Fluid dynamics, viscosity and flow in ultrarelativistic heavy-ion collisions

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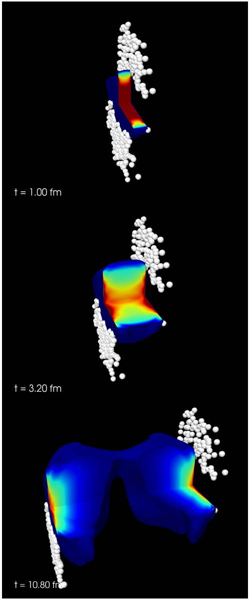
based on

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
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

with

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

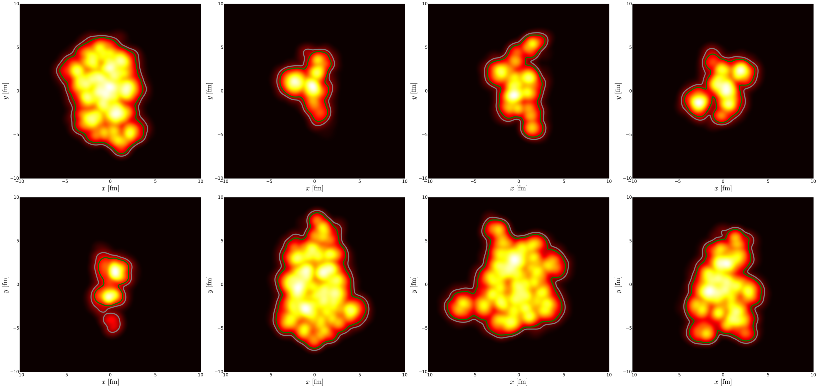


EKRT model: pQCD + saturation + hydro

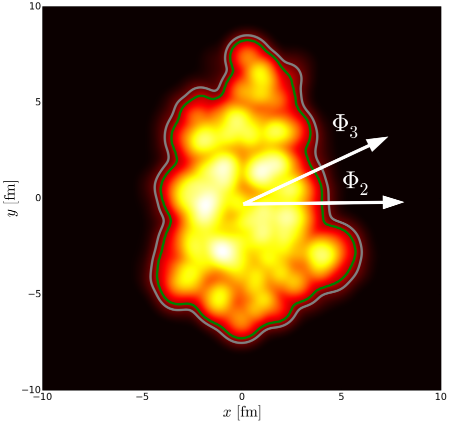
- QCD based computation of E_T production
  $\longrightarrow$ Initial conditions for fluid dynamics
  $\longrightarrow$ Predicted $(\sqrt{s}, A, \mathrm{centrality})$-dependence
- Fluid dynamical evolution
- Cooper-Frye freeze-out

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

Initial states comes in all sizes and shapes:



Initial temperature profiles in transverse plane (orthogonal to the beam axis)



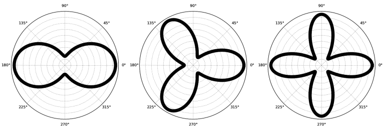
Global shape of the initial density profile characterized by eccentricities:

$$\varepsilon_n e^{in\Phi_n} = \{r^n e^{in\phi}\}/\{r^n\}$$

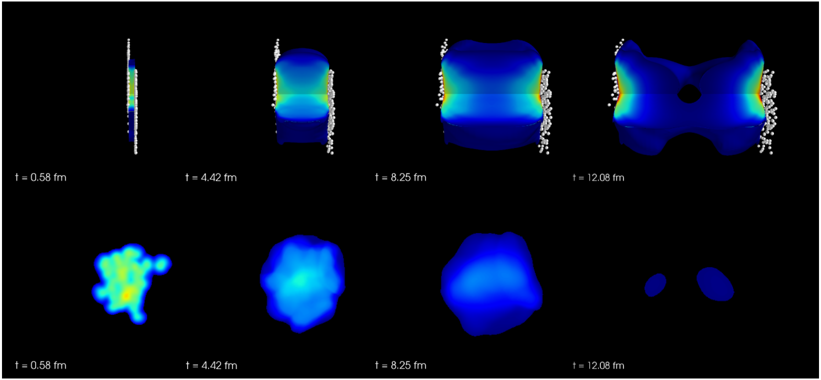
$$\{(\cdots)\} = \int dxdye(x,y,\tau_0)(\cdots)$$

