Latest results from the EbyE NLO EKRT model

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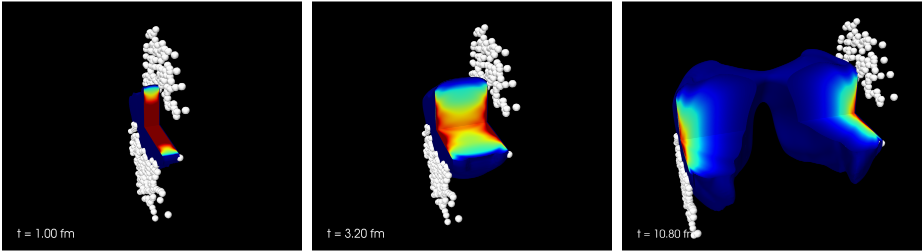
based on
HN, K. J. Eskola and R. Paatelainen, PRC **93**, 024907 (2016), arXiv:1505.02677
HN, K. J. Eskola, R. Paatelainen and K. Tuominen, PRC **93**, 014912 (2016), arXiv:1511.04296

with
Kari J. Eskola, University of Jyväskylä, Finland
Risto Paatelainen, University of Jyväskylä, Finland
Kimmo Tuominen, University of Helsinki, Finland

Search for QCD matter properties



Extract limits for η/s from experimental data

- Initial state: pQCD + saturation (EKRT)
- Fluid dynamical evolution
- Cooper-Frye freeze-out

Initial energy density from the EKRT model

- NLO pQCD calculation of transverse energy E_T
- EPS09 nuclear parton distributions (Eskola et. al. JHEP **0904**, 065 (2009)) with impact parameter dependence (Helenius et. al. JHEP **1207** 073 (2012))

$$d\sigma^{AB\to kl\cdots} \sim f_{i/A}(x_1,Q^2)\otimes f_{j/B}(x_2,Q^2)\otimes\hat{\sigma}$$

Essential quantity $\sigma\langle E_T\rangle$ with p_T cut-off p_0

$$\sigma\langle E_T\rangle(p_0,\Delta y,\beta)=\int_0^{\sqrt{s}} dE_T E_T \frac{d\sigma}{dE_T}\theta(y_i\in\Delta y, p_T>p_0, E_T>\beta p_0)$$

- $2\to 2$ processes $p_{T1}+p_{T2}>2p_0$
- $2\to 3$ processes $p_{T1}+p_{T2}+p_{T3}>2p_0$
- In $2\to 3$ processes can still require for the total E_T in the rapidity window Δy: $E_T>\beta p_0$, with $\beta\in[0,1]$

$$\frac{dE_T}{d^2\mathbf{s}}=T_A(\mathbf{s}-\frac{\mathbf{b}}{2})T_A(\mathbf{s}+\frac{\mathbf{b}}{2})\sigma\langle E_T\rangle_{p_0,\Delta y}$$

$$e=\frac{dE_T}{\tau_0\Delta y d^2\mathbf{s}}=T_A(\mathbf{s}-\frac{\mathbf{b}}{2})T_A(\mathbf{s}+\frac{\mathbf{b}}{2})\frac{\sigma\langle E_T\rangle_{p_0,\Delta y}}{\tau_0\Delta y}$$

Local saturation condition

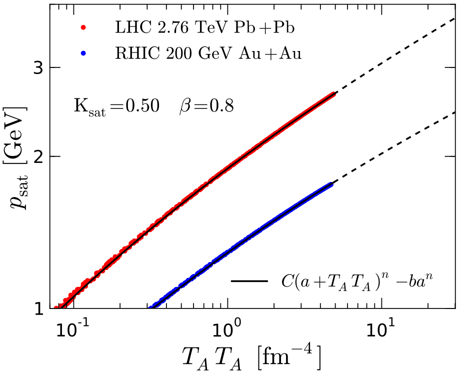
- Lower cut-off p_0 determined from a local saturation condition

$$\frac{dE_T}{d^2\mathbf{s}}(p_0, \sqrt{s}, \mathbf{s}, \mathbf{b}, \Delta y) = \frac{K_{\mathrm{sat}}}{\pi} p_0^3 \Delta y$$

or equivalently

$$T_A(\mathbf{s} - \frac{\mathbf{b}}{2}) T_A(\mathbf{s} + \frac{\mathbf{b}}{2}) \sigma \langle E_T \rangle_{p_0, \Delta y} = \frac{K_{\mathrm{sat}}}{\pi} p_0^3 \Delta y$$

- In principle $\sigma \langle E_T \rangle_{p_0, \Delta y}$ depends also on the transverse coordinate **s** through the **s**-dependent nuclear parton distributions, but it turns out that in this particular application the dependence is weak.
- Parametrize the solution of the saturation condition $p_0 = p_{\mathrm{sat}}$ to be a function of $T_A T_A$ alone.



