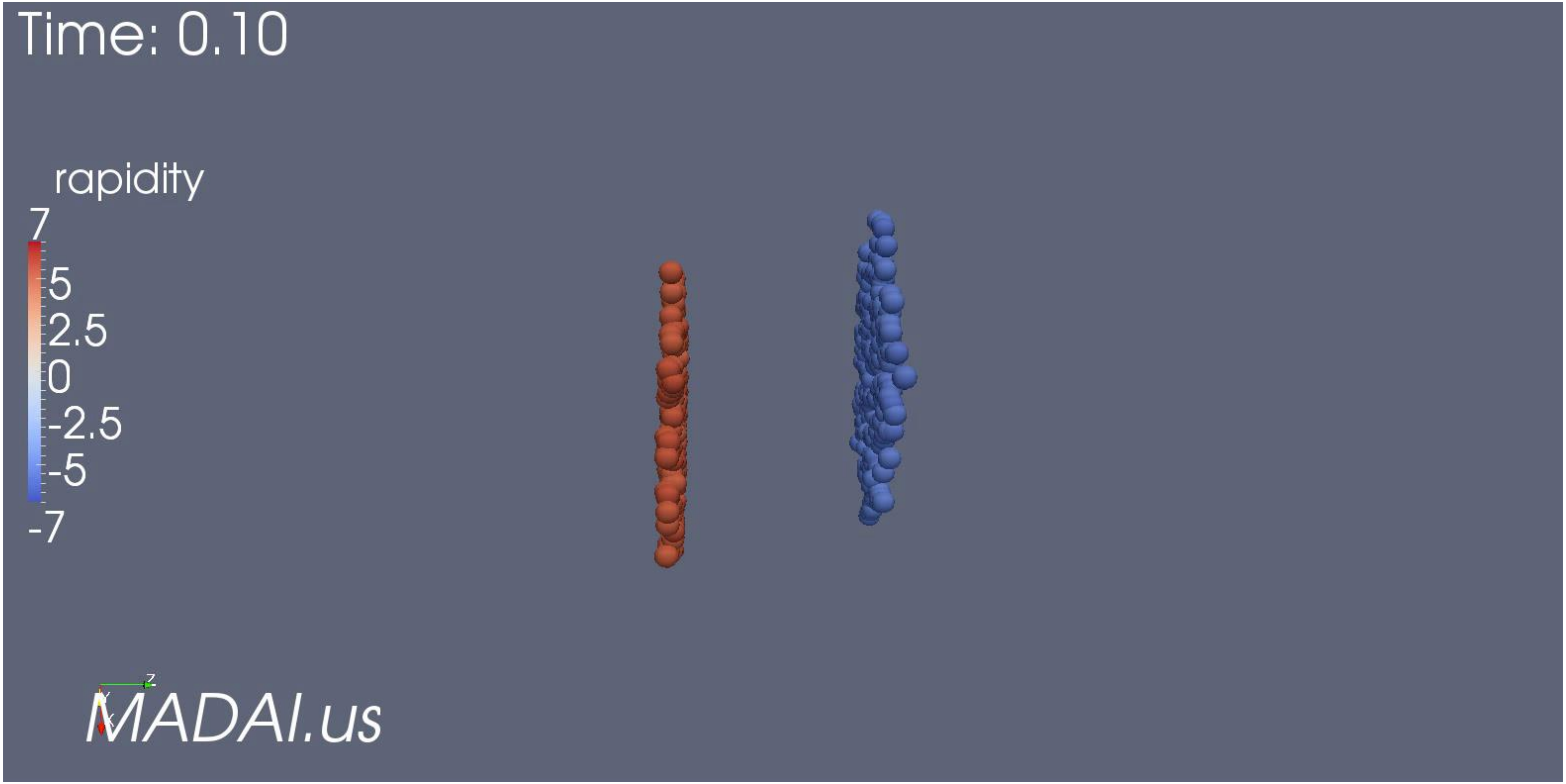
Non-Equilibrium Dynamics in Nuclear Collisions

