The Role of higher-order flow harmonics in the search for the critical point

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Essential message!

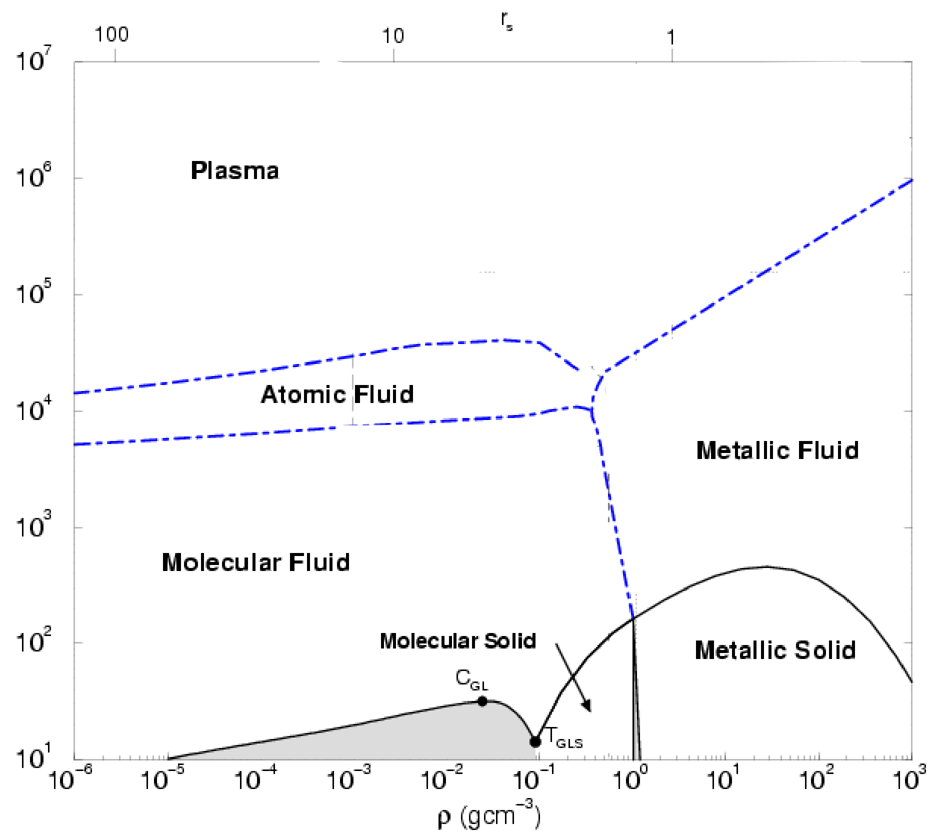
- **Much emphasis currently placed on stationary state variables**
- **Dynamic variables may offer robust probes of the CEP**

Phase Diagram (H_2)

A fundamental understanding requires knowledge of:

i) The location of the Critical End Point (CEP)
ii) The location of phase coexistence lines
iii) The properties of each phase

H_2 phase diagram is rich

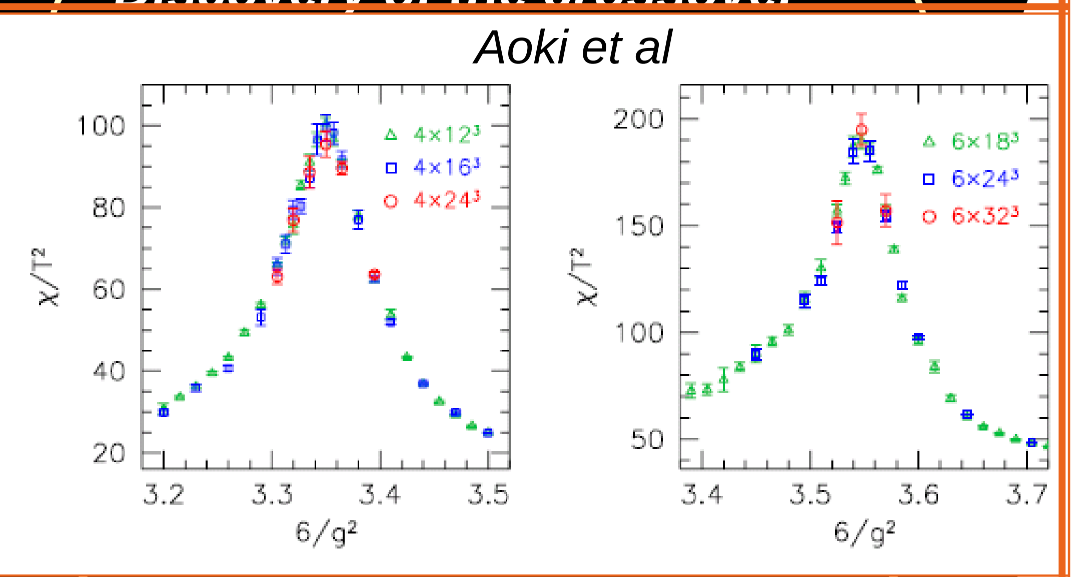


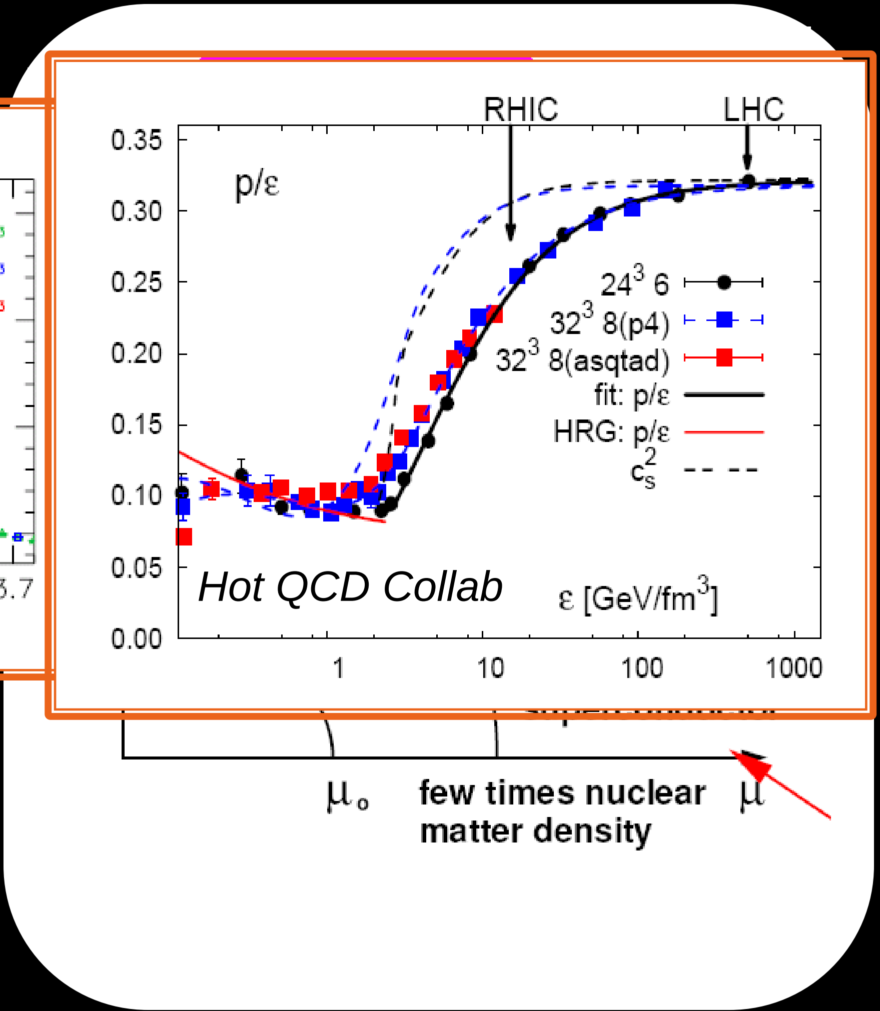
This knowledge is elemental to the phase diagram of any substance !

What Motivates the Search for the Critical end point (CEP)?

