

“Perfect fluidity” in relativistic heavy-ion collisions*

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Relaxation, Turbulence and Non-Equilibrium Dynamics of Matter Fields
(RETUNE 2012)

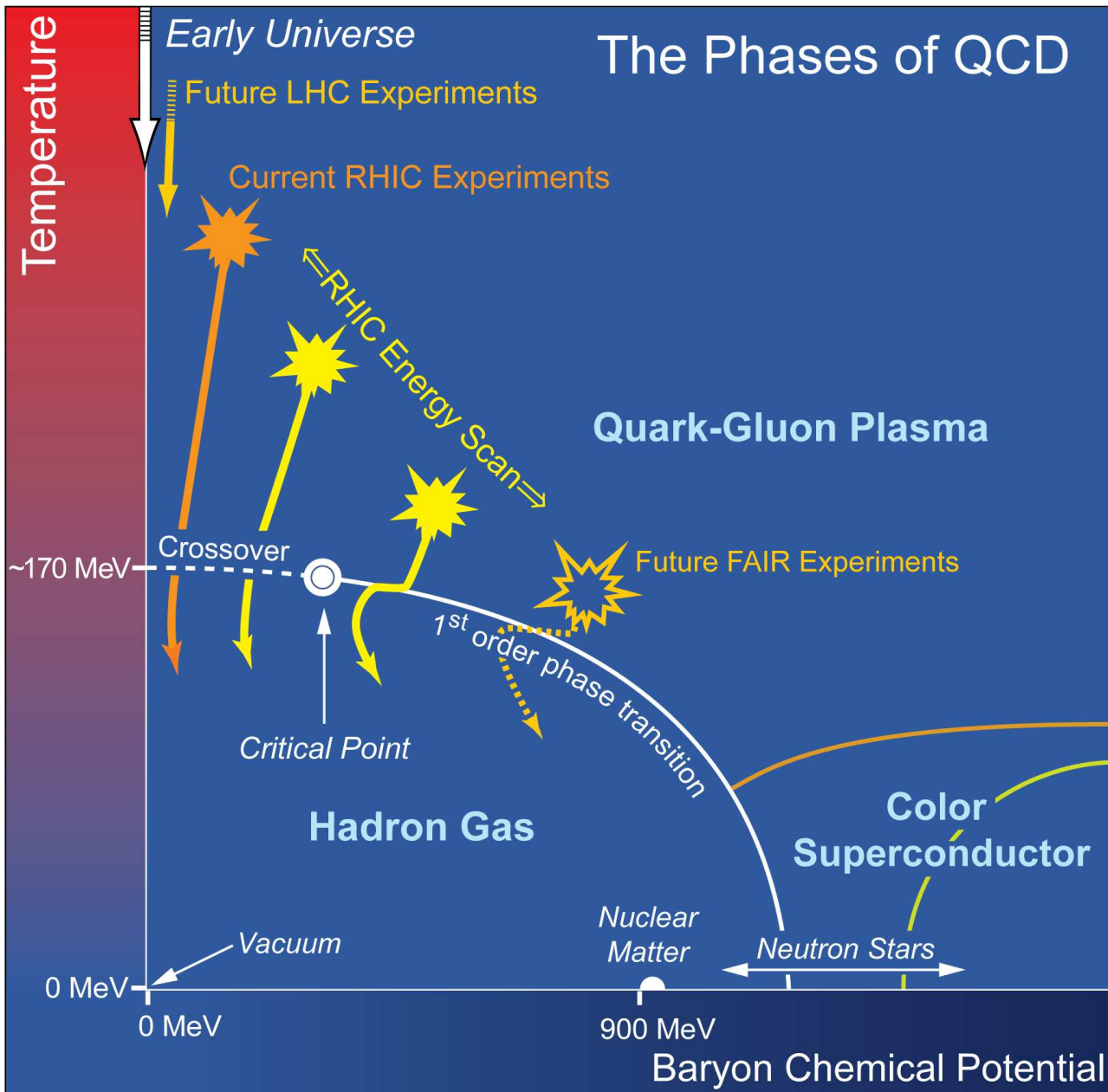
Heidelberg, 20-24 June, 2012



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



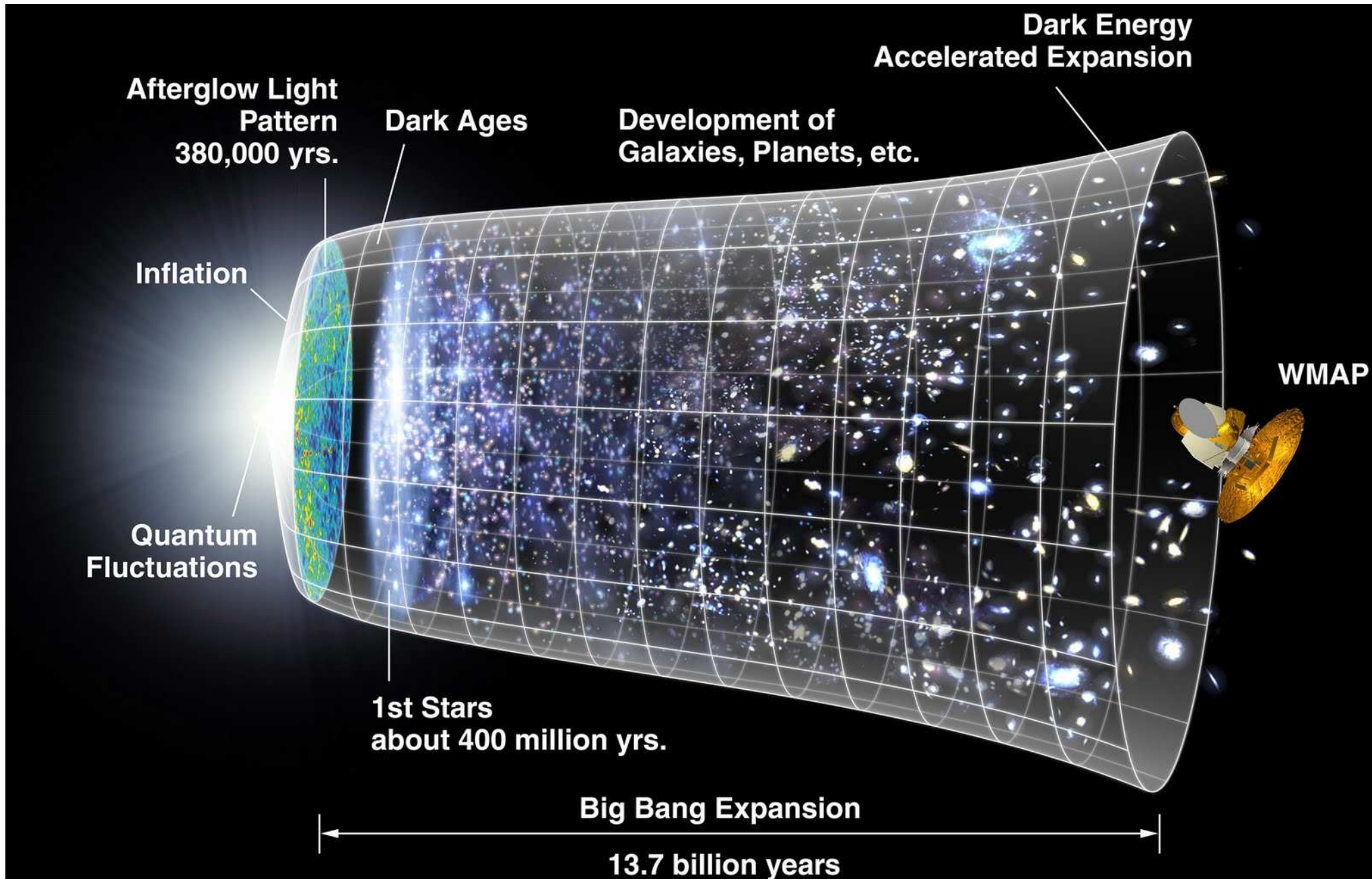
The landscape of QCD matter: The future is now



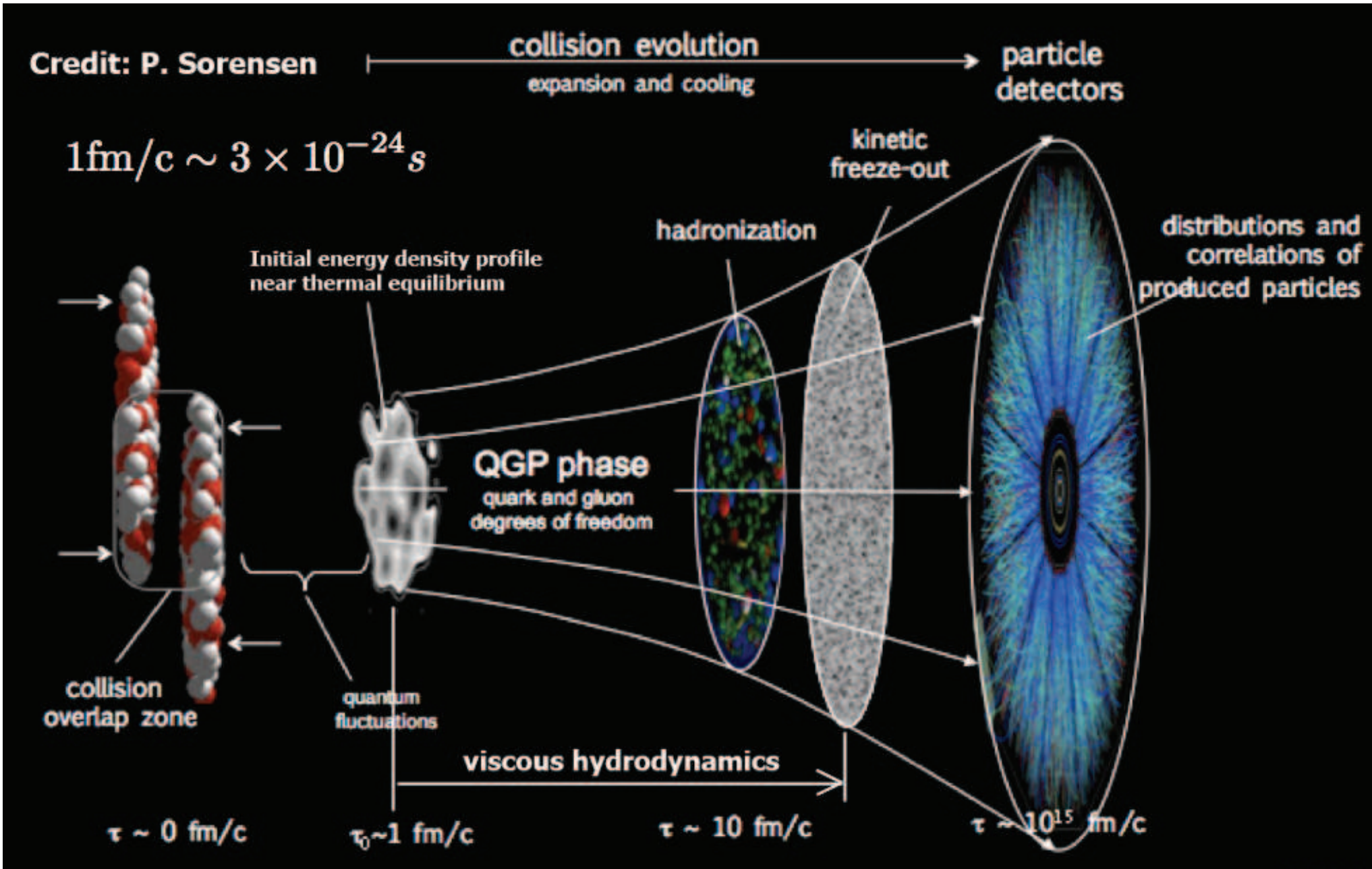
Probes:

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

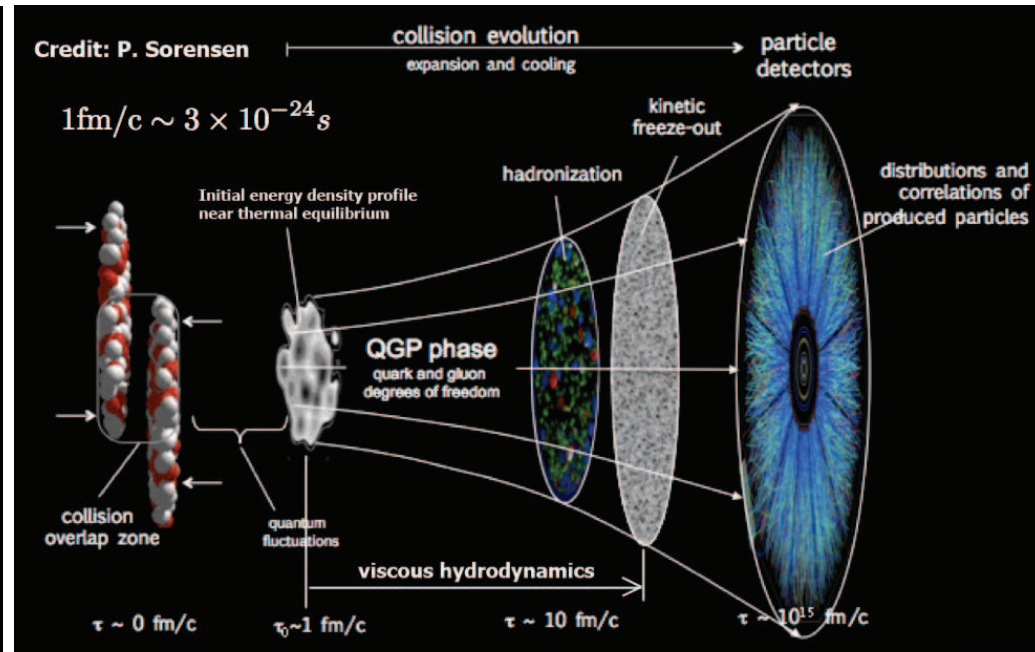
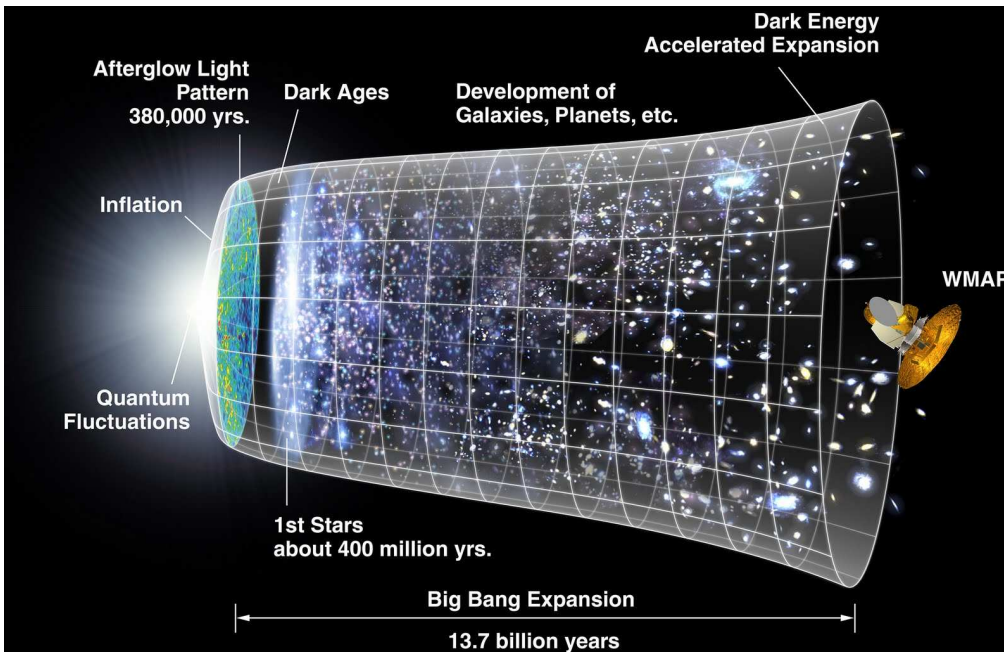
The Big Bang



The Little Bang



Big Bang vs. Little Bang



Similarities: Hubble-like expansion, expansion-driven dynamical freeze-out
 chemical freeze-out (nucleo-/hadrosynthesis) before thermal freeze-out (CMB, hadron p_T -spectra)
 initial-state quantum fluctuations imprinted on final state

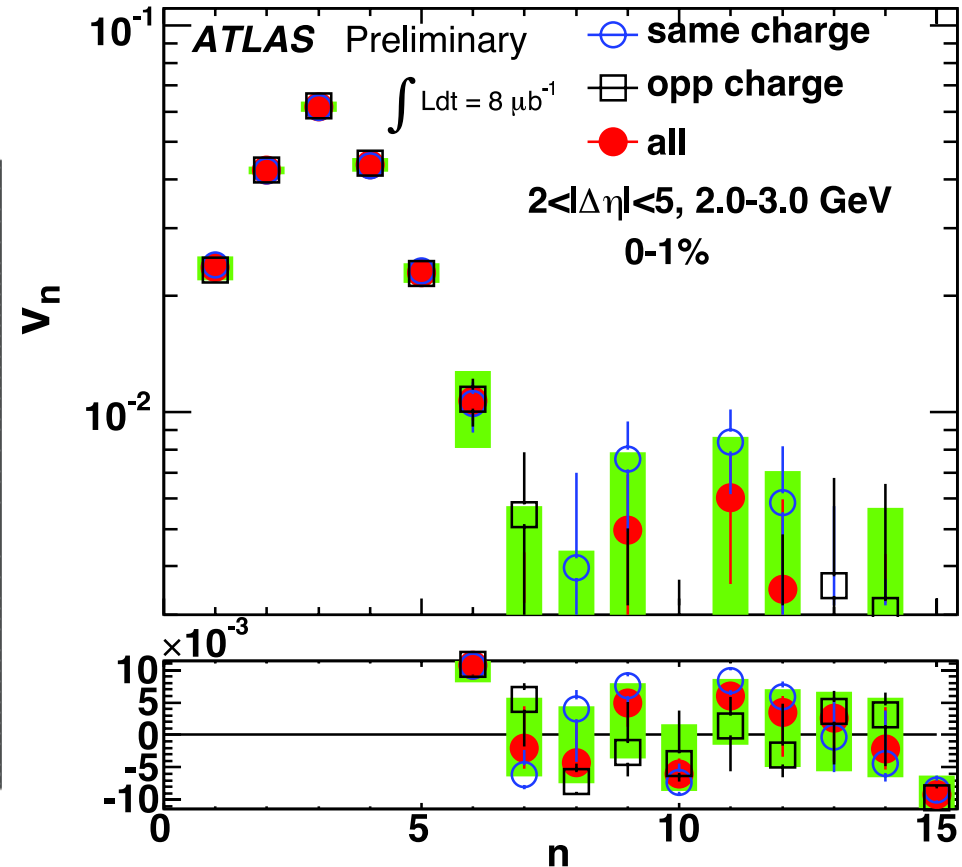
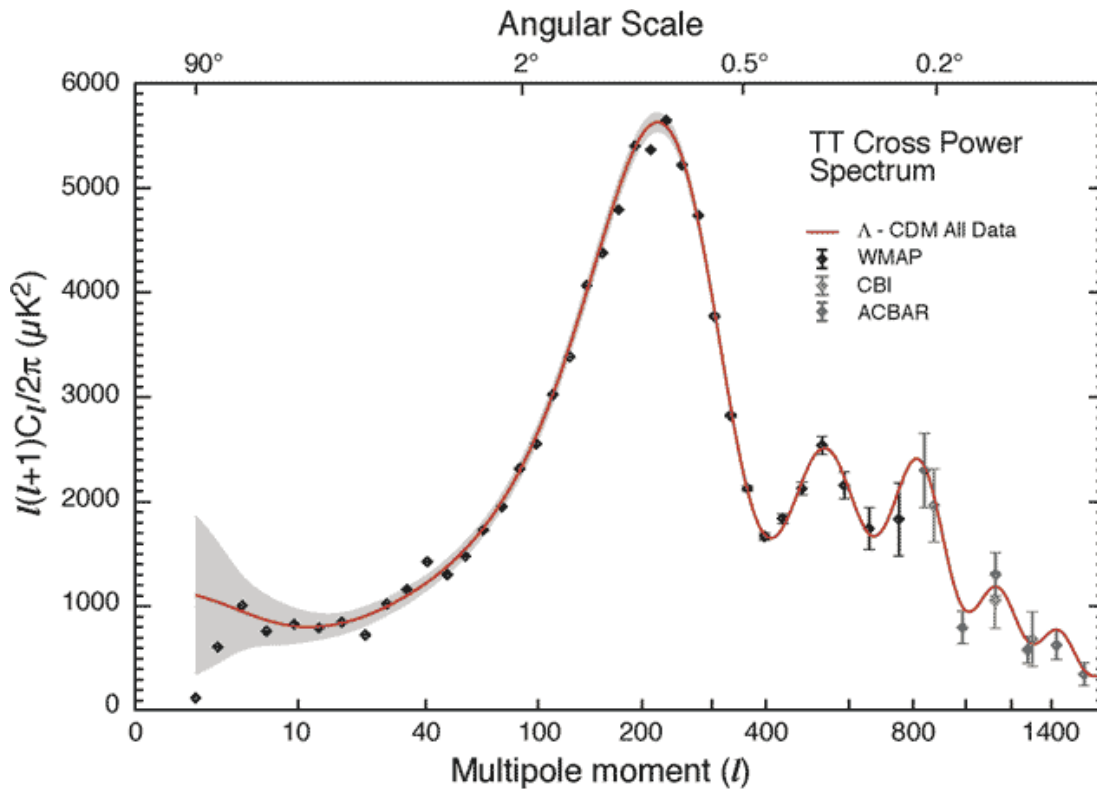
Differences: Expansion rates differ by 18 orders of magnitude
 Expansion in 3d, not 4d; driven by pressure gradients, not gravity
 Time scales measured in fm/c rather than billions of years
 Distances measured in fm rather than light years

“Heavy-Ion Standard Model” still under construction \implies **this talk**

Big vs. Little Bang: The fluctuation power spectrum

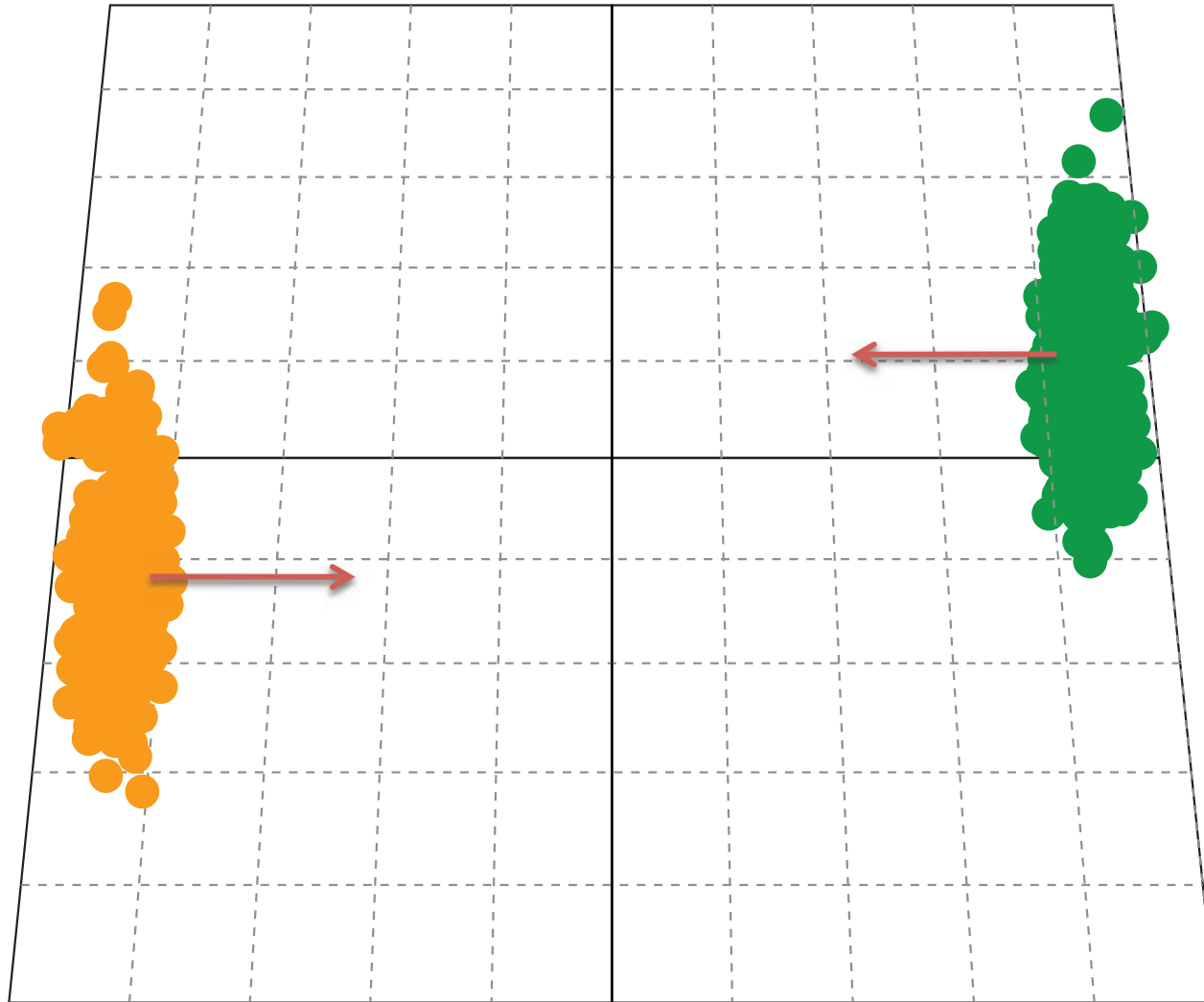
Mishra, Mohapatra, Saumia, Srivastava, PRC77 (2008) 064902 and C81 (2010) 034903

