EbyE fluctuations in the EKRT pQCD+saturation+hydrodynamics model: Determining QCD matter shear viscosity in ultrarelativistic A+A collisions

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Reviewing the results from:

Phys.Rev. C93 (2016) 024907, arXiv:1505.02677 [hep-ph]
Phys.Rev. C93 (2016) 014912, arXiv:1511.04296 [hep-ph]

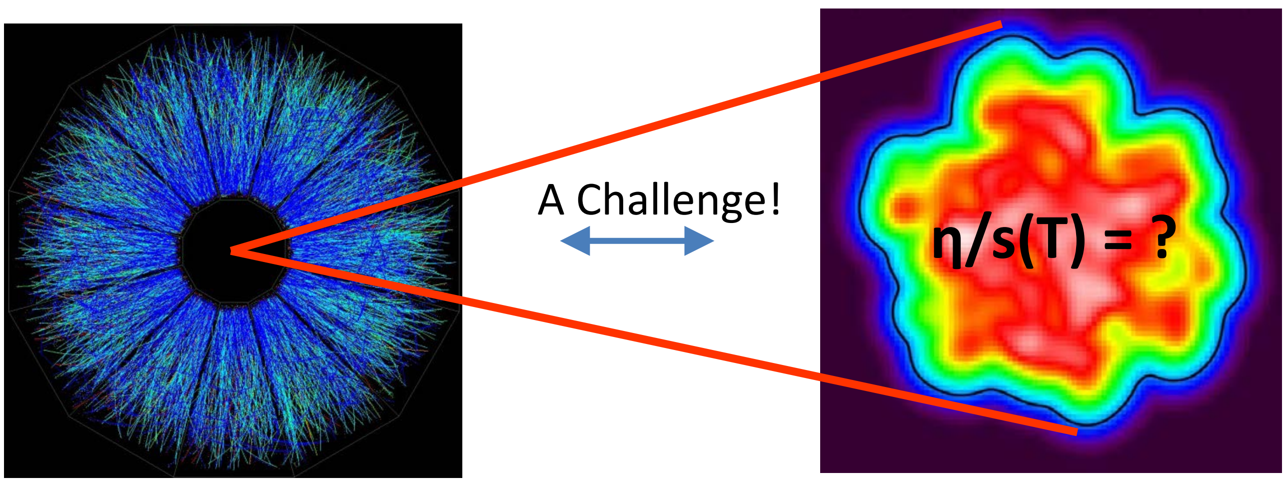
Talk plan

1. Background and some history

- original EKRT model

2. Recent developments in EKRT [Phys.Rev. C93 (2016) 024907]

- NLO pQCD, EbyE viscous hydro framework
- **Comparison with LHC & RHIC data → $\eta/s(T)$**



3. Predictions for the 5.02 TeV Pb+Pb LHC run

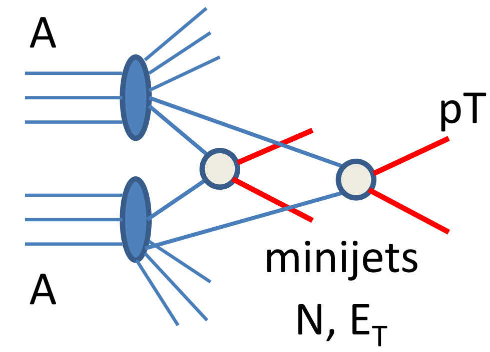
- **Compare** [Phys.Rev. C93 (2016) 014912] **with measurements**

1. Background: pQCD + saturation + hydro = EKRT model

[KJE,Kajantie,Ruuskanen,Tuominen, hep-ph/9909456, NPB570 (2000) 379]

Collinear factorization + pQCD

→ # few-GeV gluon "minijets" in A+A, y at ΔY, $p_T \geq p_0$



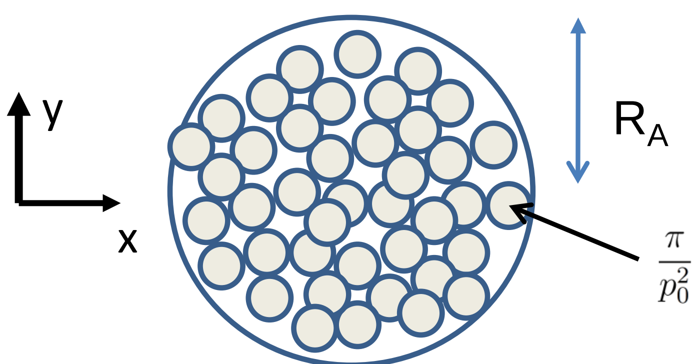
Collision geometry

$$N_{AA}(p_0, \sqrt{s}, \mathbf{0}, \Delta Y) = 2T_{AA}(\mathbf{0})\sigma_{\rm jet}(p_0, \sqrt{s}, \Delta Y, A)$$

$$T_{AA}(\mathbf{b}) = \int d^2\mathbf{s}\, T_A(\mathbf{s})\, T_A(\mathbf{b}-\mathbf{s}) \qquad T_A(\mathbf{b}) = \int dz\, n_A(r)$$

$$\sigma_{\rm jet}(p_0, \sqrt{s}, \Delta Y, A) = K \frac{1}{2} \sum_{\substack{ijkl=\\ g,q,\bar{q}}} \int_{\substack{p_0^2\\ \Delta Y}} dp_T^2 dy_1\, dy_2\, x_1 f_{i/A}(x_1, Q^2) x_2 f_{j/A}(x_2, Q^2) \frac{d\hat{\sigma}}{d\hat{t}}^{ij\to kl},$$

pQCD + nuclear PDFs

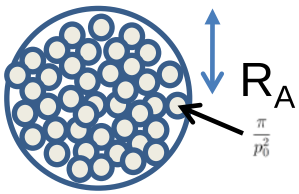


Saturation of minijet (= gluon) production

when p_0 = 1…2 GeV: lower-p_T gluons conjectured to be not relevant due to fusion of produced gluons

[Concept of saturation introduced by Gribov,Levin&Ryskin '83, Mueller&Qiu '86, and in the CGC framework by McLerran&Venugopalan '94, and noticed by us in '96]

[Original EKRT model]



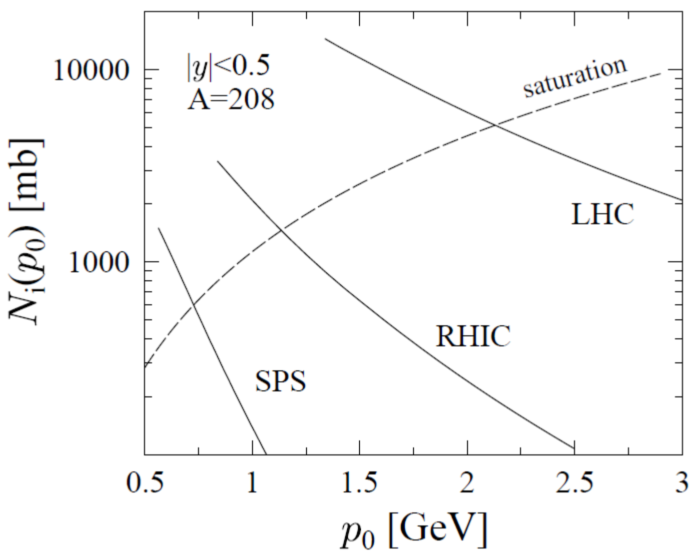
Saturation of gluon production in A+A at b=0 in ΔY=1 when

$$N_{AA}(p_0, \sqrt{s}, \mathbf{0}, \Delta Y = 1) \times \frac{\pi}{p_0^2} = \pi R_A^2$$

→ $p_{sat}=p_0$(**√s, A**)

→ minijet $N_i(p_{sat})$ and $E_T(p_{sat})$

[EKRT, hep-ph/9909456, NPB570 (2000) 379]



$$dN/dy \propto A^{0.92} s^{0.19...0.2}$$

- QGP **forms early:** τ_i=1/p_{sat} = 0.1 …0.2 fm
- the produced QGP looks "thermal" in E_T/N :
  - may assume early thermalization, τ_0= τ_i
  - **initial conditions for ideal hydro (1 D BJ)**

$N_i(p_{sat})$ or $E_T(p_{sat})$ → S_i = S_f → N_f

- **Predicted very definite scaling laws, before any(!) RHIC data**

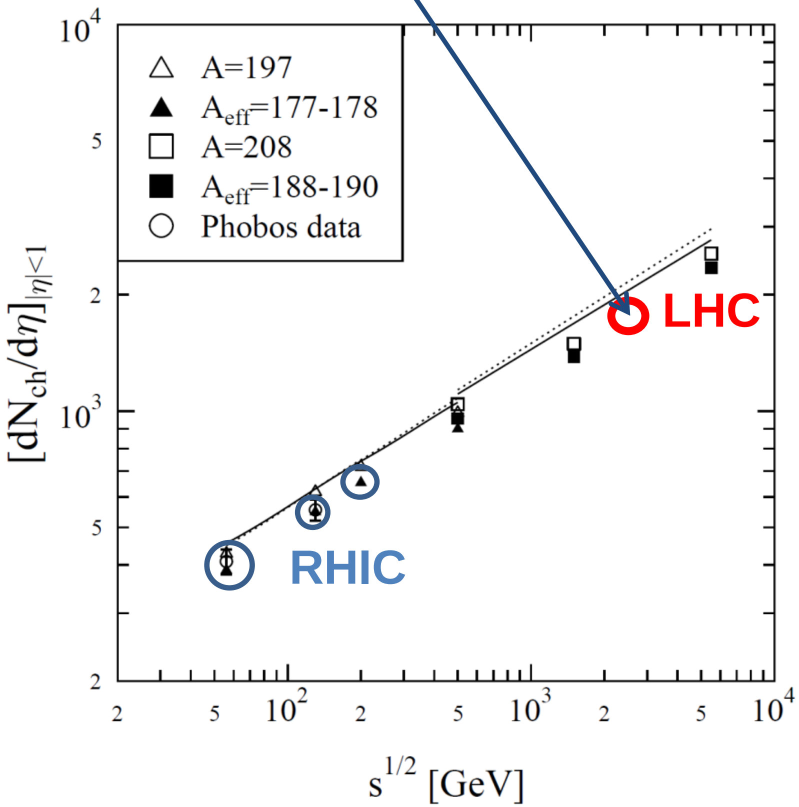
[EKRT, hep-ph/9909456, NPB570 (2000) 379]

Hard scaling $A^{4/3}$ was tamed to ~A & Power law in cms-energy !

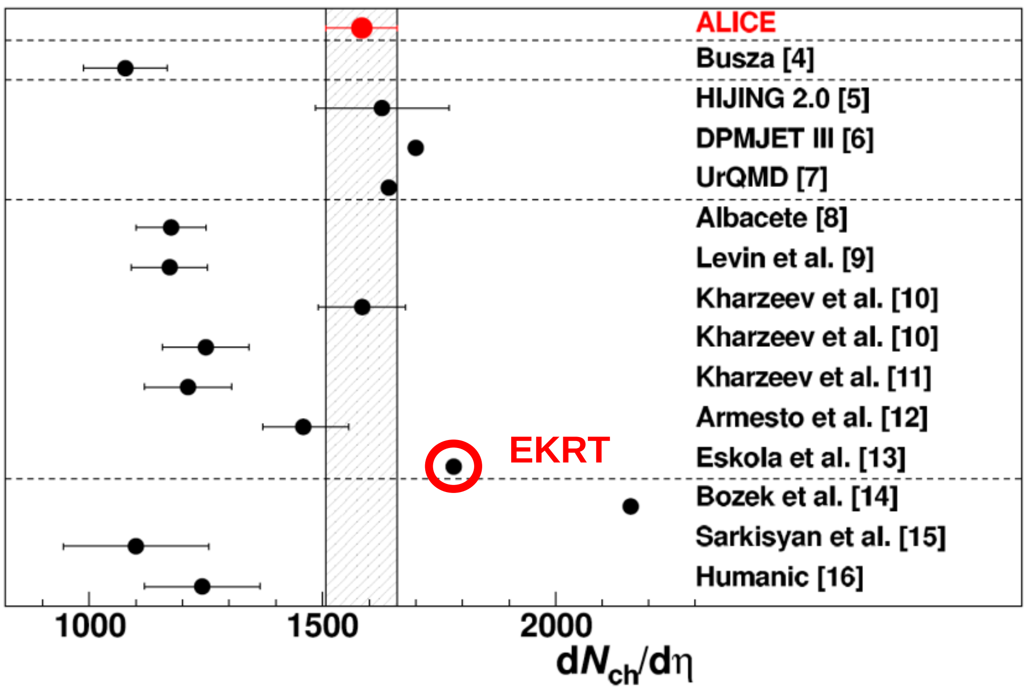
[Comment in 2001 in CERN (=after the first RHIC data) "It can never be a power-law in s!"]

A more detailed EKRT-model prediction

- ideal 1+1 D hydro, LO nPDFs + pQCD partly NLO [KJE, Tuominen, Phys.Rev. D63 (2001) 114006]
  [KJE,Ruuskanen,Räsänen, Tuominen,NPA696:715,**2001**]
- made **before** the 200 GeV RHIC data
- $dN_{ch}/d\eta$ = 1782 for 2.76 ATeV



ALICE, PRL105:252301,**2010**
1584 +- 76

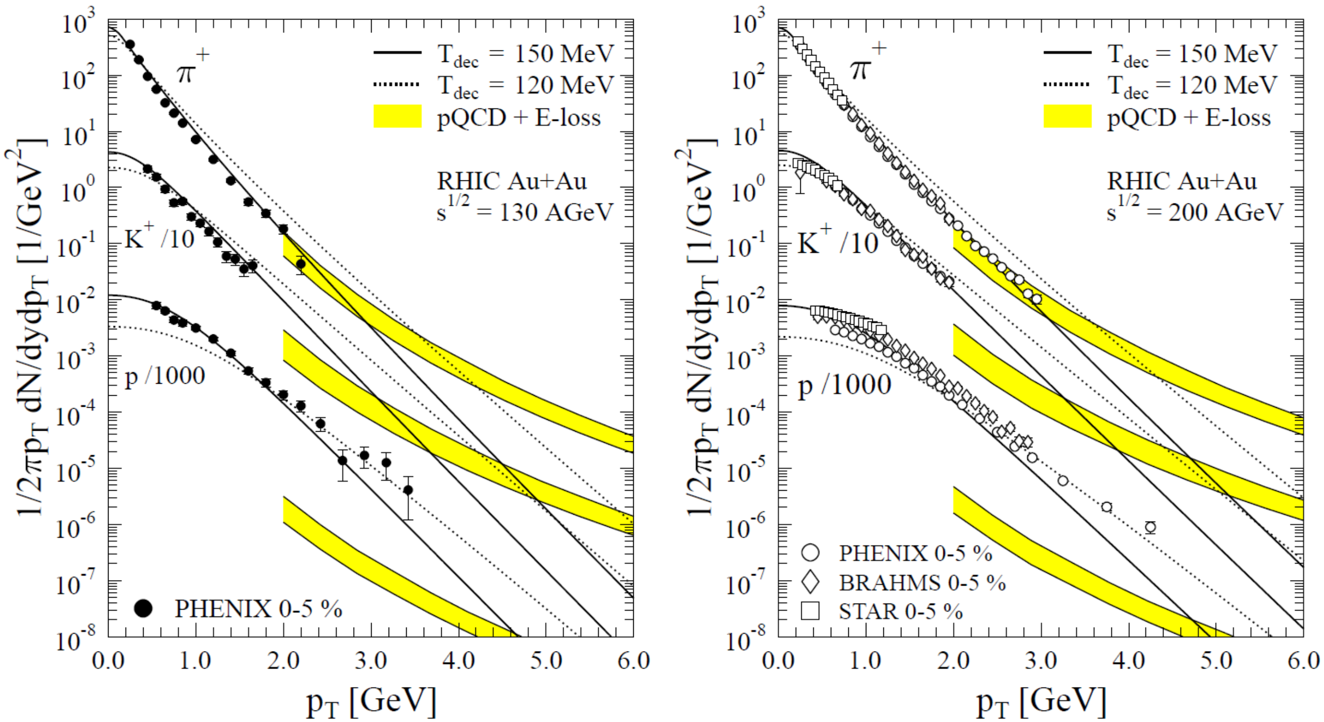


EKRT correct within ~7%

Our prediction 2560 for the max cms-energy was VERY LOW AT THE TIME, << 8000,
but after RHIC 200 GeV data, suddenly **WE** were on the **high-side** of predictions!
[Miklos in 2007 at CERN: ”I’m glad your knees don’t wobble!” (but they did…)]

Successful framework tests in Au+Au at RHIC (still with **ideal hydro**)

[KJE, Honkanen, Niemi, Ruuskanen, Räsänen, PRC72 (2005) 044904]



EKRT observation: To get these pT spectra right means a factor THREE(!) reduction from the computed $E_{T\mathrm{initial}}(p_{sat})$ to the measured $E_{T\mathrm{final}}$
= PRESSURE at work during the hydrodynamic stage!

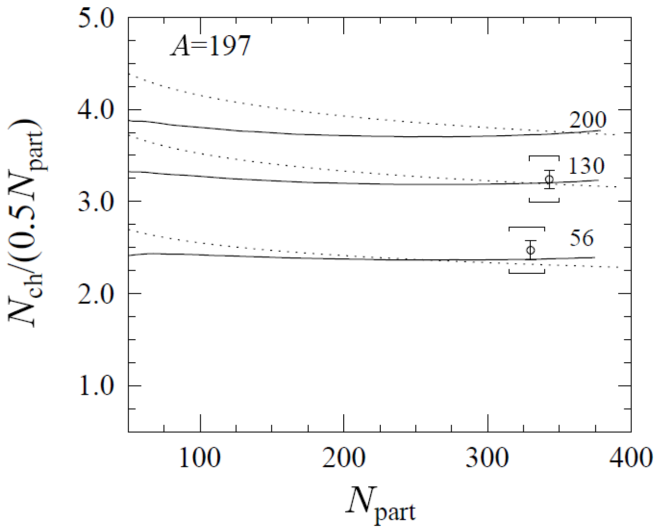
OK but how about the detailed properties of QCD matter…?

