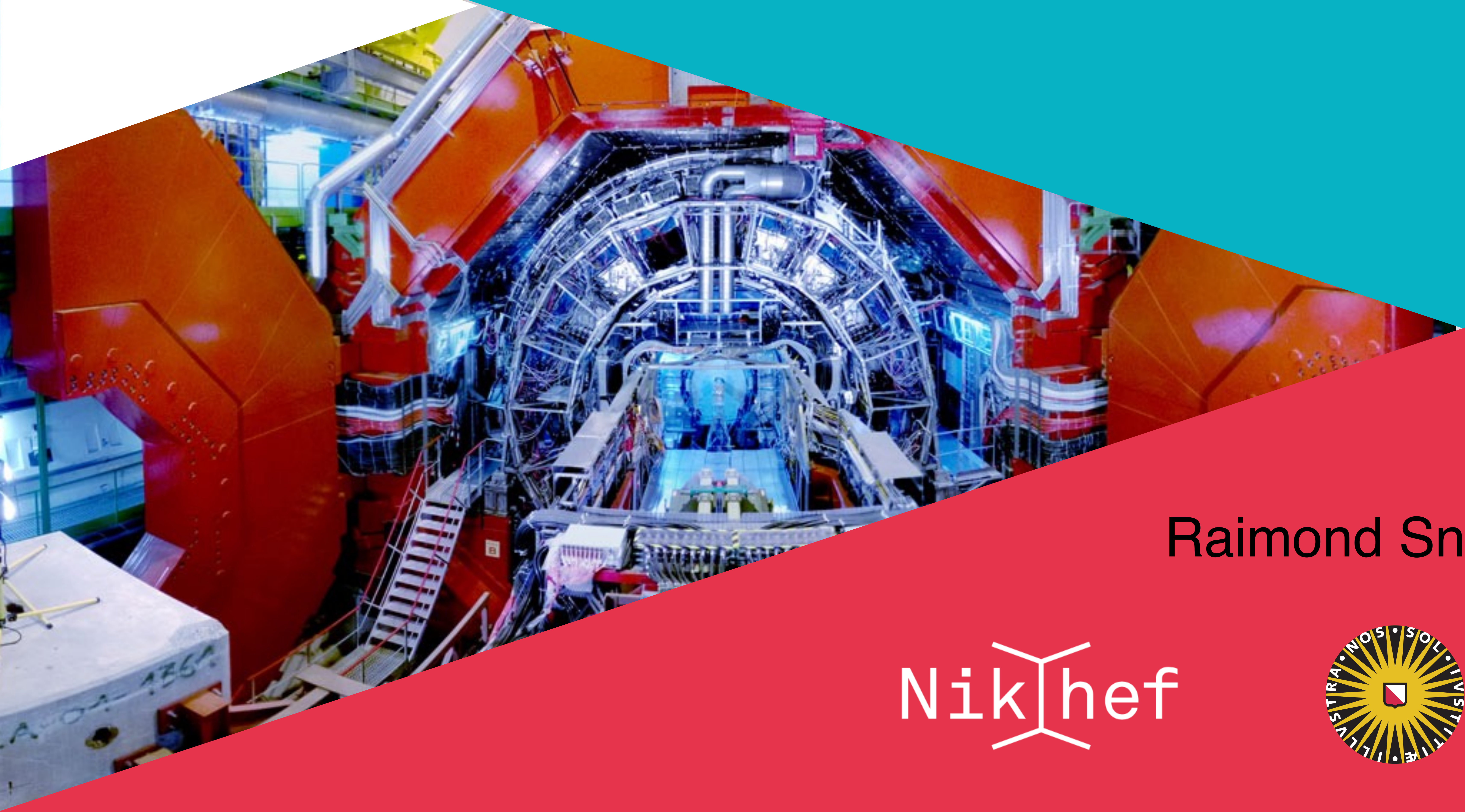
The characterisation of the Quark Gluon Plasma



Raimond Snellings

Nikhef

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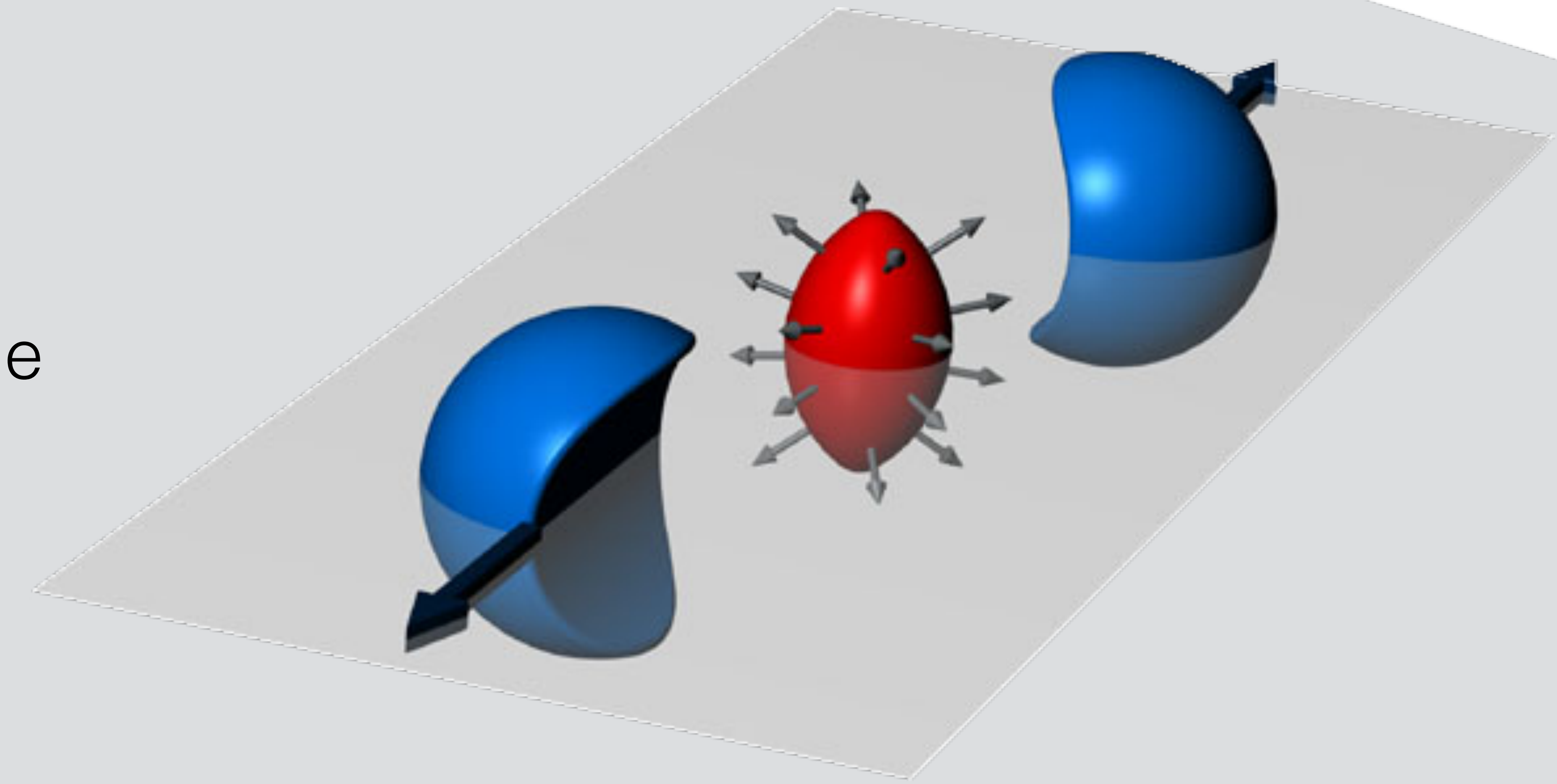
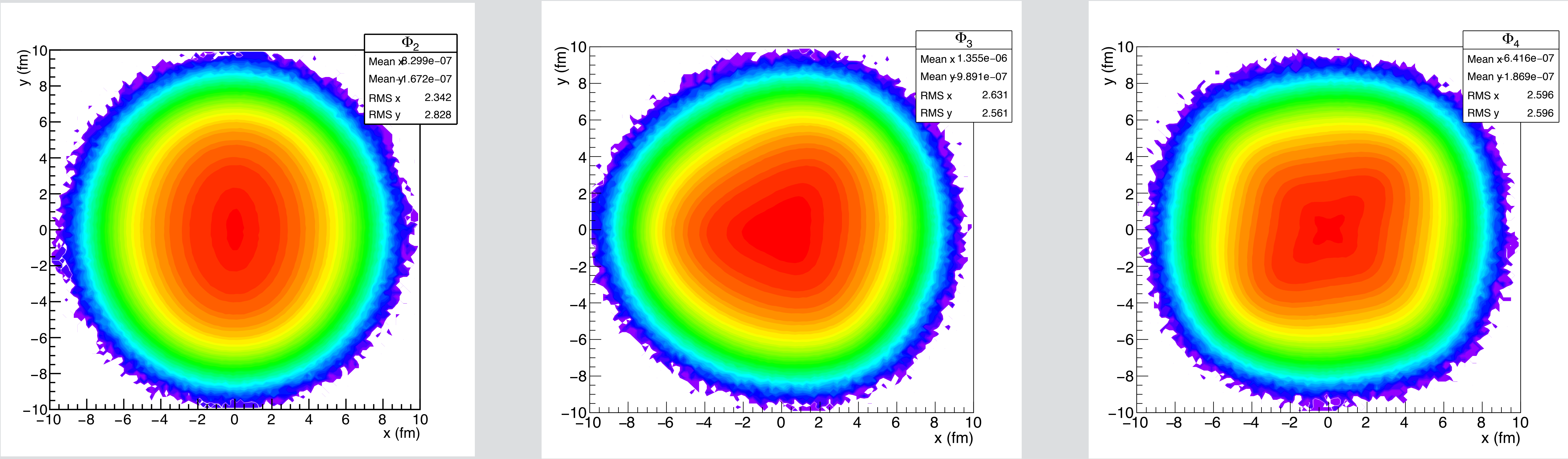
Using the geometry

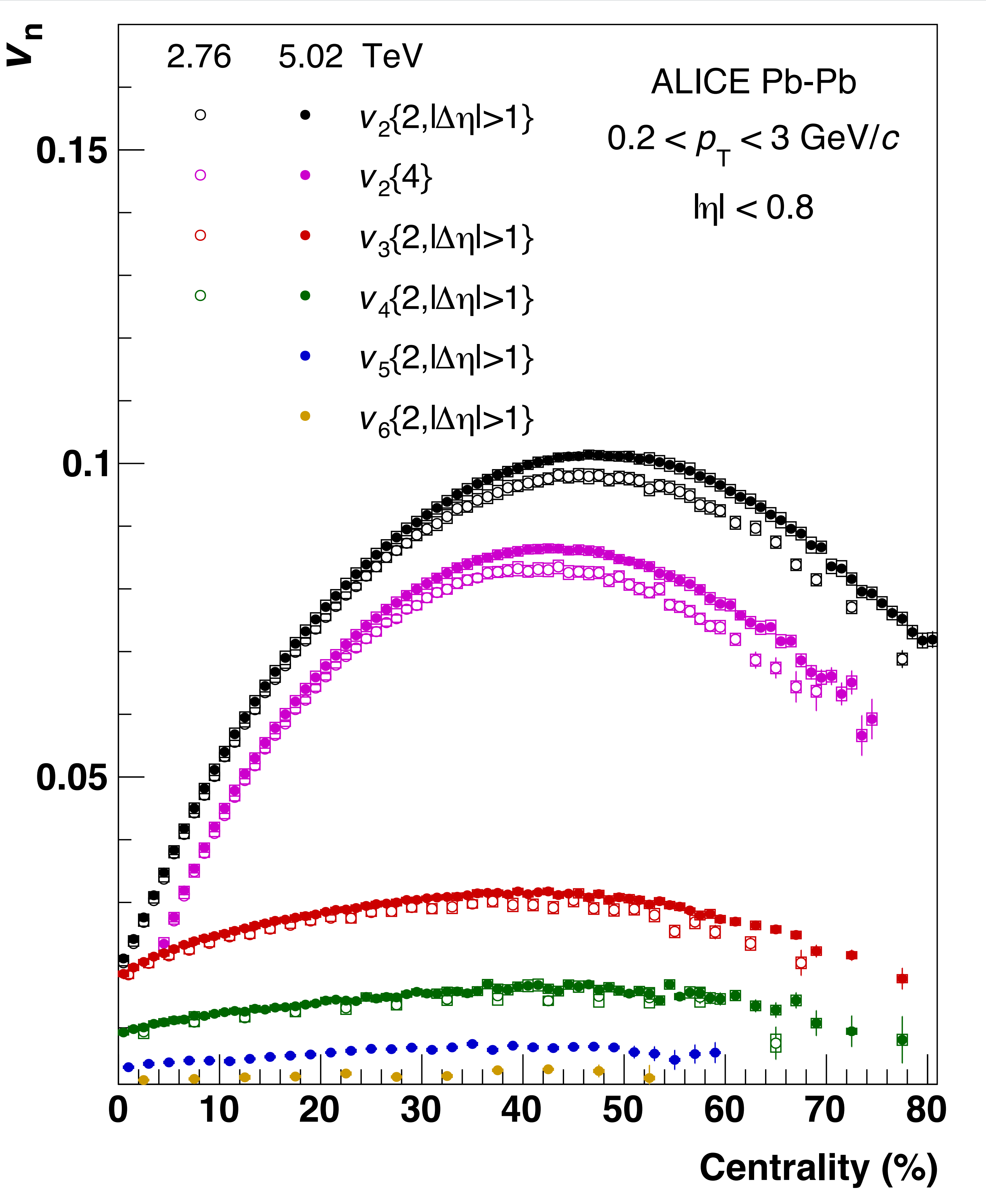
- **Use geometry as a control parameter**
  - anisotropic flow
    - use to constrain initial conditions and the transport parameters of the created system
  - use the geometry to learn about parton energy loss and the opacity of the system

