Collective flow without Hydrodynamics

Paul Romatschke
CU Boulder & CTQM

Based on arXiv: 1504.02529

Collective flow

- Collective flow: measured in experiment
- Precise data for radial flow & v_n
- We know QGP in A+A has large collective flow and we think we know why (hydrodynamics)
- Large radial flow and v_2 also found in p+A
- Large radial flow also found in p+p

- Large radial flow in A+A, p+A, p+p
- Large v_2 (v_3) in p+A

Hydro in p+A, p+p?

Can non-hydro evolution create large radial flow, v_2, v_3 in p+A, p+p?

If yes, can non-hydro evolution create large radial flow, v_2, v_3 in A+A?

Non-hydro collective flow

- Bozek et al., 1503.03655: AMPT with σ=1.5-3 mb describes v_2,v_3 in p+Pb
- He et al., 1502.05572: AMPT creates large v_2,v_3 because of 'escape mechanism' (independent of σ)

This talk

- Side-by-side comparison of two models for p+A
- **Model I**: event-by-event MCGlauber**+visc. Hydro**+hadron cascade ("hydro")
- **Model II**: event-by-event MCGlauber**+free streaming**+hadron cascade ("free-streaming")
- Same ICs; same EoS
- Same grid size, resolution, time-step
- Same Freeze-Out procedure (algorithm)

Methodology

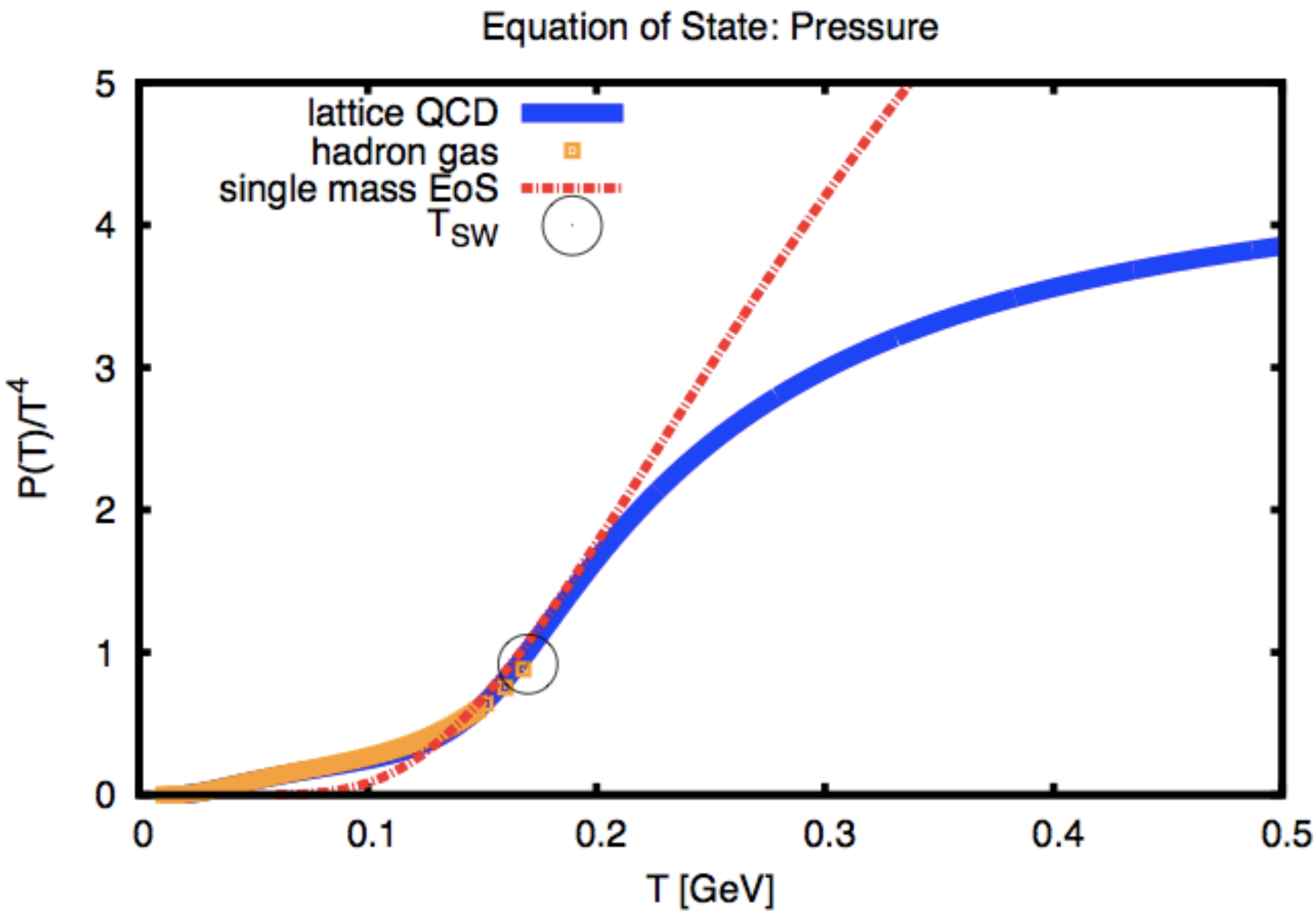
Equation of State (EoS)

- Massive particle EoS with Z dofs

$$\epsilon = \frac{Z\, m^2 T}{2\pi^2}\left(3TK_2\left(\frac{m}{T}\right) + mK_1\left(\frac{m}{T}\right)\right)\,, \quad p = \frac{Z\, m^2 T^2}{2\pi^2} K_2\left(\frac{m}{T}\right)\,.$$

- Used in both hydro and free-streaming model
- m,Z chosen to latch onto hadronic EoS at T_S=170 MeV (“freeze-out”)

Equation of State (EoS)



Initial Conditions (1/2)

- Event-by-Event MonteCarlo-Glauber
- MC position of nucleons using pdfs (WS for A, vanHulthen/GFMC for d/^{3}He)
- Positions (x,y) of nucleons undergoing at least one collision recorded ("participants")
- Assumed to contribute to energy density at (x,y) in form of a Gaussian with width 0.4 fm
- Total energy density is sum over all Gaussians

Initial Conditions (2/2)

- Assume $T^{ab}(\tau=\tau_0,x,y)$ to be isotropic
- Then energy density fixes T^{ab}
- For simplicity, velocities and viscous stresses at $\tau=\tau_0$ set to zero

Hydro evolution

$$T^{ab} = \epsilon u^a u^b - (P - \Pi)\left(g^{ab} - u^a u^b\right) + \pi^{ab}$$

$$\nabla_a T^{ab} = 0$$

Solved numerically in 2+1d using vh2+1

Cooper-Frye freeze-out for cells reaching T=170 MeV

Free-streaming evolution

$$T^{ab} = \int \frac{d^2p_\perp dp^\xi \tau}{(2\pi)^3} \frac{p^a p^b}{p^\tau} f(\tau, \mathbf{x}_\perp, \xi, \mathbf{p}_\perp, p^\xi)\,,$$

$$p^a \partial_a f - \frac{2p^\xi p^\tau}{\tau} \partial_\xi^{(p)} f = 0\,,$$

Analytic solution:

$$f = f\left(\mathbf{p}_\perp, p_\xi, \mathbf{x}_\perp - \frac{\tau \mathbf{p}_\perp p^\tau}{p_\perp^2 + m^2}, \xi + \ln\left[\frac{p^\tau}{p_\xi} + \frac{1}{\tau}\right]\right)\,.$$

