XXIV QUARK MATTER
DARMSTADT 2014

Beam energy dependence of the viscous damping of anisotropic flow in relativistic heavy ion collisions

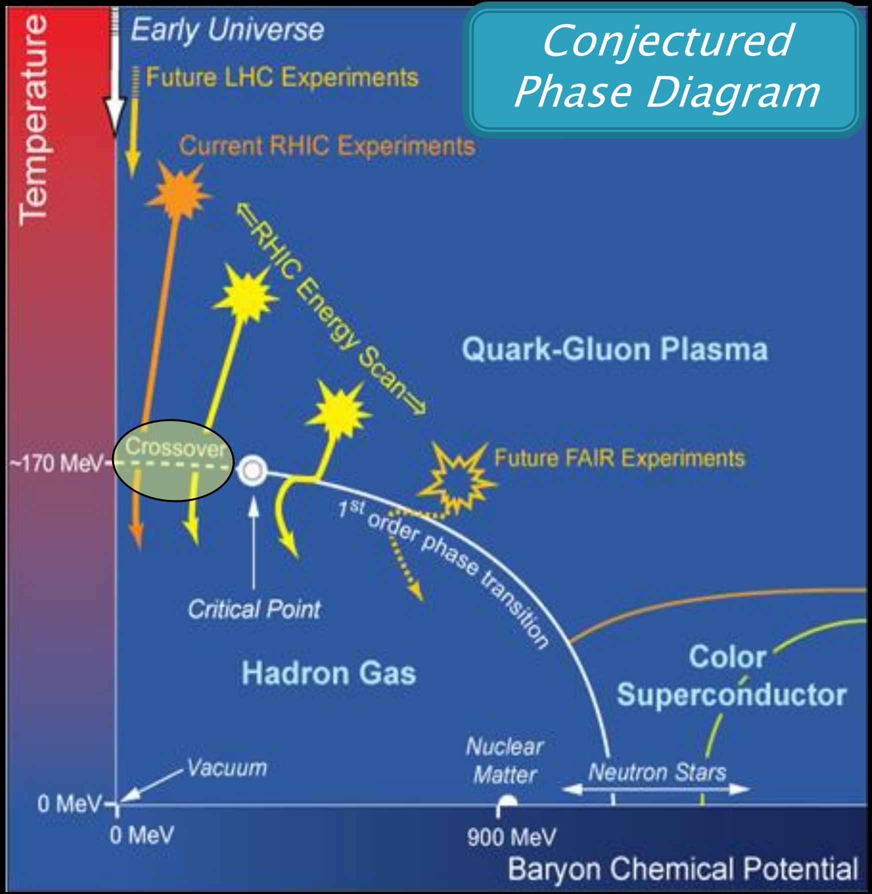
Roy A. Lacey
Stony Brook University

Outline:

- ***I. Motivation.***
  - ***Interest and observables***
- ***II. Available data and scaling***
  - ***Demonstration of scaling in visc. hydro***
- ***III. Results***
- ***IV. Conclusion***

We now have strong indications for a change in the dynamics with $\sqrt{s_{NN}}$

Quantitative study of the QCD phase diagram is a central current focus of our field



A Known known

- *Spectacular achievement:*

Validation of the crossover transition leading to the QGP
→ Necessary requirement for CEP

Known unknowns

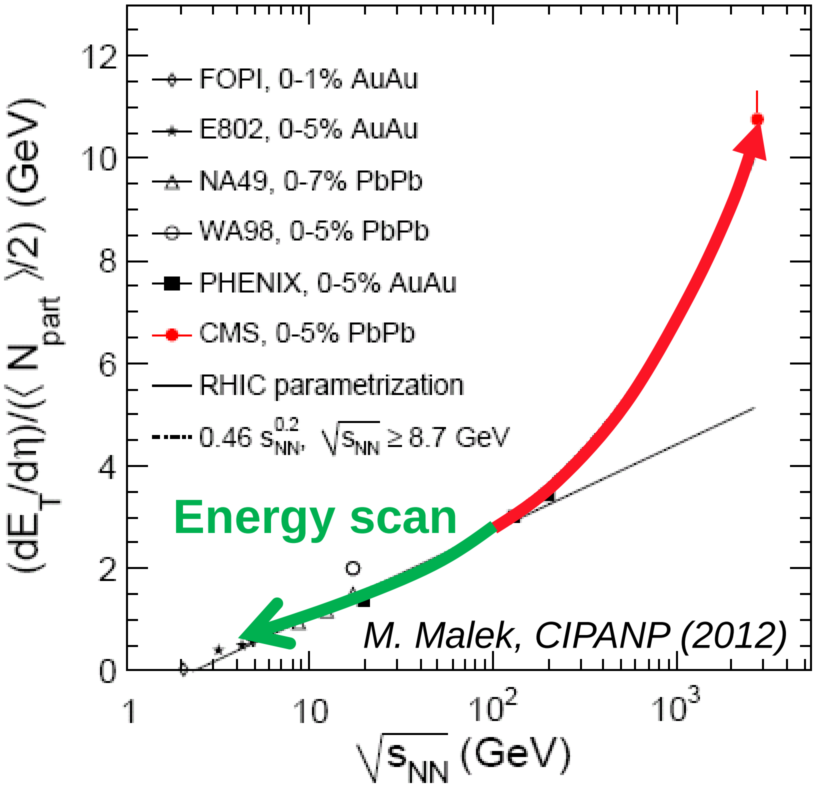
- **Location of the critical End point (CEP)?**
- **Location of phase coexistence regions?**
- **Detailed properties of each phase?**

All are fundamental to the phase diagram of any substance

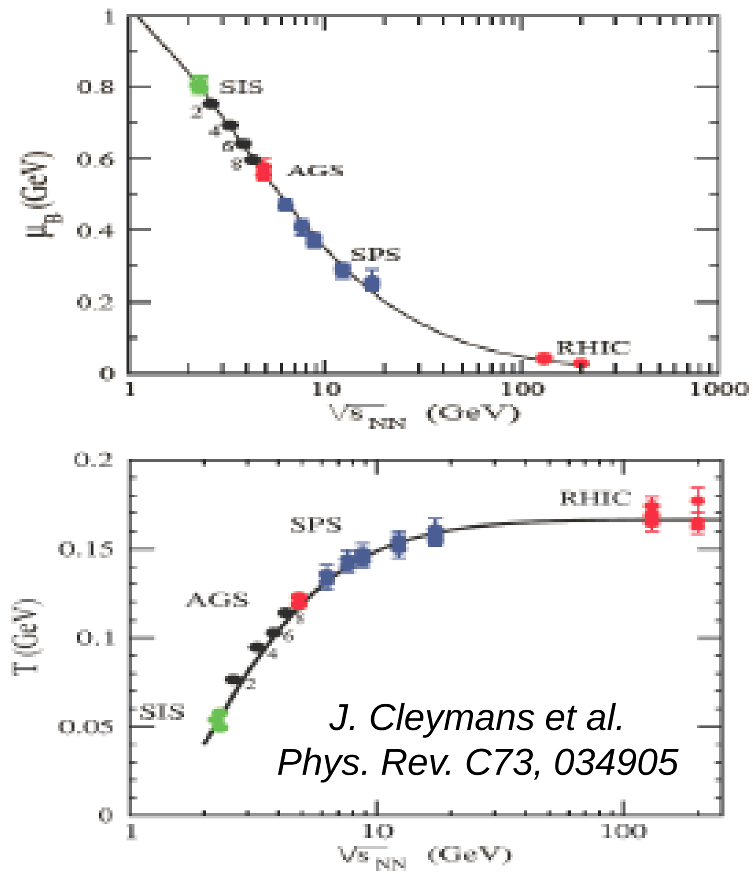
*Measurements which span a broad range of the **(T, μ_B)-plane** are essential for detailed studies of the phase diagram*

A Current Strategy

Exploit the RHIC-LHC beam energy lever arm



(μ_B,*T*) at freeze-out



- ***LHC → access to high T and small μ_B***
- ***RHIC → access to different systems and a broad domain of the (μ_B,T)-plane***

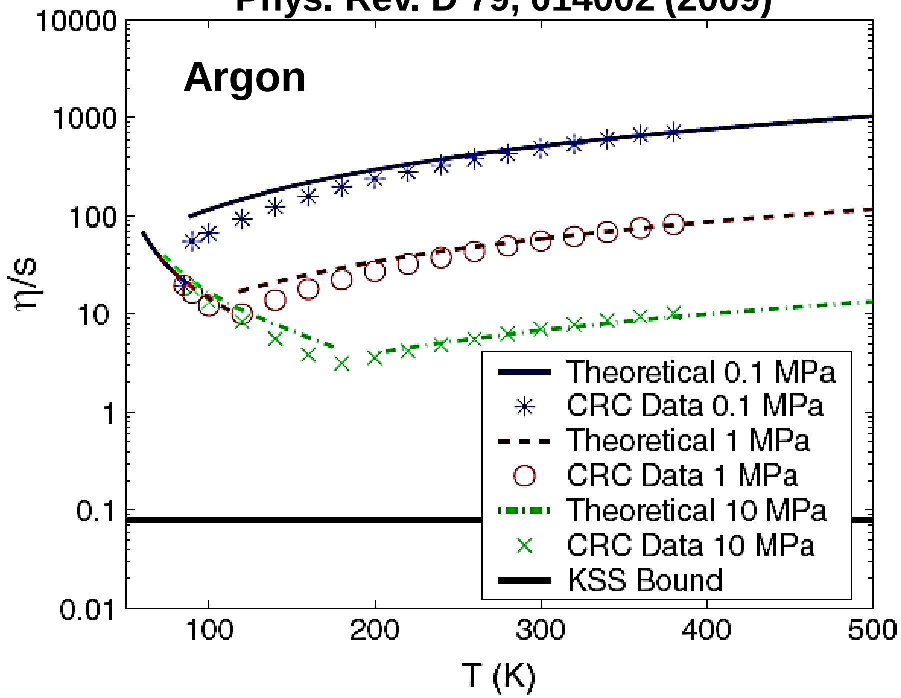
$RHIC_{BES}$ to LHC → ~360 $\sqrt{s_{NN}}$ increase

- ***LHC + BES → access to an even broader domain of the (μ_B,T)-plane***

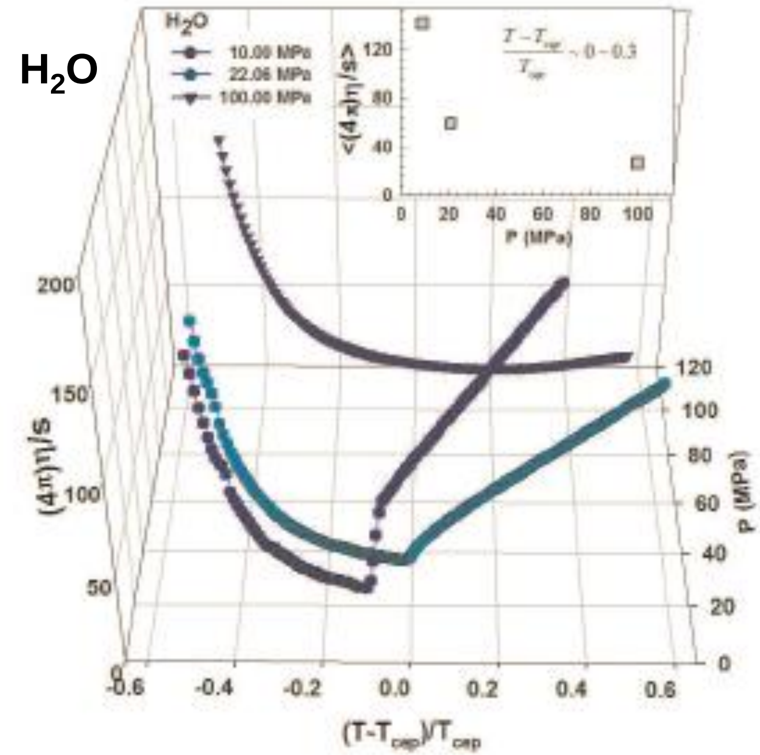
Challenge → identification of robust signals

Possible signals

Csernai et. al,
Phys.Rev.Lett. 97 (2006) 152303
A. Dobado et. al,
Phys. Rev. D 79, 014002 (2009)



Lacey et. al,
Phys. Rev.Lett. 98 (2007) 092301
arXiv:0708.3512 ***(2008)***



At the CEP or close to it, anomalies in the dynamic properties of the medium can drive abrupt changes in transport coefficients

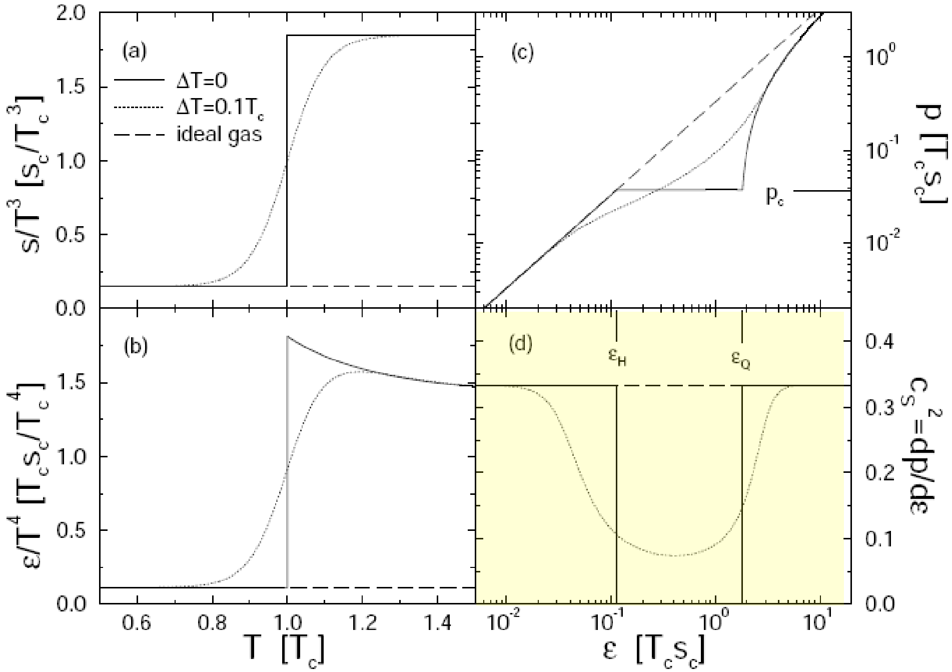
Anisotropic flow (v_n) measurements are an invaluable probe

