v_4 FROM IDEAL AND VISCOUS HYDRODYNAMICS

Matthew Luzum

(In collaboration with Jean-Yves Ollitrault and Clément Gombeaud)

Institut de Physique Théorique
CEA/Saclay

9 April 2010
Rencontres Ions Lourds

Outline

1. Introduction/Review
   - Hydrodynamics
   - Azimuthal correlations—v_2, v_4
   - Previous results
2. Results from hydrodynamics
   - RHIC results
   - LHC prediction
3. Conclusions

OUTLINE

1. INTRODUCTION/REVIEW
   - Hydrodynamics
   - Azimuthal correlations—v_2, v_4
   - Previous results
2. RESULTS FROM HYDRODYNAMICS
   - RHIC results
   - LHC prediction
3. CONCLUSIONS

HYDRODYNAMICS

A system close to local thermal equilibrium will behave according to hydrodynamic equations, consisting of:

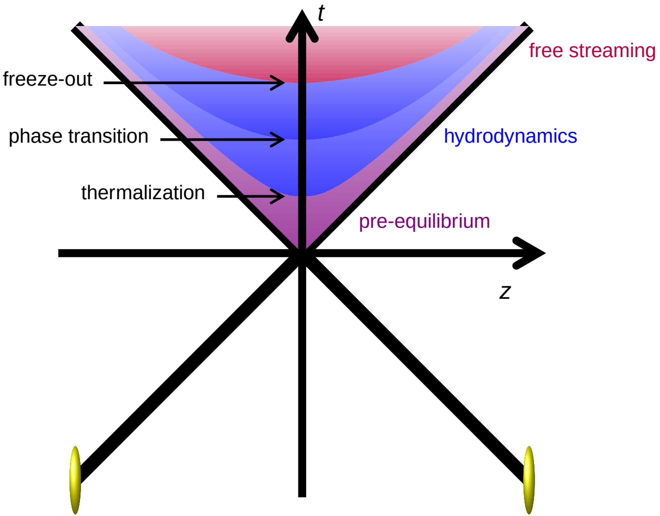
- Conservation of energy-momentum:

$$0 = \partial_\mu T^{\mu\nu} \equiv \partial_\mu (T_0^{\mu\nu} + \Pi^{\mu\nu}) = \partial_\mu \left((\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} + \Pi^{\mu\nu} \right)$$

- Any other conservation laws: $\partial_\mu j^\mu = 0$
- Equation of state: $p = p(\epsilon)$

With appropriate boundary conditions, we can model a heavy ion collision.

HYDRODYNAMIC EVOLUTION OF A NUCLEAR COLLISION



Freeze Out

- At freeze out the fluid is converted into particles

$$\frac{dN}{dY\, d^2p_t} \propto \int p_\mu d\Sigma^\mu f(p^\mu)$$

- with a distribution function given by kinetic theory

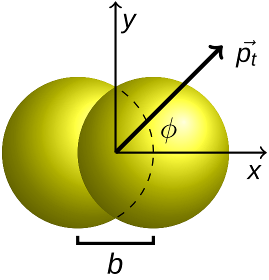
$$f = f_0 + \delta f = e^{(-E/T)}\left[1 + (g(p)?)p_i p_j \Pi^{ij}\right]$$

- (form of δf depends on microscopic dynamics)

v_2, v_4, etc.

To compare to experiment, compute azimuthal moments:

$$\frac{dN}{dY\, d^2p_t} = v_0 \left[1 + \sum_n 2v_n \cos(n\,\phi)\right]$$

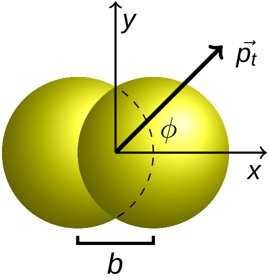


v_2, v_4, ETC.

To compare to experiment, compute azimuthal moments:

$$\frac{dN}{dY\, d^2p_t} = v_0 \left[1 + \sum_n 2 v_n \cos(n\,\phi) \right]$$

Elliptic flow: $v_2 \equiv \langle \cos(2\,\phi) \rangle$



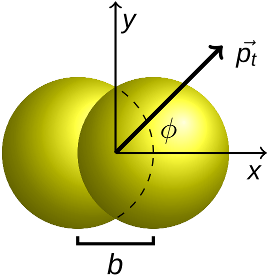
v_2, v_4, ETC.

