Initial state and fluid dynamics

Björn Schenke, Brookhaven National Laboratory

SORRY, I COULD NOT MAKE IT!

BROOKHAVEN
NATIONAL LABORATORY

Fluid nature of nuclear matter in heavy-ion collisions

ANTICANCER BLOCKBUSTER? • RISE AND FALL OF THE SLIDE RULE

SCIENTIFIC AMERICAN

Bringing
DNA Computers
to Life

Quark Soup

PHYSICISTS RE-CREATE
THE LIQUID STUFF OF
THE EARLIEST
UNIVERSE

Stopping
Alzheimer's

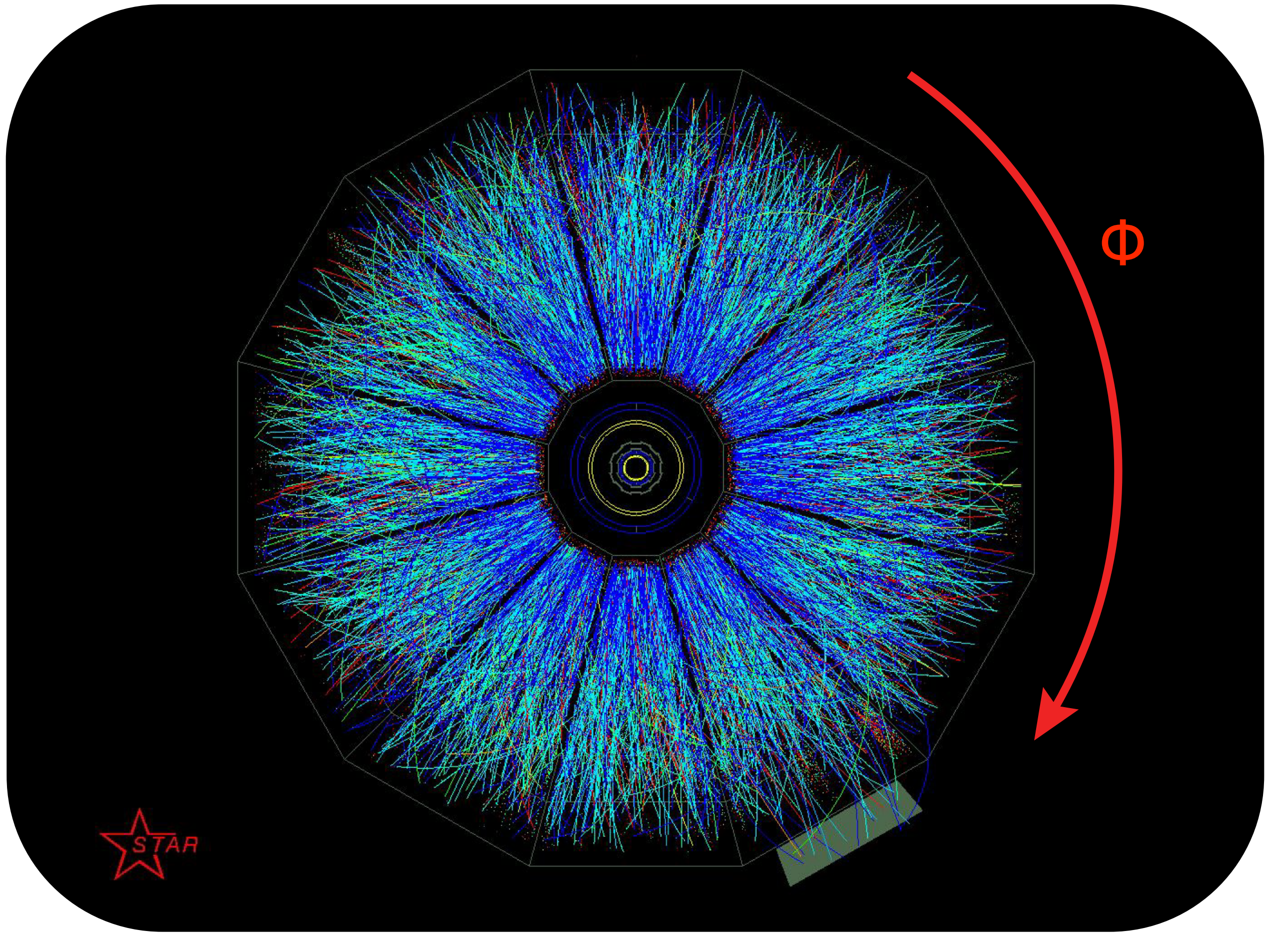
Birth of
the Amazon

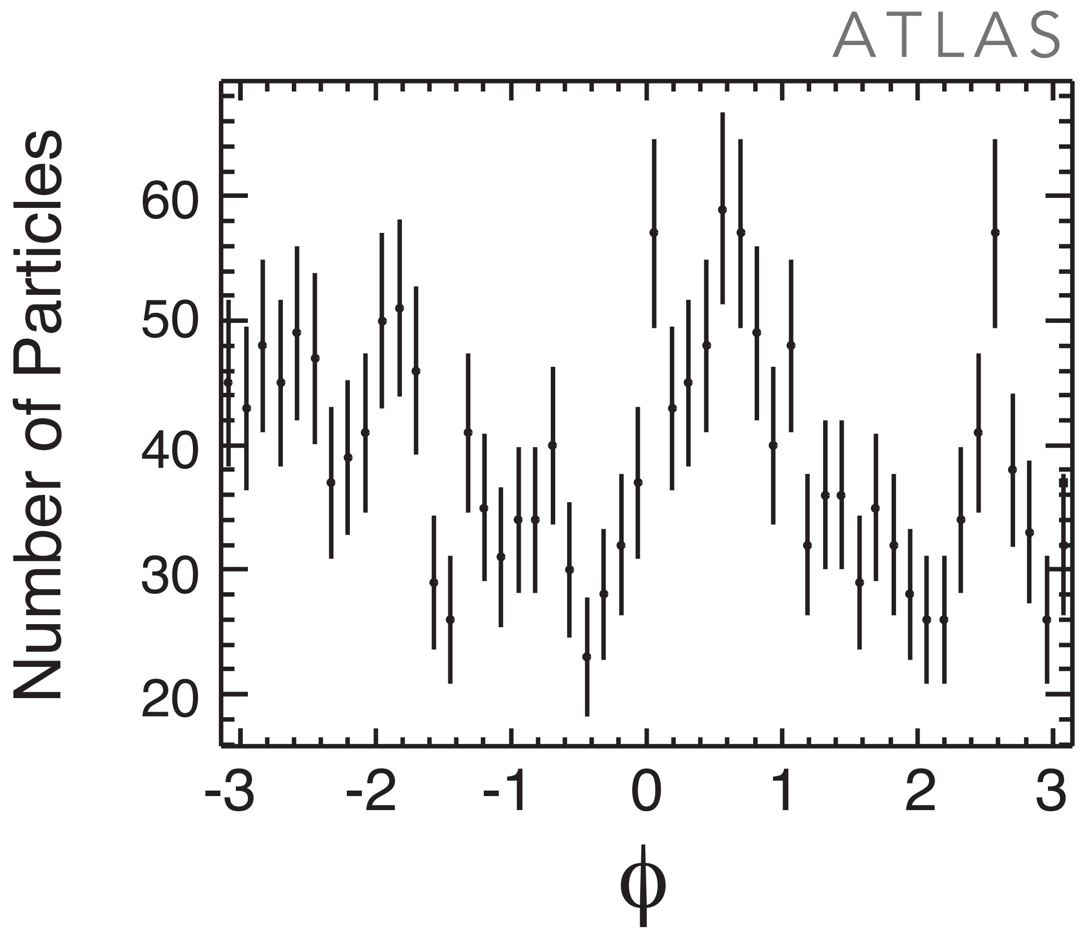
Future
Giant Telescopes

- 2005: Quark Gluon Plasma (QGP) created in Heavy Ion Collisions at RHIC behaves like a fluid
- This fluid is almost perfect
- 2007: 2+1D viscous fluid dynamics
- 2010: Fluctuations are important
- 2011: 3+1D viscous fluid dynamics + fluctuating initial conditions

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra



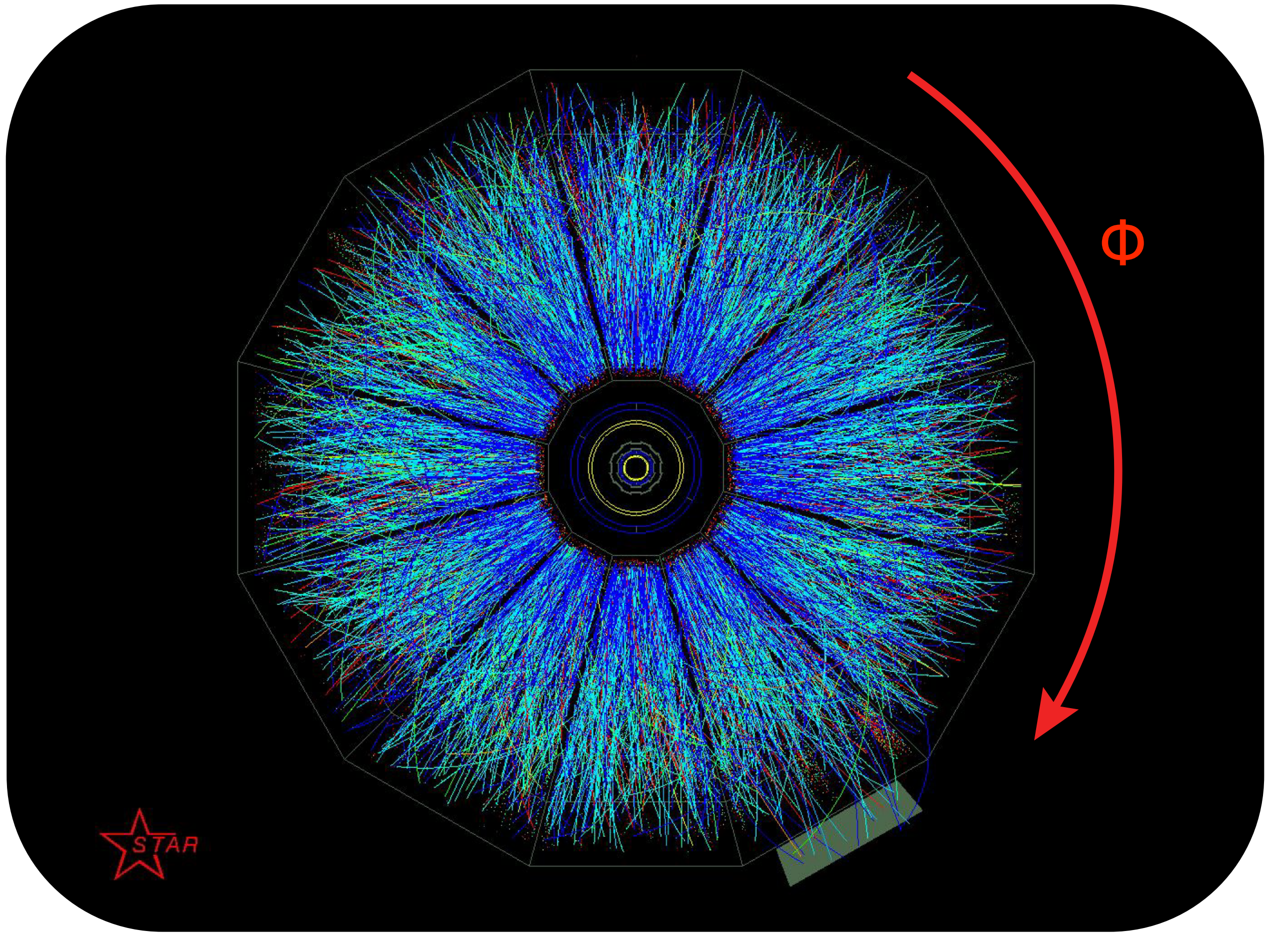


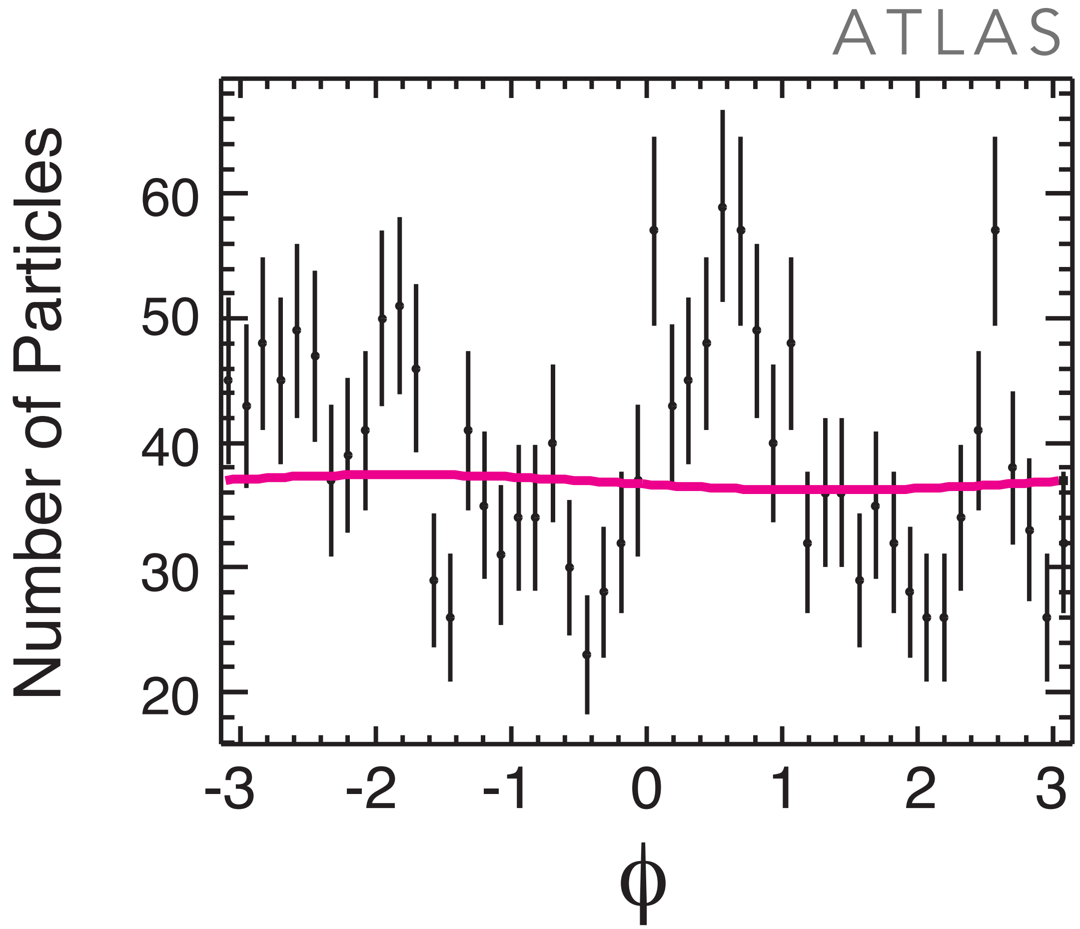
Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n 2v_n \cos(n\phi)\right)$$

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra





Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi))\Big)$$

How do we know we created an almost perfect fluid?

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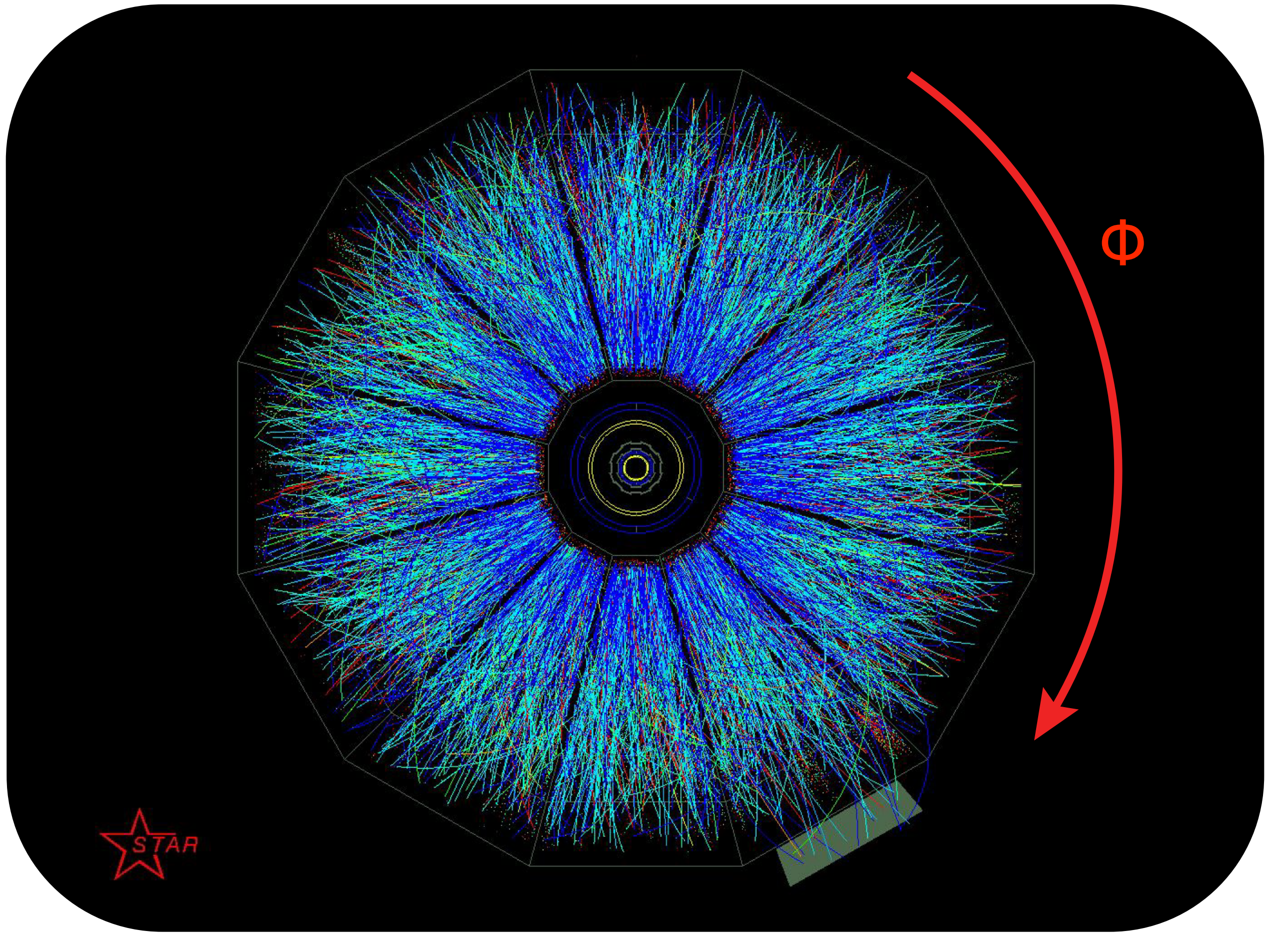
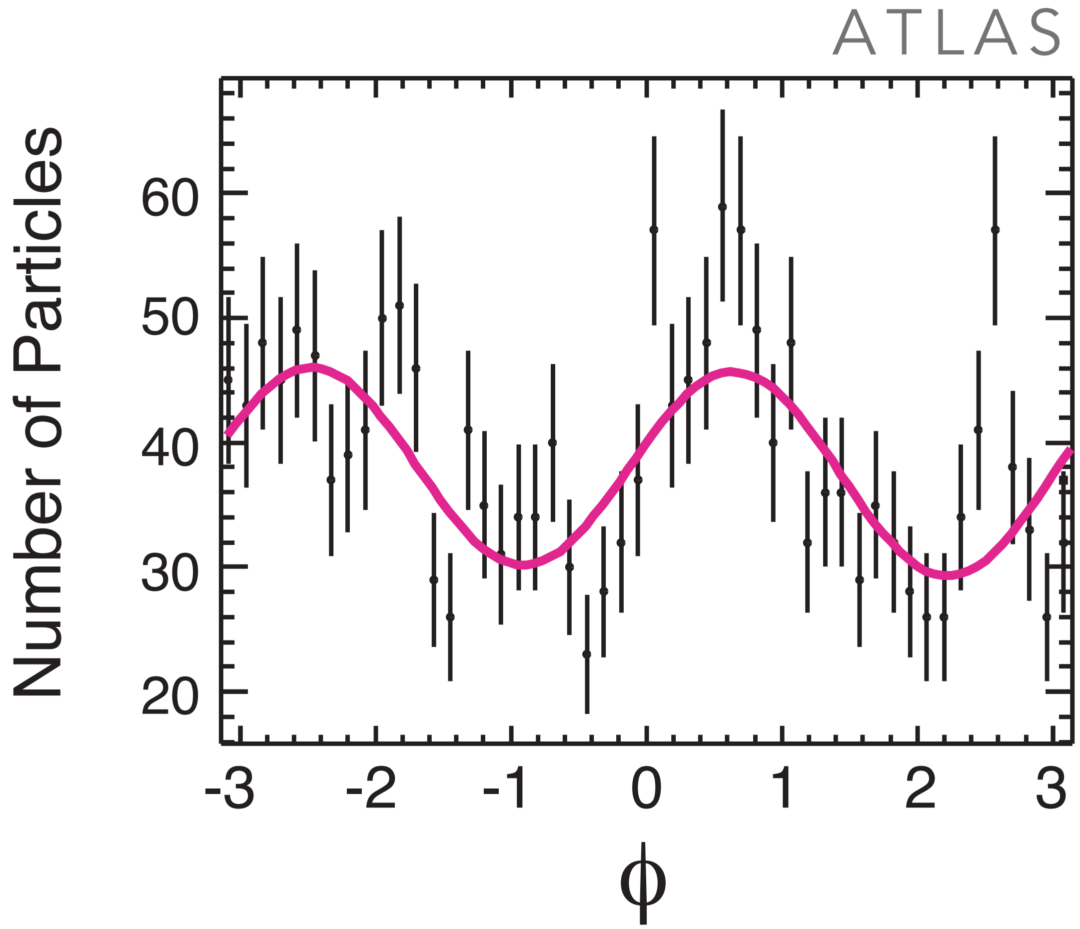


