

# EKRT-model predictions for 5.02 TeV Pb+Pb collisions at the LHC

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IS2016 Lisbon, May 25

In collaboration with

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Results from:

**Phys.Rev. C93** (2016) 024907, arXiv:1511.04296 [hep-ph]

**Phys.Rev. C93** (2016) 014912, arXiv:1505.02677 [hep-ph]

# Outline

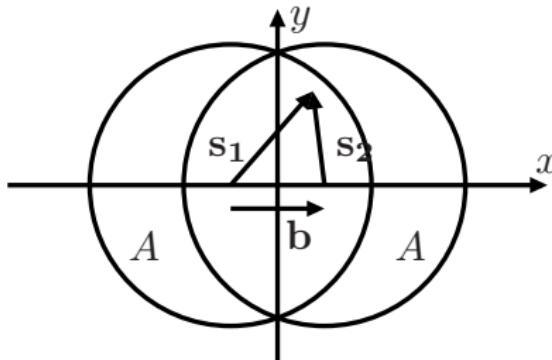
- ▶ Compute EbyE fluctuating EKRT **initial state** for hydro evolution in A+A collisions from saturated NLO pQCD minijet production
- ▶ Describe space-time evolution of QCD-matter with 2+1D **viscous hydrodynamics**, Event-by-Event
- ▶ Compare with LHC & RHIC data for bulk (low  $p_T$ ) observables, to
  - ▶ Test the initial state calculation & its predictive power
  - ▶ **Determine** QCD matter  $\eta/s(T)$
- ▶ New: **EKRT predictions** for LHC run II 5.02 TeV Pb+Pb collisions

## Initial state calculation: step I

Compute the initial minijet ( $p_T = \text{a few GeV}$ )  $E_T$  production in A+A and  $\Delta y$

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

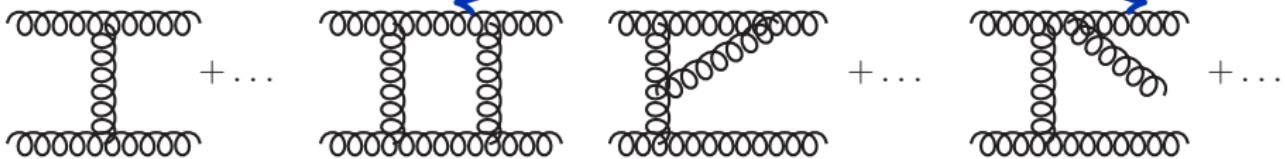
- $T_A T_A$  accounts for the nuclear collision geometry (WS density)



- $\mathbf{s}$  = transverse position ( $x, y$ ),  $\mathbf{b}$  = impact parameter
- $\sigma\langle E_T \rangle$  =  $E_T$ -weighted minijet cross section

## Computation of $\sigma\langle E_T \rangle$ in NLO

$$\sigma\langle E_T \rangle_{p_0, \Delta y} = \int d[PS]_2 \frac{d\sigma^{2 \rightarrow 2}}{d[PS]_2} S_2 + \int d[PS]_3 \frac{d\sigma^{2 \rightarrow 3}}{d[PS]_3} S_3$$



Partonic cross sections  $d\sigma^{2 \rightarrow n}/d[PS]_n$  at NLO

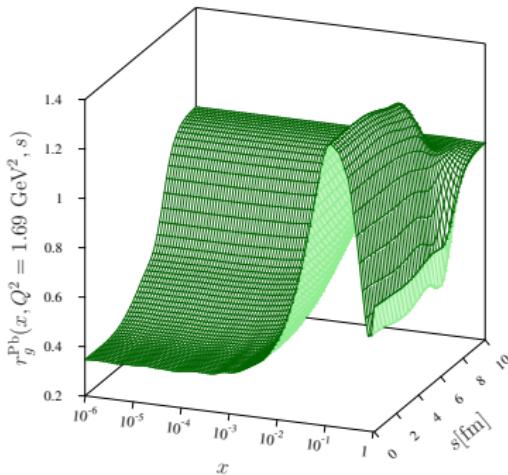
- Collinear factorization in A+A
- pQCD in  $2 \rightarrow 2$  and  $2 \rightarrow 3$  scatterings

$$\frac{d\sigma^{2 \rightarrow n}}{d[PS]_n} \sim \sum_{g, q, \bar{q}} f_{i/A}(x_1, Q^2, \mathbf{s}_1) \otimes f_{j/A}(x_2, Q^2, \mathbf{s}_2) \otimes |\mathcal{M}|^2(2 \rightarrow n)$$

PDFs for each parton flavor  $i$  ( $= g, q, \bar{q}$ )

$$f_{i/A}(x, Q^2, \mathbf{s}) \equiv r_i^A(x, Q^2, \mathbf{s}) \otimes f_i^p(x, Q^2)$$

- ▶  $f_i^p$ : CTEQ6M NLO parton densities
- ▶  $R_i^A$ : EPS09s ( $\mathbf{s}$  dependent) NLO nuclear modifications  
Helenius, Eskola et al. JHEP 1207 (2012) 073

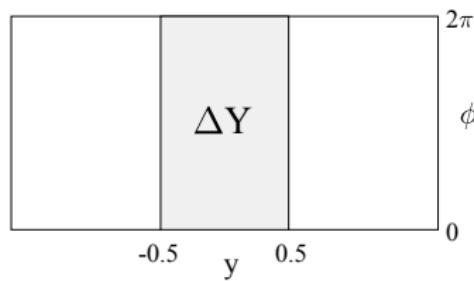


- ▶  $\mathbf{s}$  dependence of the nPDFs is quite weak near the centres of A

## Measurement functions $S_2$ and $S_3$ for computing minijet $E_T$ in NLO

- Analogous to jet production;

$$S_n = \underbrace{\left[ \sum_{i=1}^n p_{T,i} \Theta(y_i \in \Delta y) \right]}_{\text{Minijet } E_T \in \Delta y} \times \underbrace{\left( \sum_{i=1}^n p_{T,i} \geq 2p_0 \right)}_{\text{Hard scat. of partons}} \times \underbrace{\Theta\left(E_{T,n} \geq \beta \times p_0\right)}_{\text{Minimum } E_T \in \Delta y}$$



- IR/CL safeness:  $S_3 \rightarrow S_2$  at IR & CL limits
- Any  $\beta$  in  $[0, 1]$  is OK but a free parameter [RP et al., PRC87 (2013) 4, 044904]

These  $S_n$  + nPDFs: Well defined NLO computation of minijet  $E_T$ !

