How Does Triangular Flow Constrain The Initial State Granularity?

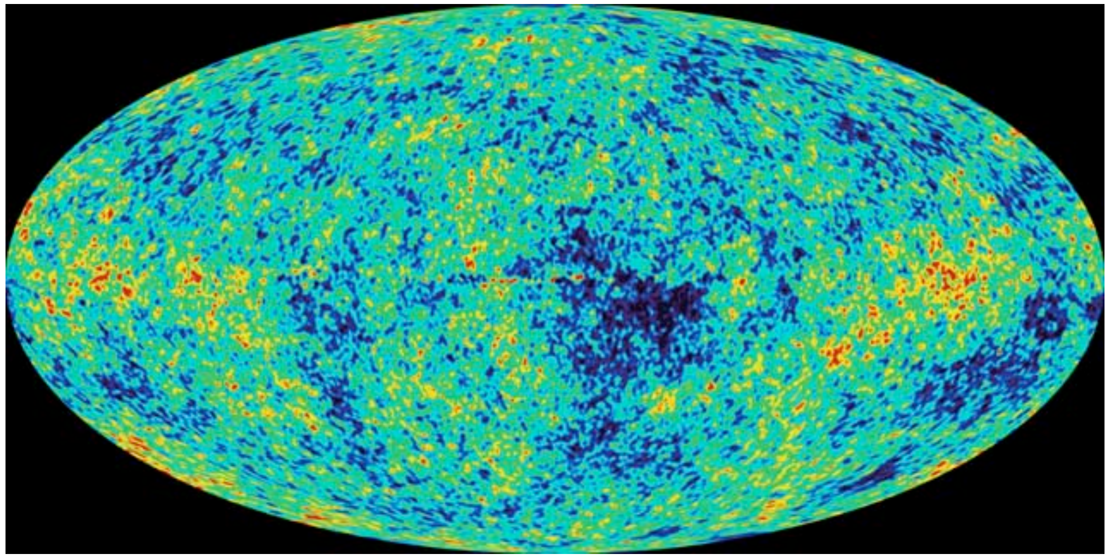
NeD/Turic Workshop, Hersonissos, Greece

06/27/2012

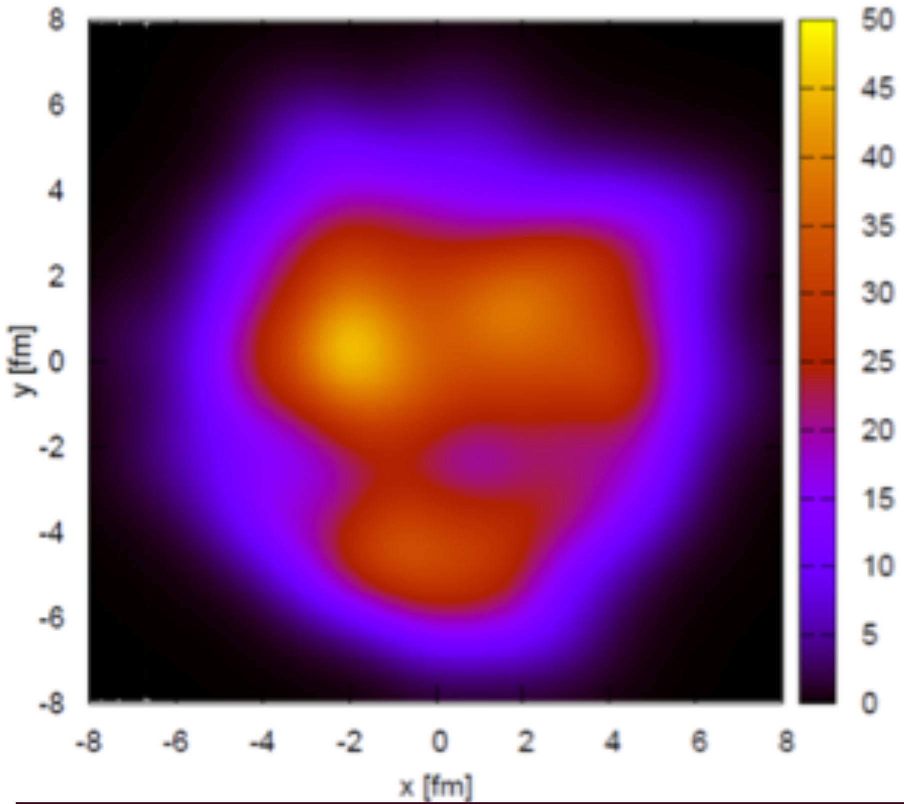
Hannah Petersen, Duke University, Durham, NC

Outline

- Realistic event-by-event description
  - Hybrid approach
- Initial conditions
  - Quantification of **initial state** structures
  - Parameter study
- Triangular flow results and their sensitivity to initial state granularity
- Flow results at RHIC/LHC
- Challenge: Multi-Parameter fit



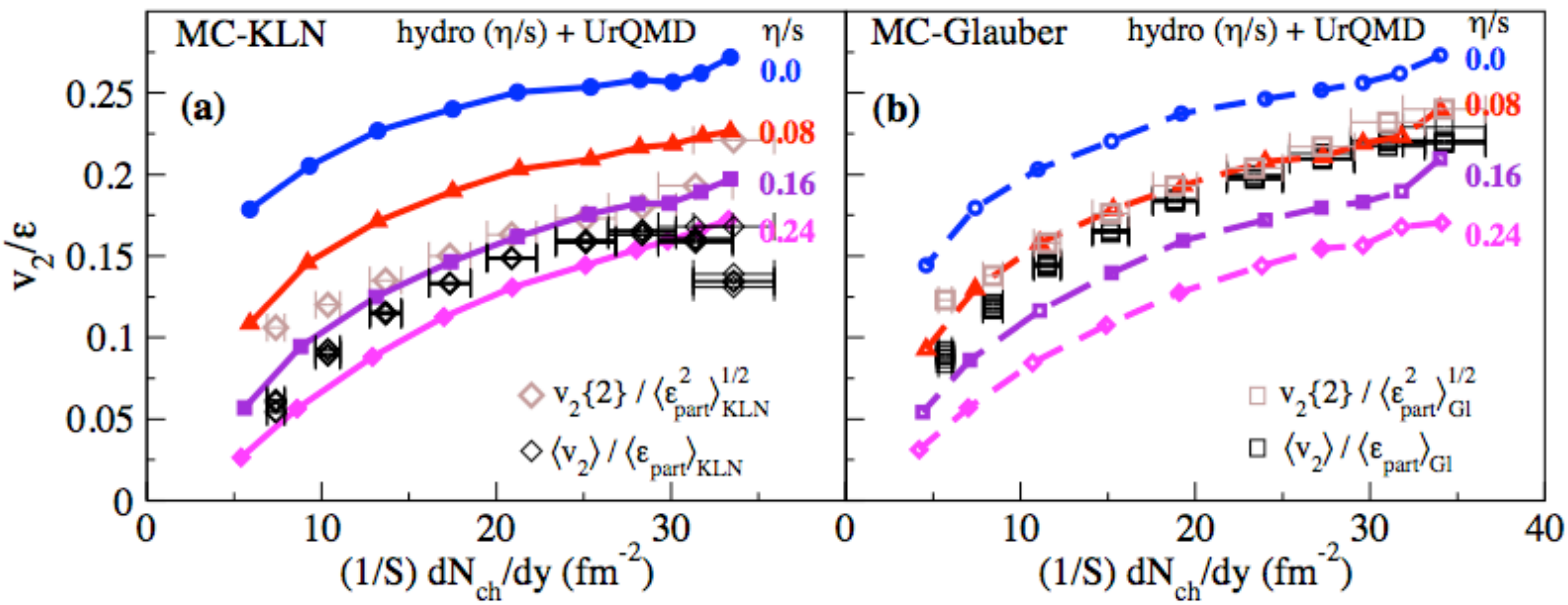
Cosmic microwave background



Initial energy density profile in a heavy ion reaction

Motivation

Elliptic flow from viscous hydrodynamics+hadron transport



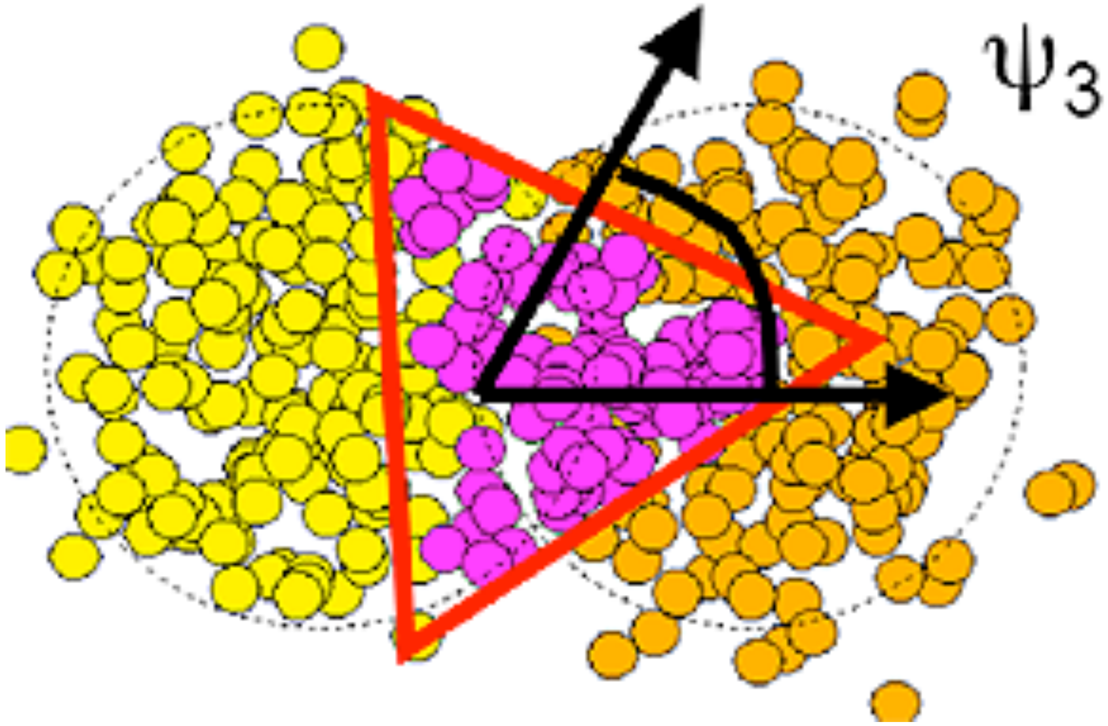
H.Song et al, PRL 106, 192301 (2011)

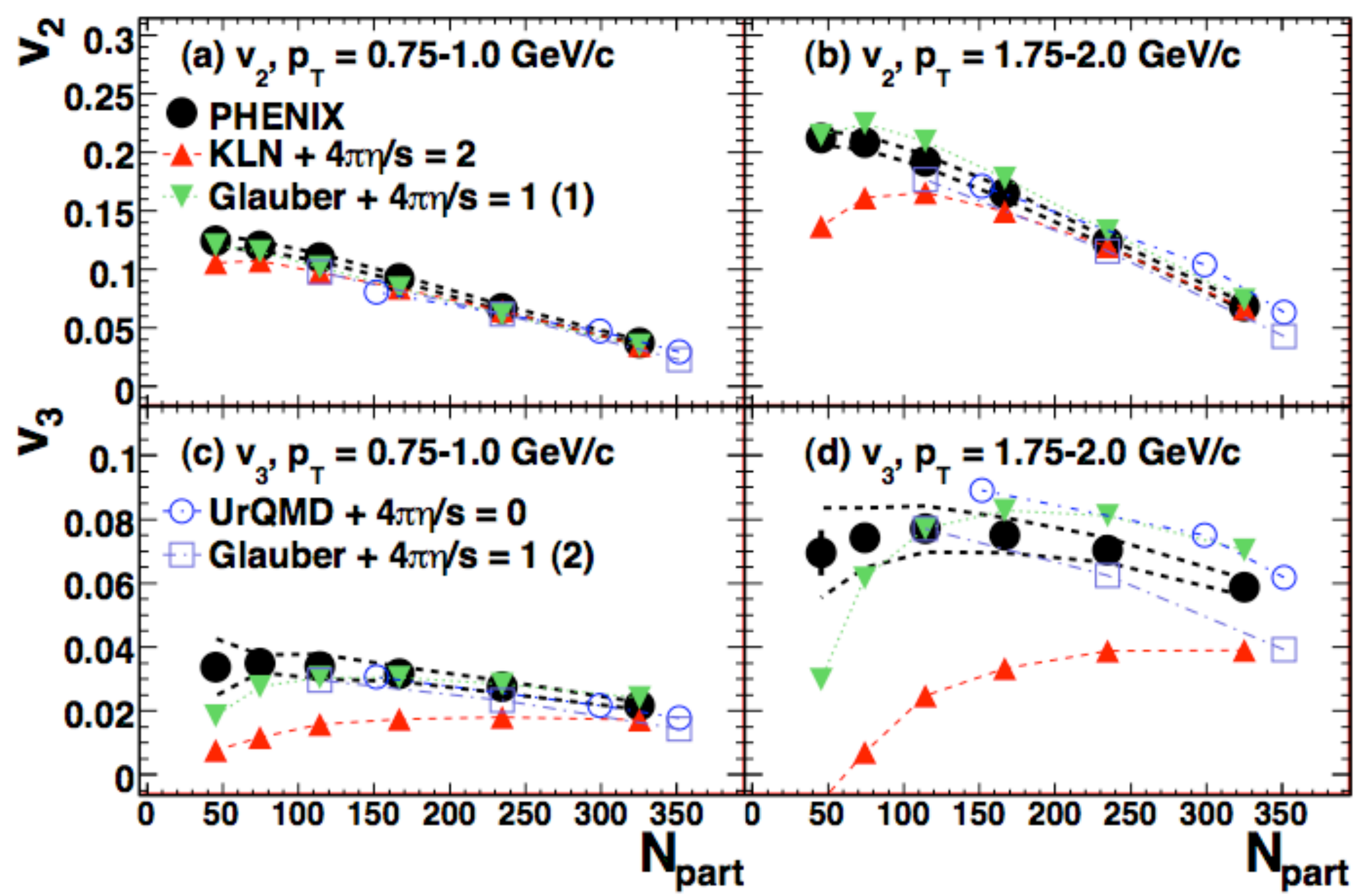
- Different initial conditions ~ factor of 2 difference in η/s
→ Major **uncertainty** to constrain transport coefficients in the quark gluon plasma

Triangular Flow

Initial State Fluctuations

Third Harmonic Coefficient



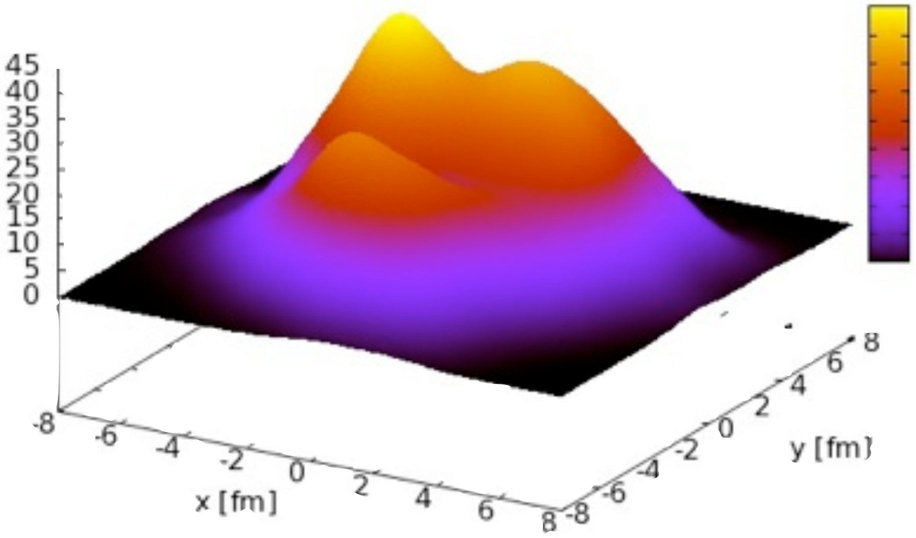


- Fluctuations introduce higher order flow coefficients that have been observed at the RHIC and LHC experiments (see QM 2011)
- How can we quantitatively learn something from this observable?

