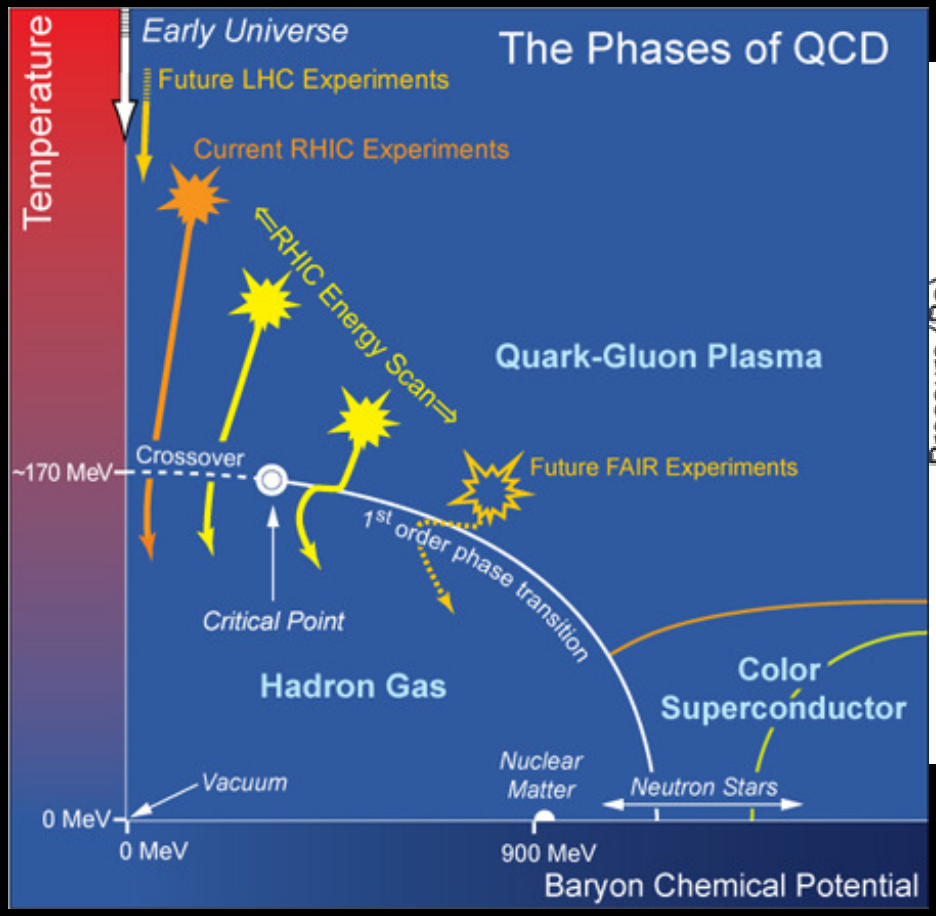
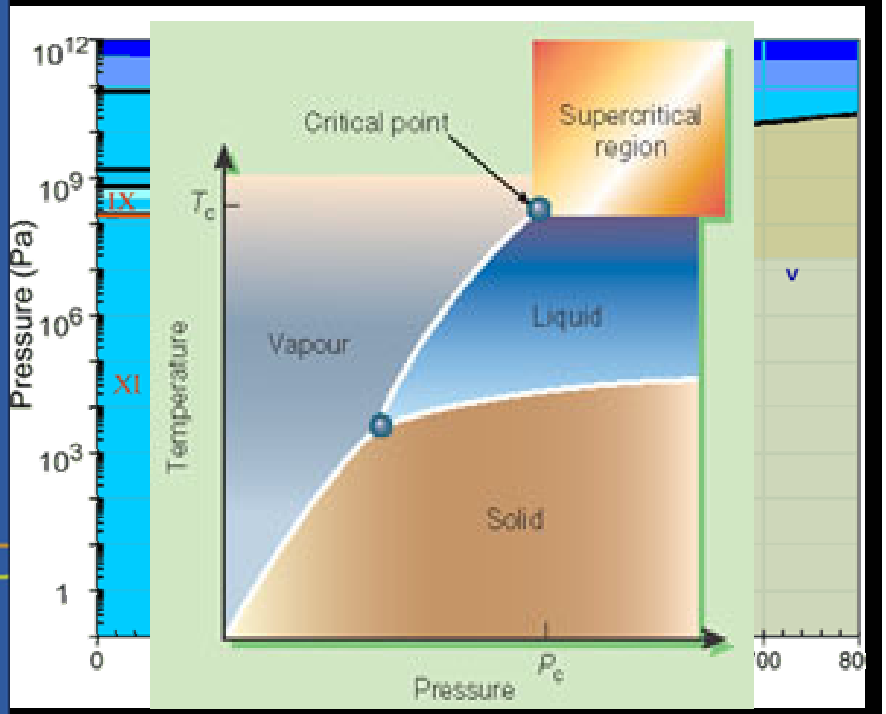
New Prospects for locating the QCD Critical End Point (CEP) at RHIC

Roy A. Lacey

NUCLEAR CHEMISTRY
@ STONY BROOK

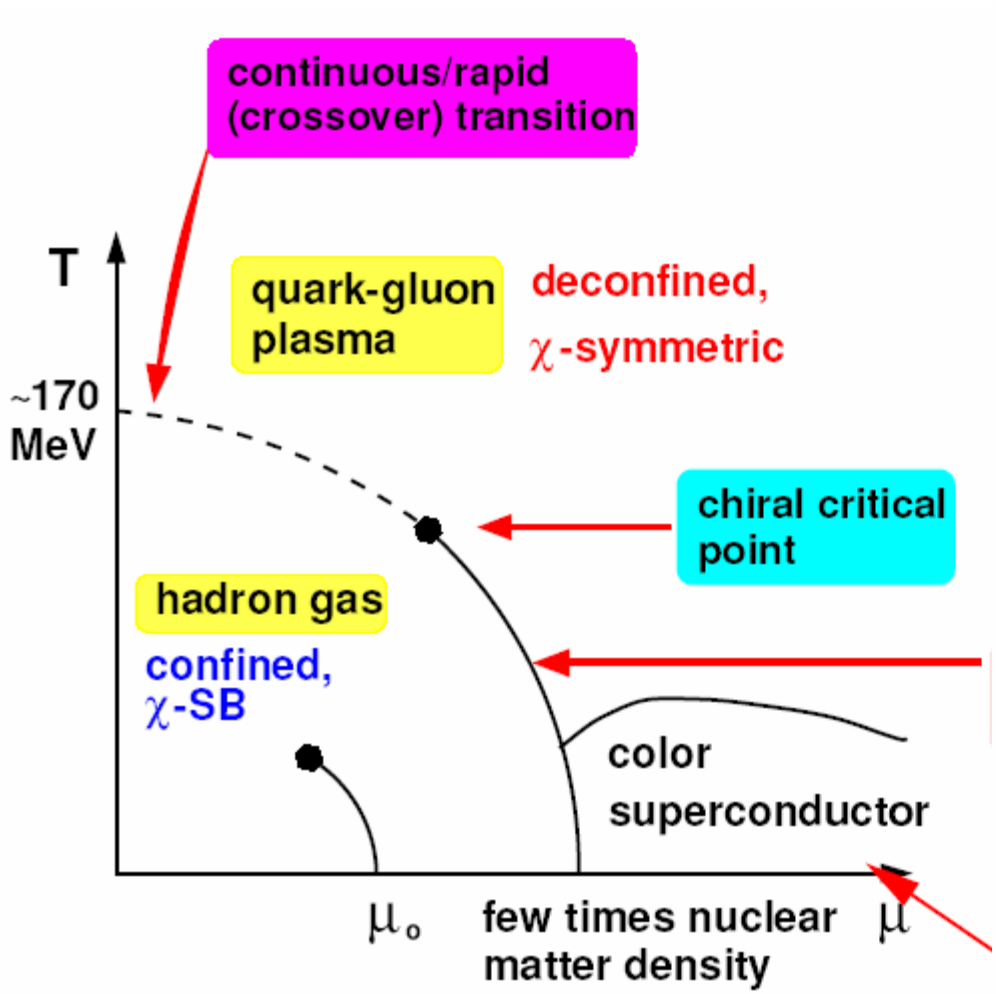
A Central Question for the QCD Lab!

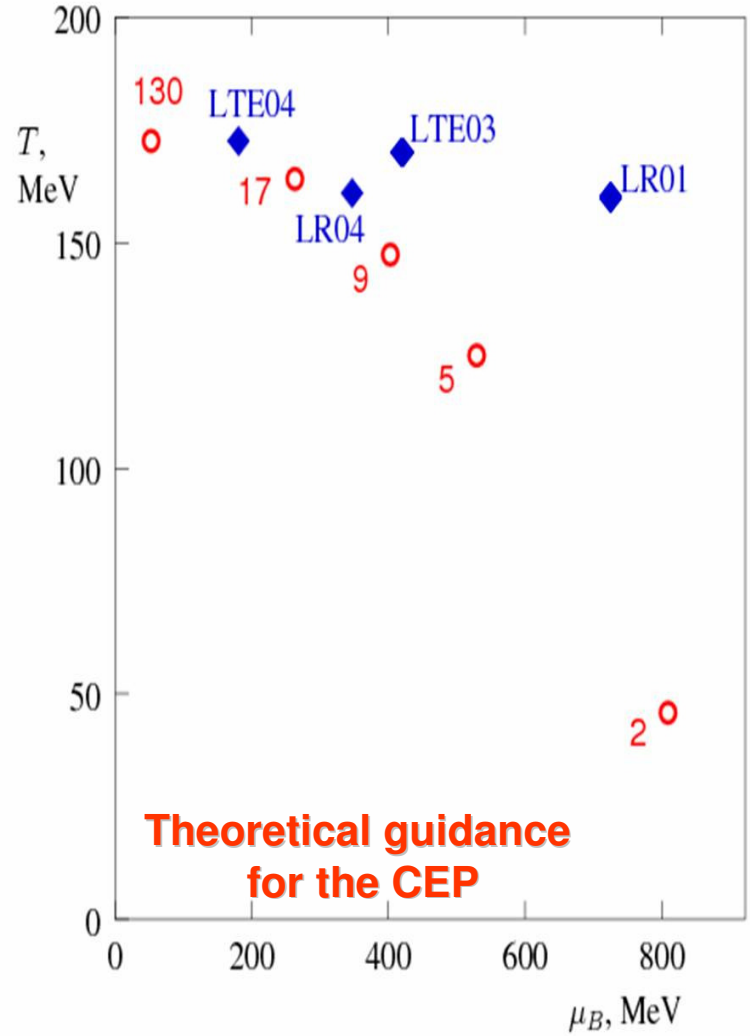




The location of the critical End point and the phase boundaries are fundamental to the QCD phase diagram !

Theoretical Guidance ?