To compare to experiment, compute azimuthal moments:

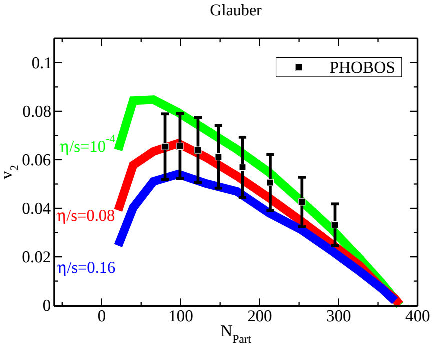
$$\frac{dN}{dY\, d^2p_t} = v_0 \left[1 + \sum_n 2v_n \cos(n\,\phi)\right]$$

Elliptic flow: $v_2 \equiv \langle \cos(2\,\phi) \rangle$

Hexadecapole flow: $v_4 \equiv \langle \cos(4\,\phi) \rangle$



ELLIPTIC FLOW (v_2)



(ML / Romatschke arXiv:0804.4015)

- Large measured v_2 indicates small viscosity, but exact value depends on initial eccentricity.

IDEAL HYDRODYNAMICS PREDICTION: $v_4/(v_2)^2 = 1/2$

Perform a saddle point approximation:

$$\frac{dN}{dY\, d^2p_t} = \frac{d}{(2\pi)^3} \int p_\mu d\Sigma^\mu e^{\left(\frac{-p\cdot u}{T}\right)}$$

For large p_t, saddle point is at the maximum u parallel to momentum:

$$u_{\max}(\phi) = U(1 + 2V_2 \cos(2\phi) + 2V_4 \cos(4\phi) + \ldots)$$

$$\Longrightarrow v_2(p_t) = \frac{V_2 U}{T}(p_t - m_t v)$$

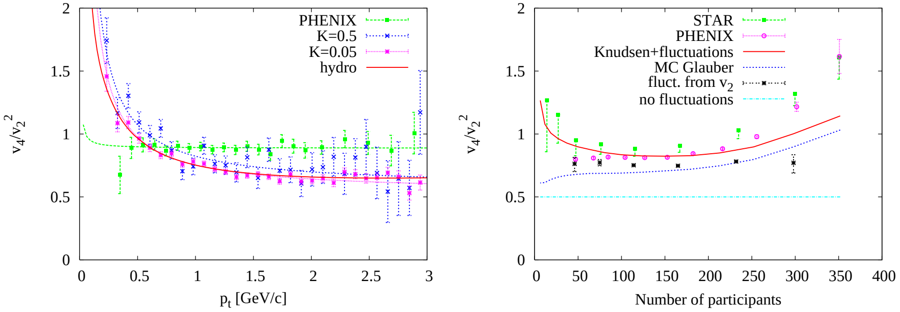
$$v_4(p_t) = \frac{1}{2}\frac{(V_2 U)^2}{T^2}(p_t - m_t v)^2 + \frac{V_4 U}{T}(p_t - m_t v)$$

$$= \frac{1}{2} v_2(p_t)^2 + \frac{V_4}{V_2} v_2(p_t)$$

$(v \equiv U/\sqrt{1+U^2})$

(Borghini / Ollitrault nucl-th/0506045)

EXISTING DATA / CALCULATIONS FOR $v_4/(v_2)^2$

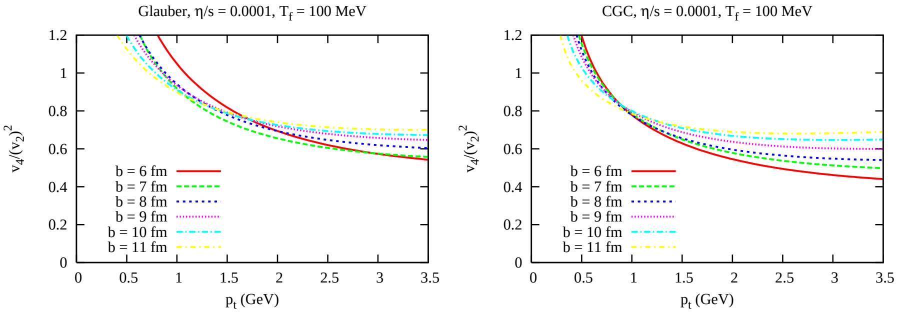


(Gombeaud / Ollitrault arXiv:0907.4664)

