Probing QCD Critical Fluctuations from Intermittency Analysis in Relativistic Heavy-Ion Collisions

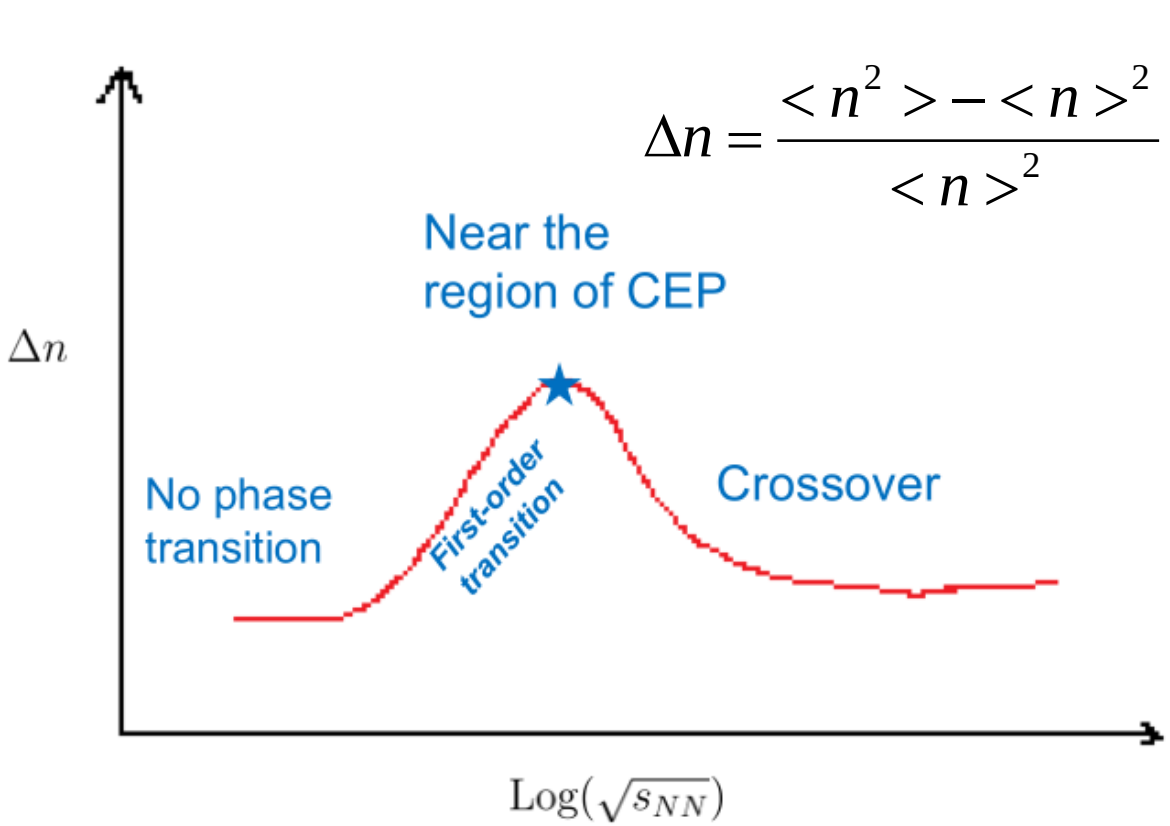
Jin Wu
Central China Normal University
Key Laboratory of Quark and Lepton Physics (MOE)

