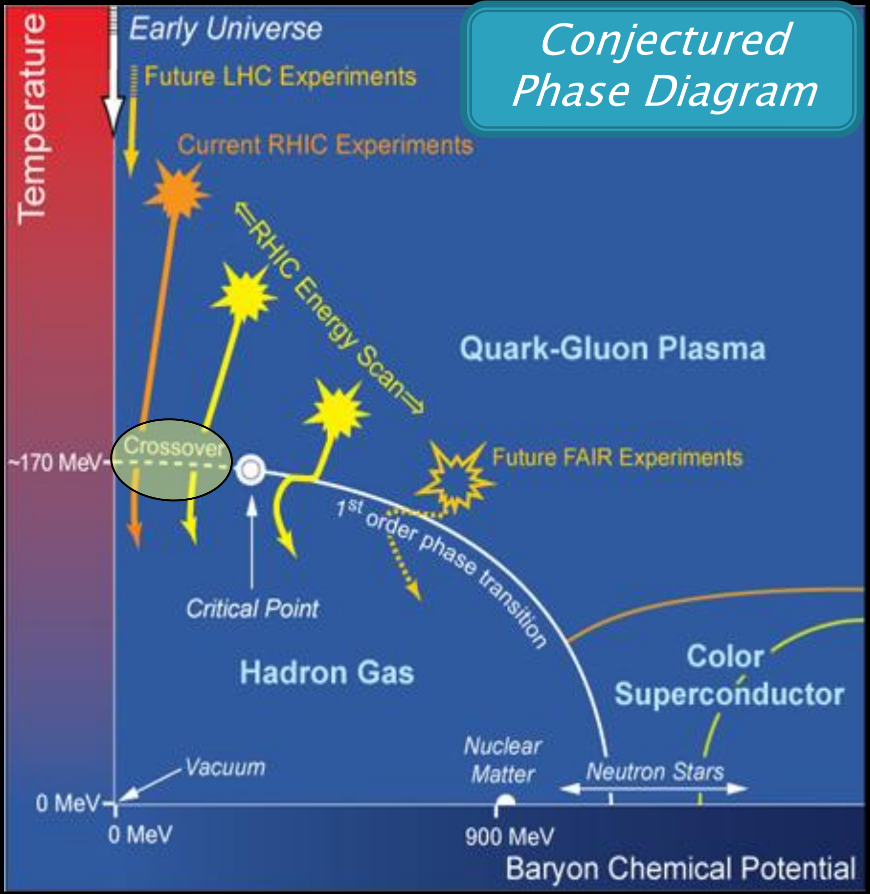
Beam energy dependence of the expansion dynamics in relativistic heavy ion collisions: Indications for the critical end point?

Roy A. Lacey
Stony Brook University

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

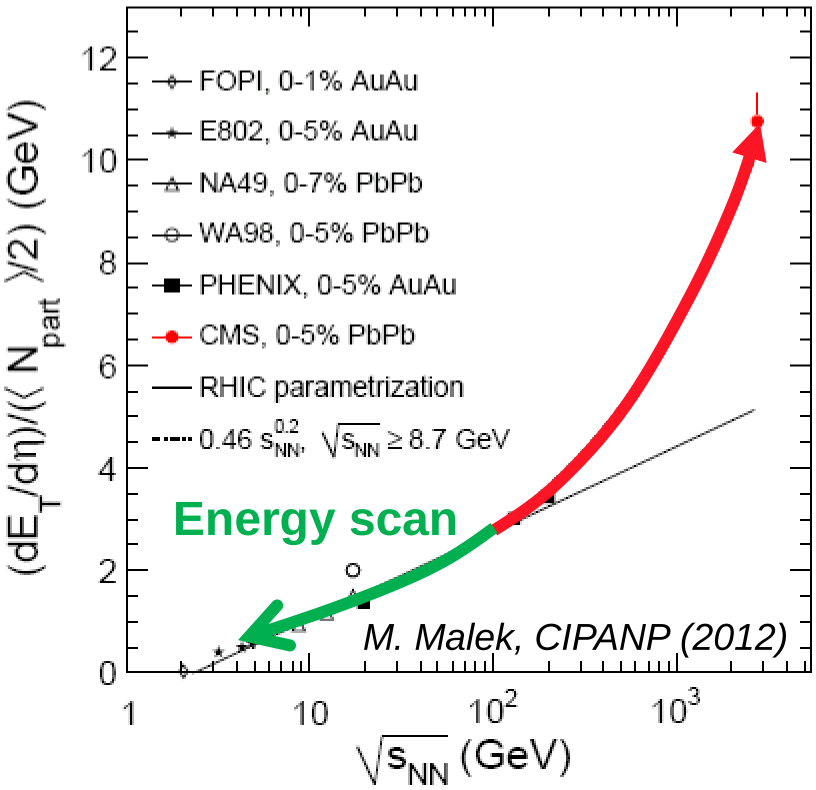
- **Location of the critical End point (CEP)?**
- **Location of phase coexistence regions?**
- **Detailed properties of each phase?**

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

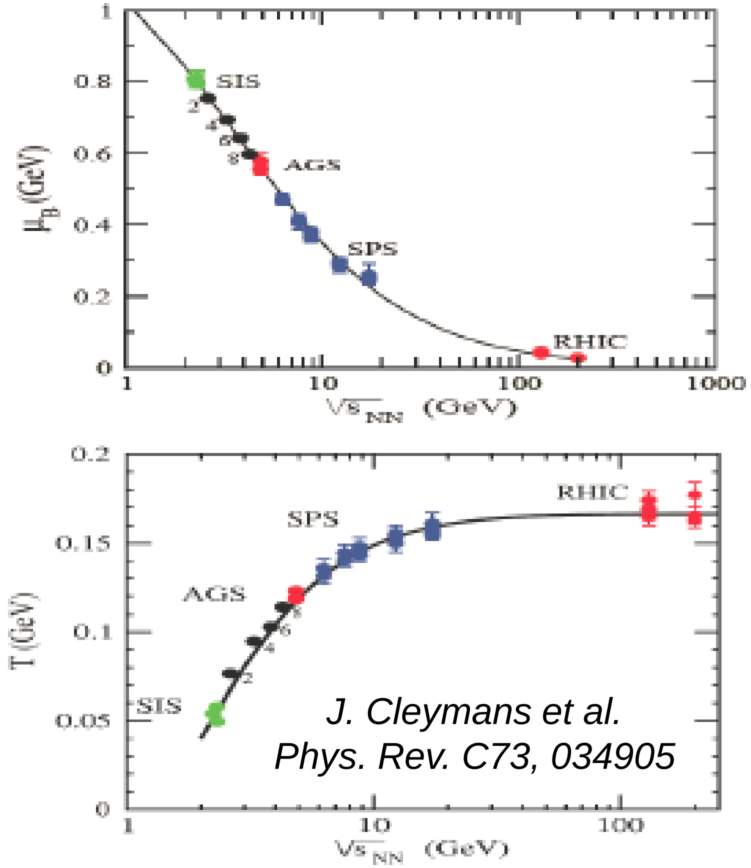
Exploit the RHIC-LHC beam energy lever arm



Energy scan

M. Malek, CIPANP (2012)

(μ_B,*T*) at freeze-out



J. Cleymans et al.
Phys. Rev. C73, 034905

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

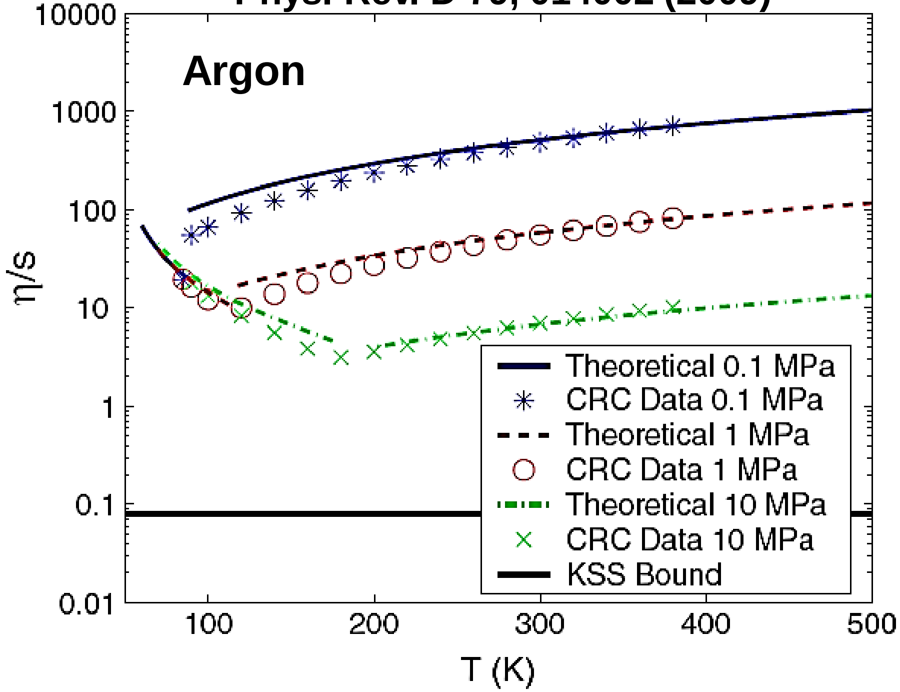
RHIC$_{BES}$ to LHC → ~360 $\sqrt{s_{NN}}$ increase

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

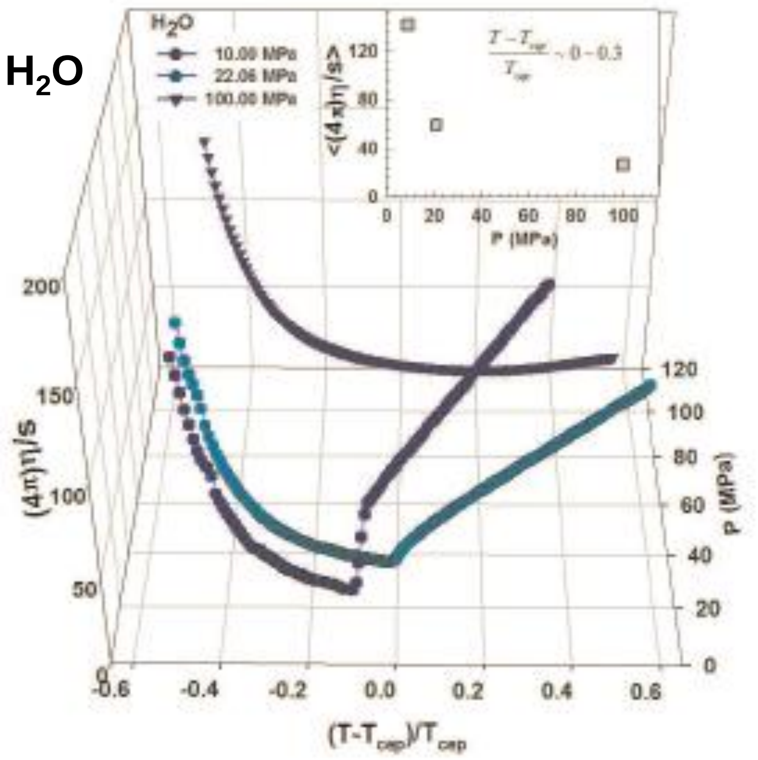
Challenge → leverage signals from full span of energies

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

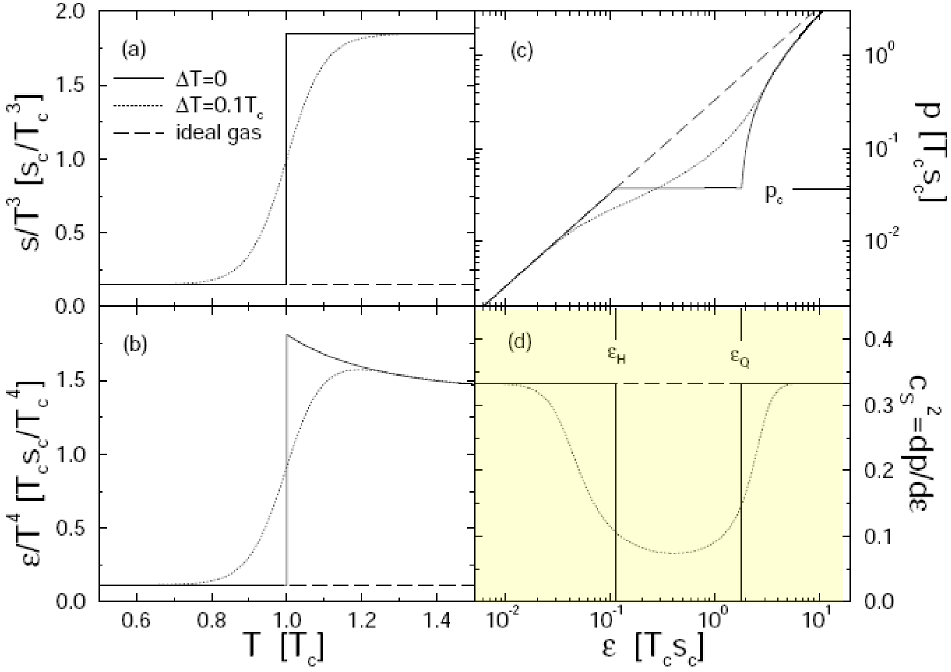
Anisotropic flow (v_n) measurements are an invaluable probe

Possible signals

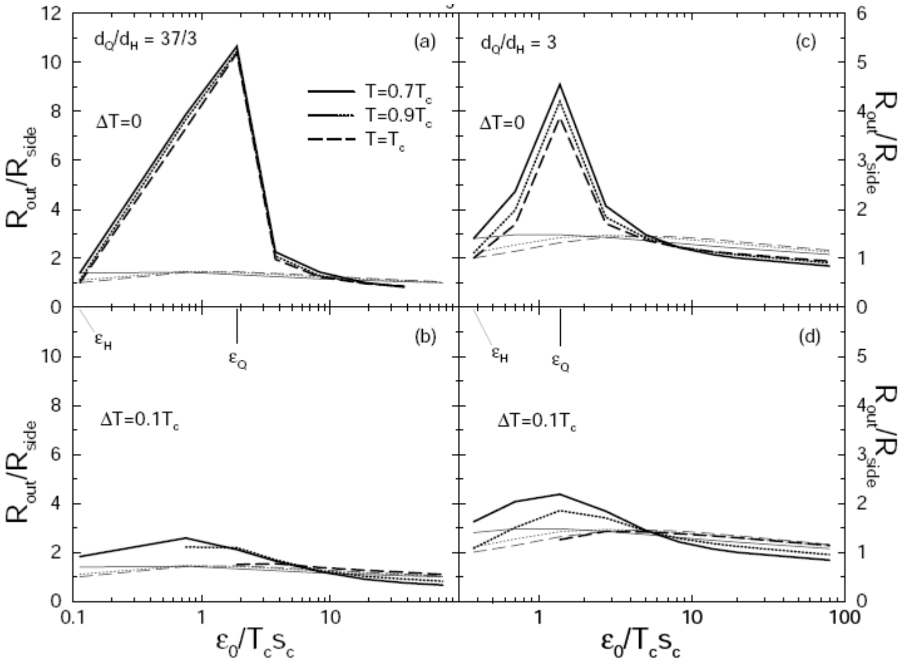
Collapse of directed flow

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



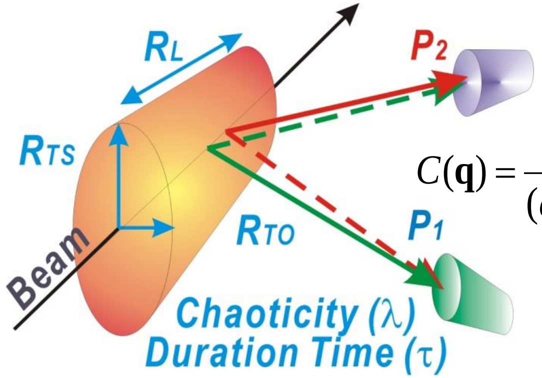
In the vicinity of a phase transition or the CEP, the sound speed is expected to soften considerably.

