Triangular Flow in Relativistic Heavy Ion Collisions in an Event-by-Event Hybrid Approach

DPF Meeting 2011, Brown University, Providence

08/09/2011

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Thanks to: Rolando La Placa and Steffen A. Bass

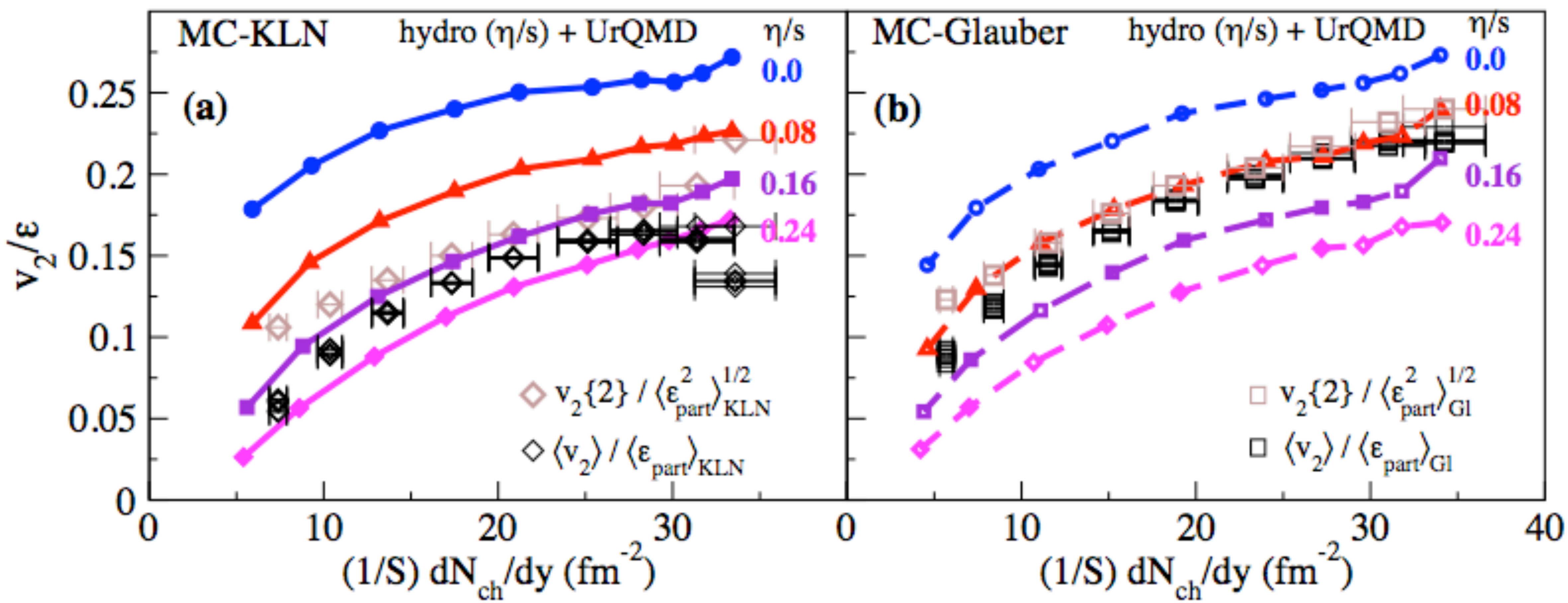
Unterstützt von / Supported by Alexander von Humboldt Stiftung / Foundation

Outline

- Motivation
  - Initial State Fluctuations & Triangular Flow
- The Hybrid Approach
  - Fluctuating Initial Conditions
  - Ideal Hydrodynamic Evolution
  - Full Final Phase-Space Distribution
- Constraining Granularity
  - Eccentricity Distributions
  - Sensitivity of Elliptic and Triangular Flow
  - Comparison to experimental data from RHIC
- Going to Higher Energies: LHC
- Summary

Motivation

Elliptic flow from viscous hydrodynamics+hadron transport



H.Song et al, PRL 106, 192301 (2011)

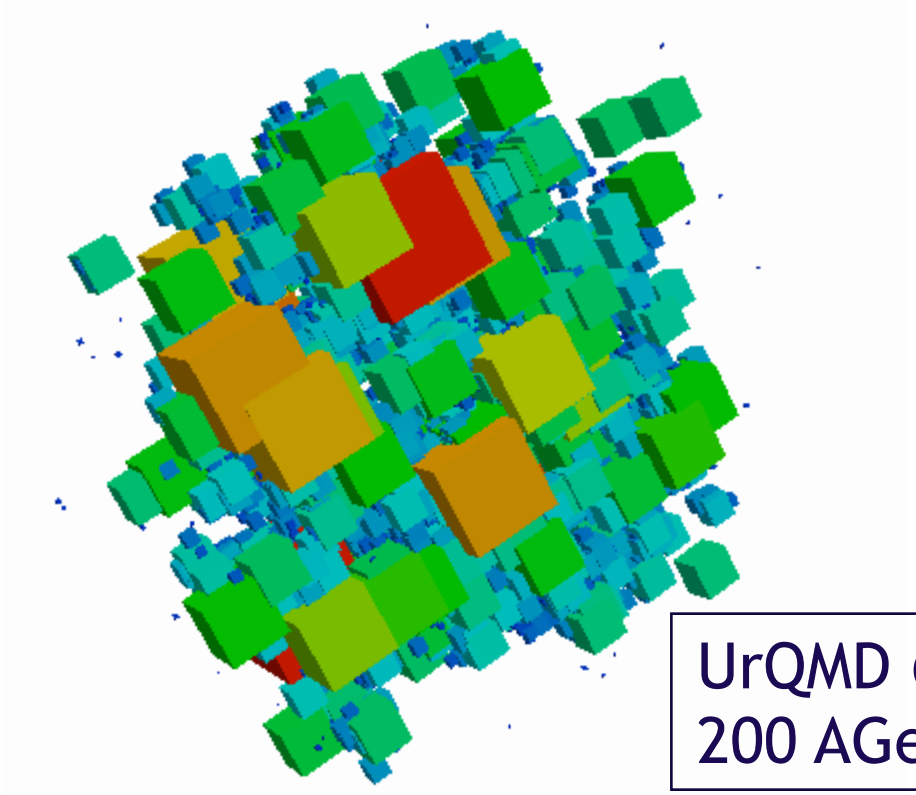
- Different initial conditions ~ factor of 2 difference in η/s
  → Major **uncertainty** to constrain transport coefficients in the quark gluon plasma

Initial Conditions from Dynamical Approaches

- The **initial $T^{\mu\nu}$** for hydrodynamics has to be given via:

$$\epsilon(x,y,z),\ p(x,y,z)\ \text{and}\ n(x,y,z)$$

- **Energy deposition** model needs to describe final dE_T/dy in p-p and A-A correctly
- Granularity is influenced by
  - Shape of the incoming nuclei
  - Distribution of binary collisions
  - Interaction mechanism
  - Degree of thermalization



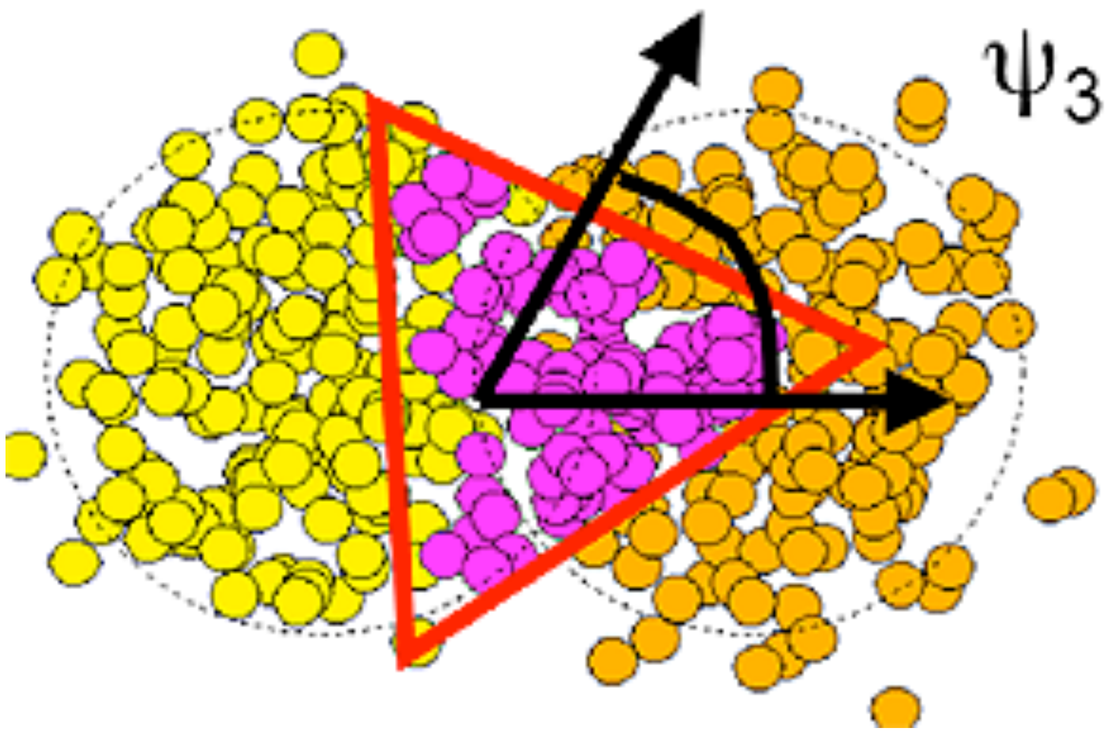
UrQMD @ 200 AGeV

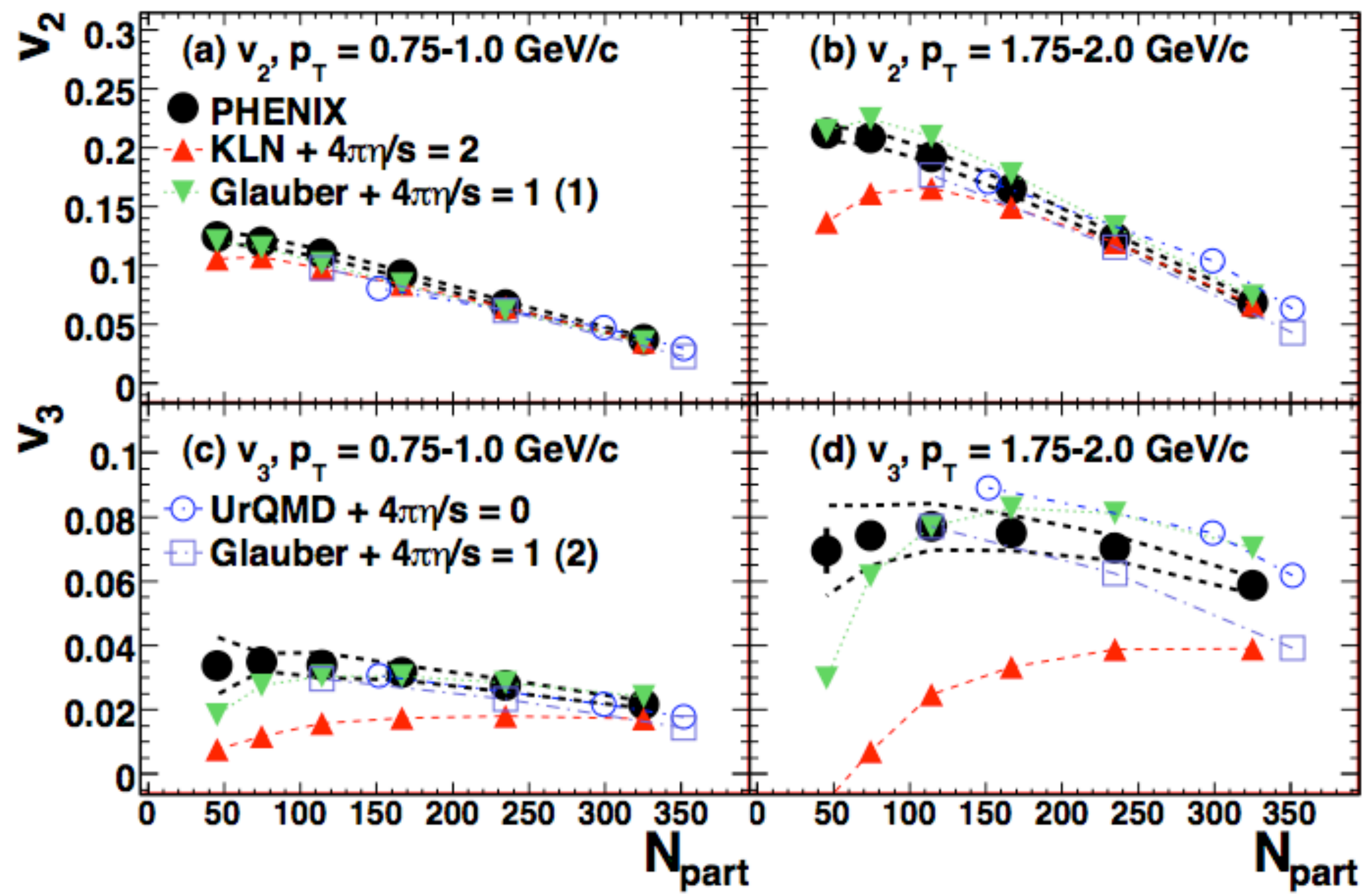
- Differences in **shape** and **fluctuations** need to be quantified
  – First attempt: use **higher** Fourier coefficients

Triangular Flow

Initial State Fluctuations

Third Harmonic Coefficient



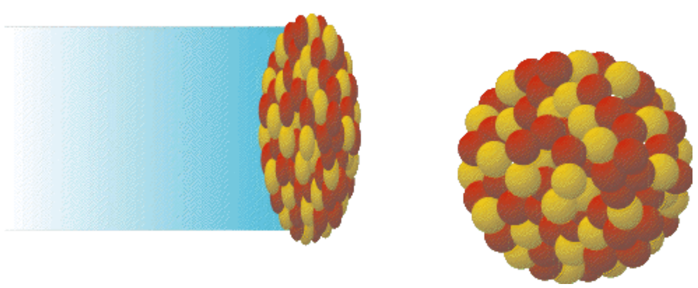


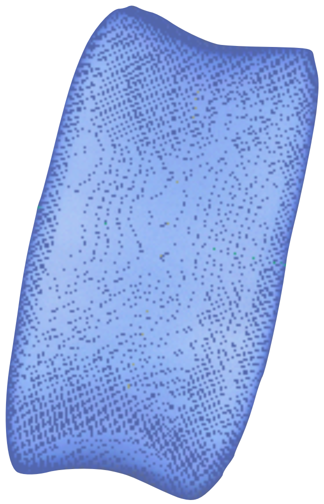
- Fluctuations introduce higher order flow coefficients that have been observed at the RHIC and LHC experiments (see QM 2011)
- How can we quantitatively learn something from this observable?

