Proton Intermittency analysis in Au + Au Collisions: Exploring Critical Behavior in the FAIR Energy Range

Presenter : Anjali Sharma[1]

Collaborators : Omveer Singh[2] , Supriya Das[1]

[1] Bose Institute, Kolkata, India; [2] Goethe- Universität, Frankfurt am Main

Motivation

The Critical Point (CP)

- **Definition**:
  - A hypothesized endpoint of the first-order phase transition line between quark-gluon plasma (QGP) and hadronic matter (HM) in the (T, μ_B) plane.
  - Exhibits properties like scale-invariant correlations.
- **Significance**:
  - Serves as a bridge between two distinct phases of matter.
  - Characterized by fluctuations in thermodynamic quantities (e.g., temperature and baryonic chemical potential).

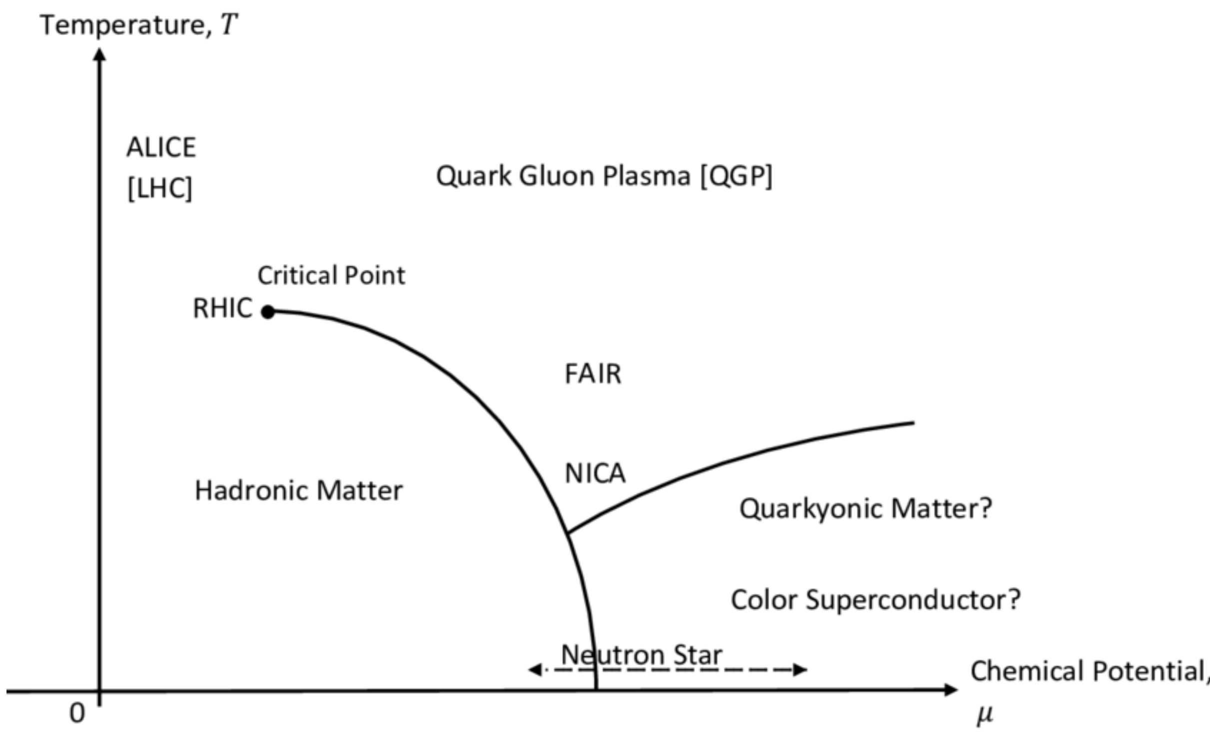
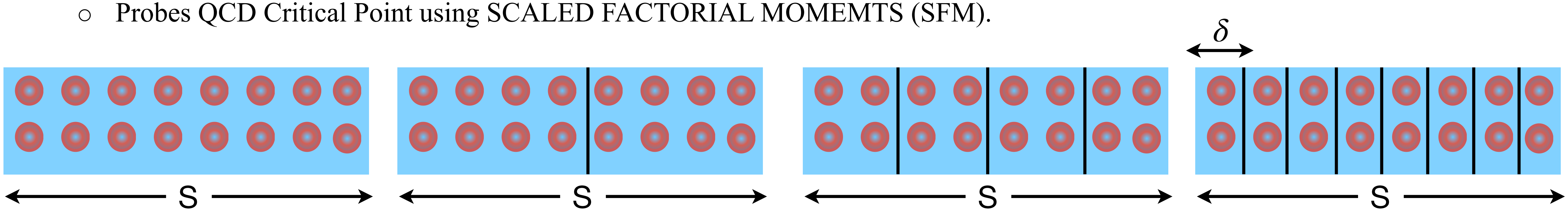


Figure taken from : Nuclear Physics B,Volume 911,2016,Pages 173-190

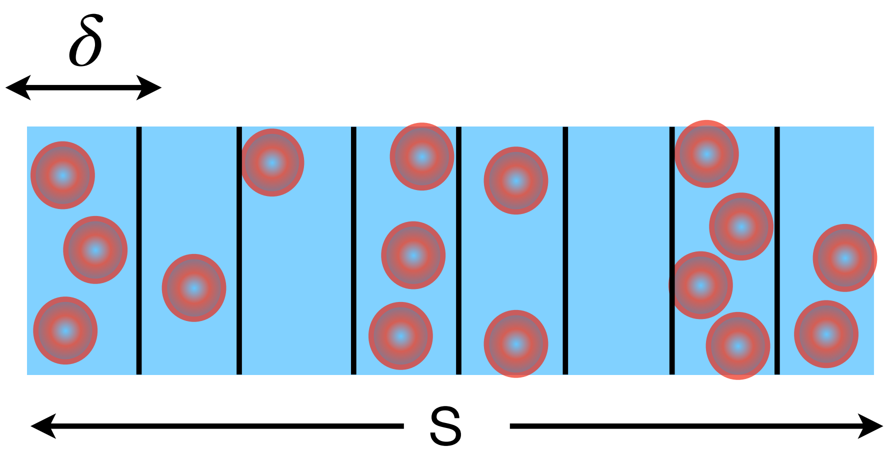
Intermittency:

- Random, non-uniform deviations from regular behavior observed in high-energy physics.
- **Importance**:
  - Critical for identifying **scale-invariant fluctuations**.
  - Probes QCD Critical Point using SCALED FACTORIAL MOMEMTS (SFM).



