Collective dynamics in relativistic nuclear collisions

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XXIV QUARK MATTER
DARMSTADT 2014

Limits for the viscosity of strongly interacting matter:

- No direct measurements $\longrightarrow$ extracting transport coefficients requires model for the spacetime evolution of the matter

Fluid dynamics

- Transport coefficients direct input to the model
- Easy to include transition from QGP to hadronic matter (EoS)
- Need: small gradients and close to local thermal equilibrium

Conservation laws

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = e u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

Israel-Stewart equations for dissipative parts of $T^{\mu\nu}$

shear-stress:

$$\tau_\pi \frac{d}{d\tau}\pi^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle} + \cdots$$

bulk pressure:

$$\tau_\Pi \frac{d}{d\tau}\Pi + \Pi = -\zeta\nabla_\mu u^\mu + \cdots$$

Microscopic properties integrated into the coefficients:
$\eta(T, \{\mu_i\})$ = shear viscosity (resistance to deformations)
$\zeta(T, \{\mu_i\})$ = bulk viscosity (resistance to volume changes)

- Model for initial conditions (initial $T^{\mu\nu}$)
- $\longrightarrow$ Spacetime evolution of $T^{\mu\nu}$ from fluid dynamics
- $\longrightarrow$ Convert to observable particle spectra

Azimuthal deformations characterized by Fourier coefficients:

v_1 = directed flow, v_2 = elliptic flow, v_3 = triangular flow

$$\frac{\mathrm{d}N}{\mathrm{d}y\mathrm{d}p_T^2\mathrm{d}\phi} = \frac{\mathrm{d}N}{\mathrm{d}y\mathrm{d}p_T^2}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos\left(\phi - \psi_n\right)\right]$$

Event-plane angle (direction of the deformation):

$$\psi_n = (1/n)\arctan\left(\langle p_T \sin n\phi\rangle \,/\, \langle p_T \cos n\phi\rangle\right)$$

- $v_n(p_T)$, $\psi_n(p_T)$, dN/dy, ... characterize single event

Ensemble of events: Full characterization

- Averages: $\langle v_n\rangle$, $\langle\psi_n\rangle$, ...
- Probability distributions: $\mathcal{P}(v_n)$, $\mathcal{P}(\psi_n)$, ...
- Correlations: $\langle v_n, v_m\rangle$, $\langle\psi_n, \psi_m\rangle$, ...

Azimuthal deform. of initial density characterized by eccentricities:

$$\epsilon_{m,n} = -\frac{\int \mathrm{d}x\mathrm{d}y\ r^m \cos\left[n\left(\phi - \Psi_{m,n}\right)\right] \varepsilon\left(x, y, \tau_0\right)}{\int \mathrm{d}x\mathrm{d}y\ r^m \varepsilon\left(x, y, \tau_0\right)}$$

Usually $\epsilon_2 = \epsilon_{2,2}$, $\epsilon_3 = \epsilon_{3,2}$, ...

$$\Psi_{m,n} = \frac{1}{n} \arctan \frac{\int \mathrm{d}x\mathrm{d}y\ r^m \sin\left(n\phi\right) \varepsilon\left(x, y, \tau_0\right)}{\int \mathrm{d}x\mathrm{d}y\ r^m \cos\left(n\phi\right) \varepsilon\left(x, y, \tau_0\right)} + \pi/n$$

$\Psi_{m,n}$ = participant plane angle (direction of deformation)

- $\epsilon_{m,n}$, $\Psi_{m,n}$ characterize single event (initial energy density)

Ensemble of events (initial conditions): Full characterization

- Averages: $\langle \epsilon_{m,n} \rangle$, $\langle \Psi_{m,n} \rangle$, ...
- Probability distributions: $\mathcal{P}(\epsilon_{m,n})$, $\mathcal{P}(\Psi_{m,n})$
- Correlations: $\left\langle \epsilon_{m,n}, \epsilon_{m',n'} \right\rangle$, $\left\langle \Psi_{m,n}, \Psi_{m',n'} \right\rangle$, ...

Fluid dynamics converts initial eccentricities to non-zero flow coefficients: $\varepsilon_n \longrightarrow v_n$

Ensemble of events (initial conditions): Full characterization

- Averages: $\langle e_{m,n} \rangle$, $\langle \Psi_{m,n} \rangle$, ...
- Probability distributions: $\mathcal{P}(e_{m,n})$, $\mathcal{P}(\Psi_{m,n})$
- Correlations: $\left\langle e_{m,n}, e_{m',n'} \right\rangle$, $\left\langle \Psi_{m,n}, \Psi_{m',n'} \right\rangle$, ...

$\downarrow$ **Hydrodynamic response** (EoS, η/s, ζ/s, ...)

Ensemble of events (spectra): Full characterization

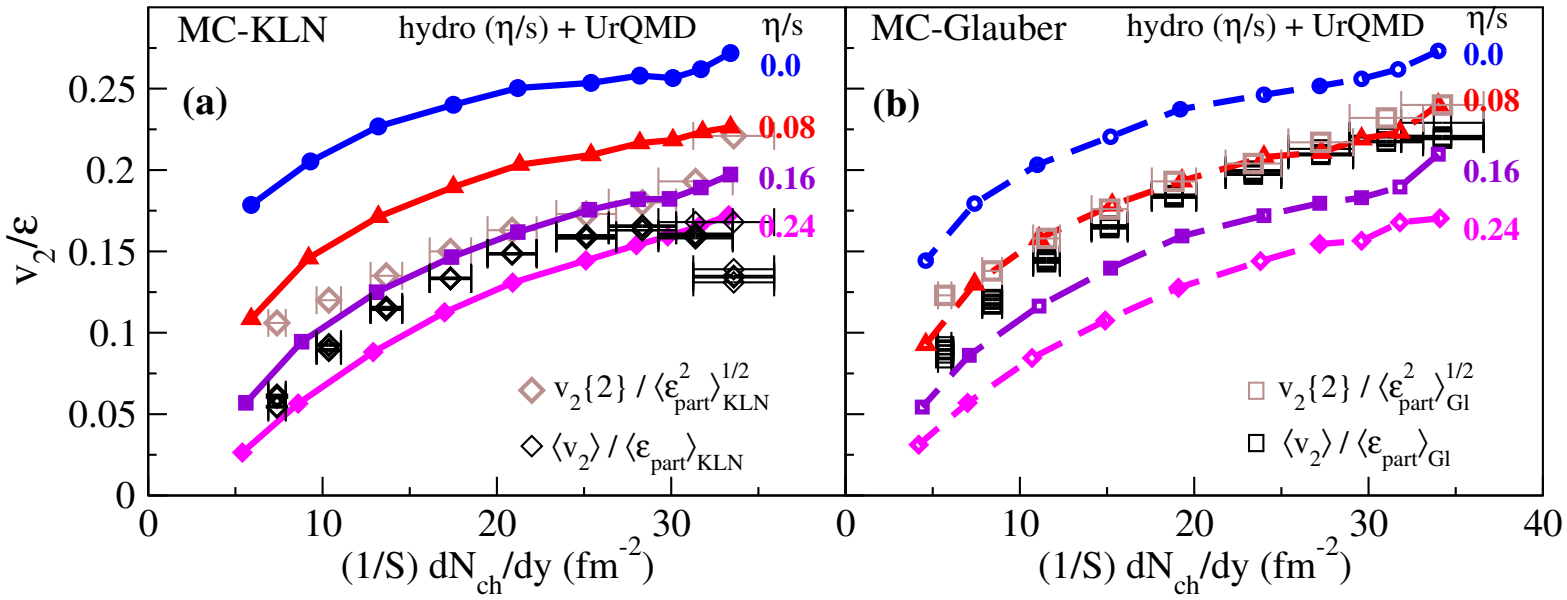
- Averages: $\langle v_n \rangle$, $\langle \psi_n \rangle$, ...
- Probability distributions: $\mathcal{P}(v_n)$, $\mathcal{P}(\psi_n)$, ...
- Correlations: $\langle v_n, v_m \rangle$, $\langle \psi_n, \psi_m \rangle$

- Determine matter properties: $\eta/s(T, \mu_i)$, $\zeta/s(T, \mu_i)$, ...
- Initial state must be determined simultaneously

limits for η/s
(assume $\eta/s =$ constant)

Uncertainty from initial conditions

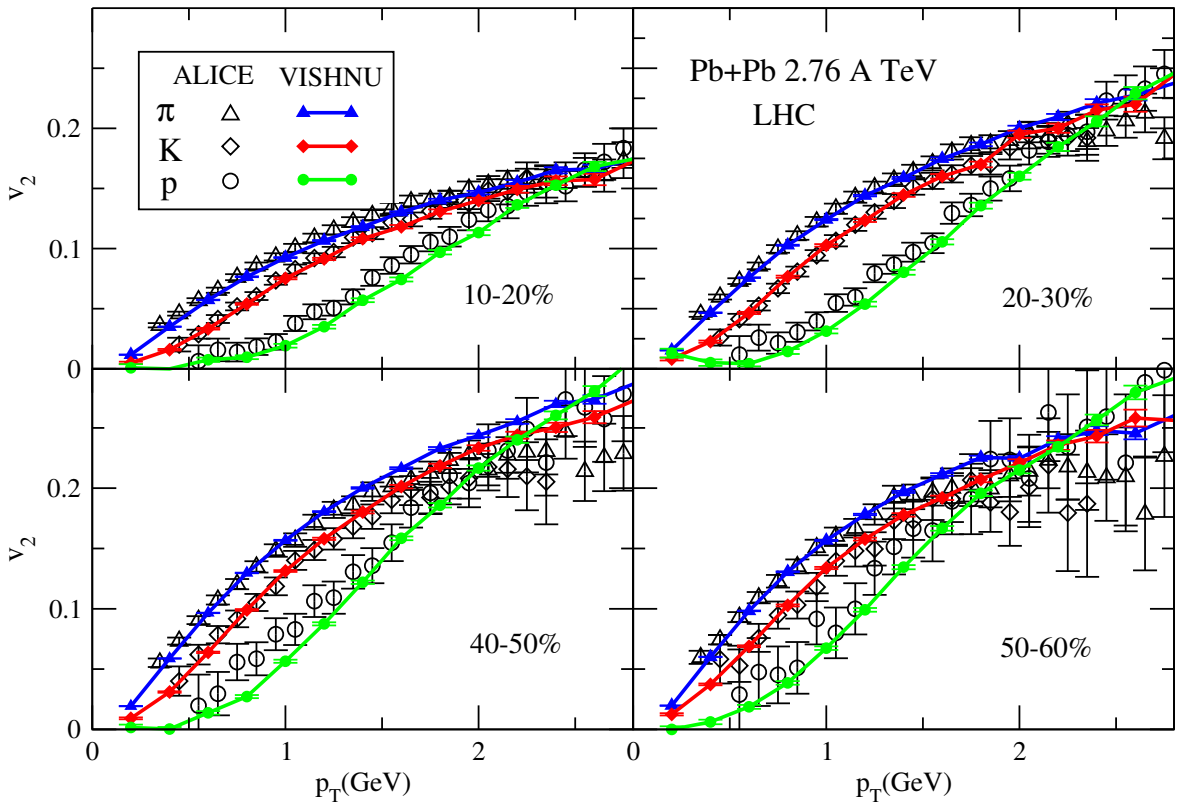
C. Shen, S. A. Bass, T. Hirano, P. Huovinen, Z. Qiu, H. Song and U. Heinz, J. Phys. G **38**, 124045 (2011) [arXiv:1106.6350 [nucl-th]]