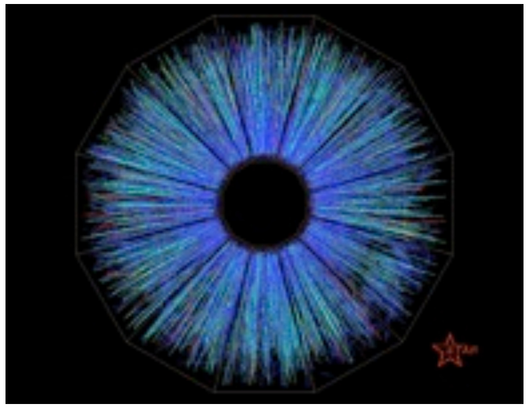
B. Alver and G. Roland, PRC 2010; NEXspheRIO, PRL 103,242301, 2009; P. Sorensen, JPG, 37, 094011,2010 ... and many more, results taken from PHENIX in arXiv: 1105.3928

Hybrid Approach

- Use advantages of **transport** and **hydrodynamics** and create combined model
- Modular Setup: Fix the hydro evolution and freeze-out
  → learn something about the influence of different **initial conditions**







1) Non-equilibrium initial conditions via UrQMD

2) Hydrodynamic evolution

3) Freeze-out via hadronic cascade (UrQMD)

H.P. et al., PRC 78:044901, 2008

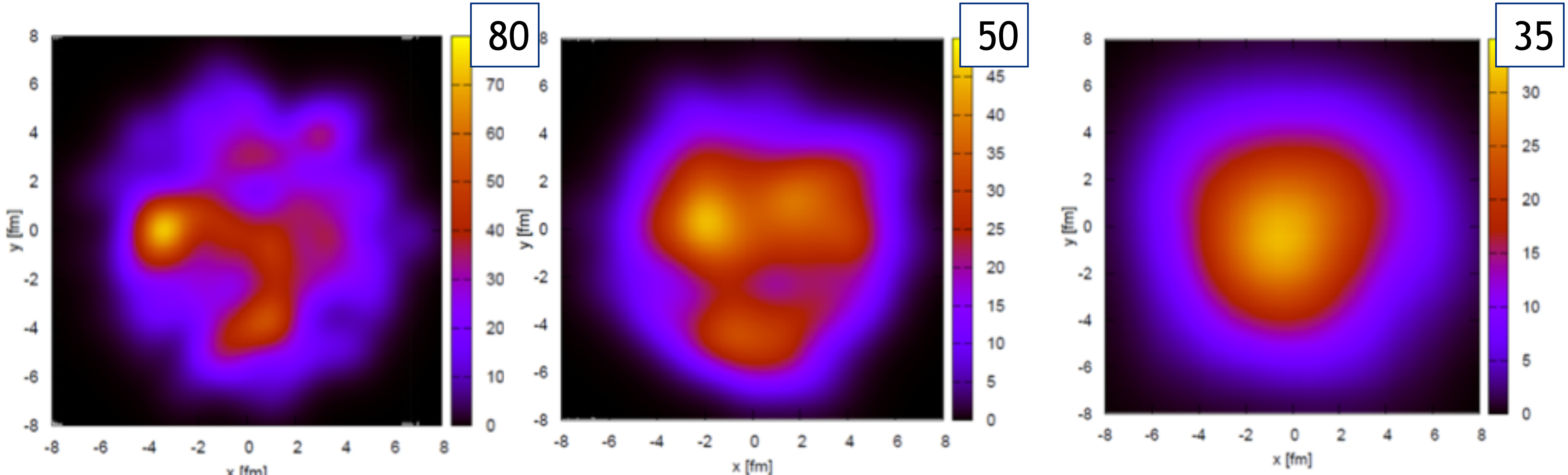
UrQMD-3.3p1 is available at http://urqmd.org

Initial State at RHIC

- Energy-, momentum- and baryon number densities are mapped onto the hydro grid using for each particle

$$\epsilon(x,y,z) = \left(\frac{1}{2\pi}\right)^{\frac{3}{2}} \frac{\gamma_z}{\sigma^3} E_p \exp - \frac{(x-x_p)^2 + (y-y_p)^2 + (\gamma_z(z-z_p))^2}{2\sigma^2}$$

- Changing σ leads to different granularities, but also changes in the overall profile



σ = 0.8 fm | σ = 1.0 fm | σ = 2.0 fm

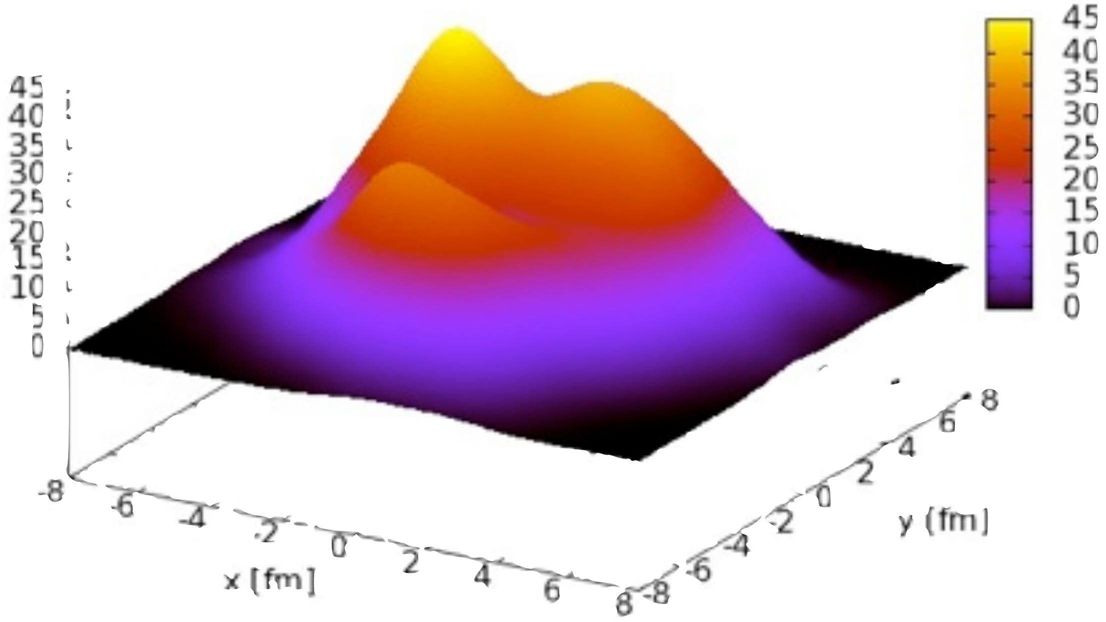
- To fit yields and elliptic flow: $\sigma \sim 1$ fm and t_{start} ~ 0.5 fm

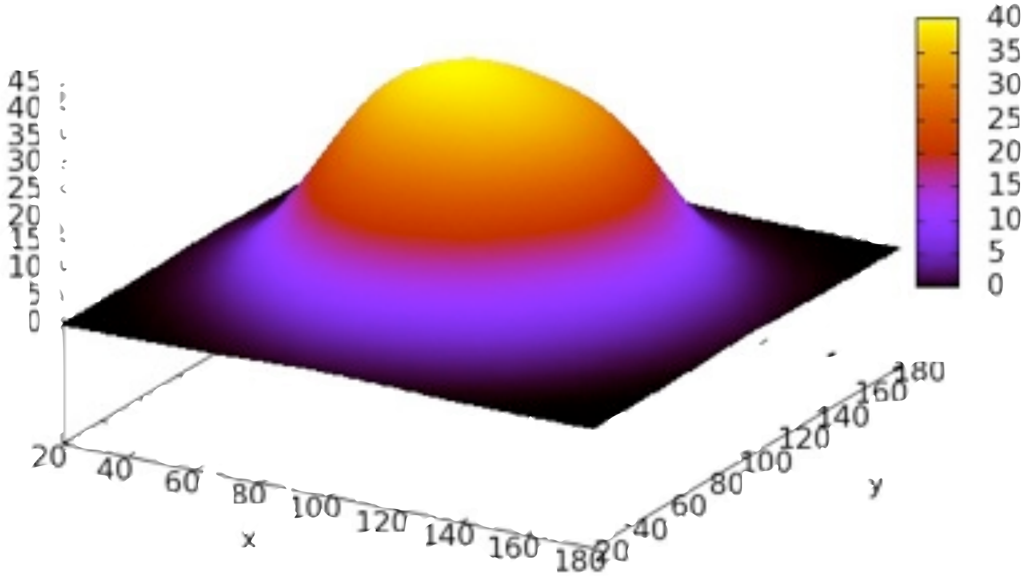
H.P. et al, PRC 83, 014916, 2011 and JPG 38, 045102, 2011

Constraining Granularity

Fluctuating (default)

Averaged (over 100 events)



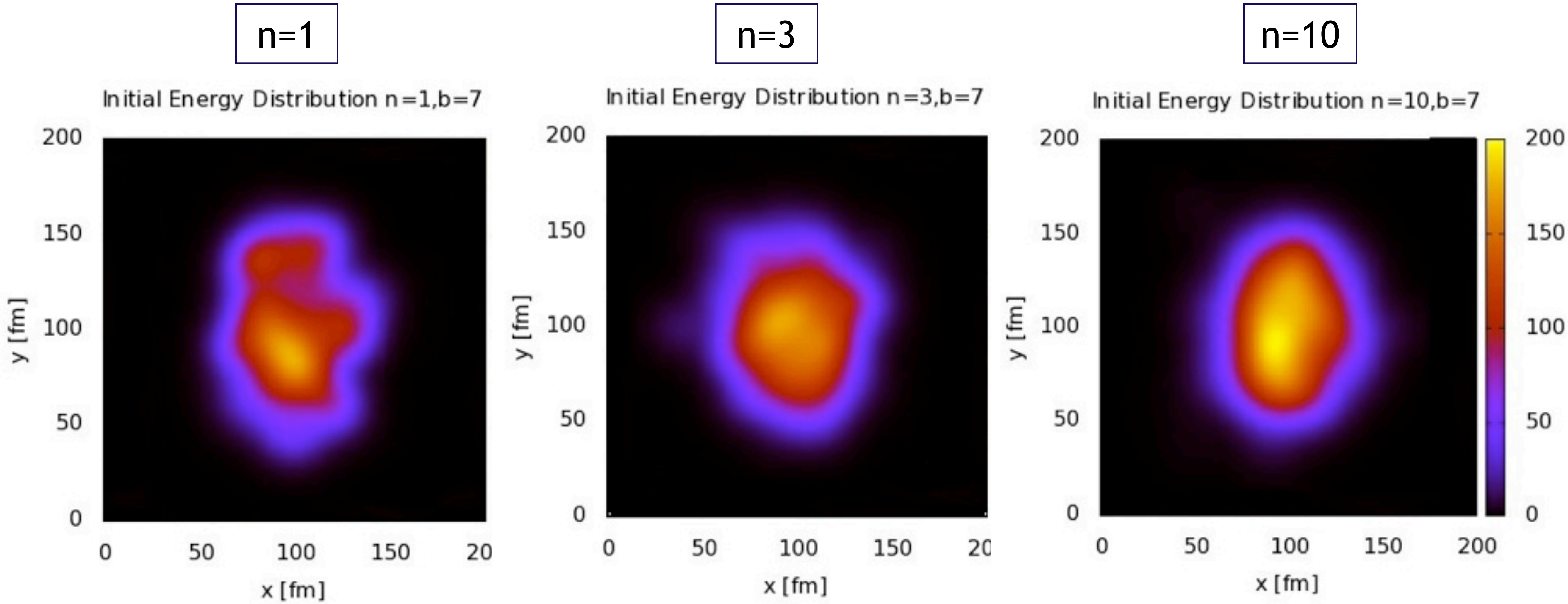


Triangular flow ≈ 2 %

Triangular flow ≈ 0

- Dialing different **granularities** by averaging initial configuration over 1,2, 5, 10, ... 100 events
- Yields, spectra and elliptic flow are **identical**
- **Triangular flow** ranges from zero (smooth) to a few percent

