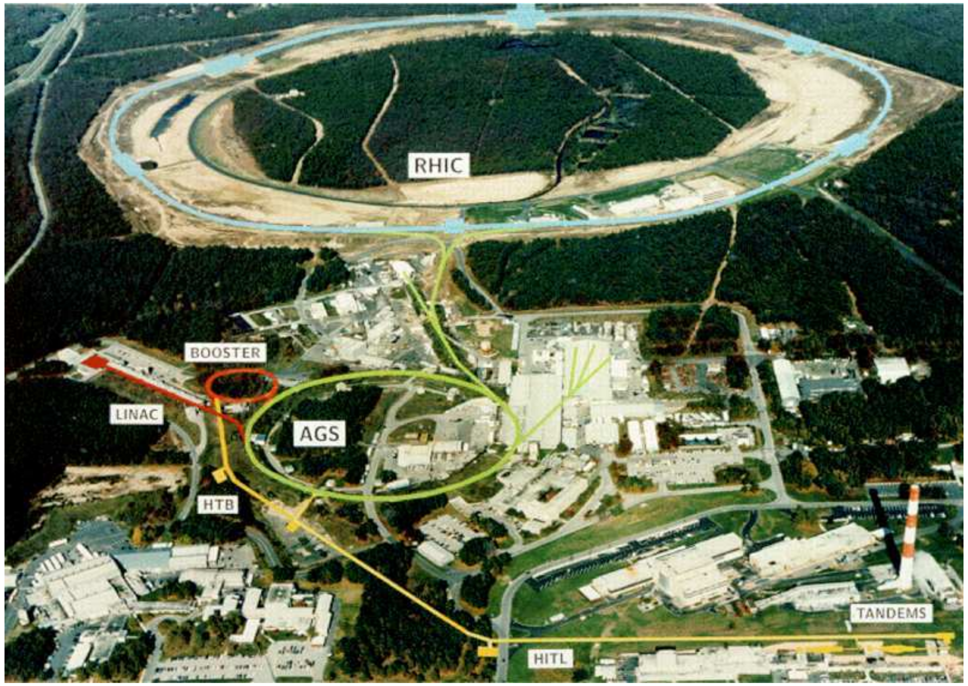
Initial shape and final flow fluctuations in event-by-event hydrodynamics for RHIC and LHC*

Ulrich Heinz, The Ohio State University



Exploring QCD Frontiers: From RHIC and LHC to EIC
Stellenbosch, Jan. 30 - Feb. 3, 2012

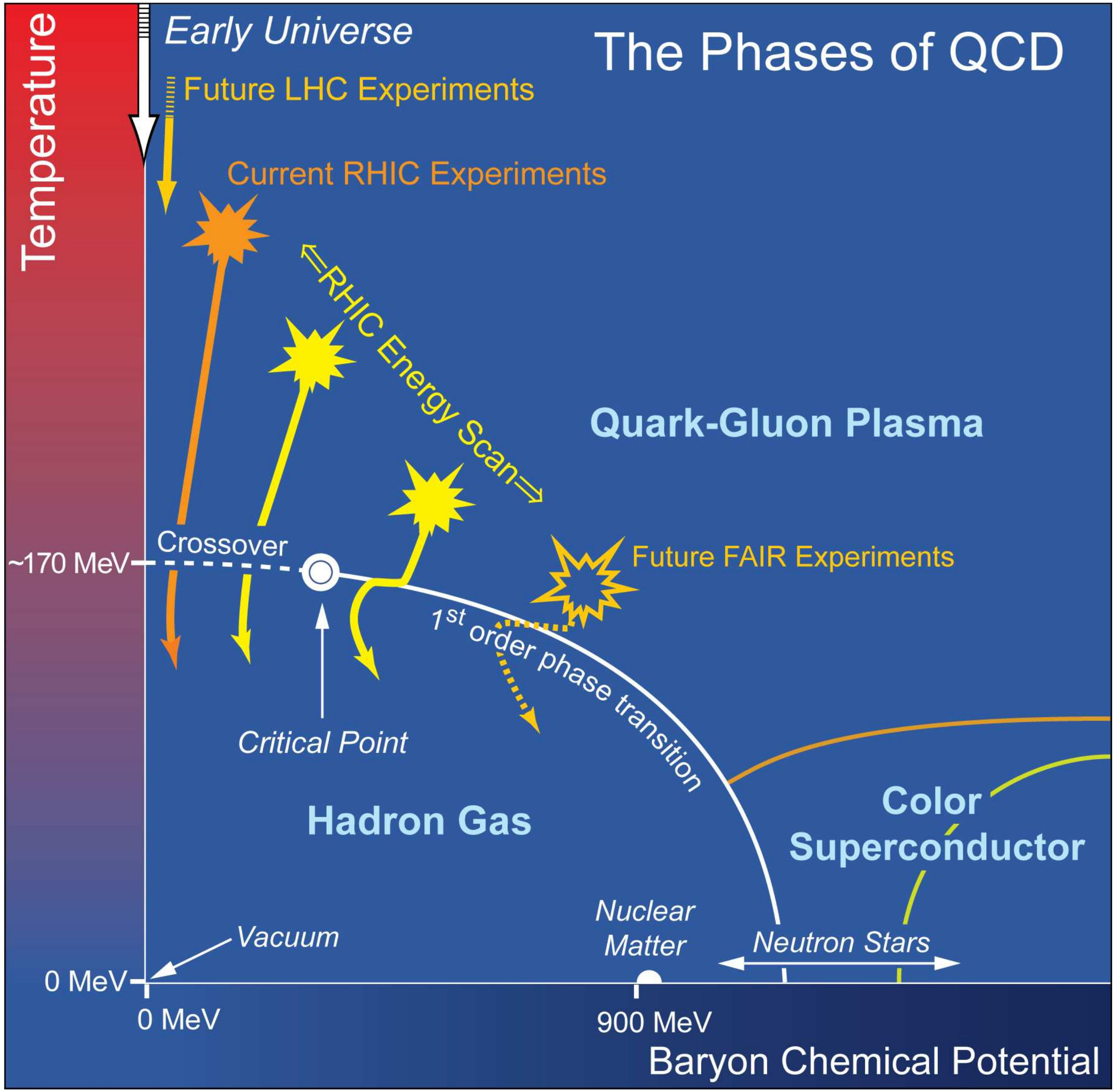
THE OHIO STATE UNIVERSITY DEPARTMENT OF PHYSICS

with Zhi Qiu, Chun Shen & Huichao Song

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

JET Collaboration

Probing the landscape of QCD matter: The future is now

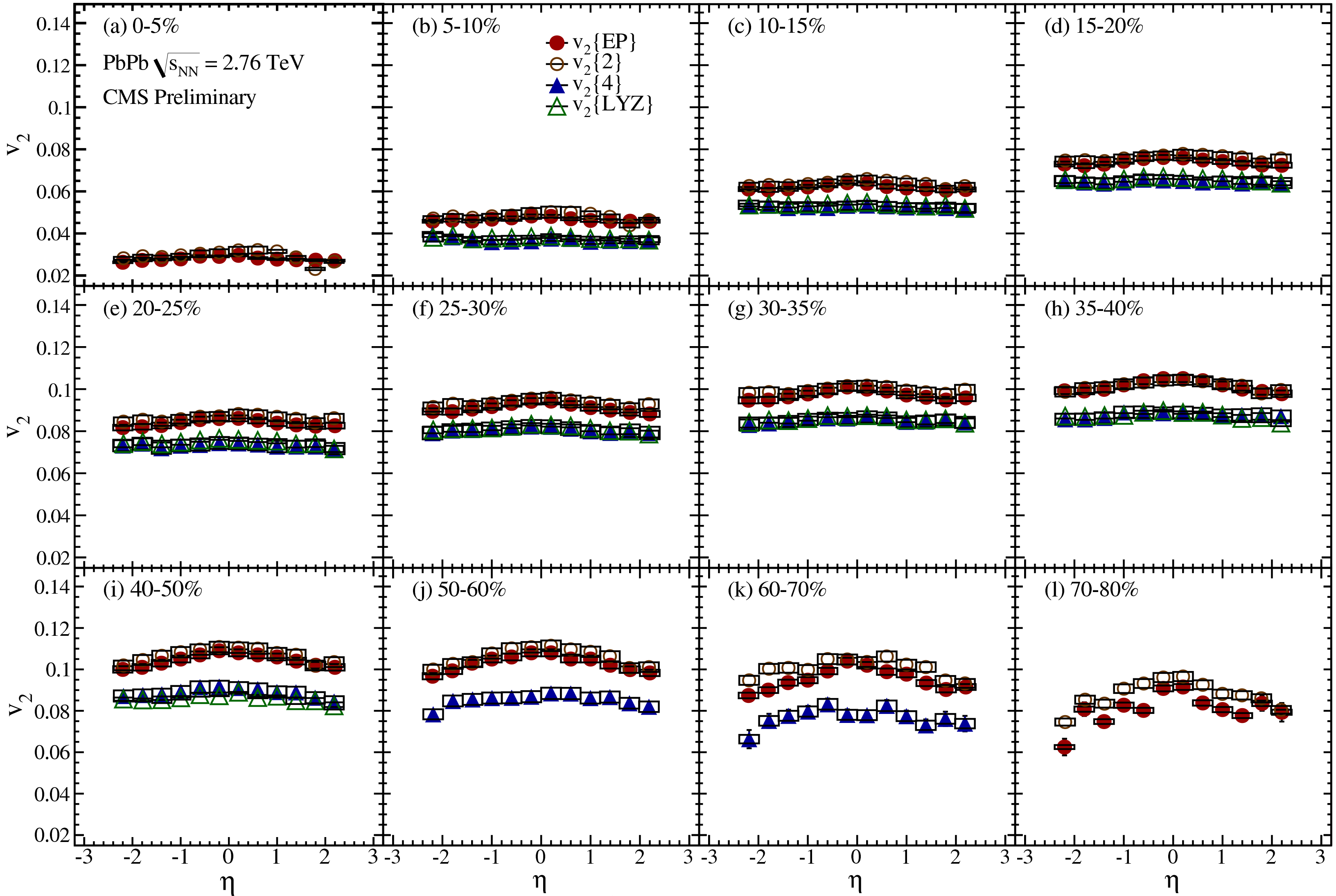


Probes:

- Collective flow
- Jet modification and quenching
- Thermal electro-magnetic radiation
- Critical fluctuations
- . . .

PbPb@LHC: Bjorken boost-invariance finally observed!

CMS (J. Velkovska) Quark Matter 2011

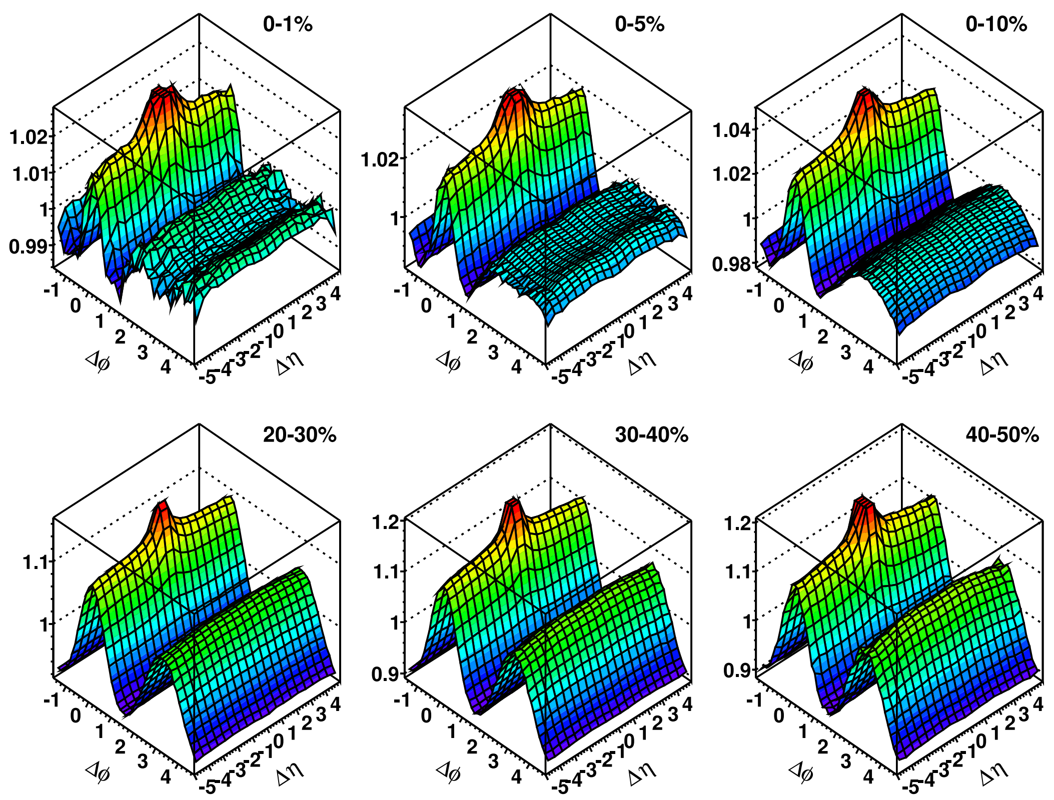


Small narrow bump near $\eta = 0$ due to Jacobian $\frac{dN}{d\eta} = \int d^2p_T \frac{p_T \cosh\eta}{\sqrt{m^2 + p_T^2\cosh^2\eta}} \frac{dN}{dy\, d^2p_T}$

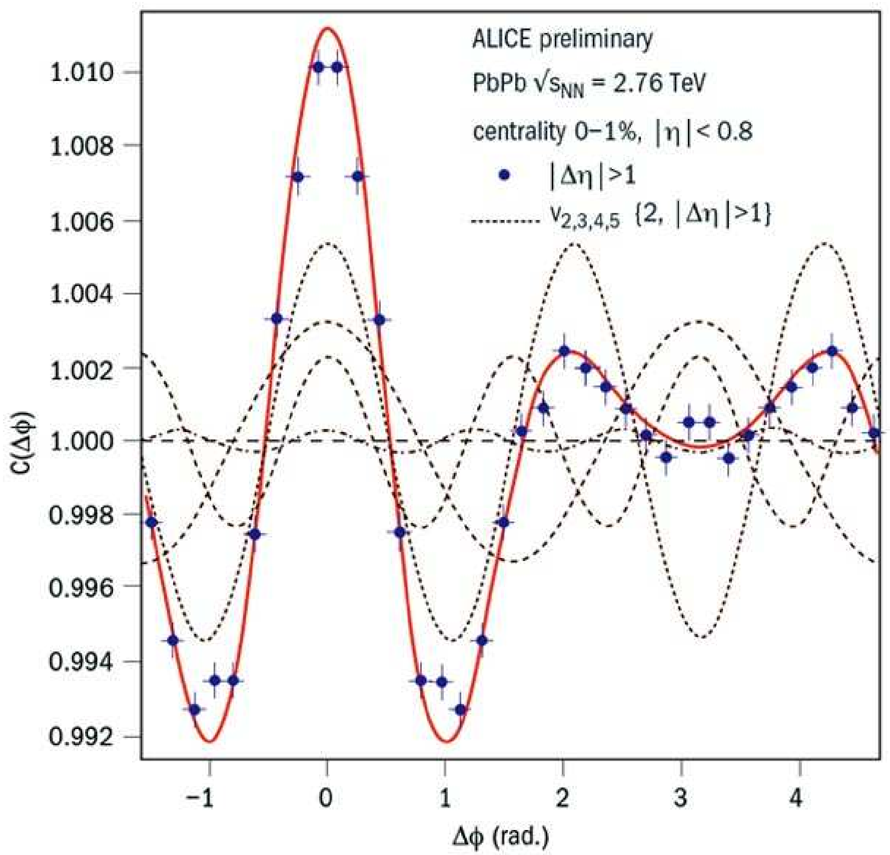
(dip in $dN/d\eta$ corresponds to bump in $v_2(\eta)$)

Panta rhei: “soft ridge”=“Mach cone”=flow!

ATLAS (J. Jia), Quark Matter 2011



ALICE (J. Grosse-Oetringhaus), QM11

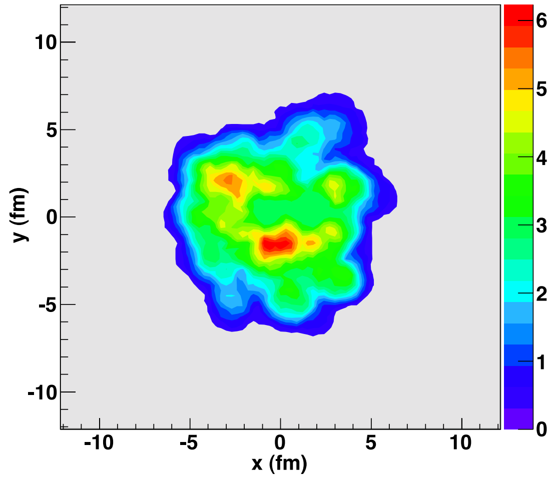


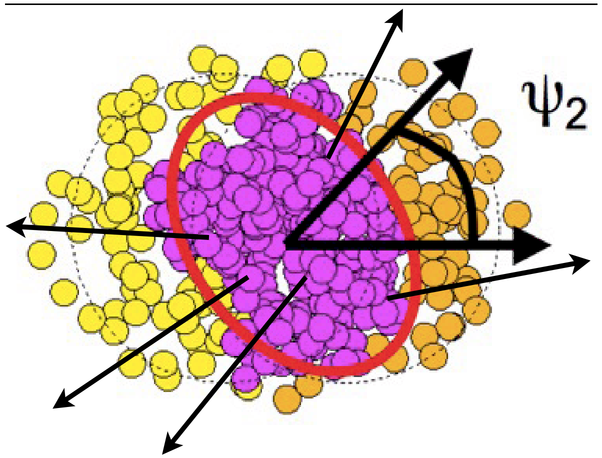
- anisotropic flow coefficients v_n and flow angles ψ_n correlated over large rapidity range!
  M. Luzum, PLB 696 (2011) 499: All long-range rapidity correlations seen at RHIC are consistent with being entirely generated by hydrodynamic flow.

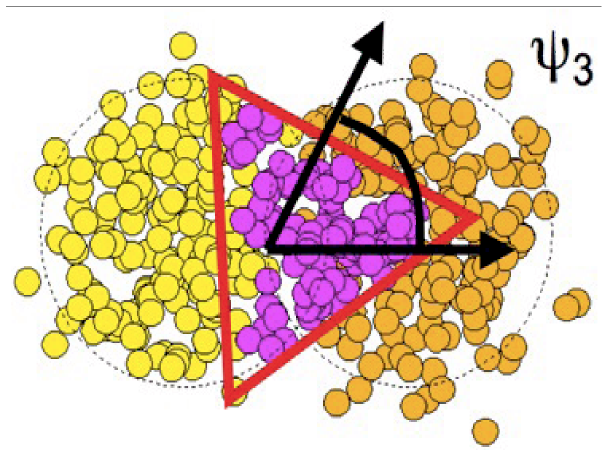
- in the 1% most central collisions $v_3 > v_2$
  $\Longrightarrow$ prominent “Mach cone”-like structure!
  $\Longrightarrow$ event-by-event eccentricity fluctuations dominate!

Event-by-event shape and flow fluctuations rule!

(Alver and Roland, PRC81 (2010) 054905)

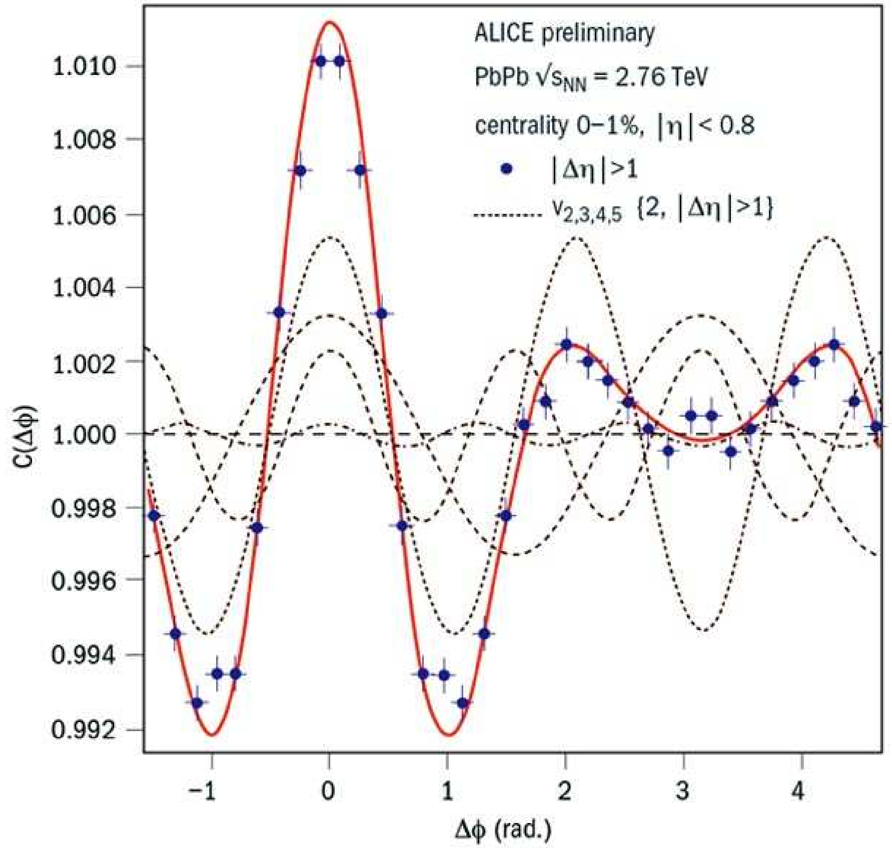




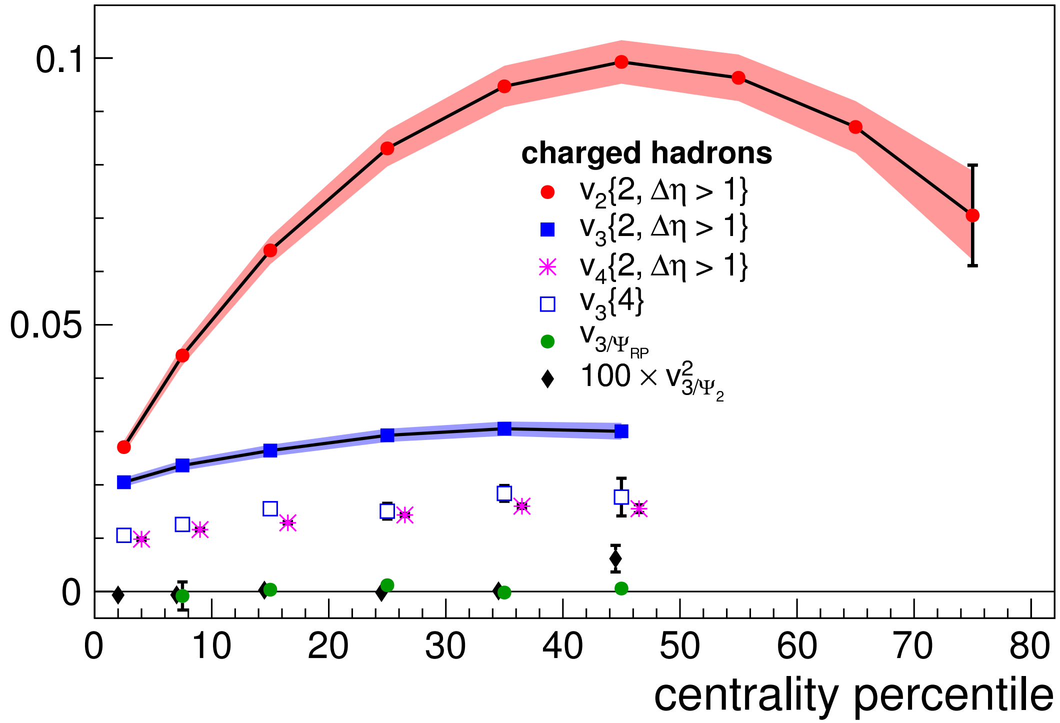


- Each event has a different initial shape and density distribution, characterized by different set of harmonic eccentricity coefficients ε_n
- Each event develops its individual hydrodynamic flow, characterized by a set of harmonic flow coefficients v_n and flow angles ψ_n
- At small impact parameters 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

