From fluctuating minijet initial state to global observables in AA collisions at LHC and RHIC

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Frankfurt – 11.2.2015

with
R. Paatelainen and K. J. Eskola


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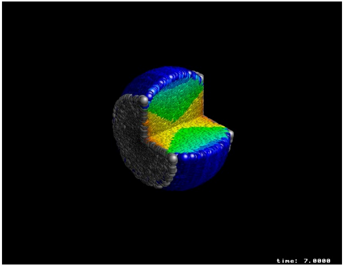
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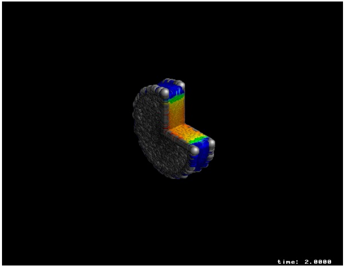
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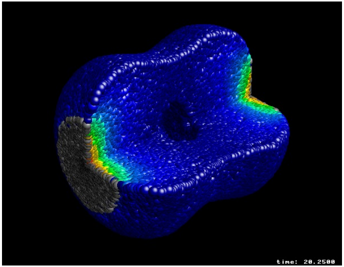
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Initial energy density from pQCD

- 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))

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

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

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

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

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

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

Saturation condition (average) for central AA collisions

Original EKRT saturation condition
(K. J. Eskola, K. Kajantie, P. V. Ruuskanen and K. Tuominen, Nucl. Phys. B **570**, 379 (2000).)

$$N_{AA}(p_0, \sqrt{s_{NN}}, \Delta Y = 1, \mathbf{b} = \mathbf{0}) \times \frac{\pi}{p_0^2} = K_{\rm sat}\pi R_A^2,$$

Average saturation condition in terms of transverse energy (R. Paatelainen, K. J. Eskola, H. Holopainen and K. Tuominen, Phys. Rev. C 87, 044904 (2013))

$$E_T^{AA}(p_0, \sqrt{s_{NN}}, \Delta Y, \mathbf{0}) = K_{\rm sat} R_A^2 p_0^3 \Delta Y,$$

Local saturation condition

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

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

or equivalently

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

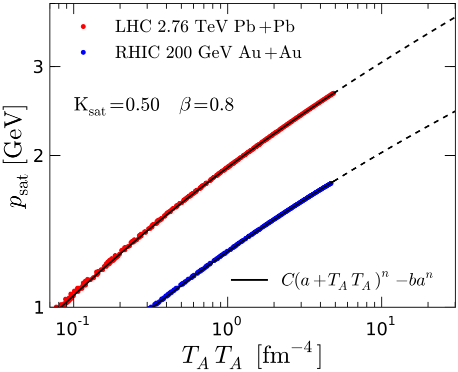
- In principle $\sigma \left\langle E_T \right\rangle_{p_0, \Delta y}$ depends also on the transverse coordinate $\mathbf{s}$ through the $\mathbf{s}$-dependent nuclear parton distributions, but it turns out that in this particular application the dependence is weak.
- Parametrize the solution of the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

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.

p_{sat}



- The full calculation can be summarized by a simple parametrization
- This also shows that the assumption $p_{\rm sat} = f(T_A T_A)$ works

evolution to same τ

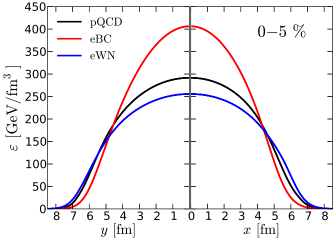
Naively $e = K_{\rm sat} p_{\rm sat}^4/\pi$, **but all at different times** $\tau_0 = 1/p_{\rm sat}$**!**

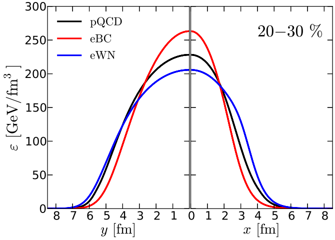
- For fluid dynamics we need $e(x, y)$ at fixed proper time τ_0.
- Need to evolve all the energy densities to a same time.
- Latest time given by $\tau_{max} = 1/p_{min}$, where $p_{min} \sim 1$ GeV, the smallest scale we think we can still trust the pQCD calculation

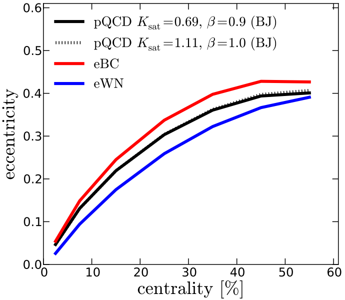
- Here: Bjorken scaling ($\sim$ conserves entropy)

  $e(\tau_{max}) = e(\tau = 1/p_{sat}) \left(\frac{\tau}{\tau_{max}}\right)^{4/3}$

Energy density profiles







- Initial energy density and eccentricities compared to eBC and eWN profiles with the same initial entropy $dS/d\eta$.

$$\varepsilon_{m,n} e^{in\Psi_{m,n}} = -\{r^m e^{in\phi}\}/\{r^m\},$$

$$\{\cdots\} = \int dxdy\, \epsilon(x,y,\tau_0)(\cdots)$$

Ebye fluctuations

How to generalize the nuclear thickness function to ebye case:

- Nucleon (gluonic) profile from HERA $\gamma^* p \to J/\Psi + p$ data

$$T_n(r) = \frac{1}{2\pi\sigma^2} e^{-\frac{r^2}{2\sigma^2}},$$

with $\sigma = 0.43$ fm.