Possible signals

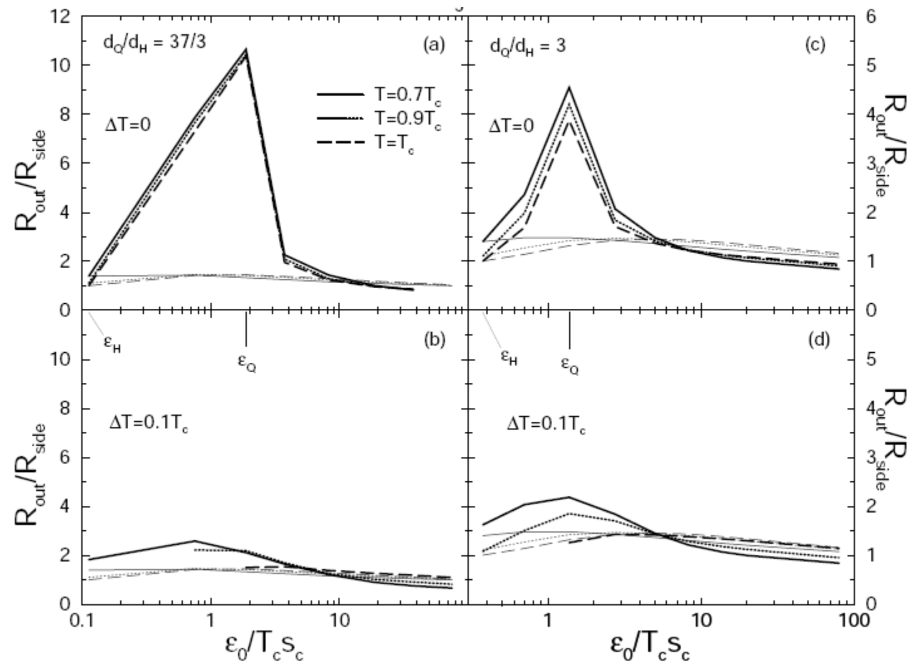
Collapse of directed flow

H. Stoecker, NPA 750, 121 (2005)

Dirk Rischke and Miklos Gyulassy
Nucl.Phys.A608:479-512,1996



Dirk Rischke and Miklos Gyulassy
Nucl.Phys.A608:479-512,1996



In the vicinity of a phase transition or the CEP, the sound speed is expected to soften considerably.

In the vicinity of a phase transition or the CEP anomalies in the space-time dynamics can enhance the time-like component of emissions.

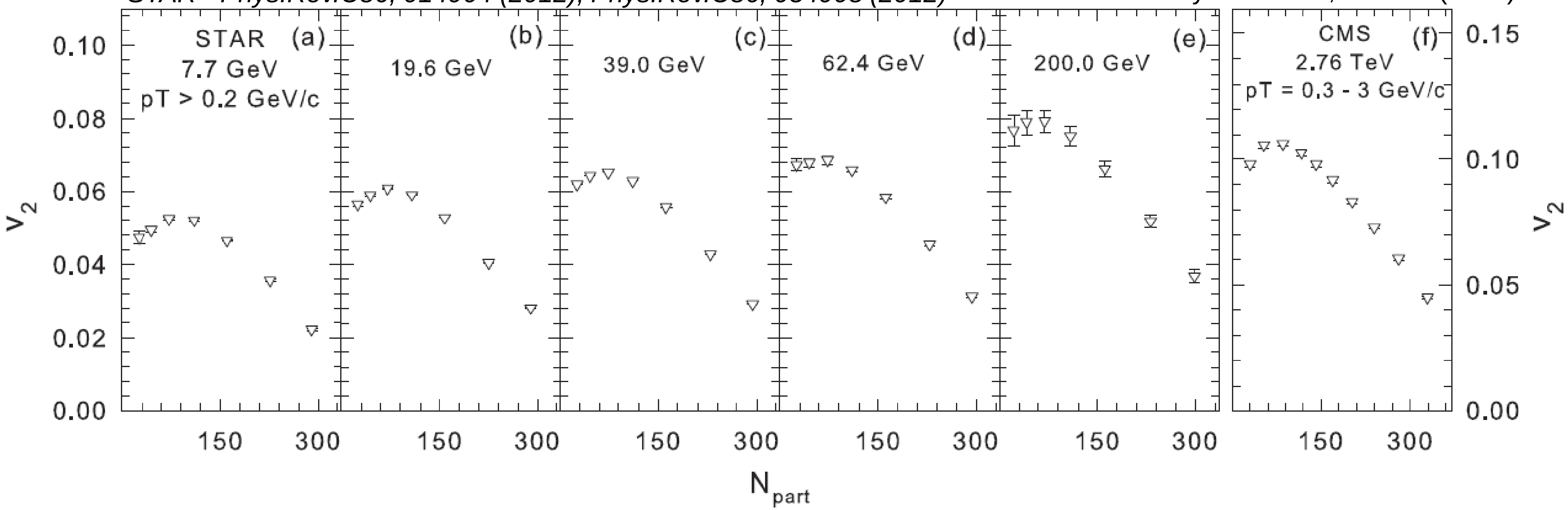
v_1 and HBT measurements are invaluable probes

Anisotropic flow Measurements

Lacey et. al, Phys.Rev.Lett. 112 (2014) 082302

STAR - Phys.Rev.C86, 014904 (2012); Phys.Rev.C86, 054908 (2012)

CMS - Phys.Rev.**C87**, 014902 (2013)



- ***An extensive set of flow measurements now span a broad range of beam energies (T, μ_B).***

HBT Measurements

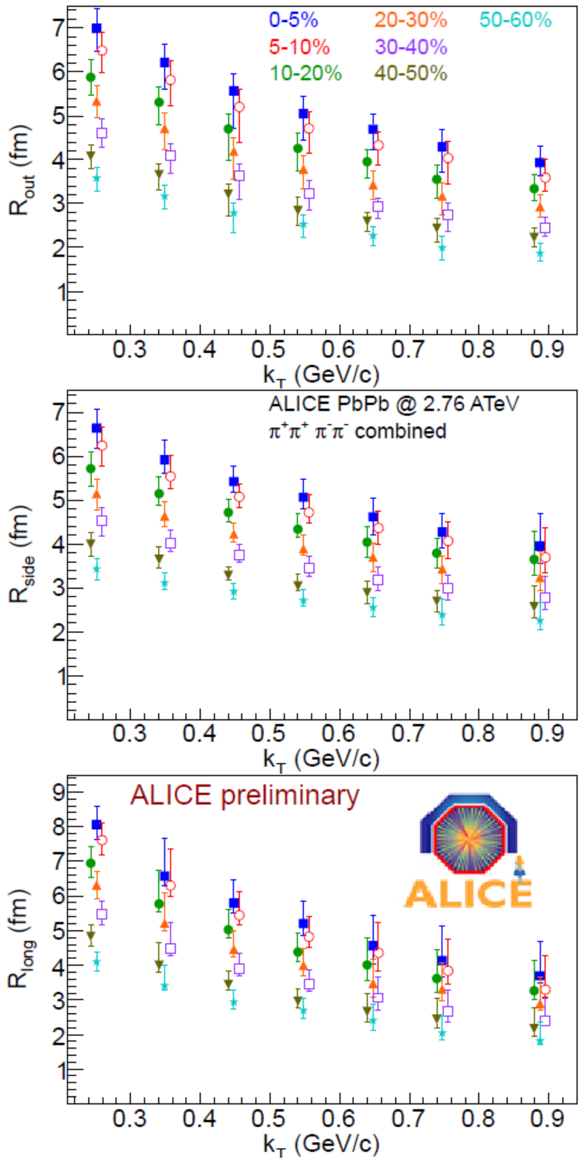
For detailed presentations of PHENIX data

See talks by:

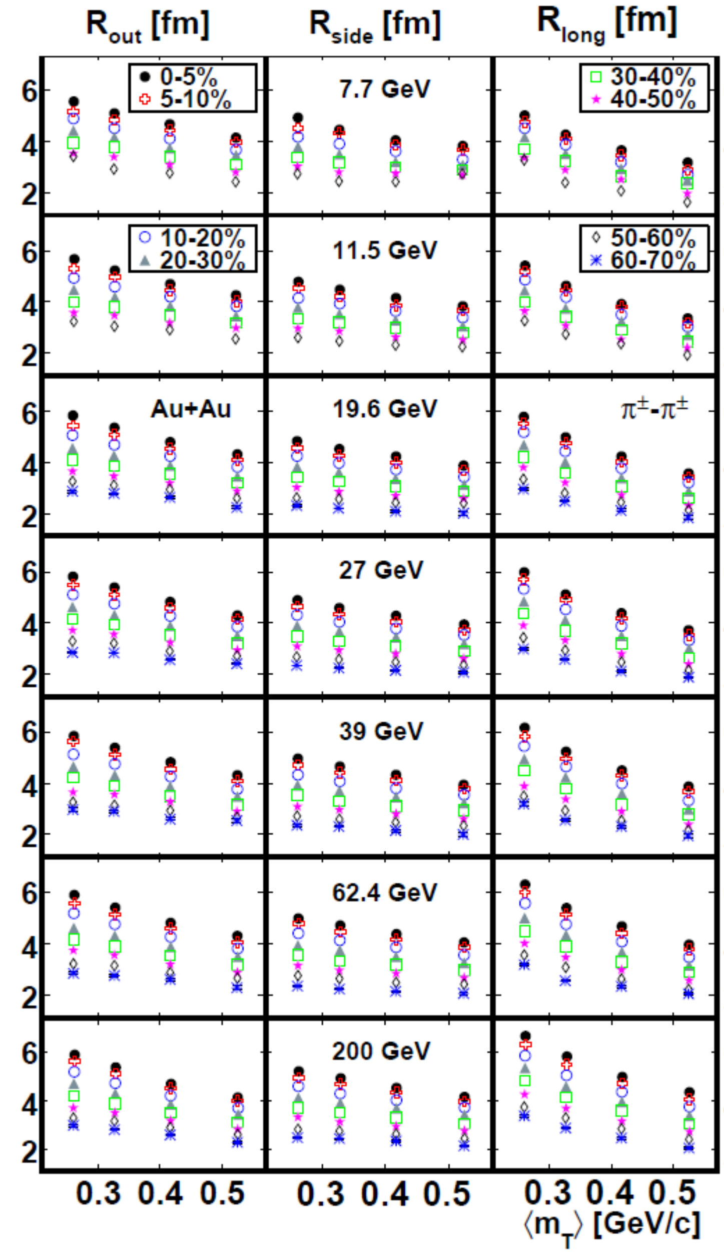
Ron Soltz
Tue.
15:00 - 15:20
Helium
Darmstadtium

Nuggehalli Ajitanand
Wed.
12:30 - 12:50
Europium
Darmstadtium

ALICE -PoS**WPCF2011**



STAR - 1403.4972



Exquisite data set for combined RHIC-LHC results?

Acoustic Scaling

Essential Questions

I. *Can the wealth of data be understood in a consistent framework?*

II. *If it can, what new insight/s are we afforded?*

- *Do we see evidence for the CEP?*

YES!

I. *Expansion dynamics is pressure driven and is therefore acoustic!*

- *This acoustic property leads to several testable scaling predictions for anisotropic flow and HBT*

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

Staig & Shuryak
arXiv:1008.3139

Lacey et. al, arXiv:1301.0165

$$t \propto \bar{R}$$

$$R_{out}, R_{side}, R_{long} \propto \bar{R}$$

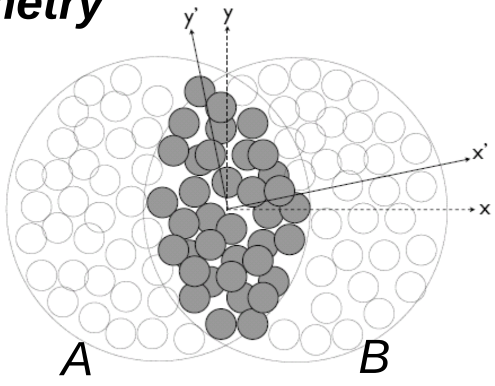
$^1/_{\bar{R}}$ *scaling for anisotropic flow*

$\bar{R}$ *scaling for the HBT radii*

These scaling properties are evidenced by viscous hydrodynamics

Geometric quantities for scaling

Geometry



Phys. Rev. C 81, 061901(R) (2010)

$$S_{nx} \equiv S_n \cos(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\cos(n\phi)$$