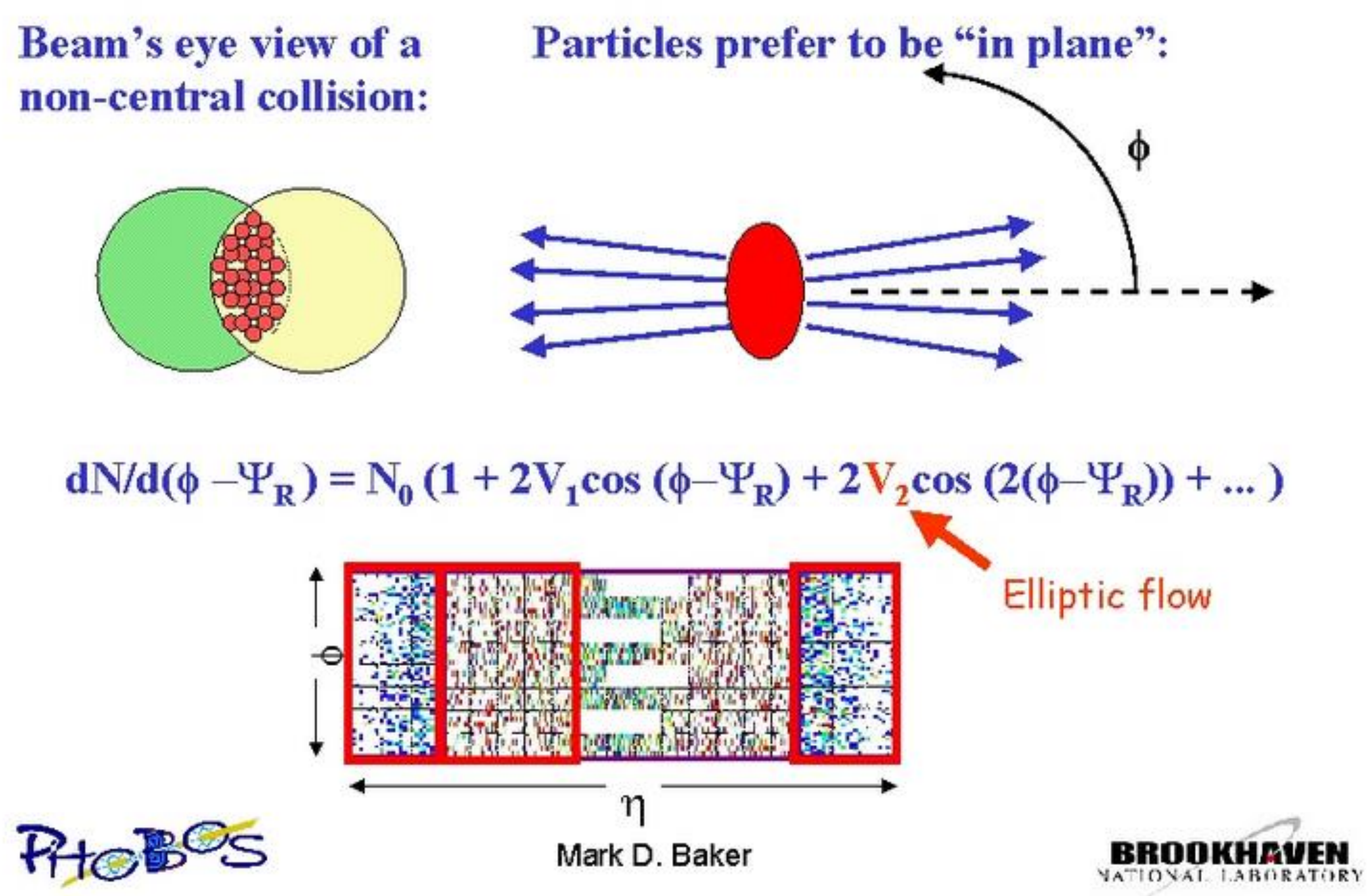
Paul Romatschke

CU Boulder & CTQM Boulder

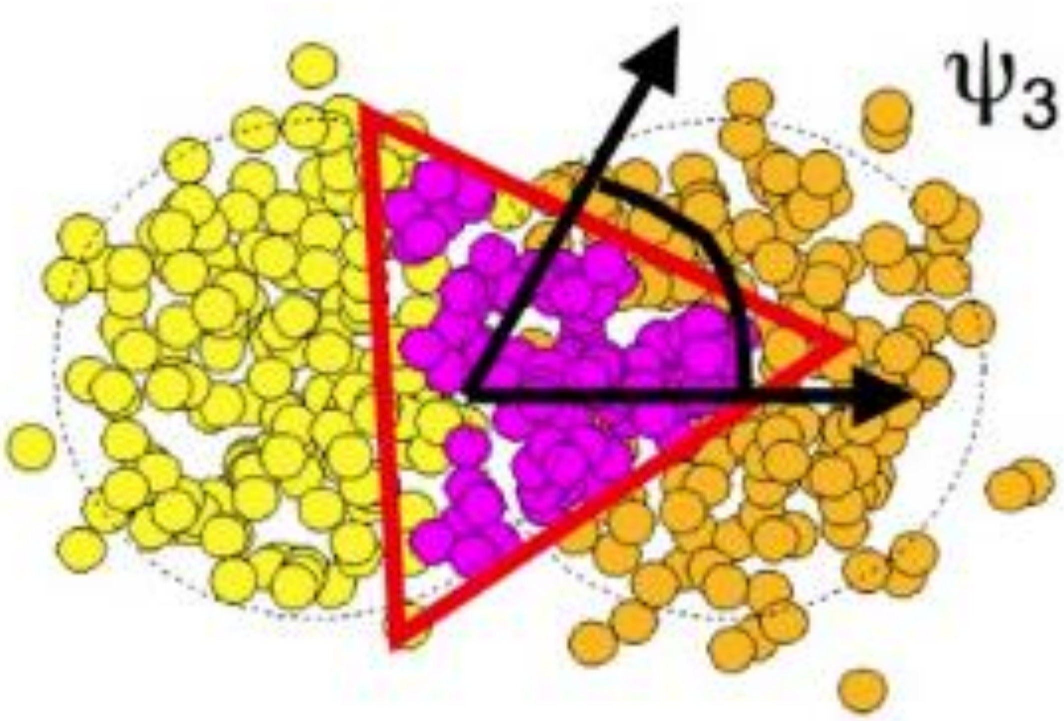
Heavy-Ion Collisions and Elliptic flow



Heavy-Ion Collisions and Elliptic flow V_2

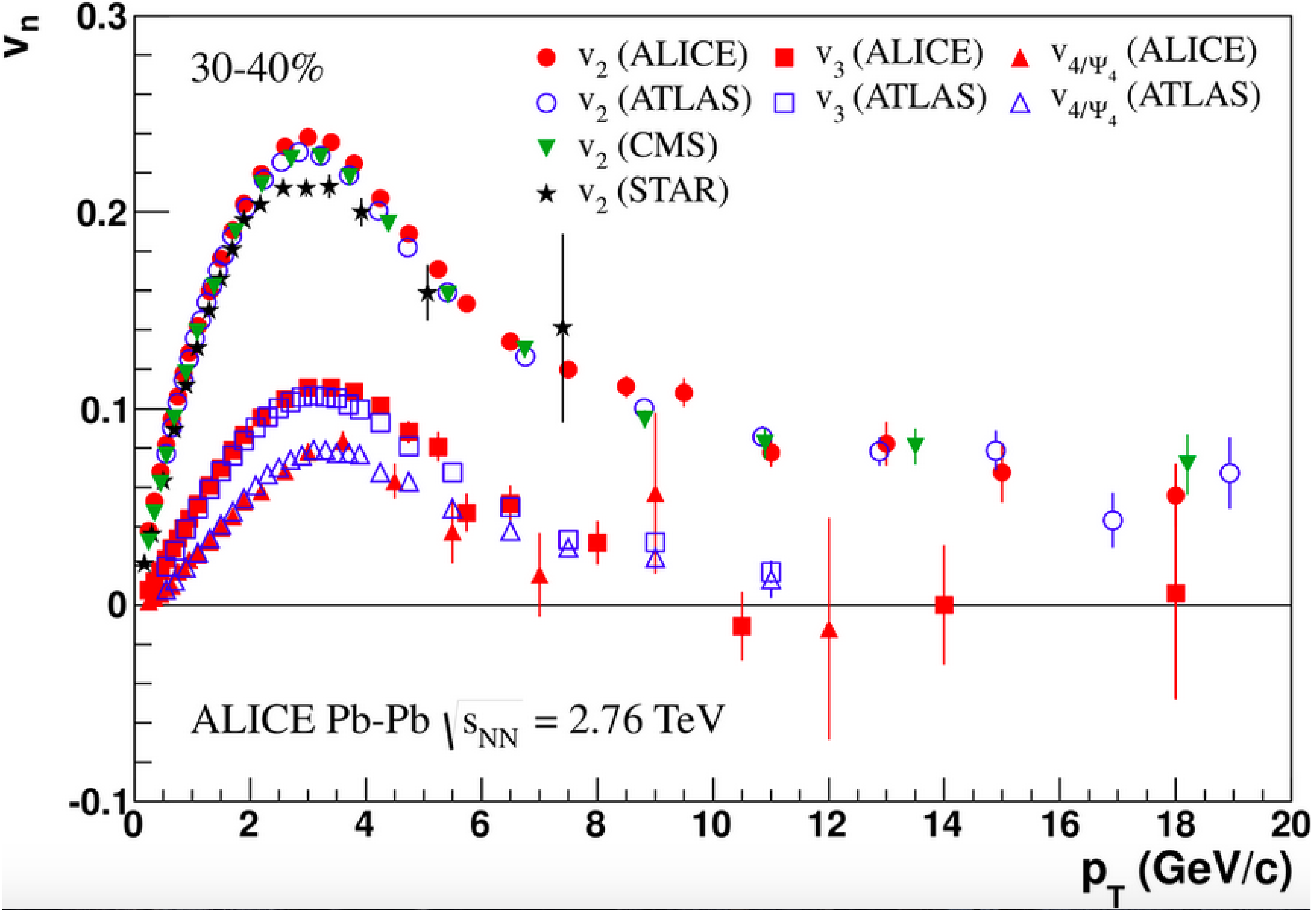


Heavy-Ion Collisions and Triangular flow V_3

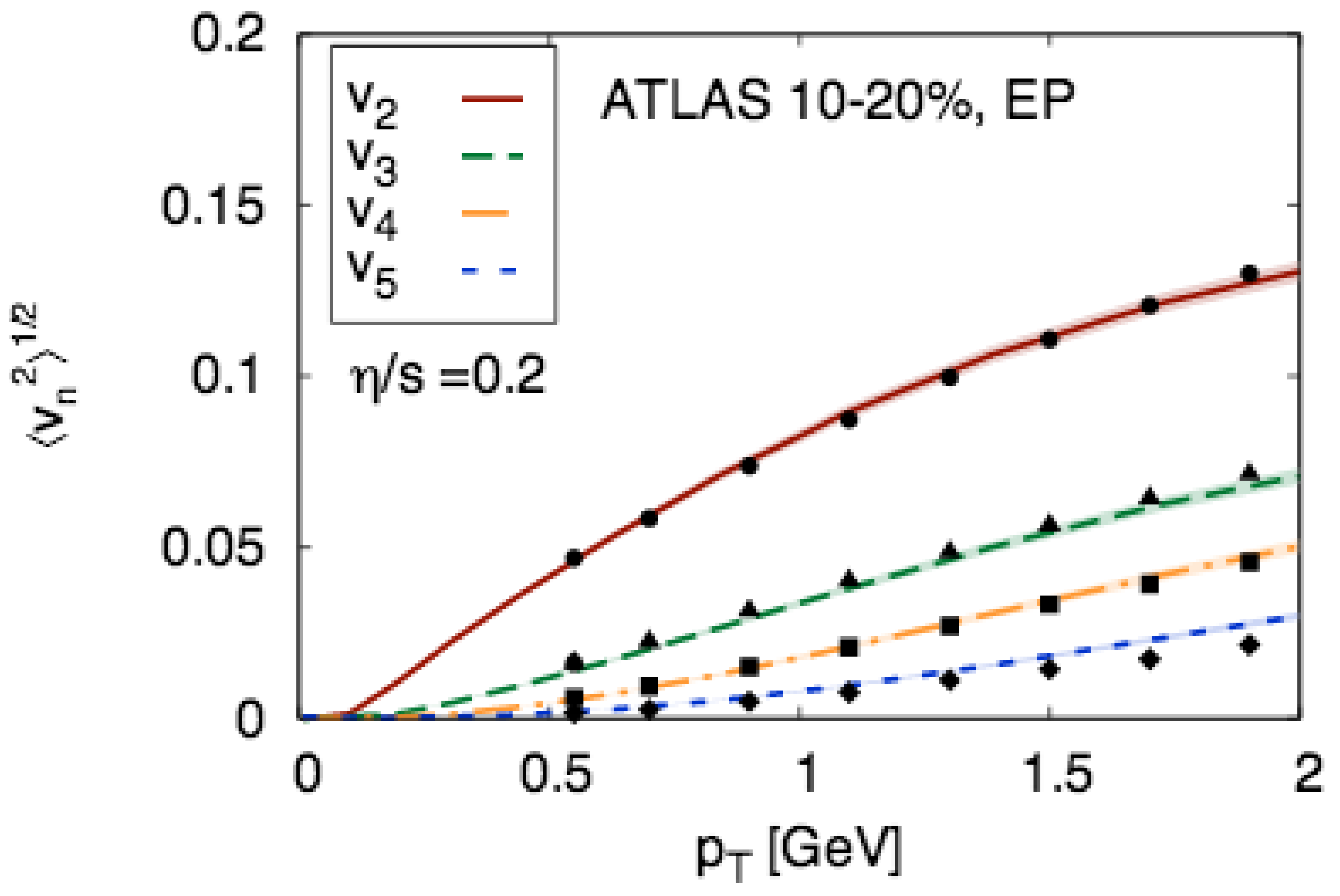


$dN/d\phi \sim V_3 \cos(3\phi)$

In Heavy-Ion collisions (e.g. Au+Au, P+Pb), V_2, V_3, V_4, …are all measured experimentally



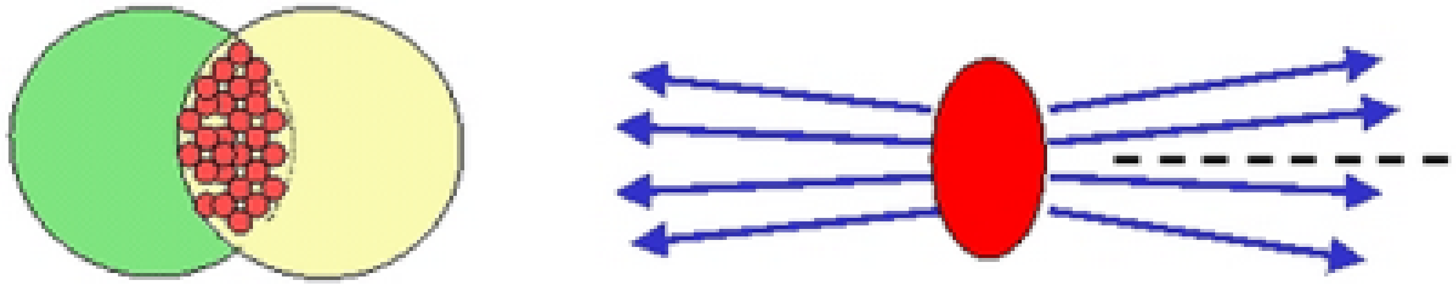
Hydro well describes A-A collisions



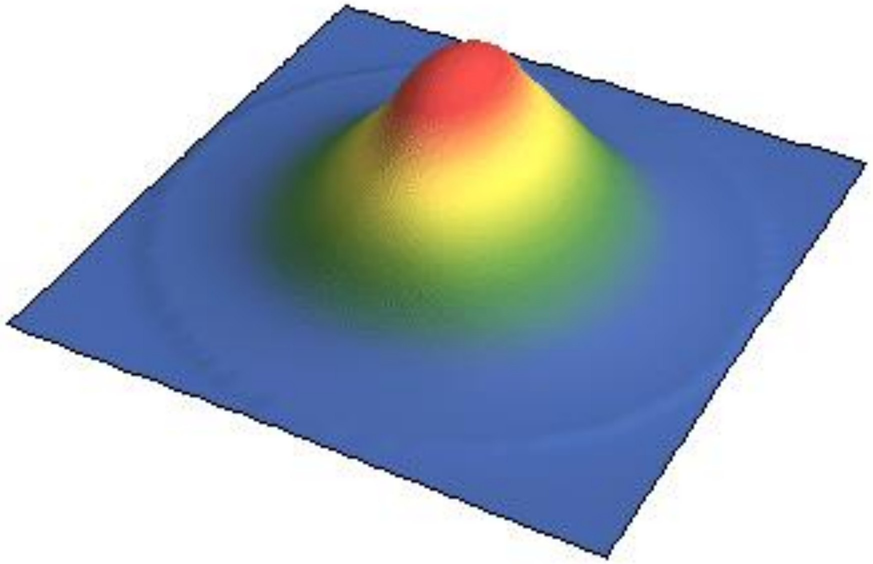
Contitutes major piece of evidence for formation of Quark-Gluon Plasma in the laboratory!

[Gale et al. 2012]

Hydrodynamics

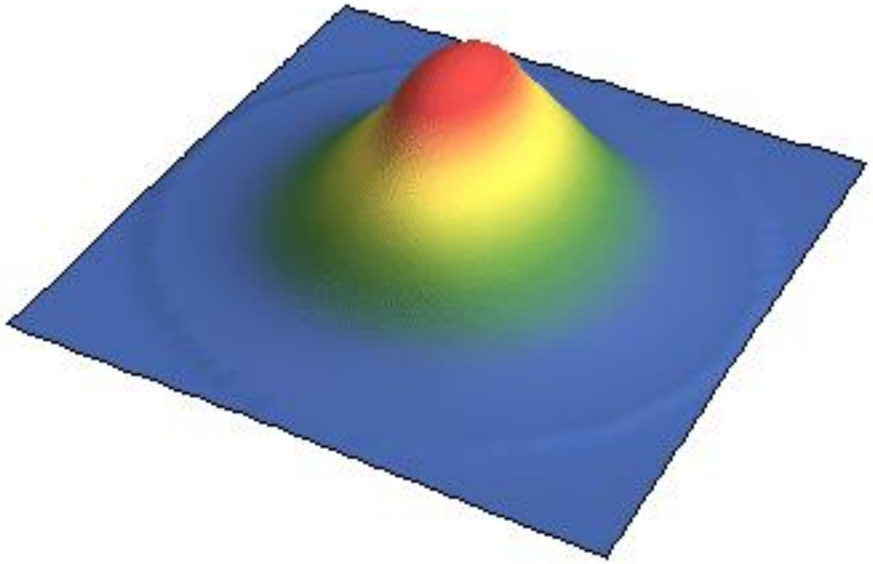


Hydrodynamics



Hydrodynamics converts gradients into velocities

Hydrodynamics



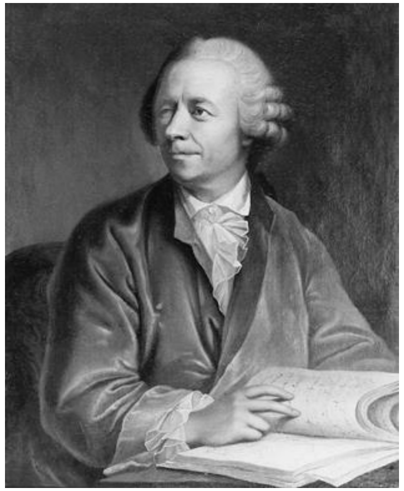
Hydrodynamics converts gradients into velocities

$$\partial_\tau v \sim \partial_r p$$

(Relativistic) Hydro History

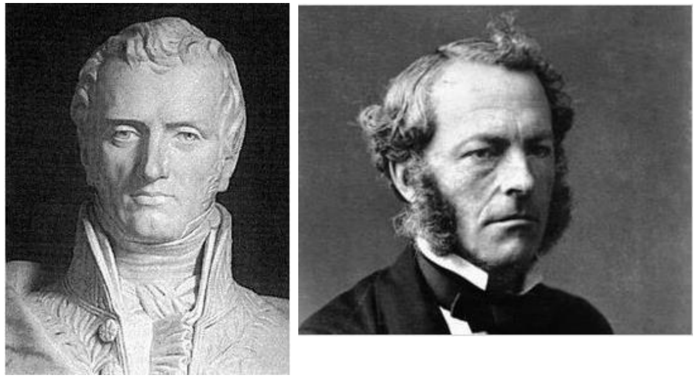
Hydro (gradient) order

0^{th}



Euler

1^{st}



Navier & Stokes

2^{nd}

& many others!

(Relativistic) Hydro Equations: Transport coefficients

Hydro (gradient) order

0^{th}	1^{st}	2^{nd}
Speed of sound c_s	Shear and bulk viscosities η & ς	Second order coefficients: τ_π, λ_1, λ_2, λ_3, κ, κ^*, ξ_1, ξ_2, ξ_3,…
Equilibrium	Non-equilibrium, but “close” to equilibrium	“Far” from Equilibrium

Example: Effective Pressure in Hydro

- Ideal Hydrodynamics: $T^{ab}=T^{ab}_{(0)}=\mathrm{diag}(-\varepsilon,P,P,P)$

  Just equilibrium pressure

- Navier-Stokes: $T^{ab}=T^{ab}_{(0)}+\pi^{ab}$; $\pi^{ab}=-\eta\ \sigma^{ab}$; so $P_{eff}=P-\eta\ \nabla u$

  Equilibrium pressure+ “small” corrections

- 2nd order hydro (BRSSS) : $T^{ab}=T^{ab}_{(0)}+\pi^{ab}$; $D_t\ \pi^{ab}=-(\pi^{ab}+\eta\ \sigma^{ab})/\tau_R$

  Non-equilibrium pressure; OK as long as close to NS

Can this be checked?

- Simple setup for equilibration: space-time initially at rest starts to expand in one dimension (“Bjorken flow”); matter reacts to ST

$$ds^2 = -dt^2 + dx^2 + dy^2 + g(t)dL^2$$

- t<<0: g(t)=1 (Minkowski)
- t>>0: g(t)=t^2 (Bjorken)
- g(t) interpolating between Minkowski and Bjorken
- ST flat except for small region around t=0

[Keegan et al, 1512.05347]

Can this be checked?

