The 7th Sino-Thai Symposium on High Energy Physics, Astrophysics, Materials Science and Beyond

Understanding the Intermittency Signal in RHIC-STAR Data through Modeling

Jin Wu[1]

Collaborators: Yuanfang Wu[2], Zhiming Li[2], Xiaofeng Luo[2], Mingmei Xu[2]

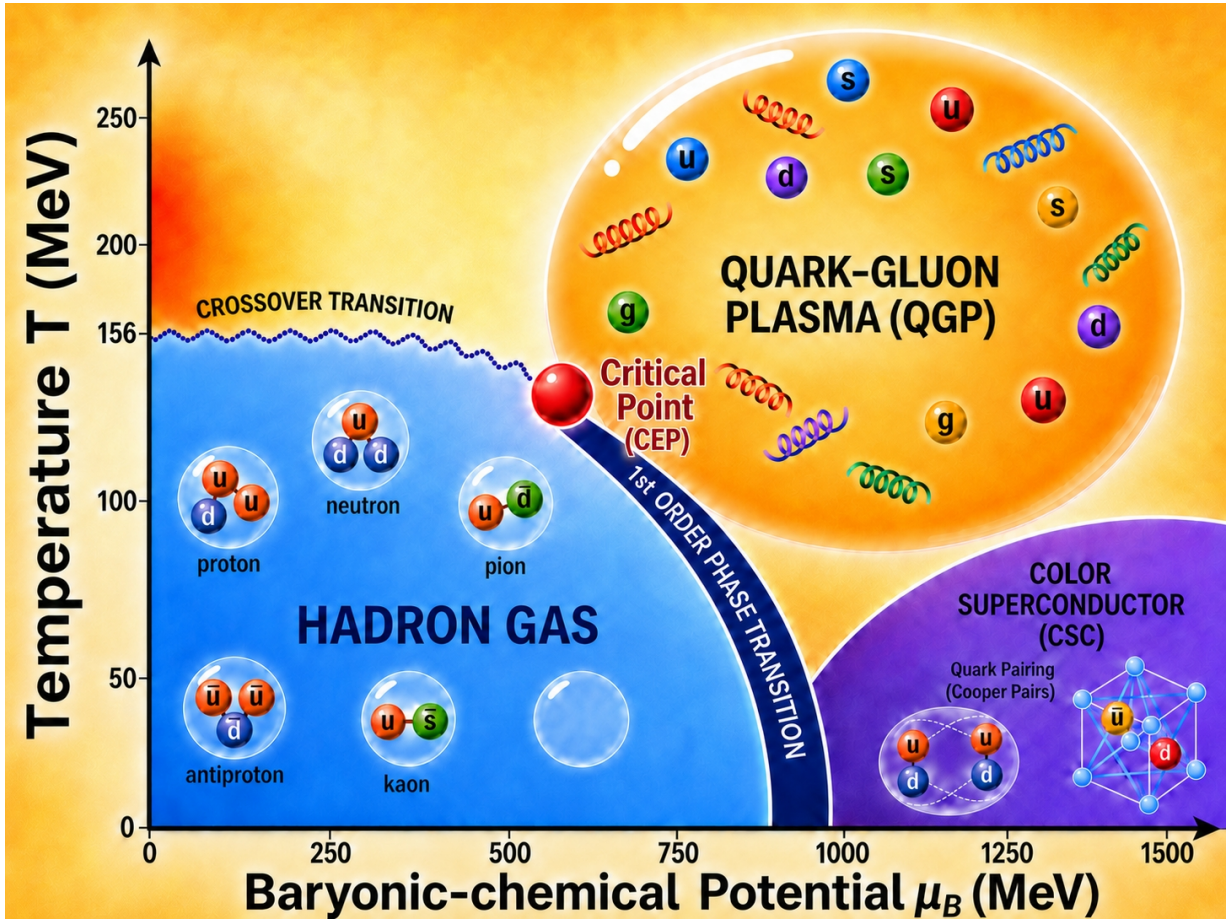
1. College of Physics and Electronic Engineering, Guilin University of Technology
2. Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University

arXiv:2606.24436 (2026)
Physics Letters B 845, 138165 (2023)

Outline

- 1 The QCD critical point.
- 2 The framework of intermittency analysis.
- 3 Measurements from the heavy-ion collision experiments.
- 4 Results from the transport UrQMD model and the CMC model.
- 5 Results from an enhanced UrQMD+CMC model
- 6 Summary and outlook.

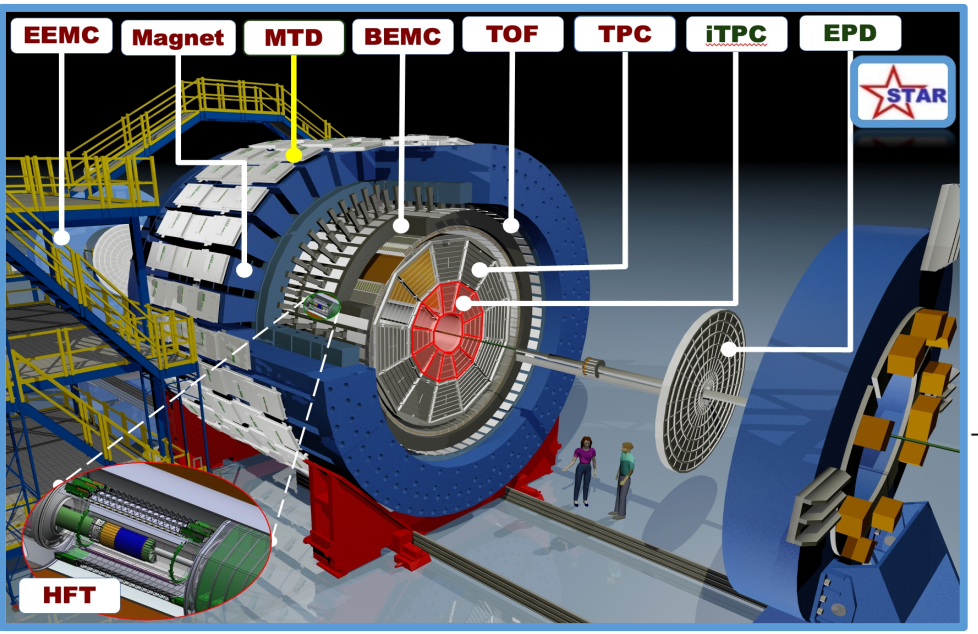
1.1 QCD Phase Diagram and the Critical Point



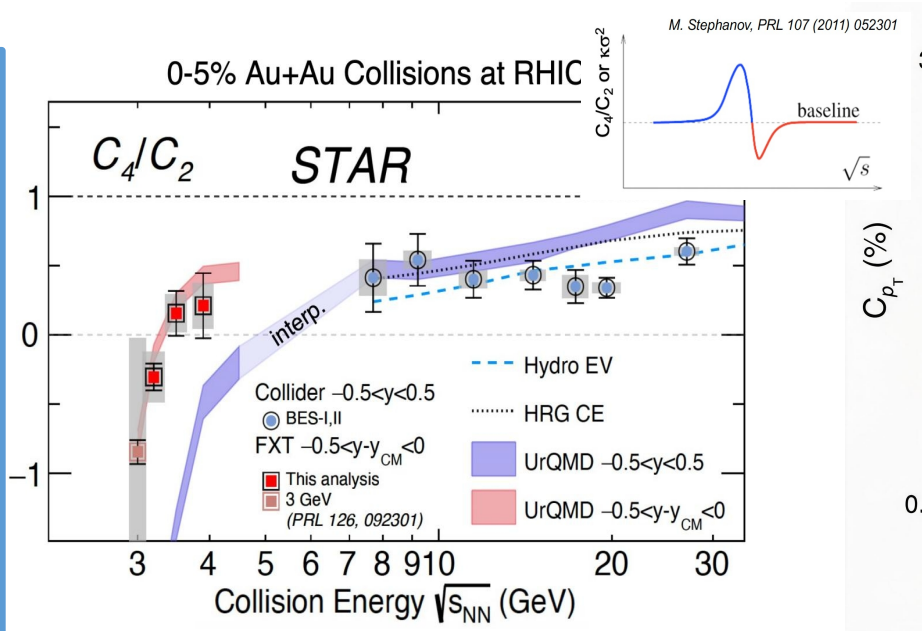
- Quark-Gluon Plasma (**QGP**) : a state of strongly interacting matter in which quarks and gluons are no longer confined within hadrons and which is created in relativistic heavy-ion collisions.
- Phase diagram of QCD matter in T and μ_B.
- QCD-based model calculations suggested that the phase transition is first-order at large μ_B
- The QCD critical point (CP): a significant point at which the first-order phase-transition boundary terminates.
  - Upon approaching the critical point, the correlation length of the system diverges
  - → A physical signature: enhanced density fluctuations.

A. Bzdak, S. Esumi, V. Koch, J. Liao, M. Stephanov, and N. Xu, Phys. Rept. 853, 1 (2020);
Y.G. Ma, N. Xu, F. Liu, Sci. Sin. Phys. Mech. Astron. 50, 112009 (2020);
S. Ejiri, Phys. Rev. D 78, 074507 (2008);
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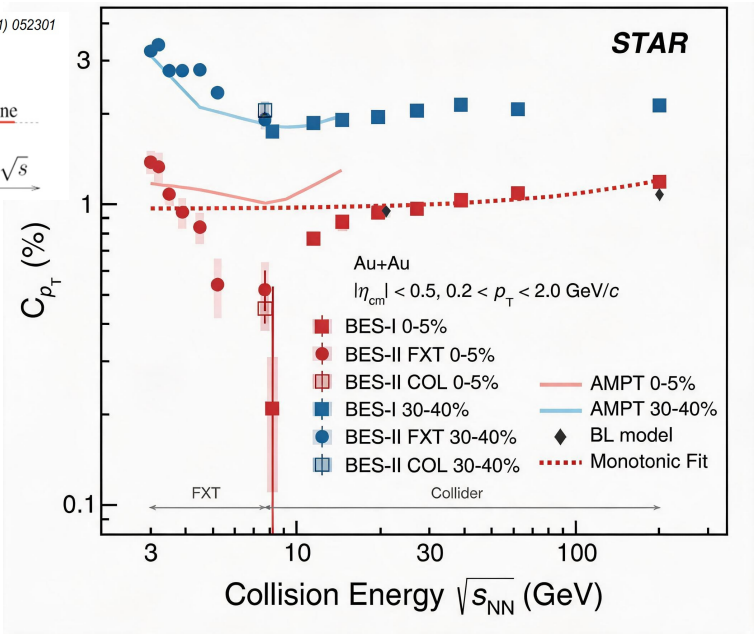
1.2 Nonmonotonic Energy Dependence of Observables in Heavy-Ion Collisions



STAR Note 0598: BES-II whitepaper



B. E. Aboona et al. (STAR), Phys. Rev. Lett. 135.142301(2025);
Y. Zhang, Z. Wang, X. Luo, and N. Xu, Eur. Phys. J. Spec. Top. (2026)



B. E. Aboona et al. (STAR), Phys. Rev. Lett. 137, 132301 (2026)

- The observation of nonmonotonic behavior in correlations and fluctuations of global quantities is often quoted as a key search strategy for the QCD critical point.

