The Role of Energy Scans at RHIC

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Outline

III. Why an energy scan ?
- ✓ Is there an overarching reasons for it ?

IV. Status of studies of the low μ_B high T region of the phase diagram

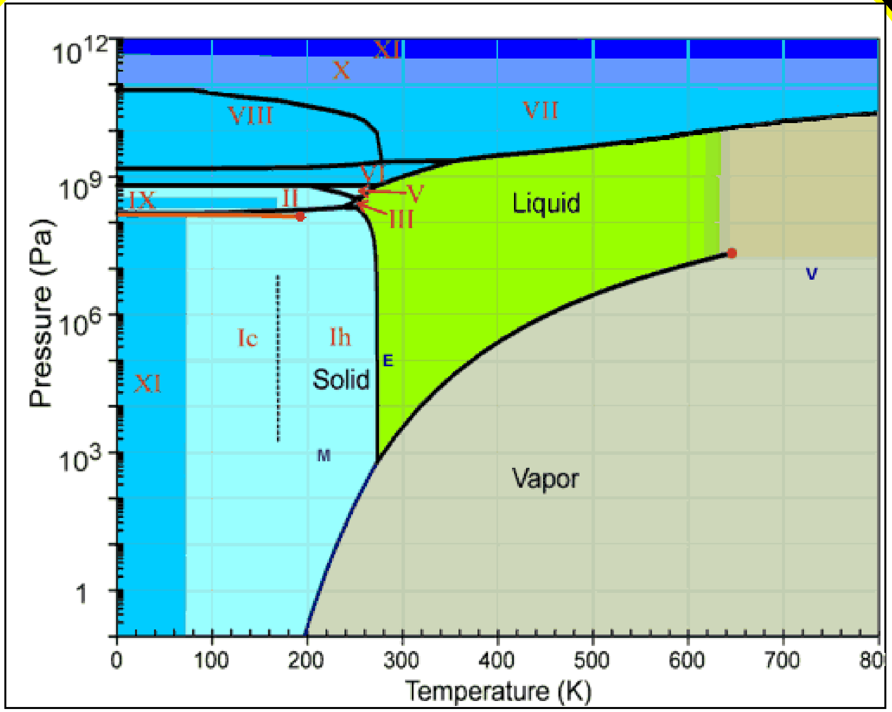
VI. What new insights will an energy scan afford?
- ✓ Lingering Questions
  - ➢ Onset of opacity for light and heavy quarks
  - ➢ Onset of quark number scaling
    - ❖ Requirements

VII. Opportunities for Discovery & New Constraints
  - ➢ Search for the critical point
  - ➢ Studies of the first order phase transition
  - ➢ New constraints for the hadronic EOS
    - ❖ Requirements

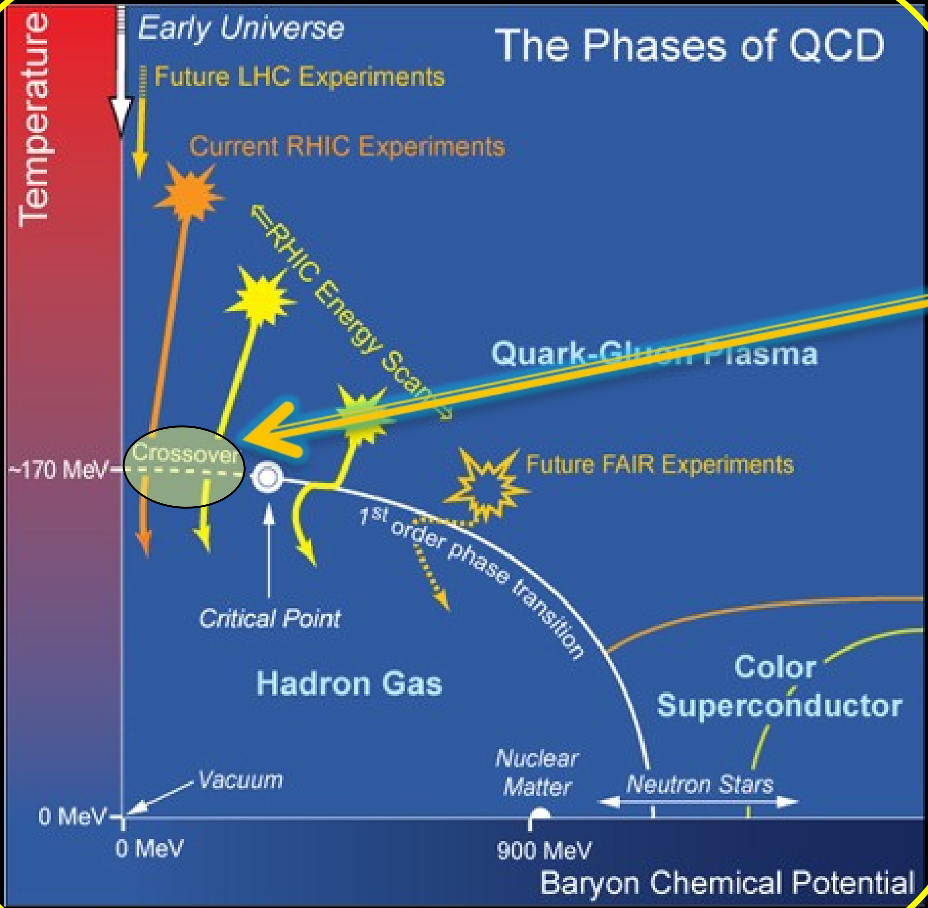
VIII. Summary

Phase Diagram for H_2O

The location of the critical End point and the phase coexistence lines are fundamental to the phase diagram of any substance !



Conjectured Phase Diagram for QCD?



Consensus (I)

Continuous/rapid Crossover Transition

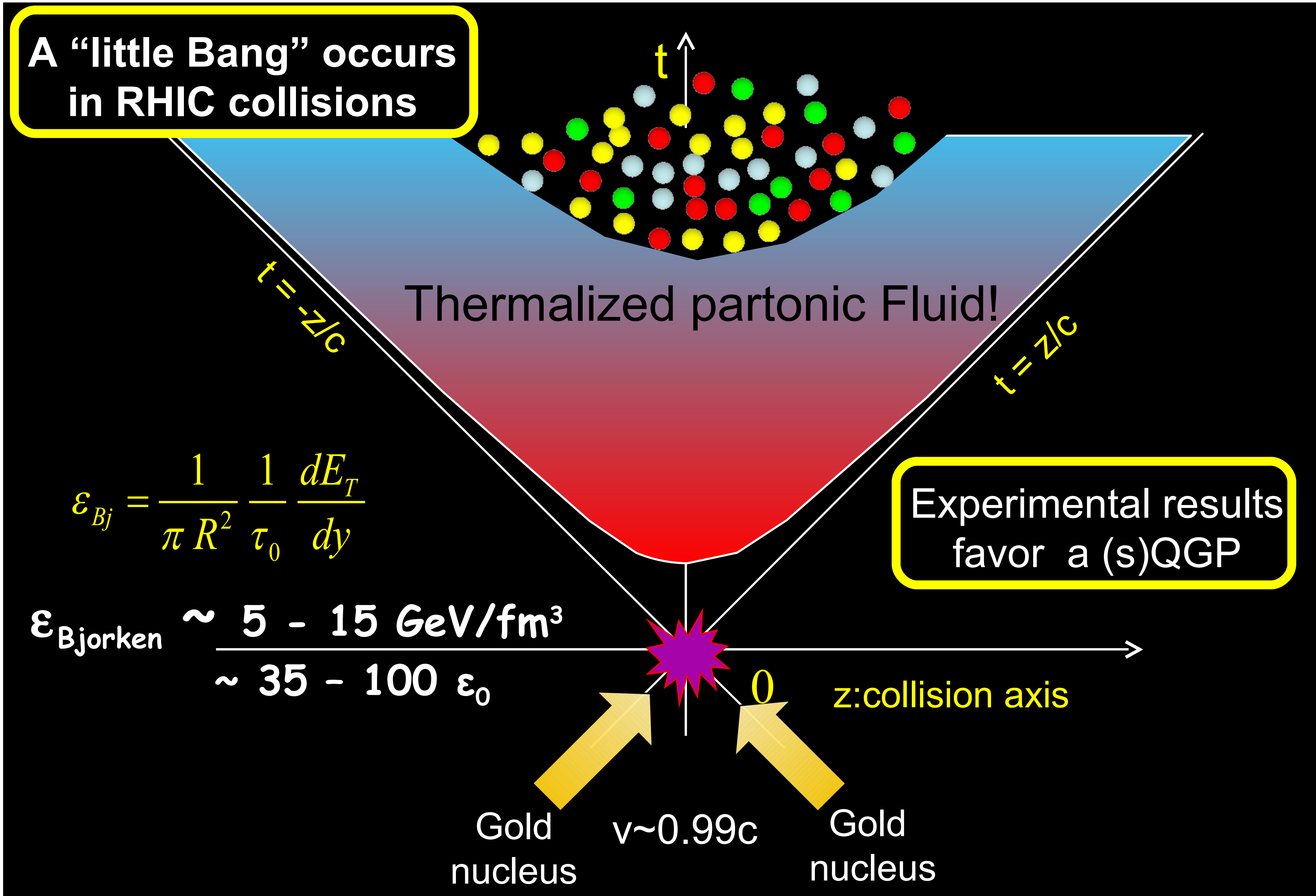
Consensus (II)

Our understanding of the QCD Phase diagram, as well as the properties of the different phases is still limited

Energy scans at RHIC provide access to a broad range of the μ -T plane!

Learn the past, charge the present and create the future!

A quick summary of the present !



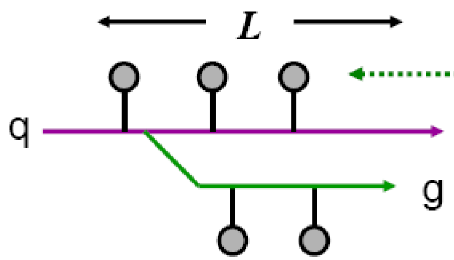
Challenge: → Develop Constraints for the Properties of the sQGP ?

Which observable/s provide important constraints?