- The full calculation can be summarized by a simple parametrization
- Event-by-event fluctuations through fluctuations in $T_A T_A$.

Once we know the solution of the saturation equation we can write energy density at time $\tau_0 = 1/p_{\rm sat}$

$$e(\mathbf{s}, \tau_0 = 1/p_{\rm sat}) = K_{\rm sat}\, p_{\rm sat}(\mathbf{s})^4/\pi$$

- Two parameters: $K_{\rm sat}$ in the saturation condition, and β in the definition of transverse energy in the measurement function.

Israel-Stewart hydrodynamics

Model the space-time evolution of A+A collisions by relativistic fluid dynamics:

Neglect net-baryon number, bulk viscosity & heat flow

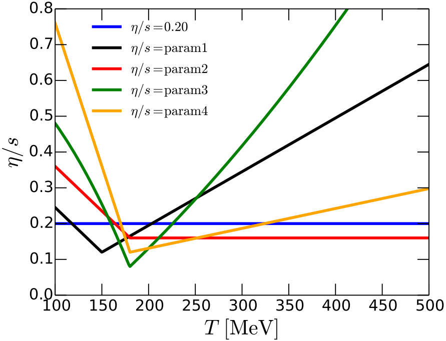
$$\partial_\mu T^{\mu\nu} = 0$$

$$D\pi^{\langle\mu\nu\rangle} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}\right) - \frac{4}{3}\pi^{\mu\nu}\left(\nabla_\lambda u^\lambda\right) - \frac{10}{7}\pi_\lambda{}^{\langle\mu}\sigma^{\nu\rangle\lambda}$$

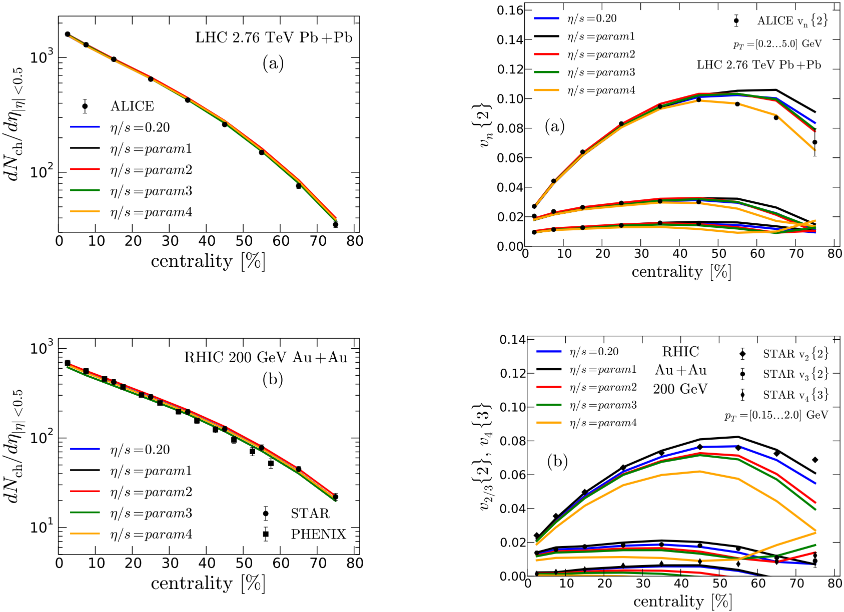
Longitudinal expansion is treated using boost invariance: $\frac{\partial p}{\partial \eta_s} = 0$, $v_z = \frac{z}{t}$

- Equation of state: Petreczky/Huovinen: NPA **837**, 26-53 (2010)
- Chemical freeze-out $T = 175$ MeV, kinetic $T = 100$ MeV
- $\delta f \propto f_{eq} p^\mu p^\nu \pi_{\mu\nu}$

