Is the quark gluon plasma strongly or weakly coupled?

Roy A. Lacey

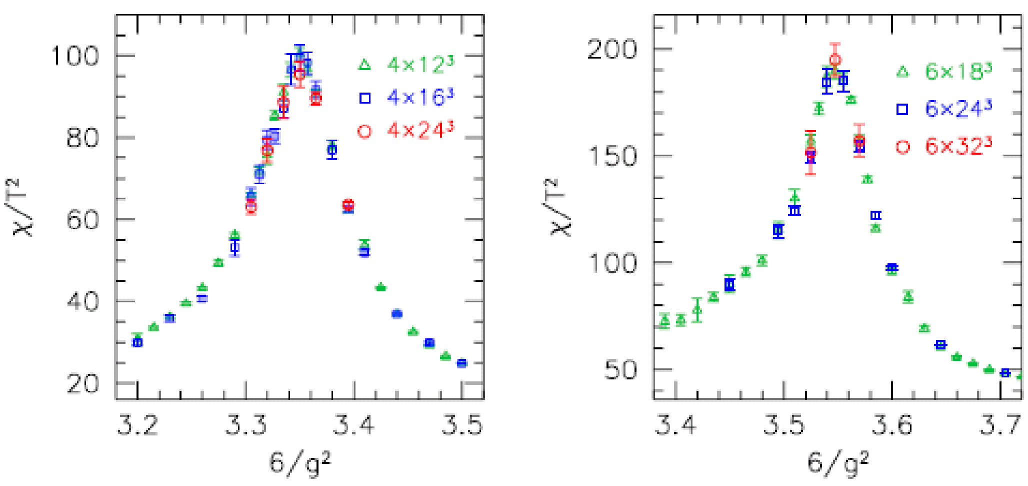
NUCLEAR CHEMISTRY
@ STONY BROOK

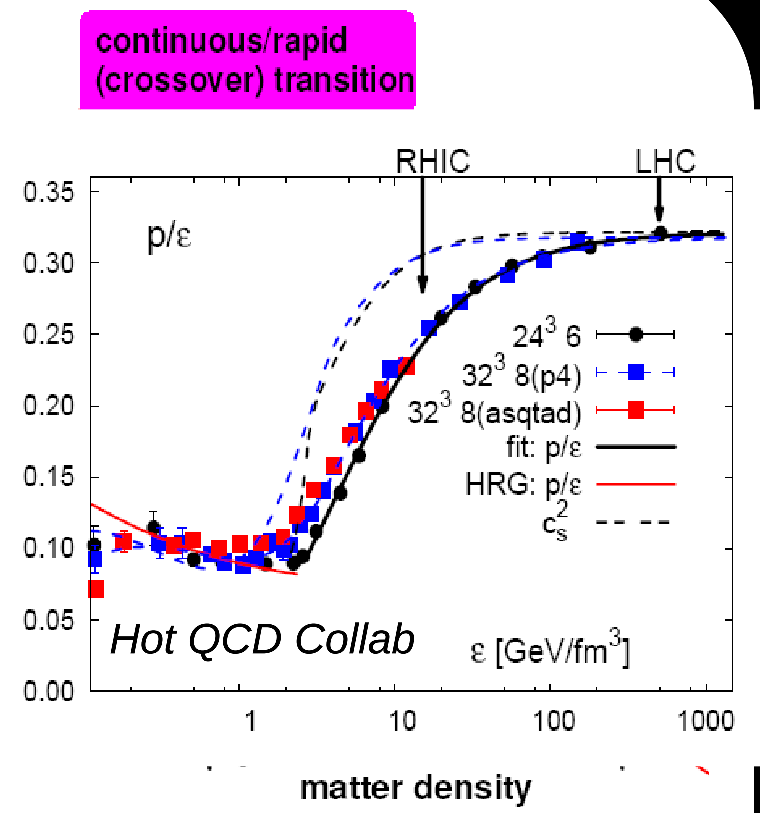
What Motivates the Search for the Critical end point (CEP)?

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

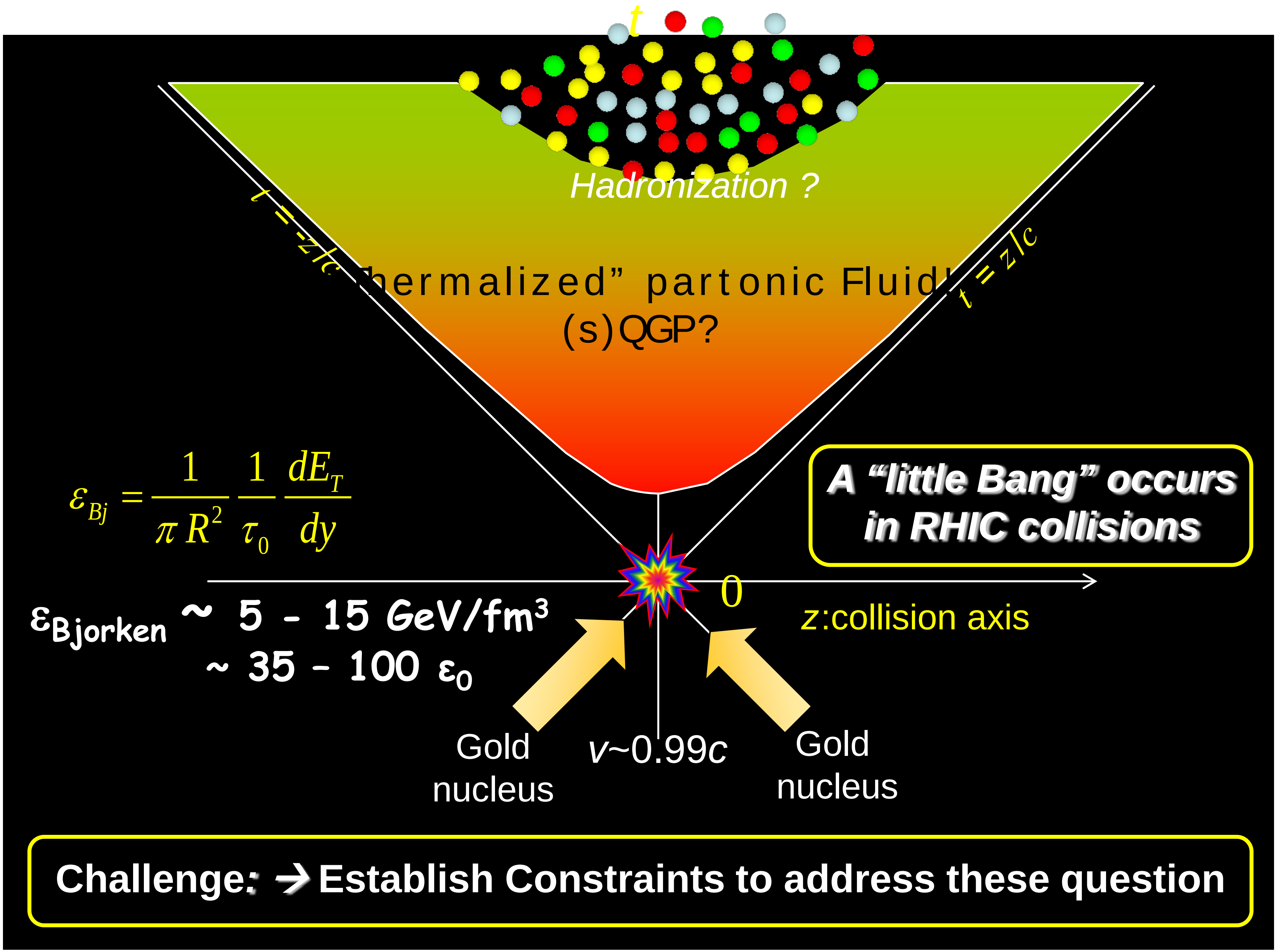
Discovery of the crossover transition from the Quark

Aoki et al





The Crossover is a necessary requirement for existence the CEP


t
Hadronization ?
"Thermalized" partonic Fluid!
(s)QGP?
t = -z/c
t = z/c
$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$
A "little Bang" occurs in RHIC collisions
0
z:collision axis
$\varepsilon_{Bjorken}$ ~ 5 - 15 GeV/fm^3
~ 35 - 100 ε_0
Gold nucleus
v~0.99c
Gold nucleus
Challenge: → Establish Constraints to address these question

Truth, Myth or Propaganda ?

The QGP is strongly Coupled!

Yes!
E. V. Shuryak,
Nucl. Phys. A750, 64 (2005)
η/s is very small

The qu… the QGP
produc… strongly
co… ed !

The related question as to the degree of local Equilibrium achieved is also unsettled?

Perhaps Not!

No!
N. Borghini and J.-Y. Ollitrault,
Phys. Lett. B642, 227
65 (2006),

Truth, Myth or Propaganda ?

The degree of local Equilibrium is known!

How do we address the strength of the coupling and the degree of thermalization?

Prerequisite: First Rate Flow Data

The extraction of a small value of η/s linked to a short mean free path λ, would lend decisive insight

Viscous hydro

Transport

Several Hybrids of Hydro and Transport

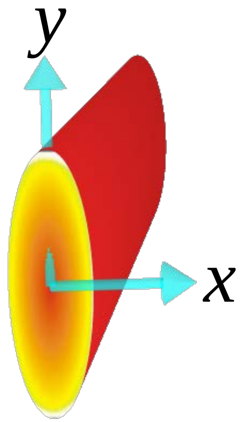
First rate differential flow data is an asset!

Why Flow Measurements?

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.

$\tau_0,\ \varepsilon,\ c_s,\ \eta$
$+FrzOut$

Expect Large Pressure Gradients → Hydro Flow

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

→

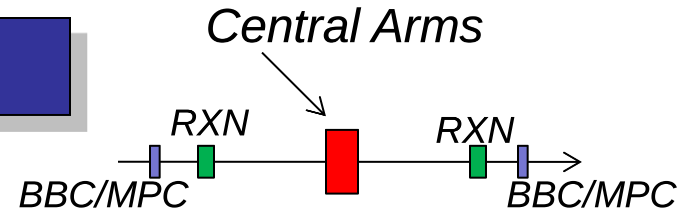
$$v_n = \langle\cos(2n[\varphi - \Psi_R])\rangle$$

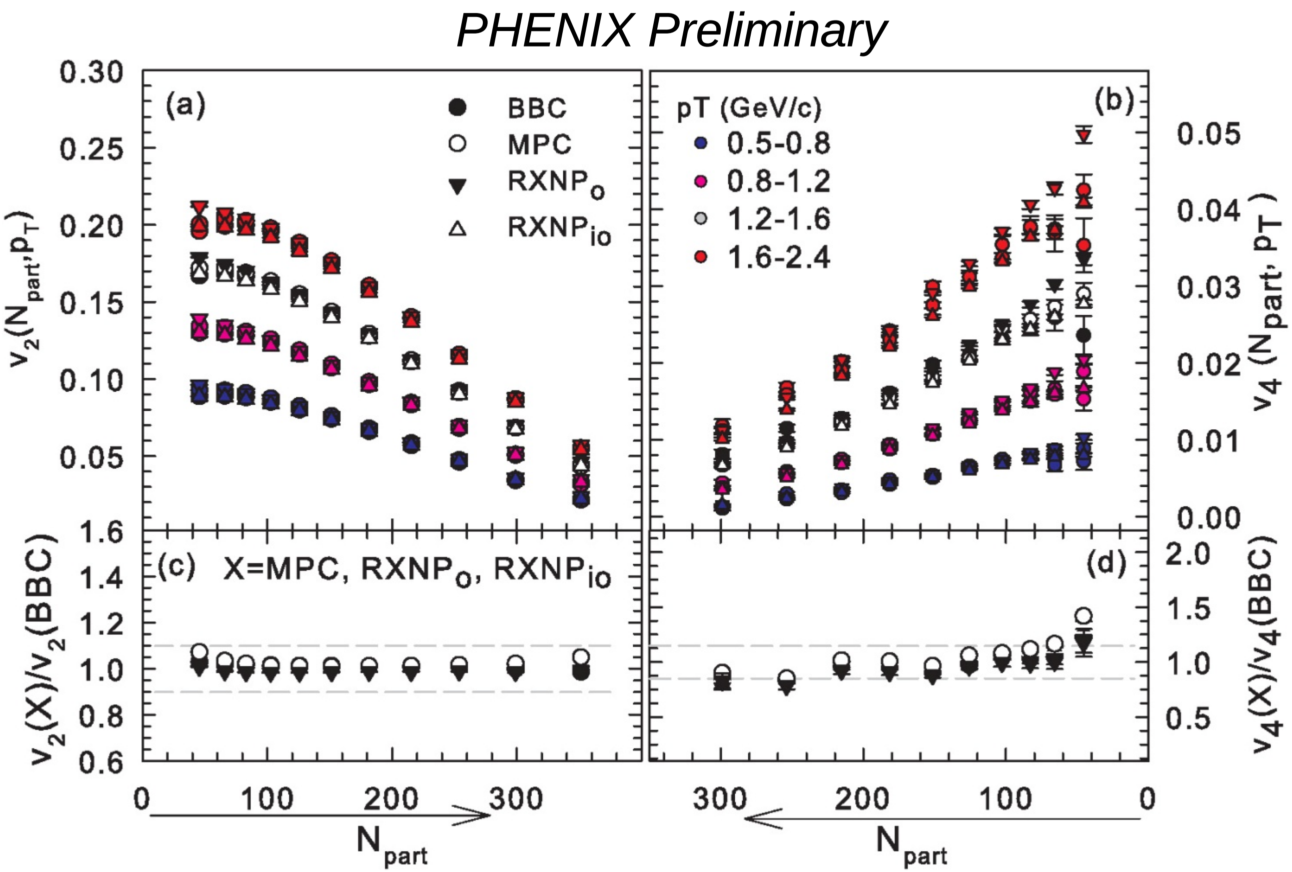
Deviations of Elliptic & hexadecapole flow from ideal hydrodynamic expectations -> Constraints for thermalization, sound speed, viscosity, etc.