- Jet Quenching
  - ✓ Scattering power
- Flow
  - ✓ sound speed
  - ✓ shear viscosity
- Medium Response
  - ✓ sound speed,
  - ✓ shear viscosity
  - ✓

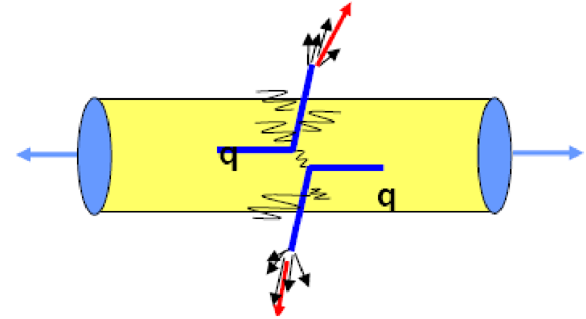
Jet Quenching

High Energy partons lose energy by re-scattering in the hot and dense medium



Radiative:

$$\frac{dE}{dx} \sim \sigma\rho L \left\langle k_T^2 \right\rangle$$



Color charge scattering centers

Range of Color Force

$$\hat{q} \sim \rho\sigma \left\langle k_T^2 \right\rangle$$

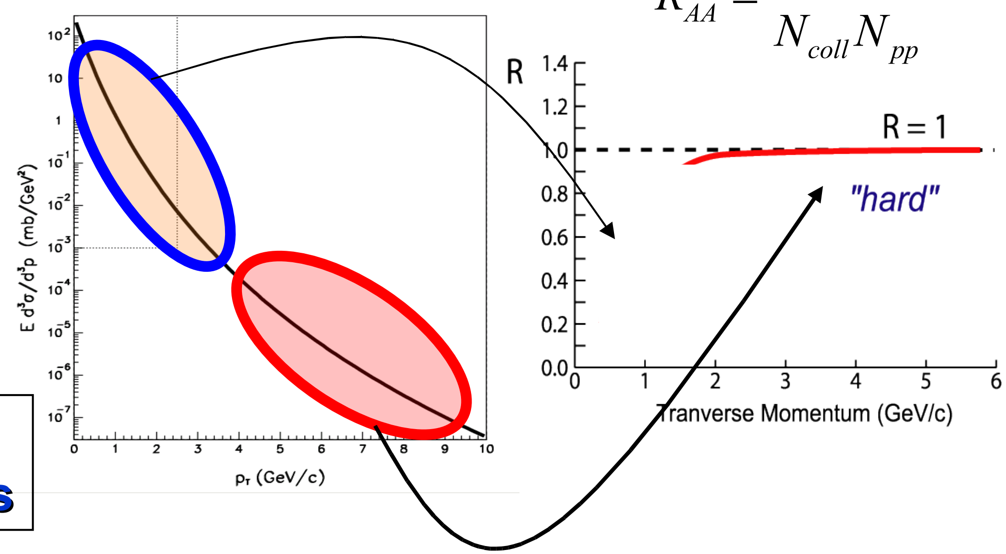
Can access
ρ and $\hat{q}$

Scattering Power Of Medium

Density of Scattering centers

Nuclear Modification Factor

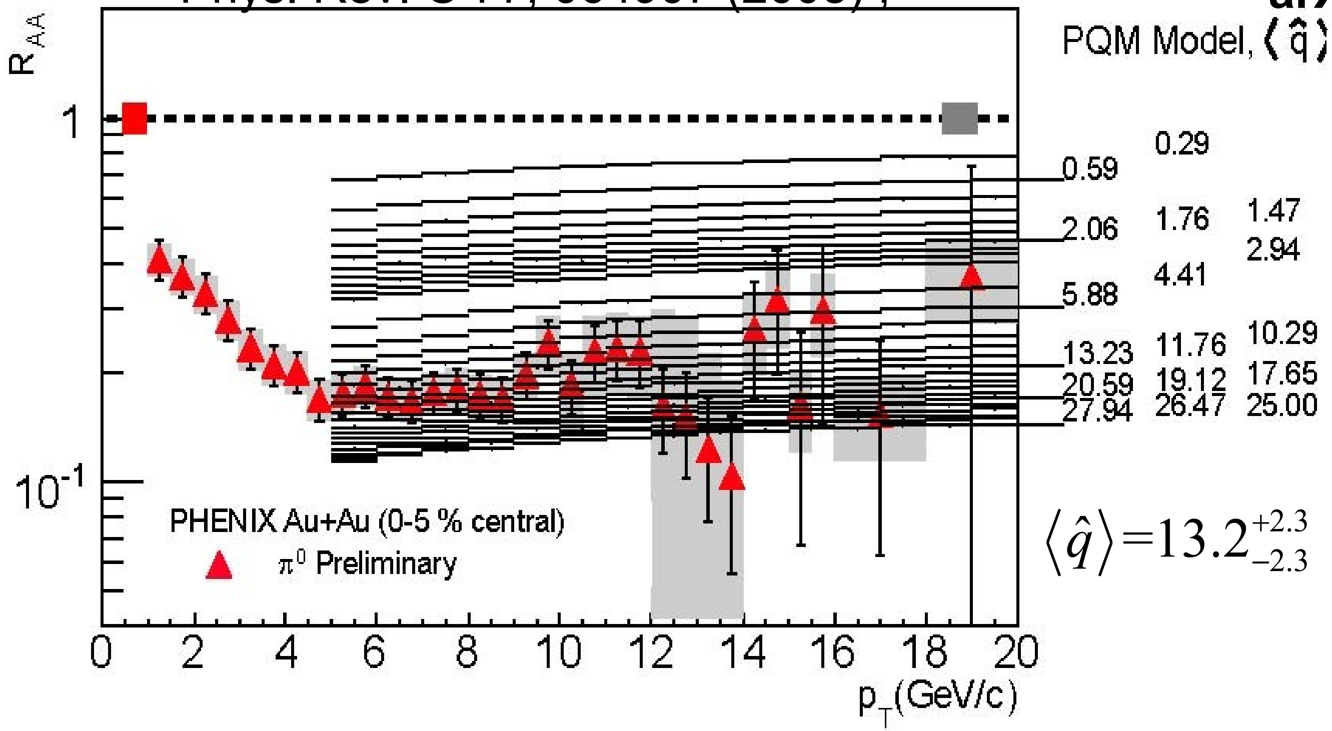
$$R_{AA} = \frac{N_{AA}}{N_{coll} N_{pp}}$$



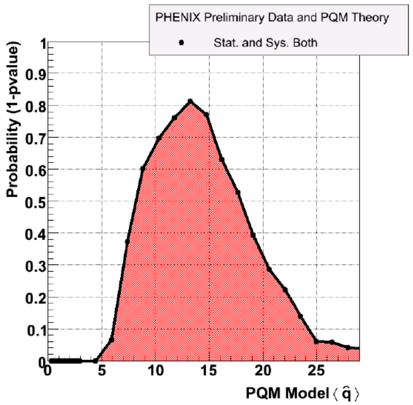
R_{AA} measurements can provide estimates

Light Quark Opacity

Phys. Rev. C 77, 064907 (2008) ,



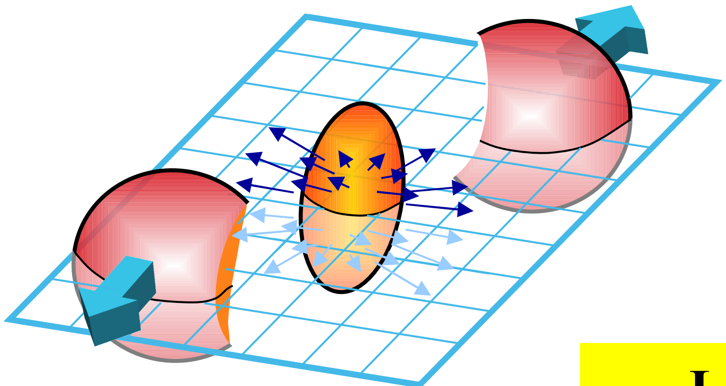
arXiv:0801.4555



$$\langle \hat{q} \rangle = 13.2^{+2.3}_{-2.3} \quad \mathrm{GeV}^2/\mathrm{fm}$$

Initial estimate from inclusive measurements suggests a large scattering Power

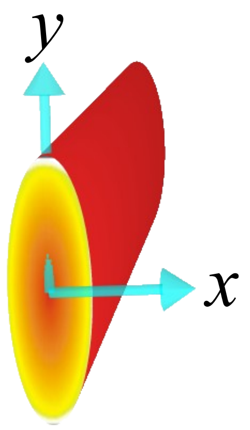
The Flow Probe



From E_T Distributions

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

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



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

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

Large Pressure Gradients → Hydro Flow of partons

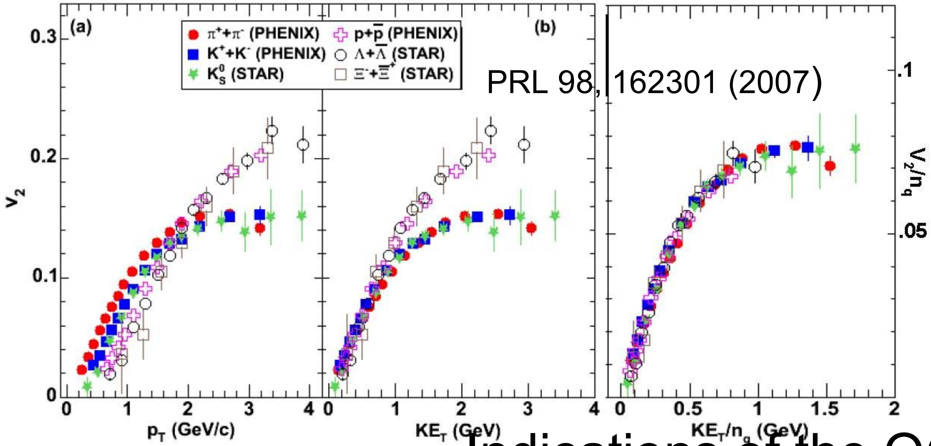
"Control Params." $\varepsilon, \; c_s, \; \eta$

$$E\frac{d^3N}{d^3p} = \frac{1}{\pi} d^2 \frac{N}{dp_T^2 dy}\left[1 + 2v_1 \cos(\varphi - \Psi_R) + 2v_2(2[\varphi - \Psi_R]) + \ldots\right] \;\rightarrow\; v_{2n} = \langle \cos(2n[\varphi - \Psi_R]) \rangle$$

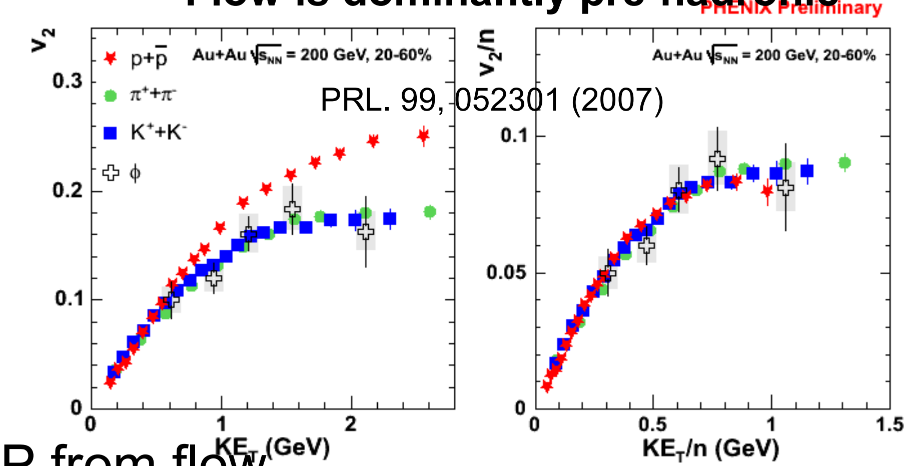
Hydro Flow exhibit specific scaling properties which can be (in)validated

Indications of the QGP from flow

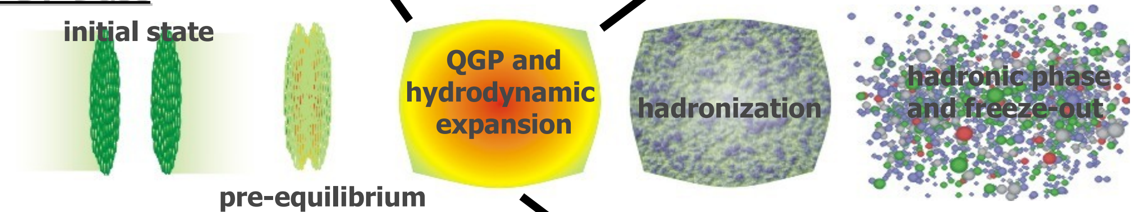
Flow shows KE_T and quark number scaling