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

Constraining the Initial State Profile

- First principle treatment of non-equilibrium QCD is still **'wishful thinking'**
- Practical Approach: **Going backward** from the measured final state
  - Nearly-ideal hydrodynamic evolution + hadronic afterburner is **well-established**
  - Look at experimental data in the final state and constrain the **structures** of the needed initial state profile
  - Establish connection between the found features in terms of
    - Shape of the profile
    - Amount of fluctuations



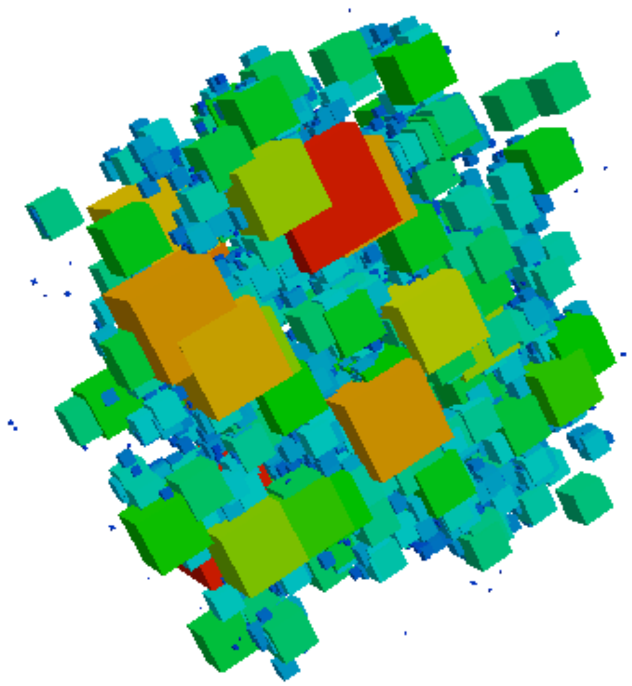
  - and **initial state physics** and eliminate models that do not generate the required structures

Initial Conditions from Dynamical Approaches

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

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

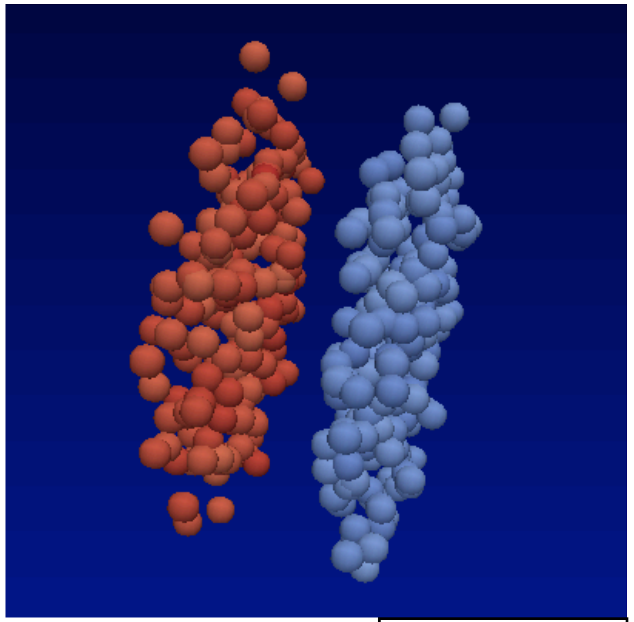
- **Energy deposition** model needs to describe final dE_T/dy in p-p and A-A correctly
- Granularity is influenced by
  - Shape of the incoming nuclei
  - Distribution of binary collisions
  - Interaction mechanism
  - Degree of thermalization

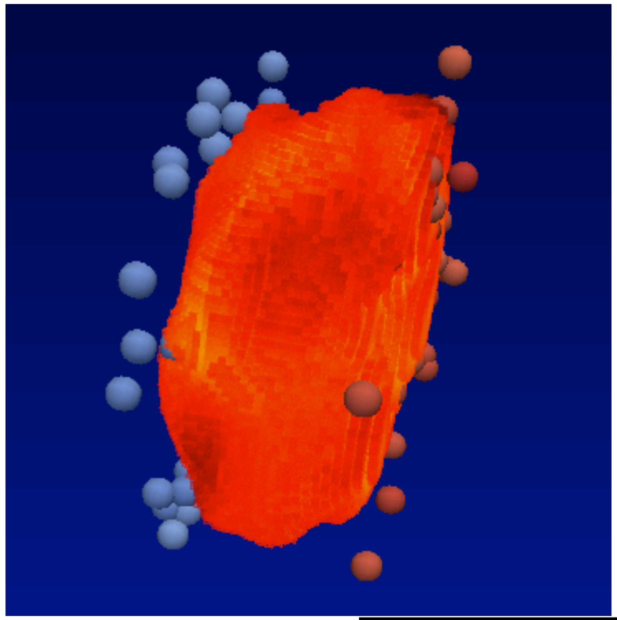


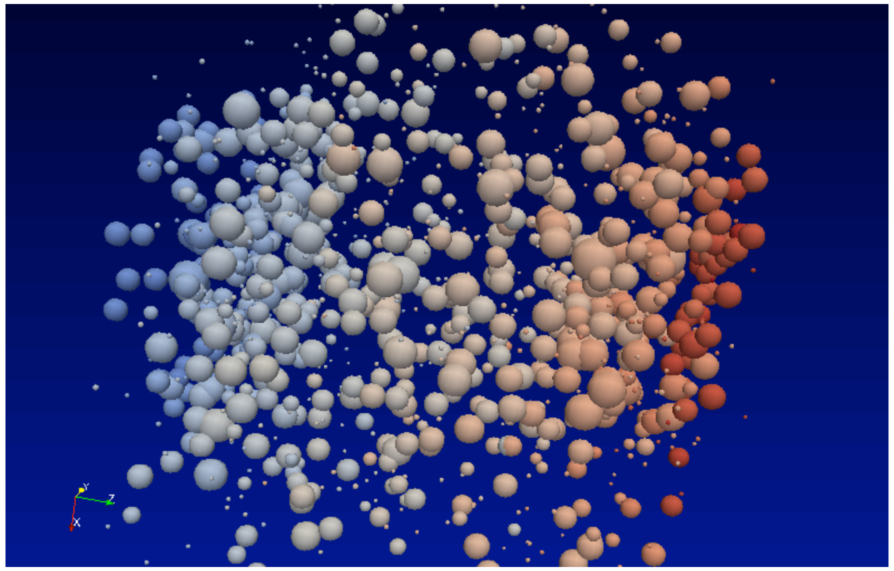
- Differences in **shape** and **fluctuations** need to be quantified
  - First attempt: use **higher** Fourier coefficients

Evolution of Heavy Ion Reactions

UrQMD for non-equilibrium energy deposition	Ideal hydro for hot and dense stage	UrQMD for hadronic rescattering and decays







<1 fm/c

1-10 fm/c

10-30 fm/c

- Initial and final state require non-equilibrium treatment
- Nearly ideal hydrodynamics provides framework for the hot and dense stage of the evolution including a phase transition

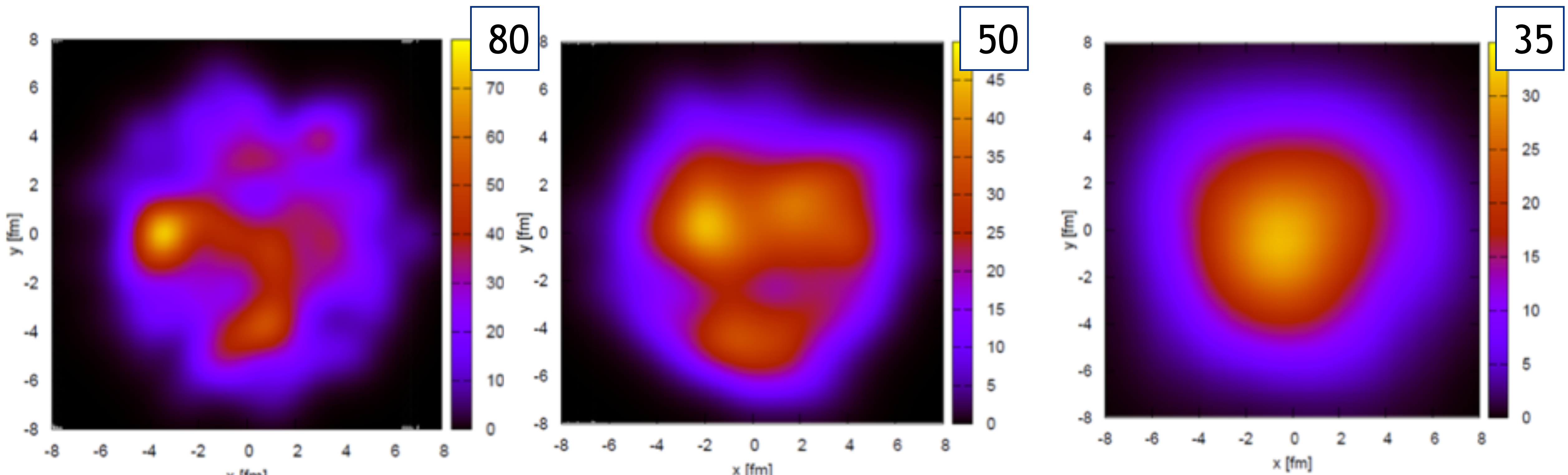
Hybrid models achieve realistic description

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

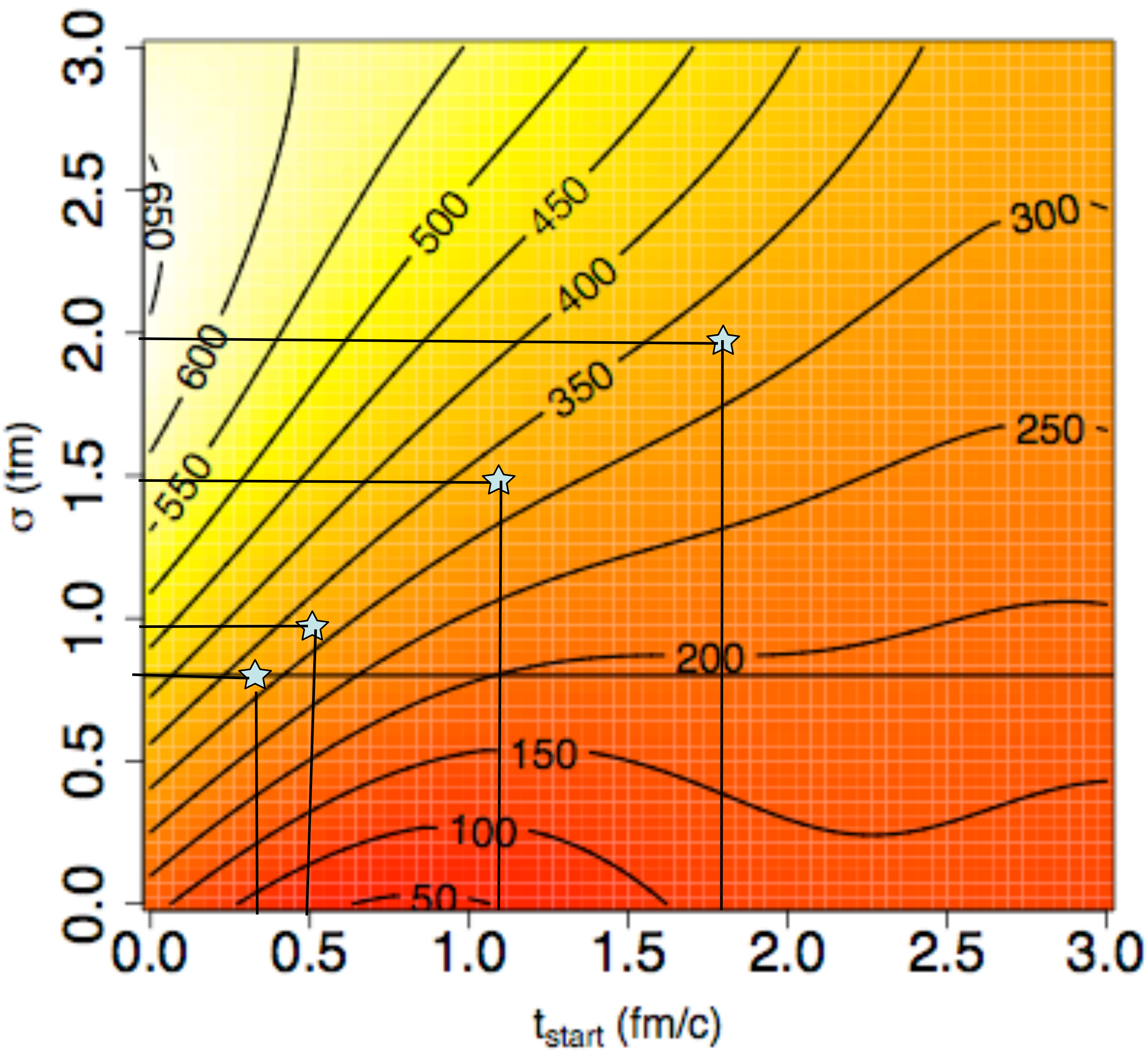


σ = 0.8 fm | σ = 1.0 fm | σ = 2.0 fm

- How does changing the starting time affect the picture?