[Original EKRT model]

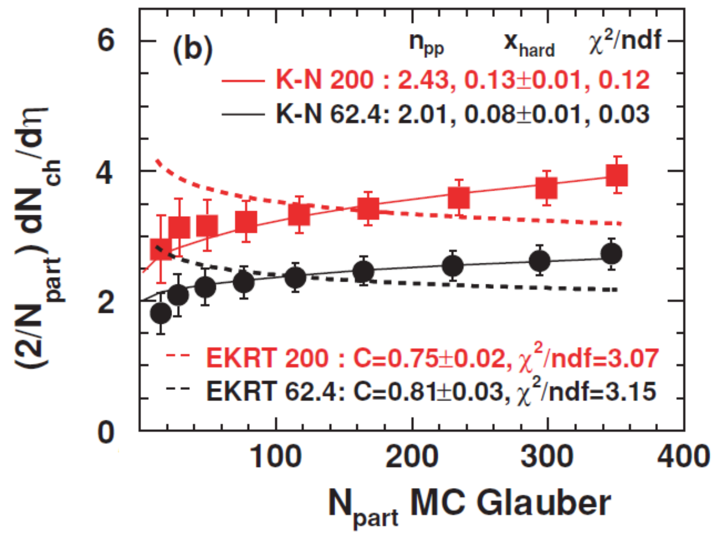
History remark: Centrality dependence in EKRT was in fact not a problem !

Localizing the model for non-central collisions: $p_{sat}=p_0(\sqrt{s}, A, x,y)$

[KJE, Kajantie, Tuominen, Phys.Lett. B497 (2001) 39]



[STAR, PRC79, 034909 (2009)]



EKRT prediction: N_{ch}/N_{part} vs N_{part} flat or even slightly rising towards non-central A+A, **seemed not agree with data…**

[Original EKRT model]

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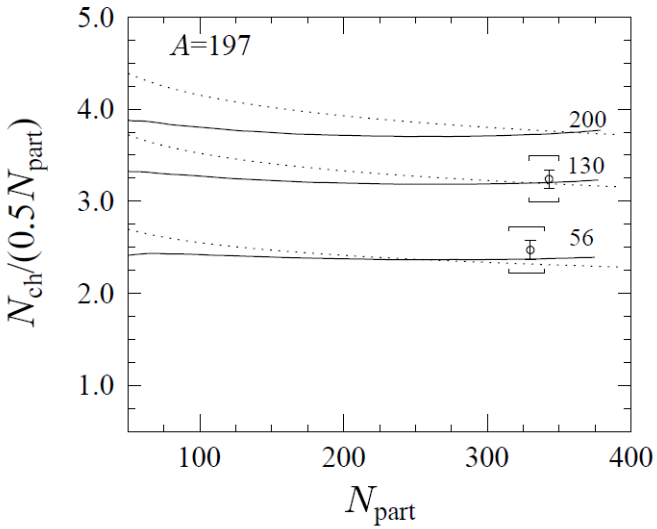
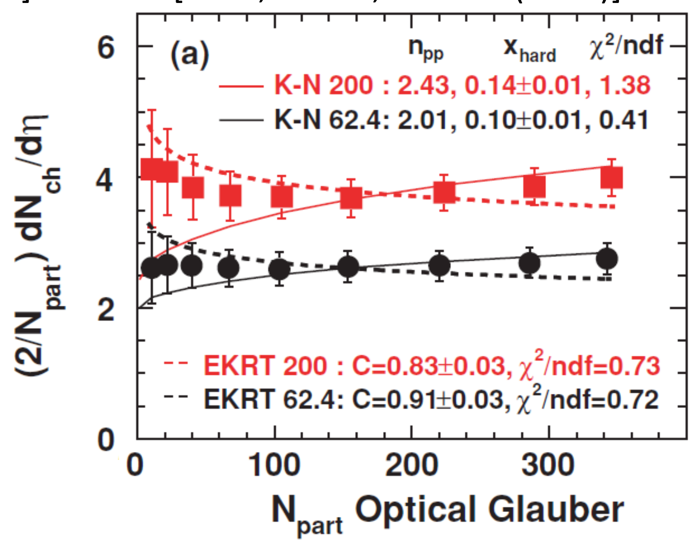


[STAR, PRC79, 034909 (2009)]



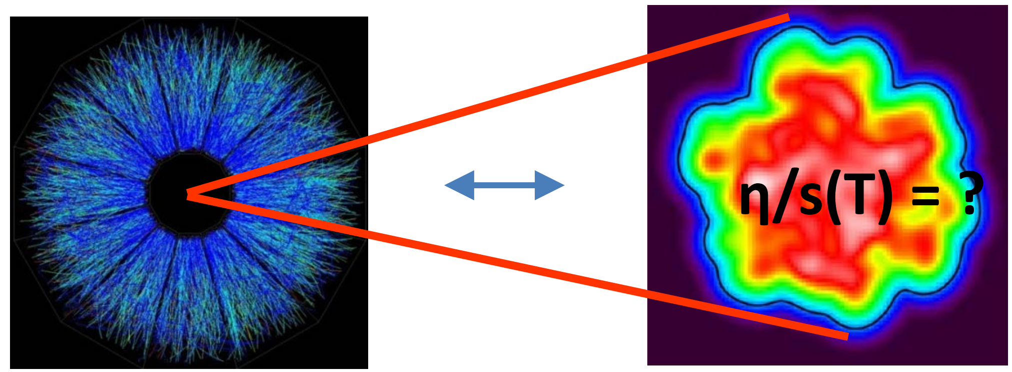
EKRT prediction N_{ch}/N_{part} vs N_{part} is flat or even slightly rising towards non-central A+A, **did agree with data when the same optical Glauber model was used for Npart !**

[This thorough STAR analysis revived also my interest in the more detailed EKRT studies discussed next]

2. Recent developments in EKRT

[Phys.Rev. C87 (2013) 044904]
[Phys.Lett. B731 (2014) 126]
[**Phys.Rev. C93 (2016) 024907**]

- full NLO pQCD & improved minijet ET definition
- new angle to saturation
- viscous 2+1 D hydro
- **EbyE framework**



Basic idea:

1. Compute minijet (=gluons, pT= a few GeV) ET production in A+A, using **NLO perturbative QCD** + **saturation** conjecture for ET

2. Describe space-time evolution of QCD matter with **viscous hydrodynamics** initialized with **fluctuating** pQCD+saturation initial conditions, **event by event**

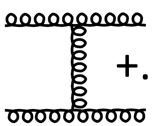
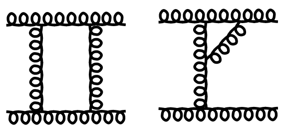
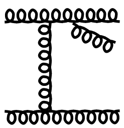
3. Compare with LHC & RHIC data for bulk (=low pT) observables, to
   - pin down QCD matter η/s(T)
   - test the initial state calculation and its predictive power
   - study the applicability region of viscous hydro

Minijet ET production in A+A and Δy from NLO pQCD

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

- **s**=(x,y) transverse position,   Δy = unit rapidity window
- $T_A T_A$ accounts for nuclear collision geometry
- Collinear factorization, NLO pQCD in 2→2 and 2→ 3 parton scatterings:

$$\sigma\langle E_T\rangle_{p_0,\Delta y} = \int \mathrm{d}[\mathrm{PS}]_2 \frac{\mathrm{d}\sigma^{2\to2}}{\mathrm{d}[\mathrm{PS}]_2} S_2 + \int \mathrm{d}[\mathrm{PS}]_3 \frac{\mathrm{d}\sigma^{2\to3}}{\mathrm{d}[\mathrm{PS}]_3} S_3$$

 +...  +...  +...

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

- $f_{i/A}$ = spatially dependent nPDFs (see next page)
- UV-renormalized $|M|^2$ [Ellis,Sexton,Nucl.Phys. B269 (1986) 445, Paatelainen's PhD thesis]
- Ellis-Kunszt-Soper subtraction method [see KS, Phys.Rev. D46 (1992) 192; KJE, Tuominen, Phys.Rev. D63 (2001) 114006] with IR/CL safe measurement functions S_2 & S_3 to define the minijet ET in NLO

Spatially dependent nPDFs

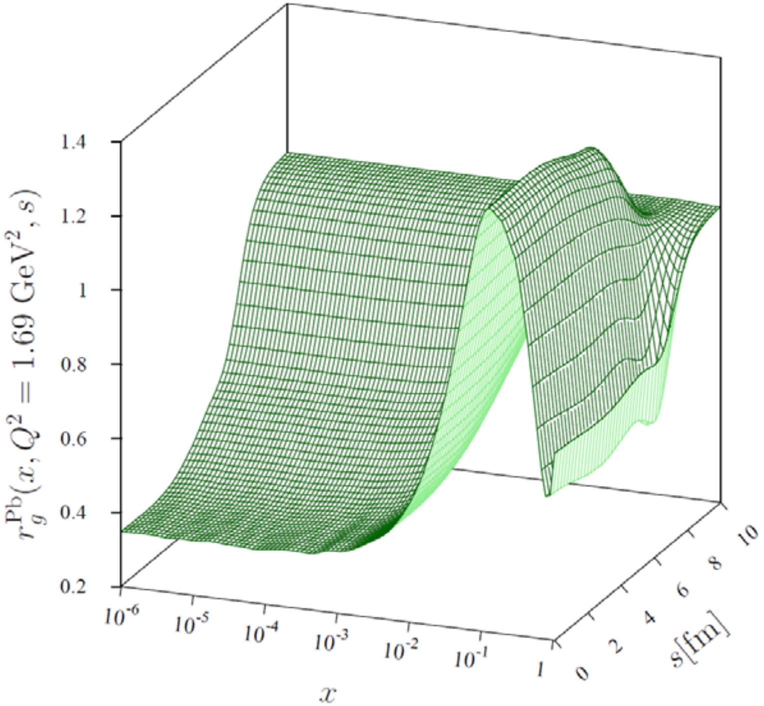
$$f_{i/A}(x, Q^2, \mathbf{s}) \equiv r_i^A(x, Q^2, \mathbf{s}) \otimes f_i^p(x, Q^2)$$

- $f_i^p(x,Q^2)$: free proton PDFs from CTEQ6M
- $r_i^A(x,Q^2,s)$: **spatially dependent** NLO **EPS09s** nuclear PDF modifications from [Helenius et al, JHEP 1207 (2012) 073], where the A-dependences of the EPS09 nPDF modification factors $R_i^A(x,Q^2)$ were converted into **s**-dependences via

$$r_i^A(x, Q^2, \mathbf{s}) = 1 + \sum_{j=1}^{n} c_j^i(x, Q^2)\,[T_A(\mathbf{s})]^j$$

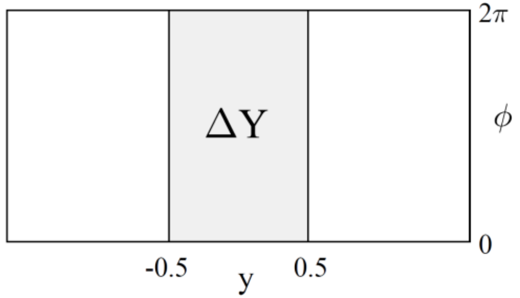
$$R_i^A(x, Q^2) \equiv \frac{1}{A}\int d^2\mathbf{s}\, T_A(\mathbf{s})\, r_i^A(x, Q^2, \mathbf{s})$$

Nuclear modifications are strongest near the center of a nucleus, and **weaken towards the edge**



Measurement functions for computing minijet ET in NLO

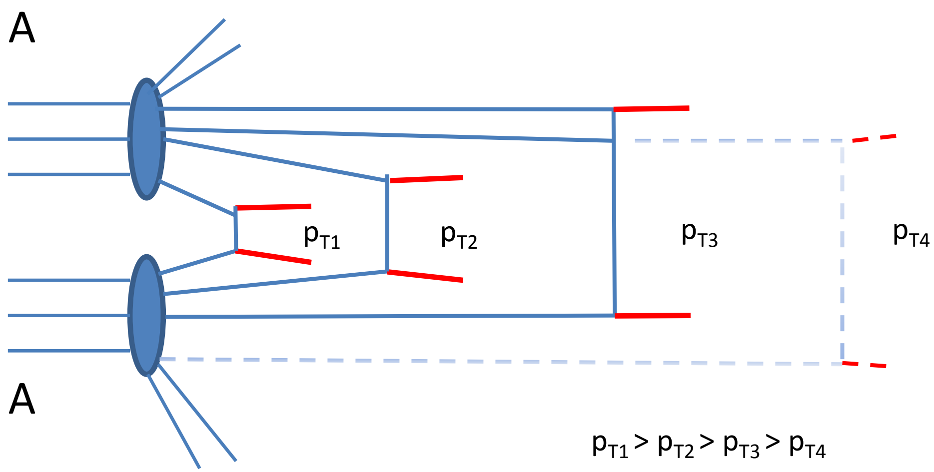
$$S_n = \underbrace{\left[\sum_{i=1}^{n} p_{T,i}\Theta(y_i \in \Delta y)\right]}_{\text{Minijet } E_T \in \Delta y} \times \Theta \underbrace{\left(\sum_{i=1}^{n} p_{T,i} \geq 2p_0\right)}_{\text{Hard scat. of partons}} \times \underbrace{\Theta(E_{T,n} \geq \beta \times p_0)}_{\text{Minimum } E_T \in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



- analogous to jet definition; S_n define
  - the minijet ET in Δy
  - what we mean by hard scattering (p0)
  - what is the min ET we may require in Δy
- IR & CL safeness: $S_3 \rightarrow S_2$ at IR & CL limits
- any β in [0,1] is **OK** → leave β as a free parameter
  since the minijet ET is not a direct observable
  [Paatelainen, KJE, Holopainen, Tuominen, Phys. Rev. C87 (2013) 4, 044904]
- with these S_n + given nPDFs, minijet NLO ET computation is **well defined!**

A new angle to saturation [Paatelainen,KJE,Holopainen,Tuominen, PRC87 (2013) 044904]

instead of fusion of produced gluons, we conjecture saturation to happen when E_T from 3→2, 4→2,… processes becomes of the same order as the E_T from 2→2:

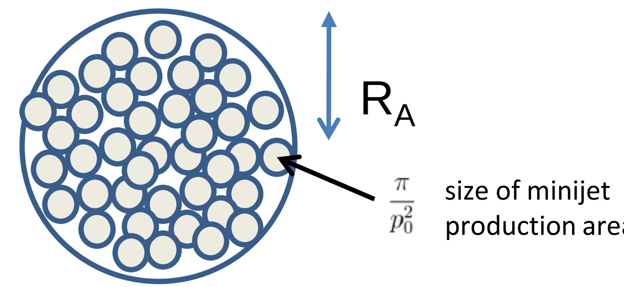


$$\frac{dE_T}{\mathrm{d}^2\mathbf{s}dy}(2\to 2) \sim \frac{dE_T}{\mathrm{d}^2\mathbf{s}dy}(3\to 2) \sim \text{H.O.}$$

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

$\Rightarrow$ **Saturation criterion** like in the original EKRT but now consistently **for ET**:

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



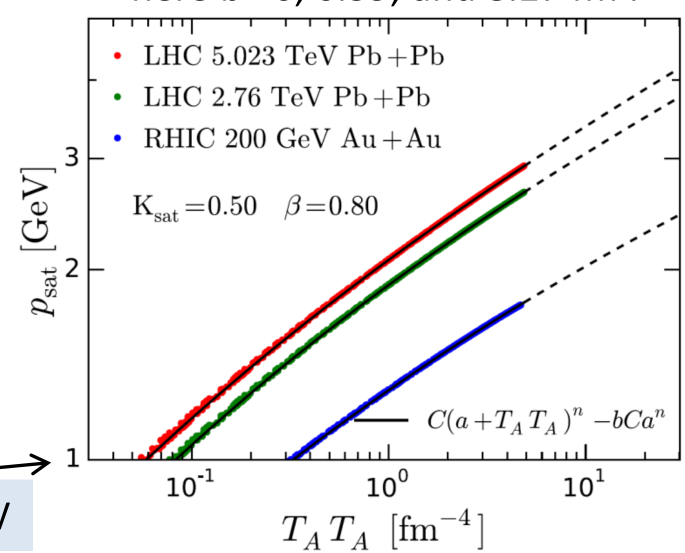
$$\Rightarrow \quad p_0 = p_{sat}(\sqrt{s_{NN}}, A, \mathbf{b}, \mathbf{s}; \beta, K_{sat})$$

K_{sat} from data

Key observation: **p_{sat} scales with $T_A T_A$**:
This enables the EbyE framework for us…

[Paatelainen, KJE, Niemi, Tuominen, Phys.Lett. B731 (2014) 126]

here b= 0, 6.59, and 8.27 fm :



min(p_{sat})=1 GeV

[Niemi, KJE, Paatelainen, Tuominen, Phys.Rev. C93 (2016) 014912]

NLO EKRT EbyE framework

[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

- Nucleon positions in A: sample **WS distribution**
- Around each nucleon, set a **gluon cloud of transverse density**

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

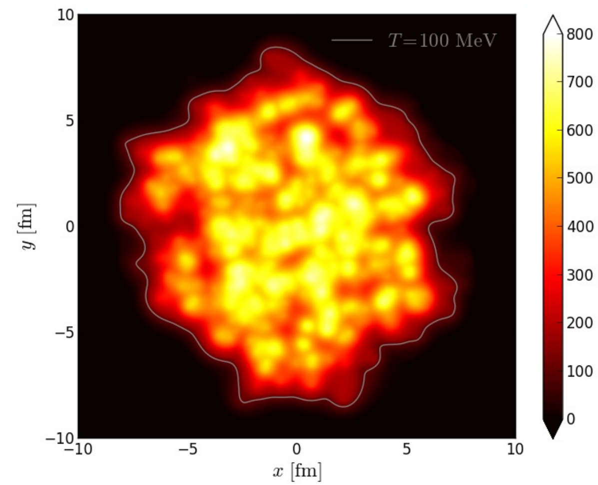
σ= 0.43 fm from HERA $\gamma^\star p \to J/\psi + p$ data

⇒ **Overlap functions $T_{A1}(x,y)$ & $T_{A2}(x,y)$** ⇒ $p_{sat}=p_{sat}(T_{A1}*T_{A2})$ (*)

⇒ Local energy density at $\tau_{\rm sat} = 1/p_{\rm sat}(\mathbf{s})$

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

- "Pre-thermal" evolution from $\tau_{sat}= 1/p_{sat}(x,y)$ to $1/p_{sat}^{min}$ = **0.2 fm/c** here done simply with 1 D Bjorken hydro at each (x,y) (we tested also free streaming, both OK)
- Below p_{sat}^{min} = 1 GeV, connect smoothly to BC profile



run 2+1 D viscous hydro EbyE

(*) Parametrization of $p_{sat}(T_{A1}T_{A2})$ vs (K_{sat},β) is available for public use in Phys.Rev. C93 (2016) 024907

Viscous Hydrodynamics [Niemi et al]

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + (P + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

Neglect heat conductivity & bulk viscosity;
Keep **shear viscosity η**;
2nd order dissipative relativistic hydrodyn.

