Latest predictions from the EbyE NLO EKRT model

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with
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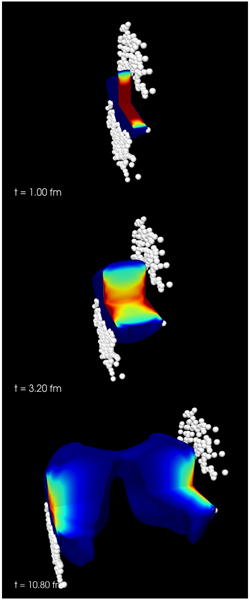
based on
HN, K. J. Eskola and R. Paatelainen, PRC **93**, 024907 (2016), arXiv:1505.02677
HN, K. J. Eskola, R. Paatelainen and K. Tuominen, PRC **93**, 014912 (2016), arXiv:1511.04296
K. J. Eskola, HN, R. Paatelainen and K. Tuominen, PRC **97**, no. 3, 034911 (2018), arXiv:1711.09803



EKRT model: pQCD + saturation + hydro

- QCD based computation of E_T production
  $\longrightarrow$ Initial conditions for fluid dynamics
  $\longrightarrow$ Predicted $(\sqrt{s}, A, \mathrm{centrality})$-dependence
- Fluid dynamical evolution
- Cooper-Frye freeze-out

$\longrightarrow$ Constraints for $\eta/s(T)$ from experimental data

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))

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

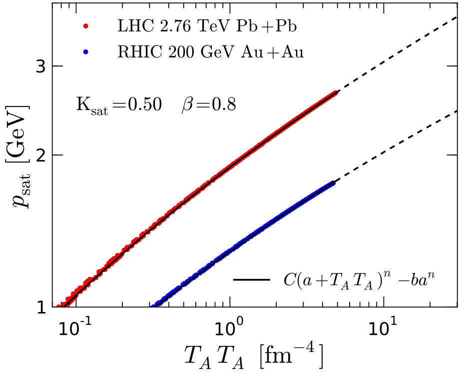
Essential quantity $\sigma \langle E_T \rangle$ with p_T cut-off p_0

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

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

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

Local saturation condition



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

Energy density at time $\tau_0 = 1/p_{sat}$

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

- K_{sat} free parameter that need to be fixed once.

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

Neglect net-baryon number, bulk viscosity & heat flow

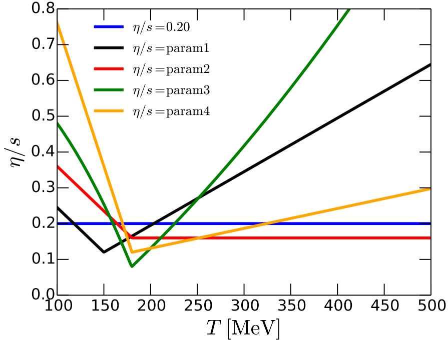
$$\partial_\mu T^{\mu\nu} = 0$$

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

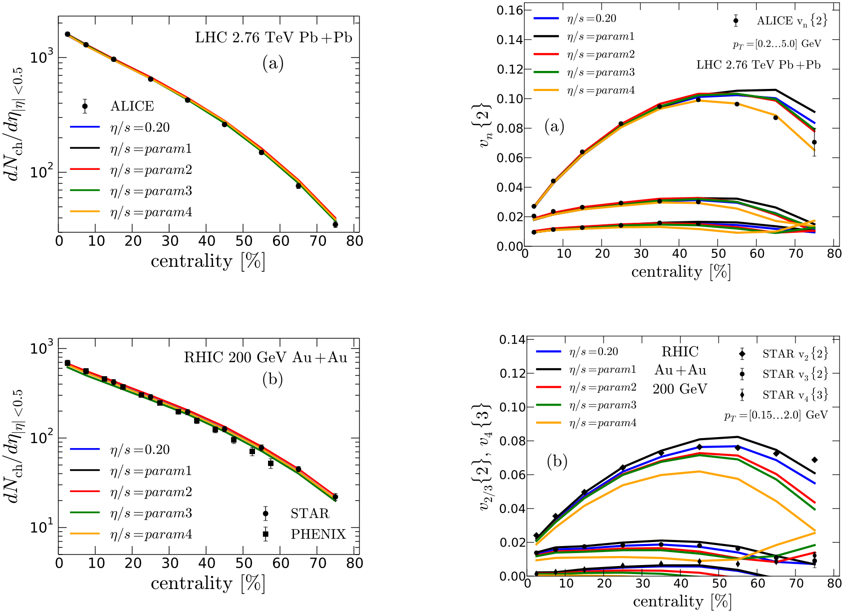
Longitudinal expansion is treated using boost invariance: $\frac{\partial p}{\partial \eta_s} = 0$, $v_z = \frac{z}{t}$

