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

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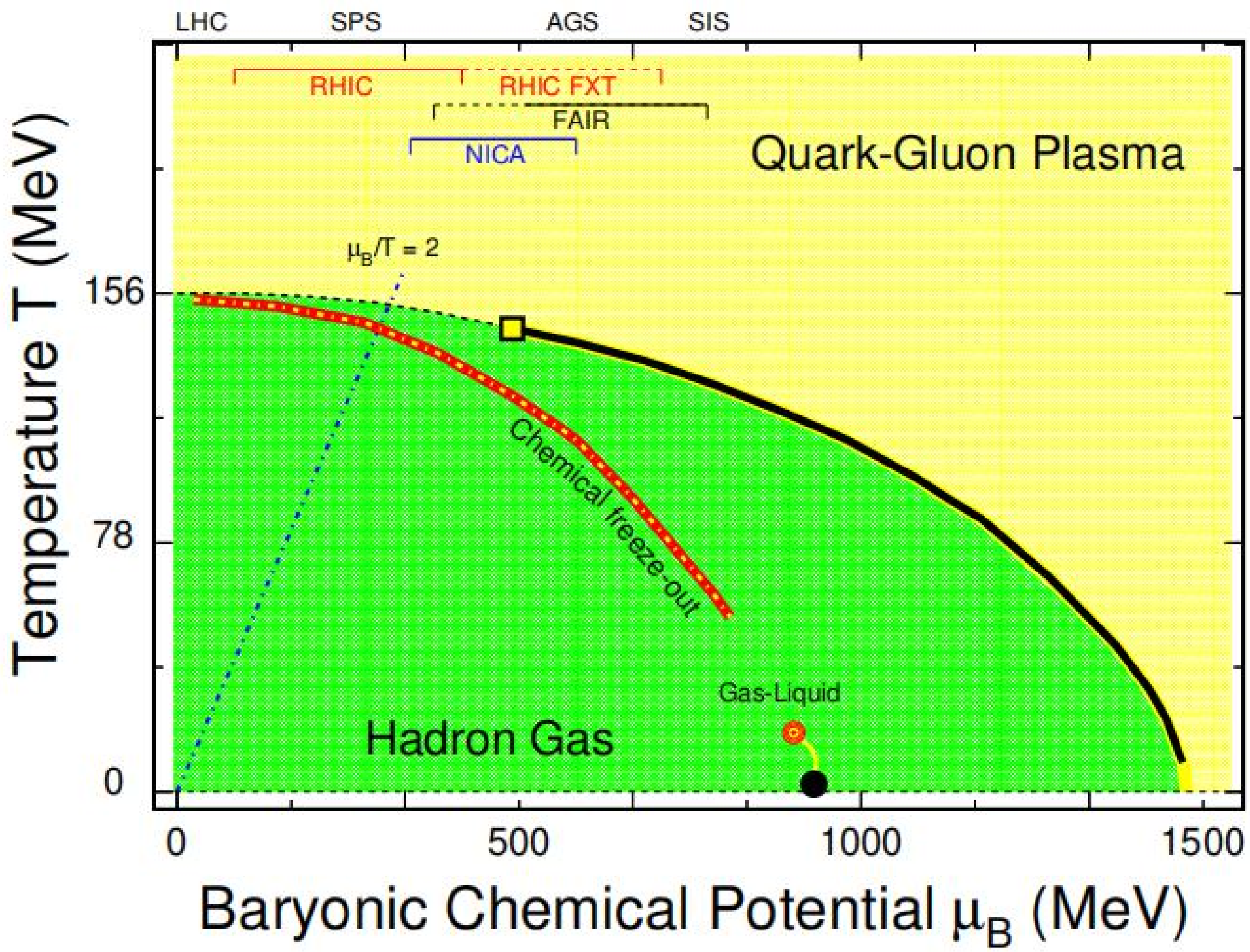
QCD Phase Diagram



X. L. Luo, N. Xu, Nucl. Sci. Tech. 28, 112 (2017)

- **Conjectured phase diagram of strong interactions.**
- Phase diagram of strongly interacting matter in T and μ_B.
- Phase transitions from hadronic matter to quark-gluon plasma:
  ⟶ 1st order transition line ends at critical point.
- Critical point: self-similar, scaling, universality, density fluctuation…
  ⟶ physical signatures.

Objective: detection of the QCD critical point.

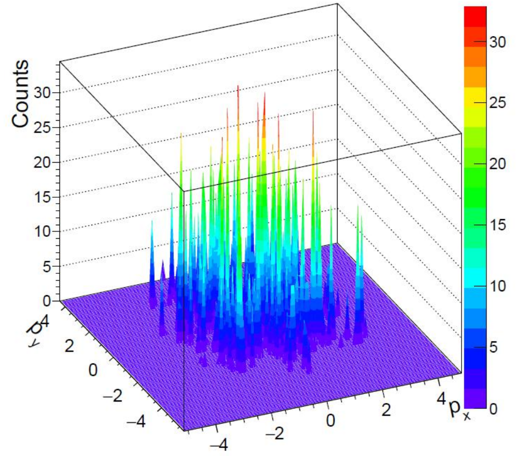
Density fluctuations and Intermittency

- Experimental observation of **local**, **power-law density fluctuations** ⟶ Intermittency analysis in transverse momentum space (critical opalescence in ion collisions).

Density-density correlation function obeys a power-law:

$$< \rho\,(k)\rho(k') > \sim |k - k'|^{-d_F}$$

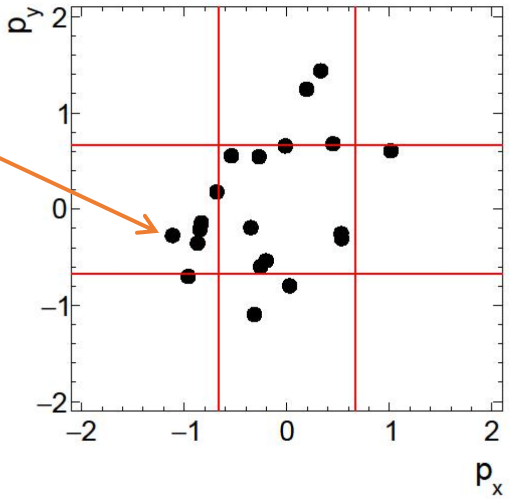
N. G. Antoniou et al, PRL 97, 032002 (2006);
T. Anticic et al. (NA49 Coll.), Eur. Phys. J. C 75, 587 (2015)
J. Wu et al, PLB 801, 135186 (2020).



- Intermittency: local power-law density fluctuations can be detected through the measurement of scaled factorial moments, $F_q(M)$, defined as:

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

n_i denotes multiplicity in the *i*-th cell



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

Observables of Intermittency

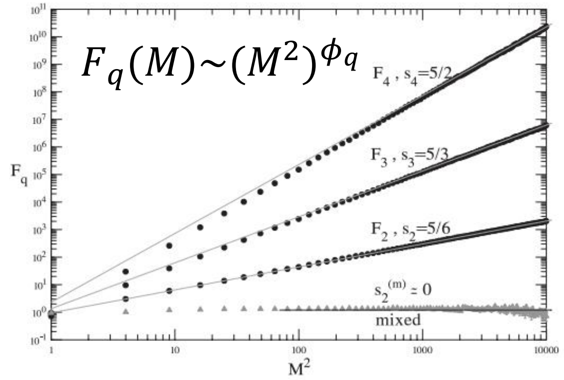
- Intermittency refers to the scaling behavior (power-law) of $F_q(M)$.

