FIAS Frankfurt Institute for Advanced Studies

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Bumpy Initial Conditions and a Double-Hump Structure

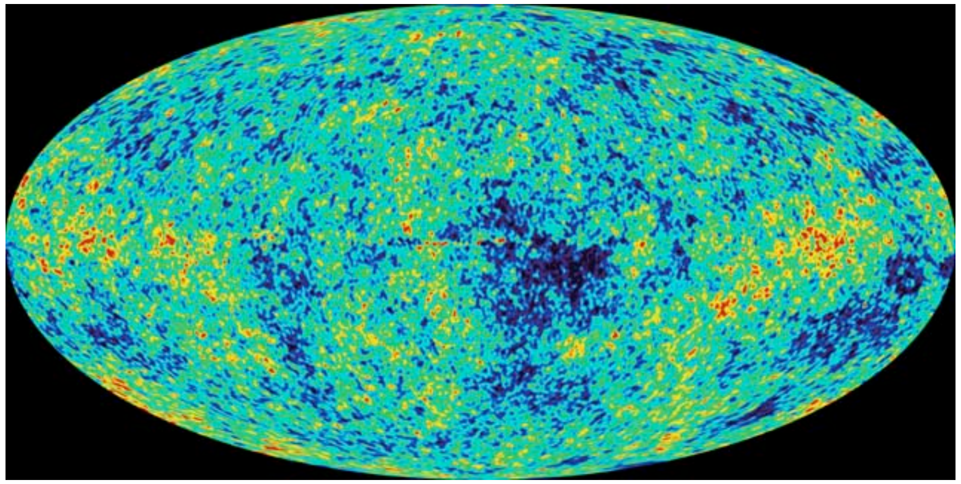
24.10.13, RANP 2013

Hannah Petersen

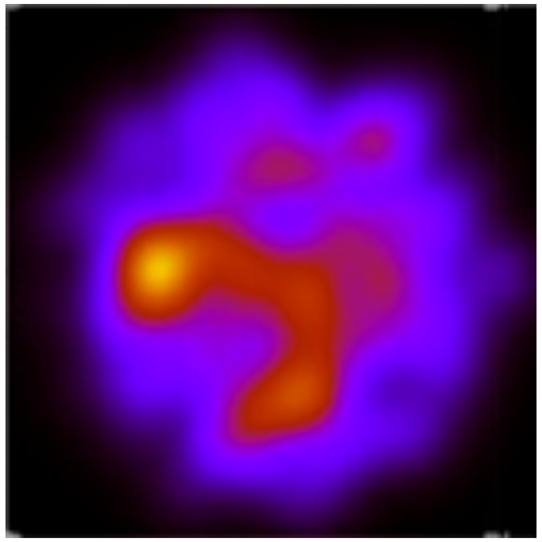
in collaboration with C. Coleman-Smith, R. Wolpert (Duke) and J. Auvinen (FIAS)

Initial State Fluctuations

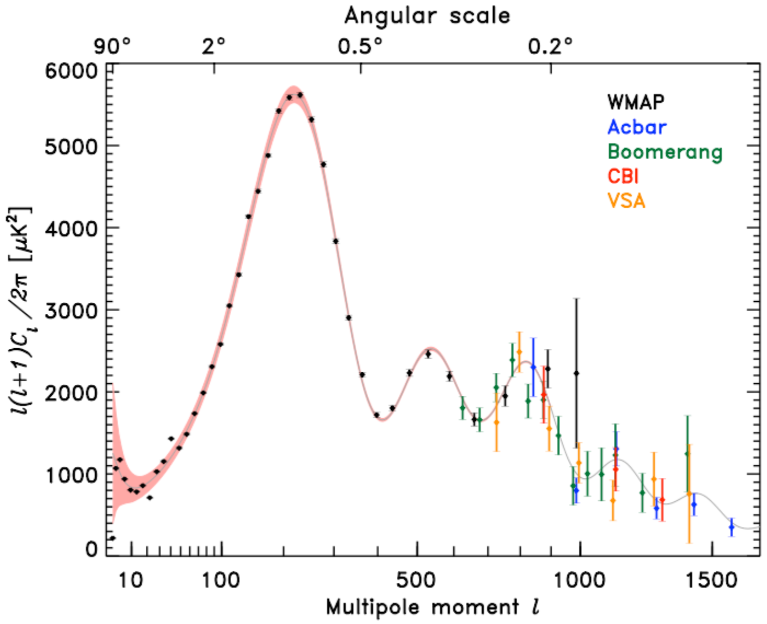
Temperature fluctuations from the early universe



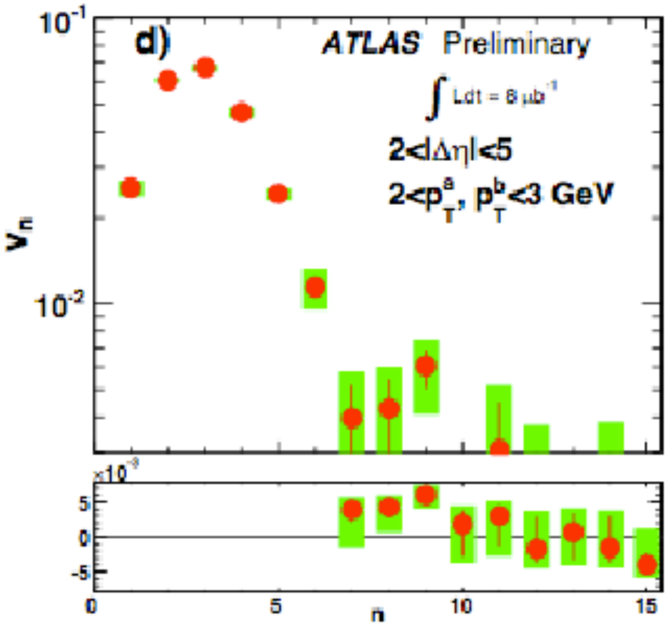
Energy density fluctuations from 2 highly excited colliding nuclei



Multipole moment analysis



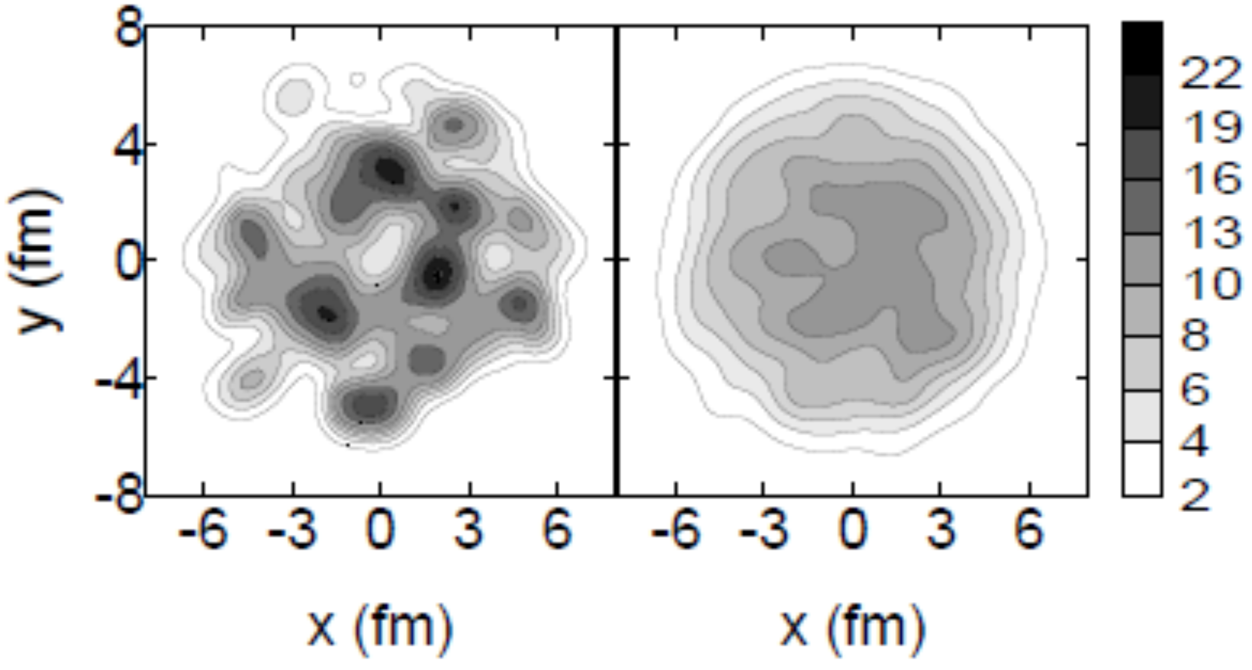
Anisotropic flow analysis

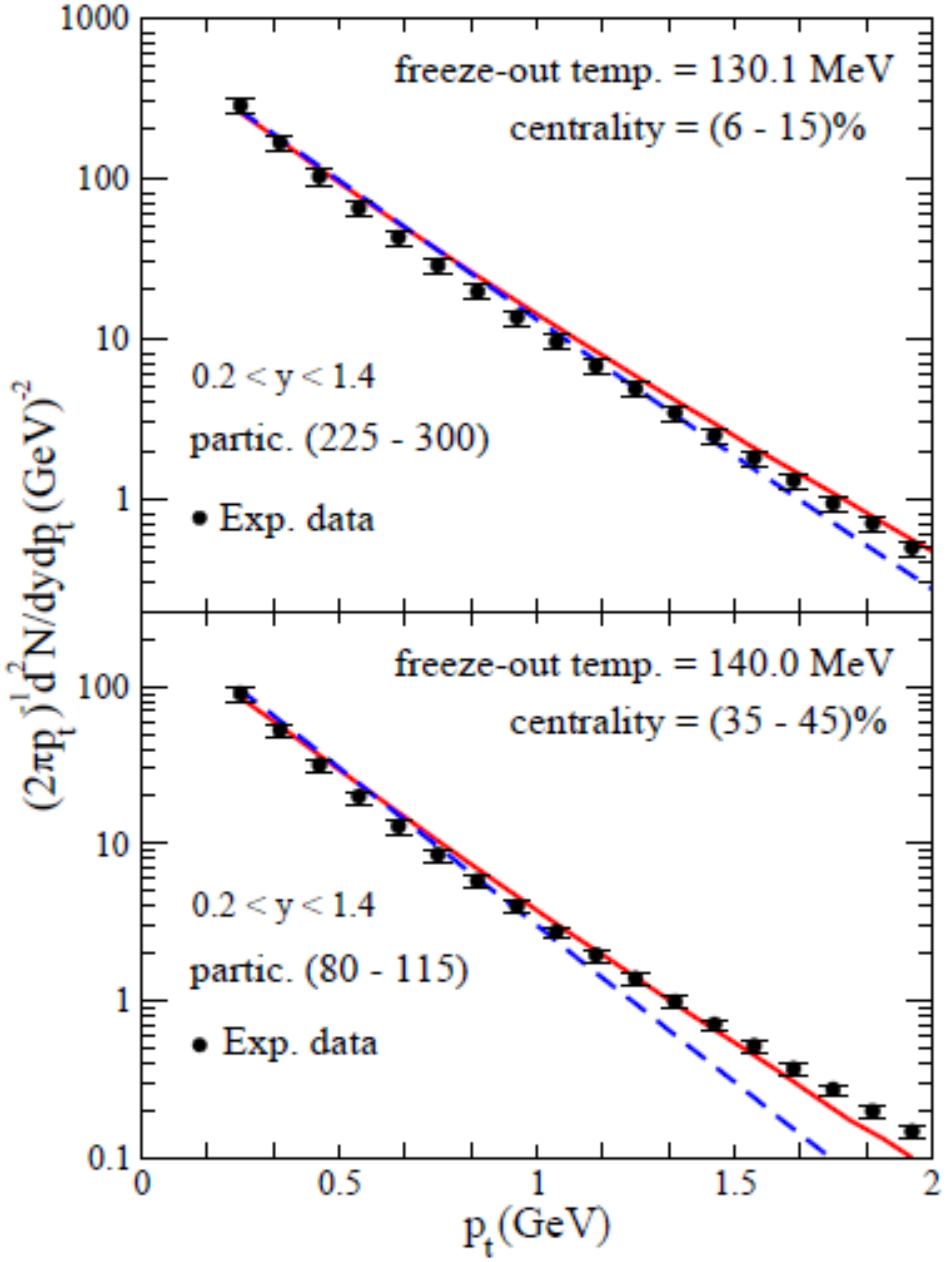


→ Precise knowledge about the matter content in the universe

→Precise knowledge about QCD matter under extreme conditions ?