Collaborators: Yufu Lin, Yuanfang Wu, and Zhiming Li

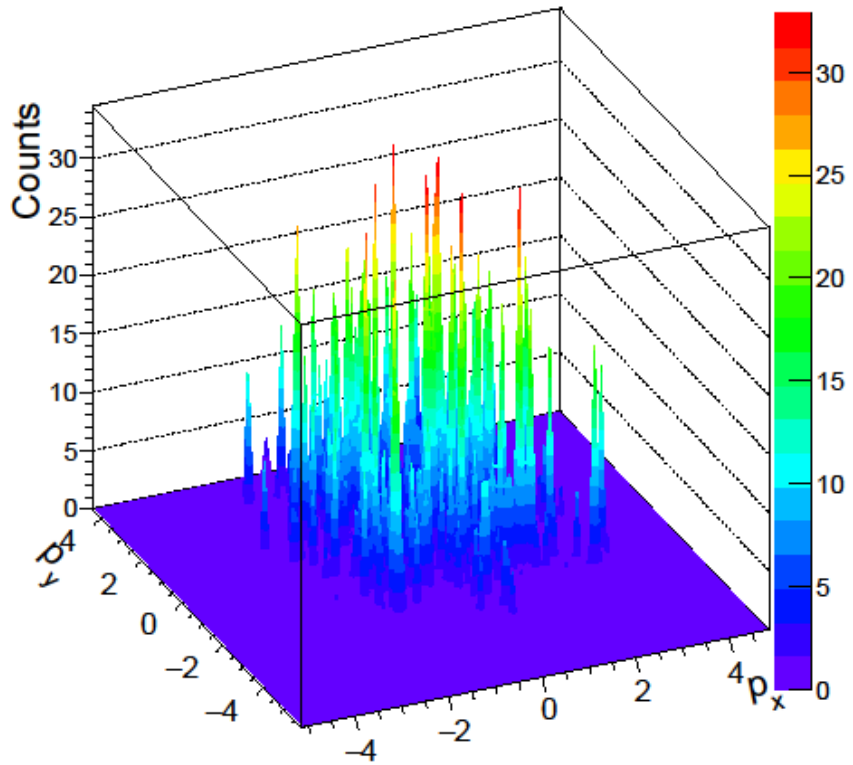
Outline

1 Introduction:Density Fluctuations and CEP

The created matter could develop **strong baryon density fluctuations** in the vicinity of the CEP, and it is argued that the baryon **density fluctuations** at kinetic freeze-out may provide a **unique signal** to the phase transition in the QCD phase diagram.



K. J. Sun, L. W. Chen, et al., Phys. Lett. B 774, 103 (2017); Phys. Lett. B 781, 499 (2018).



Local strong density fluctuations in transverse momentum space by 3D Ising universality-Critical Monte Carlo model

N.G.Antoniou,PRL 97,032002(2006)

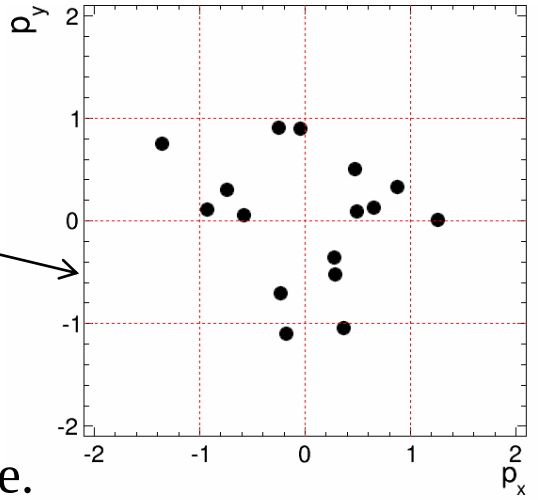
1 Introduction:Scaled Factorial Moment

It is predicted that the local **density fluctuations** near critical point exhibit power law scaling, which can be probed with a **intermittency analysis** of the **scaled factorial moments F_q** .

$$F_q(M) = \frac{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i(n_i-1)...(n_i-q+1) >}{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i >^q}$$

T.Anticic et. al. (NA49 Coll.),Eur.Phys.J.C7,5:587(2015);

Particle multiplicity in the i-th cell, $\mathbf{n_i}$



q is the order of moments, M^D is the number of equally sized cells in D dimension of space.

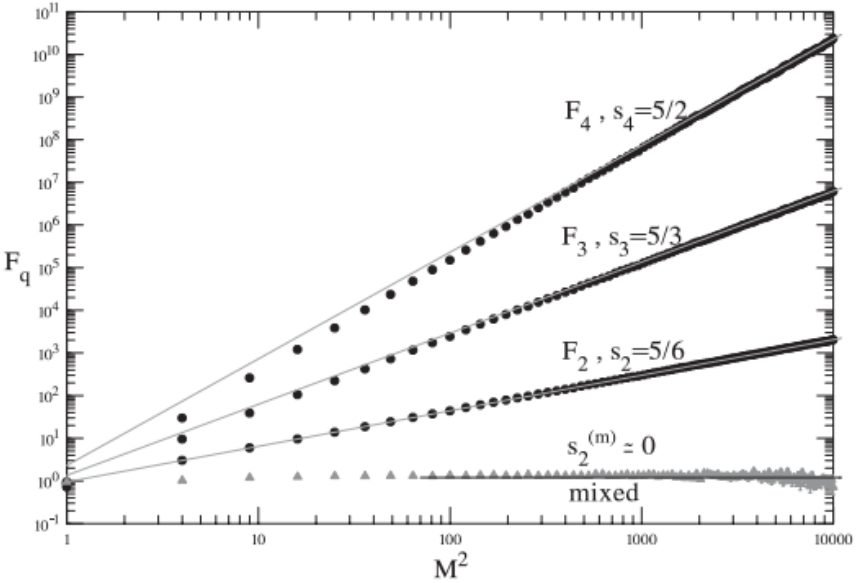
Intermittency refers to the **power law behavior:**

