SQM 2024

The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

Experimental Search on the QCD Critical Point

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2024/6/6

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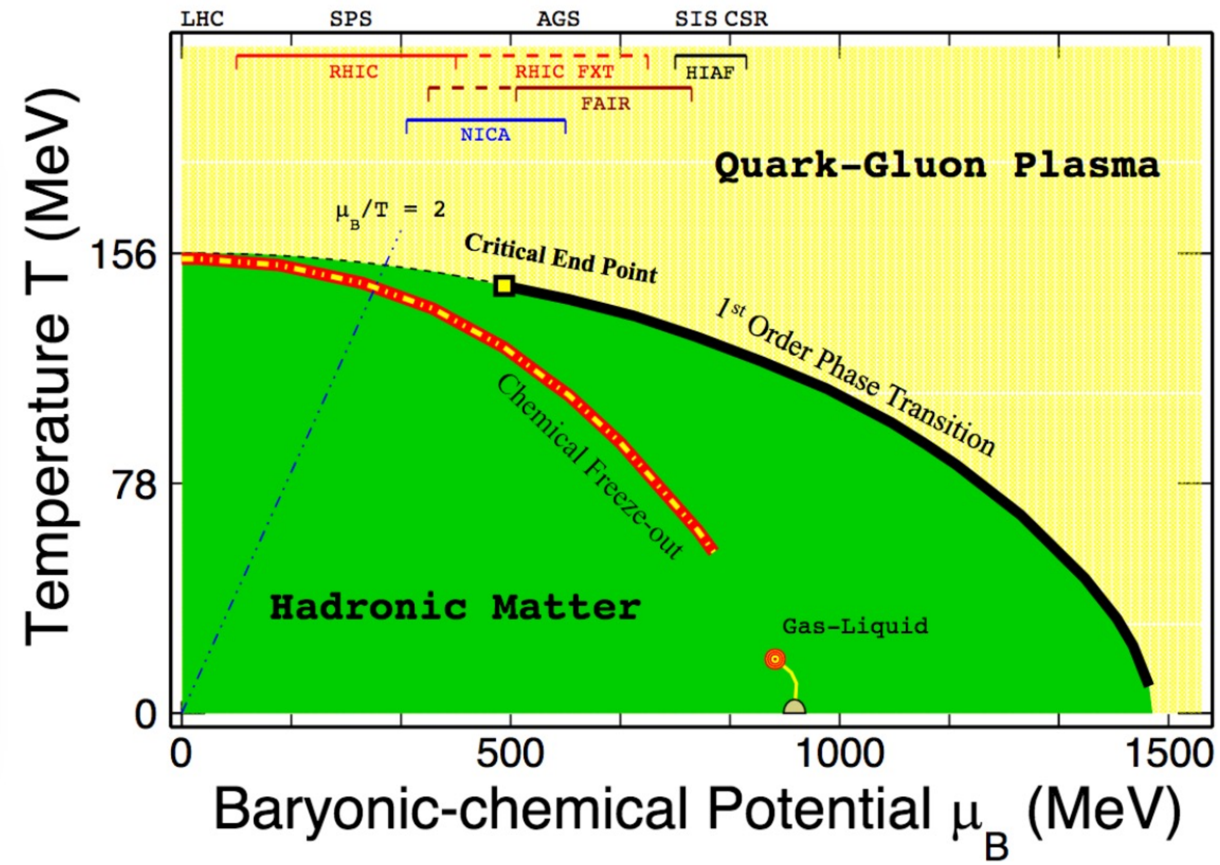
Outline

1. **Introduction**
2. **Selected Experimental Results**
   ① Intermittency Analysis
   ② Light Nuclei Yield Ratio
   ③ Baryon-strangeness Correlation
   ④ Net-proton Cumulants
3. **Summary**

Introduction

QCD Phase Diagram



Predictions:

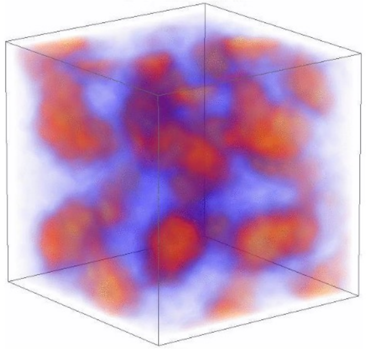
1. Smooth crossover at μ_B = 0 MeV by Lattice QCD
2. 1^{st}-order phase transition at large μ_B by various models
3. QCD critical point (CP)?

Need confirmations from experiments!

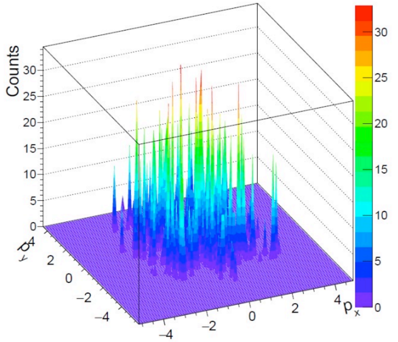
Y. Aoki et al, Nature 443, 675(2006)
A. Bzdak et al, Physics Reports 853,1-87(2020)
X. Luo, N. Xu, Nucl. Sci. Tech. 28, 112 (2017)
X. Luo, Q. Wang, N. Xu, P. F. Zhuang. Properties of QCD Matter at High Baryon Density. Springer, 2022, doi:10.1007/978-981-19-4441-3
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

① Intermittency Analysis

density fluctuation



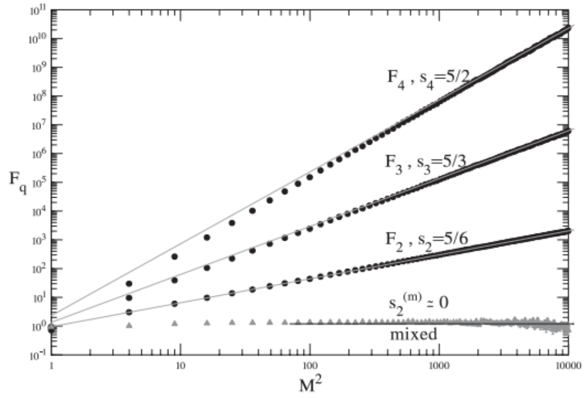
Intermittency



Power-law scaling

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

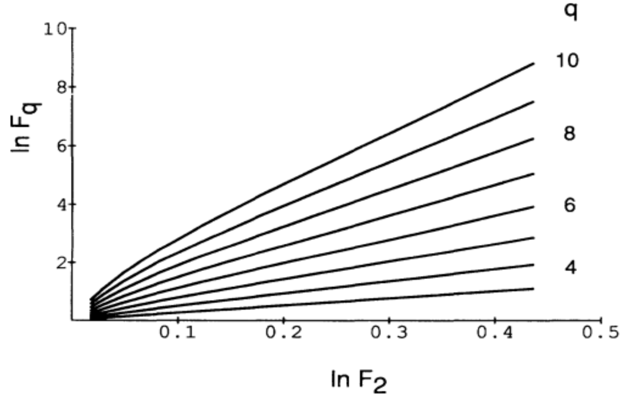
$$F_q(M) \propto F_2(M)^{\beta_q}$$



1. Large baryon density fluctuation near critical point
2. The baryon density fluctuation expressed in density-density correlator of baryon number follows a self similar or power-law behavior
3. The power-law behavior can be measured by intermittency analysis using scaled factorial moments

Critical exponent ν

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



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

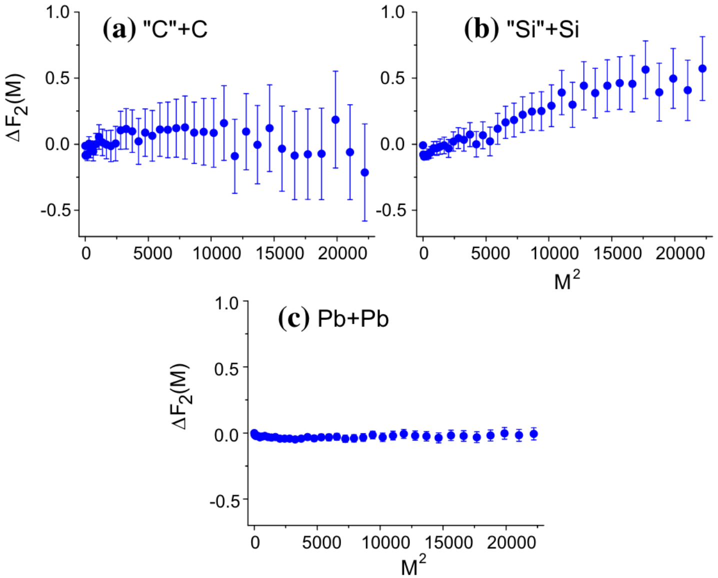
n: number of particle
M: number of cells, q: order

Prediction of ν for 2nd phase transition:
ν = 1.304 (Ginzburg-Landau)
ν = 1.0 (2D Ising)

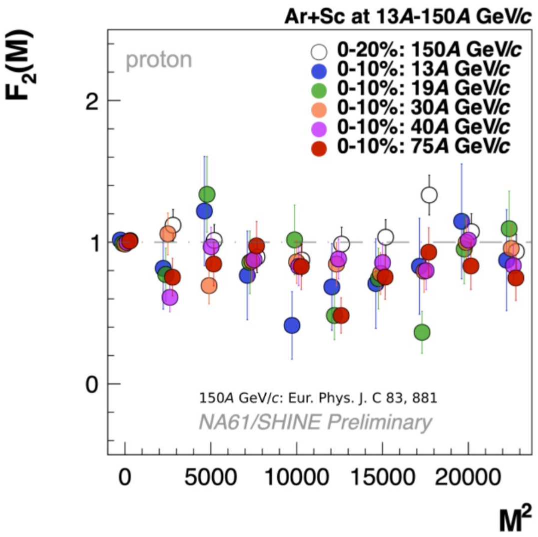
A. Bialas, R. Peschanski, NPB 308,857-867(1988)
S. Helmut, NPB 326,613-618(1989)
Rudolph C. Hwa and M. T. Nazirov, PRL 69,741(1992)
N. G. Antoniou et. al, PRL 97, 032002 (2006)