Concept of Intermittency : Intermittency refers to the uneven and highly variable distribution of entities within a system, observed by subdividing it into smaller cells of same size while keeping the total size and number of entities constant

Motivation

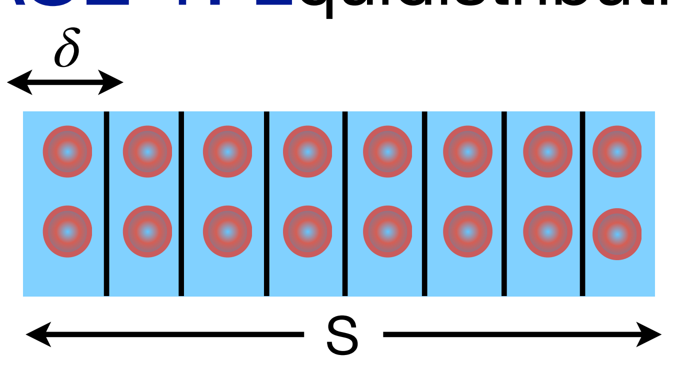


r-order factorial moment :

$$f_r(M) = \frac{[\frac{1}{M}\sum_{i=1}^{M} n_i^r]}{[\frac{1}{M}\sum_{i=1}^{M} n_i]^r} = M^{r-1}N^{-r}\sum_{i=1}^{M} n_i^r$$

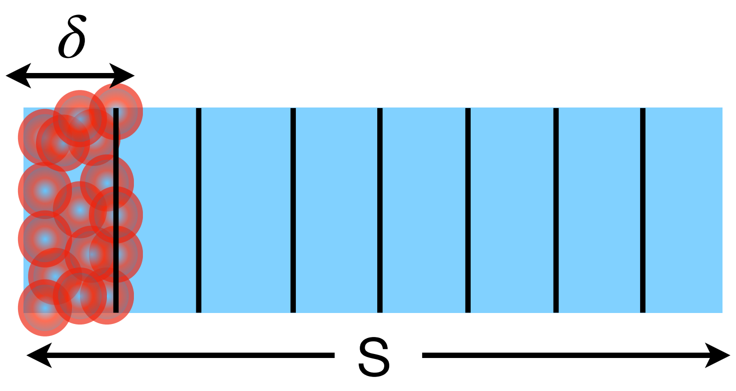
where M is no. of cells; N is total no. of particles and n_i is no. of particles in i^{th} cell.

CASE 1: Equidistribution



$$n_i = \frac{N}{M}$$ and $$f_r(M) = 1$$

CASE 2: Extreme fluctuation (all particles in one cell)

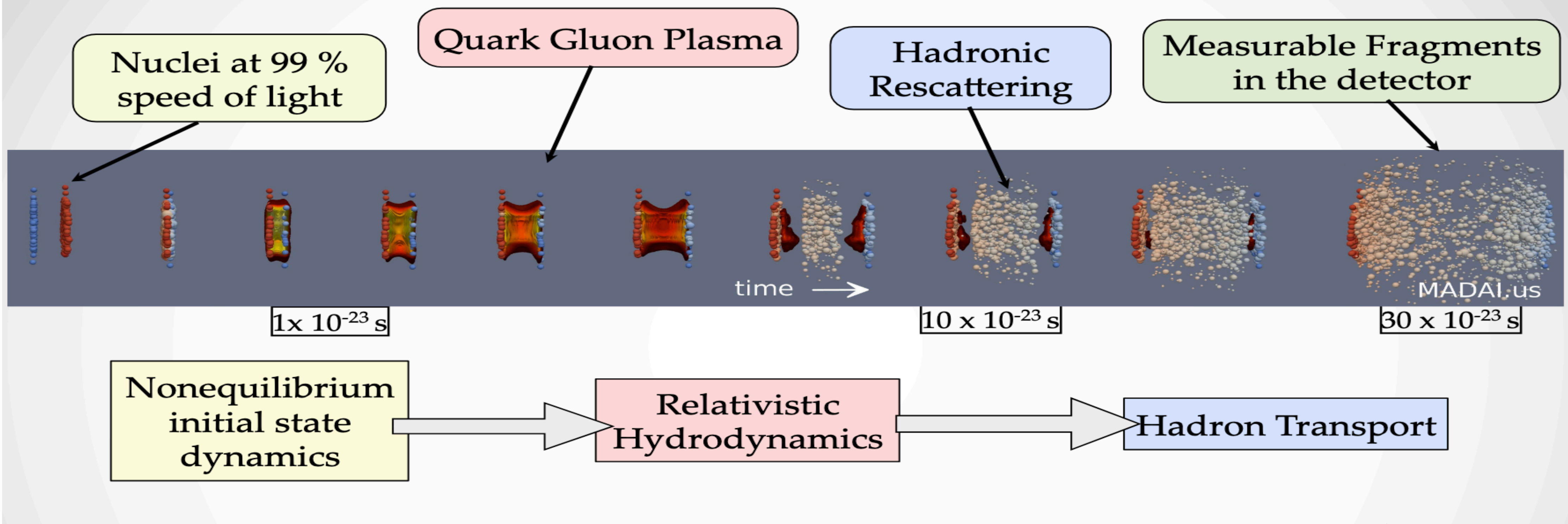


$$f_r(M) = M^{r-1}$$

It is intermittent behavior if ln(f_r(M)) varies linearly with ln(δ)

Slide inspiration : Slides of Valeria Zelina Reyna Ortiz in 24th ZIMÁNYI SCHOOL WINTER WORKSHOP ON HEAVY ION PHYSICS Budapest, Hungary – December 3, 2024

Time Evolution as modeled in UrQMD



- **Ultra-relativistic Quantum Molecular Dynamics Model**: A Microscopic hybrid Transport model for simulating the full space-time evolution of heavy-ion collisions.

- **Key Scientific Features :**
  - Microscopic Framework: Simulates hadron-hadron, hadron-string, and string-string interactions based on established cross-sections.
  - Phase Transition Insights: Enables exploration of the Quark-Gluon Plasma (QGP) and critical phenomena.
  - Energy Range: Effective across $\sqrt{s}$ = 2 GeV to 200 GeV, bridging RHIC, LHC, and FAIR regimes.