$\partial_\mu T^{\mu\nu} = 0$ + transient fluid-dynamics EoM for $\pi^{\mu\nu}$
[Denicol,Niemi,Molnar,Rischke,PRD85(2012)114047]
+ s95p-PCE-v1 QCD EoS: T_{chem}= 175 MeV; T_{fo}=100 MeV
[Huovinen,Petreczky,NPA837(2010)26]

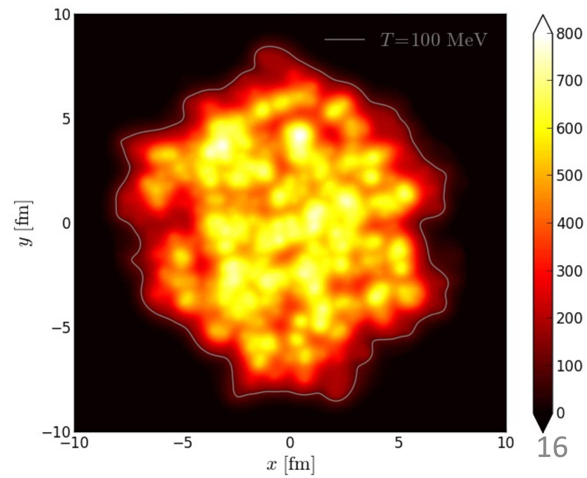
Viscosity effects:

- reduced flow-velocity gradients **during the evolution**
- **entropy increase** from initial to final state
- Non-equilibrium particle distributions **on the freeze-out surface**

$$f_i(x,p) = f_{0i}(x,p) + \delta f_i = f_{0i}(x,p)\left[1 + \frac{p_{i\mu}p_{i\nu}\pi^{\mu\nu}}{2T^2(e+P_0)}\right]$$

Initial conditions in our EbyE case:

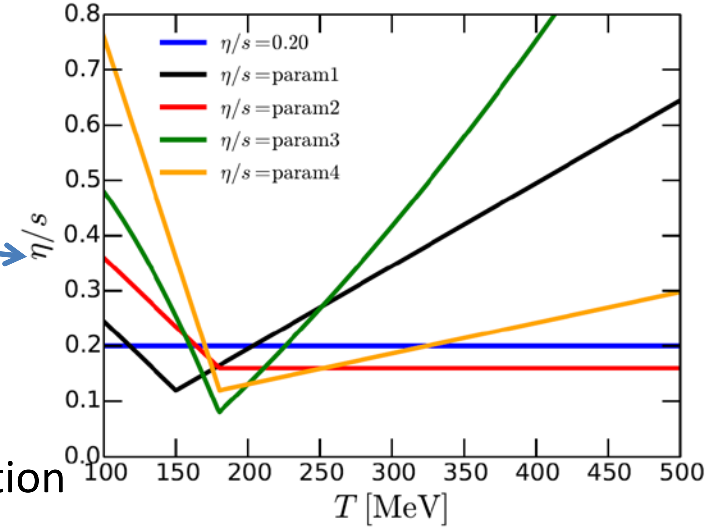
- The **computed** EbyE-fluctuating energy densities $\varepsilon(x,y,\tau_i$=0.2 fm)
- Initial $\mathbf{v}_T$= 0
- Initial $\pi^{\mu\nu}$ = 0



[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

Comparison with LHC and RHIC data

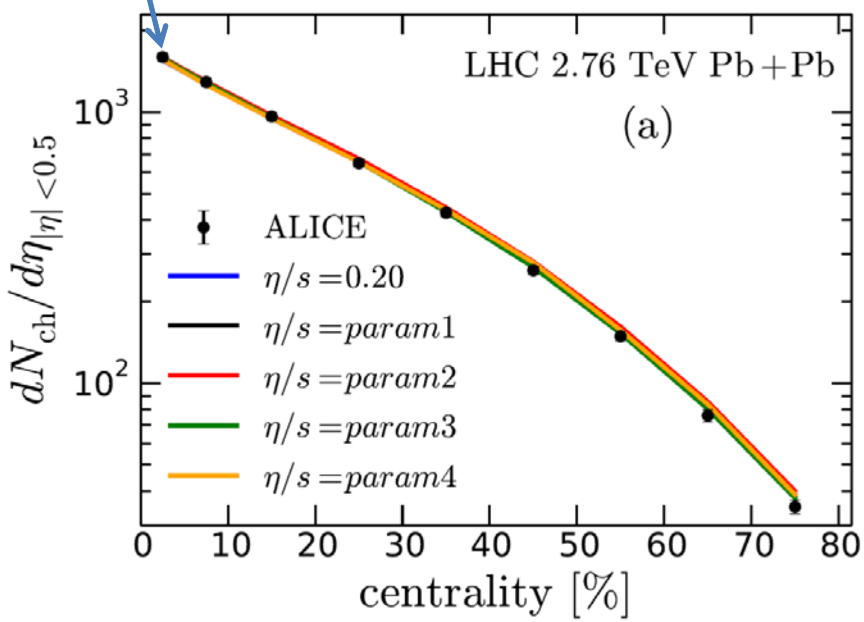
Map the possible T dependence of η/s(T) with these parametrizations, reproducing the measured v_2 at LHC



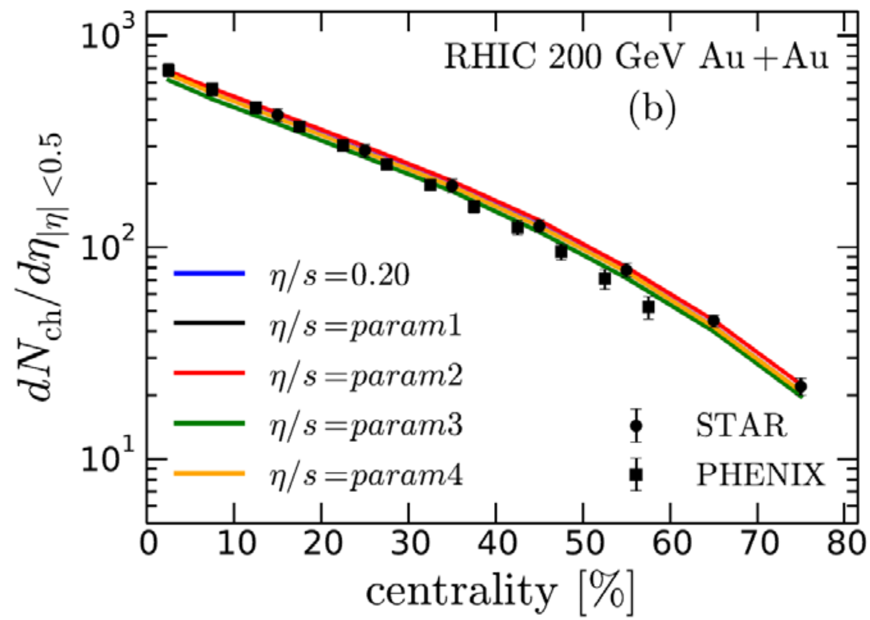
Centrality dependence of N_{ch} comes out correctly;

-- only <u>**one**</u> LHC-point (K_{sat} & β) is fitted, the rest is prediction

LHC



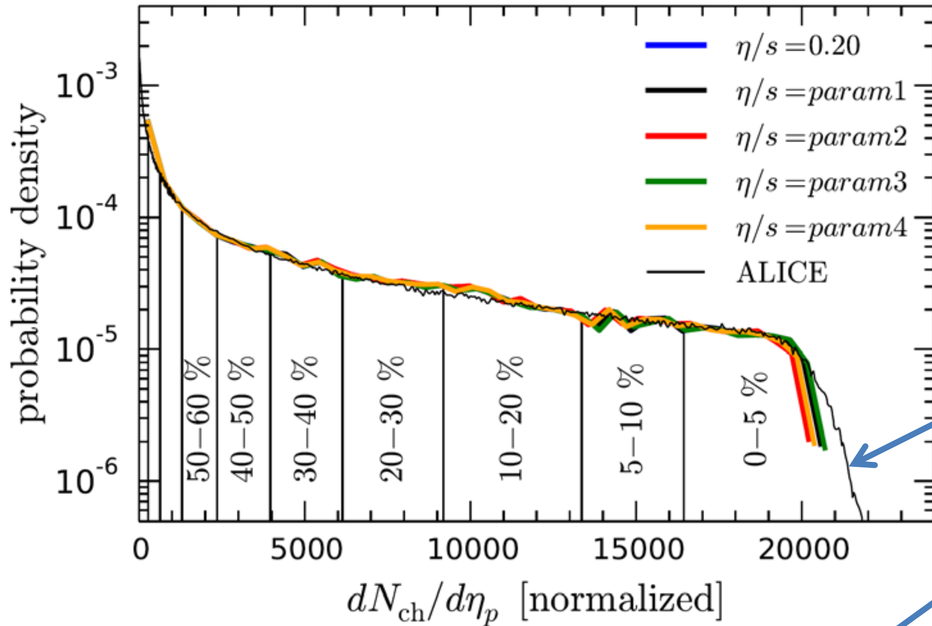
RHIC



⇒ Our **<initial transverse densities> [width of the gluon cloud!] are under control**, but essentially no constraints for η/s(T) from this observable

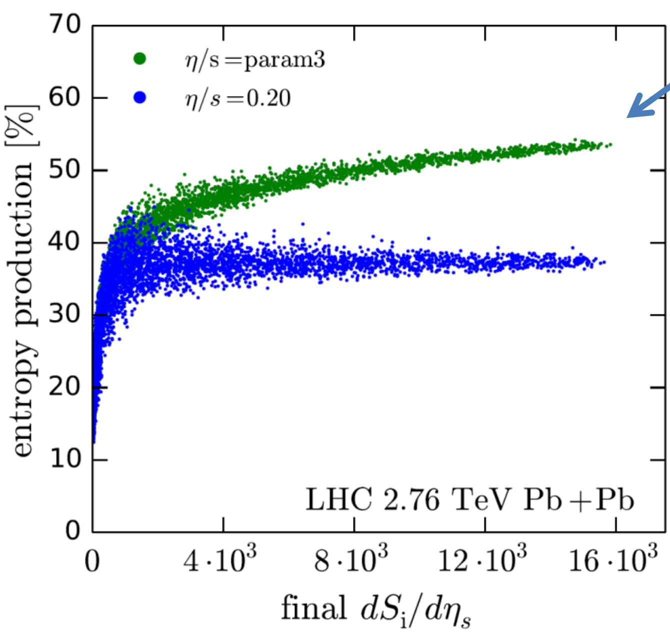
[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

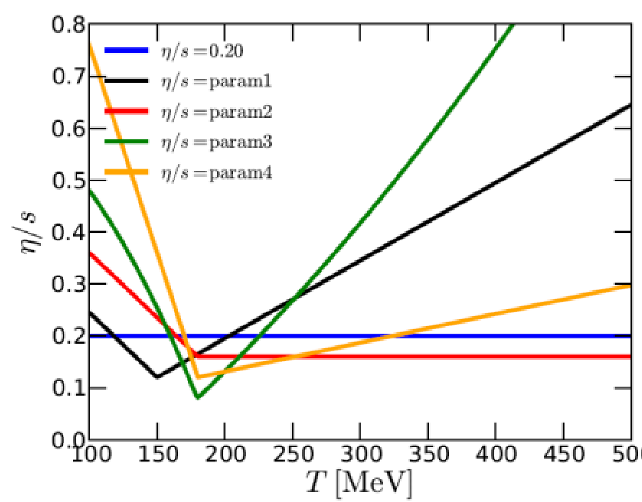
Our centrality classification is under control



We do **not** yet include dynamical fluctuations of p_{sat}, hence we **do not (should not!)** reproduce the highest-multiplicity tail

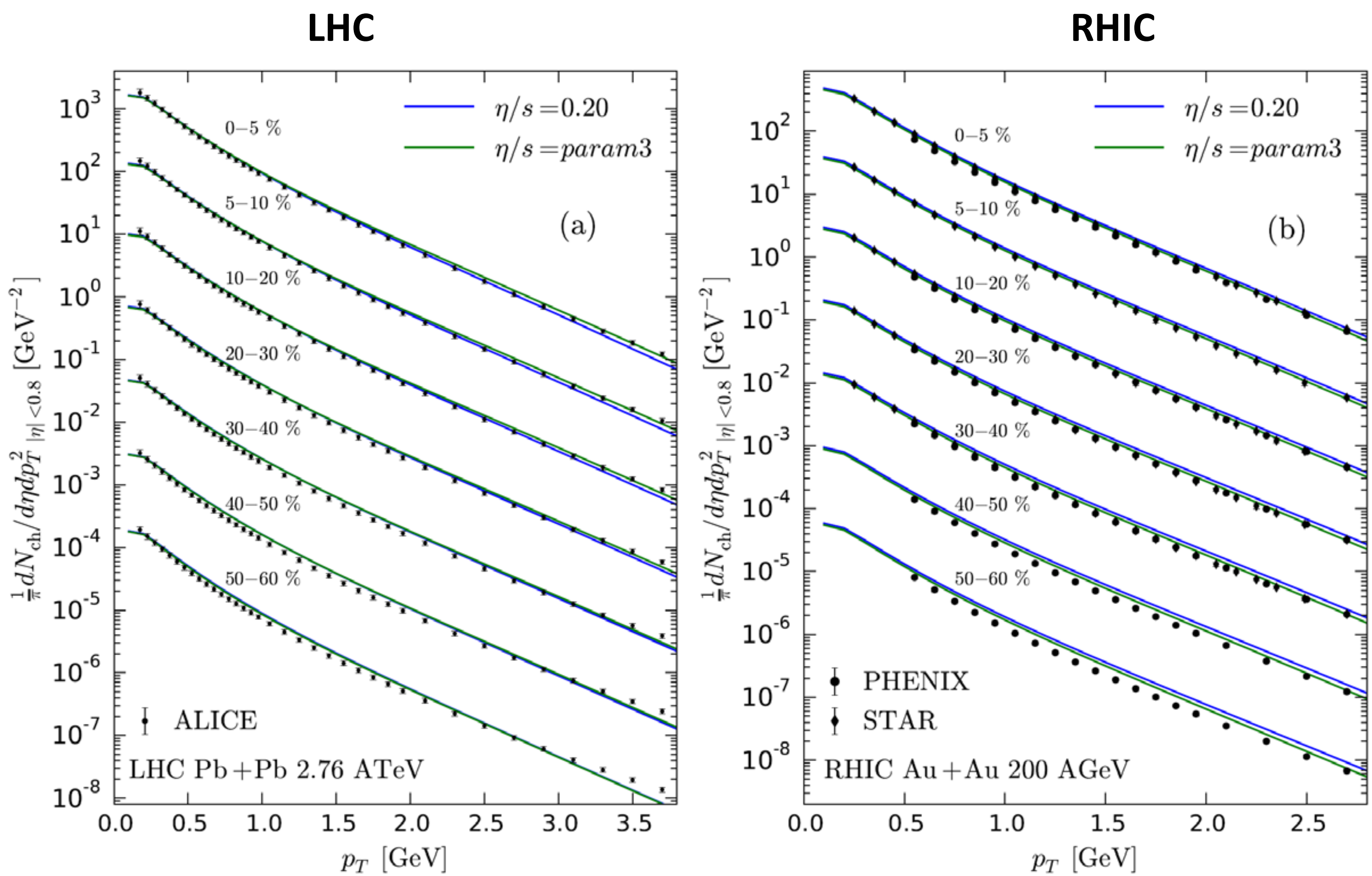
Entropy increases from initial to final state the more the QGP viscosity is!





[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

Centrality dependence of charged-hadron pT spectra ~OK

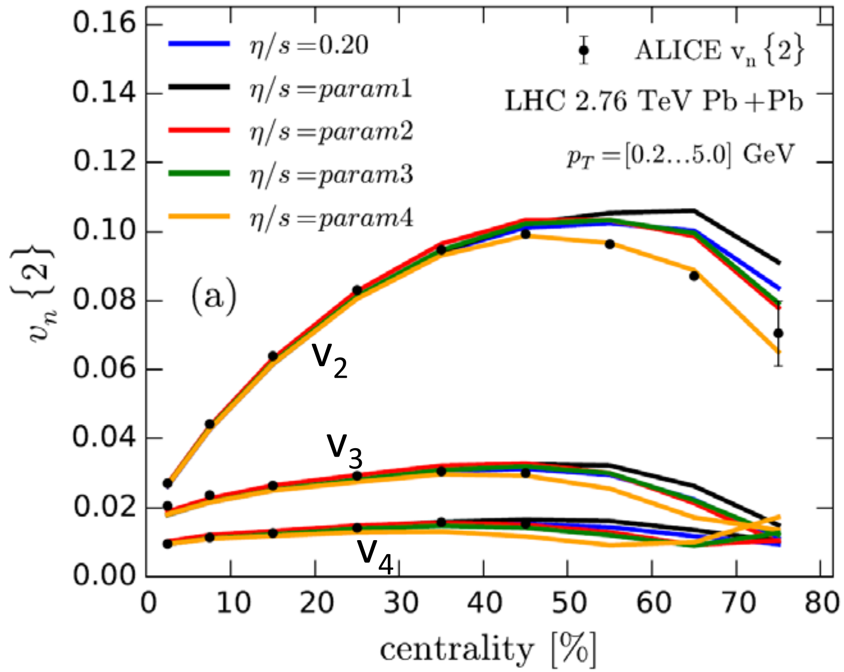


⇒ Our **QCD matter EoS is under (sufficient) control** but essentially no constraints for η/s(T) from here, either

