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

Jin Wu (for the STAR collaboration)
Central China Normal University

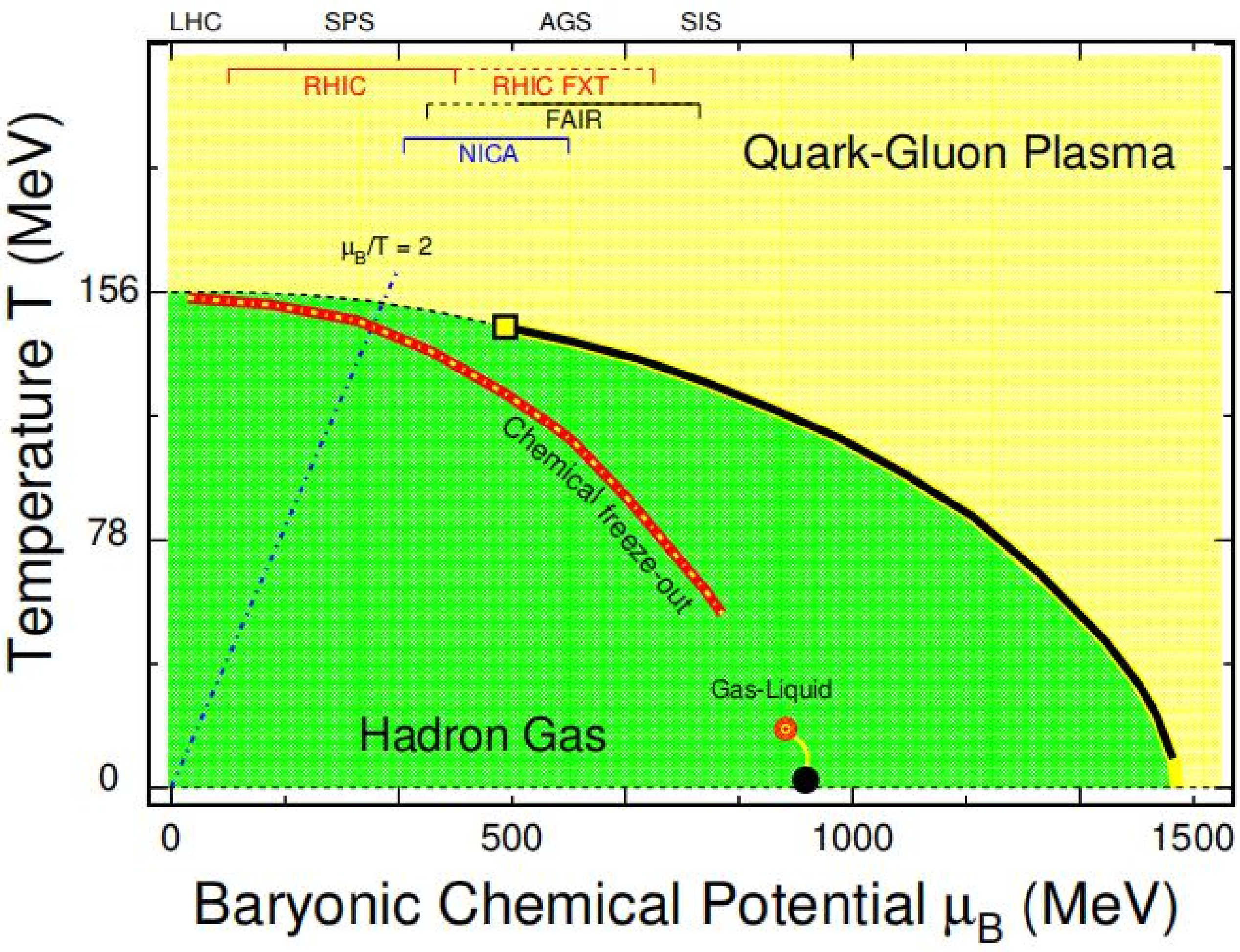
ISMD2021 50th International Symposium on Multiparticle Dynamics (ISMD2021)

U.S. DEPARTMENT OF ENERGY | Office of Science
This work is supported by the grant from DOE office of science

Outline

- QCD Phase Transition and Critical Point
- Intermittency Analysis
- The STAR Experiment Setup
- Results
- Summary

QCD Phase Diagram



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.

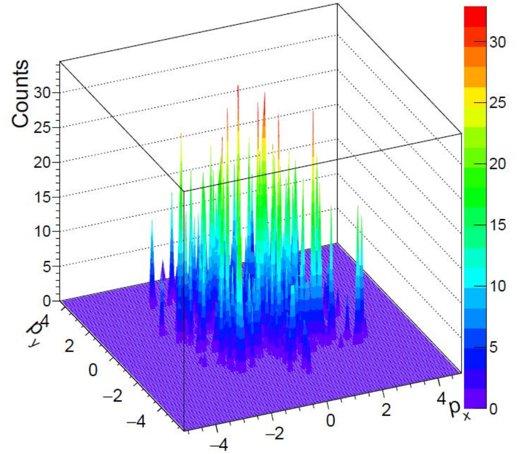
Objective: detection of the QCD critical point.

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

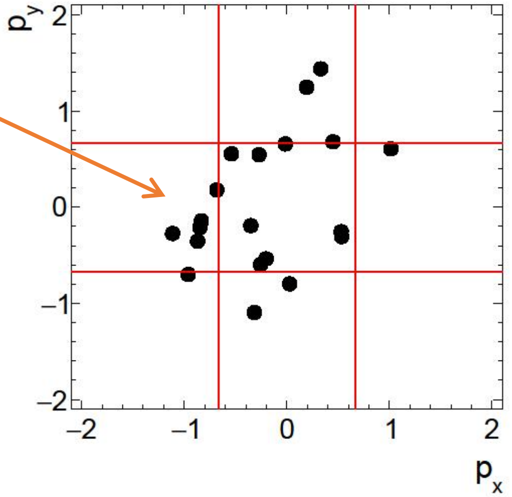
PRL 97, 032002 (2006);
EPJC 75, 587 (2015);
PLB 801, 135186(2020).



- 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 particle 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, $<\ \ >$ denotes averaging over events.