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



Relativistic Nucleus-Nucleus Collisions

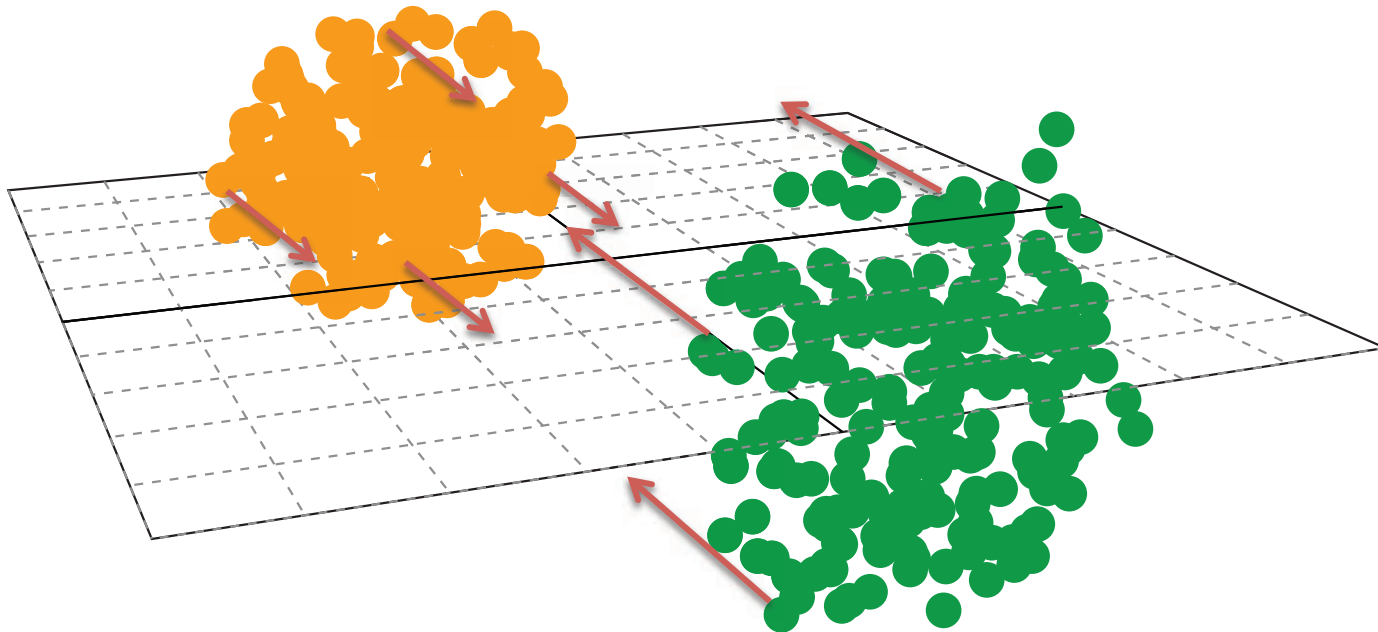
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

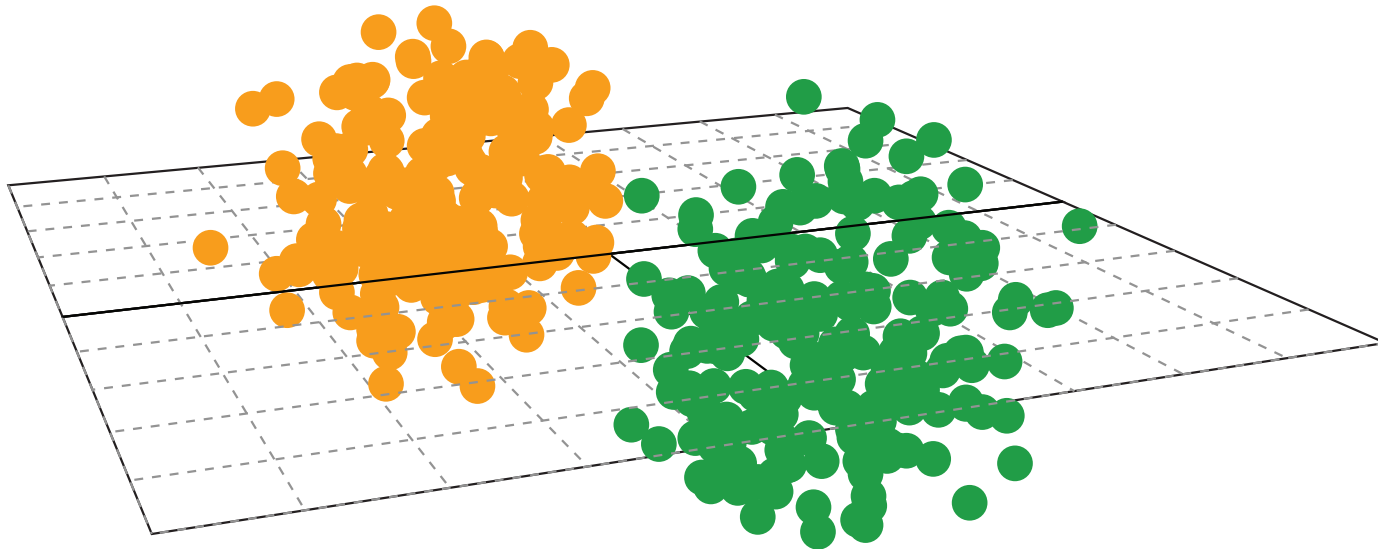
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

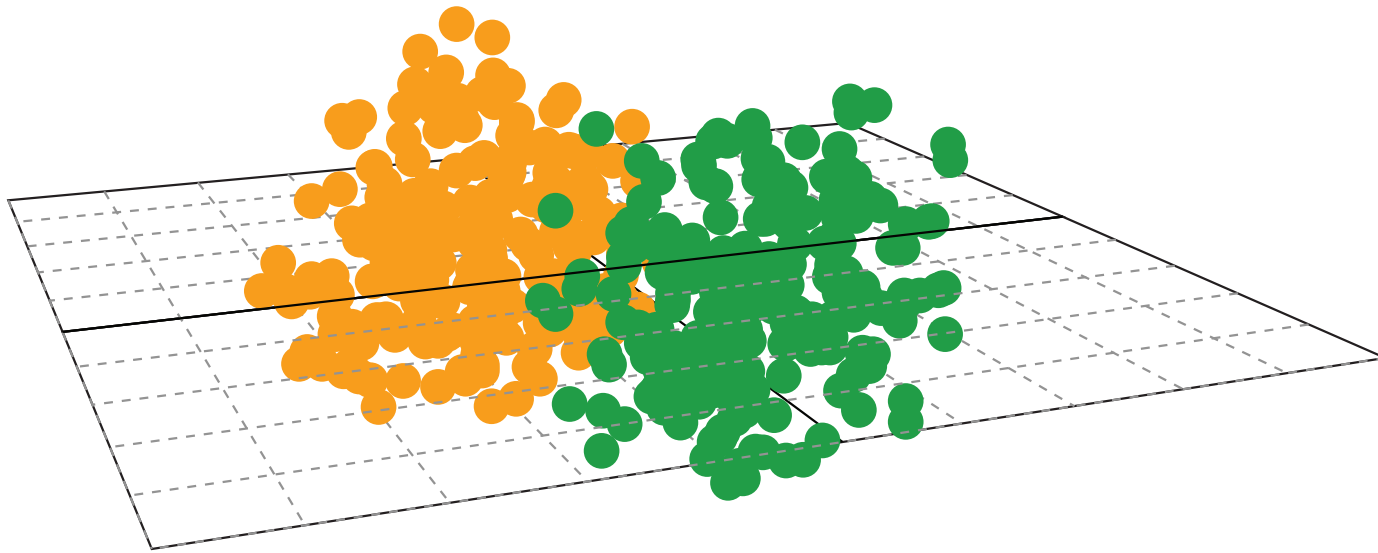
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

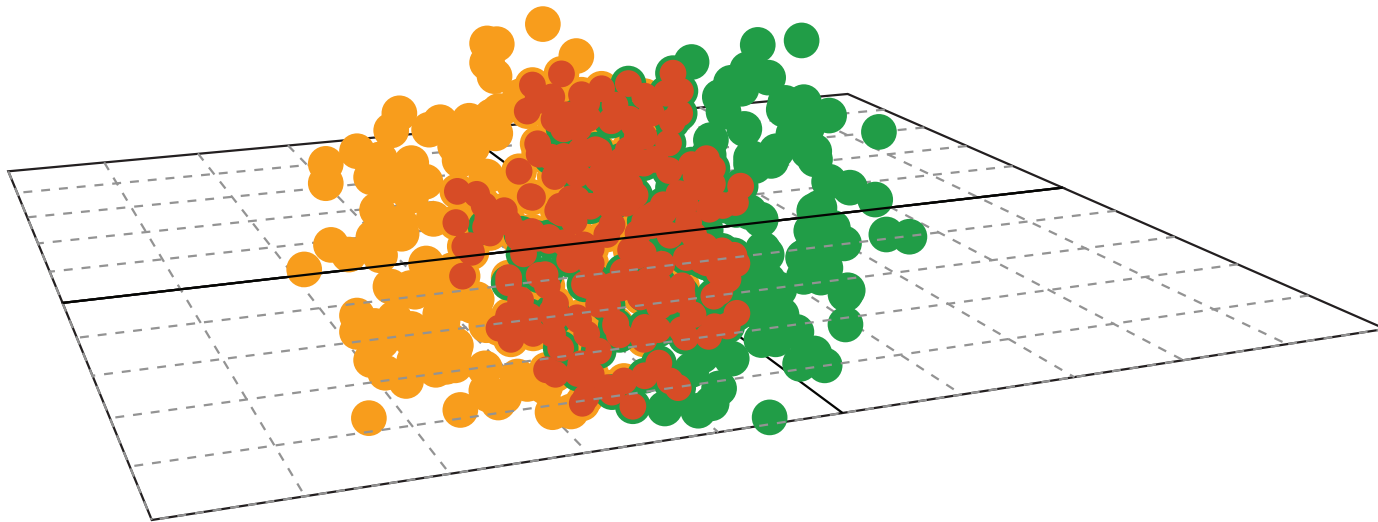
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

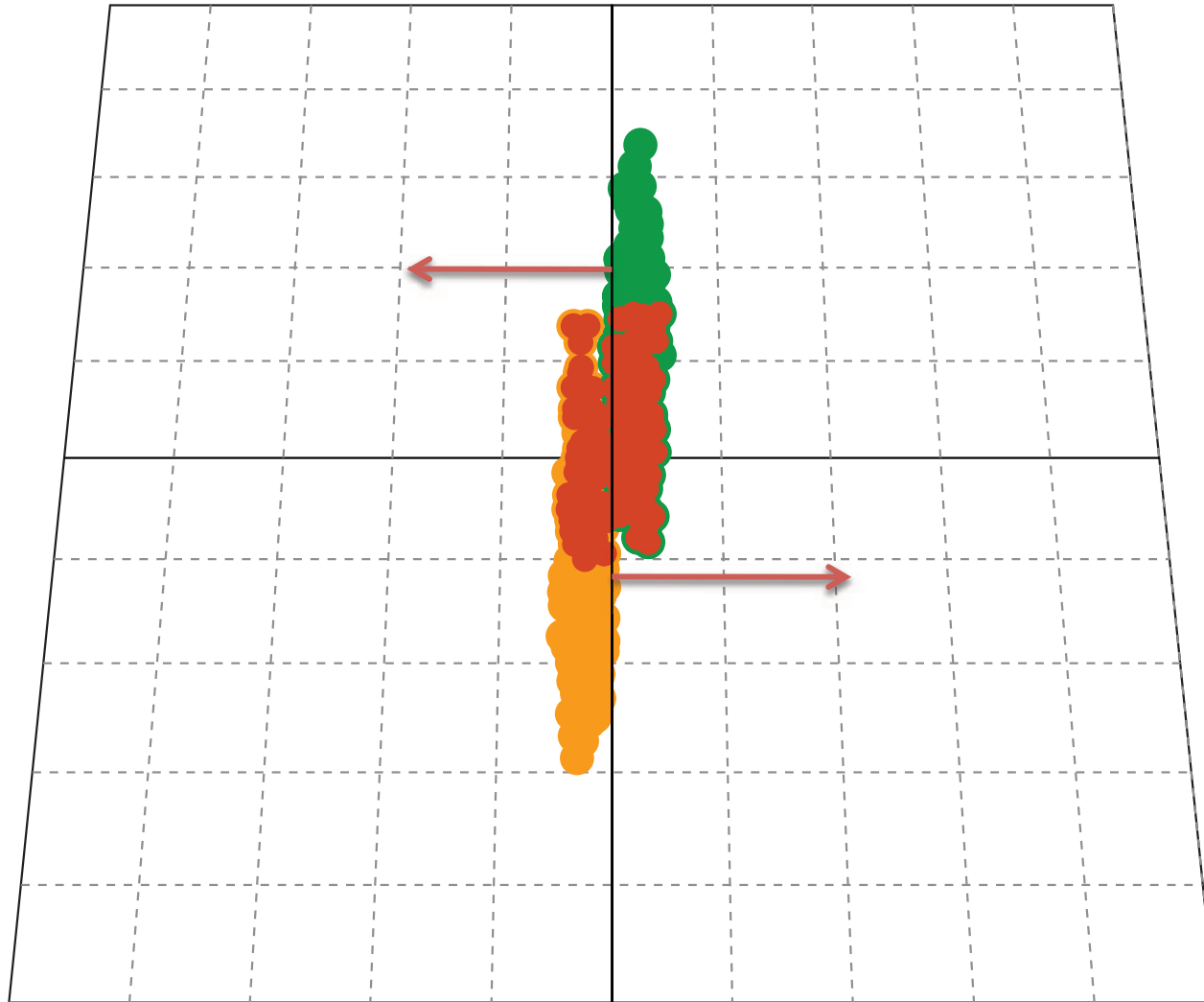
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

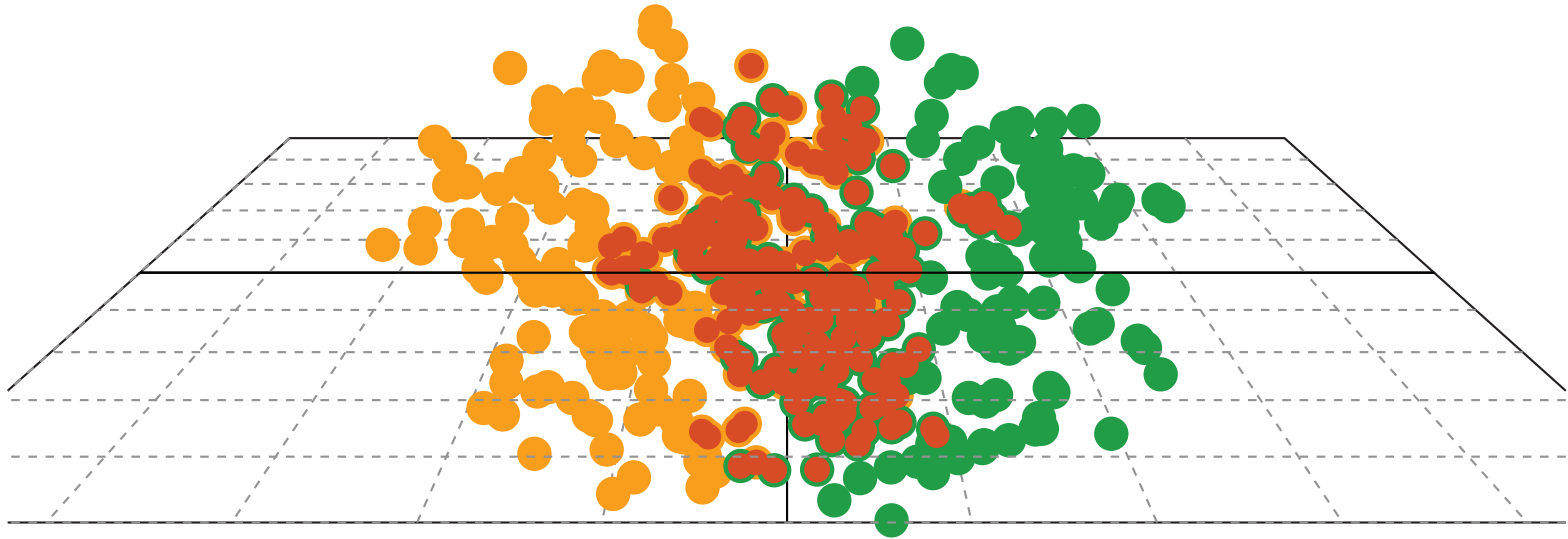
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

Animation: P. Sorensen

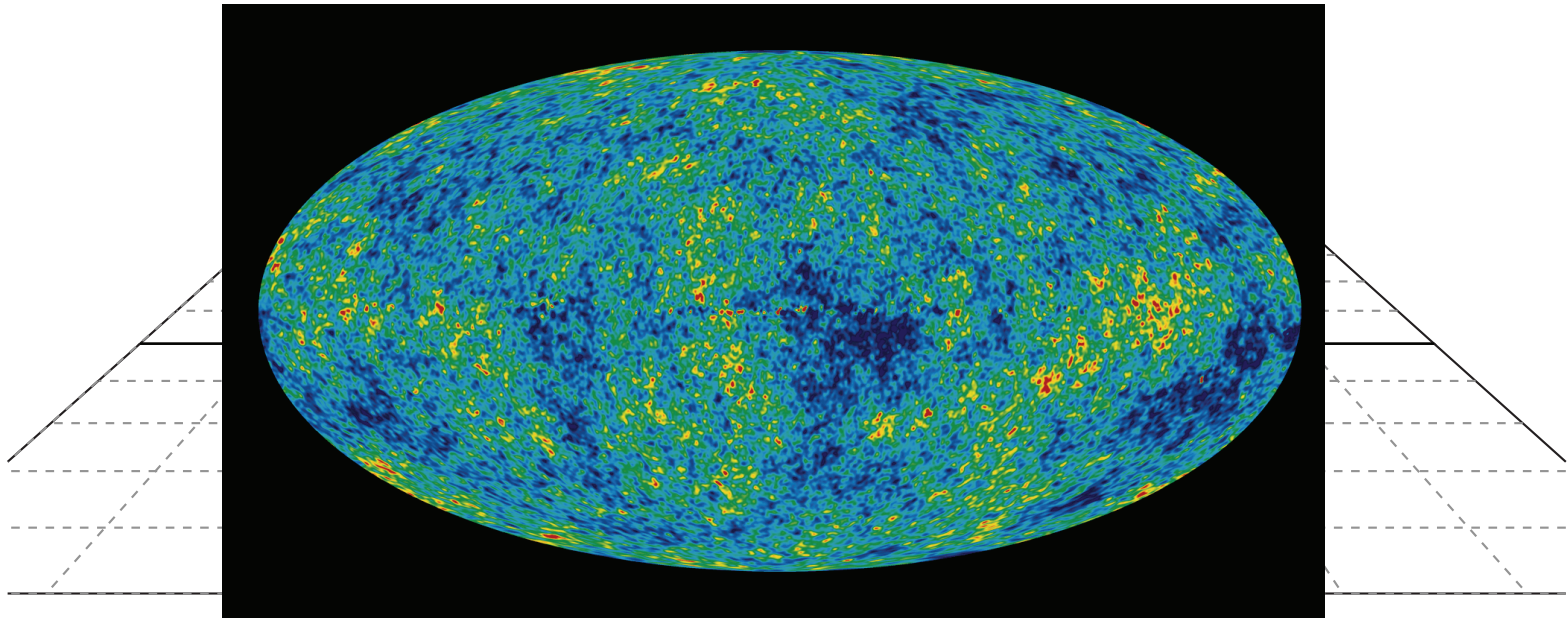


Produced fireball is $\sim 10^{-14}$ meters across
and lives for $\sim 5 \times 10^{-23}$ seconds

Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

Animation: P. Sorensen

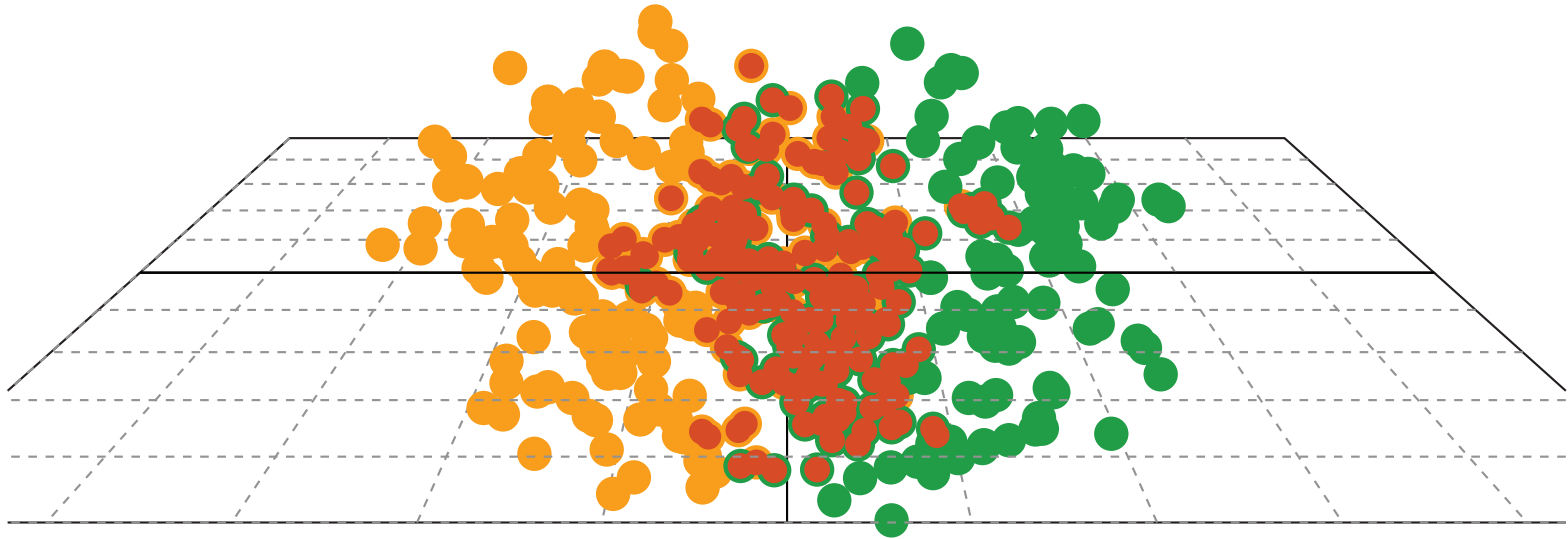


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Relativistic Nucleus-Nucleus Collisions

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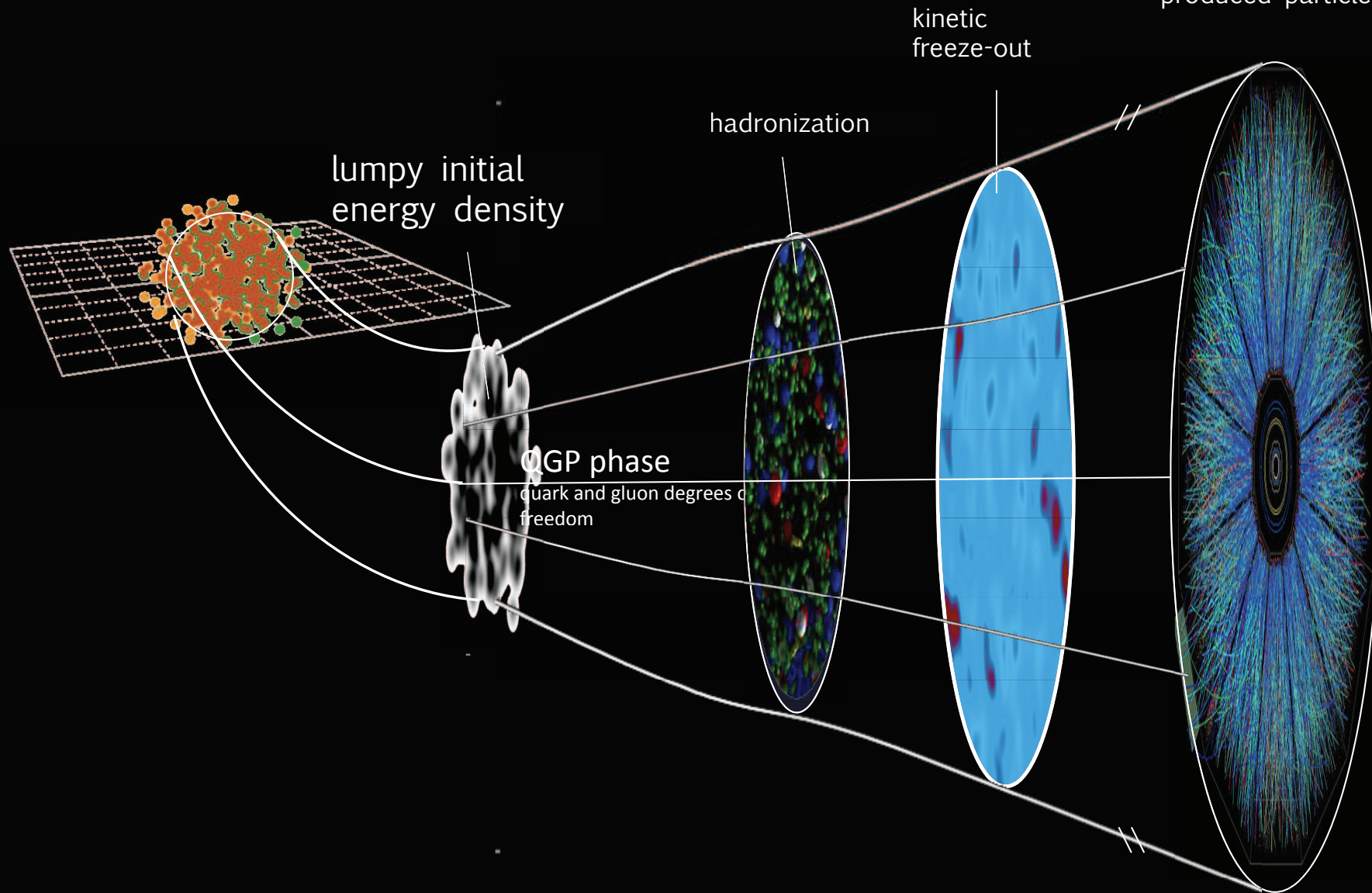


