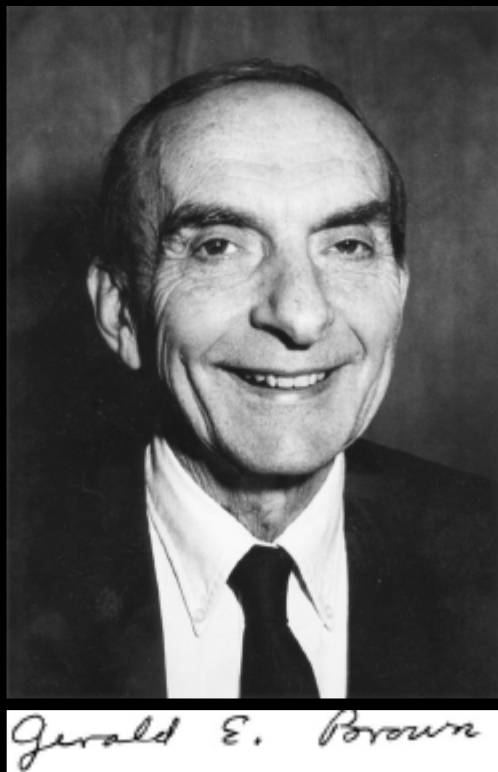
Celebrating Gerry's Life



A few thoughts about Gerry:

I. "Most people say that it is the intellect which makes a great scientist. They are wrong: it is character."

- Albert Einstein -

II. "The scientist does not study nature because it is useful; he studies it because he delights in it, and he delights in it because it is beautiful."

- Henri Poincare -

"Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less."

- Marie Curie

New insights from flow measurements in heavy ion collisions

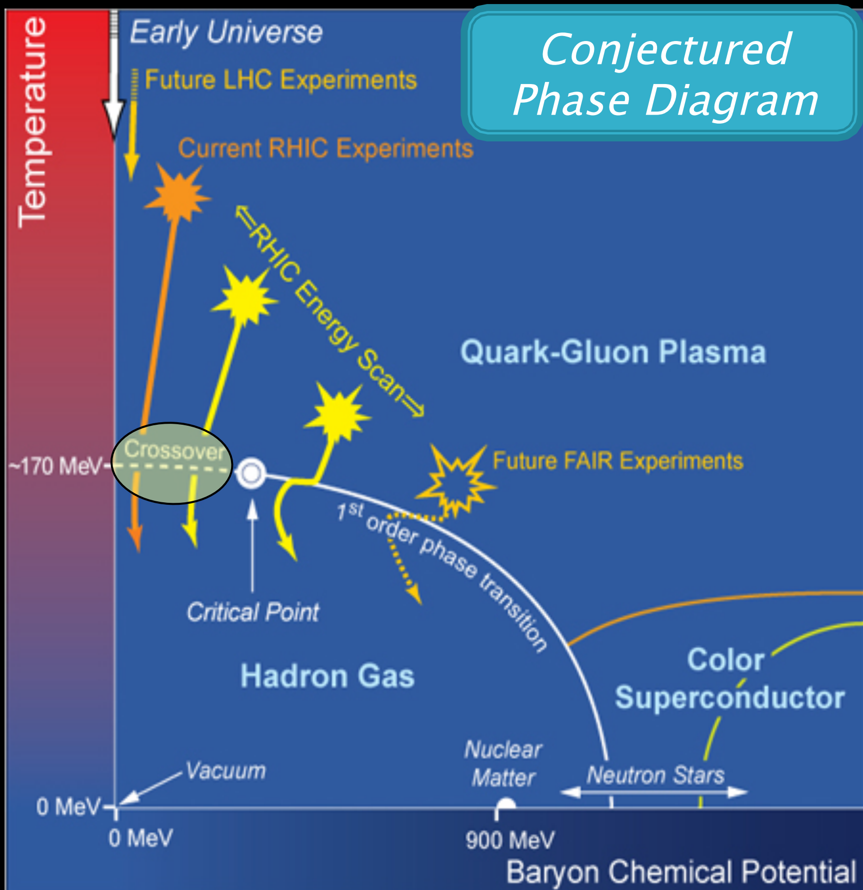
Roy A. Lacey
Stony Brook University

Motivation

- ❑ *Introduce acoustic property of anisotropic flow*
- ❑ *Validate acoustic scaling property*
  - ✓ *Constraints for initial state fluctuations*
  - ✓ *Extract $\frac{\eta}{s}$ from scaling coefficients*
- ❑ *Show & discuss beam energy dependence of viscous damping*
  - ✓ ***(T, μ_B)-dependence of $\frac{\eta}{s}$***
  - ✓ *Critical End Point :(CEP)?*
- ❑ *Summary*

A Current Focus of our Field

Quantitative study of the QCD phase diagram



Interest

- Location of the critical End point (CEP)
- Location of phase coexistence lines
- Properties of each phase

All are fundamental to the phase diagram of any substance

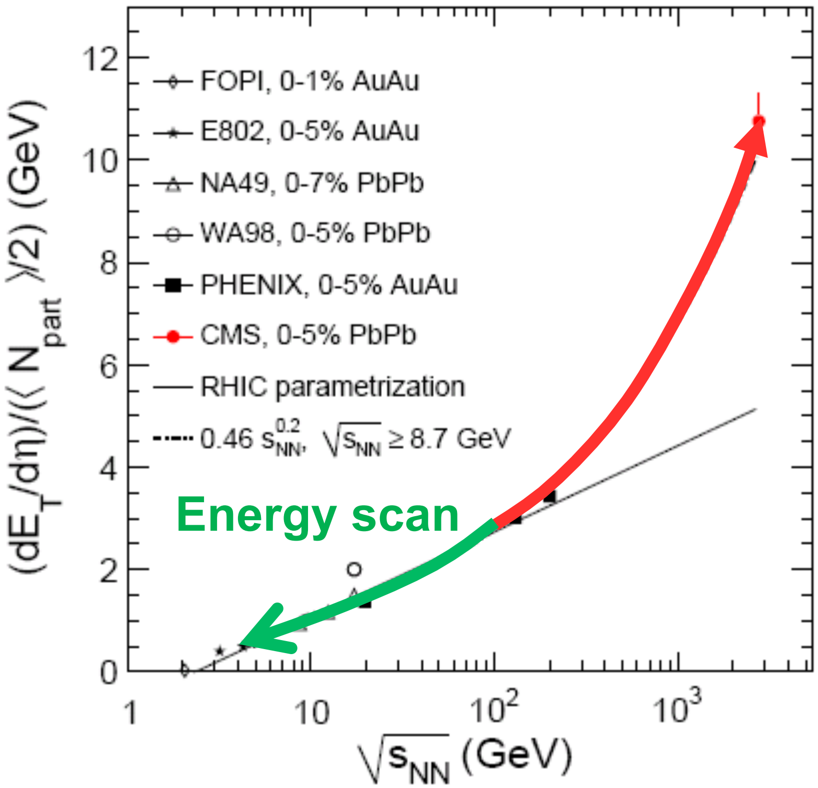
Spectacular achievement:

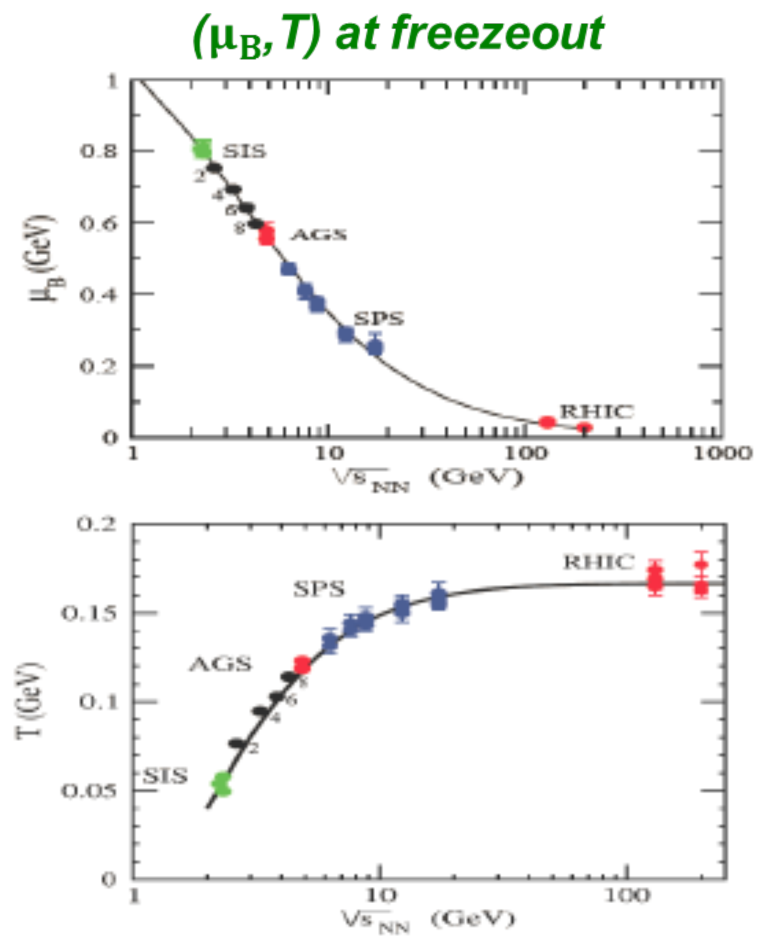
Validation of the crossover transition leading to the QGP → Necessary for the CEP?

A major current focus is the characterization of the QGP produced at RHIC and the LHC, as well as a search for the CEP at RHIC

Current Strategy

Exploit system size and the energy density lever arm





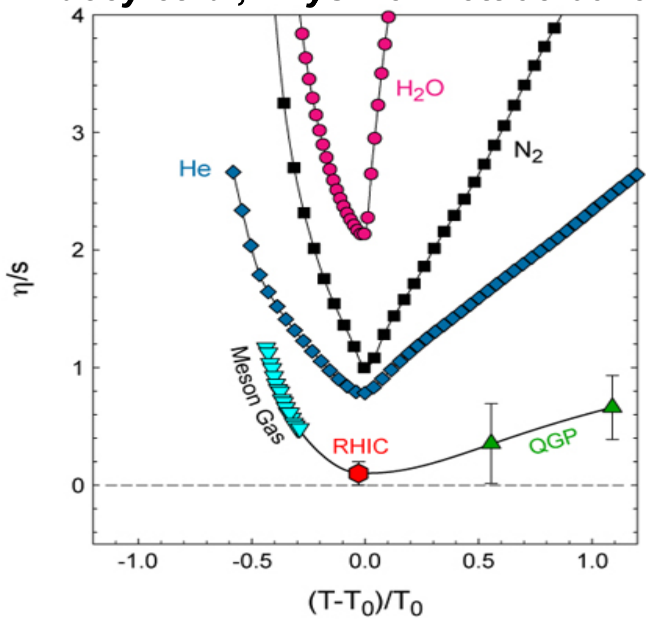
- **LHC → access to high T and small μ_B**
- **RHIC → access to different systems and a broad domain of the (μ_B, T)-plane**

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

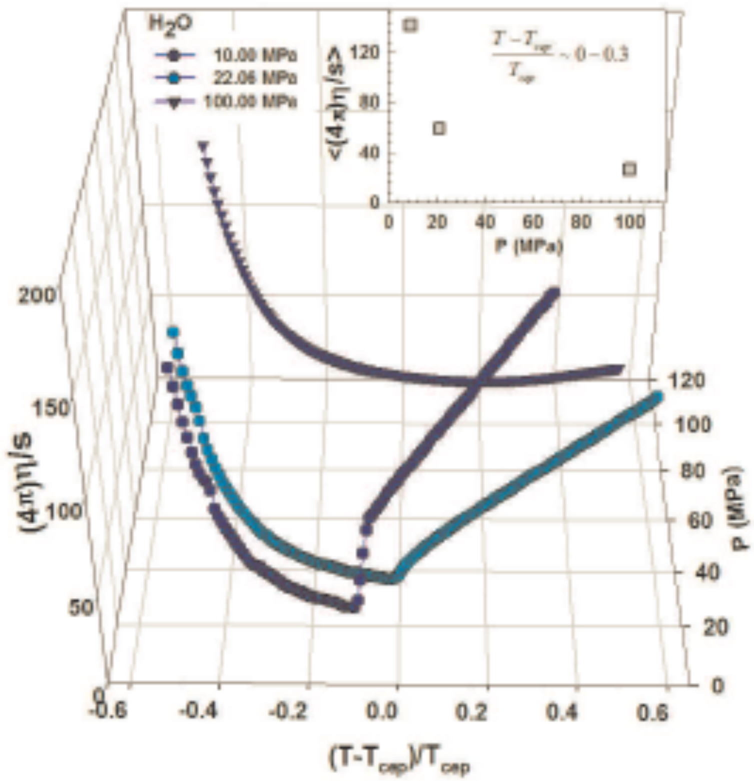
- **LHC + BES → access to an even broader domain of the (μ_B, T)-plane**

Essential Questions

Lacey et. al, Phys.Rev.Lett.98:092301



- ✓ ***(T, μ_B)-dependence of transport coefficients $\langle c_s \rangle$, $\left\langle \frac{\eta}{s} \right\rangle$?***
- ✓ *The role of system size and fluctuations?*
- ✓ *Location of phase boundaries?*
- ✓ ***Indications for a CEP?***



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

Take home message

The acoustic nature of flow leads to specific scaling patterns which :

I. Give profound mechanistic insight on viscous damping

II. Provide constraints for

- ✓ *initial state geometry and its fluctuations*
- ✓ *Extraction of the specific viscosity*

