A Large Ion Collider Experiment

European Organisation for Nuclear Research

UNIVERSITY of HOUSTON

Results on Thermalisation and Harmonics from ALICE

Anthony Timmins for the ALICE Collaboration

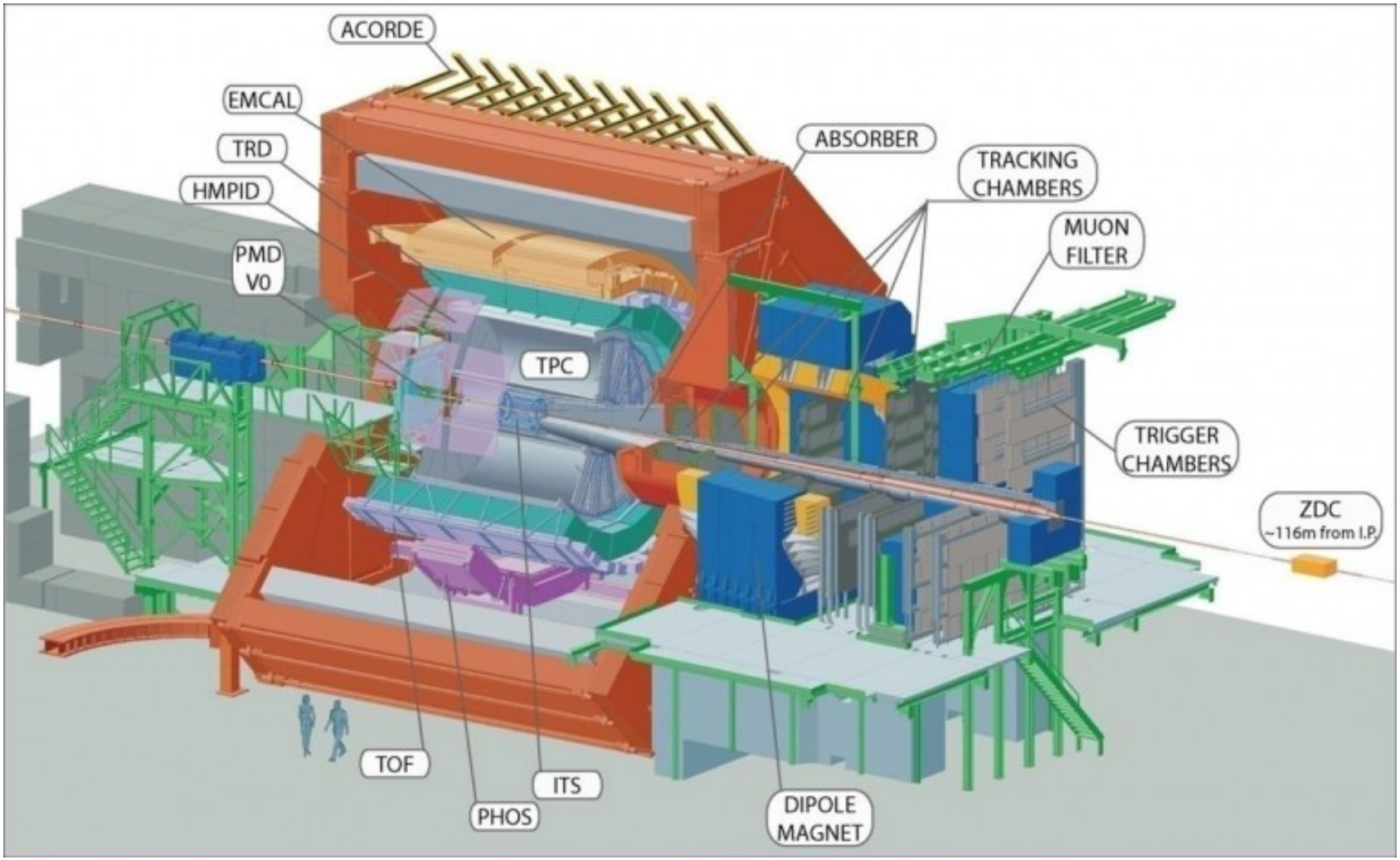
Overview

1. ALICE performance
   - ✓ Detector overview and capabilities
   - ✓ Delivered luminosities

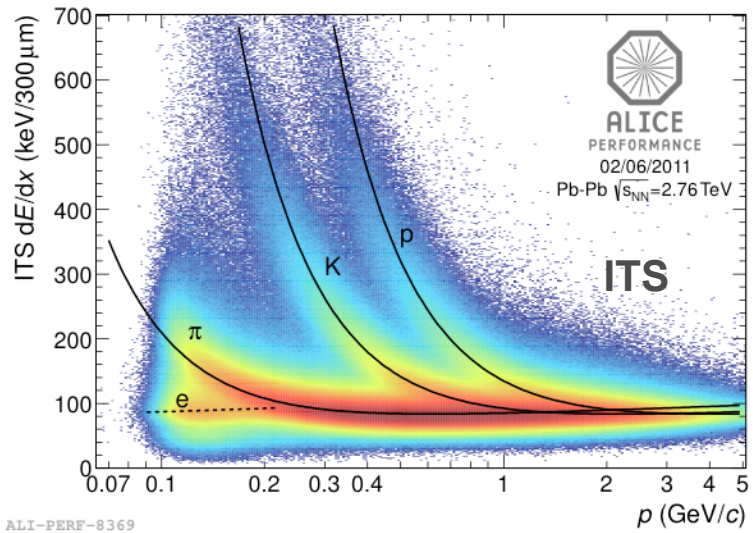
2. Identified particle production and thermalisation
   - ✓ Chemical freeze out and radial flow in Pb-Pb
   - ✓ Strangeness dependent freeze out temperatures
   - ✓ Radial flow studies in p-Pb collisions

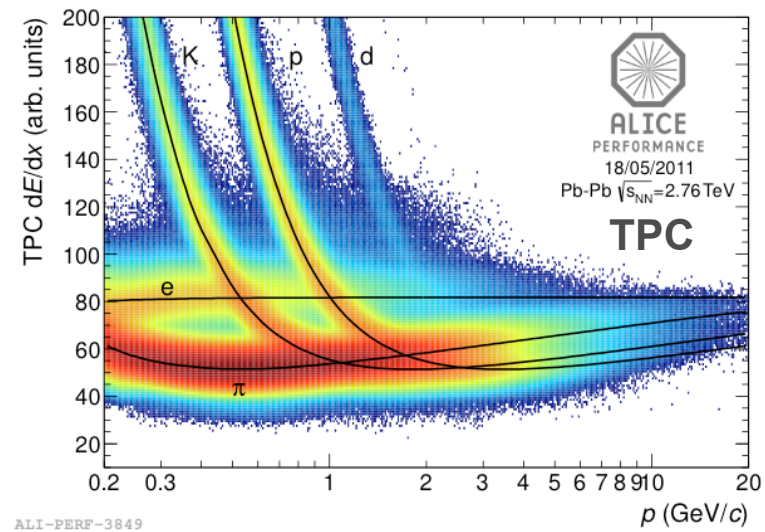
3. Flow harmonics and initial conditions
   - ✓ v_n fluctuations
   - ✓ Chiral Magnetic Effect (CME) searches
   - ✓ Event shape engineering
   - ✓ Multi-particle correlations and mixed harmonics