For this analysis Chiral+HG EoS is used :

- **Chiral Symmetry Restoration**: Models the restoration of chiral symmetry at high temperatures/densities, affecting hadron masses and interactions, critical for studying the QCD phase diagram.
- **Unified EoS**: Combines chiral effective field theory for the hadronic phase with lattice QCD inputs for the QGP phase, enabling smooth transitions (crossover or first-order) between hadronic matter and the QGP.
- **Applications**: Critical for investigating QGP signals, collective flow (v_2), and locating the critical point in heavy-ion collision experiments (e.g., RHIC, FAIR).

Methodology

Scaled factorial moments

Horizontal averaging: Calculates the moments for each event and then averages them.

Vertical averaging: Calculates the moments for a particular bin in all events and then averages them over all bins.

Present analysis is done with horizontal averaging method :

$$\langle F_q \rangle = \frac{1}{N} \sum_{j=1}^{N} M^{q-1} \sum_{i=1}^{M} \frac{n_{i,j}(n_{i,j}-1)\ldots(n_{i,j}-q+1)}{\langle n \rangle^q}$$

where, N is total no. of events, M is no. of bins, $n_{i,j}$ is no. of particles of i^{th} bin in j^{th} event, $\langle n \rangle$ is average no. of particles in entire phase space.

Any intermittent pattern can be confirmed by examining the power-law relationship between these moments and the number of bins.

$$\langle F_q \rangle \propto M^{\alpha_q}$$

The linear relationship between $ln\langle F_q \rangle$ and ln M indicates that the SFMs exhibit power-law scaling behavior, which predicts an intermittent pattern in non-statistical multiparticle production.

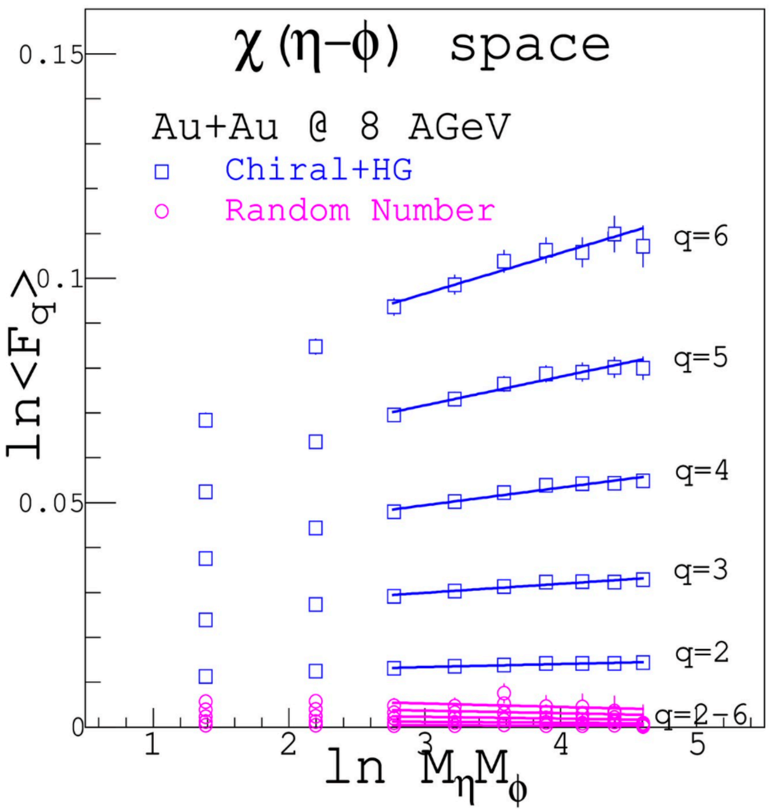
$$D_q = \frac{\alpha_q}{q-1}$$

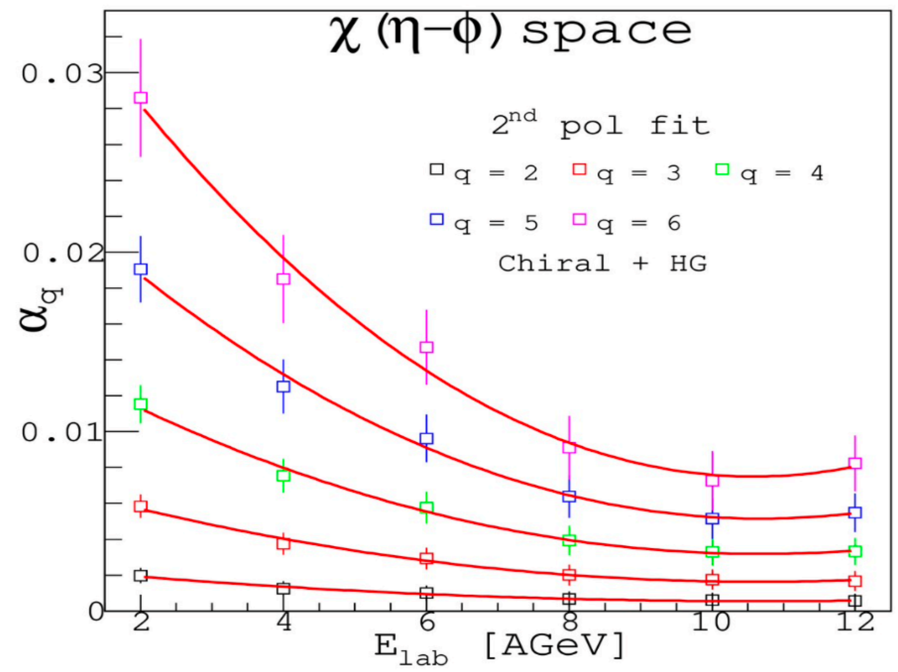
Anomalous fractal dimensions (D_q):