## Initial state calculation: step II

**Conjecture:** minijet  $E_T$  production saturates when

$$\frac{dE_T}{d^2\mathbf{s}dy}(2 \rightarrow 2) \sim \frac{dE_T}{d^2\mathbf{s}dy}(3 \rightarrow 2) \sim \text{H.O.}$$

- Using scaling law arguments (LO  $\alpha_s$ ):

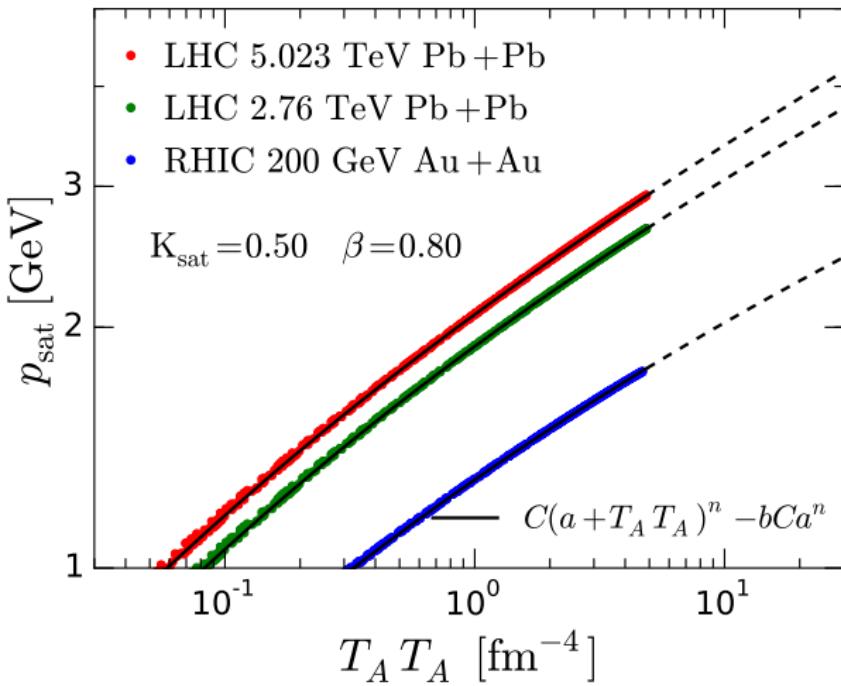
$$(T_A g_A)^2 \frac{\alpha_s^2}{p_0} \sim (T_A g_A)^3 \left( \frac{\alpha_s}{p_0} \right)^3 \Rightarrow T_A g_A \sim \frac{p_0^2}{\alpha_s} \Rightarrow \frac{dE_T}{d^2\mathbf{s}dy} \sim p_0^3$$

- We obtain a **saturation criterion** for  $E_T$  (IR/CL safe):

$$\underbrace{\frac{dE_T}{d^2\mathbf{s}}(p_0, \sqrt{s}, \dots, \beta)}_{= \text{NLO pQCD part}} = \left( \frac{K_{\text{sat}}}{\pi} \right) p_0^3 \Delta y$$

- and the **saturation scale**  $p_0 = p_{\text{sat}}(\sqrt{s_{\text{NN}}}, A, \mathbf{b}, \mathbf{s}; \beta, K_{\text{sat}})$

Solve the saturation equation for  $p_{\text{sat}}(\mathbf{b}, \mathbf{s})$  at different  $\mathbf{b}$



[HN et al. Phys.Rev. C93 (2016) 024907]

- Observation:  $p_{\text{sat}}$  scales with  $T_A T_A$

$$p_{\text{sat}}(\mathbf{b}, \mathbf{s}) \propto [T_A(\mathbf{s} + \mathbf{b}/2)T_A(\mathbf{s} - \mathbf{b}/2)]^n$$

- $p_{\text{sat}}(\mathbf{b}, \mathbf{s})$  can be parameterized! [RP et al. PLB 731 (2014) 126]

## Initial state calculation: step III

Include the EbyE fluctuations arising from the fluctuating nucleon configurations

- ▶ Nucleon position in A: sample WS distribution
- ▶ Around each nucleon, set a gluon transverse density

$$T_n(s) = \frac{1}{2\pi\sigma^2} e^{-\frac{s^2}{2\sigma^2}}, \quad \sigma = 0.43 \text{ fm} \text{ from HERA } \gamma^* p \rightarrow J/\Psi + p \text{ data}$$

In each event the nuclear thickness function  $T_A(\mathbf{s}) = \sum_i^A T_n(|\mathbf{s} - \mathbf{s}_i|)$

- ▶ Collisions of **gluon clouds**

Key point: fluctuations for  $p_{\text{sat}} = p_{\text{sat}}(T_A T_A)$

- Transverse profile of initial energy density  $\epsilon(\mathbf{s}, \tau_{\text{sat}})$  at time  $\tau_{\text{sat}}(\mathbf{s}) = 1/p_{\text{sat}}(\mathbf{s})$

$$\epsilon(\mathbf{s}, \tau_{\text{sat}}) = \frac{dE_T(p_{\text{sat}}, \dots, \beta)}{d^2\mathbf{s}} \frac{1}{\tau_{\text{sat}}(\mathbf{s}) \Delta y} = \frac{K_{\text{sat}}}{\pi} p_{\text{sat}}(\mathbf{s})^4$$

- Here  $p_{\text{sat}}^{\min} = 1 \text{ GeV} \gg \Lambda_{\text{QCD}}$
- Below  $p_{\text{sat}}^{\min}$  smoothly connect the computed  $\epsilon$ -profile to  $\epsilon \propto \rho_{\text{bin}}$
- "Pre-thermal" evolution from  $\tau_{\text{sat}}(\mathbf{s})$  to  $\tau_0 = 1/p_{\text{sat}}^{\min} = 0.2 \text{ fm}$

$$\varepsilon(\mathbf{s}, \tau_0) = \varepsilon(\mathbf{s}, \tau_{\text{sat}}) \left( \frac{\tau_{\text{sat}}}{\tau_0} \right)^{4/3}$$

done with 1D Bjorken hydro at each  $\mathbf{s}$

# Viscous Hydrodynamics [Niemi et al]

Run 2+1 D (2nd order) dissipative hydro, Event-by-Event

$$\partial_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = \varepsilon u^\mu u^\nu + (P + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

- ▶ Neglect the bulk pressure  $\Pi = 0$ :  $\Pi \propto \zeta$  = **bulk viscosity**
- ▶ Keep the shear stress  $\pi^{\mu\nu}$ :  $\pi^{\mu\nu} \propto \eta$  = **shear viscosity**

Evolution equation for  $\pi^{\mu\nu}$  from kinetic theory [Denicol, et al., PRD85 (2012) 114047]

