The 20th International Conference on QCD in Extreme Conditions (XQCD 2024), IMP, Lanzhou

Study the QCD Phase Structure with Beam Energy Scan at RHIC

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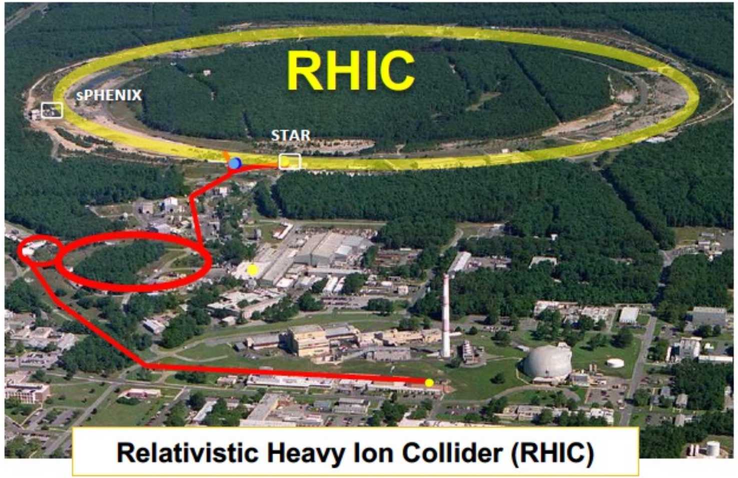
Outline

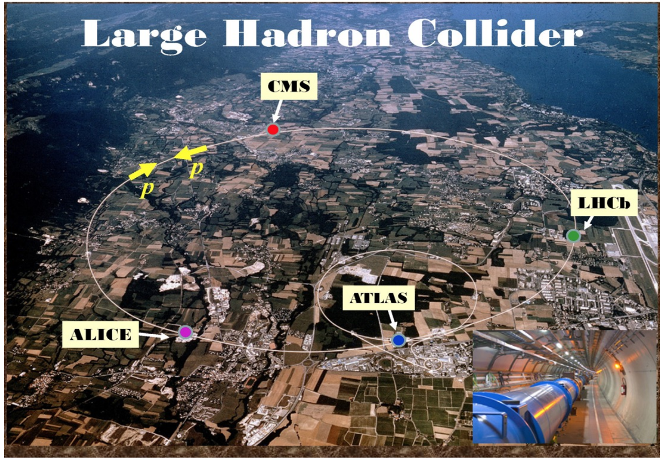
- Introduction

- Selected Results from RHIC Beam Energy Scan
  1) Net-Proton Fluctuations (BES-II Collider)
  2) Baryon-Strangeness Correlations (BES-I&BES-II)
  3) Light Nuclei Production (BES-I)

- Summary and Outlook

Relativistic Heavy-Ion Collisions



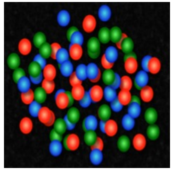


Matter under Strong Interaction

Quantum Chromodynmaics (QCD) is the fundamental theory of strong interaction

Phase Transition

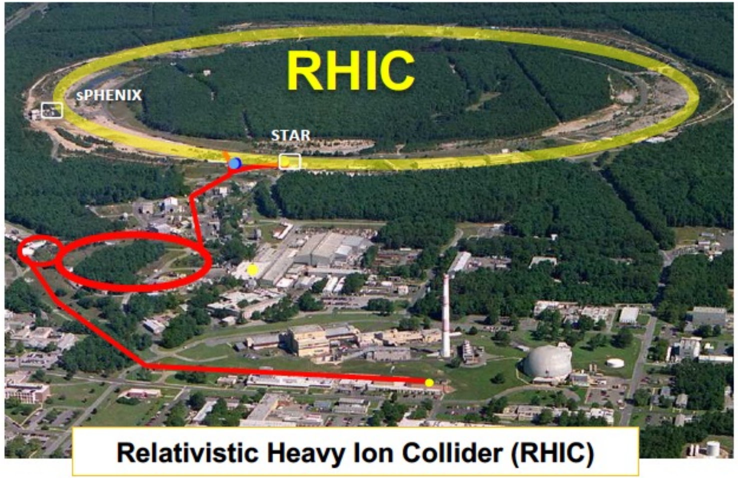
Vary T and density

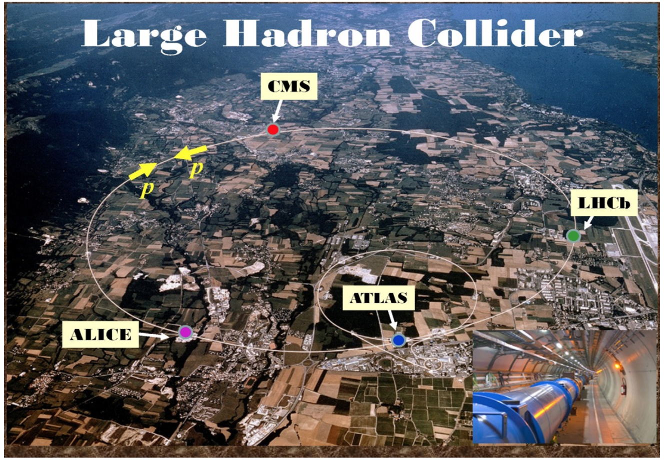


Ordinary Nuclear Matter

Quark-Gluon Plasma (QGP)

Relativistic Heavy-Ion Collisions





sQGP: Perfect liquid

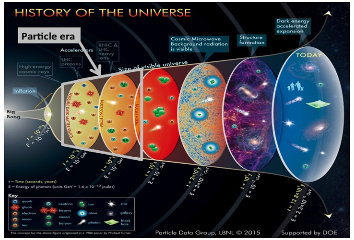
- Small eta/s ~ quantum limit
- Strong electromagnetic field
- Large vorticity

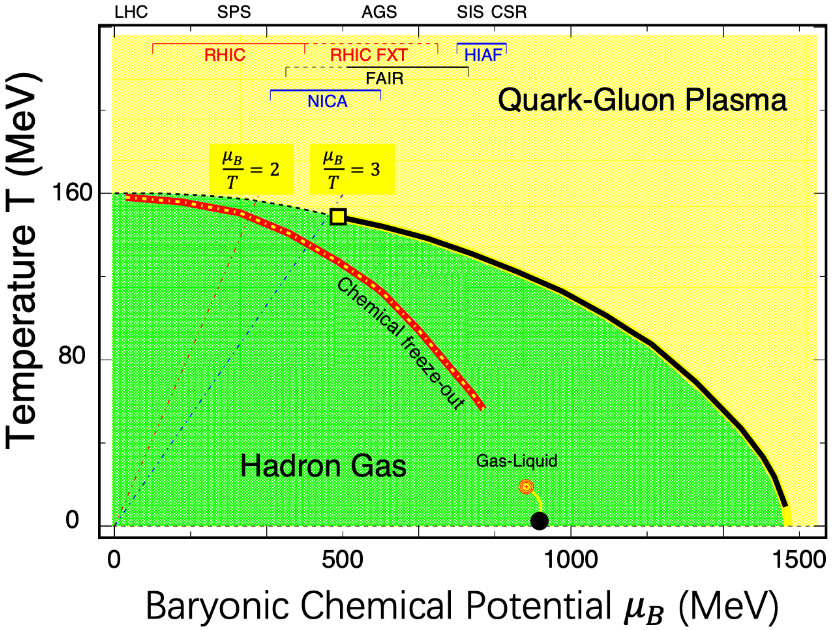
RHIC White Paper :nucl-ex/0501009
Hot QCD White Paper：2303.17254
ALICE: 2211.04384 (review)

- ➢ **Properties of Quark-Gluon Plasma (QGP)**
- ➢ **Phase structure of Strongly Interacting Matter (QCD phase structure)**

QCD Phase Diagram

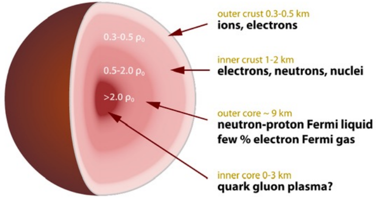
Emergent Properties of Strong Interactions, rich structure at high baryon density





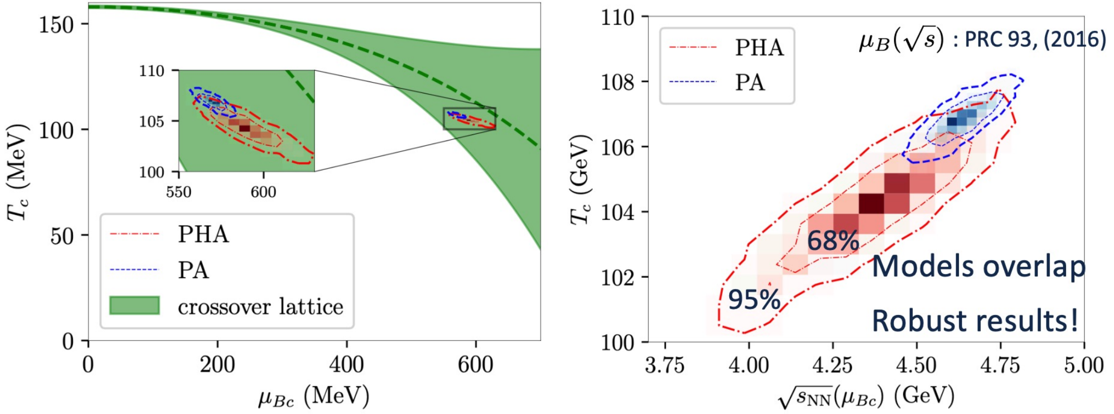
Lattice QCD : at $\mu_B = 0$, smooth crossover.
Large μ_B : 1st order phase transition and QCD critical point ?

Y. Aoki et al., Nature 443, 675 (2006) ;
A. Bazavov et al (HotQCD), PRD 85, 054503 (2012).
K. Fukushima and C. Sasaki, Prog. Part. Nucl. Phys, 72, 99 (2013).
A. Bzdak et al., Phys. Rep. 853, 1 (2020).

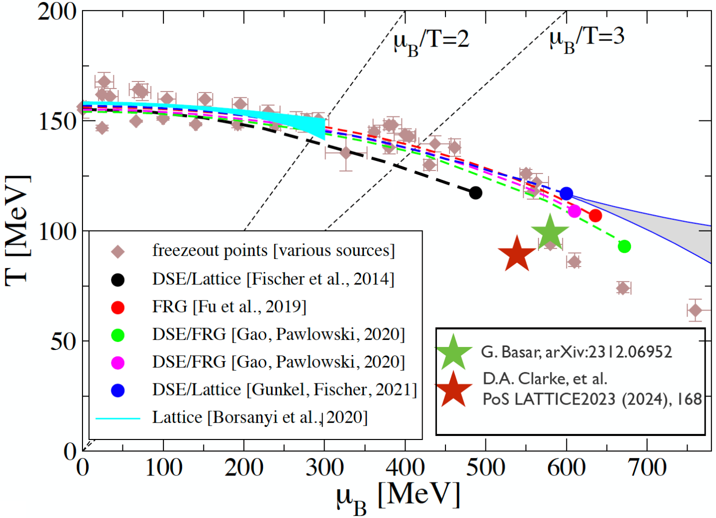


Q1 : Can we find the experimental signature of the smooth crossover ?
Q2 : Can we map out the 1st order phase boundary and find the QCD Critical Point ?
Q3 : What is the equation of state of the dense nuclear matter ?