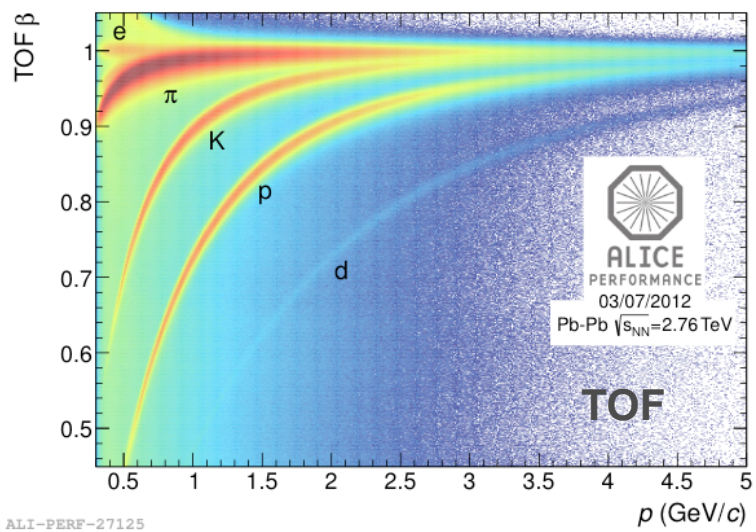
The ALICE detector

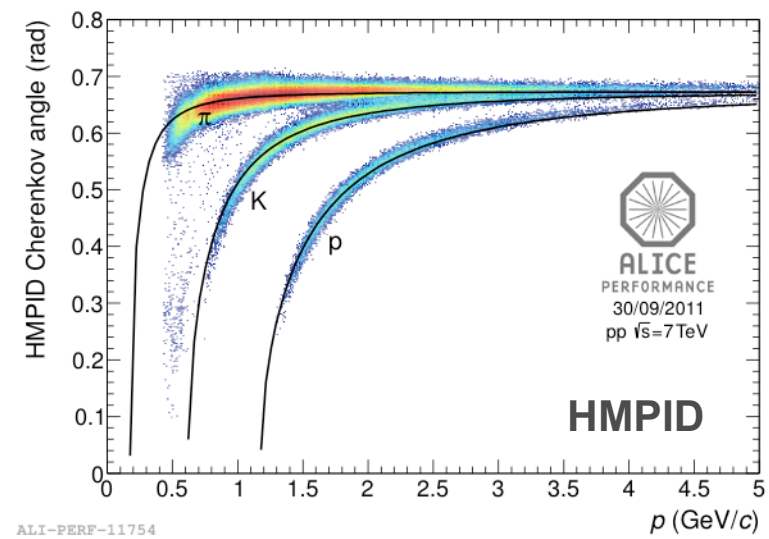


PID capacities



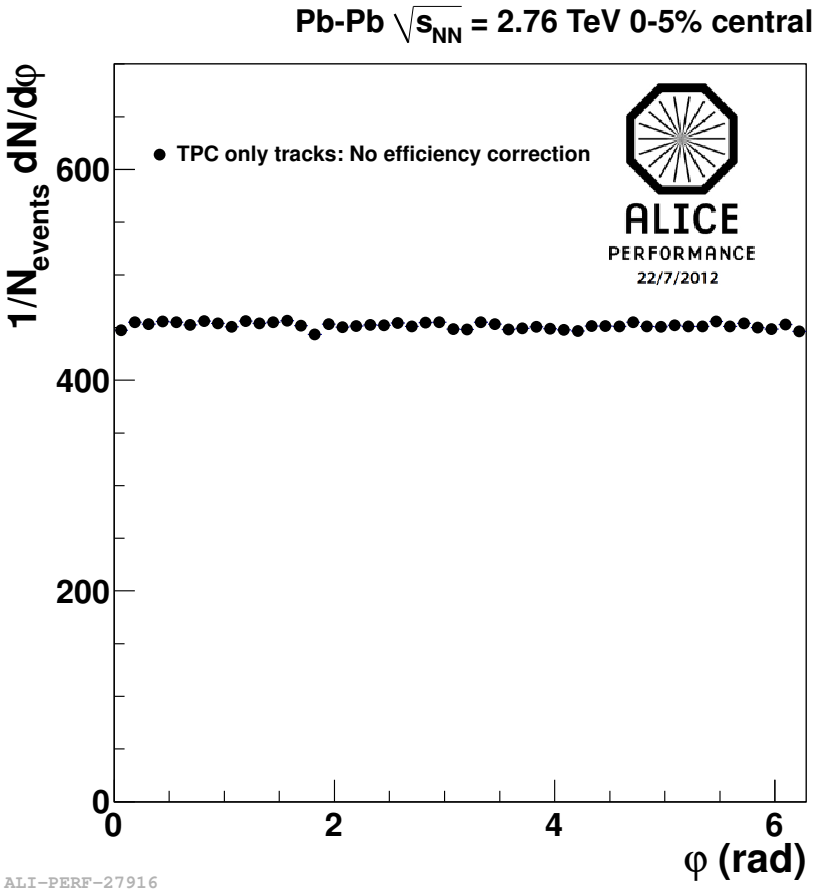


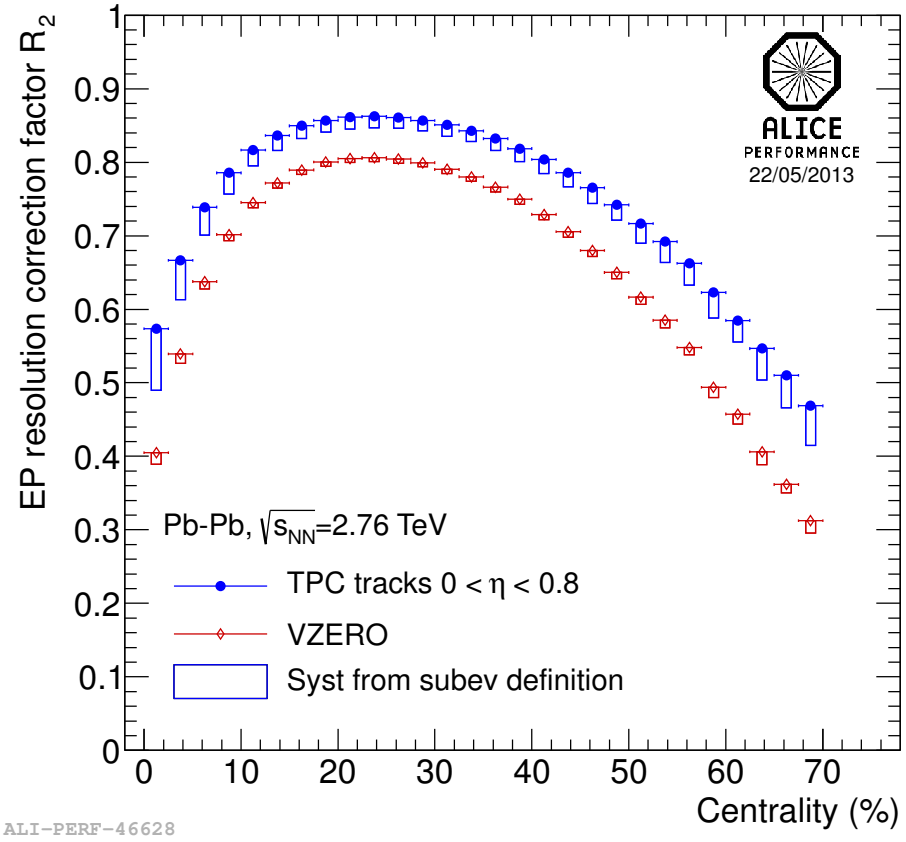




- Suite of detectors available, ALICE optimised for PID

Angular correlation capacities





- Highly uniform TPC φ distribution
  - ✓ Extended to TPC tracks with ITS hits
- VZERO detectors
  - ✓ Large η separation from TPC
  - ✓ Minimises non-flow in reaction plane studies

LHC heavy-ion running

Year	System	Energy $\sqrt{s_{NN}}$ (TeV)	Delivered Integrated luminosity
2010	Pb-Pb	2.76	10 μb^{-1}
2011	Pb-Pb	2.76	0.1 nb^{-1}
2013	p-Pb	5.02	30 nb^{-1}

- Two Pb-Pb runs
  - ✓ In 2010 - commissioning and first data taking
  - ✓ In 2011 – Second run, factor 10 increase in luminosity
- p-Pb occurred this year
  - ✓ LHC delivered target luminosity
- Long shutdown now (LS1)
  - ✓ Various upgrades and maintenance in progress

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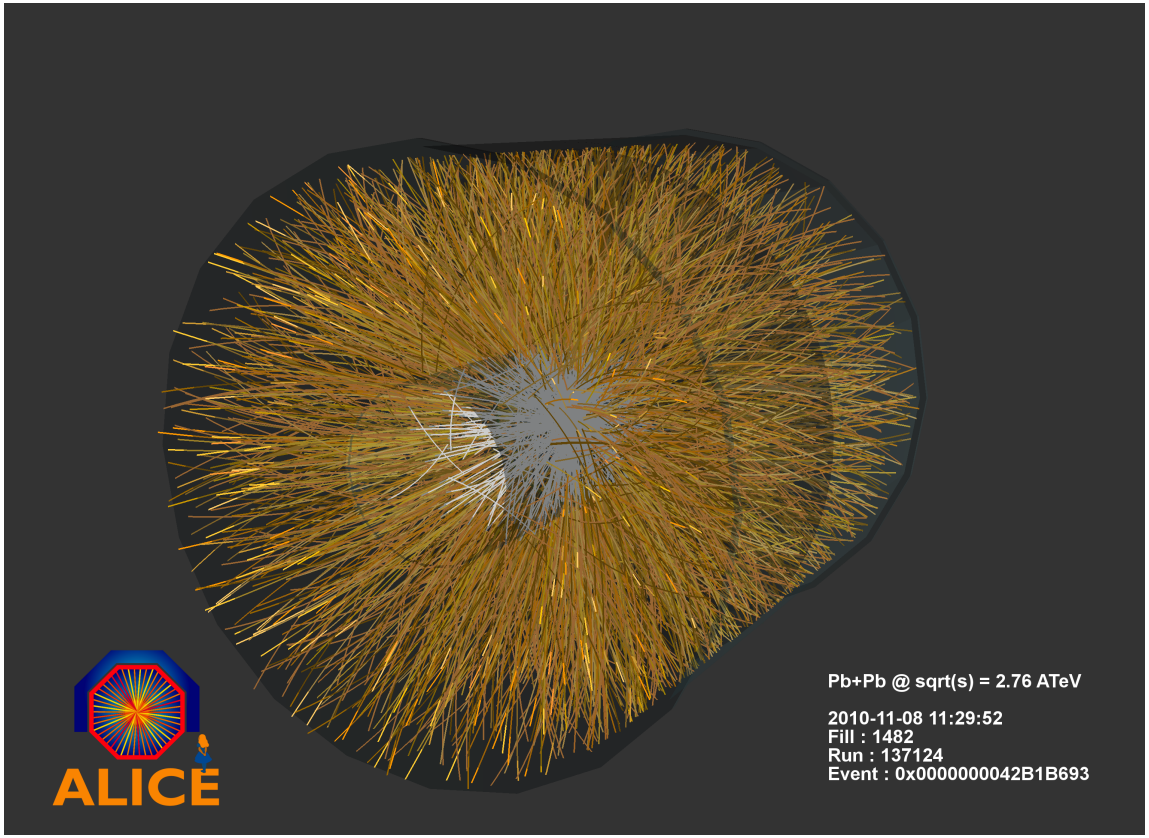
Identified particle production and thermalisation