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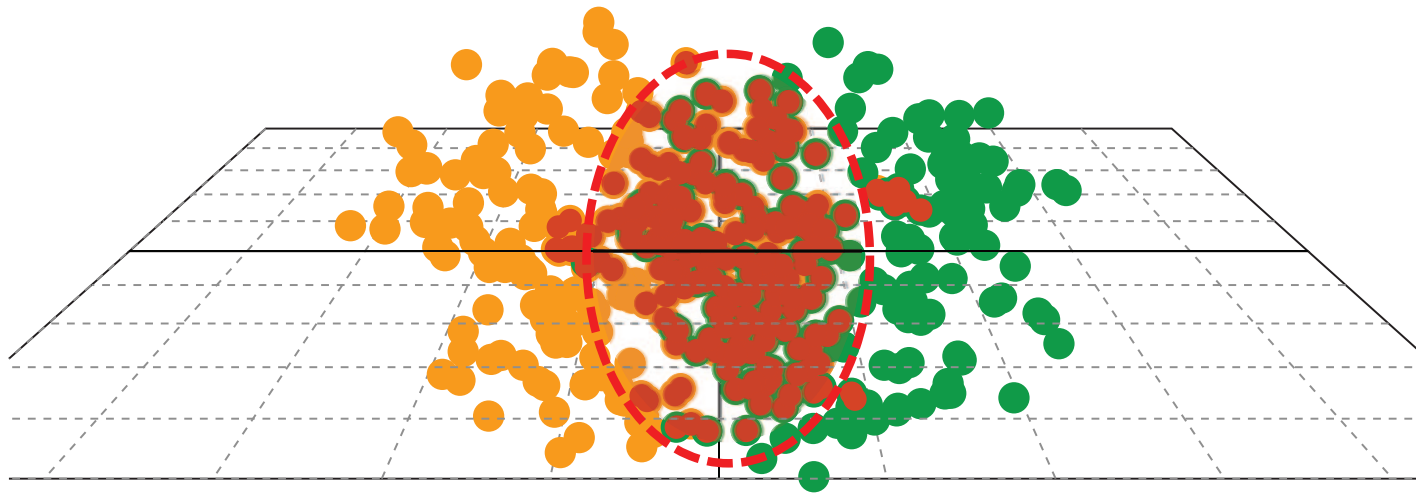
Collision of two Lorentz contracted gold nuclei

Expansion of the Little Bang

distributions and correlations of produced particles



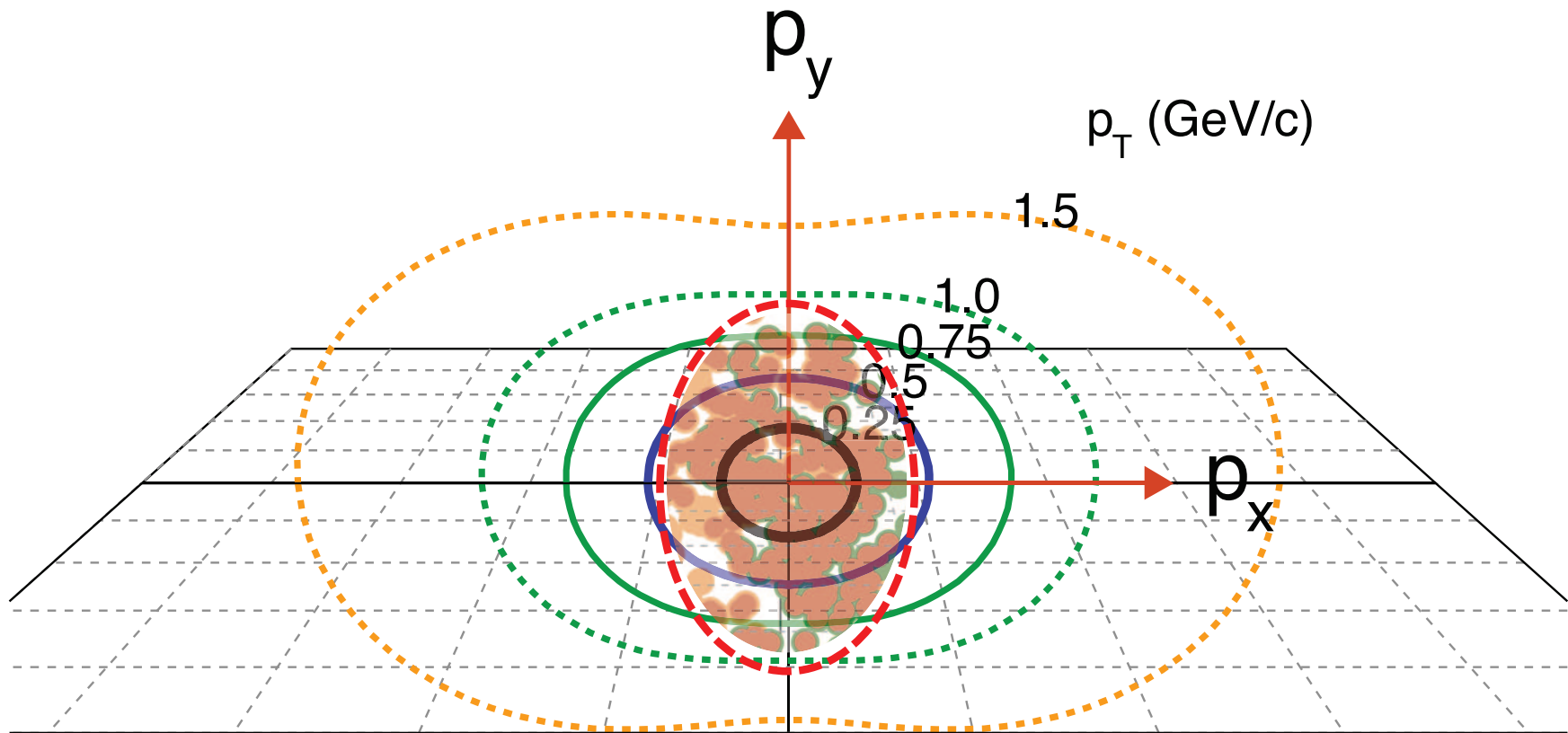
Azimuthal Distributions: x-space



Are particles emitted at random angles?

No. They remember the initial geometry!

Azimuthal Distributions: p-space



Are particles emitted at random angles?

No. They remember the initial geometry!

“The Little Bang”

The Movie

**Featuring the QGP in one of its
finest performances**

Producer: Chun Shen

How anisotropic flow is measured:

Definition of flow coefficients:

$$\frac{dN^{(i)}}{dy p_T dp_T d\phi_p}(b) = \frac{dN^{(i)}}{dy p_T dp_T}(b) \left(1 + 2 \sum_{n=1}^{\infty} v_n^{(i)}(\mathbf{y}, \mathbf{p}_T; \mathbf{b}) \cos(\phi_p - \Psi_n^{(i)}) \right).$$

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

Flow coefficients v_n typically extracted from azimuthal correlations (k -particle cumulants). E.g. $k = 2, 4$:

$$c_n\{2\} = \langle \{e^{ni(\phi_1 - \phi_2)}\} \rangle = \langle \{e^{ni(\phi_1 - \psi_n)}\} \{e^{-ni(\phi_2 - \psi_n)}\} + \delta_2 \rangle = \langle v_n^2 + \delta_2 \rangle$$

$$c_n\{4\} = \langle \{e^{ni(\phi_1 + \phi_2 - \phi_3 - \phi_4)}\} \rangle - 2 \langle \{e^{ni(\phi_1 - \phi_2)}\} \rangle = \langle -v_n^4 + \delta_4 \rangle$$

v_n is correlated with the event plane while δ_n is not (“non-flow”). $\delta_2 \sim 1/M$, $\delta_4 \sim 1/M^3$.
4th-order cumulant is free of 2-particle non-flow correlations.

These measures are affected by event-by-event flow fluctuations:

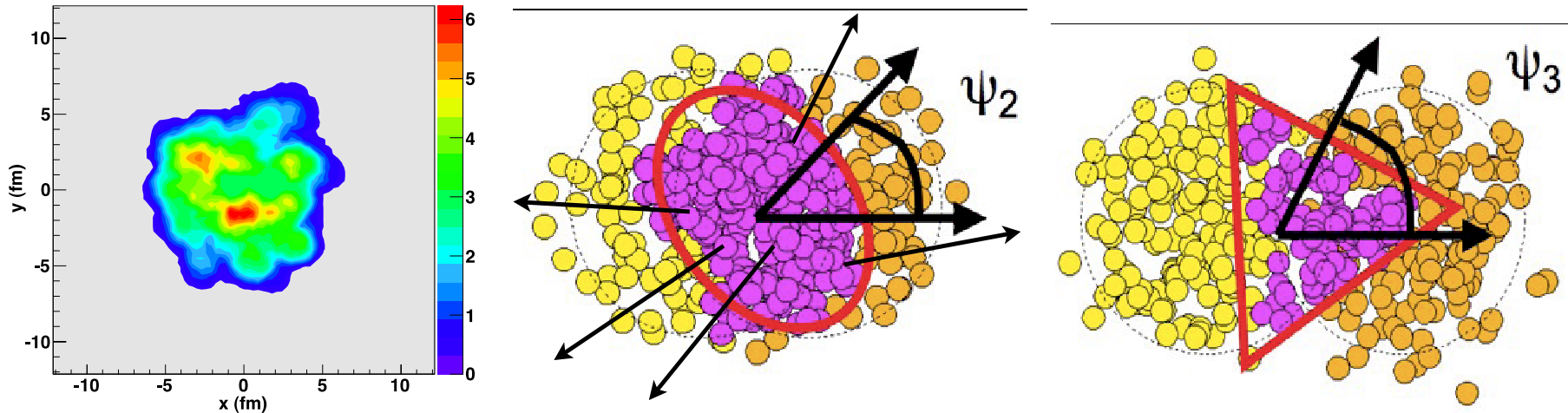
$$\langle v_2^2 \rangle = \langle v_2 \rangle^2 + \sigma^2, \quad \langle v_2^4 \rangle = \langle v_2 \rangle^4 + 6\sigma^2 \langle v_2 \rangle^2$$

$v_n\{k\}$ denotes the value of v_n extracted from the k^{th} -order cumulant:

$$v_2\{2\} = \sqrt{\langle v_2^2 \rangle}, \quad v_2\{4\} = \sqrt[4]{2\langle v_2^2 \rangle^2 - \langle v_2^4 \rangle}$$

Event-by-event shape and flow fluctuations rule!

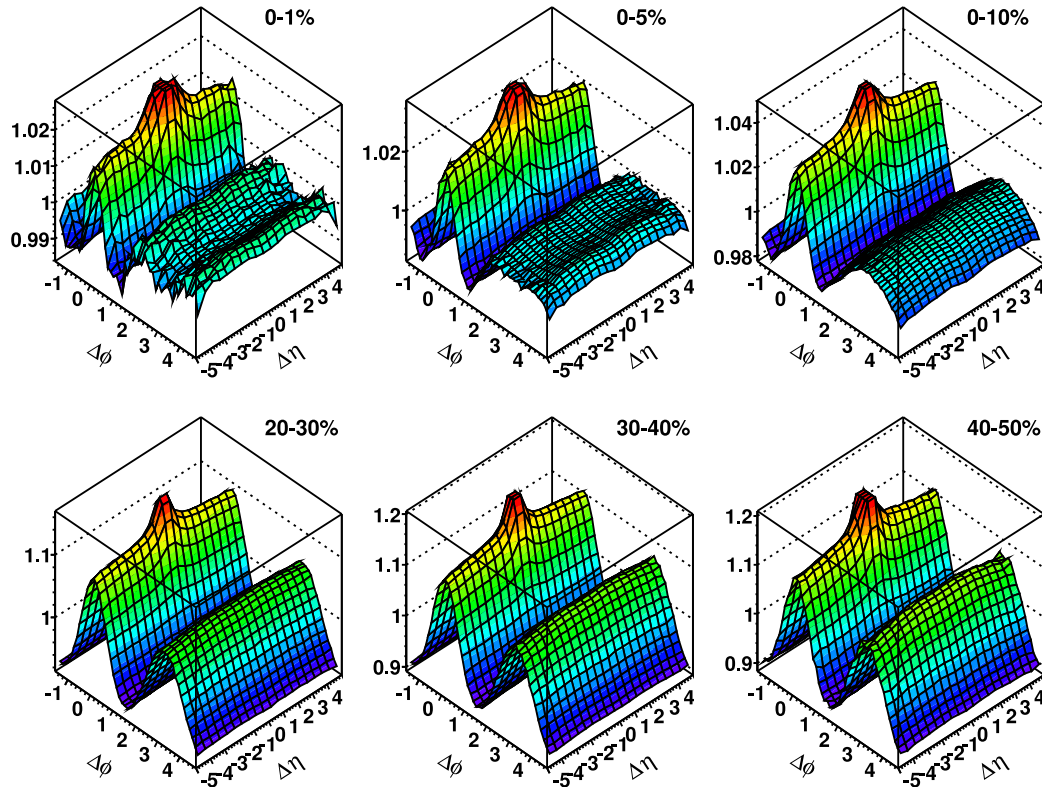
(Alver and Roland, PRC81 (2010) 054905)



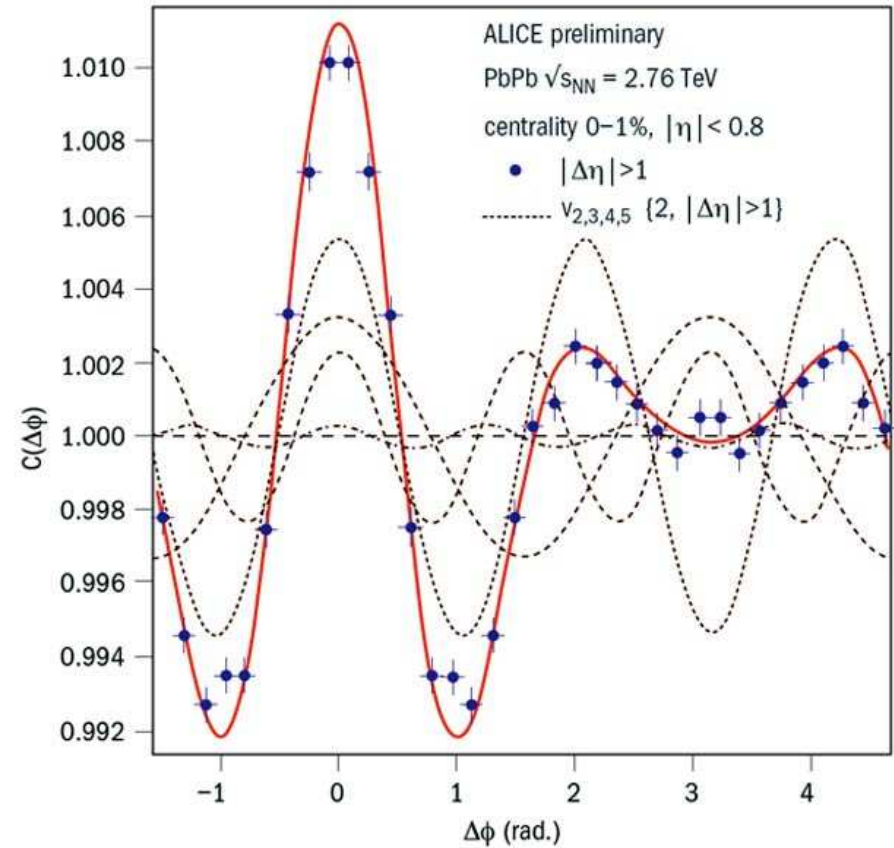
- Each event has a different initial shape and density distribution, characterized by different set of harmonic eccentricity coefficients ε_n
- Each event develops its individual hydrodynamic flow, characterized by a set of harmonic flow coefficients v_n and flow angles ψ_n
- At small impact parameters fluctuations (“hot spots”) dominate over geometric overlap effects
(Alver & Roland, PRC81 (2010) 054905; Qin, Petersen, Bass, Müller, PRC82 (2010) 064903)

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

ATLAS (J. Jia), Quark Matter 2011

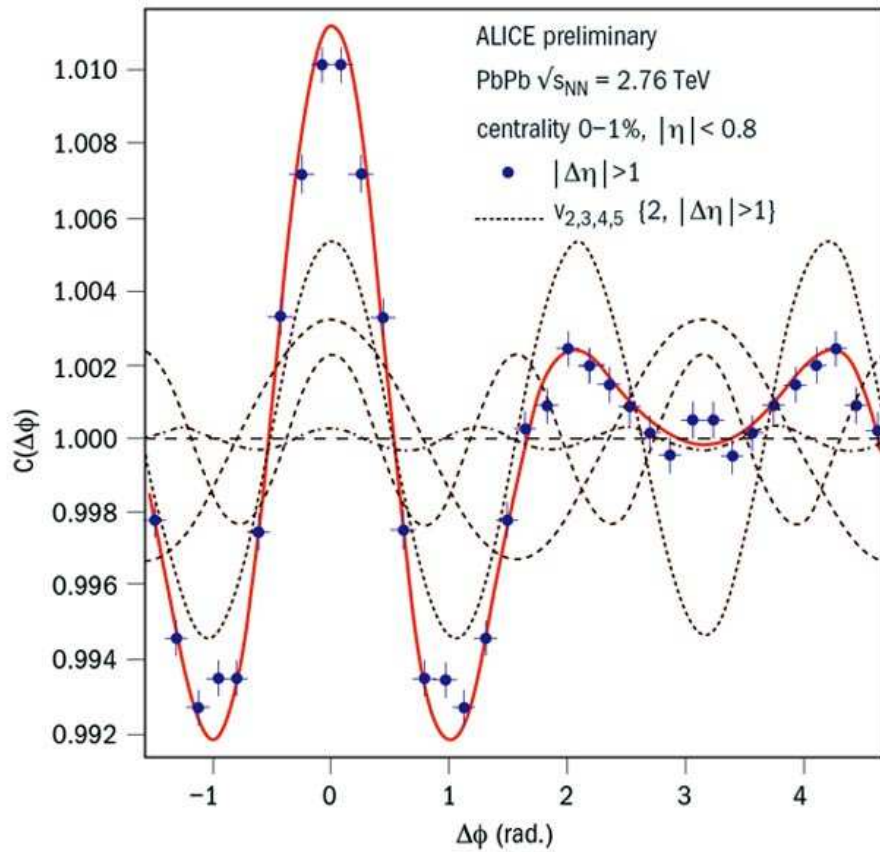


ALICE (J. Grosse-Oetringhaus), QM11

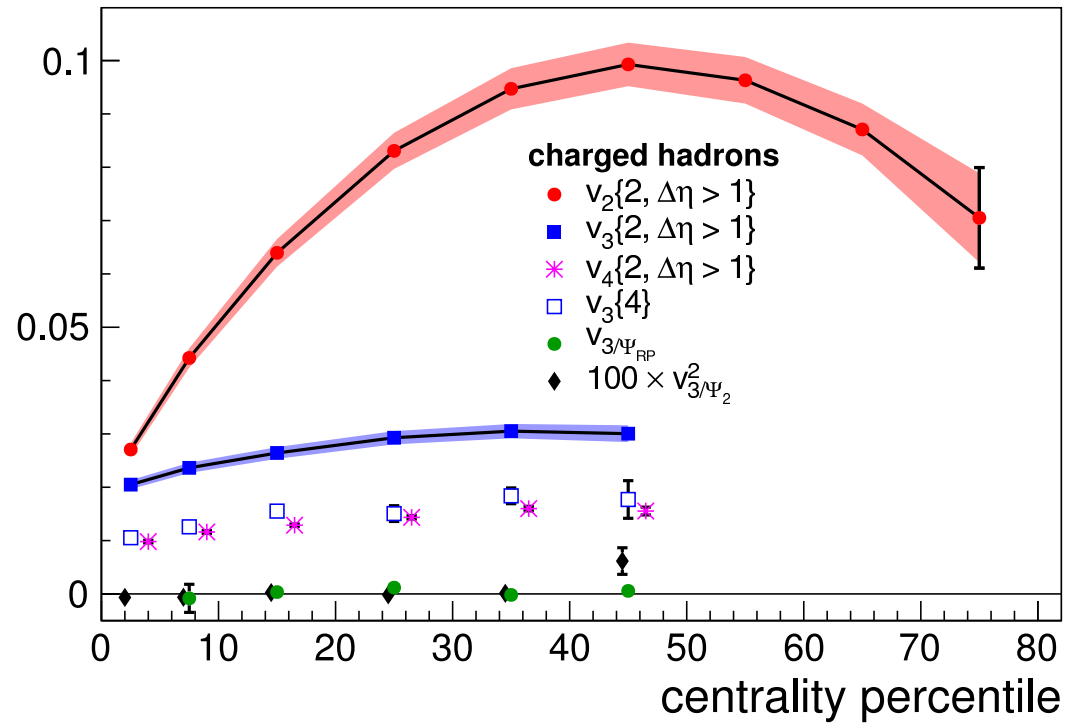


- anisotropic flow coefficients v_n and flow angles ψ_n correlated over large rapidity range!
M. Luzum, PLB 696 (2011) 499: All long-range rapidity correlations seen at RHIC are consistent with being entirely generated by hydrodynamic flow.
- in the 1% most central collisions $v_3 > v_2$
 - ⇒ prominent “Mach cone”-like structure!
 - ⇒ event-by-event eccentricity fluctuations dominate!

Event-by-event shape and flow fluctuations rule!