Location of the QCD Critical Point : Theoretical Estimation/Prediction



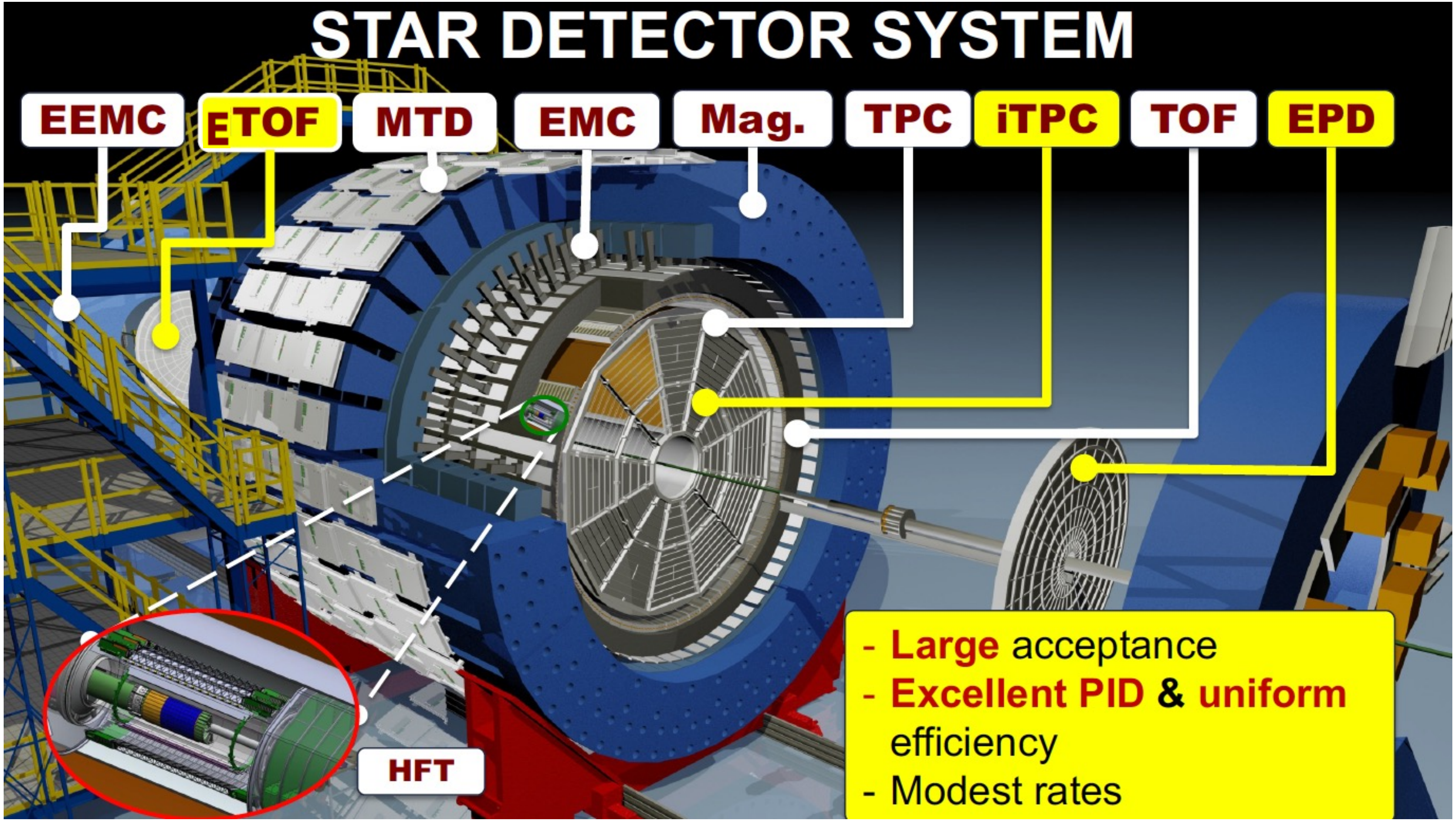
Holography+ Bayesian : Hippert et al., arXiv : 2309.00579



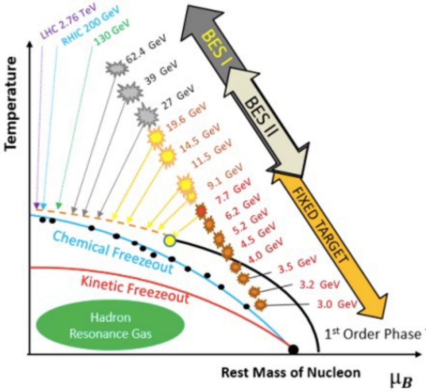
CPOD2024

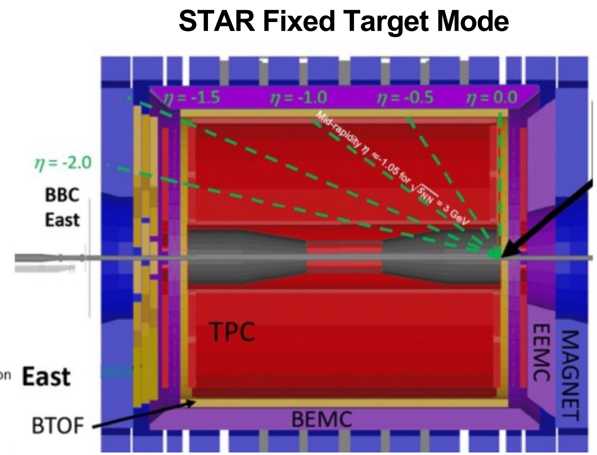
Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

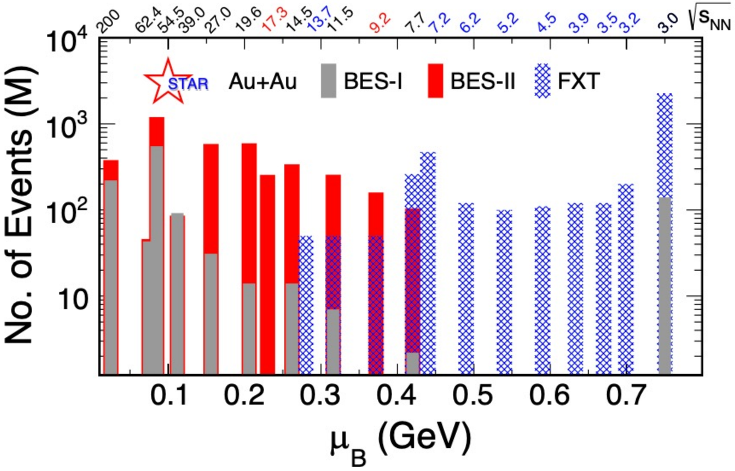
$(\mu_c, T_c) = (495 - 654, 100 - 119)$ MeV → $3.5 < \sqrt{s_{NN}} < 4.9$ GeV


STAR DETECTOR SYSTEM
EEMC
ETOF
MTD
EMC
Mag.
TPC
iTPC
TOF
EPD
HFT
- Large acceptance
- Excellent PID & uniform efficiency
- Modest rates

RHIC Beam Energy Scan (BES) Program (2010-2021)

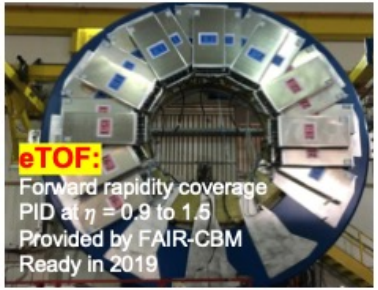




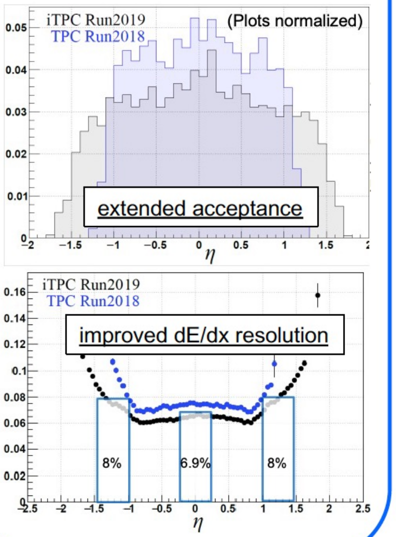


- x10-20 more statistics in BES-II compared to BES-I at collider energies
- BES-II: Collider energies (7.7 – 27 GeV), FXT energies (3.0 - 13.7 GeV)
- μ_B coverage : $25 < \mu_B < 750$ MeV

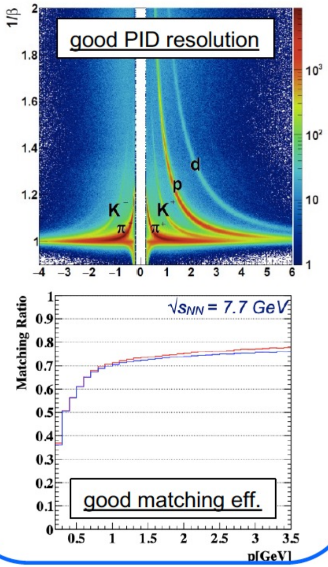
Detector Upgrade and Performance in BES-II



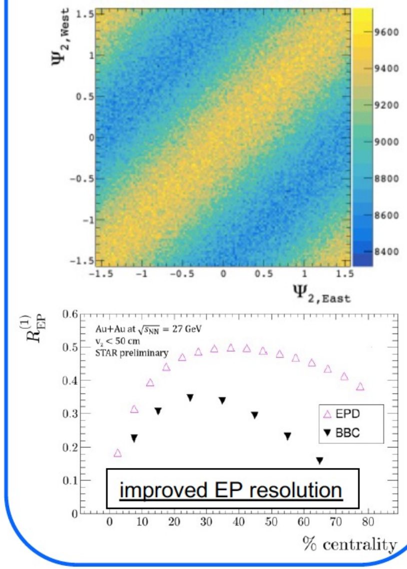
iTPC (2019+)



eTOF (2019+)



EPD (2018+)



1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/event plane resolution

Observables: Higher Moments of Conserved Charge Distributions

Conserved Charges: Net Baryon Number (B), Net Charge (Q), Net Strangeness (S)

Measured multiplicity N, $\langle \delta N \rangle = N - \langle N \rangle$

mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3 / C_2^{3/2}$

kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 = C_4 / C_2^2$

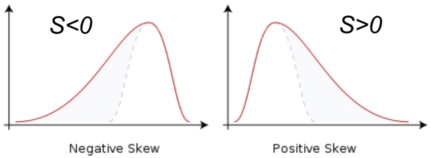
Moments, cumulants and susceptibilities:

2nd order: $\sigma^2 / M \equiv C_2 / C_1 = \chi_2 / \chi_1$

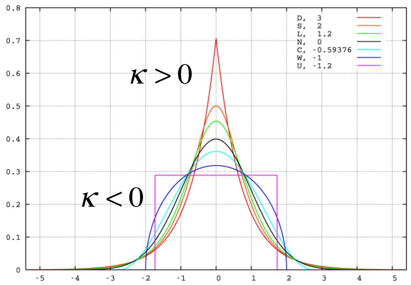
3rd order: $S\sigma \equiv C_3 / C_2 = \chi_3 / \chi_2$

4th order: $\kappa\sigma^2 \equiv C_4 / C_2 = \chi_4 / \chi_2$

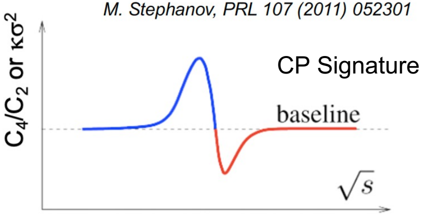
Skewness (S) → asymmetry



Kurtosis(κ) → Sharpness



M. Stephanov, PRL 107 (2011) 052301



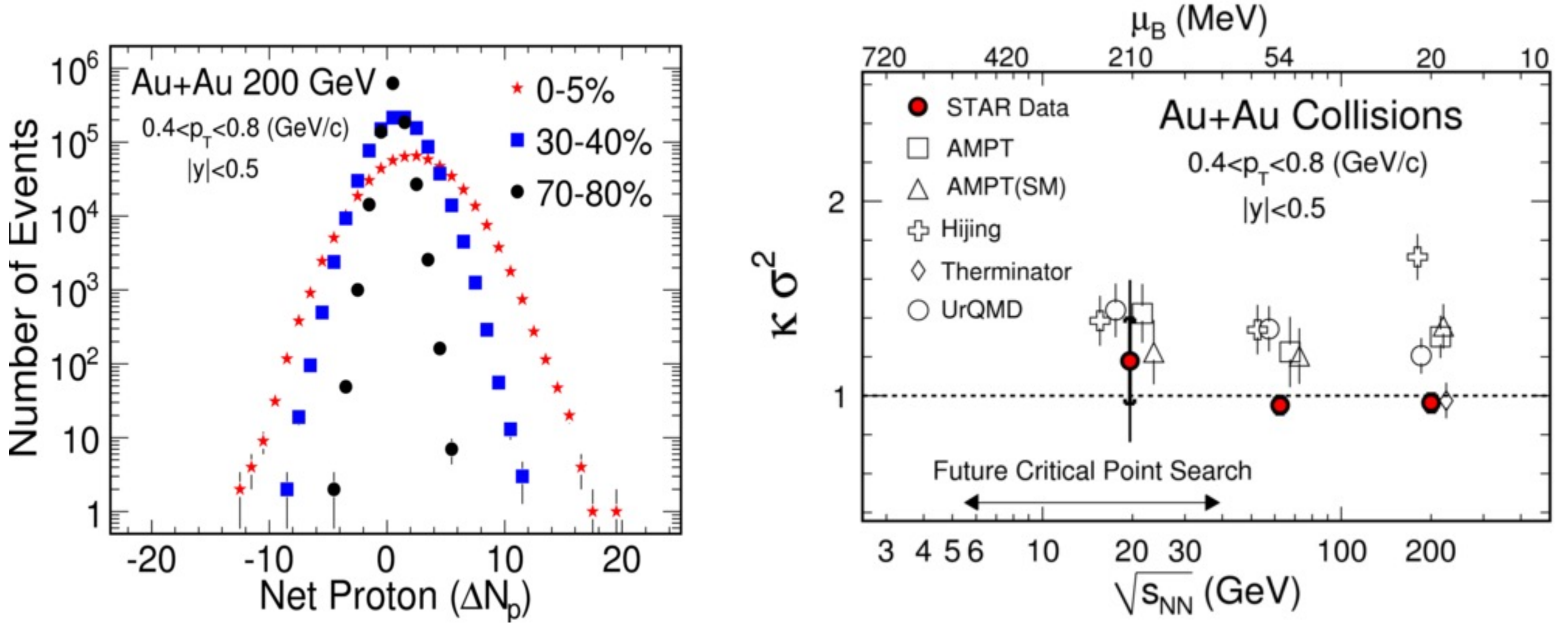
1. Sensitive to correlation length (ξ)
2. Directly related to system susceptibility (χ)

$$\langle (\delta N)^3 \rangle_c \approx \xi^{4.5}, \quad \langle (\delta N)^4 \rangle_c \approx \xi^7$$

$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial (\mu_q)^n}, q = B, Q, S$$

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009); 107, 052301 (2011). M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009). Cheng et al, PRD (2009) 074505. F. Karsch and K. Redlich , PLB 695, 136 (2011). B. Friman et al., EPJC 71 (2011) 1694. *S. Gupta, et al., Science, 332, 1525(2012). A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13)*

Higher Moments of Net-Proton Multiplicity Distributions

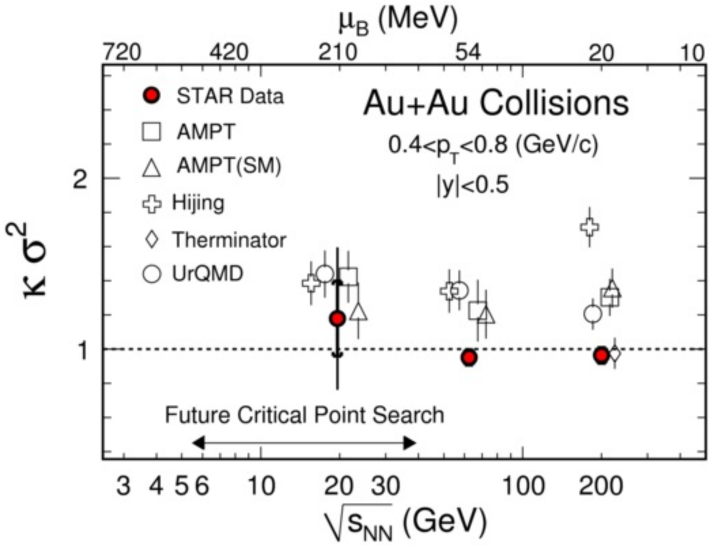


STAR, Phys. Rev. Lett. 105, 022302 (2010)

First measurement

Verified the feasibility of the high moments observable in heavy-ion experiment.