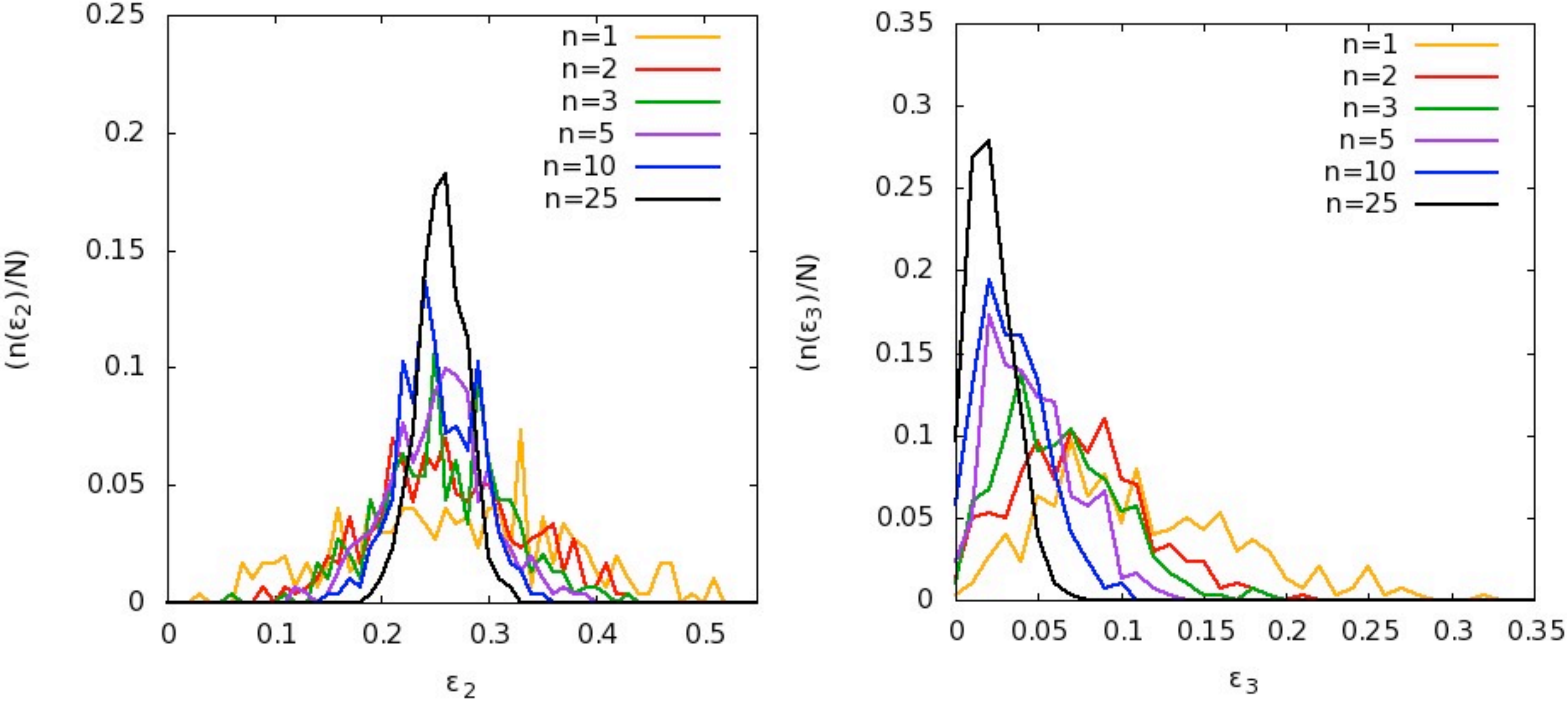
Non-Central Collisions



- Different averages lead to different **granularities**
- Overall **features** of the initial state profile are preserved
- Direct connection to initial state dynamics lost
- Good setup for **systematic** study

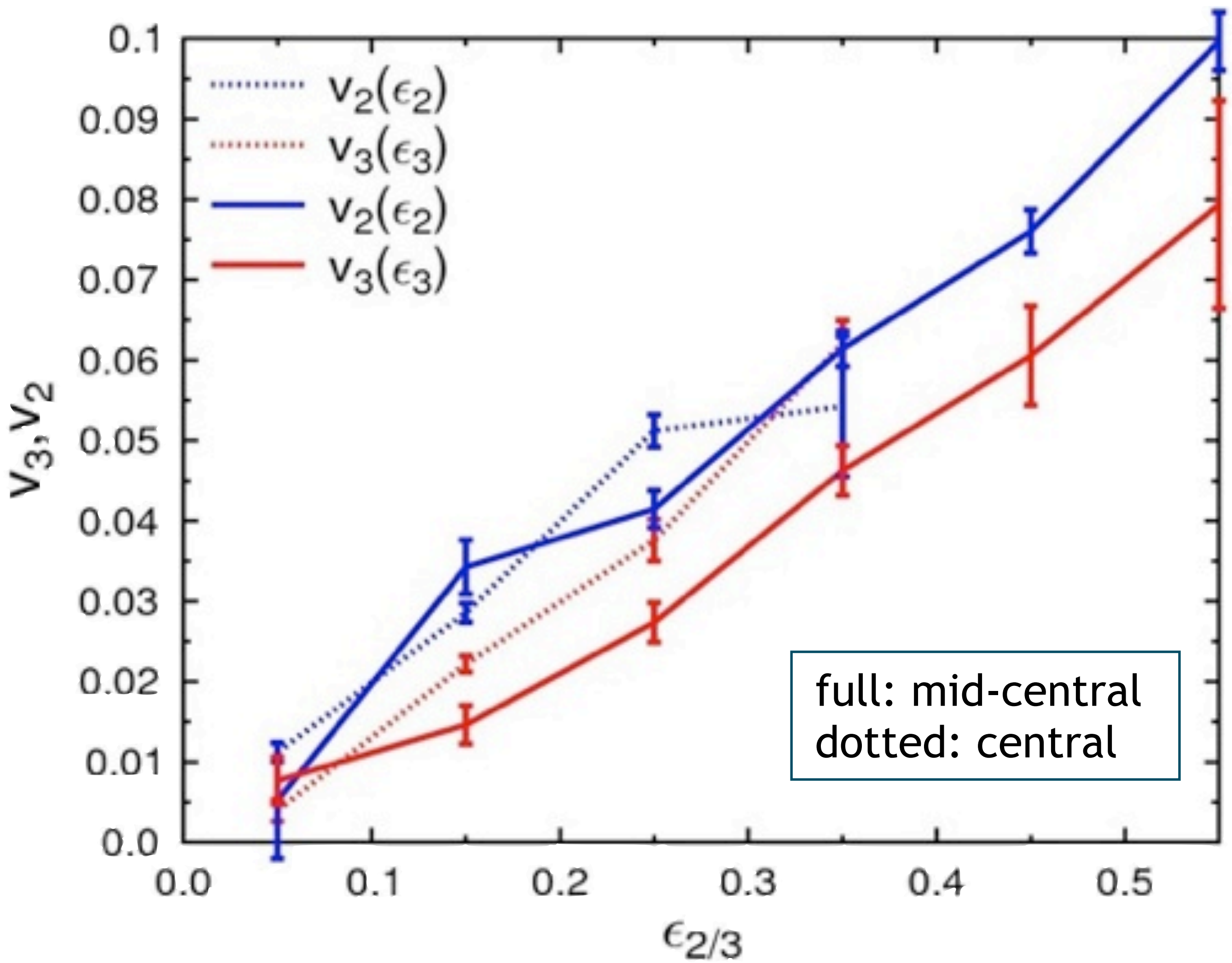
Eccentricity and Triangularity

- **Coefficients** are calculated from the initial energy density distribution in the hydrodynamic calculation



- Probability distribution of ε_2 gets narrower, while for ε_3 the mean value decreases for smoother initial conditions

From Initial to Final State



Initial State Coordinate Space Asymmetry

$$\Phi_n = \frac{1}{n}\arctan\frac{\langle r^n \sin(n\phi)\rangle}{\langle r^n \cos(n\phi)\rangle}$$

$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

Final State Momentum Space Asymmetry

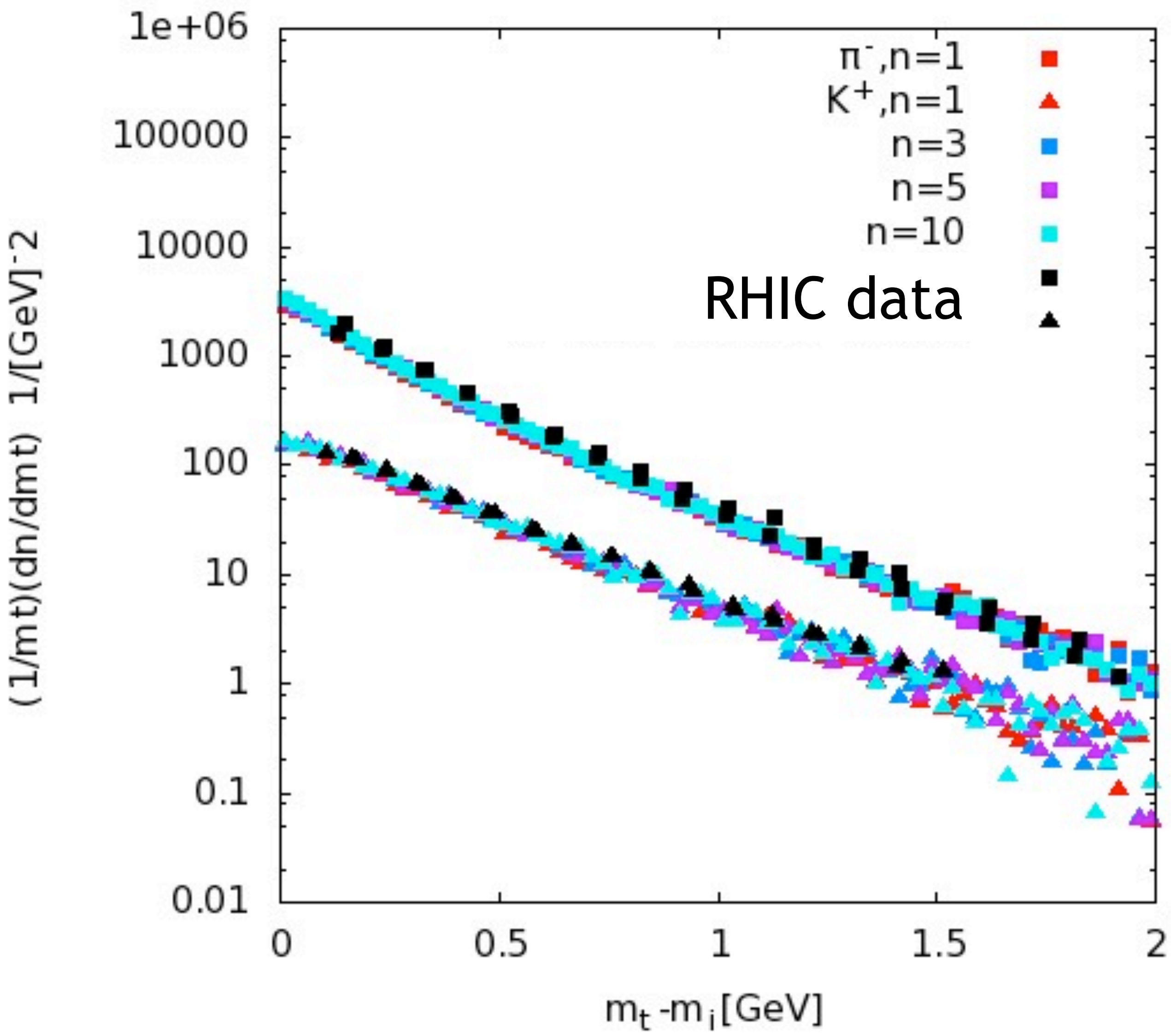
$$\Psi_n = \frac{1}{n}\arctan\frac{\langle p_T \sin(n\phi_p)\rangle}{\langle p_T \cos(n\phi_p)\rangle}$$

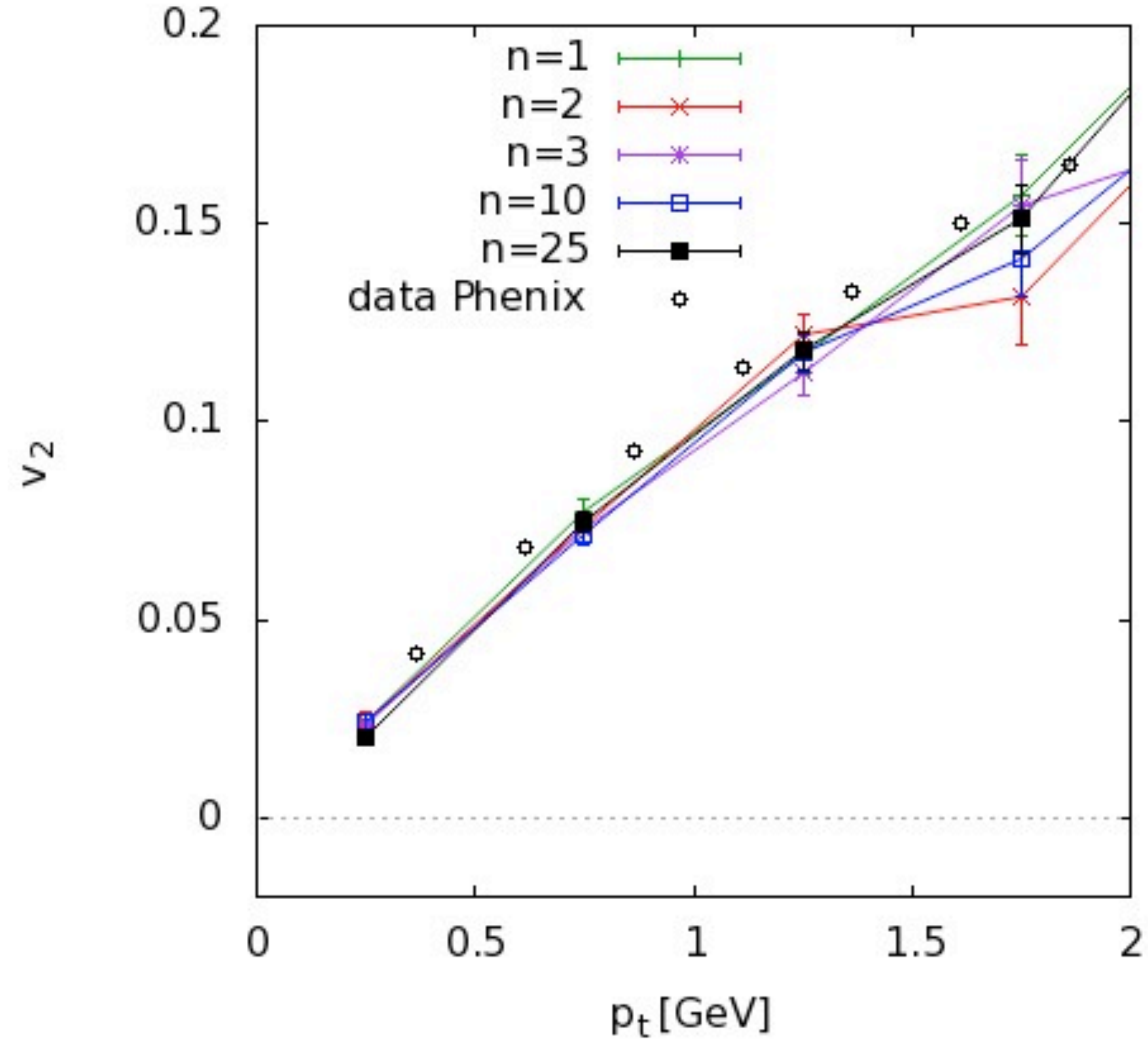
$$v_n = \langle \cos(n(\phi_p - \Psi_n))\rangle$$

- v_n and ε_n and initial and final event plane angles are correlated on an **event-by-event** basis
- Confirms collective behaviour