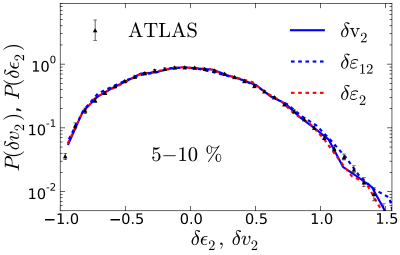
Temperature dependent η/s

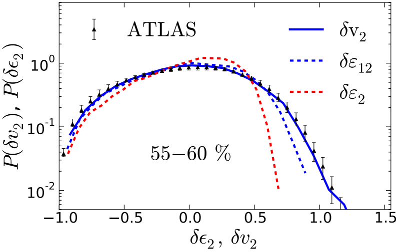


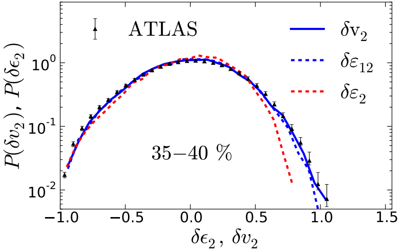
- tuned to reproduce $v_2\{2\}$ at LHC mid-peripheral collisions.
- relaxation time $\tau_\pi(T) = \frac{5\eta}{\varepsilon + p}$.


LHC 2.76 TeV Pb+Pb
(a)
ALICE
η/s=0.20
η/s=param1
η/s=param2
η/s=param3
η/s=param4
dN_ch/dη_|η|<0.5
centrality [%]
ALICE v_n{2}
p_T=[0.2...5.0] GeV
LHC 2.76 TeV Pb+Pb
v_n{2}
RHIC 200 GeV Au+Au
(b)
STAR
PHENIX
RHIC
Au+Au
200 GeV
STAR v_2{2}
STAR v_3{2}
STAR v_4{3}
p_T=[0.15...2.0] GeV
v_2/3{2}, v_4{3}

Flow fluctuations





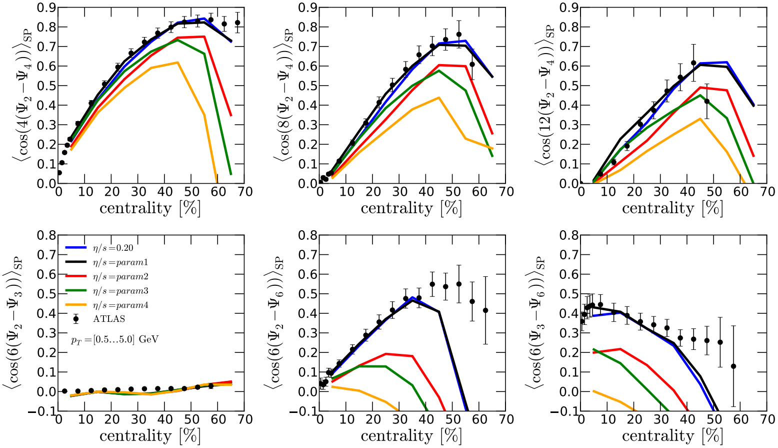


- Relative flow fluctuations insensitive to shear viscosity η/s
- $\longrightarrow$ direct constrain for the initial conditions

Event-plane correlations

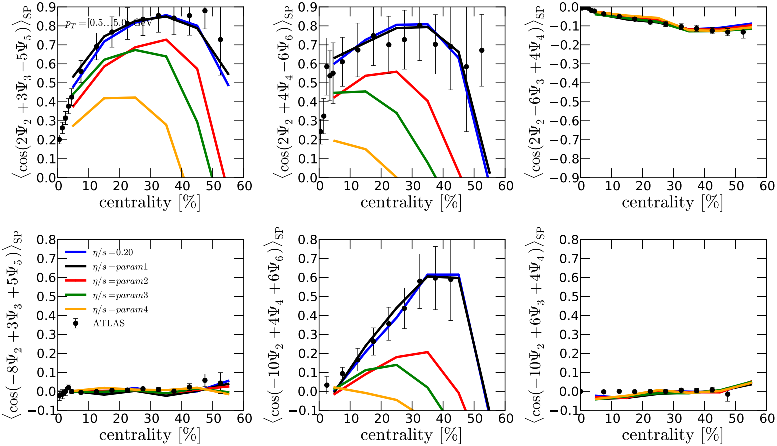
$$\langle \cos(k_1\Psi_1 + \cdots + nk_n\Psi_n)\rangle_{\rm SP} \equiv \frac{\langle v_1^{|k_1|}\cdots v_n^{|k_n|}\cos(k_1\Psi_1 + \cdots + nk_n\Psi_n)\rangle_{ev}}{\sqrt{\langle v_1^{2|k_1|}\rangle_{ev}\cdots\langle v_n^{2|k_n|}\rangle_{ev}}},$$

