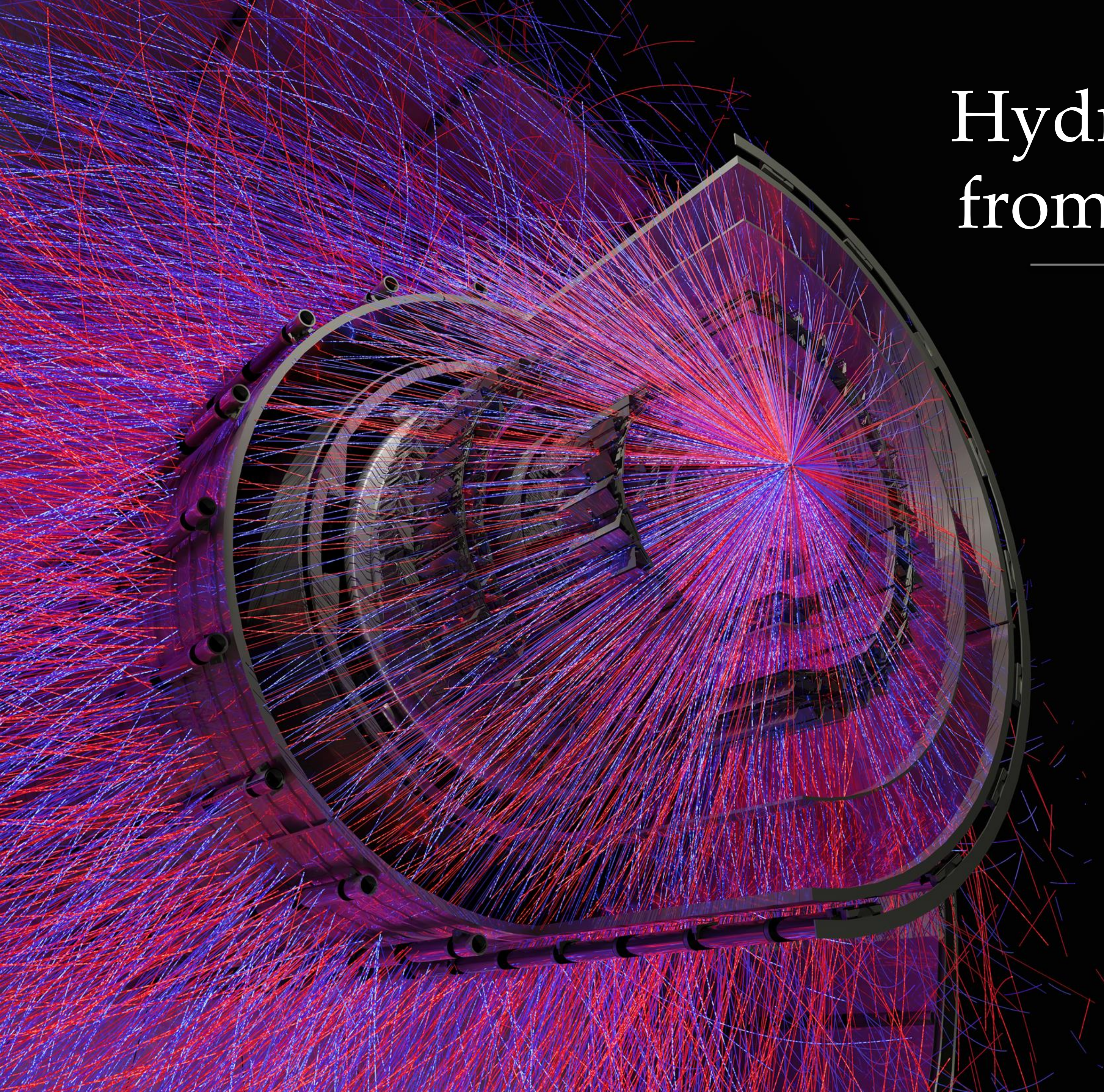


Hydro and event properties from small to large systems

Wilke van der Schee
David Dobrigkeit Chinellato

Aleksas Mazeliauskas:
Event properties and hydro in small and large systems

How many particles make a fluid?

wikipedia

Sorites ('heap') paradox:
If n grains of sand is a heap, then $n-1$ is also a heap
$\Rightarrow$ a single grain of sand is a heap?

Duck test:
If it looks like a duck, swims like a duck,
and quacks like a duck, then it probably is a duck.

Can a few-particle system **behave** like a fluid?

Aleksas Mazeliauskas:

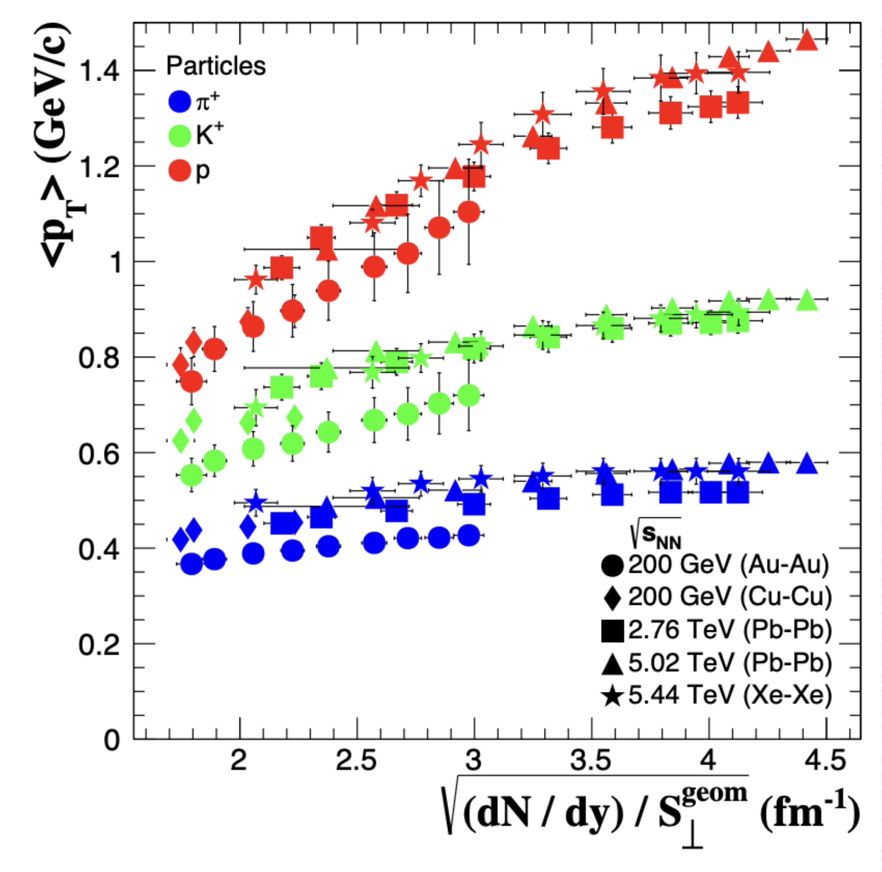
Event properties and hydro in small and large systems