Detailed integral and differential Measurements now available

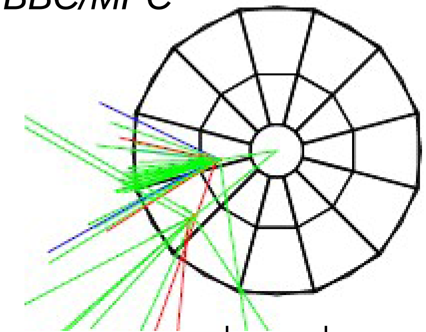
What do they tell us ?

Recent Measurements





New RXN detector



$$3.1 < |\eta_{BBC}| < 3.9$$

$$3.1 < |\eta_{MPC}| \lesssim 3.9$$

$$1.5 < |\eta_{RXN_i}| < 2.8$$

$$1.0 < |\eta_{RXNo}| < 1.5$$

$$1.0 < |\eta_{RXN_{io}}| < 2.8$$

Event planes

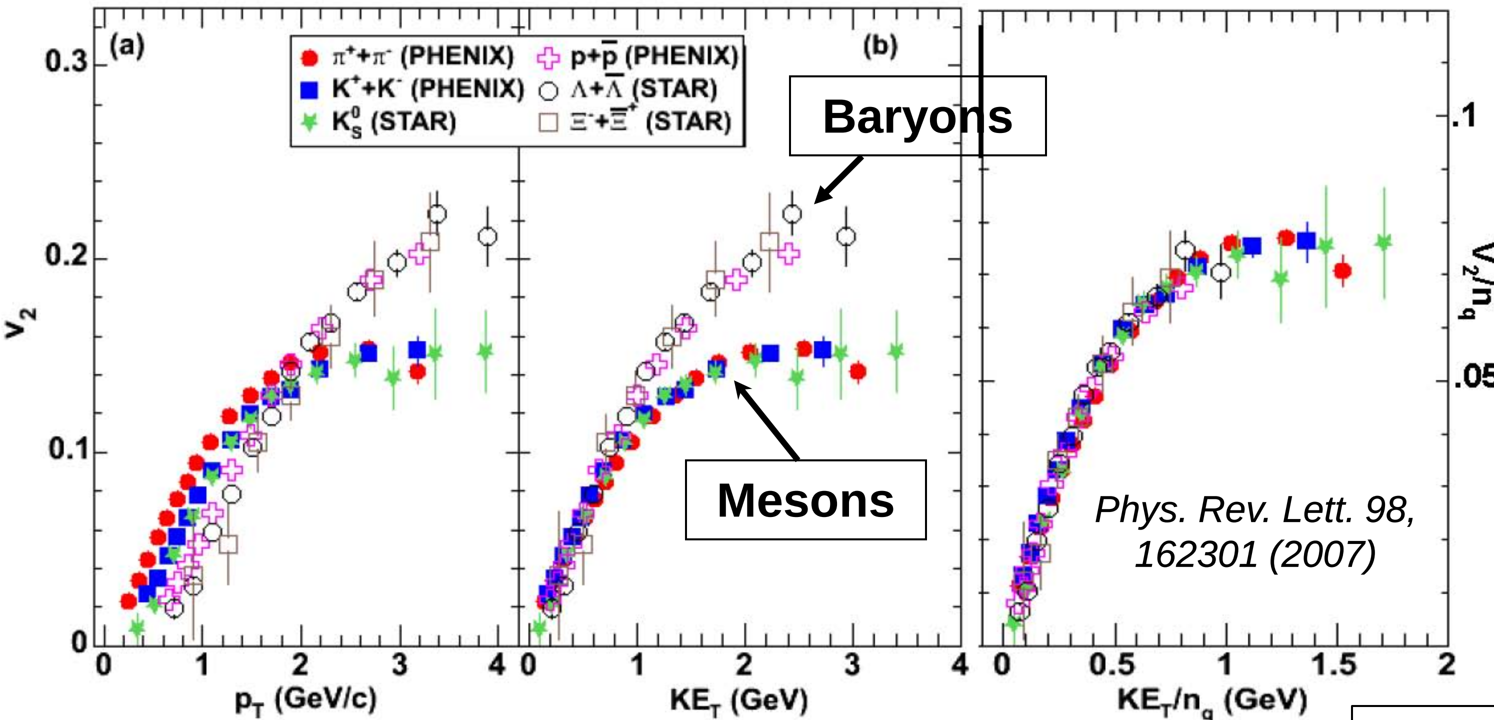
Five separate measurements of v_2 and v_4 in the same experiment is decisive

KE_T – CQN Scaling

$KE_T = m(\gamma_T - 1)$

$P \propto$ Kinetic Energy Density

It is often argued that Strong coupling is Incompatible with quark degrees of freedom



$$\eta = \rho v l$$

$$s \sim n = \frac{\rho}{m}$$

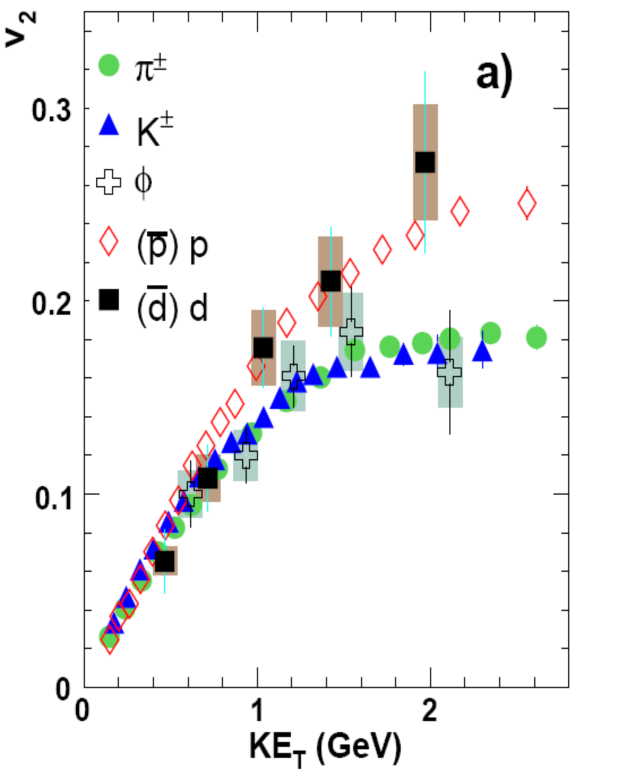
$$\frac{\eta}{s} \sim m v l$$

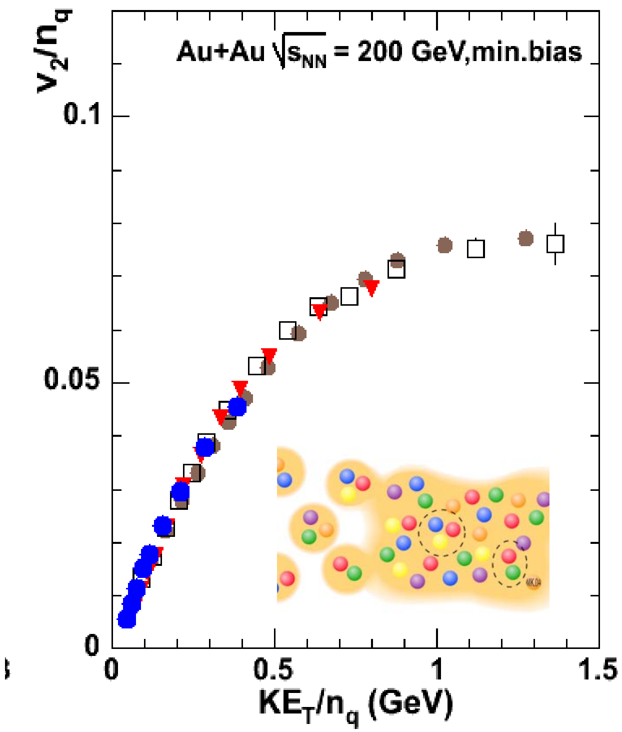
$$\sim \hbar \frac{\lambda}{\lambda_{dbr}}$$

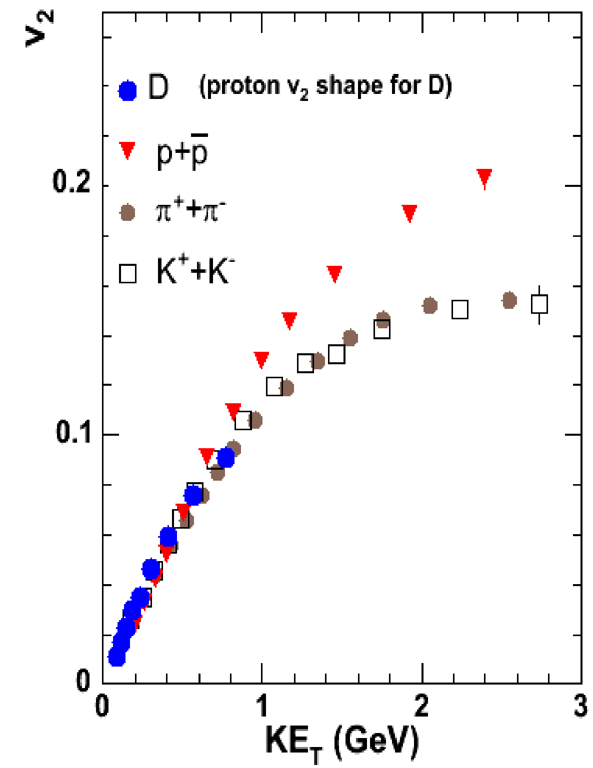
Quark-Like Degrees of Freedom Evident
Indication of strong coupling?

This argument against quark degrees of freedom is therefore ill-informed!

CQN & KE_T Scaling for OZI suppressed particle species & Heavy quarks







v2 for the φ follows that of other mesons

$$v_2^{hadron}(KE_T^{hadron}) \approx n v_2^{quark}(KE_T^{quark})$$
$$KE_T^{hadron} \approx n KE_T^{quark}$$

v2 for the D follows that of other mesons

A Phase with Quark-like dynamical degrees of freedom Dominates the flow – hadronic contributions not significant

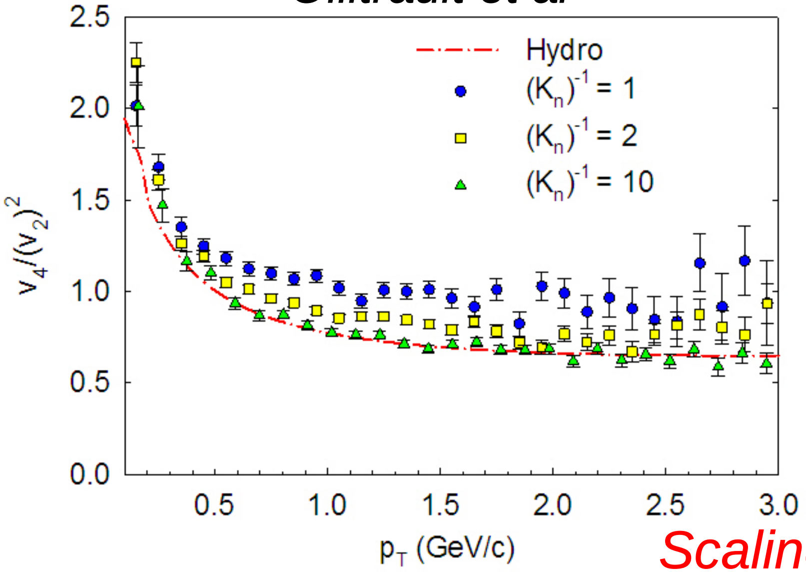
Is there value added for v_4 Measurements?