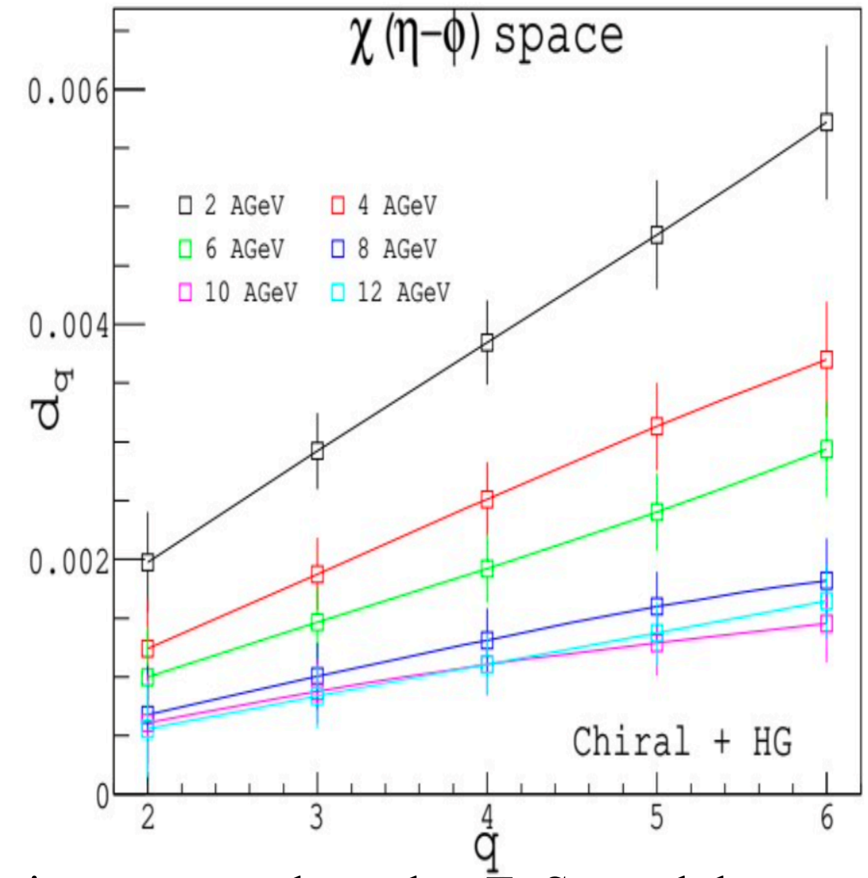
- ✦ Sensitive to the nature of phase transitions.
- ✦ 2^{nd}-order phase transition: Indicated if intermittency occurs with D_q independent of q.
- ✦ Cascading process: Anticipated if D_q shows a roughly linear dependence on q.

Previous Results

Eur. Phys. J. A 59 (2023) 4, 92







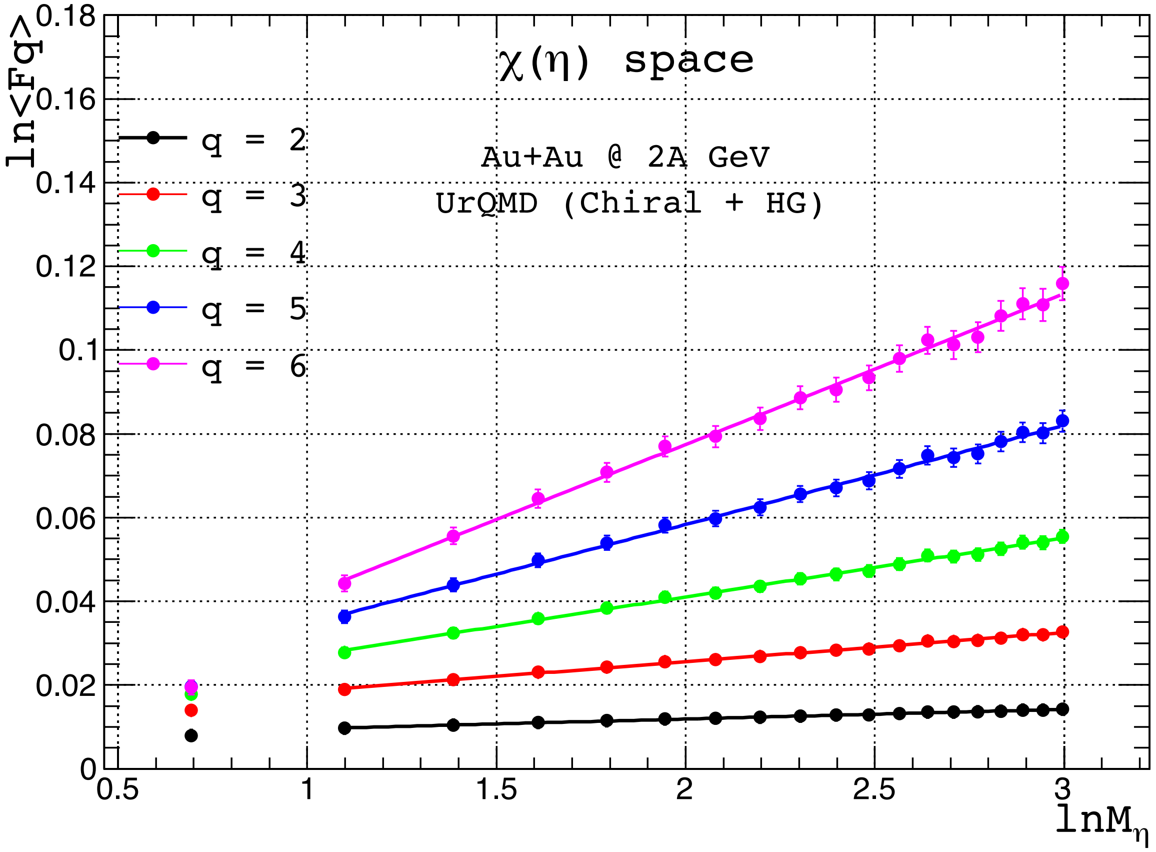
UrQMD-hydro simulations with the Bag model EoS indicate enhanced particle production compared to other EoSs, and the multifractal nature of emission spectra in Au+Au collisions at FAIR energies (2A–12A GeV) suggests a cascading particle production process with intermittent patterns observed in 1D (η, φ) and 2D (η-φ) spaces.