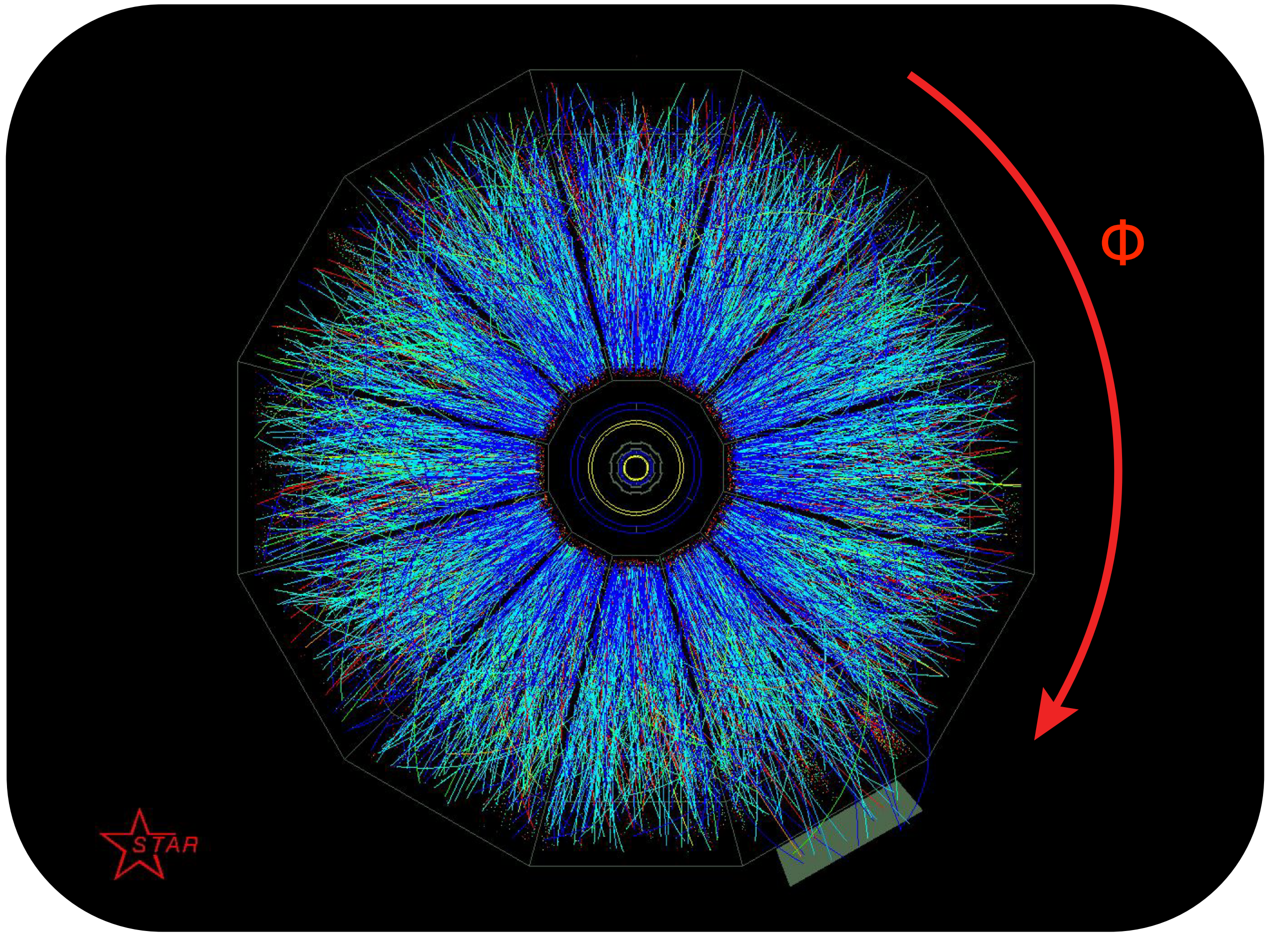


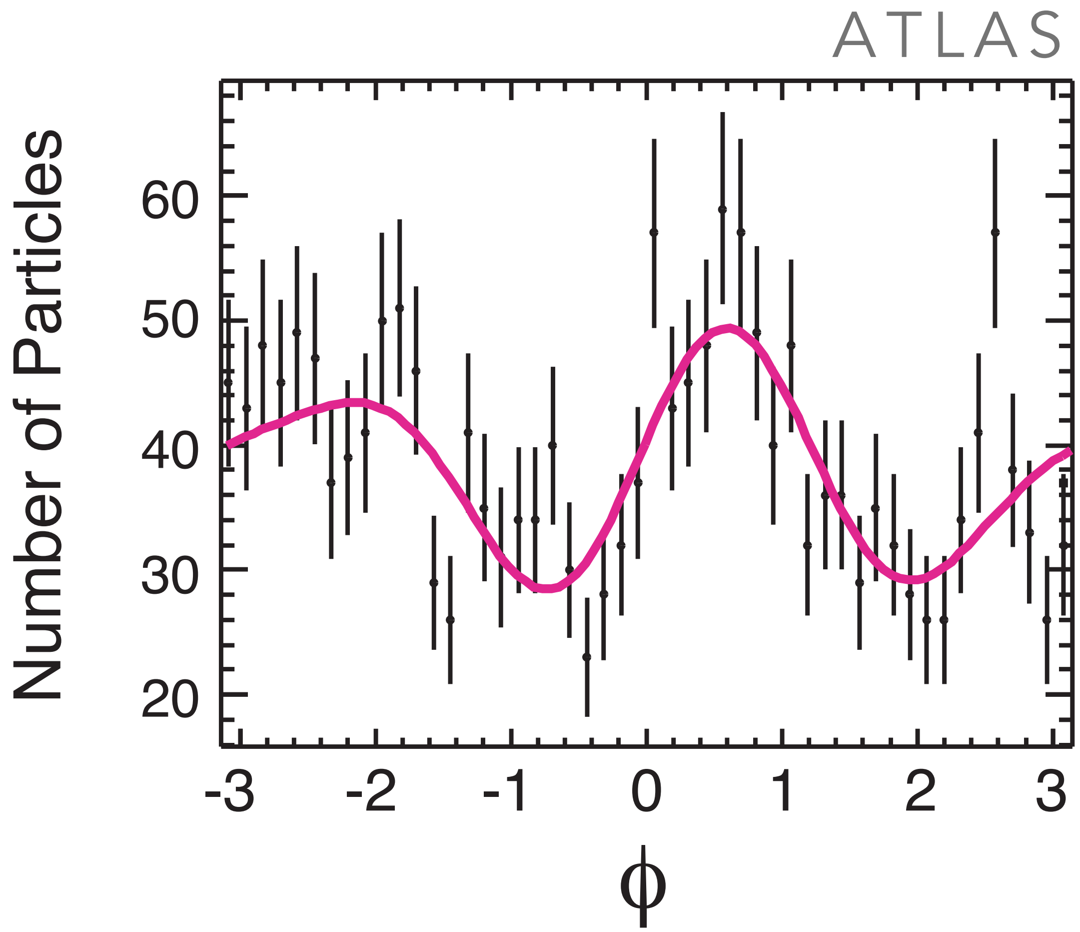
Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi))\Big)$$

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra



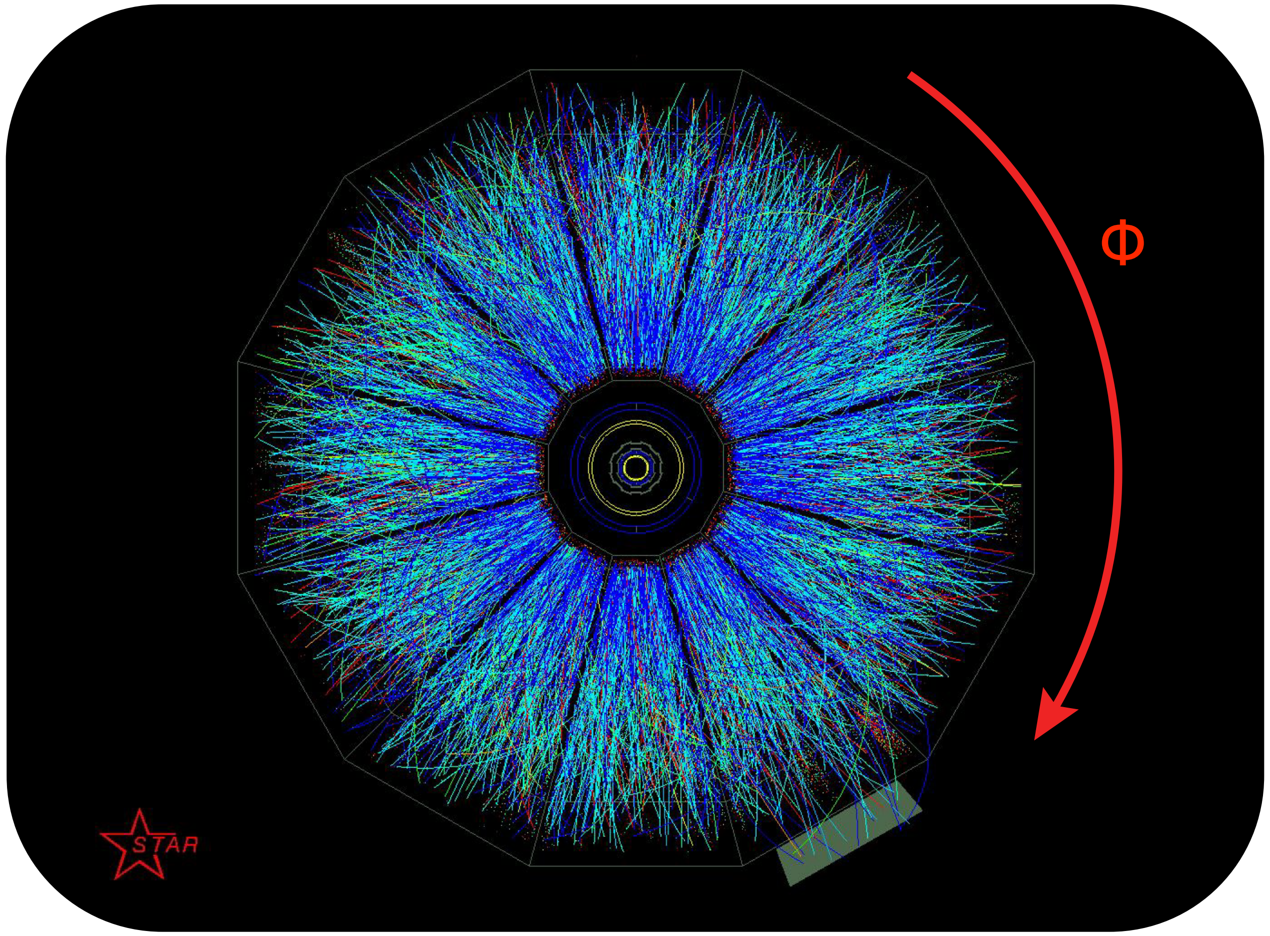


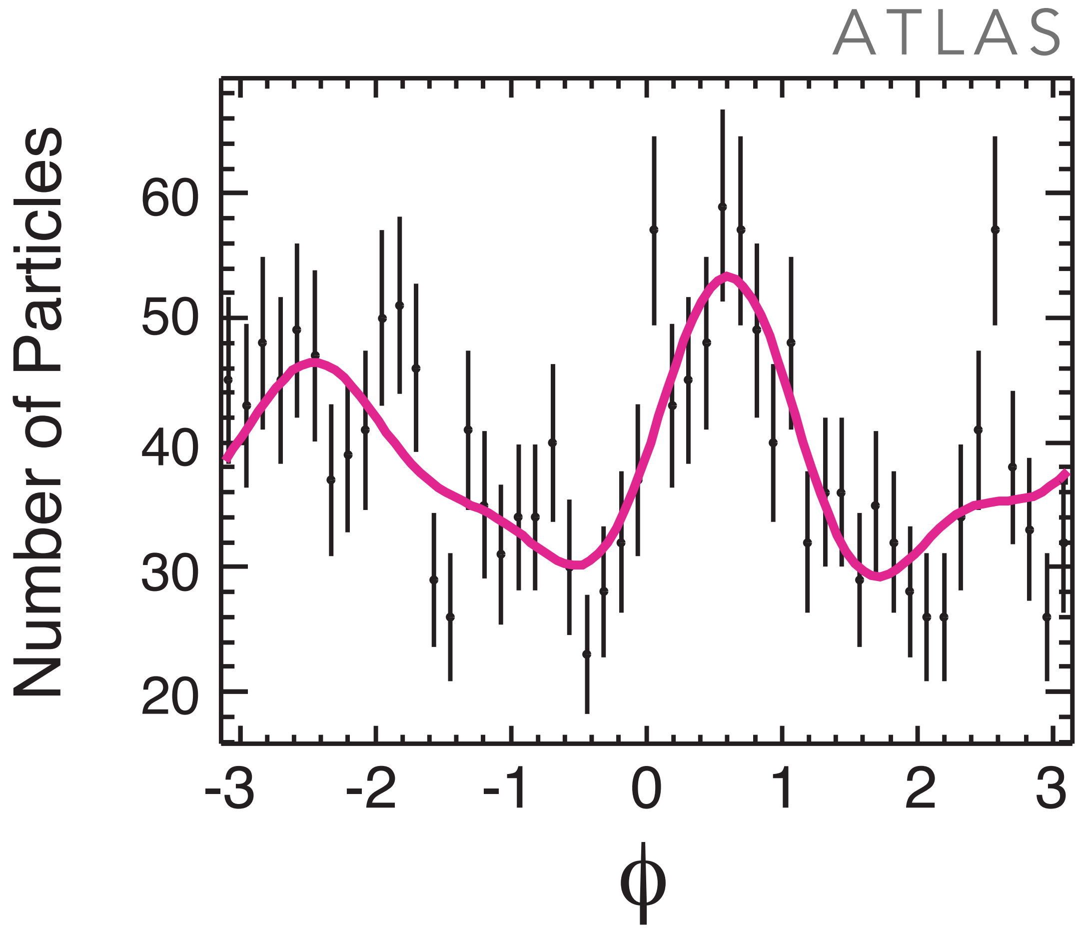
Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi))\Big)$$

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra



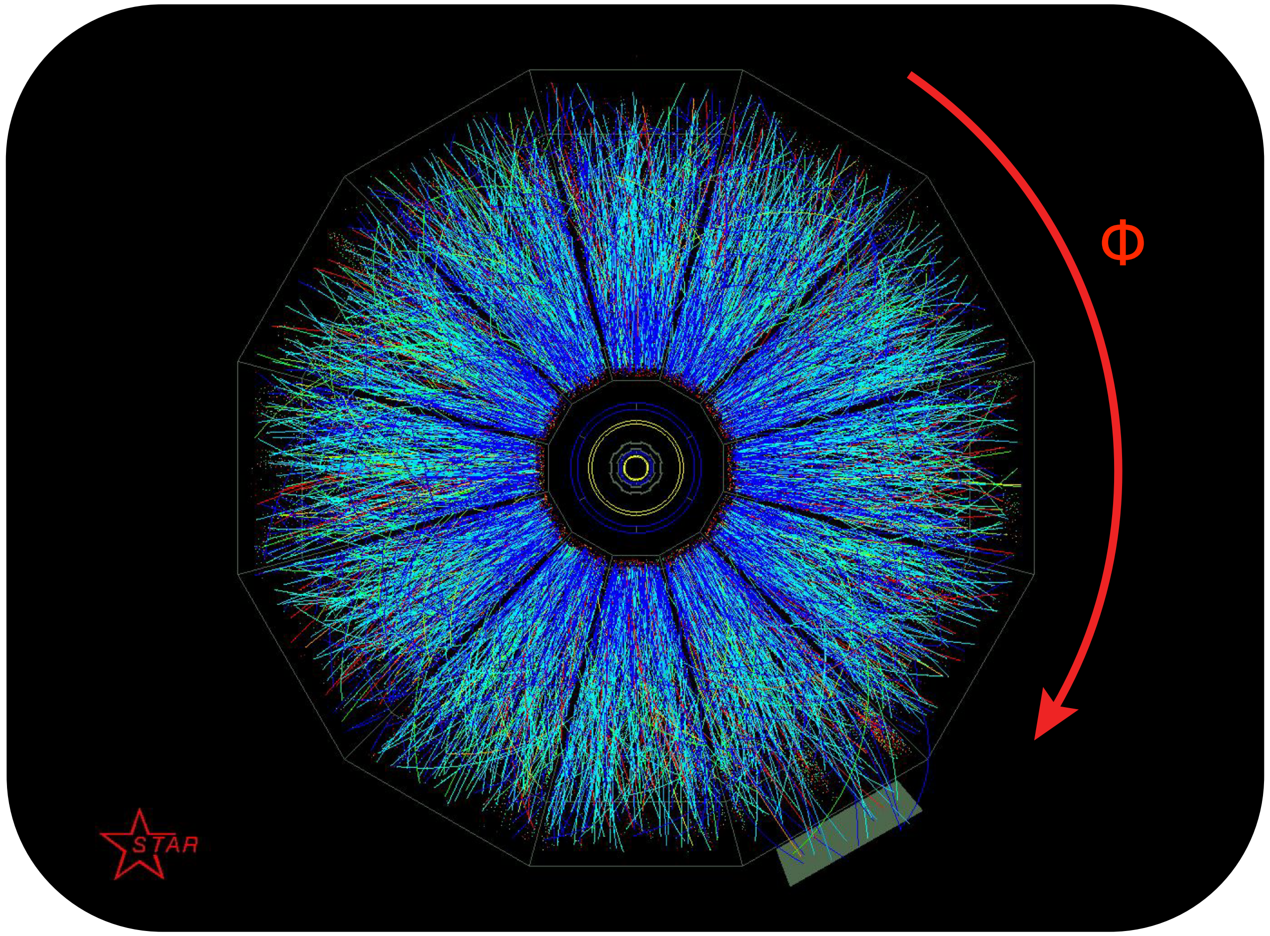


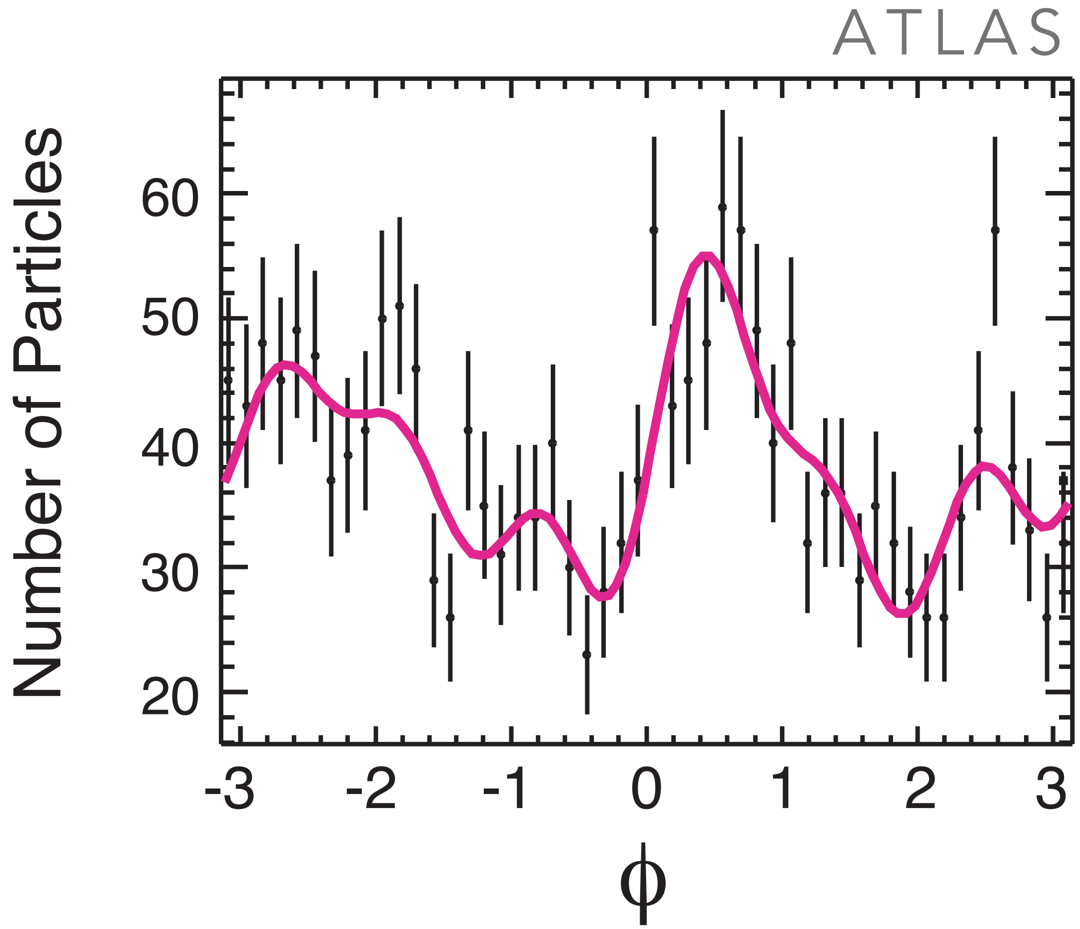
Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi) + v_4 \cos(4\phi))\Big)$$