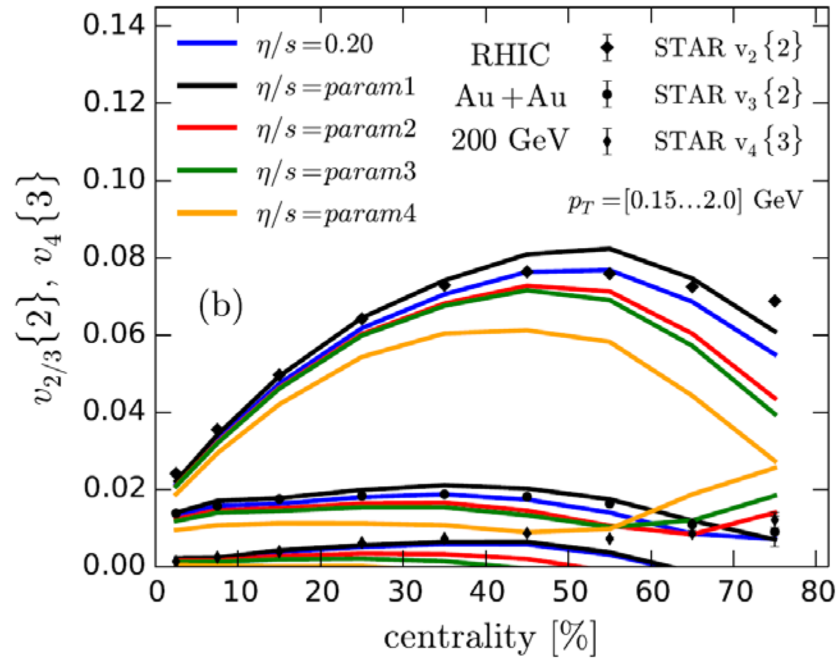
[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

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

LHC



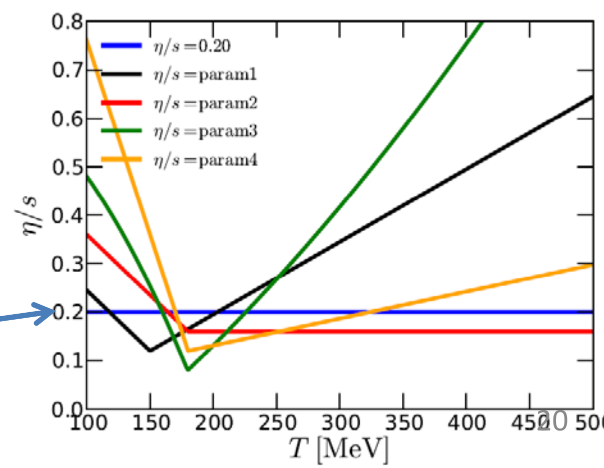
RHIC



LHC v_ns well reproduced by **all** these η/s(T)

⇒ **Simultaneous LHC & RHIC analysis very important!**

⇒ **Constraints for eta/s(T):**
Small η/s(T) in the HRG seems favored



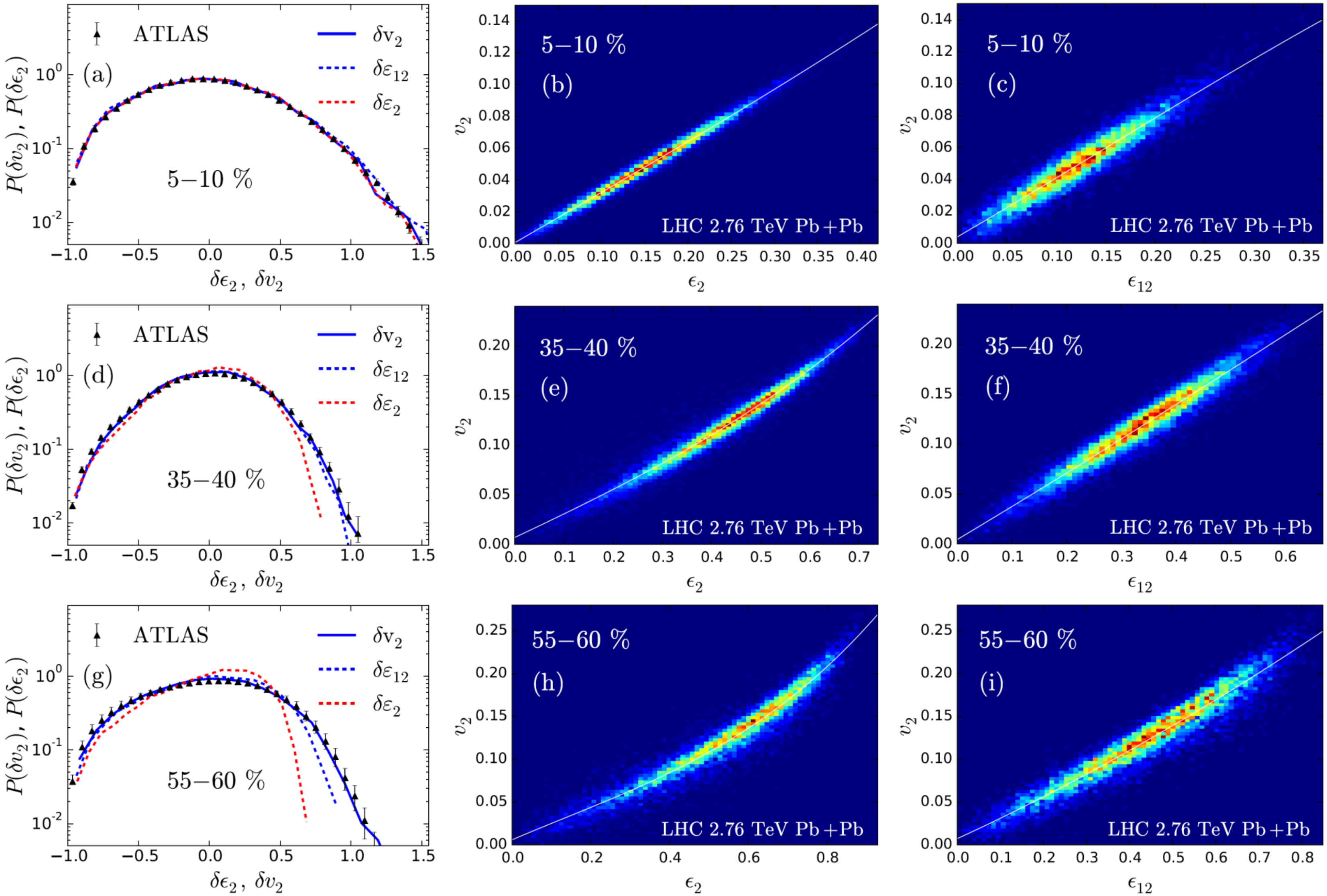
[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

Relative EbyE fluctuations of elliptic flow at LHC come out beautifully

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

$\varepsilon_2 = \varepsilon_{2,2}$

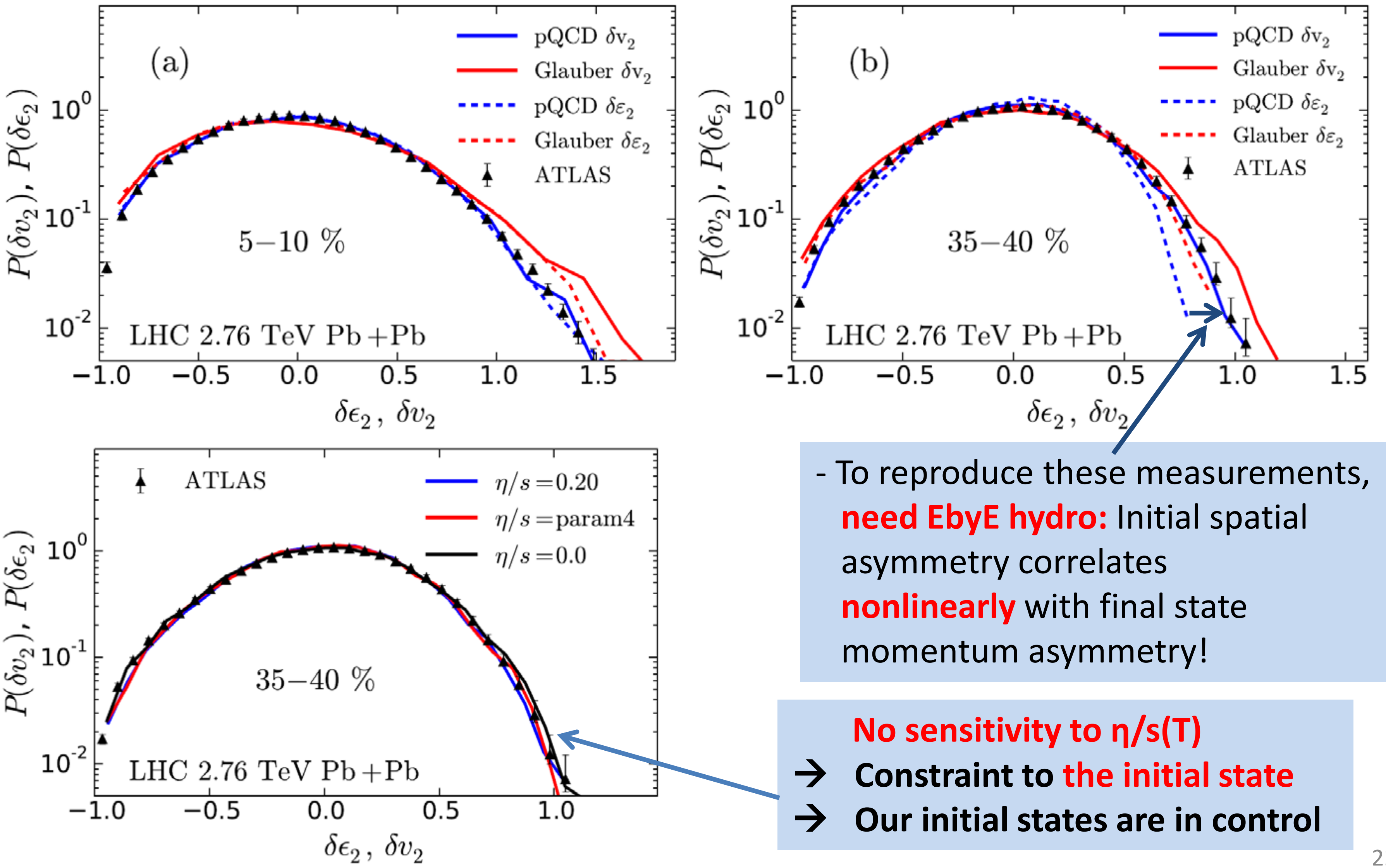
$$\varepsilon_{m,n} e^{in\Psi_{m,n}} = -\{r^m e^{in\phi}\}/\{r^m\}$$
$$\{\cdots\} = \int dxdy\, e(x,y,\tau_0)(\cdots)$$



[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

Relative EbyE fluctuations of elliptic flow at LHC come out beautifully

$$\delta v_n = \frac{v_n - \langle v_n \rangle_{\rm ev}}{\langle v_n \rangle_{\rm ev}} \qquad \delta \epsilon_n = \frac{\epsilon_n - \langle \epsilon_n \rangle_{\rm ev}}{\langle \epsilon_n \rangle_{\rm ev}} \qquad \varepsilon_2 = \varepsilon_{2,2}$$



- To reproduce these measurements, **need EbyE hydro:** Initial spatial asymmetry correlates **nonlinearly** with final state momentum asymmetry!

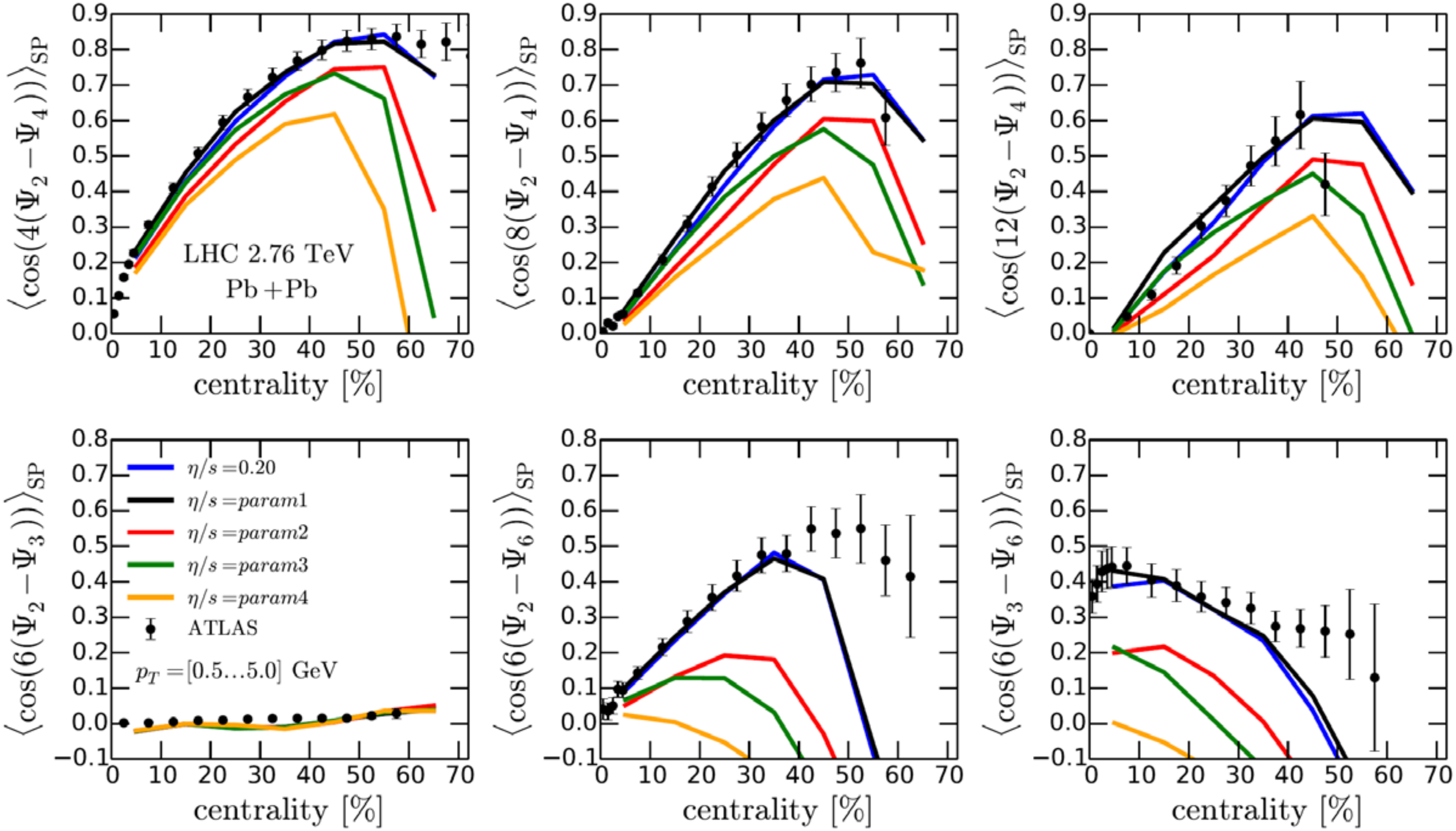
No sensitivity to η/s(T)

→ **Constraint to the initial state**

→ **Our initial states are in control**

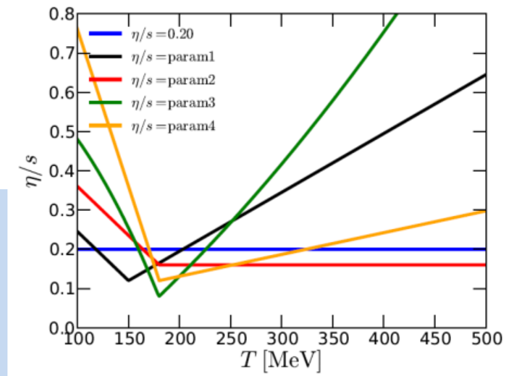
[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

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



LHC

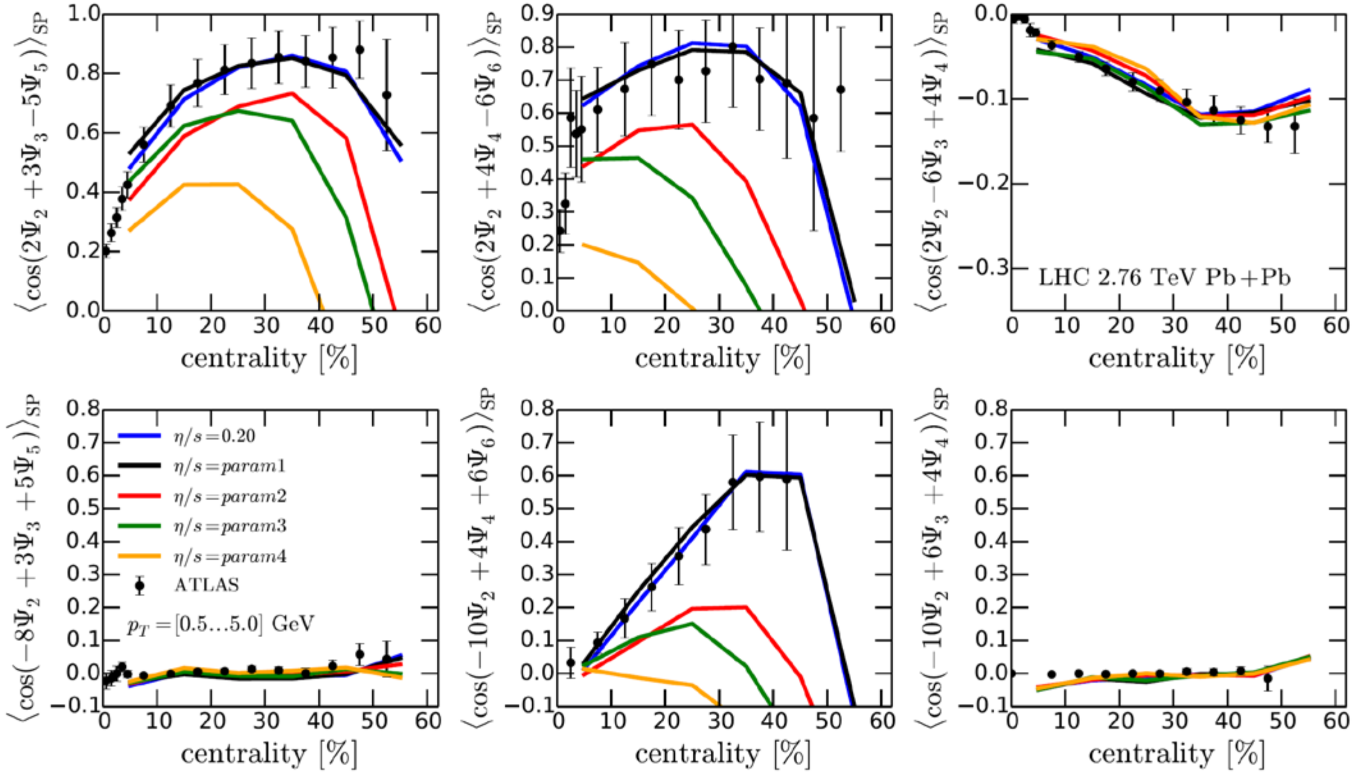
$$\langle\cos(k_1\Psi_1 + \cdots + nk_n\Psi_n)\rangle_{SP} \equiv \frac{\langle v_1^{|k_1|}\cdots v_n^{|k_n|}\cos(k_1\Psi_1 + \cdots + nk_n\Psi_n)\rangle_{ev}}{\sqrt{\langle v_1^{2|k_1|}\rangle_{ev}\cdots\langle v_n^{2|k_n|}\rangle_{ev}}}$$



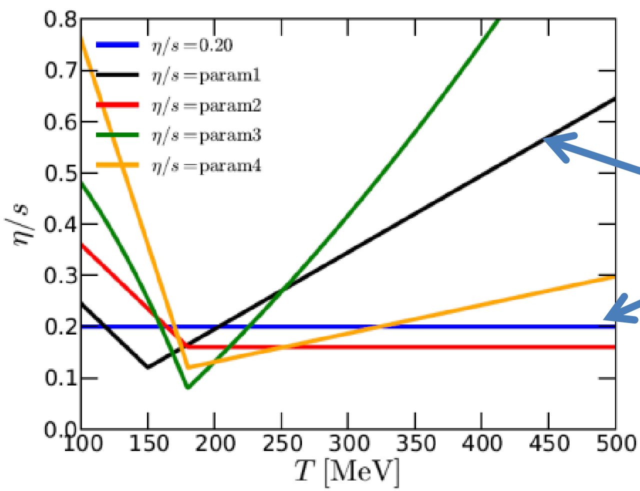
Especially since P(δv_n) constrain our ISs independently of η/s, these correlations **give further constraints for η/s(T)** and simultaneously **test the validity** of the EbyE viscous framework!