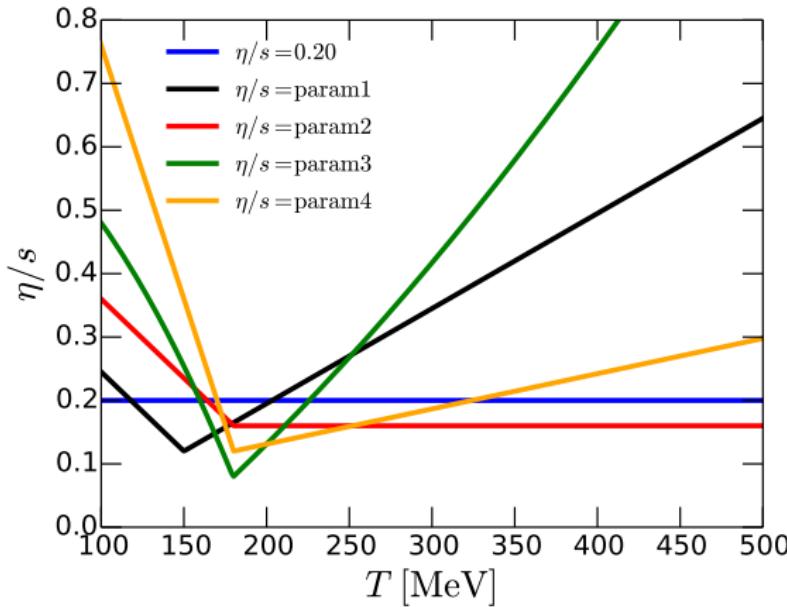
$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + \dots$$

QCD EoS: Based on lattice parametrization [Huovinen, Petreczky, NPA837 (2010) 26]

- ▶ s95p-PCE175-v1 chemical freeze-out at  $T_{\text{chem}} = 175$  MeV
- ▶ kinetic freeze-out  $T_f = 100$  MeV

Initial  $\pi^{\mu\nu}(\mathbf{s}, \tau_0)$  and transverse flow  $\mathbf{v}_T(\mathbf{s}, \tau_0)$  set to zero

- We study the temperature dependence of shear viscosity  $\eta/s$

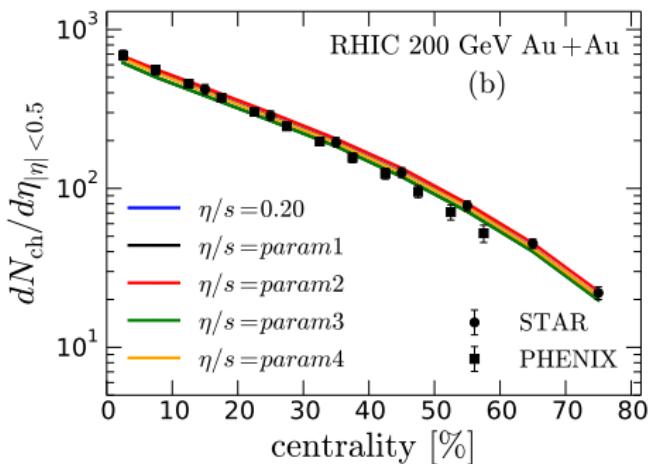
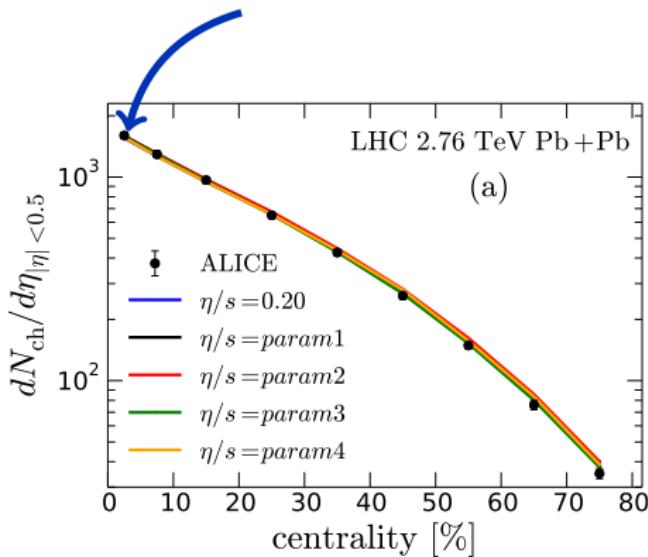


- Map the possible temperature dependence of  $\eta/s(T)$  with these parametrizations, reproducing the measured  $v_2$  at LHC

# Comparison with LHC and RHIC data

Centrality dependence of  $N_{\text{ch}}$  at mid-rapidity

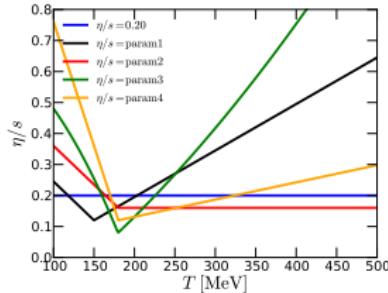
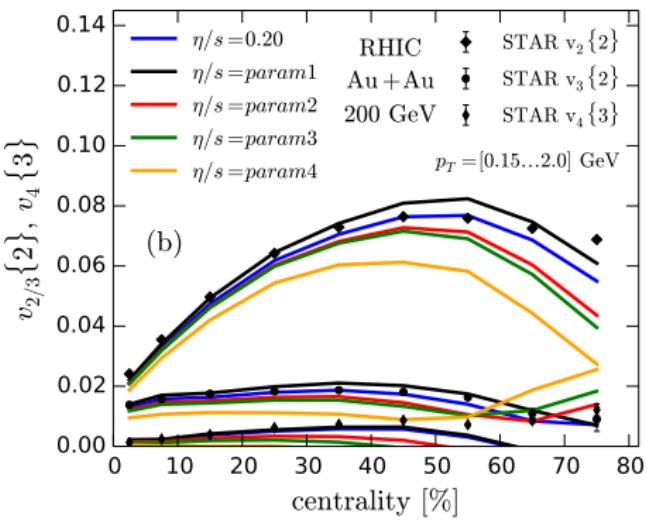
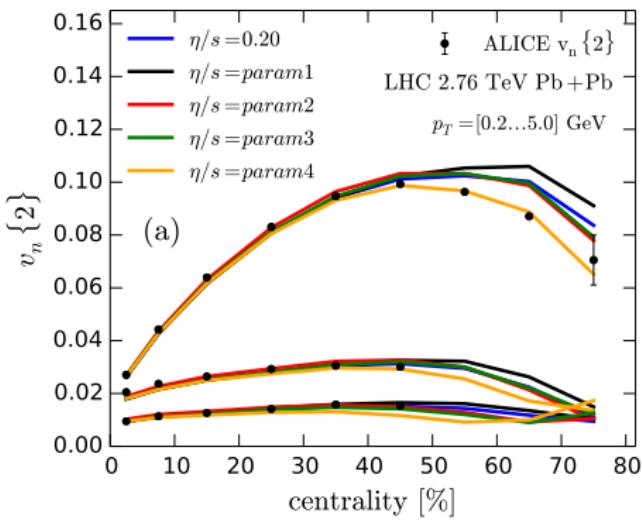
- Only **one** (0-5%) LHC point ( $K_{\text{sat}}, \beta$ ) is fitted, the rest is prediction



