A Large Ion Collider Experiment

European Organisation for Nuclear Research

UNIVERSITY of HOUSTON

Results on thermalisation and flow from ALICE

Anthony Timmins for the ALICE Collaboration

The 30th Winter Workshop on Nuclear Dynamics

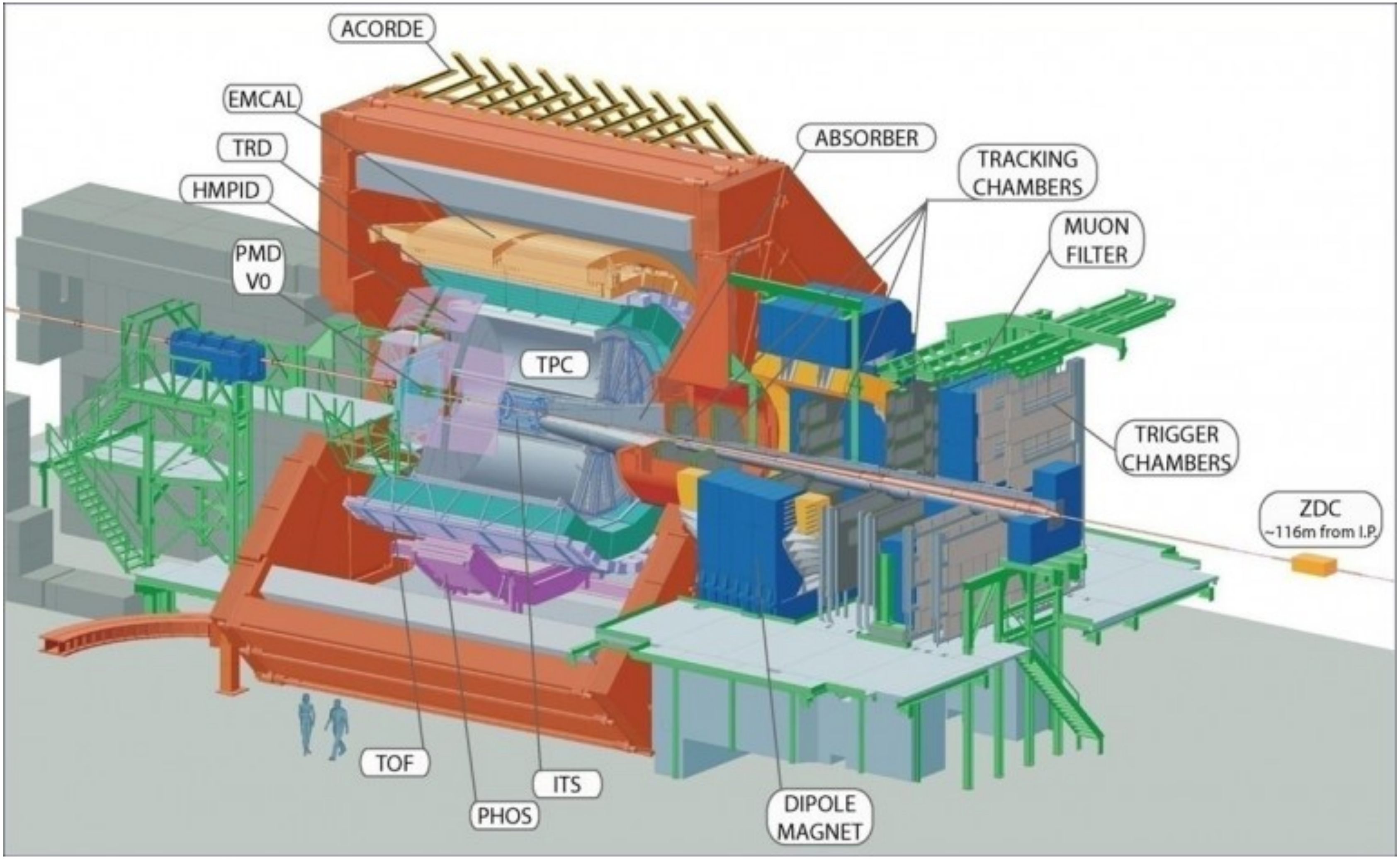
Overview

1. ALICE detectors and their performance

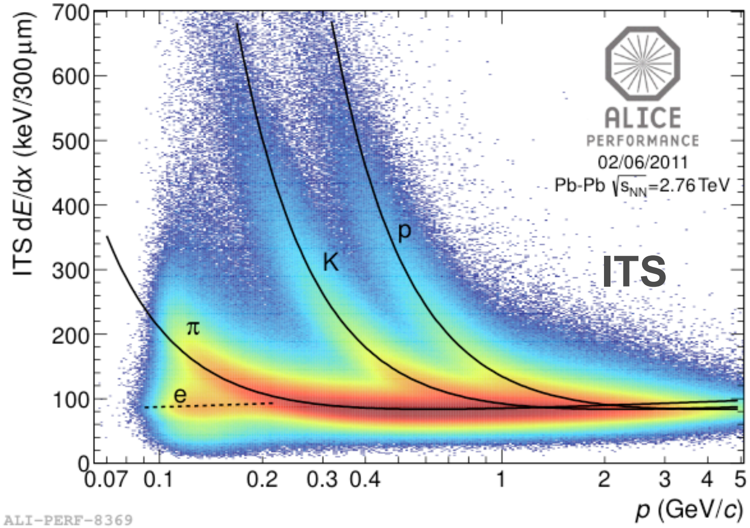
2. Identified particle production and thermalisation
   - ✓ Kinetic freeze out and radial flow in Pb-Pb
   - ✓ Chemical freeze out temperatures
   - ✓ Radial flow searches in p-Pb collisions

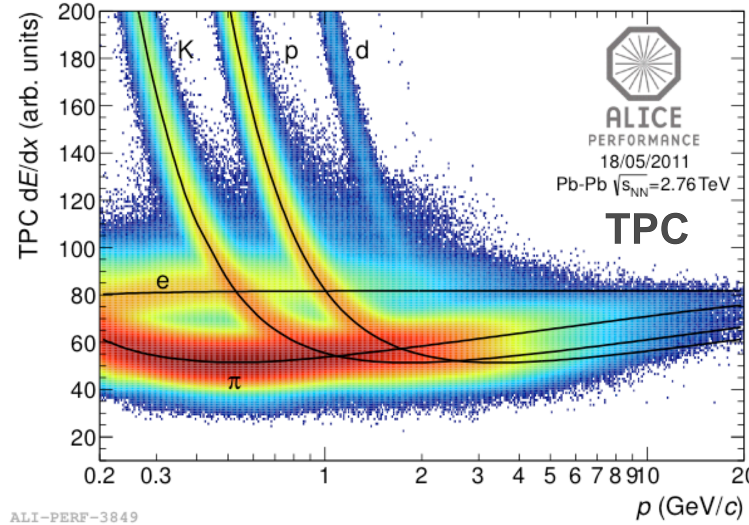
3. Flow harmonics and initial conditions
   - ✓ v_n fluctuations
   - ✓ Chiral Magnetic Effect (CME) searches
   - ✓ Event shape engineering
   - ✓ Multi-particle correlations and mixed harmonics
   - ✓ Searches for azimuthal flow in p-Pb and pp collisions