[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

Even the correlations of 3(!) Event-plane angles similarly OK, for centralities < 40-50%



LHC

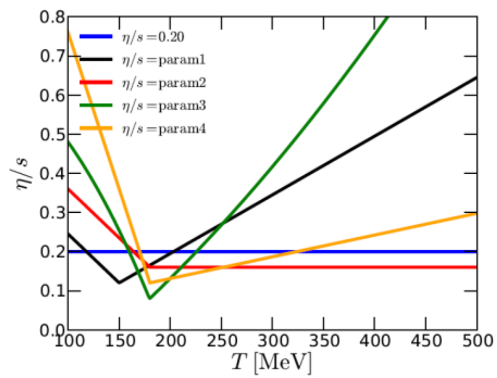


Remarkably, **the same two η/s(T) parametrizations** that explain the RHIC v_n's — the black and blue in the fig. — work best also at LHC!
For these, also the viscous hydro seems best under control…

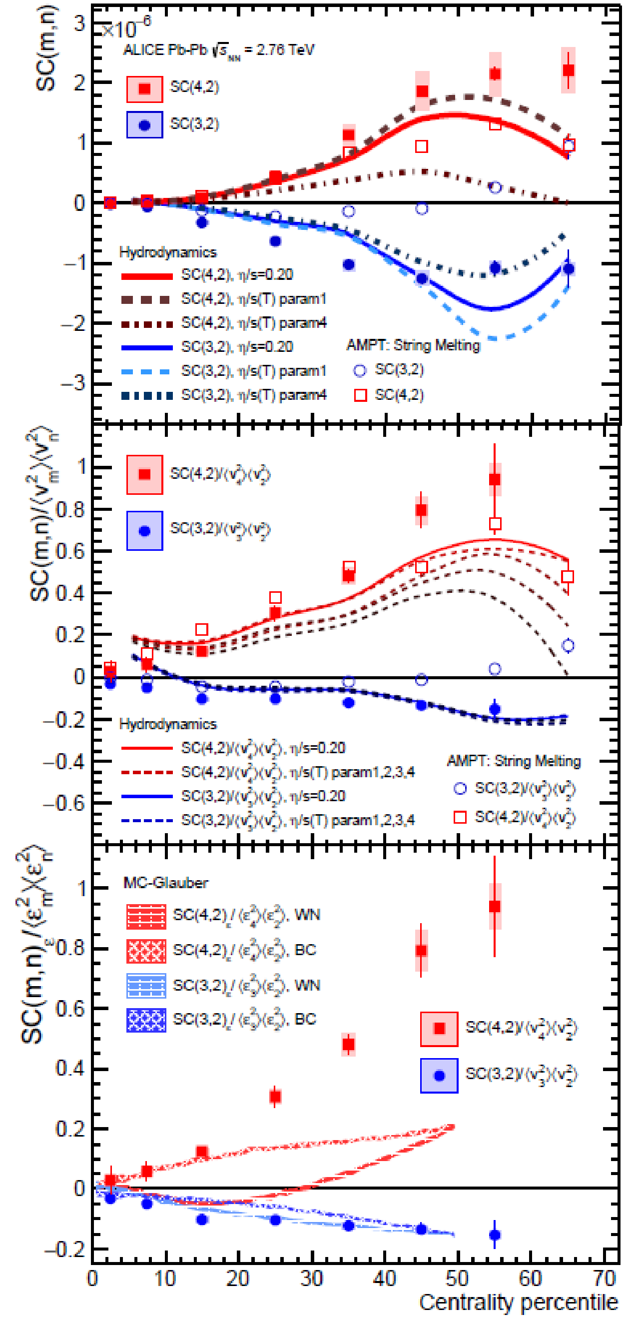
Symmetric 2-harmonic 4-particle (!) cumulants from ALICE

$$
\begin{aligned}
\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle_c &= \langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle \\
&\quad -\langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\,\langle\langle\cos[n(\varphi_1-\varphi_2)]\rangle\rangle \\
&= \left\langle v_m^2 v_n^2\right\rangle-\left\langle v_m^2\right\rangle\left\langle v_n^2\right\rangle ,
\end{aligned}
$$

ALICE, arXiv:1604.07663 [nucl-ex]
EKRT results from H.Niemi



The same two best η/s(T) parametrizations [0.2 & param1] work best also here!

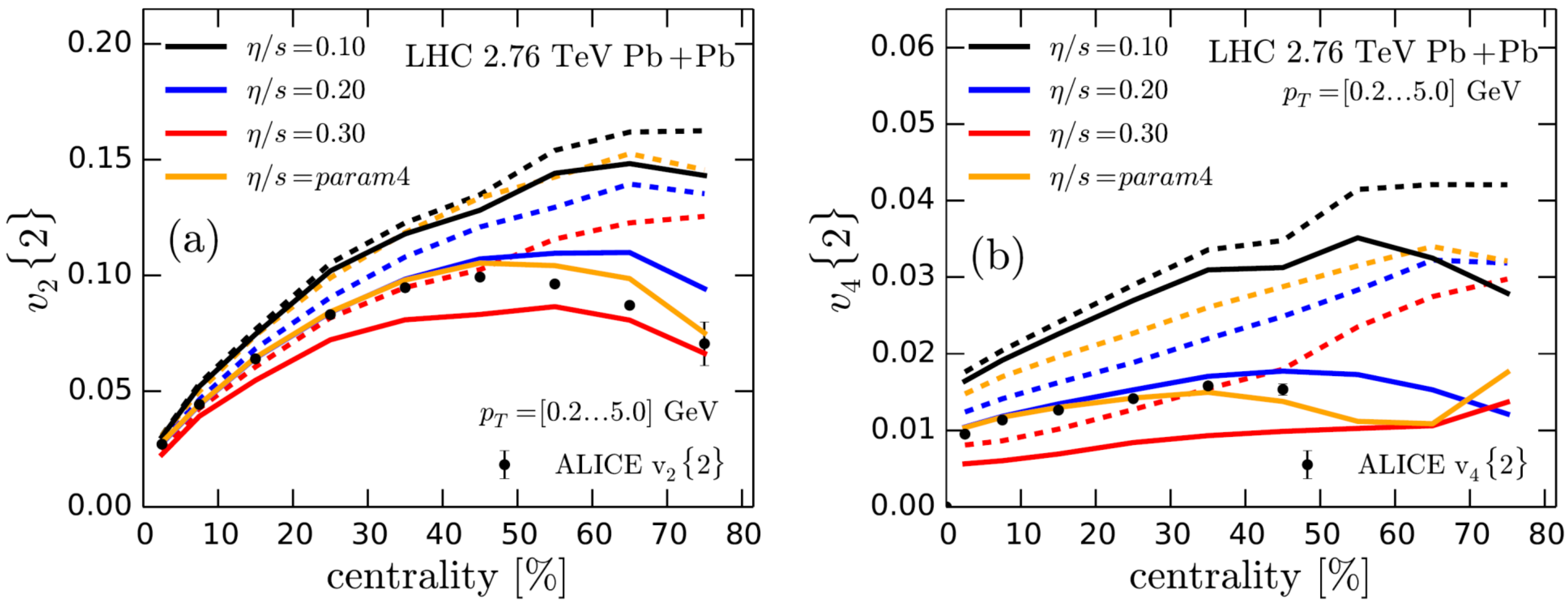


Applicability region of viscous hydro: magnitude of δf corrections?

$$f_i(x,p) = f_{0i}(x,p) + \delta f_i = f_{0i}(x,p)\left[1 + \frac{p_{i\mu}p_{i\nu}\pi^{\mu\nu}}{2T^2(e+P_0)}\right]$$

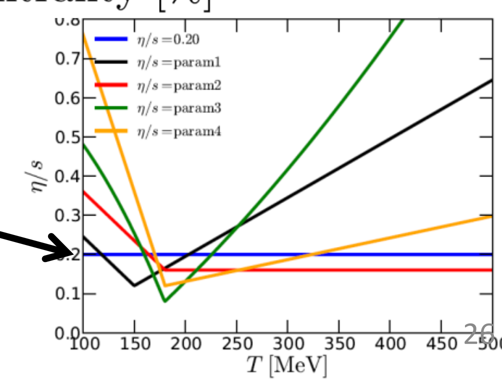
Solid lines = with δf

Dashed = without δf



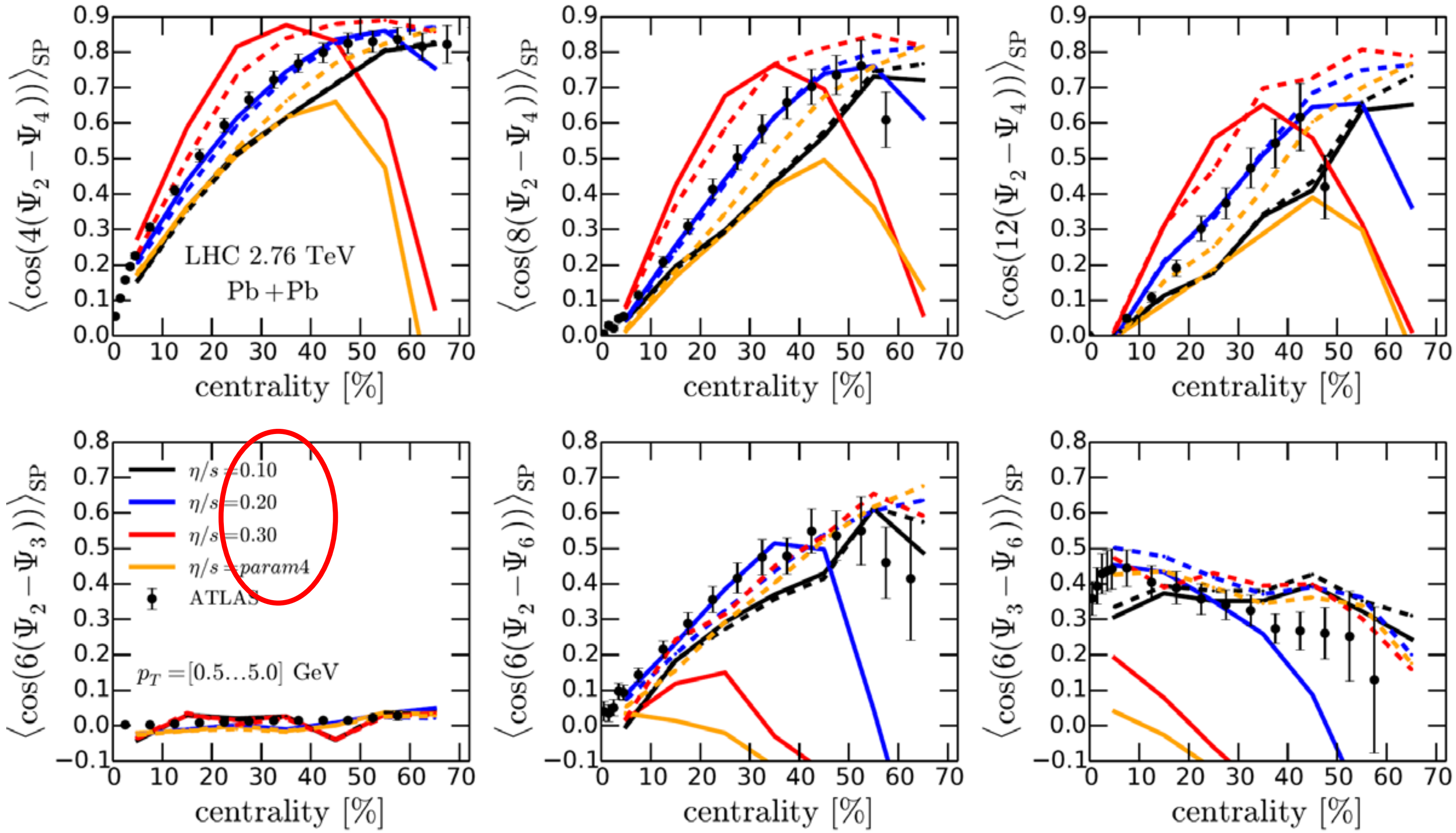
(decays not included in these figures)

Smallest hadronic viscosities (blue&black) work best:
δf effects in v_n remain small up to 40-50 % centralities



[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

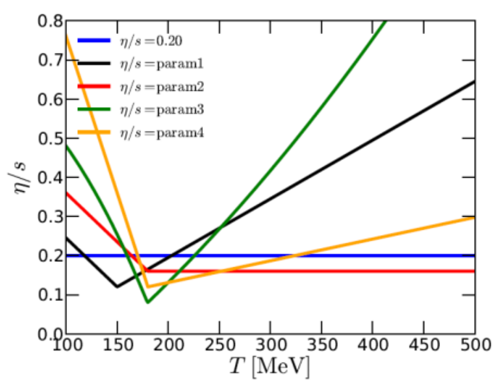
Applicability region of dissipative hydro: magnitude of δf corrections?



Solid lines = with δf

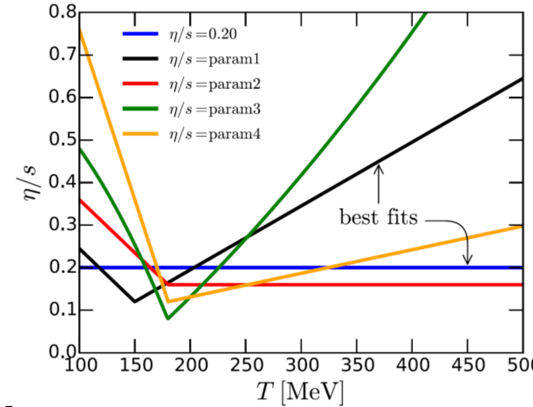
Dashed = without δf

⇒ δf effects remain (mostly) small from central to semi-central collisions: **constraints for eta/s in the applicability region of hydro!**

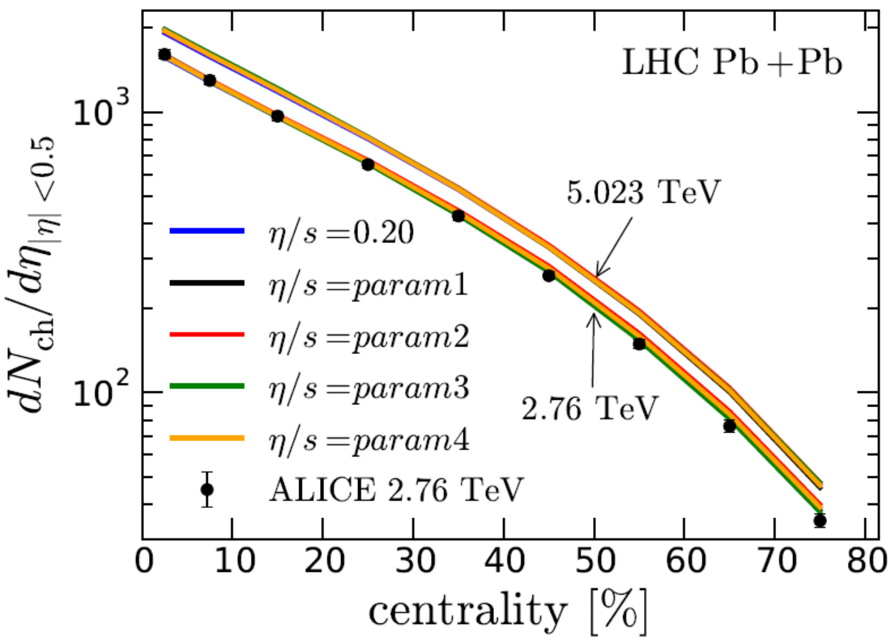


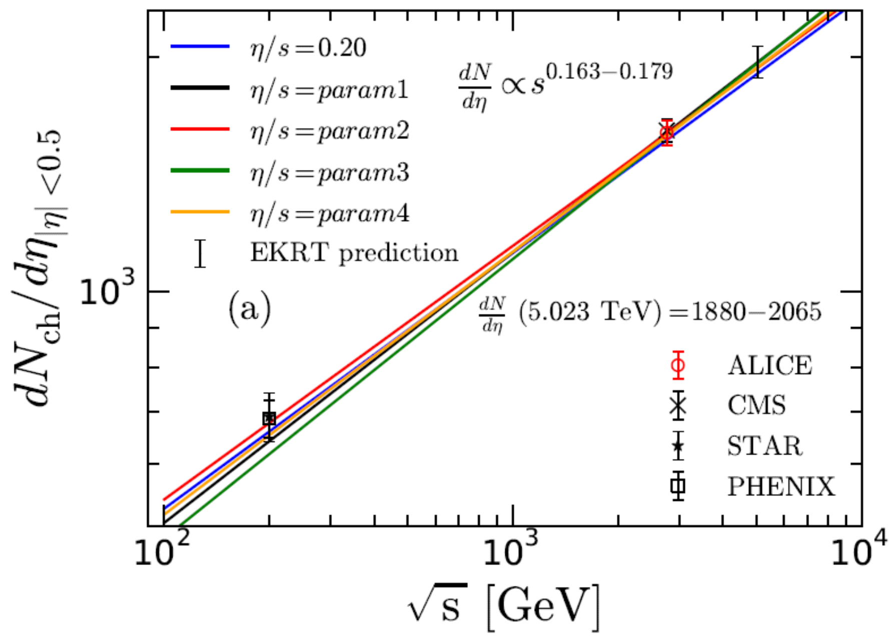
[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