- Our computed initial transverse densities are under control

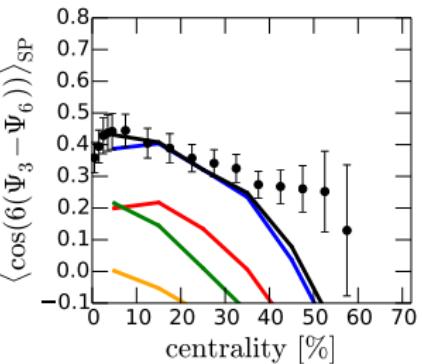
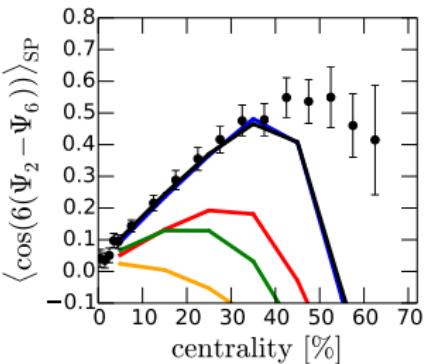
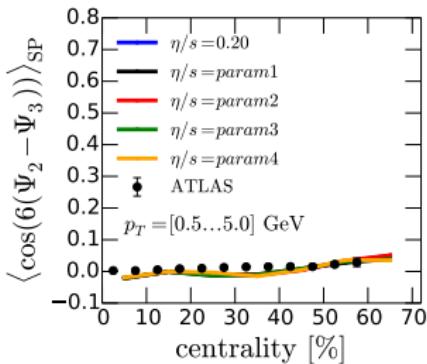
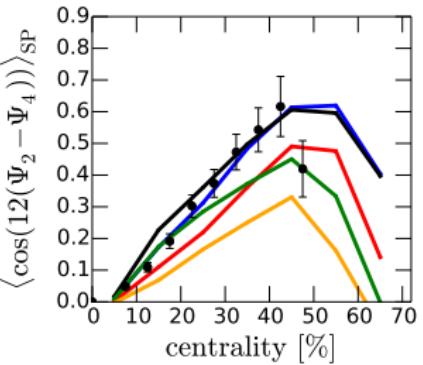
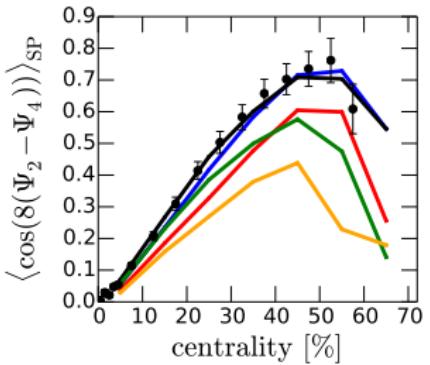
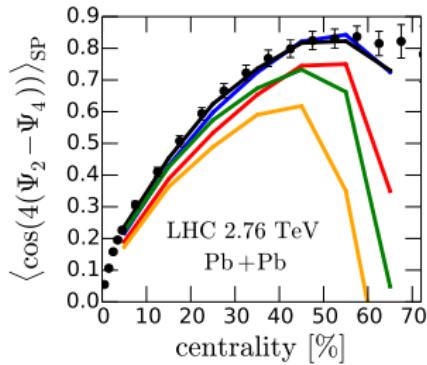
Niemi, Eskola, Paatelainen, Phys.Rev. C93 (2016) 014912

# Centrality dependence of 2,3-particle cumulant flow coefficients $v_n$



- ▶ LHC  $v_n$  well reproduced by all these  $\eta/s(T)$
- ▶ Simultaneous LHC & RHIC analysis very important!
- ▶ Constraints for  $\eta/s(T)$ : small  $\eta/s$  in the HRG (0.2 & param1) seems favored

# Correlations of 2 Event-plane angles OK, for centralities < 40 – 50 %



- Again small  $\eta/s$  in the HRG (0.2 & param1) seems favored!

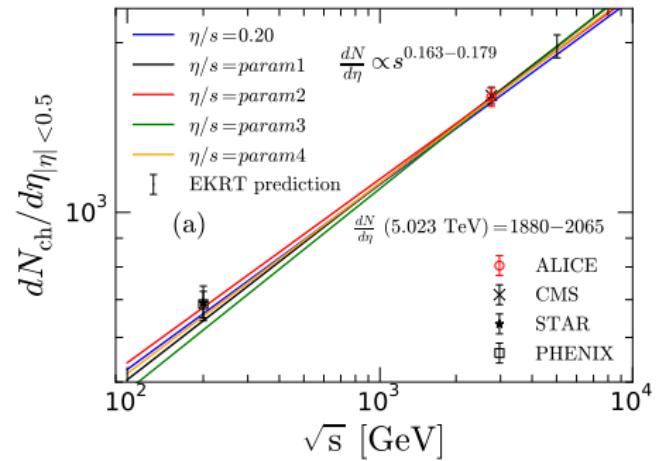
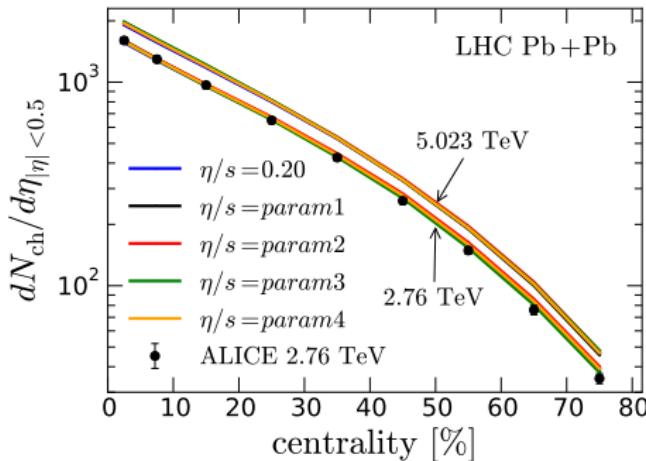
Niemi, Eskola, Paatelainen, Phys.Rev. C93 (2016) 014912