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

Parameter Sensitivity Tests

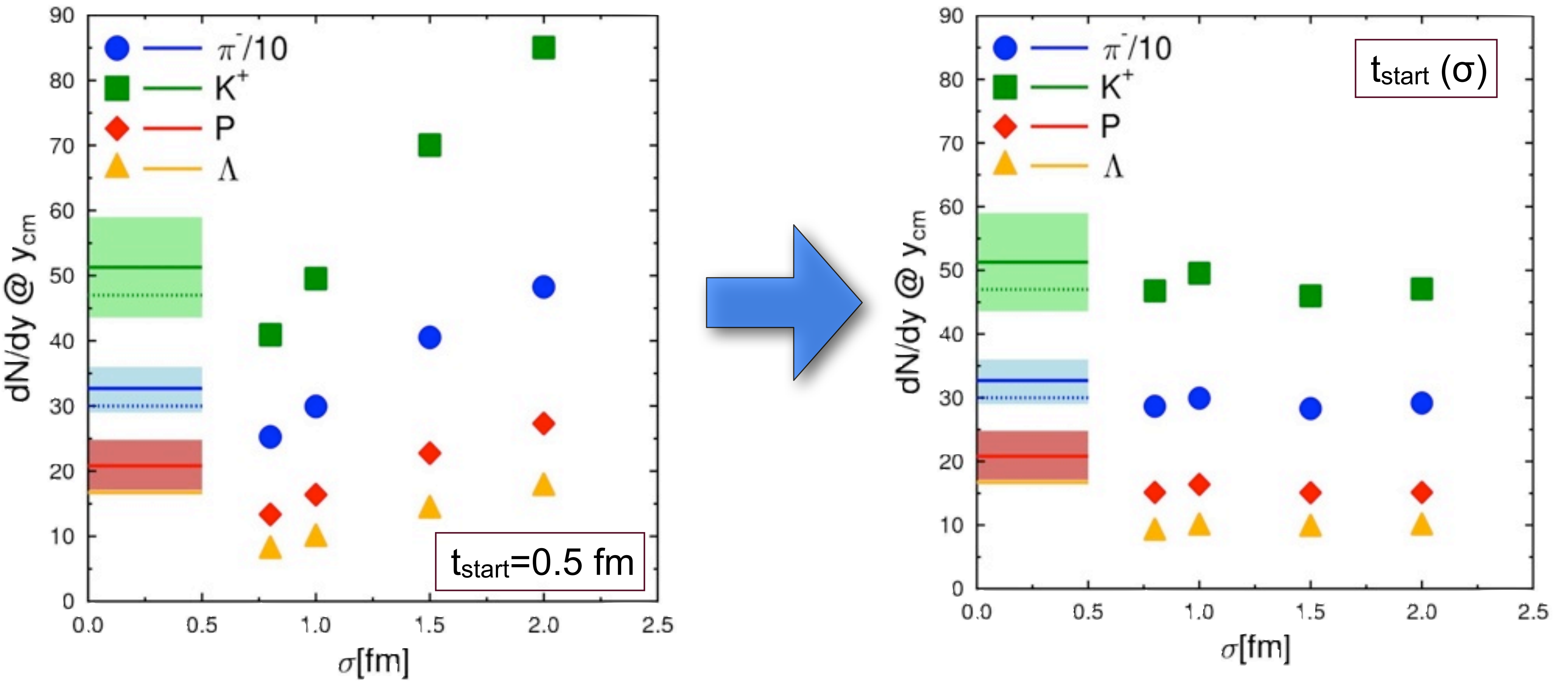


- Sophisticated statistical analysis
- **Emulator** predicts results of calculations for parameter sets by means of advanced statistics
- Number of pions in the t_{start}- σ plane

→ Determine reasonable **combinations** of parameters

H.P. et al, J.Phys.G G38 (2011) 045102

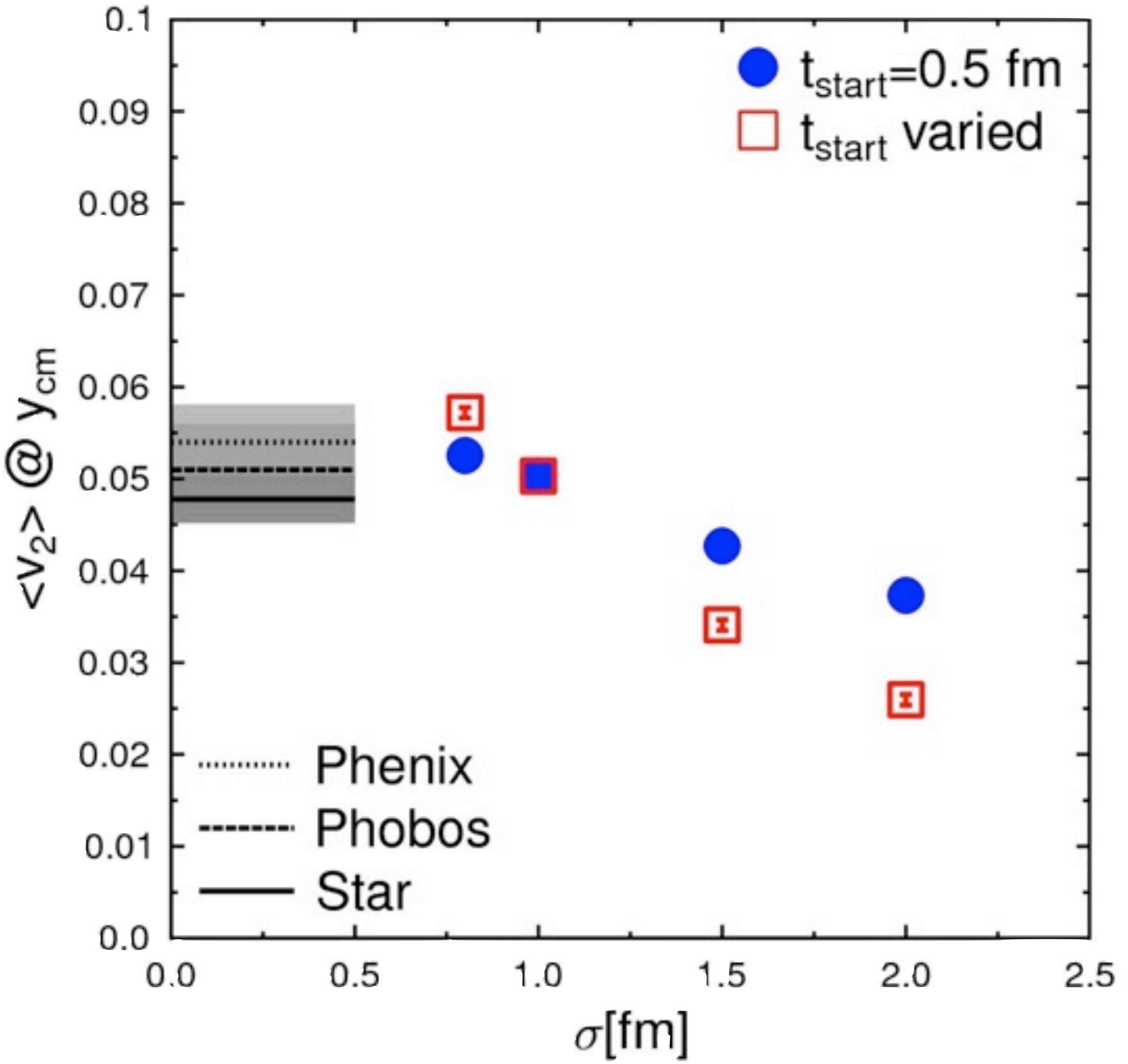
Starting Time Adjustment



→ All four cases really produce similar yields

H.P. et al, J.Phys.G G38 (2011) 045102

Influence on Elliptic Flow

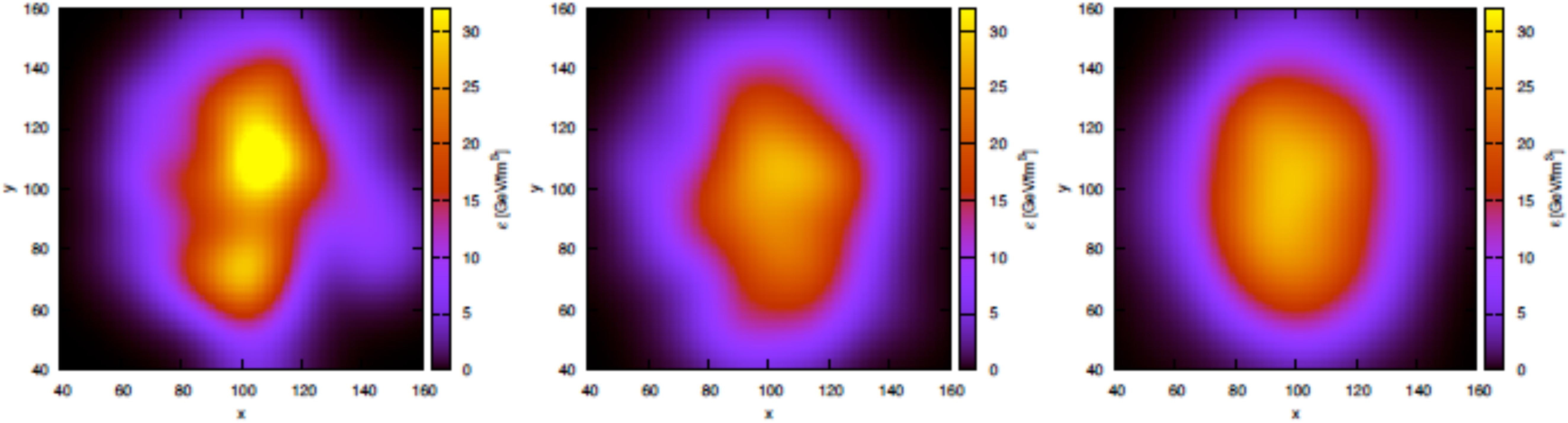


- Too **late** starting times do not allow for enough v_2
- Choose σ = 1 fm and t_{start}=0.5 fm as default parameters

H.P. et al, J.Phys.G G38 (2011) 045102

Adjusting Granularity

n=1 n=5 n=25



- Averages over the initial state profile for different numbers of events 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

H.P. et al, J.Phys.G G39 (2012) 055102

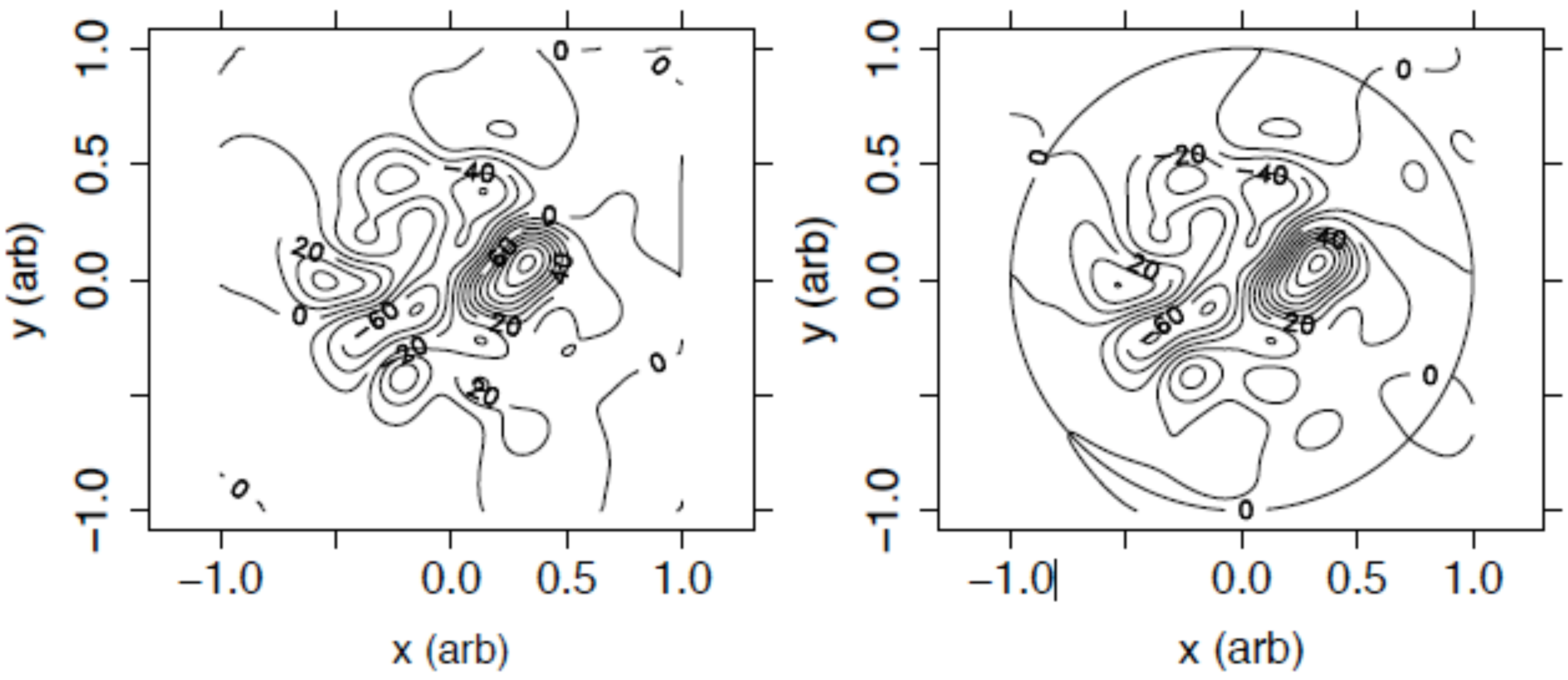
2d Fourier Decomposition

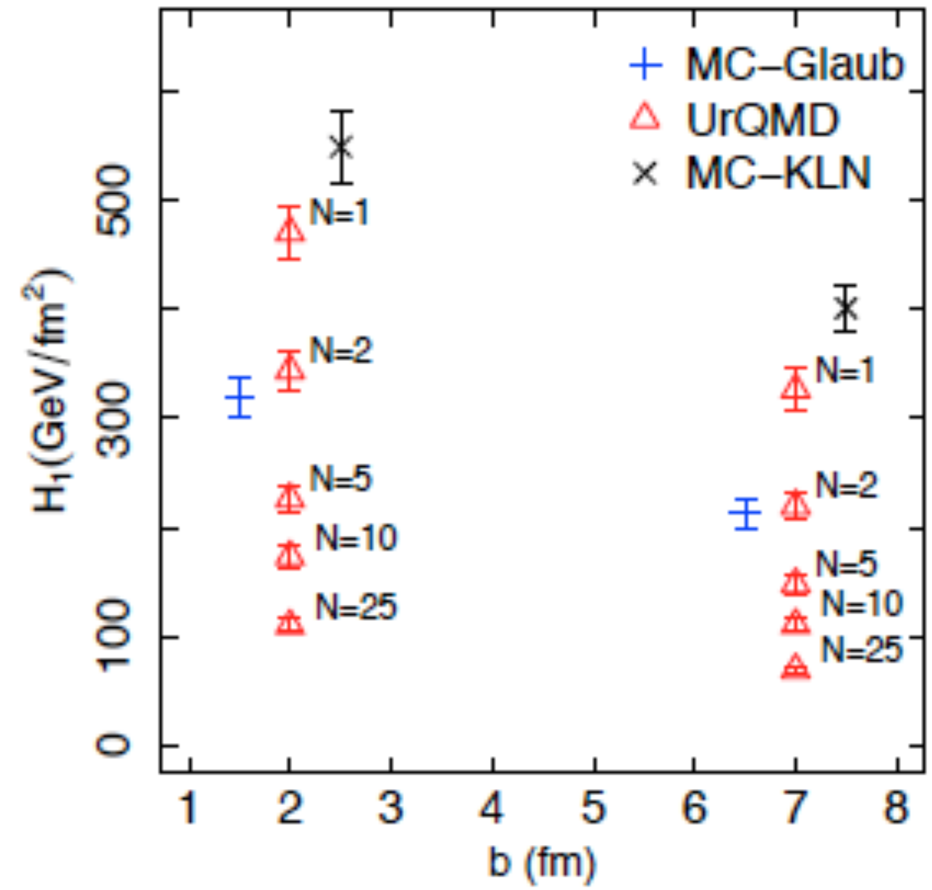
- All structures are represented by two-dimensional Fourier decomposition
- Sobolev norm measures granularity:

$$H_1(f) := \langle (-\ell^2\nabla^2 + I)f, f\rangle^{1/2} = \left[\sum (\ell^2\lambda^2_{m,n} + 1)|A_{m,n}|^2\right]^{1/2}$$