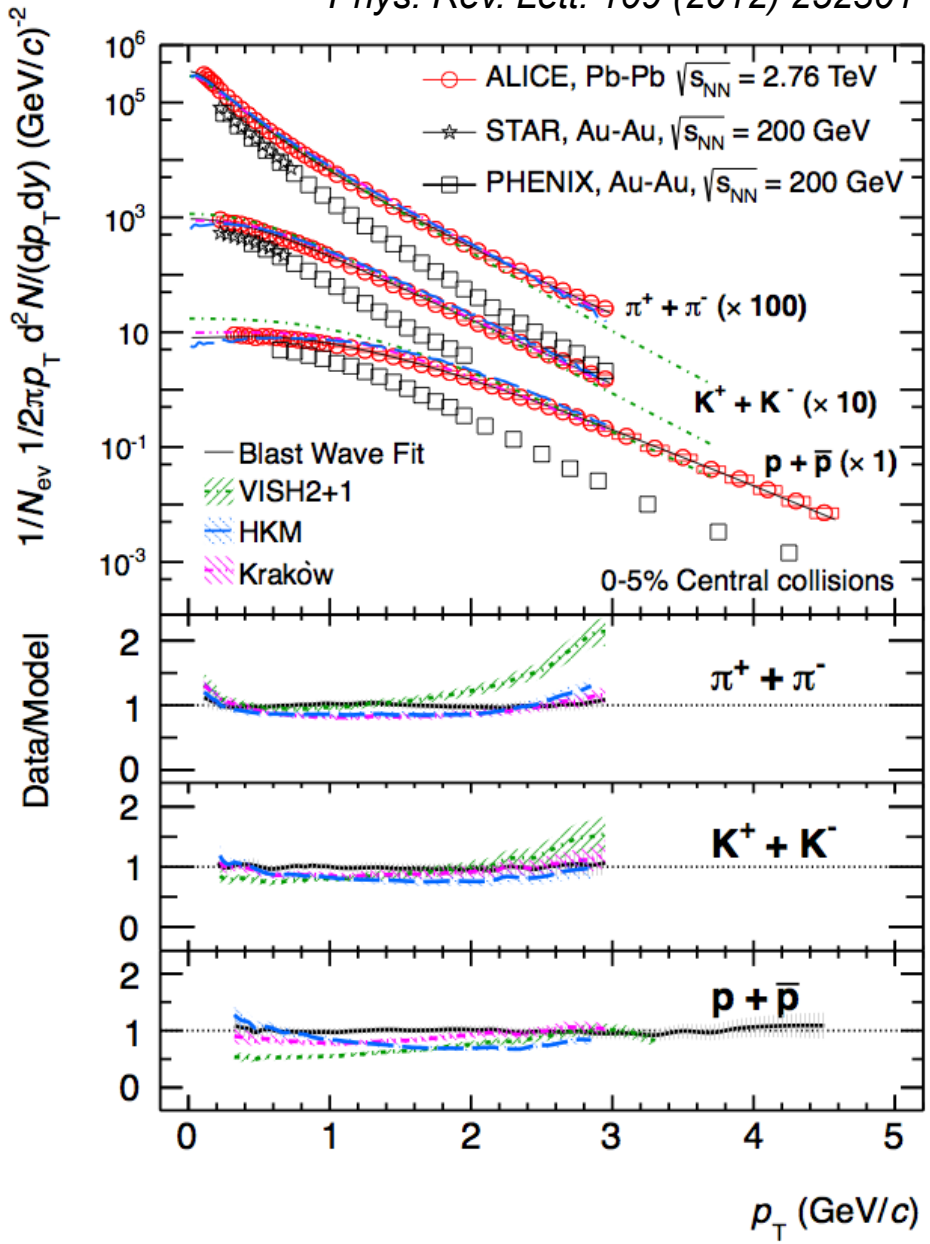


- Provide key information on freeze-out dynamics
  - ✓ Spectral shapes vs. mass => **Radial flow** and **kinetic freeze-out** temperatures
  - ✓ Yields and ratios => **Chemical freeze-out** temperatures

Identified particle spectra

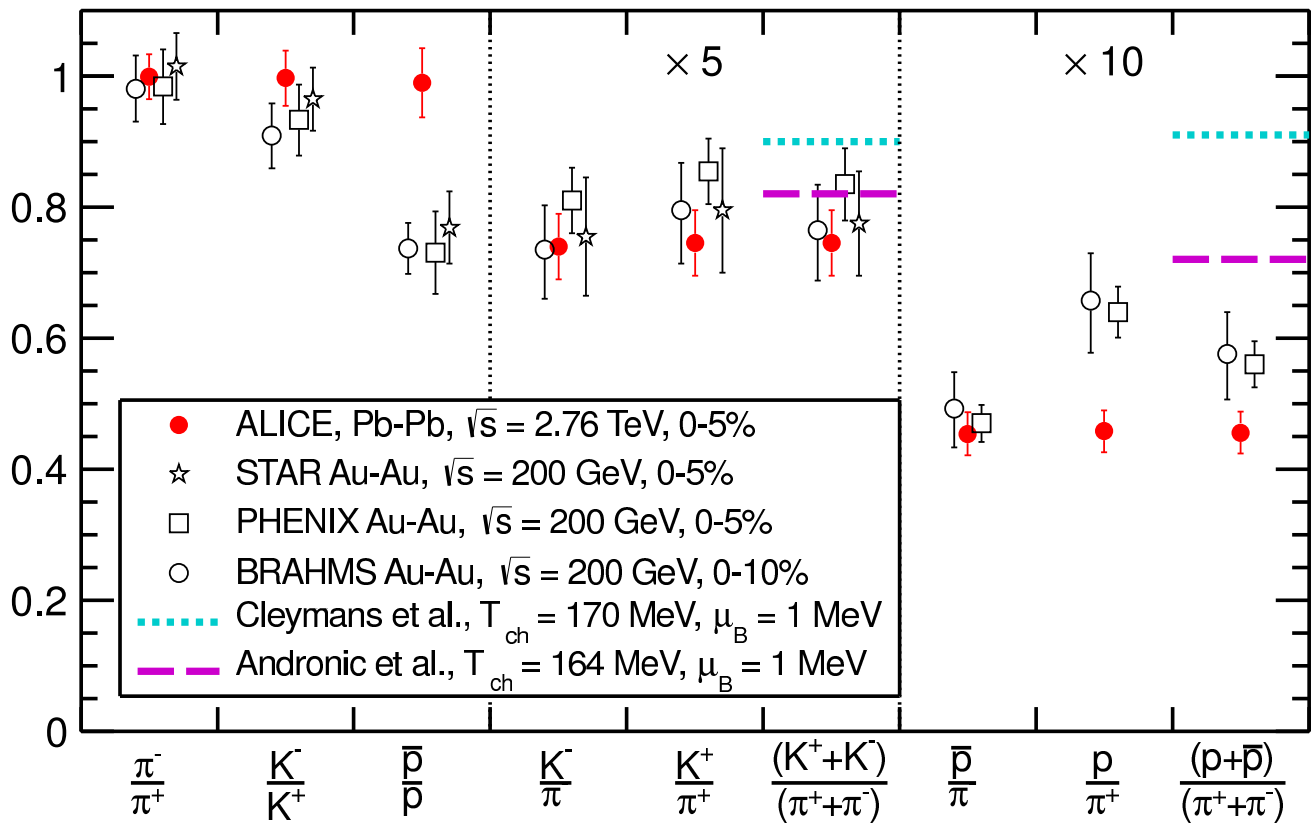
- Central Pb-Pb π,K, p spectra published last year
  - ✓ K^0_S, Λ, Ξ and Ω spectra just submitted for publication
  - ✓ arXiv's 1307.6796, 1307.5543 and 1307.5530
- **Shallower slopes** compared to RHIC data…
- Blast-wave model used to obtain radial flow velocity:
  - ✓ $\langle\beta_T\rangle = 0.65c$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