- Expected scaling behavior, $\boldsymbol{F_q(M)/M}$ **scaling:**

$$F_q(M) \propto (M^2)^{\phi_q}$$

$$\phi_q^{\text{critical}} = 5q/12(\text{Baryon}),\ \ \phi_q^{\text{critical}} = q/3(\text{pion})$$

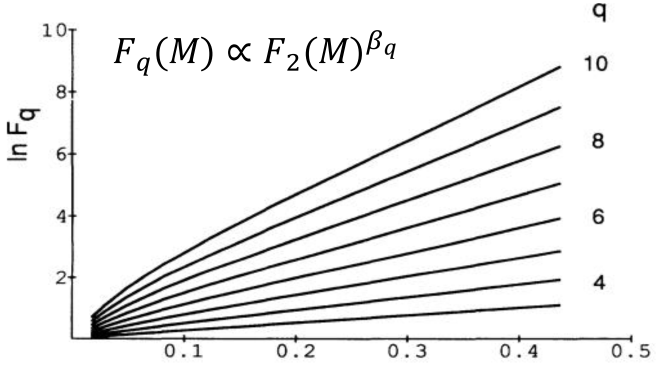
N. G. Antoniou et. al, PRL 97, 032002 (2006);
N. G. Antoniou et. al, PRD 97, 034015(2018).



- Expected $\boldsymbol{F_q(M)/F_2(M)}$ **scaling**, even if $F_q(M)/M$ scaling is not strictly satisfied:

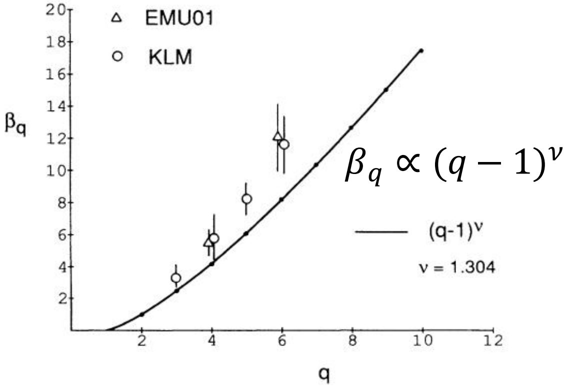
$$F_q(M) \propto F_2(M)^{\beta_q} \qquad \beta_q \propto (q-1)^{\nu}$$

R. C. Hwa et al, PRL 69, 741 (1992);
R. C. Hwa et al, PRD 47, 2773 (1993);
R. C. Hwa et al, PRC 85, 044914 (2012);
X. Y. Long et al, NPA 920, 33-34 (2013).



Scaling exponent, *ν*, quantitatively describes all the scaling indices β_q:

ν_{critical} = 1.304 (Ginzburg-Landau, entire space phase);
= 1.0 (2D Ising).



- *ν* specifies the scaling (power-law) behavior of $F_q(M)$. The energy dependence of ν could be used to search for the signature of the critical point.

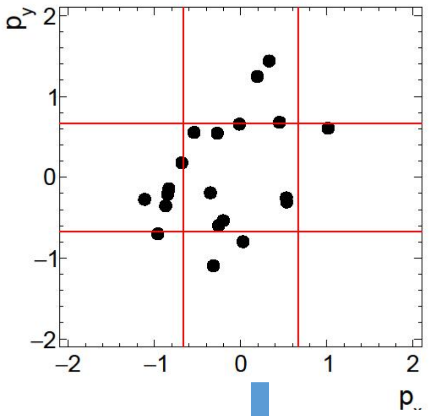
Calculations of Intermittency

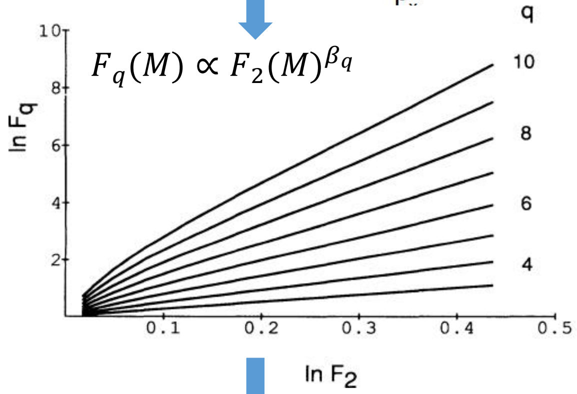
$$F_q(M) = \frac{<\frac{1}{M^D}\sum_{i=1}^{M^D} n_i(n_i-1)\ldots(n_i-q+1)>}{<\frac{1}{M^D}\sum_{i=1}^{M^D} n_i>^q}$$

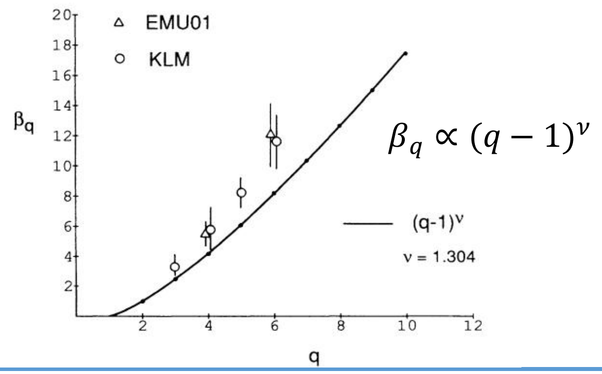
$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M)$$