Intermittency from NA49, NA61/SHINE

Proton intermittency

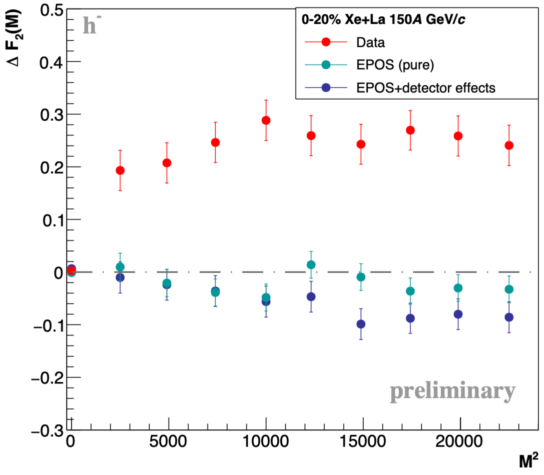


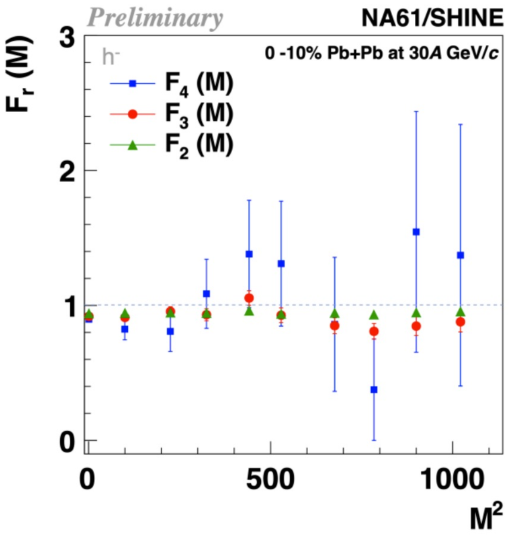
NA49, Eur. Phys. J. C (2015) 75:587



NA61/SHINE, EPJC 83 (2023) 881
NA61/SHINE, arXiv:2401.03445

Negatively charged hadron intermittency





Valeria Reyna, CPOD 2024

- Intermittency found for Si+Si

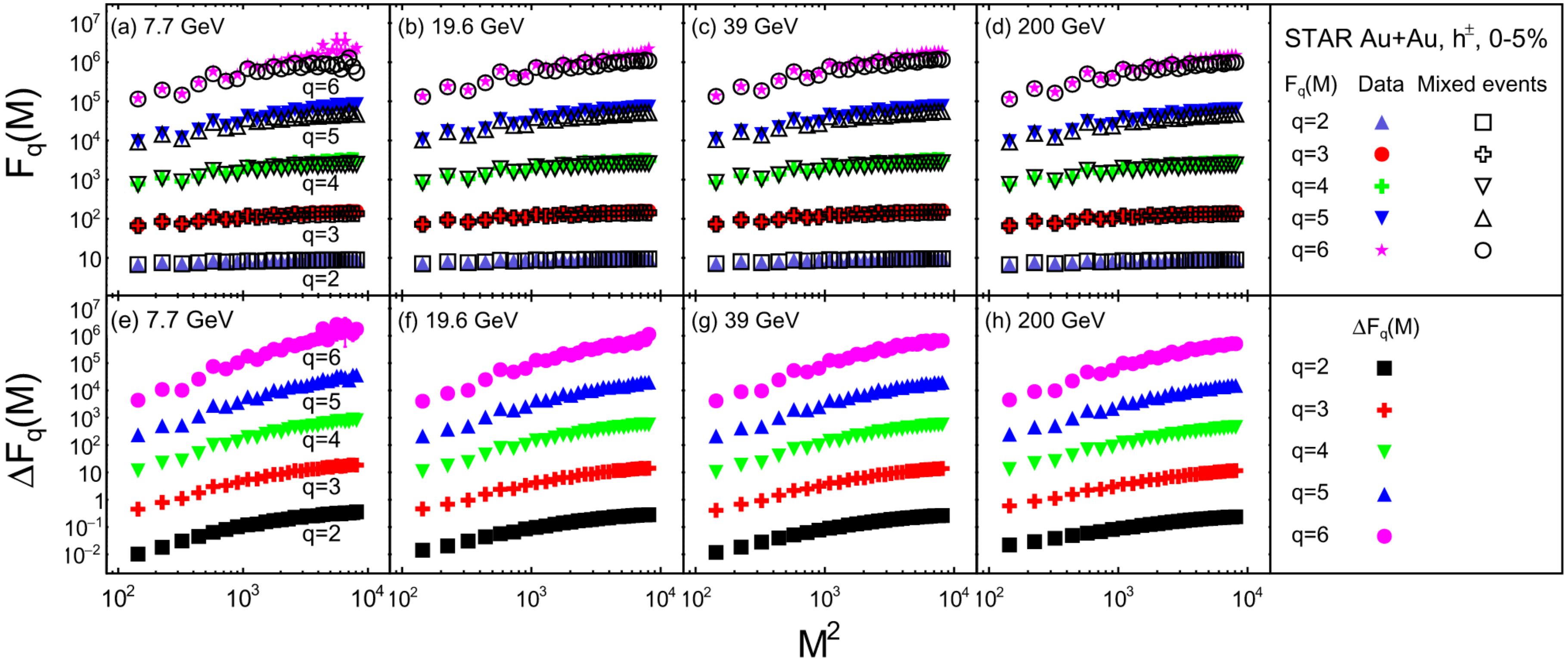
- $\Delta F_q(M)$ increases and saturates at large M^2
- Higher order are limited by statistics

Need higher statistics to draw conclusions

Intermittency from STAR

Charged hadron intermittency

STAR, PLB 845, 138165(2023)



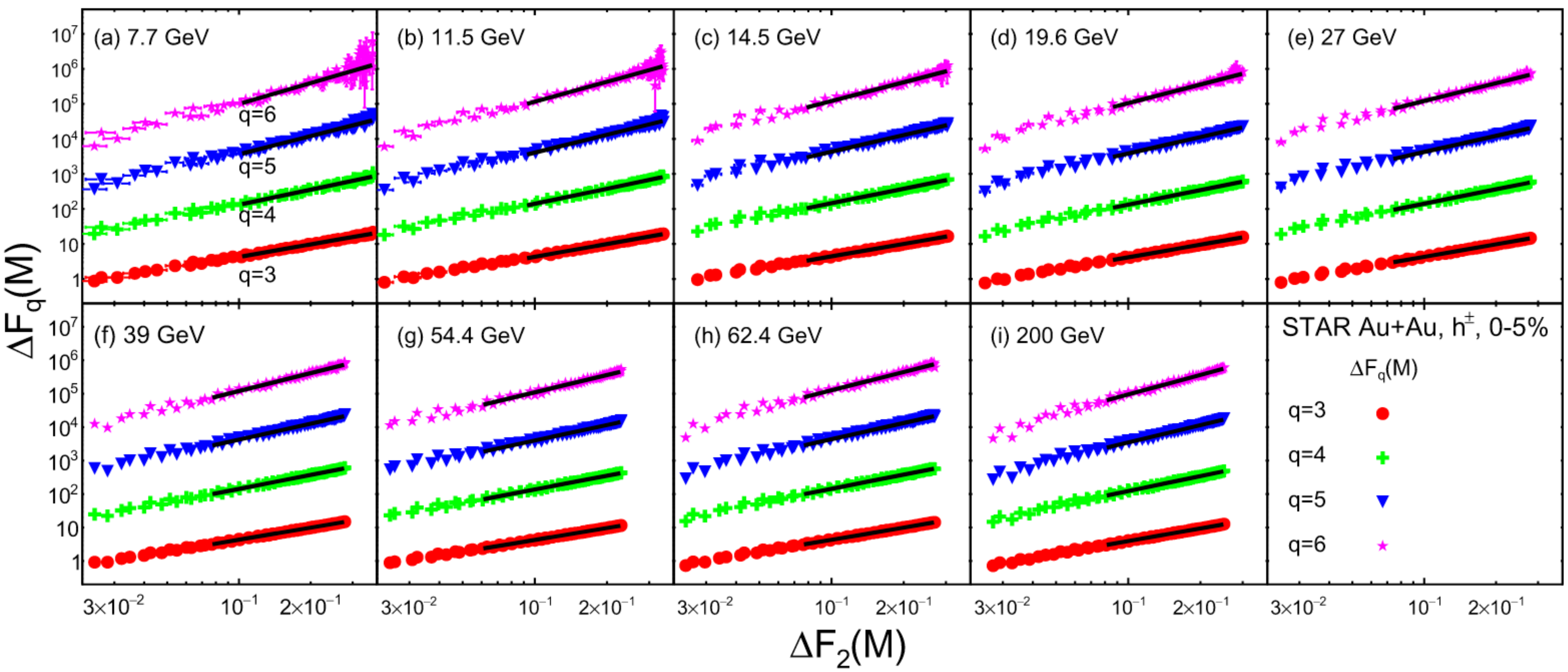
$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M) \propto (M^2)^{\phi_q}$$

1. $\Delta F_q(M)$ saturates at large M^2
2. Power-law scaling is not valid for entire M^2 range

Intermittency from STAR

Charged hadron intermittency

STAR, PLB 845, 138165(2023)

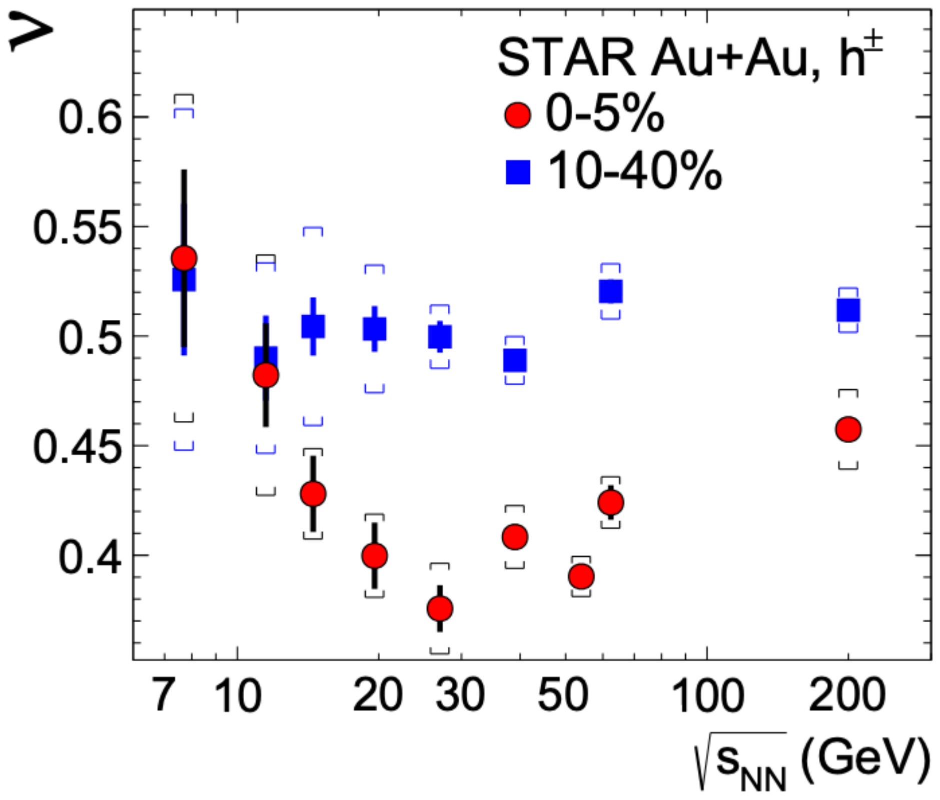


$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q} \quad \beta_q \propto (q-1)^{\nu}$$

1. Power-law of $\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$ observed at all collision energies
2. Critical exponent (ν) can be extracted from each energies

Intermittency from STAR

STAR, PLB 845, 138165(2023)