$$F_q(M) \sim (M^2)^{\phi_q}$$ where ϕ_q is **intermittency index.**

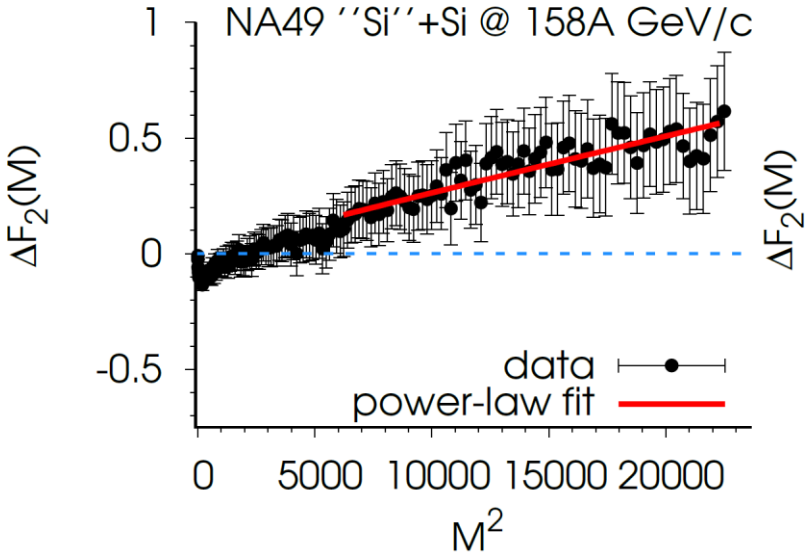
For a pure 3D Ising universality **critical system** :

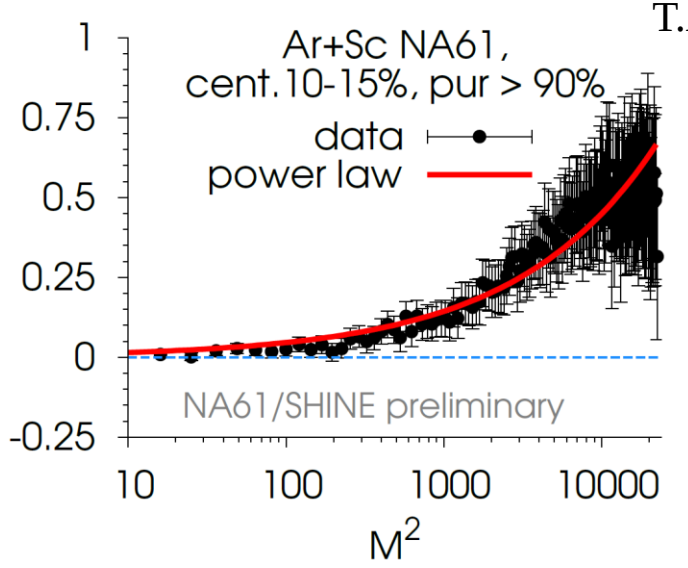
$$F_2(M) \sim (M^2)^{\phi_2} (M \to \infty) \quad \phi_2 \approx 0.833$$

N.G.Antoniou,PRL 97,032002(2006)



1 Intermittency of NA49/NA61 and Nucleon Density Fluctuations of STAR



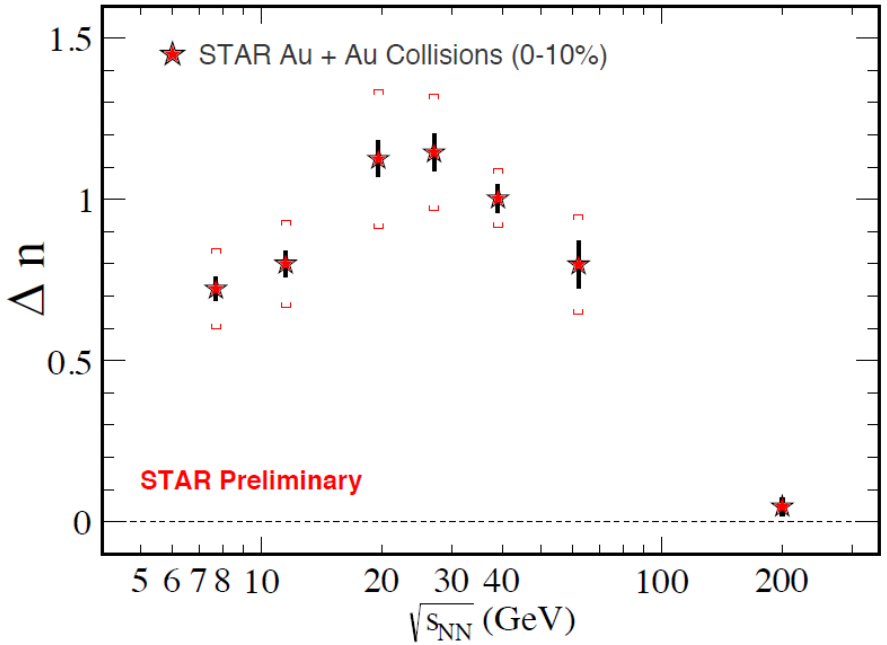


T.Anticic et. al. (NA49 Coll.), Eur.Phys.J.C(2015)75:587

QM2018,N.Davis,N.G.Antoniou et .al.(NA49 Coll.)
D.Prokhorova et.al(NA61 Coll),universe,MDPI

Intermittency of NA49/NA61 experiment revealed significant power-law fluctuations of proton density in Si+Si collisions and Ar+Sc collisions at158AGeV($\sqrt{S_{NN}} = 17.3GeV$)

$$\Delta n = \frac{< n^2 > - < n >^2}{< n >^2}$$



The relative necleon density fluctuation Δn reaches a maximum at collisions energy around 20 GeV in Au+Au collisions

D.W.Zhang et.al.(STAR Coll.) presentation at QM2018.