- E.g, transverse momentum space, D=2, q=2

$$F_2(M) = \frac{< \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i-1) >}{< \frac{1}{M^2} \sum_{i=1}^{M^2} n_i >^2}$$

Measurement of Intermittency

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

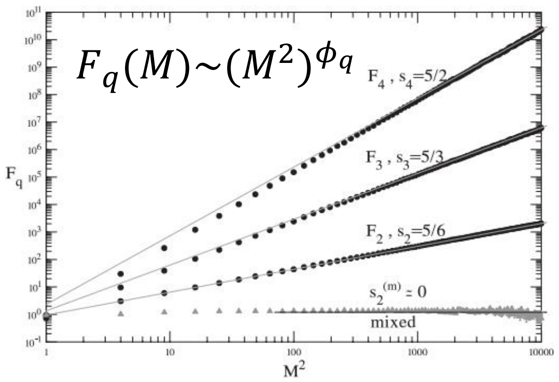
- Expected scaling behavior, $\boldsymbol{F_q(M)/M}$ **scaling:**

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

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

Critical system in transverse momentum space.

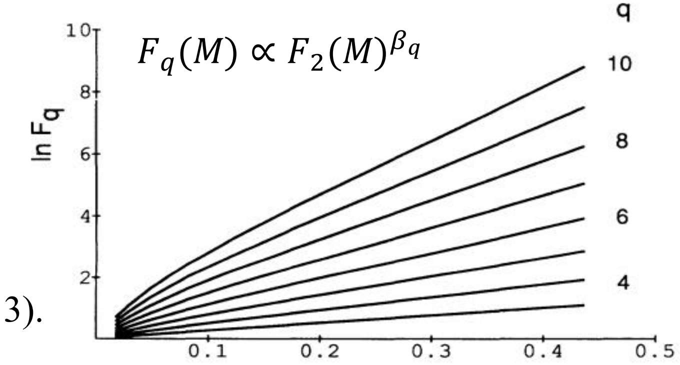
PRL 97, 032002 (2006);
PRD 97, 034015(2018).



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

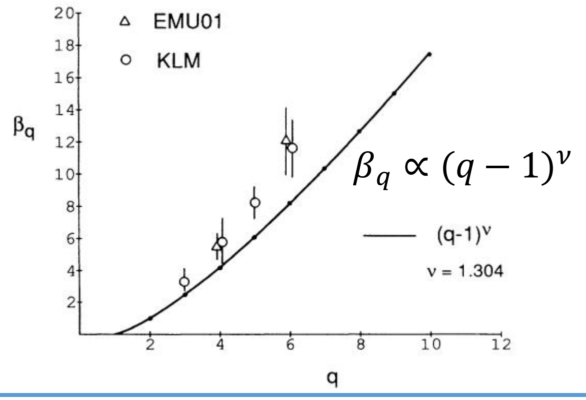
$$F_q(M) \propto F_2(M)^{\beta_q} \qquad \beta_q \propto (q-1)^{\nu}$$

PRL 69, 741 (1992); PRD 47, 2773 (1993);
PRC 85, 044914 (2012); NPA 920, 33-34 (2013).



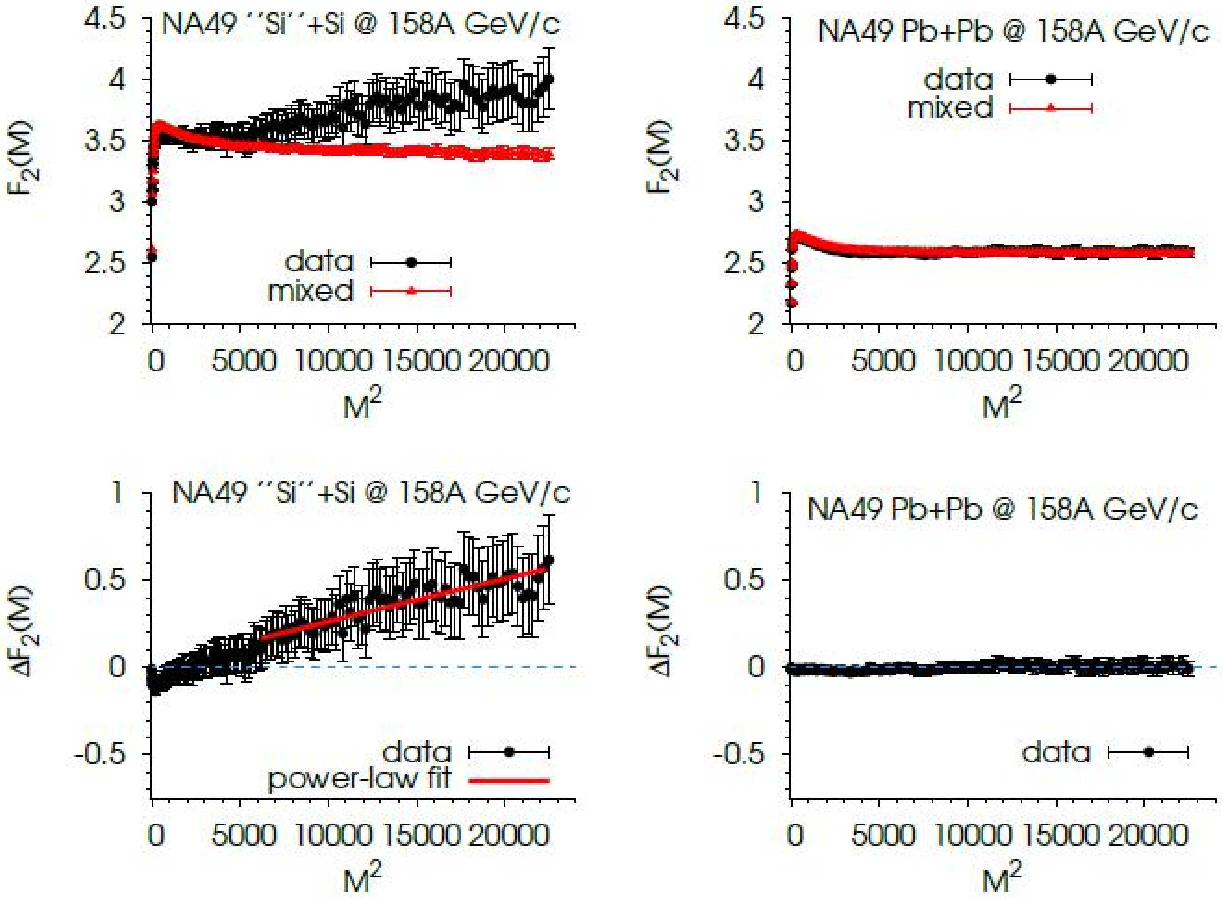
Scaling exponent, *ν*, quantitatively describes all the scaling indices β_q:

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

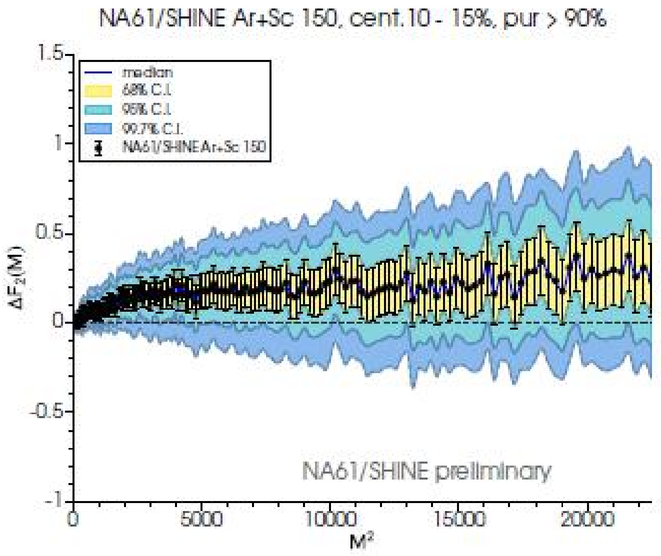


- *ν* specifies the scaling (power-law) behavior of $F_q(M)$. The energy dependence of ν could be used to search for the signature of the critical point.

Intermittency from NA49/NA61 Experiments



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



QM2019, Maja Mackowiak, et .al.(NA61 Coll.)

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

- 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.
- A non-trivial intermittency effect is observed in preliminary results in **Ar + Sc** collisions $\sqrt{s_{NN}} = 16.8$ GeV.
- No intermittent behavior is visible in **Pb + Pb** collisions and C + C collisions at $\sqrt{s_{NN}} = 17.3$ GeV.

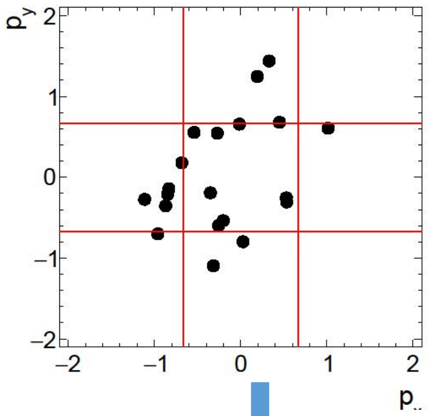
Procedure-Intermittency

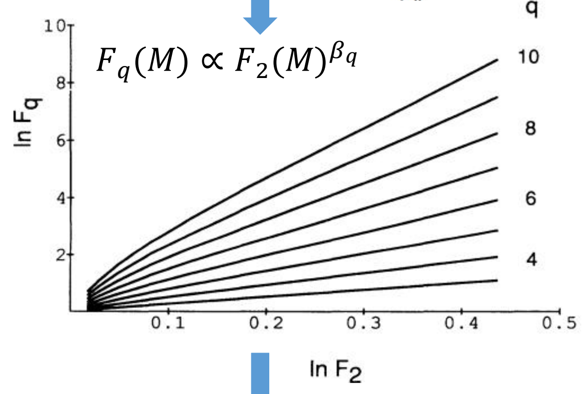
$$F_q(M) = \frac{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i(n_i-1)\ldots(n_i-q+1) >}{< \frac{1}{M^D} \sum_{i=1}^{M^D} n_i >^q}$$

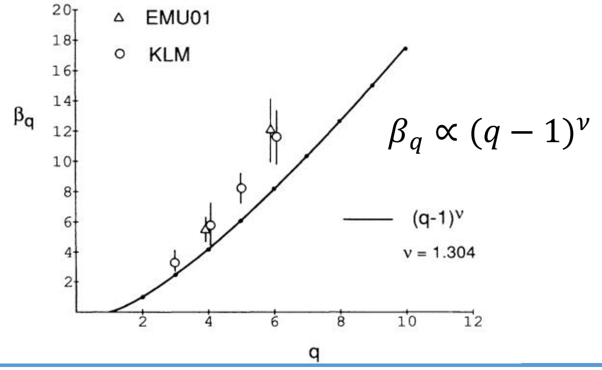
$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M)$$