Data: ATLAS collaboration, Phys. Rev. C 90 (2014) 2, 024905

# EKRT predictions for 5.02 TeV LHC Pb+Pb

Niemi, Eskola, Paatelainen, Tuominen, Phys.Rev. C93 (2016) 024907

- Centrality & cms-energy dependence of  $N_{\text{ch}}$

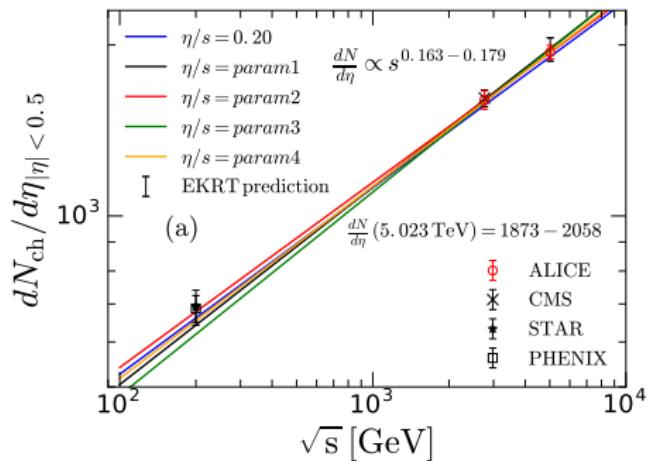
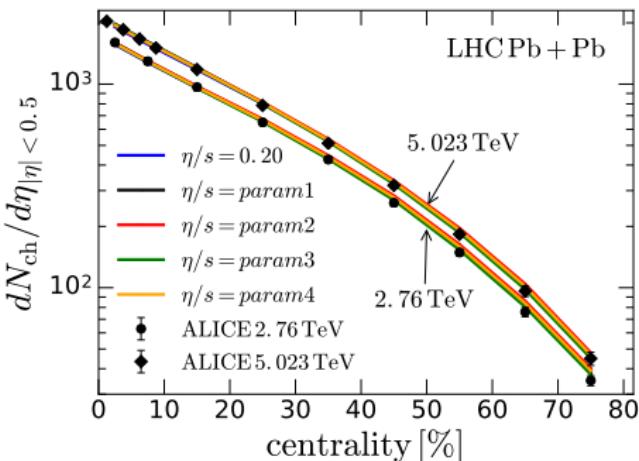


Data: ALICE collaboration, arXiv:1512.06104

# EKRT predictions for 5.02 TeV LHC Pb+Pb

Niemi, Eskola, Paatelainen, Tuominen, Phys.Rev. C93 (2016) 024907

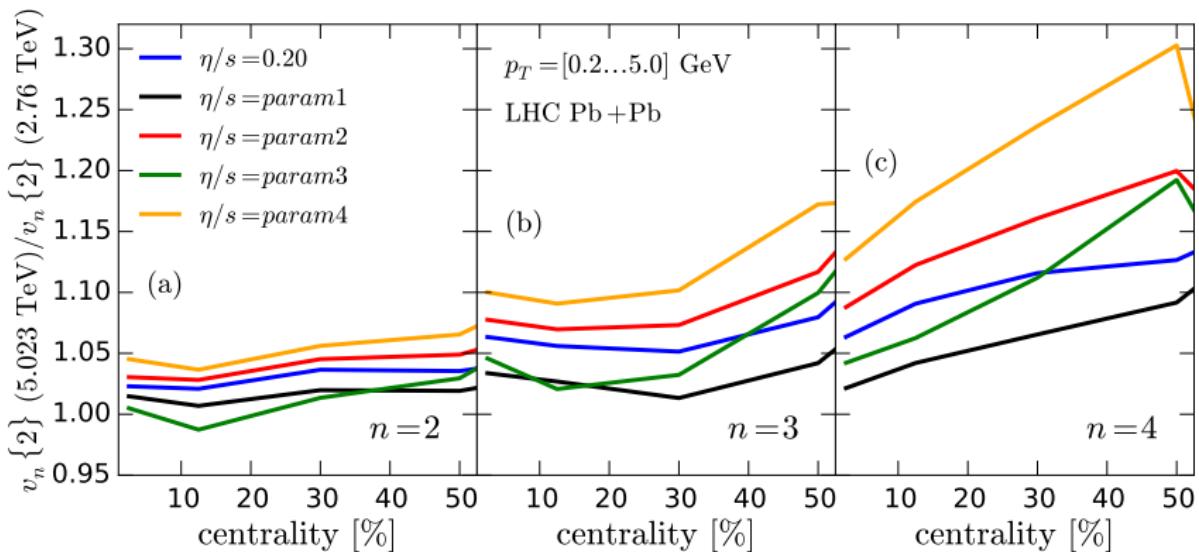
- Centrality & cms-energy dependence of  $N_{\text{ch}}$



Data: ALICE collaboration, arXiv:1512.06104

# Ratio of the flow coefficients $v_n\{2\}$ at 5.02 TeV and 2.76 TeV

Niemi, Eskola, Paatelainen, Tuominen, Phys.Rev. C93 (2016) 024907

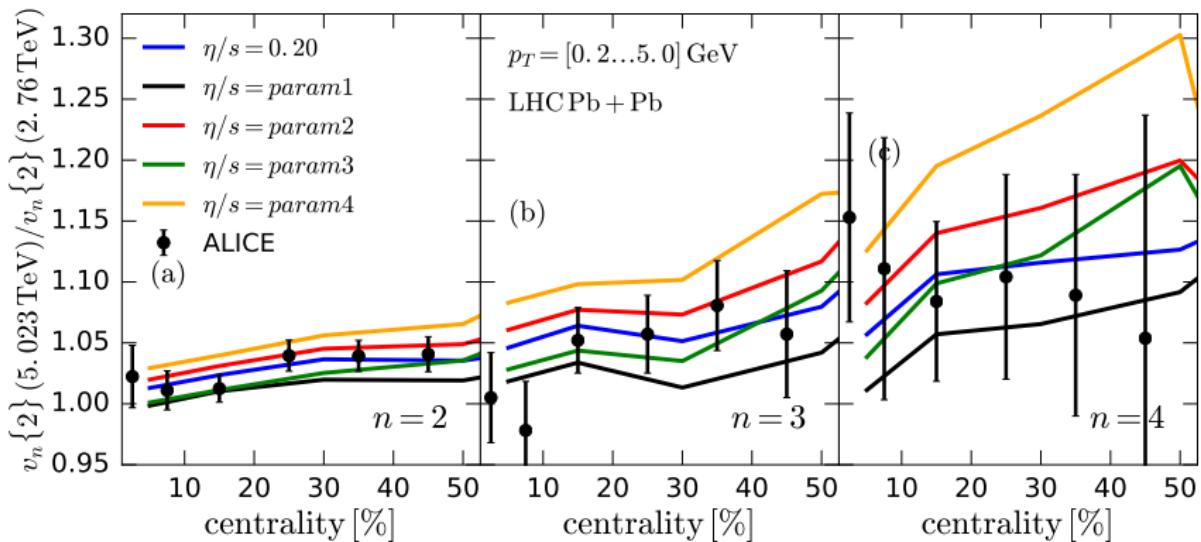


- ▶ Higher harmonics  $n > 2$  more sensitivity to  $\eta/s(T)$
- ▶ Constraints for  $\eta/s(T)$

