Mode-by-Mode Evolution in Pb-Pb Collisions

Renata Krupczak[1], **Nicolas Borghini**[1] **and Hendrik Roch**[2]

[1]Fakultät für Physik, Universität Bielefeld, Germany

[2]Department of Physics and Astronomy, Wayne State University, USA

1. Objective

Describe the energy profile from heavy-ion collisions as the **average state** of a sample of events plus a linear decomposition into **modes**:

$$\Phi^{(i)}(\boldsymbol{x}) = \bar{\Psi}(\boldsymbol{x}) + \sum_l c_l^{(i)} \Psi_l(\boldsymbol{x})$$

with $\langle c_l \rangle = 0$ and $\langle c_l c_{l'} \rangle = \delta_{ll'}$.

Our goal is to **relate initial-state fluctuation modes to final-state observables**, to better pin down the initial-state model.

2. Theory

The modes are extracted from the **density matrix**, which corresponds to the autocorrelation of the fluctuation:

$$\rho = \frac{1}{N_{\rm ev}} \sum_{i=1}^{N_{\rm ev}} \Phi^{(i)} \Phi^{(i)\intercal} - \bar{\Psi}\bar{\Psi}^\intercal$$

Diagonalize: $\rho \Psi_l = \lambda_l \Psi_l$

The eigenvalues characterize the relative importance of the fluctuation modes.

Some **observables**, both in the initial state and at the end of dynamical evolution, can be expressed by:

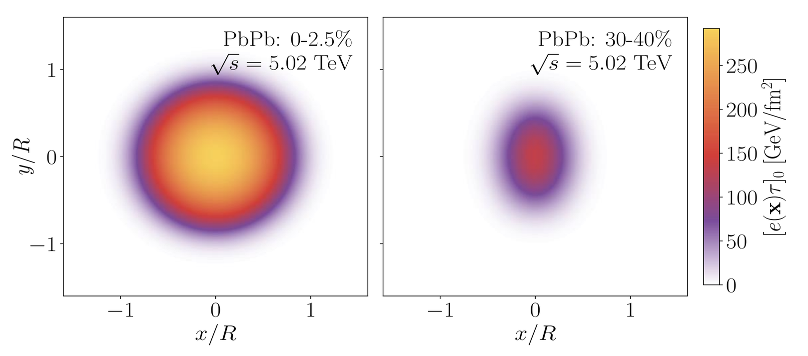
$$O_\alpha(\Phi) = O_\alpha(\bar{\Psi}) + \sum_l L_{\alpha;l} c_l + \frac{1}{2} \sum_{ll'} Q_{\alpha;ll'} c_l c_{l'}$$

with **linear and quadratic response coefficients** $L_{\alpha;l}$ and $Q_{\alpha;ll'}$.

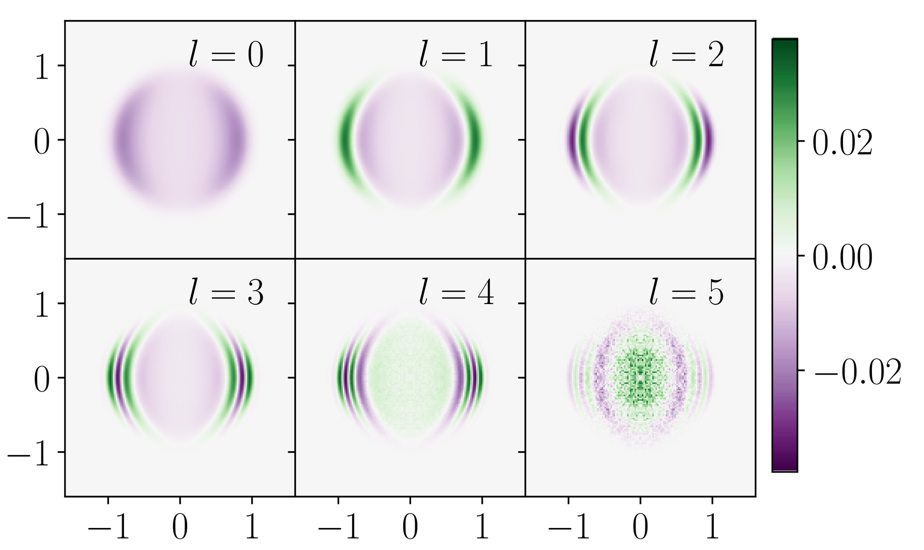
These coefficients can be used to deduce the event-by-event statistics of other observables (not shown here).