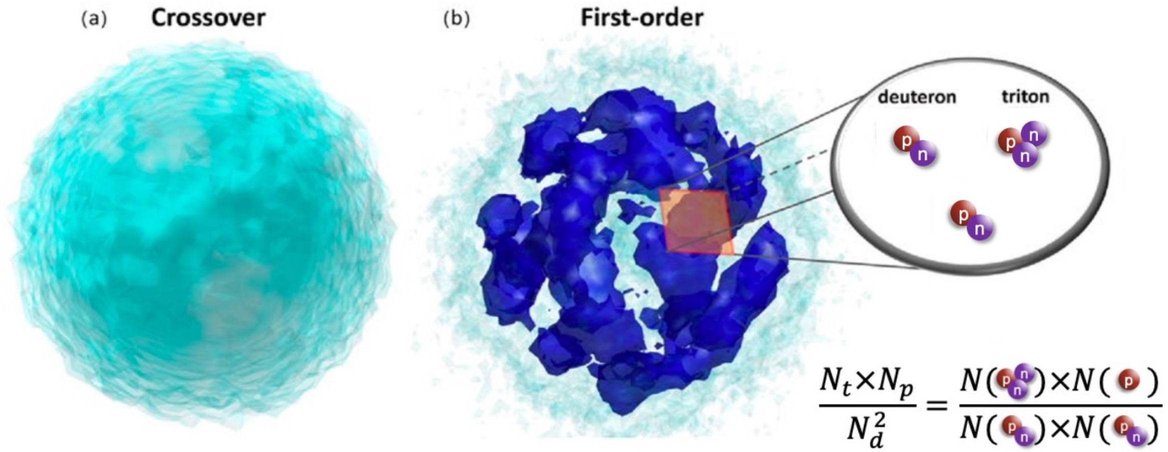


$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q} \quad \beta_q \propto (q-1)^{\nu}$$

critical exponent:
ν = 1.304 (Ginzburg-Landau theory)
ν = 1.0 (2D Ising model)

1. **Scaling exponent (ν) exhibits a non-monotonic energy dependence in central Au+Au collisions with a minimum around 20-30 GeV**
2. Theoretical calculations are necessary to understand the measured ν

② Light Nuclei Yield Ratio



C.M. Ko, NUCL SCI TECH 34, 80 (2023)

1. Related to neutron density fluctuation (Δn) due to 1st order phase transition and correlation length (ξ)
2. The non-monotonic behavior of the ratio might be a signal of 1st order phase transition and QCD critical point

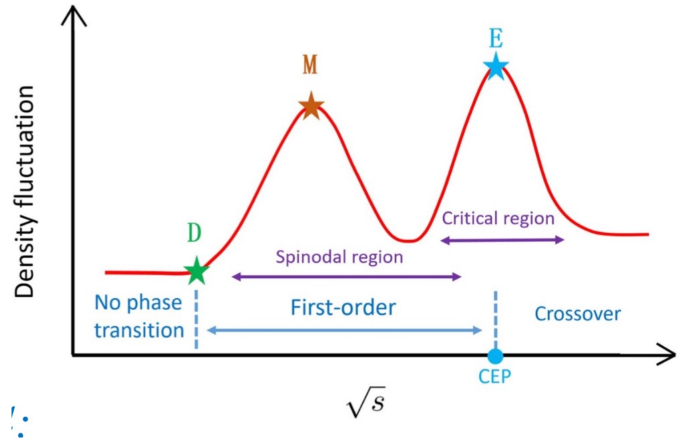
Compound yield ratio in coalescence picture:

$$\frac{N_t \times N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}}[1 + \Delta n + \frac{\lambda}{\sigma}G(\frac{\xi}{\sigma})]$$

Δn → Neutron density fluctuation

$G(\frac{\xi}{\sigma})$ → Long range correlation

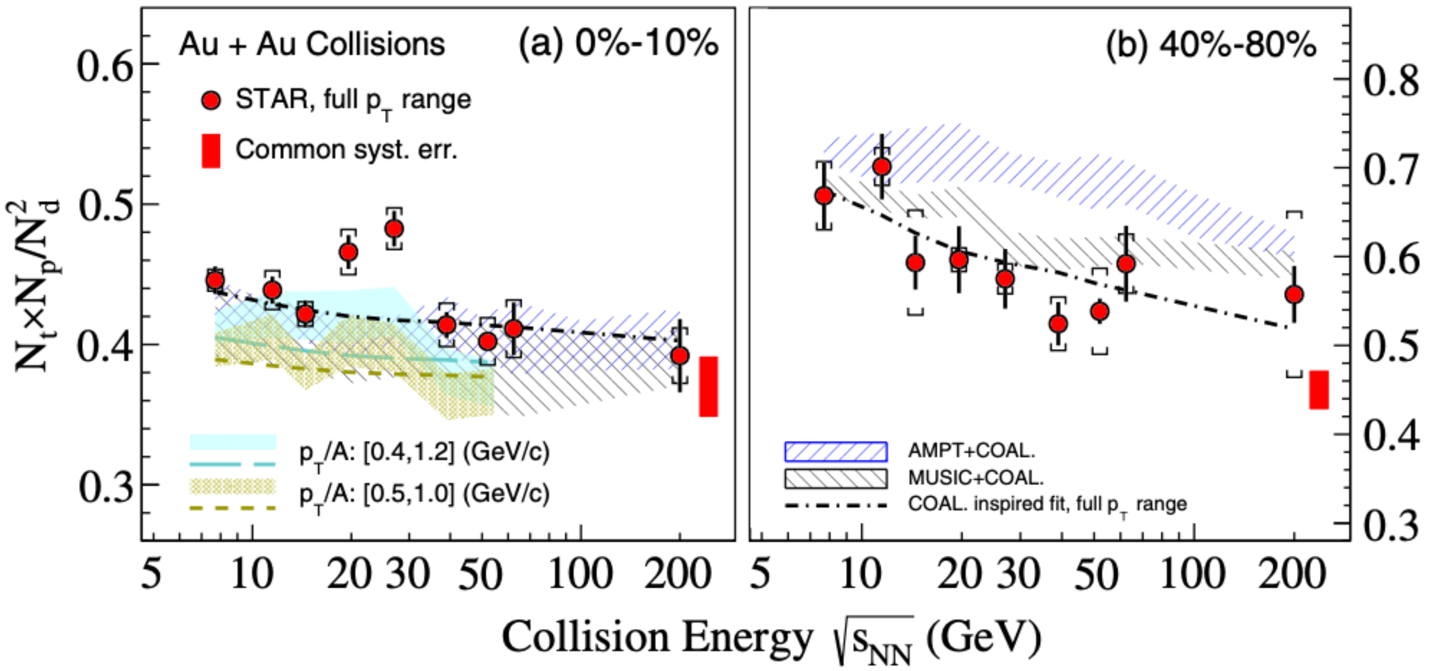
p: proton
d: deuteron
t: triton



K.J. Sun et al, Phys.Lett.B 792, 132-137
W.B. Zhao et al, Phys.Rev.C 102 (2020) 4, 044912
H. Liu et al, Phys.Lett.B 805 (2020) 135452

Measurement from STAR

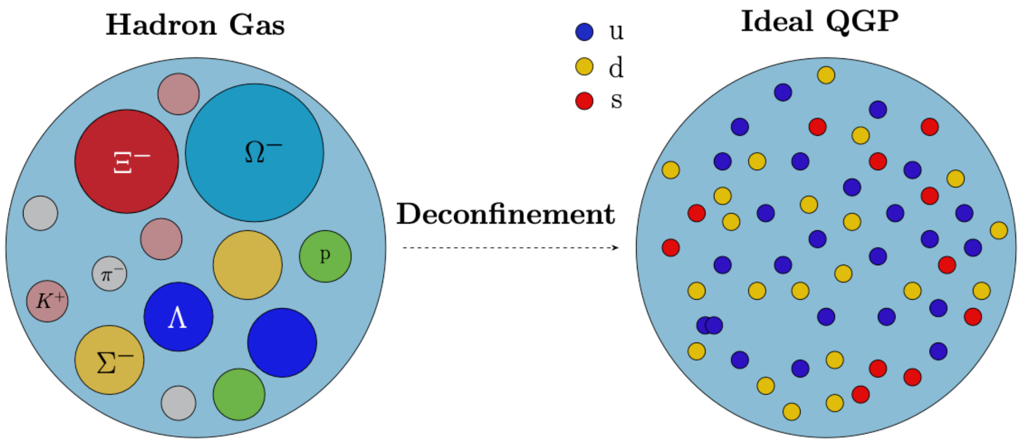
STAR, PRL 130, 202301(2023)

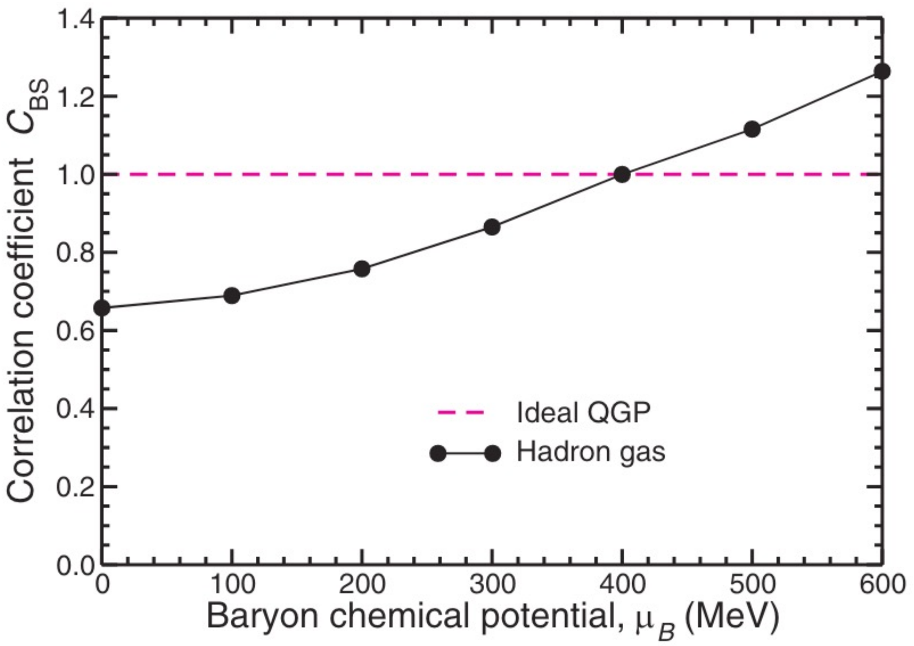


BESII, Yixuan Jin, Track3-Res&Hyp

1. **Non-monotonic behavior observed in 0-10% central Au+Au collisions around 19.6 and 27 GeV with 4.1σ significance deviated from coalescence baseline (black dashed line)**
2. Within uncertainties, peripheral data can be well described by the coalescence baseline but over-estimated by calculations from AMPT and MUSIC models

③ Baryon-strangeness Correlation





V. Koch and A. Majumder and J. Randrup, PRL 95, 182301(2005)

Definition:

$$C_{BS} = -3\frac{\sigma_{BS}}{\sigma_S^2} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2}$$