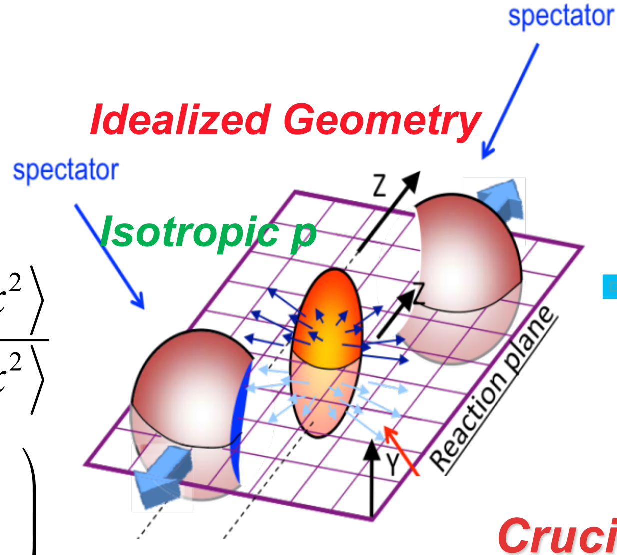
- ✓ *(μ_B, T) dependence of the viscous coefficients*
  - ❖ *Hints for a possible critical point?*

The Flow Probe

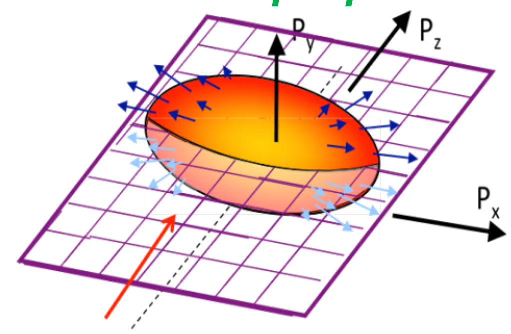
$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy} \sim 5-45\ \frac{GeV}{fm^3} \qquad \varepsilon = \frac{\langle y^2 - x^2\rangle}{\langle y^2 + x^2\rangle}$$

$$\left(\mathrm{P} = \rho^2 \cdot \left(\partial \varepsilon_{Bj} \big/ \partial \rho \right)\Big|_{s/\rho} \right)$$

Idealized Geometry



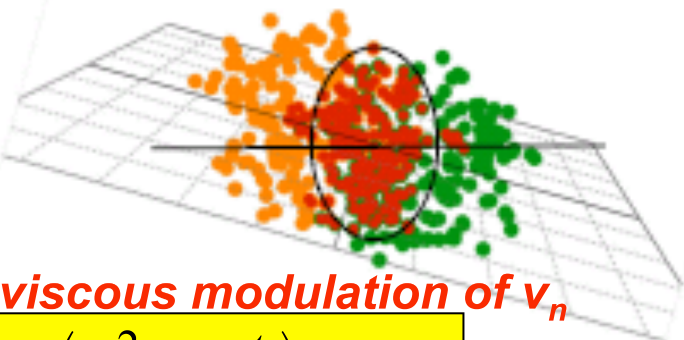
Anisotropic p



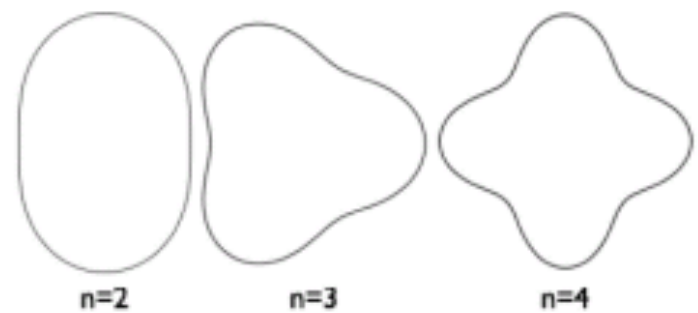
Yield$(\phi) = 2\, \mathbf{v_2} \cos[2(\phi - \Psi_2)]$

Crucial parameters $\varepsilon,\ c_s,\ \eta/s,\ \delta f,\ T_f$

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

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

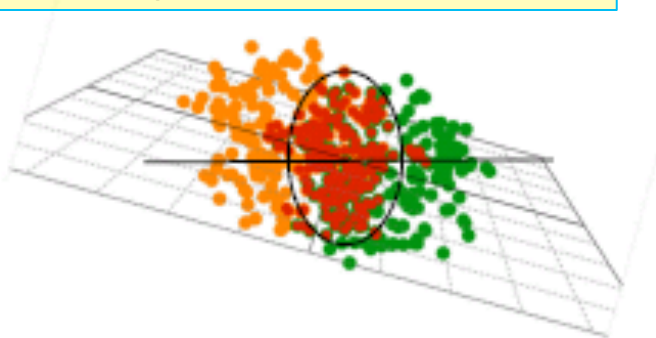
Staig & Shuryak **arXiv:1008.3139**

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

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

Scaling properties of flow

(II) Scaling properties of flow



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

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

Acoustic viscous modulation of v_n

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

Staig & Shuryak **arXiv:1008.3139**

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

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

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

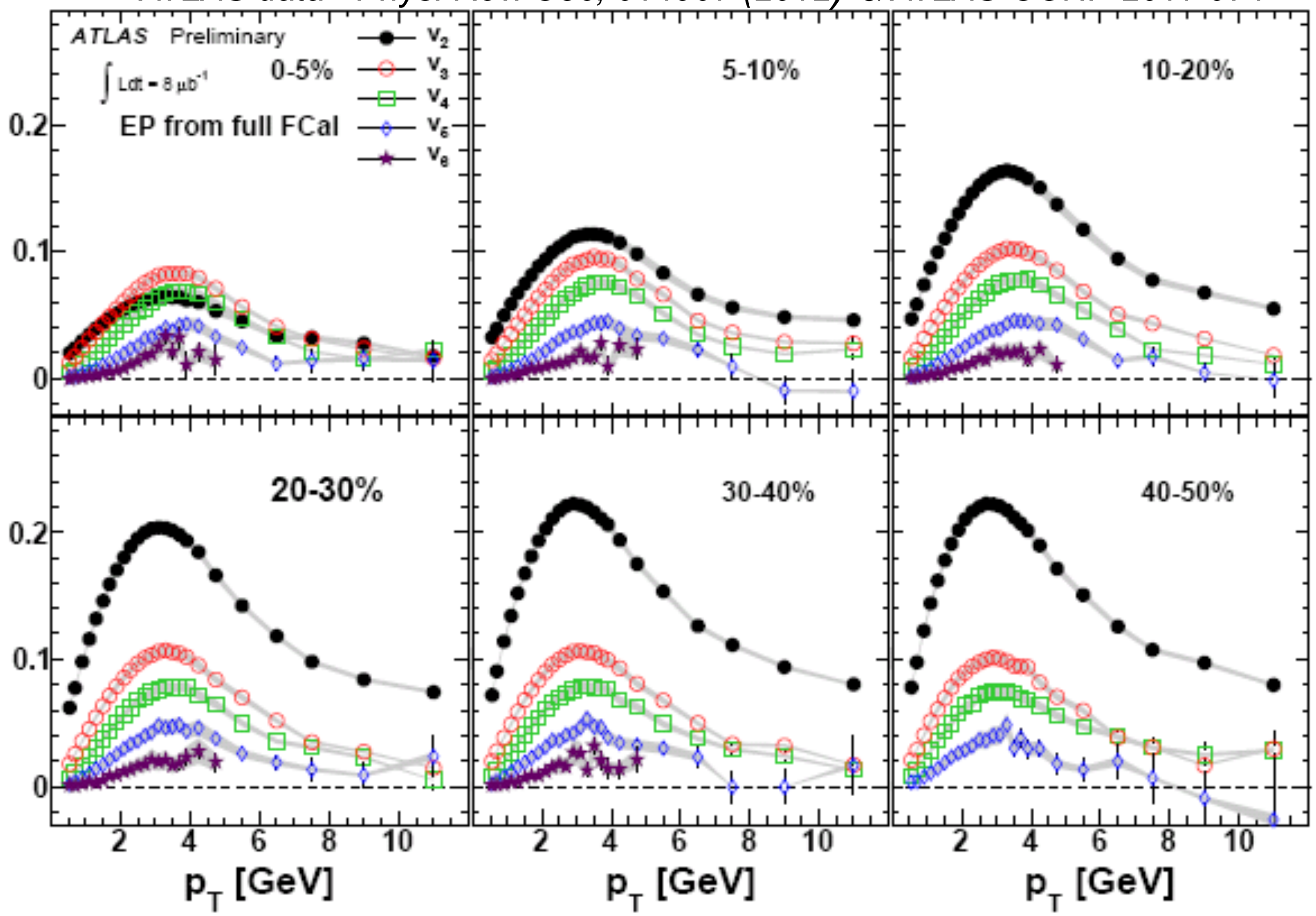
$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{\bar{R}}$$

Each of these scaling expectations has been validated

➢ *A quick review of the data?*

Anisotropy Measurements

ATLAS data - Phys. Rev. C86, 014907 (2012) & ATLAS-CONF-2011-074

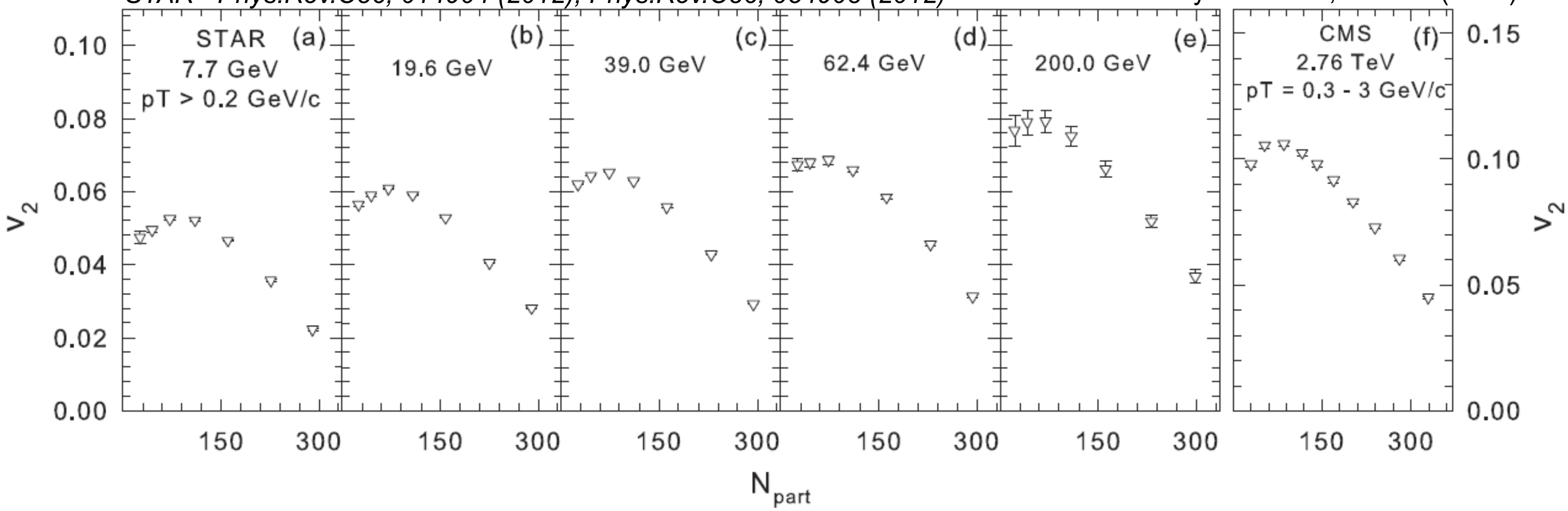


High precision double differential measurements obtained for higher harmonics at RHIC and the LHC.

Anisotropy Measurements

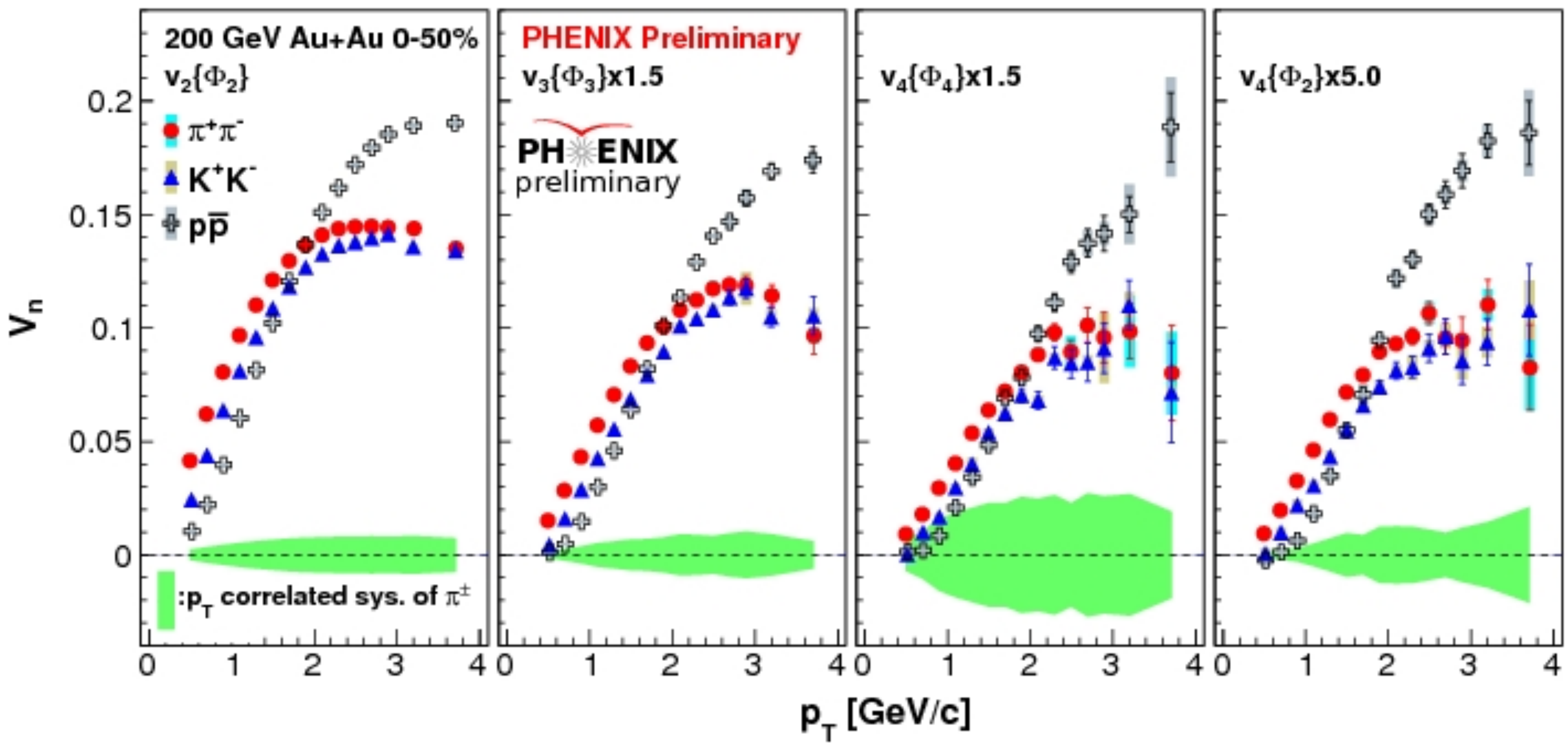
arXiv:1305.3341

STAR - Phys.Rev.C86, 014904 (2012); Phys.Rev.C86, 054908 (2012) CMS - Phys.Rev.**C87**, 014902 (2013)