Event-plane correlations: 2 angles

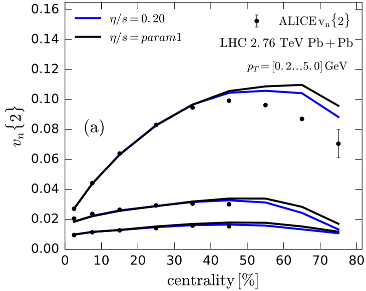


- Already from the LHC data more constraints to $\eta/s(T)$.
- Small hadronic viscosity needed to reproduce the data.

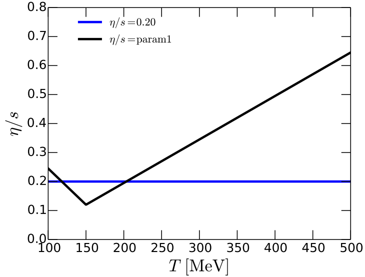
Event-plane correlations: 3 angles



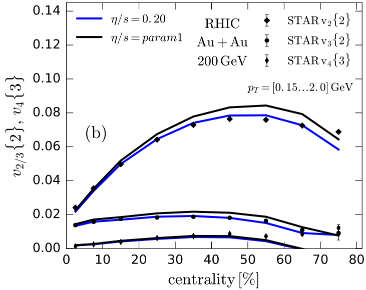
- Equally well described by the same parametrizations that describe 2-angle correlations.



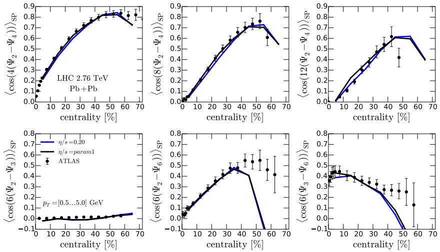
$\eta/s = 0.20$
$\eta/s = param1$
ALICE $v_n\{2\}$
LHC 2.76 TeV Pb+Pb
$p_T = [0.2 \ldots 5.0]$ GeV
(a)
$v_n\{2\}$
centrality [%]
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
10
20
30
40
50
60
70
80



$\eta/s = 0.20$
$\eta/s = $param1
η/s
T [MeV]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
100
150
200
250
300
350
400
450
500

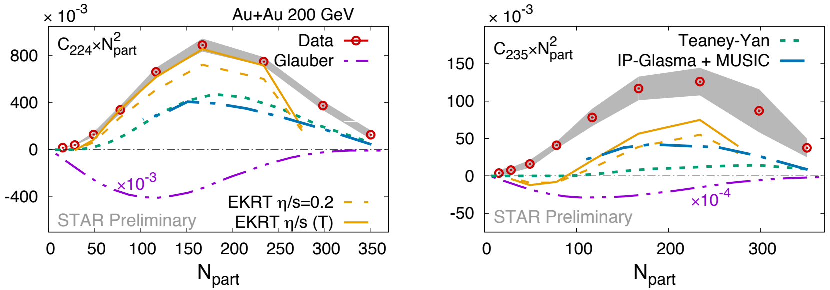


$\eta/s = 0.20$
$\eta/s = param1$
RHIC
Au+Au
200 GeV
STAR $v_2\{2\}$
STAR $v_3\{2\}$
STAR $v_4\{3\}$
$p_T = [0.15 \ldots 2.0]$ GeV
(b)
$v_{2/3}\{2\}$, $v_4\{3\}$
centrality [%]
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
10
20
30
40
50
60
70
80