- Sample nucleon positions from the Wood-Saxon profile.

$$T_A(\mathbf{r}) = \sum_{i=1}^{A} T_n(|\mathbf{r} - \mathbf{r}_i|),$$

$$\longrightarrow T_A T_A \longrightarrow p_{\rm sat} \longrightarrow e$$

Israel-Stewart hydrodynamics

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

Neglect net-baryon number, bulk viscosity & heat flow

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

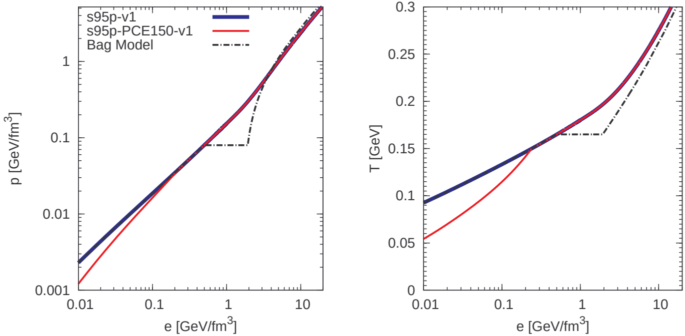
$$D\pi^{\langle\mu\nu\rangle} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}\right) - \frac{4}{3}\pi^{\mu\nu}\left(\nabla_\lambda u^\lambda\right) - \frac{10}{7}\pi_\lambda{}^{\langle\mu}\sigma^{\nu\rangle\lambda}$$

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

To solve this set of equations we need at $\tau = \tau_0$

- Equation of state $p = p(e)$ and $T = T(e)$
- Initial condition $T^{\mu\nu}(\tau_0, x, y)$
- Shear viscous coefficient $\eta(T)$ and relaxation time $\tau_\pi(T)$.

Equation of State



- Lattice parametrization by Petreczky/Huovinen: Nucl. Phys. **A837**, 26-53 (2010), [arXiv:0912.2541 [hep-ph]].
- Chemical equilibrium (s95p-v1)
- **(partial) chemical freeze-out at** $T_{\rm chem} = 175$ **MeV (s95p-PCE150-v1)**
- for comparison bag-model EoS
- Hadron Resonance Gas (HRG) includes all hadronic states up to $m \sim 2$ GeV

Freeze-out

Converting fluid to particles

$$e,\ u^\mu,\ \pi^{\mu\nu} \longrightarrow E\frac{dN}{d^3\mathbf{p}}$$

- Standard Cooper-Frye freeze-out for particle i

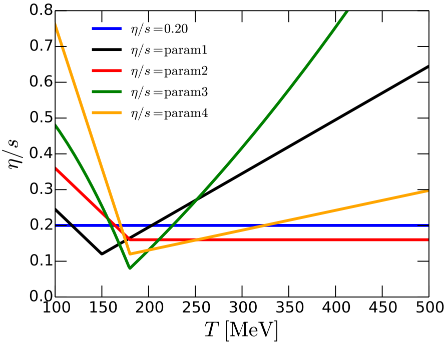
$$E\frac{dN}{d^3\mathbf{p}} = \frac{g_i}{(2\pi)^3}\int d\sigma^\mu p_\mu f_i(\mathbf{p},x),$$

where

$$f_i(\mathbf{p},x) = f_{i,\mathrm{eq}}(\mathbf{p},u^\mu,T,\{\mu_i\})\left[1+\frac{\pi^{\mu\nu}p_\mu p_\nu}{2T^2(e+p)}\right]$$

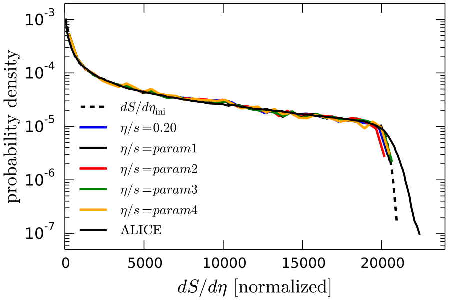
- Integral over constant temperature hypersurface
- 2- and 3-body decays of unstable hadrons included
- Here $T_{\mathrm{dec}} = 100$ MeV

Temperature dependent η/s



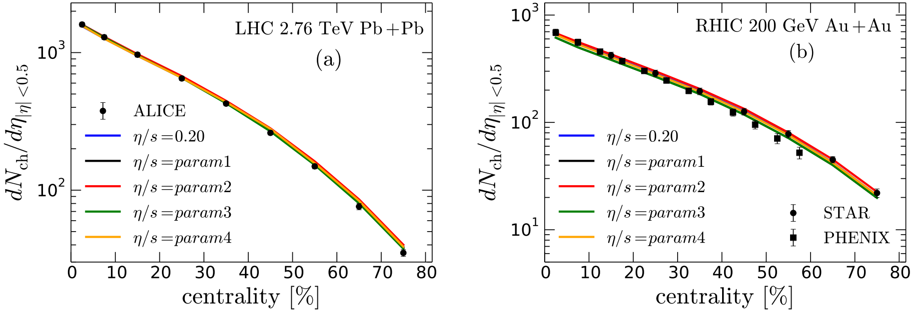
- relaxation time $\tau_\pi(T) = \frac{5\eta}{\varepsilon + p}$.

