第二十届全国中高能核物理大会暨第十四届全国中高能核物理专题研讨会

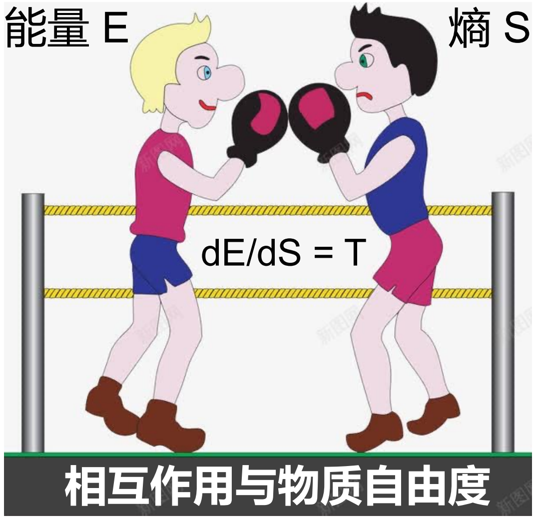
QCD临界点和相边界实验研究进展

罗晓峰
华中师范大学

2025年4月25日

物态与相变

相互作用与物质自由度搭台，能量与熵的竞争



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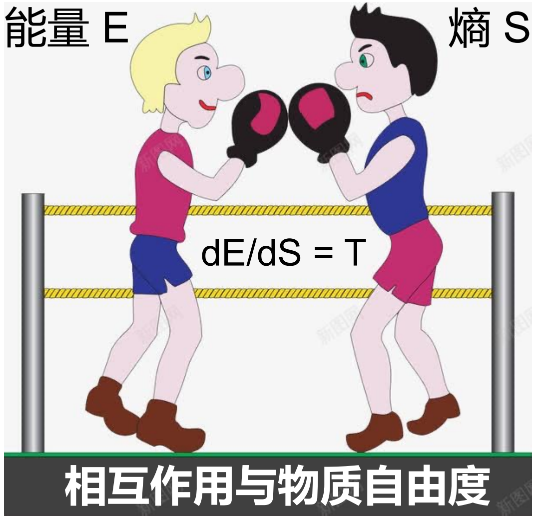

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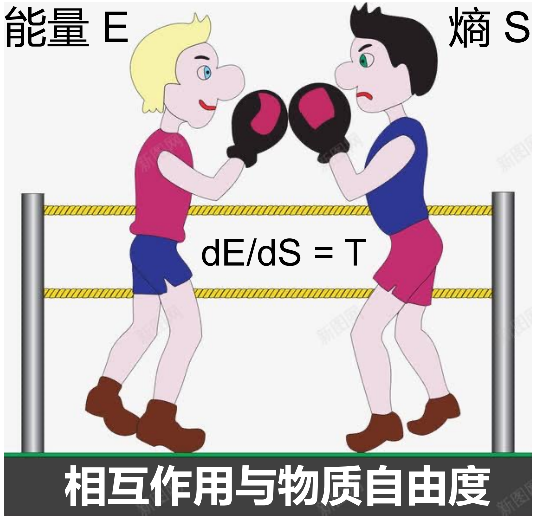
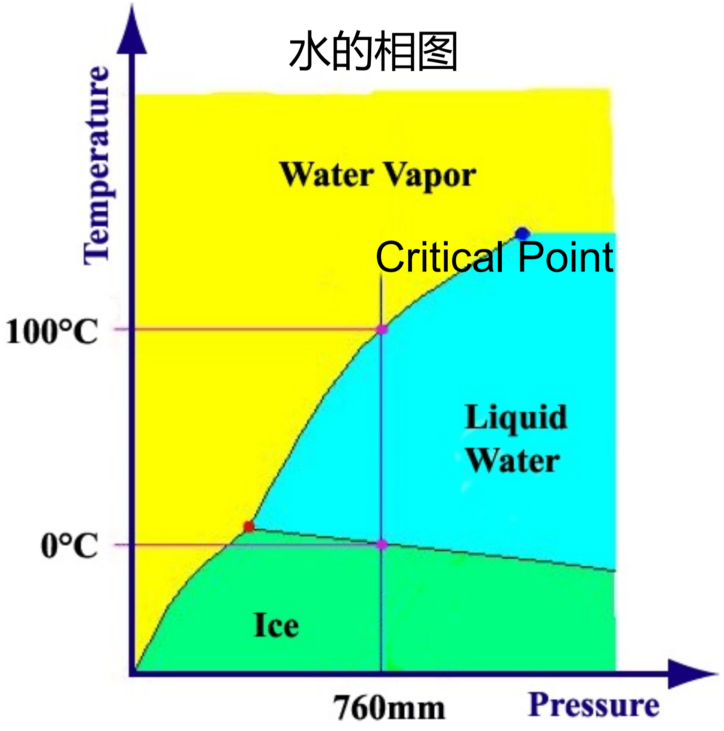
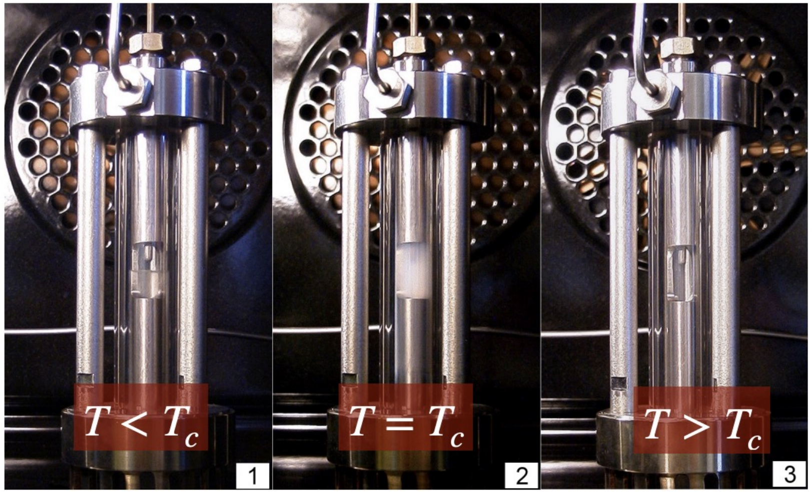


? ?

Critical Point and Critical Phenomena



水的液气相变临界点温度：374摄氏度



critical opalescence of ethane [Wikipedia]

临界点附近：
关联长度发散 、密度涨落增强
-> 临界乳光

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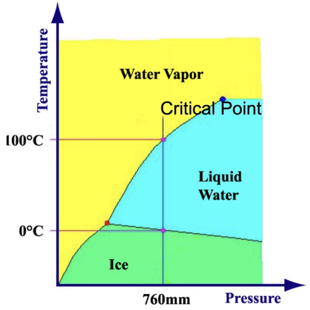

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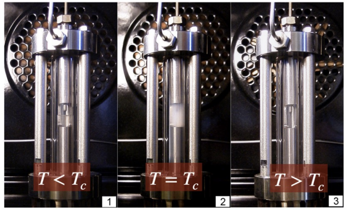

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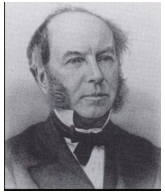
1822年



1869年, 英国物理化学家托马斯安德鲁斯在二氧化碳液气相变实验中发现“超临界流体”，发表论文《论物质气态与液态的连续性》并首次命名“临界点”

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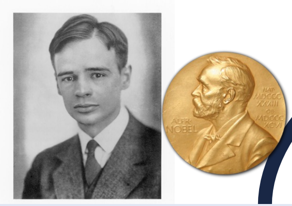

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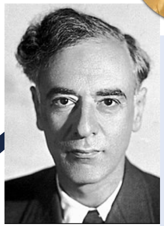

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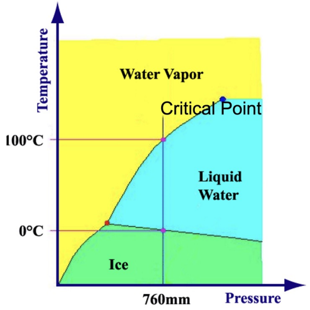
Critical Point and Critical Phenomena



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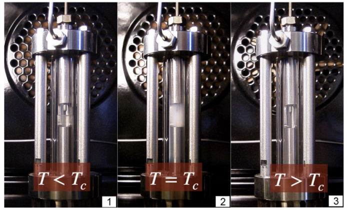

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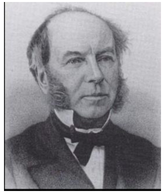

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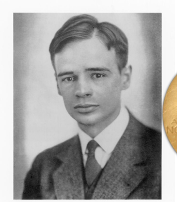

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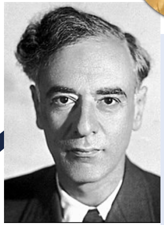

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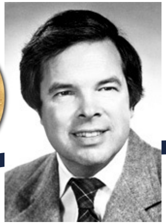

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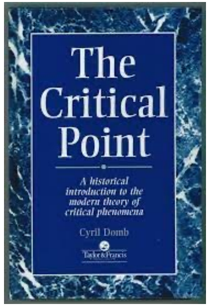
1971年

科普书(国家科技进步奖获奖丛书)
边缘奇迹：相变和临界现象
于渌，郝柏林，陈晓松 著

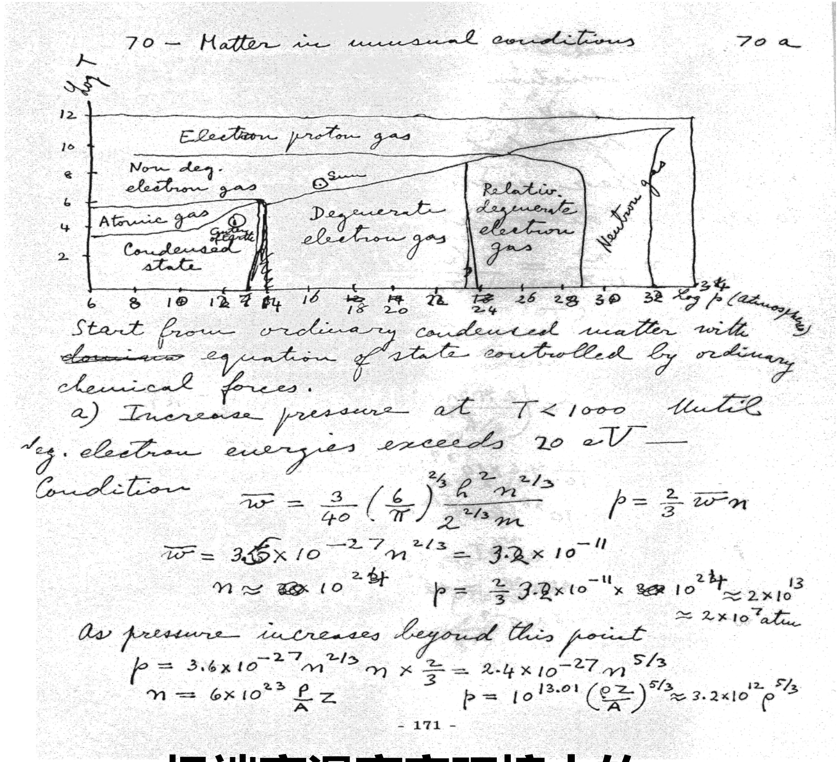


Cyril Domb, The Critical Point, Taylor and Francis, 1993

Matters and Phase Transition in Extreme Condition

E. Fermi: *"Notes on Thermodynamics and Statistics" (1953)*

E. Fermi



70 – Matter in unusual conditions 70 a

Start from ordinary condensed matter with ~~domain~~ equation of state controlled by ordinary chemical forces.