Flow is dominantly pre-hadronic



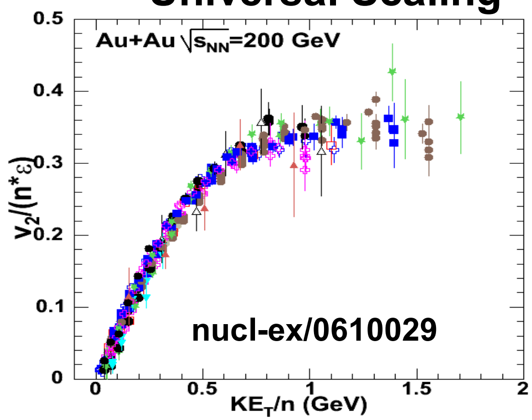
Courtesy S. Bass



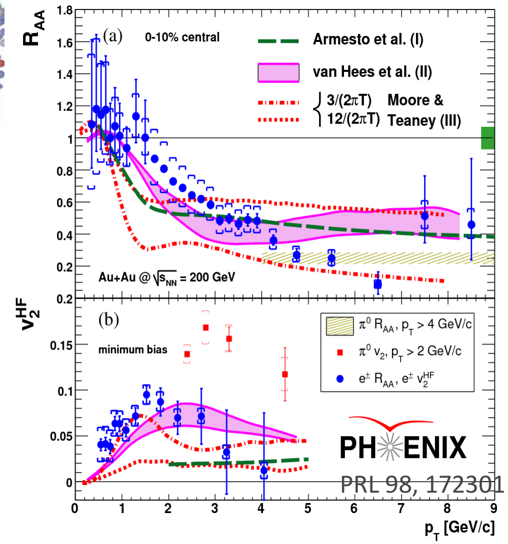
$$\frac{\eta}{s} \sim 2-4\left(\frac{1}{4\pi}\right)$$

$$c_s \sim 0.35$$

Universal Scaling



Charm Flow



PRL 98, 172301 (2007)

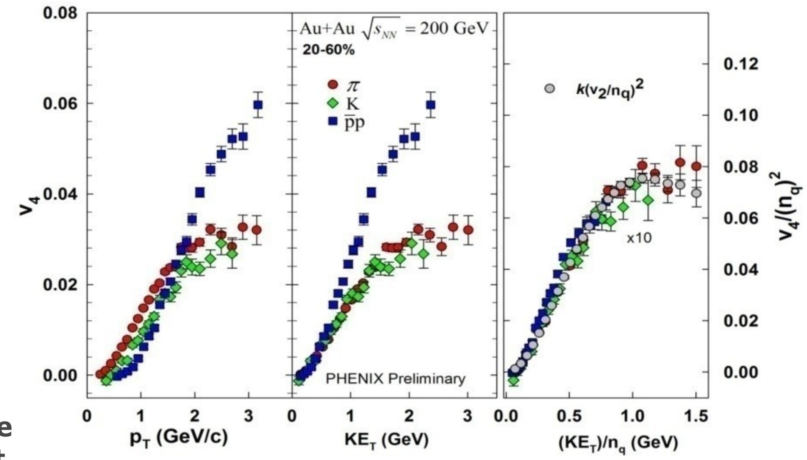
We hold these truths to be self evident !

Roy A. Lacey, Stony Brook; INT Workshop on the QCD Critical Point, July 28 - Aug. 22, 2008

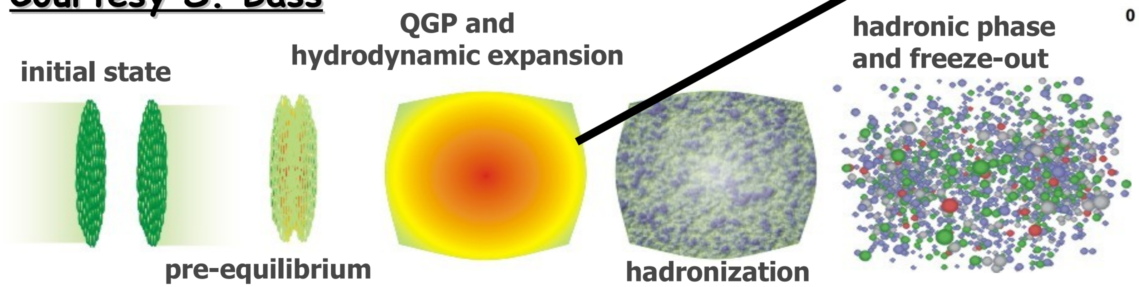
$$\frac{v_{4,M}(2p_T)}{v_{2,M}^2(2p_T)} \approx \frac{1}{4} + \frac{1}{2} \times \frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)}$$

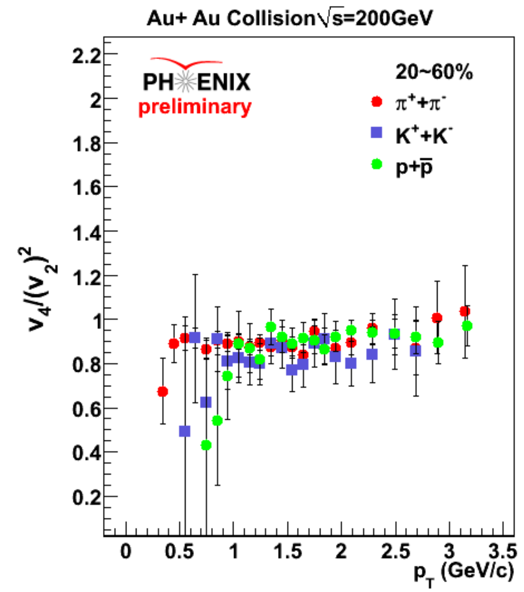
$$\frac{v_{4,B}(3p_T)}{v_{2,B}^2(3p_T)} \approx \frac{1}{3} + \frac{1}{3} \times \frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)}$$

Scaling for Higher Harmonics



Courtesy S. Bass



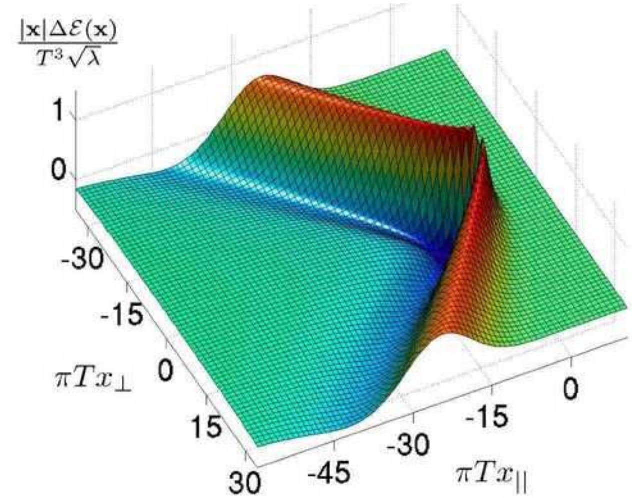


$$\frac{v_{4,M}(2p_T)}{v_{2,M}^2(2p_T)} \approx a\left(\frac{1}{4} + \frac{1}{2} \times \frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)}\right) \qquad \frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)} \approx \frac{1}{2}$$

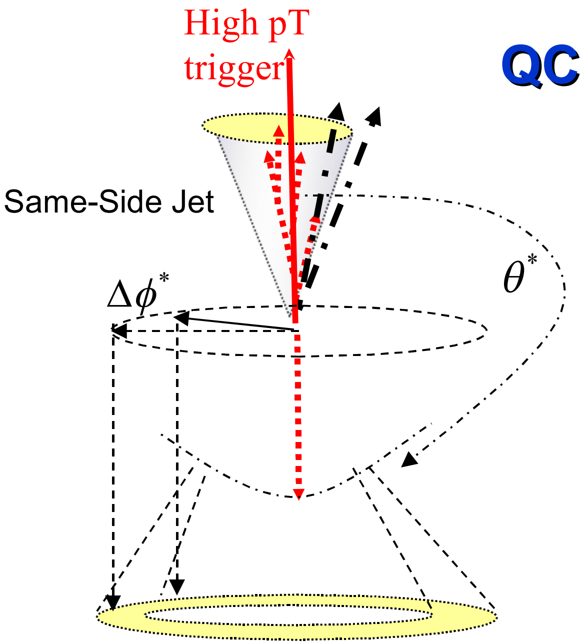
$$\frac{v_{4,B}(3p_T)}{v_{2,B}^2(3p_T)} \approx a\left(\frac{1}{3} + \frac{1}{3} \times \frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)}\right) \qquad a \approx 1.8$$

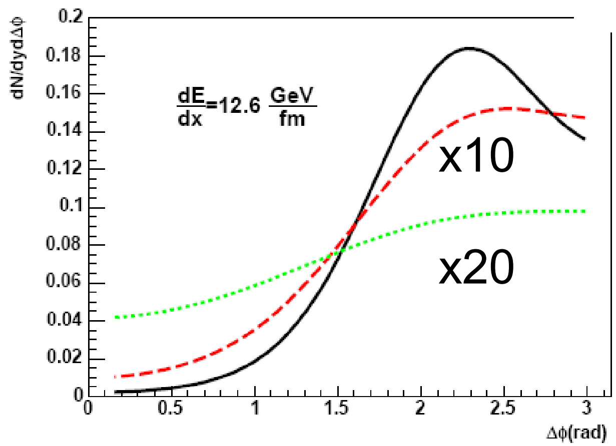
The ratio of the flow harmonics for quarks is compatible with hydrodynamic prediction

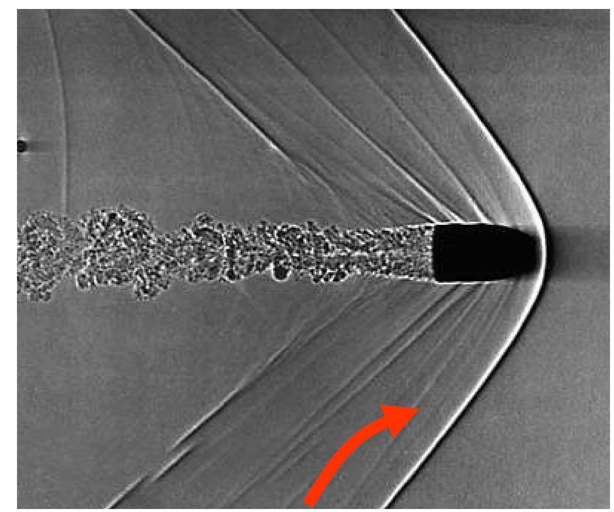
Medium Response & Transport Coefficients

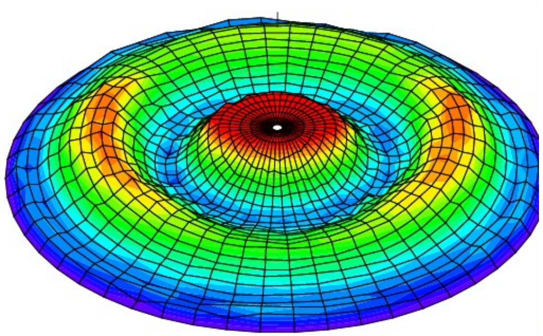


QCD Sonic Boom









$$\Gamma_s = \frac{4}{3}\frac{\eta}{sT} \sim 0.1,\ 0.2,\ 0.5\ \left(\frac{1}{T}\right)$$

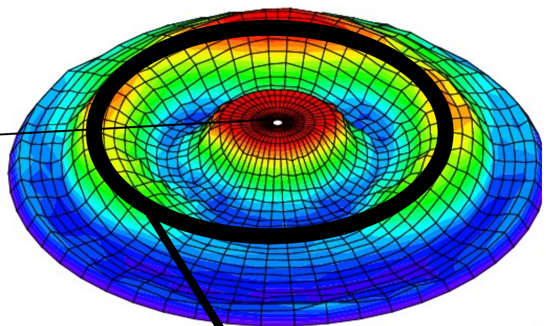
$$\cos\left(\theta_M\right) = c_s$$

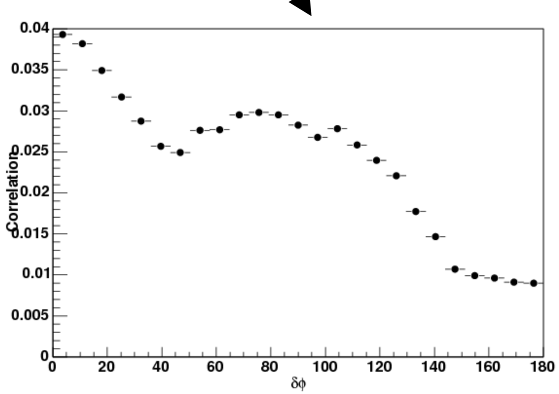
Gives sound speed directly; Sets upper limit on viscosity.