Data: ALICE collaboration, Phys.Rev.Lett. 116 (2016) no.13, 132302

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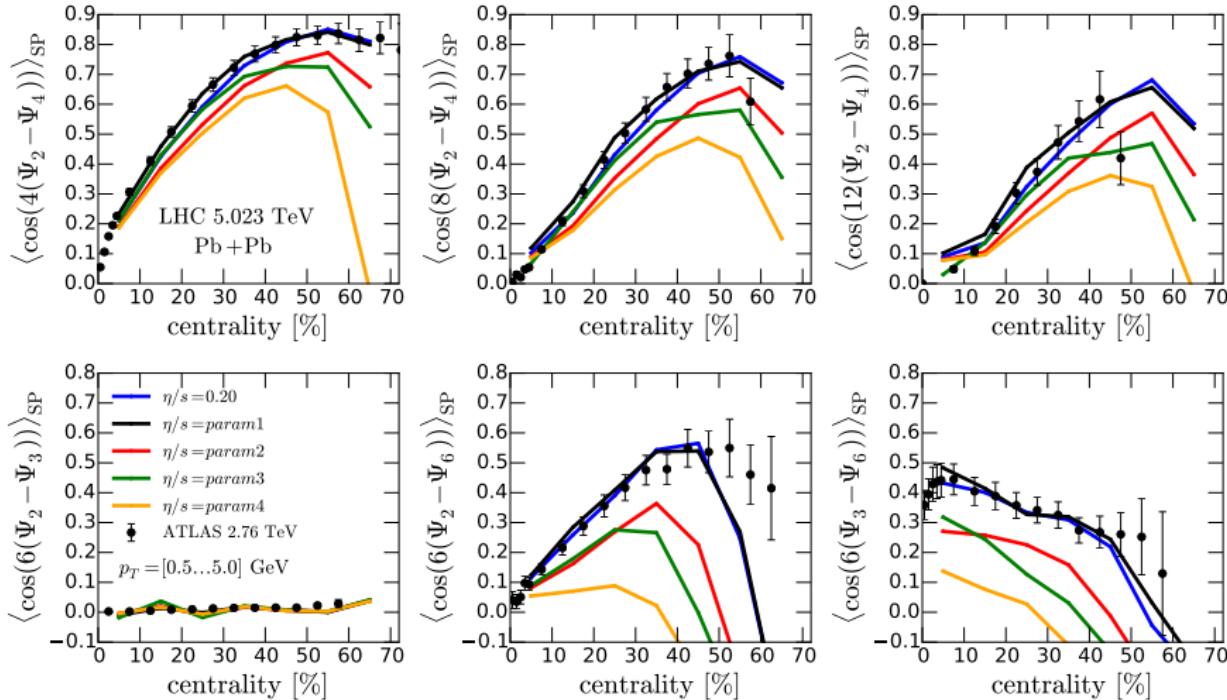
Niemi, Eskola, Paatelainen, Tuominen, Phys.Rev. C93 (2016) 024907



- Higher harmonics  $n > 2$  more sensitivity to  $\eta/s(T)$
- Constraints for  $\eta/s(T)$

Data: ALICE collaboration, Phys.Rev.Lett. 116 (2016) no.13, 132302

# Correlations of two EP angles for charged hadrons in 5.02 TeV Pb+Pb



- Small changes in the magnitude of 2 EP correlations from 2.76 TeV to 5.02 TeV

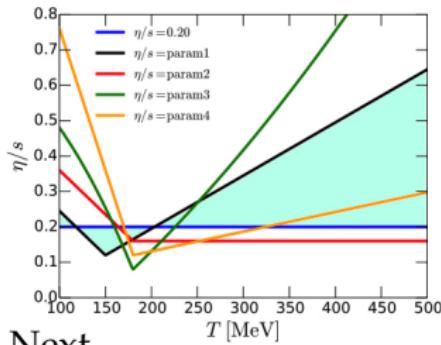
Niemi, Eskola, Paatelainen, Tuominen, Phys.Rev. C93 (2016) 024907

2.76 TeV Pb+Pb Data: ATLAS collaboration, Phys. Rev. C 90 (2014) 2, 024905

# Conclusions & Outlook

## The EbyE NLO EKRT framework

- ▶ Successfully explains the LHC and RHIC bulk observables in A+A collisions
- ▶ Has clear predictive power in cms energy, centrality, A
- ▶ Is a promising tool for getting a controlled estimate of the QCD matter shear viscosity



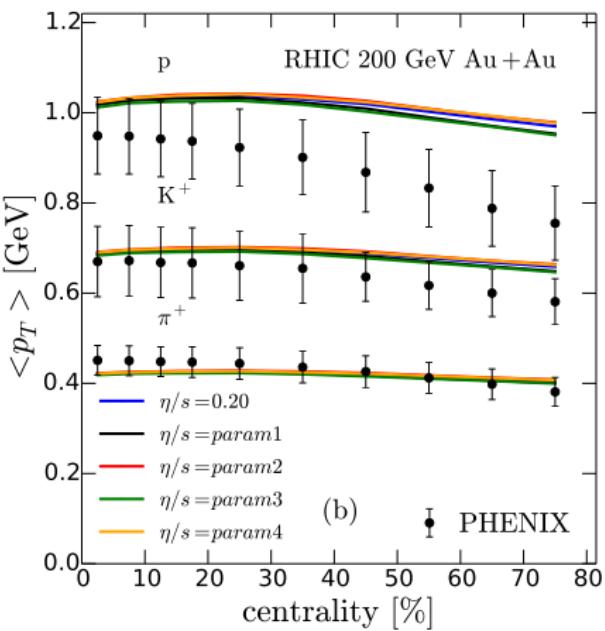
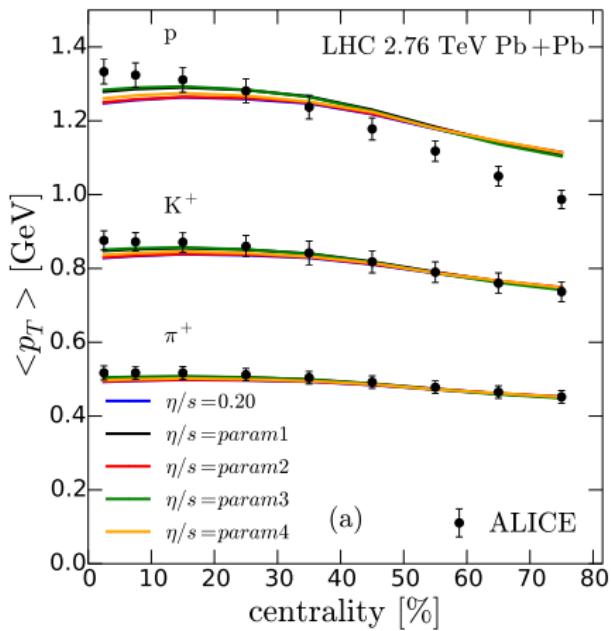
- ▶ Our "best" estimate currently for  $\eta/s(T)$
- ▶ But this is not yet a true error band, statistical global analysis needed (talk by S. Moreland)

Next ...