a) Increase pressure at $T < 1000$ until deg. electron energies exceeds 20 eV — Condition

$$\overline{w} = \frac{3}{40}\left(\frac{6}{\pi}\right)^{2/3}\frac{h^2 n^{2/3}}{2^{2/3} m} \qquad p = \frac{2}{3}\overline{w}\, n$$

$$\overline{w} = 3.5\times 10^{-27} n^{2/3} = 3.2\times 10^{-11}$$

$$n \approx 10^{24} \qquad p = \frac{2}{3}\, 3.2\times 10^{-11}\times 10^{24} \approx 2\times 10^{13}$$

$$\approx 2\times 10^{7}\,\text{atm}$$

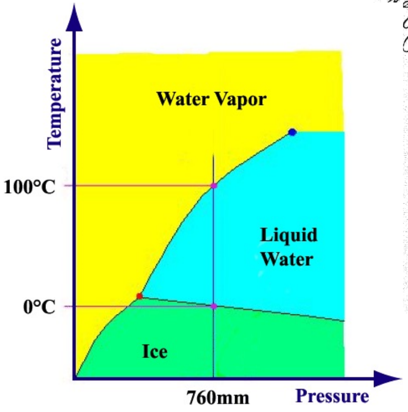
As pressure increases beyond this point

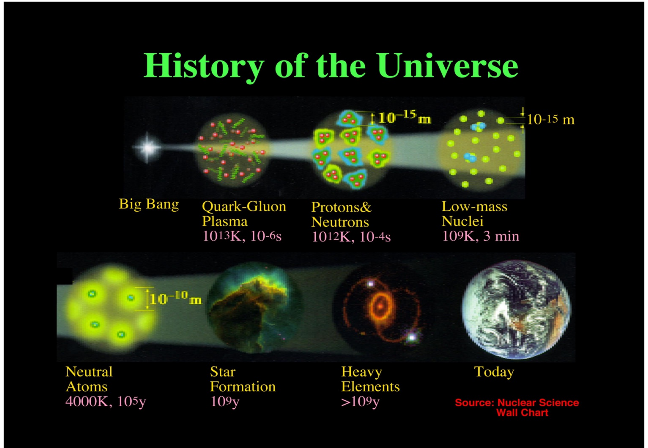
$$p = 3.6\times 10^{-27} n^{2/3}\, n \times \frac{2}{3} = 2.4\times 10^{-27} n^{5/3}$$

$$n = 6\times 10^{23}\frac{\rho}{A}Z \qquad p = 10^{13.01}\left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2\times 10^{12}\rho^{5/3}$$

- 171 -

Water Phase Diagram

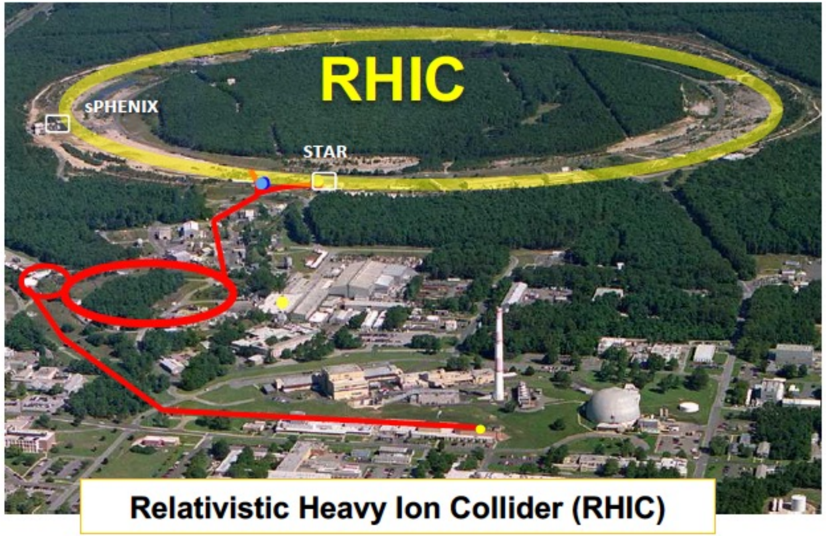


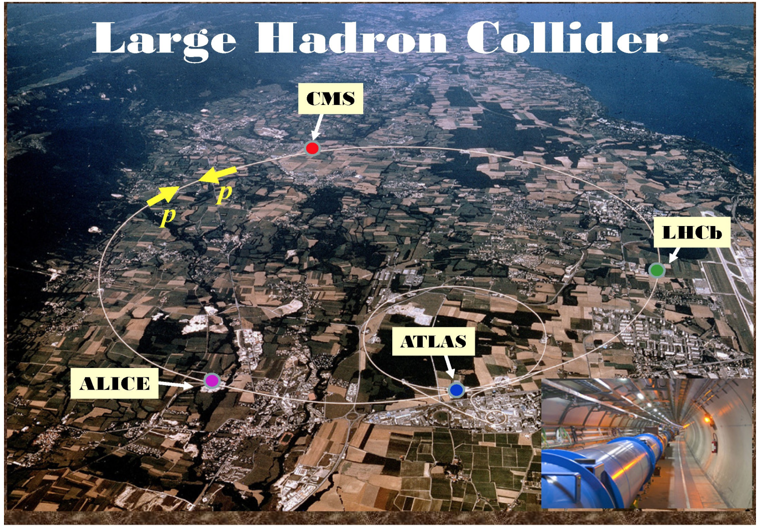


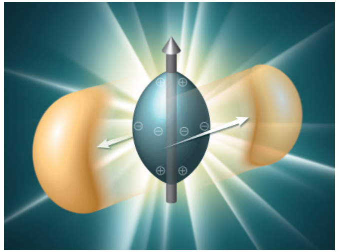
极端高温高密环境中的物质形态及相结构是什么?

1) **早期宇宙演化**
2) **可见物质结构**
3) **致密星体状态方程**

Relativistic Heavy-Ion Collisions







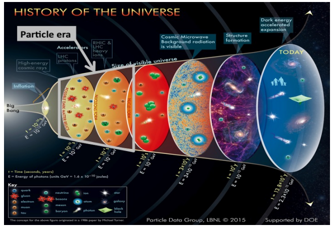
sQGP: Perfect liquid

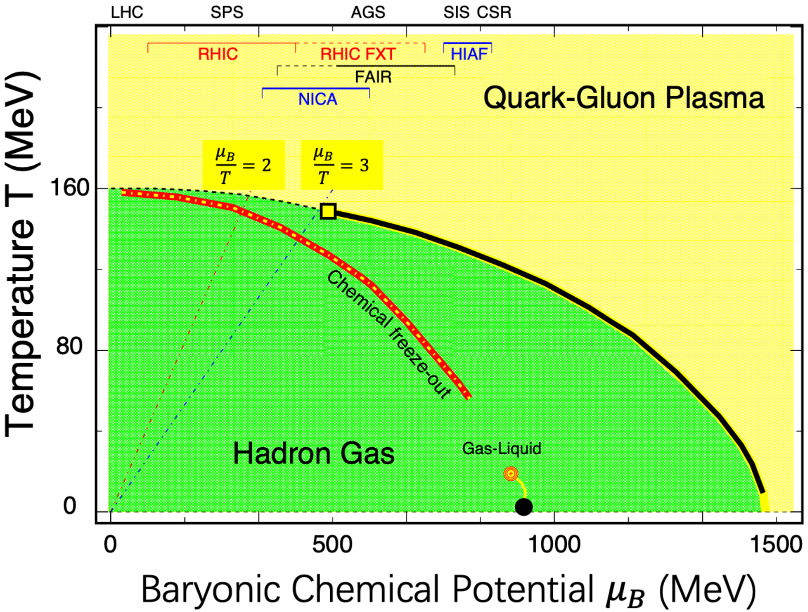
- Small eta/s ~ quantum limit
- Strong electromagnetic field
- Large vorticity

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

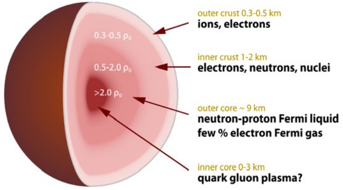




Lattice QCD : at $\mu_B = 0$, smooth crossover. T_c ~ 156 MeV
Large μ_B : 1st order phase transition and QCD critical point ?

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

中子星



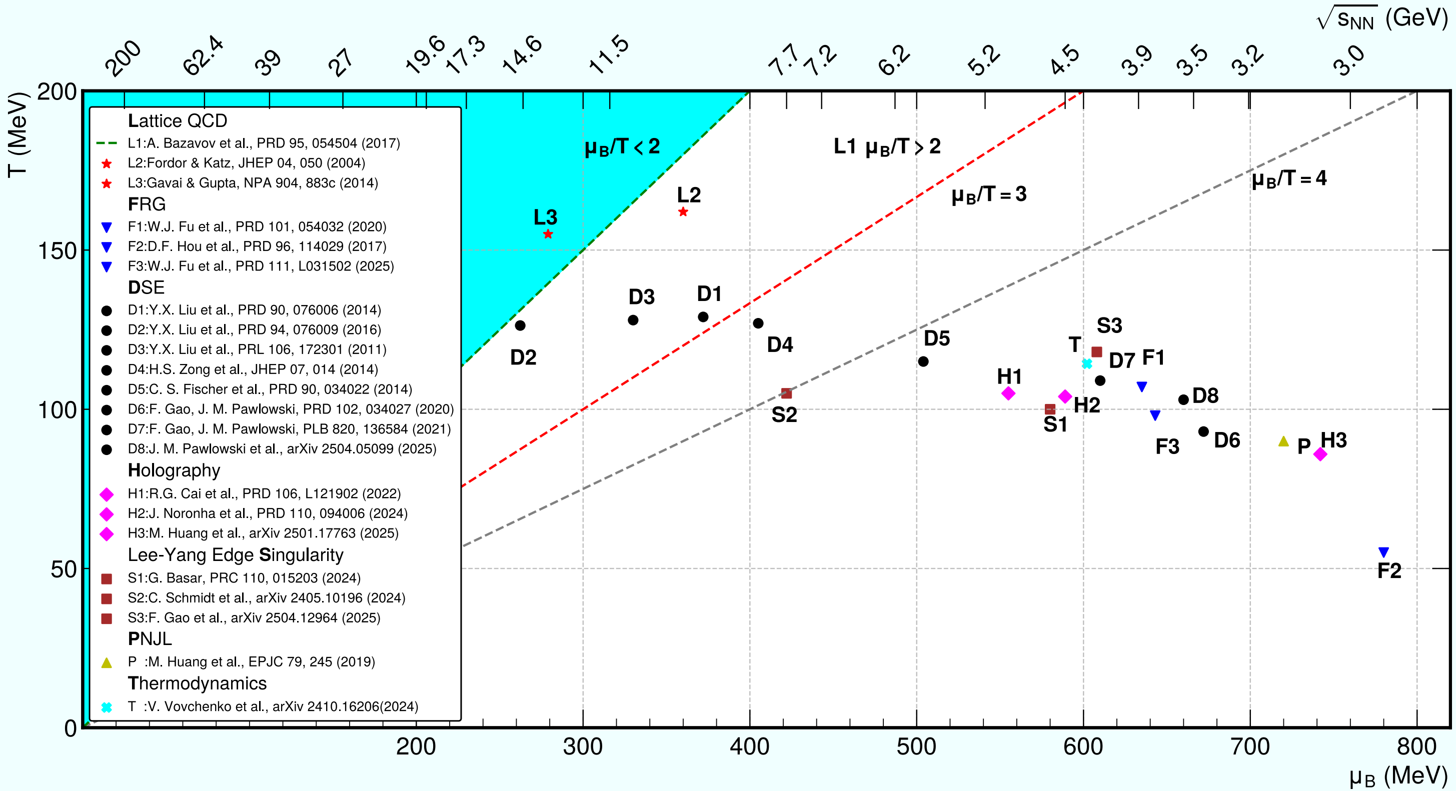
关键科学问题：高重子密度区是否存在QCD临界点和一级相变边界？

被写入国家科技部十四五规划和核物理学科长远规划，是我国大科学装置强流离子加速器HIAF(计划2025年12月建成)的主要物理目标之一

马余刚、许怒、刘峰，基于HIAF集群的QCD相结构研究，中国科学:物理学 力学 天文学,2020,50(11):124
赵红卫，从HIAF到CNUF，现代物理学知识，第36卷(2024年)，第1期

HIAF Physics, NU XU, 28号

理论或模型估计的QCD临界点位置 (2004-2025)