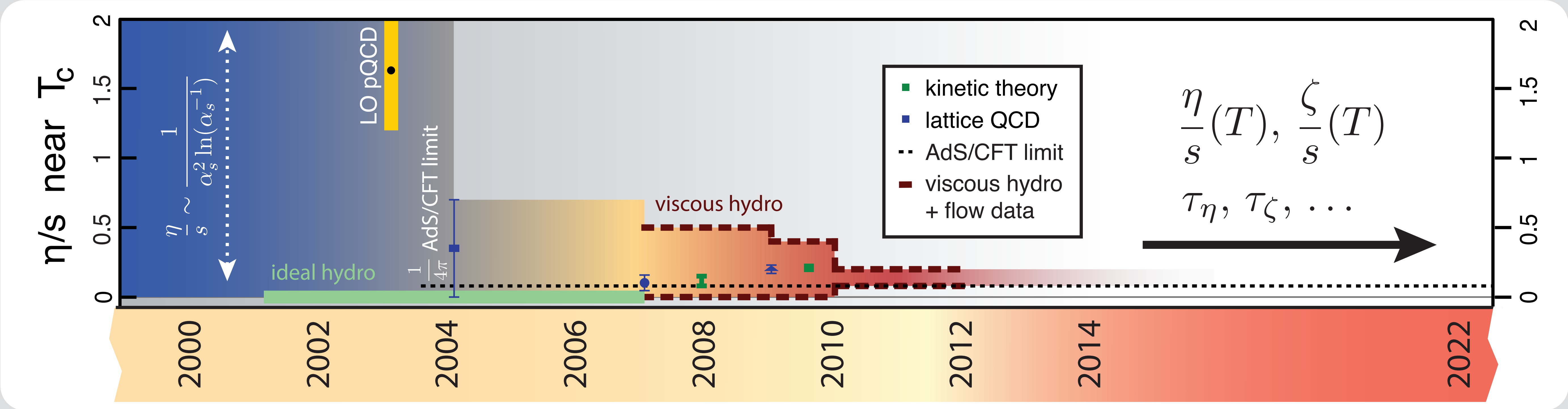




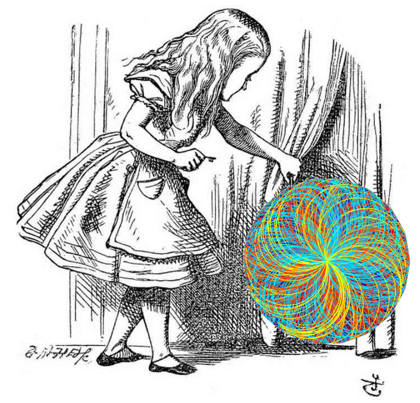
Due to event-by-event fluctuations of the initial conditions not only v_2 but also higher harmonics are generated v_3, v_4 etc

Anisotropic Flow

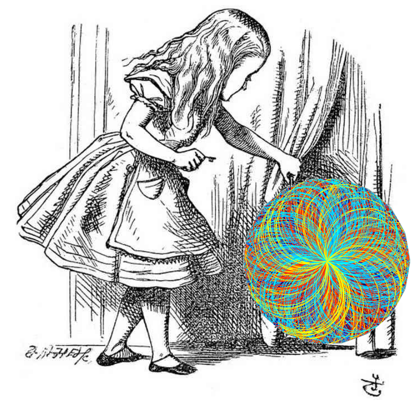




- Our constraints on transport parameters come from the comparison between anisotropic flow measurements and viscous hydrodynamic model and parton energy loss calculations
  - Why do we believe these constraints?



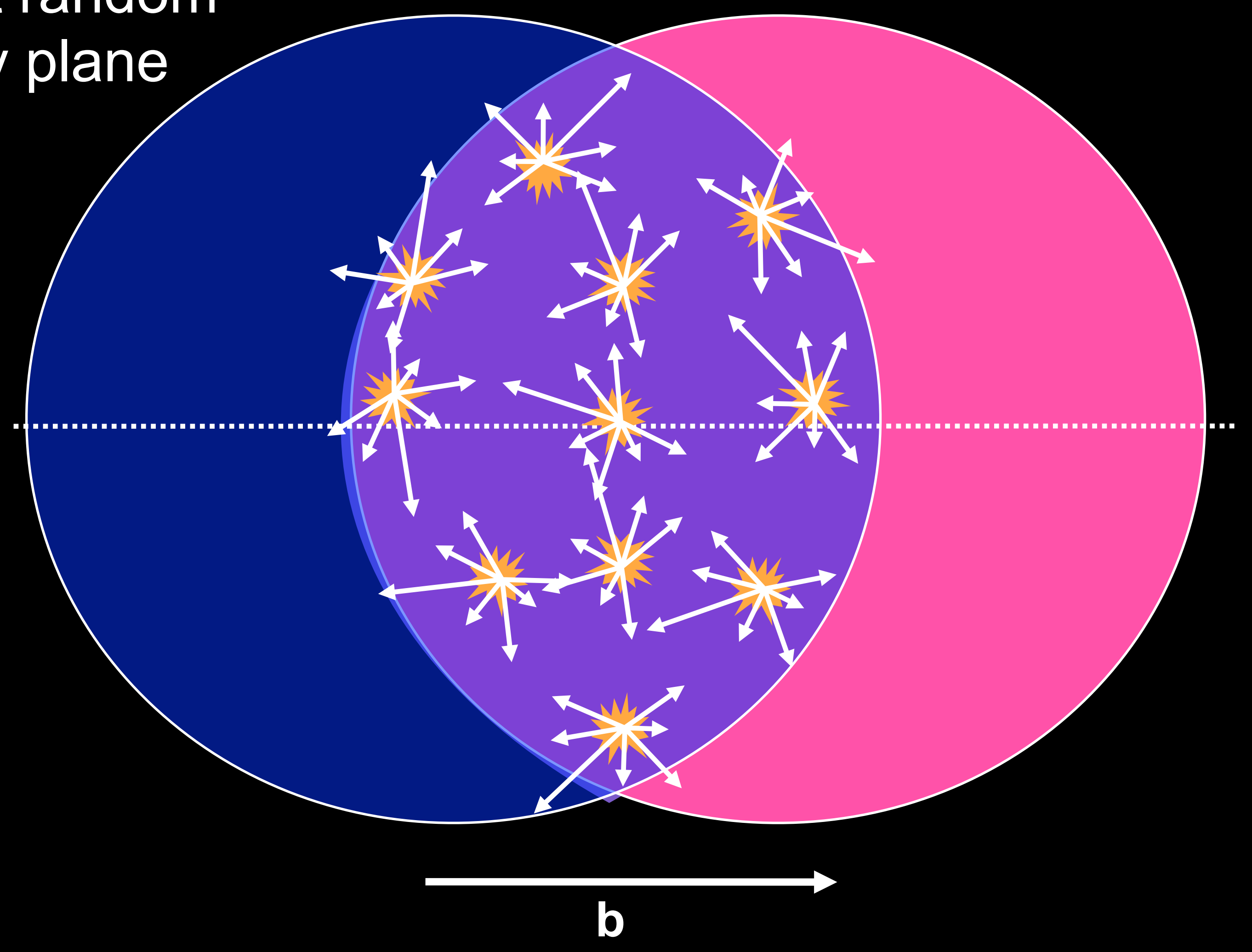
Anisotropic Flow

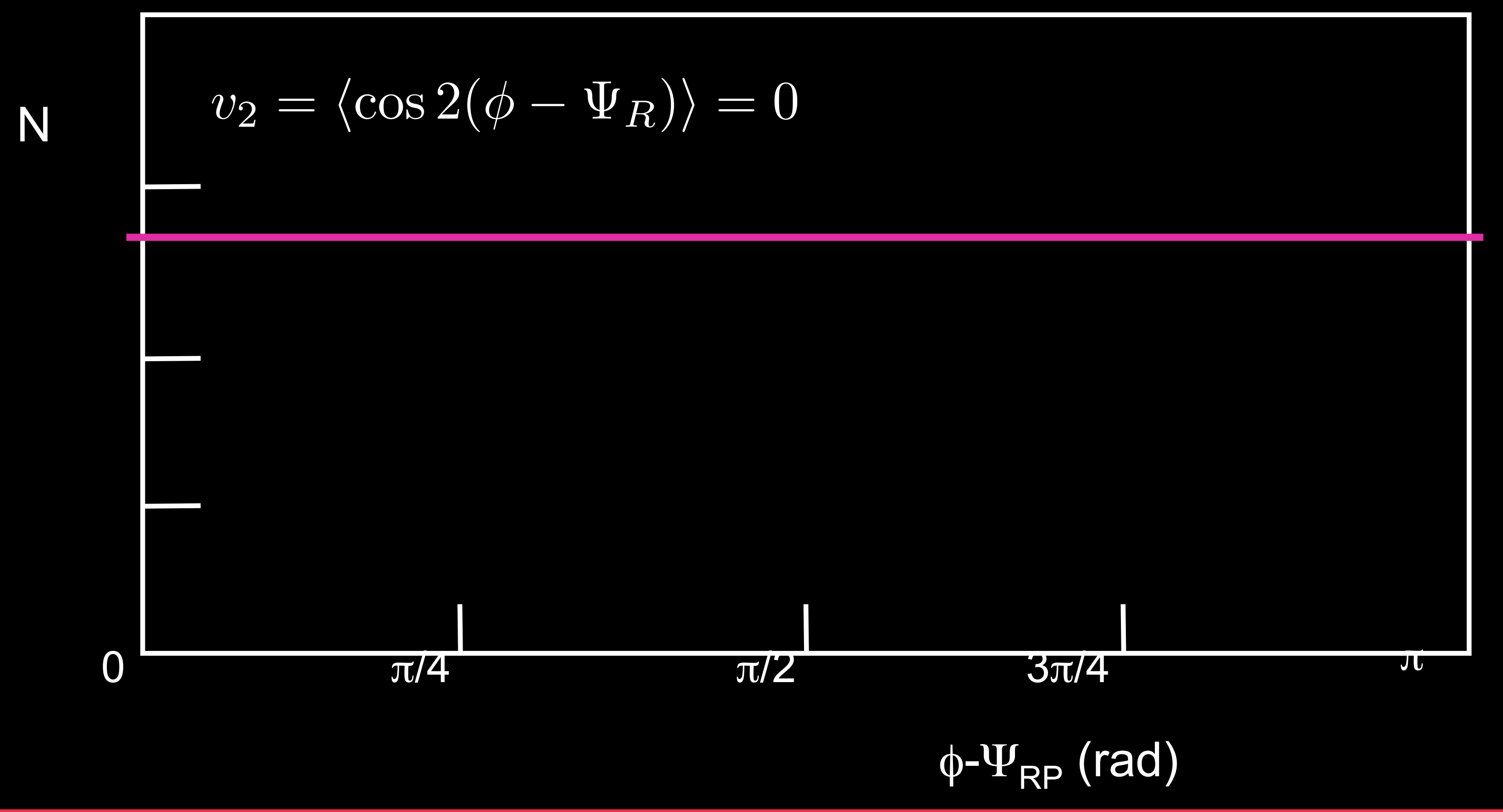


Ollitrault 1992

1) superposition of independent p+p:

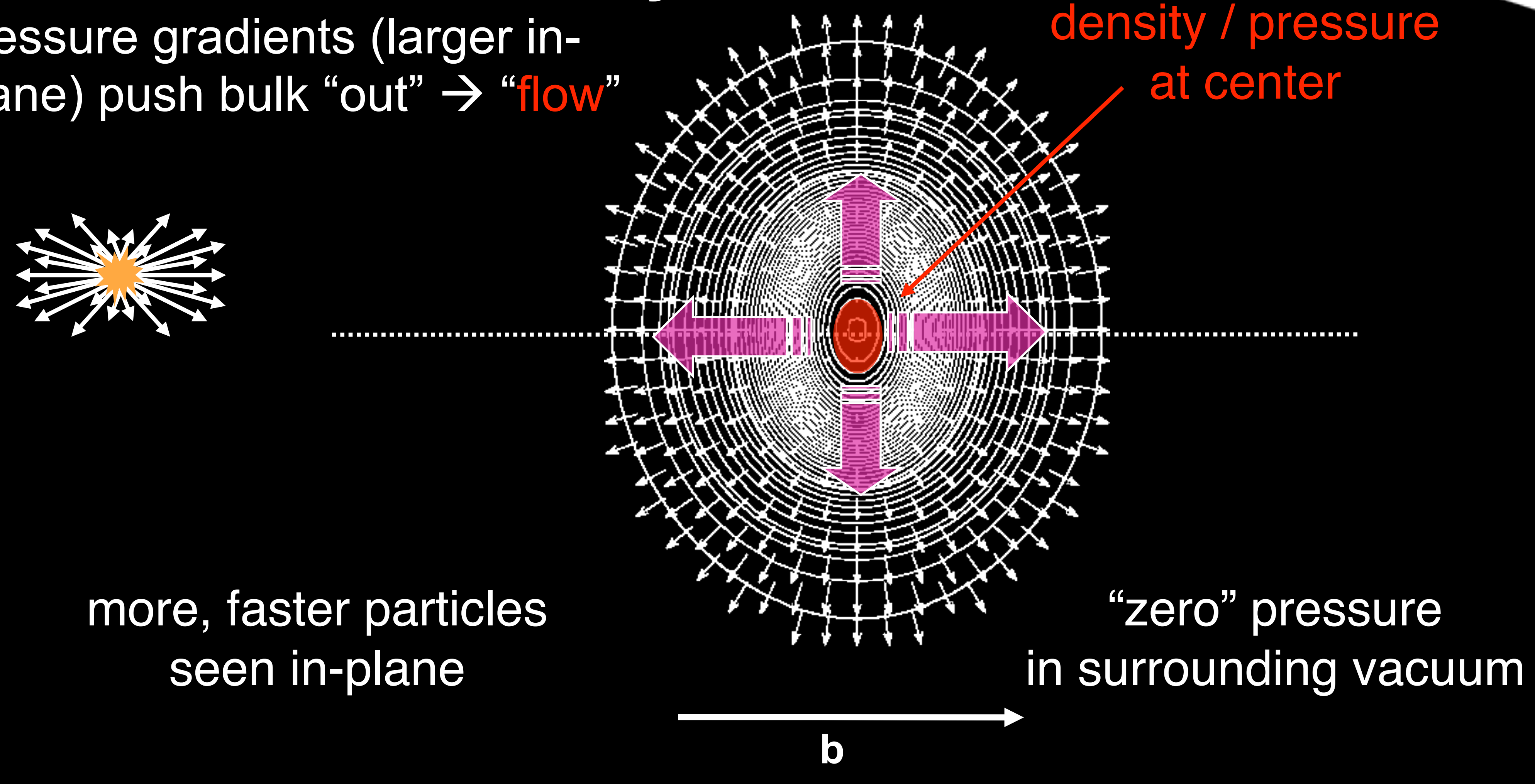
momenta pointed at random
relative to symmetry plane

