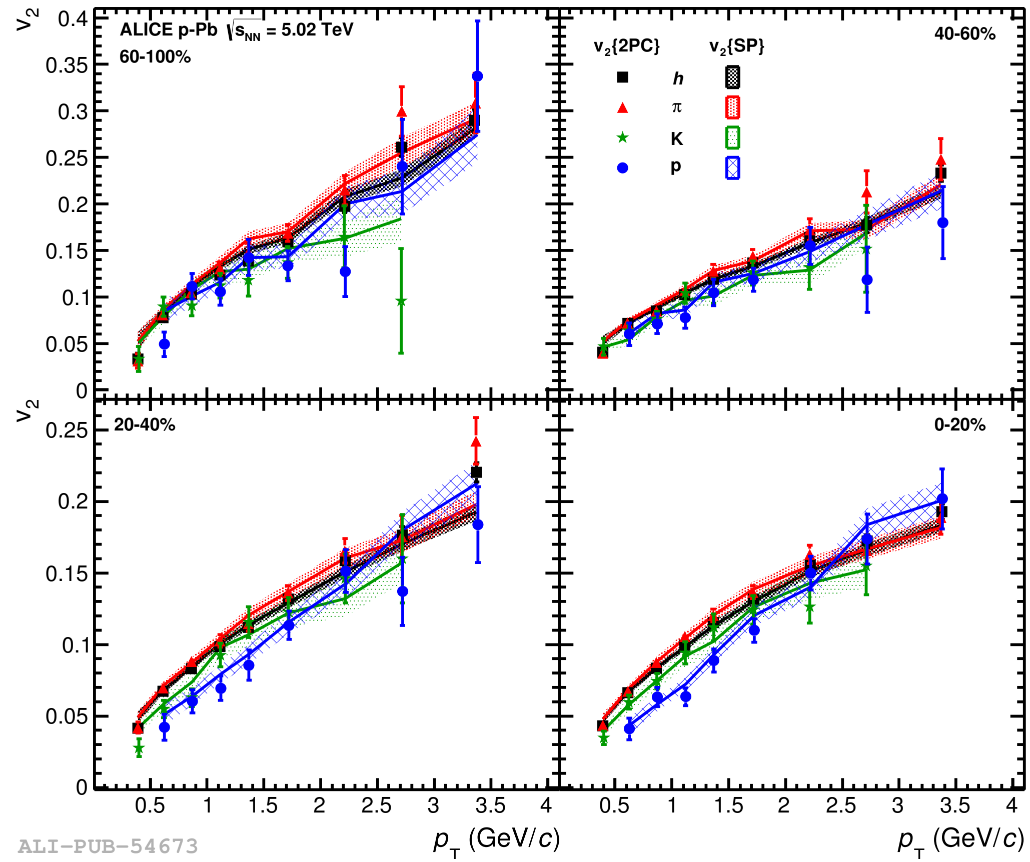


- Non-flow expected to play large role in pp
- Mass ordering
  - ✓ $v_2(\pi) > v_2(p)$
  - ✓ $v_2(p) \sim v_2(K)$

Identified particle flow

Phys. Lett. B 726 (2013) 164–177



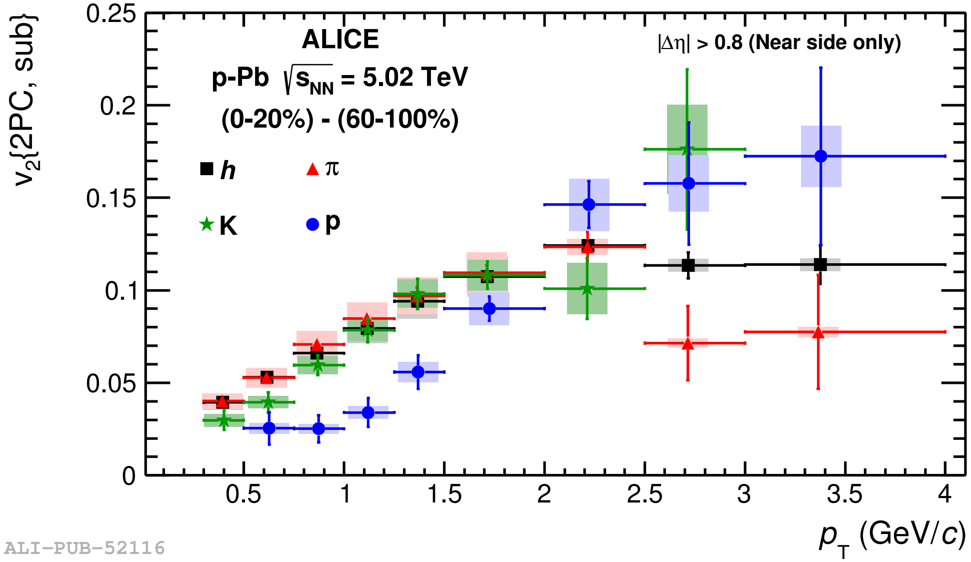


- Non-flow expected to play large role in pp
- Mass ordering
  - ✓ $v_2(\pi) > v_2(p)$
  - ✓ $v_2(p) \sim v_2(K)$
- Appears to change for “central” p-Pb
  - ✓ $v_2(\pi) \sim v_2(K)$