$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$

$$\beta_q \propto (q-1)^{\nu}$$

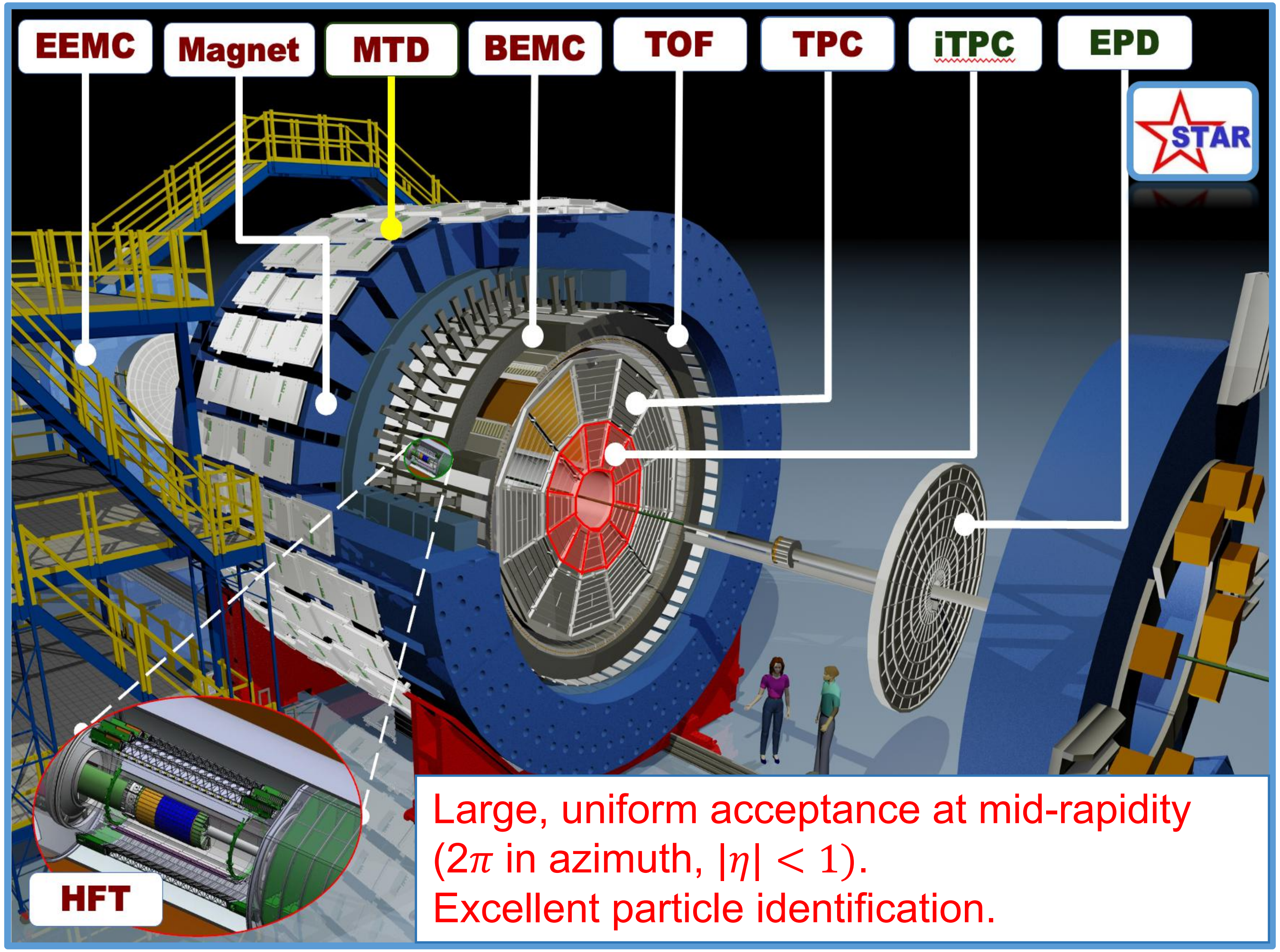






- $F_q(M)$ in transverse momentum space (p_x-p_y).
- Looking for scaling (power-law) behaviors of $F_q(M)$ in Au + Au collisions.
- Energy and centrality dependence of ν in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 200 GeV.

STAR Detector System && Beam Energy Scan Phase I (2010-2017)



Large, uniform acceptance at mid-rapidity (2π in azimuth, $|\eta| < 1$).
Excellent particle identification.

$\sqrt{s_{NN}}$ (GeV)	Year	$^*\mu_B$ (MeV)	$^*T_{CH}$ (MeV)	Events (Million)
7.7	2010	422	140	3
11.5	2010	316	152	7
14.5	2014	264	156	13
19.6	2011	206	160	16
27	2011	156	162	32
39	2010	112	164	89
54.4	2017	83	165	442
62.4	2010	73	165	47
200	2010	25	166	236

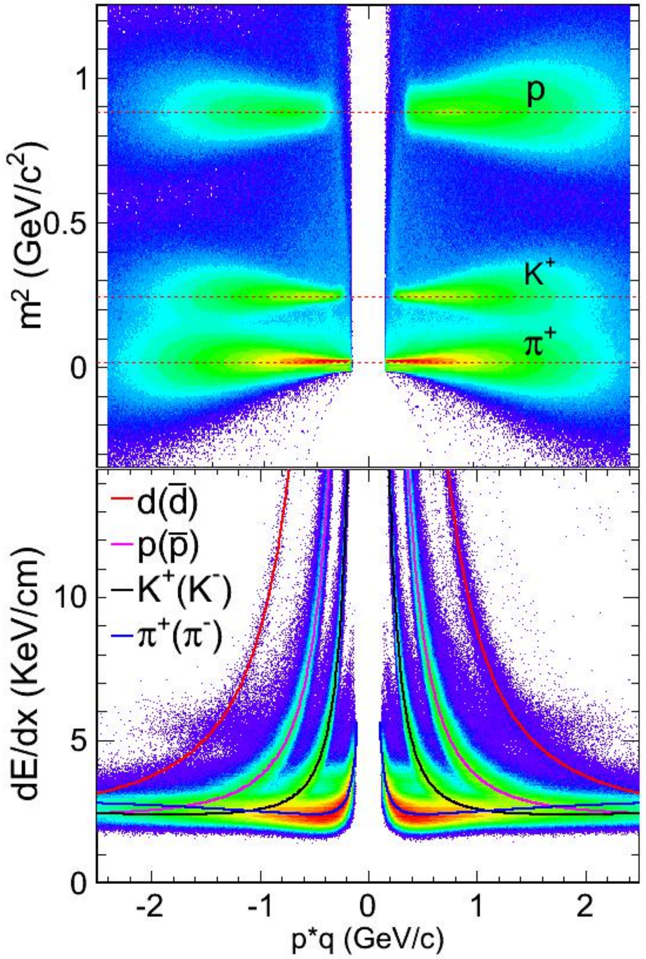
J. Cleymans et. al, PRC 73, 034905 (2006)

- Measurement of intermittency in Au + Au collisions over a much broader energy range of $\sqrt{s_{NN}}$ = 7.7 - 200 GeV.

Analysis Techniques

❑ **Particle identification**:

$p, \bar{p}$	K^+, K^-	π^+, π^-
$\lvert\eta\rvert<0.5$		
$0.4<p_T< 0.8$ (GeV/c)→TPC $0.4<p_T<0.8$ (GeV/c)→TPC+TOF	$0.2<p_T< 0.4$ (GeV/c)→TPC $0.4<p_T<1.6$ (GeV/c)→TPC+TOF	$0.2<p_T< 0.4$ (GeV/c)→TPC $0.4<p_T<1.6$ (GeV/c)→TPC+TOF



Excellent particle identification: uses TPC and TOF.

❑ **Centrality determination:**

Use charged particles ($0.5 < |\eta| < 1$) excluding particles of interest in order to avoid the auto-correlation.

❑ **Mixed event method** is used to remove background and trivial fluctuations:

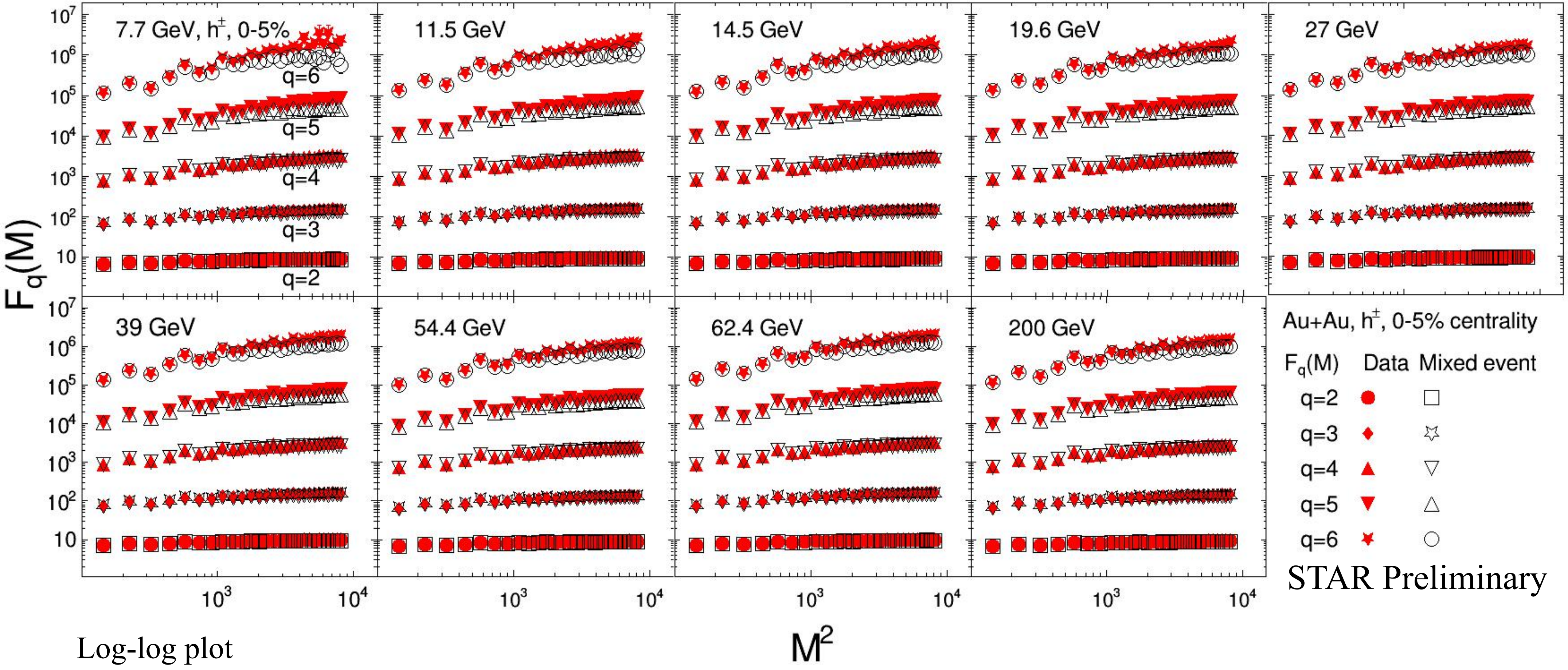
$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M)$$

