Zeroing in on the initial state

— tomography using bulk, jets and photons

Thorsten Renk

in collaboration with R. Chatterjee, H. Holopainen, H. Niemi, I. Helenius and K. J. Eskola

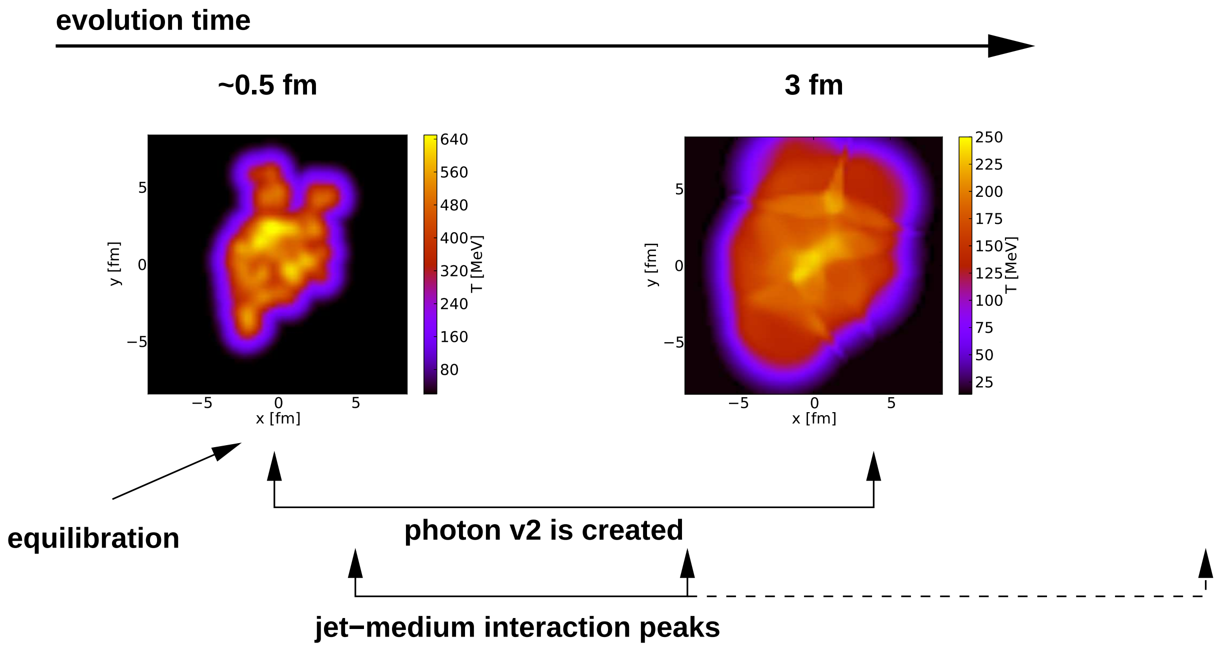
UNIVERSITY OF JYVÄSKYLÄ

Suomen Akatemia

HELSINKI INSTITUTE OF PHYSICS

- Introduction
- Bulk Tomography
- Jet Tomography
- Photon Tomography
- Conclusions

Tomographic probes



- some bulk properties show the initial state (almost) directly
- photon v_n largely builds up between equilibration and 3 fm
- jet energy loss peaks between 1 and 2 fm