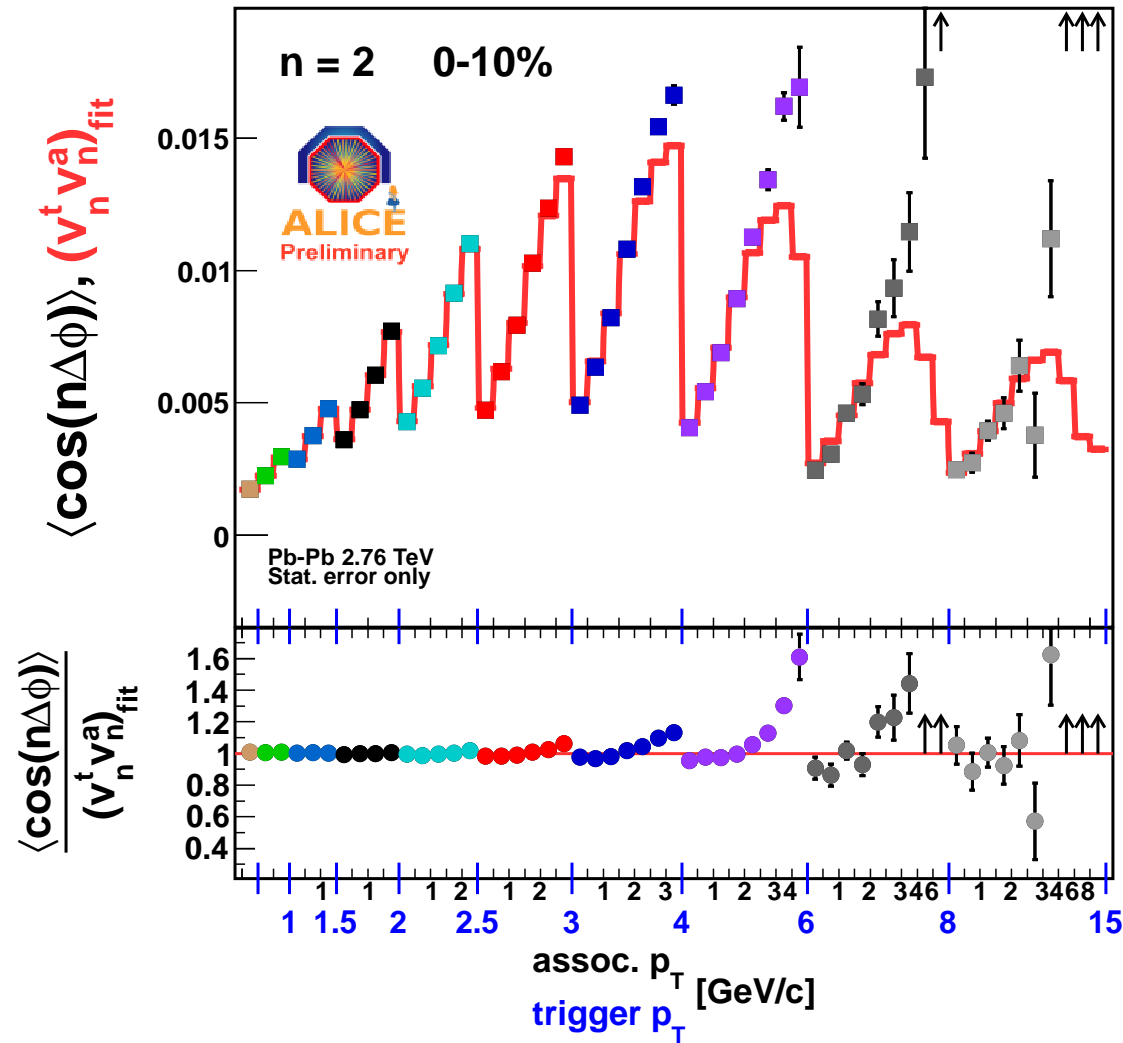
ALICE (A. Bilandzic) Quark Matter 2011



- in the 1% most central collisions $v_3 > v_2 \implies$ prominent “Mach cone”-like structure!
- triangular flow angle uncorrelated with reaction plane and elliptic flow angles
 \implies 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 $p_{T1}, p_{T2} < 3 \text{ GeV}/c$ (bulk matter)

Converting initial shape
fluctuations into
final flow anisotropies –
the QGP shear viscosity

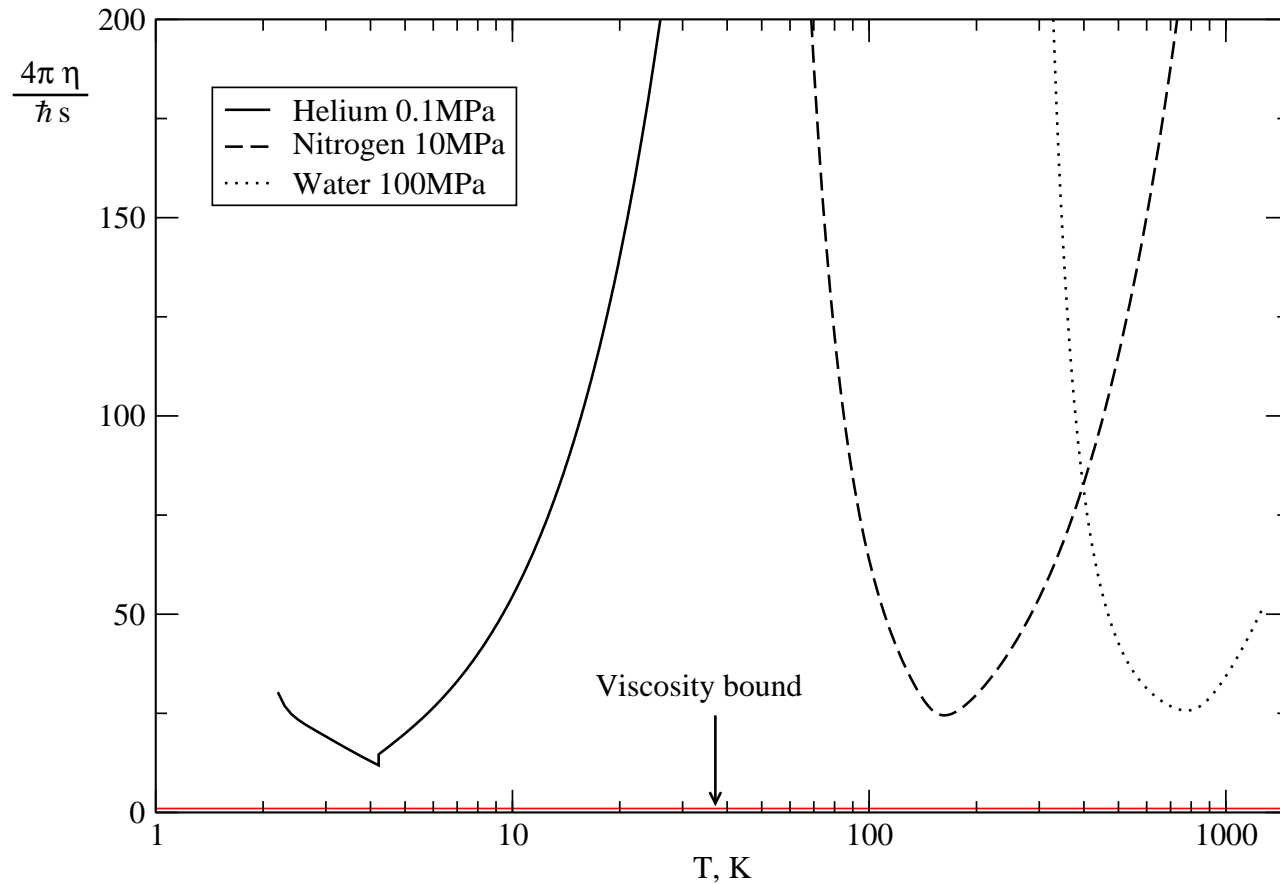
$$(\eta/s)_{\text{QGP}}$$

QGP – the most ideal fluid ever observed!

AdS/CFT universal lower viscosity bound conjecture:

$$\frac{\eta}{s} \gtrsim \frac{\hbar}{4\pi k_B}$$

Kovtun, Son, Starinets, PRL 94 (2005) 111601



Will show that the QGP viscosity is close to this bound!

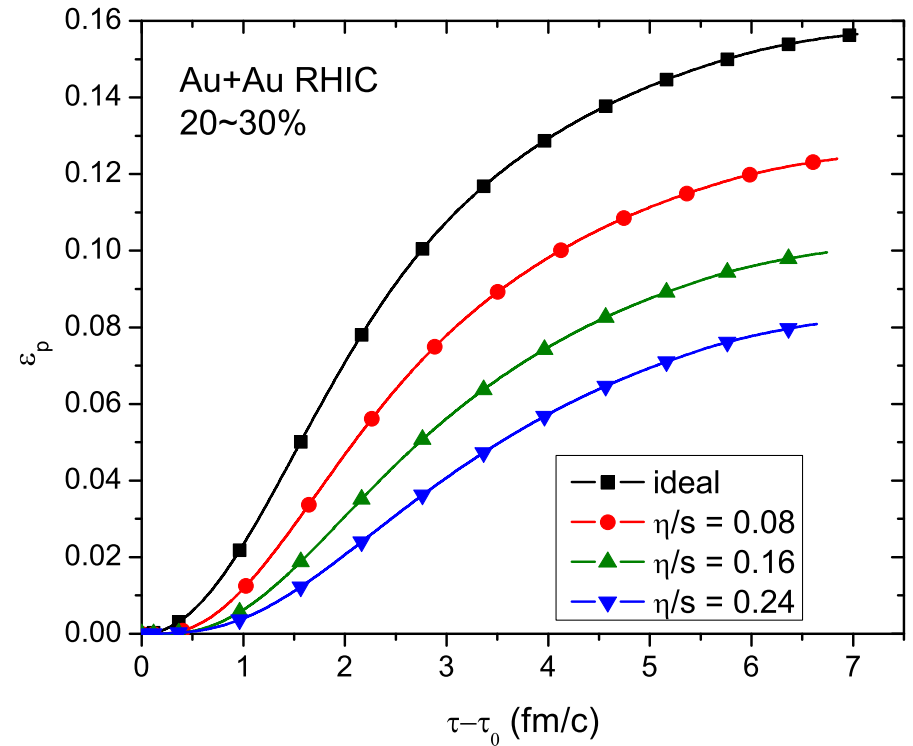
How to use elliptic flow for measuring $(\eta/s)_{\text{QGP}}$

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

Shear viscosity degrades conversion efficiency

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

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}** :

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

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

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

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

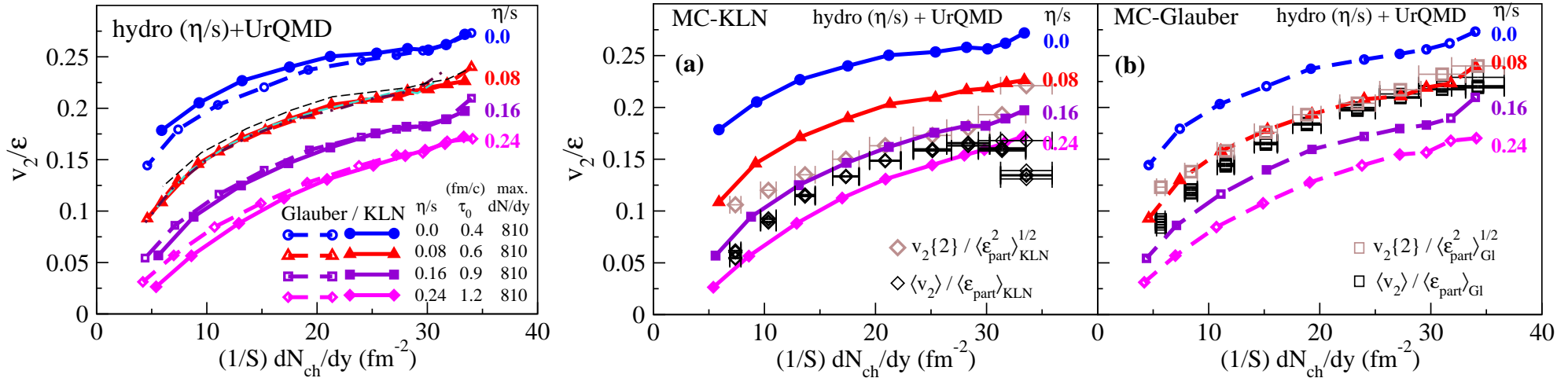
\Rightarrow need hybrid code that couples viscous hydrodynamic evolution of QGP to **realistic microscopic dynamics** of late-stage hadron gas phase

\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 $(\eta/s)_{\text{QGP}}$ from AuAu@RHIC

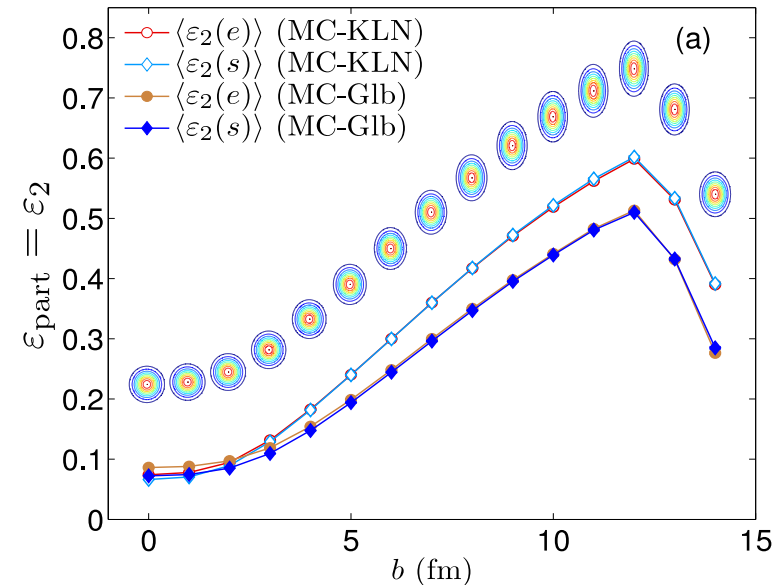
H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRL106 (2011) 192301



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

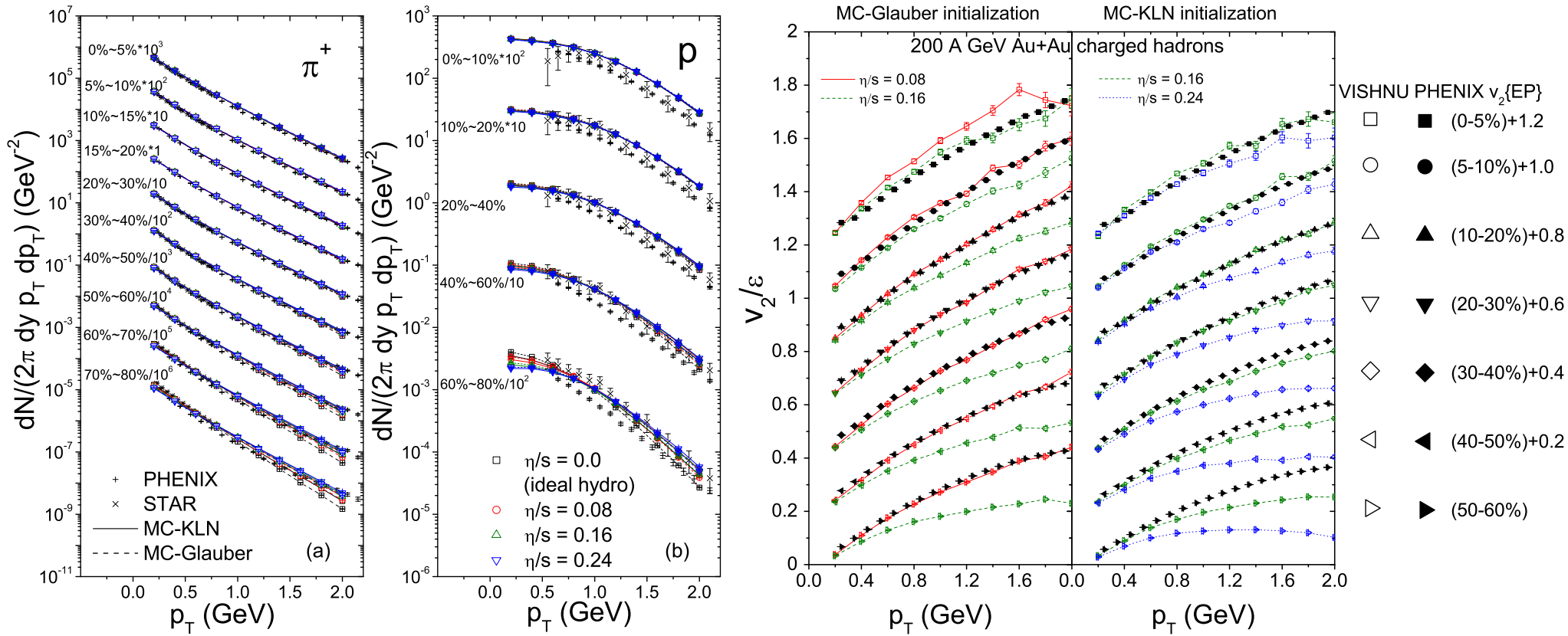
- All shown theoretical curves correspond to parameter sets that correctly describe centrality dependence of charged hadron production as well as p_T -spectra of charged hadrons, pions and protons at all centralities
- $v_2^{\text{ch}}/\epsilon_x$ vs. $(1/S)(dN_{\text{ch}}/dy)$ is “universal”, i.e. depends **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: ϵ_x^{Gl} vs. ϵ_x^{KLN} \rightarrow
- smaller effects: *early flow* \rightarrow increases $\frac{v_2}{\epsilon}$ by \sim few % \rightarrow larger η/s
bulk viscosity \rightarrow affects $v_2^{\text{ch}}(p_T)$, but \approx not v_2^{ch}

Zhi Qiu, UH, PRC84 (2011) 024911



Global description of AuAu@RHIC spectra and v_2

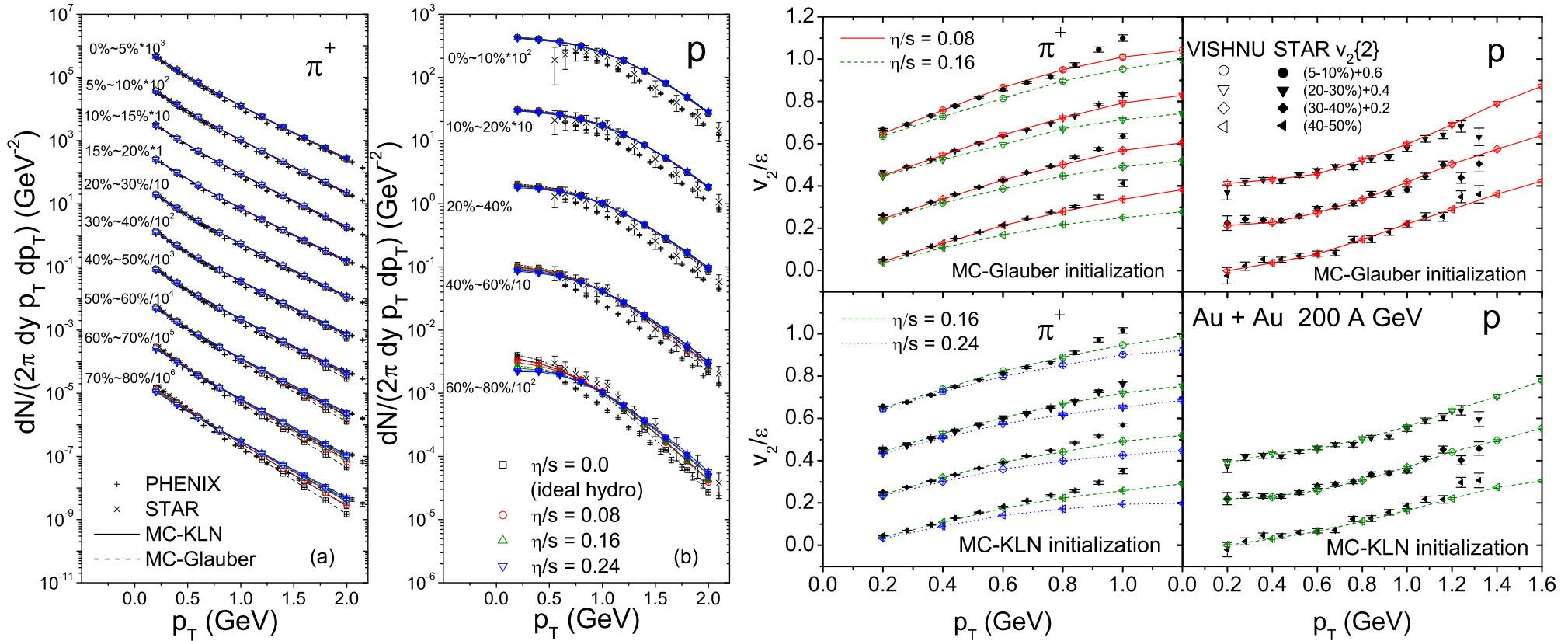
VISHNU (H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRC83 (2011) 054910)



- $(\eta/s)_{QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{QGP} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities
- Note: $T_{chem} = 165$ MeV reproduces the proton spectra from STAR, but not from PHENIX! \implies Slightly incorrect chemical composition in hadronic phase? Not enough $p\bar{p}$ annihilation in UrQMD?

Global description of AuAu@RHIC spectra and v_2

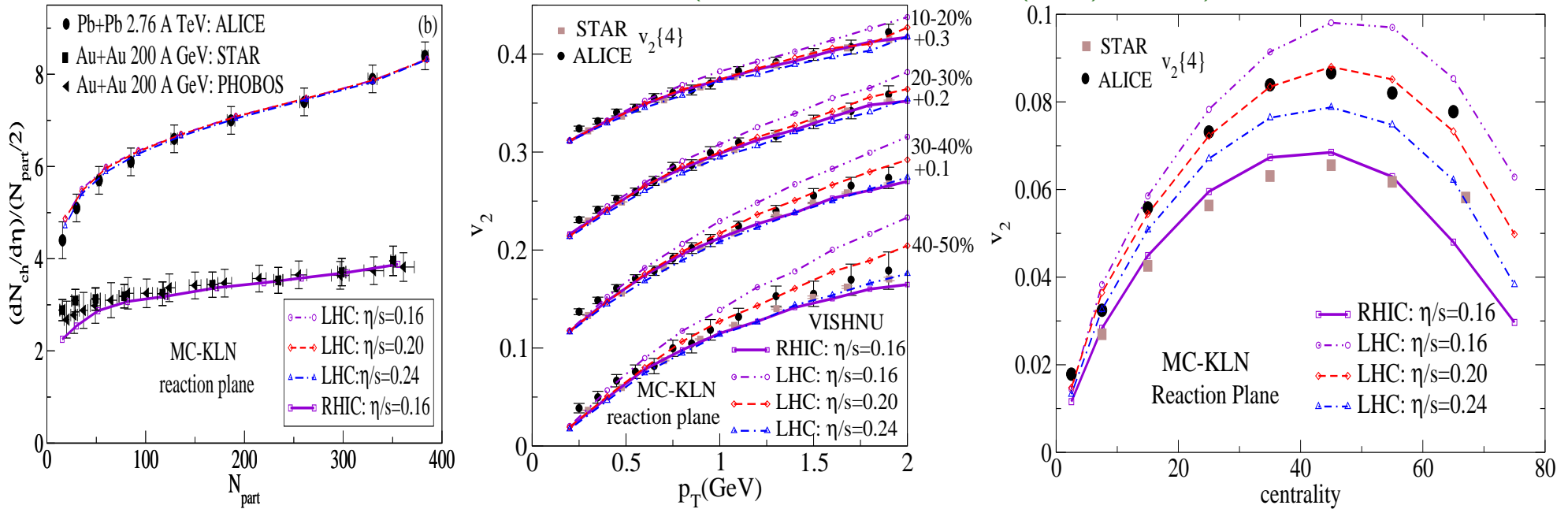
VISHNU (H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRC83 (2011) 054910)



- $(\eta/s)_{\text{QGP}} = 0.08$ for MC-Glauber and $(\eta/s)_{\text{QGP}} = 0.16$ 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 $1.05 \text{ fm}/c$), 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 \implies 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)

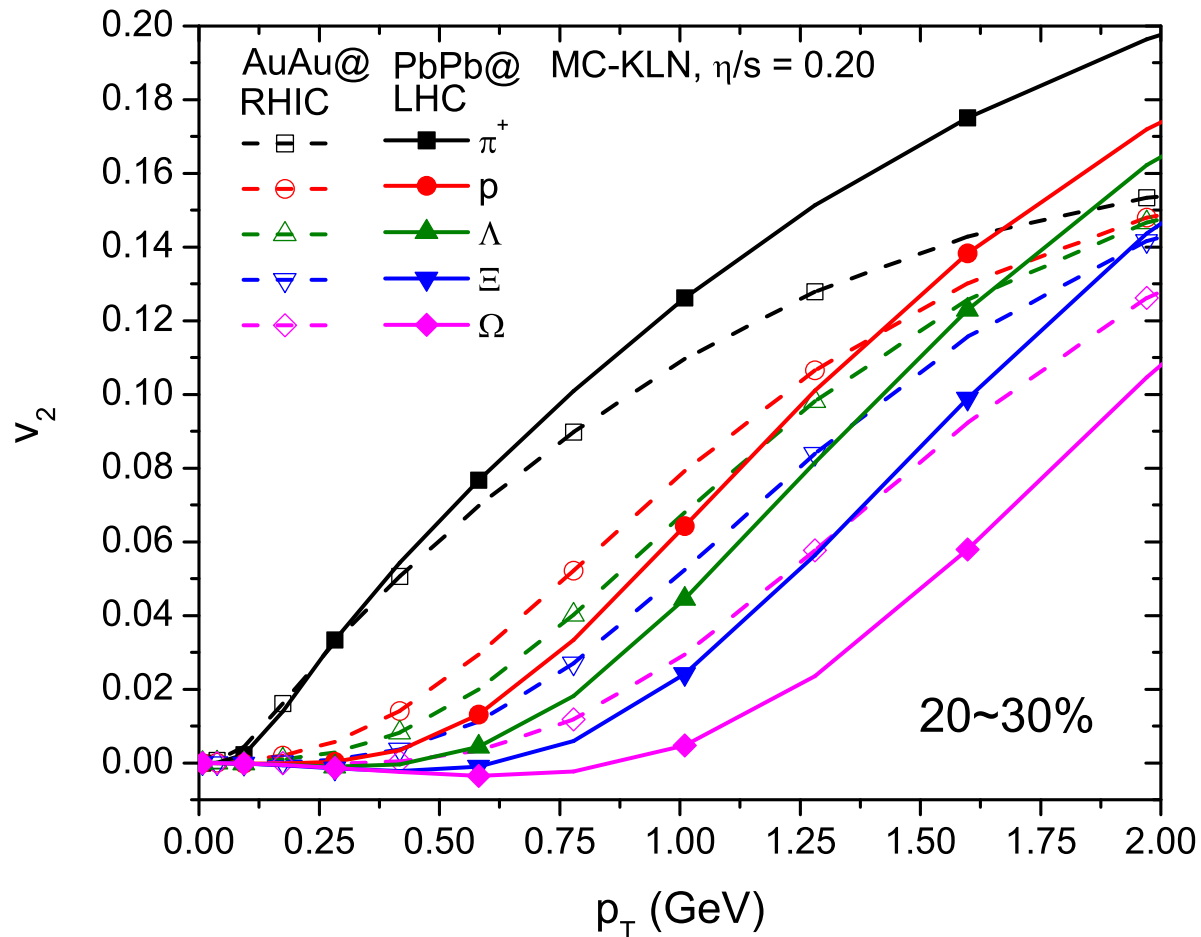


- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of $dN_{ch}/d\eta$ well in both AuAu@RHIC and PbPb@LHC
- $(\eta/s)_{QGP} = 0.16$ for MC-KLN works well for charged hadron $v_2(p_T)$ 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) \implies need pre-equilibrium model.
 \implies **QGP at LHC not much more viscous than at RHIC!**

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

Answer: Pure accident! (Kestin & UH EPJC61 (2009) 545; Shen & UH, PRC85 (2012) 054902)