- Simple setup for equilibration: space-time initially at rest starts to expand in one dimension (“Bjorken flow”); matter reacts to ST

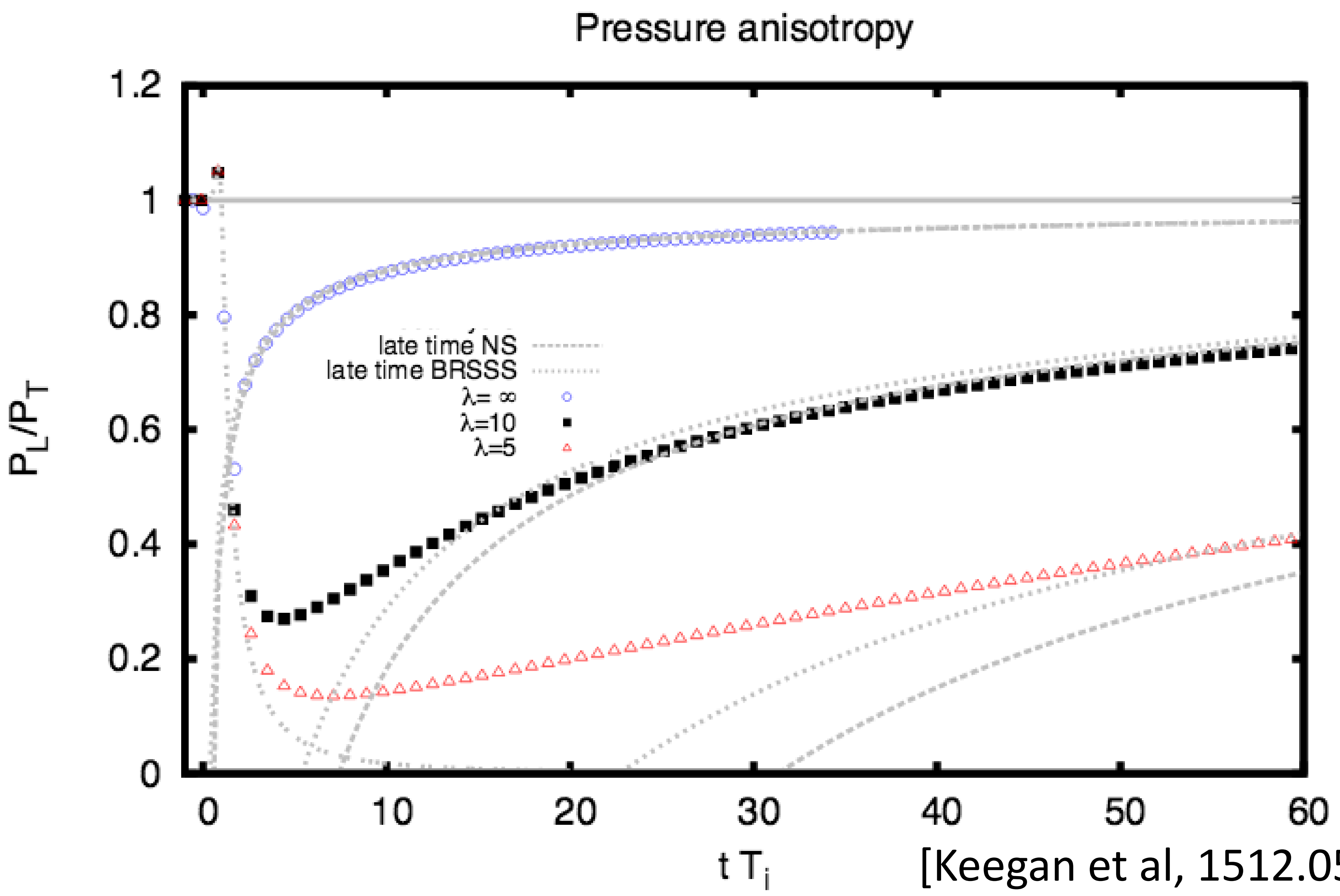
$$ds^2 = -dt^2 + dx^2 + dy^2 + g(t)dL^2$$

- Simulate solution **exactly** (using AdS/CFT & kinetic theory) and compare to hydrodynamics
- Pressure anisotropy: “how far from equilibrium”

$$\frac{P_L}{P_\perp} = \frac{1 - 4H(t)}{1 + 2H(t)} \,.$$

- Navier-Stokes $H_{NS}(t) = \frac{2}{3}\frac{\eta}{s}\frac{g'(t)}{g(t)T(t)}\,,$

[Keegan et al, 1512.05347]



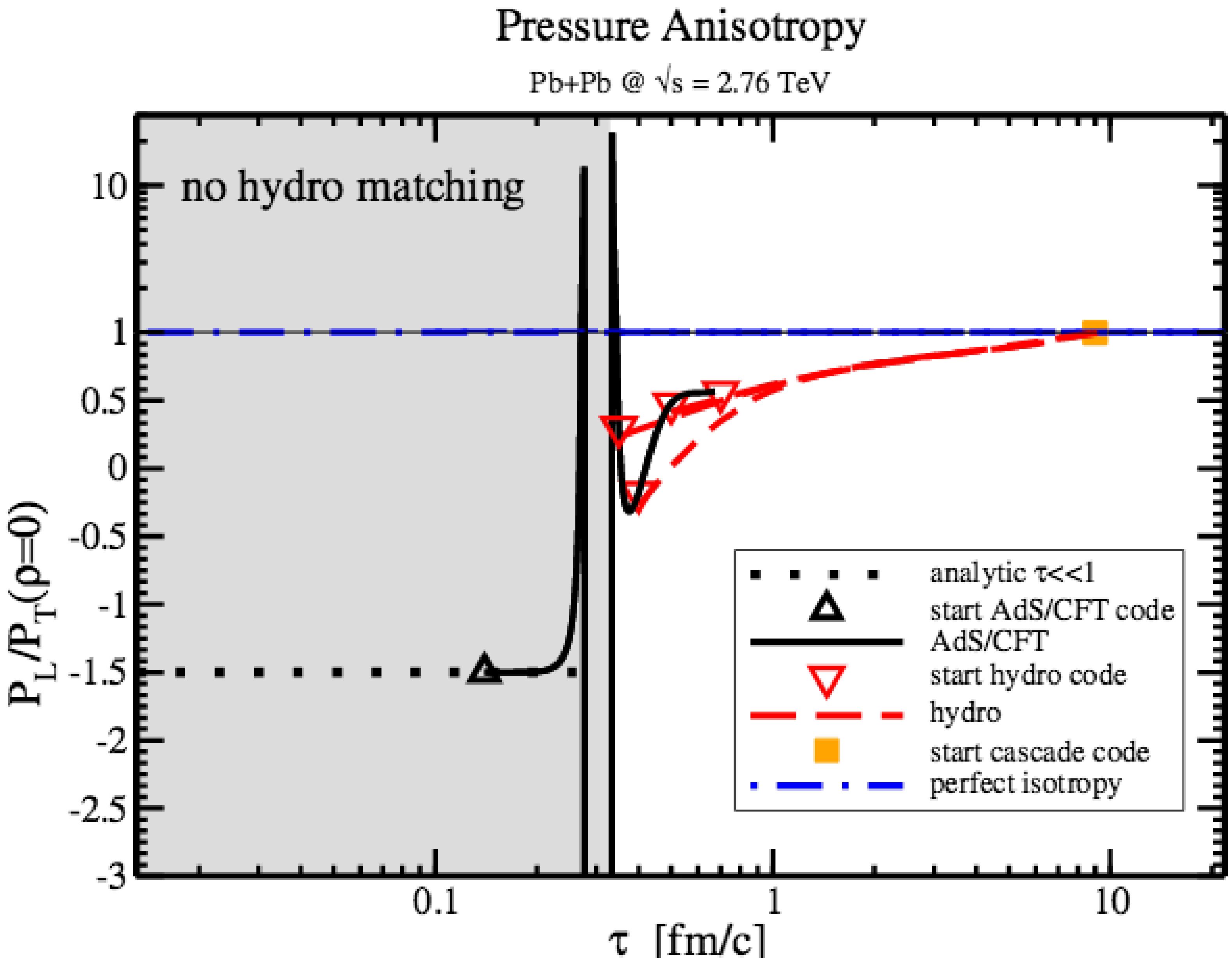
[Keegan et al, 1512.05347]

“Unreasonable” Effectiveness of Hydro

- Hydrodynamics describes exact result when non-equilibrium corrections are 50-80%
- Order unity deviation from Equilibrium Dynamics!
- (2^{nd} order) Hydro works for non-equilibrium situations!

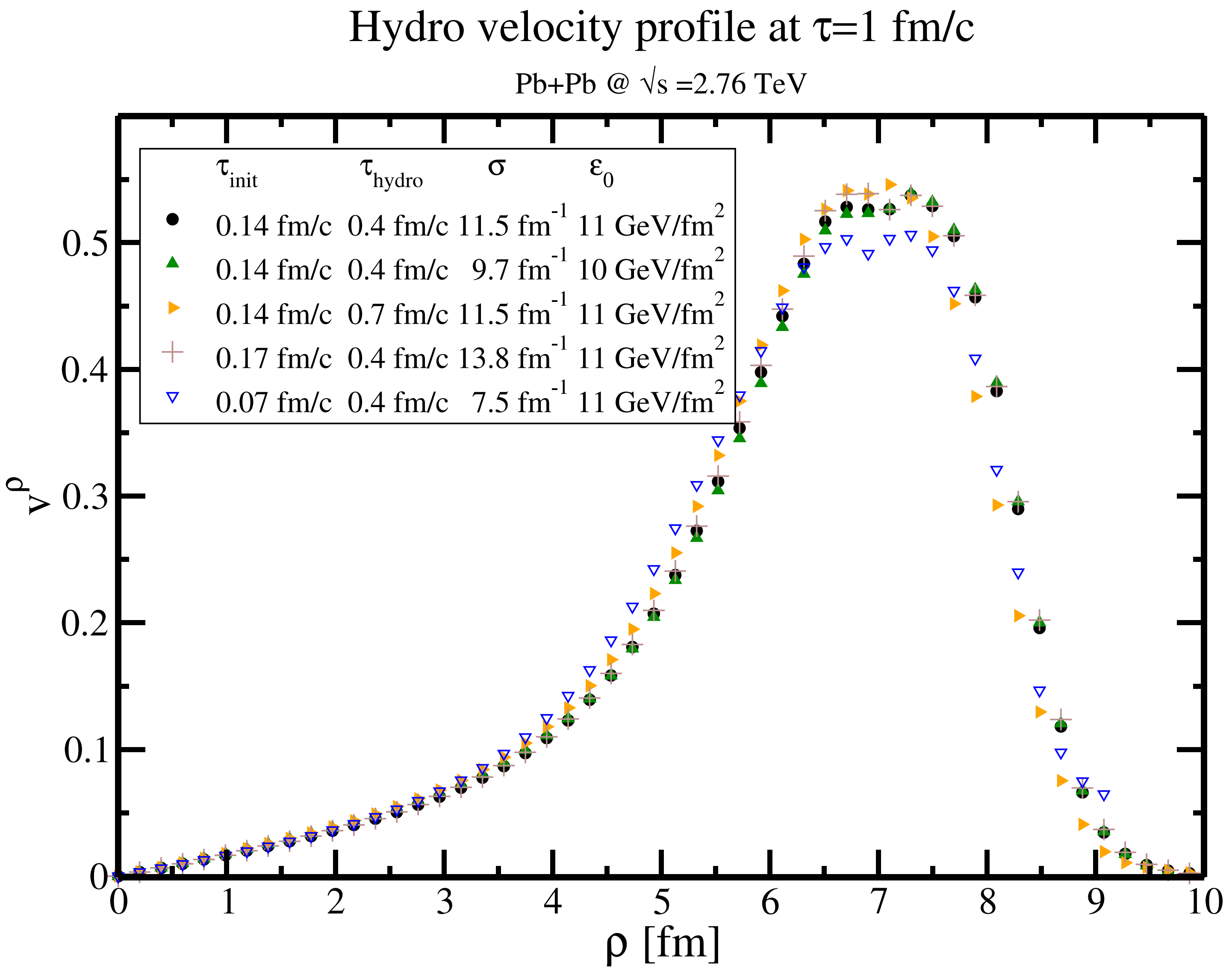
Is this relevant for Heavy-Ion Physics?

Simulating Pb+Pb using AdS+hydro+cascade



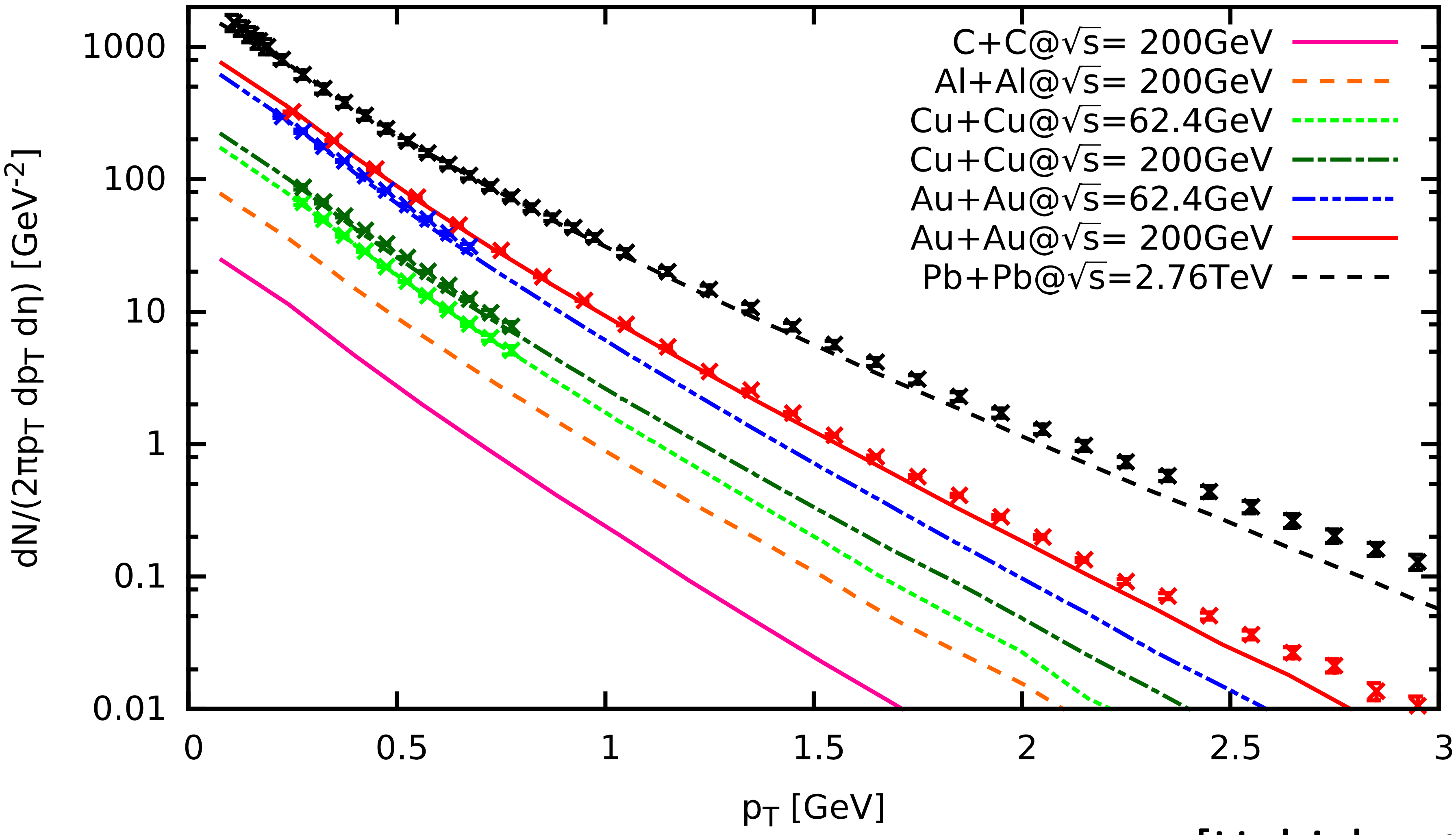
[van der Schee et al., 1307.2539]

Simulating Pb+Pb using AdS+hydro+cascade



[van der Schee et al., 1307.2539]

Reality-check: comparison to exp' data



[Habich, et al., EPJ 2015]

Non-equilibrium dynamics in Pb+Pb

- Pressure anisotropy O(1) in hydro simulations of HIC (all hydro groups)
- Clear non-equilbrium phenomena!
- Nevertheless, can be described by (2^{nd} order) hydro!
- Applicability of hydro not obvious from “standard” mean-free path argument (mean free path ~ system size)
- Needed first-principles strong-coupling dynamics (e.g AdS/CFT) to verify

Why does it work? When does hydro break down?