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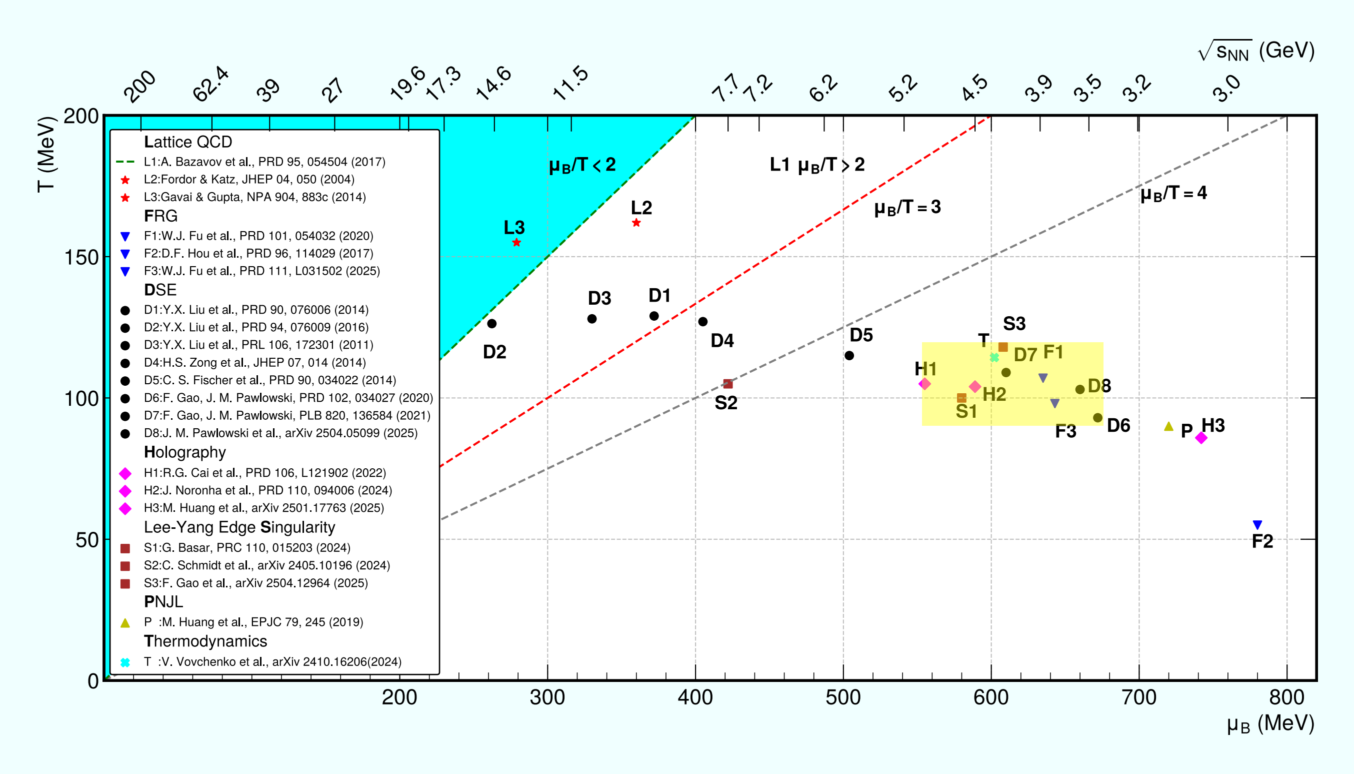

格点QCD: F. Karsch, H.-T. Ding, et al., (HotQCD): $\mu_B/T_c > 3$

聚焦区: μ_B^{CEP}: ~ 550 – 650 MeV, T^{CEP}: ~ 90 – 118 MeV

更多理论细节，请见
黄梅老师、庄鹏飞老师报告

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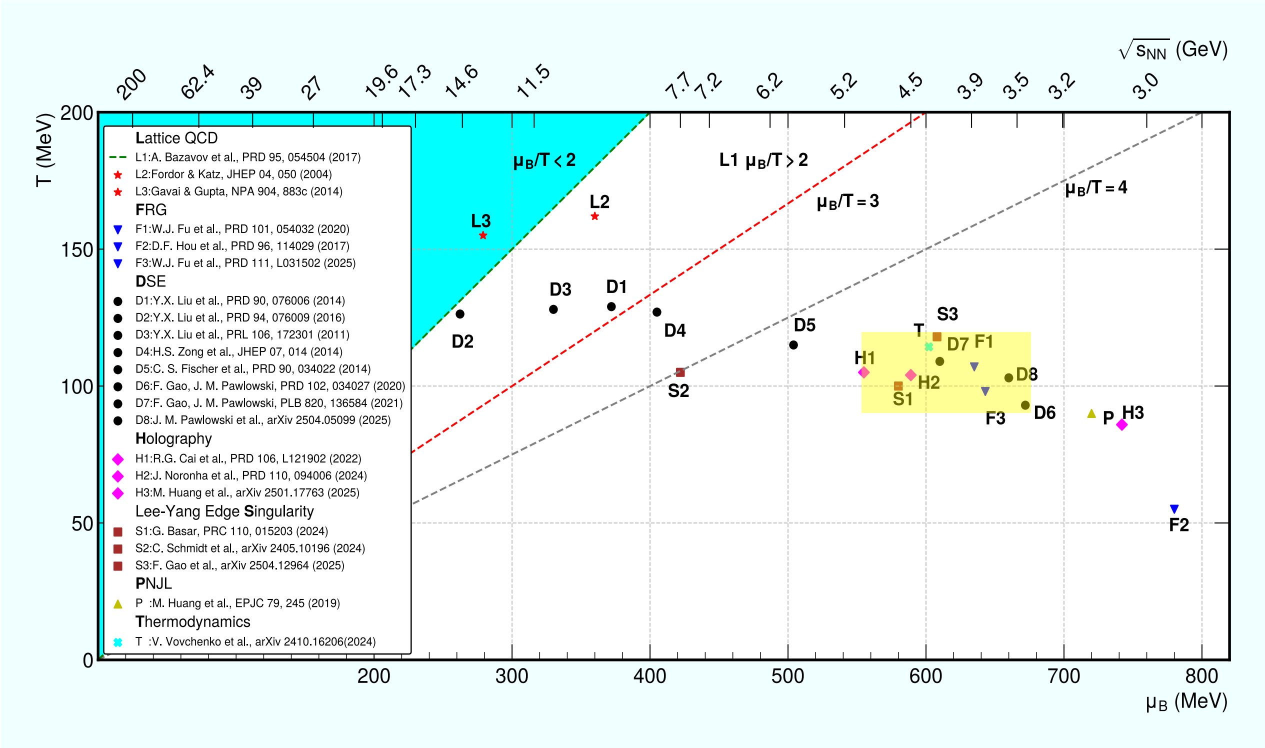

2019-2020年，付伟杰、高飞与其合作者率先基于FRG、DSE方法分别计算出落在聚焦区的临界点位置：（T^{CEP}, μ_B^{CEP}) = (107, 635), (109, 610) MeV. 结果一致, 需要进一步研究其误差范围。

付伟杰, J. M. Pawlowski, and F. Rennecke, Phys. Rev. D 101, 054032 (2020) [# of citations : 335]

高飞, J. M. Pawlowski, Phys. Lett. B 820, 136584 (2021) [# of citations : 121]

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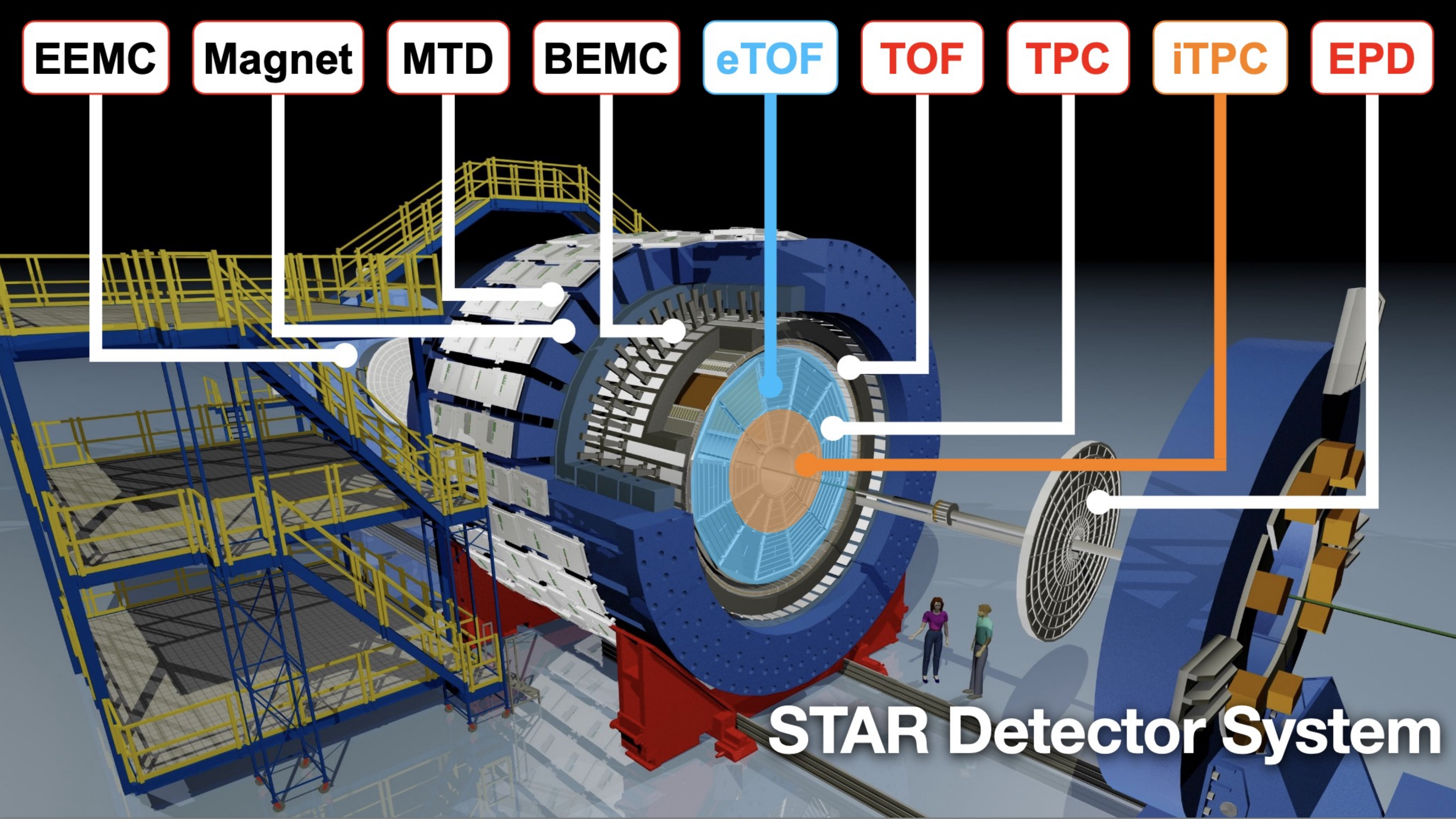
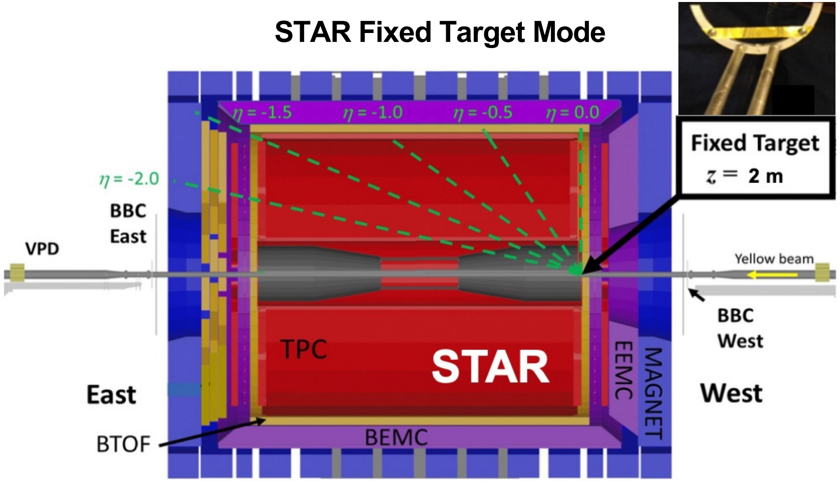
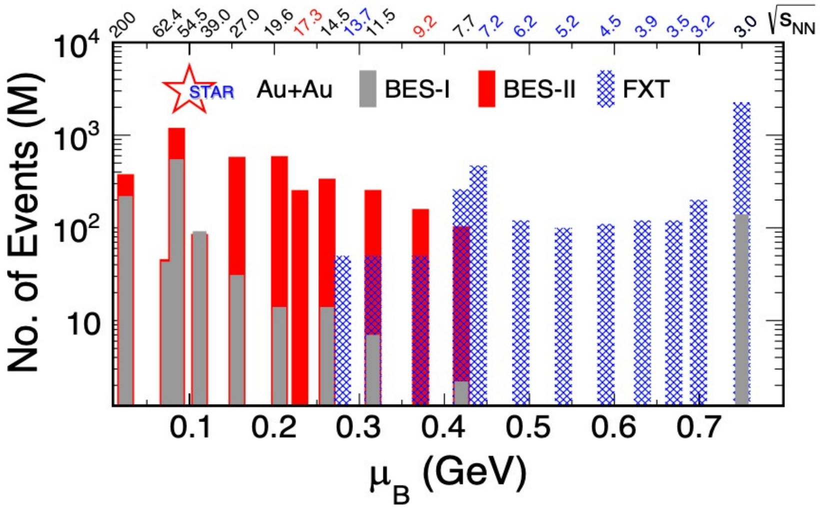