Recombination

Predicted Signal for hydrodynamic behavior -> local equilibrium

$$\frac{v_4}{(v_2)^2} \sim 0.66$$

Ollitrault et al



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

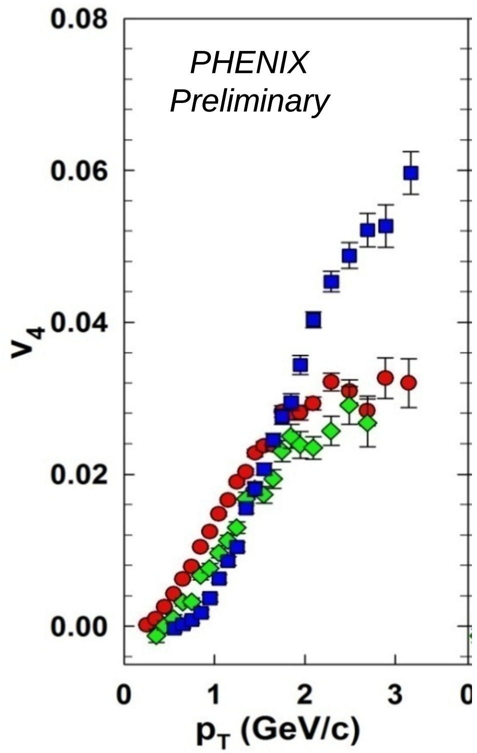
$$\frac{v_{4,B}(3p_T)}{v_{2,B}^2(3p_T)} \approx \frac{1}{3} + \frac{1}{3} \times \frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)}$$

$$\frac{v_{4,B}(3p_T)}{v_{2,B}^2(3p_T)} \approx \frac{2}{3} \times \frac{v_{4,M}(2p_T)}{v_{2,M}^2(2p_T)} + \frac{1}{6}$$

Quark recombination models predict specific relationship between the ratio $v_4/(v_2)^2$ for hadrons and partons

Scaling relation between Baryons and Mesons

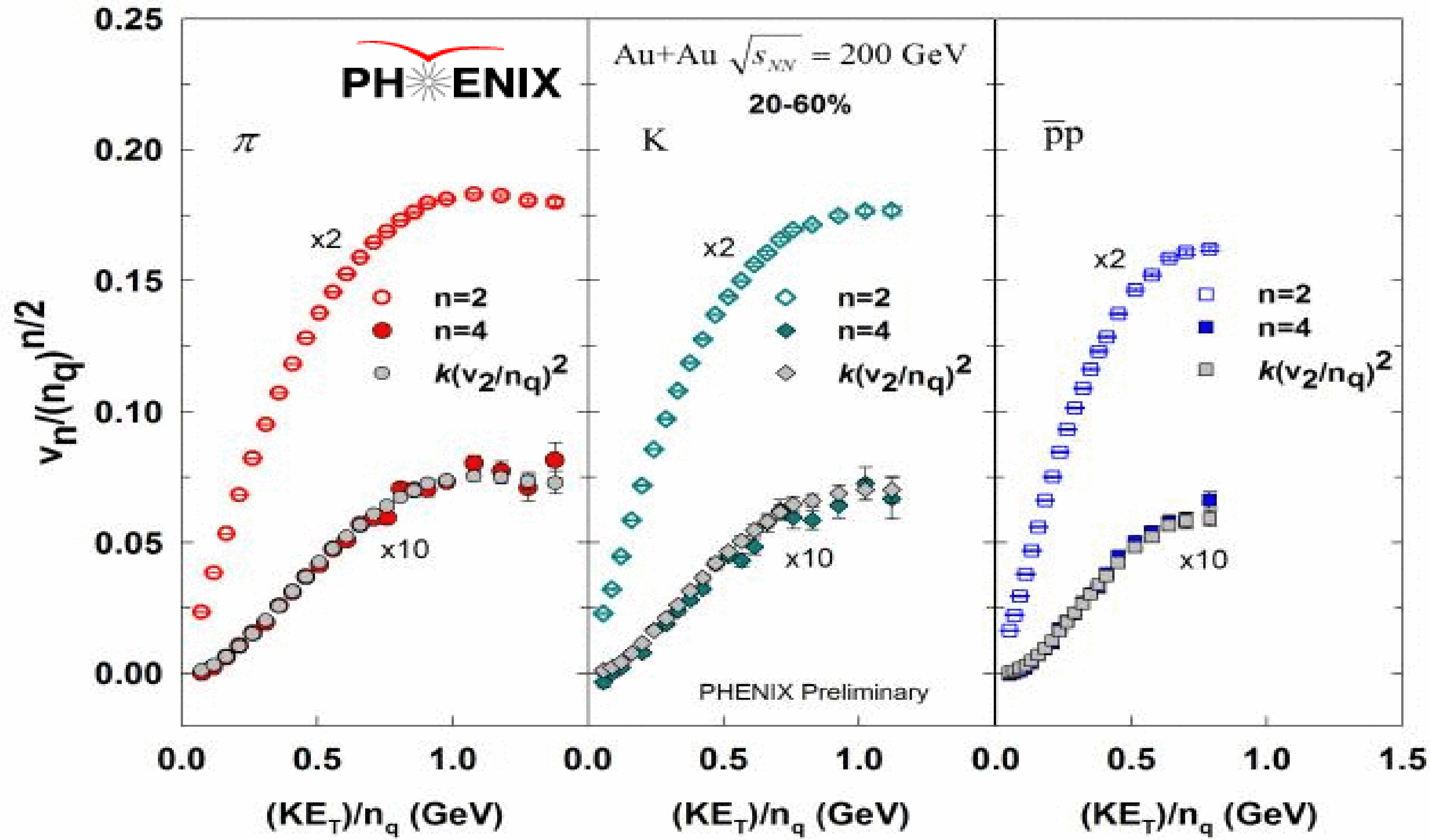
KE_T and CQN Scaling for v_4



KE_T & n_q^2 scaling validated for v_4

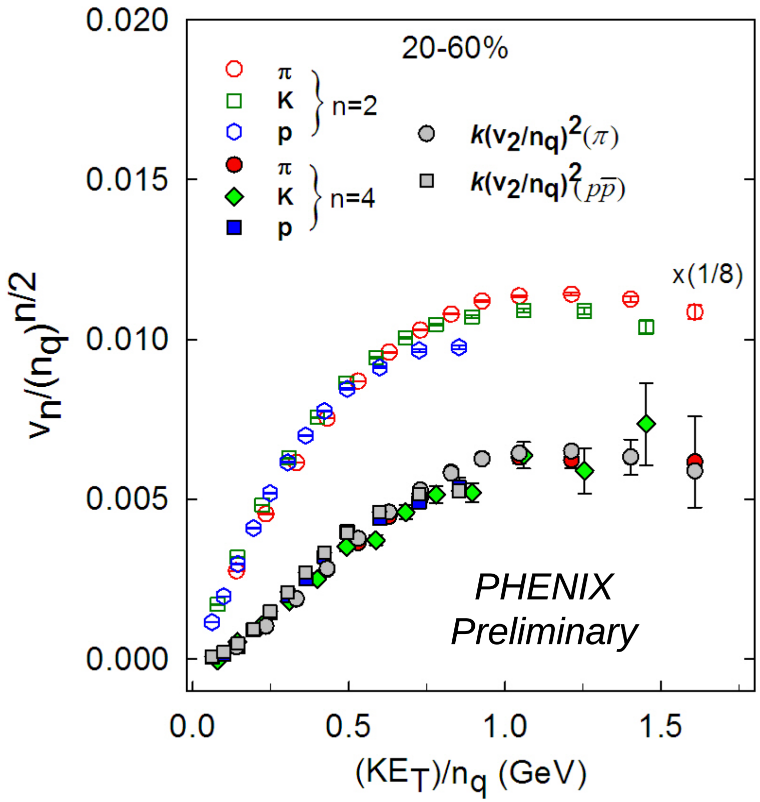
Further Indication of strong coupling?

$v_4/(v_2)^2$ ratio for different particle species



$V_4 = k(v_2)^2$ where k is the same for different particle species

Flow is universal



$V_4 = k(v_2)^2$ where k is the same for different particle species. Demonstrates the universal nature of v_n

Is this an indication that the partonic fluid is thermalized?

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

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

→

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

α
Related to η/s ?

Lessons

1. Hardoniaztion?
2. Partonic Thermalization?

Can we estimate the strength of the coupling and the degree of thermalization ?

Prerequisite: First Rate Flow Data

The extraction of a small value of η/s linked to a short mean free path λ, would lend decisive insight

Viscous hydro

Transport

Several Hybrids of Hydro and Transport

We now consider one hybrid approach

Hybrid Approach

Operational Ansatz (Ollitrault)

The Boltzmann equation reduces to hydrodynamics when the mean free path is small

C. Marle, Annales Poincare Phys.Theor. 10,67 (1969).

System characterized by two Dimensionless numbers

The liquidity or dilution number (D)

$$\frac{d}{\lambda}$$

Applicability of Boltzmann
D << 1

The Knudsen number (K_n)

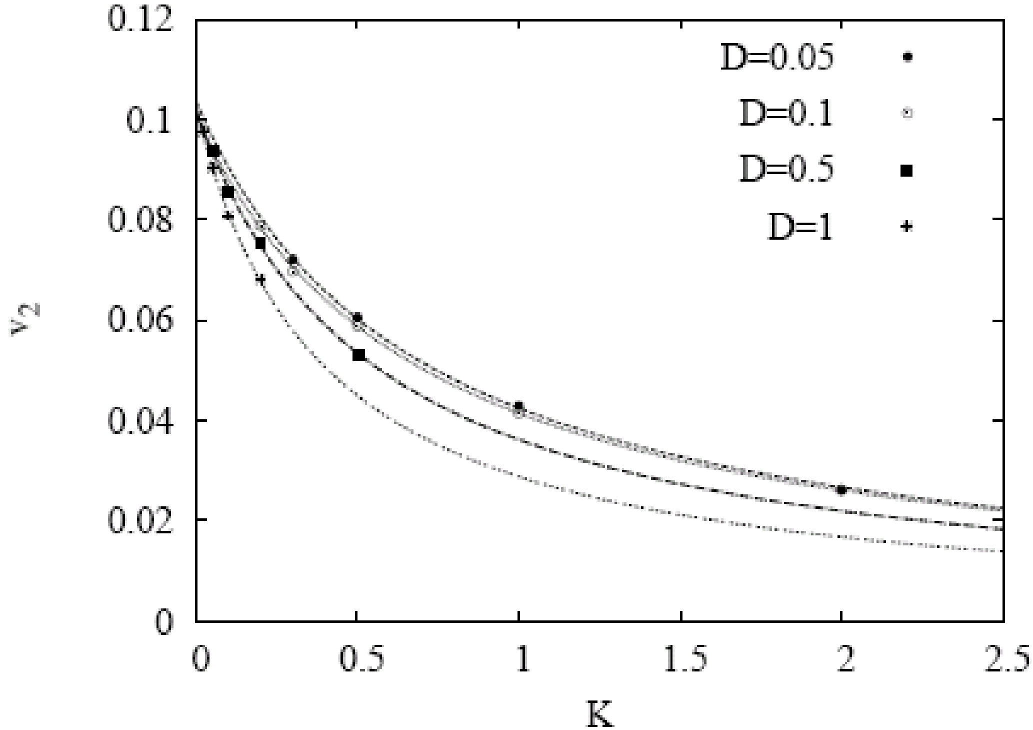
$$\frac{\lambda}{\overline{R}}$$

Hydrodynamics is the limit
K_n << 1

One can then use transport to study and parameterize the approach to hydrodynamic behavior (local equilibrium)

Hybrid Approach

Schematic calculation



Degree of local equilibrium

For a given value of D

$$\frac{v_2}{v_2^{hydro}} = \frac{K_n^{-1}}{K_n^{-1} + K_{n_0}^{-1}}$$

Functional form does not depend on D

$$\frac{\eta}{s} \sim \lambda T c_s \equiv K_n (RT) c_s$$

Determined from fit to calculations

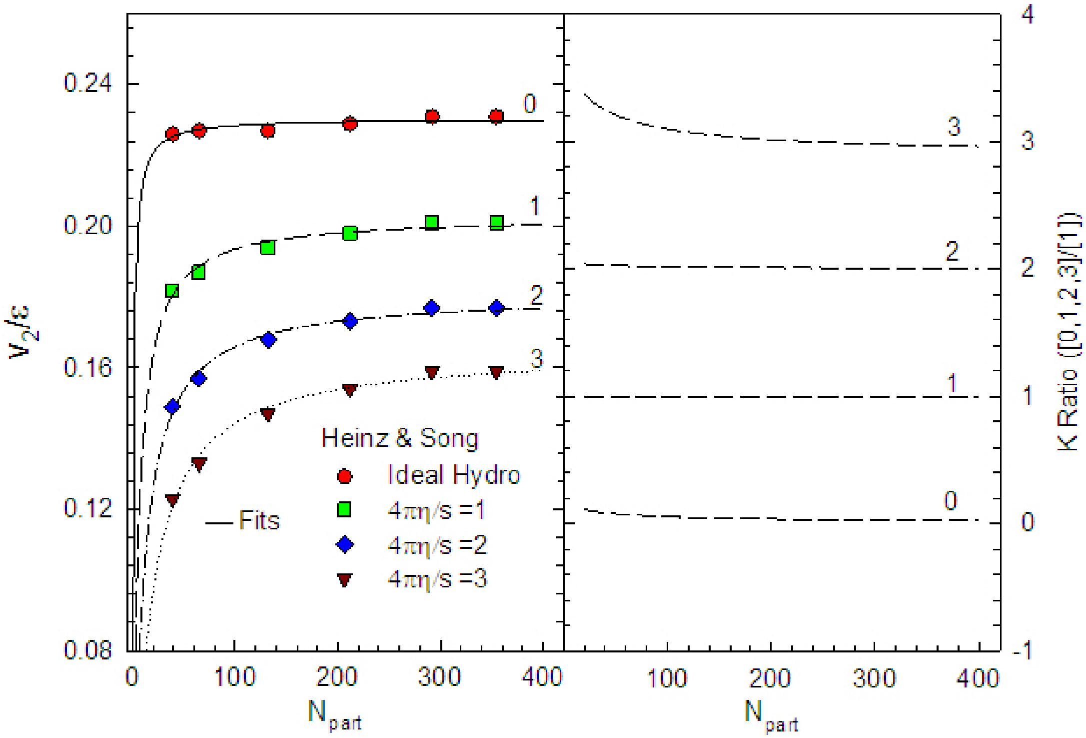
This provides a simple fitting ansatz for the data and