3. Predictions for the 5.02 TeV Pb+Pb LHC run



[Phys.Rev. C93 (2016) 014912, arXiv:1511.04296 [hep-ph]]

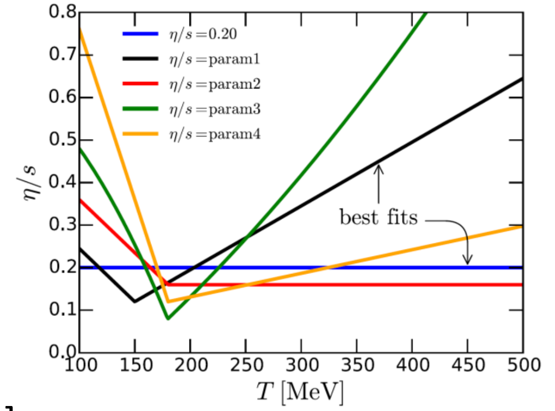




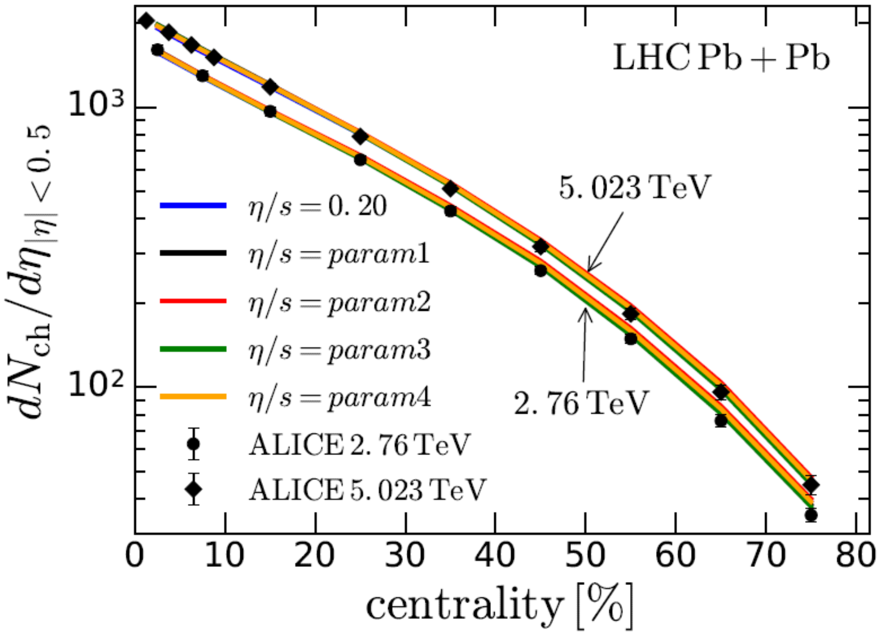
0-5% central: **EKRT** $\left.\frac{dN_{\rm ch}}{d\eta}\right|_{|\eta|\leqslant 0.5} = 1876\ldots 2046$ blue . . . black

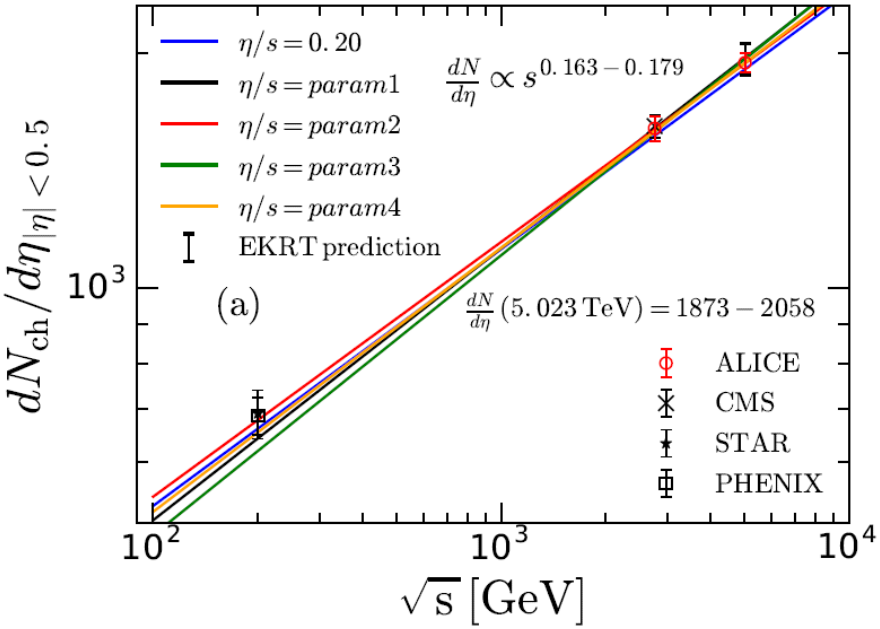
$$\left.\frac{dN_{\rm ch}}{d\eta}\right|_{|\eta|\leqslant 0.5} \propto s^{0.164\ldots 0.174}$$

3. Predictions for the 5.02 TeV Pb+Pb LHC run



[Phys.Rev. C93 (2016) 014912, arXiv:1511.04296 [hep-ph]]





vs. 5.02 TeV ALICE data [Phys.Rev.Lett. 116 (2016) 222302, arXiv:1512.06104 [nucl-ex]]

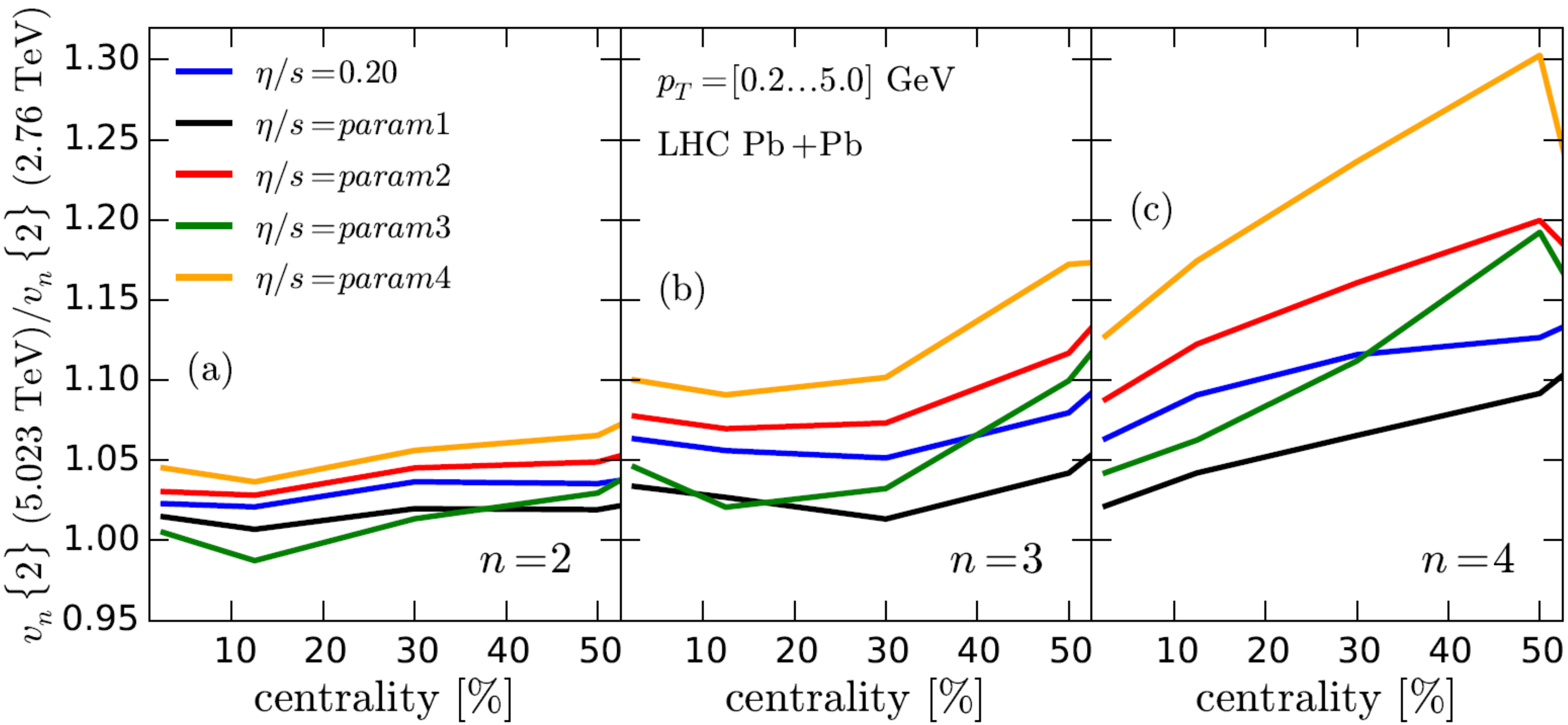
0-5% central: **EKRT** $\left.\frac{dN_{ch}}{d\eta}\right|_{|\eta|\leqslant 0.5} = 1876 \ldots 2046$ blue . . . black

ALICE: 1943 +- 54

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

[Phys.Rev. C93 (2016) 014912, arXiv:1511.04296 [hep-ph]]

EKRT prediction…

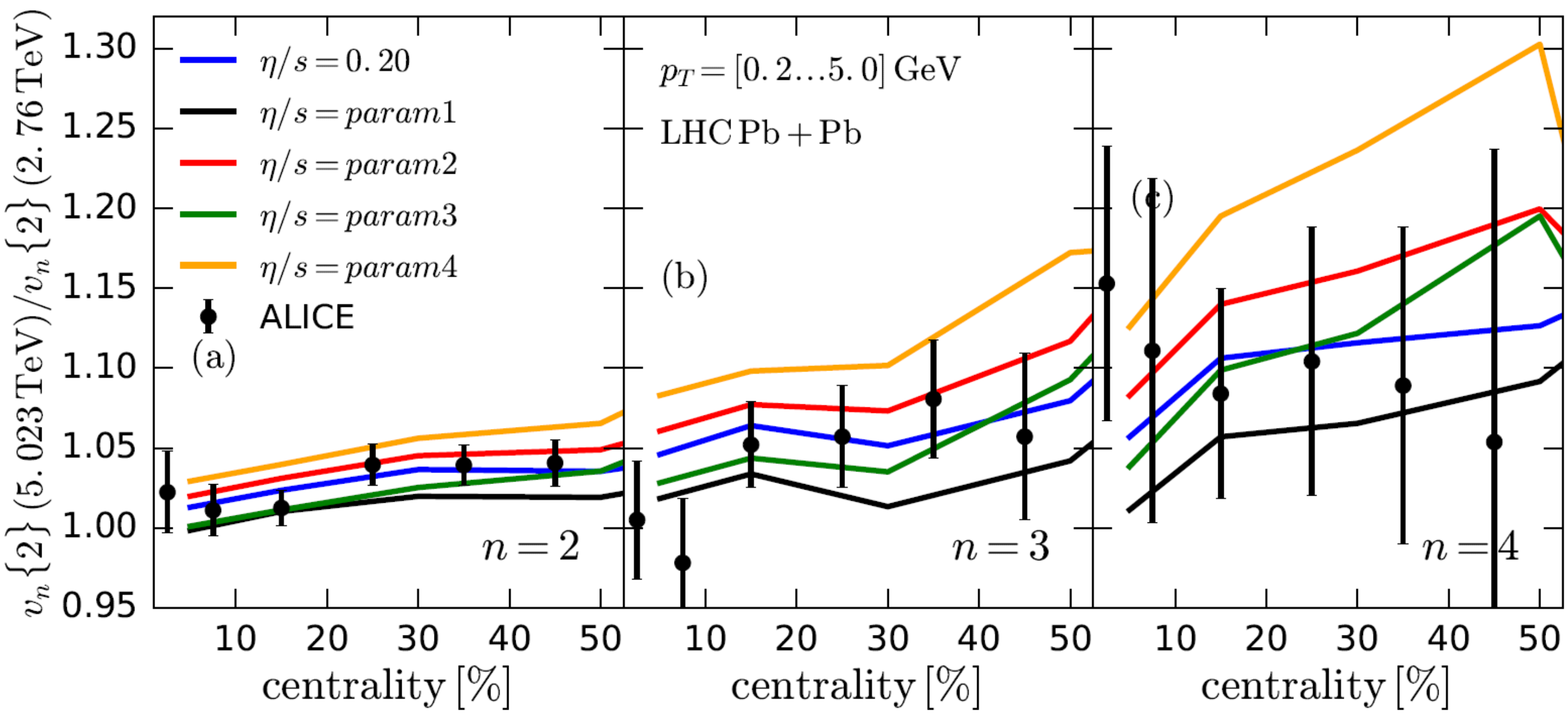


- **Higher harmonics n > 2 more sensitive to η/s(T)**
- **Further constraints for η/s(T)**

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

[Phys.Rev. C93 (2016) 014912, arXiv:1511.04296 [hep-ph]]

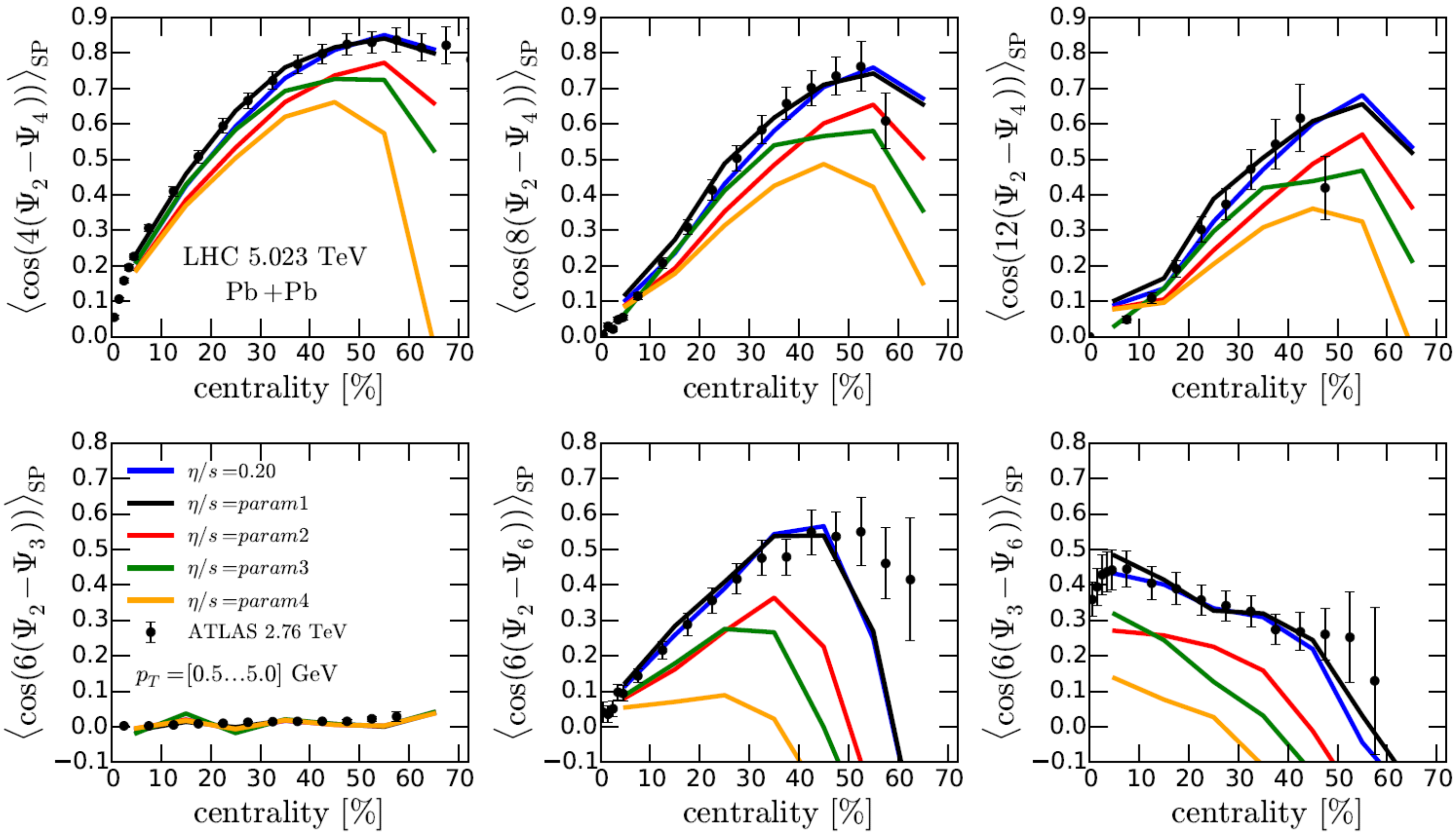
EKRT prediction vs ALICE data [Phys.Rev.Lett. 116 (2016) 132302]



- **Higher harmonics n > 2 more sensitive to η/s(T)**
- **Further constraints for η/s(T)**

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

EKRT 5.02 TeV prediction [Phys.Rev. C93 (2016) 014912, arXiv:1511.04296 [hep-ph]]
vs. **ATLAS 2.76 TeV data** [Phys. Rev. C 90 (2014) 2, 024905]

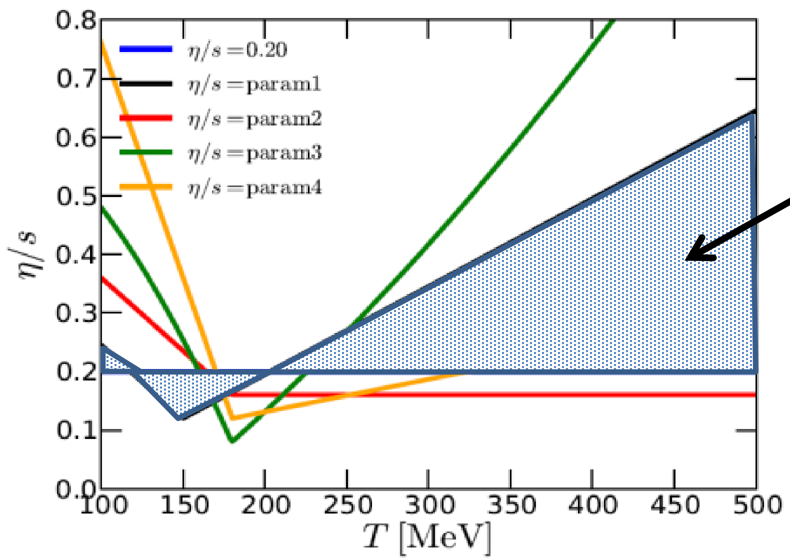


Very similar to the 2 EP correlations at 2.76 TeV,
i.e. similar constraining power for η/s(T) as at 2.76 TeV

Conclusions & outlook

- **NLO-improved pQCD+saturation+viscous hydro** ***EbyE framework*** (EKRT model)
  - explains consistently the LHC and RHIC bulk observables in URHIC
  - has clear predictive power in cms energy, centrality, A
  - enables estimation of the ***QCD matter* η/s(T)** and its uncertainties

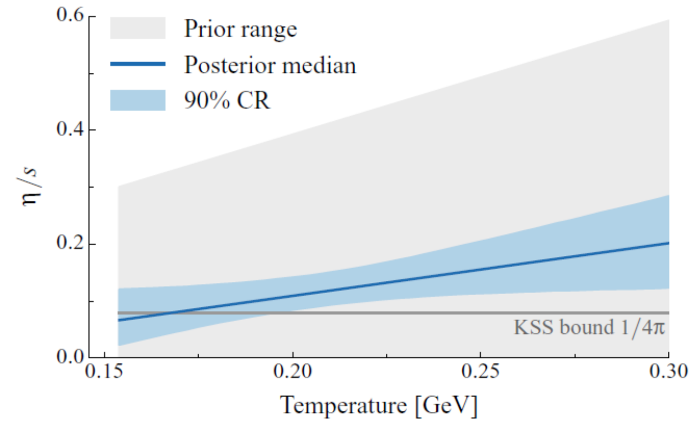
- Now there starts to be **enough orthogonal data constraints** available from LHC and RHIC, for *(i)* pinning down the initial conditions,
  (ii) probing the validity of the framework and
  (iii) probing & determining the QCD matter η/s(T)
  – a **simultaneous LHC and RHIC multiobservable analysis** is required!