Centrality selection



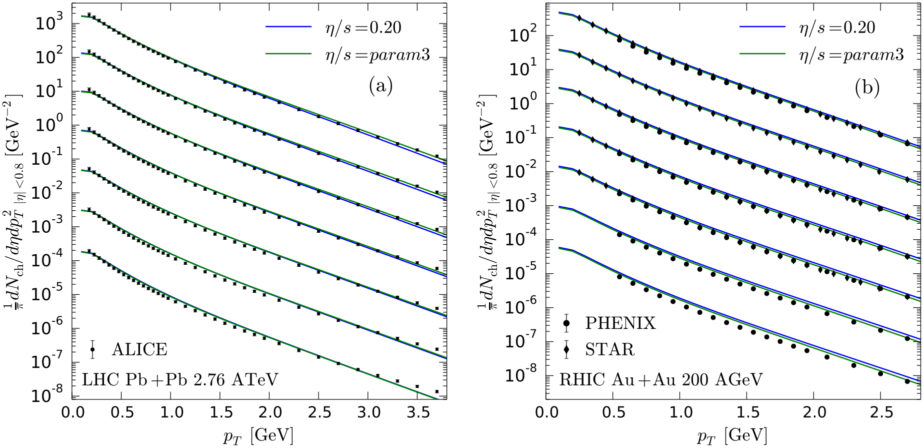
- Run random events
- Divide events into centrality classes according to final multiplicity.
- Still missing: ebye multiplicity fluctuations (with fixed $T_A T_A$)

multiplicity



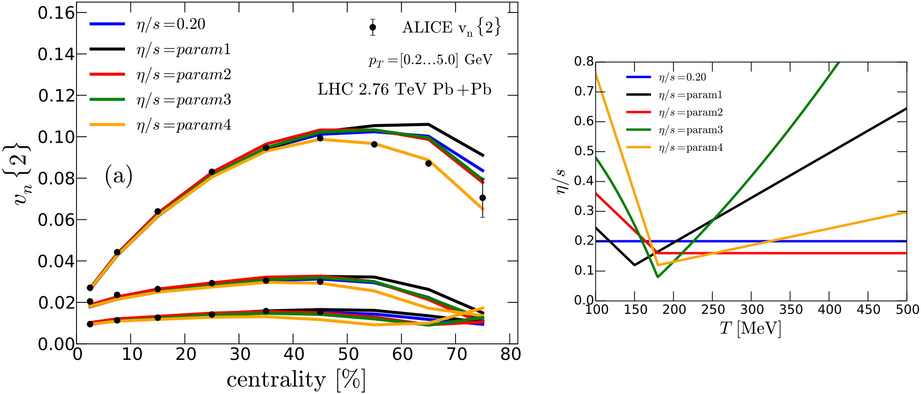
- $\beta = 0.8$
- $K_{\rm sat} \sim 1$ fixed to reproduce the charged hadron multiplicity in 0-5 % Pb+Pb collisions at the LHC.
- Centrality and $\sqrt{s}$ dependence prediction of the model

Transverse momentum spectra



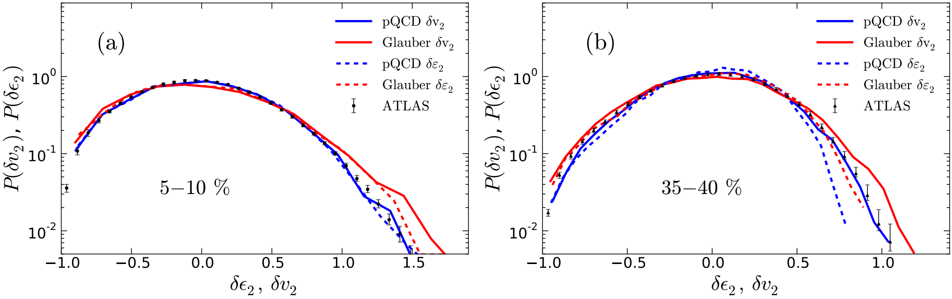
- kinetic ($T_{\rm dec}$) and chemical ($T_{\rm chem}$) decoupling temperatures are the most important parameters that determine the shape of p_T-spectra.
- $T_{\rm dec} = 100$ MeV
- $T_{\rm chem} = 175$ MeV

$\eta/s(T)$ from v_n data



- $\eta/s(T)$ parametrizations tuned to reproduce the v_n data at the LHC.
- No strong constraints to the temperature dependence (all give equally good agreement)
- Deviations mainly in peripheral collisions, where the applicability of the framework most uncertain.