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

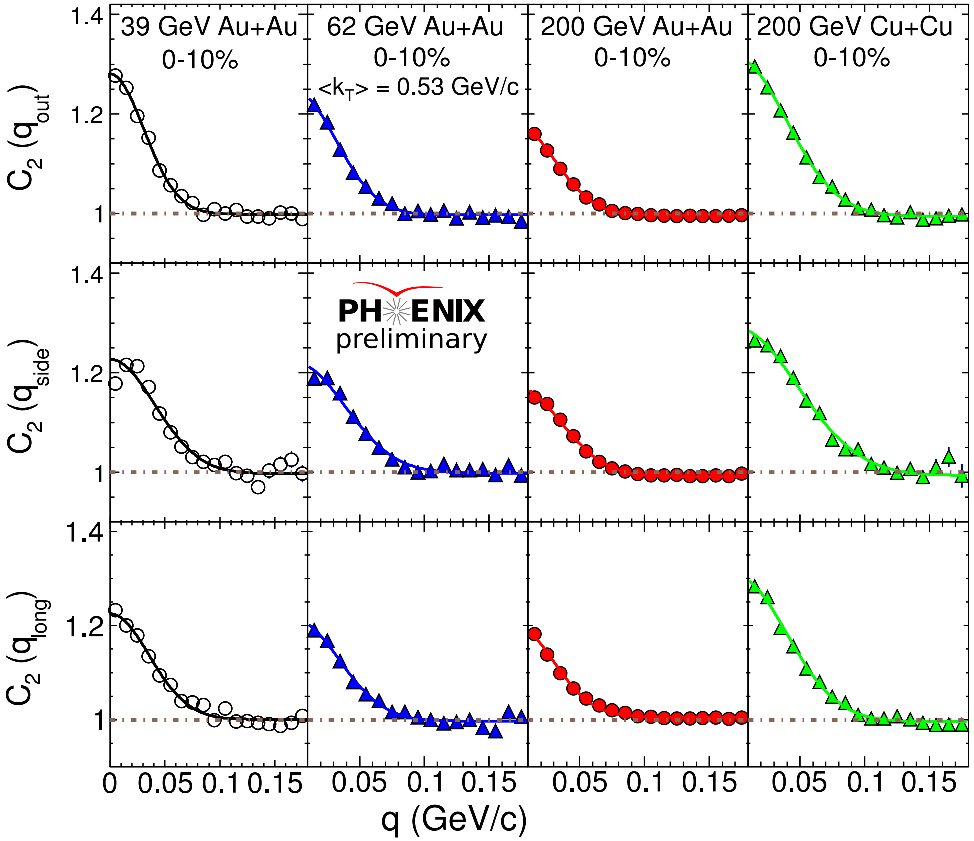
v_1 and HBT measurements are invaluable probes

HBT measurements

Two particle Interferometry Studies



$$C(\mathbf{q}) = \frac{dN_2/d\mathbf{p}_1 d\mathbf{p}_2}{(dN_1/d\mathbf{p}_1)(dN_1/d\mathbf{p}_2)}$$



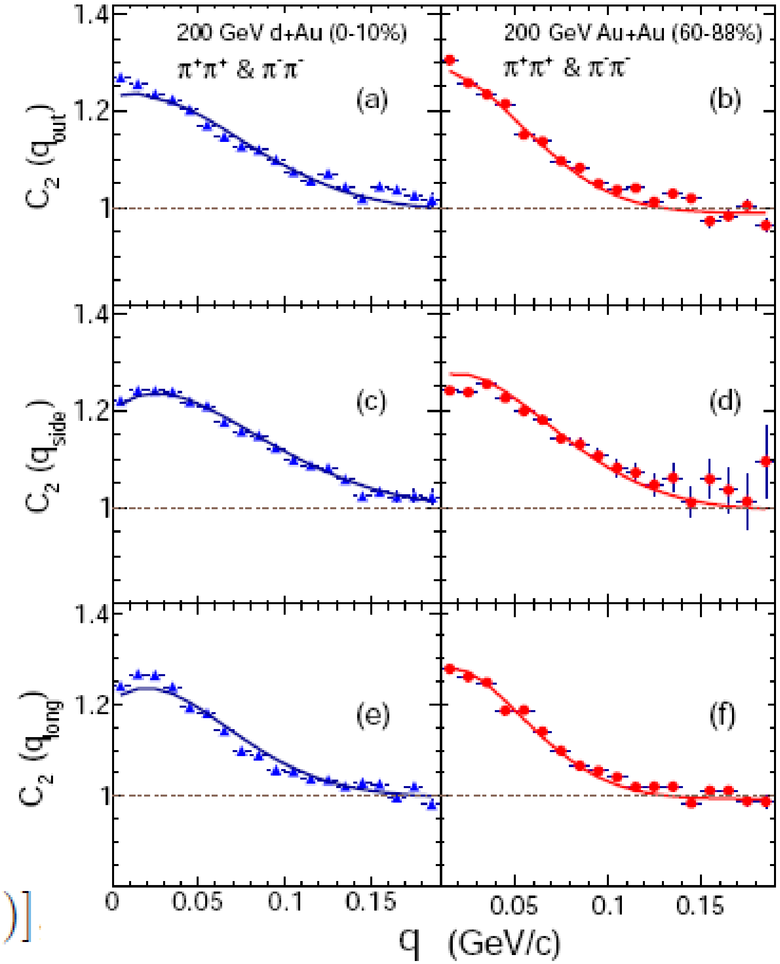
$$C_2(\mathbf{q}) = N[(\lambda(1+G(\mathbf{q})))F_c + (1-\lambda)]$$

$$G(\mathbf{q}) \cong \exp(-R^2_{\mathrm{side}}q^2_{\mathrm{side}} - R^2_{\mathrm{out}}q^2_{\mathrm{out}} - R^2_{\mathrm{long}}q^2_{\mathrm{long}})$$

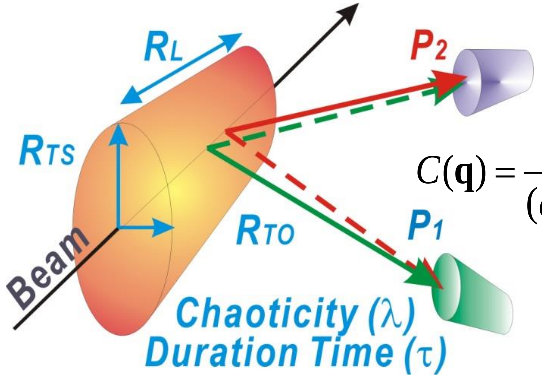
Fits to the correlation functions

→ HBT radii (R_{out}, R_{side}, R_{long}) as a function of centrality, m_T, etc

HBT measurements



Two particle Interferometry Studies



$$C(\mathbf{q}) = \frac{dN_2 / d\mathbf{p}_1 d\mathbf{p}_2}{(dN_1 / d\mathbf{p}_1)(dN_1 / d\mathbf{p}_2)}$$

$$C_2(\mathbf{q}) = N[(\lambda(1 + G(\mathbf{q})))F_c + (1 - \lambda)]$$

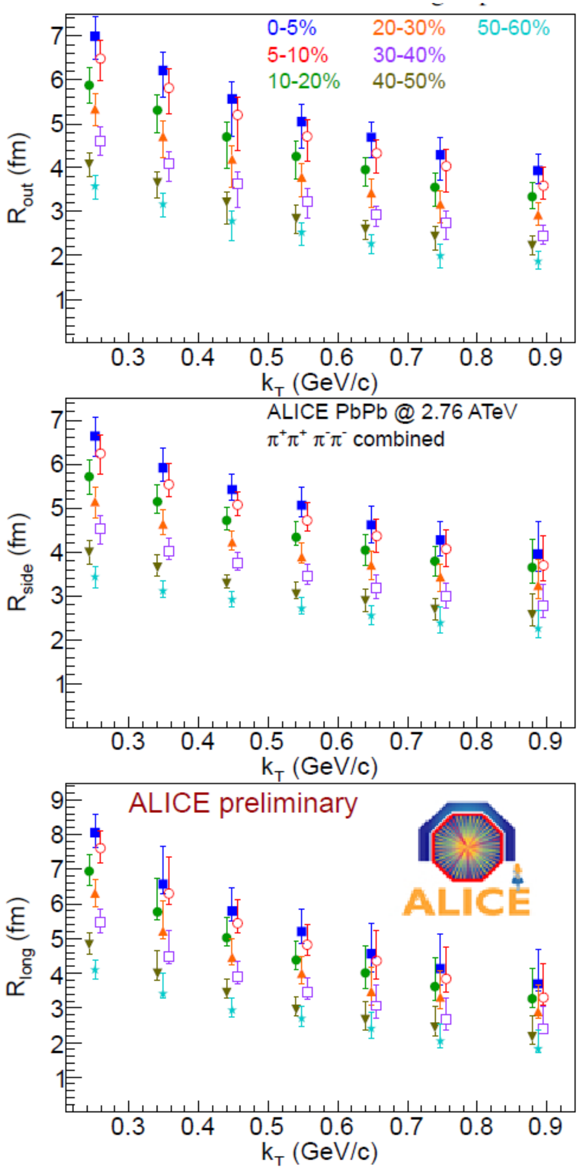
$$G(\mathbf{q}) \cong \exp(-R^2_{\mathrm{side}} q^2_{\mathrm{side}} - R^2_{\mathrm{out}} q^2_{\mathrm{out}} - R^2_{\mathrm{long}} q^2_{\mathrm{long}})$$

Fits to the correlation functions

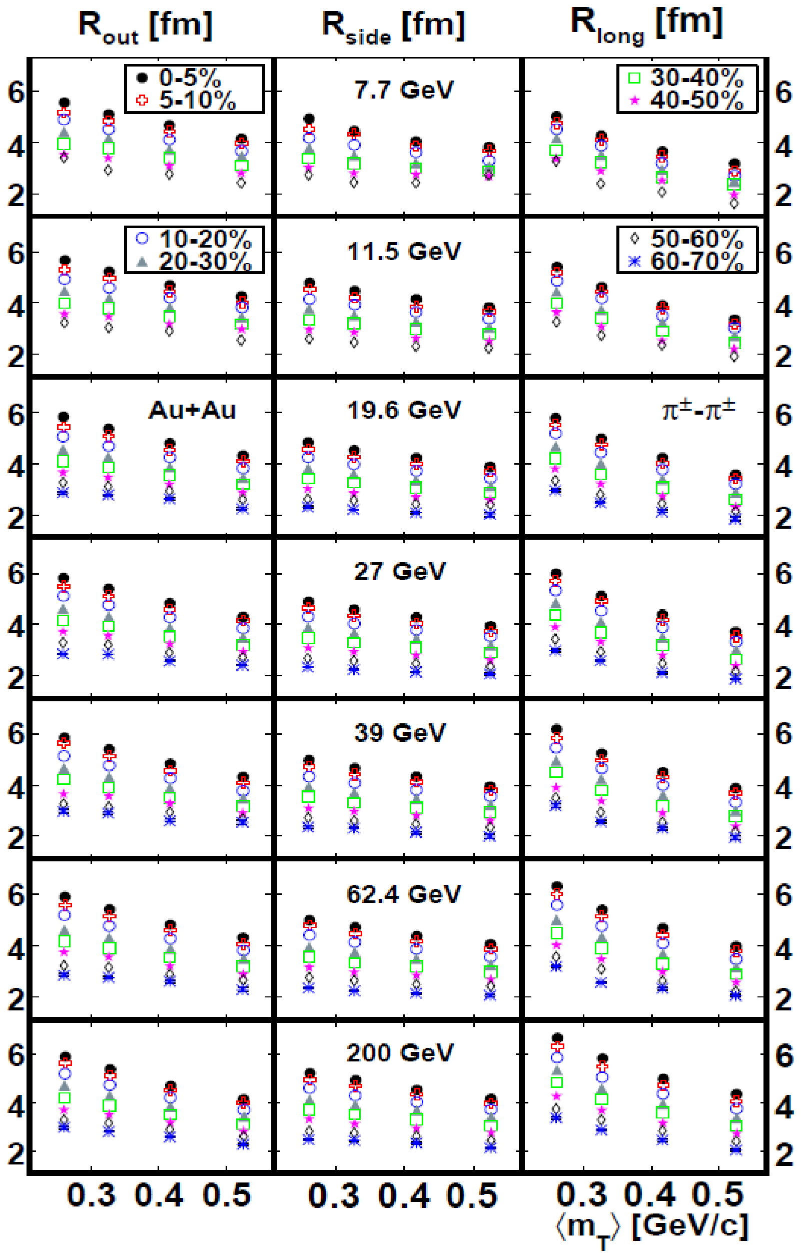
→ HBT radii (R_{out}, R_{side}, R_{long}) as a function of centrality, m_T, etc