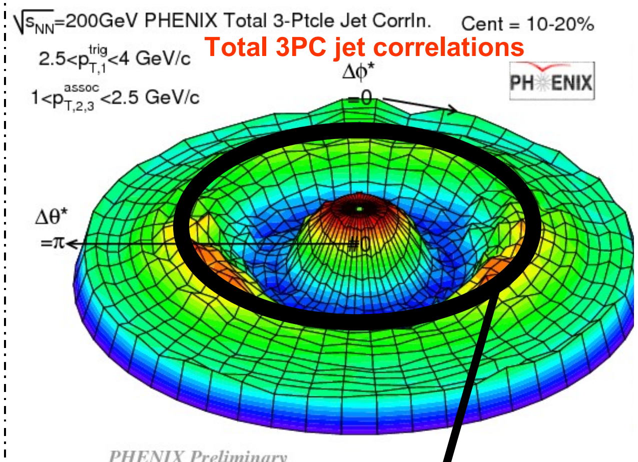
QCD Sonic Boom?

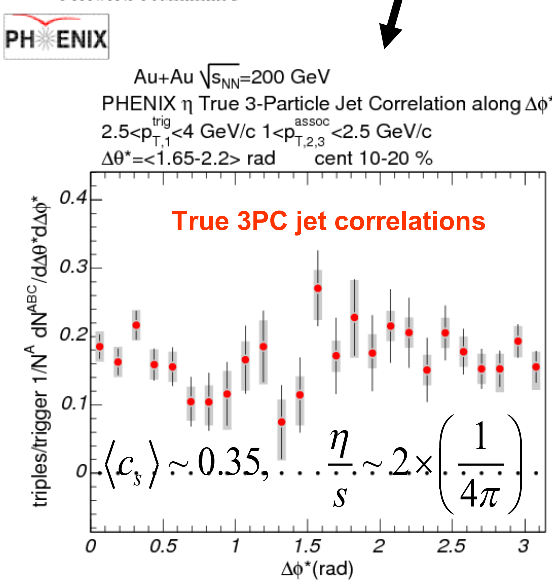
Data

Simulated Deflected jet

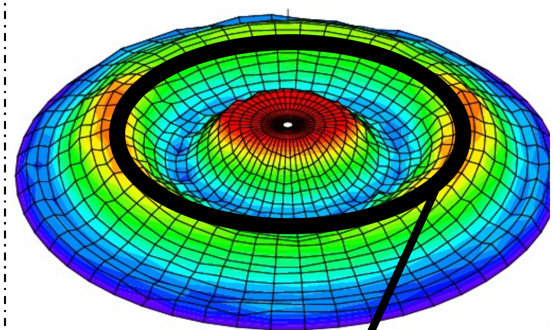


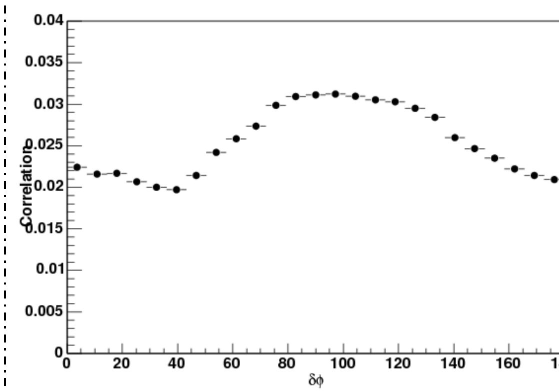






Simulated Mach Cone





Data compatible with the presence of a Mach Cone away-side jet

Transport Coefficient Estimates

Lacey & Taranenko nucl-ex/0610029

$$c_s$$

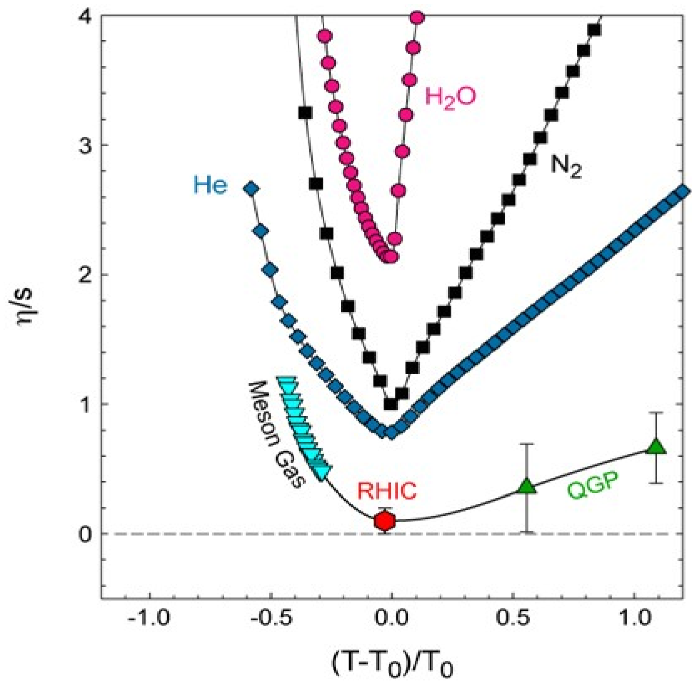
$$\frac{\eta}{s} \sim T\lambda_f c_s,$$

$$\varsigma$$

$$\Gamma_s = \frac{4}{3}\frac{\eta}{sT}$$

$$D \sim \frac{3}{2\pi T}$$

$$\tau_{\mathrm{Relax}} = \frac{M}{T} D$$

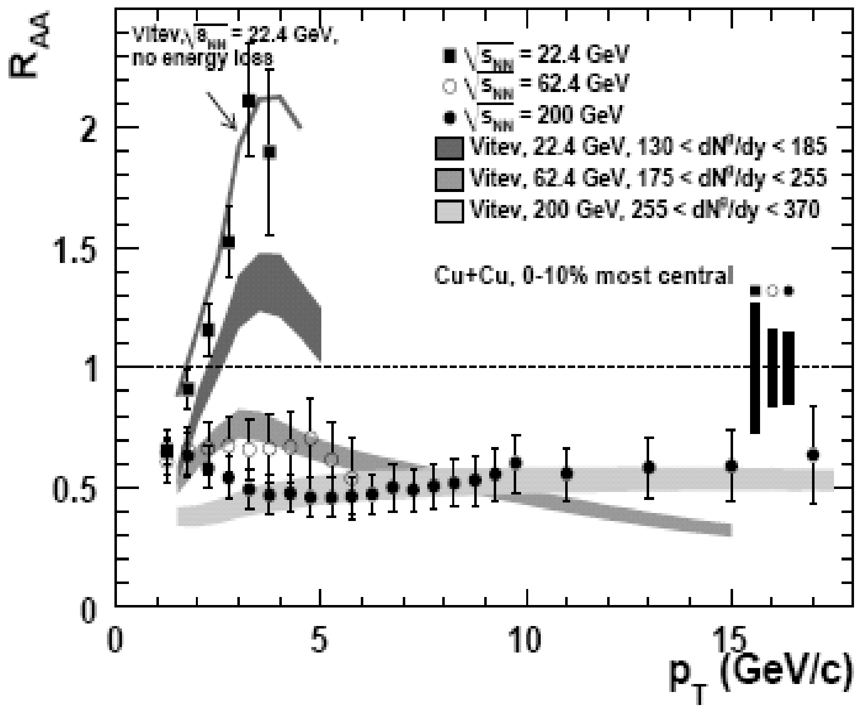


1-2 X the conjectured lower bound

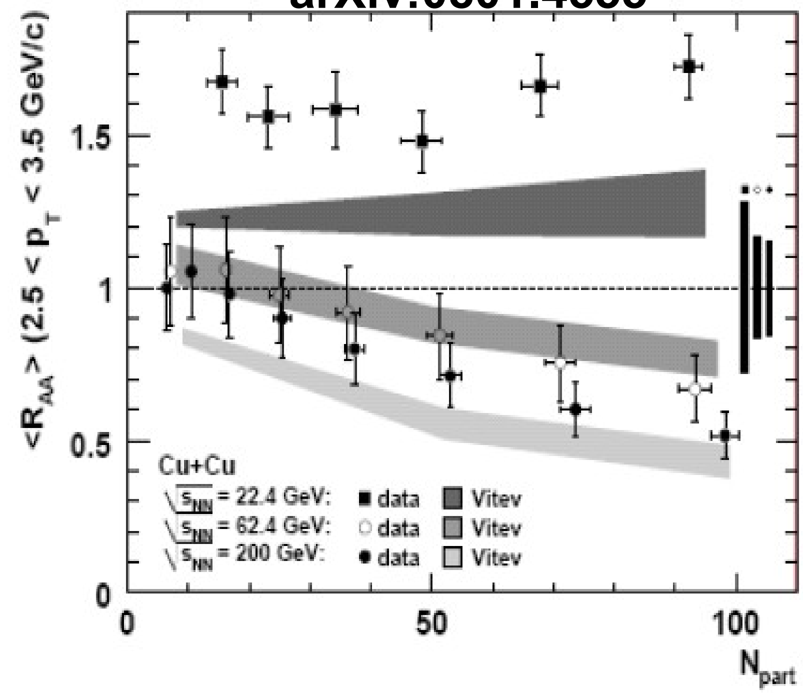
What new insights will an Energy Scan afford?

Lingering questions about the (s)QGP?

