Intermittency analysis of proton numbers in heavy-ion collisions at RHIC energies

arXiv: 2104.11524 (2021)
Phys. Lett. B, 801, 135186 (2020)

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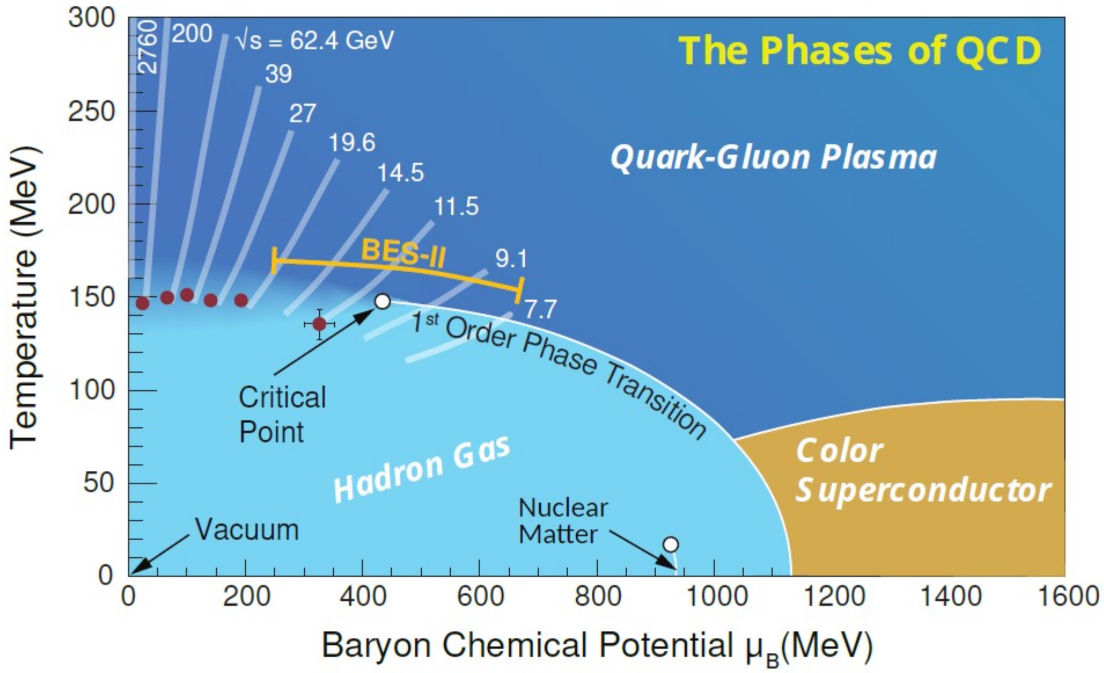
Outline

- Motivation
- Energy and centrality dependence of scaled factorial moment (SFM) from UrQMD model
- Background subtraction
- Efficiency correction
- Summary and outlook

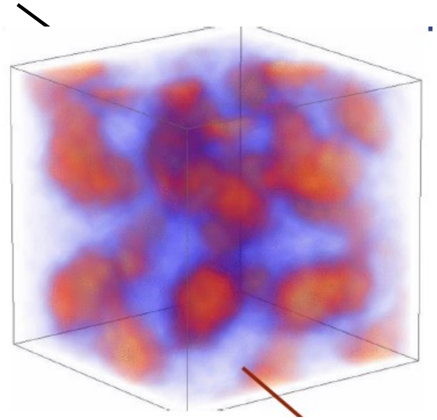
Phase diagram of QCD



Physics Reports, 853, 1–87 (2020)

CP observables:

- Event-by-event (global) fluctuations: Variance, Skewness, Kurtosis.
- Light nuclei production.
- Local density fluctuation (cluster): Intermittency (self-similar behavior)
- ...



PRL 97,032002(2006), PLB 801, 135186(2020)

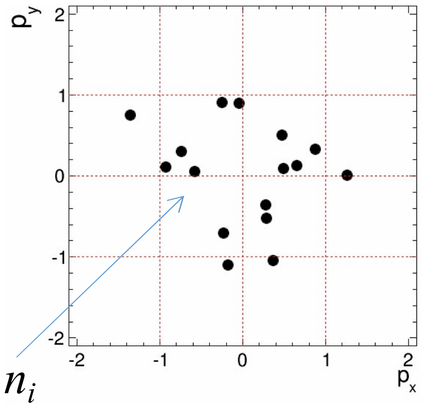
Goal: exploring the QCD phase diagram and Critical Point.

Intermittency

- Measurement of the scaled factorial moments $F_q(M)$, $F_q(M)$ is defined as:

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

Transverse momentum space is partitioned into M^2 cells, q is the order of moments, < > denotes averaging over events.



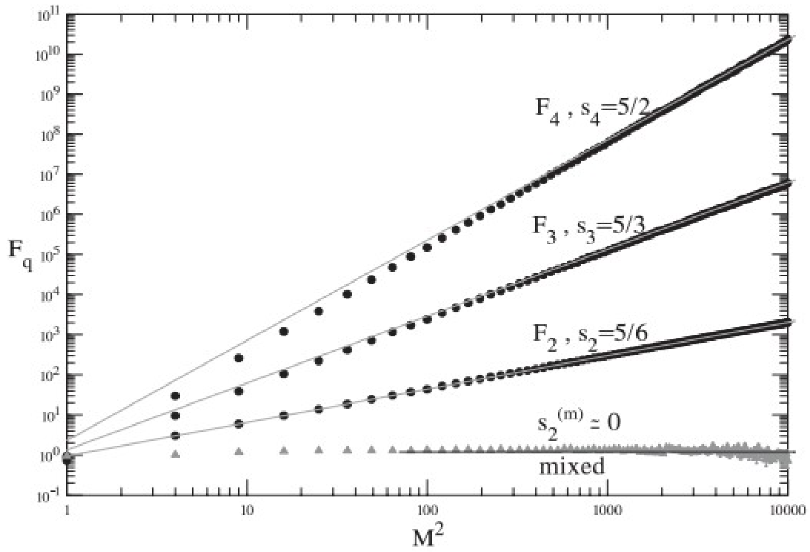
Particle multiplicity in the *i-th* cell n_i

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

$$F_q(M) \sim (M^D)^{\phi_q}, M \to \infty$$

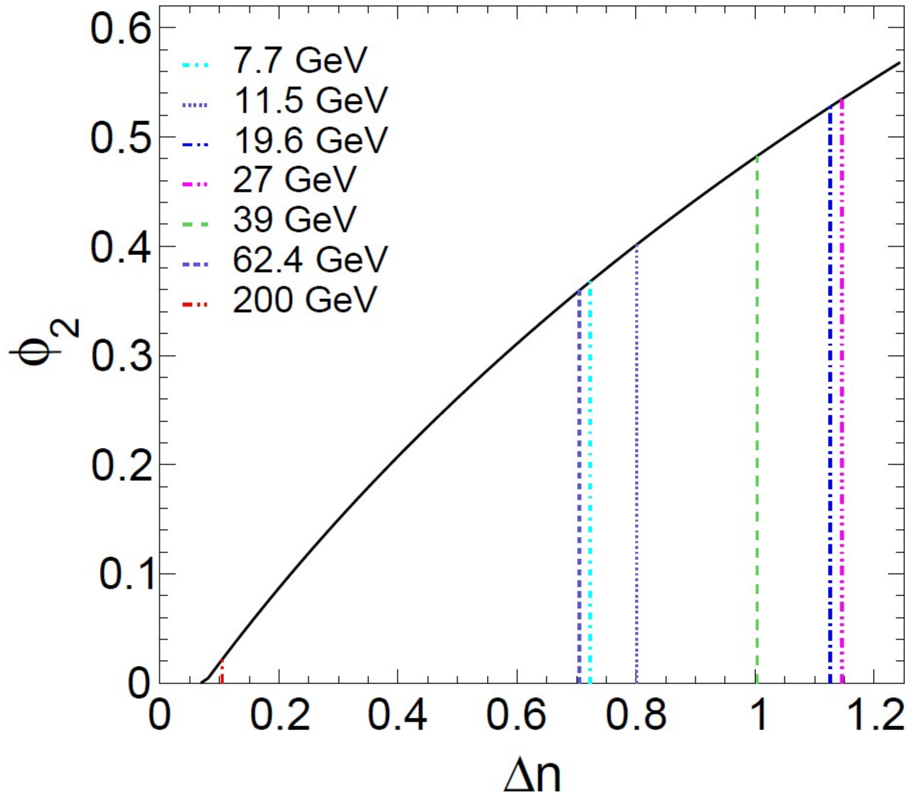
- For a critical system of the 3D Ising universality class:

$$F_2(M) \sim (M^2)^{\phi_{2,critical}} \quad , \quad \phi_{2,\ critical}^{Baryon} = \frac{5}{6}$$



PRL 97,032002(2006), Eur Phys.J.C7,5:587(2015)

Intermittency and relative density fluctuation

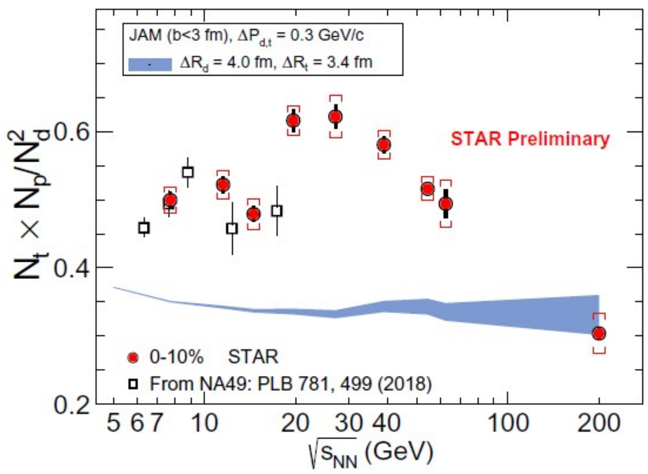


PLB 801, 135186(2020)

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

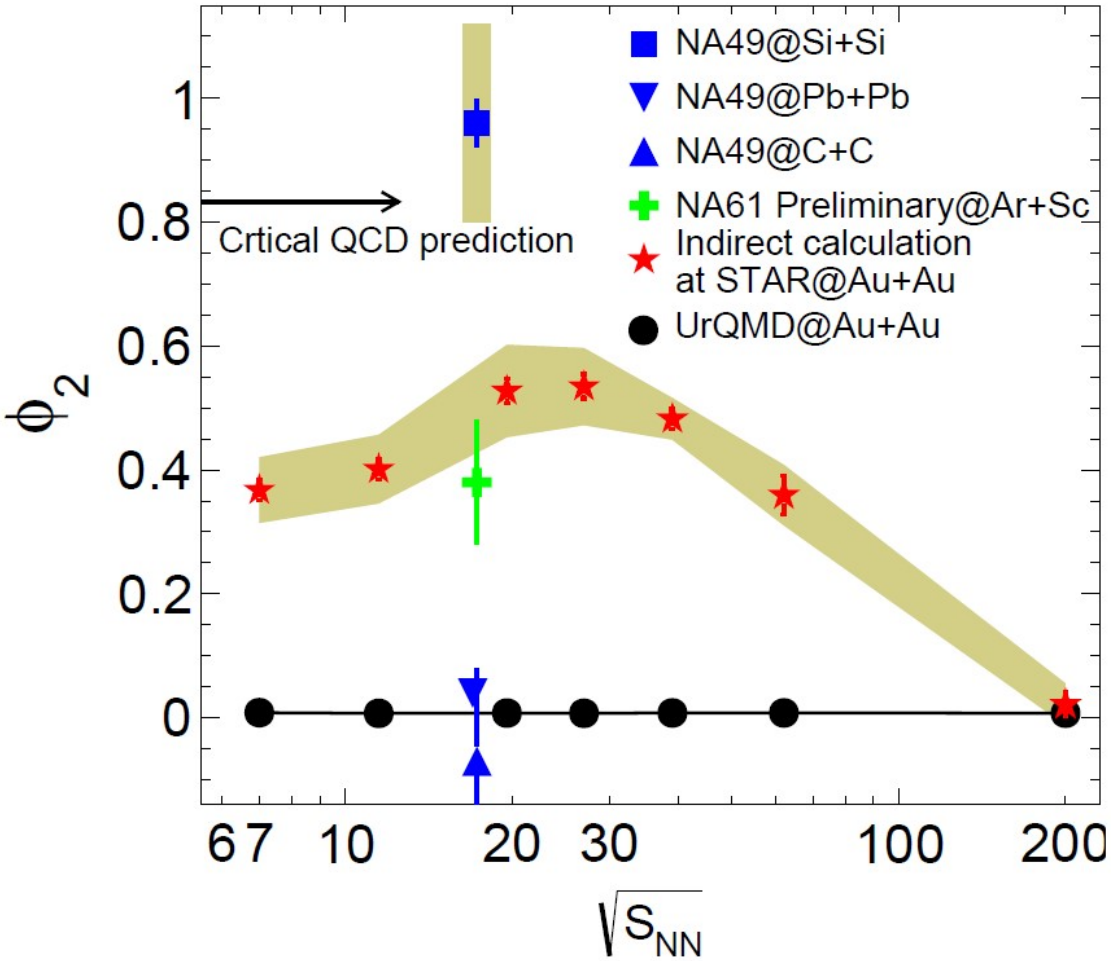


The dash lines display Δn measured by SATR

$$(N_t \times N_p)/N_d^2 = g(1 + \Delta n)$$

D.W, Zhang(STAR Coll.), NPA1005,12185(2021).

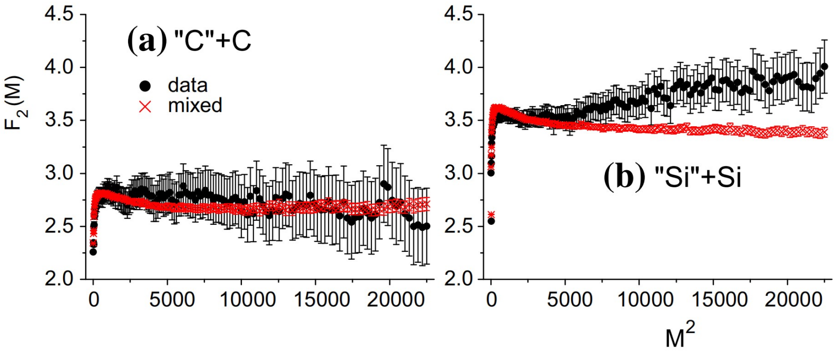
Indirect mapping of intermittency in RHIC/STAR experiment