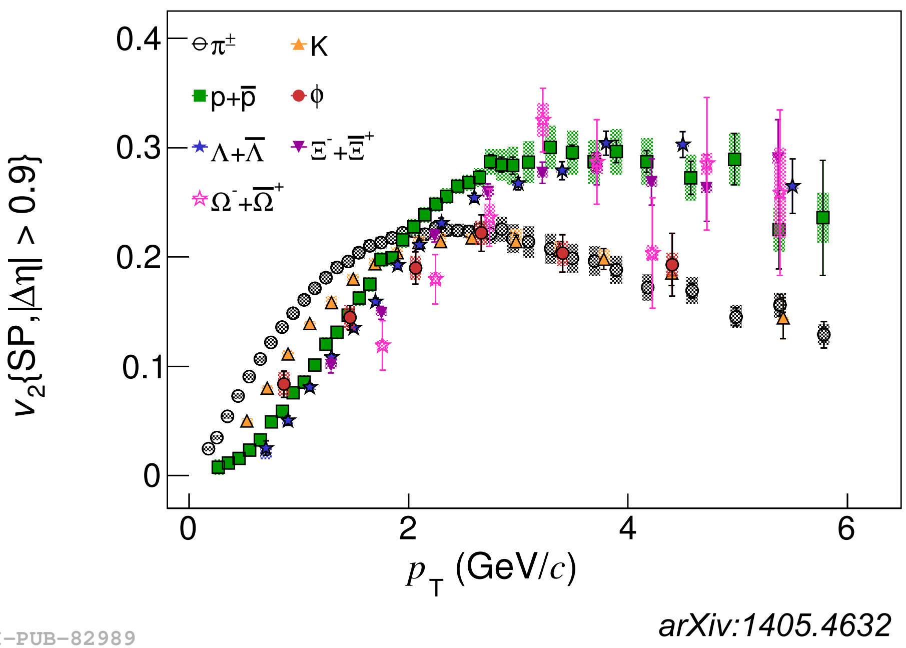
ALICE

Identified particle flow

Phys. Lett. B 726 (2013) 164–177



ALICE 40-50% Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV



arXiv:1405.4632

- $v_2\{2PC, sub\}$: Obtained via high multiplicity yields – low multiplicity 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.

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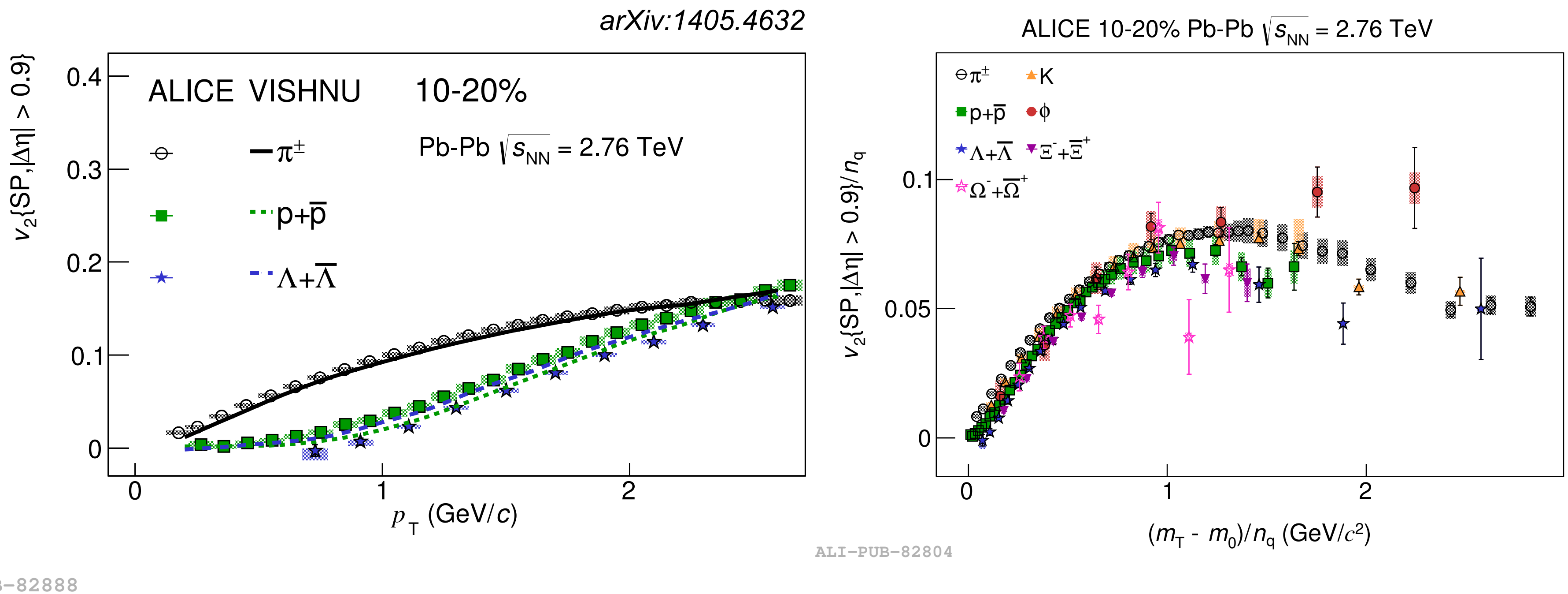
Identified particle flow