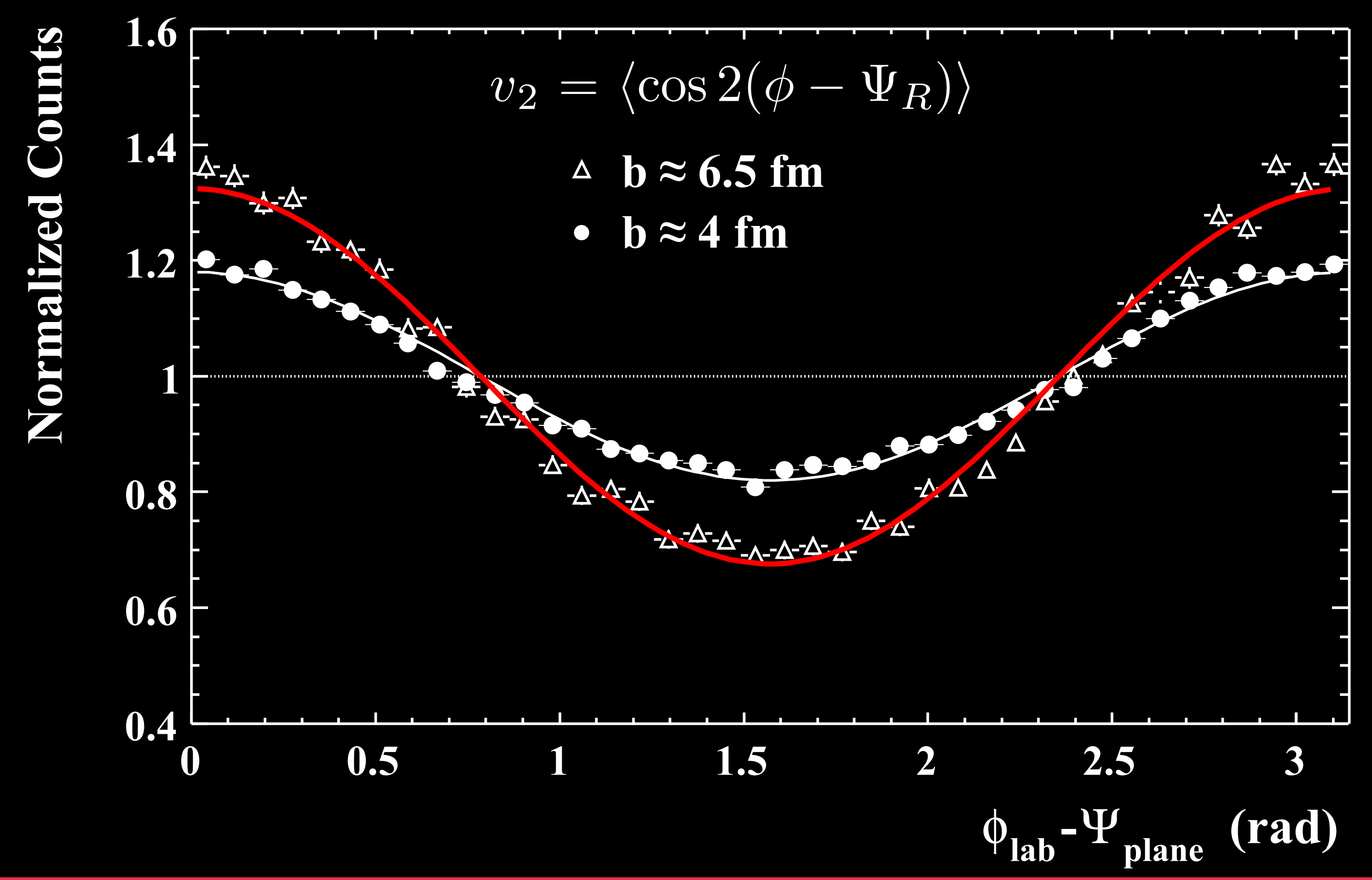




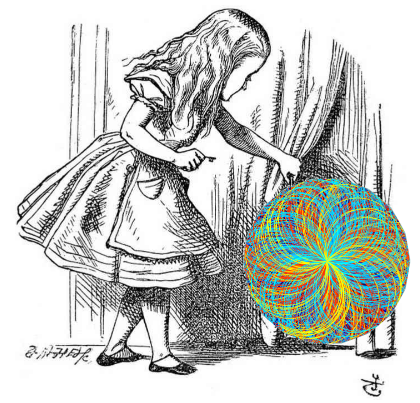
2) evolution as a **bulk <u>system</u>**

pressure gradients (larger in-plane) push bulk “out” → “flow”





Anisotropic Flow (momentum space)



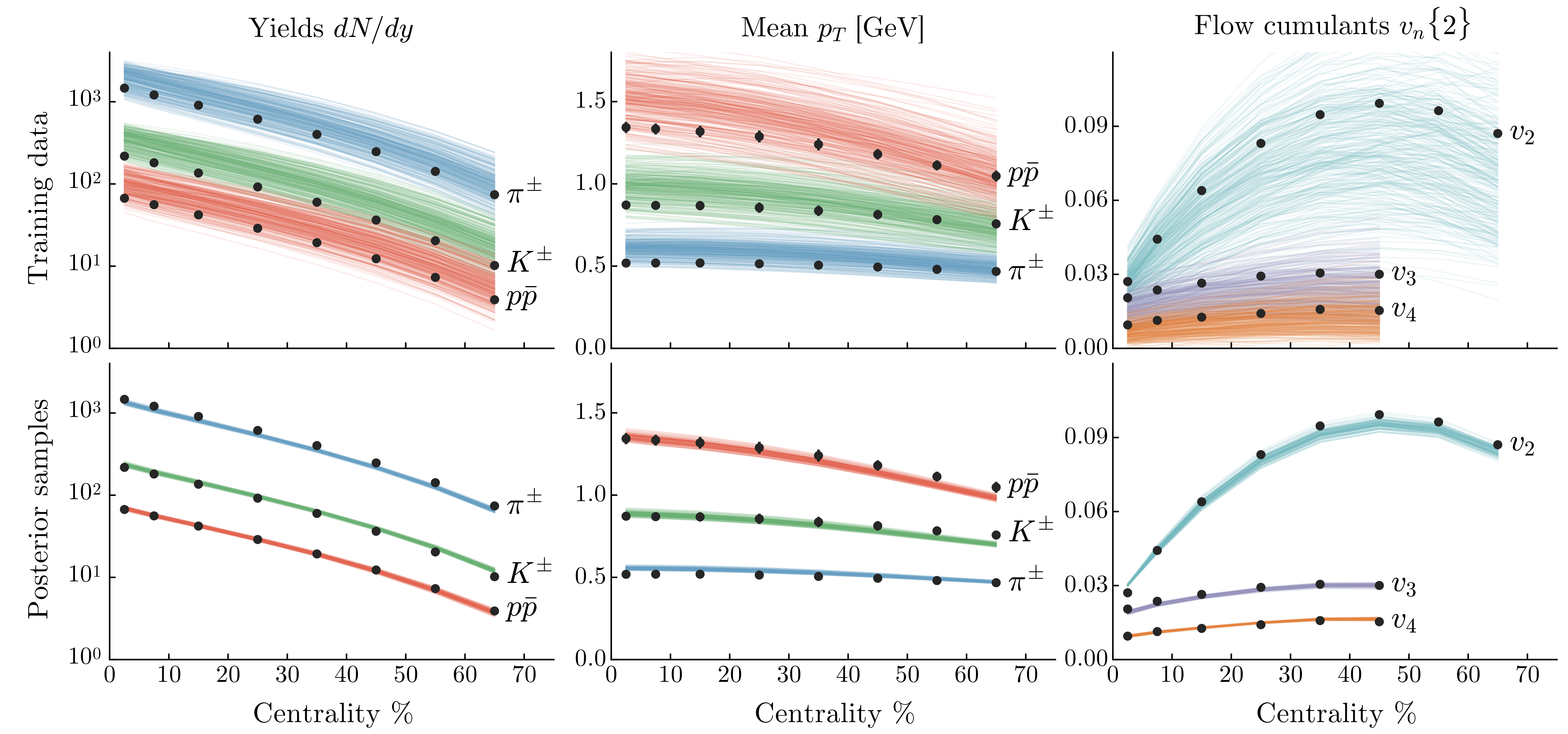


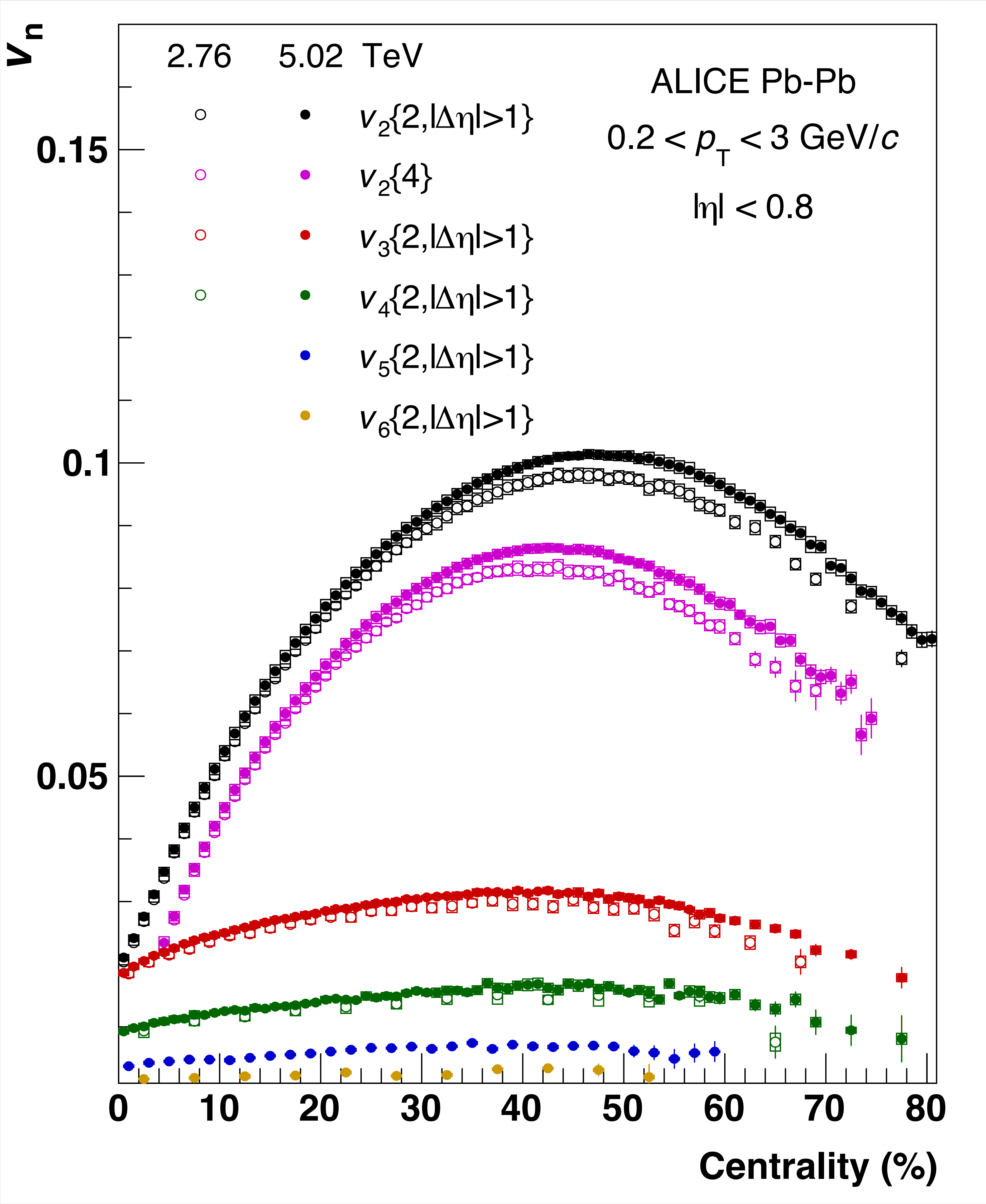
FIG. 8. Simulated observables compared to experimental data from the ALICE experiment [108, 109]. Top row: explicit model calculations for each of the 300 design points, bottom: emulator predictions of 100 random samples drawn from the posterior distribution. Left column: identified particle yields dN/dy, middle: mean transverse momenta $\langle p_T \rangle$, right: flow cumulants $v_n\{2\}$.

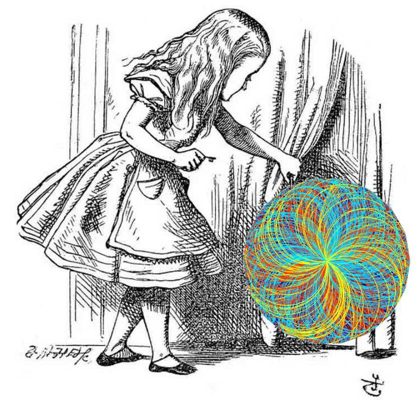
- Use geometry as a control parameter
- If the constituents interact they convert the coordinate space asymmetries into momentum space asymmetries
- The v_n coefficients provide information about the initial state anisotropies, the transport parameters and the EoS, and can be used to constrain them
- viscous hydro is very successful in describing the measured v_n