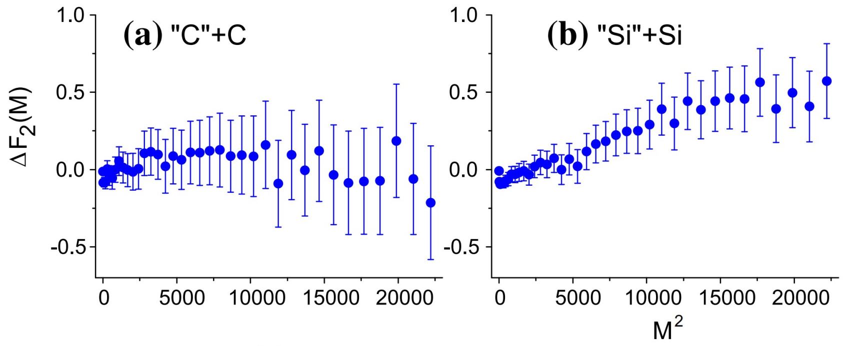


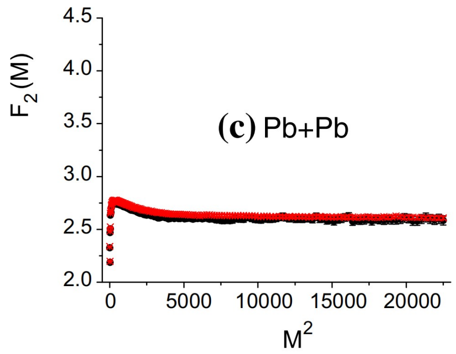
- The second-order intermittency index gained indirectly by mapping the relative density fluctuations into the relation between Δn and ϕ_2.
- The energy dependence of ϕ_2 displays a non-monotonic behavior with a peak at energy around 20-27GeV, indicating that the strength of intermittency becomes the largest in this region.
- The calculations from UrQMD show a flat trend with ϕ_2 around 0 at $\sqrt{s_{NN}}$ = 7.7 – 200GeV .

PLB 801, 135186(2020)

Intermittency in NA49 experiment

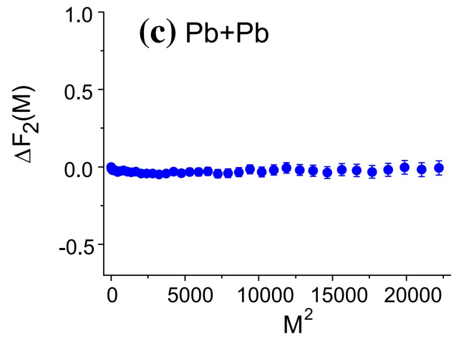






$$\Delta F_2^{(e)}(M) = F_2^{(d)}(M) - F_2^{(m)}(M)$$

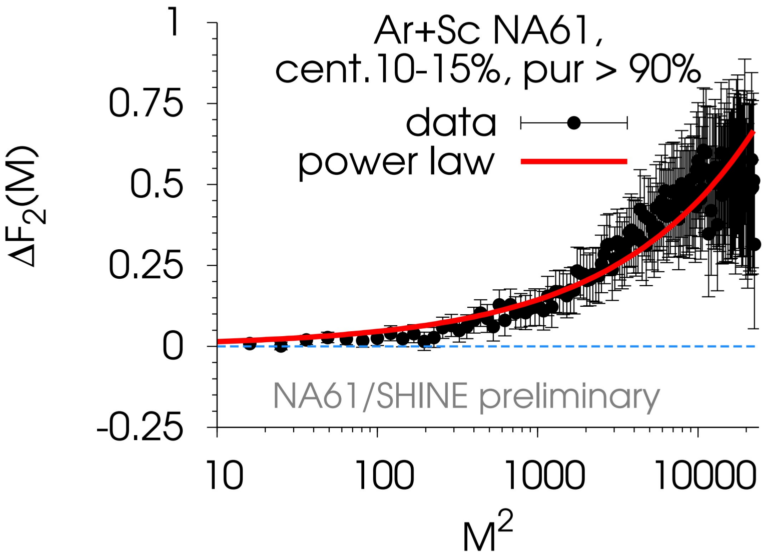
N. Davis, et .al. (NA49 Coll.), QM2018; T. Anticic, et. al. (NA49 Coll.), Eur. Phys. J. C 75: 587 (2015).



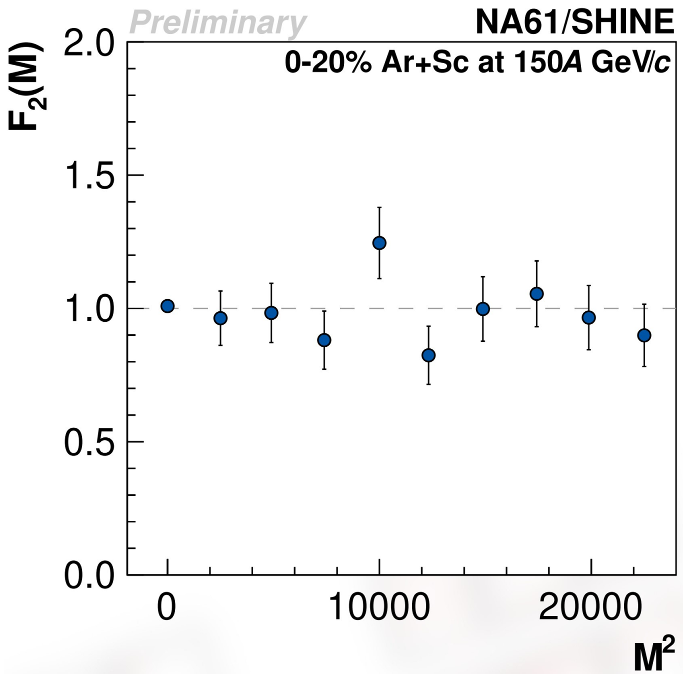
$$\phi_2 = 0.96^{+0.38}_{-0.25}\ (\text{stat.}) \pm 0.16\ (\text{syst.})$$

- Intermittency of NA49 experiment revealed significant power-law fluctuations of proton density in **Si + Si** collisions at $\sqrt{s_{NN}}$ = 17.3 GeV. And no intermittent behavior is visible in **Pb + Pb** collisions and **C+C** collisions.
- NA49 use the mixed event method to estimate and subtract background by assuming that the particle multiplicity in each cell can be simply divided into background and critical contributions.

Intermittency in NA61/SHINE experiment



N. Davis, et .al. (NA61/SHINE Coll.), CPOD2018; Universe 2019, 5, 103.

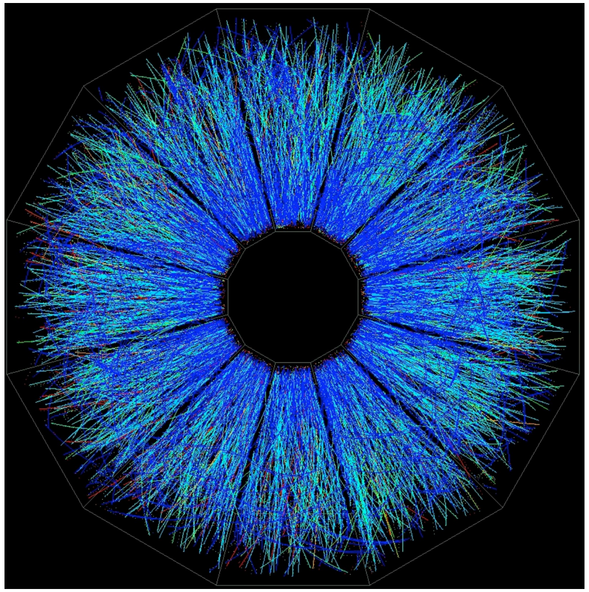


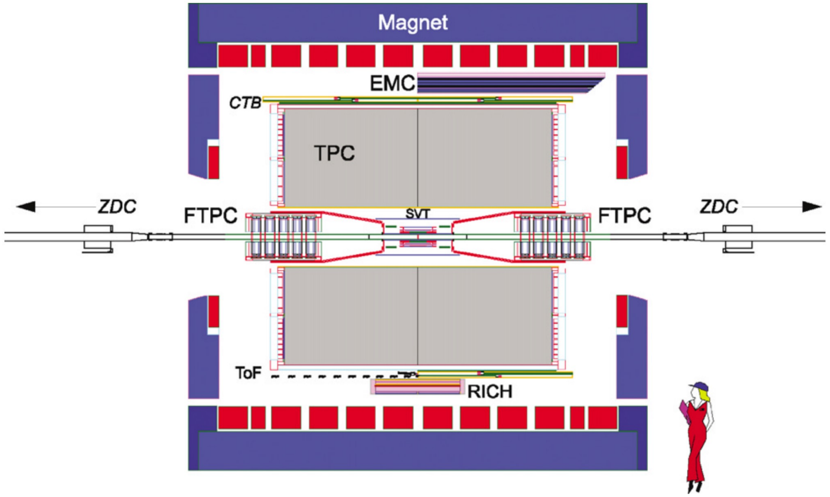
T. Czopowicz (NA61/SHINE Coll.), CPOD2021.