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

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

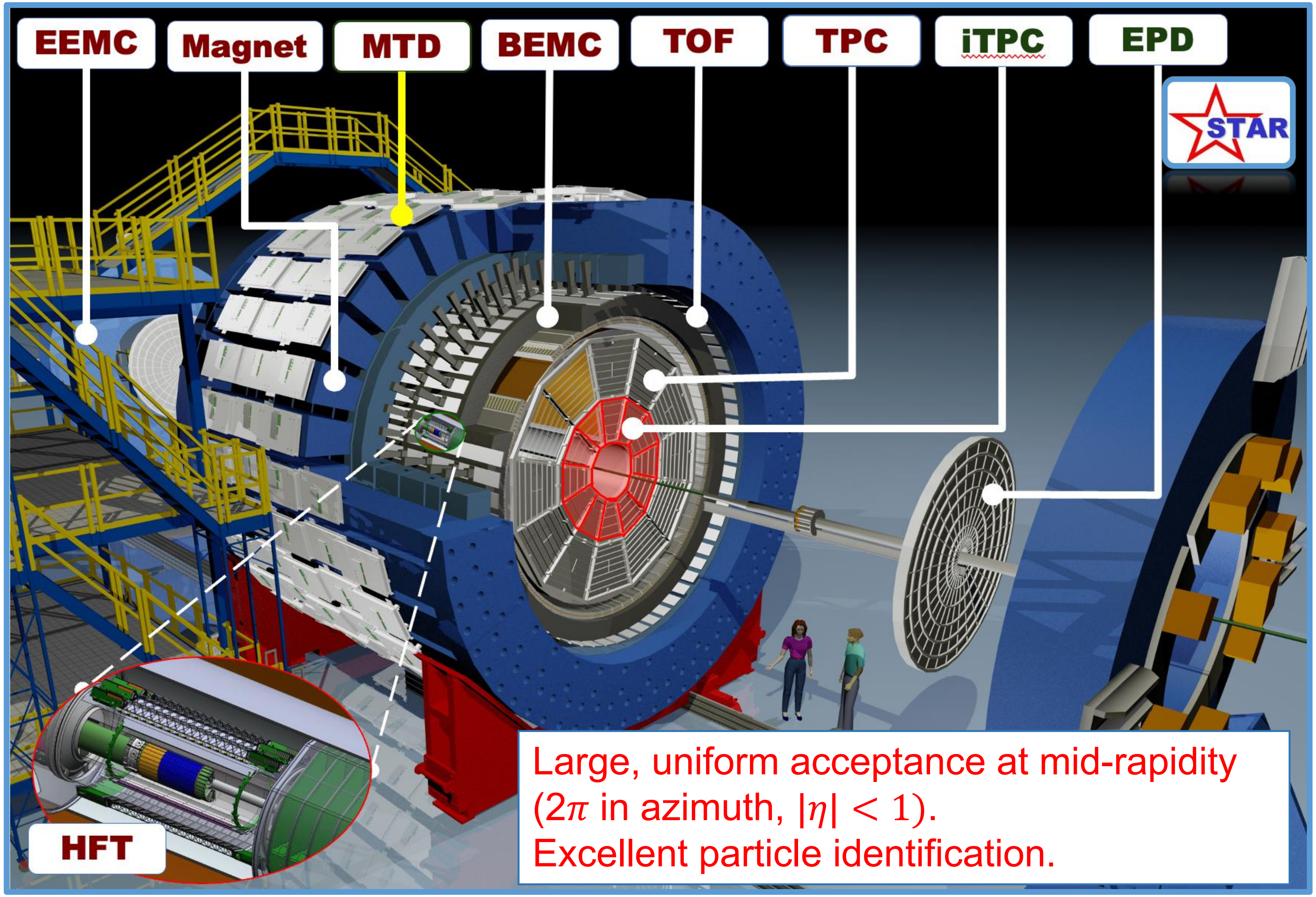






- $F_q(M)$ in transverse momentum space (p_x-p_y).
- Looking for scaling (power-law) behaviors of $F_q(M)$ in Au + Au collisions.
- Energy and centrality dependence of ν in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 200 GeV.

STAR Detector System

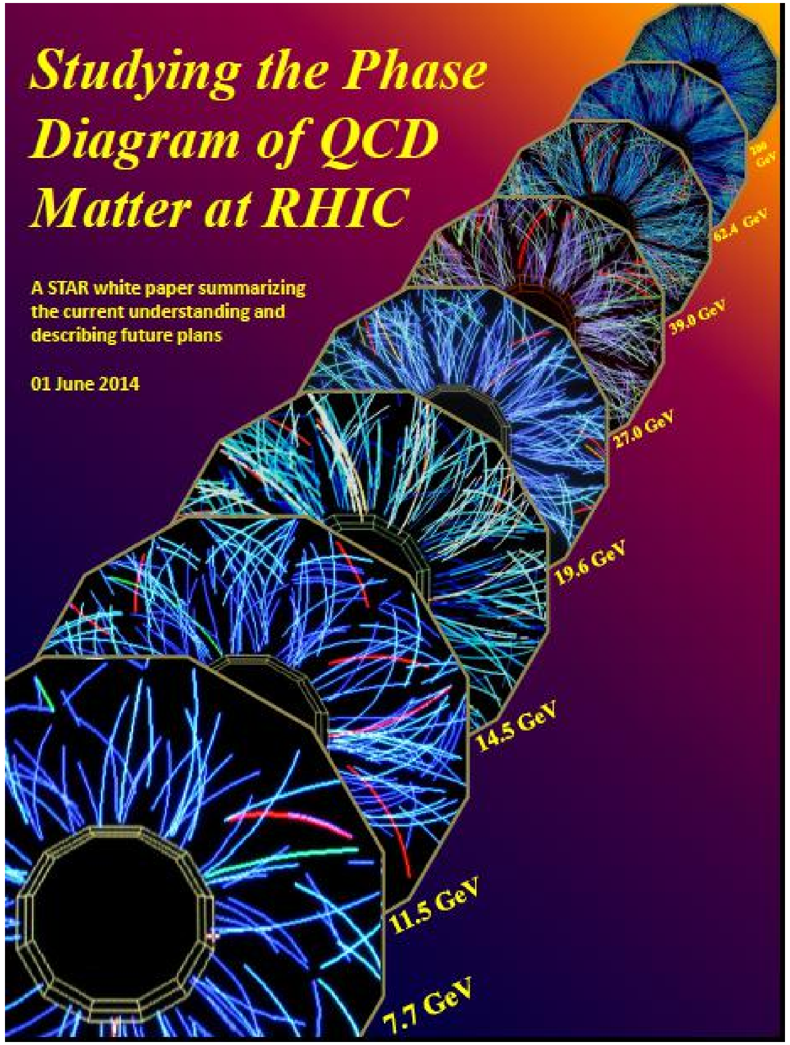


Large, uniform acceptance at mid-rapidity
(2π in azimuth, $|\eta| < 1$).
Excellent particle identification.

RHIC Beam Energy Scan Phase I (2010-2017)

$\sqrt{s_{NN}}$ (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

PRC 73, 034905 (2006)