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



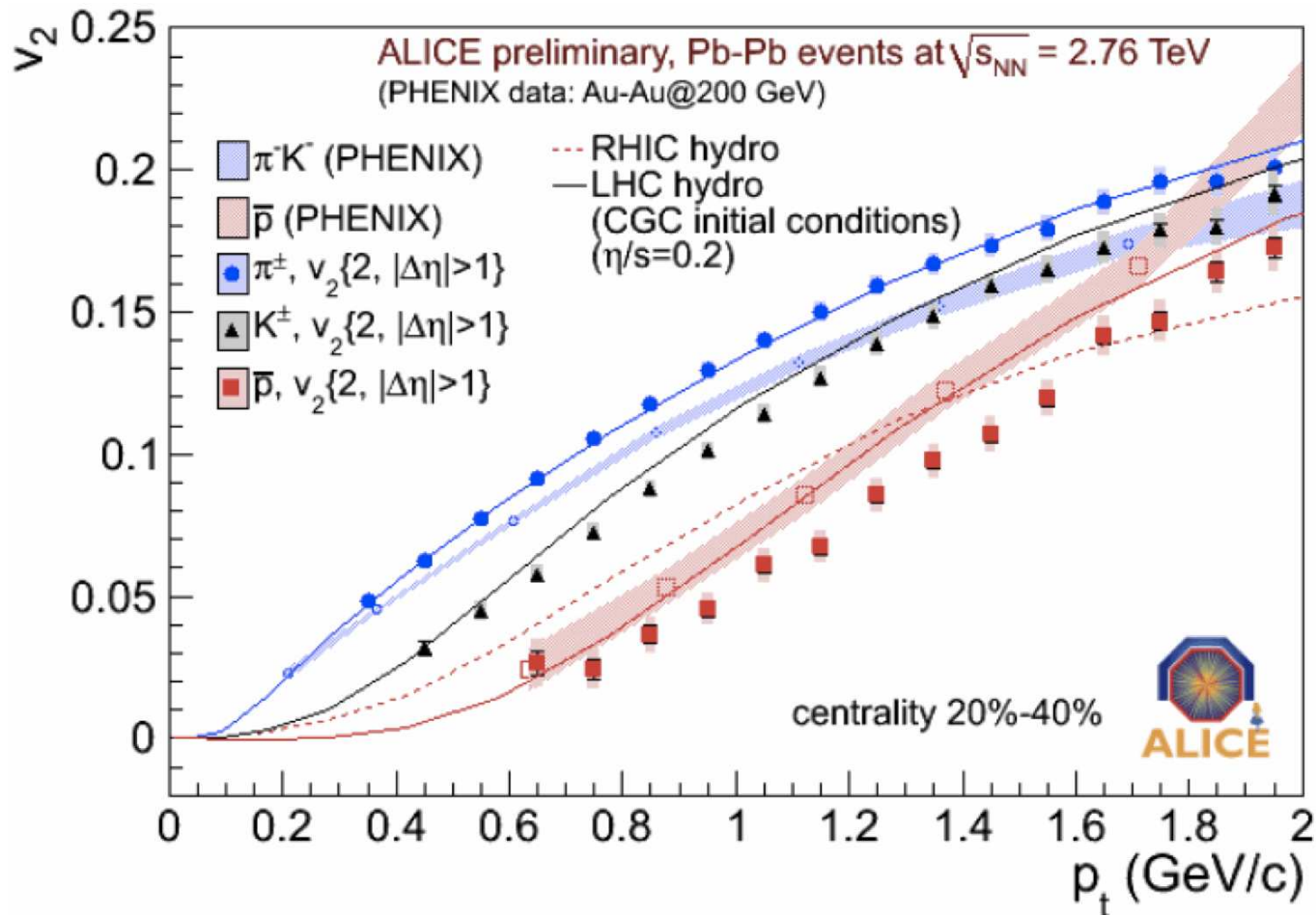
$v_2^\pi(p_T)$ increases a bit from RHIC to LHC, for heavier hadrons $v_2(p_T)$ at fixed p_T decreases (radial flow pushes momentum anisotropy of heavy hadrons to larger p_T)

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, $\eta/s=0.2$)

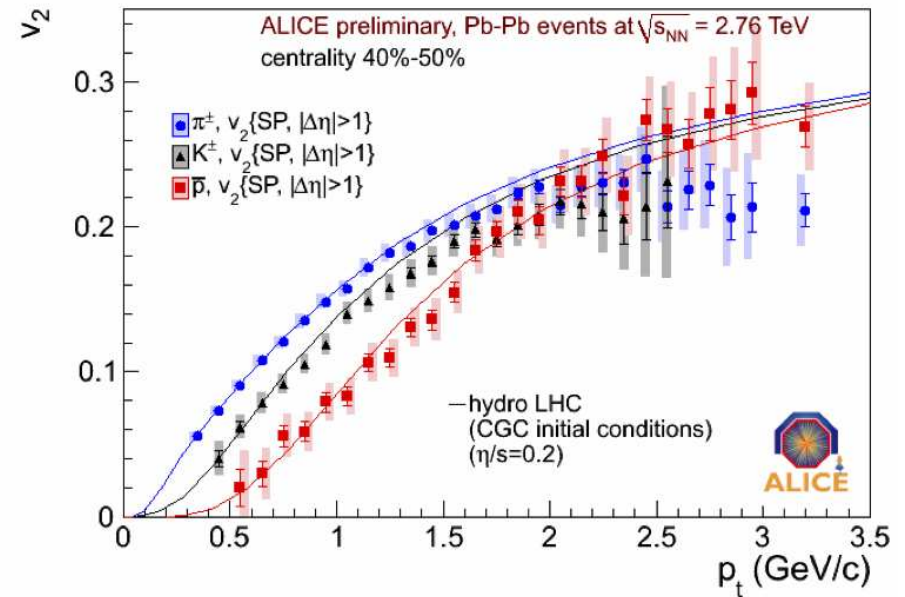
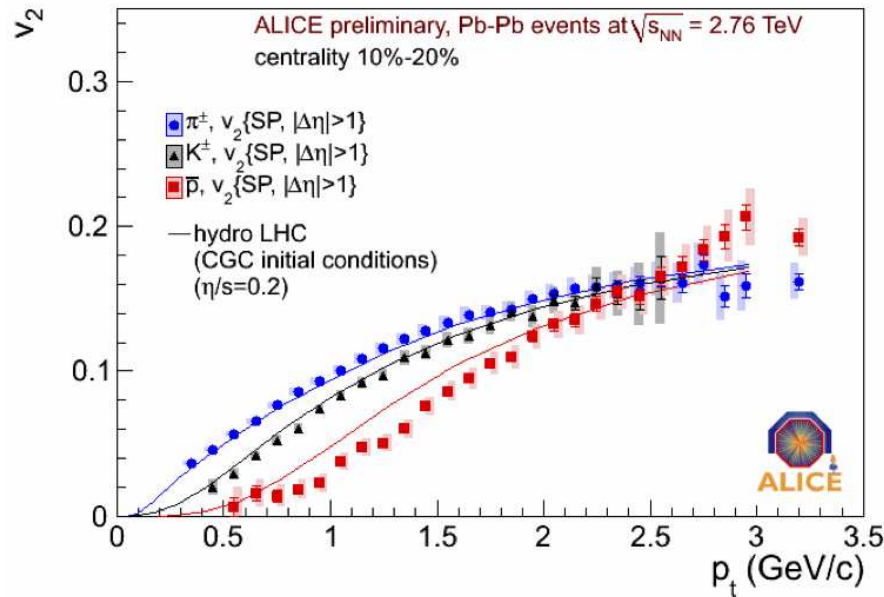


- Qualitative features of data agree with VISH2+1 predictions
- VISH2+1 does not push proton v_2 strongly enough to higher p_T , both at RHIC and LHC
- At RHIC we know that this is fixed when using VISHNU – is the same true at LHC?

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

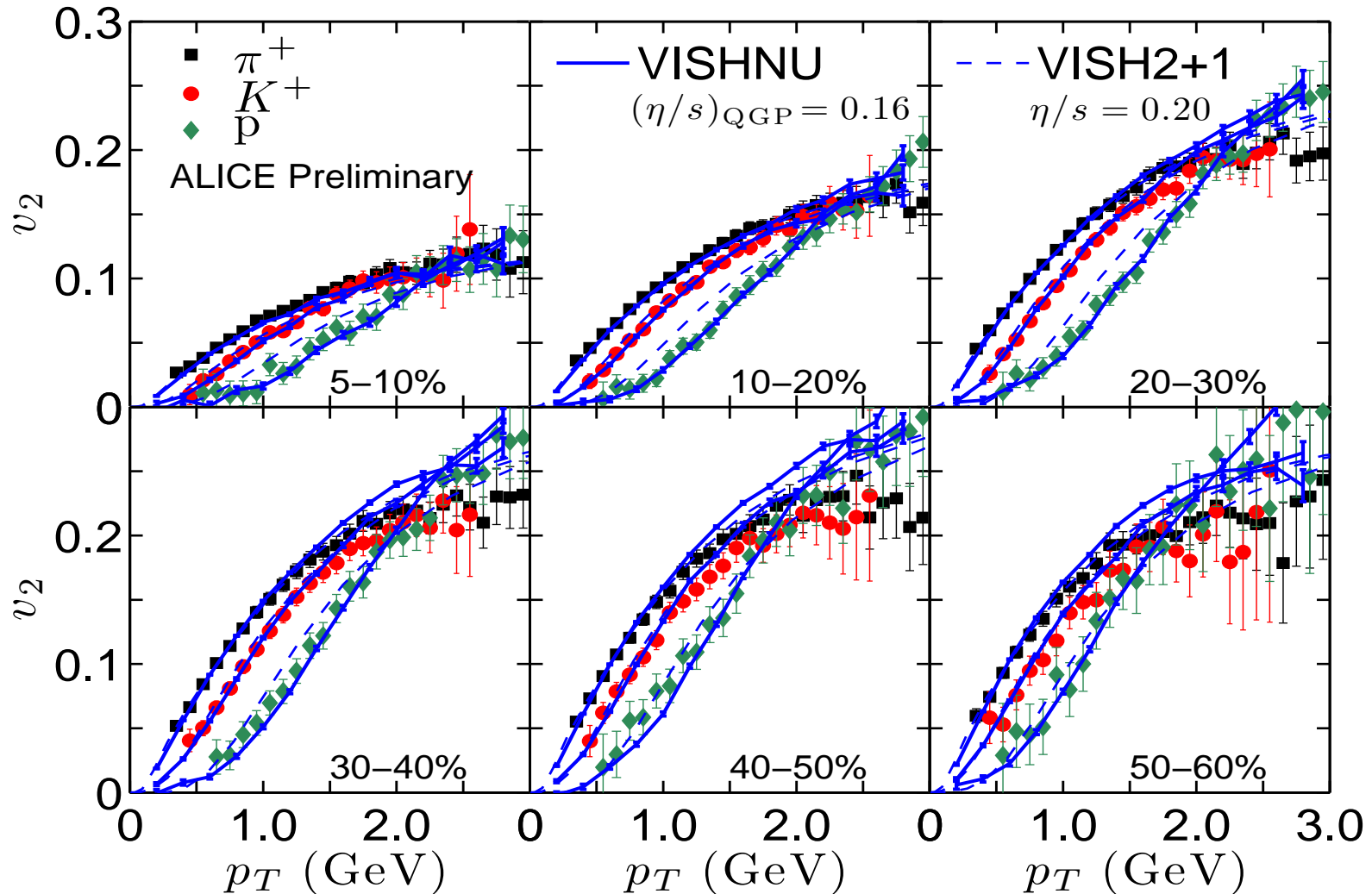
Adding the hadronic cascade (VISHNU) helps:

$v_2(p_T)$ 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, $(\eta/s)_{QGP}=0.2$)

Solid lines: Song, Shen, UH 2011 (VISHNU, MC-KLN, $(\eta/s)_{QGP}=0.16$)



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

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

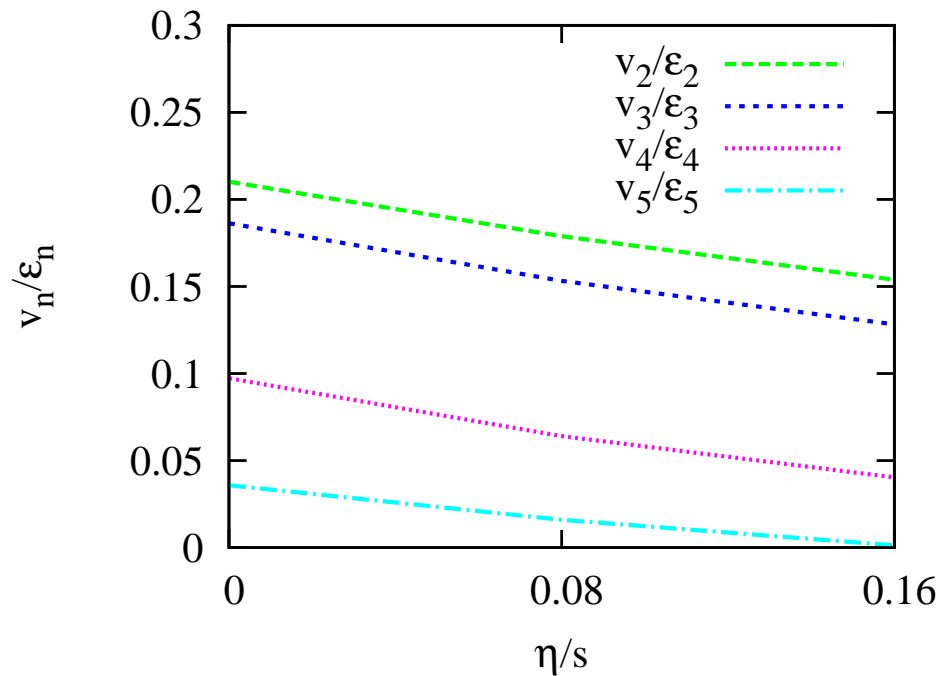
**Back to the
“elephant in the room”:
How to eliminate the large
model uncertainty
in the initial eccentricity?**

Two observations:

I. Shear viscosity suppresses higher flow harmonics more strongly

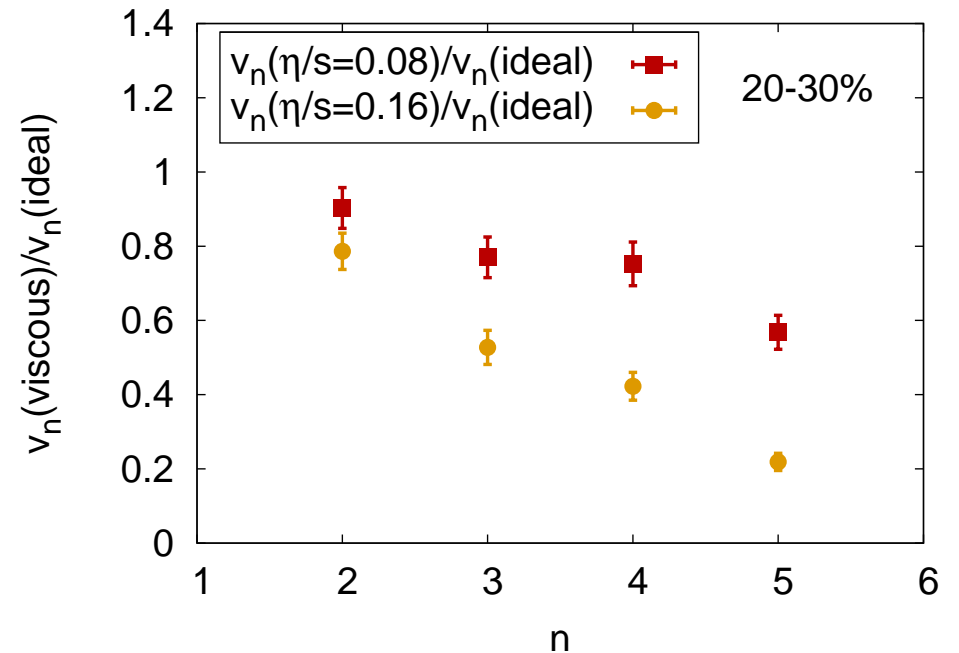
Alver et al., PRC82 (2010) 034913

(averaged initial conditions)



Schenke et al., arXiv:1109.6289

(event-by-event hydro)

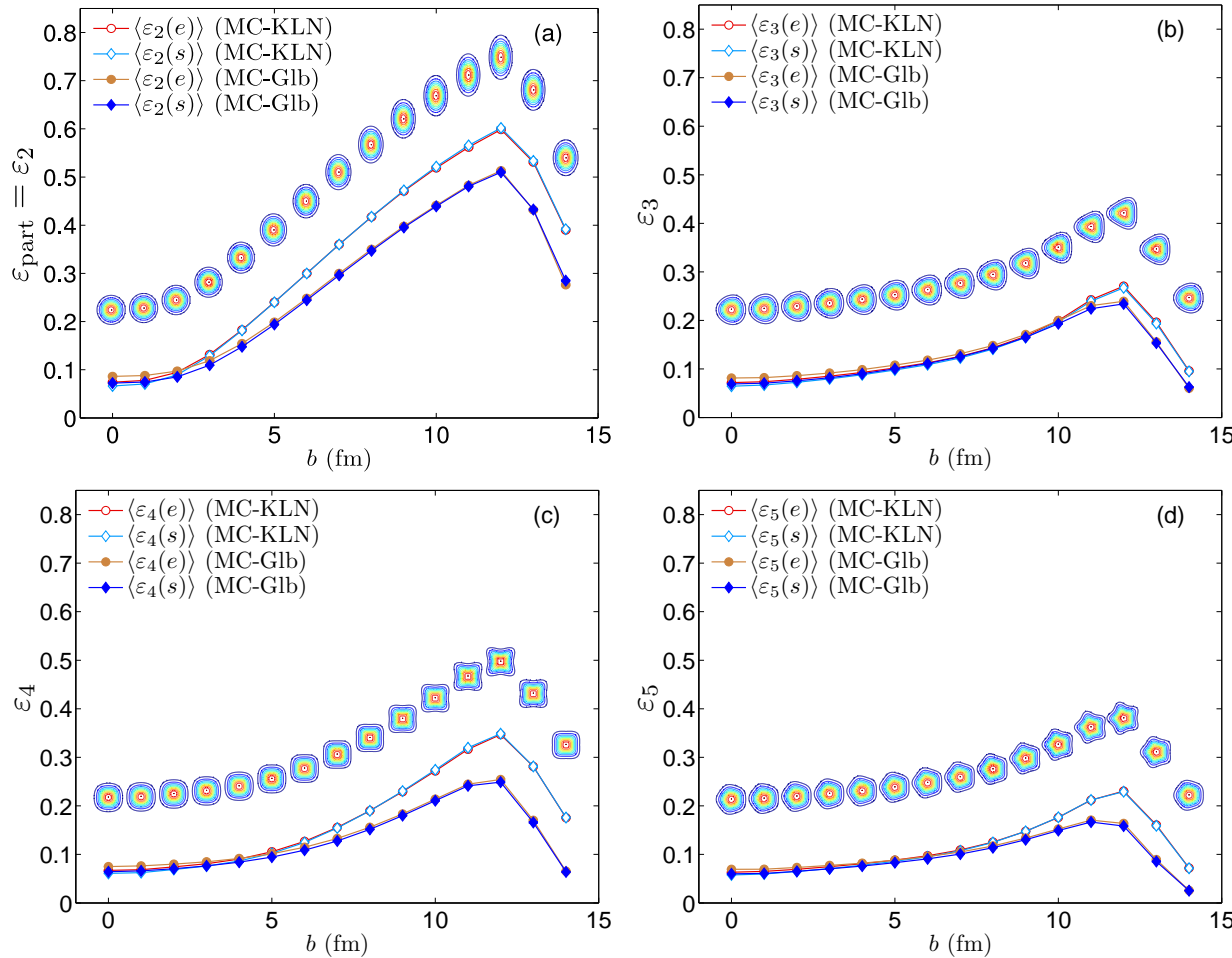


⇒ **Idea:** Use simultaneous analysis of elliptic and triangular flow to constrain initial state models (see also Bhalerao, Luzum Ollitrault, PRC 84 (2011) 034910)

Two observations:

II. ε_3 is \approx model independent

Zhi Qiu, UH, PRC84 (2011) 024911



Initial eccentricities ε_n and angles ψ_n :

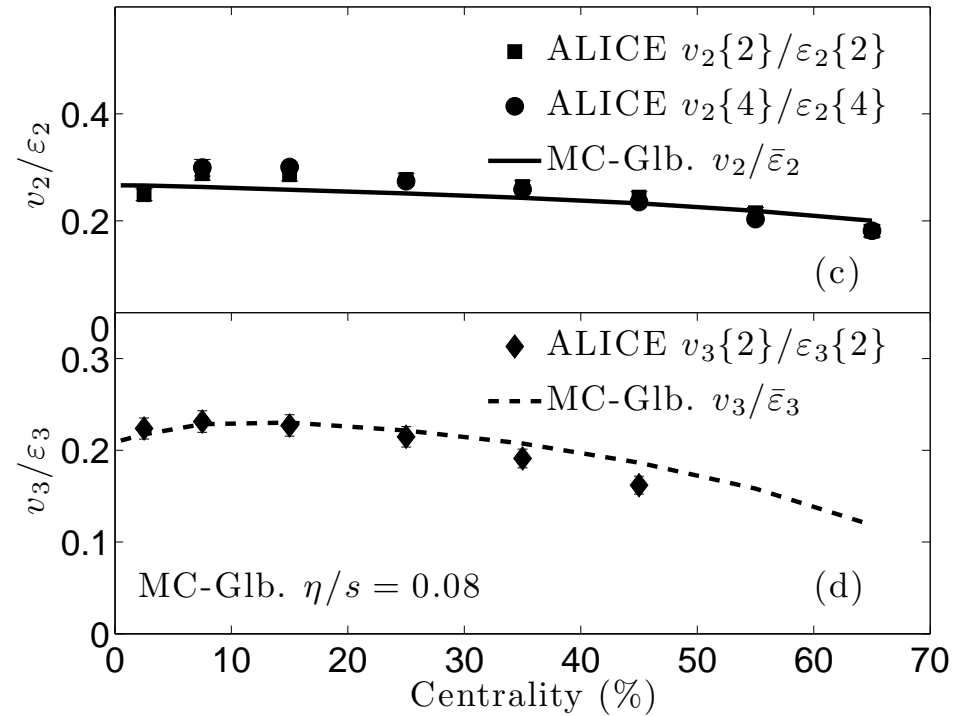
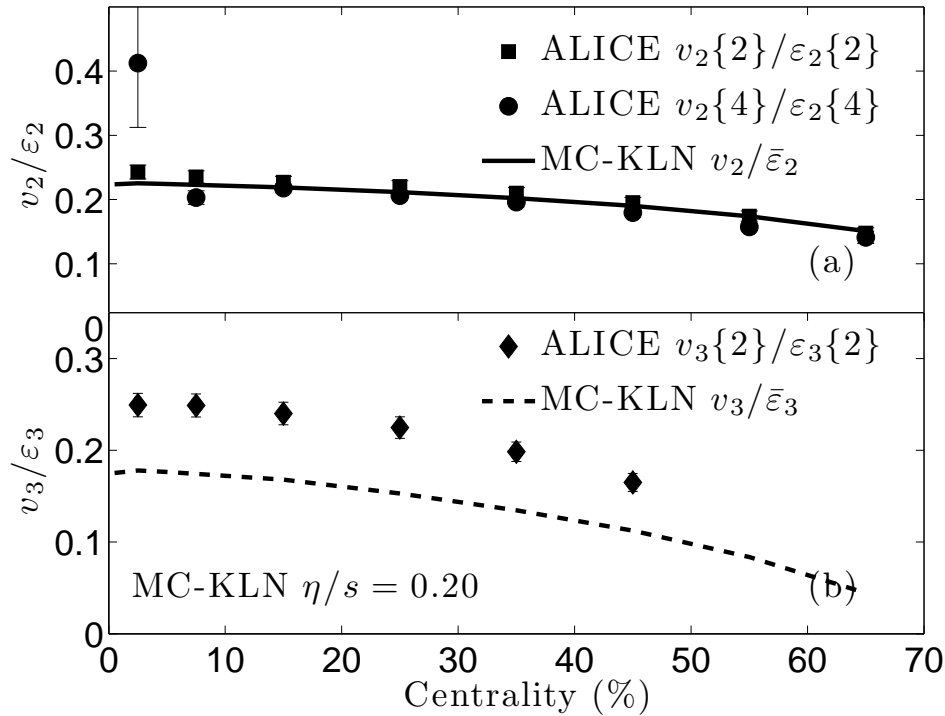
$$\varepsilon_n e^{in\psi_n} = - \frac{\int r dr d\phi r^2 e^{in\phi} e(r, \phi)}{\int r dr d\phi r^2 e(r, \phi)}$$

- MC-KLN has larger ε_2 and ε_4 , but similar ε_3 and almost identical ε_5 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 $v_3/\varepsilon_3 \approx \text{const.}$ over a wide range of centralities

\implies **Idea:** Use total charged hadron v_3^{ch} to determine $(\eta/s)_{\text{QGP}}$,
then check v_2^{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 (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 $(\eta/s)_{\text{QGP}} \simeq 1/(4\pi)$ unless the fluctuations predicted by both models are completely wrong and ε_3 is really 50% larger than we presently believe!**