$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M) \sim (M^2)^{\phi_2}$$

- Preliminary NA61/SHINE result at CPOD2018 exhibit power-law scaling of $\Delta F_2(M)$ of proton density for **Ar + Sc** collisions at 150*A* GeV/c.
- New NA61/SHINE result at CPOD2021, which is with statistically independent points and cumulative variables, show no indication for a power-law increase.

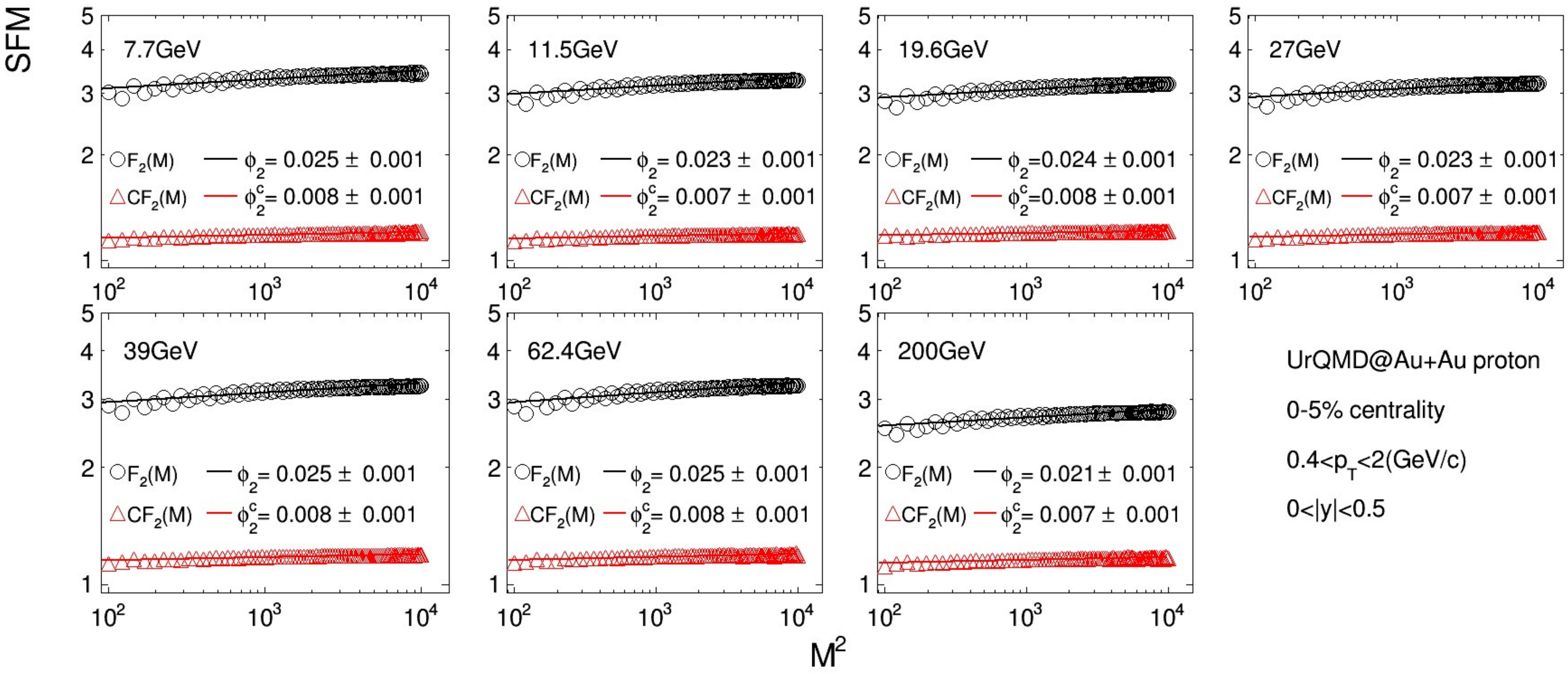
Two important issues for measuring intermittency





- **Background subtraction:** the non-critical background will change the inclusive single-particle multiplicity distributions in the measured finite momentum space
- **Experimental detector efficiency correction:** not all particles are detected, some leave the detector without any trace (neutrinos), some escape through not sensitive detector areas (holes, cracks for e.g. water cooling and gas pipes, electronics, mechanics)

Energy dependence of SFM from UrQMD model

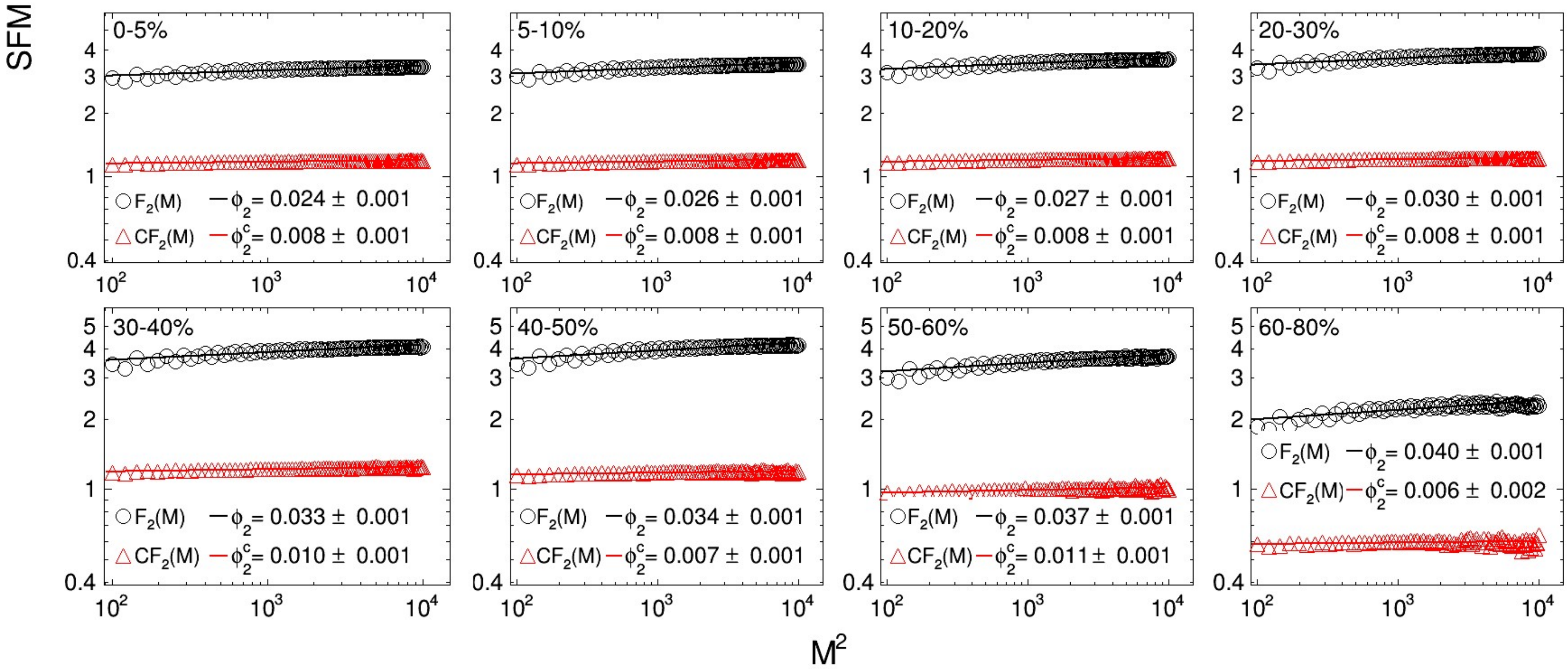


- SFM increases slowly with increasing number of dividing bins

$$F_2(M) \sim (M^2)^{\phi_2}$$

- The slopes of the fitting, *i.e.* the intermittency indices ϕ_2, are found to be small at all energies.