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra



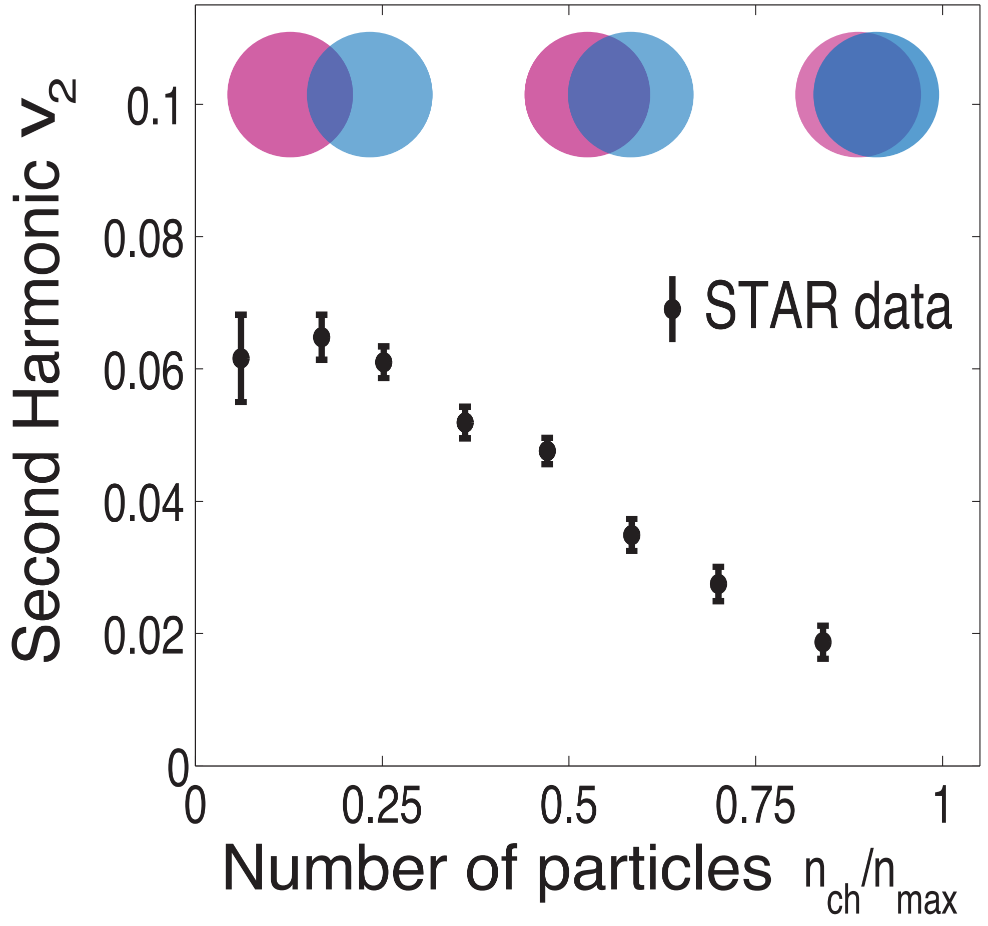


Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi) + v_4 \cos(4\phi) + \ldots)\Big)$$

How do we know we created an almost perfect fluid?

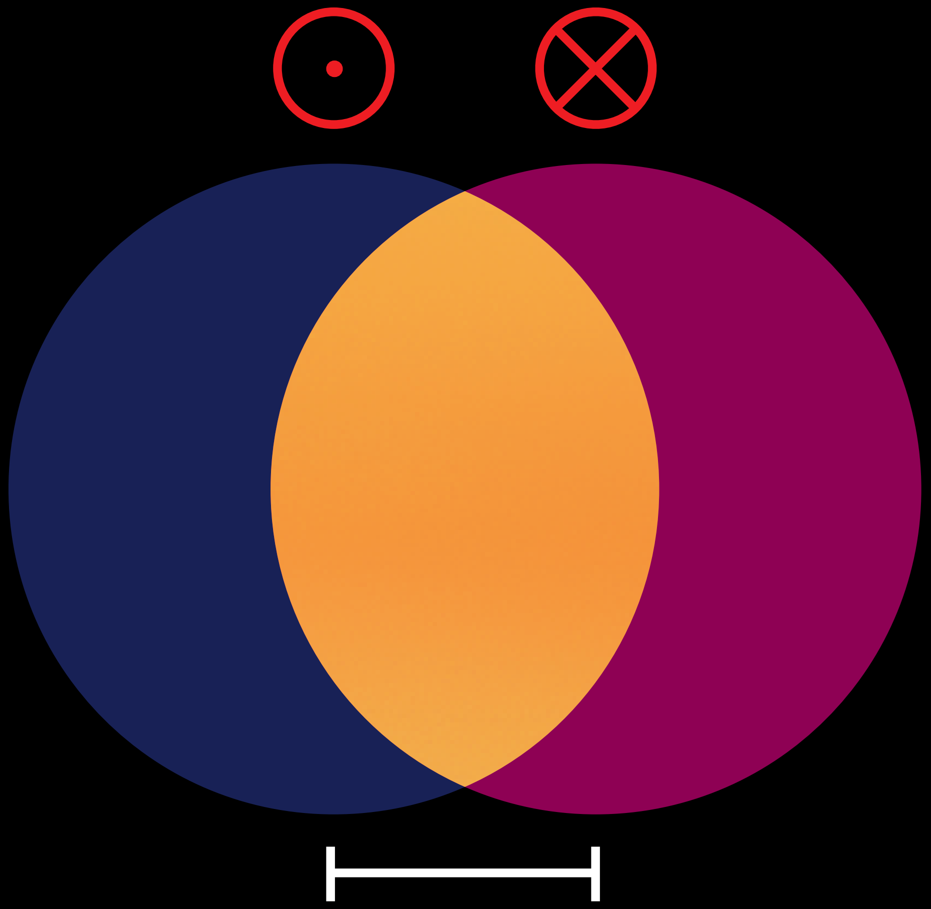
- v_n coefficients of charged hadrons are large - in particular v_2
- value of v_2 is (anti-)correlated with the total number of particles via the collision geometry



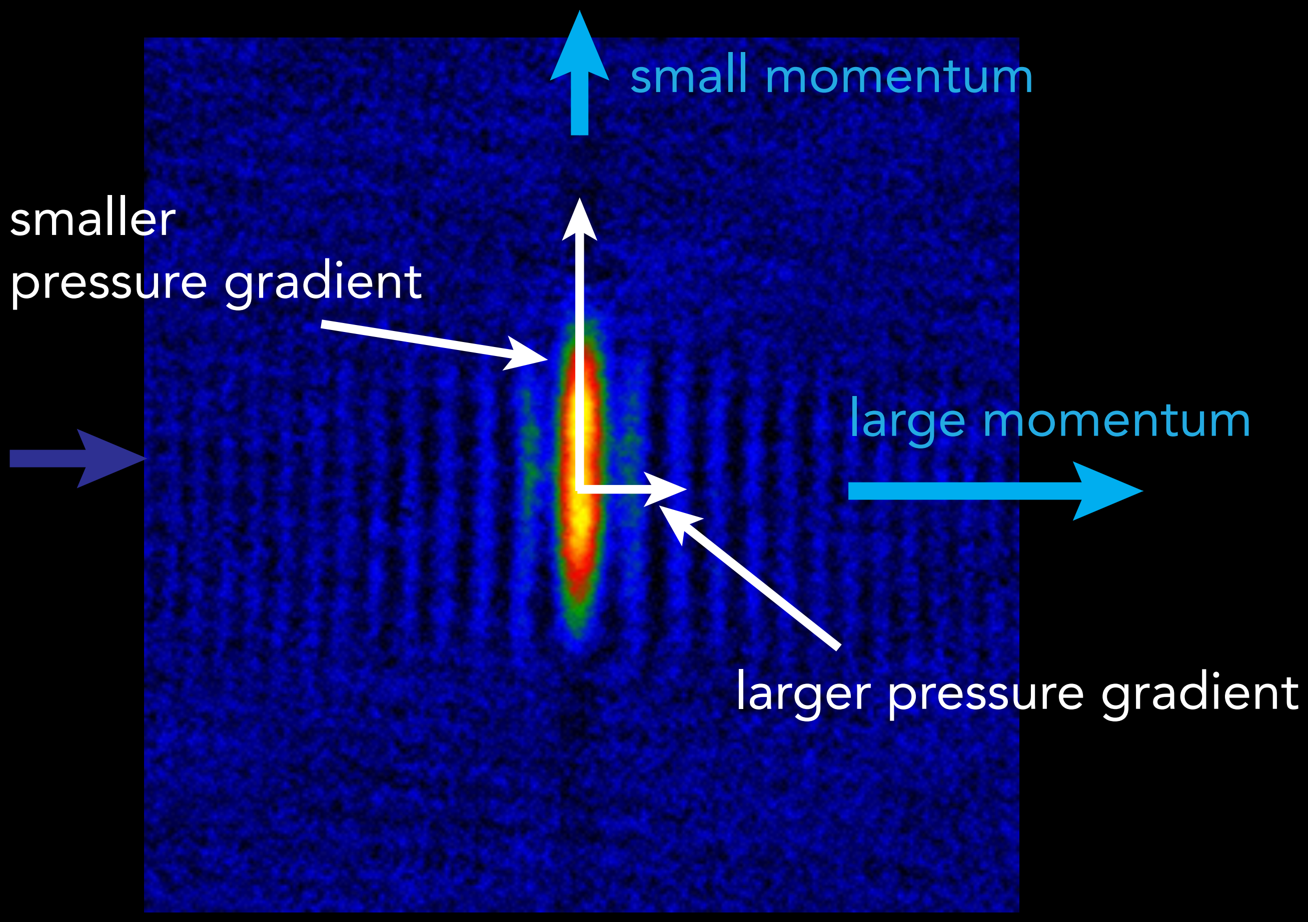
- When I say v_2 is large, I mean almost as large as it can be when generated by the response of the system to the initial geometry: Ideal fluid dynamics reproduces data quite well

Fluid dynamic expansion of the medium

Beam directions



Impact parameter *b*



small momentum

smaller
pressure gradient

large momentum

larger pressure gradient

K. M. O’Hara et al., Science 298, pp. 2179-2182 (2002)

Cheating of course: Animation is an ultra cold quantum gas

Relativistic viscous fluid dynamics

- Basic equations: energy and momentum conservation

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\overset{\substack{\text{energy density}\\ \downarrow}}{\varepsilon} + P)\underset{\substack{\uparrow\\ \text{flow velocity}}}{u^\mu} u^\nu - \overset{\substack{\text{pressure}\\ \downarrow}}{P} g^{\mu\nu} + \underset{\substack{\uparrow\\ \text{viscous correction}}}{\Pi^{\mu\nu}}$$

- constituent equations for $\Pi^{\mu\nu}$ (shear viscosity η only)

$$\Delta^\mu_\alpha \Delta^\nu_\beta (u \cdot \partial)\Pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\Pi^{\mu\nu} - S^{\mu\nu}) - \frac{4}{3}(\partial \cdot u)\Pi^{\mu\nu}$$

$$\text{with } S^{\mu\nu} = \eta\left(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}(\partial \cdot u)\right)$$

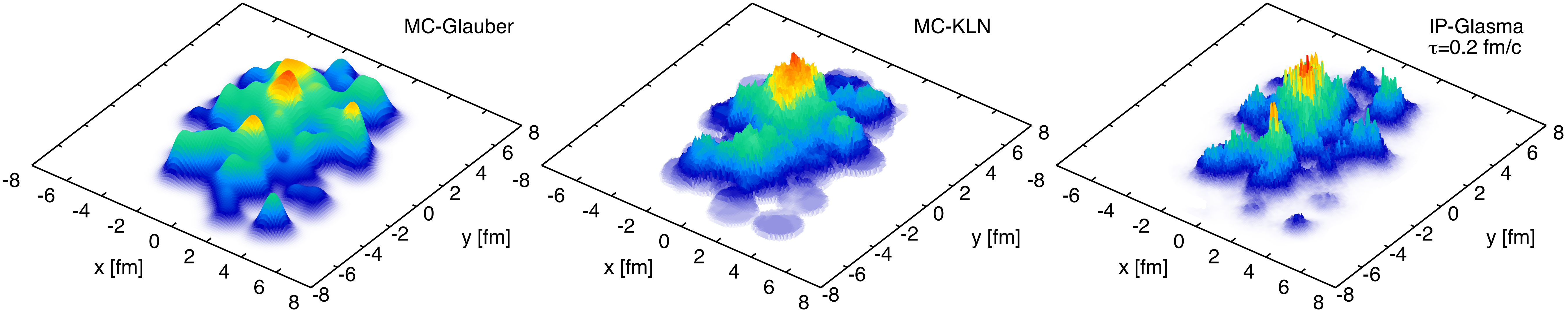
$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu \text{ and } \nabla^\mu = \Delta^{\mu\nu}\partial_\nu$$

τ_π: relaxation time

- equation of state $P(\varepsilon)$ relates pressure to energy density

Initial conditions

- Models need to provide input for fluid dynamic simulations: initial energy density, flow velocities, shear stress tensor
- Initial conditions fluctuate from event to event
- Main source of fluctuations: nucleon positions
- Different models give different *energy density distributions*



C. Gale, S. Jeon, B. Schenke, Int.J.Mod.Phys. A28 (2013) 1340011

Computing the initial state at high energies

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Gluon number increases with decreasing gluon momentum
- Gluon saturation at $p_T \lesssim Q_s(x, \mathbf{b})$
- Strong fields with occupation $\sim 1/\alpha_s$
  Classical description possible
- IP-Sat model parametrizes $Q_s(x, \mathbf{b})$
  (simple way to include impact parameter dependence)
  KOWALSKI, TEANEY, PHYS.REV. D68 (2003) 114005
- Fit parameters to HERA diffractive data

Computing the initial state

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Sample nucleons from Woods-Saxon distribution
- Sample color charge density $\rho^{A/B}(\mathbf{x}_T)$
- For nucleus A and B compute the path-ordered exponential over its longitudinal extend

$$V_{A/B}(\mathbf{x}_T) = \prod_{k=1}^{N_y} \exp\Big(- ig \frac{\rho_k^{A/B}(\mathbf{x}_T)}{\nabla_T^2 + m^2} \Big)$$

- m is an infrared cutoff of order Λ_{QCD}
- Wilson lines after the collision are then obtained from V_A and V_B via the Yang-Mills equations

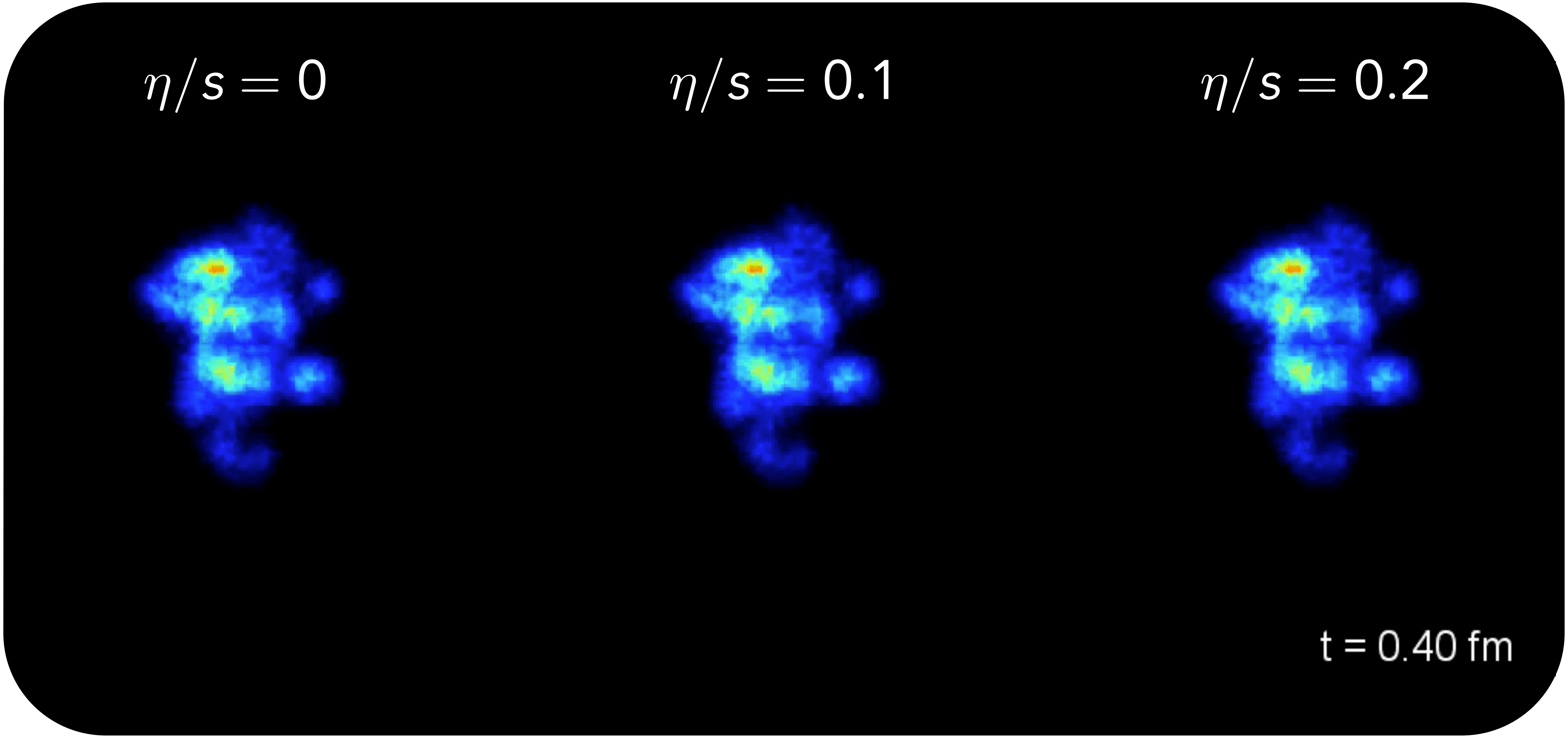
Computing the initial state

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Yang-Mills equations determine:
  - Initial gluon fields from color charges