NEXSpheRIO Results



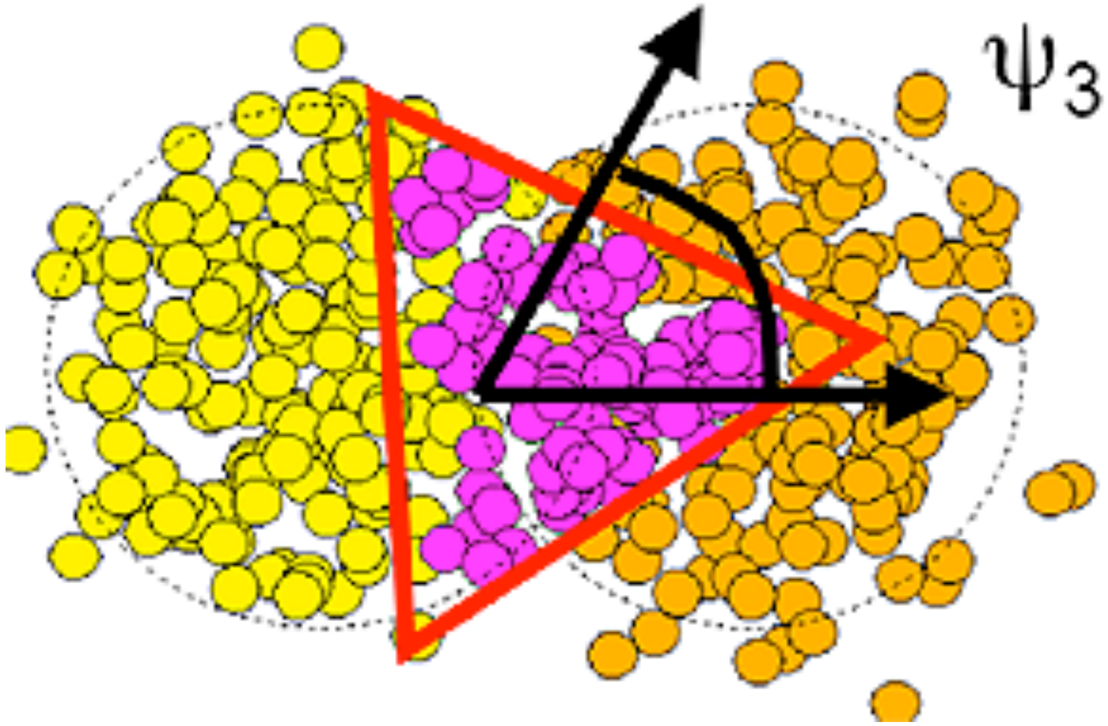


Andrade et al, PRL101,112301,2008

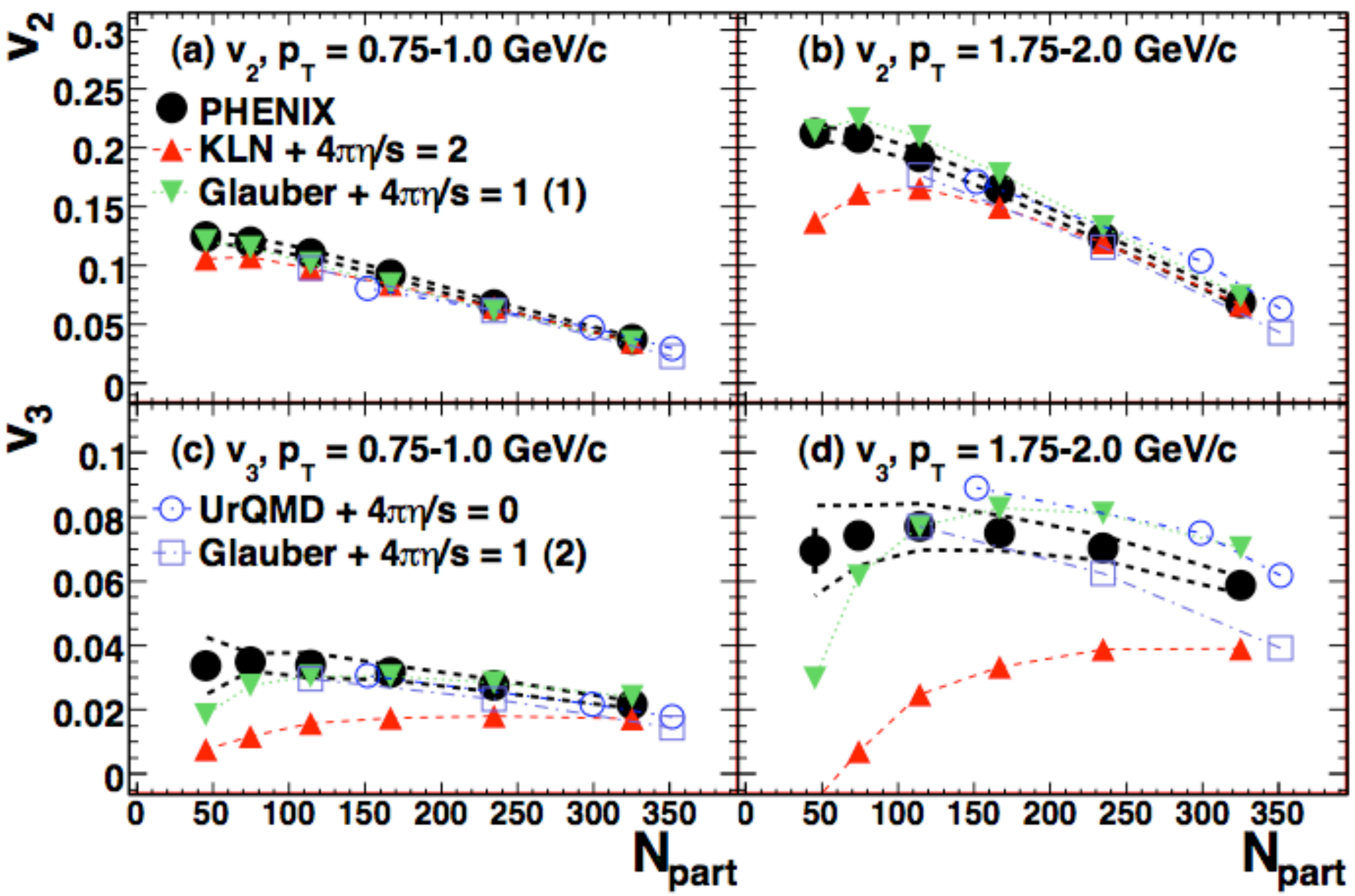
- Early results on initial state fluctuations
- Development of tube model

Triangular Flow

Initial State Fluctuations



Third Harmonic Coefficient

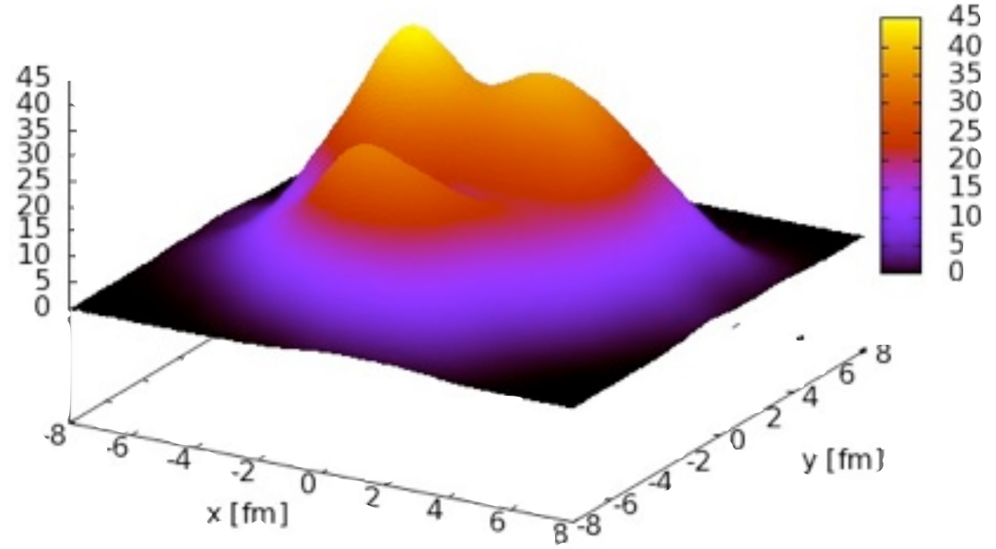


- Fluctuations introduce higher order flow coefficients that have been observed at the RHIC and LHC experiments (see QM 2011)
- How can we quantitatively learn something from this observable?

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 **the ultimate goal**
- Going backward from the measured final state distributions to confirm theoretical predictions requires
  - Understanding of other sources of fluctuations in the evolution
  - Elimination of model dependencies
- 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 properties of non-equilibrium QCD



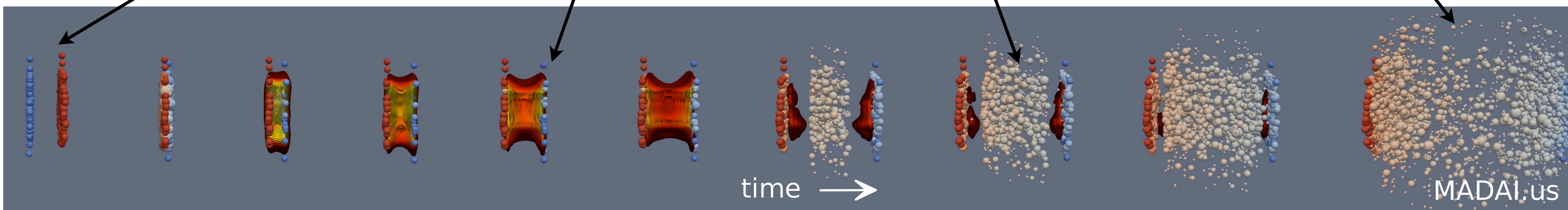
Time Evolution of Heavy Ion Collisions

Nuclei at 99 % speed of light

Quark Gluon Plasma

Hadronic Rescattering

Measurable Fragments in the detector



1×10^{-23} s

10×10^{-23} s

30×10^{-23} s

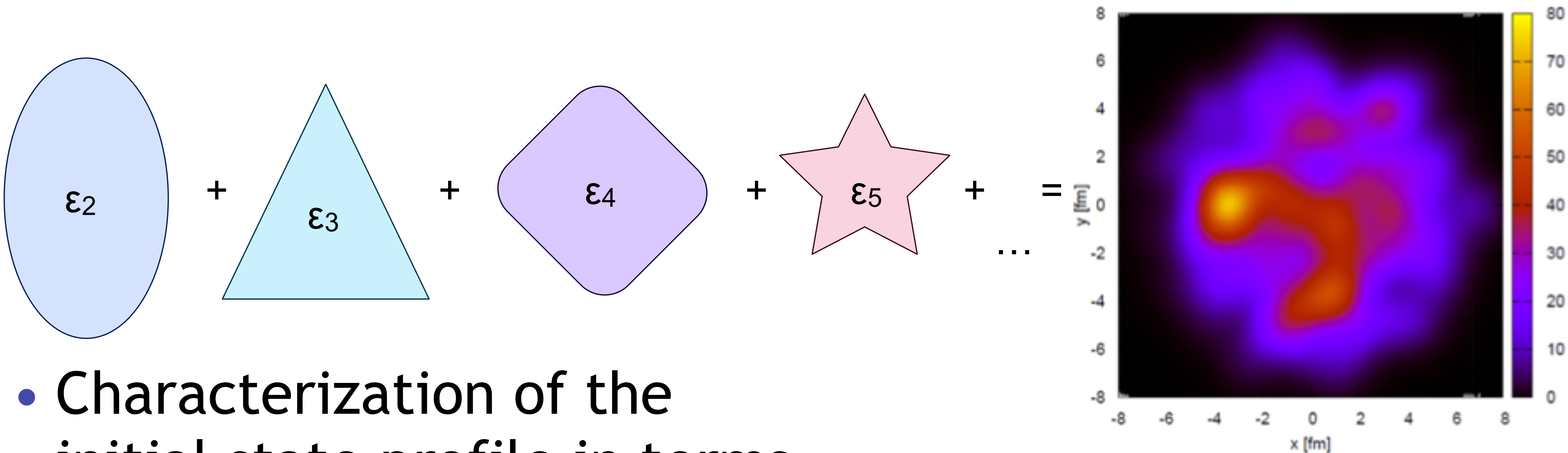
Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

Hybrid approaches are very successful for the description of the dynamics

- **Initial state** is influenced by:

Degrees of freedom; Interaction mechanism; Thermalization

Azimuthal Decomposition



- 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

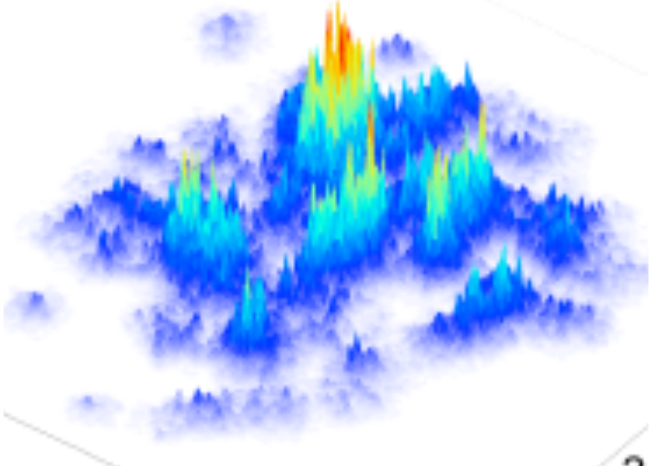
$$\Phi_n = \frac{1}{n}\arctan\frac{\langle r^n \sin(n\phi)\rangle}{\langle r^n \cos(n\phi)\rangle}$$

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

Current Status of IC Description

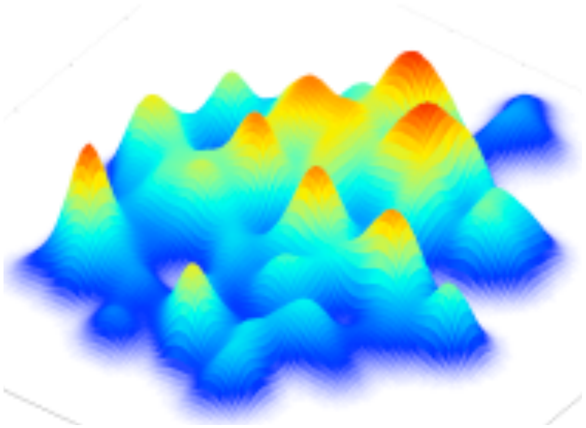
- **Parametrizations:**
  - Monte Carlo Glauber + improvements
  - CGC based models: MC-KLN, IP-Glasma ...
- **Dynamic** Approaches:
  - NEXUS, UrQMD, AMPT, EPOS, ...
- **Qualitative** Studies:
  - Color field fluctuations
  - AdS/CFT colliding sheets
- Many more...
- How can we **characterize** the differences and similarities in a more complete way?

Glasma, IP Sat Model



B. Schenke et al, arXiv: 1202.6646

MC Glauber Model



Both initial conditions have similar ε_2 and ε_3 and describe experimental data

2d Fourier Decomposition

- **Idea:** Make use of the radial direction in addition to the azimuthal direction in coordinate space
- **Method:** Generate many initial energy distributions and subtract the average -> only fluctuations are quantified
- Basis functions:

$$\phi_{m,n}(r,\theta) := \frac{1}{J_{|m|+1}(\lambda_{m,n})} J_m\left(\frac{r}{r_0}\lambda_{m,n}\right)e^{im\theta}$$

- Any function f:

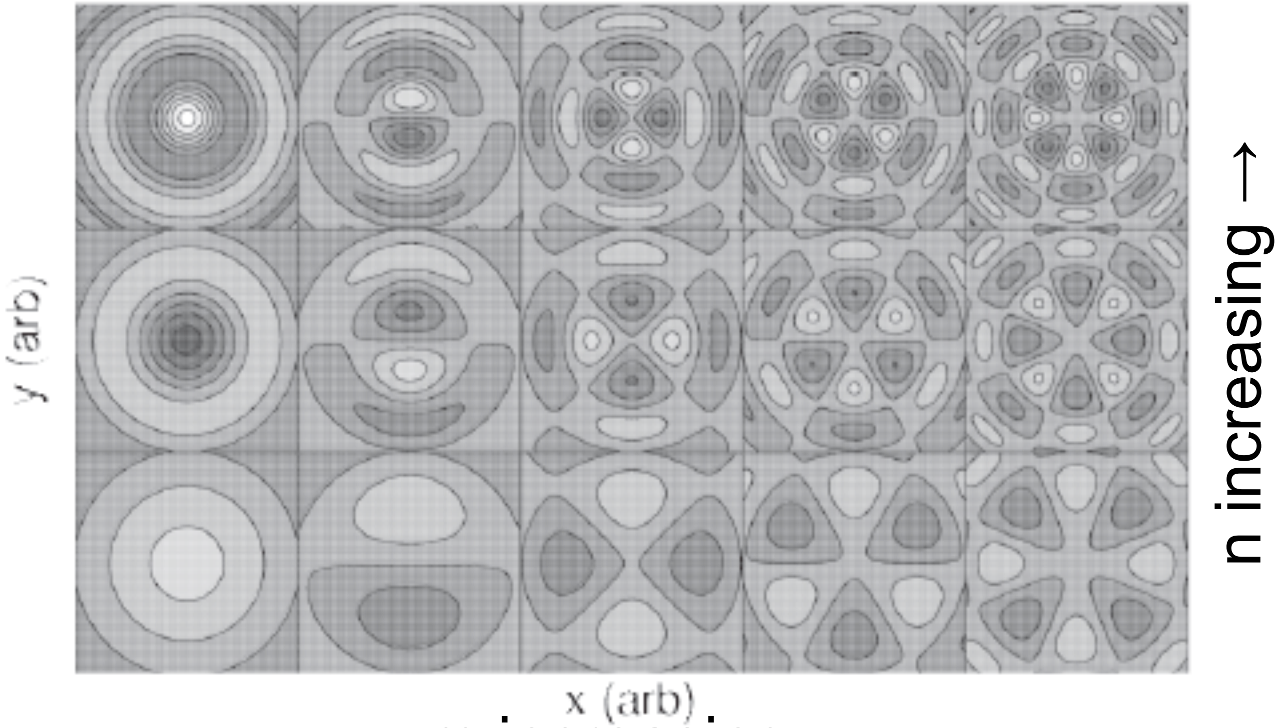
$$f(r,\theta) = \sum_{m,n} A_{m,n}\phi_{m,n}(r,\theta),$$

