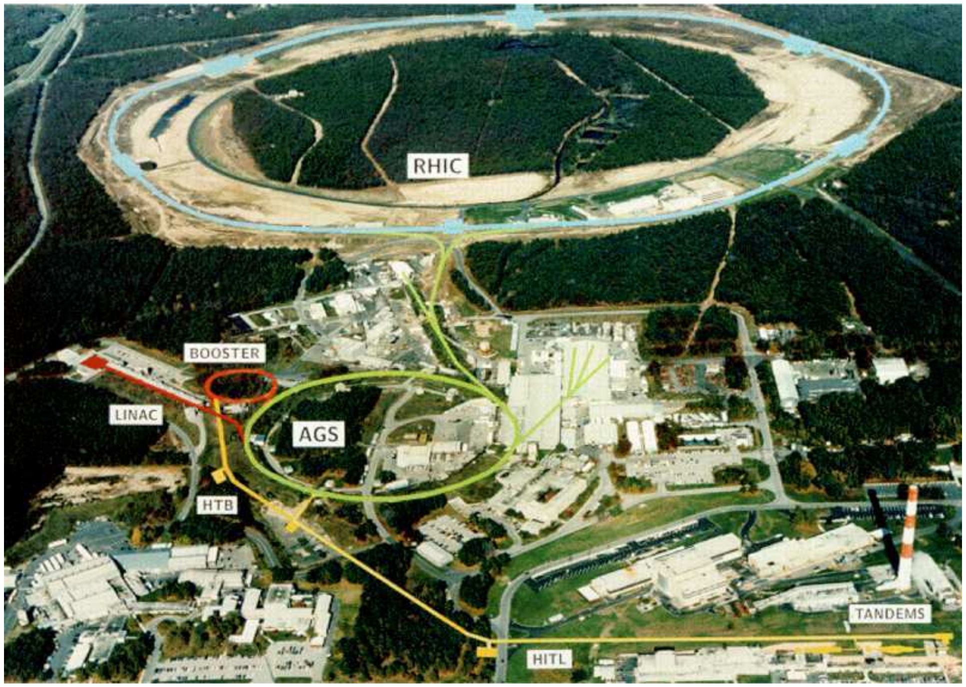
Theory Flow Overview: Describing the evolving medium in heavy-ion collisions*

Ulrich Heinz, The Ohio State University



QM12 Satellite Workshop "Jet Modification in the RHIC and LHC Era"
Wayne State University, August 20-23, 2012

*Work supported by the U.S. Department of Energy

What QGP tomographers need

- (3+1)-dimensional color charge density or temperature profiles of the medium
- (3+1)-dimensional flow velocity profiles
- information on deviations from local momentum isotropy

Since these medium characteristics fluctuate significantly from event to event (due to quantum fluctuations in the initial state of the "Little Bang"), providing this information in the form of an ensemble average is not sufficient

$\Longrightarrow$ **Event-by-event (3+1)-dimensional viscous fluid dynamics**

(Boost-invariant (2+1)-d good enough near midrapidity!)

What QGP tomographers need (contd.)

Questions that I will address in this talk:

- Which value of η/s? $(\eta/s)(T)$?
- Which initial conditions?
- Pre-equilibrium evolution?

Questions that need to be addressed at lower than top RHIC energies:

- Which equation of state (EOS)?

Questions that have been resolved in the last couple of years and that I won't discuss:

- EOS at RHIC and LHC (including early chemical freeze-out)
- Microscopic description of late hadronic rescattering stage and final decoupling
- Hydro-cascade interface

“The Little Bang”

The Movie

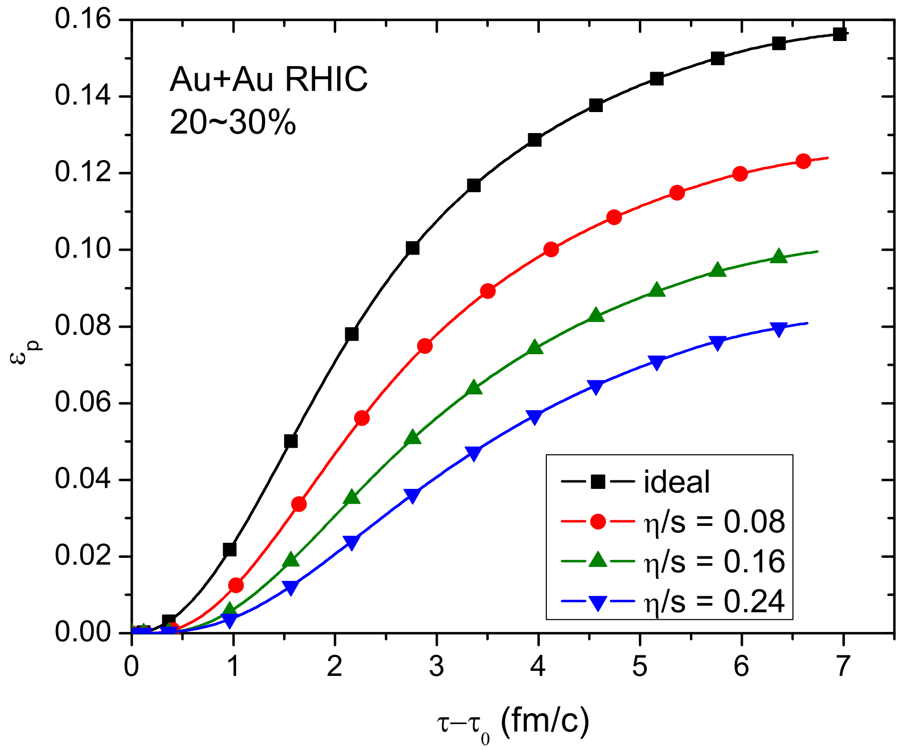
Featuring the QGP in one of its finest performances

Producer: Chun Shen

$$(\eta/\boldsymbol{s})_{\mathrm{QGP}}$$

How to use elliptic flow for measuring $(\eta/s)_{\mathrm{QGP}}$

Hydrodynamics converts
spatial deformation of initial state $\Longrightarrow$
momentum anisotropy of final state,
through anisotropic pressure gradients



Shear viscosity degrades conversion efficiency

$$\varepsilon_x = \frac{\langle\langle y^2 - x^2\rangle\rangle}{\langle\langle y^2 + x^2\rangle\rangle} \Longrightarrow \varepsilon_p = \frac{\langle T^{xx} - T^{yy}\rangle}{\langle T^{xx} + T^{yy}\rangle}$$

of the fluid; the suppression of ε_p is monotonically related to η/s.

The observable that is most directly related to the total hydrodynamic momentum anisotropy ε_p is the **total (p_T-integrated) charged hadron elliptic flow v_2^{ch}**:

$$\varepsilon_p = \frac{\langle T^{xx} - T^{yy}\rangle}{\langle T^{xx} + T^{yy}\rangle} \Longleftrightarrow \frac{\sum_i \int p_T dp_T \int d\phi_p \, p_T^2 \, \cos(2\phi_p) \frac{dN_i}{dy p_T dp_T d\phi_p}}{\sum_i \int p_T dp_T \int d\phi_p \, p_T^2 \frac{dN_i}{dy p_T dp_T d\phi_p}} \Longleftrightarrow v_2^{\mathrm{ch}}$$

How to use elliptic flow for measuring $(\eta/s)_{\rm QGP}$ (ctd.)

- **If ε_p saturates** before hadronization (e.g. in PbPb@LHC (?))

$\Rightarrow$ $v_2^{\rm ch} \approx$ not affected by details of hadronic rescattering below $T_{\rm c}$

but: $v_2^{(i)}(p_T)$, $\frac{dN_i}{dyd^2p_T}$ change during hadronic phase (addl. radial flow!), and these changes depend on details of the hadronic dynamics (chemical composition etc.)

$\Rightarrow$ $v_2(p_T)$ of a single particle species **not** a good starting point for extracting η/s

- **If ε_p does not saturate** before hadronization (e.g. AuAu@RHIC), dissipative hadronic dynamics affects not only the distribution of ε_p over hadronic species and in p_T, but even the final value of ε_p itself (from which we want to get η/s)

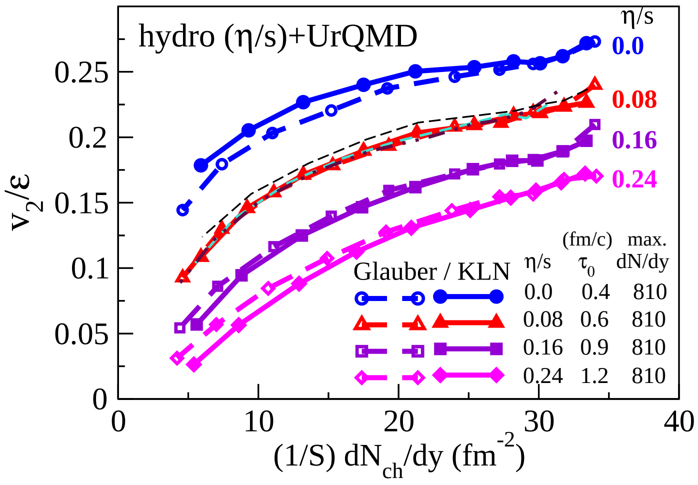
$\Rightarrow$ need hybrid code that couples viscous hydrodynamic evolution of QGP to **realistic microscopic dynamics** of late-stage hadron gas phase

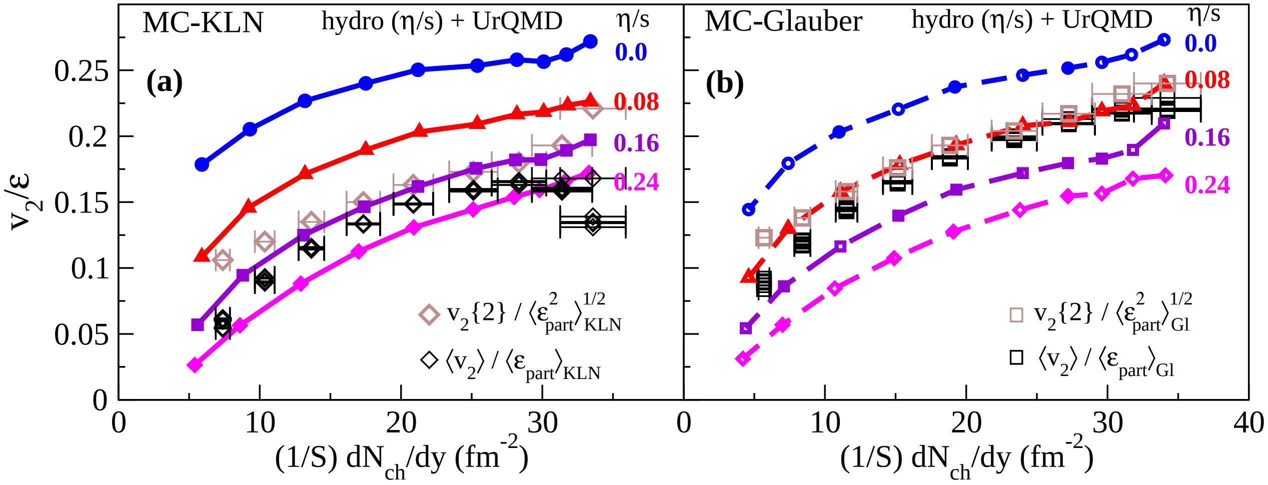
$\Rightarrow$ **VISHNU** ("Viscous Israel-Steward Hydrodynamics 'n' UrQMD")

(Song, Bass, UH, PRC83 (2011) 024912) Note: this paper shows that UrQMD $\neq$ viscous hydro!

Extraction of $(\eta/s)_{\rm QGP}$ from AuAu@RHIC

H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRL106 (2011) 192301



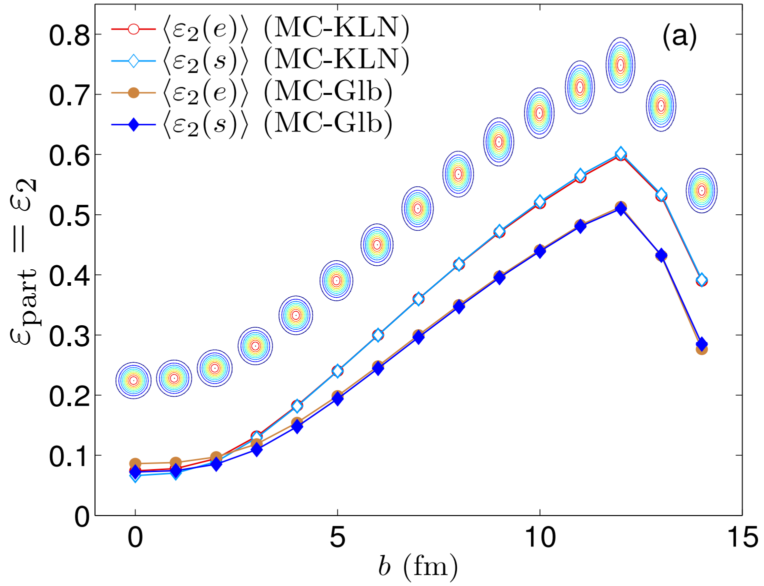


$$1 < 4\pi(\eta/s)_{\rm QGP} < 2.5$$

- All shown theoretical curves correspond to parameter sets that correctly describe centrality dependence of charged hadron production as well as p_T-spectra of charged hadrons, pions and protons at all centralities
- $v_2^{\rm ch}/\varepsilon_x$ vs. $(1/S)(dN_{\rm ch}/dy)$ is "universal", i.e. depends **only on** $\boldsymbol{\eta/s}$ but (in good approximation) not on initial-state model (Glauber vs. KLN, optical vs. MC, RP vs. PP average, etc.)
- dominant source of uncertainty: $\varepsilon_x^{\rm Gl}$ vs. $\varepsilon_x^{\rm KLN}$ ⟶
- smaller effects: *early flow* → increases $\frac{v2}{\varepsilon}$ by ~ few % → larger η/s