Centrality dependence of SFM from UrQMD model



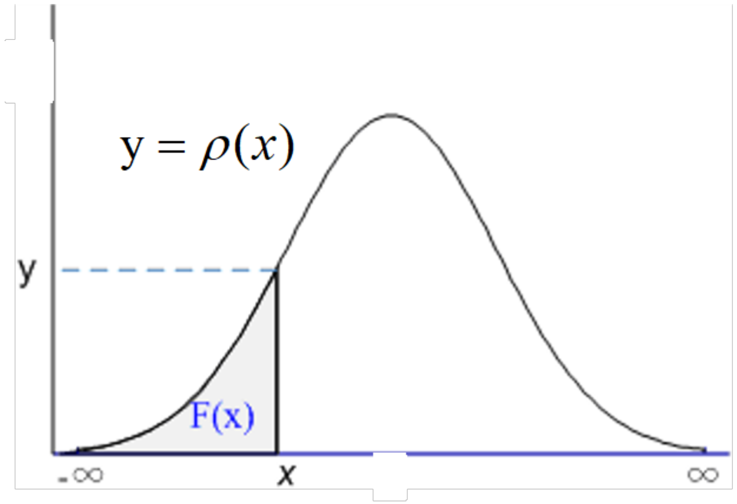
- The directly calculated SFMs can be fitted with a small but non-zero intermittency index.
- The values of ϕ_2 increase slightly from the most central (0−5%) to the most peripheral (60 − 80%) collisions.

Background subtraction

- Following Ochs and Bialas, the cumulative variable $X(x)$ is related to the single-particle density distribution $\rho(x)$ through:

$$X(x) = \frac{\int_{x_{min}}^{x} \rho(x)dx}{\int_{x_{min}}^{x_{max}} \rho(x)dx}$$

Phys. Lett. B 214, 617 (1988);
Phys. Lett. B 247, 101 (1990);
Z. Phys. C 50, 339 (1991);
Phys. Lett. B 252,483 (1990)



Instead of using p_x and p_y, one can use cumulative variables P_X and P_Y

$$P_X = \frac{\int_{p_{x,min}}^{p_x} \rho(p_x)dp_x}{\int_{p_{x,min}}^{p_{x,max}} \rho(p_x)dp_x} \qquad P_Y = \frac{\int_{p_{y,min}}^{p_y} \rho(p_y)dp_y}{\int_{p_{y,min}}^{p_{y,max}} \rho(p_y)dp_y}$$

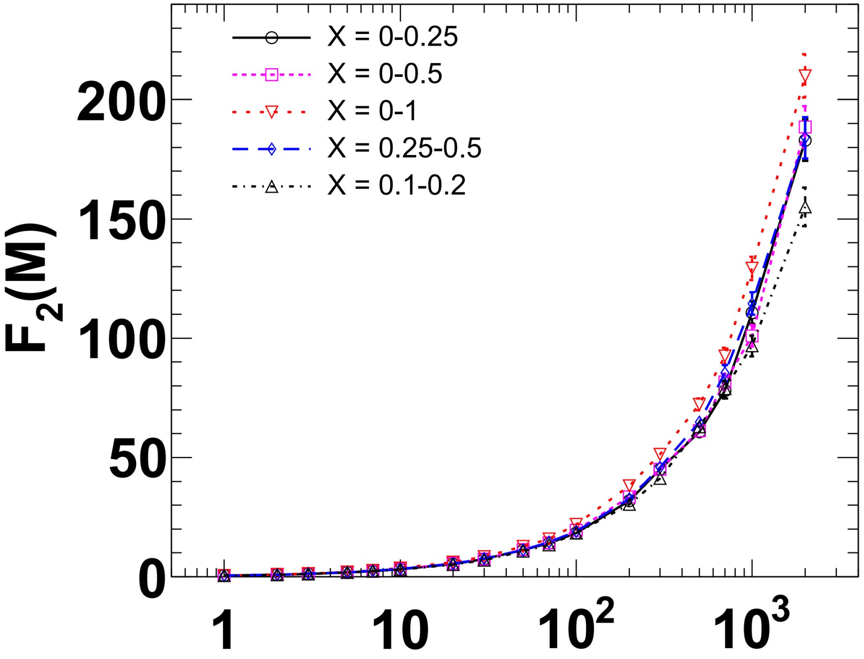
Advantages of cumulative variable:

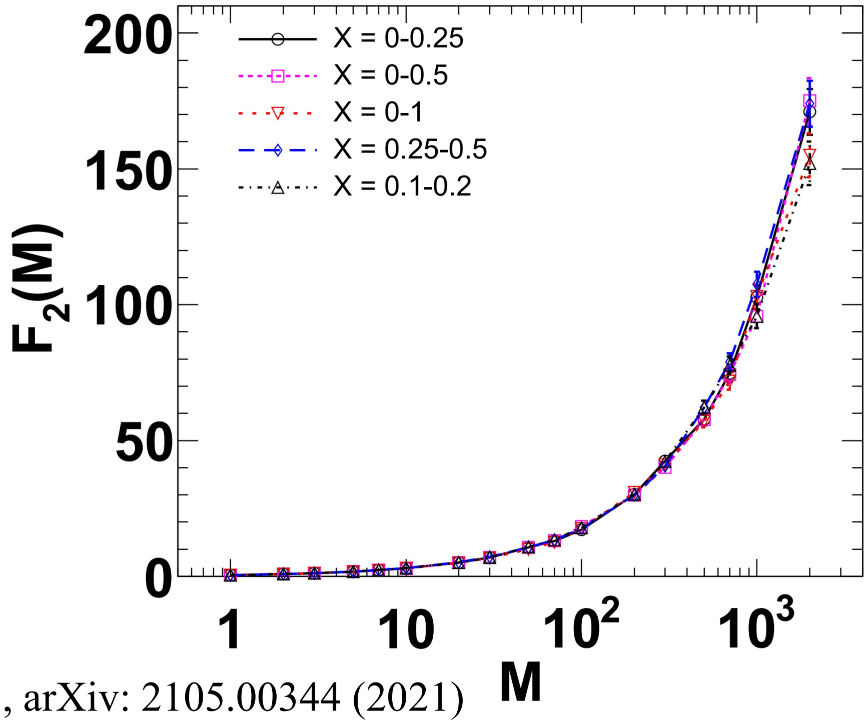
a) It does not depend on the choice of the original variable x for a given particle, but determined by the shape of density distribution $\rho(x)$.

b) The density distribution of cumulative variable, $X(x)$, is uniform in the interval from 0 to 1 with $\rho(X) = \text{const}$.