- with generalized coefficients

$$A_{m,n} = \frac{1}{\pi r_0^2}\int f(r,\theta)\phi^{\star}_{m,n}(r,\theta)r dr d\theta.$$

- Angular and radial structures are captured

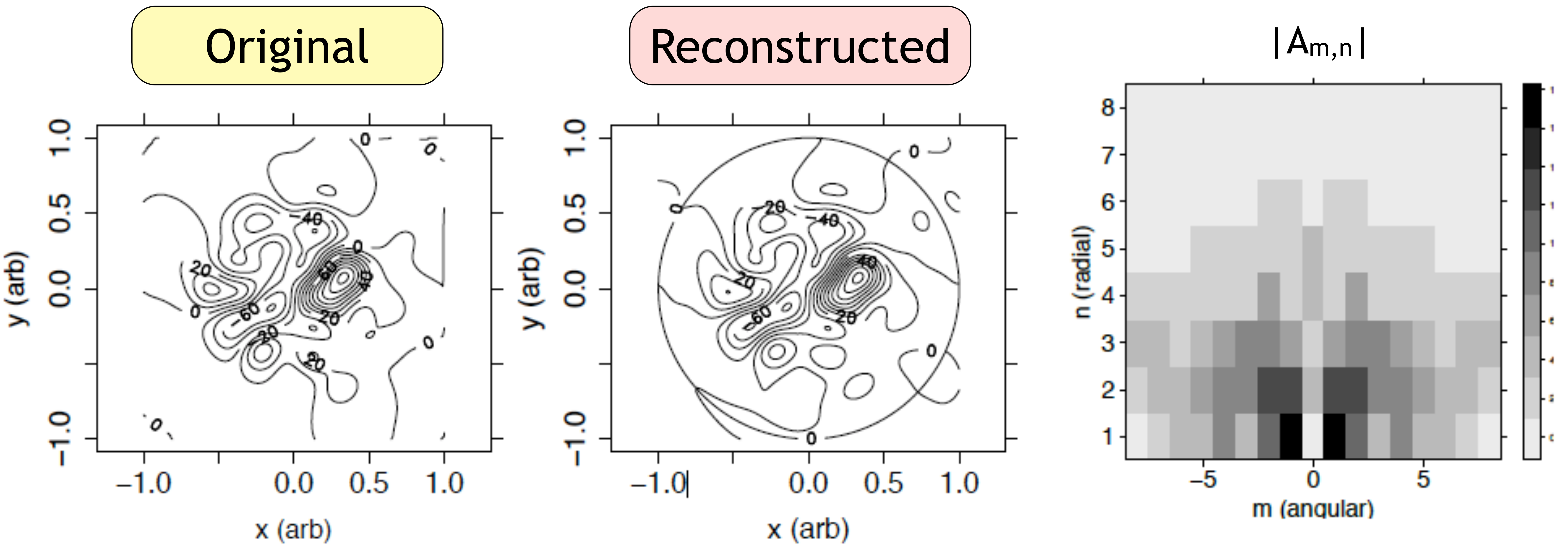
Real parts of $\Phi_{m,n}$



C. Coleman-Smith, HP et al, J. Phys G40 (2013) 095103

Application to Single Event

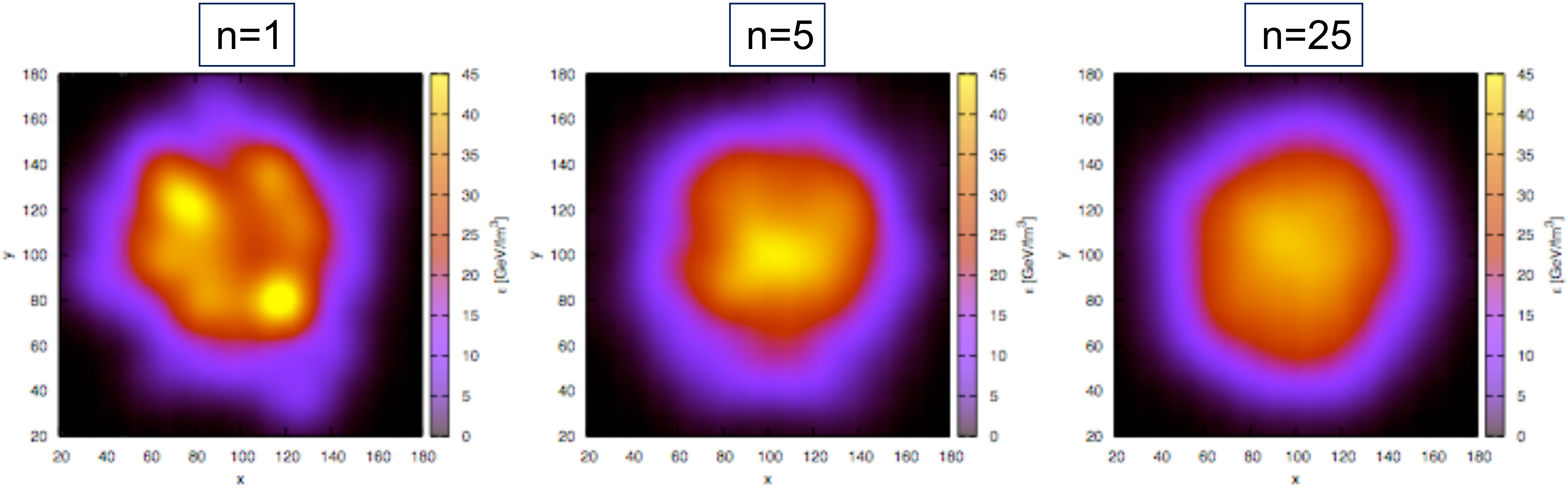
- The original energy density distribution can be reconstructed with n<8 and |m|<8



- Energy density profile is represented by ~35 numbers
- Norms are useful to condense information

UrQMD Example

- Systematic study in a hadronic transport approach



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

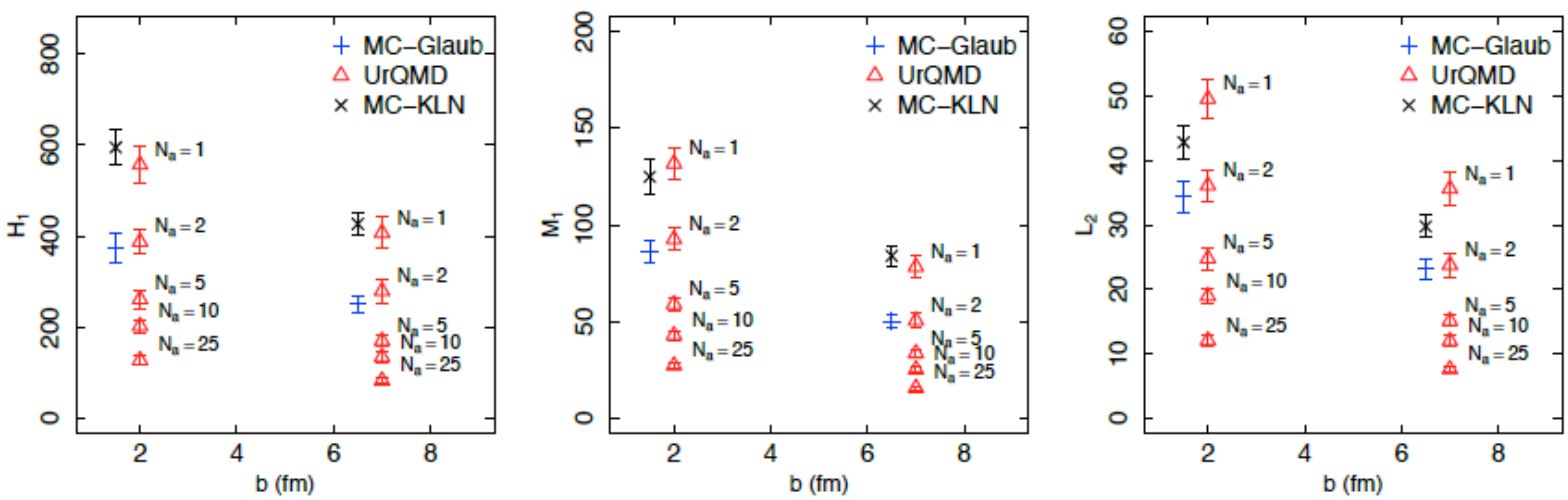
- Averages over the initial state profile for different numbers of events lead to different **granularities**
  - Overall **features** of the initial state profile are preserved
  - Direct connection to initial state dynamics lost
  - How does the 2d decomposition distinguish ?

Properties of Norms

L_2 norm: $L_2(f) := \langle f, f\rangle^{1/2} = \left[\sum |A_{m,n}|^2\right]^{1/2}$ → total mass of the function

H_1 norm: $$H_1(f) := \langle(-\ell^2\nabla^2 + I)f, f\rangle^{1/2} = \left[\sum \left(\frac{\ell^2\lambda_{m,n}^2}{r_0^2} + 1\right)|A_{m,n}|^2\right]^{1/2}$$ → Sobolev norm, contains radial gradients

M_1 norm: $M_1(f) := \langle \partial_\theta^2 f, f\rangle^{1/2} = \left[\sum m^2|A_{m,n}|^2\right]^{1/2}$ → contains angular gradients

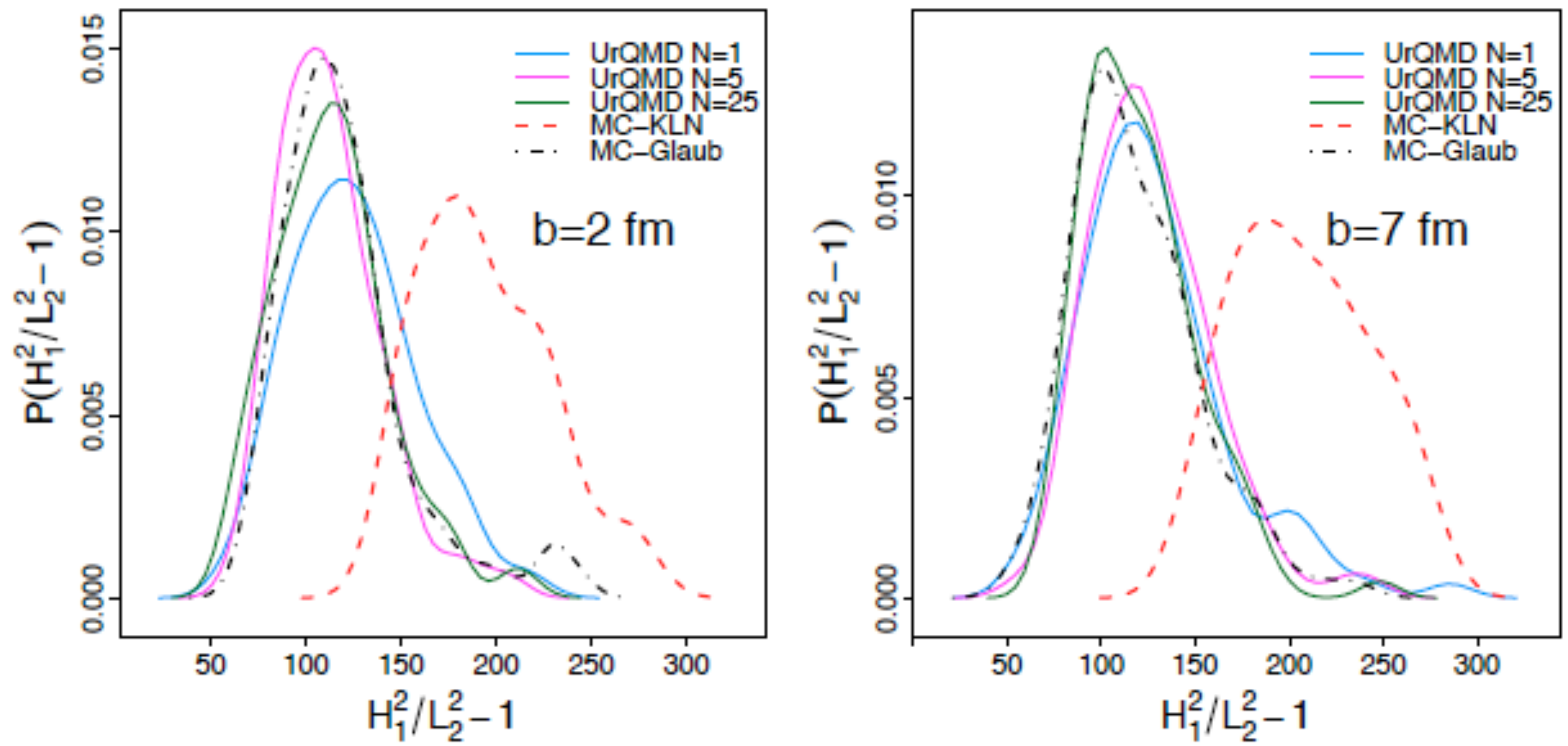


Hadron-based models very similar; larger radial gradients in partonic model

Roughness Measure

- Dividing out the total mass of the event provides a **scale invariant** measure of the behavior of the gradients

$$\mathcal{R}^2 = \frac{H_1^2}{L_2^2} - 1 = \frac{\langle -\ell^2 \nabla^2 f, f\rangle}{\langle f, f\rangle} = \frac{\ell^2 \sum \lambda_{m,n}^2 |A_{m,n}|^2}{r_0^2 \sum |A_{m,n}|^2}$$



- All UrQMD lines and Glauber collapse to one curve, but MC-KLN is clearly different → Distinguish partonic and hadronic initial **degrees of freedom**