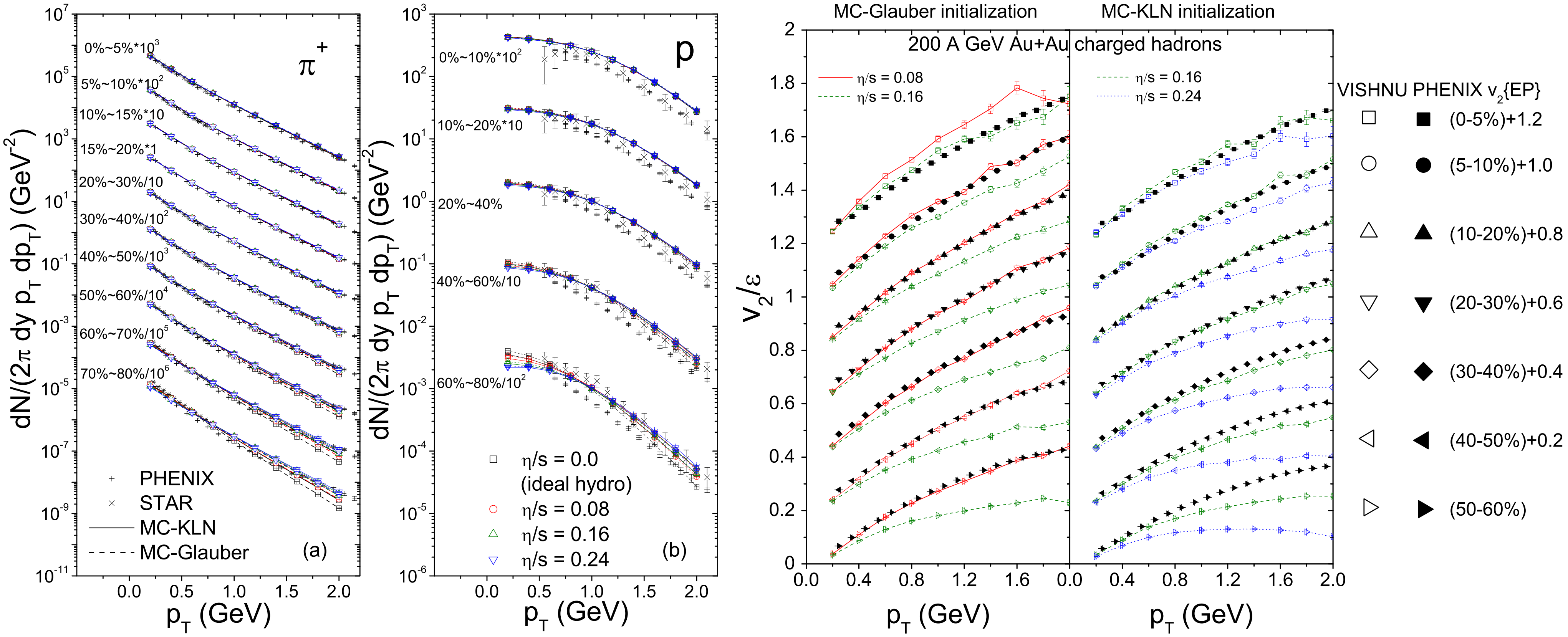
  bulk viscosity → affects $v_2^{\rm ch}(p_T)$, but ≈ not $v_2^{\rm ch}$

Zhi Qiu, UH, PRC84 (2011) 024911



Global description of AuAu@RHIC spectra and v_2

VISHNU (H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRC83 (2011) 054910)

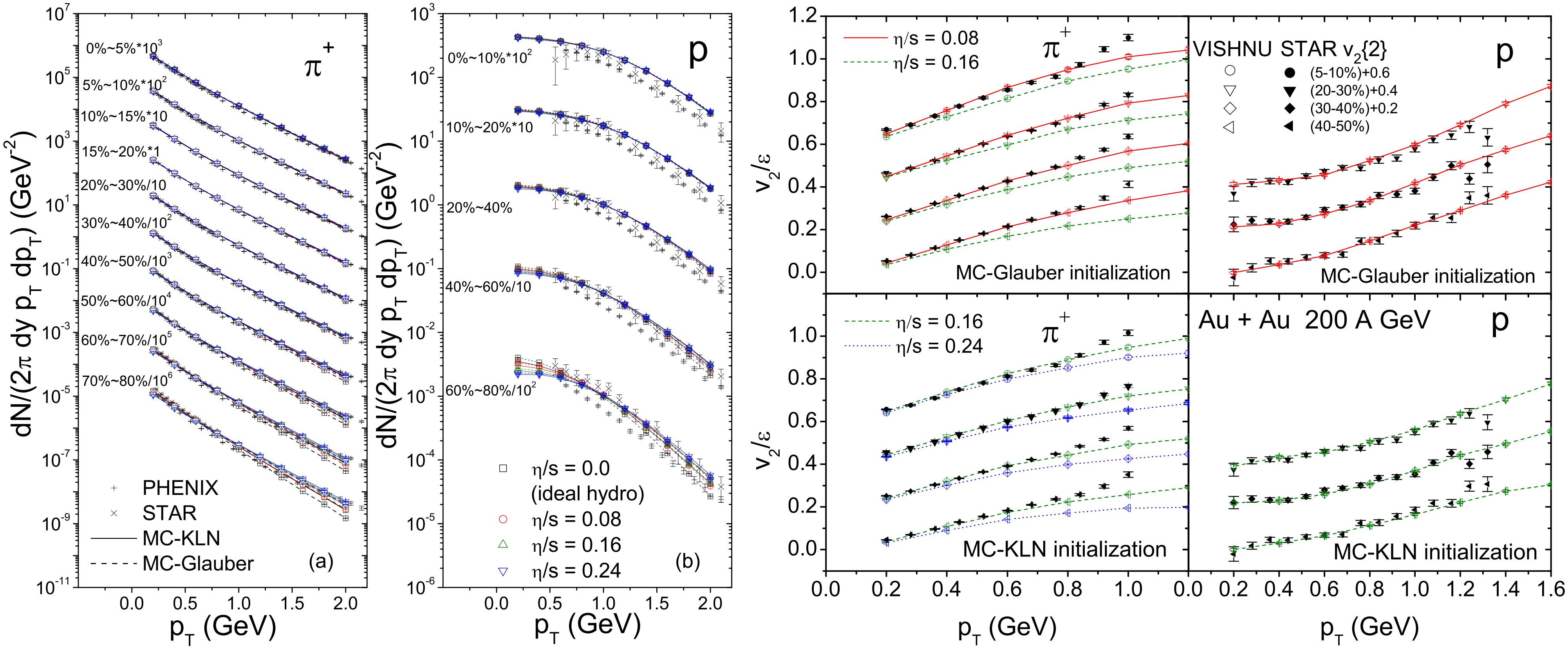


- $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities

- Note: $T_{\rm chem} = 165\,{\rm MeV}$ reproduces the proton spectra from STAR, but not from PHENIX! $\Longrightarrow$ Slightly incorrect chemical composition in hadronic phase? Not enough $p\bar{p}$ annihilation in UrQMD?

Global description of AuAu@RHIC spectra and v_2

VISHNU (H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRC83 (2011) 054910)



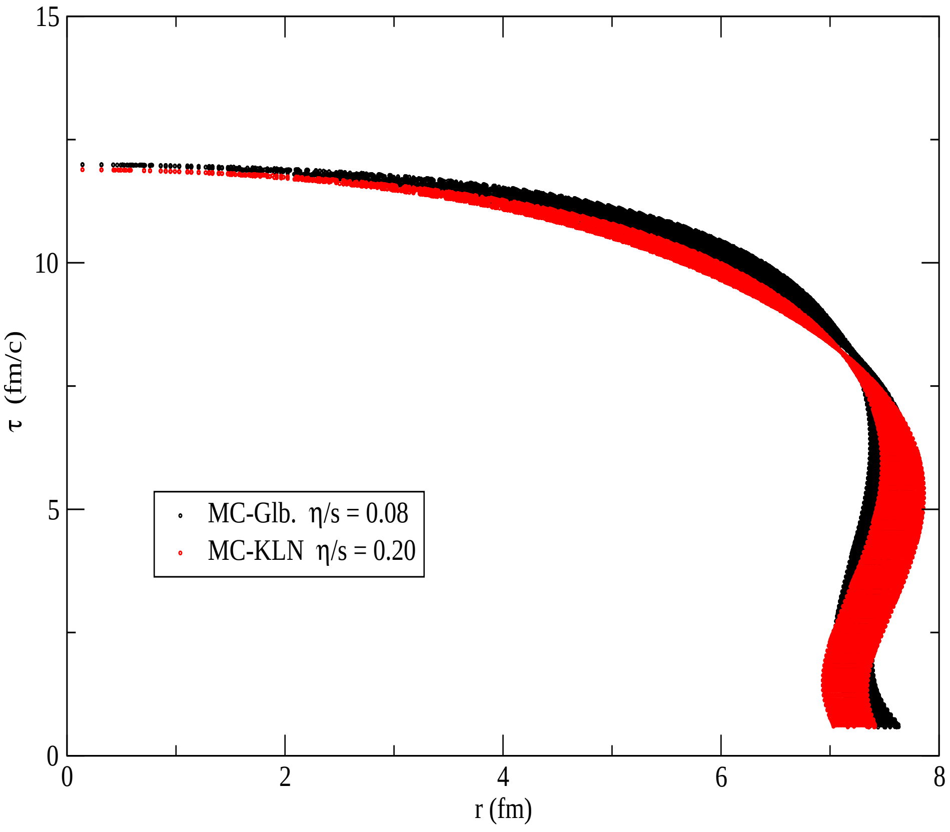
- $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities
- A purely hydrodynamic model (without UrQMD afterburner) with the same values of η/s does almost as well (except for centrality dependence of proton $v_2(p_T)$) (C. Shen et al., PRC84 (2011) 044903)
  Main difference: VISHNU develops more radial flow in the hadronic phase (larger shear viscosity), pure viscous hydro must start earlier than VISHNU ($\tau_0 = 0.6$ instead of 1.05 fm/c), otherwise proton spectra are too steep
- These η/s values agree with Luzum & Romatschke, PRC78 (2008), even though they used EOS with incorrect hadronic chemical composition $\Longrightarrow$ shows robustness of extracting η/s from total charged hadron v_2

Differences in evolution for η/s=0.08 and 0.2 (for tomographers)

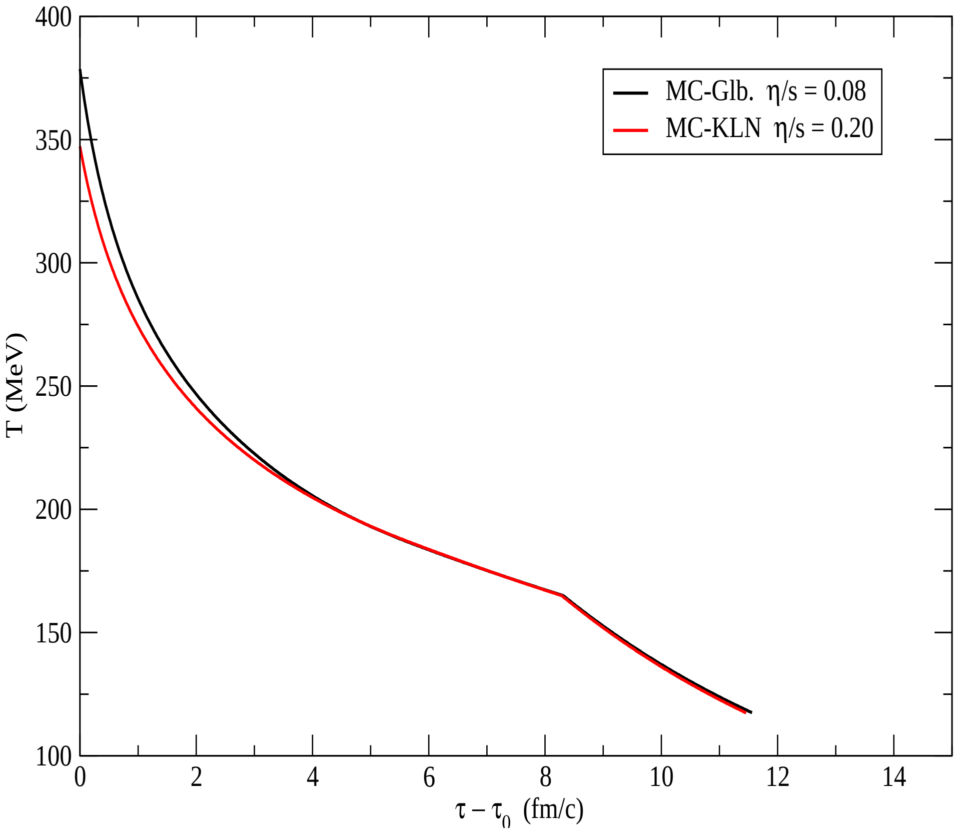
(Au+Au@RHIC200, 0-5%, ensemble averaged)

Chun Shen 2011, unpublished

Freeze-out surface



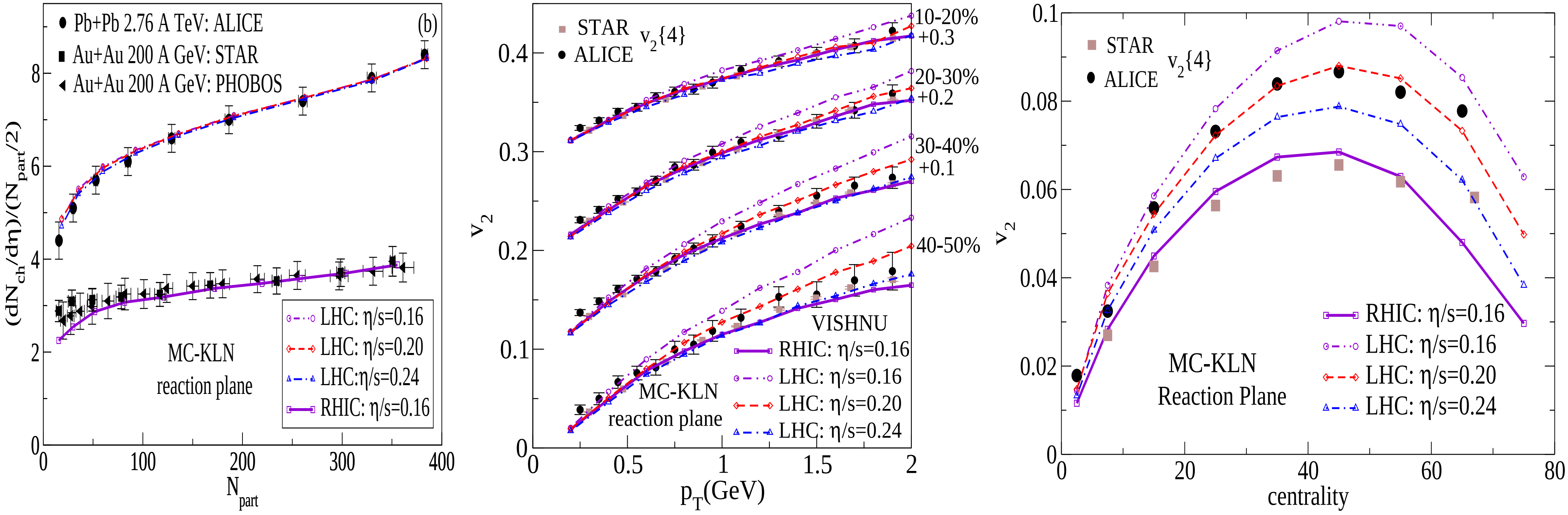
Evolution of central temperature



Only small differences (?).
Much less uncertainty than between “hydro I” and “hydro II” in Renk’s analysis