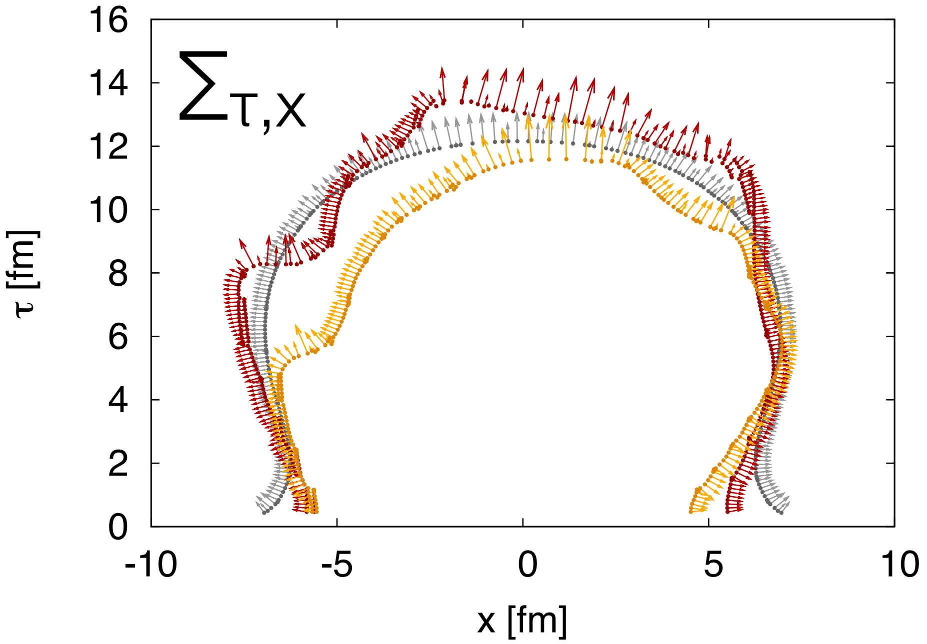
    KRASNITZ, VENUGOPALAN, NUCL.PHYS. B557 (1999) 237
  - Energy density after the collision
  - Early non-equilibrium time evolution
- Then match fields' $T^{\mu\nu}$ to hydrodynamics by extracting ε and u^μ

Effect of viscosity in a single event



Late stage and freeze-out

- System expands, becomes dilute, stops interacting strongly
- Convert fluid into particles using the Cooper-Frye formula



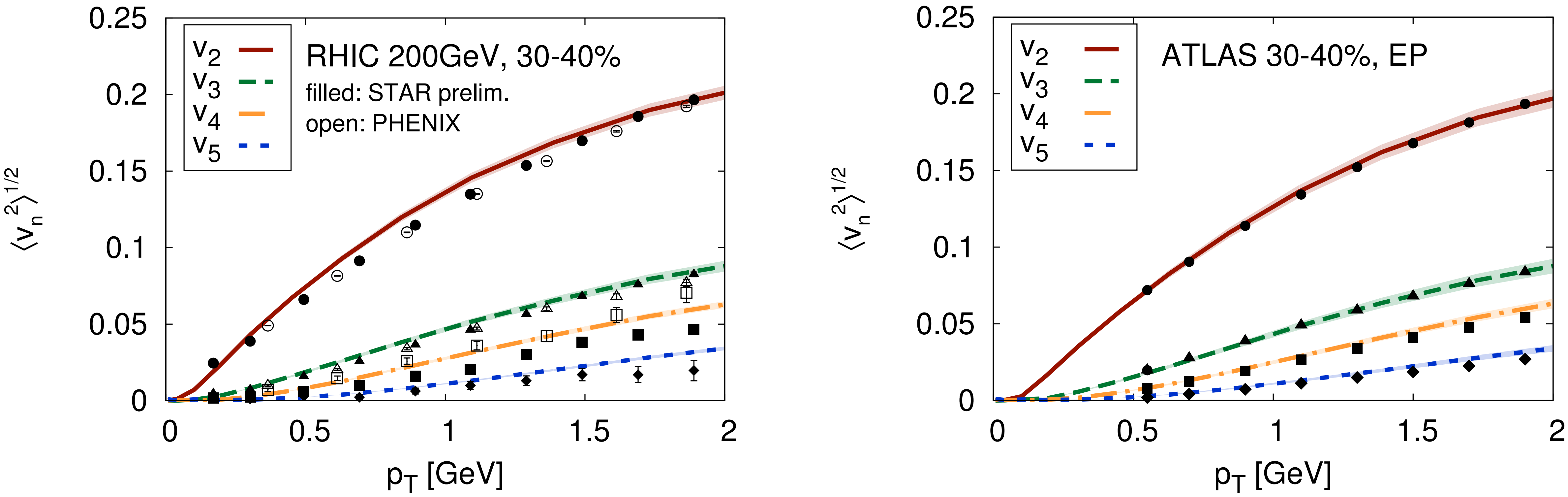
$$E\frac{dN}{d^3p} = \int_\Sigma d\Sigma_\mu p^\mu f(x, p_\mu u^\mu)$$

- Then either feed particles into hadronic cascade like UrQMD or just assume free streaming and let the unstable resonances decay

IP-Glasma fluctuating initial state

Include more QCD dynamics and reduce free parameters

Consistently describes all flow harmonics for a given η/s

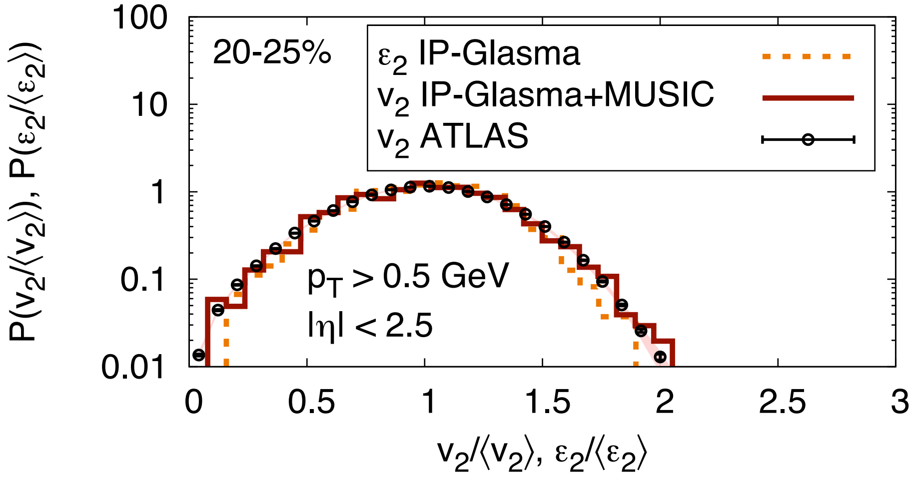


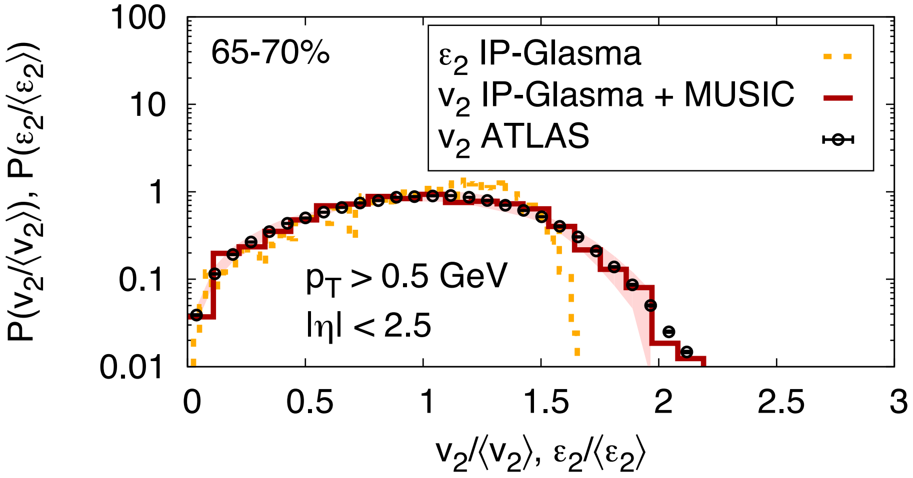
$\eta/s \approx 0.12$ at $\sqrt{s} = 0.2$ TeV $\eta/s \approx 0.2$ at $\sqrt{s} = 2.76$ TeV

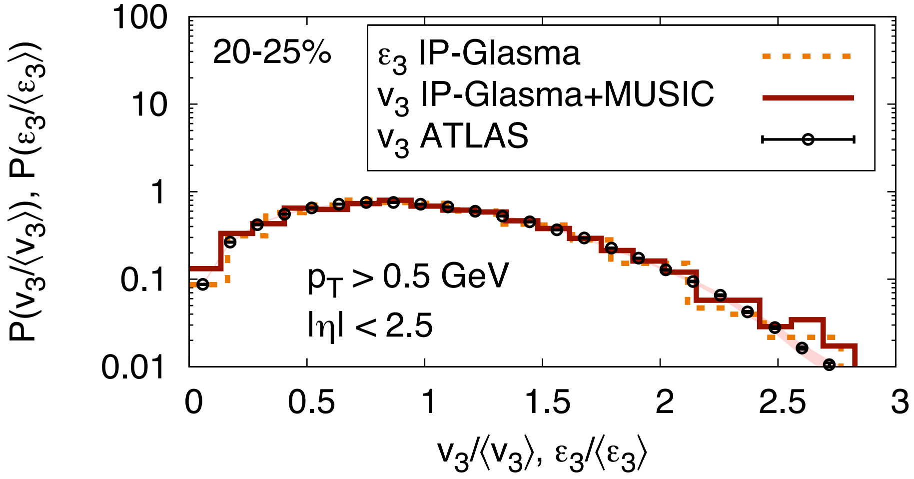
C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 110, 012302 (2013)
Experimental data:
A. Adare et al. (PHENIX Collaboration), Phys.Rev.Lett. 107, 252301 (2011)
Y. Pandit [for the STAR collaboration], Quark Matter 2012; Phys. Rev. C 88, 14904 (2013)
G. Aad et al. (ATLAS Collaboration), Phys.Rev. C86, 014907 (2012).

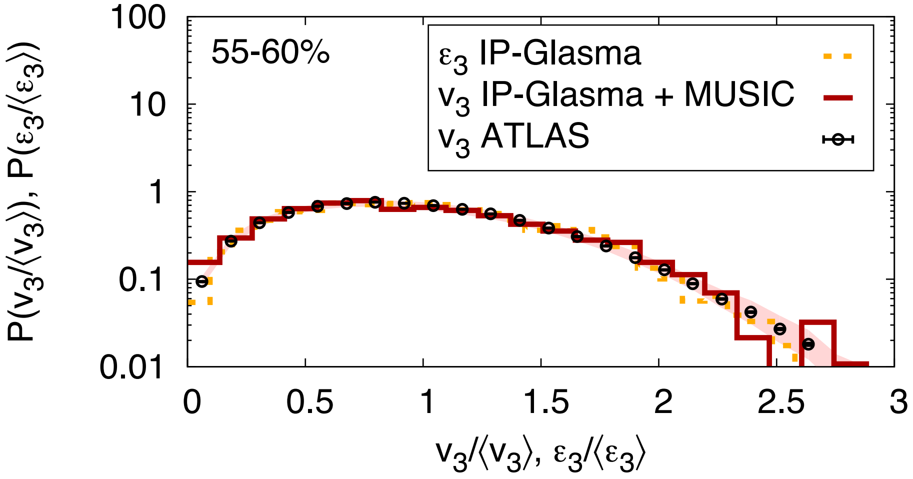
Event-by-event fluctuations of flow coefficients

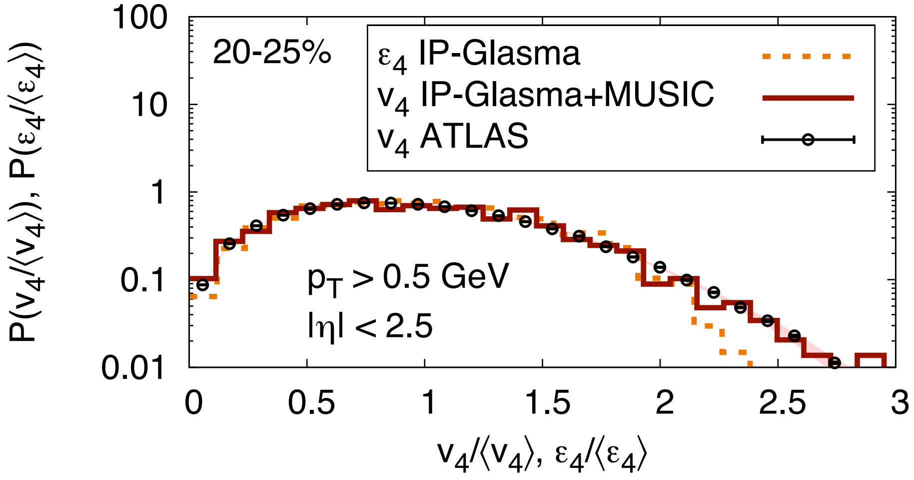
C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 110, 012302 (2013)
Experimental Data: ATLAS Collaboration, JHEP 1311, 183 (2013)







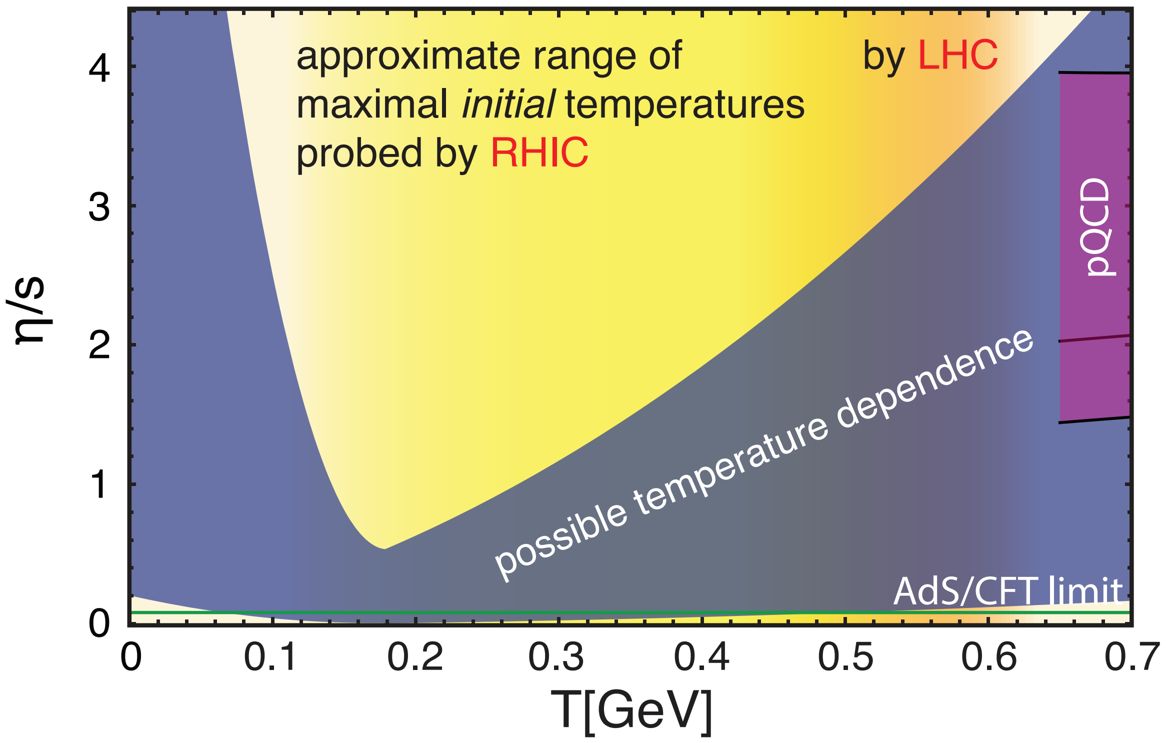




- Flow fluctuations reflect initial state fluctuations
- Support collectivity interpretation

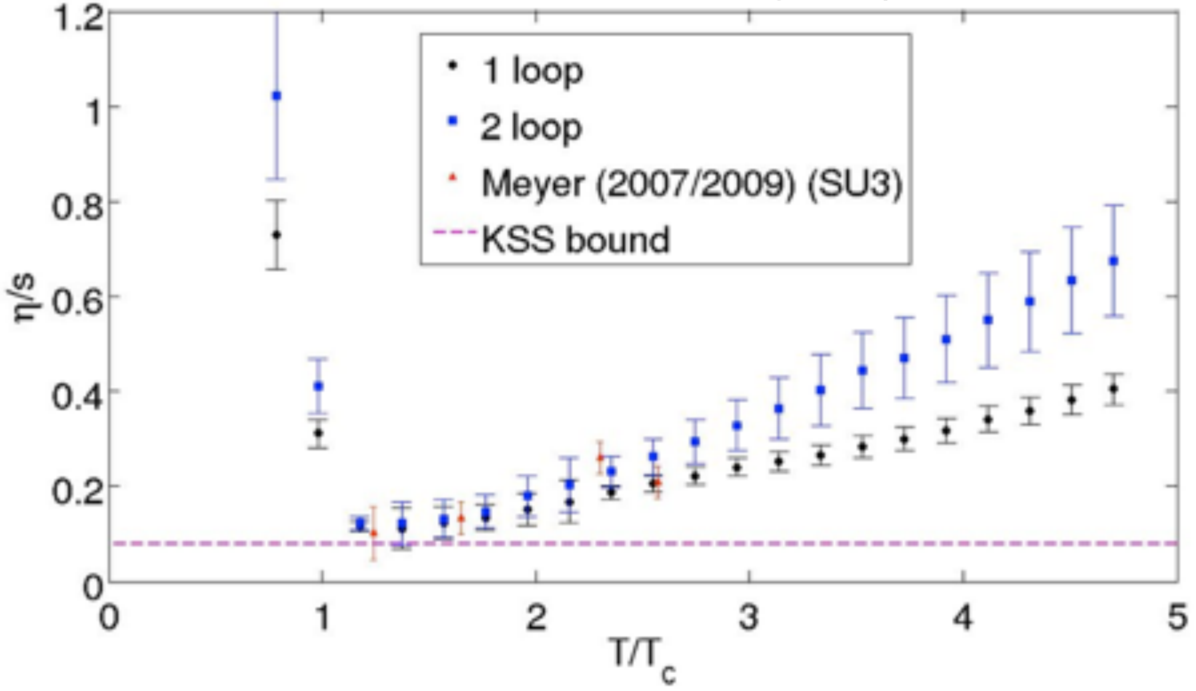
Temperature dependent transport parameters

Extract information on (η/s)(T) from experimental data



- Need to vary collision energy over wide range

Maximum entropy method and functional renormalization group



J. Pawlowski at Quark Matter 2014
(Christiansen, Haas, Pawlowski, Strodthoff)

- Compare to non-perturbative QCD approaches (Lattice, FRG)

- Detailed simulations needed

Effect of bulk viscosity

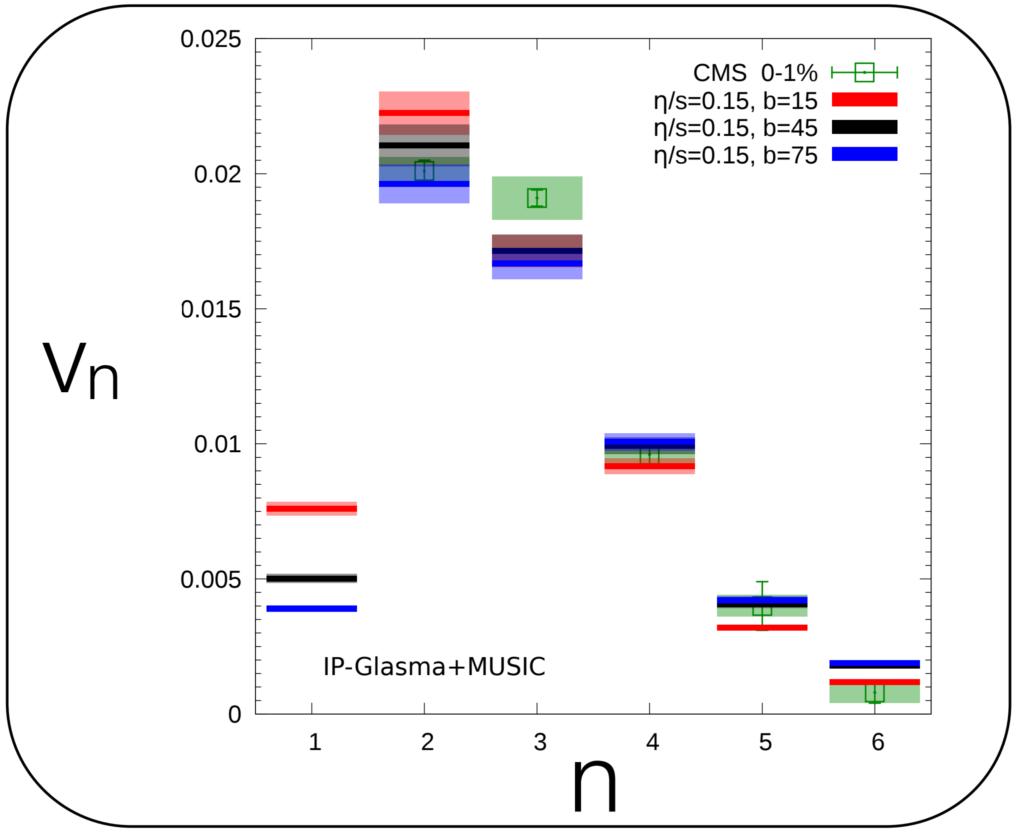
Include bulk viscosity

G.S.Denicol, H.Niemi, E.Molnar and D.H.Rischke,Phys. Rev. D85, 114047 (2012)
G.S.Denicol,S.Jeon and C.Gale, PRC, arXiv:1403.0962[nucl-th].