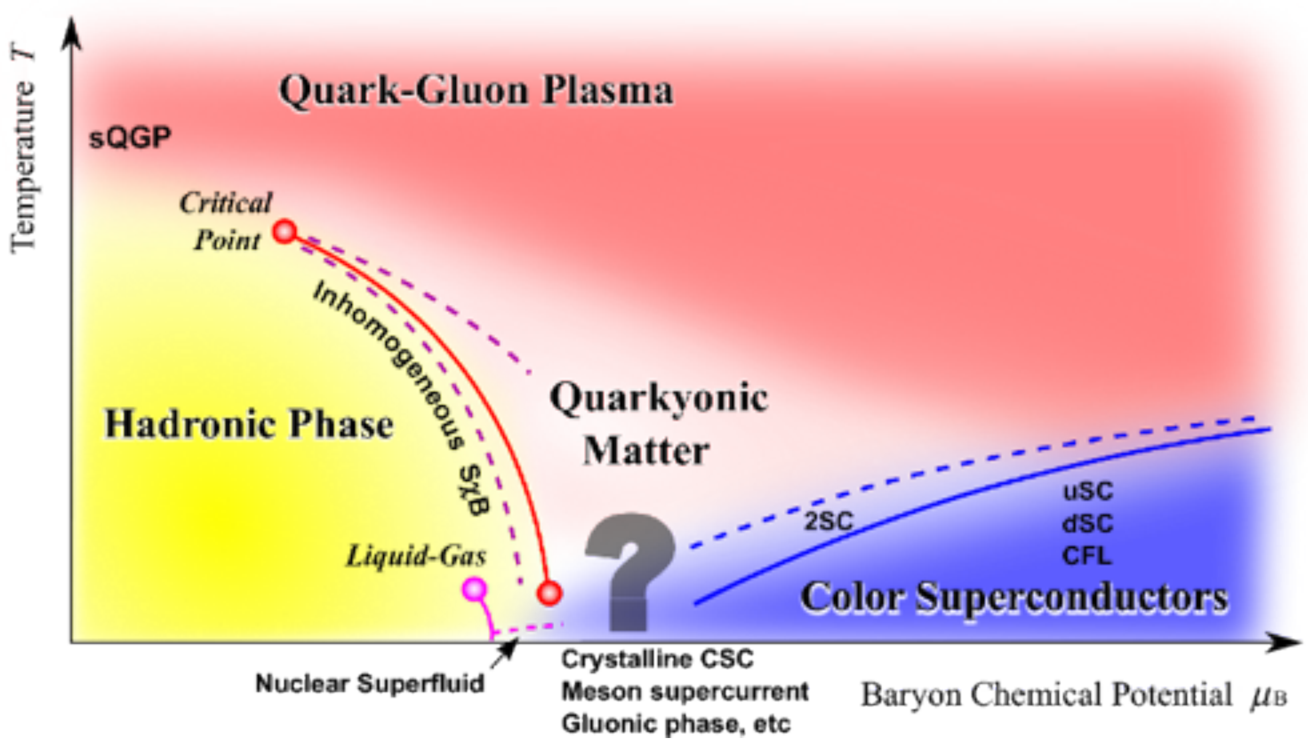
What next?

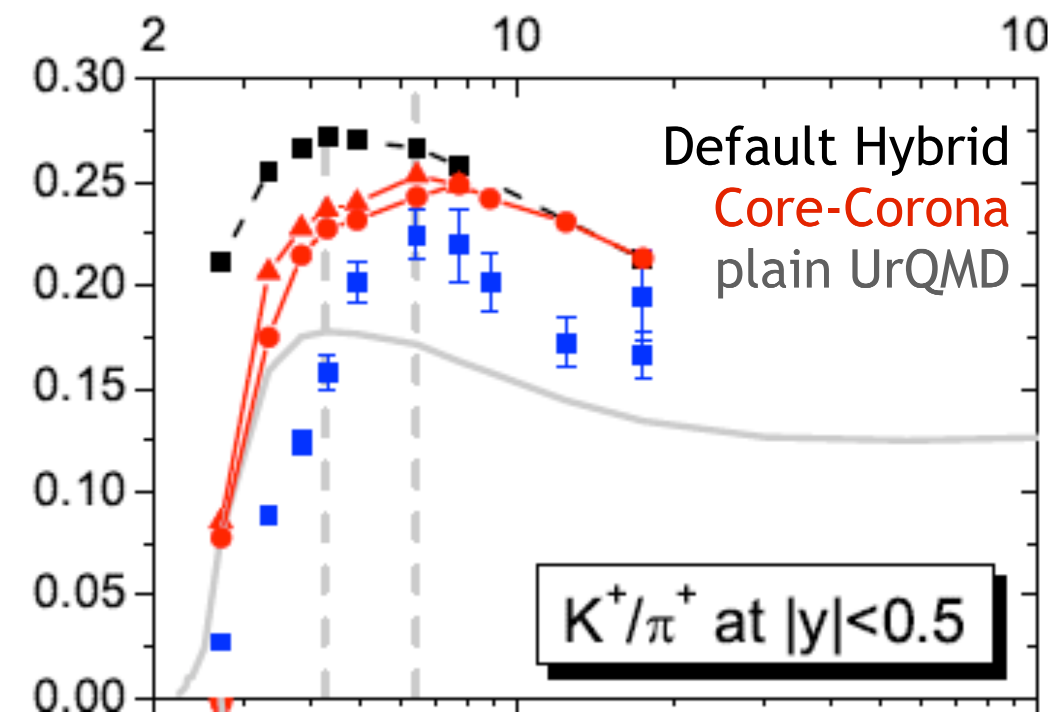
- The 2d Fourier decomposition:
  - **Applicable** to analytical calculations and Monte Carlo simulations
  - Provides a good tool for **apples-to-apples** comparison of initial state models by extracting essential features, differences or similarities
  - Easy to generalize to **3D** and other quantities, e.g. initial velocity profiles
- To do:
  - Connect these norms and coefficients to final state **observables**

    see also recent study by Wiedemann, Floerchinger
  - → Constrain initial degrees of freedom and their interactions

Lower Beam Energies

- Differences in the evolution at lower beam energies:
  - Finite **net-baryochemical potential** needs to be taken into account in equation of state
  - **Conserved quantum numbers** need to be considered in evolution
  - **Dissipative effects** grow at lower energies (hadronic evolution gains importance)





J. Steinheimer, M. Bleicher PRC84 (2011)

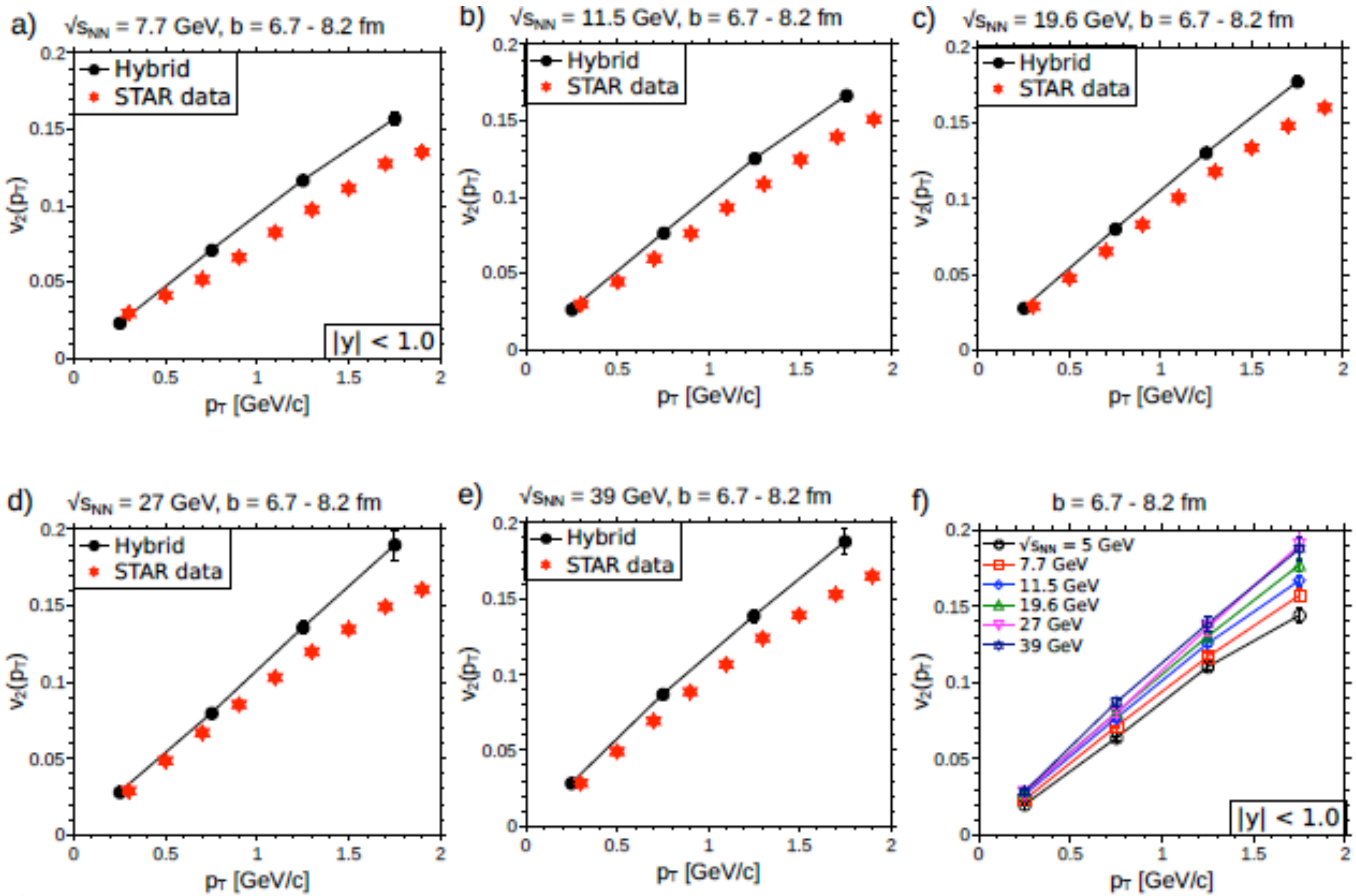
- Opportunity to extract temperature and density dependence of viscosity
- How far down does the hybrid approach work?

UrQMD hybrid

H.P. et al, PRC78 (2008) 044901

- Initial State:
  - Initialization of two nuclei
  - Non-equilibrium hadron-string dynamics
  - Mapping of energy, momentum and net baryon density with **3d Gaussians** + instant thermalization
  - Initial state fluctuations are included naturally
- 3+1d Hydro +EoS:
  - **SHASTA** ideal relativistic fluid dynamics
  - Net baryon density is explicitly propagated
  - Chiral model + Polyakov loop, fitted to lattice and nuclear ground state properties, applicable in whole T-mu_b plane
- Final State:
  - **Cooper-Frye** switching transition
  - Chemical and kinetic freeze-out with **hadron cascade**
  - Full phase-space information of final particles