https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493

- 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

- **Centrality determination:**

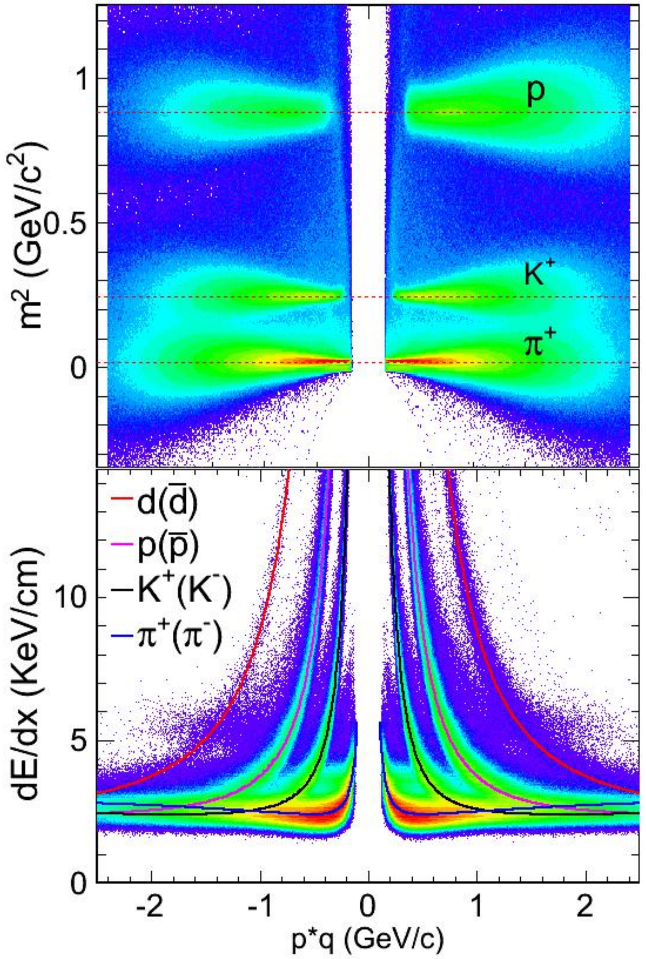
Use charged particles ($0.5 < |\eta| < 1$) excluding particles of interest in order to avoid the auto-correlation.

- **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.



Excellent particle identification: uses TPC and TOF.

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:

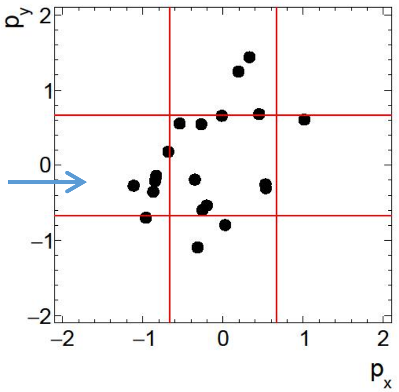
$$f_q^{corrected} = \frac{f_q^{measured}}{\varepsilon^q} = \frac{< n(n-1)\ldots(n-q+1) >}{\varepsilon^q} \qquad (1)$$

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

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

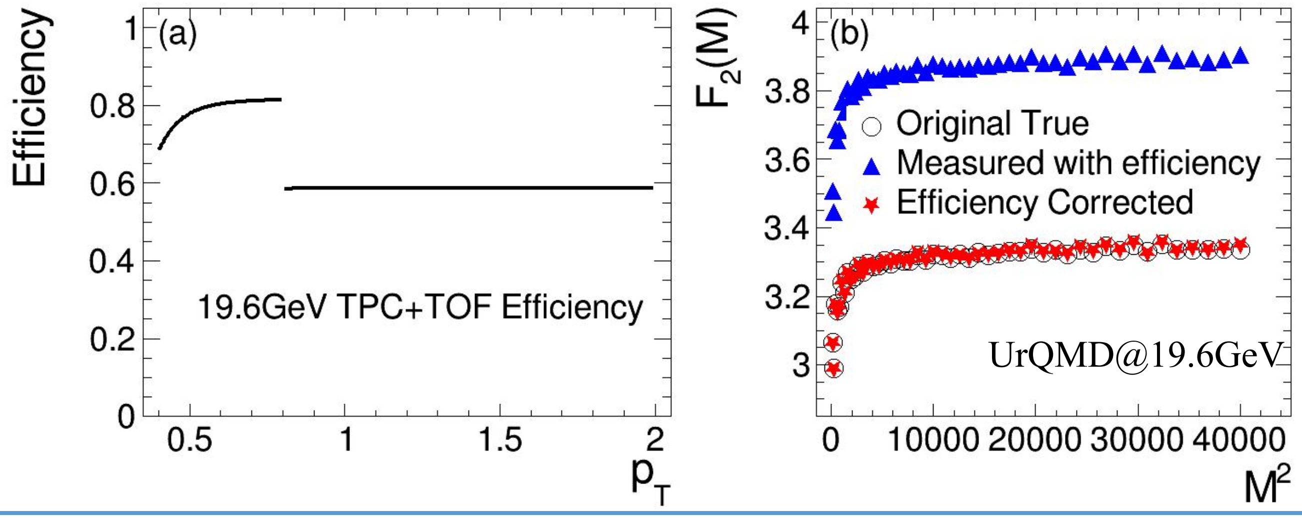
$$F_q^{corrected}(M) = \frac{< \frac{1}{\mathrm{M}^2}\sum_{i=1}^{M^2} \frac{n_i(n_i-1)\ldots(n_i-q+1)}{\bar{\varepsilon}_i^q} >}{< \frac{1}{M^2}\sum_{i=1}^{M^2} \frac{n_i}{\bar{\varepsilon}_i} >^q} \qquad (3)$$