In addition to $\partial_\mu T^{\mu\nu} = 0$ solve the following equations

$$\begin{aligned} \tau_\Pi \dot{\Pi} + \Pi &= -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} \,, \\ \tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} &= 2\eta\sigma^{\mu\nu} + 2\tau_\pi \pi_\alpha^{\langle\mu}\omega^{\nu\rangle\alpha} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} \end{aligned}$$

Bulk viscosity is parametrized as $\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2$



Effect in ultra-central collisions

J.-B. Rose, J.-F. Paquet, G. S. Denicol, M. Luzum
B. Schenke, S. Jeon, C. Gale, arXiv:1408.0024
Data: S.Chatrchyanetal [CMS Collaboration], JHEP1402, 088 (2014)

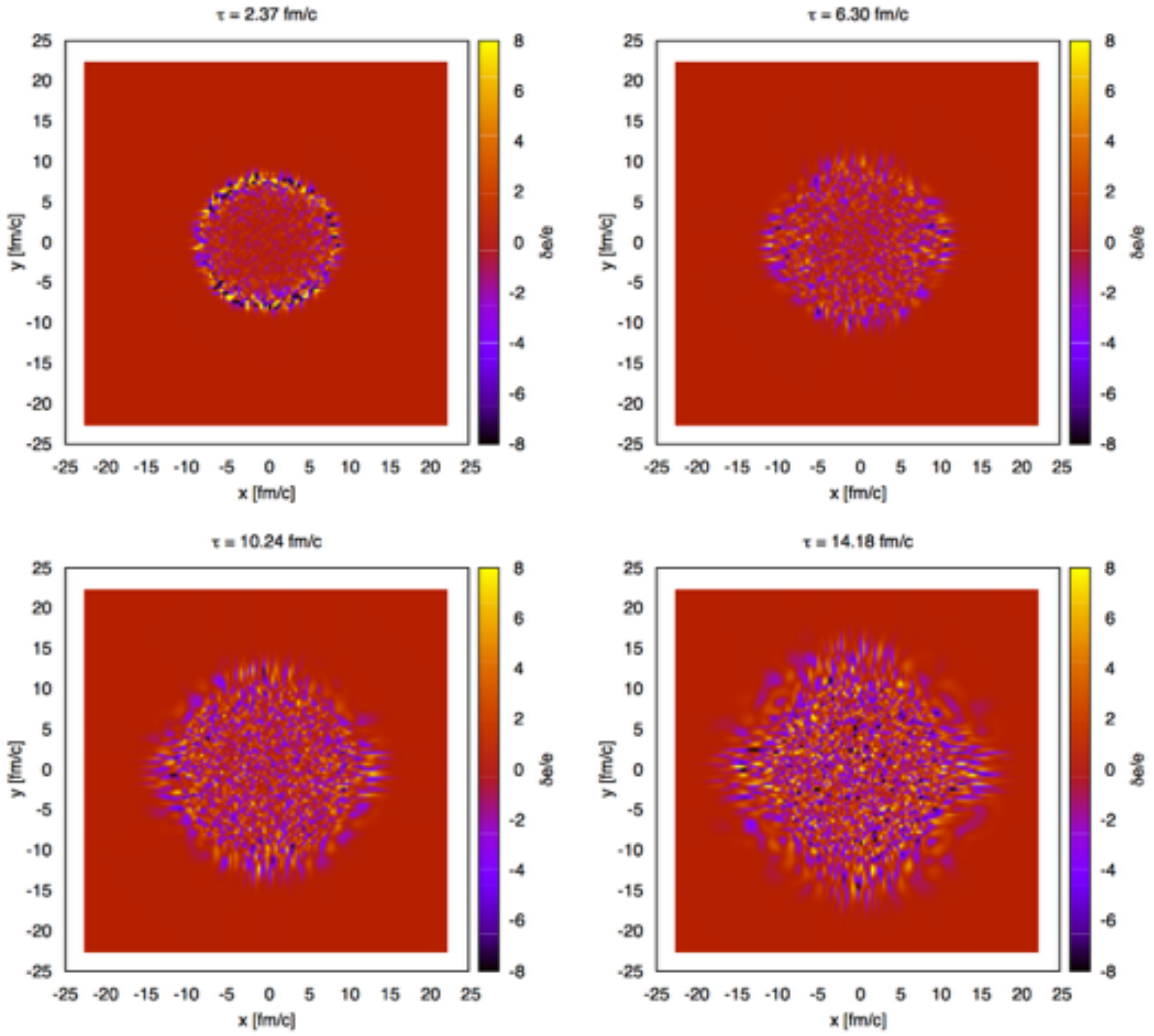
Hydrodynamic fluctuations

C. Young, J.I. Kapusta, C. Gale, S. Jeon, B. Schenke, arXiv:1407.1077

$$T^{\mu\nu}_{\rm tot} = T^{\mu\nu}_0 + \delta T^{\mu\nu}_{\rm id} + \delta W^{\mu\nu} + \Xi^{\mu\nu} \longleftarrow \text{noise}$$

In linear response one can derive coupled equations for the evolution of the fluctuating parts of $T^{\mu\nu}$

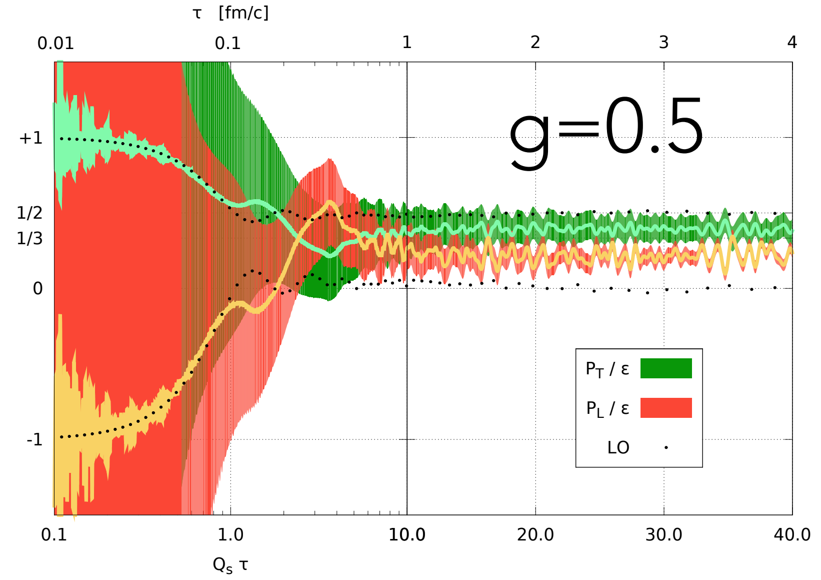
They are separate from the evolution of the average quantities

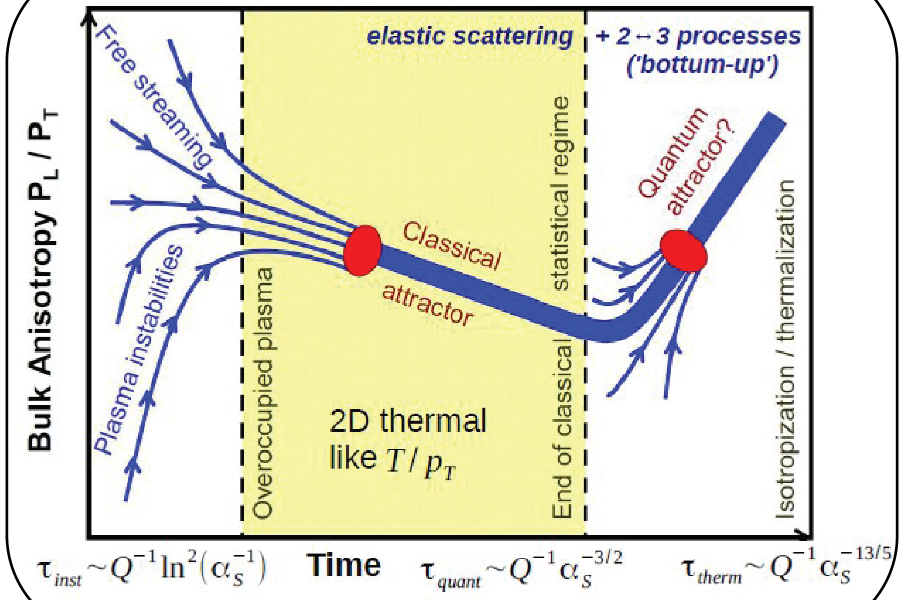


Pre-equilibrium dynamics - thermalization?

More sophisticated first principles computations of non-equilibrium early time dynamics

- Addressing the still open issue of rapid isotropization and thermalization
- Field has advanced significantly but issue is still under debate



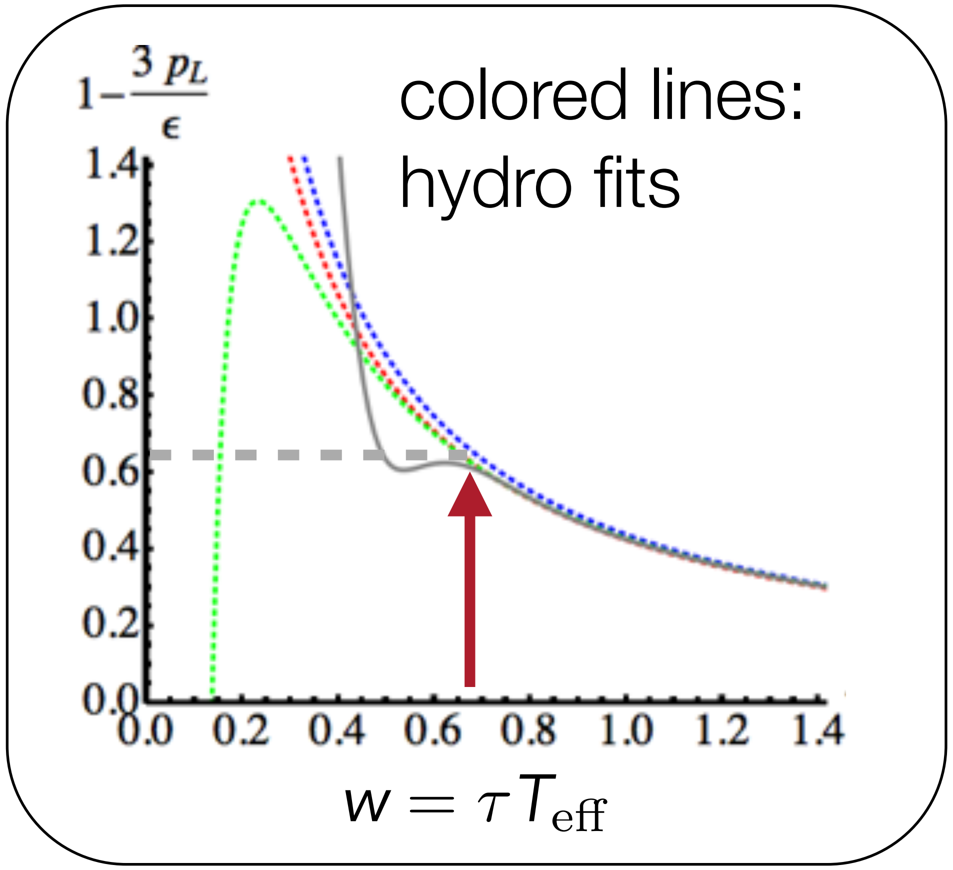


T. Epelbaum, F. Gelis, Phys.Rev.Lett. 111 (2013) 232301
J. Berges, K. Boguslavski, S. Schlichting, R. Venugopalan Phys.Rev. D89 (2014) 074011
M. Attems, A. Rebhan, M. Strickland, Phys.Rev. D87 (2013) 025010

Pre-equilibrium dynamics - thermalization?

Strong coupling limit:

AdS/CFT calculation shows
"hydrodynamization"
but no pressure isotropization
at early times τ≈0.25 fm/c



colored lines:
hydro fits

The pressure anisotropy is completely explained by dissipative hydrodynamics for τ≳0.25 fm/c

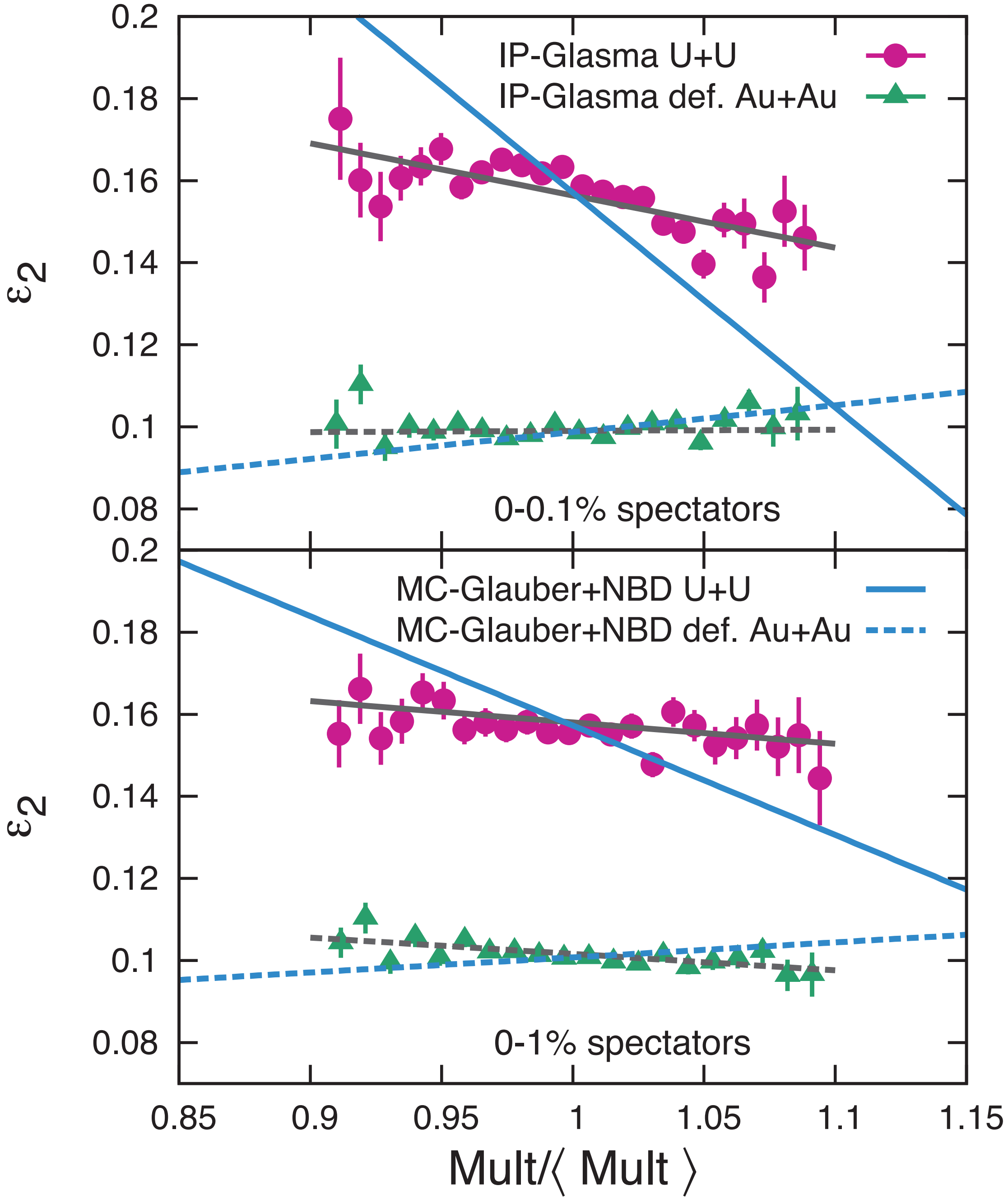
Before that non-equilibrium effects are important

M. P. Heller, R. Janik, P. Witaszczyk, Phys.Rev.Lett. 108 (2012) 201602

Deformed Nuclei

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN
PHYS. REV. C89, 064908 (2014)

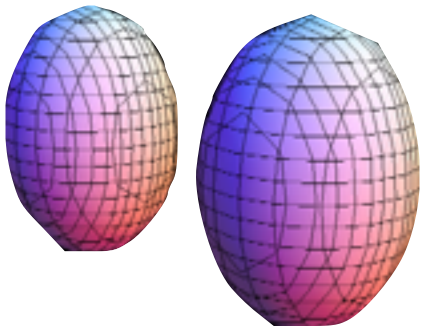
- Select ultra-central events based on neutrons in the ZDC
- Study correlation between and multiplicity
- MC-Glauber gets (anti-)correlation because of N_{coll} in
  $$\frac{dN}{d\eta} = n_{\text{pp}}\left(xN_{\text{coll}} + (1-x)\frac{N_{\text{part}}}{2}\right)$$
- IP-Glasma finds weaker anti-correlation