Phys. Rev. Lett. 109 (2012) 252301



Chemical freeze-out fits

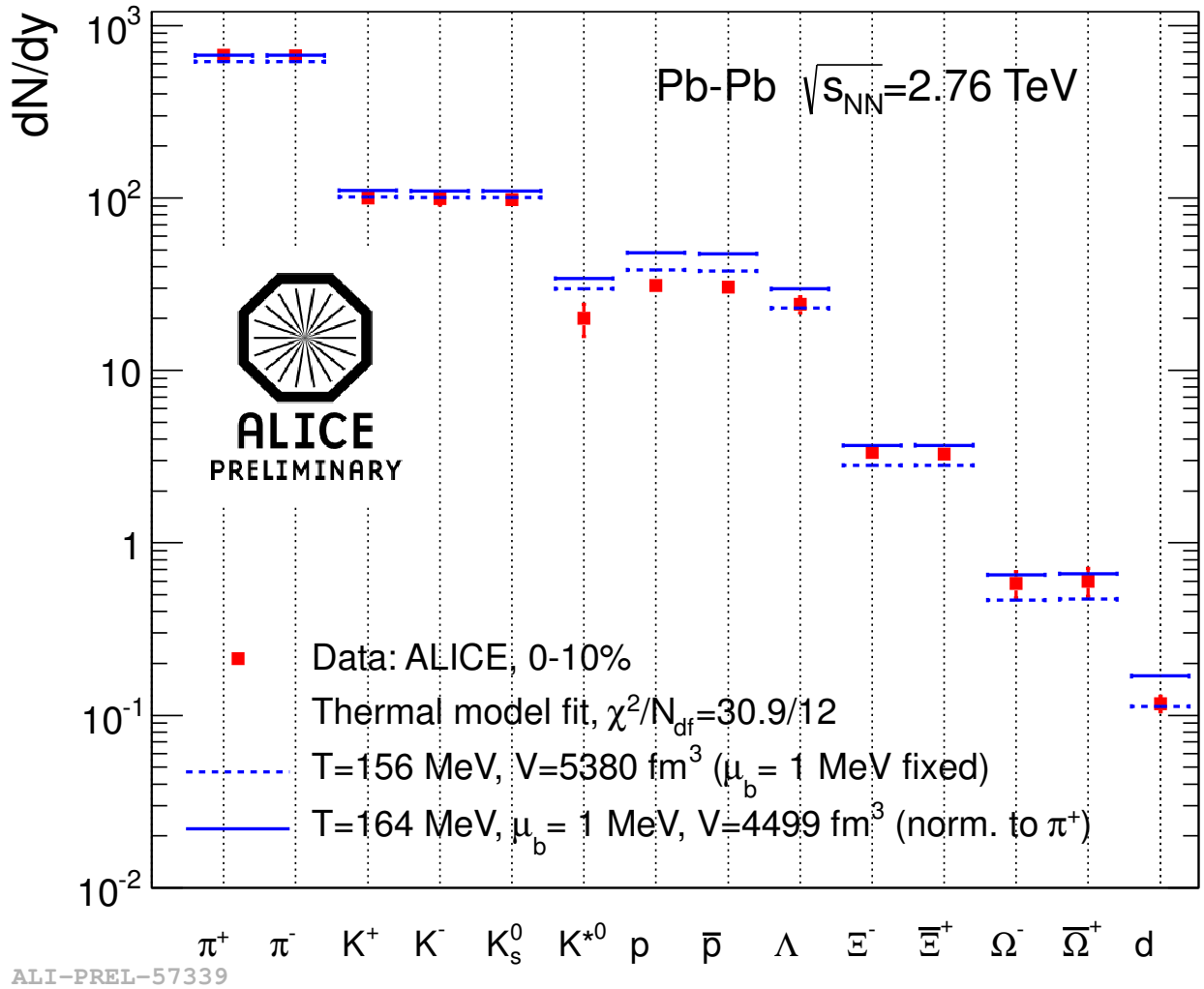
Phys. Rev. Lett. 109 (2012) 252301



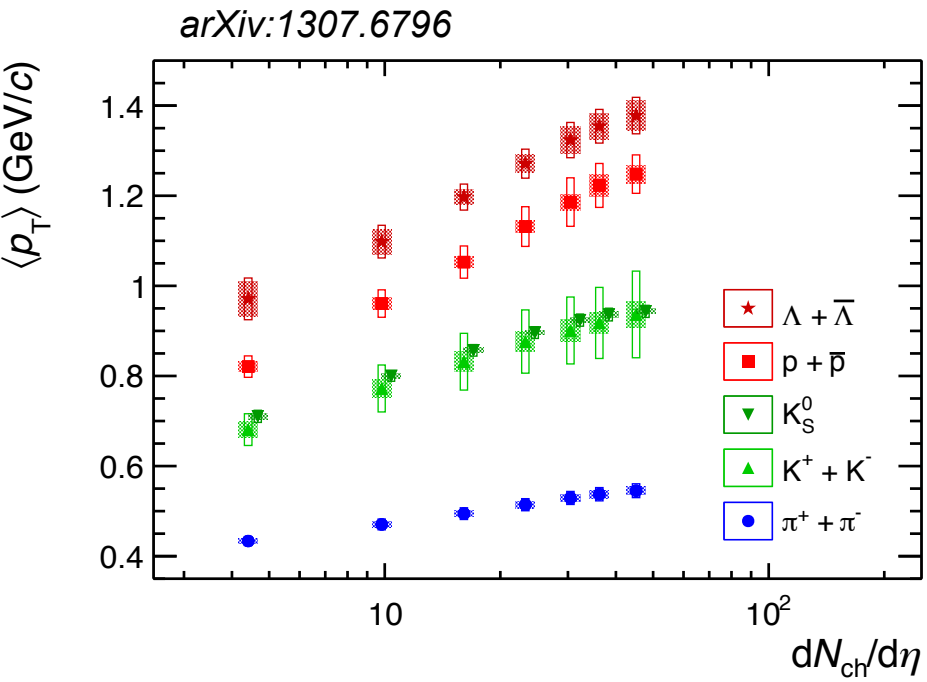
- Chemical freeze-out fits with just π,K, p data:
  - ✓ T_{ch} ~ 170 MeV
  - ✓ Similar to RHIC data
- **Deviations observed for proton** data…

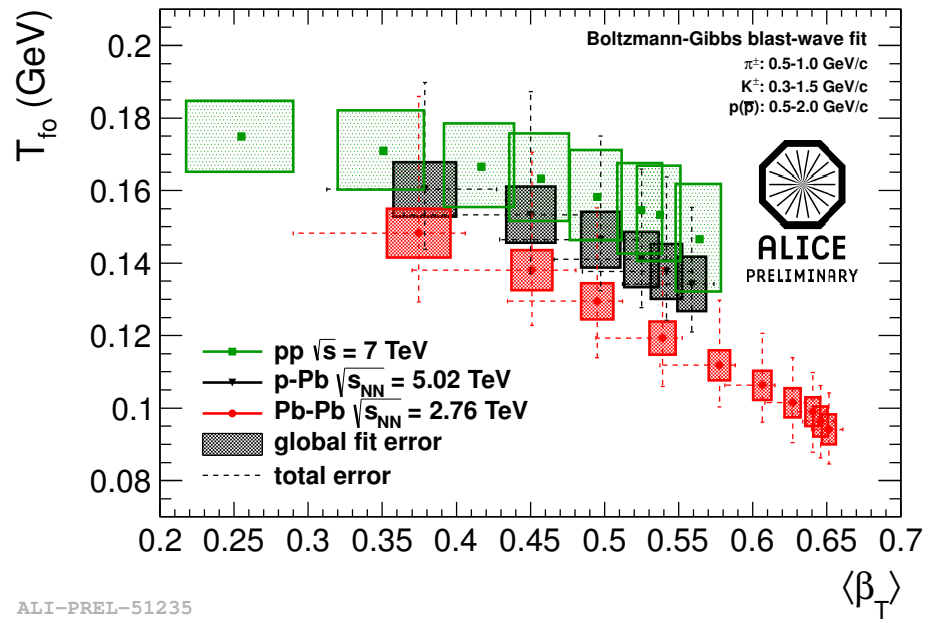
Inclusion of strangeness yields

- **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} ? Differing particle re-scattering?