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

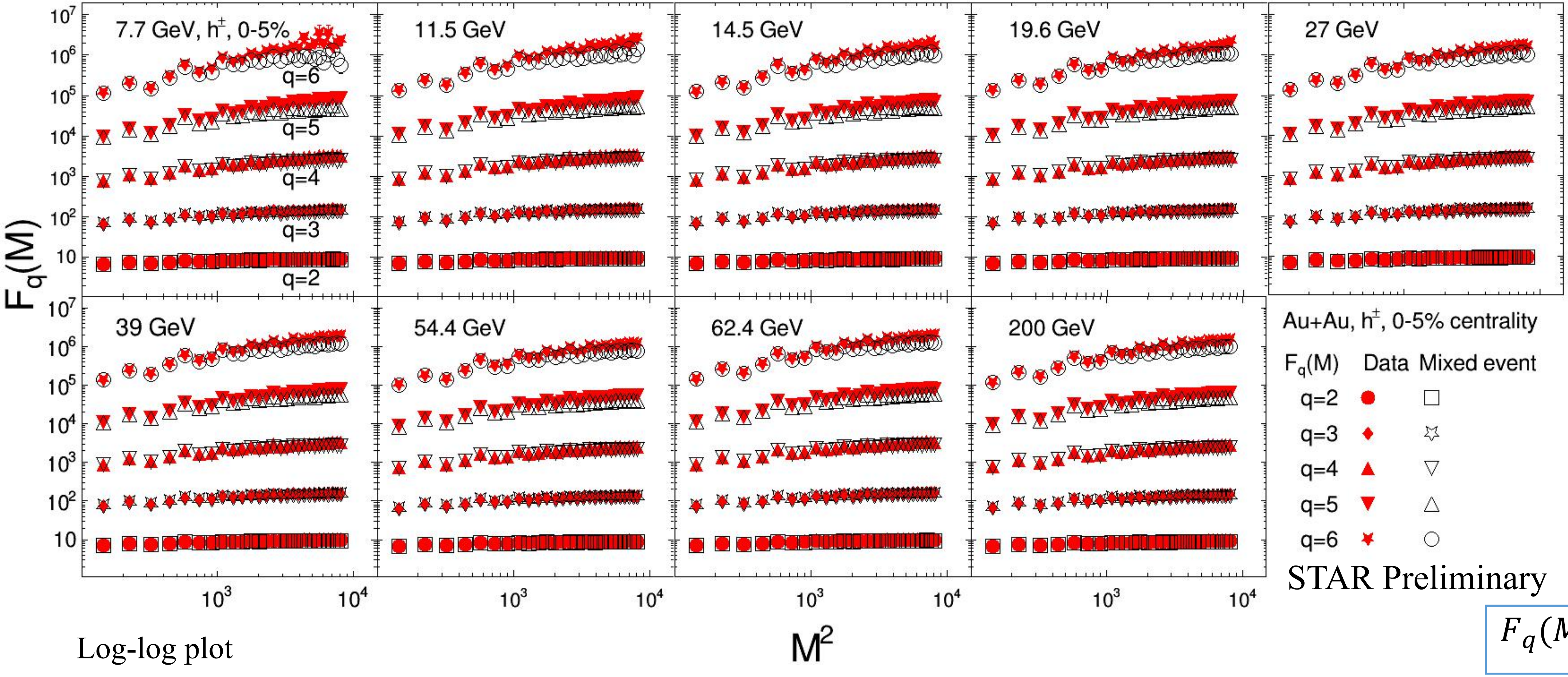


- Experimental p_T-dependent efficiency for TPC+TOF detector is employed into the samples at $\sqrt{s_{NN}} = 19.6$ GeV from UrQMD model. The efficiency corrected $F_q(M)$ are found to be well consistent with the original true one.

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



$F_q(M)$ in Most Central Au + Au Collisions



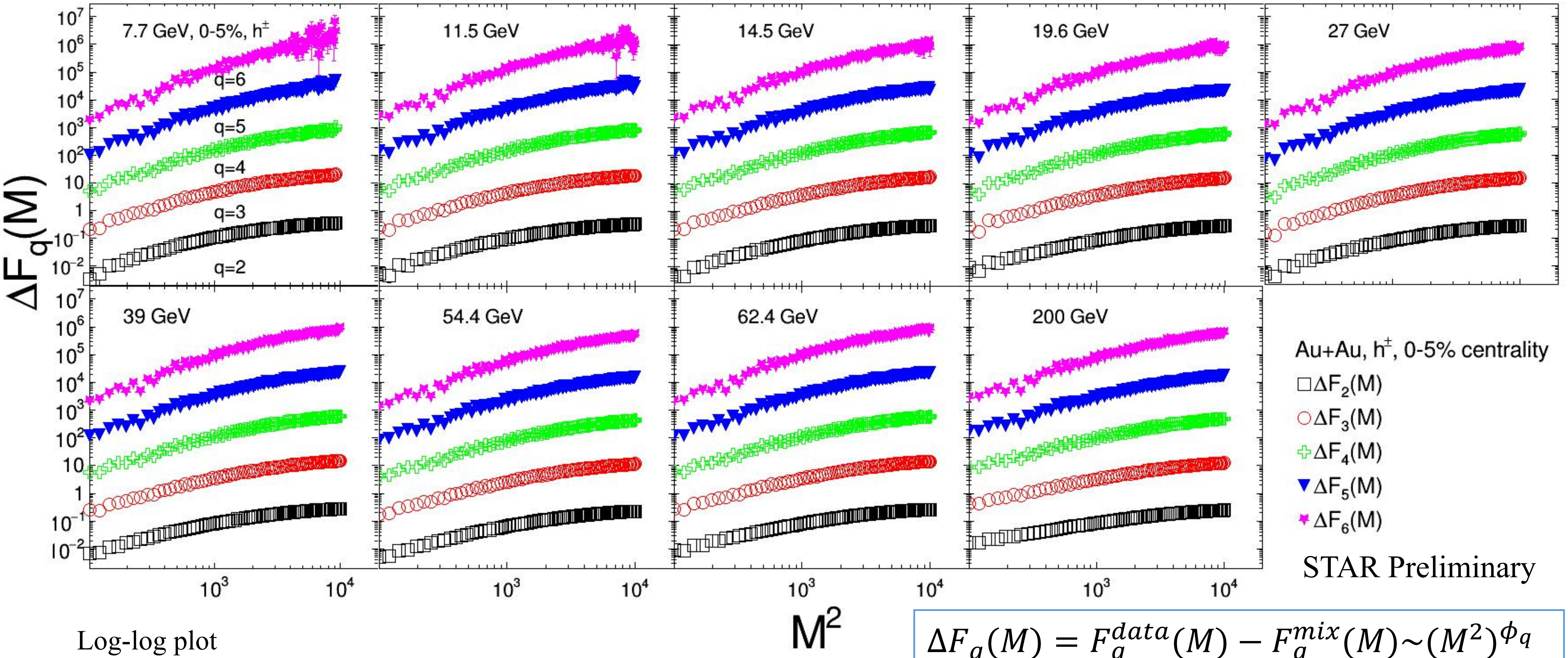
Log-log plot

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

- The calculations of $F_q(M)$ were performed in the $M^2 \in [1^2,\ 100^2]$ and up to six order ($q = 2\sim6$). 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. Intermittency effect is detected in central Au + Au collisions.