ε_n = eccentricity
Φ_n = "participant plane" angle

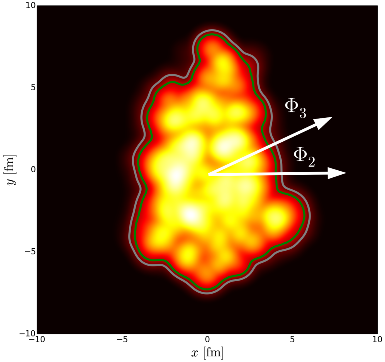
$n = 2$ $\quad$ $n = 3$ $\quad$ $n = 4$



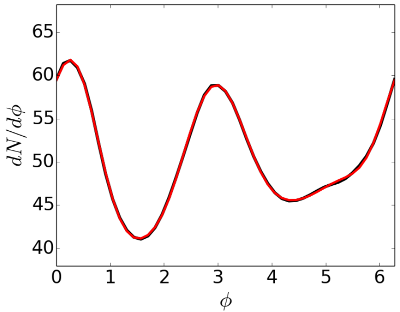
Fluid dynamical evolution: spatial structure $\longrightarrow$ momentum space



Characterize azimuthal momentum distribution by its Fourier coefficients v_n:



$\longrightarrow$



$$\varepsilon_n,\ \Phi_n \longrightarrow v_n,\ \Psi_n$$

$$\frac{dN}{dyd\phi} = \frac{dN}{dy}\left(1 + 2v_n \cos[n(\phi - \Psi_n)]\right)$$

Conversion efficiency from ε_n to v_n depends on the properties of QCD matter (viscosity, equation of state)

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

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

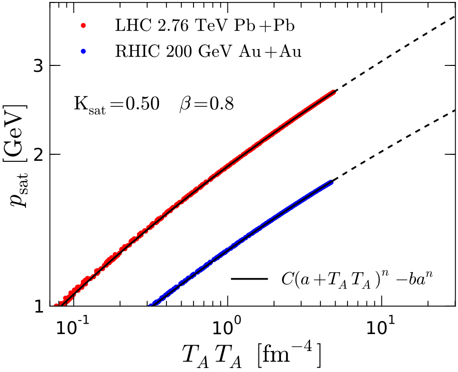
$$e = \frac{dE_T}{\tau_0 \Delta y d^2\mathbf{s}} = T_A(\mathbf{s} - \frac{\mathbf{b}}{2}) T_A(\mathbf{s} + \frac{\mathbf{b}}{2}) \frac{\sigma \langle E_T \rangle_{p_0, \Delta y}}{\tau_0 \Delta y}$$

T_A = (fluctuating) nucleon density

Local saturation condition

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

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



- 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 $\tau_0 = 1/p_{\rm sat}$

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

- $K_{\rm sat}$ 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

Conservation of energy and momentum:

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

Viscosity (Israel-Stewart theory):

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

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

Transverse momentum spectrum: Cooper-Frye integral over decoupling surface

$$E\frac{dN}{d^3k} = \frac{dN}{dyd^2\mathbf{p}_T} = \int_\Sigma d\Sigma_\mu k^\mu f(x,k),$$

where $f(x,k)$ is the particle momentum distribution at the decopling.

- Need to convert fluid quantities to momentum distributions: $T^{\mu\nu} \longrightarrow f(x,k)$

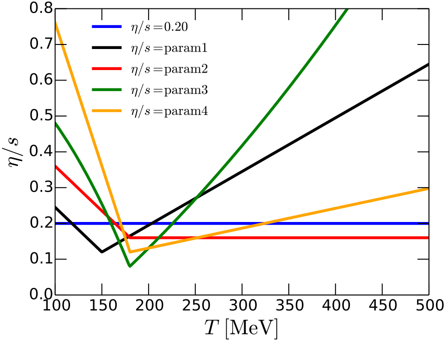
Momentum distribution function: 14-moment approximation

$$f_\mathbf{k} = f_{0\mathbf{k}} + \delta f_\mathbf{k} = f_{0\mathbf{k}} + f_{0\mathbf{k}}\frac{1}{2(e+p)T^2}k_{\langle\mu}k_{\nu\rangle}\pi^{\mu\nu}$$

is consistent with $T^{\mu\nu}$:

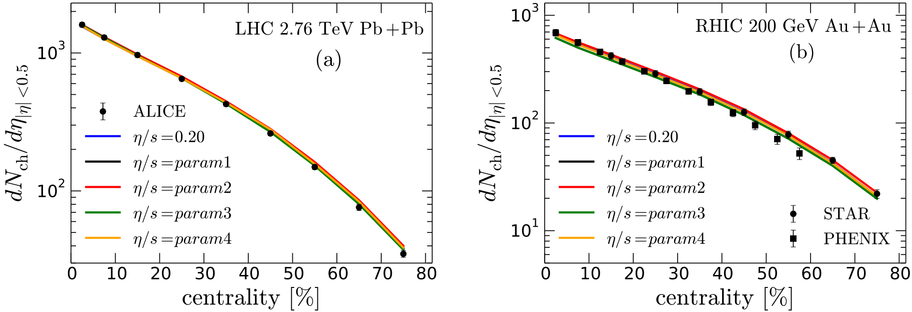
$$T^{\mu\nu}(x) = \int \mathrm{dK} k^\mu k^\nu f(x,k)$$

Temperature dependent η/s



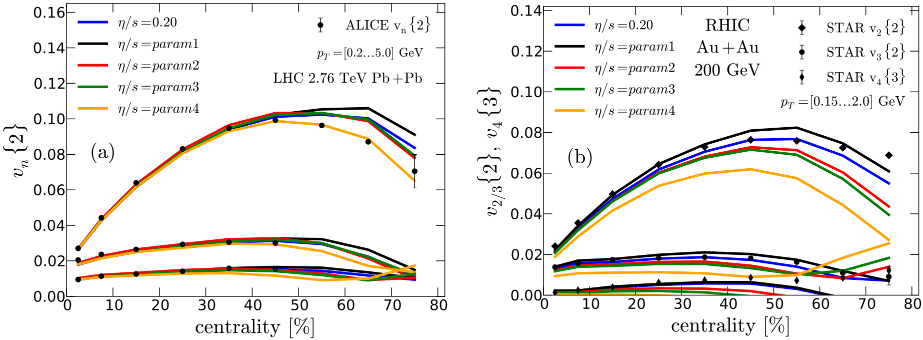
- tuned to reproduce $v_2\{2\}$ at LHC mid-peripheral collisions.
- relaxation time $\tau_\pi(T) = \frac{5\eta}{\varepsilon+p}$.

charged hadron multiplicity, LHC 2.76 TeV and RHIC 200 GeV



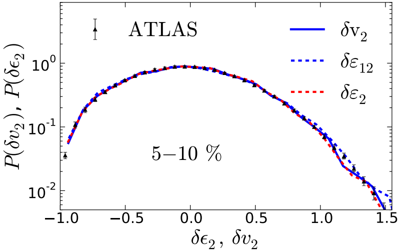
- Important check for the initial conditions
- EKRT model: centrality, $\sqrt{s}$ and nuclear mass number dependence

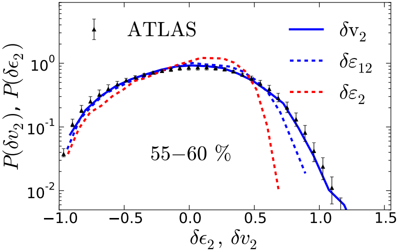
Flow coefficients, LHC 2.76 TeV and RHIC 200 GeV

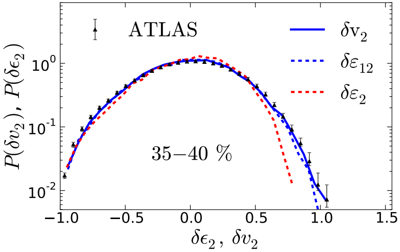


- The magnitude of the flow coefficients is the most direct constrain for η/s
- $\sqrt{s}$ dependence $\longrightarrow$ constraints for T-dependence

Flow fluctuations: $\delta v_2 = \frac{v_2 - \langle v_2 \rangle}{\langle v_2 \rangle}$







- Relative flow fluctuation spectra insensitive to shear viscosity η/s.
- driven mainly by the initial eccentricity fluctuations
- $\longrightarrow$ direct constrain for the initial conditions

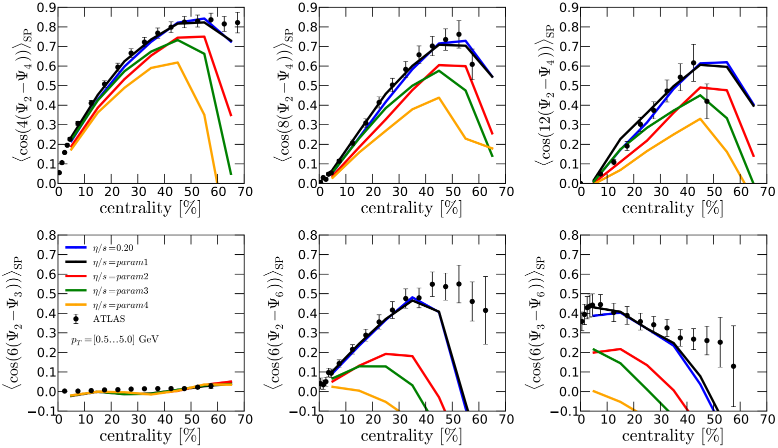
- Flow coefficients v_n and the corresponding event-plane angles Ψ_n are not independent
- Strong correlations due to correlations in initial eccentricities ε_n and due to the non-linear fluid dynamical evolution