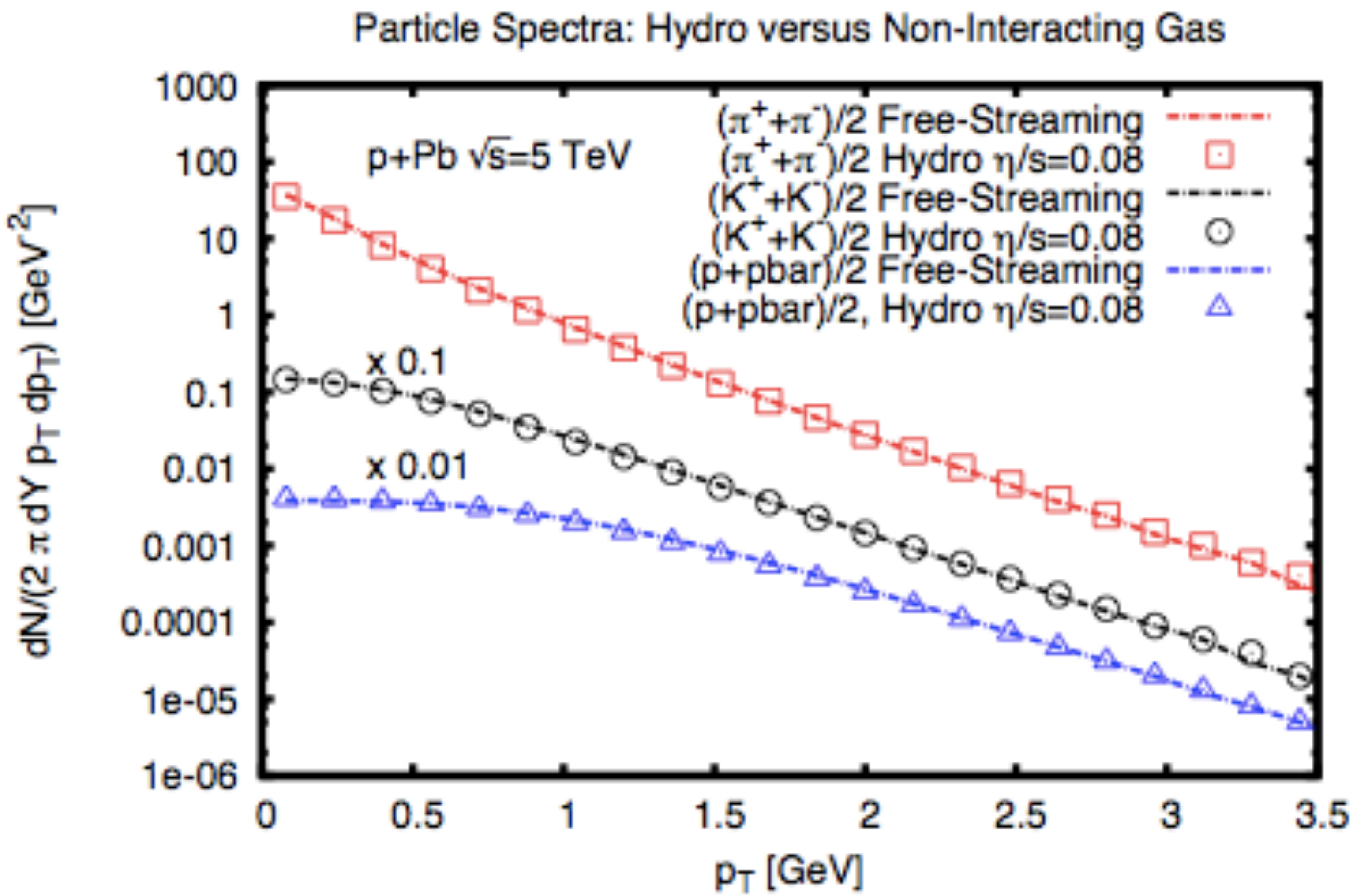
Cooper-Frye freeze-out for cells reaching T=170 MeV

Hadron Cascade

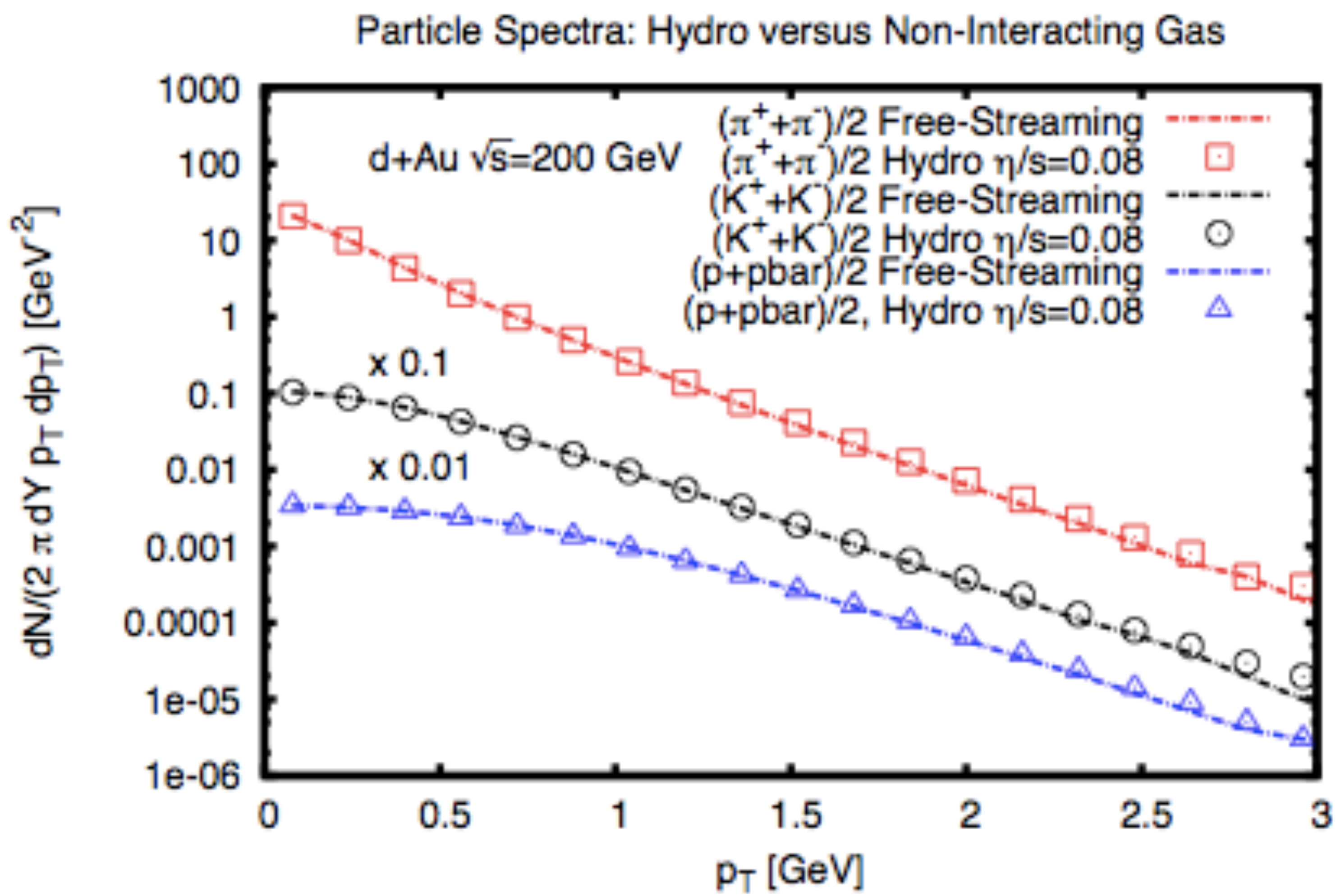
- Once all cells have cooled below T=170 MeV, evolution simulated using hadron cascade (B3D)
- All stable particle resonances up to M=2.2 GeV
- Conversion fully matching T^{ab} incl. viscous stresses (not only ideal fluid part)
- Typically 100,000 B3D events per hydro/FS event
- Particle spectra, v_n calculated from B3D events