1 Motivation

- Since baryon density fluctuations and intermittency properties are both sensitive to the QCD critical phenomena, whether there exists a relationship between them.

- We study this issue and try to get the relation based on a critical Monte-Carlo model of the 3D Ising universality class . Moreover, from analyzing the experimental results on the baryon density fluctuations at STAR BES I energies, we obtain the energy dependence of intermittency index , and compare it with the results from the transport UrQMD model.

arXiv:1901.1191v1[nul-th]

2 Critical Monte-Carlo(CMC) Model

For a pure **3D Ising universality critical** system, the density-density correlator for a small transverse momentum transfer κ obeys a power law:

$$< \rho_{\vec{k}} \rho^{*}_{\vec{k}} > \sim | \vec{k} |^{-d_F} \qquad (1)$$

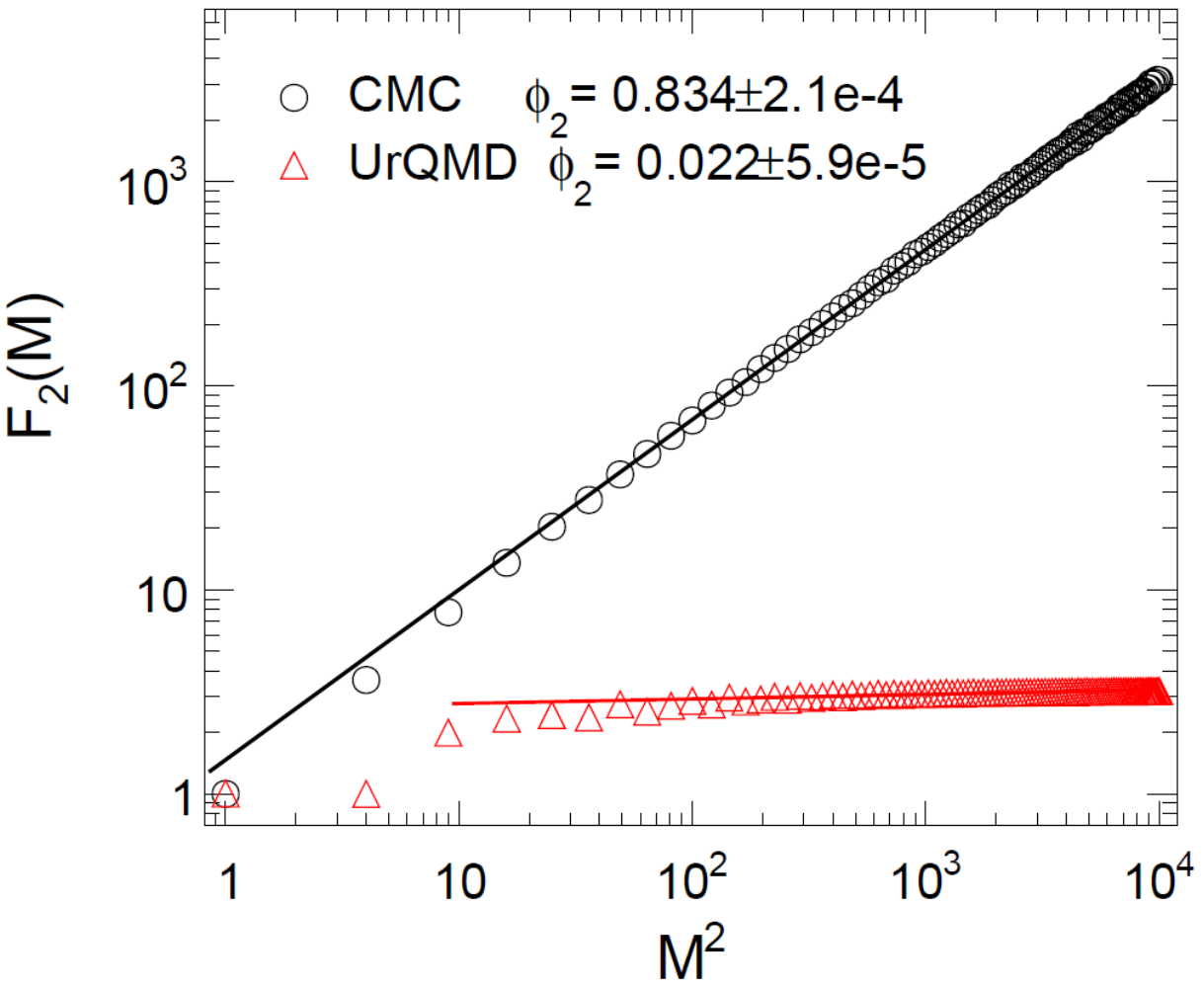
N.G.Antoniou,PRL 97,032002(2006)

In order to make the CMC sample involve the critical fluctuations according to the power law of Eq(1), a Levy random walk method is proposed to produce the momentum of the final state particles, with the probability density between two adjacent walk (Levy function) :

$$\rho(p) = \frac{\nu \; p_{\min}^{\nu}}{1-(p_{\min} / p_{\max})^{\nu}} \, p^{-1-\nu}$$

where p is the momentum distance of two particles, ν is Levy index .The model parameters can be set to ν=1/6, $p_{mix}/p_{max}=10^{-7}$ for the 3D Ising universality with the second intermittency index ϕ_2 =5/6.