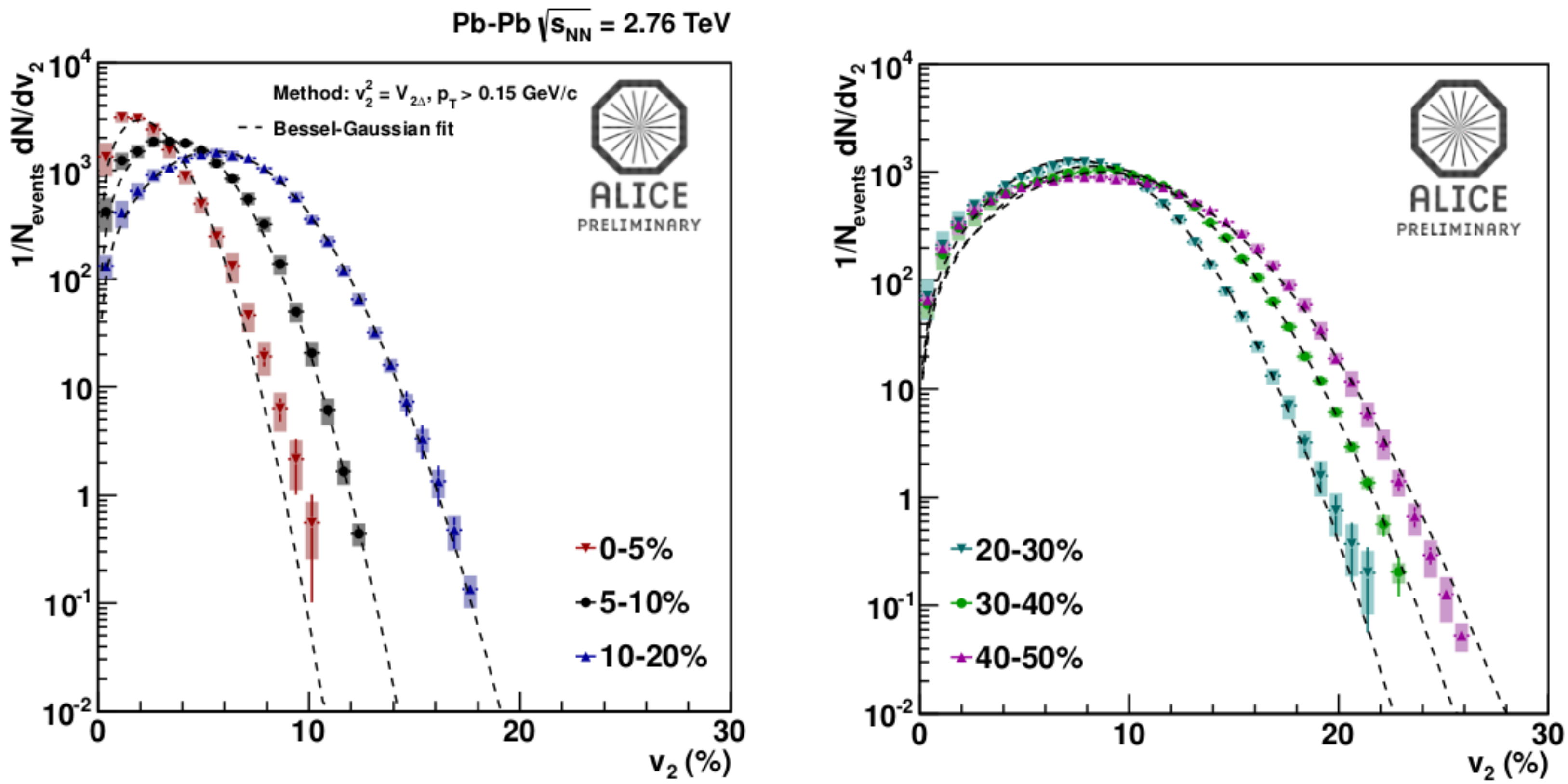
- ***An extensive set of measurements now span a broad range of beam energies (T, μ_B).***

Anisotropy Measurements



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

Anisotropy Measurements

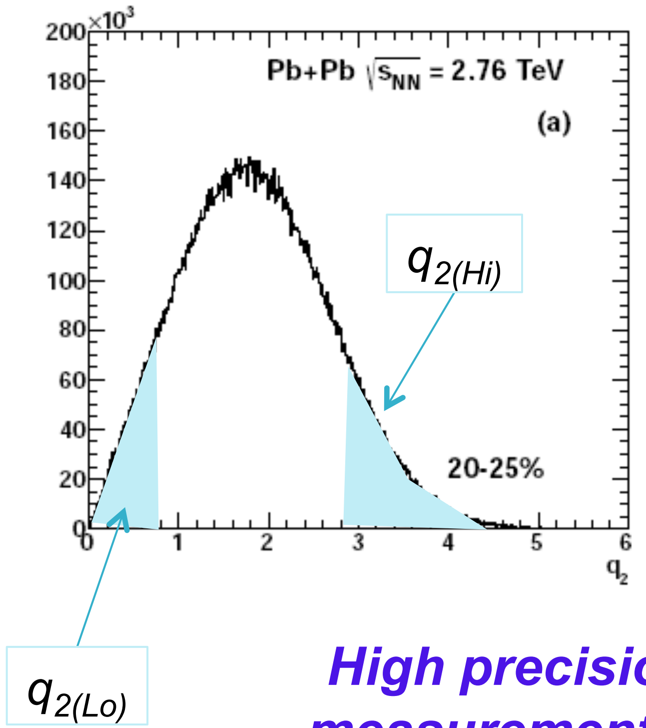


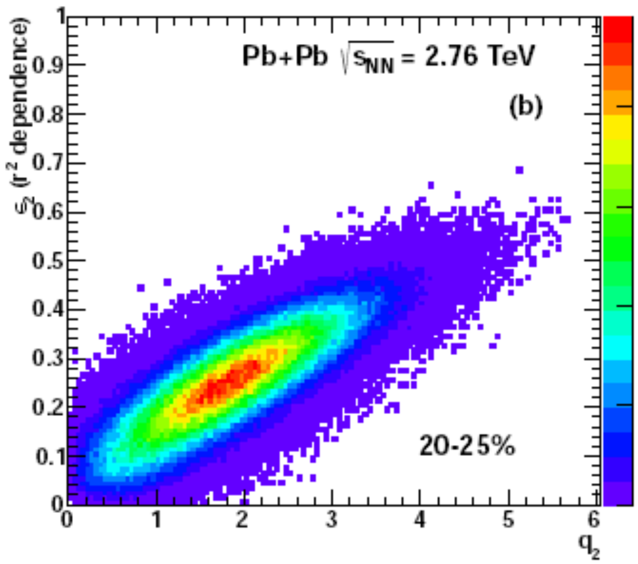
Event-by-Event v_2 measurements obtained via 2PC followed by unfolding.

✓ **v_2 described by Bessel-Gaussian distribution: Contribution from mean geometry+fluctuations.**

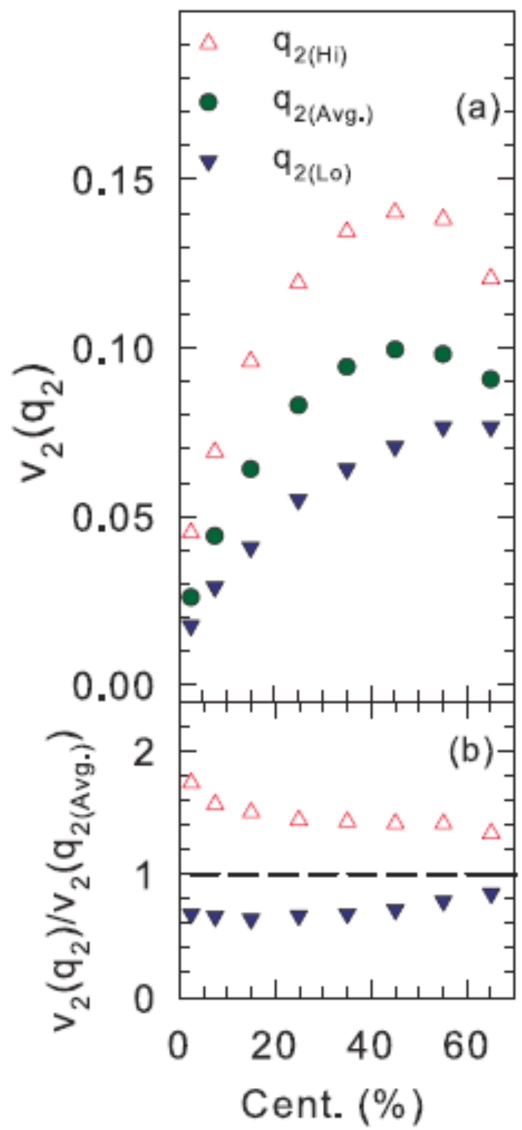
Anisotropy Measurements

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





ALICE data



High precision double differential measurements obtained for shape-engineered events at RHIC and the LHC;

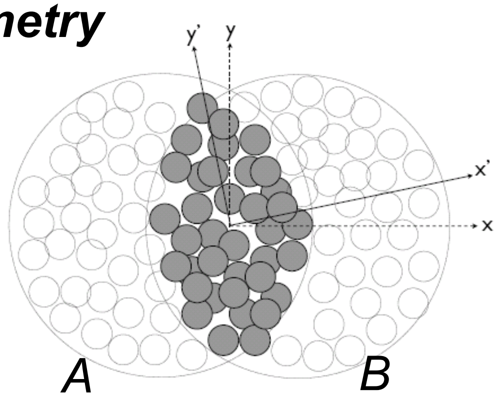
→ Sizable variation of v_n at a given centrality due to fluctuations

- ***Do the wealth of anisotropy measurements show a consistent scaling pattern?***

- ***What do we learn from these scaling patterns?***

Geometric quantities for scaling

Geometry



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

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

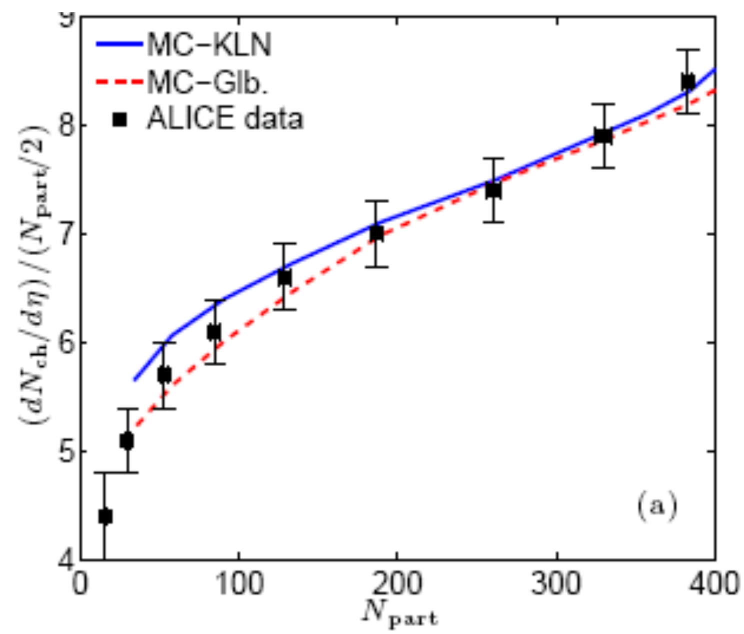
$$S_{ny} \equiv S_n \sin(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\sin(n\phi),$$