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

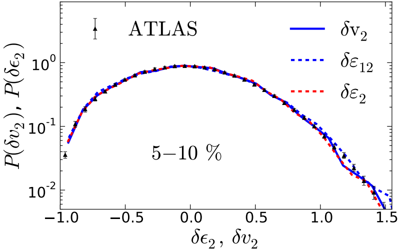
Temperature dependent η/s

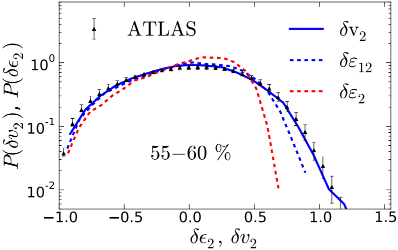


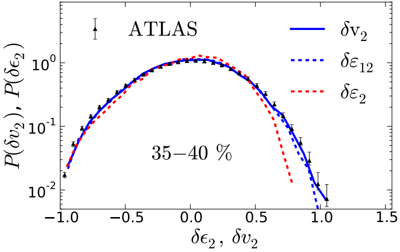
- tuned to reproduce $v_2\{2\}$ at LHC mid-peripheral collisions.
- relaxation time $\tau_\pi(T) = \frac{5\eta}{\varepsilon + p}$.


LHC 2.76 TeV Pb+Pb
(a)
ALICE
η/s = 0.20
η/s = param1
η/s = param2
η/s = param3
η/s = param4
$dN_{ch}/d\eta_{|\eta|<0.5}$
centrality [%]
ALICE $v_n\{2\}$
p_T = [0.2…5.0] GeV
$v_n\{2\}$
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





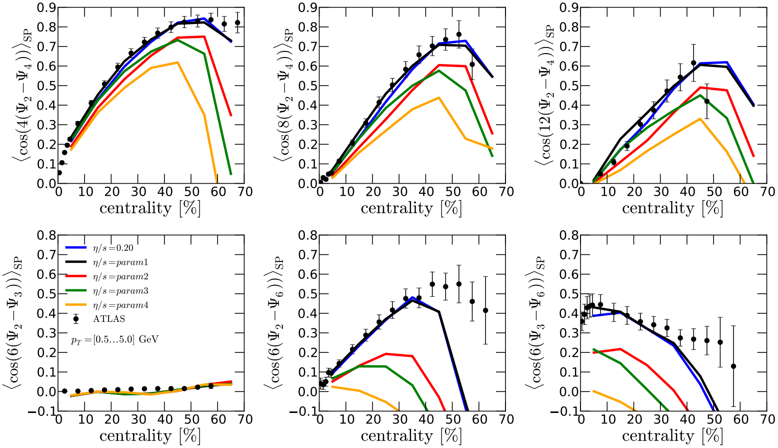


- Relative flow fluctuations insensitive to shear viscosity η/s
- $\longrightarrow$ direct constrain for the initial conditions

Event-plane correlations

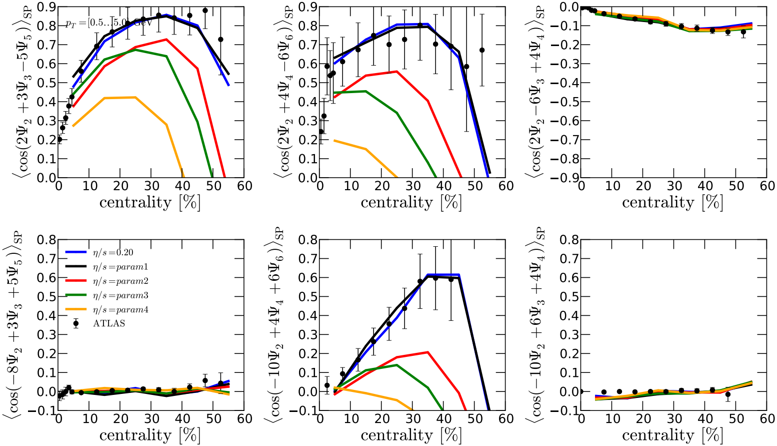
$$\langle \cos(k_1\Psi_1 + \cdots + nk_n\Psi_n)\rangle_{\mathrm{SP}} \equiv \frac{\langle v_1^{|k_1|}\cdots v_n^{|k_n|}\cos(k_1\Psi_1 + \cdots + nk_n\Psi_n)\rangle_{ev}}{\sqrt{\langle v_1^{2|k_1|}\rangle_{ev}\cdots\langle v_n^{2|k_n|}\rangle_{ev}}},$$