Results

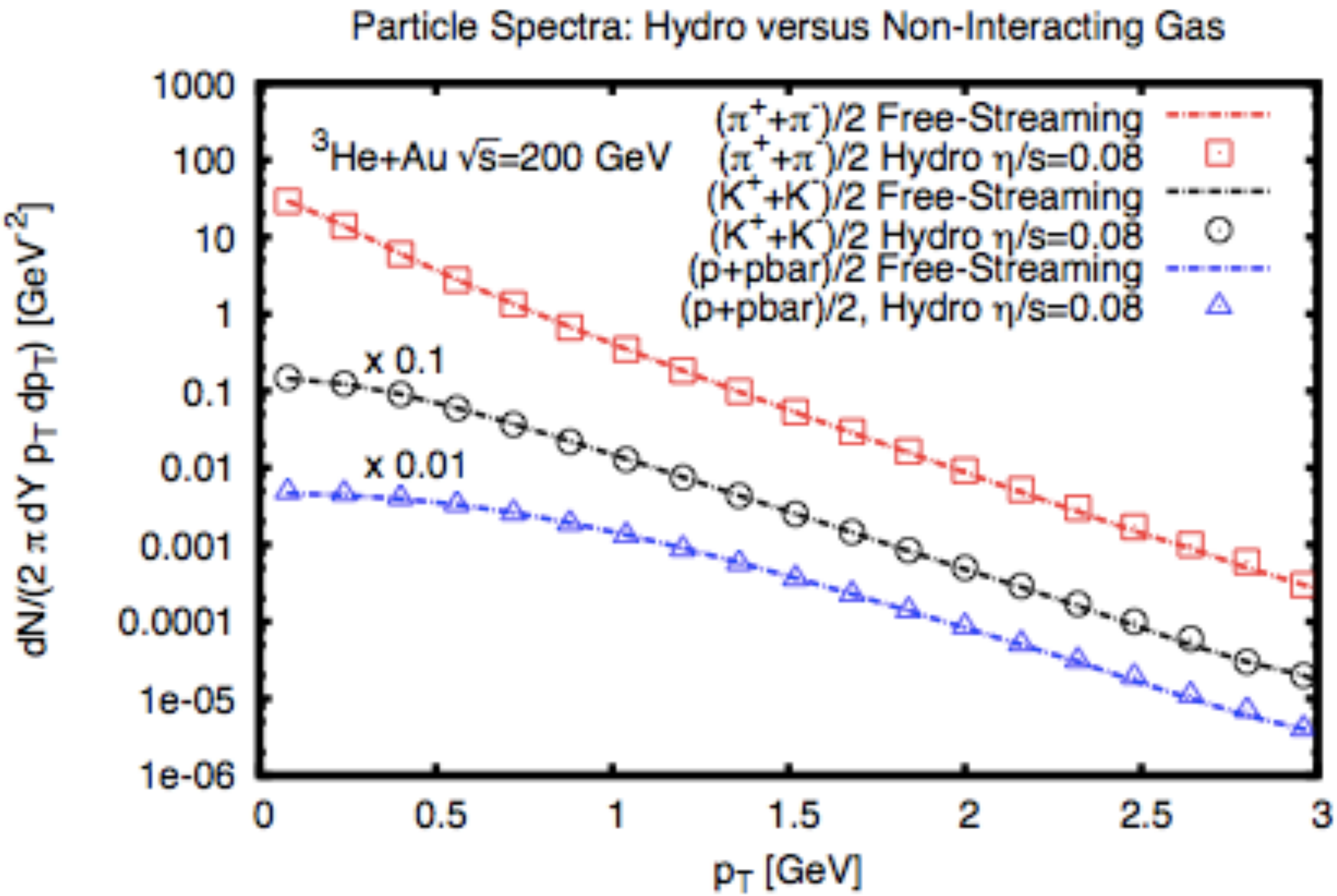
Radial flow in p+A



Radial flow in p+A



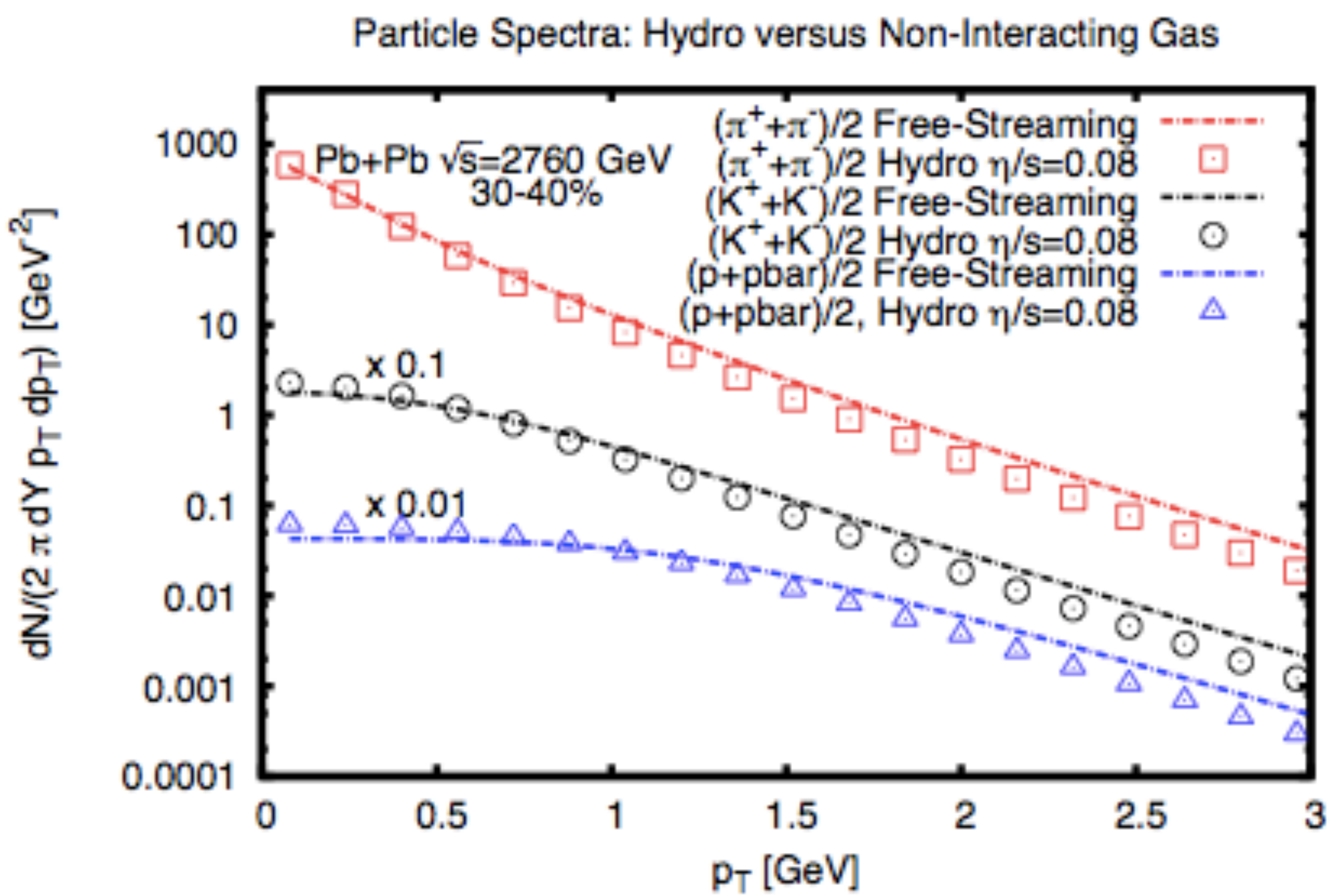
Radial flow in p+A



Radial flow in p+A

- Finding: radial flow in almost ideal hydro ($\eta/s=0.08$) and free-streaming ($\eta/s=\infty$) essentially identical for p+A