$\langle\cos(4(\Psi_2-\Psi_4))\rangle_{SP}$
$\langle\cos(8(\Psi_2-\Psi_4))\rangle_{SP}$
$\langle\cos(12(\Psi_2-\Psi_4))\rangle_{SP}$
$\langle\cos(6(\Psi_2-\Psi_3))\rangle_{SP}$
$\langle\cos(6(\Psi_2-\Psi_6))\rangle_{SP}$
$\langle\cos(6(\Psi_3-\Psi_6))\rangle_{SP}$
LHC 2.76 TeV
Pb+Pb
$\eta/s = 0.20$
$\eta/s = param1$
ATLAS
$p_T = [0.5 \ldots 5.0]$ GeV
centrality [%]

Event-plane correlations at RHIC:
P. Tribedy [STAR Collaboration], arXiv:1612.05593 [nucl-ex].



$$C_{224} = \langle v_2^2 v_4 \cos(4(\Psi_2 + \Psi_4)) \rangle$$

$$C_{235} = \langle v_2 v_3 v_5 \cos(2\Psi_2 + 3\Psi_3 - 5\Psi_5) \rangle$$

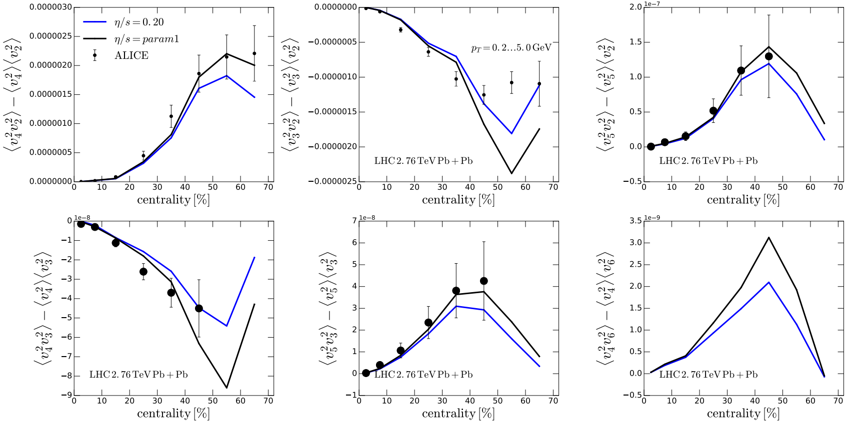
- Not normalized
- (v_5, Ψ_5) large δf corrections at RHIC (too large?)

Symmetric cumulants

$$
\begin{aligned}
SC(n,m) &= \langle \cos(m\phi_1 + n\phi_2 - m\phi_3 - n\phi_4) \rangle \\
&\quad - \langle \cos(m(\phi_1 - \phi_2)) \rangle \langle \cos(n(\phi_1 - \phi_2)) \rangle \\
&= \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle
\end{aligned}
$$

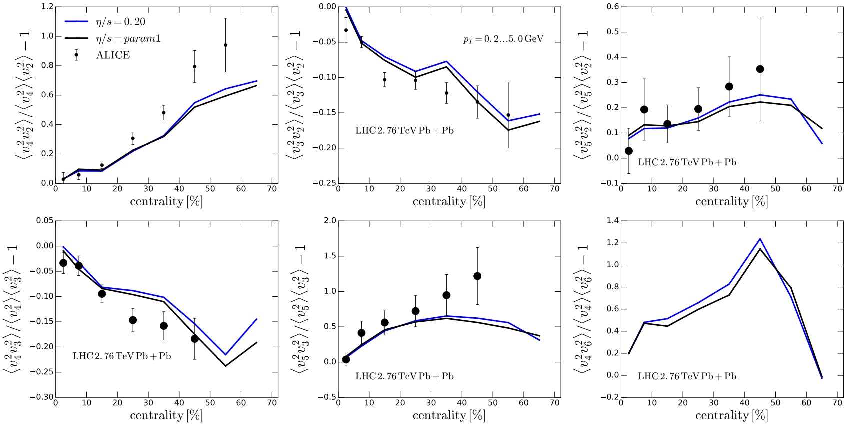
$$
NSC(n,m) = \frac{SC(n,m)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}
$$