Event-plane correlations: 2 angles

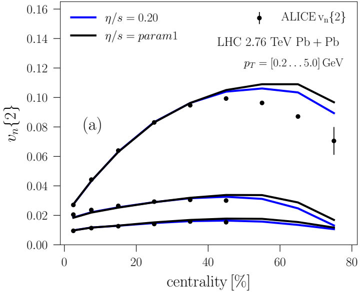


- Already from the LHC data more constraints to $\eta/s(T)$.
- Small hadronic viscosity needed to reproduce the data.

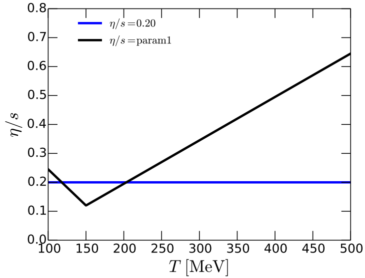
Event-plane correlations: 3 angles



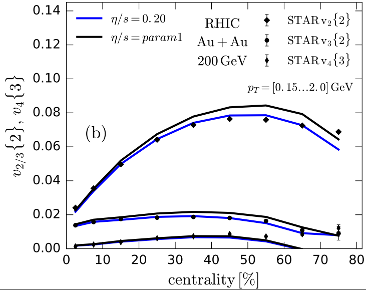
- Equally well described by the same parametrizations that describe 2-angle correlations.



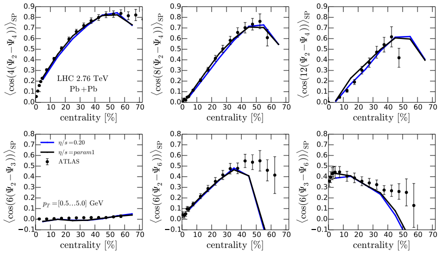
$\eta/s = 0.20$
$\eta/s = param1$
ALICE $v_n\{2\}$
LHC 2.76 TeV Pb + Pb
$p_T = [0.2 \ldots 5.0]$ GeV
(a)
$v_n\{2\}$
centrality [%]



$\eta/s = 0.20$
$\eta/s = $param1
η/s
T [MeV]

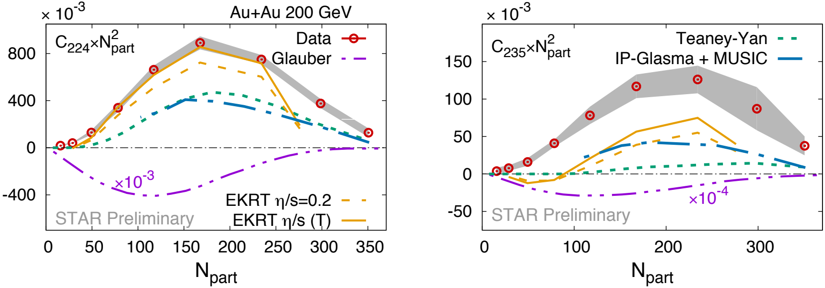


$\eta/s = 0.20$
$\eta/s = param1$
RHIC
Au + Au
200 GeV
STAR $v_2\{2\}$
STAR $v_3\{2\}$
STAR $v_4\{3\}$
$p_T = [0.15 \ldots 2.0]$ GeV
(b)
$v_{2/3}\{2\}, v_4\{3\}$
centrality [%]