Radial flow in A+A

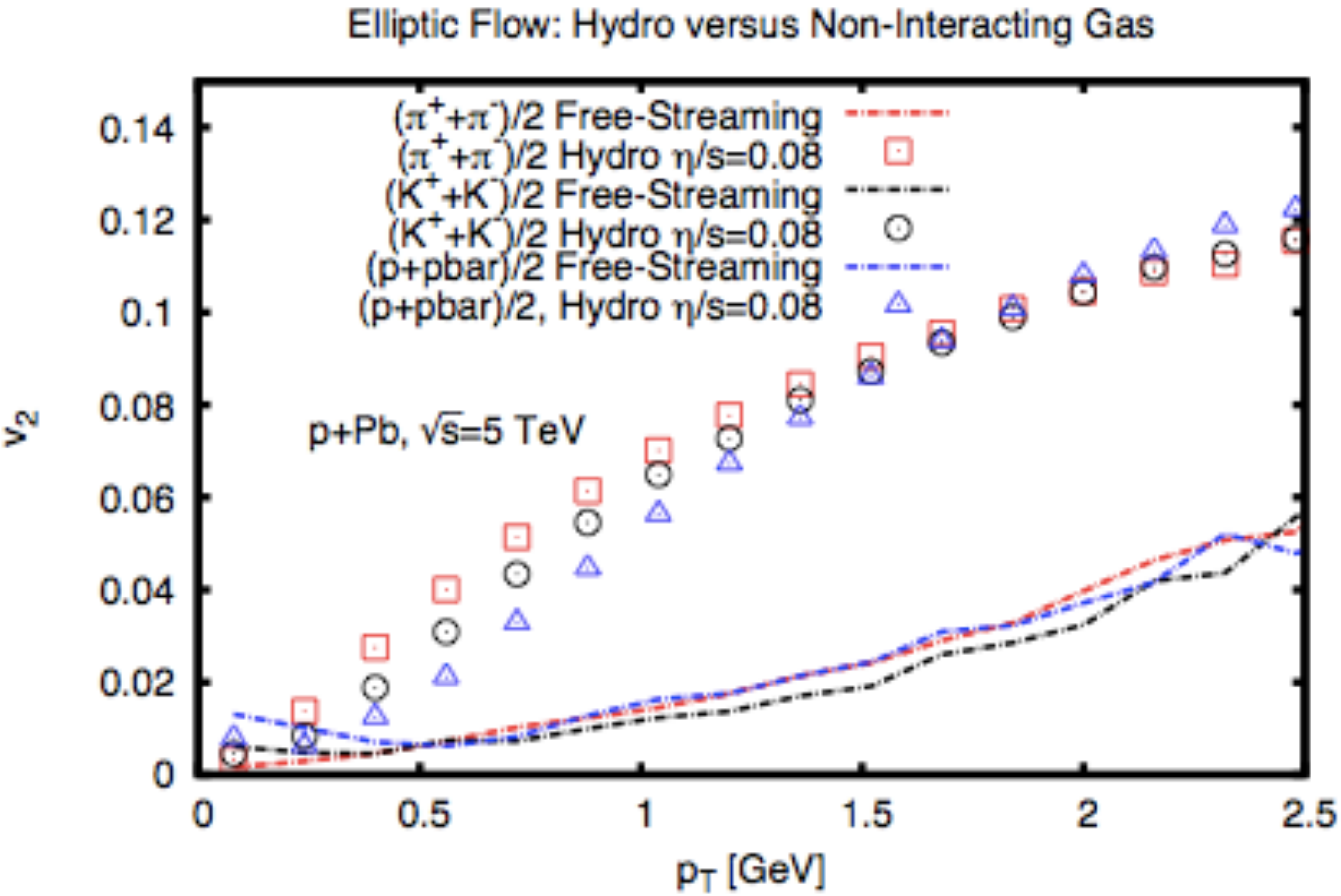


Radial flow Conclusions

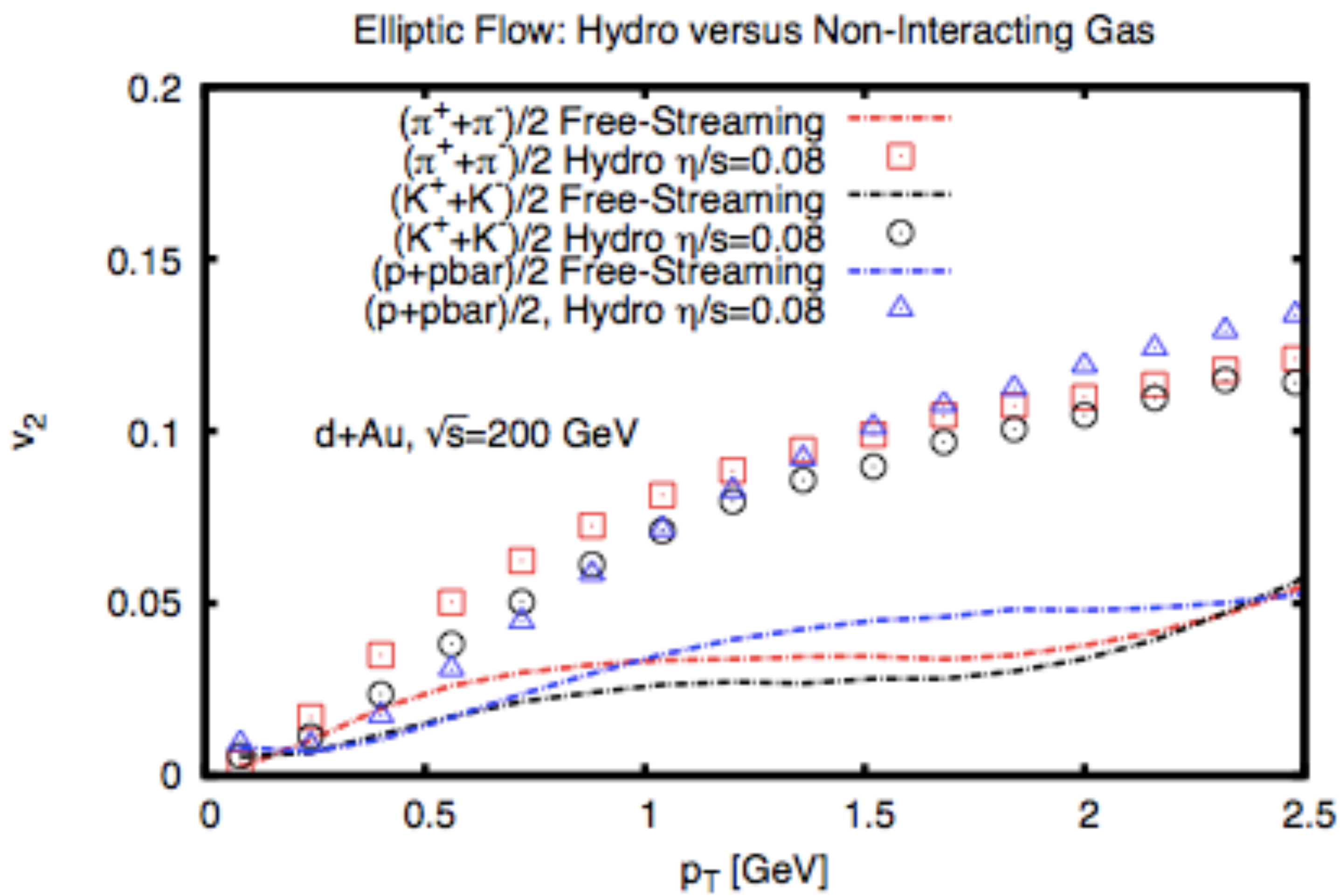
- Finding 1: radial flow in viscous hydro ($\eta/s=0.08$) almost the same as in free-streaming ($\eta/s=\infty$) for p+A
- Finding 2: radial flow in free-streaming **larger** than in almost ideal hydro