3 Result: Intermittency in the 3D Ising CMC Model



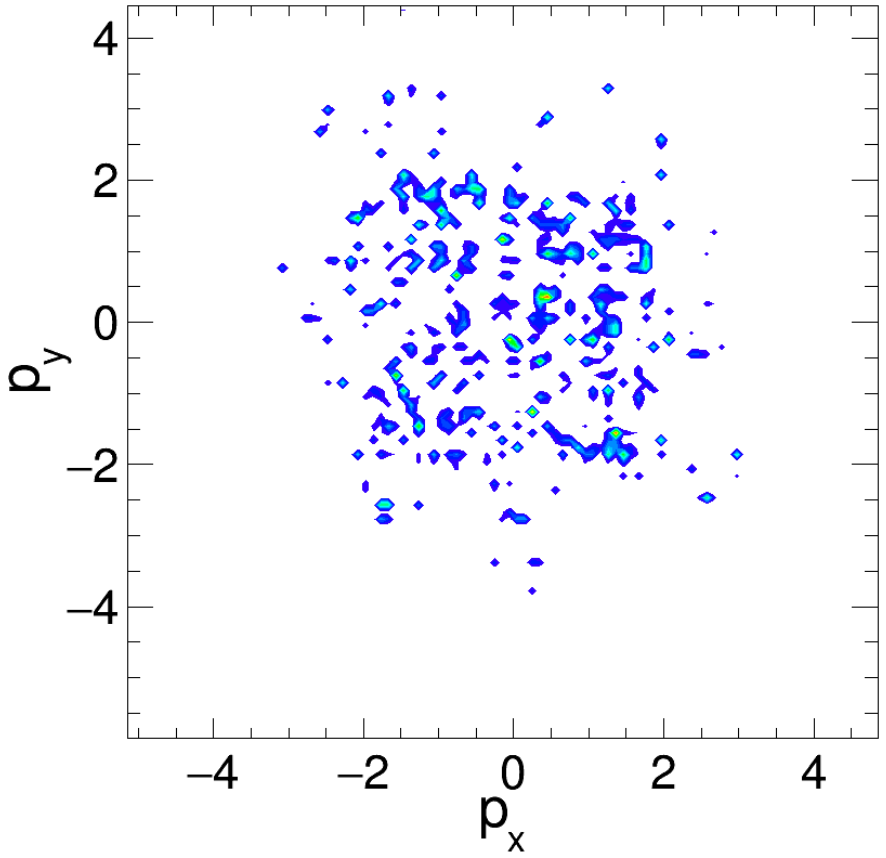
Log-log plot $F_2(M) \sim (\mathrm{M}^2)^{\phi_2}, \ M \to \infty$

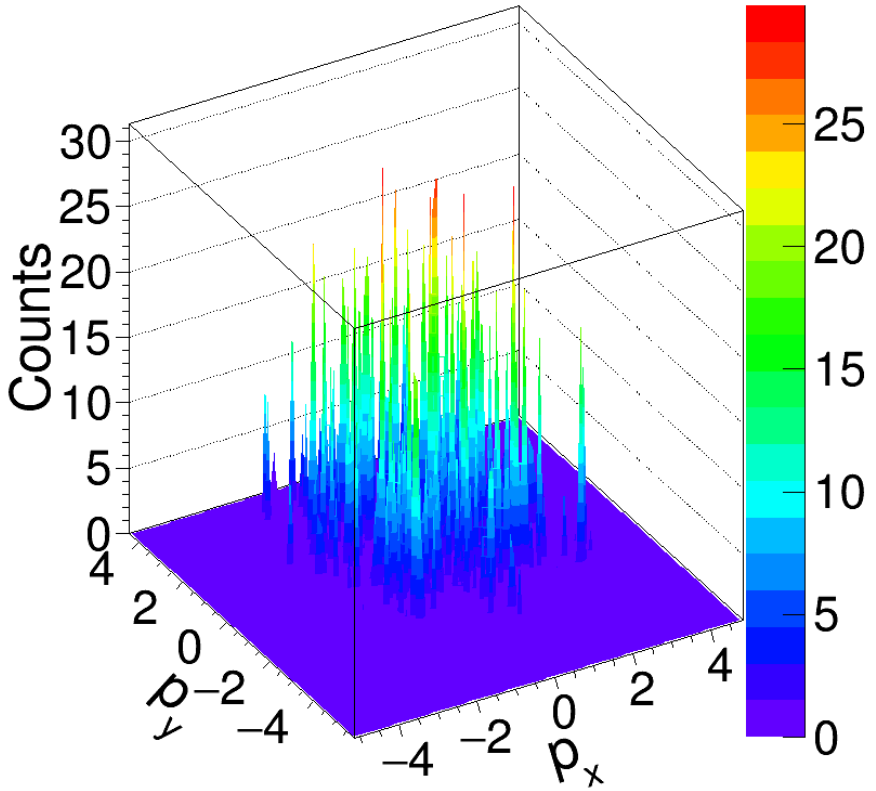
An ensemble of 600 critical events is generated by CMC model.