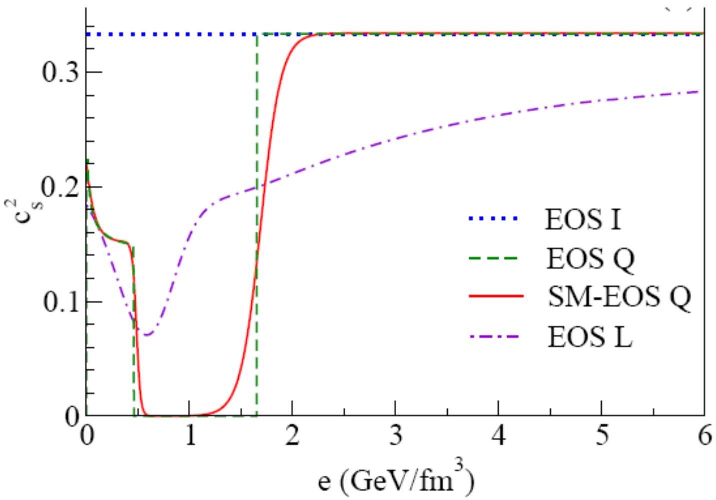
Straightforward procedure for local equilibrium estimate

"Any untaken shot is 100% missed "

Wayne Gretzky

An Operational Test





Use procedure to study simulated data

$$\frac{v_2}{\varepsilon} = \frac{v_2^{hd}}{\varepsilon}\left[\frac{K_n^{-1}}{K_n^{-1} + K_0^{-1}}\right]$$

$$K_n \sim \alpha + \frac{\beta}{N_{part}}$$

$$\frac{\eta}{s} \sim \lambda T c_s \equiv K_n(RT)c_s$$

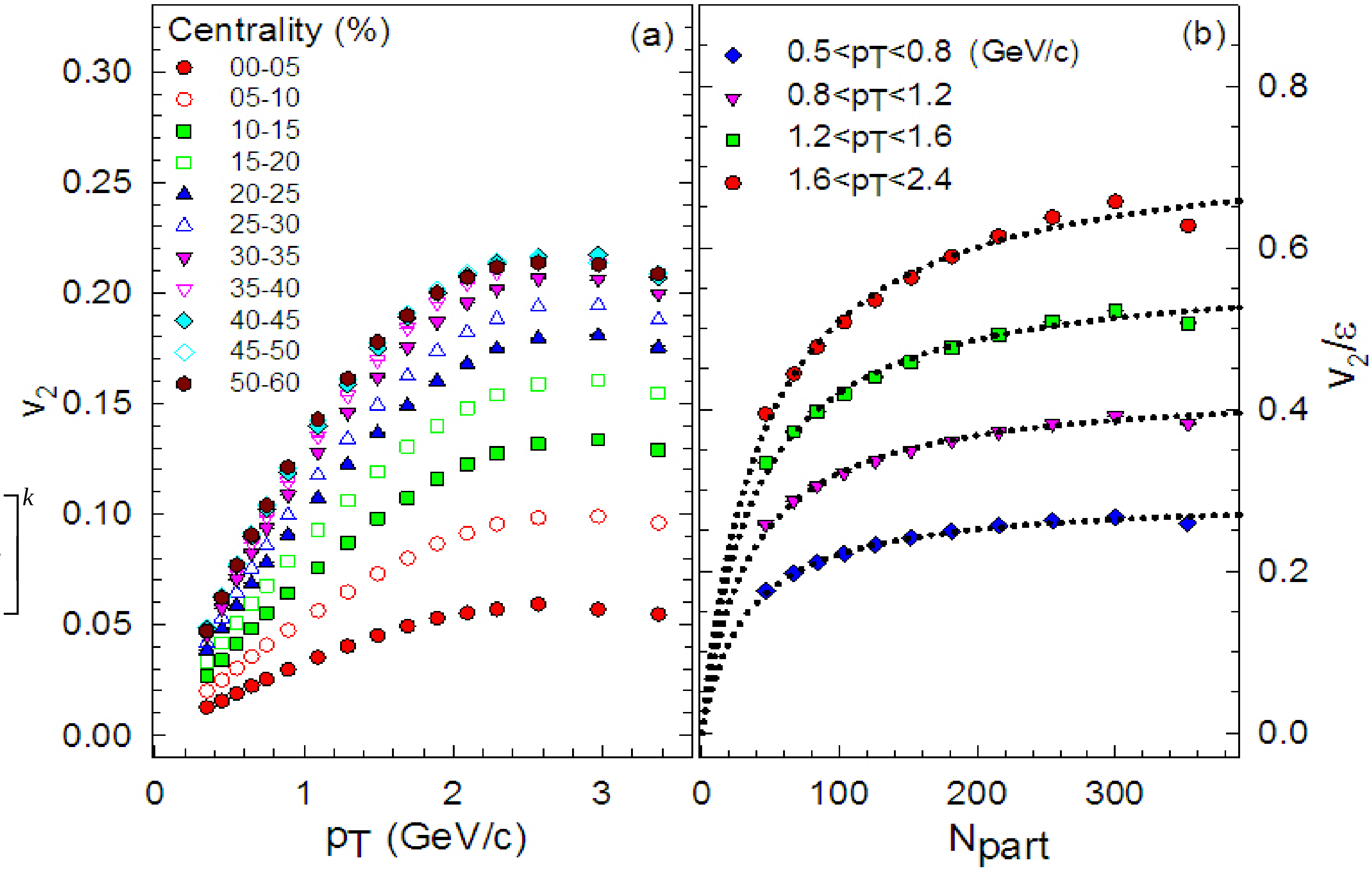
Operational ansatz validated

Truth or Myth – Good fits to the data

PHENIX Preliminary

$$K_n \sim \alpha + \frac{\beta}{N_{part}}$$

$$\frac{v_{2k}}{\varepsilon^k} = \frac{v_{2k}^{hd}}{\varepsilon^k}\left[\frac{K_n^{-1}}{K_n^{-1} + K_0^{-1}}\right]^k$$



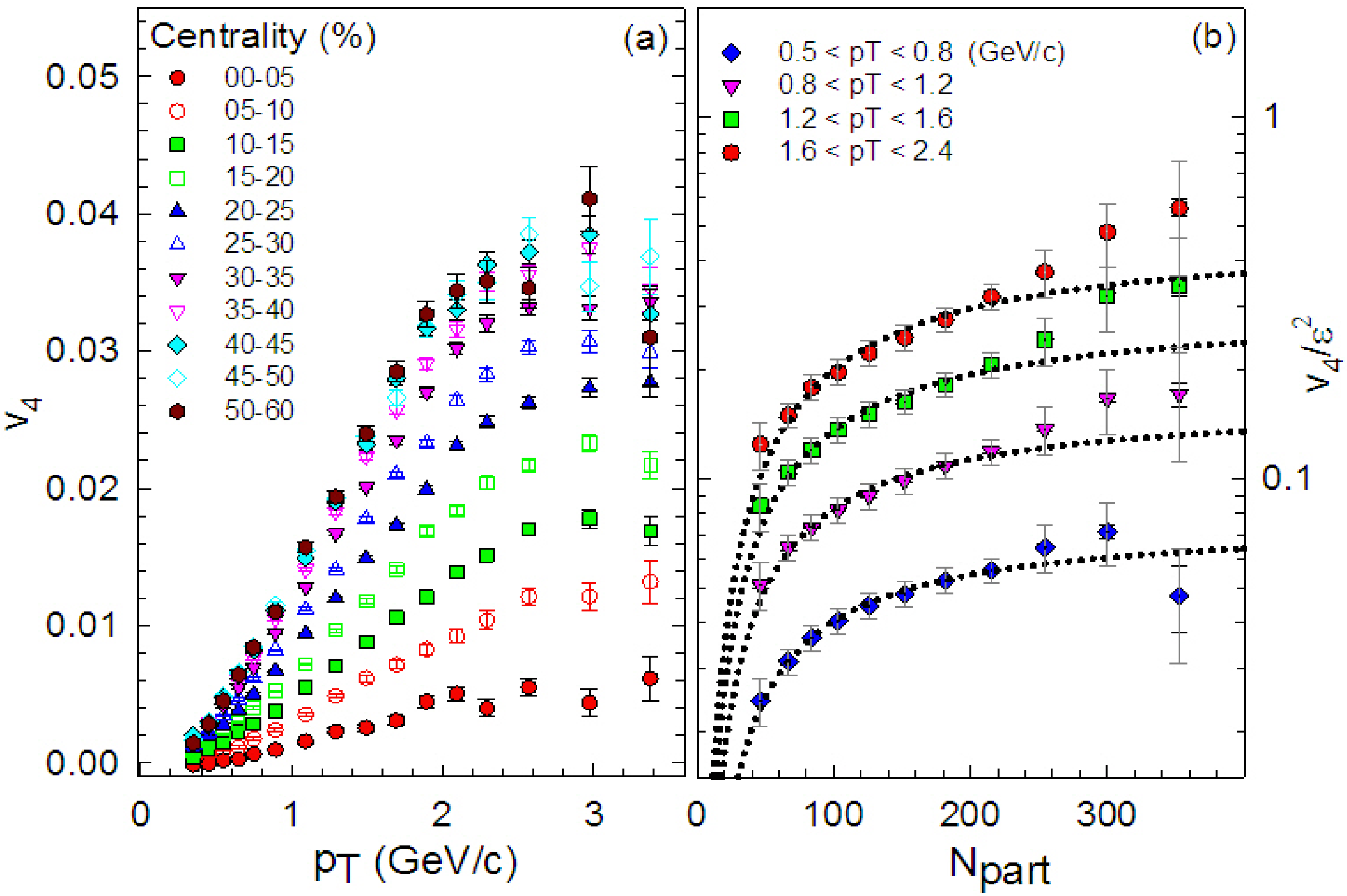
Within model ansatz straightforward to extract degree of local equilibrium!
10-15% larger than for fluid with η/s =1/4π in central events.