Radial flow studies in p-Pb in collisions





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

- More details see talk by P. Christiansen on Thursday…

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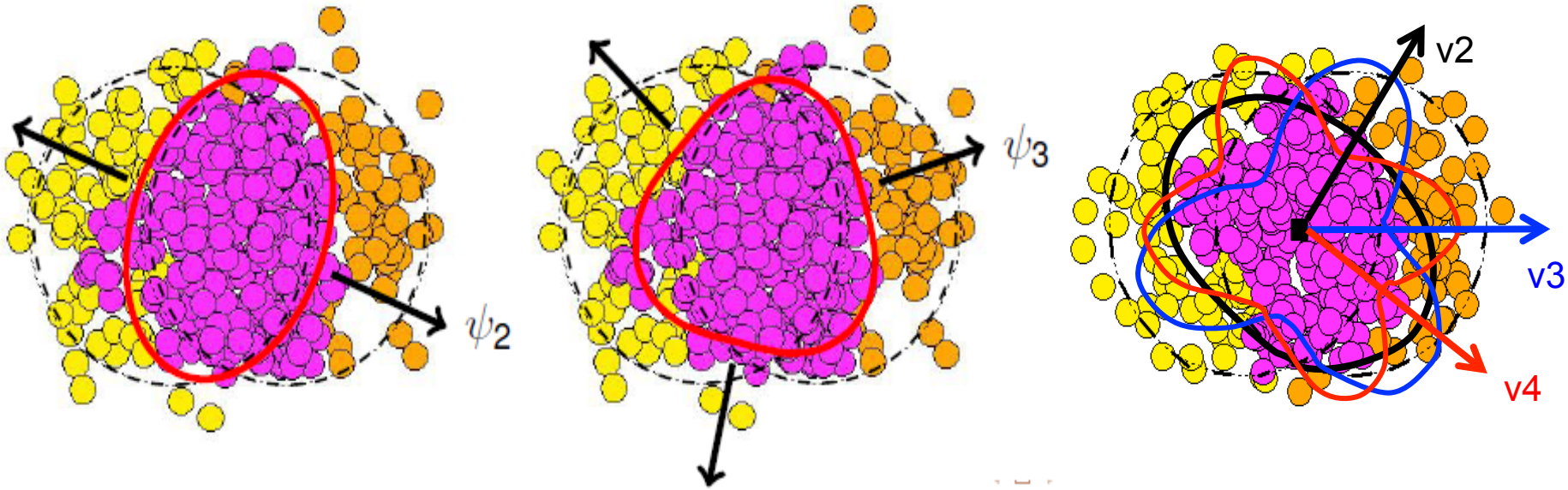
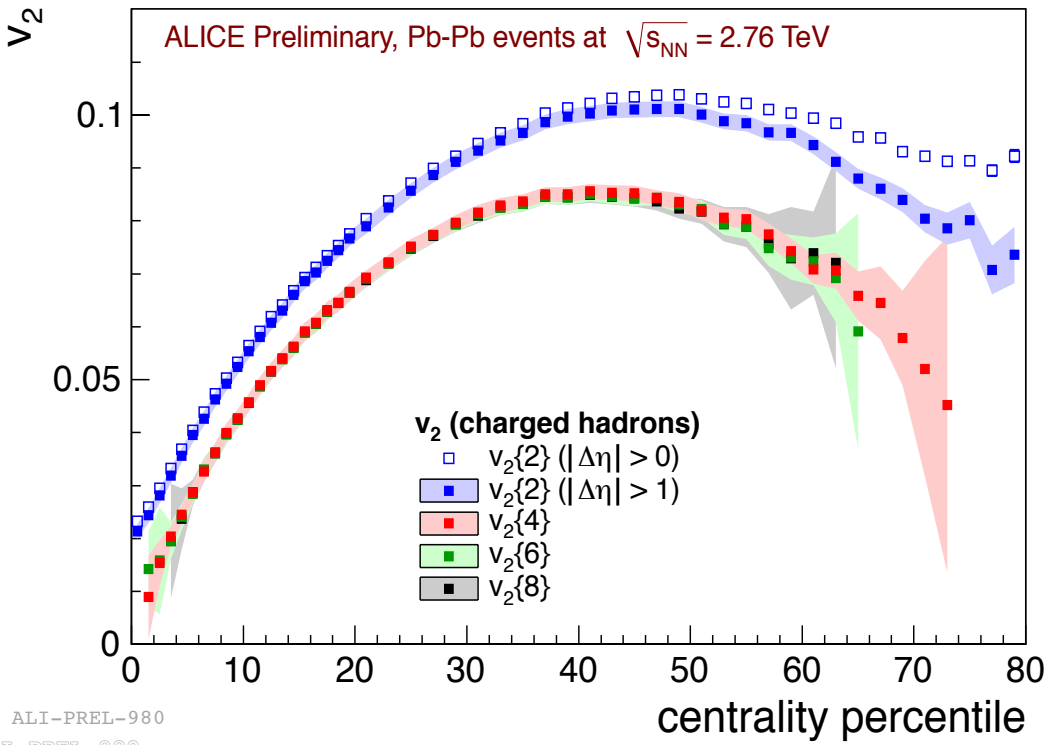
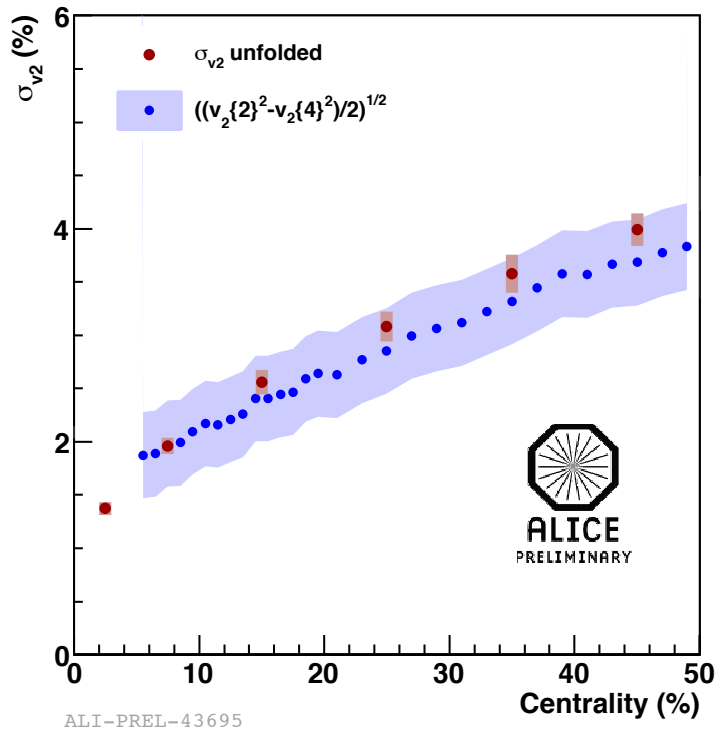
Flow harmonics and initial conditions



- Many tools to investigate fluctuations in initial conditions with flow harmonics:
  - ✓ Comparison of 2 and 4 particle flow cumulants
  - ✓ Unfolded v_2 distributions
  - ✓ Multi-particle correlations and mixed harmonics

v_2 fluctuations



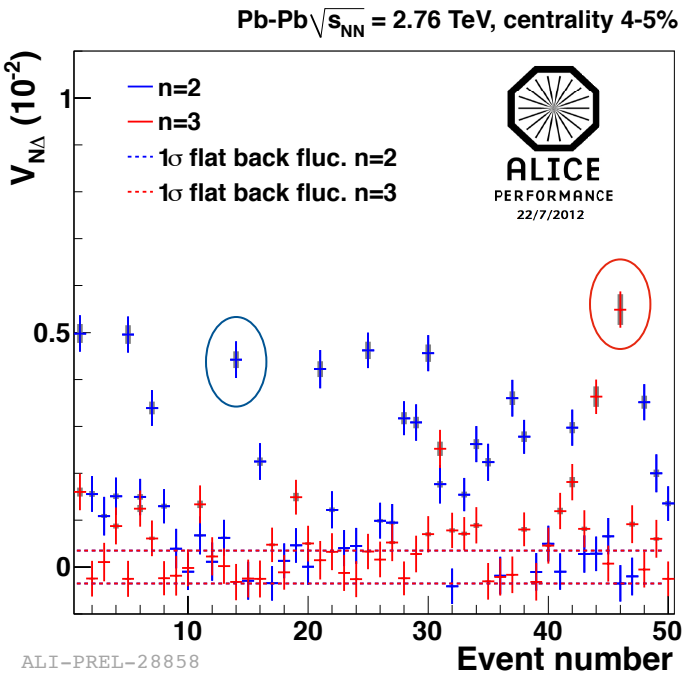


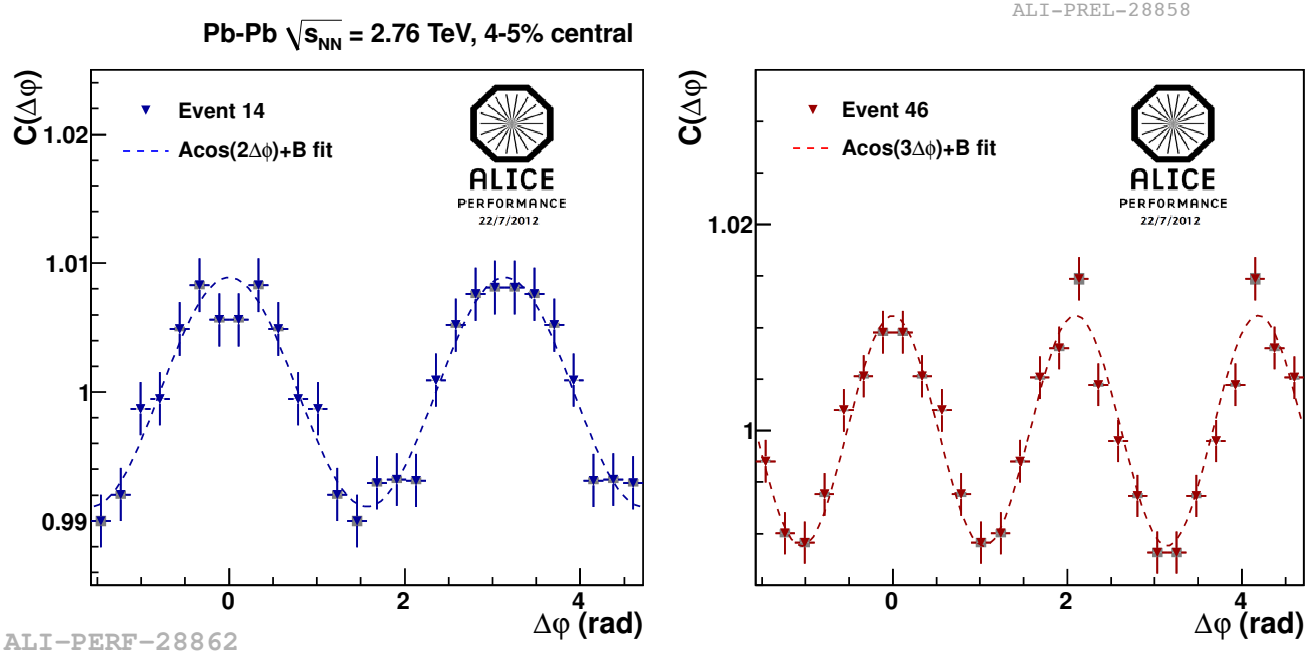
- Differences in $v_2\{2\}$ and $v_2\{4\}$ arise from v_2 fluctuations
  - ✓ Strength of flow fluctuations σ_{v2} can also be determined