arXiv:1405.4632



- Hydrodynamic models describe PID v_2 reasonably well
- Number of Constituent Quark Scaling (NCQ) brings different particle v_2 closer together

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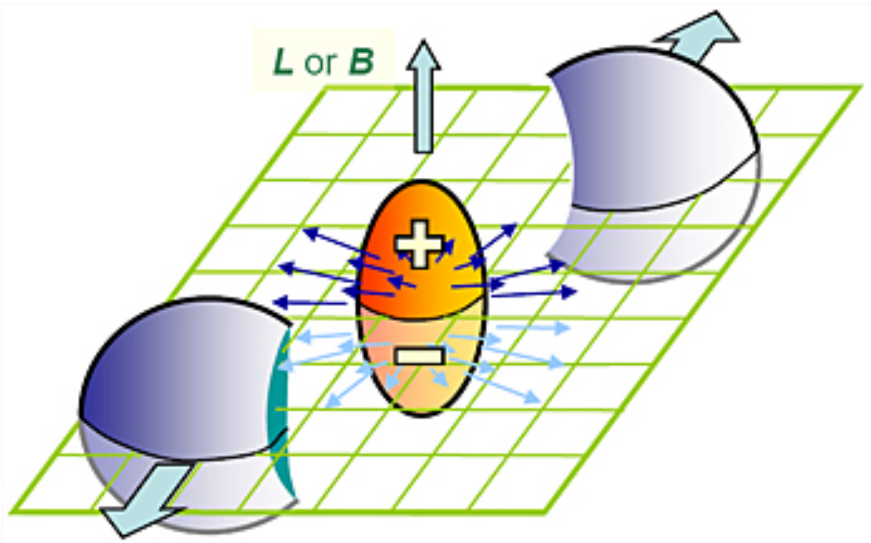
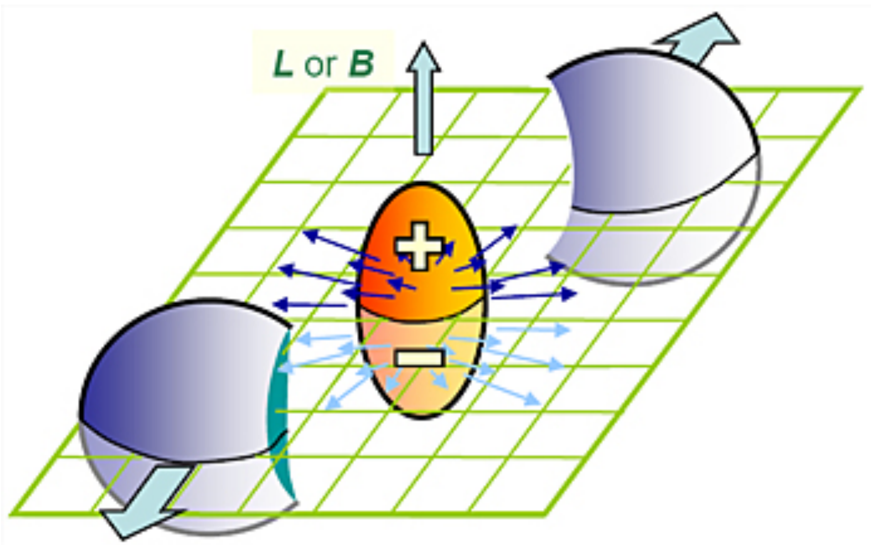
Searches for strong parity violation