M. A. Stephanov, K. Rajagopal and E. V. Shuryak,
Phys. Rev. Lett. **81** (1998) 4816; Phys. Rev. D **60** (1999) 114028

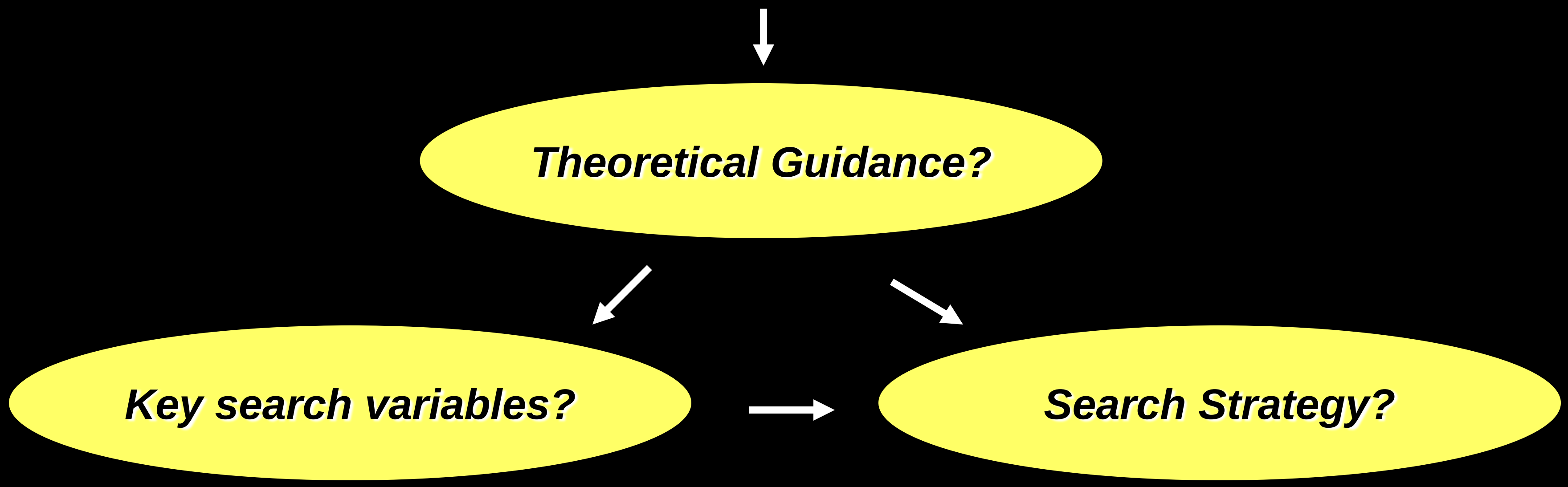
Discovery of the crossover



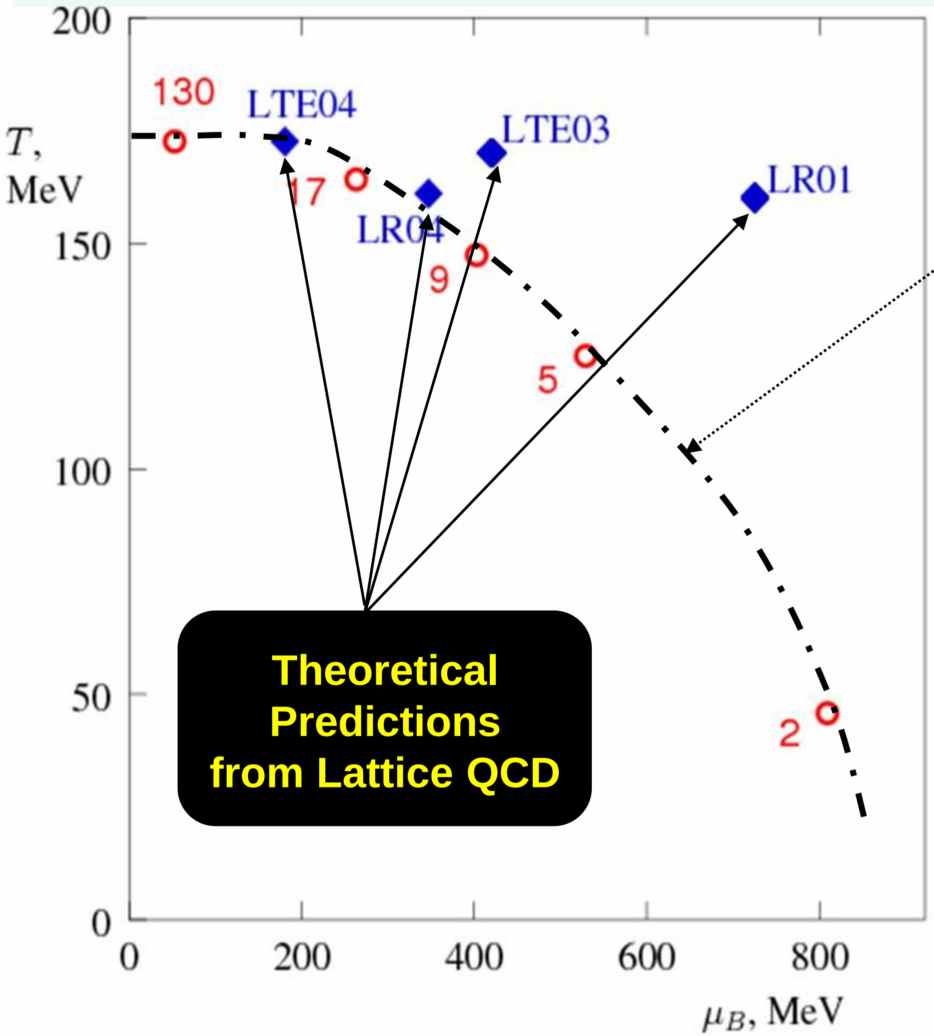


The Crossover is a necessary requirement for existence the CEP

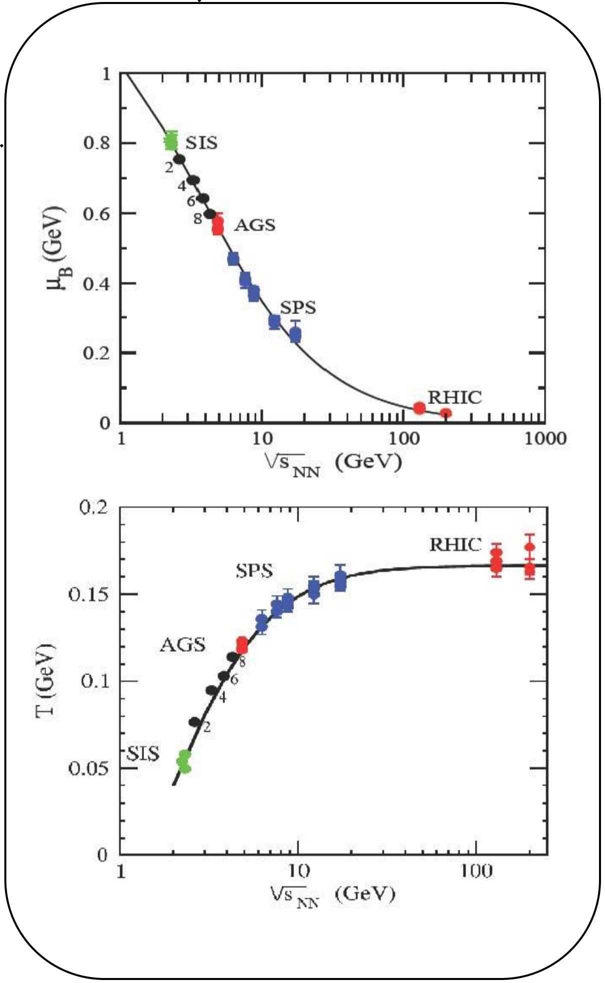
How do we search for the CEP?



Theoretical Guidance for CEP ?



Chemical Freeze-out Curve



Search strategy for the CEP requires experimental investigations over a broad range of μ & T.

Which search variable/s?

Operational Ansatz

- *The physics of the critical point is universal.*
- *Members of a given universality class show "identical" critical properties*

Stationary state variables ↓ ***Dynamic variables***

The CEP belongs to the same dynamic universality class (Model H) as the liquid gas phase transition

Son & Stephanov

Singular behavior of stationary state variables near the CEP

$$\sigma \propto \xi^2$$

Stephanov, Rajagopal,Shuryak, Phys. Rev. D 60, 114028 (1999)

Fluctuations ← σ; ξ → *Correlation length*

Divergence of ξ restricted:

- *Finite system size* $\xi <$ *size*
- *Finite evolution time* $\xi < (\mathit{time})^{1/z}$

$$\tau \sim \xi^z \quad z=3$$

- **Non-monotonic dependence of event-by-event fluctuations as a function of** $\sqrt{s_{NN}}$

Net proton number fluctuation, higher moments, etc.

Singular behavior of Dynamic variables near the CEP

$D \sim \xi^{-1}$

Son & Stephanov,

$\bar{\eta} \sim \xi^{.05-.06}$

Diffusion Constant | *Correlation length* | *viscosity*

Divergence of ξ restricted:

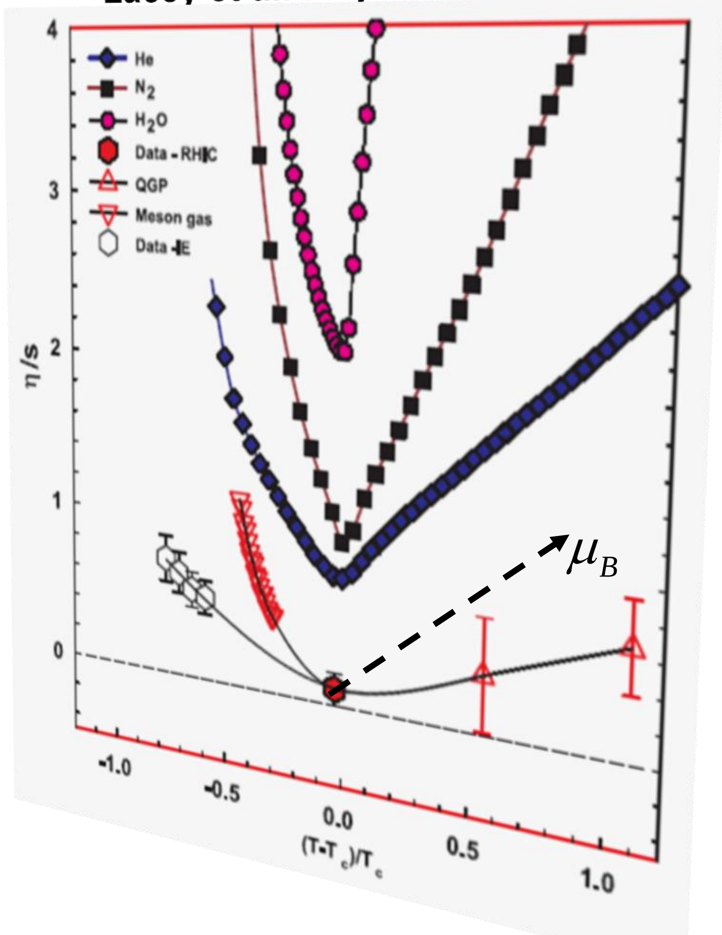
- *Finite system size* $\xi <$ *size*
- *Finite evolution time* $\xi <$ *(time)*$^{1/z}$

$\tau \sim \xi^{z}$ *z=3*

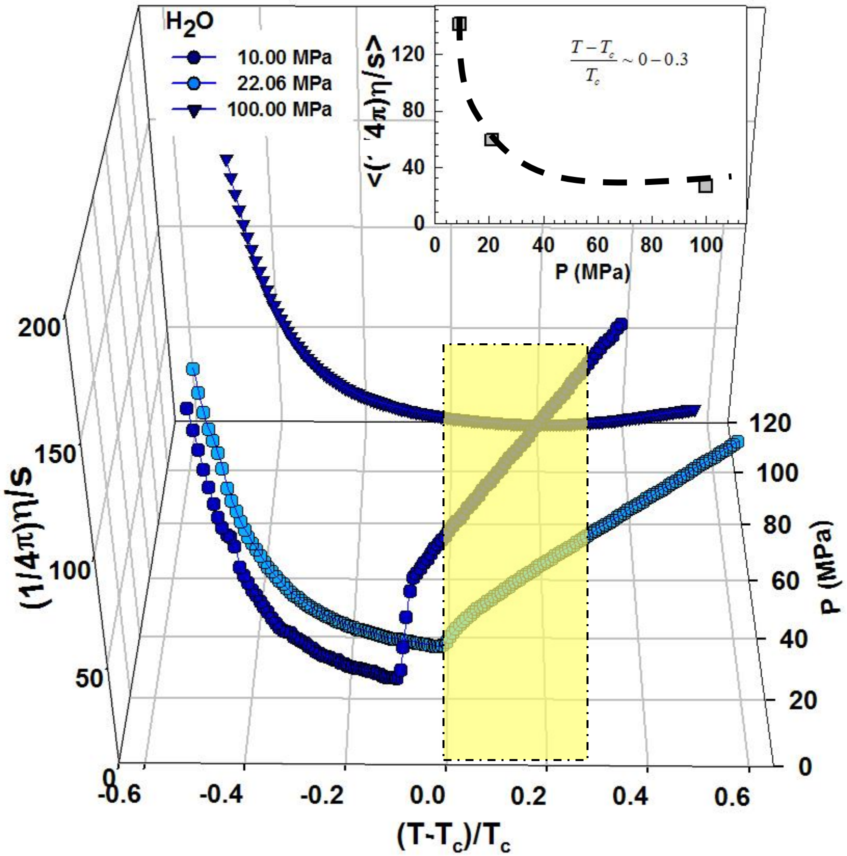
- **D "vanishes" at the CEP**
- **"mild" dependence for viscosity**

The CEP belongs to the Model H dynamic universality class –*Son & Stephanov*

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



Lacey et al.
arXiv:0708.3512 [nucl-ex]



- *η/s could be a potent signal for the CEP*
- **Evolution in the degrees of freedom (dof)**

How to access η/s and dof?