HBT Radii

ALICE -PoS**WPCF2011**

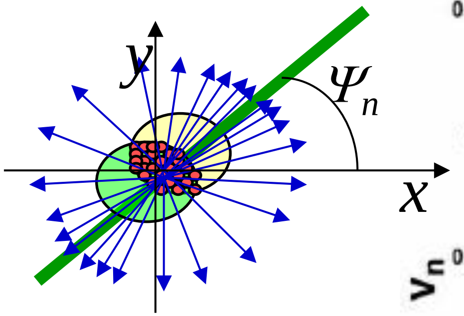


STAR - 1403.4972

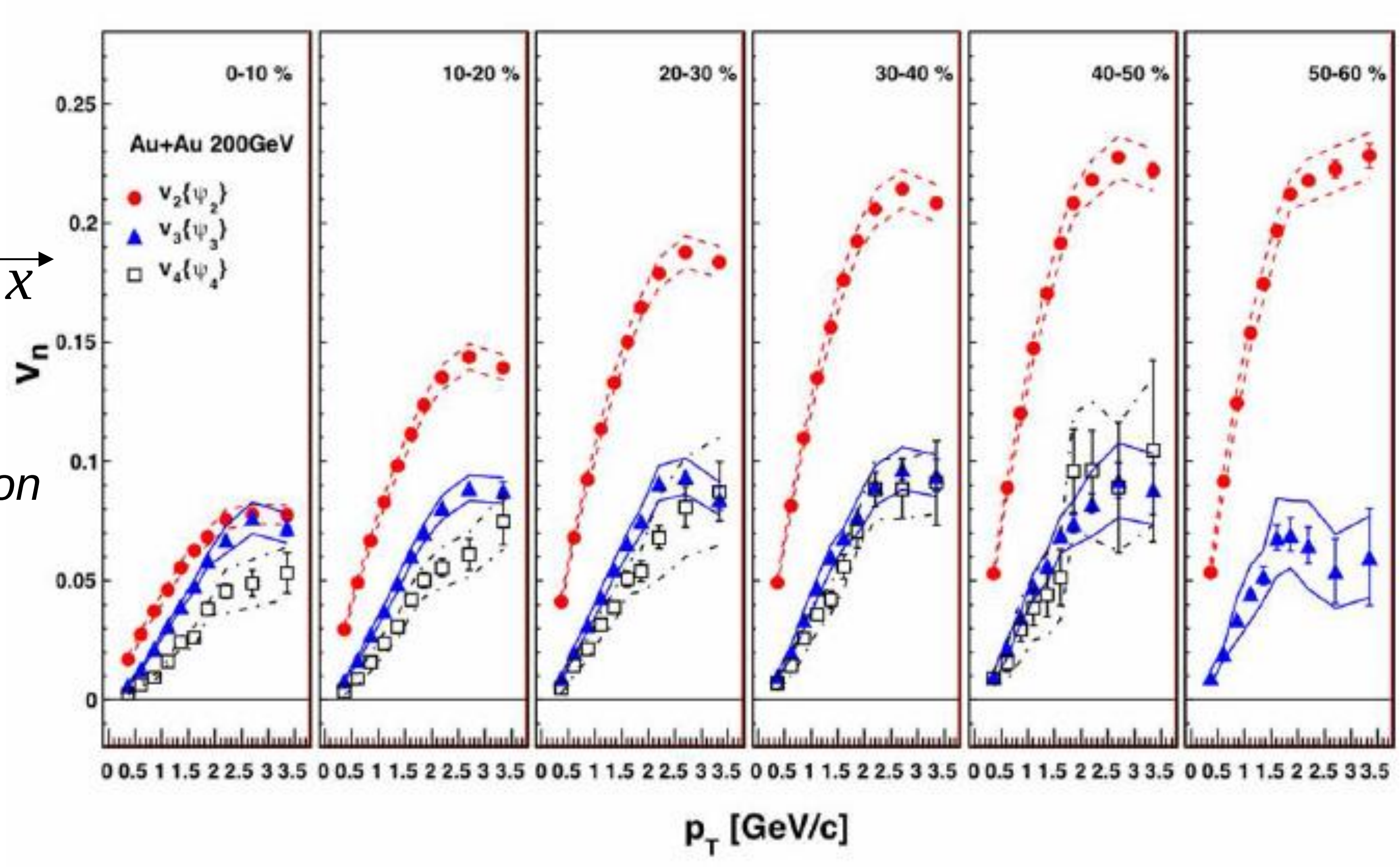


Exquisite data set for combined RHIC-LHC results?

V_n measurements



Measure distribution relative to Ψ_n

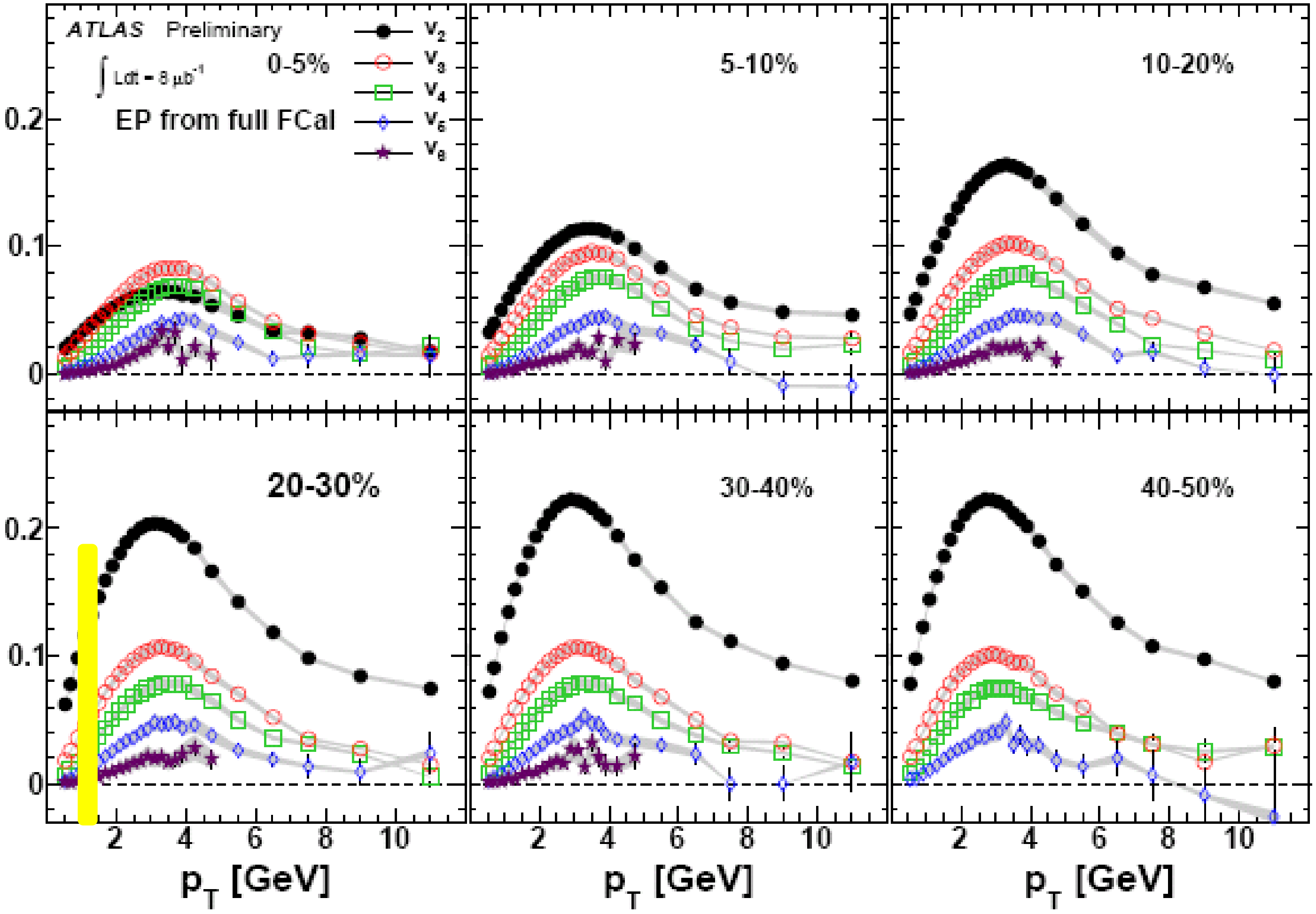


$$v_n = \langle \cos(2n[\varphi - \Psi_n]) \rangle$$

Extensive set of v_n measurements at RHIC and the LHC

$v_n(\psi_n)$ Measurements - ATLAS

ATLAS-CONF-2011-074



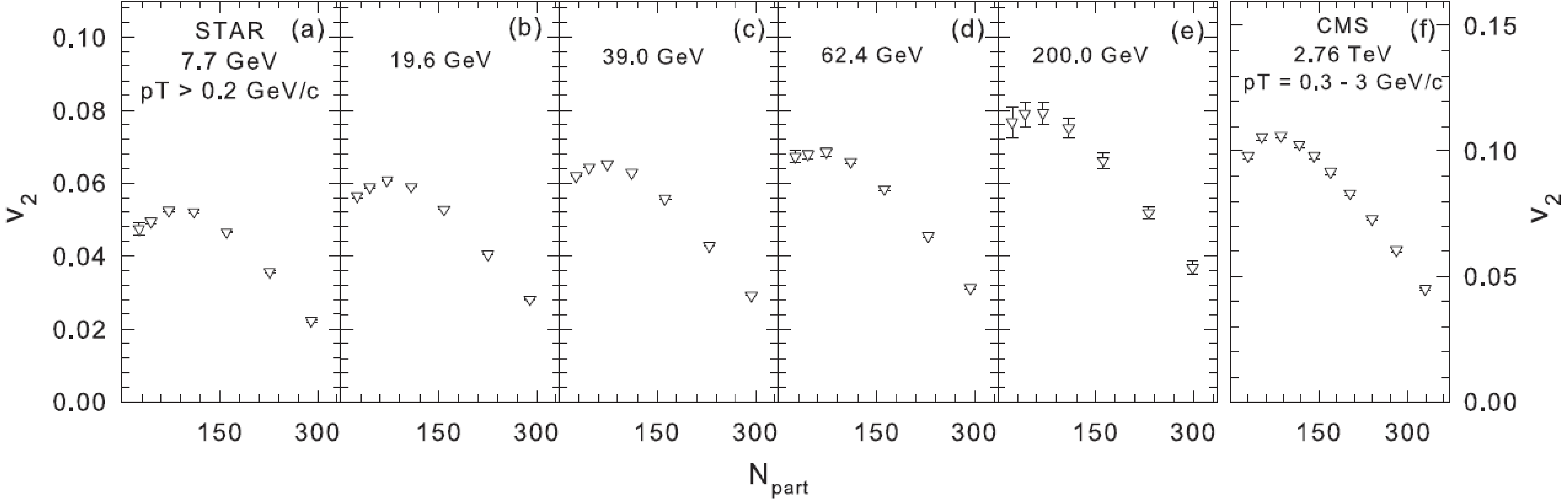
High precision double differential Measurements are pervasive

Anisotropy Measurements

arXiv:1305.3341

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

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



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

Roy A. Lacey, Stony Brook University, WPCF2014

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 indications for the phase transition / CEP?

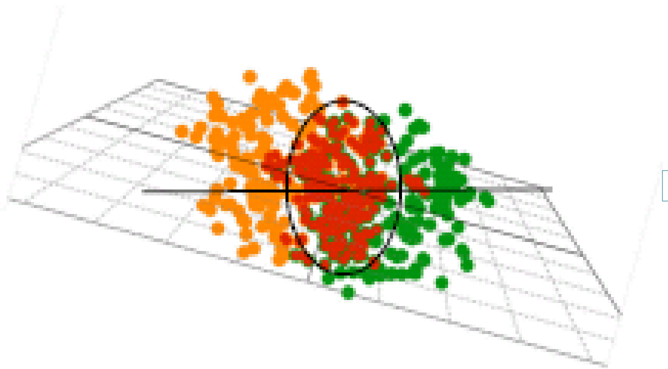
YES!

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

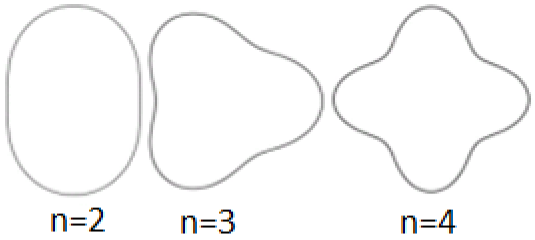
- This acoustic property leads to several testable scaling predictions for anisotropic flow and HBT – with implications

This constitutes an important development

Scaling properties of expansion dynamics



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**

$$k = n / \bar{R}$$

HBT scaling expectations:

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

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

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

V_n 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

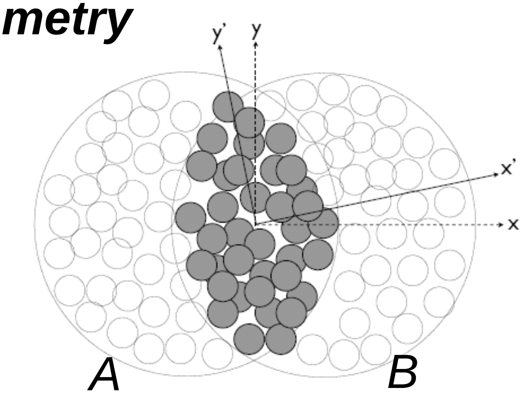
$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

Each of these scaling expectations can been validated

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

Geometric quantities for scaling

Geometry



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

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

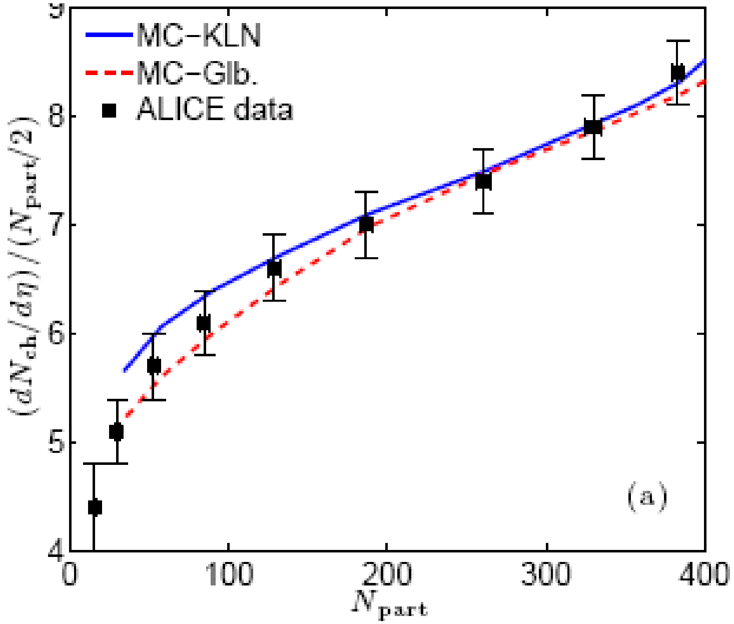
$$S_{ny} \equiv S_n \sin\left(n\Psi_n^*\right) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\sin(n\phi),$$

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

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

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

arXiv:1203.3605



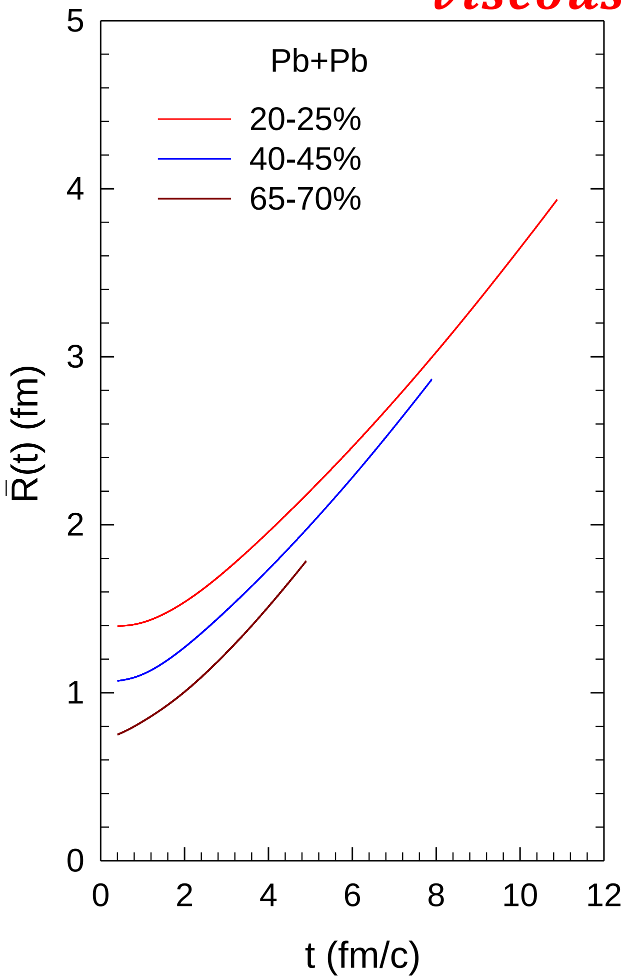
σ_x & σ_y → RMS widths of density distribution