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

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

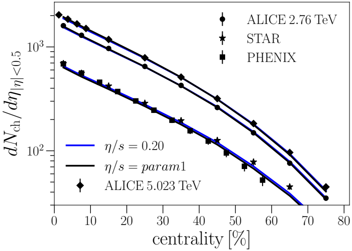


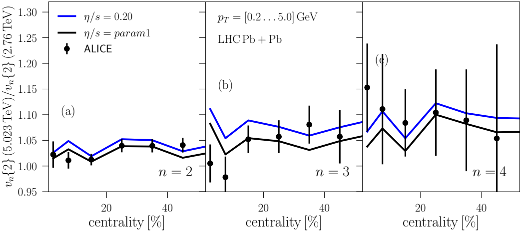
$$C_{224} = \langle v_2^2 v_4 \cos(4(\Psi_2 - \Psi_4)) \rangle$$

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

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

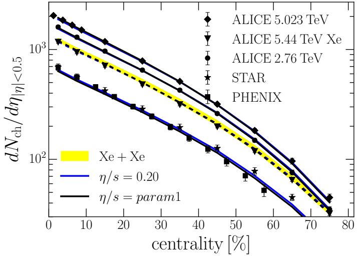
$\frac{dN_{\rm ch}}{d\eta}$ and v_n predictions: 5.023 TeV Pb+Pb

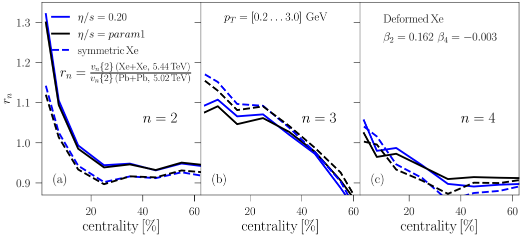




- The framework now essentially fixed (no retuning of parameters)
- Both the charged hadron multiplicity and the sligth inreaces in vn's correctly predicted

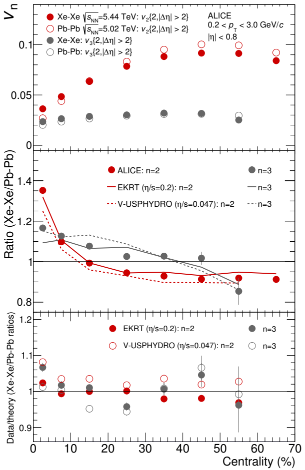
$\frac{dN_{\rm ch}}{d\eta}$ and v_n predictions: 5.44 TeV Xe+Xe





- Charged hadron multiplicity: error band from the experimental error in 0-5% 2.76 TeV multiplicity measurement (where EKRT model parameter $K_{\rm sat}$ fixed)
- The v_n ratio with and without nuclear deformation
- Quite strong influence of the Xe nuclear deformation on the v_2 ratio. (As noted in G. Giacalone et. al. PRC **97**, 034904 (2018))

v_n predictions: 5.44 TeV Xe+Xe



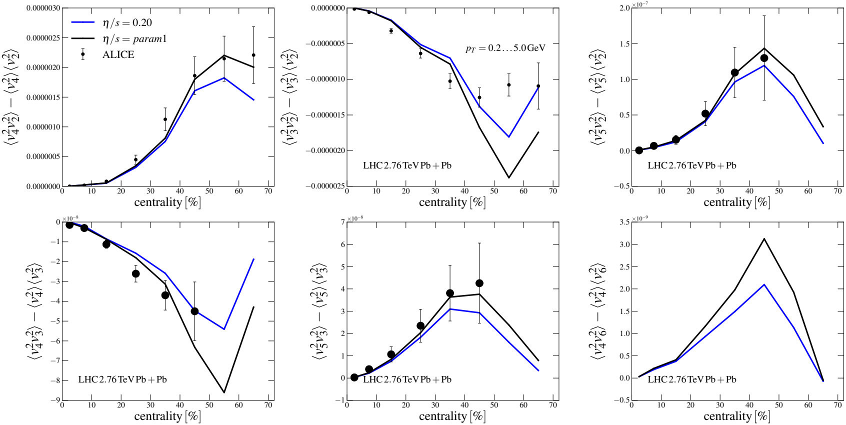
- Figure from ALICE publication: arXiv:1805.01832

Symmetric cumulants

$$SC(n,m) = \langle \cos(m\phi_1 + n\phi_2 - m\phi_3 - n\phi_4)\rangle$$
$$- \langle \cos(m(\phi_1 - \phi_2))\rangle\langle \cos(n(\phi_1 - \phi_2))\rangle$$
$$= \langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle$$