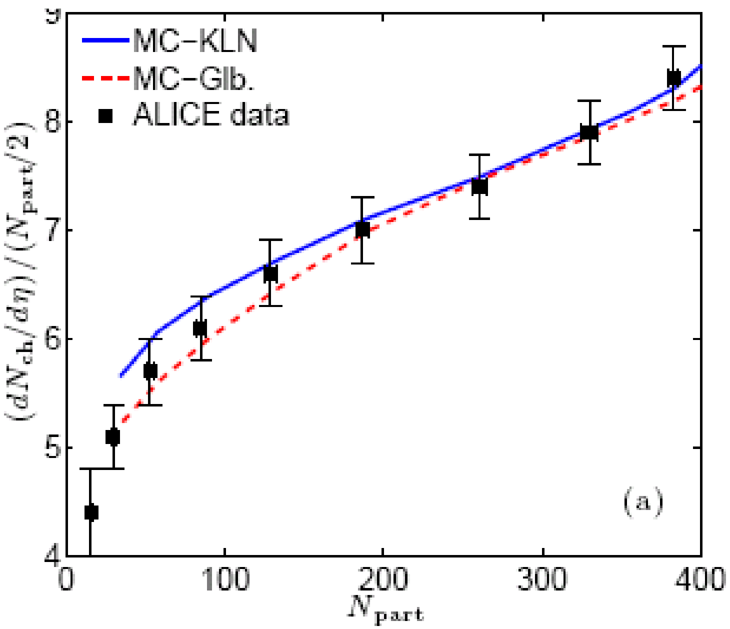
$$S_{ny} \equiv S_n \sin(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\sin(n\phi),$$

$$\Psi_n^* = \frac{1}{n}\tan^{-1}\left(\frac{S_{ny}}{S_{nx}}\right)$$

$$\varepsilon_n = \left\langle \cos n\left(\phi - \psi_n^*\right)\right\rangle$$

$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

arXiv:1203.3605



σ_x & σ_y → RMS widths of density distribution

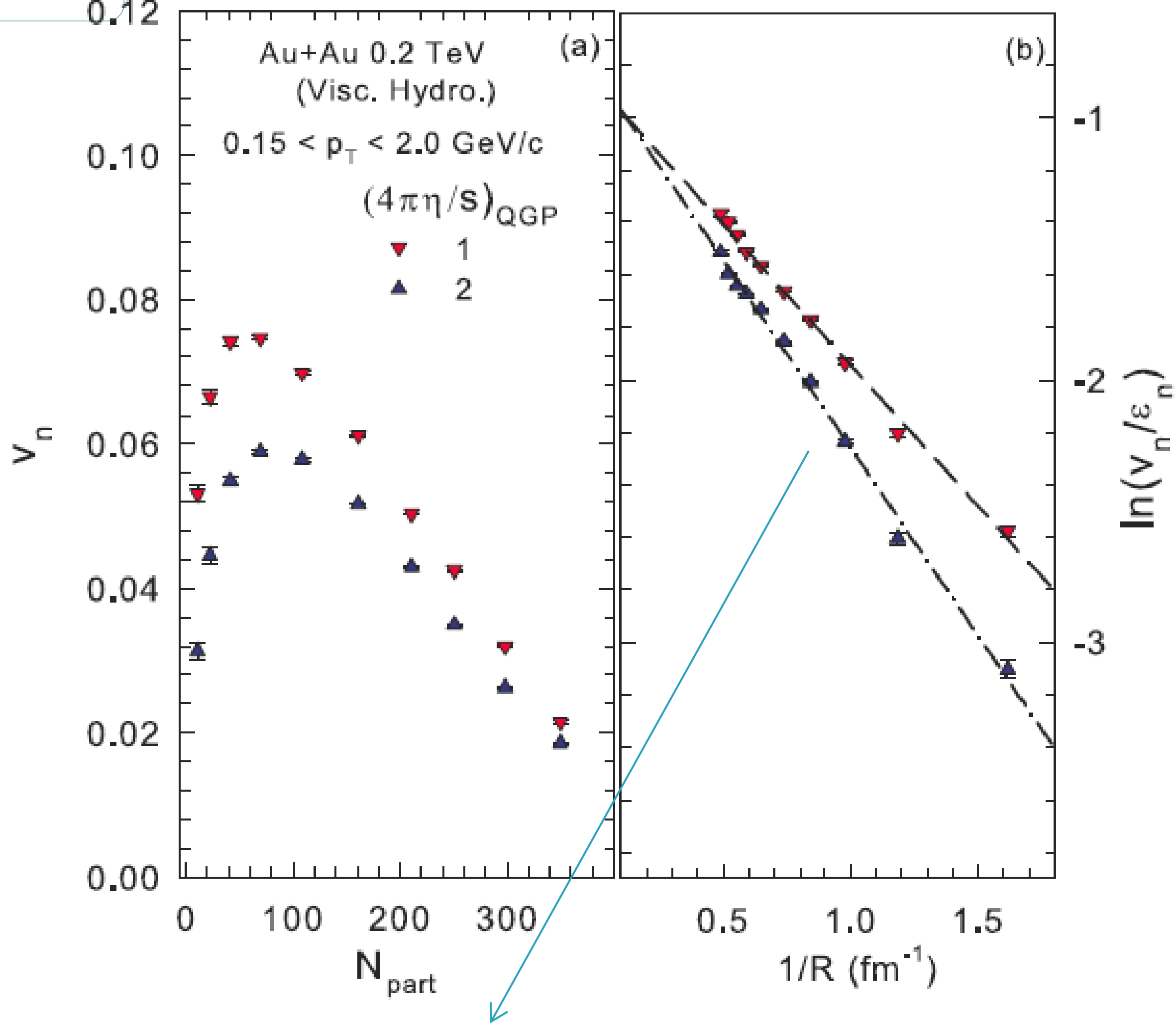
- ***Geometric fluctuations included***
- ***Geometric quantities constrained by multiplicity density.***

$1/\bar{R}$ scaling of anisotropic flow

- Viscous Hydrodynamics

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

✓ **Characteristic** ***acoustic scaling validated for viscous hydrodynamics***



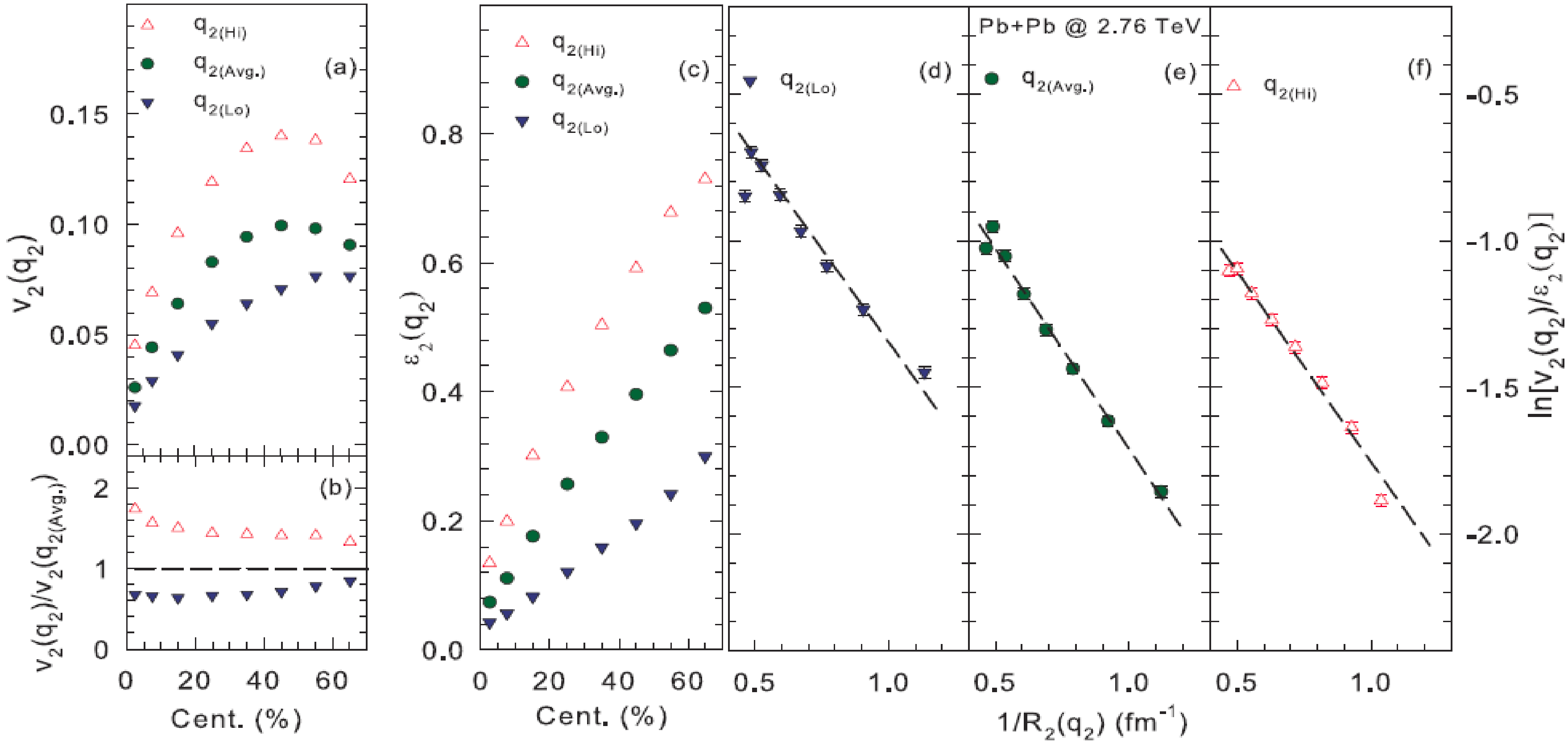
✓ ***viscous coefficient β′′ shows clear sensitivity to η/s***

Scaling properties of flow

$$Q_{n,x} = \sum_i^M \cos(n\phi_i); \; Q_{n,y} = \sum_i^M \sin(n\phi_i)$$

$$q_n = Q_n/\sqrt{M},$$

Acoustic Scaling of shape-engineered events



✓ **Characteristic $1/\bar{R}$ viscous damping validated for different event shapes at the same centrality**

✓ ***A strong constraint for initial-state models and η/s***

✓***4πη/s for RHIC plasma ~ 1.3 ± 0.2***

✓***4πη/s for LHC plasma ~ 2.2 ± 0.2***

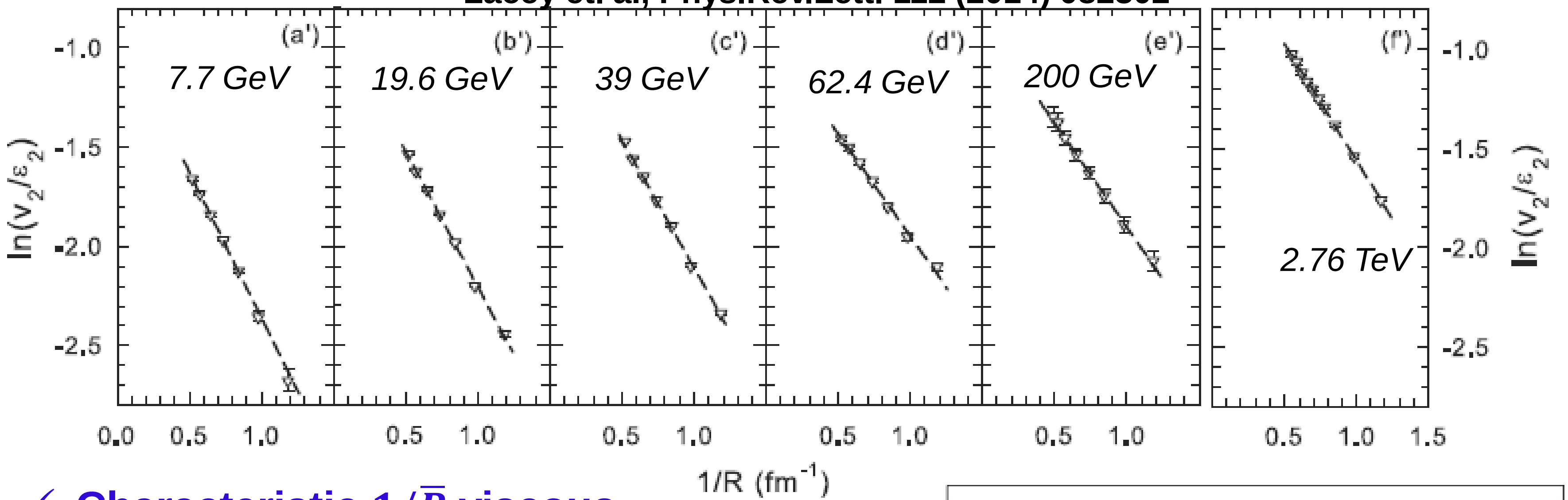
} *Following calibration*

Scaling properties of flow

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

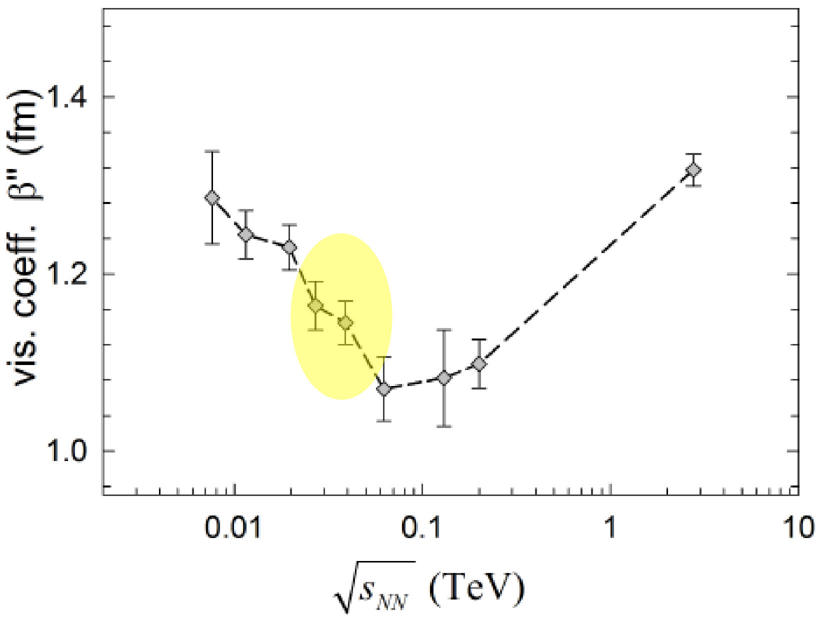
Acoustic Scaling – $\frac{1}{\bar{R}}$ Scaling for the Beam Energy Scan

Lacey et. al, Phys.Rev.Lett. 112 (2014) 082302



- ✓ **Characteristic $1/\bar{R}$ viscous damping validated across beam energies**
- ✓ **First experimental indication for *η/s variation in the* (T, μ_B)-plane**
- ✓ **CEP?**

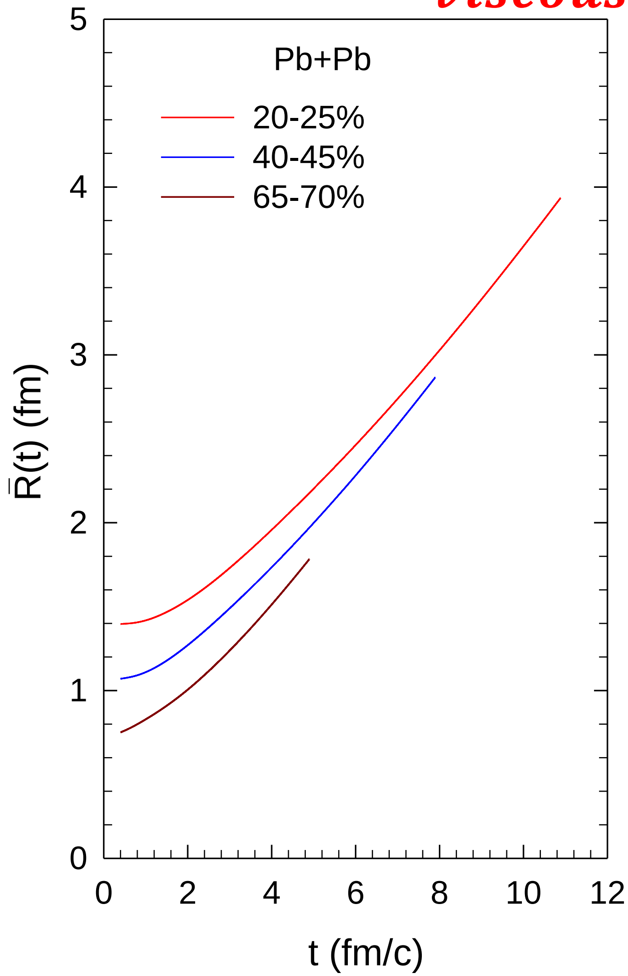
HBT should show complimentary signals for similar $\sqrt{s_{NN}}$