Why does it work?

- I do not know...
- ...but I have an argument!

Hydro vs. Non-hydro modes

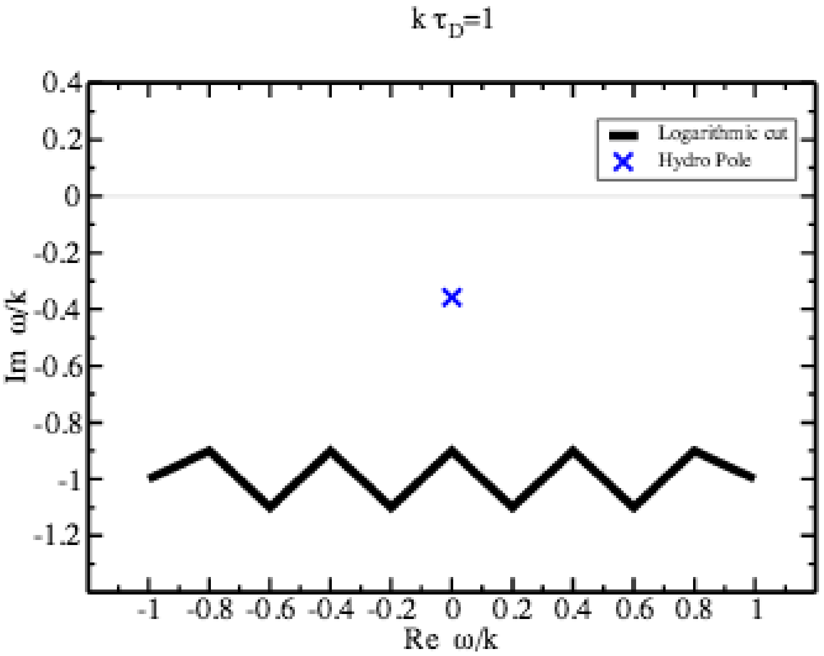
- Hydro modes: genuine low energy degrees of freedom (EFT)
- Non-hydro modes: everything else

As long as non-hydro modes are not (strongly) excited, hydro offers a good description!

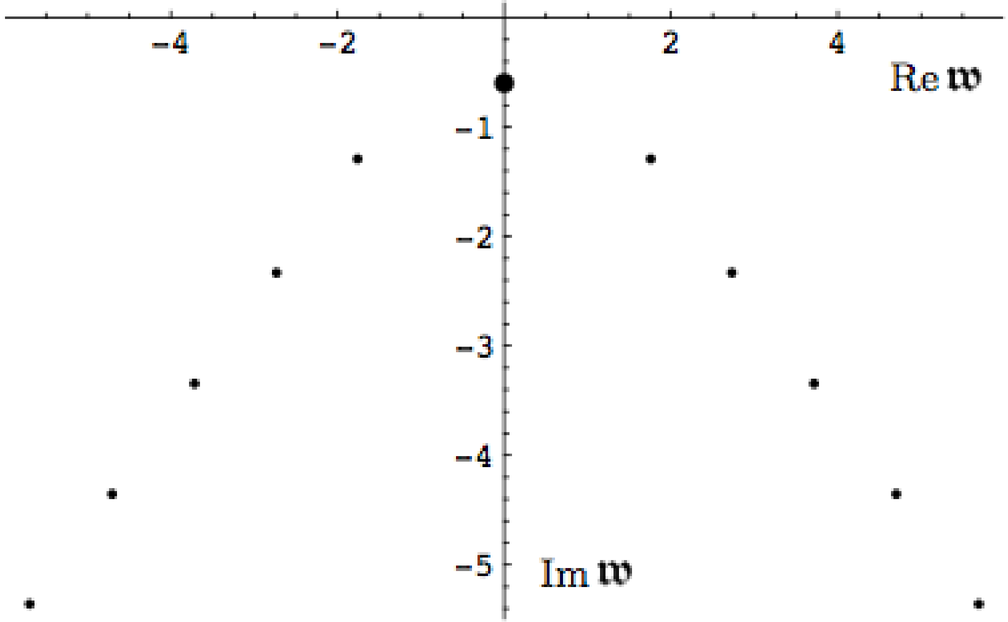
This criterion is not (trivially) related to “usual” mean free path vs. system size. Thus hydro may work in non-equilibrium situations.

What are non-hydro modes?

- Non-hydro QNMs in black holes
- Branch cuts in kinetic theory



[PR, 1512.02641]



[Kovtun, Starinets, hep-th/0506184]

New criterion for applicability of hydro

Hydrodynamics good approximation of non-equilibrium dynamics as long as non-hydro modes not excited

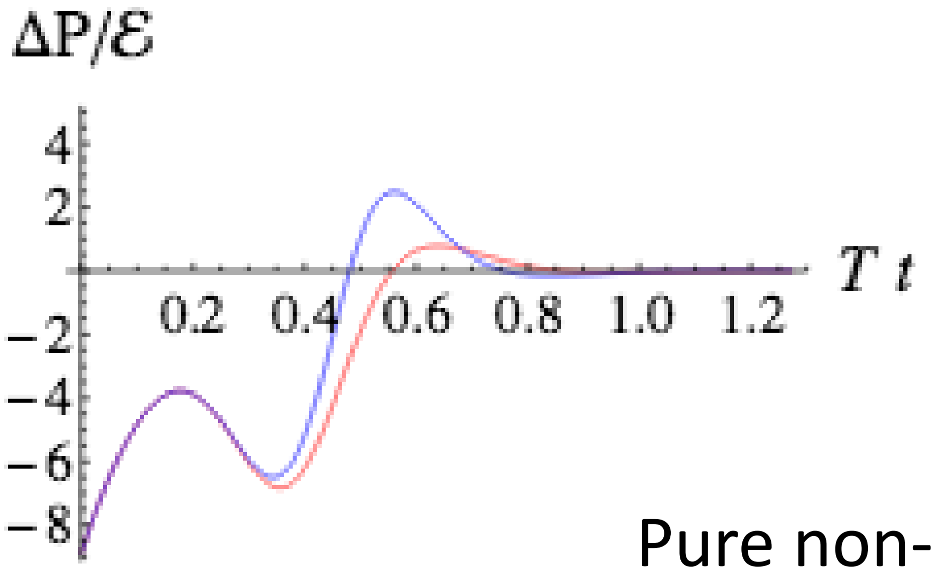
What happens if non-hydro modes excited?

- Non-hydrodynamic transport
- Example: pressure anisotropy in homogeneous system, e.g.

$$T^{ab}=\text{diag}(-\varepsilon,P_T,P_T,P_T+\Delta P)$$

- Hydrodynamics: no change of initial state (no flow in hom' system)
- Actual QFT evolution

[Heller et al, 1304.5172]

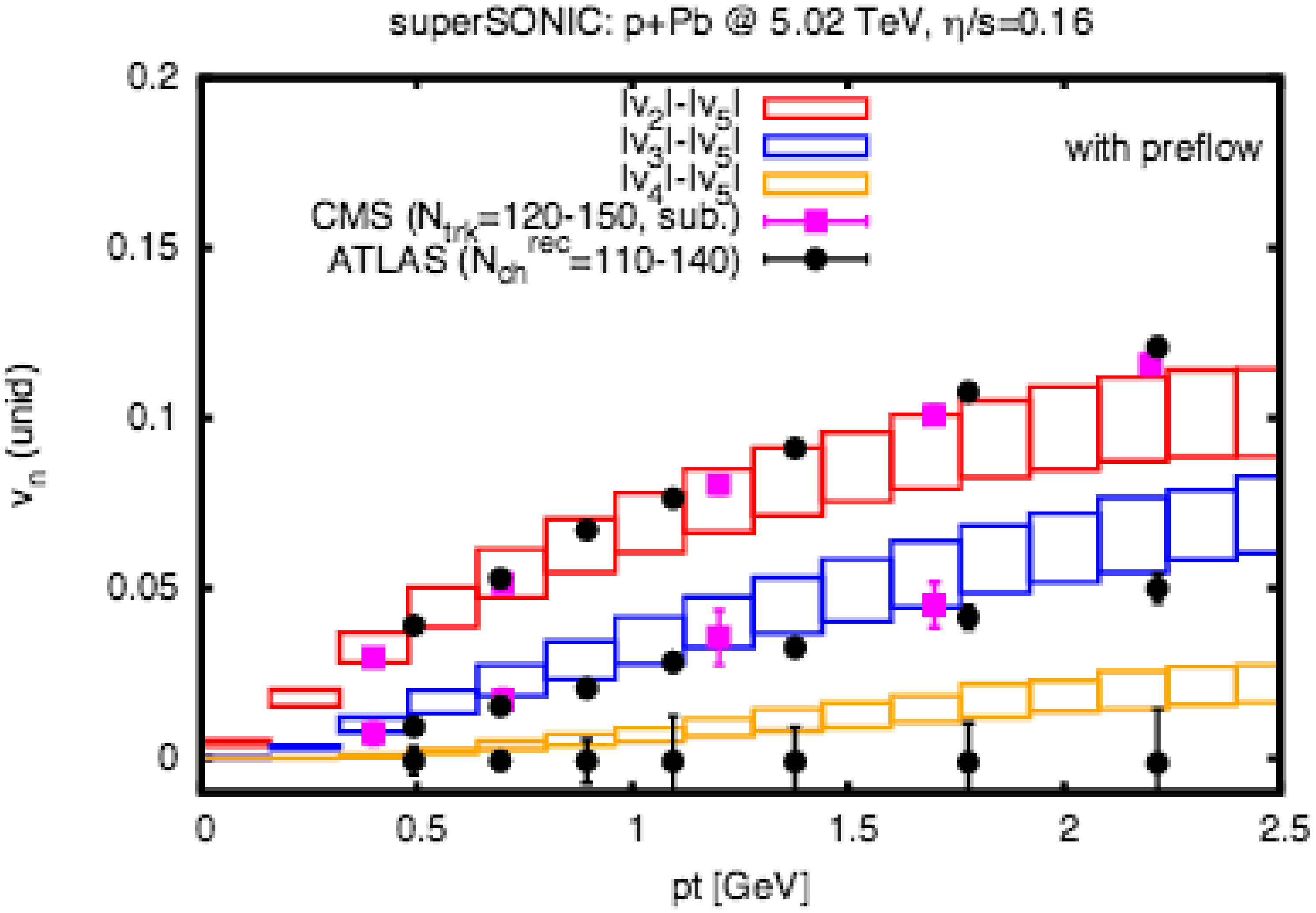


Pure non-hydro transport!

How to test if non-hydro modes excited?

- 2^{nd} order hydro has non-hydro mode controlled by τ_R
- Can test sensitivity of final results on τ_R
- Practical criterion: vary τ_R by factor 2, see how much results change
- Large variations: strong non-hydro contribution, hydro has broken down
- Small variations: weak non-hydro contribution, hydro is in good shape

Testing Hydro for light-heavy ion collisions

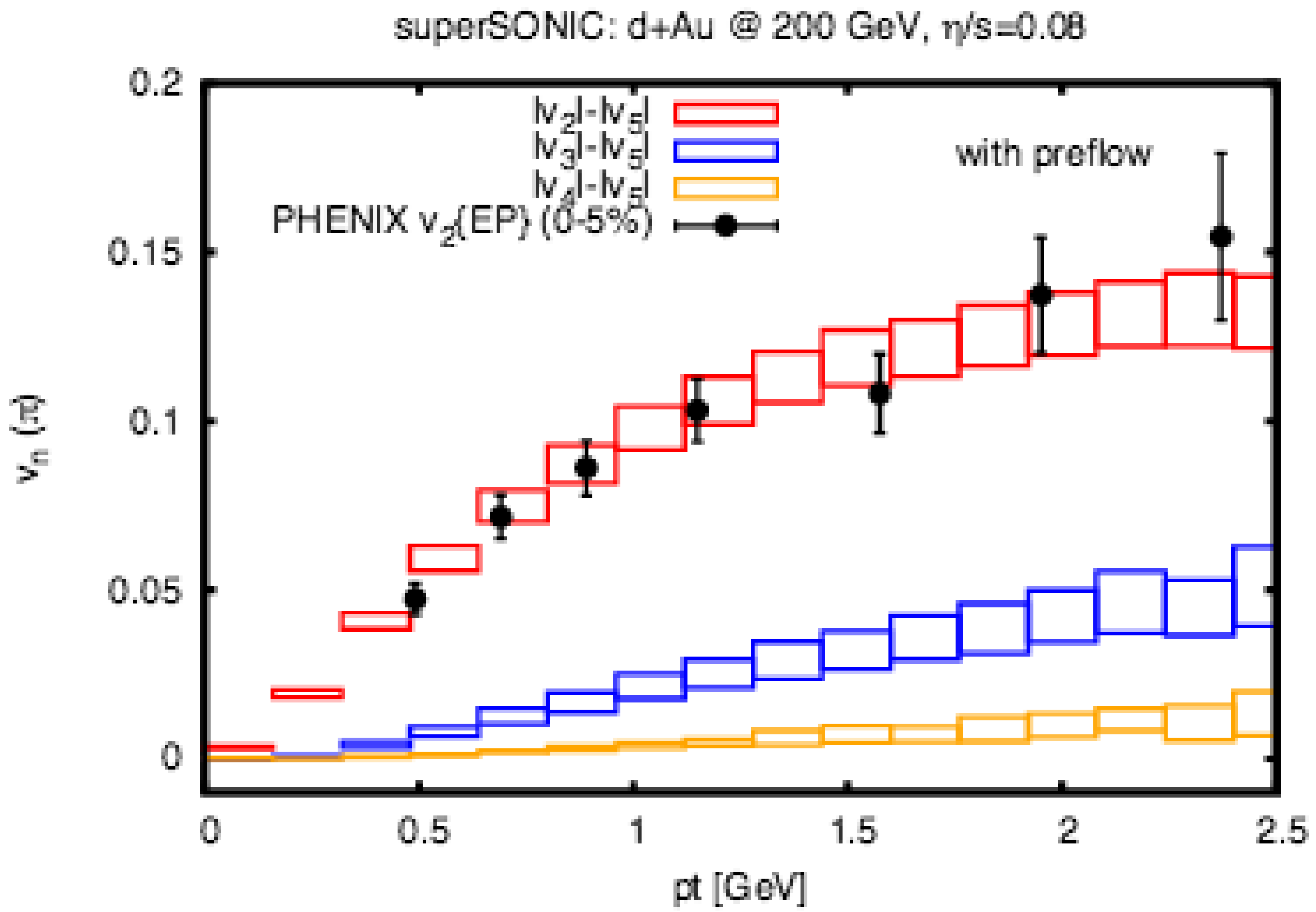


[PR, 1502.04745]

Testing Hydro for light-heavy ion collisions

- Non-equilibrium dynamics
- Sensitivity to non-hydro modes small
- Hydro reliable!
- Can make predictions!