My conclusion: observation of radial flow is no indication of hydro phase

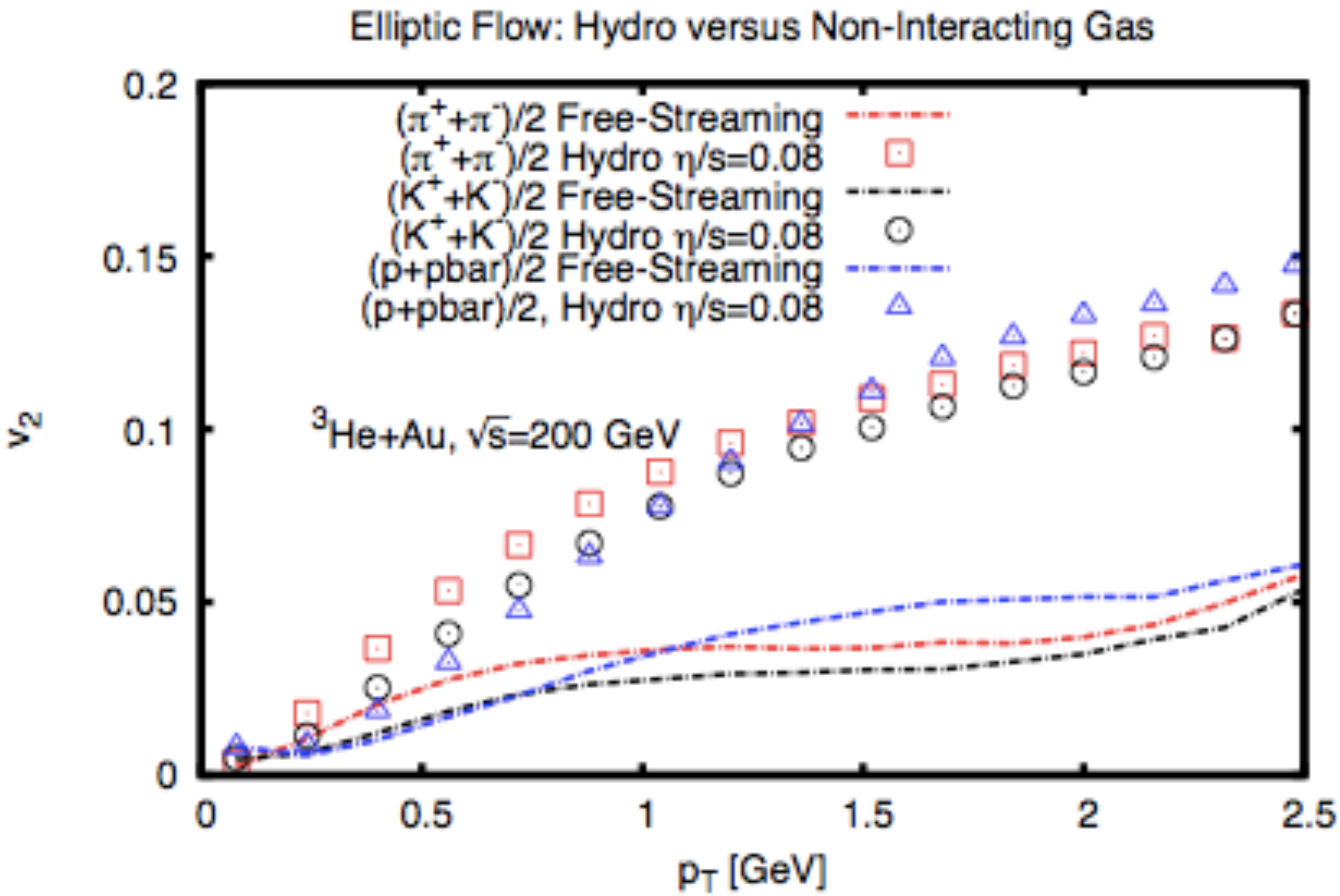
Elliptic flow in p+A



Elliptic flow in p+A



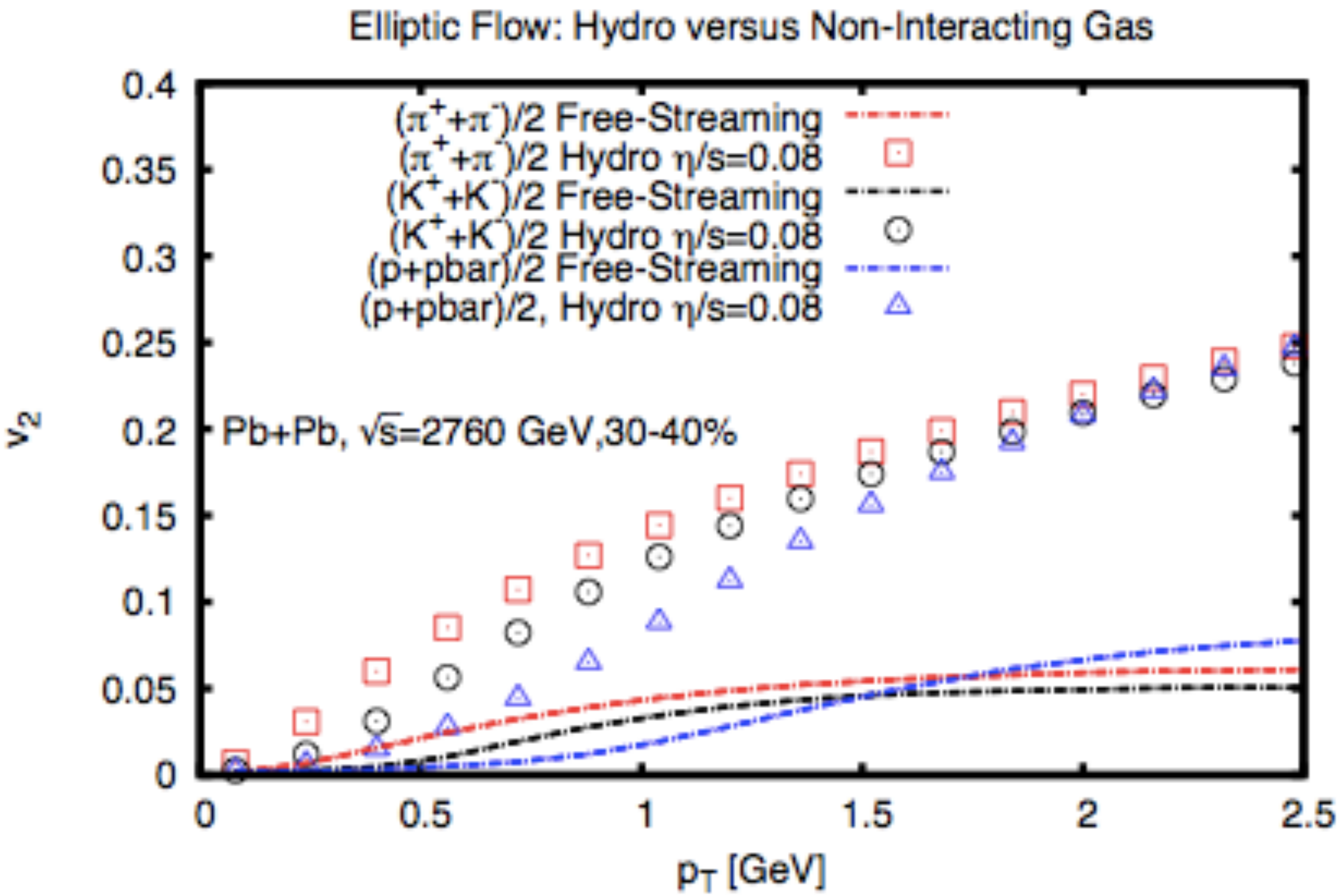
Elliptic flow in p+A



Elliptic flow in p+A

- Finding 1: there is some elliptic flow generated in free-streaming ($\eta/s=\infty$) + hadron cascade dynamics in p+A
- Finding 2: the amount of elliptic flow in free-streaming ($\eta/s=\infty$) + hadron cascade dynamics is only about 1/3 of that in almost ideal hydro ($\eta/s=0.08$) +hadron cascade in p+A