- Recent results from the STAR BES-II experiment at RHIC, including the net-proton kurtosis, two-particle transverse momentum (p_T) correlations …

2.1 Density Fluctuations and Intermittency Analysis in Heavy-ion Collisions

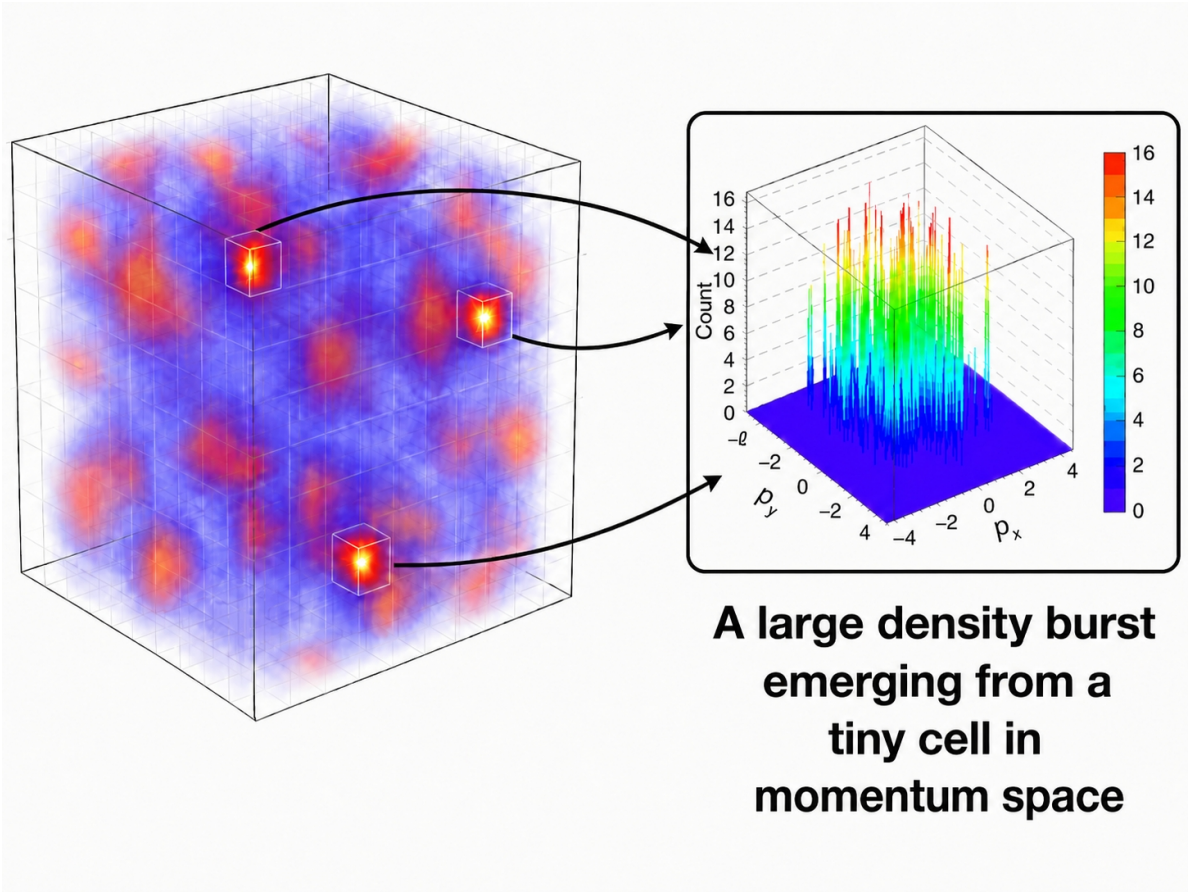
- Intermittency, often described as large fluctuations arising from small regions (cells) of phase space, signals unusual density fluctuations in the system.

- Based on the Ising-QCD theory, the density-density correlation function has a power-law (self-similar) behavior:

$$< \rho\,(\kappa)\rho^{*}(\kappa) > \sim |\kappa|^{-d_F}$$

where $\rho\,(\kappa)$ is the density function, κ is small momentum transfer, $d_F \cong \frac{5}{3}$ is the fractal dimension.

- This power-law behavior reflects the fractal structure of a critical system and implies critical intermittency in transverse-momentum space, which can be probed through reconstructed σ quasiparticles ($\pi^{+}\pi^{-}$ pairs) or net-proton density fluctuations.

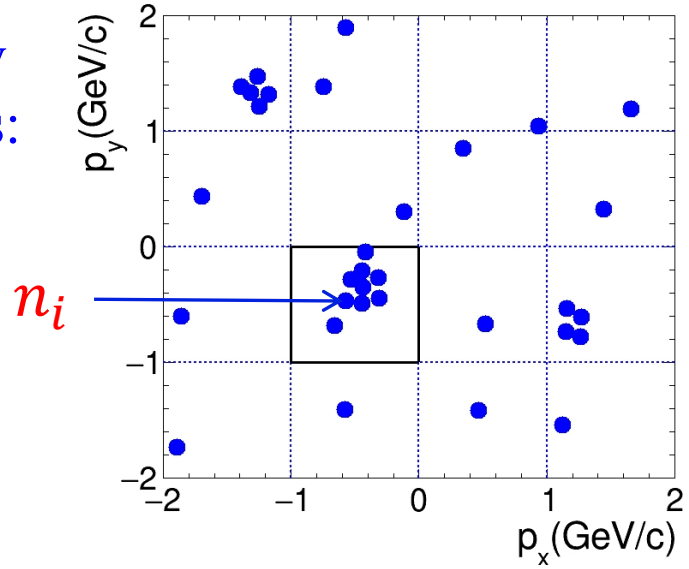


N. G. Antoniou et al., Phys. Rev. Lett. 97, 032002 (2006):
N. G. Antoniou et al., Phys. Rev. C 97, 034015 (2018);
K. J. Sun, et al., Phys. Lett. B 774, 103 (2017);
N. G. Antoniou, et al., Nucl. Phys. A 693, 799 (2001).

2.2 The Observables in Intermittency Analysis

- Density fluctuations can be probed via an intermittency analysis by utilizing the scaled factorial moments, SFMs or $F_q(M)$, defined as:

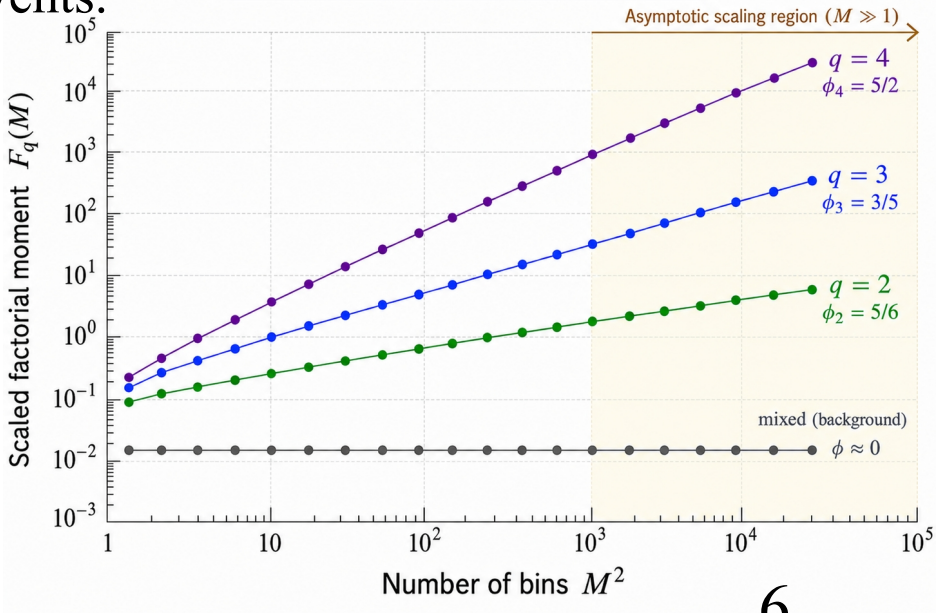
$$F_q(M) = \frac{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i(n_i-1)\dots(n_i-q+1) >}{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i >^q},$$



N. G. Antoniou et al., Phys. Rev. Lett. 97, 032002 (2006);
N. G. Antoniou, et al., Nucl. Phys. A 693, 799 (2001);
T. Anticic et al. (NA49 Coll.), Eur. Phys. J. C 75, 587 (2015)

where M^D is the number of equal-size cells in which the D-dimensional space is partitioned, q is the order of moments, $< \dots >$ denotes averaging over events.

$$F_q(M) \propto (M^2)^{\phi_q}, \quad M \gg 1$$



- If a system exhibits intermittency, we expect a power-law behavior of $F_q(M)$, equivalently, $F_q(M)/M$ scaling:

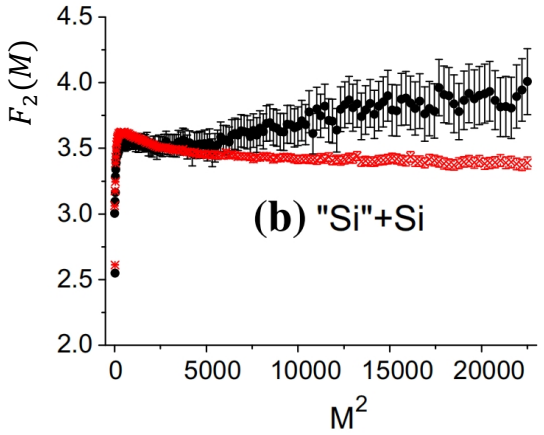
$$F_q(M) \propto (M^2)^{\phi_q}, \; M \gg 1$$

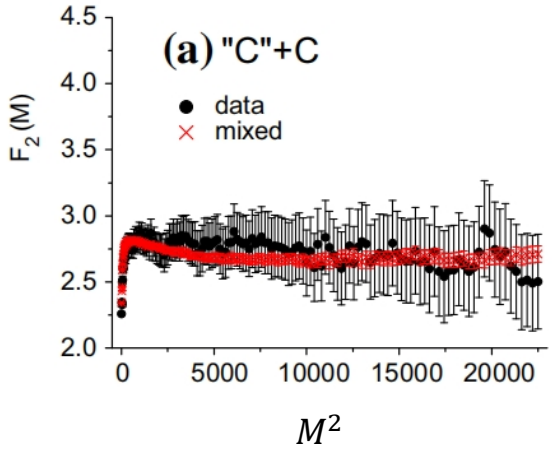
where ϕ_q is the intermittency index.