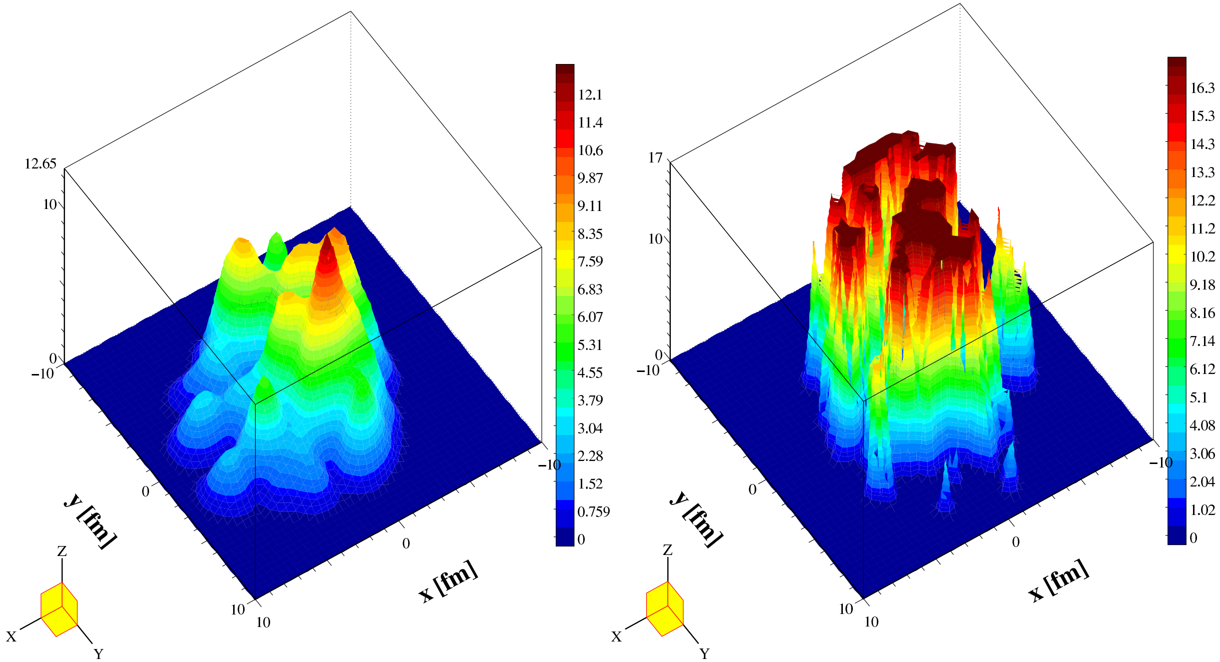
$\rightarrow$ but high P_T v_n is sensitive to hadronic phase around 5-7 fm

Different tomographic probes image different timeslices of the medium. We can not expect to see 'the same' medium in all of them as the medium evolves.

T. R., Phys. Rev. C **88** (2013) 044905, H. Niemi *et al*, Phys. Rev. C **87** (2013) 054901; R. Chatterjee *et al*, Phys. Rev. C **88** (2013) 034901

Bulk

Bulk tomography



Do we distinguish these initial states?

T. R. and H. Niemi, 1401.2069 [nucl-th].

Tomographic bulk probes

Idea: Some observables are insensitive to hydrodynamical evolution:

• Niemi, Denicol, Holopainen and Huovinen:
$\rightarrow \langle v_n \rangle = C_n \epsilon_n$ when averaging over many events with same eccentricity ϵ_n
$\rightarrow v_2 \approx C_2 \epsilon_2$ even for individual events

$\Rightarrow C_n$ is the expensive quantity requiring viscous fluid dynamics

• for $\delta v_2 = (v_2 - \langle v_2 \rangle)/\langle v_2 \rangle$ the coefficients cancel
$\rightarrow$ direct comparison of $P(\delta\epsilon_2)$ to experimental EbyE fluctuations $P(\delta v_2)$

• for a sufficiently narrow centrality range, say 0-5%, viscous corrections evolve slowly
$\rightarrow$ in this range, C_n is independent of centrality
$\rightarrow$ evolution of $v_n(\text{centrality}) = C_n \epsilon_n(\text{centrality})$ probes response to geometry

• multiplicity production can also be written $N_{final} = C N_{initial}$

Dramatic decrease in computation time from $O(1)$ hour to 0.1 seconds per event, allows to search a vast parameter space systematically.

H. Niemi, G. S. Denicol, H. Holopainen and P. Huovinen, Phys. Rev. C **87** (2013) 054901

The parameter space

Strategy: Parametrize initial state, test many scenarios, analyze sensitivity

• What are the relevant colliding degrees of freedom?
→ nucleons, constituent quarks, color charges

• How are they initially distributed?
→ Woods-Saxon with varying skin thickness, hard sphere, 2d sheet

• What produces entropy?
→ binary collisions, wounded participants

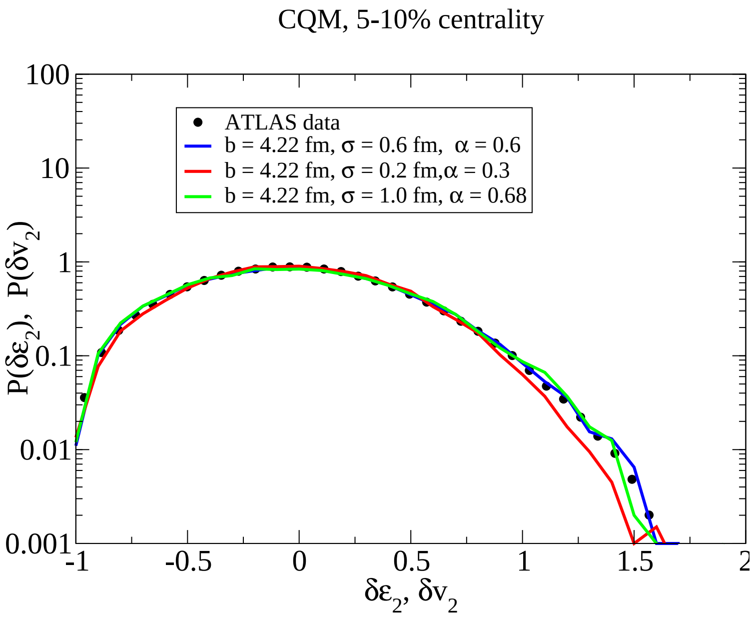
• How is entropy produced?
→ (variable) production region size scale, negative binomial multiplicity fluctuations