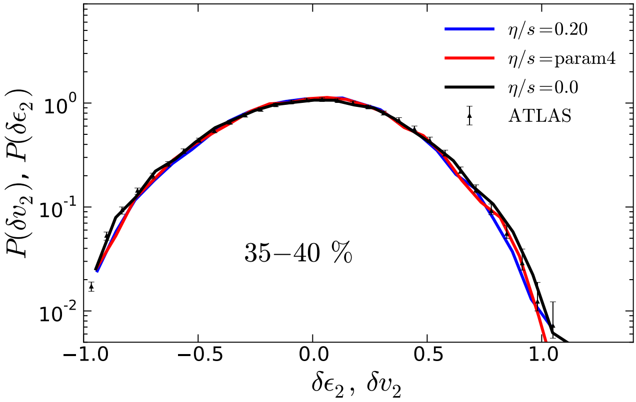
Flow fluctuations



$$\delta v_n = \frac{v_n - \langle v_n \rangle_{ev}}{\langle v_n \rangle_{ev}}$$

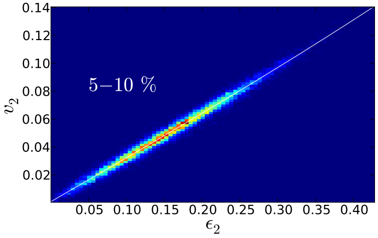
- Direct constrain to initial conditions.
- δv_2 spectra well described in all centralities (Glauber eWN+eBC mixture as comparison)
- Non-linear hydro response in peripheral collisions?

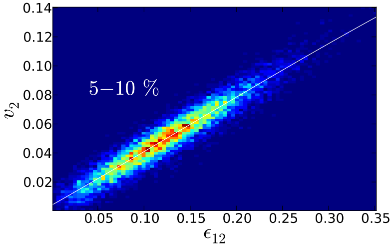
Sensitivity of $P(\delta v_2)$ to viscosity



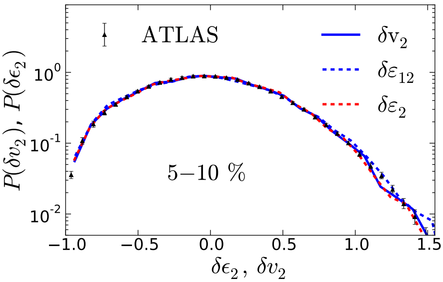
- Hydro response shows no sensitivity to η/s. (Note: we scale out the average v_2)

(non)linear-response?





5-10 %

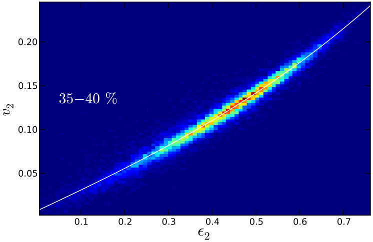


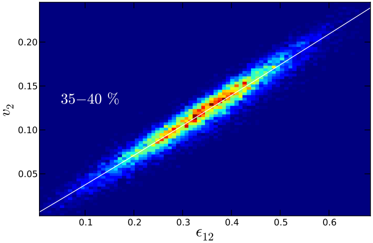
$$\varepsilon_{m,n} e^{in\Psi_{m,n}} = -\{r^m e^{in\phi}\}/\{r^m\},$$

$$\varepsilon_2 \equiv \varepsilon_{2,2} \text{ vs } \varepsilon_{1,2}$$

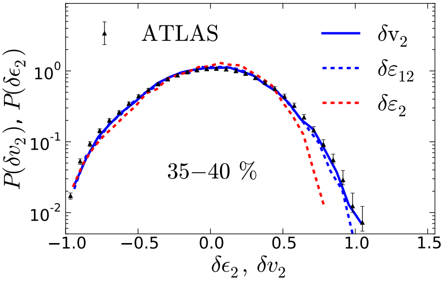
Full azimuthal structure: $m = 0, \ldots, \infty$

(non)linear-response?





35-40 %



$$\varepsilon_{m,n} e^{in\Psi_{m,n}} = -\{r^m e^{in\phi}\}/\{r^m\},$$

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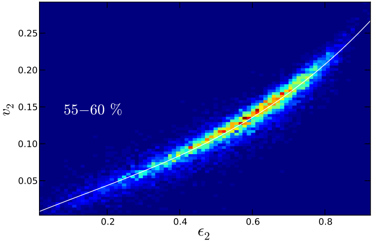
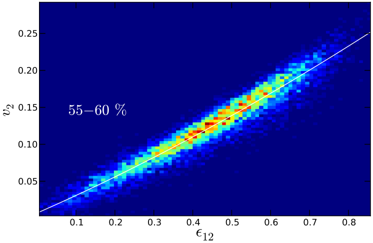
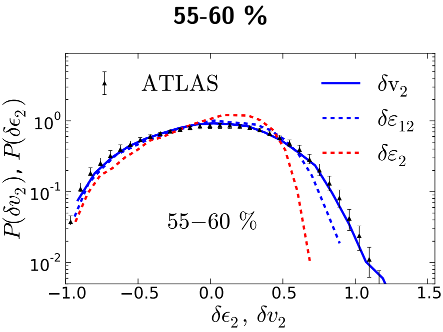
Full azimuthal structure: $m = 0, \dots, \infty$

(non)linear-response?