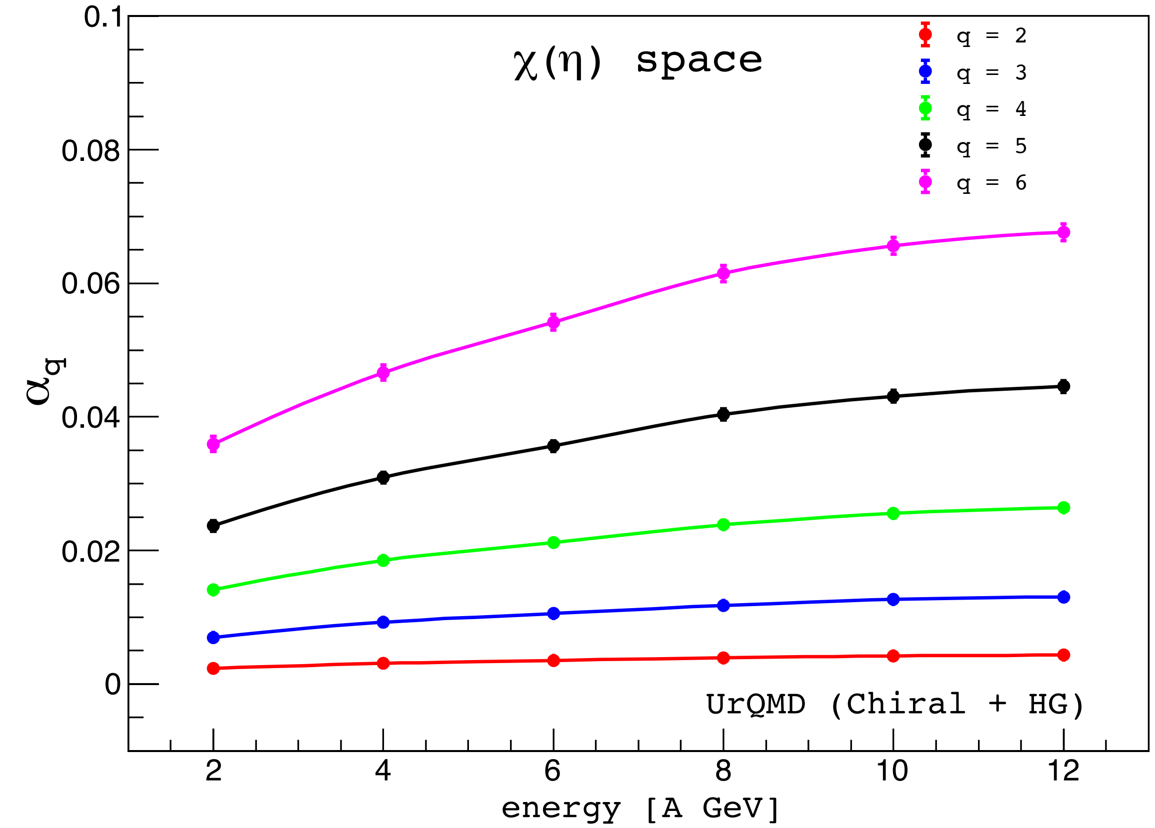
Why Proton now ????

- Protons act as proxies for net-baryon density, reflecting critical fluctuations tied to the chiral condensate.
- Proton detection is experimentally feasible and provides measurable scaling behavior near the critical point.
- Analyzing proton fluctuations offers key insights into QCD phase transitions and the critical point.

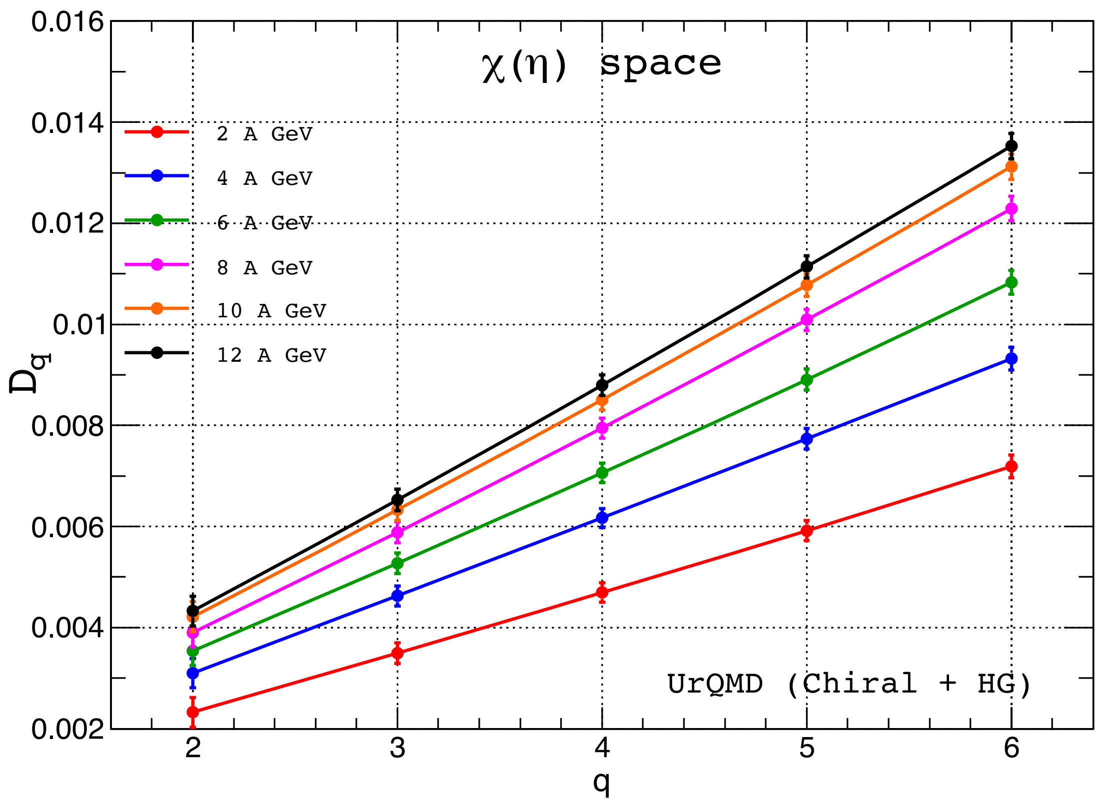
For present Analysis : 0-5% central 50K events of Au+Au at CBM energies (2, 4, 6, 8, 10 and 12 A GeV)