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

J. Bernhard, J. Scott Moreland, S. Bass, J. Liu, U. Heinz, arXiv:1605.03954

Anisotropic Flow: experimental constraints

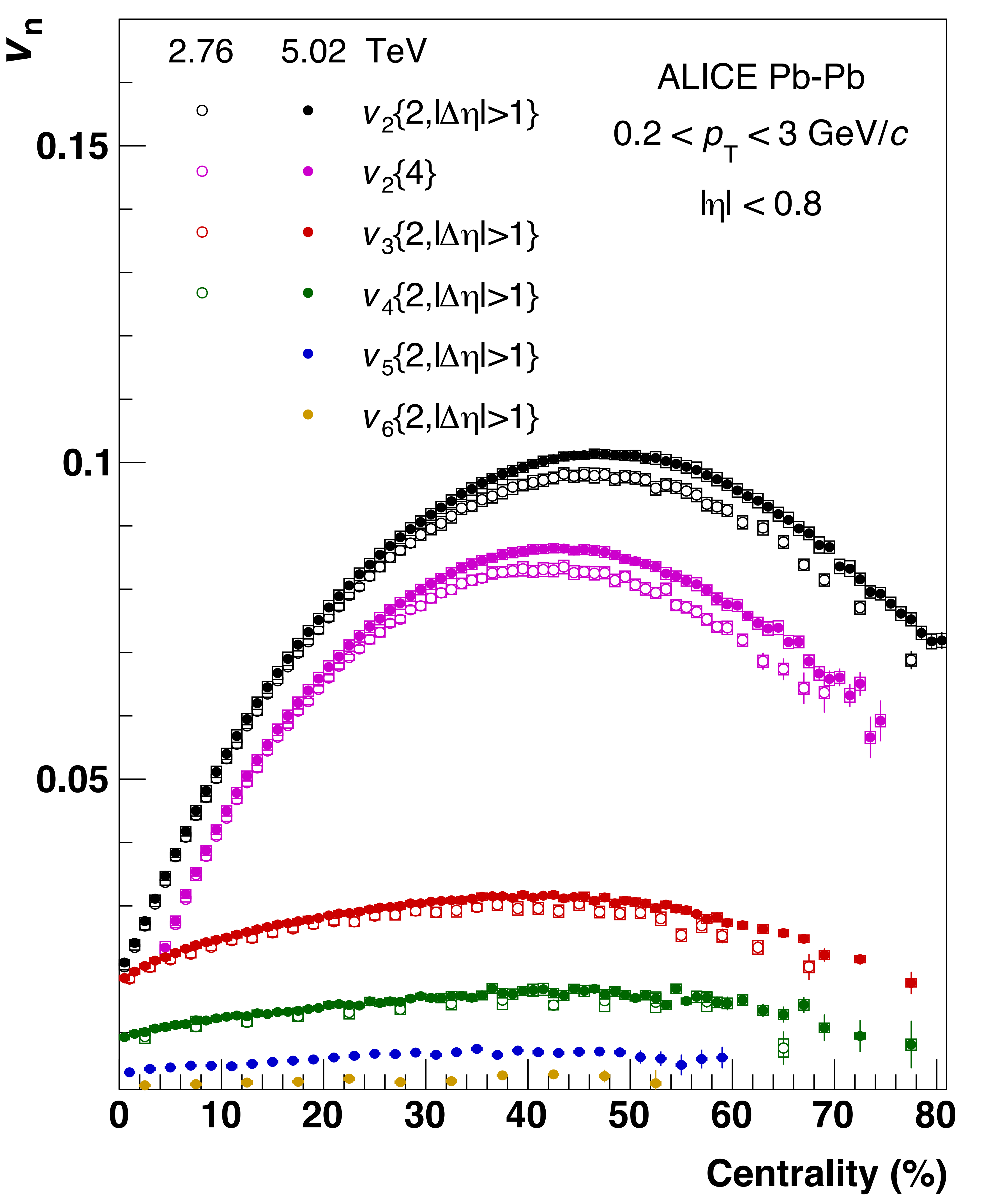


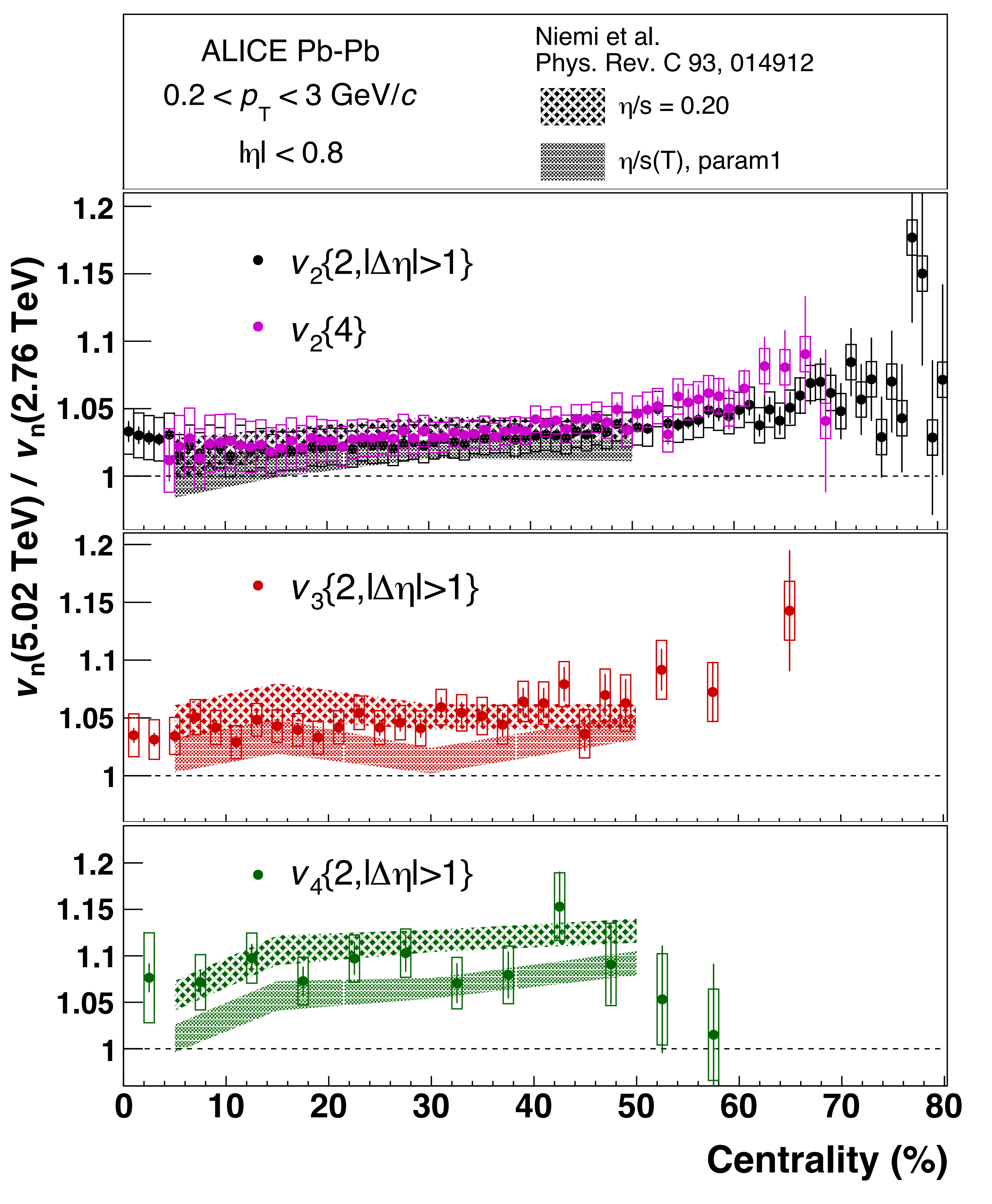


- The v_n coefficients provide information about the initial state anisotropies, the transport parameters and the EoS
  - However, these are many important physics parameters; how to constrain all of them to better precision?

- Experimentally we can use within one experiment detailed measurements of the energy dependence of the v_n to constrain the temperature dependence of the parameters on which they depend the most
- In addition we can use detailed cumulant measurements to constrain the p.d.f. of the v_n and with that constrain the initial spatial distributions

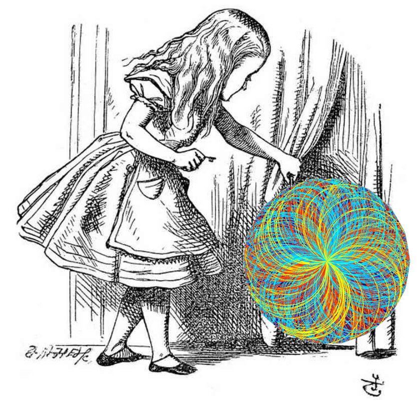
Anisotropic Flow: η/s

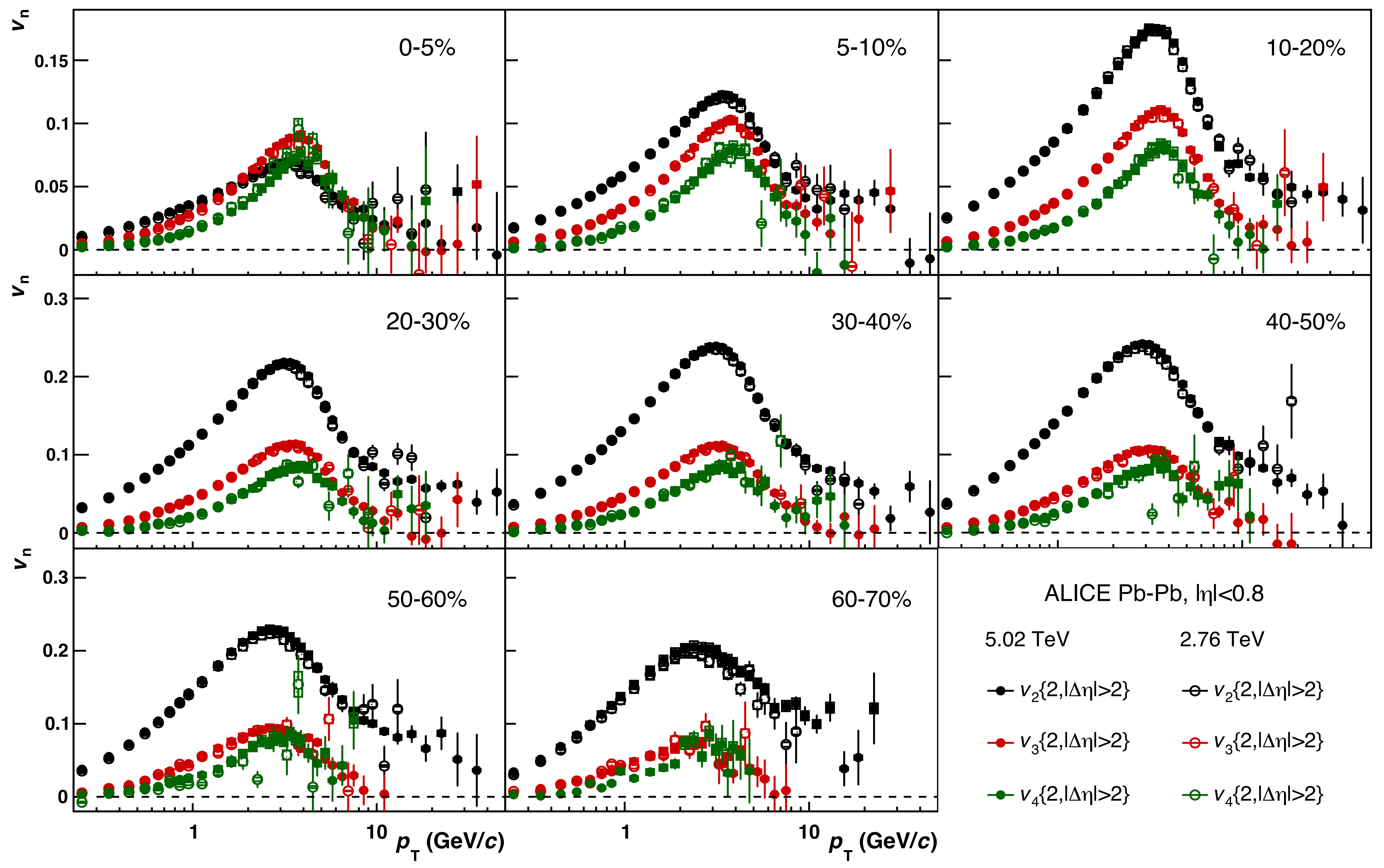




- The difference between $v_2\{2\}$ and $v_2\{4\}$ depends on the v_2 event-by-event fluctuations (later in this talk) and provide a constraint on the v_n p.d.f.
- A small increase between 2-10% for the v_n is observed from 2.76 to 5.02 TeV
- The two parameterisations of η/s which describe the data indicate no or a small dependence on temperature