EEMC
Magnet
MTD
BEMC
eTOF
TOF
TPC
iTPC
EPD
STAR Detector System

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





- BES-I (2010 – 2014): 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 GeV.
- BES-II (2018-2021): Collider mode (7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27 GeV),
  FXT mode: (**3.0, 3.2, 3.5, 3.9, 4.5**, 5.2, 6.2,…,13.7 GeV)
- μ_B coverage : $25 < \mu_B < 750$ MeV

Review Article : Properties of the QCD matter: review of selected results from the relativistic heavy ion collider beam energy scan (RHIC BES) program
Jinhui Chen, et al., Nucl. Sci. Tech. 35, 214 (2024)

Observables: Cumulants of Conserved Quantities

➢ **At critical point with an infinite system**
- correlation length should diverge
- susceptibilities should diverge

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

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

➢ **Experimental Observables: Cumulants of Conserved Quantities**

1) Sensitive to correlation length (ξ)
2) Directly related to the susceptibility ratios

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

Notation: Cumulants: $C_{1,2,\ldots}$
Factorial Cumulants: $\kappa_{1,2,\ldots}$

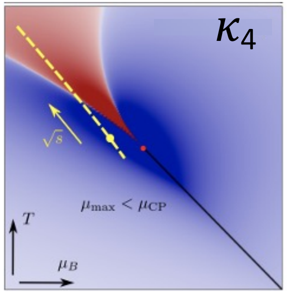
$$\kappa_1 = C_1 = \langle N \rangle,$$
$$\kappa_2 = -C_1 + C_2,$$
$$\kappa_3 = 2C_1 - 3C_2 + C_3,$$
$$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4,$$

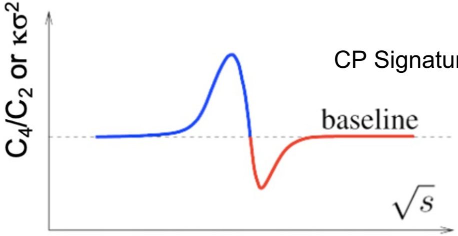
Measured multiplicity N, $\langle \delta N \rangle = N - \langle N \rangle$

$$\begin{aligned}
&\text{mean:} & M &= \langle N \rangle & &= C_1 \\
&\text{variance:} & \sigma^2 &= \langle (\delta N)^2 \rangle & &= C_2 \\
&\text{skewness:} & S &= \langle (\delta N)^3 \rangle / \sigma^3 & &= C_3/C_2^{3/2} \\
&\text{kurtosis:} & \kappa &= \langle (\delta N)^4 \rangle / \sigma^4 - 3 & &= C_4/C_2^2
\end{aligned}$$

Moments, cumulants and susceptibilities:

$$\begin{aligned}
&2^{nd}\ \text{order:} & \sigma^2/M &\equiv C_2/C_1 = \chi_2/\chi_1 \\
&3^{rd}\ \text{order:} & S\sigma &\equiv C_3/C_2 = \chi_3/\chi_2 \\
&4^{th}\ \text{order:} & \kappa\sigma^2 &\equiv C_4/C_2 = \chi_4/\chi_2
\end{aligned}$$

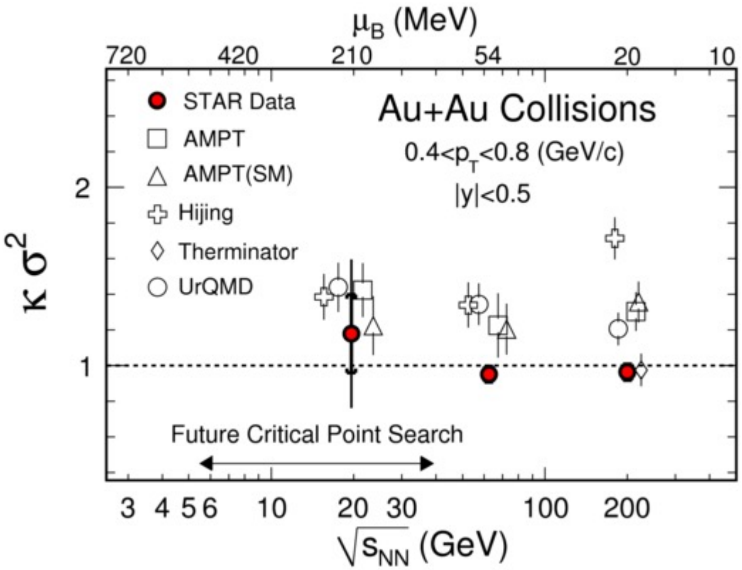




M. A. Stephanov, PRL 102 (2009) 032301

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)

净质子数分布高阶矩的首次测量



净质子数涨落的首次测量，
验证了该观测量的可行性

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

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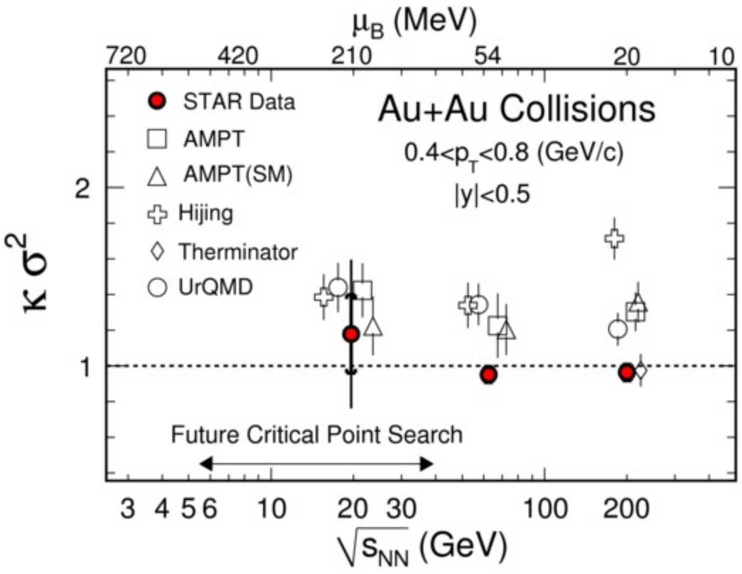

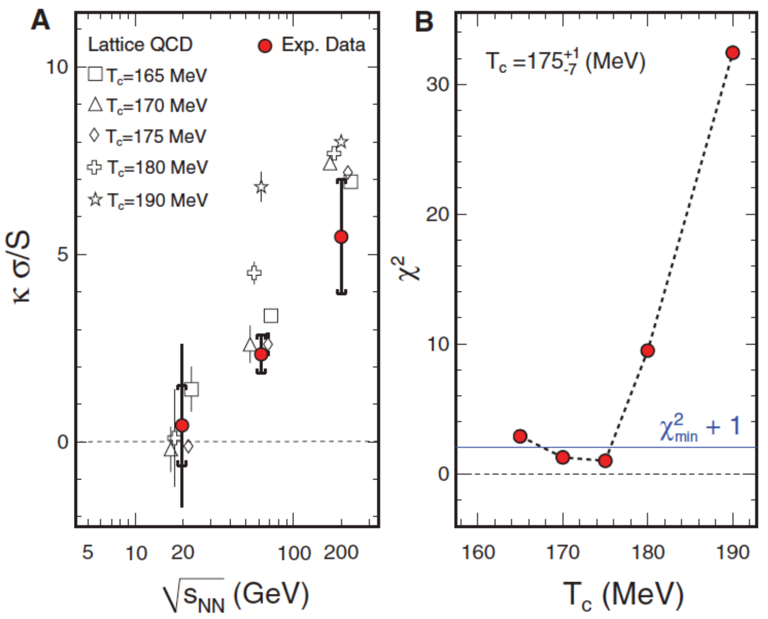

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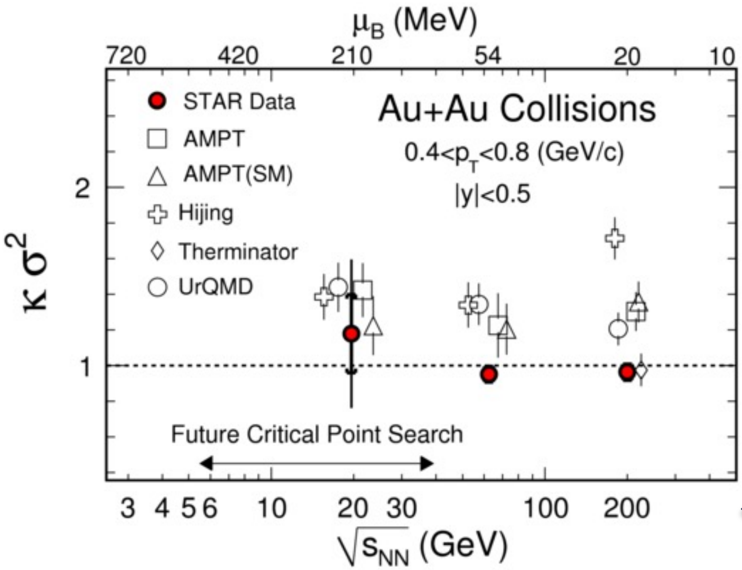
Science AAAS

RESEARCH ARTICLE

Scale for the Phase Diagram of Quantum Chromodynamics

Sourendu Gupta[1], Xiaofeng Luo[2,3], Bedangadas Mohanty[4,*], Hans Georg Ritter[3], Nu Xu[5,3]

寻找QCD临界点：BES-I守恒荷分布的高阶矩测量



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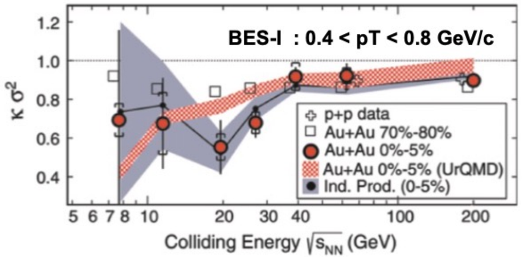
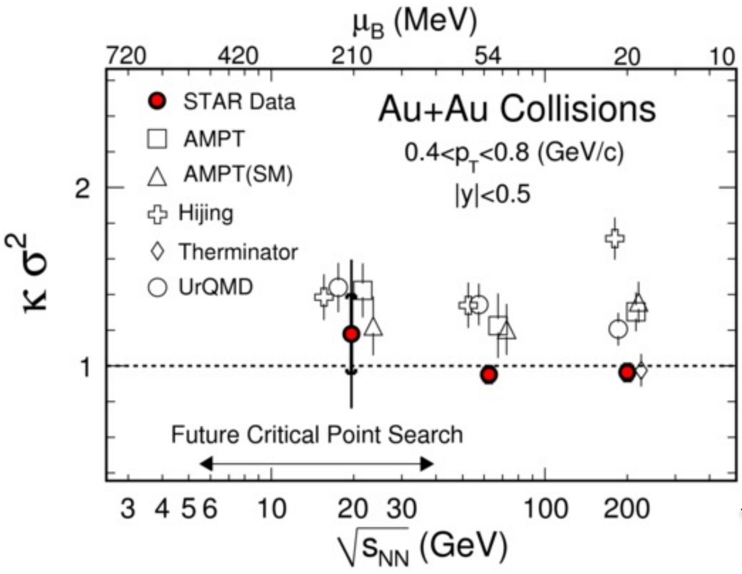
STAR, Phys. Rev. Lett. 105, 022302 (2010)



净质子数涨落

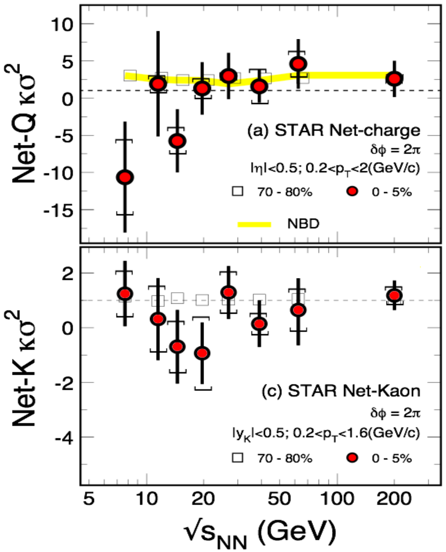
STAR, Phys. Rev. Lett. 112, 032302 (2014)
(横动量范围：0.4<p_T<0.8 GeV/c)

寻找QCD临界点：BES-I守恒荷分布的高阶矩测量



净质子数涨落的**首次测量**，
验证了该观测量的可行性

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

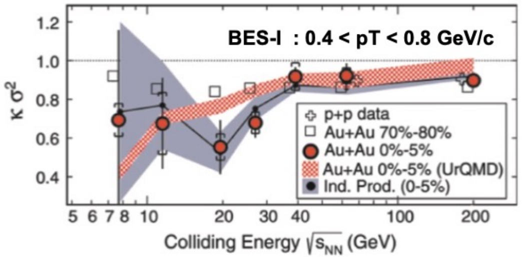


净电荷数涨落

STAR, Phys. Rev. Lett. 113, 092301 (2014).