Original

Reconstructed

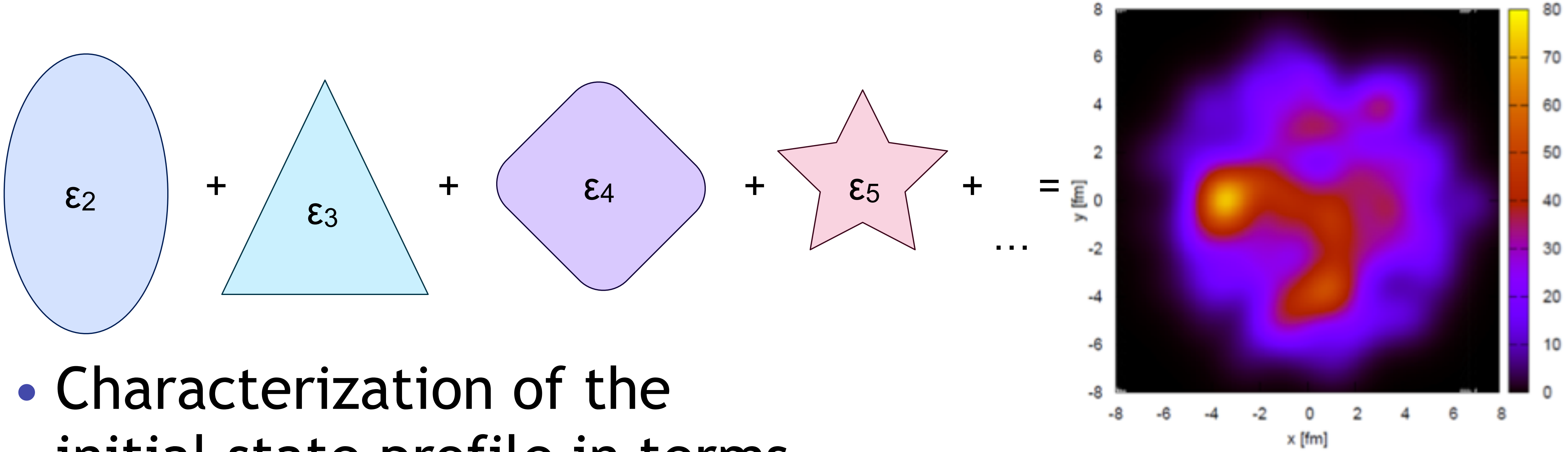




- Classification of initial state fluctuations only, average has been subtracted

C. Coleman-smith et al, arXiv: 1204.5774

Coordinate Space Asymmetry



- Characterization of the initial state profile in terms of **Fourier coefficients**
- Odd harmonics vanish for symmetric initial conditions
- The event planes are not necessarily independent
- Is that enough to **capture** all structures?

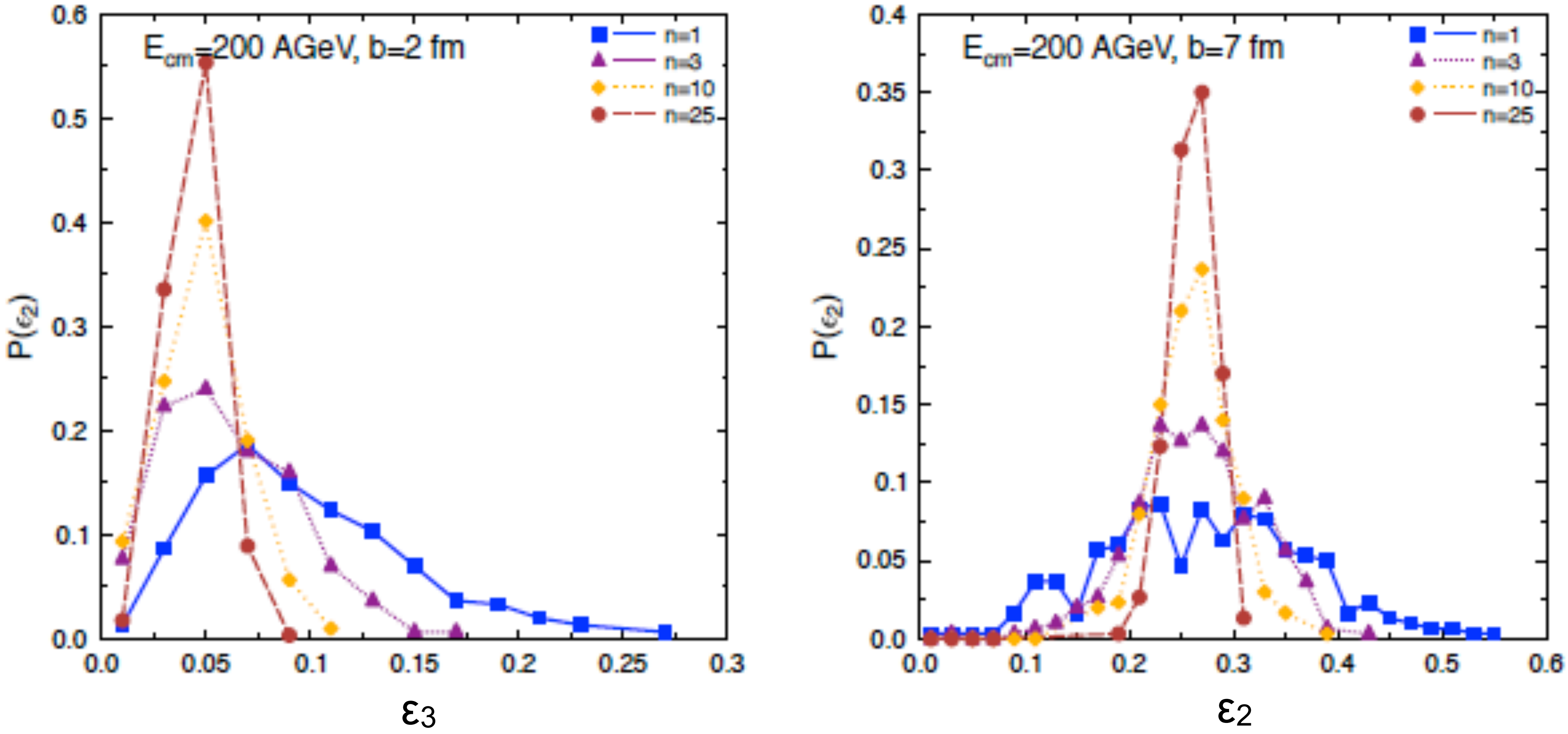
Initial State Coordinate Space Asymmetry

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

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

Eccentricity and Triangularity

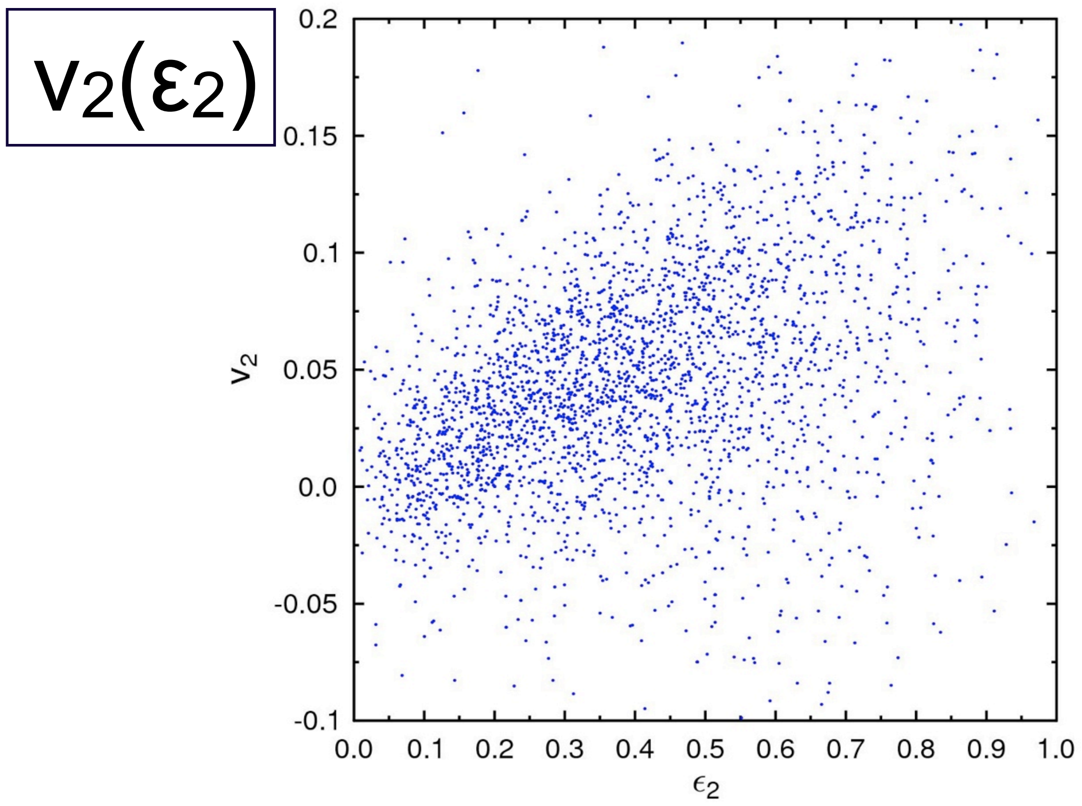
- **Coefficients** are calculated from the initial energy density distribution in the hydrodynamic calculation

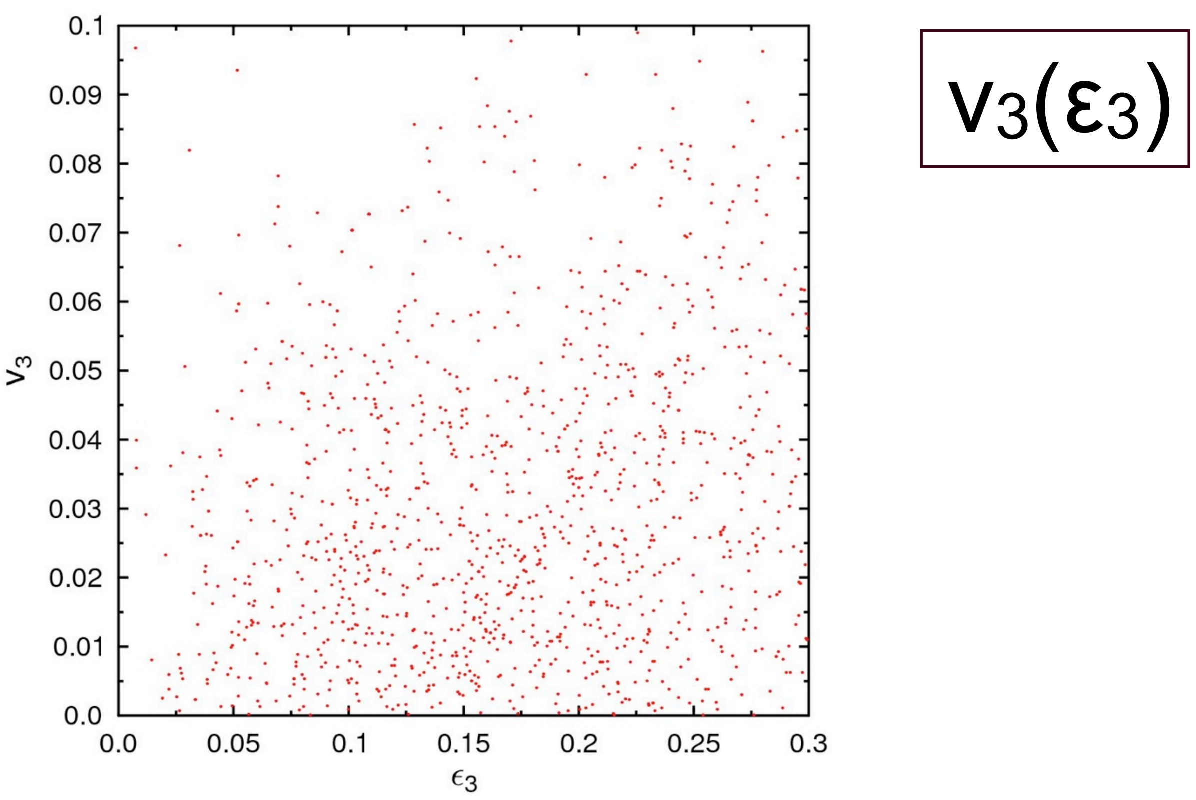


- Probability distribution of ε_2 gets narrower, while for ε_3 the mean value decreases for smoother initial conditions