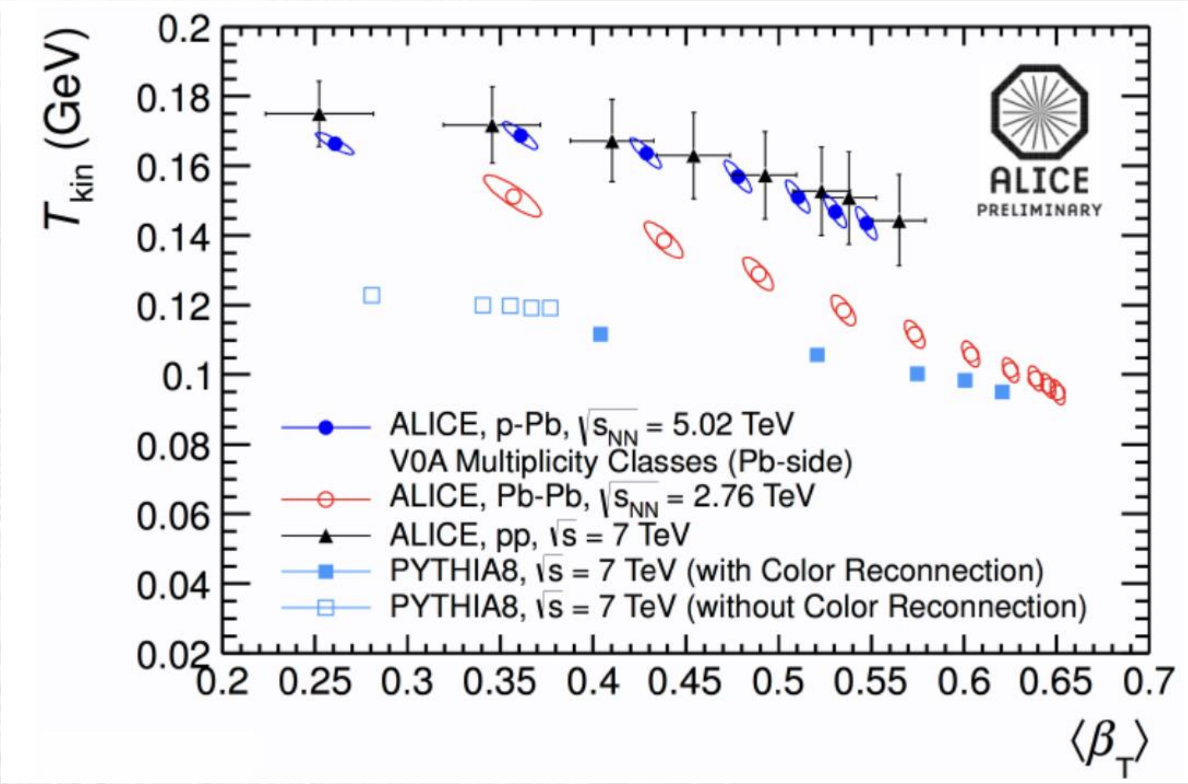
QGP passes the "Duck test" as a near perfect fluid in large systems, but there are many challenges to interpretation in small systems

- Matching to microscopic dynamics (not discussed)
  $\longrightarrow$ see talks by Victor and Nicolas
- Systematic uncertainties in transport of hydrodynamics
  $\longrightarrow$ η/s, but of which hydrodynamics?
- Missing contributions of thermal noise
  $\longrightarrow$ why does average hydrodynamics work so well?
- Sorites paradox
  $\longrightarrow$ what can we learn from mesoscopic cold atom systems?

Mihai Petrovici

An overview on some global trends observed in heavy ion collisions based on experimental results from AGS up to LHC energies and on similarities between pp and Pb-Pb collisions at LHC

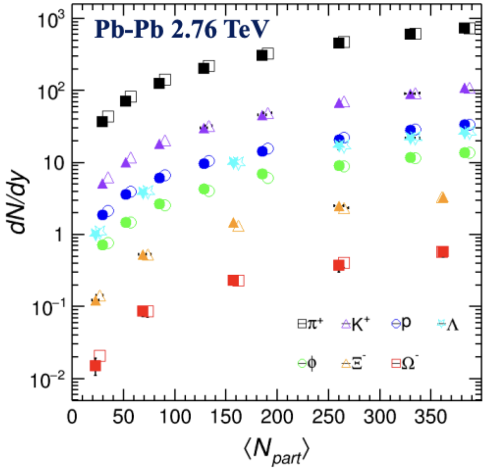




- Description of AA collisions via entropy density: some patterns may appear
- Blast wave description of pp and p-Pb spectra

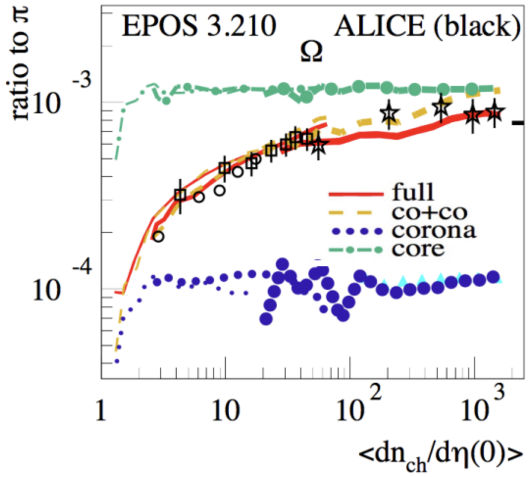
Strangeness: core-corona description to separate two dynamics

$$\left(\frac{dN}{dy}\right)_i^{cen} = N_{part}[(1-f_{core})M_i^{ppMB} + f_{core}M_i^{core}] \quad (1)$$



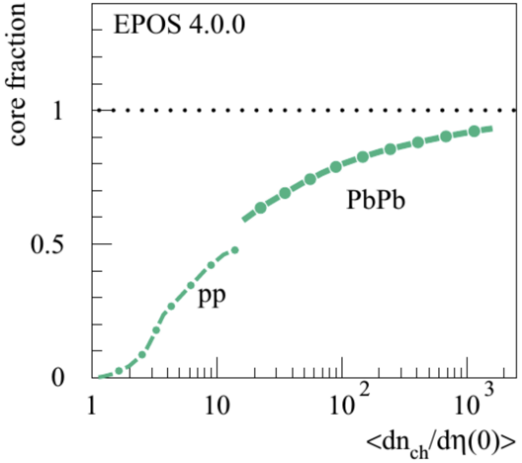
open symbols - Eq.1
full symbols - exp. points

M. Petrovici et al., Phys.Rev. C96(2017)014908



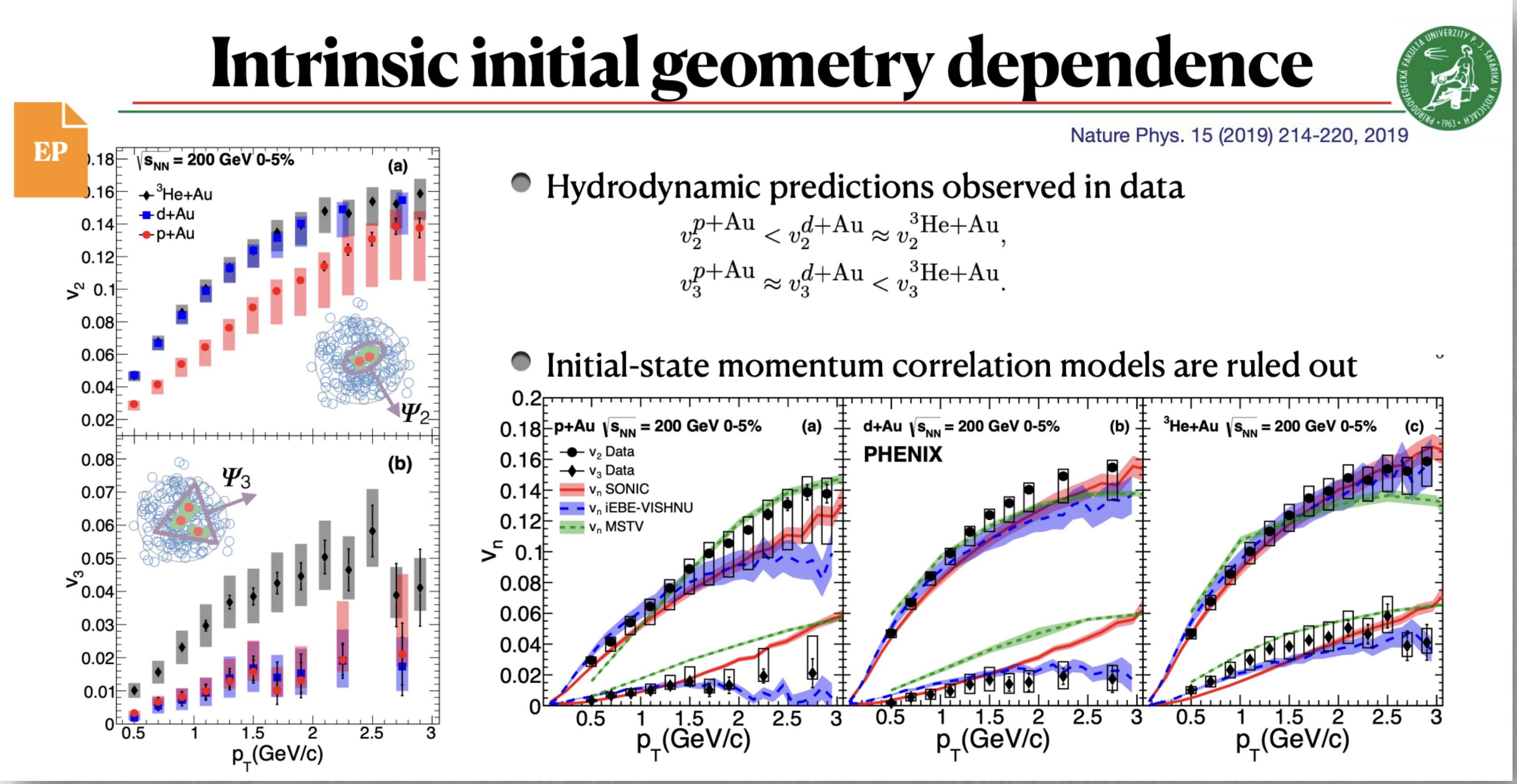
thin lines = pp (7TeV)
intermediate lines = pPb (5TeV)
thick lines = PbPb (2.76TeVVV)
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