净K介子数涨落

STAR, Phys. Lett. B 785, 551 (2018).



净质子数涨落

STAR, Phys. Rev. Lett. 112, 032302 (2014)
(横动量范围：0.4<p_T<0.8 GeV/c)

建立数据分析方法、完成BES-I中净质子数涨落测量

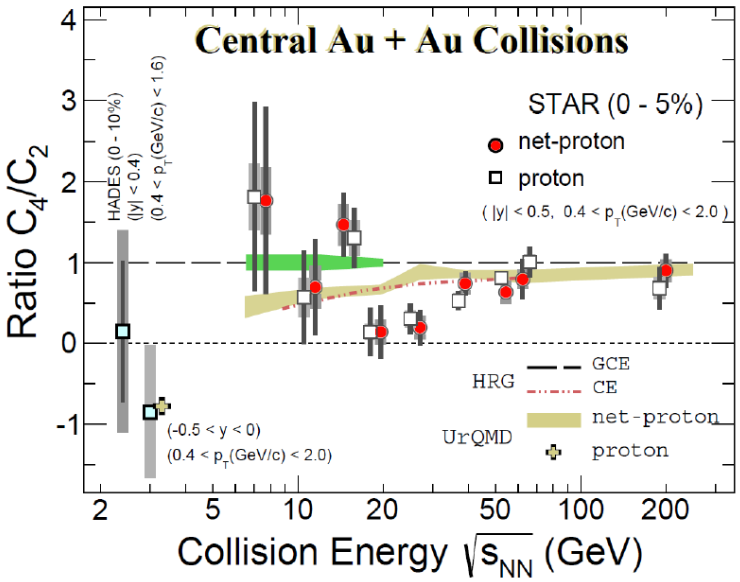
STAR分析团队建立观测量的统计误差计算、去除自关联、压低体积涨落、探测效率修正等分析方法

a) 运用统计中的Delta定理，推导出高阶矩统计误差解析公式并将其应用到实验数据，精确计算出观测量统计误差
X.Luo, J.Phys.G:39, 025008 (2012)

b) 提出中心度宽度修正, 压低体积涨落及消除自关联背景影响
X.Luo, J. Xu, B. Mohanty, N. Xu, J.Phys.G:40, 105104 (2013)

c) 发展逐粒子探测效率修正方法, 使效率修正更加简化和精确
X. Luo, Phys. Rev. C 91, 034907(2015)
X. Luo,T. Nonaka, Phys. Rev. C 99, 044917(2019)
A Chatterjee, S. Esumi, X. Luo, T. Nonaka, CPC45, 104001 (2021)
Fan Si, Y. Zhang, X. Luo, Chin. Phys. C 45, 124001 (2021)

d) 发展出修正高阶矩测量中的事件堆叠效应方法
Y. Zhang, Y. Huang, T. Nonaka, X. Luo, NIMA1026,166246 (2022)



- 首次在中心碰撞中观测到净质子数分布四阶涨落的非单调能量依赖(3.1σ)
- 3 GeV结果与输运模型一致，强子相互作用占主导。为寻找QCD相变临界点给出能量下限

综述文章：X. Luo, N. Xu, Nucl. Sci. Tech. 28,112 (2017)
STAR, Phys. Rev. C 104, 024902 (2021)
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)

其他实验合作组陆续开展守恒荷涨落测量

ALICE实验合作组

Physics Letters B 844 (2023) 137545

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Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

Closing in on critical net-baryon fluctuations at LHC energies: Cumulants up to third order in Pb–Pb collisions

ALICE Collaboration *

ARTICLE INFO

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ABSTRACT

Fluctuation measurements are important sources of information on the mechanism of particle production at LHC energies. This article reports the first experimental results on third-order cumulants of the net-proton distributions in Pb–Pb collisions at a center-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV recorded by the ALICE detector. The results on the second-order cumulants of net-proton distributions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV are also discussed in view of effects due to the global and local baryon number conservation. The results demonstrate the presence of long-range rapidity correlations between protons and antiprotons. Such correlations originate from the early phase of the collision. The experimental results are compared with HIJING and EPOS model calculations, and the dependence of the fluctuation measurements on the phase-space coverage is examined in the context of lattice quantum chromodynamics (LQCD) and hadron resonance gas (HRG) model estimations. The measured third-order cumulants are consistent with zero within experimental uncertainties of about 4% and are described well by LQCD and HRG predictions.

Physics Letters B 807 (2020) 135564

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Physics Letters B

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ELSEVIER

Global baryon number conservation encoded in net-proton fluctuations measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE Collaboration *

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ABSTRACT

Experimental results are presented on event-by-event net-proton fluctuation measurements in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, recorded by the ALICE detector at the CERN LHC. These measurements have as their ultimate goal an experimental test of Lattice QCD (LQCD) predictions on second and higher order cumulants of net-baryon distributions to search for critical behavior near the QCD phase boundary. Before confronting them with LQCD predictions, account has to be taken of correlations stemming from baryon number conservation as well as fluctuations of participating nucleons. Both effects influence the experimental measurements and are usually not considered in theoretical calculations. For the first time, it is shown that event-by-event baryon number conservation leads to subtle long-range correlations arising from very early interactions in the collisions.

NA61/SHINE实验合作组

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2023-290
December 22, 2023

Measurements of higher-order cumulants of multiplicity and net-electric charge distributions in inelastic proton-proton interactions by NA61/SHINE

The NA61/SHINE Collaboration

This paper presents the energy dependence of multiplicity and net-electric charge fluctuations in p+p interactions at beam momenta 20, 31, 40, 80, and 158 GeV/c. Results are corrected for the experimental biases and quantified with the use of cumulants and factorial cumulants. Data are compared with the Epos1.99 and FTFP-BERT model predictions.

arXiv:2312.13706v1 [hep-ex] 21 Dec 2023

HADES实验合作组

PHYSICAL REVIEW C **102**, 024914 (2020)

Editors' Suggestion

Proton-number fluctuations in $\sqrt{s_{NN}} = 2.4$ GeV Au + Au collisions studied with the High-Acceptance DiElectron Spectrometer (HADES)

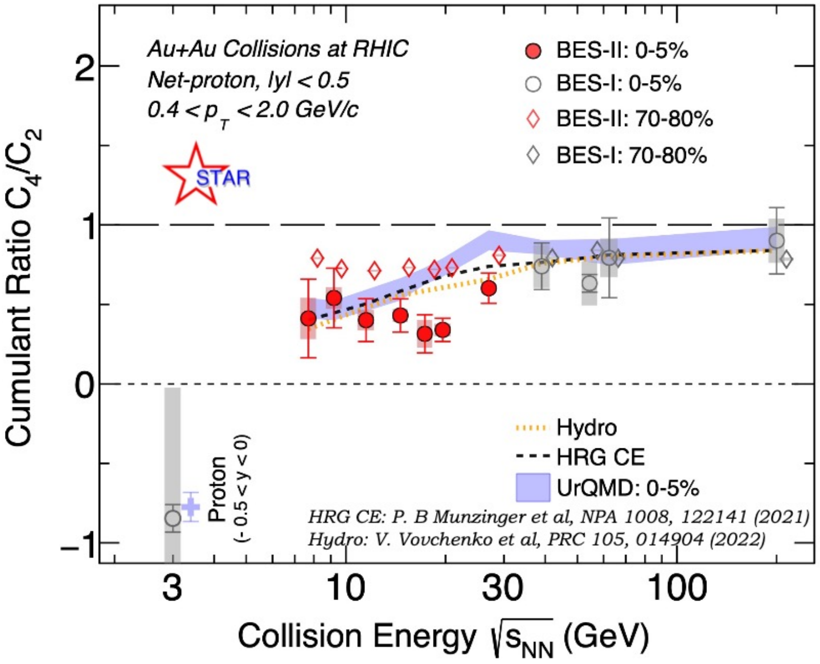
J. Adamczewski-Musch,[5] O. Arnold,[11,10] C. Behnke,[9] A. Belounnas,[17] A. Belyaev,[8] J. C. Berger-Chen,[11,10] A. Blanco,[2] C. Blume,[9] M. Böhmer,[11] P. Bordalo,[2] S. Chernenko,[8,*] L. Chlad,[18] I. Ciepał,[3] C. Deveaux,[12] J. Dreyer,[7] E. Epple,[11,10] L. Fabbietti,[11,10] O. Fateev,[8] P. Filip,[1] P. Fonte,[2,†] C. Franco,[2] J. Friese,[11] I. Fröhlich,[9] T. Galatyuk,[6,5] J. A. Garzón,[19] R. Gernhäuser,[11] M. Golubeva,[13] R. Greifenhagen,[7,‡] F. Guber,[13] M. Gumberidze,[5,6] S. Harabasz,[6,4] T. Heinz,[5] T. Hennino,[17] S. Hlavac,[1] C. Höhne,[12,5] R. Holzmann,[5] A. Ierusalimov,[8] A. Ivashkin,[13] B. Kämpfer,[7,‡] T. Karavicheva,[13] B. Kardan,[9] I. Koenig,[5] W. Koenig,[5] M. Kohls,[9] B. W. Kolb,[5] G. Korcyl,[4] G. Kornakov,[6] F. Kornas,[6] R. Kotte,[7] A. Kugler,[18] T. Kunz,[11] A. Kurepin,[13] A. Kurilkin,[8] P. Kurilkin,[8] V. Ladygin,[8] R. Lalik,[4] K. Lapidus,[11,10] A. Lebedev,[14] L. Lopes,[2] M. Lorenz,[9] T. Mahmoud,[12] L. Maier,[11] A. Malige,[4] A. Mangiarotti,[2] J. Markert,[5] T. Matulewicz,[20] S. Maurus,[11] V. Metag,[12] J. Michel,[9] D. M. Mihaylov,[11,10] S. Morozov,[13,15] C. Müntz,[9] R. Münzer,[11,10] L. Naumann,[7] K. Nowakowski,[4] Y. Parpottas,[16,§] V. Pechenov,[5] O. Pechenova,[5] O. Petukhov,[13] K. Piasecki,[20] J. Pietraszko,[5] W. Przygoda,[4] K. Pysz,[3] S. Ramos,[2] B. Ramstein,[17] N. Rathod,[4] A. Reshetin,[13] P. Rodriguez-Ramos,[18] P. Rosier,[17] A. Rost,[6] A. Rustamov,[5] A. Sadovsky,[13] P. Salabura,[4] T. Scheib,[9] H. Schuldes,[9] E. Schwab,[5] F. Scozzi,[6,17] F. Seck,[6] P. Sellheim,[9] I. Selyuzhenkov,[5,15] J. Siebenson,[11] L. Silva,[2] U. Singh,[4] J. Smyrski,[4] Yu. G. Sobolev,[18] S. Spataro,[21] S. Spies,[9] H. Ströbele,[9] J. Stroth,[9,5] C. Sturm,[5] O. Svoboda,[18] M. Szala,[9] P. Tlusty,[18] M. Traxler,[5] H. Tsertos,[16] E. Usenko,[13] V. Wagner,[18] C. Wendisch,[5] M. G. Wiebusch,[9] J. Wirth,[11,10] D. Wójcik,[20] Y. Zanevsky,[8,*] and P. Zumbruch[5]
(HADES Collaboration)

High Statistics BES-II Datasets (2019-2021)