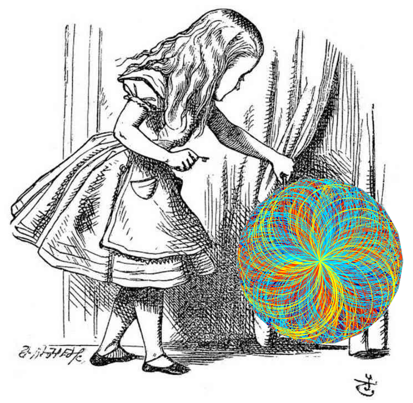
Anisotropic Flow

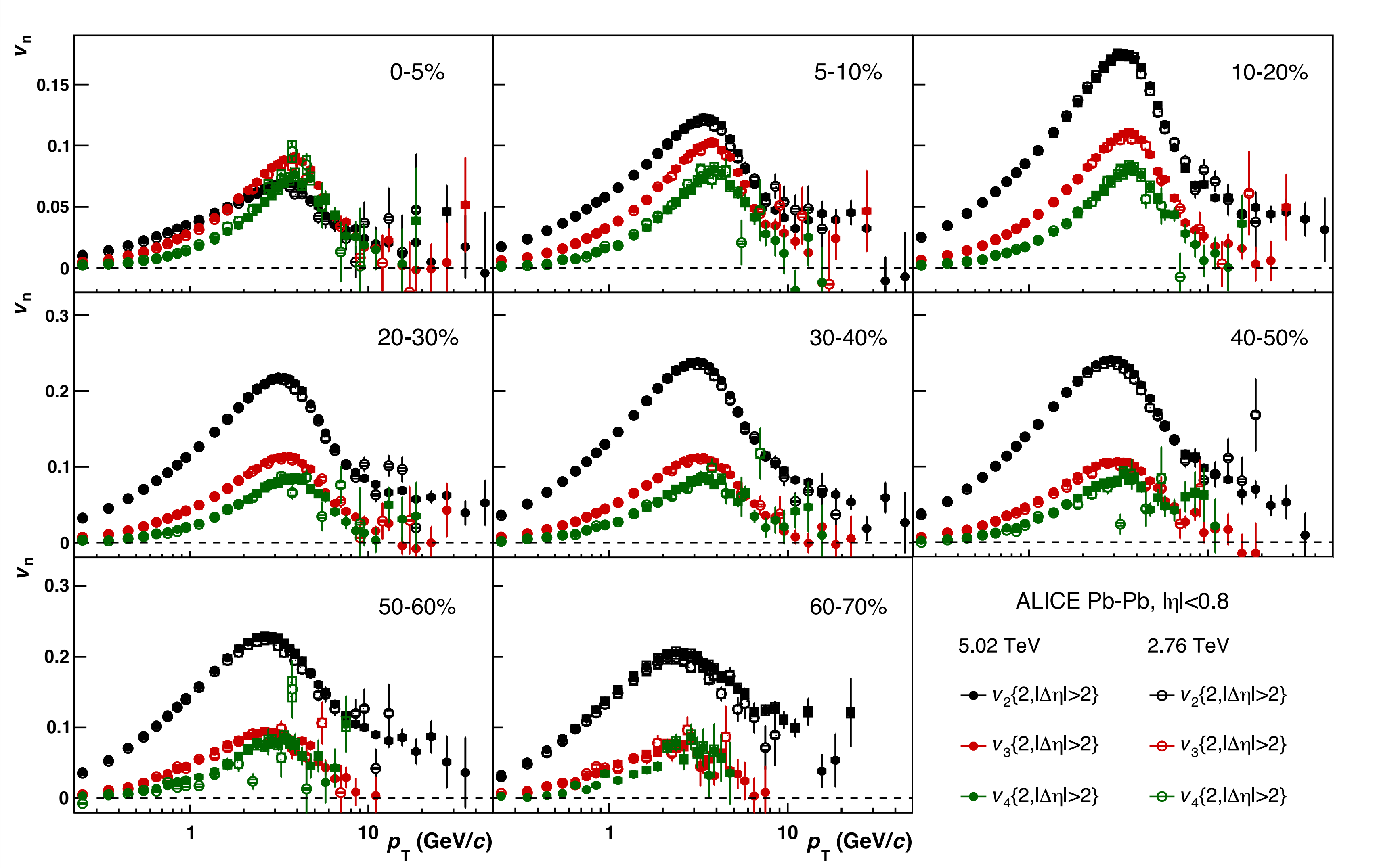




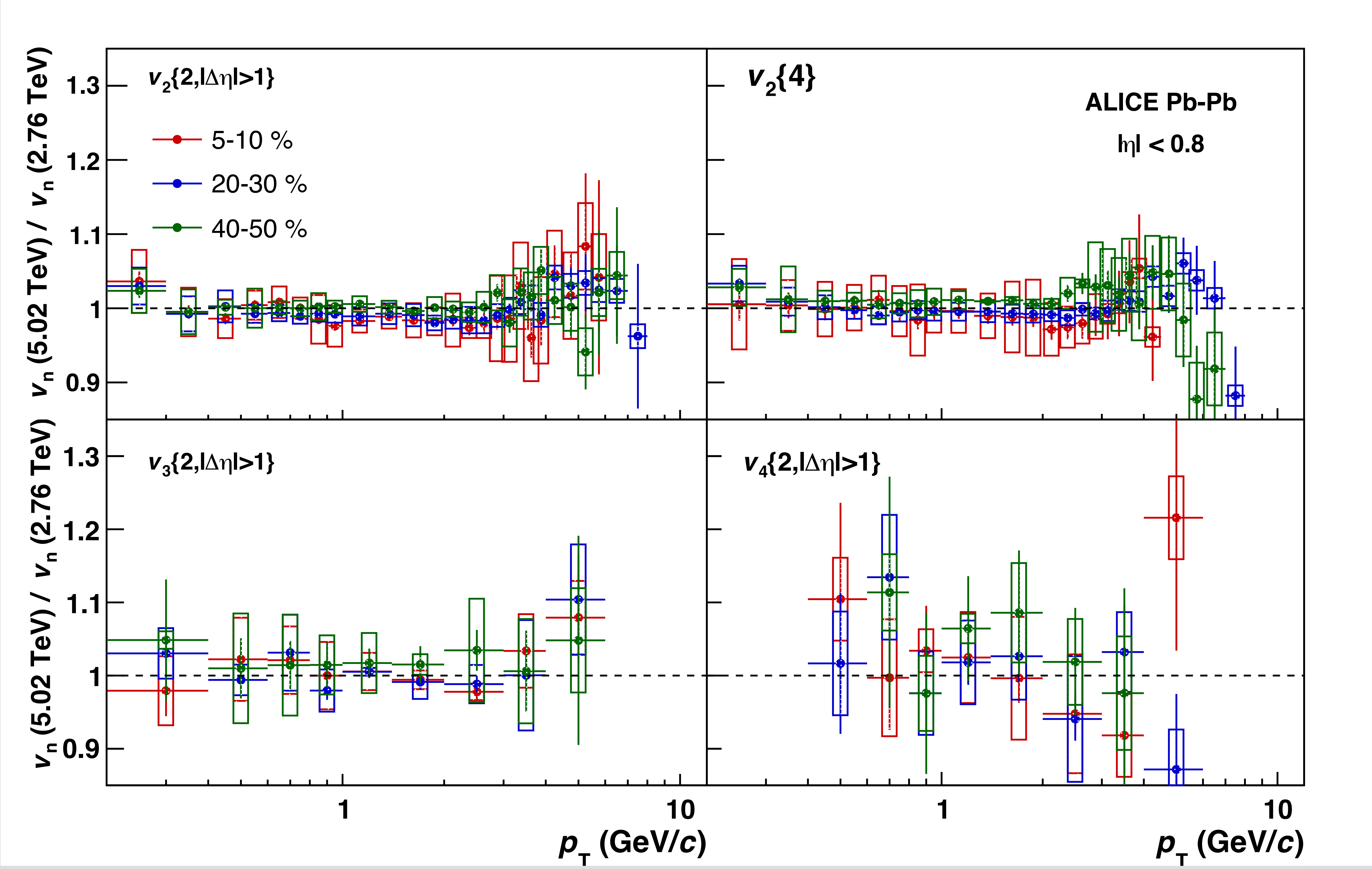
- The dependence of v_n on transverse momentum provides more differential information
- At low transverse momentum the data can be interpreted in a "hydrodynamical" picture while at high-p_t the dominant mechanism is though to be path length dependent energy loss of high energetic partons
- The v_2 coefficients dominates over all transverse momenta except for the most central collisions
- The v_2 is significant up to the highest transverse momenta

Anisotropic Flow: η/s

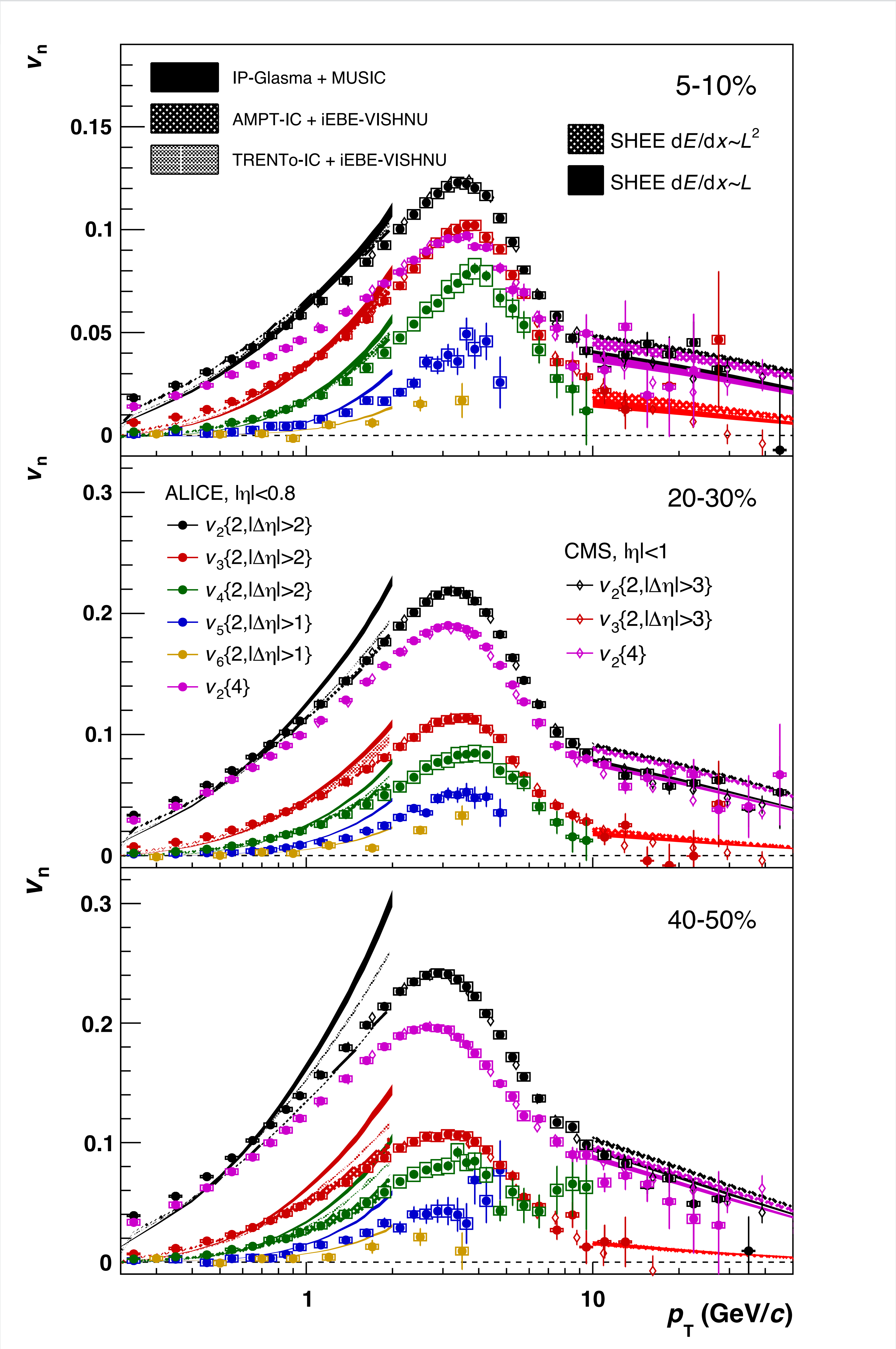


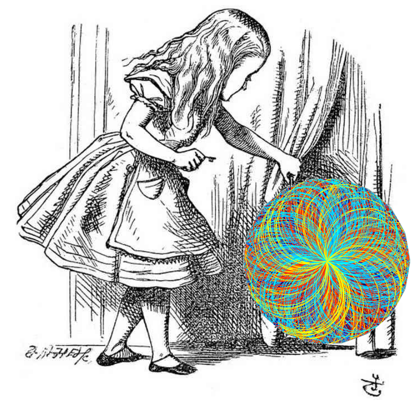


- The ratios between v_n at 5.02 and 2.76 TeV are consistent with unity
  - The increase in integrated v_n due to increase in $<p_t>$ (due to radial flow in hydro picture)
- Also consistent with almost no change of η/s between the two beam energies



Anisotropic Flow; compared to models

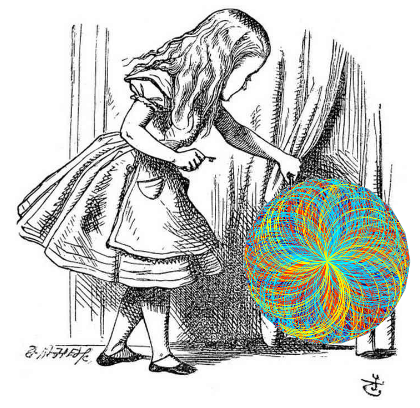


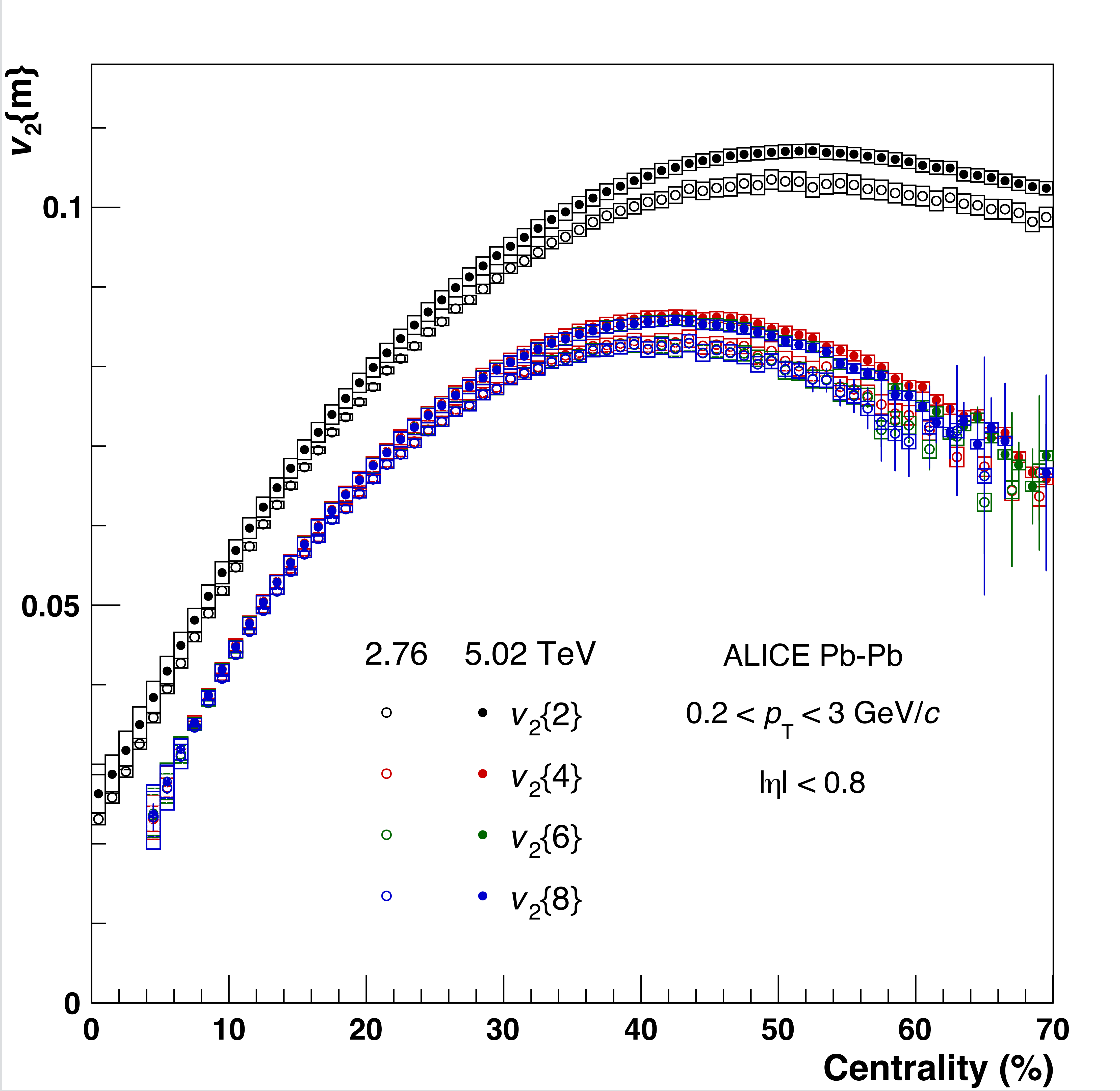


- Models use IP-Glasma, AMPT-IC or TRENTo initial conditions and all use UrQMD for the hadronic phase
  - All models qualitatively describe the low-p_t data
  - The measurement of $v_n(p_t)$ by itself is not enough to constrain the initial conditions
- At large p_t the azimuthal asymmetries are though to be due to path length dependent parton energy loss
  - The model compared to the data uses an event-by-event hydro description (v-USPhydro) and jet quenching model (BBMG)
  - Tested is a linear dE/dx ~L and quadratic energy loss
    - The v_2 at large p_t is compatible with linear energy loss

arXiv:1804.02944 [nucl-ex] 9 April 2018

Anisotropic Flow Fluctuations: Constraints on Initial Conditions





$$v_n\{2\} = \sqrt[2]{\langle v_n^2\rangle}$$

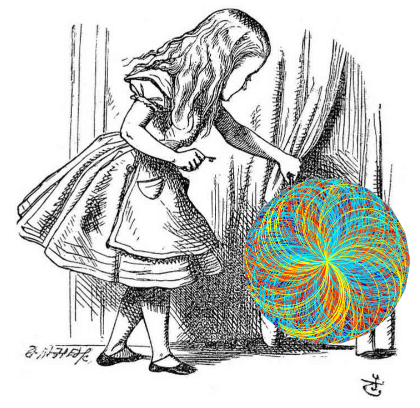
$$v_n\{4\} = \sqrt[4]{2\langle v_n^2\rangle^2 - \langle v_n^4\rangle}$$