K. Werner, SQM 2017, July 10-15 2017, Utrecht



K. Werner, Phys.Rev. C109(2024)014910

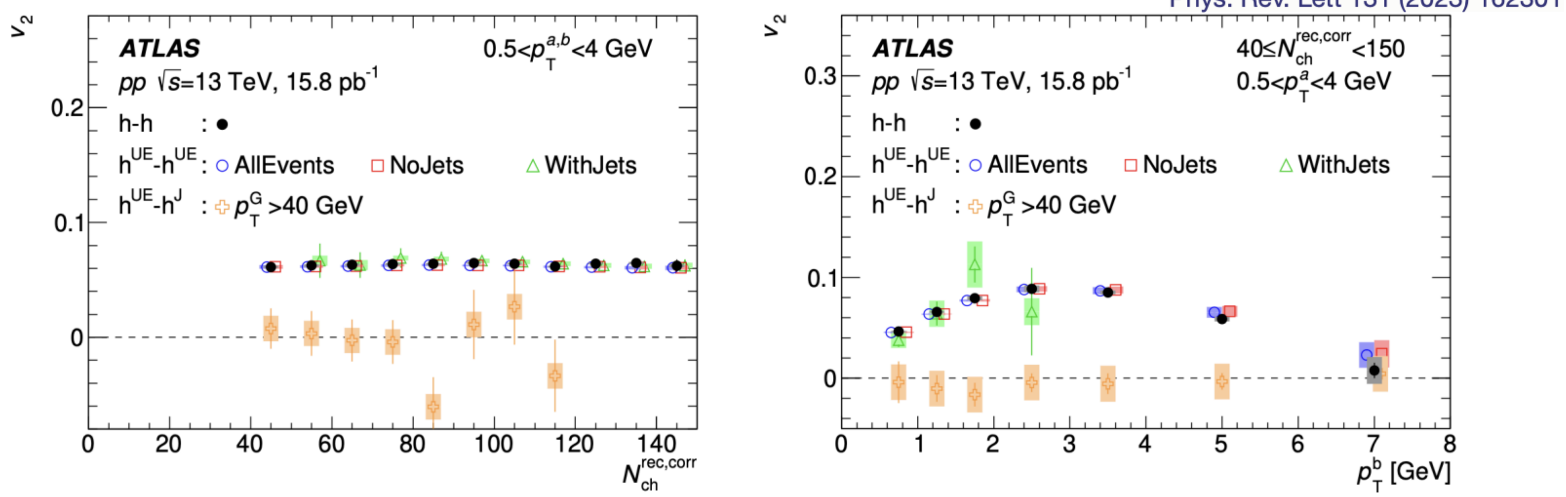
Lucia Tarasovicova
Flow measurements from large to small systems



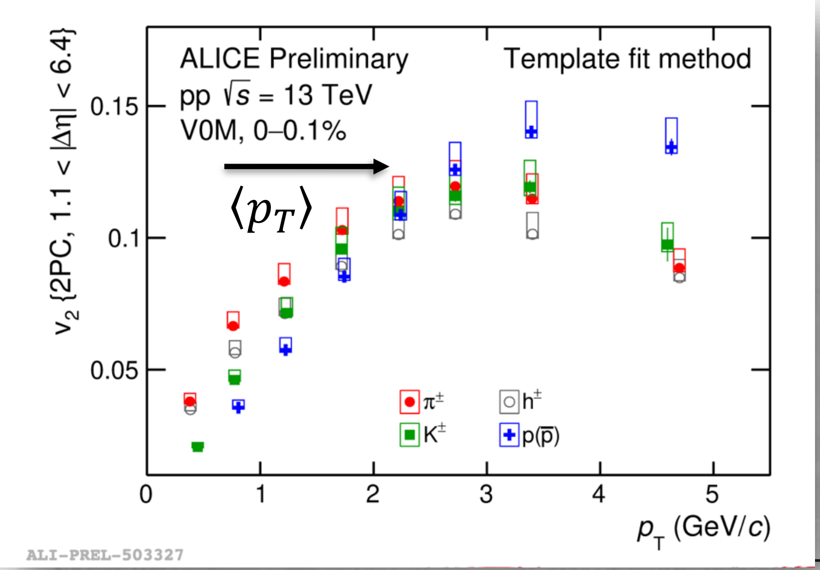
- Applicability of hydro to small systems questionable ?
- Different outcomes from different experiments (PHENIX, STAR): important to perform detailed test with theory/experiment integration

Flow in events with jets

Phys. Rev. Lett 131 (2023) 162301



- Presence of a jet with $p_T > 15$ GeV/c does not influence the v_2 of h^{UE}
  - No multiplicity dependence
- v_2 of h^J compatible with zero



- Jets are uncorrelated with the underlying event
- Underlying event exhibits v2 coefficient (from 2pc) that is multiplicity independent
- Is this expected?
- Is this consistent with the $v_2(p_T)$ and the increase of $\langle p_T \rangle$ vs multiplicity?
  - Not entirely clear …