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

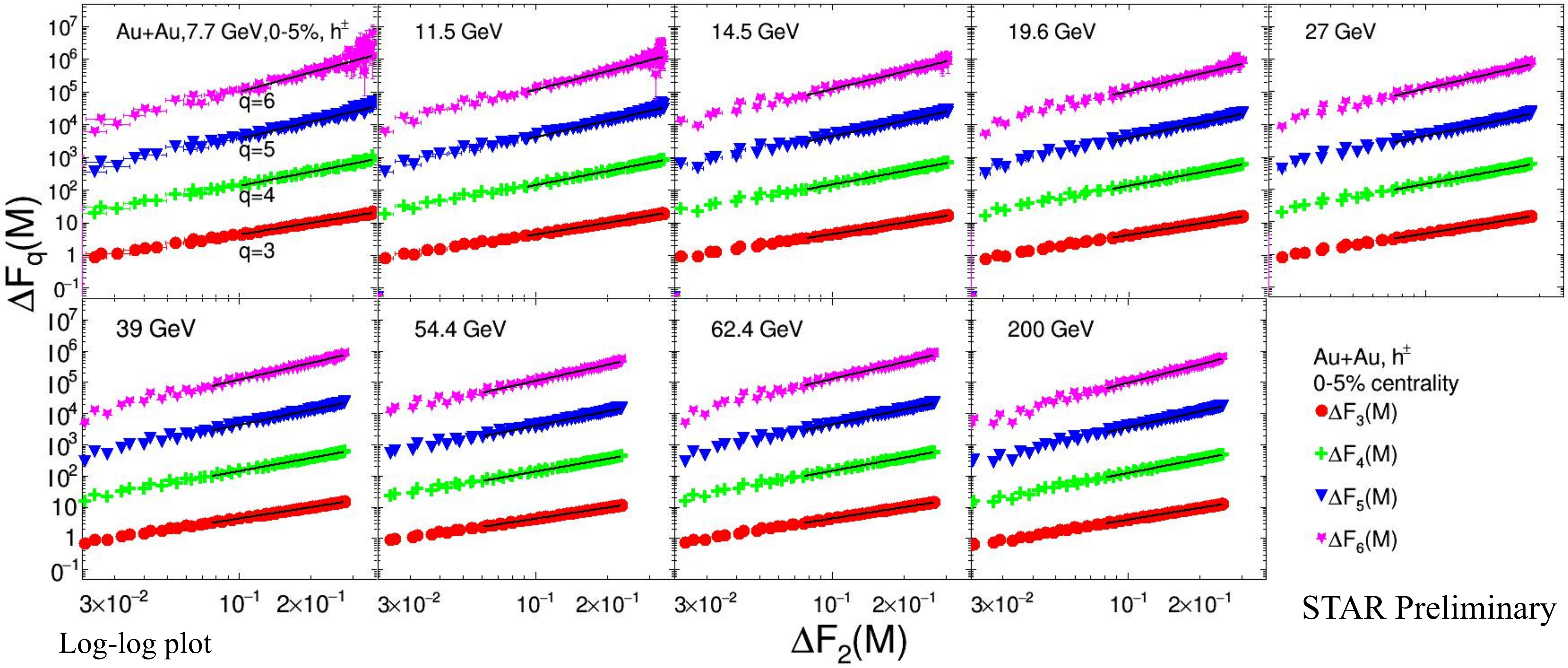


Log-log plot

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

- All orders of $F_q(M)$ rise with increasing M^2, but can not be fitted by $F_q(M)/M$ scaling function. A clear $F_q(M)/M$ scaling (power-law) behavior isn't visible in Au + Au collisions.