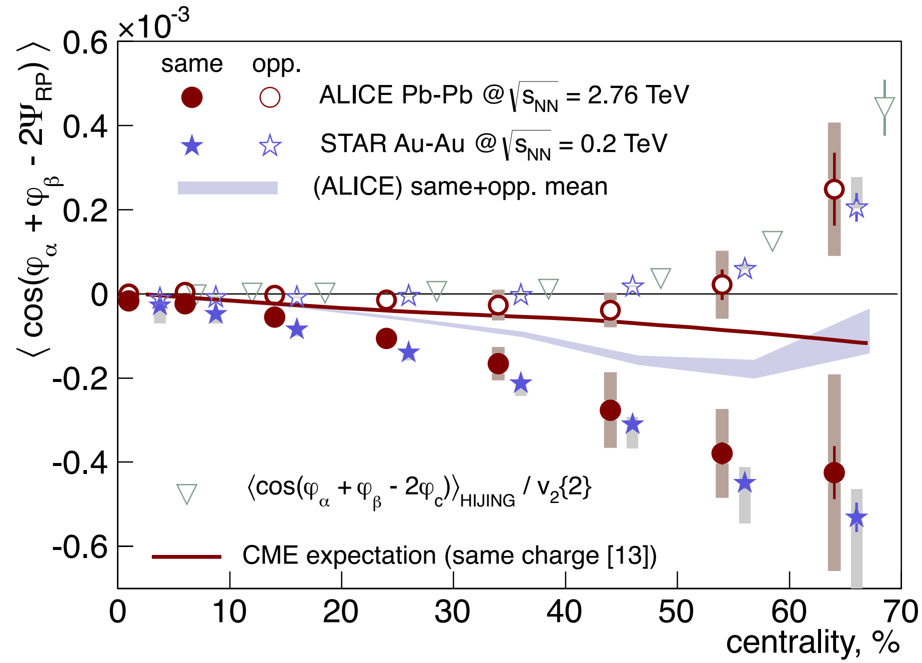


- Correlator <$\cos(\varphi_\alpha+\varphi_\beta-2\Psi)$> indicates charge separation along the reaction plane

Searches for strong parity violation



Phys. Rev. Lett. 110 (2013) 012301



- Correlator <cos(φ_α+φ_β-2Ψ)> indicates charge separation along the reaction plane

- Evidence of Chiral Magnetic Effect (CME) and strong parity violation
  - ✓ Need to understand contributions from other sources

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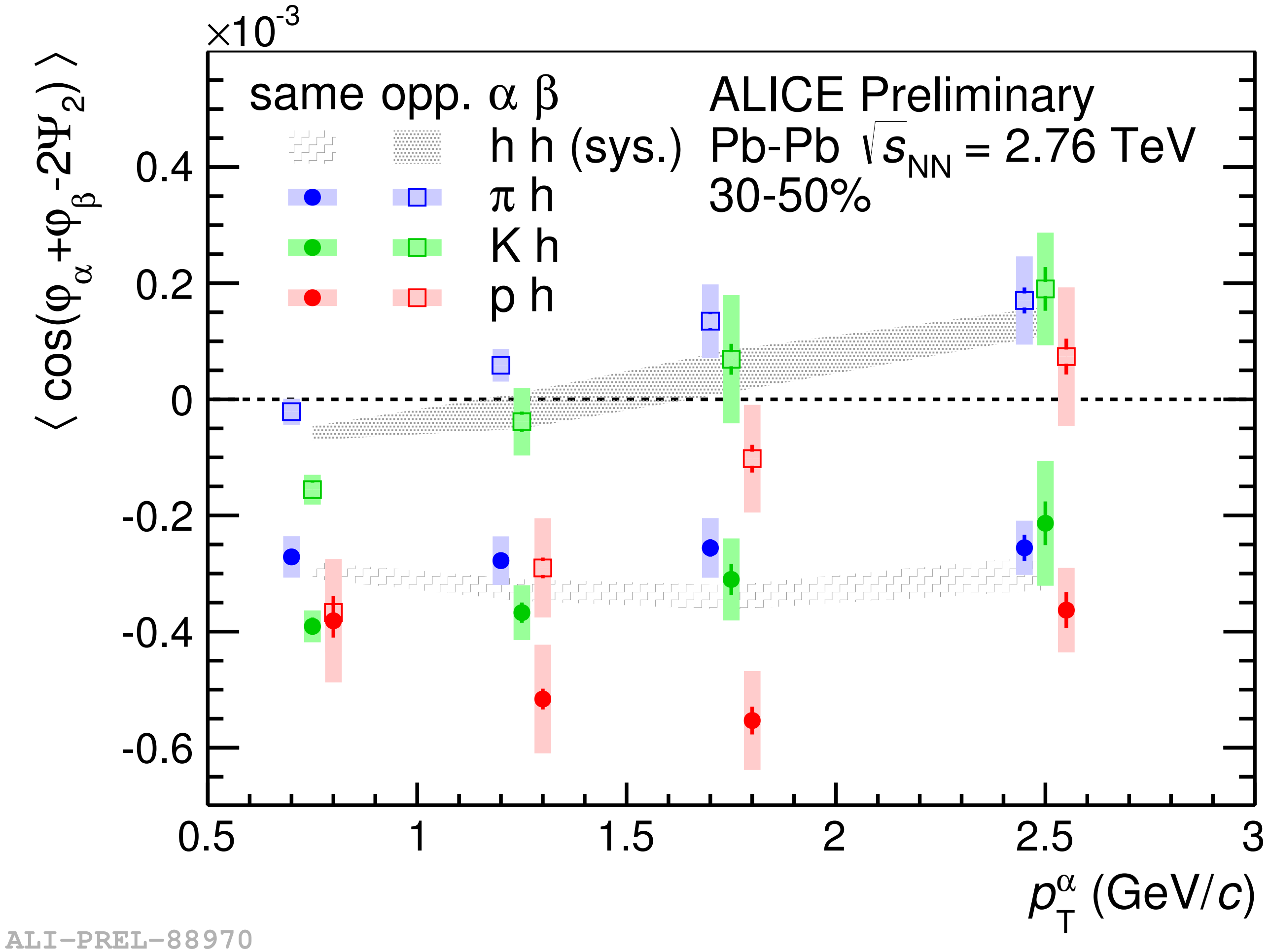
Searches for strong parity violation