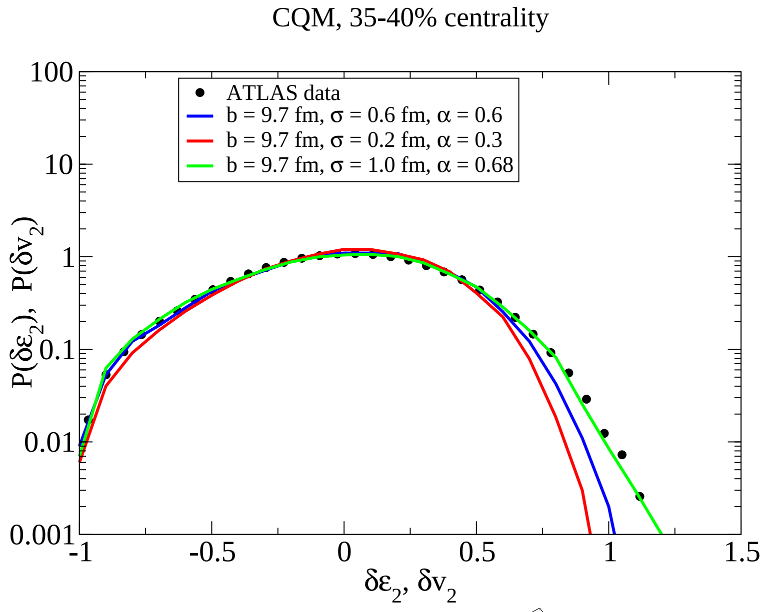
• Does non-linearity in entropy production play a role?
→ no, saturation ρ^α, $f\rho_{wn} + (1-f)\rho_{bc}$, threshold

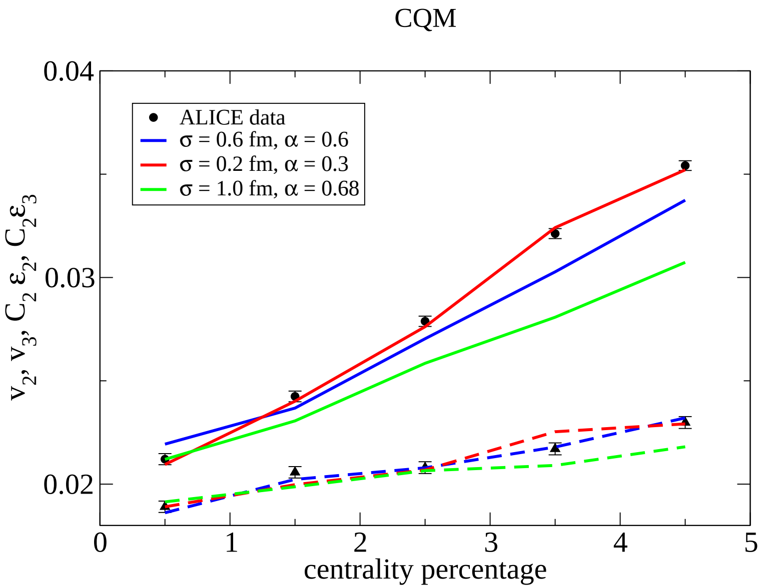
• Are there additional fluctuations?
→ no, size fluctuations, imposed cell-by-cell relative fluctuations

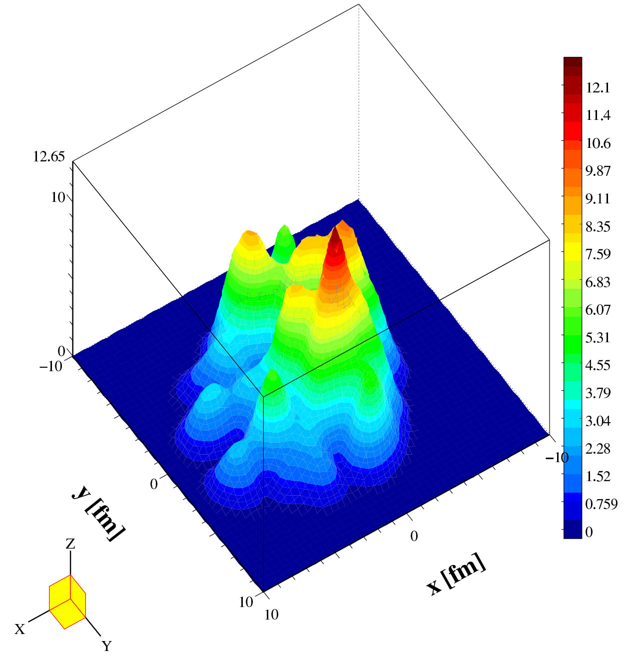
T. R. and H. Niemi, 1401.2069 [nucl-th]; T. R. and H. Niemi, work in progress.