$\longrightarrow$ further independent constraints to initial conditions and viscosity

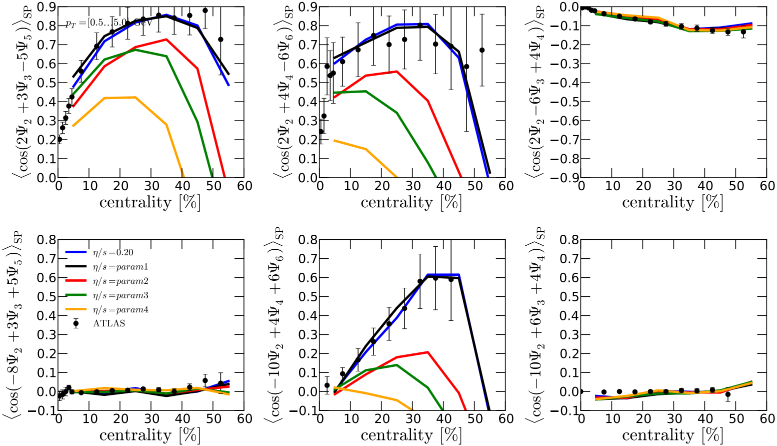
Event-plane correlations:

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

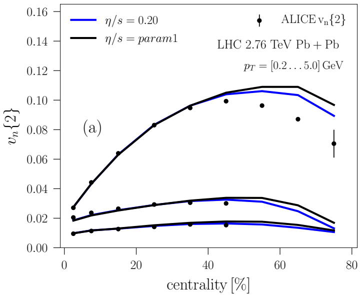
Event-plane correlations: 2 angles

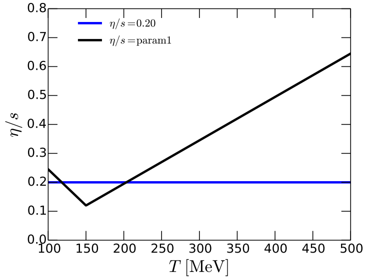


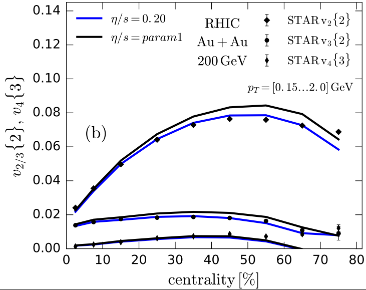
- Already from the LHC data more constraints to $\eta/s(T)$.
- Small hadronic viscosity needed to reproduce the data.

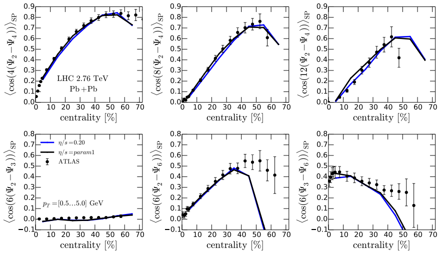


- Equally well described by the same parametrizations that describe 2-angle correlations.

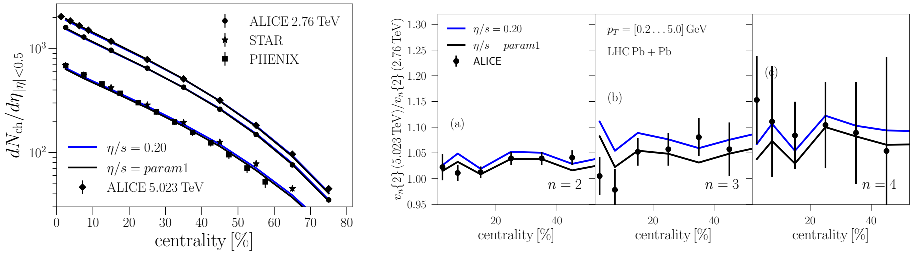

$\eta/s = 0.20$
$\eta/s = param1$
ALICE $v_n\{2\}$
LHC 2.76 TeV Pb + Pb
$p_T = [0.2 \ldots 5.0]$ GeV
(a)
$v_n\{2\}$
centrality [%]