Scaling properties of HBT

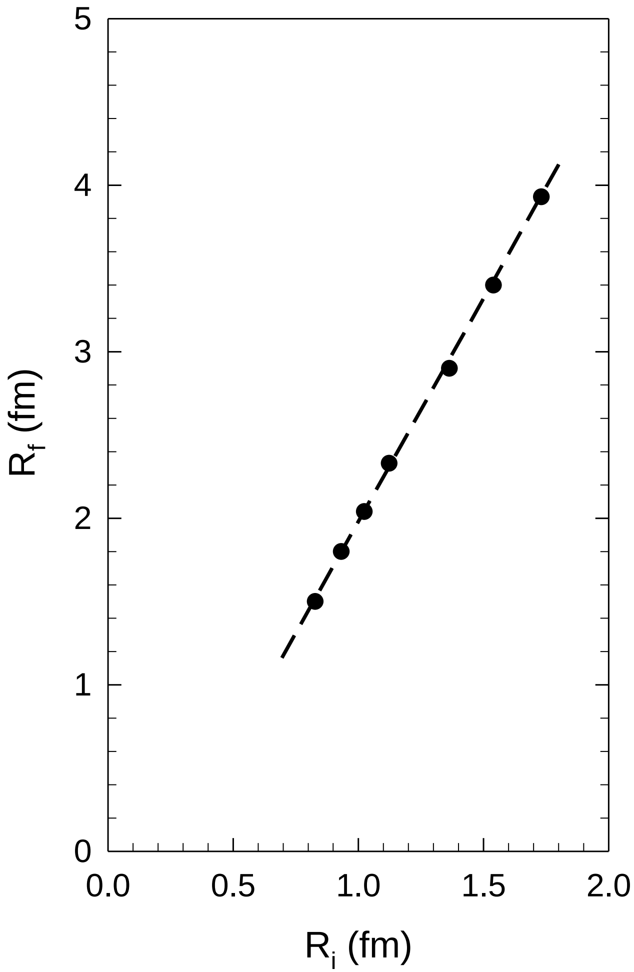
Viscous Hydrodynamics – B. Schenke

✓ **Characteristic** *acoustic scaling validated for viscous hydrodynamics*



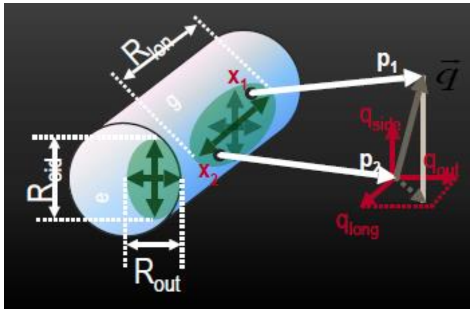
Freeze-out time varies with initial size

$t \propto \bar{R}$



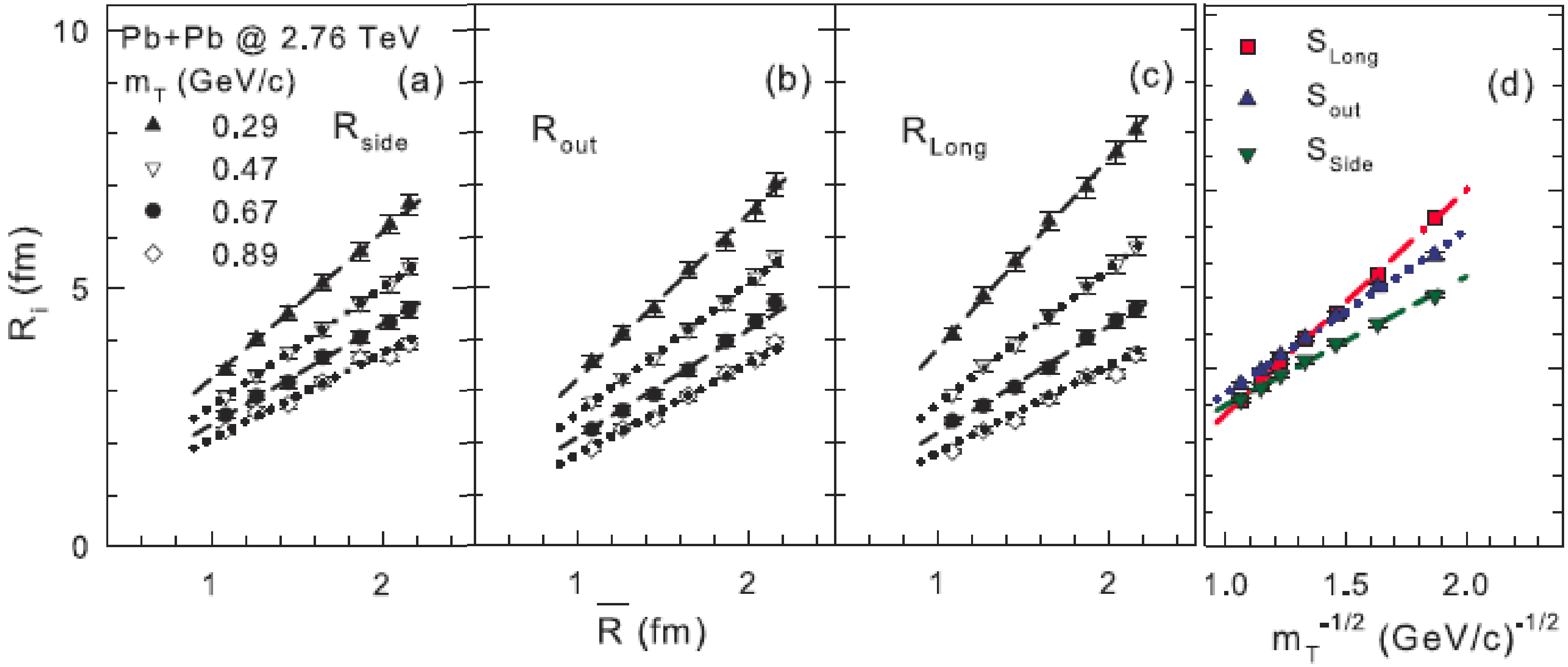
Freeze-out transverse size proportional to initial transverse size

Acoustic Scaling of HBT Radii



$$t \propto \bar{R}$$

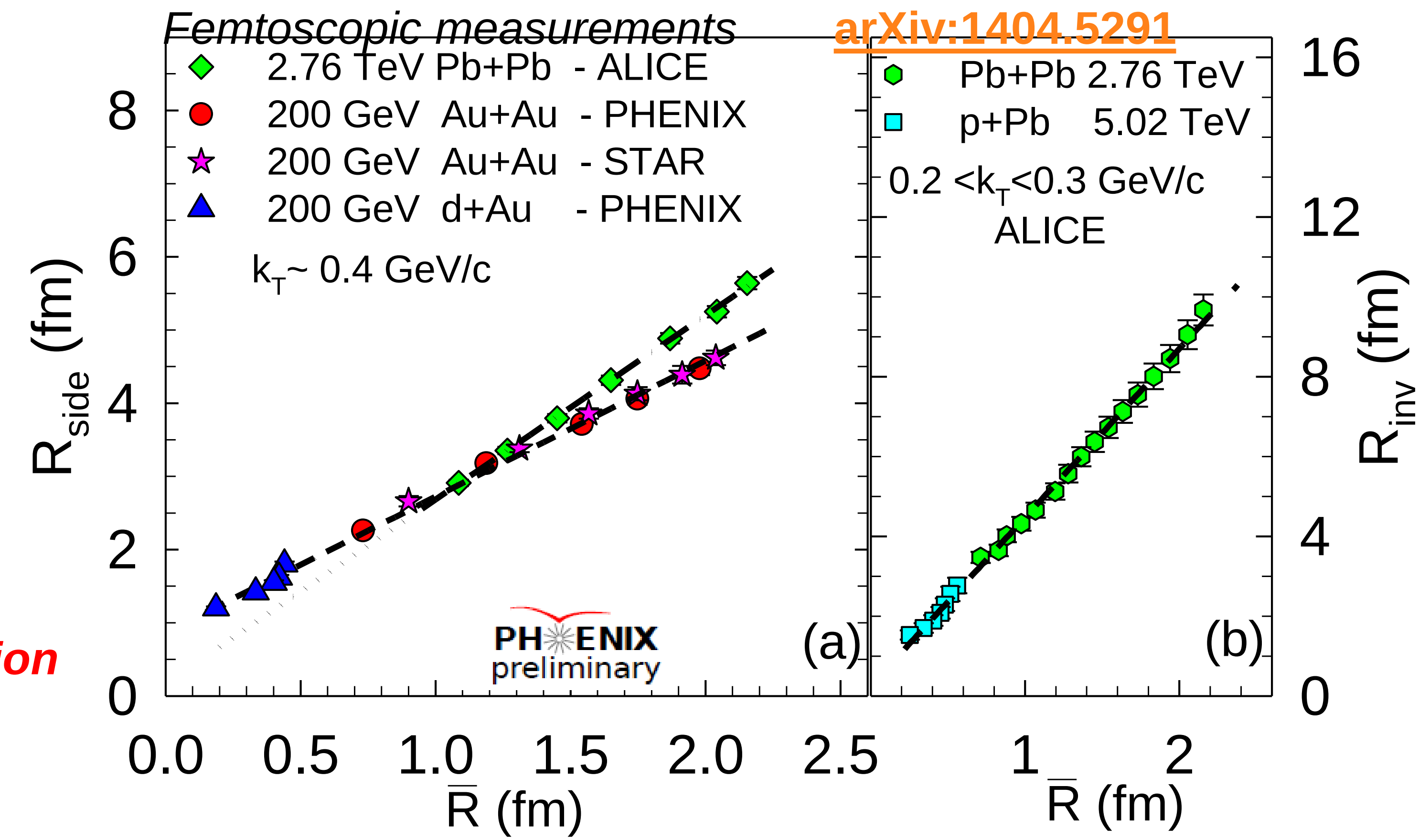
$$R_{out}, R_{side}, R_{long} \propto \bar{R}$$



- $\bar{R}$ ***and*** m_T ***scaling of the full RHIC and LHC data sets***
- ***The centrality and*** m_T ***dependent data scale to a single curve for each radii.***
- ***Qualitatively similar expansion dynamics at RHIC & LHC***

Acoustic Scaling of HBT Radii

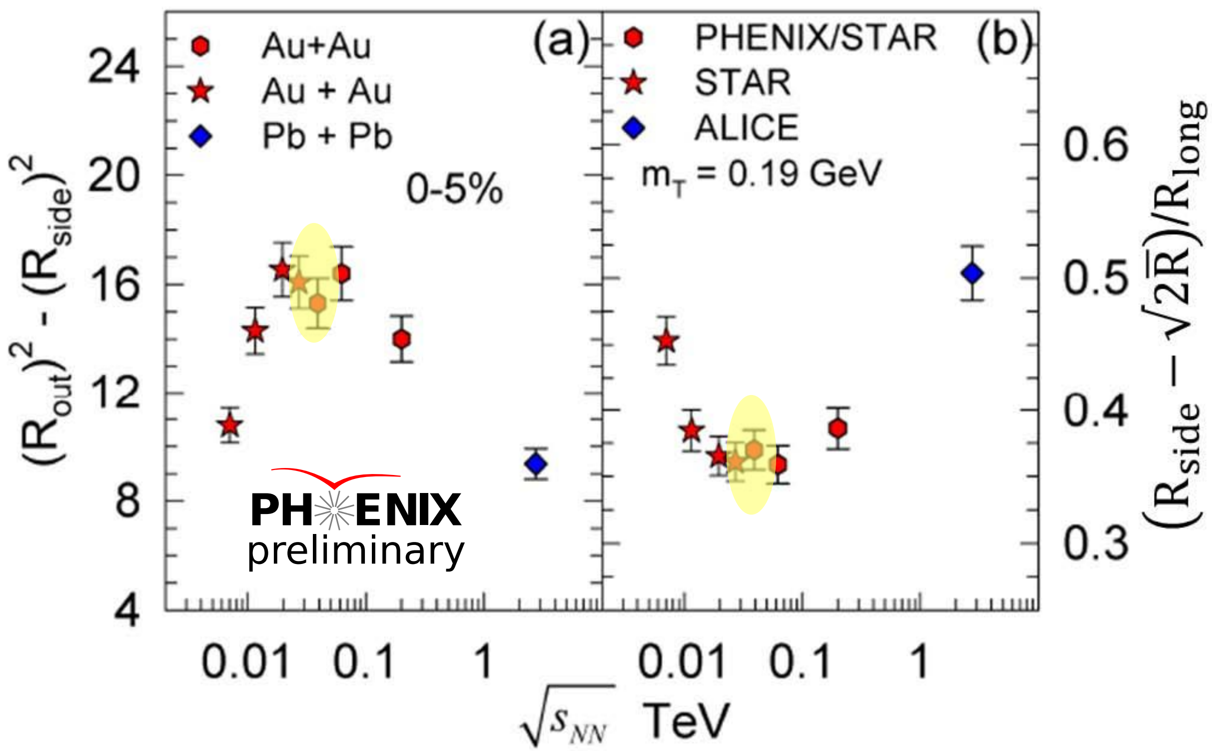
Nuggehalli Ajitanand
Wed.
12:30 - 12:50
Europium
Darmstadtium



- ***Larger expansion rate at the LHC***

$t \propto \bar{R}$ ***exquisitely demonstrated via HBT measurement for several systems***