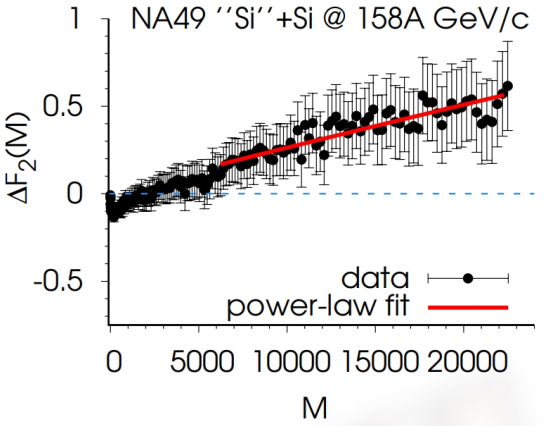
Critical intermittency in the $p_x - p_y$ phase space near the CP:

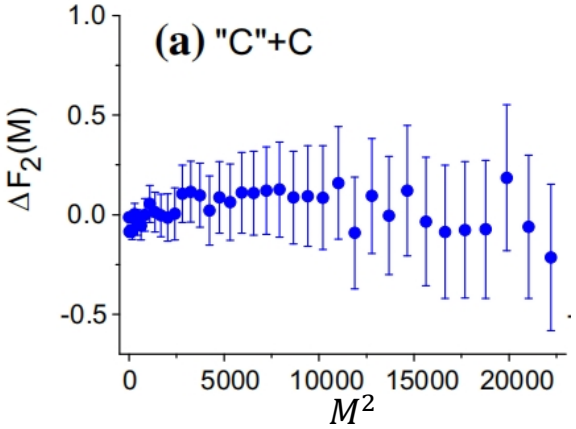
$$\phi_q^{\text{critical}} = 5(q-1)/6 \,(\text{Baryon}) = 2(q-1)/3 \,(\text{Pion})$$

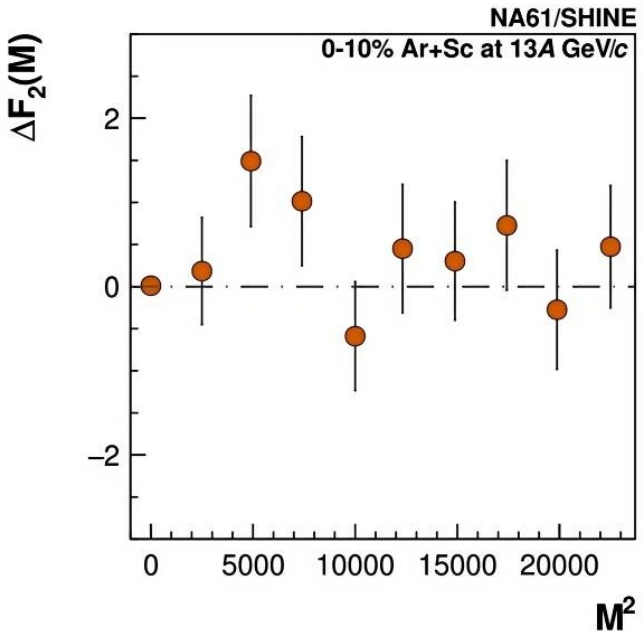
3.1 Intermittency measurements from the NA49 and NA61/SHINE Experiments

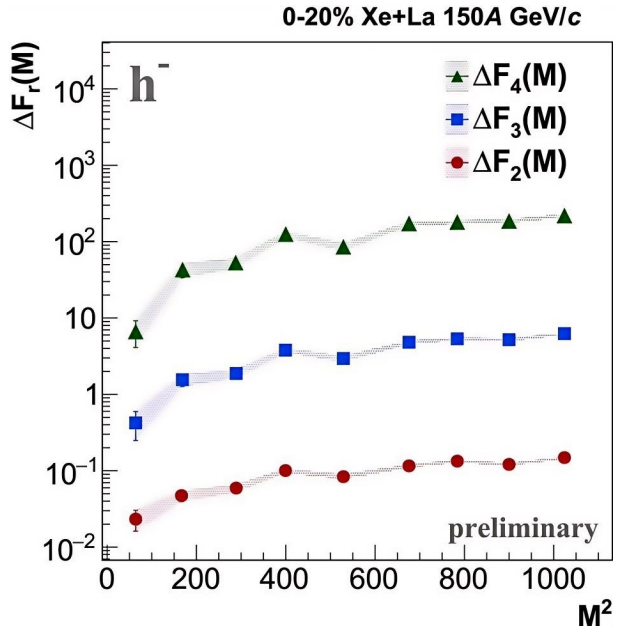










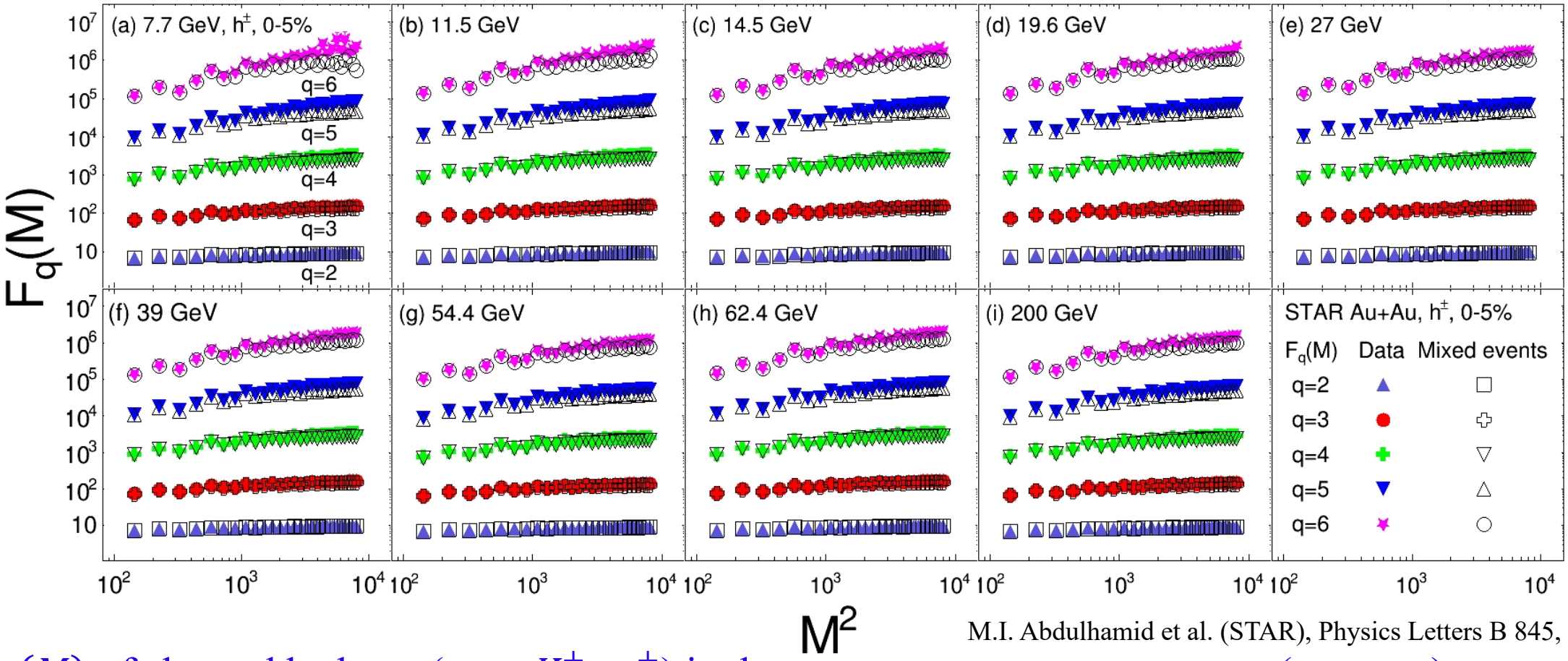


T. Anticic et al. (NA49 Coll.), Eur. Phys. J. C 75, 587 (2015);
H. Adhikary et al. (NA61/SHINE), Eur. Phys. J. C 84, 741 (2024);
V. Z. Reyna Ortiz (NA61/SHINE), Ukr. J. Phys. 69, 858 (2024).

- The NA49 experiment has observed a significant power-law fluctuations of proton in **Si** + **Si** collisions at $\sqrt{s_{NN}}$ = 17.3 GeV. No power-law behavior of the SFM is visible in **Pb** + **Pb** collisions and **C** + **C** collisions.
- No intermittency signal was found for protons in Ar+Sc collisions at $\sqrt{s_{NN}}$ = 5.1, 6.1, 7.6, 8.8, 11.9, and 16.8 GeV, while an increasing trend in the SFM correlator was observed for negatively charged hadrons in central Xe+La collisions at $\sqrt{s_{NN}}$ = 16.8 GeV.