❑ **Statistical error**: Bootstrap method.

❑ **Efficiency correction**: cell-by-cell method.

J. Wu et al., arXiv: 2104. 11524

$F_q(M)$ (up to sixth order) in Central Au + Au Collisions

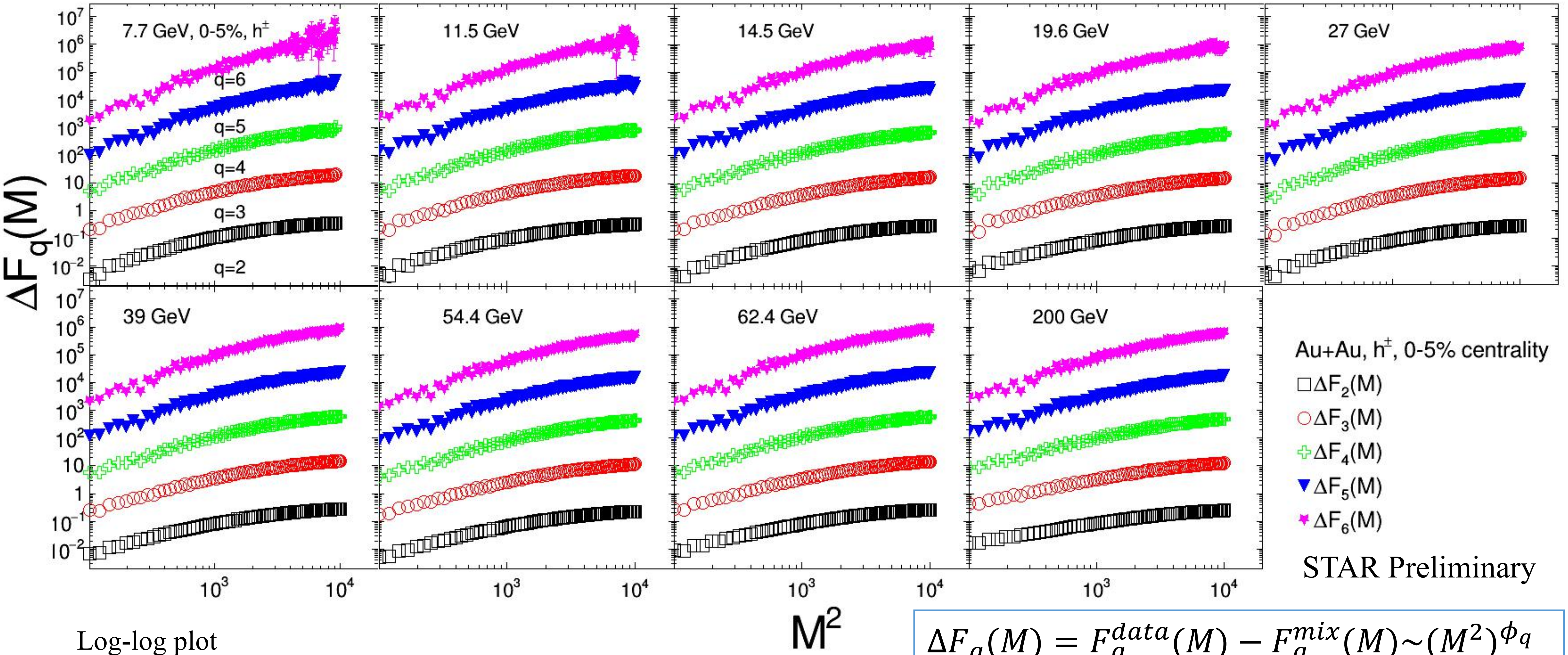


Log-log plot

- The calculations of $F_q(M)$ were performed in the $M^2 \in [1^2,\ 100^2]$ and up to sixth order ($q = 2 \sim 6$). Statistical uncertainties are shown but smaller than maker size.
- $F_q^{data}(M)$ are larger than $F_q^{mix}(M)$ at large M^2 region.