Truth or Myth – Good fits to the data

$$K_n \sim \alpha + \frac{\beta}{N_{part}}$$

$$\frac{v_{2k}}{\varepsilon^k} = \frac{v_{2k}^{hd}}{\varepsilon^k}\left[\frac{K_n^{-1}}{K_n^{-1}+K_0^{-1}}\right]^k$$

PHENIX Preliminary



Hydro like N_{part} dependence for v_4

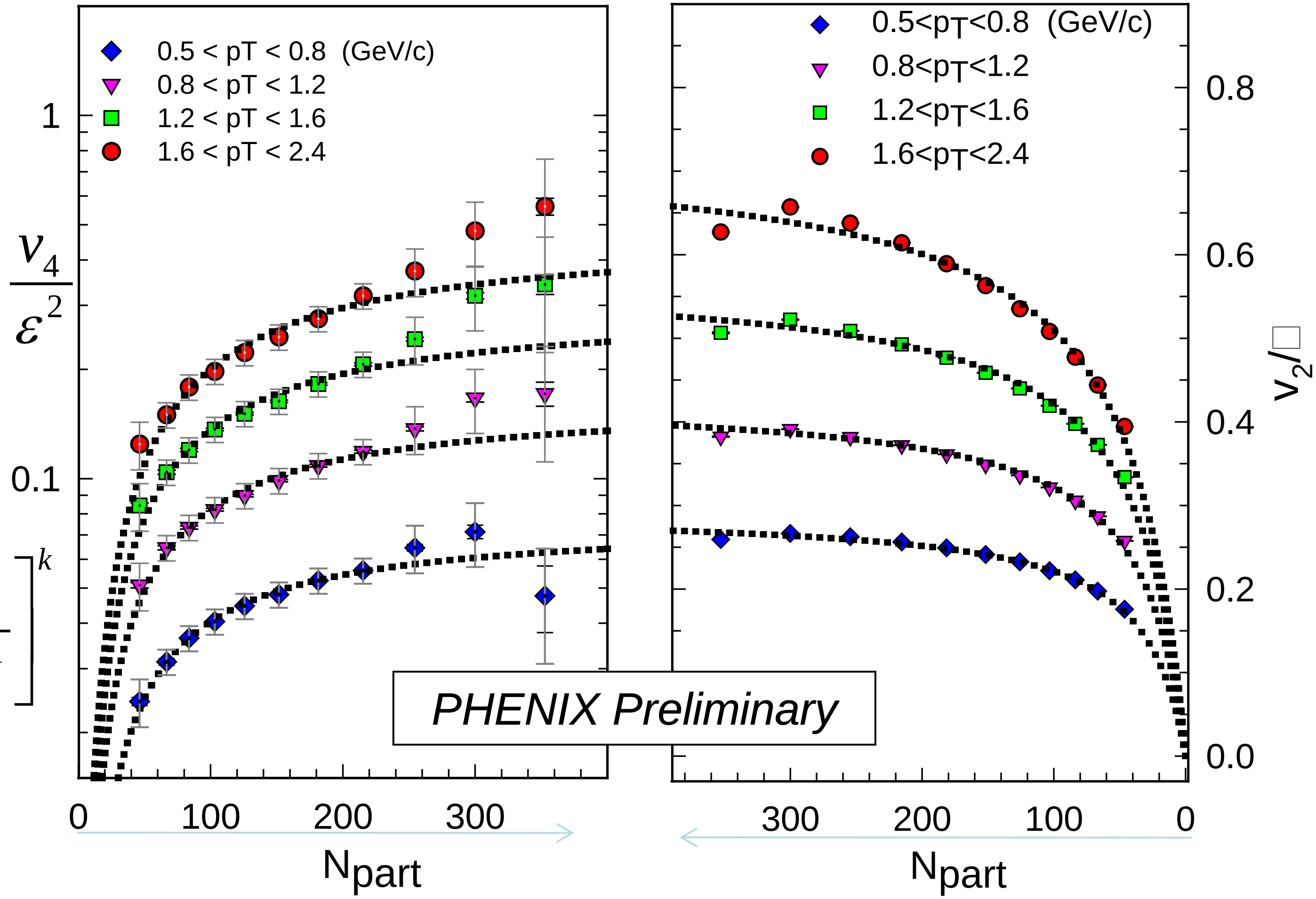
Similar Conclusions

Summary of v_2 and v_4

$$\frac{\eta}{s} \sim \lambda T c_s \equiv K_n (RT) c_s$$

$$\frac{v_{2k}}{\varepsilon^k} = \frac{v_{2k}^{hd}}{\varepsilon^k}\left[\frac{K_n^{-1}}{K_n^{-1} + K_0^{-1}}\right]^k$$

$\lambda = 0.3 – 0.35$



Straightforward estimation of the degree of local equilibrium and η/s as a function of centrality!

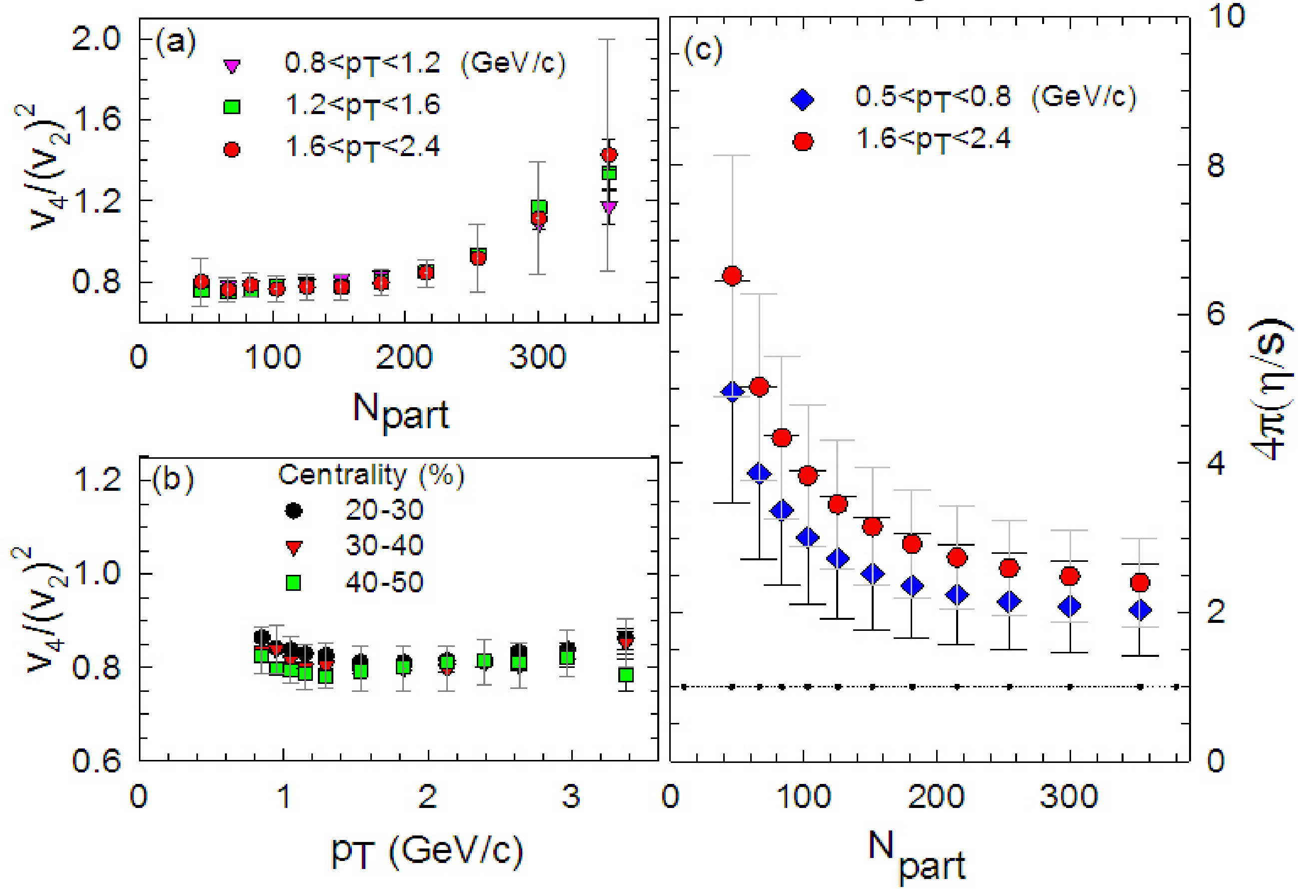
10-15% larger than for fluid with η/s =1/4π in central events.

Data Fits

$$\frac{v_{2k}}{\varepsilon^k} = \frac{v_{2k}^{hd}}{\varepsilon^k}\left[\frac{K_n^{-1}}{K_n^{-1}+K_0^{-1}}\right]^k$$

$$\frac{\eta}{s} \sim \lambda T c_s \equiv K_n(RT)c_s$$

PHENIX Preliminary

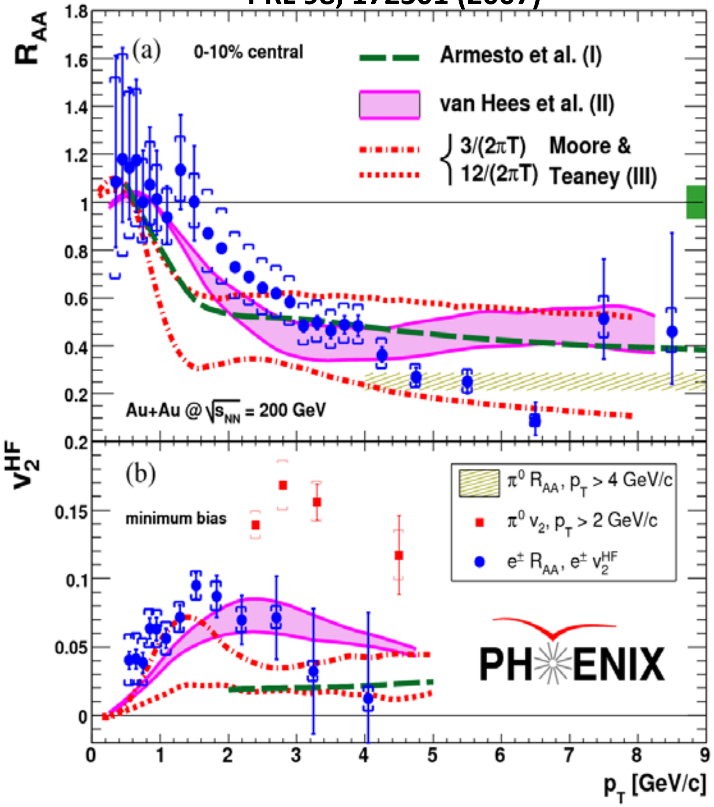


Fits allow η/s estimate as function of centrality etc.

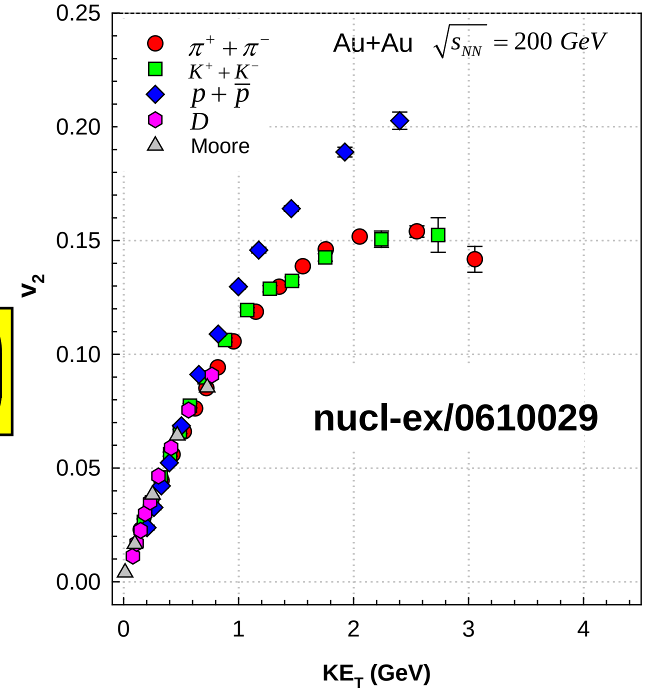
$\lambda = 0.3 - 0.35$

Heavy Quark Constraint

PRL 98, 172301 (2007)

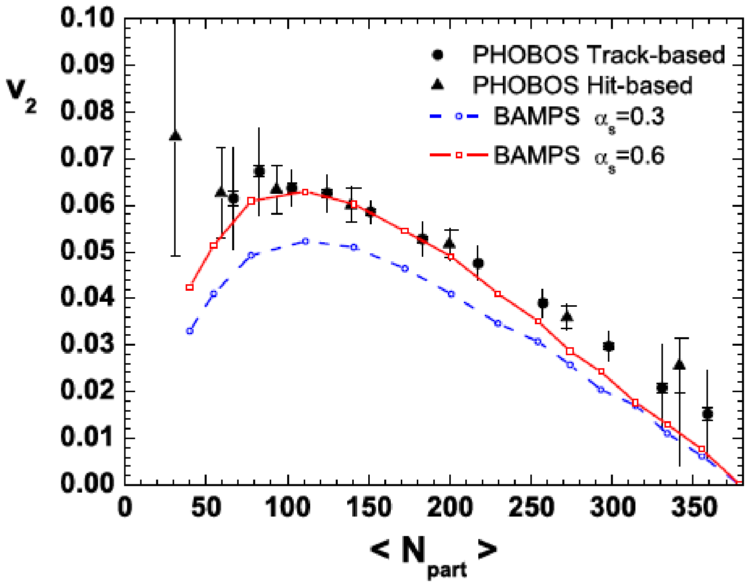


$$\frac{\eta}{s} \sim 2-4\left(\frac{1}{4\pi}\right)$$



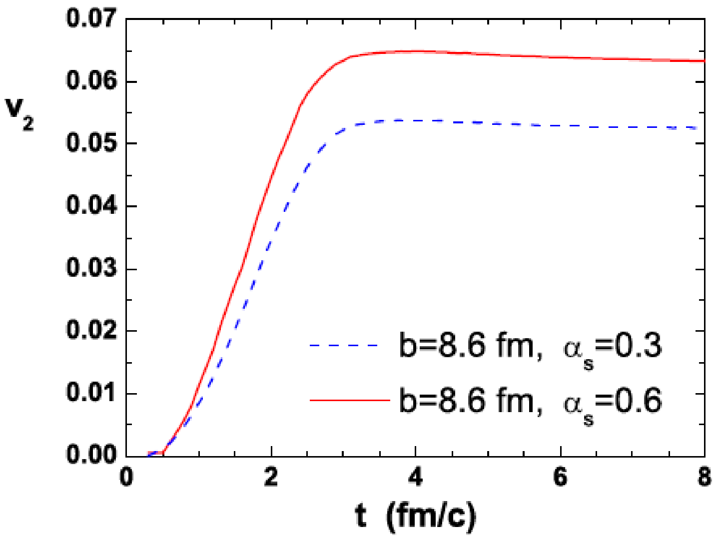
Heavy quarks provide a compatible constraint?