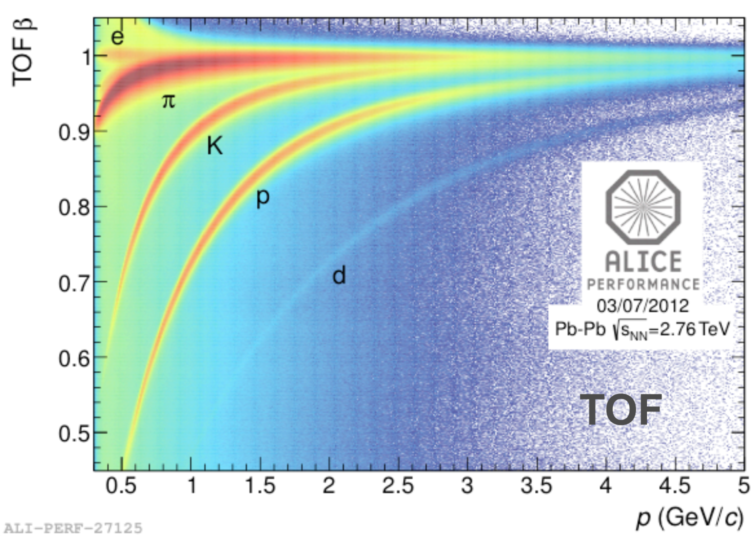
The ALICE detector

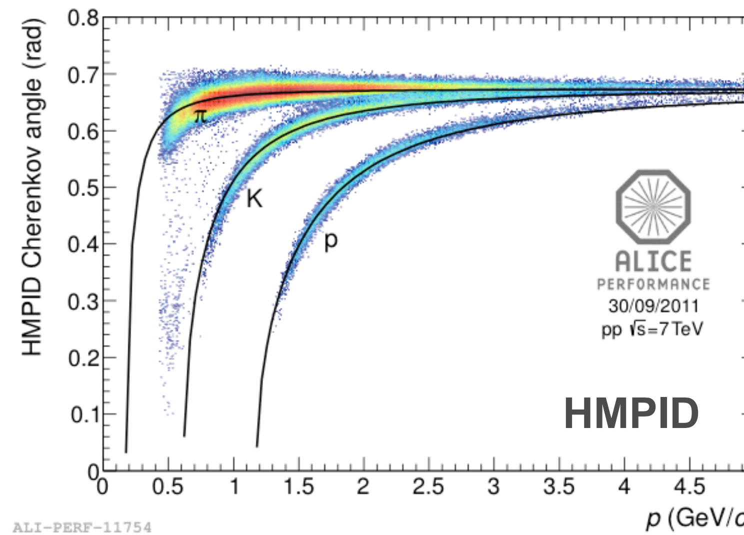


PID capabilities





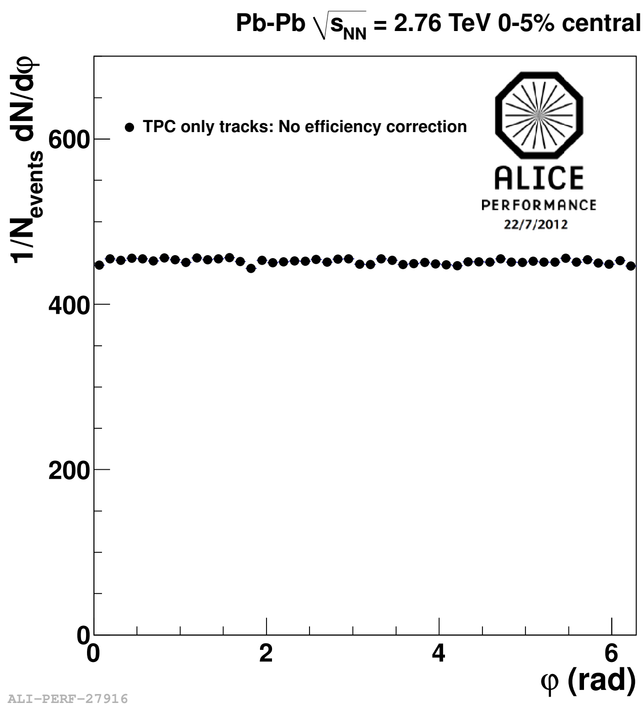


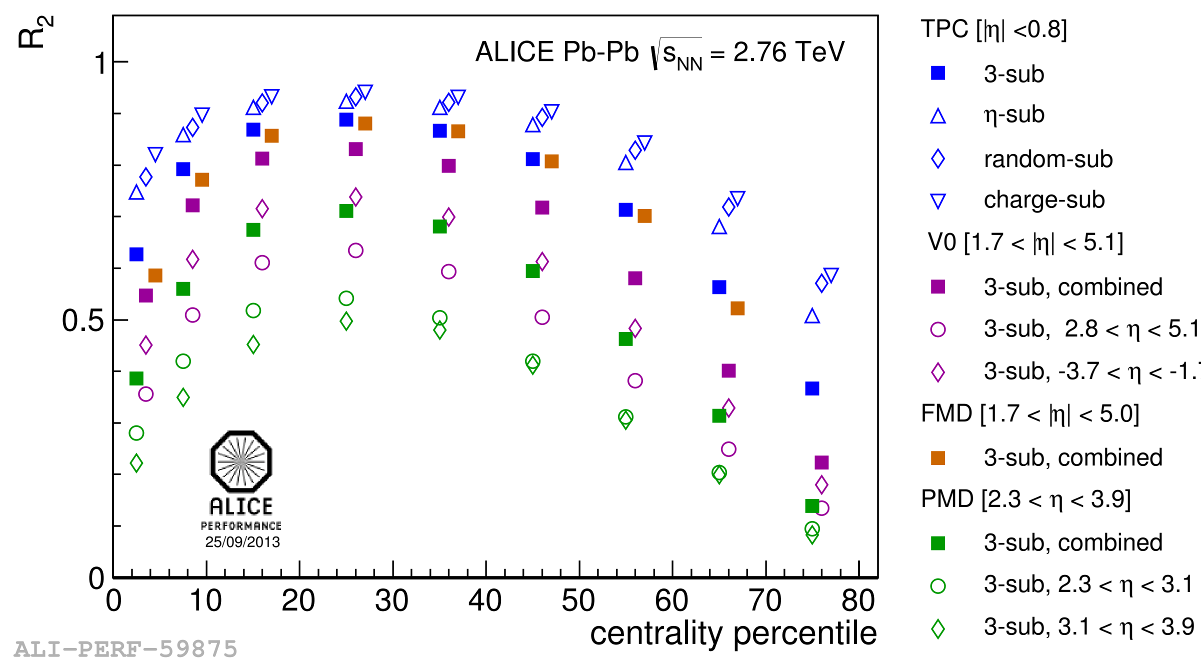


- Suite of detectors available, ALICE optimised for PID

ALICE

Angular correlation capabilities

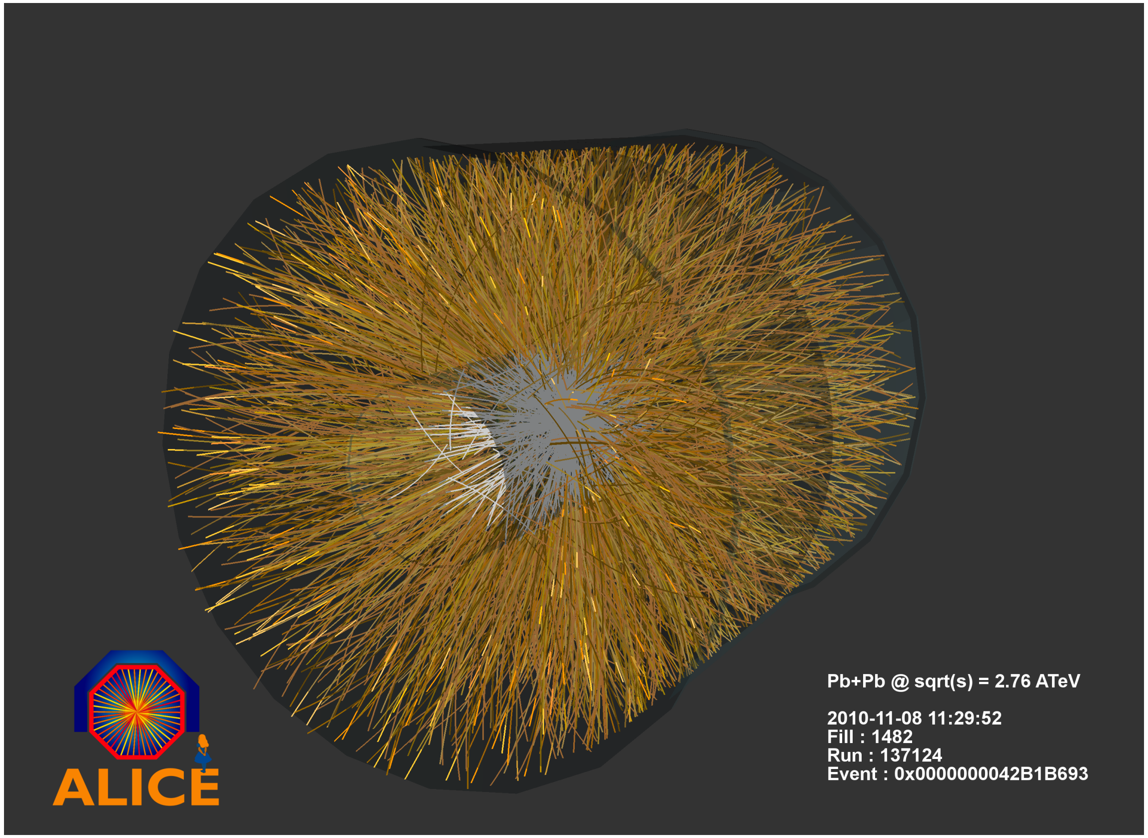




- Highly uniform φ distribution of mid-rapidity tracks.

- Reaction plane resolution
  - ✓ Determined with various detectors
  - ✓ Close to 1 in best case

Identified particle production and thermalisation

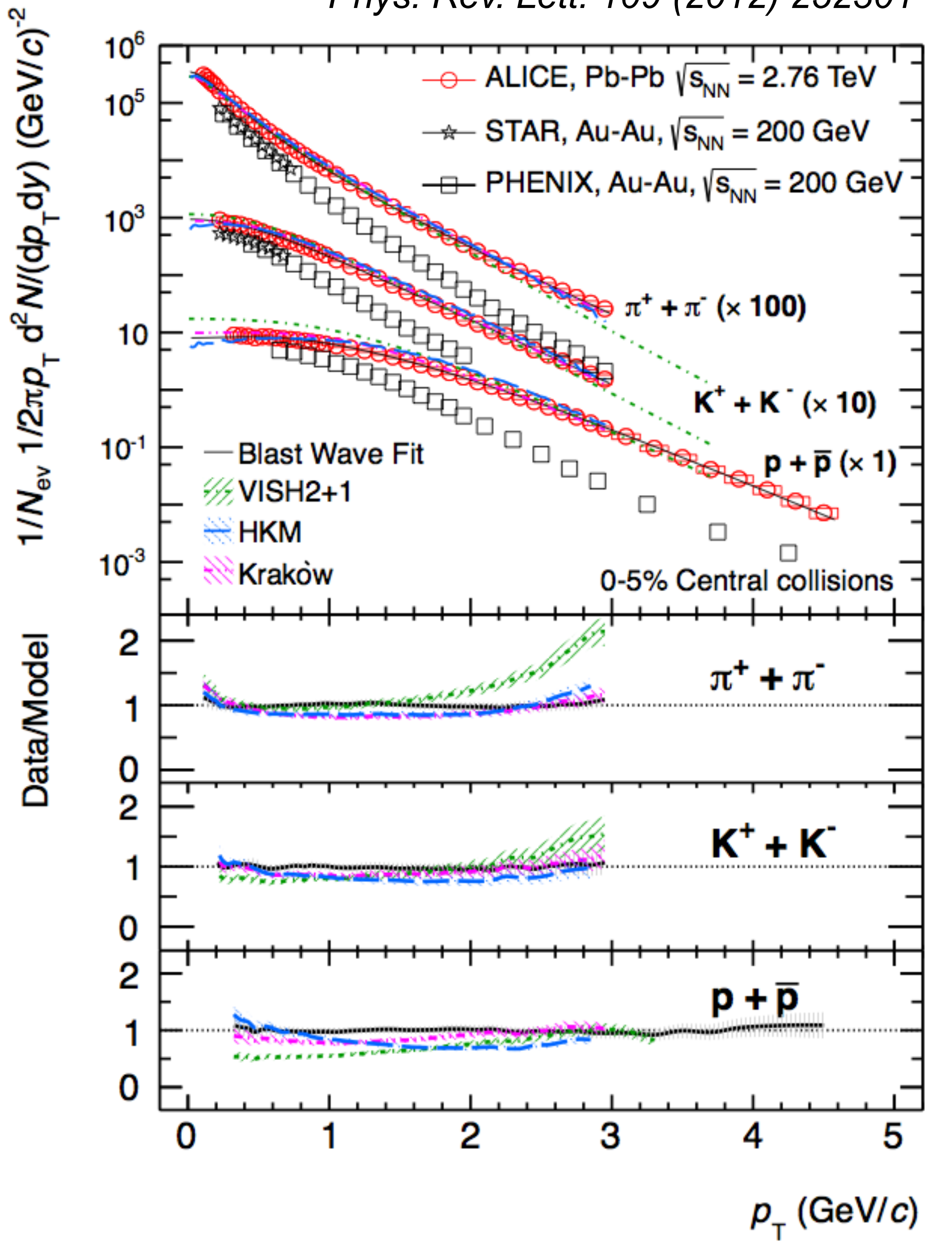


- Provide key information on freeze-out dynamics
  - ✓ Spectral shapes vs. mass => **Radial flow** and **kinetic freeze-out** temperatures
  - ✓ Yields and ratios => **Chemical freeze-out** temperatures