- Experimental results are larger than 1/2.
- Most of the discrepancy can be understood from fluctuations.

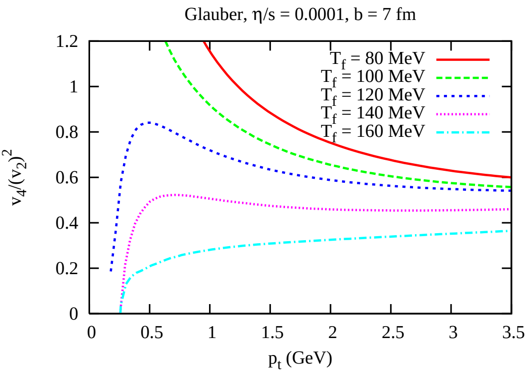
Outline

Compare to previous results: Ideal hydro with T_f = 100 MeV



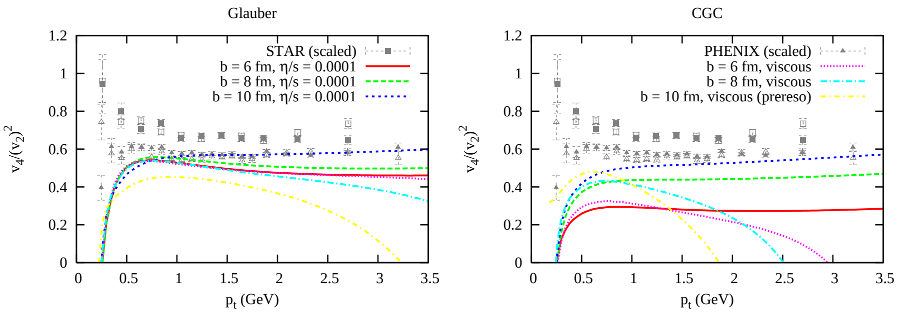
- Like previous calculations: Asymptotes to $\sim$1/2 with corrections like $1/p_t$
- Some unexpected impact parameter dependence, but **not** due to initial eccentricity.

SENSITIVITY TO T_f



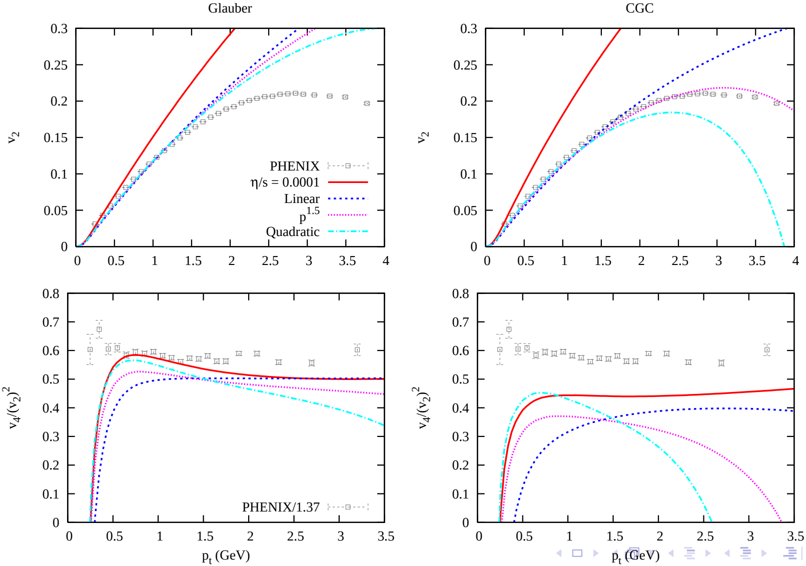
- $v_4/(v_2)^2$ sensitive to T_f
- (For ideal hydro) best-fit T_f for other observables (140 MeV) also results in flat $v_4/(v_2)^2$

