Bulk Properties at RHIC

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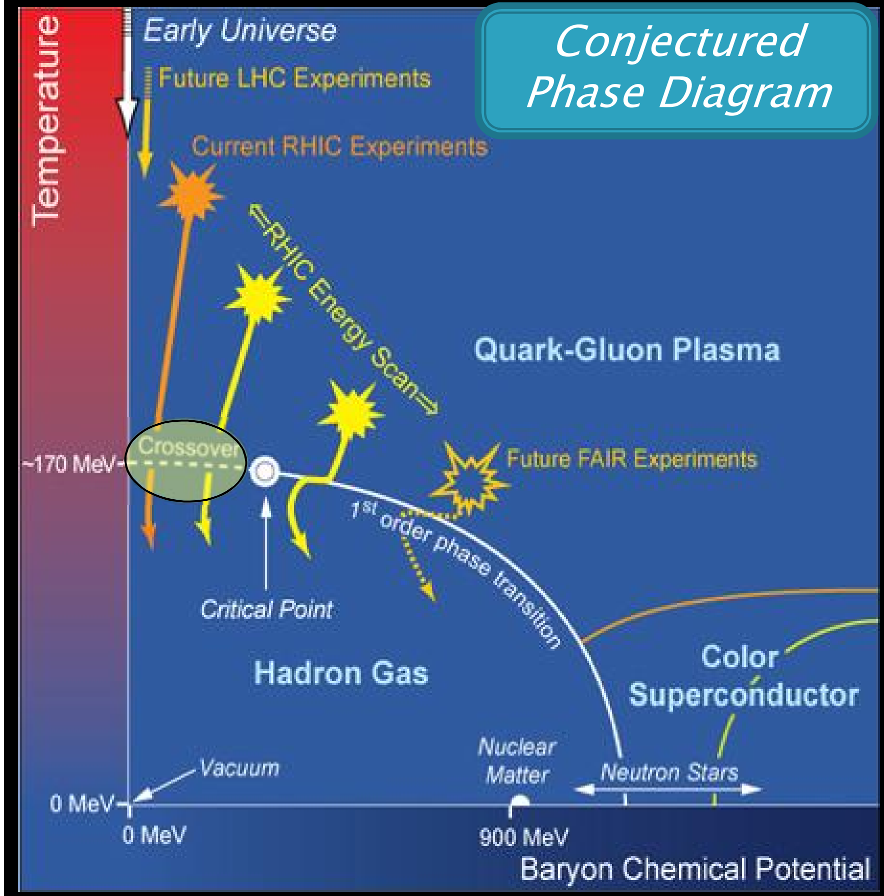
I. Introduction
II. What is meant by the bulk?
III. The role of the bulk in reaction studies?
IV. Selected studies of bulk properties and what we learn from them

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?**

$$\frac{\eta}{s}(T,\mu),\ \frac{\zeta}{s}(T,\mu),\ c_s(T),\ \hat{q}(T),\ \alpha_s(T), \text{etc}$$

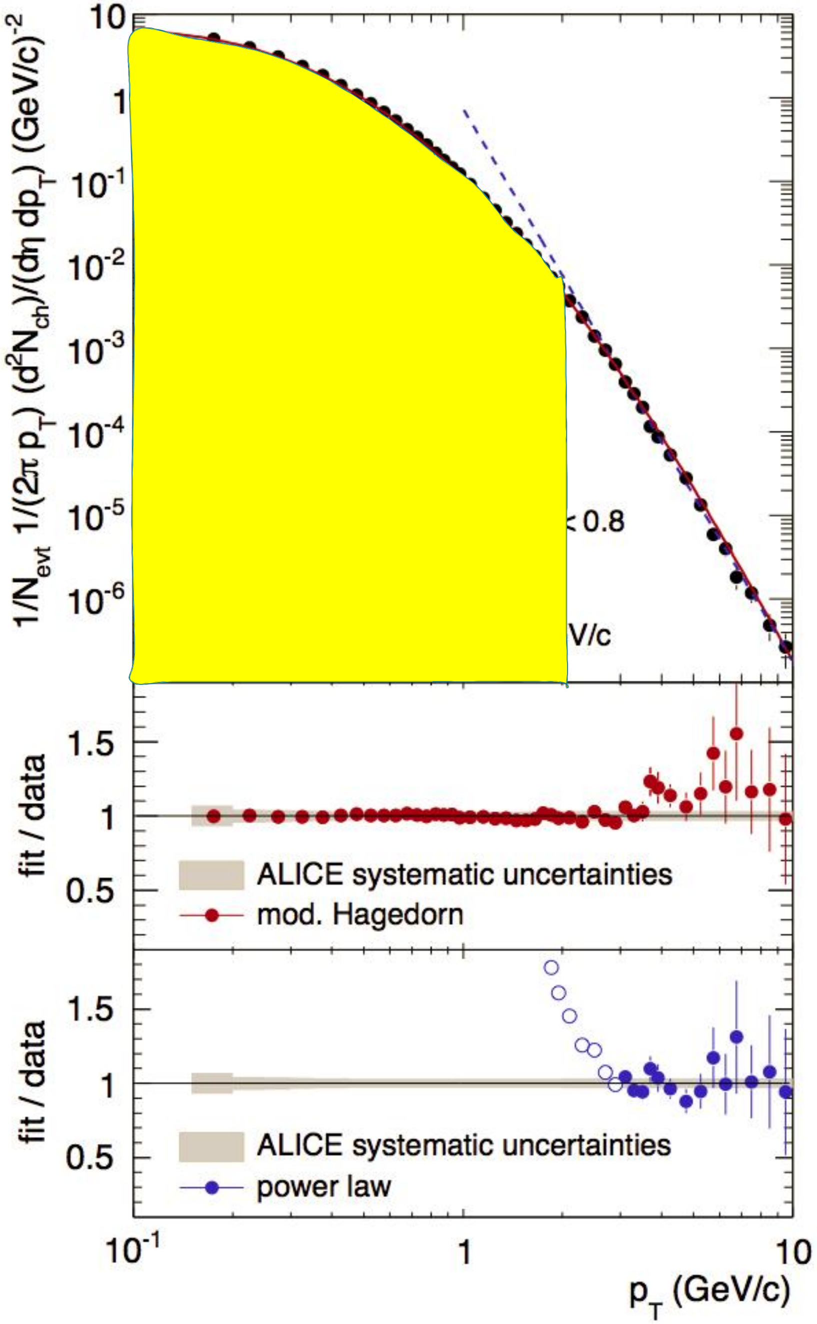
*Measurements which span a broad range of the **(T, μ_B)-plane** are essential for a mapping of he phase diagram. Bulk properties play an essential role*

What is the bulk?

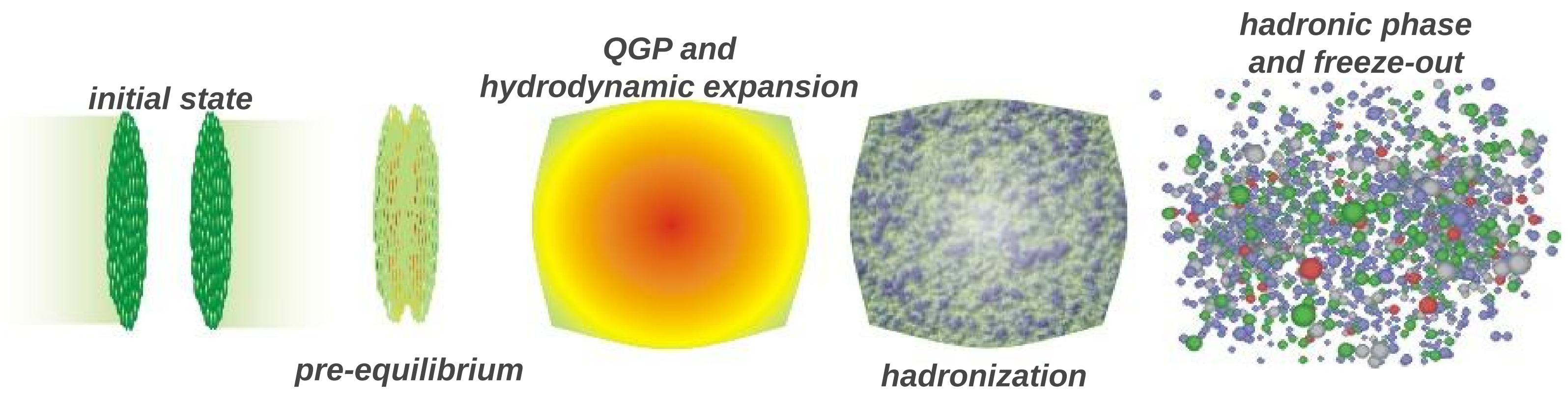
Phenomenological definition:

We can distinguish between *a soft part (exponential shape)* and a *hard part* (power-law shape) of the measured p_T spectra

~98% of all particles are produced with $p_T < 2$ GeV/c.



The role of bulk properties



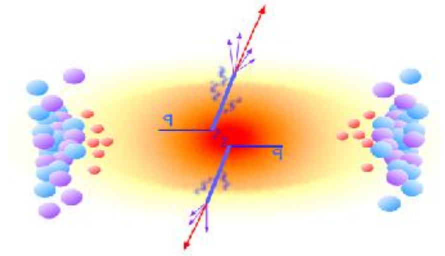
Constraints for
Initial state geometry
and fluctuations
(flow measurements)

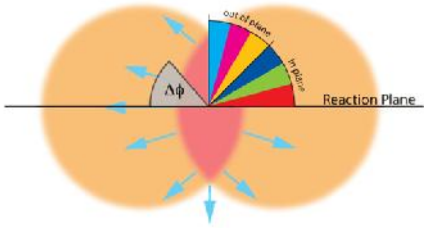
Constraints for
QGP properties,
degrees of freedom
and CEP
(flow measurements)

Constraints for
Local thermal
Equilibrium
(particle yields)

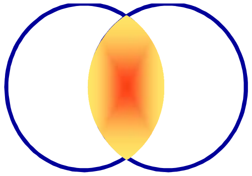
Constraints for
Space-time dynamics
EOS and CEP
(HBT measurements)

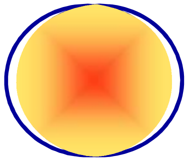
Bulk properties also play a crucial role for control variables in studies involving hard and soft processes





Collision centrality & Geometry

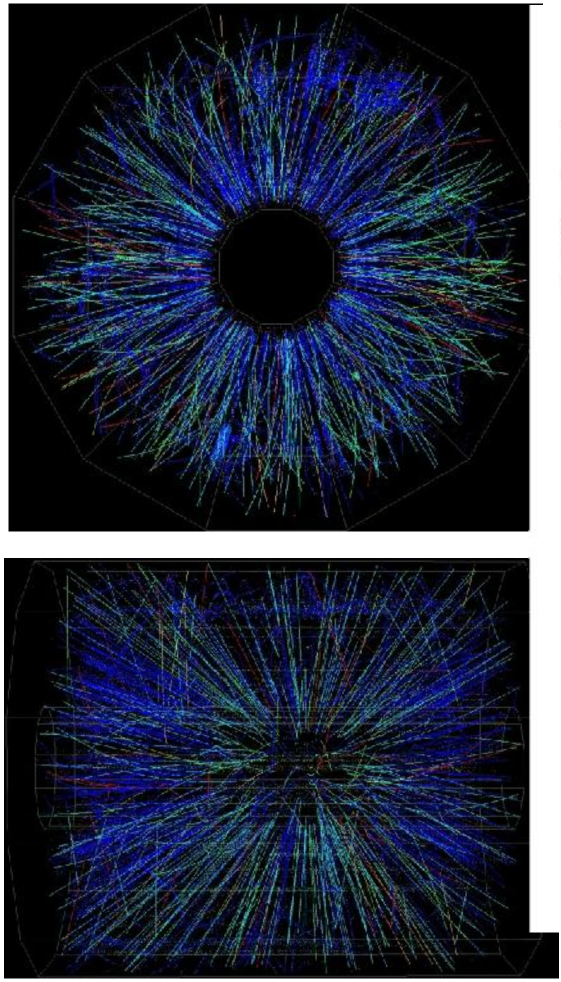


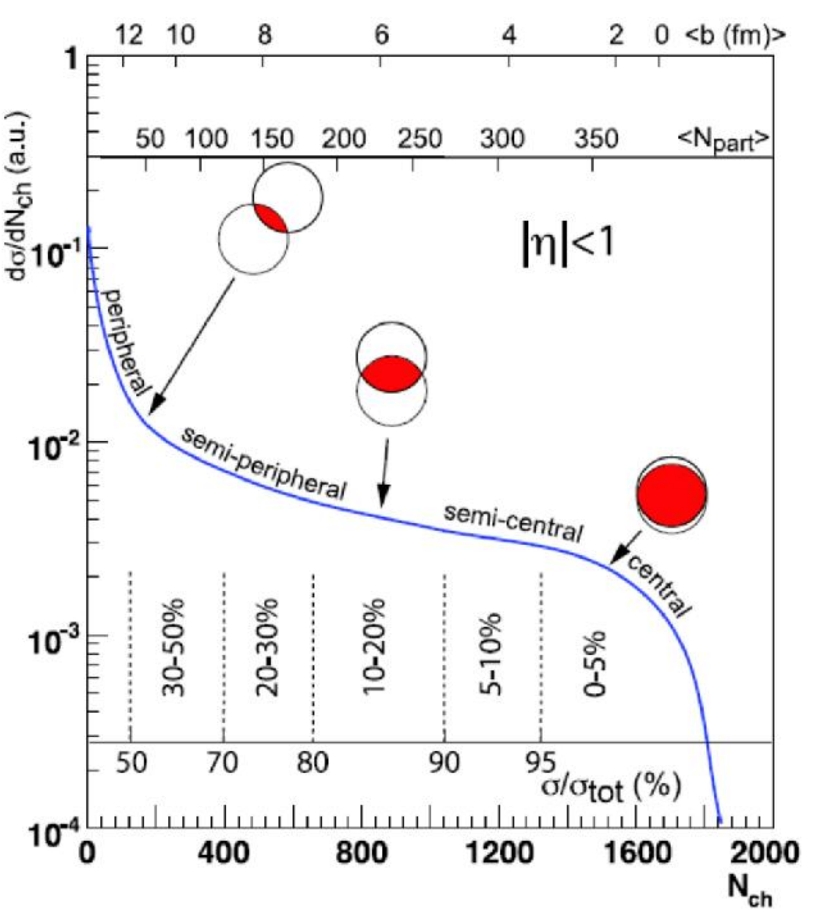


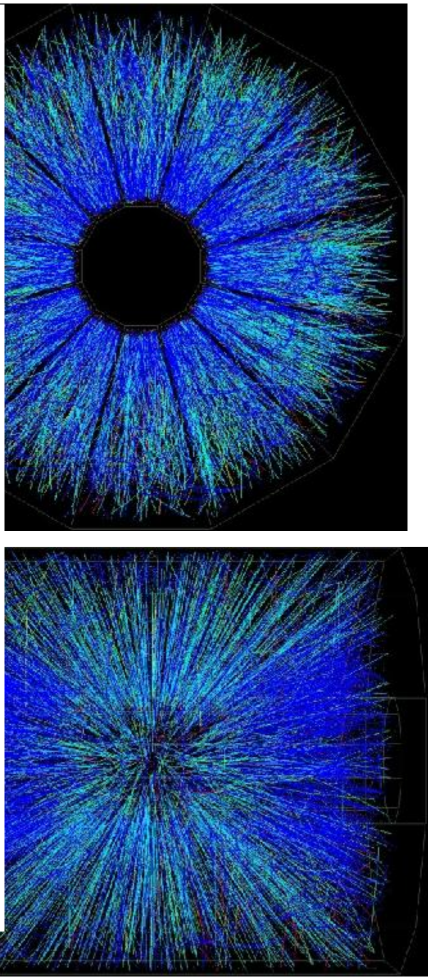
peripheral

mid-central

central





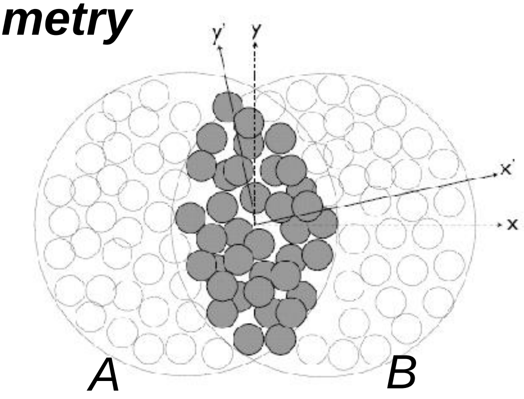


Bulk particles are used to calibrate collision centrality and the associated initial-state geometry

Roy A. Lacey, Stony Brook University, JC Summer School, June 19-21, 2014

Geometric quantities

Geometry



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

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

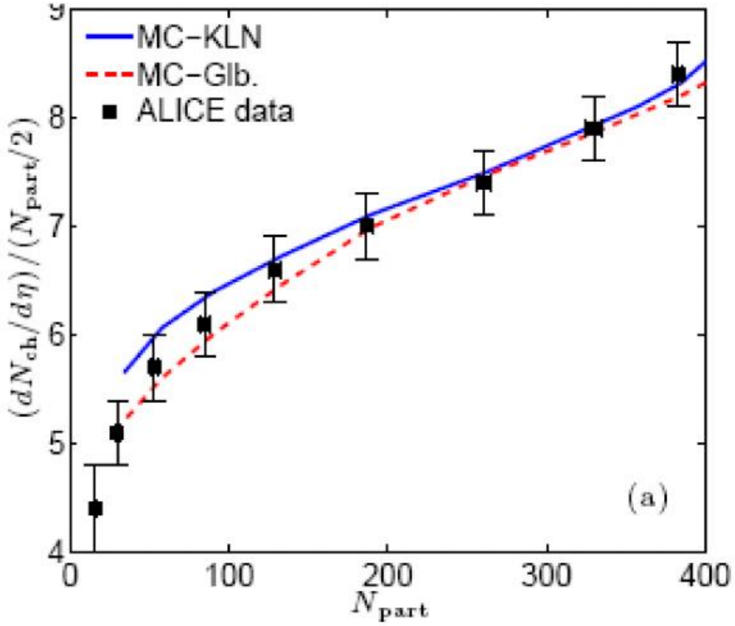
$$S_{ny} \equiv S_n \sin\left(n\Psi_n^*\right) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\sin(n\phi),$$

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

$$£_n = \left\langle \cos n\left(¤ - \cdot\,_n^*\right)\right\rangle$$

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

arXiv:1203.3605



σ_x & σ_y → RMS widths of density distribution

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

Event plane

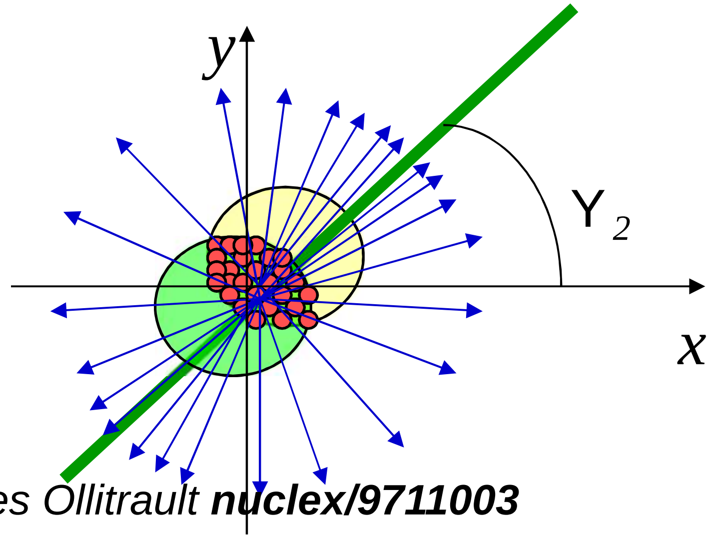
Bulk particles are used to determine the event plane

$$\mathbf{Q}_n = \sum_{j=1}^{N} w_n(j)\, e^{in\phi_j} = |\mathbf{Q}_n|\, e^{in\Phi_n}$$

$$Q_n \cos(n\Psi_n) = X_n = \sum_i w_i \cos(n\phi_i),$$

$$Q_n \sin(n\Psi_n) = Y_n = \sum w_i \sin(n\phi_i),$$

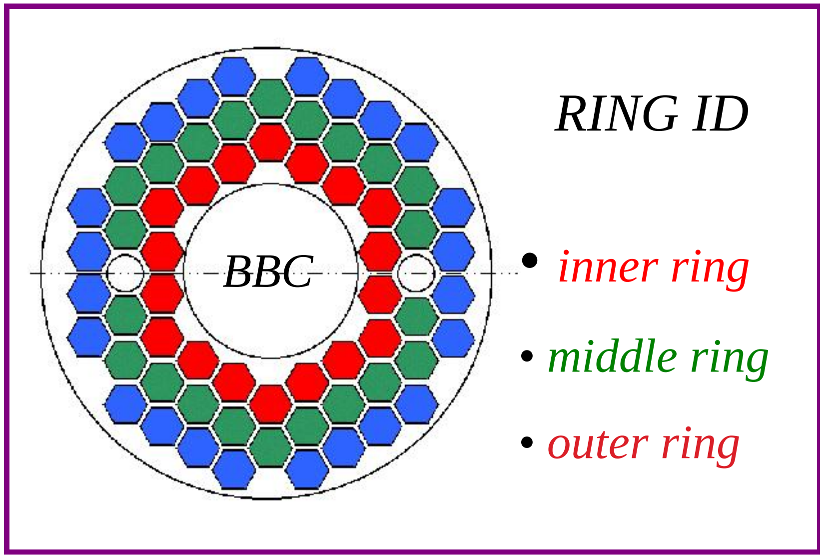
$$\Psi_n = \left(\tan^{-1}\frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)}\right)/n$$



Jean-Yves Ollitrault **nuclex/9711003**

For a given event and a given harmonic n.