3.2 Results from the STAR BES-I Experiment: Energy Dependence of SFMs

$|\eta| < 0.5$, $0.2 < p_T(K^{\pm}, \pi^{\pm}) < 1.6$ (GeV/c), $0.4 < p_T(p, \bar{p}) < 2.0$ (GeV/c)

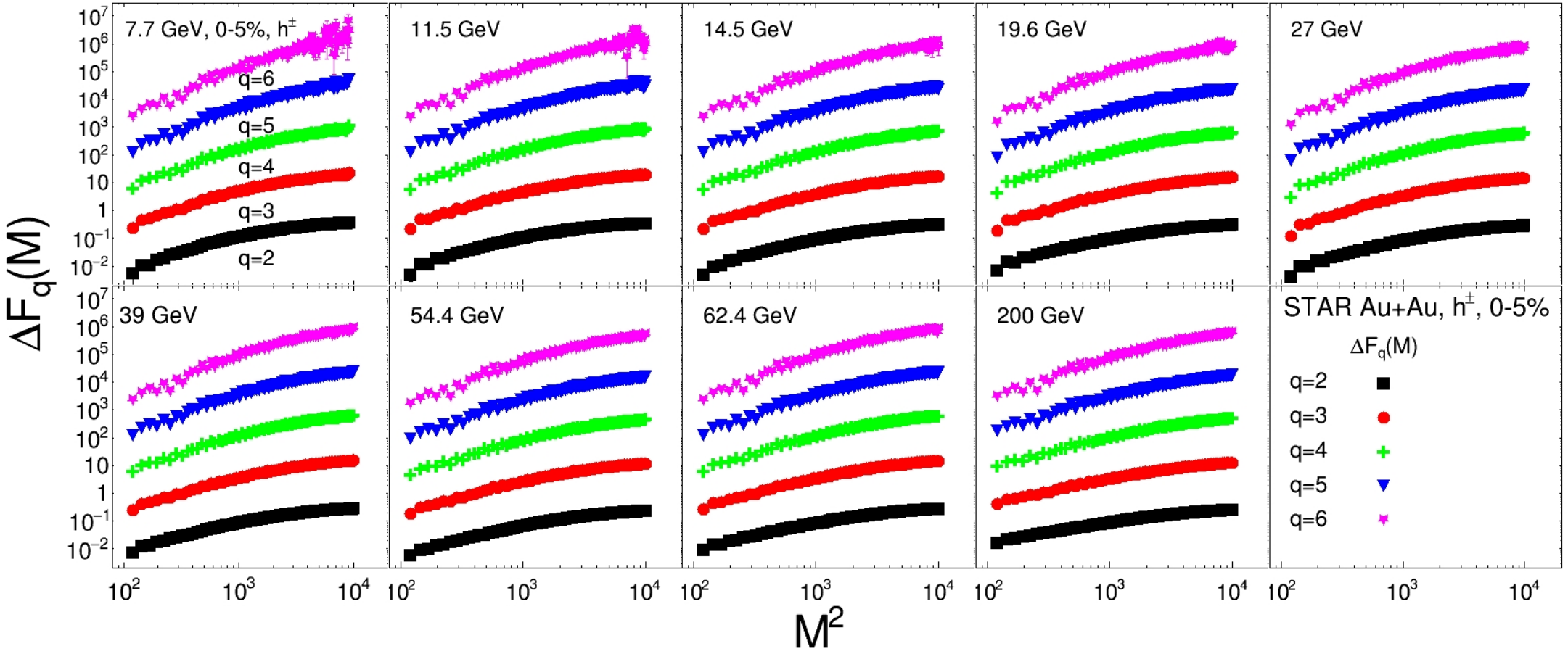


M.I. Abdulhamid et al. (STAR), Physics Letters B 845, 138165 (2023)

- $F_q(M)$ of charged hadrons (p, $\bar{p}$, $K^{\pm}$, $\pi^{\pm}$) in the transverse momentum space ($p_x - p_y$).
- The calculations of $F_q(M)$ were performed in the $M^2 \in [1^2, 100^2]$ and up to sixth order ($q = 2{\sim}6$).
- $F_q^{data}(M)$ are larger than $F_q^{mix}(M)$ in large M^2 region.

$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M).$$

3.3 Results from the STAR BES-I Experiment: Energy Dependence of $\Delta F_q(M)$



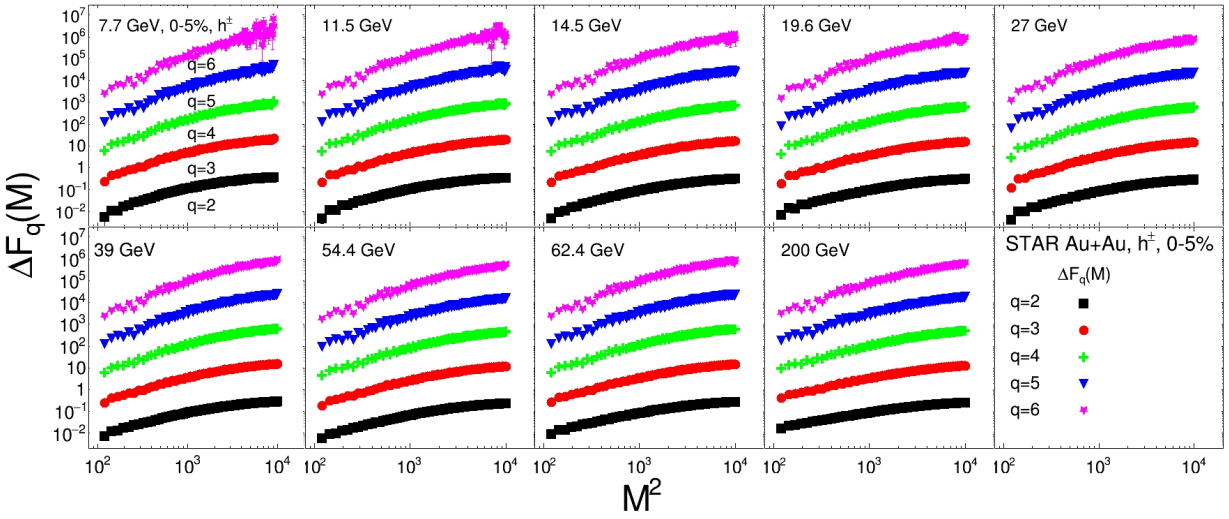
$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M) \propto (M^2)^{\phi_q}$

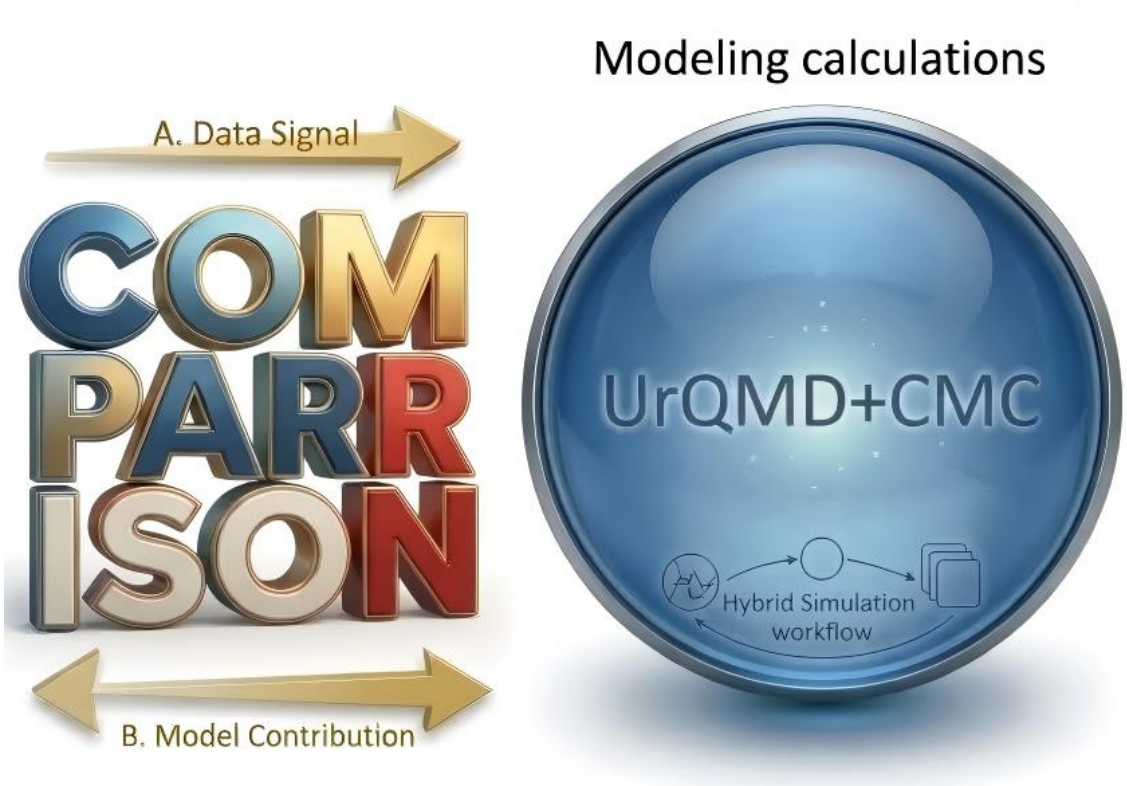
M.I. Abdulhamid et al. (STAR), Physics Letters B 845, 138165 (2023)

- A common behavior is observed at all collision energies: $\Delta F_q(M)$ (q=2-6) increases with M^2 and gradually saturates for $M^2 \gtrsim 4000$, revealing non-trivial intermittency in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7-200 GeV.

Motivation: Constrain the Critical-like Signal at Different Collision Energies through Modeling