Results : $\chi\{\eta\}$ space

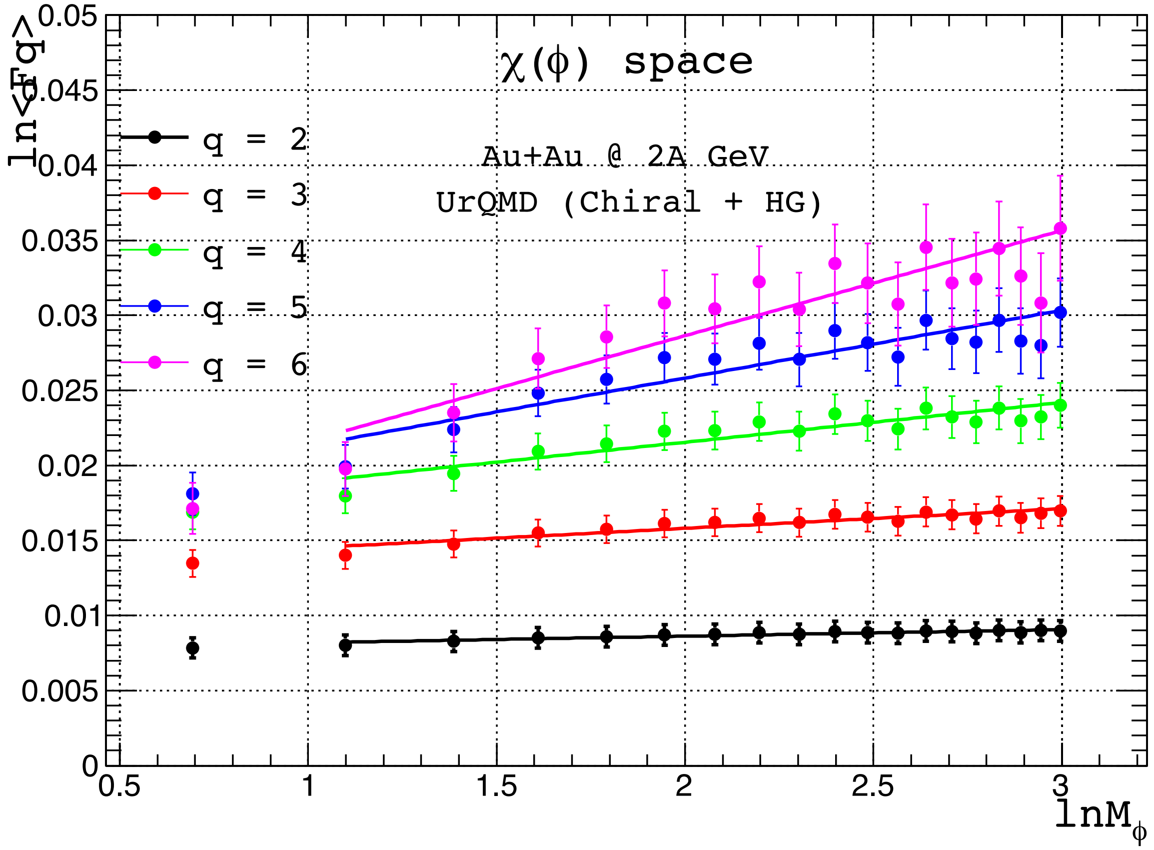


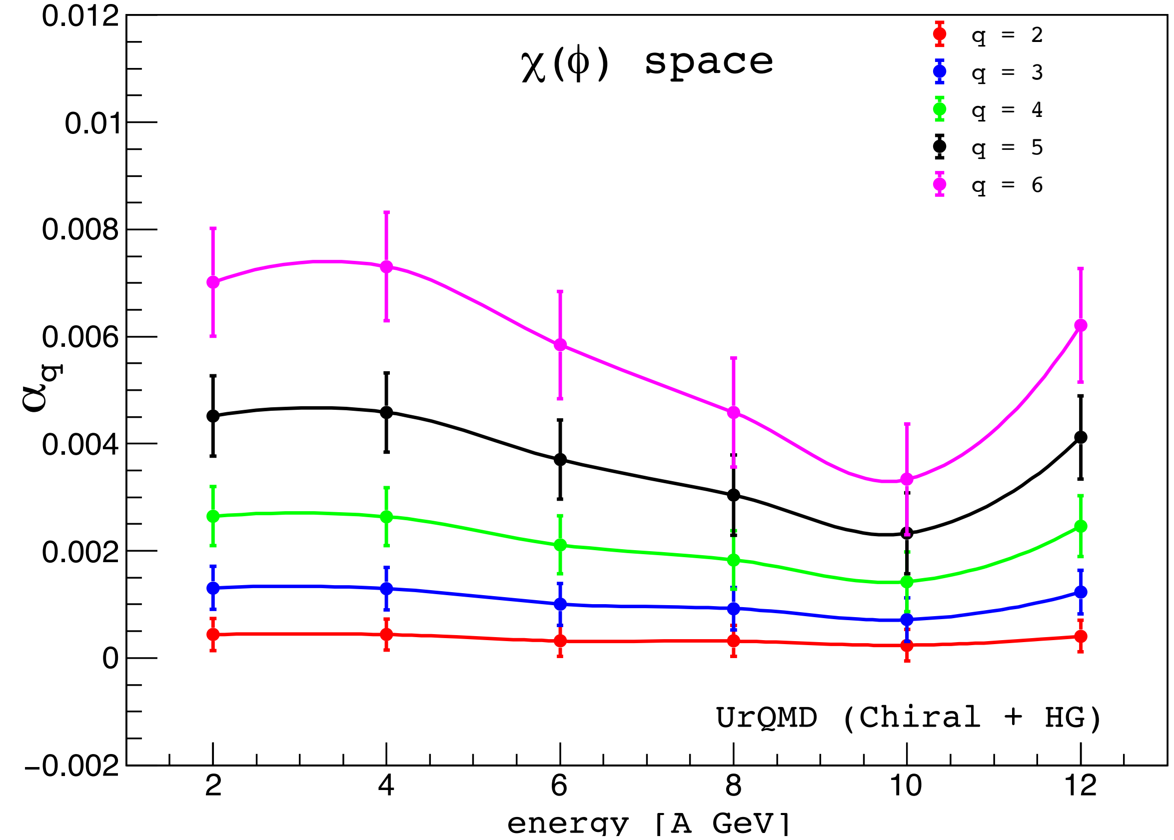


- The linear dependence of ln<F_q> on ln M shows the SFMs follow the power-law scaling behavior that predict an intermittent pattern in non-statistical multiparticle production.
- The intermittency index, α_q, shows an increasing trend with different orders of moments for all energies.
- A significant q dependence of D_q suggests particle production via a self-similar cascade process and as the energy increases D_q increases.