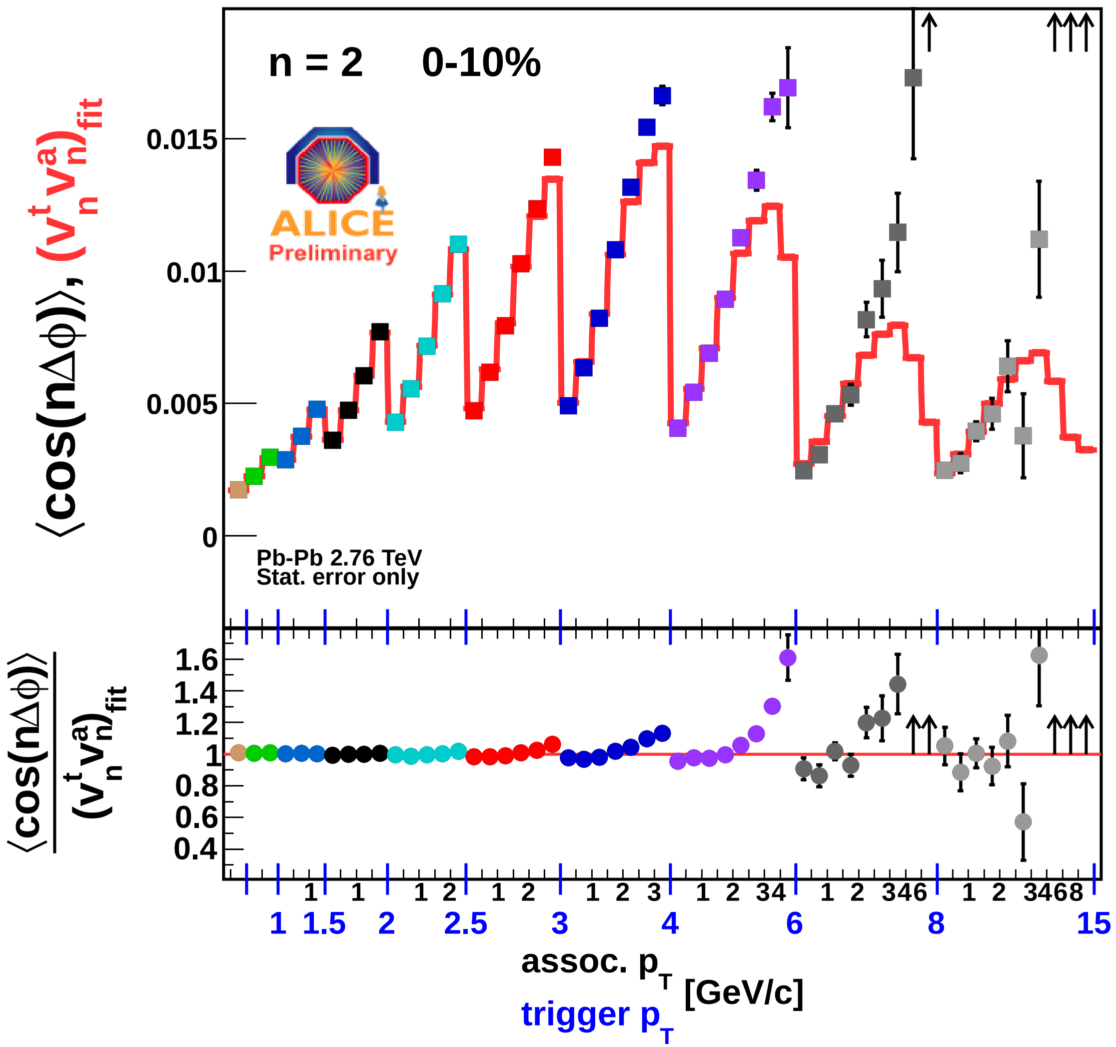


- in the 1% most central collisions $v_3 > v_2 \Longrightarrow$ prominent "Mach cone"-like structure!

- 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

Fluctuation-driven anisotropic flow is indeed collective!

ALICE (J. Grosse-Oetringhaus) Quark Matter 2011

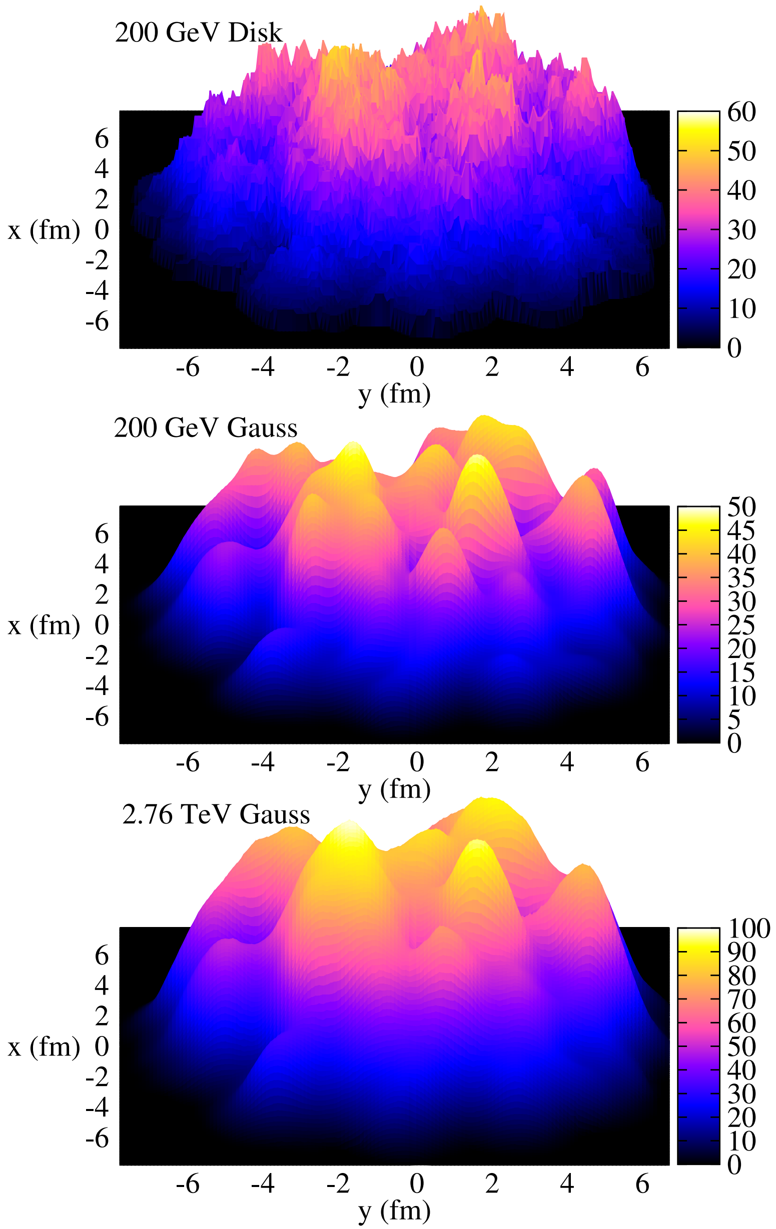


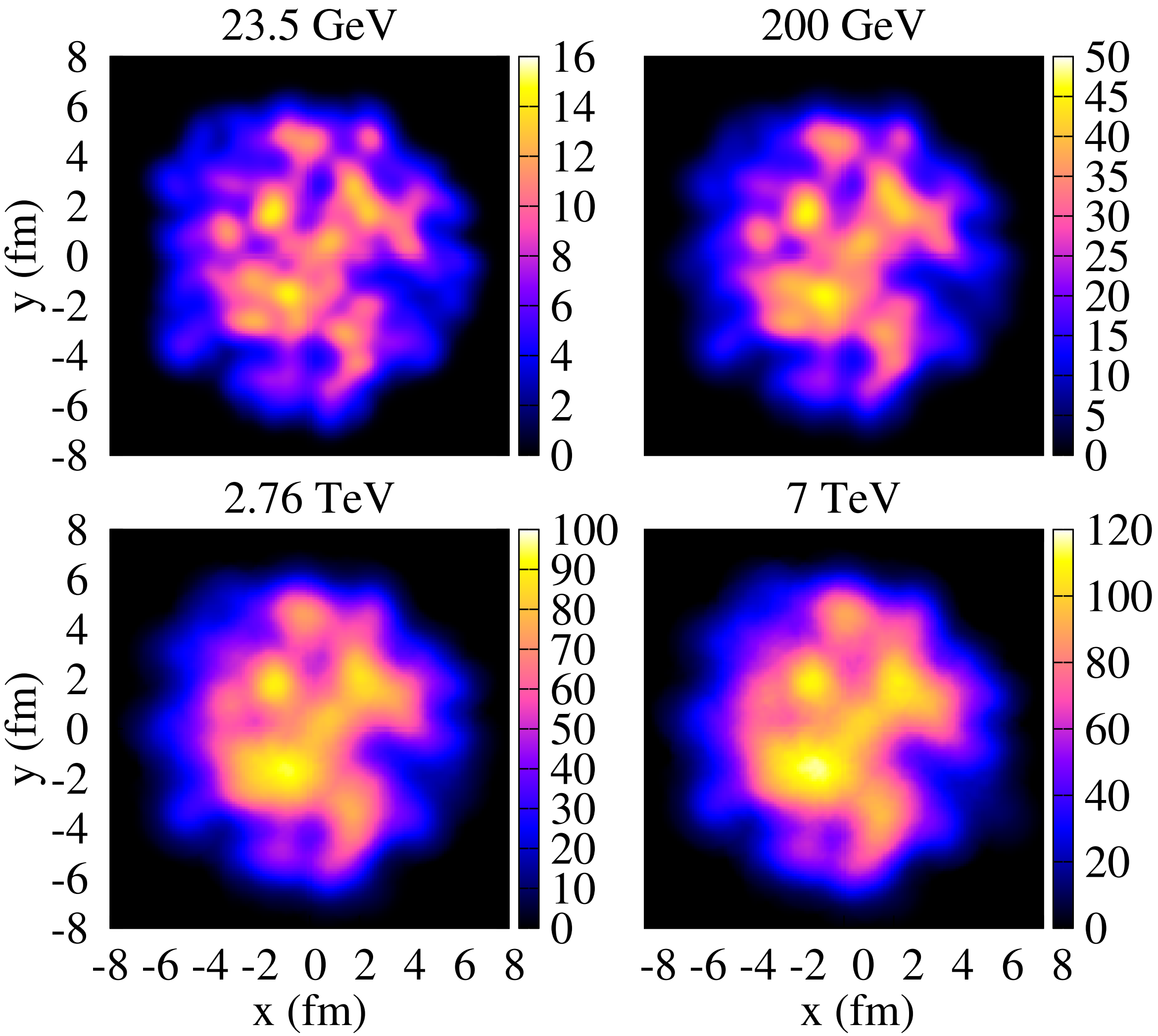
- Two-particle Fourier coefficients factorize $(v_{n\Delta}(p_{T1}, p_{T2}) = v_n(p_{T1}) v_n(p_{T2}))$ as required
- Factorization shown to work for $n = 2, 3, 4, 5$ as long as both $p_{T1}, p_{T2} < 3\,\mathrm{GeV}/c$ (bulk matter)

Initial-state shape fluctuations

Smearing effects from nucleon growth at high energies

UH & Scott Moreland, PRC84 (2011) 054905





Between $\sqrt{s} = 23.5$ and 7,000 GeV, nucleon area grows by factor $\mathcal{O}(2) \Longrightarrow$ significant smoothing of event-by-event density fluctuations from RHIC to LHC

Eccentricity definitions:

Define event average $\{\ldots\}$, ensemble average $\langle\ldots\rangle$

Two choices for weight function in event average: (i) Energy density $e(\boldsymbol{x}_\perp; b)$
(ii) Entropy density $s(\boldsymbol{x}_\perp; b)$

Define $\sigma_x^2 = \{x^2\}-\{x\}^2,\ \sigma_{xy} = \{xy\}-\{x\}\{y\}$, etc.,
where x, y are reaction-plane coordinates ($\boldsymbol{e}_x \parallel \boldsymbol{b}$)

1. Standard eccentricity: $\varepsilon_s \equiv \bar{\varepsilon}_{\mathrm{RP}} = \frac{\langle\sigma_y^2-\sigma_x^2\rangle}{\langle\sigma_y^2+\sigma_x^2\rangle}$ (calculated from RP-averaged $\langle e\rangle$ or $\langle s\rangle$)

2. Average reaction-plane eccentricity: $\langle\varepsilon_{\mathrm{RP}}\rangle = \left\langle \frac{\sigma_y^2-\sigma_x^2}{\sigma_y^2+\sigma_x^2} \right\rangle$

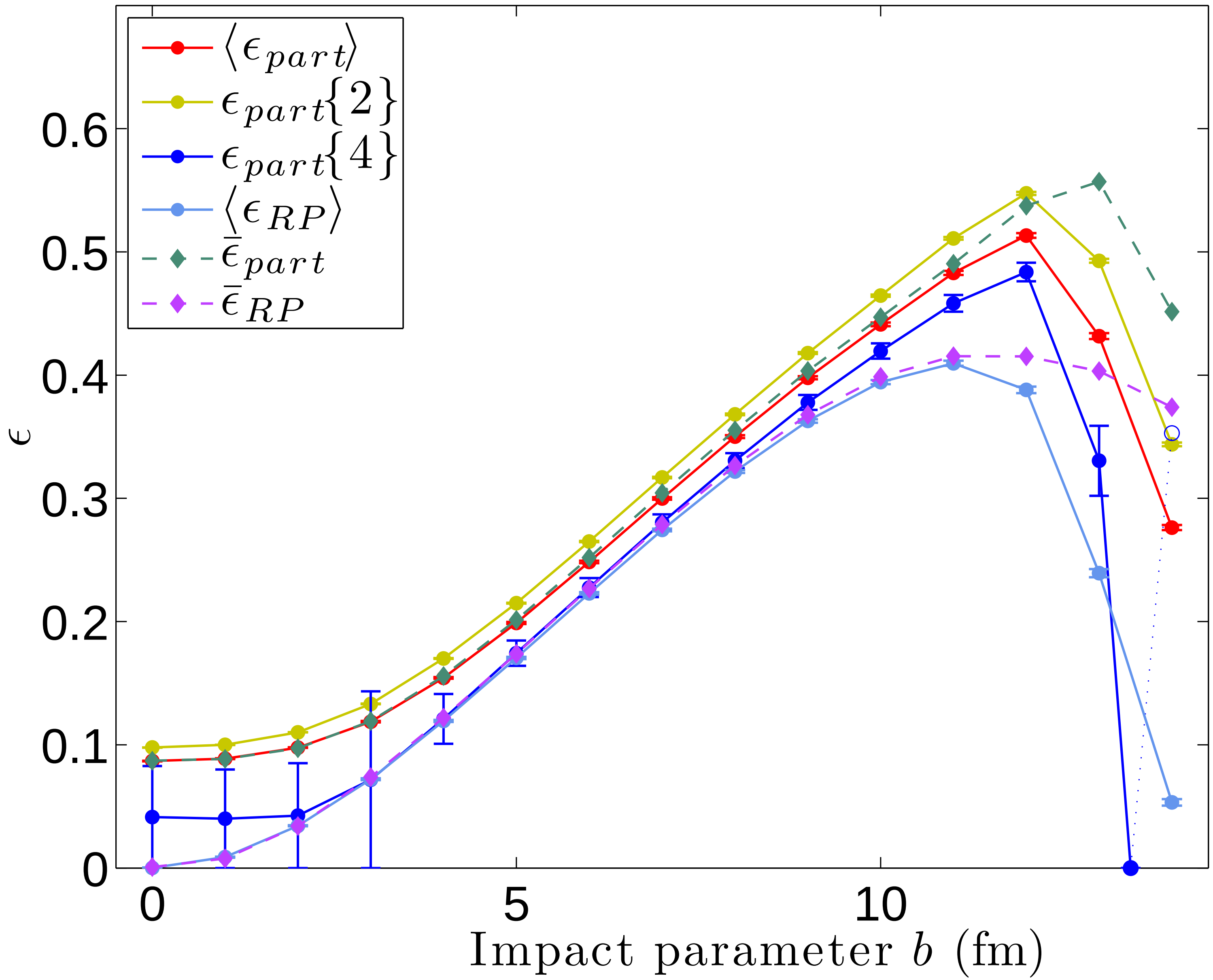
3. Eccentricity of the participant-plane averaged source: $\bar{\varepsilon}_{\mathrm{part}} = \frac{\left\langle\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}\right\rangle}{\langle\sigma_y^2+\sigma_x^2\rangle}$

4. Average participant-plane eccentricity: $\langle\varepsilon_{\mathrm{part}}\rangle = \left\langle \frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}}{\sigma_y^2+\sigma_x^2} \right\rangle$

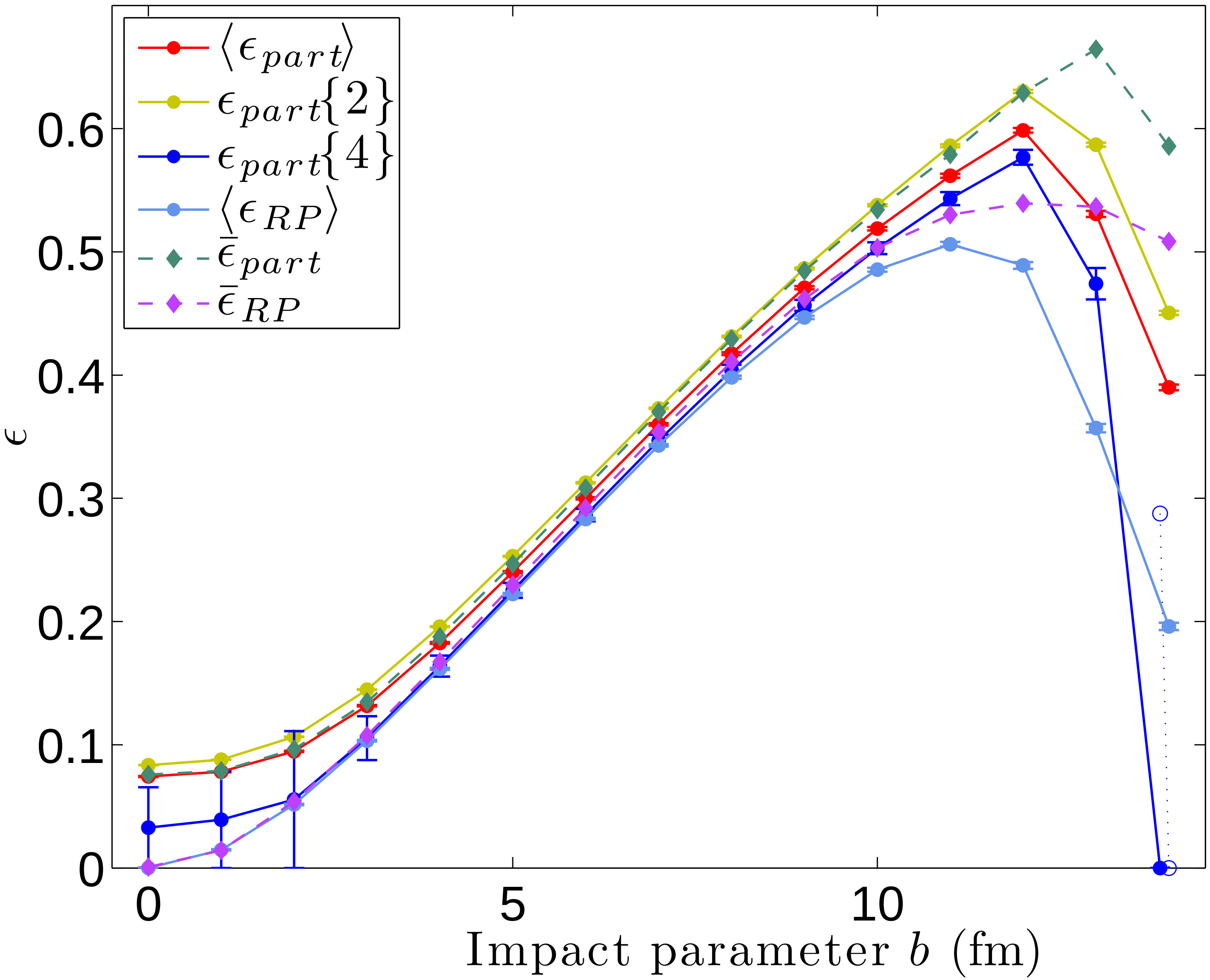
5. r.m.s. part.-plane eccentricity: $\varepsilon_{\mathrm{part}}\{2\} \equiv \sqrt{\langle\varepsilon_{\mathrm{part}}^2\rangle}$ ($=\sqrt{\langle\varepsilon_{\mathrm{part}}\rangle^2+\sigma_\varepsilon^2/2}$ for Gauss. fl.)

6. 4th cumulant eccentricity: $\varepsilon_{\mathrm{part}}\{4\} \equiv \left[\langle\varepsilon_{\mathrm{part}}^2\rangle^2 - \left(\langle\varepsilon_{\mathrm{part}}^4\rangle - \langle\varepsilon_{\mathrm{part}}^2\rangle^2\right)\right]^{1/4}$
($=\sqrt{\langle\varepsilon_{\mathrm{part}}\rangle^2-\sigma_\varepsilon^2/2}$ for Gauss. fl.)