H.P. at al, PRC 82, 041901

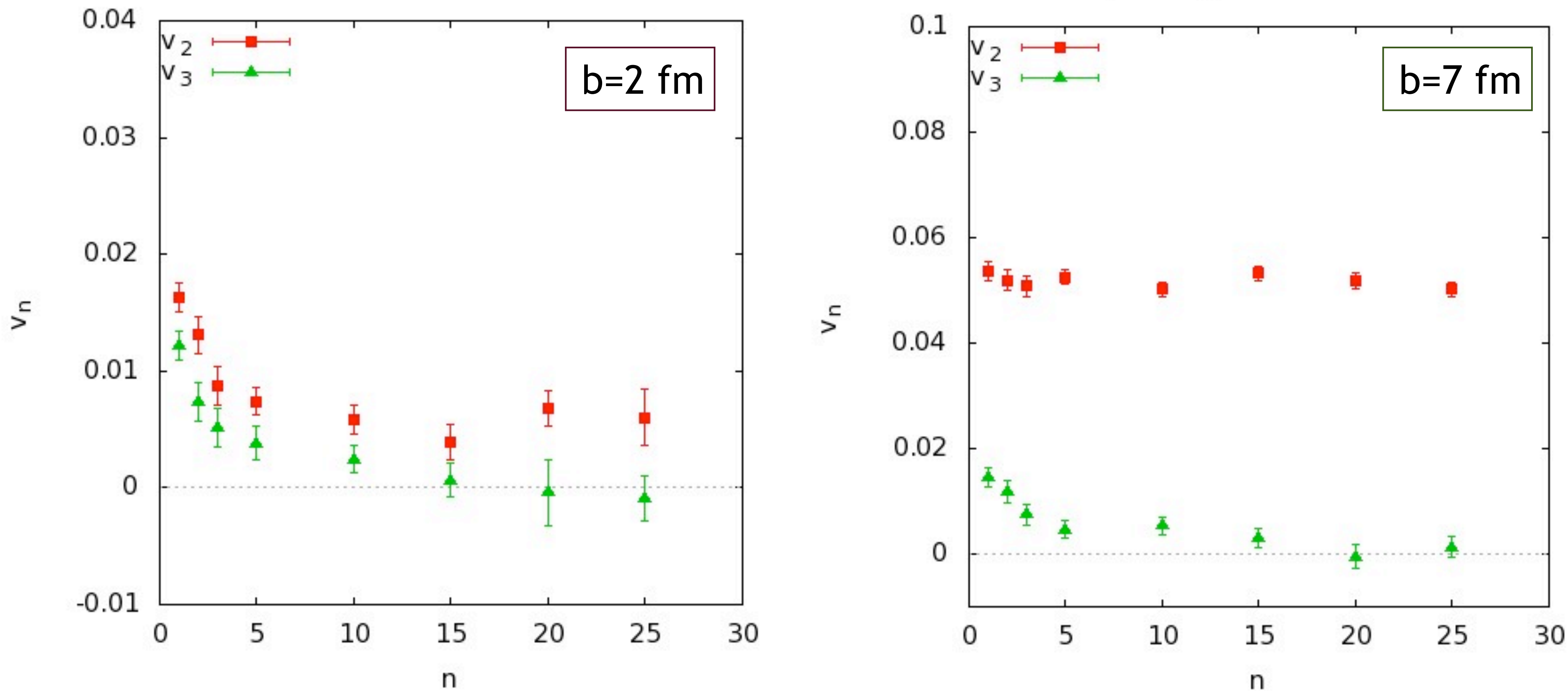
Bulk Observables





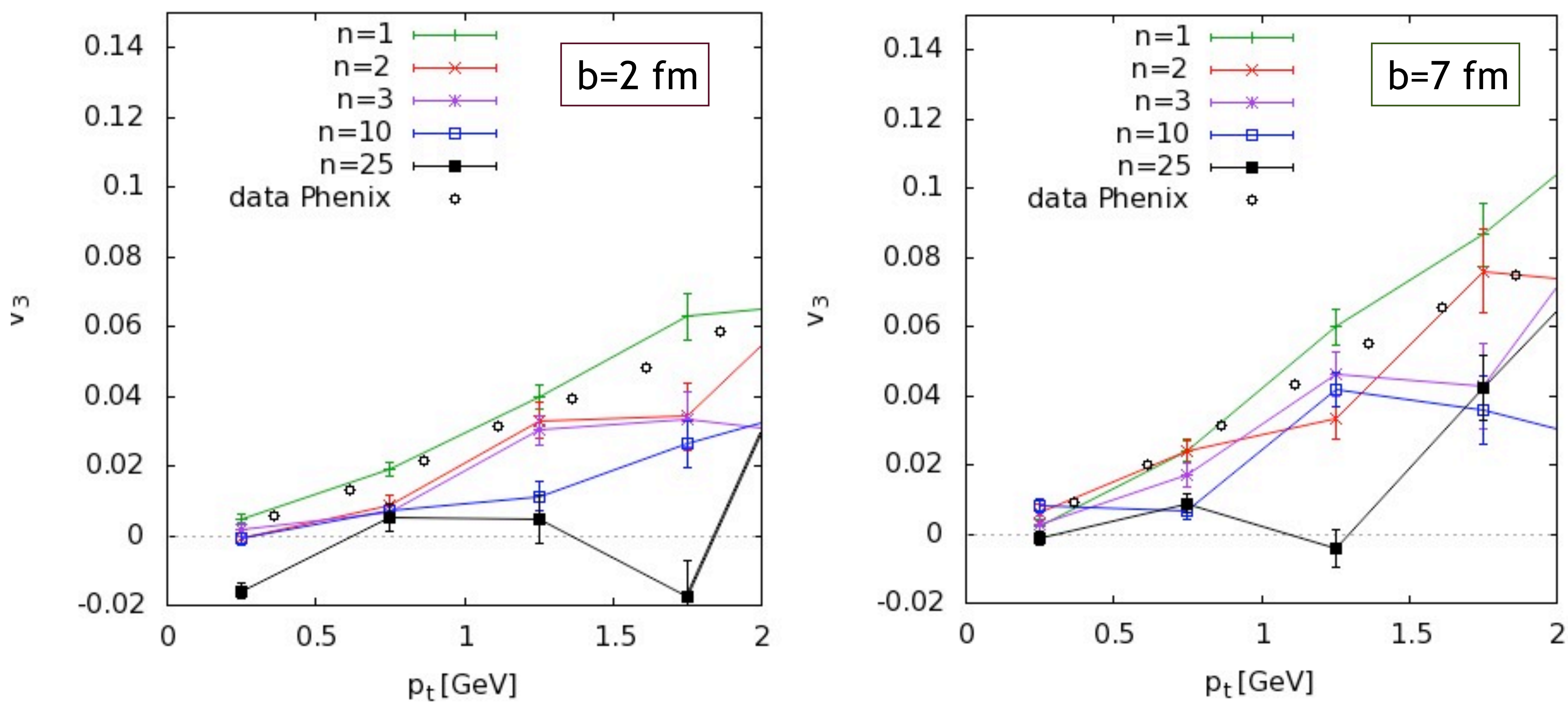
- First check: Transverse mass spectra and elliptic flow are **very similar** for different granularities
- Reasonable **agreement** with experimental data, using EoS that fits lattice calculations

Anisotropic Flow Results



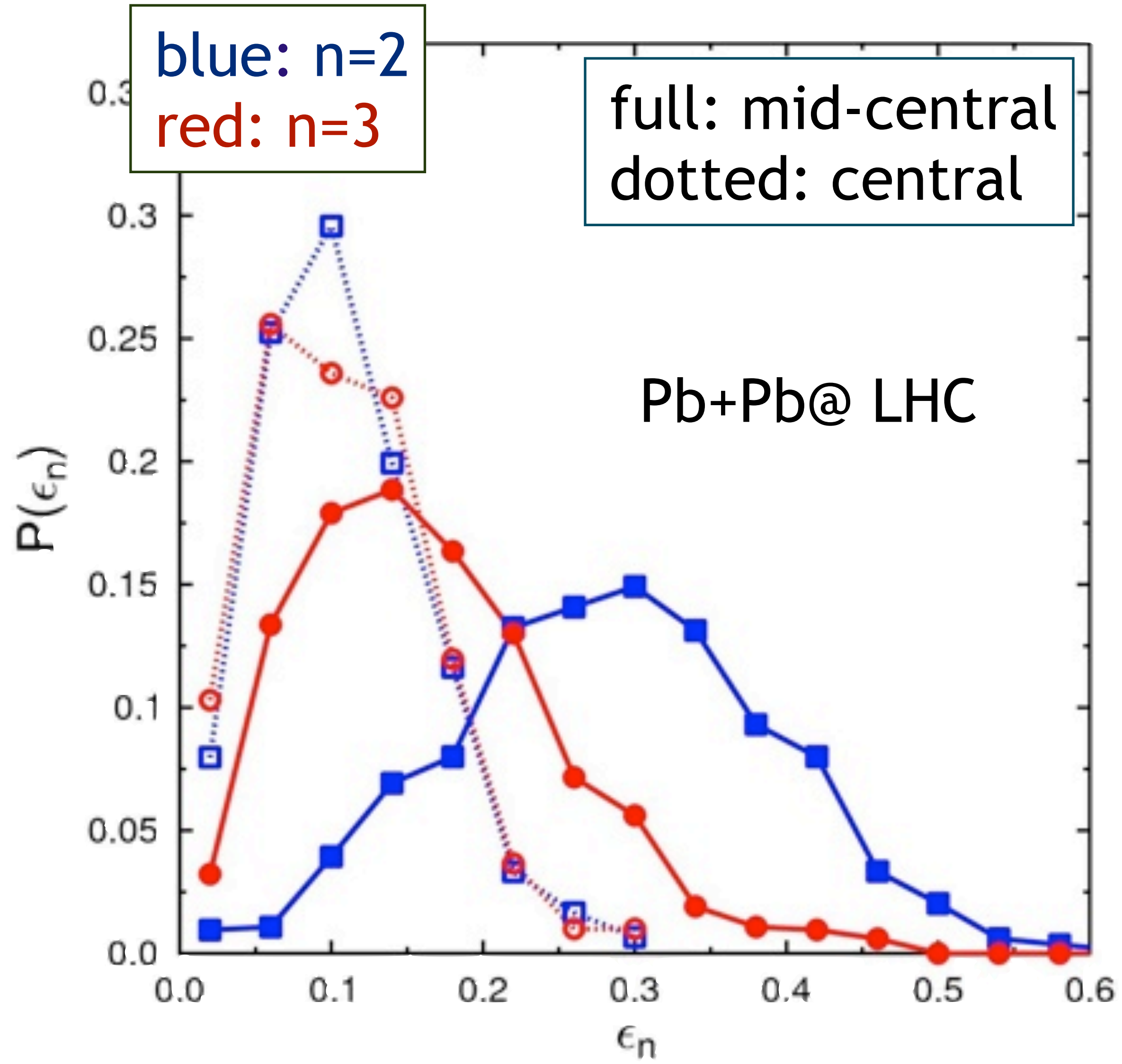
- v_3 is more **sensitive** to the fluctuations as expected
- **NO** resolution correction applied to see qualitative behavior
- How does that compare to the measured values?

Comparison to PHENIX



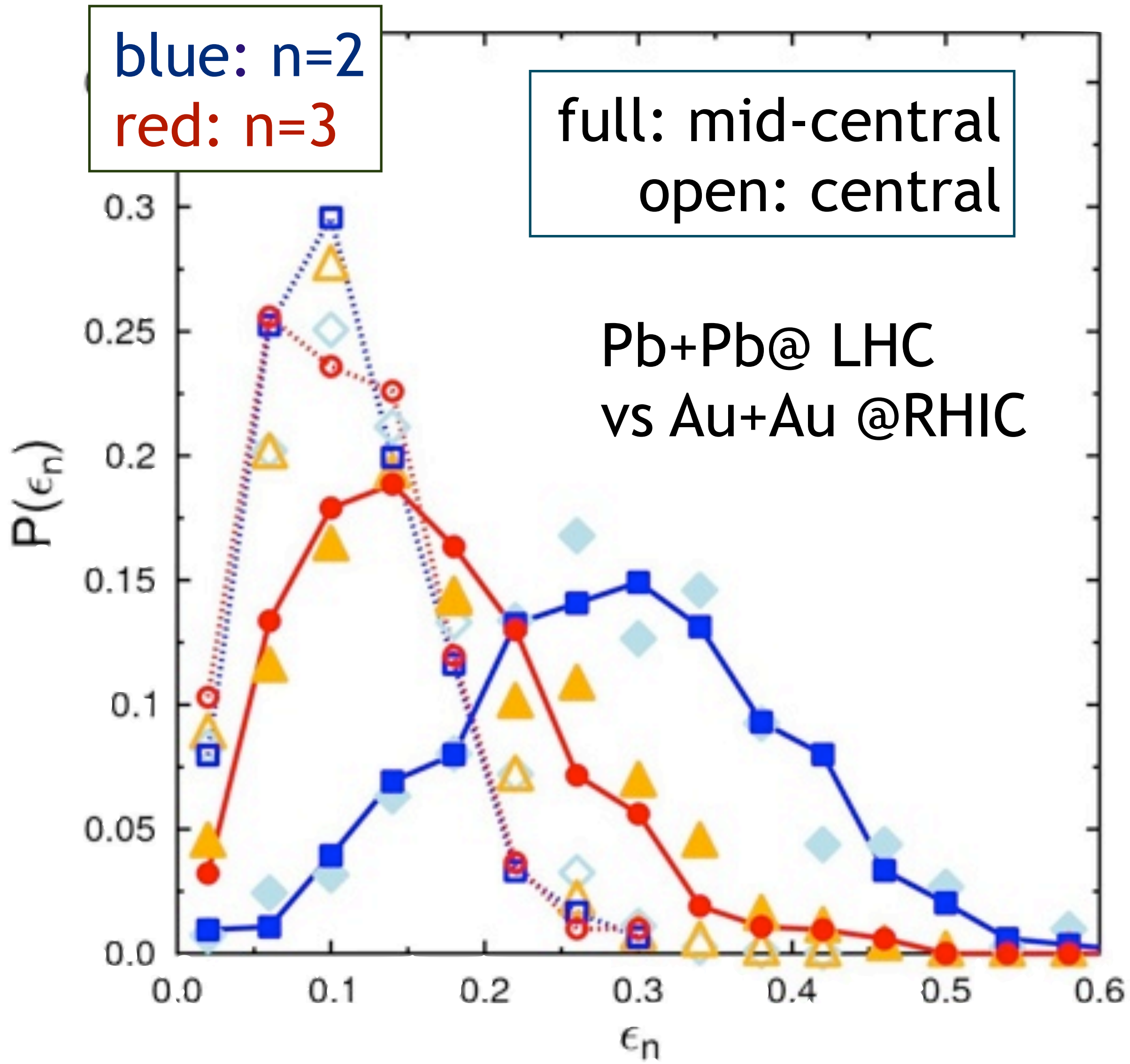
- PHENIX data is in between **n=1** and **n=3**
- **Lower limit** for initial state granularity
- Finite shear **viscosity** during hydro evolution smoothes fluctuations out faster