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

$\Delta F_q(M)$ in Central Au + Au Collisions

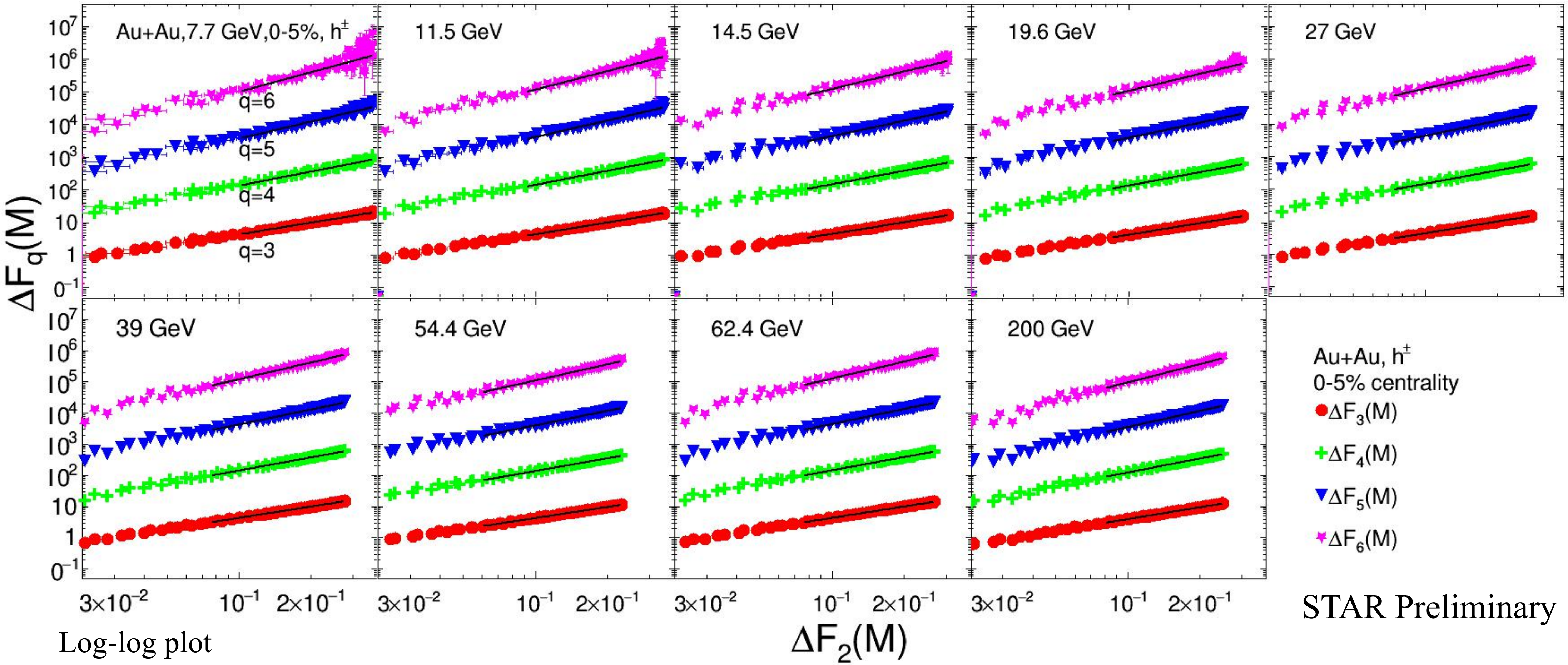


Log-log plot

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

- All orders of $\Delta F_q(M)$ rise with increasing M^2, but can not be fitted well by $\Delta F_q(M)/M$ scaling function. $\Delta F_q(M)/M$ scaling behavior is not strictly satisfied.

$\Delta F_q(M)$ / $\Delta F_2(M)$ Scaling in Central Au + Au Collisions



STAR Preliminary

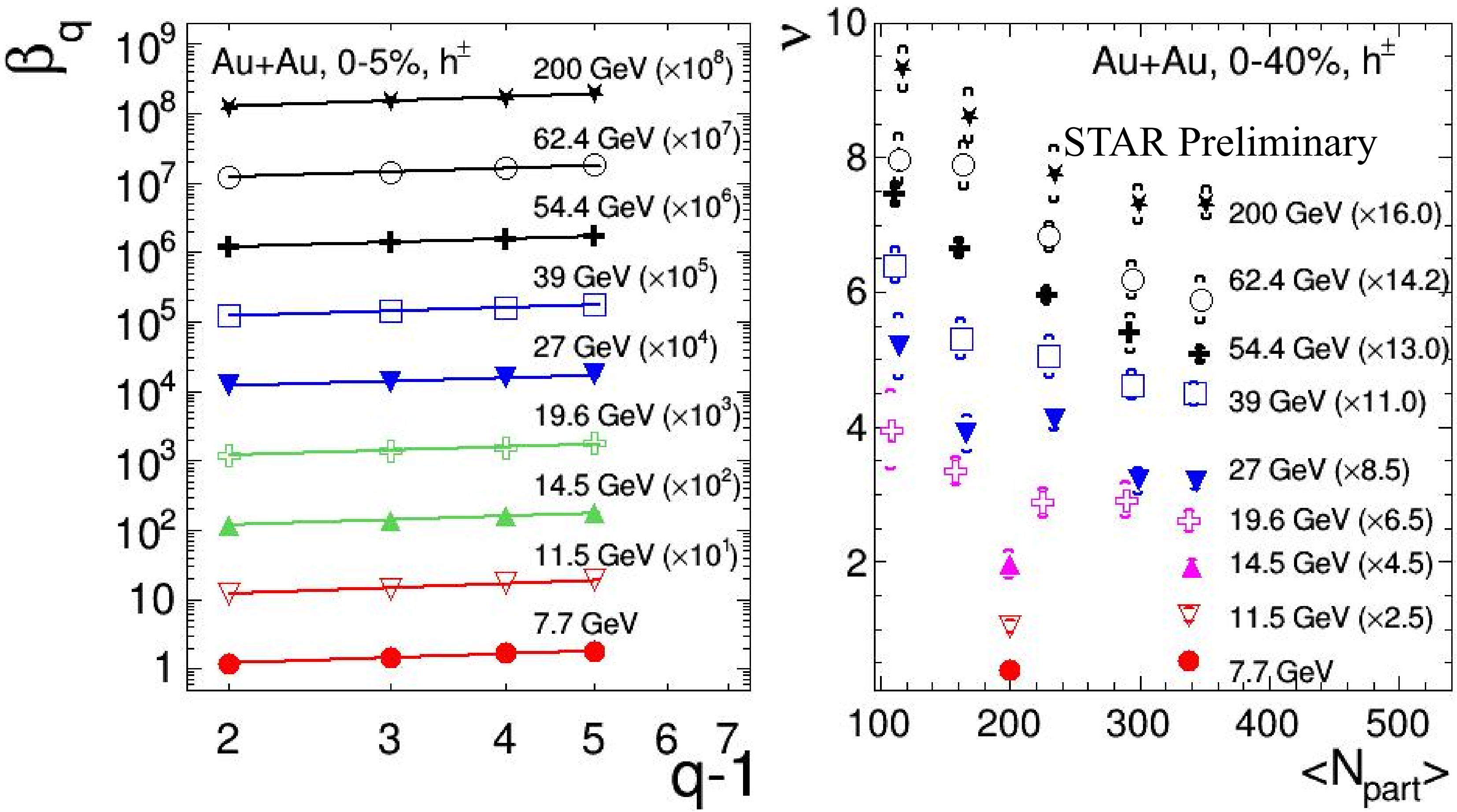
Log-log plot

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

$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$

- The index β_q is obtained through a power-law fit of $\Delta F_q(M)/\Delta F_2(M)$ scaling. Its error is determined by the fit.
- Clear $\Delta F_q(M)/\Delta F_2(M)$ scaling behaviors are visible with $\beta_6>\beta_5>\beta_4>\beta_3$.