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

v_2 and v_3 fluctuations

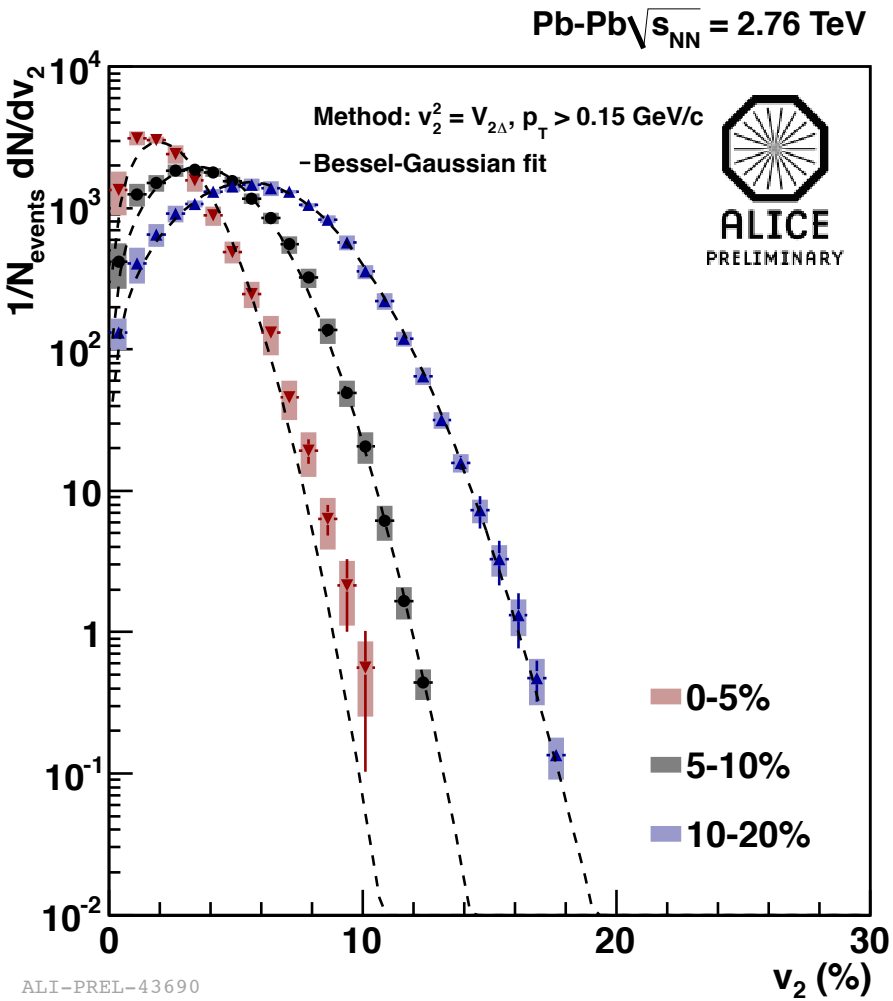
- **Large fluctuations in v_2^2 and v_3^2** observed event by event
  - ✓ Appear largely independent
- 2 particle correlations in circled events dominated by v_2 and v_3
  - ✓ Allows v_n distributions to be obtained…

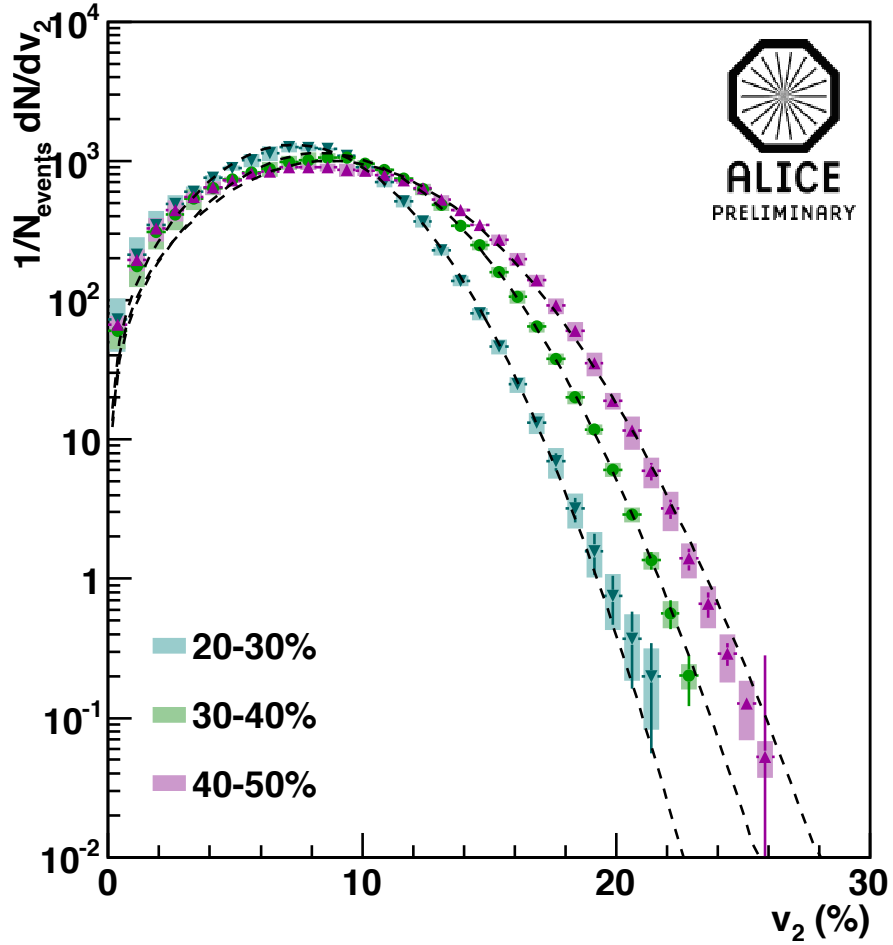




$$V_{n\Delta} = v_n^2$$

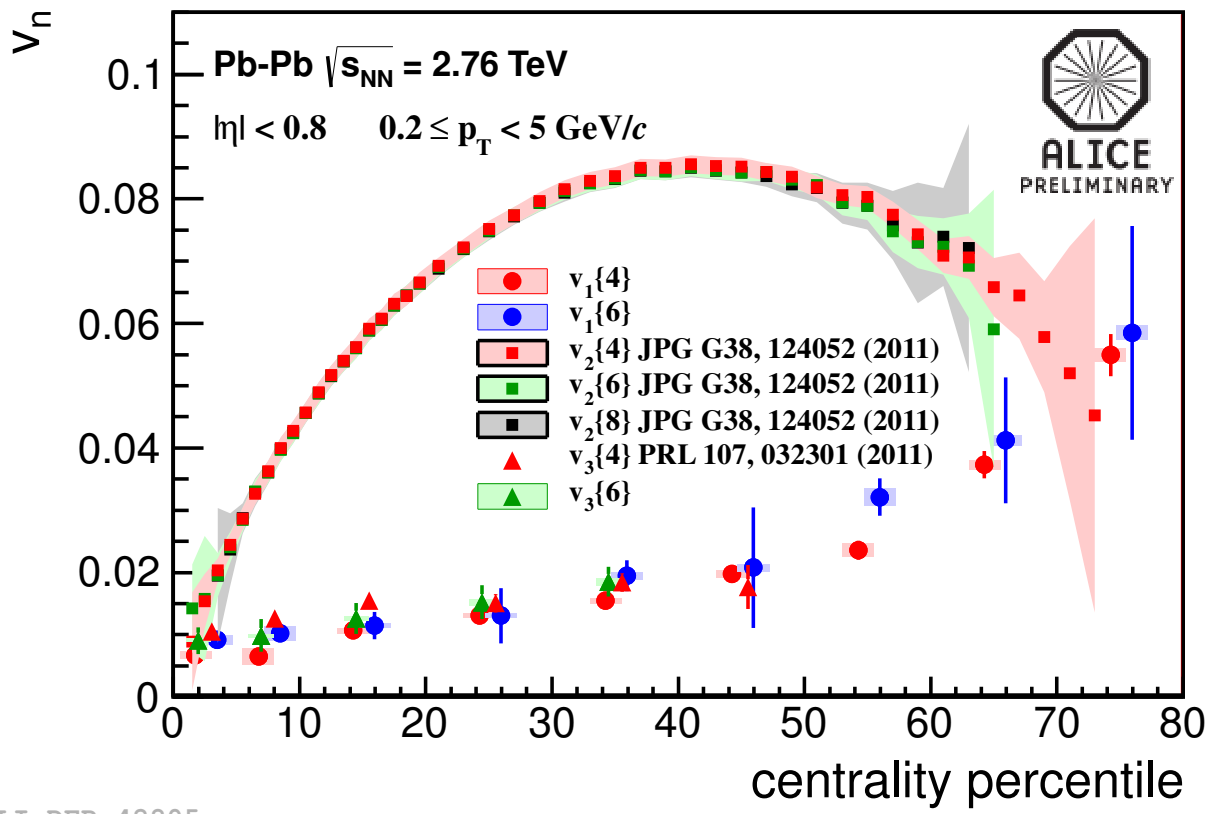
Unfolded v_2 distributions





- Unfolding removes effects of finite 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



ALI-DER-42805

- Multi-particle correlations $v_n\{4\}$, $v_n\{6\}$, and $v_n\{8\}$ less sensitive to non-flow
- Strong signals observed for n=1,2 and 3
  - ✓ Suggests driven by collective effects
- $v_1\{4\}$~$v_1\{6\}$~$v_3\{4\}$ ~$v_3\{6\}$…

Submitted v1 vs. reaction plane for publication (arXiv:1306.4145)