Identified particle spectra

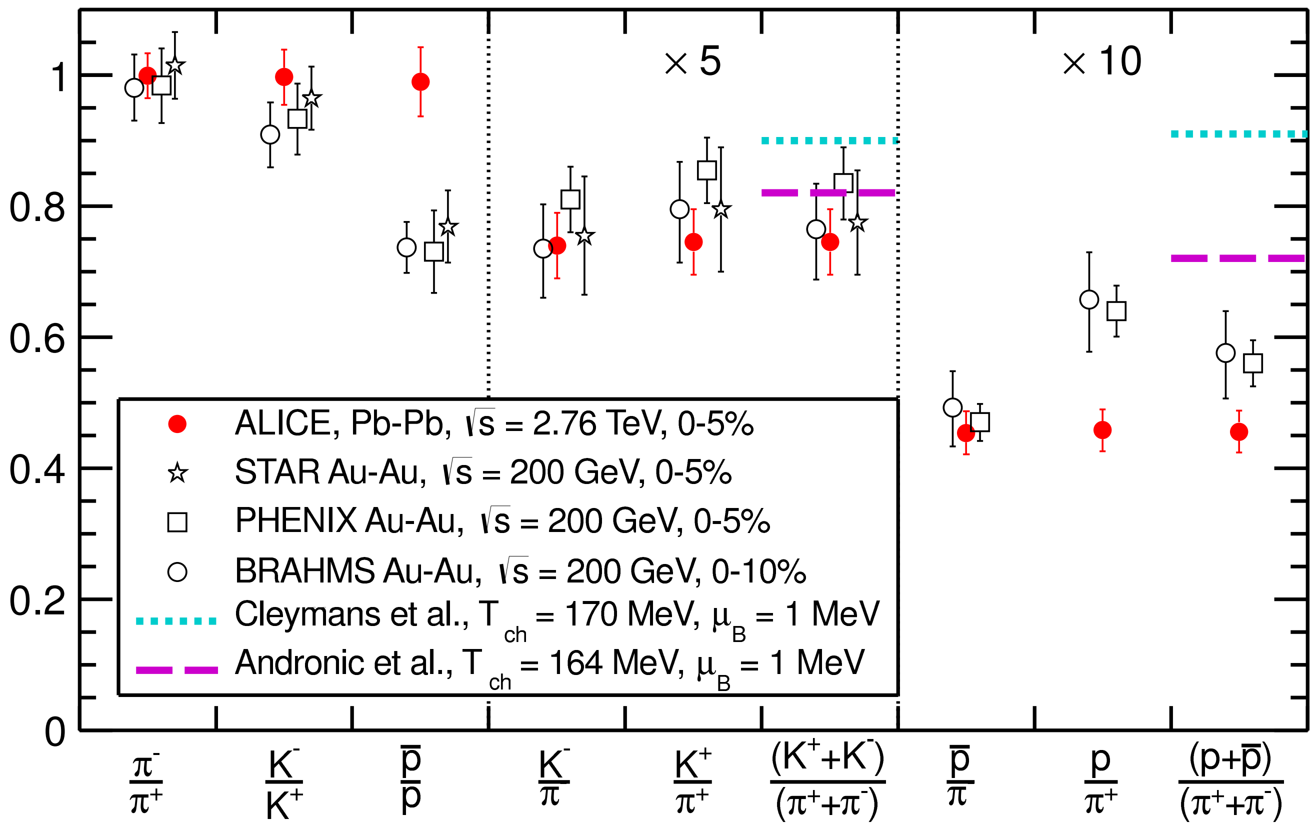
- Central Pb-Pb π,K, p spectra published last year
  - ✓ K^0_S, Λ, Ξ and Ω spectra just submitted for publication
  - ✓ arXiv's 1307.6796, 1307.5543 and 1307.5530
- **Shallower slopes** compared to RHIC data…
- Blast-wave model used to obtain radial flow velocity:
  - ✓ $\langle\beta_T\rangle = 0.65c$
  - ✓ 10% higher than RHIC
  - ✓ $T_{kinetic}$ = 80-95 MeV

Phys. Rev. Lett. 109 (2012) 252301



Chemical freeze-out fits

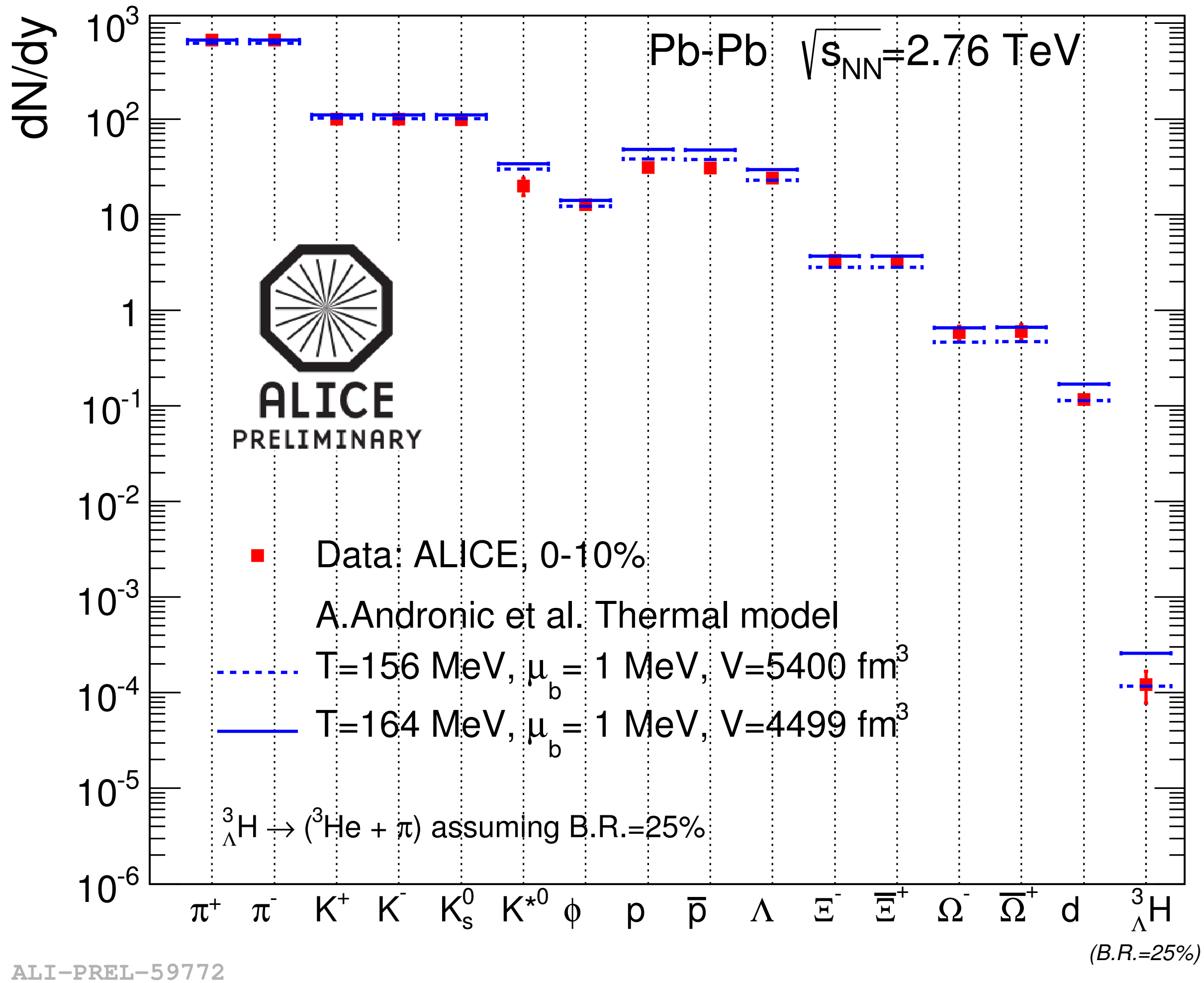
Phys. Rev. Lett. 109 (2012) 252301



- Chemical freeze-out fits with just π,K, p data:
  - ✓ T_{ch} ~ 170 MeV
  - ✓ Similar to RHIC data
- **Deviations observed for proton** data…