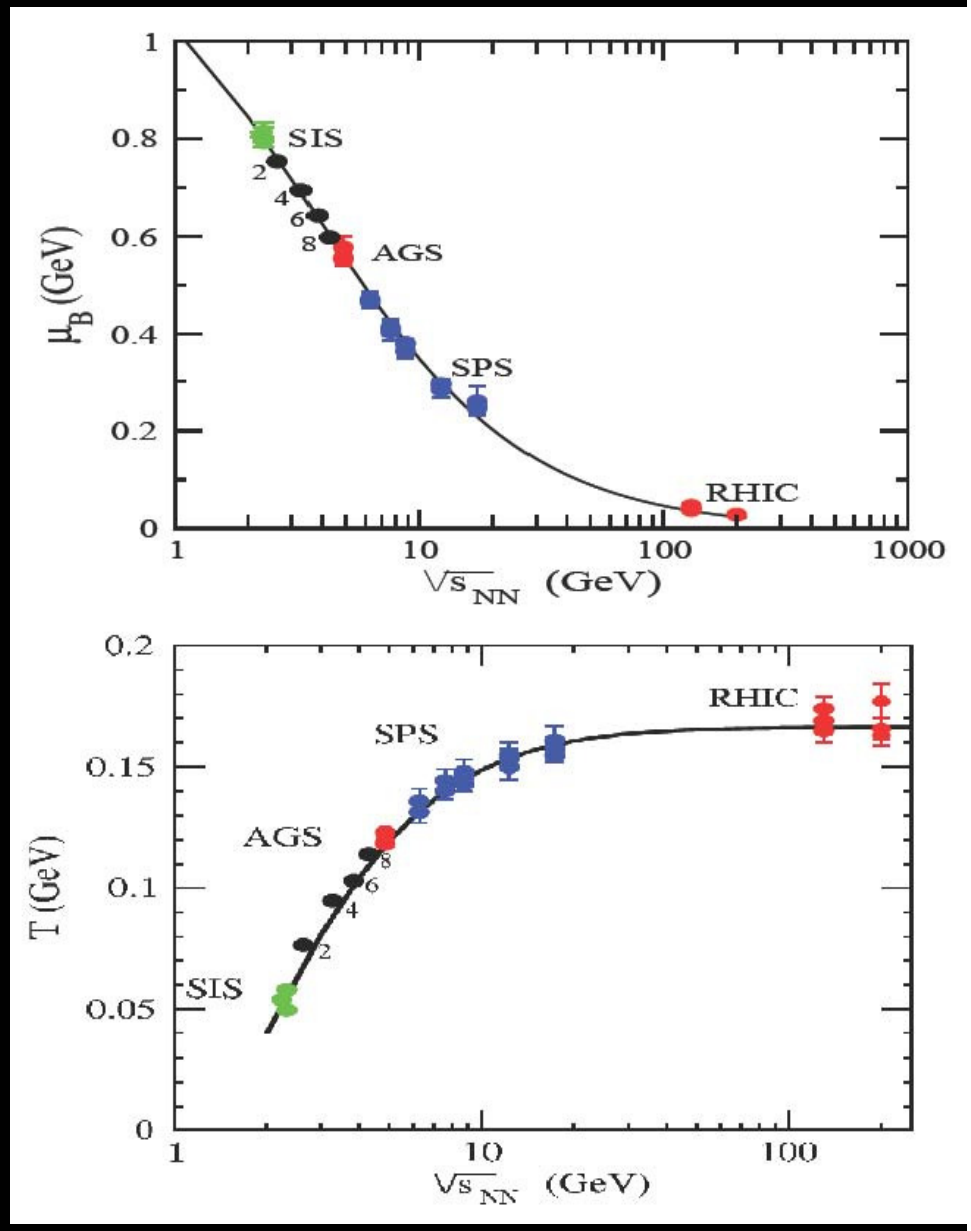




Any search for the CEP requires investigations over a broad range of μ & T.

Good News !

This is the Golden Age for the CEP Search



For the first time (at last) we have access to the full range Of μ and T.
(via Energy scans at RHIC, SPS & FAIR)

Better News !

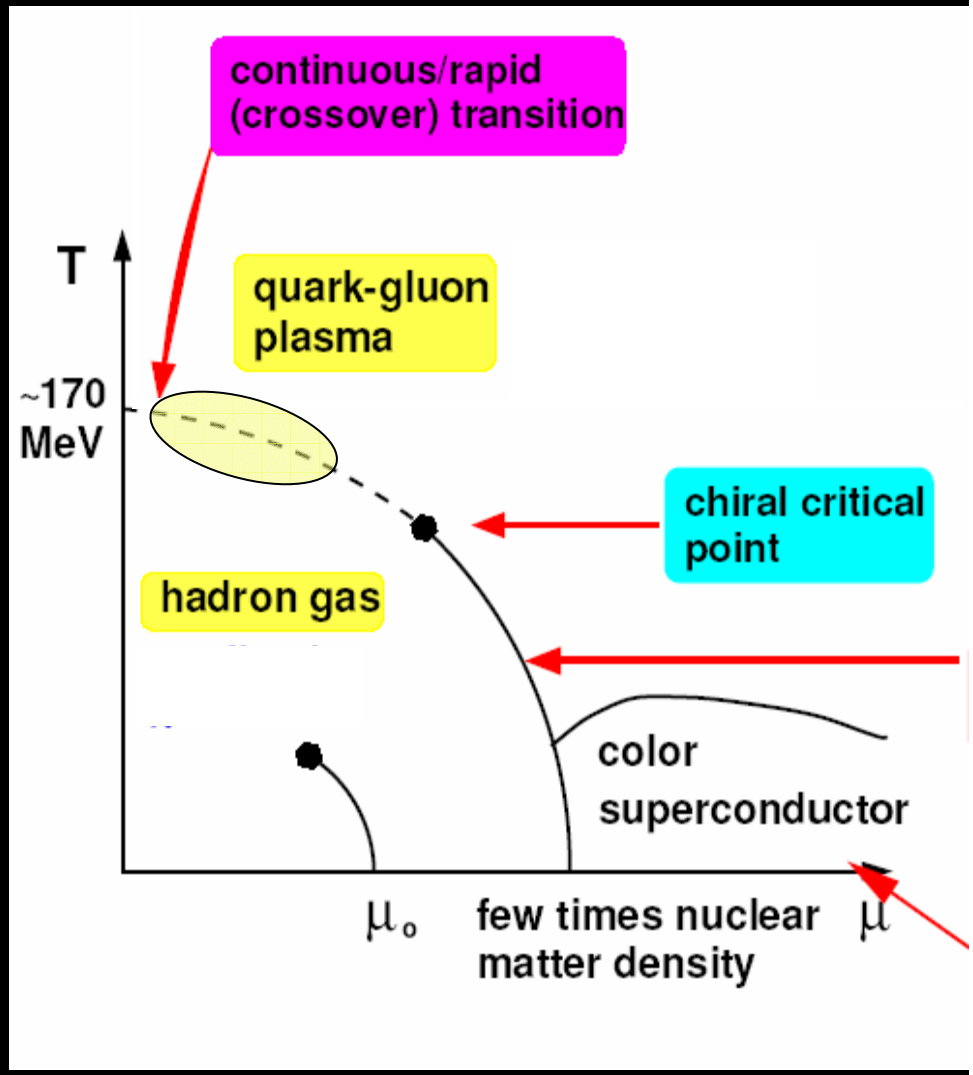
1) *The Crossover Transition to the QGP is made clear at RHIC*

- *Space-time measurements*
- *Flow Measurements*
- *Jet Quenching*

This is a necessary requirement for locating the CEP

2) *The viscosity to entropy ratio offers a new dynamical probe for the CEP*

- *Contrasts Stationary State variables*

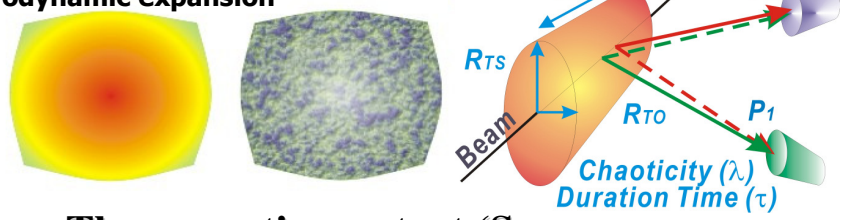


Life Time measurements As a probe for the transition

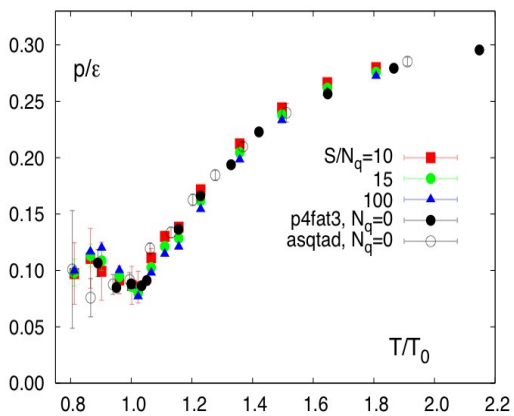
Are source Imaging measurements consistent with the crossover transition ?