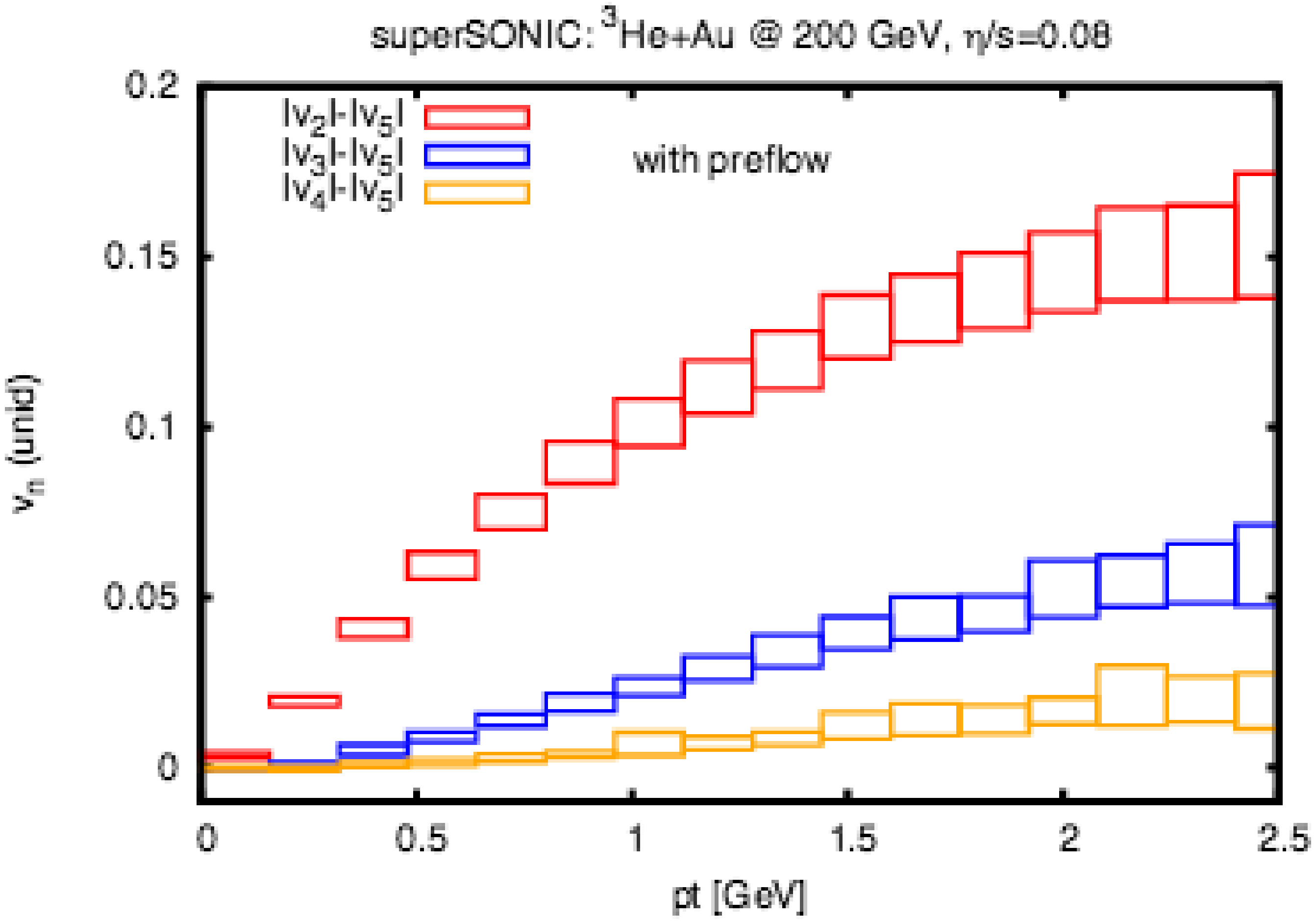
Hydro for d-Au @ 200 GeV



Prediction (to be tested): small but non-vanishing v_3 in central d+Au @ 200 GeV

[PR, 1502.04745]

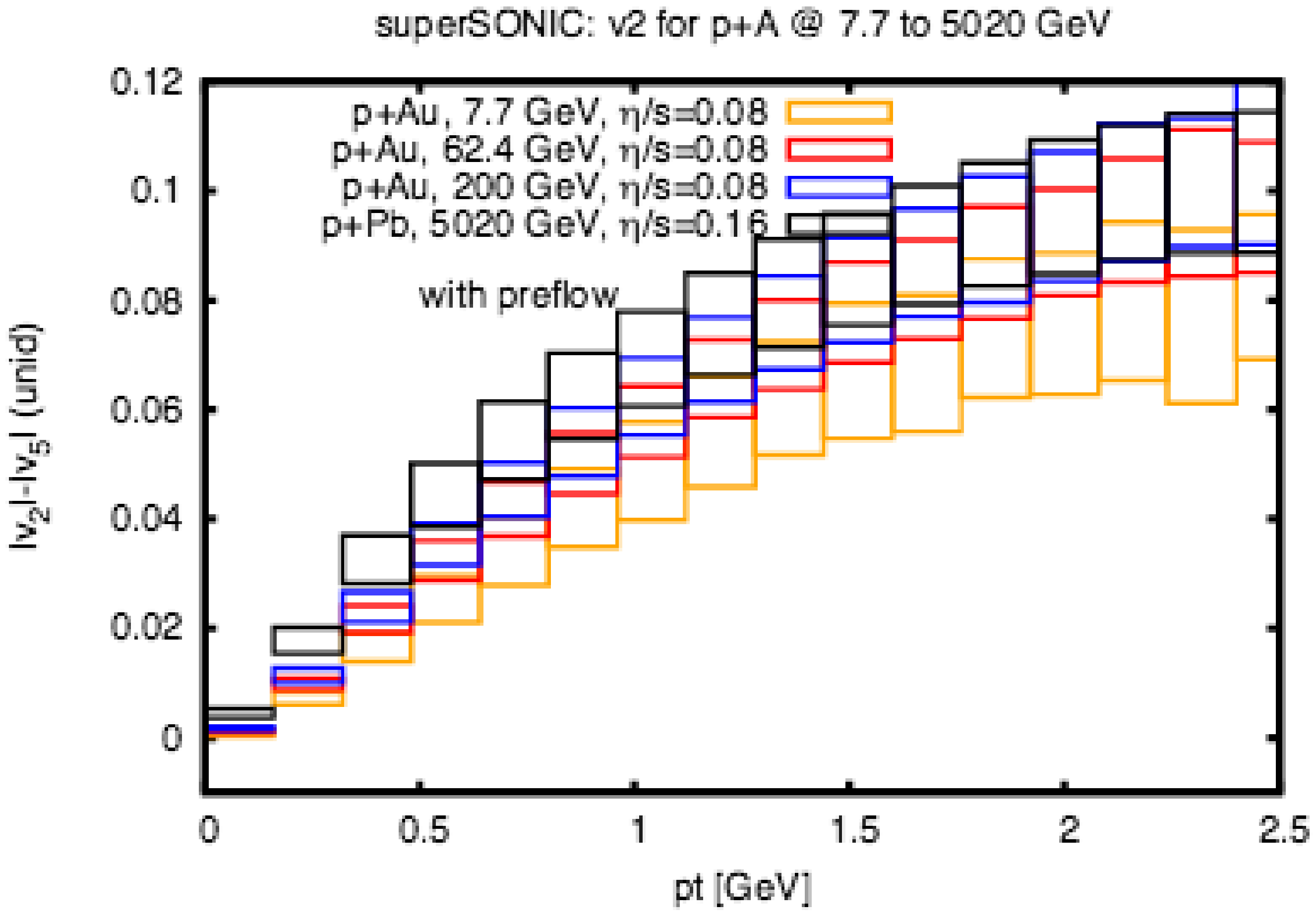
Hydro for ^{3}He-Au @ 200 GeV



Prediction (tested): v_2, v_3 in central ^{3}He+Au @ 200 GeV

[PR, 1502.04745]

Hydro for p-A from 7.7 GeV to 2760 GeV

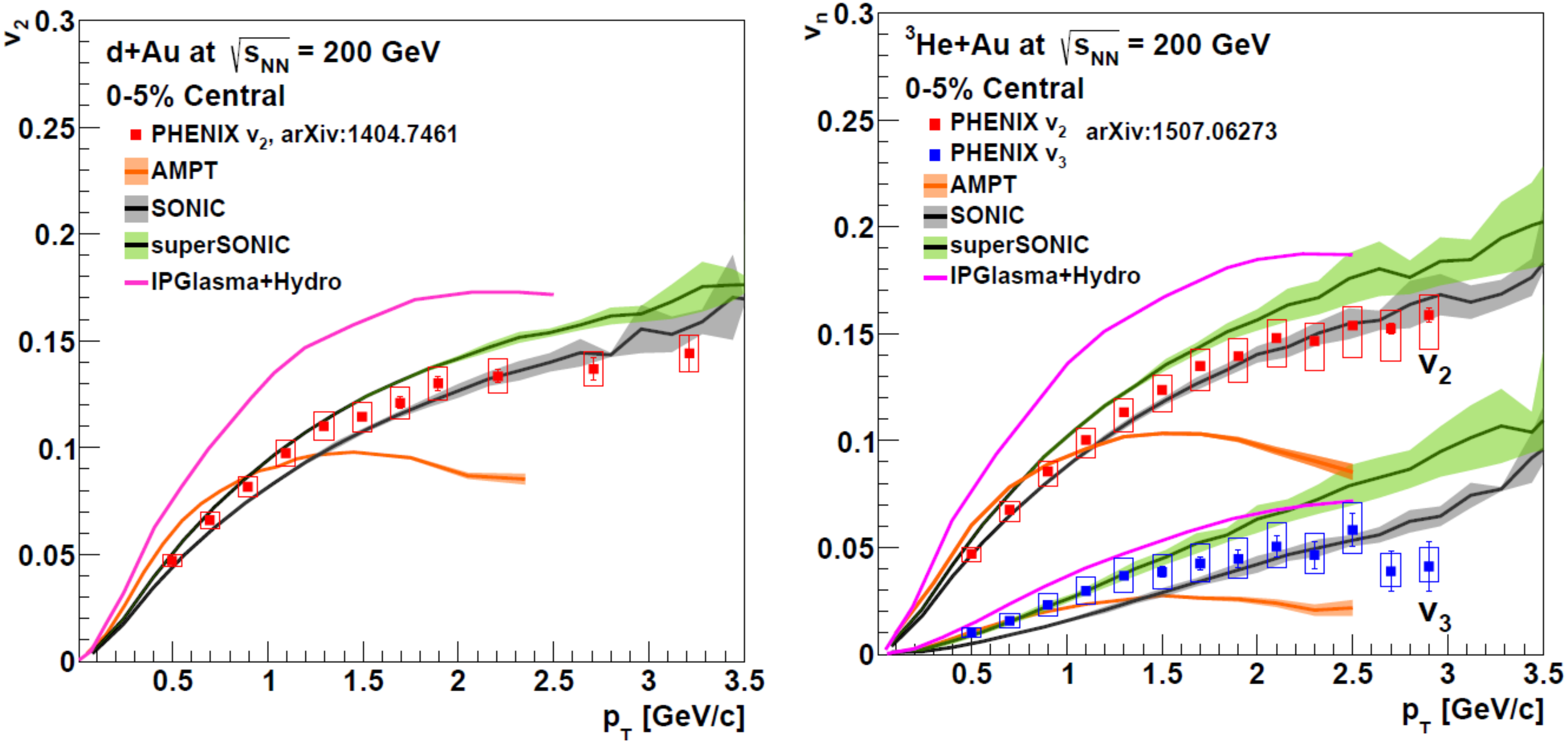


Prediction (tested): v_2 for central pAu @ 200 GeV

[PR, 1502.04745]

How do predictions hold up to experimental tests?