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

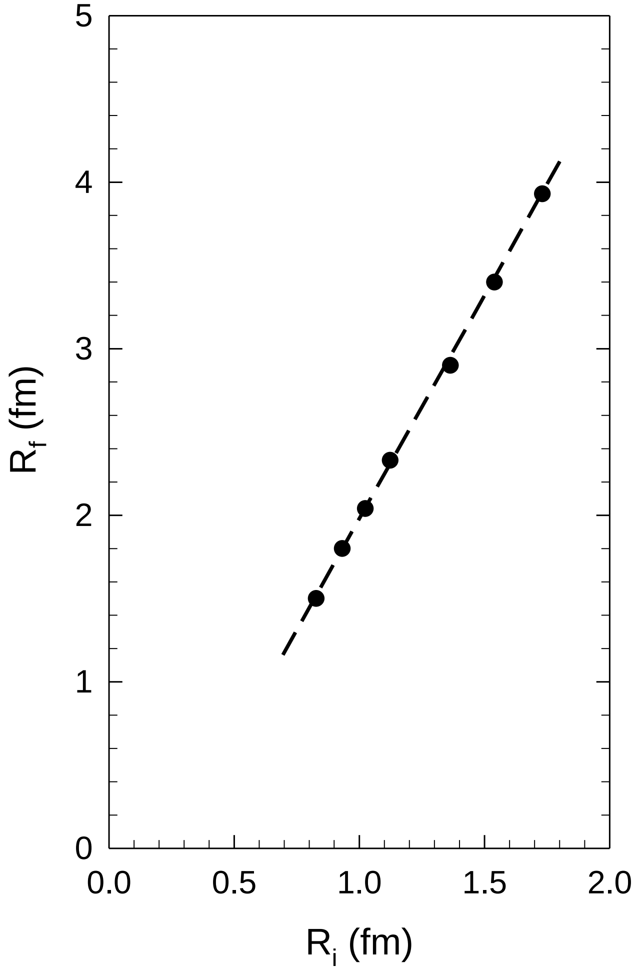
Scaling properties of HBT

Viscous Hydrodynamics – B. Schenke

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



$t \propto \bar{R}$



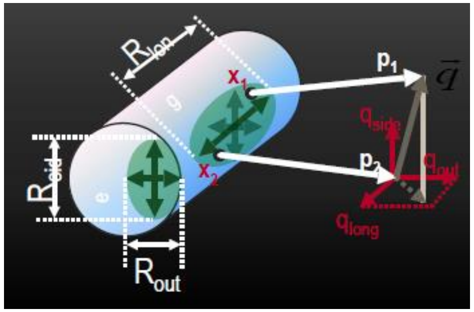
Freeze-out time varies with initial size

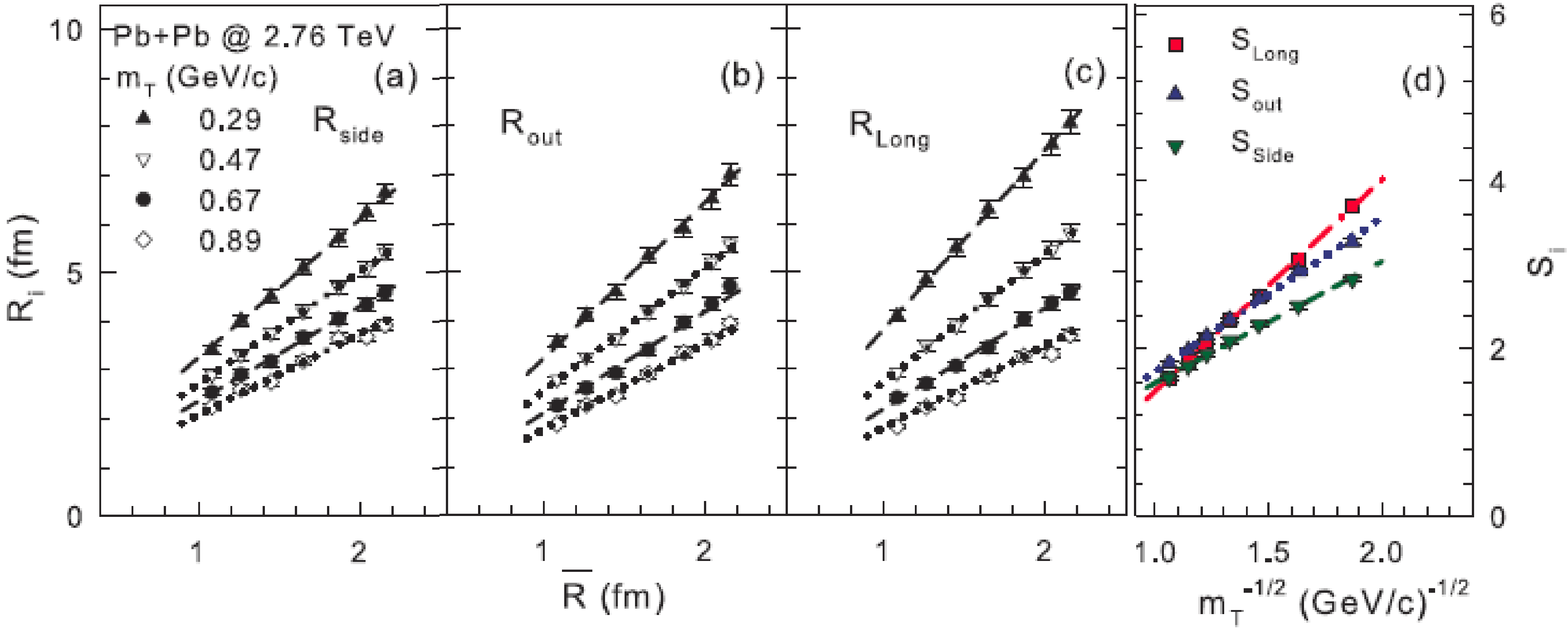
Freeze-out transverse size proportional to initial transverse size

Acoustic Scaling of HBT Radii

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

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

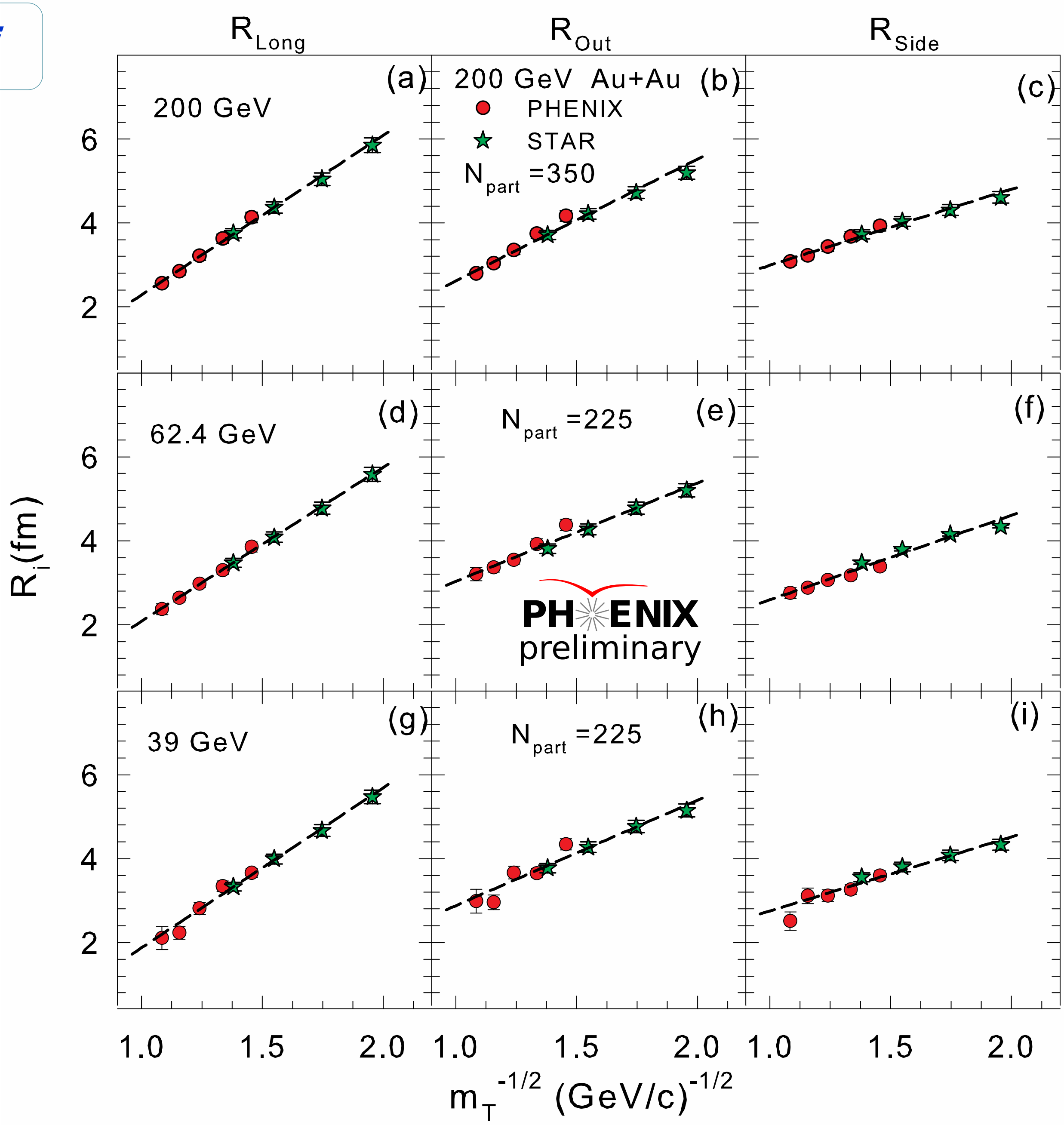




- $\bar{R}$ ***and*** m_T ***scaling of the full LHC data set***
- ***The centrality and*** m_T ***dependent data scale to a single curve for each radii.***

m_T Scaling of HBT Radii

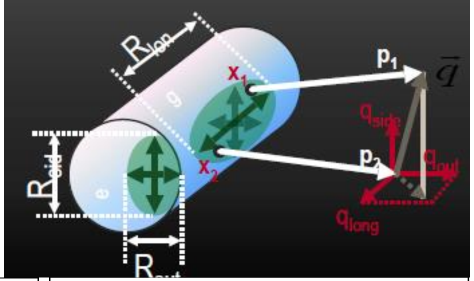
- PHENIX and STAR consistent [arxiv:1403.4972]
  - all radii linear
    - $R_i = a + b/\sqrt{m_T}$
  - Useful to interpolate to common m_T

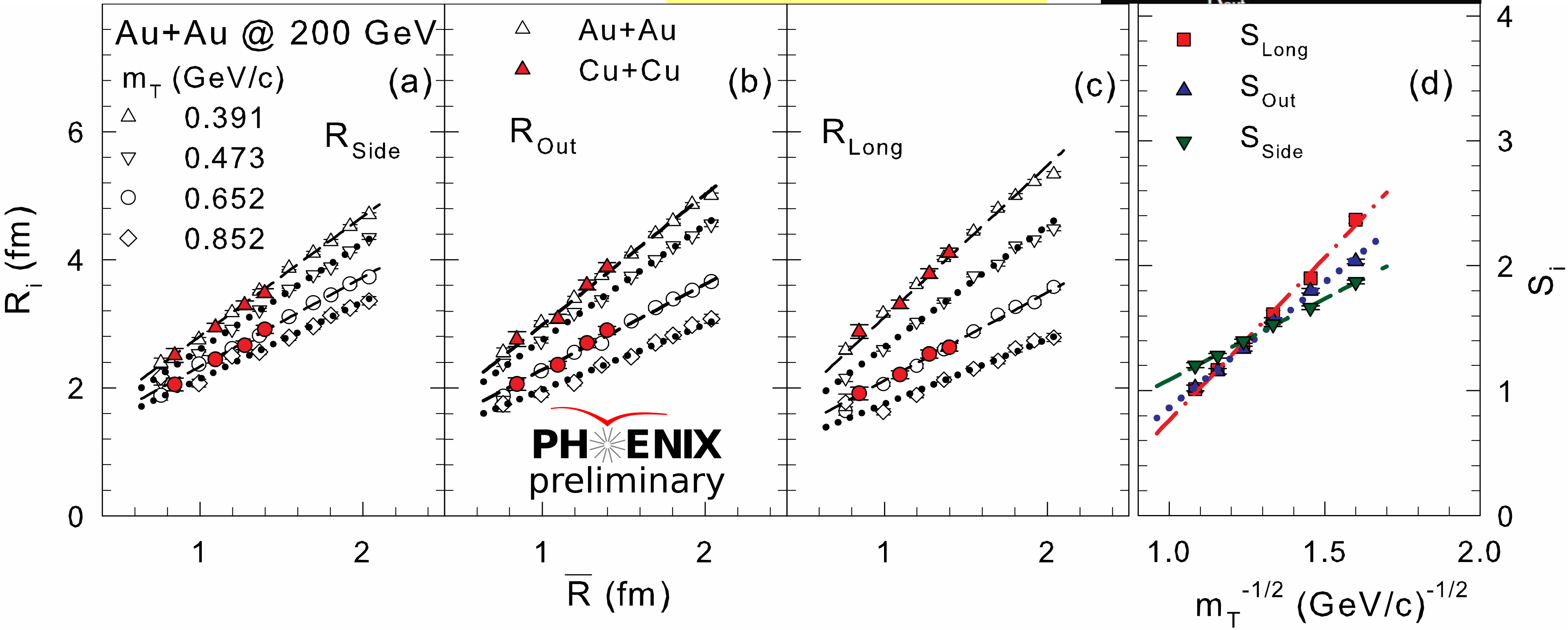


Acoustic Scaling of HBT Radii

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

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

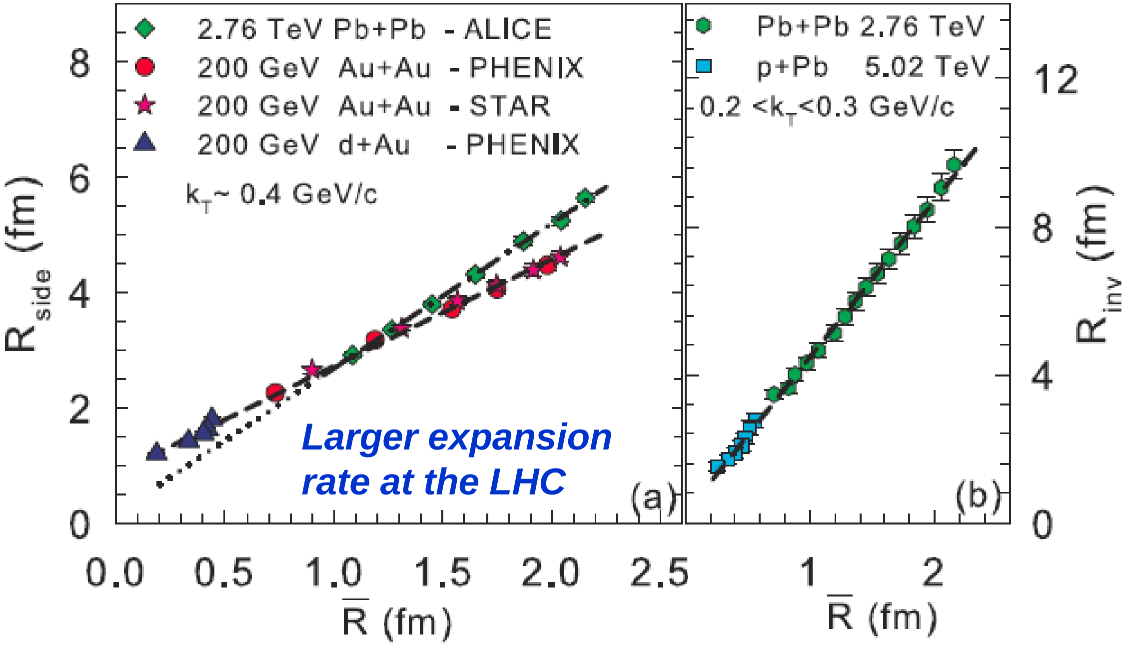




- ***$\bar{R}$ and m_T scaling of the full RHIC and LHC data sets***
- ***The centrality and m_T dependent data scale to a single curve for each radii.***
- ***Qualitatively similar expansion dynamics at RHIC & LHC***