- ▶ Study also bulk viscosity effects
- ▶ Improve the pre-thermal evolution (combine EKRT & EKT [A. Kurkela])

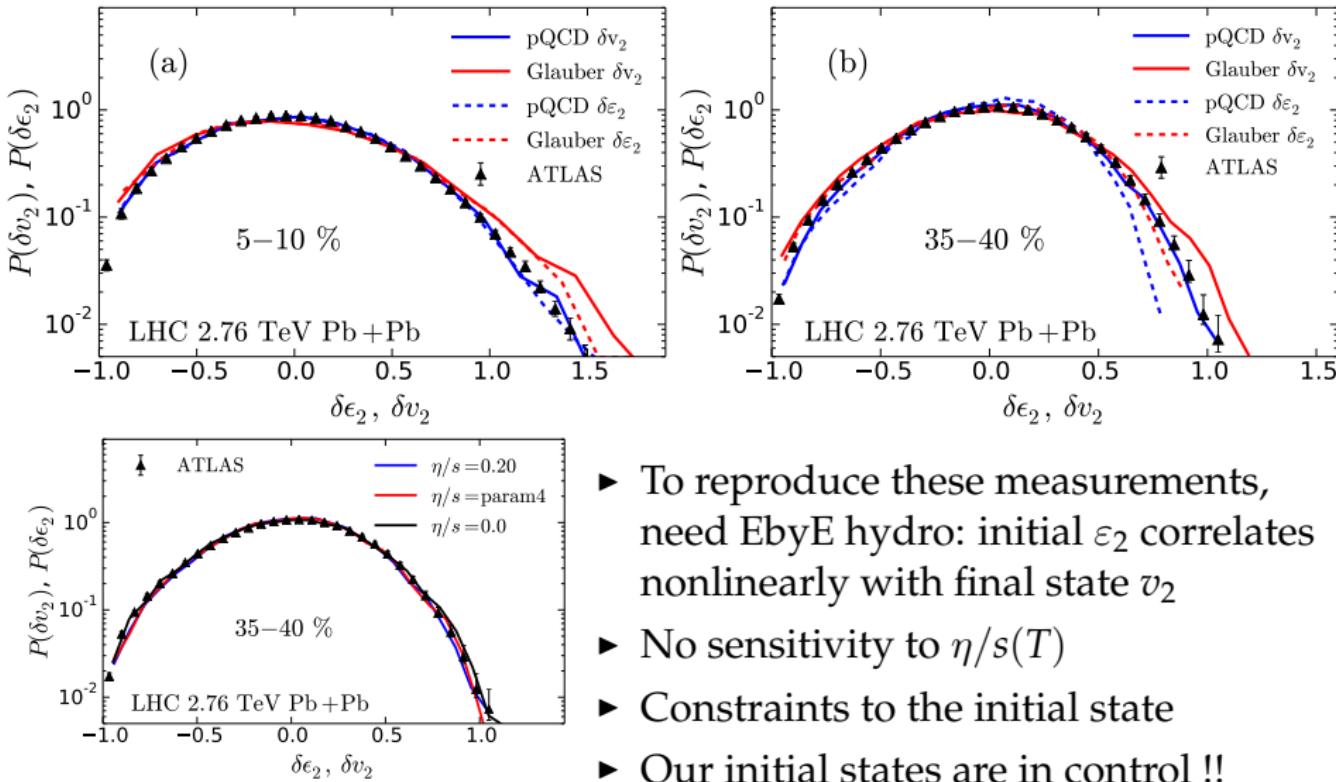
## BACKUP SLIDES

Also centrality dependence of the average  $p_T$  for pions, kaons and protons looks OK



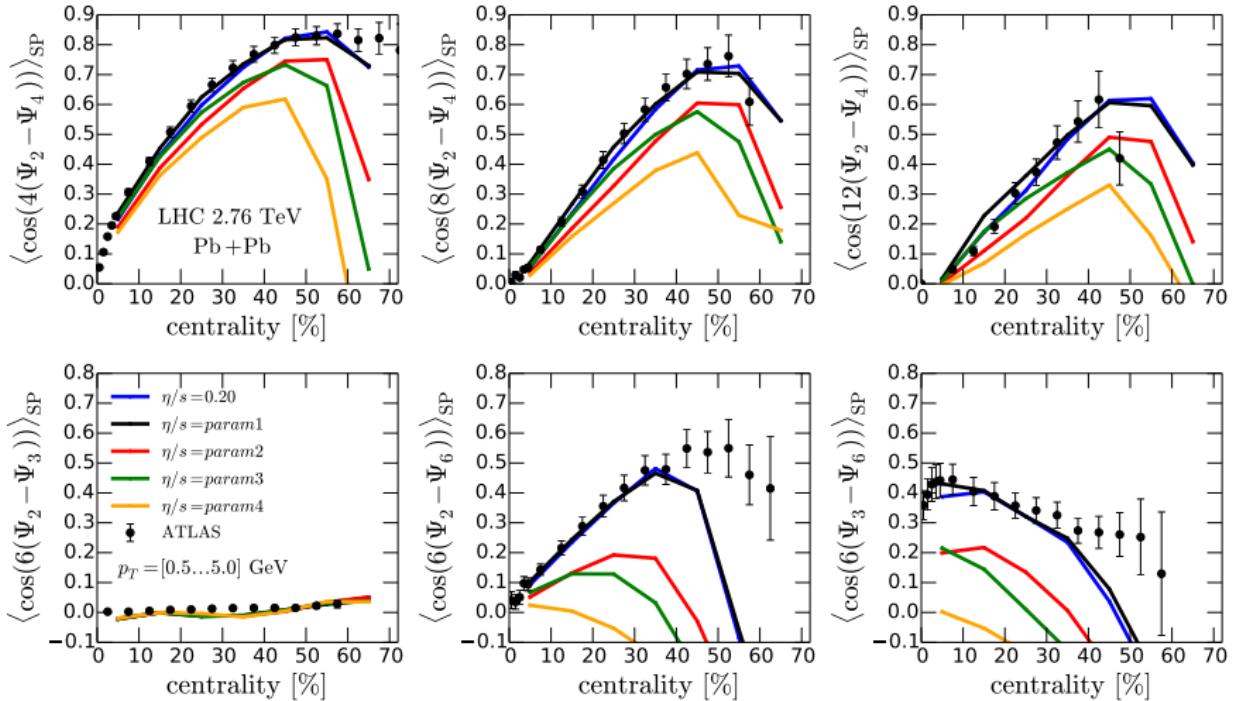
- Our QCD matter EoS is under (sufficient) control but essentially no constraints for  $\eta/s(T)$  from here, either