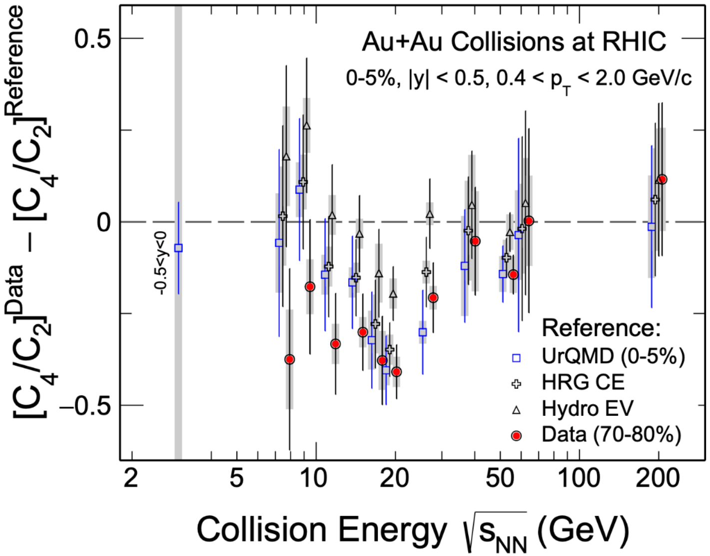
Au+Au Collisions at RHIC （RHIC 金核-金核碰撞）										
Collider Runs （对撞模式）					Fixed-Target Runs （固定靶模式）					
	$\sqrt{s_{NN}}$ (GeV) 碰撞能量	#Events 事例率	μ_B(MeV) 重子化学势	Run 采集时间		$\sqrt{s_{NN}}$ (GeV) 碰撞能量	#Events 事例率	μ_B(MeV) 重子化学势	Run 采集时间
1	200	380 M	25	Run-10,19	1	13.7 (100)	50 M	280	Run-21
2	62.4	46 M	75	Run-10	2	11.5 (70)	50 M	320	Run-21
3	54.4	1200 M	85	Run-17	3	9.2 (44.5)	50 M	370	Run-21
4	39	86 M	112	Run-10	4	7.7 (31.2)	260 M	420	Run-18,19,20
5	27	585 M	156	Run-11,18	5	7.2 (26.5)	470 M	440	Run-18,20
6	19.6	595 M	206	Run-11,19	6	6.2 (19.5)	120 M	490	Run-20
7	17.3	256 M	230	Run-21	7	5.2 (13.5)	100 M	540	Run-20
8	14.6	340 M	262	Run-14,19	8	4.5 (9.8)	110 M	590	Run-20
9	11.5	57 M	316	Run-10,20	9	3.9 (7.3)	120 M	633	Run-20
10	9.2	160 M	372	Run-10,20	10	3.5 (5.75)	120 M	670	Run-20
11	7.7	104 M	420	Run-21	11	3.2 (4.59)	200 M	699	Run-19
					12	3.0 (3.85)	2300 M	750	Run-18,21

BES-II : Au+Au Collisions at 3 - 27 GeV (Collider + FXT)

回顾：BES-II 对撞能区(7.7-27 GeV)净质子涨落测量结果



Comparing to non-CP baselines

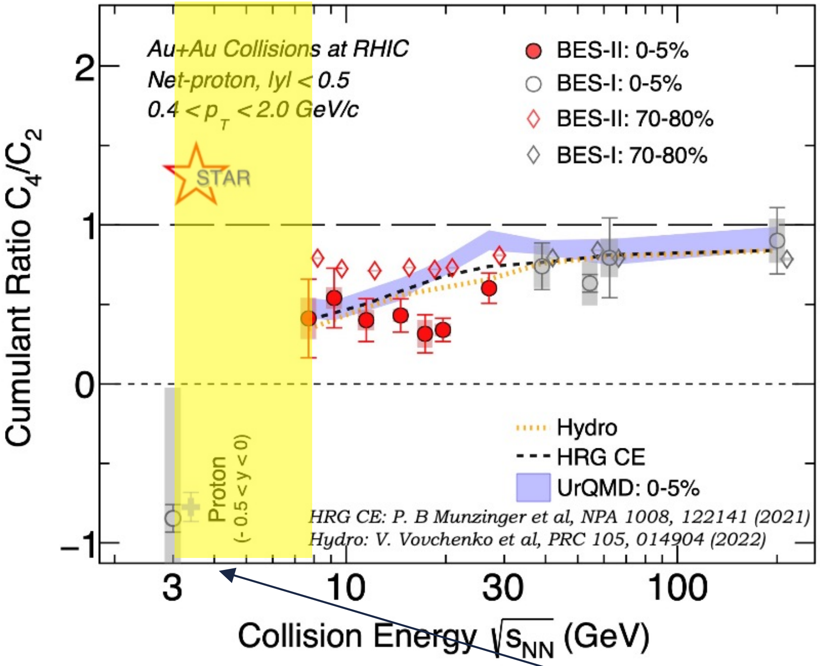


STAR: 2504.00817 CPOD2024, SQM2024

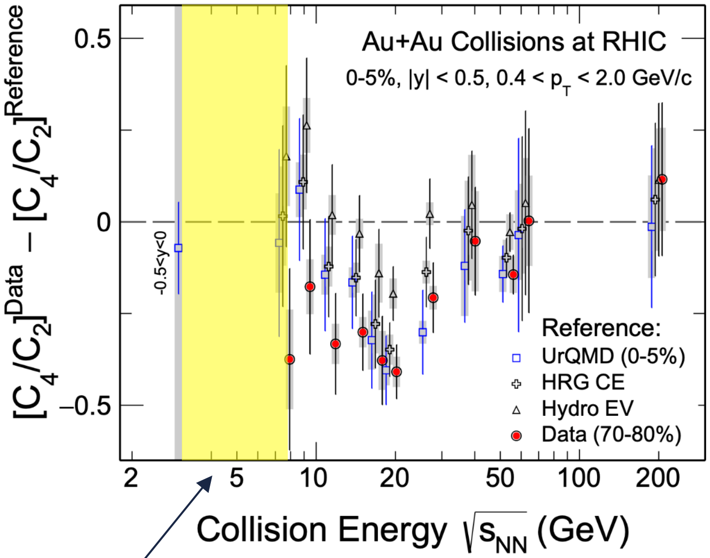
STAR: PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

- 2-5σ deviations to non-CP baselines at 19.6 GeV
- Data from low energies are needed to establish the oscillation pattern of CP signal.

回顾：BES-II 对撞能区(7.7-27 GeV)净质子涨落测量结果



Comparing to non-CP baselines

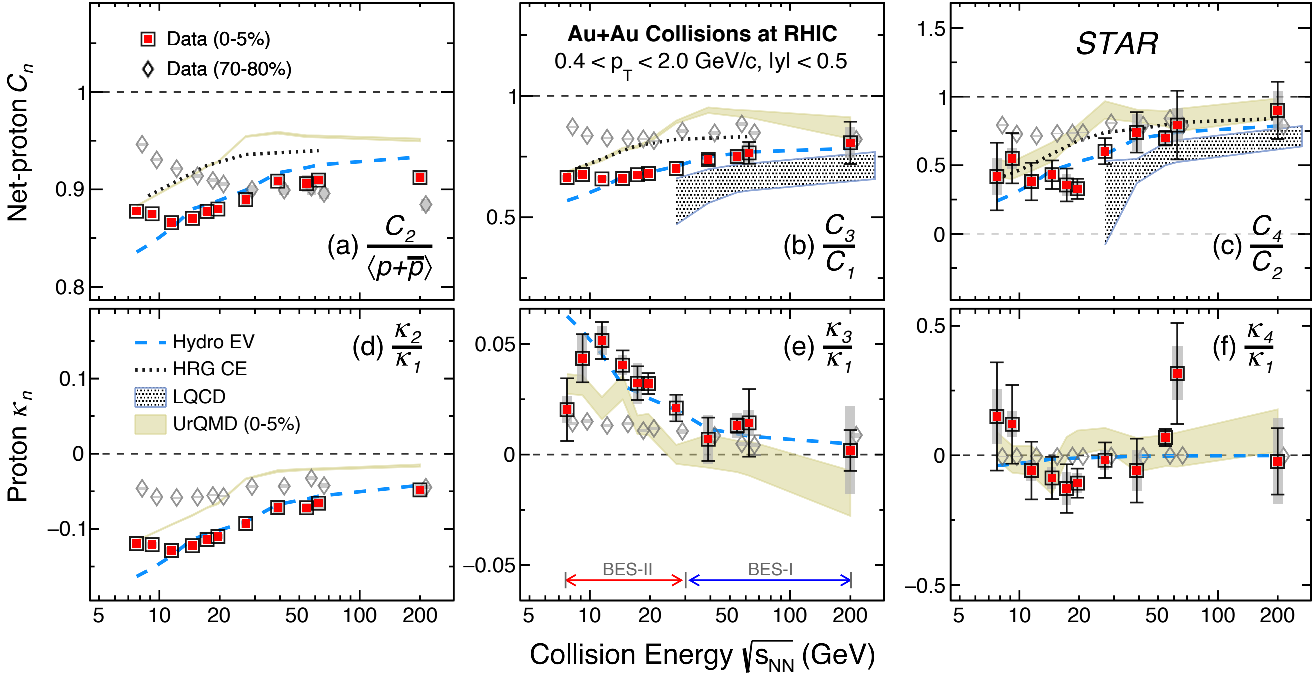


STAR: 2504.00817

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

Experimental results between 3 and 7.7 GeV : are crucial for the **Critical Point** search ！

Energy Dependence of (factorial) Cumulant Ratios



1) UrQMD: hadronic transport and the results are analyzed in the same way as data. S. Bass *et al*., Prog. Part. Nucl. Phys., **41**, 255 (1998);

2) HRG CE: P.B. Munzinger *et al.* Nucl. Phys. **A1008**, 122141(2021);

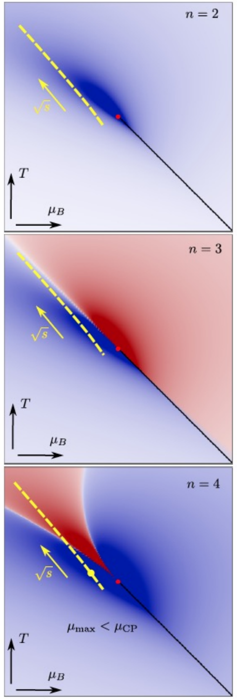
3) Hydro: HRG CE + EV, V. Vovchenko *et al*., Phys. Rev. **C105**, 014904 (2022).

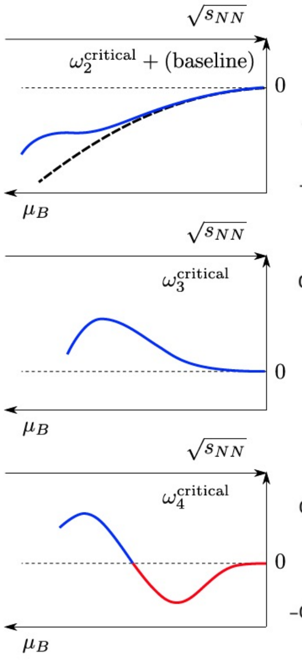
4) LQCD: done for net-baryon A. Bazavov *et al.,* Phys. Rev. D101, 074502 (2020). arXiv : 2407.09335

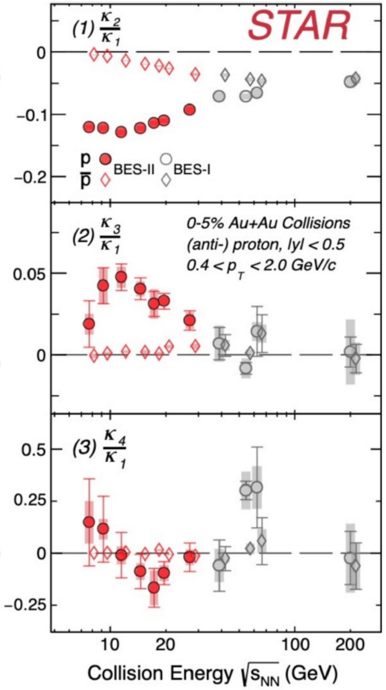
1) All cumulant ratios deviate below Poisson baseline (unity). C_4/C_2 shows deviation at ~ 20 GeV w.r.t non-CP references (models and peripheral data) 2 – 5σ.
2) Negative κ_2, positive κ_3; κ_4/κ_1 consistent with Poisson baseline at zero within uncertainties
3) Lattice QCD (net-baryon) describe the data up to 27 GeV.

STAR: 2504.00817

Consistent with the expectation of CP ?