Acoustic Scaling of HBT Radii

arXiv:1404.5291

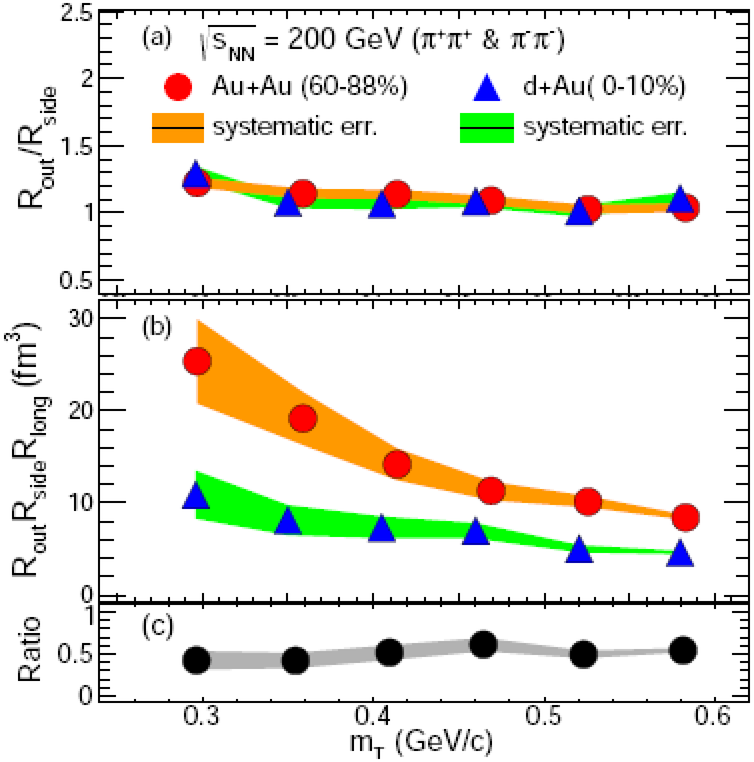


Larger expansion rate at the LHC

$t \propto R$

Exquisitely demonstrated for asymmetric systems → similar reaction dynamics

Similar m_T dependence For Au+Au and d+Au



Expansion dynamics similar for Pb+Pb, Au+Au, p+Pb and d+Au
Final-State interactions dominate

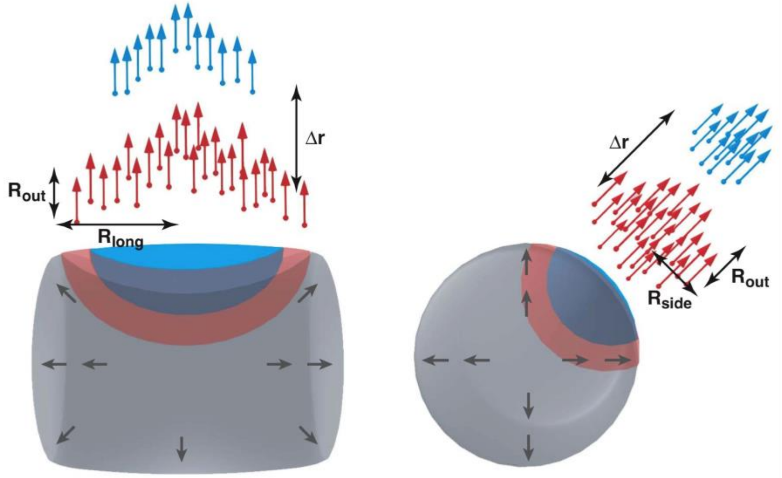
Reaction Dynamics and HBT Radii

Chapman, Scotto, Heinz, PRL.74.4400 (95)

$$R^2_{side} = \frac{R^2_{geo}}{1+\frac{m_T}{T}b^2_T}$$

$$R^2_{out} = \frac{R^2_{geo}}{1+\frac{m_T}{T}b^2_T} + \underline{b^2_T(\mathrm{D}t)^2}$$

$$R^2_{long} \approx \frac{T}{m_T}t^2$$



$$R_i = a + \frac{b}{\sqrt{m_T}}$$

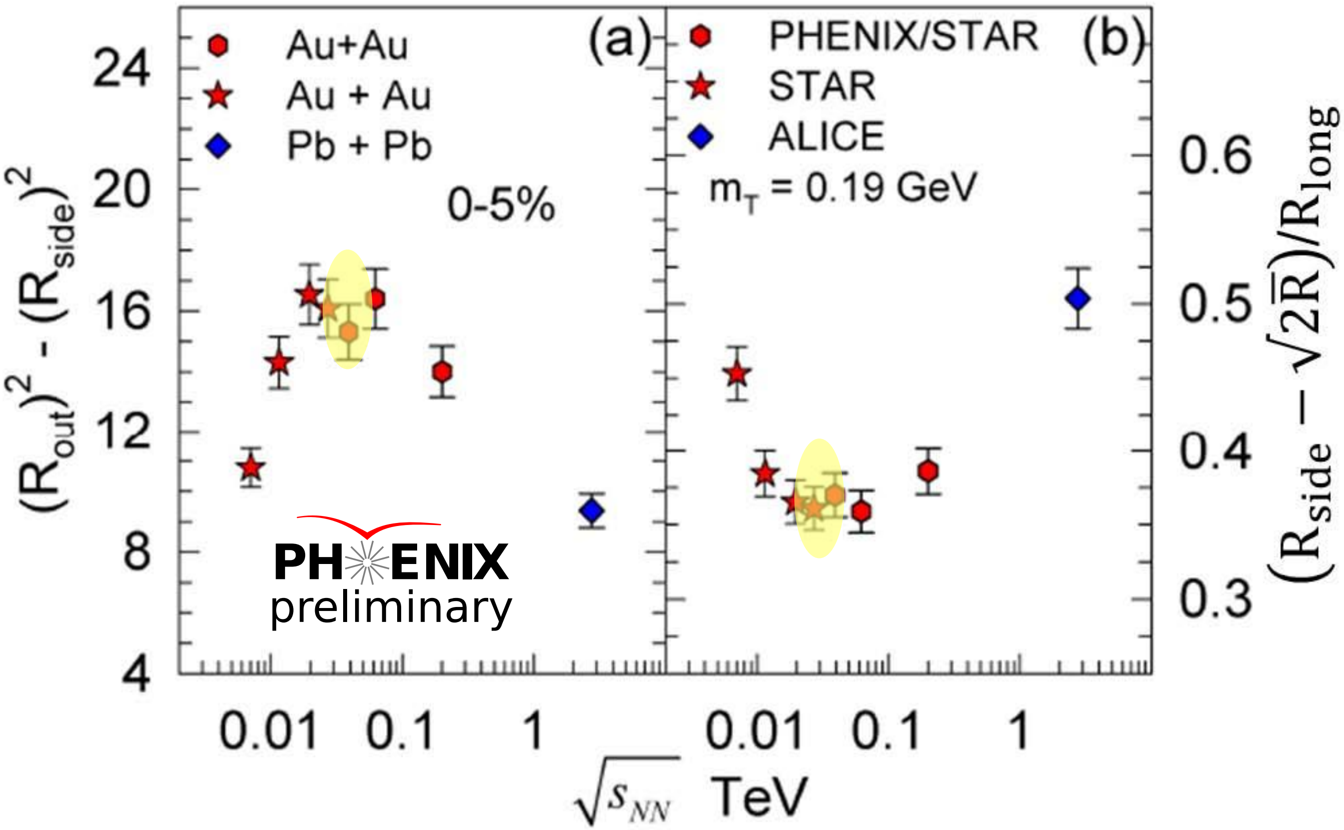
Empirical Observation

Makhlin, Sinyukov, ZPC.39.69 (88)

(R^2_{out}-R^2_{side}) sensitive to emission duration

Anticipate extended emission duration with phase transition/CEP

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



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

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

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

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

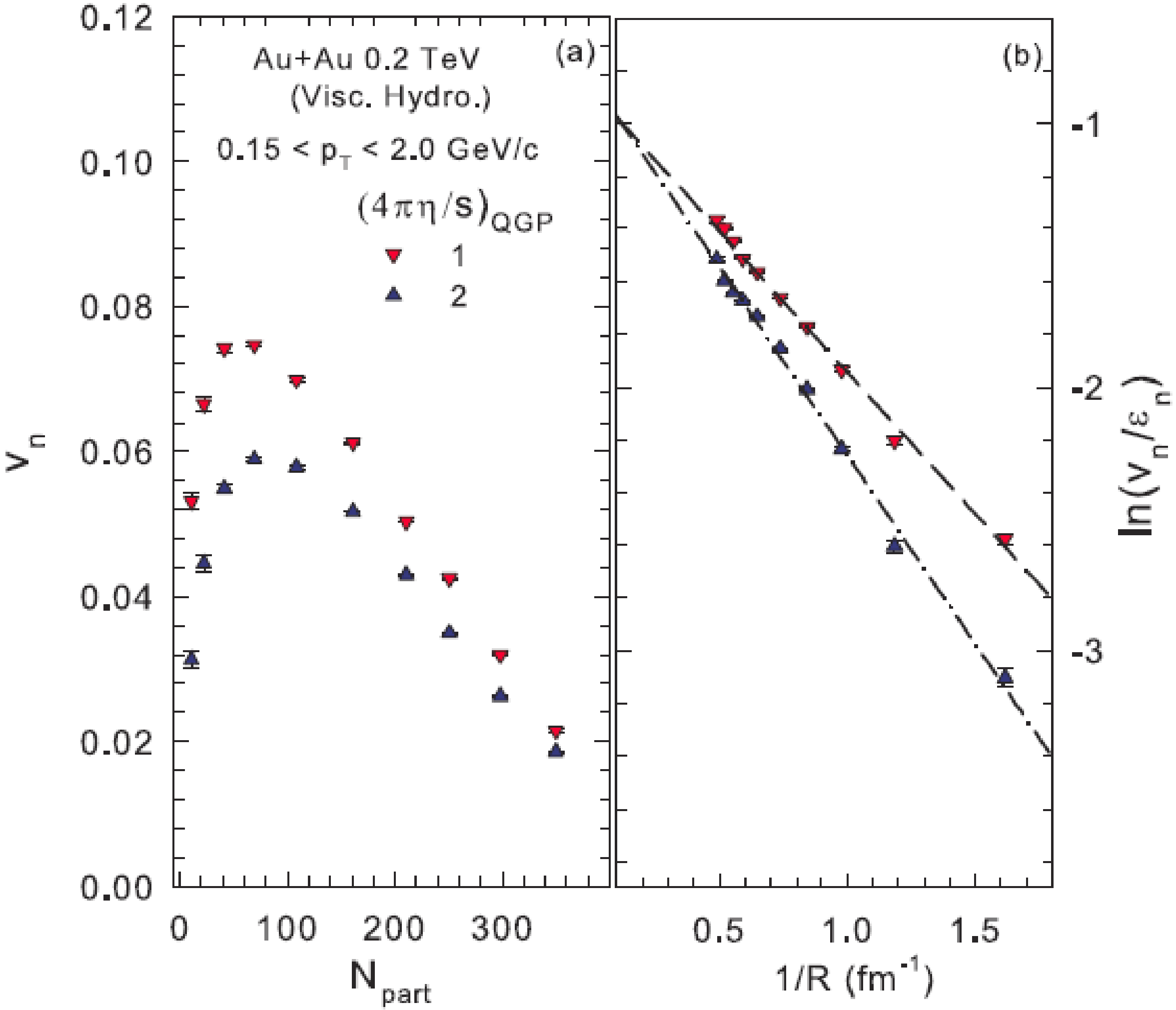
These non-monotonic patterns signal an important change in the reaction dynamics; CEP? Phase transition?

A similar non-monotonic pattern for η/s signals the CEP

Scaling properties of flow

- *Viscous Hydrodynamics*

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



✓ **Characteristic a*coustic scaling validated for viscous hydrodynamics***

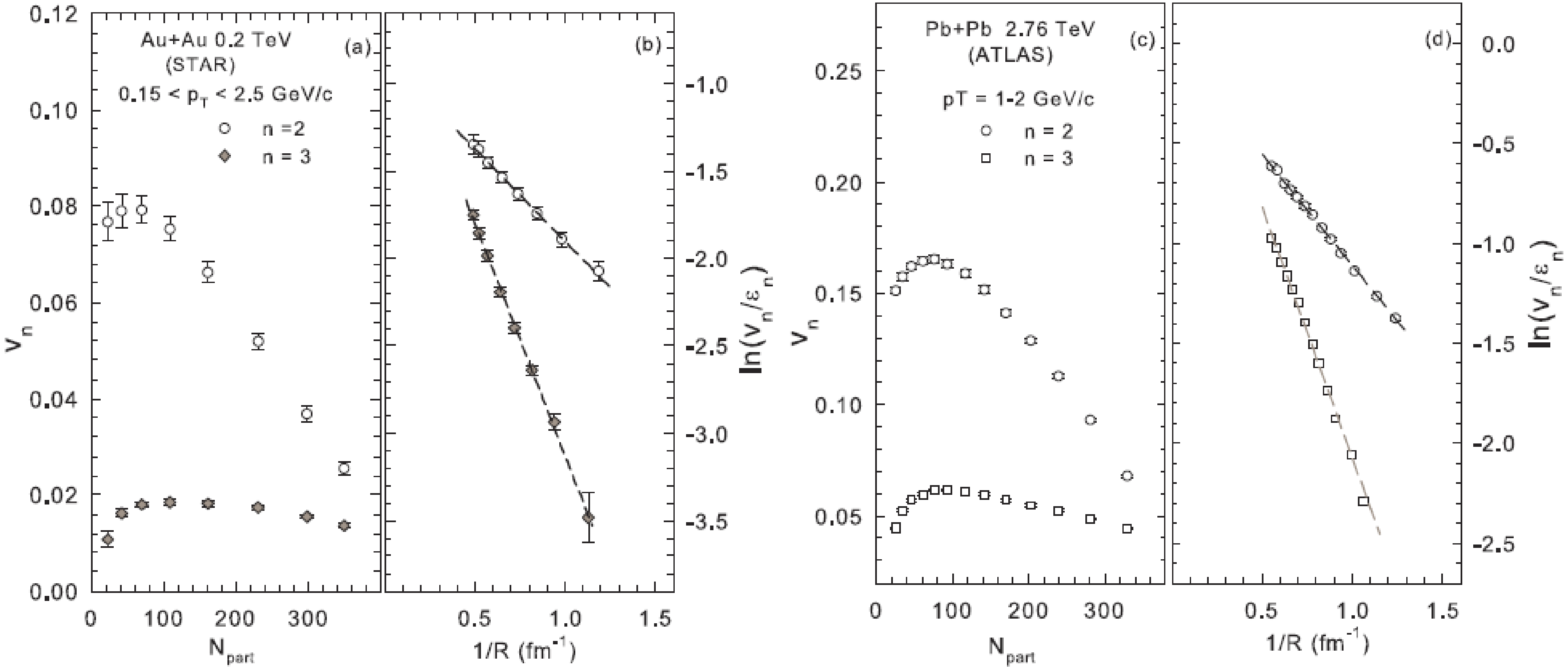
✓ ***β′ shows clear sensitivity to η/s***