$\sqrt{s_{NN}}$ dependence of HBT signals



$R_{long} \propto \tau$

$\left(R_{out}^2 - R_{side}^2\right) \propto \Delta\tau$

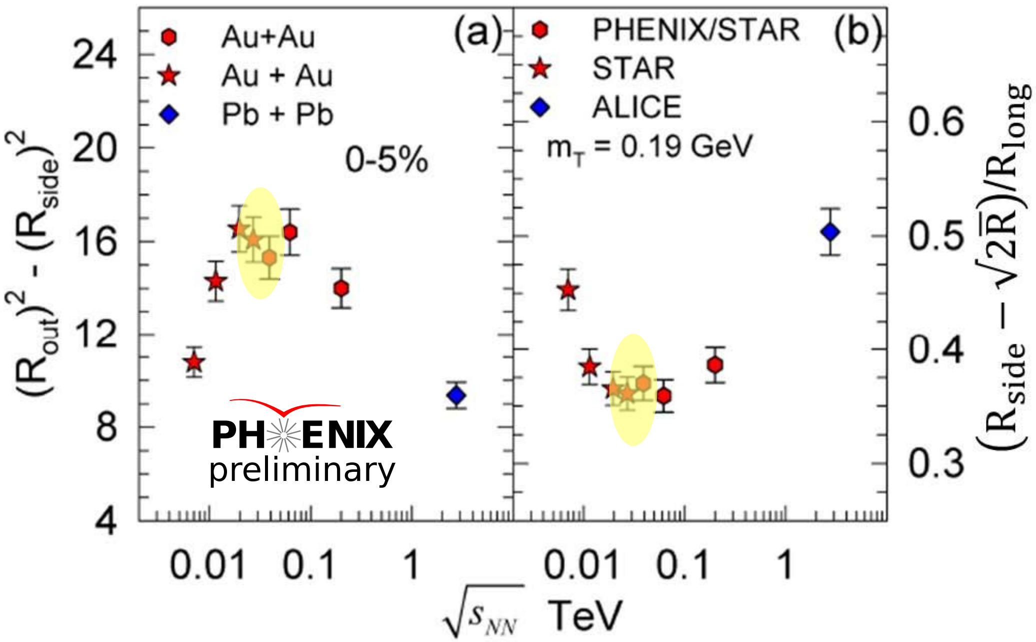
$\left(R - R_i\right) / R_{long} \propto u$

$R_i = \sqrt{2}\bar{R}$

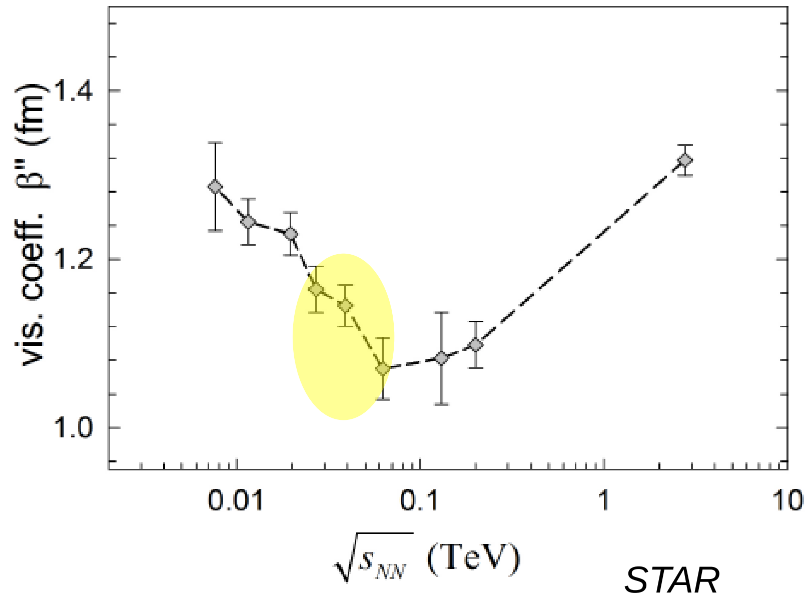
Ron Soltz
Tue.
15:00 - 15:20
Helium
Darmstadtium

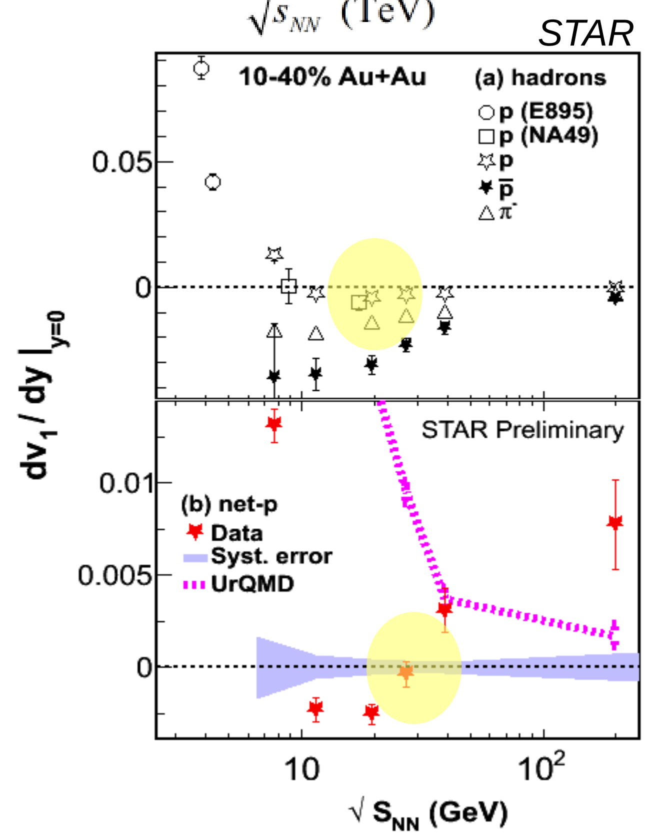
These characteristic patterns signal an important change in the reaction dynamics CEP? Phase transition?

$\sqrt{s_{NN}}$ dependence of HBT signals



Lacey et. al, Phys.Rev.Lett. 112 (2014) 082302





Combined results
→ Strongest indications for the CEP to date!

Epilogue

Acoustic scaling of anisotropic flow and HBT radii *lend profound mechanistic insights, as well as new constraints for key observables*

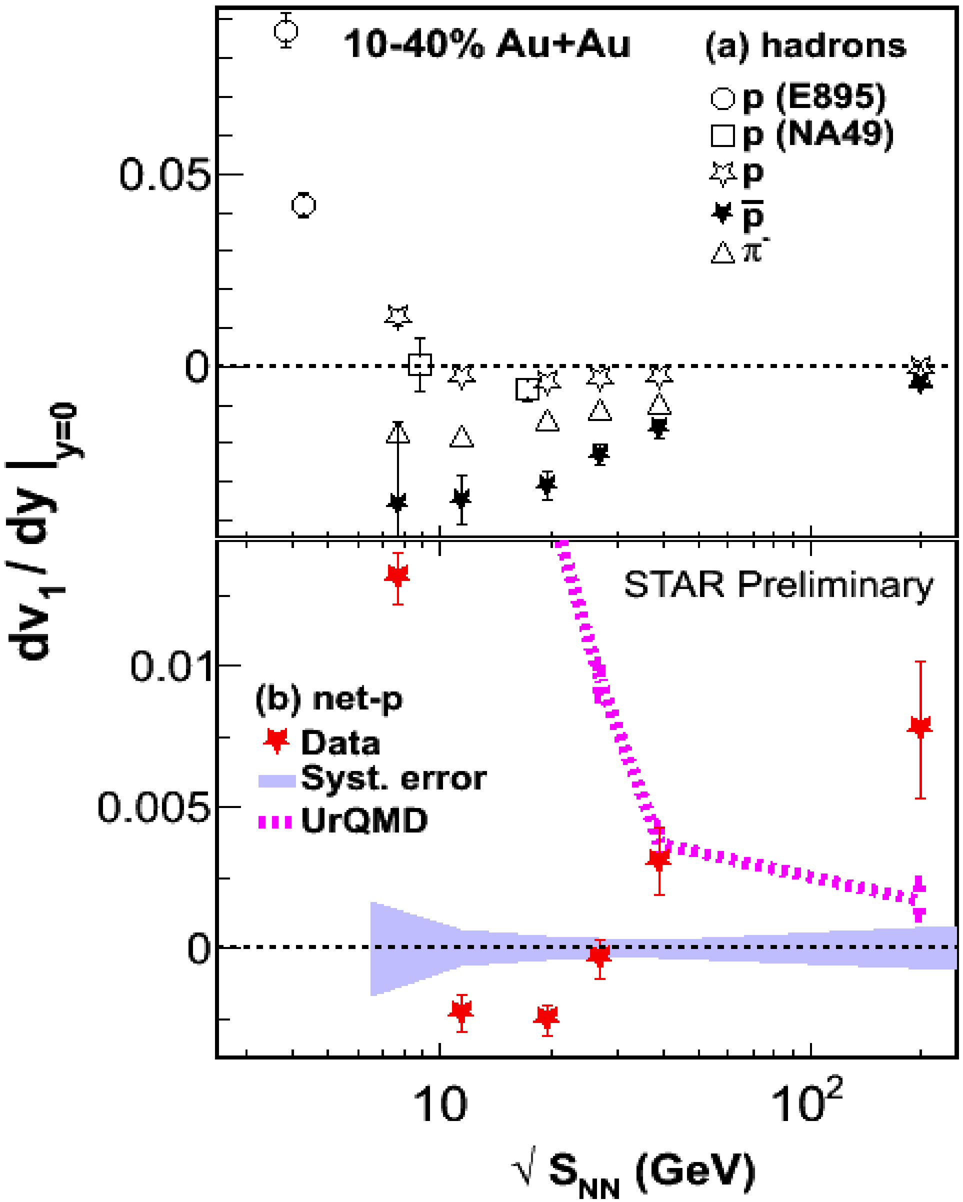
What do we learn?

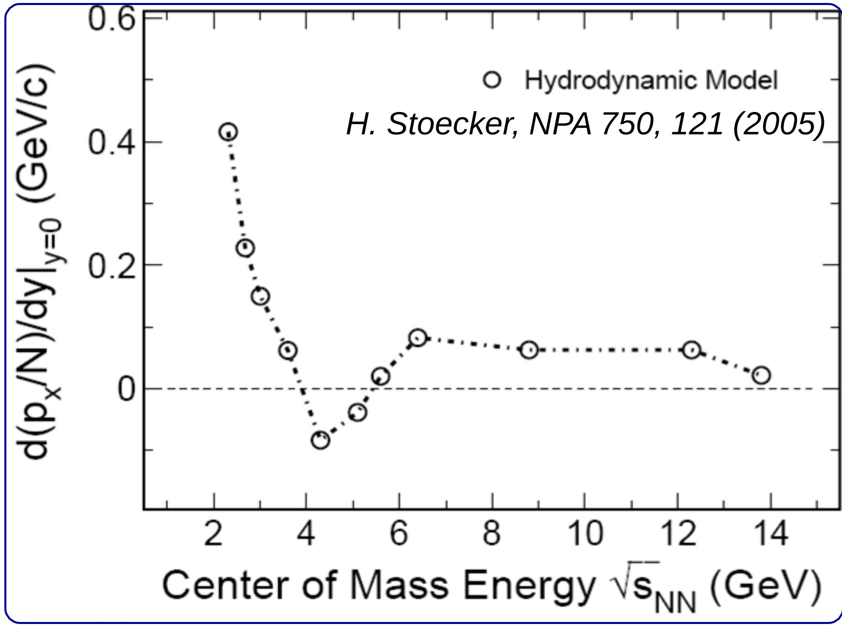
- ***The expansion dynamics is acoustic – "as it should be"***
  - ***Validates expected acoustic scaling of flow and HBT radii***
    - ✓***constraints for 4πη/s & viable initial-state models***
    - ✓***4πη/s for RHIC plasma ~ 1.3 ± 0.2 ~ my 2006 estimate***
    - ✓***4πη/s for LHC plasma ~ 2.2 ± 0.2***
    - ✓***Extraction insensitive to initial geometry model***

- ***Characteristic dependence of viscous coefficient β" $and\ v1, as\ well\ as\ "c_s"\ and\ \Delta\tau$ on $\sqrt{s_{NN}}$ give new constraints which could be an indication for reaction trajectories in close proximity to the CEP?***

End

Directed flow of transported protons

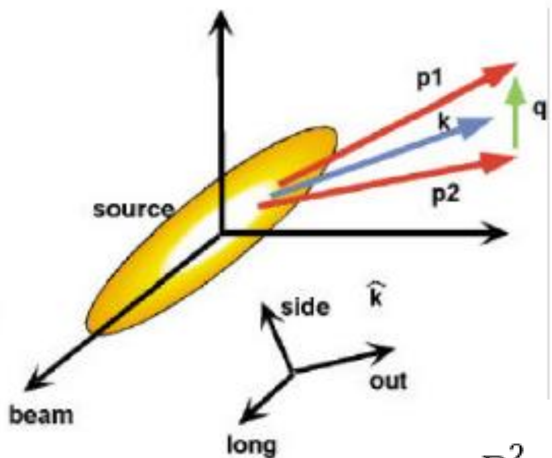




Data qualitatively resembles predictions of a hydrodynamic model with a first-order phase transition