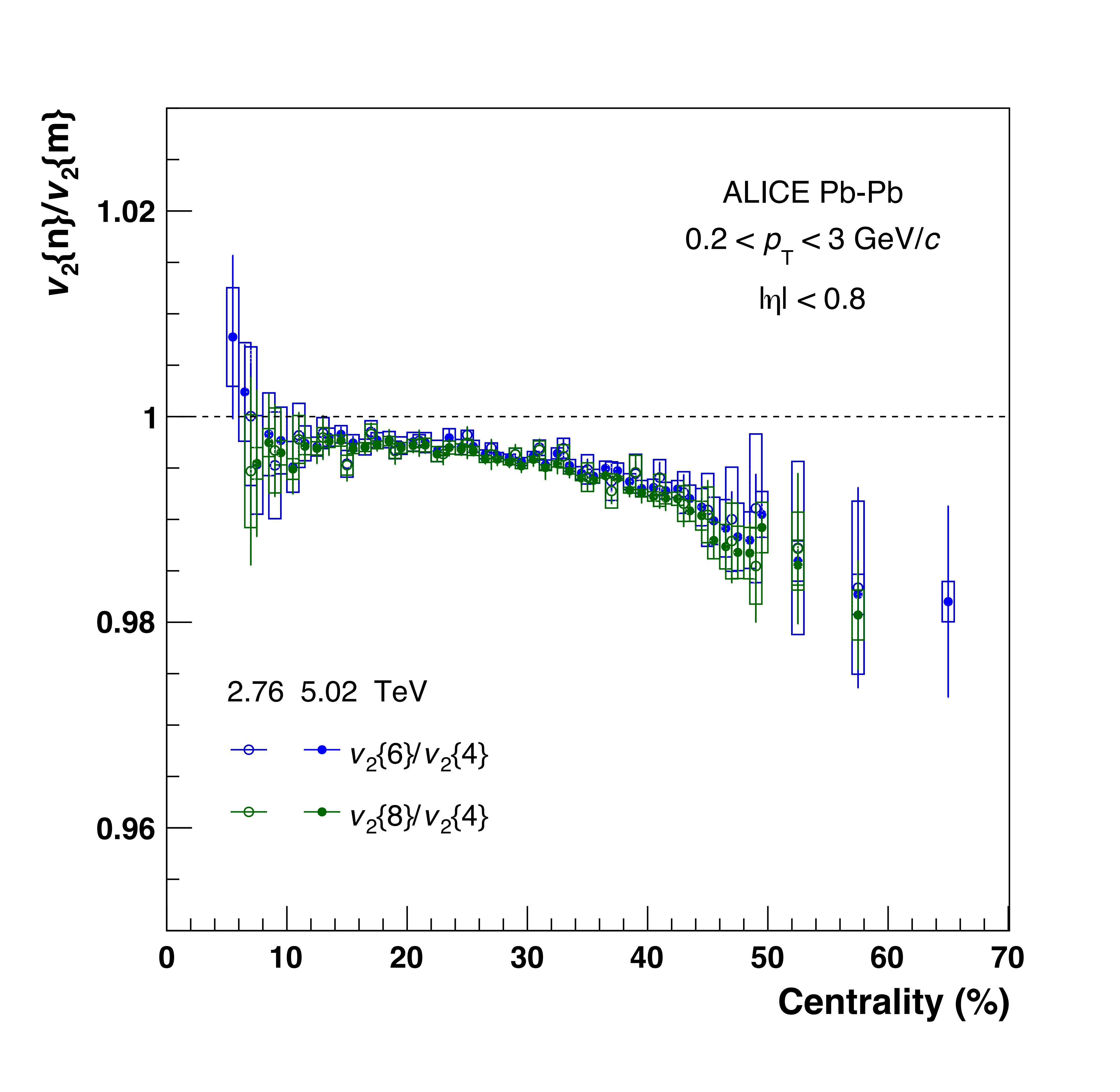
$$v_n\{6\} = \sqrt[6]{\langle v_n^6\rangle - 9\langle v_n^2\rangle\langle v_n^4\rangle + 12\langle v_n^2\rangle^3}$$

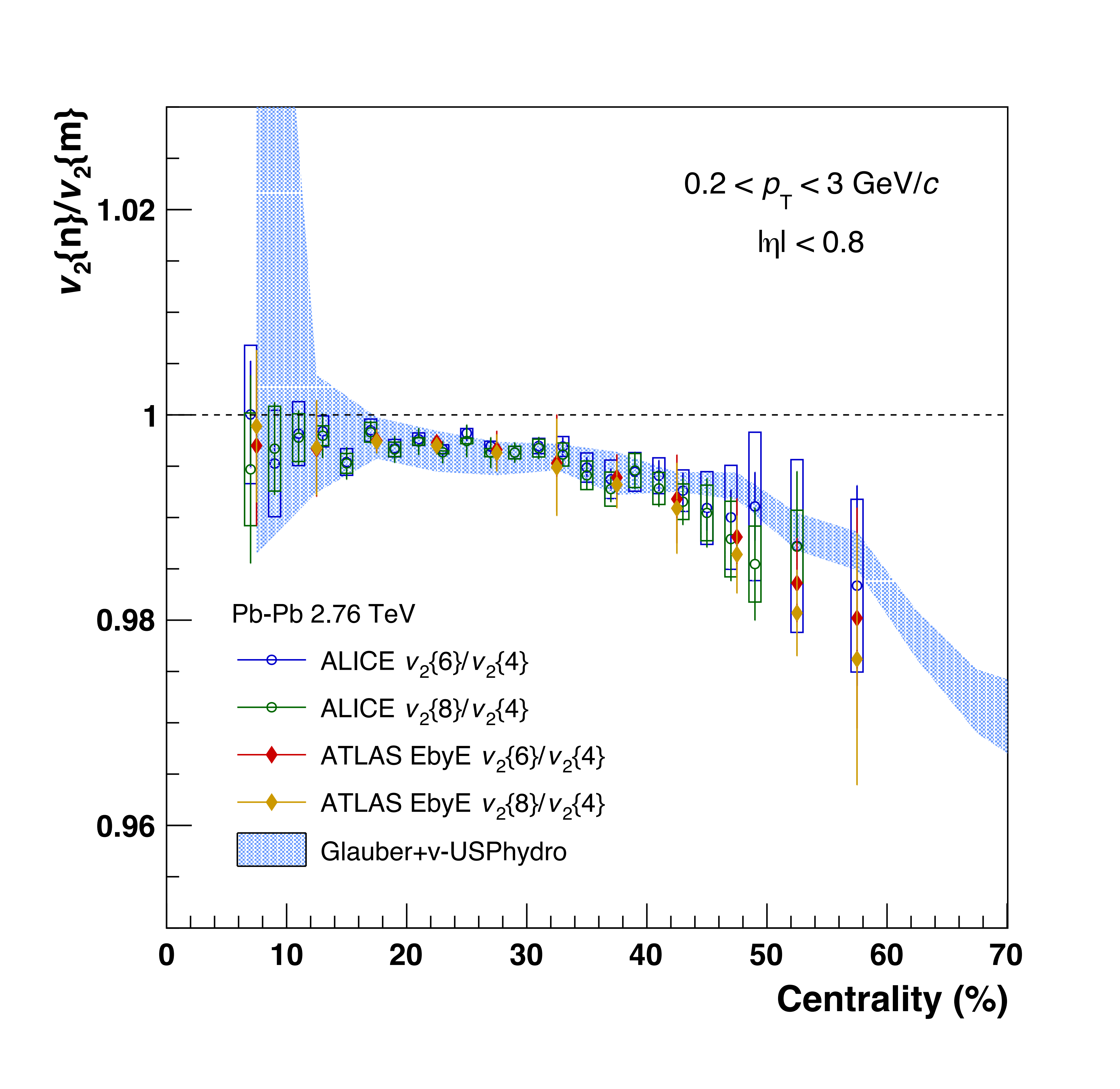
$$v_n\{8\} = \sqrt[8]{\langle v_n^8\rangle - 16\langle v_n^2\rangle\langle v_n^6\rangle - 18\langle v_n^4\rangle^2 + 144\langle v_n^2\rangle^2\langle v_n^4\rangle - 144\langle v_n^2\rangle^4}$$

The different estimates of v_2 are sensitive to the moments of the v_2 distribution, if $v_2\{4\}=v_2\{6\}=v_2\{8\}$ the distribution is a Bessel-Gaussian p.d.f.

Anisotropic Flow Fluctuations: Constraints on Initial Conditions







A fine splitting is observed which is centrality dependent showing the non Bessel Gaussian contribution

The splitting does not depend on the p_t range used and collision energy

The results agree well with model calculations as well as with ATLAS results based on a different technique

Anisotropic Flow Fluctuations: Constraints on Initial Conditions

$$\gamma_1 = \frac{\langle (v_n\{RP\} - \langle v_n\{RP\}\rangle)^3 \rangle}{\langle (v_n\{RP\} - \langle v_n\{RP\}\rangle)^2 \rangle^{3/2}}$$

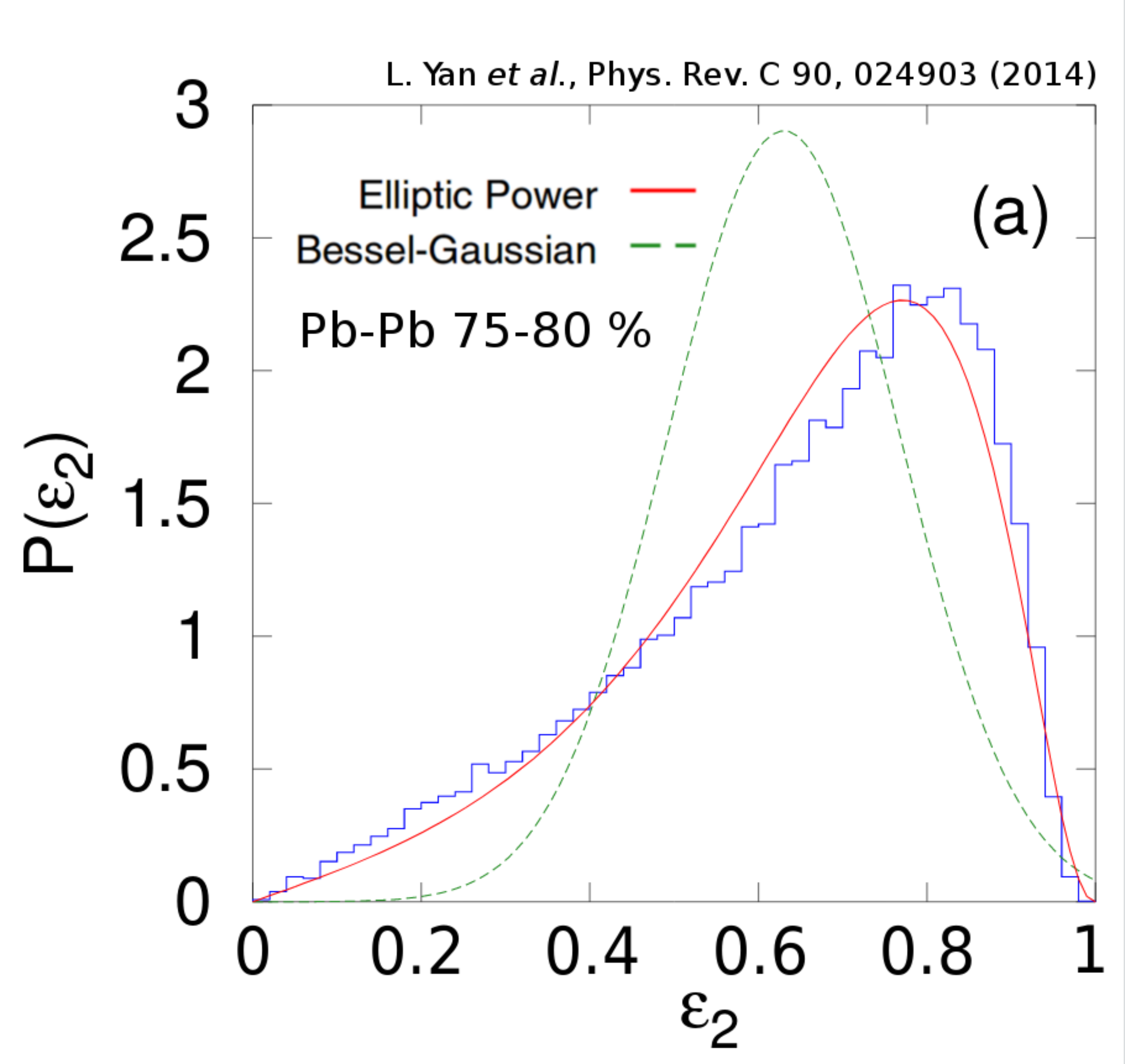
The standardised skewness

$$\gamma_1^{exp} = -6\sqrt{2}\,v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}$$

The standardised skewness can estimated using the multi-particle cumulants

$$v_2\{6\} - v_2\{8\} = \frac{1}{11}(v_2\{4\} - v_2\{6\})$$

This experimental estimate depends on the fact that the higher order moments, e.g. kurtosis are small, which can be tested