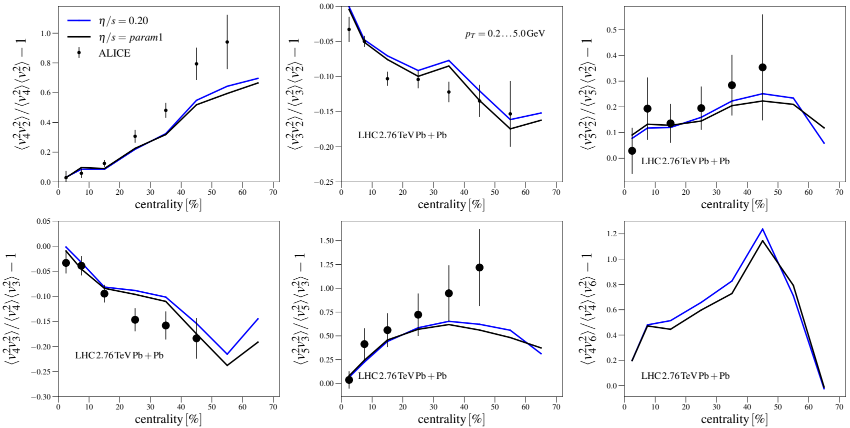
$$NSC(n,m) = \frac{SC(n,m)}{\langle v_m^2\rangle\langle v_n^2\rangle}$$

Symmetric cumulants $SC(n,m)$



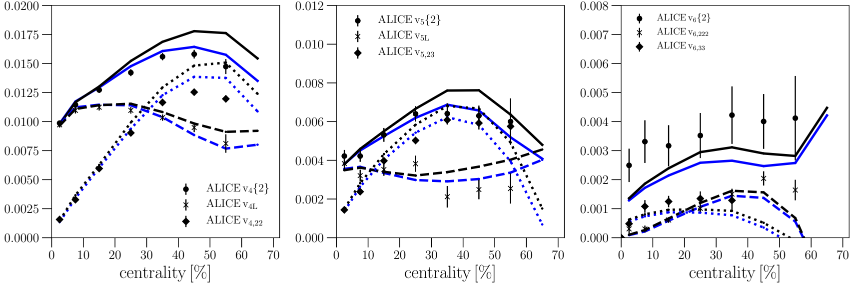
- Correlation between the magnitudes of v_n (independent of the event-plane angles Ψ_n)
- $SC(n,m)$ also very sensitive to the absolute values of v_n's

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.

v_5, v_6, linear/non-linear flow coefficients



$$v_{4,22} = \frac{\langle v_4 v_2^2 \cos(4\Psi_4 - 4\Psi_2)\rangle}{\sqrt{\langle v_2^4 \rangle}}$$

$$v_{5,23} = \frac{\langle v_5 v_3 v_2 \cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2)\rangle}{\sqrt{\langle v_3^2 v_2^2 \rangle}}$$

$$v_{6,222} = \frac{\langle v_6 v_2^3 \cos(6\Psi_6 - 6\Psi_2)\rangle}{\sqrt{\langle v_2^6 \rangle}}$$

$$v_{6,33} = \frac{\langle v_6 v_3^2 \cos(6\Psi_6 - 6\Psi_3)\rangle}{\sqrt{\langle v_3^4 \rangle}}$$

$$v_{4L} = \sqrt{v_4^2\{2\} - v_{4,22}^2}$$

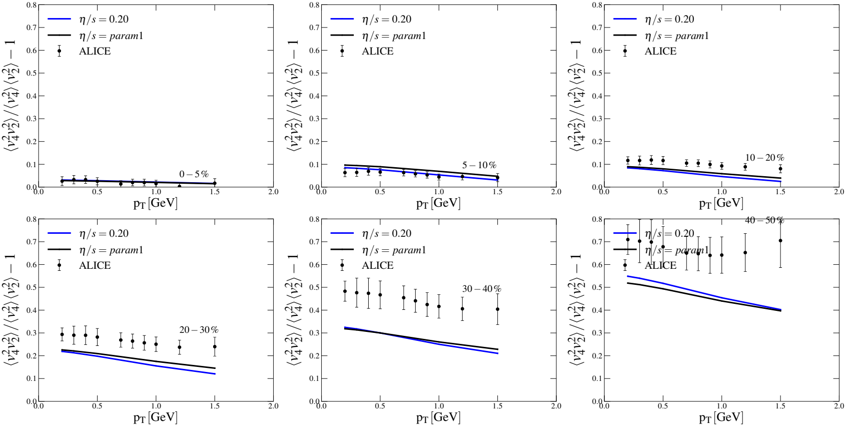
$$v_{5L} = \sqrt{v_5^2\{2\} - v_{5,23}^2}$$