Pre- and postdictions for PbPb@LHC

VISHNU with MC-KLN (Song, Bass, UH, PRC83 (2011) 054912)

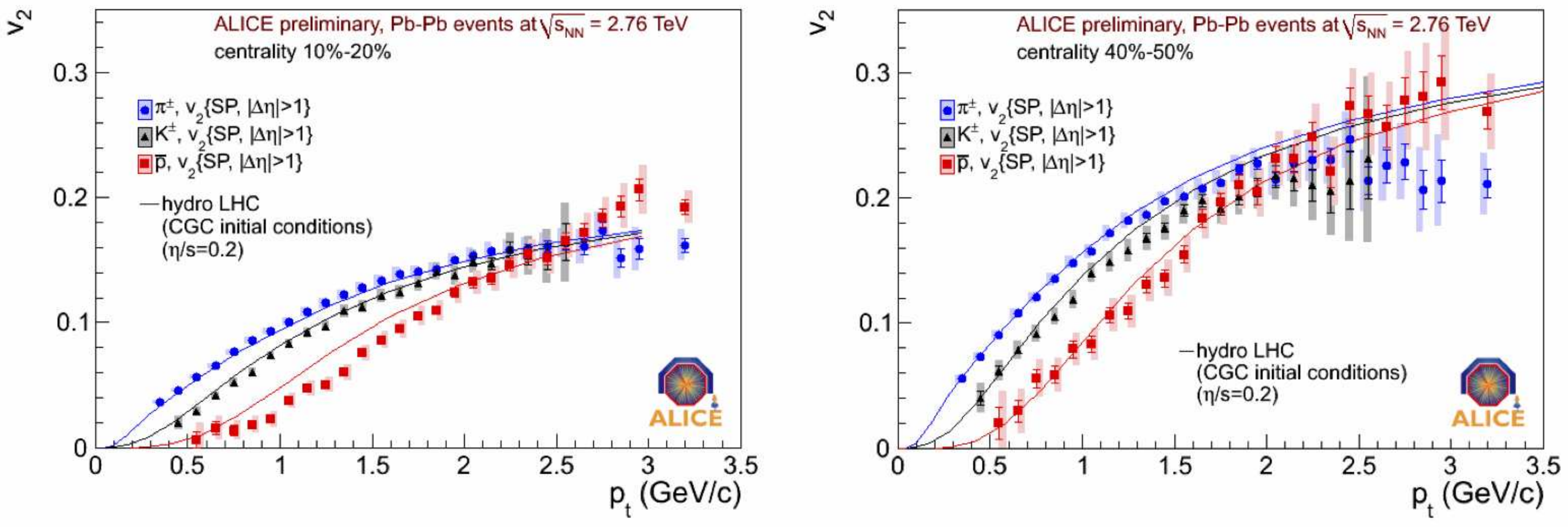


- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of $dN_{\rm ch}/d\eta$ well in both AuAu@RHIC and PbPb@LHC
- $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN works well for charged hadron $v_2(p_T)$ and integrated v_2 in AuAu@RHIC, but overpredicts both by about 10-15% in PbPb@LHC
- Similar results from predictions based on pure viscous hydro (C. Shen et al., PRC84 (2011) 044903)
- **but:** At LHC significant sensitivity of v_2 to initialization of viscous pressure tensor $\pi^{\mu\nu}$ (Navier-Stokes or zero) $\Longrightarrow$ need pre-equilibrium model.

  $\Longrightarrow$ **QGP at LHC not much more viscous than at RHIC!**

Successful prediction of $v_2(p_T)$ for identified hadrons in PbPb@LHC

Data: ALICE, Quark Matter 2011 Prediction: Shen et al., PRC84 (2011) 044903 (VISH2+1)



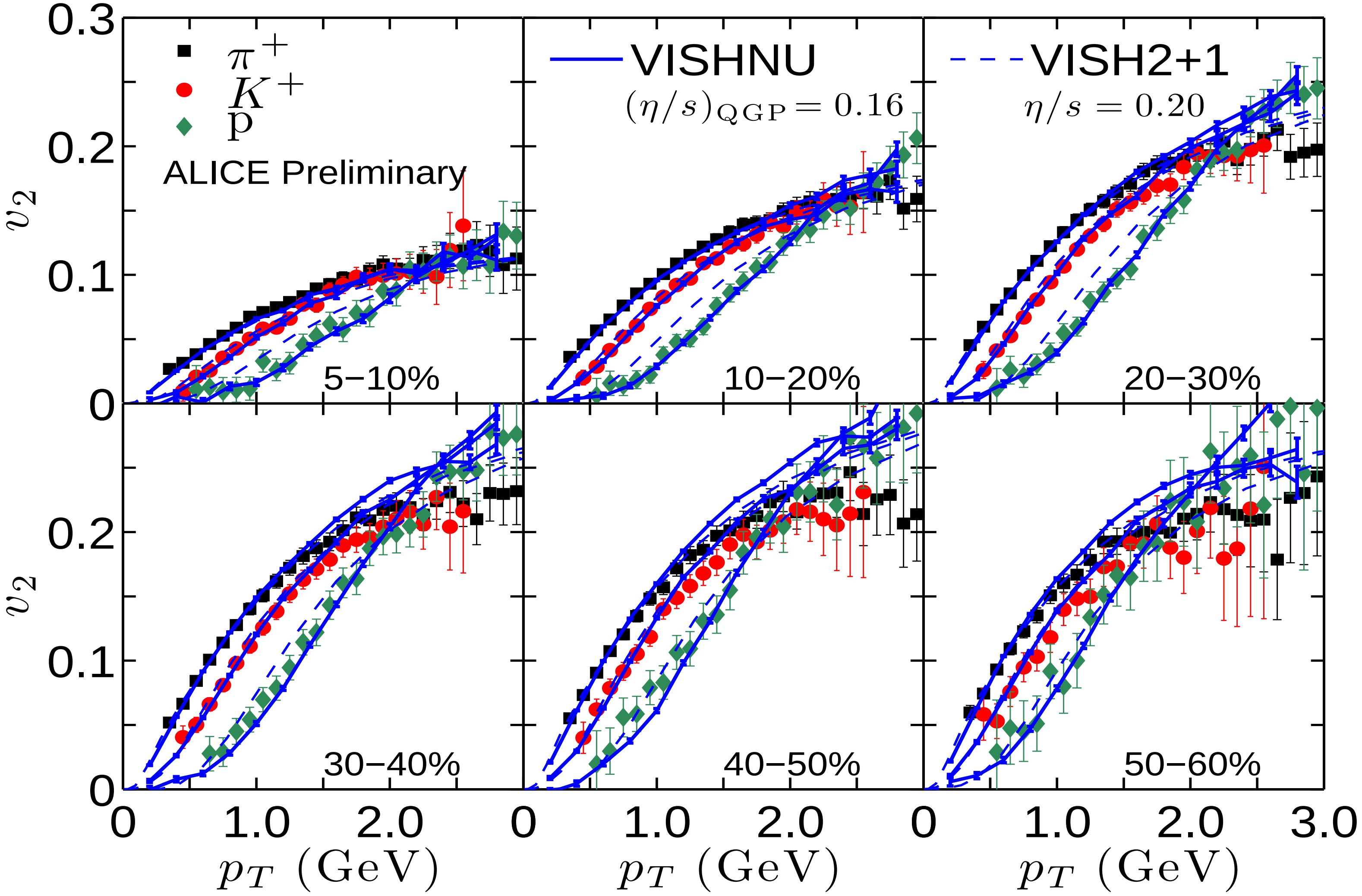
Perfect fit in semi-peripheral collisions!

The problem with insufficient proton radial flow exists only in more central collisions

Adding the hadronic cascade (VISHNU) helps:

$v_2(p_T)$ in PbPb@LHC: ALICE vs. VISHNU

Data: ALICE, preliminary (Snellings, Krzewicki, Quark Matter 2011)
Dashed lines: Shen et al., PRC84 (2011) 044903 (VISH2+1, MC-KLN, $(\eta/s)_{\mathrm{QGP}}=0.2$)
Solid lines: Song, Shen, UH 2011 (VISHNU, MC-KLN, $(\eta/s)_{\mathrm{QGP}}=0.16$)



VISHNU yields correct magnitude and centrality dependence of $v_2(p_T)$ for pions, kaons **and protons!**

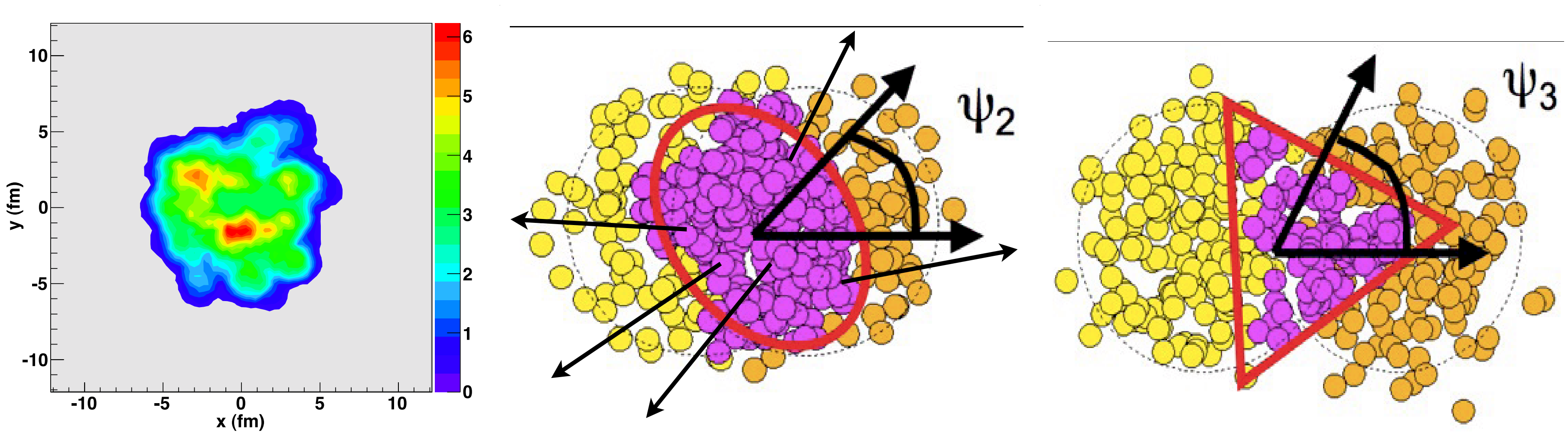
Same $(\eta/s)_{\mathrm{QGP}} = 0.16$ (for MC-KLN) at RHIC and LHC!

Event-by-event hydro (ideal and viscous):

Flow fluctuations and flow-angle correlations

Event-by-event shape and flow fluctuations rule!

(Alver and Roland, PRC81 (2010) 054905)

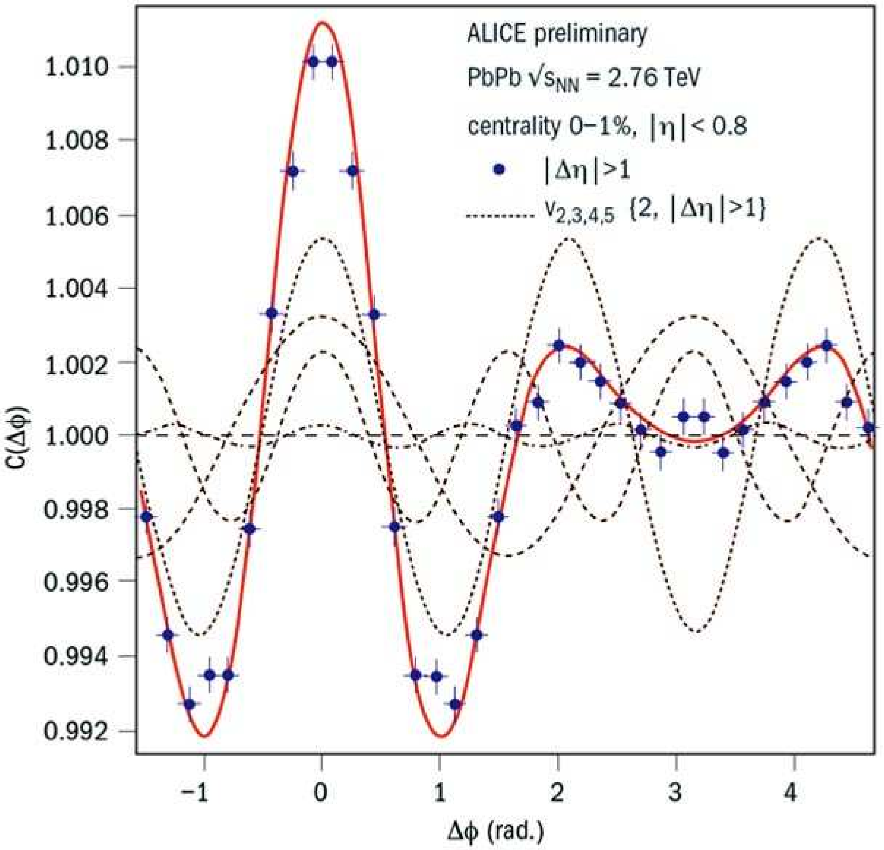


- Each event has a different initial shape and density distribution, characterized by different set of harmonic eccentricity coefficients ε_n

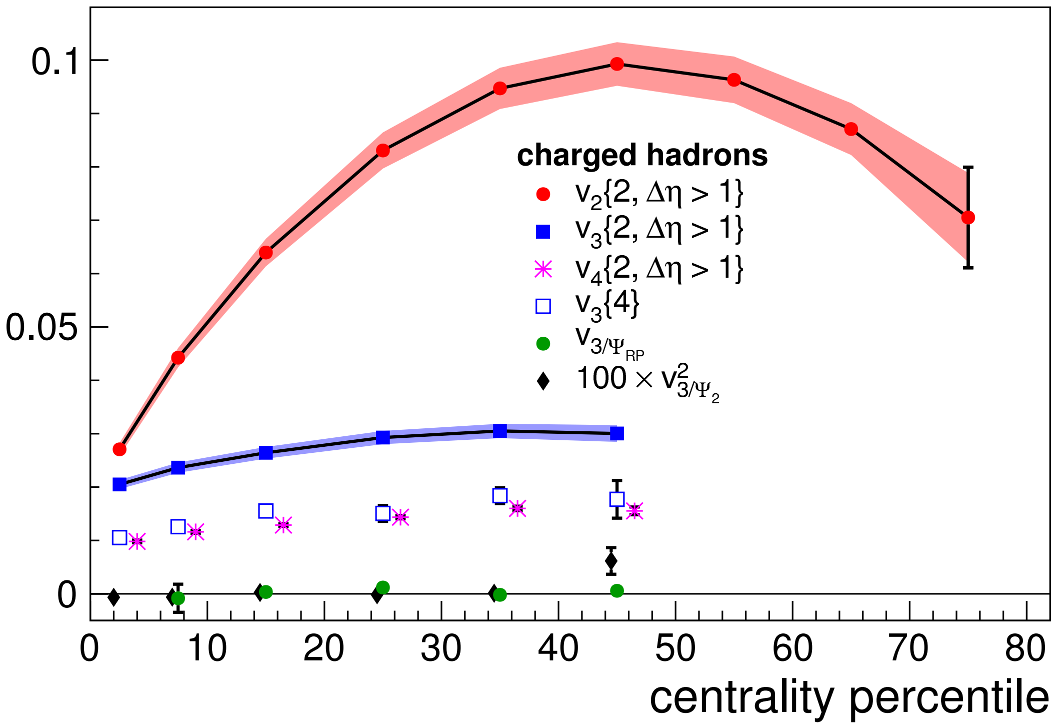
- Each event develops its individual hydrodynamic flow, characterized by a set of harmonic flow coefficients v_n and flow angles ψ_n

- At small impact parameters fluctuations ("hot spots") dominate over geometric overlap effects
  (Alver & Roland, PRC81 (2010) 054905; Qin, Petersen, Bass, Müller, PRC82 (2010) 064903)

Event-by-event shape and flow fluctuations rule!