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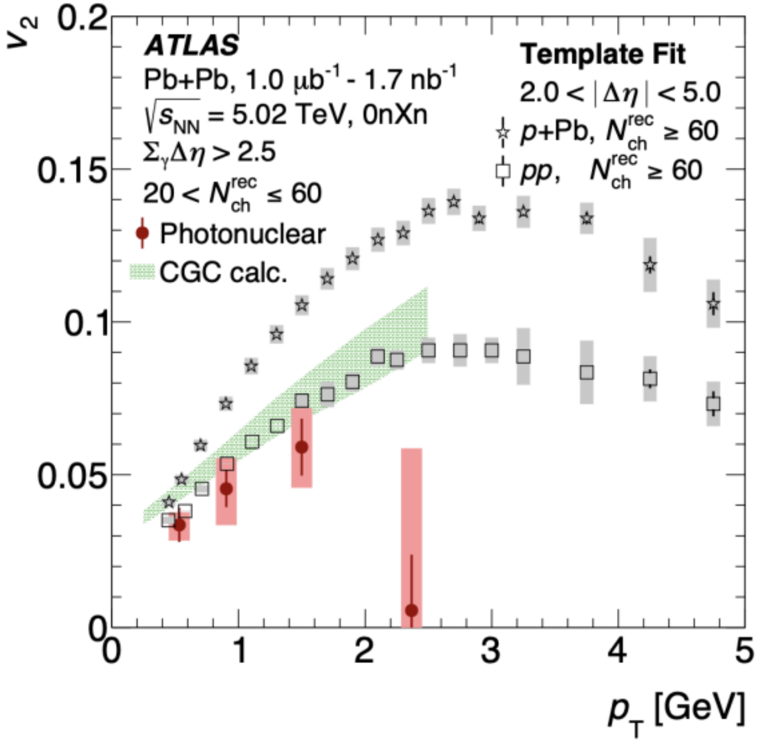
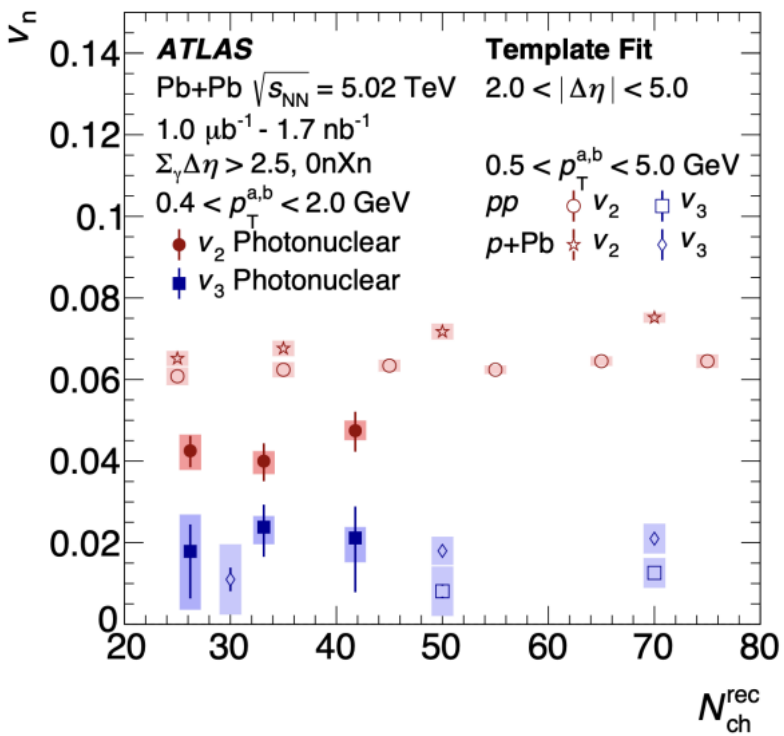
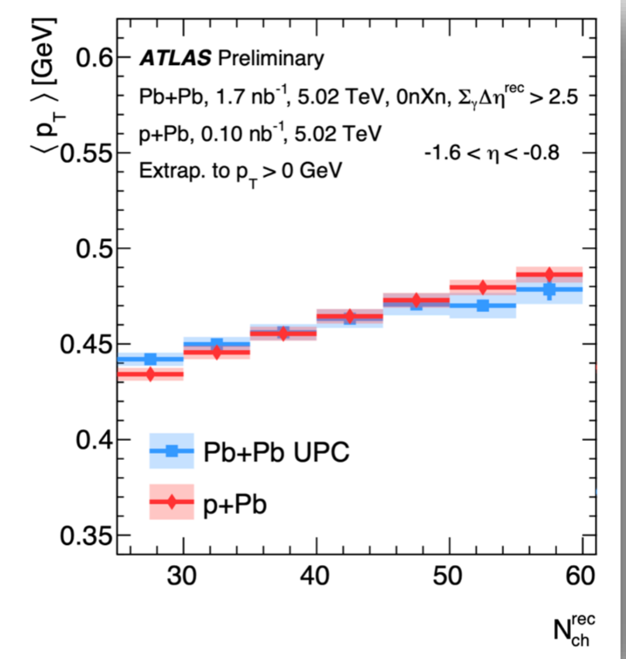
Down to the smallest systems - γPb

Phys. Rev. C. 104 (2021) 014903



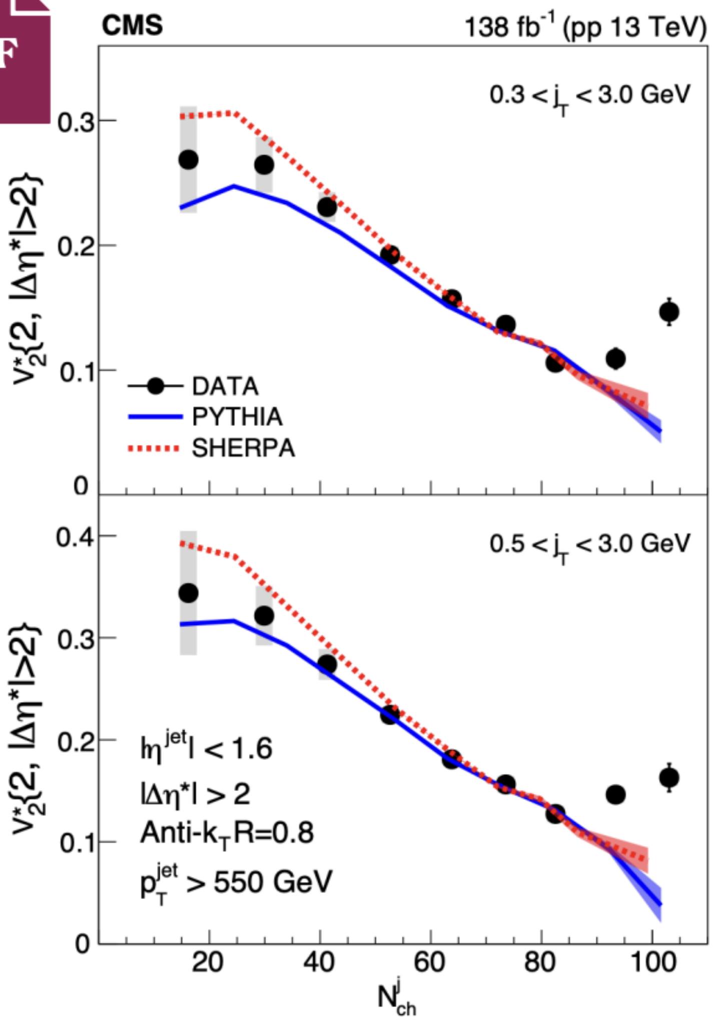




- New set of measurements performed by ATLAS in gamma-Pb collisions
- Events further selected in charged-particle multiplicity
- Multiplicity larger than min-bias pp: likely hadronic environment "again"
  - vector meson (ρ) – Pb collision → same signatures as p-Pb not surprising

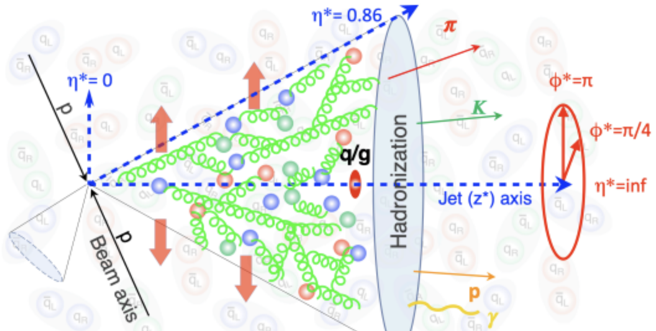
Flow measurement within a jet

FF



arXiv:2312.17103, accepted to PRL

- v_2 measured inside jets, in coordinates w.r.t. jet axis
- Short range correlations ~$1/N^j_{ch}$
  - Observed up to 80 and described by models
- Deviations at larger jet multiplicities
  - 5σ deviation from models
- Indication of an onset of novel QCD phenomena related to non-perturbative dynamics of a parton fragmenting in the vacuum?