Elliptic flow in A+A

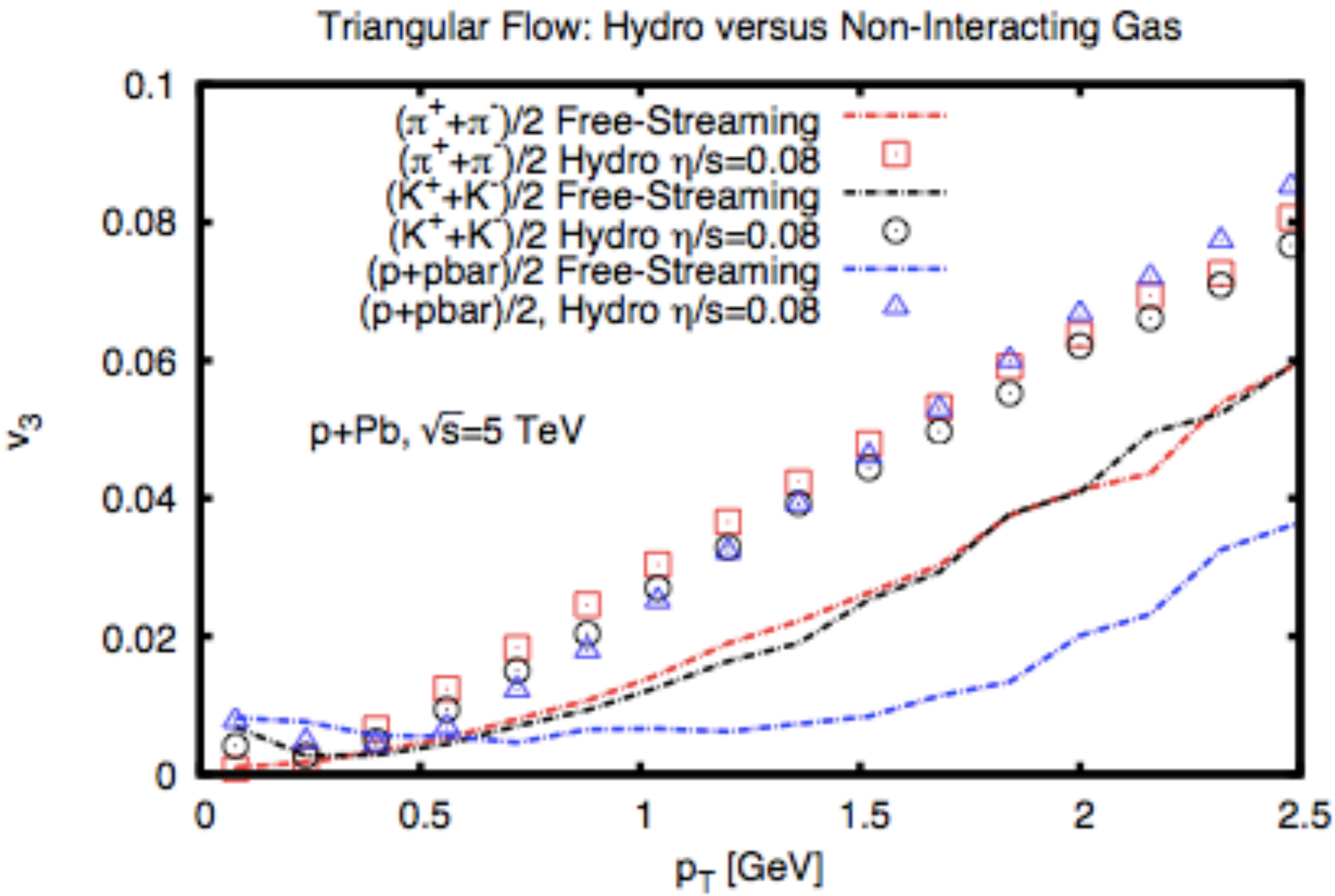


Elliptic flow Conclusions

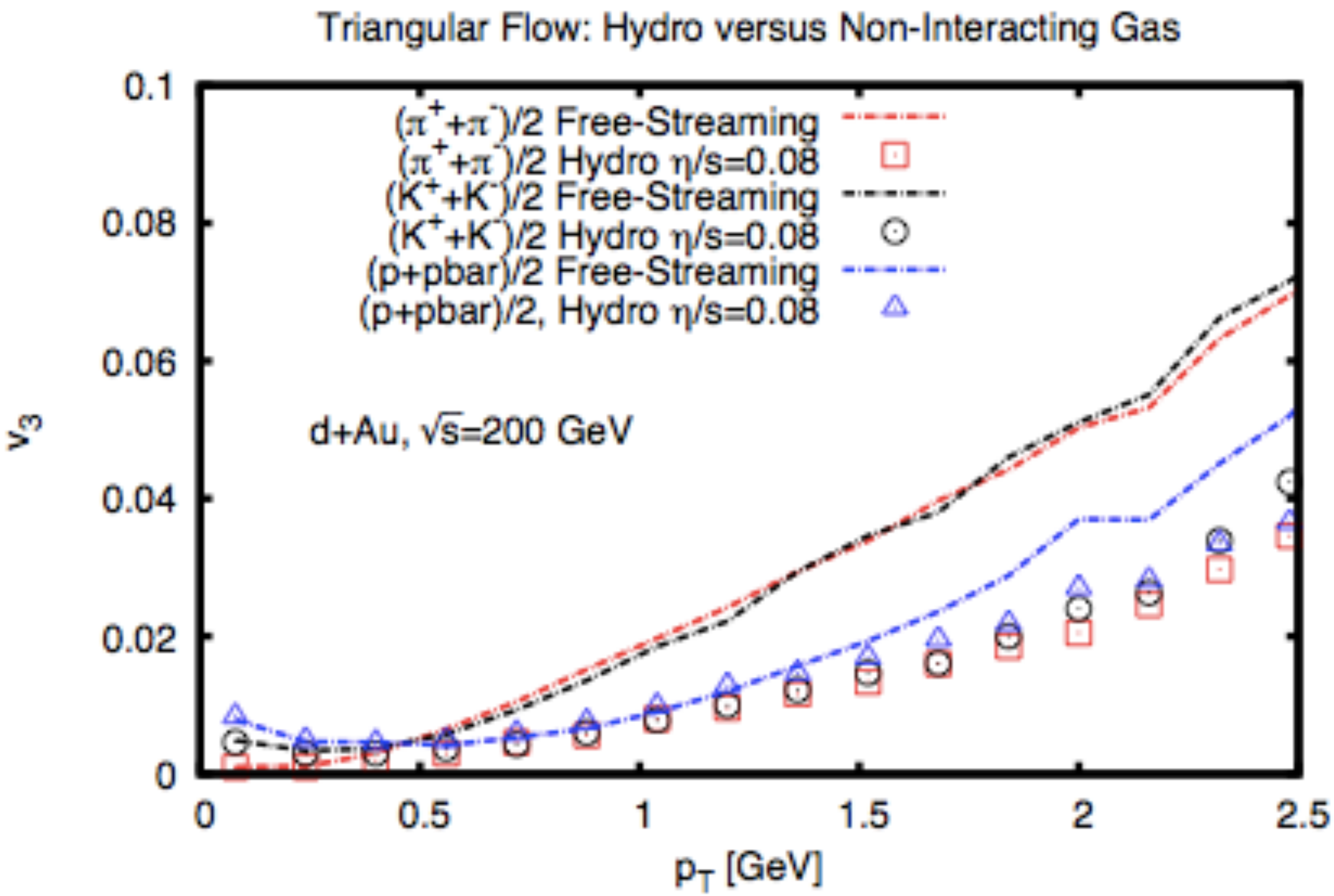
- Finding 1: big differences of elliptic flow between viscous hydro ($\eta/s=0.08$) and free-streaming ($\eta/s=\infty$) for p+A and AA