ALICE (A. Bilandzic) Quark Matter 2011



- in the 1% most central collisions $v_3 > v_2 \Longrightarrow$ prominent "Mach cone"-like structure!
- triangular flow angle uncorrelated with reaction plane and elliptic flow angles
  $\Longrightarrow$ due to event-by-event eccentricity fluctuations which dominate the anisotropic flows in the most central collisions

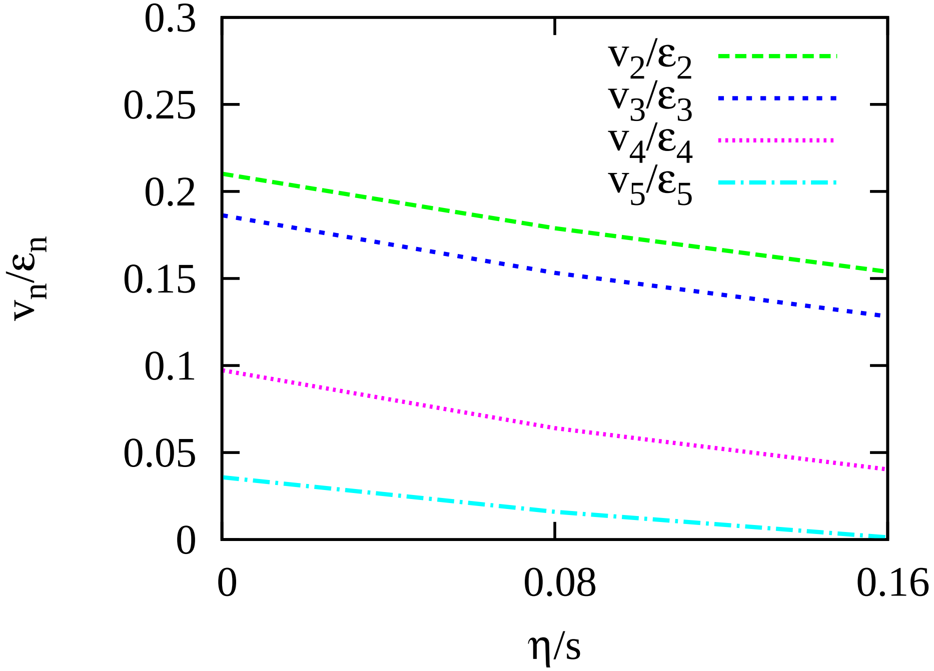
Back to the
“elephant in the room”:
How to eliminate the large
model uncertainty
in the initial eccentricity?

Two observations:

I. Shear viscosity suppresses higher flow harmonics more strongly

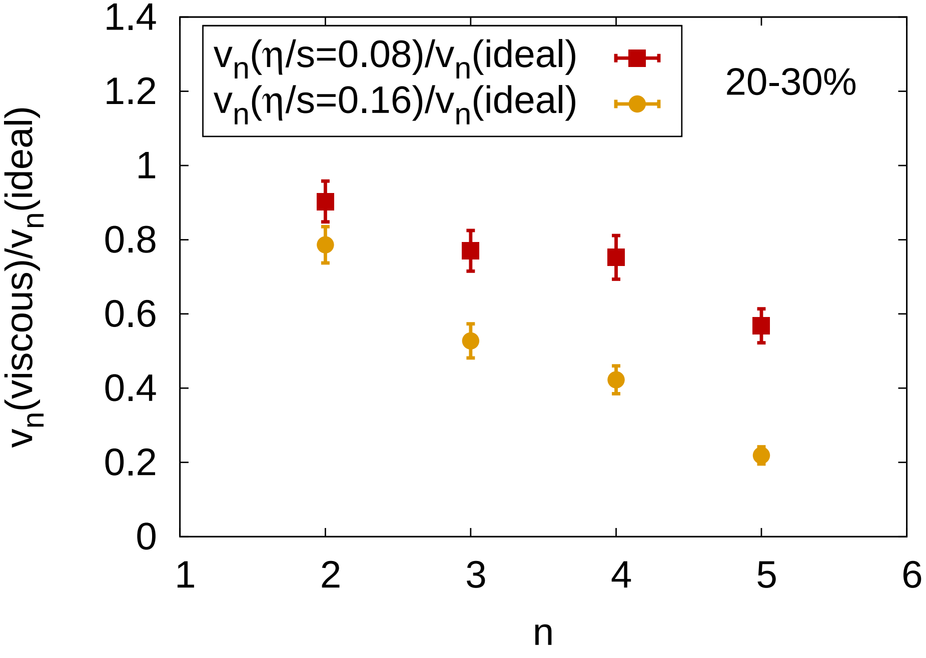
Alver et al., PRC82 (2010) 034913

(averaged initial conditions)



Schenke et al., arXiv:1109.6289

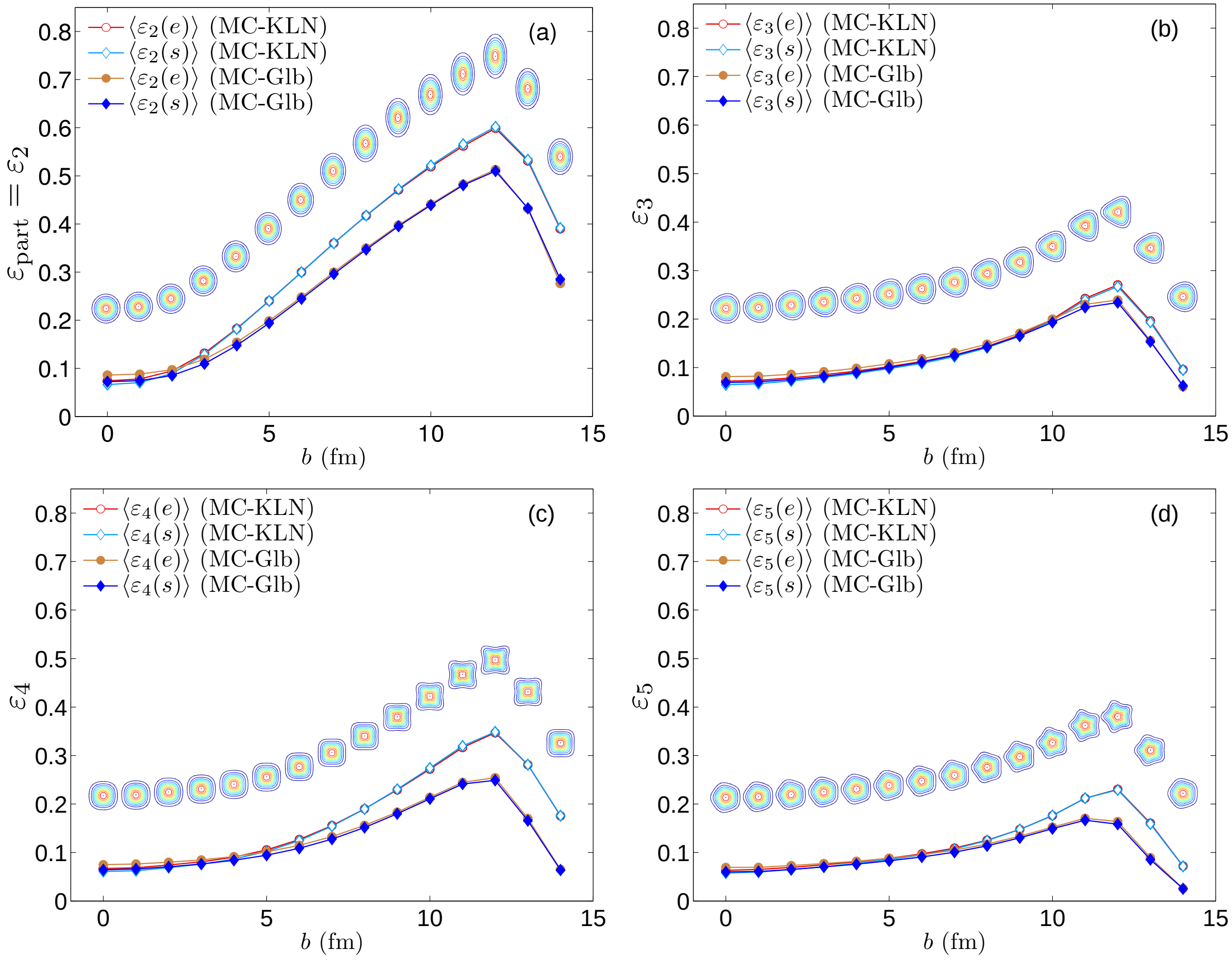
(event-by-event hydro)



$\Longrightarrow$ **Idea:** Use simultaneous analysis of elliptic and triangular flow to constrain initial state models (see also Bhalerao, Luzum Ollitrault, PRC 84 (2011) 034910)

Two observations:
II. ε_3 is $\approx$ model independent

Zhi Qiu, UH, PRC84 (2011) 024911



Initial eccentricities ε_n and angles ψ_n:

$$\varepsilon_n e^{in\psi_n} = -\frac{\int r dr d\phi\, r^2 e^{in\phi}\, e(r,\phi)}{\int r dr d\phi\, r^2\, e(r,\phi)}$$

- MC-KLN has larger ε_2 and ε_4, but similar ε_5 and almost identical ε_3 as MC-Glauber

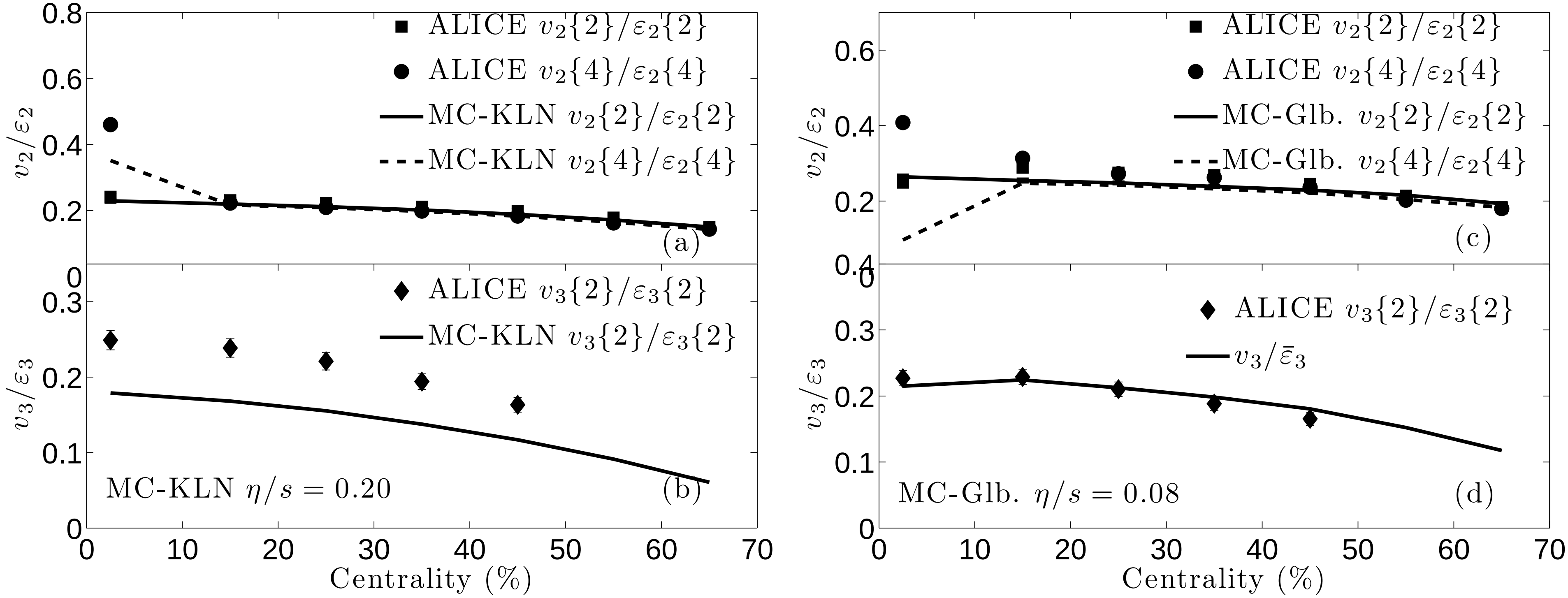
- Angles of ε_2 and ε_4 are correlated with reaction plane by geometry, whereas those of ε_3 and ε_5 are random (purely fluctuation-driven)

- While v_4 and v_5 have mode-coupling contributions from ε_2, v_3 is almost pure response to ε_3 and $v_3/\varepsilon_3 \approx$const. over a wide range of centralities

$\Longrightarrow$ **Idea:** Use total charged hadron $v_3^{\rm ch}$ to determine $(\eta/s)_{\rm QGP}$,
then check $v_2^{\rm ch}$ to distinguish between MC-KLN and MC-Glauber!

Combined v_2 & v_3 analysis: η/s is small!