Subhasis Samanta, et al.,
arXiv: 2105.00344 (2021);
arXiv: 2105.01763 (2021)

Cumulative variable method



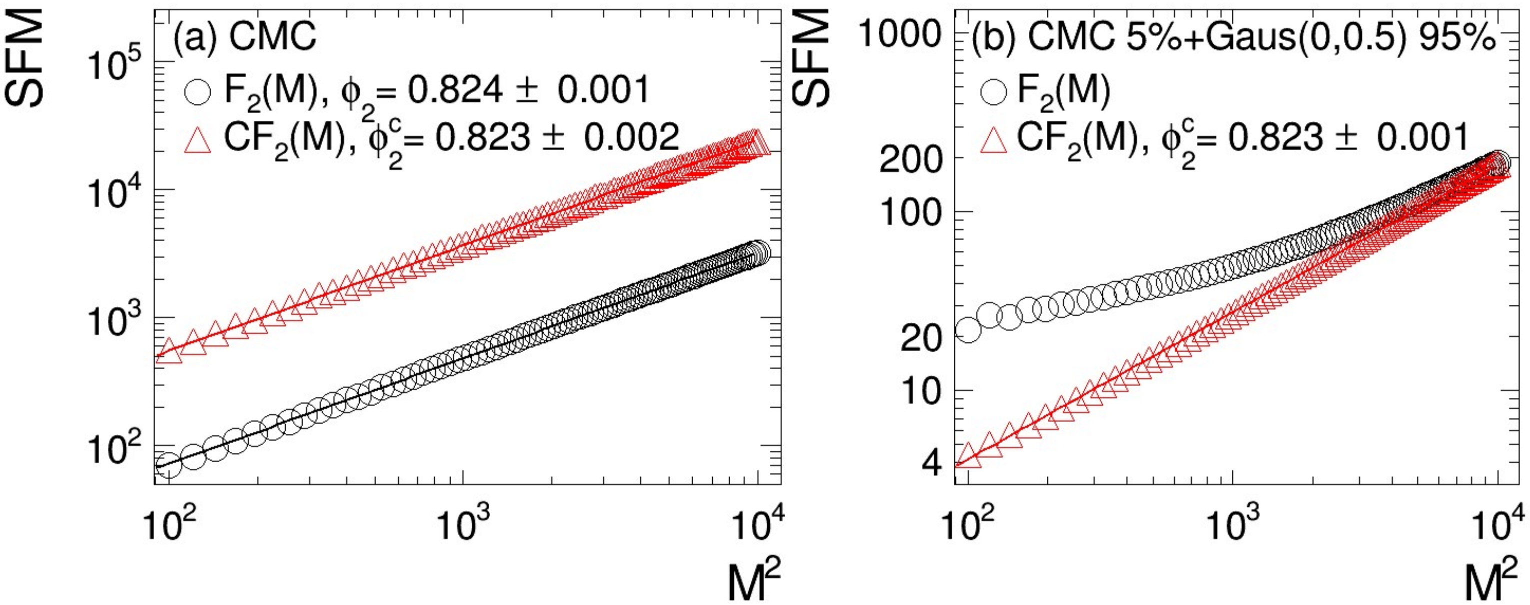


Subhasis Samanta, et al., arXiv: 2105.00344 (2021)

- $F_2(M)$ is different for different X intervals, i.e., it depends on the size and position of the p_T interval .

- $CF_2(M)$ is almost the same for all tested X intervals. Thus $CF_2(M)$ calculated in the cumulative variable is independent of selected interval in X for the analysis. The scaling behaviour of $CF_2(M)$ for the cumulative variable is observed.

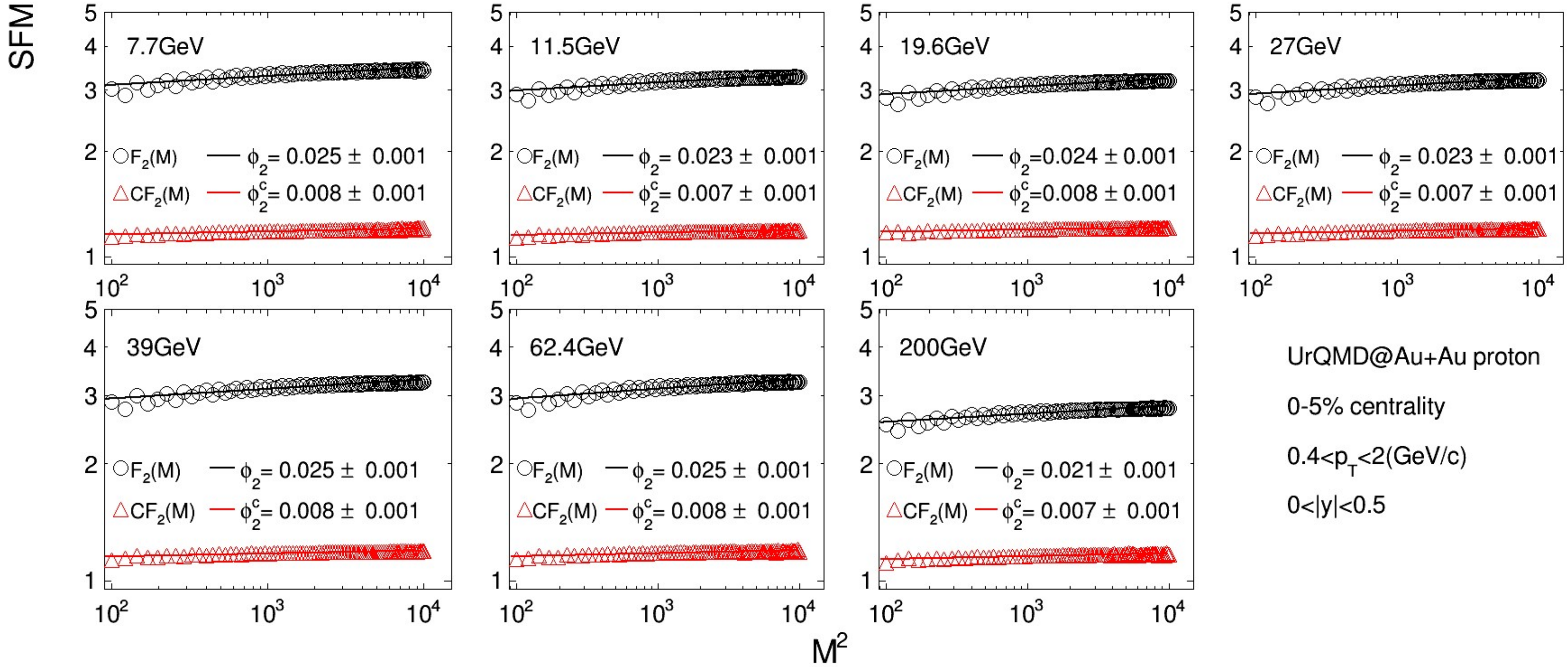
Testing the validity of the cumulative variable method



- $CF_2(M)$ follows a good power-law behavior as $F_2(M)$. Cumulative variable method does not change the intermittency behavior for a pure critical signal event sample.