My conclusion: observation of large elliptic flow is evidence for hydro phase

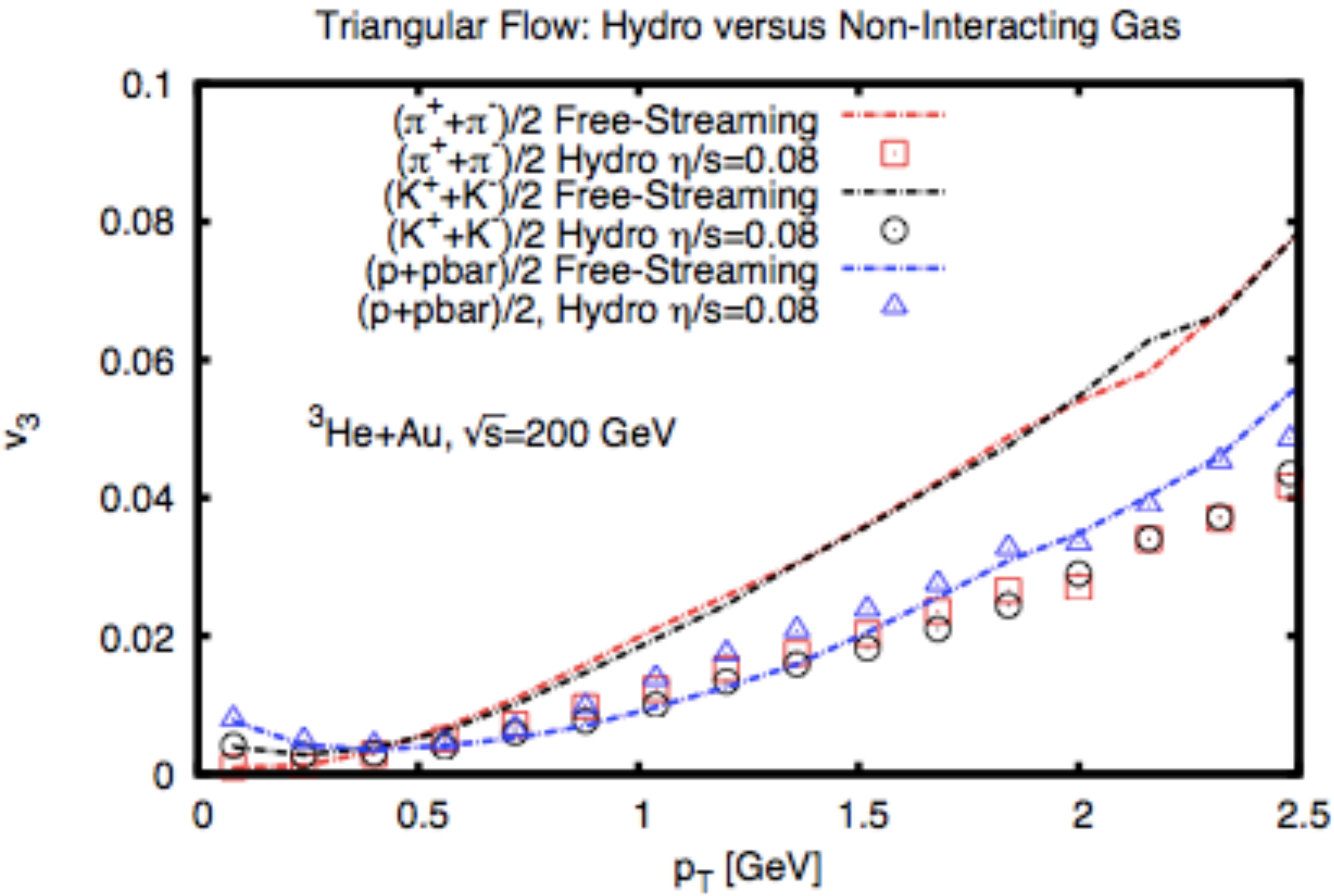
Triangular flow in p+A



Triangular flow in p+A



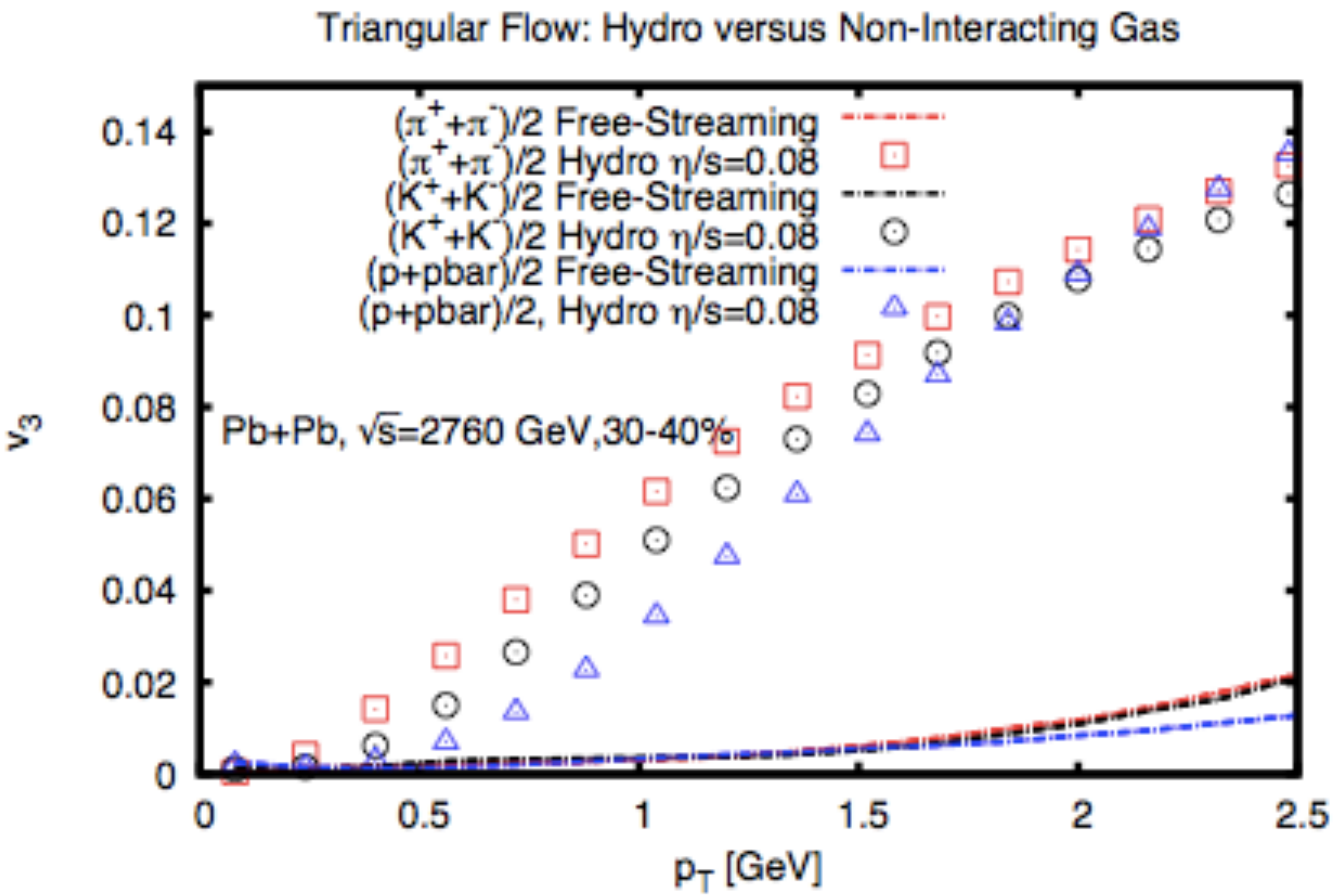
Triangular flow in p+A



Triangular flow in p+A

- Finding: triangular flow in free-streaming ($\eta/s=\infty$) +hadron cascade similar to (p+Pb) or larger than (d+Au, ^{3}He+Au) in almost ideal hydro ($\eta/s=0.08$)+cascade