- Can divide flow into linear and non-linear parts
- non-linear parts similar to event-plane correlators

Summary

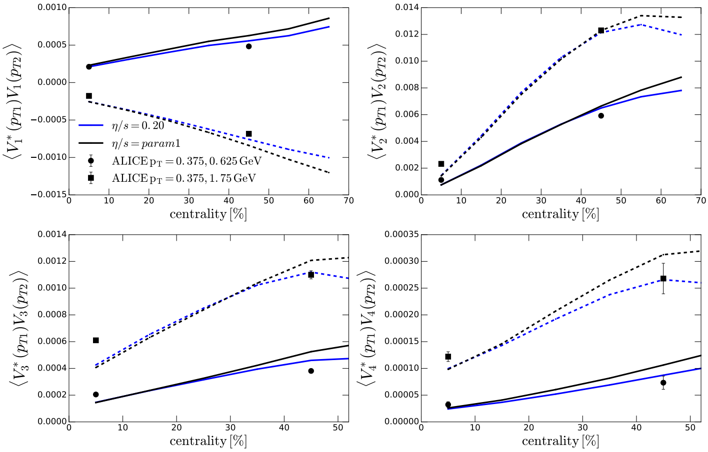
- Presented EbyE EKRT framework: NLO pQCD + saturation & viscous hydro
- The model parameters fixed at 200 GeV Au+Au and 2.76 TeV Pb+Pb collisions
- Constraints for the IS from the v_2 fluctuations and the ratio v_2/v_3 both are now very well reproduced!
- LHC v_n's alone do not stringently constrain 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 give similar agreement with the data
- Predictions for 5.023 TeV Pb+Pb and 5.44 TeV Xe+Xe collisions.
- The computed $\sqrt{s}$, A and centrality dependence of $dN_{\rm ch}/d\eta$ and v_n agree very well with LHC and RHIC data.

Normalized symmetric cumulants: p_T dependence

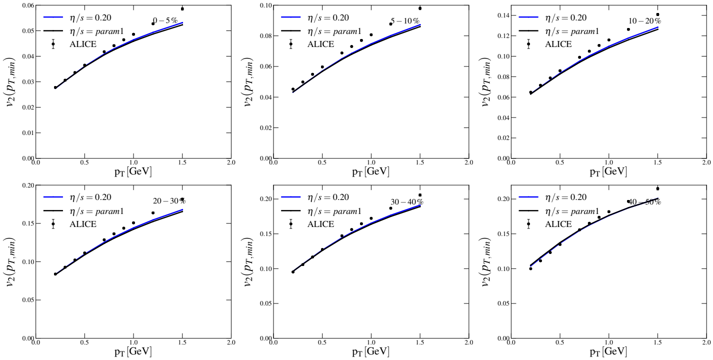


- Fluid dynamics gives the correct p_T-dependence.

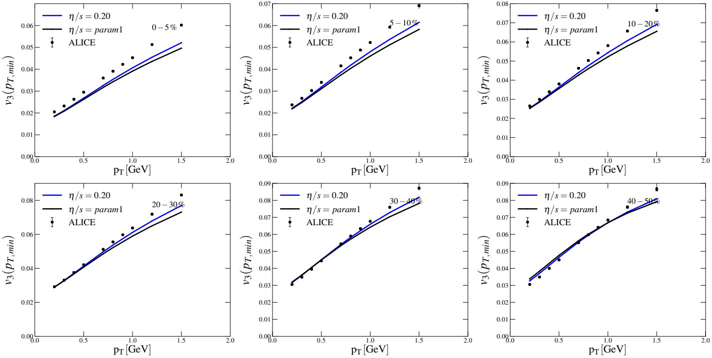
$(v_n(p_{T1}), v_n(p_{T2}))$ correlations



v_2 as function of $p_{T,\rm min}$



v_3 as function of $p_{T,\mathrm{min}}$



v_4 as function of $p_{T,\mathrm{min}}$