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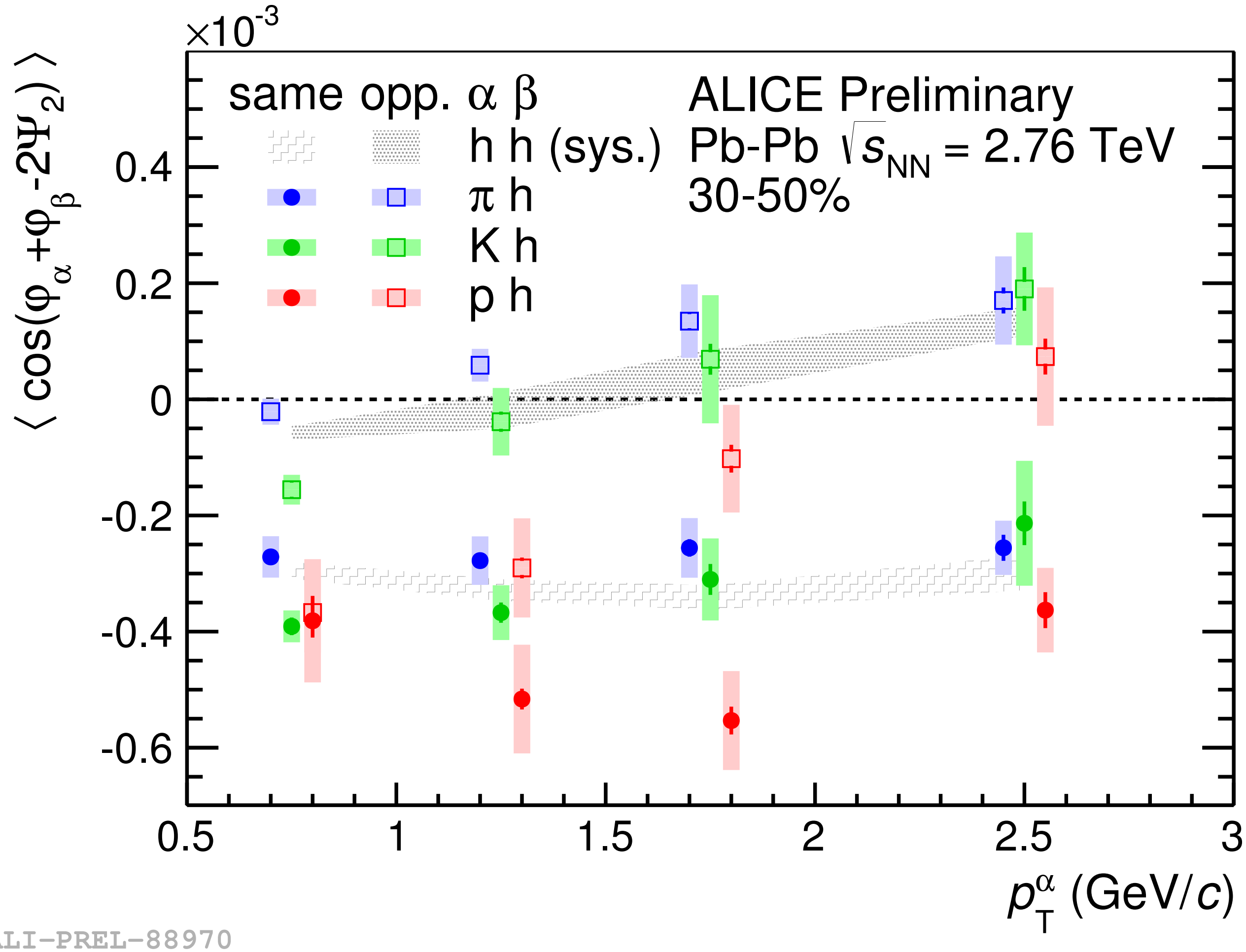
Searches for strong parity violation