- Very extreme jet selection: still reliable?
- Follow-up needed. From hadronization group: study jet substructure to know if this is reasonable?

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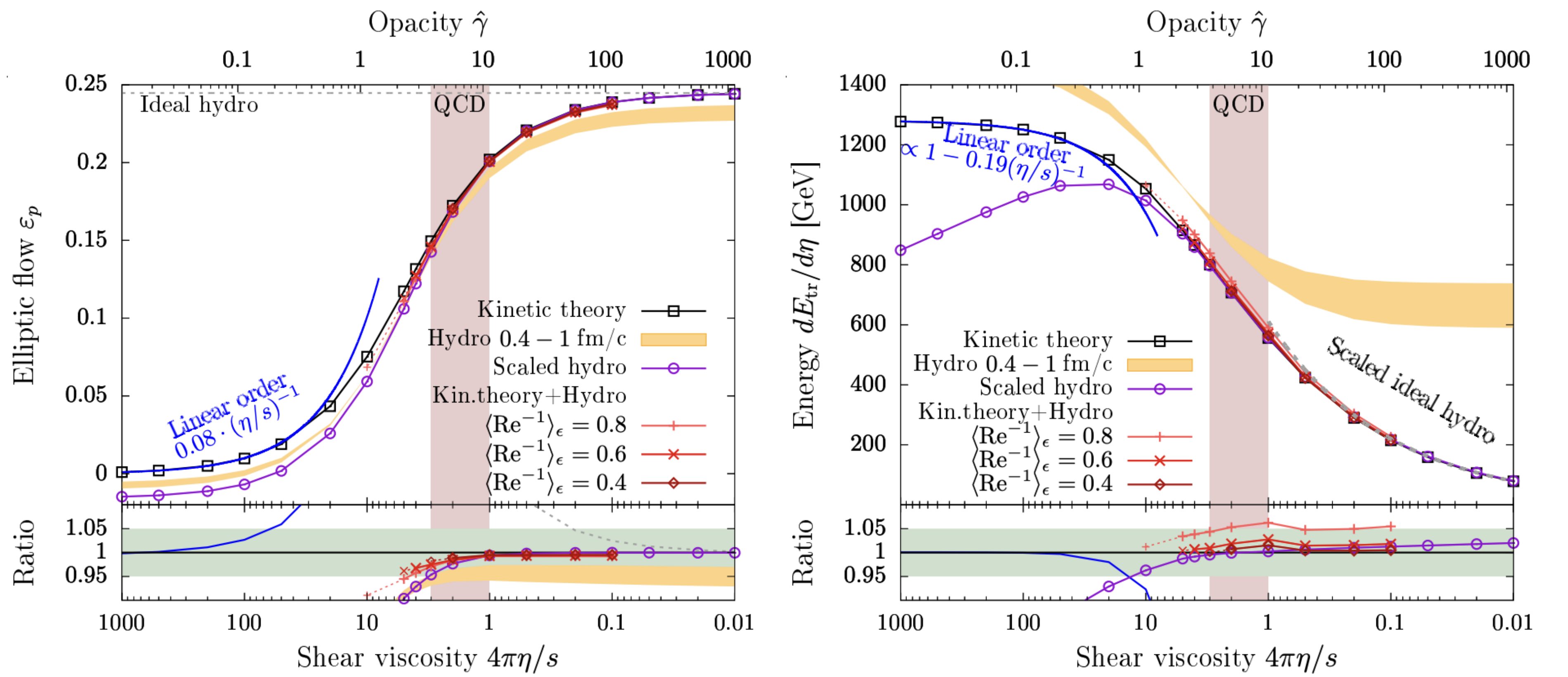
Victor Ambrus

Applicability of hydrodynamics in large and small systems



- Naive hydro, initialized with same ϵ_0 as RKT at $\tau_0 = 0.4$–1 fm$/c$ underestimates ε_p and overestimates $dE_{\mathrm{tr}}/d\eta$.
- Scaled hydro is in perfect agreement at large $\hat{\gamma}$ but loses applicability as $\hat{\gamma} \lesssim 3$–4.

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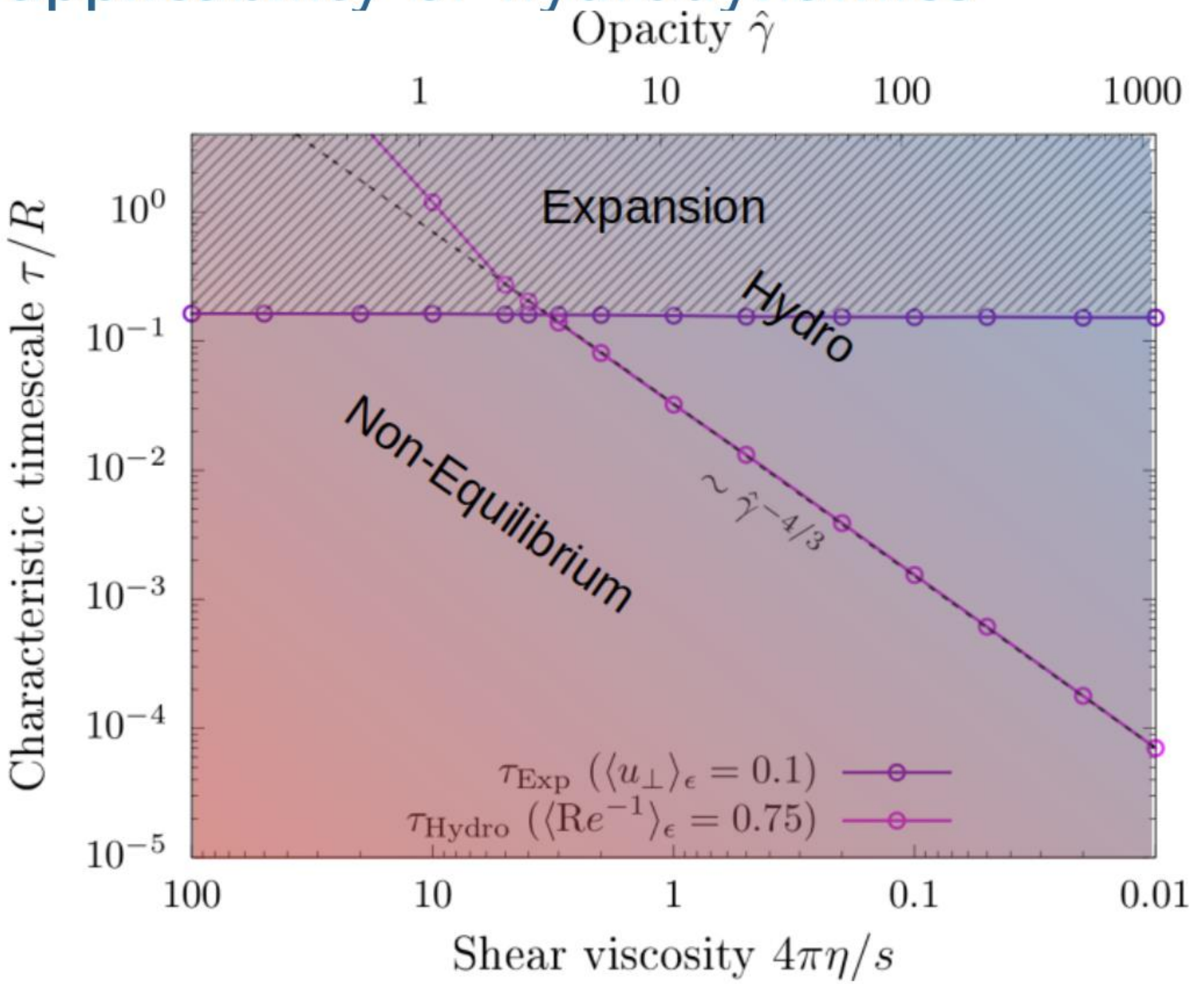
Regime of applicability of hydrodynamics



- Transverse expansion sets in at $\tau_{\mathrm{Exp}} \sim 0.2R$, independent of opacity.
- Hydro applicable when $\mathrm{Re}^{-1} \lesssim 0.75$.
- When $\hat{\gamma} \lesssim 3$, hydrodynamization is interrupted by transv. expansion.