QGP: $B = \frac{1}{3}(U + D - S)$

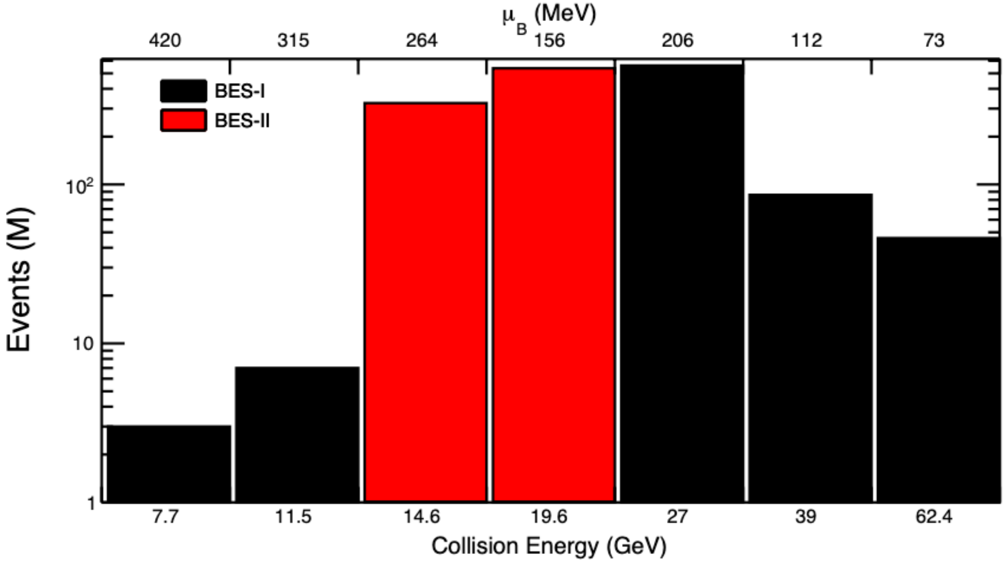
if quark flavors are uncorrelated

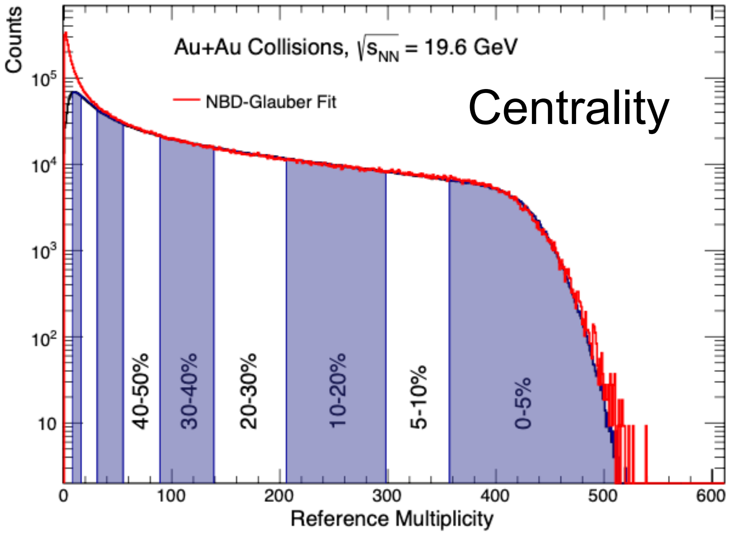
$$\sigma_{BS} = -\frac{1}{3}\sigma_{S^2} \quad \rightarrow \quad C_{BS} = 1$$

1. A diagnostic of degree of freedom and correlations of strongly interacting matter
2. Used to identify the onset of deconfinement

Event-by-event Measurement from STAR

STAR BES datasets



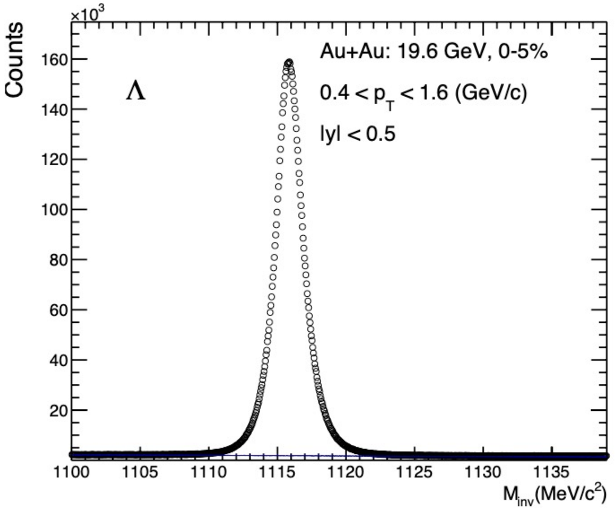


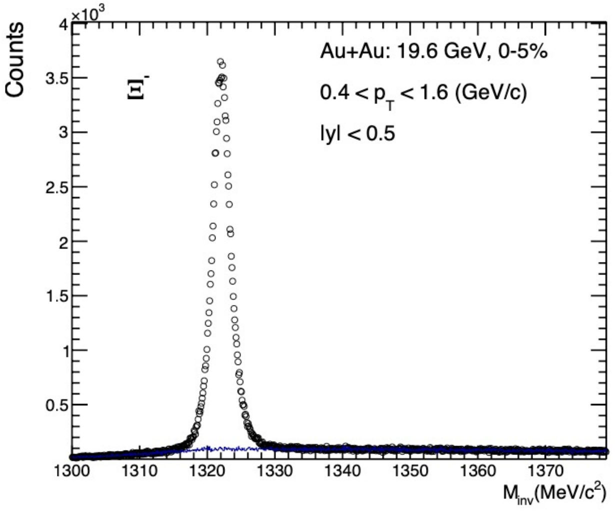
Number of $\pi^{\pm}$ are used to define centrality.

Particles measured in this analysis:

① Baryon: p, Λ, Ξ^-

② Strangeness: $K^{\pm}$, Λ, Ξ^-





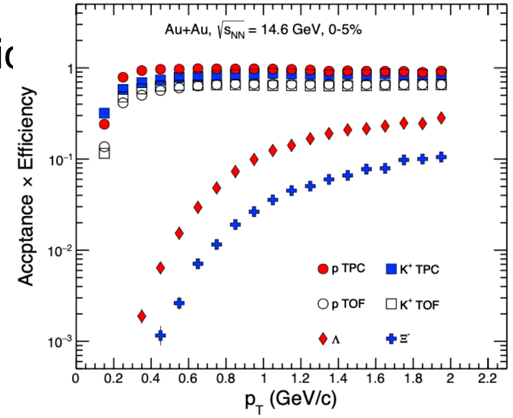
Analysis procedure:

① Purity correction (reconstructed partic

② Efficiency correction

③ Centrality bin width correction

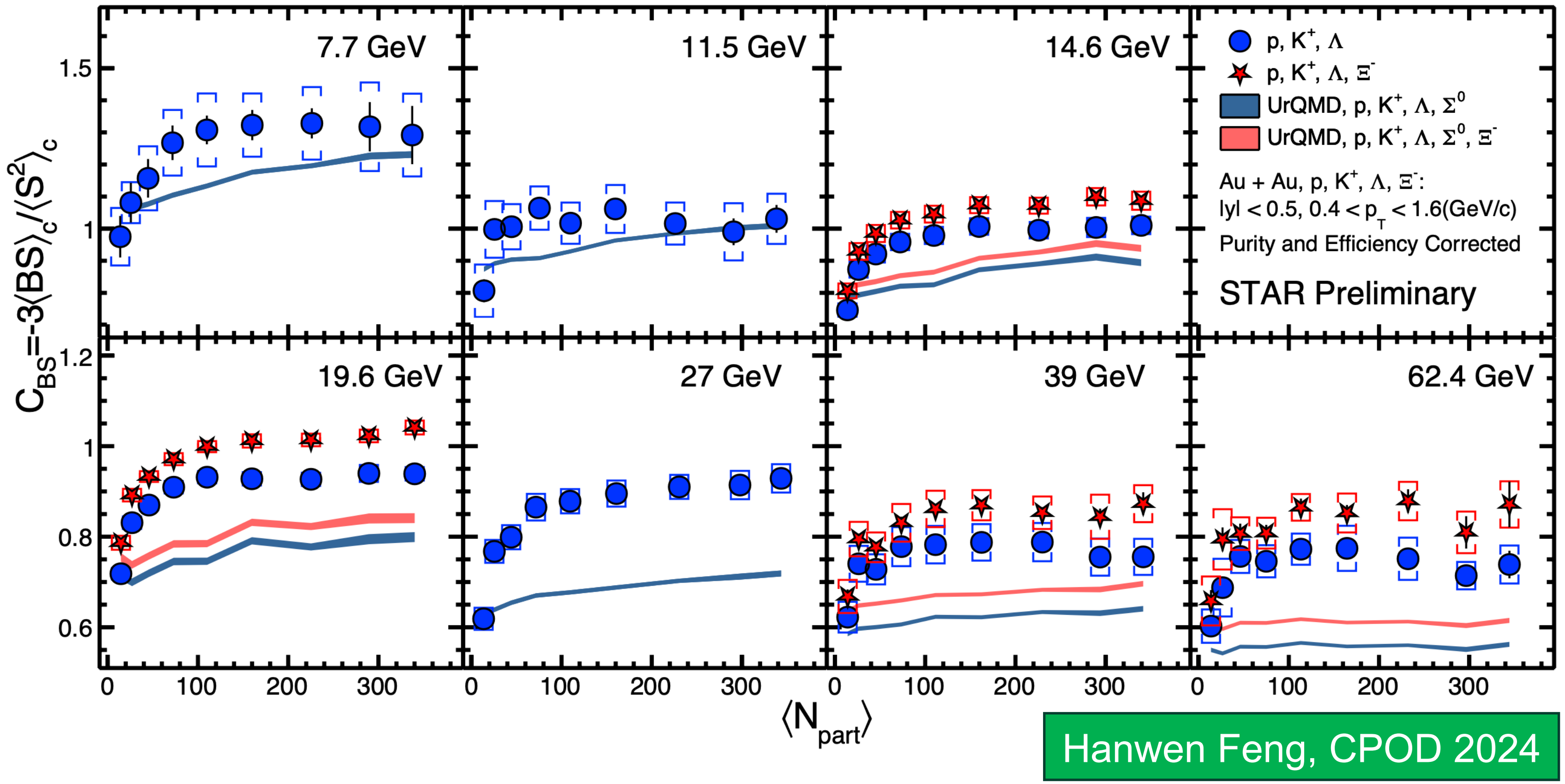
Efficiency



Refs:

T. Nonaka, NIM A 1039 (2022) 167171
A. Bzdak and V. Koch, PRC 91, 027901 (2015)
X. Luo, T. Nonaka , PRC 99, 044917 (2019)
X. Luo et al, J. Phys. G: Nucl. Part. Phys. 40 (2013)