- Measurements of different species helps disentangle such sources
  - ✓ Particle dependence for opposite sign CME correlator

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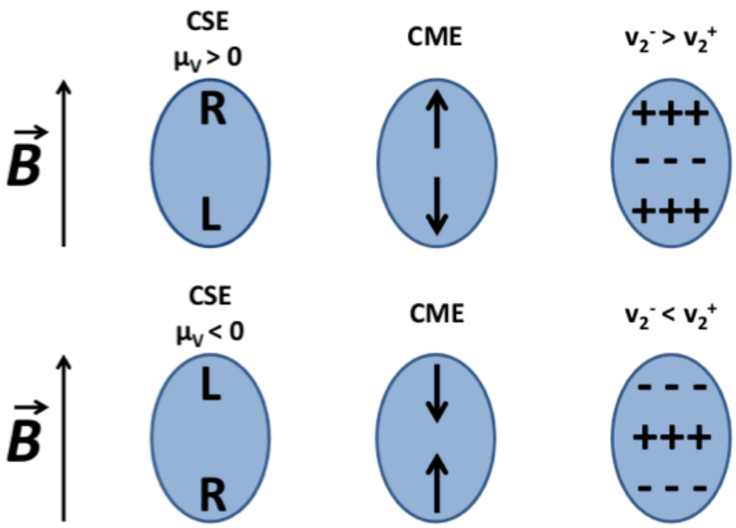
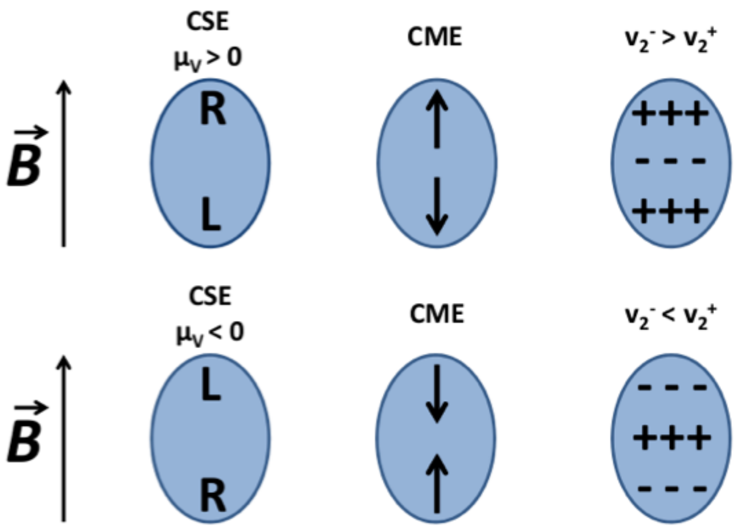
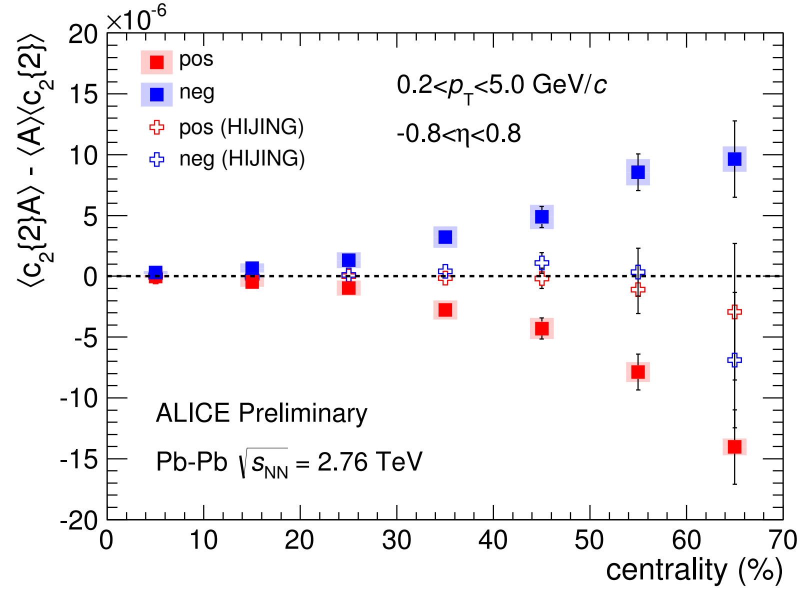
Searches for strong parity violation



- Chiral Magnetic Effect (CME) + Chiral Separation Effect (CSE) = Chiral Magnetic Wave (CMW)