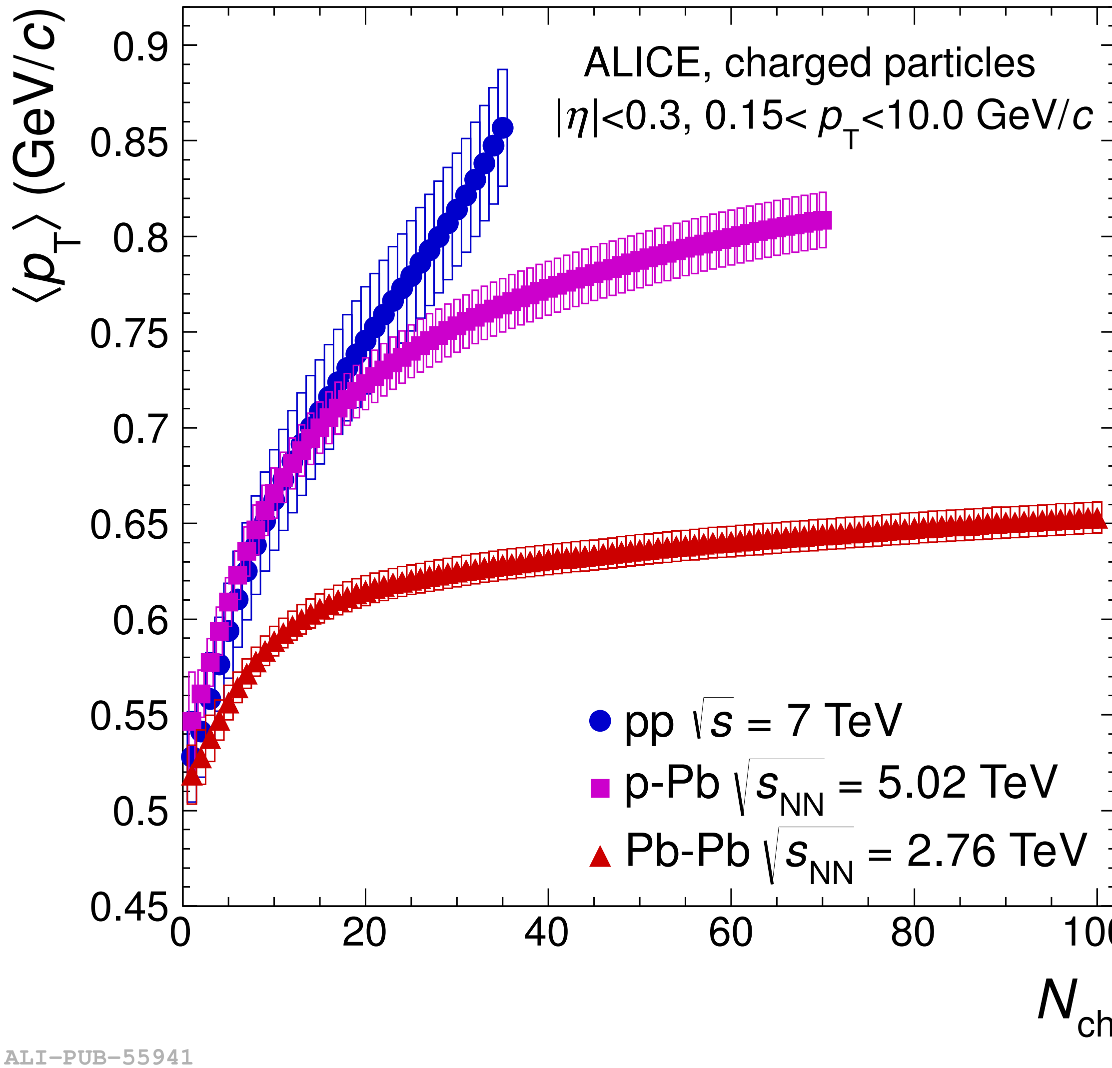
Inclusion of particles with higher mass

- **Difficult to fit all yields** well with common T_{chem}
  - ✓ Higher T_{chem} suits mulit-strange, lower T_{chem} suits proton and Λ
- K^{*0} not included in fit…
- Particle dependent T_{chem} ? Differences due to re-scattering effects



$\langle p_T \rangle$ in pp, p-Pb and Pb-Pb collisions

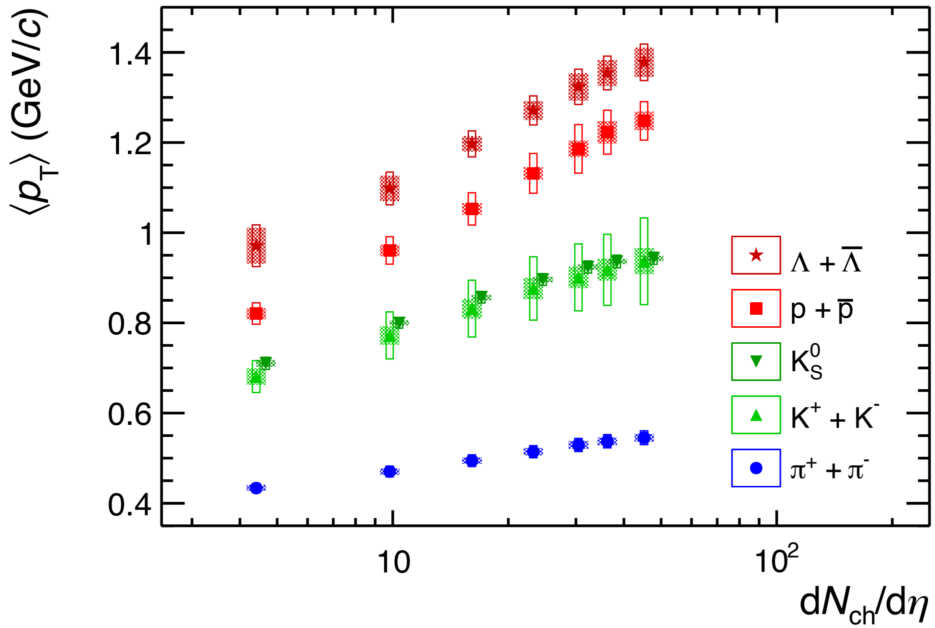
- Hierarchy observed.
- Smaller systems increase more rapidly.
- At high N_{ch}
  - ✓ pp selects on type of production of process (jets, MPIs etc)
  - ✓ p-Pb selects processes+ geometry
  - ✓ Pb-Pb selects geometry

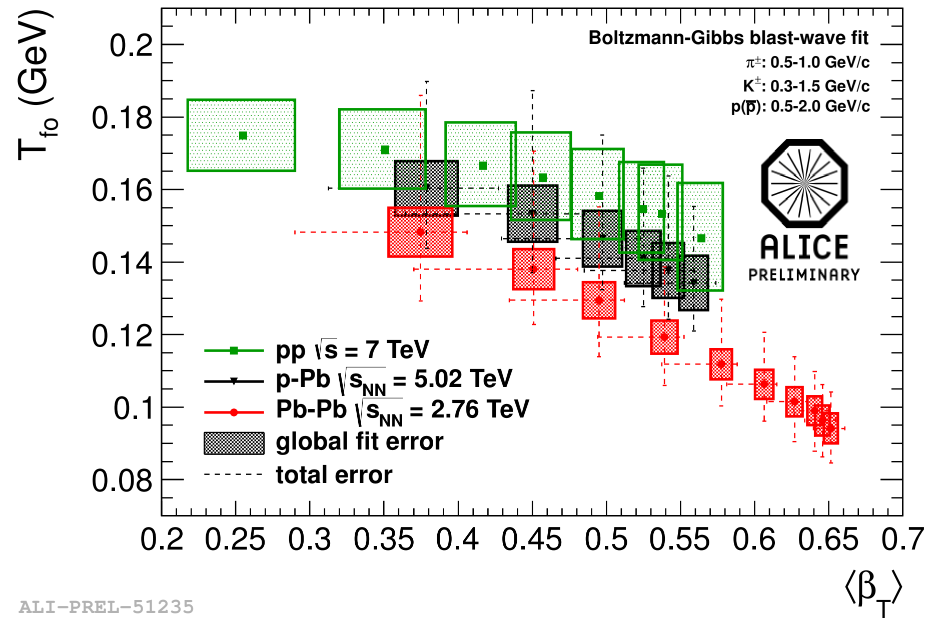


Phys. Lett B 727 (2013) 371–380

Radial flow searches in p-Pb in collisions

Phys. Lett. B728 (2014) 25-38

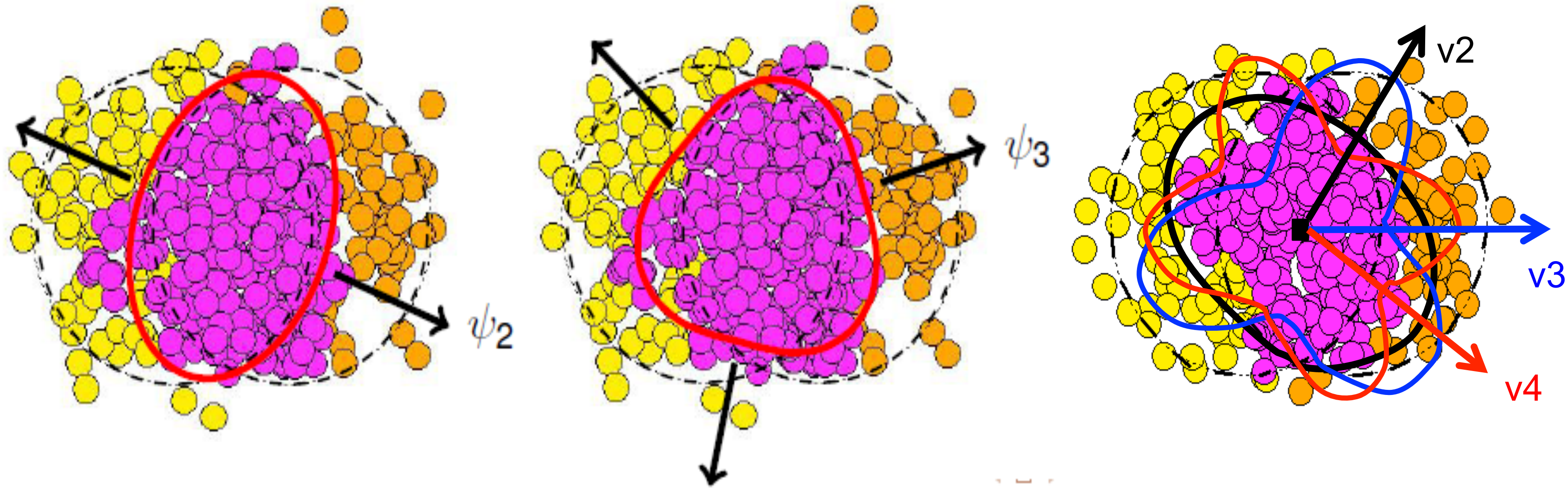




- Resembles Pb-Pb: mean p_T increases with mass of particle.
  - ✓ Blast wave fits $<\beta_T>$ ~ 0.5c central p-Pb
  - ✓ Similar values observed in pp