Our "best" estimate currently for η/s(T) but this is **not yet a true error band — statistical global analysis needed**

- Similar η/s magnitudes also from
  - **IP-glasma** ISs: η/s = 0.12 (RHIC) … 0.2 (LHC) [Gale, Jeon, Schenke, Tribedy, Venugopalan, Phys. Rev. Lett. 110 (2013) 012302]
  - **MCG/MC-KLN+VISHNU**: 0.08 < const. η/s < 0.2 [Song, Bass,Heinz,Hirano, Shen, Phys. Rev. Lett. 106, 192301 (2011)]

- First attempt towards a statistical global analysis of data in [Bernhard,Moreland, Bass, Liu, Heinz, Phys.Rev. C94 (2016) 024907]
  → supports EKRT (and IP-glasma)-type initial states
  → η/s(T) trend similar to EKRT
  → indications of bulk viscosity(?)

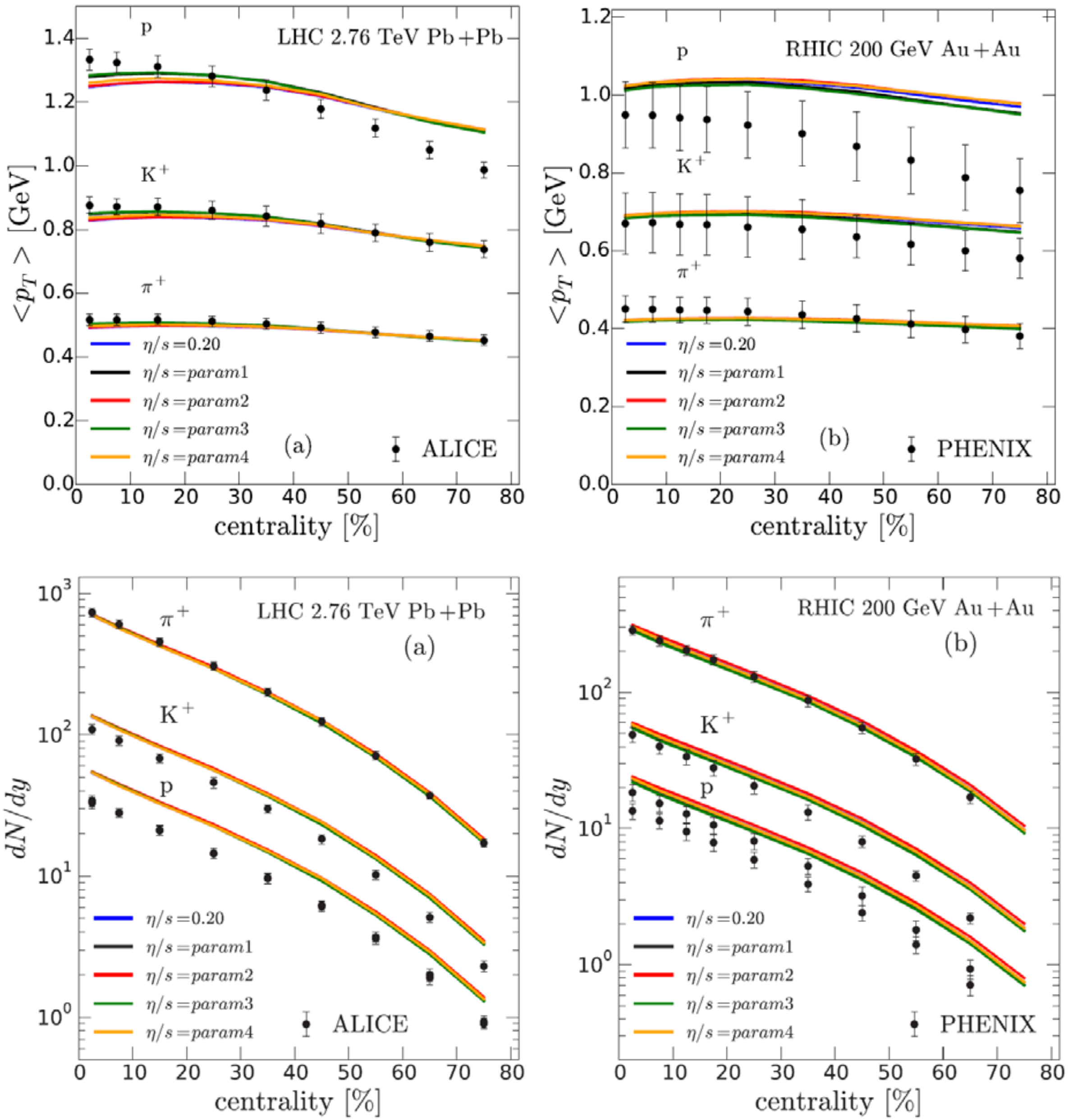


Next in EKRT:

- Include dynamical fluctuations of p_{sat} → EKRT predictions **in p+A** collisions (?)
- Develop a **global analysis** of these observables→ **a statistical error band to η/s(T)**
- Improve the description of "pre-thermal" evolution [Eff.Kin.Th./BAMPS]
- Study also **bulk viscosity** effects, see e.g.
  Ryu et al, Phys. Rev. Lett. 115 (2015) 132301
  Bernhard, et al., Phys.Rev. C94 (2016) 024907
- Need a "MC-EKRT" event generator to study also y-dependent observables

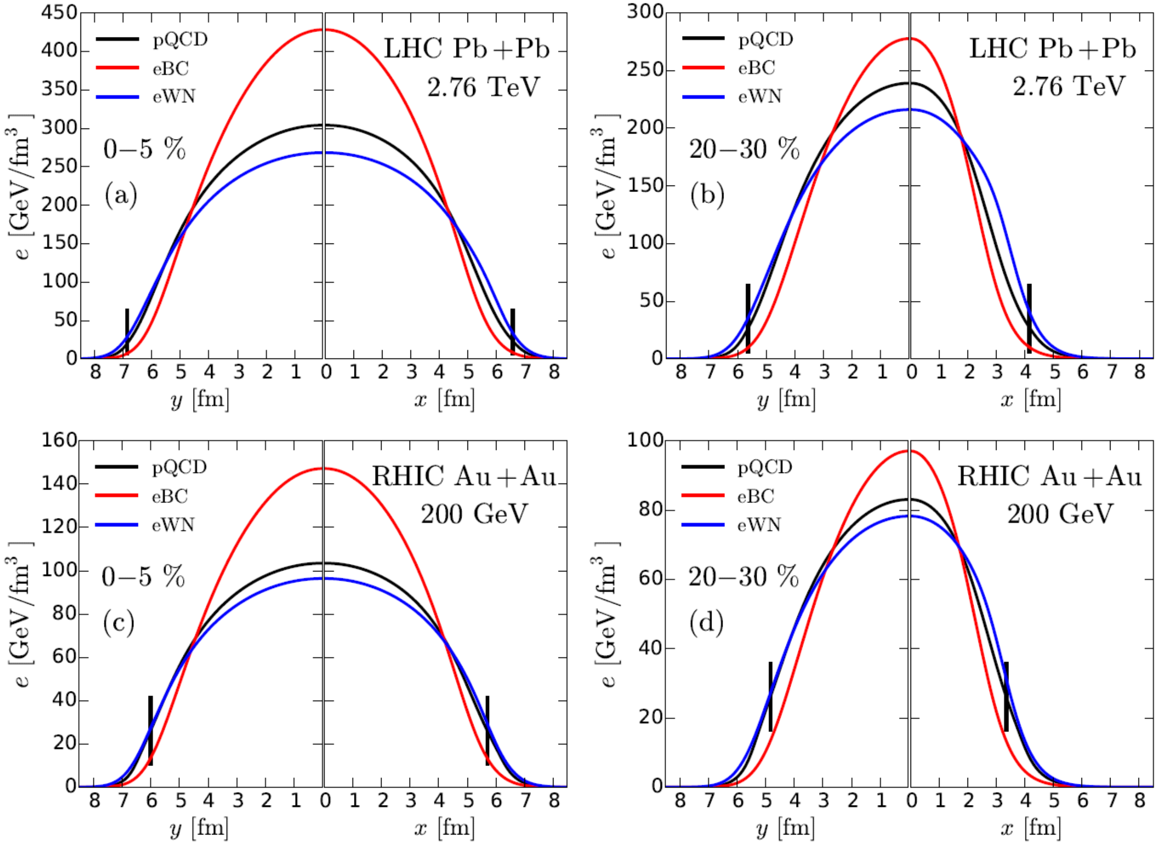
Back up slides

[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]



bulk <pT> ~OK

bulk dN/dy ~OK



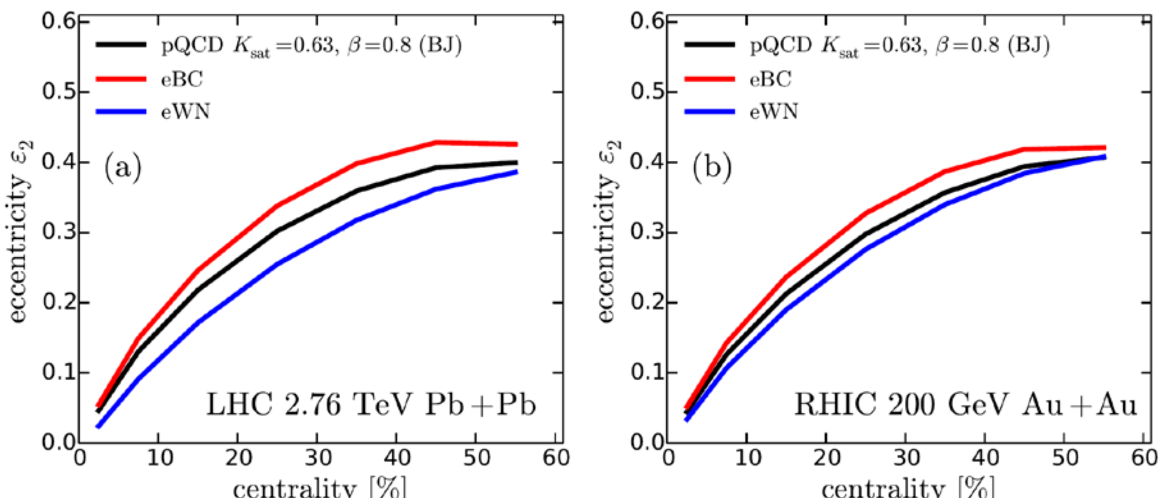
Average energy densities

$$K_{\text{sat}} = 0.63 \text{ and } \beta = 0.8$$

$$\tau_0 = 0.20 \text{ fm}$$

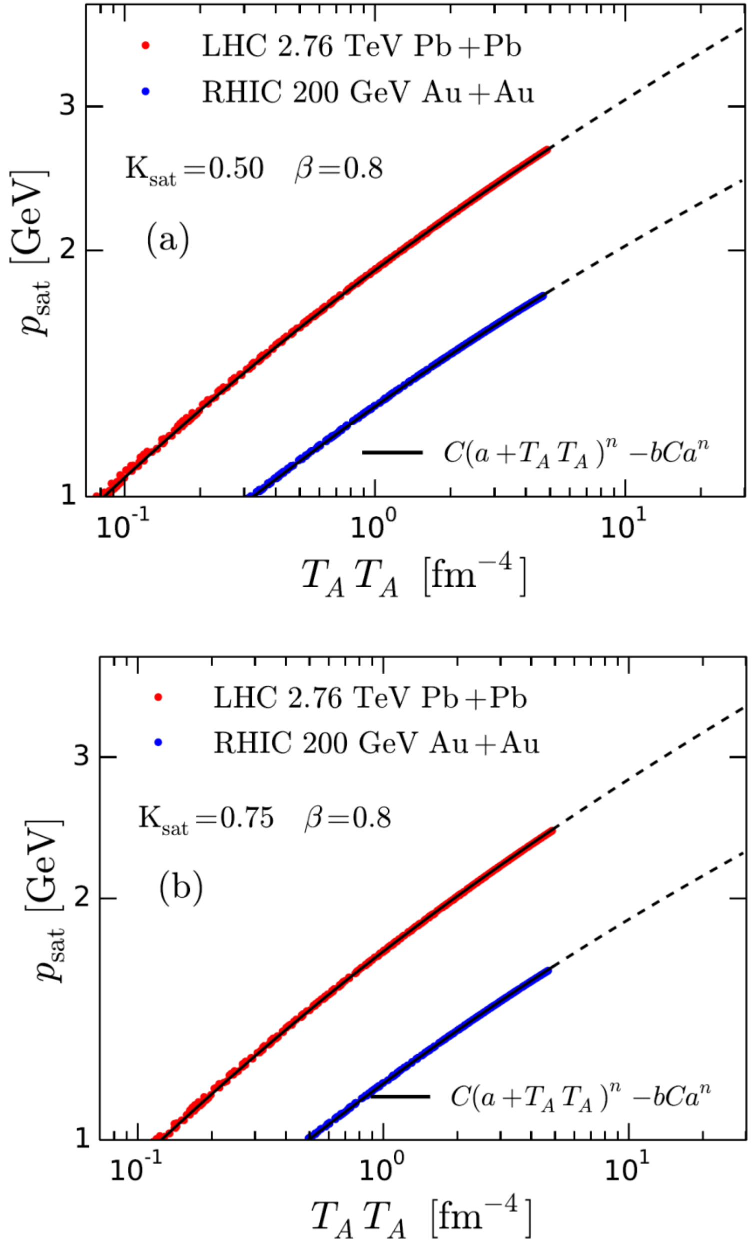
⇔ eta/s=0.2

The vertical lines show where p_{sat}<1 GeV and where matching to BC profile is made



Average initial eccentricities are btw eBC and eWN

[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]



Parametrization of $p_{sat}(K_{sat},\beta)$ available:

$$p_{sat}(\rho_{AA}) = C\left[a + \rho_{AA}\right]^n - bCa^n$$

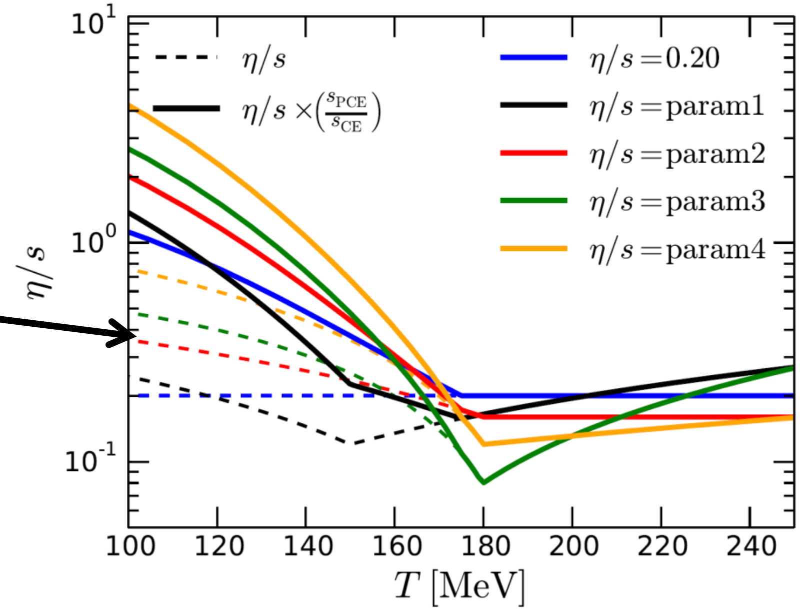
$$P_i(K_{sat},\beta) = a_{i0} + a_{i1}K_{sat} + a_{i2}\beta + a_{i3}K_{sat}\beta + a_{i4}\beta^2 + a_{i5}K_{sat}^2$$

TABLE II. The parametrization of $p_{sat}(K_{sat},\beta)$ for $\sqrt{s_{NN}} =$ 2.76 TeV Pb+Pb collisions for $K_{sat} \in [0.4, 2.0]$ and $\beta < 0.9$

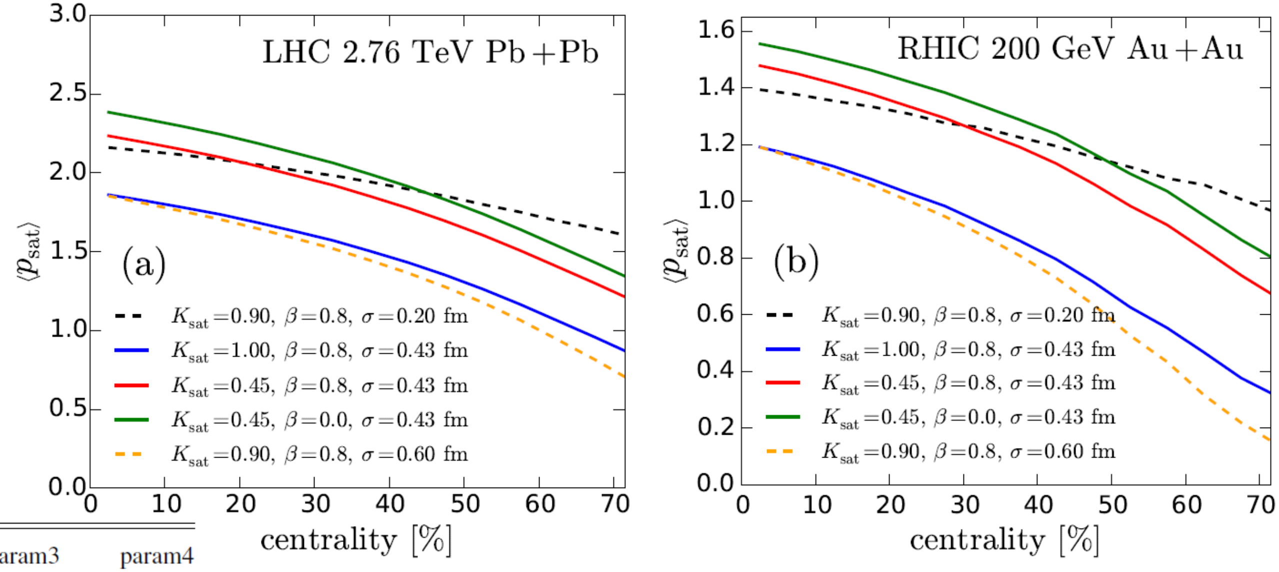
$P_i \rightarrow$	C	n	a	b
a_{i0}	3.9027590	0.1312476	-0.0044020	0.8537670
a_{i1}	-0.6277216	-0.0157637	0.0220154	-0.0580163
a_{i2}	1.0703962	-0.0362980	-0.0005974	0.0957157
a_{i3}	0.0692793	-0.0022506	0.0125320	-0.0016413
a_{i4}	-1.9808449	0.0615129	-0.0032844	-0.1788390
a_{i5}	0.1106879	0.0052116	-0.0033841	0.0220187

[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

Interestingly,
the modest T-dependence of the hadronic viscosity obtained here **in PCE** is in fact **not** inconsistent with microscopic calculations in **CE** [e.g. Cernai, Kapusta, McLerran, PRL 97 (2006) 152303]



η/s	0.20	param1	param2	param3	param4
K_{sat}	0.63	0.50	0.75	0.45	0.64



Average $p_{\rm sat}$ as a function of centrality in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions at the LHC (a), and in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC (b) with different values of $K_{\rm sat}$, β and σ.