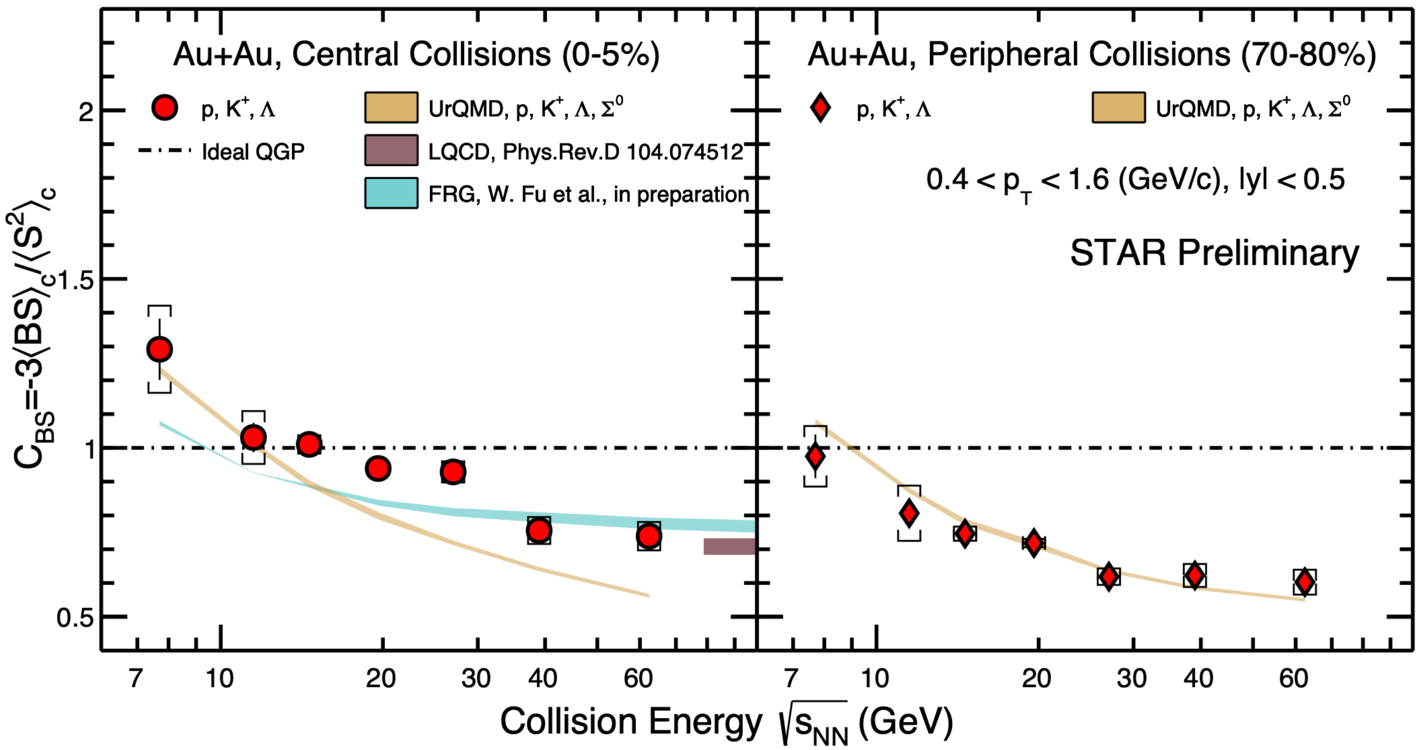
Centrality Dependence of C_{BS}

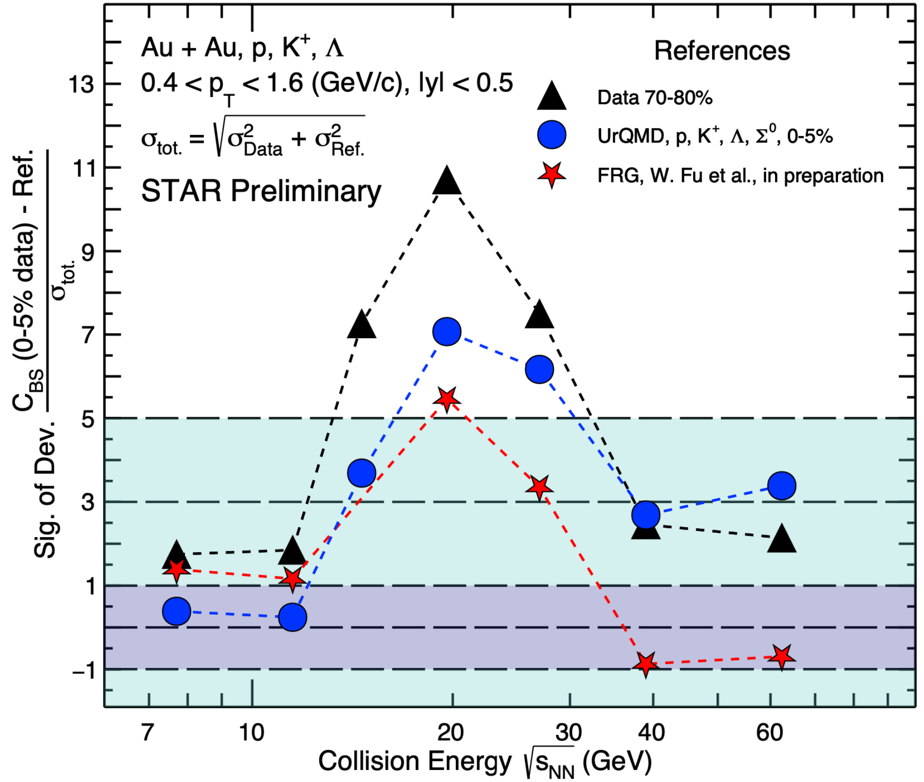


- The UrQMD calculation qualitatively describe 7.7 and 11.5 GeV while underestimates higher energy

Energy Dependence of C_{BS} from STAR

Hanwen Feng, CPOD 2024





1. Central (0-5%): UrQMD qualitatively describes 7.7 and 11.5 GeV while underestimates other energies
2. Peripheral (70-80%): qualitatively described by UrQMD

3. At around 20 GeV, the deviation of central data reaches a maximum

④ Cumulants of Conserved Quantities

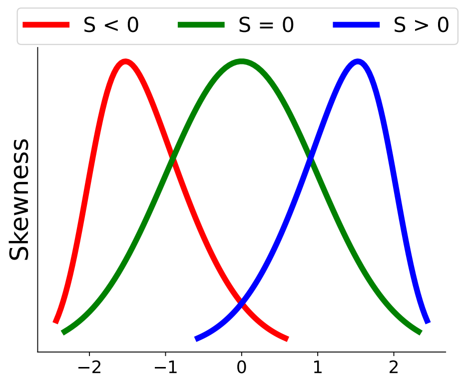
- Cumulants of conserved quantities

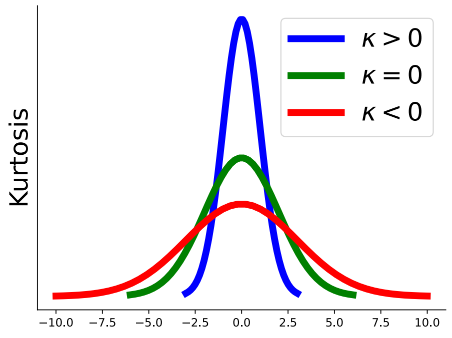
Net-baryon (B) (net-proton as proxy)
Net-electric charge (Q)
Net-strangeness (S) (net-kaon as proxy)

$$\delta N = N - \langle N \rangle$$
$$C_1 = \langle N \rangle = M$$
$$C_2 = \langle (\delta N)^2 \rangle = \sigma^2$$
$$C_3 = \langle (\delta N)^3 \rangle$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$

$$\frac{C_2}{C_1} = \frac{\sigma^2}{M}, \quad \frac{C_3}{C_2} = S\sigma$$
$$\frac{C_4}{C_2} = \kappa\sigma^2$$

N : event-wise net-particle multiplicity





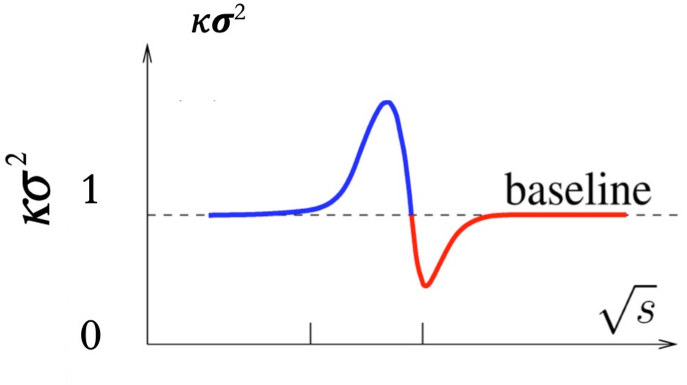
1. Sensitive to correlation length

$$C_3 = \langle (\delta N)^3 \rangle \sim \xi^{4.5}$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle \sim \xi^7$$

2. Related to susceptibility

$$\frac{\chi_4^q}{\chi_2^q} = \kappa\sigma^2 = \frac{C_4^q}{C_2^q}, \quad \frac{\chi_3^q}{\chi_2^q} = S\sigma = \frac{C_3^q}{C_2^q}$$
$$\chi_n^q = \frac{1}{VT^3} \cdot C_n^q = \frac{\partial^n (p/T^4)}{\partial (\mu^q)^n}, \quad q = B, Q, S$$