MC-Glauber eccentricities (e-weighted):

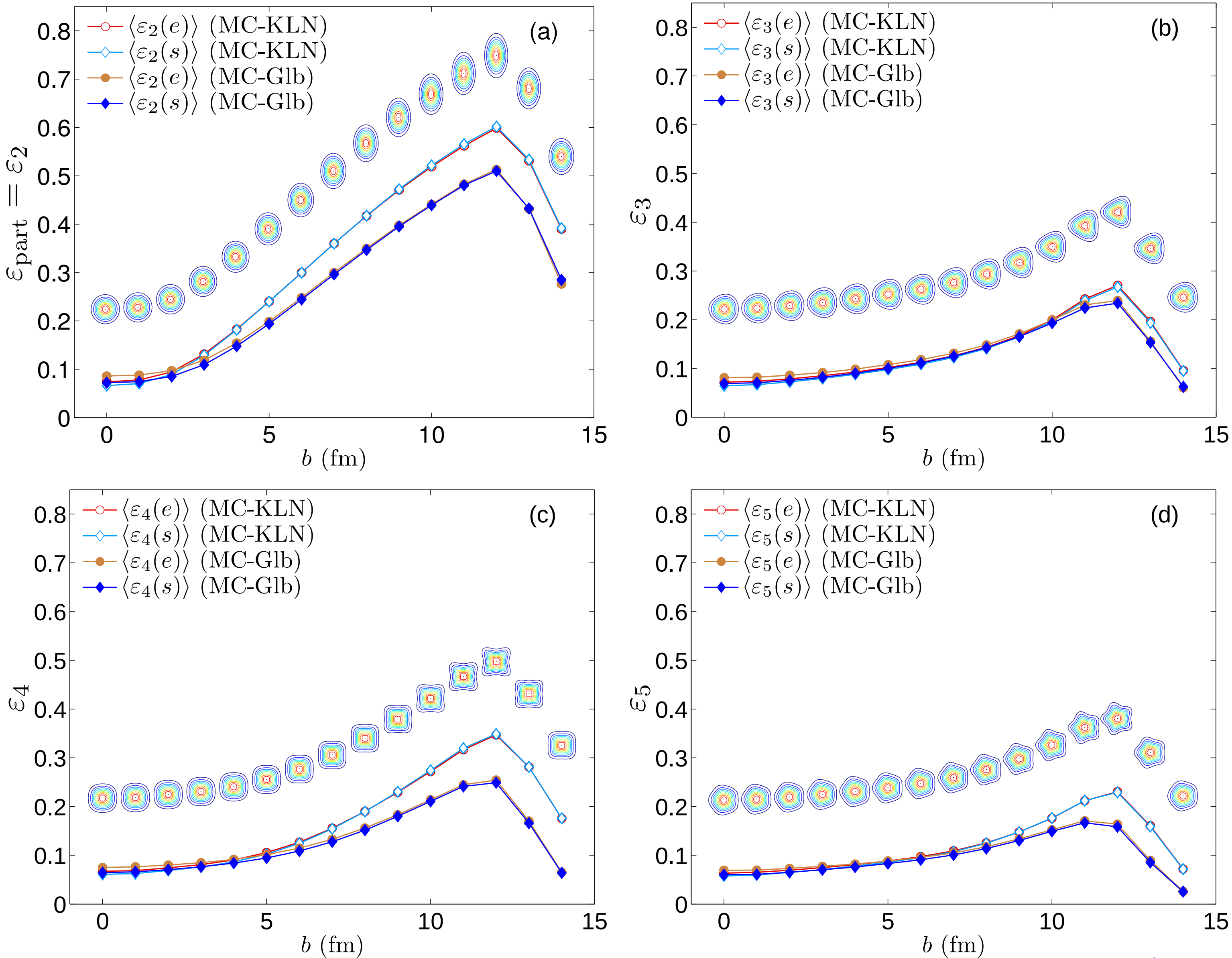


MC-KLN eccentricities (e-weighted):



Initial eccentricities $\varepsilon_n(n=2-5)$ vs. impact parameter

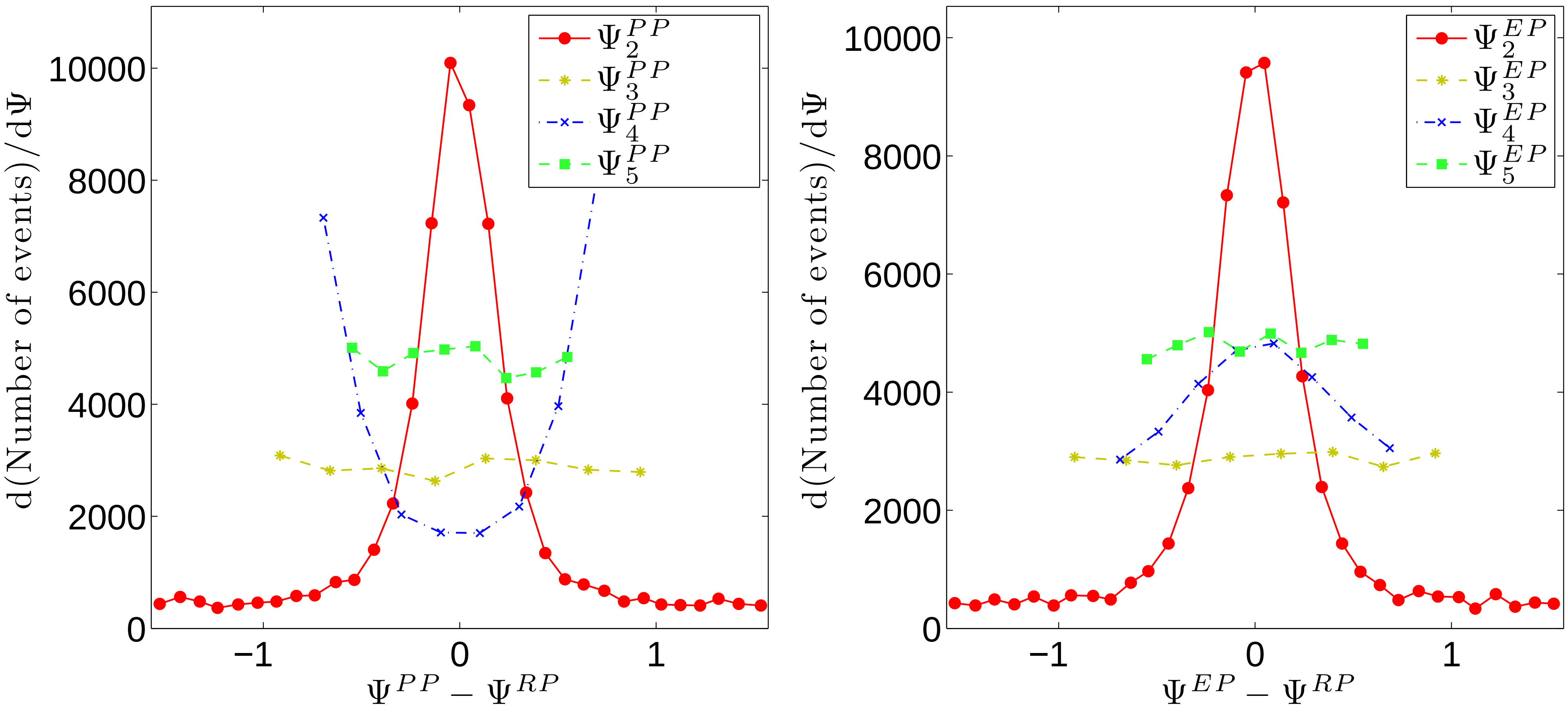
Zhi Qiu, UH, PRC84 (2011) 024911



- Contours: $e(r,\phi) = e_0 \exp\left[-\frac{r^2}{2\rho^2}\left(1+\varepsilon_n \cos(n(\phi-\psi_n))\right)\right]$ where $\varepsilon_n e^{in\psi_n} = -\frac{\int r dr d\phi\, r^2 e^{in\phi}\, e(r,\phi)}{\int r dr d\phi\, r^2\, e(r,\phi)}$
- MC-KLN has larger ε_2 and ε_4, but similar ε_5 and almost identical ε_3 as MC-Glauber ($\varepsilon_{3,5}$ are purely fluctuation-driven!)

Flow fluctuations in event-by-event hydro

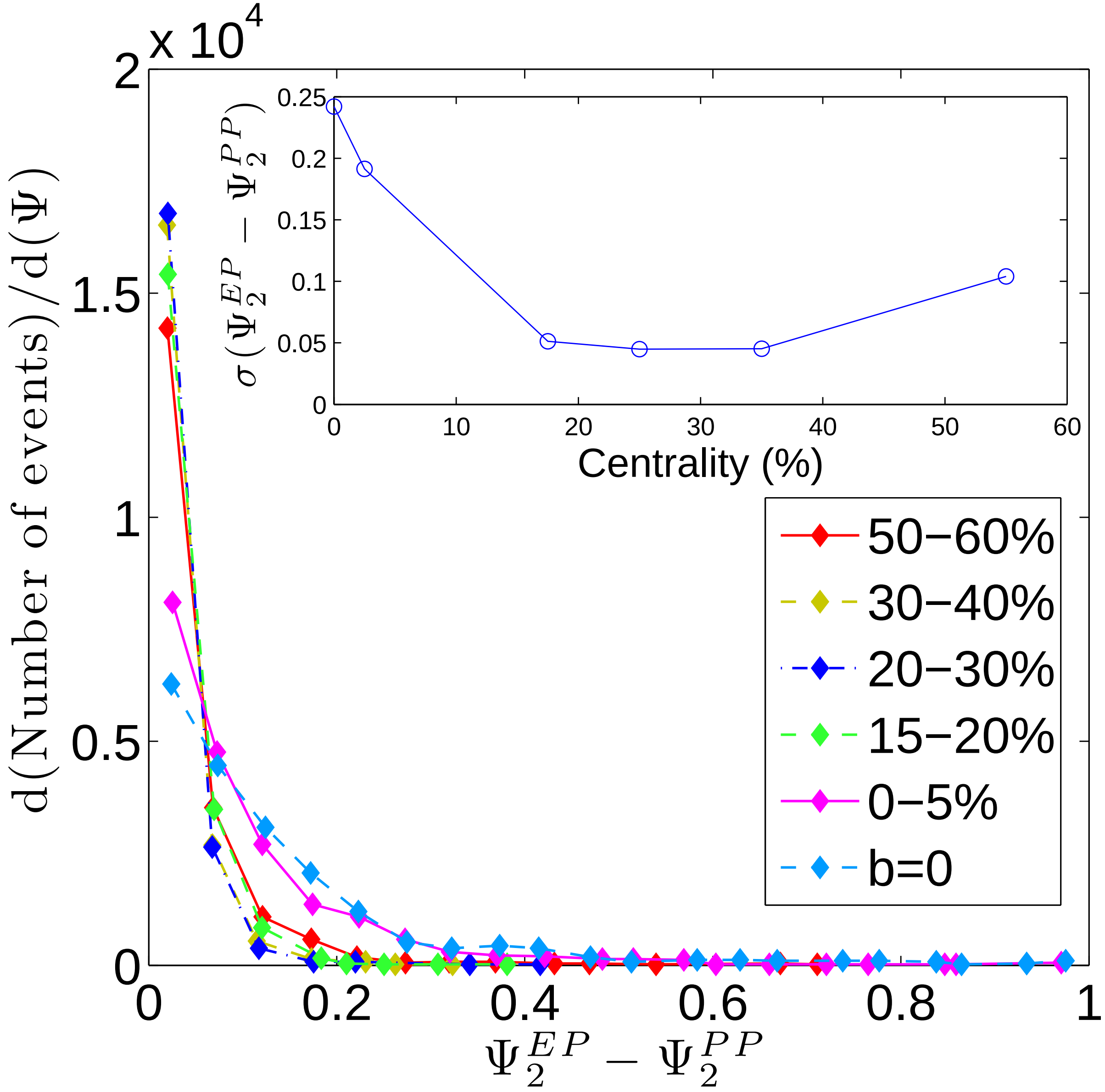
Flow angle distributions (0–60% centrality):



$$\varepsilon_n e^{in\psi_n^{\mathrm{PP}}} = -\frac{\int r dr d\phi\, r^2 e^{in\phi}\, e(r,\phi)}{\int r dr d\phi\, r^2\, e(r,\phi)} \qquad v_n e^{in\psi_n^{\mathrm{EP}}} = \frac{\int d\phi_p\, e^{in\phi_p}\, (dN/d\phi_p)}{\int d\phi_p\, (dN/d\phi_p)}$$

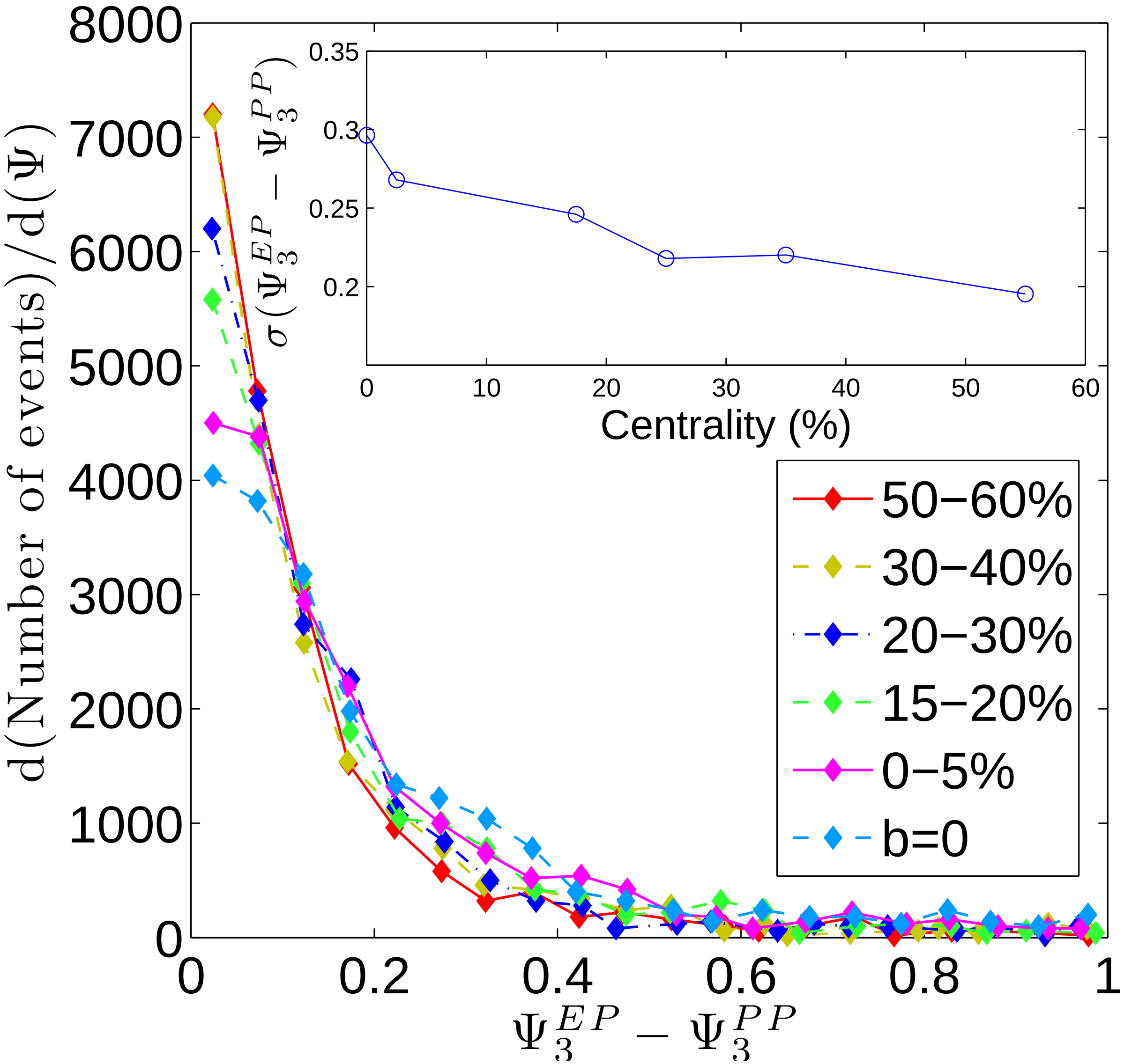
- Angles of $\varepsilon_{3,5}$ and $v_{3,5}$ uncorrelated with reaction plane (Qin et al., PRC 82 (2010) 064903)
- v_4-angle ψ_4^{EP} lies (on average) in the reaction plane even though ε_4-angle ψ_4^{PP} points at $\pm\frac{\pi}{4} = \pm 45^\circ \Longrightarrow$ **v_4 driven mostly by elliptic deformation ε_2, not ε_4.**

Correlation between flow and eccentricity angles: $\psi_2^{\rm EP}-\psi_2^{\rm PP} \mod \frac{\pi}{2}$



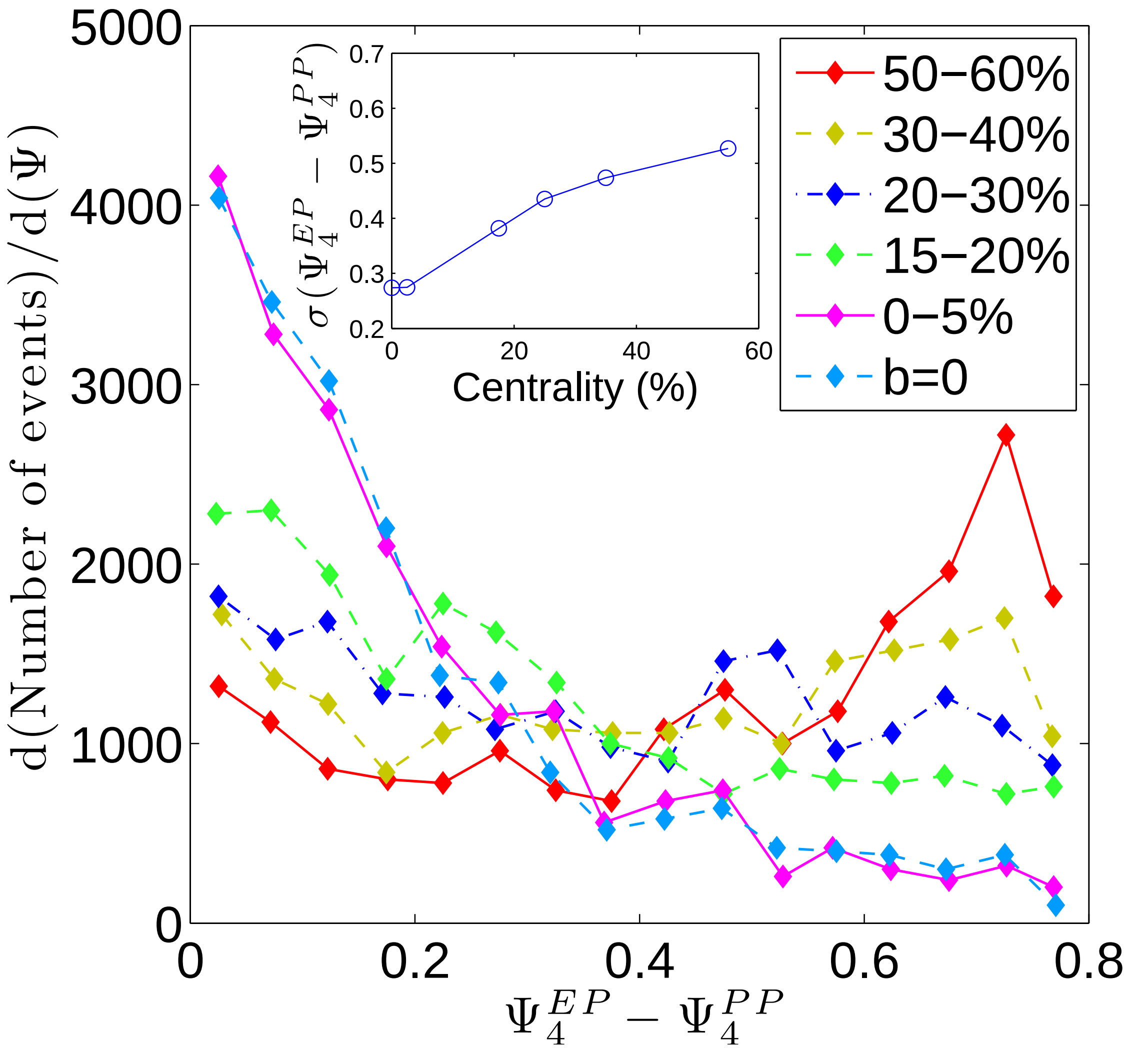
Strong angular correlation between elliptic flow and eccentricity, except near $b=0$.

Correlation between flow and eccentricity angles: $\psi_3^{\rm EP}-\psi_3^{\rm PP} \mod \frac{\pi}{3}$



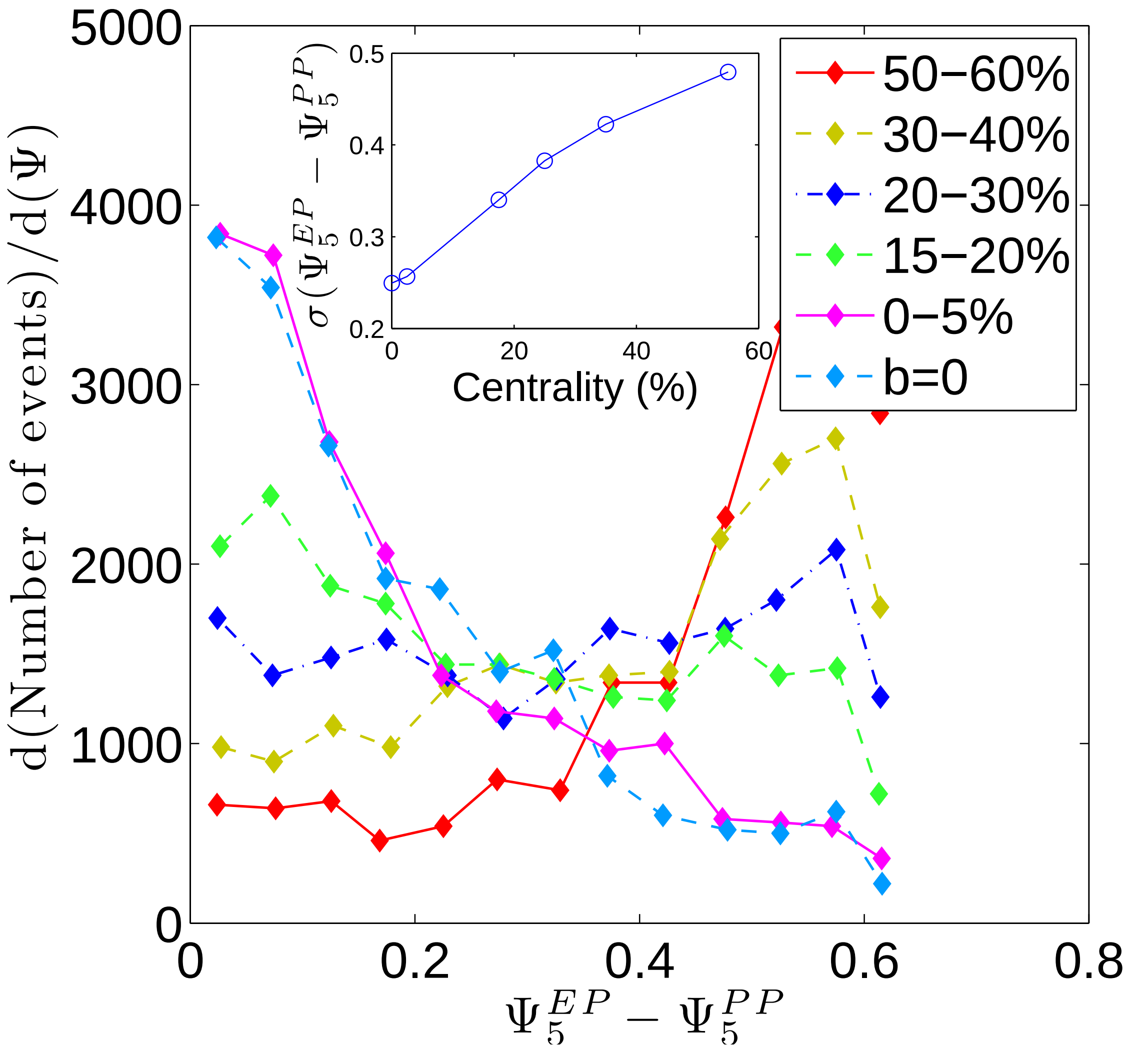
Four times weaker angular correlation between triangular flow and triangularity than for 2nd harmonic.