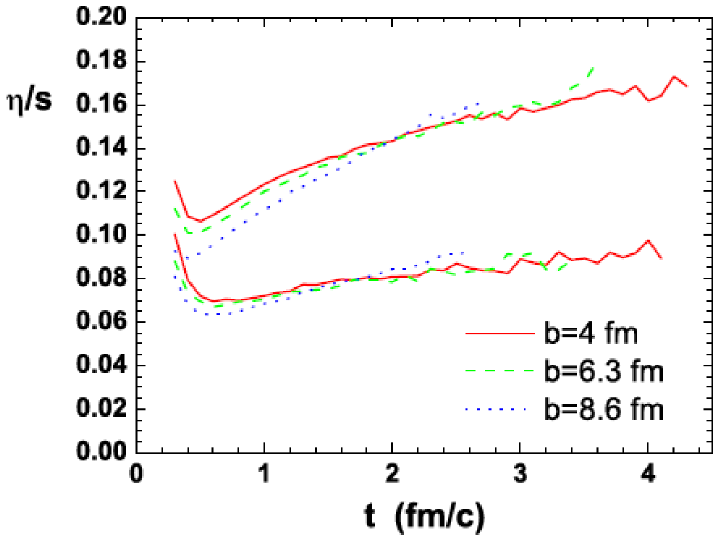
Coefficients from Transport



C. Greiner et al

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

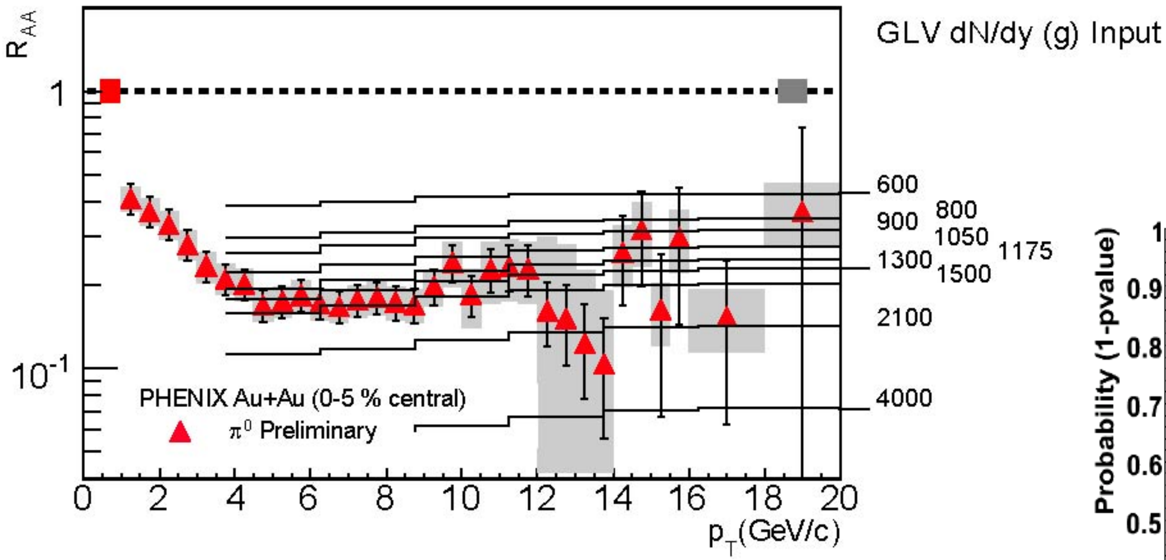


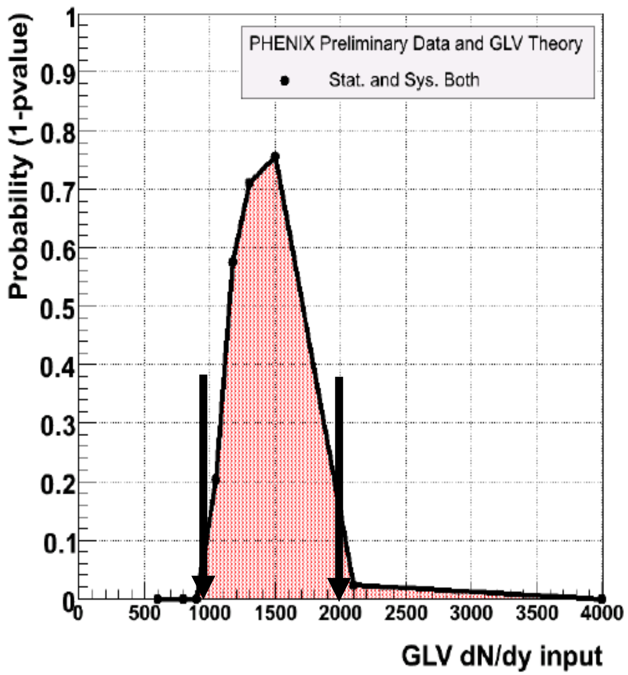


Thermalization facilitated by 2→3 processes

The Matter is Dense and Quenches Jets

An estimate of the density





$$1000 \leq {dN_g}/{dy} \leq 2000$$

$$(\text{Probability} > 10\%)$$

Estimates indicate sizeable density

Transport Coefficient Estimates

Lacey & Taranenko nucl-ex/0610029

c_s

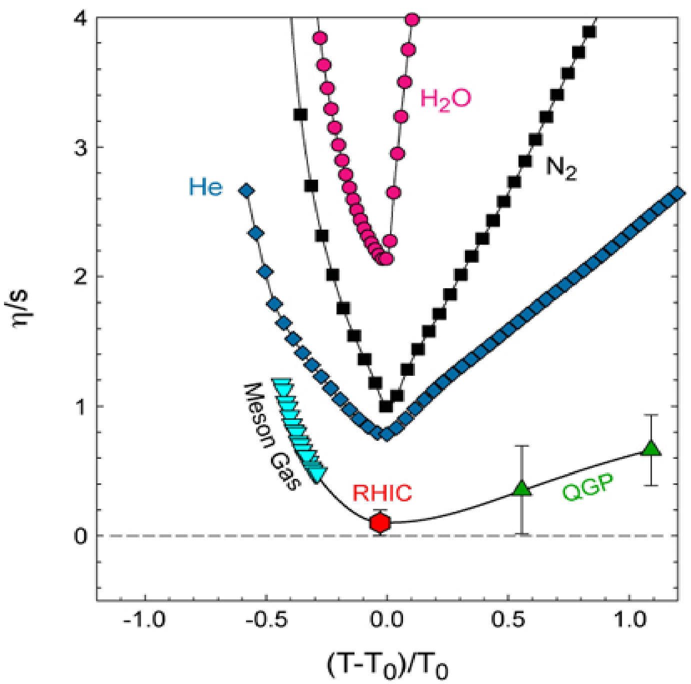
$$\frac{\eta}{s} \sim T\lambda_f c_s,$$

ς

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

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

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

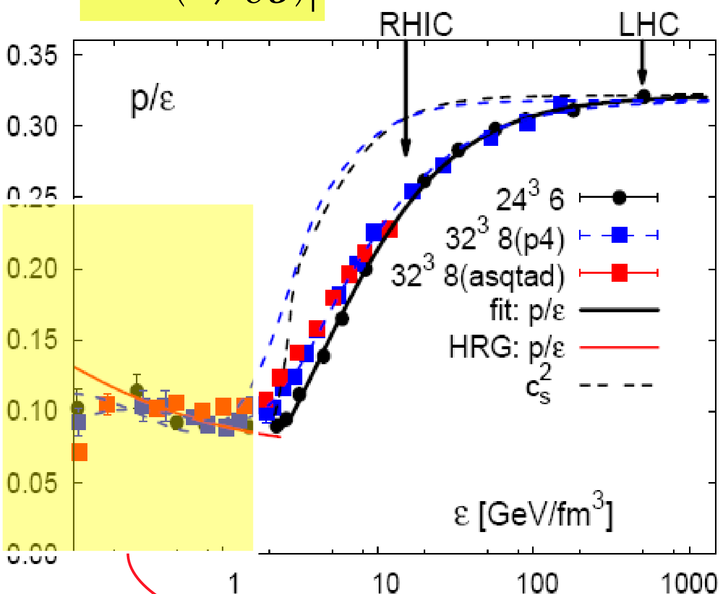


$$\langle c_s \rangle \sim 0.35, \qquad \frac{\eta}{s} < 2 \times \left(\frac{1}{4\pi}\right)$$

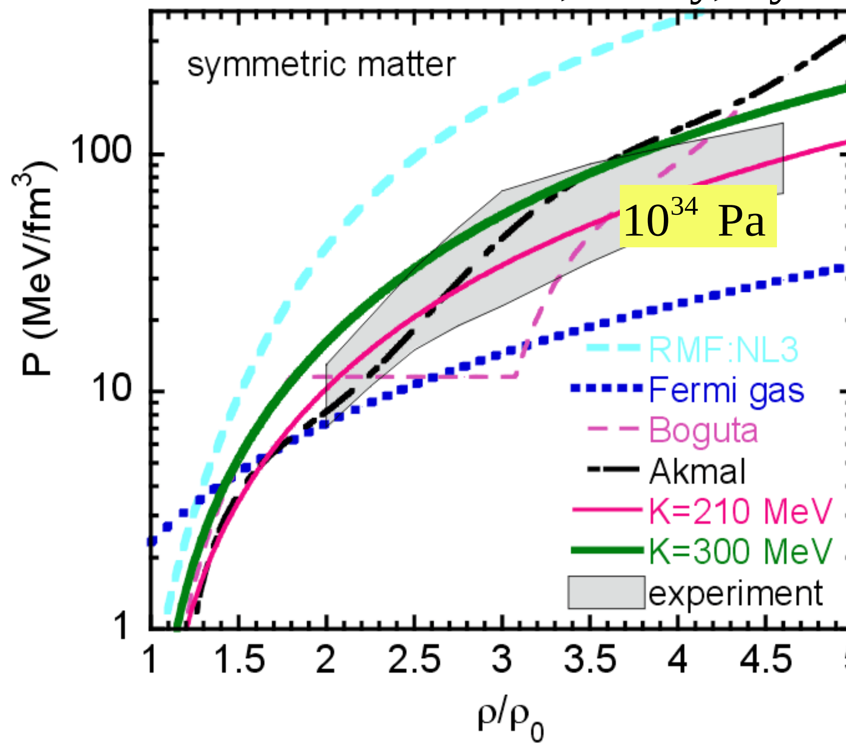
2 X the conjectured lower bound

New Constraints for the Hadronic EOS?

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



Danielewicz, Lacey, Lynch



EOS not very well constrained experimentally

$$c_s = \sqrt{K / 9m_N}$$

*Soft and **hard** EOS*

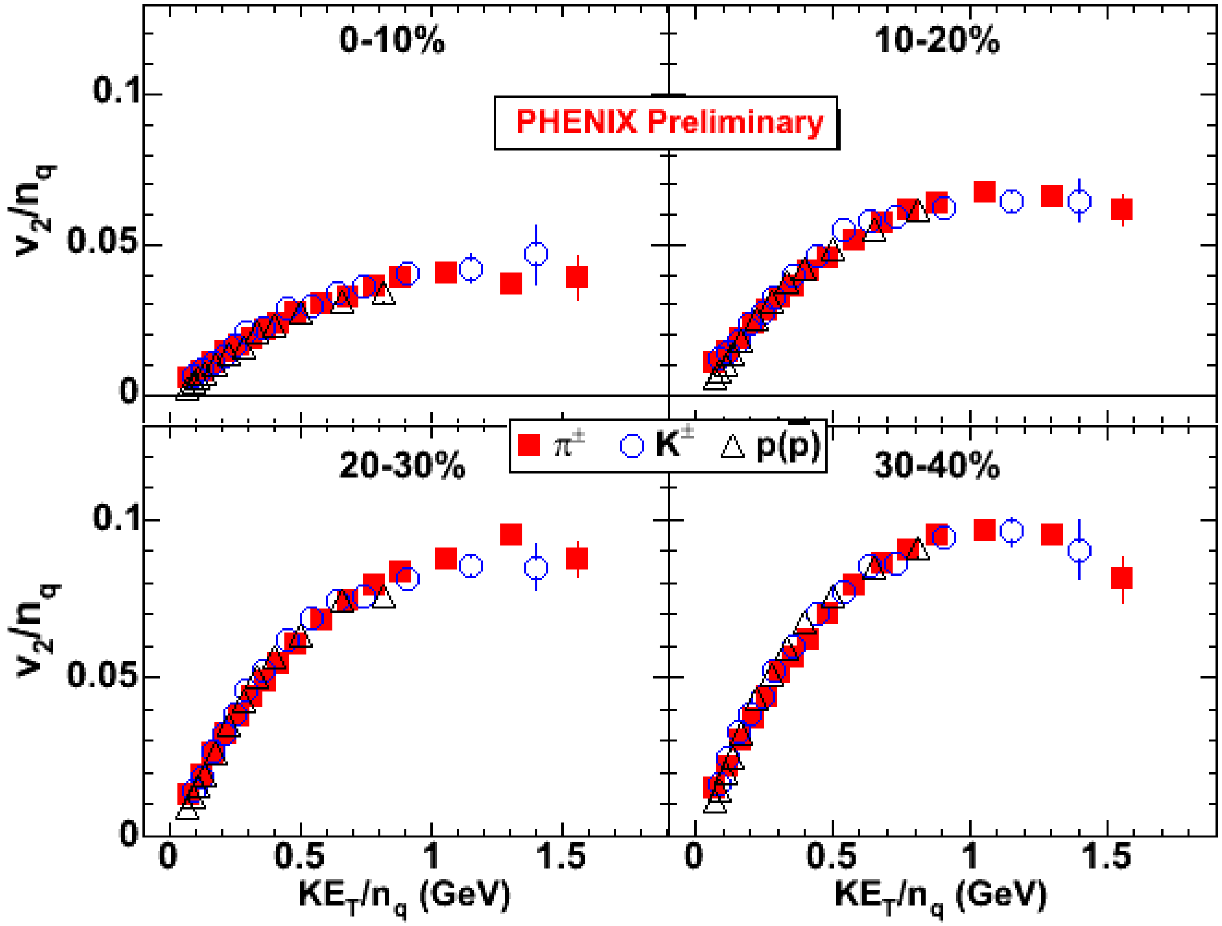
Further constraints for the hadronic EOS