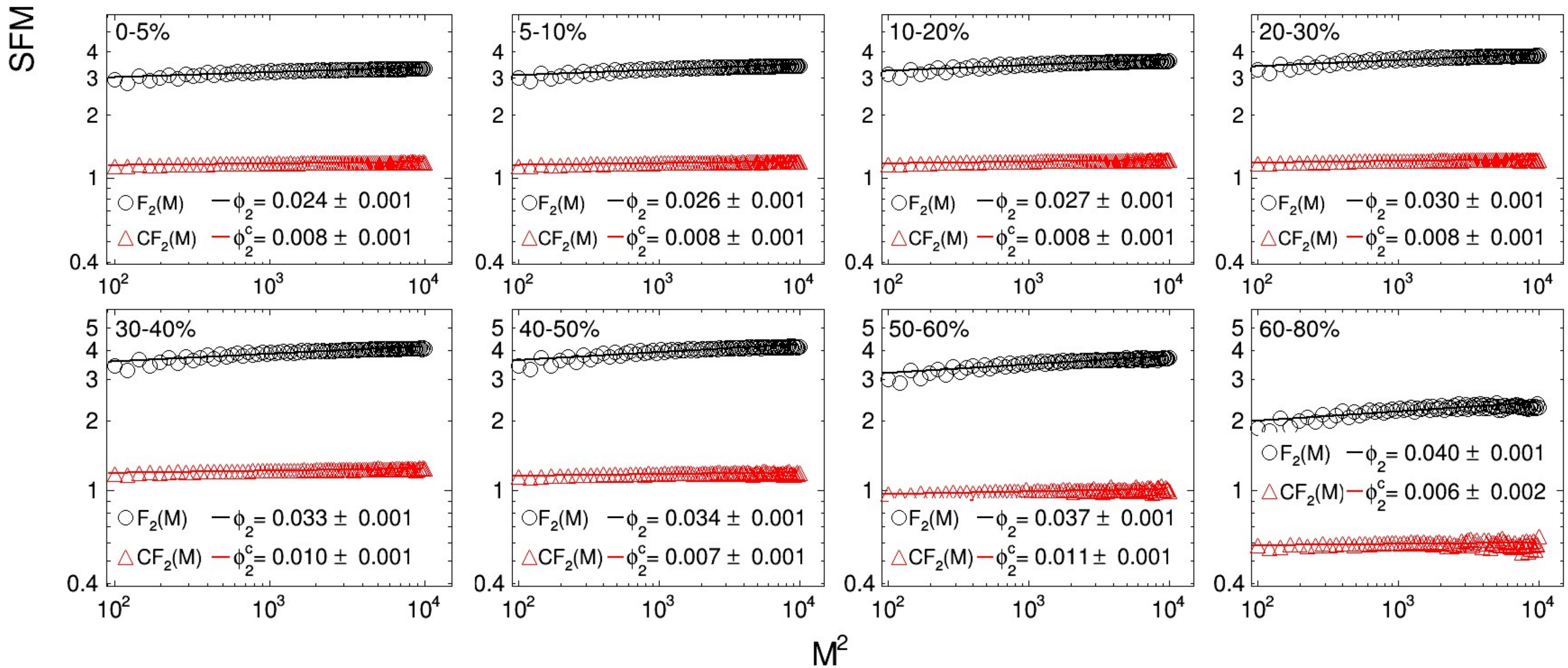
- The directly calculated $F_2(M)$ deviates substantially from the linear dependence, i.e. violation of the scaling law because of the Gaussian background contribution. However, ϕ_2 calculated from $CF_2(M)$ keeps unchanged when comparing to the one in original CMC sample.

Energy dependence of $CF_2(M)$ from UrQMD model



- $CF_2(M)$ is found to be nearly flat with increasing number of cells. The intermittency index, ϕ_2, with the value nearly around 0, is much smaller than the one directly calculated from $F_2(M)$.
- It verifies that the background of non-critical effect can be efficiently removed by the cumulative variable method in the calculation of SFMs in UrQMD model.

Centrality dependence of $CF_2(M)$ from UrQMD model



- $CF_2(M)$ is found to be nearly flat with increasing number of cells. The intermittency index, ϕ_2, with the value nearly around 0, is much smaller than the one directly calculated from $F_2(M)$.
- It verifies that the background of non-critical effect can be efficiently removed by the cumulative variable method in the calculation of SFMs in UrQMD model.

Efficiency correction (cell-by-cell method)

- The detector response is assumed to follow a binomial probability distribution function.

$$B(n, N; \varepsilon) = \frac{N!}{n!\,(N-n)!}\epsilon^{n}(1-\varepsilon)^{(N-n)}$$

- The true factorial moment is recovered by dividing the measured factorial moment with appropriate powers of the detection efficiency.

$$f_q^{corrected} = \frac{f_q^{measured}}{\varepsilon^q} = \frac{< n(n-1)...(n-q+1) >}{\varepsilon^q}$$

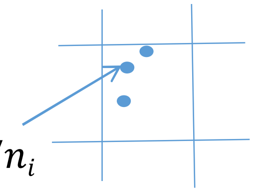
- Definition of $F_q(M)$:

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

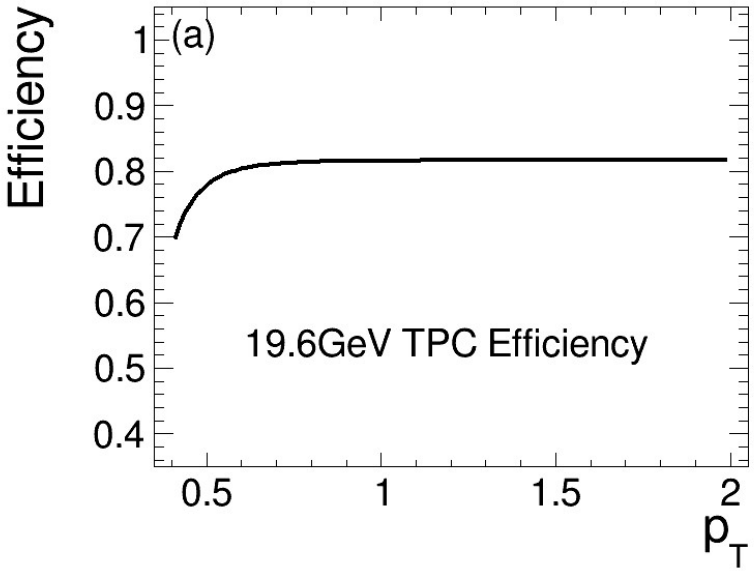
- Since the available region of phase space is partitioned into a lattice of M^2 equal-size cells, every element, $f_{q,i}^{measured}$, of measured $F_q(M)$ should be corrected one by one.

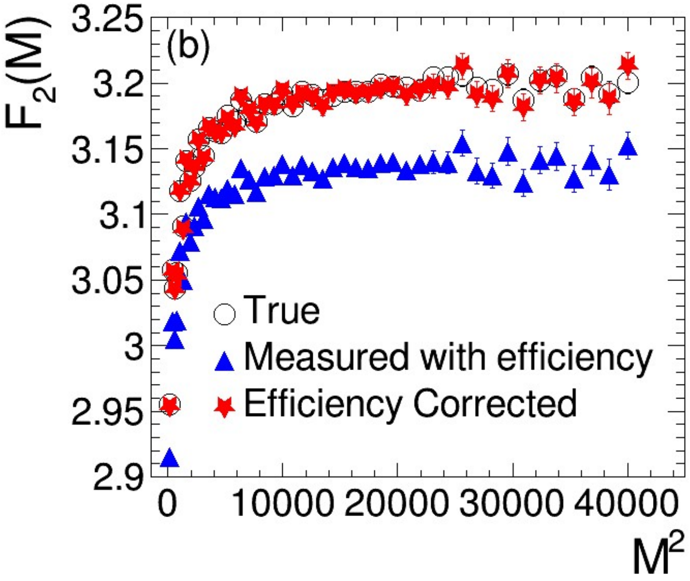
$$F_q^{corrected}(M) = \frac{< \frac{1}{M^2}\sum_{i=1}^{M^2} \frac{f_{q,i}^{measured}}{\bar{\varepsilon}_i^q} >}{< \frac{1}{M^2}\sum_{i=1}^{M^2} \frac{f_{1,i}^{measured}}{\bar{\varepsilon}_i} >^q} = \frac{< \frac{1}{M^2}\sum_{i=1}^{M^2} \frac{n_i(n_i-1)\ldots(n_i-q+1)}{\bar{\varepsilon}_i^q} >}{< \frac{1}{M^2}\sum_{i=1}^{M^2} \frac{n_i}{\bar{\varepsilon}_i} >^q}$$