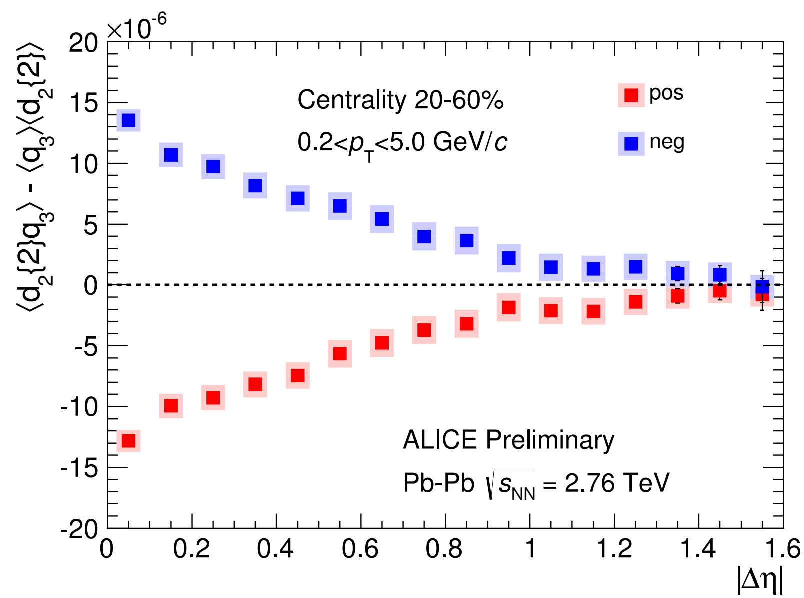
Searches for strong parity violation





ALI-PREL-70914

- Chiral Magnetic Effect (CME) + Chiral Separation Effect (CSE) = Chiral Magnetic Wave (CMW)
- **Observable:** Charge dependence of elliptic flow with charge asymmetry
- ALICE data demonstrate *Δη* dependence

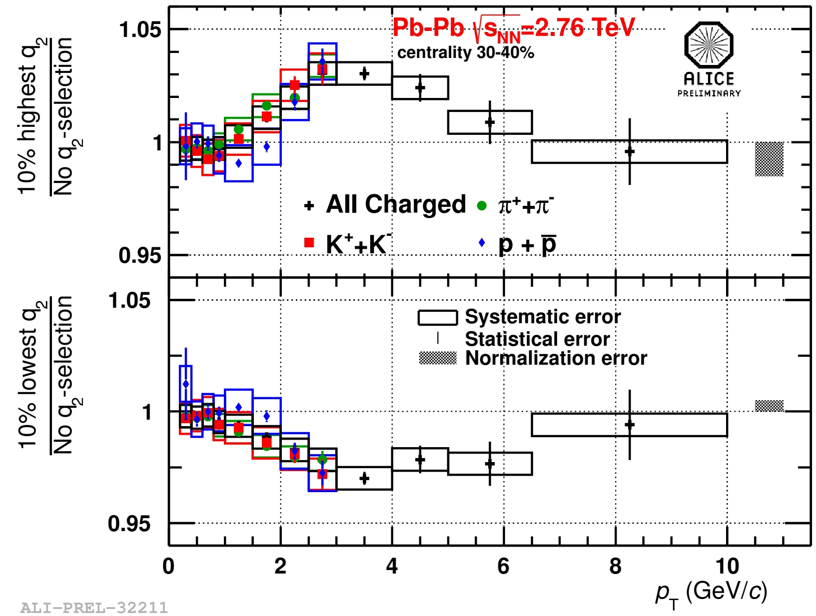


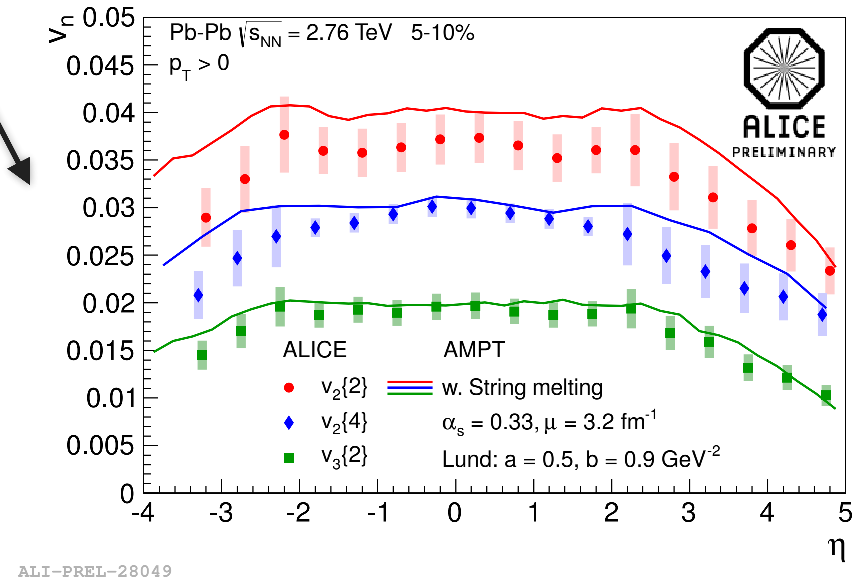
ALI-PREL-70929

ALICE

Papers in progress…

1. Event shape engineering and spectral shapes
2. Rapidity dependence of azimuthal flow
3. Long paper on flow fluctuations
4. Searches for p_T dependent symmetry planes