ALICE

Azimuthal flow and initial conditions



- Many tools to investigate flow and flow fluctuations:
  - ✓ Flow cumulants
  - ✓ Unfolded v_2 distributions
  - ✓ Multi-particle correlations and mixed harmonics

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n cos[n(\varphi - \psi_n)]$$

$$v_n = \langle cos[n(\varphi - \psi_n)]\rangle$$

Cumulants and flow coefficients

- Cumulants formed from moments of v_n distribution.

$$c_n\{2\} = \langle\langle 2\rangle\rangle = \langle v_n\rangle^2 + \sigma_{vn}^2$$

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

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

- Flow coefficients formed from cumulants

$$v_n\{2\} = \sqrt{c_n\{2\}}$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

$$v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$$

- $\sigma_{v2}/\langle v_2\rangle$ can be approximated from flow coefficients

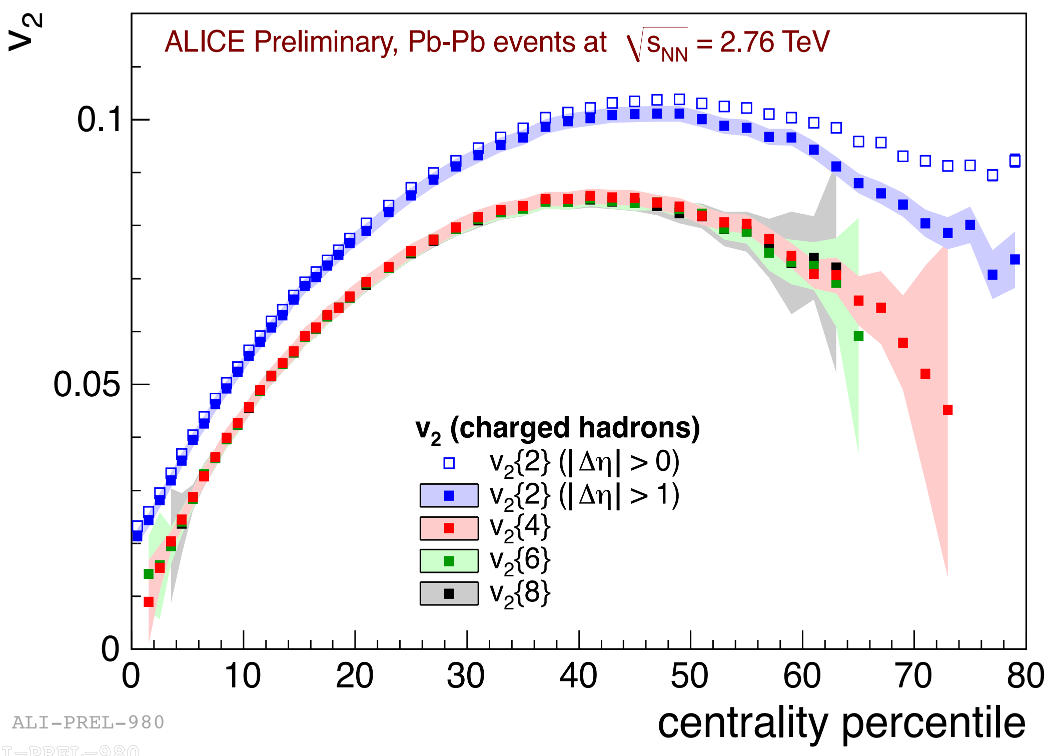
$$R_n = \sqrt{\frac{v_n\{2\}^2 - v_n\{4\}^2}{v_n\{2\}^2 + v_n\{4\}^2}}$$

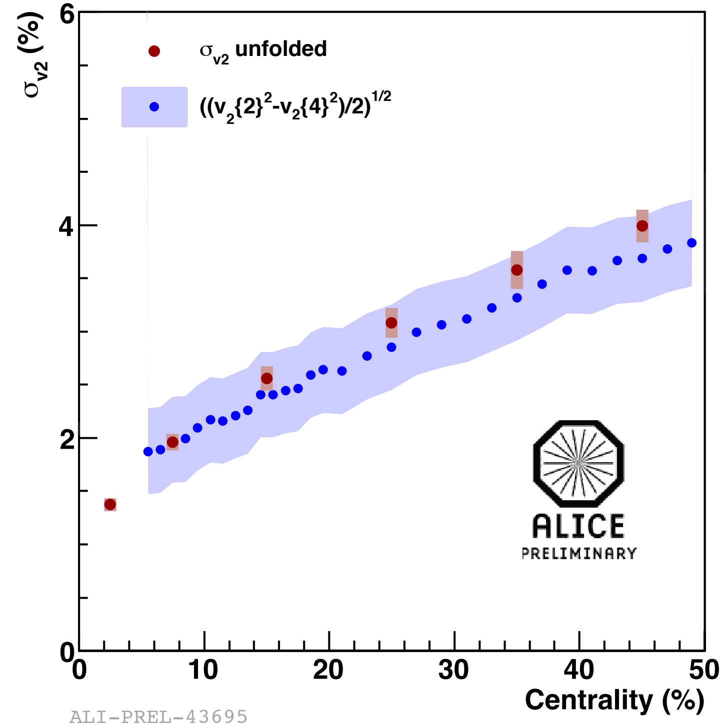
- Sensitivity to few particle correlations (M=Multiplicity):

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

ALICE

v_2 fluctuations





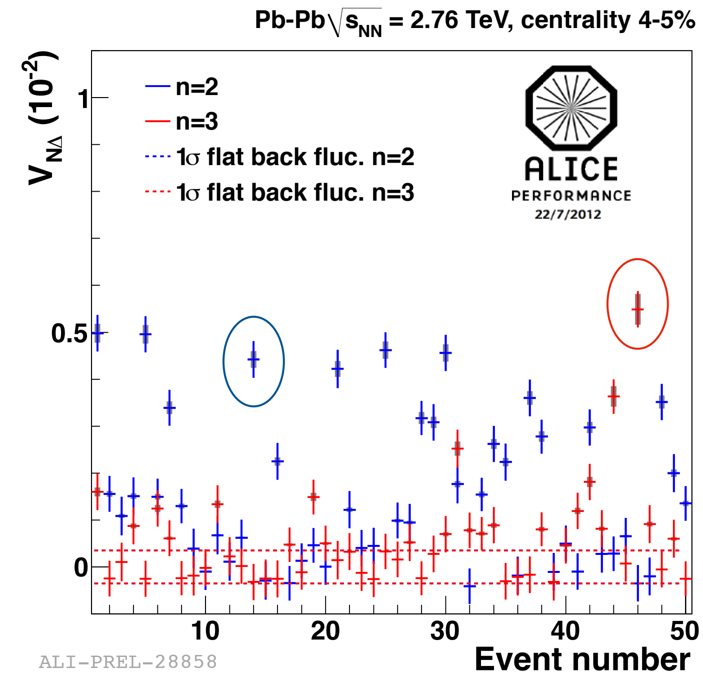
- Differences in $v_2\{2\}$ and $v_2\{4\}$ arise from v_2 fluctuations
  - ✓ Strength of flow fluctuations σ_{v2} can also be determined

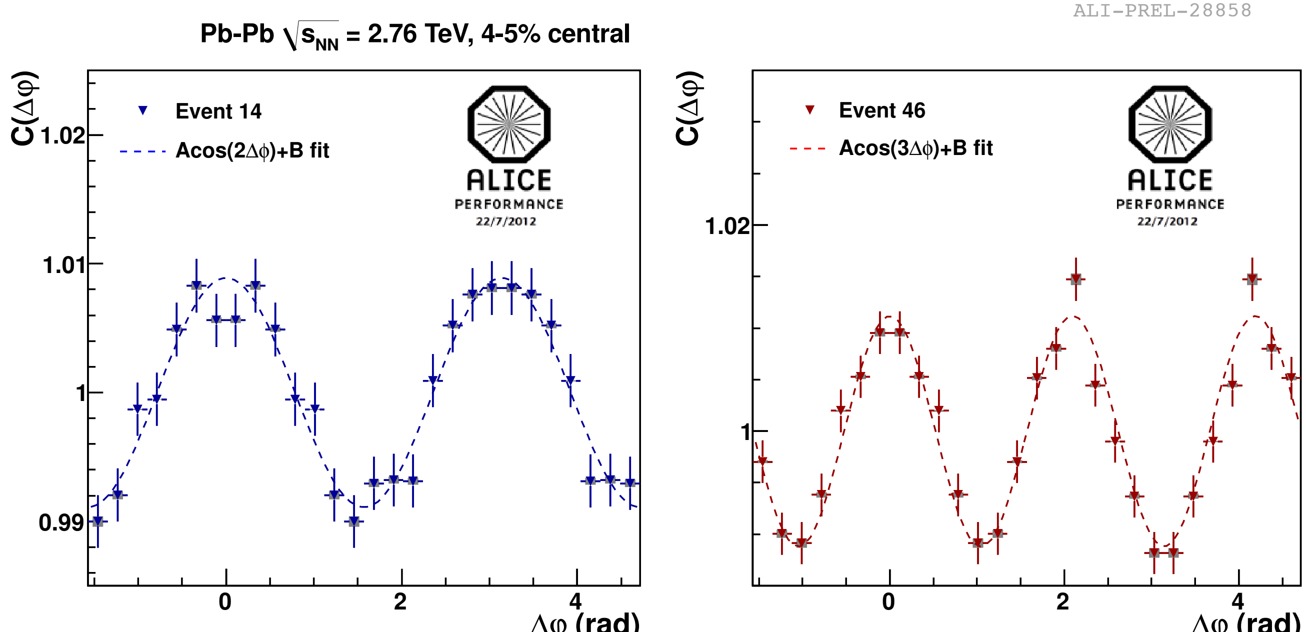
- $v_2\{4\}$~$v_2\{6\}$ ~$v_2\{8\}$ characteristic of **Bessel Gaussian** form for v_2 fluctuations