Correlation between flow and eccentricity angles: $\psi_4^{\rm EP}-\psi_4^{\rm PP} \mod \frac{\pi}{4}$



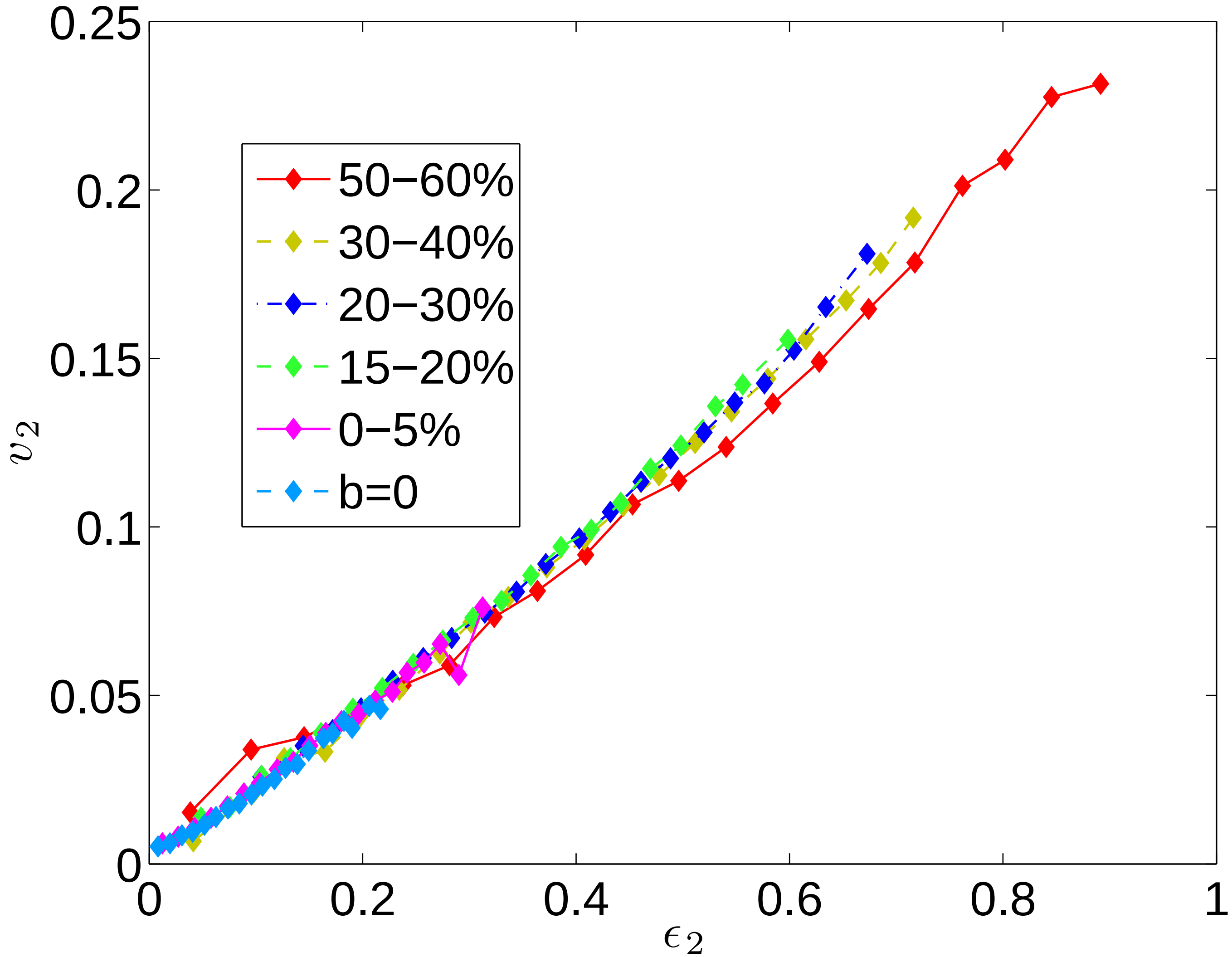
- Near-central collisions: $\psi_4^{\rm EP}$ (weakly) correlated with $\psi_4^{\rm PP}$ $\Longleftrightarrow$ v_4 driven by ε_4
- Peripheral collisions: $\psi_4^{\rm EP}$ (weakly) anti-correlated with $\psi_4^{\rm PP}$ $\Longleftrightarrow$ v_4 driven by ε_2
- Mid-central to mid-peripheral: no correlation between $\psi_4^{\rm EP}$ and $\psi_4^{\rm PP}$

Correlation between flow and eccentricity angles: $\psi_5^{\rm EP}-\psi_5^{\rm PP} \mod \frac{\pi}{5}$



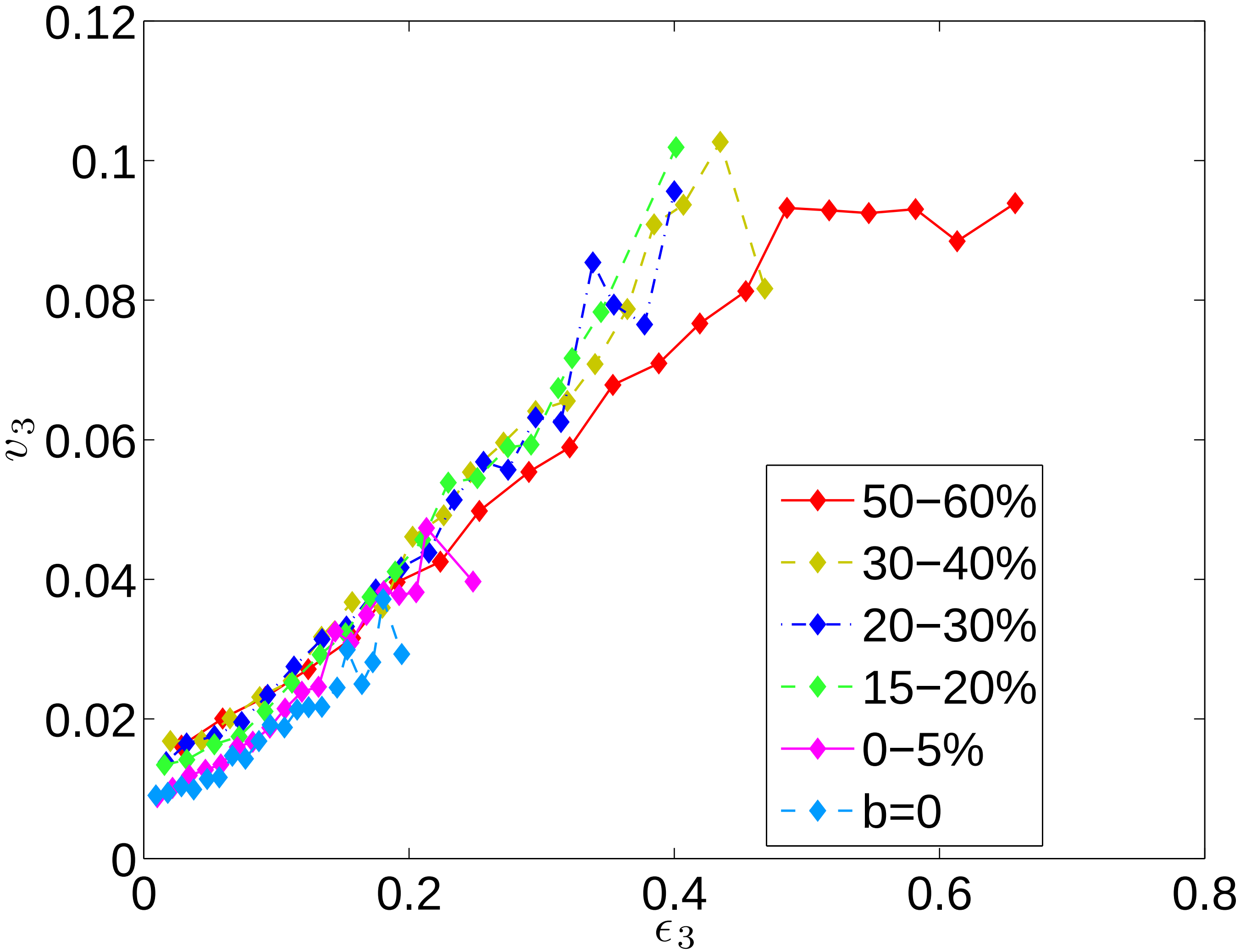
- Near-central collisions: $\psi_5^{\rm EP}$ (weakly) correlated with $\psi_5^{\rm PP}$ $\Longleftrightarrow$ v_5 driven by ε_5
- Peripheral collisions: $\psi_5^{\rm EP}$ (weakly) anti-correlated with $\psi_5^{\rm PP}$ $\Longleftrightarrow$ v_5 strongly influenced by $\varepsilon_{n\neq 5}$
- Mid-central to mid-peripheral: no correlation between $\psi_5^{\rm EP}$ and $\psi_5^{\rm PP}$

Higher harmonic flows and associated eccentricities: v_2 vs. ε_2 (MC-KLN, e-weighted)



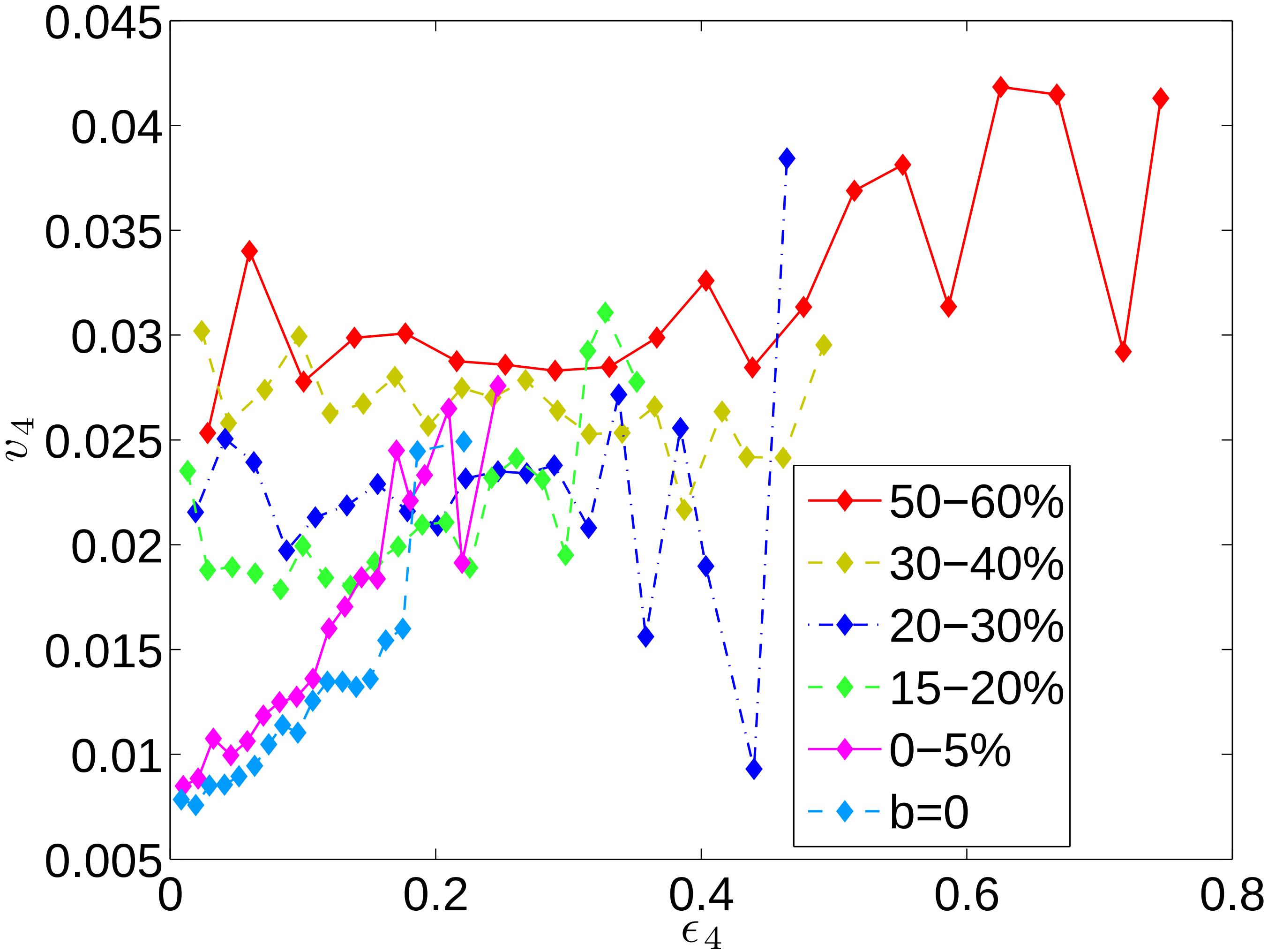
- Slightly non-linear dependence of v_2 on ε_2, especially in central and very peripheral collisions
- In the most peripheral centrality classes, slope of $v_2(\varepsilon_2)$ decreases

Higher harmonic flows and associated eccentricities: v_3 vs. ε_3 (MC-KLN, e-weighted)



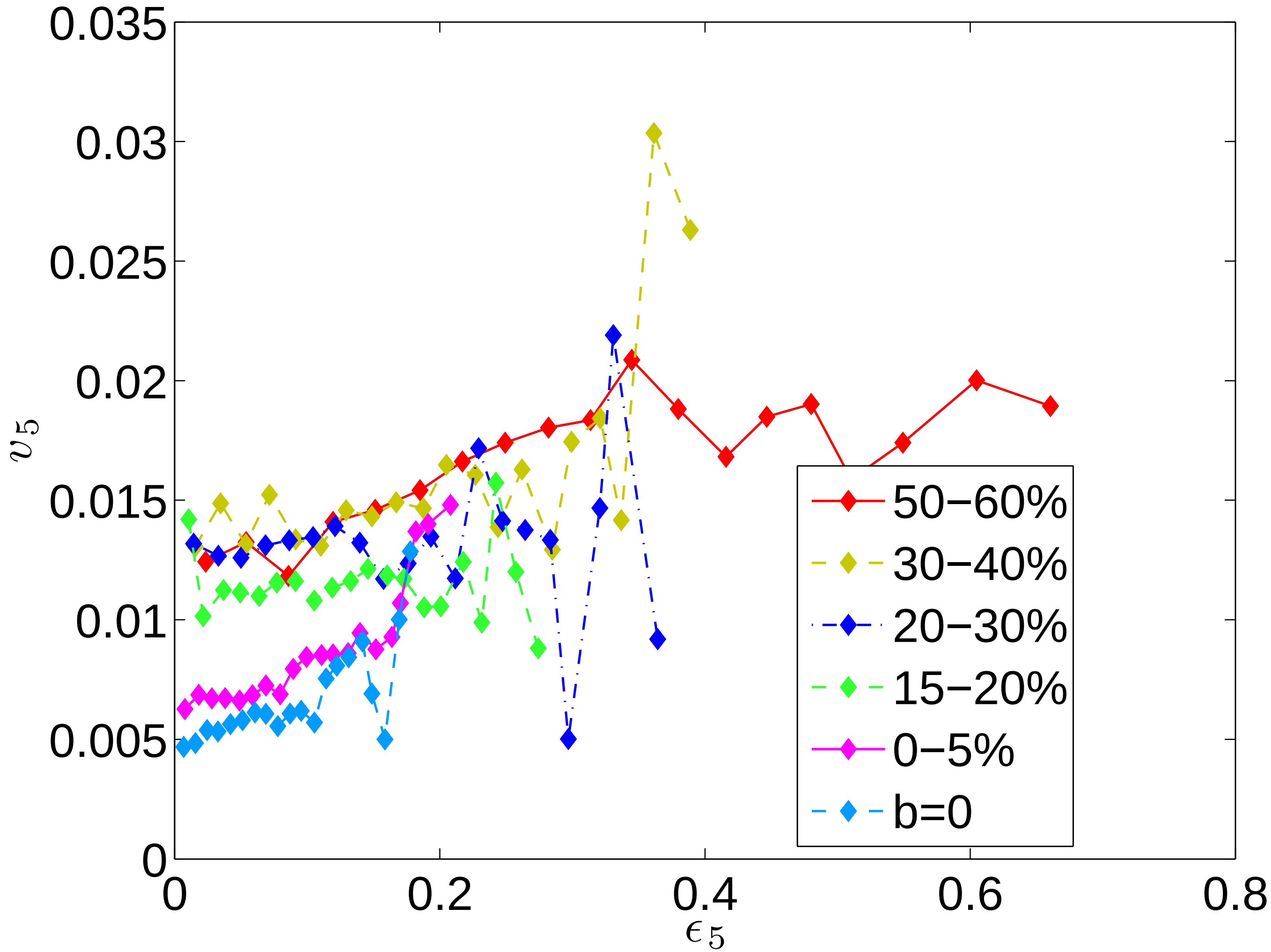
- Slope of $v_3(\varepsilon_3)$ and value of v_3/ε_3 depend on centrality class
- Non-zero triangular flow $v_3 \sim 1{-}2\%$ even for zero triangularity ε_3
  $\Longrightarrow$ other (odd) harmonic eccentricity coefficients feed into v_3

Higher harmonic flows and associated eccentricities: v_4 vs. ε_4 (MC-KLN, e-weighted)



- Correlation between v_4 and ε_4 strongly centrality dependent
- In mid-central and peripheral collisions, v_4 is mostly generated by $\varepsilon_{n\neq4}$, in particular ε_2
- Even in central collisions, other $\varepsilon_{n\neq4}$ feed into v_4, generating non-zero v_4 for zero ε_4

Higher harmonic flows and associated eccentricities: v_5 vs. ε_5 (MC-KLN, e-weighted)

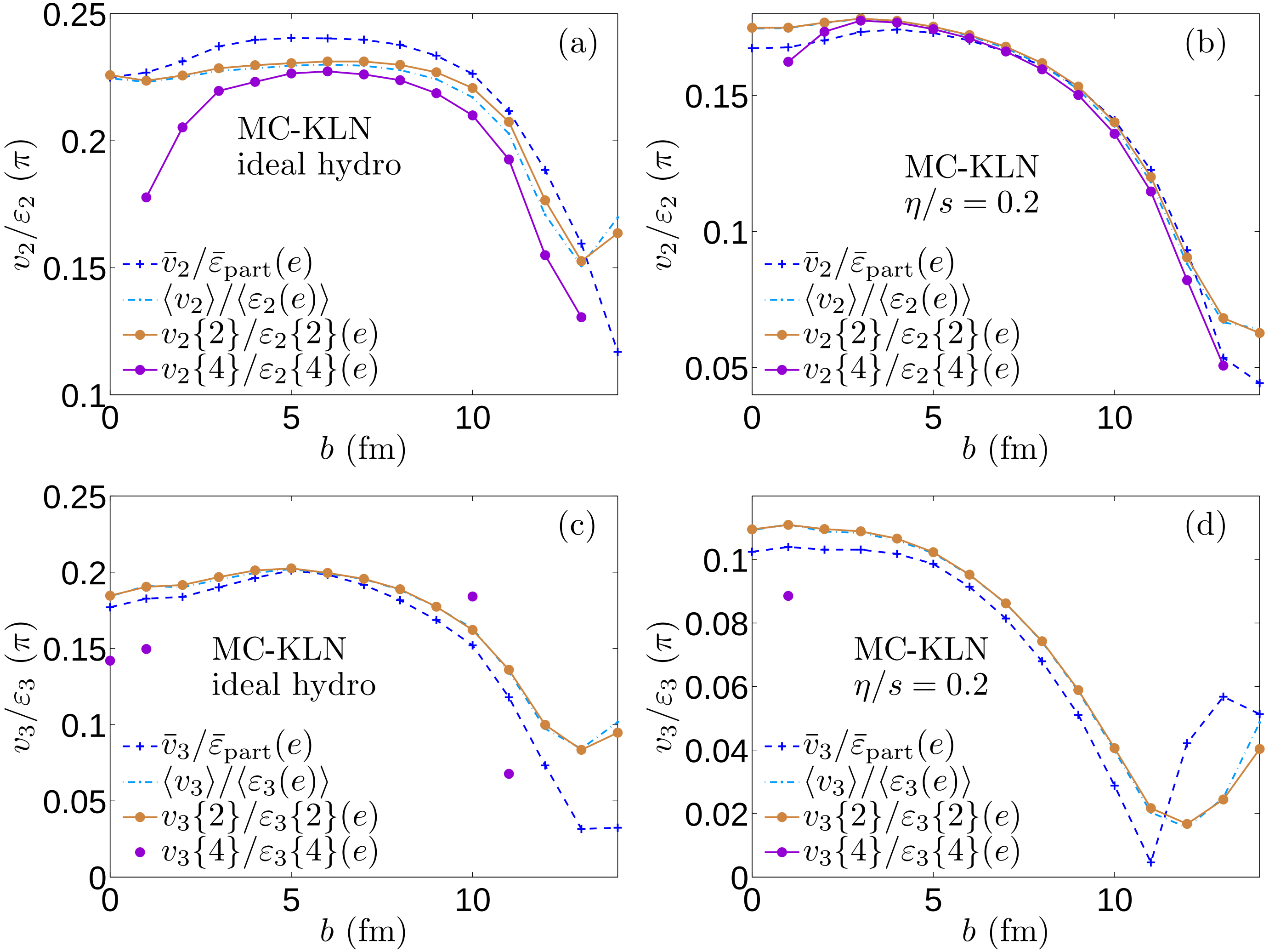


- Correlation between v_5 and ε_5 strongly centrality dependent
- In mid-central and peripheral collisions, v_5 is mostly generated by $\varepsilon_{n\neq 5}$
- Even in central collisions, other $\varepsilon_{n\neq 5}$ feed into v_5, generating non-zero v_5 for zero ε_5