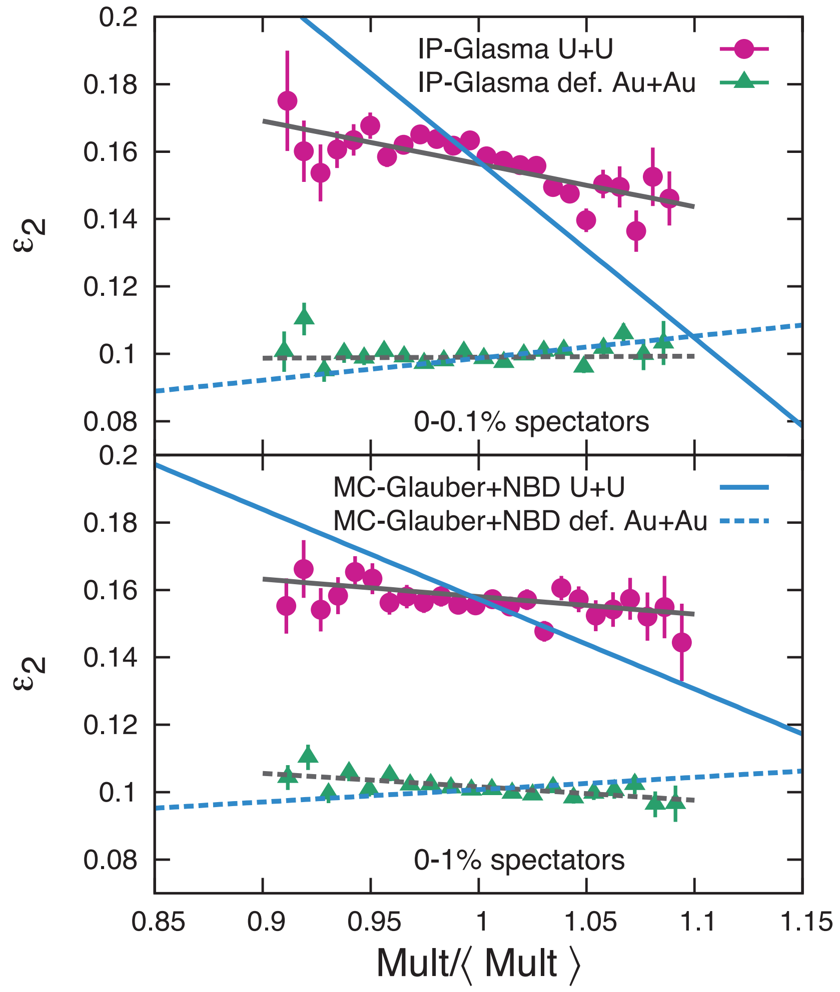
Deformed Nuclei

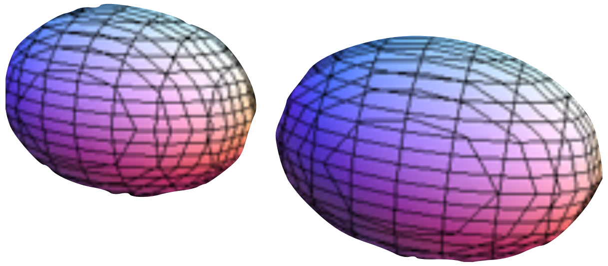
B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN
PHYS. REV. C89, 064908 (2014)

- Uranium: prolate
- Gold: oblate

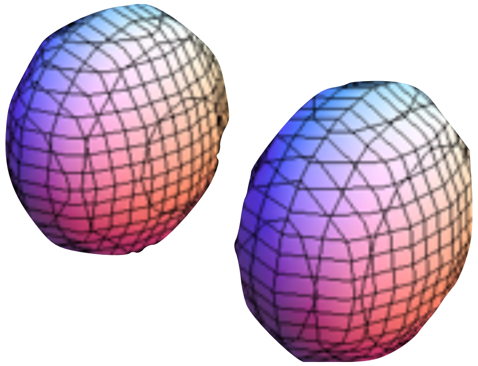


U+U, side-side

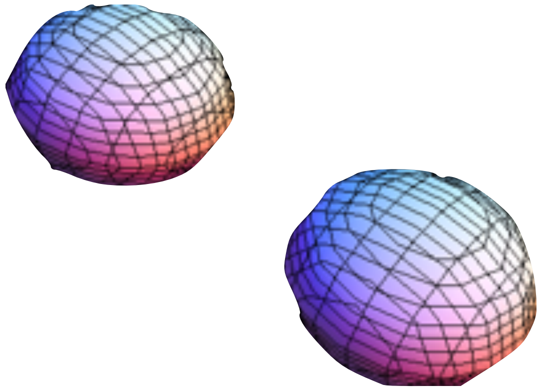




U+U, tip-tip



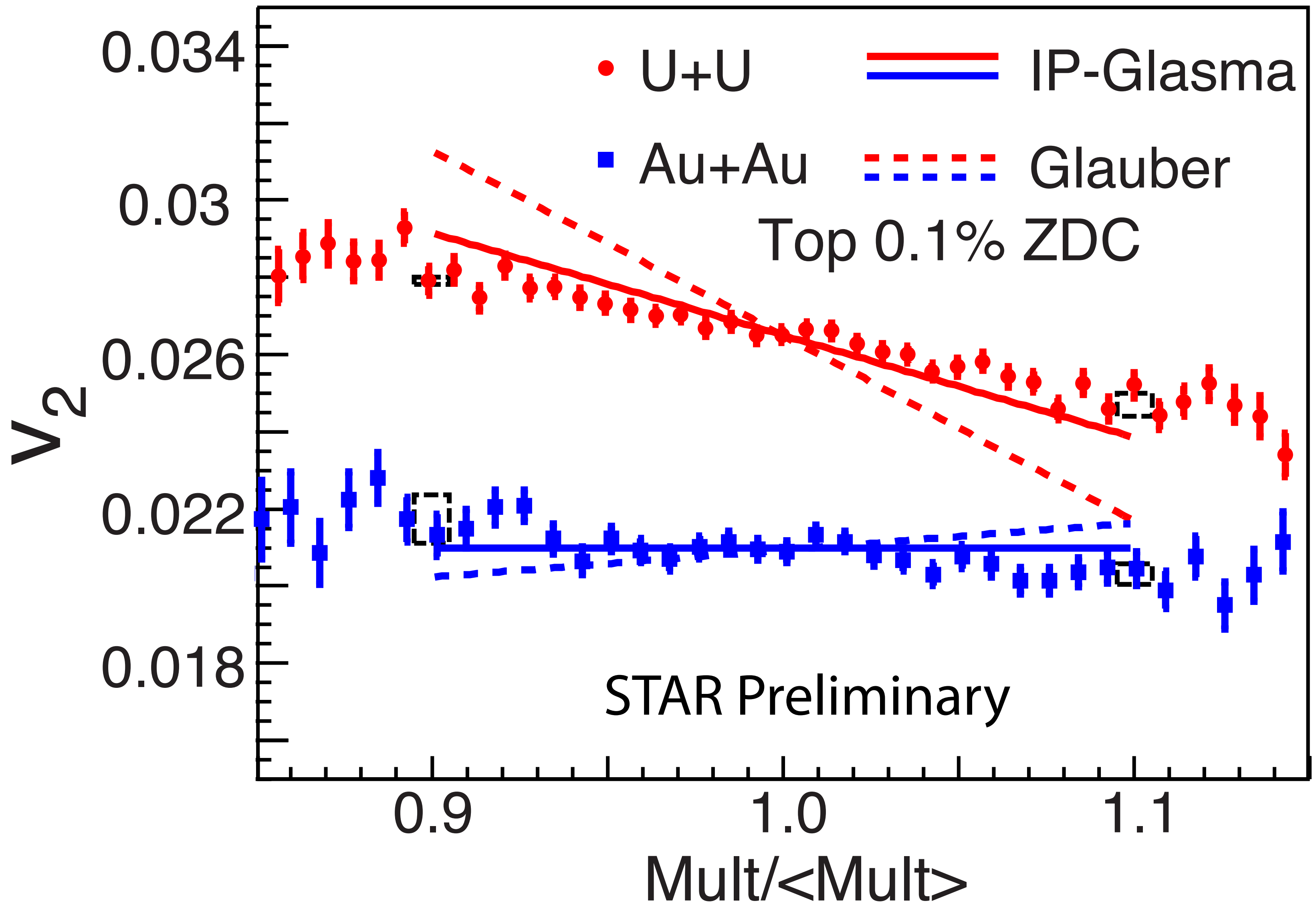
Au+Au, side-side



Au+Au, “tip-tip”

Testing the initial state model in U+U collisions

B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. C89, 064908 (2014)
Experimental Data: STAR Collaboration, H. Wang, Nucl. Phys. A (in press, 10.1016/j.nuclphysa.2014.08.086)

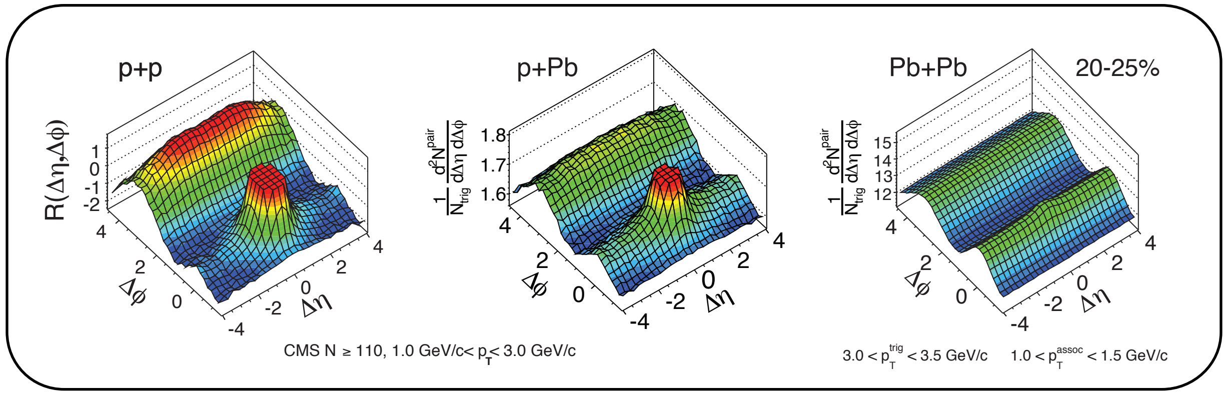


Ultra-central collisions of deformed nuclei distinguish between different models of particle production - IP-Glasma preferred

Small systems: New questions, new opportunities

- High multiplicity p+p and p+Pb collisions at LHC show similar features as Pb+Pb collisions (ridge, v_n)

- d+Au at RHIC also seems to show similar features



- Interpretation not yet clear:
  - Initial correlations? Theory on this is developing: new insights
  - Initial geometry + collective effects? Even fluid dynamics?

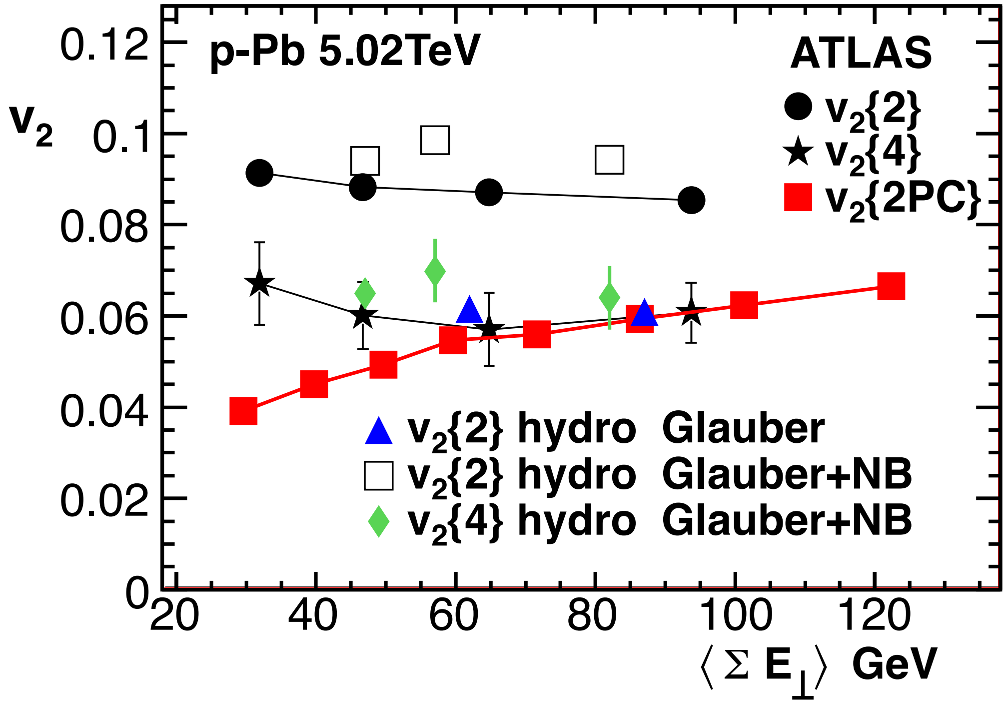
- Versatility of RHIC helps to address these questions for example by running ^{3}He+Au collisions (different geometry)

CMS: JHEP 1009 (2010) 091, Phys.Lett. B718 (2013) 795-814, JHEP 1107 (2011) 076 , Eur.Phys.J. C72 (2012)

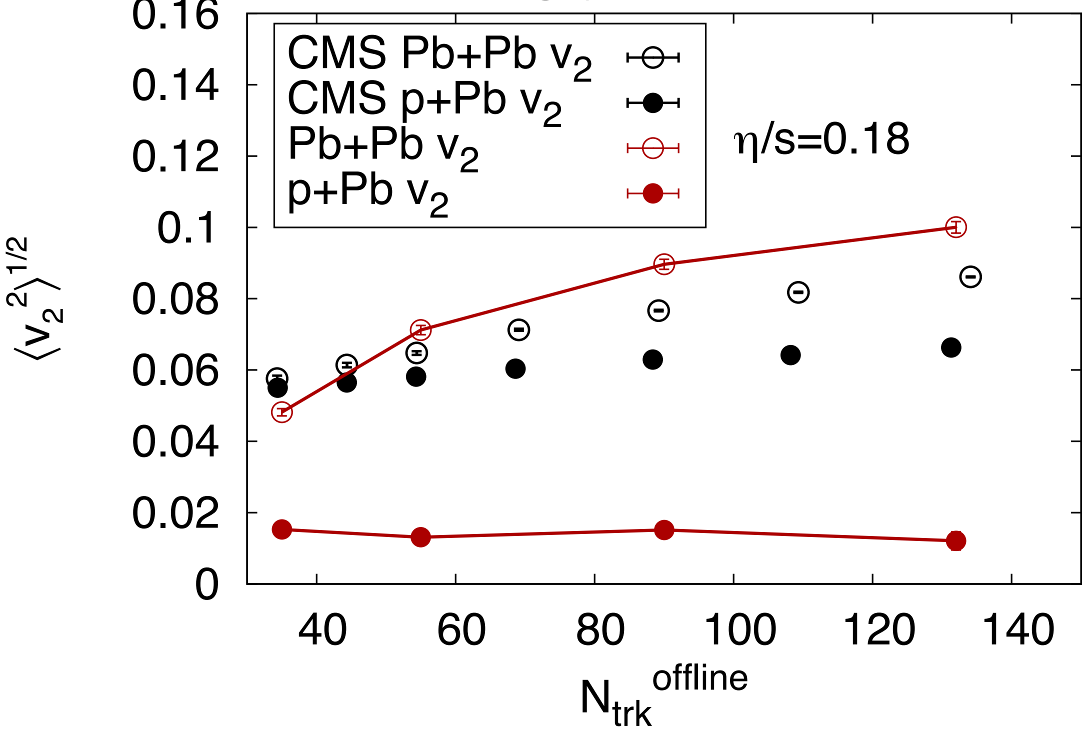
Small systems: New questions, new opportunities

- Can fluid dynamics work in such small systems?
  Viscous corrections become very large
- Initial state strongly depends on model
- Some models work, some don't. Not yet settled…

Bozek, Broniowski, Phys.Rev. C88 (2013) 014903



Schenke, Venugopalan, arXiv:1405.3605 (2014)



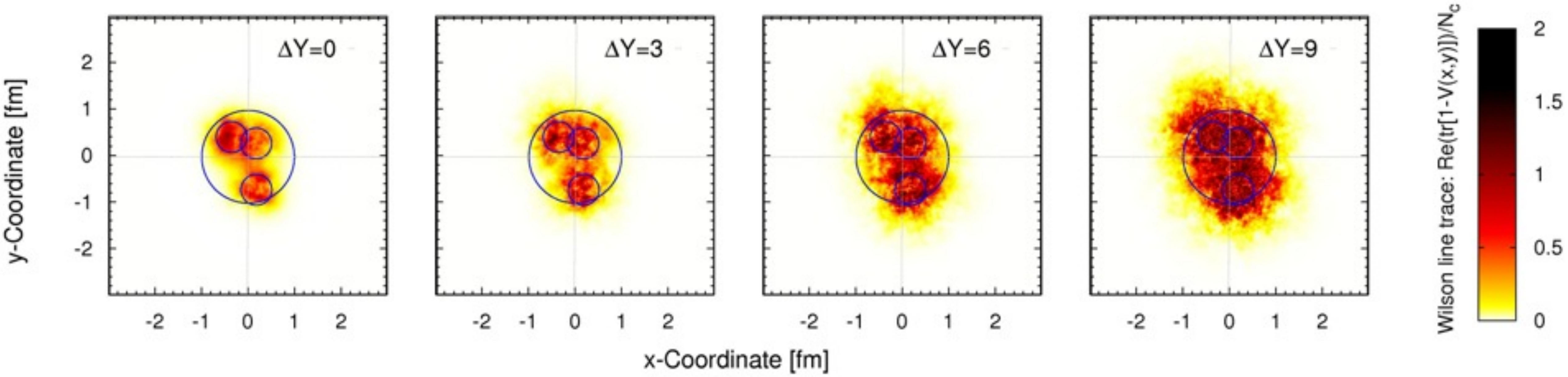
Are we sensitive to the shape of the proton?

S. SCHLICHTING, B. SCHENKE, ARXIV:1407.8458

- Three "Constituent quarks" at large *x*

- JIMWLK evolution with infrared regulator to get gluon distribution at smaller *x*

decreasing *x*



Is viscous fluid dynamics even valid?

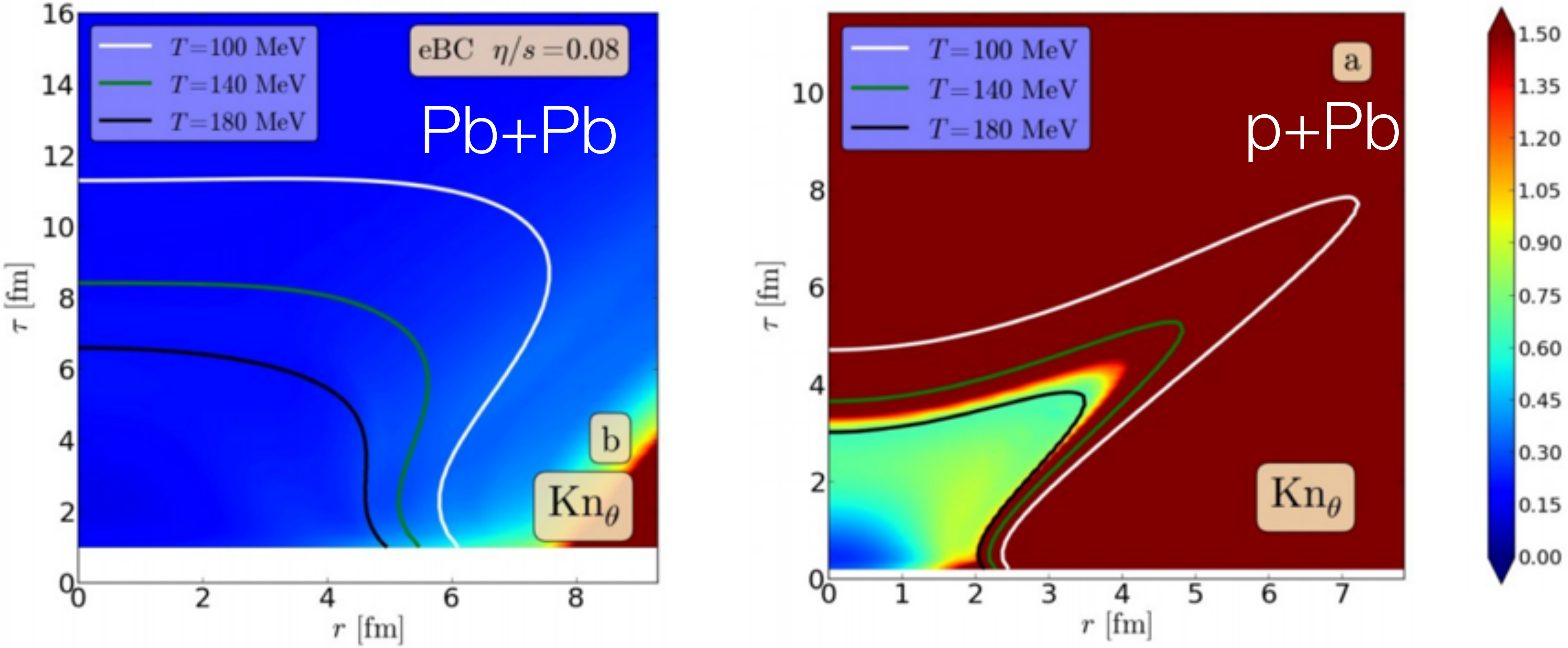
H. Niemi, G.S. Denicol, e-Print: arXiv:1404.7327