Higher Energies - LHC



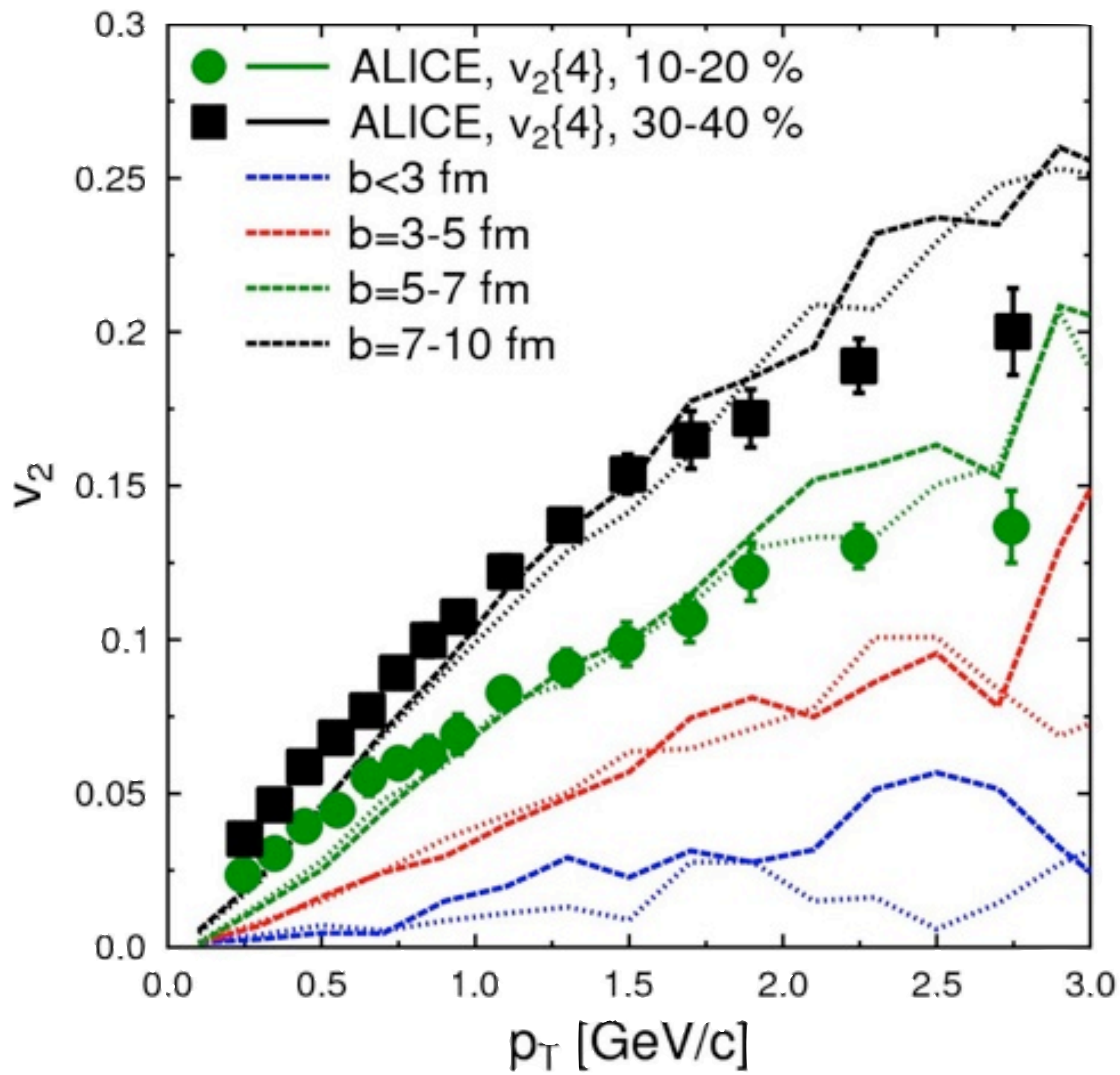
- **Probability distribution** contains information about initial state profile and fluctuations
- Eccentricity and triangularity in central collisions are very similar
- Mid-central collisions: $\varepsilon_2 > \varepsilon_3$ and $P(\varepsilon_2)$ is wider

Higher Energies - LHC



- In UrQMD the whole probability distribution is almost **identical** at RHIC and LHC
- Higher multiplicity has no visible effect on fluctuations
- Energy fluctuation per binary interaction larger?

Comparison to LHC data

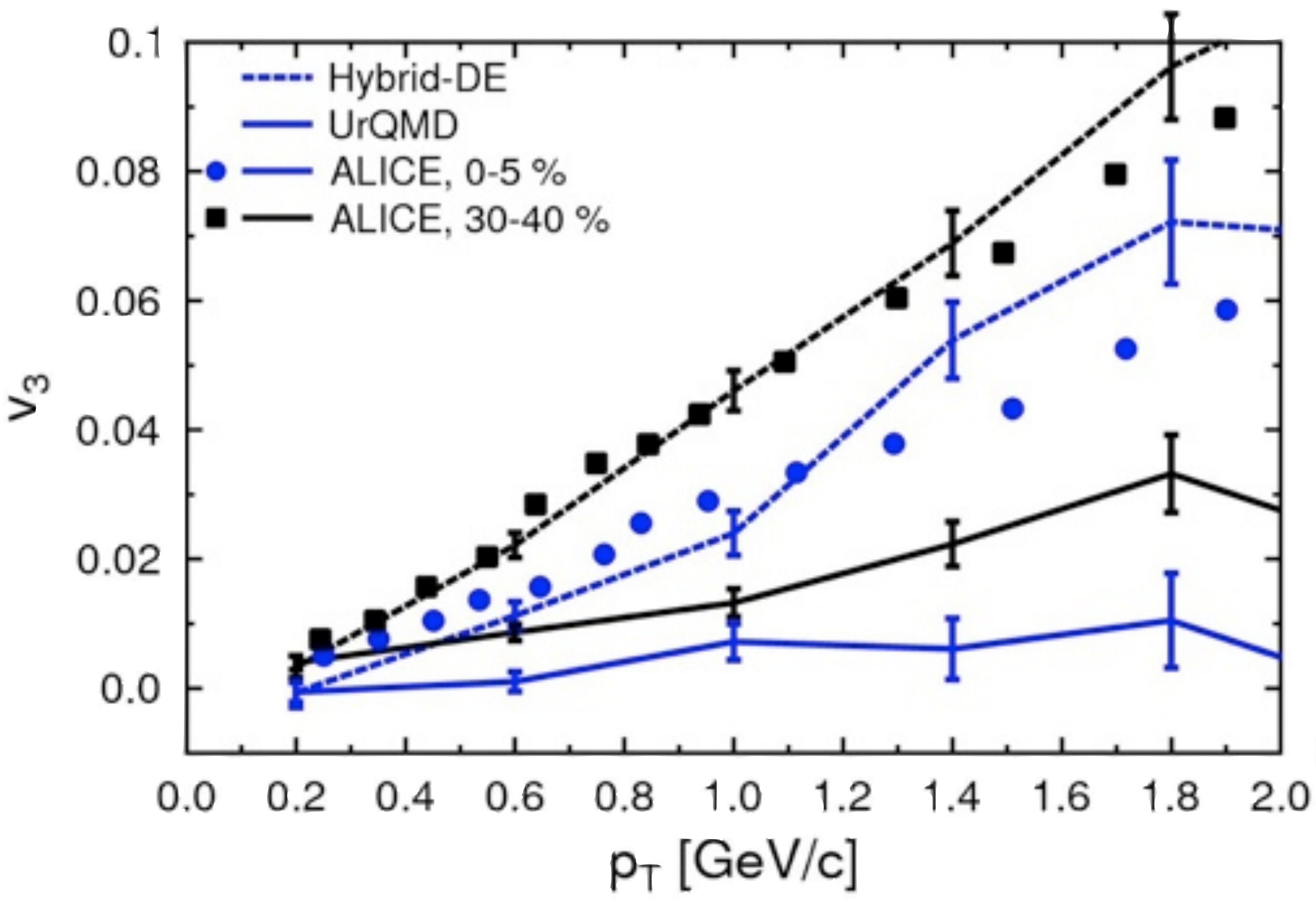


dashed line: DE-EoS
dotted line: HG-EoS

- Exact **same parameter** set as applied at RHIC
- Hybrid approach is in good **agreement** at low p_T
- Different **EoS** give similar results

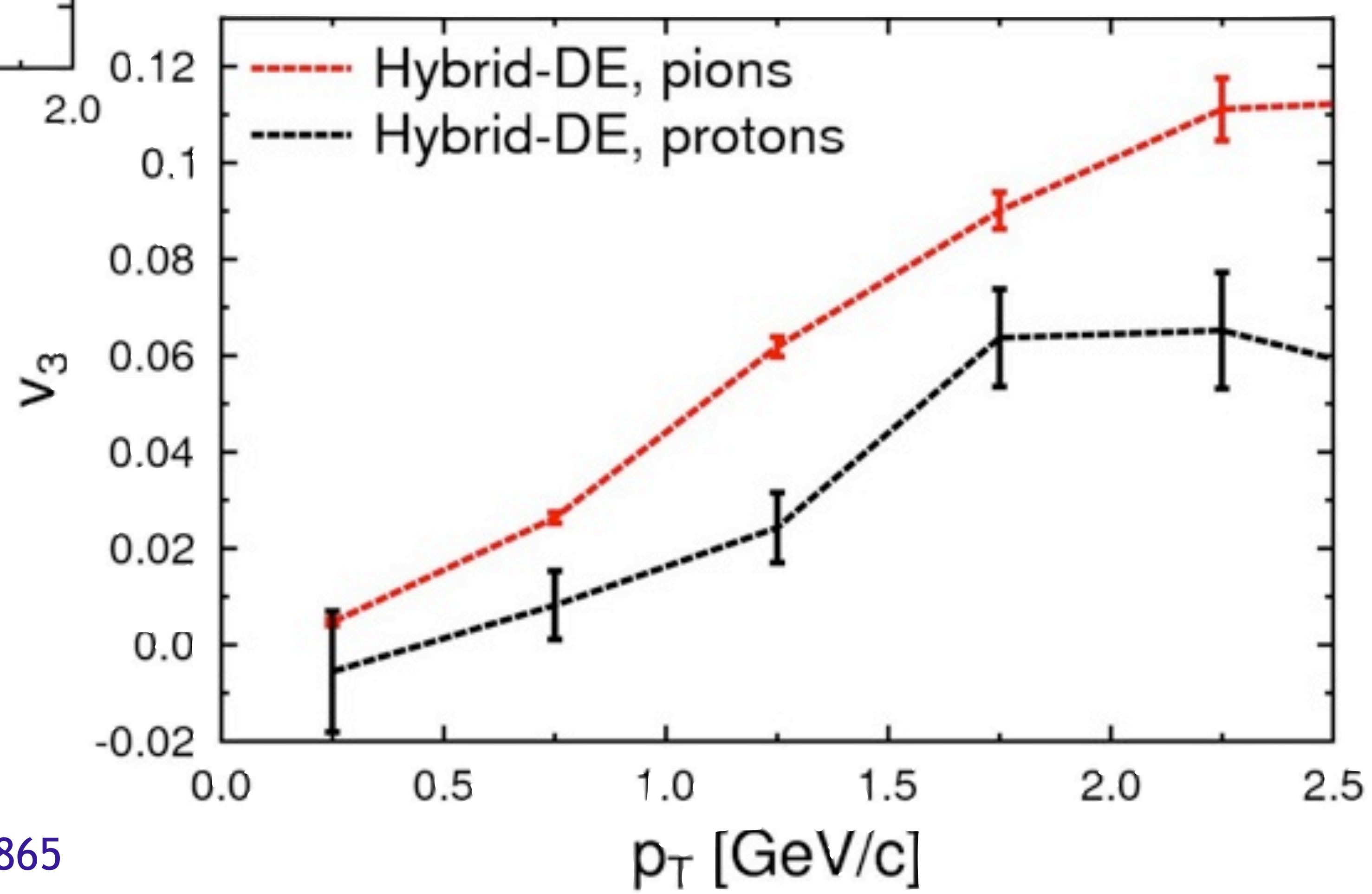
H.P., arXiv: 1105.1766

Triangular Flow at LHC



- Triangular flow is almost **zero** in UrQMD
  → Very sensitive to viscosity
- Same **granularity** is in reasonable agreement with experimental data