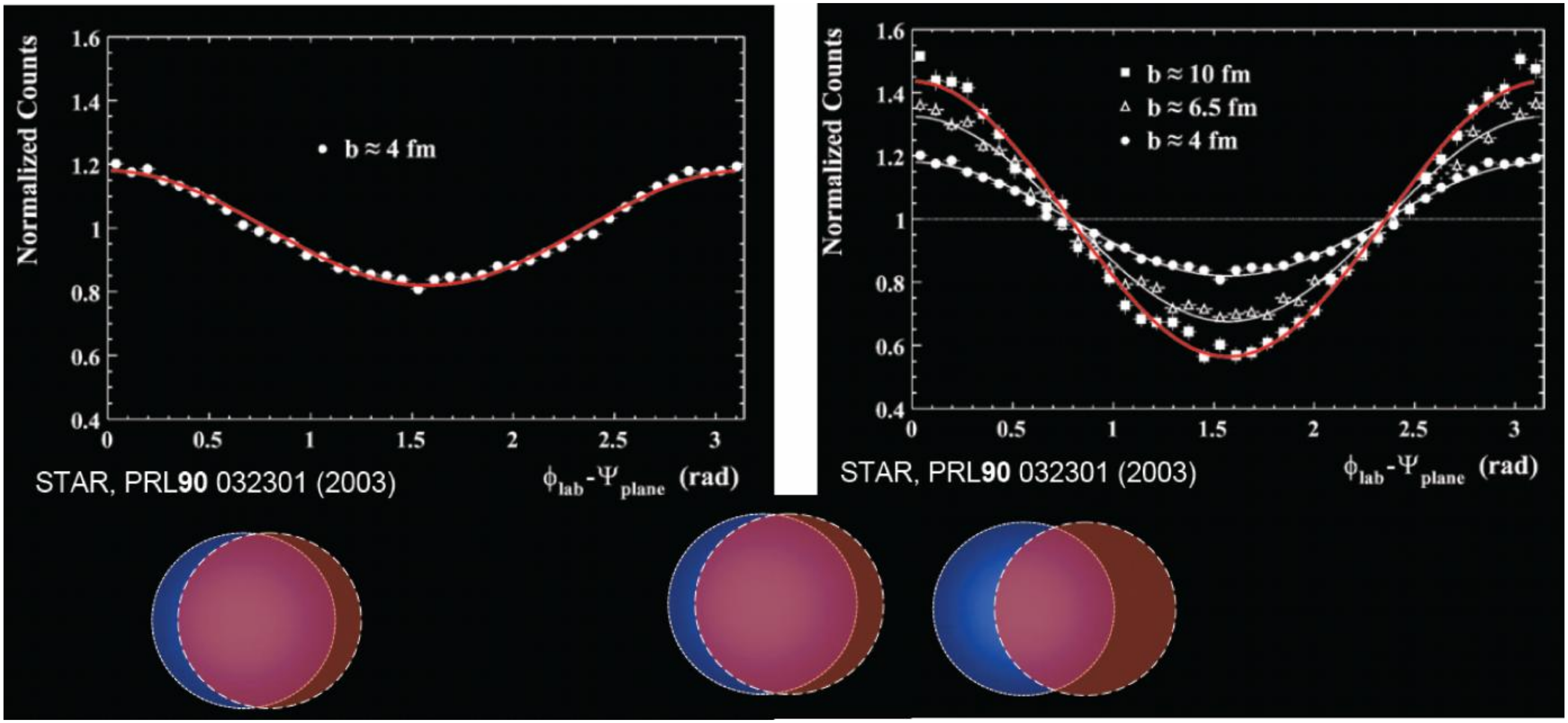
- N = Particle multiplicity
- φ_i = particle azimuthal angles
- w_i = weight for particle i



There are well established correction procedures for event plane dispersion

Azimuthal distribution

A variety of variables are measured relative to the event plane



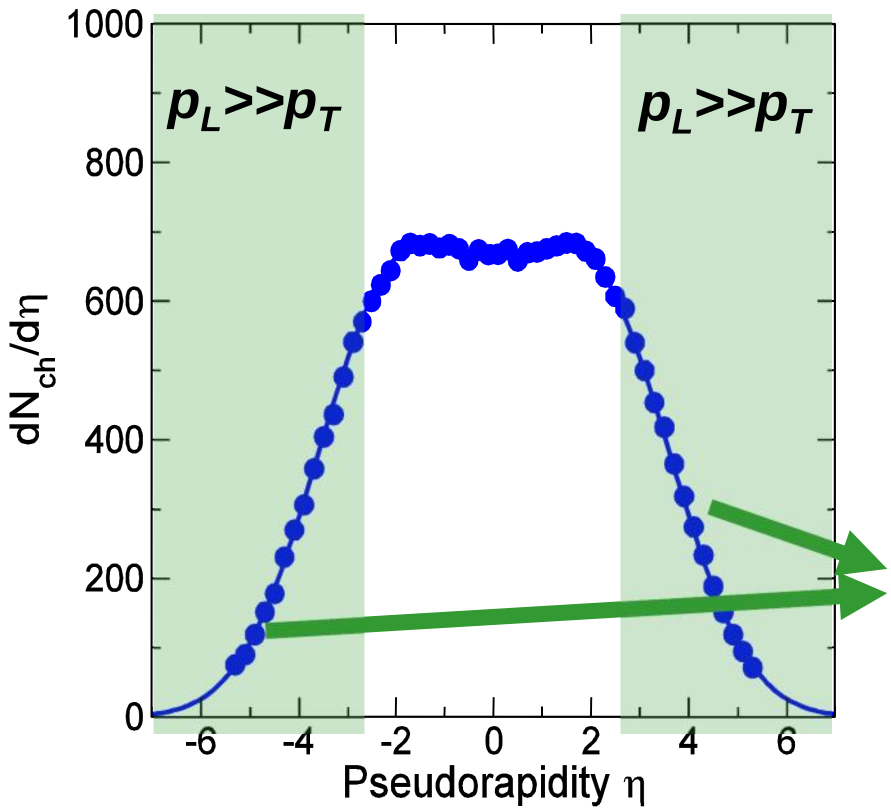
STAR, PRL**90** 032301 (2003)

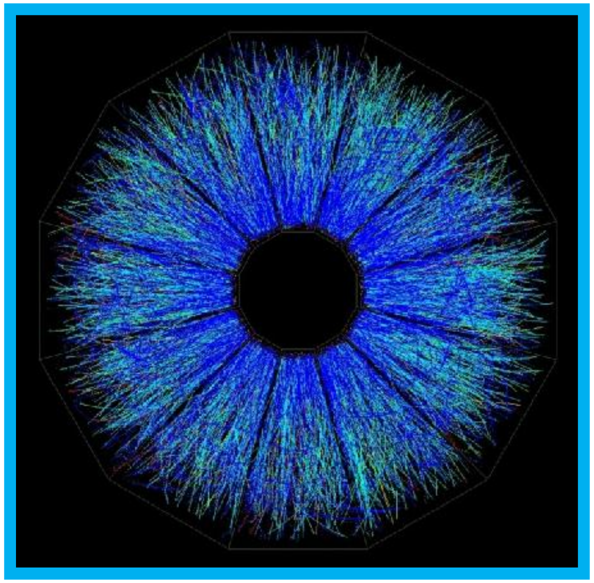
STAR, PRL**90** 032301 (2003)

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

Energy Density

Bulk particles are used to estimate the energy density





- In central AuAu collisions at RHIC (Ěs=200 GeV) about 5000 particles are created

$$£_{BJ} = \frac{\langle m_T \rangle}{Ac{}^2{}_0}\left(\frac{dN}{dy}\right)_{y=0} = \frac{0.6\ \text{GeV}/c^2}{145\ \text{fm}^2 \times c \times {}^2{}_0} \times \left(700 \times \frac{3}{2} \times 1.1\right)$$

$$¦ = \frac{1}{2}\cdot\ln\left(\frac{|\mathbf{p}|+p_L}{|\mathbf{p}|-p_L}\right) = -\ln\left[\tan\left(\frac{g}{2}\right)\right]$$

$$y = \frac{1}{2}\cdot\ln\left(\frac{E+p_L}{E-p_L}\right)$$

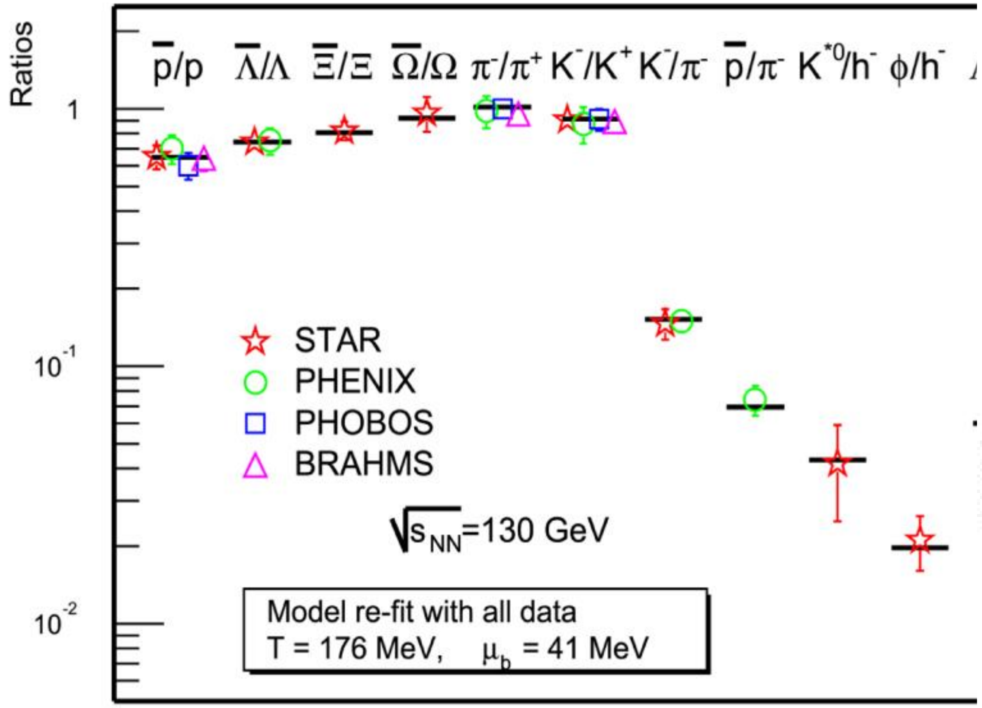
e_{BJ} ~ 5 - 15 GeV/fm^3

~ 35 - 100 ε_0

$$m_T = m(¥_T - 1)$$

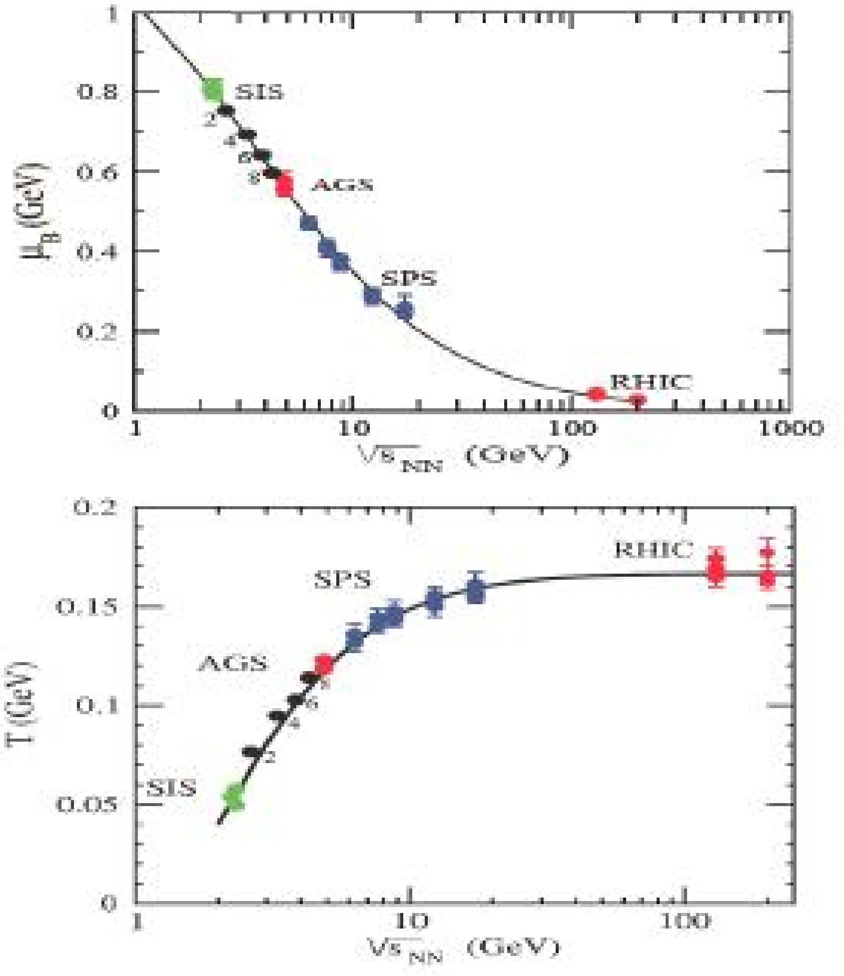
Hadronization

$$\ln Z_{GK_i} = \pm g_i \frac{V}{2\pi^2\hbar^3}\int_0^\infty dp\, p^2 \ln\left(1 \pm e^{-\beta(\epsilon(p)-\mu_i)}\right)$$



Braun-Munzinger et al., PLB 518 (2001) 41

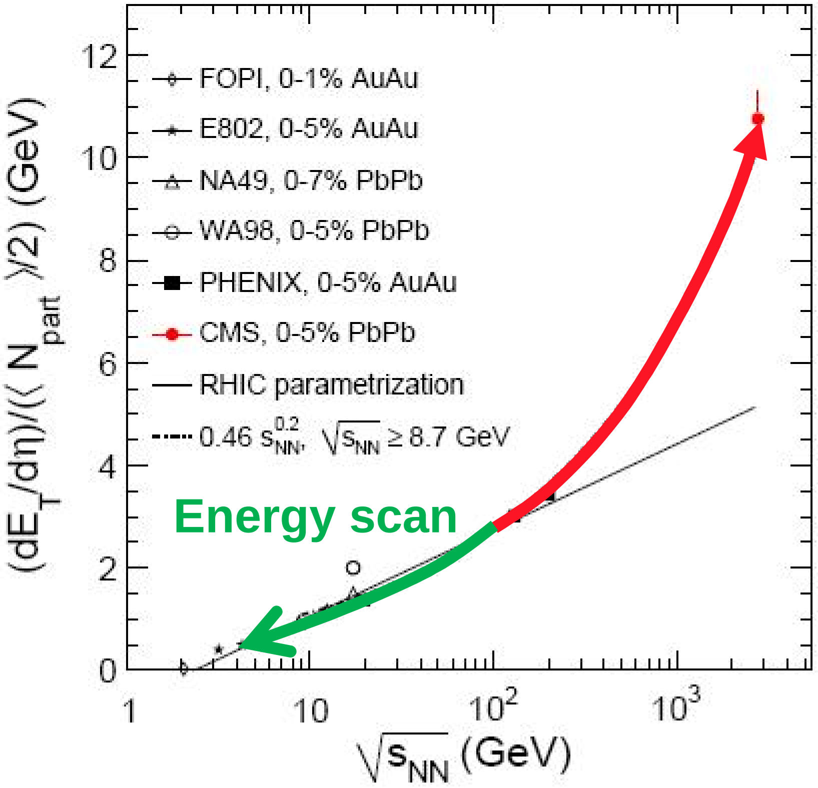
(μ_B, T) at freeze-out



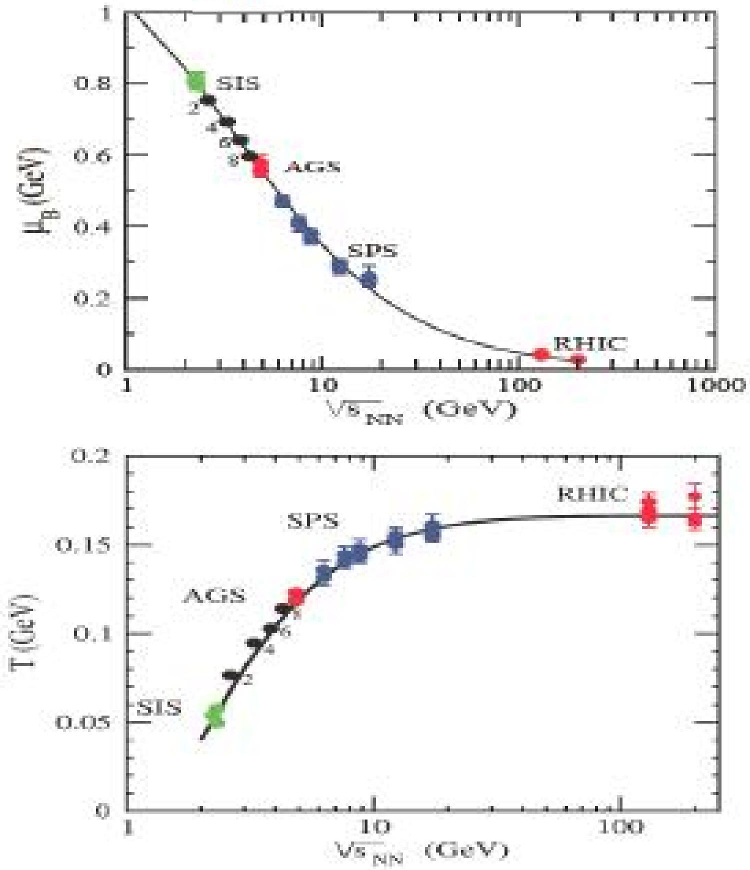
The success of **thermal models** describing **bulk hadron yields** supports the idea of matter in local thermal equilibrium?