QM15: ^{3}He+Au @ 200 GeV

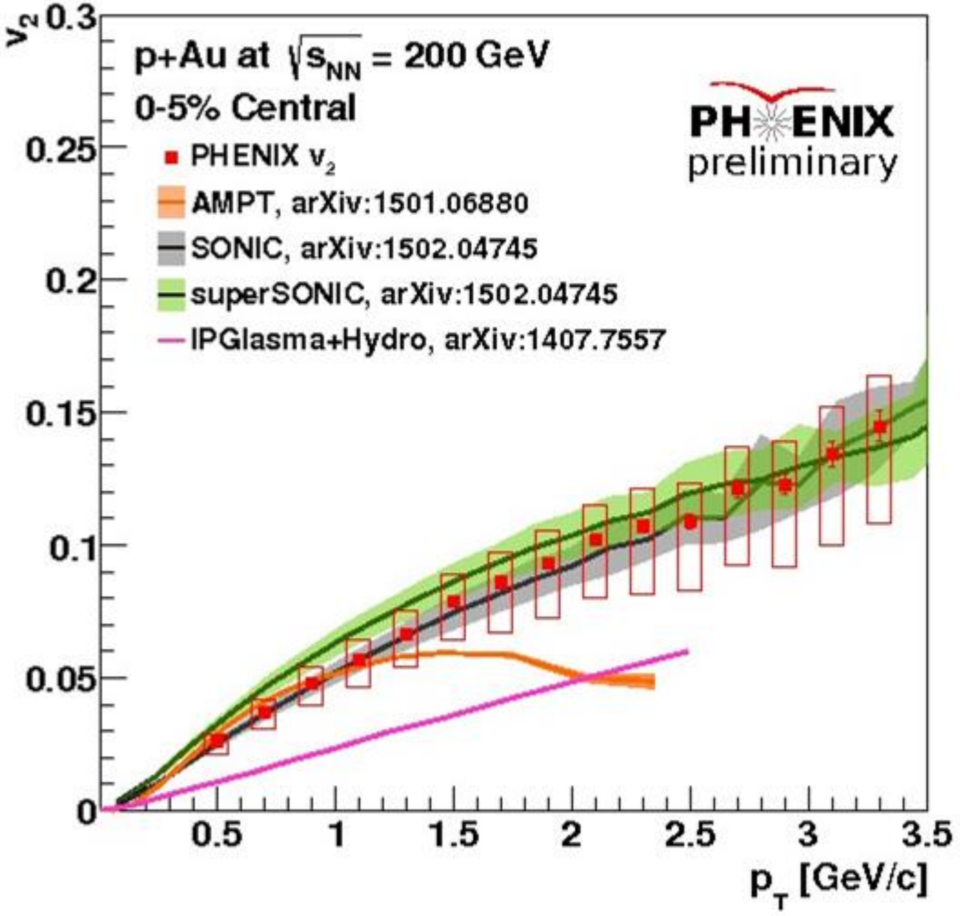


AMPT: arXiv:1501.06880 SONIC: arXiv:1502.04745 IP+Hydro:arXiv:1407:7557

Several models can reproduce the v_n measurements in d+Au and ^{3}He+Au collisions simultaneously

[Slide by Shengli Huang, Quark Matter 2015, Kobe, Japan]

QM15: p+Au @ 200 GeV

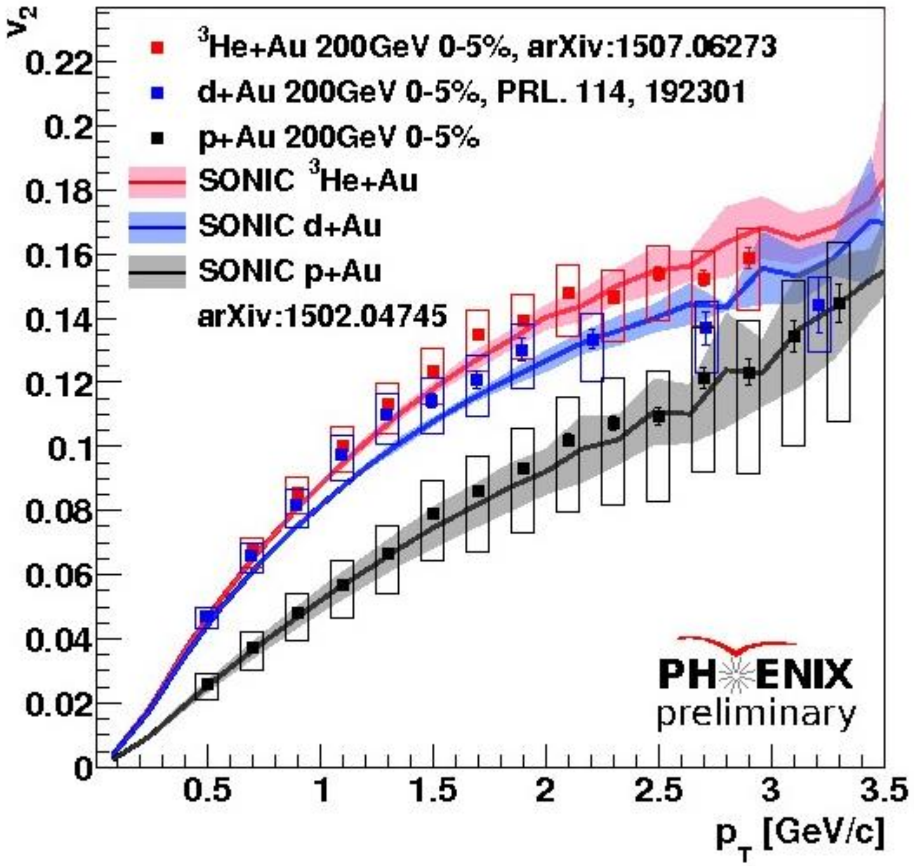


- "SONIC and superSONIC with Glauber initial conditions agrees with data within uncertainties"
- "Hydrodynamics with IPGlasma initial conditions underpredicts v2 by x2."
- "AMPT agrees up to pT ~ 1 GeV/c, then underpredicts"

[Slide by Itaru Nakagawa, Quark Matter 2015, Kobe, Japan]

QM 15: p+Au, d+Au, 3He+Au @ 200 GeV

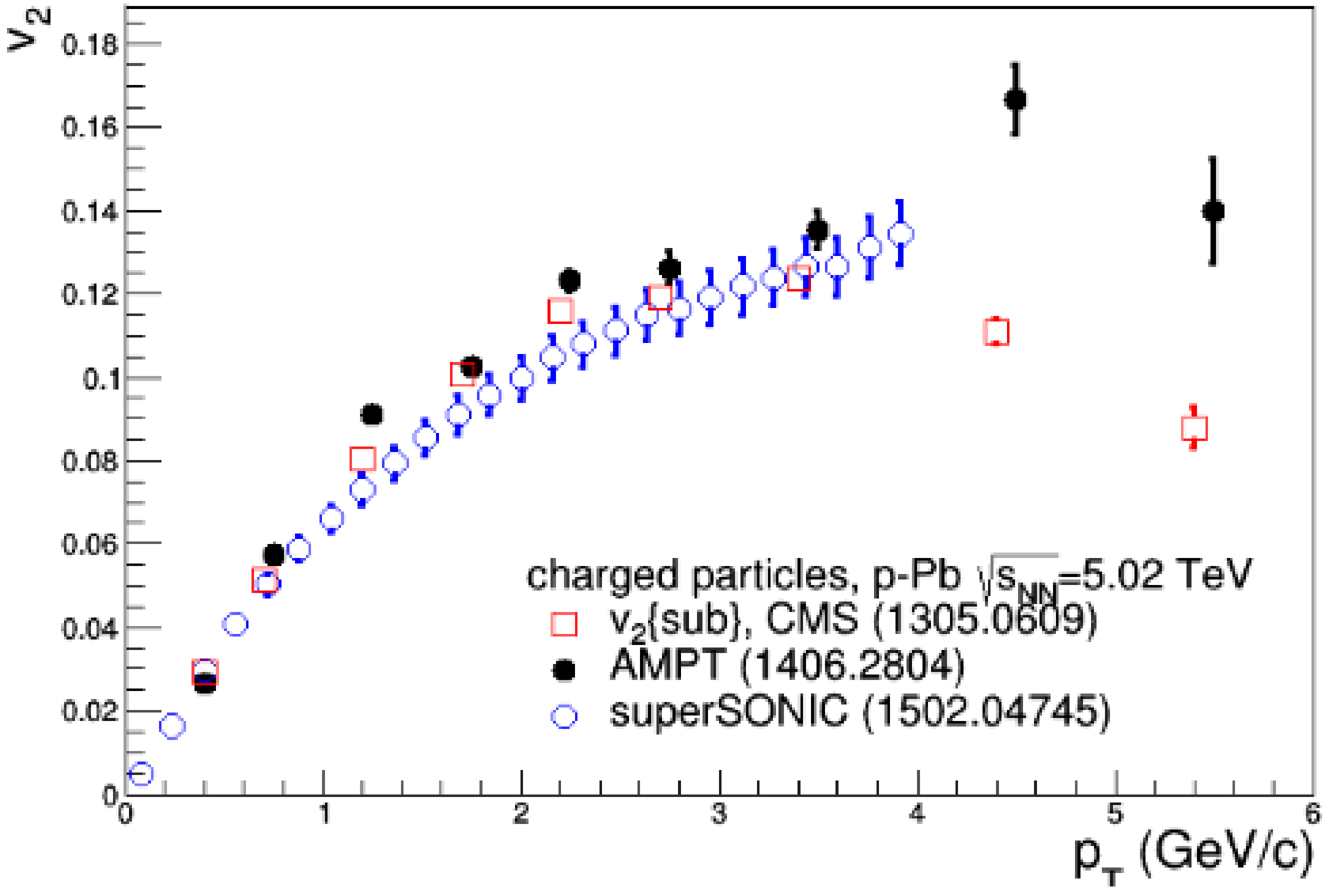
Glauber-like initial condition hydro + hadronic cascade



- SONIC Calculations reproduce v_2 for p+Au, d+Au, ^{3}He+Au within systematic errors.

[Slide by Itaru Nakagawa Quark Matter 2015, Kobe, Japan]

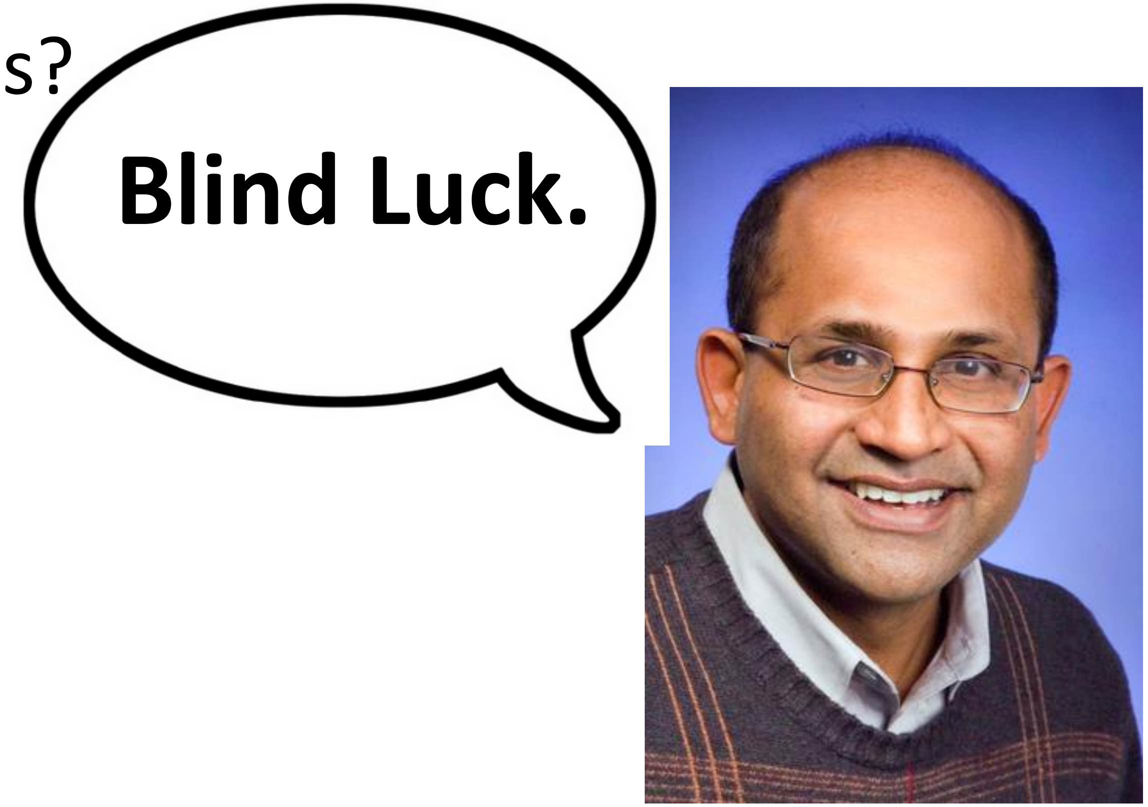
QM15: p+Pb @ 2760 GeV



[Slide by Constantin Loizides, QM15]

Comparison of hydro predictions to experimental data

- Predictions from Hydro in small systems verified
- Reaction from colleagues?



Beware of models that never fail!