Distribution of IS eccentricity ε_2 in MC-Glauber

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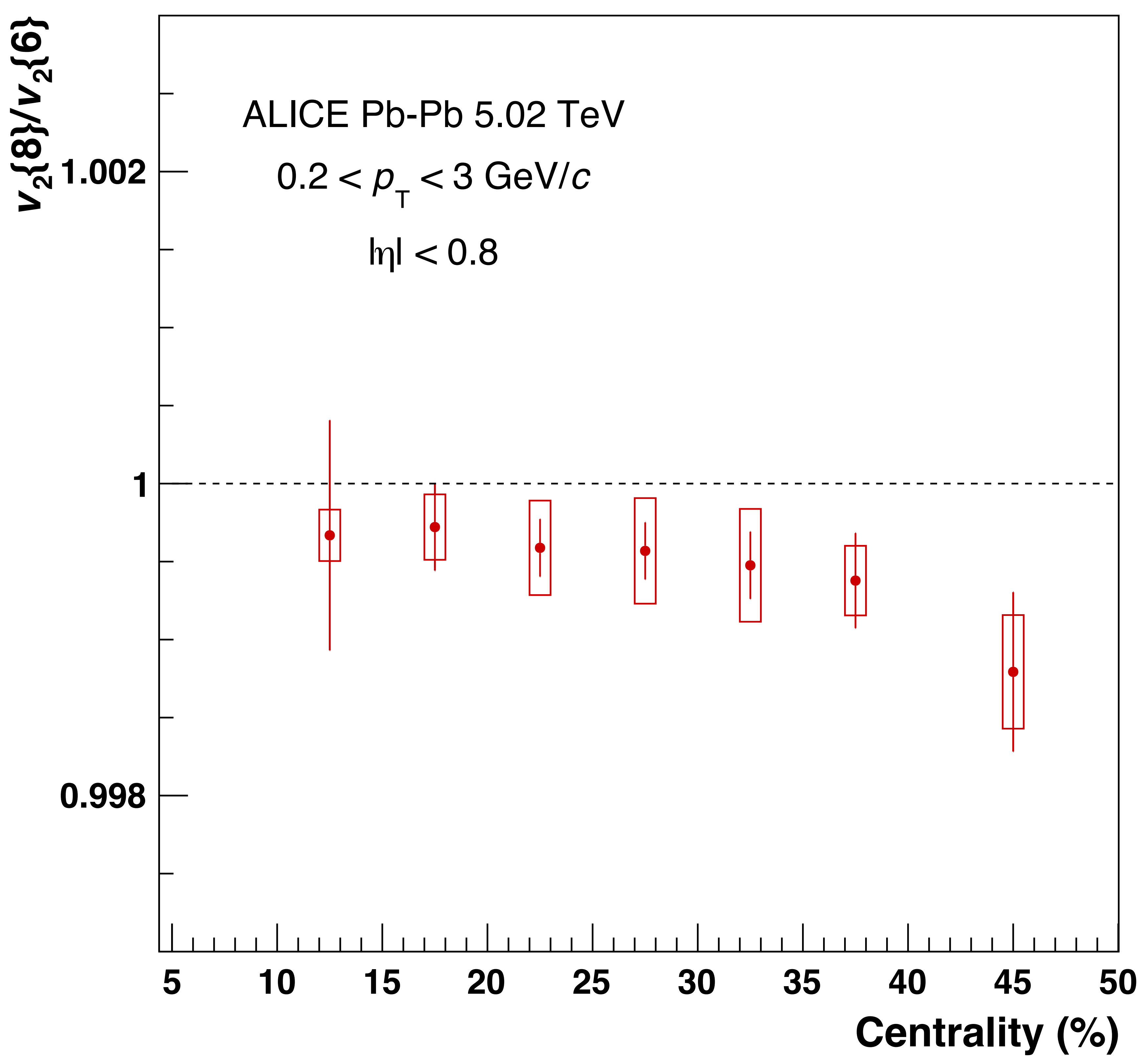
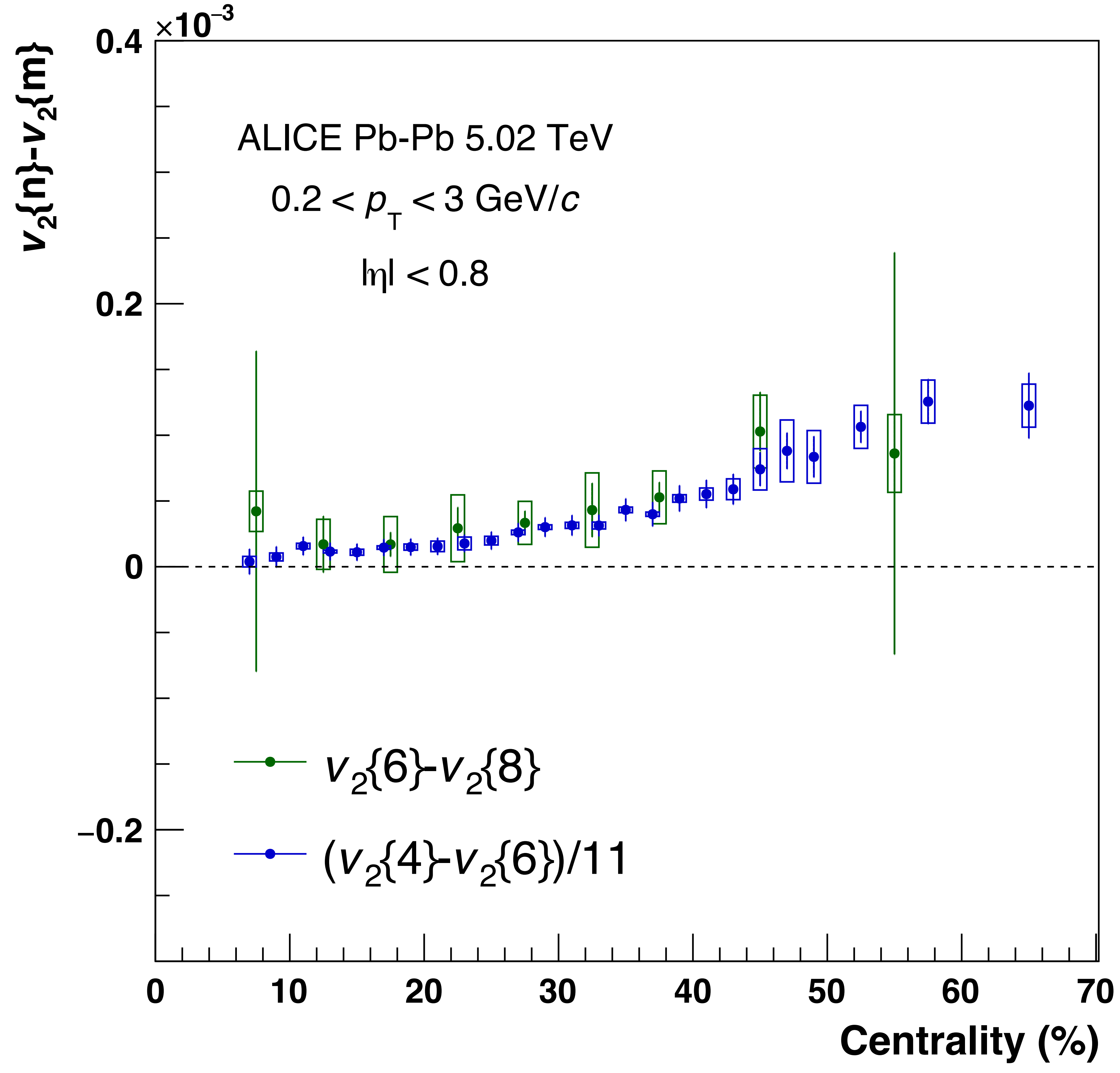
Anisotropic Flow Fluctuations: Constraints on Initial Conditions





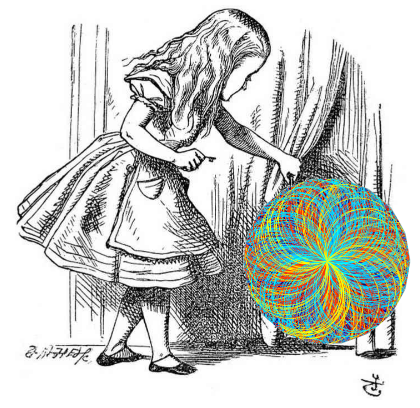
A fine splitting is observed between v2{8} and v2{6}

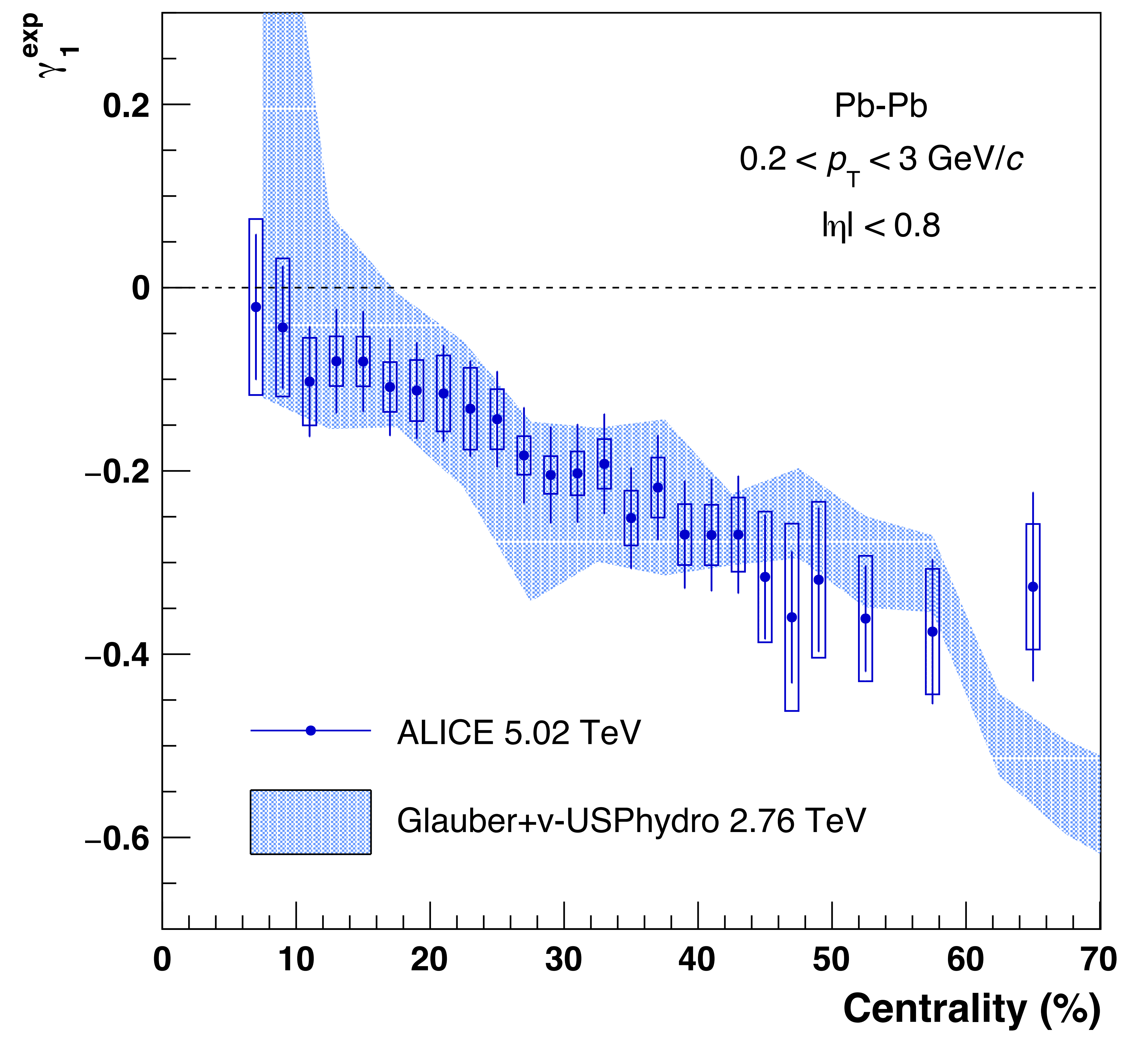
Can be contributed to the skewness of the p.d.f.

Higher order contributions are constrained in the equality

$$v_2\{6\} - v_2\{8\} = \frac{1}{11}(v_2\{4\} - v_2\{6\})$$

Anisotropic Flow Fluctuations: Constraints on Initial Conditions





$$\gamma_1^{exp} = -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}$$

- A negative skewness is observed as expected due to the constrains on ε_2 between 0-1
- The skewness agrees well with model calculations and increases towards peripheral collisions due to the constraint of 1

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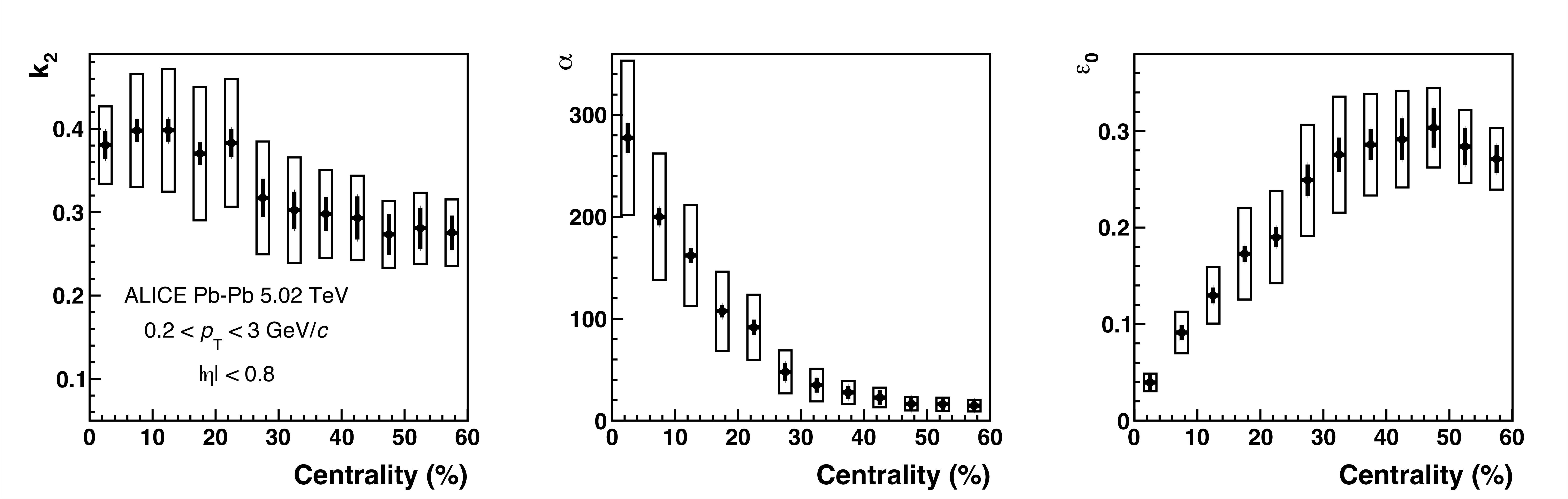
Anisotropic Flow Fluctuations: Constraints on Initial Conditions

$$P(\varepsilon_2) = \frac{1}{k_2} 2\alpha\varepsilon_2 (1-\varepsilon_2^2)^{\alpha-1}(1-\varepsilon_0^2)^{\alpha+1/2}\frac{1}{\pi}\int_0^{\pi}(1-\varepsilon_2\varepsilon_0\cos\varphi)^{-2\alpha-1}d\varphi$$