An example

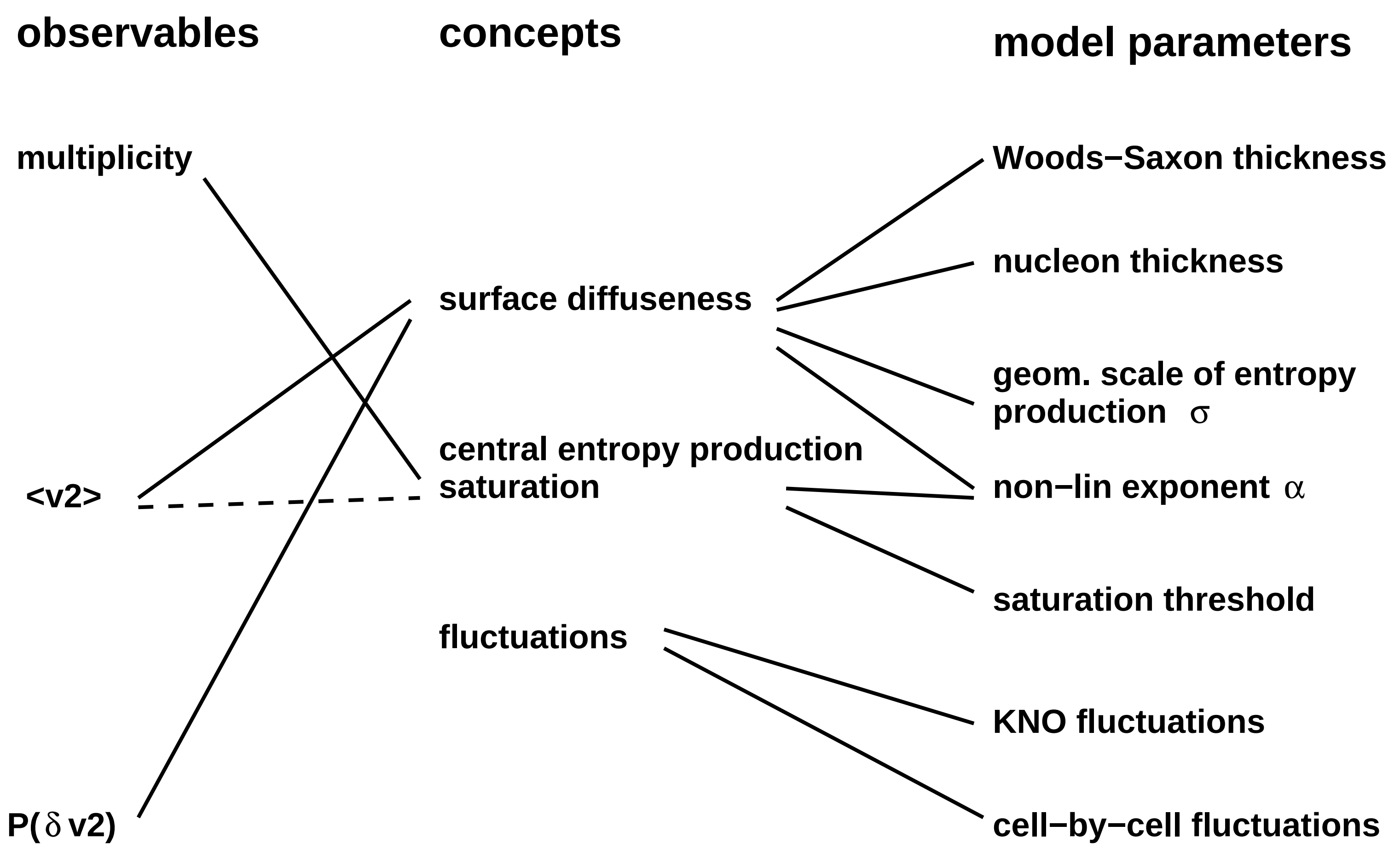

CQM, 5-10% centrality
ATLAS data
b = 4.22 fm, σ = 0.6 fm, α = 0.6
b = 4.22 fm, σ = 0.2 fm,α = 0.3
b = 4.22 fm, σ = 1.0 fm, α = 0.68
P(δε2), P(δv2)
δε2, δv2