- The F_2 follow a good power-law behavior with the increasing number bins M^2 , which confirms that the CMC model includes the giant density fluctuations. The fitting slope is consistent with the theoretic expectation ϕ_2 =5/6.

- The F_2 are found to be nearly flat in various binning M^2 in UrQMD model, with the second intermittency index is around 0 .

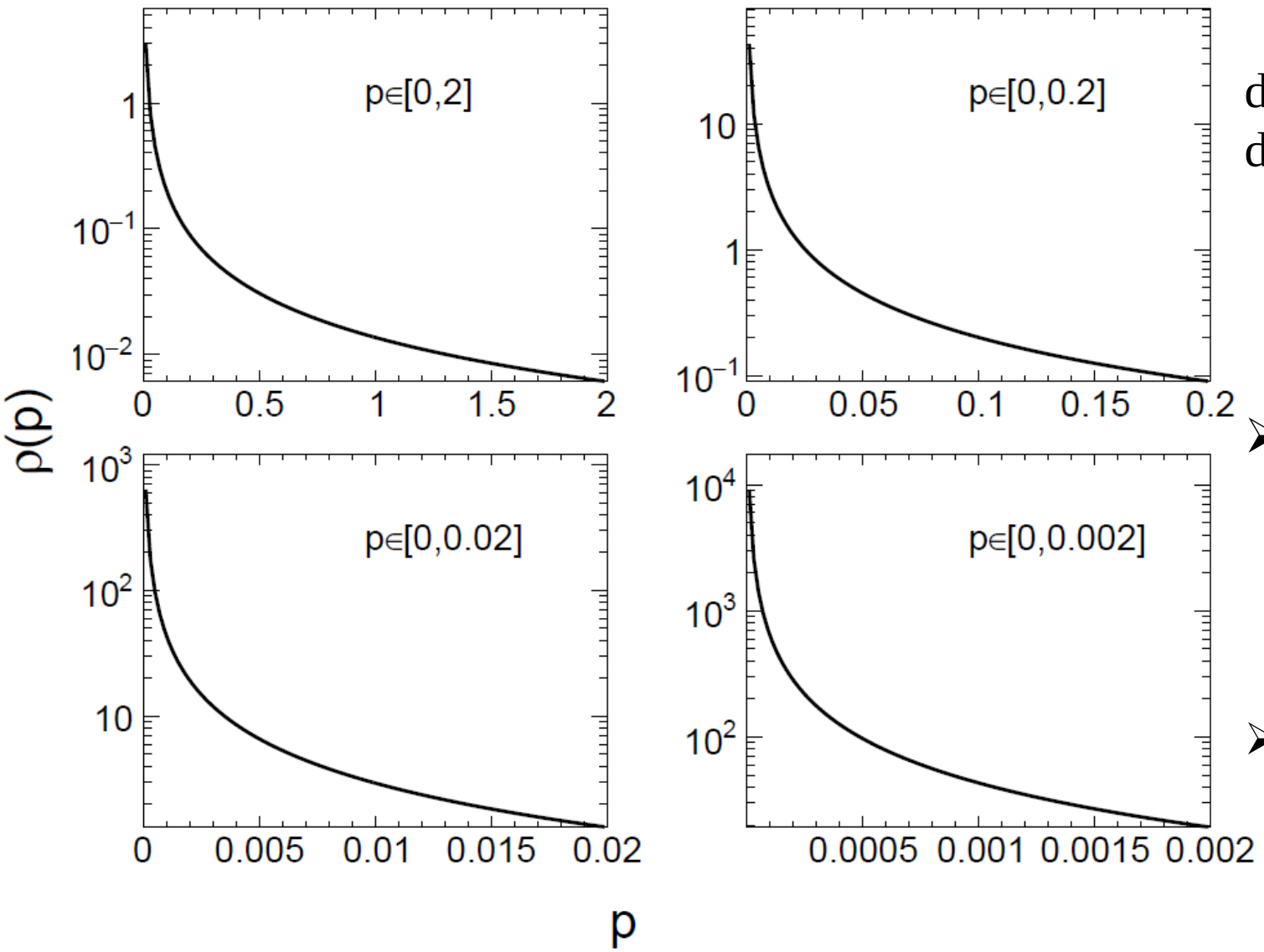
3 Result: Density Fluctuations and Self-Similar Correlations





Large density fluctuation is found in the 2D momentum space . The observed large density fluctuations are probes of critical system belong to the Ising universality class, also are suggested to be manifestation of intermittency.