Hydro in p+p collisions

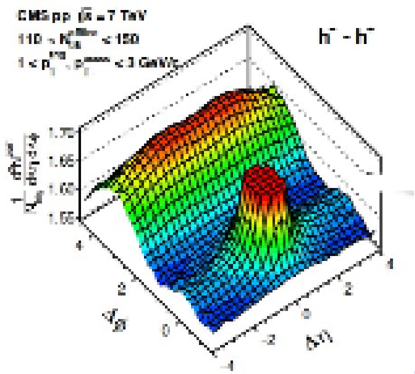
Dn/dy~5 for p-p

- Handful of particles
- Would not expect so few particles to behave as a fluid

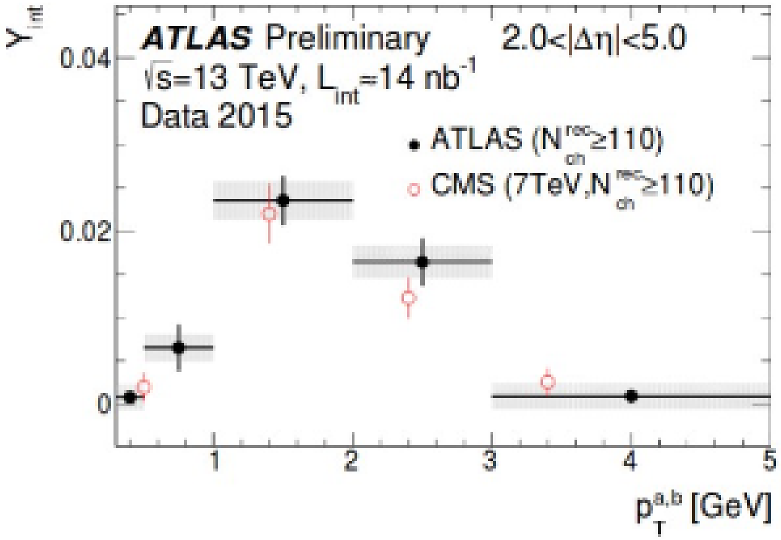
For “rare” high-multiplicity events P. Bozek [0911.2392]; Casalderrey-Solana & Wiedemann [0911.4400] conjecture:

Collective flow in pp collisions

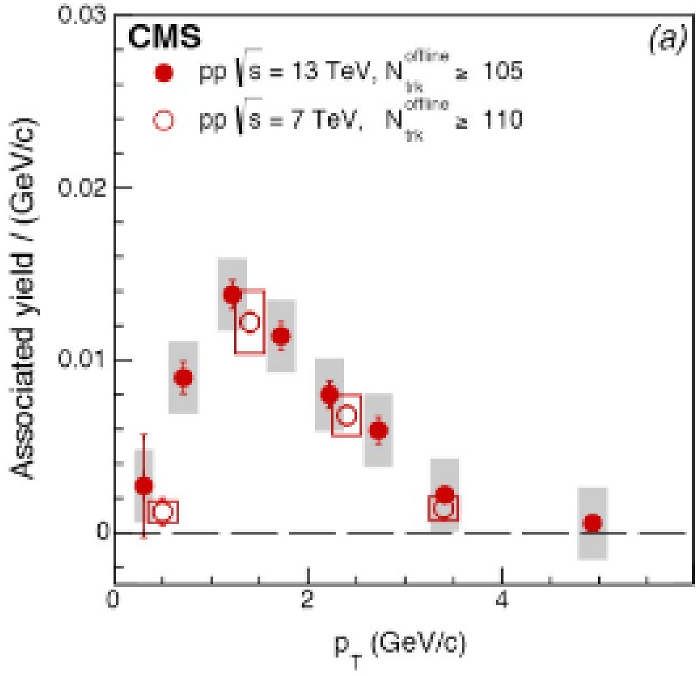
13 NS ridge in pp



ATLAS-CONF-2015-027



CMS-FSQ-PAS-15-002

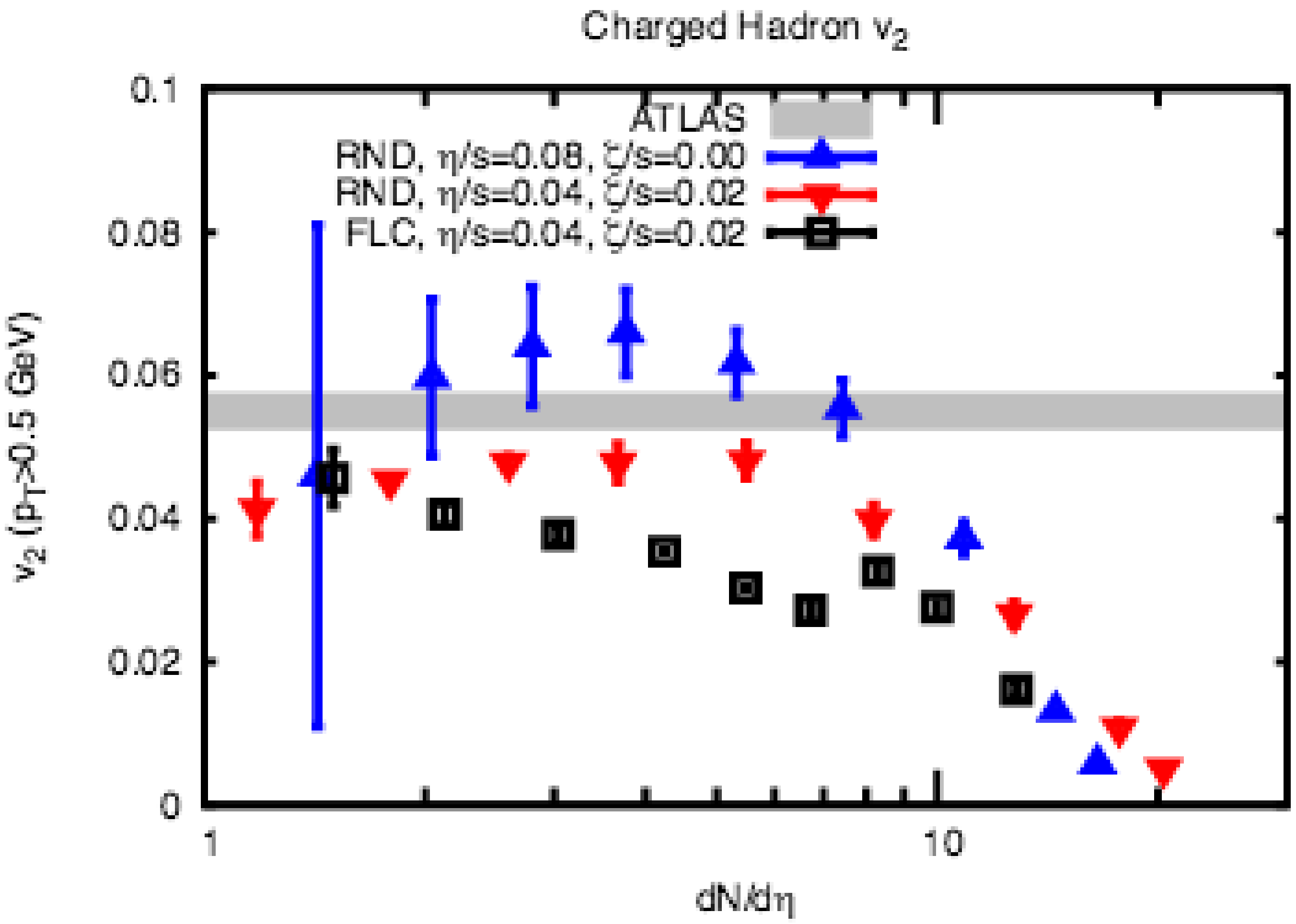


The ridge yield does not significantly change with collision energy (Confirmation by two experiments!)

[Loizides, QM15]

Testing Hydrodynamics in pp collisions

Hydro for p-p collisions



Hydro breaks down for peripheral pp, but seems OK for min-bias!

Naïve min-bias result for round protons matches exp' data!!!

[Miller et al., 1512.05345]

Hydro with <5 particles

- Hydro with 5 particles does not make sense
- If system is strongly coupled, there are no good quasiparticles, just (quantum) fields
- It is possible to derive hydrodynamics without ever using particle concepts
- It is irrelevant how many particles there are in final state!
- It is only marginally relevant that system is non-equilibrium

Hydro can apply to small systems if strongly coupled

Hydro for p-A !

Hydro for p-p !

Hydro for e^+-e^- ???

Looking for Hydro in $e^+ e^-$

- Use modern analysis techniques on “old” LEP data
- Hunt for the same type of signatures as found in pp
- Need “raw” data, cannot do with published results

Possible analysis from LEP data looking for collective effects Inbox x

Jamie Nagle Aug 9 (6 days ago)
to Stefan, Peter, Dennis.Perepel., Paul, Kenneth

Hello Stefan (cc Peter, Dennis, Paul, Ken),

I was given your contact information from Bill Gary (UCR) as someone who might still have access to analyzing LEP data.

[...]

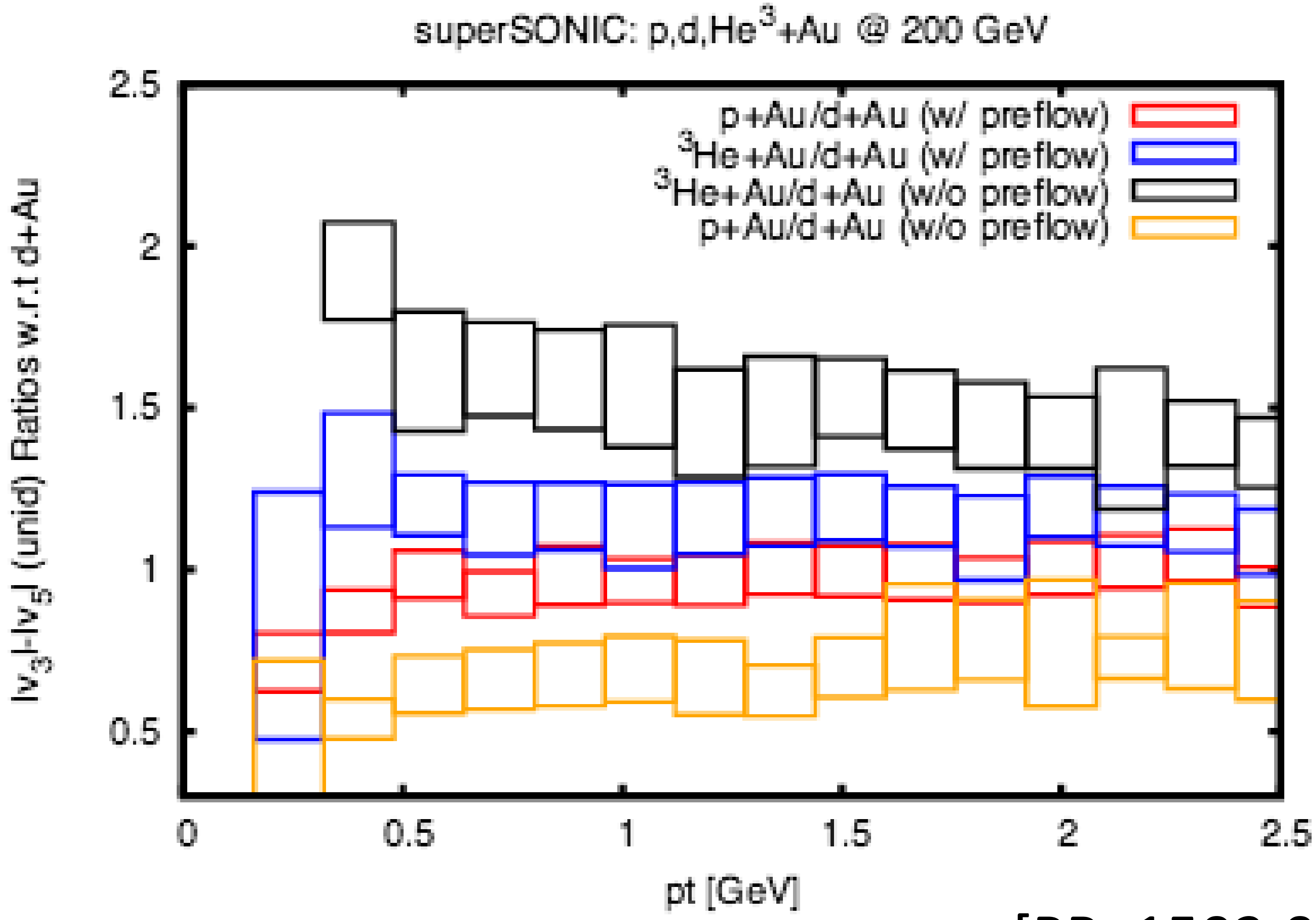
Hydrodynamics as Non-equilibrium Tool

- Hydrodynamics describes (and predicts) non-equilibrium systems
- Works when non-equilibrium corrections are O(1) "Large"
- This "unreasonable" success continues to be surprising to some
- Hydrodynamics does break down when non-hydro modes become important
- I would argue that we understand hydro and have it under control!

Let's use hydrodynamics to study non-equilibrium properties of QCD experiments!

Small systems as QCD laboratory

- Small sy ration?)
- Small sy :ions (Pre-eq flow?



[PR, 1502.04745]

Conclusions

- (2nd order) Hydro is genuine non-equilibrium tool
- Hydro reliable as long as non-hydro modes unimportant
- Can test importance of non-hydro modes in practice
- Nuclear Collisions offer experimental probe of non-eq’ effects
- The smaller the collision system, the larger the non-eq effects
- Predictions for QCD non-eq’ effects in light-heavy ion collisions
- Maybe there are some gems still in e+ e- data!