The STAR BES-I measurements

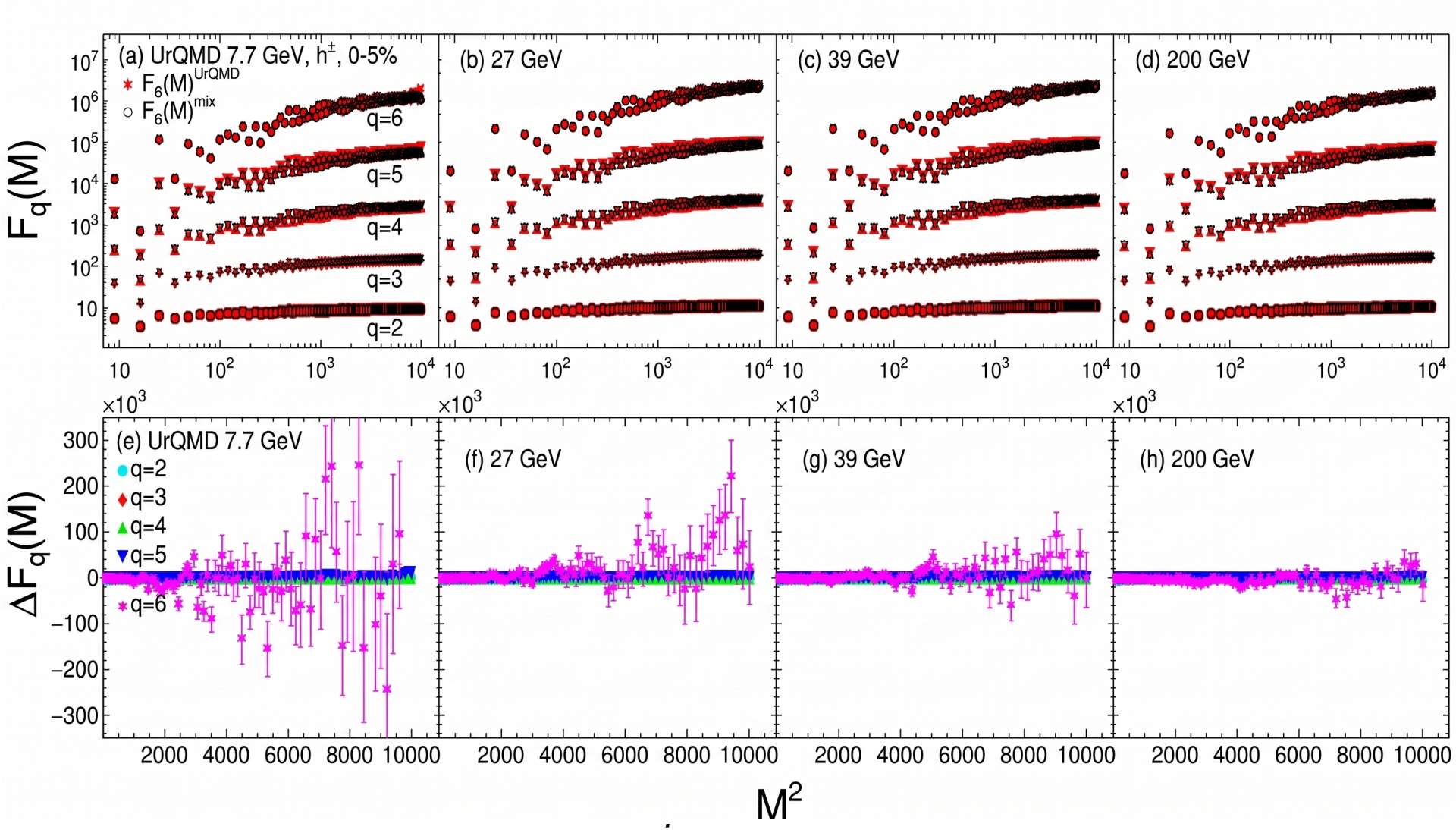




- The intermittency measurements reported by the STAR BES-I experiment call for a quantitative assessment of the signal strength and a clearer physical understanding of its collision-energy dependence, particularly regarding which collision energy exhibits the largest signal.

- We perform a quantitative study to constrain the possible critical-like contribution to the intermittency signal measured in the STAR BES-I data, using an enhanced hybrid UrQMD+CMC model.

4.1 Results from the UrQMD model: Energy Dependence of SFMs



- $F_q^{data}(M)$ was observed to overlap with $F_q^{mix}(M)$ and $\Delta F_q(M) \approx 0$ from the UrQMD calculations.

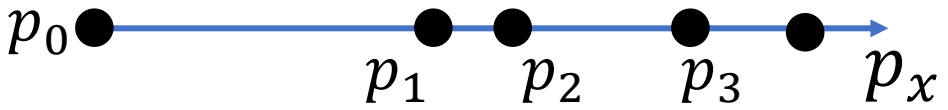
  Neither $\Delta F_q(M) \propto (M^2)^{\phi_q}$ or $\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$ scaling was observed after background subtraction.

4.2 Results from the Critical Monte Carlo (CMC) Model

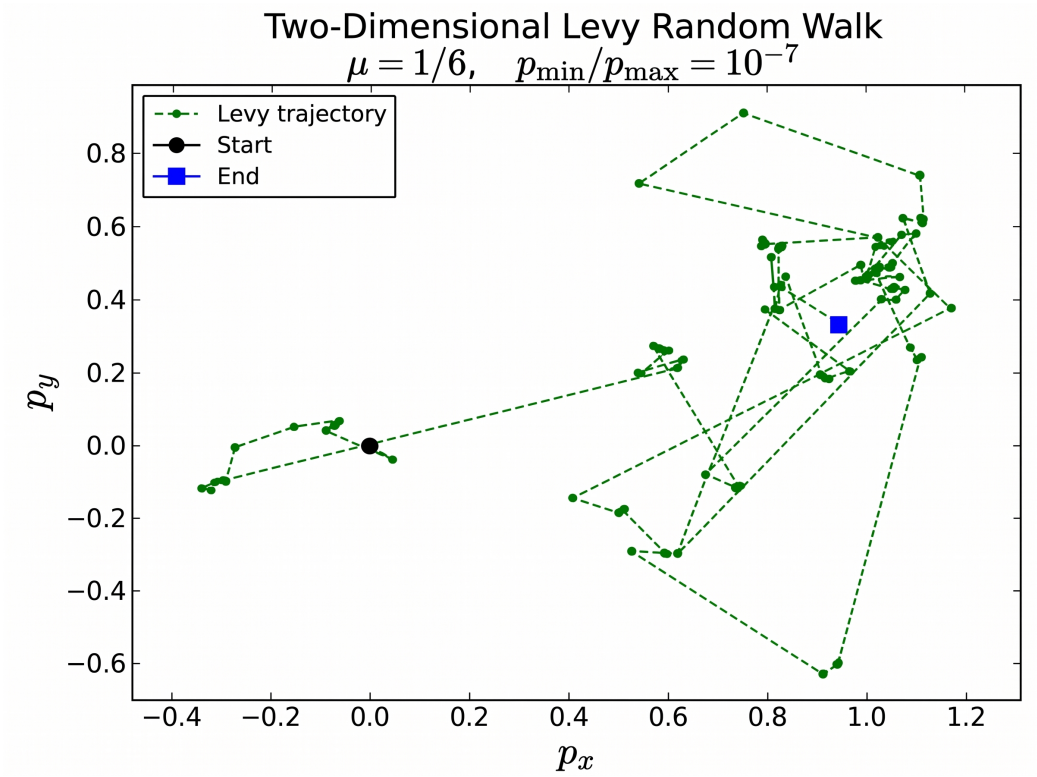
- To simulate the critical intermittency signal expected from self-similar density fluctuations near the QCD critical endpoint, we employ the Critical Monte Carlo (CMC) model.

- Levy random walk method is proposed to produce the momentum of the final state particles, with a probability density (ρ) between two adjacent steps of the walk:

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

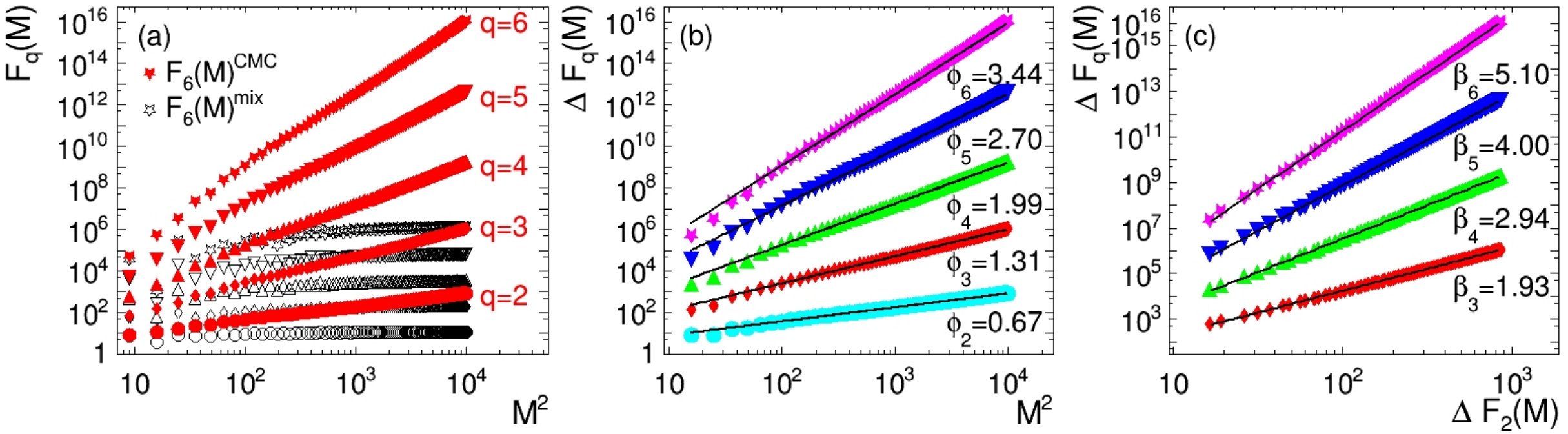


$$p = p_n - p_{n-1}$$



p (GeV/c) is the momentum separation between two particles, μ is Levy index. μ=1/6, p_{mix}/p_{max}=10^{-7} for the 3D Ising universality with $\phi_2 = 5/6$.

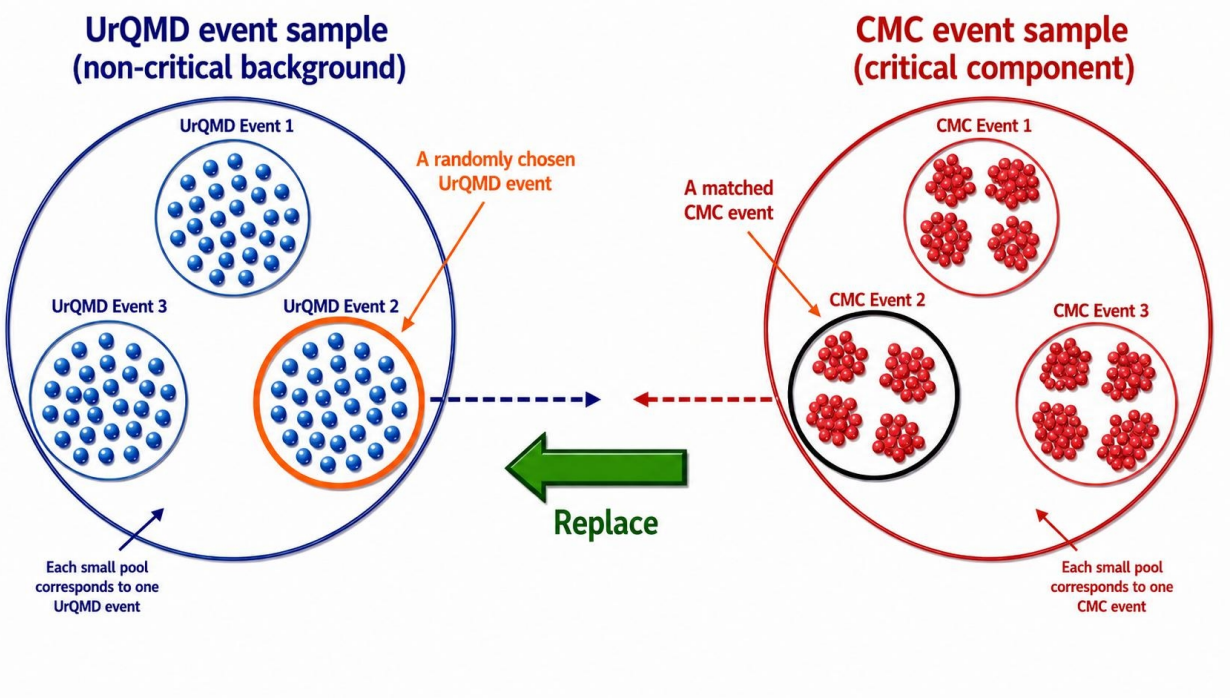
4.2 Critical Intermittency from the CMC Model