CQM, 35-40% centrality
ATLAS data
b = 9.7 fm, σ = 0.6 fm, α = 0.6
b = 9.7 fm, σ = 0.2 fm, α = 0.3
b = 9.7 fm, σ = 1.0 fm, α = 0.68
P(δε2), P(δv2)
δε2, δv2


CQM
ALICE data
σ = 0.6 fm, α = 0.6
σ = 0.2 fm, α = 0.3
σ = 1.0 fm, α = 0.68
v2, v3, C2 ε2, C2ε3
centrality percentage


y [fm]
x [fm]

WHAT IS THE DATA MEASURING?



⇒ most striking: fluctuations in the entropy production mechanism are **not** probed
→ only fluctuations in the geometry are

Physics conclusions

Some (provocative) conclusions:

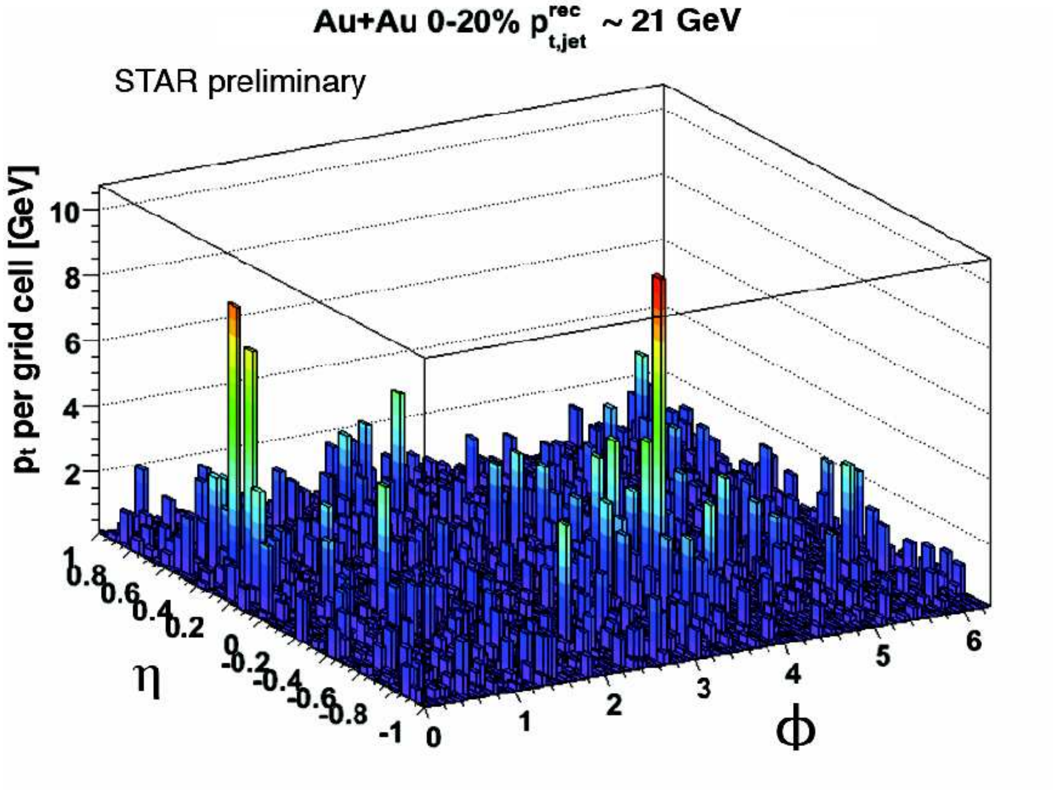
• the relevant DOF for entropy production are unlikely to be nucleons
$\longrightarrow$ constituent quarks produce the required surface diffuseness naturally

• non-linearity of entropy production is important in all cases
$\longrightarrow$ indicates the need for some saturation
$\longrightarrow$ **caution:** non-linear exponents ρ^α can unphysically alter the surface diffuseness!