Differential Elliptic Flow

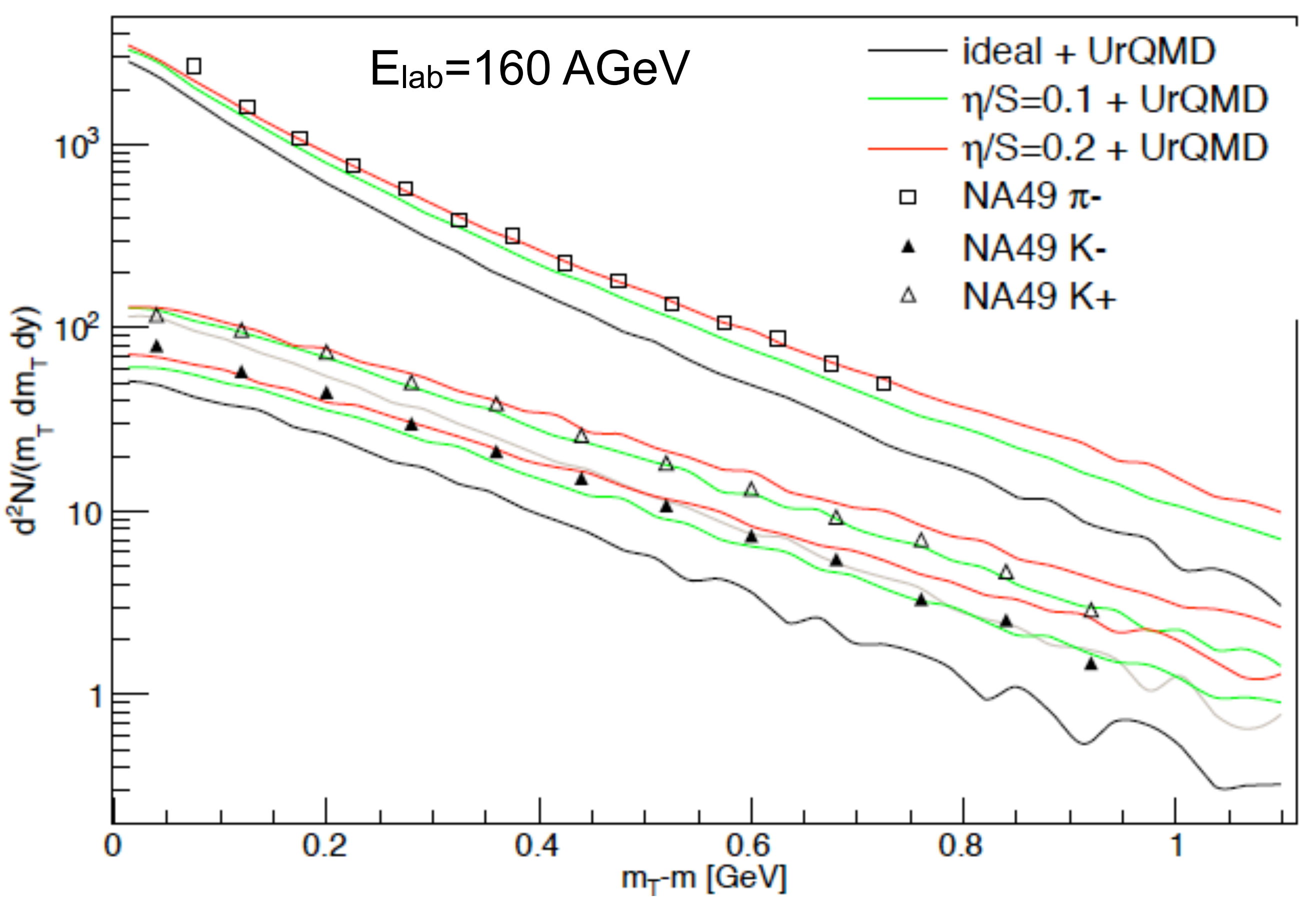


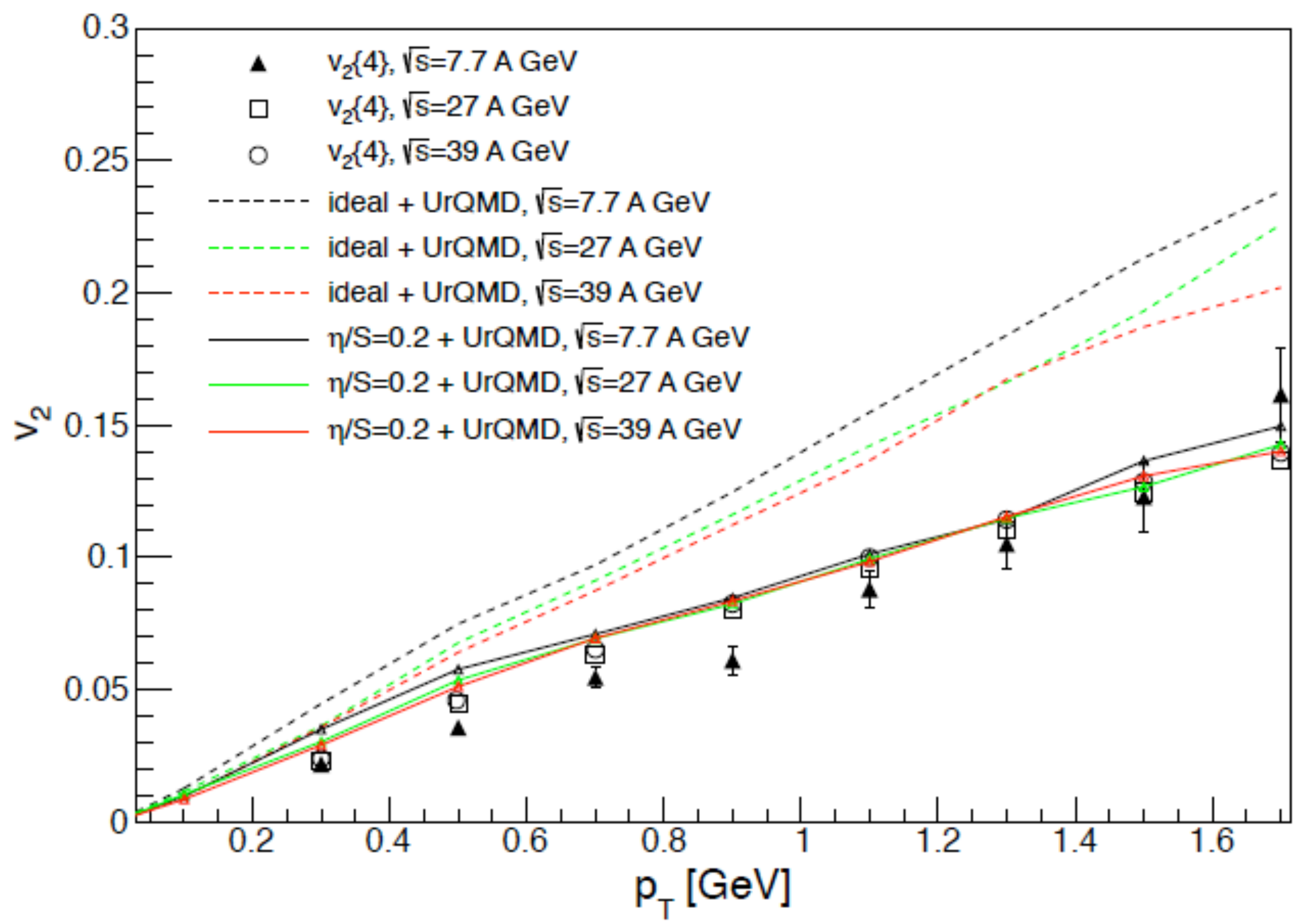
- $v_2(p_T)$ independent of beam energies
- Slight overestimation due to ideal hydro

J. Auvinen, HP arXiv:1306.0106

Viscous Hybrid Approach

- 3+1d viscous hydro + UrQMD hybrid approach
- EoS at finite baryo-chemical potential



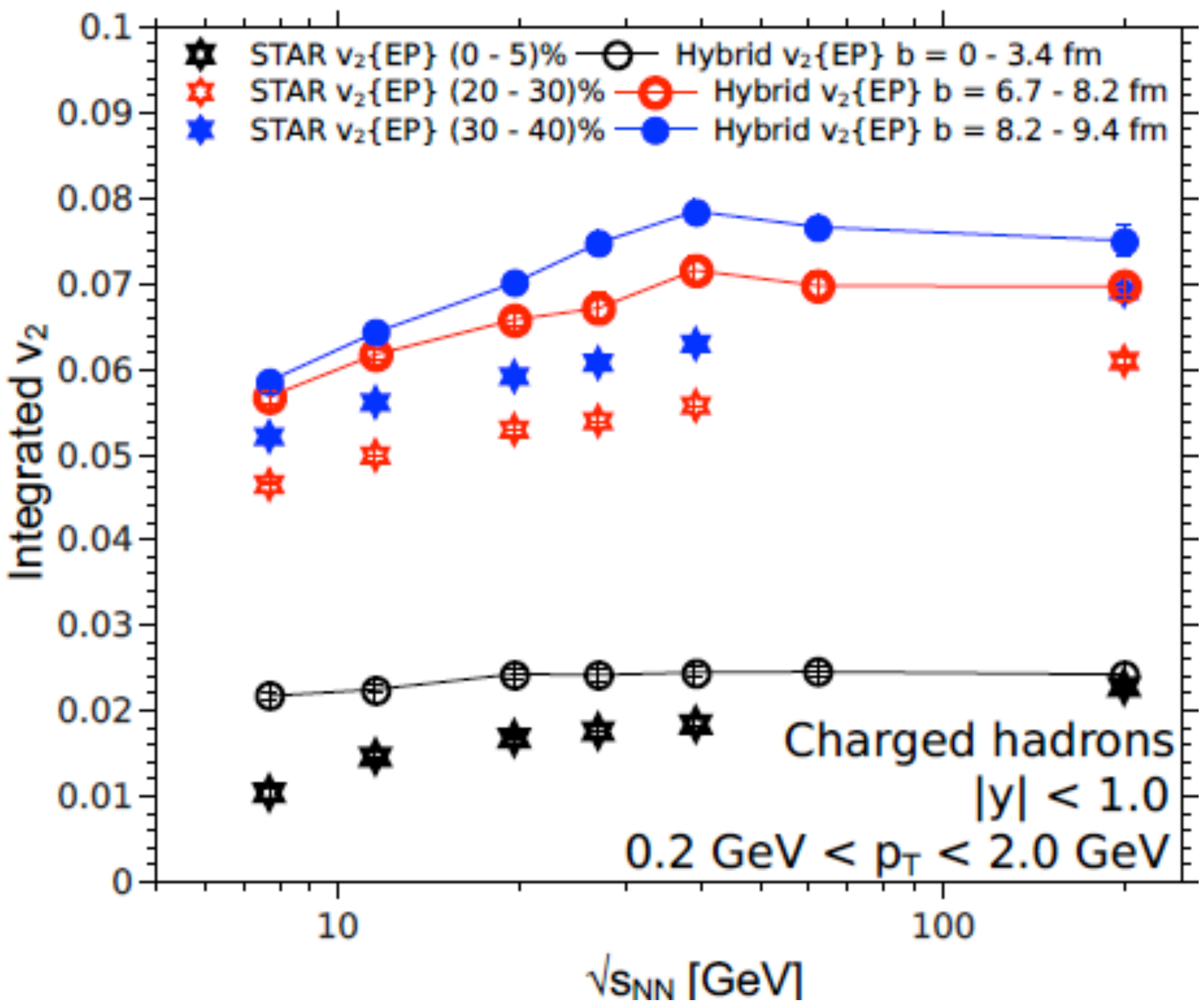


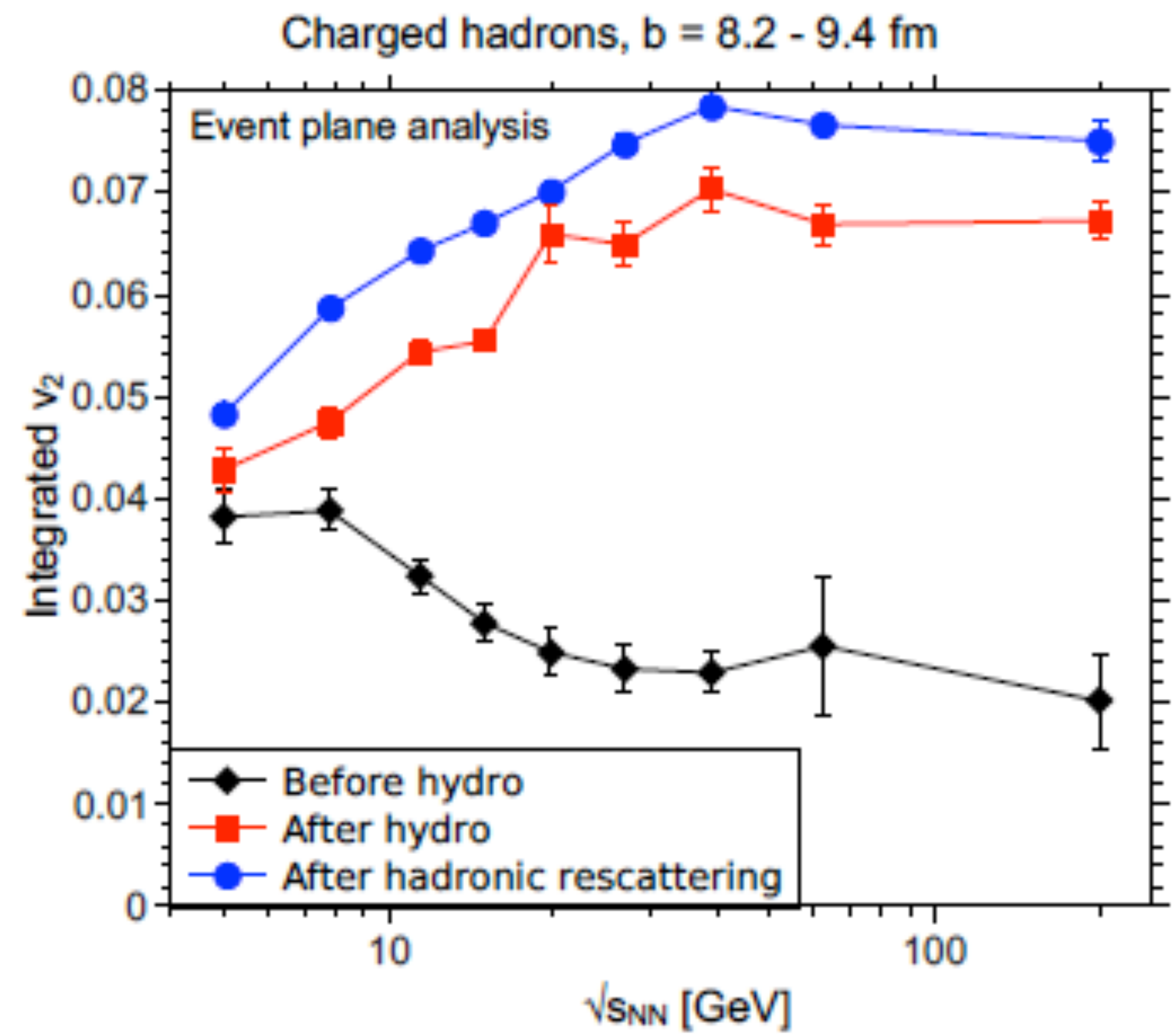
- Spectra and elliptic flow favor η/s ~ 0.2

Y. Karpenko, P. Huovinen, HP, M. Bleicher, SQM 2013

Excitation Function

- Contribution of different stages to integrated v_2

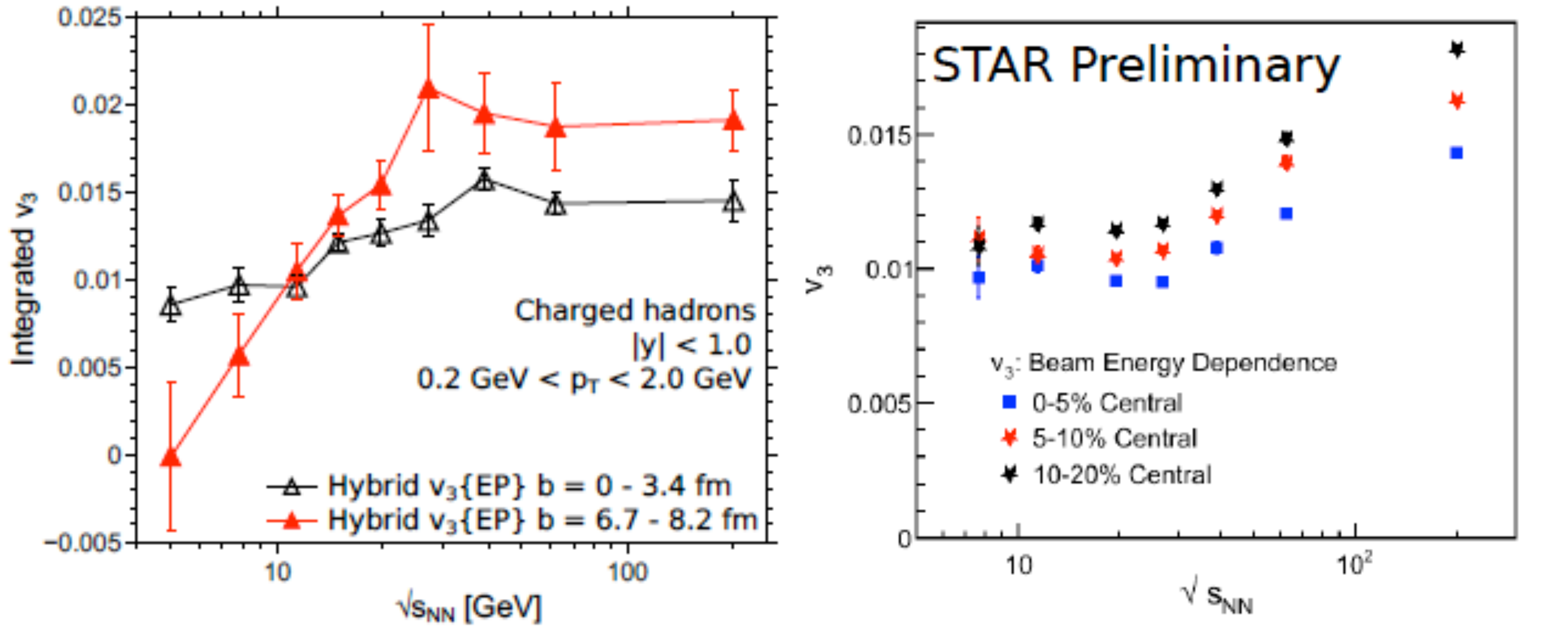




- Transport compensates for decreasing hydro phase at lower beam energies
- Integrated elliptic flow overestimated due to missing viscosity in hydrodynamic evolution