- UrQMD + (2+1)D viscous fluid dynamics (VISHNU)
- $\eta/s \sim 0.08 - 0.24$ (RHIC)
- Large uncertainty (factor 2-3) from the initial conditions (MC-KLN $\eta/s \sim 0.20$ vs. MC-Glauber $\eta/s \sim 0.08$)

Identified hadrons π, K, p : elliptic flow

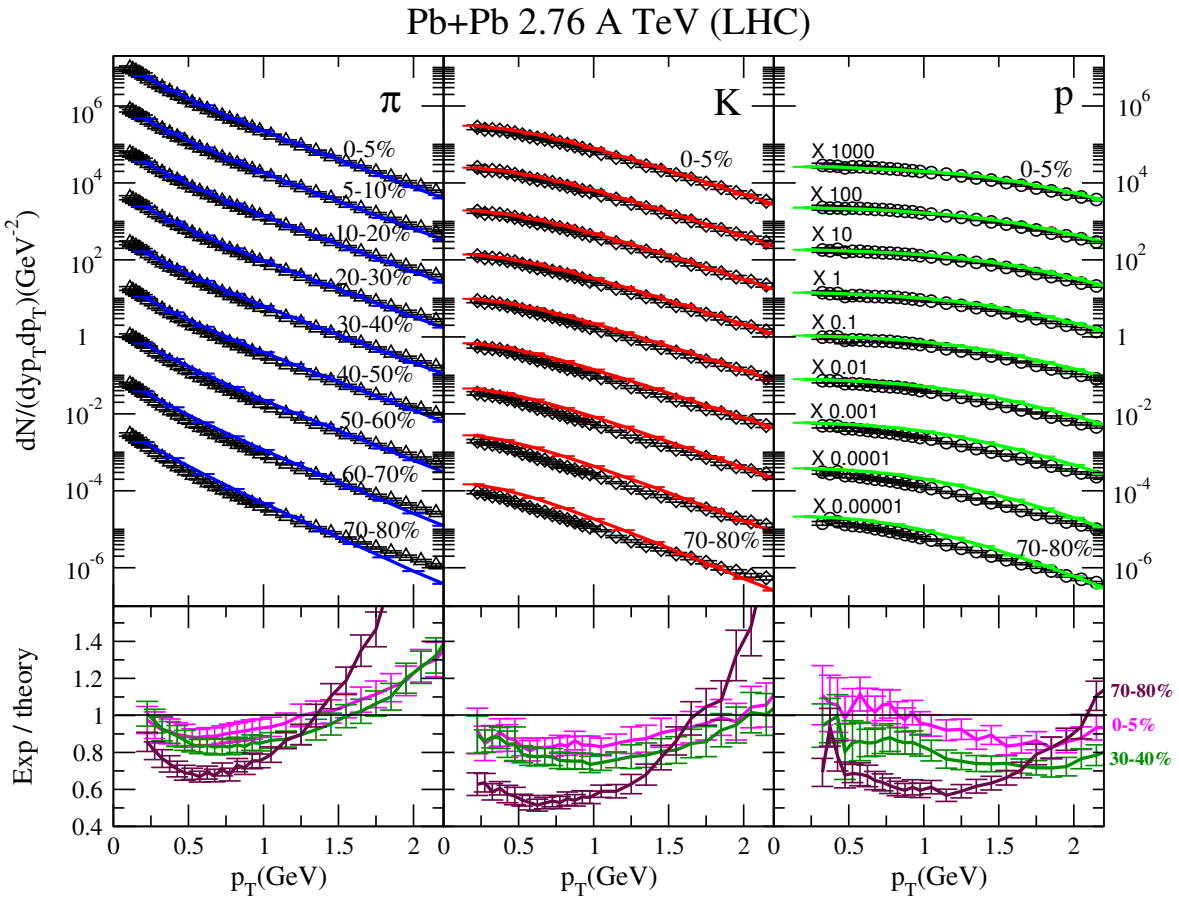
H. Song, S. Bass and U. W. Heinz, Phys. Rev. C **89**, 034919 (2014)



- UrQMD + (2+1)-D viscous hydro (VISHNU)
- Mass ordering of elliptic flow (prediction of hydrodynamics)
- Good agreement with the data

Identified hadrons π, K, p : p_T-spectra

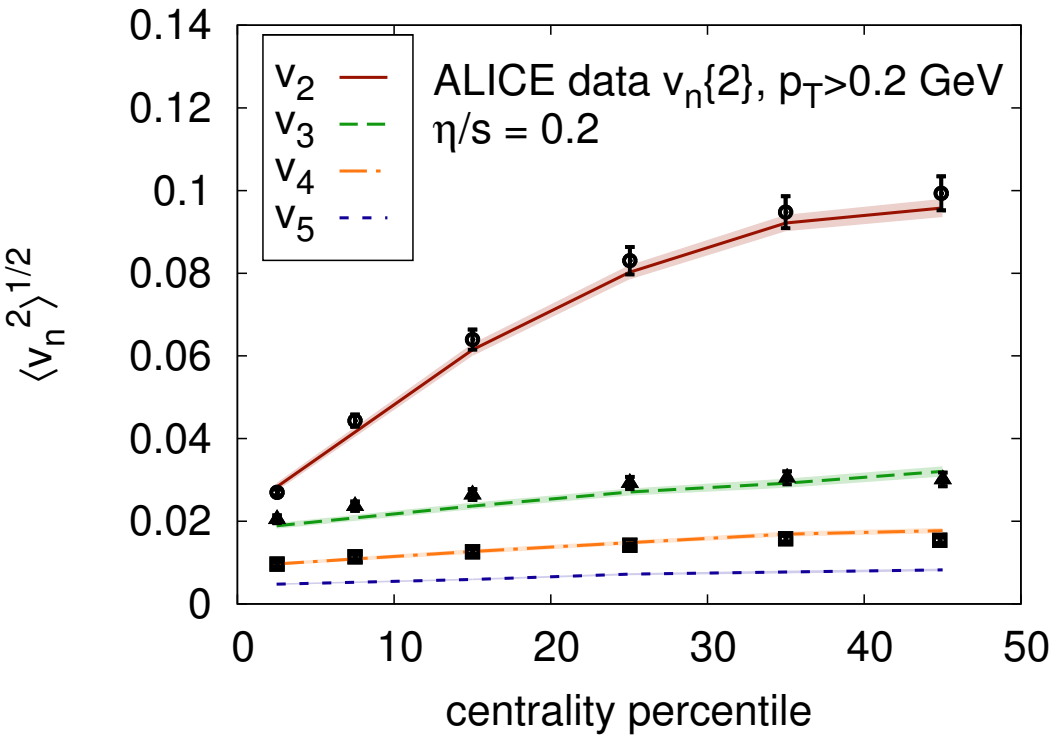
H. Song, S. Bass and U. W. Heinz, Phys. Rev. C **89**, 034919 (2014)



- UrQMD + (2+1)-D viscous hydro (hybrid)
- Mass dependence of p_T slopes & multiplicities

Higher harmonics: v_2, v_3, v_4, ...

Gale, Jeon, Schenke, Tribedy and Venugopalan, PRL **110**, 012302 (2013)



- Constraints to initial conditions: v_2/v_n ratio depends on IC
- IP-Glasma initial state + viscous hydrodynamics (MUSIC) $\longrightarrow$ v_n's with $\eta/s = 0.20$ (LHC) or $\eta/s = 0.12$ (RHIC)
- η/s (RHIC) $\neq$ η/s (LHC): indication of T-dependence of η/s?

Fluid dynamical behaviour:
all the data explained by functions:

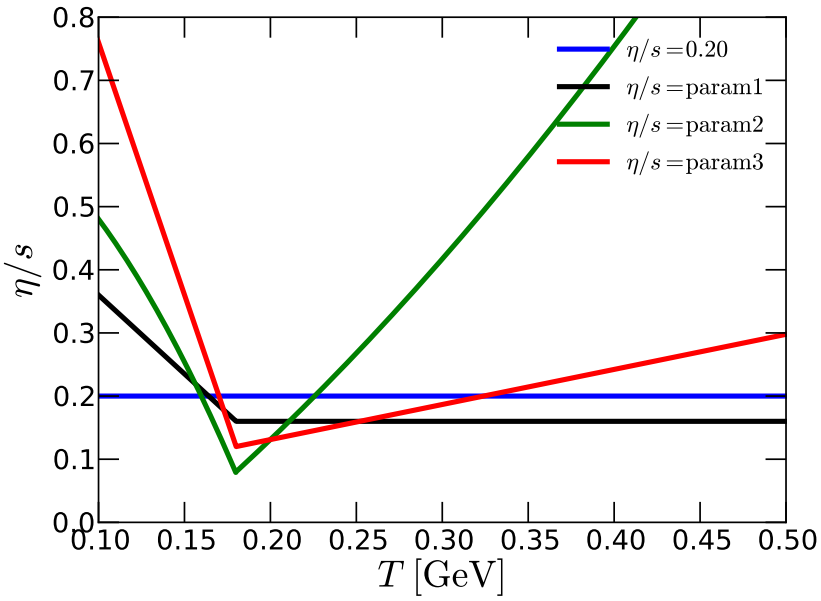
$$p(T, \{\mu_i\}),\ \eta/s(T, \{\mu_i\}),\ \zeta/s(T, \{\mu_i\}),\ \ldots$$