Hydrodynamics in real collision systems

What does the criterion $\hat{\gamma} \gtrsim 3$ imply for the applicability of hydro to realistic collisions?

$$\mathrm{p+p}: \hat{\gamma} \overset{\text{min.bias}}{\sim} 0.7 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{0.12\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{7.1\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{42.25}\right)^{-1/4}$$

far from hydrodynamic behaviour

$$\mathrm{p+Pb}: \hat{\gamma} \overset{\text{min.bias}}{\sim} 1.5 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{0.81\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{24\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{42.25}\right)^{-1/4} \overset{\text{high mult.}}{\lesssim} 2.7$$

very high multiplicity events approach regime of applicability, but do not reach it

$$\mathrm{O+O}: \hat{\gamma} \overset{30-40\%}{\sim} 2.2 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{1.13\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{55\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{42.25}\right)^{-1/4} \sim \overset{70-80\%}{1.4} - \overset{0-5\%}{3.1}$$

probes transition region to hydrodynamic behaviour

$$\mathrm{Pb+Pb}: \hat{\gamma} \overset{30-40\%}{\sim} 5.7 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{2.78\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{1280\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{42.25}\right)^{-1/4} \sim \overset{70-80\%}{2.7} - \overset{0-5\%}{9.0}$$

hydrodynamic behaviour in all but peripheral collisions

- Oxygen-oxygen is especially interesting: the onset of applicability of hydro
- What does this mean experimentally?

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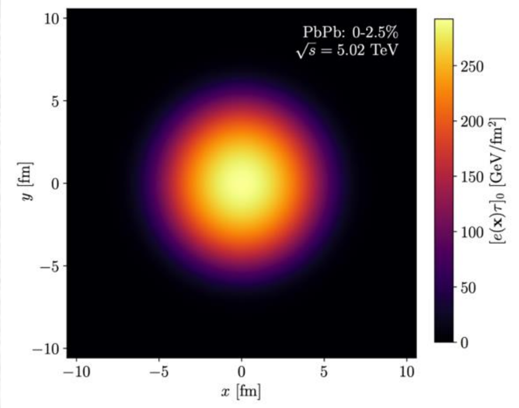
Nicolas Borghini:

Statistical description of the initial state fluctuations and mode-by-mode dynamical evolution

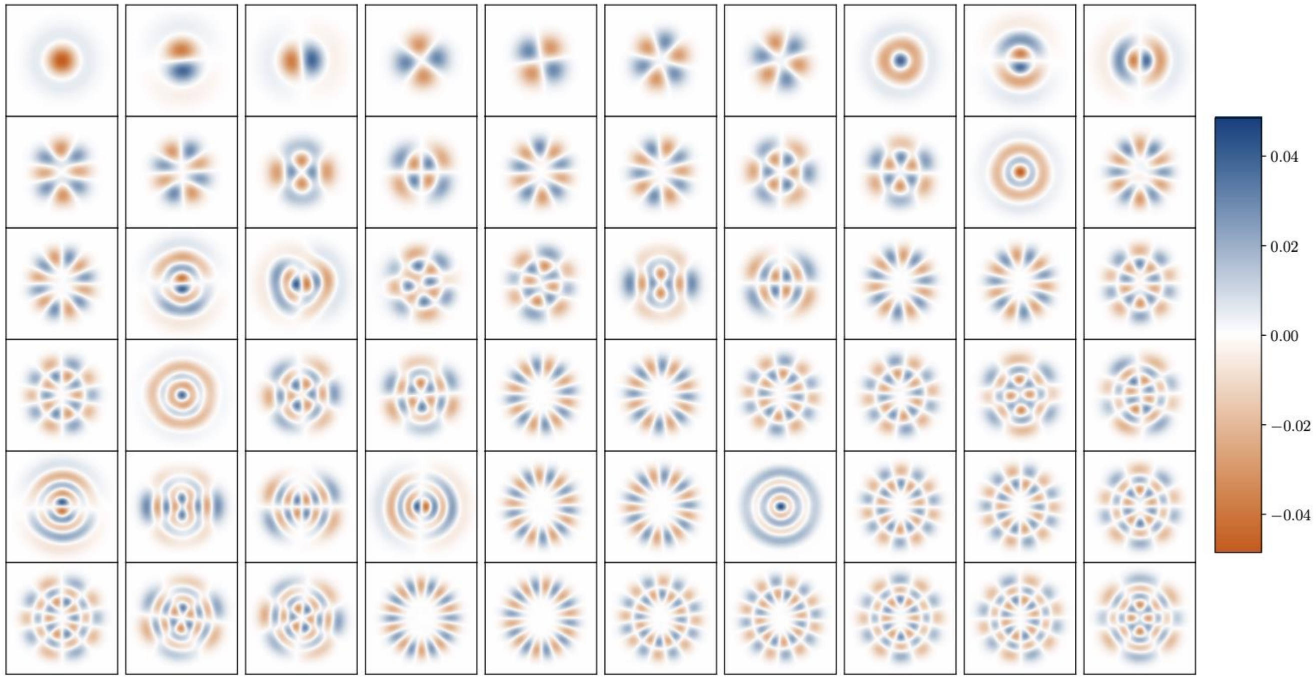


☞ A random initial state may be seen as a random fluctuation about this average state:

$$\Phi^{(i)}(\mathbf{x}) = \bar{\Psi}(\mathbf{x}) + \delta\Phi^{(i)}(\mathbf{x})$$

The goal is now to characterize the fluctuating parts $\{\delta\Phi^{(i)}(\mathbf{x})\}$.

Pb-Pb at 5.02 TeV, 0-2.5% centrality
(nucleon-based MCGlauber, fixed impact-parameter direction)



- Hydro simulation of average state plus one mode at a time
- Calculate medium response to IS fluctuation eigenvectors

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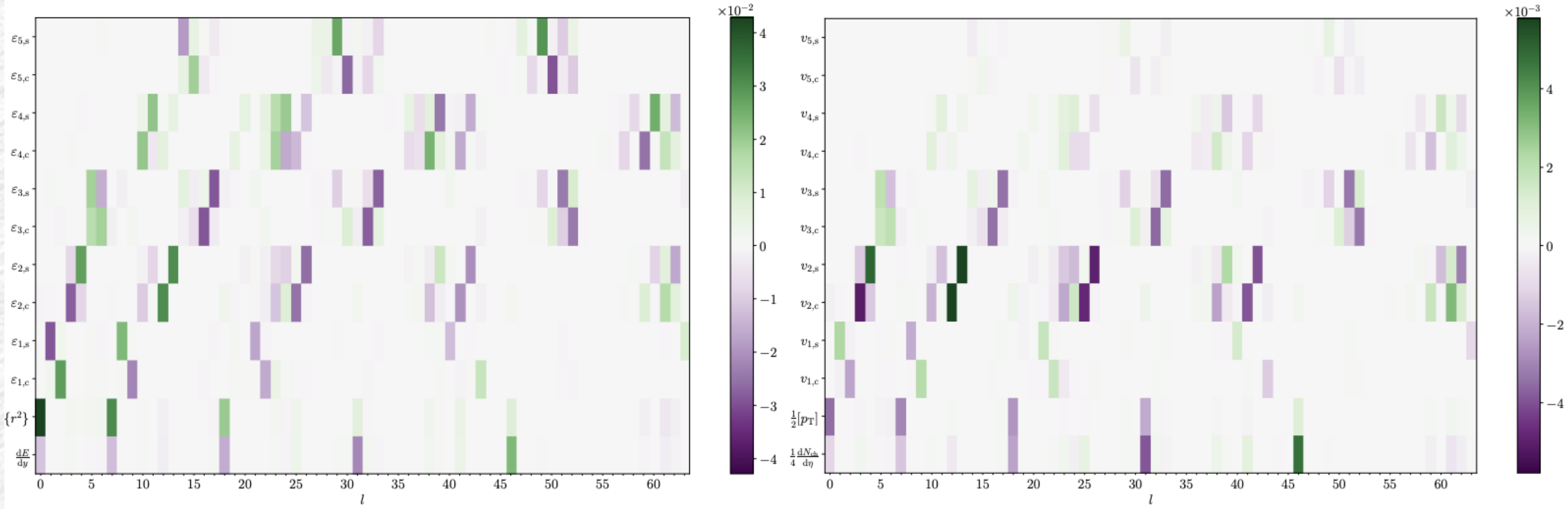
Influence of individual fluctuation modes on "observables"