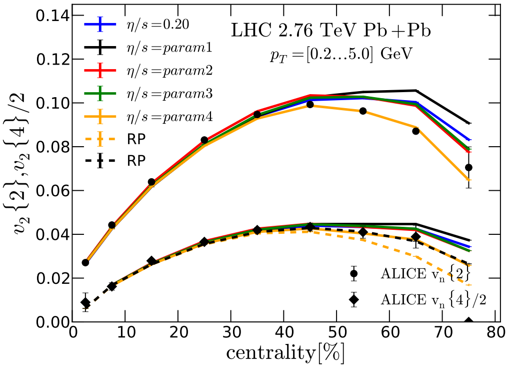


$$\varepsilon_{m,n} e^{in\Psi_{m,n}} = -\{r^m e^{in\phi}\}/\{r^m\},$$

$\varepsilon_2 \equiv \varepsilon_{2,2}$ vs $\varepsilon_{1,2}$

Full azimuthal structure: $m = 0, \ldots, \infty$

Flow fluctuations from $v_n\{2\}$ and $v_n\{4\}$



$v_n\{2\}$ and $v_n\{4\}$ measure different moments of the v_n–fluctuation spectrum:

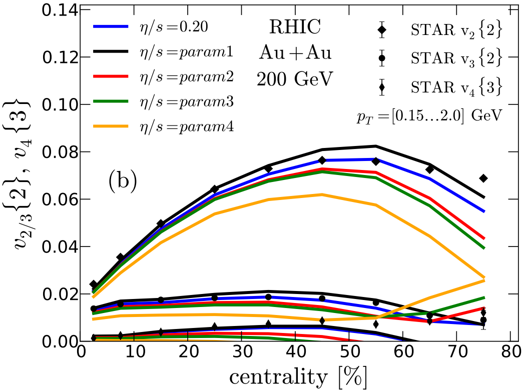
$$v_n\{2\} \overset{\text{flow}}{=} \langle v_n^2 \rangle_{ev}^{1/2}$$

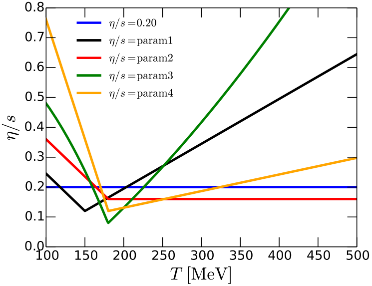
$$v_n\{4\} \overset{\text{flow}}{=} \left(2\langle v_n^2 \rangle_{ev}^2 - \langle v_n^4 \rangle_{ev} \right)^{1/4}$$

- Same information as in the fluctuation spectrum (assuming non-flow is not significant)

RHIC 200 AGeV Au+Au: more contraints to $\eta/s(T)$

Constraints for $\eta/s(T)$ from RHIC v_n data

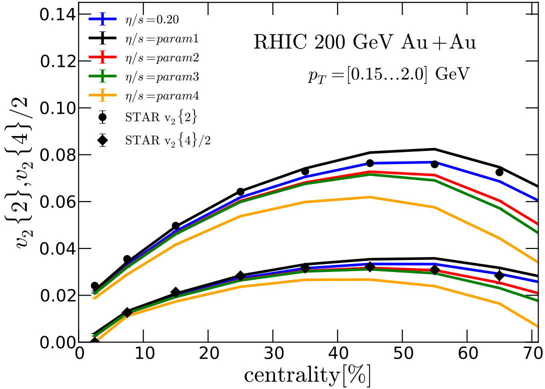




$$v_4\{3\} \equiv \frac{\langle v_2^2 v_4 \cos(4\,[\Psi_2 - \Psi_4])\rangle_{ev}}{\langle v_2^2\rangle_{ev}}.$$

- $\eta/s = param4$ clearly below data

Flow fluctuations

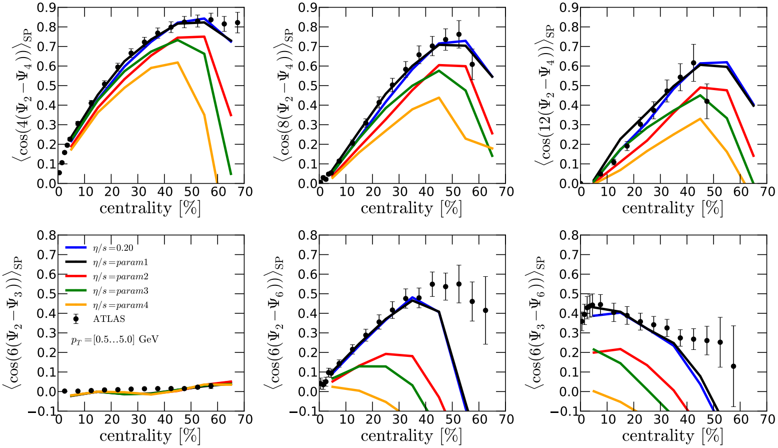


- No distributions directly, but $v_2\{2\}$ and $v_2\{4\}$ simultaneously described