Epilogue

- **Flow measurements tell us that the hot QCD matter created at RHIC is a strongly coupled plasma:**
  - ***flows*** **as a (nearly) perfect fluid with systematic patterns consistent with** ***quark degrees of freedom.***
  - **has a soft EOS and a viscosity to entropy density ratio close to** ***the conjectured quantum bound*****.**
  - **η/s decreases as collisions become more central**
  - **The mean free path (λ) in central collisions is short ~ 0.3 - 0.35**

Will be interesting to see what other approaches have to say
-- The ball is now in the Theorists court!!

KE_T/n scaling across collision centralities



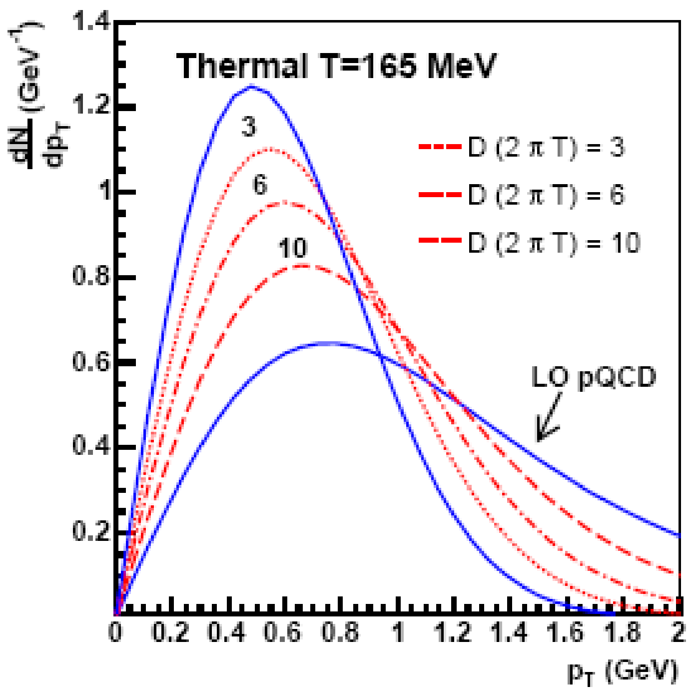
KE_T/n scaling observed across centralities

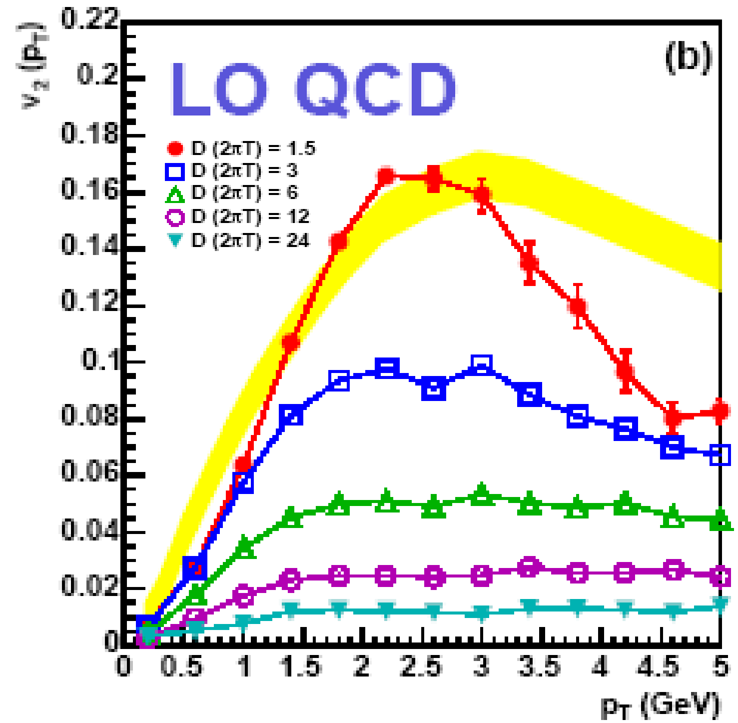
The Charm of D meson flow

Heavy quark relaxation time $\tau_R \sim \frac{M}{T}\frac{\eta}{e+p}$,

Moore & Teaney

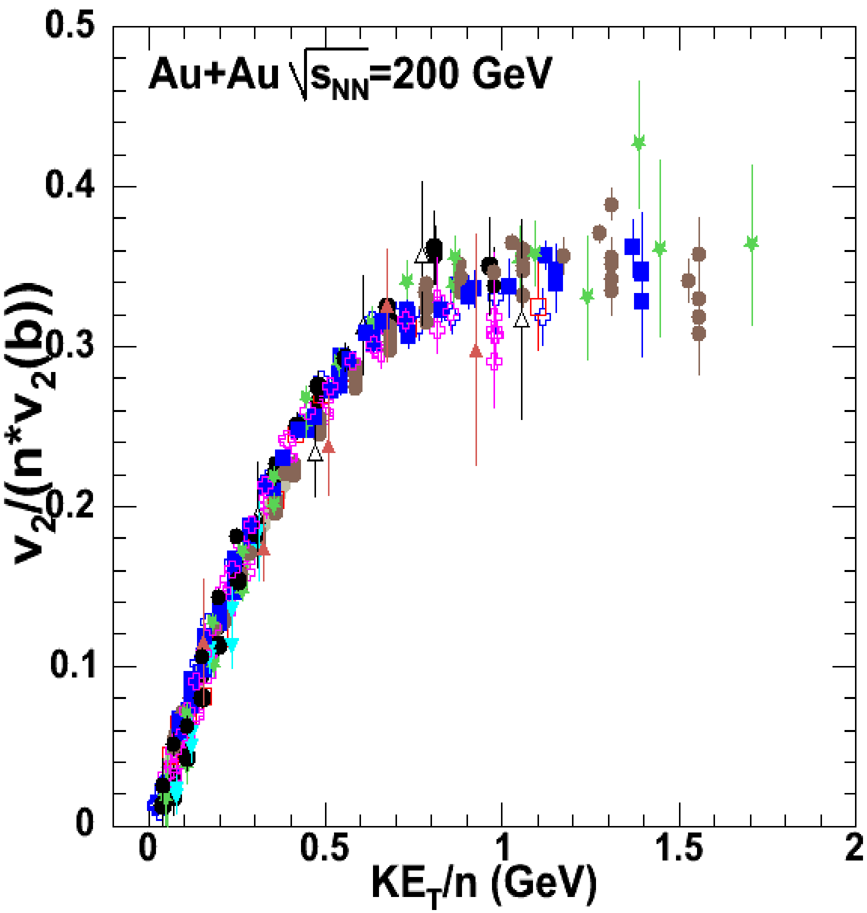
Equilibration rate $\frac{1}{\eta_D} = \frac{M}{T} D$ ← *Diffusion Coefficient*





V_2 of charm quark can provide invaluable access to the diffusion coefficient (D)

Overall Scaling of Elliptic Flow at RHIC



PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)

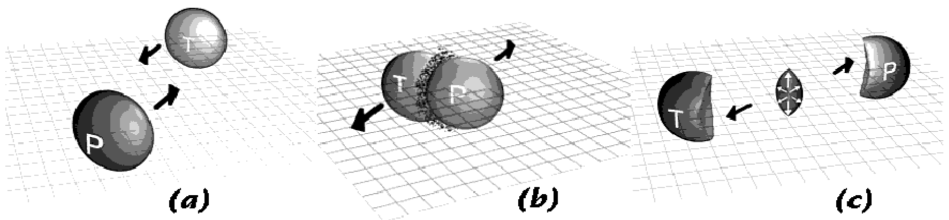
- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $p + \bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- d : min.bias, 10-50%
- ϕ : 20-60%

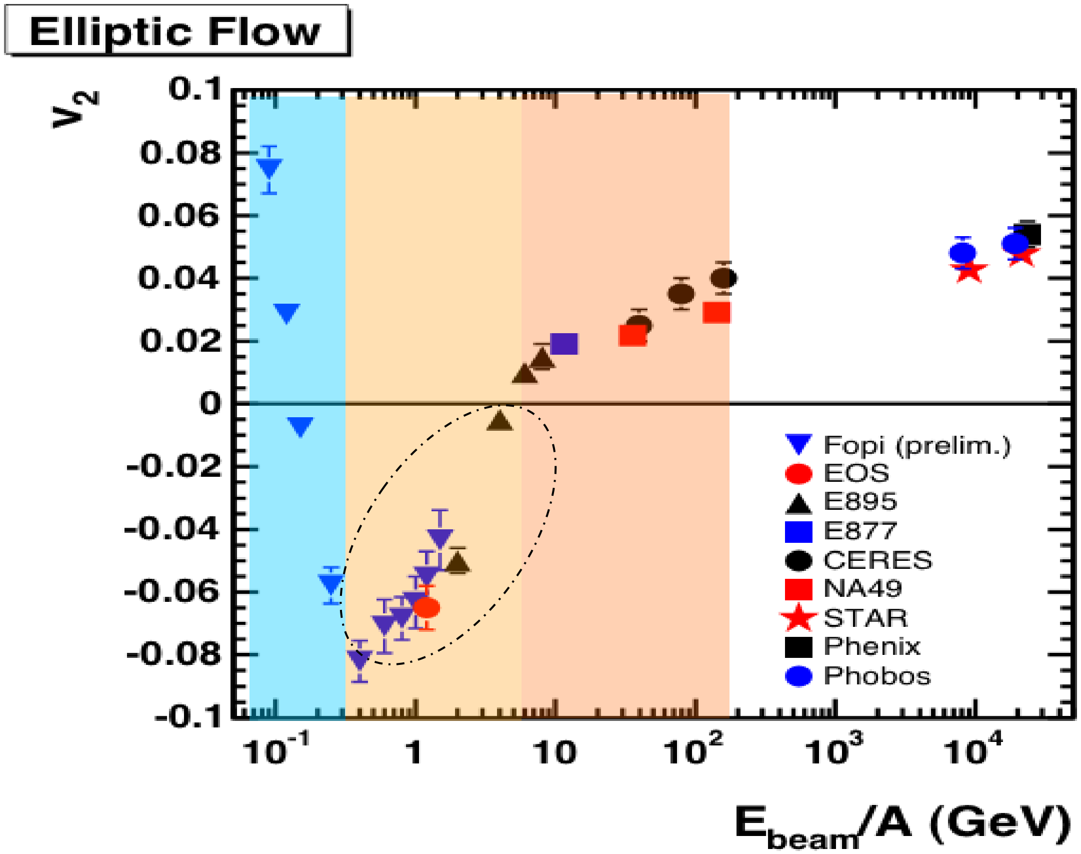
STAR (Phys. Rev. Lett. 92,Phys. Rev. C 72 (2005), Preliminary QM05, SQM06)

- $\pi^+ + \pi^-$: min.bias
- K^0_S : min.bias, 5-30%,30-70%
- $p + \bar{p}$: min.bias
- $\Lambda + \bar{\Lambda}$: min.bias, 5-30%,30-70%
- $\Xi + \bar{\Xi}$: min.bias
- $\Omega + \bar{\Omega}$: min.bias
- ϕ : min.bias