J. Auvinen, HP arXiv:1306.0106

v_3 Excitation Function



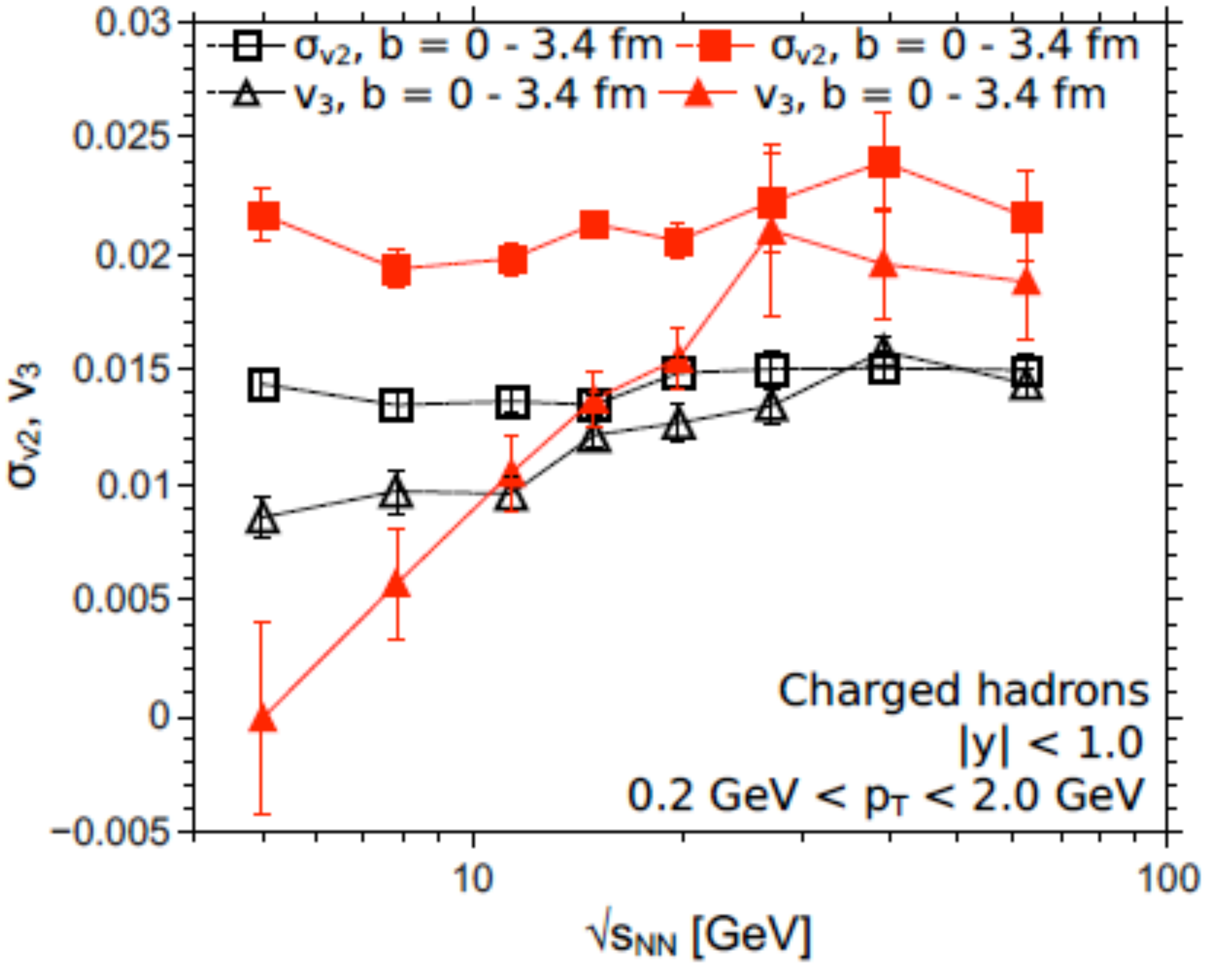
- Triangular flow in central collisions matches STAR data
- More peripheral collisions: v_3 goes to zero in hybrid approach

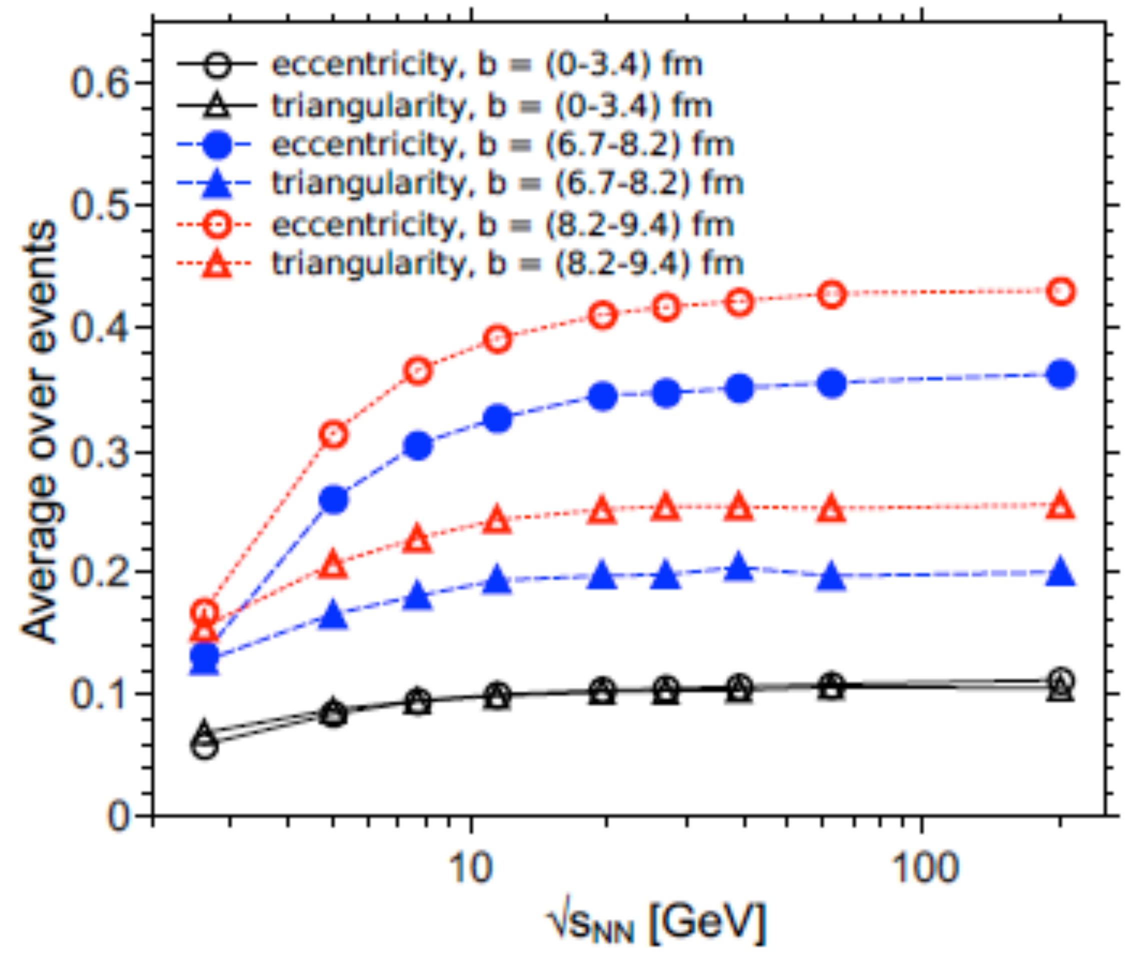
J. Auvinen, HP arXiv:1306.0106

Measuring Fluctuations

- At high energies v_3 is equal to σ_{v2}

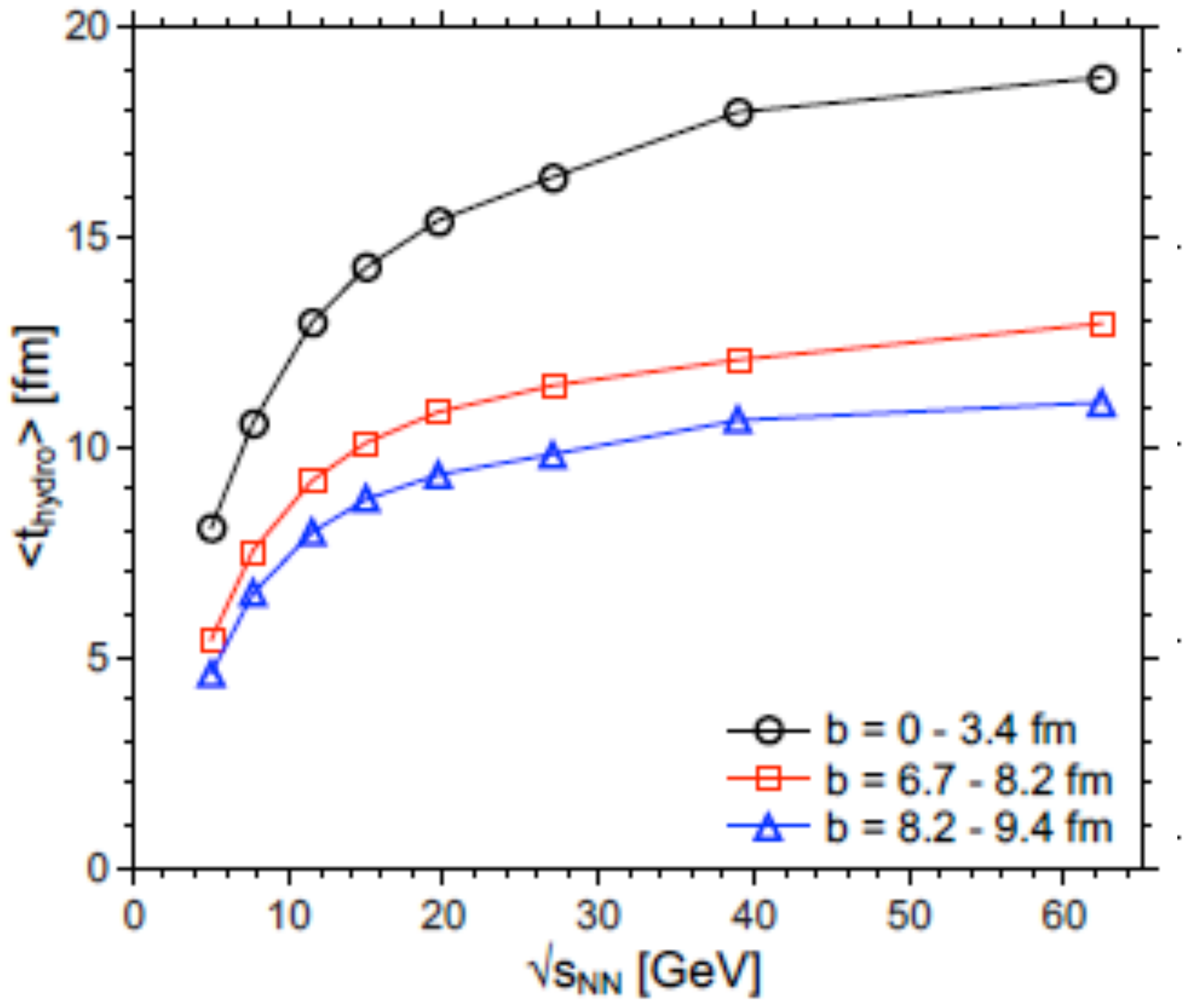
$$\sigma_{v2} = \sqrt{\frac{1}{2}(v_2\{\mathrm{EP}\}^2 - v_2\{\mathrm{RP}\}^2)}$$

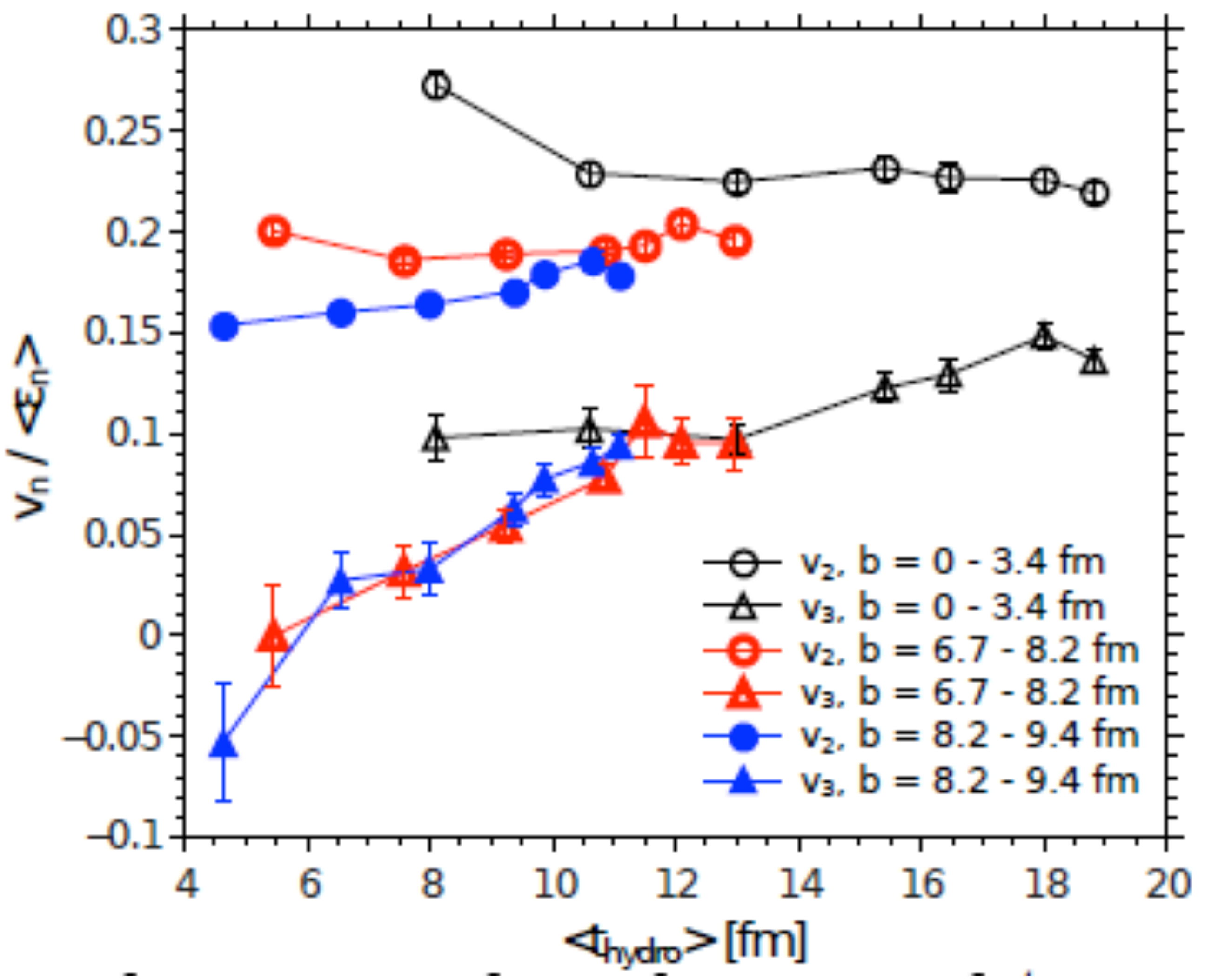




- Initial state geometry and fluctuations rather independent of beam energy

Sensitivity to ⟨t_{hydro}⟩





- v_3/ε_3 shows universal behaviour as a function of total duration of hydro phase
- v_2 does not follow scaling because of transport contribution