Higher order flow harmonics provide new constraints for:

- *partonic flow*
- *initial eccentricity model*
- *sound speed c_s*
- *δf*
- *etc*

Crucial for reliable η/s extraction

Flow is acoustic!

The Flow Probe

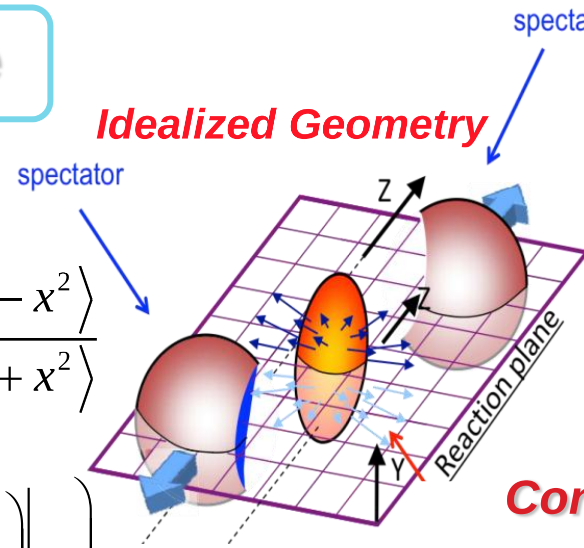
$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

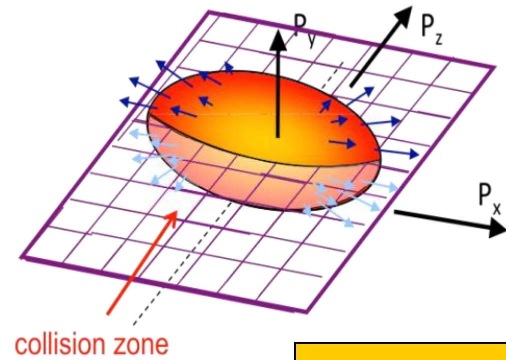
$$\sim 5-15\ \frac{GeV}{fm^3}$$

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

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

Idealized Geometry

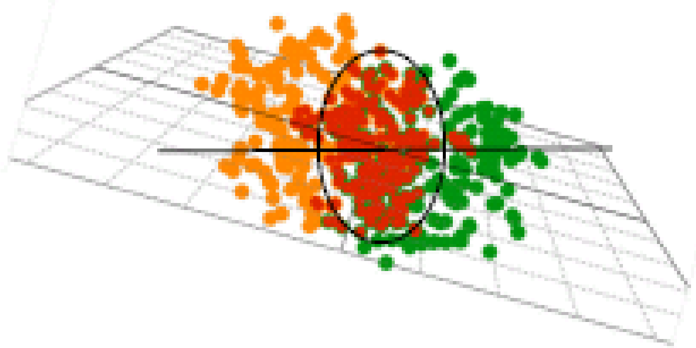




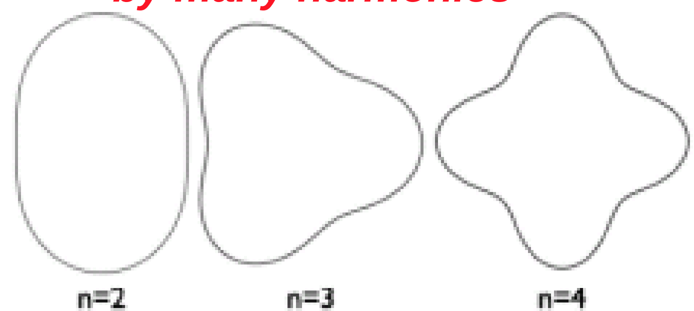
Control parameters

$$\varepsilon,\ c_s,\ \frac{\eta}{s},\ \mathrm{T}$$

Actual collision profiles are not smooth, due to fluctuations!



Initial Geometry characterized by many harmonics



$$\varepsilon_n = \frac{\langle r^n \cos(n\varphi_{part}) \rangle^2 + \langle r^n \sin(n\varphi_{part}) \rangle^2}{\langle r^n \rangle^2}$$

Initial eccentricity (and its attendant fluctuations) ε_n drive momentum anisotropy v_n

Quantifying Flow

Two complimentary analysis methods employed:

Correlate hadrons in central Arms with event plane (RXN, etc)

$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right) \quad \textbf{(I)}$$

$$v_n\{\psi_n\} = \left\langle \cos\left[n\left(\varphi - \psi_n\right)\right]\right\rangle, \quad n = 1, 2, 3..,$$

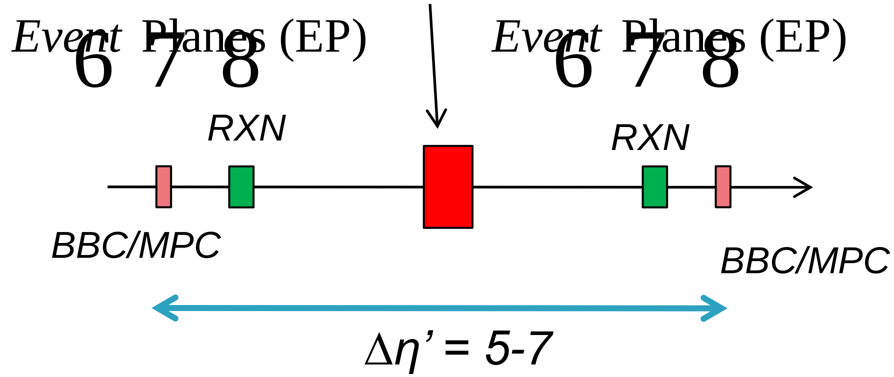
- **Δφ correlation function for EP_N - EP_S**

$$\frac{dN^{\text{pairs}}}{d(\Delta\varphi)} \propto \left(1 + \sum_{n=1} 2 v_n^a v_n^b \cos(n\Delta\varphi)\right) \quad \textbf{(II)}$$

- **Δφ correlation function for EP - CA**

Schematic Detector Layout

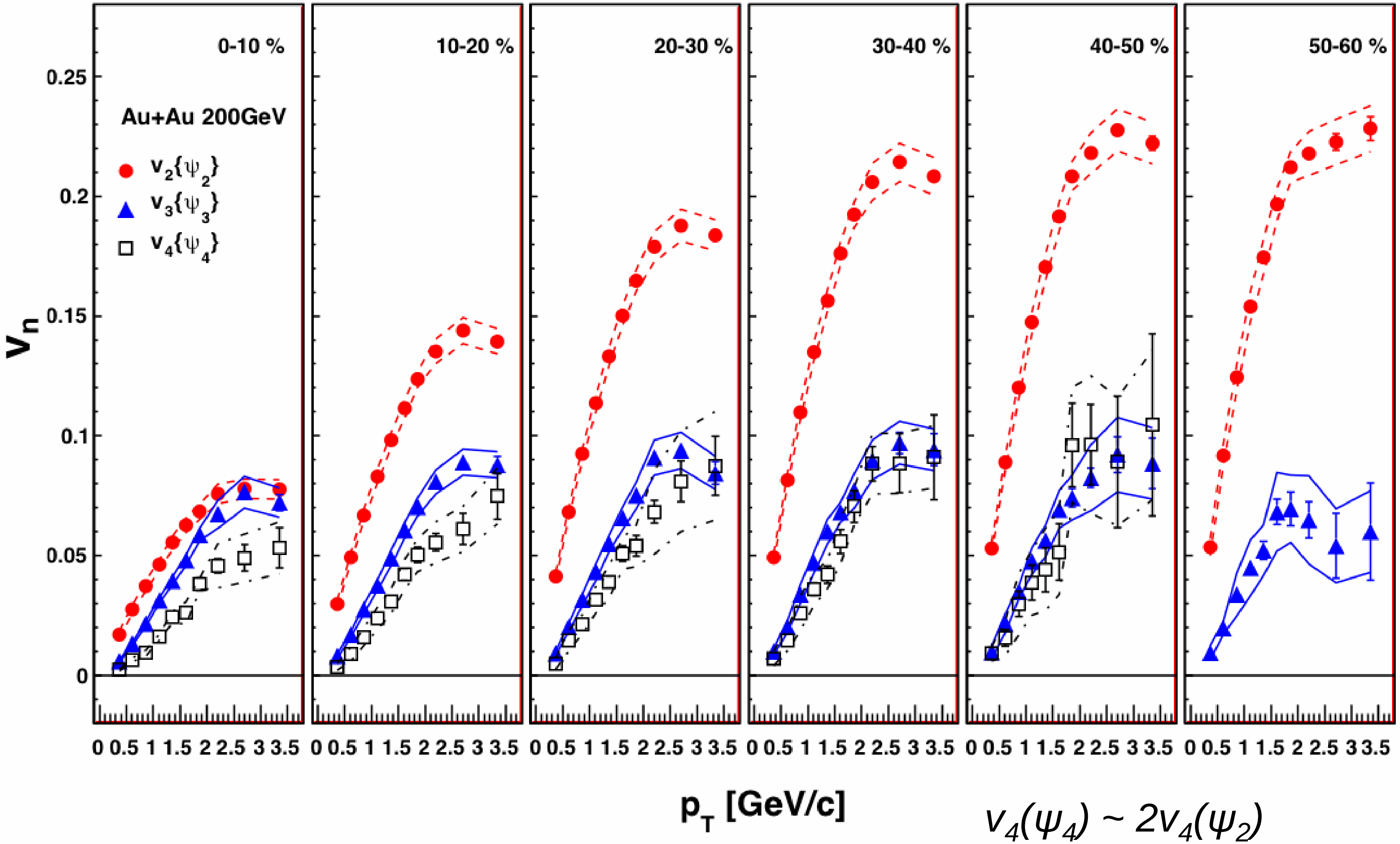
PHENIX Central Arms (CA) $|\eta'| < 0.35$ (particle detection)



ψ_n RXN $(|\eta|=1.0\sim2.8)$
MPC $(|\eta|=3.1\sim3.7)$
BBC $(|\eta|=3.1\sim3.9)$