Light Quark Opacity

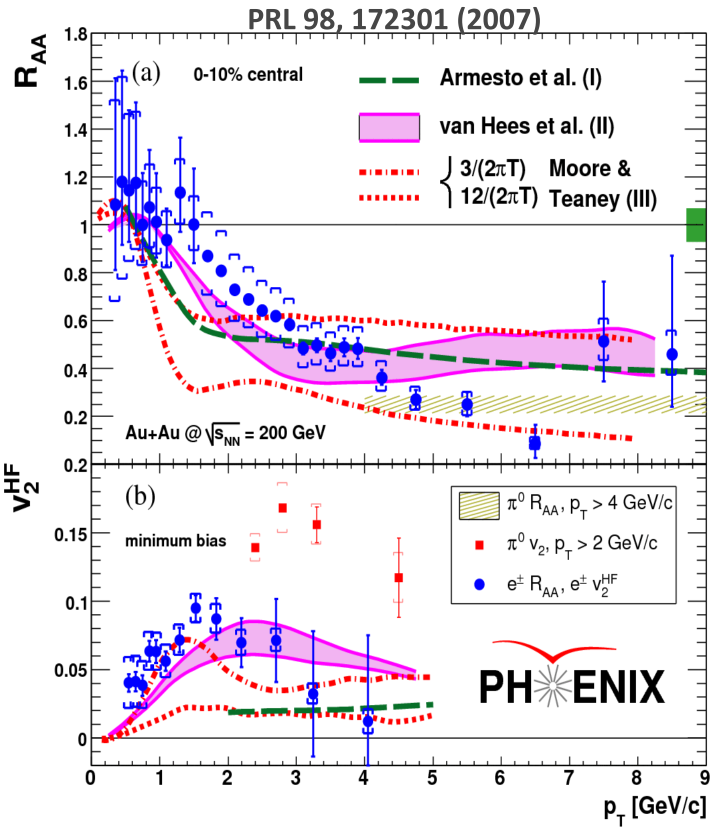


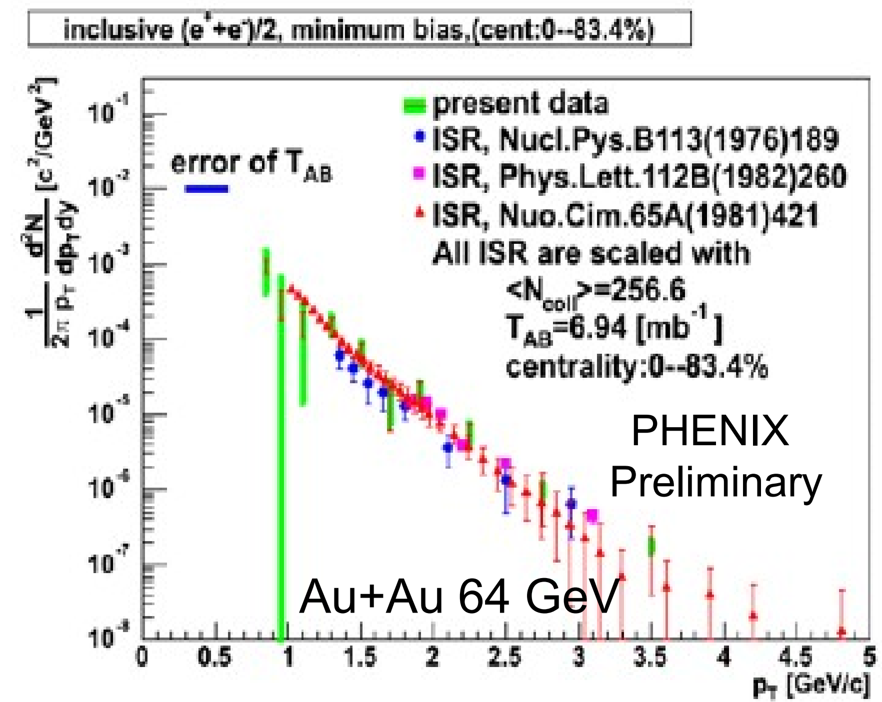
arXiv:0801.4555



At what collision energy does the onset of light quark opacity occur?; what drives it?; additional constraint $\hat{q}$?

Heavy Quark Opacity



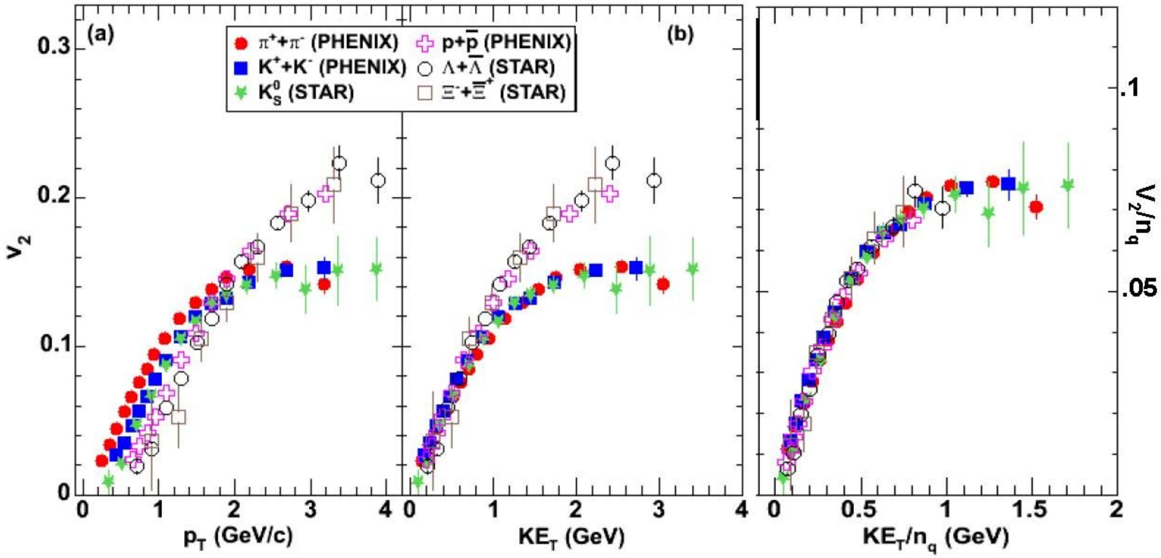


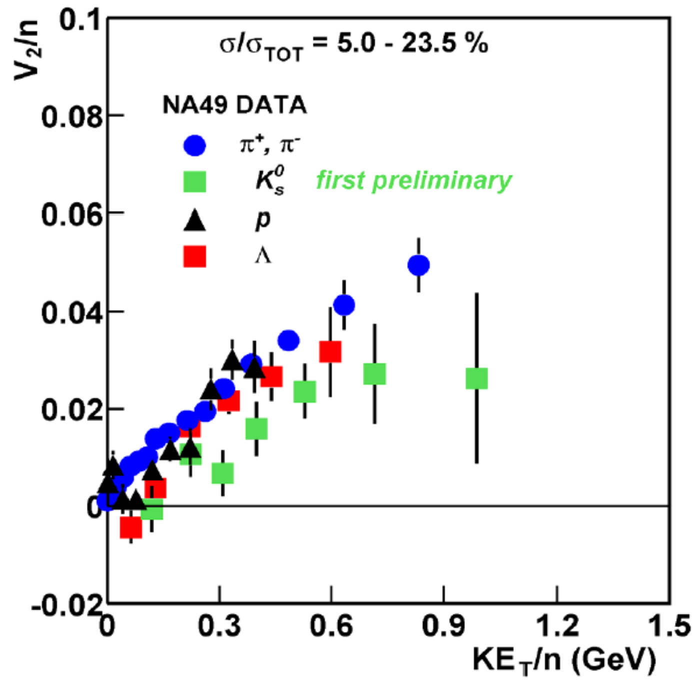
R_{AA}~1

KE_T (GeV)

Where ($\sqrt{s_{NN}}$) is the onset of heavy quark opacity?; what drives it?; Why a different energy range?; constraints?

Onset of Quark Number Scaling?





✓ Passing time scaling at very low energy
✓ particle-mass scaling at very low energy

Where ($\sqrt{s_{NN}}$) is the onset of quark number scaling? Relationship to Quark dof ?

Requirements for Heavy/Light Quark Opacity measurements

Probes:
- Standard R_{AA} measurements for non-photonic electrons and π^0
- Di-hadron correlations
- Comparison samples from p+p and d+Au collisions

π^0

$\sqrt{s_{NN}}$	# Events
38 GeV	26M - 34M
30 GeV	43M - 62M
22 GeV	76M - 124M

- Energy scaling of actual yields
- 30 π^0 in 4-5 GeV pT bin for 0-10%

Non-photonic electrons

$\sqrt{s_{NN}}$	# Events
100 GeV	75 M
60 GeV	260 M
40 GeV	780 M
20 GeV	2340 M

- Energy scaling of expected yields

Di-hadron Correlations

$\sqrt{s_{NN}}$ (GeV)	# Events
5	374 M
6.3	297 M
7.6	246 M
8.8	213 M
12.3	152 M
17.2	109 M
27.4	68 M
62.4	30 M
100	19 M

Events ⟵⟶ (Weeks)

Energy	300M	100M	50M	5M	1M
17.2	73	24	12	1	0
27.4	9	3	2	0	0
38.8	5	2	1	0	0

p+p & d+Au Samples for Quark Opacity measurements

Probes:

- Standard R_{AA} measurements for non-photonic electrons and π^0
- Di-hadron correlations

$\sqrt{s_{NN}}$ (GeV)	# Sampled pp Events	# Sampled dAu Events
22	2.5 B	1.2 B
30	1.2 B	600 M
38	750 M	360 M
60	6.5 B	3.1 B
100	2 B	900 M

π^0

- Binary Collision scaling

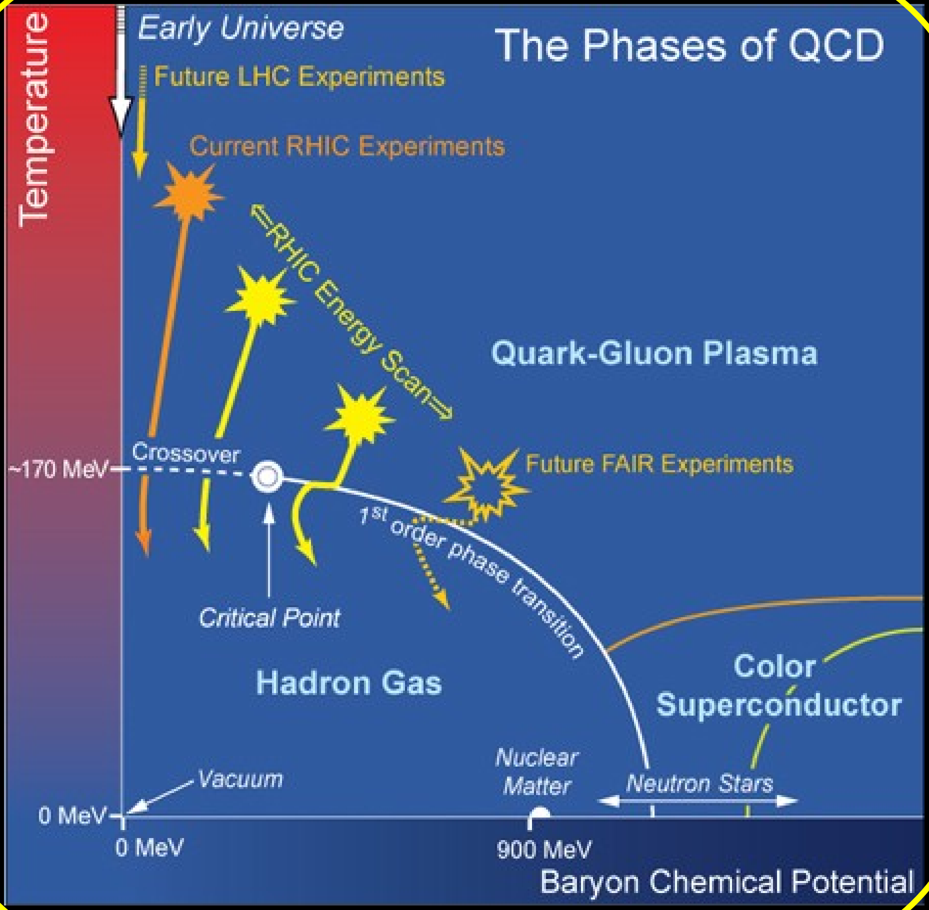
No show stoppers !