Conclusion

- Higher flow coefficients are sensitive to initial state fluctuations and viscosity
- 2D Fourier decomposition is introduced to characterize initial state profiles
- Beam energy dependence of elliptic and triangular flow explored in hybrid approach
  - v_2: Transport compensates for hydro at lower energies
  - v_3: More sensitive to viscosity
- Outlook: 3+1D Viscous hydro+transport at finite net baryon density

Y. Karpenko, P. Huovinen, HP, M. Bleicher, SQM 2013

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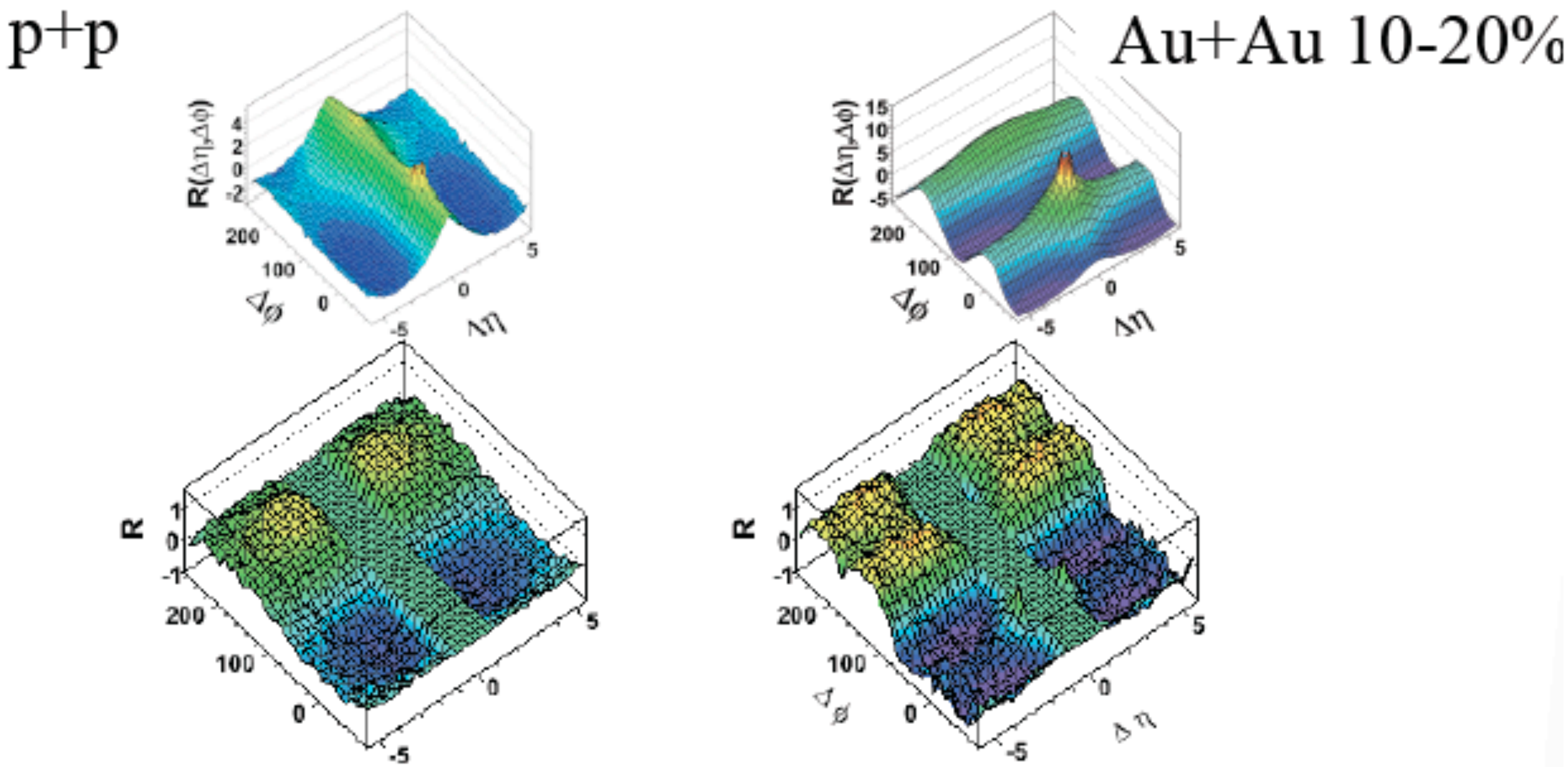
Y. Karpenko, P. Huovinen, HP, M. Bleicher, SQM 2013

- And what about the double-hump structure??

Double-Hump Structure

Ridge and broad–away side

Actually:
Ridge and broad away side at low p_T out to $\Delta\eta$=5.5



Taking out all $V_{2\Delta}$

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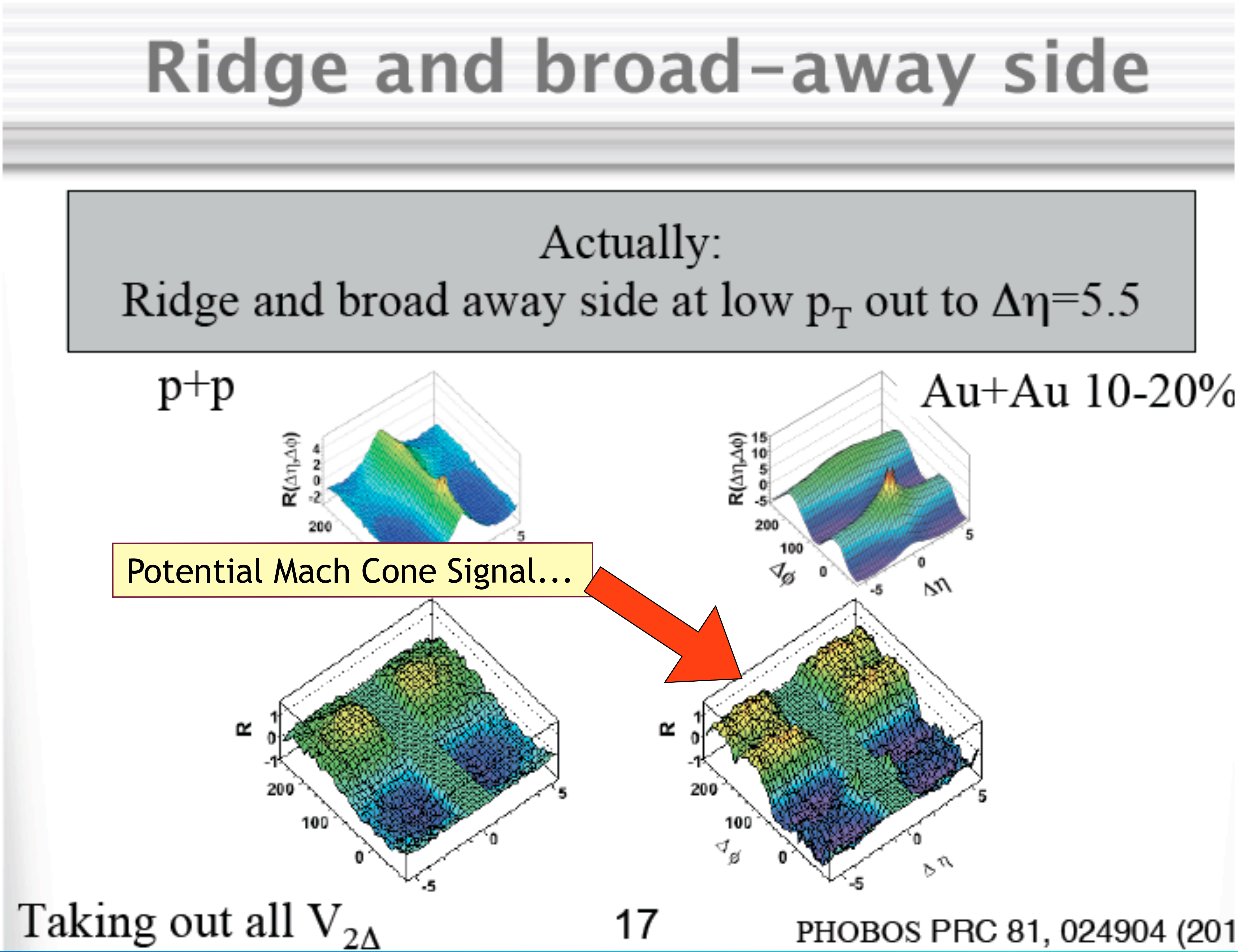
PHOBOS PRC 81, 024904 (201

Slide from B. Alver, INT Workshop

Double-Hump Structure



Slide from B. Alver, INT Workshop

WPCF/ISMD Berkeley 2007

- We wanted to see the Golden Gate Bridge, but

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- Takeshi became creative...

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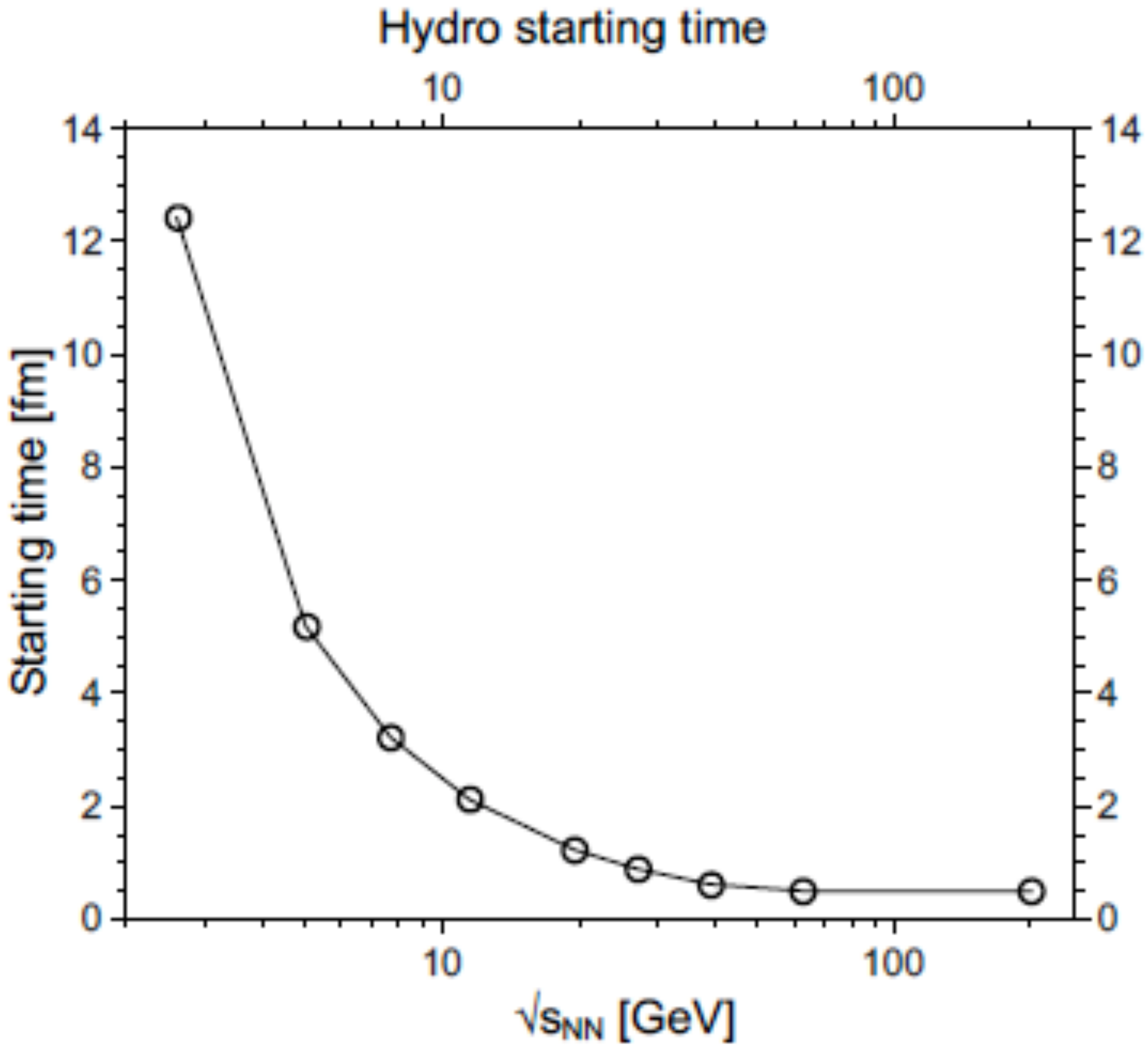
HAPPY BIRTHDAY!

- Takeshi became creative...