• multiplicity chiefly probes medium center, v_n the surface
$\longrightarrow$ v_n do not test saturation, just the prescription used at the surface

• sub-nucleon sized fluctuations are allowed by the data
$\longrightarrow$ however not required and in fact not constrained by anything

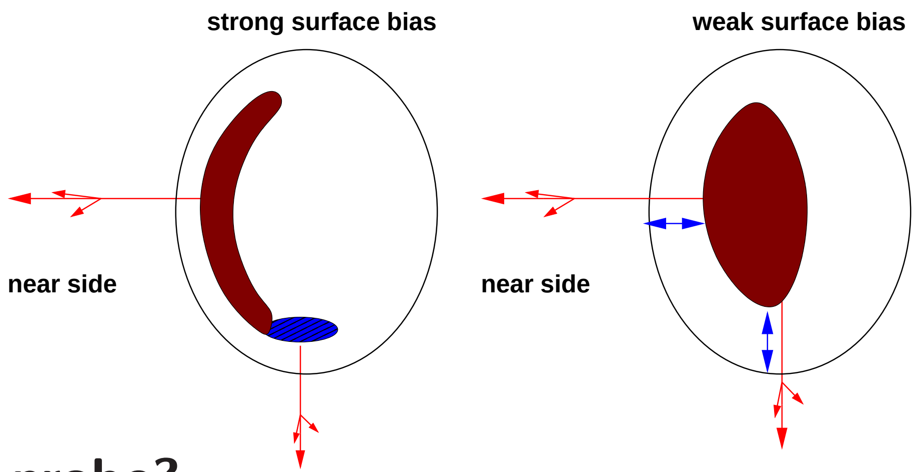
Jet tomography



How does high P_T constrain medium geometry?

v_2 AT HIGH P_T

If you must call it v_2, never call it elliptic flow coefficient — it is attenuation physics!



What does the data probe?

• probes jet quenching **pathlength dependence** and fluid model **geometry** equally

• rel. influence of various other hydro properties on v_2 for the same geometry: medium formation time: 50%, viscous entropy production: 35%, spatial profile: 15%

• v_2 is a tomographic observable — pathlength dep. and geometry equally important
$\rightarrow$ use key observables with low sensitivity to hydro to constrain jet quenching
$\rightarrow$ I_{AA} for back-to-back hadrons has $< 20\%$ sensitivity to fluid model, $v_2 \sim 100\%$

$\Rightarrow$ then tomographic observables (largely) constrain the fluid model properties above

T. R., H. Holopainen, U. Heinz and C. Shen, Phys. Rev. C **83** (2011) 014910

Does high P_T v_2 factorize ?

Starting from some base scenario, v_2 can be enhanced due to a change in hydro background or jet quenching pathlength dependence:

model	ASW $\epsilon^{3/4}$	ASW NTC	AdS T^4	AdS NTC	YDE $\epsilon^{3/4}$
3d /2d hydro	1.49	1.74	2.33	2.35	2.22

$\longrightarrow$ rel. enhancement from different hydro geometry rather different across models
$\Rightarrow$ these models have different pathlength dependence, no factorization

model	ASW	YDE 3d	YDE 2d
NTC/$\epsilon^{3/4}$	1.17	1.22	1.20

$\longrightarrow$ effect of a near T_C enhancement approximately factorizes across different models

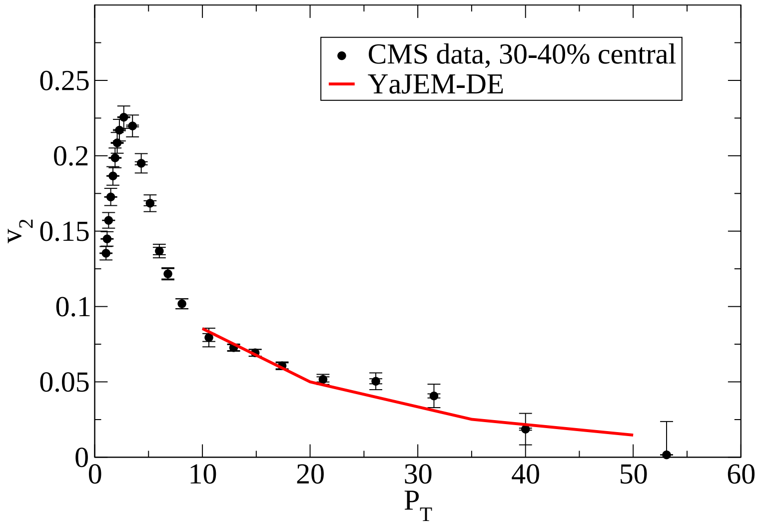
model	ASW	AdS	YDE
visc/ideal	1.51	1.44	1.55