Event-by-event vs. single-shot hydro

Eccentricity-scaled $v_{2,3}$ flow from e-by-e and single-shot hydro

Zhi Qiu, UH, in preparation

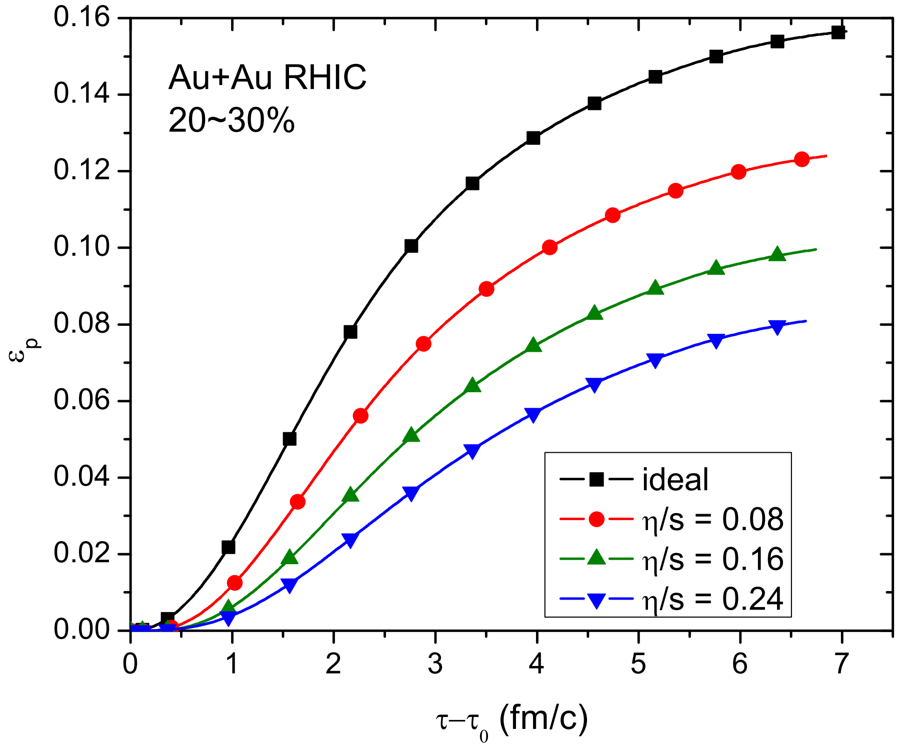


- For most centralities, eccentricity-scaled $v_{2,3}$ from e-by-e and single-shot hydro agree within 5-10%
- Agreement between $\langle v_{2,3}\rangle/\langle\varepsilon_{2,3}\rangle$ and $v_{2,3}\{2\}/\varepsilon_{2,3}\{2\}$ is excellent at all centralities
- Agreement between $v_2\{2\}/\varepsilon_2\{2\}$ and $v_2\{4\}/\varepsilon_2\{4\}$ is good over most of the centrality range, but the analog relation for triangular flow does not work (note, however, limited statistics)
- $\Longrightarrow$ **Can use single-shot hydro to compute $\langle v_{2,3}\rangle/\langle\varepsilon_{2,3}\rangle = v_{2,3}\{2\}/\varepsilon_{2,3}\{2\}$**

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

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

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 $v_2^{\rm ch}$**:

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

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

- **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: $v_2^{(i)}(p_T)$, $\frac{dN_i}{dy d^2p_T}$ 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)

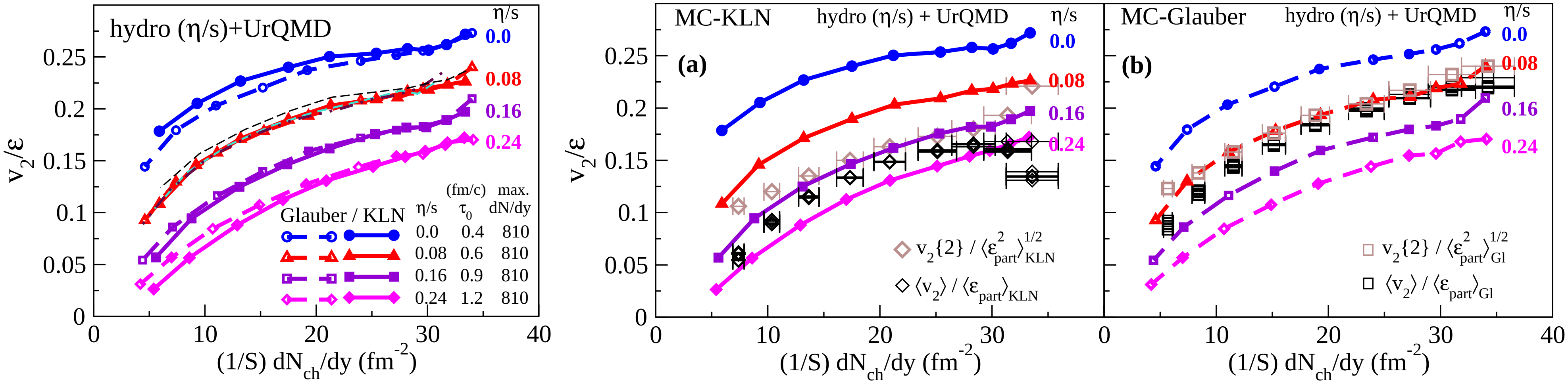
  $\Rightarrow$ need hybrid code that couples viscous hydrodynamic evolution of QGP to **realistic microscopic dynamics** of late-stage hadron gas phase

  $\Rightarrow$ **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

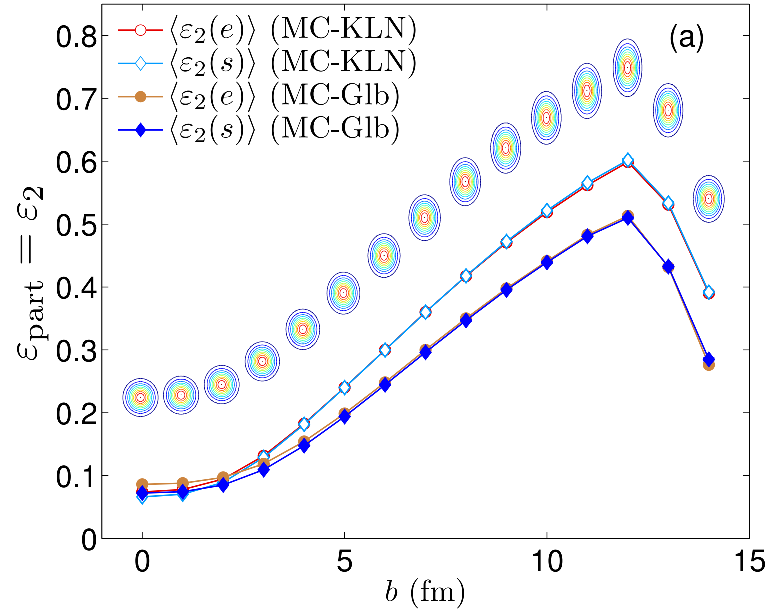


$$1 < 4\pi(\eta/s)_{\rm QGP} < 2.5$$

Zhi Qiu, UH, PRC84 (2011) 024911

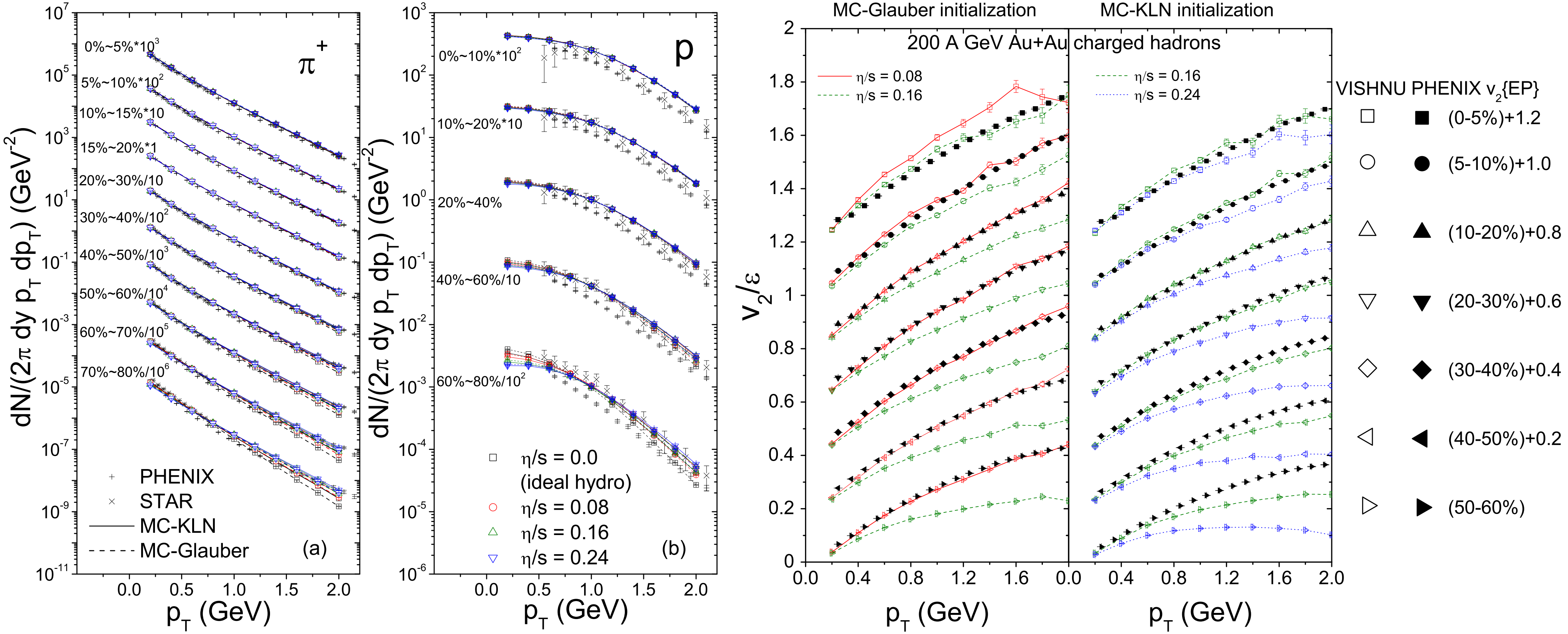
- All shown theoretical curves correspond to parameter sets that correctly describe centrality dependence of charged hadron production as well as p_T-spectra of charged hadrons, pions and protons at all centralities
- $v_2^{\rm ch}/\varepsilon_x$ vs. $(1/S)(dN_{\rm ch}/dy)$ is "universal", i.e. depends **only on** η/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. $\varepsilon_x^{\rm KLN}$ $\longrightarrow$
- smaller effects: *early flow* $\to$ increases $\frac{v_2}{\varepsilon}$ by $\sim$ few % $\to$ larger η/s

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



Global description of AuAu@RHIC spectra and v_2

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

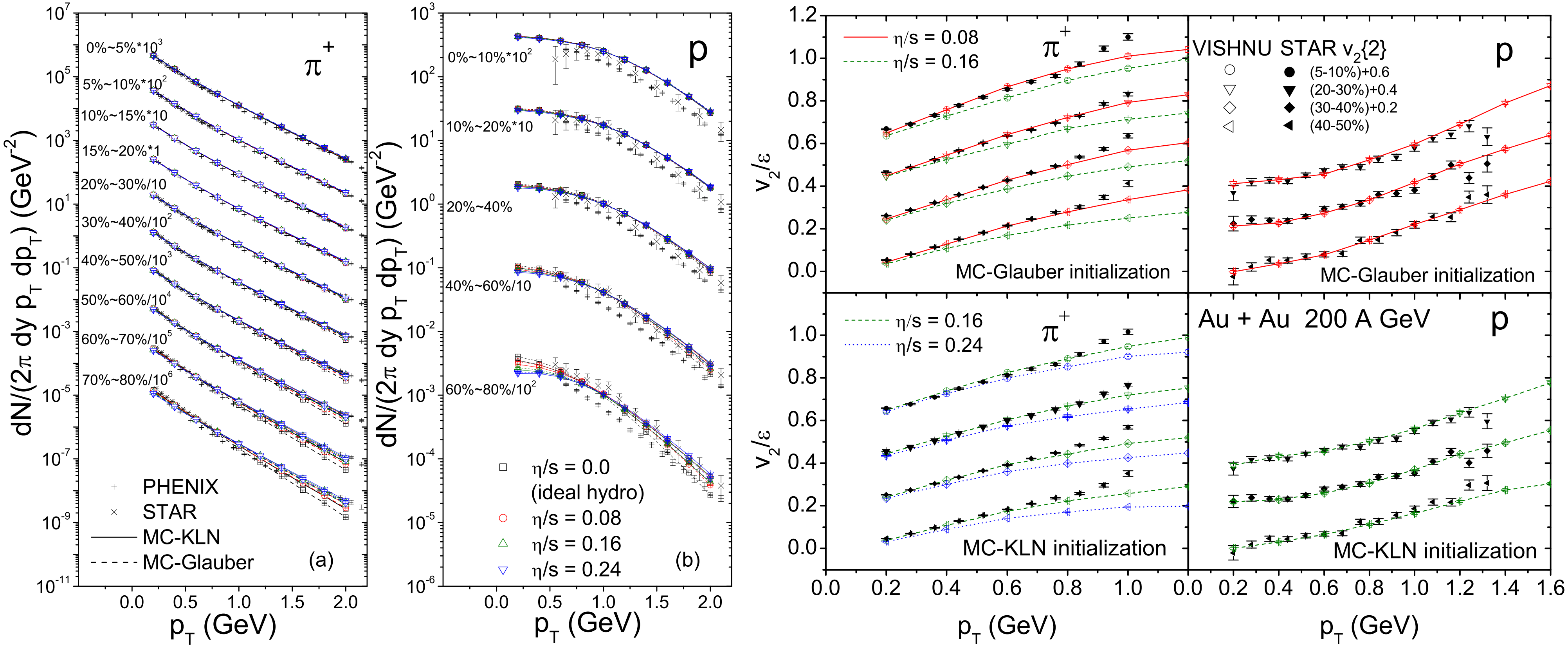


- $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities

- Note: $T_{\rm chem} = 165$ 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

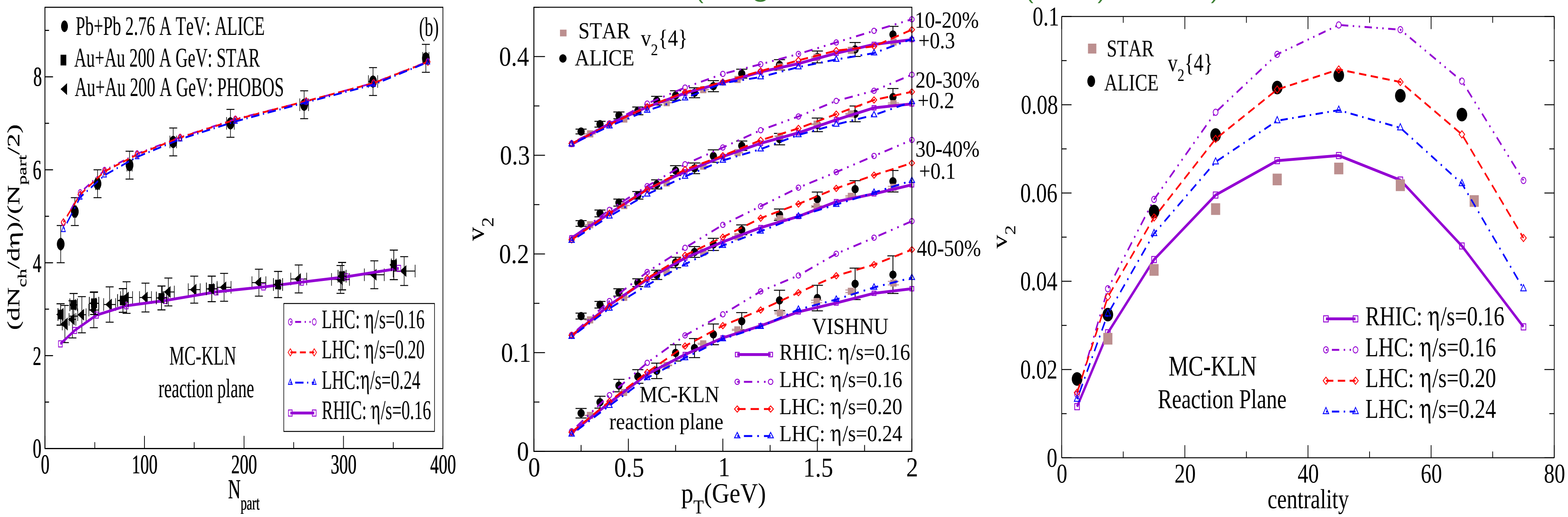
VISHNU (H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRC83 (2011) 054910)



- $(\eta/s)_{\rm QGP}=0.08$ 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

Pre- and postdictions for PbPb@LHC

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



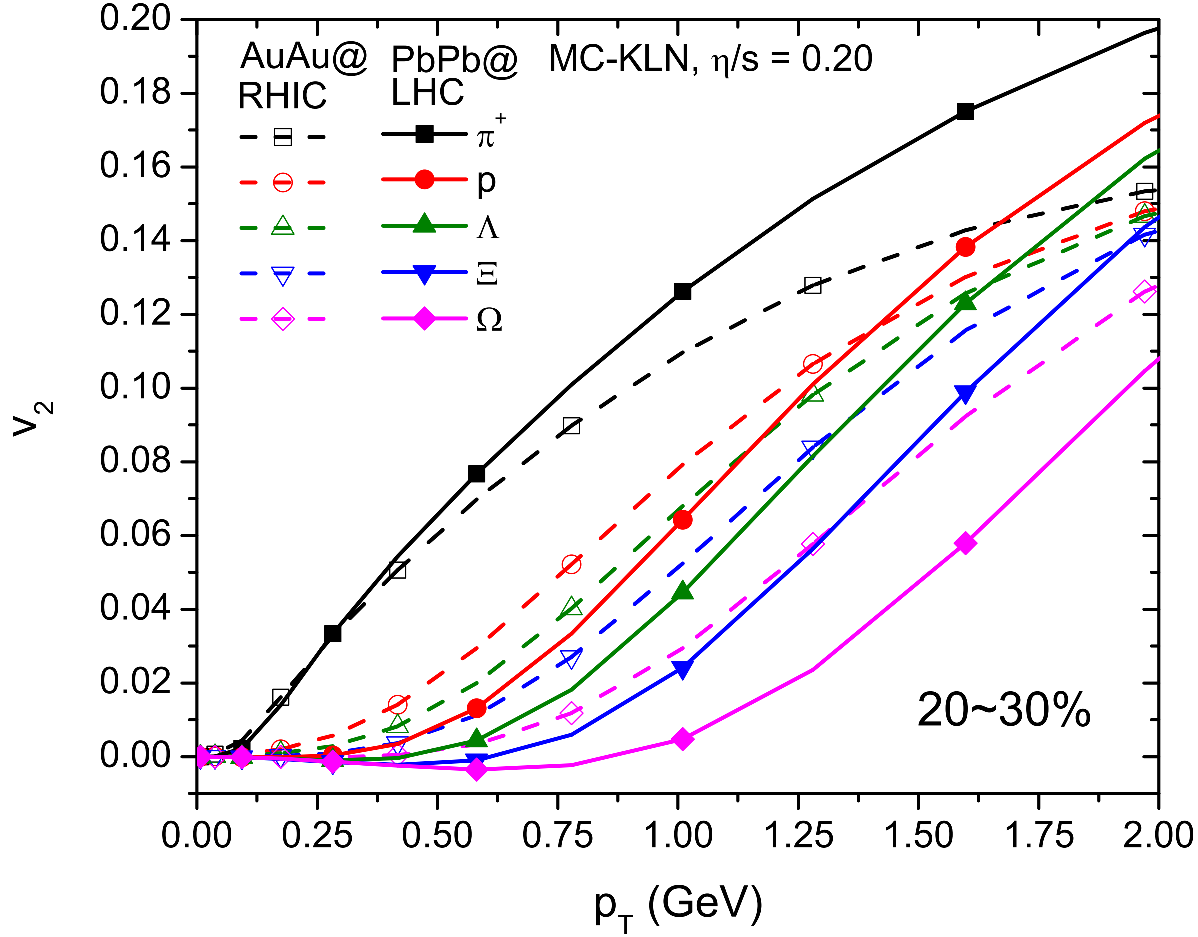
- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of $dN_{\rm ch}/d\eta$ well in both AuAu@RHIC and PbPb@LHC
- $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN works well for charged hadron $v_2(p_T)$ 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!**

Why is $v_2^{\mathrm{ch}}(p_T)$ the same at RHIC and LHC?