$$O_\alpha(\bar{\Psi} + \xi\Psi_l) = O_\alpha(\bar{\Psi}) + L_{\alpha,l}\xi + \frac{Q_{\alpha,ll}}{2}\xi^2 + \mathcal{O}(\xi^3)$$

Pb-Pb at 5.02 TeV, 0-2.5% centrality; linear-response coefficients $L_{\alpha,l}$ at the end of MUSIC (+ decays).

Initial state → Final state



Nice correspondence, e.g. $\varepsilon_{n,c/s} \rightarrow v_{n,c/s} \propto \varepsilon_{n,c/s}$

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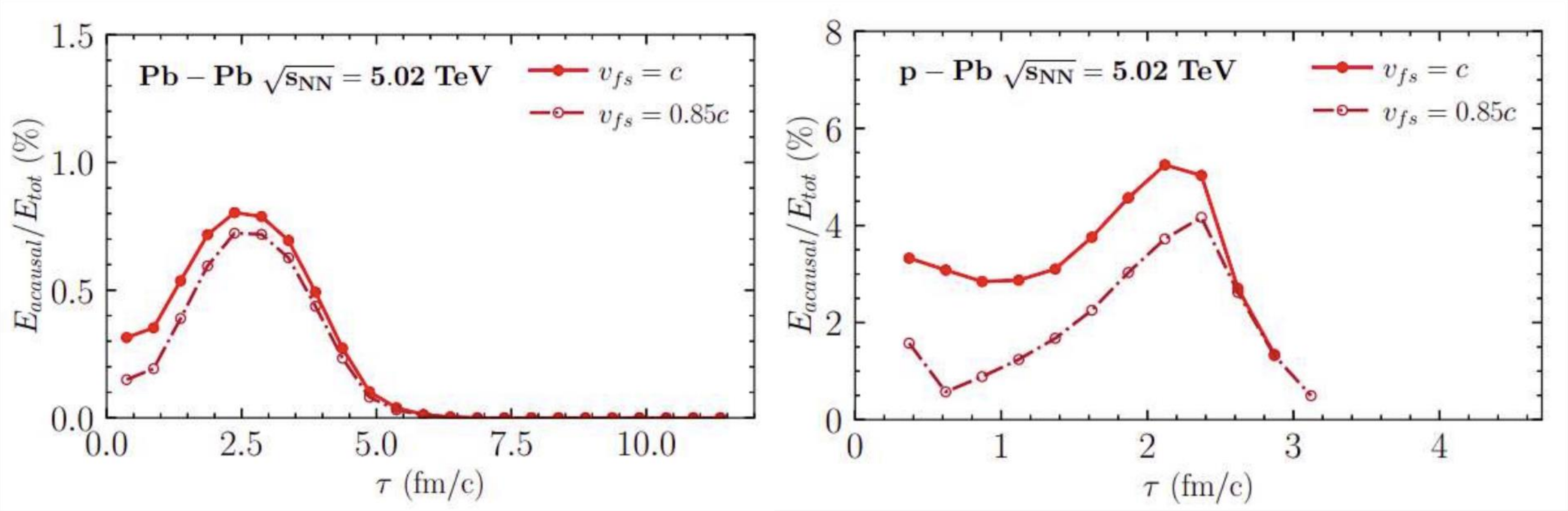
Questions / Ideas / Outlook

- How does the statistical analysis of initial-state fluctuations help?
  - (Dream?) To define a distance between initial-state models?
  - From the response coefficients, one can compute the (co)variances of observables (e.g.: with linear coefs, covariances at order c_l^2)
- Extensions
  - Other systems (e.g.: B.Bachmann, MSc thesis on Ru+Ru vs. Zr+Zr at 200 GeV)
  - More final-state observables (Dream: "golden observables", due to very few modes ☞ reverse engineering)
  - Going 3D; adding conserved charges
  - Inclusion of further effects in toy hot-spot model
  - ...

Renata Krupczak

Causality conditions as constraints in hydrodynamics

Calculating the percentage of acausal energy

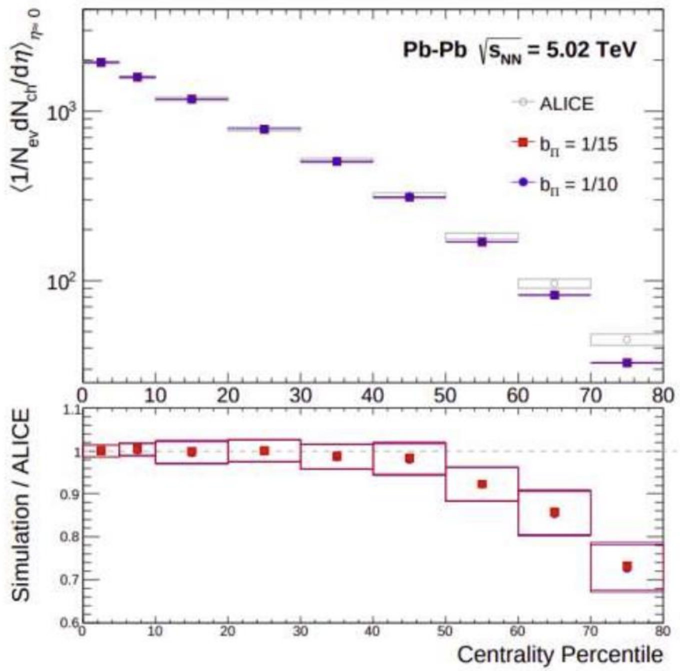


- Small fraction of acausal energy in Pb-Pb
- But more significant in p-Pb and smaller systems