A current strategy for navigating the (μ_B, T)-plane

Exploit system size and beam energy lever arm



(μ_B, T) at freeze-out



- ***LHC → access to high T and small μ_B***

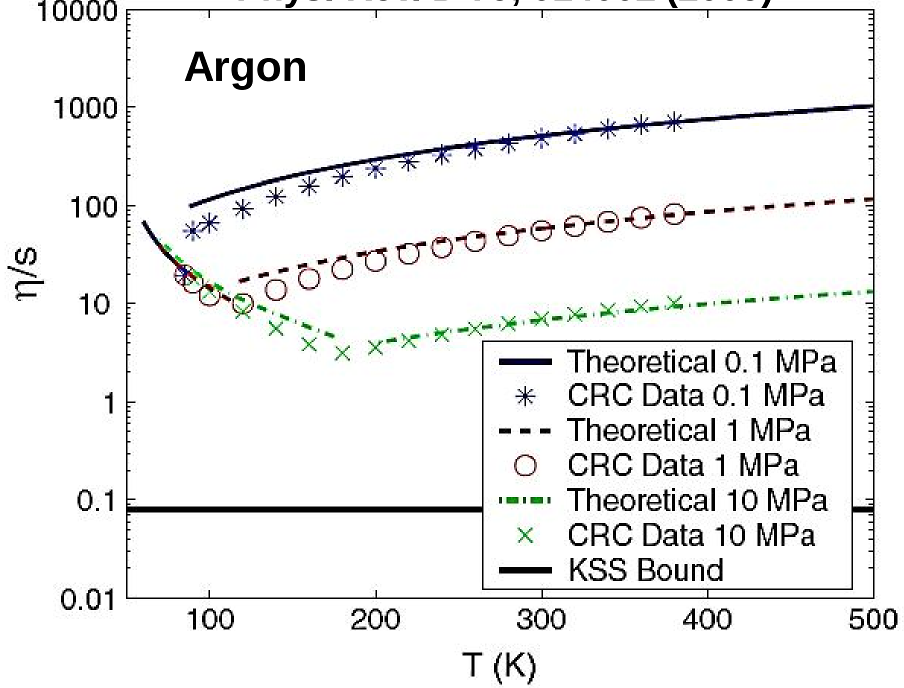
- ***RHIC → access to different systems and a broad domain of the (μ_B, T)-plane***

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

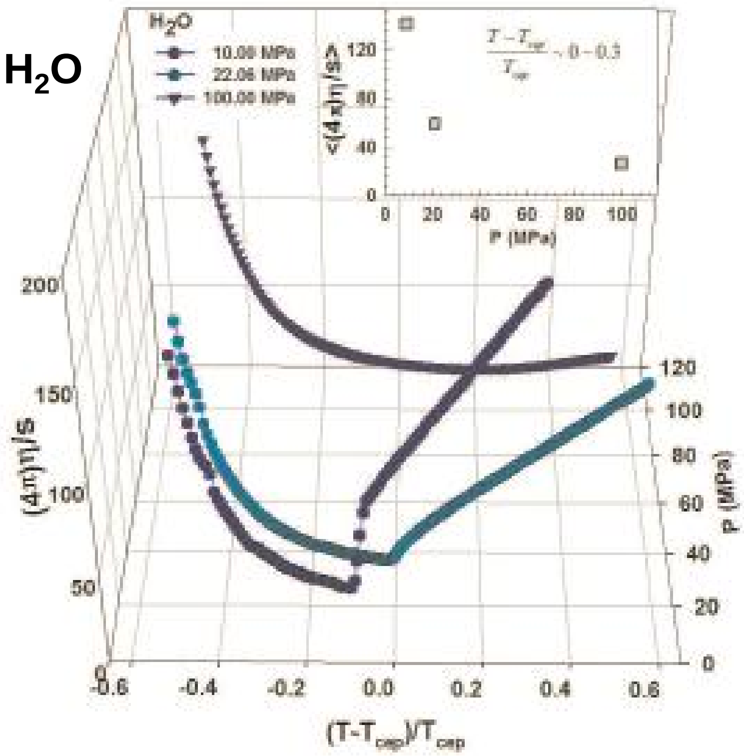
- ***LHC + BES → access to an even broader domain of the (μ_B, T)-plane***

Possible signals for the CEP

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)***



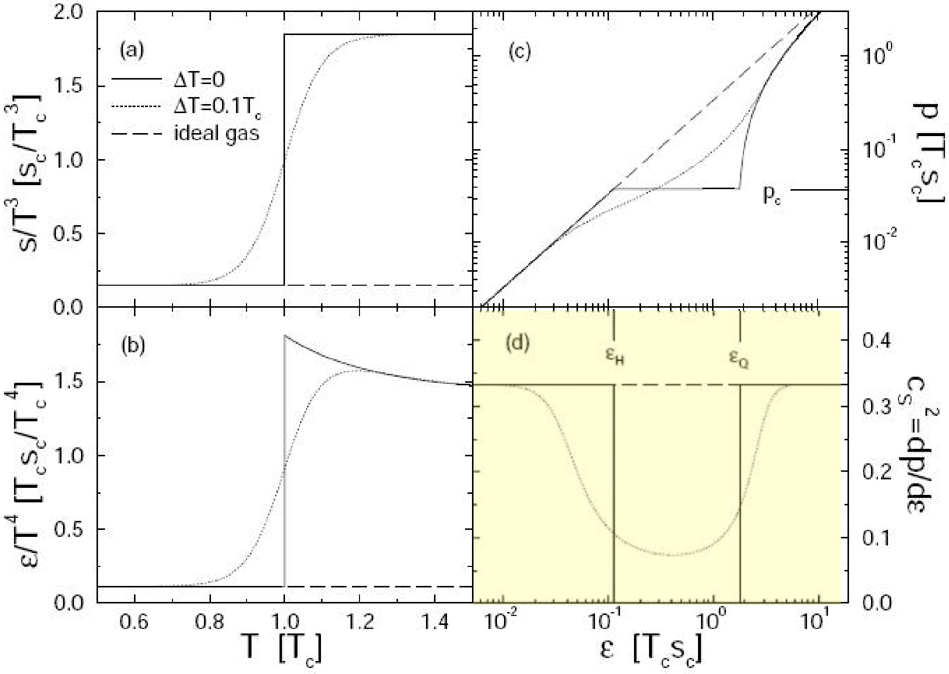
At the CEP or close to it, anomalies in the dynamic properties of the medium can drive abrupt changes in transport coefficients

Anisotropic flow (v_n) measurements are an invaluable probe

Possible signals for the CEP

Collapse of directed flow
H. Stoecker, NPA 750, 121 (2005)

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



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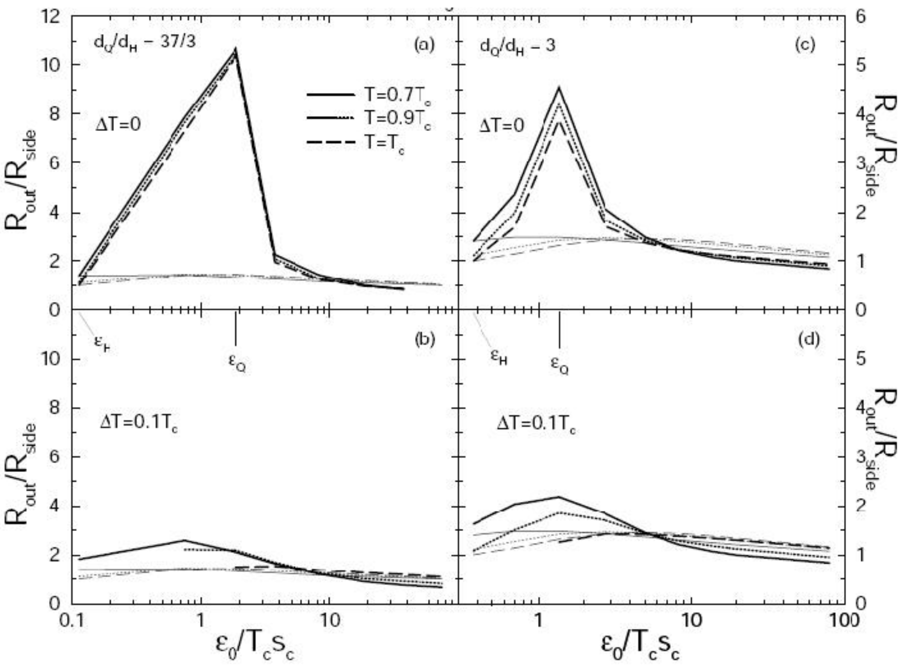


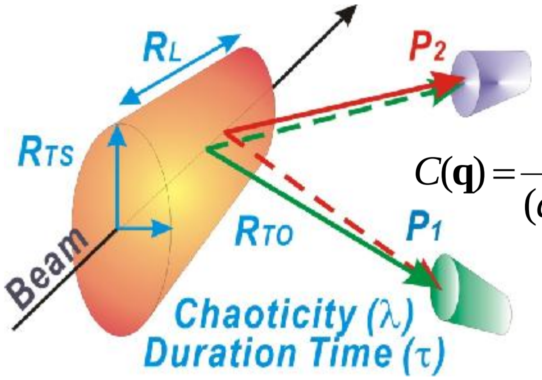
In the vicinity of a phase transition or the CEP, the sound speed is expected to soften considerably.

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

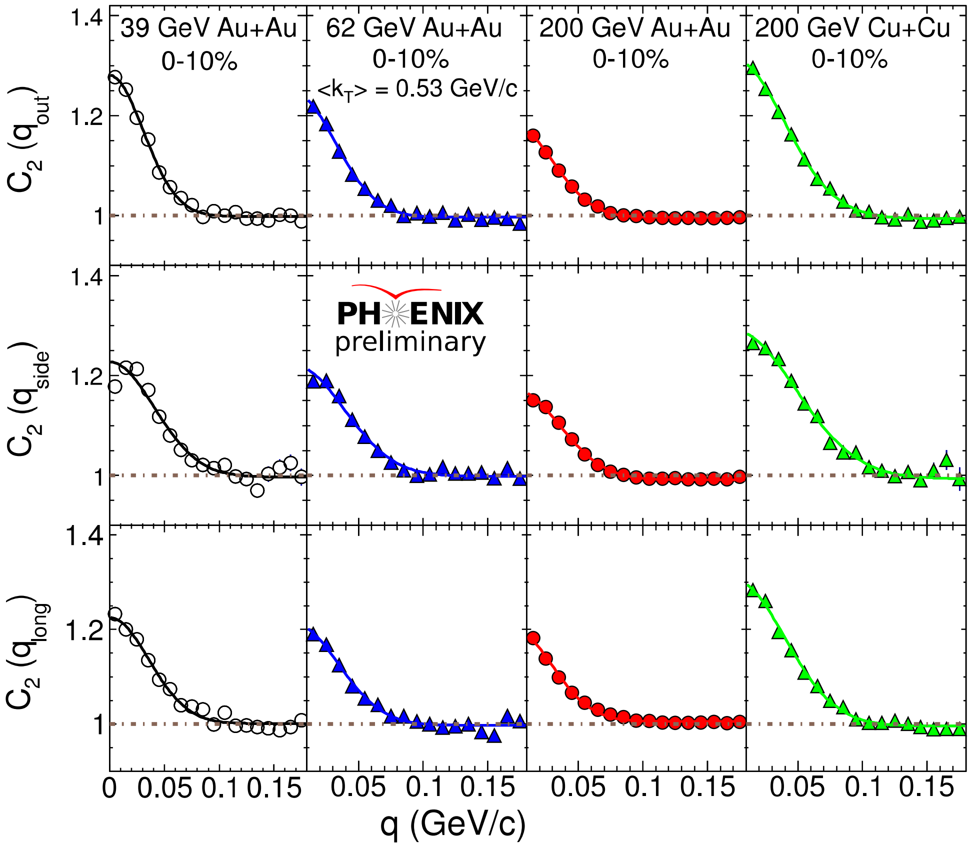
HBT measurements are an invaluable probe

HBT measurements

Two particle Interferometry Studies



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



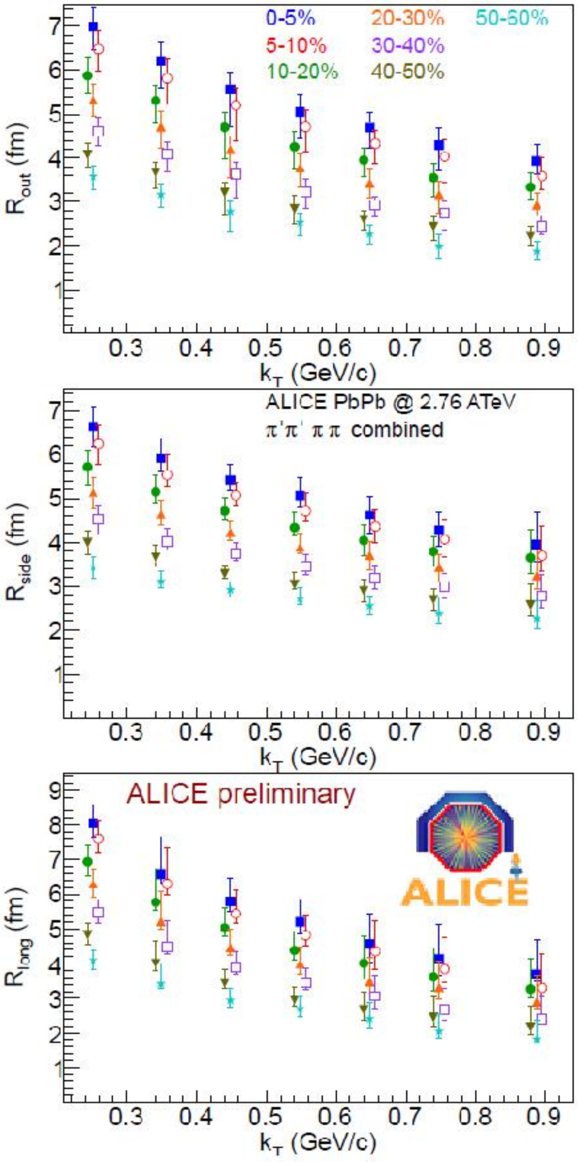
$$C_2(\mathbf{q}) = N[(\lambda(1 + G(\mathbf{q})))F_c + (1 - \lambda)]$$
$$G(\mathbf{q}) \cong \exp(-R^2_{\mathrm{side}}q^2_{\mathrm{side}} - R^2_{\mathrm{out}}q^2_{\mathrm{out}} - R^2_{\mathrm{long}}q^2_{\mathrm{long}})$$

Fits to the correlation functions

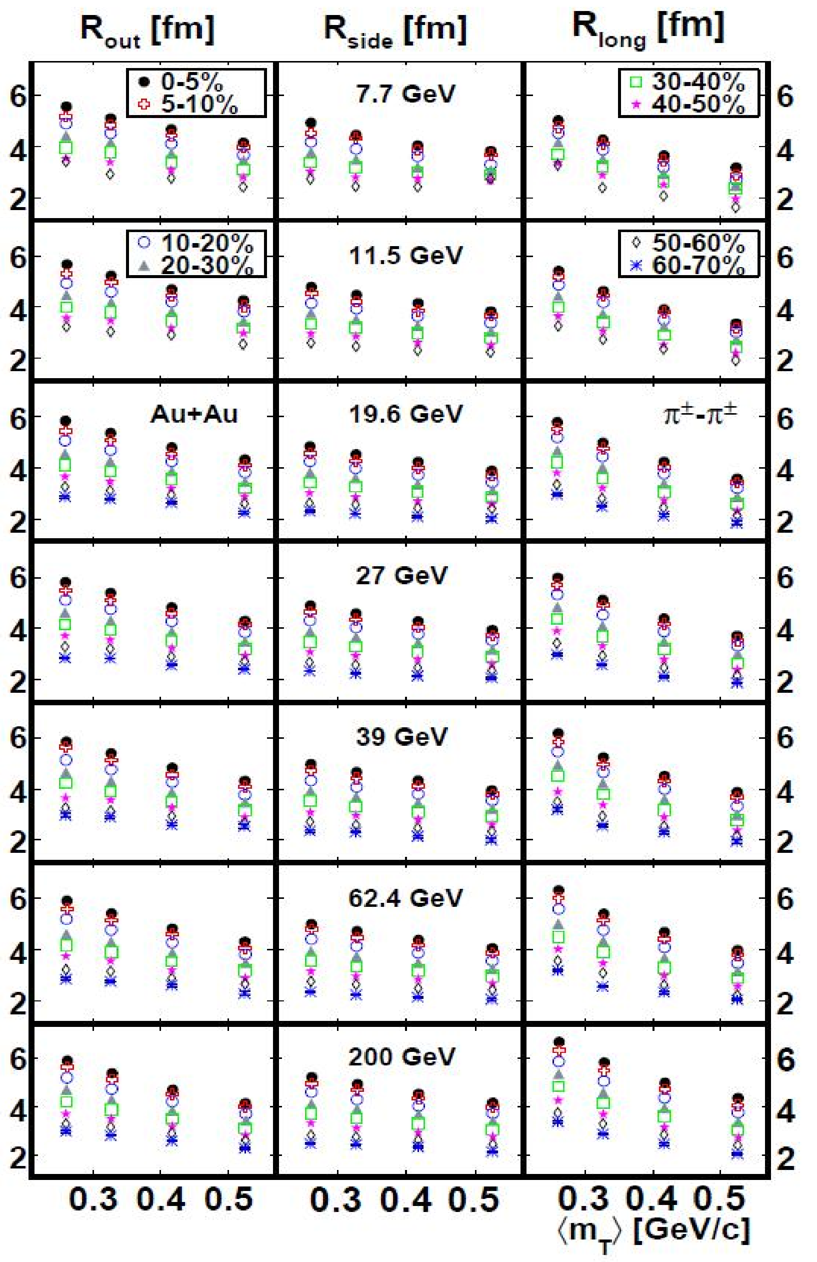
→HBT radii (R_{out}, R_{side}, R_{long}) as a function of centrality, m_T, etc

HBT Radii

ALICE -PoS**WPCF2011**

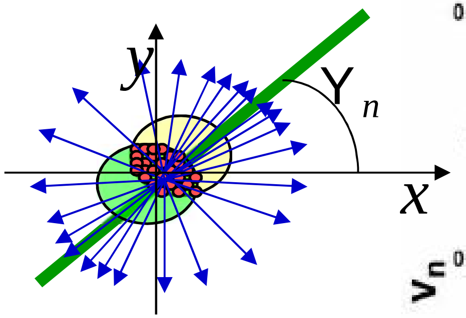


STAR - 1403.4972

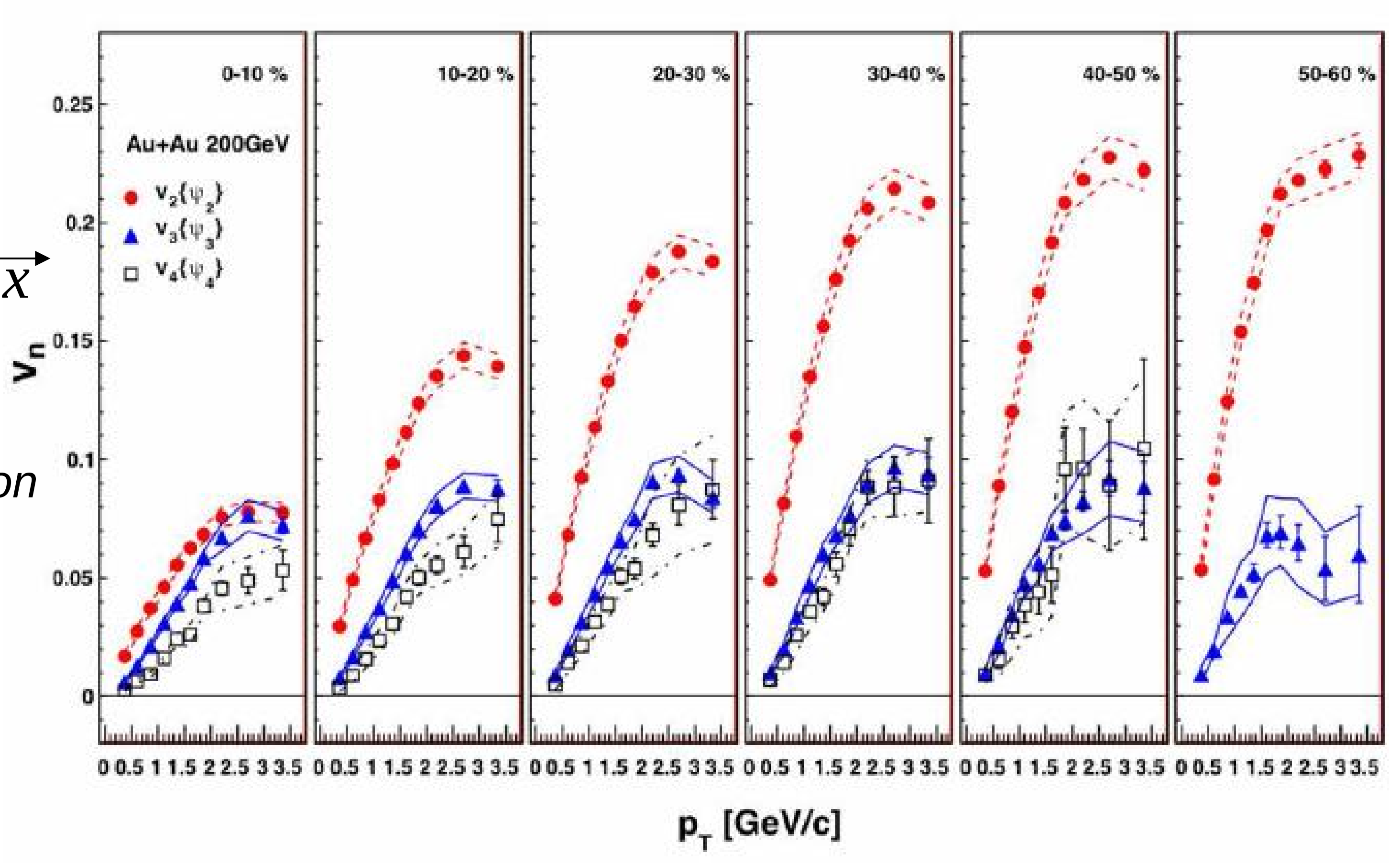


Exquisite data set for combined RHIC-LHC results?