$\eta/s = 0.20$
$\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 [%]

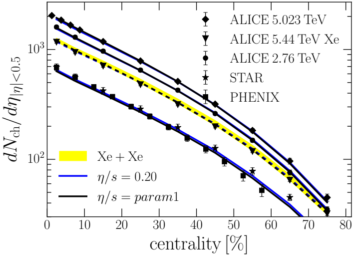

LHC 2.76 TeV
Pb+Pb
$\eta/s = 0.20$
$\eta/s = param1$
ATLAS
$p_T = [0.5 \ldots 5.0]$ GeV
$\langle\cos(4(\Psi_2 - \Psi_4))\rangle_{SP}$
$\langle\cos(8(\Psi_2 - \Psi_4))\rangle_{SP}$
$\langle\cos(12(\Psi_2 - \Psi_4))\rangle_{SP}$
$\langle\cos(6(\Psi_2 - \Psi_3))\rangle_{SP}$
$\langle\cos(6(\Psi_2 - \Psi_6))\rangle_{SP}$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

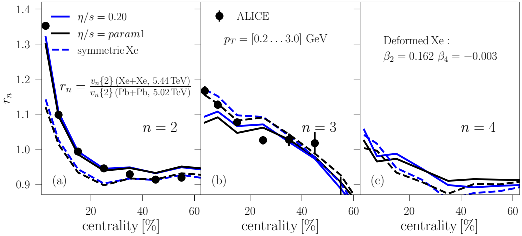
$\frac{dN_{\mathrm{ch}}}{d\eta}$ and v_n predictions: 5.023 TeV Pb+Pb



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

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





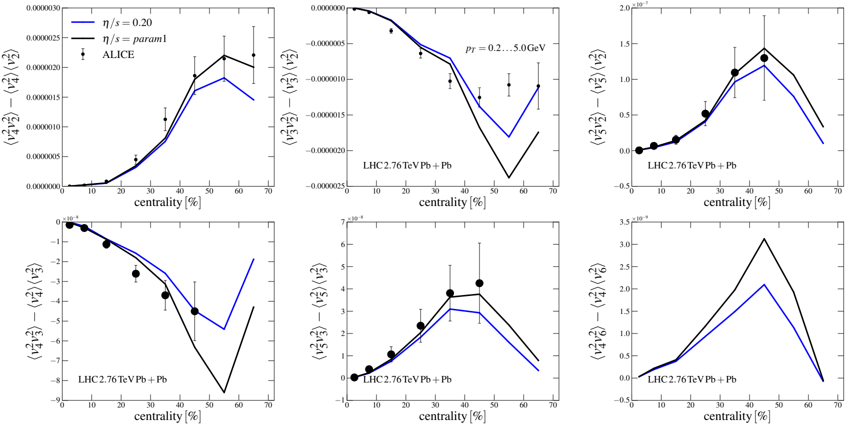
- Charged hadron multiplicity: error band from the experimental error in 0-5% 2.76 TeV multiplicity measurement (where EKRT model parameter K_{sat} fixed)
- The v_n ratio with and without nuclear deformation
- Quite strong influence of the Xe nuclear deformation on the v_n ratio. (As noted in G. Giacalone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

Symmetric cumulants

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

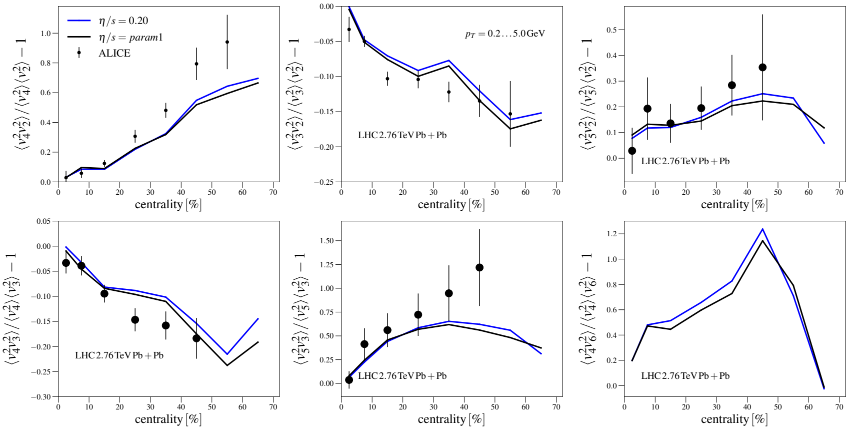
$$NSC(n,m) = \frac{SC(n,m)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$

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.

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