Event-plane correlations

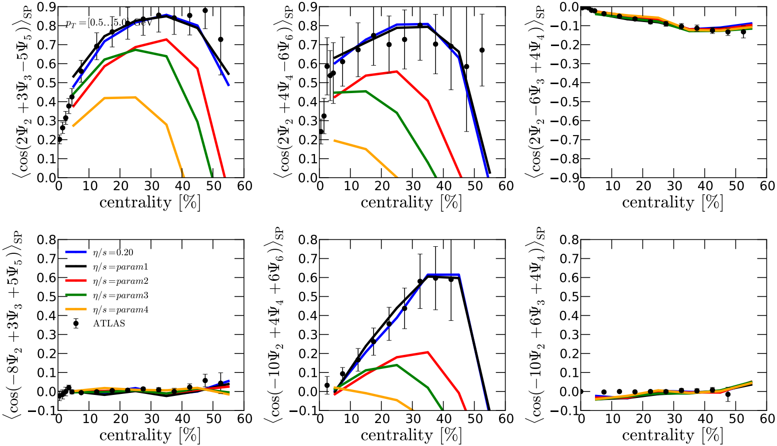
$$\langle \cos(k_1\Psi_1 + \cdots + nk_n\Psi_n)\rangle_{\mathrm{SP}} \equiv \frac{\langle v_1^{|k_1|}\cdots v_n^{|k_n|}\cos(k_1\Psi_1 + \cdots + nk_n\Psi_n)\rangle_{ev}}{\sqrt{\langle v_1^{2|k_1|}\rangle_{ev}\cdots\langle v_n^{2|k_n|}\rangle_{ev}}},$$

Event-plane correlations: 2 angles



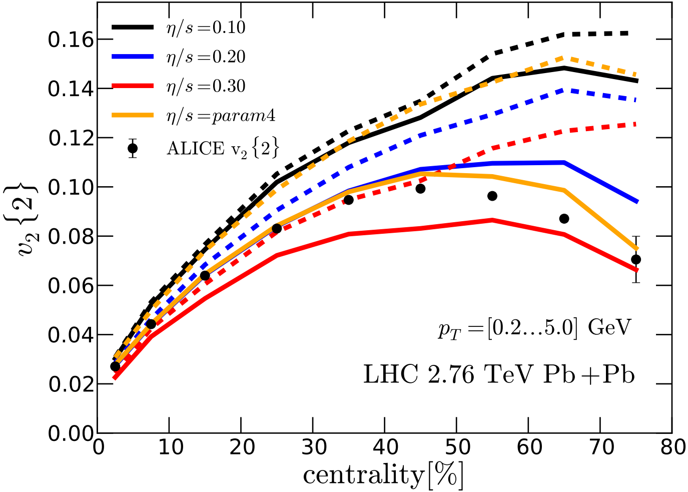
- Already from the LHC data more constraints to $\eta/s(T)$.
- Small hadronic viscosity needed to reproduce the data.

Event-plane correlations: 3 angles



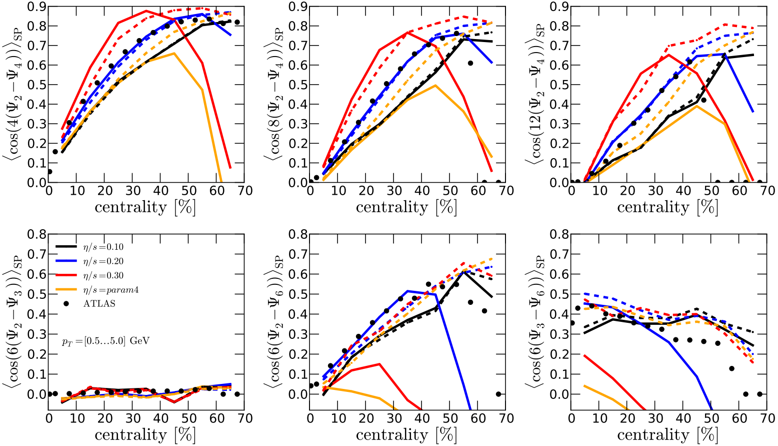
- Equally well described by the same parametrizations that describe 2-angle correlations.