✓ ***Viscous hydrodynamics can be used for calibration***

Scaling properties of flow

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

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



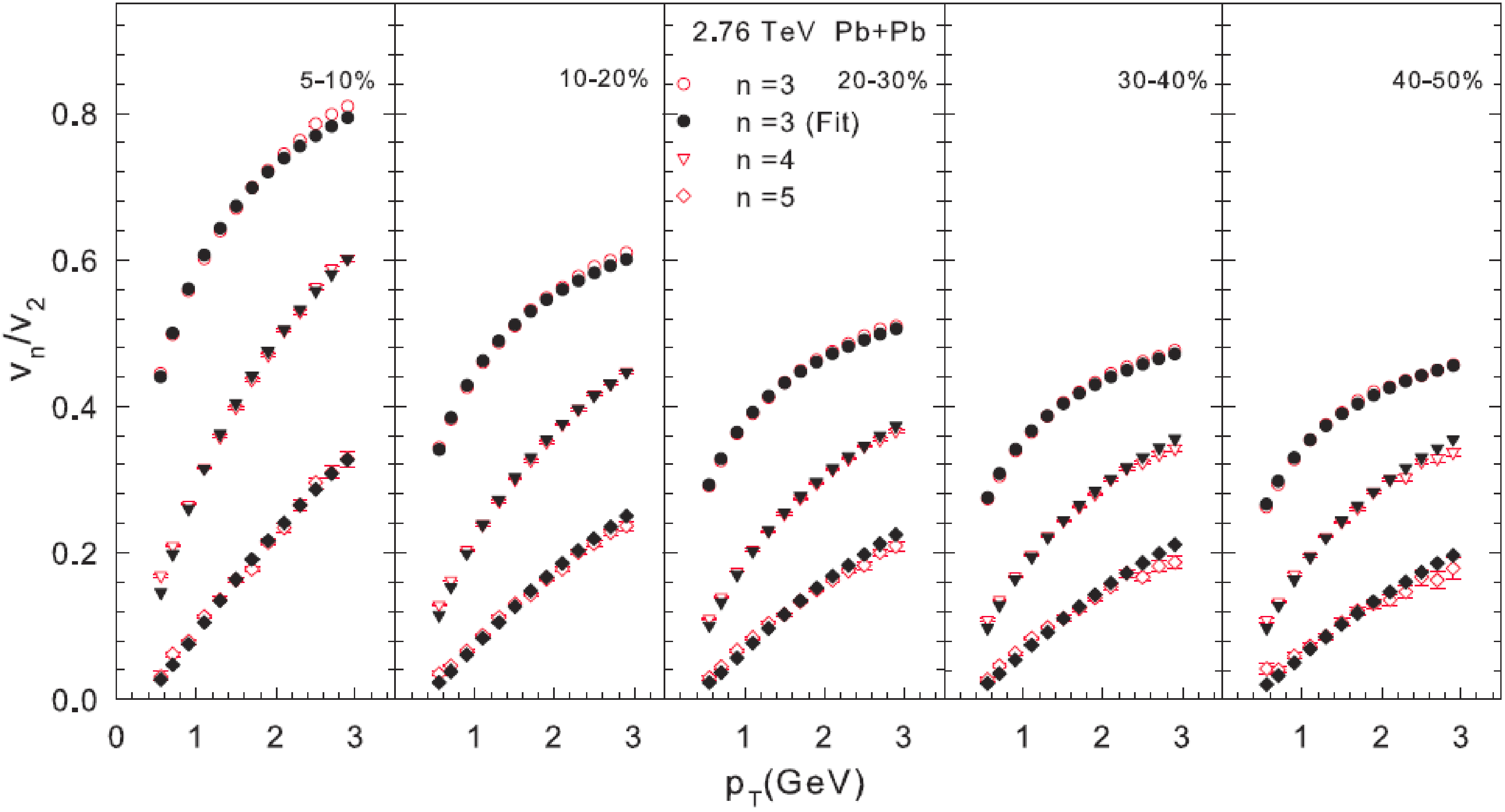
- ✓ **Characteristic $1/\bar{R}$ viscous damping validated with n^2 dependence at RHIC & the LHC**
- ✓ ***A further constraint for η/s***

Acoustic Scaling - Ratios

$$v_n(p_T) \propto (v_2)^{n/2}$$

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

arXiv:1301.0165



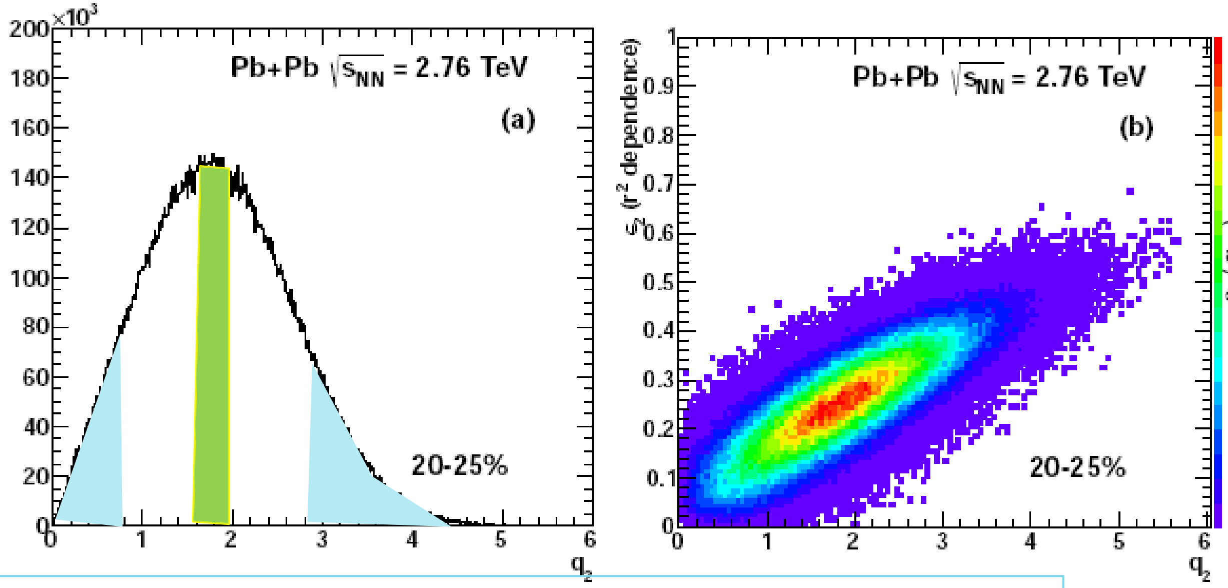
- ✓ **Characteristic ($n^2 – 4$) viscous damping validated**
- ✓ ***Constraint for η/s***

Shape-engineered events

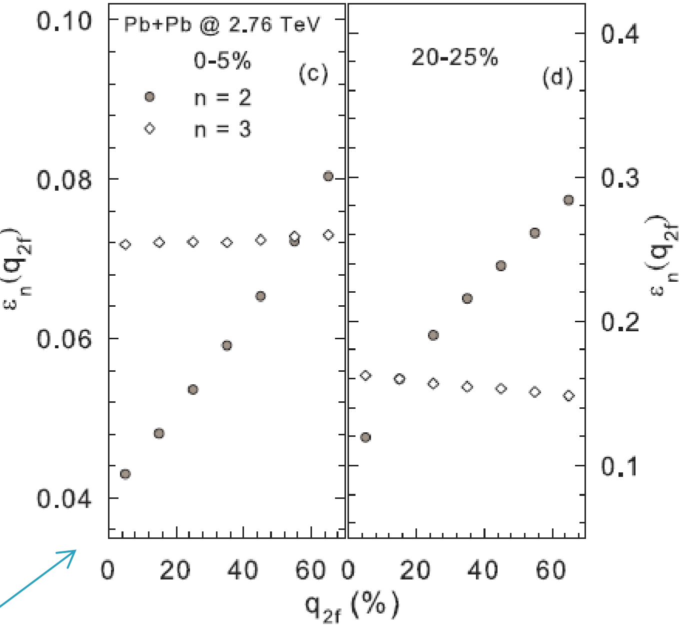
Shape fluctuations lead to a distribution of the Q vector <u>at a fixed centrality</u>

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

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



Lacey et. al, arxiv:1311.1728



- ***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***

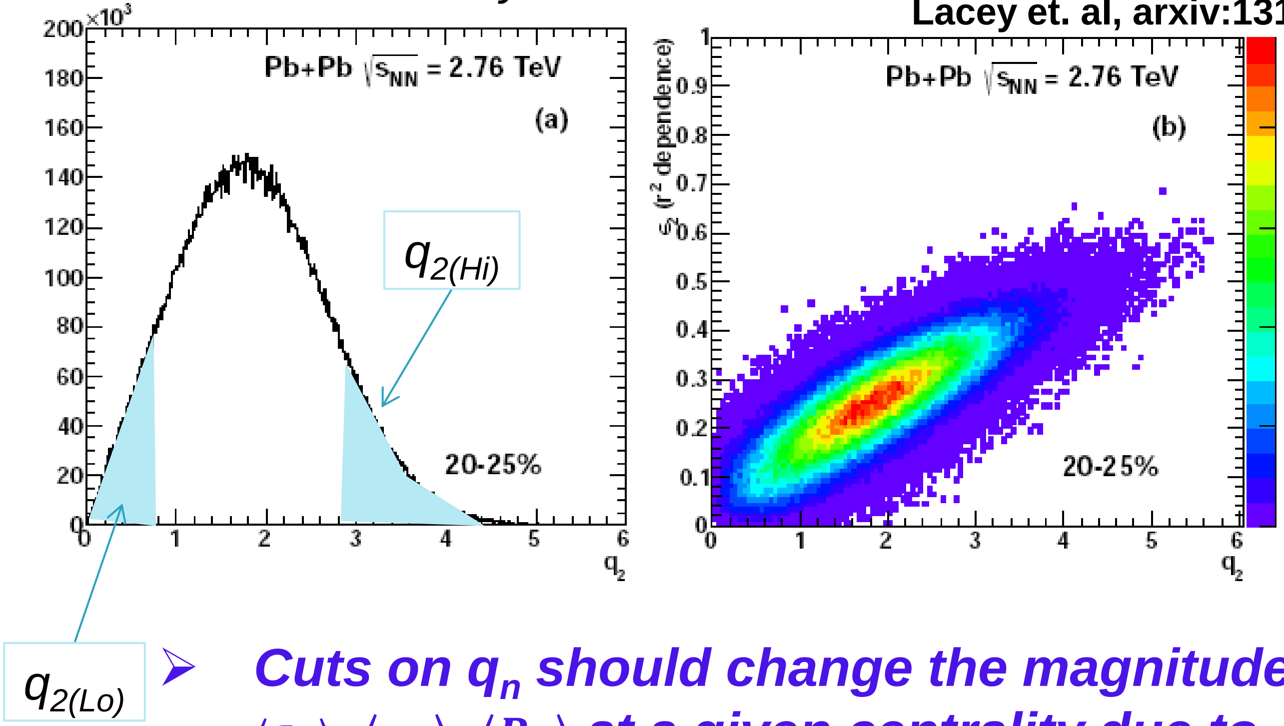
Shape-engineered events

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

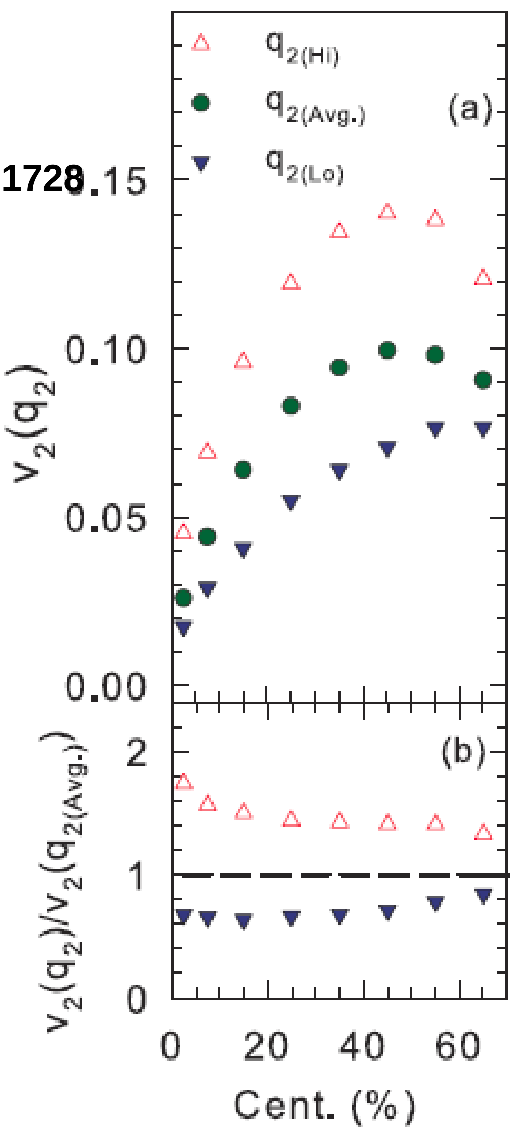
$$Q_{n,x} = \sum_{i}^{M} \cos(n\phi_i);\ Q_{n,y} = \sum_{i}^{M} \sin(n$$