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



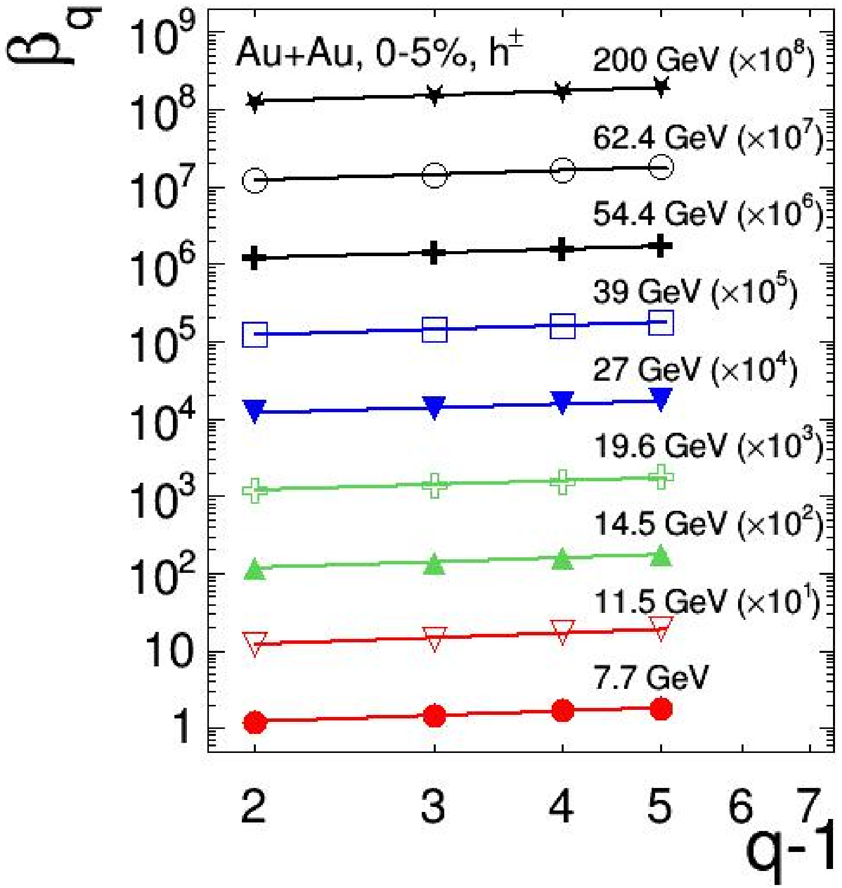
Log-log plot

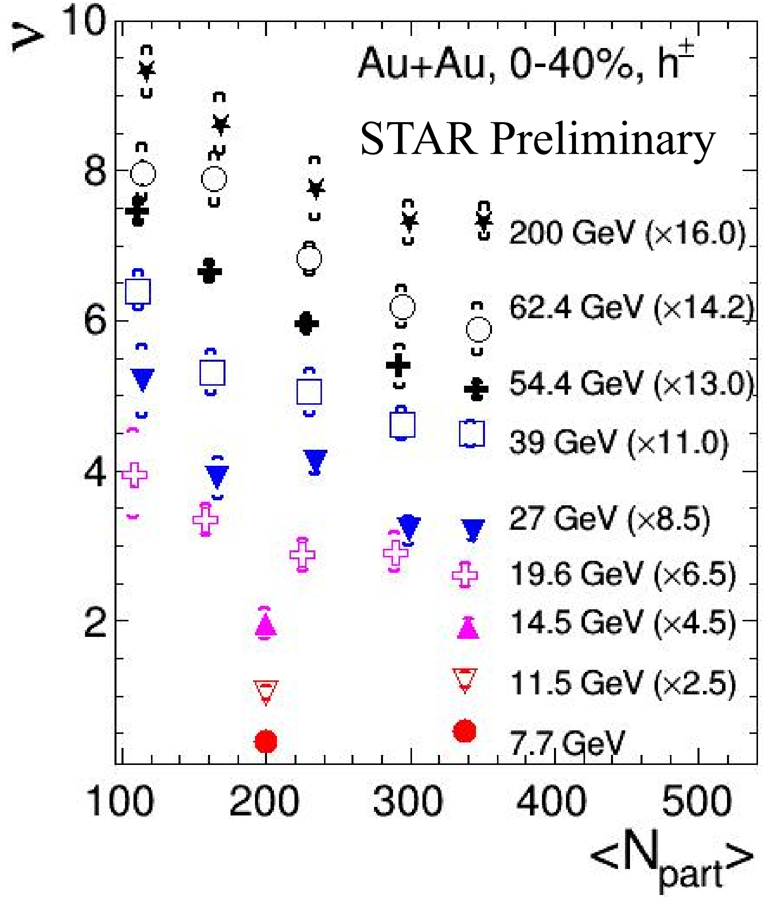
$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M)$$

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

- 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



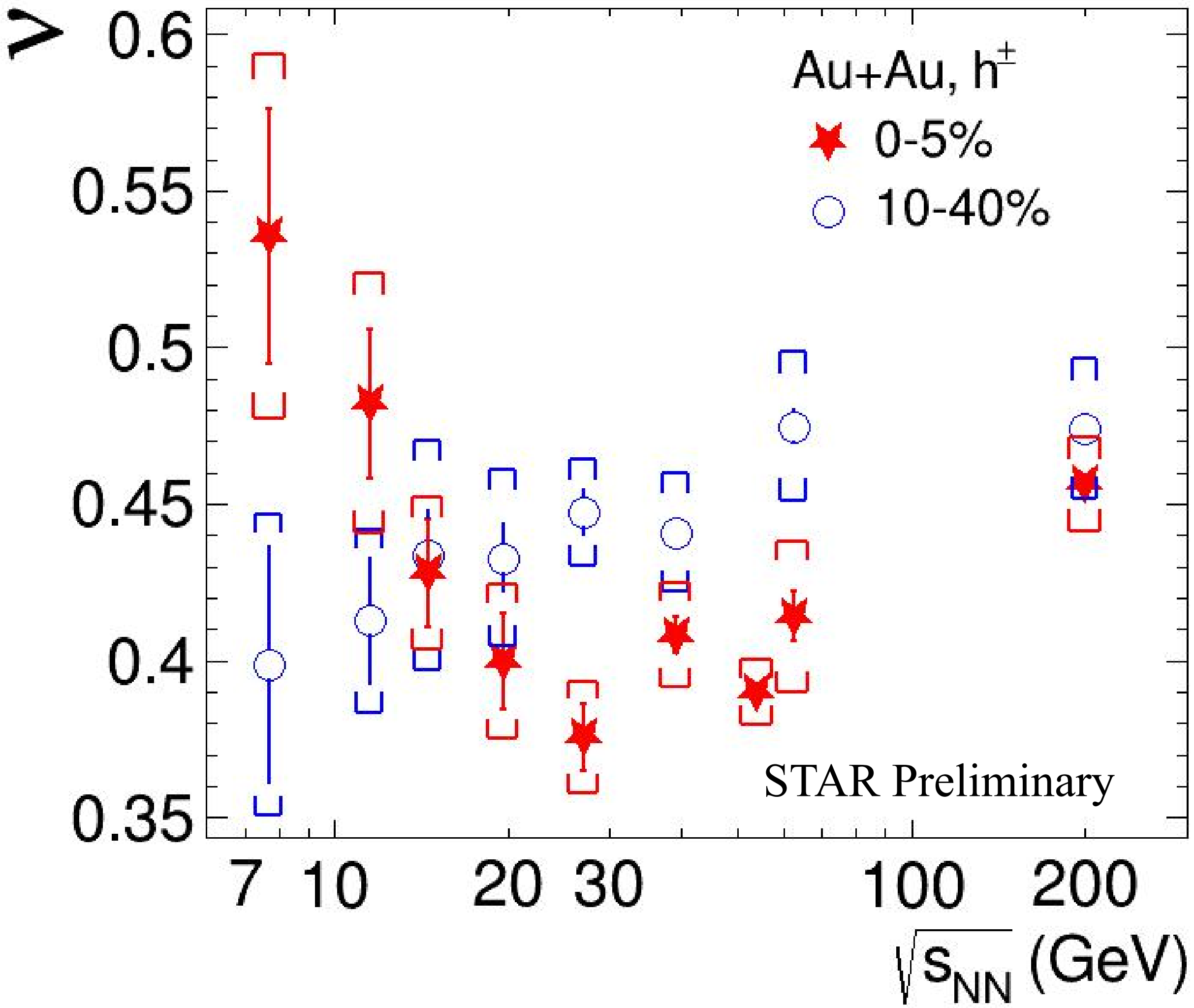


- β_{q} as a function of $q-1$ and v as a function of $< N_{part} >$ at different energies are scaled by different factors.
- Clear β_q/q scaling behaviors are visible in central Au + Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 7.7-200 GeV.
- The scaling exponent, ν, is obtained through a power-law fit 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.

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

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

Energy Dependence of v



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

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

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

- 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, v monotonically increases with increasing collision energy at $\sqrt{s_{NN}}$ = 7.7 – 200 GeV.

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. However, $\Delta F_q(M)/M$ scaling behavior is not strictly satisfied.
- Scaling exponent, *ν*, decreases from mid-central (30-40%) to the most central (0-5%) Au + Au collisions. *ν* can not be extracted in peripheral (40-80%) collisions.
- More importantly, scaling exponent 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. In 10-40% central collisions, v monotonically increases with increasing collision energy at $\sqrt{s_{\mathrm{NN}}}$ = 7.7 – 200 GeV.

Thank you!