β_q/q Scaling and Centrality Dependence of ν



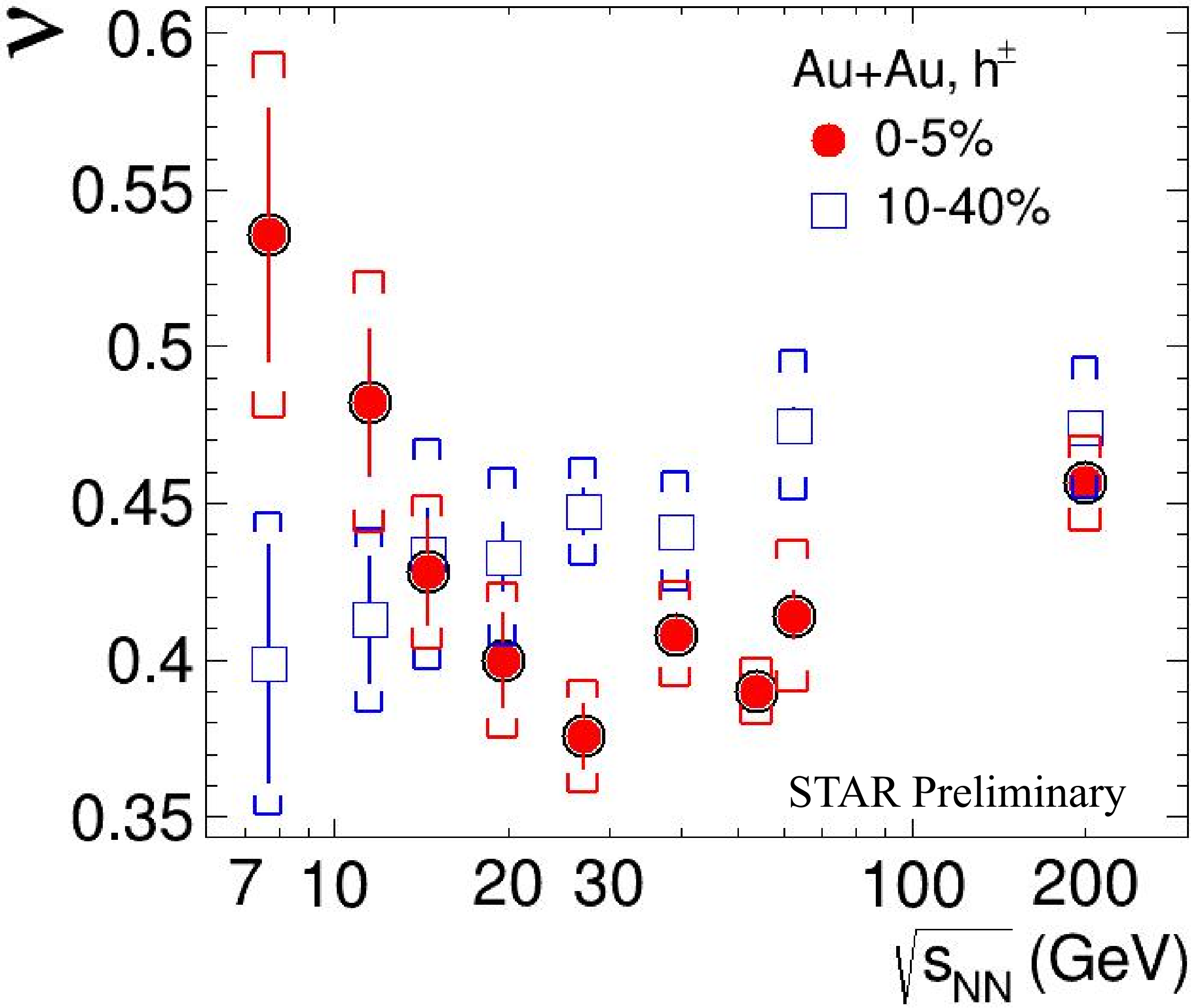
$$F_q(M) = \frac{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i(n_i-1)\ldots(n_i-q+1) >}{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i >^q}$$

$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$

$$\beta_q \propto (q-1)^{\nu}$$

- Clear β_q/q scaling behaviors are visible in central Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7-200 GeV.
- The scaling exponent, ν, is obtained through a power-law fit of β_q/q scaling. Its error is determined by the fit.
- Scaling exponent, ν, decreases from mid-central (30-40%) to the most central (0-5%) Au + Au collisions.

Energy Dependence of ν



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

$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$

$$\beta_q \propto (q-1)^{\nu}$$

- Scaling exponent exhibits a non-monotonic behavior on collision energy and seems to reach a minimum around $\sqrt{s_{NN}}$ = 20-30 GeV in the most central collisions.
- In 10-40% central collisions, ν monotonically increases with increasing collision energy at $\sqrt{s_{NN}}$ = 7.7 – 200 GeV.

Summary and Outlook

Summary:

- We report the first measurement of intermittency for charged particles in Au + Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 7.7 - 200 GeV measured by STAR experiment in the first phase of RHIC beam energy scan.

- A clear $\Delta F_q(M)/\Delta F_2(M)$ scaling (power-law) behavior is visible in central Au + Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 7.7 - 200 GeV. β_q can be extracted from $\Delta F_q(M)/\Delta F_2(M)$ scaling.

- In 10-40% central collisions, scaling exponent, ν, monotonically increases with increasing collision energy. More importantly, ν exhibits a non-monotonic energy dependence with a minimum around $\sqrt{s_{\mathrm{NN}}}$ = 20-30 GeV in the most central Au + Au (0-5%) collisions.

Outlook:

- The RHIC BES Phase-II program will allow precise measurement of intermittency for exploring the QCD phase structure within $200 < \mu_B < 720$ (MeV).

Thank you!

Backup slides

$F_q(M)/F_2(M)$ Scaling

- In experiments, even if the $F_q(M)/M$ scaling behaviors is not strictly obeyed, it is possible that:

$$F_q(M) \propto F_2(M)^{\beta_q}, \quad \beta_q = \phi_q / \phi_2$$

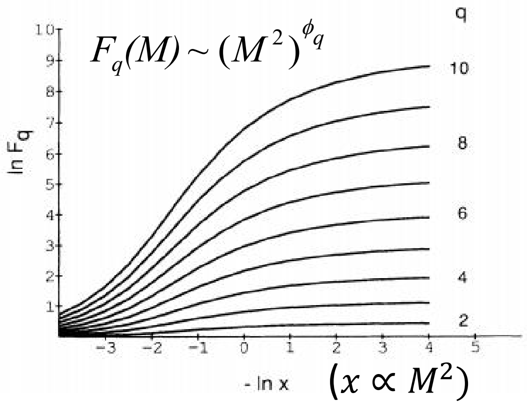
- Using Ginzburg-Landau formalism, $F_q(M)$ can be written as:

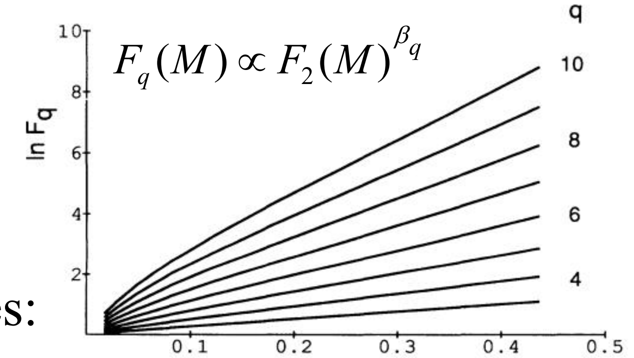
$$f_q = Z^{-1}\delta^q \pi \int_0^\infty d|\phi|^2 |\phi|^{2q} e^{-\delta(b|\phi|^4 - |a||\phi|^2)}$$

- Where ϕ is coherent state, δ is the size of a small cell and is depended on M^2. The values of a and b would vary with time since these values are regarded to depend on temperature T.

- β_q is independent of GL parameters, however, ϕ_q is not.

- The **scaling exponent, *ν***, quantitatively describes all the intermittency indices:



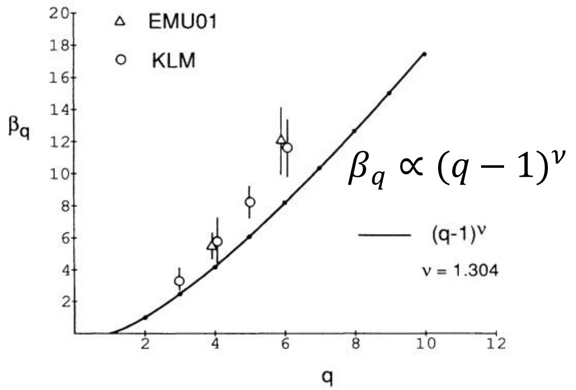


$$\beta_q \propto (q-1)^\nu$$

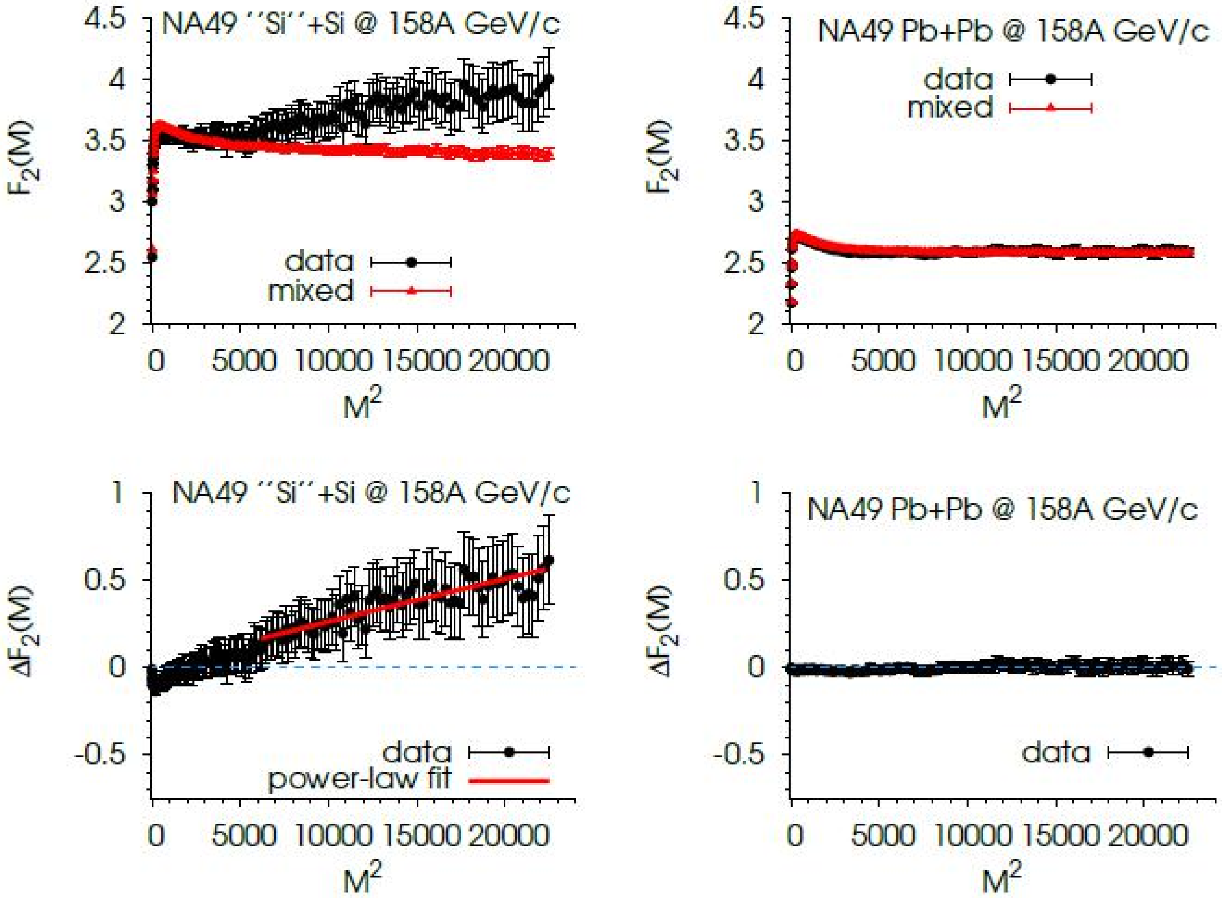
R. C. Hwa et al, PRL 69, 741 (1992);
R. C. Hwa et al, PRD 47, 2773 (1993);
R. C. Hwa et al, PRC 85, 044914 (2012);
X. Y. Long et al, NPA 920, 33-34 (2013).

$\nu_{critical}$ = 1.0 (2D Ising);
= 1.304 (Ginzburg-Landau, entire space phase);

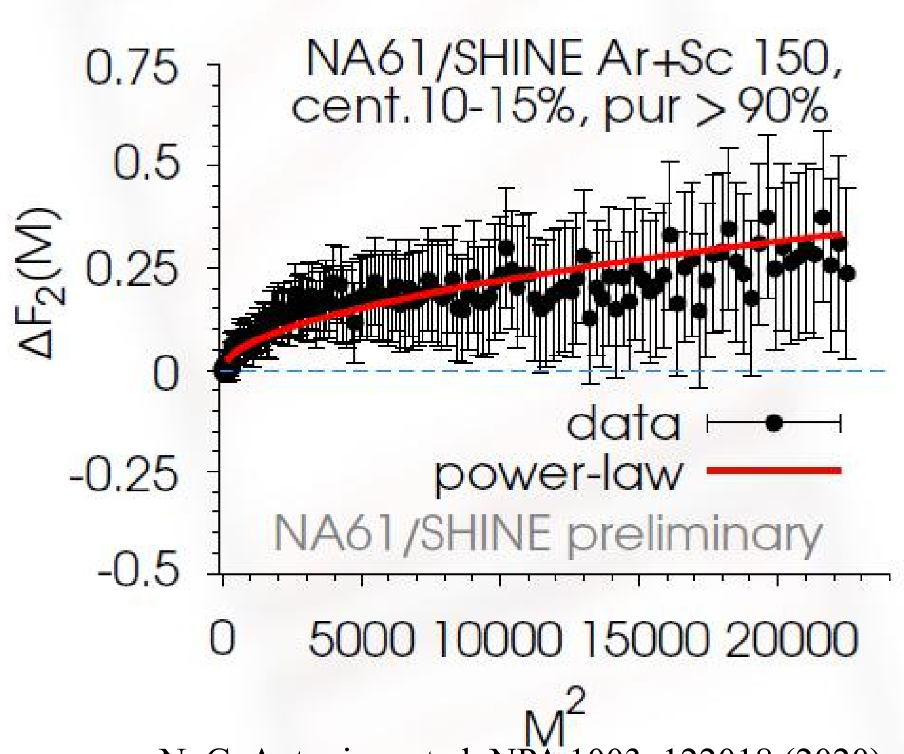
ν = 1.743 from UrQMD model. S. Bhattacharyya, EPJP 136, 471 (2021).
ν = 1.94 from AMPT model. X. Y. Long et al, NPA 920, 33-34 (2013).



Intermittency from NA49/NA61 Experiments



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



N. G. Antoniou, et al, NPA 1003, 122018 (2020).
T. Czopowicz (NA61 Coll.), CPOD2021.

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

- Intermittency of NA49/NA61 experiment revealed significant power-law (scaling) fluctuations of proton density in **Si + Si** collisions at $\sqrt{s_{NN}} = 17.3$ GeV.
- No intermittent behavior is visible in **Pb + Pb** collisions and C + C collisions at $\sqrt{s_{NN}} = 17.3$ GeV.
- A non-trivial intermittency effect is observed in preliminary results in **Ar + Sc** collisions $\sqrt{s_{NN}} = 16.8$ GeV.

Efficiency Correction: Cell-by-cell Method

- Assuming detector efficiency follows binomial distribution, f_q^{ture} is recovered by dividing the $f_q^{measured}$ with appropriate power of the efficiency:

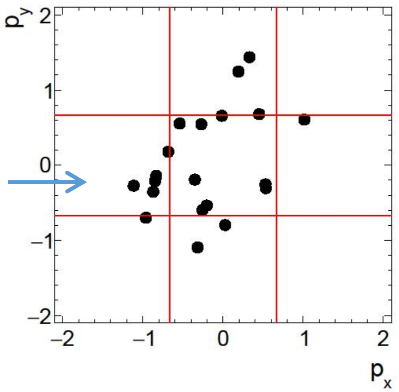
$$f_q^{corrected} = \frac{f_q^{measured}}{\varepsilon^q} = \frac{< n(n-1)...(n-q+1) >}{\varepsilon^q} \qquad (1)$$

- Definition of $F_q(M)$: $$F_q(M) = \frac{< \frac{1}{M^D}\sum_{i=1}^{M^D} n_i(n_i-1)\ldots(n_i-q+1) >}{< \frac{1}{M^D}\sum_{i=1}^{M^D} n_i >^q} \qquad (2)$$

- Every factors of measured $F_q(M)$ should be corrected one by one.