Answer: Pure accident! (Kestin & Heinz EPJC61 (2009) 545)

C. Shen, UH, P. Huovinen, H. Song, PRC84 (2011) 044903



$v_2^\pi(p_T)$ increases a bit from RHIC to LHC, for heavier hadrons $v_2(p_T)$ at fixed p_T decreases

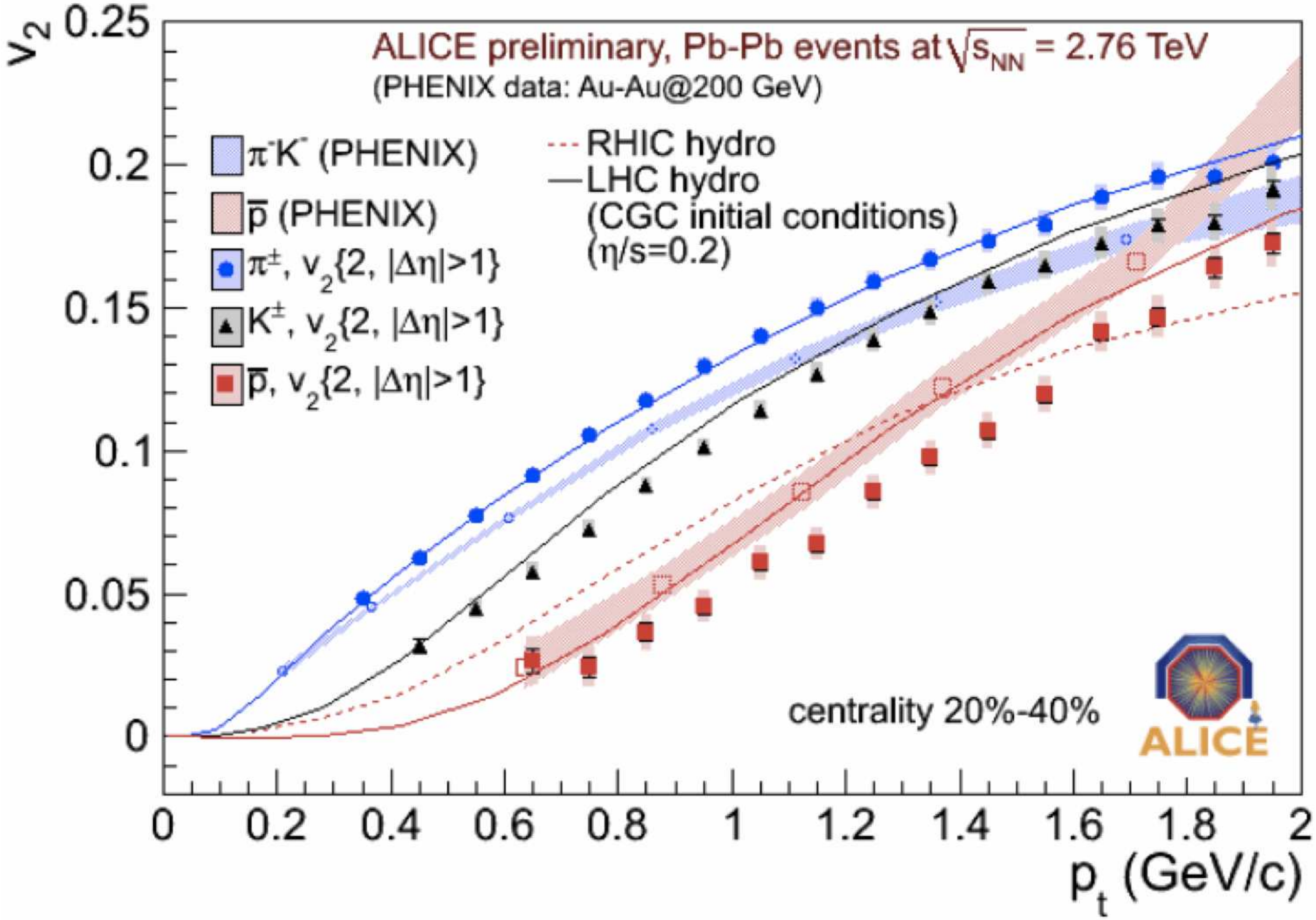
(radial flow pushes momentum anisotropy of heavy hadrons to larger p_T)

This is a hard prediction of hydrodynamics! (See also Nagle, Bearden, Zajc, NJP13 (2011) 075004)

Confirmation of increased mass splitting at LHC

Data: ALICE @ LHC, Quark Matter 2011 (symbols), PHENIX @ RHIC (shaded)

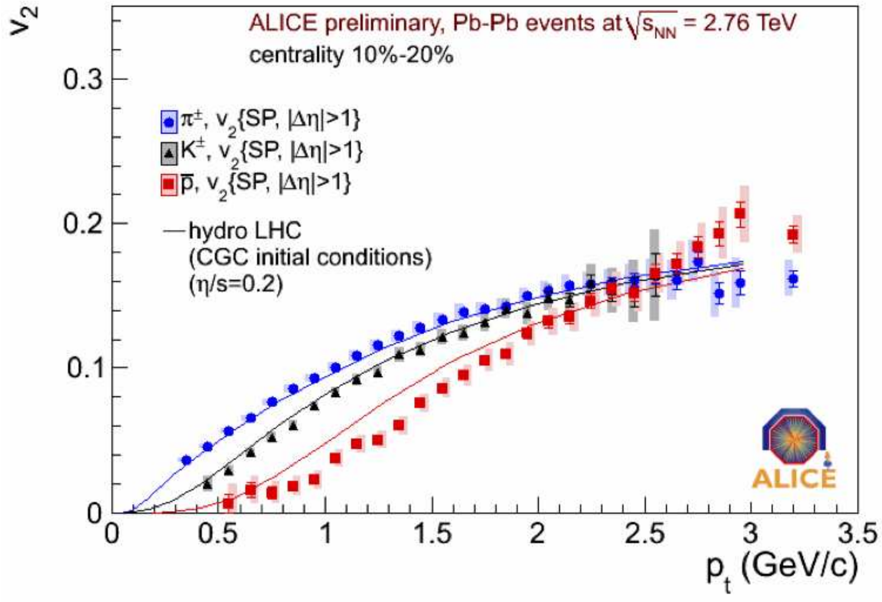
Lines: Shen et al., PRC84 (2011) 044903 (VISH2+1 + MC-KLN, η/s=0.2)



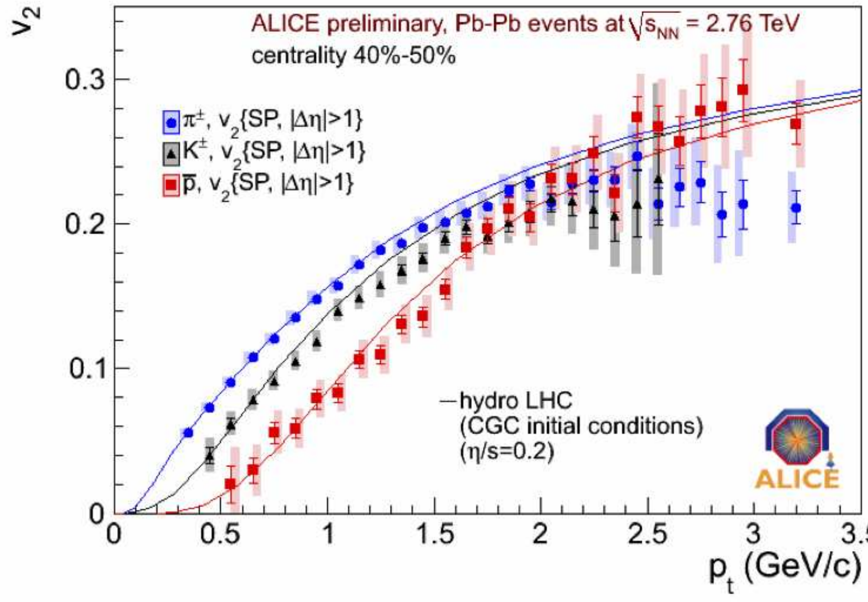
- Qualitative features of data agree with VISH2+1 predictions
- VISH2+1 does not push proton v_2 strongly enough to higher p_T, both at RHIC and LHC
- At RHIC we know that this is fixed when using VISHNU – is the same true at LHC?

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)



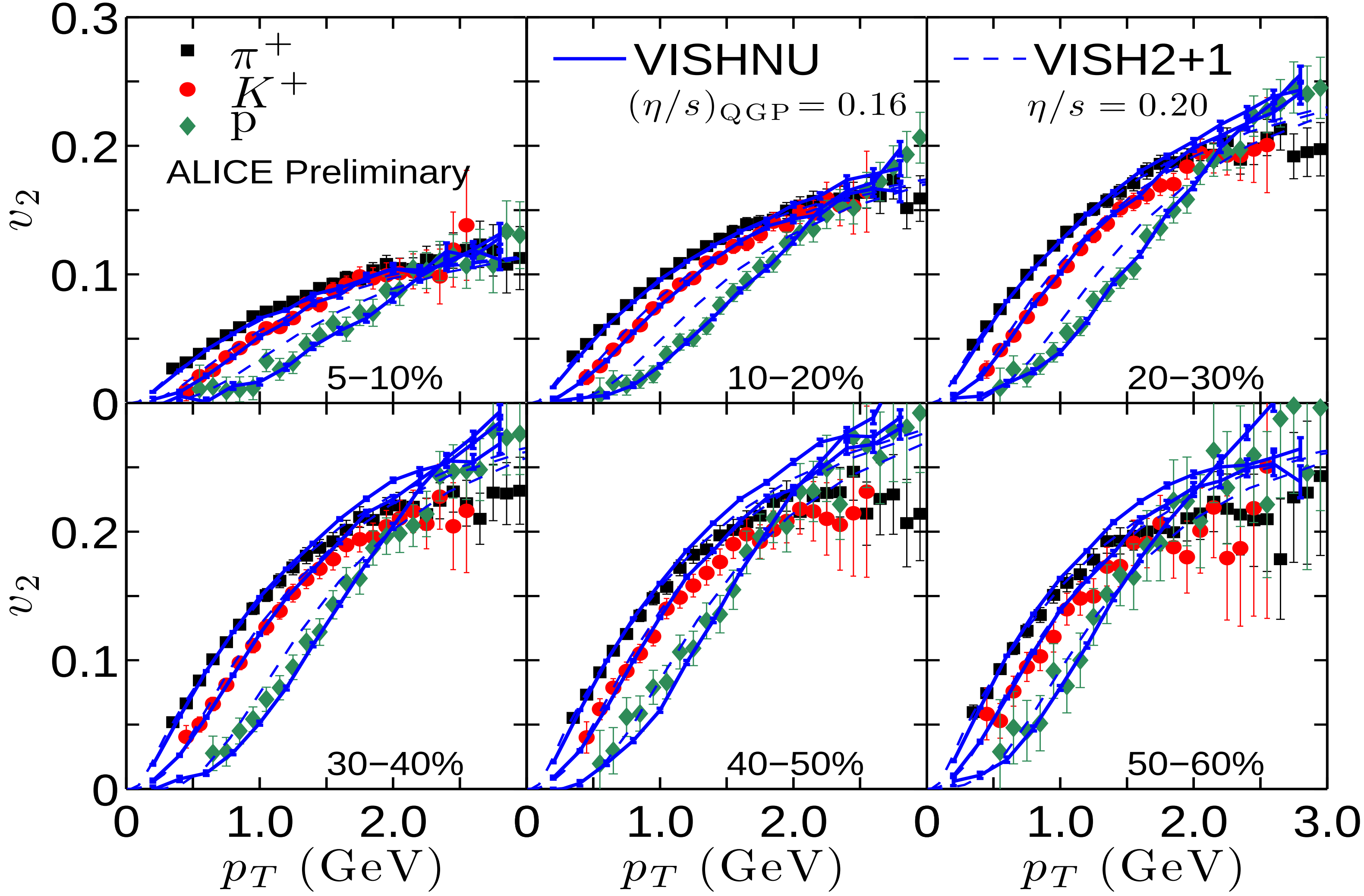
Perfect fit in semi-peripheral collisions!

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

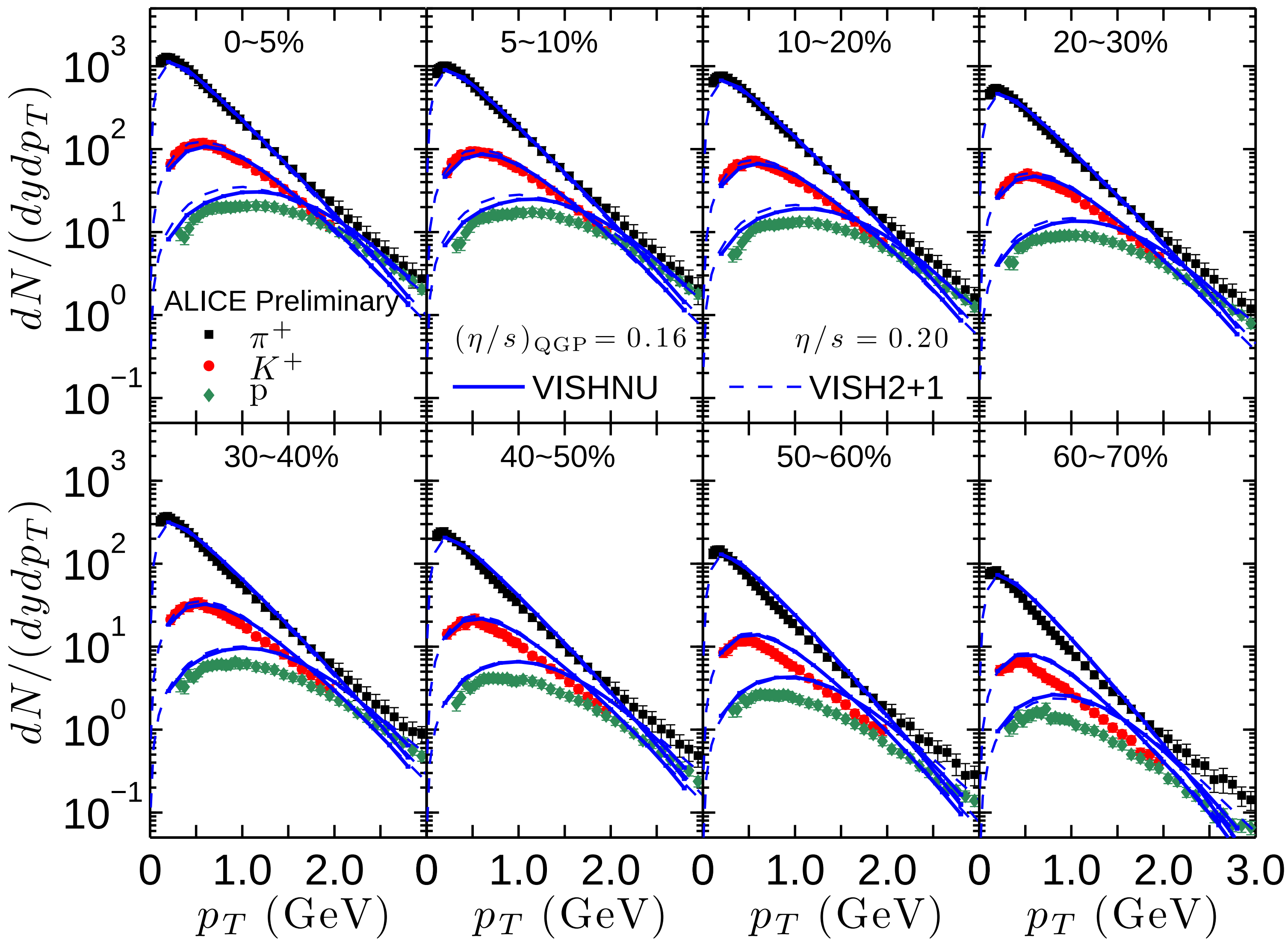
Data: ALICE, preliminary (Snellings, Krzewicki, Quark Matter 2011)
Dashed lines: Shen et al., PRC84 (2011) 044903 (VISH2+1, MC-KLN, $(\eta/s)_{\rm QGP}$=0.2)
Solid lines: Song, Shen, UH 2011 (VISHNU, MC-KLN, $(\eta/s)_{\rm QGP}$=0.16)



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

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

PbPb@LHC p_T-spectra: ALICE vs. VISH2+1 and VISHNU:

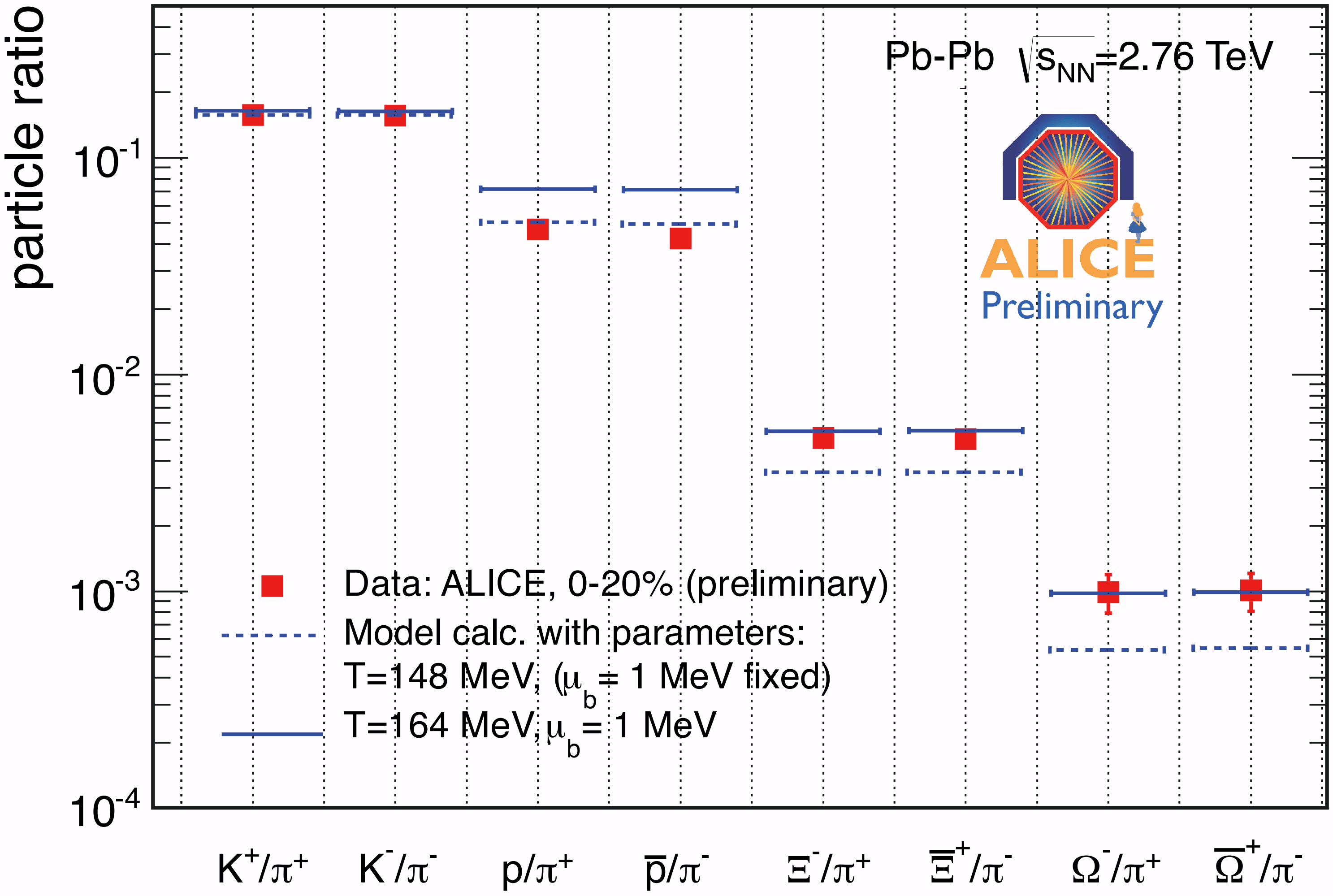


- Good description also of identified hadron spectra for centralities $< 50\%$
- VISHNU better than VISH2+1 in central collisions (more radial flow)
- Both models give too much radial flow in peripheral collisions $\Longrightarrow$ initial conditions?
- Both models overpredict proton yield by 50-70%!?

The new "proton anomaly": disagreement with the thermal model

Data: ALICE, preliminary (A. Kalweit, Strange Quark Matter 2011)

Model: A. Andronic et al., PLB673 (2009) 142; similar: S. Wheaton et al. (THERMUS), Comp. Phys. Comm. 180 (2009) 84



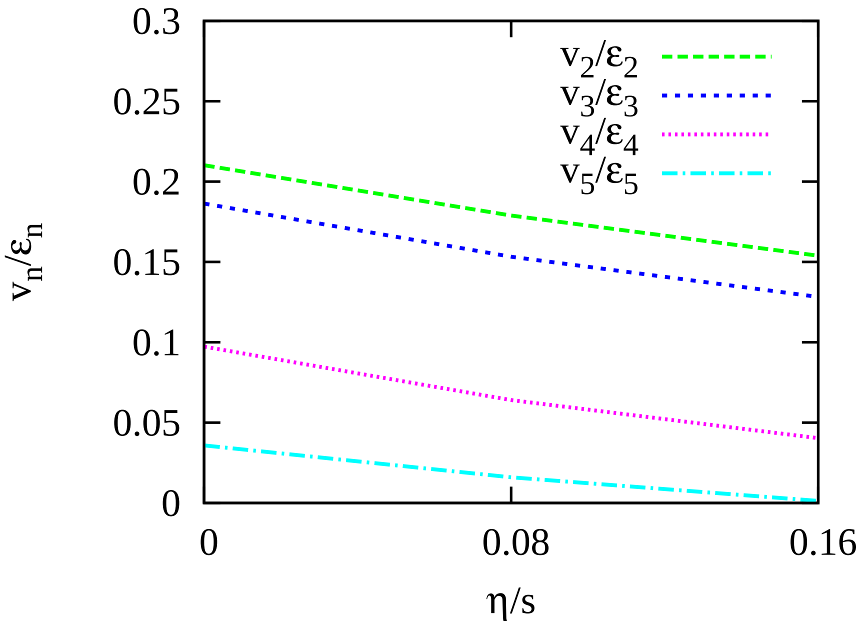
- "Standard" $T_{\rm chem} = 164\,$MeV reproduces strange hadrons but overpredicts (anti-)protons by 50%!
- $p\bar{p}$ annihilation in UrQMD not strong enough to repair this
- Similar problem already seen at RHIC but not taken seriously (STAR/PHENIX disagreement)

???

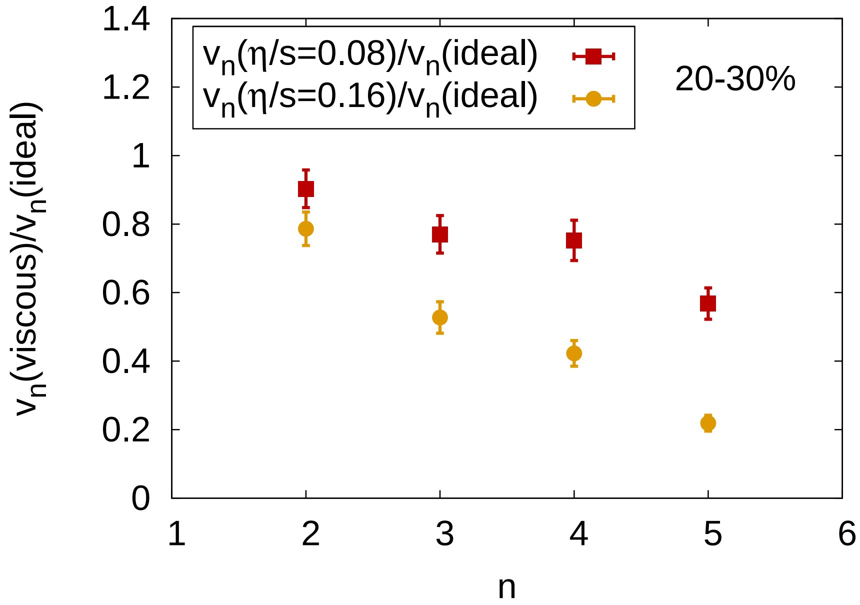
Back to the "elephant in the room": How to eliminate the large model uncertainty in the initial eccentricity?

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)

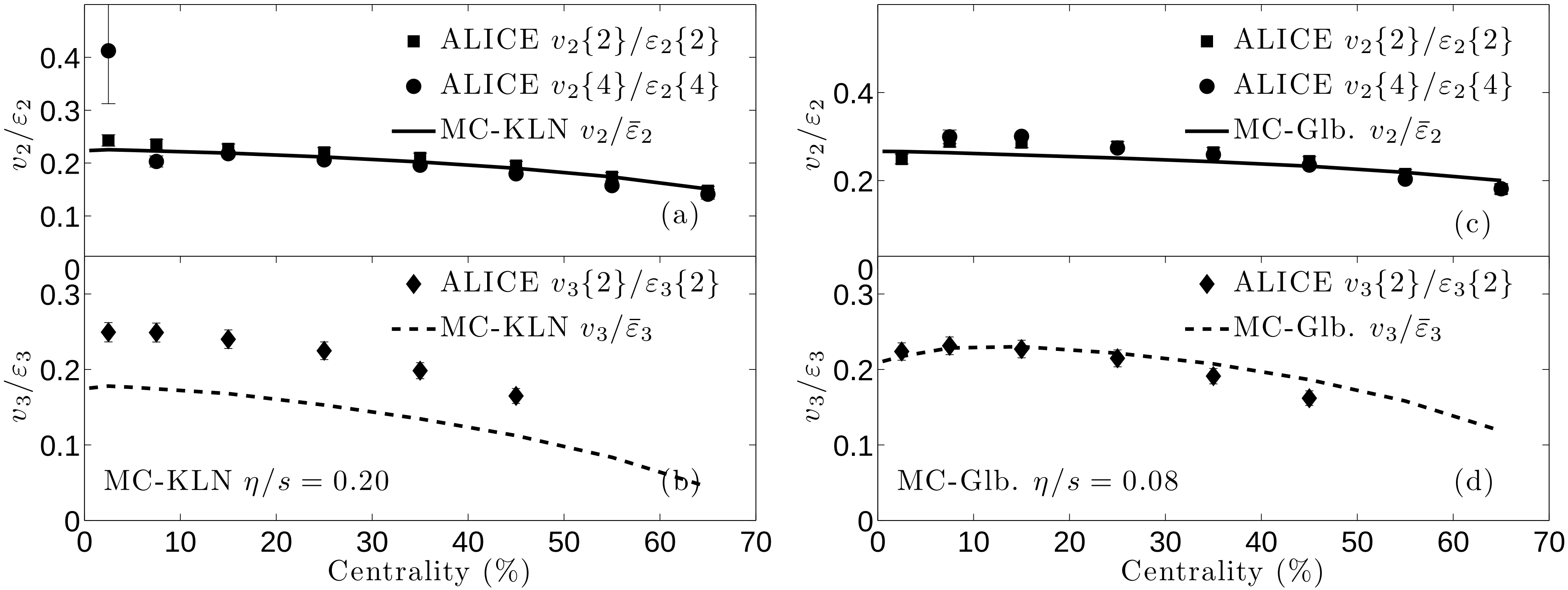
II. ε_3 is $\approx$ model independent

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!