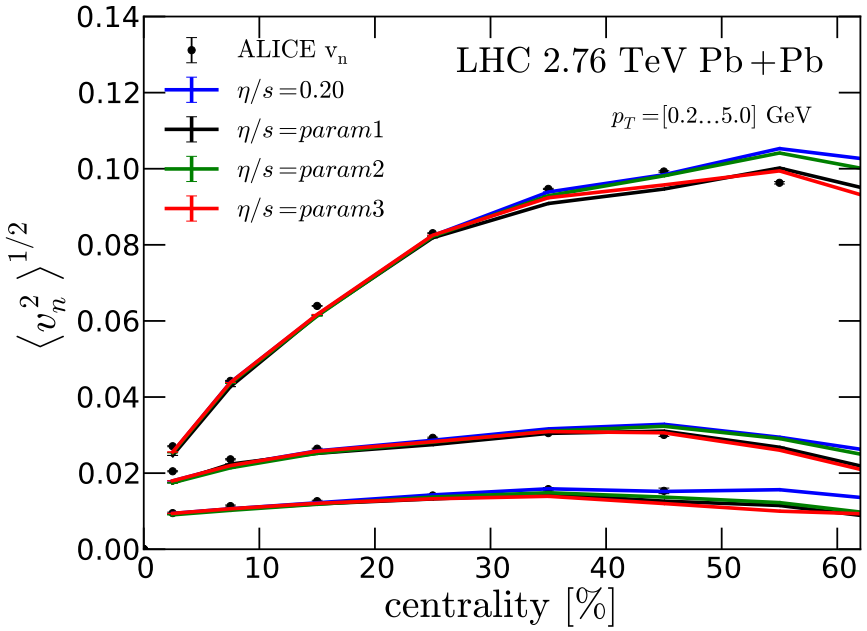
properties of matter:
should not change with $\sqrt{s}$ or initial state

$$\eta/s = \text{constant} \longrightarrow \eta/s(T)$$

$\eta/s(T)$ from LHC v_n's

Paatelainen, Eskola, Niemi and Tuominen, Phys. Lett. B **731**, 126 (2014)
+ fluctuations (preliminary results) poster by R. Paatelainen

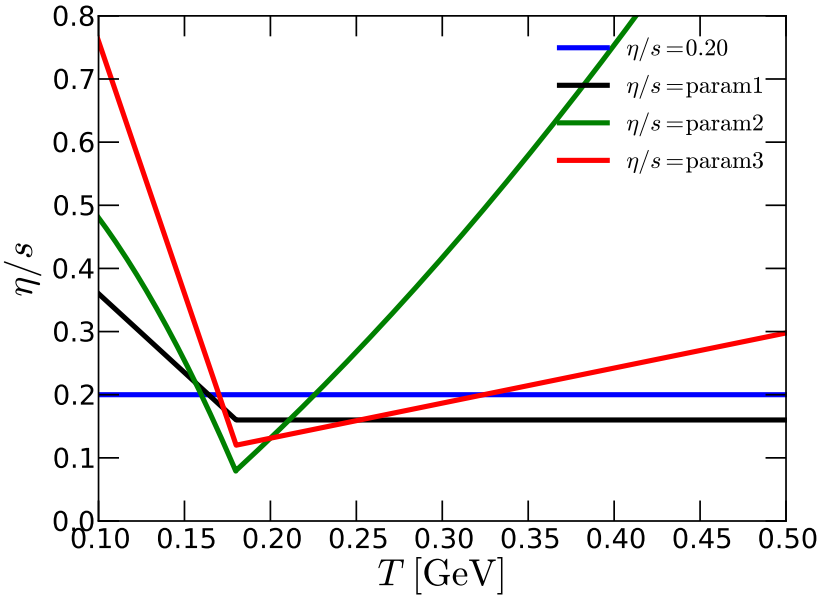


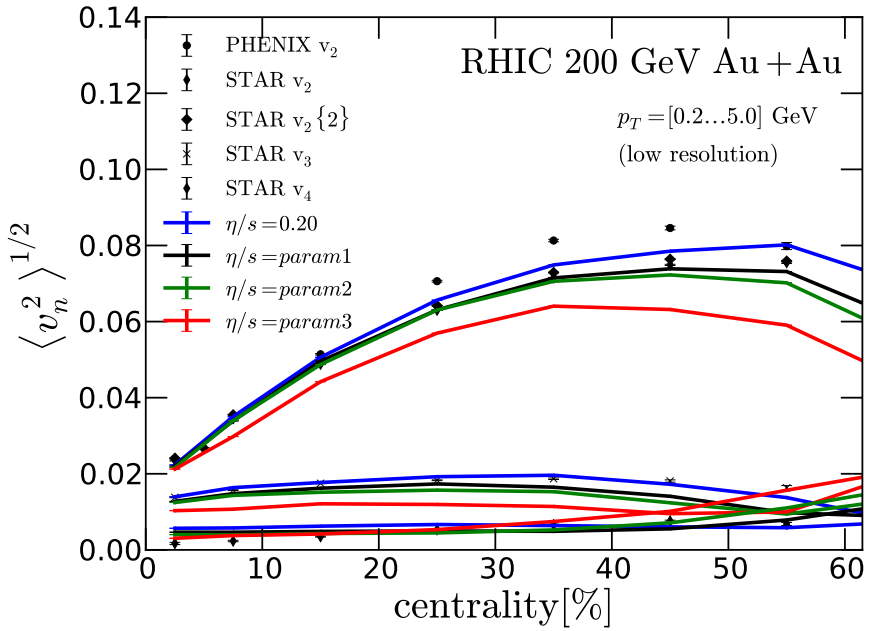


- initial state: pQCD + local saturation (EKRT revisited)
- v_n's do not give unique constraints to $\eta/s(T)$
- If we require minimum near $T_c \longrightarrow$ Constant η/s gives upper limit for $\eta/s(T \sim T_c)$

$\eta/s(T)$ from LHC and RHIC v_n's

Paatelainen, Eskola, Niemi and Tuominen, Phys. Lett. B **731**, 126 (2014)
+ fluctuations (preliminary results) poster by R. Paatelainen



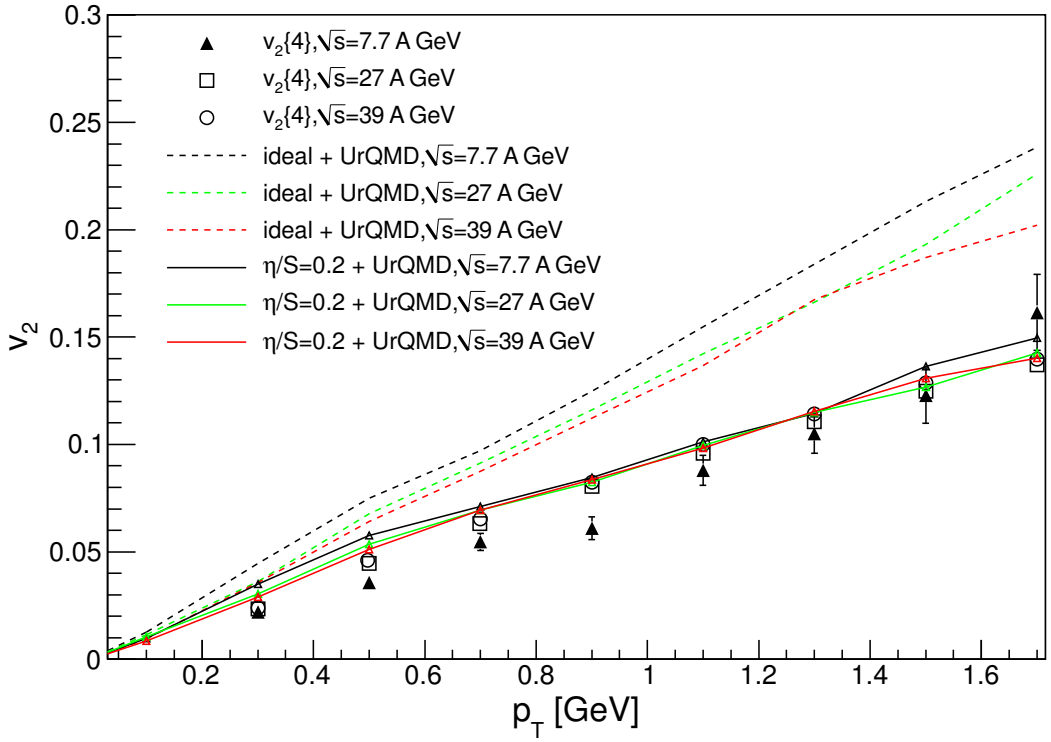


- LHC $\longrightarrow$ RHIC: more sensitivity to hadronic viscosity

Beam energy scan

- More sensitivity to the properties of hadronic matter

Karpenko, Bleicher, Huovinen and Petersen, arXiv:1310.0702 [nucl-th]