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

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

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

arXiv:1203.3605



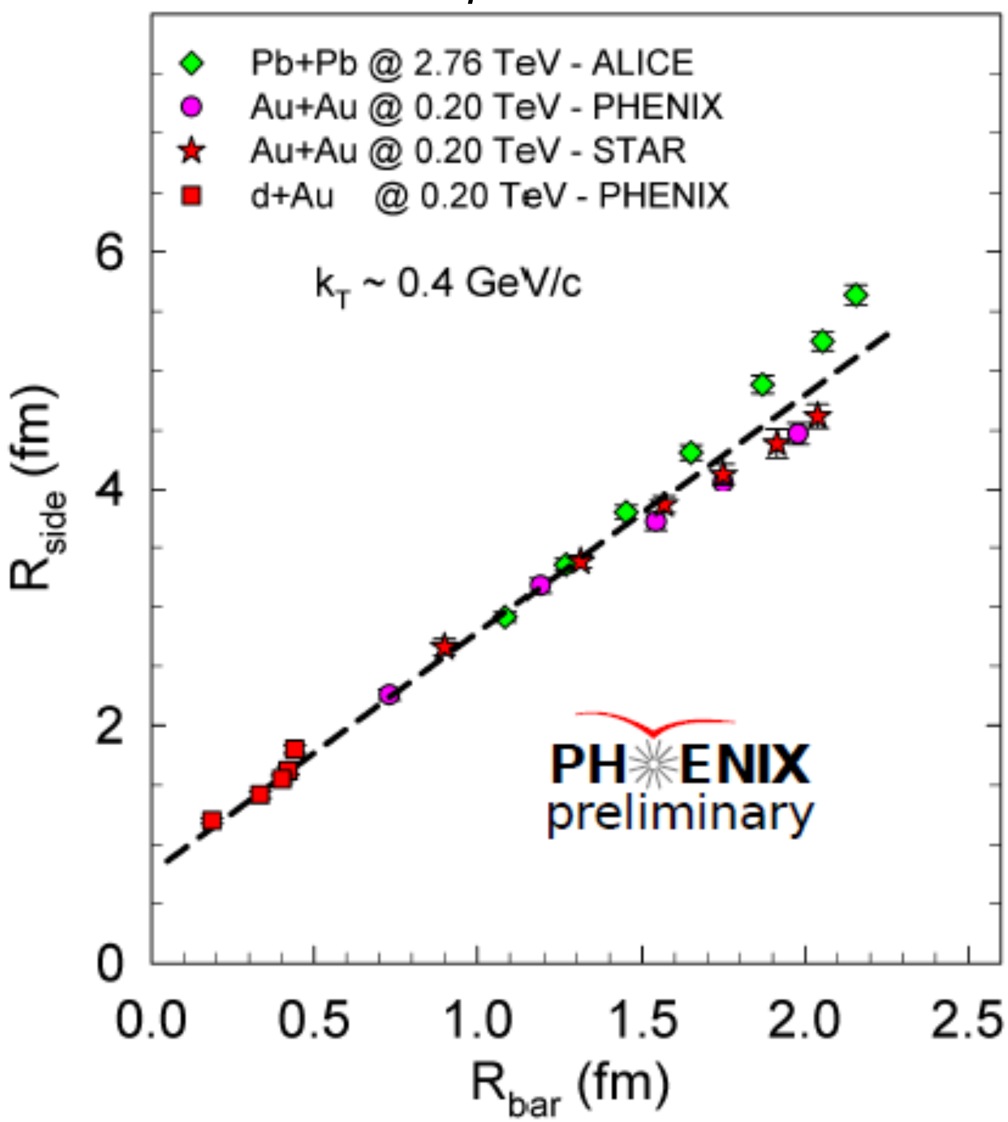
σ_x & σ_y → RMS widths of density distribution

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

Geometric quantities for scaling

R_side scales with R_bar for a broad range of system sizes and beam energies

Femtoscopic measurements

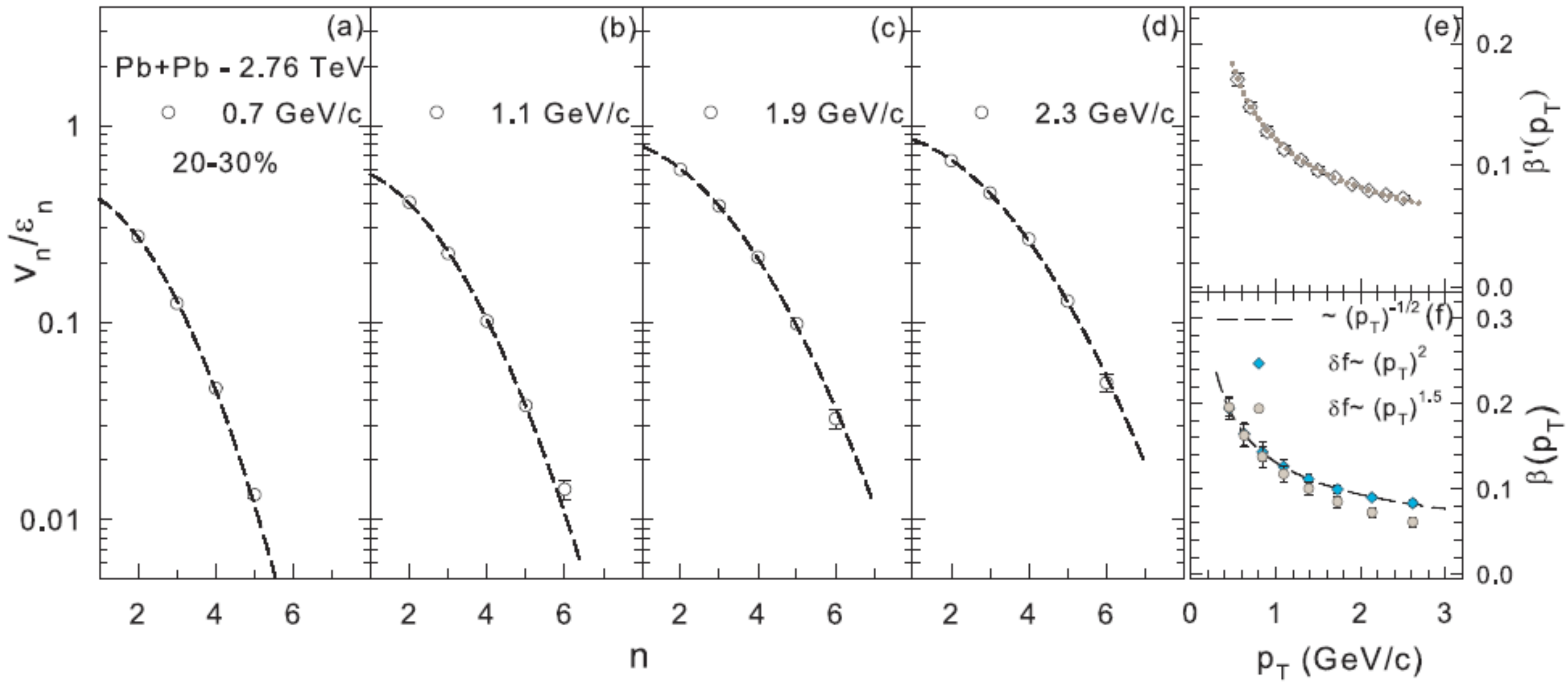


Acoustic Scaling – n^2

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

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

arXiv:1301.0165



✓ **Characteristic n^2 viscous damping validated**

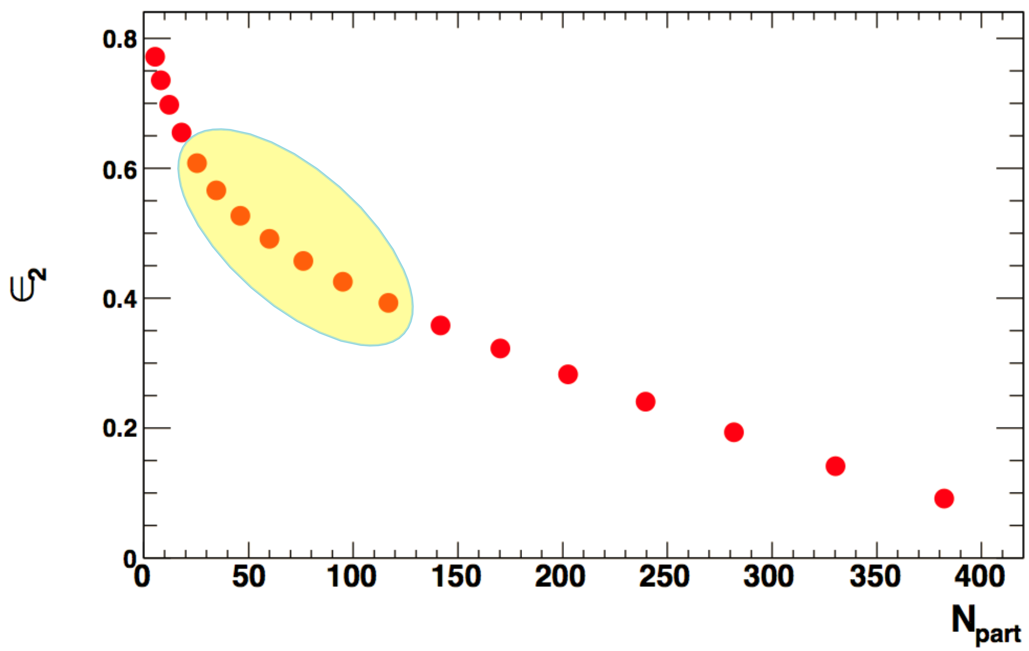
✓ ***Characteristic $1/(p_T)^{\alpha}$ dependence of extracted β values validated***

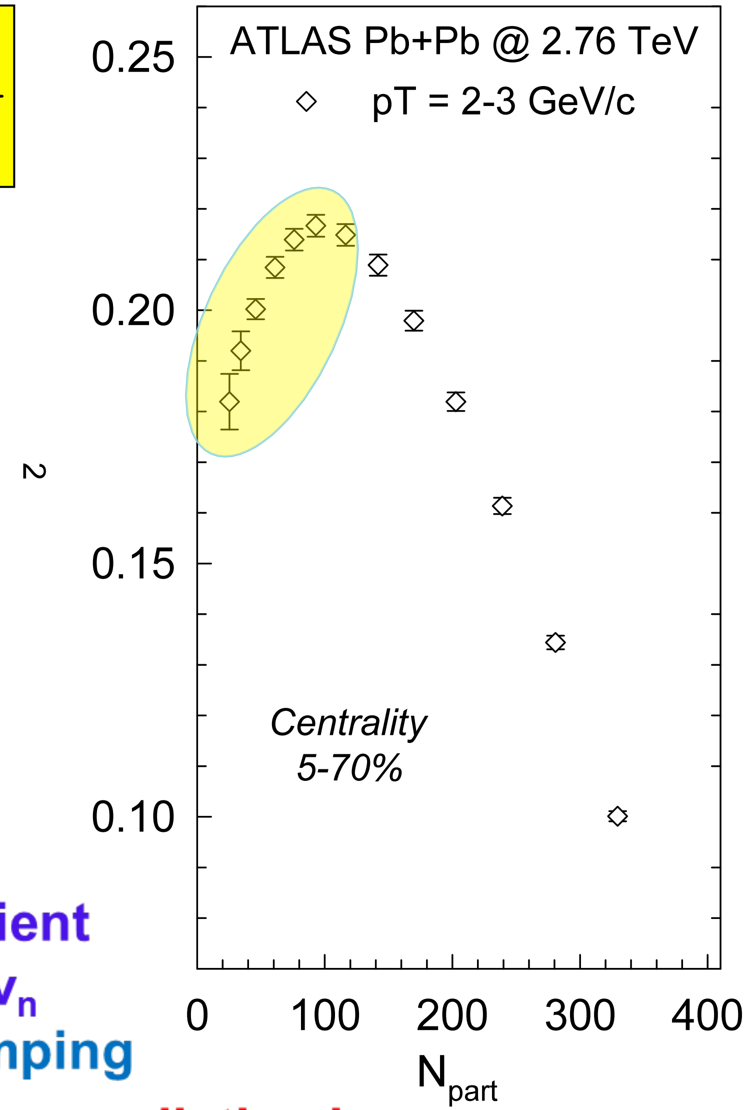
Constraint for η/s and δf

Scaling properties of flow

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

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





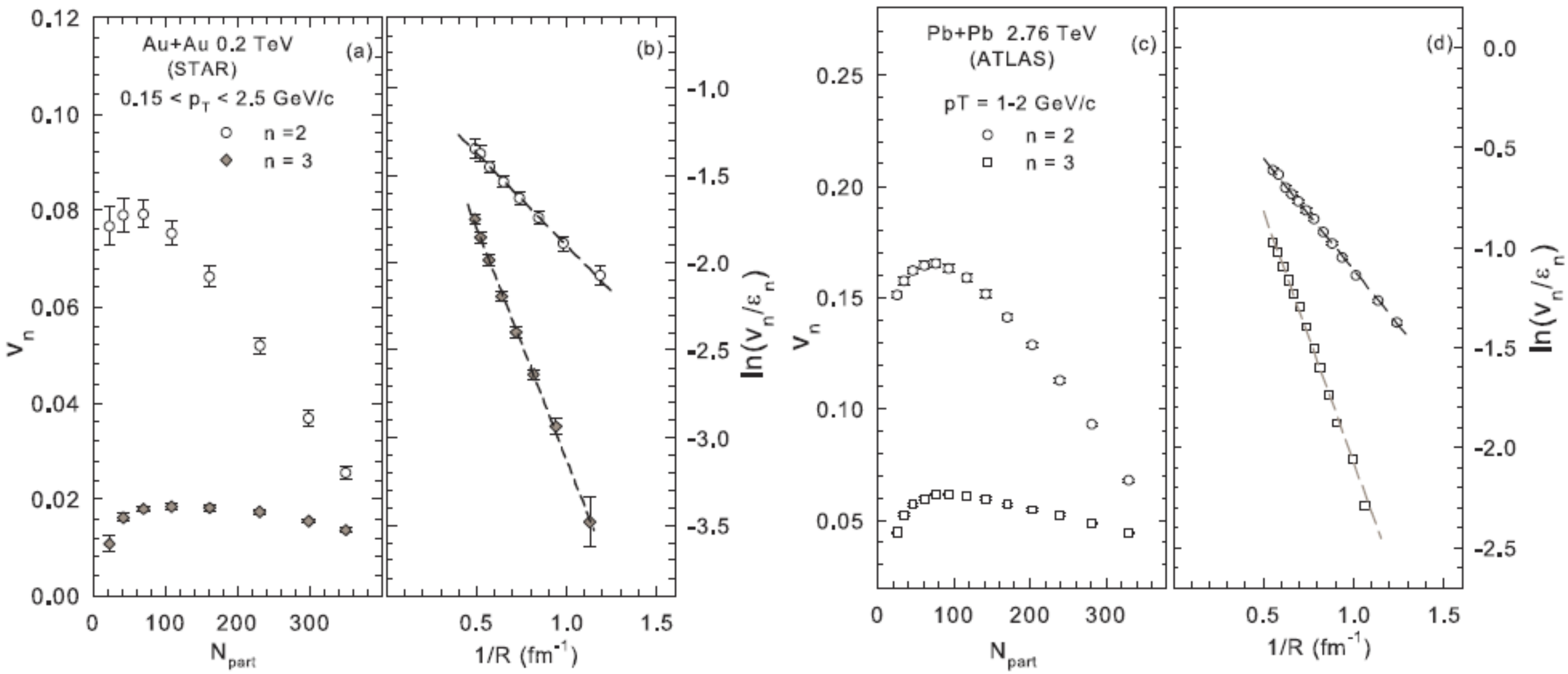
- ➤ **Eccentricity change alone is not sufficient**
  To account for the N_{part} dependence of v_n
  Transverse size ($\bar{R}$) influences viscous damping