Conclusions

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

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

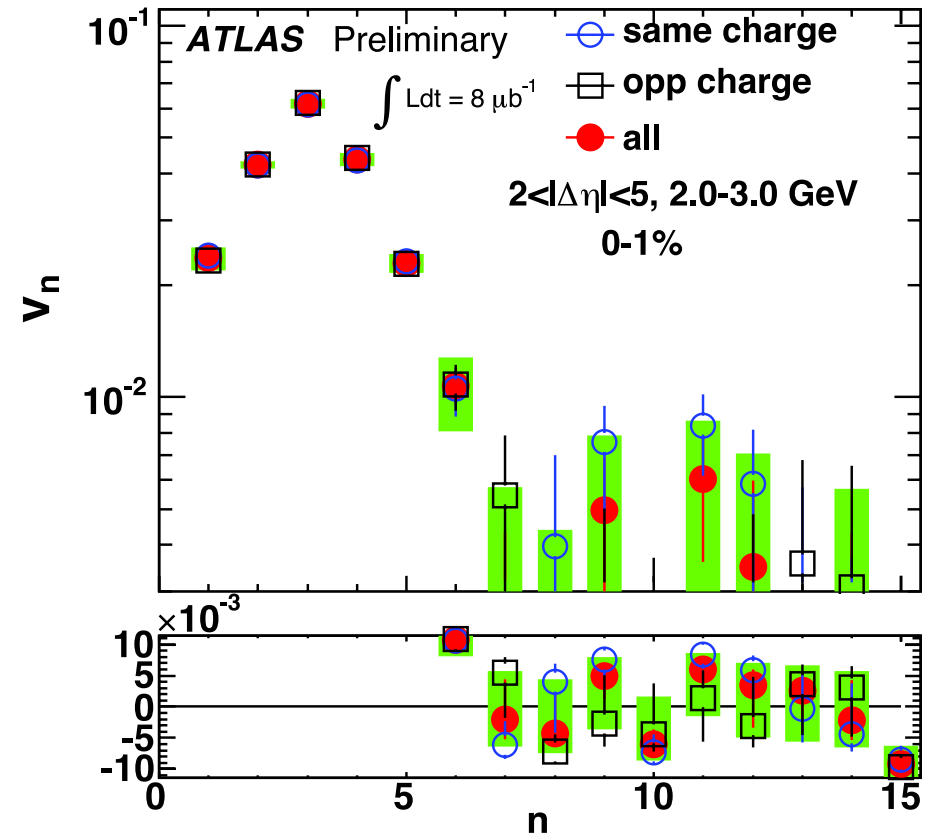
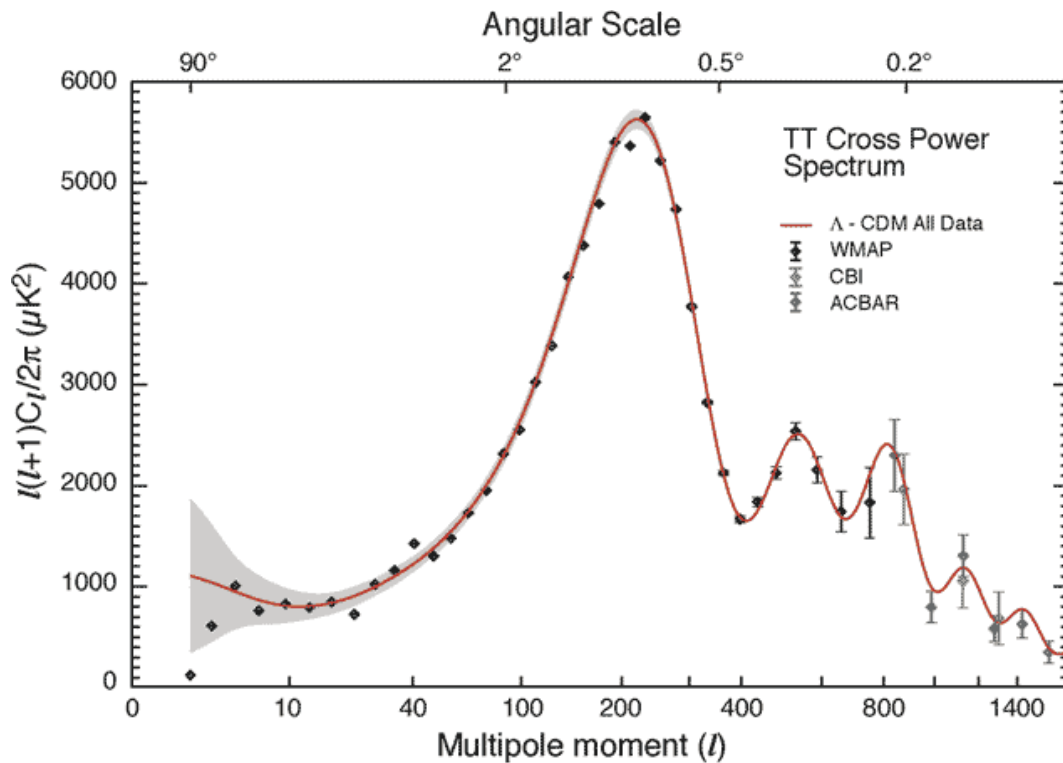
A moderate increase between $2T_c$ and $3T_c$ can at present not be excluded but is not mandated by the data.

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

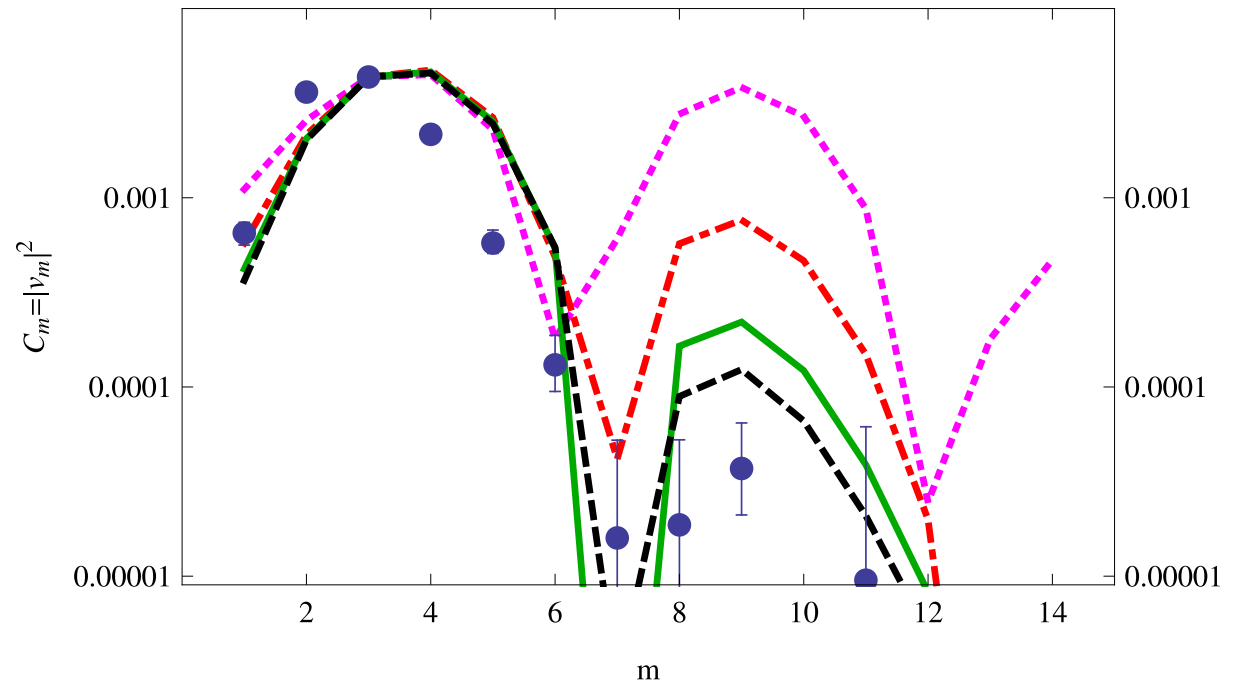
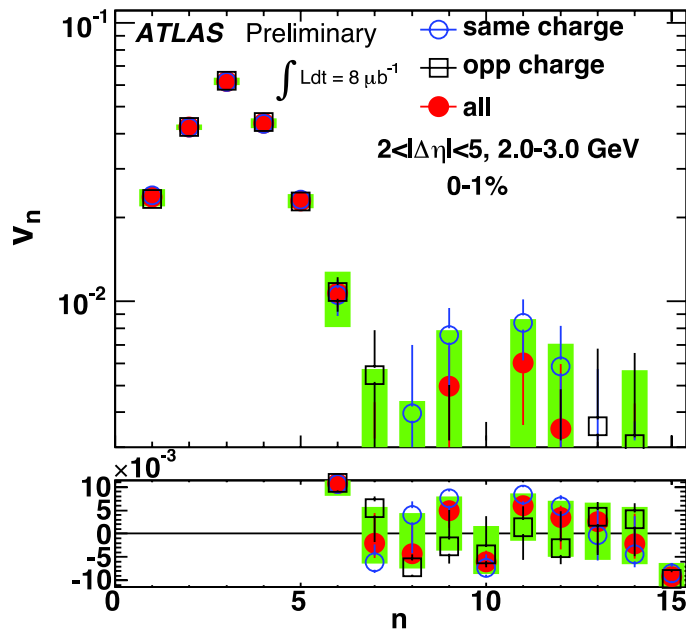
Outlook: The fluctuation power spectrum



We need theory curves through the right plot!

The fluctuation power spectrum of the Little Bang: a first try

Staig & Shuryak, arXiv:1106.3243



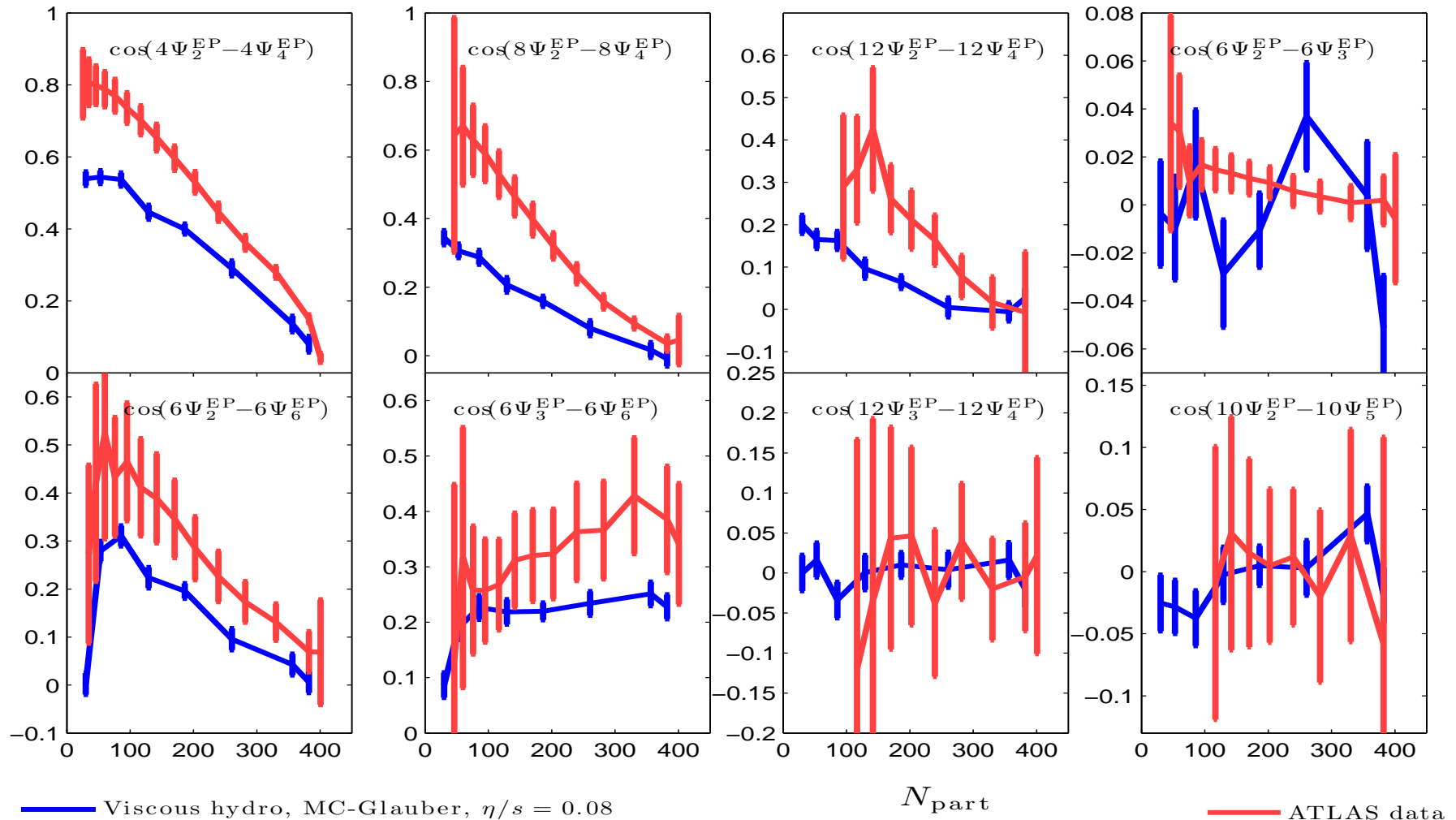
- Relating the measured “anisotropic flow power spectrum” (i.e. v_n vs. n) to the “initial fluctuation power spectrum” (i.e. ε_n vs. n) provides access to the QGP transport coefficients (likely not only η/s , but also ζ/s , τ_π , τ_Π . . .)
- Power spectrum of initial fluctuations (in particular its \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

→ **The Concordance Model of Little Bang Cosmology!**

Higher order event plane correlations in PbPb@LHC

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

Event-by-event hydrodynamics: Zhi Qiu (VISH2+1, MC-Glauber, $(\eta/s)_{\text{QGP}}=0.08$)



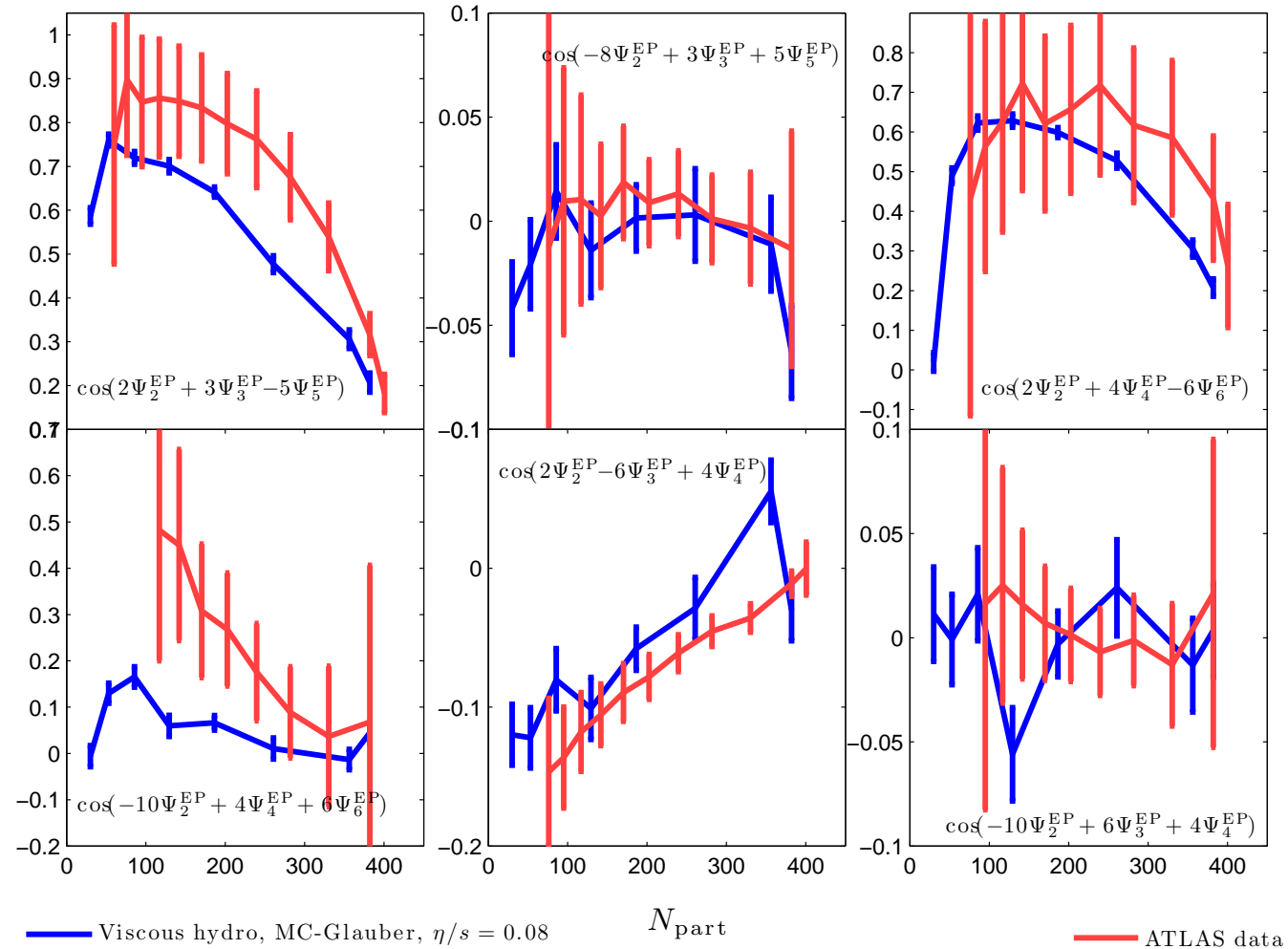
Very preliminary assessment:

VISH2+1 reproduces qualitative features of the centrality dependence of all measured event-plane correlations but is quantitatively off by up to 50%

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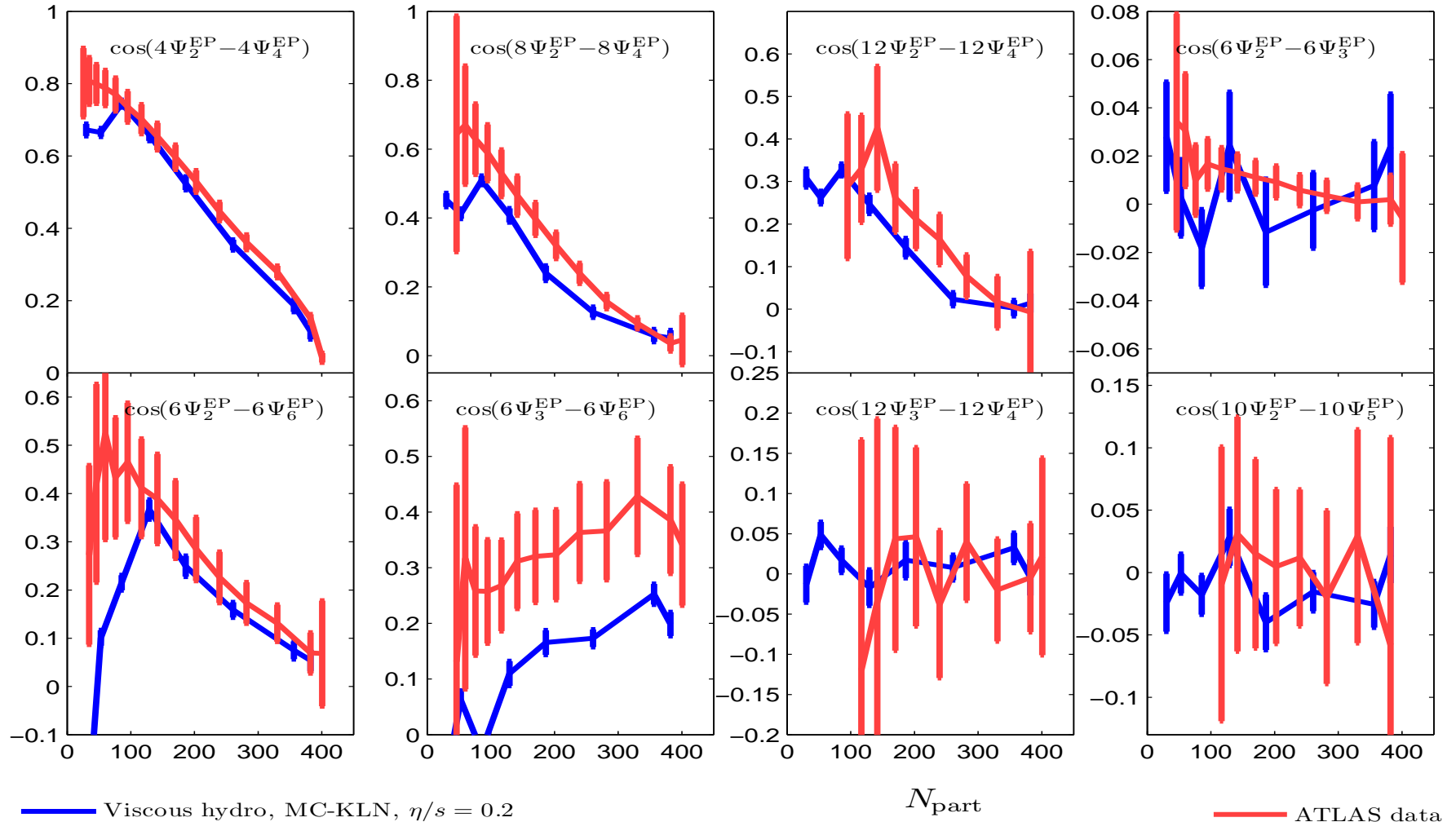
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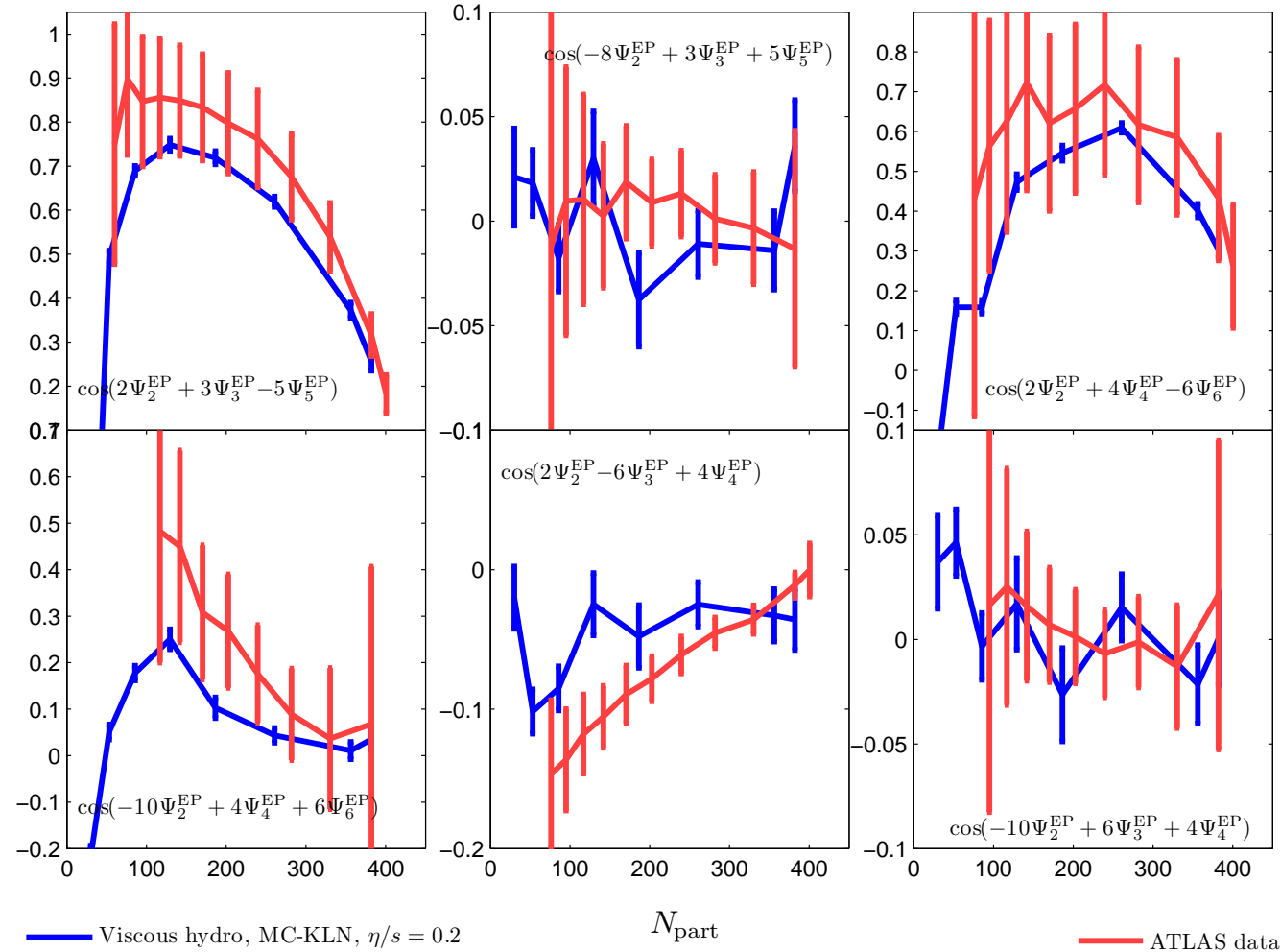
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Very preliminary assessment:

VISH2+1 reproduces qualitative features of the centrality dependence of all measured event-plane correlations but is quantitatively off by up to 50%

Thanks to:

Paul Sorensen for the animations

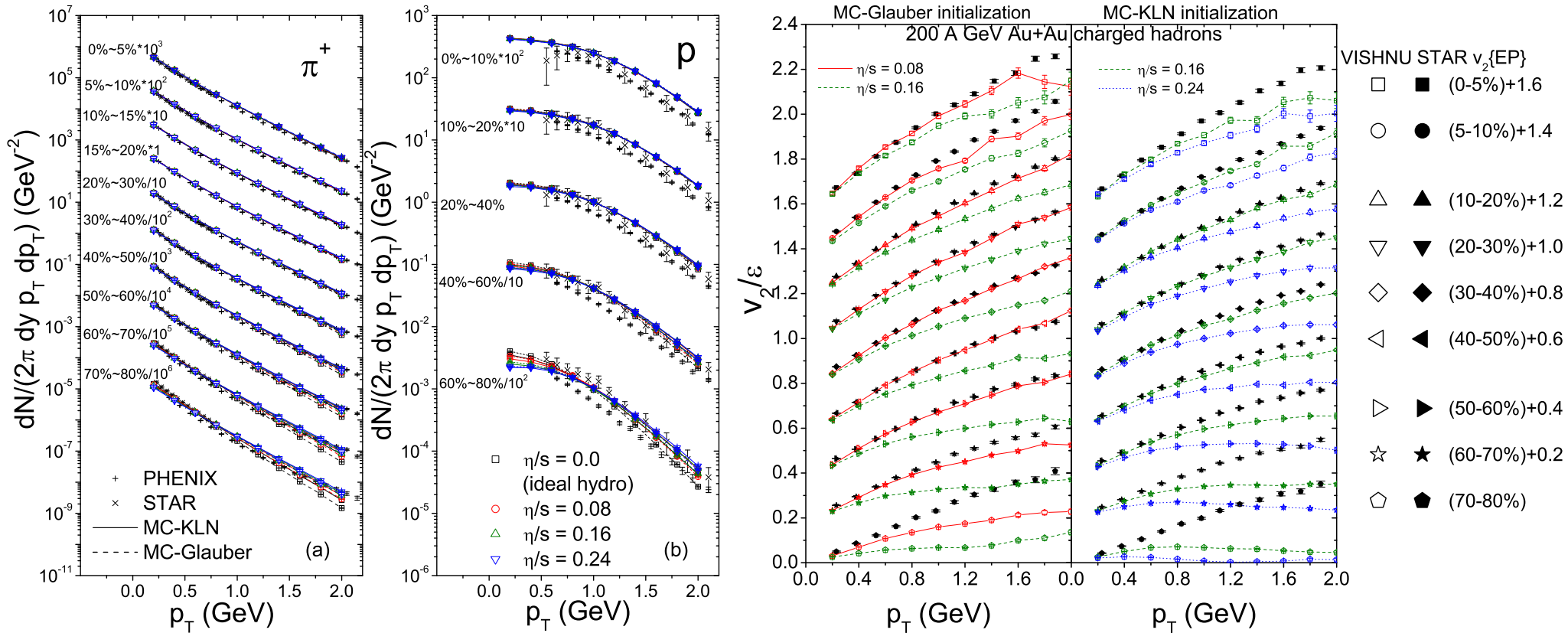
Chun Shen for the movie

Huichao Song, Steffen Bass, Zhi Qiu, Chun Shen,
Pasi Huovinen, Tetsu Hirano, and Peter Kolb for their
collaboration

Supplements

Global description of AuAu@RHIC spectra and v_2

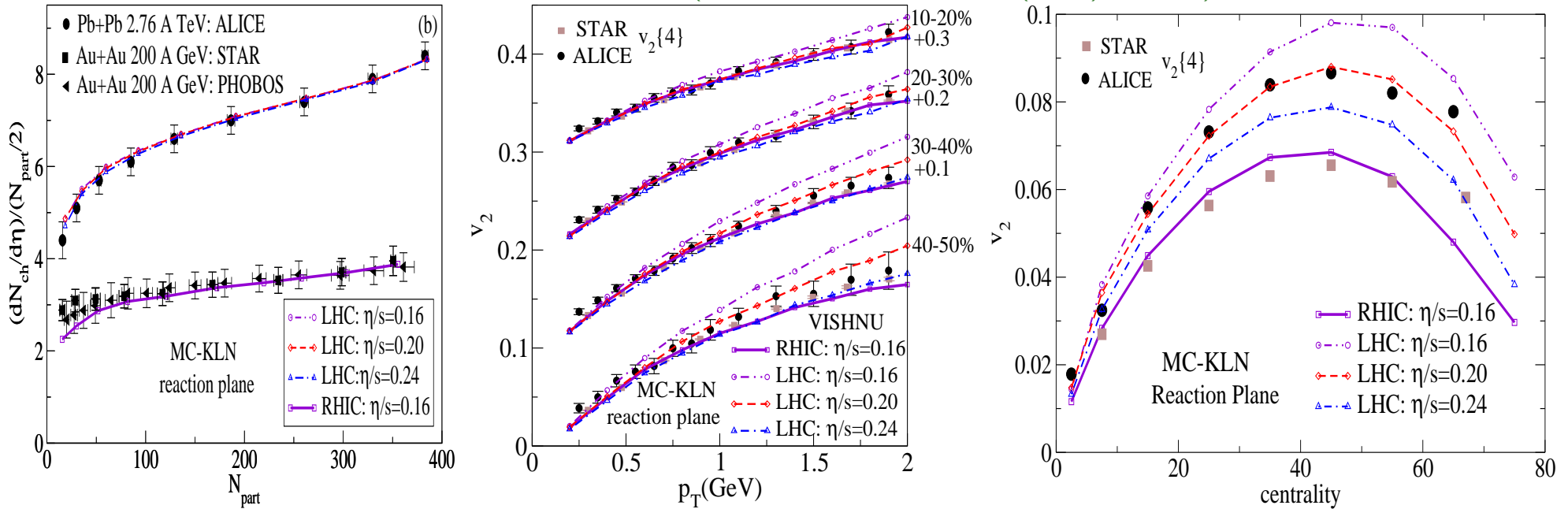
VISHNU (H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRC83 (2011) 054910)



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

Pre- and postdictions for PbPb@LHC

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

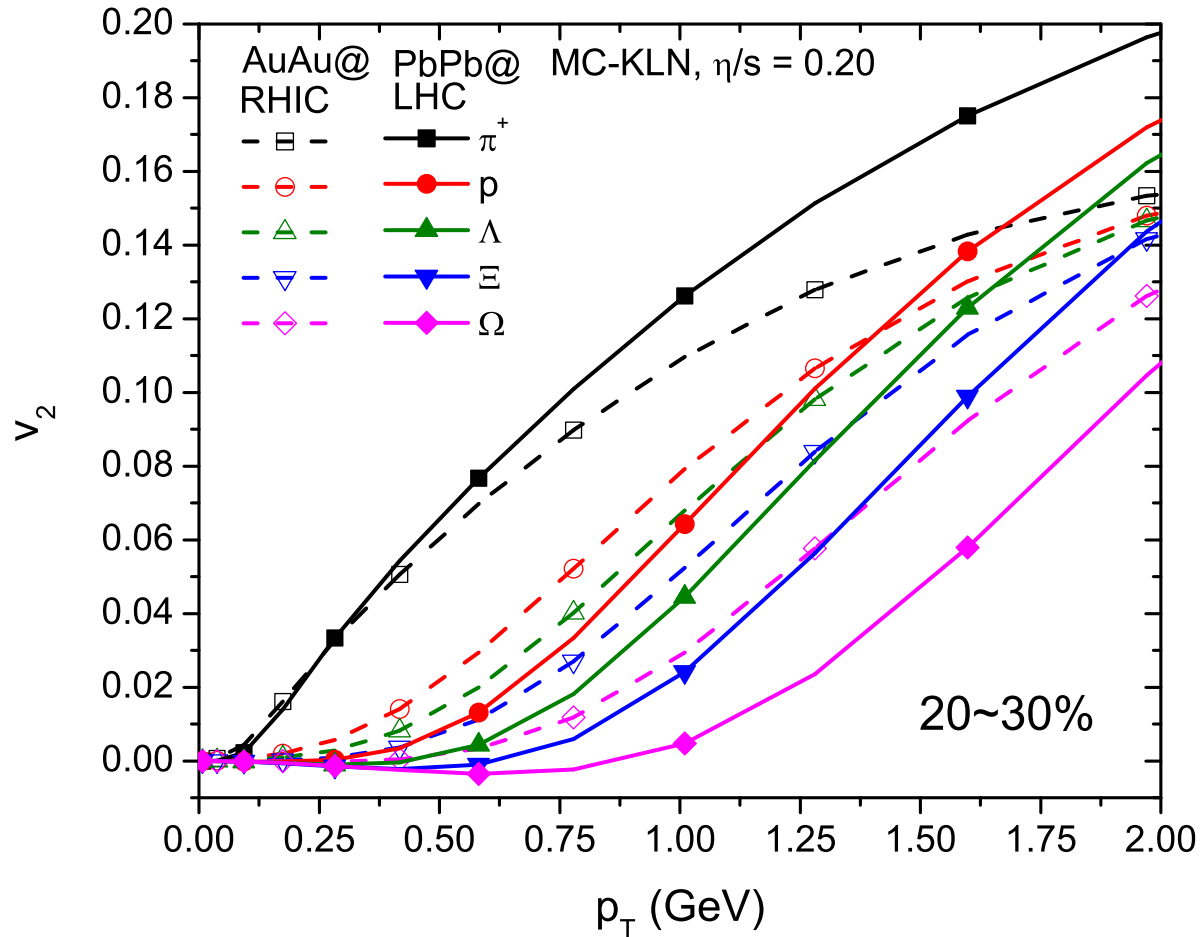


- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of $dN_{ch}/d\eta$ well in both AuAu@RHIC and PbPb@LHC
- $(\eta/s)_{QGP} = 0.16$ for MC-KLN works well for charged hadron $v_2(p_T)$ 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) \implies need pre-equilibrium model.
 \implies **QGP at LHC not much more viscous than at RHIC!**

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

Answer: Pure accident! (Kestin & UH EPJC61 (2009) 545; Shen & UH, PRC85 (2012) 054902)

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



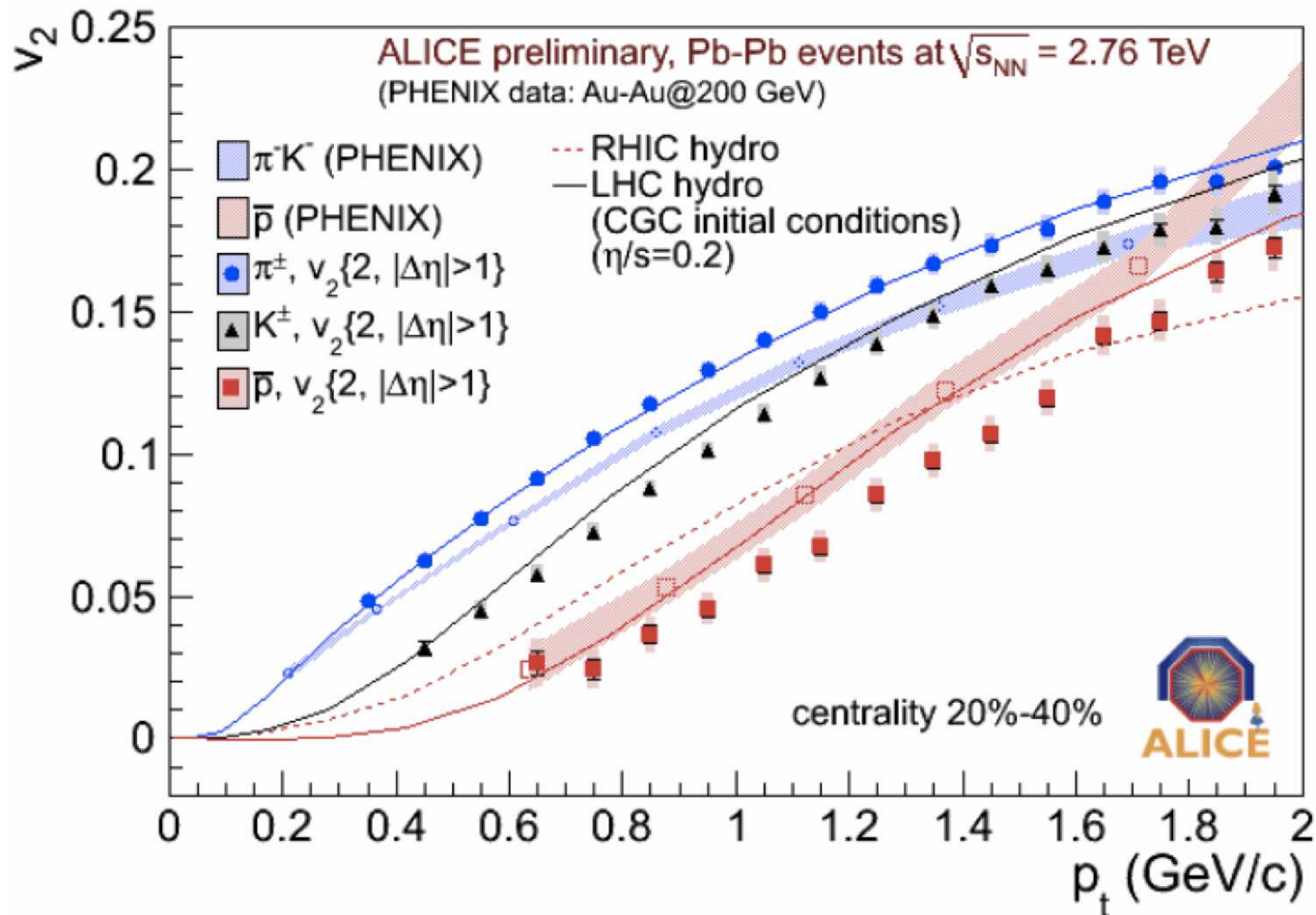
$v_2^\pi(p_T)$ increases a bit from RHIC to LHC, for heavier hadrons $v_2(p_T)$ at fixed p_T decreases (radial flow pushes momentum anisotropy of heavy hadrons to larger p_T)

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, $\eta/s=0.2$)

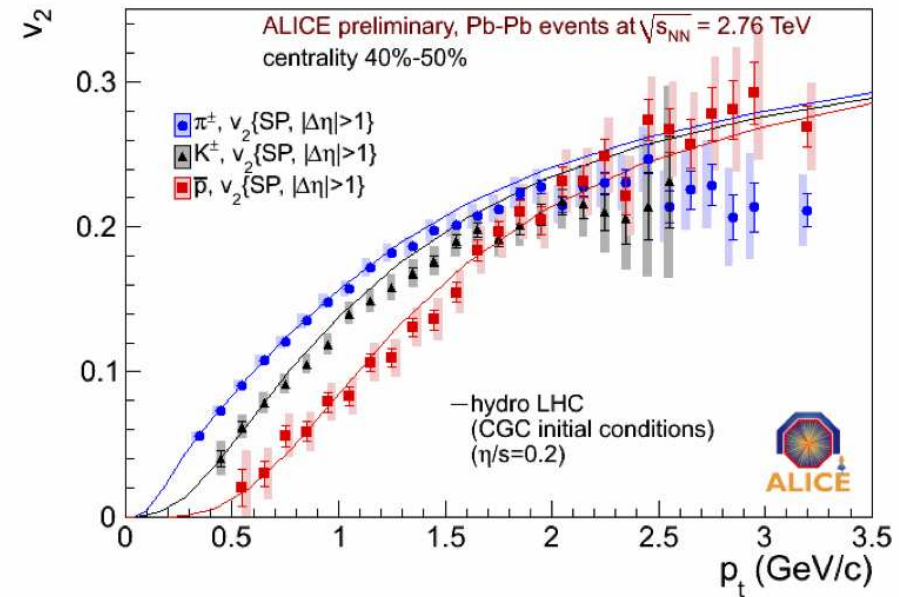
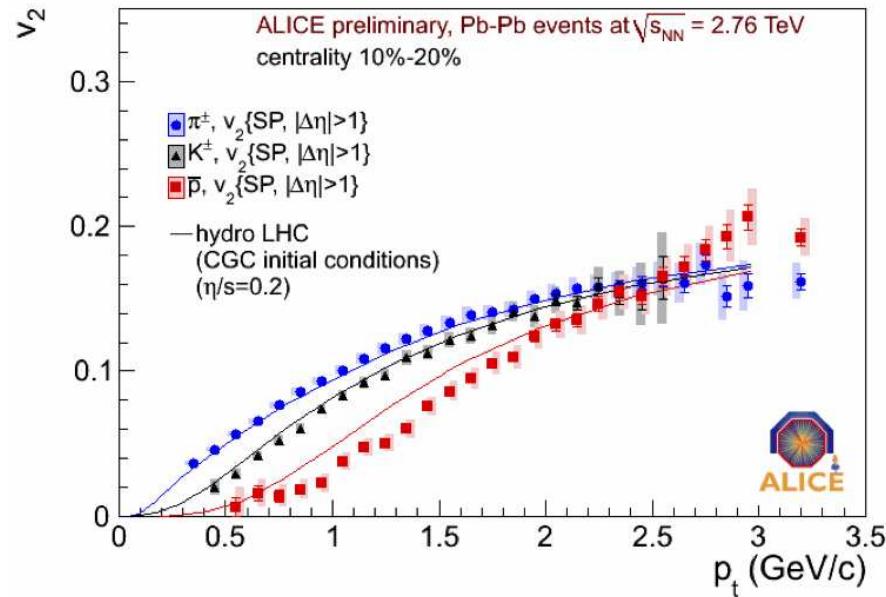


- Qualitative features of data agree with VISH2+1 predictions
- VISH2+1 does not push proton v_2 strongly enough to higher p_T , both at RHIC and LHC
- At RHIC we know that this is fixed when using VISHNU – is the same true at LHC?

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

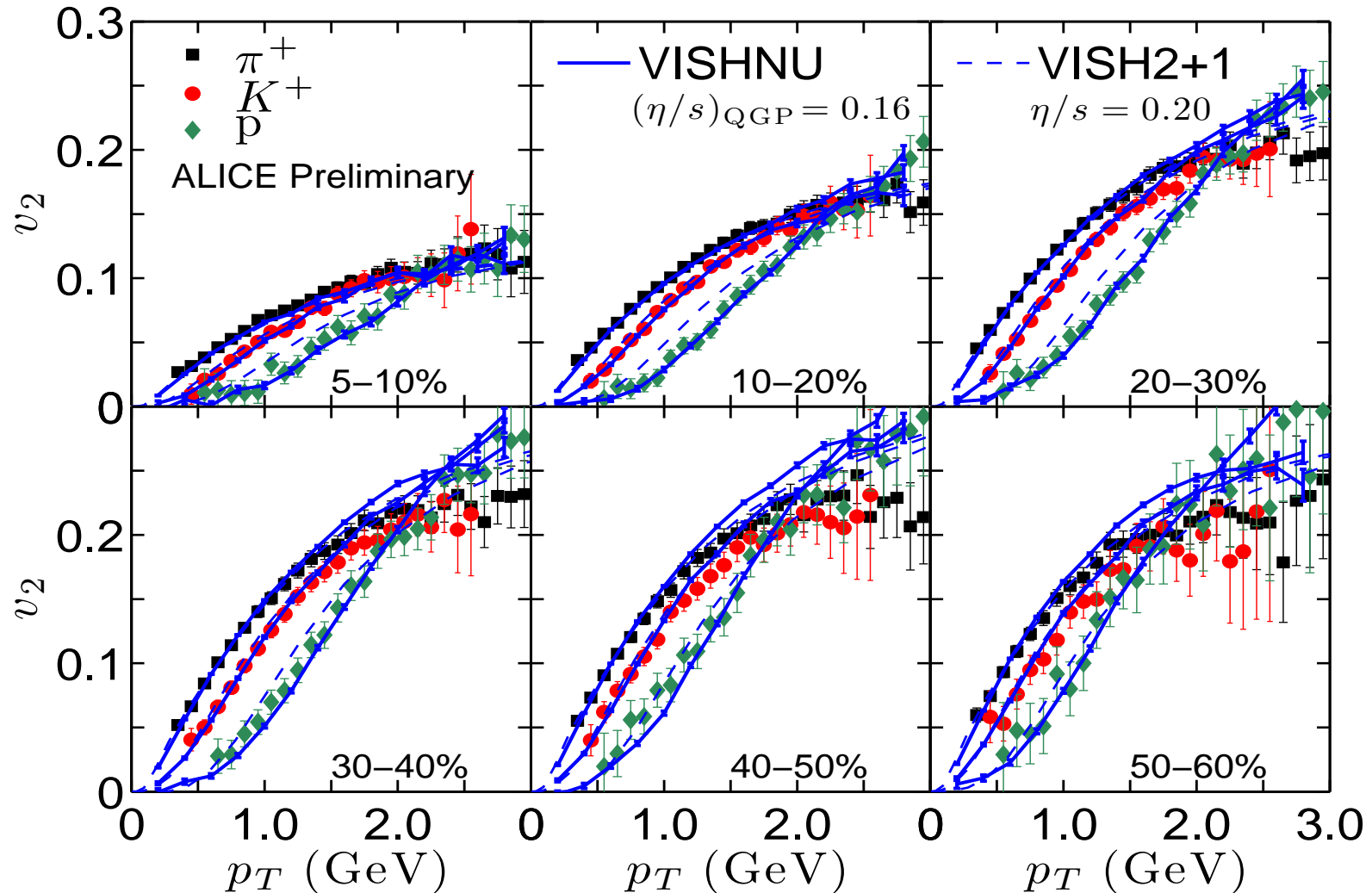
Adding the hadronic cascade (VISHNU) helps:

$v_2(p_T)$ 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, $(\eta/s)_{QGP}=0.2$)

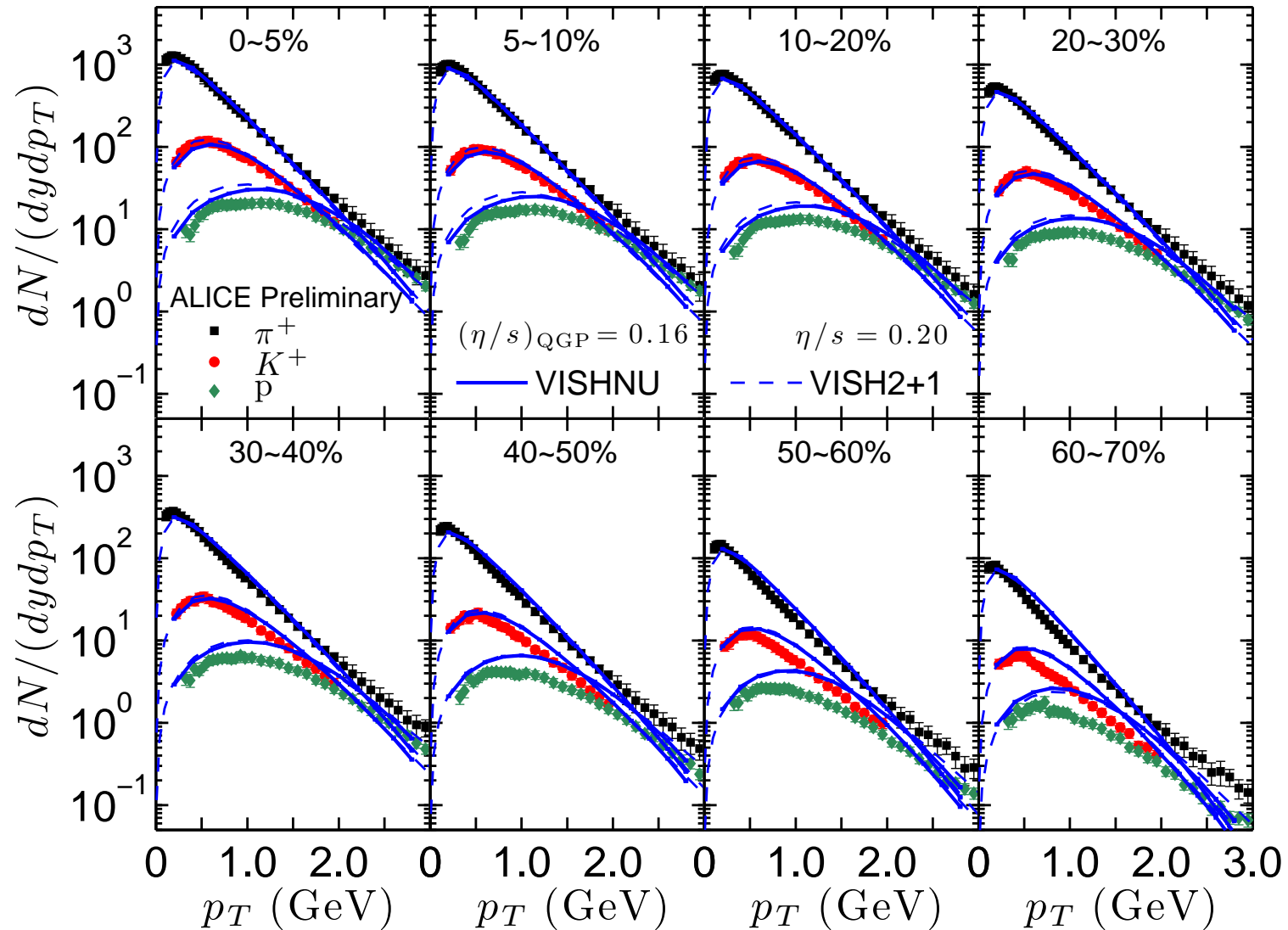
Solid lines: Song, Shen, UH 2011 (VISHNU, MC-KLN, $(\eta/s)_{QGP}=0.16$)



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

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

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

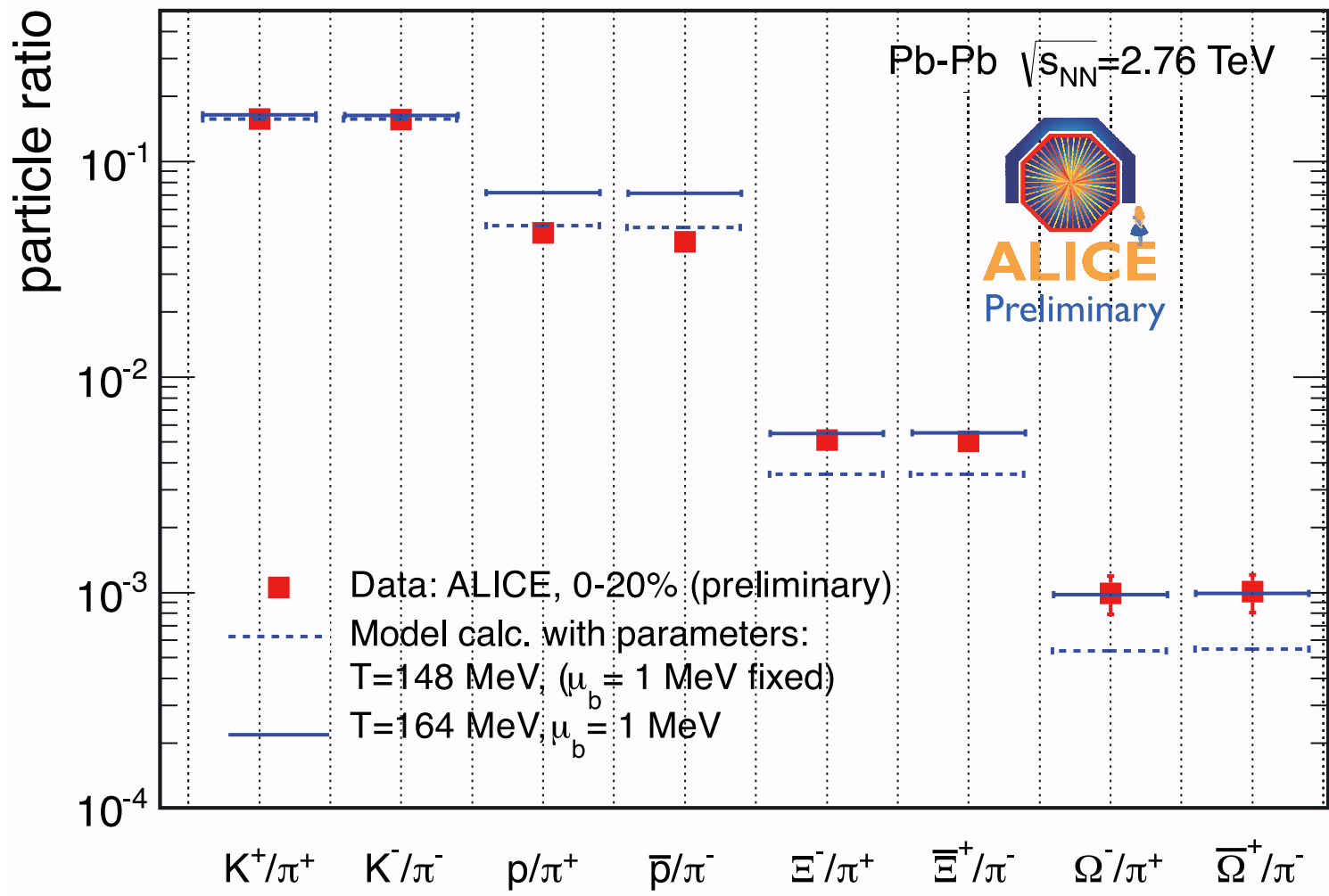


- Good description also of identified hadron spectra for centralities $< 50\%$
- VISHNU better than VISH2+1 in central collisions (more radial flow)
- Both models give too much radial flow in peripheral collisions \implies initial conditions?
- Both models overpredict proton yield by 50-70%!?