Higher Moments of Net-Proton Multiplicity Distributions



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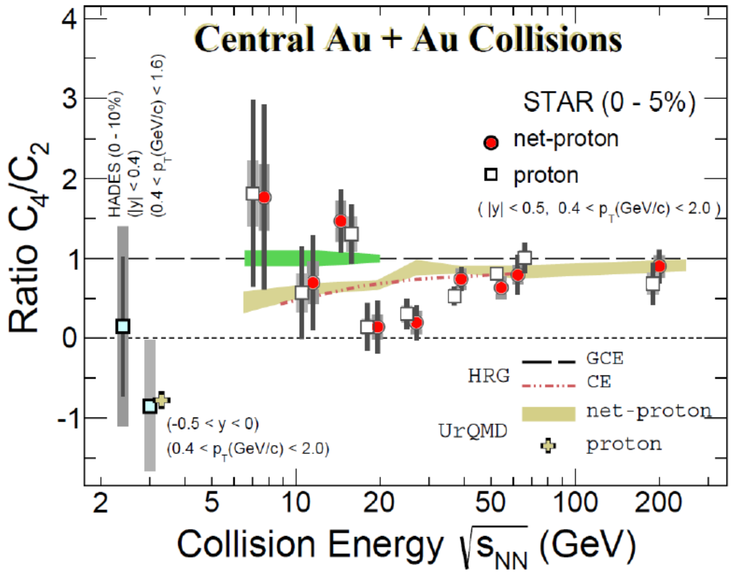

BES-I : Phys. Rev. Lett. 126, 092301 (2021)
Phys. Rev. C 104, 024902 (2021)
3 GeV: Phys. Rev. Lett. 128, 202303 (2022)
Phys. Rev. C 107, 024908 (2023)

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X.Luo, J. Phys. G39, 025008 (2012); A. Bzdak and V. Koch, PRC86, 044904 (2012); X.Luo, et al. J. Phys. G40,105104(2013); X.Luo, Phys. Rev. C 91, 034907 (2015); A . Bzdak and V. Koch, PRC91, 027901 (2015). T. Nonaka et al., PRC95, 064912 (2017). M. Kitazawa and X. Luo, PRC96, 024910 (2017). S. He, X. Luo, Chin. Phys. C43, 104001 (2018), X. Luo and T. Nonaka, PRC99, 044917 (2019); Arghya Chatterjee, PRC 101,034902 (2020) Fan Si, et al. CPC 45, 124001 (2021), X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017), T. Nonaka et al, Nucl. Inst. Meth. A 984(2020)164632, Y. Zhang et al. Nucl. Inst. Meth. A 1026(2022)166246

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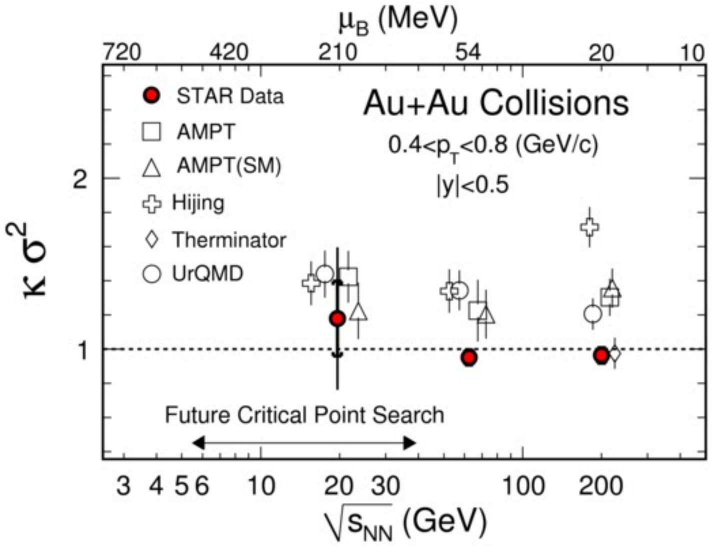

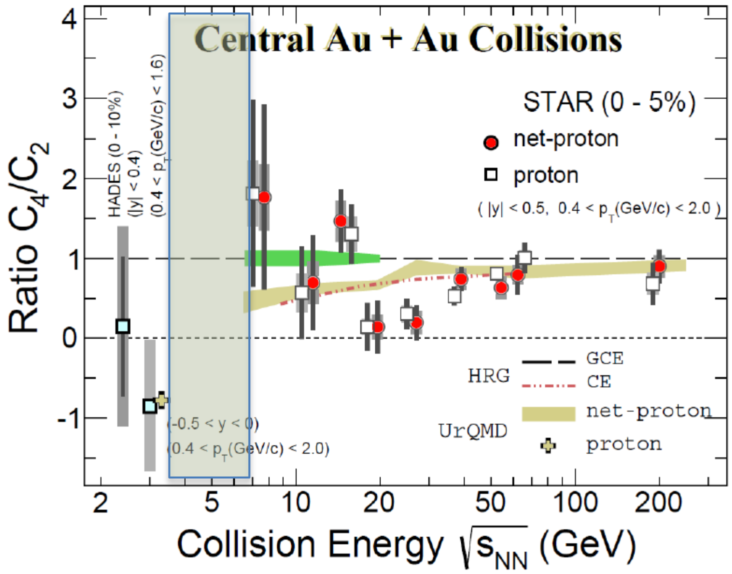

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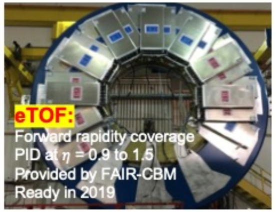
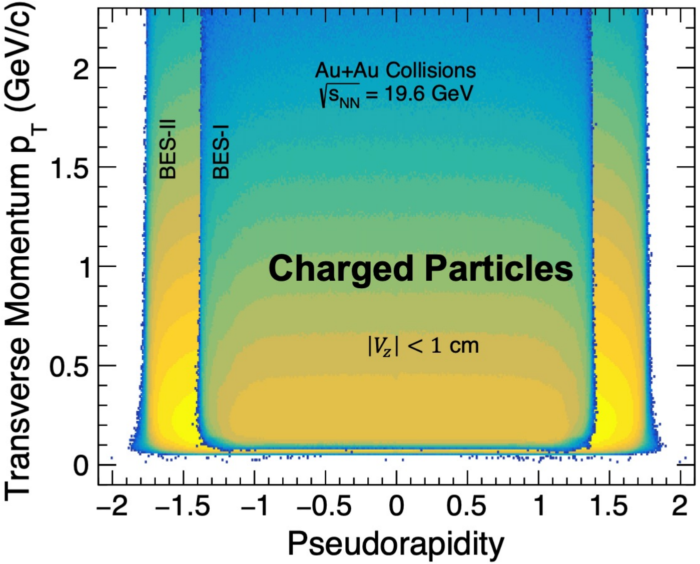
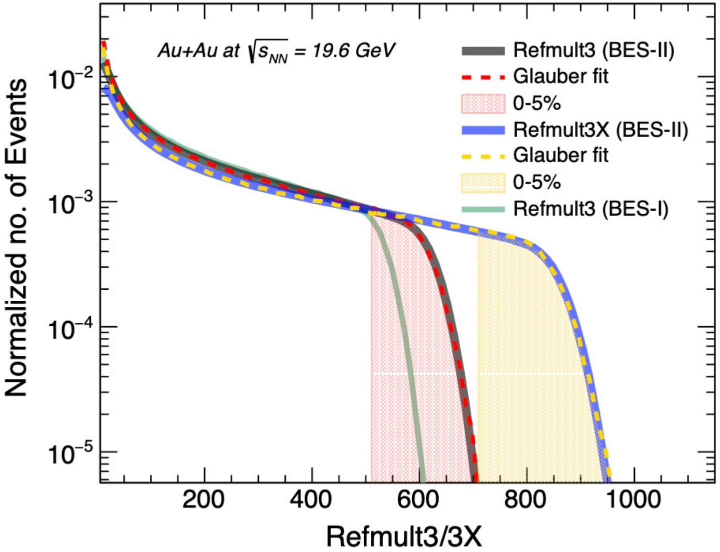
BES-II : Centrality Determination







1. Multiplicity of charged particles except (anti-)protons is used for centrality determination

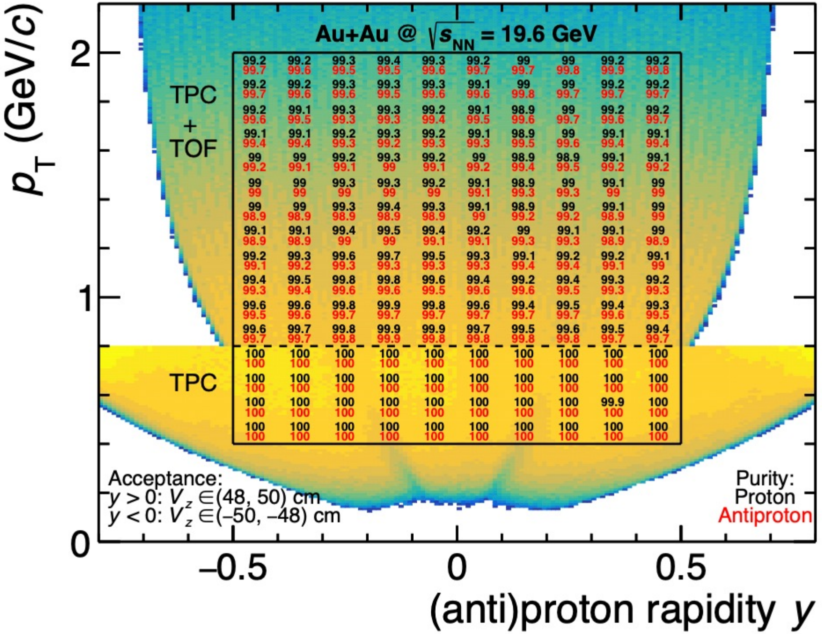
2. Larger acceptance and multiplicity lead to better centrality resolution:
   RefMult3X (BES-II, $|\eta|<1.6$) > RefMult3 (BES-II, $|\eta|<1$) > RefMult3 (BES-I, $|\eta|<1$)
   w/ iTPC w/ iTPC w/o iTPC

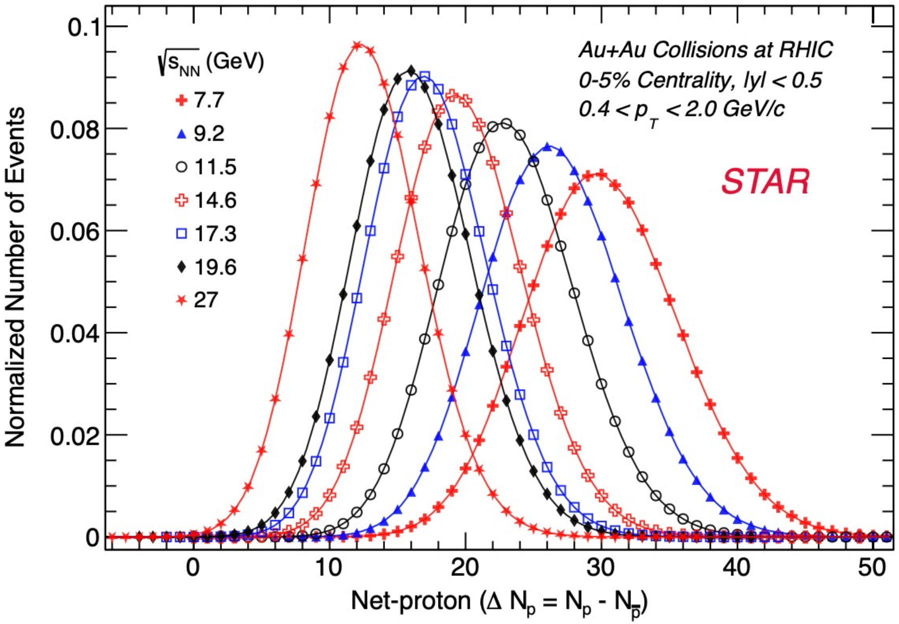
(Anti-)Proton Particle Identification and Net-Proton Distributions