V_n measurements



Measure distribution relative to Ψ_n



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

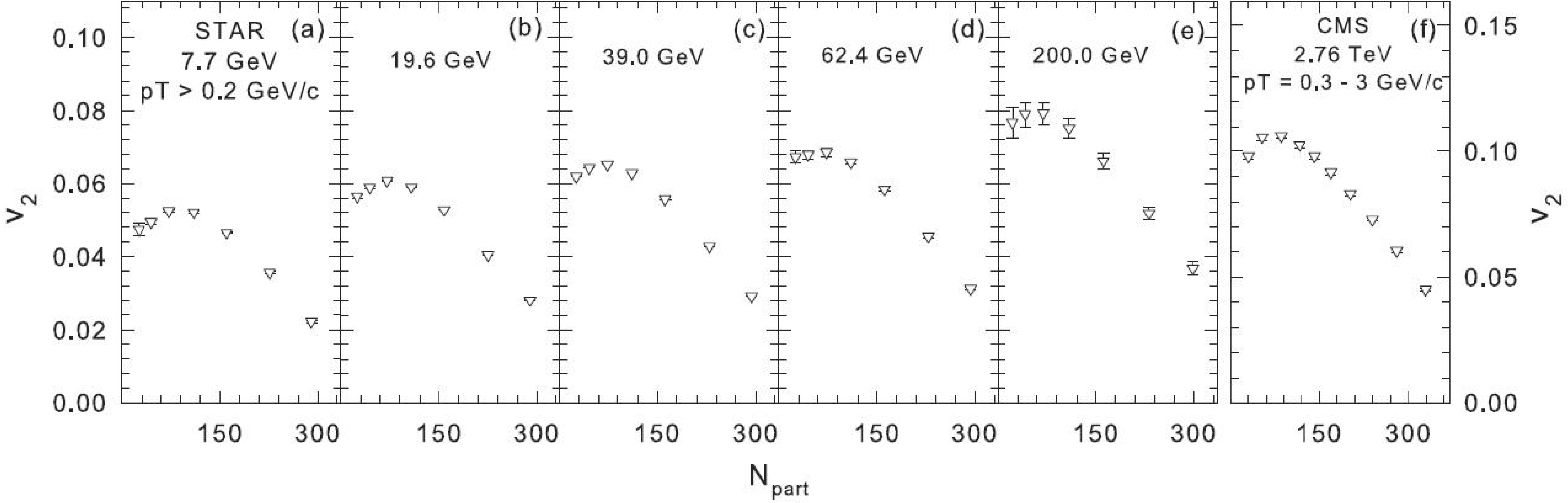
Extensive set of v_n measurements at RHIC and the LHC

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).***

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

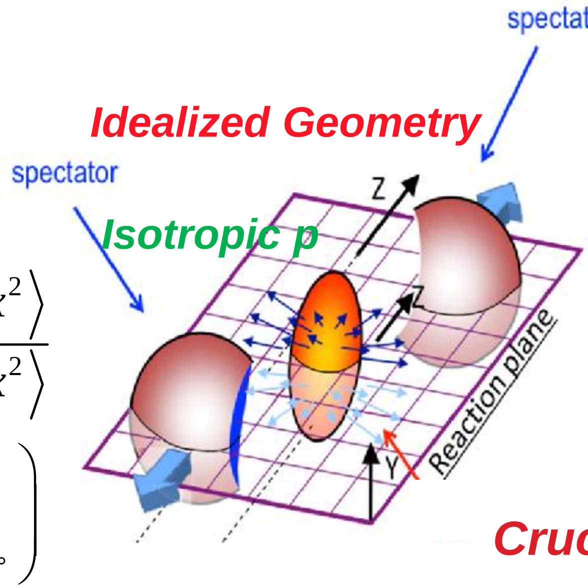
This constitutes an important recent development

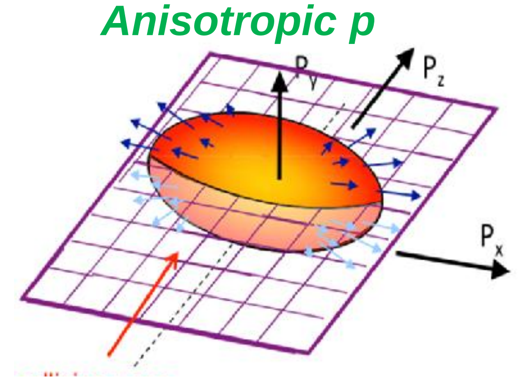
The Flow Probe

$$\text{£}_{Bj} = \frac{1}{\text{®}\, R^2} \frac{1}{2_0} \frac{dE_T}{dy}$$

$$\sim 5-45\ \frac{GeV}{fm^3} \qquad \text{£} = \frac{\left\langle y^2 - x^2 \right\rangle}{\left\langle y^2 + x^2 \right\rangle}$$

$$\left(\mathrm{P} = \text{°}\,2 \,.\left({\partial \text{£}_{Bj}} \big/ {\partial \text{°}} \right)\Big|_{\mathrm{s/°}} \right)$$



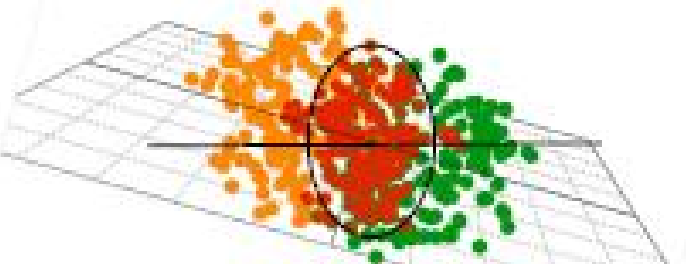


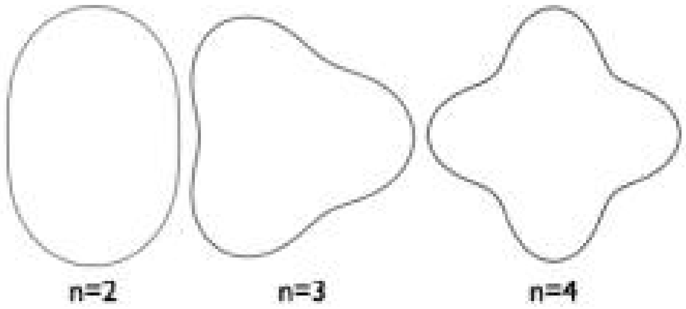
Yield(f) =2 ***v_2*** *cos[2(f - Y $_2$]*

Crucial parameters $\text{£},\ c_s,\ \text{¦}/\mathrm{s},\ etc.$

Actual collision profiles are not smooth, due to fluctuations!

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





Acoustic viscous modulation of v_n

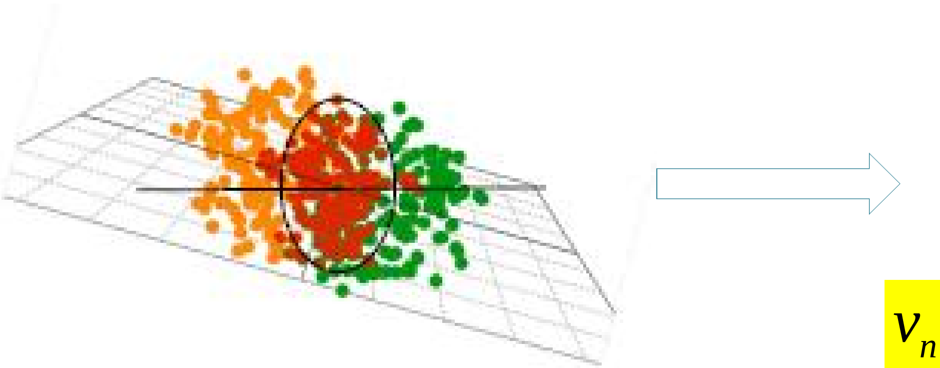
$$\boxed{\text{¢}T_{\text{«¬}}\left(t,k\right) = \exp\left(-\frac{2}{3}\frac{\text{¦}}{s}k^2\frac{t}{T}\right)\text{¢}T_{\text{«¬}}\left(0\right)}$$

Staig & Shuryak **arXiv:1008.3139**

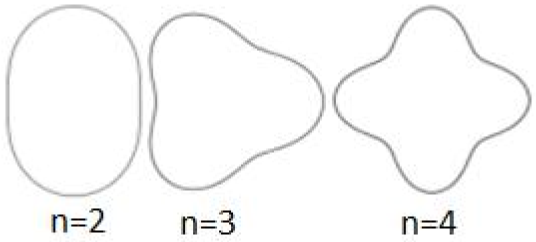
$$\frac{dN}{d\text{¤}} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\text{¤} - \Psi_n\right)\right]\right)$$

Initial eccentricity (and its attendant fluctuations) ε_n drive momentum anisotropy v_n with specific viscous modulation

Scaling properties of flow



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



$$v_n \propto £_n$$

Acoustic viscous modulation of v_n

$$\text{¢}T_{\text{«¬}}(t,k) = \exp\left(\frac{2}{3}\frac{\text{¦}}{s}k^2\frac{t}{T}\right)\text{¢}T_{\text{«¬}}(0)$$

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

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

v_n is related to v_2

$$\frac{v_n(p_T)}{v_2(p_T)} = \frac{£_n}{£_2}\cdot\exp\left(-\ '(n^2-4)\right)$$

System size dependence

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

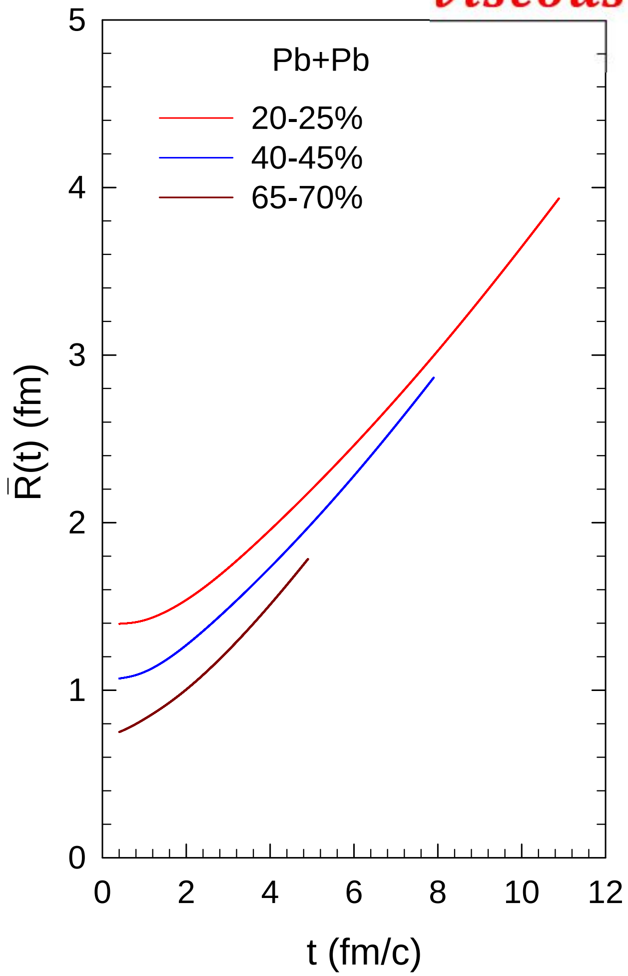
Each of these scaling expectations can been validated

η/s □ [illegible] , [illegible] ’

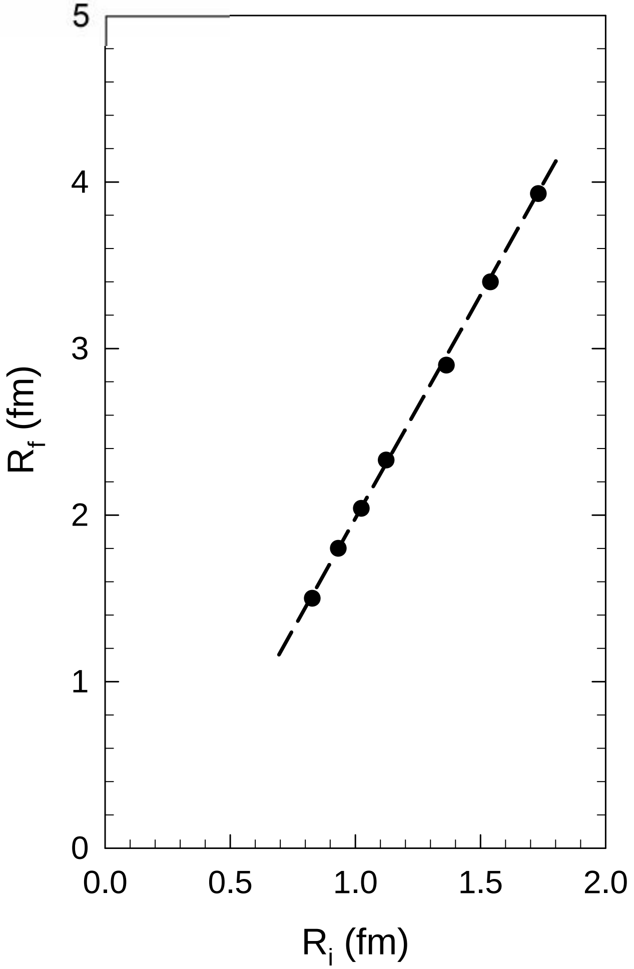
Scaling properties of HBT

Viscous Hydrodynamics – B. Schenke

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



$t \propto \bar{R}$



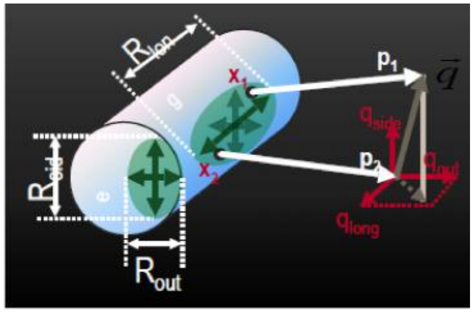
Freeze-out time varies with initial size

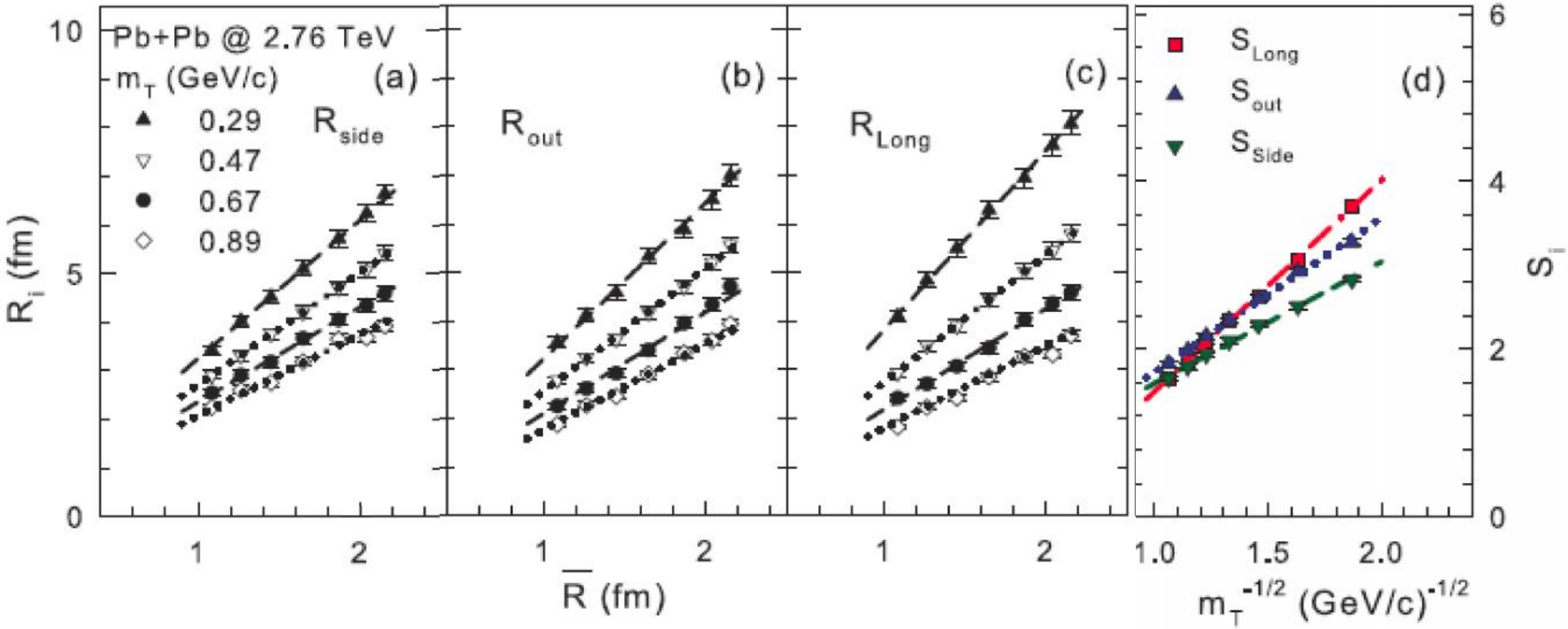
Freeze-out transverse size proportional to initial transverse size