HBT Observables

Chapman, Scotto, and Heinz



$$R_l^2 = \tau_0^2 \frac{T}{m_\perp}\left[1+\left(\frac{1}{2}+\frac{1}{1+\frac{m_\perp}{T}v^2}\right)\frac{T}{m_\perp}\right]$$

$$R_{long} \propto \tau$$

$$R_s^2 = \frac{R^2}{1+(m_\perp/T)v^2} \qquad R_o^2 = \frac{R^2}{1+(m_\perp/T)v^2} + \frac{1}{2}\left(\frac{T}{m_\perp}\right)^2 \beta_\perp^2 \tau_0^2$$

$$\left(R_{out}^2 - R_{side}^2\right) \propto \Delta\tau$$

proxy for the sound speed c_s

$$\left(R - R_i\right)/R_{long} \propto u$$

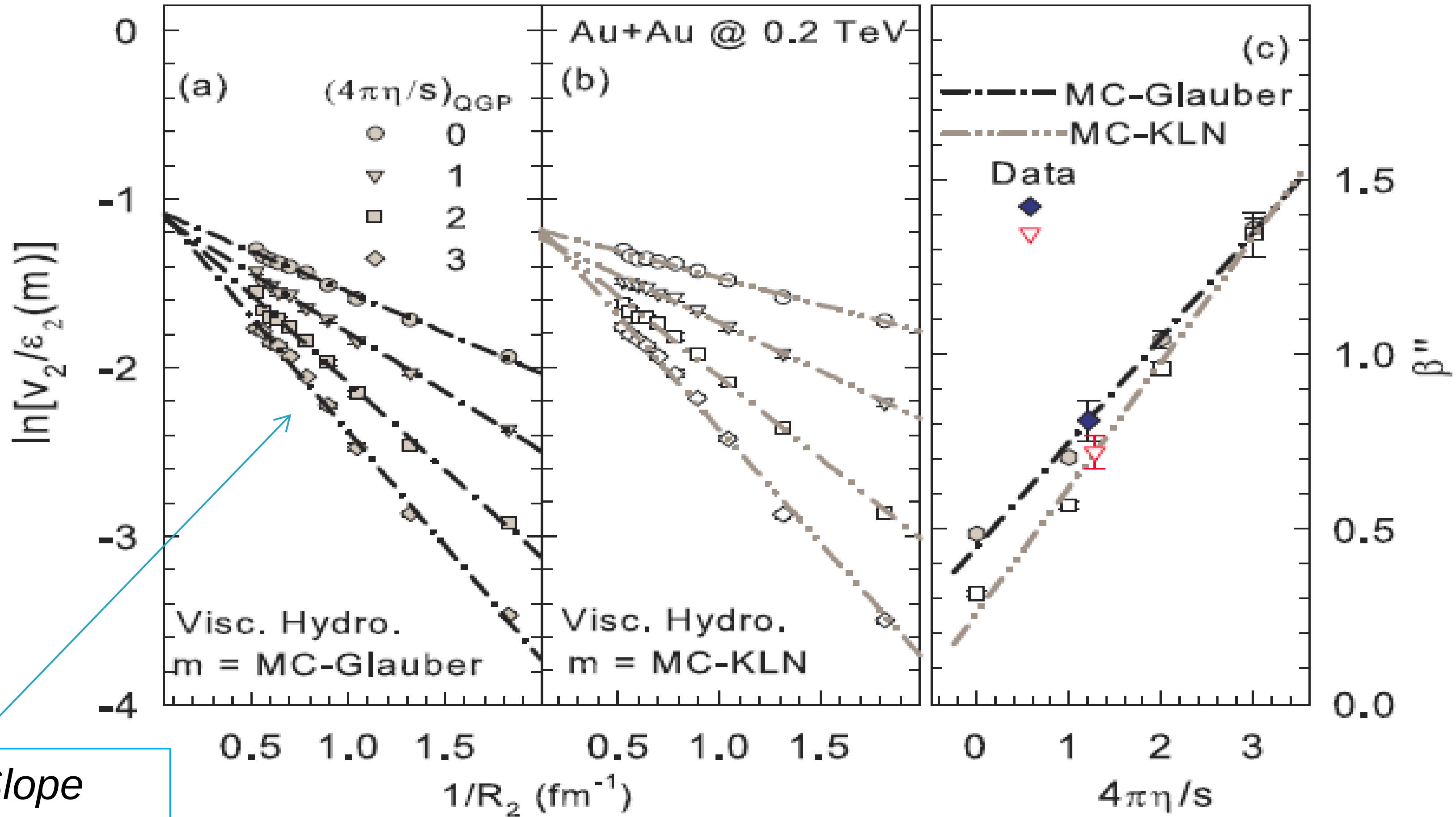
$$R_i = \sqrt{2}\bar{R}$$

estimate for initial size in central events

Study HBT observables as a function of $\sqrt{s_{NN}}$

Extraction of η/s

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$



Slope sensitive to $4\pi\eta/s$

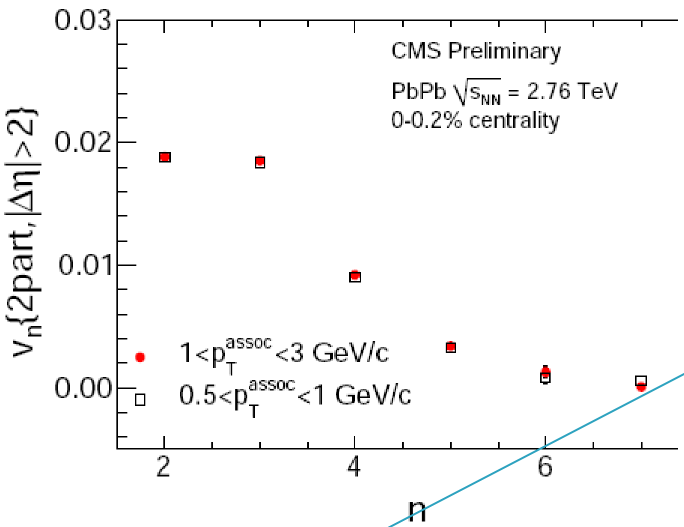
Characteristic $1/\bar{R}$ viscous damping validated in viscous hydrodynamics; calibration → $4\pi\eta/s \sim 1.3 \pm 0.2$

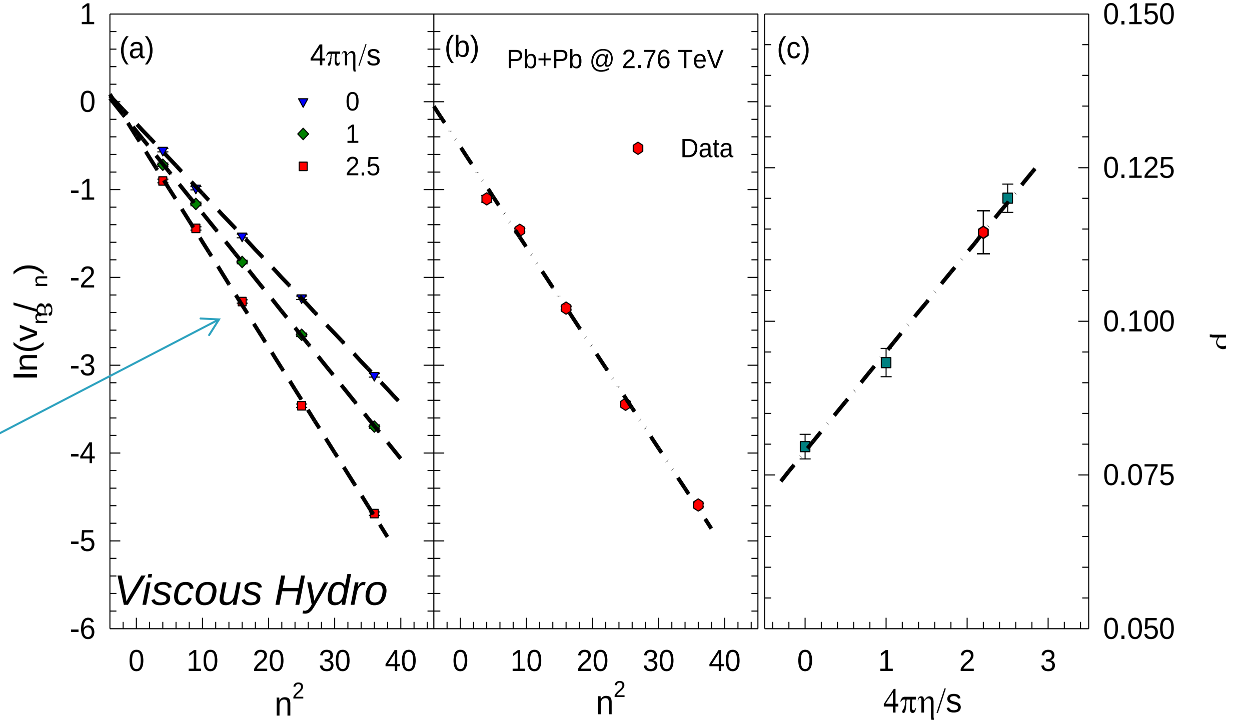
Extracted η/s value insensitive to initial conditions

Extraction of η/s

$$\frac{v_n(p_T)}{\varepsilon_n} \propto \cdot \exp\left(-\beta' n^2\right)$$

arXiv:1301.0165 & CMS PAS HIN-12-011



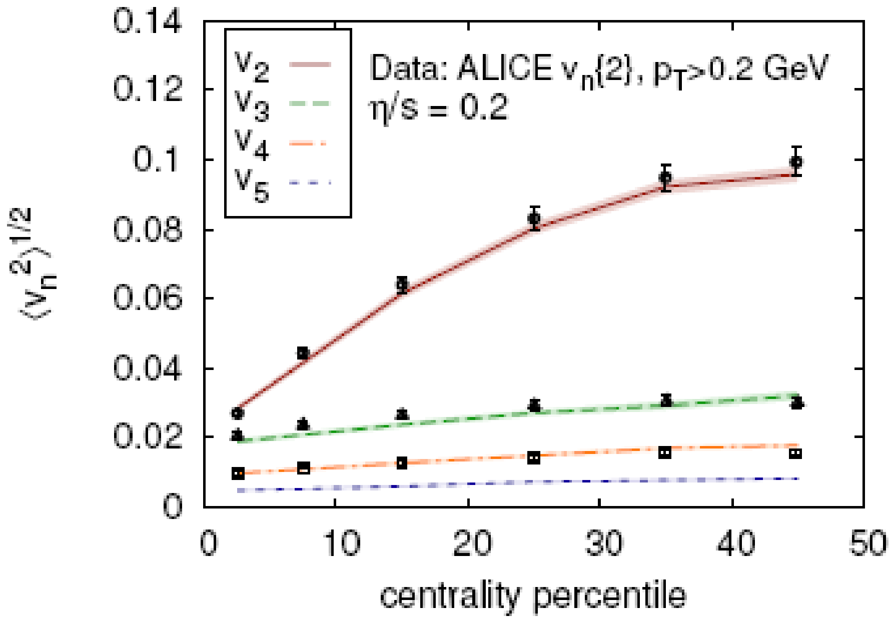


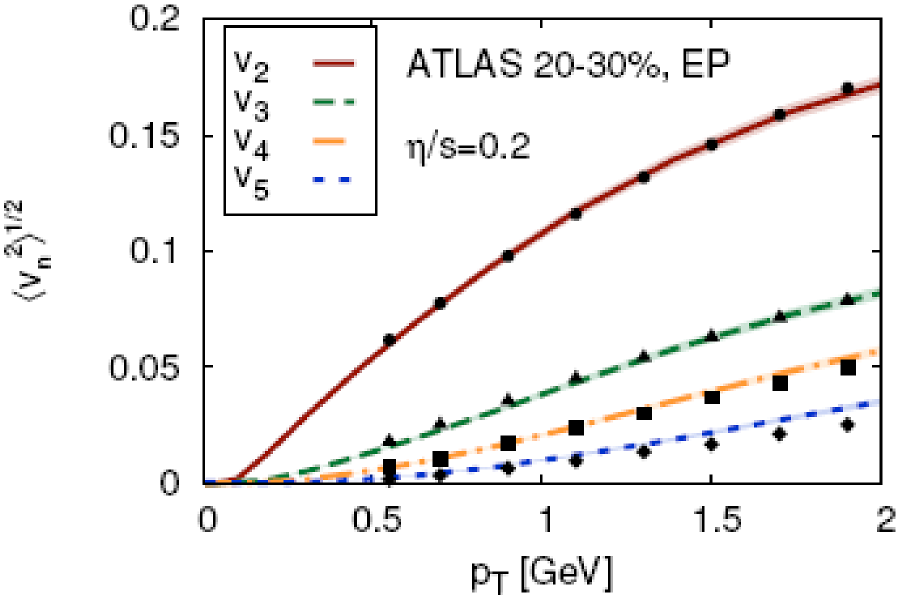
Slope sensitive to η/s

n^2 scaling validated in experiment and viscous hydrodynamics;
calibration → $4\pi\eta/s \sim 2.2 \pm 0.2$
Note agreement with Schenke et al.

Improved Methodology

Bjoern Schenke et. al. **arXiv:1301.5893**





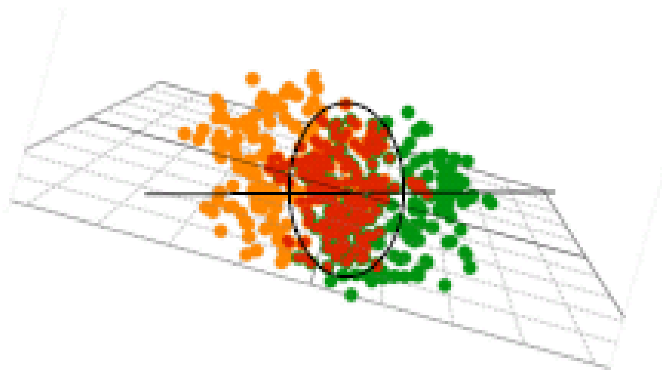
$4\pi\eta/s$ for LHC plasma ~ 2.5

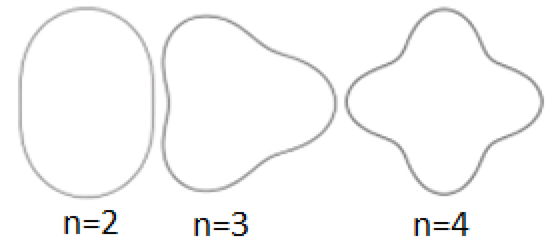
Higher harmonics provide important constraints!

Can we find methodologies and constraints which are insensitive to the initial-state geometry?