- Identified protons in selected kinetic region are used for analysis:
  $0.4 < p_T < 2.0$ GeV/c and $|y| < 0.5$

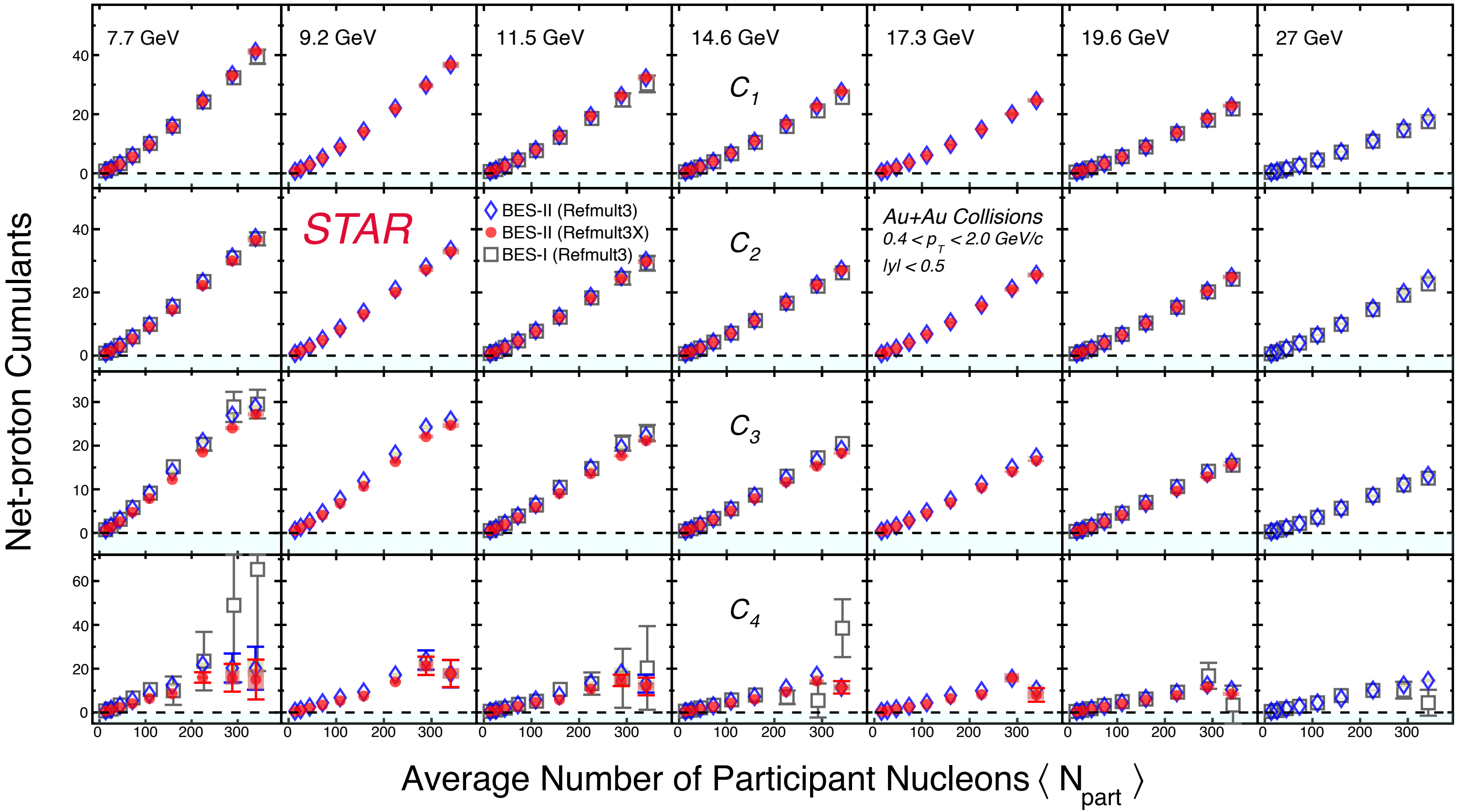
✓ Bin-by-bin proton/antiproton purity > **99%**

Stat. error $C_r \propto \frac{\sigma^r}{\sqrt{N}}$

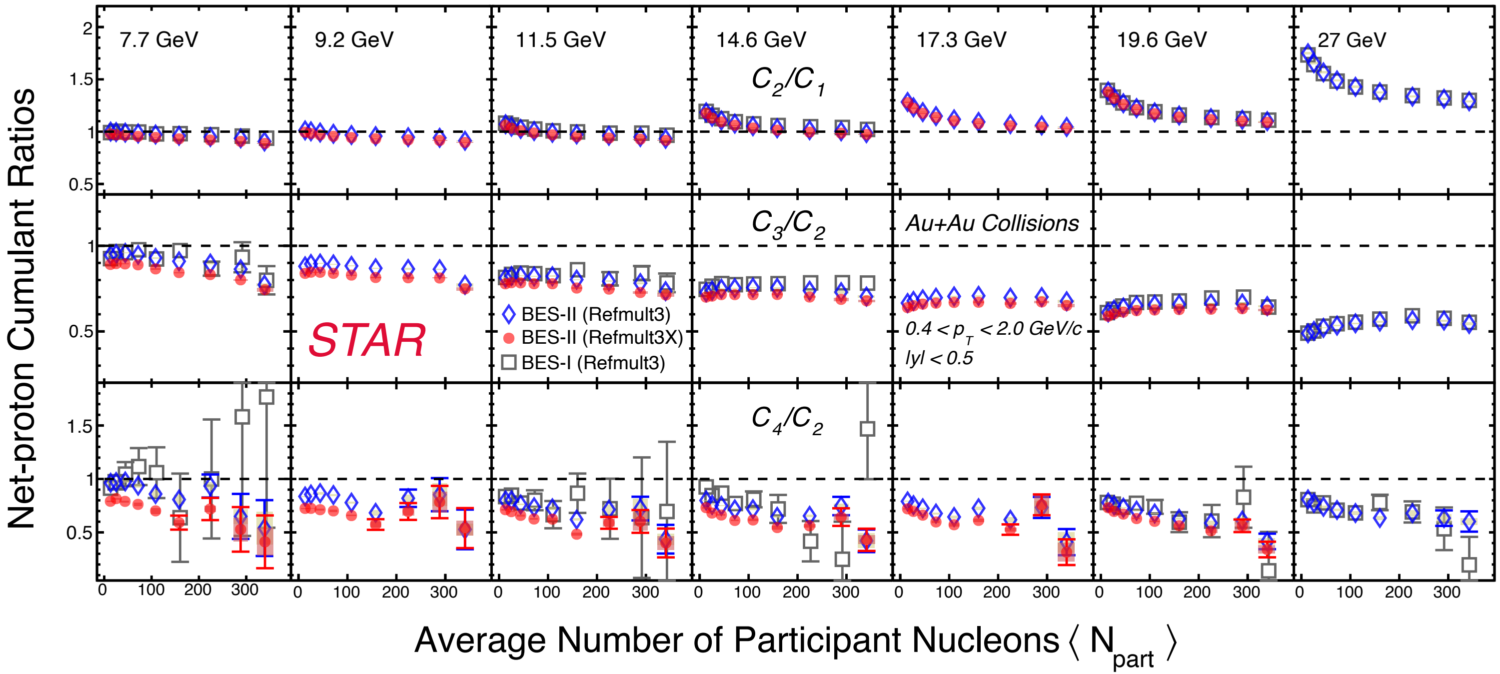




Centrality Dependence: Net-proton Cumulants

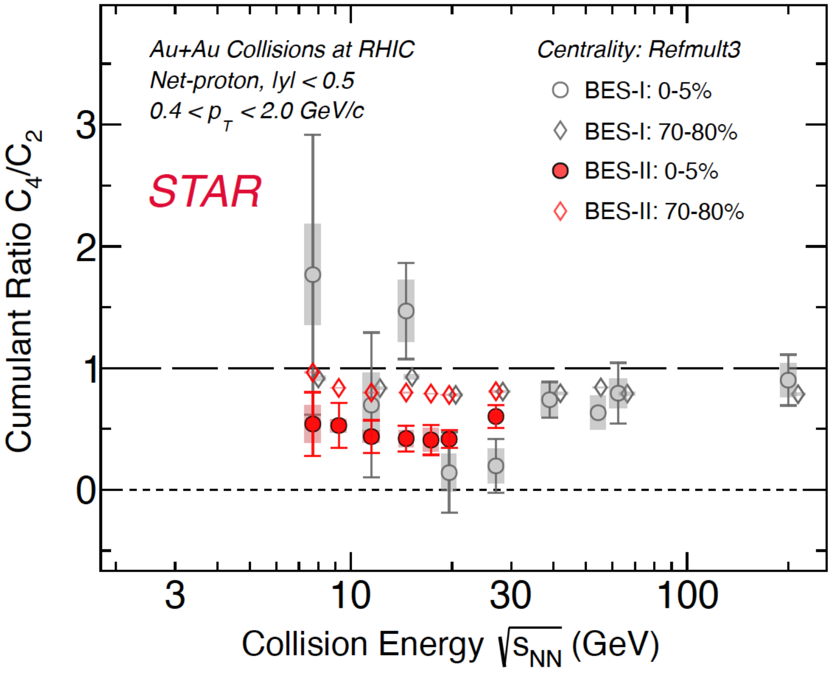


Centrality Dependence: Net-proton Cumulant Ratios



1. Smooth variation across centrality and collision energy is seen from BES-II measurement;
2. Better centrality resolution leads to lower cumulant ratios (especially for mid-central collisions): Calculations from RefMult3X < RefMult3 < RefMult3 (BES-I)
3. For 0-5% most central collisions, weak effect of centrality resolution of C_4/C_2 is observed

Cumulant Ratios from BES-II and BES-I



Events used for net-proton fluctuation studies

$\sqrt{s_{NN}}$ (GeV)	Events BES-I (10^6)	Events BES-II (10^6)
7.7	3	**45**
9.2	-	**78**
11.5	7	**110**
14.5	20	**178**
17.3	-	**116**
19.6	15	**270**
27	30	**220**

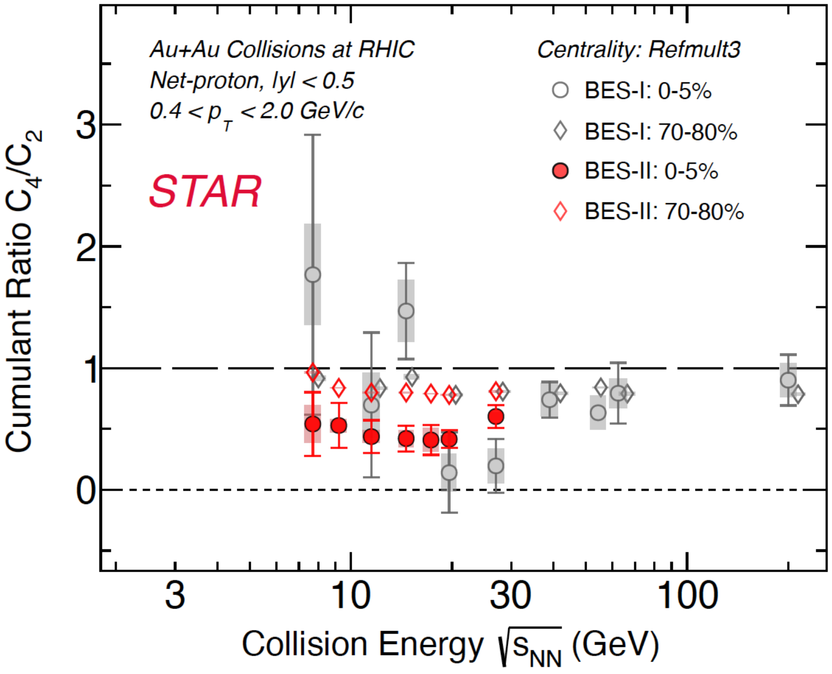
Deviation between BES-II and BES-I data

$\sqrt{s_{NN}}$ (GeV)	0-5%	70-80%
7.7	1.0σ	0.9σ
11.5	0.4σ	1.3σ
14.6	2.2σ	2.5σ
19.6	0.7σ	0.0σ
27	1.4σ	0.2σ

BES-II and BES-I results are consistent !