The Role of Femtoscopy

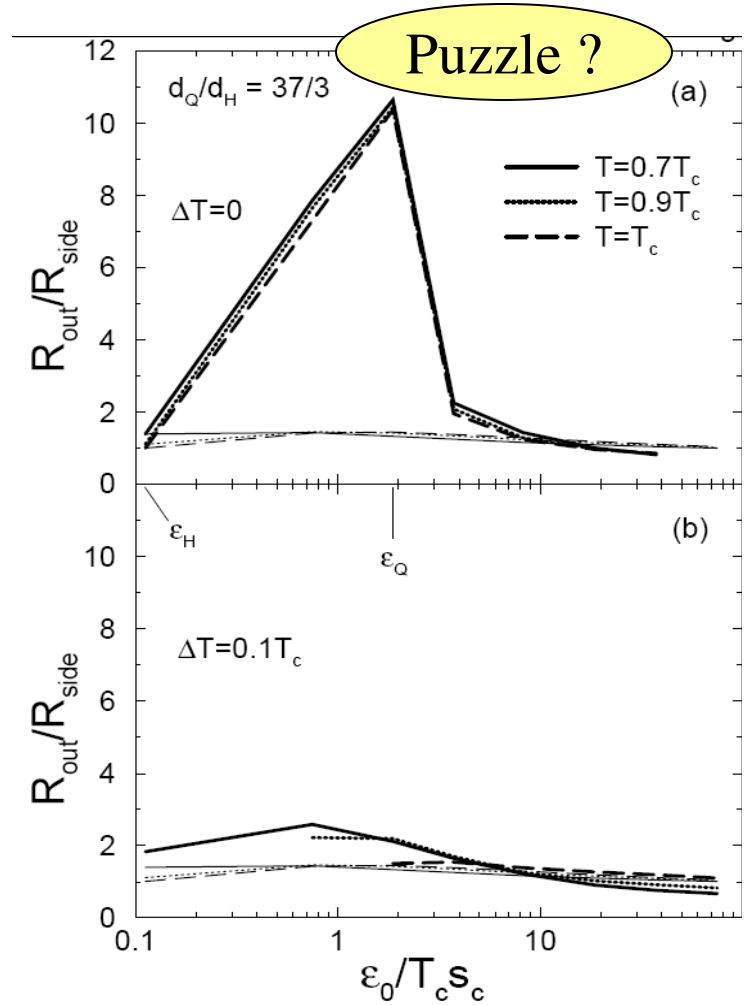
QGP and hydrodynamic expansion



The space-time extent (Source Image) can lend crucial insights



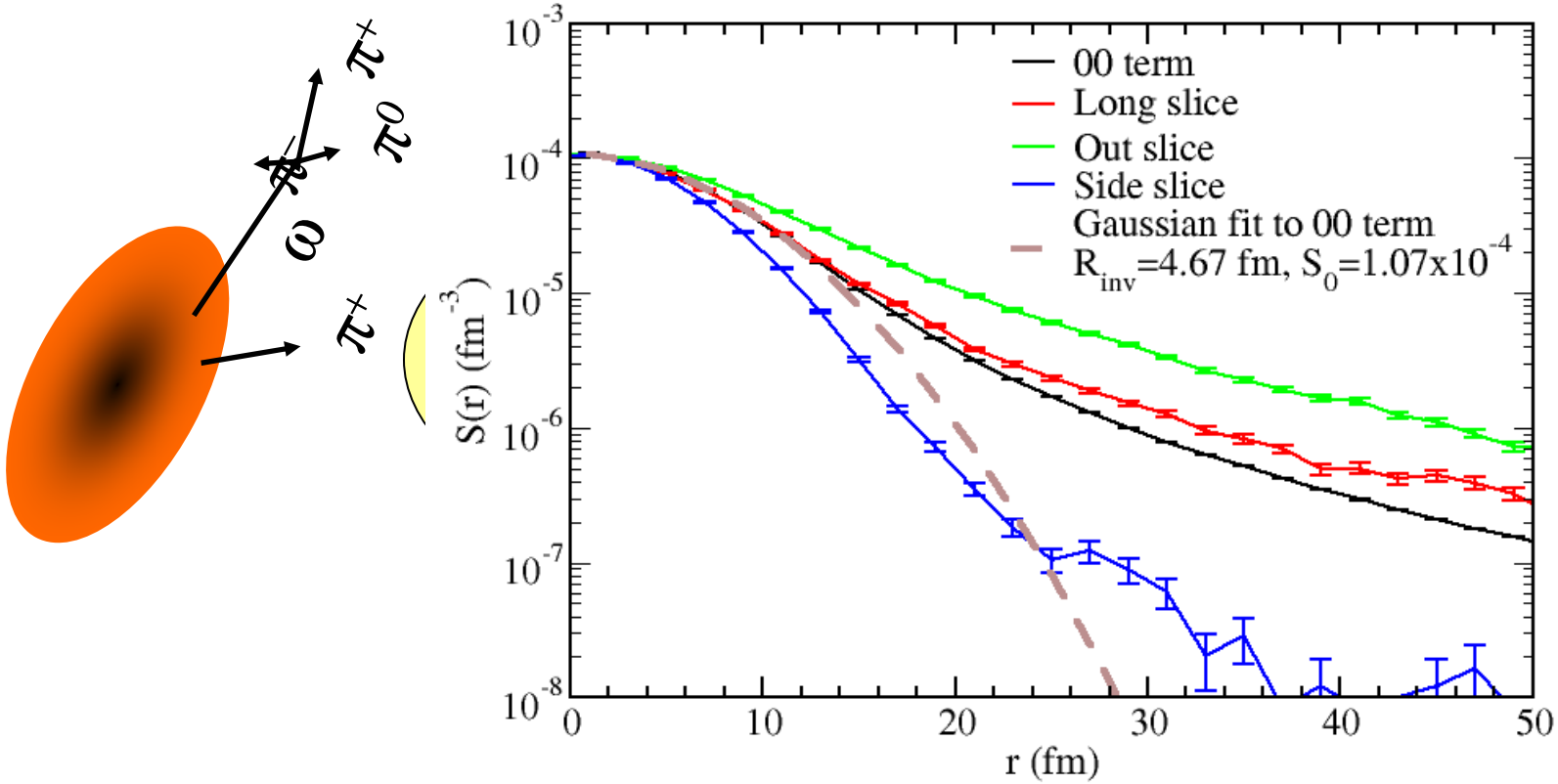
Theory indicate a crossover transition



A Cross Over strongly affects the Space-time Dynamics

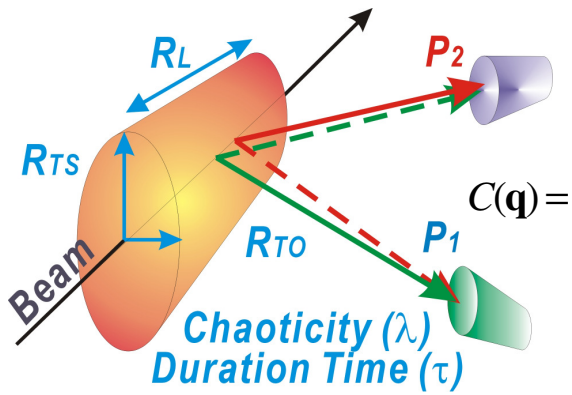
Dave Brown
WPCF - 2005

Set $R_x=R_y=R_z=4$ fm, $\tau_{f/o}=10$ fm/c, $T=175$ MeV, $f=0.56$



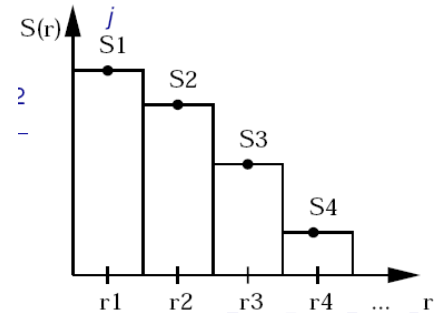
Source Imaging gives access to important space-time information which is inaccessible via "traditional approach"

Source Imaging Methodology (1D)



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

Discretize Integral



$$R_j = \sum_j 4\pi\Delta r K_0(q_i, r_j) S(r_j) \equiv \sum K_{ij} S_j$$

Vary $S(r_j)$ to minimize

$$\chi^2 = \sum_i \frac{(\sum_j K_{ij} S_j - \mathcal{R}_i^{exp})^2}{\sigma_i^2}$$

Brown & Danielewicz PRC 57(98)2474

1D Koonin Pratt Eqn.

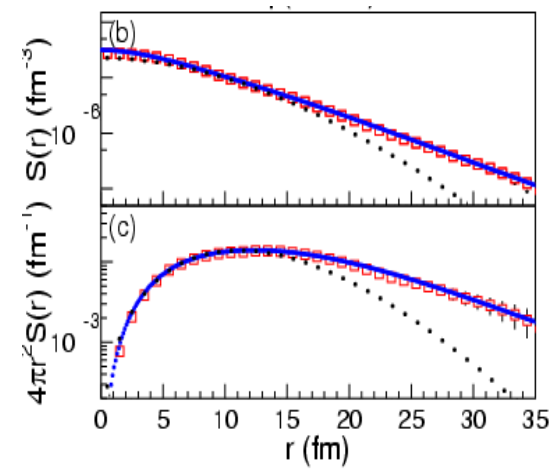
$$R(q) = C(q) - 1 = 4\pi \int dr r^2 K_0(q,r) S(r) \quad (1)$$

Correlation function

Encodes FSI

Source function (Distribution of pair separations)

Direct Fit

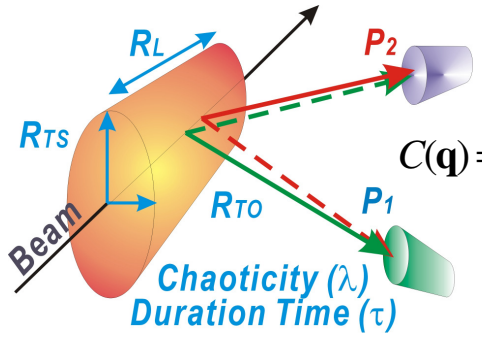


Inversion of this integral equation

➔ **Source Function**

Reliable measurement of the full 1D Source Function !

Source Imaging Methodology (3D)



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

Expand R(q) and S(r) in Cartesian Harmonic basis

(Danielewicz and Pratt nucl-th/0501003)

$$R(\vec{q}) = \sum_l \sum_{\alpha_1 \ldots \alpha_l} R^l_{\alpha_1 \ldots \alpha_l}(q)\, \mathrm{A}^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) \quad (2)$$

$$S(\vec{r}) = \sum_l \sum_{\alpha_1 \ldots \alpha_l} S^l_{\alpha_1 \ldots \alpha_l}(r)\, \mathrm{A}^l_{\alpha_1 \ldots \alpha_l}(\Omega_r) \quad (3)$$

3D Koonin Pratt Eqn.

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

Substitute (2) and (3) into (1)

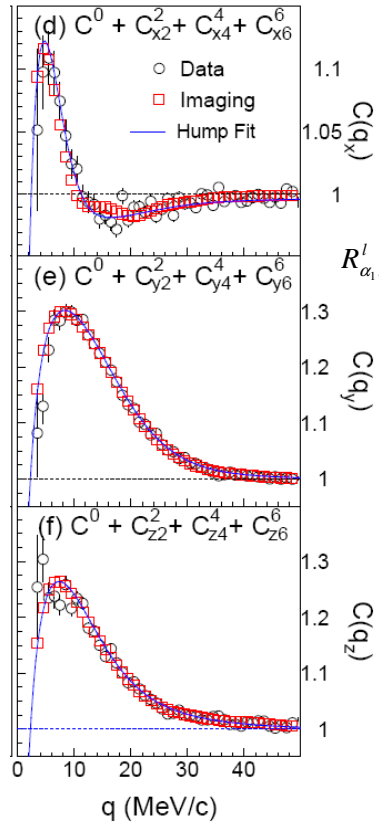
The 3D integral equation is reduced to a set of 1D relations for different l coefficients → moments

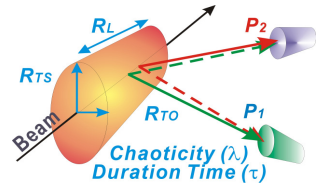
$$R^l_{\alpha_1 \ldots \alpha_l}(q) = 4\pi \int dr r^2 K_l(q,r) S^l_{\alpha_1 \ldots \alpha_l}(r) \quad (4)$$

$$R^l_{\alpha_1 \ldots \alpha_l}(q) = \frac{(2l+1)!!}{l!} \int \frac{d\Omega_q}{4\pi} \mathrm{A}^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) R(\vec{q}) \quad (4)$$

Reliable measurement of the full Source Function in 3D !

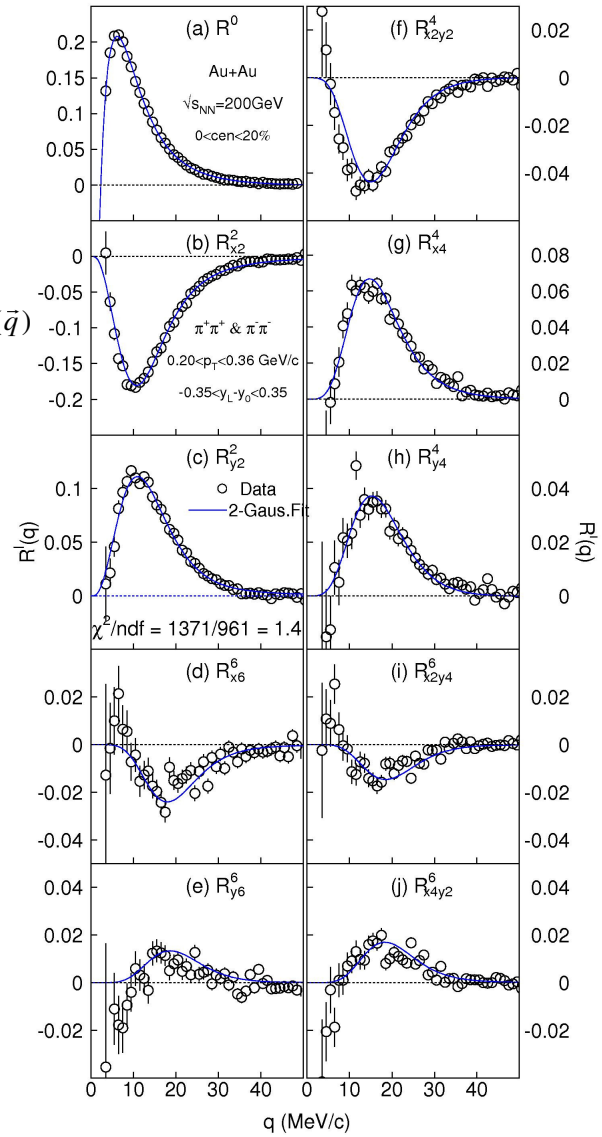
PHENIX Data





$$R^l_{\alpha_1 \ldots \alpha_l}(q) \propto \int \frac{d\Omega_q}{4\pi} A^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) R(\vec{q})$$

Correlation Moments



Contributions from $l > 6$ is negligible

$$R(\vec{q}) = \sum_l \sum_{\alpha_1 \ldots \alpha_l} R^l_{\alpha_1 \ldots \alpha_l}(q)\, A^l_{\alpha_1 \ldots \alpha_l}(\Omega_q)$$

$$S(\vec{r}) = \sum_l \sum_{\alpha_1 \ldots \alpha_l} S^l_{\alpha_1 \ldots \alpha_l}(r)\, A^l_{\alpha_1 \ldots \alpha_l}(\Omega_r)$$

Robust Experimental Source Functions obtained from moments

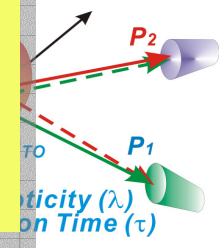
The transition is Not a Strong First order Phase Transition?