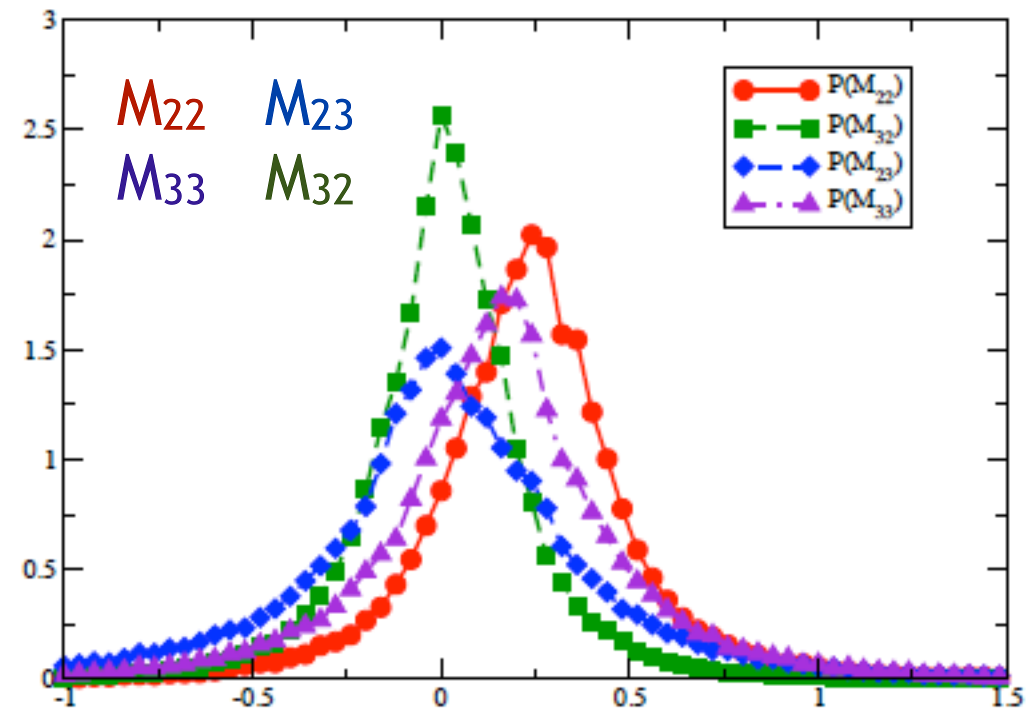
H.P. et al, J.Phys.G G39 (2012) 055102

Event-by-Event Correlation





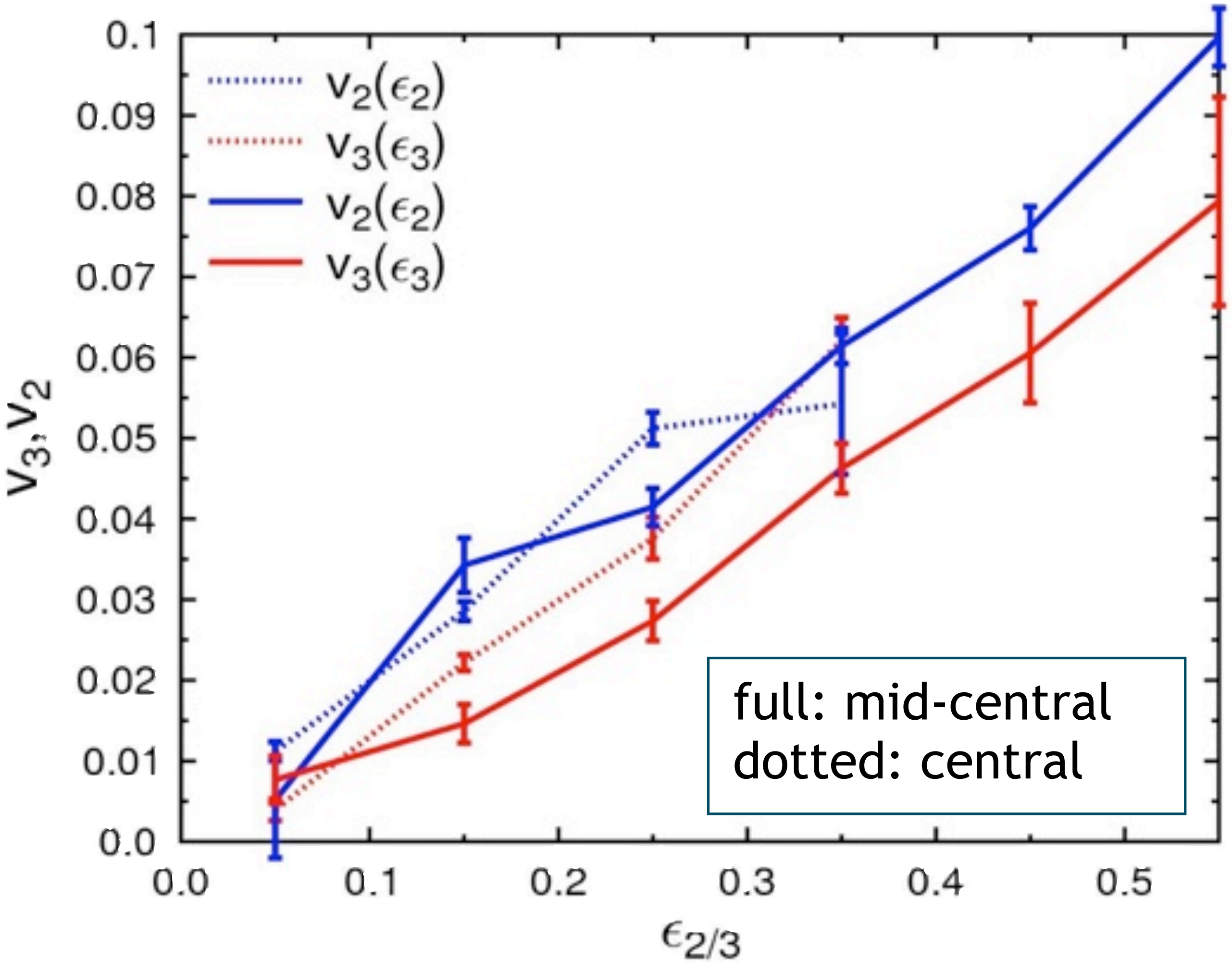
- For **single events** the initial eccentricity is not necessarily correlated to the final state flow anisotropy
- Cross-feeding of different moments, quantified by correlation matrix $v_n = \sum_m M_{nm}\epsilon_m$



G. Qin et al, Phys.Rev. C82 (2010) 064903

Flow Coefficients

H. P. et al, Phys.Rev. C82 (2010) 041901



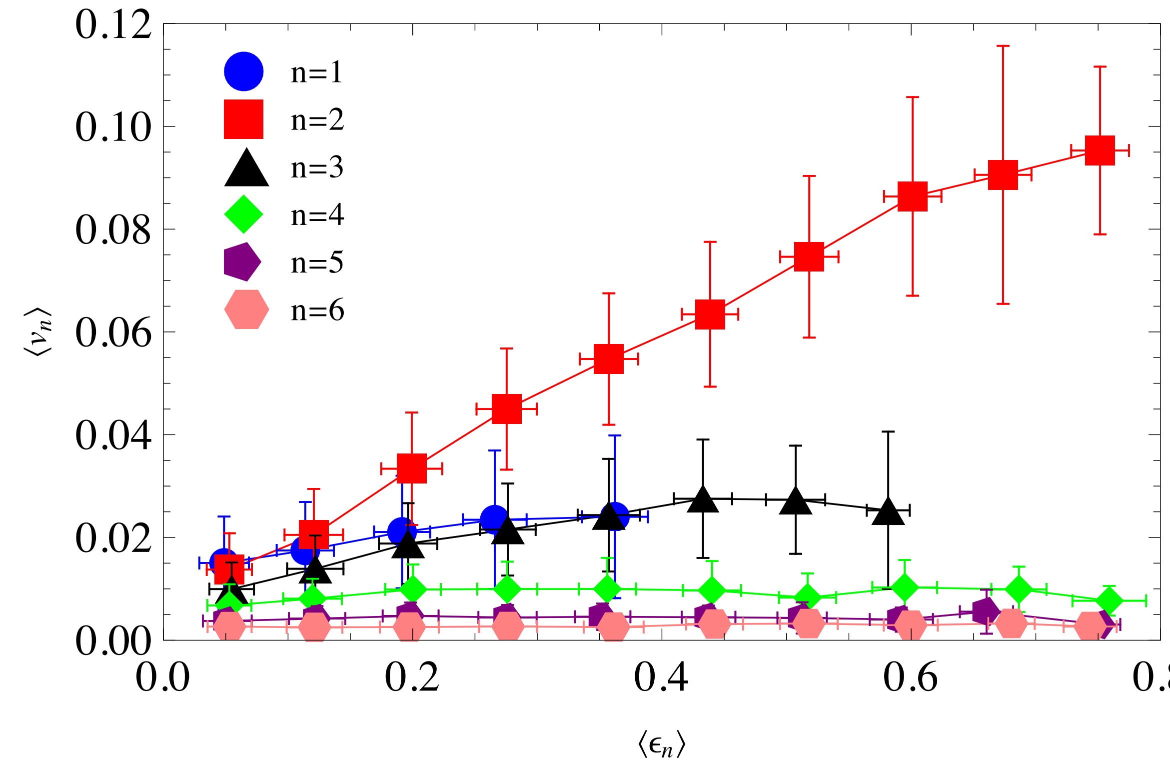
full: mid-central
dotted: central

Initial State Coordinate Space Asymmetry

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

Final State Momentum Space Asymmetry

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

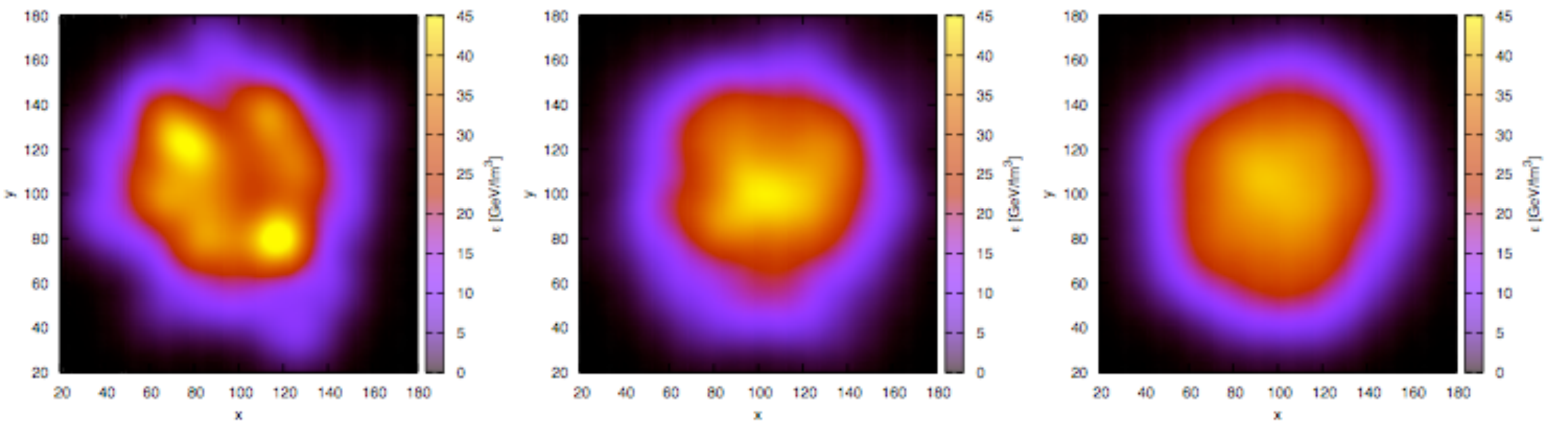


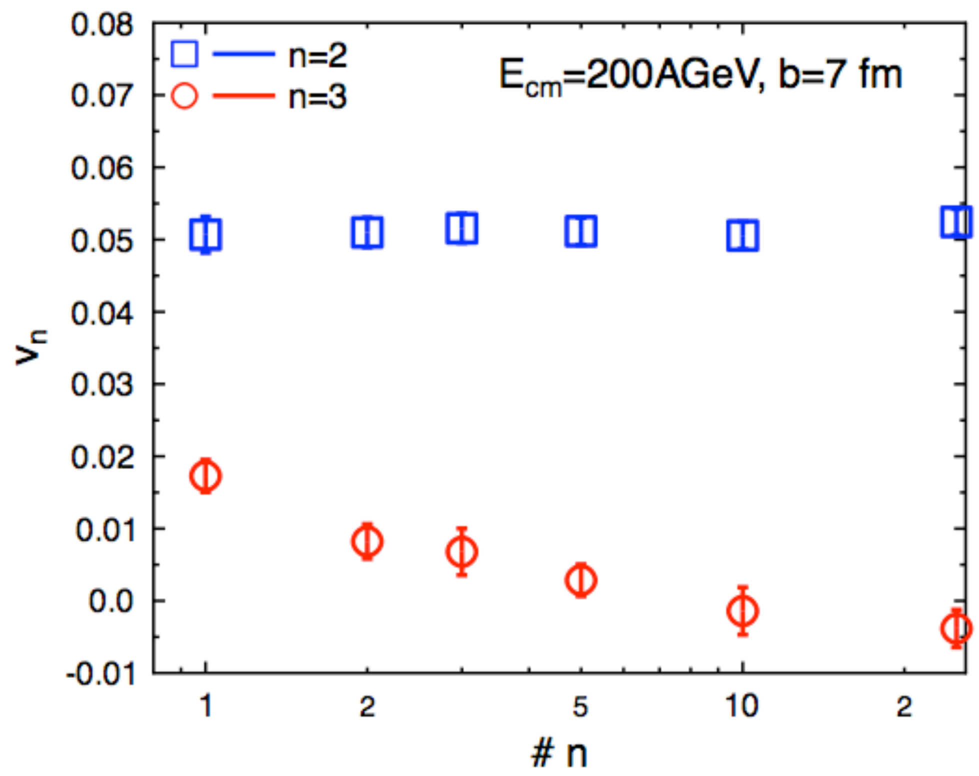
F. Gardim et al, arXiv:1110.5658

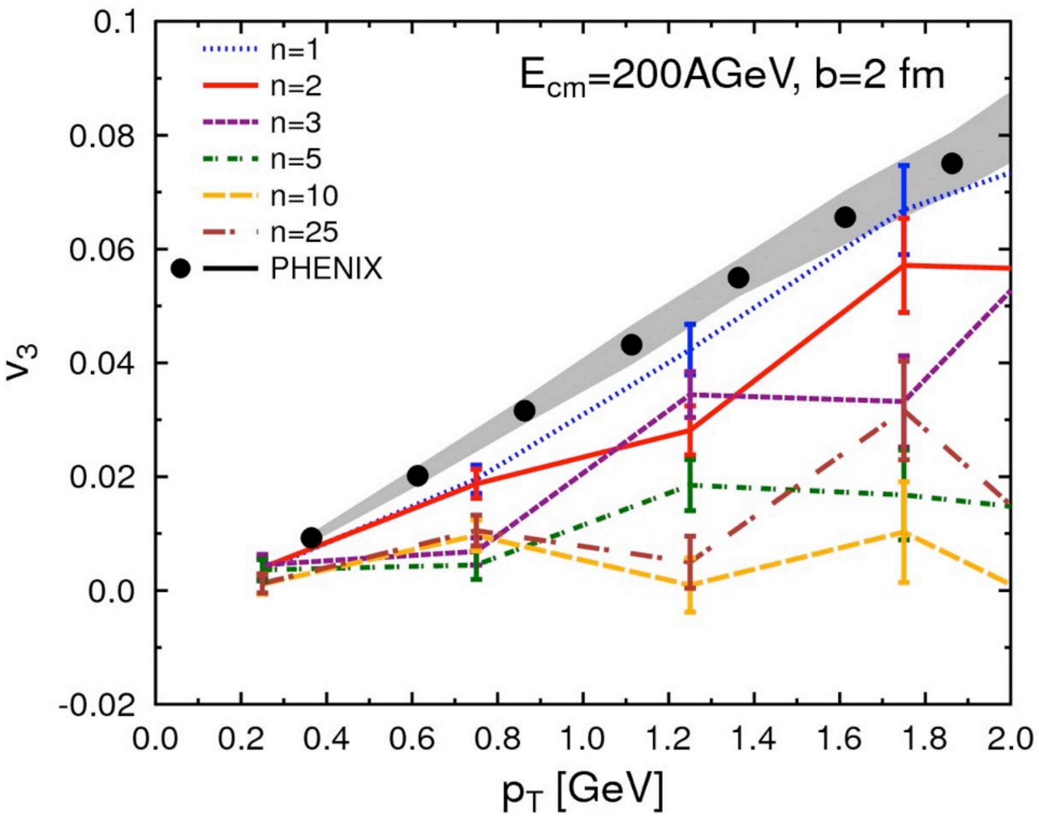
- v_n and ε_n are correlated on the **average** over many events
- Confirms collective behavior
- For n>3 correlation is very weak, if at all visible