3. Results

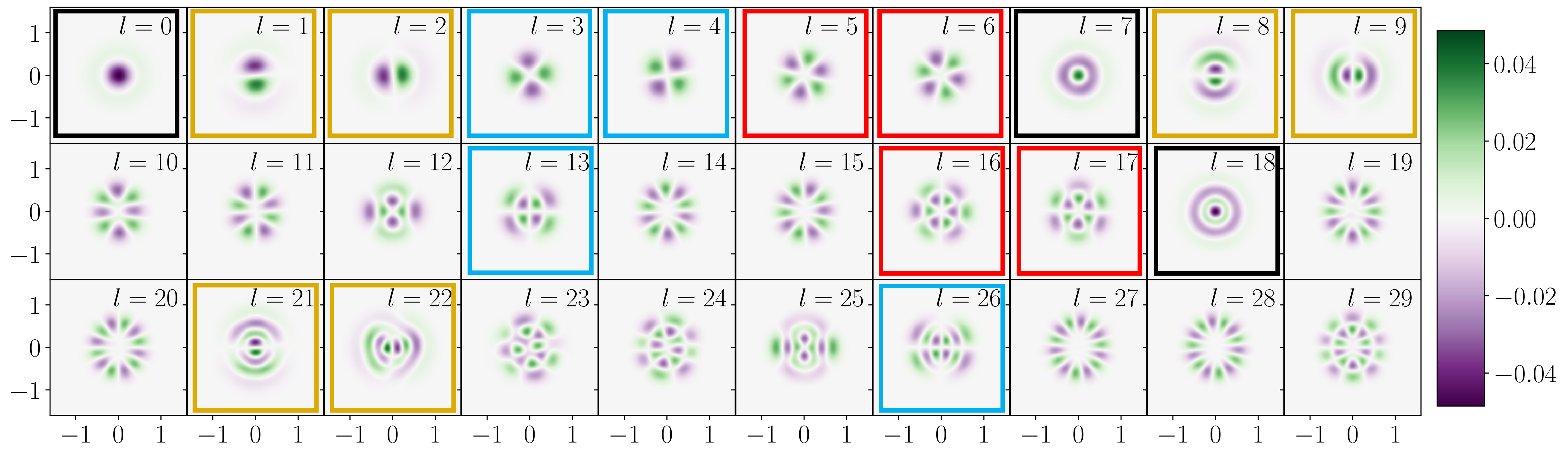
Monte Carlo Glauber simulations of **Pb-Pb** collisions at **5.02 TeV** were performed at centralities of 0-2.5% and 30-40% (2^{21} events each), with fixed impact parameter direction. The smooth average state:



To assess the influence of purely **geometric fluctuations**, optical Glauber simulations were performed (10^3 events at each centrality). Only very few modes have a sizeable influence, e.g., only 6 in central events:



These geometric fluctuations carry energy, ε_2 and ε_4, and arise from **impact parameter variations within the centrality range.**