3 Result: Density Fluctuations and Self-Similar Correlations

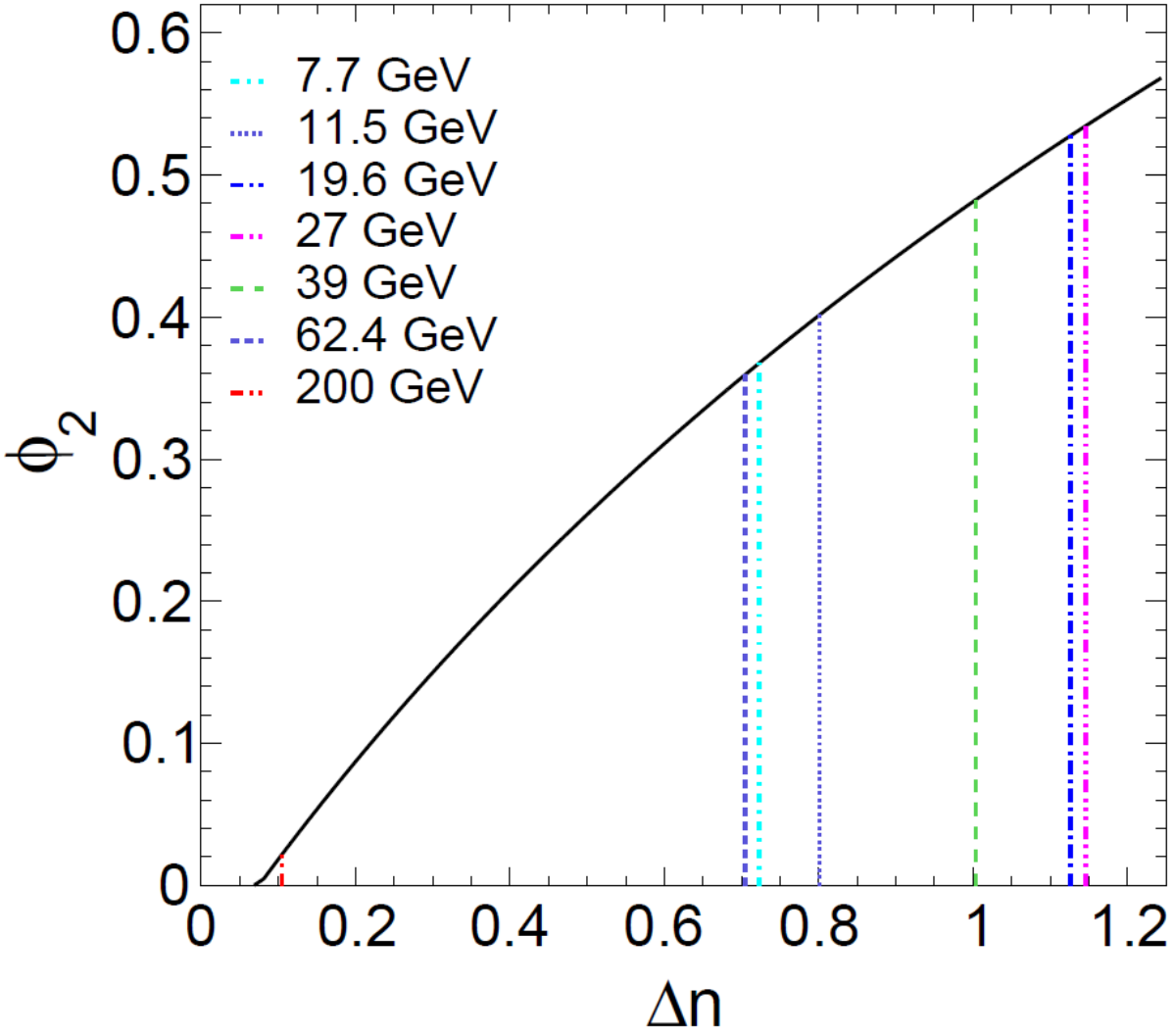


In the CMC model, the probability density distribution of two-particles with distance p in momentum space is given by

$$\rho(p) = \frac{\nu\ p_{\min}^{\nu}}{1-(p_{\min}\ /\ p_{\max})^{\nu}}\ p^{-1-\nu}$$

- The curves look the same at every level of magnification, ie. scale invariant . It is a typical character of a self-similar fractal system.
- The self-similar or intermittency nature of particle correlations is closely related to the large baryon density fluctuations in CMC model.

3 Result: Relation Between Intermittency Index and Relative Density Fluctuation



The relative density fluctuations is defined as:

$$\Delta n = \frac{<(\delta n)^2>}{<n>^2} = \frac{<n^2> - <n>^2}{<n>^2}$$

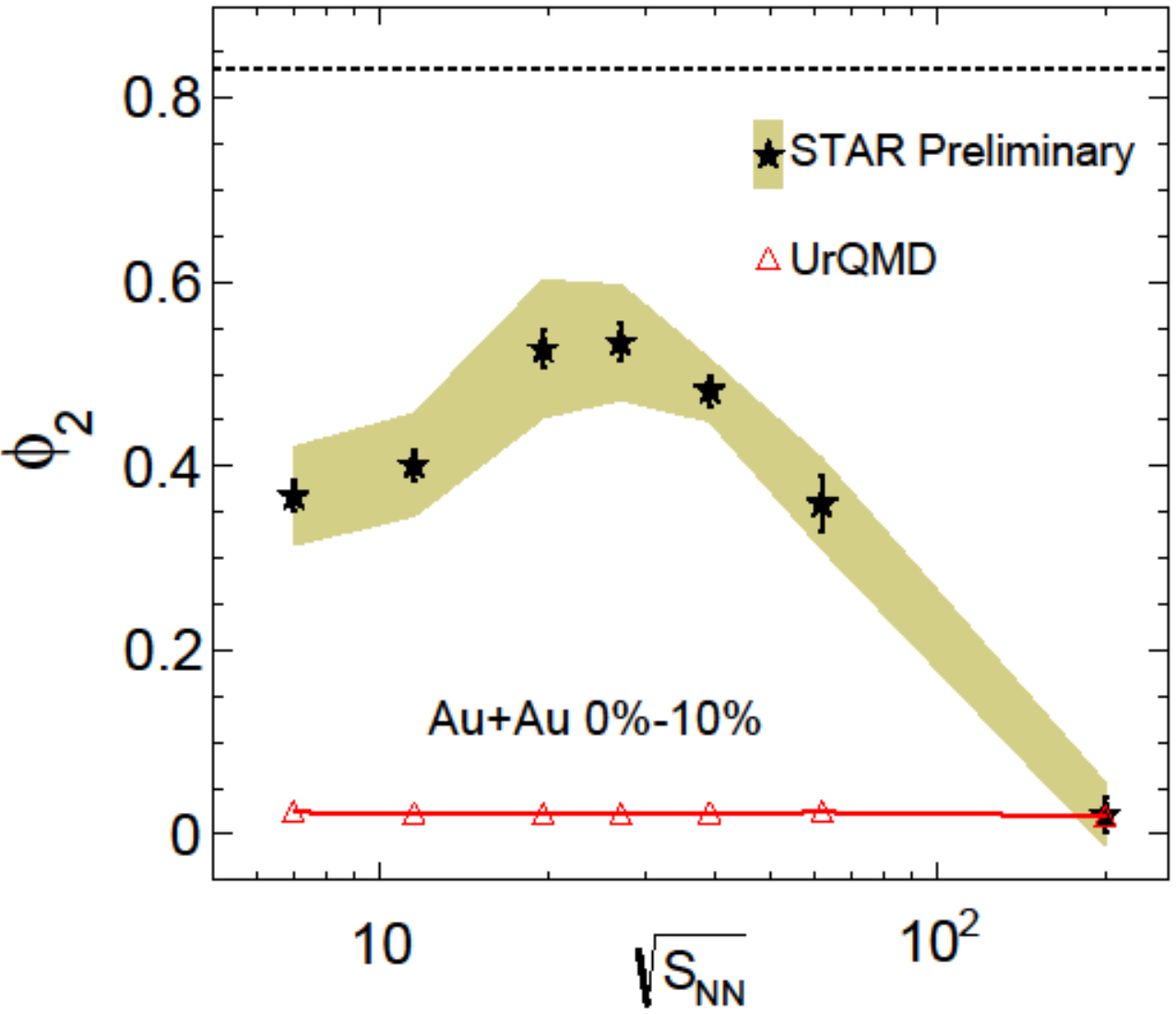
- The second-order intermittency index is found to be **monotonically increased** with increasing relative density fluctuation.

- Large intermittency is expected if giant baryon density fluctuations are developed near QCD critical region.

$$\sqrt{S_{NN}} \rightarrow \Delta n \rightarrow \phi_2$$

The dash lines display the values of relative density fluctuations measured by RHIC/SATR collaboration. D.W.Zhang et.al.(STAR Coll.) presentation at QM2018

3 Result: Energy Dependence of Intermittency Index



$$\sqrt{S_{NN}} \rightarrow \Delta n \rightarrow \phi_2$$

- The second-order intermittency index gained indirectly by mapping the relative density fluctuations ϕ_2 into the relation between Δn and
- The indirect energy dependence of ϕ_2 displays a **non-monotonic behavior** with a peak at energy around 20-27GeV, indicating that the strength of intermittency becomes the largest in this region.
- The results of UrQMD show a **flat trend** with the values of ϕ_2 **around 0** at all energies, the non-monotonic behavior cannot be described by the UrQMD model without implementing critical physics

4 Conclusion and Outlook

- With a 3D Ising universality class CMC model, we have demonstrated that large baryon density fluctuations are observed in transverse momentum space. Moreover, the self-similar or intermittency nature of particle correlations is closely related to this large baryon density fluctuations.

- The ϕ_2 is found to be monotonically increased with increasing relative density fluctuation Δn , therefore, large intermittency is expected if giant baryon density fluctuations are developed near QCD critical region.

- The extracted intermittency indices from the density fluctuations measured by STAR at RHIC BES I energies exhibits a non-monotonic energy dependence with a peak at around 20-27GeV.

- The intermittency indices are around 0 at all energies from UrQMD model, the non-monotonic behavior cannot be described by the UrQMD model without implementing critical physics.

Outlook:

We are directly measuring the intermittency in Au+Au collisions at $\sqrt{S_{NN}}$ = 7.7-200 GeV from STAR.

arXiv:1901.1191v1[nul-th]