Zhi Qiu, C. Shen, UH, PLB707 (2012) 151 and QM2012 (e-by-e VISH2+1)



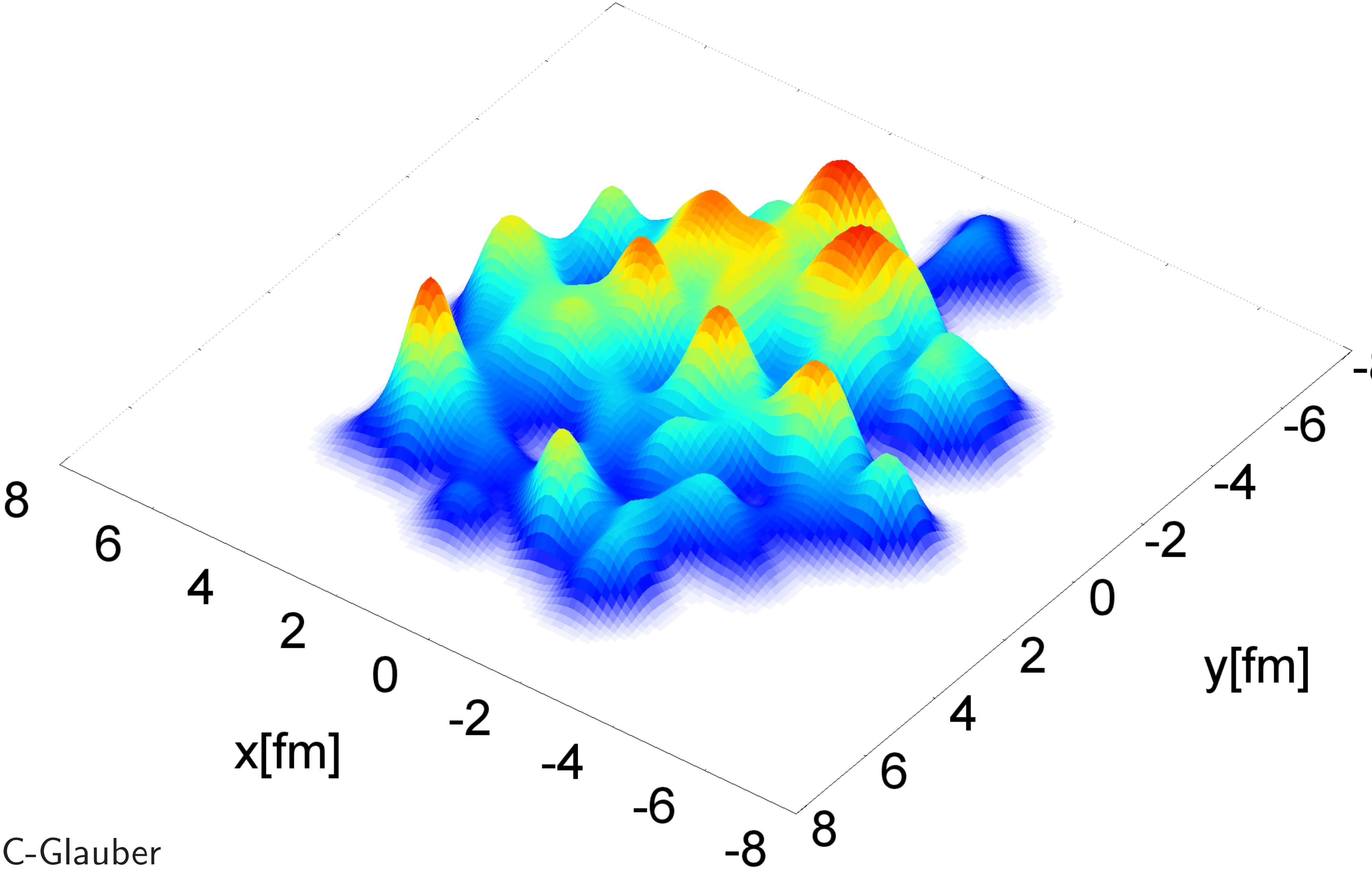
- Both MC-KLN with $\eta/s = 0.2$ and MC-Glauber with $\eta/s = 0.08$ give very good description of v_2/ε_2 at all centralities.
- **Only $\eta/s = 0.08$ (with MC-Glauber initial conditions) describes v_3/ε_3!**

  PHENIX, comparing to calculations by Alver et al. (PRC82 (2010) 034913), come to similar conclusions at RHIC energies (Adare et al., arXiv:1105.3928, and Lacey et al., arXiv:1108.0457)
- **Large v_3 measured at RHIC and LHC requires small $(\eta/s)_{\mathrm{QGP}} \simeq 1/(4\pi)$** unless the fluctuations in these models are completely wrong and ε_3 is really 50% larger than these models predict!

Sub-nucleonic fluctuations

Adding sub-nucleonic quantum fluctuations

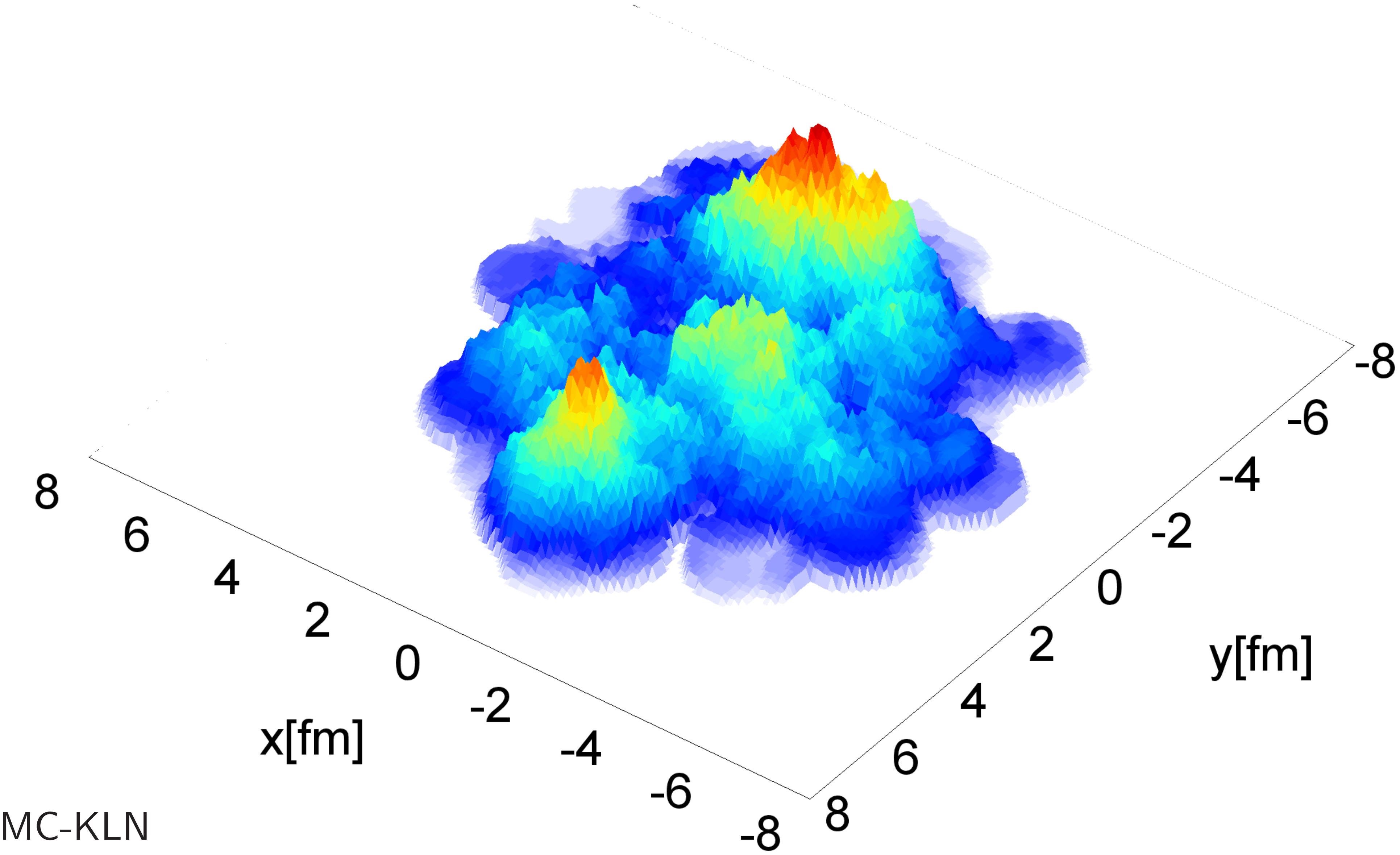
Schenke, Tribedy, Venugopalan, PRL108, 252301 (2012)



MC-Glauber

Adding sub-nucleonic quantum fluctuations

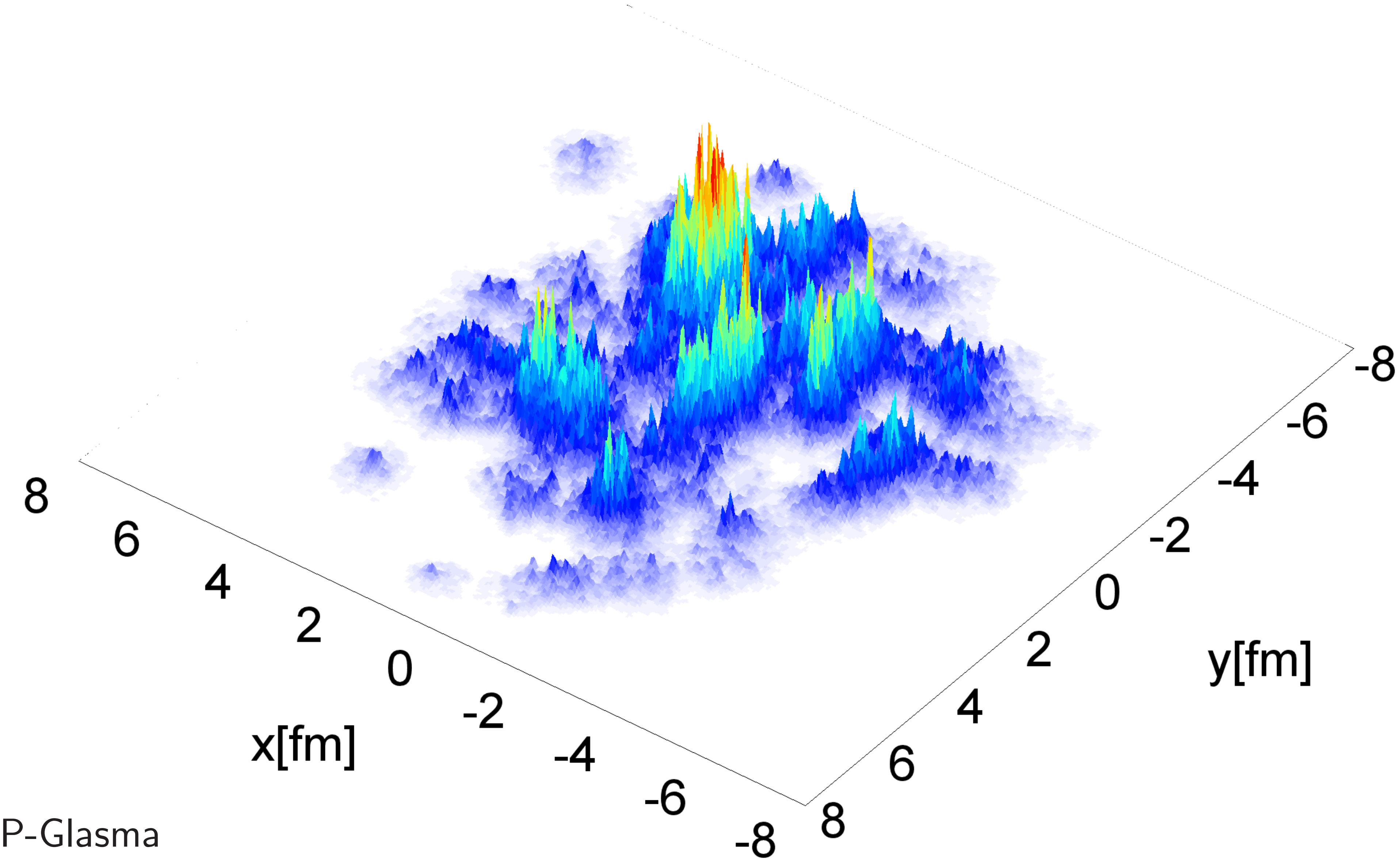
Schenke, Tribedy, Venugopalan, PRL108, 252301 (2012)



MC-KLN

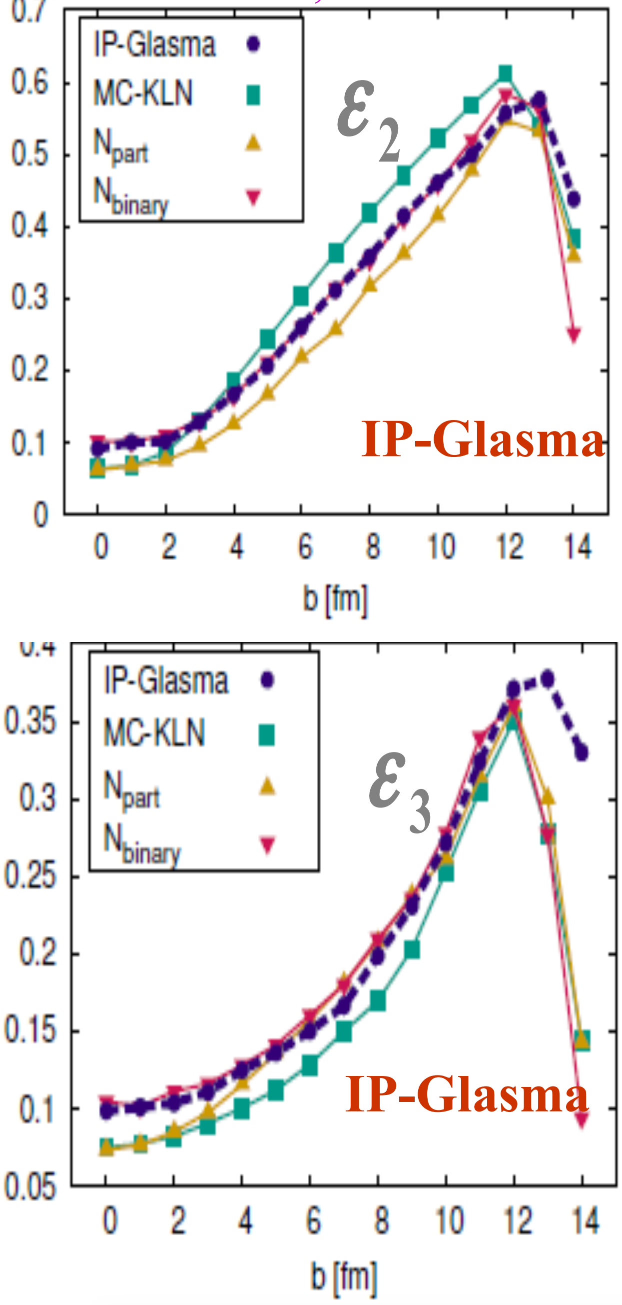
Adding sub-nucleonic quantum fluctuations

Schenke, Tribedy, Venugopalan, PRL108, 252301 (2012)