Acoustic Scaling of HBT Radii

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

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



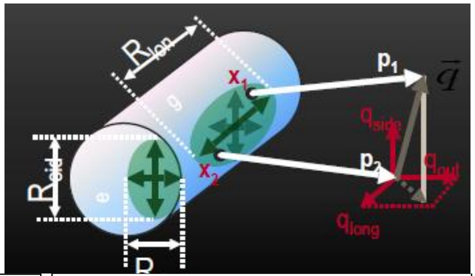


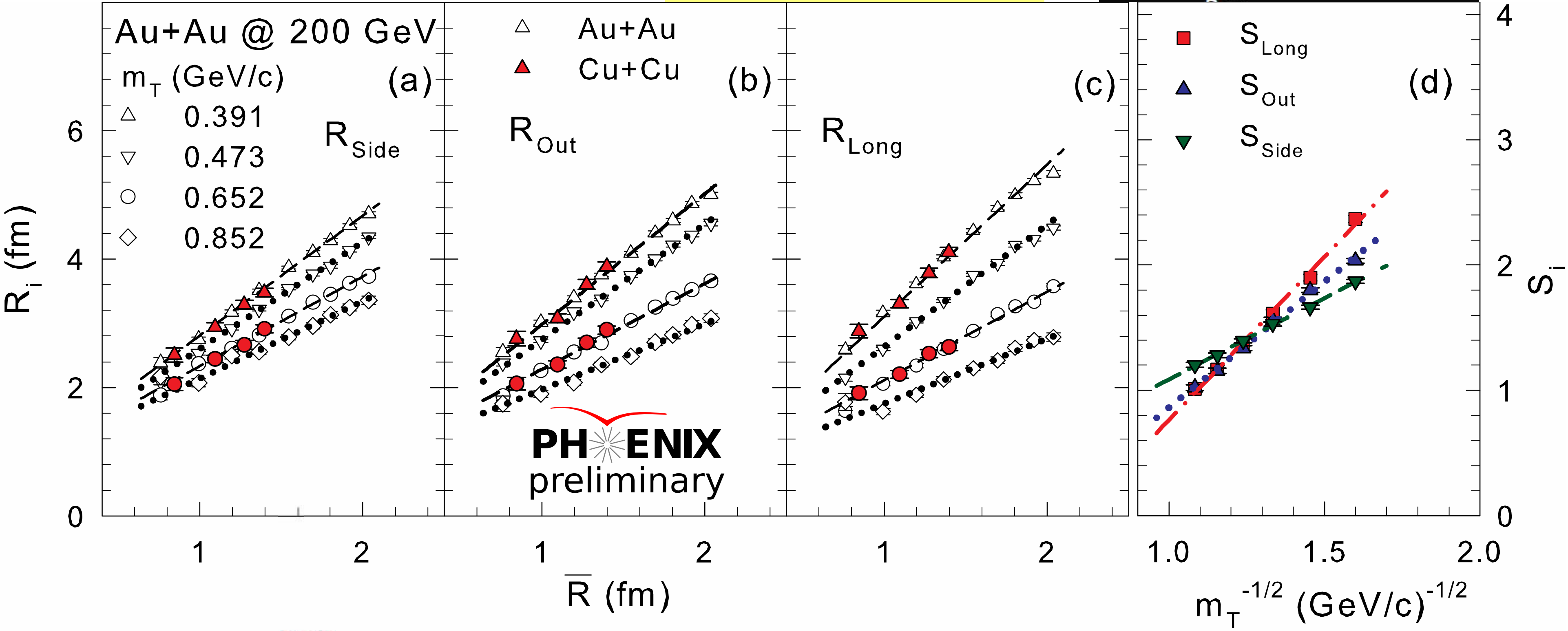
- ➢ **$\bar{R}$ and m_T scaling of the full LHC data set**
- ➢ **The centrality and m_T dependent data scale to a single curve for each radii.**

Acoustic Scaling of HBT Radii

$$t \propto \overline{R}$$

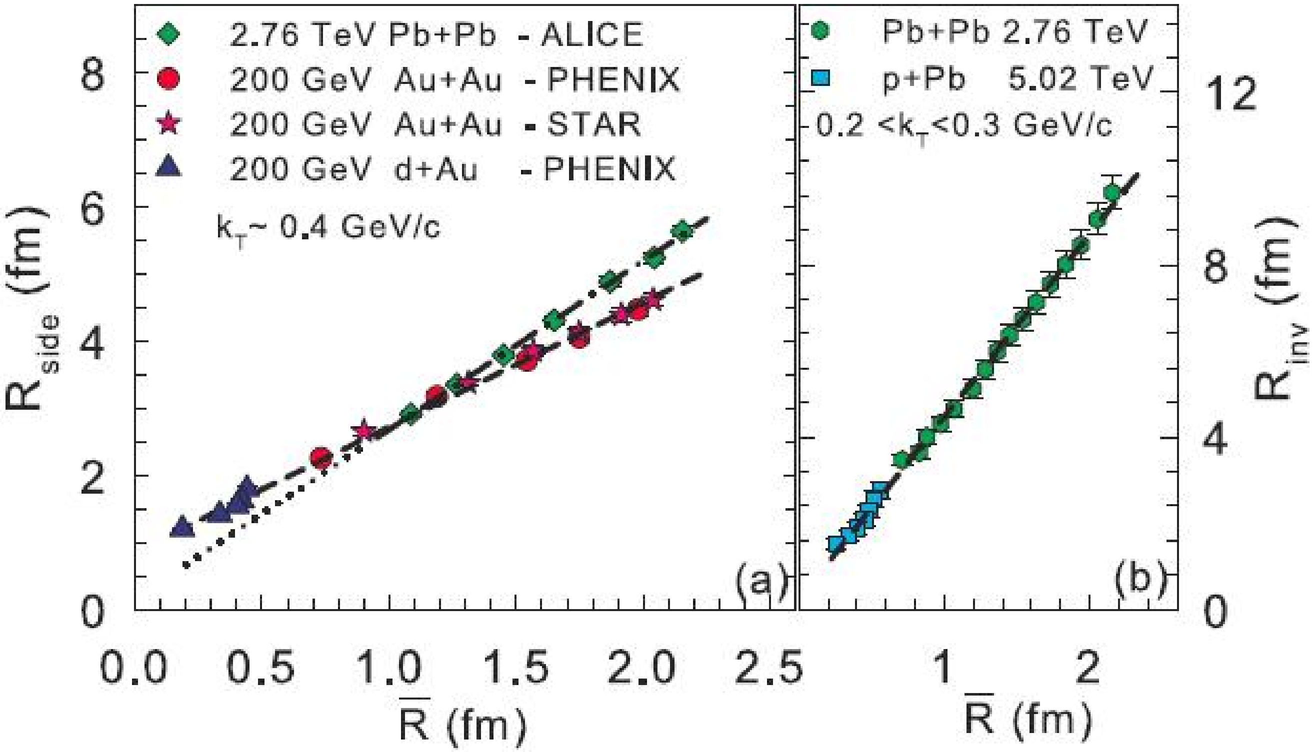
$$R_{out}, R_{side}, R_{long} \propto \overline{R}$$





- ➢ ***$\overline{R}$* 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



$t \propto \bar{R}$

Exquisitely demonstrated for asymmetric systems → similar reaction dynamics

Scaling of HBT Radii

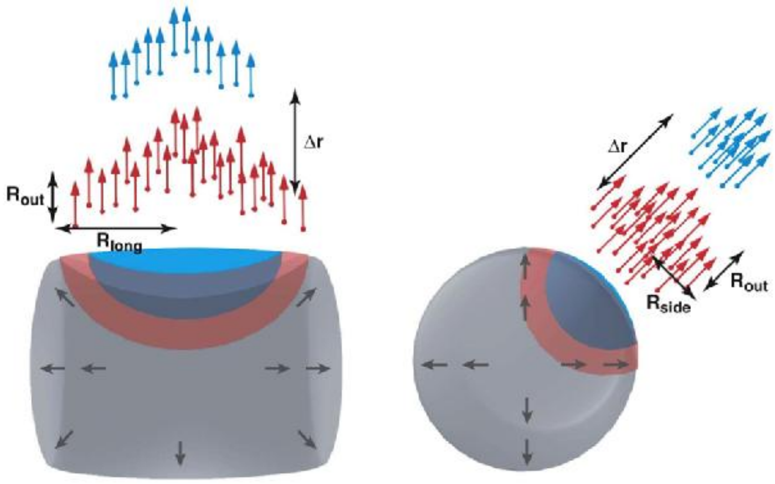
Chapman, Scotto, Heinz, PRL.74.4400 (95)

$$R_{side}^2 = \frac{R_{geo}^2}{1 + \frac{m_T}{T} b_T^2}$$

$$R_{out}^2 = \frac{R_{geo}^2}{1 + \frac{m_T}{T} b_T^2} + b_T^2 (\Delta t)^2$$

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

Makhlin, Sinyukov, ZPC.39.69 (88)



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

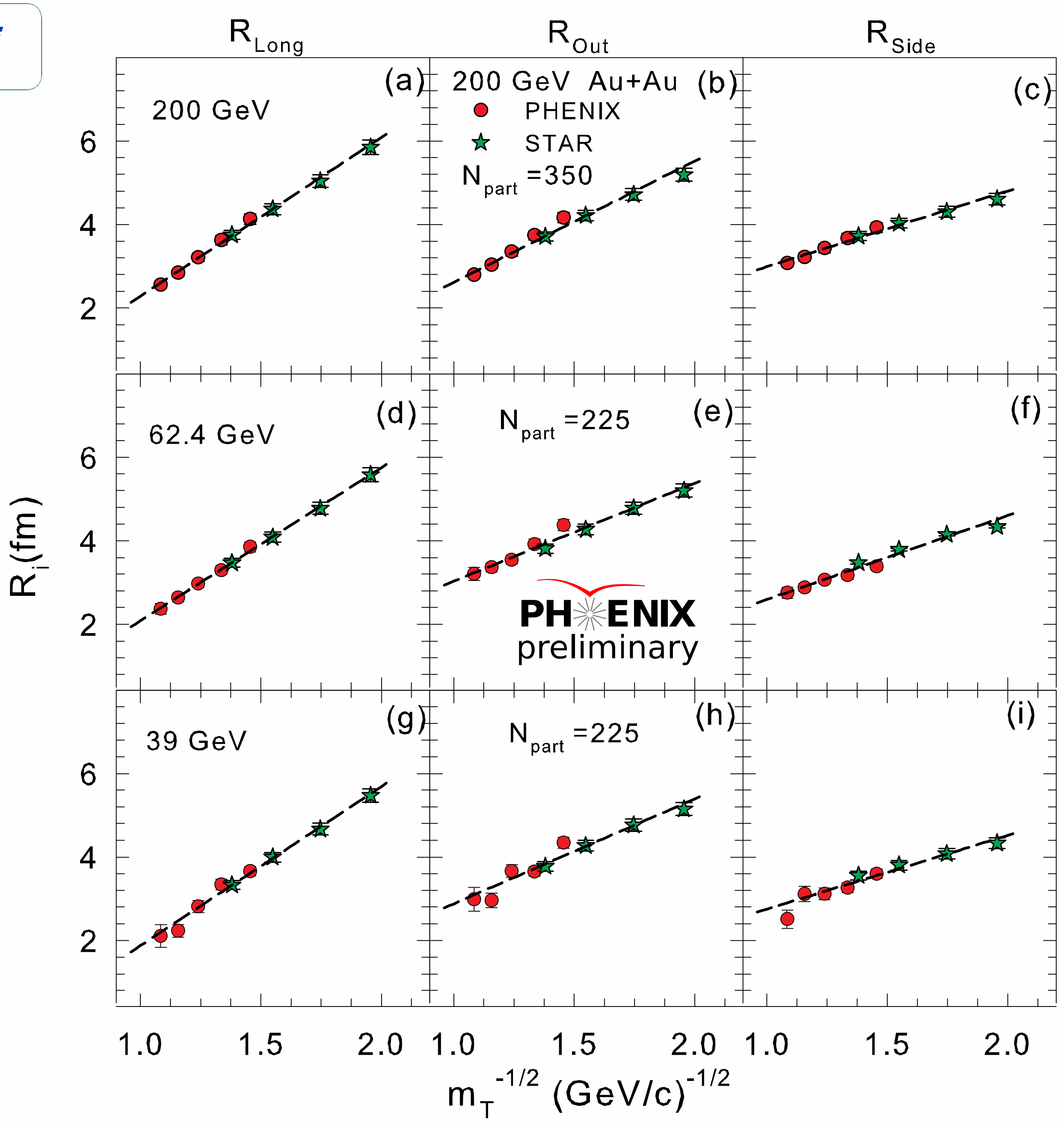
empirical fit just as effective

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

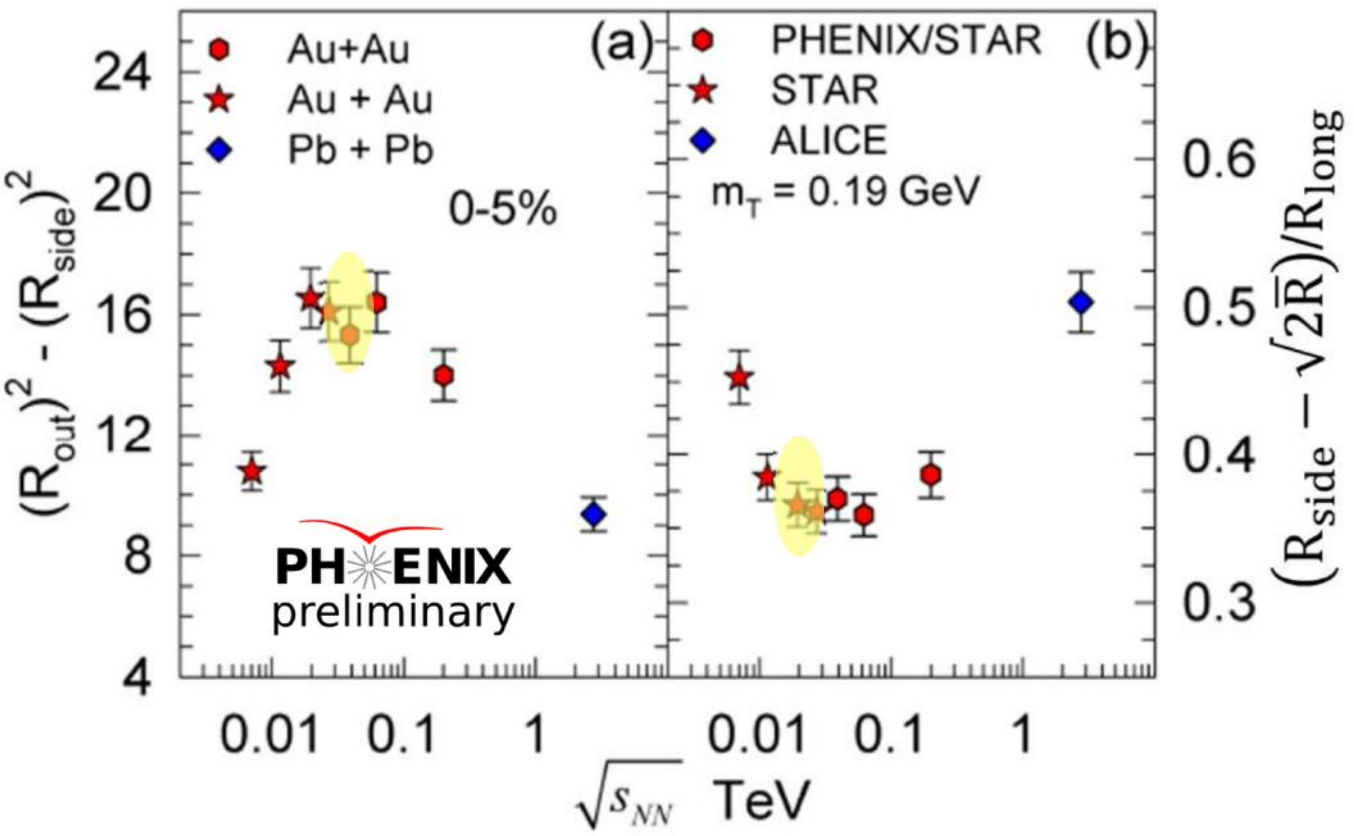
Anticipate extended emission duration with phase transition/CEP

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



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



$$R_{long} \propto \tau^2$$

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

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

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

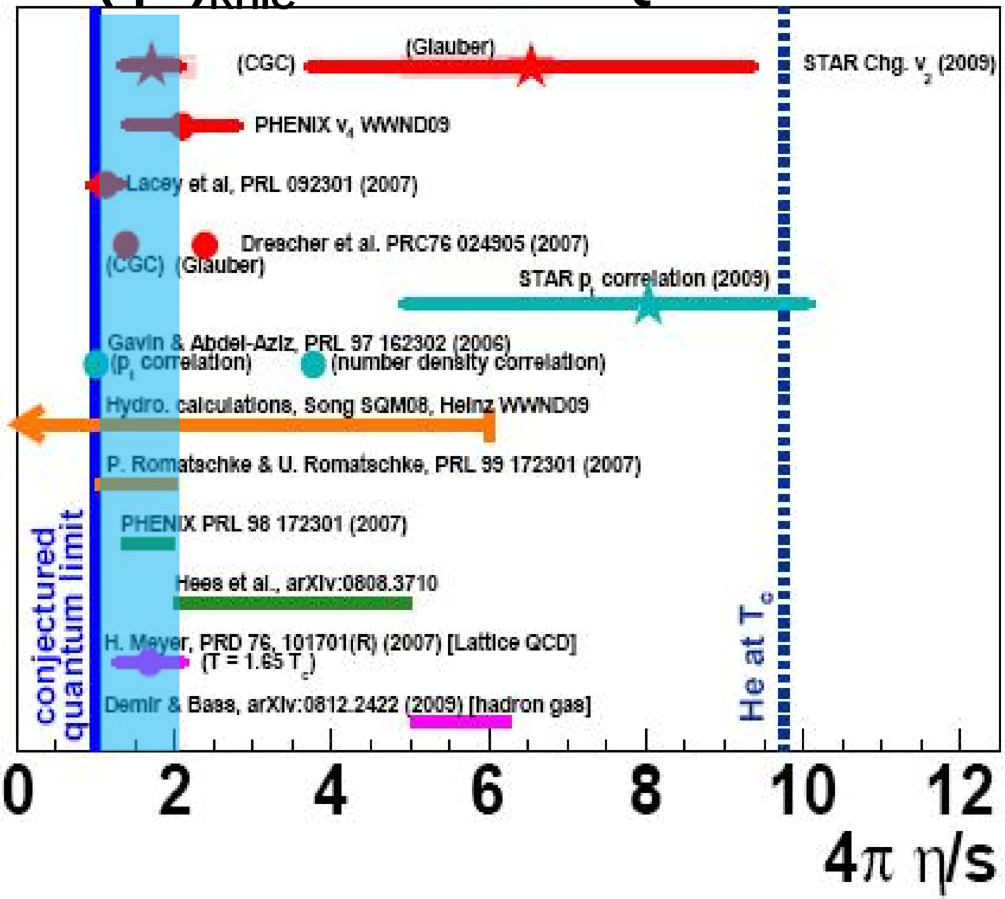
These characteristic patterns signal an important change in the reaction dynamics

CEP? Phase transition?