- Use the Knudsen number as a measure

$$Kn_\theta = l_{\rm micro}/L^\theta_{\rm macro} = \tau_\pi/\theta$$ (this is one specific choice)

where τ_π is the shear relaxation time and $\theta = \partial_\mu u^\mu$

- Small Knudsen number means fluid dynamics is valid



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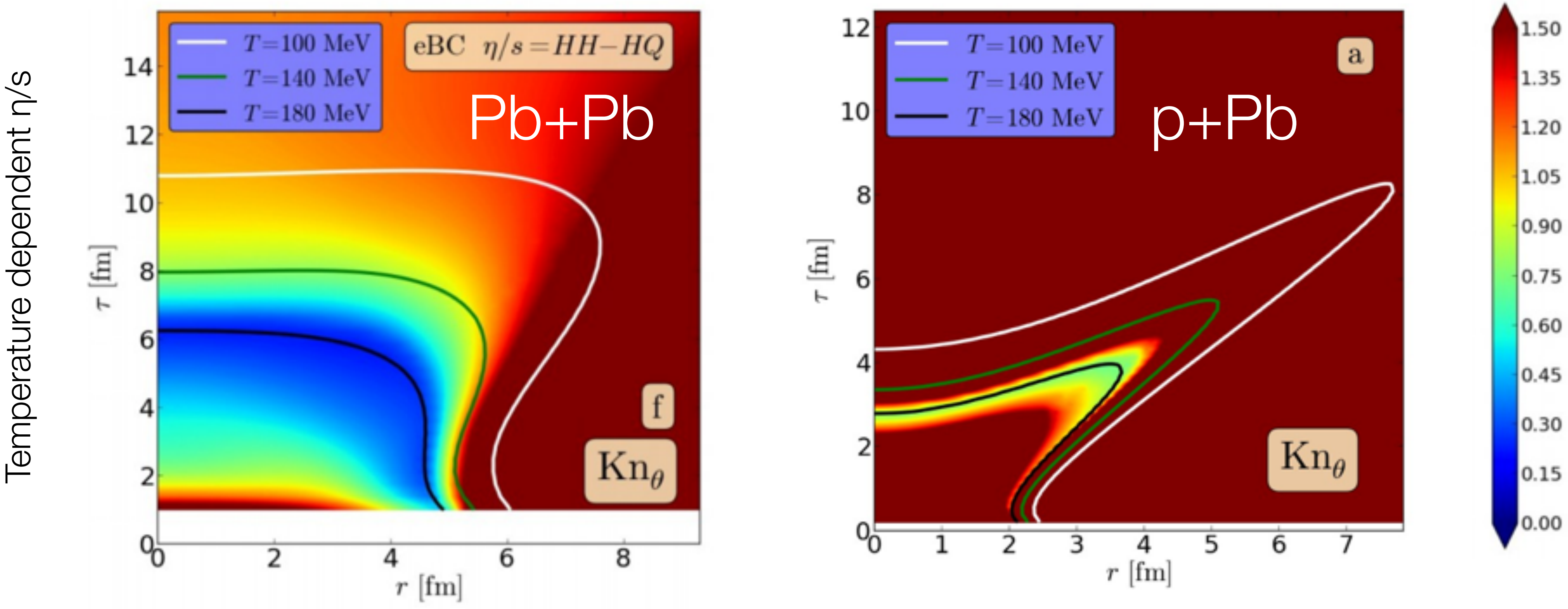
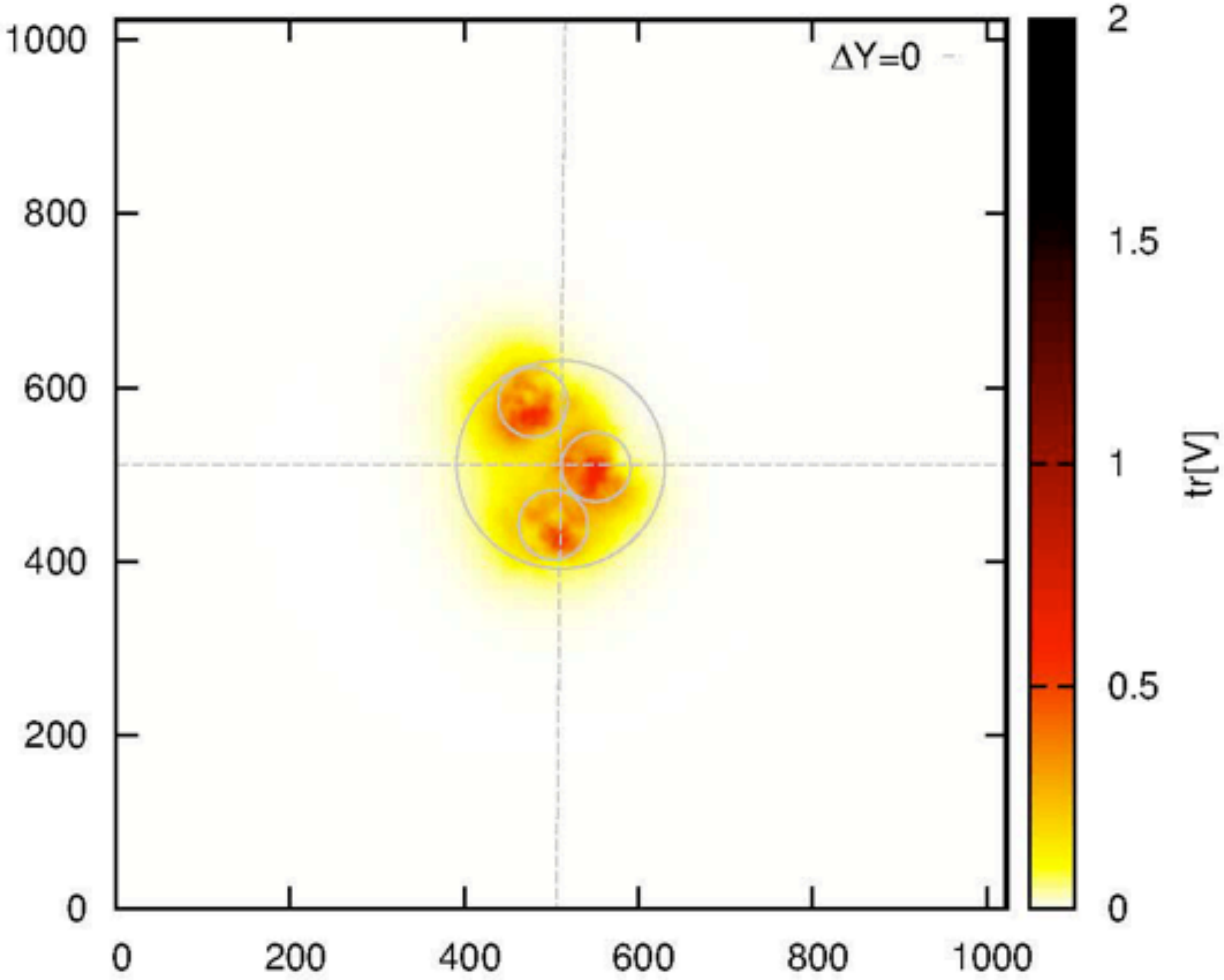


Conclusions

- Relativistic fluid dynamics has been very successful in describing the bulk properties of high energy heavy ion collisions
- Fluctuating initial conditions seem well under control at high energies - they allow the prediction of all flow harmonics
- Many recent advances: bulk viscosity, temperature dependence of transport parameters, pre-equilibrium dynamics, small systems
- We are now able to extract important quantitative information on the properties of hot and dense QCD matter
  from experimental data

BACKUP

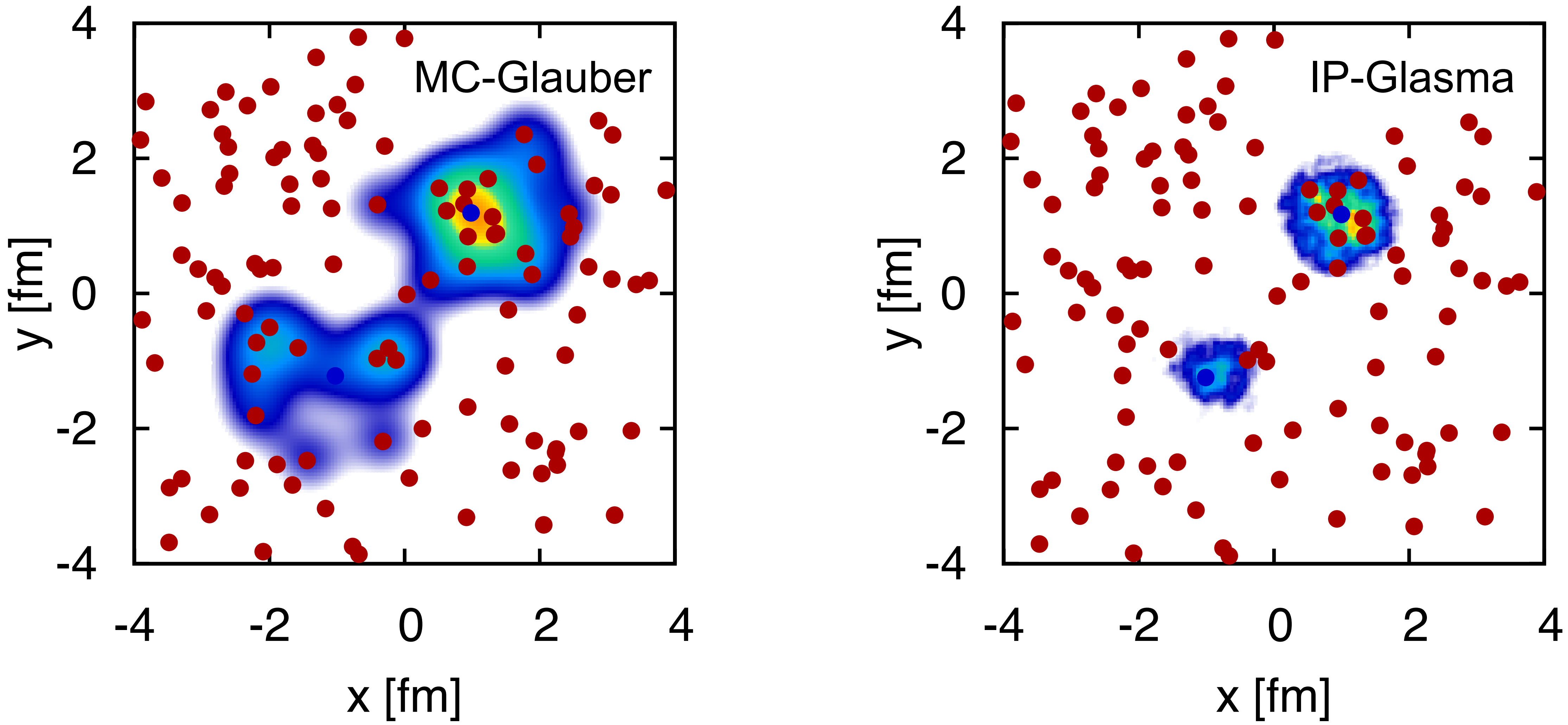
-



FIXED COUPLING JIMWLK EVOLUTION OF TRACE OF THE WILSON LINE

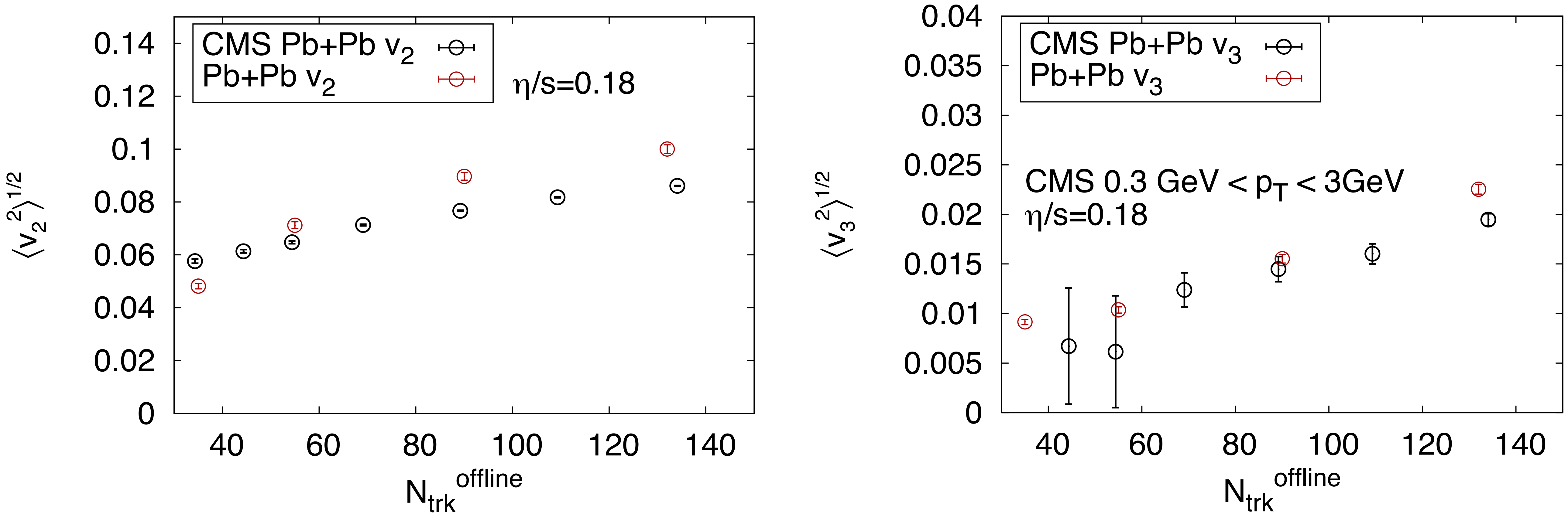
small systems

A. BZDAK, B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PRC87, 064906 (2013)



Fourier Harmonics in p+Pb

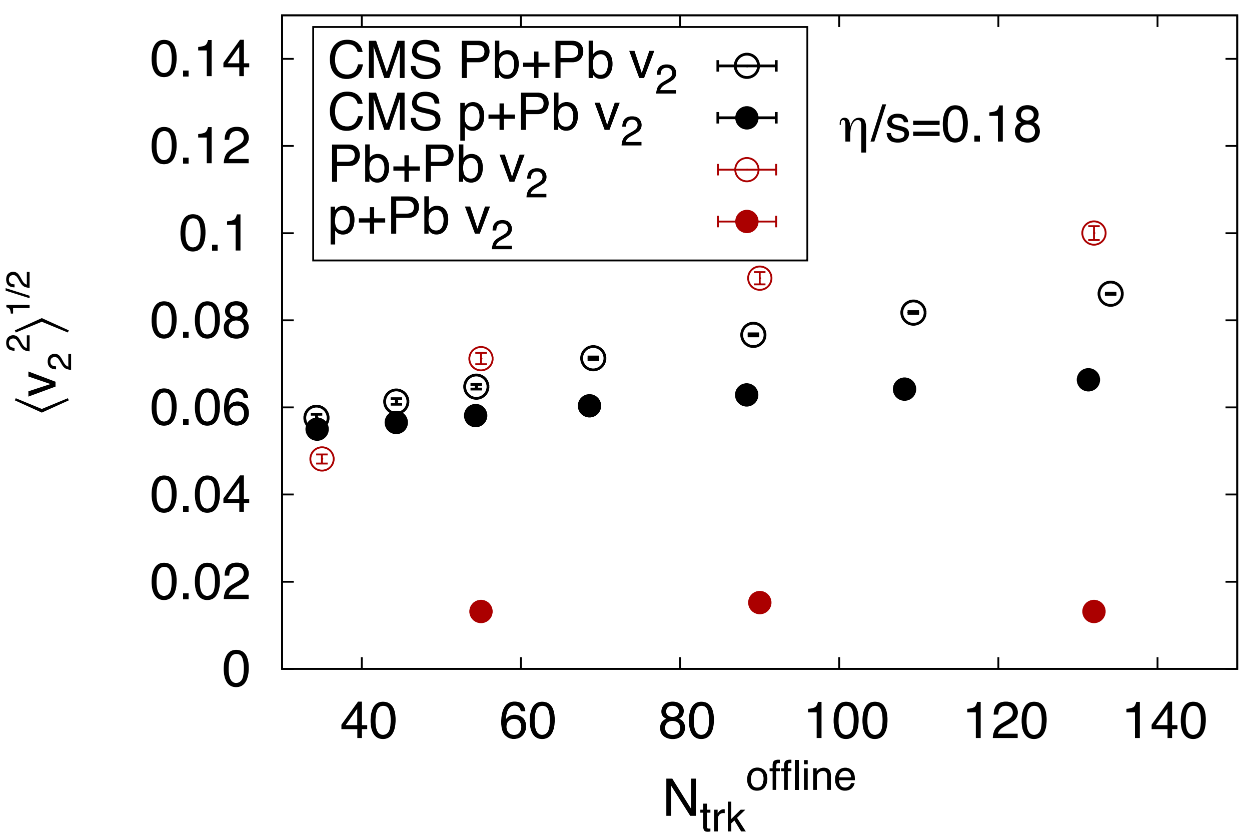
CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240