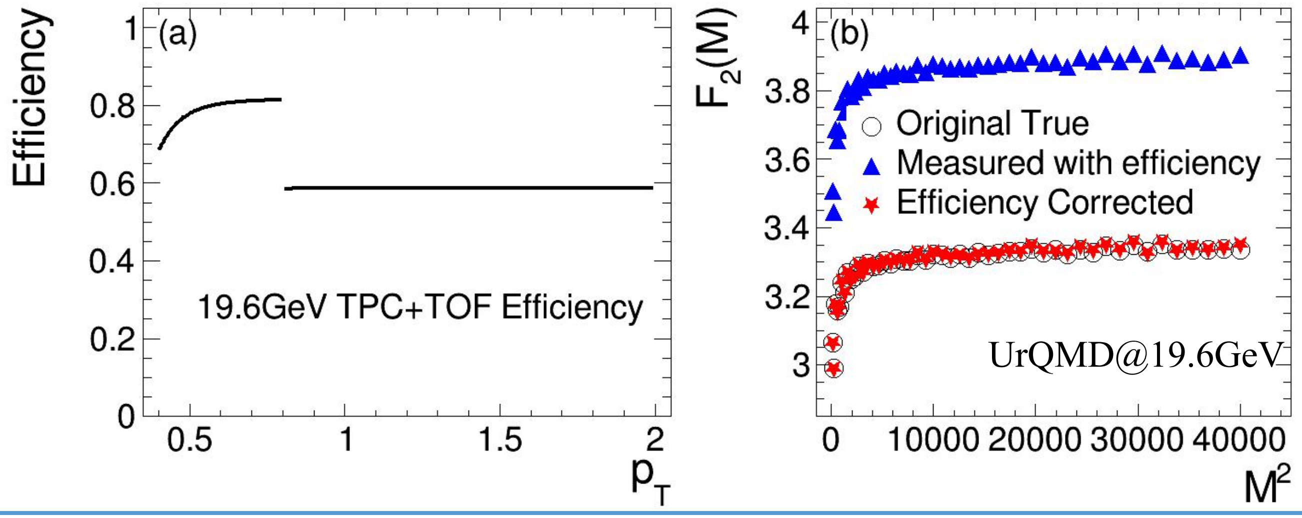
$$F_q^{corrected}(M) = \frac{< \frac{1}{\mathrm{M}^2}\sum_{i=1}^{M^2} \frac{n_i(n_i-1)\ldots(n_i-q+1)}{\bar{\varepsilon}_i^q} >}{< \frac{1}{M^2}\sum_{i=1}^{M^2} \frac{n_i}{\bar{\varepsilon}_i} >^q} \qquad (3)$$

$\bar{\varepsilon}_i = < \frac{1}{n_i}\sum_{j=1}^{n_i} \varepsilon_j >$ in i-th cell

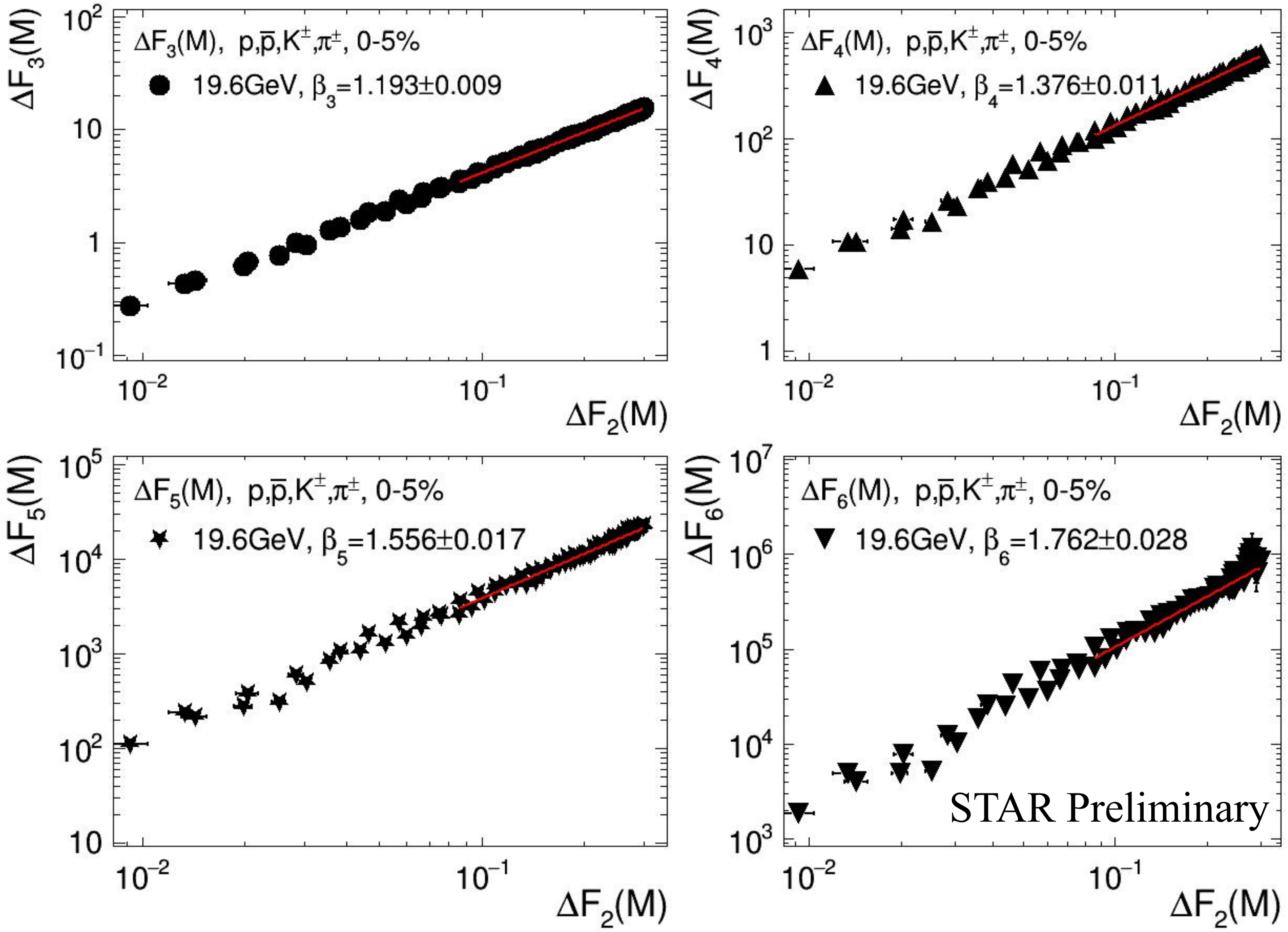


- Experimental p_T -dependent efficiency for TPC+TOF detector is employed into the samples at $\sqrt{s_{NN}} = 19.6$ GeV from UrQMD model. The efficiency corrected $F_q(M)$ are found to be well consistent with the original true one.

J. Wu et al., arXiv: 2104. 11524



$\Delta F_q(M)$ / $\Delta F_2(M)$ Scaling in Most Central Au + Au Collisions



- The effect of scaling is associated with small momentum scales. Therefore M^2 should be large enough.

  T. A et al. (NA49 Coll.) PRC 81,064907 (2010).

  Fitting range $\Delta F_2(M) \sim M^2 (30^2, 100^2)$.

- The index β_q is obtained through a power-law fit of $\Delta F_q(M)/\Delta F_2(M)$ scaling. Its error is determined by the fit.

- Clear $\Delta F_q(M)/\Delta F_2(M)$ scaling behaviors are found with $\beta_6 > \beta_5 > \beta_4 > \beta_3$.

$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$