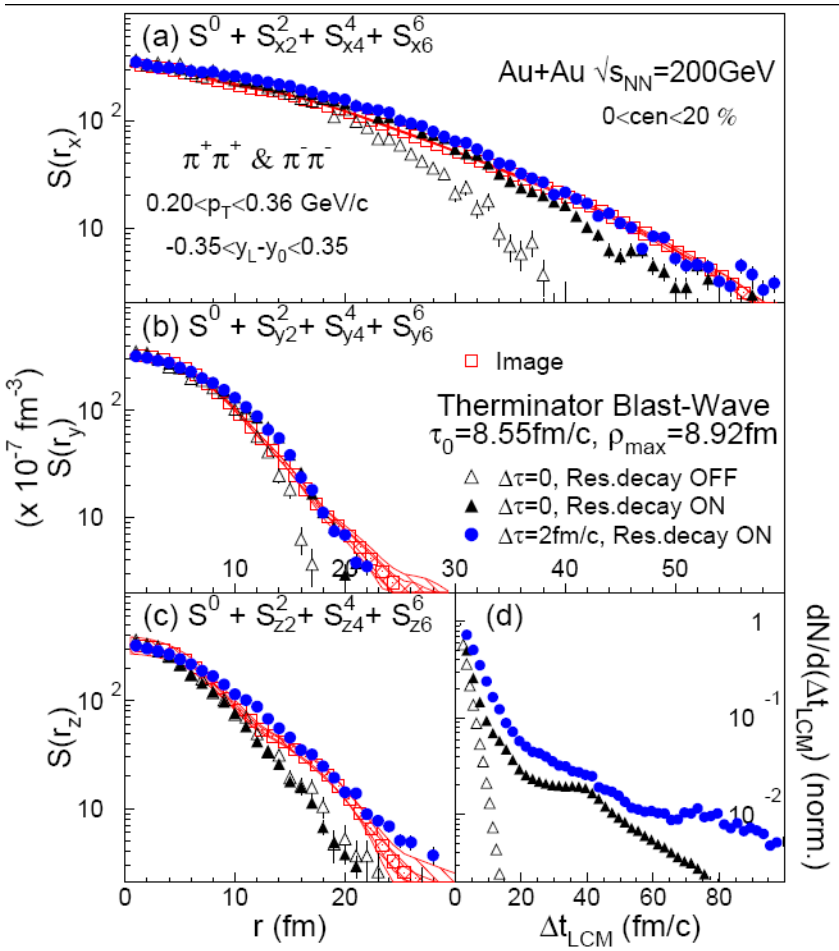
$\tau \sim 9\ fm$

$\Delta\tau \sim 2\ fm$

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

Outside-in burning





Therminator:

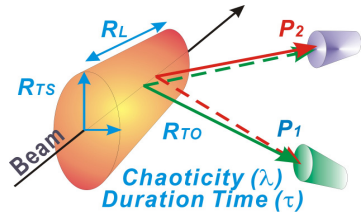
A.Kisiel et al. Comput.Phys.Commun.174, 669 (2006)

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

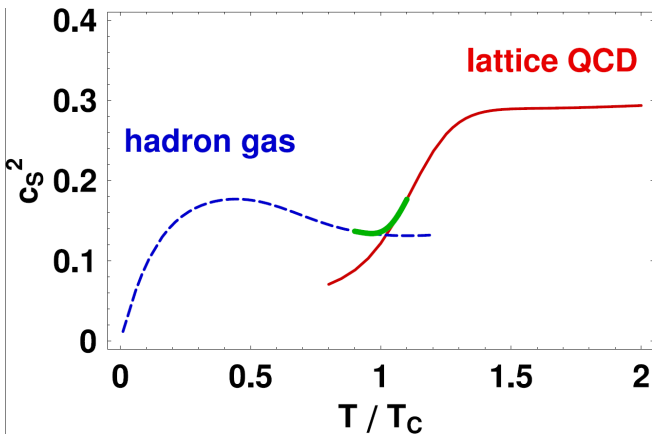
QM-2008

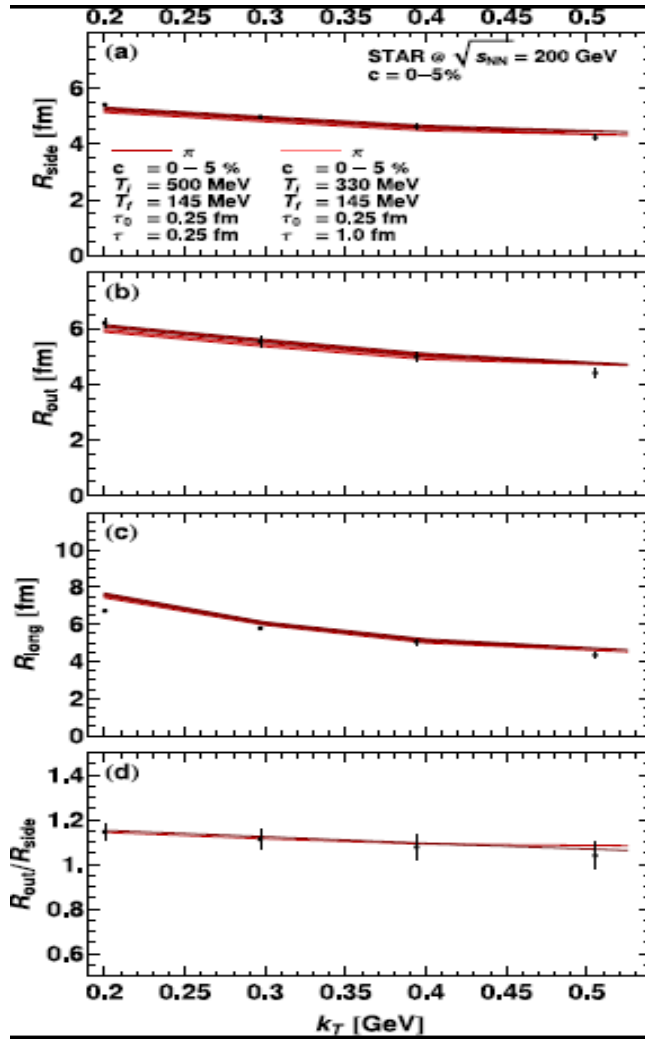


Poster 189

Mikolaj Chojnacki, Wojciech Florkowski, Wojciech Broniowski, Adam Kisiel

arXiv:0712.0947[nucl-th]



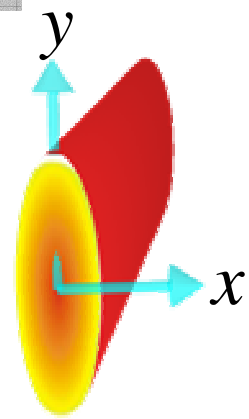


The Flow Probe

From E_T Distributions

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

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



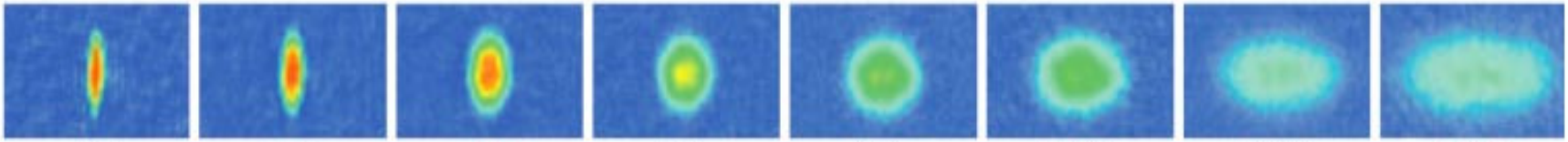
$$\left(P = \rho^2 \cdot \left(\partial\varepsilon / \partial\rho \right)\Big|_{s/\rho} \right)$$

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

Control Params.

$$\tau_0, \varepsilon,\ c_s,\ \eta$$

Expect Large Pressure Gradients → Hydro Flow



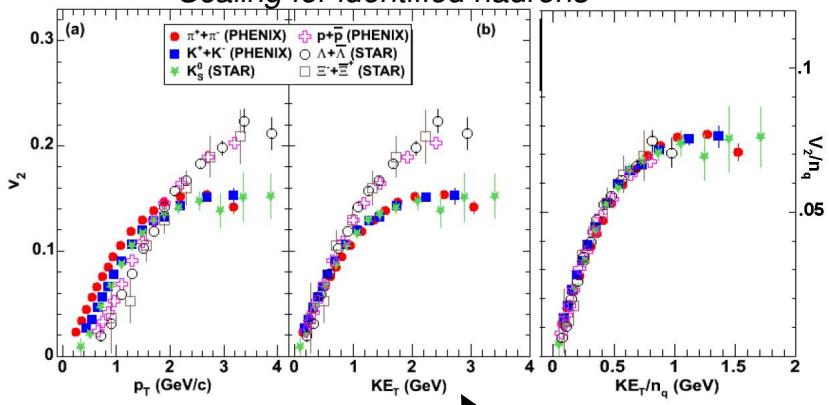
$$E\frac{d^3N}{d^3p} = \frac{1}{\pi}d^2\frac{N}{dp_T^2 dy}\left[1 + 2v_1\cos(\varphi - \Psi_R) + 2v_2(2[\varphi - \Psi_R]) + \ldots\right] \rightarrow v_2 = \langle \cos(2[\varphi - \Psi_R]) \rangle$$

Substantial elliptic flow signals should be present for a variety of particle species → → Constraints for sound speed and viscosity

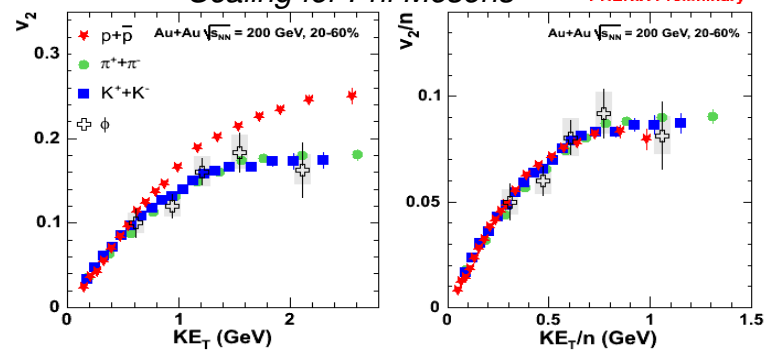
Detailed integral and differential Measurements now available for