Scaling properties of flow

Initial Geometry characterized by many shape harmonics (ε_n) → drive v_n





$$v_n \propto \varepsilon_n$$

Acoustic viscous modulation of v_n

$$\delta T_{\mu\nu}(t,k) = \exp\left(\frac{2}{3}\frac{\eta}{s}k^2\frac{t}{T}\right)\delta T_{\mu\nu}(0)$$

Staig & Shuryak **arXiv:1008.3139**

$$k = n / \bar{R} \qquad t \propto \bar{R}$$

$$\delta T_{\mu\nu}(n,t) = \exp\left(-\beta n^2\right)\delta T_{\mu\nu}(0), \quad \beta = \frac{2}{3}\frac{\eta}{s}\frac{1}{\bar{R}^2}\frac{t}{T},$$

Scaling expectations:

n^2 dependence

$$\frac{v_n(p_T)}{\varepsilon_n} \propto \exp\left(-\beta' n^2\right)$$

v_n is related to v_2

$$\frac{v_n(p_T)}{v_2(p_T)} = \frac{\varepsilon_n}{\varepsilon_2}\cdot\exp\left(-\beta'(n^2-4)\right)$$

System size dependence

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

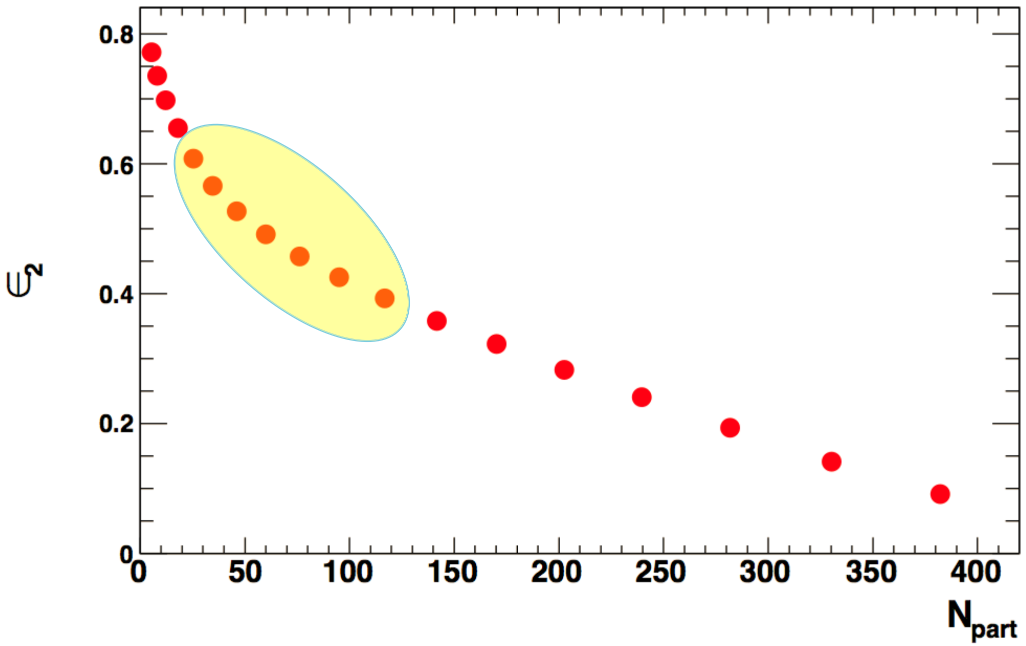
Each of these scaling expectations can been validated

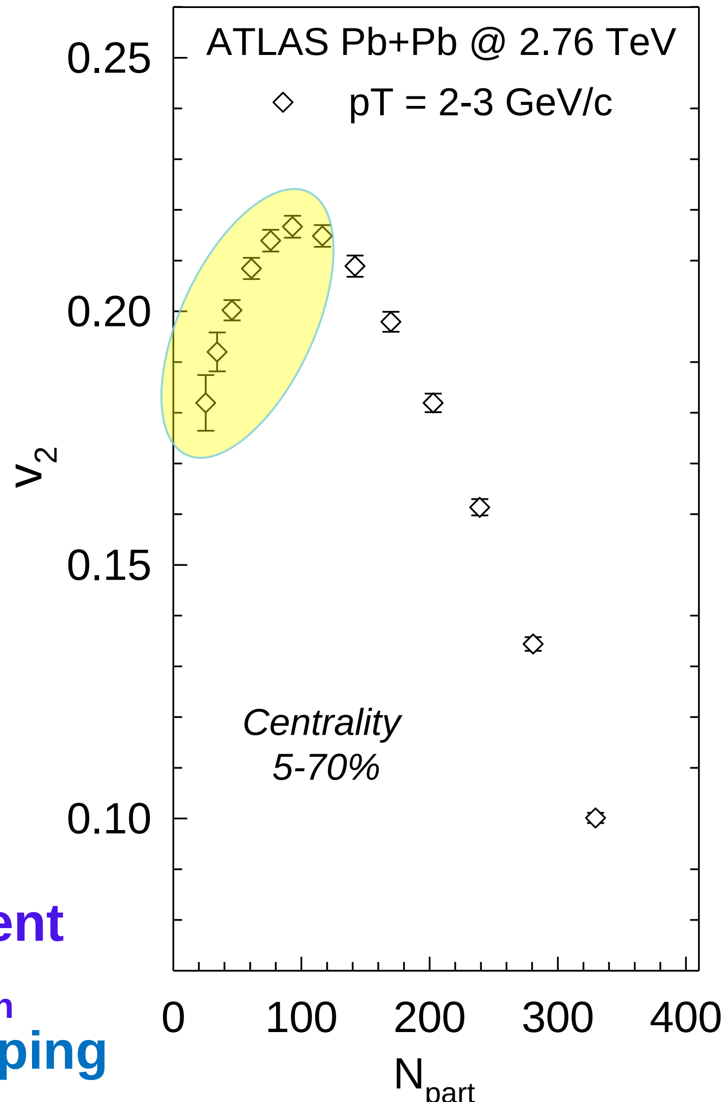
$\eta/s \propto \beta', \beta''$

Scaling properties of flow

Acoustic Scaling – $\frac{1}{\bar{R}}$

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$





- **Eccentricity change <u>alone</u> is not sufficient**

To account for the N_{part} dependence of v_n

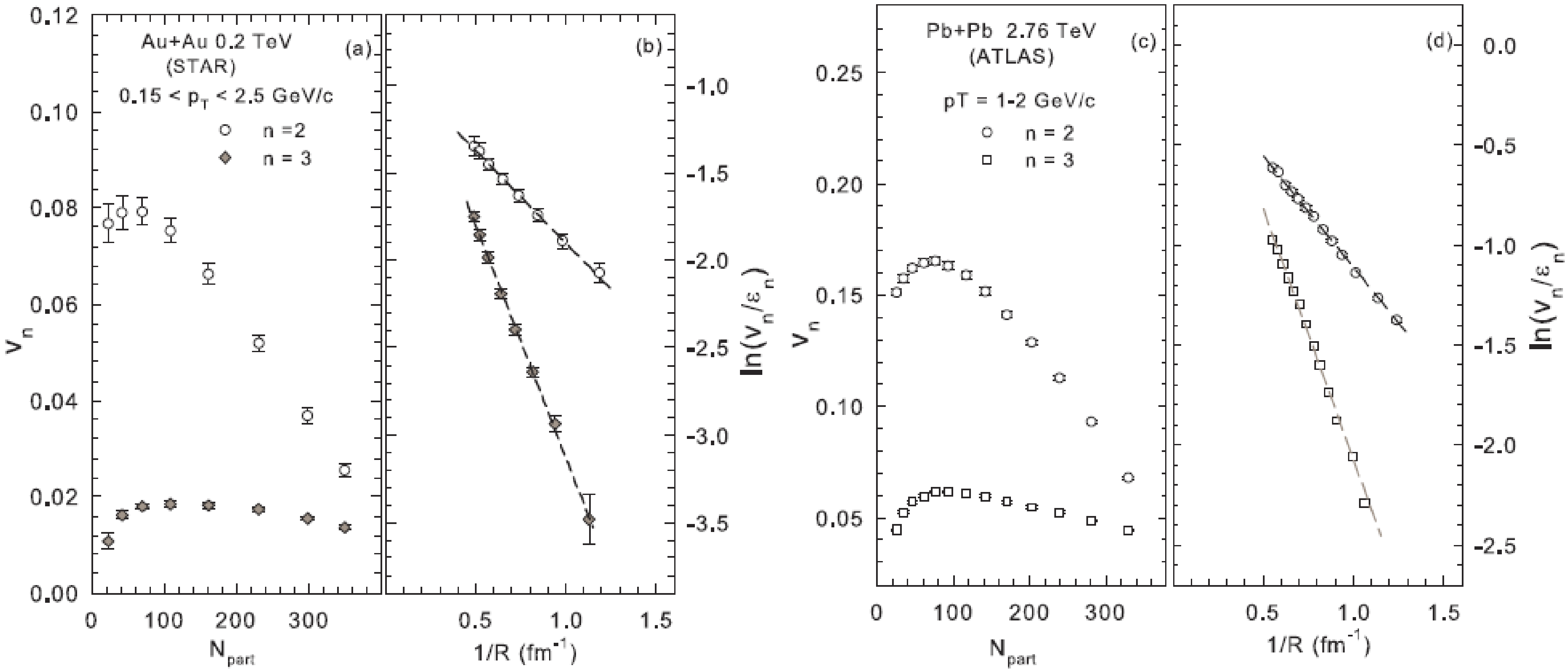
Transverse size ($\bar{R}$) influences viscous damping

✓ **Characteristic $1/\bar{R}$ scaling prediction is non-trivial**

Scaling properties of flow

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

Acoustic Scaling – $\frac{1}{\bar{R}}$



✓ **Characteristic $1/\bar{R}$ viscous damping validated at RHIC & the LHC**

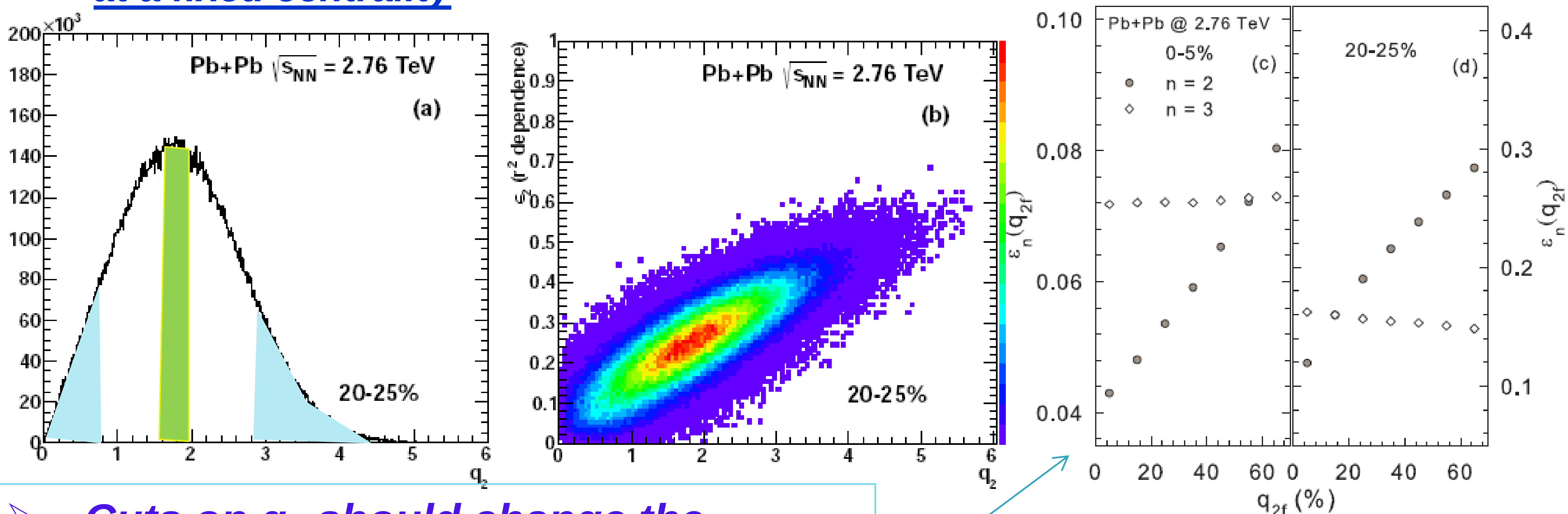
✓ ***A further constraint for η/s***

Shape-engineered events

Shape fluctuations lead to a distribution of the Q vector <u>at a fixed centrality</u>

$$Q_{n,x} = \sum_i^M \cos(n\phi_i);\ Q_{n,y} = \sum_i^M \sin(n\phi_i)$$

$$q_n = Q_n/\sqrt{M},$$



- ***Cuts on q_n should change the magnitudes $\langle \epsilon_n \rangle$, $\langle v_n \rangle$, $\langle R_n \rangle$ at a given centrality due to fluctuations***
- ***These magnitudes can influence scaling***

- ***Note characteristic anti-correlation predicted for $v_3(q_2)$ in mid-central events***

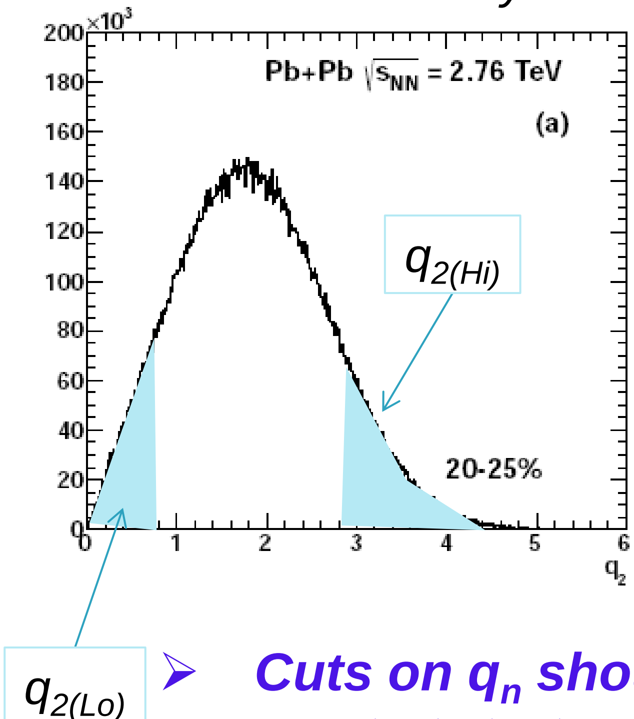
- ***Crucial constraint for initial-geometry models***