Symmetric cumulants $SC(n, m)$



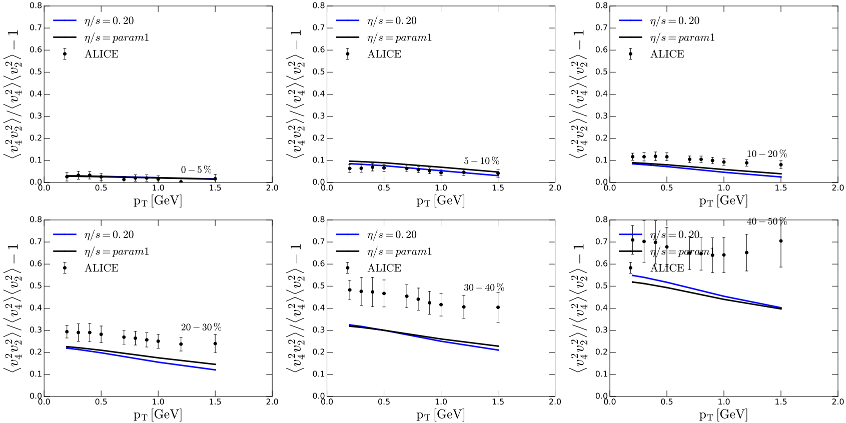
- Correlation between the magnitudes of v_n (independent of the event-plane angles Ψ_n)
- $SC(n, m)$ also very sensitive to the absolute values of v_n's

Normalized symmetric cumulants $NSC(n, m)$



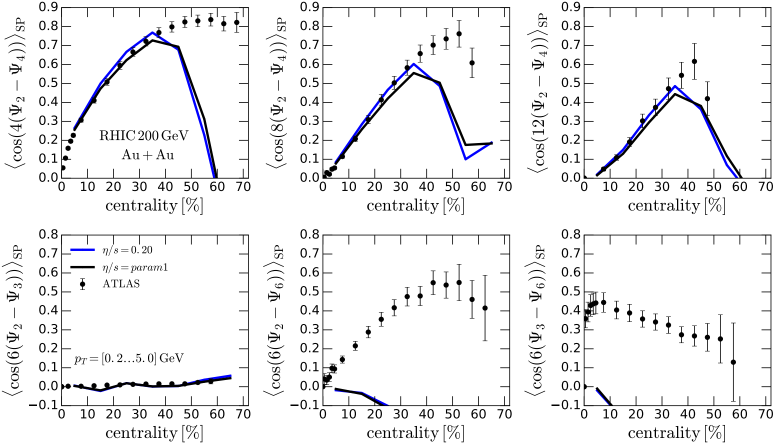
- Correlation between the magnitudes of v_n (independent of the event-plane angles Ψ_n)
- measures the correlation, do not directly depend on the absolute values of v_n.

Normalized symmetric cumulants: p_T dependence



- Fluid dynamics gives the correct p_T-dependence.

Event-plane correlations: 2 angles at RHIC

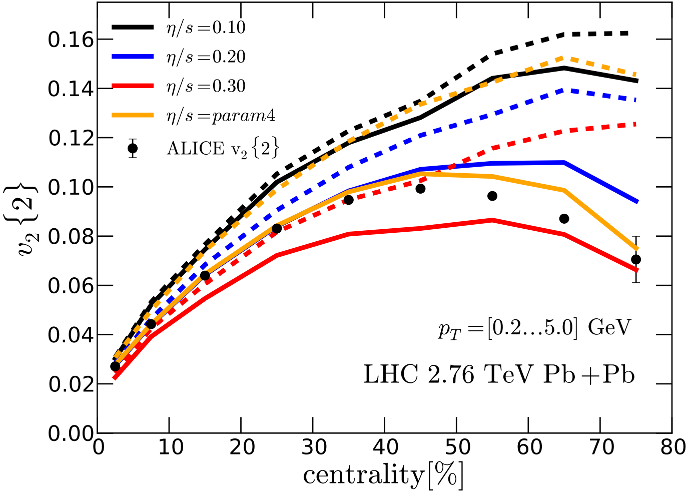


- Mostly similar to those at the LHC
- peripheral collisions and correlators involving v_6: δf decorrelates everything.