Results: $v_n(\psi_n)$

http://arxiv.org/abs/1105.3928

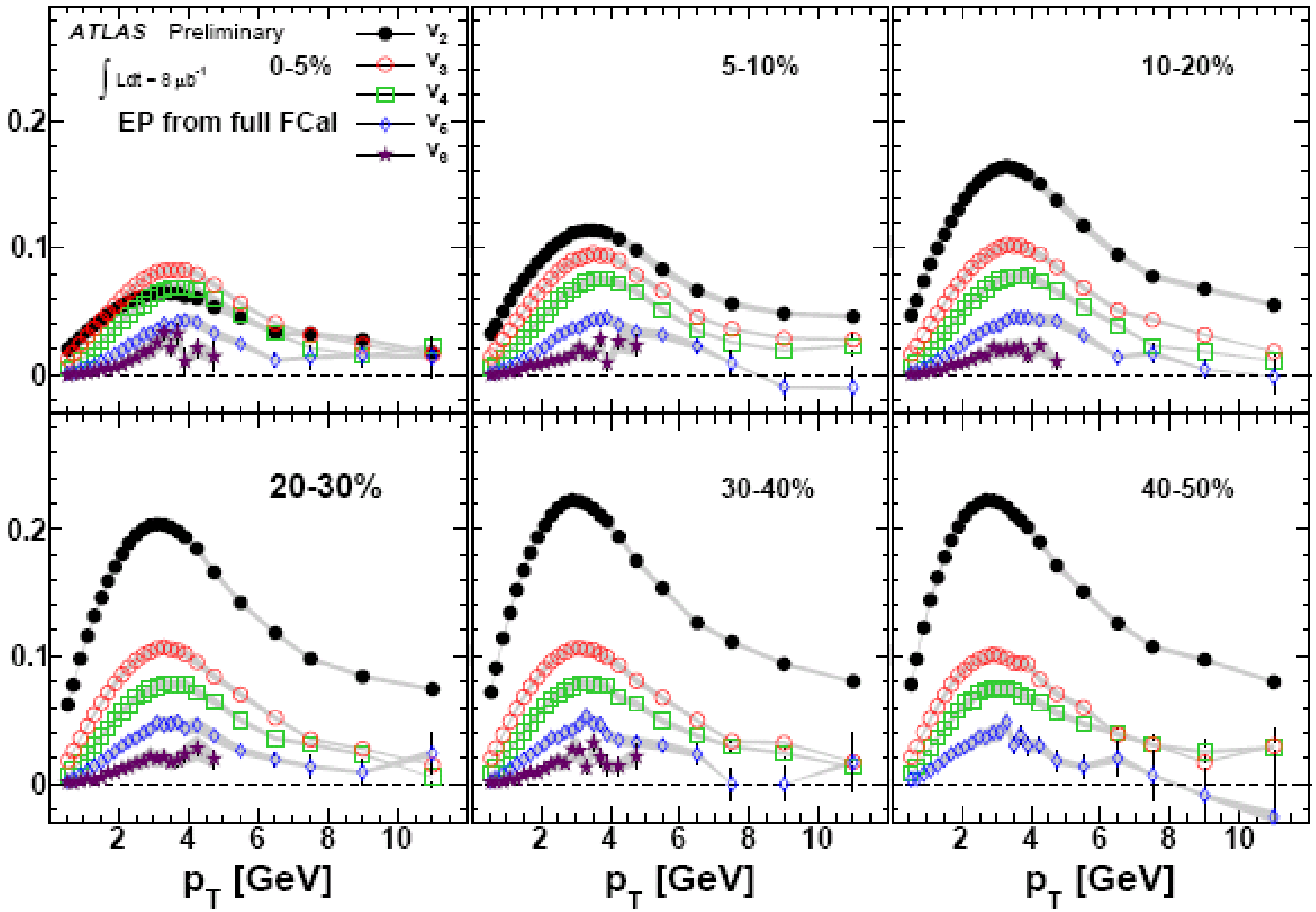


$v_4(\psi_4) \sim 2v_4(\psi_2)$

Robust PHENIX measurements performed at 200 GeV
(Crosschecked with correlation method)

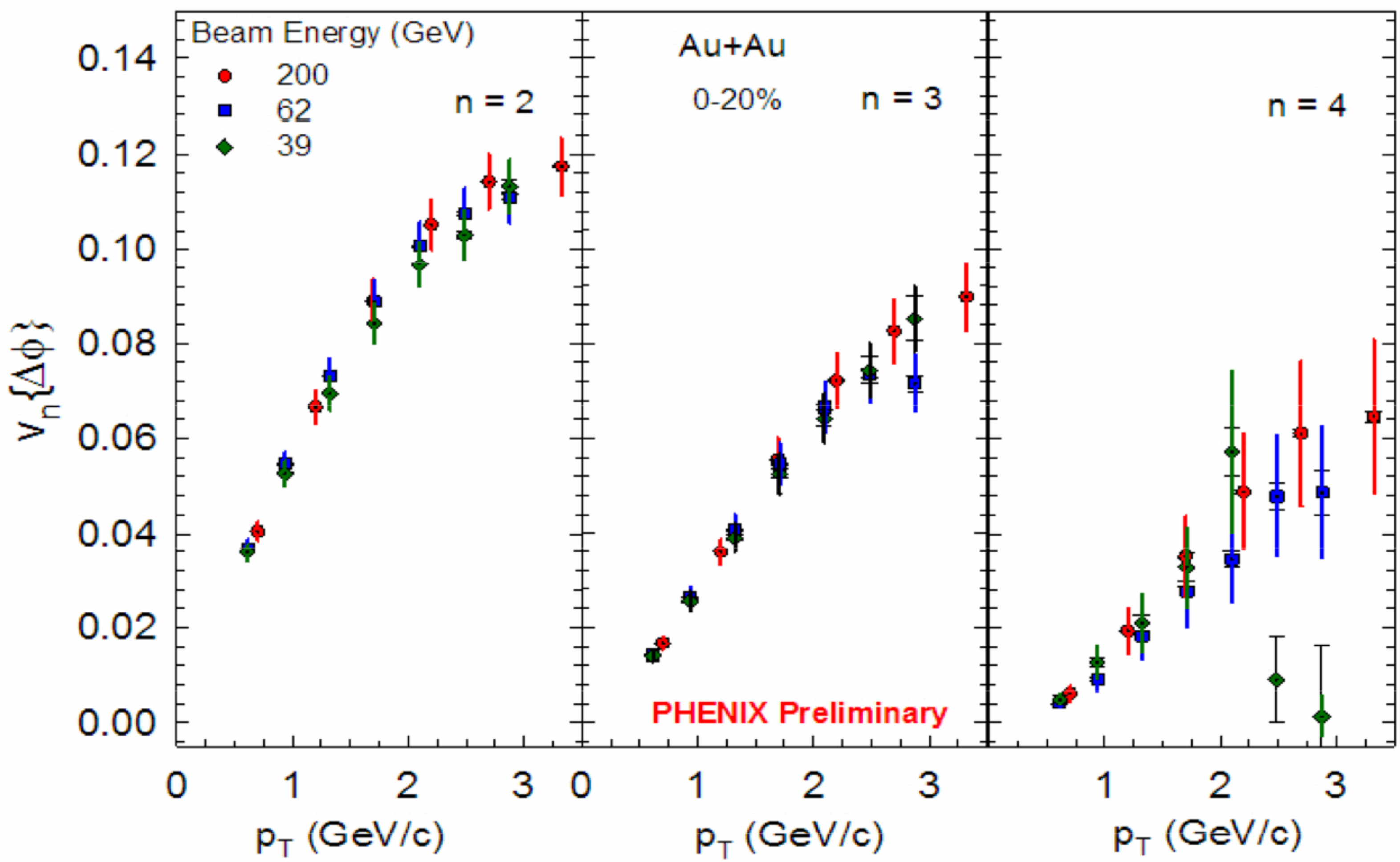
Results: $v_n(\psi_n)$

ATLAS-CONF-2011-074



Robust ATLAS measurements performed at 2.75 TeV
(Crosschecked with several methods)

Results: $v_n(\Delta\varphi)$



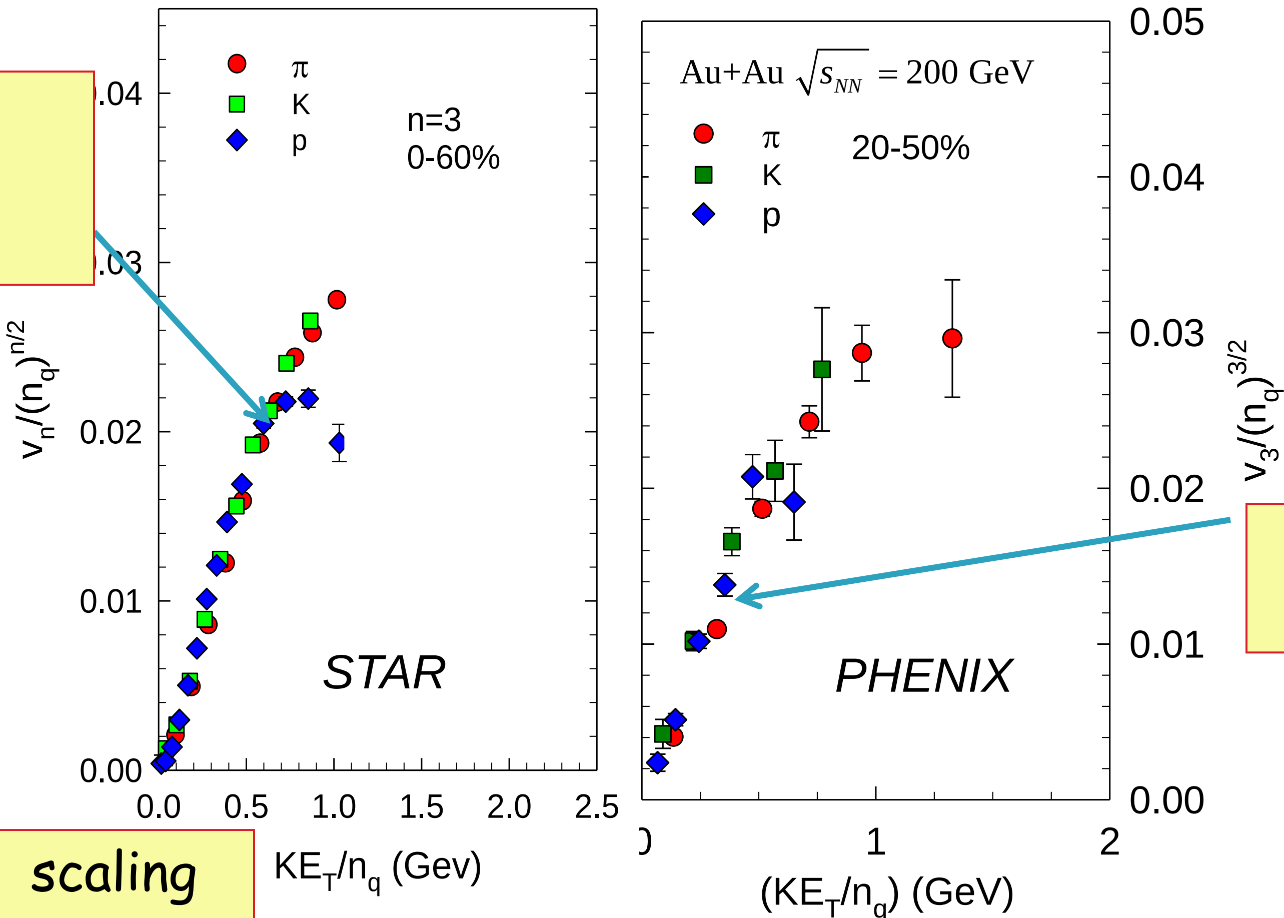
$v_{2,3,4}$ saturates for the range $\sqrt{s_{NN}}$ 39 - 200 GeV