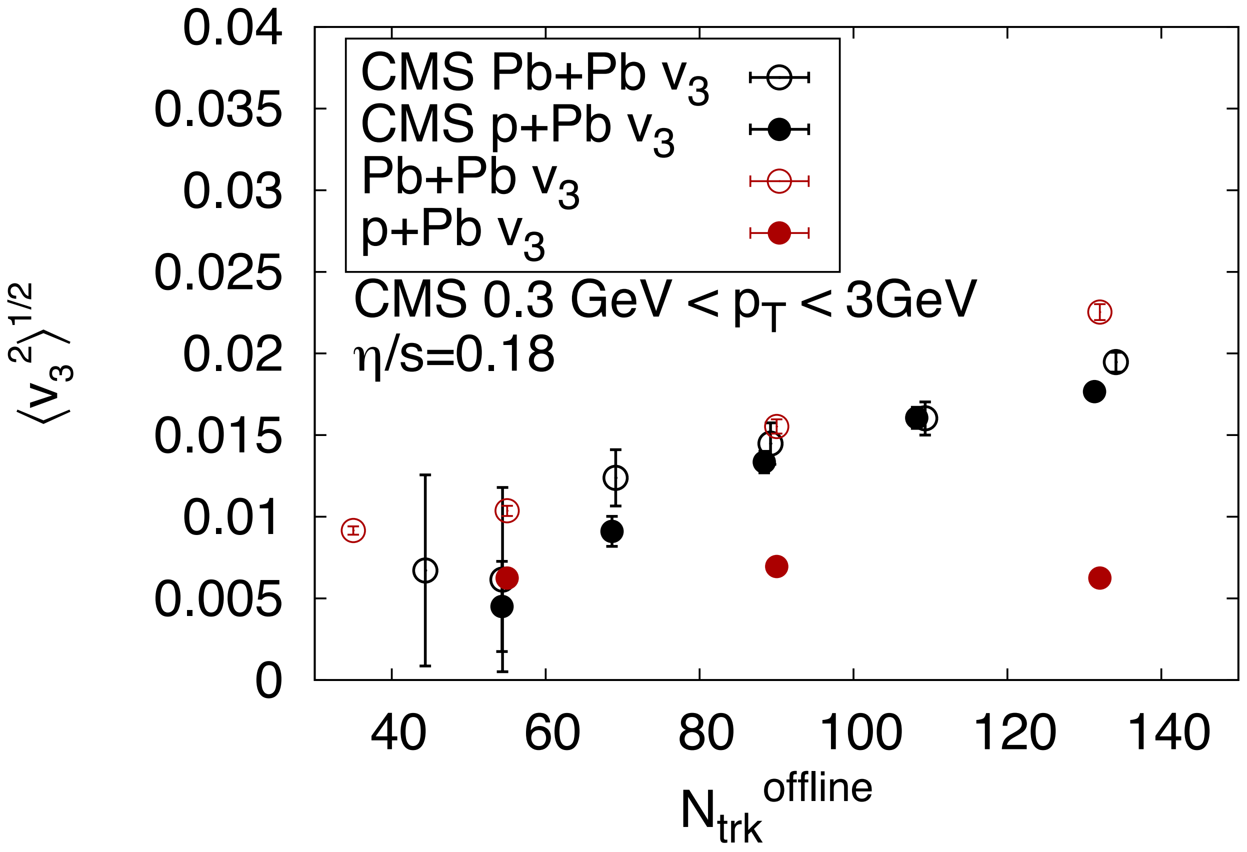


Red points: IP-Glasma + MUSIC

Fourier Harmonics in p+Pb

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240





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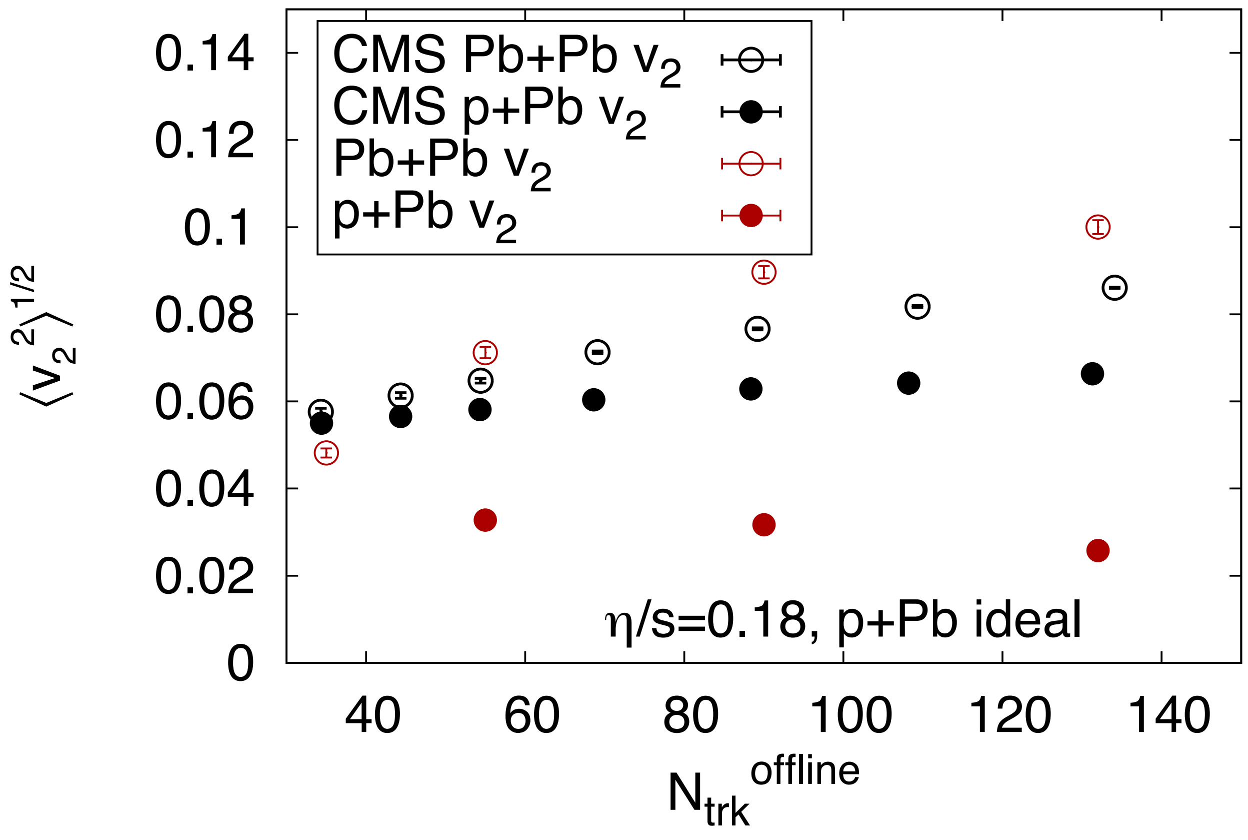
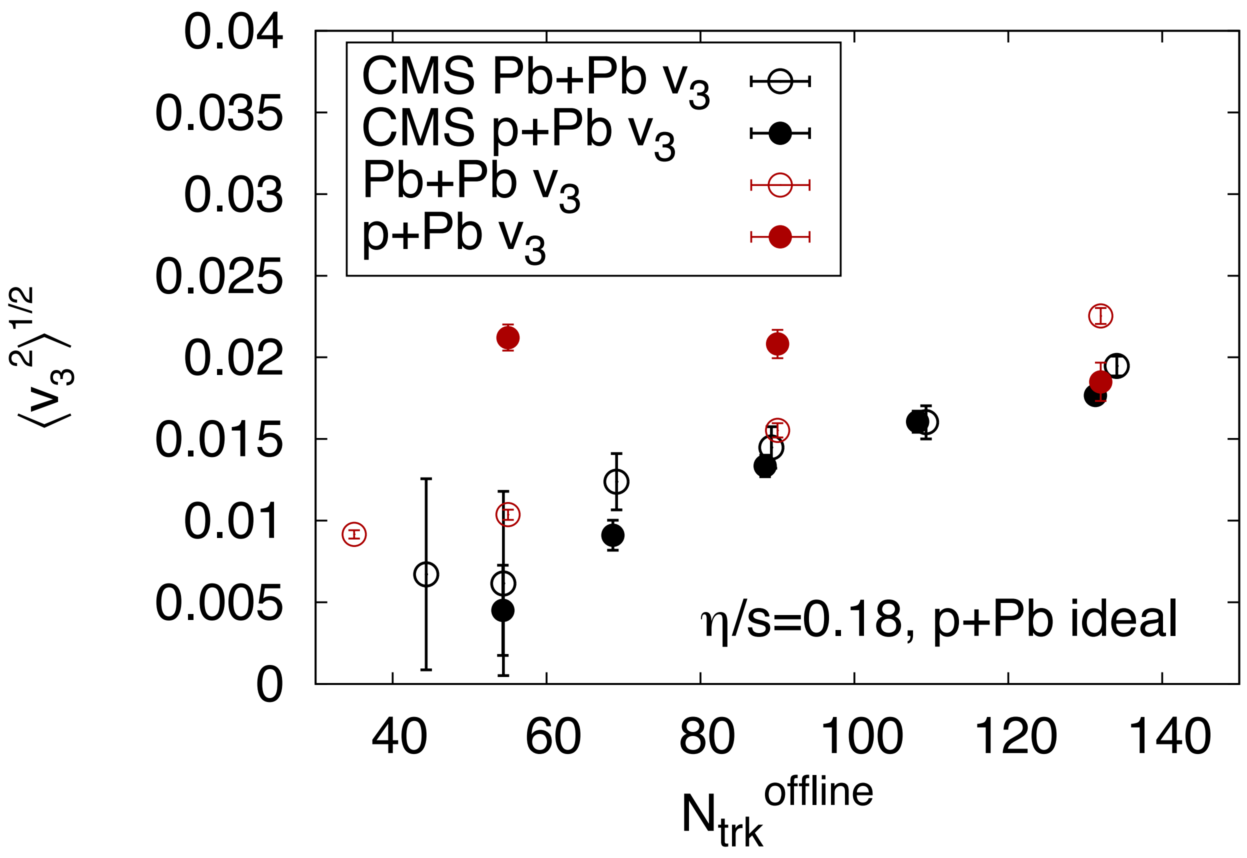
Fourier Harmonics in p+Pb

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240

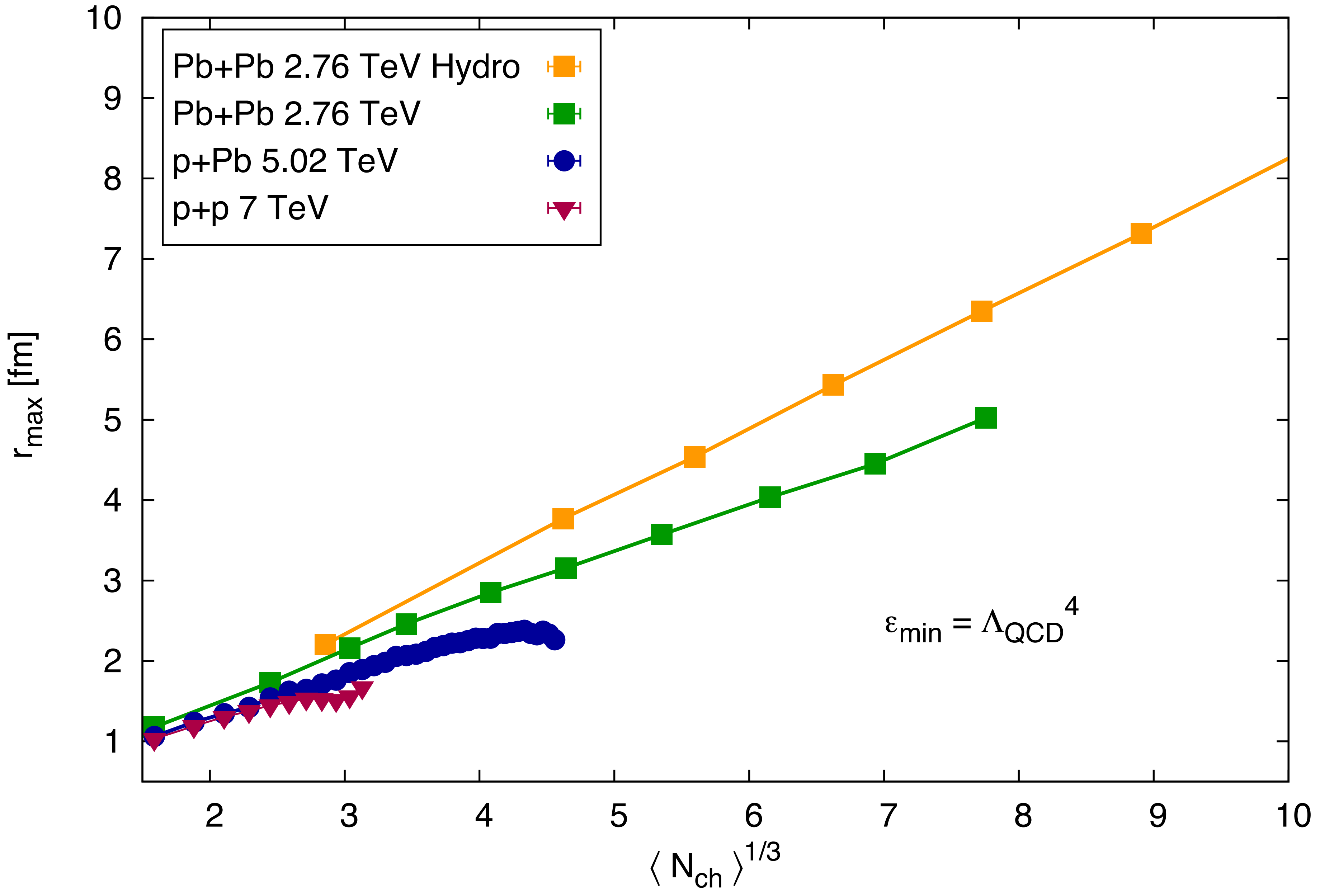




Red points: IP-Glasma + MUSIC

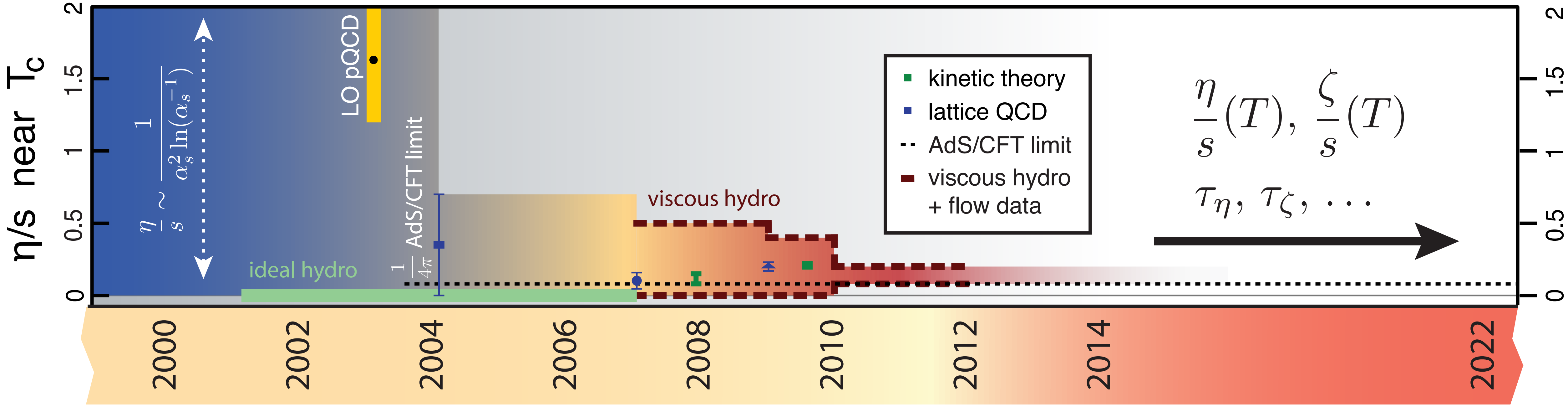
System Size

A. BZDAK, B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PRC87, 064906 (2013)



Achieving quantitative understanding

Example: Shear viscosity to entropy density ratio η/s
Broad theoretical efforts and experimental advances lead to increasingly precise determination of η/s



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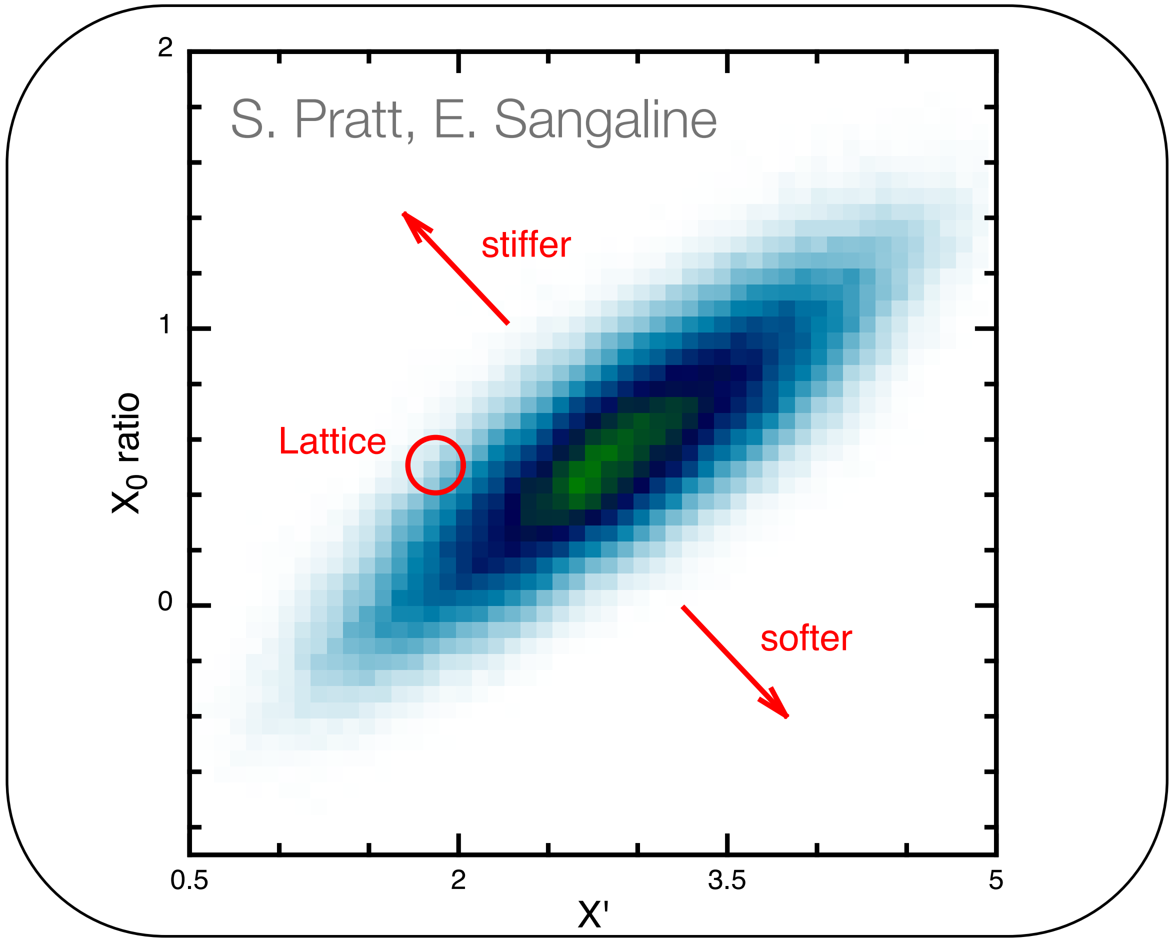
Model - Data comparison

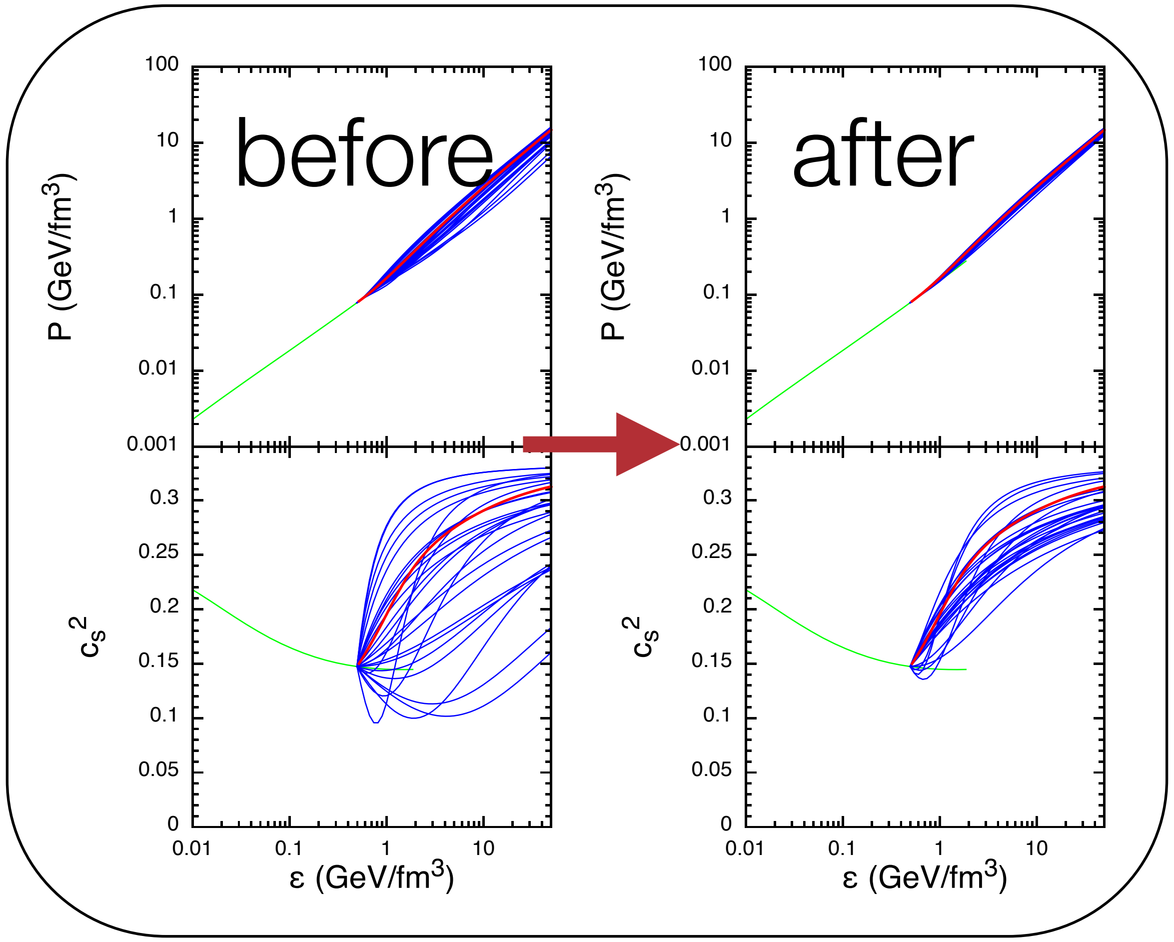
Models are reaching a level of sophistication that makes systematic model to data comparisons useful, essential

- Simultaneous study of many observables
- Simultaneous variation of all parameters
- Model emulators
- Extract quantitative information on fundamental properties of nuclear matter under extreme conditions

Model - Data comparison

Detailed model to experimental data comparisons via model emulators will allow to **constrain** for example the **QCD equation of state**





Constraining parameters in a parametrization of the EoS