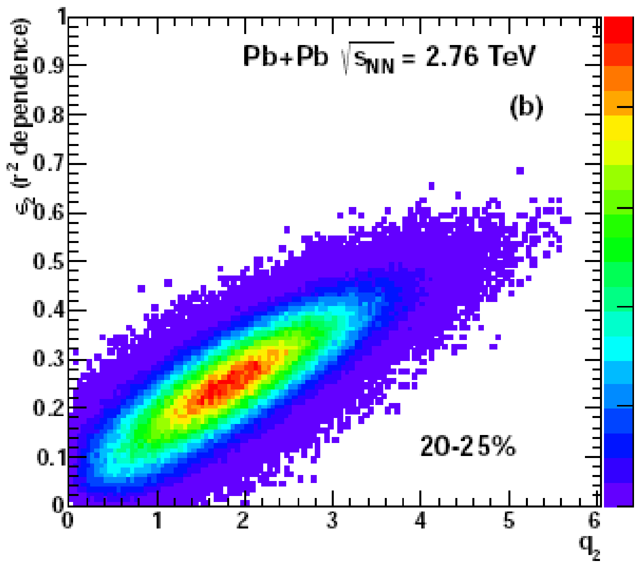
Shape-engineered events

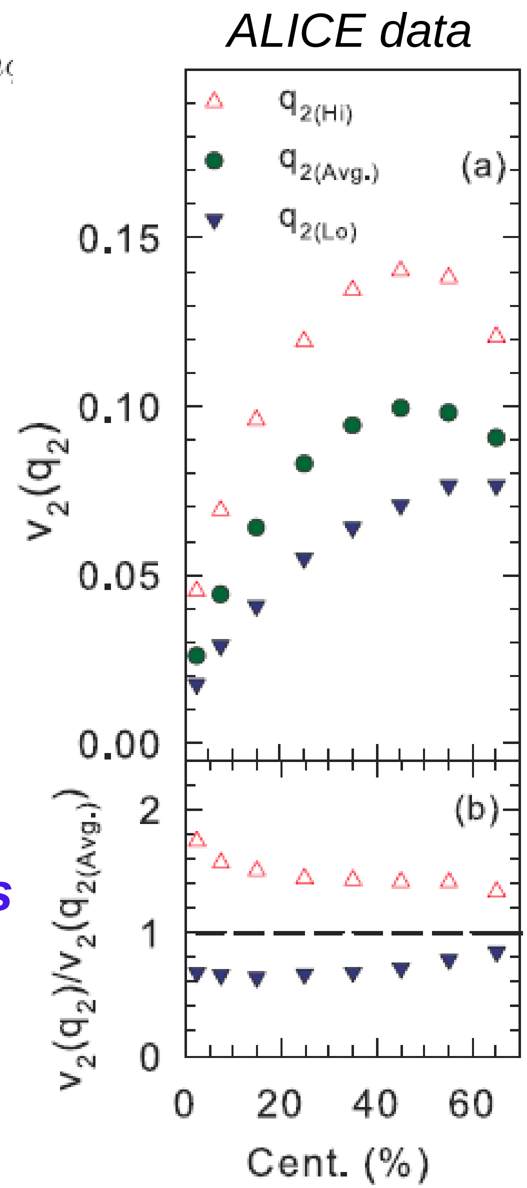
Shape fluctuations lead to a distribution of the Q vector at a fixed centrality

$$Q_{n,x} = \sum_{i}^{M} \cos(n\phi_i);\; Q_{n,y} = \sum_{i}^{M} \sin(n$$

$$q_n = Q_n/\sqrt{M},$$



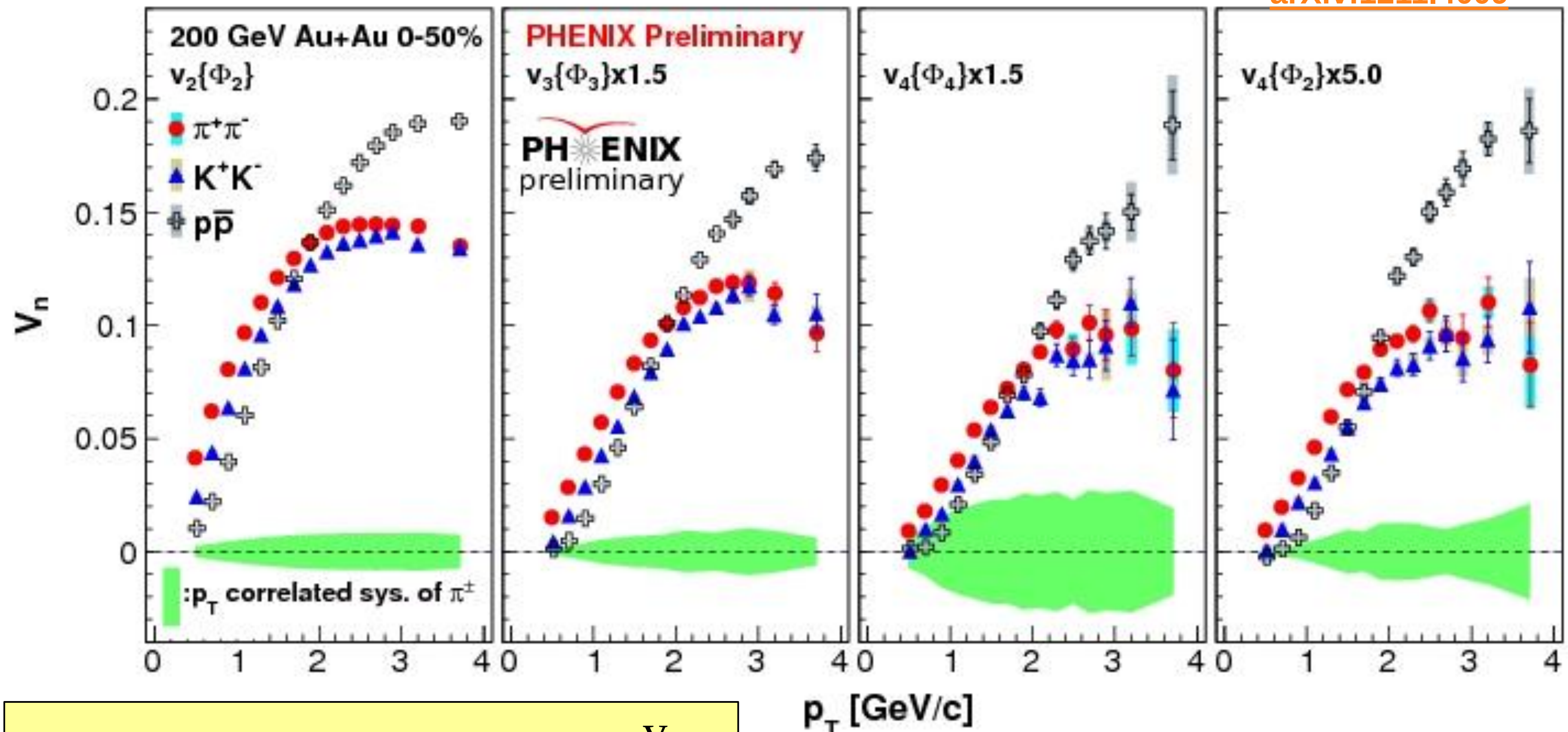




- ***Cuts on q_n should change the magnitudes $\langle \epsilon_n \rangle$, $\langle v_n \rangle$, $\langle R_n \rangle$ at a given centrality due to fluctuations***
- ***Viable models for initial-state fluctuations should still scale***

Flow is partonic & Acoustic?

arXiv:1211.4009



Expectation: $v_n(KE_T) \sim v_2^{n/2}$ or $\frac{v_n}{(n_q)^{n/2}}$

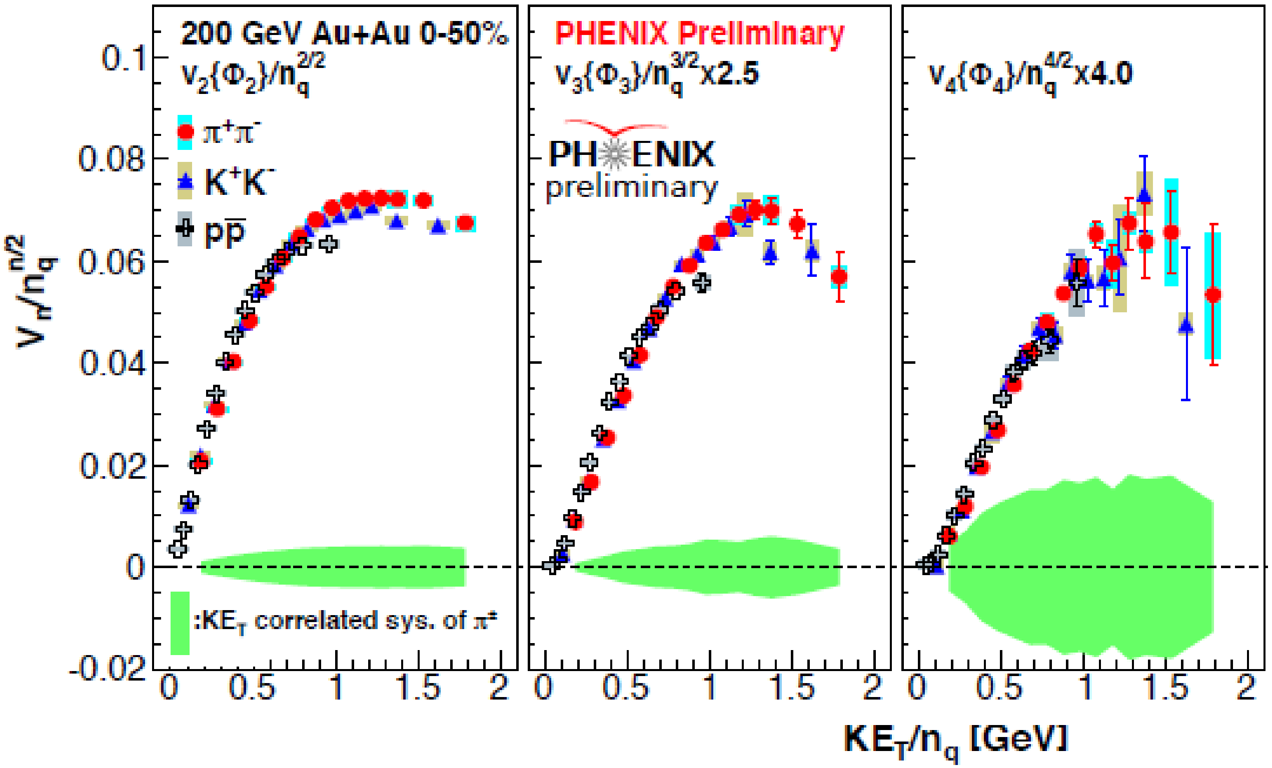
Note species dependence for all v_n

For partonic flow, quark number scaling expected
→ single curve for identified particle species v_n

Scaling properties of flow

Acoustic Scaling – Ratios

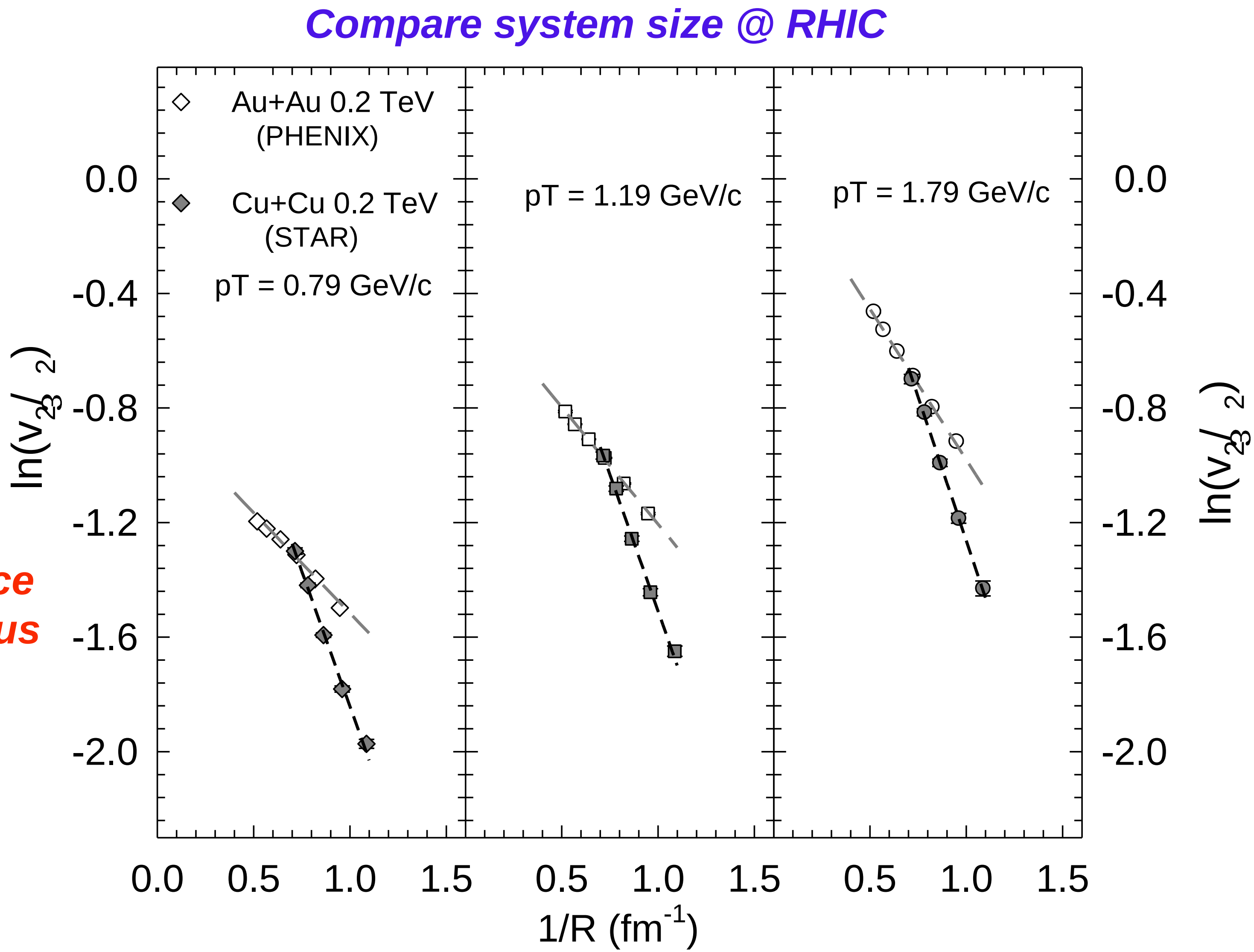
v_n PID scaling



Expectation validated: $v_n(KE_T) \sim v_2^{n/2}$ or $\frac{v_n}{(n_q)^{n/2}}$

Acoustic Scaling – 1/R

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$



Slope difference encodes viscous coefficient difference

✓ **Viscous coefficient larger for more dilute system**