3. Non-monotonic energy dependence of $\kappa\sigma^2$ (C_4/C_2) → existence of a critical point

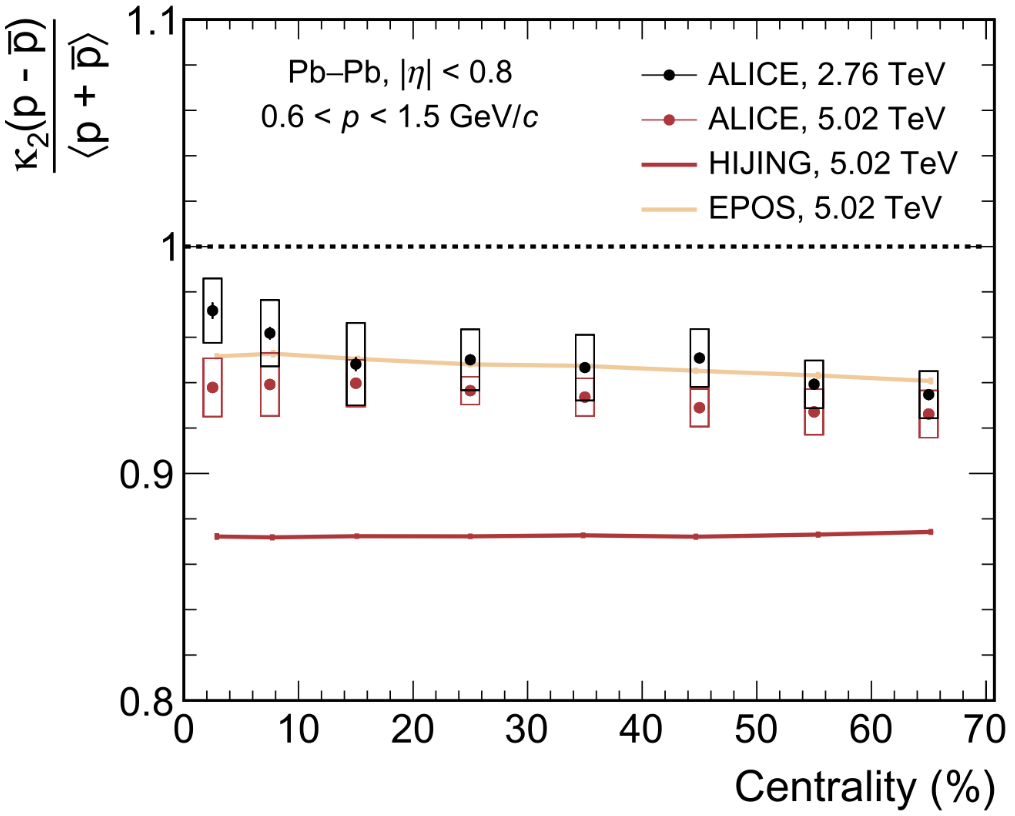


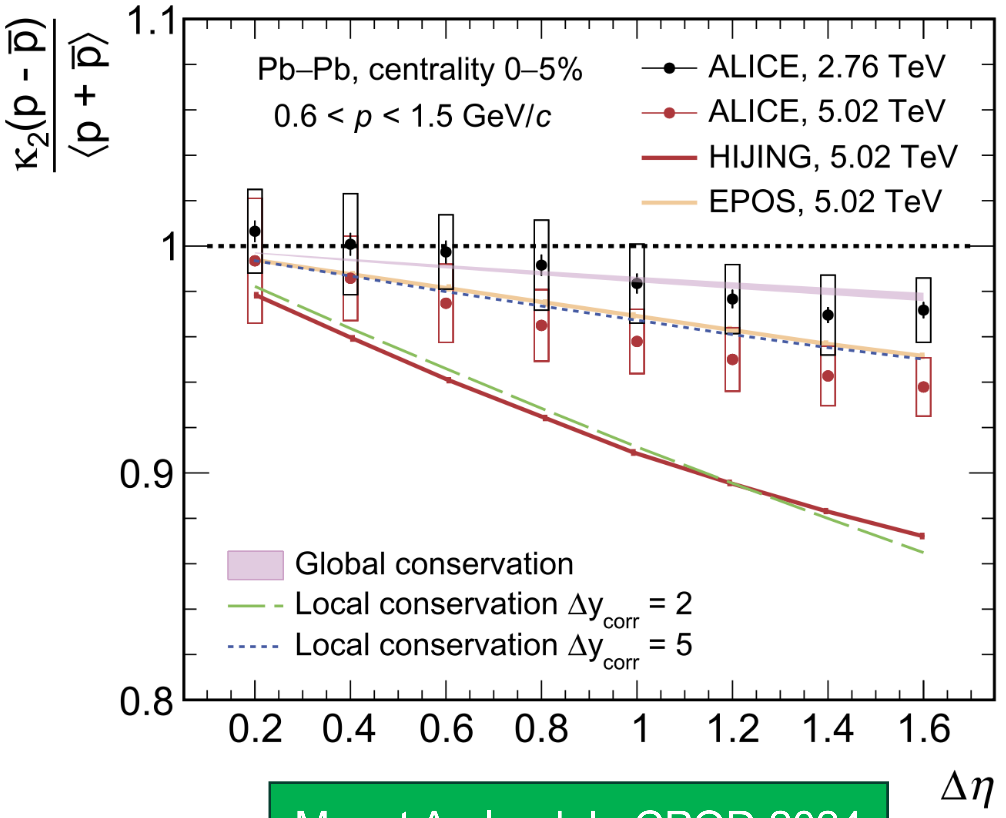
$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

M. A. Stephanov, PRL 102, 032301 (09);
M. Asakawa, S. Ejiri and M. Kitazawa, PRL 103, 262301 (09)
S.Ejiri et al, PLB 633, 275(06);
M. A. Stephanov, PRL 107, 052301 (11); F. Karsch and K. Redlich, PLB 695, 136 (11)

Net-proton Cumulants from ALICE

ALICE, PLB 844(2023)137545



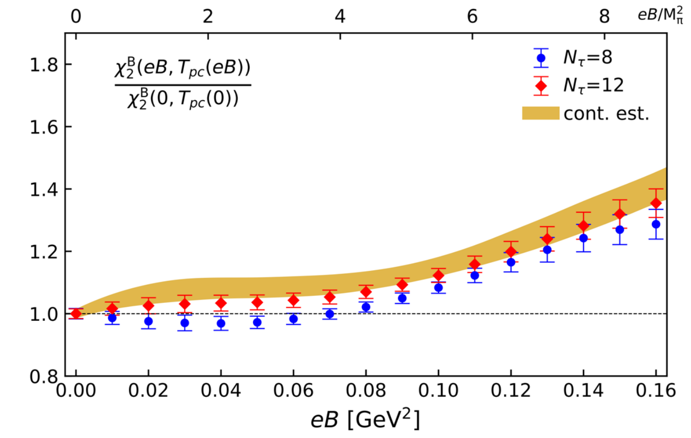


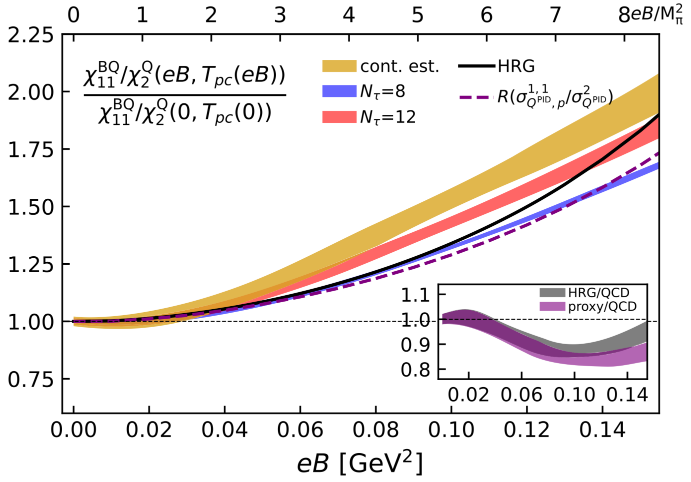
Mesut Arslandok, CPOD 2024

1. ALICE data **suggest long range correlation of proton and antiproton**: $\Delta y = \pm 2.5$ or longer
2. HIJING reflects a smaller correlation length: $\Delta y = \pm 1$

Measurements from ALICE

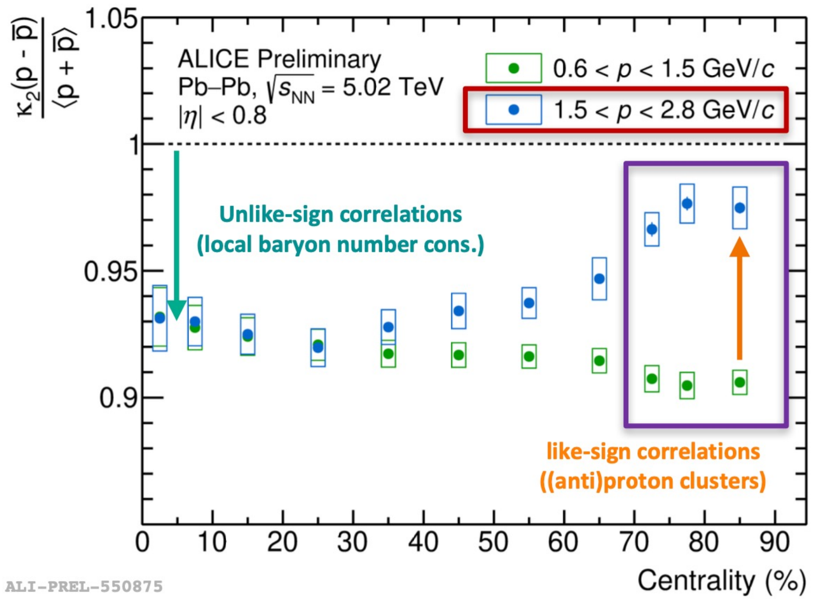
H.-T. Ding et al,
Acta Phys. Pol. B Proc. Suppl. 16, 1-A134 (2023)
H.-T. Ding et al, PRL 132(2024)201903

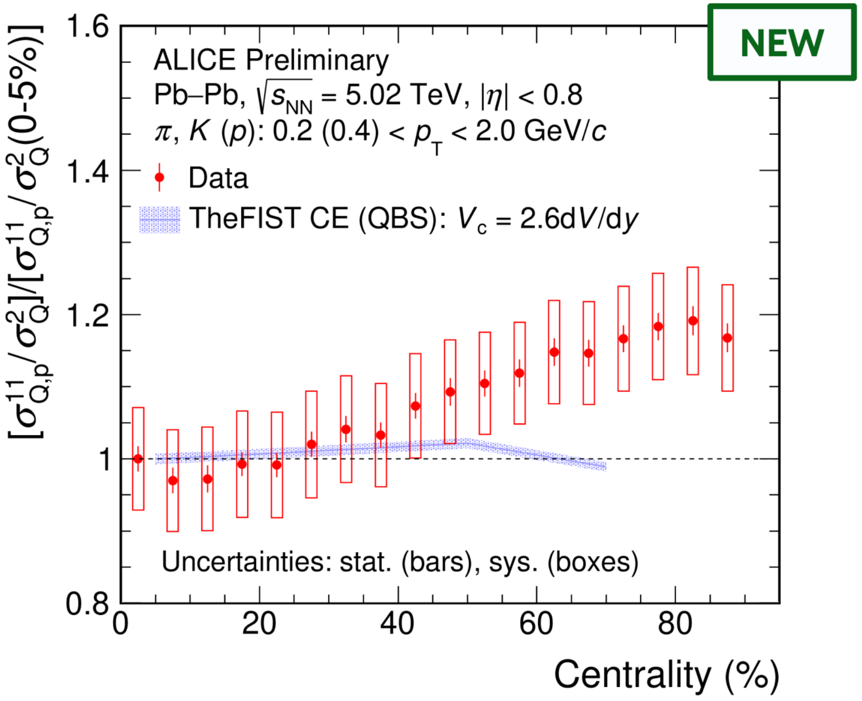




Swati Saha, June 4, Track4-Bulk&Phase
Mesut Arslandok, CPOD 2024

More peripheral and larger momentum

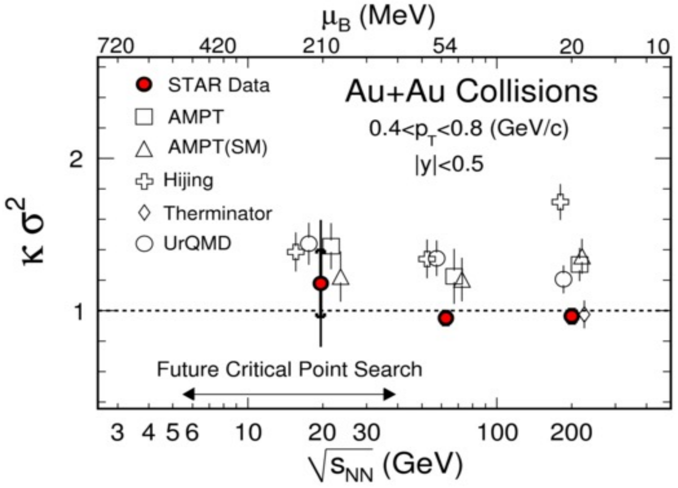




1. A rise of χ_2^B, χ_{11}^{BQ} in peripheral collisions due to magnetic field suggested by LQCD
2. **Hint of magnetic field in peripheral collisions in data?**