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

Scaling properties of flow

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

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

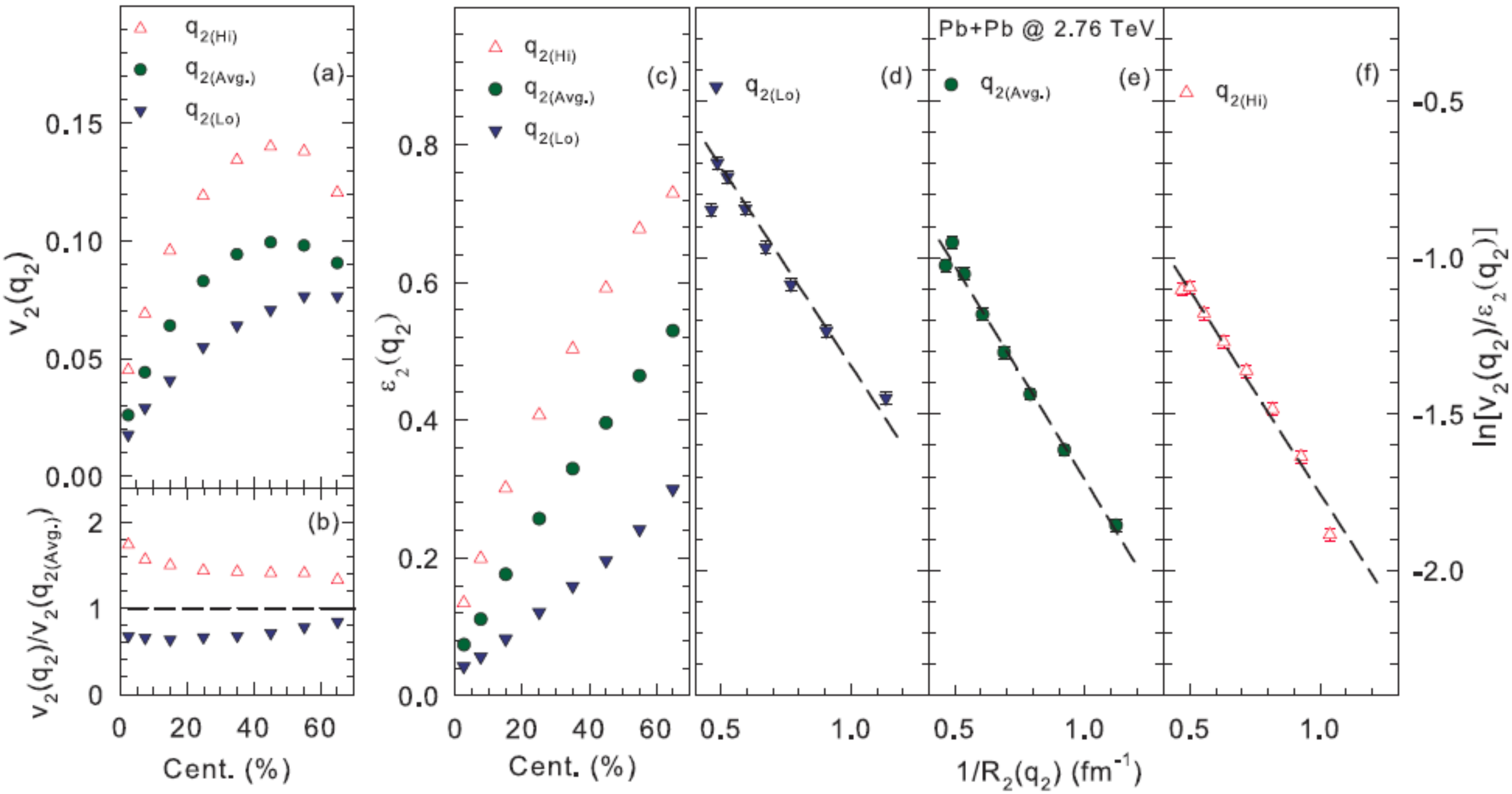


✓ **Characteristic $1/\bar{R}$ viscous damping validated at RHIC & the LHC**

✓ ***A further constraint for η/s***

Scaling properties of flow

Acoustic Scaling of shape-engineered events



✓ **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***

Scaling properties of flow

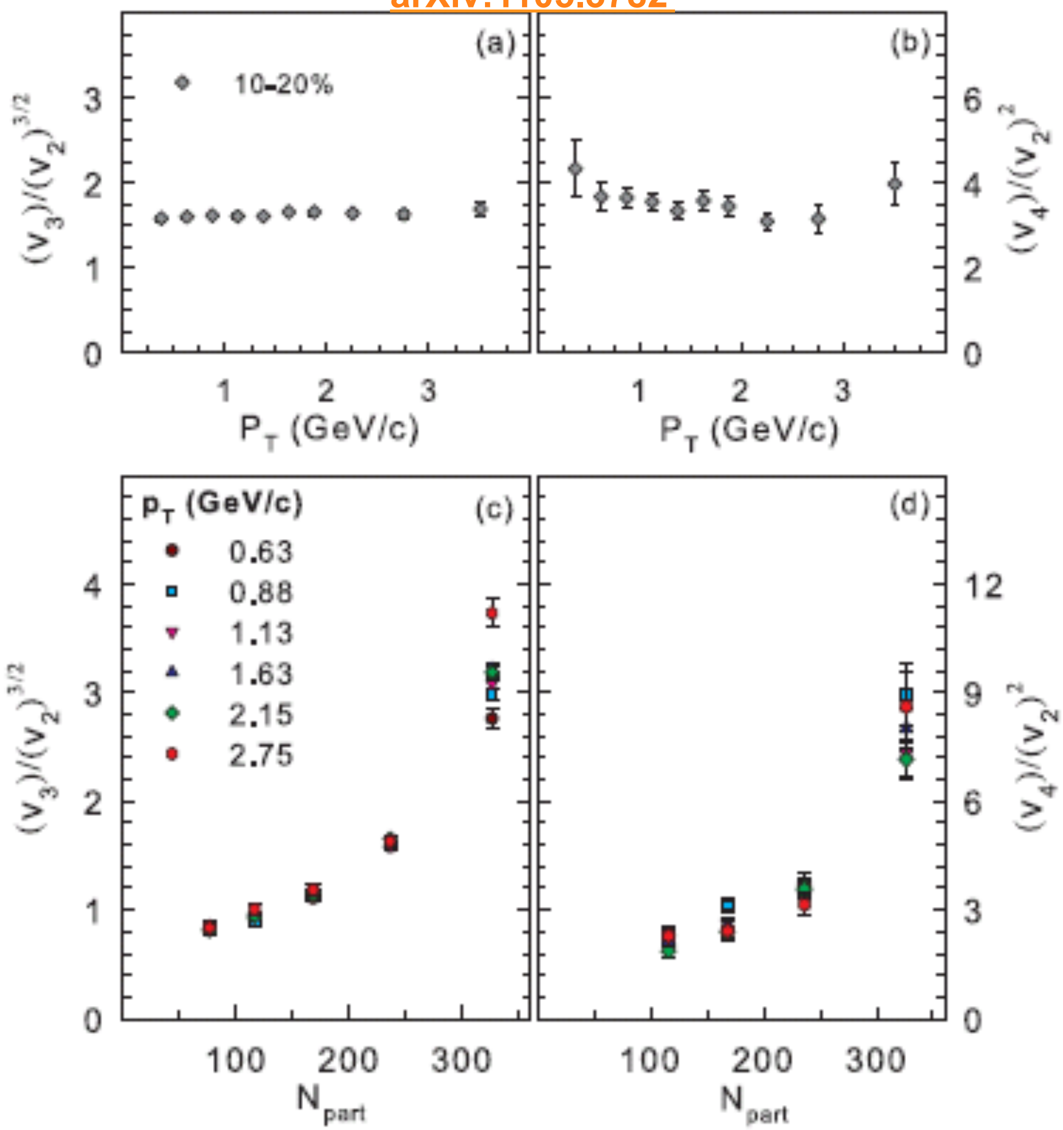
Acoustic Scaling – Ratios

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

$$v_n(p_T) \propto \left[v_2(p_T)\right]^{n/2}$$

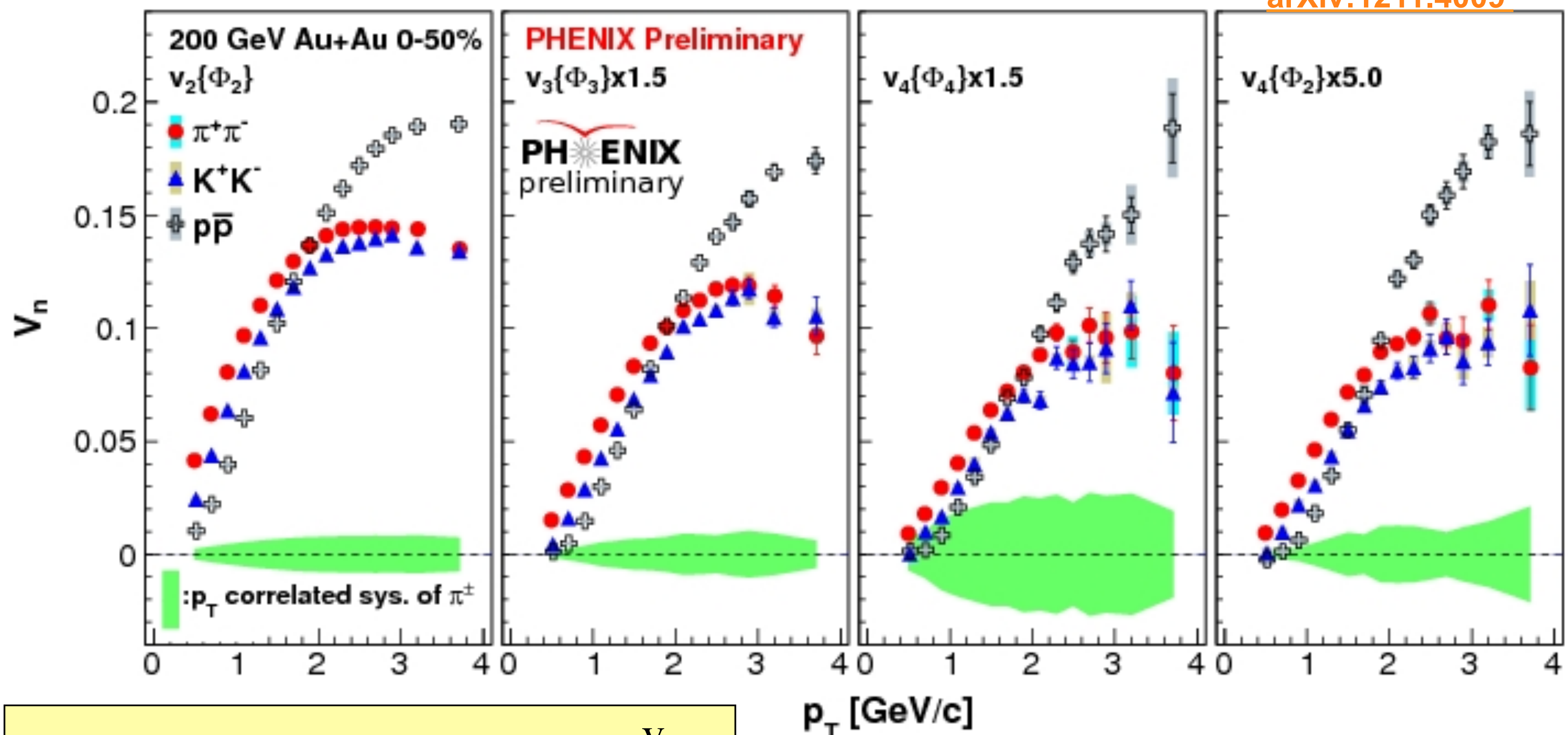
The expected relation between v_n and v_2 is validated

arXiv:1105.3782



Flow is partonic & Acoustic?

arXiv:1211.4009



$$\text{Expectation: } \mathrm{v}_n(KE_T) \sim \mathrm{v}_2^{n/2} \text{ or } \frac{\mathrm{v}_n}{(n_q)^{n/2}}$$