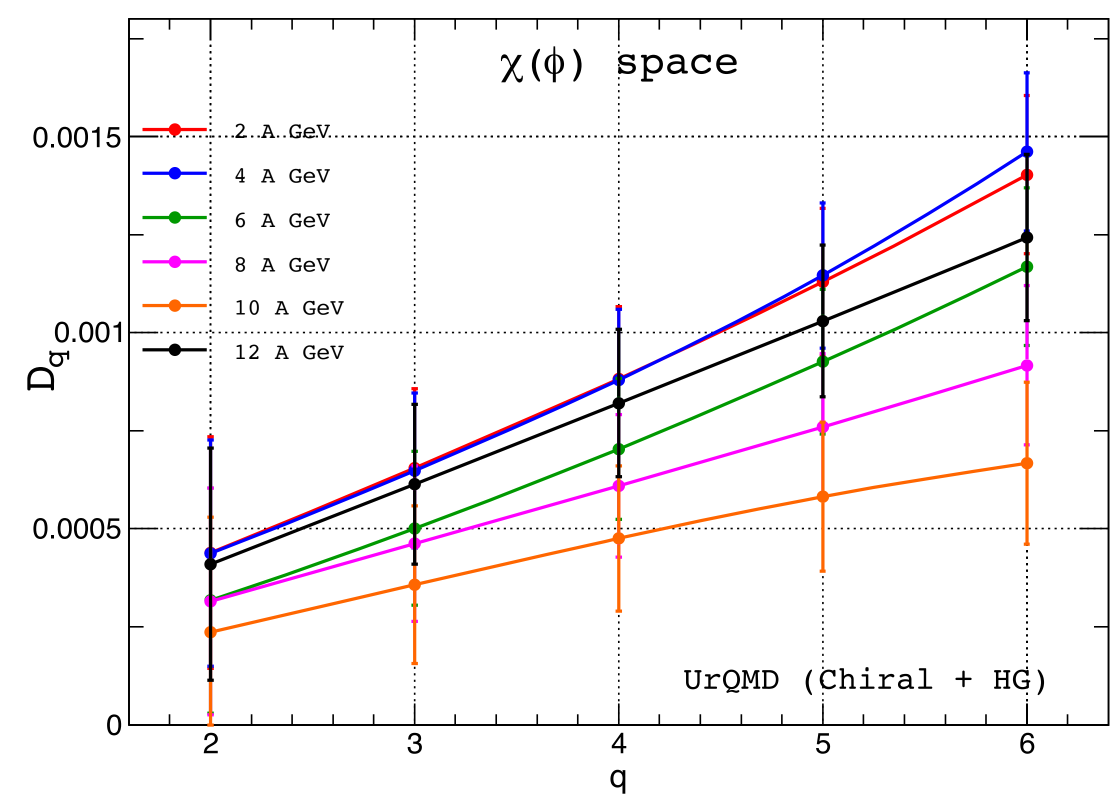


Results : $\chi\{\phi\}$ space

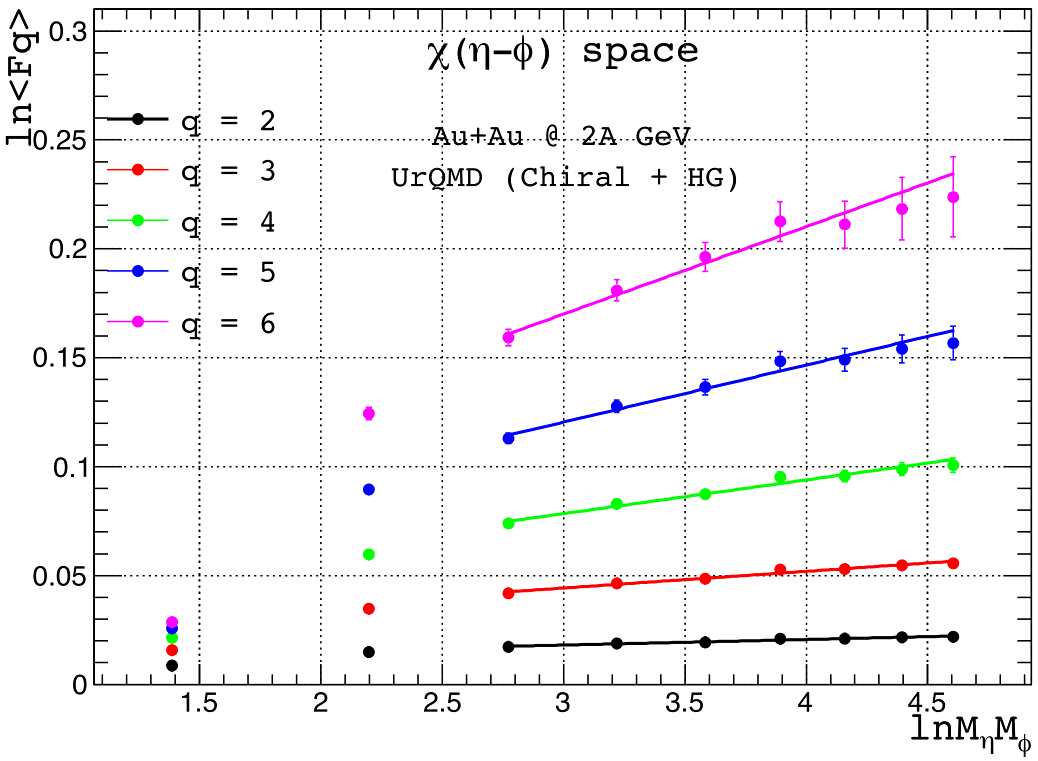


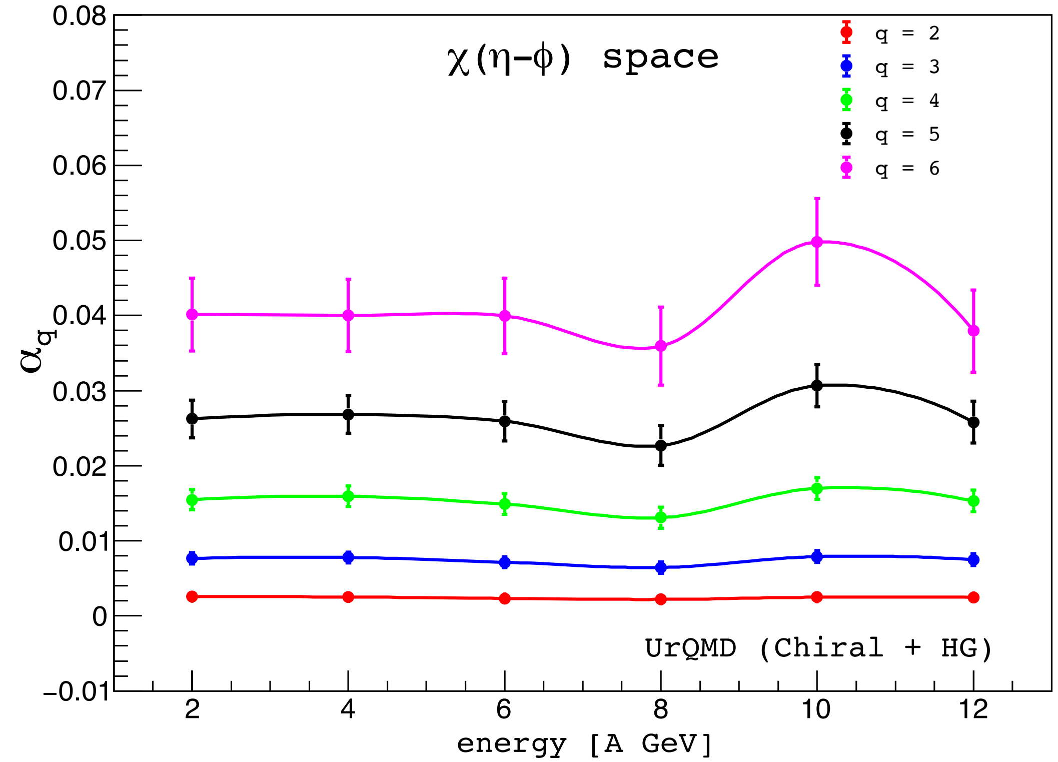


- The power-law scaling behavior is shown similar to $\chi\{\eta\}$ phase space but with increased q scaling is not smooth.
- The intermittency index, α_q, also shows an increasing trend with different q for all energies but a dip around 10 AGeV.
- Again, significant q dependence of D_q suggests particle production via a self-similar cascade process.

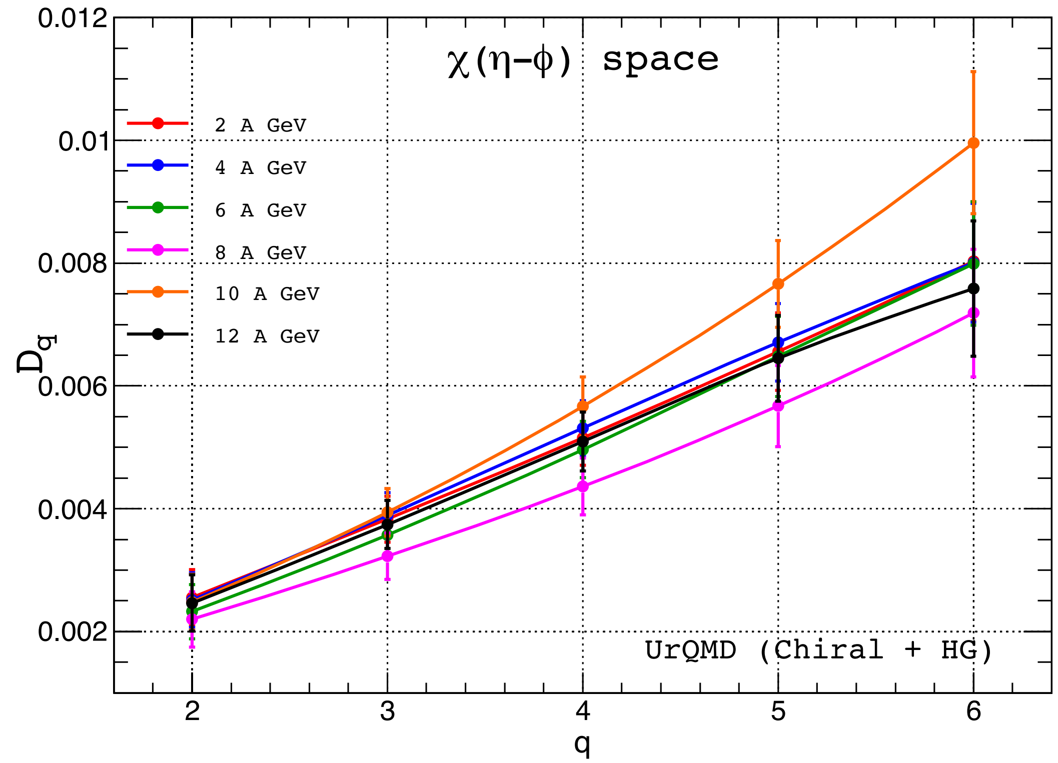


Results : $\chi\{\eta - \phi\}$ space





- The plots for the combined η−φ space exhibit a linear relationship of ln⟨Fq⟩ with lnM, similar to 1D spaces. This confirms that SFMs follow power-law scaling even in 2D, indicating intermittent patterns in particle production.
- The trend of α_q increasing with q is consistent, signifying stronger scale-invariant fluctuations in 2D compared to 1D spaces.
- The significant variation in D_q with q indicates a more complex multifractal behavior in η-φ space. This aligns with the idea of particle production through a self-similar cascade process.



Summary

❖ The study utilized UrQMD-hydro simulations with Chiral + HG EoS to analyze proton intermittency in Au+Au collisions at FAIR energies (2A–12A GeV).

❖ Observed results in 1D (η or ϕ) and 2D (η-ϕ) spaces revealed:

- ✦ Power-law scaling behavior of scaled factorial moments ($\langle F_q \rangle$).
- ✦ Increasing intermittency index (α_q) across different moment orders.
- ✦ Multifractal emission spectra characterized by variations in anomalous fractal dimensions (D_q).

❖ These findings suggest particle production via a cascading process, confirming intermittent patterns.

Future Outlook

Increasing the Statistics: Expand the analysis by incorporating larger datasets to ensure statistical reliability and refine observed trends.
Incorporating Additional Equations of State (EoS): Extend the study to include other EoS such as the Bag model EoS, to comprehensively compare intermittency behavior.

Acknowledgement

- ✦ I would like to express my gratitude to Prof. Sanjay K. Ghosh, Dr. Saikat Biswas and colleagues at Bose Institute, Kolkata, for their invaluable guidance and support.

- ✦ Special thanks to the ATHIC 2025 organizers for providing the platform to present this work.

Thank you for the attention !!!