The elliptic power distribution can be used to describe the underlying p.d.f. of ε_2

The parameter α qualifies the magnitude of the flow fluctuations, ε_0 the mean eccentricity in the reaction plane and k_2 the proportionality between ε_2 and v_2; $v_2 = k_2\,\varepsilon_2$

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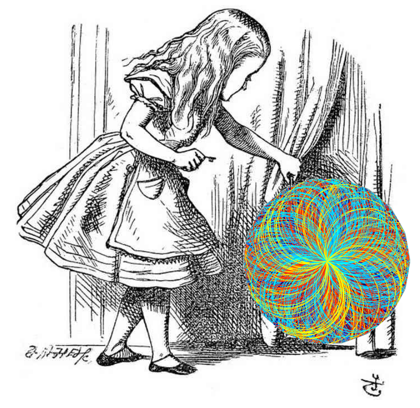
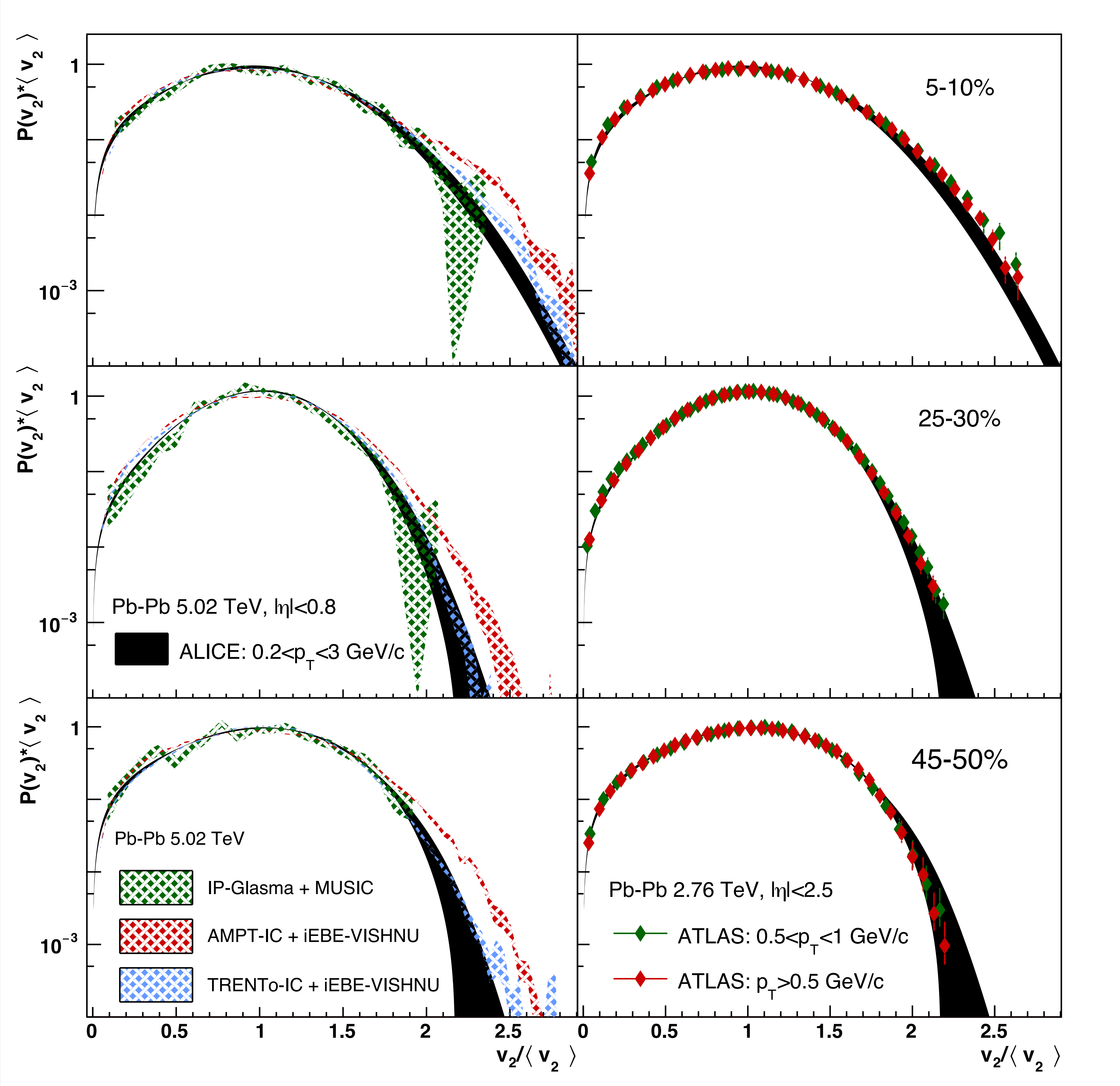
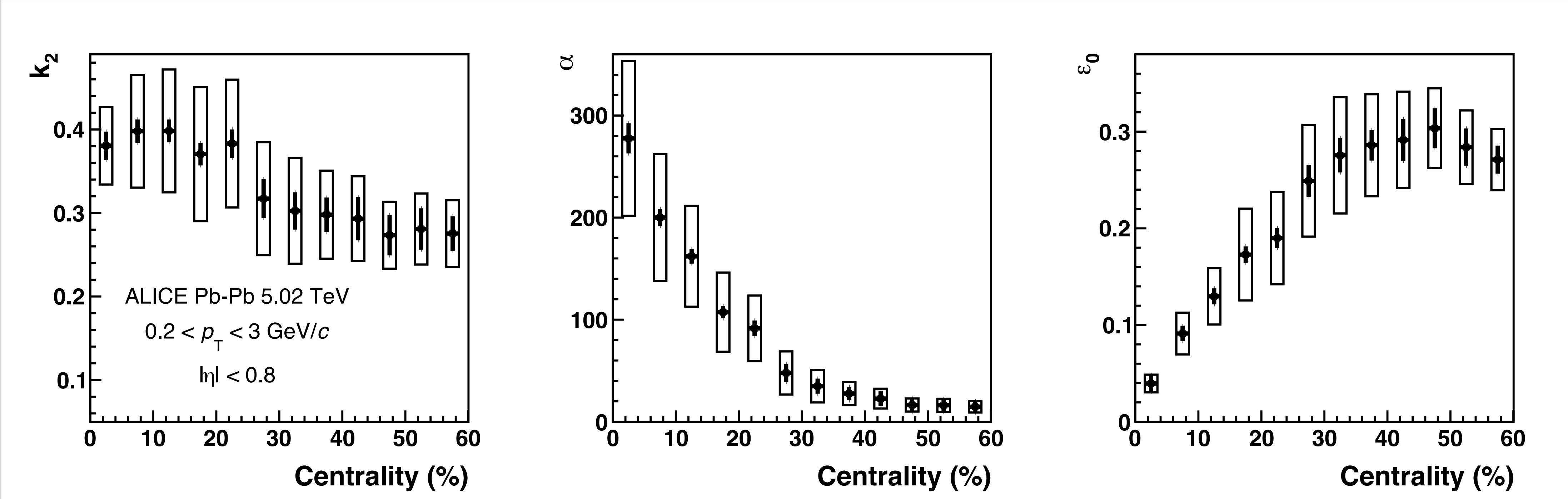
Anisotropic Flow p.d.f.: Constraints on Initial Conditions





$$P(\varepsilon_2) = \frac{1}{k_2} 2\alpha\varepsilon_2 (1-\varepsilon_2^2)^{\alpha-1} (1-\varepsilon_0^2)^{\alpha+1/2} \frac{1}{\pi} \int_0^{\pi} (1-\varepsilon_2\varepsilon_0\cos\varphi)^{-2\alpha-1} d\varphi$$



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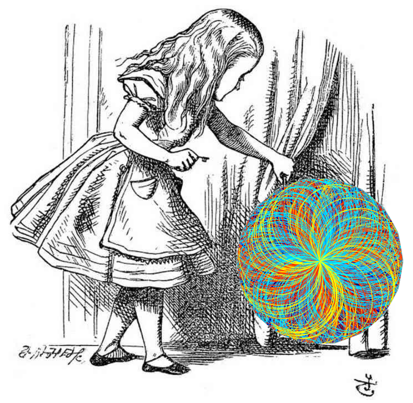
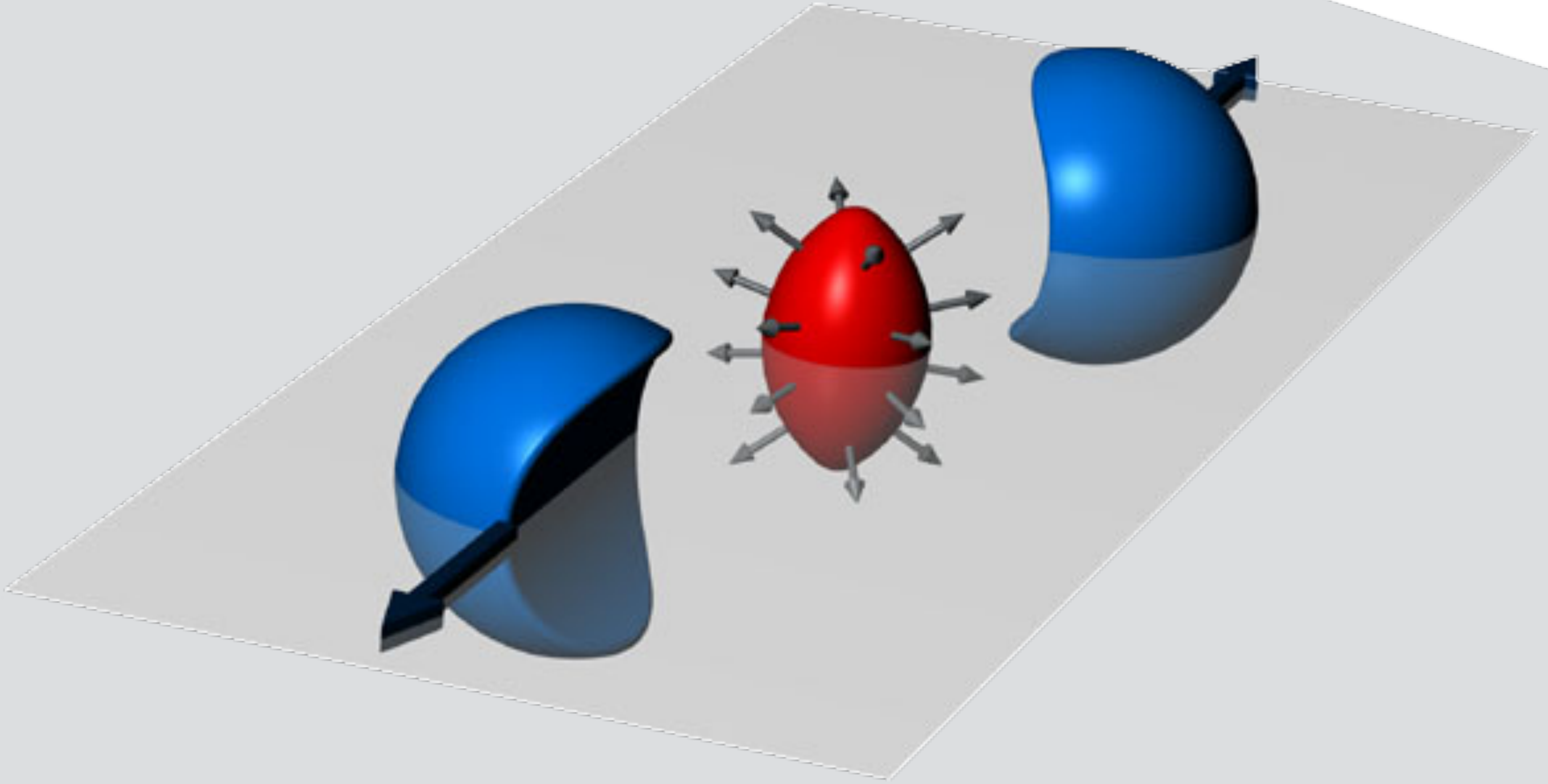
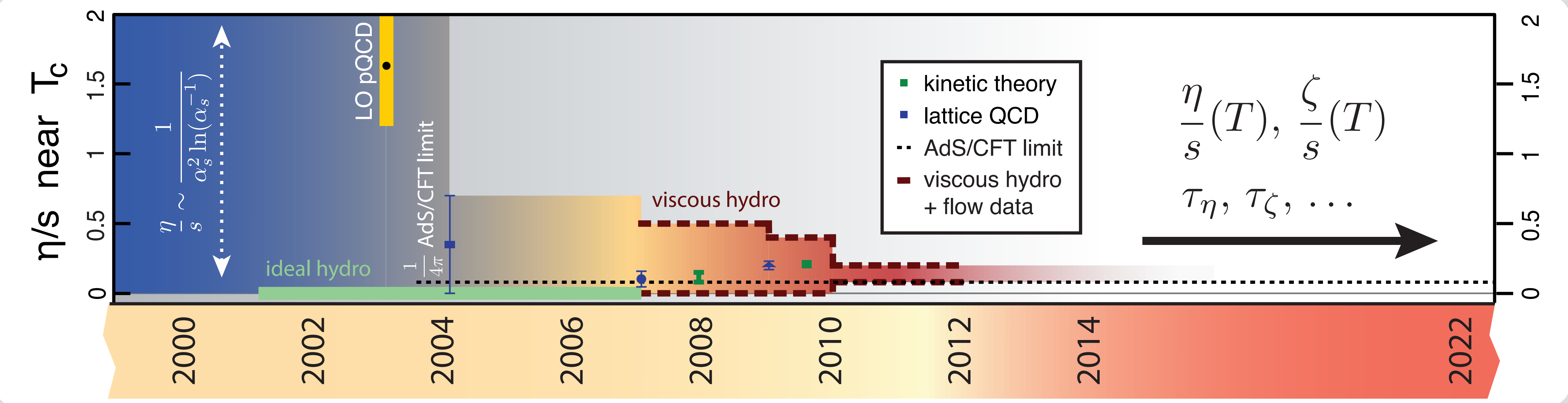
Summary





- Anisotropic flow is precisely measured at the LHC as function of collision energy using multi-particle cumulants
- The underlying p.d.f. of v_2 can be determined with high precision using the cumulants and are used to constrain the initial conditions
- Viscous hydrodynamical calculations with these initial conditions describe well the centrality, energy and collision system dependence of the v_n
- The measurements provide strong constrains on the temperature dependence of the transport coefficients and the path length dependence of parton energy loss



Thanks!