Opportunities for CEP Discovery

&

New constraints for the EOS

QCD Critical End Point



``The discovery of the critical point would in a stroke transform the map of the QCD phase diagram from one based only on reasonable inference from universality, lattice gauge theory and models into one with a solid experimental basis''

Krishna Rajagopal – Phys.Rev.D61:105017,2000

Knowledge of the position of the CEP is a powerful constraint on possible models of QCD thermodynamics

Search for the CEP must be a central objective

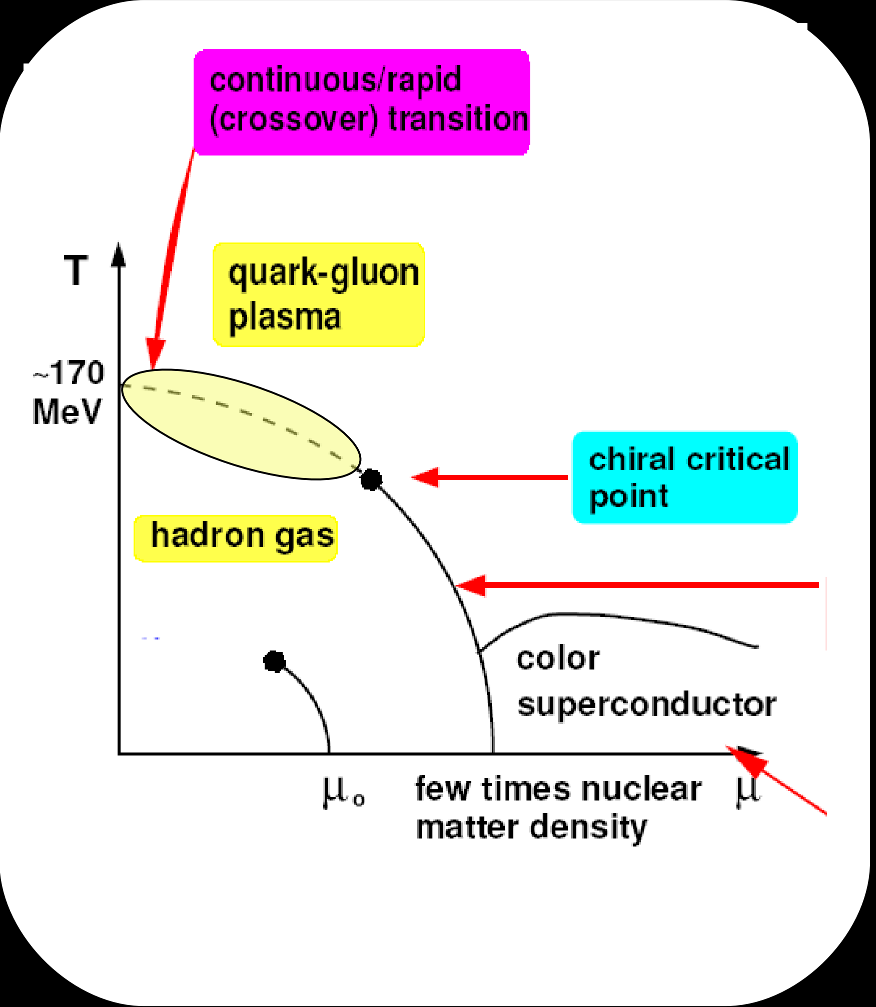
What Motivates the CEP Search at RHIC?

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 transition to the Quark Gluon Plasma

- Flow Measurements
- Space-time measurements
- Jet Quenching

The Crossover is a necessary requirement for existence the CEP



How do we search for the CEP?

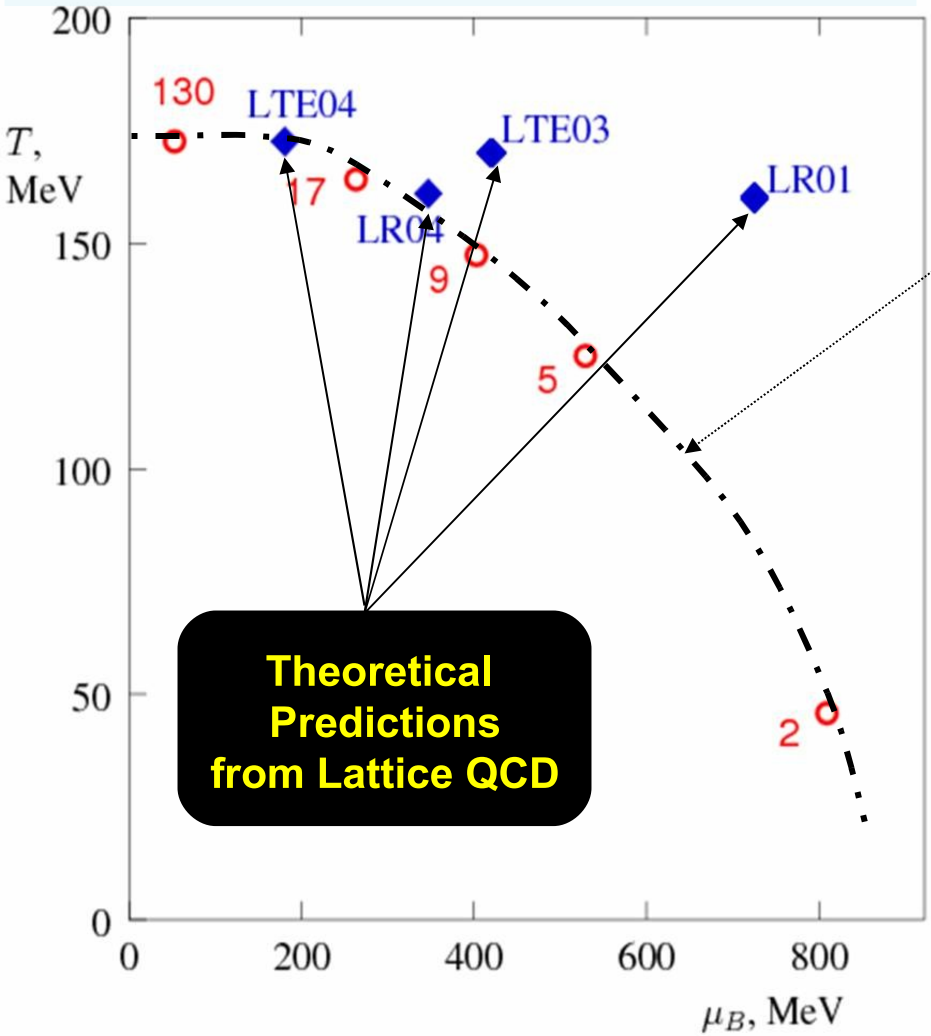
↓

Theoretical Guidance?

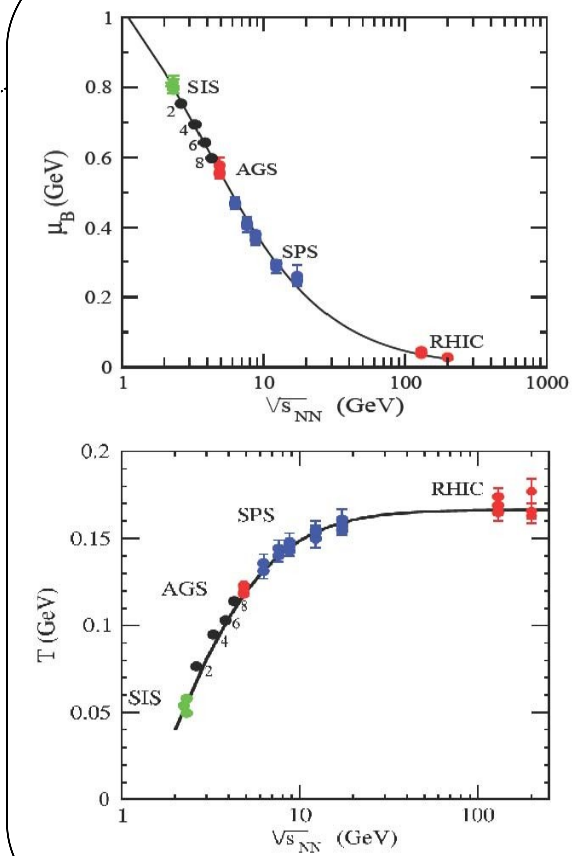
Which variables?

Search Strategy?

Theoretical Guidance ?



Chemical
Freeze-out Curve



J. Cleymans, et al
Phys. Rev. C73, 034905 (2006)

Intriguing predictions but search for the CEP may require 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

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

Fluctuations ← σ; ξ → Correlation length

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

Divergence of ξ restricted:

- Finite system size — ξ < size
- Finite evolution time — ξ < (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

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:

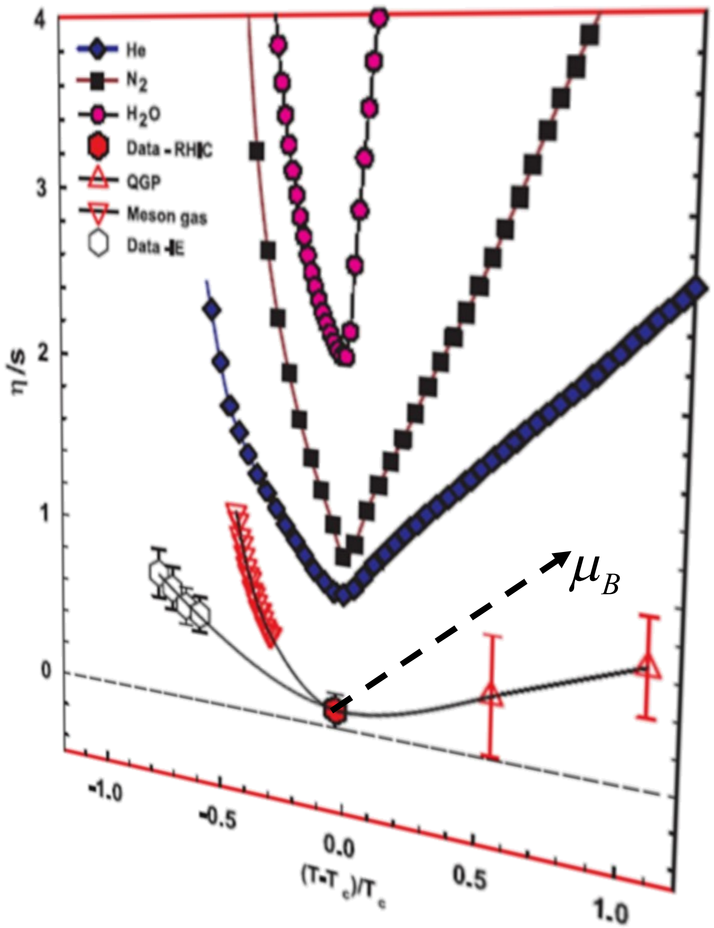
- Finite system size $\xi <$ size
- Finite evolution time $\xi < (\text{time})^{1/z}$