➢ ***Extract η/s and dof as a function of beam energy***

Flow is partonic

v_3 PID scaling

Flow is pressure driven



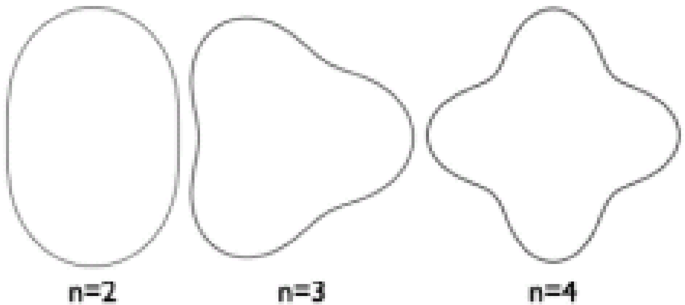
Flow is partonic

KE_T & scaling validated for v_3
→ Partonic flow

Consistent partonic flow picture for v_n

Flow is acoustic

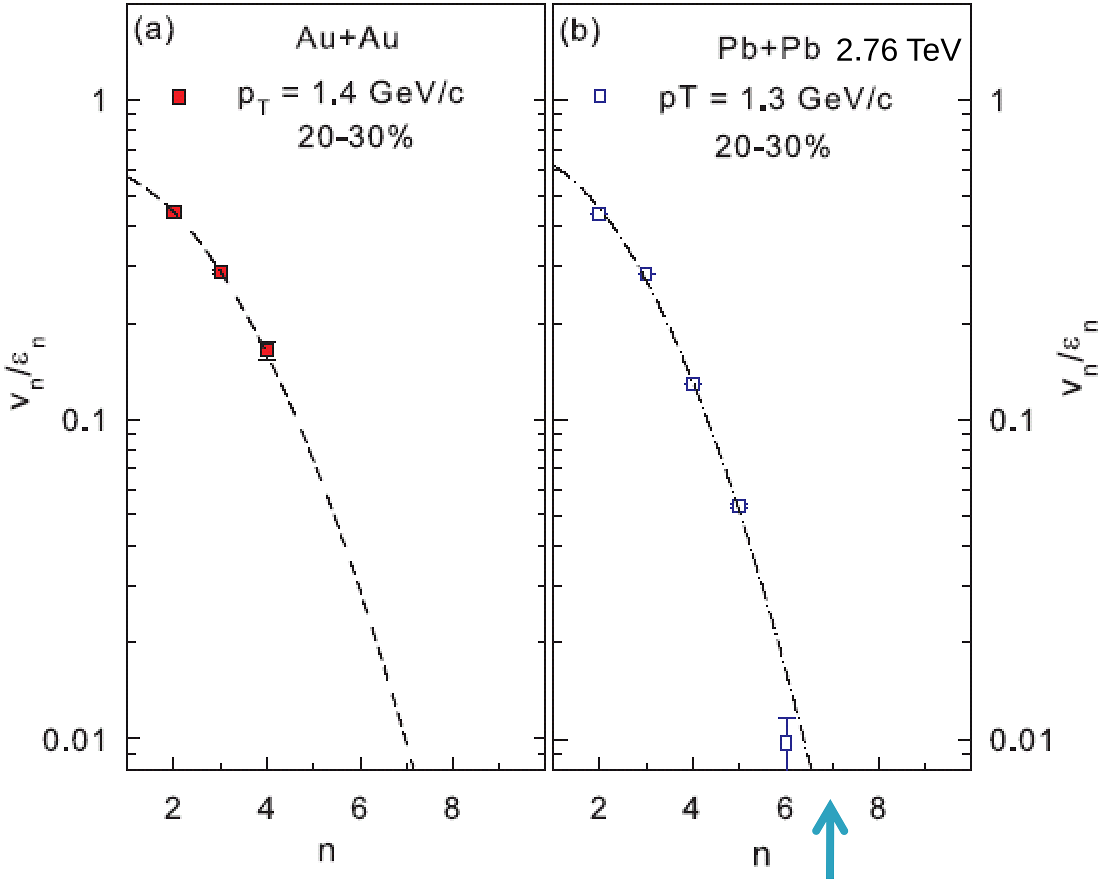
The viscous horizon (r_v) is the length-scale which characterizes the highest harmonic that survives viscous damping



$$2\pi\bar{R} = n\lambda_g$$

Deformation $$k = \frac{n}{\bar{R}}$$

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



Characteristic viscous damping
For higher harmonics

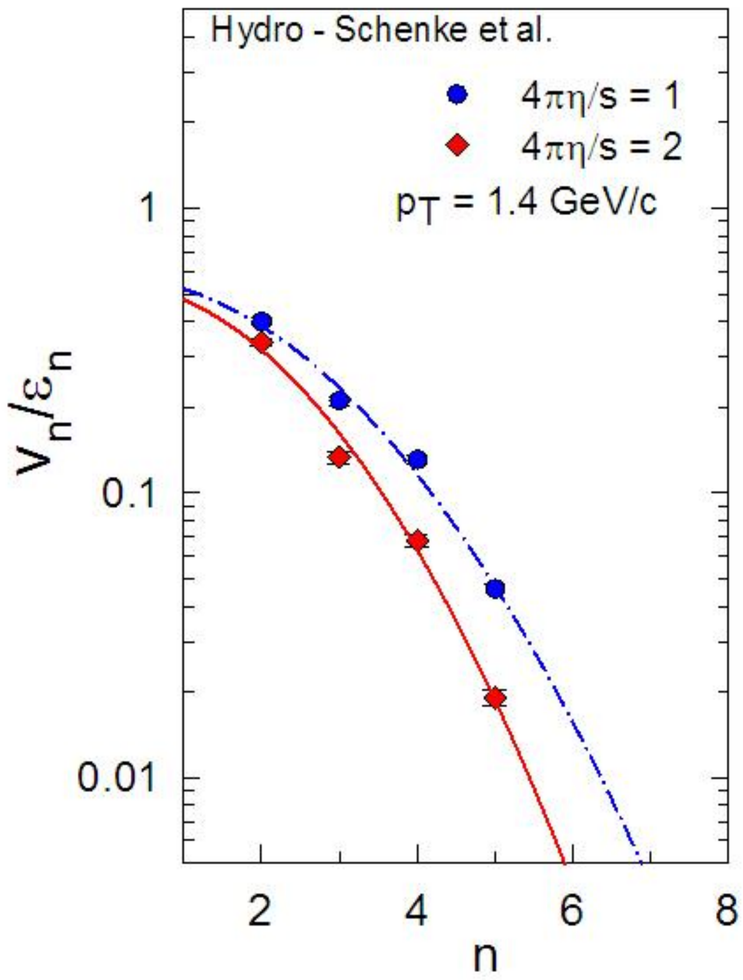
arxiv:1105.3782

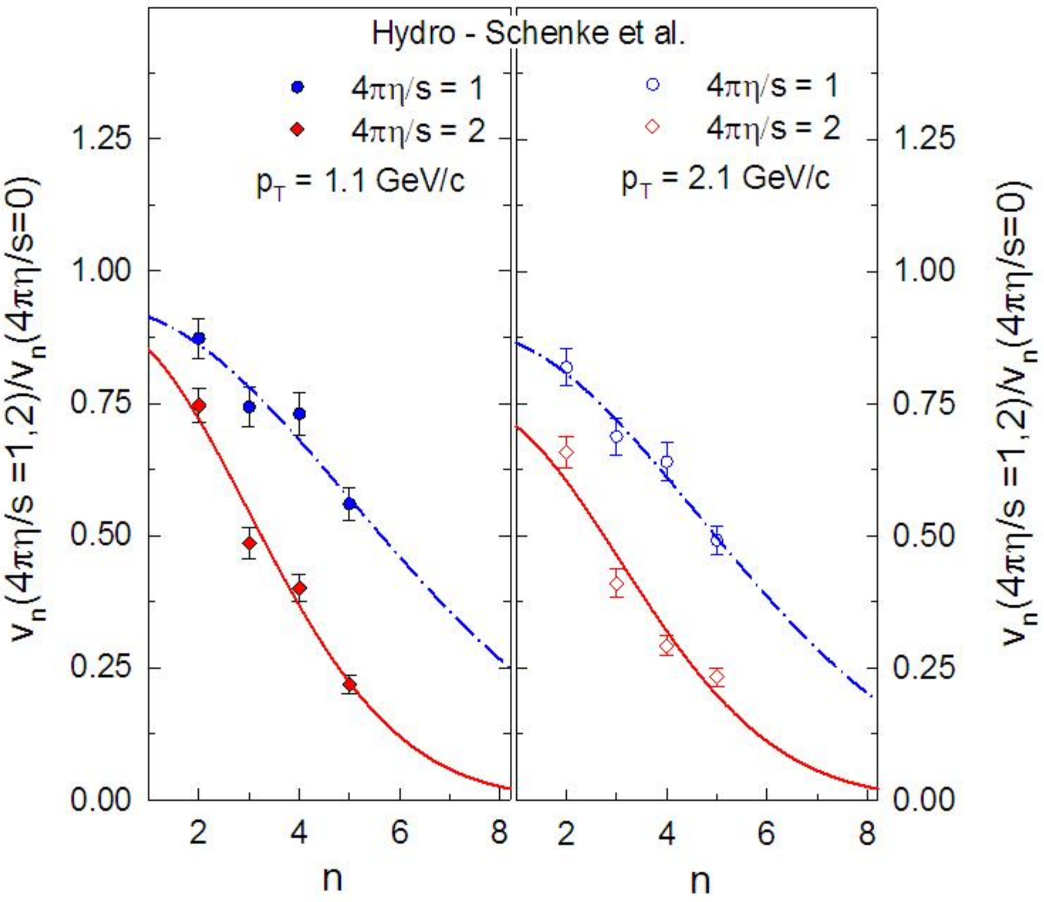
$$r_v = \frac{2\pi\bar{R}}{n_v} \sim 1.8\, fm$$

Viscous horizon

Flow is acoustic

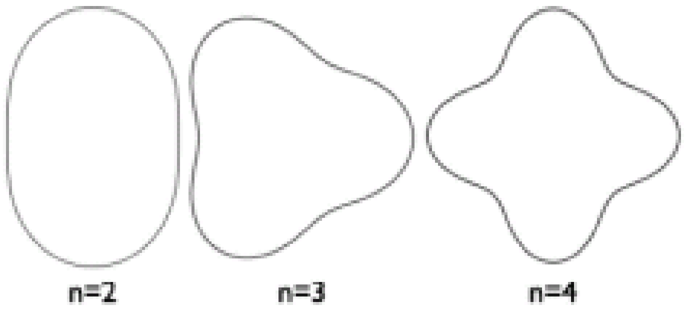
$$\delta T_{\mu\nu}(t,k) = \exp(-\beta n^2)\,\delta T_{\mu\nu}(0)$$





Acoustic patterns validated in (3+1)D viscous relativistic Hydrodynamics calculations