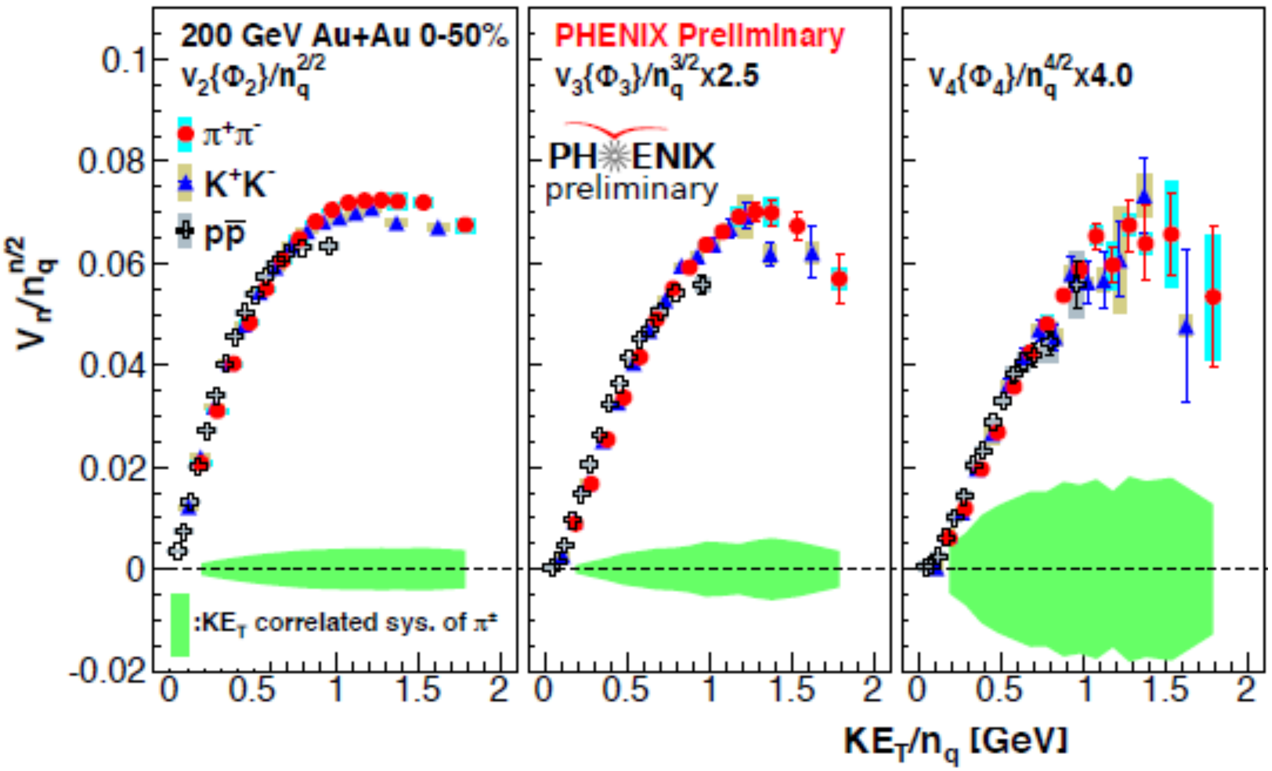
Note species dependence for all v_n

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

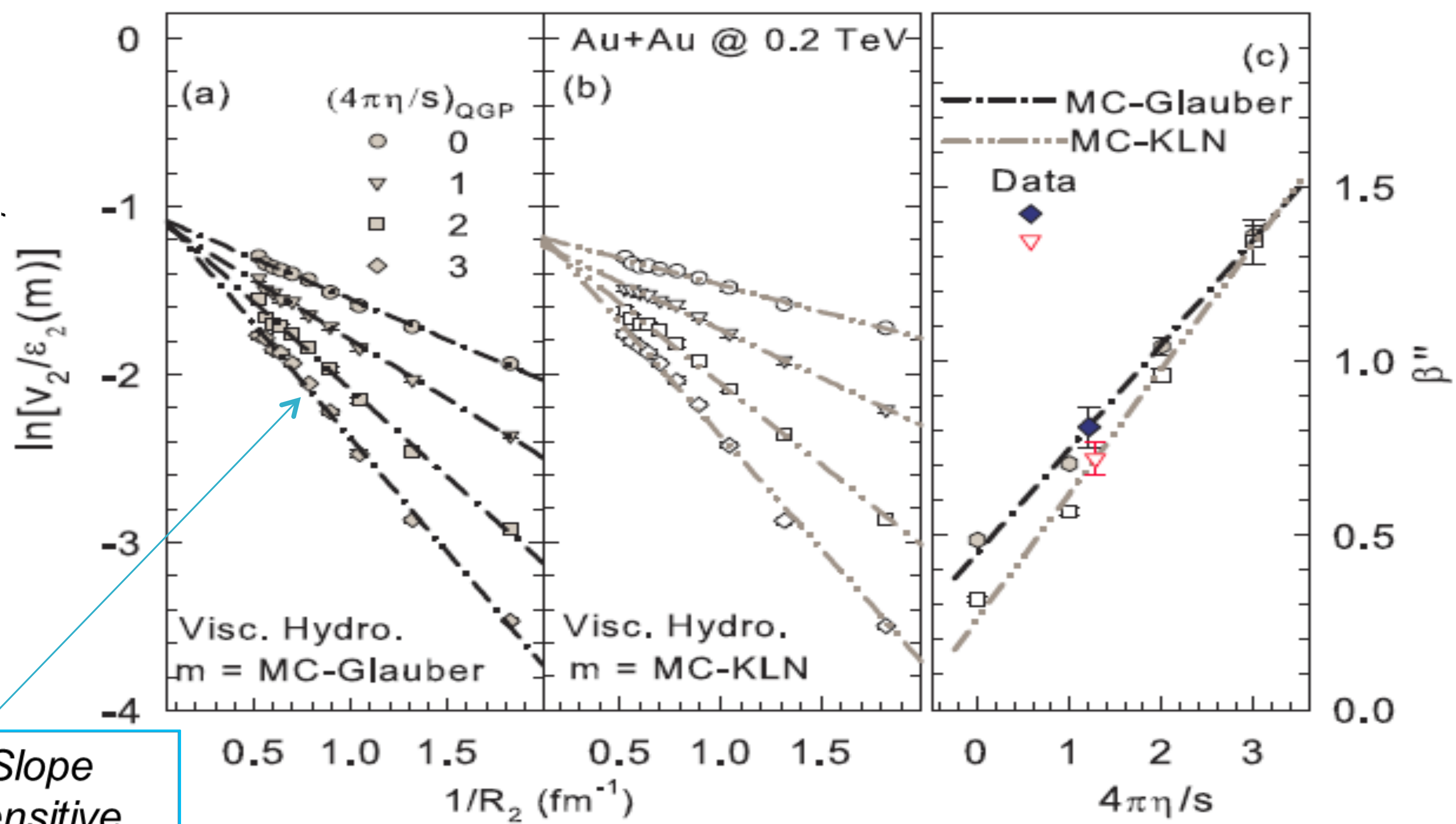


Expectation validated: $v_n(KE_T) \sim v_2^{n/2}$ or $\frac{v_n}{(n_q)^{n/2}}$

Extraction of η/s

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

Song et al



Slope sensitive to 4πη/s

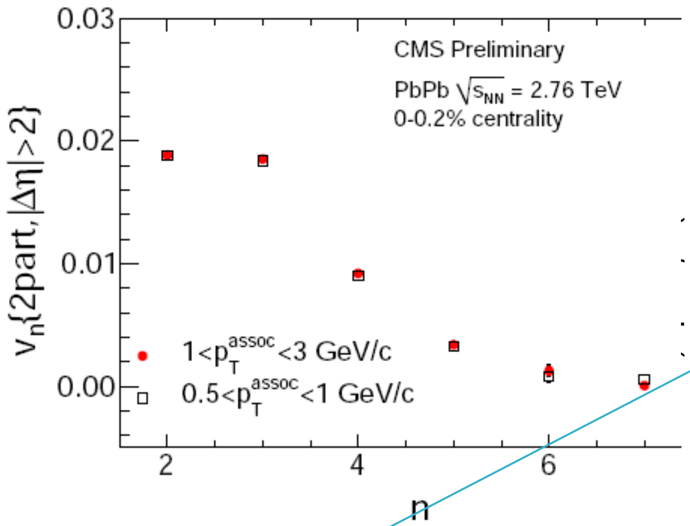
Characteristic $1/\bar{R}$ viscous damping validated in viscous hydrodynamics; calibration → 4πη/s ~ 1.3 ± 0.2

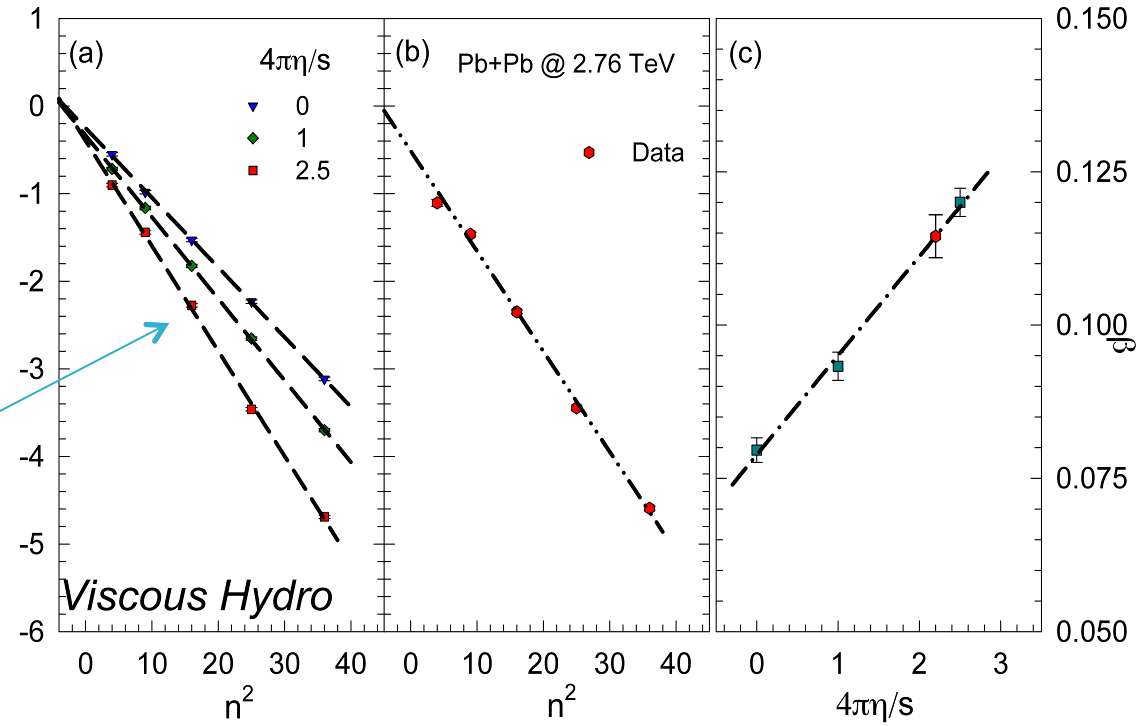
Extracted η/s value insensitive to initial conditions

Extraction of η/s

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

arXiv:1301.0165 & CMS PAS HIN-12-011





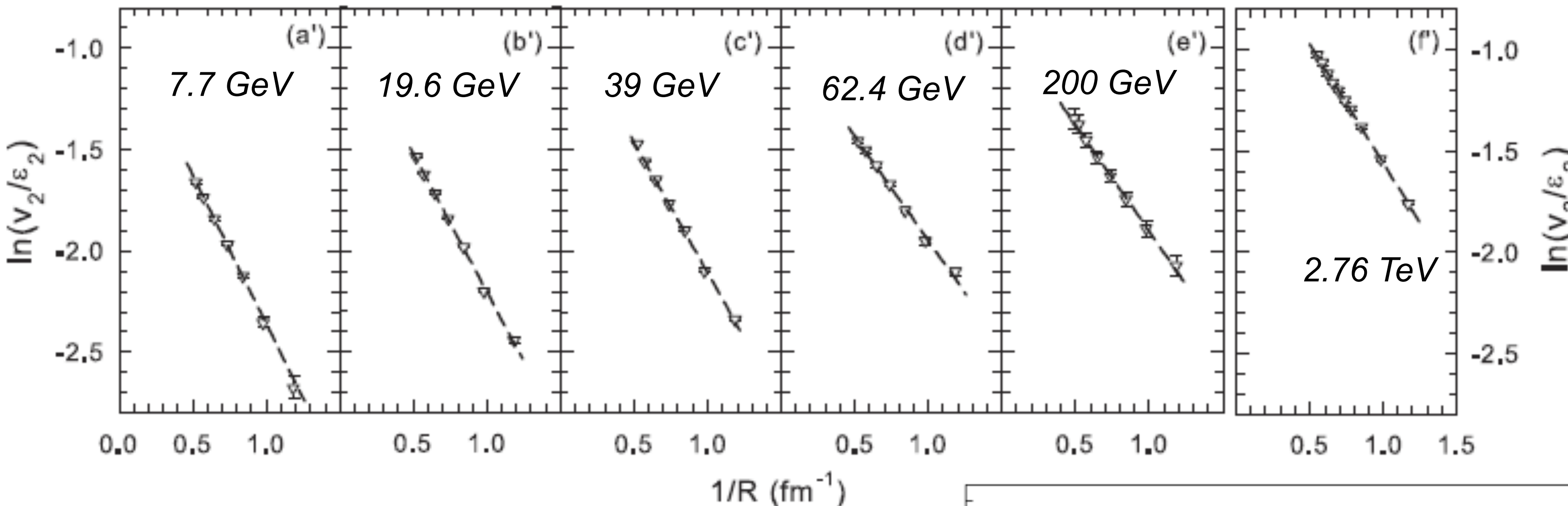
*Slope sensitive to **η/s***

n^2 scaling validated in experiment and viscous hydrodynamics; calibration → $4\pi\eta/s \sim 2.2 \pm 0.2$