Summary

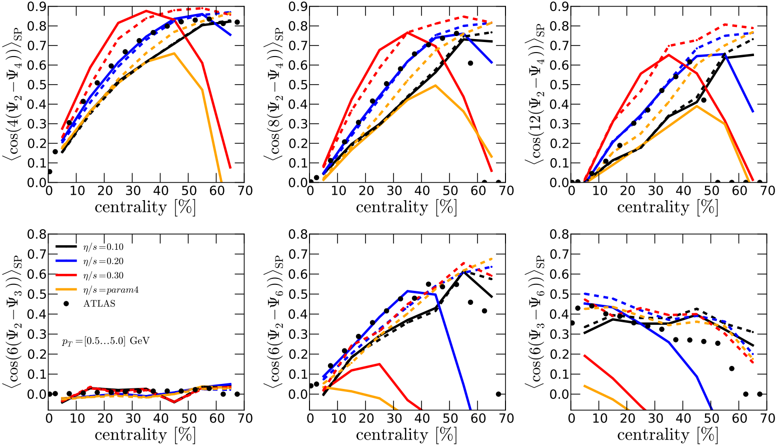
- Presented a new EbyE framework for NLO pQCD + saturation & viscous hydro
- The computed $\sqrt{s}$ and centrality dependence of $dN_{\rm ch}/d\eta$ agree very well with LHC and RHIC data: predictive power!
- Most direct constraints for the IS come from the v_2 fluctuations and the ratio v_2/v_3 both are now very well reproduced!
- LHC v_n's alone do not stringently constrain the T-dependence of η/s
- Further constraints for $\eta/s(T)$ from the v_ns at RHIC and the EP correlations at the LHC
- $\eta/s = 0.2$ (blue) and param1 with minimum at $T = 150$ MeV (black) and small hadronic η/s work best in our framework

δf in v_2



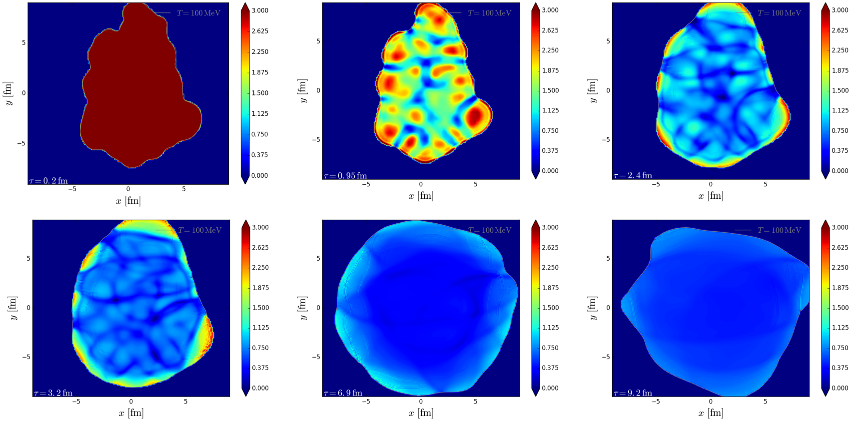
- δf

δf in event-plane correlations

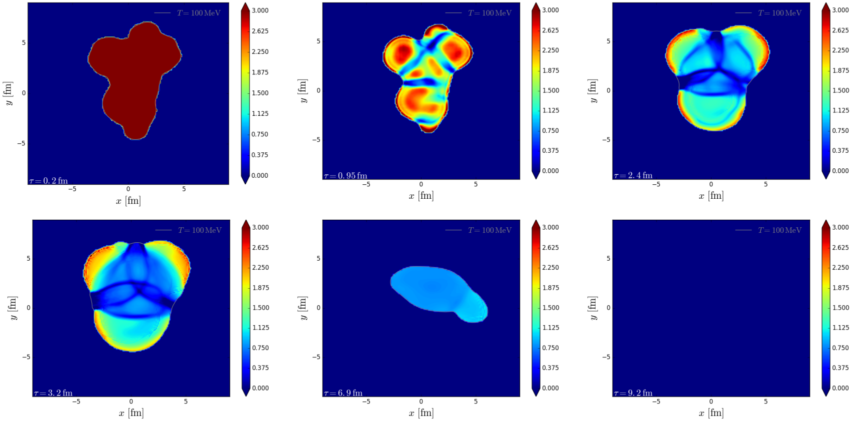


- δf

Spacetime evolution of Knudsen number $\tau_\pi \theta$: centrality $\sim$ 20-30 %



Spacetime evolution of Knudsen number $\tau_\pi \theta$: centrality $\sim$ 50-60 %



spacetime averaged Knudsen number($\tau_\pi \theta$) and average inverse Reynolds number (π/p) at the freeze-out surface