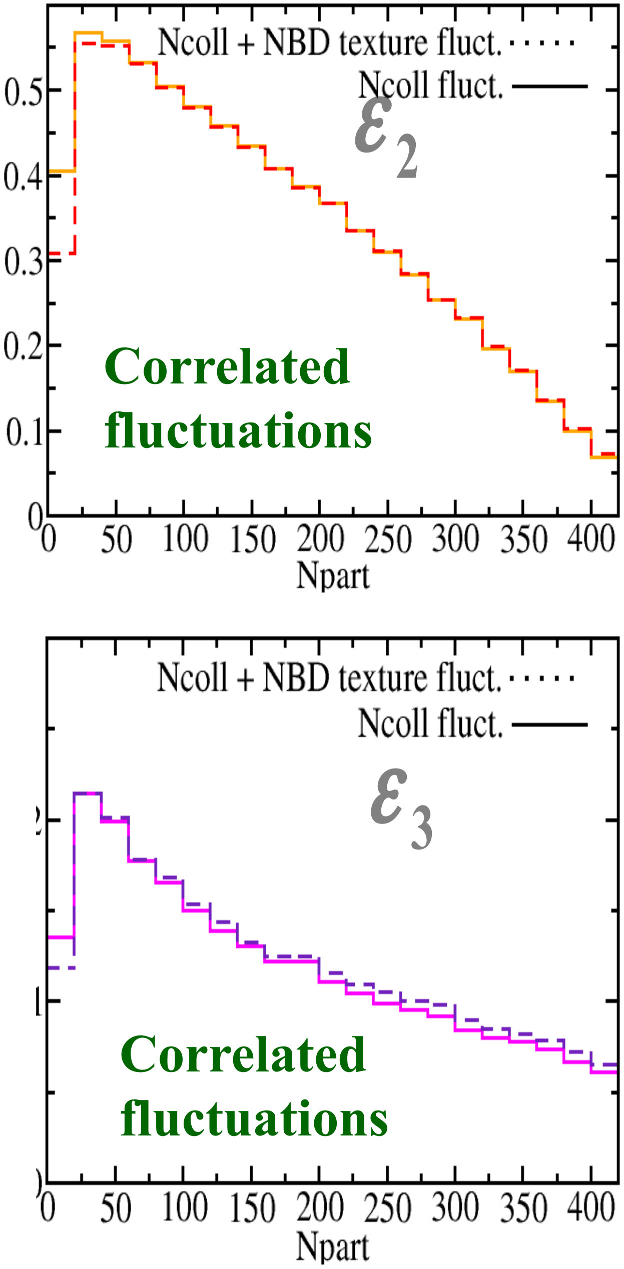


IP-Glasma

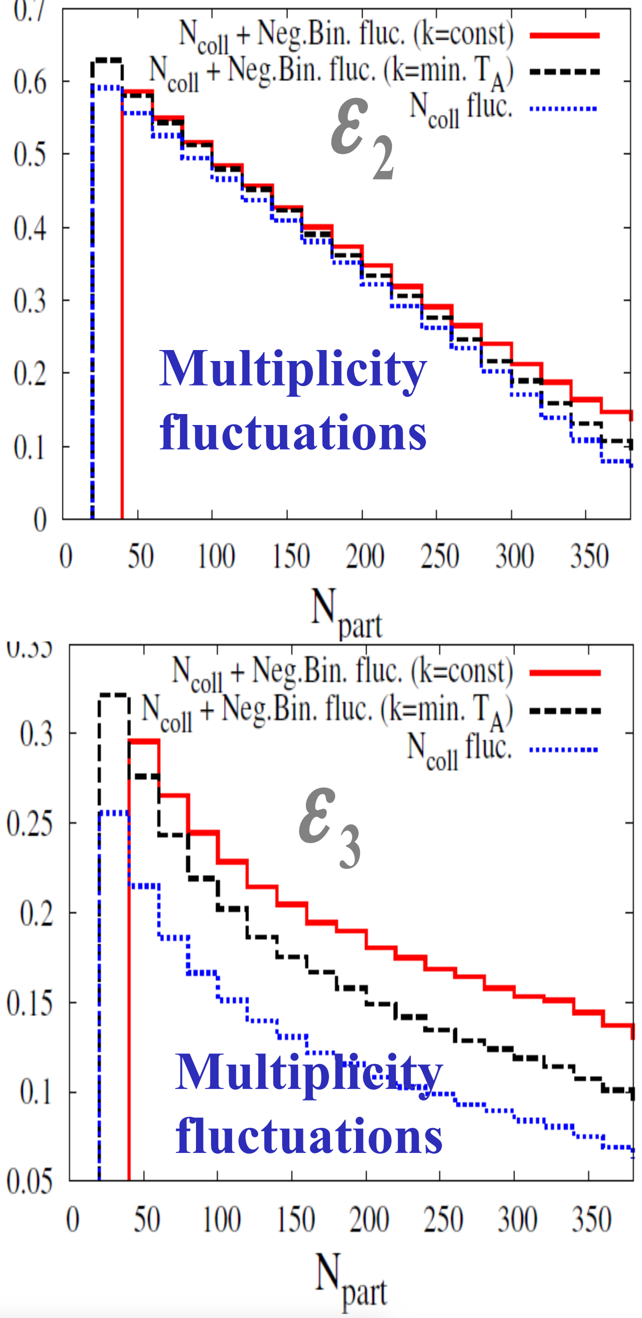
Schenke, et al.



Moreland+ Heinz



Dumitru +Nara



Please also refer to **talk of B. Schenke, S. Moreland & A. Dumitru**

Energy density

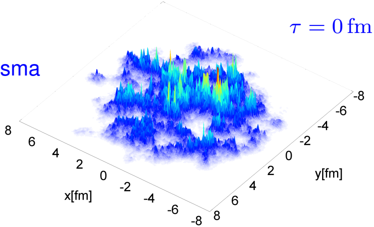
B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 108, 252301 (2012)

Solve for gauge fields after the collision in the forward lightcone
Compute energy density in the fields at $\tau = 0$ and later times with CYM evolution

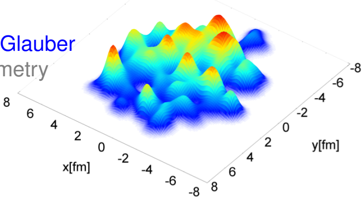
Lattice: Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237

$\tau = 0\,\mathrm{fm}$

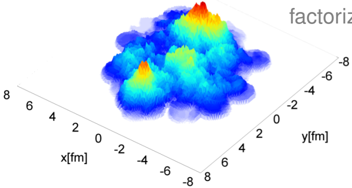
Glasma



MC-Glauber
geometry



MC-KLN
uses k_T-factorization



Very different initial energy density distributions in the models

MC-KLN: Drescher, Nara, nucl-th/0611017
mckln-3.52 from `http://physics.baruch.cuny.edu/files/CGC/CGC_IC.html` with defaults, energy density scaling

Energy density

B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 108, 252301 (2012)

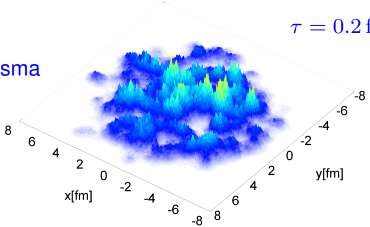
Solve for gauge fields after the collision in the forward lightcone

Compute energy density in the fields at $\tau = 0$ and later times with CYM evolution

Lattice: Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237

$\tau = 0.2\,\mathrm{fm}$

Glasma

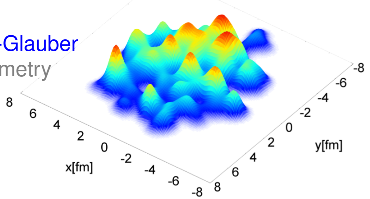


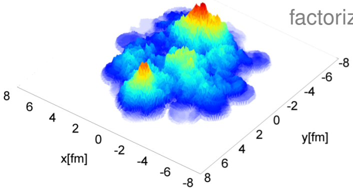
MC-KLN

uses k_T-factorization

MC-Glauber

geometry





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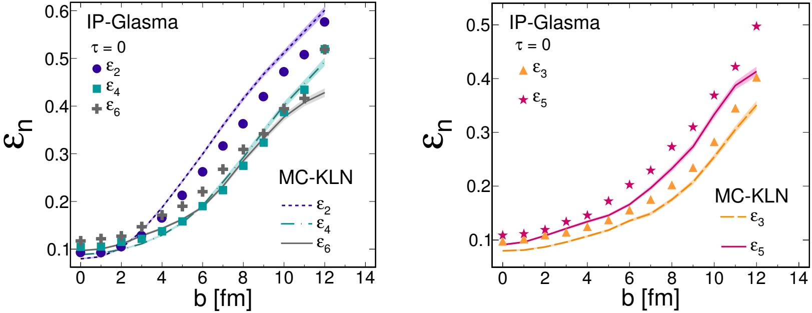
mckln-3.52 from `http://physics.baruch.cuny.edu/files/CGC/CGC_IC.html` with defaults, energy density scaling

Eccentricities

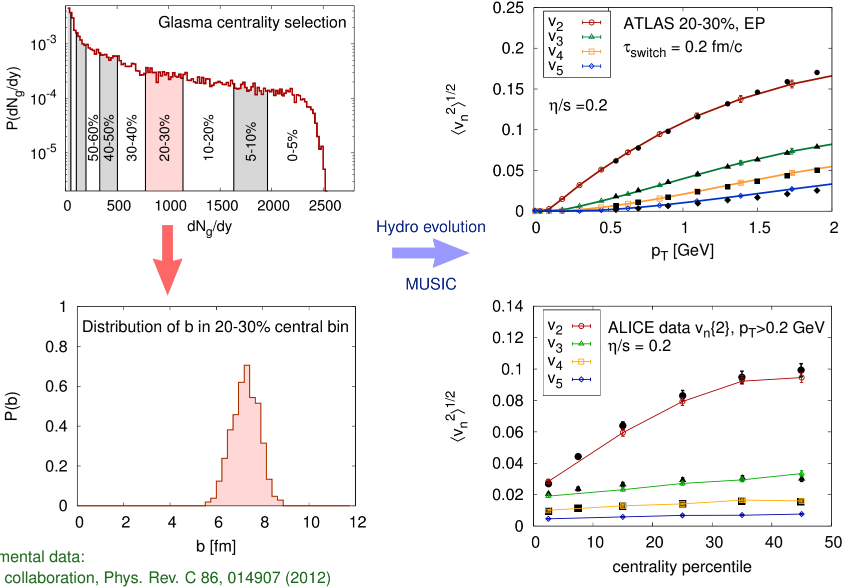
$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

Averages are weighted by the energy density



- ε_n larger in Glasma model for odd n
- ε_n smaller in Glasma model for $n = 2$ (for $b > 3\,\mathrm{fm}$)
  about equal for $n = 4$, larger for $n = 6$

Centrality selection and flow

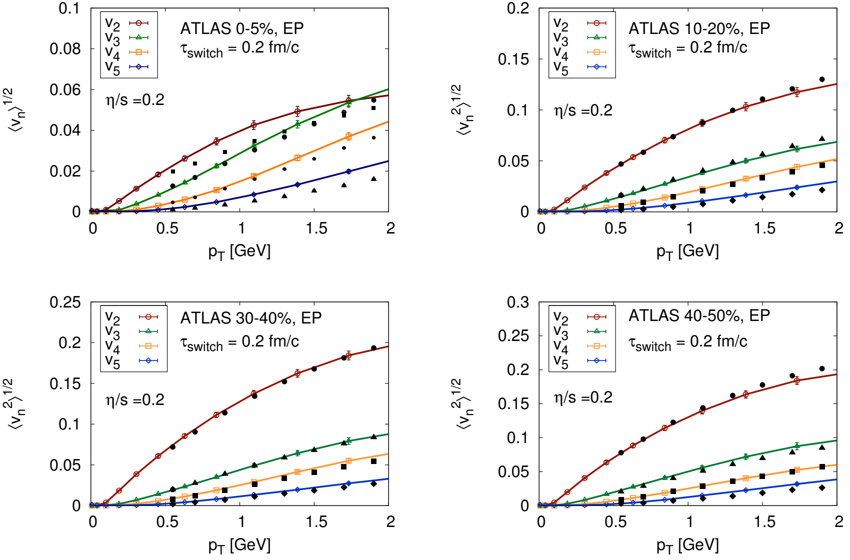


Experimental data:

ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)

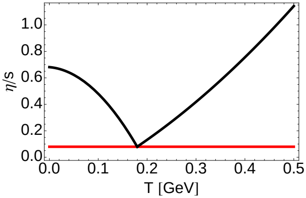
ALICE collaboration, Phys. Rev. Lett. 107, 032301 (2011)

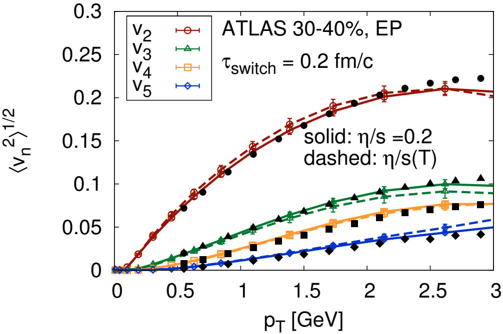
More centrality classes: IP-Glasma + MUSIC



Temperature dependent η/s

Use $\eta/s(T)$ as in Niemi et al., Phys.Rev.Lett. 106 (2011) 212302 and arXiv:1203.2452



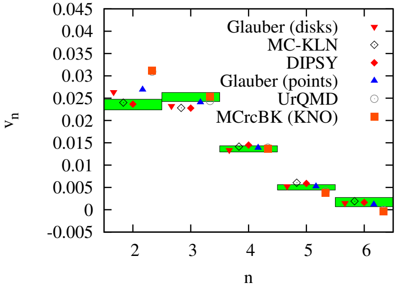


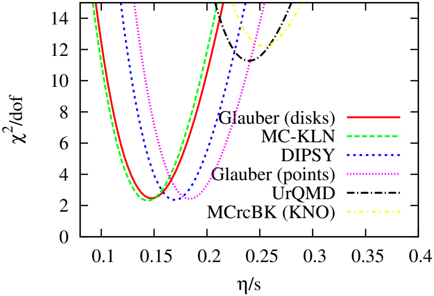
$v_n(p_T)$ for given $\eta/s(T)$ indistinguishable from constant $\eta/s = 0.2$

More detailed study needed

Experimental data:
ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)