Constraining Granularity

H.P. et al, J.Phys.G G39 (2012) 055102

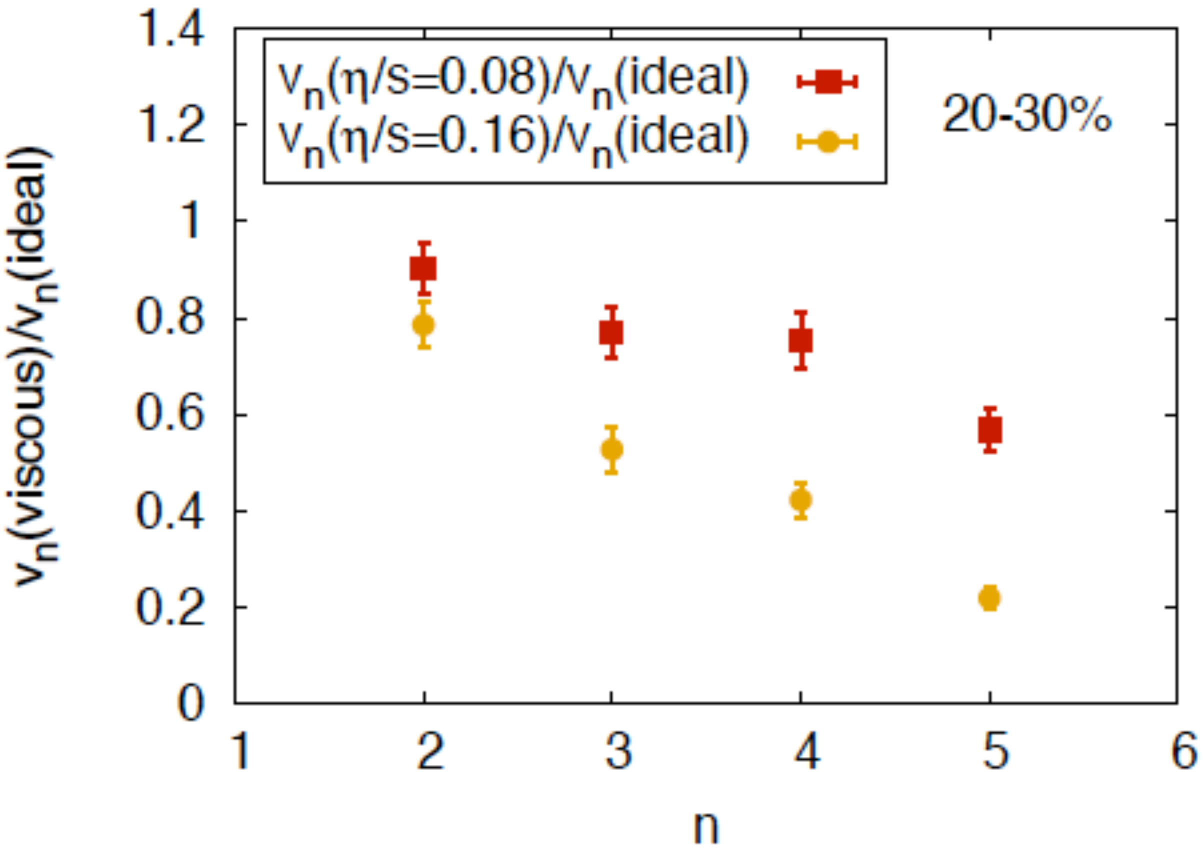


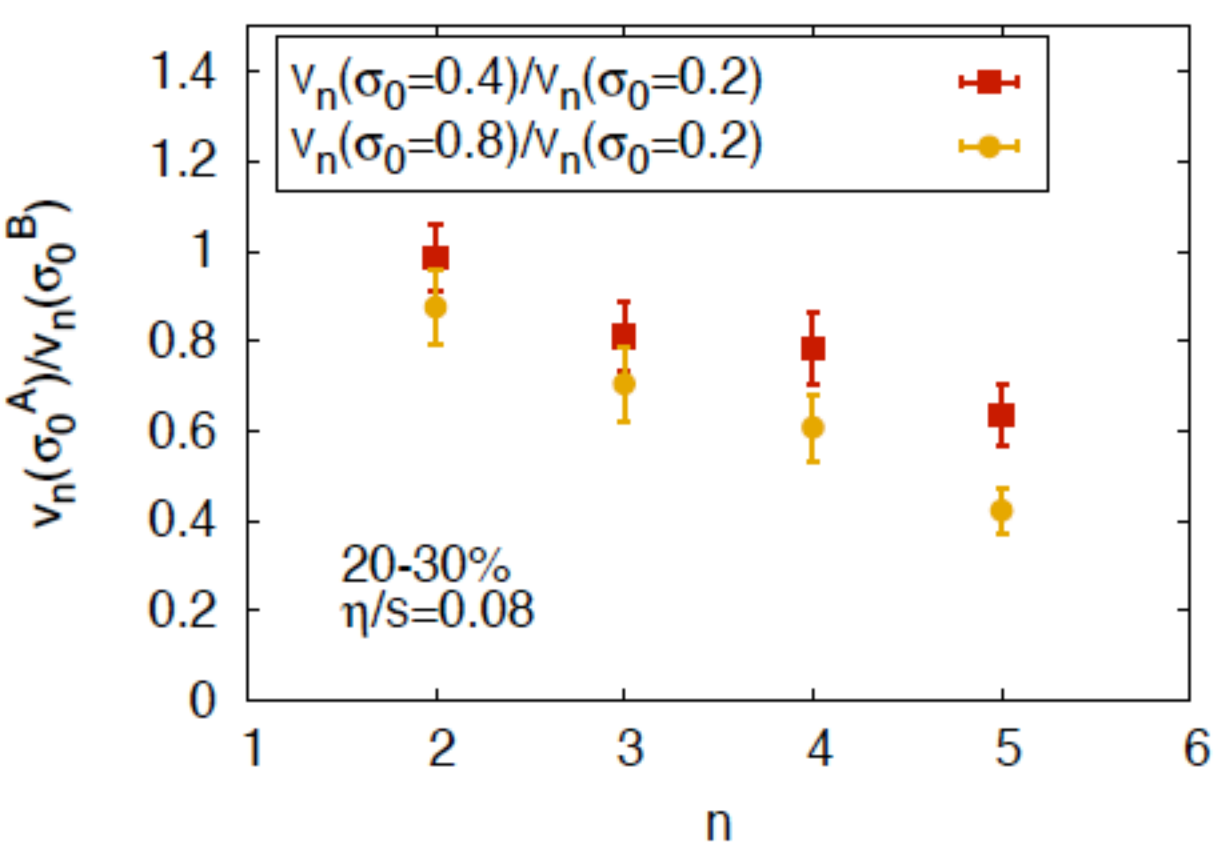


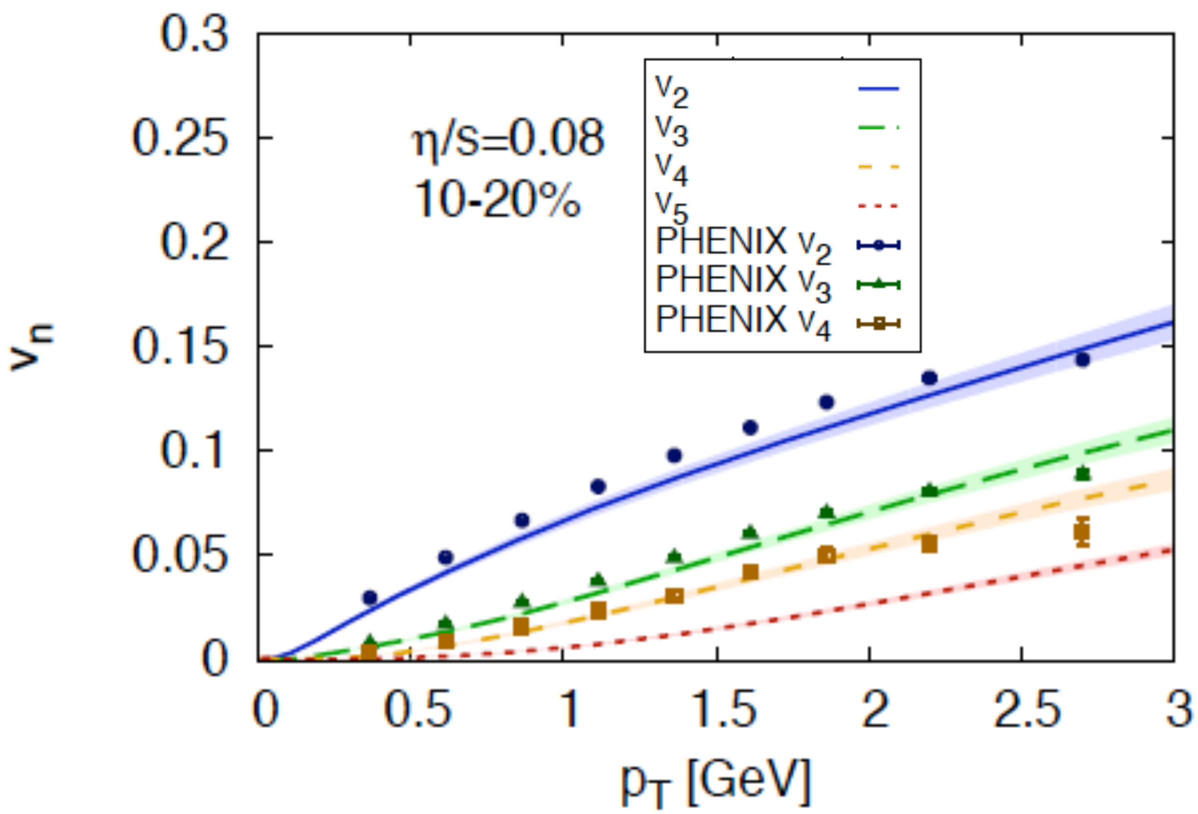


- Triangular flow is **very sensitive** to amount of initial state fluctuations
- It is important to have final state particle distributions to apply **same analysis** as in experiment
- Single-event initial condition provides best agreement with PHENIX data
- Does that imply that the initial state is well-described by binary nucleon interactions +PYTHIA?
- Lower bound for fluctuations!

Event-by-Event Viscous Hydro



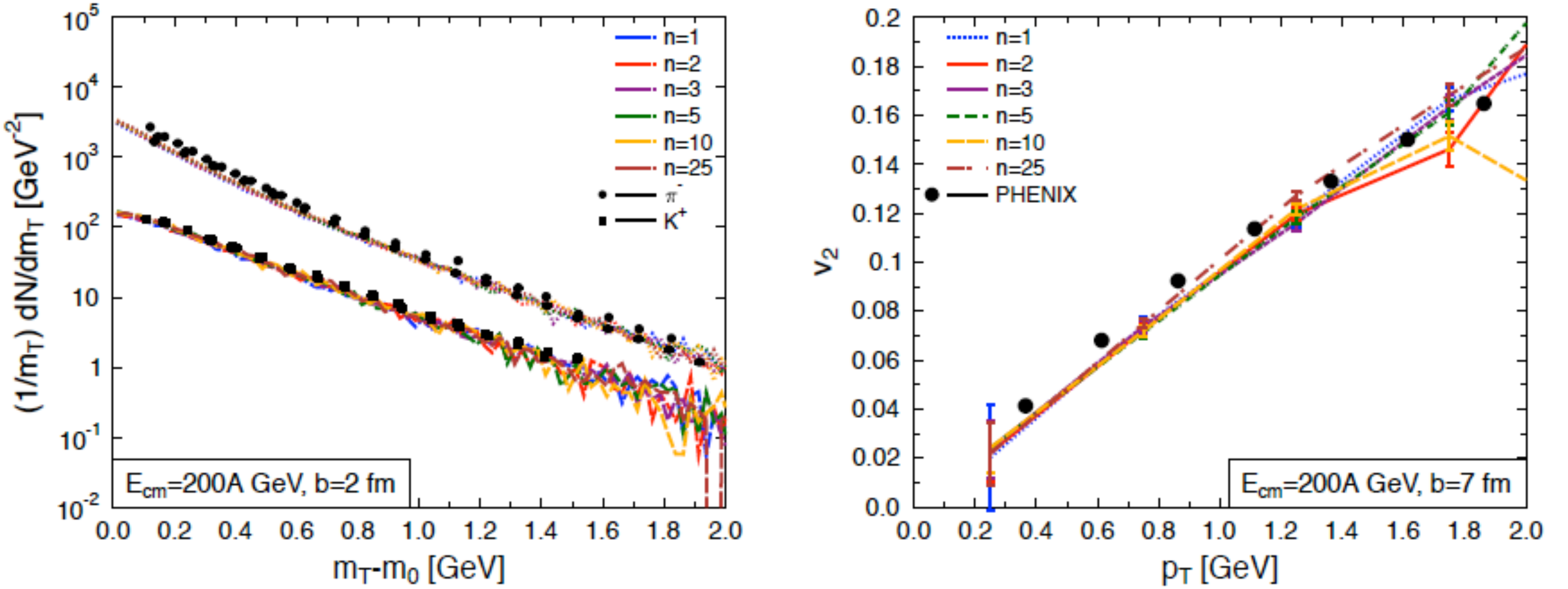




- Current state-of-the-art: Viscous Hydro e-by-e
  - Interplay between η/s and σ smoothing kernel width
  - Viscosity has to be very small to keep width reasonable