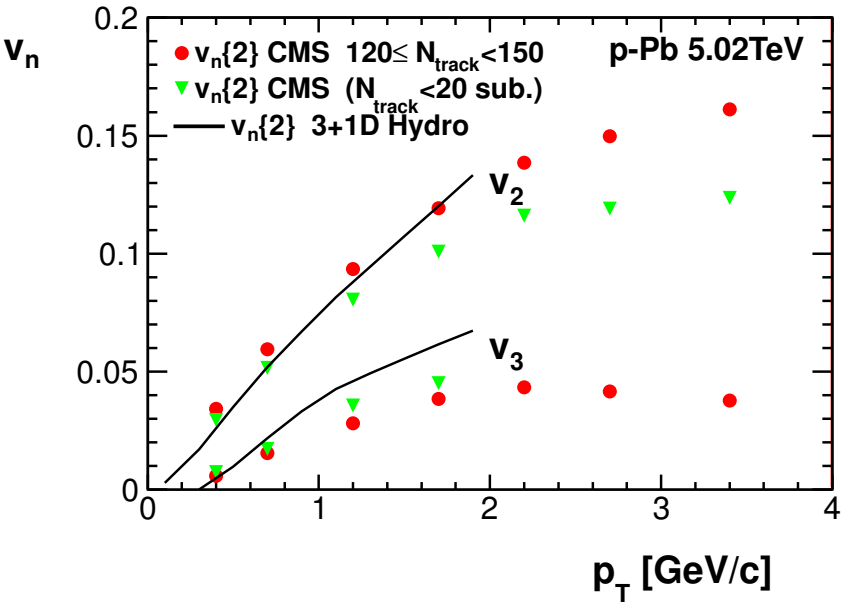


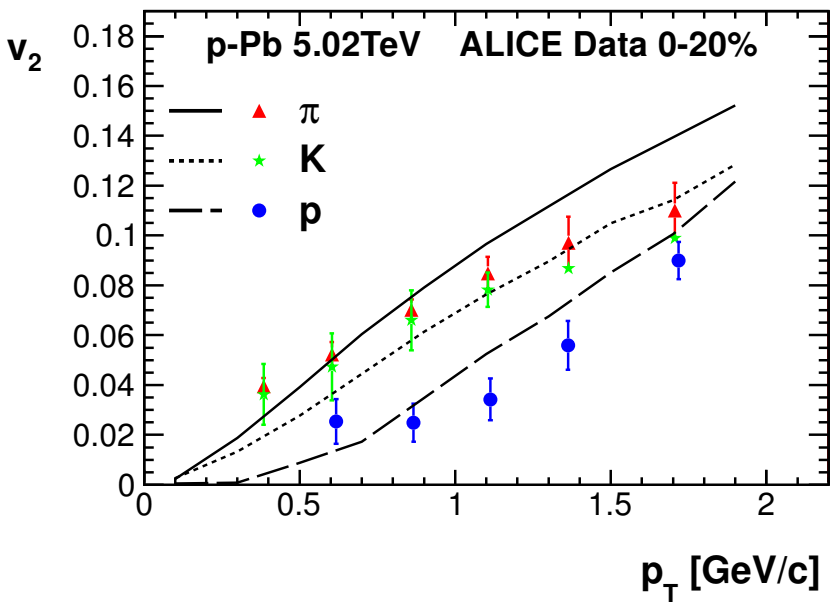
- Same model that works at LHC and top RHIC energy works at lower $\sqrt{s}$ as well
- J. Auvinen (talk): $\sqrt{s}$ dependence of v_3 more sensitive probe of hadronic viscosity

pA collisions

P. Bozek, W. Broniowski and G. Torrieri, Phys. Rev. Lett. **111**, 172303 (2013)

talk: P. Bozek





- Similar mass ordering of v_n (also $\langle p_T \rangle$) as in AA collisions
- Here $\eta/s = 0.08$ (consistent with AA collisions with Glauber $N_{bin} + N_{wn}$ mixture, but not with MC-KLN/IP-Glasma/pQCD + saturation that require larger η/s)
- $\eta/s = 0.08$ also in other models that describe the flow data. talks: P. Romatschke, V. Kozlov, K. Werner

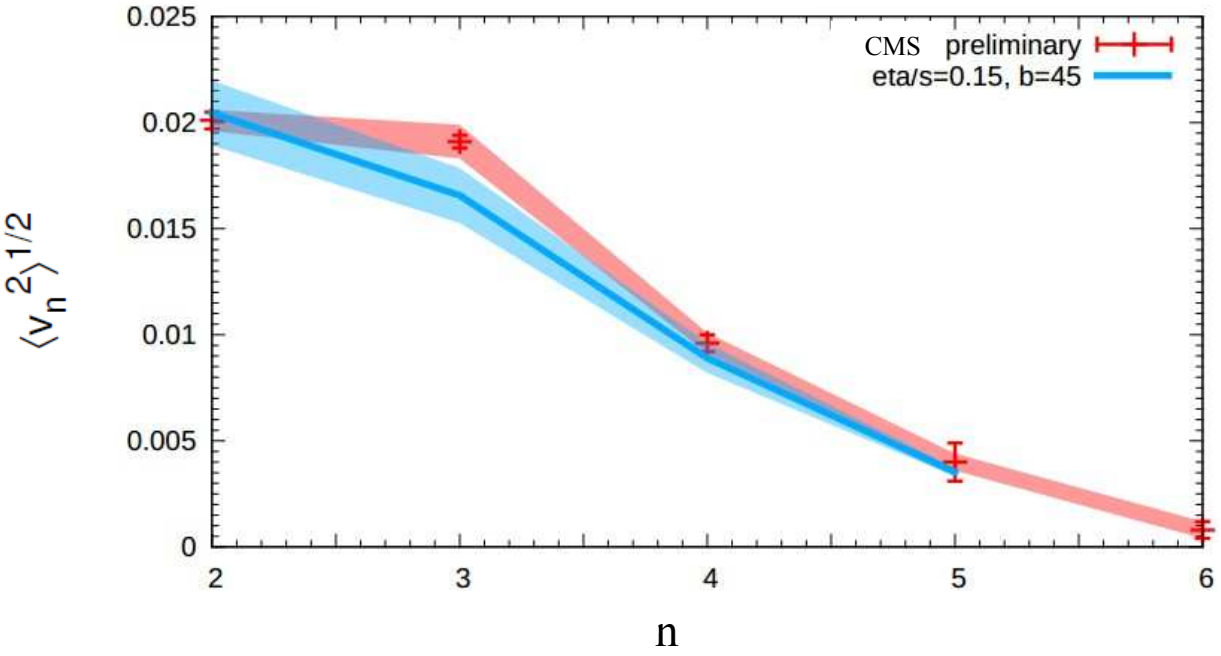
Ultracentral AA: Bulk viscosity and NN-correlations

- CMS ultracentral AA collisions $v_2 \sim v_3$
- Hard to reproduce with η/s alone
- add bulk viscosity + NN-correlations (talk by G. Denicol)

Bulk viscosity + correlations - IPGlasma **MUSIC 2.0**

$$\frac{\zeta}{s} = \mathrm{b} \times \frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$

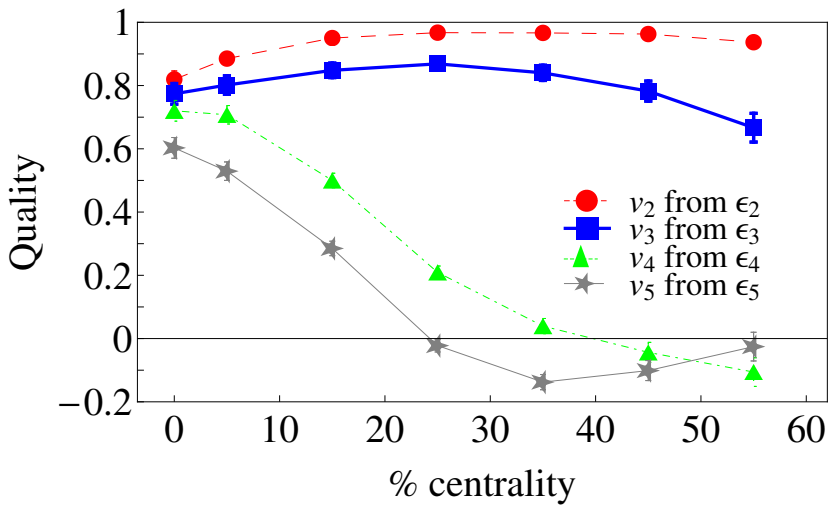
0-1% - LHC

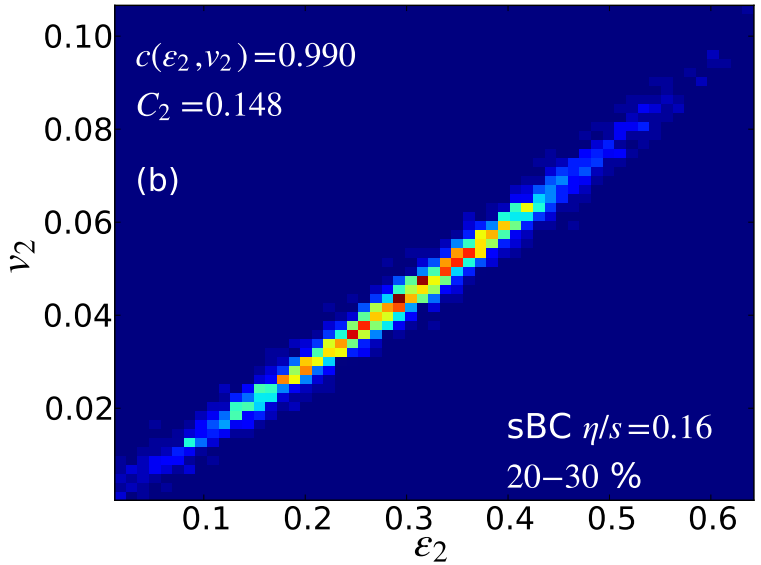


Flow fluctuations: constraints to initial conditions

Gardim, Grassi, Luzum and Ollitrault, Nucl. Phys. A904-905 **2013**, 503c (2013)

HN, Denicol, Holopainen and Huovinen, Phys. Rev. C **87**, 054901 (2013)