η/s FROM ULTRA-CENTRAL COLLISIONS

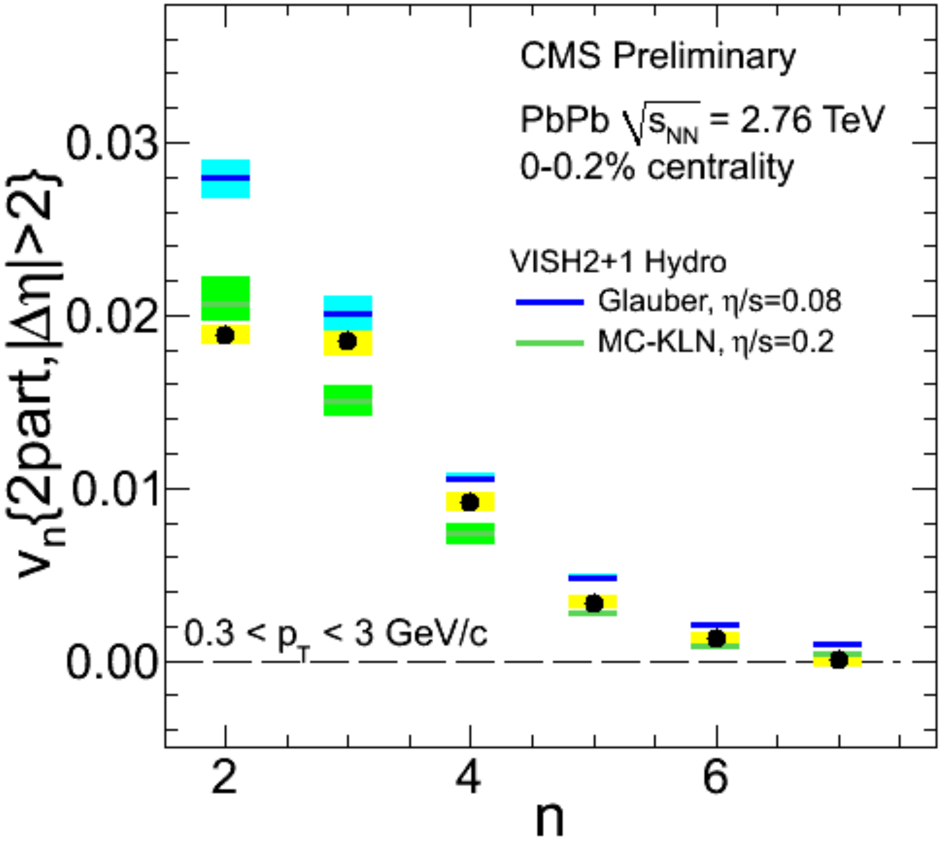




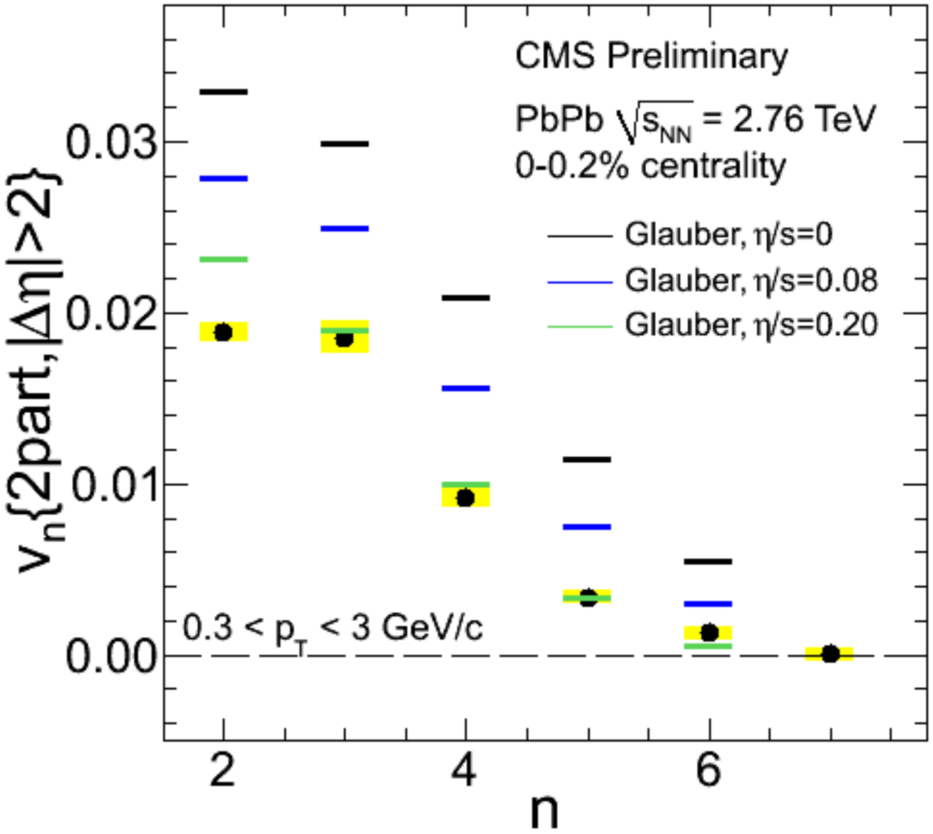
- A simultaneous fit of v_2–v_6 gives a preferred extracted η/s for each initial condition
- Range of results quantifies uncertainty
- Uncertainty due to initial ε_n: $\sim \pm 0.05$

v_n vs. n comparison with hydro

C. Shen, Z. Qiu, and U. Heinz.

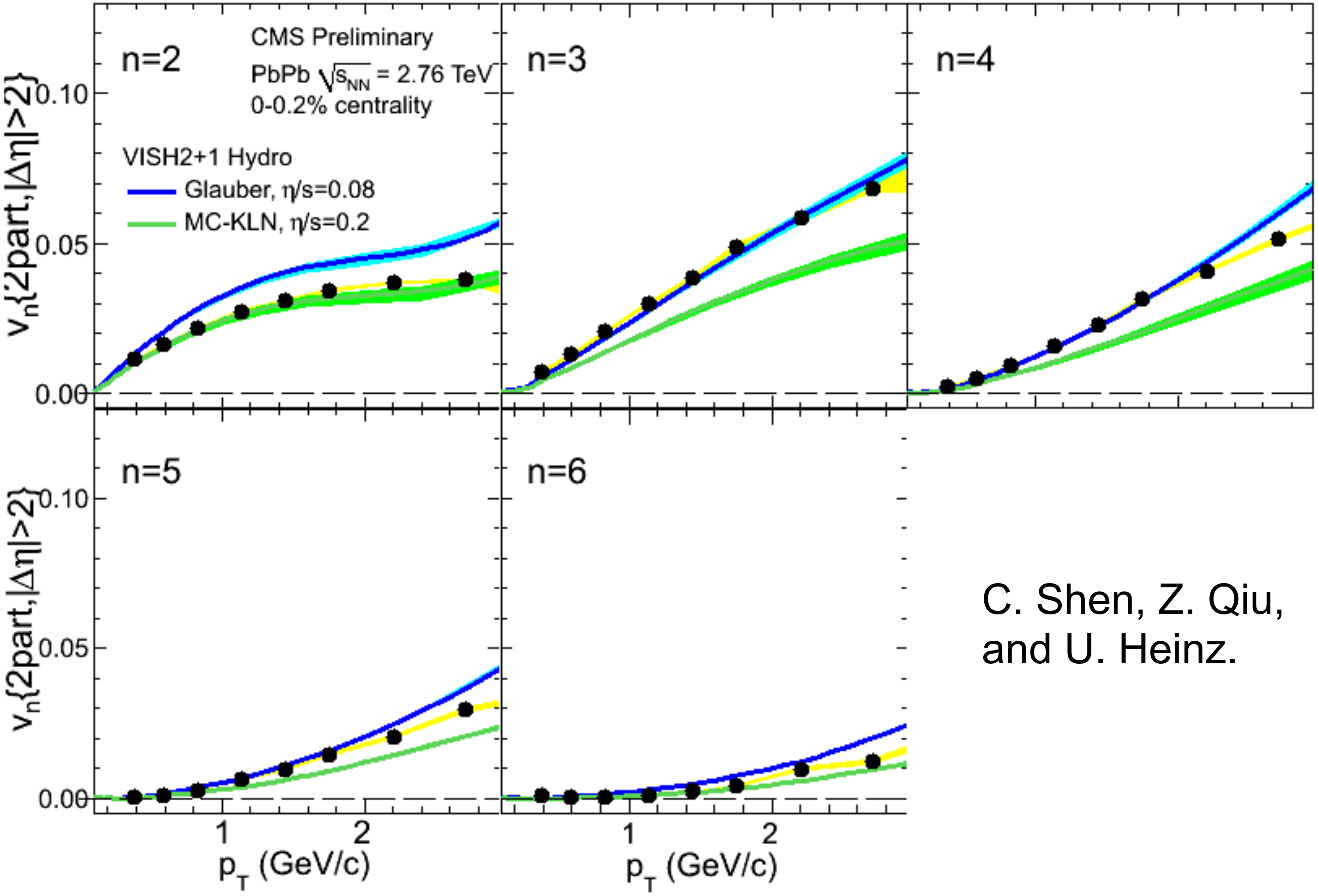


M. Luzum and J. Ollitrault.



- Theory reproduces ordering of harmonics with n > 2 quite well
- Centrality fluctuations need to be explored further

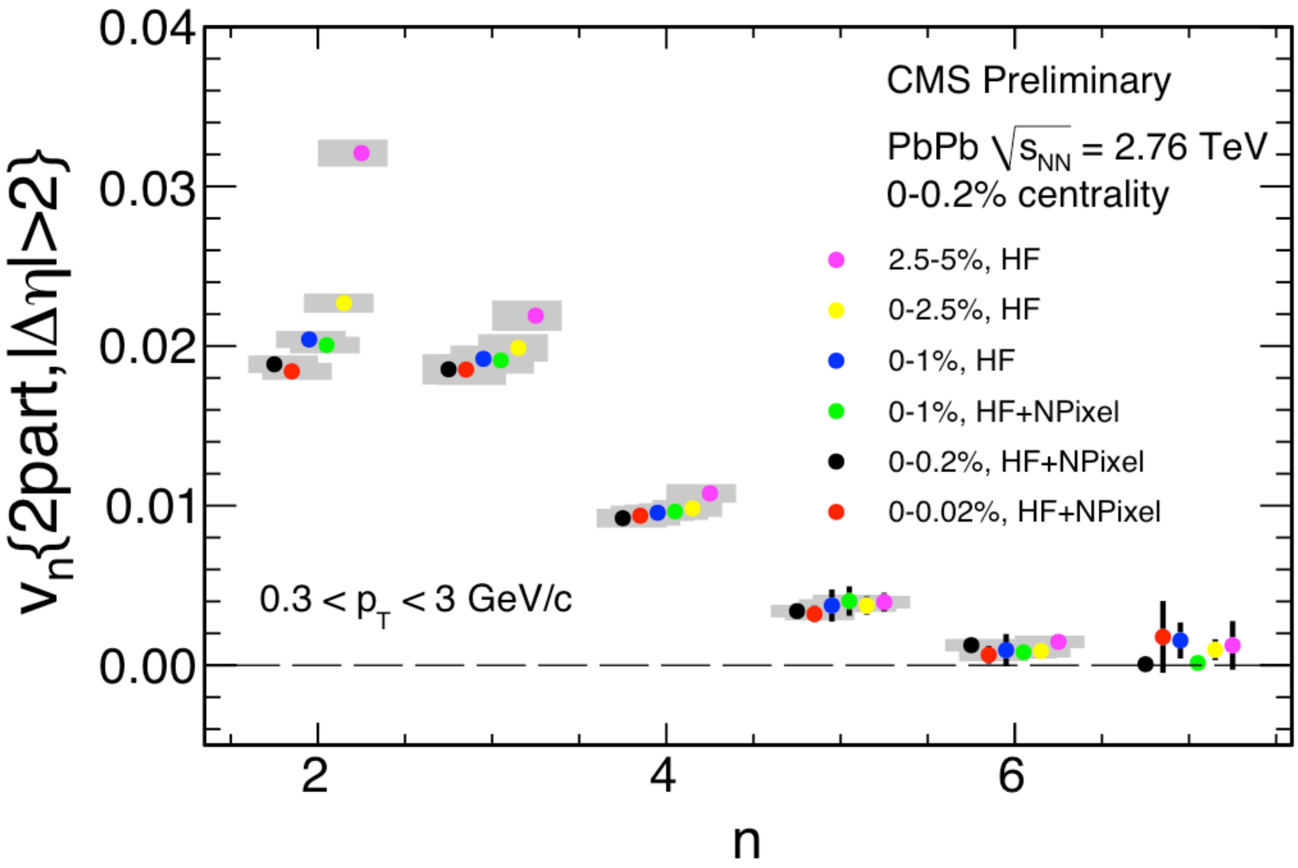
$v_n(p_T)$ comparison with hydro



C. Shen, Z. Qiu, and U. Heinz.

η/s ~ 0.08-0.2 with the model; More theoretical studies are needed

UCC, v_n vs. n and centrality



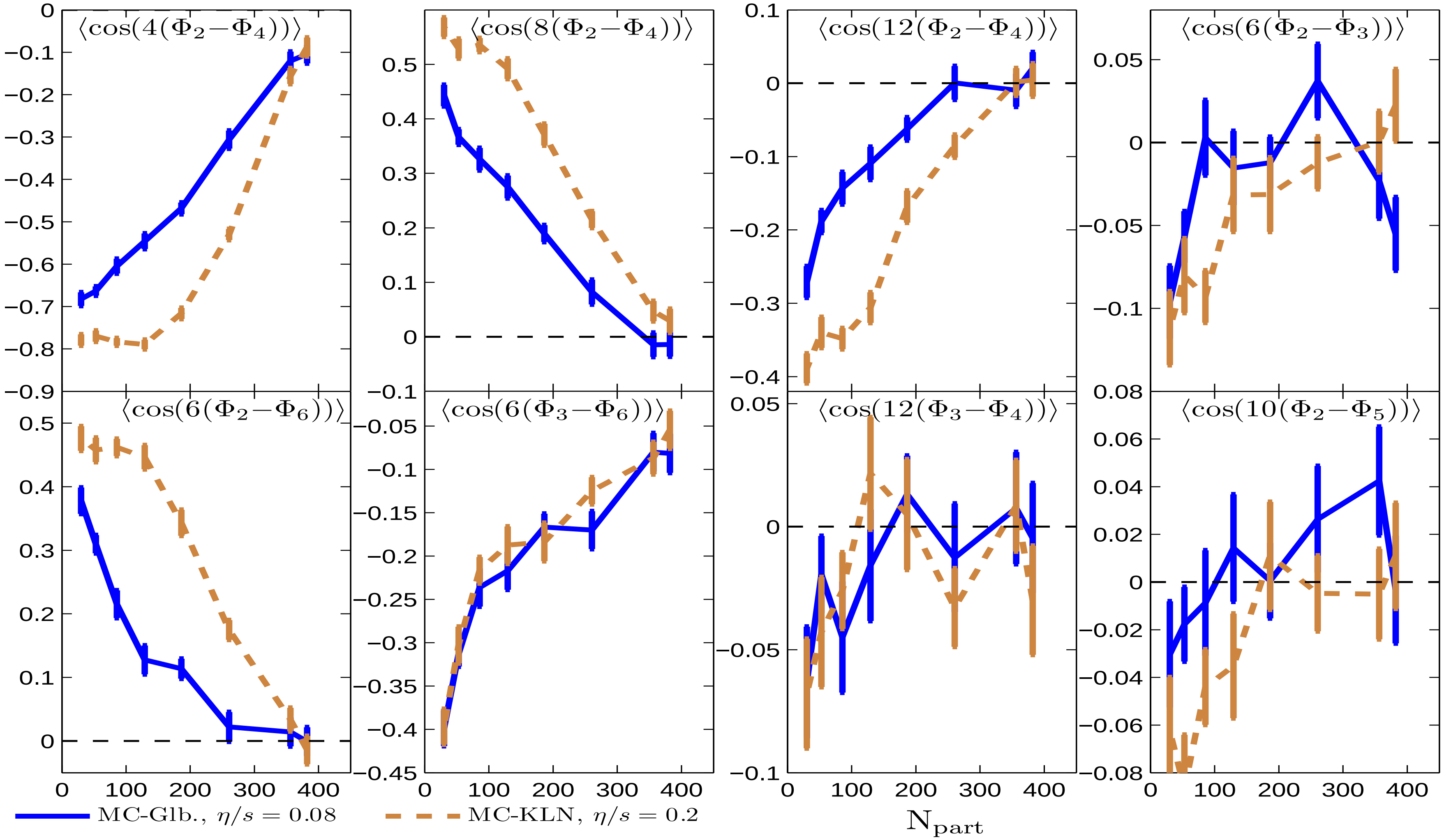
The effects from centrality fluctuations should be small since v_n do not change much from 0-0.02% to 0-0.2%

CMS-HIN-12-011

Figure 9: Comparison of p_T-integrated (0.3–3.0 GeV/c) v_n as a function of n in five centrality bins (2.5–5%, 0–2.5%, 0–1%, 0–0.2% and 0–0.02%) of PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. Error bars denote the statistical uncertainties, while the grey bands correspond to the systematic uncertainties.