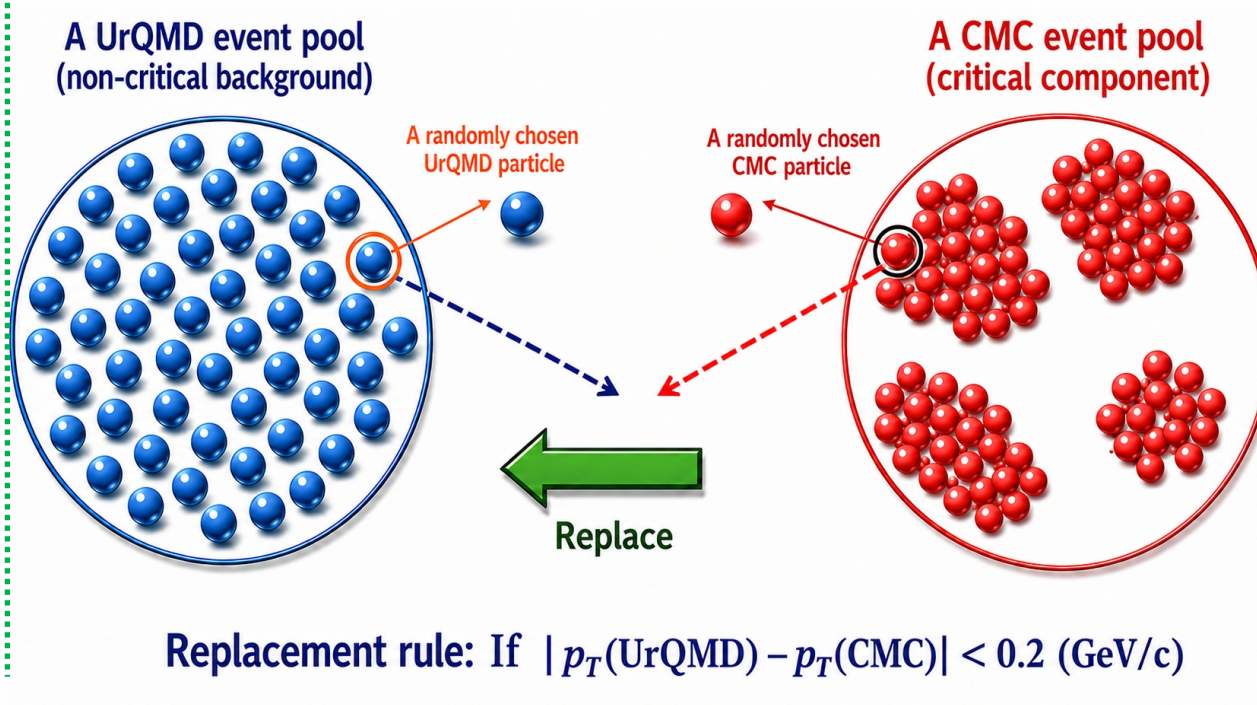


- The CMC sample, which incorporates the same statistics, total multiplicity and p_T distributions as the UrQMD sample at $\sqrt{s_{NN}}$ = 19.6 GeV, exhibits strong power-law scaling of $\Delta F_q(M) \propto (M^2)^{\phi_q}$ and $\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$.

Phys. Rev. C 106, 054905 (2022)

5.1 The Hybrid UrQMD+CMC Model



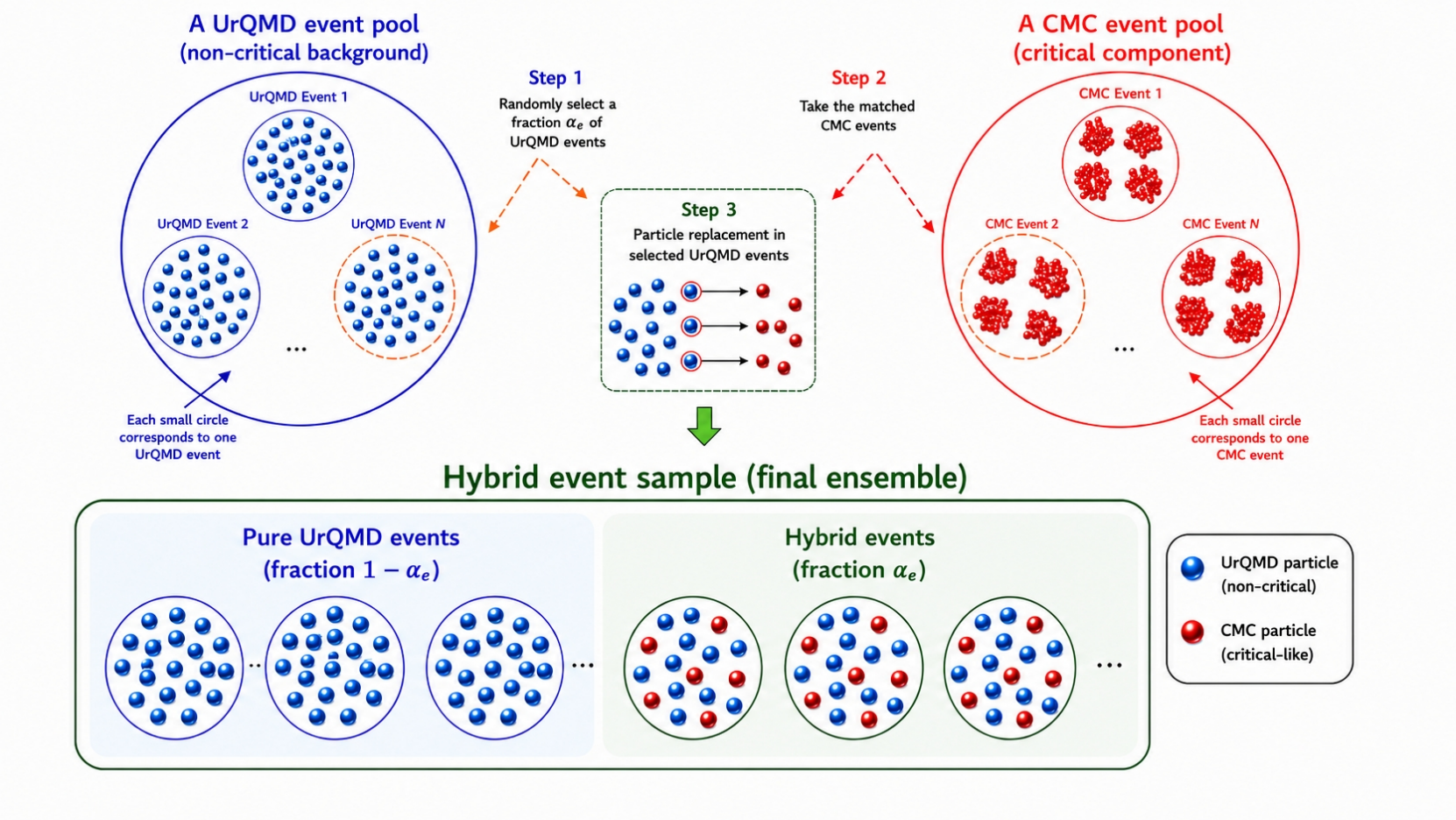


The hybrid UrQMD+CMC samples are constructed through momentum-space replacement of particles between the UrQMD and CMC models.

- The event-level replacement fraction: $\alpha_e = \frac{N_{\mathrm{CMC\ events}}}{N_{\mathrm{CMC\ events}} + N_{\mathrm{UrQMD\ events}}}$, controls the occurrence probability of critical events within a heavy-ion event ensemble.

- The particle-level replacement fraction: $\alpha_p = \frac{N_{\mathrm{CMC\ particles}}}{N_{\mathrm{CMC\ particles}} + N_{\mathrm{UrQMD\ particles}}}$, controls the fraction of particles within signal events that retain critical information throughout the collision evolution.