Transport properties –η/s

Reminder

$(\eta/s)_{RHIC}$ estimates – QM2009



Subsequently

- *Excellent Convergence on the magnitude of η/s at RHIC*

$4\pi\eta/s \sim 1 - 2$

- *T dependence of η/s?*
- *μ_B dependence of η/s?*
- *Possible signal for CEP?*

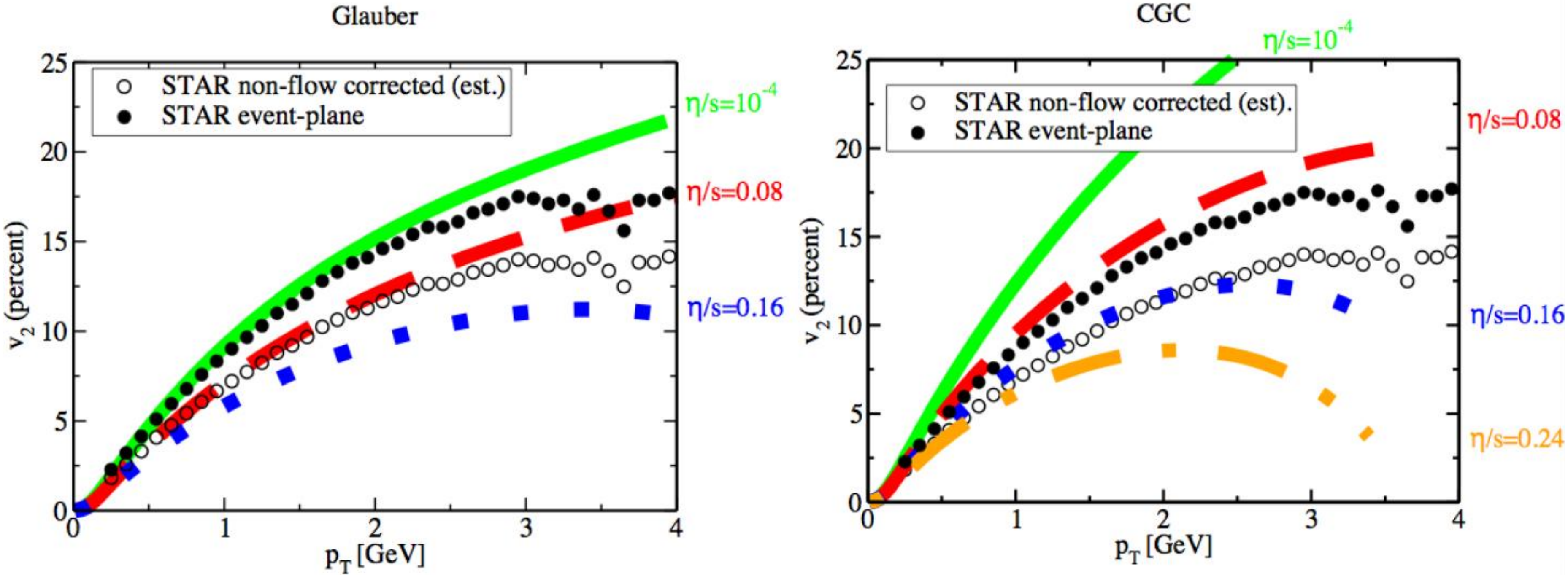
Status Quo

A major uncertainty in the extraction of η/s stems from Incomplete knowledge of the Initial-state eccentricity model

ε_n – η/s interplay?

Status Quo

Luzum et al. arXiv 0804.4015



<u>Status Quo</u>

A major uncertainty in the extraction of η/s stems from Incomplete knowledge of the Initial eccentricity?

ε_n – η/s interplay?

η/s is a property of the medium and should not depend on initial geometry!
The dependence on initial geometry is NOT an uncertainty;

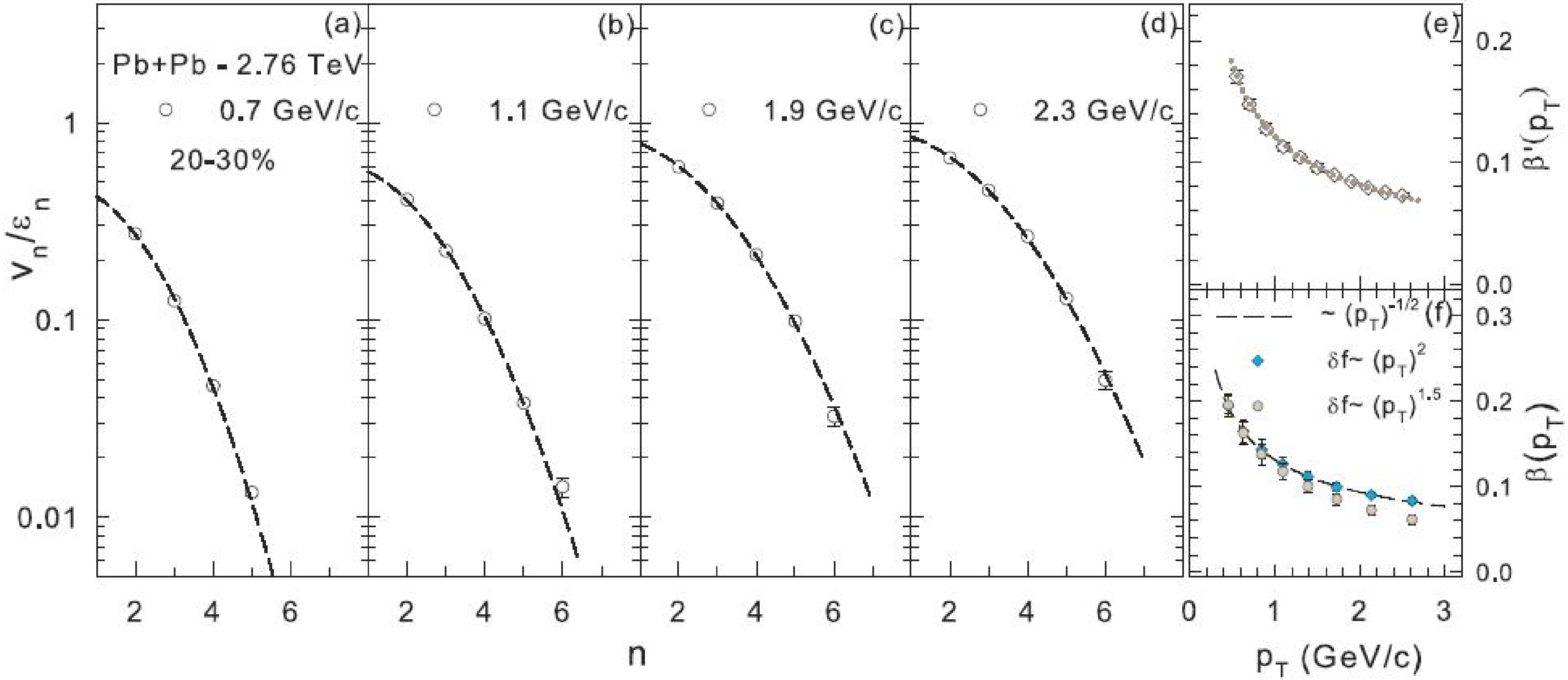
New methodology and constraints required
→ We use acoustic scaling

Acoustic Scaling – n^2

ATLAS data - Phys. Rev. C86, 014907 (2012)

$$\frac{v_n(p_T)}{£_n} \propto \cdot \exp\left(- \quad 'n^2\right)$$

arXiv:1301.0165



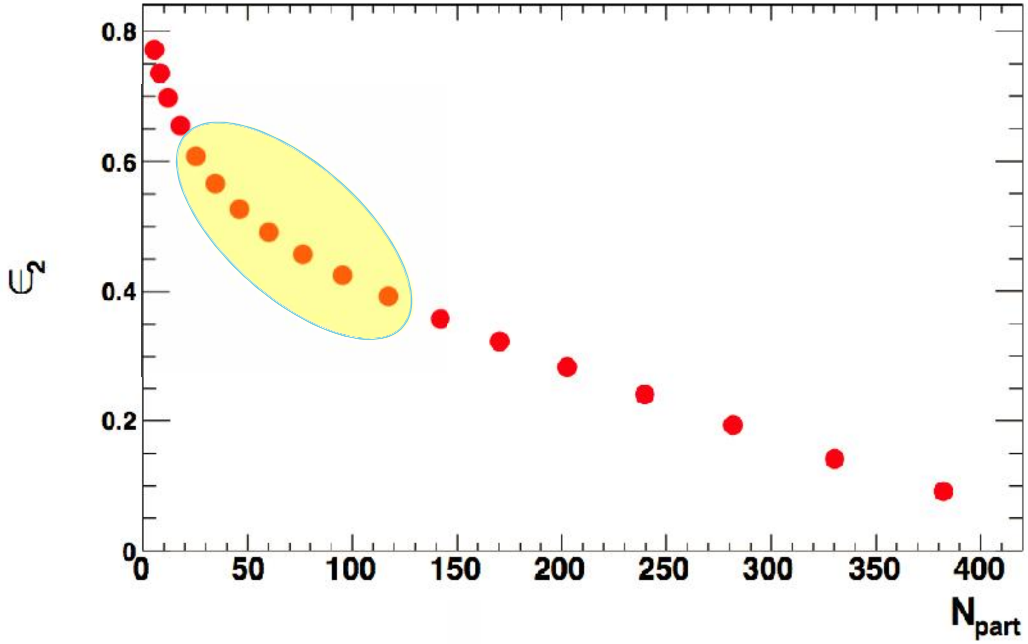
- ✓ **Characteristic n^2 viscous damping validated**
- ✓ **Characteristic *$1/(p_T)^\alpha$ dependence of extracted β values validated***

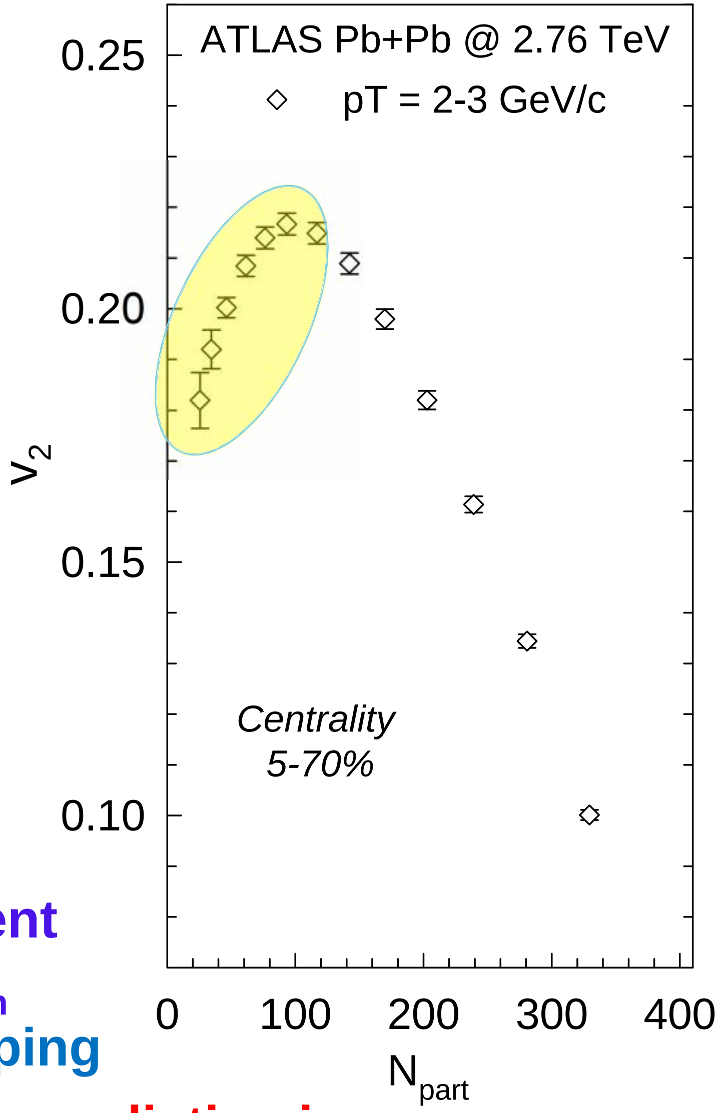
Constraint for η/s and δf

Scaling properties of flow

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

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





- **Eccentricity change alone is not sufficient**

To account for the N_{part} dependence of v_n

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

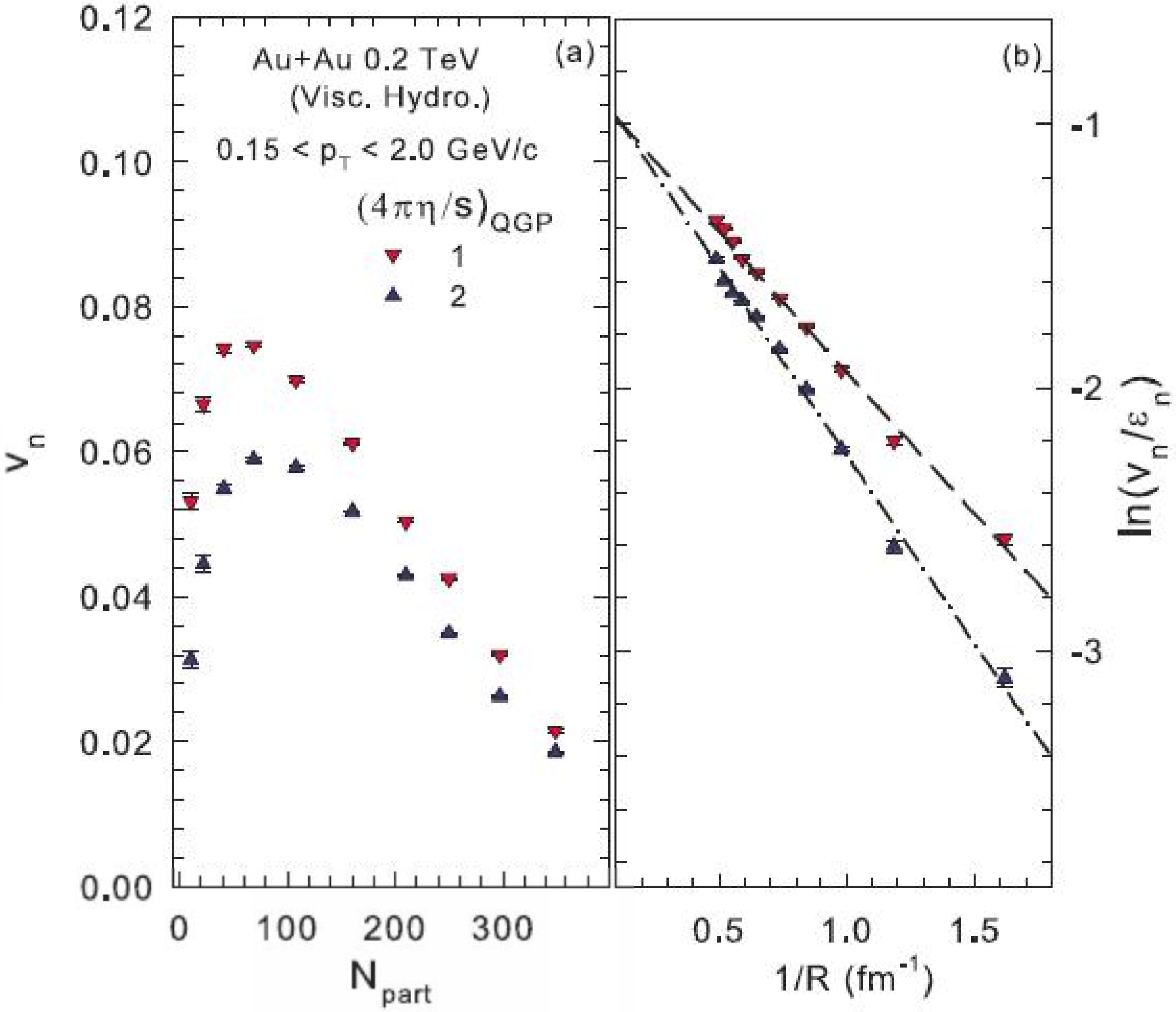
✓ **Characteristic $1/\bar{R}$ scaling prediction is non-trivial**

Scaling properties of flow

- Viscous Hydrodynamics

$$\ln\left(\frac{v_n}{£_n}\right) \propto \frac{-\quad ''}{\bar{R}}$$

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



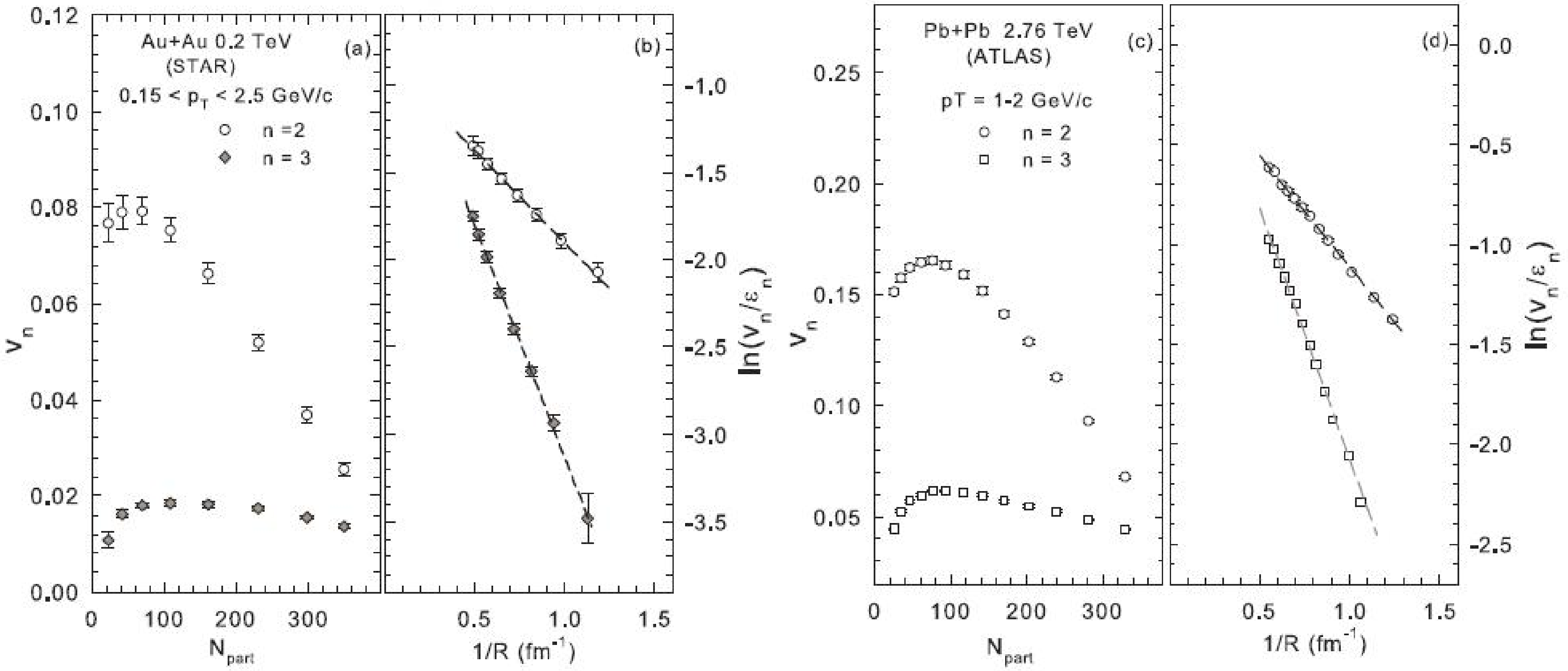
✓ ***β′′ shows clear sensitivity to* η/s**

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

Scaling properties of flow

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

$$\ln\left(\frac{v_n}{£_n}\right) \propto \frac{-\quad ''}{\bar{R}}$$



- ✓ **Characteristic $1/\bar{R}$ viscous damping validated with n² dependence at RHIC & the LHC**
- ✓ ***A further constraint for η/s***