STAR : **CPOD2024, SQM2024**

Cumulant Ratios from BES-II and BES-I



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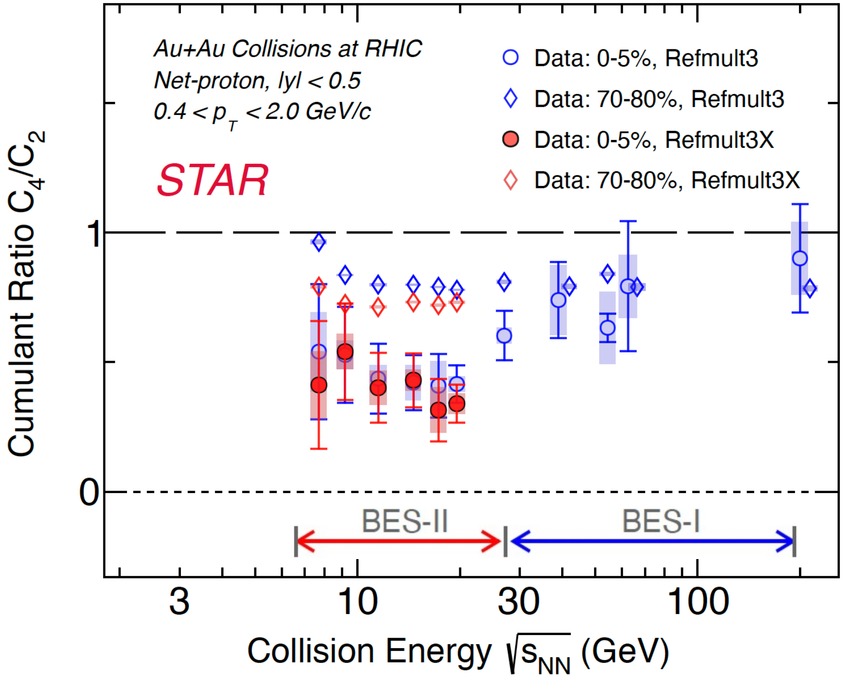
Reduction factor (BES-II vs. BES-I) in uncertainties on 0-5%

7.7 GeV		19.6 GeV	
stat. error	sys. error	stat. error	sys. error
4.7	3.2	4.5	4

BES-II and BES-I results are consistent !

BES-II : Better statistical precision
Better control on systematics !

Cumulant Ratios from BES-II and BES-I



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stat. error	sys. error	stat. error	sys. error
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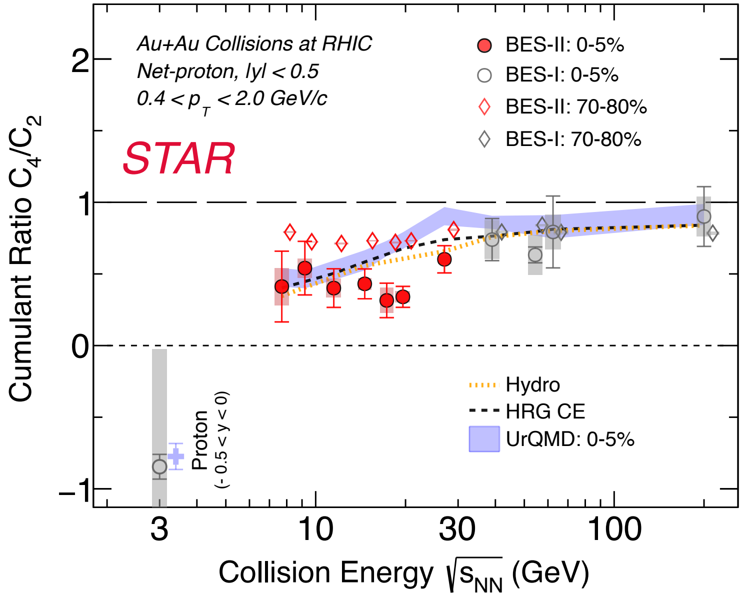
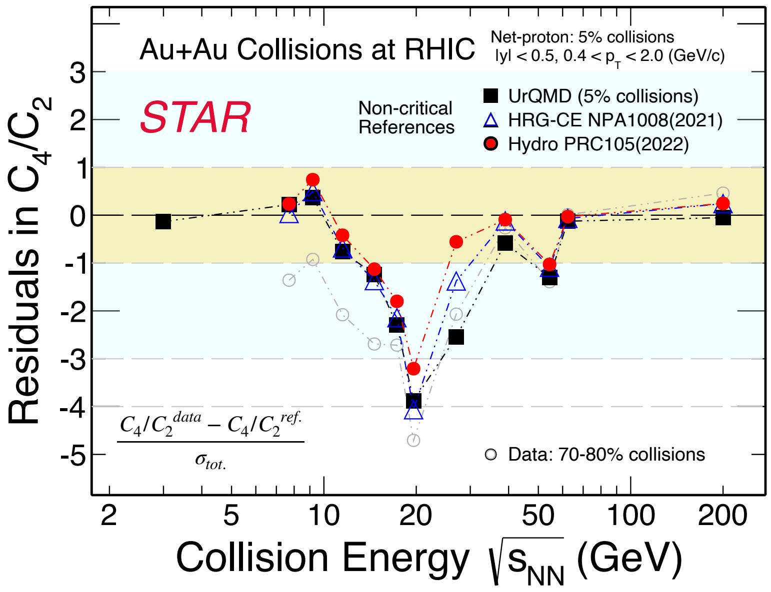
- **0-5% centrality** results show good agreement between Refmult3 and Refmult3X and centrality resolution effect is small.

Energy Dependence and Model Comparison

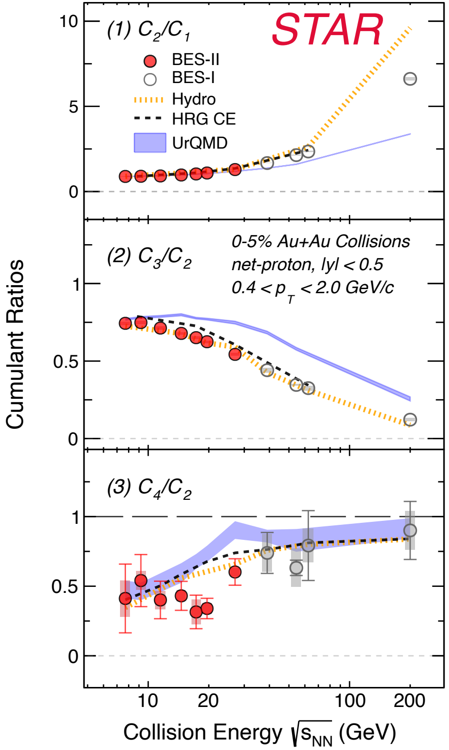




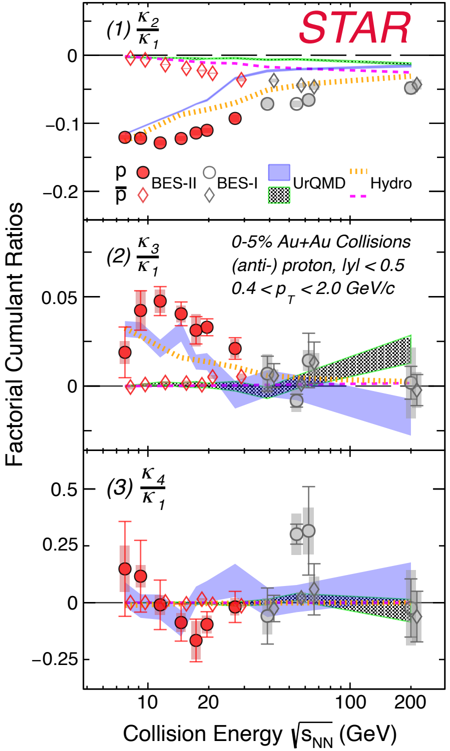
- Most central C_4/C_2 shows minimum around 20 GeV comparing to non-CP models and 70-80% collisions
  1) Maximum deviation: $3.2 - 4.7\sigma$ at 20 GeV ($1.3 - 2\sigma$ at BES-I)
  2) Overall deviation from $\sqrt{s_{NN}} = 7.7$ to 27 GeV: $1.9 - 5.4\sigma$ ($1.4 - 2.2\sigma$ at BES-I)

Energy Dependence and Model Comparison

Net-proton Cumulant Ratios



(anti-)Proton Factorial Cumulant Ratios



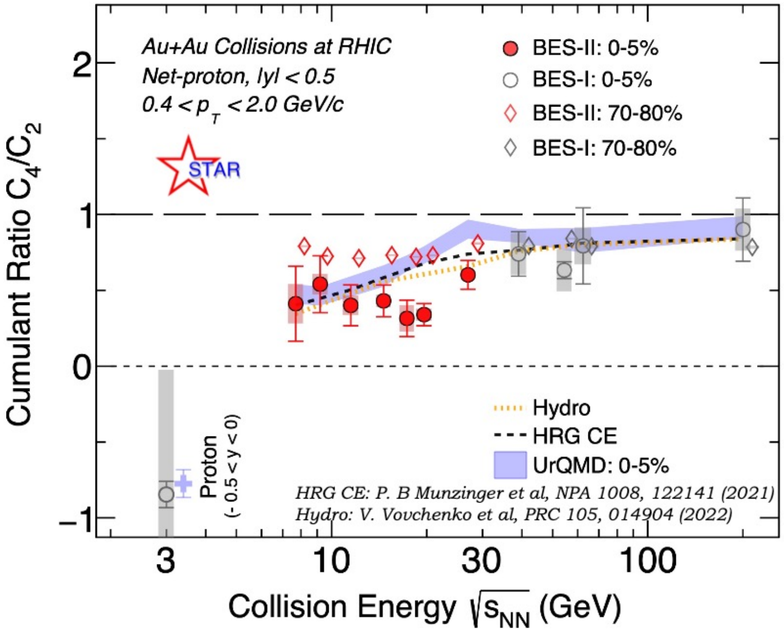
1. C_2/C_1 and C_3/C_2 change smoothly as a function of collision energy;
2. C_4/C_2 decreases with decreasing $\sqrt{s_{NN}}$;
3. Proton factorial cumulant ratios deviate from Poisson baseline at 0;
4. Antiproton's κ_3/κ_1 and κ_4/κ_1 are close to 0;
5. Non-CP models are used for comparison:
    1) Their trends follow STAR data qualitatively;
    2) Quantitative differences exist between them and STAR measurements

- Hydro: hydrodynamical model
  V. Vovchenko et. al.: Phys. Rev. C 105 (2022) 1, 014904
- HRG CE: thermal model with canonical treatment of baryon charge
  P. Braun-Munzinger et. al.: Nucl.Phys.A 1008 (2021) 122141
- UrQMD: hadronic transport model
  M. Bleicher et. al.: J.Phys.G 25 (1999) 1859-1896

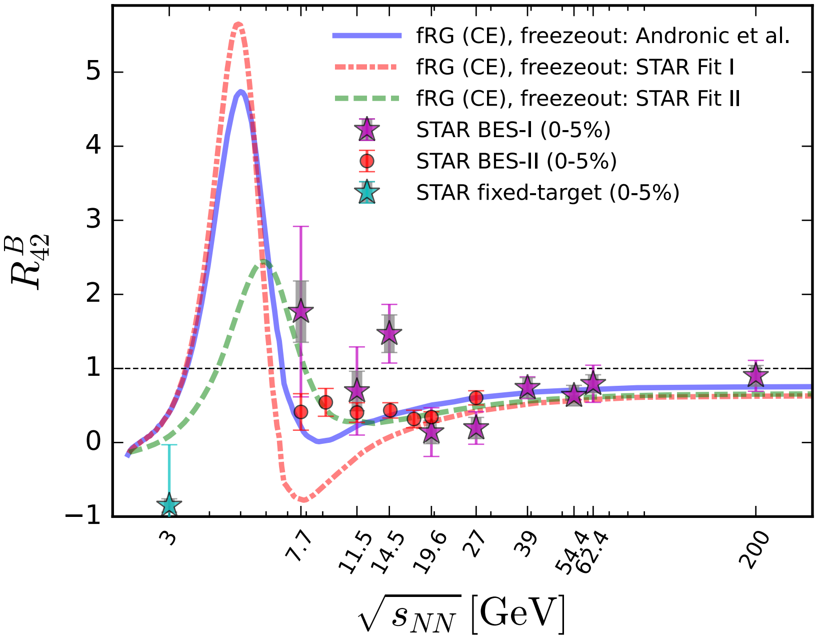
✓Baryon number conservation is included in all models

Continue the Critical Point Search

STAR Measurement：Au+Au 3-200 GeV



Wei-jie Fu, et al., arXiv : 2308.15508



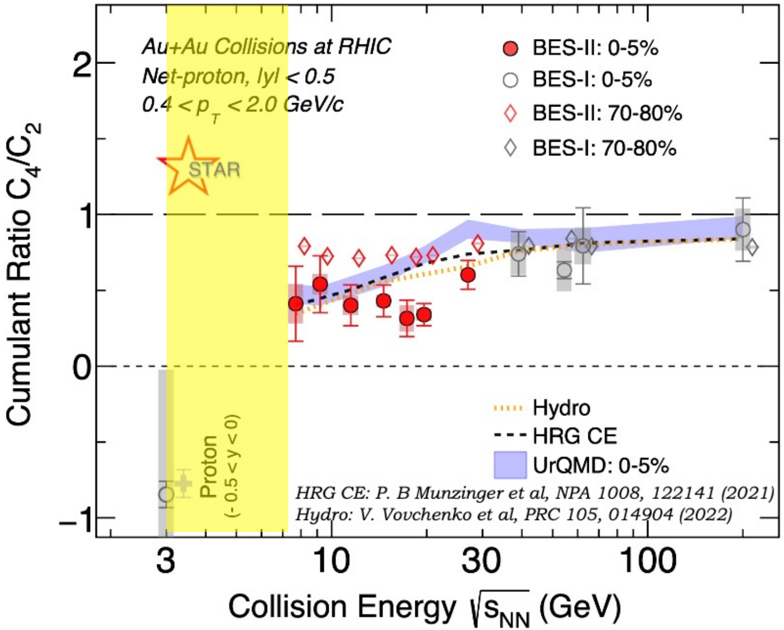
STAR: PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