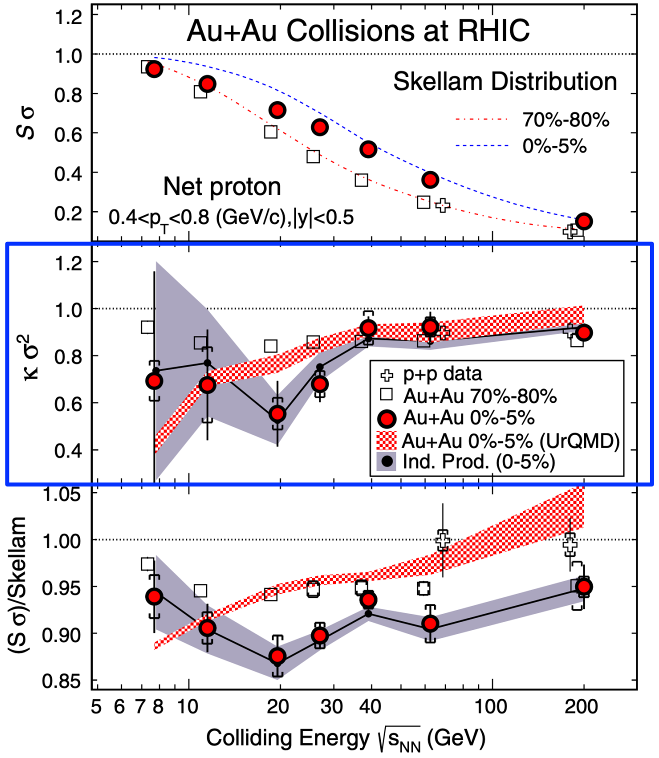
Measurements from STAR

Net-proton
STAR, PRL 105, 022302(2010)



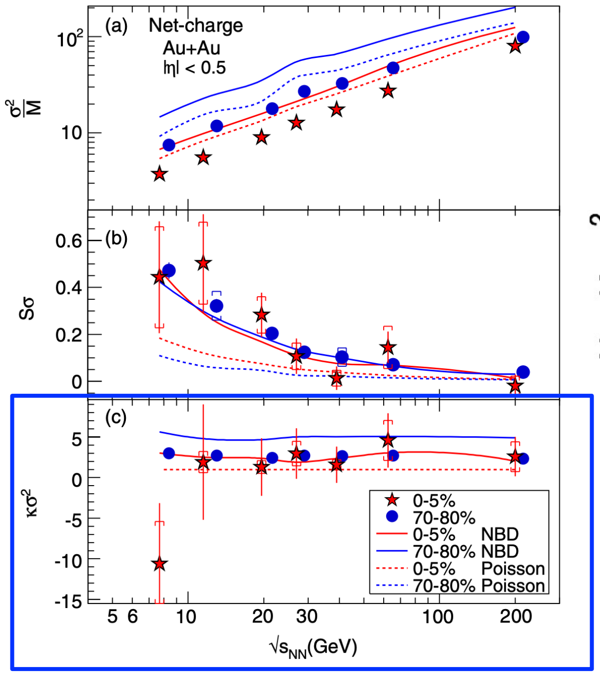
1. First measurement on net-proton cumulant from STAR.
2. Results lack detector efficiency correction.

Net-proton
STAR, PRL 112, 032302 (2014)

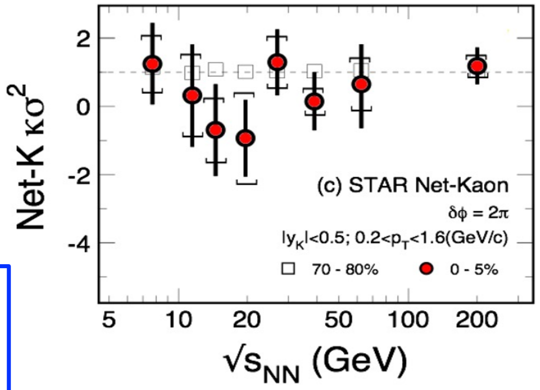


- Measurements within $0.4<p_T<0.8$ GeV/c show deviations from Poisson baseline below 39 GeV.

Net-Charge
STAR, PRL113, 092301 (2014)



Net-Kaon
STAR, PLB 785, 551 (2018)



- Net-charge, kaon results of BES-I show weak energy dependence and are consistent with Poisson baseline within uncertainties.

Net-proton Cumulants from STAR BES-I

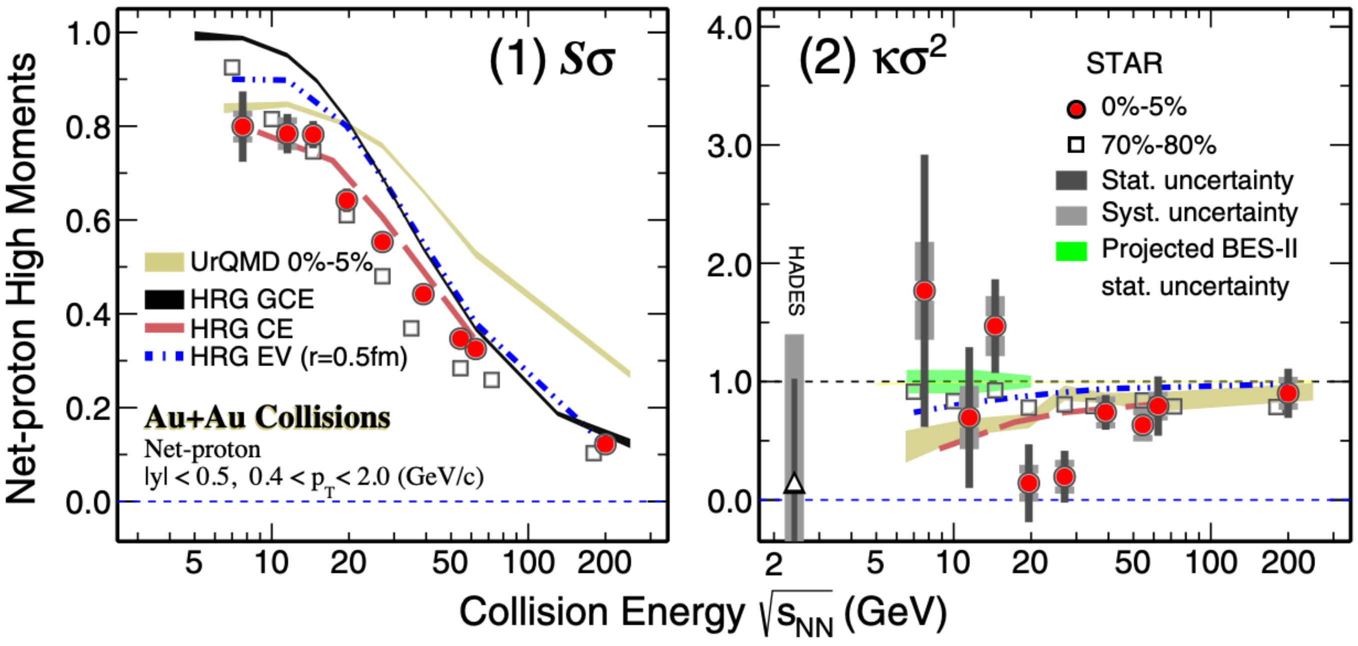
STAR BES-I Program: Au+Au collisions

$\sqrt{s_{NN}}$ (GeV)	Events / 10^6	μ_B (Mev)
200	220	25
62.4	43	75
54.4	550	85
39	92	112
27	31	156
19.6	14	206
14.5	14	264
11.5	7	315
7.7	3	420
3.0	140	750

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

Net-proton

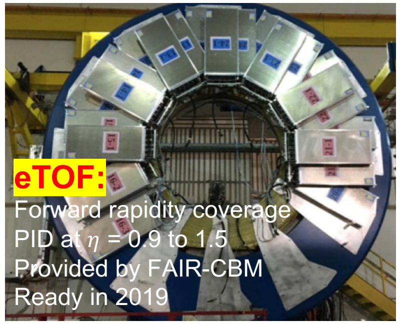
HADES, PRC 102(2020) 024914
STAR, PRL 126 (2021) 092301



1. Full measurement on BES-I datasets
2. With TOF detector, p_T coverage is extended to 2.0 GeV/c
3. **Non-monotonic energy dependence trend is observed with 3.1σ significance**

Net-proton Cumulants from STAR BES-II

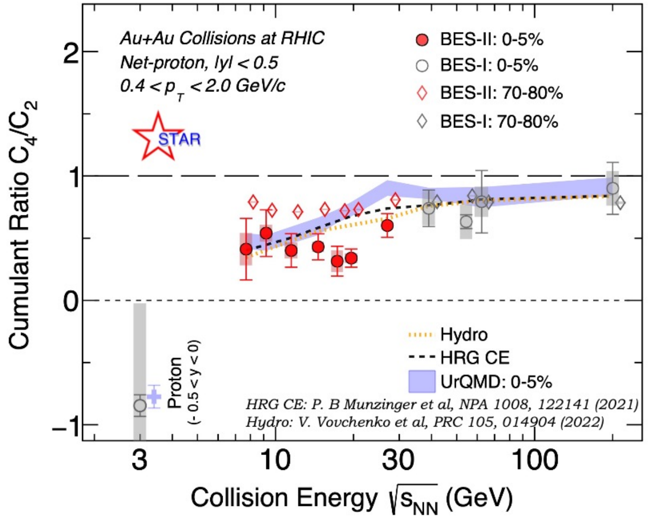
STAR Major Upgrades for BES-II

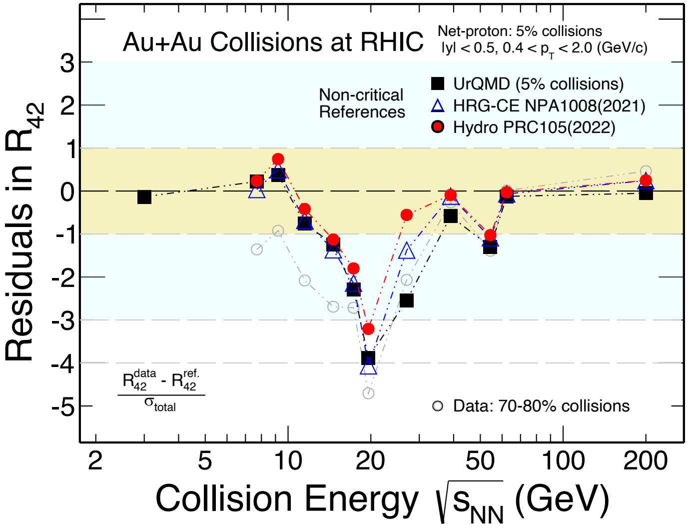


STAR BES Program: Au+Au collisions

$\sqrt{s_{NN}}$ (GeV)	Events BES-I (10^6)	Events BES-II (10^6)
7.7	3	**45**
9.2	-	**78**
11.5	7	**110**
14.6	20	**178**
17.3	-	**116**
19.6	15	**270**
27	30	**220**