Backup

Starting Times

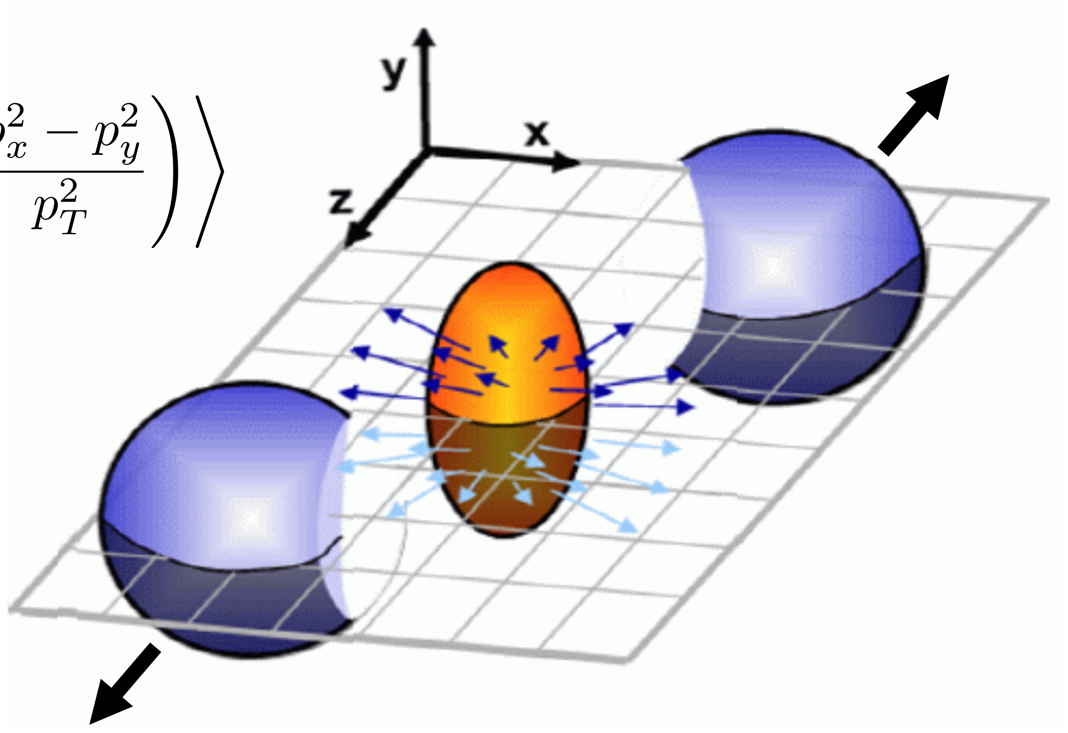


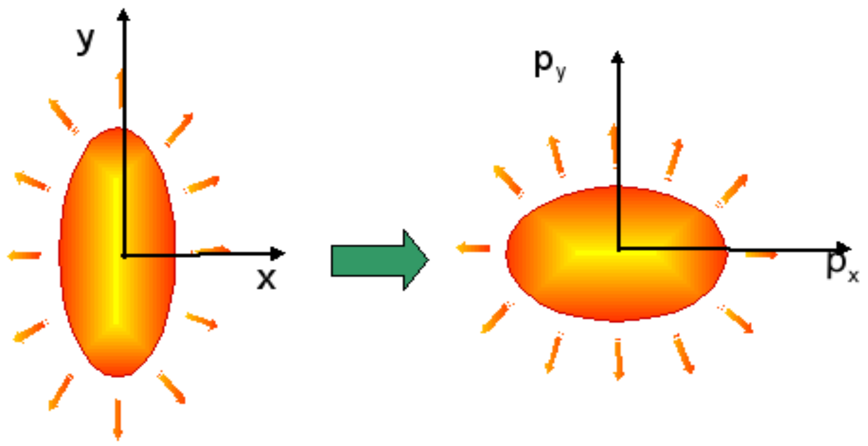
Anisotropic Flow

Simplified picture:

Coordinate space asymmetry
→ momentum space anisotropy

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





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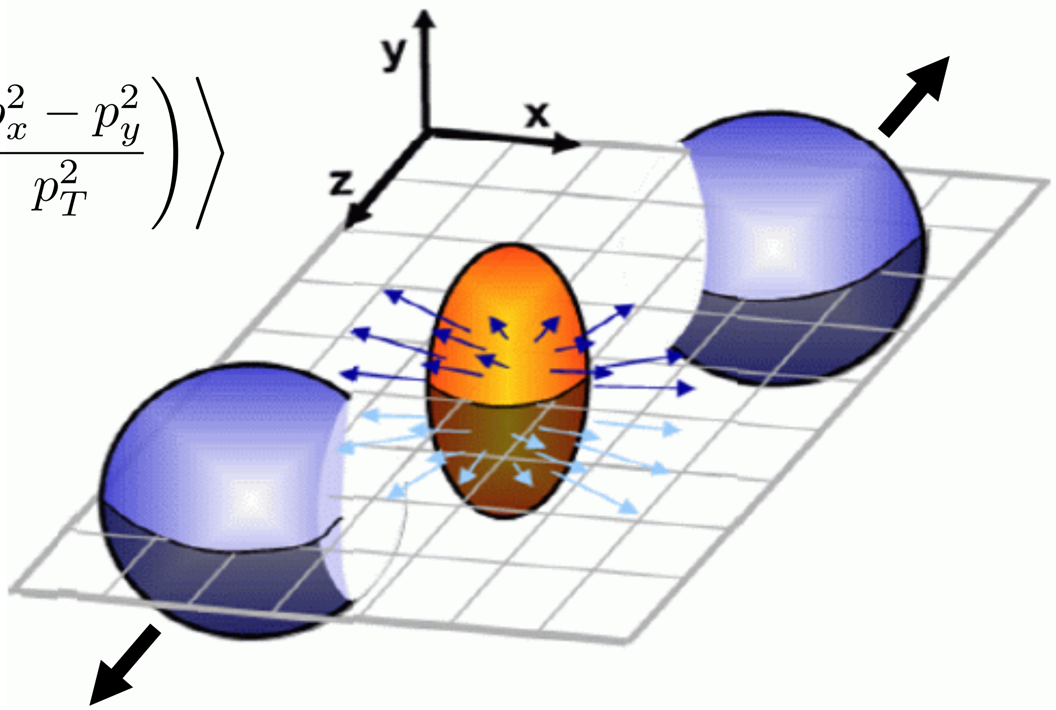
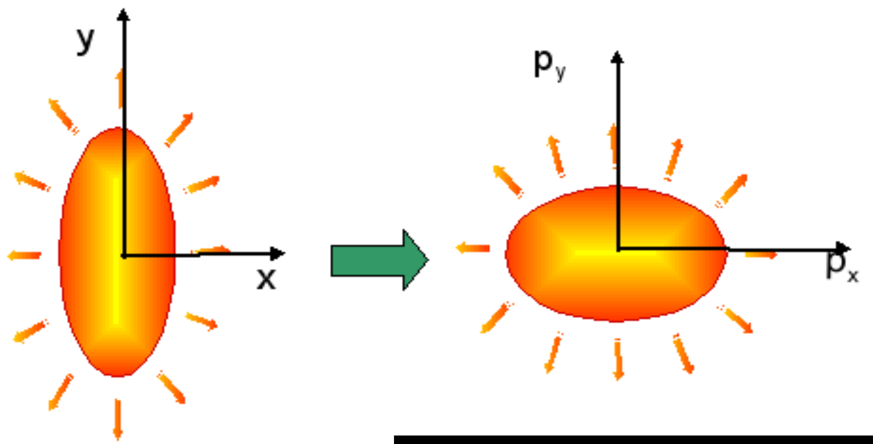
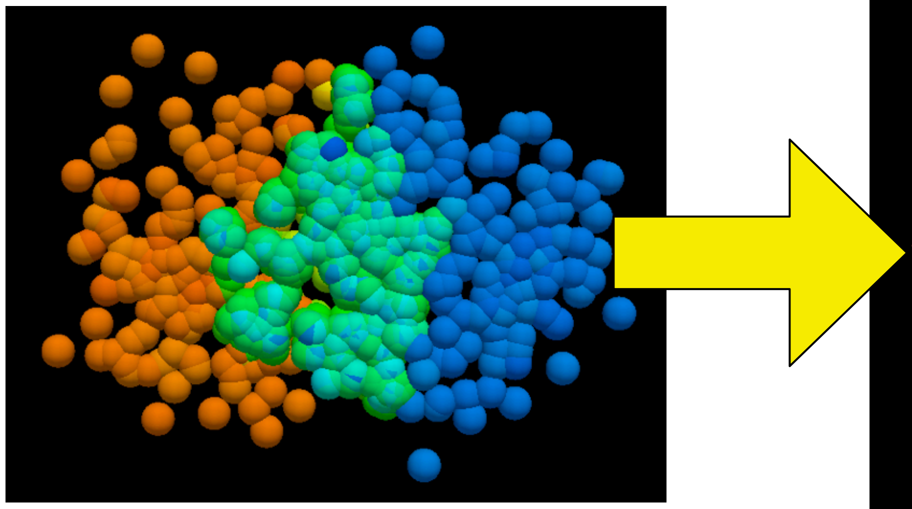
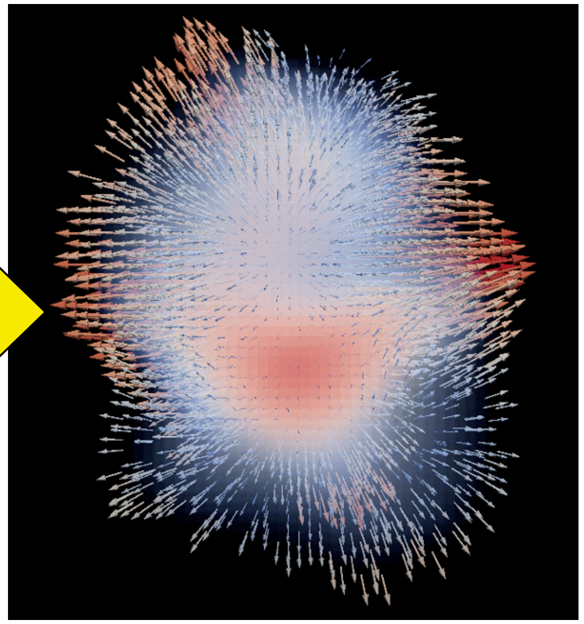




Including fluctuations in Event-by-event approaches





by MADAI.us

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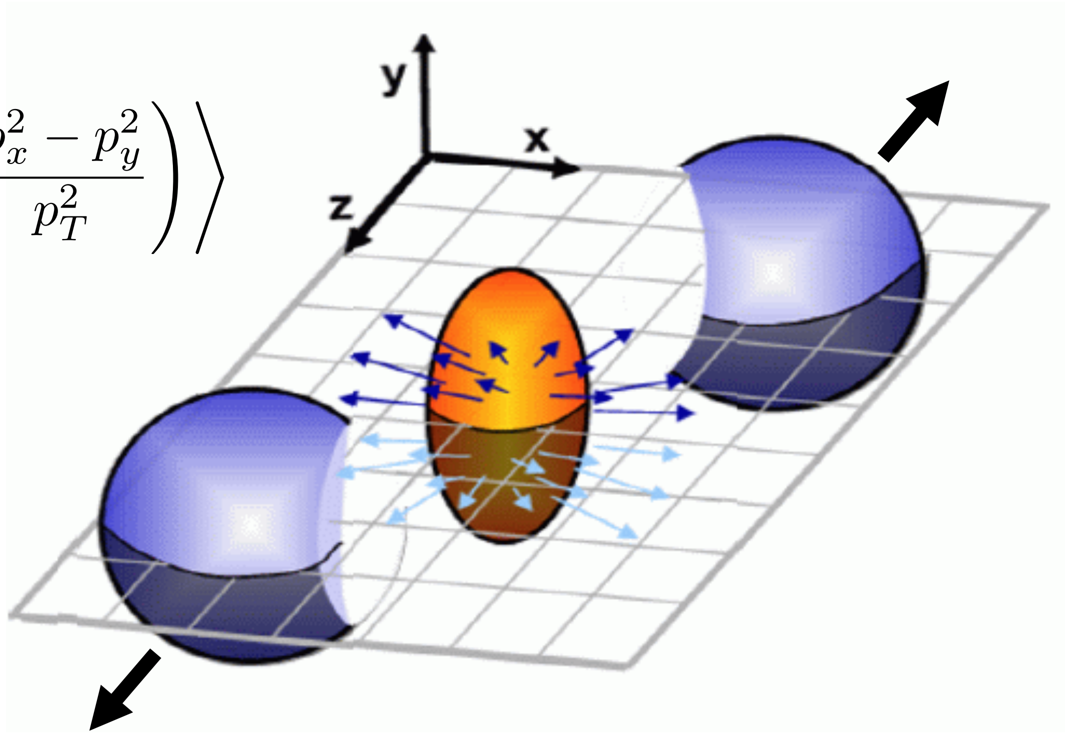

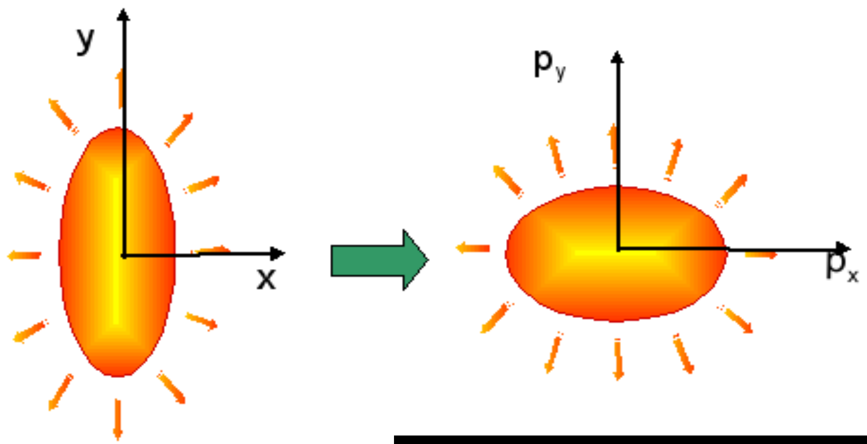

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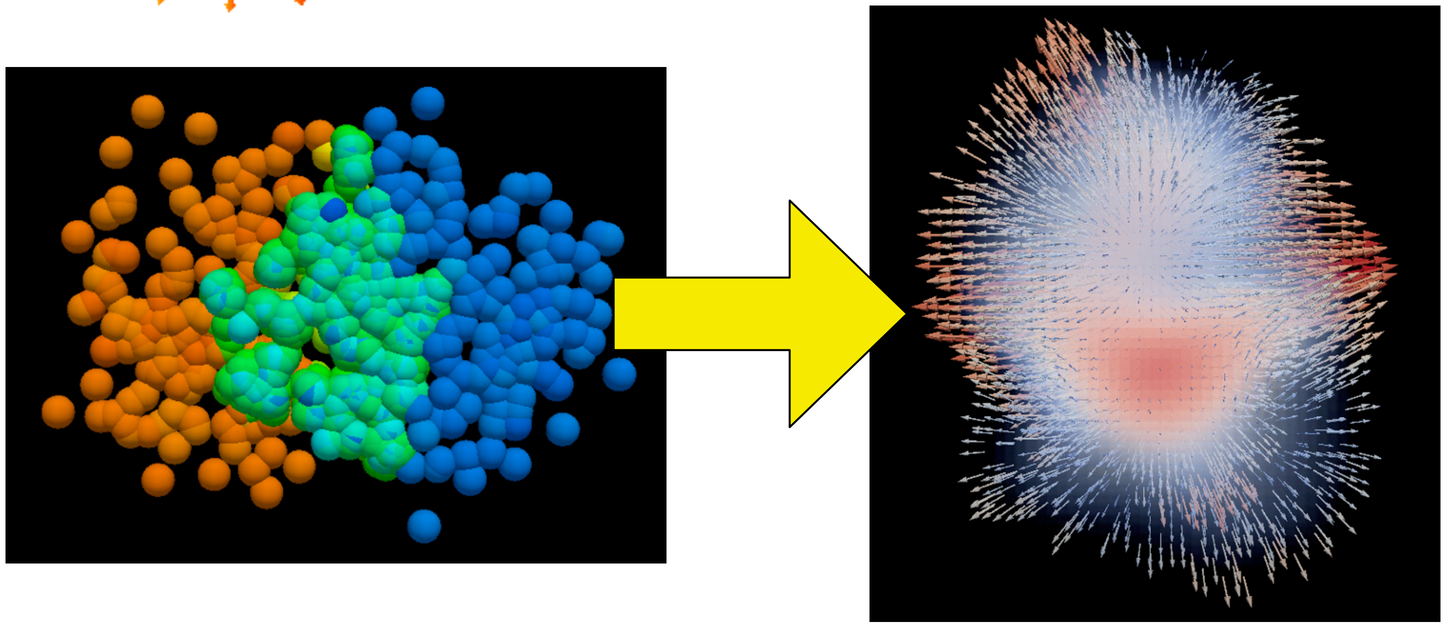

by MADAI.us

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