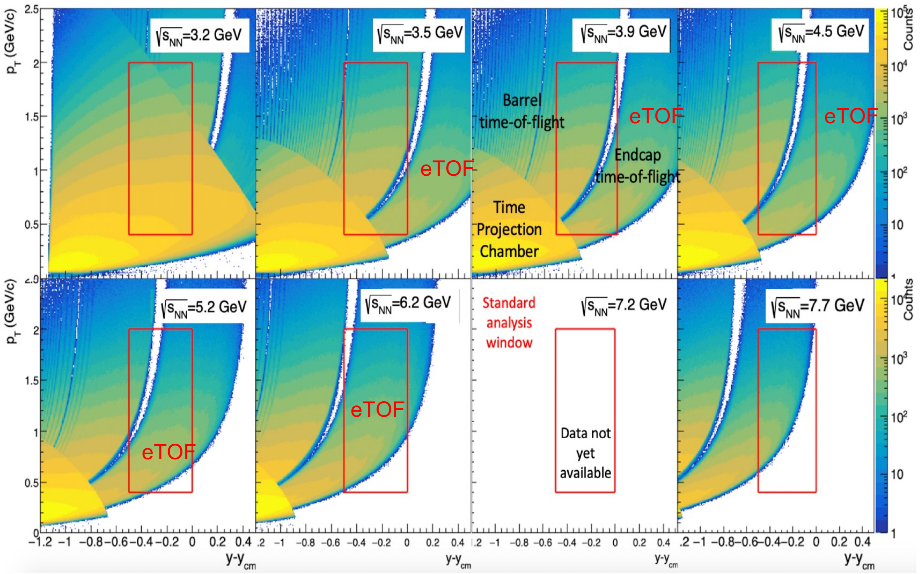
Two important things :

- Experimental Results between 3 – 5 GeV
- Precise dynamical modeling and non-CP baselines

Continue the Critical Point Search

STAR Measurement：Au+Au 3-200 GeV





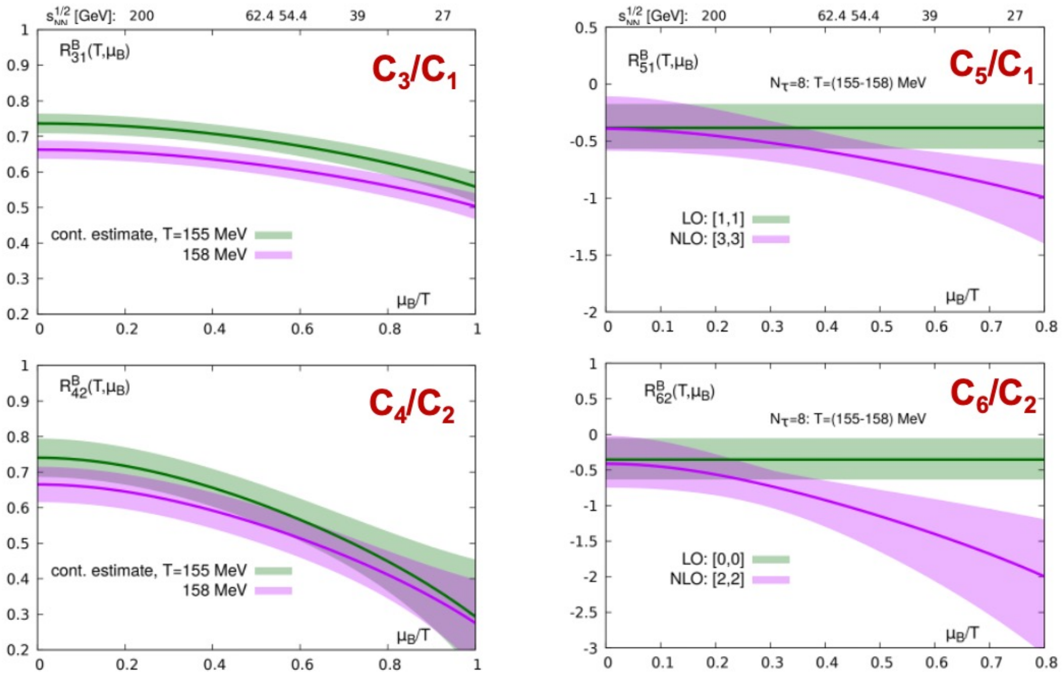
eTOF is crucial for mid-rapidity coverage at 3.5– 4.5 GeV

STAR: PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

Two important things :

- Experimental Results between 3 – 5 GeV
- Precise dynamical modeling and non-CP baselines

Baryon Number Fluctuations from Lattice QCD



$$R^B_{12}(T,\mu_B) \equiv \frac{\chi^B_1(T,\mu_B)}{\chi^B_2(T,\mu_B)} \equiv \frac{M_B}{\sigma^2_B},$$

$$R^B_{31}(T,\mu_B) \equiv \frac{\chi^B_3(T,\mu_B)}{\chi^B_1(T,\mu_B)} \equiv \frac{S_B\sigma^3_B}{M_B}$$

$$R^B_{42}(T,\mu_B) \equiv \frac{\chi^B_4(T,\mu_B)}{\chi^B_2(T,\mu_B)} \equiv \kappa_B\sigma^2_B$$

Tylor expansion at small μ_B:

$$\frac{P(T,\vec{\mu})}{T^4} = \sum_{i,j,k=0}^{\infty} \frac{1}{i!j!k!}\chi^{BQS}_{ijk}(T)\hat{\mu}^i_B\hat{\mu}^j_Q\hat{\mu}^k_S$$

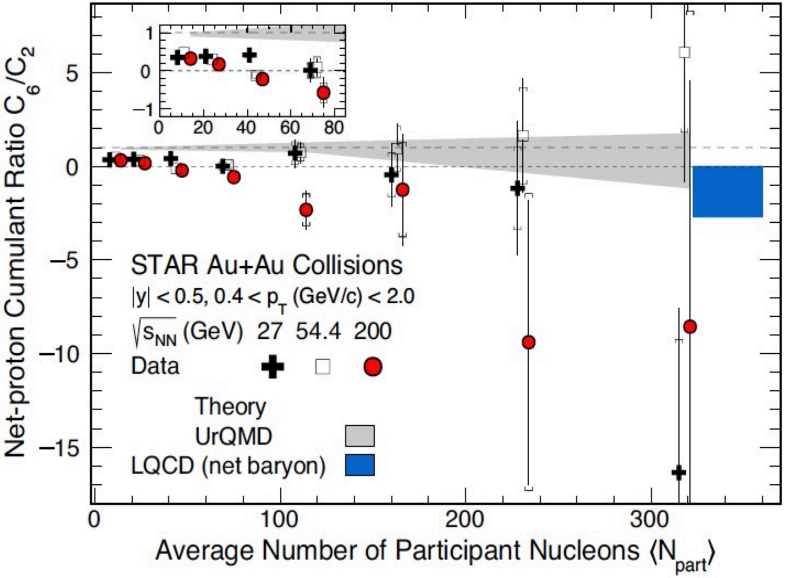
$$\chi^{BQS}_{ijk}(T) = \left.\frac{\partial^{(i+j+k)}P/T^4}{\partial\hat{\mu}^i_B\partial\hat{\mu}^j_Q\partial\hat{\mu}^k_S}\right|_{\vec{\mu}=0}$$

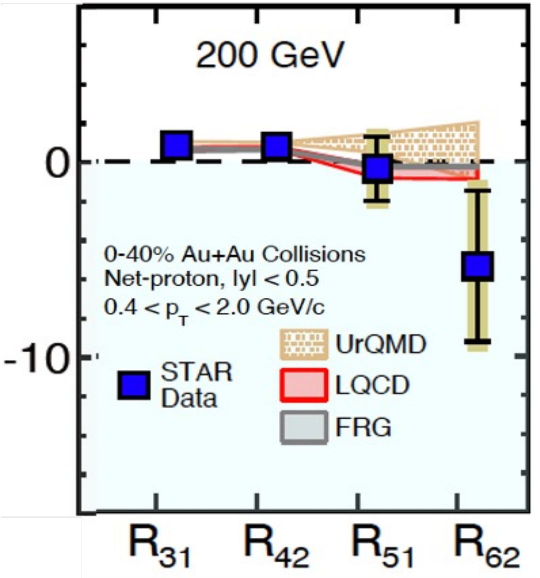
Two features: 1) Ordering of cumulant ratios, 2) Negative in fifth and sixth order fluctuations

$$C_3/C_1 > C_4/C_2 > 0 > C_5/C_1 > C_6/C_2$$

A. Bazavov, D. Bollweg, H.-T. Ding, et al. (HotQCD), Phys. Rev. D 101, 074502 (2020);

Higher-Order Net-Proton Fluctuations



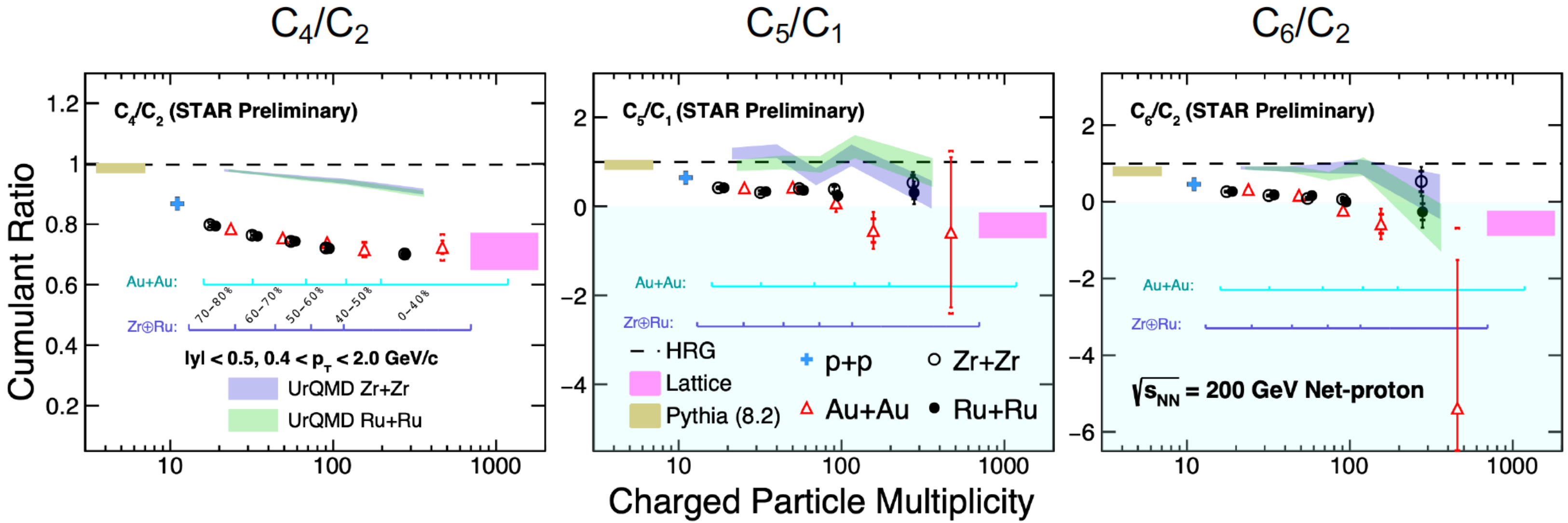


Consistent with Lattice QCD :

1) The sixth-order net-proton fluctuations progressively become negative values from peripheral to central collisions
2) Ordering from lower to higher orders in central collisions.
3) Analysis of BES-II data is ongoing

STAR : PRL 127, 262301 (2021).
STAR : PRL 130, 082301 (2023).

C_5/C_1 and C_6/C_2 : System Size Dependence



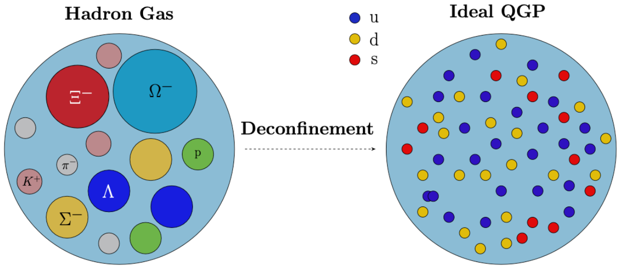
200 GeV : p+p, Ru+Ru, Zr+Zr and Au+Au

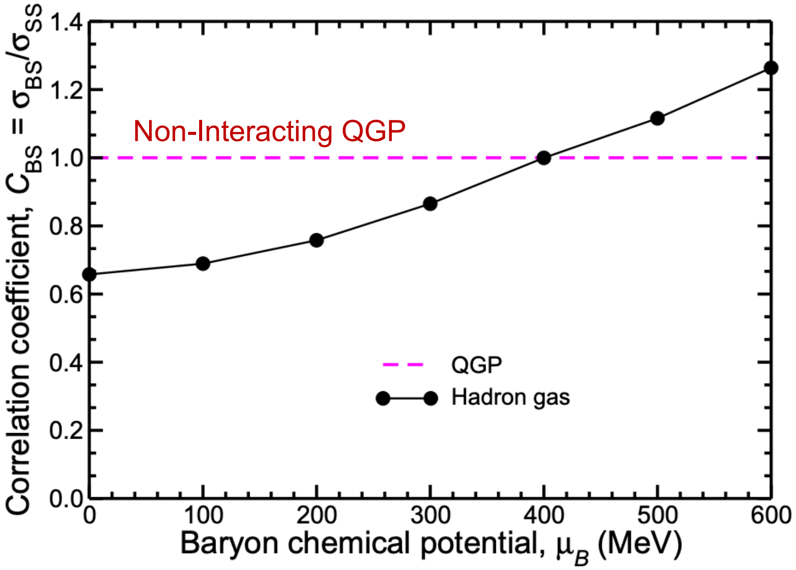
p+p : STAR, arXiv : 2311.00934
200 GeV Au+Au: PRC 104 (2021) 024902; PRL 126.092301 (2021), PRL 127, 262301 (2021).