ALICE

v_2 and v_3 fluctuations

- **Large fluctuations in v_2^2 and v_3^2** observed event by event
  - ✓ Appear largely independent
- 2 particle correlations in circled events dominated by v_2 and v_3
  - ✓ Allows v_n distributions to be obtained…

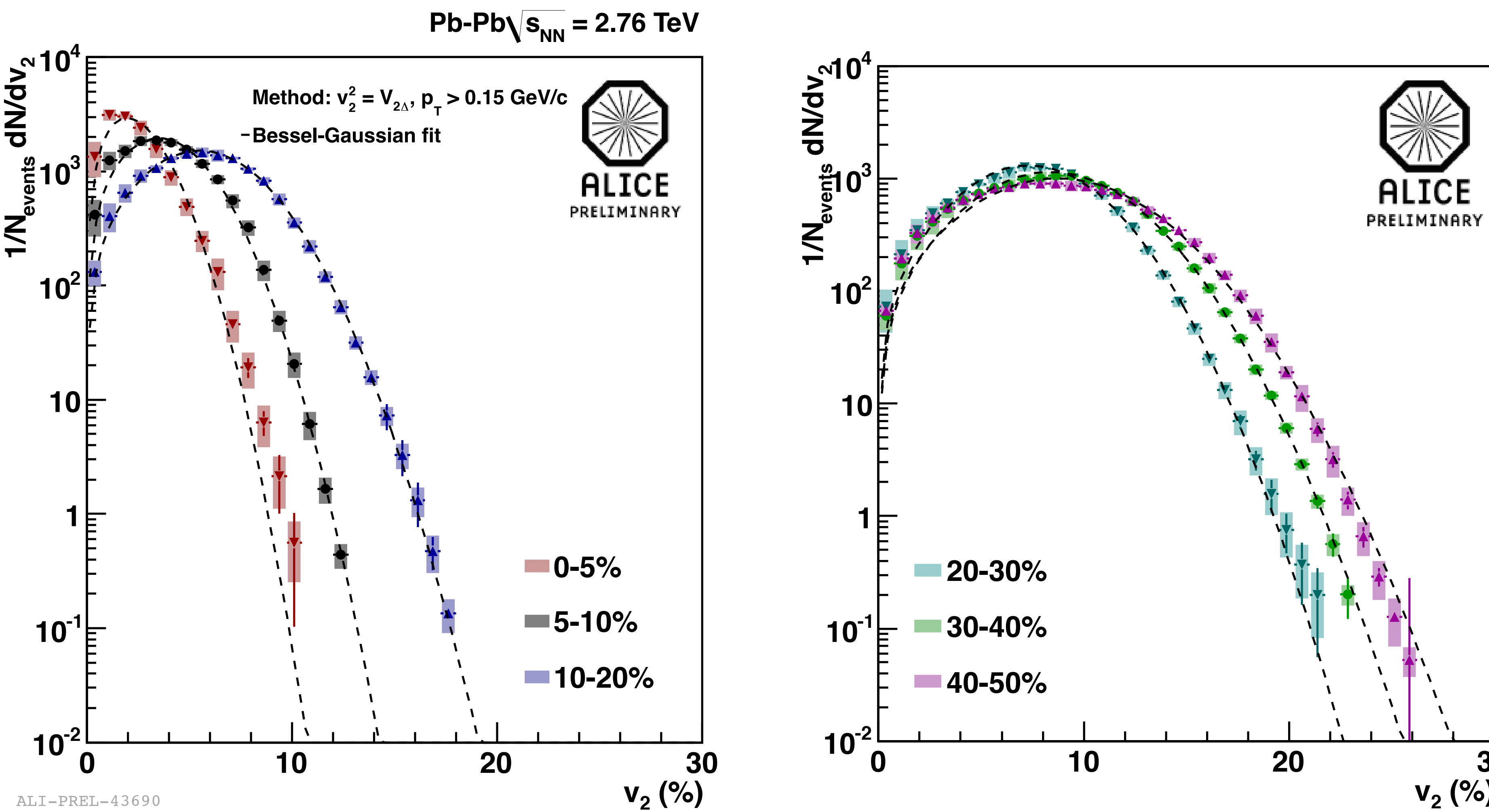




$$V_{n\Delta} = v_n\{2\}^2$$

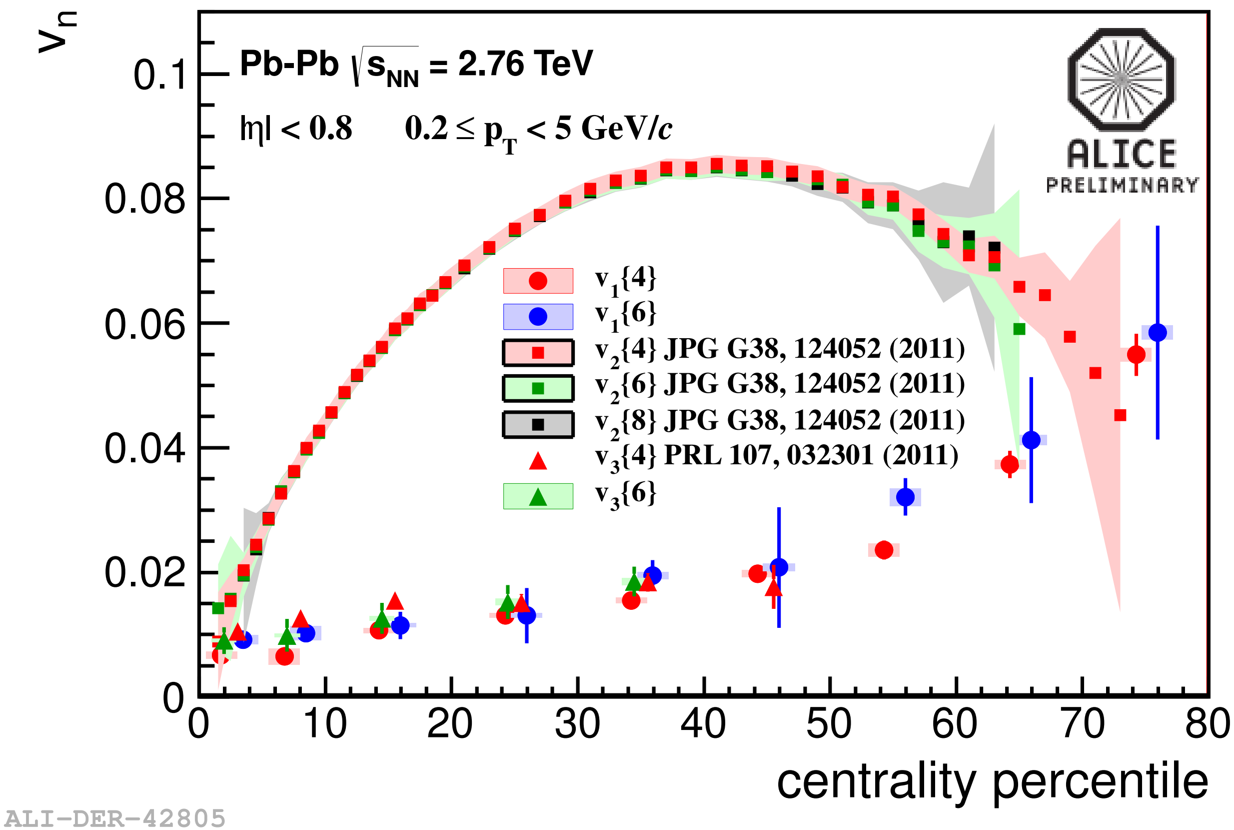
ALICE

Unfolded v_2 distributions



- Unfolding removes effects of limited statistics
  - ✓ Expected to reflect eccentricity fluctuations of initial state (arix:1212.1008)
  - ✓ Bessel Gaussian fits work nearly always.

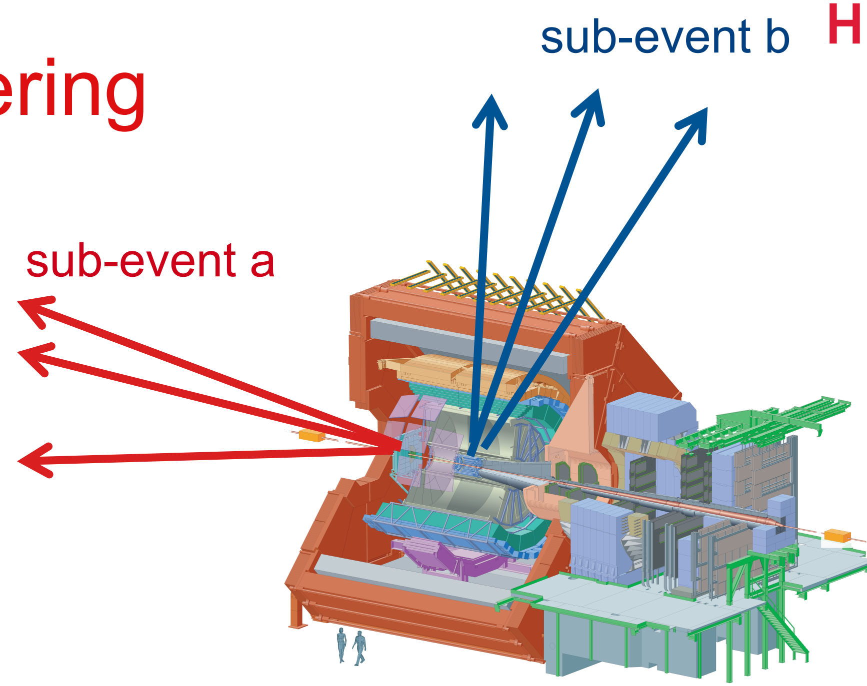
Multi-particle correlations of v_1 and v_3