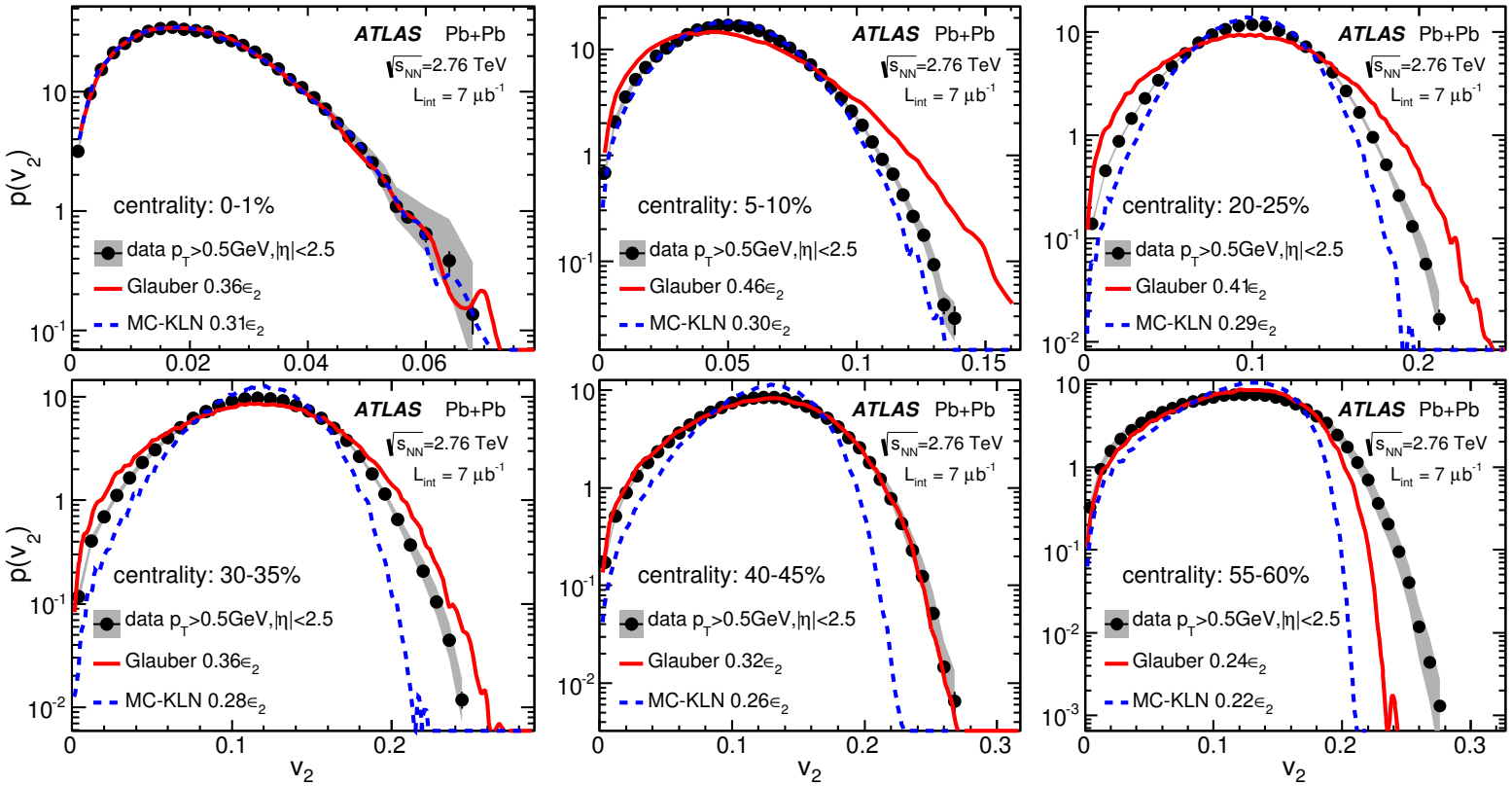




- Strong correlation between $v_{2/3}$ and $\varepsilon_{2/3}$, i.e. $v_n \sim C\varepsilon_n$
- At least within sufficiently narrow centrality bin: $v_n/\varepsilon_n \sim \text{constant}$ $(n = 2, 3)$
- Relative fluctuations of $\varepsilon_n \longrightarrow$ relative fluctuations of v_n
- Probability distributions $P(\delta v_n) = P(\delta\varepsilon_n)$, $\delta v_n = (v_n - \langle v_n \rangle)/\langle v_n \rangle$

Flow fluctuations

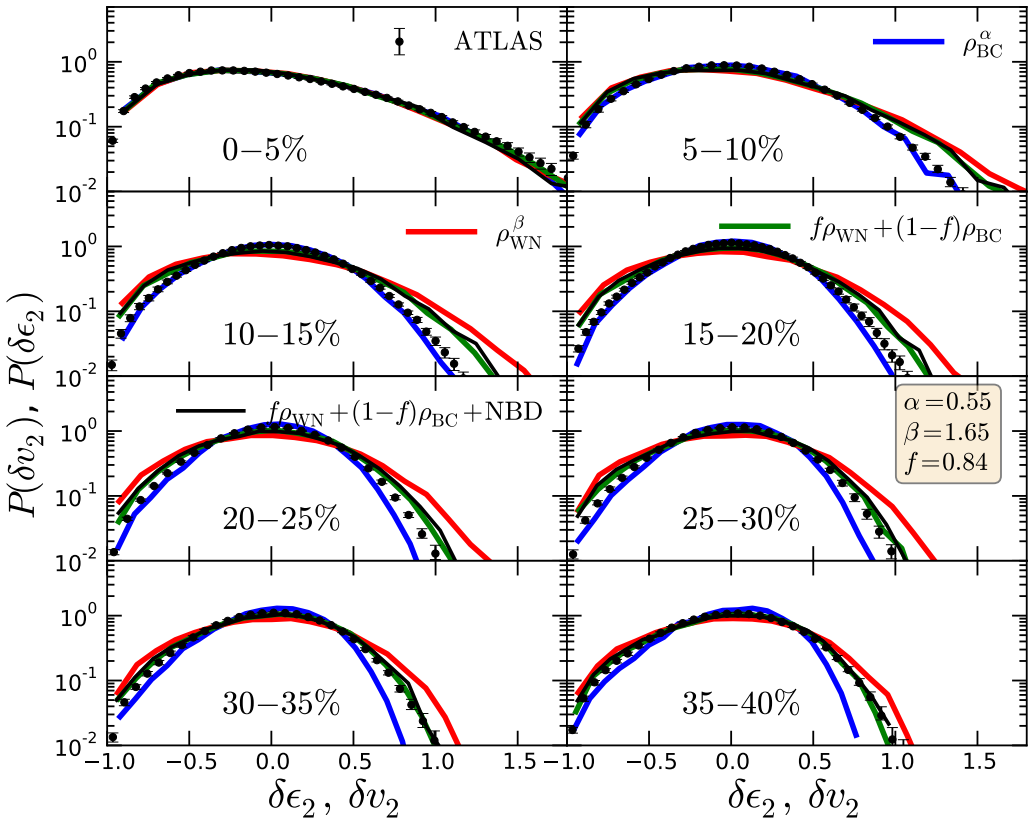
G. Aad *et al.* [ATLAS Collaboration], JHEP **1311**, 183 (2013)



- $P(v_2)$ compared to MC-Glauber and MC-KLN $P(\varepsilon_2)$
- MC-KLN: too narrow
- MC-Glauber: too wide

Variations of MC Glauber model

T. Renk and H. Niemi, arXiv:1401.2069 [nucl-th]



- $s \propto \rho^{\alpha}_{bc}$
- $s \propto \rho^{\beta}_{wn}$
- $s \propto f\,\rho_{bc} + (1-f)\,\rho_{wn}$

$$\rho_{wn/bc} = \sum_{i=1}^{N_{\rm wn,bc}} C_i e^{-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{2\sigma^2}}$$

r_i: positions of wounded nucleons or binary collisions from MC Glauber

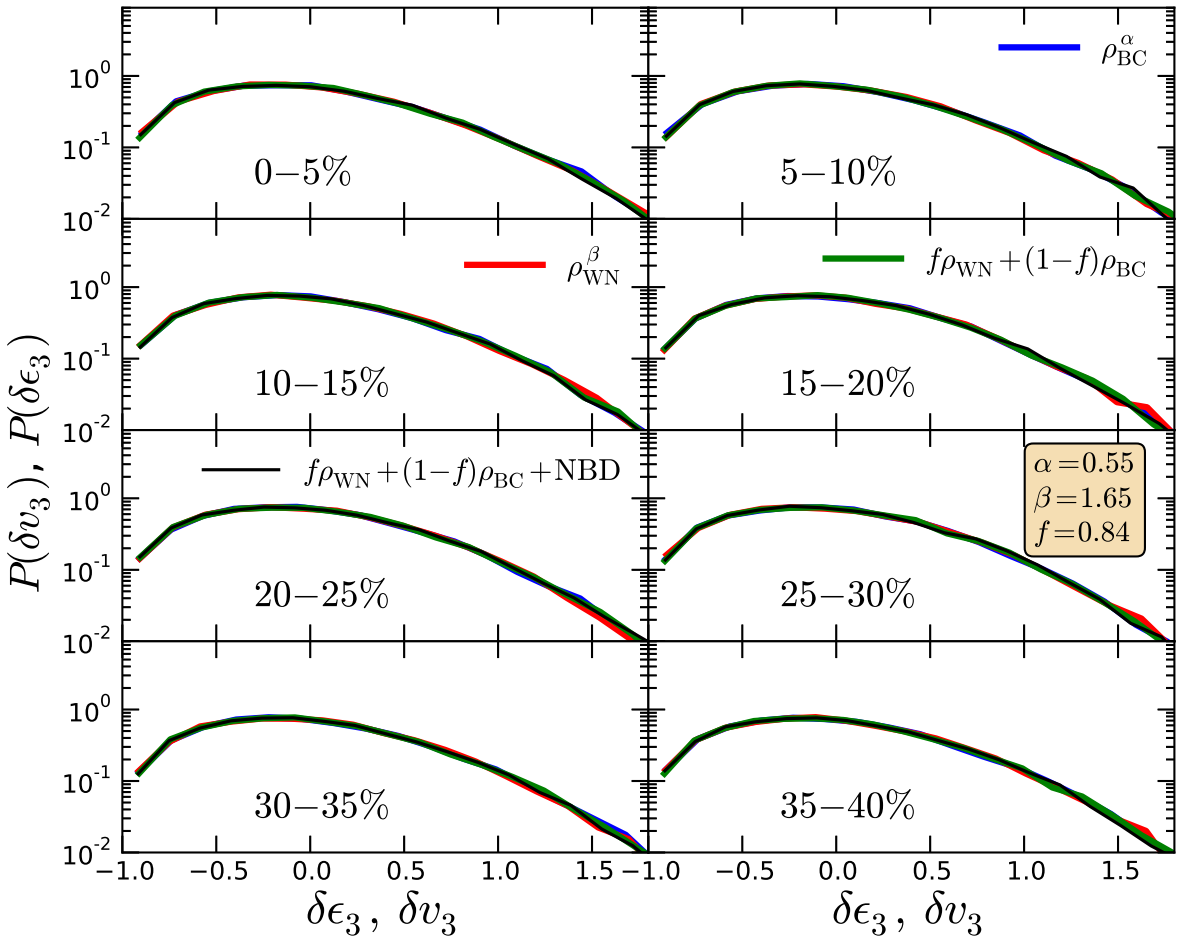
Fluctuations in C_i or σ do not matter:

P(δv_n) measures geometry fluctuations, not fluctuations in particle/entropy production (Talk by T. Renk)

v_3 fluctuations

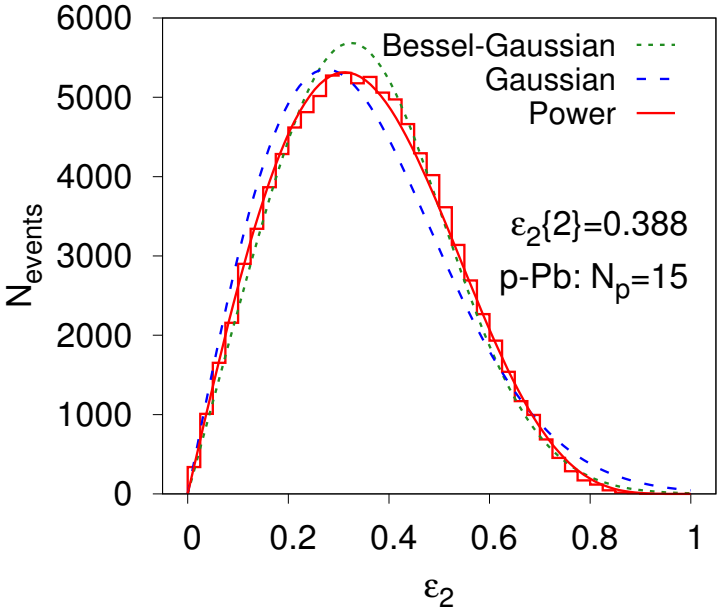
v_3 fluctuations identical for each case/centrality (v_3 is from random geometry fluctuations, not from underlying average nuclear overlap geometry)

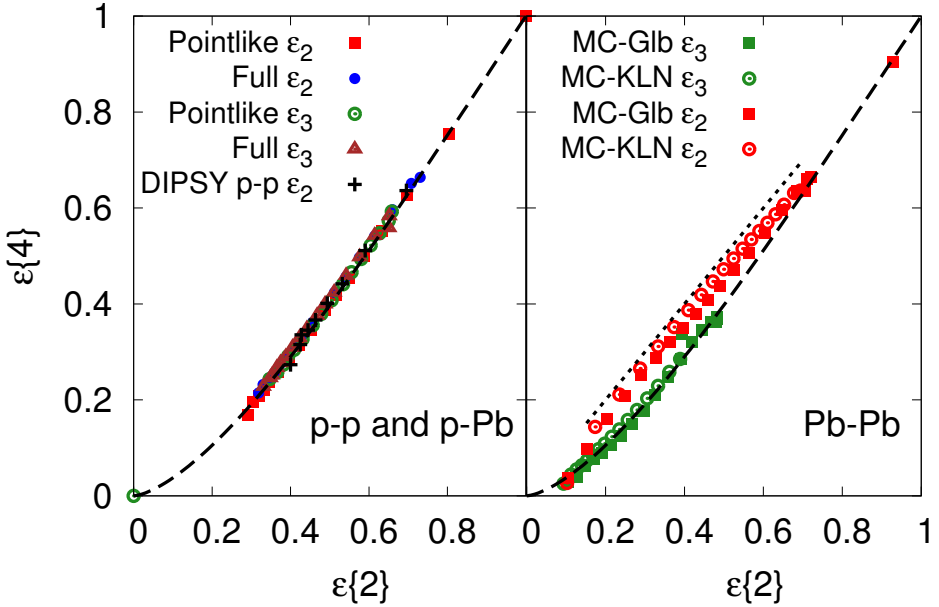
T. Renk and H. Niemi, arXiv:1401.2069 [nucl-th]



Universal fluctuation-driven eccentricities

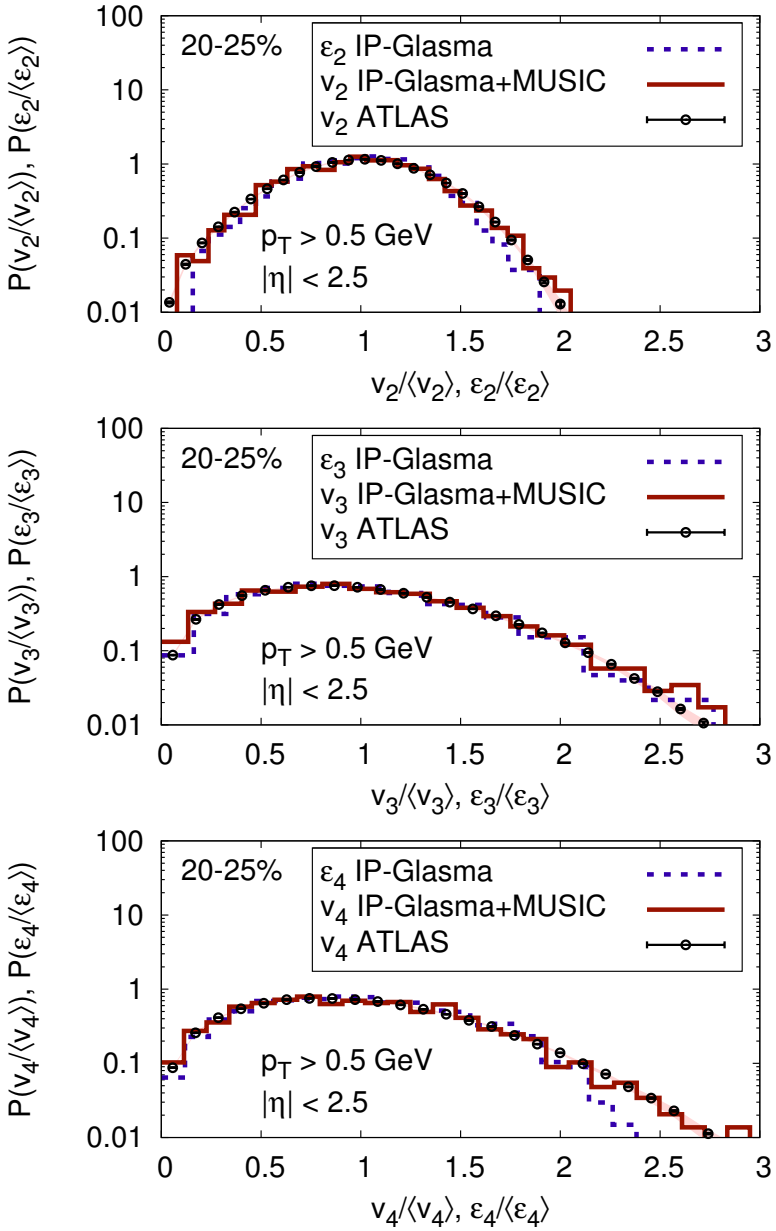
L. Yan and J. -Y. Ollitrault, Phys. Rev. Lett. **112**, 082301 (2014)
(talk by L. Yan)





- Universal fluctuation spectrum, $P(\varepsilon) = 2\alpha\varepsilon(1-\varepsilon^2)^{\alpha-1}$
- Assume linear response $v_n = C_n\varepsilon_n$
- $\longrightarrow$ predictions for $v_2\{2\}/v_2\{4\}$, $v_2\{4\}/v_2\{6\}$, $v_2\{6\}/v_2\{8\}$
- Confirmed by CMS: talk by Quan Wang

Gale, Jeon, Schenke, Tribedy and Venugopalan, PRL **110**, 012302 (2013)

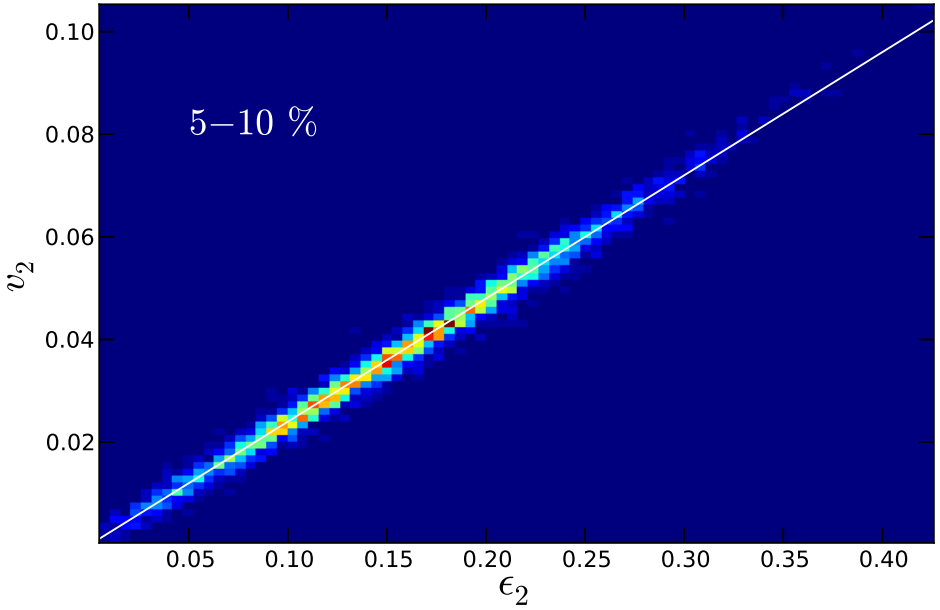


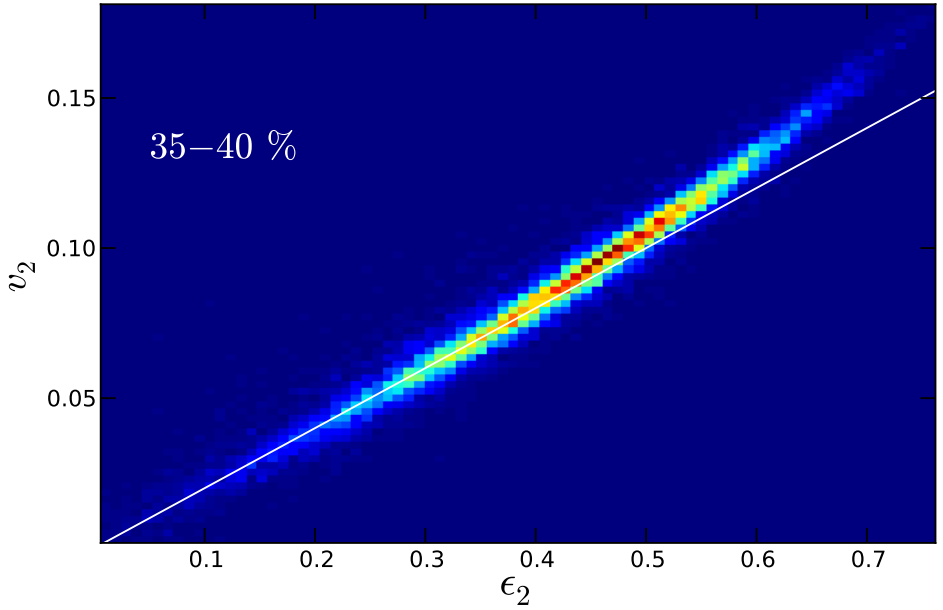
IP-Glasma initial conditions

- Classical Yang-Mills pre-thermal evolution
- Viscous fluid dynamics (MUSIC)
- Good agreement with the data over several centrality classes (talk by B. Schenke)

non-linear v_2, ε_2 correlation

Paatelainen, Eskola, Niemi and Tuominen, Phys. Lett. B **731**, 126 (2014)
+ fluctuations (preliminary results) poster by R. Paatelainen