QCD critical point: recent developments

arXiv : 2410.02861

Mikhail Stephanov[1,2,*]

[1]Department of Physics, University of Illinois, Chicago, Illinois 60607, USA

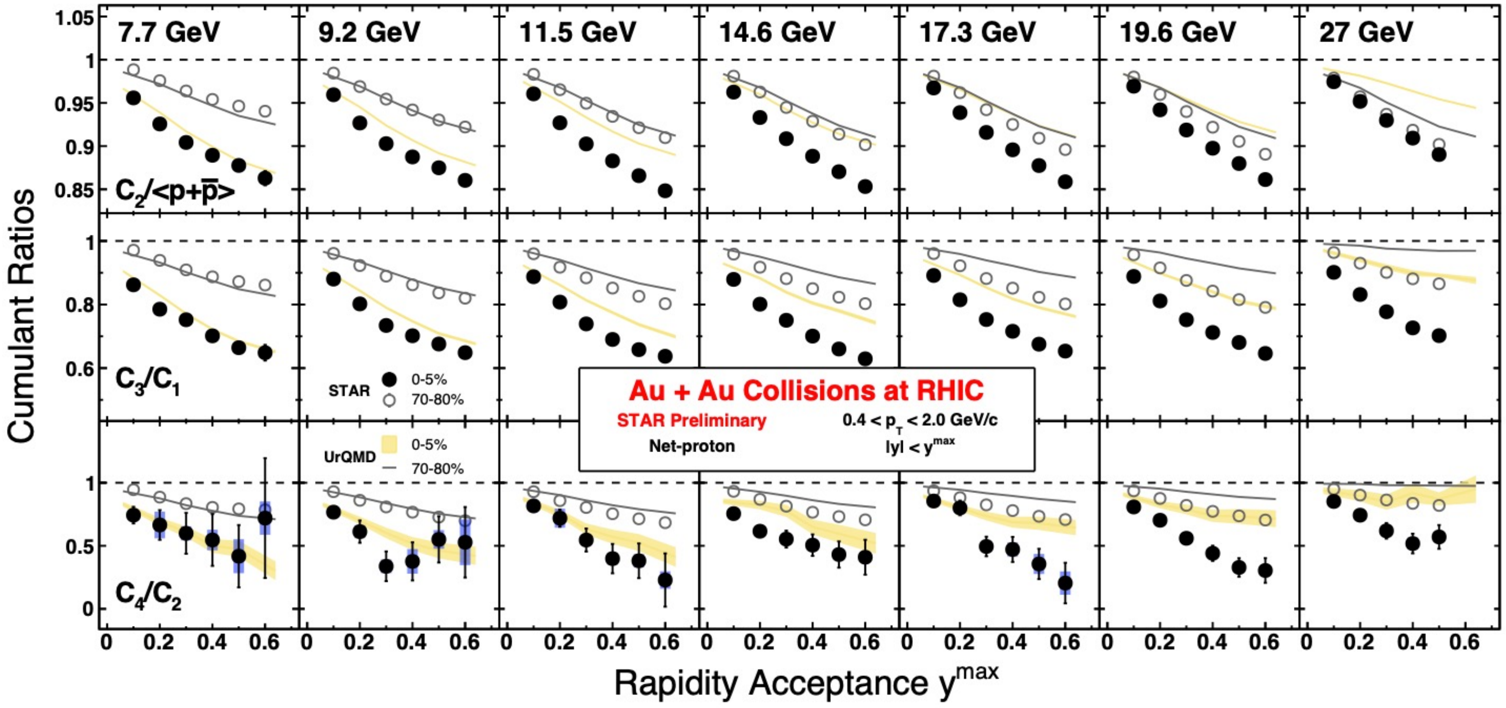
[2]Kadanoff Center for Theoretical Physics, University of Chicago, Chicago, Illinois 60637, USA

"The release of the BES-II data by STAR represents a major step towards uncovering the structure of the QCD phase diagram. It is remarkable that the non-monotonic features of the data are in qualitative agreement with the expectations from equilibrium thermodynamics near the QCD critical point, if one assumes such a point is located at $\mu_B \gtrsim 420$ MeV. Such a location of the critical point would be consistent with recent estimates from various theoretical approaches….. "

Precise dynamical modelling (non-equilibrium) with CP is needed to compare with the data.

Y. Shen, et al.,Phys. Rev. C 111, 014916 (2025) ;
S Mukherjee, R. Venugopalan, Y Yin, PRL 117, 222301 (2016);
S. Wu, Z. Wu, H. Song, PRC 99, 064902 (2019).

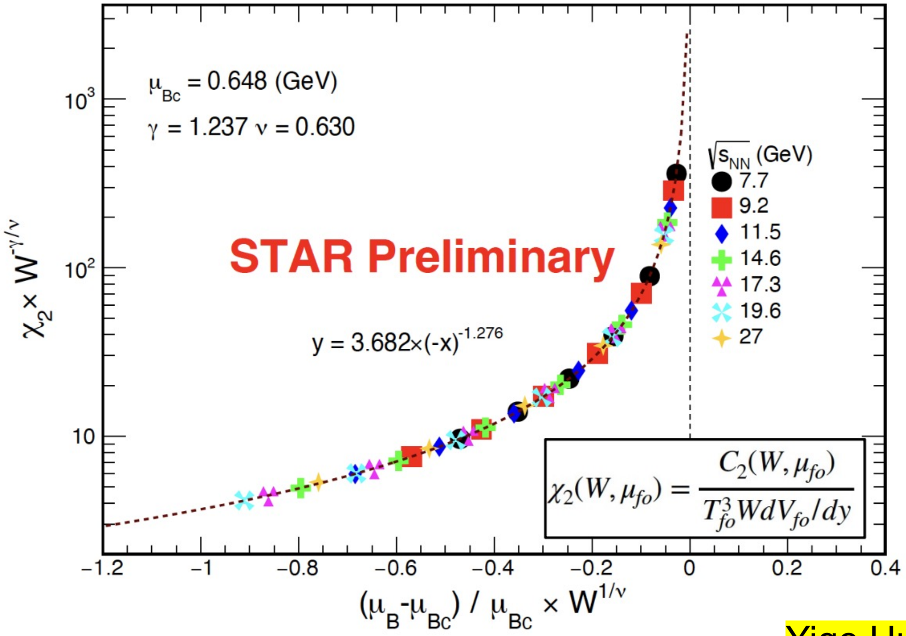
Net-Proton Cumulant Ratios Vs. Rapidity Window

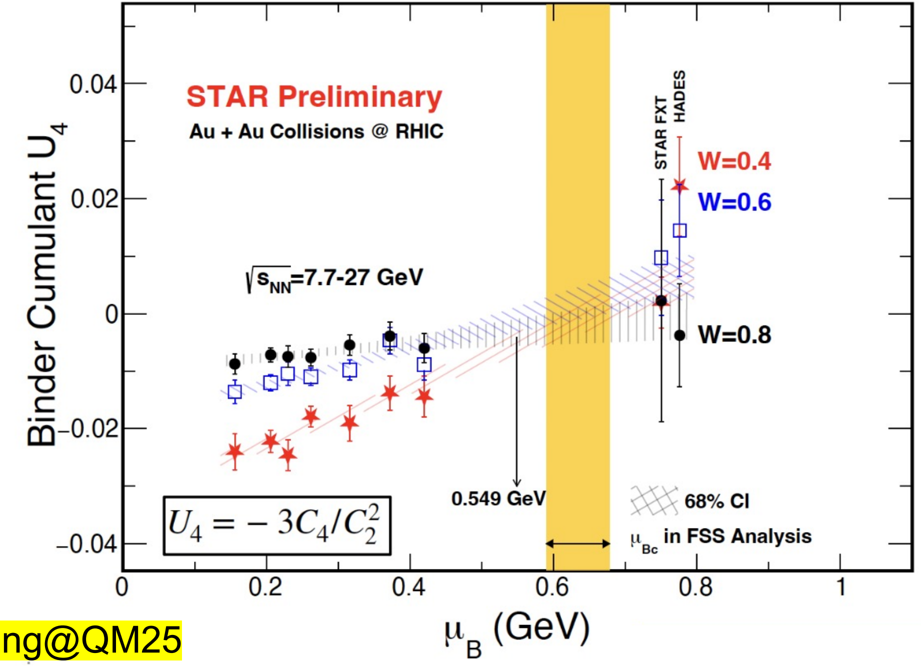


1. Rapidity coverage extended upto |y|<0.6 with iTPC upgrade.
2. Cumulant ratios decrease smoothly as rapidity window grows
3. UrQMD follows the trend, but deviate quantitatively at higher energies

Yige Huang@QM25

Finite Size Scaling Study





Yige Huang@QM25

1) Finite size scaling study for C_2 based on thermodynamic behavior

$$\mu_{Bc} = 648^{+30/+2}_{-24/-58} \text{ MeV}$$

2) Consistent estimation from Binder cumulants fit results

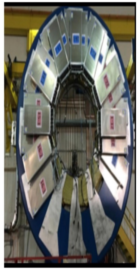
A. Sorensen and P. Sorensen, arXiv: 2405.10278

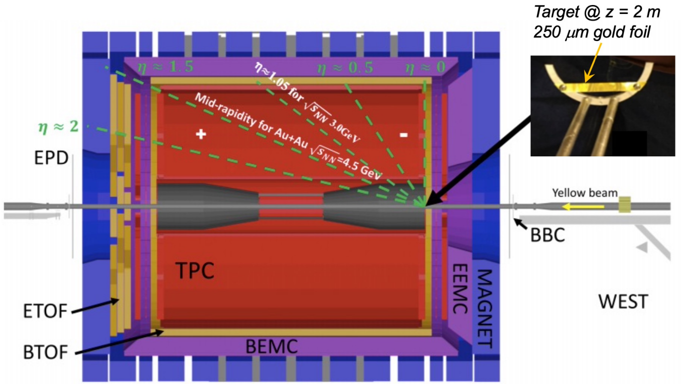
Proton Number Fluctuations from STAR Fixed-Target Program

3.2, 3.5, 3.9 GeV：

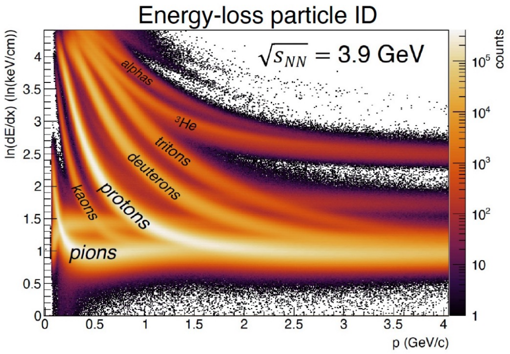
Data Set Details

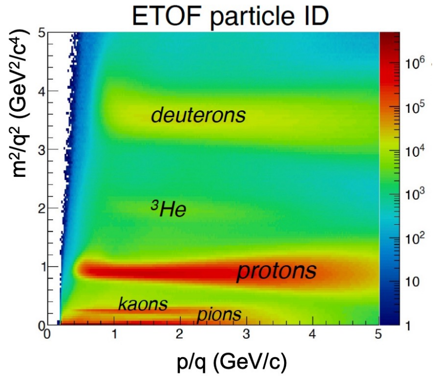
Nominal $\sqrt{s_{NN}}$ (GeV)	Precision $\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV)	# Good Events	CoM Rapidity	Chemical Pot. μ_B (MeV)
3.2	3.208	4.593	201M	1.139	697
3.5	3.531	5.761	116M	1.254	666
3.9	3.918	7.309	117M	1.375	632





Particle Identification

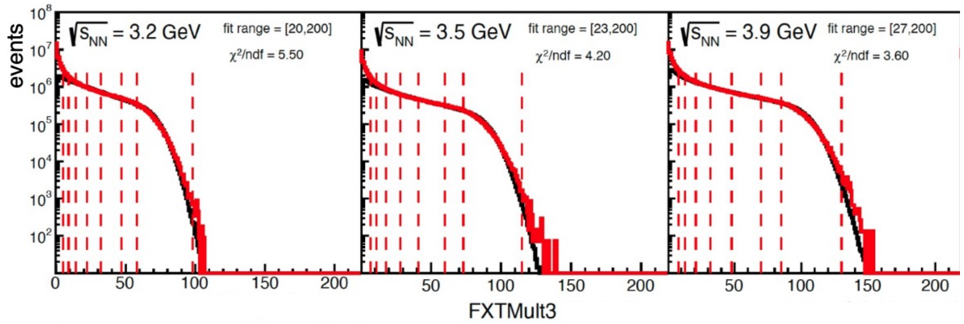


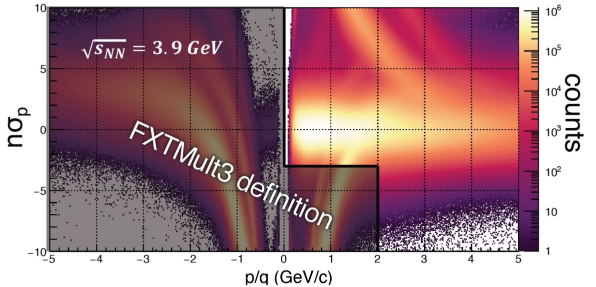


- ➢ ETOF provided by CBM-FAIR, crucial for PID at BES-II, especially for the FXT program
- ➢ Good detector performance (timing resolution, matching efficiency, stability)