Glauber in, KLN out!

Zhi Qiu, C. Shen, UH, arXiv:1110.3033 (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 MC-Glauber initial conditions with $\eta/s = 0.08$ describe 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 $(\eta/s)_{QGP} \simeq 1/(4\pi)$** unless the fluctuations predicted by both models are completely wrong and ε_3 is really 50% larger than we presently believe!

Conclusions

- We have come a long way over the last couple of years:
  I believe that the issue of the QGP shear viscosity at RHIC and LHC energies is now settled:

$$(\eta/s)_{\mathrm{QGP}}(T_c < T < 2T_c) = \frac{1}{4\pi} \pm 50\%$$

  A moderate increase between $2T_c$ and $3T_c$ can at present not be excluded but is not mandated by the data.

- Ingredients that matter at the 50% level and are under control:
  - relativistic viscous fluid dynamics
  - realistic EOS with correct non-equilibrium composition in HG phase
  - microscopic description of the highly dissipative hadronic stage, including all resonance decays
  - fluctuating initial conditions, simultaneous study of v_2 and v_3

- Ingredients that matter at the $< 25\%$ level and require further study:
  - bulk viscosity
  - temperature dependence of $(\eta/s)_{\mathrm{QGP}}$
  - pre-equilibrium flow
  - event-by-event hydro evolution vs. single-shot hydro with averaged initial profiles
  - (3+1)-d vs. (2+1)-d evolution
  - study of higher harmonics; influence of nucleon growth with $\sqrt{s}$ on fluctuations
  - flow fluctuations and flow angle correlations for different harmonics

The ultimate theoretical question:

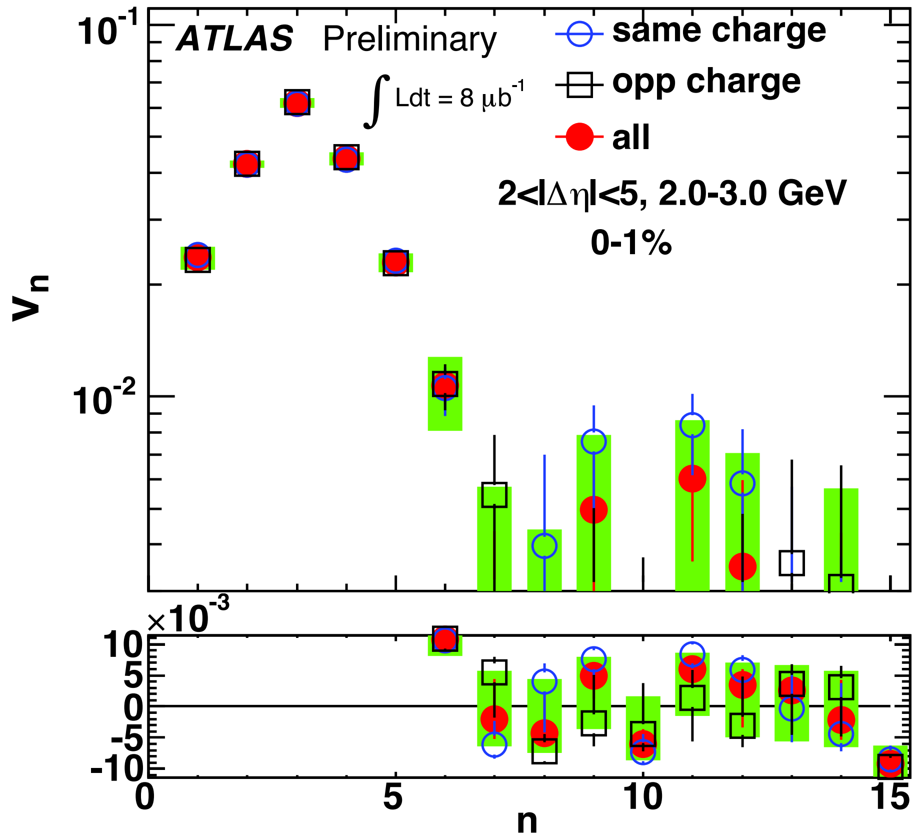
Why is $(\eta/s)_{\mathrm{QGP}}$ as small as it is?

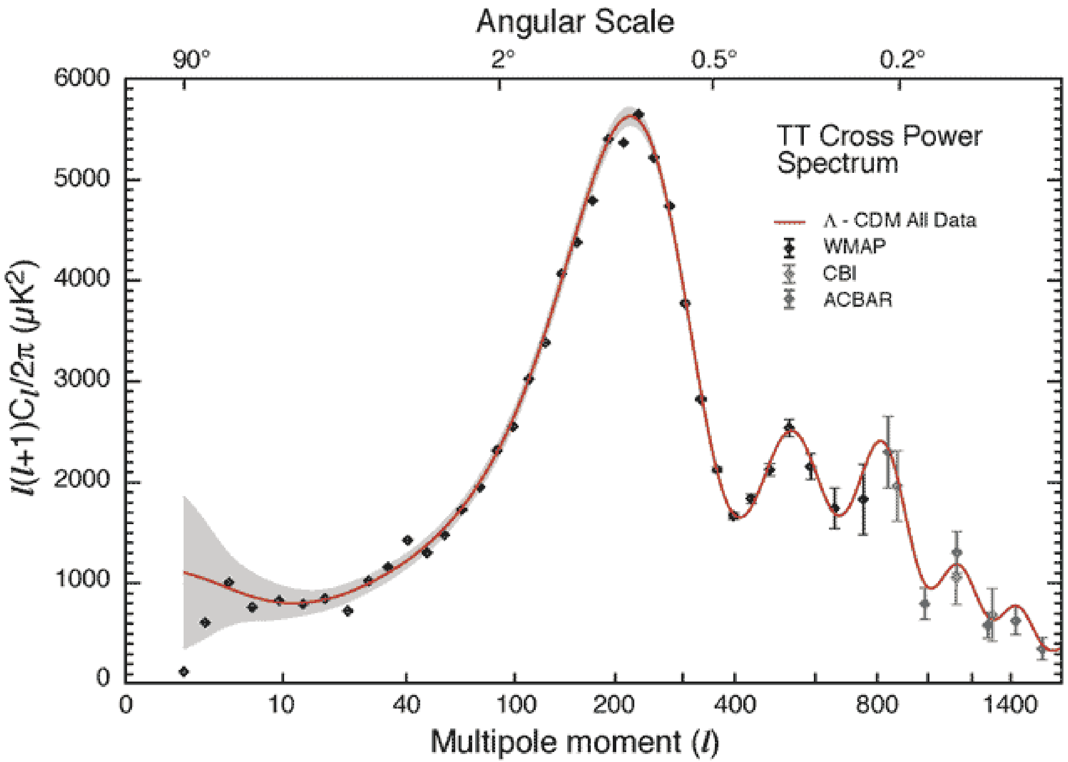
Outlook: A beautiful analogy with the Big Bang:

The fluctuation "power spectrum" of the Little Bang

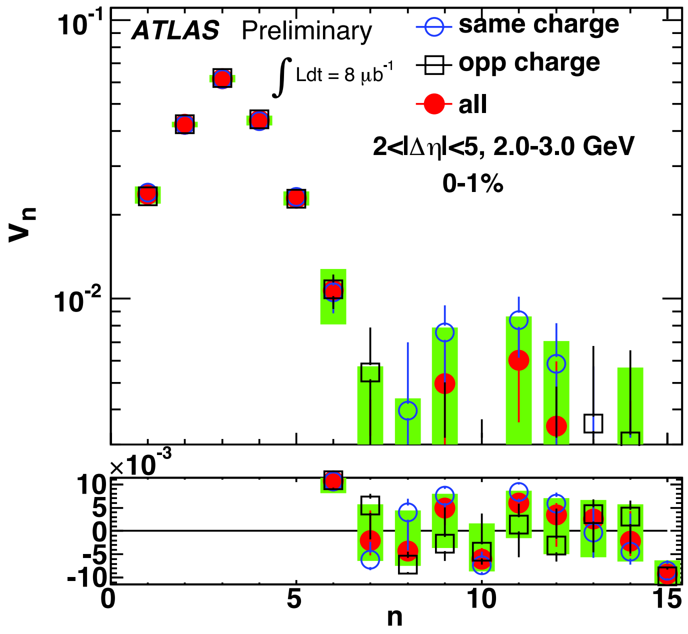
Mishra, Mohapatra, Saumia, Srivastava, PRC77 (2008) 064902 and C81 (2010) 034903

Mocsy & Sorensen, NPA855 (2011) 241, PLB705 (2011) 71

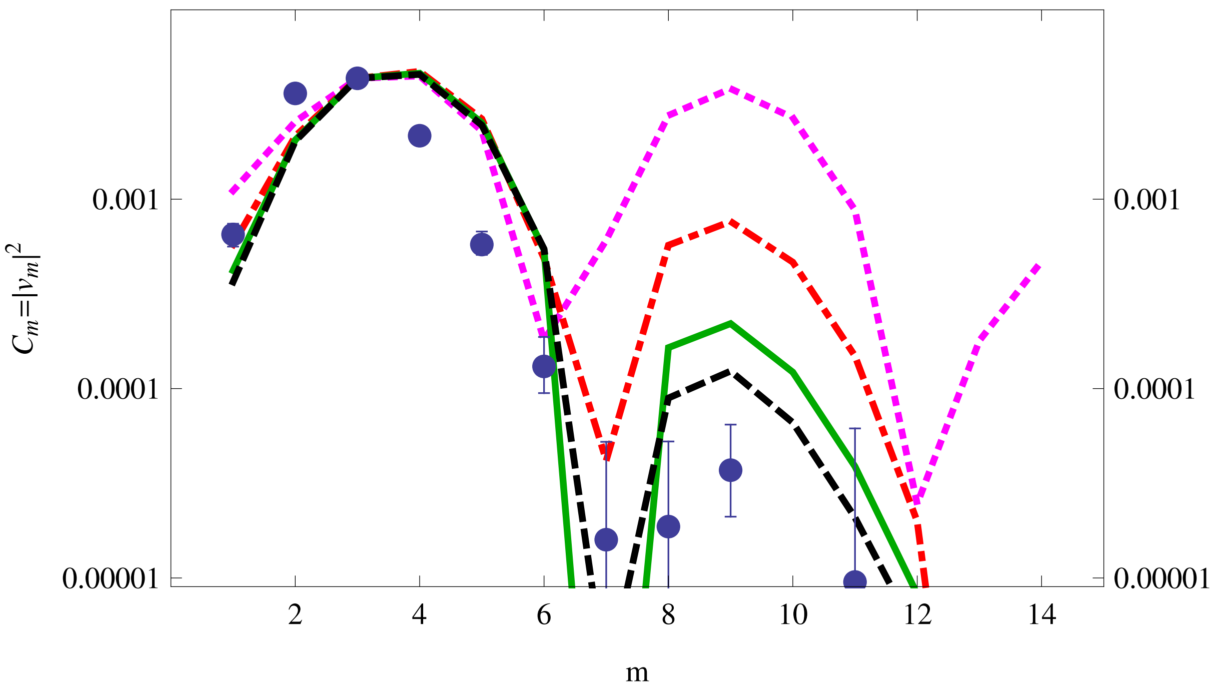




The fluctuation "power spectrum" of the Little Bang



Staig & Shuryak, arXiv:1106.3243



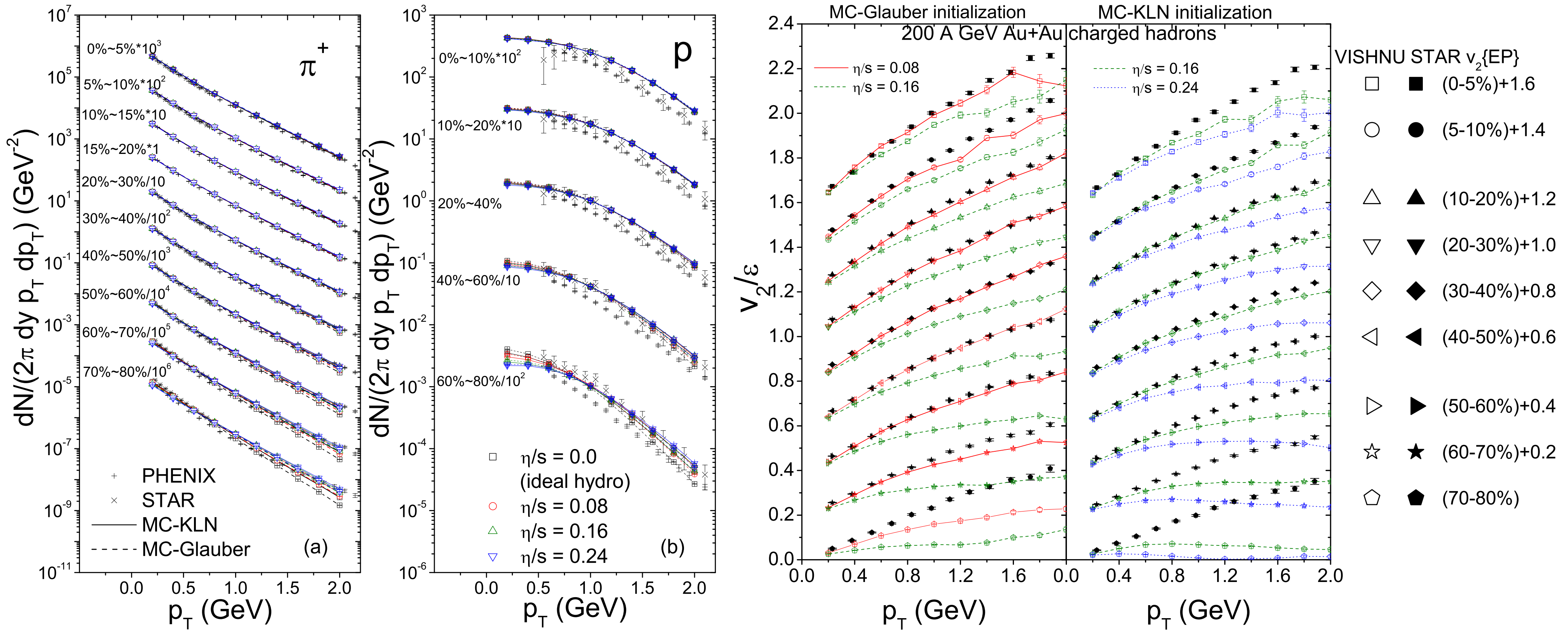
- Relating the measured "anisotropic flow power spectrum" (i.e. v_n vs. n) to the "initial fluctuation power spectrum" (i.e. ε_n vs. n) provides access to the QGP transport coefficients (likely not only η/s, but also ζ/s, τ_π, τ_Π ...)
- Power spectrum of initial fluctuations (in particular its $\sqrt{s}$ dependence) can (probably) be calculated from first principles via CGC effective theory (Dusling, Gelis, Venugopalan, arXiv:1106.3927)
- Collisions between different species, at different collision centralities, and at different $\sqrt{s}$ create Little Bangs with characteristically different power spectra

$\longrightarrow$ The Concordance Model of Little Bang Cosmology!

Supplements

Global description of AuAu@RHIC spectra and v_2

VISHNU (H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRC, arXiv:1101.4638)

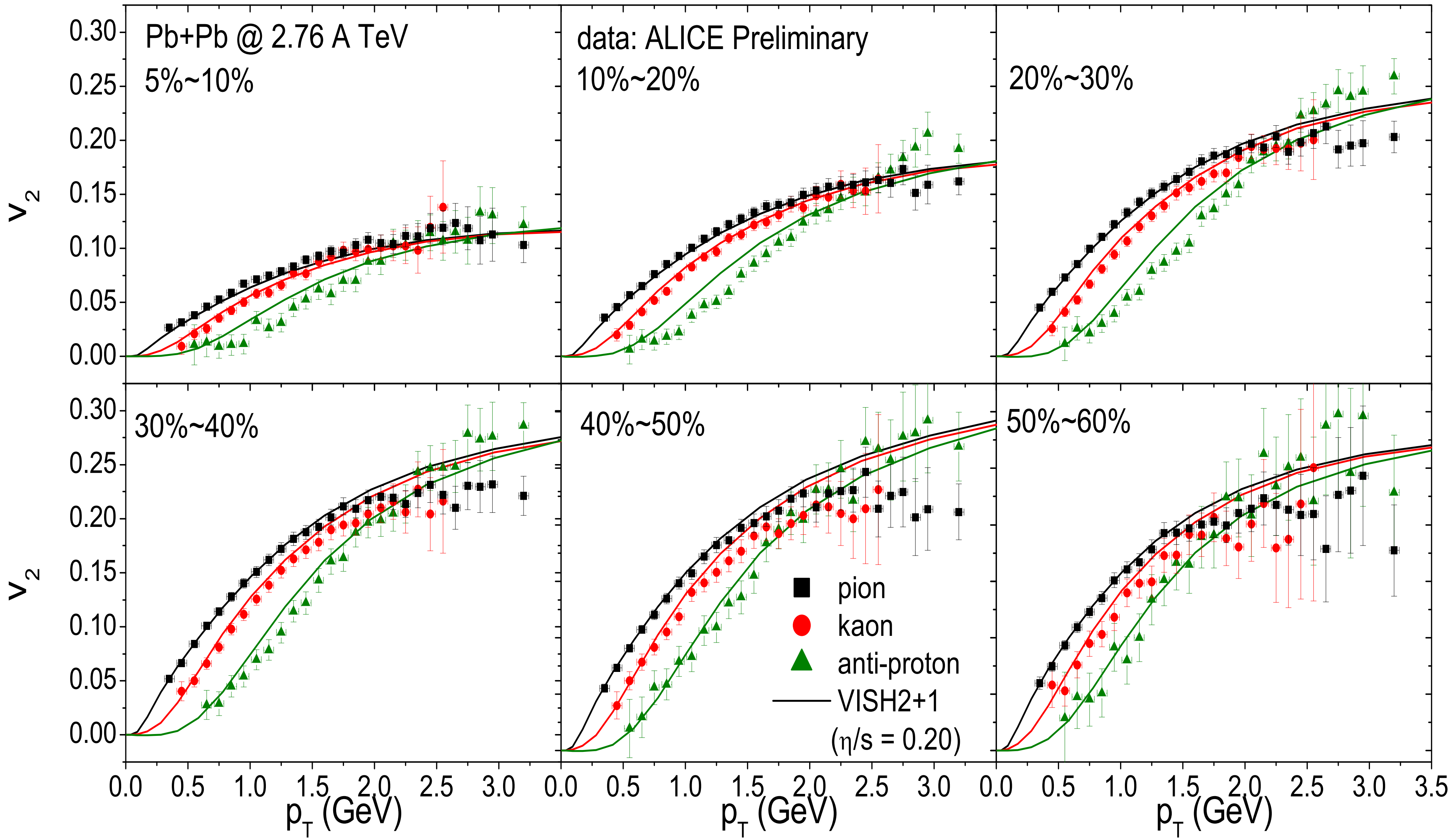


- $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN works well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities

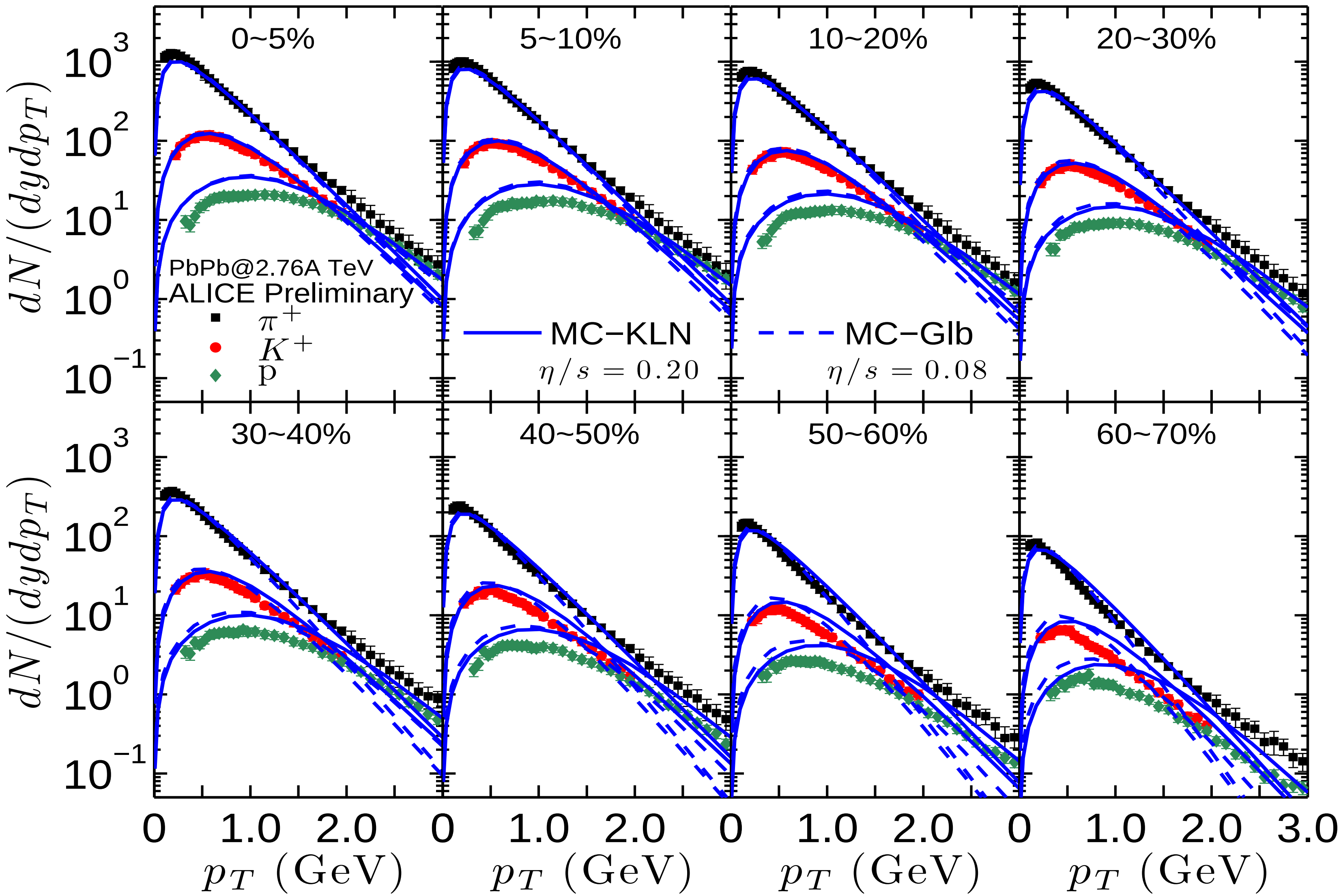
Comparison of ALICE PbPb@LHC v_2 data with VISH2+1