- Minimum bias result for **identified** particles
- Mass splitting



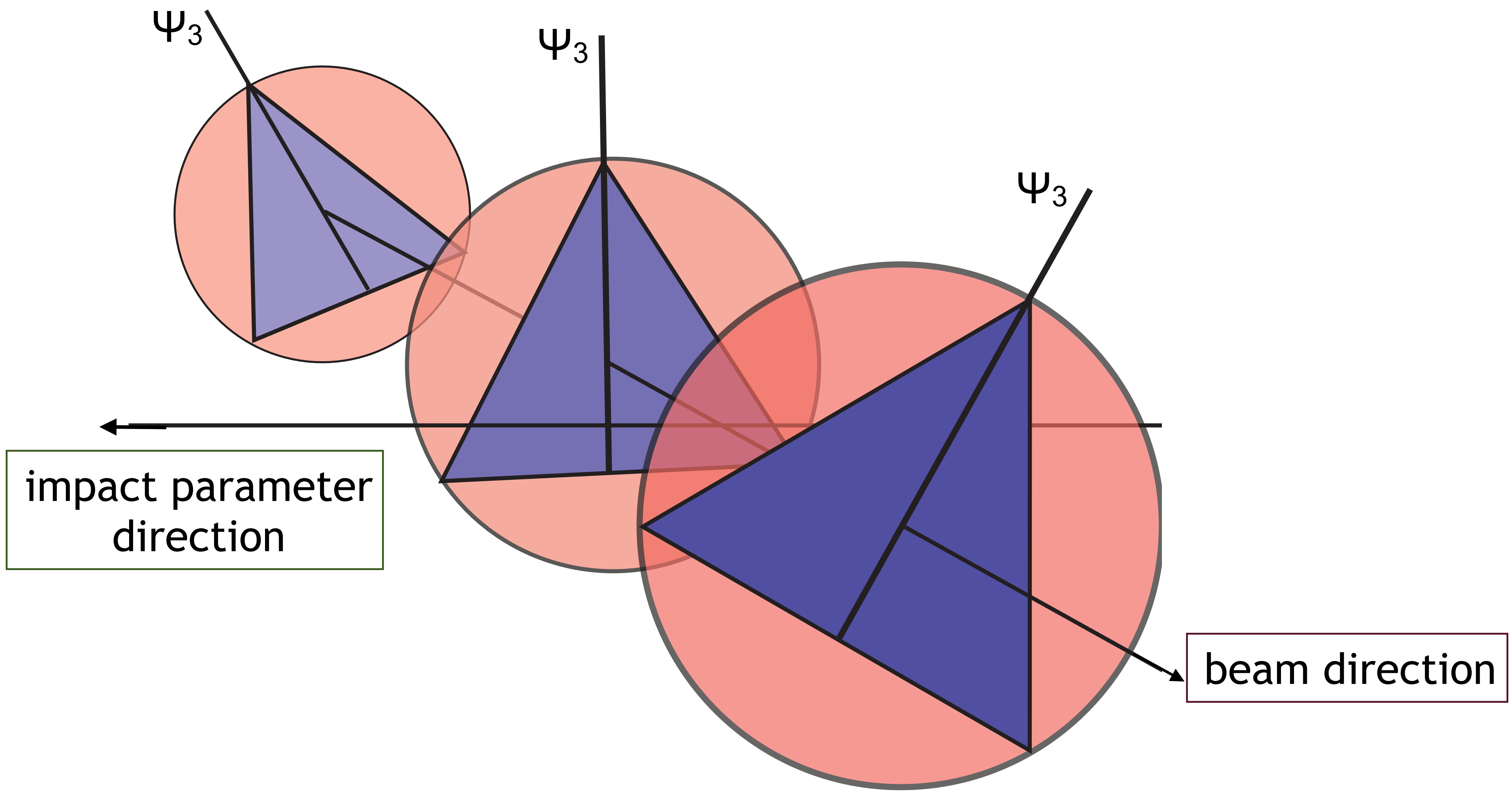
H.P., arXiv: 1105.1766, ALICE data from arXiv:1105.3865

Conclusions

- Dynamic transport approaches provide **fluctuating initial conditions**
- The **amount** of initial state fluctuations can be **tuned** by averaging over different numbers of events
- Probability **distributions** of eccentricity and triangularity encode information about shape and fluctuations
- Proof that triangular flow provides a good measure for initial state **granularity** by a **systematic** study that allows to place a lower limit on the initial state granularity
- LHC results from **event-by-event** hydro are in reasonable agreement with the data with the same granularity
- Further strategy to a quantitative understanding:
  - Constrain the shear viscosity by elliptic flow in mid-central collisions
  - Tune the granularity to match the triangular flow result
  - Central collisions, LHC results and smaller systems provide lots of room for determining the shape of the profile

Backup

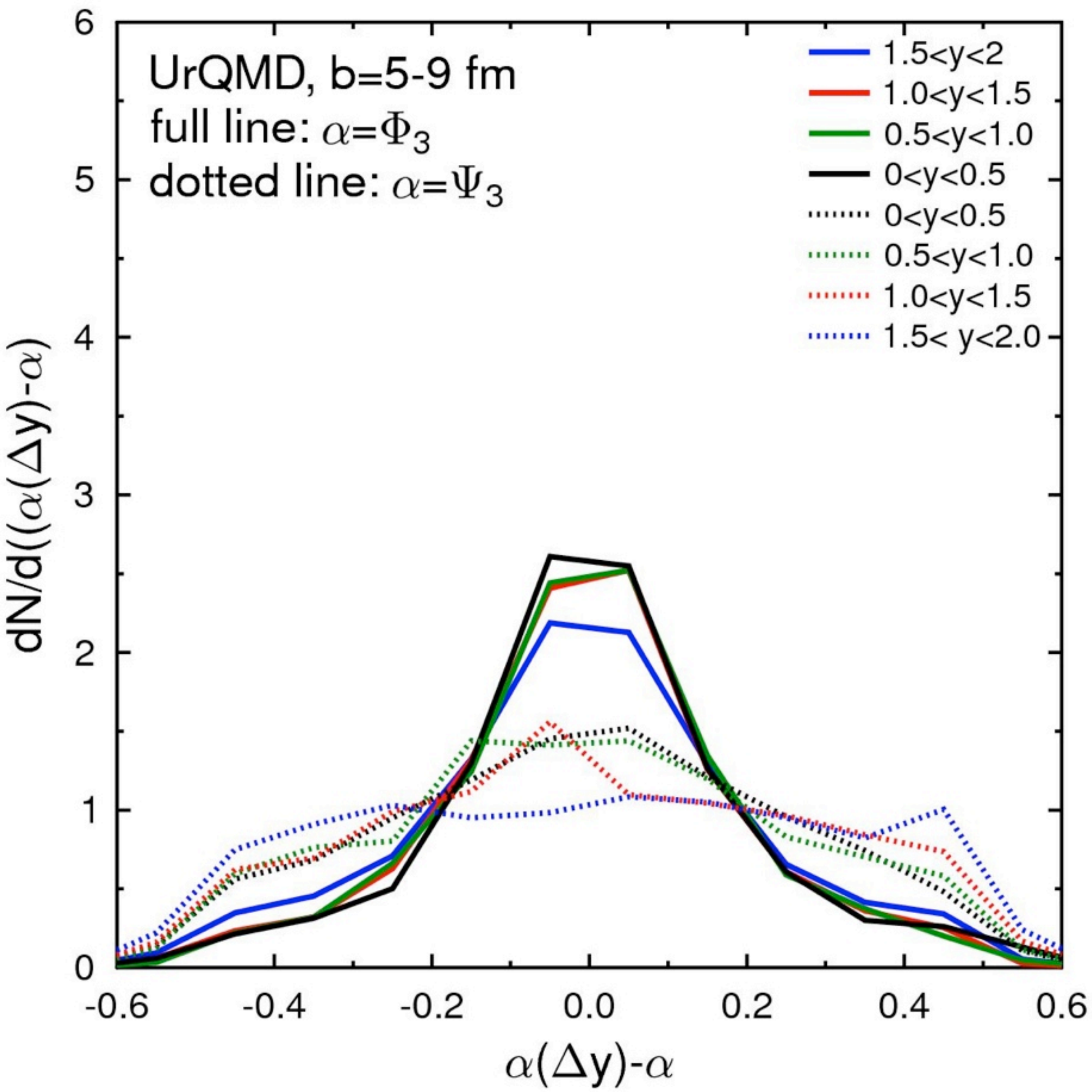
Longitudinal Correlation



- Idea: look at event plane angles in different rapidity **slices**
- Important verification of the **event plane method** which relies on a single plane for the whole event

Longitudinal Correlation

- Calculate overall event plane angle and angle in each bin
- Look at the distribution of the **differences** of these angles

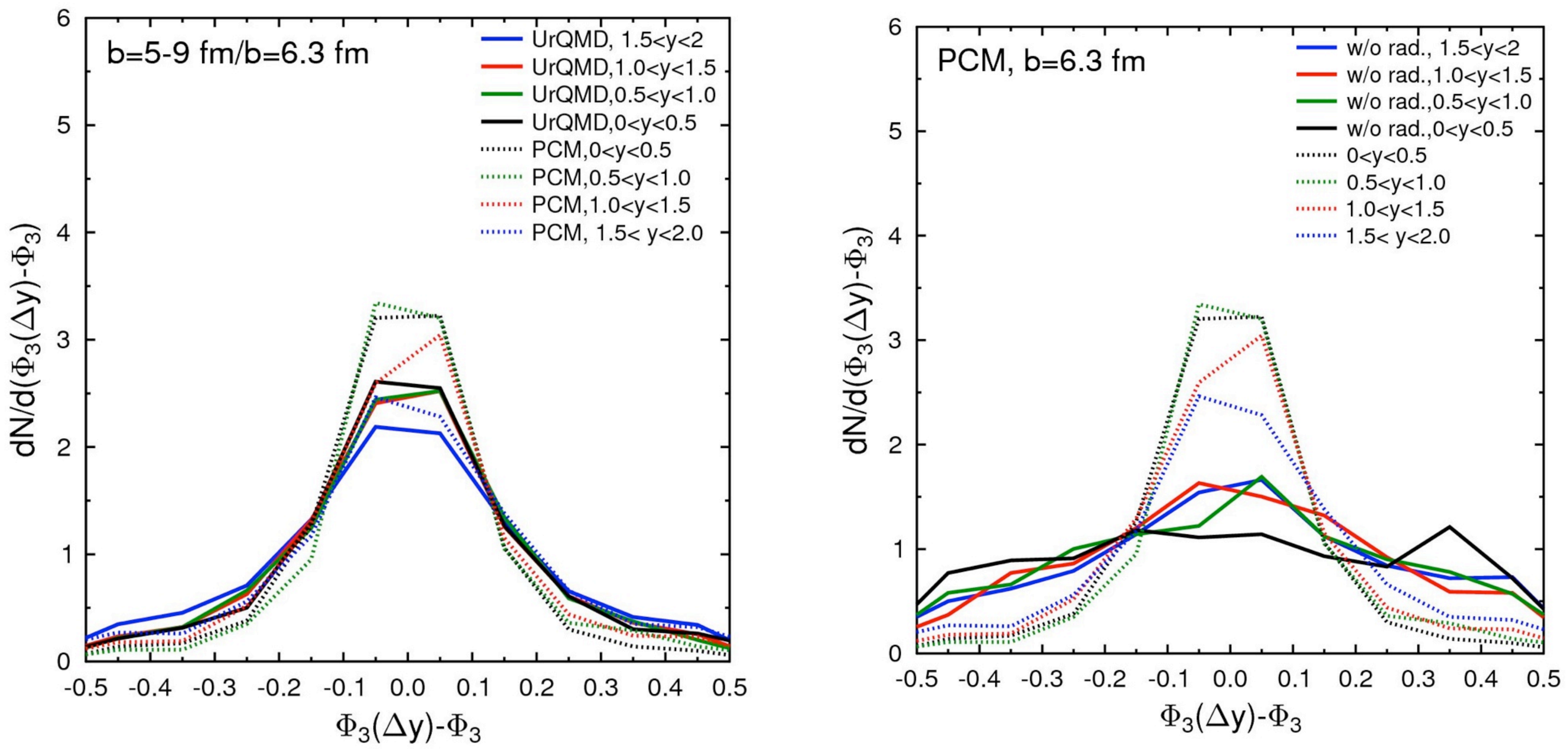


H.P. et al, arXiv: 1105.0340

→ There is a **correlation** in the initial state generated by **string** fragmentation
→ Stronger at midrapidity
→ Gets **smeared** out during hydro evolution

Compare to **parton cascade** initial conditions to explore a different initial scenario

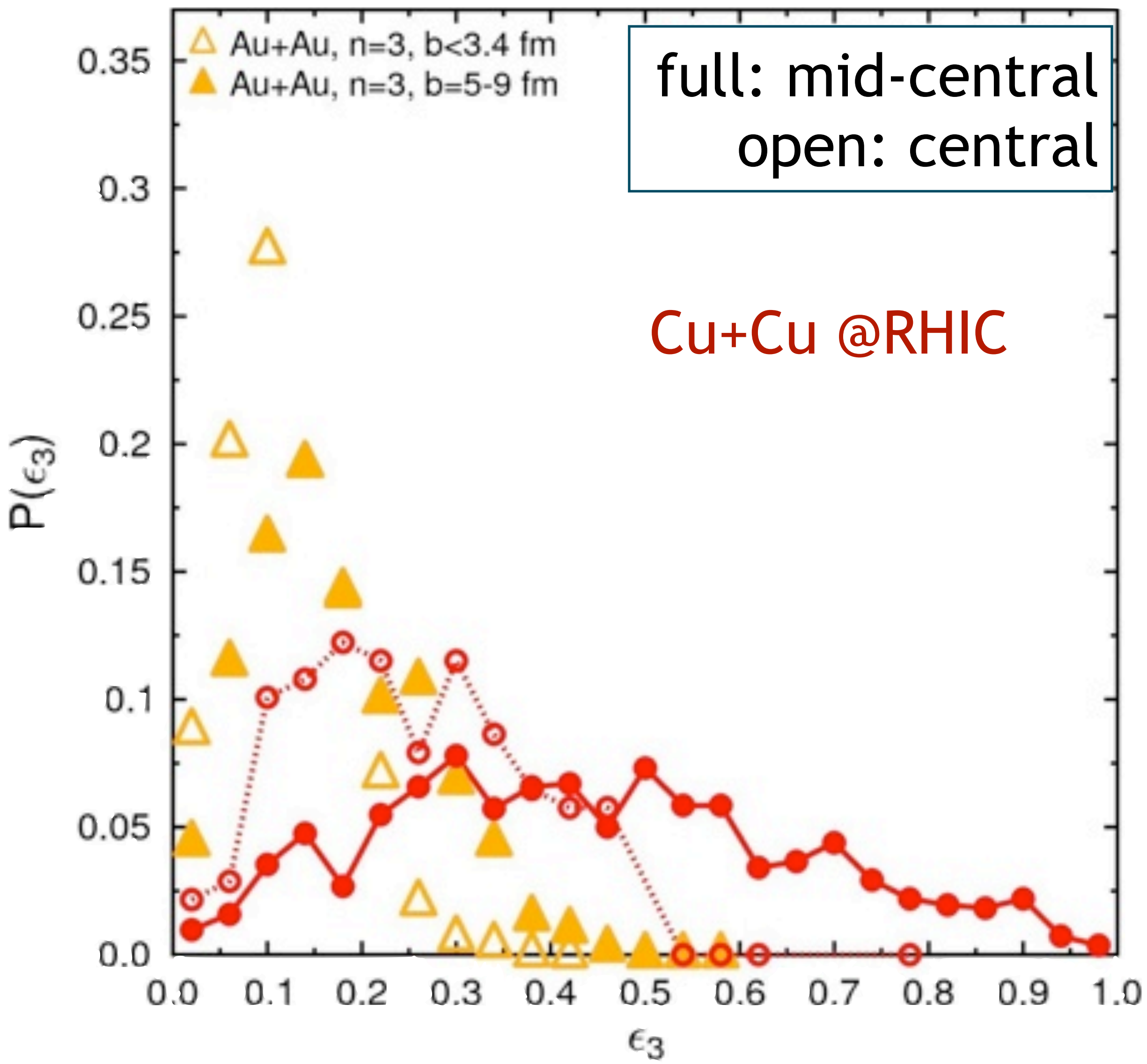
PCM Initial State



- **Time-like branchings** following binary scattering also introduce long-range longitudinal correlation
- Not **unique** to flux tube/string picture