$$h, p, \pi, K, \Lambda, \Omega, \phi, \Xi, d, D$$

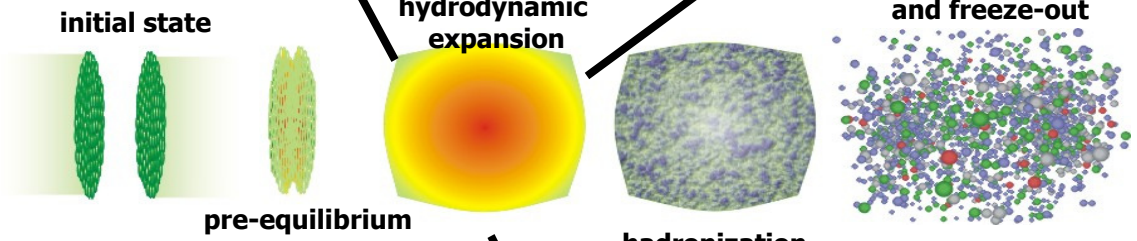
Scaling for identified hadrons



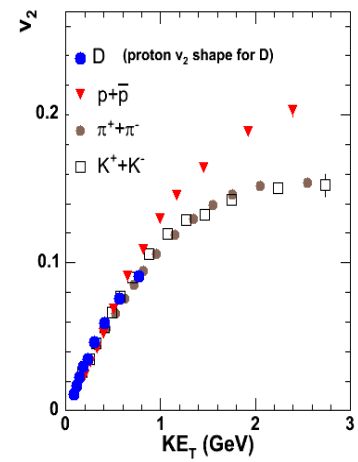
Scaling for Phi Mesons

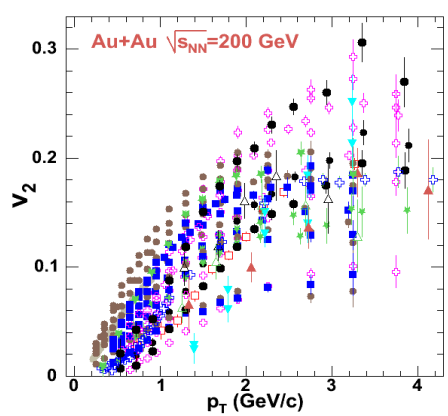


Courtesy S. Bass

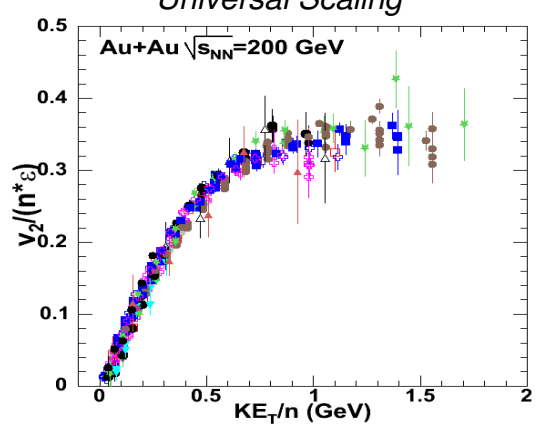


Scaling for Heavy Quark





Universal Scaling

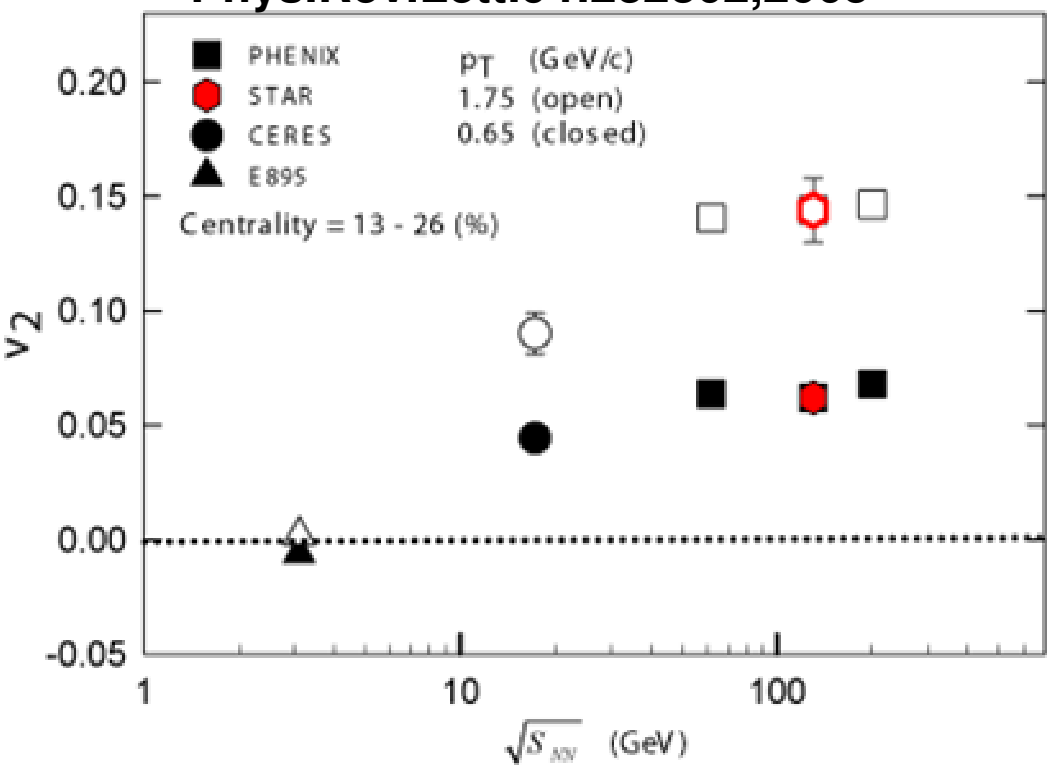


We hold these truths to be self evident !

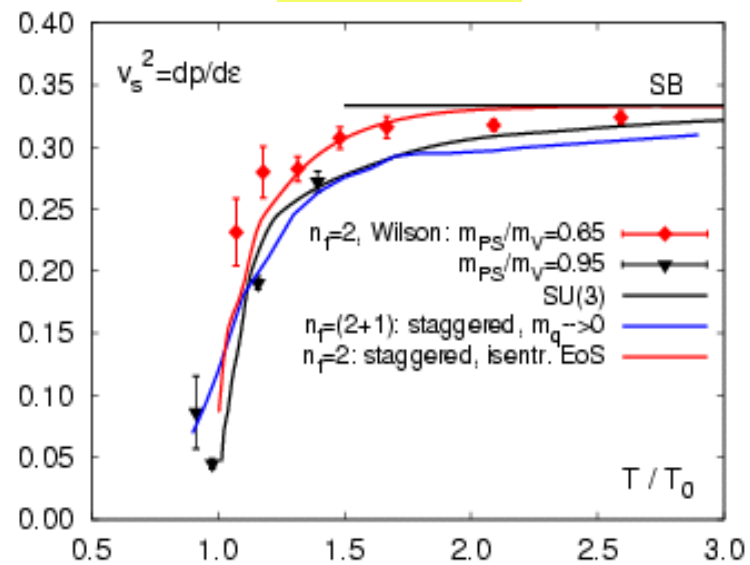
Roy A. Lacey, Stony Brook; BNL, April 18, 2007

The expected saturation of v_2 Is observed

Phys.Rev.Lett.94:232302,2005



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



F. Karsch, hep-lat/0601013

Saturation of Elliptic flow consistent with a soft EOS associated with Crossover

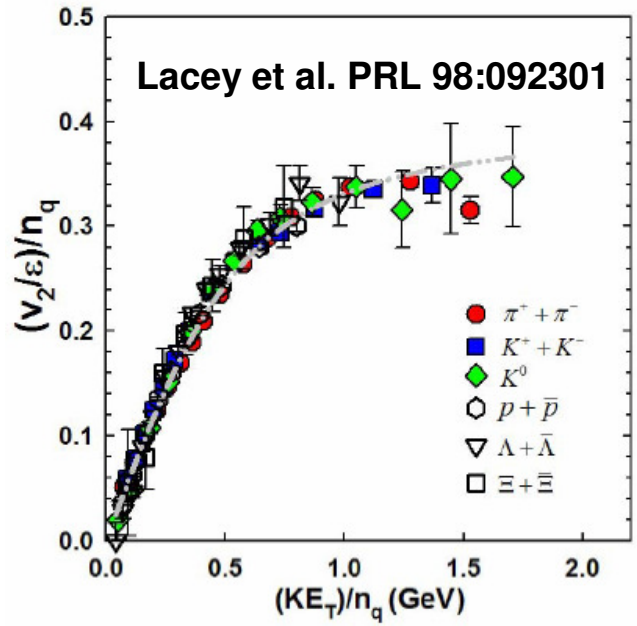
Partonic Fluid Flow Is near Perfect

$$\omega^2 - v_s^2 + iD_l \omega k^2 = 0$$

$$D_t = \frac{\eta}{Ts} \qquad D_l = \frac{4\eta/3 + \varsigma}{Ts}$$

$$\frac{\eta}{s} \sim T\lambda_f c_s, \qquad \sim 1.3\times\left(\frac{1}{4\pi}\right)$$

$$\Gamma_s = \frac{4}{3}\frac{\eta}{sT} \sim 0.16\,fm$$

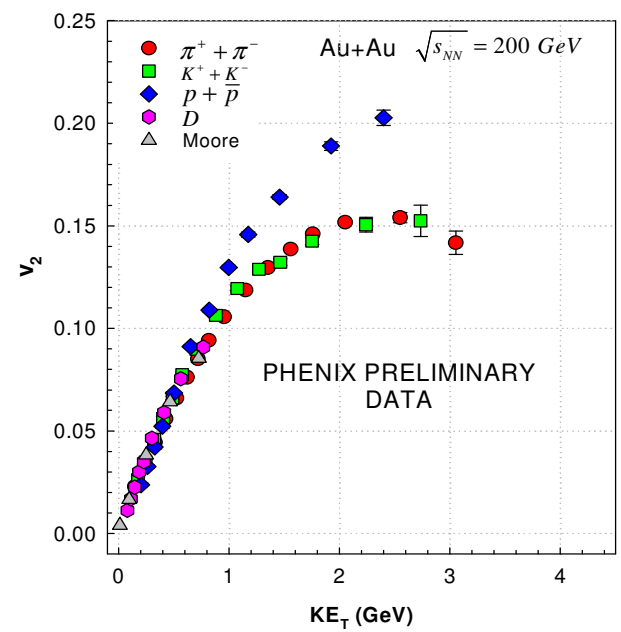


Model Comparison

$$\frac{\eta}{s} \sim 1.9\times\left(\frac{1}{4\pi}\right)$$

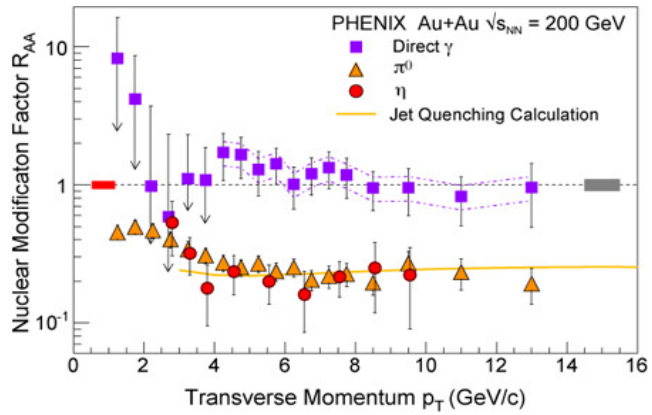
$$D \sim \frac{3}{2\pi T} \sim 0.5\,fm$$

$$\tau_{Relax} = \frac{1}{\eta_D} = \frac{M}{T} D \sim 4\,fm$$

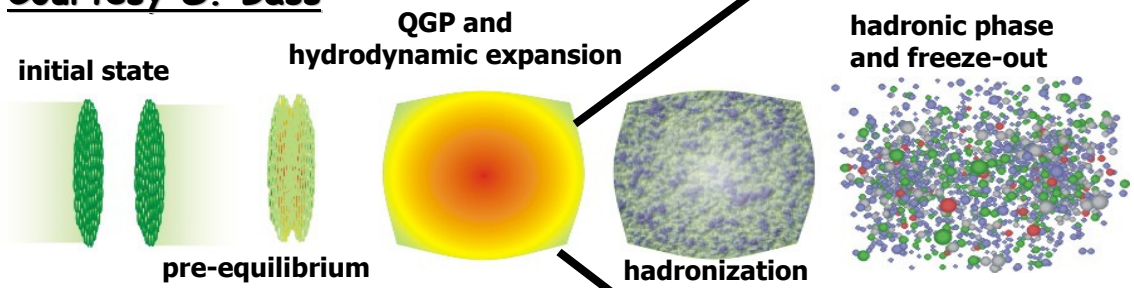


$\frac{\eta}{s} \sim$ ***1-2 X the conjectured lower bound***

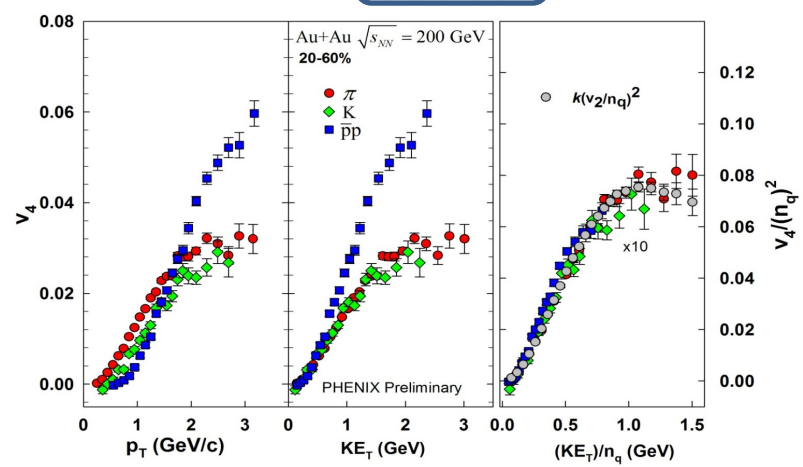
A Crossover transition to the strongly coupled thermalized QGP occurs at RHIC



Courtesy S. Bass

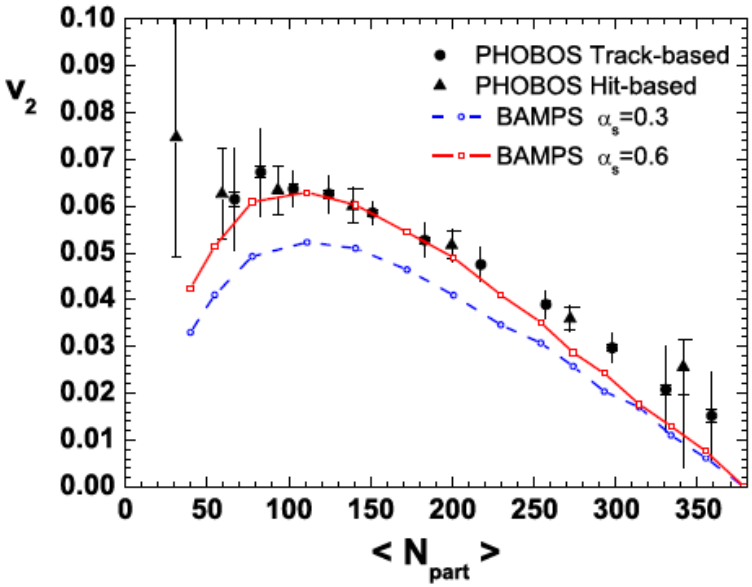


$$\frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)} \approx \frac{1}{2}$$



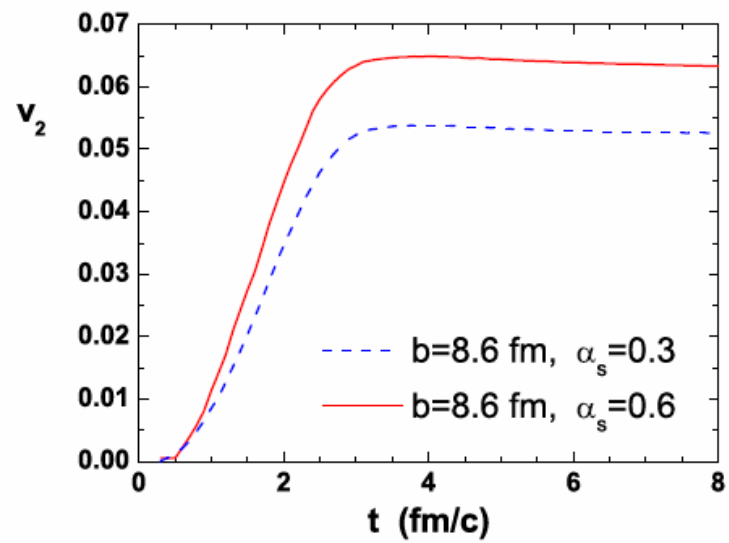
We hold these truths to be self evident !