Effect of acausality in (some) final-state observables

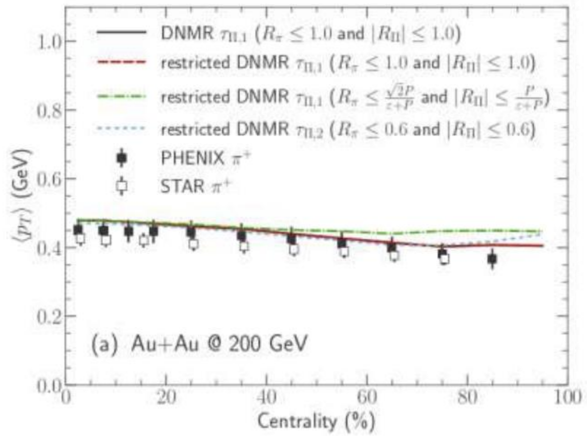
4. Validation Through Simulations

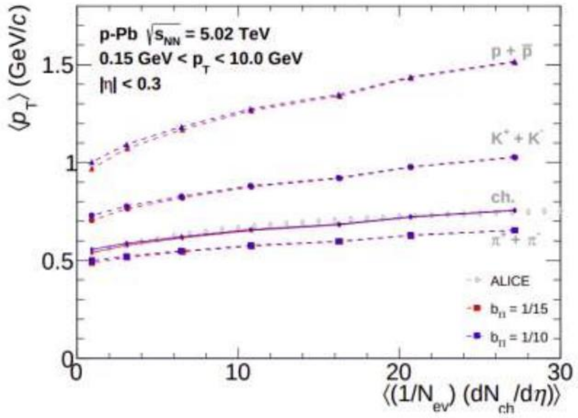
No Impact on final observables



Krupczak et al., Phys. Rev. C, 2024

Chiu & Shen, Phys. Rev. C, 2021

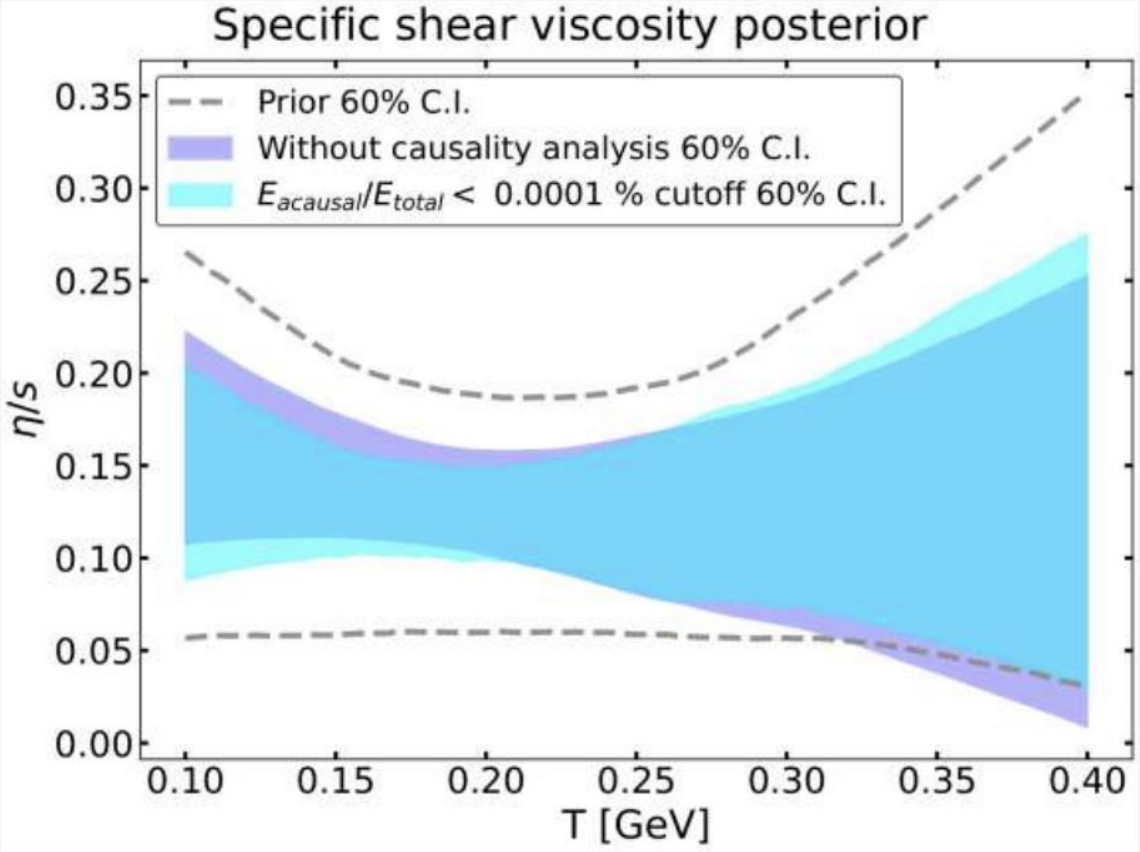


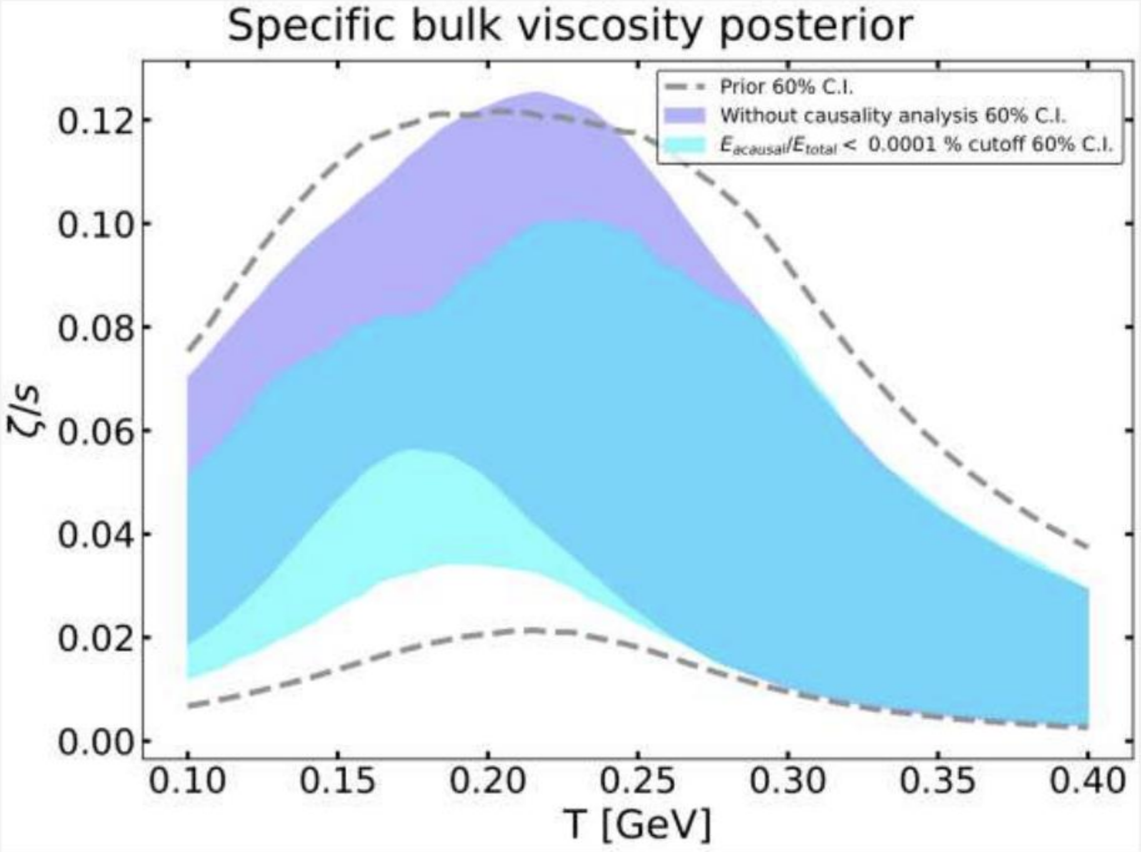


Krupczak et al., Phys. Rev. C, 2024

- Not very significant in primary observables (N_{ch}, mean p_T)
- More significant effects in other observables?

Effect of acausality in QGP property extraction in bayesian analysis





Broader questions in the hydro track

- **Flow inside a single jet and the CMS measurement**
  - Very extreme measurement, substructure could be studied for sanity
- **Speed of sound: use of extreme centrality selections to probe system properties directly**
- **Expanding and characterising the initial state and response to it**
  - "Fundamental" variables vs "detailed" variables: dependent on a few modes vs dependent on one very specific (potentially higher order) mode
- **Extremely small: proton-proton system and hydrodynamics ("the duck test" scenario)**
  - What about UPC?
- **Applicability of hydro: may not be valid but "so what"?**
  - Oxygen-oxygen: Which observables to look at?
  - Kinetic theory versus hydro and how they map into one another
  - Extremely important: integration between theory and experiment to overcome difficulties in comparisons
- **ALICE 3 and eta acceptance: what does that stand to teach us?**

Thank you!