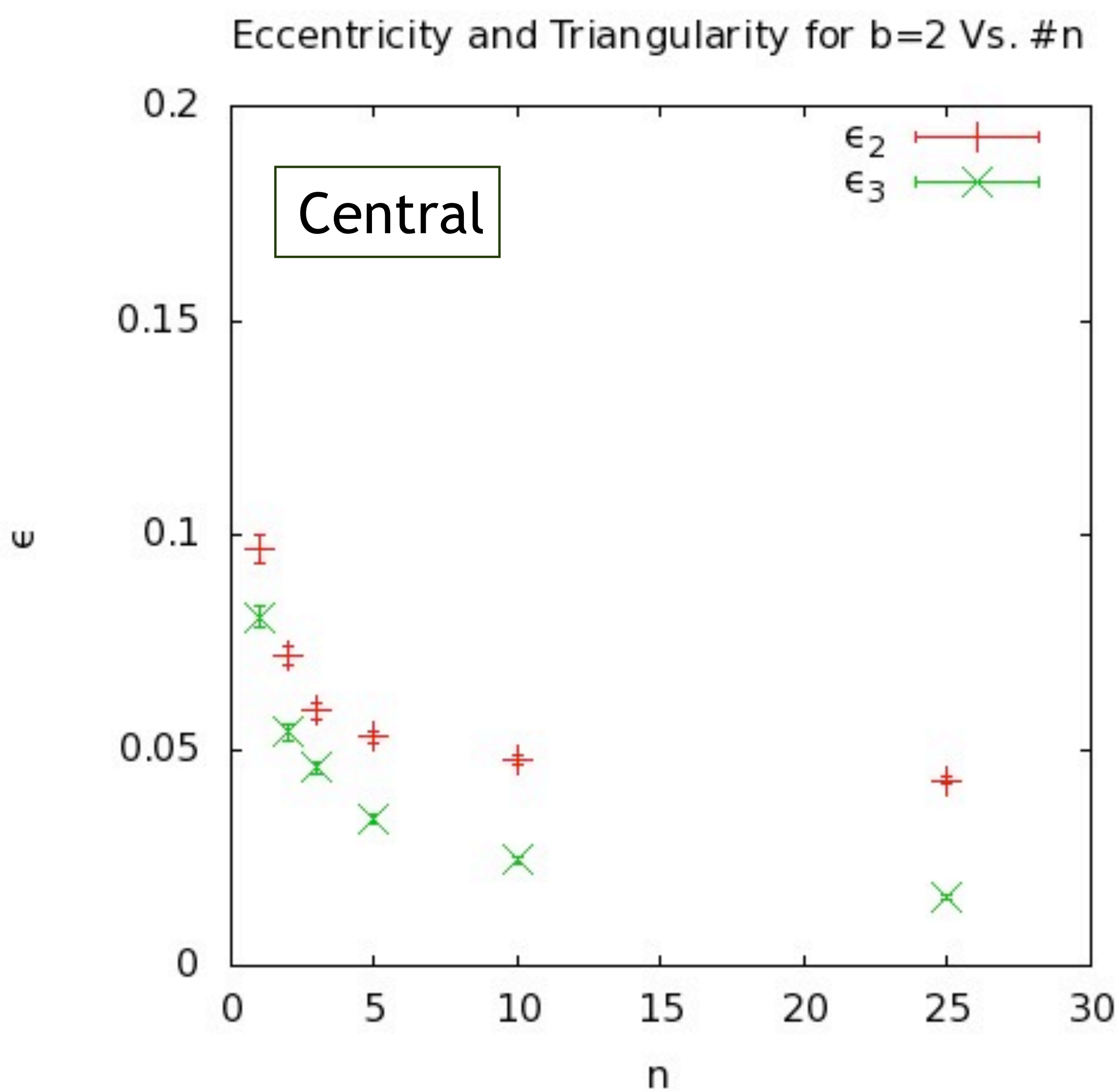
H.P. et al, arXiv: 1105.0340

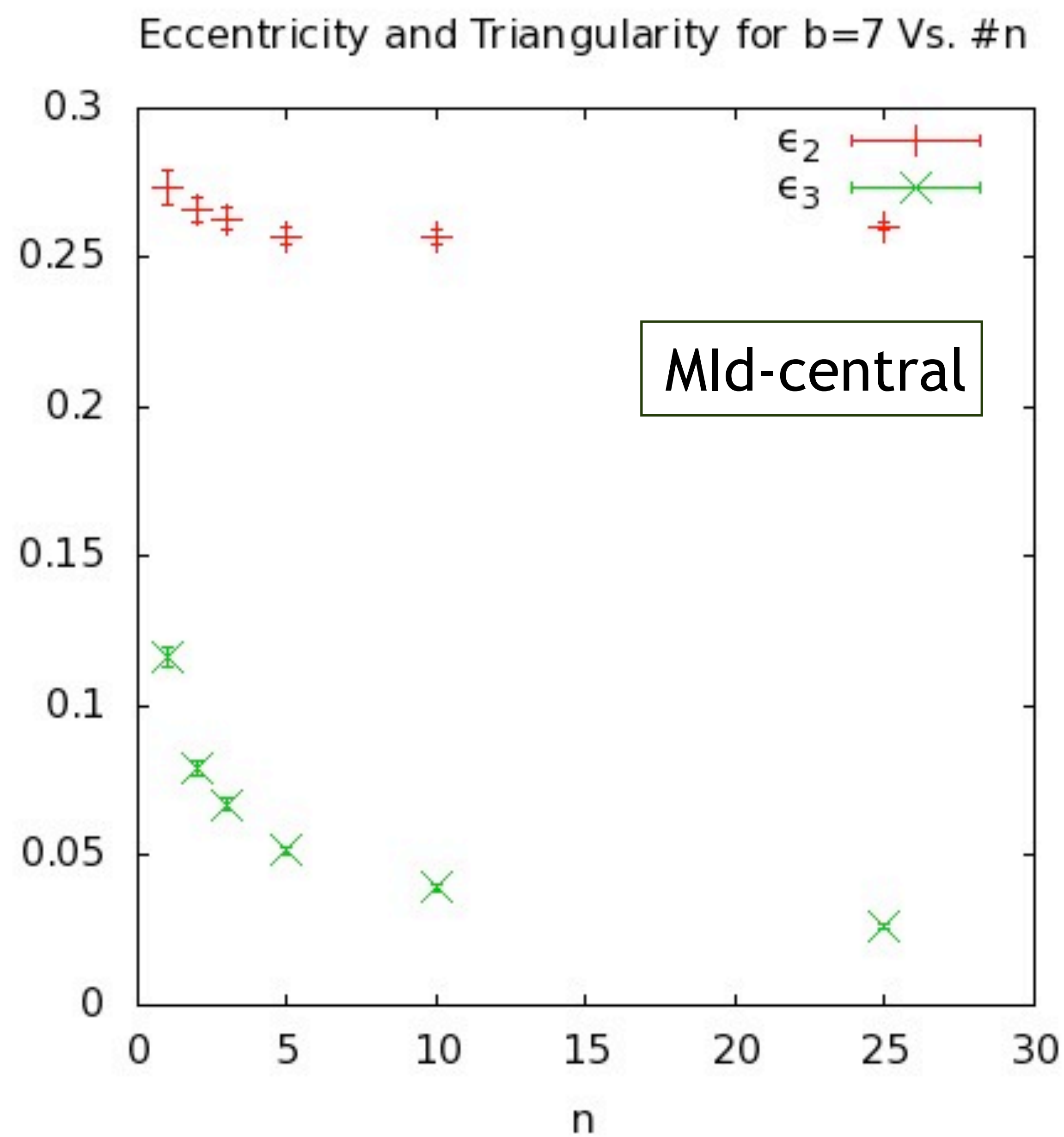
Smaller Systems - CuCu



- In UrQMD the whole probability distribution is almost **identical** at RHIC and LHC
- Geometry of overlap region does not change
- Higher multiplicity has no visible effect on fluctuations

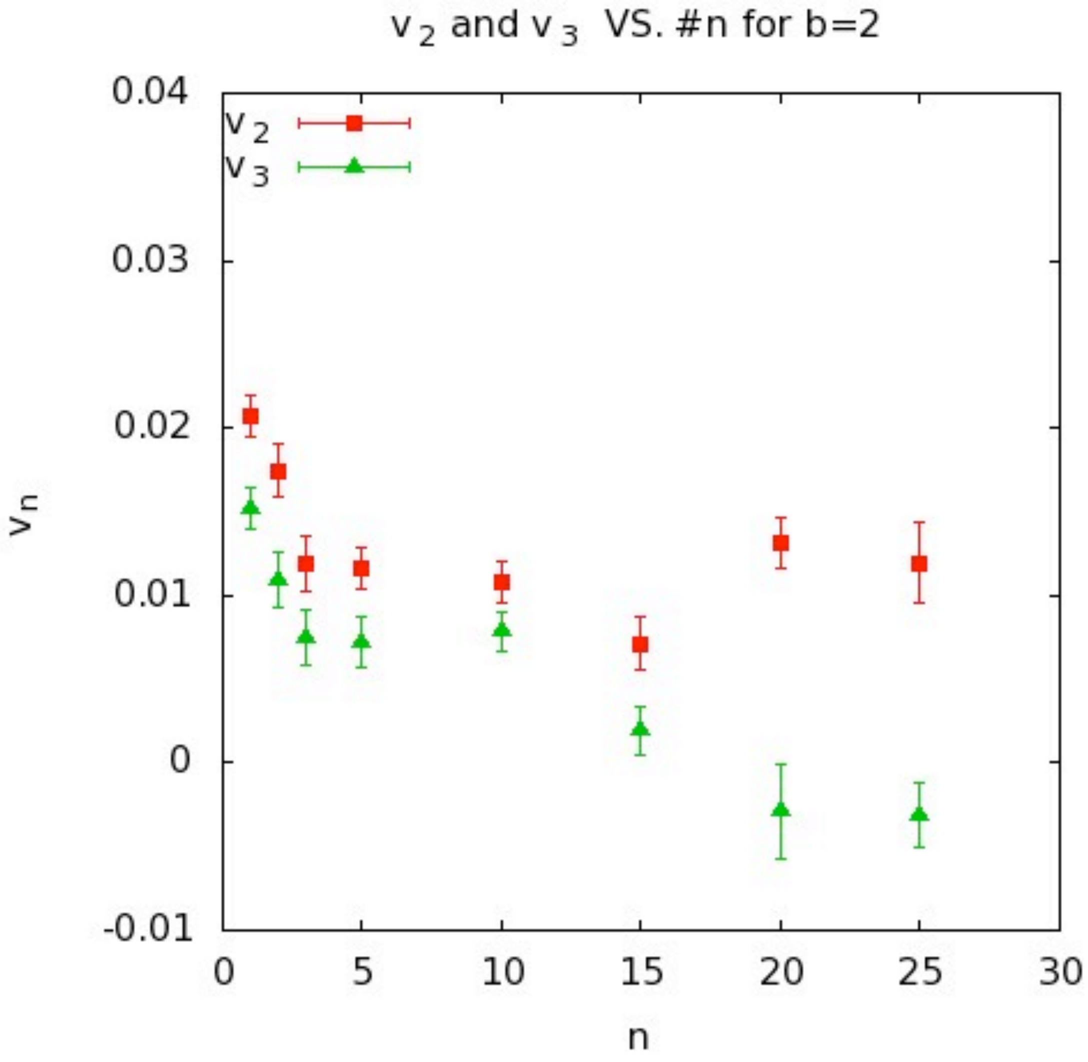
Sensitivity to Granularity

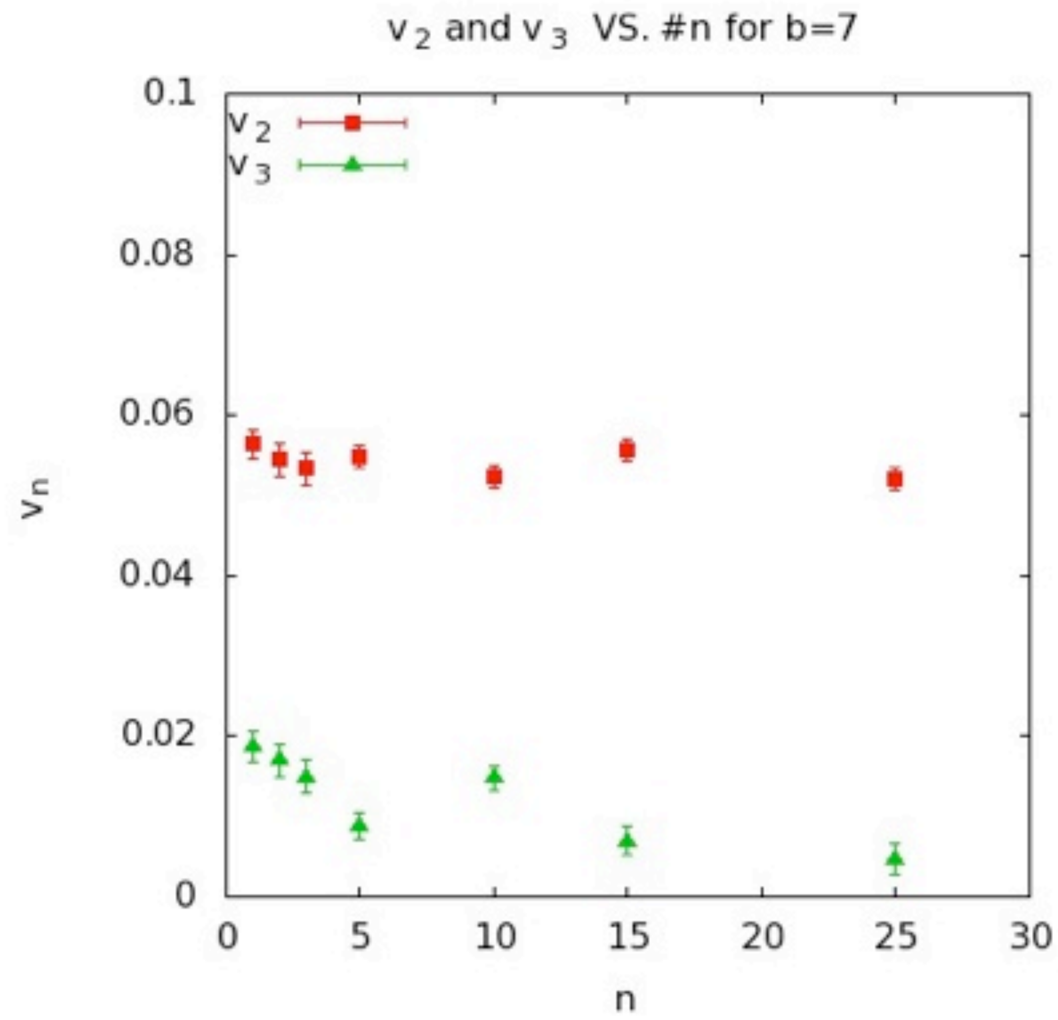




- Central collisions: ε_2 and ε_3 **similar** as a function of granularity
- Mid-Central collisions: **ε_2 constant** due to almond-shaped geometry, while **ε_3 sensitive** to amount of fluctuations