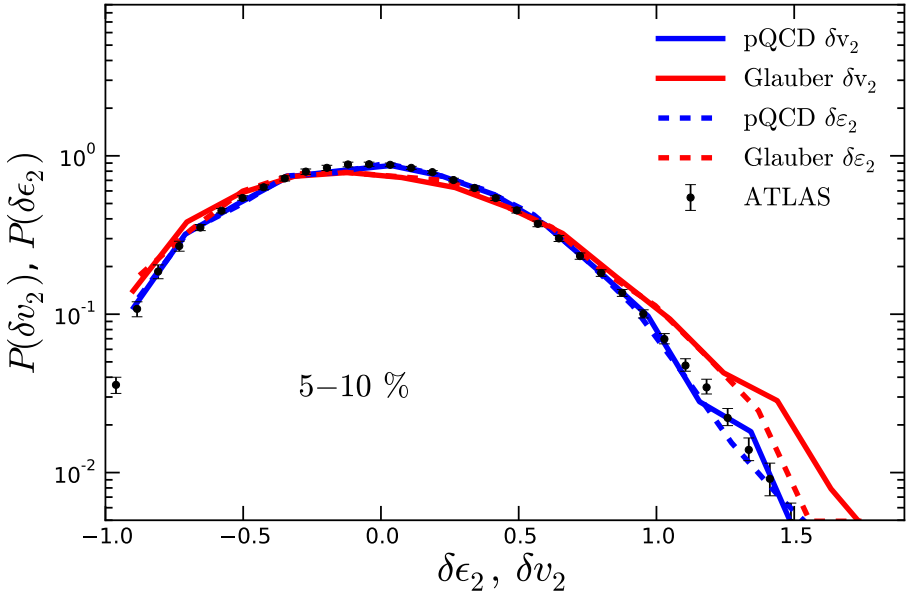


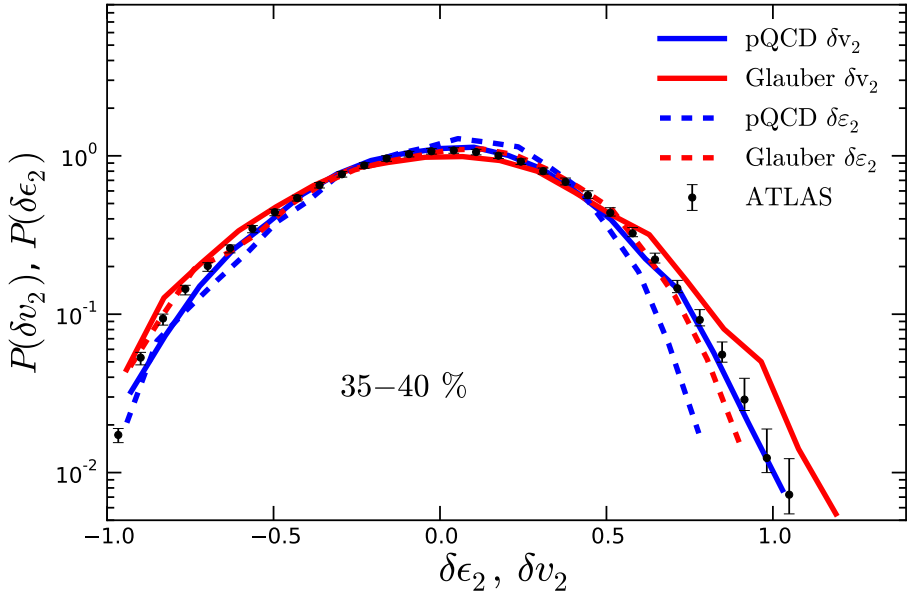


- Near-central collisions (small ε_2): $v_2 \propto \varepsilon_2$
- Peripheral collisions (large ε_2): v_2 still strongly correlated to ε_2 (but not linearly)

effect on distributions

Paatelainen, Eskola, Niemi and Tuominen, Phys. Lett. B **731**, 126 (2014)
+ fluctuations (preliminary results) poster by R. Paatelainen

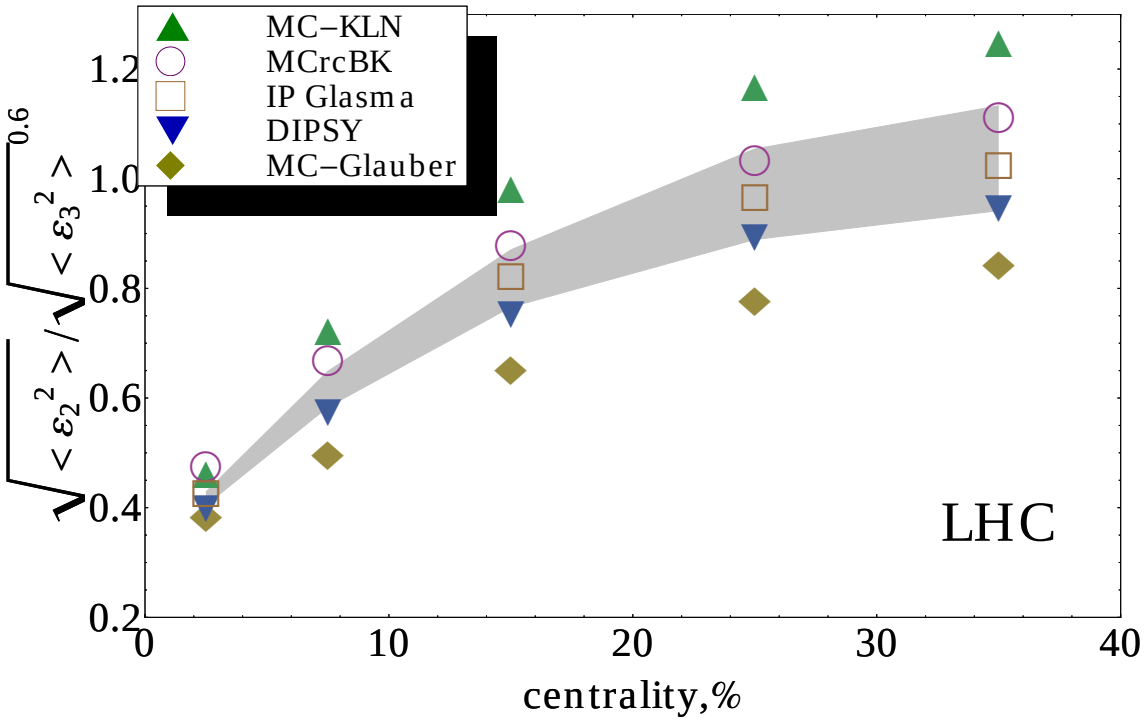




- Near-central collisions: follows from eccentricity
- Peripheral collisions: **wider distributions after hydro**
- Same observation with IP-Glasma IC (talk by B. Schenke)
- pQCD + saturation IC: works (blue)
- MC Glauber $N_{\rm bin} + N_{\rm wn}$: too wide (red)

Initial state constraints from $\varepsilon_2/\varepsilon_3$ ratio

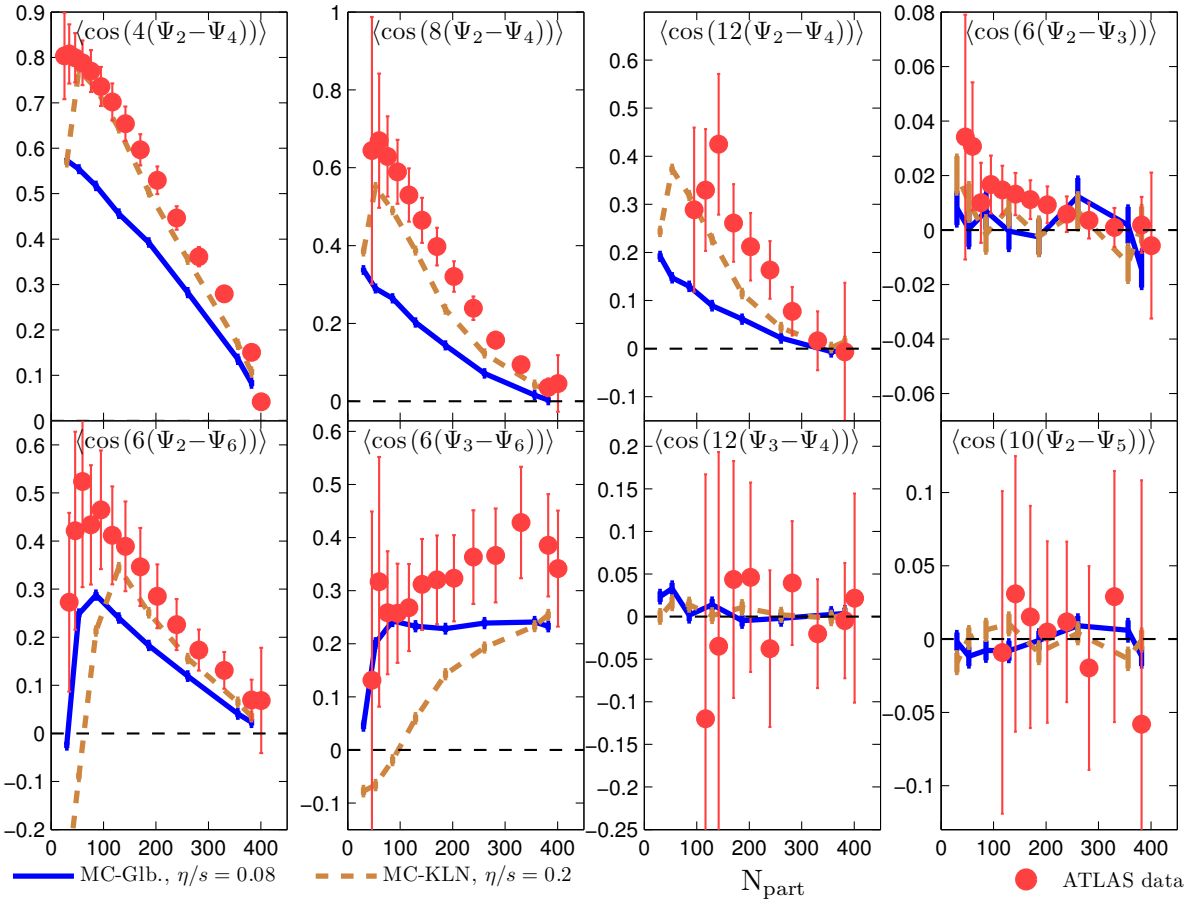
E. Retinskaya, M. Luzum and J. -Y. Ollitrault, arXiv:1401.3241 [nucl-th]