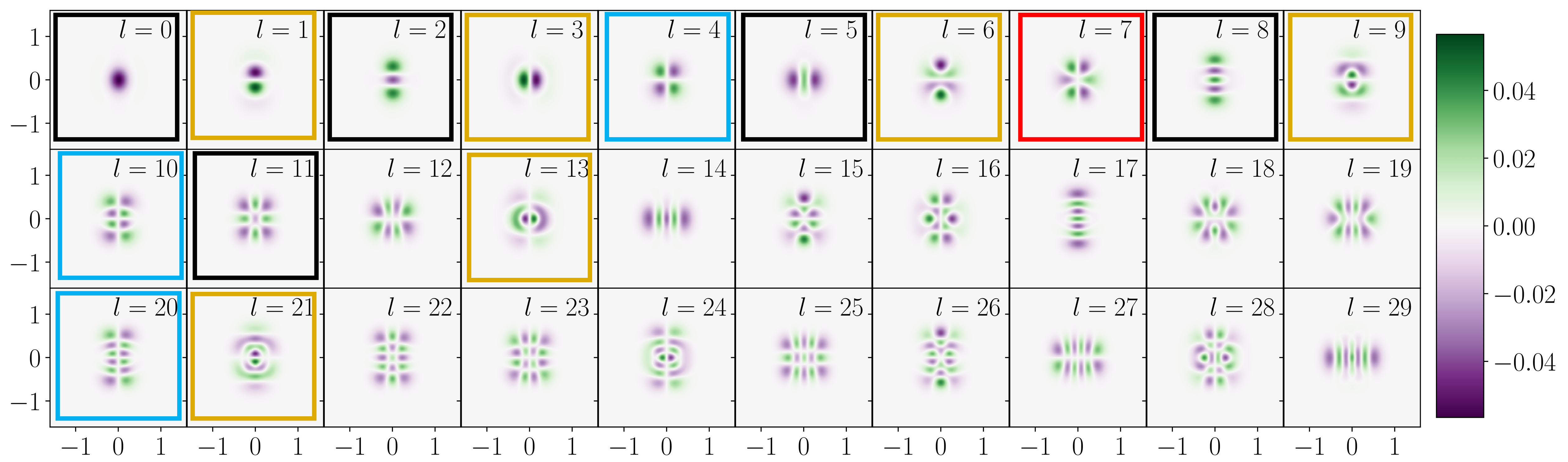


Modes in the transverse plane for centrality 0-2.5%

Modes can be qualitatively described as:

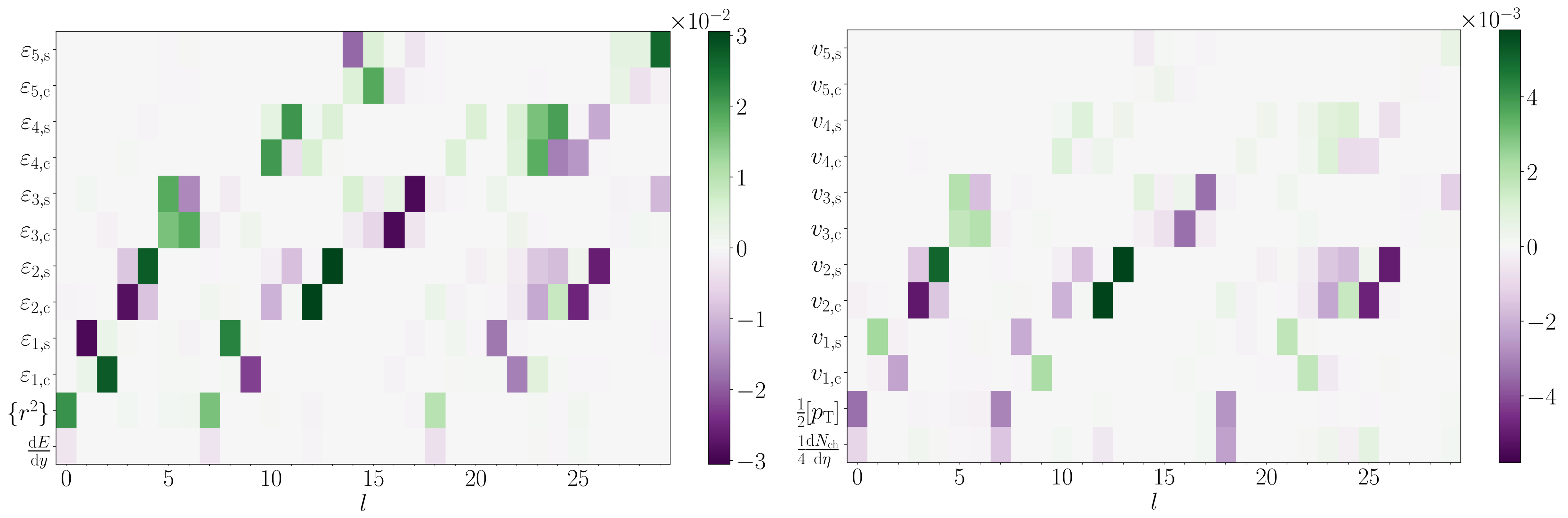
- **Same symmetry as the average state**, responsible for carrying **energy**
- **Dipole** structure, generating $\boldsymbol{\varepsilon_1}$
- **Quadrupole** structure, generating $\boldsymbol{\varepsilon_2}$
- **Sextupole** structure, generating $\boldsymbol{\varepsilon_3}$
- Other modes involve eccentricities $\varepsilon_{n\gg1}$ or a mix between different eccentricities
- In non-central events, each mode generally contributes to several observables, in particular eccentricities.