Flow is acoustic



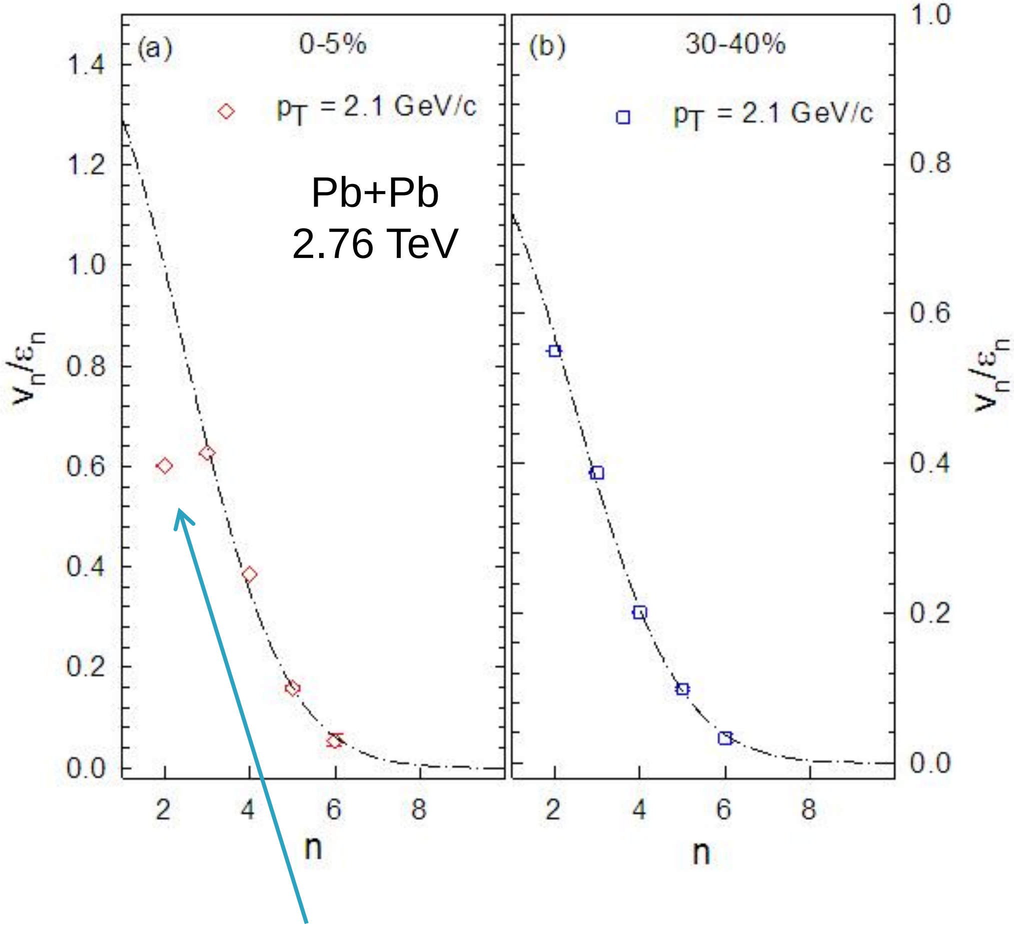
Deformation $k = \frac{n}{\bar{R}}$

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

$$r_s = \int_{\tau_0}^{\tau_f} d\tau c_s(\tau)$$

$$\frac{2\pi R_f}{n} > 2r_s$$

$\rightarrow$ suppression



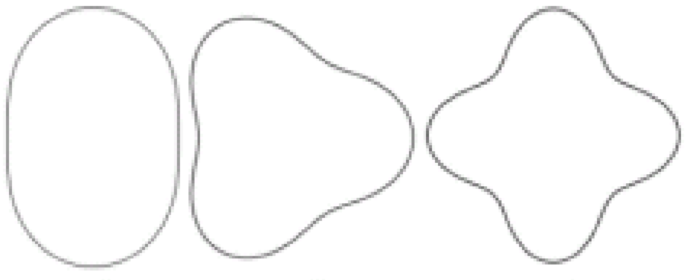
Low frequency

Super-horizon modes are suppressed

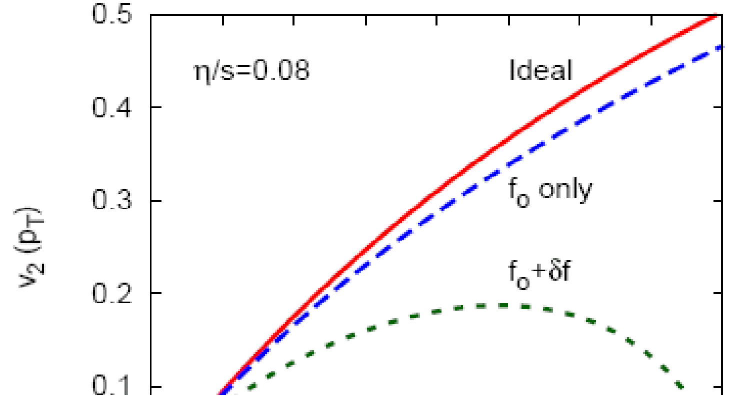
$$R_f = \bar{R} + r_s$$

$\rightarrow$ constraint for c_s

Constraint for δf



Deformation $k = \frac{n}{\bar{R}}$

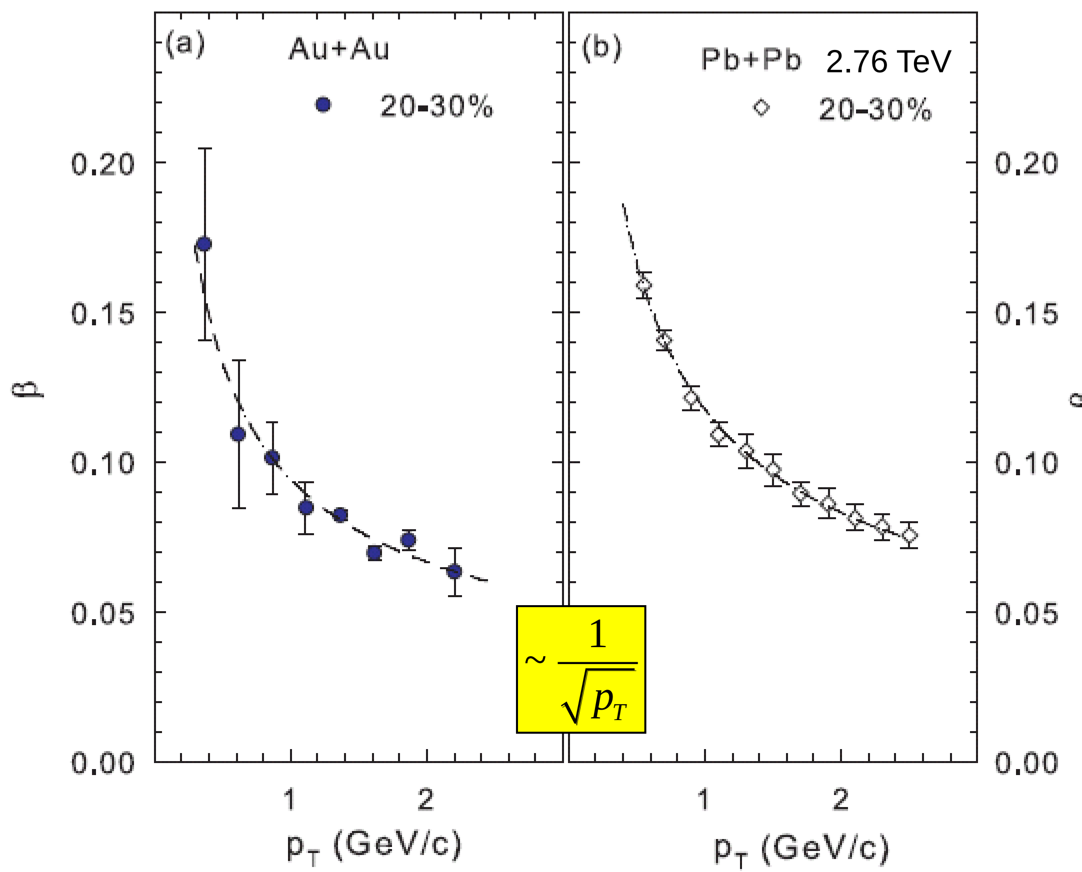


$$\delta T_{\mu\nu}(t,k) = \exp\left(-\beta n^2\right)\delta T_{\mu\nu}(0)$$

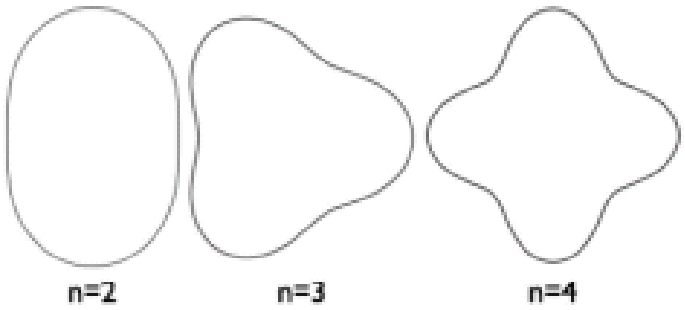
Particle Dist. $f = f_0 + \delta f(p_T)$