δf in v_2



- δf

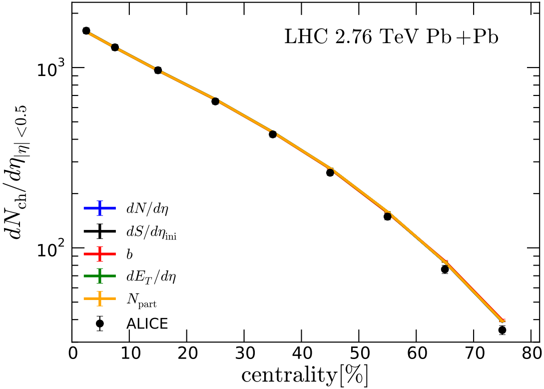
δf in event-plane correlations

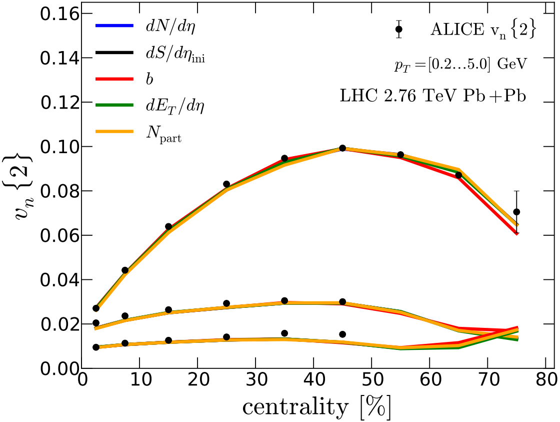


- δf

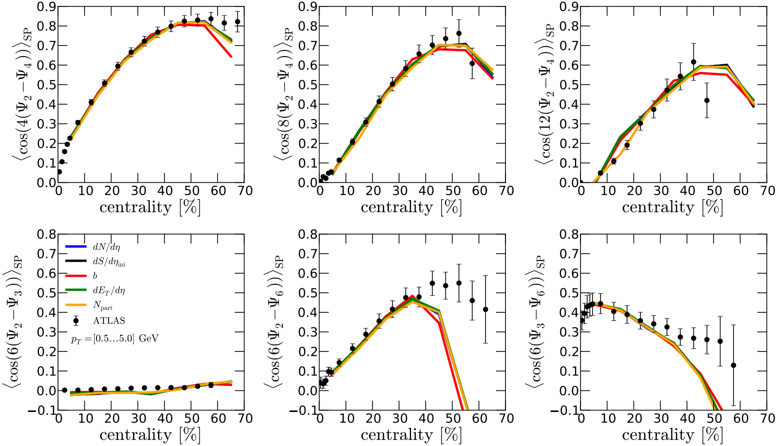
Summary

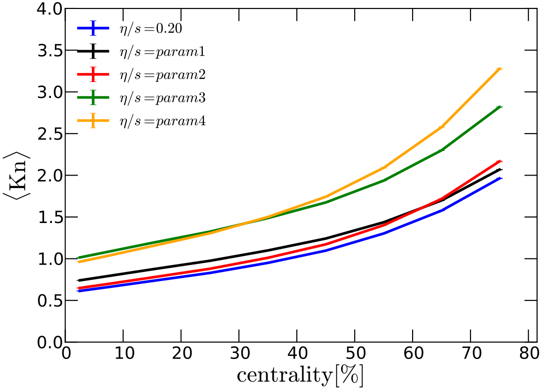
- Presented a new EbyE framework for NLO pQCD + saturation & viscous hydro
- The computed $\sqrt{s}$ and centrality dependence of $dN_{\rm ch}/d\eta$ agree very well with LHC and RHIC data: predictive power!
- Most direct constraints for the IS come from the v_2 fluctuations and the ratio v_2/v_3 both are now very well reproduced!
- LHC v_ns alone do not stringently constrain the T-dependence of $1\eta/s$
- 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
- Very promising results but we should keep in mind the uncertainties when ruling out a large hadronic viscosity: peripheral collisions and large hadronic $\eta/s \longrightarrow$ large δf at decoupling $\longrightarrow$ applicability of fluid dynamics ?


LHC 2.76 TeV Pb+Pb
$dN_{\rm ch}/d\eta_{|\eta|<0.5}$
centrality[%]
$dN/d\eta$
$dS/d\eta_{\rm ini}$
b
$dE_T/d\eta$
$N_{\rm part}$
ALICE

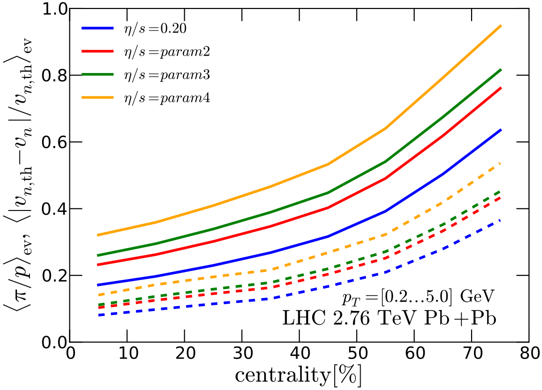


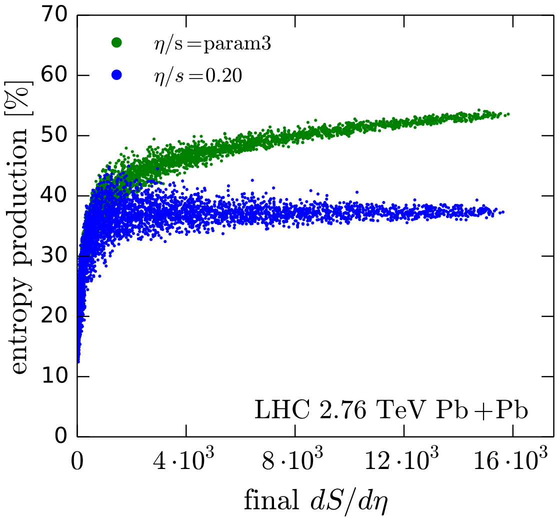
$dN/d\eta$
$dS/d\eta_{\rm ini}$
b
$dE_T/d\eta$
$N_{\rm part}$
ALICE $v_n\{2\}$
$p_T = [0.2 \ldots 5.0]$ GeV
LHC 2.76 TeV Pb+Pb
$v_n\{2\}$
centrality [%]
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0
10
20
30
40
50
60
70
80