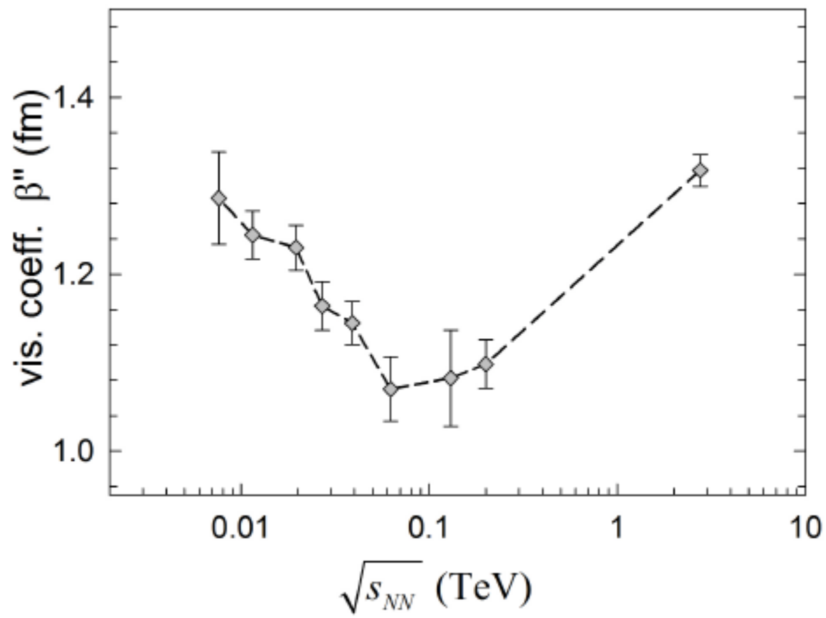
Scaling properties of flow – Beam Energy dependence

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

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



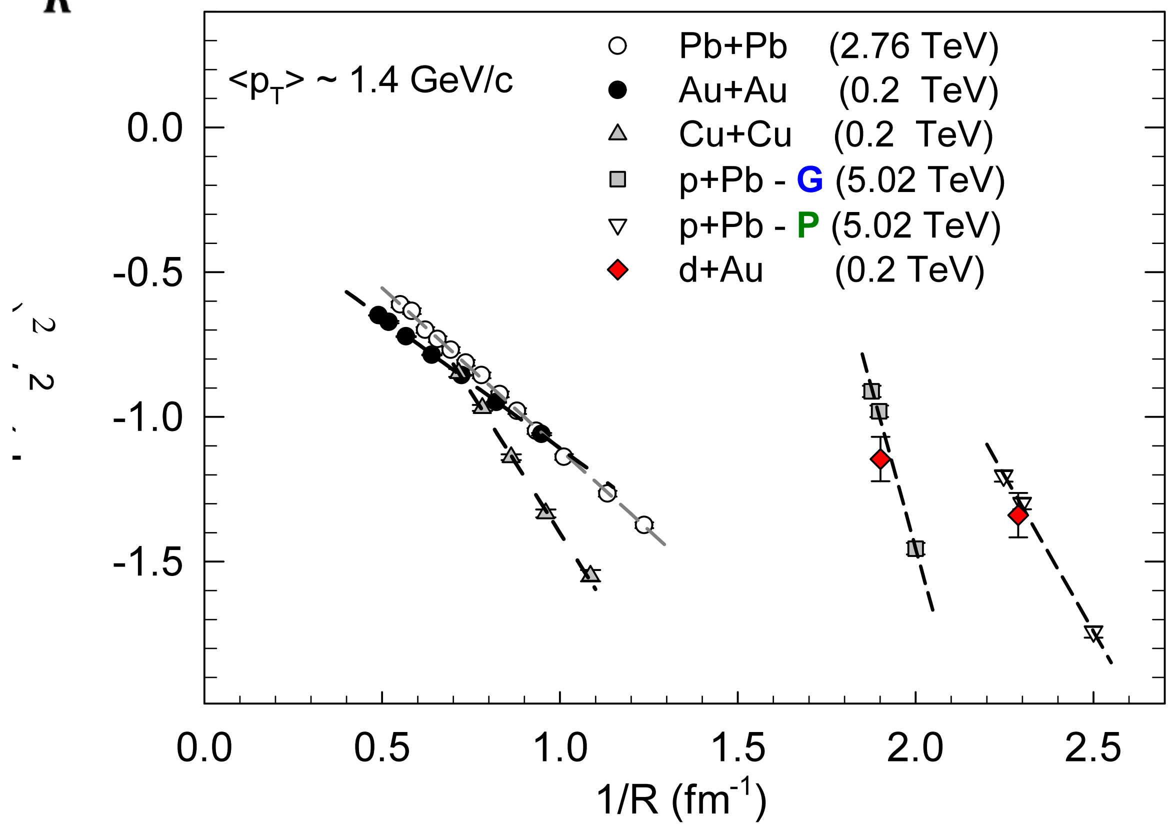
- ✓ **Characteristic $1/\bar{R}$ viscous damping validated across beam energies**
- ✓ ***First experimental indication for η/s variation in the (T, μ_B)-plane***



Scaling properties of flow

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

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



- ✓ **Characteristic $1/\bar{R}$ viscous damping validated across systems**
  - **→ Similar mechanism**
- ✓ ***Clear system size dependence of β'' → signature of dilute fluid?***

Summary

Scaling properties of anisotropic flow *lend profound mechanistic insights, as well as new constraints for transport coefficients*

What do we learn?

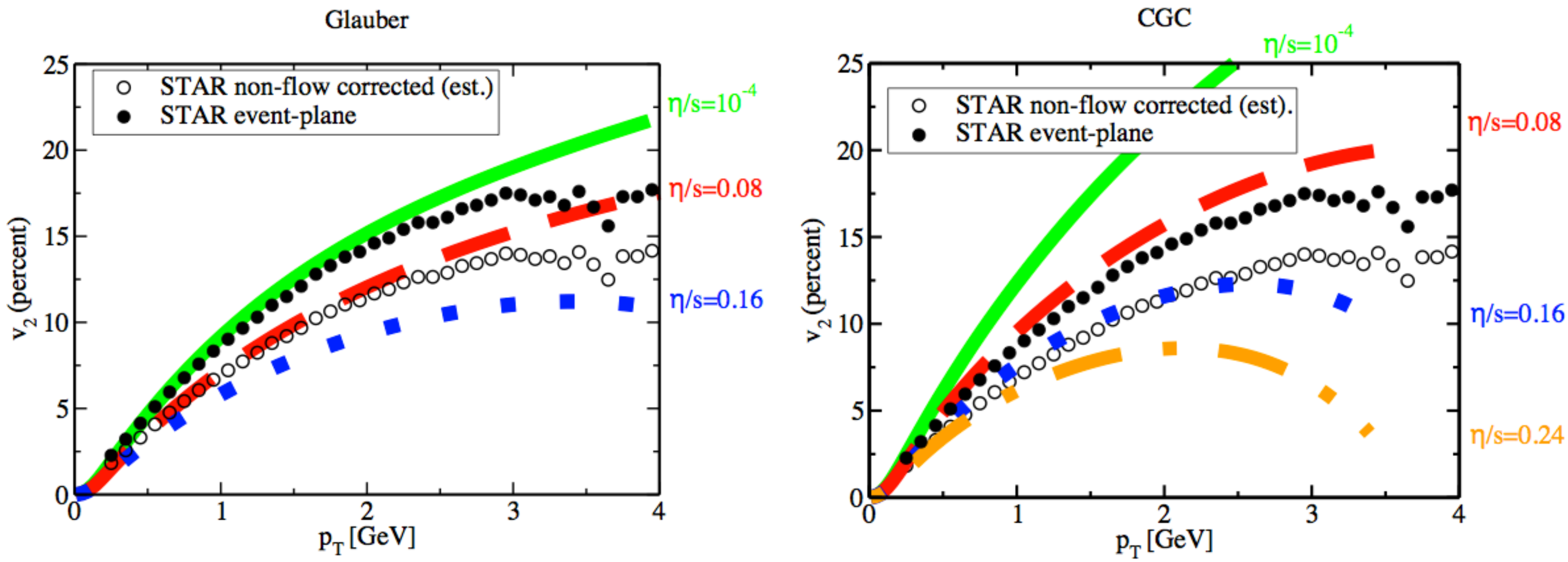
- ***Flow is acoustic –** "as it should be"*
  - ***Obeys the dispersion relation for sound propagation***
    - ✓ *(n^2 & $1/\bar{R}$) → constraints for 4πη/s*
    - ✓ *4πη/s for RHIC plasma ~ 1.3 ± 0.2*
    - ✓ *4πη/s for LHC plasma ~ 2.2 ± 0.2*
    - ✓ *Extraction insensitive to initial geometry model*
    - ✓

- ***Characteristic dependence of β on beam energy give constraints for:***
  - ✓ *(T, μ_B)-dependence η/s*
  - ✓ *Indication for CEP??*

End

Essential Questions

Luzum et al. arXiv 0804.4015

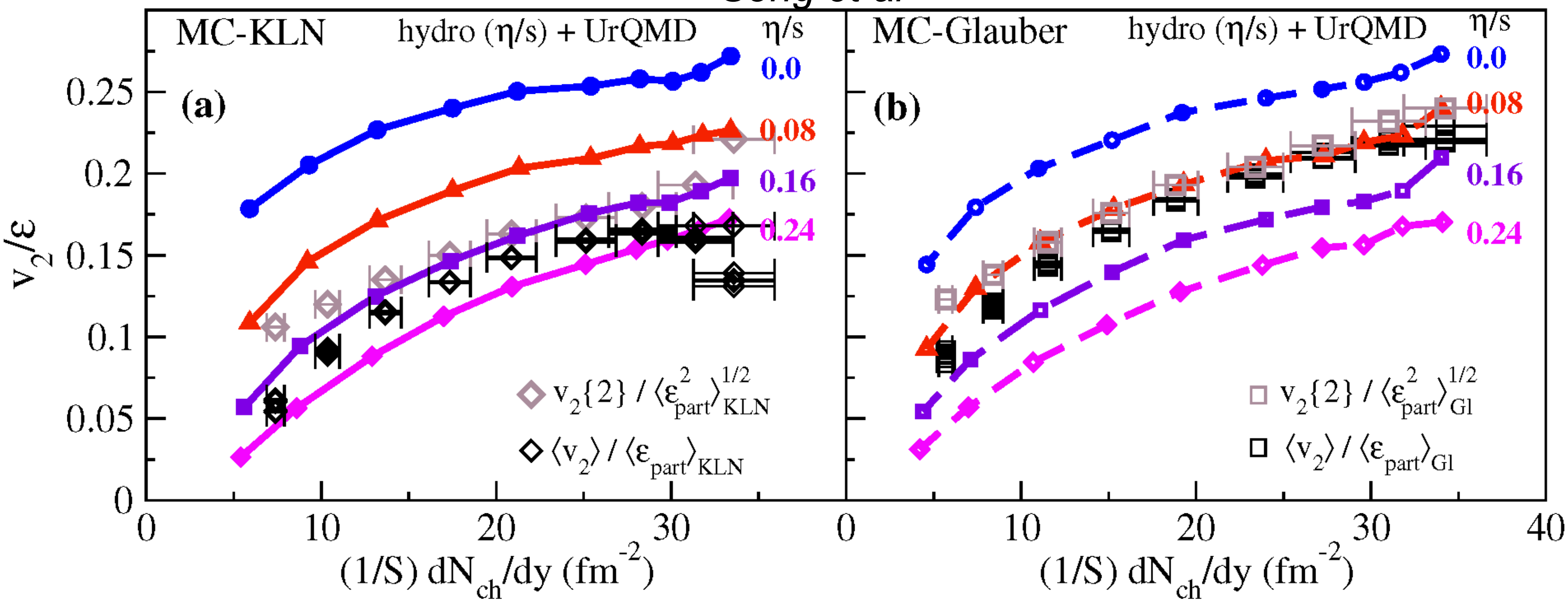


- ***LHC → access to high T and small μ_B***
- ***RHIC → access to different systems and a broad domain of the (μ_B,T)-plane***

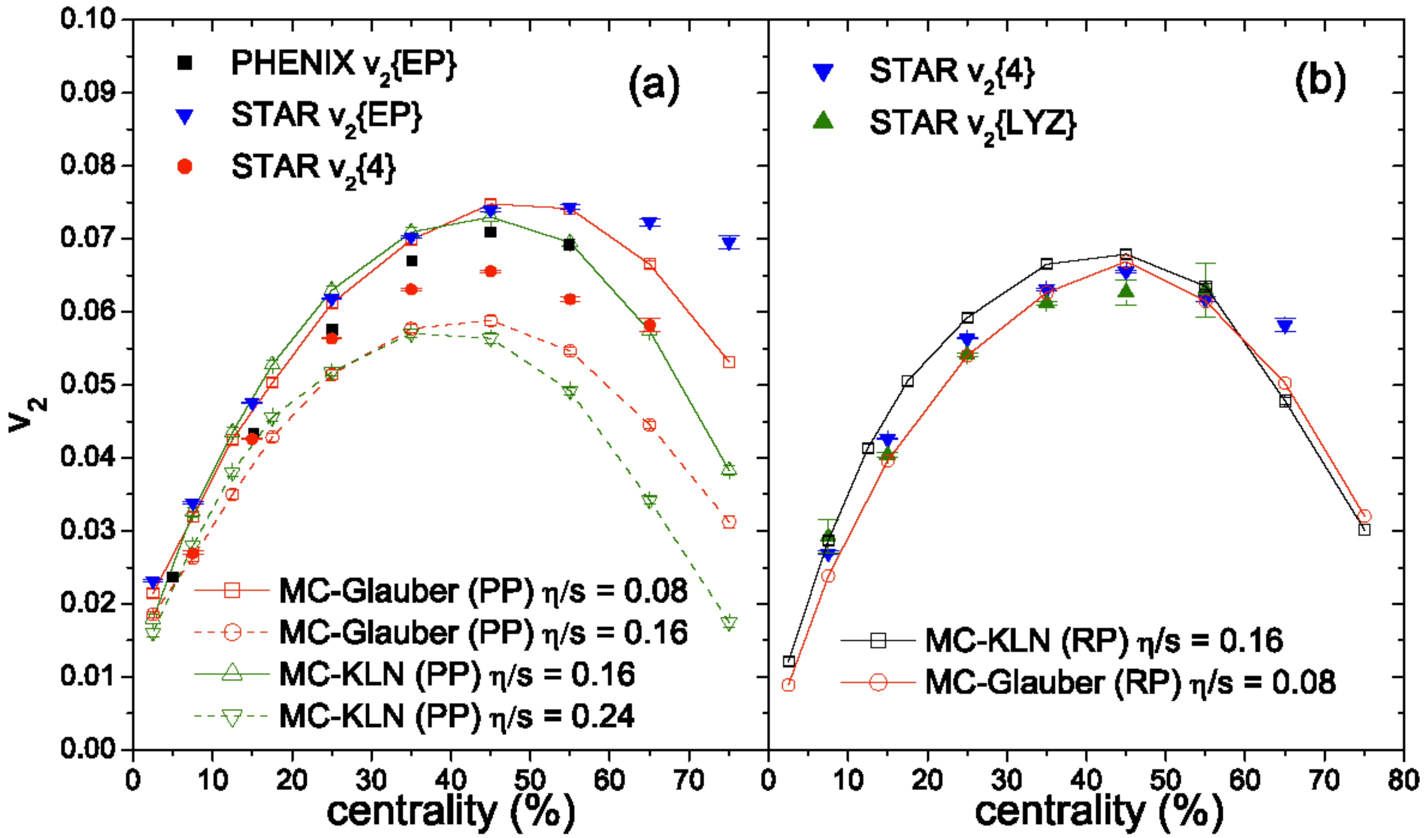
$RHIC_{BES}$ to LHC → ~360 $\sqrt{s_{NN}}$ increase