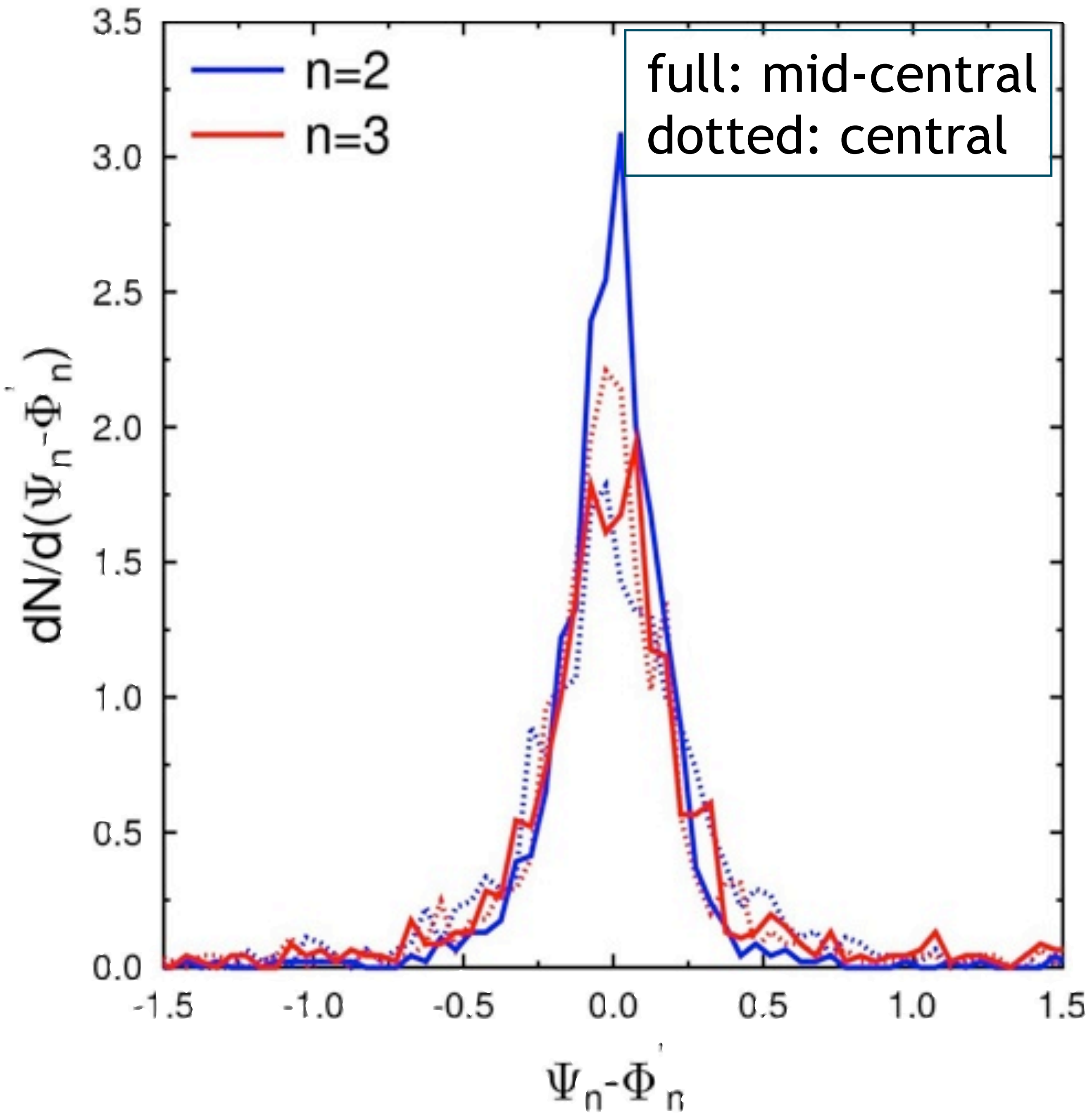
Anisotropic Flow Results





- Resolution correction increases the values and is granularity dependent
- General trends are still preserved

From Initial to Final State

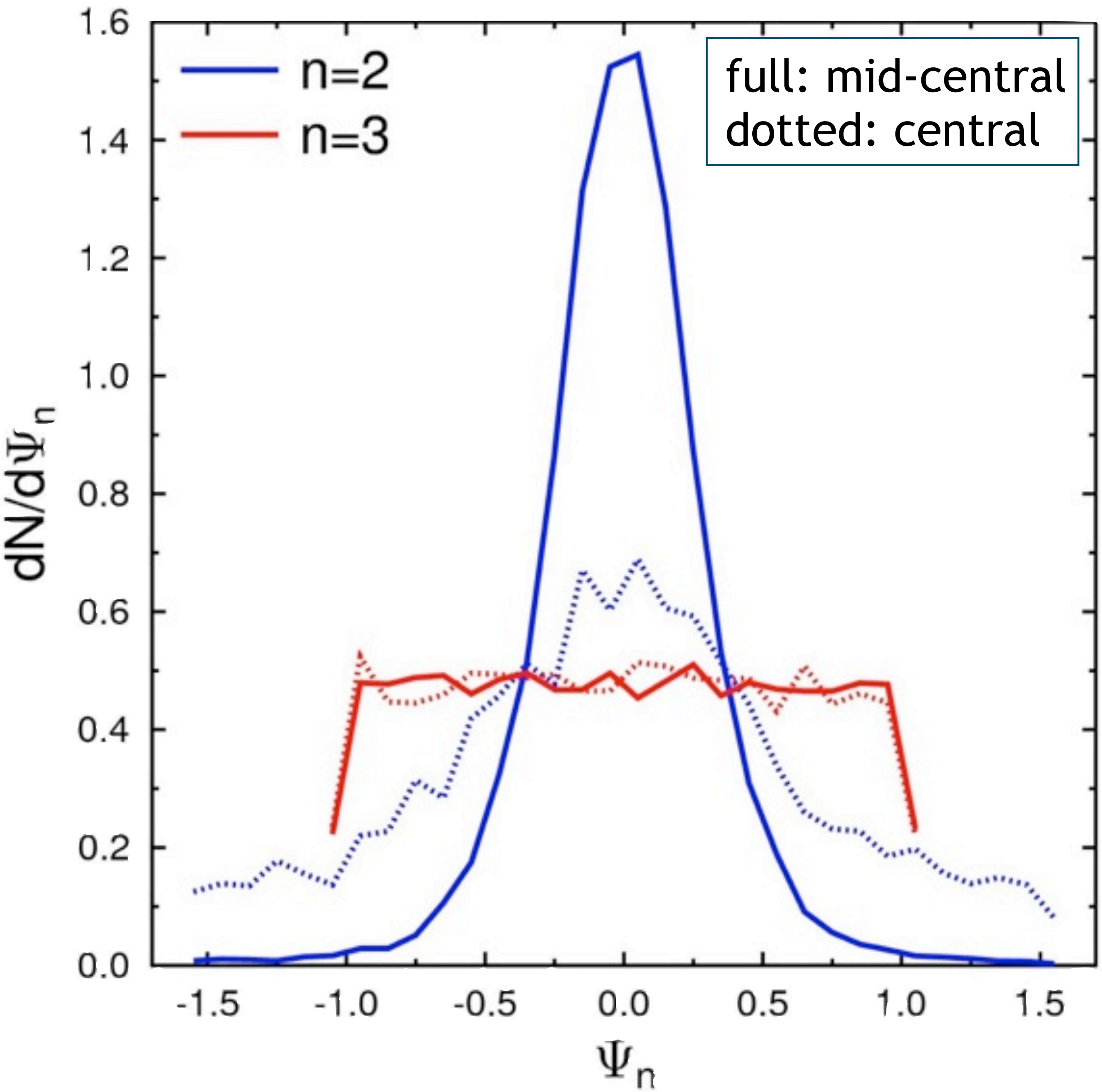


- Φ_n is calculated in **initial** coordinate space
- Ψ_n from **final** momentum space distribution
- There is a strong **correlation** between the two angles
- For elliptic flow stronger in more peripheral events

$$\Phi_n = \frac{1}{n}\arctan\frac{\langle r^n \sin(n\phi)\rangle}{\langle r^n \cos(n\phi)\rangle} \longrightarrow \Psi_n = \frac{1}{n}\arctan\frac{\langle p_T \sin(n\phi_p)\rangle}{\langle p_T \cos(n\phi_p)\rangle}$$

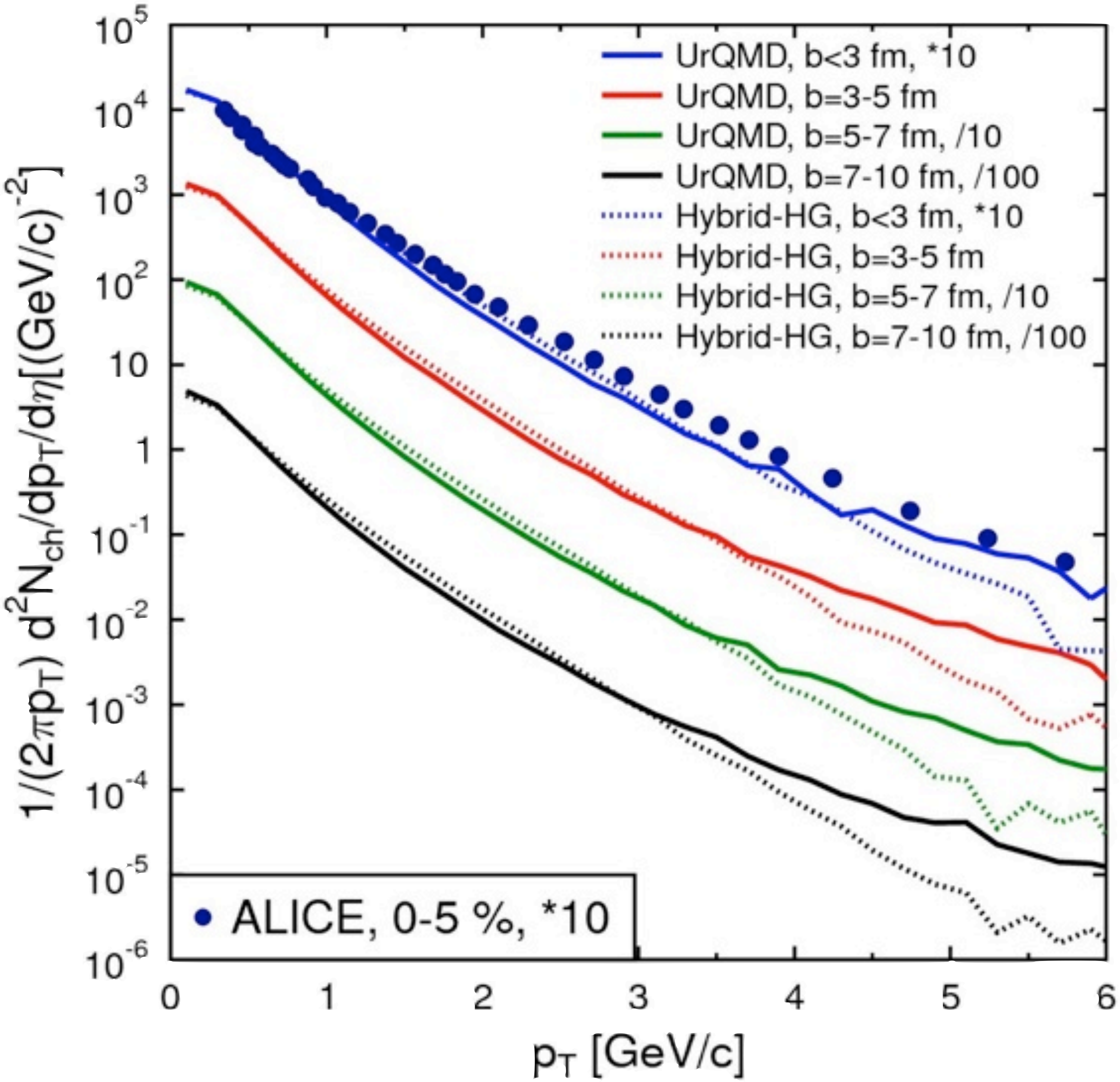
H.P. et al., PRC 82, 041901, 2010, arXiv:1008.0625

Event Plane Angles



- Ψ_2 is **correlated** to reaction plane
- Ψ_3 distribution is **flat**
- **Only** fluctuations, no geometry in contrast to elliptic flow where both are mixed
- Triangular flow can be used for measuring granularity

Spectra at LHC



- Hybrid works well for pt<3 GeV