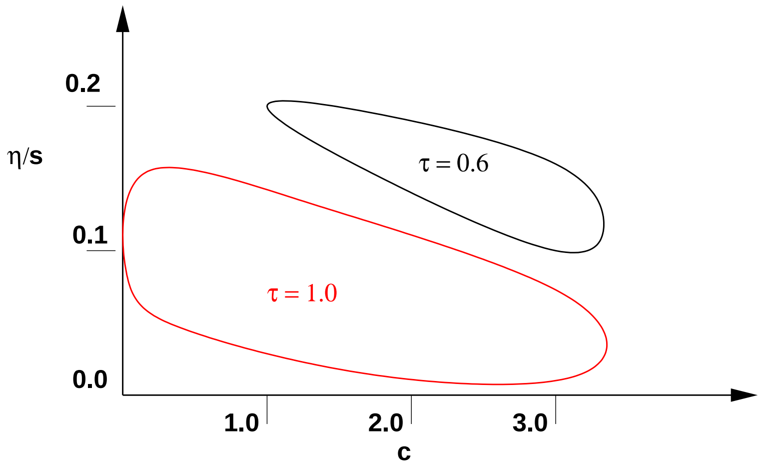
$\longrightarrow$ effect of viscosity enhancement approximately factorizes across different models

Several influences on v_2 do factor approximately. We can use this to quickly scan a large parameter space!

If so, there is no puzzle

• YaJEM-DE, pathlength dependence constrained by I_{AA} in h-h and jet-h
$\longrightarrow$ predicts P_T dependence of v_2 correctly





• finds 'allowed regions' of
- viscous corrections
- near T_C enhancement strength
- initial time

• remains to be tested outside the factorization assumption

Physics conclusions

Some more (provocative) conclusions:

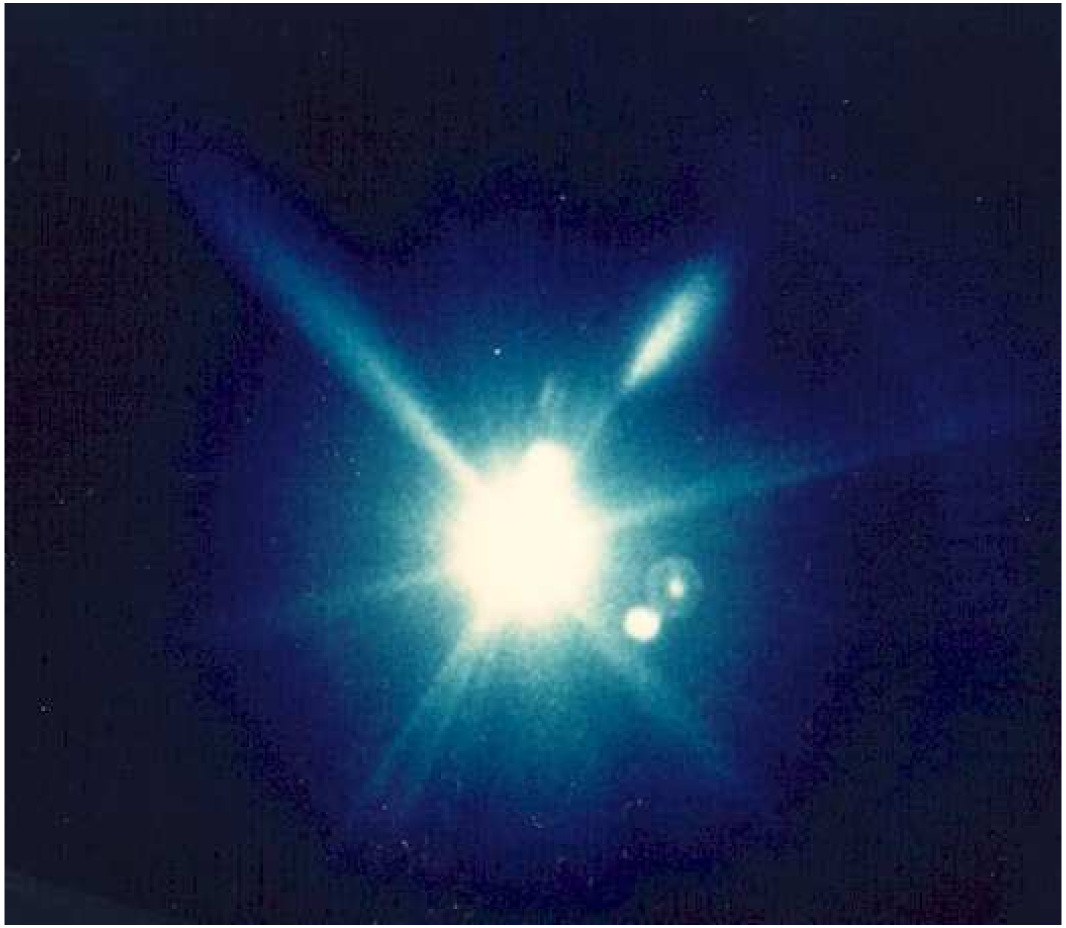
• jet quenching has fairly low sensitivity to actual eccentricity profile
$\longrightarrow$ but probes when jet-medium interaction starts and how medium changes with T

• need to constrain pathlength dependence using correlation observables
$\longrightarrow$ otherwise all conclusions are drowned in uncertainty

• data require 'late' jet-medium interaction, but don't say how:
$\longrightarrow$ late formation of a dense medium, with minimal jet quenching before?
$\longrightarrow$ strong enhancement of interaction close to T_C?
$\longrightarrow$ substantial viscous entropy production?
$\longrightarrow$ or a combination?