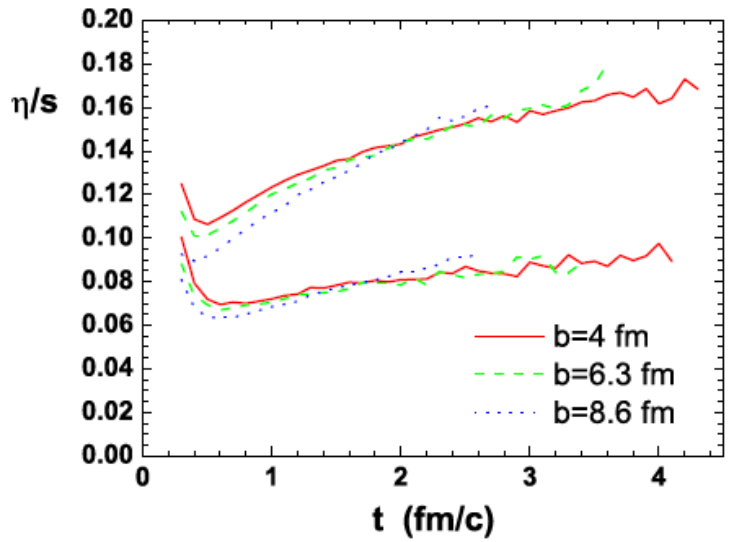
Transport Coefficient



C. Greiner et al

$$4\pi\frac{\eta}{s} \sim 1-2$$



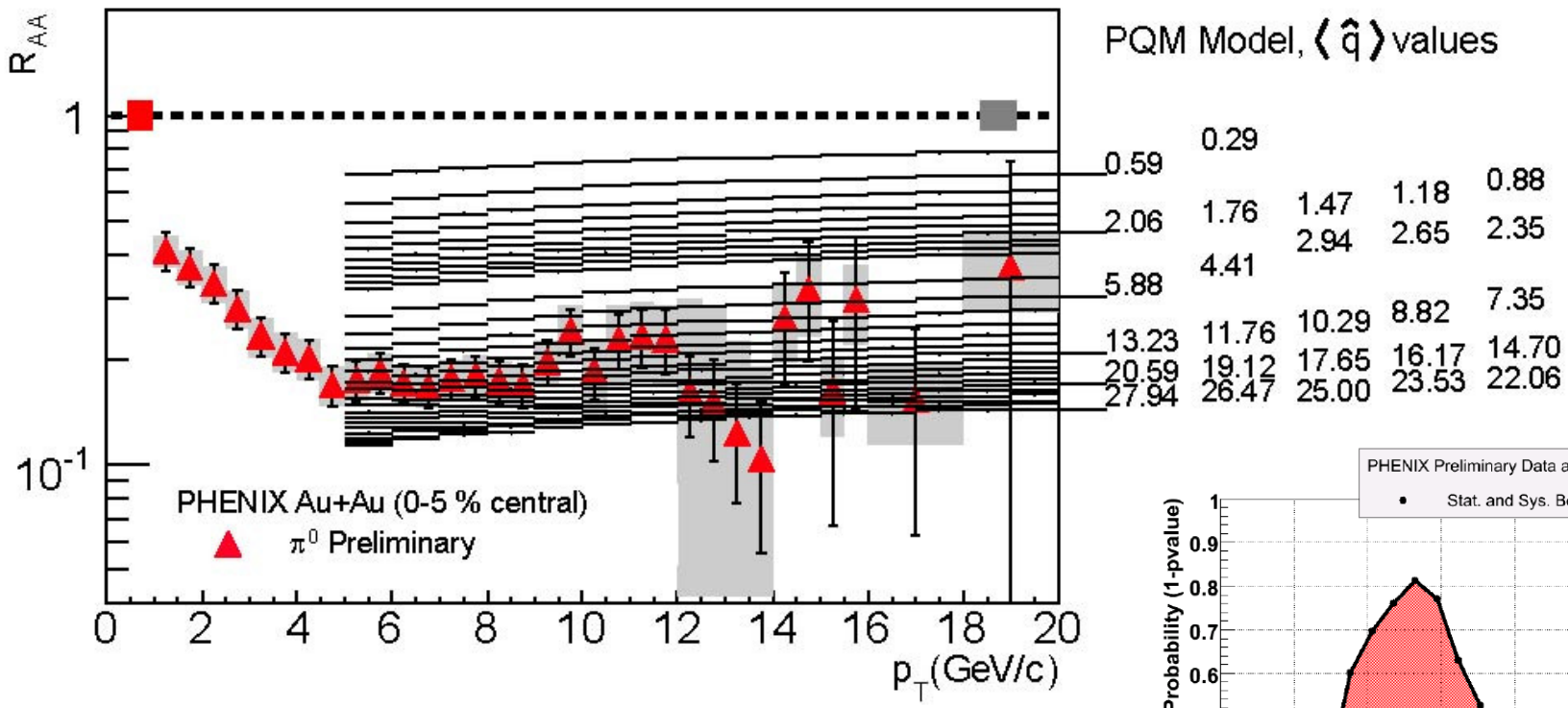


Thermalization facilitated by 2→3 processes

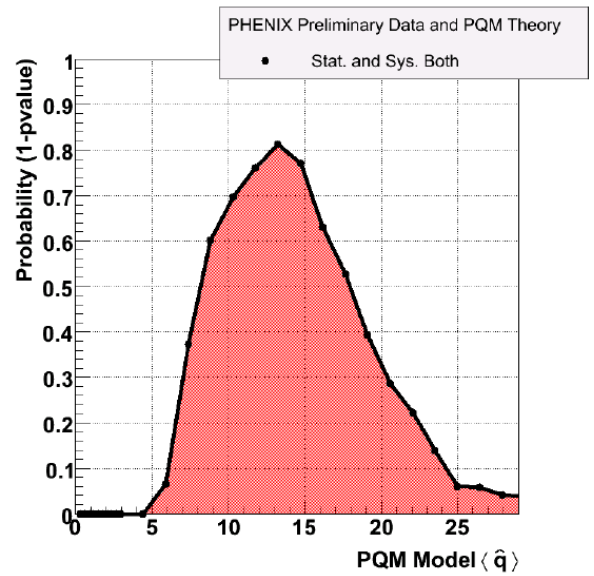
Small viscosity results in large suppression

$$\frac{\eta}{s} \geq 3.75C \times \left(\frac{T^3}{\hat{q}}\right)$$

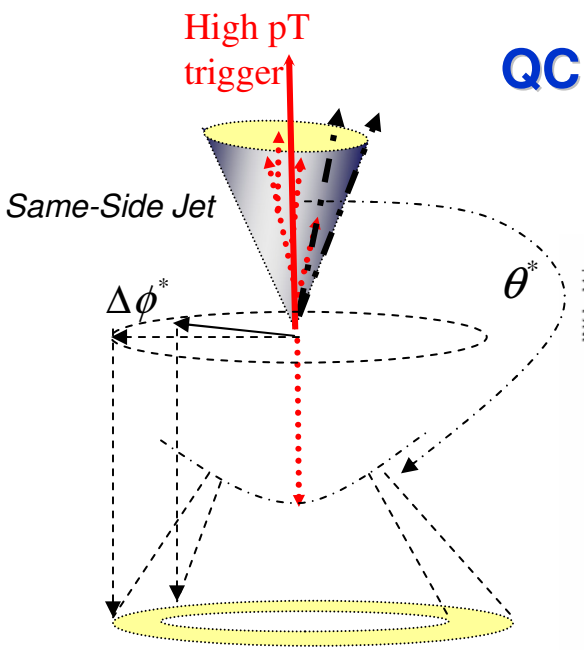
An estimate of the scattering power



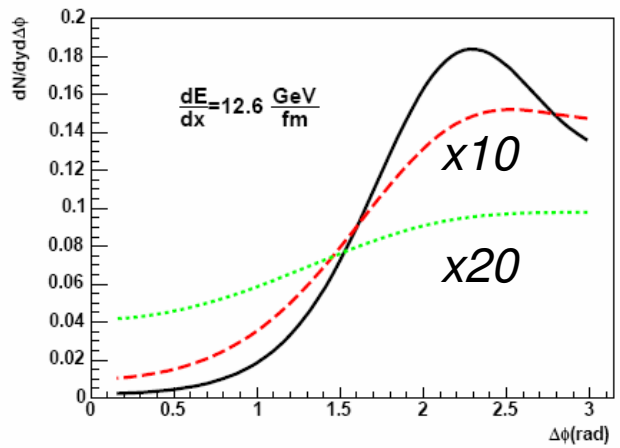
$$6 \leq \langle \hat{q} \rangle \leq 24 \ \ \mathrm{GeV}^2/\mathrm{fm}$$
$$(\mathrm{Probability} > 10\%)$$