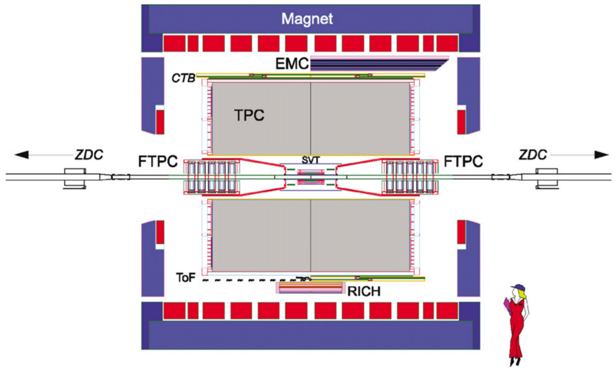
$$\bar{\varepsilon}_i = (\varepsilon_1 + \varepsilon_2 + \varepsilon_{n_i})/n_i$$



Efficiency correction (TPC only)



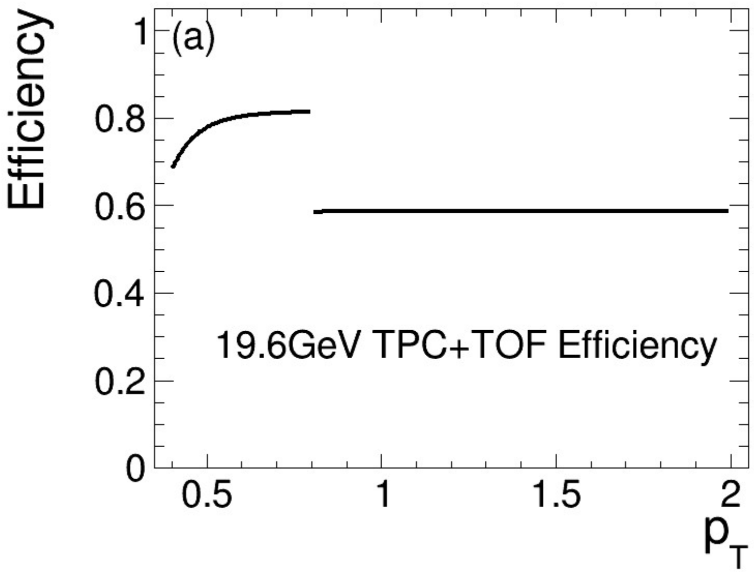


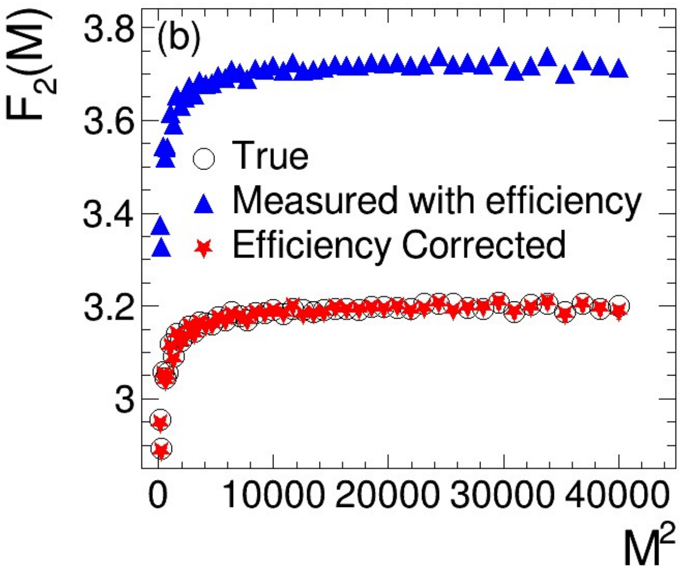


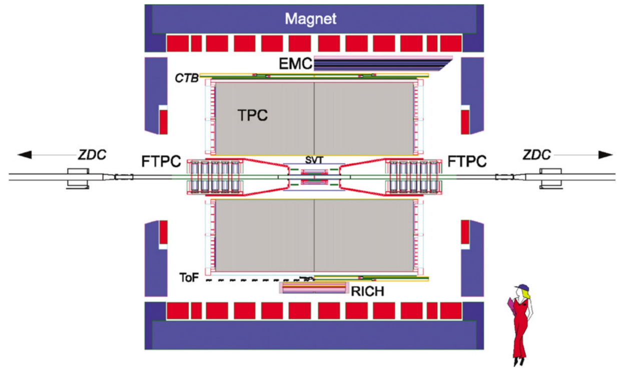
- The STAR TPC tracking efficiency firstly increases with increasing p_T , and then gets saturated in higher pT regions.

- The measured SFMs with efficiency are systematically smaller than the true ones, especially in the large number of partitioned cells. However, the efficiency corrected SFMs are found to be well consistent with the original true ones..

Efficiency correction (TPC+TOF)







- There is a steplike dependence of the efficiencies on p_T since the particle identification method is different between TPC and TOF detectors at STAR experiment.

- The SFMs corrected by the proposed cell-by-cell method are verified to be coincide with the original true ones.

Summary

- The energy and centrality dependence of the SFMs are investigated in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 – 200GeV by using the UrQMD model. The second-order intermittency index is found to be small but non-zero in the transport model without implementing any critical related self-similar fluctuations.

- A cumulative variable method can successfully reduce the distortion of a Gaussian background contribution from a pure self-similar event sample generated by the CMC model. After applying the method to the UrQMD event sample, it confirms that the non-critical background effect can be moved and the value of the intermittency index is close to zero.

- We derive a cell-by-cell formula in the calculation of SFMs in heavy-ion collisions. The validity of the method has been checked in the UrQMD event sample which is employed with both the TPC and TPC+TOF tracking efficiencies used in the RHIC/STAR experiment.

- The cell-by-cell method provides a precise and effective way for the efficiency correction on SFMs. The correction method is universal and can be applied to the ongoing studies of intermittency in heavy-ion experiments.

Outlook

Measurement of Intermittency for Charged Particles in Au + Au Collisions at $\sqrt{s_{NN}}$ = 7.7 - 200 GeV from STAR

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Abstract

One of the main goals of RHIC beam energy scan program is to search for the signature of the QCD critical point in heavy-ion collisions. 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, $F_q(M)$, for charged particles. The power-law behavior of q^{th}-order scaled factorial moments can be expressed as: $F_q(M) \sim (M^2)^{\phi_q}$, where M^2 is the number of equally sized cell in momentum space, and ϕ_q is the intermittency index. The scaling exponent, ν, is related to the critical component and can be derived from the ratio: ϕ_q/ϕ_2. The energy dependence of could be used to search for the signature of the QCD critical point. Such measurement is actively being pursued by the NA49 and NA61 Collaborations in large and small collisions at $\sqrt{s_{NN}}$ = 17.3 GeV. The BES-I data allow STAR to carry out such measurement over a much broader energy range of $\sqrt{s_{NN}}$ = 7.7 - 200 GeV. In this poster, we present the collision-energy and centrality dependence of ν of charged particles in Au + Au collisions measured by the STAR experiment. We find that scaling exponent, ν, decreases as decreasing collision energy and seem to reach a minimum around $\sqrt{s_{NN}}$ = 20 - 30 GeV in 0-5% most central collisions, and it decreases from semi-peripheral to central Au + Au collisions.

The direct measurement of intermittency in STAR experiment is ongoing!

Thank you!