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Summary

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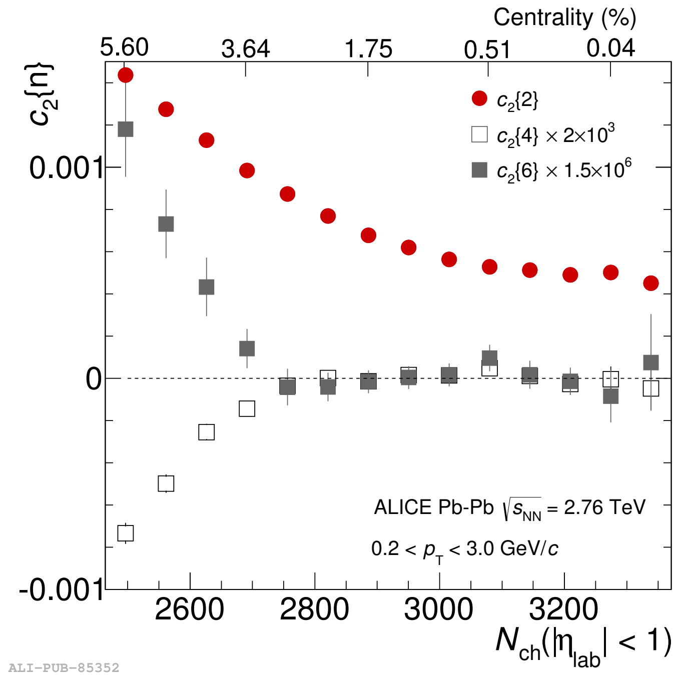
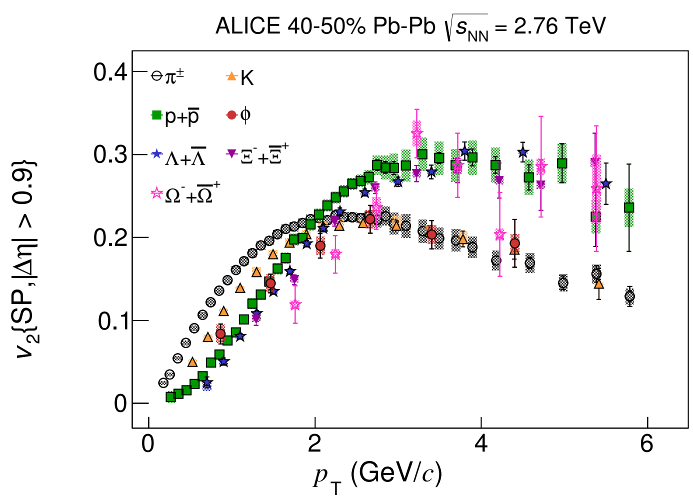
- **Flow fluctuations**
  - ✓ Evidence of non Bessel Gaussian fluctuations in Pb-Pb
  - ✓ Higher order cumulants become zero for super central collisions
  - ✓ Evidence of collective behaviour in p-Pb collisions
  - ✓ Breakdown of factorization for v_2

- **Identified particle flow**
  - ✓ Mass dependence for v_2 in pp, p-Pb and Pb-Pb
  - ✓ Reasonable hydro description for π, p, and Λ v_2

- **Searches for strong parity violation**
  - ✓ Particle species dependence for CME correlator
  - ✓ v_2 depends on charge asymmetry → Chiral Magnetic Wave?



ALI-PUB-85352



ALI-PUB-82989

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Back-up

$$\frac{dn}{d\varepsilon_{part}} = \frac{\varepsilon_{part}}{\sigma_\varepsilon^2} I_0\left(\frac{\varepsilon_{part}\langle\varepsilon_{RP}\rangle}{\sigma_\varepsilon^2}\right)\exp\left(-\frac{\varepsilon_{part}^2+\langle\varepsilon_{RP}\rangle^2}{2\sigma_\varepsilon^2}\right) \equiv \mathrm{BG}(\varepsilon_{part};\langle\varepsilon_{RP}\rangle,\sigma_\varepsilon),$$

Phys. Rev. C68 (2003) 034903