B. Schenke et al, Phys.Rev. C85 (2012) 024901

Spectra and Flow

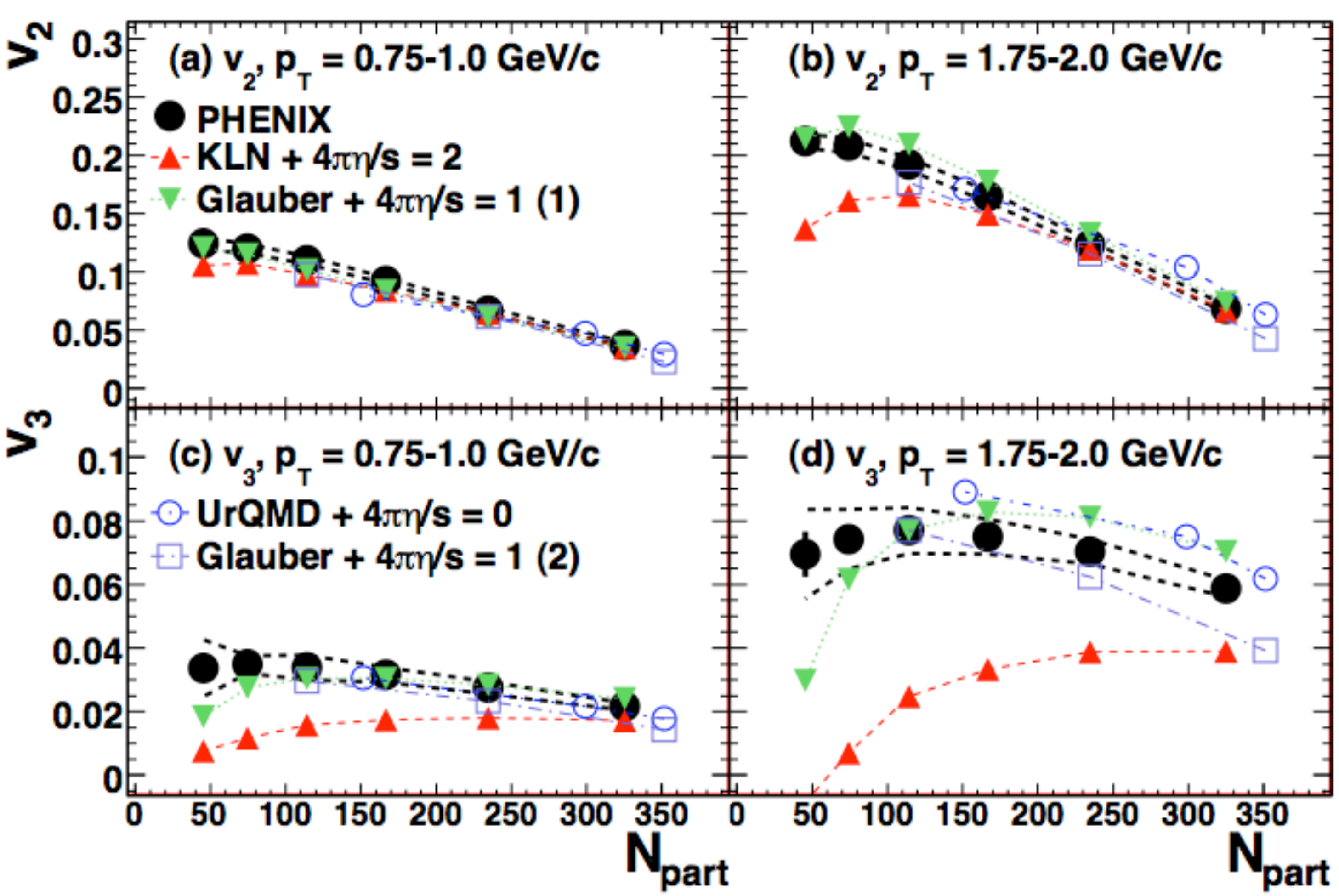


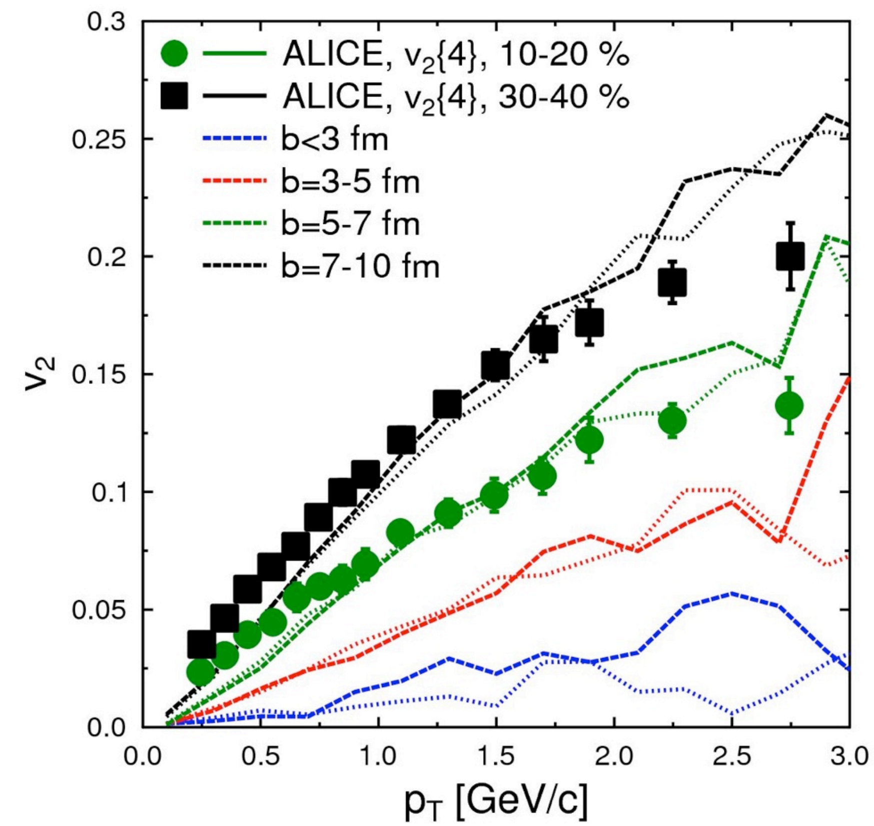
- Particle spectra and elliptic flow are **not sensitive** to amount of initial state fluctuations
- They are sensitive to **other parameters** like starting time, smoothing kernel width, freeze-out transition criterion and can be used to constrain viscosity

H.P. et al, J.Phys.G G39 (2012) 055102

Triangular Flow at RHIC and LHC

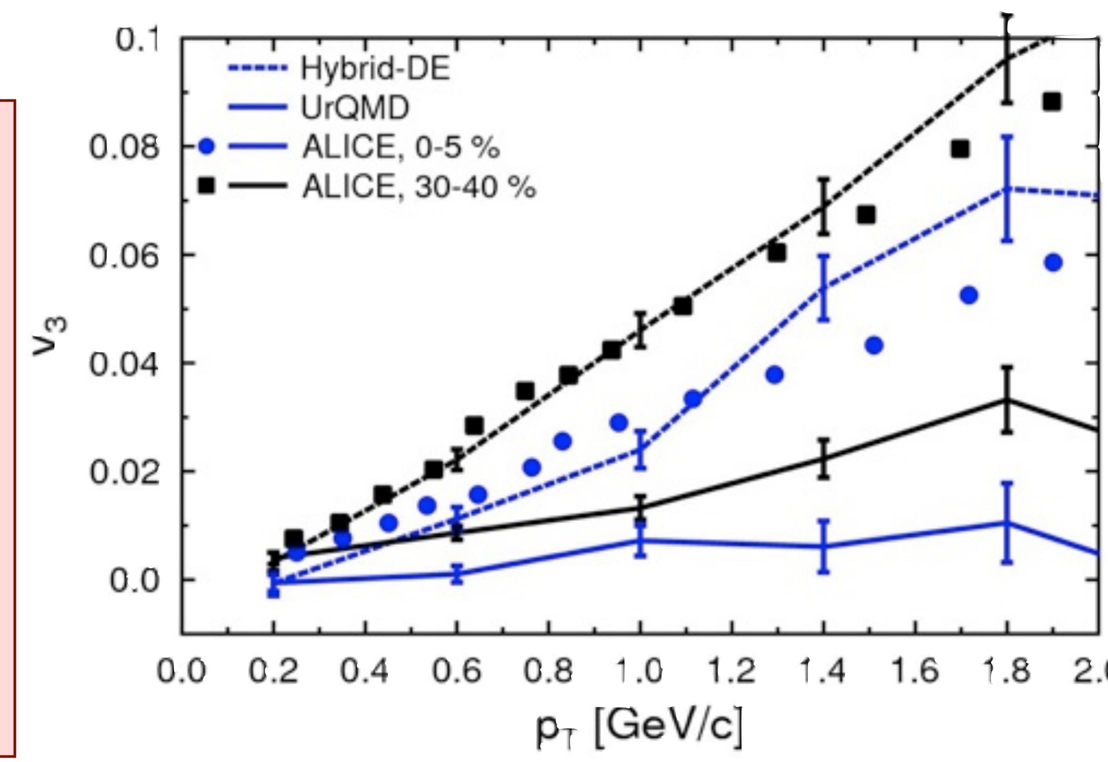
PHENIX collaboration, Phys.Rev.Lett. 107 (2011) 252301





H.P., Phys.Rev. C84 (2011) 034912

- Fluctuations from nucleon positions and energy deposition in binary collisions included
- Without tuning anything v_3 at RHIC and flow at LHC in agreement with experimental data



How to get more quantitative?

- **Qualitative** description of heavy ion reactions by hybrid approaches
- Dependence on **multitude** of parameters
- Huge amount of experimental **observables**
- How can we get **quantitative results** for quantities of interest, like viscosity, transition energy density, thermalization time,...?

M.A.D.A.I.
Modeling and Data Analysis Initiative

Modeling **a**nd **D**ata **A**nalysis **I**nitiative

- Different fields of science coping with **large data sets** and complicated dynamical models, e.g. meteorologists, galaxy cluster formation, heavy ion physics,..
- Develop **statistic** analysis tools for multi-parameter fit
- Apply new **visualization techniques** to dynamical simulation
- Extract **quantitative** statements from RHIC data

http://madai.us for examples

Summary

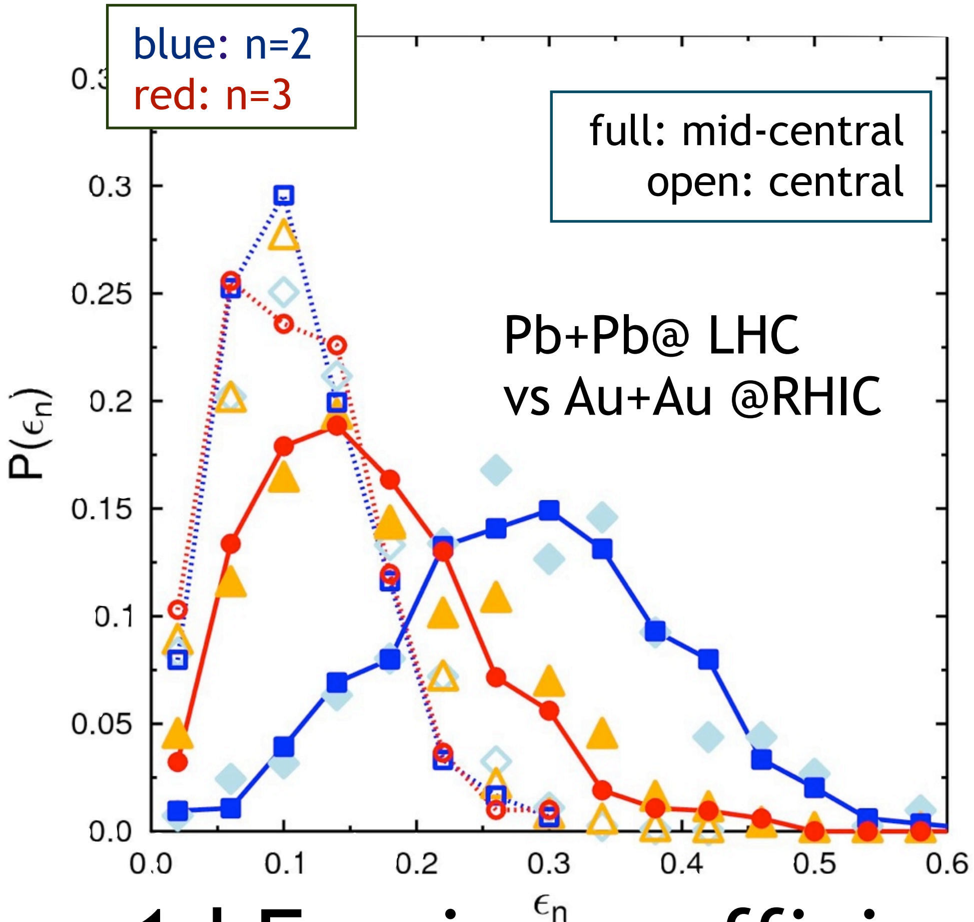
- Event-by-event hybrid approaches are state-of-the-art to study **initial state fluctuations**
- Characterization of initial state structures by **Fourier** coefficients
- Triangular flow is **sensitive** to amount of initial state fluctuations, even though event by event correlation is not obvious
- **Lower bound** of fluctuations can be determined
- RHIC and LHC flow results are in agreement with fluctuations from binary nucleon-nucleon collisions
- **Qualitative** picture is achieved, next challenge:
  - Quantitative conclusions from **multi-parameter** studies
  - Improved **initial state** description including understanding of thermalization

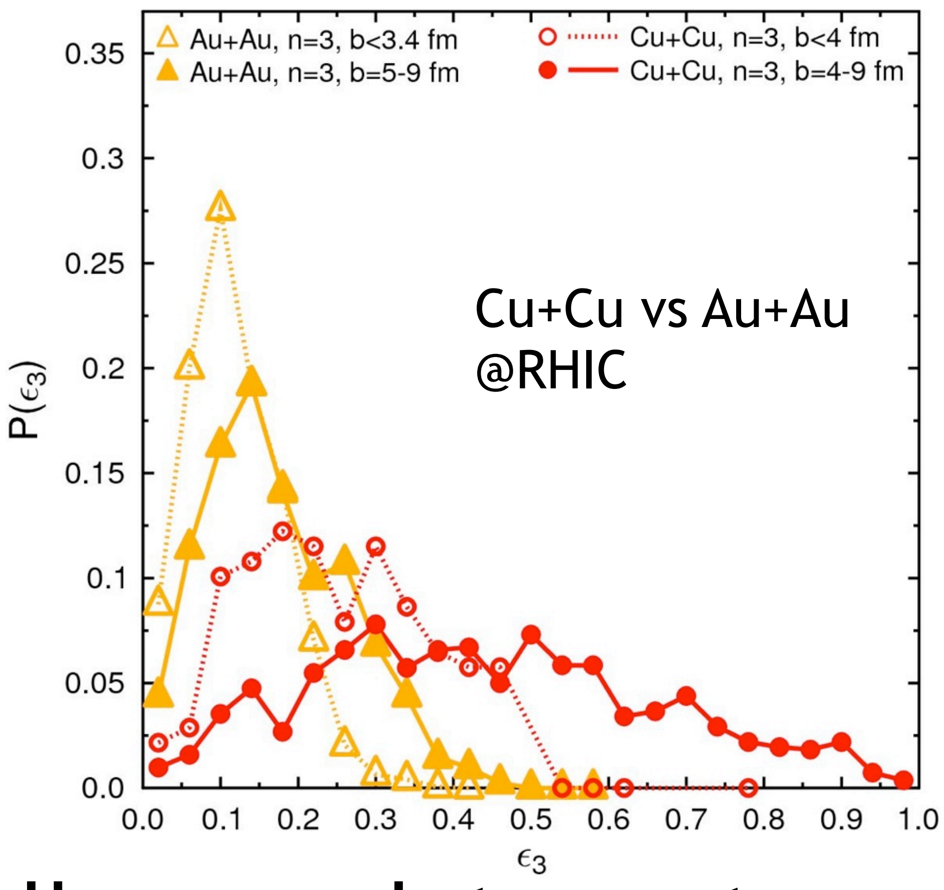
Backup

Comparison of Initial State Profiles

- Important to compare different models on **equal footing** to sort out similarities and differences
- **Probability distributions** provide more detailed information
- Different beam energies and system sizes might be helpful