Centrality 30-40%



Linear response coefficients for 0-2.5%, where c and s indices refer to the cosine and sine components, respectively.

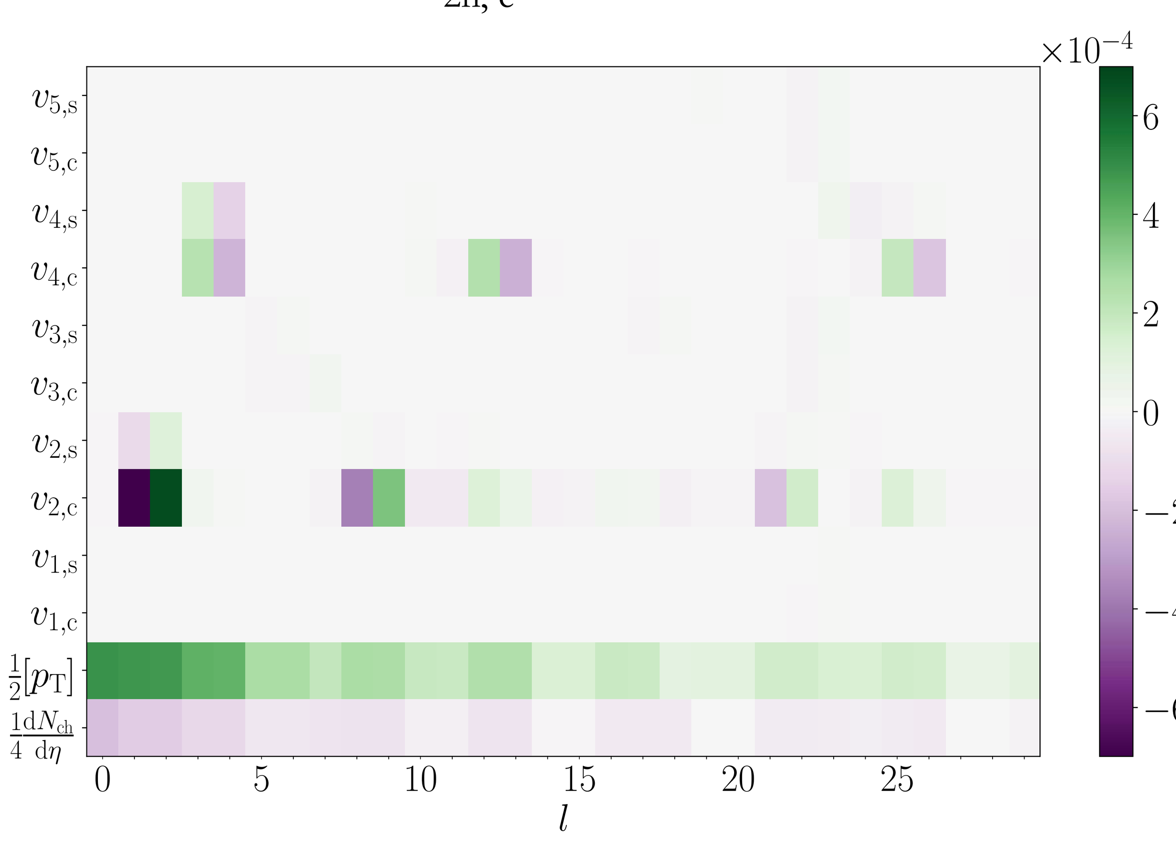
This provides a quantitative way to assess which mode is responsible for which observable.



Initial State → **Final State**

KøMPøST + MUSIC

Quadratic response coefficient for 0-2.5% for final state. Shows in particular the ε_n^2 contribution to $v_{2n,c}$.



- The influence of single modes propagates throughout the hydrodynamic evolution;
- Also holds when including a hadronic transport afterburner, yet at the cost of a large oversampling to reduce statistical noise.

4. Conclusions and Outlook

- Systematic approach to relate initial-state fluctuations to final observables.
- Extension to 3D initial-state models and their impact on longitudinal-correlation observables.

References:

N. Borghini et al., Phys. Rev. C 107 (2023) 034905

R. Krupczak et al., arXiv:2504...