- Cumulant ratios (up to C6) of net-proton from p+p, Au+Au and isobar data, systematic decreasing trend with multiplicity, approaching LQCD calculations

- Most central Au+Au collision results become consistent with Lattice QCD calculation for the formation of thermalized QCD matter and smooth crossover transition.

Baryon-Strangeness Correlations : Theory





V. Koch, et al., PRL95, 182301 (2005).

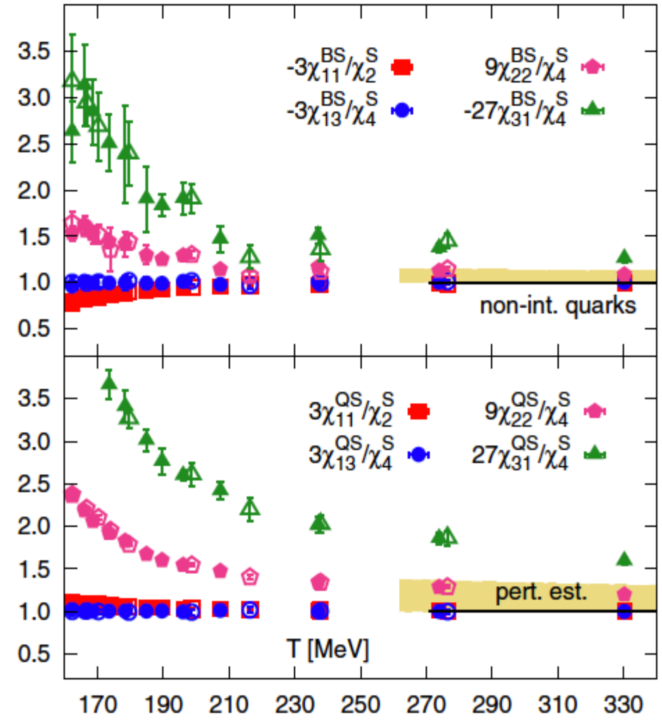
$$C_{BS} = -3\chi^{11}_{BS}/\chi^2_S = -3\frac{<BS> - <B><S>}{<S>^2}$$

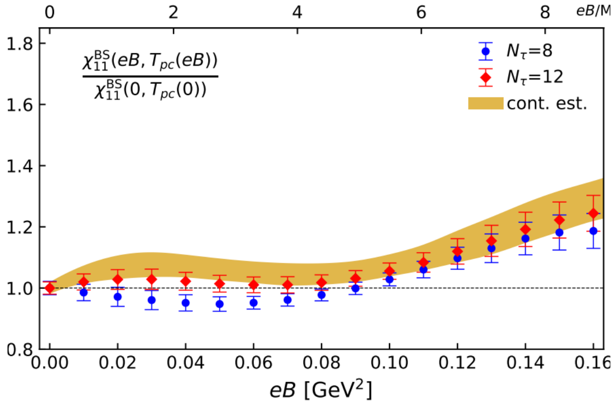
- **Ideal QGP**: $B = \frac{1}{3}(u + d + s)$
  if quarks are uncorrelated
  $\chi_{BS} = -\frac{1}{3}\chi_s{}^2 \quad \rightarrow \quad C_{BS} = 1$

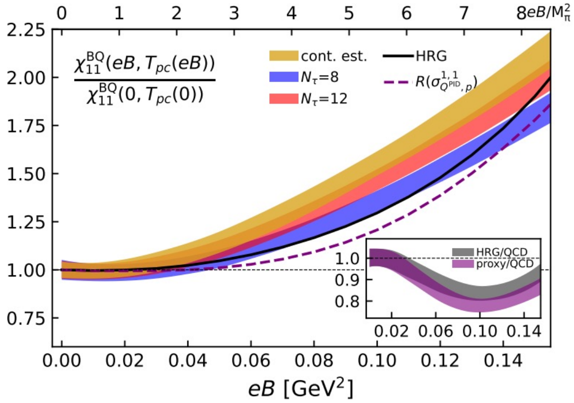
- **Hadronic Matter :**
  Only include Lambda : $C_{BS} = 3$
  Adding more strange meson make C_{BS} smaller (high energy)

- Sensitive to the degree of freedom of strongly interacting matter
- Used to search for the onset of deconfinement

Baryon-Strangeness or Baryon-Charge Correlations : Lattice QCD







Baryon Electric Charge Correlation as a Magnetometer of QCD

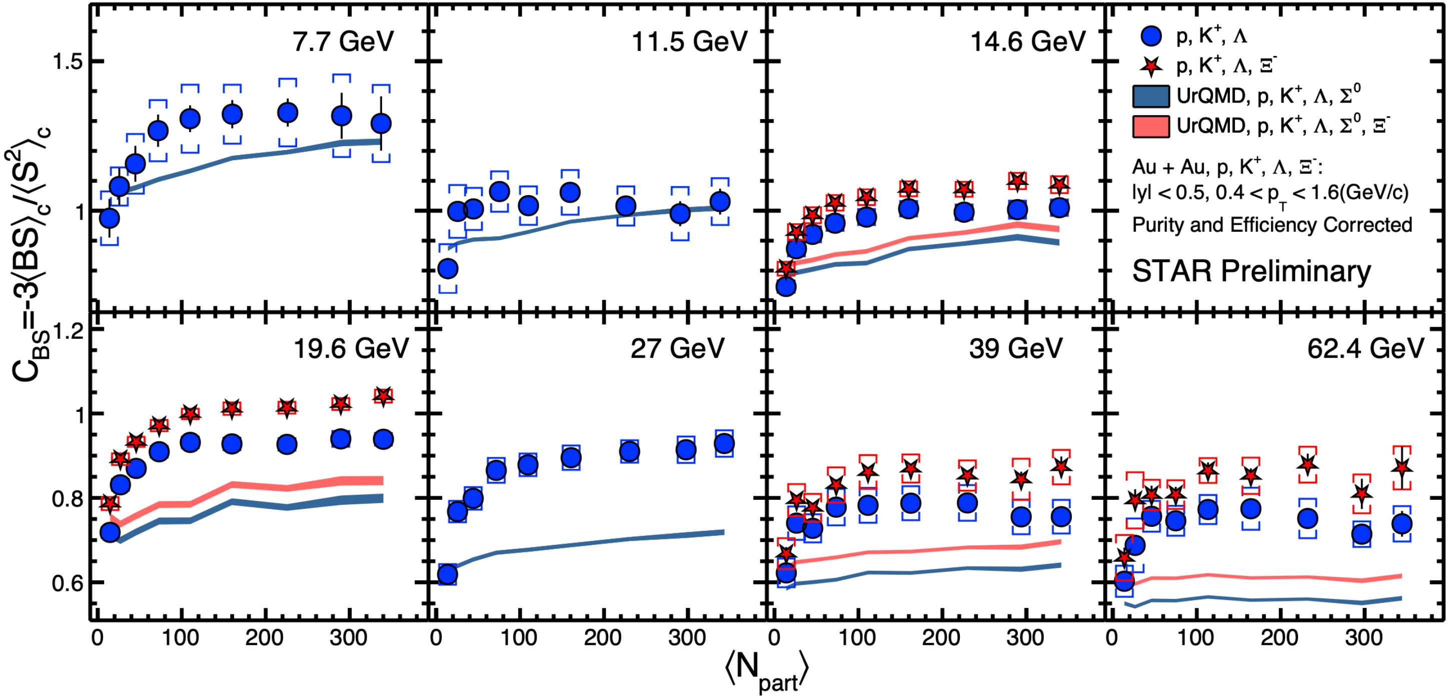
H.-T. Ding, J.-B. Gu,* A. Kumar, S.-T. Li, and J.-H. Liu
Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China

H.-T. Ding, et al., EPJA 57,202 (2021)
H.-T. Ding, et al., Phys. Rev. Lett.132.201903 (2024)

A. Bazavov, H.-T. Ding, et al. (HotQCD) Phys. Rev. Lett. 111, 082301 (2013).

1) Higher order are more sensitive to QCD phase transition
2) Baryon-charge correlation is sensitive to the magnetic effect

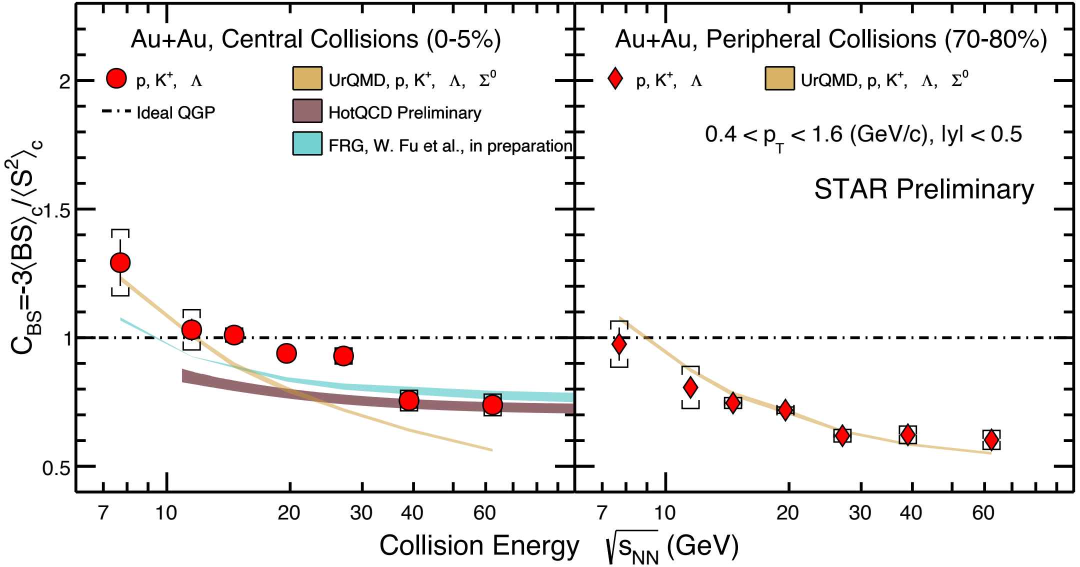
Centrality Dependence of C_{BS}

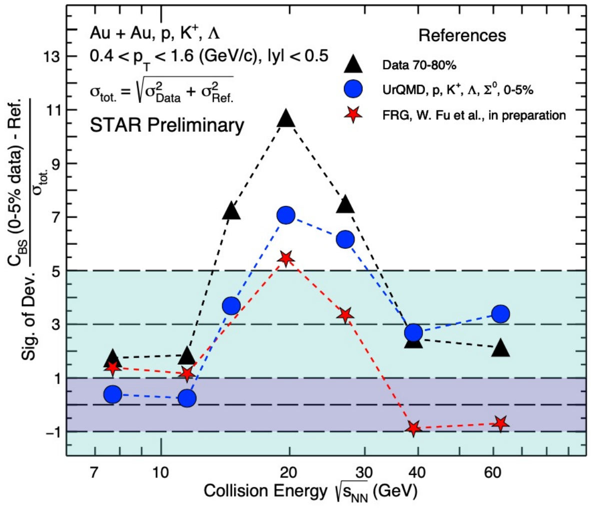


- Data of 14.6 and 19.6 GeV are from BES-II, other energies are from BES-I
- UrQMD can describe the centrality dependence of 7.7 GeV, 11.5 GeV, qualitatively and quantitatively, while it underestimates the higher energy.

STAR, CPOD2024

Energy Dependence of C_{BS} and Model Comparison

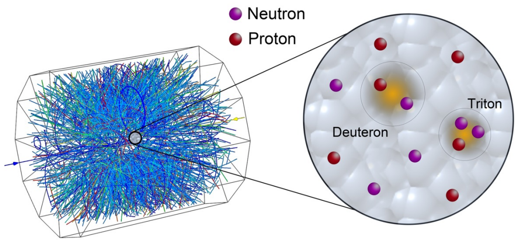


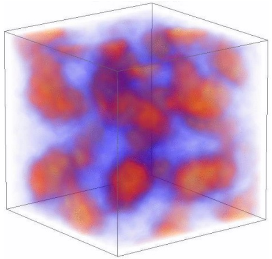


STAR, CPOD2024

- Peripheral collisions (70-80%) can be well described by UrQMD;
- For central collisions:
  1) At high energy is consistent with FRG and LQCD, 7.7 and 11.5 GeV are reproduced by UrQMD
  2) Largest deviation is found at 19.6 GeV, which is more than 5σ
- Analysis of BES-II data (both collider and FXT) and BQ correlation are ongoing.