Precision Measurement on BES-II



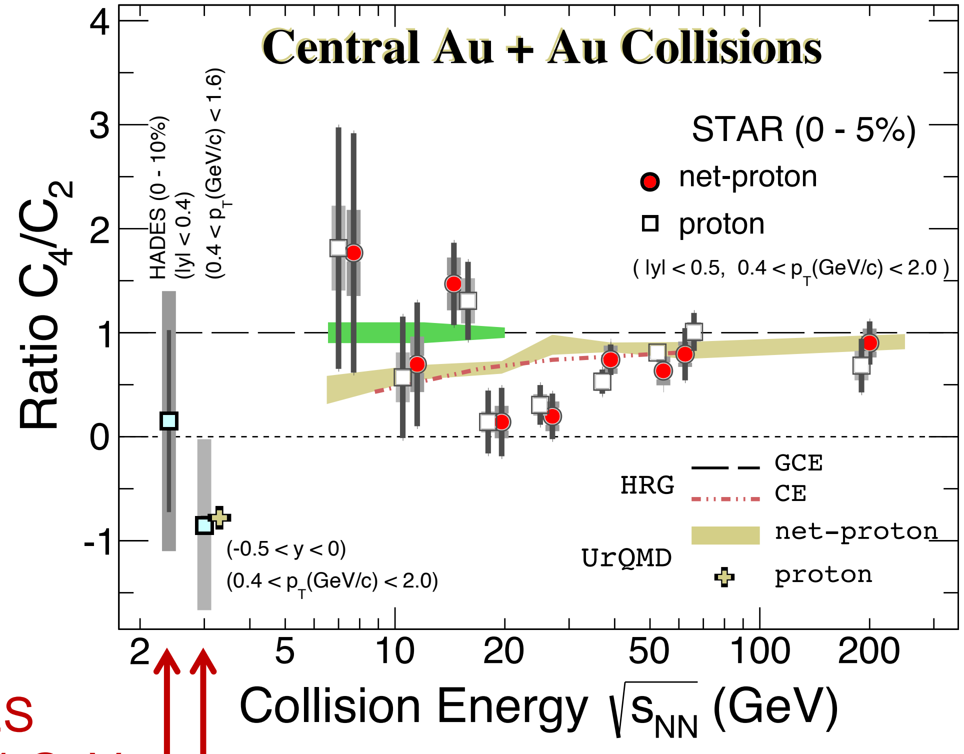


Yifei Zhang, Thurday

1. **Net-proton C_4/C_2 in 0-5% shows a minimum around ~20 GeV comparing to non-CP models (Hydro, HRG, UrQMD) and 70-80% data.**
2. Maximum deviation: 3.2-4.7σ at 20 GeV (1.3-2σ at BES-I)
3. Overall deviation from 7.7-27 GeV: 1.9–5.4σ (1.4–2.2σ at BES-I)

Proton Cumulants from Fixed-target Experiments

STAR, PRL 128 (2022) 202303
HADES, PRC 102(2020) 024914

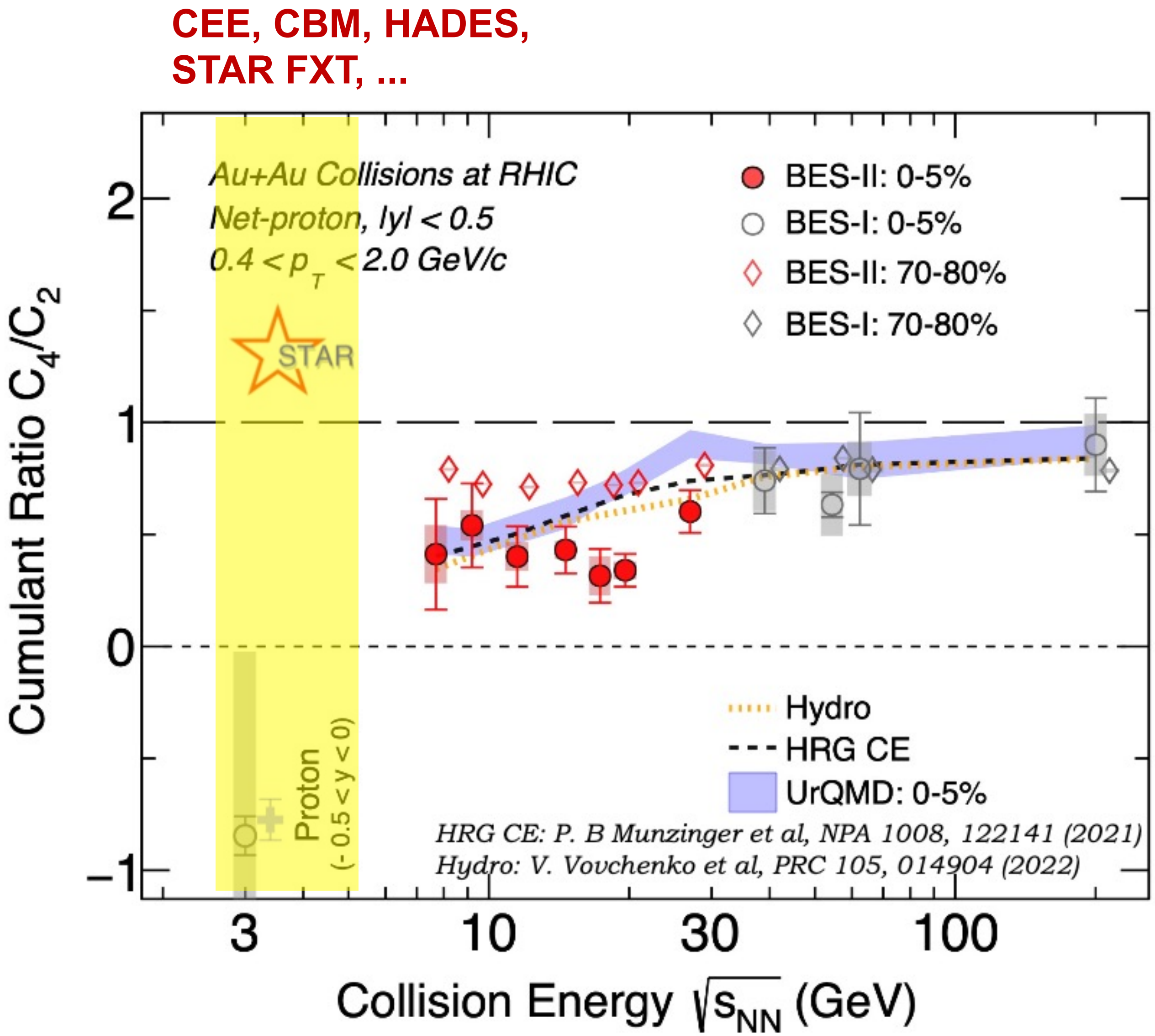


HADES
$\sqrt{s_{NN}}$ = 2.4 GeV
Au+Au collisions

STAR
$\sqrt{s_{NN}}$ = 3.0 GeV
Au+Au collisions

1. Measurements from HADES and STAR FXT are consistent within uncertainties.
2. STAR measurement found qualitatively consistent with calculation from hadronic transport model.

Proton Cumulants from Fixed-target Experiments



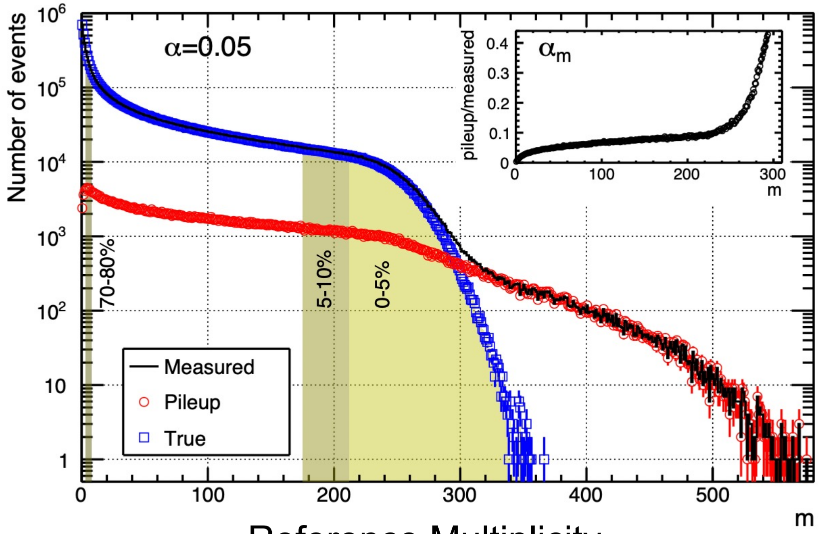
Analysis from fixed-target experiments are also important to confirm the non-monotonic behavior

Challenges in Fixed-target Experiment Analysis

Effect of event pileup

① Due to finite thickness of target.
② Distort cumulants.

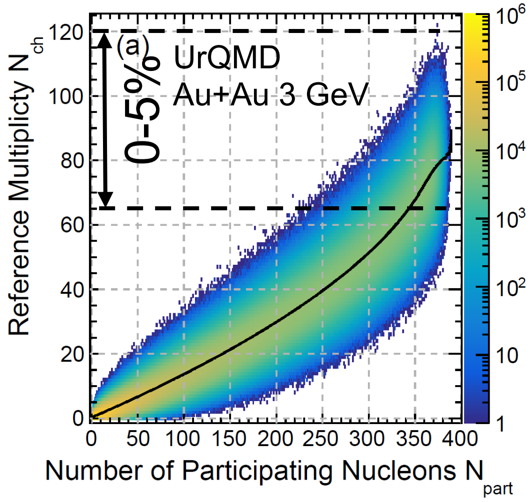
Pileup correction



T. Nonaka et al, Nucl. Inst. Meth. A 984(2020)164632
Y. Zhang et al. Nucl. Inst. Meth. A 1026(2022)166246

Volume fluctuation

Limited multiplicity
→ Worse centrality resolution.
→ Large volume fluctuation.



Volume fluctuation correction

Measured cumulant | True cumulant

Additional terms appears from the event by event participant fluctuation

$$\kappa_1(\Delta N) = \langle N_W \rangle \kappa_1(\Delta n)$$

$$\kappa_2(\Delta N) = \langle N_W \rangle \kappa_2(\Delta n) + \langle \Delta n \rangle^2 \kappa_2(N_W),$$

$$\kappa_3(\Delta N) = \langle N_W \rangle \kappa_3(\Delta n) + 3 \langle \Delta n \rangle \kappa_2(\Delta n)\kappa_2(N_W) + \langle \Delta n \rangle^3 \kappa_3(N_W),$$

$$\kappa_4(\Delta N) = \langle N_W \rangle \kappa_4(\Delta n) + 4 \langle \Delta n \rangle \kappa_3(\Delta n)\kappa_2(N_W) + 3\kappa_2^2(\Delta n)\kappa_2(N_W) + 6 \langle \Delta n \rangle^2 \kappa_2(\Delta n)\kappa_3(N_W) + \langle \Delta n \rangle^4 \kappa_4(N_W).$$

P. Braun-Munzinger et al, NPA 960 (2017) 114–130
A. Rustamov et al, NPA 1034 (2023) 122641
R. Holzmann et al, arXiv: 2403.03598
MARVIN NABROTH, CPOD 2024

Summary

Recent results from several experimental observables are shown

① Intermittency analysis: **A dip of ν at ~20-30 GeV**

② Light nuclei yield ratio: **Deviations at 20-30 GeV**

③ Baryon-strangeness correlation: **A maximum deviation at ~20GeV**

④ Net-proton cumulants: **A maximum deviation at ~20GeV**

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Collaborations for their nice results,

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