Triangular flow in A+A

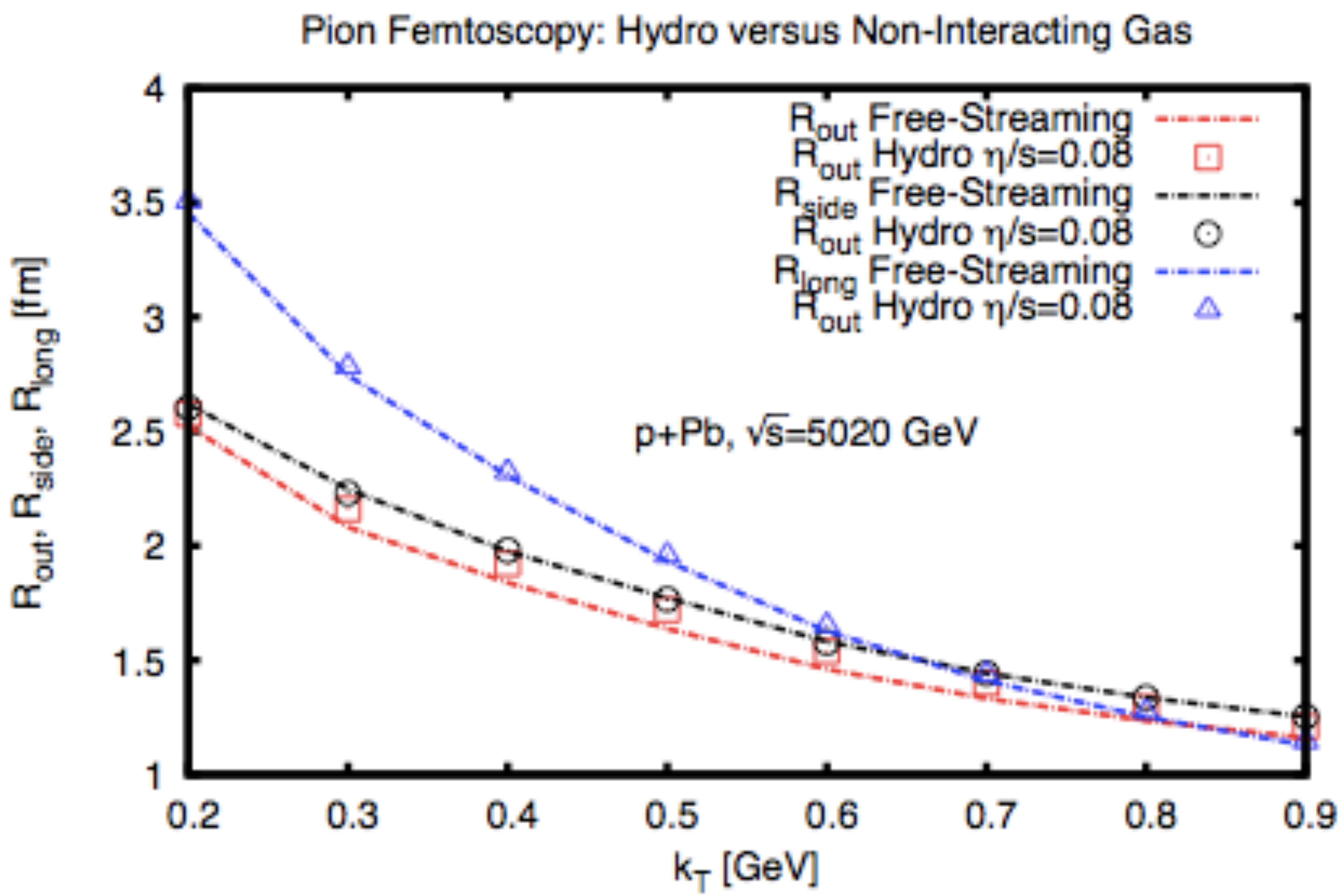


Triangular flow Conclusions

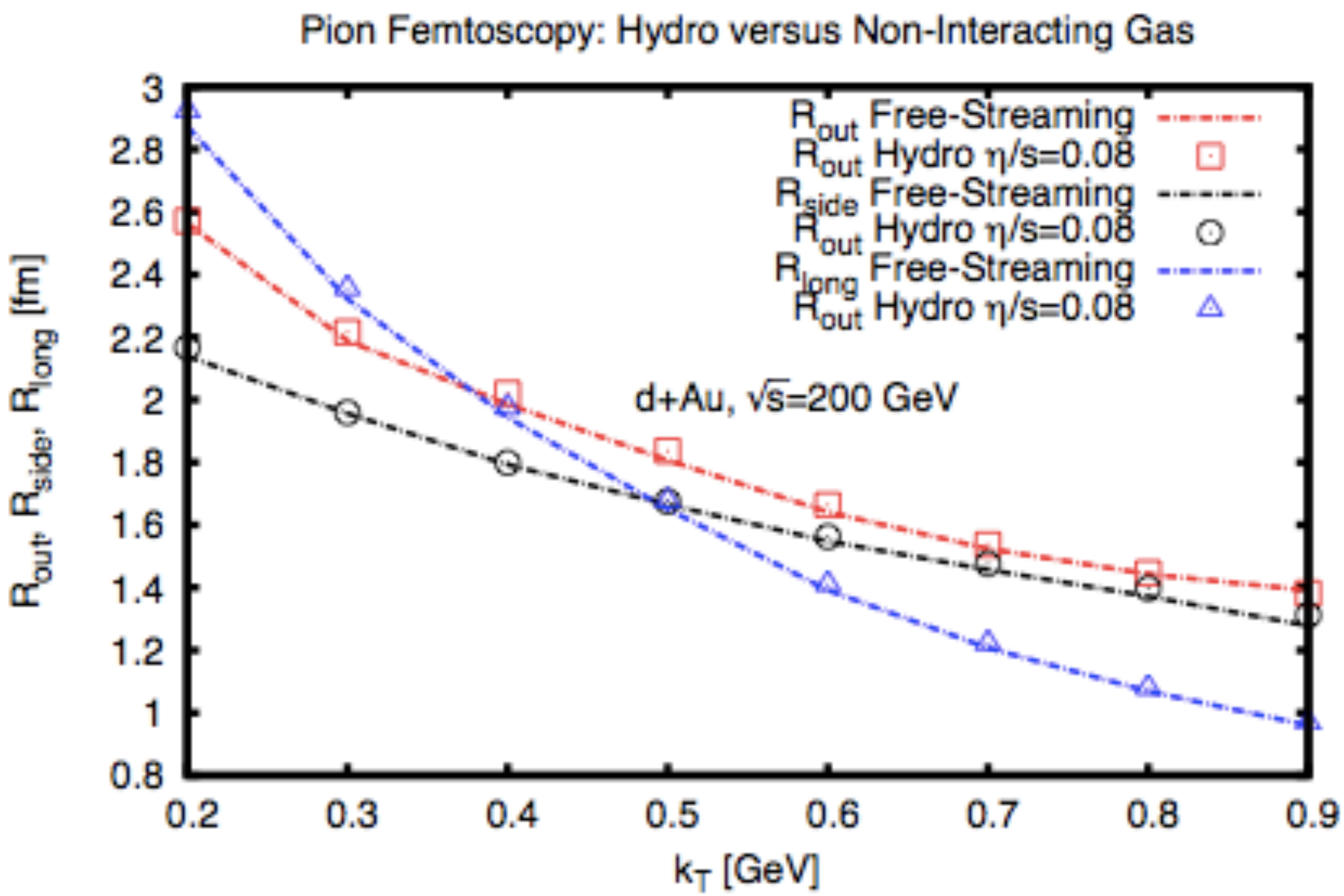
- Finding 1: triangular flow in viscous hydro ($\eta/s=0.08$) almost the same as in free-streaming ($\eta/s=\infty$) for p+Pb
- Finding 2: triangular flow in free-streaming **larger** than in almost ideal hydro for d+Au and ^{3}He+Au at RHIC

My conclusion: v_3,v_4 measurements in p+A can easily be generated by hydro-imposters; do not use as viscometer!

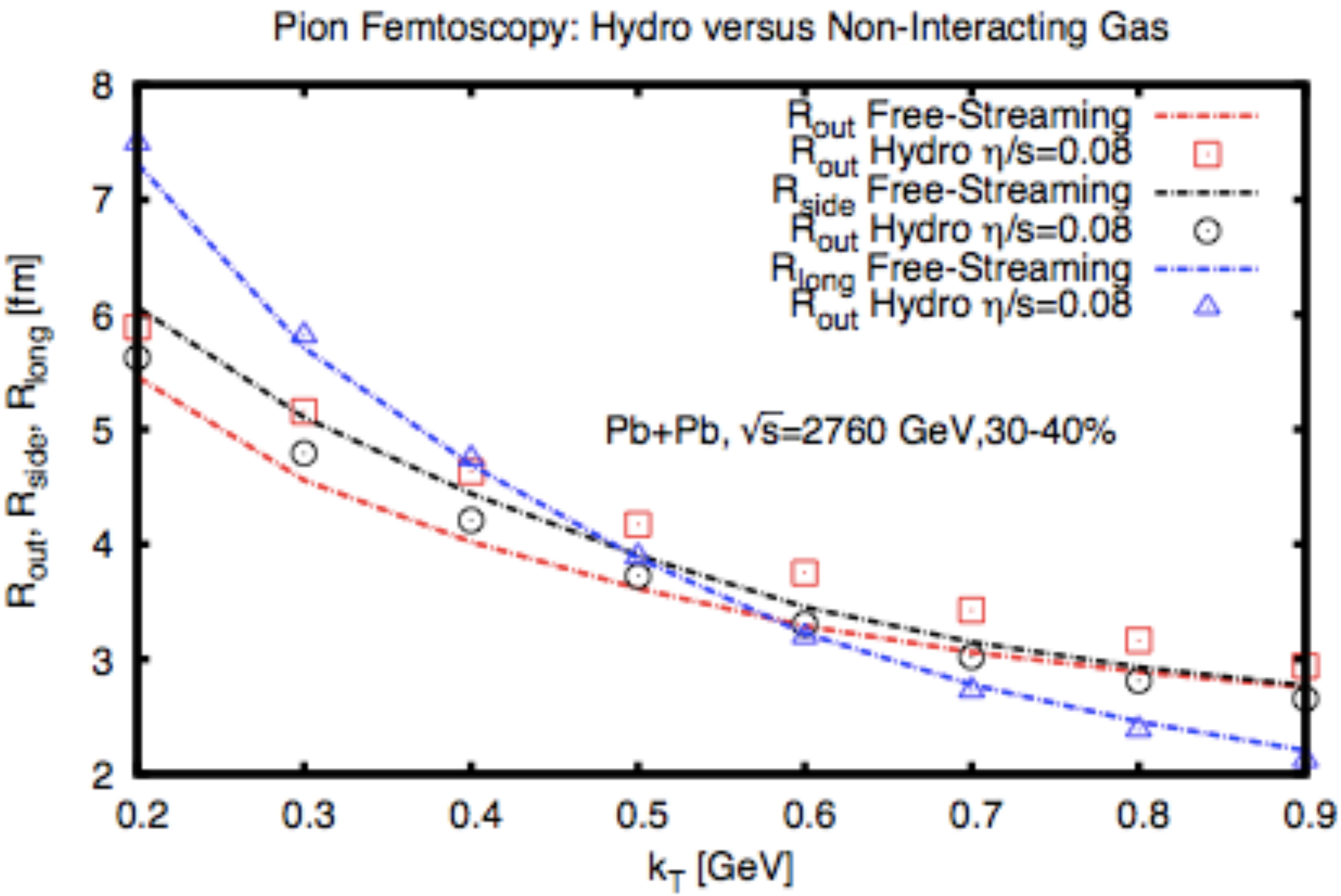
HBT radii in p+A



HBT radii in p+A



HBT radii in p+A



HBT Radii Conclusions

- Finding 1:HBT Radii are essentially identical in viscous hydro ($\eta/s=0.08$) and free-streaming ($\eta/s=\infty$) dynamics in p+A and also A+A

My conclusion: measurements of HBT Radii are not sensitive to the presence or absence of a hydro phase

Conclusions

- Apples-to-apples comparison of models for p+A collisions (hydro vs. free-streaming)
- Radial flow, HBT radii are essentially the same for hydro and FS; do not use as evidence for hydro phase
- v_3 is similar in hydro/FS in p+A; do not use as 'viscometer'
- v_2 is the gold standard: hard to fake without hydro; "large" v_2 is evidence for hydro phase