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

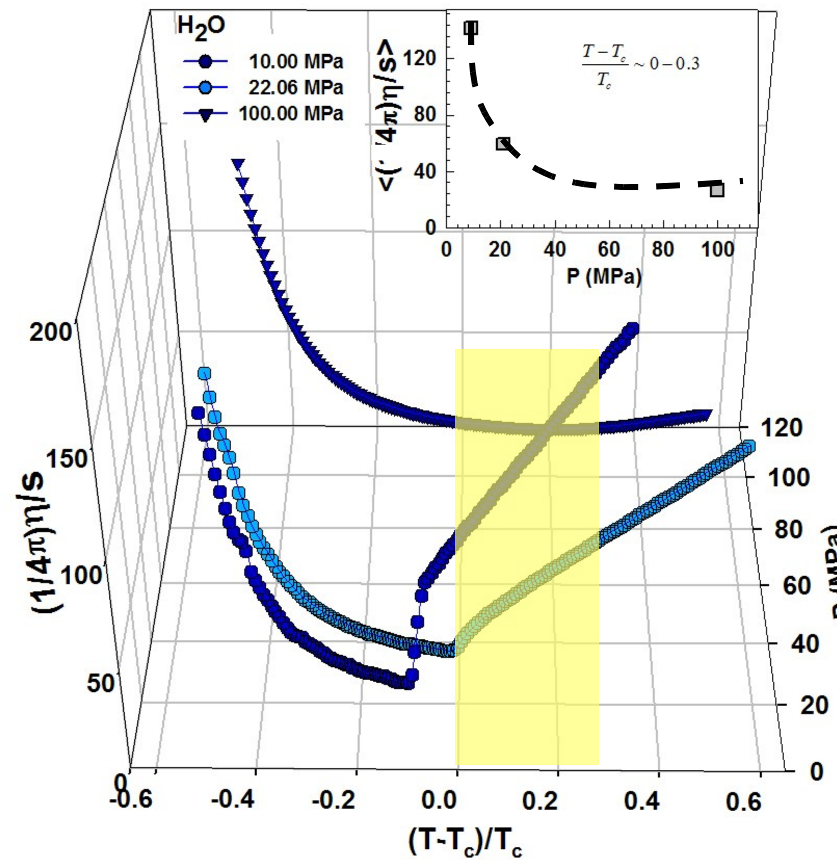
- **D "vanishes" at the CEP**
- **"mild" dependence for viscosity**

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

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

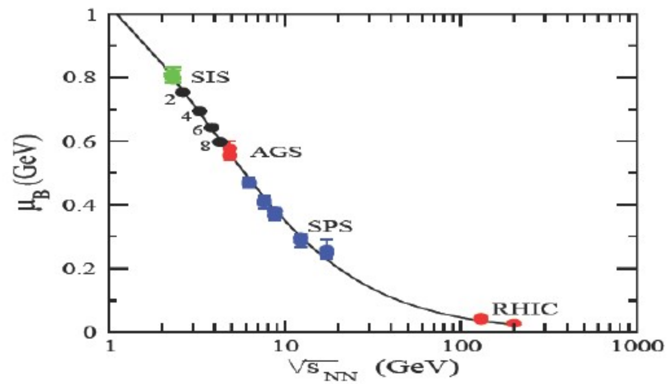


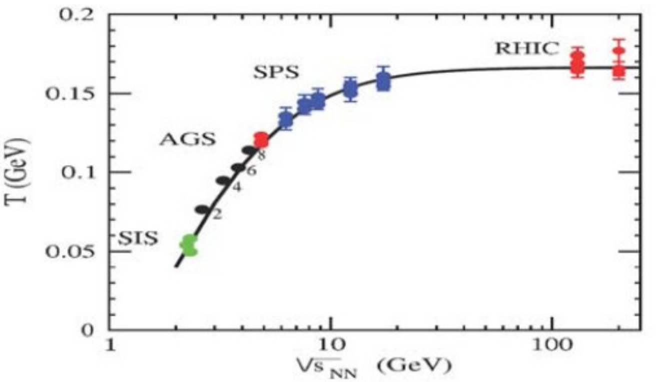
Lacey et al. arXiv:0708.3512 [nucl-ex]

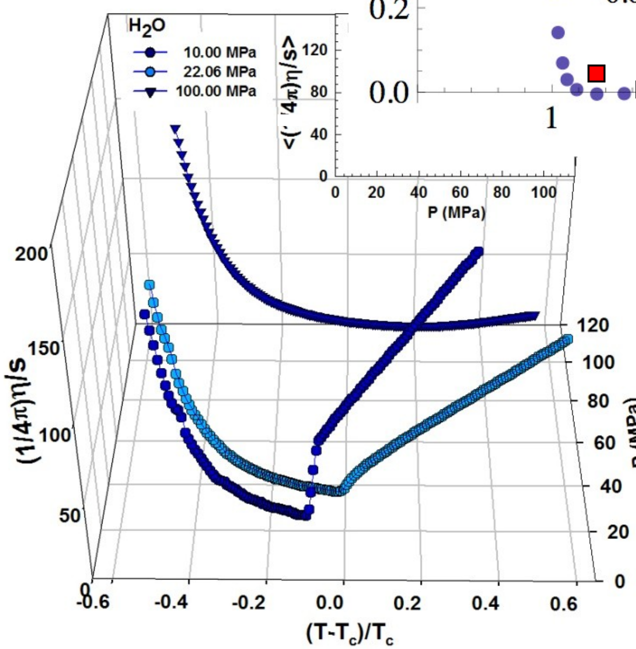


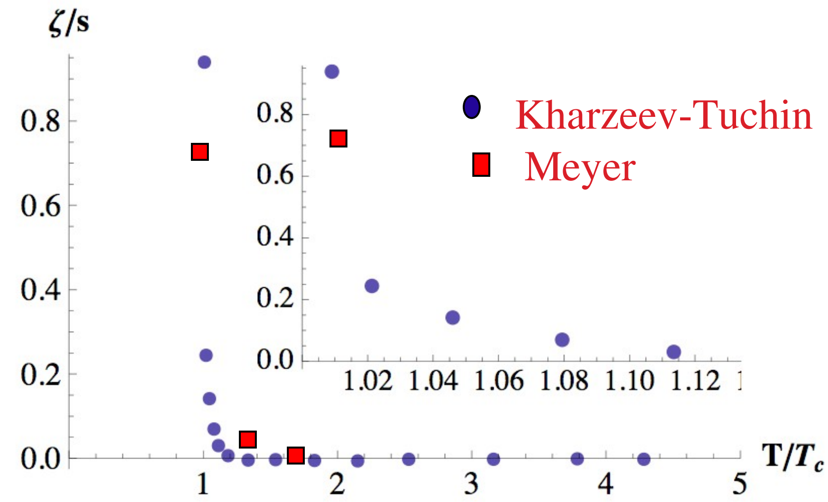
$\frac{\eta}{s}$ **is a potent signal for the CEP**

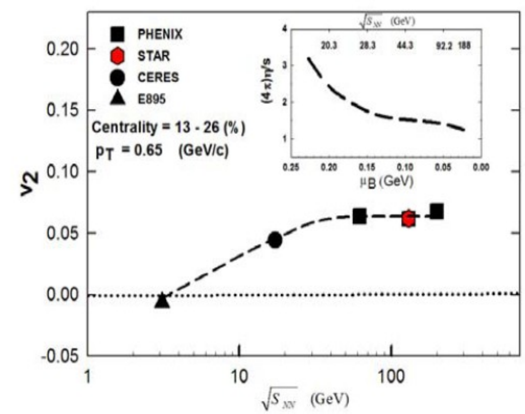
CEP Search









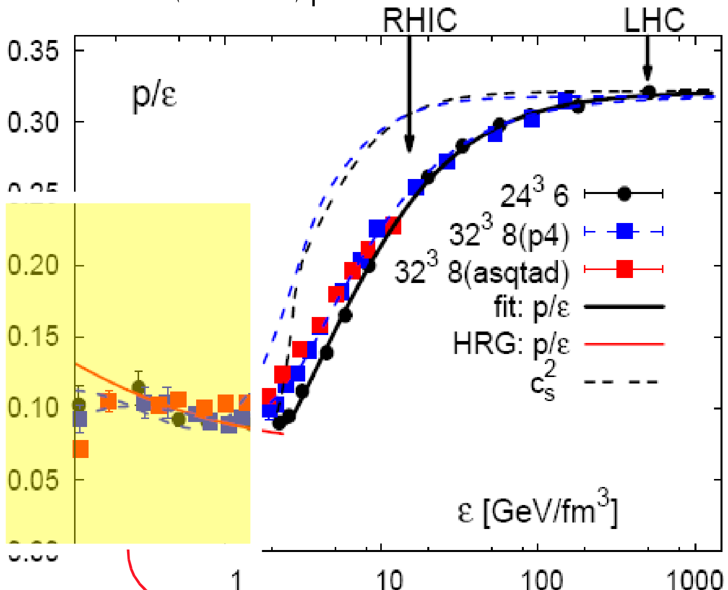


First estimate T ~ 165-170 μ ~ 150-180 MeV

Search in the region $20 \leq \sqrt{s_{NN}} \leq 62$ GeV

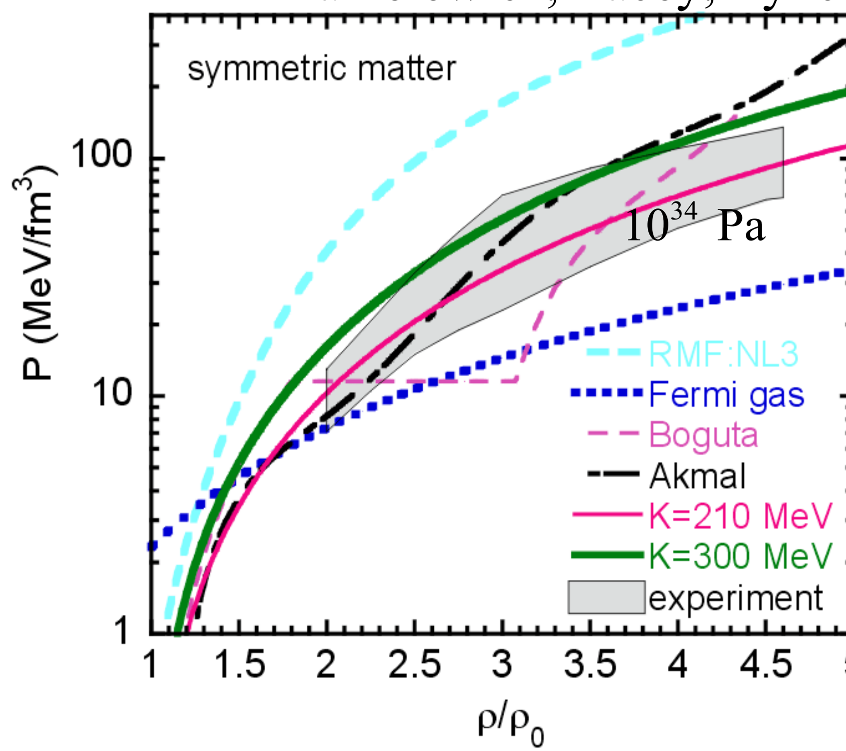
New Constraints for the Hadronic EOS?

$$c^2 = \left(\partial P / \partial \varepsilon \right) \Big|$$



EOS not very well constrained experimentally

Danielewicz, Lacey, Lynch



$$c_s = \sqrt{K / 9m_N} \approx 0.15c, 0.21c$$

Soft and **hard** EOS

Further constraints for the hadronic EOS

Requirements for Fluctuations & viscosity measurements

Probes:

- Standard fluctuations measurements for charged hadrons (+ PID)
- Flow measurements
- Femtoscopic measurements

Analysis	Energy 20 GeV	60 GeV	200 GeV
Spectra min.bias	~5M	~4M	~2M
Spectra cent.dep.	~50M	~40M	~20M
v2 min. bias	~50M	~40M	~20M
v2 cent. dep.	~500M	~400M	~200M
Assumed rxn r.p. resolution	~0.4	~0.6	~0.75

<-

Weeks

Energy	Events: 300M	100M	50M	5M	1M
17.2	73	24	12	1	0
27.4	9	3	2	0	0
38.8	5	2	1	0	0

Summary

For $20 \le \sqrt{s_{NN}} \le 100$ GeV RHIC can make an immediate and unique contribution to:

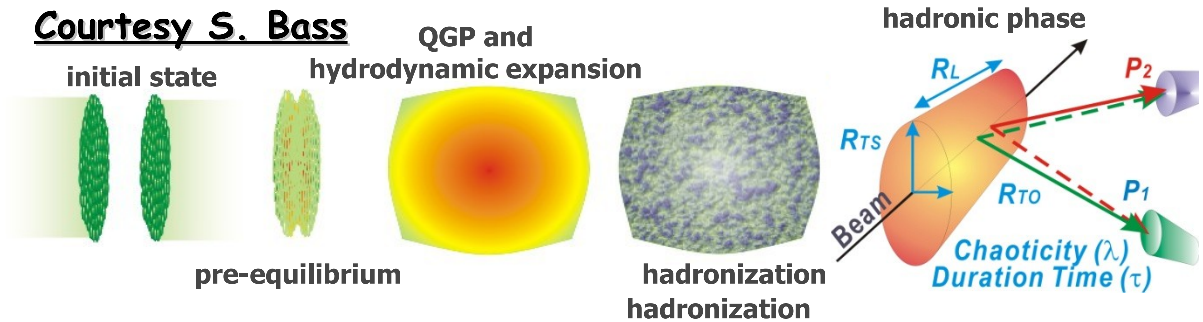
- The low-μ_B end of the critical point search
- Quantification of the onset of light-quark and heavy-quark opacities.
- Quantification of the onset of QNO scaling
- Constraining the Hadronic EOS

This is achievable within realistic running periods of ~ 20-25 weeks:

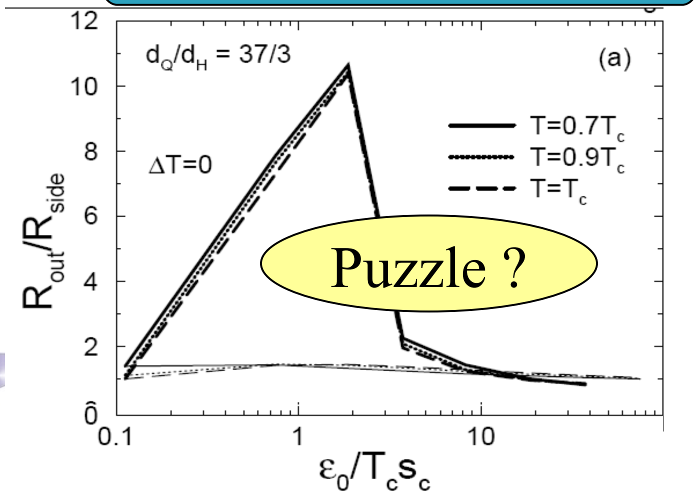
The reason people find it so hard to be happy is that they always see the past better than it was, the present worse than it is, and the **future** less resolved than it will be.
Marcel Pagnol

Indications of a crossover from space-time Measurements

Are source images consistent with the crossover transition ?



Hydrodynamic prediction



Koonin Pratt Eqn.

$$R(q) = C(q) - 1 = 4\pi \int dr r^2 K_0(q,r) S(r) \quad (1)$$

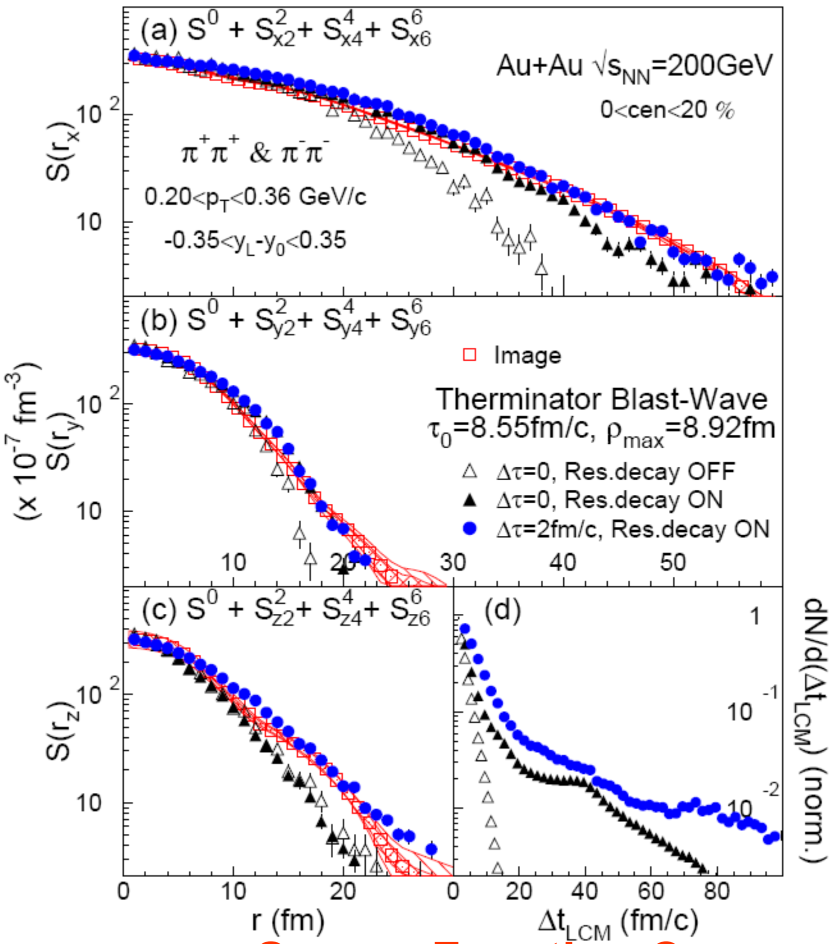
Correlation function	Encodes FSI	Source function (Distribution of pair separations)

A Cross Over strongly affects the Space-time Dynamics

Inversion of this integral equation
→ Source Function

The transition is Not a Strong First order Phase Transition?

arXiv:0712.4372

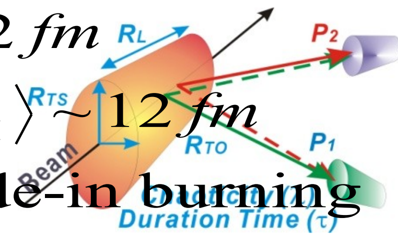


$\tau \sim 9\,fm$

$\Delta\tau \sim 2\,fm$

$\langle \Delta t_{LCM} \rangle \sim 12\,fm$

Outside-in burning



Therminator:

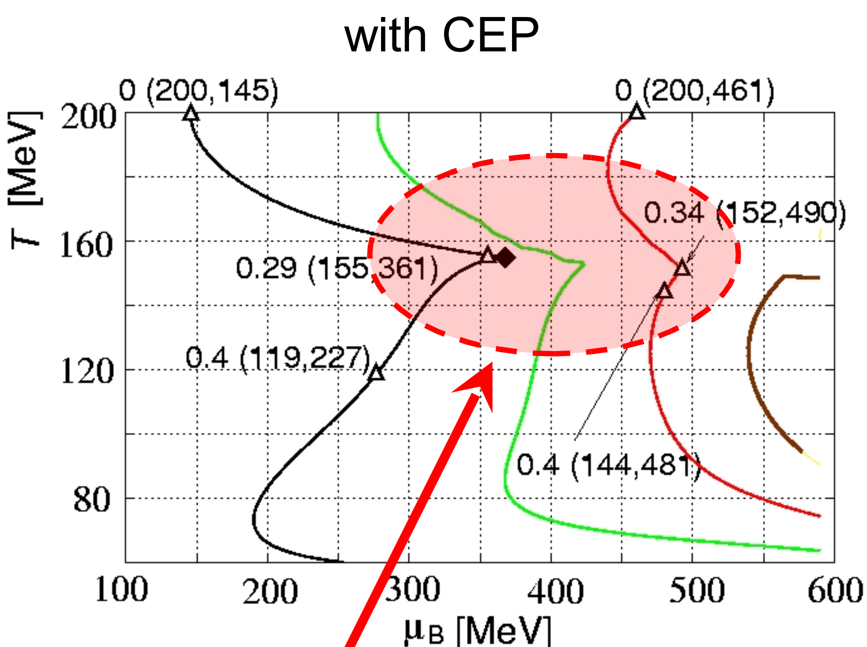
A.Kisiel et al. Comput.Phys.Commun.174, 669 (2006)

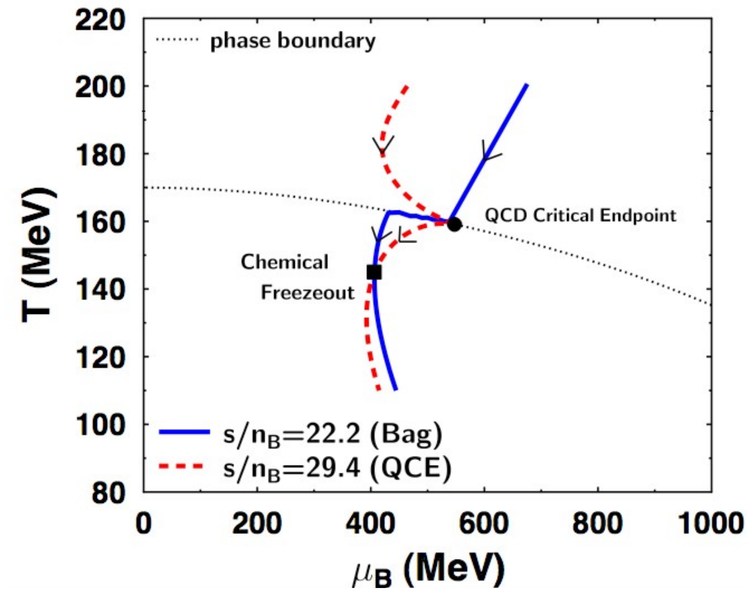
Thermal model with Bjorken longitudinal expansion and transverse Flow

- Spectra & yields constrain thermal properties
- Transverse radius ρ_{max} : controls transverse extent
- Breakup time in fluid element rest frame, τ : controls longitudinal extent
- Emission duration $\Delta\tau$: controls tails in long and out directions
- a controls x-t correlations

Source Function Comparison to Models Give robust life time estimates → Consistent with Crossover transition

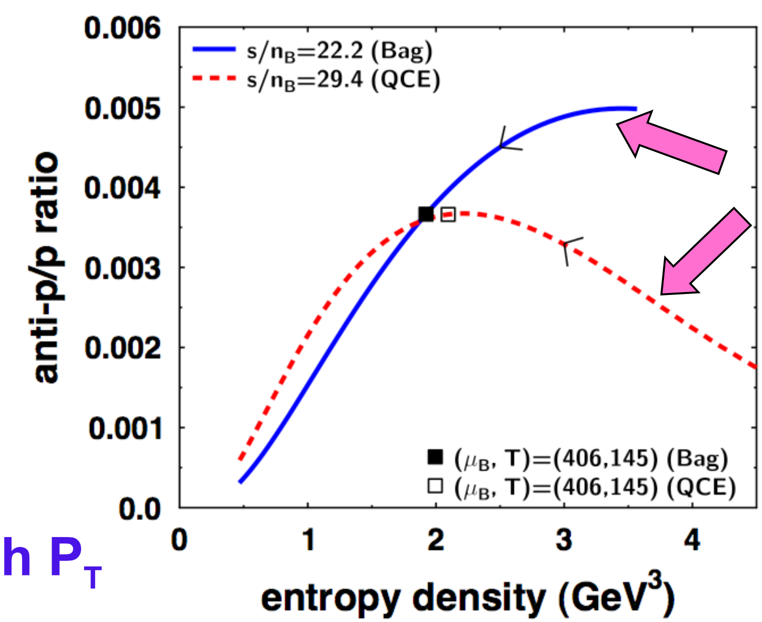
CEP Search





$$\bar{p}/p \sim \exp\left(-\frac{2\mu_B}{T}\right)$$

Focusing of Isentropic Trajectories



steeper $\bar{p}$ spectra at high P_T