$$\delta f(p_T) \sim \frac{p_T^{2-\alpha}}{T_f}$$

Constraint for the Relaxation time



Constraint for δf



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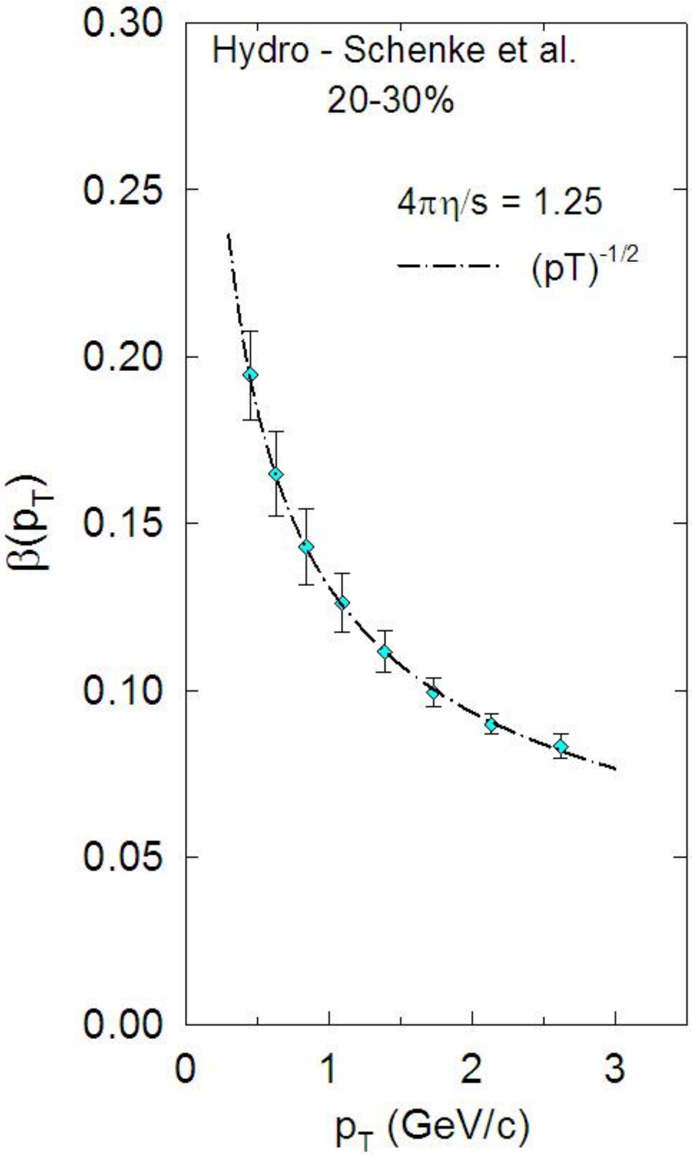
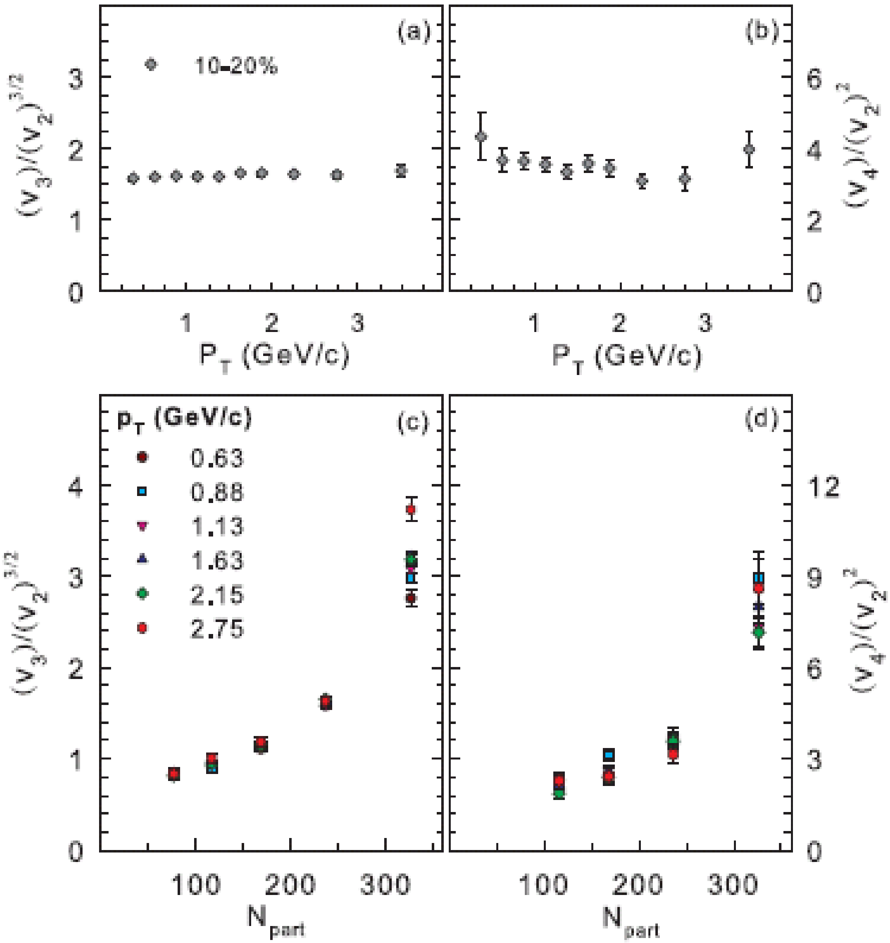
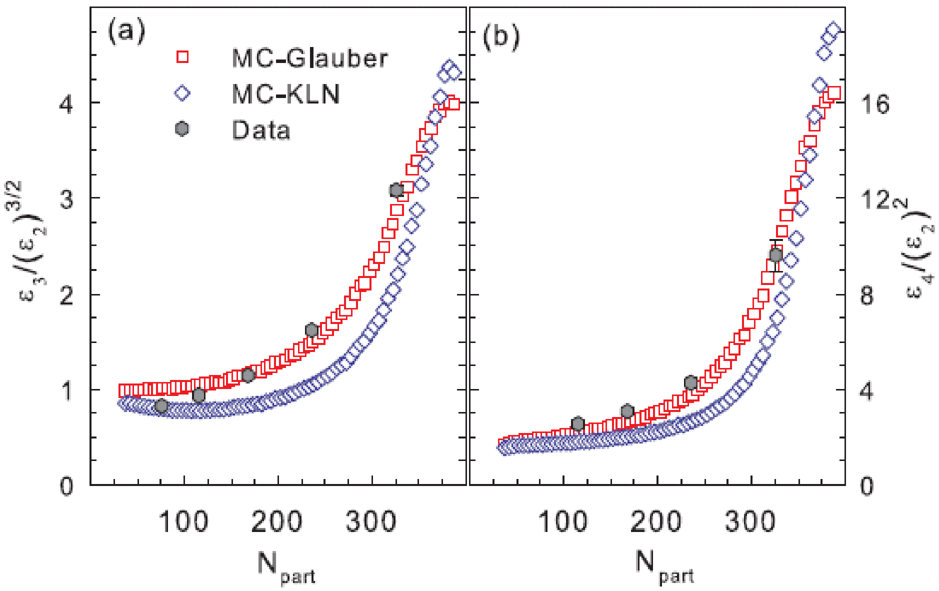


Constraint for ε_n



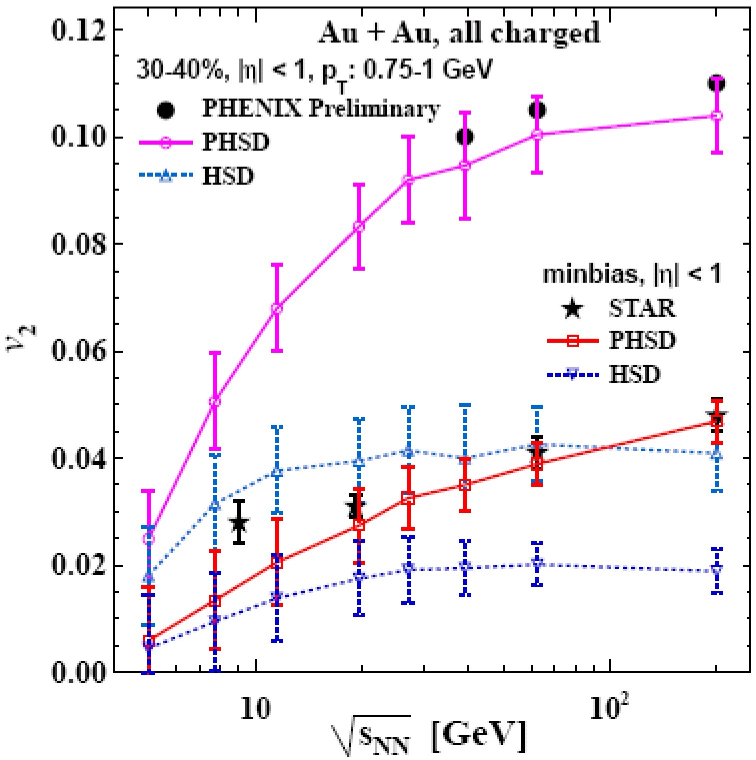
Note that data take account of the acoustic suppression



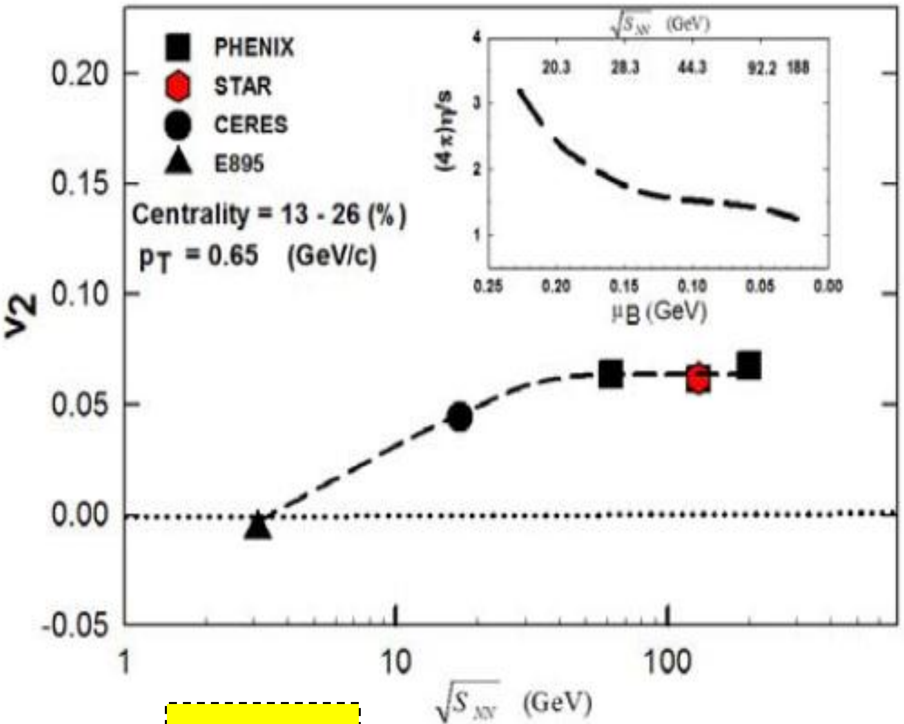
pT dependent viscous effects cancel !
Same scaling observed at the LHC

CEP Search

Konchakovski, arxiv:1109.3039



Lacey et al. arXiv:0708.3512 [nucl-ex]



Map v_n vs. beam energy to obtain η/s vs. T

$$\frac{\mu_B^c}{T^c} : 1$$

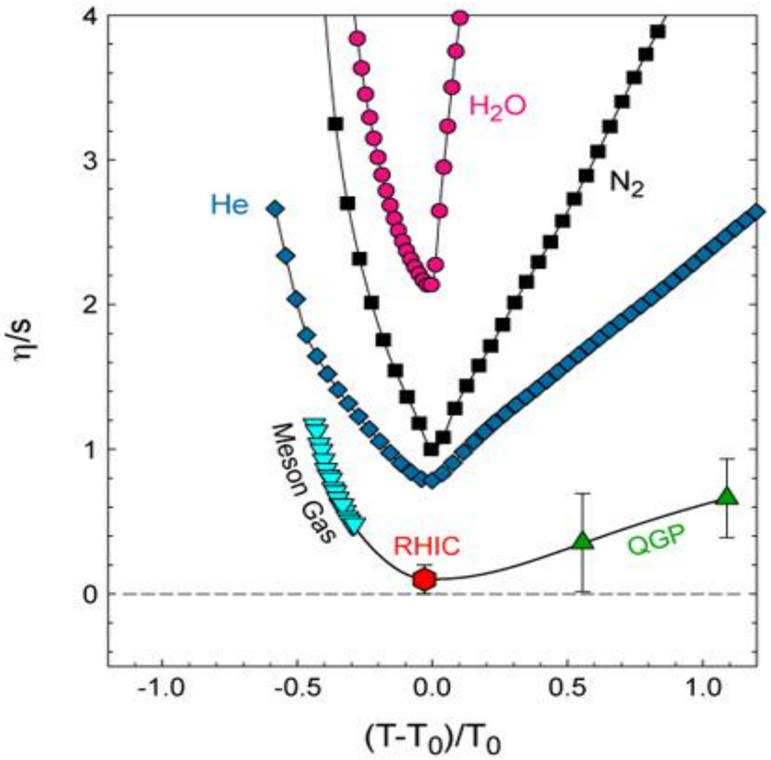
Value similar to that for recent lattice comparisons which claim an onset of deconfinement