# Relative EbyE fluctuations of elliptic flow at LHC come out beautifully



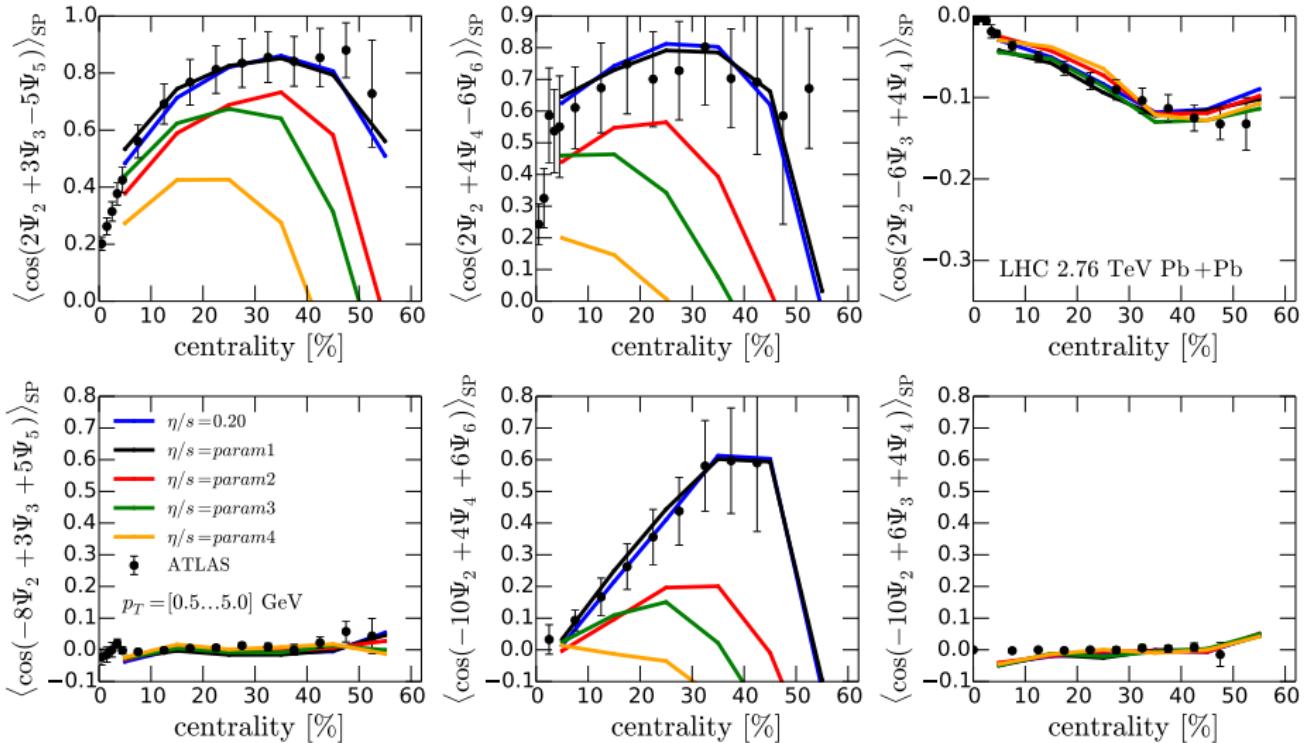
- ▶ To reproduce these measurements, need EbyE hydro: initial  $\varepsilon_2$  correlates nonlinearly with final state  $v_2$
- ▶ No sensitivity to  $\eta/s(T)$
- ▶ Constraints to the initial state
- ▶ Our initial states are in control !!

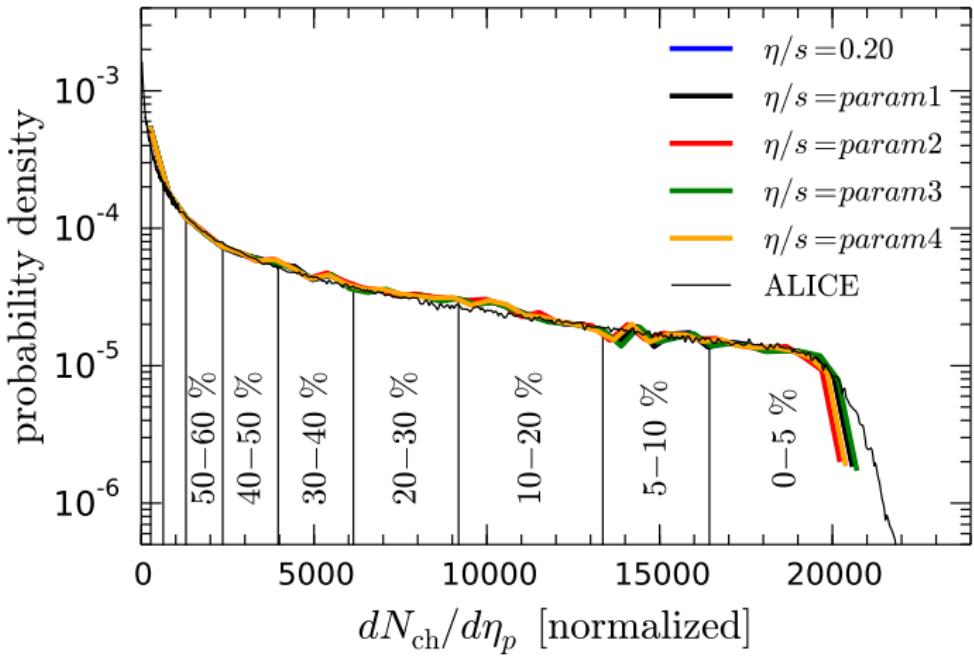
# Correlations of 2 Event-plane angles OK, for centralities < 40 – 50 %



- Since  $P(\delta v_n)$  constrain our ISs independently of  $\eta/s$ , these correlations give further constraints for  $\eta/s(T)$  and simultaneously test the validity of the EbyE viscous framework!

# Even the correlations of 3(!) Event-plane angles similarly OK





$$v_n = \left\langle \cos(n(\phi - \Psi_n)) \right\rangle / \left\langle 1 \right\rangle,$$

where

$$\left\langle \dots \right\rangle = \int dp_T^2 d\phi \frac{dN}{dy d\phi dp_T^2} (\dots)$$

$$\epsilon_{n,2} = \left\langle \epsilon(\mathbf{s}) r^2 \cos(n(\phi - \Psi_n)) \right\rangle / \left\langle \epsilon(\mathbf{s}) r^2 \right\rangle$$

where

$$\left\langle \dots \right\rangle = \int dx dy (\dots)$$

For us  $\epsilon_{2,2} = \epsilon_2$  and energy density  $\epsilon(\mathbf{s})$  from minijet initial conditions.

$$\begin{aligned} \langle \cos(k_1 \Psi_1 + \dots + nk_n \Psi_n) \rangle_{\text{SP}} &\equiv \\ \frac{\langle v_1^{k_1} \dots v_n^{k_n} \cos(k_1 \Psi_1 + \dots + nk_n \Psi_n) \rangle_{\text{ev}}}{\sqrt{\langle v_1^{2k_1} \rangle_{\text{ev}} \dots \langle v_n^{2k_n} \rangle_{\text{ev}}}} \end{aligned}$$