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

Lacey et. al, arxiv:1311.1728



ALICE data

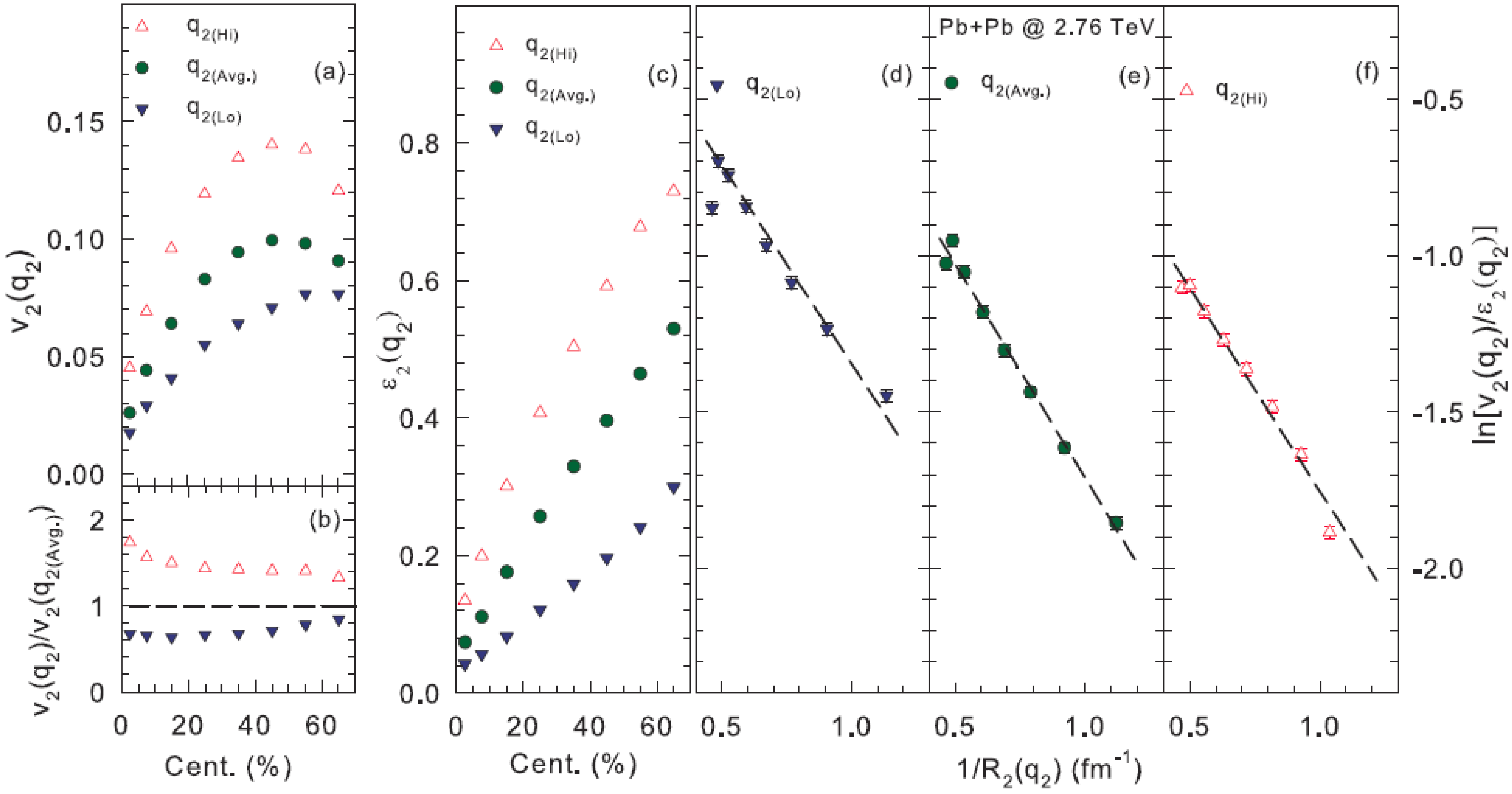


- ***Cuts on q_n should change the magnitudes $\langle \epsilon_n \rangle$, $\langle v_n \rangle$, $\langle R_n \rangle$ at a given centrality due to fluctuations***
- ***Viable models for initial-state fluctuations should still scale***

Scaling properties of flow

Acoustic Scaling of shape-engineered events

Lacey et. al, arxiv:1311.1728

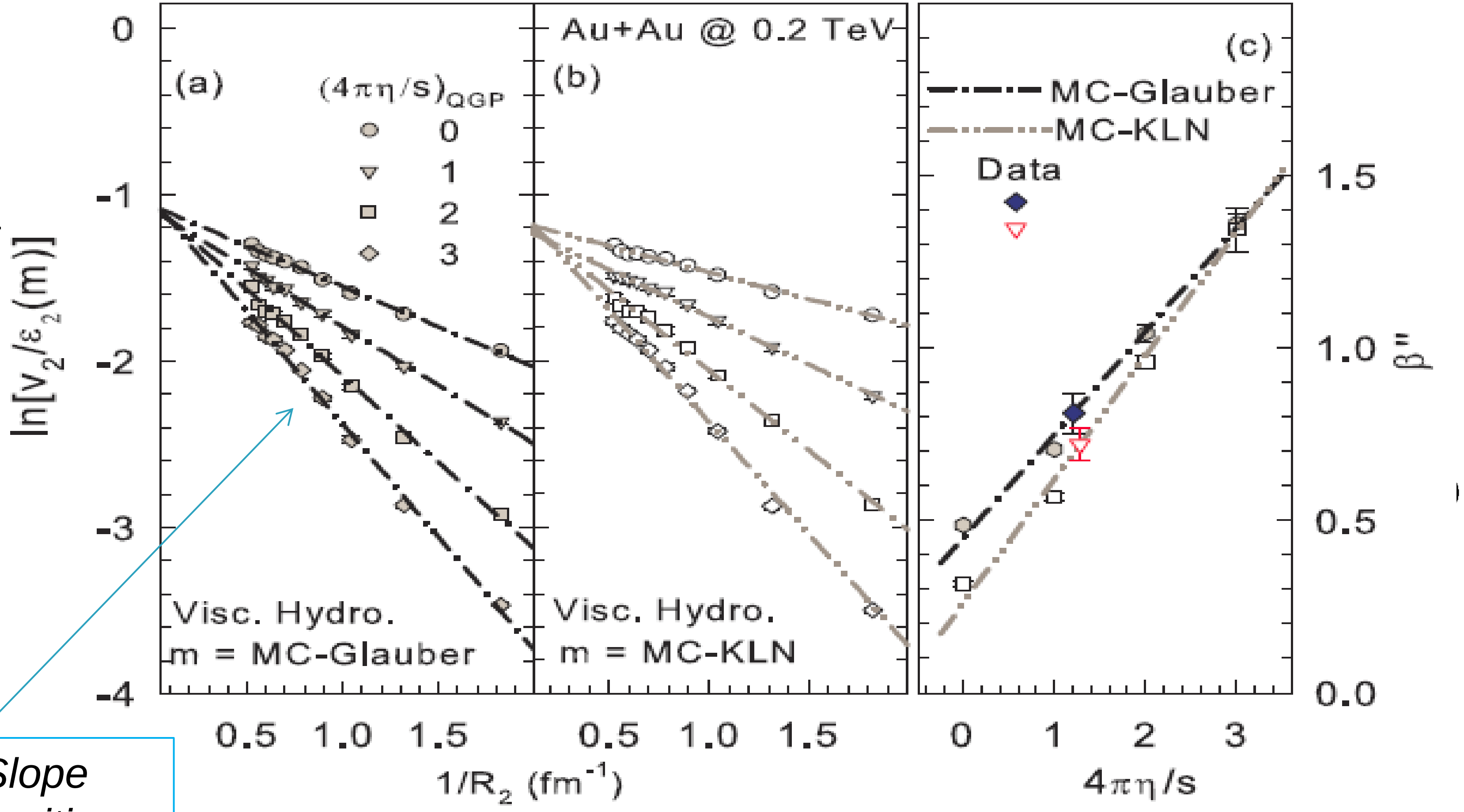


- ✓ **Characteristic $1/\bar{R}$ viscous damping validated for different event shapes at the same centrality**
- ✓ ***A further constraint for initial fluctuations model and η/s***

Extraction of η/s

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

Lacey et. al, arxiv:1311.1728



*Slope sensitive to 4π**η/s***

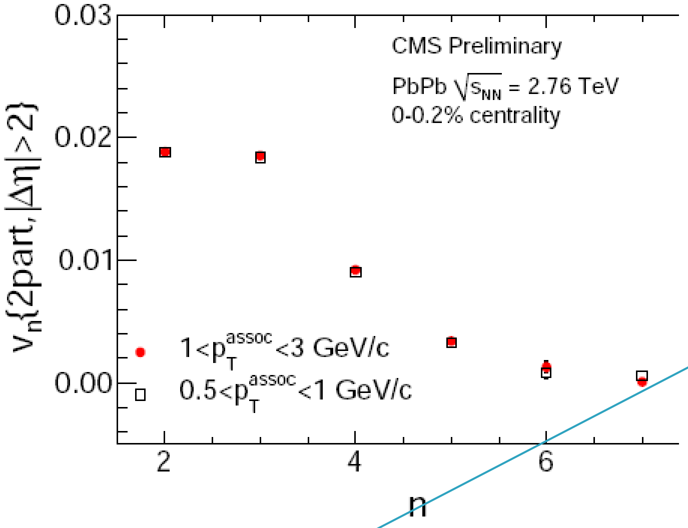
Characteristic $1/\bar{R}$ viscous damping validated in viscous hydrodynamics; calibration → 4πη/s ~ 1.3 ± 0.2

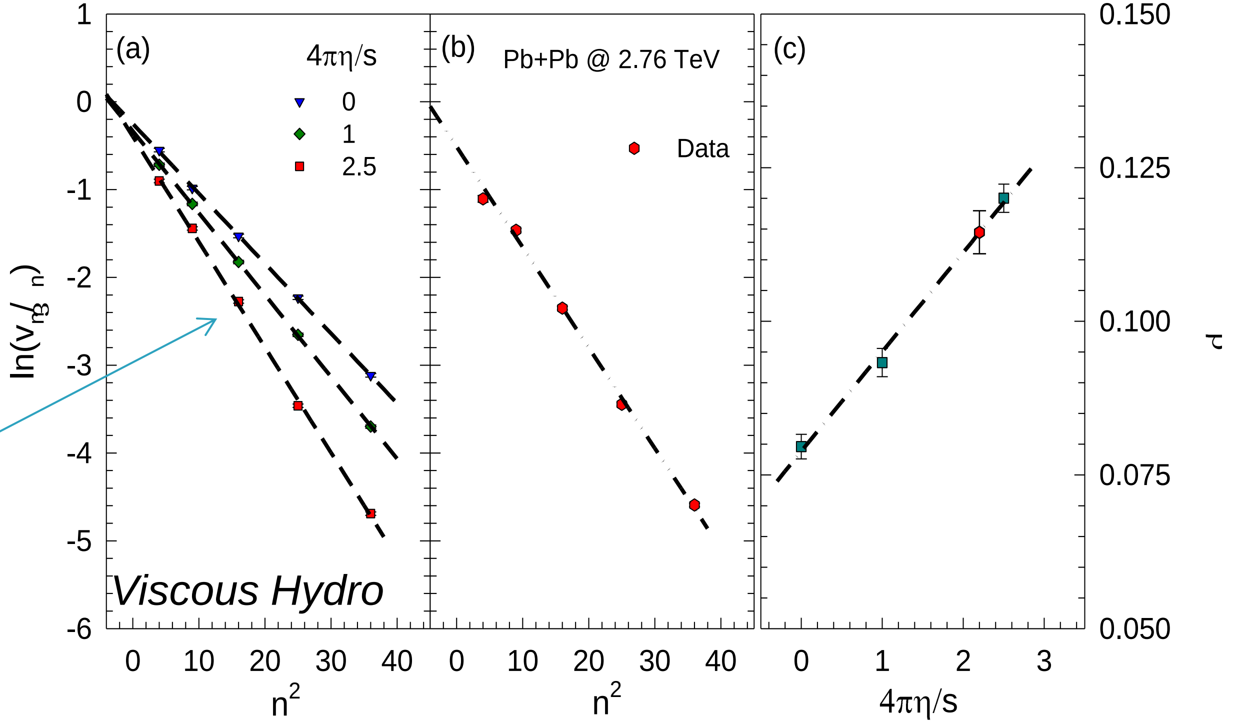
Extracted η/s value insensitive to initial conditions

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***

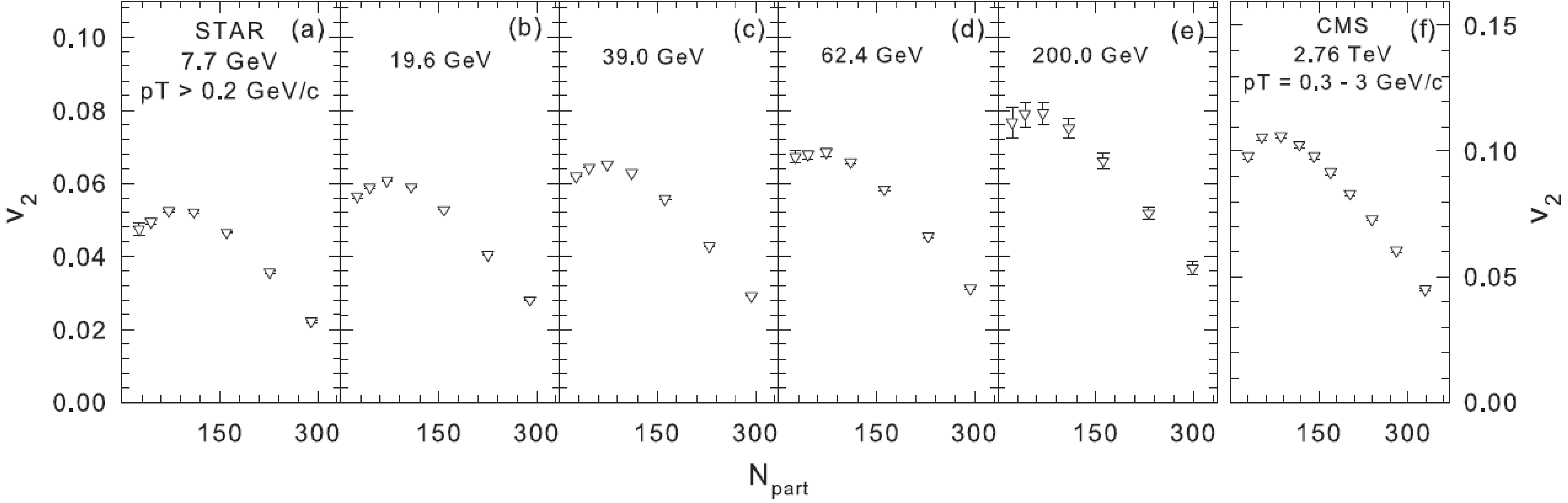
n^2 scaling validated in experiment and viscous hydrodynamics; calibration → 4π*η/s* ~ 2.2 ± 0.2

$\sqrt{s_{NN}}$ dependence of viscous coefficient

arXiv:1305.3341

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

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



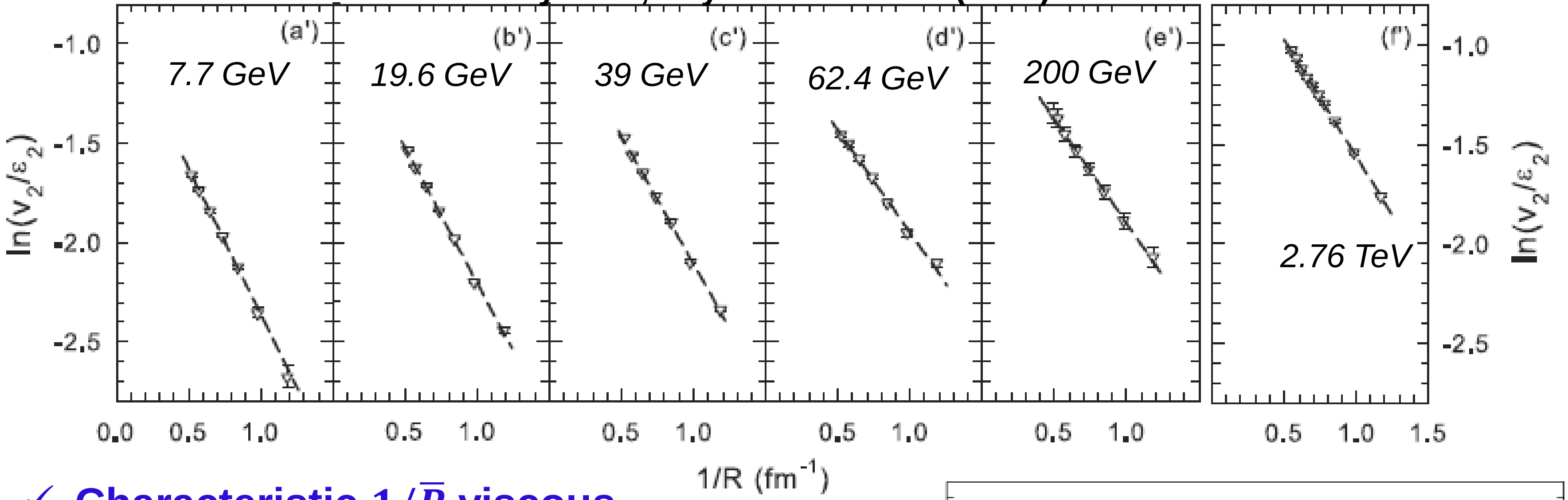
- ***An extensive set of measurements now span a broad range of beam energies (T, μ_B).***