Particles flow with common velocity field

Prologue: The Rich Structure of the Integral Flow Excitation Function



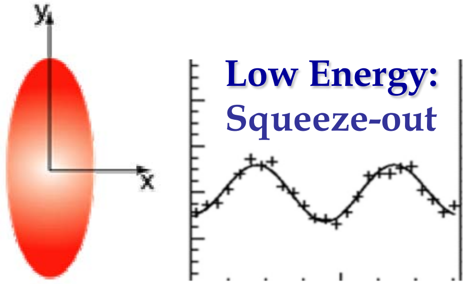


The transition from in-plane to out-of-plane and back to in-plane emission *Is understood*

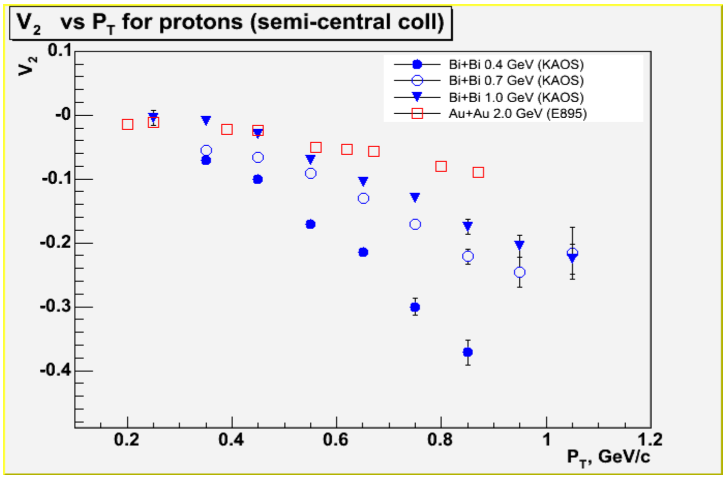
$$t_{expan} \sim \frac{R}{c_S}$$

$$t_{pass} \sim \frac{2R}{\gamma_0 v_0}$$

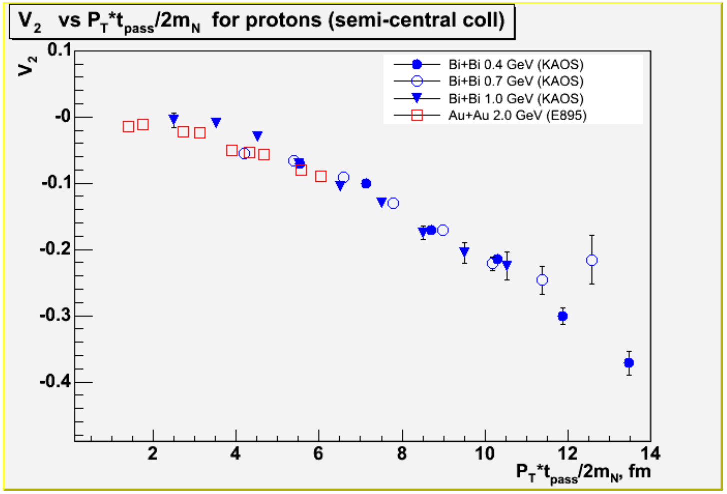
Prologue: Passing-time scaling of squeeze-out



$$\frac{dN}{d\phi} \sim \left[1 + 2v_2 \cos(2\phi)\right]$$



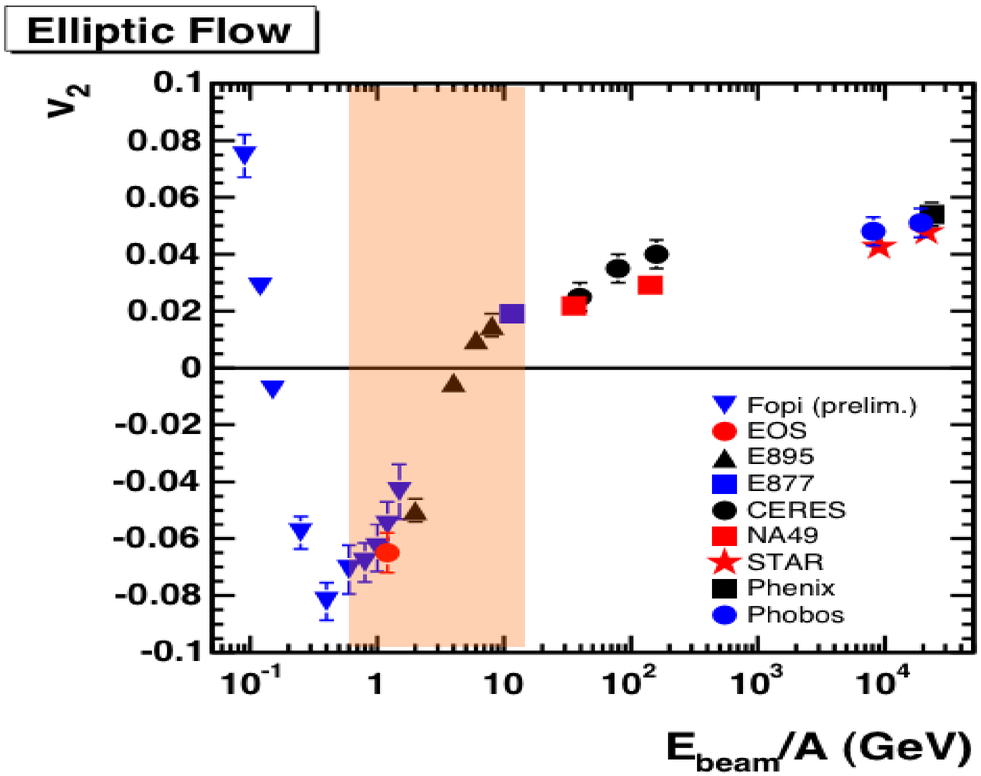
$$t_{pass} \sim \frac{2R}{\gamma_0 v_0}$$



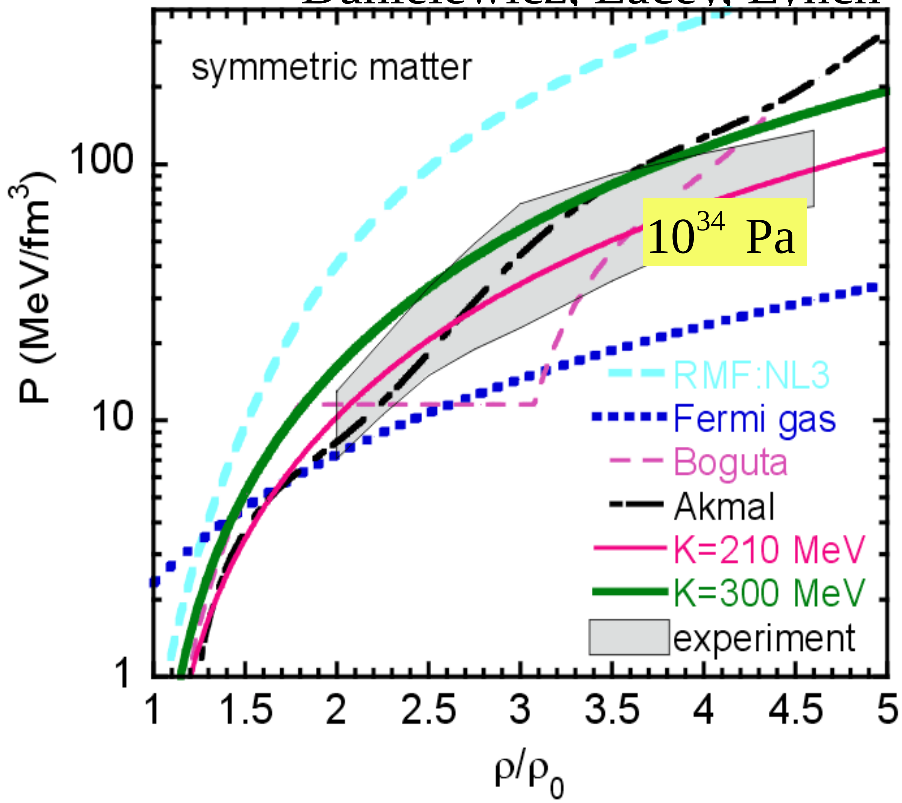
<u>DATA</u>
(KAOS – Z. Phys. A355 (1996);
(E895) - PRL 83 (1999) 1295

$$c_s \sim \frac{R}{t_{expan}} \sim 0.2c$$

Prologue: Constraints for the Hadronic EOS



Danielewicz, Lacey, Lynch

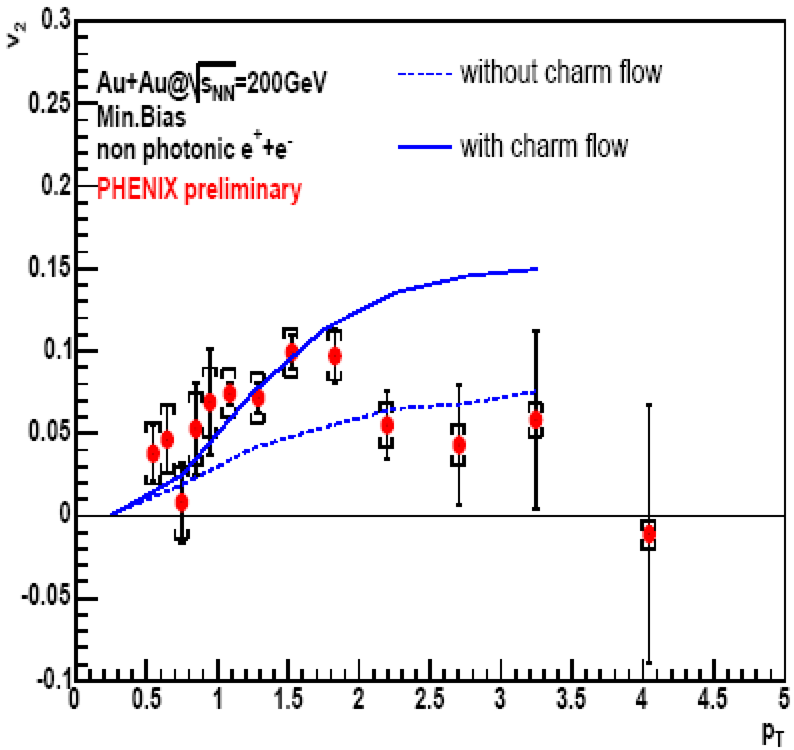


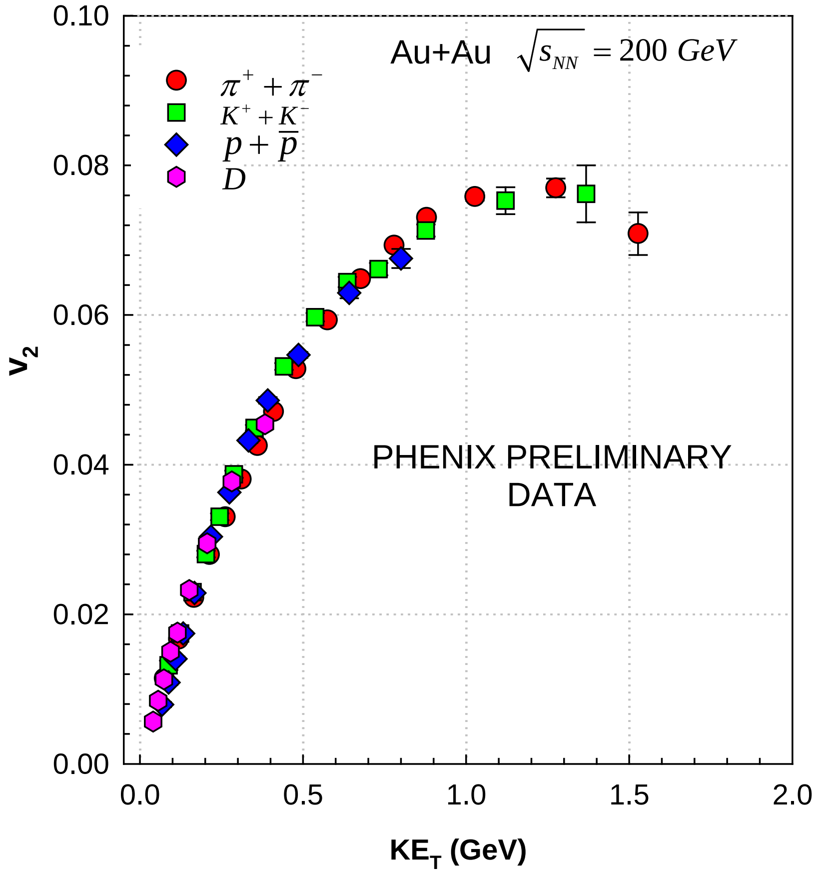
Good Constraints for the EOS achieved

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

*Soft and **hard** EOS*

The Charm of D meson flow





The D meson not only flows, it scales over the measured range

There are known knowns.

These are things we know that we know.

There are known unknowns.

That is to say, there are things that we know we don't know.

But there are also unknown unknowns.

There are things we don't know we don't know

Donald Rumsfeld

End