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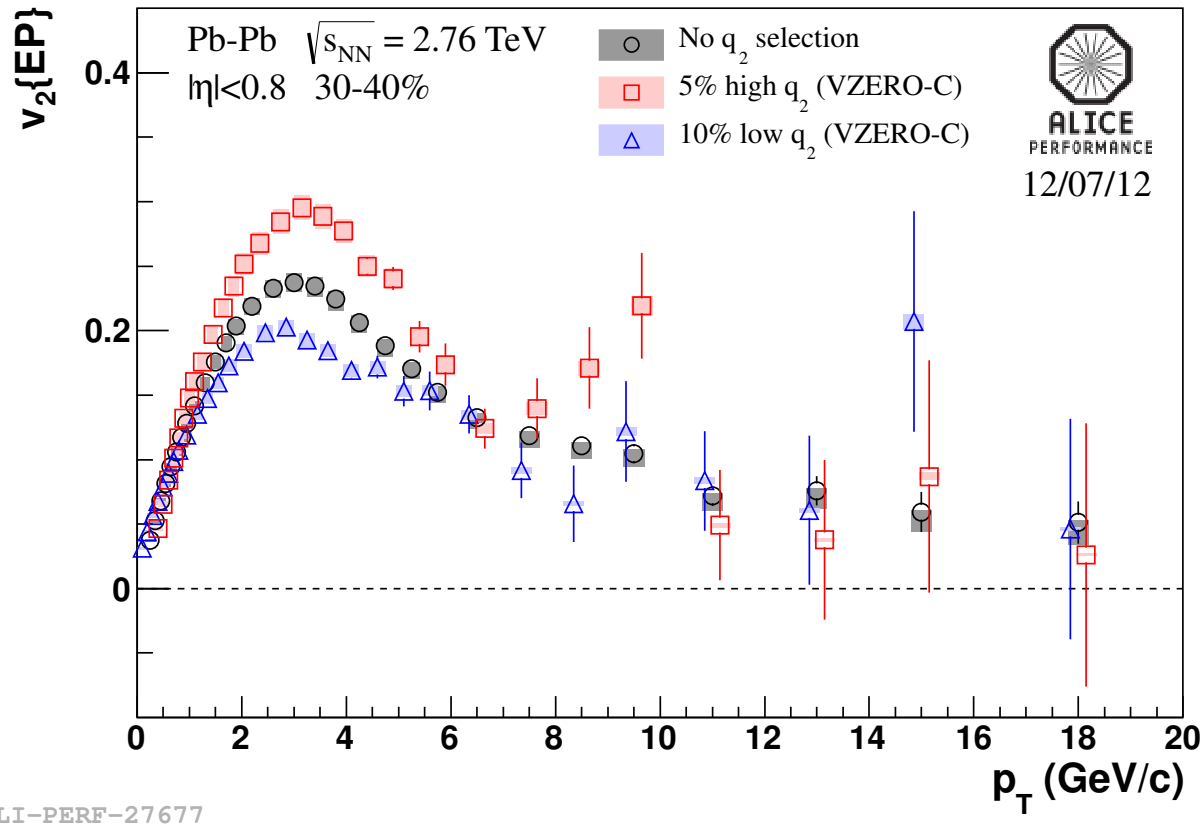
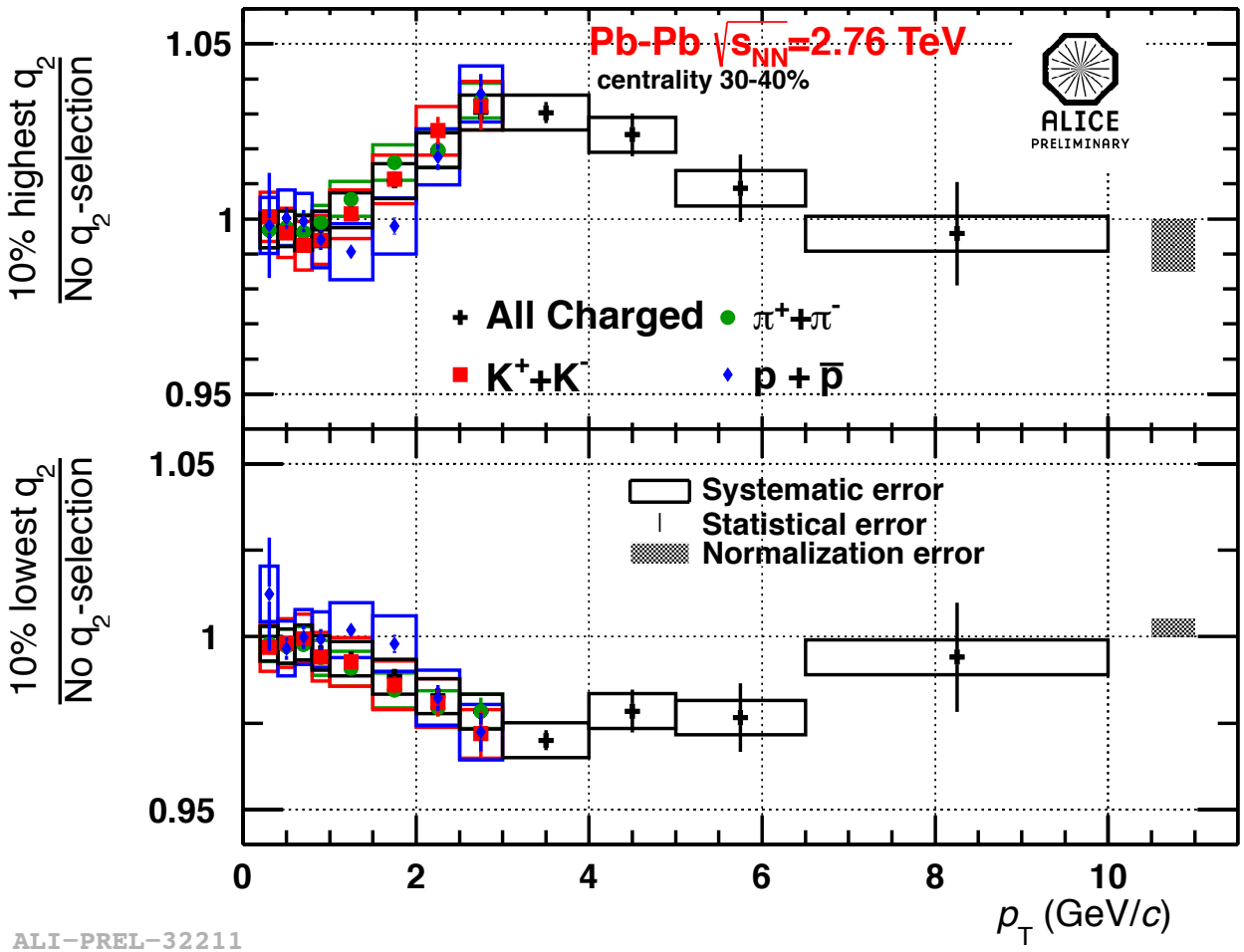
Event shape engineering

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



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

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?

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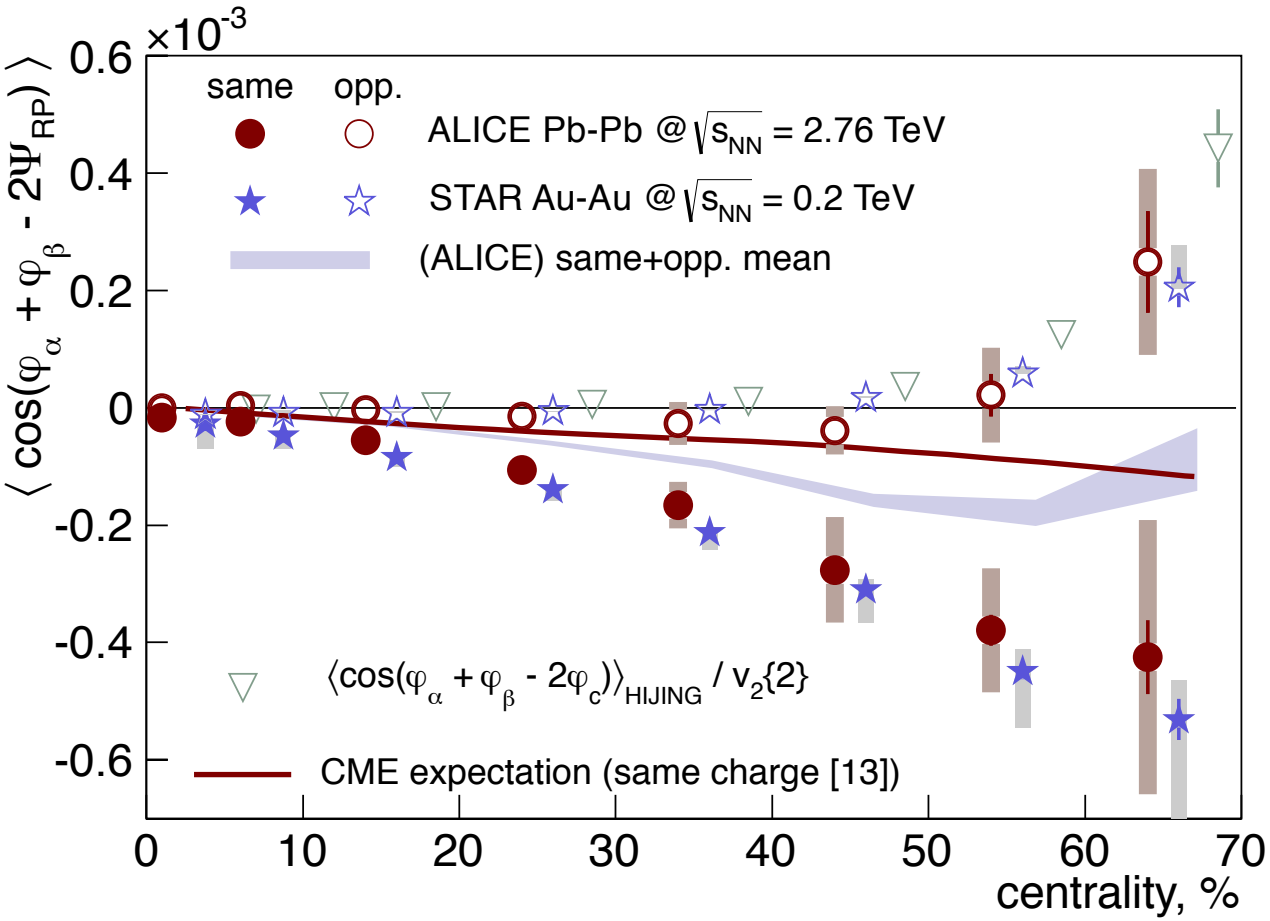
Searches for Chiral Magnetic Effect (CME)