CEP Search

Currently Mapping η/s vs. T for higher order harmonics

➢ *much more sensitive*

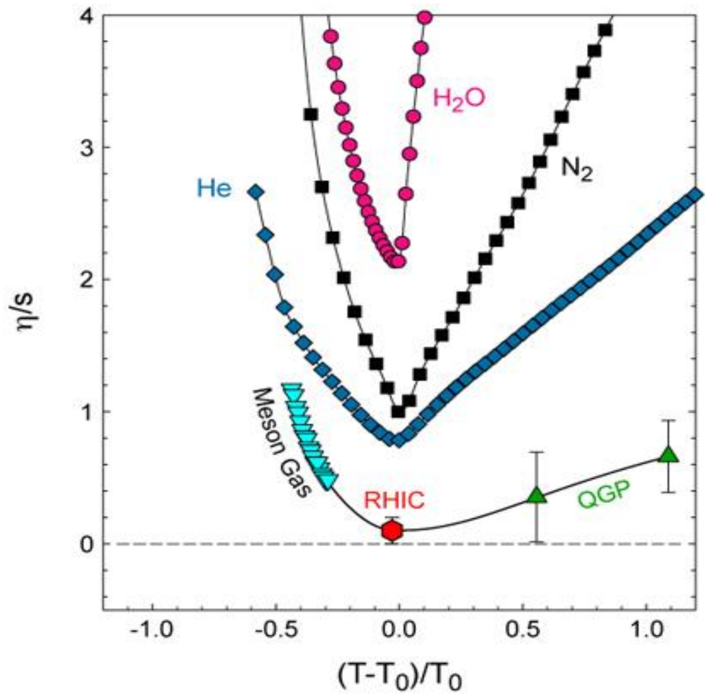
-- Work in progress --



Summary

✓*Acoustic property for higher-order flow harmonics (odd & even) validated!*

✓ *Provides important additional constraints for initial state model and several properties of the QGP*



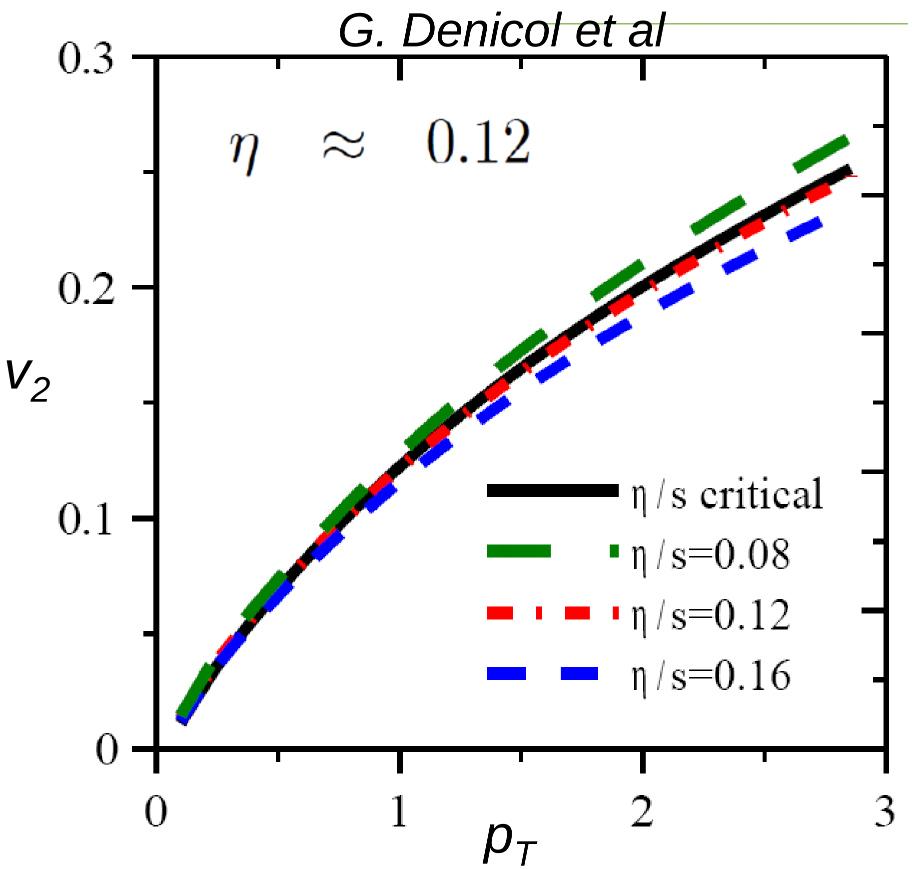
$$
\left.\begin{array}{l}
4\pi\frac{\eta}{s}:\ 1 \\
\lambda \sim 0.3\ \mathrm{fm} \\
\mathrm{r_v}\ :\ 1.8\ \mathrm{fm} \\
\mathrm{T}_f \sim 165 \pm 11\ \mathrm{MeV} \\
\delta f(p_T) \sim p_T^2
\end{array}\right\} \sqrt{s} = 200\ GeV
$$

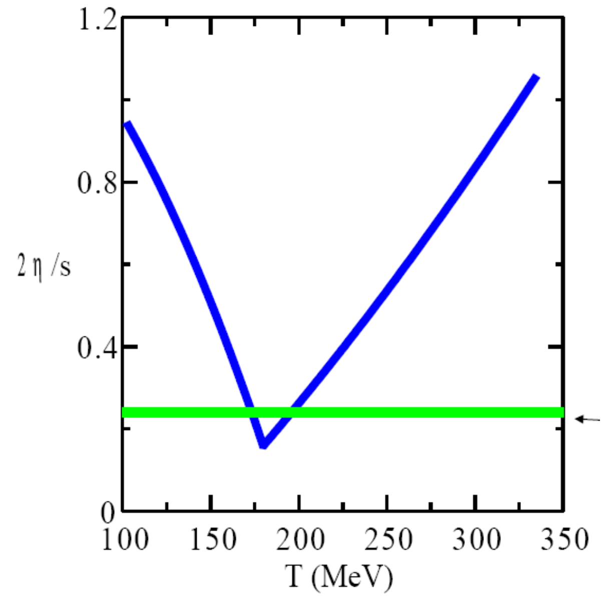
Higher-order harmonics (odd & even) currently being used to evaluate η/s vs. T [and other properties of the hot and dense matter created in RHIC & LHC collisions] to search for the CEP.

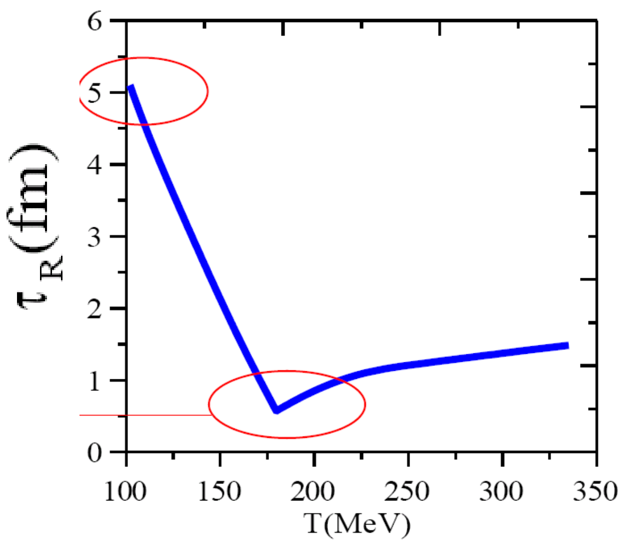
End

Temperature dependence of η/s

G. Denicol et al



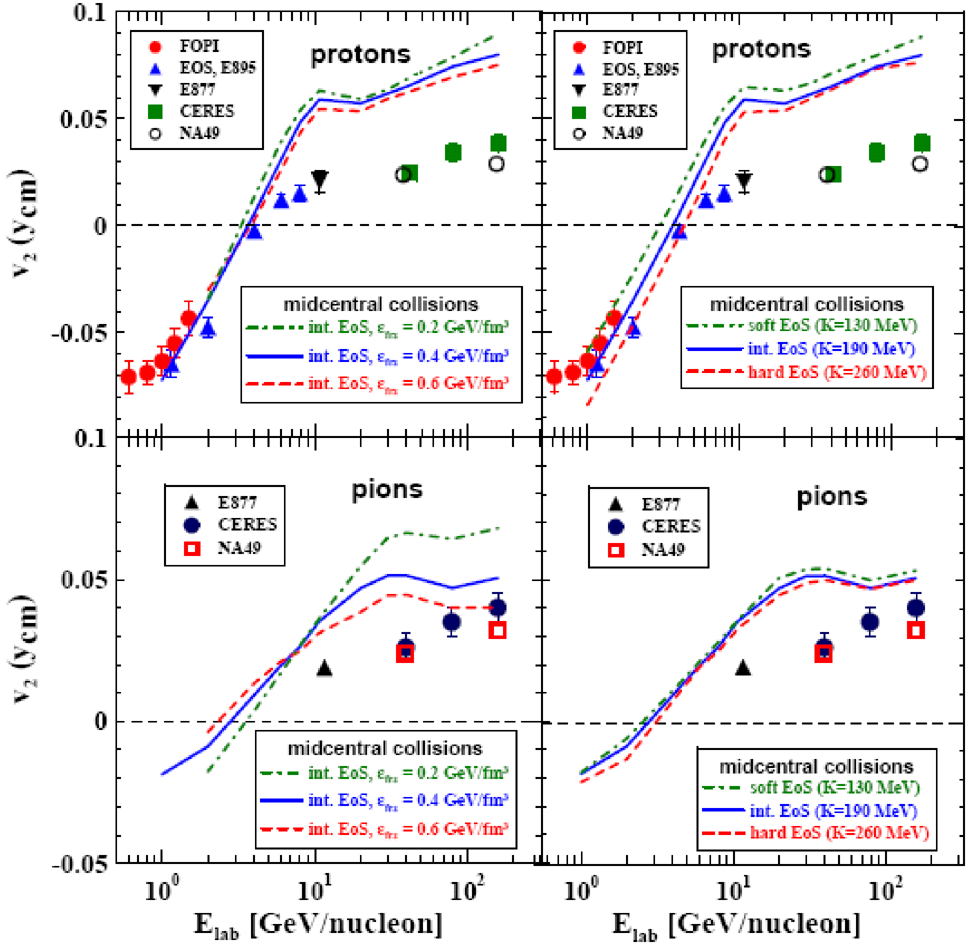




Relaxation time limits η/s to small values

Viscosity estimates at AGS - SPS

Ivanov et al



Significant deviations From hydrodynamic calculations

From fits

$$4\pi\frac{\eta}{s} \sim 12-25$$