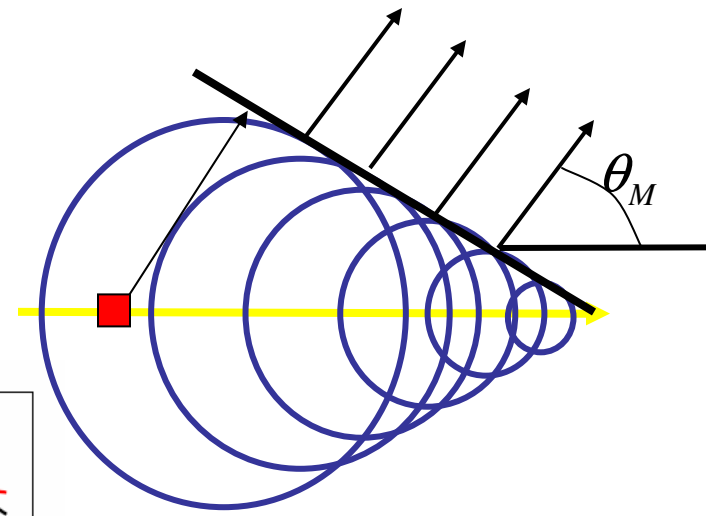


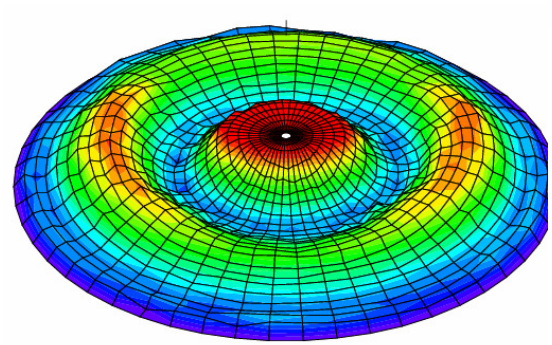
Setting an upper limit on The viscosity



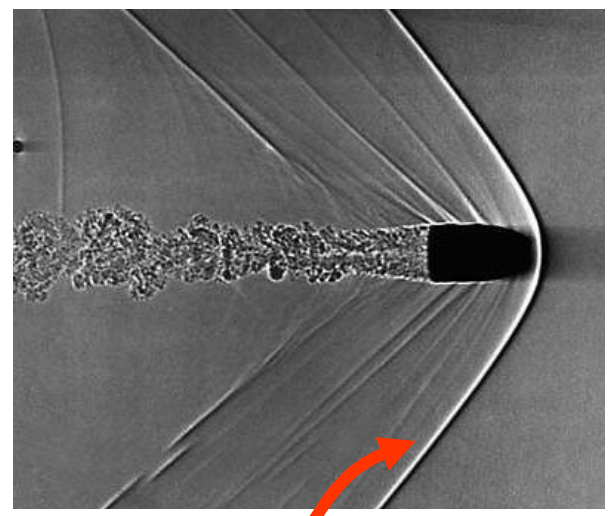
QCD Sonic Boom







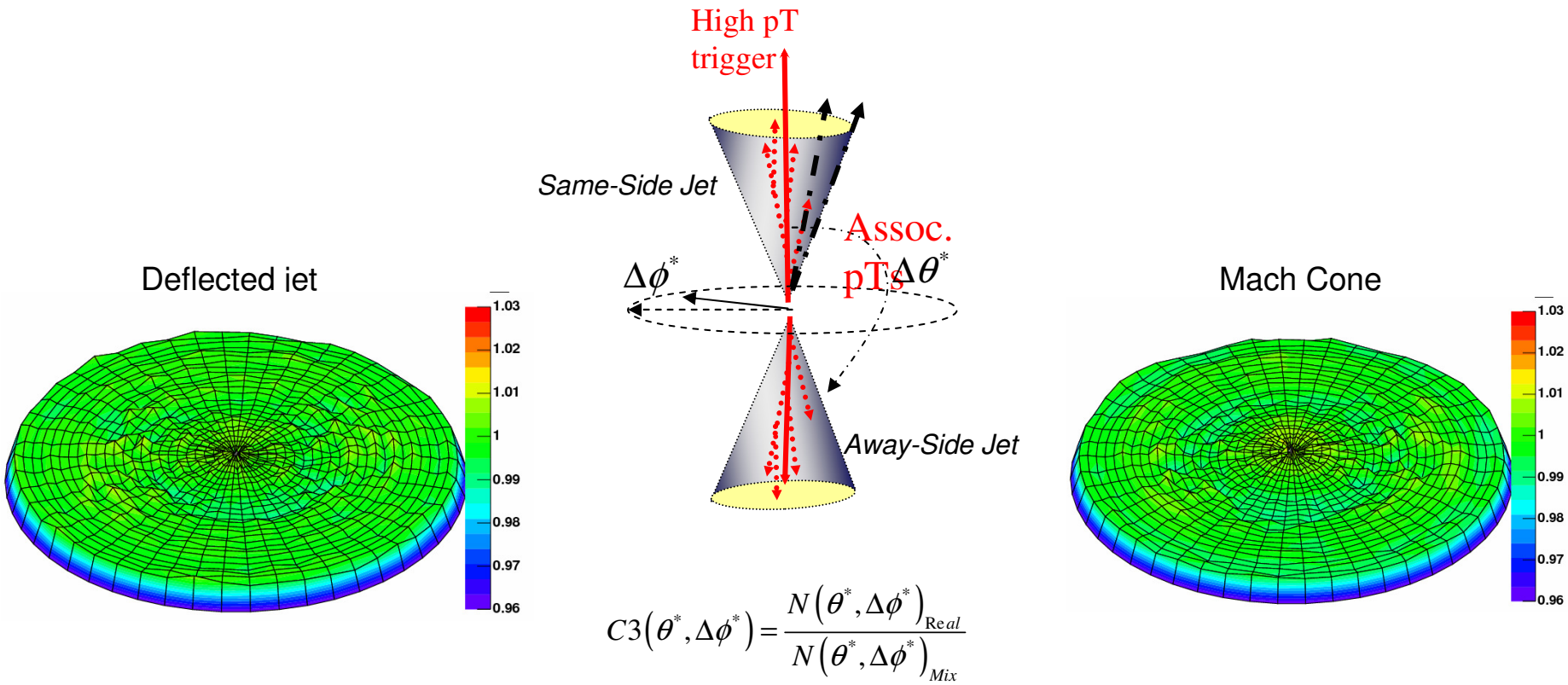
$$\Gamma_s = \frac{4}{3}\frac{\eta}{sT} \sim 0.1,\ 0.2,\ 0.5 \left(\frac{1}{T}\right)$$



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

Gives sound speed directly; Sets upper limit on viscosity.

Validation test of the use of two event mixing to remove 2+1 processes

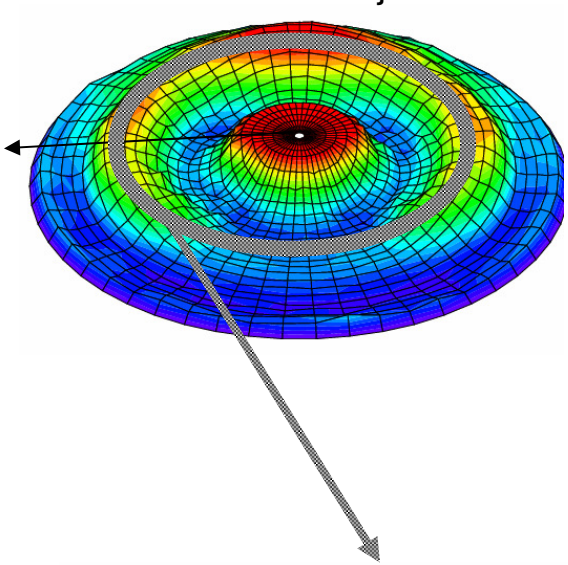


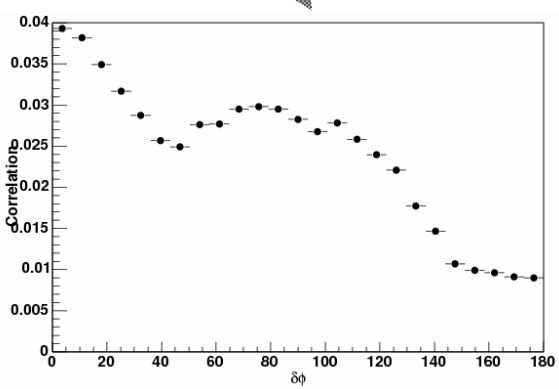
$$C3\left(\theta^*,\Delta\phi^*\right)=\frac{N\left(\theta^*,\Delta\phi^*\right)_{Real}}{N\left(\theta^*,\Delta\phi^*\right)_{Mix}}$$

(2+1) processes efficiently removed via two-event mixing to obtain true three particle correlations

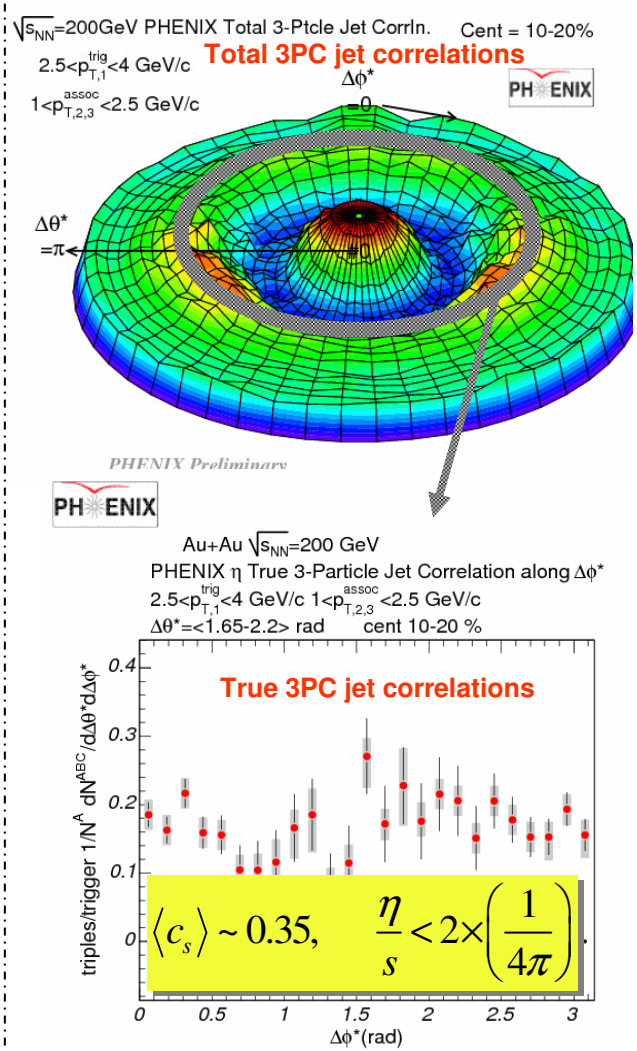
QCD Sonic Boom?