$\sqrt{s_{NN}}$ dependence of viscous coefficient

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

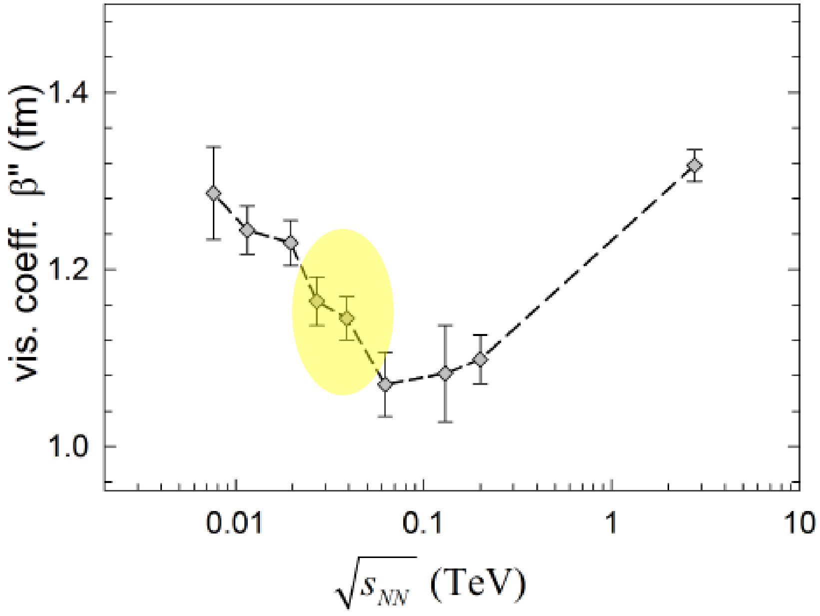
Acoustic Scaling – $\frac{1}{\bar{R}}$ Scaling for the Beam Energy Scan

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

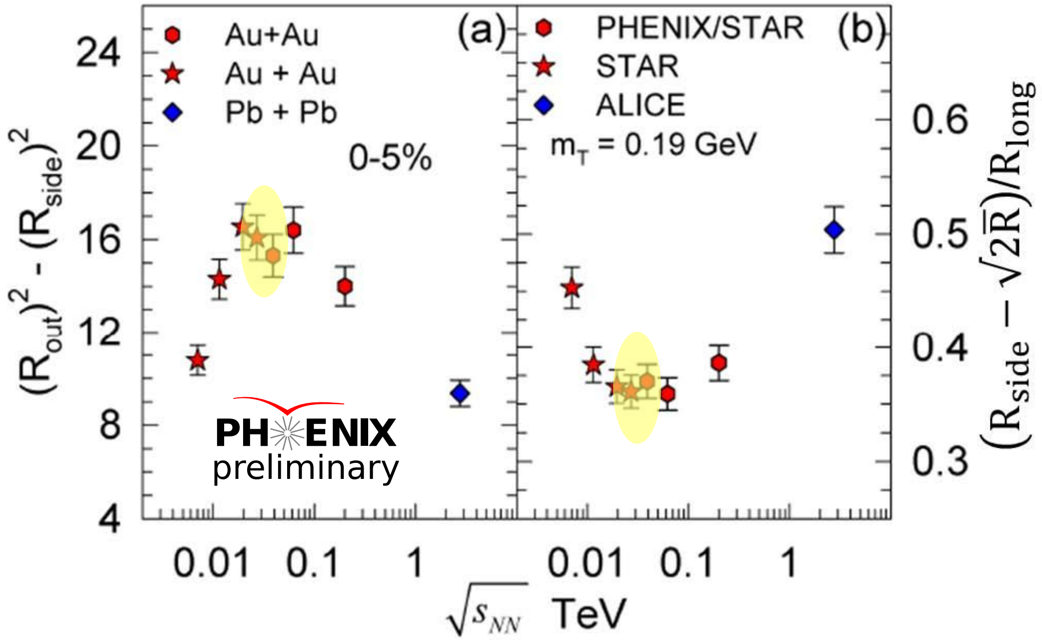


- ✓ **Characteristic $1/\bar{R}$ viscous damping validated across beam energies**
- ✓ **First experimental indication for *η/s variation in the* (T, μ_B)-plane**
- ✓ **CEP?**

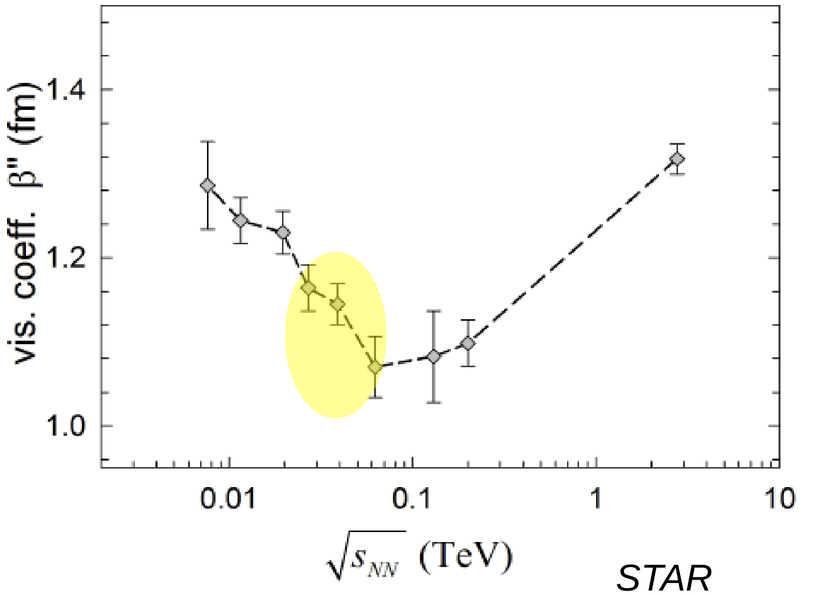
Complimentary signals for similar $\sqrt{s_{NN}}$



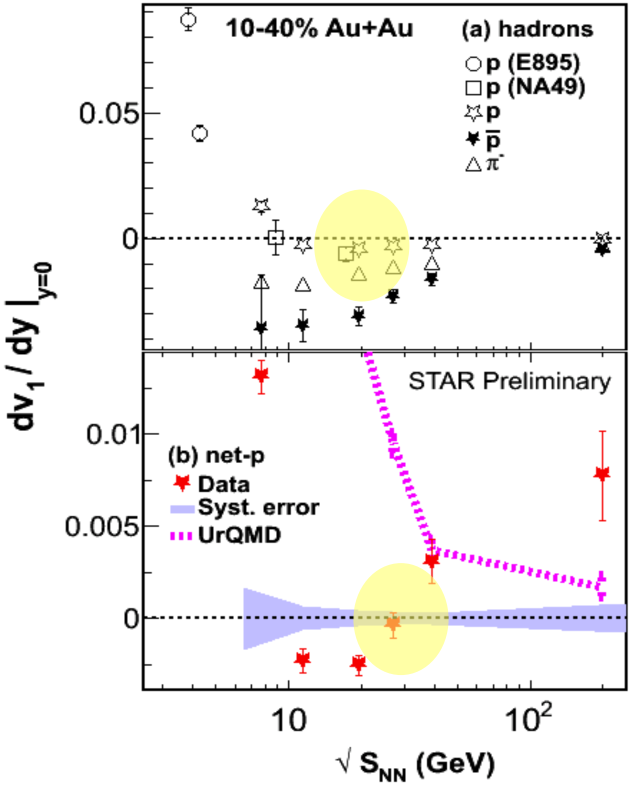
$\sqrt{s_{NN}}$ dependence of HBT signals



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



STAR



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*

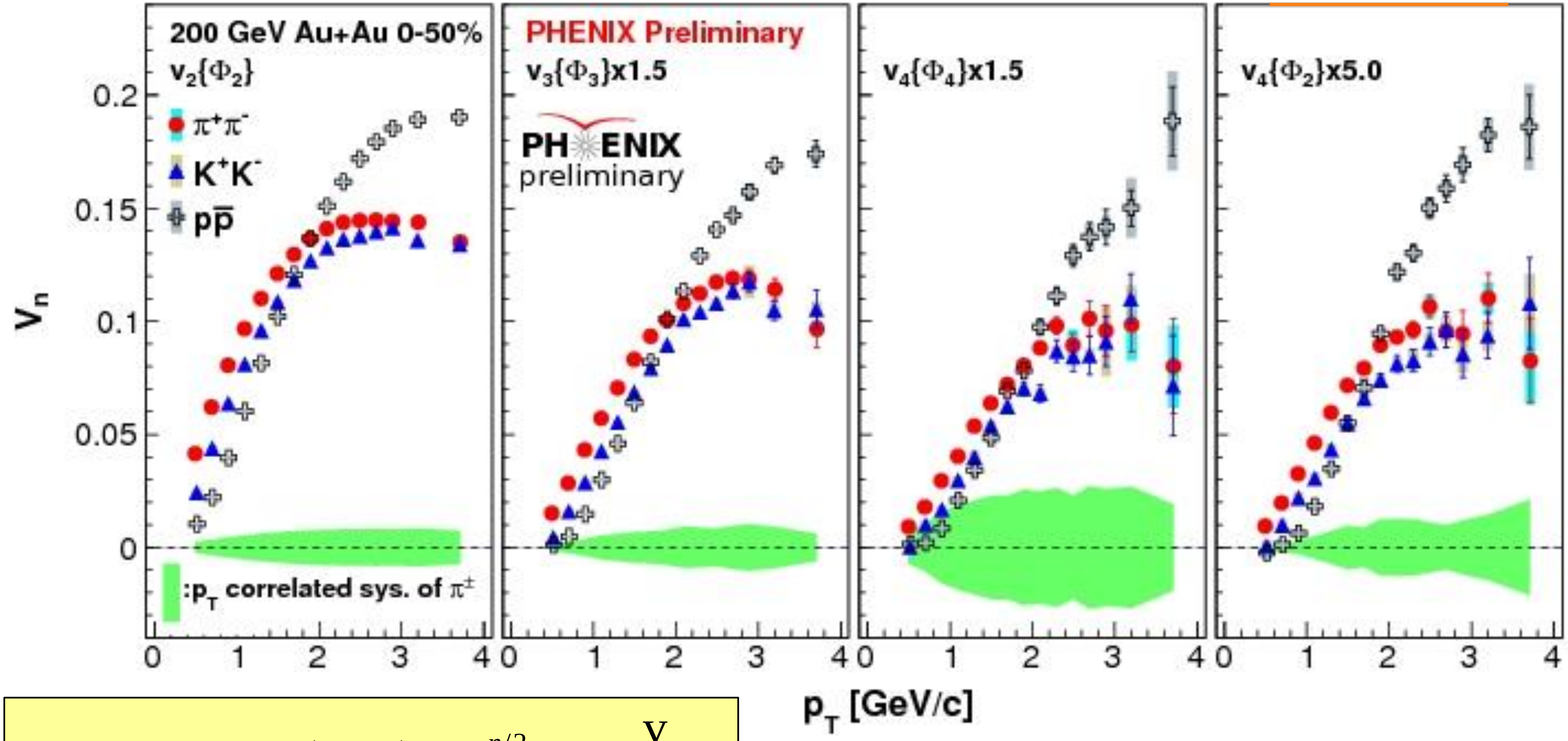
What do we learn?

- ***The expansion dynamics is acoustic –** “as it should be”*
  - ***Validates expected acoustic scaling of flow and HBT radii***
    - ✓***constraints for 4π*η/s & viable initial-state models***
    - ✓***4π*η/s for RHIC plasma** ~ 1.3 ± 0.2 **~ my 2006 estimate***
    - ✓***4π*η/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

Flow is partonic & Acoustic?

arXiv:1211.4009



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

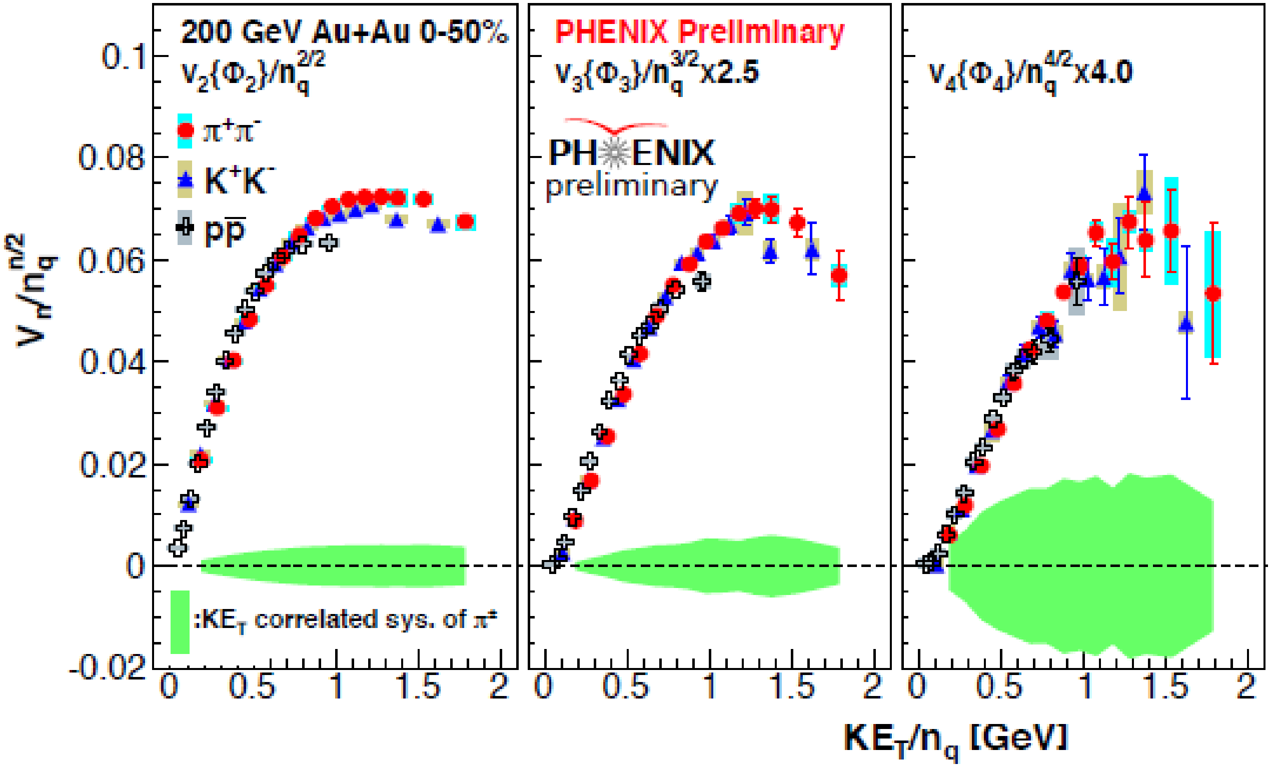
Note species dependence for all v_n

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 $\dfrac{v_n}{(n_q)^{n/2}}$