Data: ALICE, preliminary (Snellings, Krzewicki, Quark Matter 2011)

Prediction: C. Shen et al., PRC84 (2011) 044903 (VISH2+1, MC-KLN, η/s=0.2)



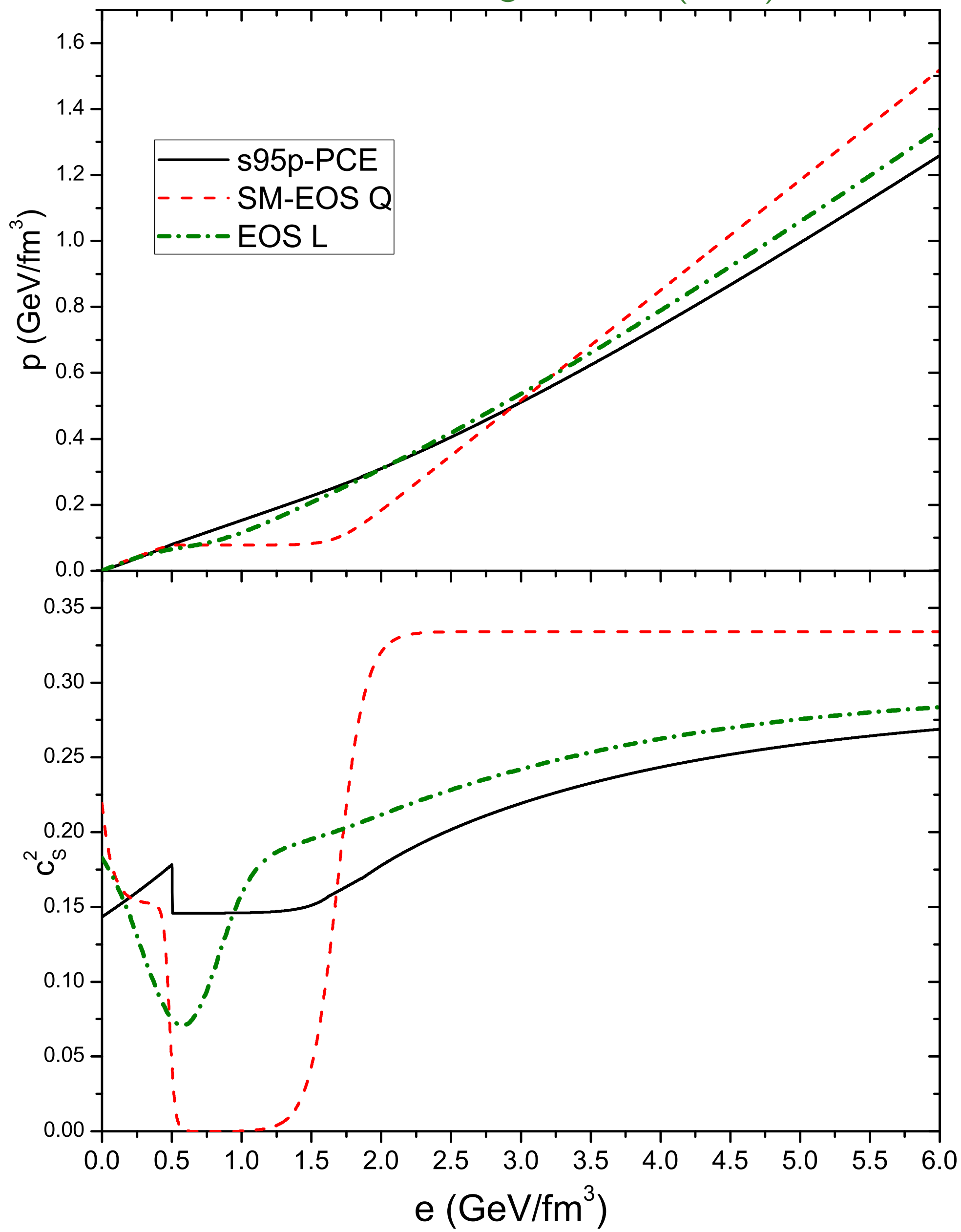
PbPb@LHC p_T-spectra: Glauber vs. KLN



- In central collisions no difference between the models.
- In peripheral collisions p_T-spectra from MC-Glauber IC too steep!
  This is an artifact of single-shot hydro with averaged initial profile; for small $\eta/s = 0.08$ (but not for $\eta/s = 0.2$!), e-by-e hydro gives flatter p_T-spectra in peripheral collisions, due to hot spots

s95p-PCE: A realistic, lattice-QCD-based EOS

Huovinen, Petreczky, NPA 837 (2010) 26
Shen, Heinz, Huovinen, Song, PRC 82 (2010) 054904



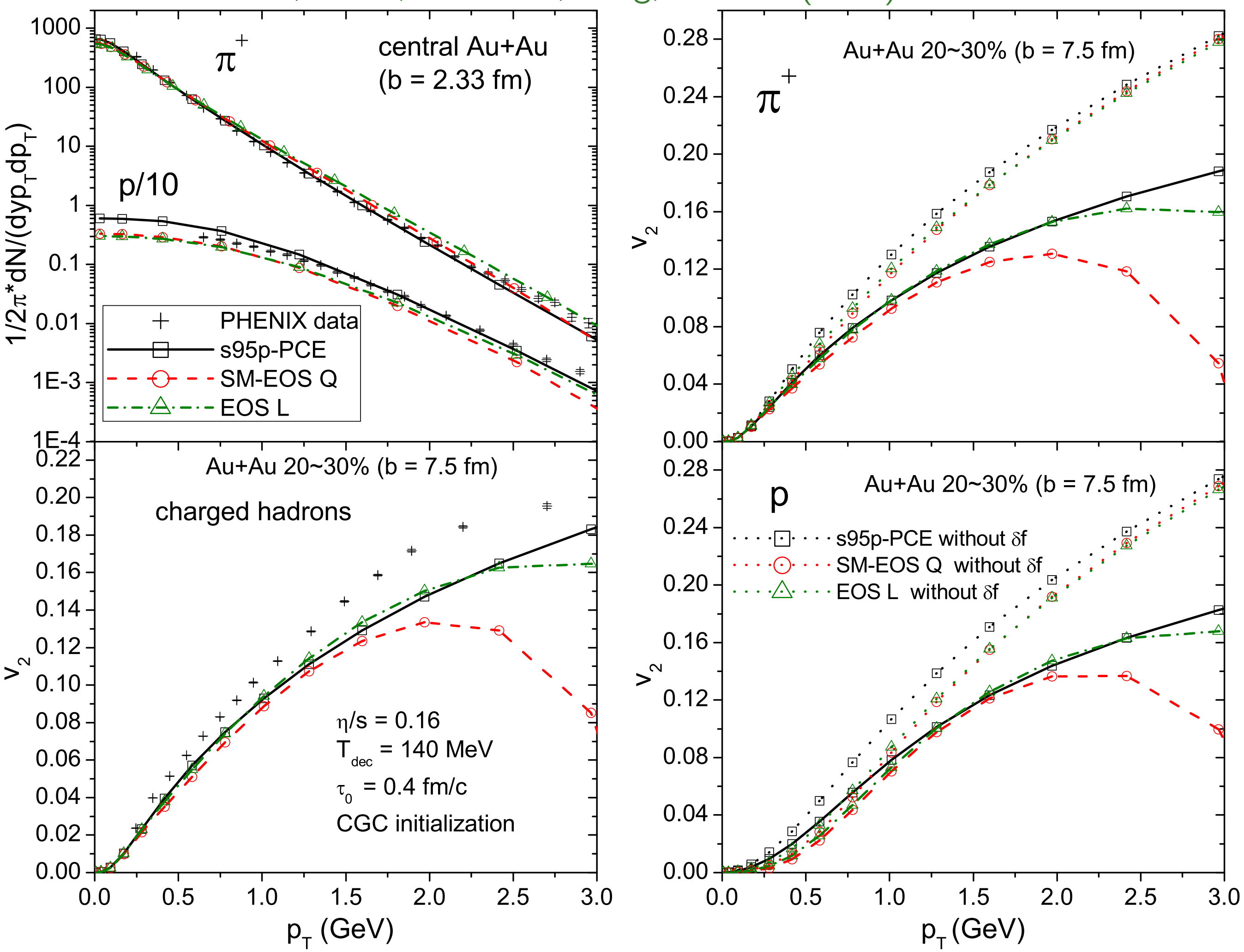
High T: Lattice QCD (latest hotQCD results)

Low T: Chemically frozen HRG ($T_{\text{chem}} = 165\,\text{MeV}$)

No softest point!

s95p-PCE: A realistic, lattice-QCD-based EOS

Huovinen, Petreczky, NPA 837 (2010) 26
Shen, Heinz, Huovinen, Song, PRC 82 (2010) 054904



Generates less radial flow than SM-EOS Q and EOS L but larger momentum anisotropy

Smooth transition leads to smaller δf at freeze-out

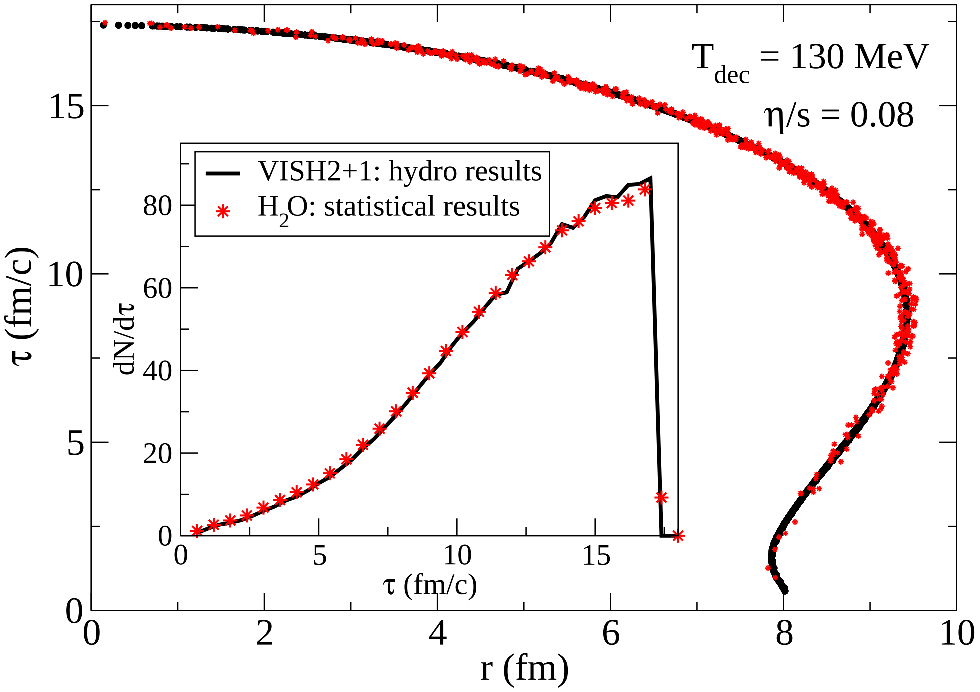
$\Longrightarrow$ larger v_2

H_2O: Hydro-to-OSCAR converter

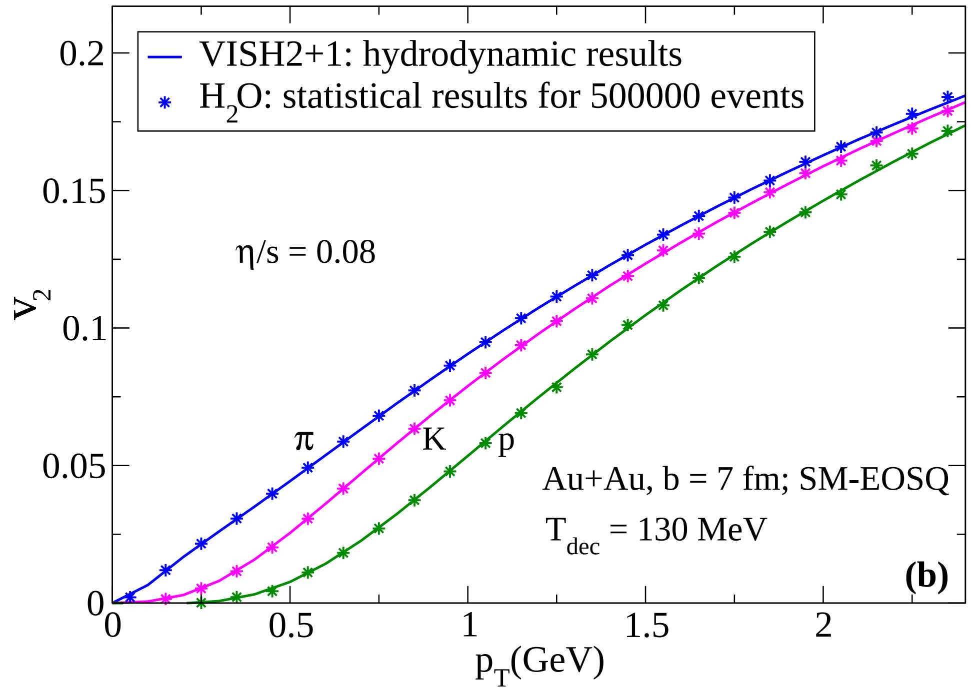
Monte-Carlo interface that samples hydrodynamic Cooper-Frye spectra (including viscous correction δf) on conversion surface to generate particles at positions x_i^μ with momenta p_i^μ for subsequent propagation in `UrQMD` (or any other OSCAR-compatible hadron cascade afterburner)

Song, Bass, Heinz, PRC 83 (2011) 024912

200 A GeV Au+Au, $b = 0$



200 A GeV Au+Au, $b = 7$ fm



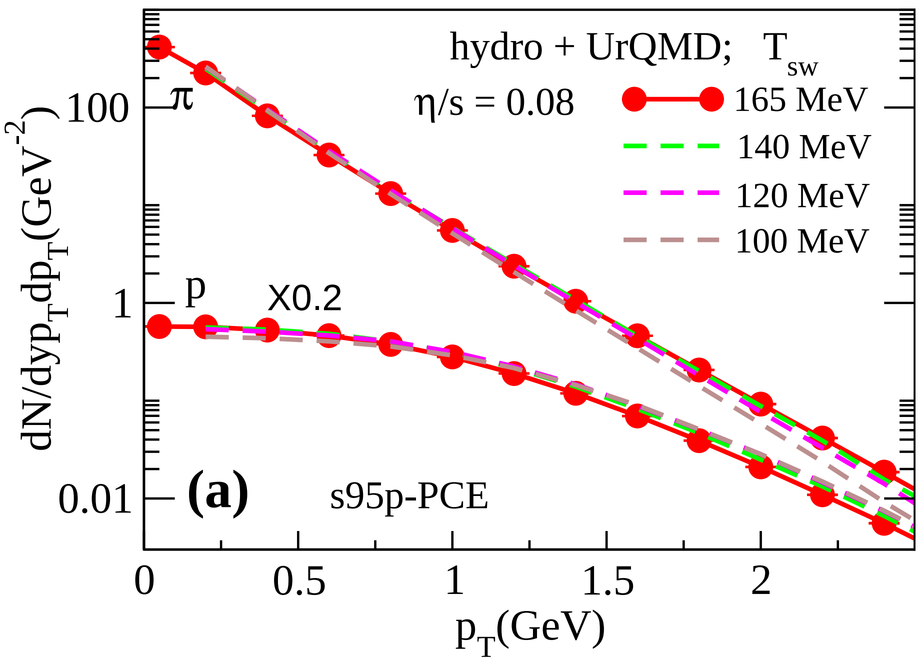
VISHNU: hydro (VISH2+1) + cascade (UrQMD) hybrid

Sensitivity to H_2O switching temperature:

With chemically frozen EOS (s95p-PCE),
p_T-spectra show very little sensitivity to $T_{\rm sw}$ (Teaney, 2000):

Song, Bass, Heinz, PRC 83 (2011) 024912

200 A GeV Au+Au, $b = 7$ fm



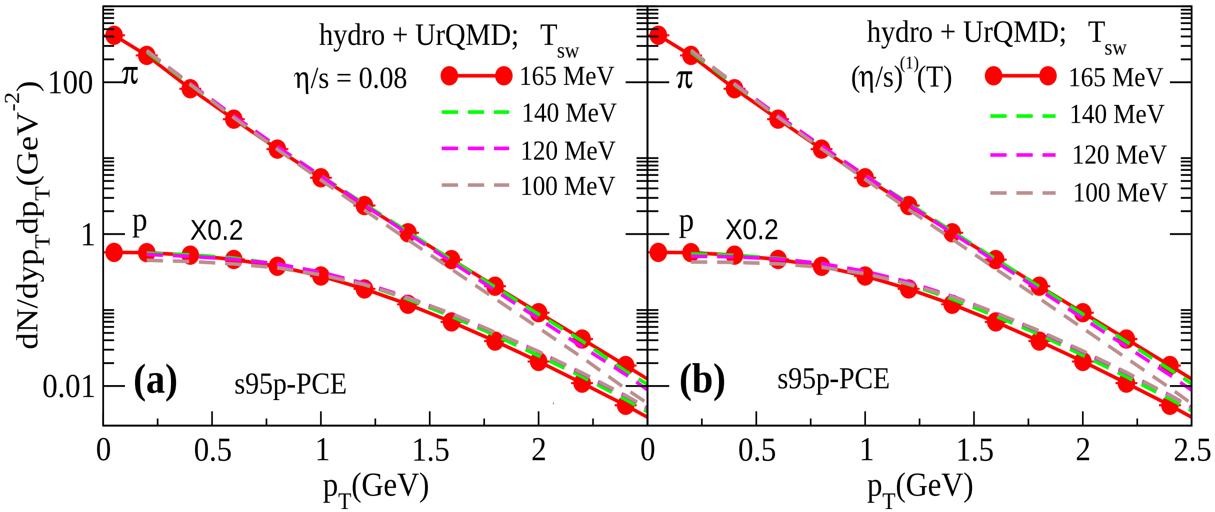
VISHNU: hydro (VISH2+1) + cascade (UrQMD) hybrid

Sensitivity to H_2O switching temperature:

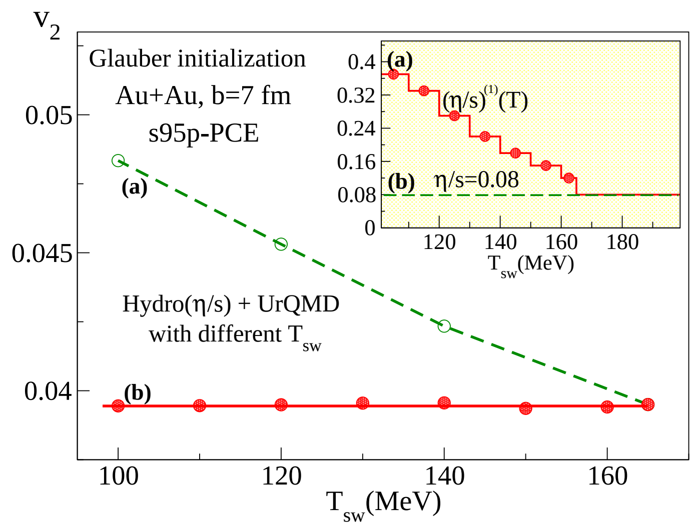
With chemically frozen EOS (s95p-PCE),
p_T-spectra show very little sensitivity to $T_{\rm sw}$ **but v_2 does:**

Song, Bass, Heinz, PRC 83 (2011) 024912

200 A GeV Au+Au, $b = 7$ fm



200 A GeV Au+Au, $b = 7$ fm



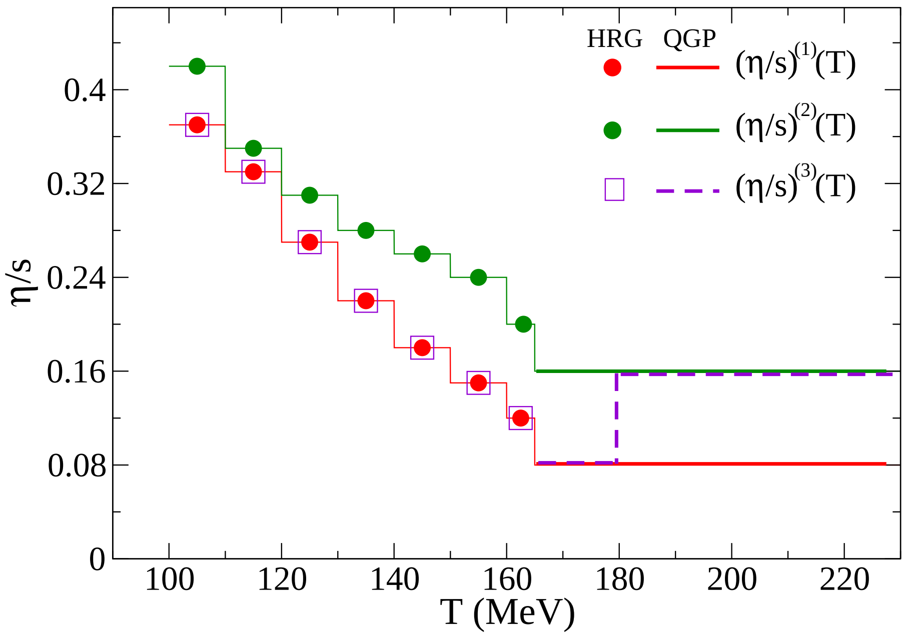
Viscous hydro with fixed $\eta/s = 0.08$ generates more v_2 below T_c than does UrQMD
$\Longrightarrow$ UrQMD is more dissipative

VISH2+1 simulation of UrQMD dynamics requires T-dependent $(\eta/s)(T)$ that increases towards lower temperature

Is there a switching window in which UrQMD can be simulated by viscous hydro?

Unfortunately NO!

Song, Bass, Heinz, PRC 83 (2011) 2011



$(\eta/s)(T)$ extracted by trying to reproduce v_2 independent of switching temperature depends on δ_f input into UrQMD from hadronizing QGP

$\Longrightarrow$ δf relaxes too slowly in UrQMD to be describable by viscous Israel-Stewart hydro

$\Longrightarrow$ extracted $(\eta/s)(T)$ not a proper UrQMD transport coefficient

$\Longrightarrow$ **UrQMD dynamics can't be described by viscous Israel-Stewart hydrodynamics**