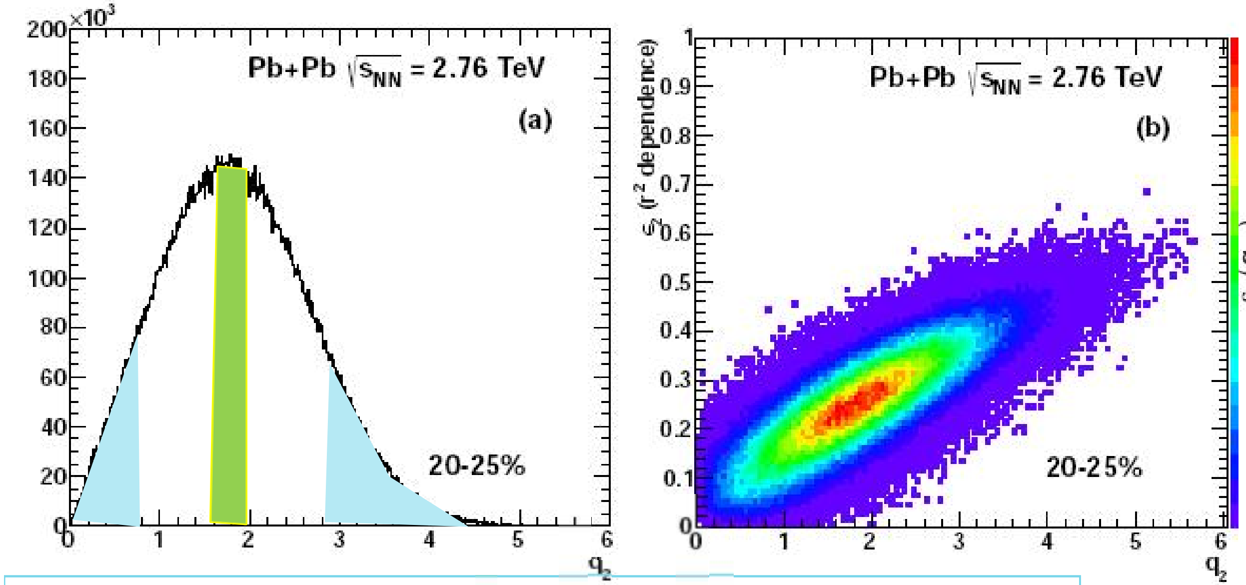
Shape-engineered events

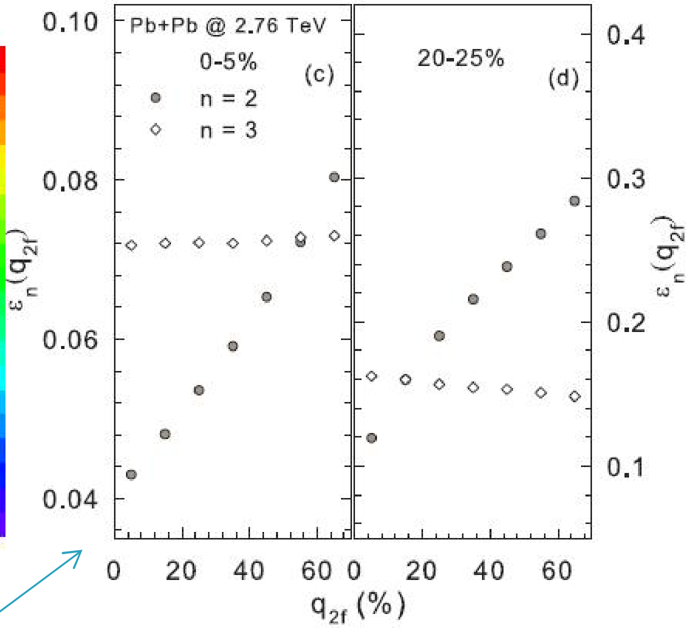
Shape fluctuations lead to a distribution of the Q vector <u>at a fixed centrality</u>

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

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

Lacey et. al, arxiv:1311.1728





- ***Cuts on q_n should change the magnitudes $\langle \square_n \rangle$, $\langle v_n \rangle$, $\langle R_n \rangle$ 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

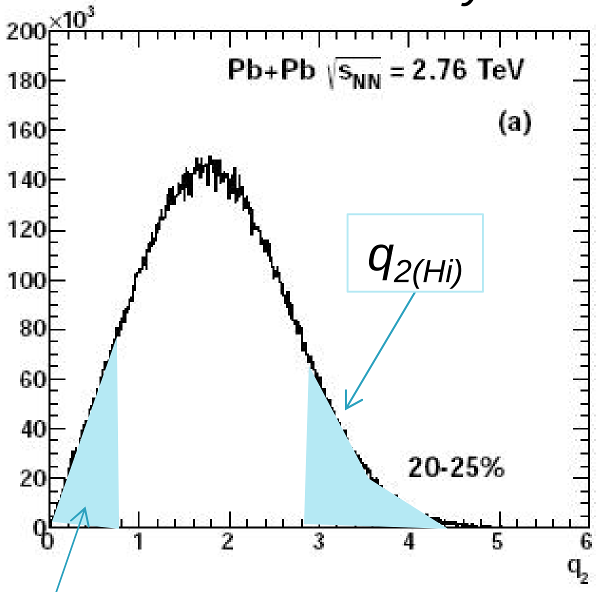
Shape fluctuations lead to a distribution of the Q vector at a fixed centrality

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

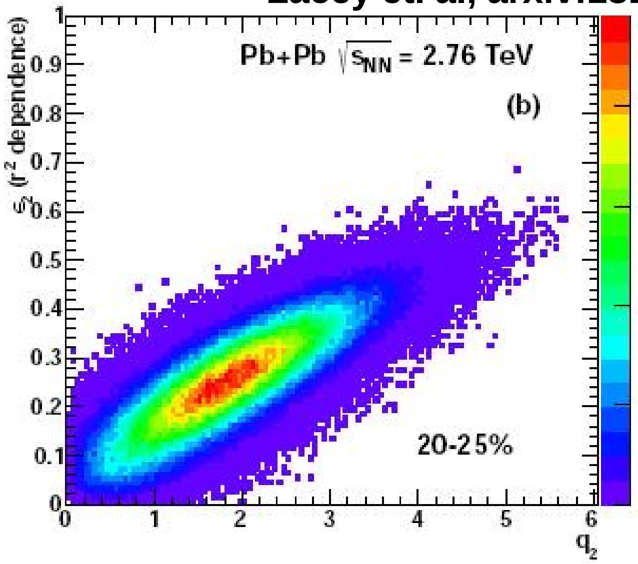
$$q_n = Q_n/\sqrt{M},$$

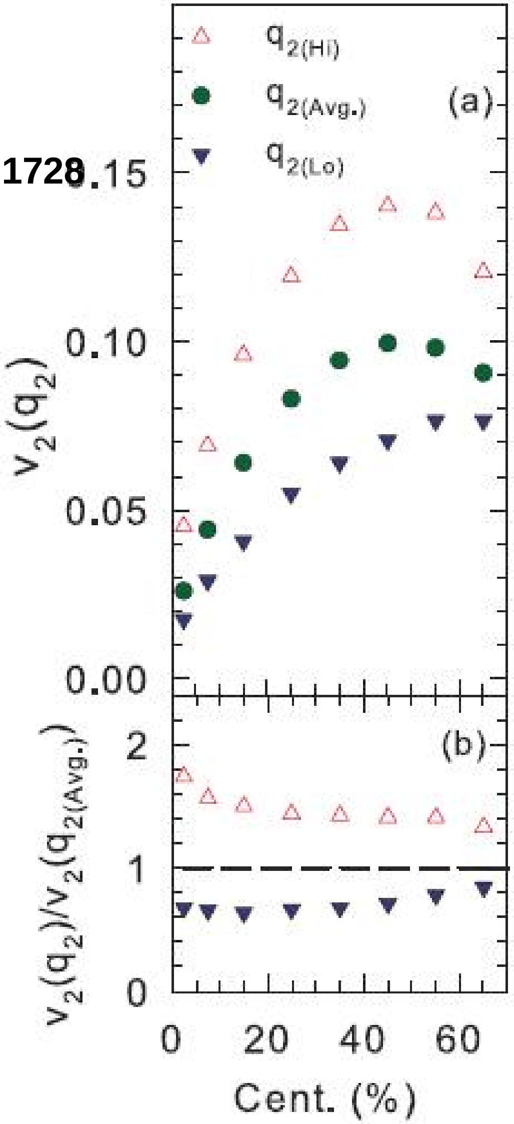
ALICE data

Lacey et. al, arxiv:1311.1728



$q_{2(Lo)}$



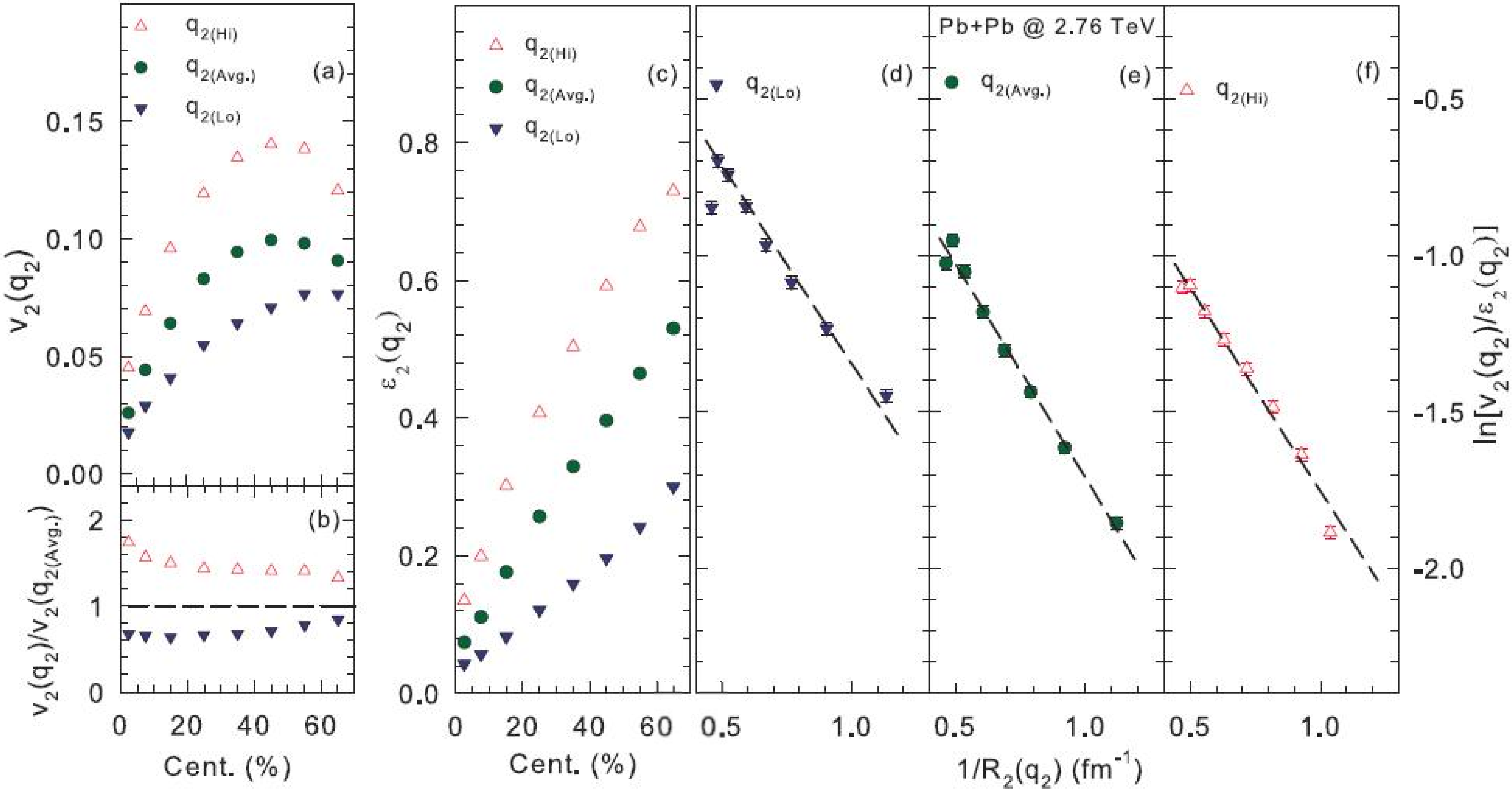


- ***Cuts on q_n should change the magnitudes $\langle \square_n \rangle$, $\langle v_n \rangle$, $\langle R_n \rangle$ at a given centrality due to fluctuations***
- ***Viable models for initial-state fluctuations should still scale***

Scaling properties of flow

Acoustic Scaling of shape-engineered events

Lacey et. al, arxiv:1311.1728

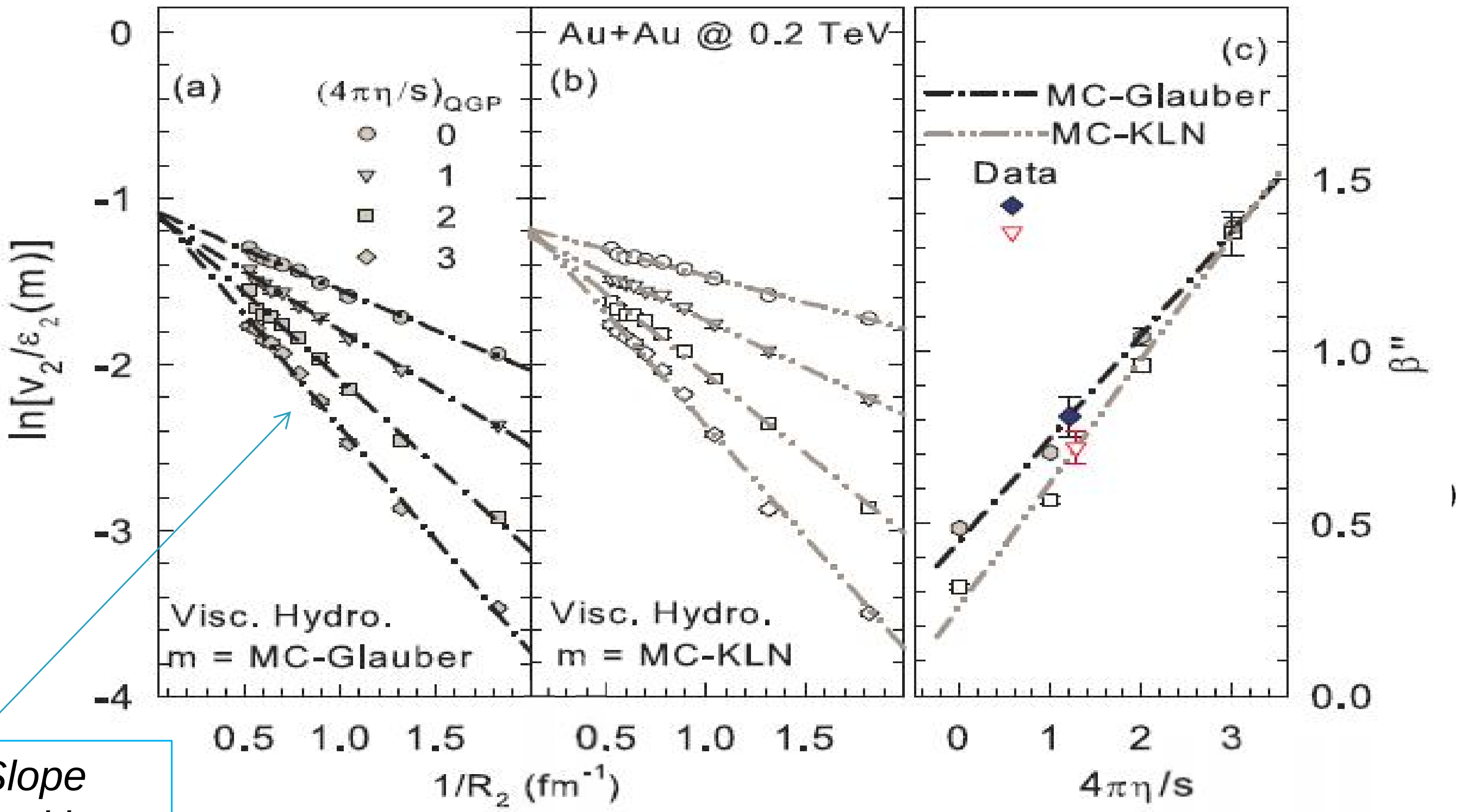


- ✓ **Characteristic $1/R$ viscous damping validated for different event shapes at the same centrality**
- ✓ ***A further constraint for initial fluctuations model and η/s***

Extraction of η/s

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

Lacey et. al, arxiv:1311.1728



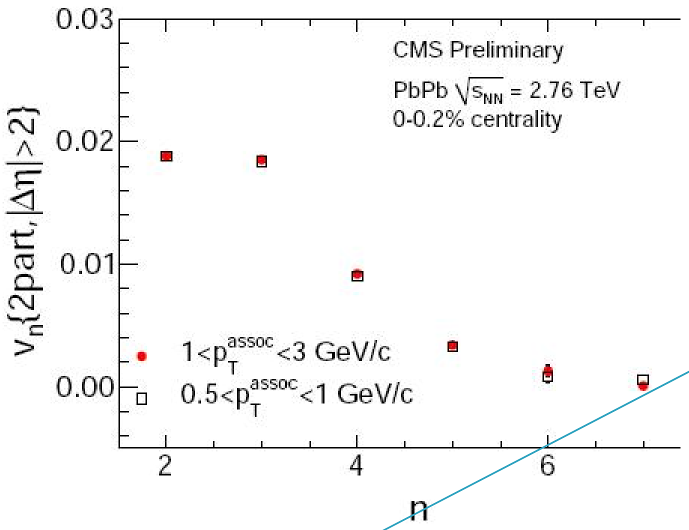
Slope sensitive to ***4πη/s***

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

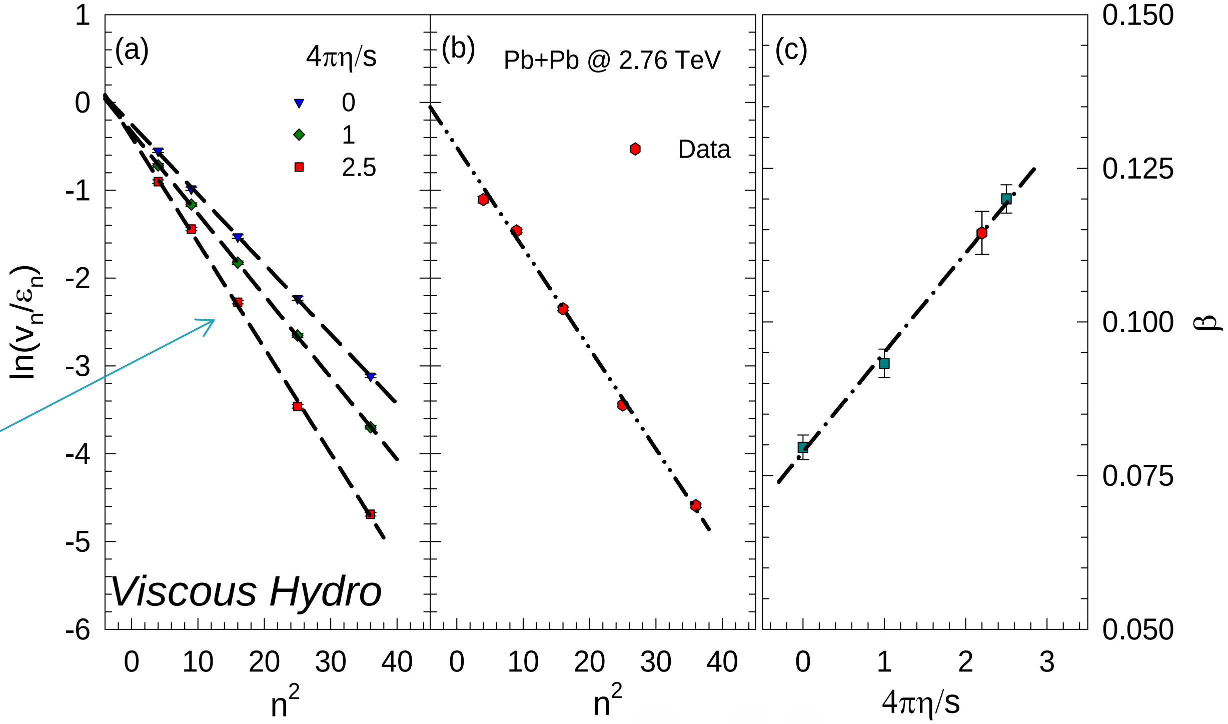
Extracted η/s value insensitive to initial conditions