$\langle\cos(4(\Psi_2-\Psi_4))\rangle_{SP}$
$\langle\cos(8(\Psi_2-\Psi_4))\rangle_{SP}$
$\langle\cos(12(\Psi_2-\Psi_4))\rangle_{SP}$
$\langle\cos(6(\Psi_2-\Psi_3))\rangle_{SP}$
$\langle\cos(6(\Psi_2-\Psi_6))\rangle_{SP}$
$\langle\cos(6(\Psi_3-\Psi_6))\rangle_{SP}$
centrality [%]
$dN/d\eta$
$dS/d\eta_{\rm ini}$
b
$dE_T/d\eta$
$N_{\rm part}$
ATLAS
$p_T = [0.5\ldots5.0]$ GeV

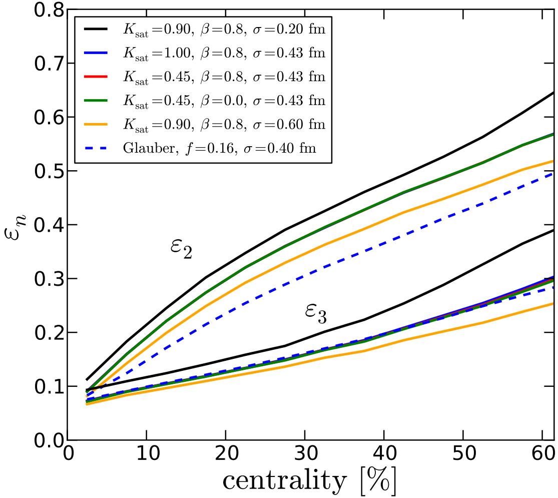


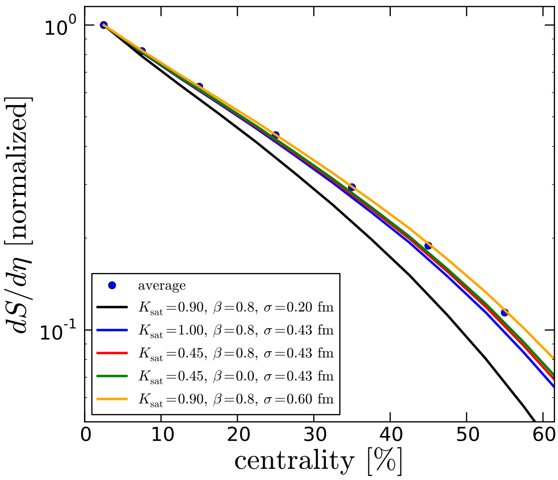
⟨Kn⟩
centrality[%]
η/s = 0.20
η/s = param1
η/s = param2
η/s = param3
η/s = param4
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
10
20
30
40
50
60
70
80


$\eta/s = 0.20$
$\eta/s = param2$
$\eta/s = param3$
$\eta/s = param4$
$p_T = [0.2 \ldots 5.0]$ GeV
LHC 2.76 TeV Pb+Pb
$\langle \pi/p \rangle_{ev}$, $\langle |v_{n,\mathrm{th}} - v_n| / v_{n,\mathrm{th}} \rangle_{ev}$
centrality[%]
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50
60
70
80



η/s =param3
η/s =0.20
entropy production [%]
LHC 2.76 TeV Pb+Pb
final $dS/d\eta$
0
10
20
30
40
50
60
70
0
$4\cdot10^3$
$8\cdot10^3$
$12\cdot10^3$
$16\cdot10^3$


$K_{sat}=0.90,\ \beta=0.8,\ \sigma=0.20$ fm
$K_{sat}=1.00,\ \beta=0.8,\ \sigma=0.43$ fm
$K_{sat}=0.45,\ \beta=0.8,\ \sigma=0.43$ fm
$K_{sat}=0.45,\ \beta=0.0,\ \sigma=0.43$ fm
$K_{sat}=0.90,\ \beta=0.8,\ \sigma=0.60$ fm
Glauber, $f=0.16,\ \sigma=0.40$ fm
ε_2
ε_3
ε_n
centrality [%]
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
0 10 20 30 40 50 60


$dS/d\eta$ [normalized]
10^0
10^{-1}
0
10
20
30
40
50
60
centrality [%]
average
$K_{\rm sat}=0.90,\ \beta=0.8,\ \sigma=0.20$ fm
$K_{\rm sat}=1.00,\ \beta=0.8,\ \sigma=0.43$ fm
$K_{\rm sat}=0.45,\ \beta=0.8,\ \sigma=0.43$ fm
$K_{\rm sat}=0.45,\ \beta=0.0,\ \sigma=0.43$ fm
$K_{\rm sat}=0.90,\ \beta=0.8,\ \sigma=0.60$ fm