Phys. Rev. Lett. 110 (2013) 012301

- CME searches with <cos(φ_1 + φ_2 - 2ψ)>
  - ✓ Below 0 for same charges
  - ✓ ~ 0 for opposite charges
- Results at LHC similar to those at RHIC…
- See talk from S. Voloshin for extensive experimental overview…

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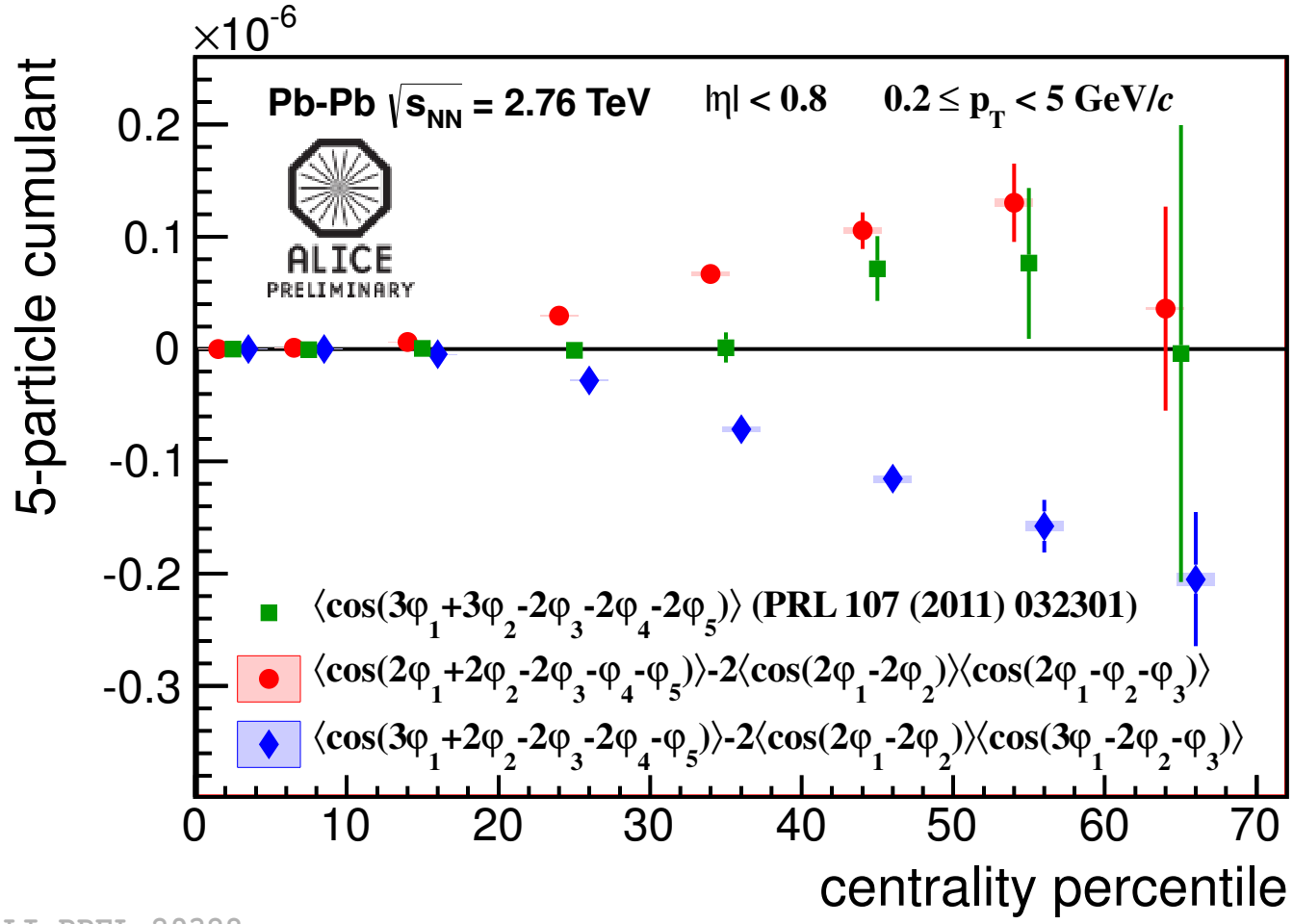
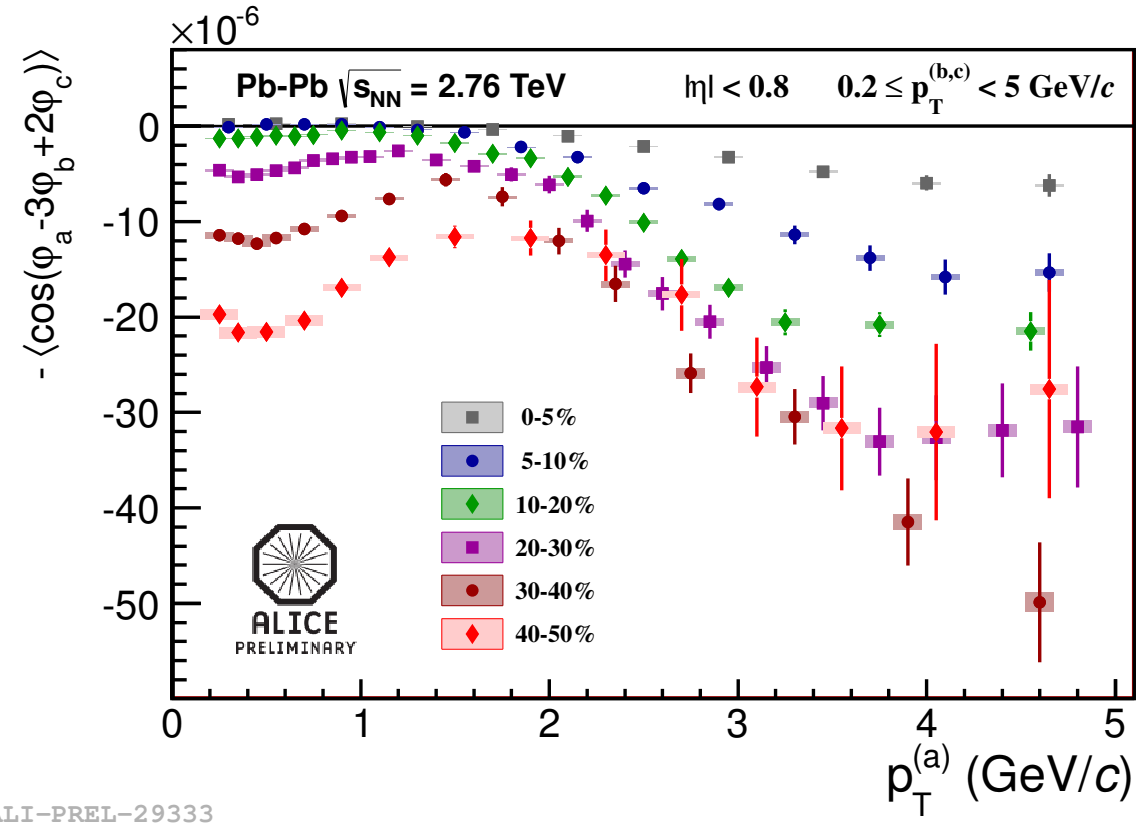
Mixed harmonics



ALI-PREL-29328

- Non-zero correlations observed between ψ_1, ψ_2 and ψ_3 plane directions

Mixed harmonics



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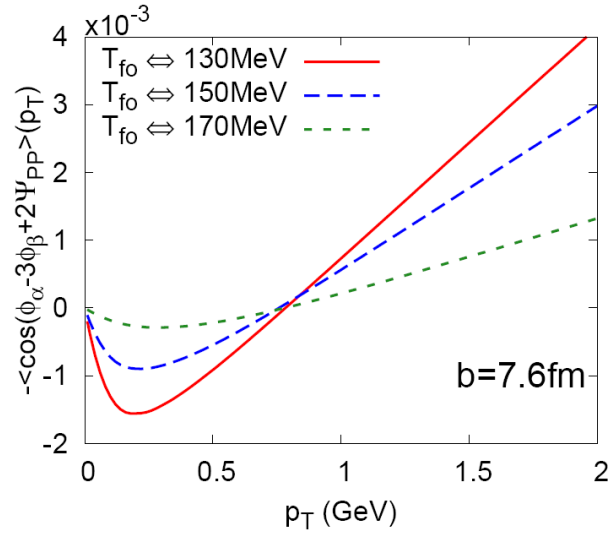

Teaney & Yan, Phys. Rev. C 83 (2011) 064904

- Teaney and Yan correlator investigates p_T dependence of such correlations
  - ✓ Hydro with Glauber initial conditions qualitatively describes data at low p_T
  - ✓ Data negative at high p_T (in contrast to model)

Summary

1 Comprehensive set off 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,
- ✓ Chemical freeze-out temperatures appear to have particle species dependence,
- ✓ “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

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