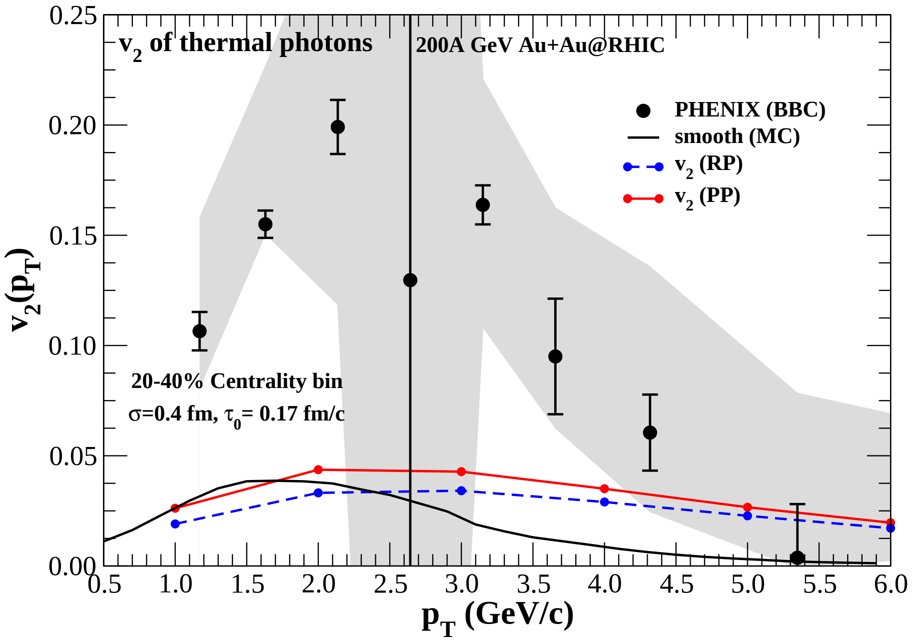
• largely complementary to bulk measurements
$\longrightarrow$ new information, but no cross-check

Photon tomography



Photon v_2

• obviously, there is some discrepancy between theory and experiment. . .



What is the problem?

• hydro is wrong?

$\longrightarrow$ seems to be working just fine everywhere else

• initial eccentricity is wrong?

• photon emission rates are wrong?

$\longrightarrow$ needs a huge margin, factor 50 or so

R. Chatterjee, H. Holopainen, I. Helenius, T. R. and K. J. Eskola, Phys. Rev. C **88** (2013) 034901

PHOTON v_2

Mechanism: ϵ_n deformation and radial flow $\Rightarrow$ v_n signal
$\longrightarrow$ granular initial state creates both deformation and more flow

R. Chatterjee: early radial flow correlates better with final v_3 strength than ϵ_3
$\longrightarrow$ strong early flow is a good predictor for strong v_3, large ϵ_3 is not

Are we missing pre-thermalization flow?

• expected from pre-equilibrium field dynamics

• reduces early medium density faster, shifts energy loss to later times
$\longrightarrow$ tends to increase v_2 at high P_T, good!

• perhaps equilibration later than expected
$\longrightarrow$ again, tends to increase v_2 at high P_T

> Circumstantial evidence for non-trivial initial state dynamics — how well do we really understand the first 3 fm of evolution?

R. Chatterjee, D. K. Srivastava and T. Renk, arXiv:1401.7464 [hep-ph].

Summary

Tomography currently seems to be able to reveal information about many aspects of the medium:

- initial surface diffuseness through bulk v_2 fluctuation studies
$\longrightarrow$ colliding degrees of freedom, geometry

- core density through entropy production and v_2
$\longrightarrow$ saturation physics

- pre-equilibrium dynamics through photons
$\longrightarrow$ classical field dynamics

- near T_C dynamics, equilibration and entropy production through jets
$\longrightarrow$ phase transition, formation of collectivity

> Subtle to understand, needs many constrains and comparison across several different observables, otherwise all is lost in systematic uncertainty. But interesting!

YaJEM is now public: See `http://www.phy.duke.edu/~trenk/yajem/`