Extraction of η/s

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



arXiv:1301.0165 & CMS PAS HIN-12-011



*Slope sensitive to **η/s***

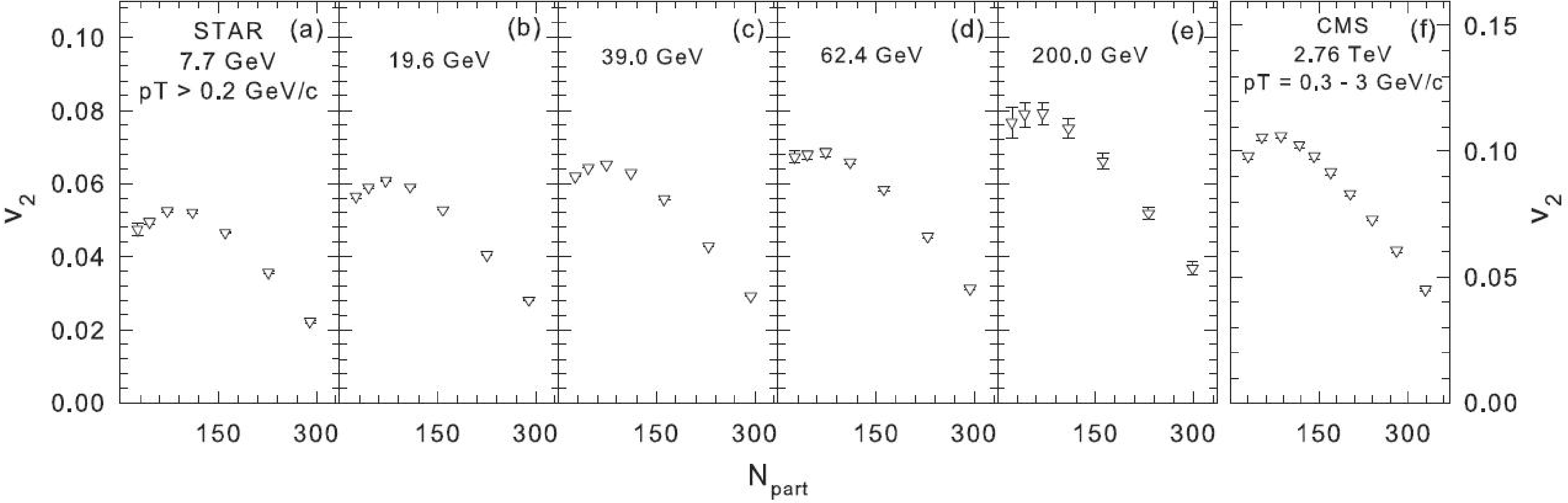
n^2 scaling validated in experiment and viscous hydrodynamics; calibration → 4πη/s ~ 2.2 ± 0.2

Anisotropy Measurements

arXiv:1305.3341

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

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



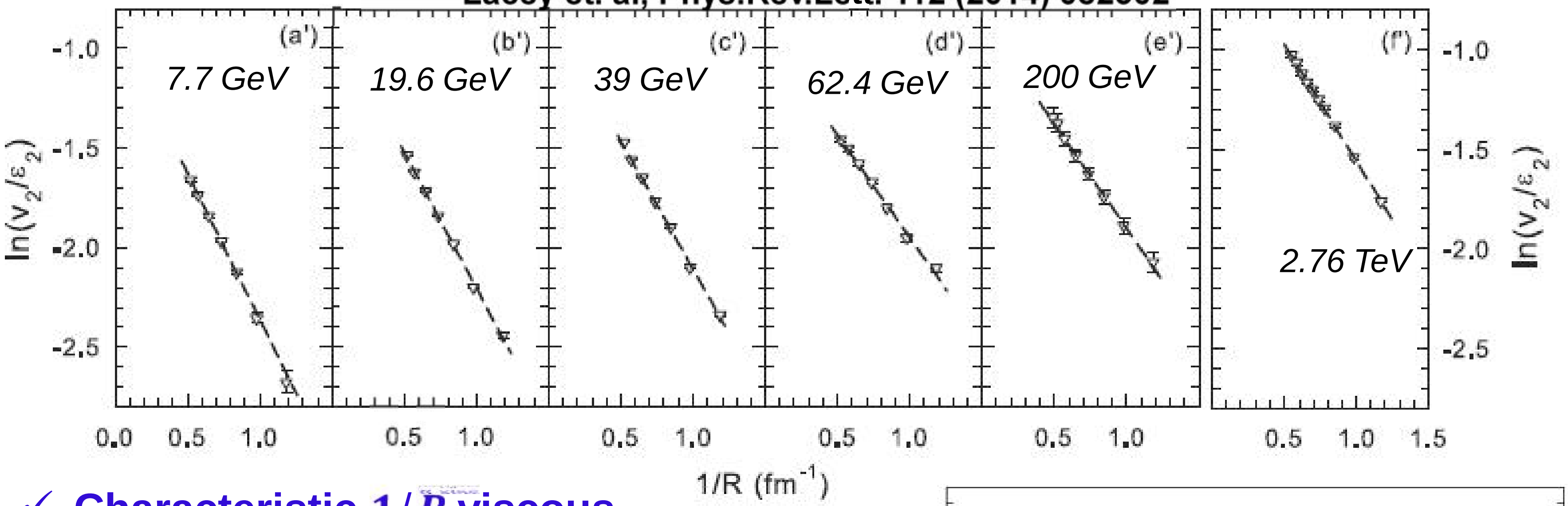
- ***An extensive set of measurements now span a broad range of beam energies (T, μ_B).***

Scaling properties of flow

$$\ln\left(\frac{v_n}{£_n}\right) \propto \frac{-\,''}{\bar{R}}$$

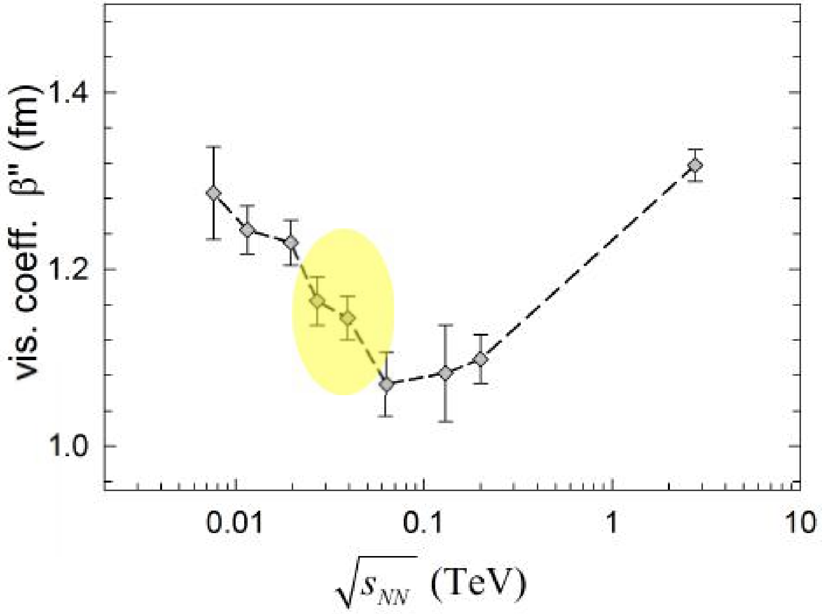
Acoustic Scaling – $\frac{1}{R}$ Scaling for the Beam Energy Scan

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

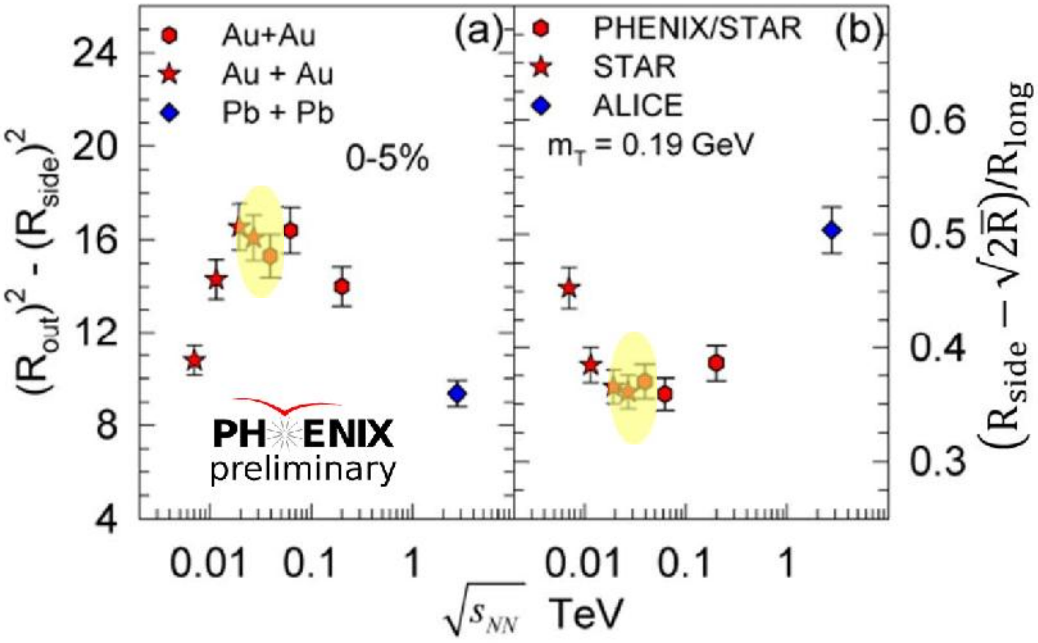


- ✓ **Characteristic $1/R$ viscous damping validated across beam energies**
- ✓ **First experimental indication for *η/s variation in the* (T, μ_B)-plane**
- ✓ **CEP?**

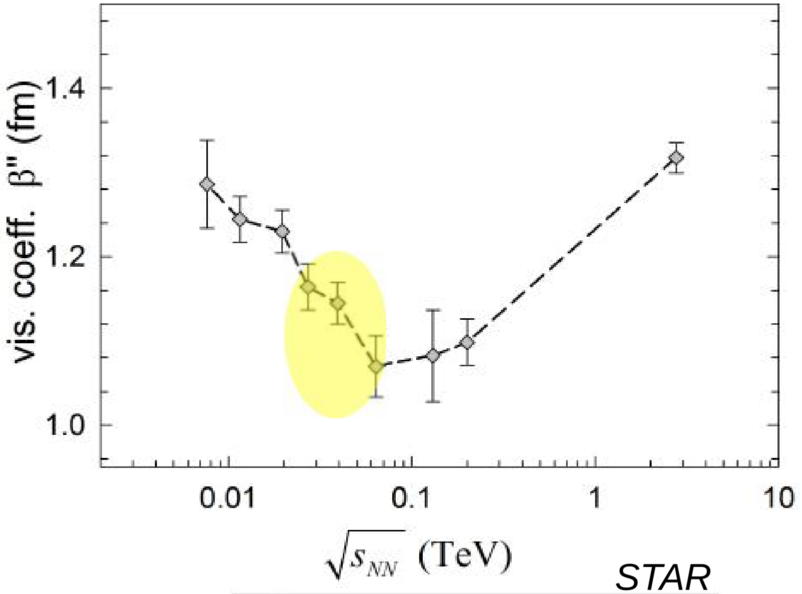
Complimentary signals for similar $\sqrt{s_{NN}}$



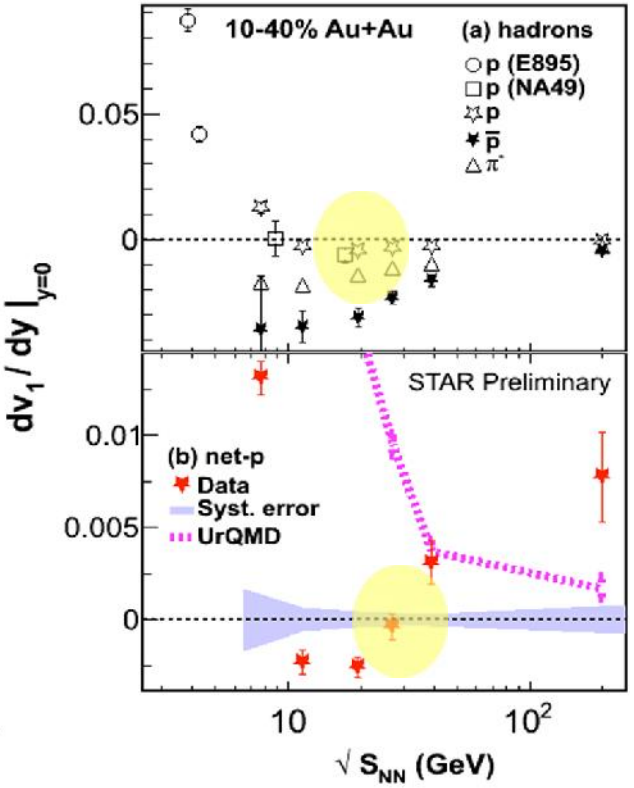
$\sqrt{s_{NN}}$ *dependence of HBT signals*



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



STAR



Combined results
→ Strongest indications for a phase transition/CEP to date!

Epilogue

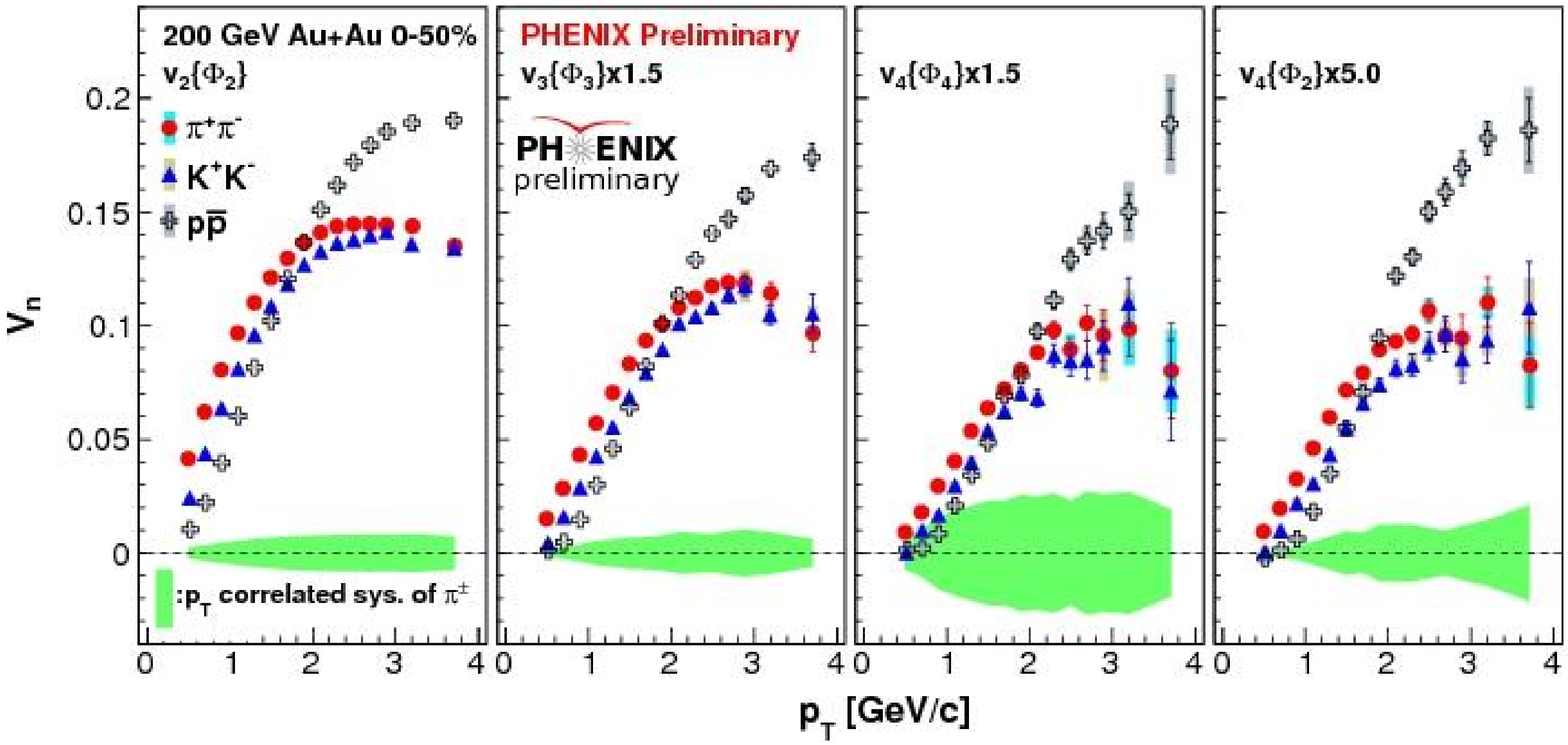
Acoustic scaling of anisotropic flow and HBT radii *lend profound mechanistic insights, as well as new constraints for mapping the QCD phase diagram*

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

Anisotropy Measurements

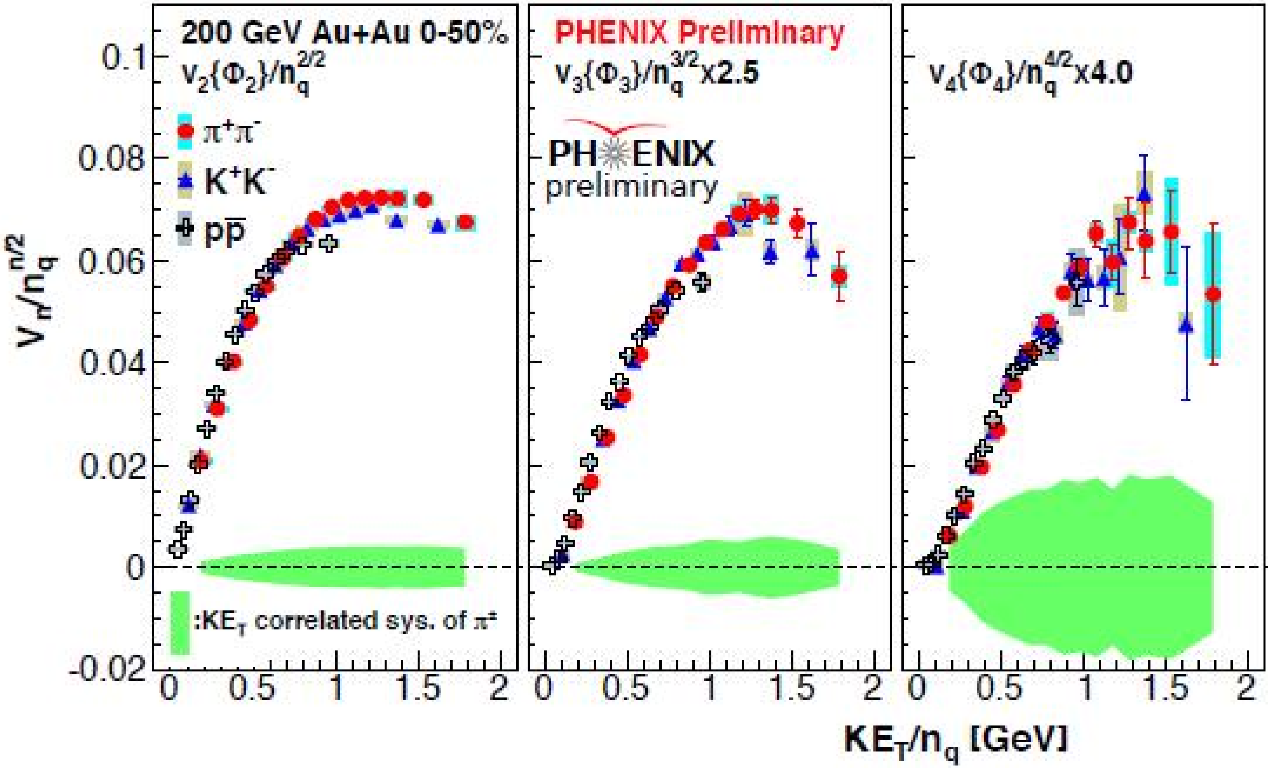


High precision double differential measurements obtained for identified particle species at RHIC and the LHC.

Scaling properties of flow

Acoustic Scaling – Ratios

v_n PID scaling



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