Viscous results at realistic $T_f = 140$ MeV

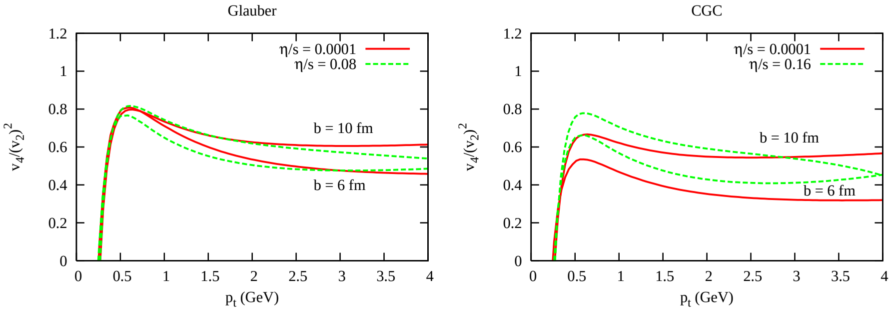


- Viscosity *lowers* $v_4/(v_2)^2$
- Standard "quadratic ansatz" for δf destroys flat curve and increases dependence on b
- Using a different δf can fix some of this:

δf dependence



LHC prediction



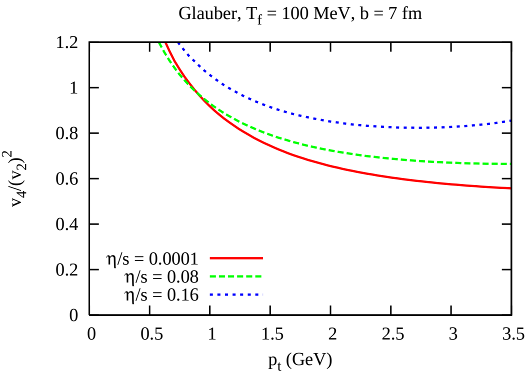
- Similar to RHIC results at slightly lower freeze out temperature
- Viscous corrections are smaller, making choice for δf less relevant.

Outline

SUMMARY/CONCLUSIONS

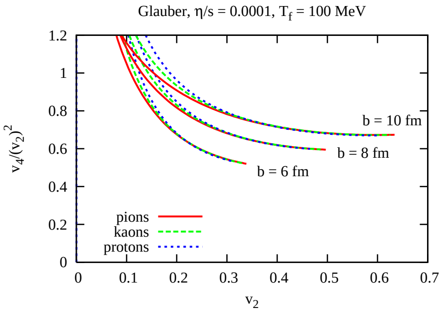
- Hydrodynamic simulations confirm expectation of $v_4/(v_2)^2 \sim 1/2$
- Sensitive to T_f, with 140 MeV giving a flat dependence on p_t in ideal hydro (and for δf with weak p_t dependence)
- $v_4/(v_2)^2$ is insensitive to initial eccentricity (unlike v_2)
- Viscosity tends to decrease $v_4/(v_2)^2$ for a realistic T_f
- Viscosity increases impact parameter dependence for standard quadratic ansatz for δf, but *decreases* it for weaker p_t dependence.
- $v_4/(v_2)^2$ at LHC should be similar to RHIC

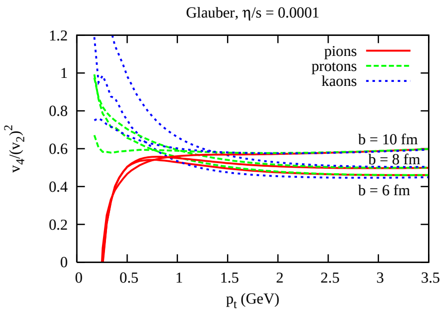
VISCOUS EFFECTS



- Like in transport calculations, viscosity increases $v_4/(v_2)^2$ (but only with a small T_f)

Identified Particles





- Identified particles have same $v_4/(v_2)^2$