Higher order event plane correlations in PbPb@LHC

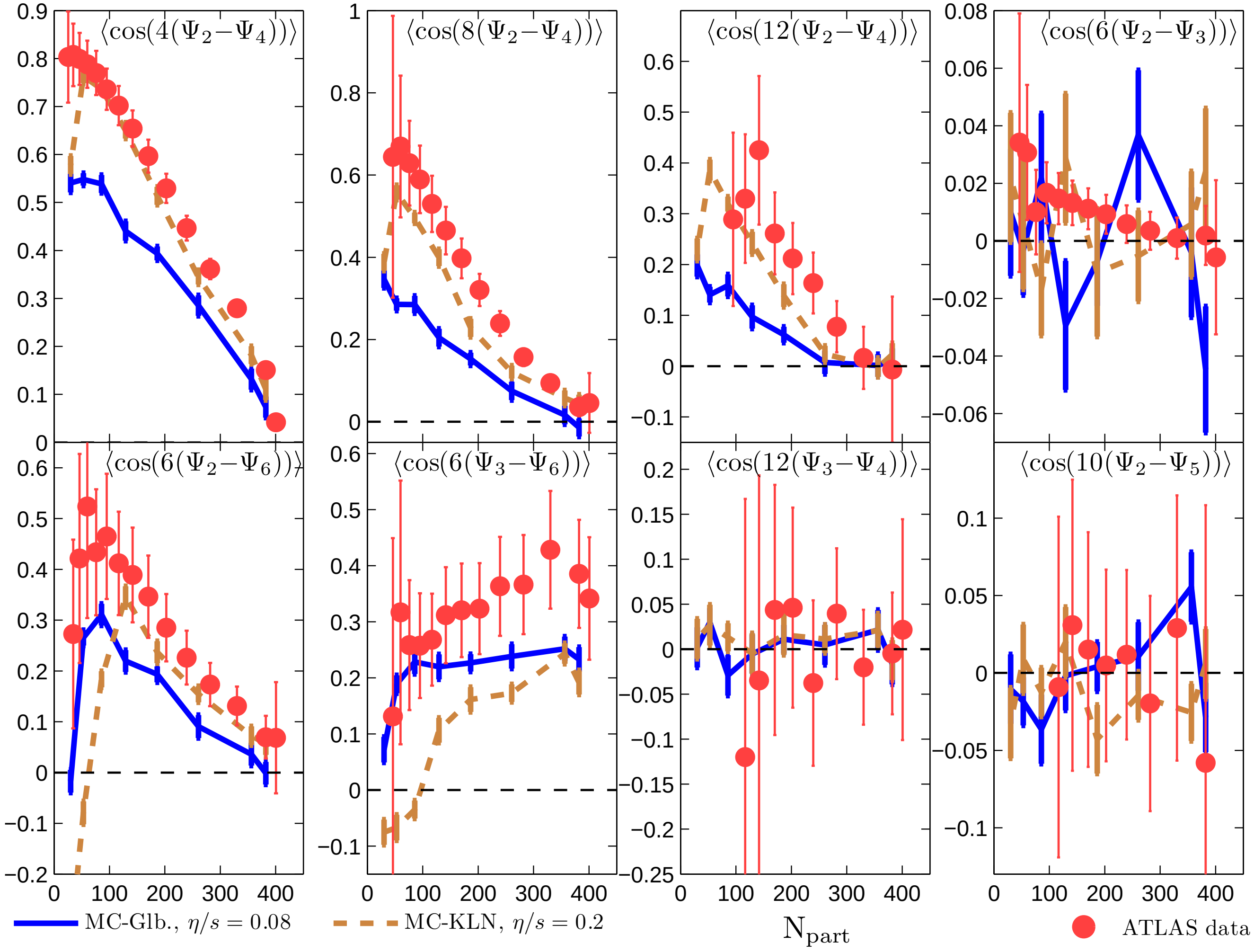
Initial-state participant plane correlations (Zhi Qiu, UH, arXiv:1208.1200)



Higher order event plane correlations in PbPb@LHC

Data: ATLAS Coll., J. Jia et al., Hard Probes 2012

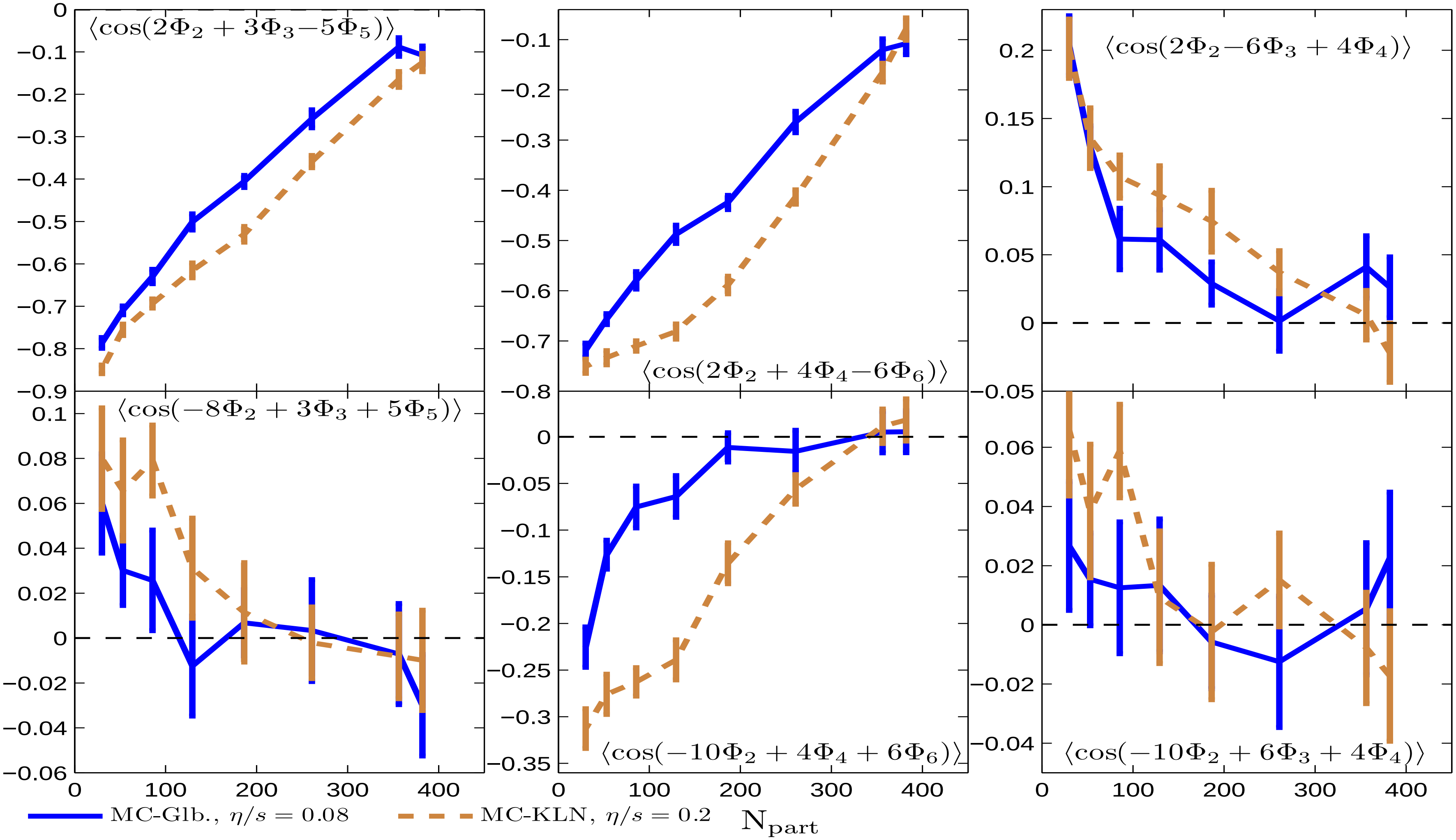
Event-by-event hydrodynamics: Zhi Qiu, UH, arXiv:1208.1200 (e-by-e VISH2+1)



VISH2+1 reproduces qualitative features of the centrality dependence of all measured event-plane correlations

Higher order event plane correlations in PbPb@LHC

Initial-state participant plane correlations (Zhi Qiu, UH, arXiv:1208.1200)



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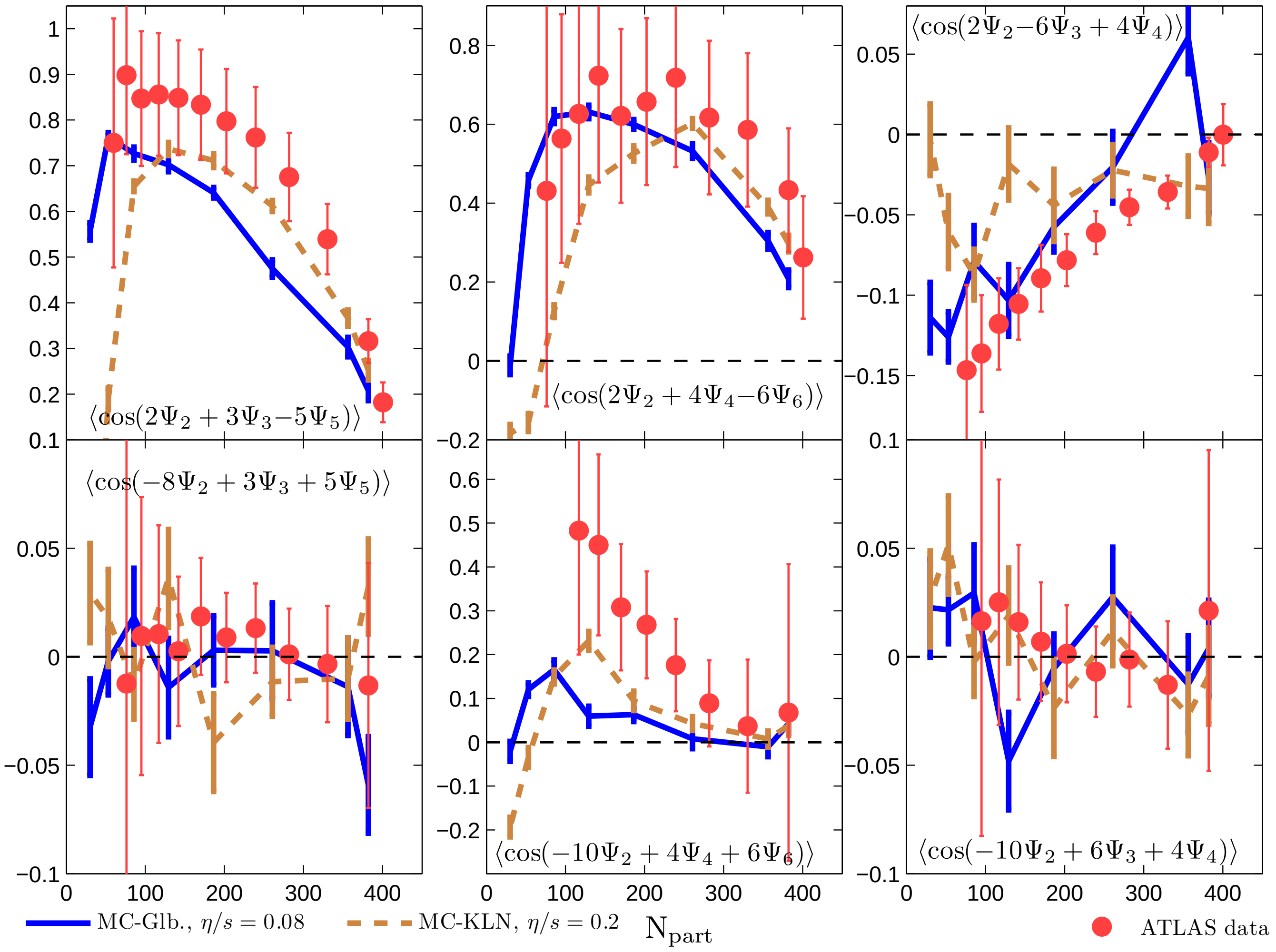

VISH2+1 reproduces qualitative features of the centrality dependence of all measured event-plane correlations

Conclusions

- The QGP is the most perfect liquid ever measured. Its specific shear viscosity at RHIC and LHC energies is

  $$(\eta/s)_{\mathrm{QGP}}(T_{\mathrm{c}}<T<2T_{\mathrm{c}}) = \frac{2}{4\pi} \pm 100\%$$

  A moderate increase between $2T_{\mathrm{c}}$ and $3T_{\mathrm{c}}$ is compatible with the data, but not (yet?) a robust conclusion from experiment
- The dominant uncertainty arises from the spectrum of quantum fluctuations in the initial state, but rapid theoretical progress is likely to eliminate most of it within a year.
- Powerful new measurements of the power and fluctuation spectra of the final anisotropic flow coefficients and correlations between the final-state flow angles have been shown to be highly constraining (both for initial state models and QGP transport coefficients).
- First serious models for pre-equilibrium dynamics and matching it to viscous hydro are appearing
- Huge progress since QM2011, but much more work to do. The path forward seems clear, though.