An Essential Question

Song et al



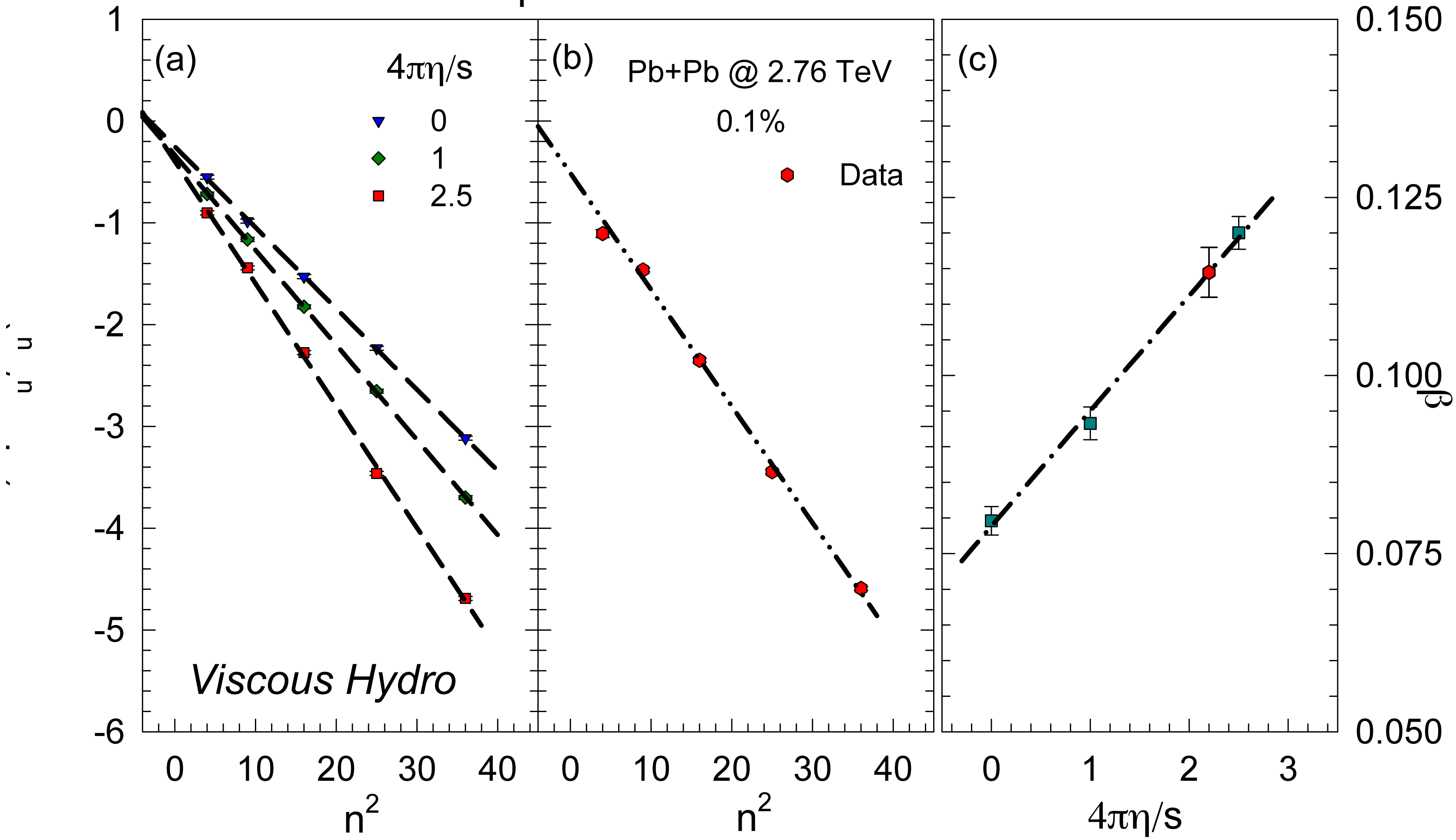
- ***Does the value of $\frac{\eta}{s}$ depend on the initial geometry model or the method of extraction?***



PHENIX v2{EP}
STAR v2{EP}
STAR v2{4}
(a)
MC-Glauber (PP) η/s = 0.08
MC-Glauber (PP) η/s = 0.16
MC-KLN (PP) η/s = 0.16
MC-KLN (PP) η/s = 0.24
STAR v2{4}
STAR v2{LYZ}
(b)
MC-KLN (RP) η/s = 0.16
MC-Glauber (RP) η/s = 0.08
v2
centrality (%)
centrality (%)

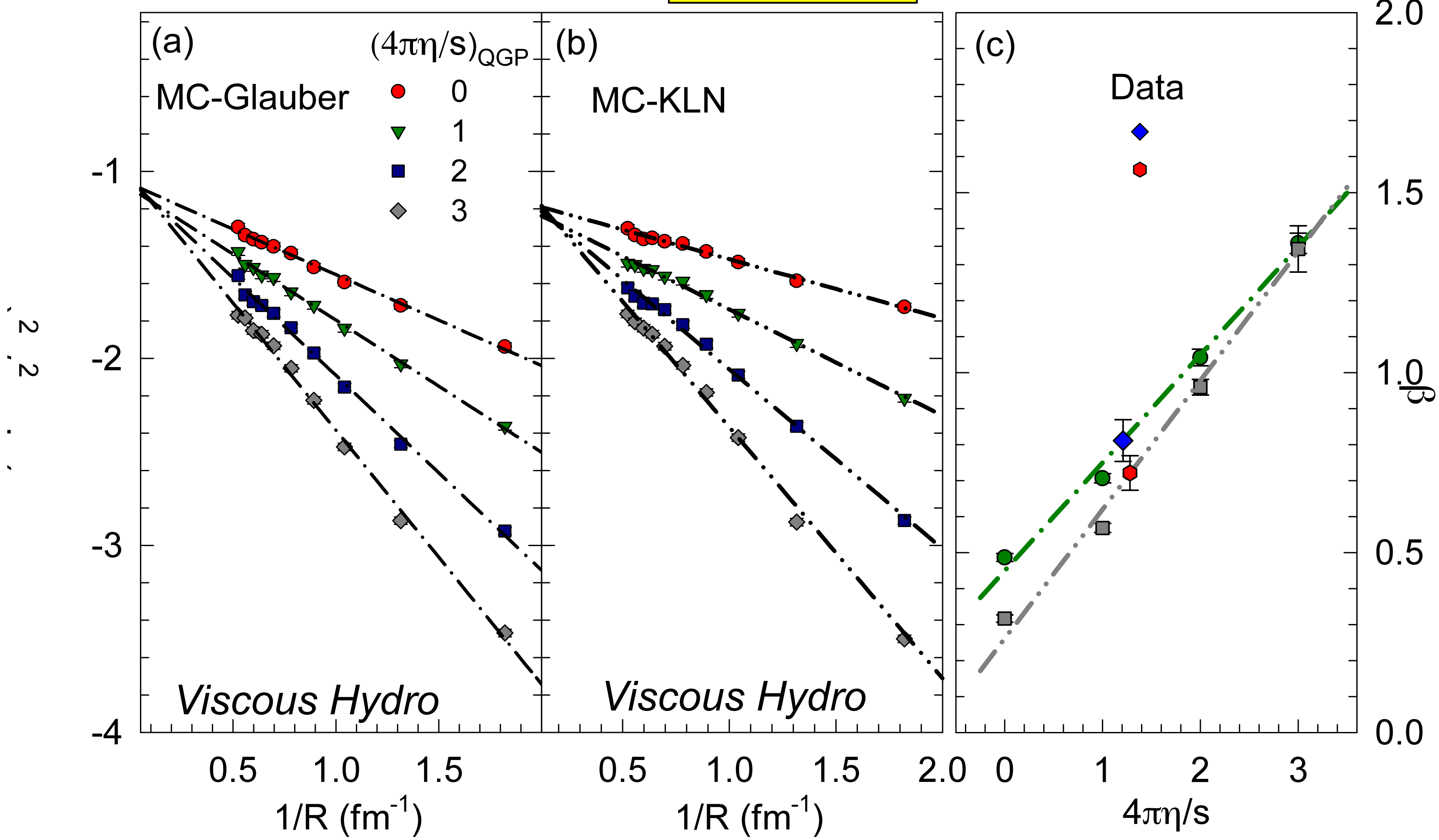
$$\frac{v_n(p_T)}{\varepsilon_n} \propto \cdot \exp\left(-\beta' n^2\right)$$

Data and calculated points from CMS PAS HIN-12-011



n^2 scaling validated in viscous hydrodynamics; calibration → $4\pi\eta/s \sim 2$

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



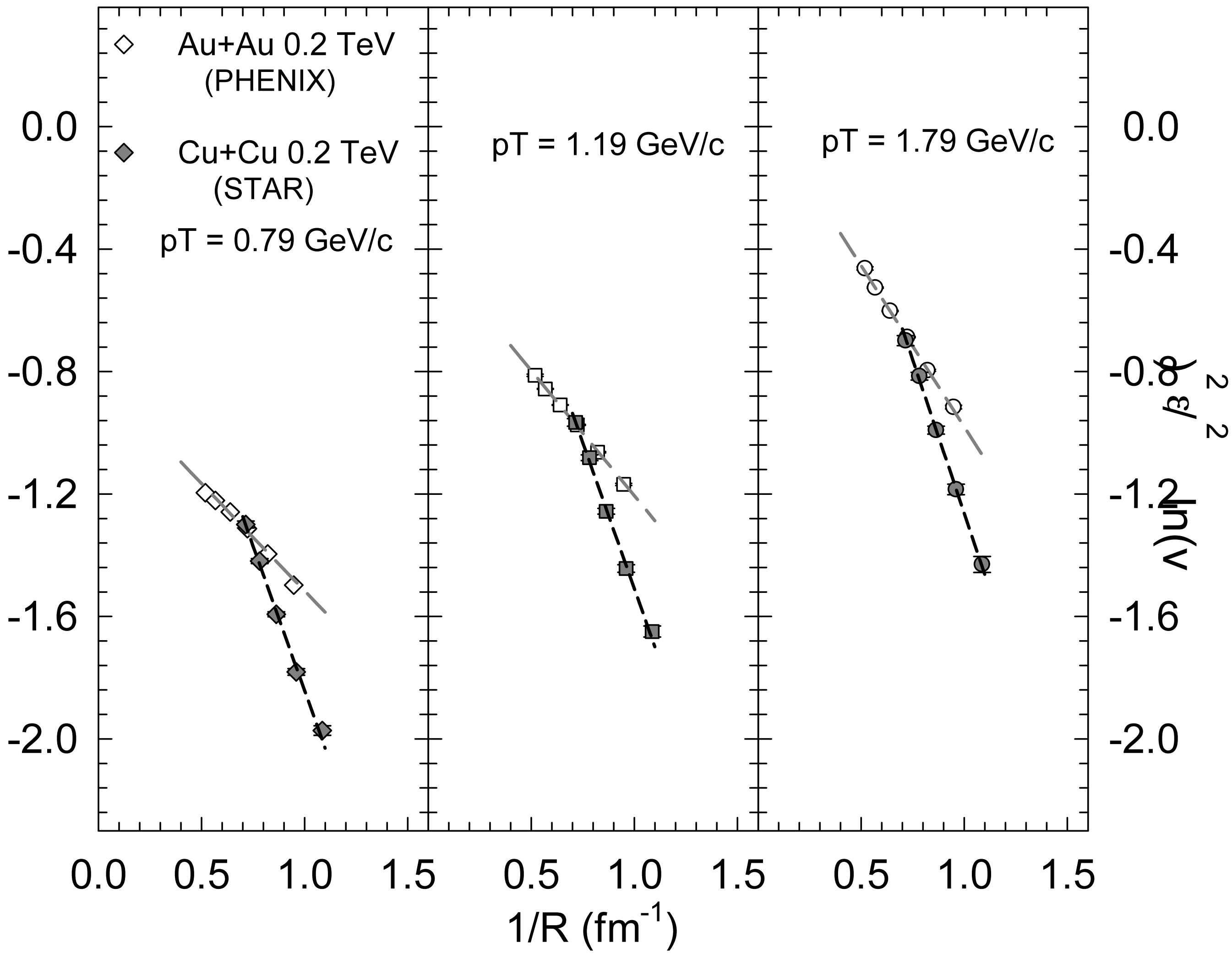
Characteristic $1/\bar{R}$ viscous damping validated in viscous hydrodynamics; calibration → $4\pi\eta/s \sim 1.3$

Acoustic Scaling – 1/R

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

Slope difference encodes viscous coefficient difference

Compare system size @ RHIC



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