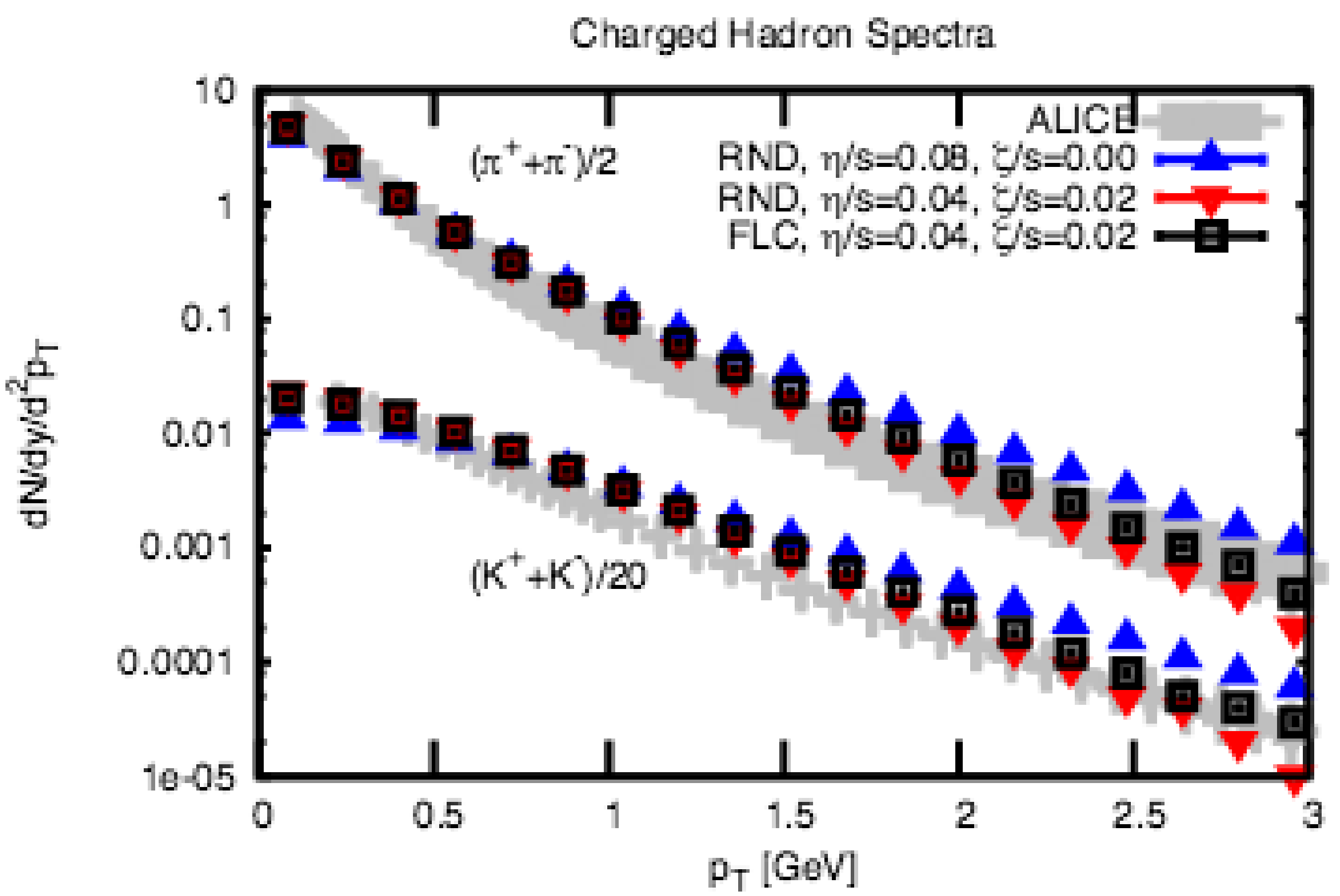
Thank you!

Conclusions

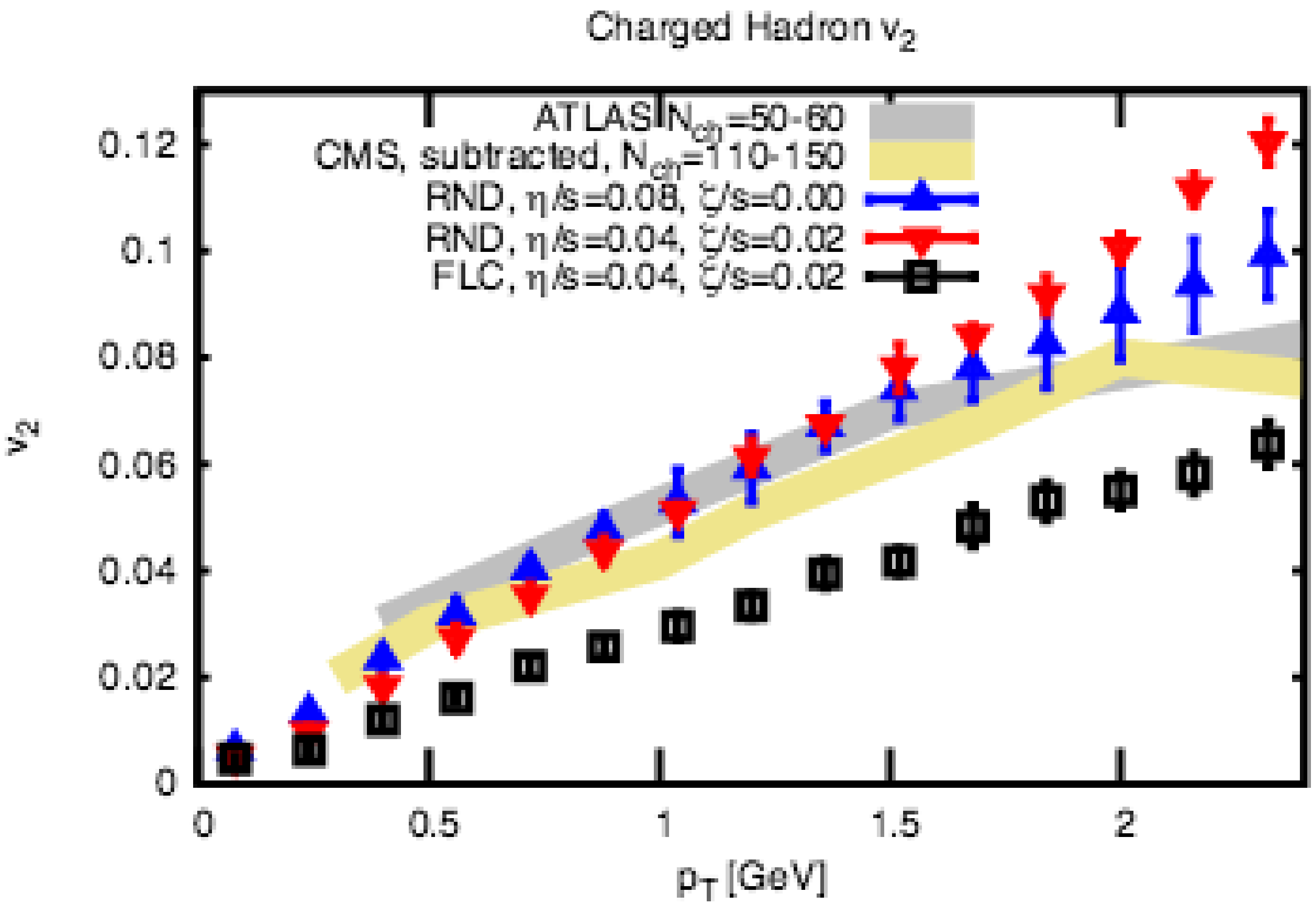
- (2nd order) Hydro is a tool for genuine non-equilibrium dynamics
- Hydro gives reliable results even is non-equilibrium corrections are O(1)
- Hydro Breaks down when non-hydro modes dominate evolution (early times, far from equilibrium)


Thank you for your attention!
MIT
Strongly Coupled Fluids Group @ CU Boulder

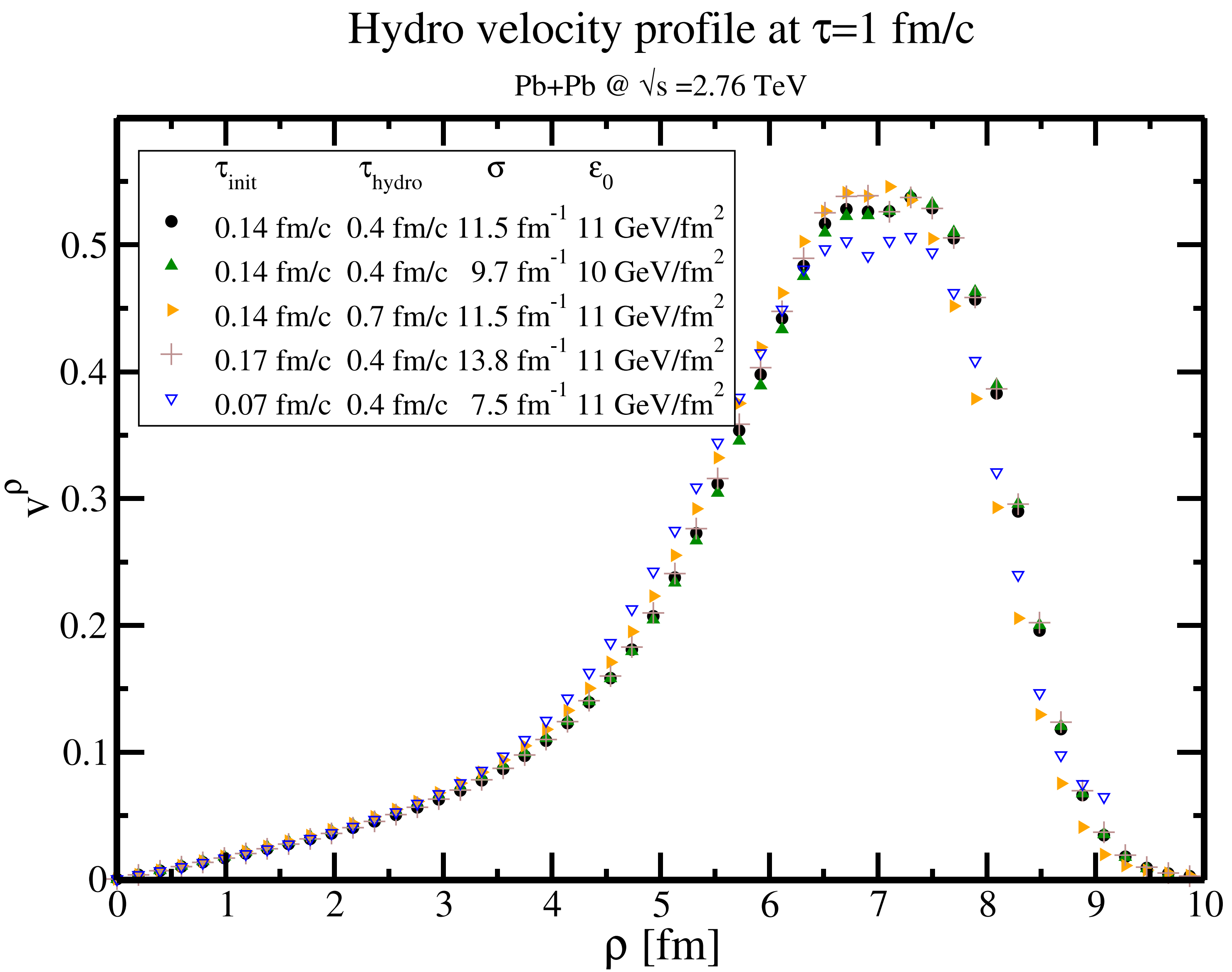
Bonus Material



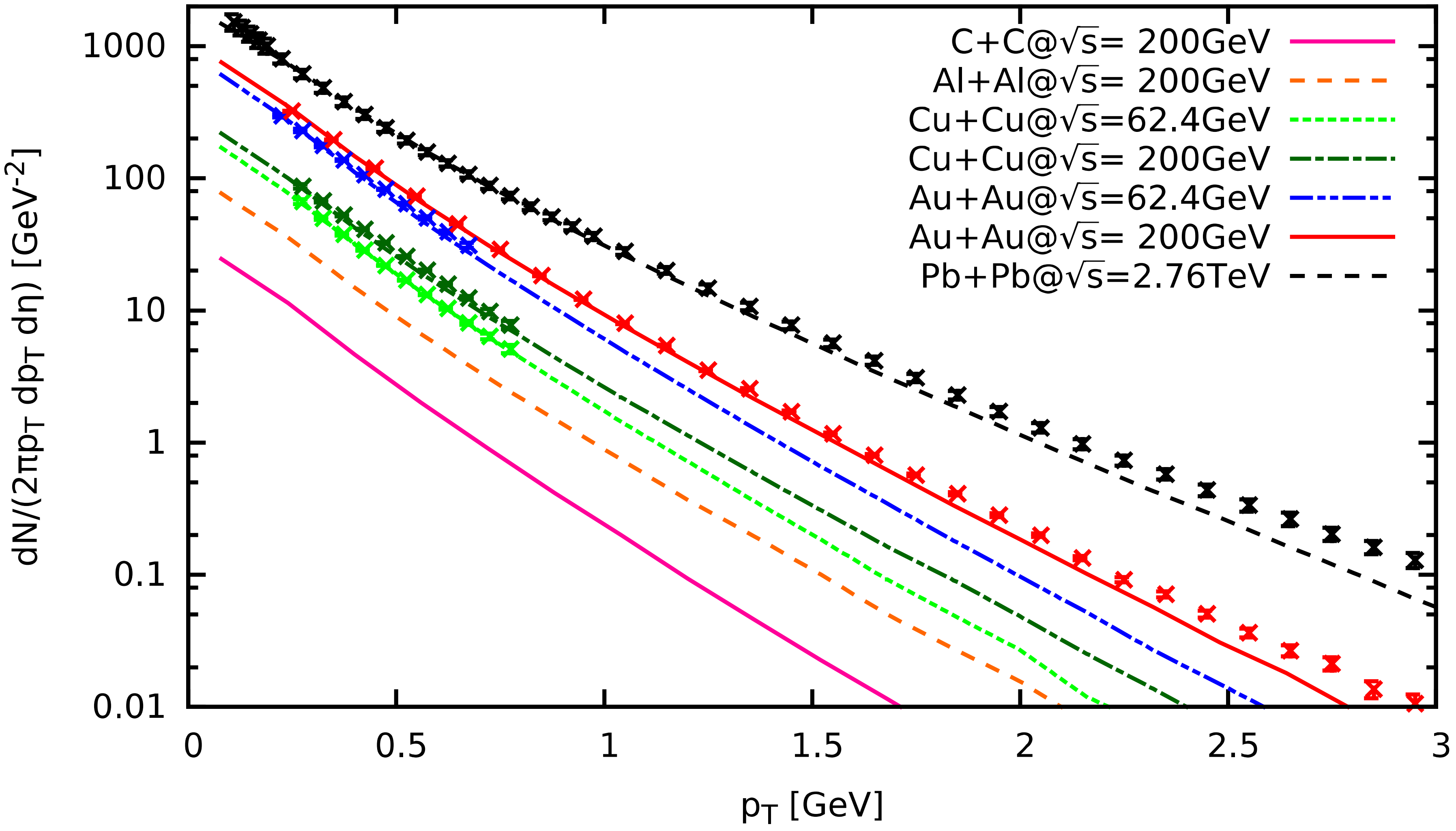
[Miller et al., 1512.05345]



[Miller et al., 1512.05345]



[van der Schee, Romatschke, Pratt, PRL2013]



[Habich, Nagle, Romatschke, EPJ 2015]