- Multi-particle correlations $v_n\{4\}$, $v_n\{6\}$, and $v_n\{8\}$ less sensitive to non-flow
- Non zero signals observed for n=1,2 and 3
- $v_1\{4\} \sim v_1\{6\} \sim v_3\{4\} \sim v_3\{6\}$…

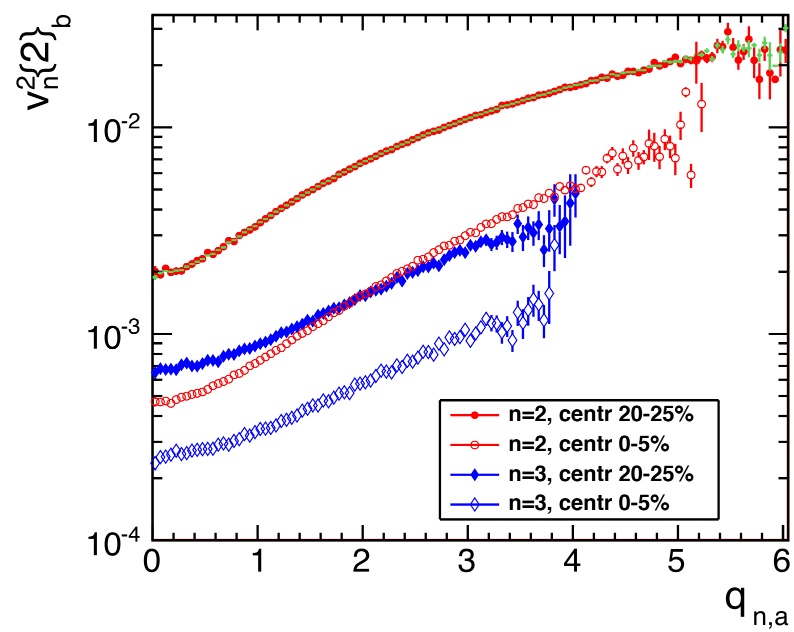
v_1 vs. reaction plane published
Phys. Rev. Lett. 111 (2013) 232302

Event shape engineering



- If we can "see" events with **low/high flow**, we can **select** them.
  - ✓ Need to be clever and avoid biases.

- Measure flow in one part of phase space (a)
  - ✓ Analyze data in another part (b)



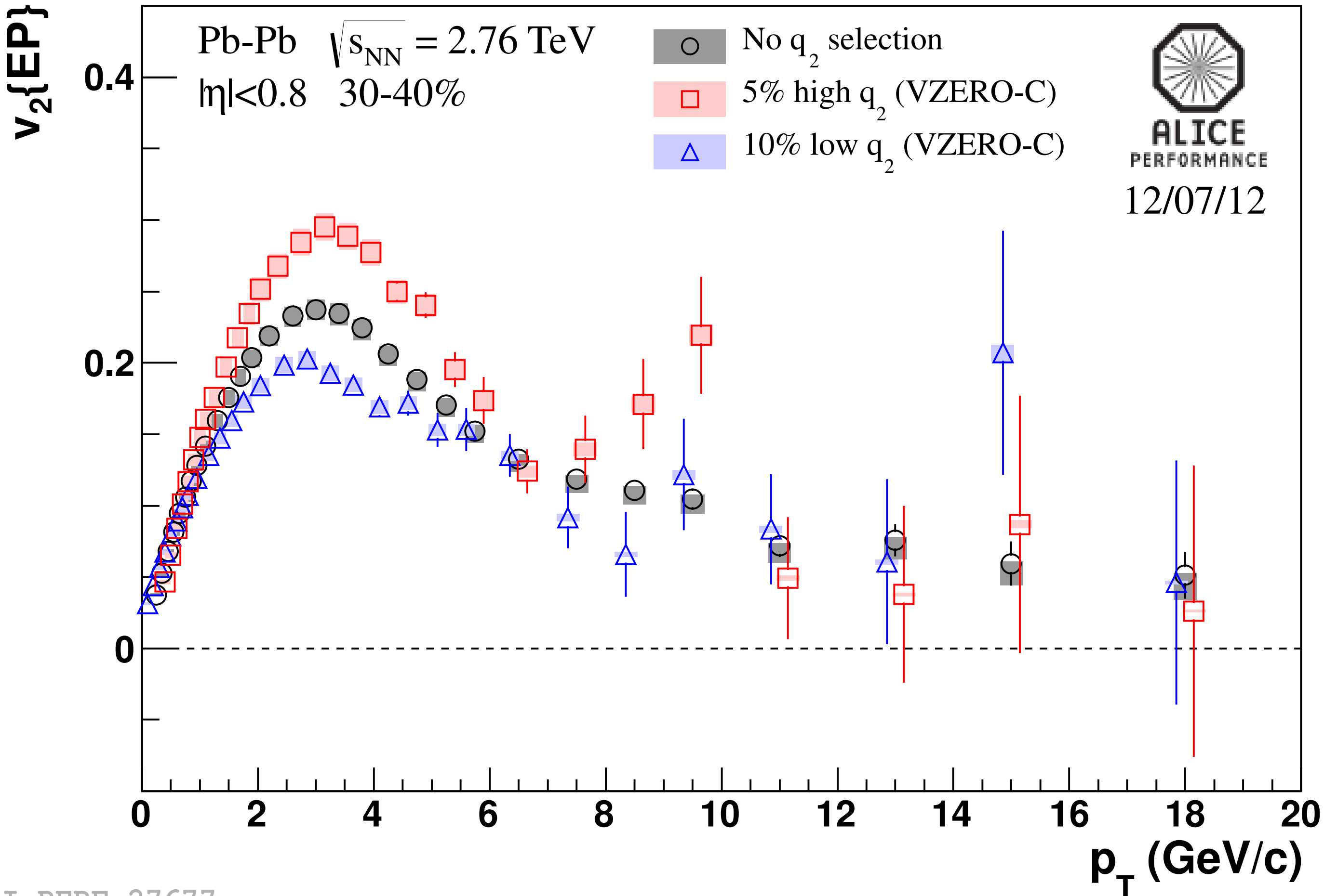
arXiv:1208.4563
arXiv:1311.7091

$$q_n^2 = 1 + (M-1)v_n^2$$

M = multiplicity

ALICE

Event shape engineering

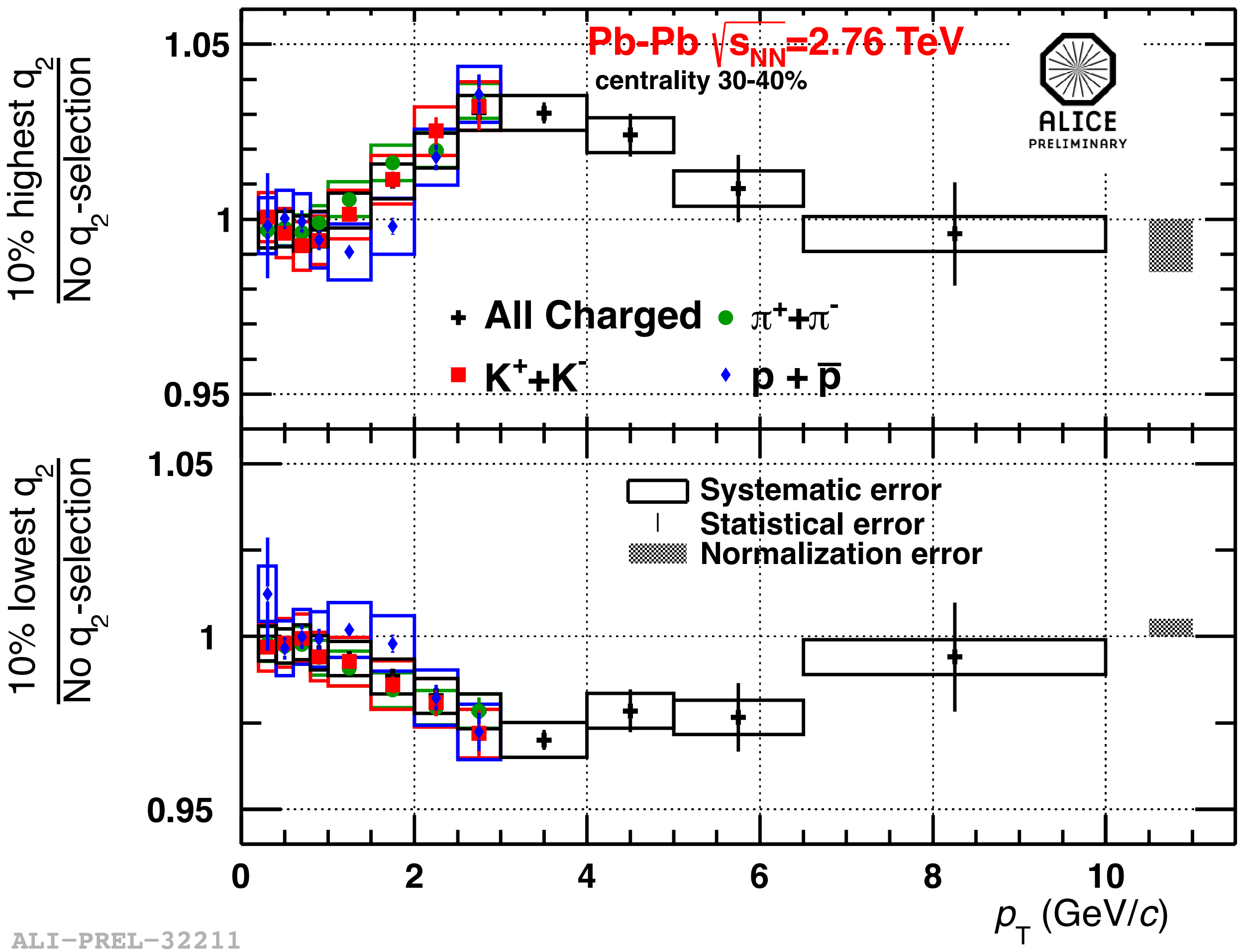


ALI−PERF−27677

- Appears to work in data
  - ✓ Select events with low/high q_2 in VZERO
  - ✓ Observe low/high v_2 measurements in TPC…