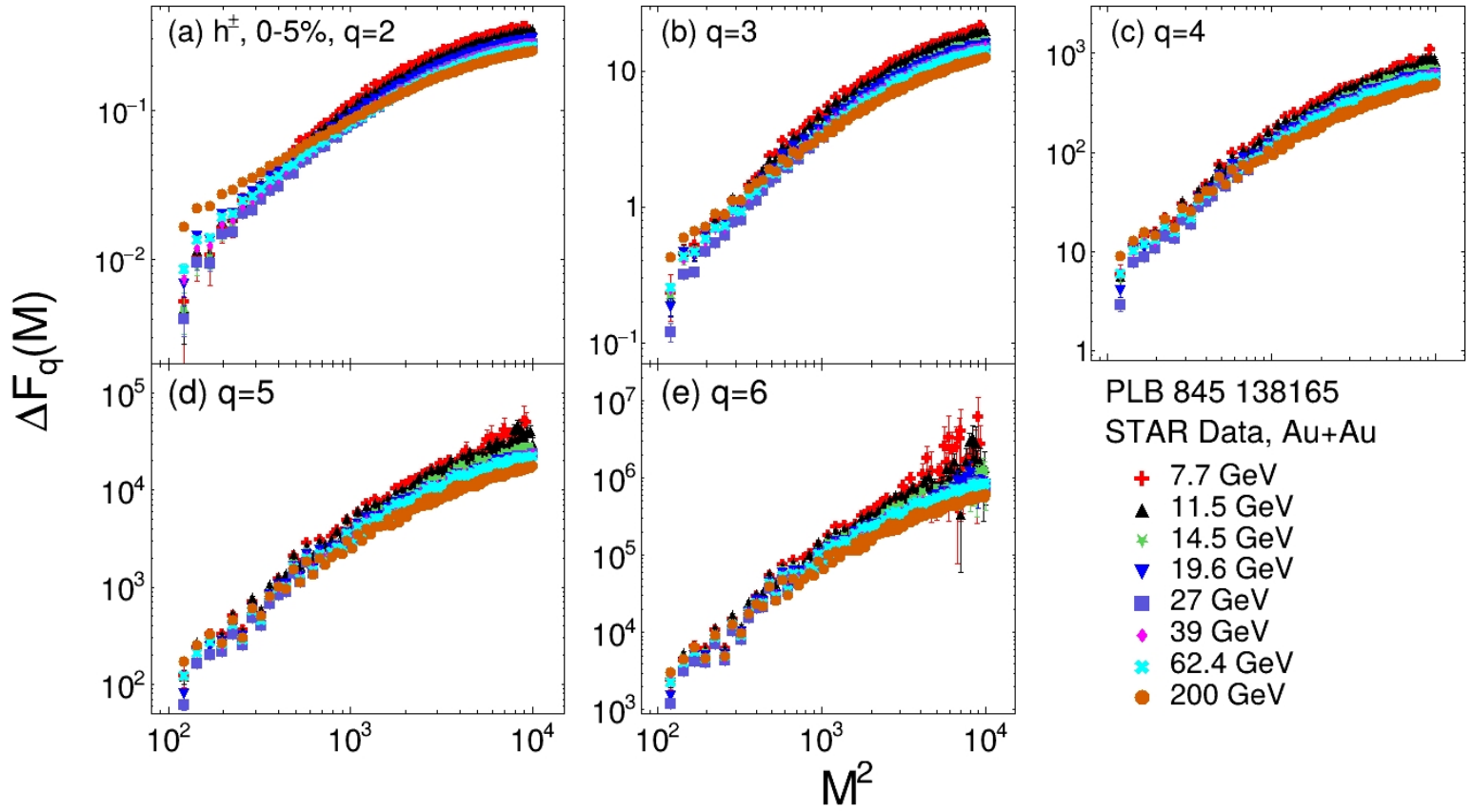
5.2 The Hybrid UrQMD+CMC Model



Combined event- and particle-level replacement

- In realistic heavy-ion collisions, only a small fraction α_e of events may develop a critical component, and even within those events only a fraction α_p of particles may retain critical information throughout the collision evolution. Consequently, a more realistic modeling framework, should incorporate both event-level and particle-level replacement schemes.

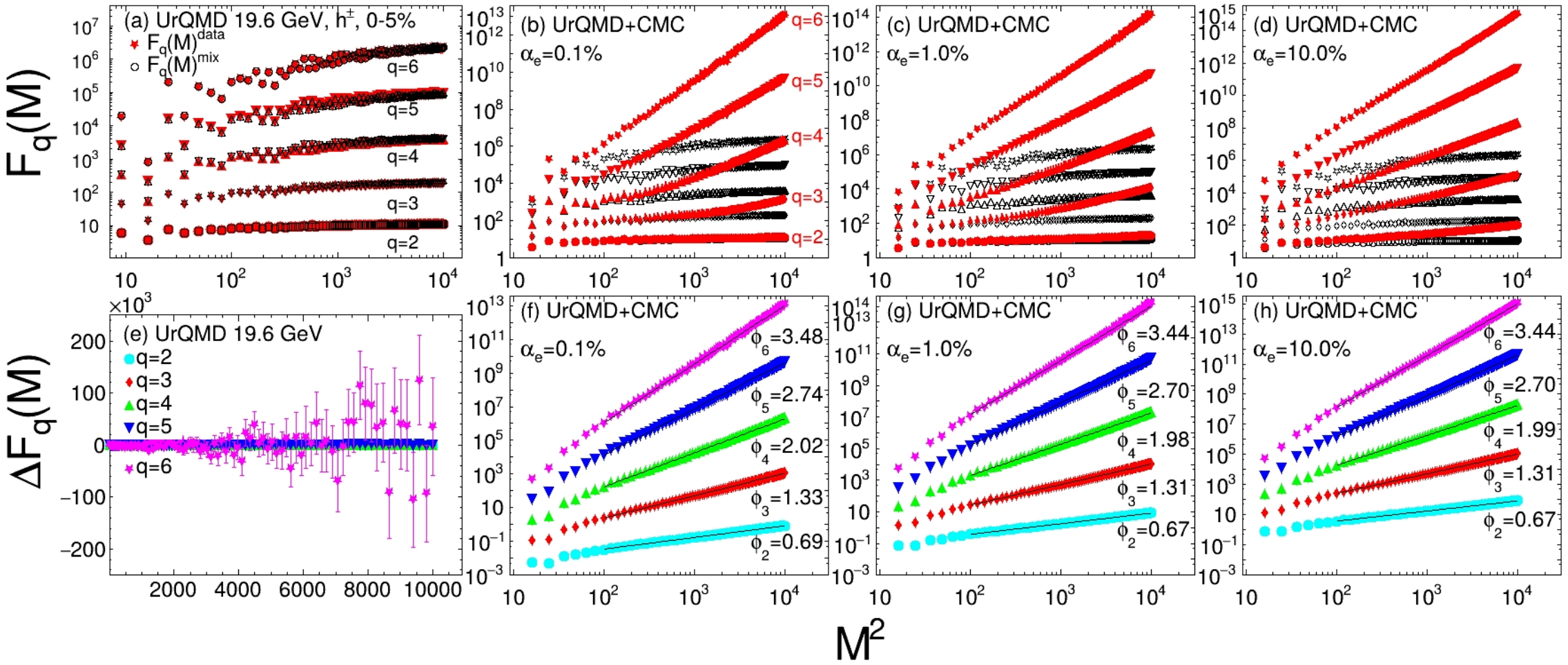
5.3 The STAR BES-I data for $\Delta F_q(M)$ at different collision energies



- We replot the STAR BES-I measurements of $\Delta F_q(M)$ to compare the intermittency behavior across different collision energies. The overall magnitude of $\Delta F_q(M)$ shows a mild decreasing trend with increasing $\sqrt{s_{NN}}$, while the differences among collision energies remain relatively small.

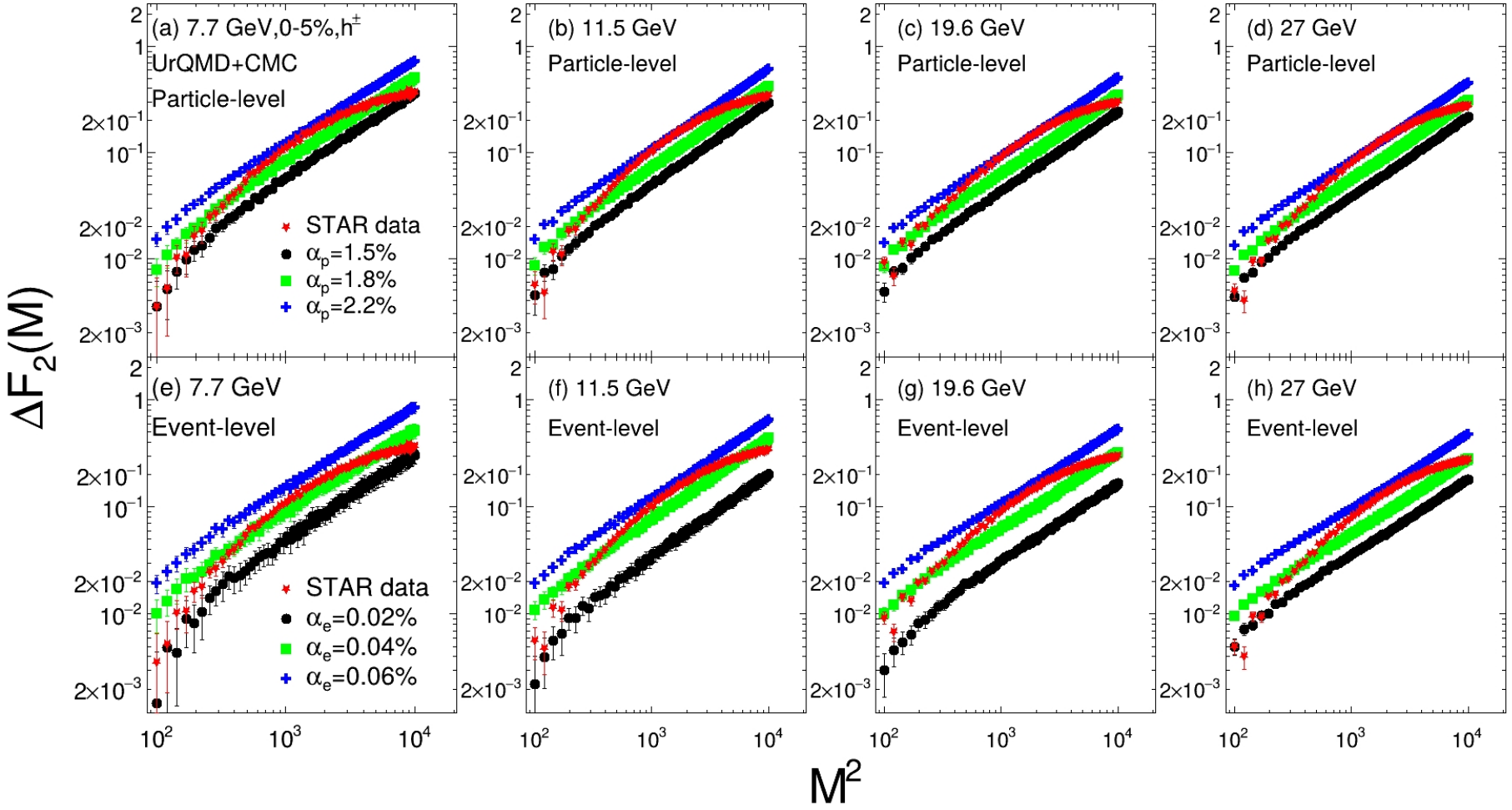
- The strength of $\Delta F_q(M)$ across the BES-I energy range is confined to a narrow range and does not show a pronounced enhancement at any particular collision energy.

5.4 Apparent Signal from the Hybrid UrQMD+CMC Model: Event-Level Replacement Only



- Even for the smallest fraction α_e=0.1%, $F_q(M)^{data}$ becomes visibly larger than $F_q(M)^{mix}$
- The magnitude of $\Delta F_q(M)$ increases systematically with the imposed critical-like fraction, thereby establishing a controlled correspondence between the measured intermittency strength and the effective critical-like fractions.