Yield Ratio of Light Nuclei from BES-I





Coalescence picture：

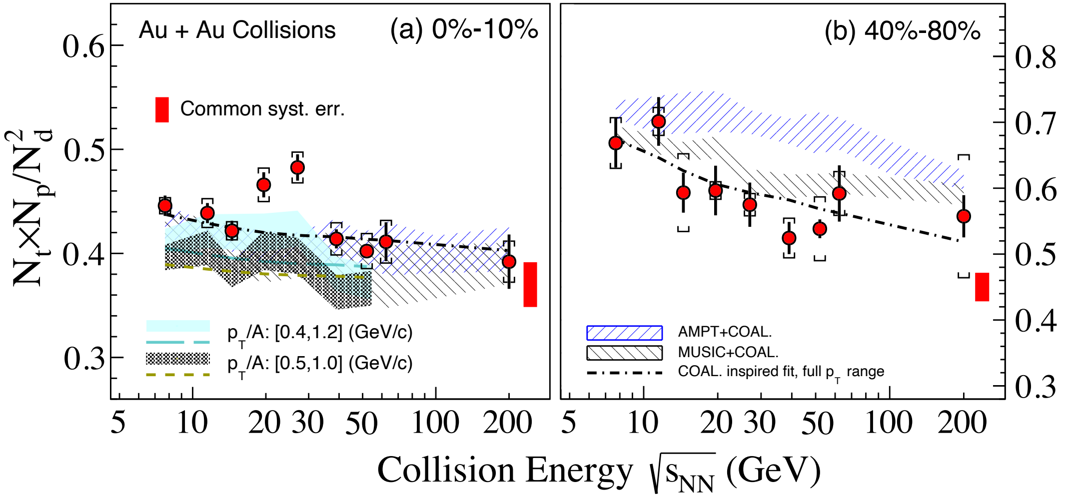
$$N_d = \frac{3}{2^{1/2}}\left(\frac{2\pi}{m_0 T_{eff}}\right)^{3/2} N_p \langle n \rangle (1 + C_{np})$$

$$N_t = \frac{3^{\frac{3}{2}}}{4}\left(\frac{2\pi}{m_0 T_{eff}}\right)^{3} N_p \langle n \rangle^2 (1 + \Delta n + 2C_{np})$$

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

Yield ratios of light nuclei are related to nucleon density fluctuations and can be used to search for the QCD critical point.

K.J. Sun, L.W. Chen, C.M. Ko, J. Pu, and Z.B. Xu, Phys. Lett. B 781, 499 (2018)



- Non-monotonic behavior observed in 0-10% central Au+Au collisions around 19.6 and 27 GeV with 4.1σ significance (combined) deviated from coalescence baseline.
- Analysis of BES-II data (both collider and FXT) are ongoing.

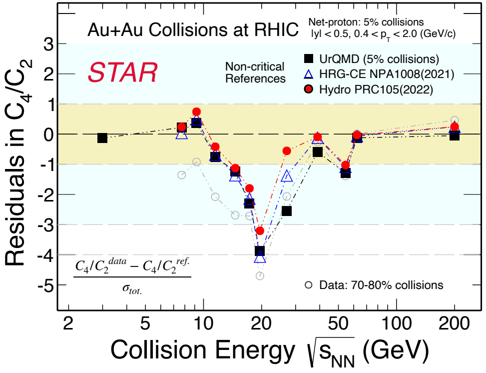
STAR, SQM2024

3 GeV, arXiv : 2311.11020

STAR: Phys. Rev. Lett. 130, 202301 (2023)

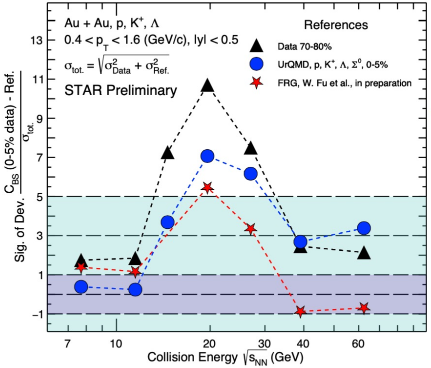
Summary and Outlook

Net-Proton Fluctuations



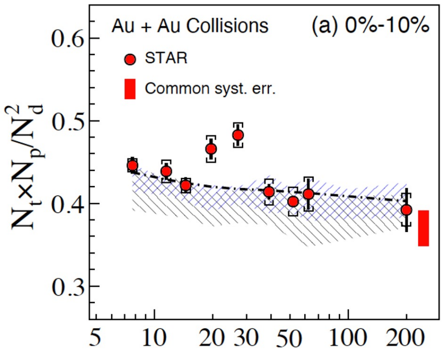
STAR, CPOD2024, SQM2024

BS correlations



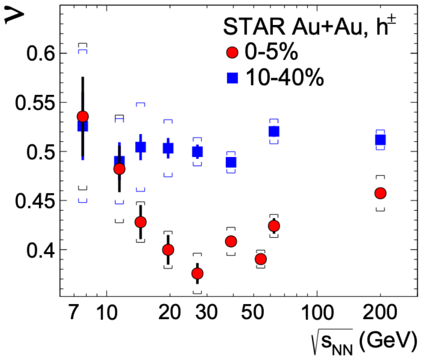
STAR, CPOD2024

Yield Ratio of Light Nuclei

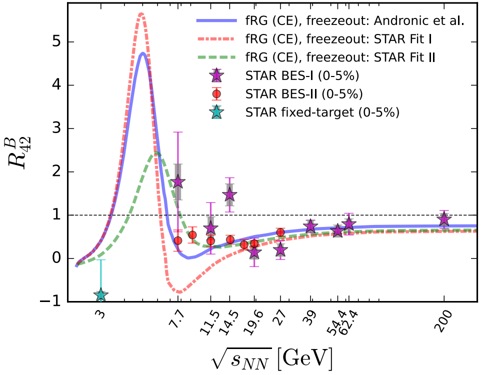


STAR: PRL130, 202301 (2023)

Intermittency



STAR, PLB 845, 138165 (2023)



BES-II : high statistics, better acceptance and systematics

1. *Continue to search for QCD critical point between 3 – 20 GeV*

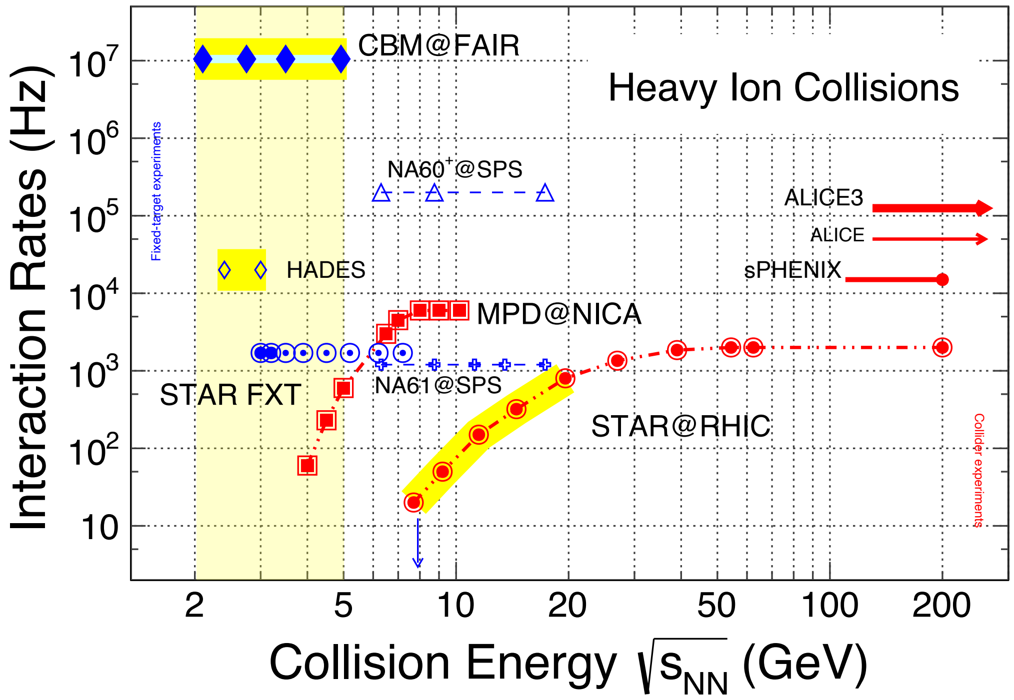
   (BES-II high moments analysis: rapidity scan, C_5, C_6)

2. *Understand the physics lead to the deviations around 20 GeV*

3. *Need reliable dynamical modeling and non-CP baselines*

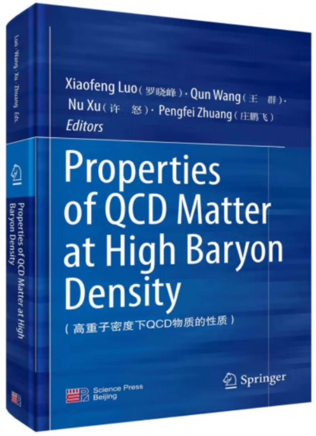
Summary and Outlook

Rich physics at high baryon density : QCD phase structure, EoS etc.



Future High Baryon Density Frontier:

- FAIR/CBM (2.4 - 4.9 GeV)
- HIAF/CEE (2.1– 4.5 GeV)
- NICA/MPD (4 - 11 GeV)



https://doi.org/10.1007/978-981-19-4441-3

International Workshop on Physics at High Baryon Density (PHD2024)

https://indico.ihep.ac.cn/event/22462/ Nov. 1-4, 2024@CCNU

International Workshop on Physics at High Baryon Density (PHD2024, 第一届高重子密度物理国际研讨会)

Nov 1 – 4, 2024
Asia/Shanghai timezone

Enter your search term

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- Confirmed Speaker
- Local Organizing Committee

袁强、马亚
yuanqiang@mail.ccnu.e...
maya@mail.ccnu.edu.cn

高能核核碰撞中产生的高重子密度物质蕴含着丰富的物理，对研究强相互作用相结构、宇宙和致密星体演化以及理解极端条件下核物质性质具有重要意义。随着未来国内外重离子大科学装置（德国FAIR/CBM、中国HIAF/CEE、俄罗斯NICA/MPD）的相继建成，高重子密度物理领域正成为国际物理研究的前沿热点。在这一背景下，系统分析和总结已有研究进展并规划未来发展路线，培养和储备高重子密度物理研究的人才队伍, 集聚国内外顶尖科学家的智慧显得尤为必要和重要。因此，我们决定发起"高重子密度物理研讨会"系列会议 (计划每年举办一次，以研讨会搭配更聚焦的小型专题讨论会形式)，旨在为国内外科研人员搭建起高水平的学术交流平台，共同探讨高重子密度区物理的挑战和机遇。同时我们将与国内外核物理理论中心紧密合作，为推动我国高重子密度物理相关研究走向国际前沿打下坚实基础。

第一届高重子密度物理研讨会于2024年11月1日-4日在华中师范大学召开，1号报到，2-4号会议。会议不收取注册费，会议报告为邀请报告。

The high baryon density matter produced in high-energy nuclear-nuclear collisions harbors rich physics, which is of great importance for exploring the phase structure of strong interactions, the evolution of the universe and compact stars, and understanding the properties of nuclear matter under extreme conditions. With the upcoming completion of major heavy-ion facilities around the world (FAIR/CBM in Germany, HIAF/CEE in China, NICA/MPD in Russia), the field of high baryon density physics is becoming a frontier hotspot in international physics research. Against this background, it is particularly necessary and important to systematically analyze and summarize existing research progress, plan future development paths, cultivate and reserve talent teams for high baryon density physics research, and gather the wisdom of top scientists. Therefore, we have decided to launch a series of "Workshop on Physics at High Baryon Density" (planned to be held annually, in the form of seminars combined with more focused small-scale topical discussions), aiming to build a high-level academic exchange platform for researchers worldwide to jointly explore the challenges and opportunities of high baryon density physics. At the same time, we will work closely with domestic and international nuclear physics theory centers to lay a solid foundation for high baryon density physics research.

The first workshop on physics at high baryon density will be held at Central China Normal University from Nov. 1 to 4, 2024, with registration on the Nov. 1st and the meeting time from the Nov. 2nd to the 4th. No registration fee will be charged. The talks are by invitation only.

Physics Topics :

1) QCD Phase Structure at High Baryon Density
2) Nuclear Matter at High Density and Equation of State
3) Dynamical Evolution of Heavy-ion Collisions
4) Nuclear Matter Under Extreme External Fields
5) Hadron Properties in Nuclear Medium
6) Nuclear Physics in Compact Stars

Local Organizing Committee:

Hengtong Ding (Central China Normal University)
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Xiaofeng Luo (Central China Normal University, co-Chair)
Guoliang Ma (Fudan University)
Zebo Tang (University of Science and Technology of China)
Chi Yang (Shandong University)
Pengfei Zhuang (Tsinghua University, co-Chair)
Yapeng Zhang (Institute of Modern Physics, CAS)

Thank you for your attention !