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



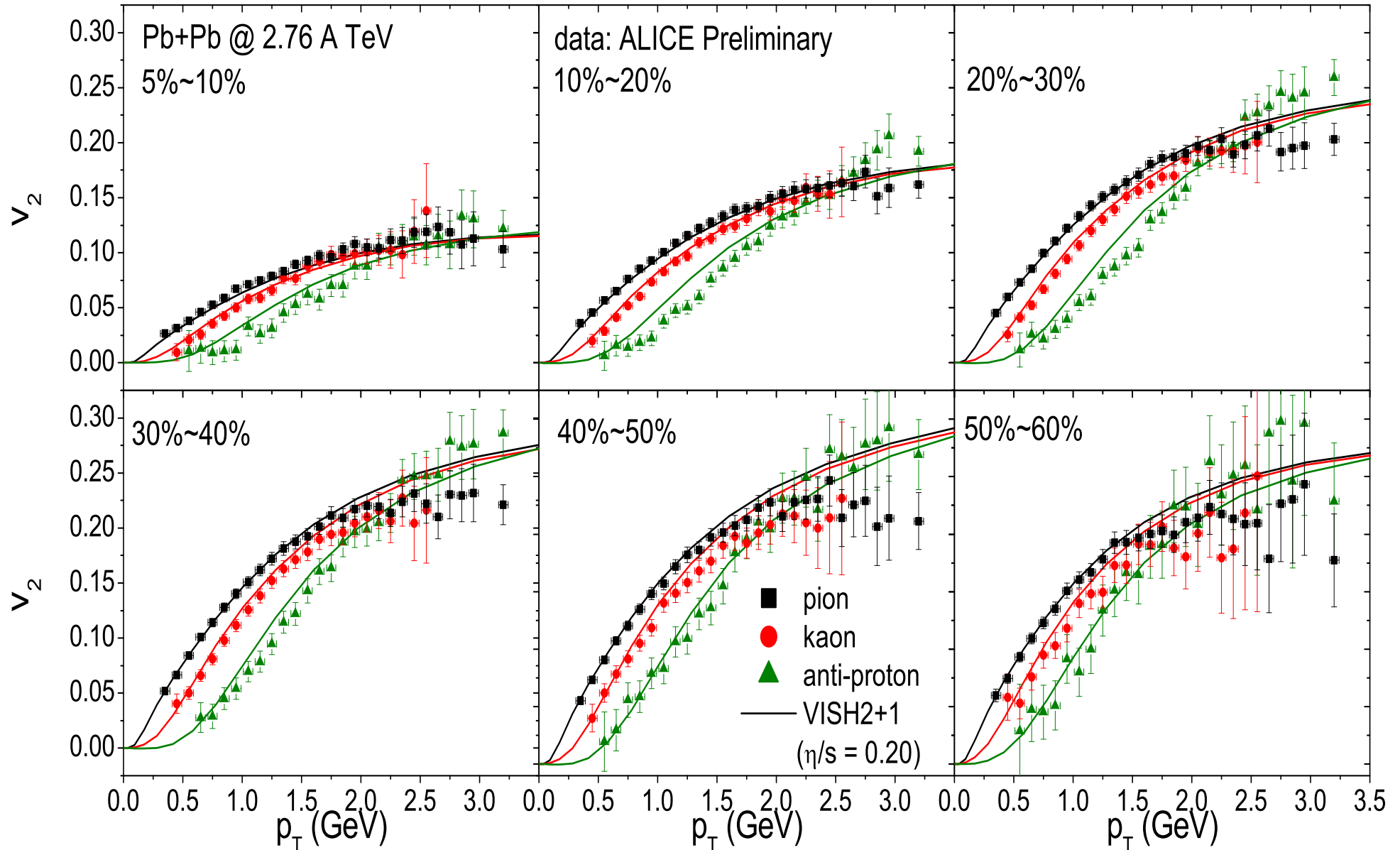
- “Standard” $T_{chem} = 164$ MeV reproduces strange hadrons but overpredicts (anti-)protons by 50%!
- $p\bar{p}$ annihilation in UrQMD not strong enough to repair this
- Similar problem already seen at RHIC but not taken seriously (STAR/PHENIX disagreement)

???

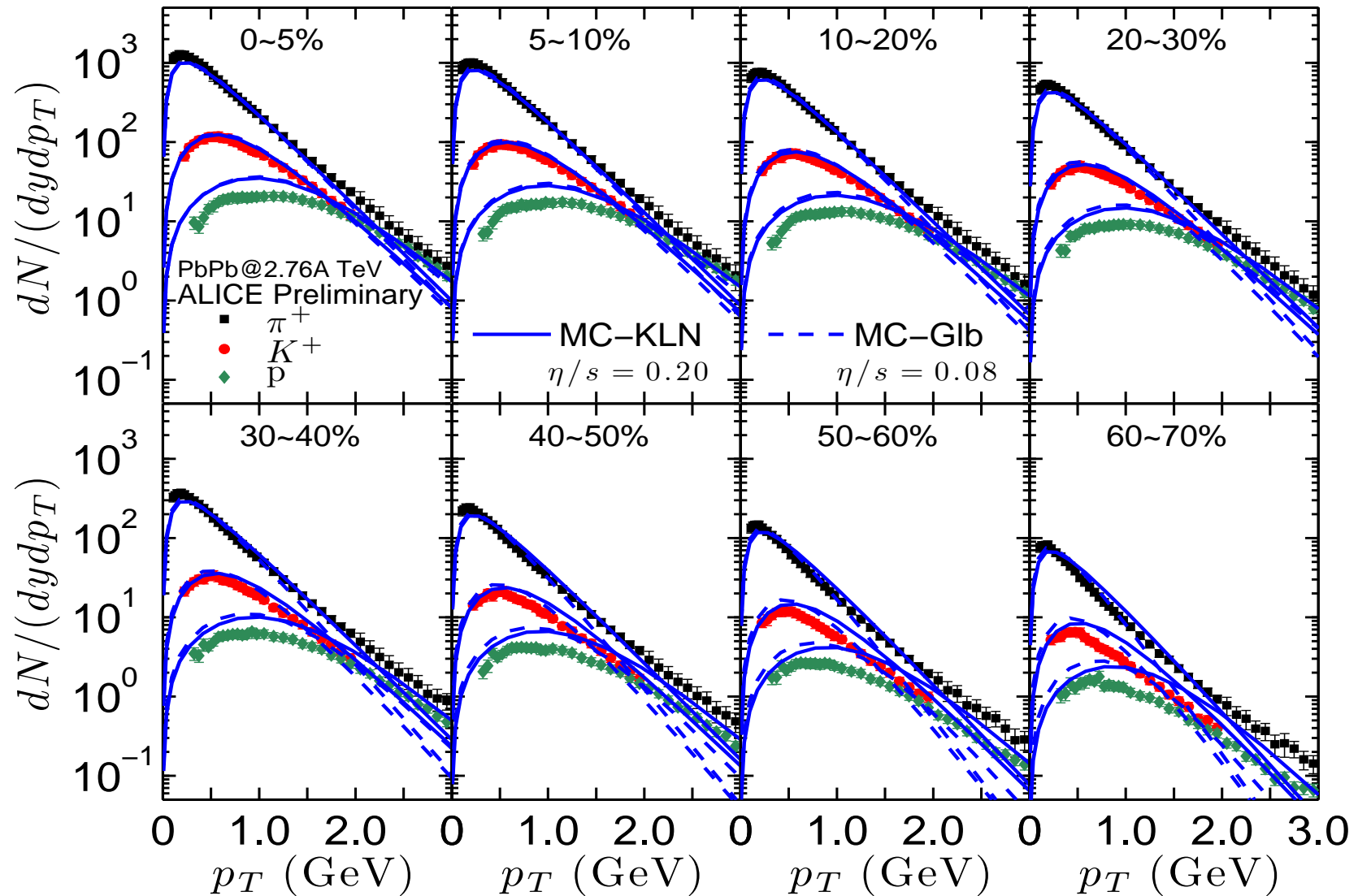
Comparison of ALICE PbPb@LHC v_2 data with VISH2+1

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

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



PbPb@LHC p_T -spectra: Glauber vs. KLN

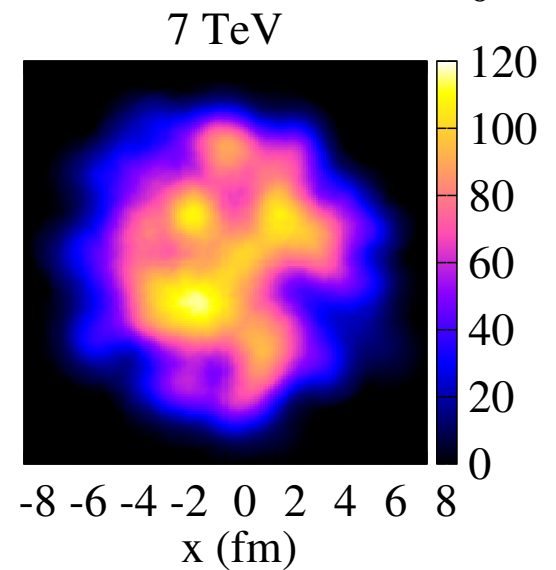
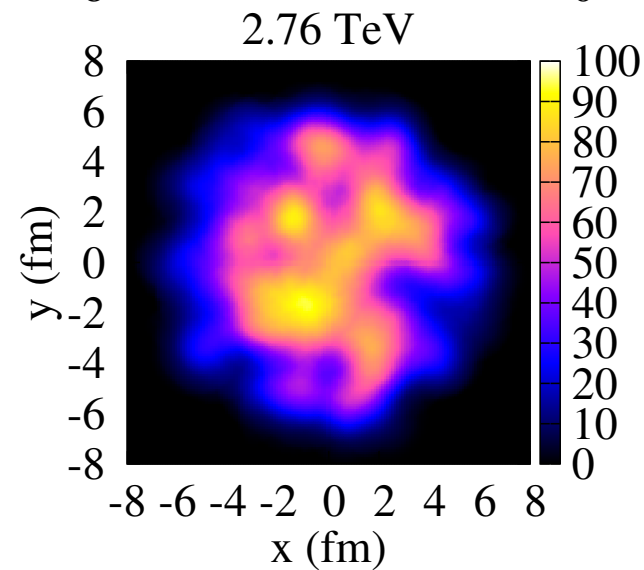
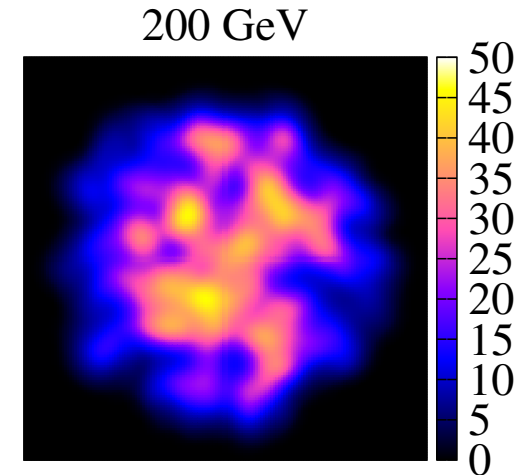
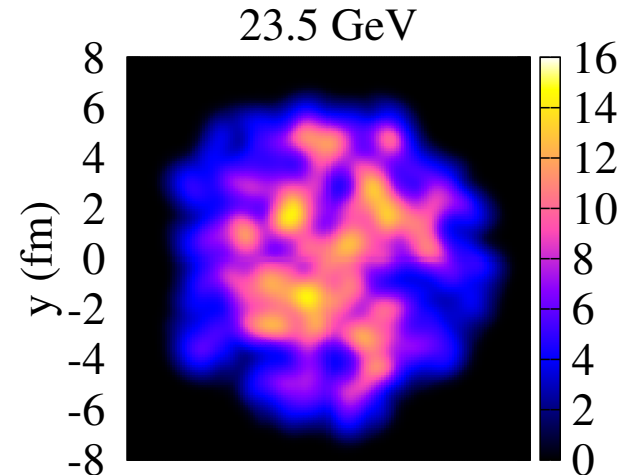
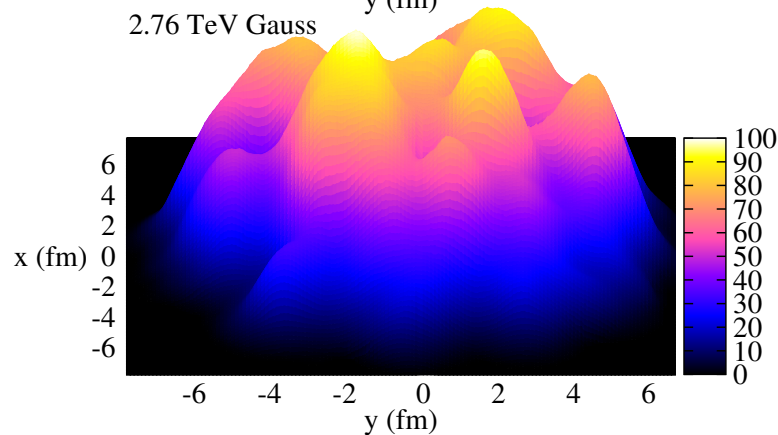
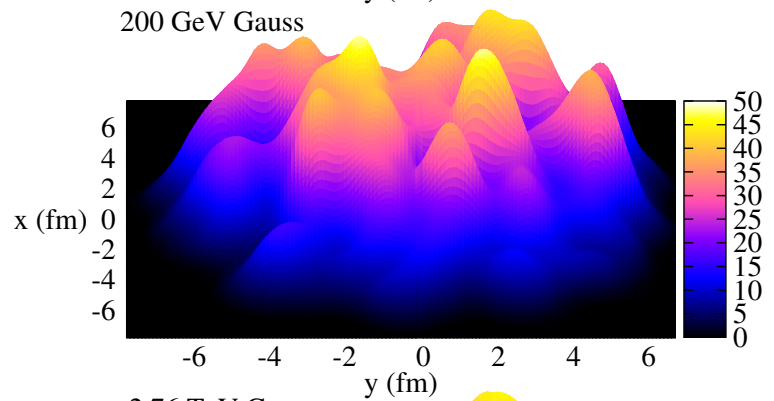
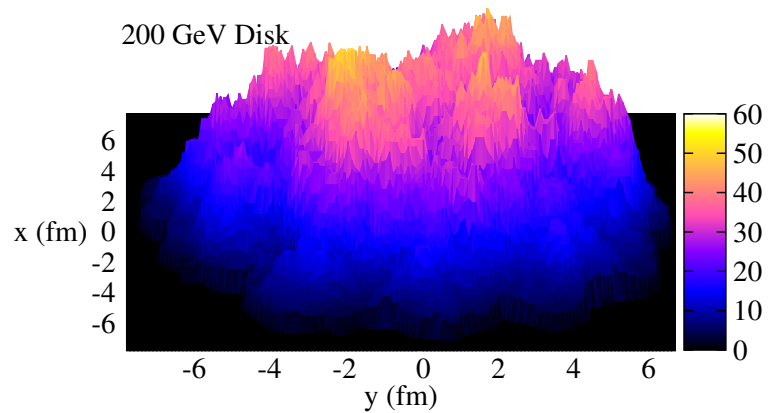


- In central collisions no difference between the models.
- In peripheral collisions p_T -spectra from MC-Glauber IC too steep!

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

Smearing effects from nucleon growth at high energies

U. Heinz & Scott Moreland, PRC84 (2011) 054905

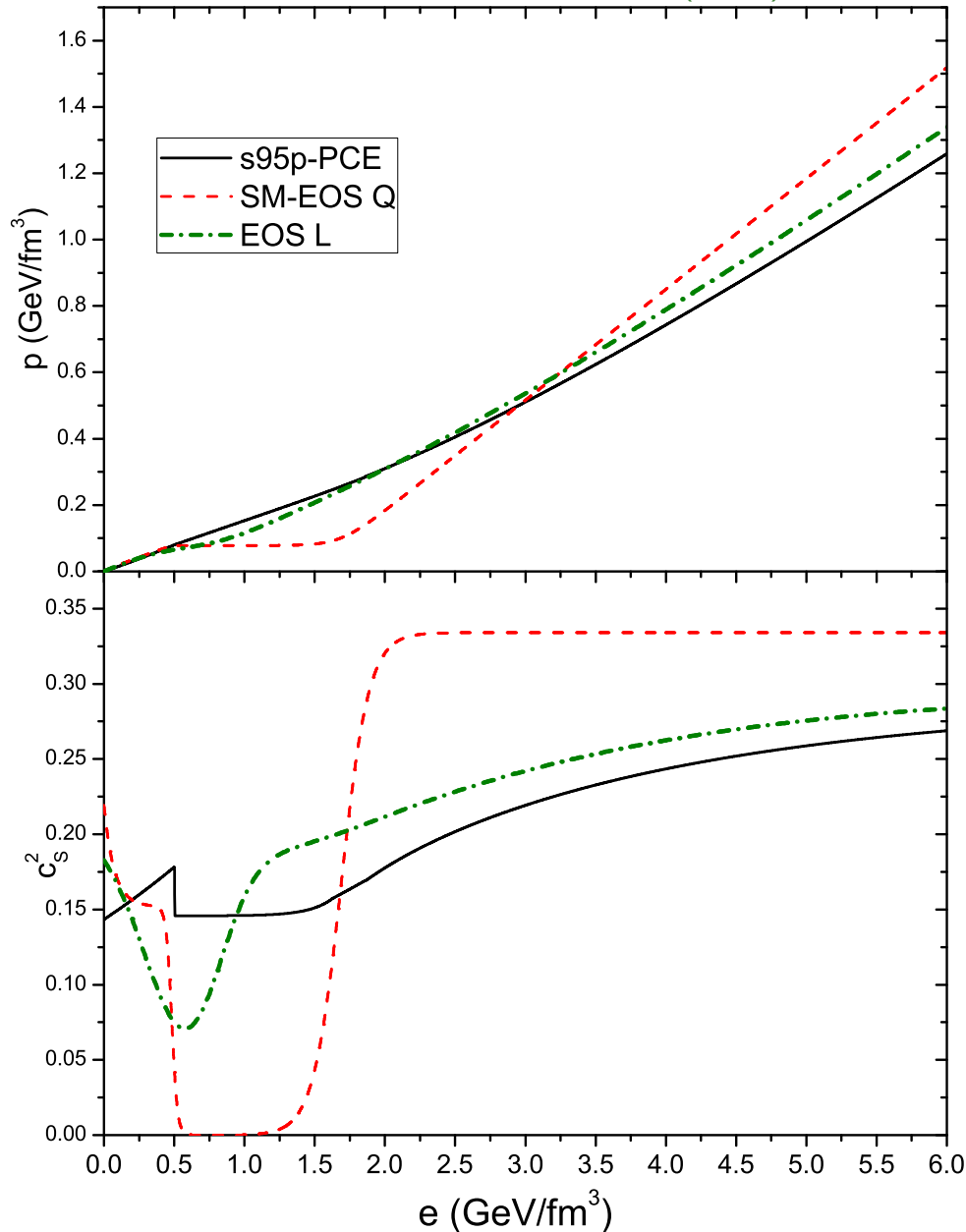


Between $\sqrt{s} = 23.5$ and 7,000 GeV, nucleon area grows by factor $\mathcal{O}(2) \implies$ significant smoothing of event-by-event density fluctuations from RHIC to LHC

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

Huovinen, Petreczky, NPA 837 (2010) 26

Shen, Heinz, Huovinen, Song, PRC 82 (2010) 054904



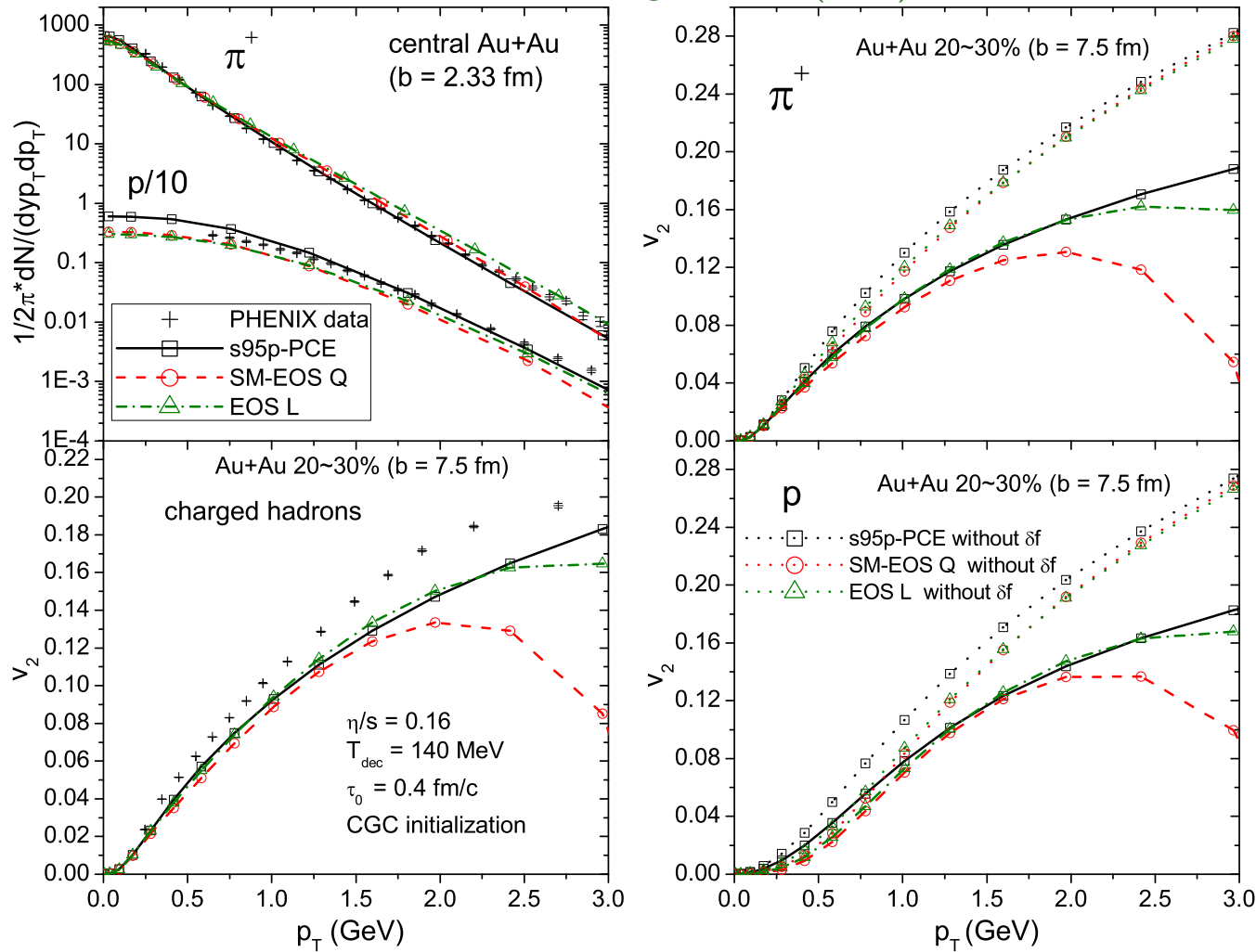
High T : Lattice QCD (latest hotQCD results)

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

\Rightarrow larger v_2