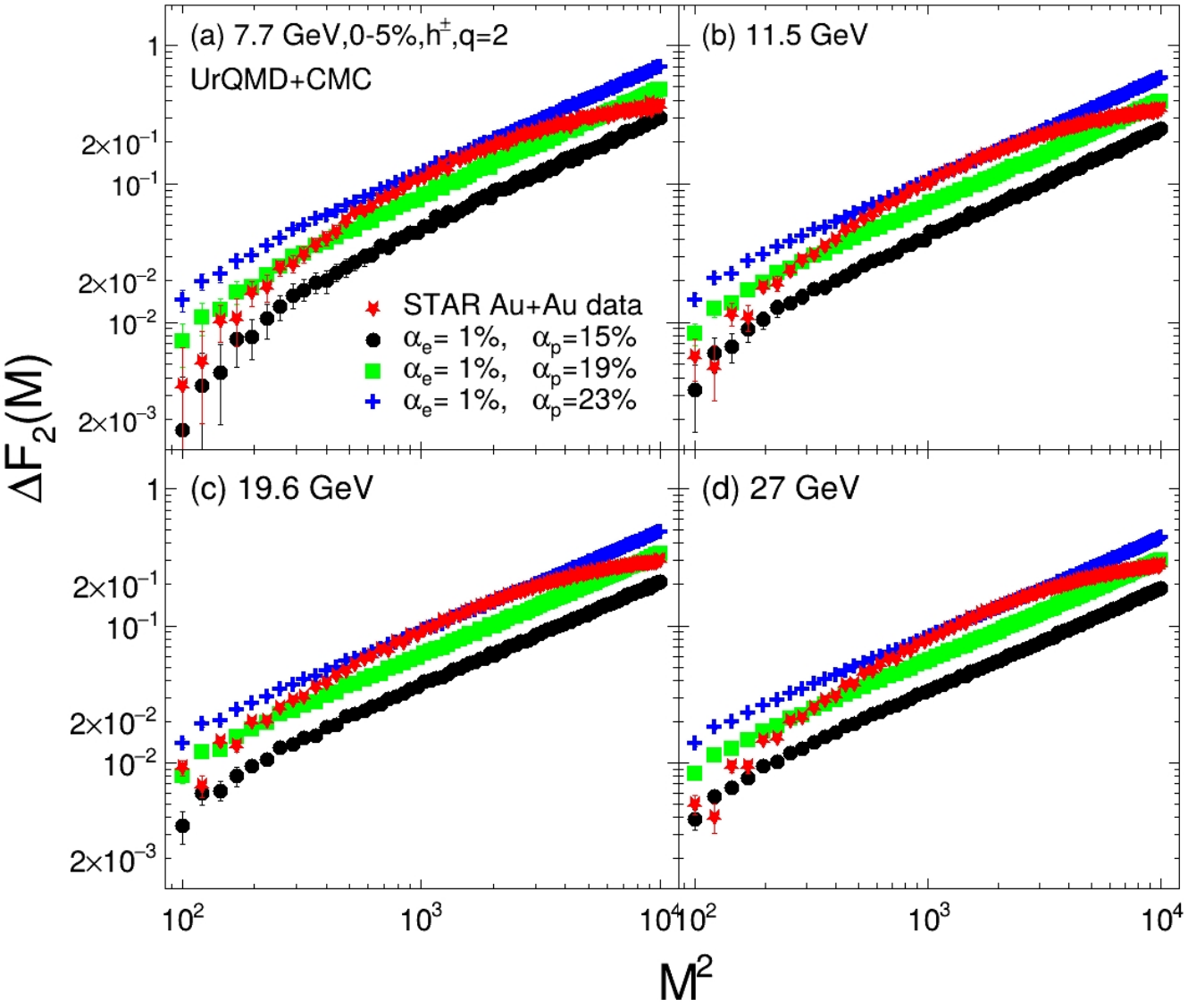
5.5 Constraining Critical-like Fractions with Individual Event-Level and Particle-Level Replacement



- For the separate replacement schemes, the STAR measurements favor $\alpha_p \approx 1.8\%$ in the particle-level scheme and $\alpha_e \approx 0.04\%$ in the event-level scheme.

- The extracted critical-like fractions are small and very similar across the collision energies.

5.6 Constraining Critical-like Fractions with Combined Event- and Particle-level Replacement



- The more realistic combined scheme favors $\alpha_p \approx 19\ \%$ when $\alpha_e = 1\%$ for all considered collision energies.
- The STAR BES-I data can be consistently described by the model only with small and nearly energy-independent effective critical-like fractions, thereby favoring only a limited critical-like contribution rather than a strong critical-point-induced enhancement localized near a specific collision energy.
- Such a weak intermittency signal may arise from non-negligible density fluctuations developing during the evolution of heavy-ion collisions or from other non-critical dynamical mechanisms, such as parton showers, jets, and string fragmentation.

6 Summary and Outlook

1) The STAR BES-I measurements of $\Delta F_q(M)$ exhibit only a weak dependence on collision energy, with a mild decreasing trend as $\sqrt{s_{NN}}$ increases, while the differences among collision energies remain relatively small.

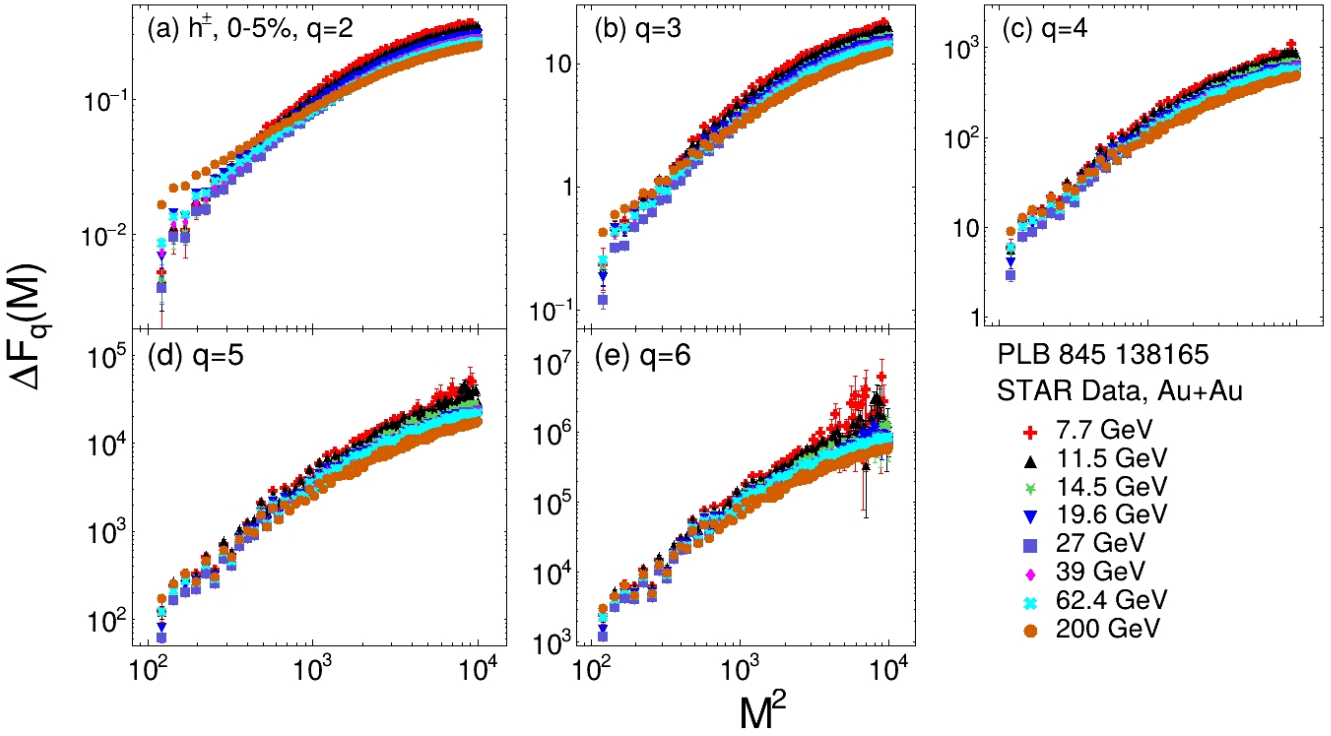
2) We study the STAR BES-I measurements using an improved hybrid UrQMD+CMC framework, where critical-like fluctuations are embedded into a realistic non-critical background through event-level, particle-level, and combined replacement schemes.

3) By performing a point-by-point comparison of $\Delta F_2(M)$ between the STAR BES-I data and the hybrid UrQMD+CMC calculations obtained with different replacement schemes, we constrain small and nearly energy-independent effective critical-like fractions compatible with the data.

4) The small and nearly energy-independent effective fractions, together with the limited variations in the STAR $\Delta F_2(M)$ results across BES-I energies, indicate a weak collision-energy dependence of intermittency. These findings suggest that the intermittency signal observed in the current BES-I data favors a limited critical-like contribution rather than a strong critical-point-induced enhancement localized near a specific collision energy.

6 Summary and Outlook

Outlook: Future intermittency measurements from the STAR Fixed-Target Program in the energy range $\sqrt{s_{NN}}$ = 3-4.5 GeV would provide an important opportunity to test whether a stronger and more localized enhancement of $\Delta F_q(M)$ emerges, and whether the preferred particle-level and event-level critical-like fractions deviate from the BES-I values.



Au+Au Collisions at RHIC							
Collider Runs				Fixed-Target Runs			
	$\sqrt{s_{NN}}$ / GeV	events / million	μ_B / MeV		$\sqrt{s_{NN}}$ / GeV	event / million	μ_B / MeV
1	200	380	25	1	13.7 (100)	50	280
2	62.4	46	75	2	11.5 (70)	50	316
3	54.4	1200	85	3	9.2 (44.5)	50	372
4	39	86	112	4	7.7 (31.2)	260	420
5	27	585	156	5	7.2 (26.5)	470	440
6	19.6	595	206	6	6.2 (19.5)	120	490
7	17.3	256	230	7	5.2 (13.5)	100	540
8	14.6	340	262	8	4.5 (9.8)	110	590
9	11.5	257	316	9	3.9 (7.3)	120	633
10	9.2	160	372	10	3.5 (5.75)	120	670
11	7.7	104	420	11	3.2 (4.59)	200	699
				12	3.0 (3.85)	260+2000	750