- Estimate allowed range of $\varepsilon_2/\varepsilon_3$ ratio
- Constraints from v_2/v_3 data + fluid dynamics

Event-plane correlations $\langle\cos(N(\Psi_n - \Psi_m))\rangle$

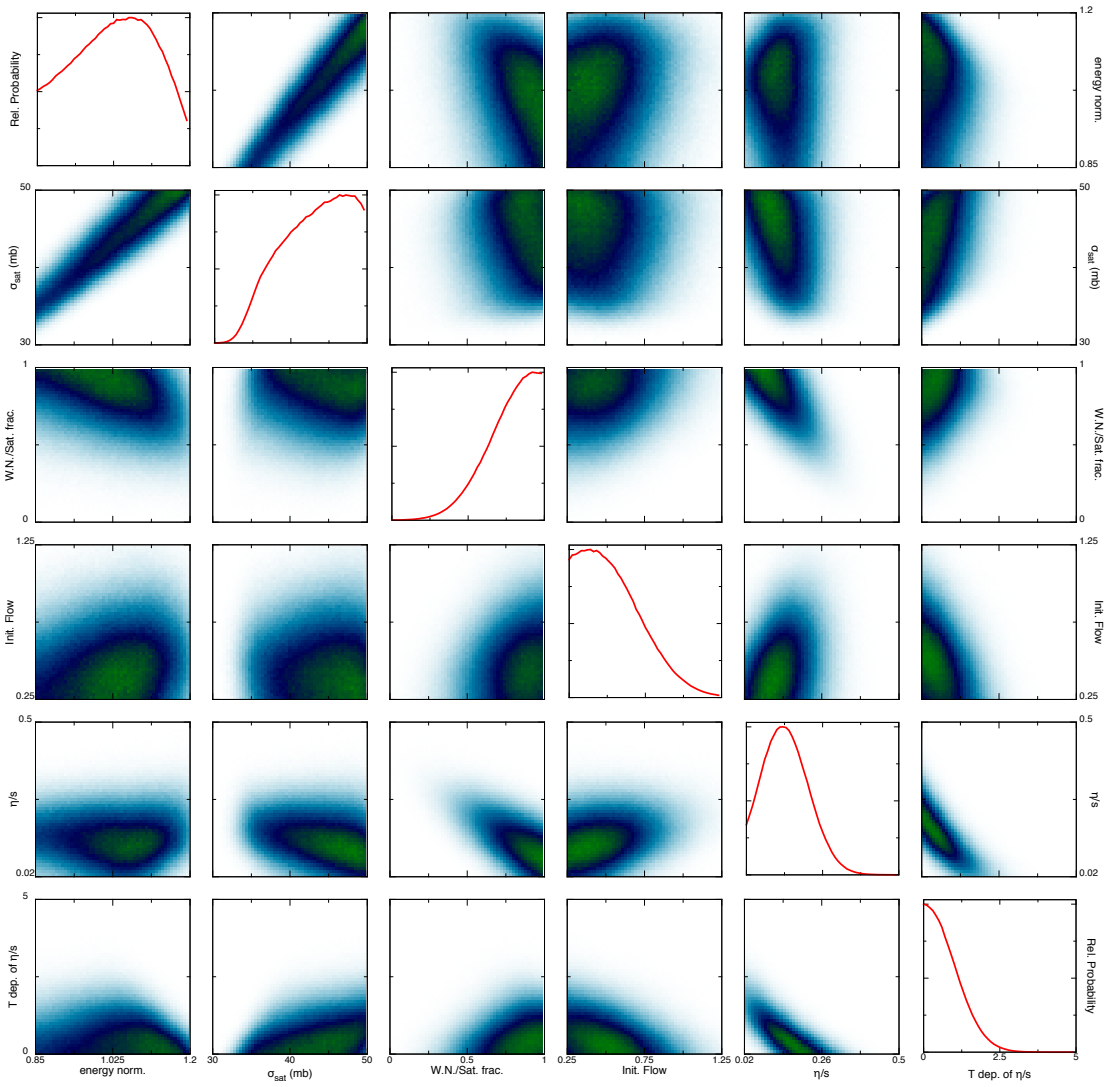
Z. Qiu and U. Heinz, Phys. Lett. B **717**, 261 (2012)



- Constraints to η/s and initial state.
- MC-Glauber ($\eta/s = 0.08$) vs MC-KLN ($\eta/s = 0.20$): clearly different correlators
- D. Teaney and L. Yan, arXiv:1312.3689 [nucl-th] Behaviour of correlators: non-linear response to initial state geometry v_4 generated by ε_4 and $(\varepsilon_2)^2$

M. Luzum and J. -Y. Ollitrault, Phys. Rev. C **87**, no. 4, 044907 (2013): $\langle\cos(N(\Psi_n - \Psi_m))\rangle$ from the event-plane method strongly dependent on the event-plane resolution

Global fits and emulators: J. Novak, K. Novak, S. Pratt, J. Vredevoogd, C. Coleman-Smith and R. Wolpert, arXiv:1303.5769 [nucl-th]



- Large number of hydro runs randomly in the parameter space $\longrightarrow$ avoid **huge** number of runs
- interpolate $\longrightarrow$ global fits
- Error estimates for the parameters (e.g. η/s) (diagonals)
- Identify correlators between the parameters (off diagonals)
- Here: example in 6–dimensional parameter space

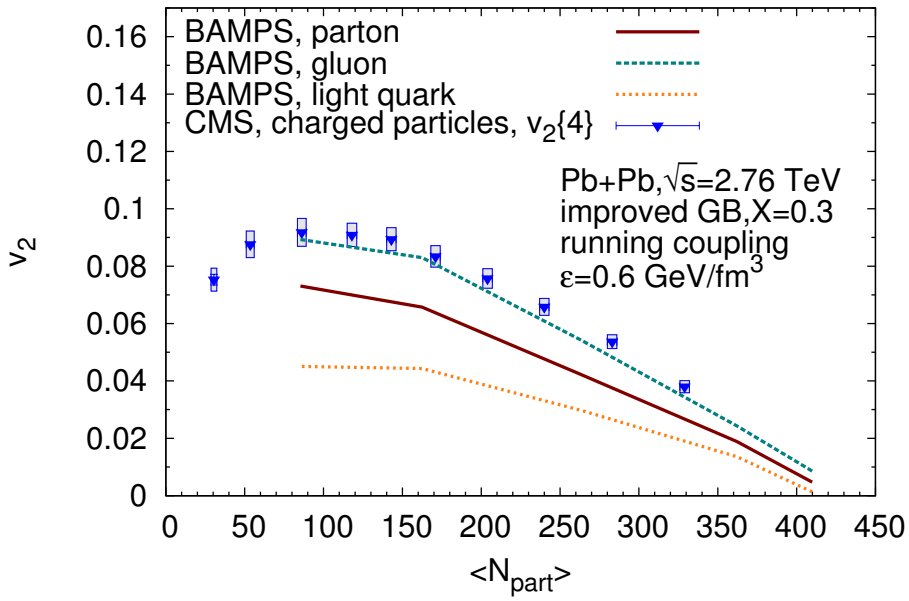
Collective flow without fluid dynamics

Uphoff, Fochler, Senzel, Wesp, Xu and Greiner, arXiv:1401.1364 [hep-ph]

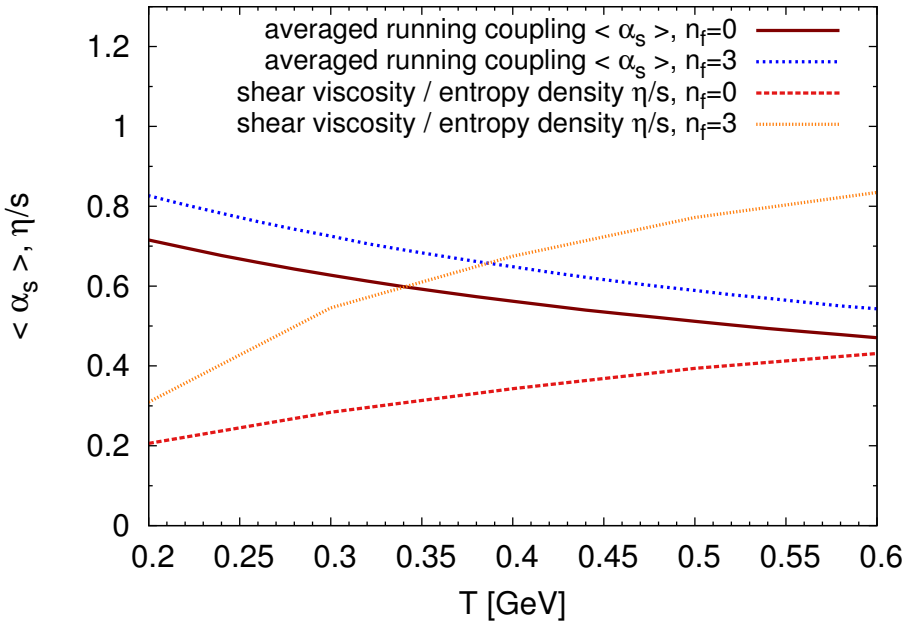
BAMPS:

Boltzmann equation with pQCD $2 \leftrightarrow 2$ and $2 \leftrightarrow 3$ cross-sections
Talk by F. Senzel

Elliptic flow:



$\eta/s(T)$:



More interesting talks not covered here:

- Including thermal fluctuations to fluid dynamics (noise):
  - T. Hirano
  - J. Kapusta
- Anisotropic hydrodynamics: change the expansion basis
  - U. Heinz
- Mode-by-mode fluid dynamics: perturbative approach to fluctuations
  - S. Flörchinger
- New hydro codes
  - C. Nonaka
  - V. Rolando (ECHO-QGP)
- η/s from acoustic scaling
  - R. Lacey
- And many more ...

Summary

- Impressive agreement with several low-p_T observables
- $\eta/s = 0.08 - 0.24$ (assuming constant η/s)
- $\eta/s(T)$ still not well constrained by v_n data
- Fluid dynamical behaviour: all systems described by same $\eta/s(T, \{\mu_i\})$ (not yet clear)
- More constraints available: Fluctuation spectra, correlations
- Call for global analysis. Practical way: emulators