Simulated
Deflected jet

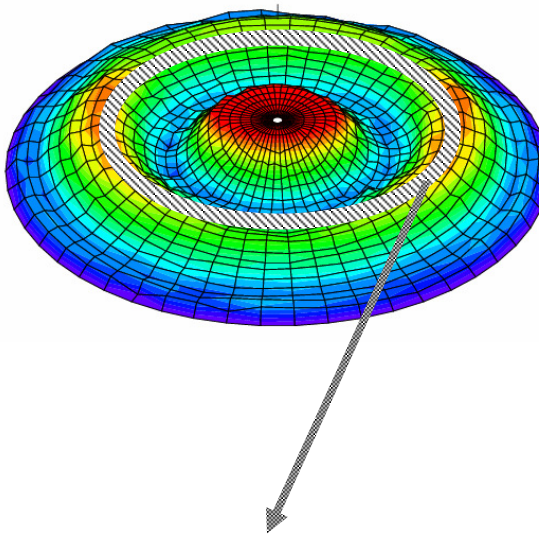


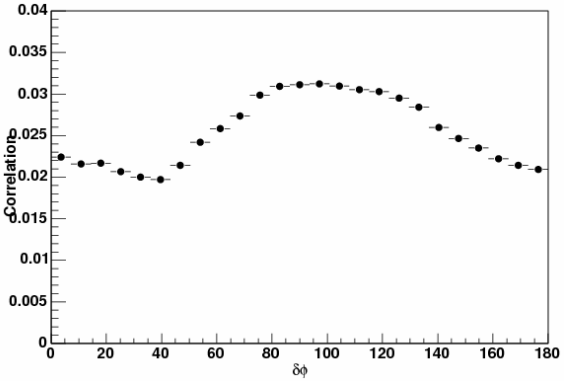


Data



Simulated
Mach Cone

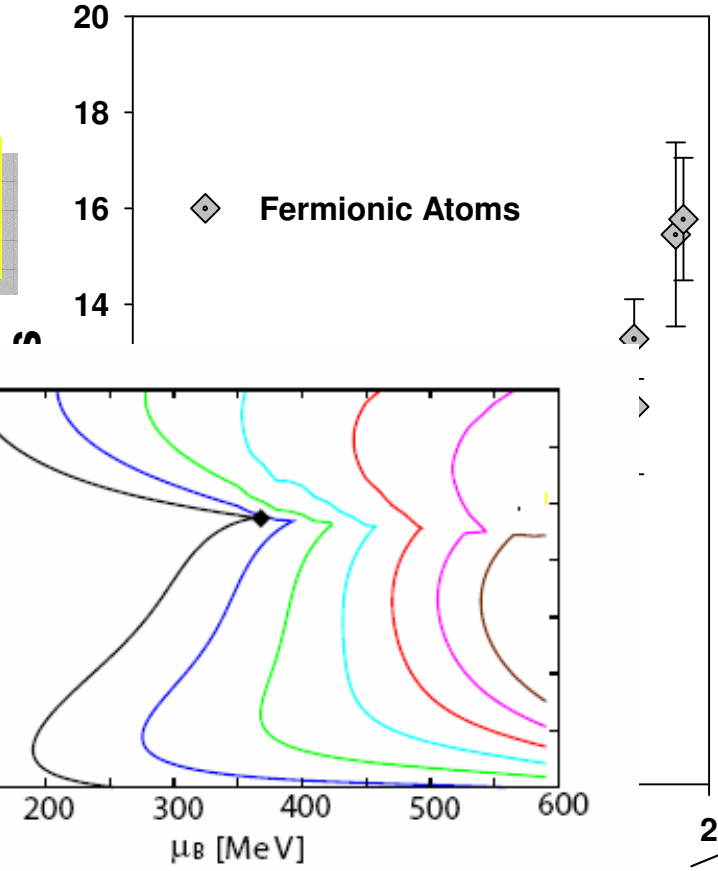




The data validates the presence of a Mach Cone away-side jet

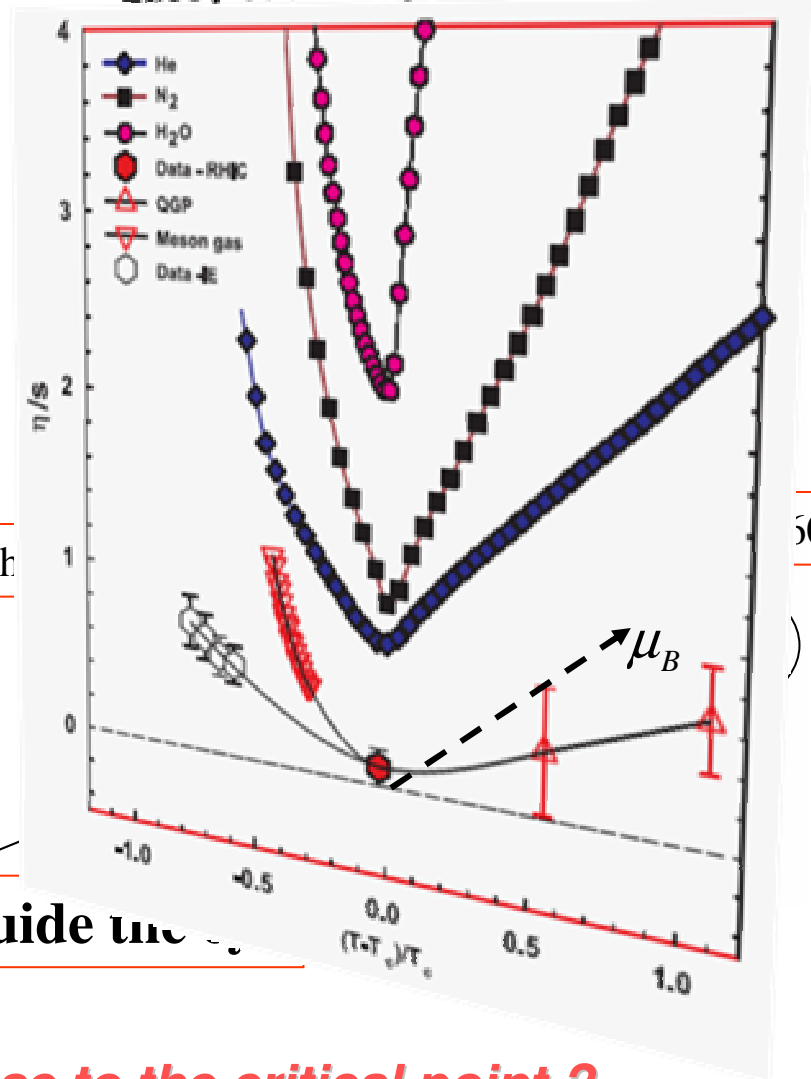
Hints of the CEP?

$$\frac{\eta}{s} \sim 0.2$$



Nonaka et al.

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

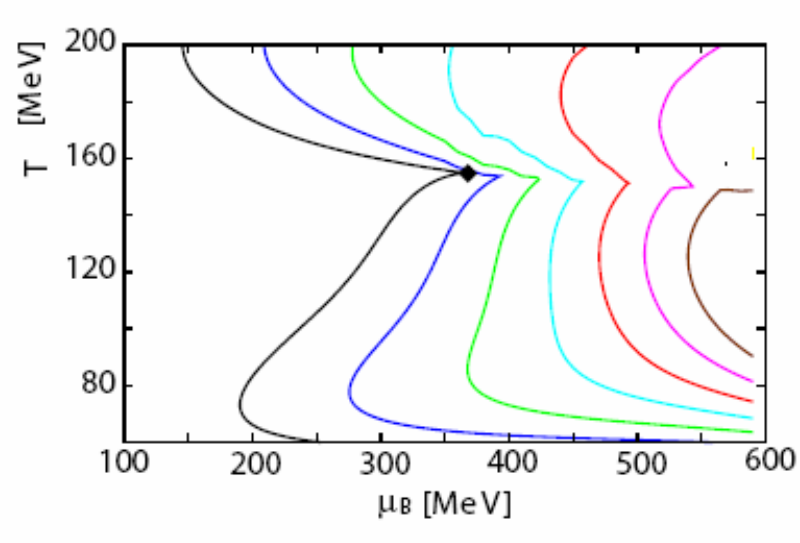


Curves to guide the

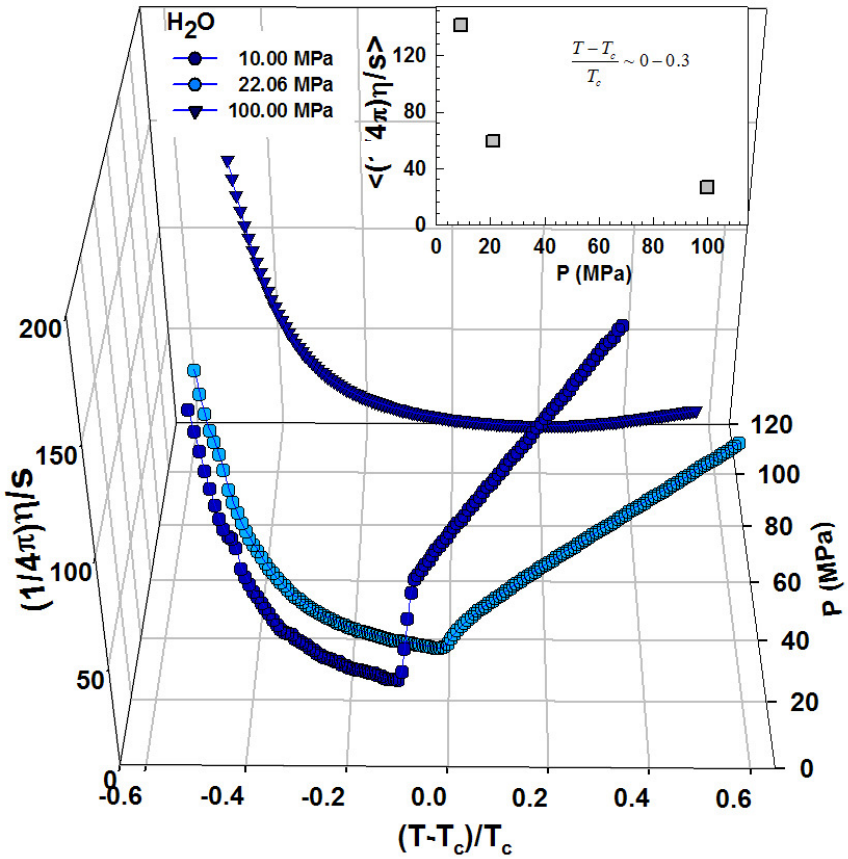
Low $\frac{\eta}{s}$ ***Suggest trajectories close to the critical point ?***

How to get there?

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

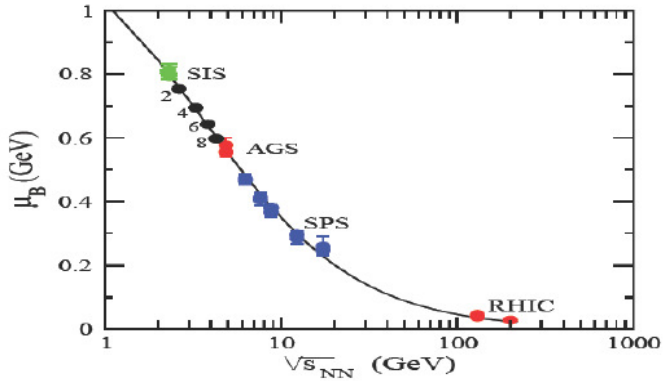


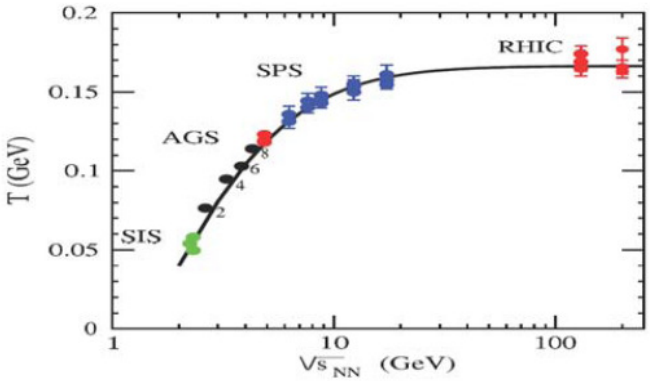
Nonaka et al.

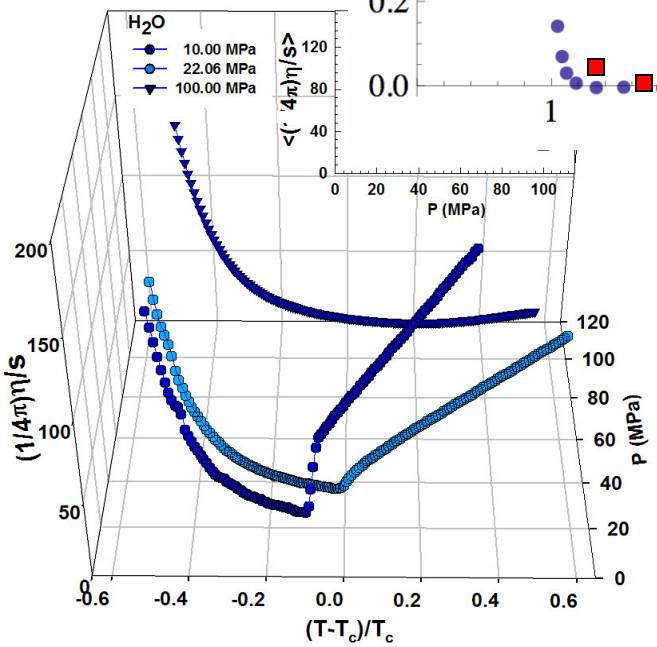


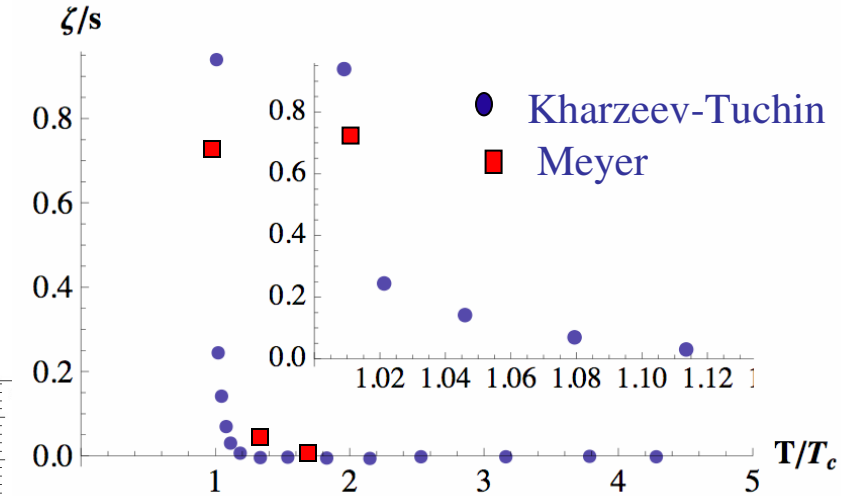
$\frac{\eta}{s}$ ***is a potent signal for the CEP***

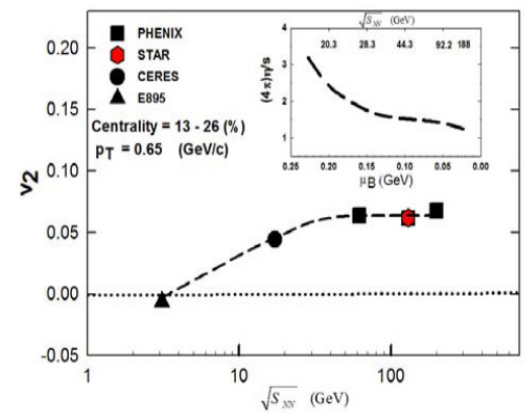
How to find the CEP?











$\frac{\eta}{s}$ & $\frac{\xi}{s}$ *are a potent signals for the CEP*

First estimate T ~ 165-170 μ ~ 120-150 MeV
Need two energies immediately