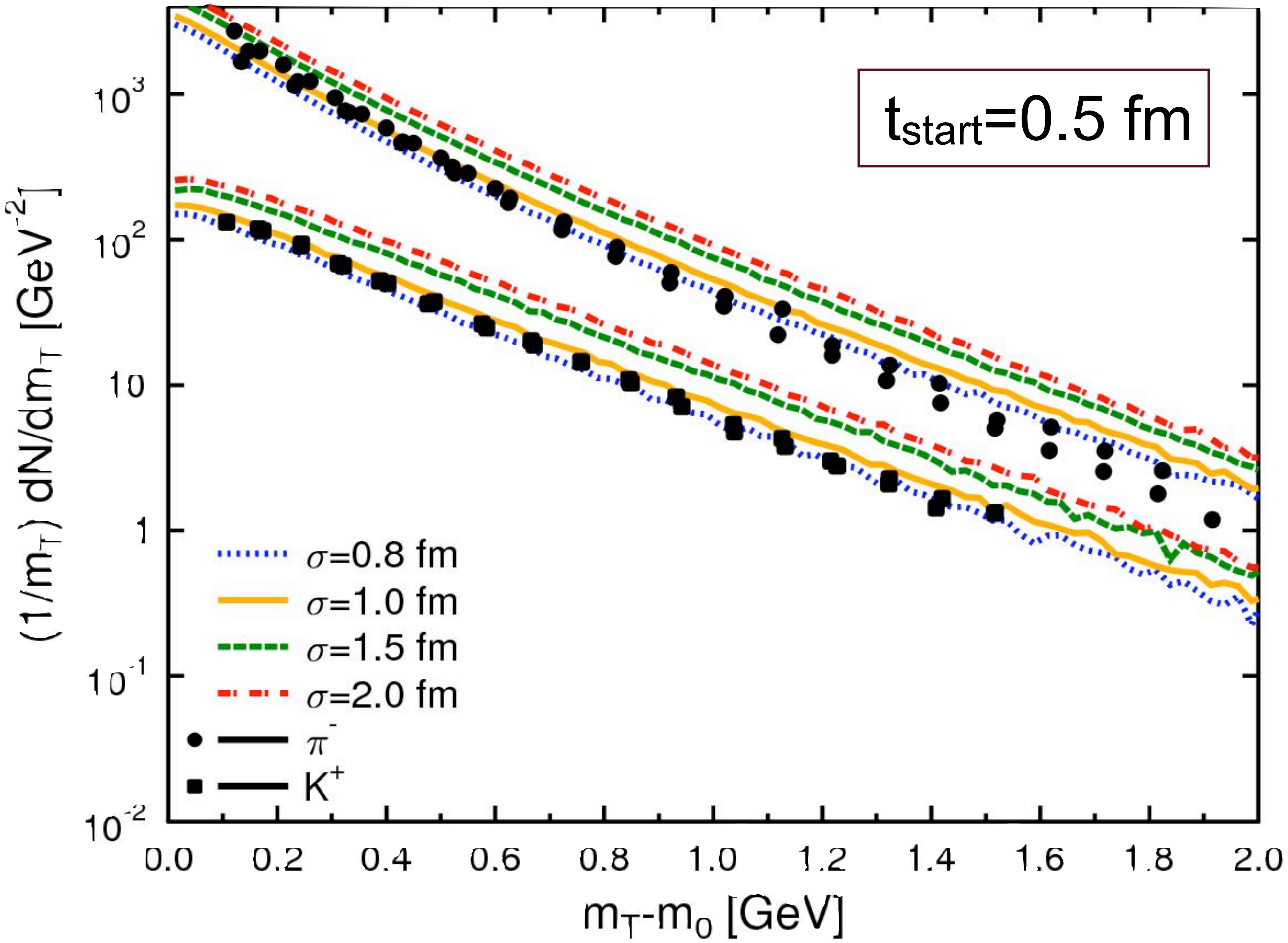
H.P., Phys.Rev. C84 (2011) 034912

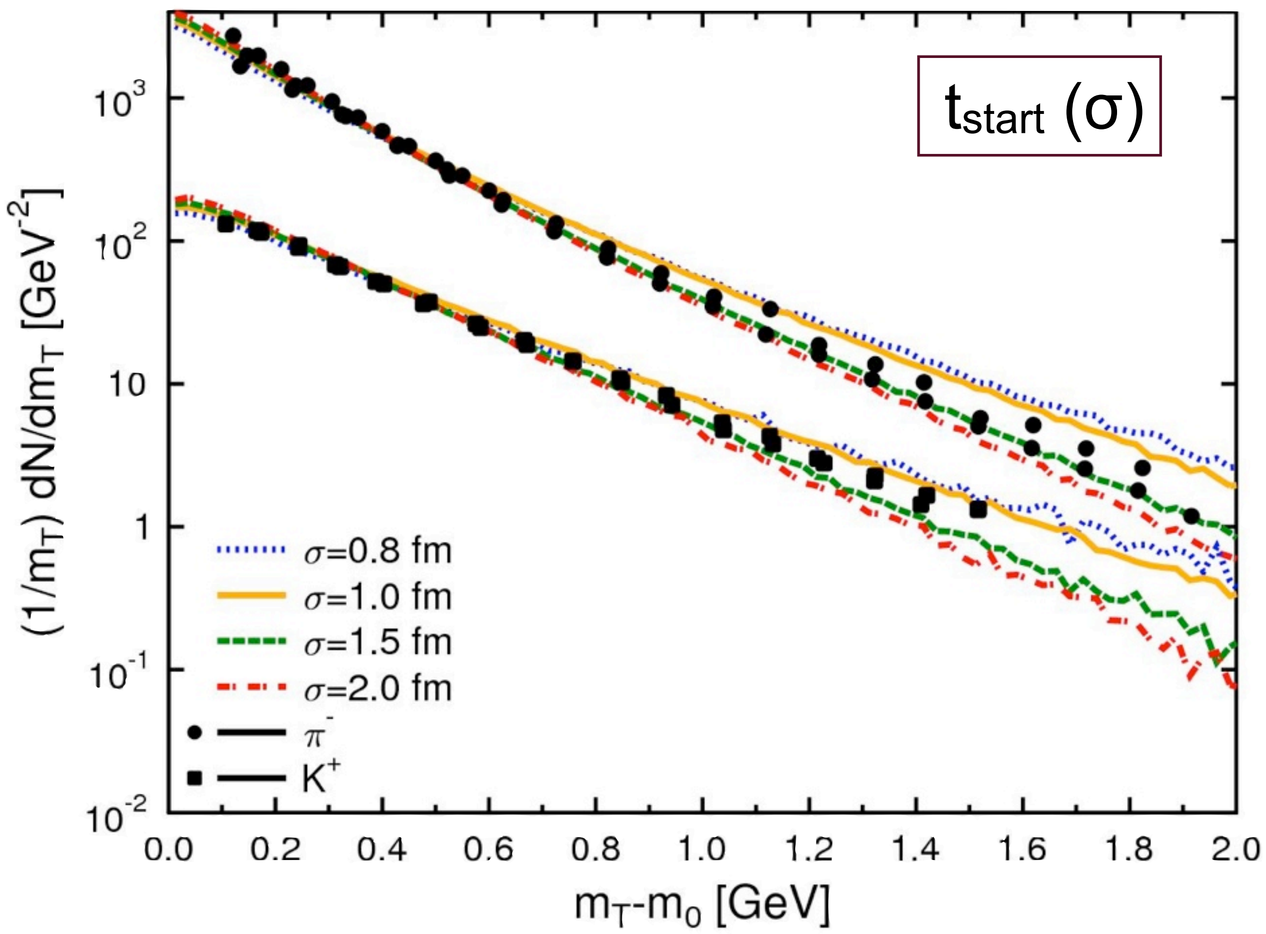




- Are 1d Fourier coefficients really enough to capture all the information? Correlations between different moments?

m_T Spectra





- Fixed starting time: Different yields, same slope
- Varied starting time: Same yield, different slopes

➔ the longer the hydro evolution, the larger the transverse flow

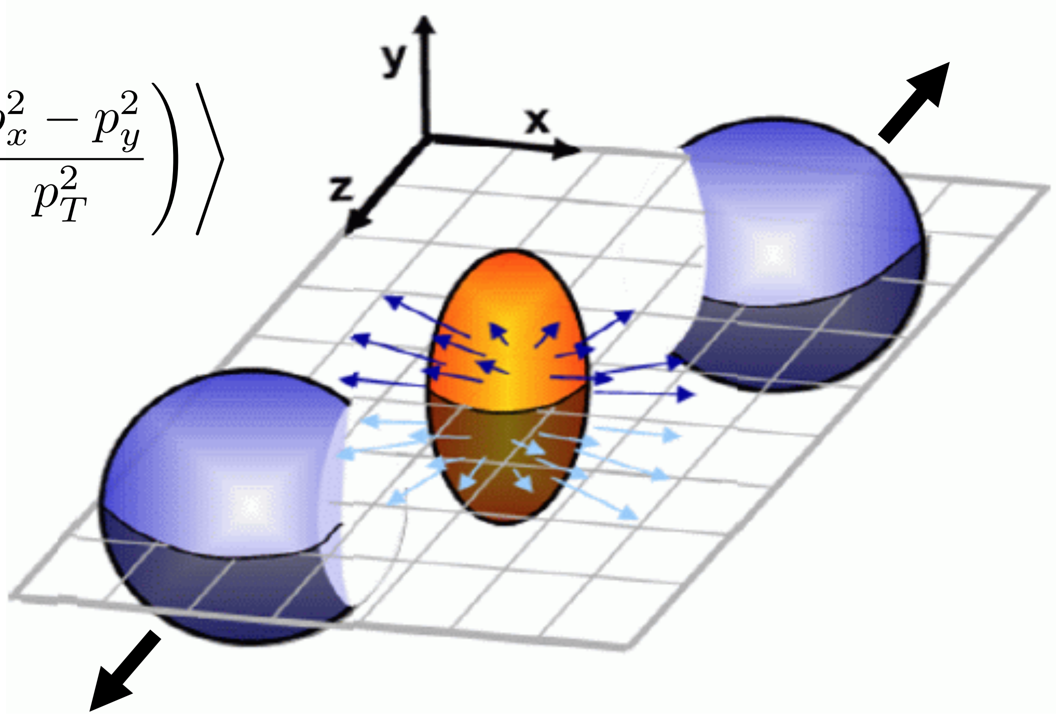
H.P. et al, J.Phys.G G38 (2011) 045102

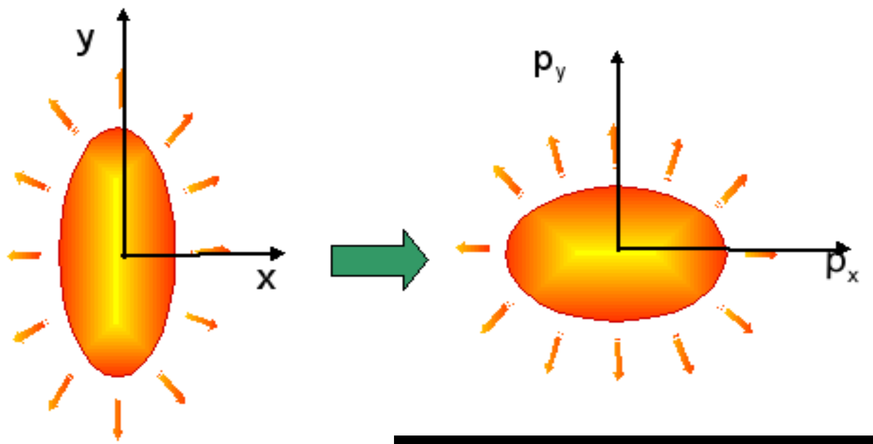
Elliptic Flow

Simplified picture:

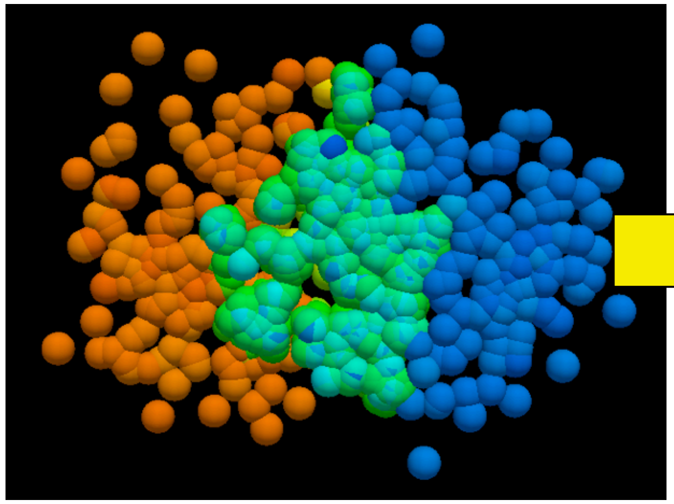
Coordinate space asymmetry
→ momentum space anisotropy

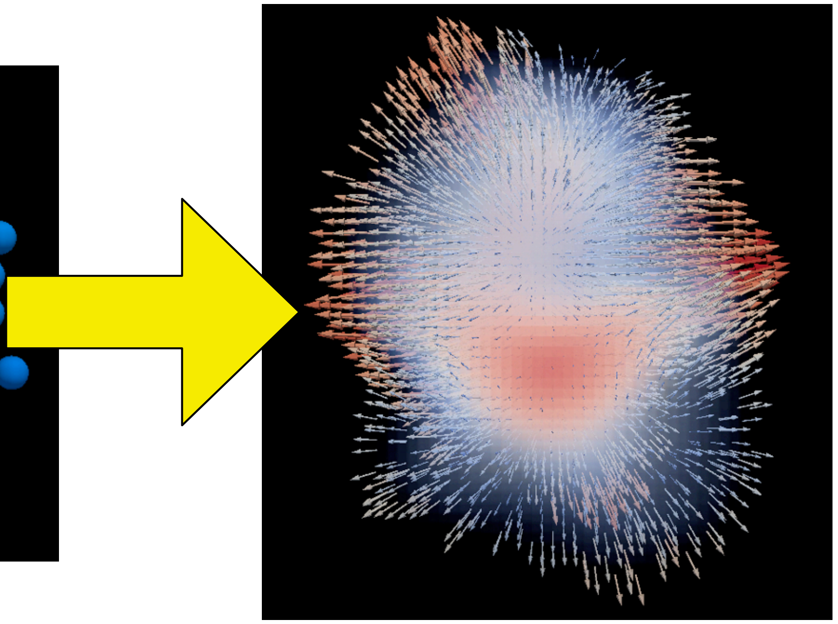
$$v_2 = \left\langle \left(\frac{p_x^2 - p_y^2}{p_T^2} \right) \right\rangle$$





Including fluctuations in Event-by-event approaches





by MADAI.us

Relativistic fluid dynamics with very low viscosity describes elliptic flow at RHIC (and LHC)