ALICE

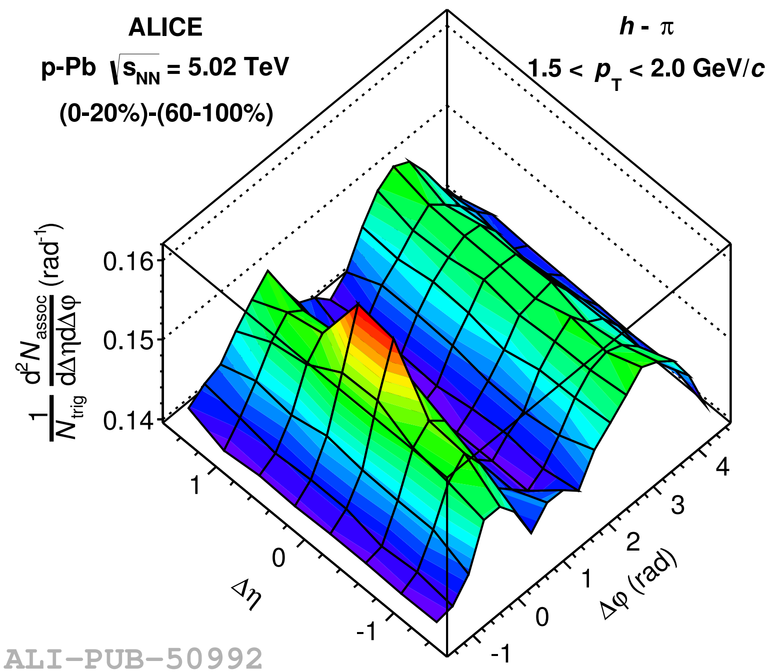
Event shape engineering



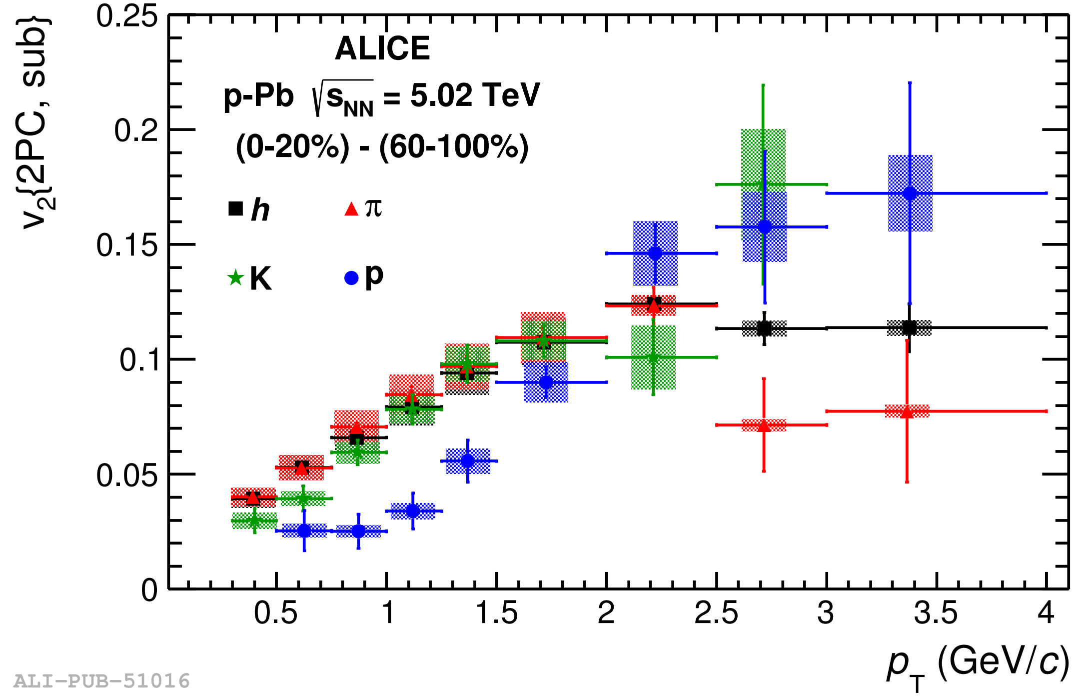
- Spectra shape appears to change with q_2
  - ✓ $\langle p_T \rangle$ increases with v_2
  - ✓ No obvious mass dependence
- Due to correlation between $\langle \varepsilon_2 \rangle$ and $\langle R^2 \rangle$?
  - ✓ High $\langle \varepsilon_2 \rangle$, small $\langle R^2 \rangle$, greater radial pressure gradient?
- Other observables we can study w.r.t q_2?

ALICE

Searches for azimuthal flow in p-Pb collisions



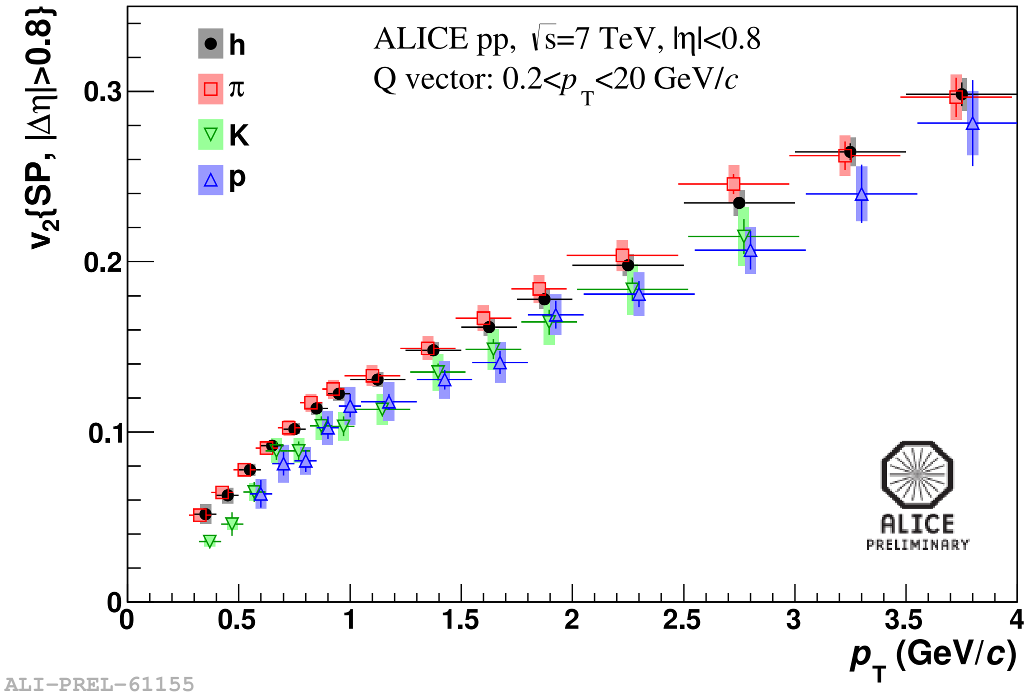
Phys. Lett. B 726 (2013) 164–177

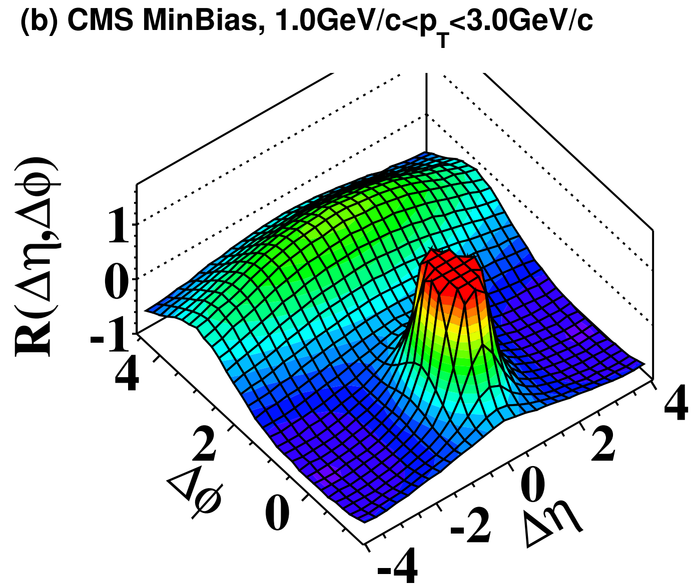


- ❑ Central – peripheral di-hadron correlations reveal double ridge
  - ✓ π, K, and p v_2 can be extracted
  - ✓ Mass ordering at low p_T
  - ✓ Cross over of π and p v_2

ALICE

Measurements of $v_2\{SP\}$ in min-bias pp collisions





pp 7 TeV (JHEP 1009 (2010) 091)

- $v_2\{SP\}$ allows Δη gap to be placed
  - ✓ Suppress short range correlations
- Small mass splitting observed even though non-flow dominates

Summary

1 Comprehensive set of spectra and flow measurements from ALICE

- ✓ Strong constraints on initial conditions and global event characteristics

2 Identified particle production,

- ✓ Radial flow 0.65c, 10% higher than RHIC,
- ✓ Tension with assumption of common chemical freeze-out temperatures for different particle species
- ✓ "Radial flow features" observed in p-Pb spectra

3 Angular correlations and flow

- ✓ v_2 fluctuations appear to follow Bessel Gaussian form
- ✓ Correlation observed between v_2 and spectra shapes
- ✓ Non zero correlations observed between ψ_1, ψ_2 and ψ_3 planes
- ✓ Mass ordering observed for v_2 in p-Pb collisions