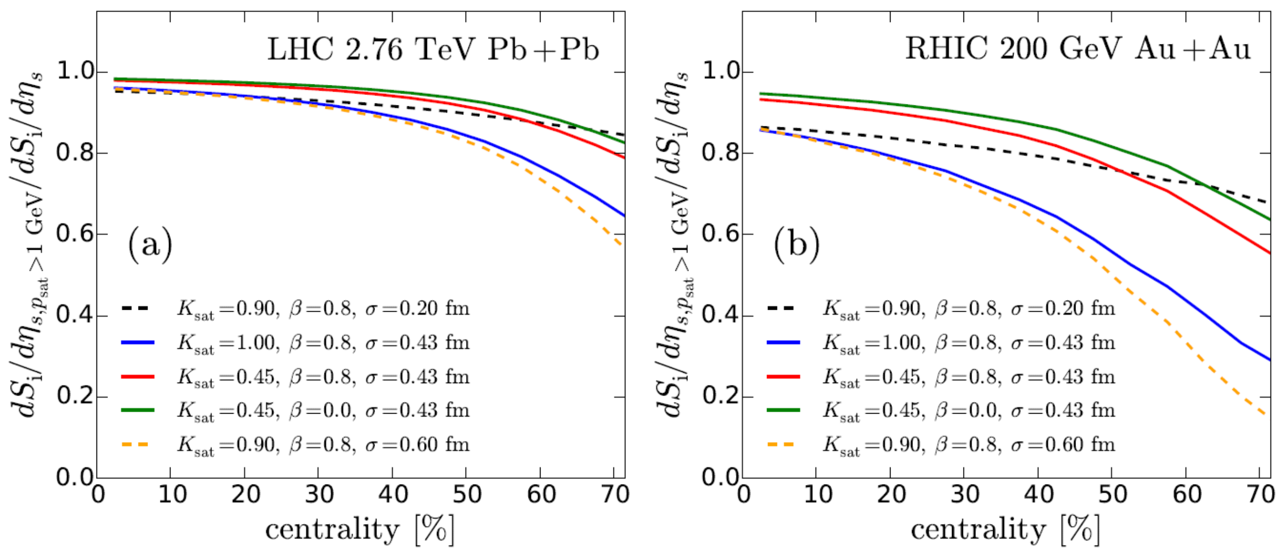
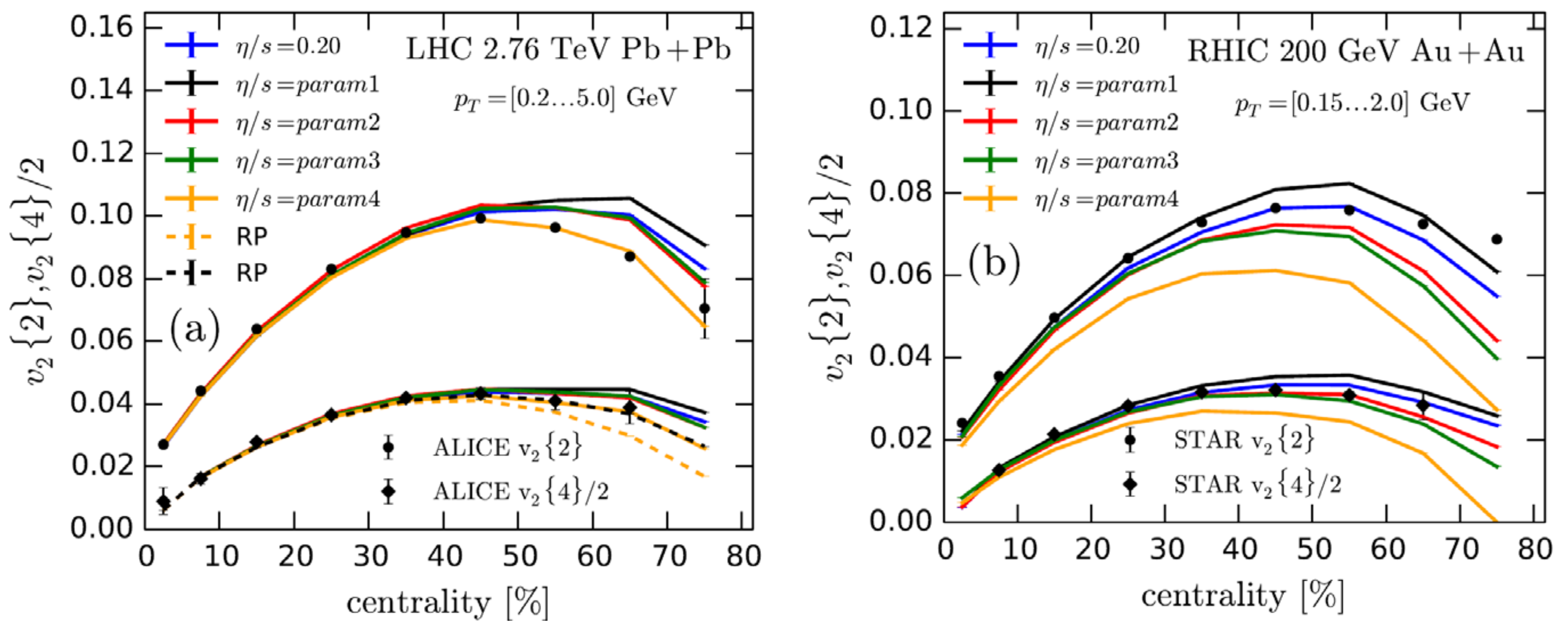


FIG. 9. (Color online) Fraction of $dS_i/d\eta_s$ from the region $p_{\rm sat} \geq 1$ GeV as a function of centrality in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions at the LHC (a), and in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC (b).

[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

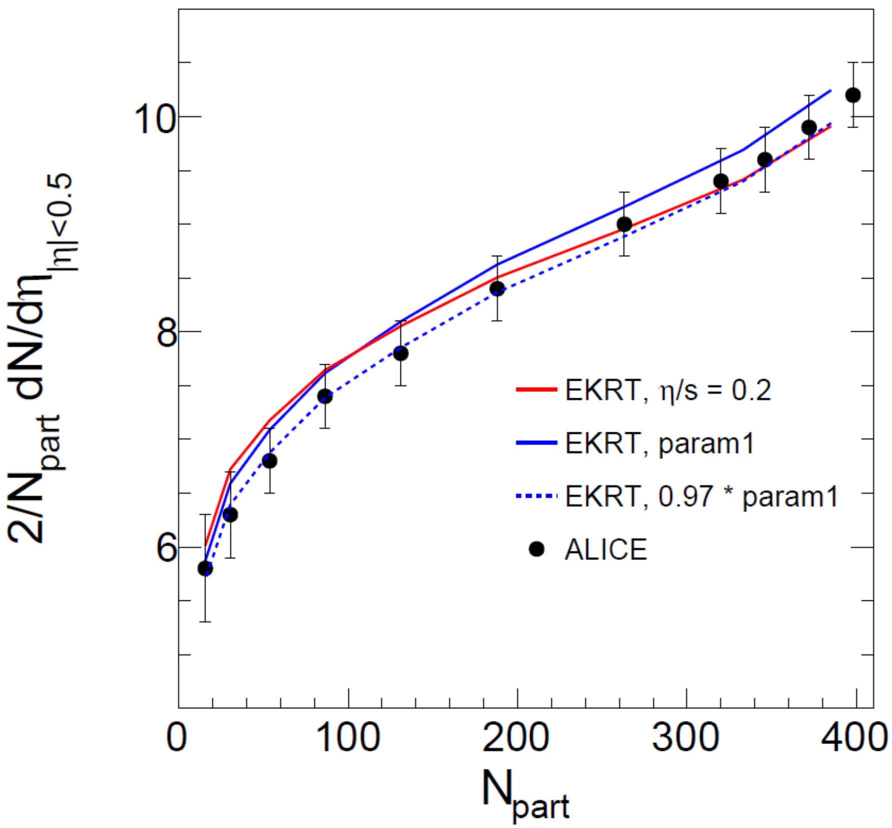
[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907

Centrality dependence of 2,4-particle cumulant flow coefficients v_n

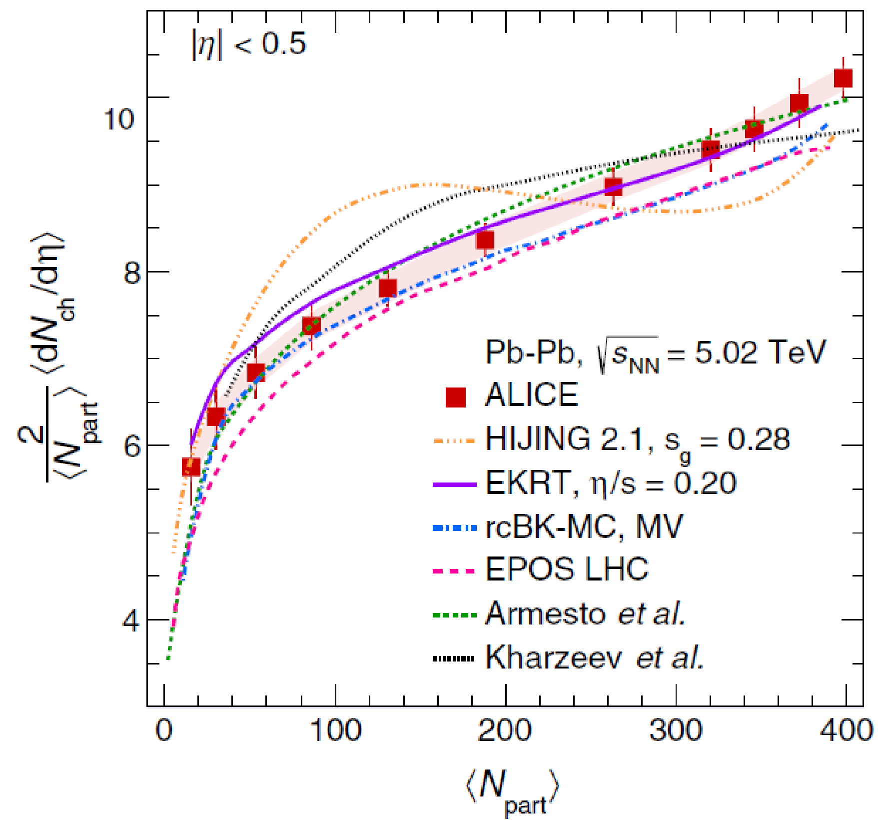


EKRT prediction [Phys.Rev. C93 (2016) 014912, arXiv:1511.04296 [hep-ph]]
vs. 5.02 TeV ALICE data [Phys.Rev.Lett. 116 (2016) 222302, arXiv:1512.06104 [nucl-ex]] ,
using ALICE's Npart

data vs best EKRT fits



data vs models



[ALICE, PRL116 (2016) 222302]

F-components for each event: $v_n(y)e^{in\Psi_n(y)} = \langle e^{in\phi}\rangle_{\phi,p_T}$

event plane angle Ψ_n = atan2(<sin nϕ >/<cos nϕ>)/n

v_n = <cos(n(ϕ - Ψ_n))> $\langle\cdots\rangle_{\phi,p_T} = \left(\frac{dN}{dy}\right)^{-1}\int d\phi dp_T^2 \frac{dN}{dy dp_T^2 d\phi}(\cdots)$

Exp's:

$$v_n\{\mathrm{EP}\}(p_T) = \langle\cos[n(\phi - \Psi_n\{\mathrm{EP}\})]\rangle_\phi\}\rangle_{\mathrm{ev}} \to \langle v_n\rangle_{\mathrm{ev}}, \langle v_n^2\rangle_{\mathrm{ev}}^{1/2}$$

high / low resolution

$$\Psi_n\{\mathrm{EP}\} = \frac{1}{n}\mathrm{atan2}(\langle w\cos(n\phi)\rangle_{\phi,p_T}, \langle w\sin(n\phi)\rangle_{\phi,p_T})$$

2-particle cumulant,
not sensitive to Ψ_n[EP]

$$v_n\{2\}^2 = \langle e^{in(\phi_1-\phi_2)}\rangle_\phi \equiv \frac{1}{N_2}\int d\phi_1 d\phi_2 \frac{dN_2}{d\phi_1 d\phi_2} e^{in(\phi_1-\phi_2)}$$

$$\frac{dN_2}{d\phi_1 d\phi_2} = \frac{dN}{d\phi_1}\frac{dN}{d\phi_2} + \delta_2(\phi_1,\phi_2)$$

$$v_n\{2\} = \left\langle v_n^2 + \delta_2\right\rangle_{\mathrm{ev}}^{1/2} \overset{\mathrm{flow}}{=} \left\langle v_n^2\right\rangle_{\mathrm{ev}}^{1/2}$$

(no non-flow in our results)

3,4-particle cumulants $v_4\{3\} \equiv \frac{\left\langle v_2^2 v_4\cos(4[\Psi_2 - \Psi_4])\right\rangle_{\mathrm{ev}}}{\left\langle v_2^2\right\rangle_{\mathrm{ev}}}$ $v_n\{4\} \equiv \left(2\left\langle v_n^2\right\rangle_{\mathrm{ev}}^2 - \left\langle v_n^4\right\rangle_{\mathrm{ev}}\right)^{1/4}$

$$\varepsilon_{m,n}e^{in\Psi_{m,n}} = -\{r^m e^{in\phi}\}/\{r^m\} \quad \{\cdots\} = \int dxdy\, e(x,y,\tau_0)(\cdots)$$

$$\Psi_{m,n} = \frac{1}{n}\mathrm{atan2}\left(\{r^m\cos(n\phi)\}, \{r^m\sin(n\phi)\}\right) + \frac{\pi}{n}$$

Participant plane angle

EoM for shear-stress tensor from 14-moment approx to UR gas

$$\tau_\pi \frac{d}{d\tau}\pi^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + c_1\pi^{\mu\nu}\nabla^\alpha u_\alpha + c_2\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + c_3\pi_\alpha^{\langle\mu}\omega^{\nu\rangle\alpha} + c_4\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha}, \qquad (4)$$

$$c_1 = -(4/3)\tau_\pi$$
$$c_2 = -(10/7)\tau_\pi$$
$$c_3 = 2\tau_\pi$$
$$c_4 = 9/(70P_0)$$

$$\tau_\pi = \frac{5\eta}{e+P_0}$$

Denicol, Koide, Rischke, Phys. Rev. Lett. 105, 162501 (2010)
Denicol, Niemi, Molnár, Rischke, Phys. Rev. D85, 114047 (2012)
Molnár, Niemi, Denicol, Rischke, Phys. Rev. D89, 074010 (2014)

$$\sigma^{\mu\nu} = \nabla^{\langle\mu}u^{\nu\rangle} \quad \omega^{\mu\nu} = \frac{1}{2}\left(\nabla^\mu u^\nu - \nabla^\nu u^\mu\right) \quad \nabla^\mu = \Delta^{\mu\nu}\partial_\nu$$

$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

Landau frame $eu^\mu = T^{\mu\nu}u_\nu$

$$T^{\mu\nu} = eu^\mu u^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$N_i^\mu = n_i u^\mu + n_i^\mu,$$

$$e = T^{\mu\nu}u_\mu u_\nu \quad P = P_0 + \Pi \qquad n_i = N_i^\mu u_\mu \quad n_i^\mu = N_i^{\langle\mu\rangle}$$

$$\pi^{\mu\nu} = T^{\langle\mu\nu\rangle} \qquad A^{\langle\mu\rangle} = \Delta^{\mu\nu}A_\nu$$

$$A^{\langle\mu\nu\rangle} = \frac{1}{2}\left[\Delta^\mu_\alpha\Delta^\nu_\beta + \Delta^\mu_\beta\Delta^\nu_\alpha - \frac{2}{3}\Delta^{\mu\nu}\Delta_{\alpha\beta}\right]A^{\alpha\beta}$$