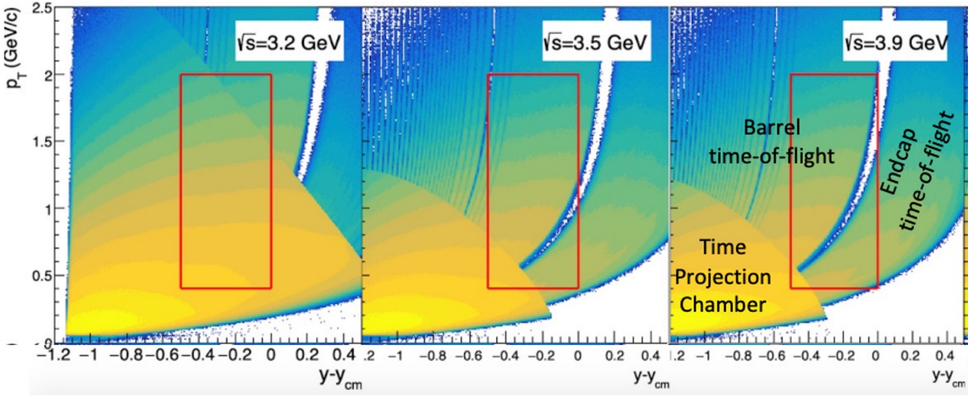
Z. Sweger, Yongcong Xu, Xin Zhang @ QM25

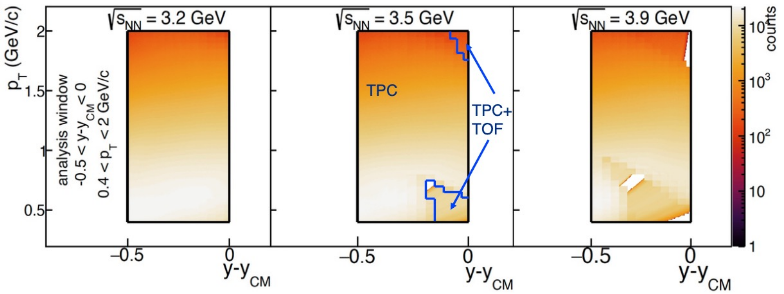
Proton Acceptance and Identification





FXTMult3: all h- and, h+ excluding protons/*d*/*t*.. within STAR detector to avoid auto-correlations.





Slow TPC/Fast TOF PID + Pile-up = Fast/Slow miss match ->
Will distort cumulant measurement

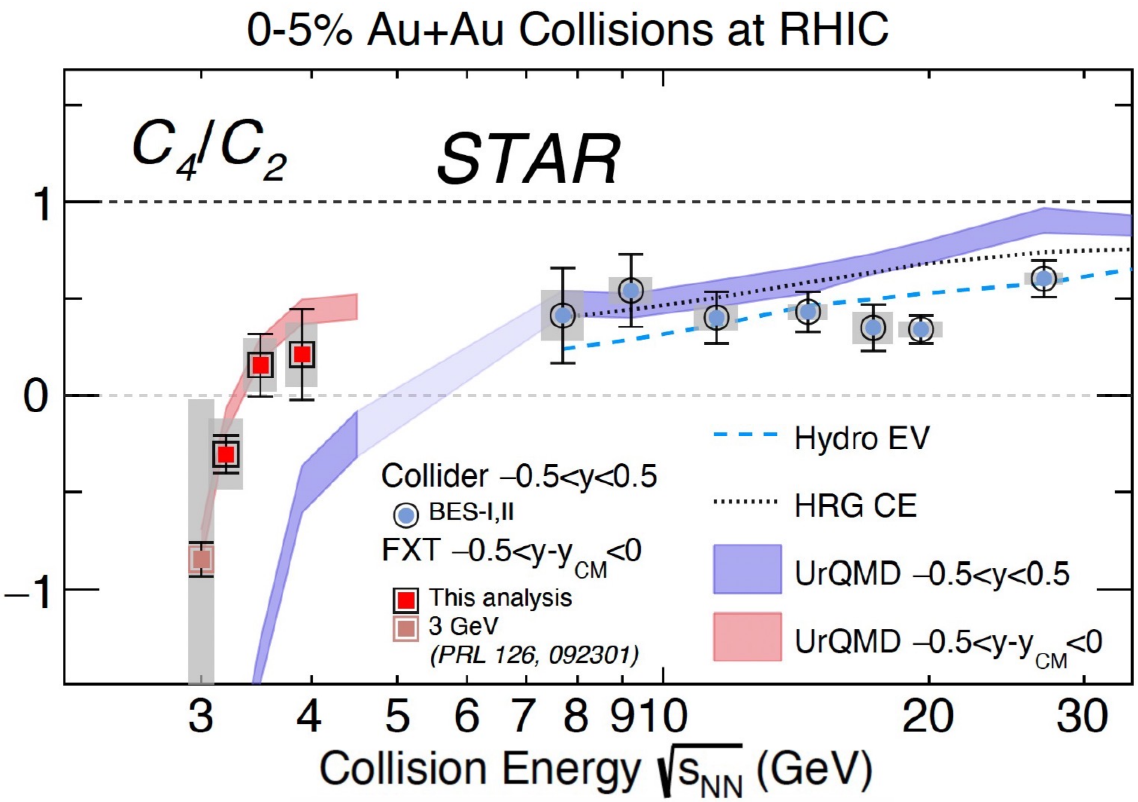
Conventional PID method for Proton :
TPC PID at low p
TPC+TOF at high p
-> Acceptance gap.

Y. Zhang, Y. Huang, T. Nonaka, X. Luo, NIMA 1026(2022)166246
STAR, Phys. Rev. C 107, 024908 (2023)
Z. Sweger, C. Daniel and X. Dong, PRC 111 (2025) 034902

Experimental methods to reduce those effects :

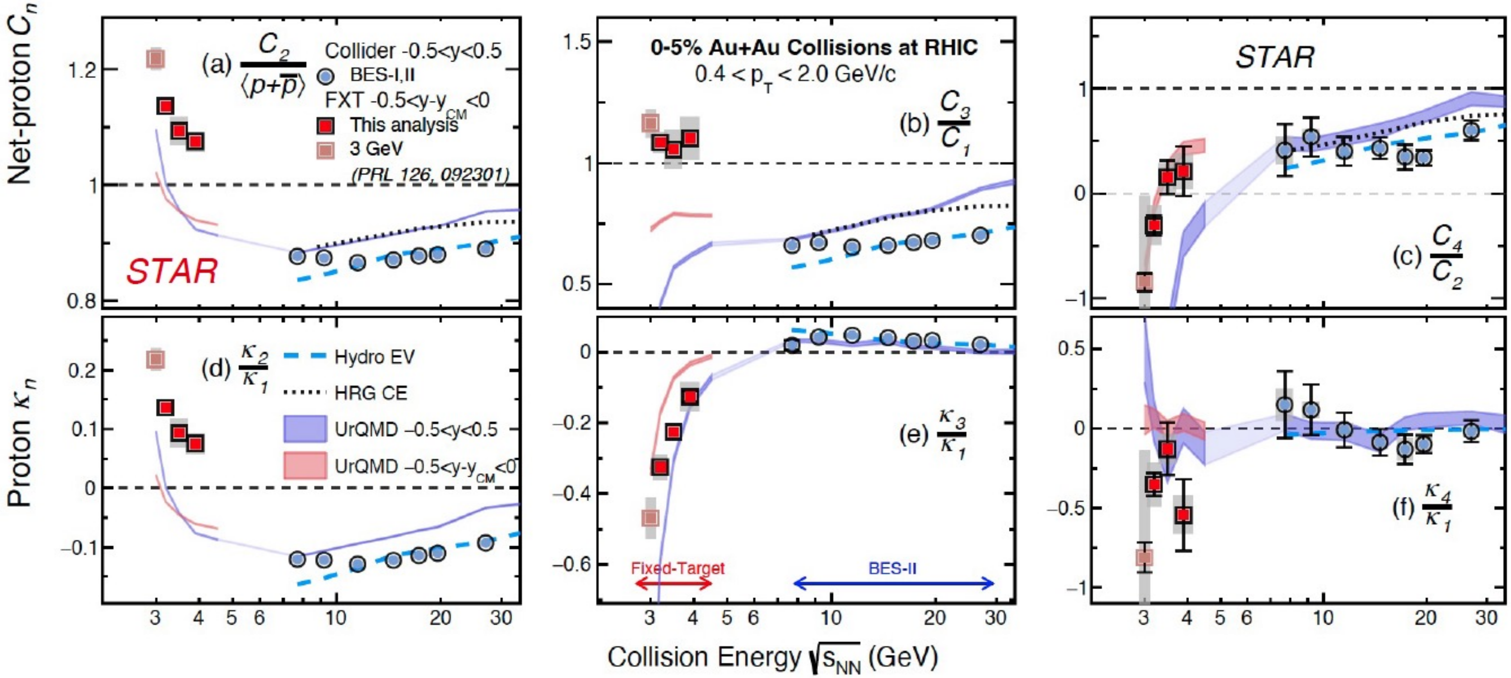
1) Pile-up rejection + dynamic dE/dx selection to maximize TPC PID and ensure >90% purity. -> (3.5 and 3.9 GeV)
2) 3.2 GeV: only TPC PID, Pile-up correction is applied.

Energy Dependence of (Net-)Proton C_4/C_2 from BES-II



Z. Sweger, Yongcong Xu, Xin Zhang @ QM25

Energy Dependence of (Factorial) Cumulant Ratios



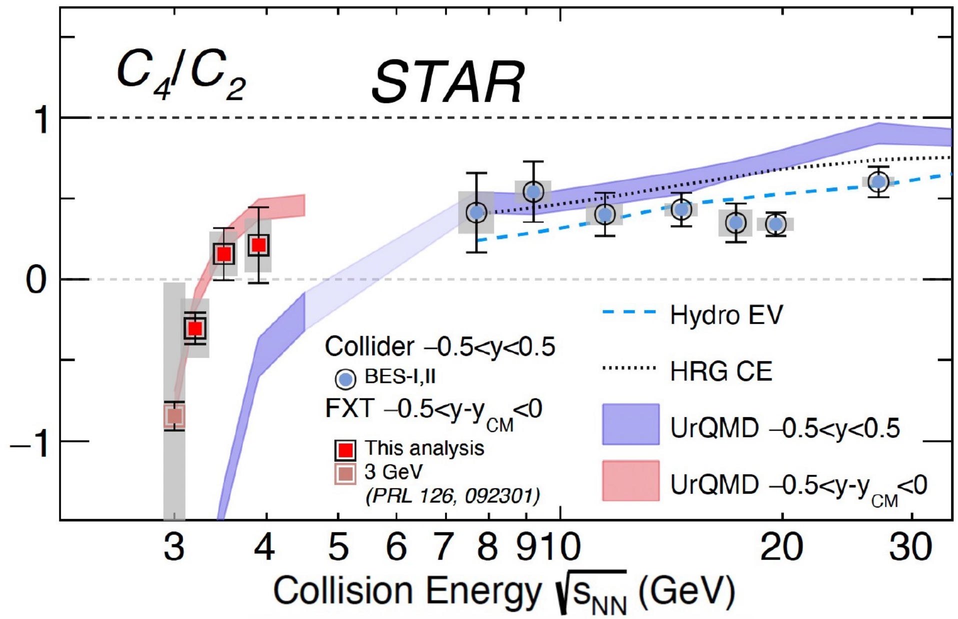
At 3.0 – 3.9 GeV central collisions (0-5%, -0.5<y<0):

1) UrQMD describe the trends of the data
2) Proton (factorial) cumulants at 2nd and 3rd order deviates from UrQMD
3) Proton C_4/C_2, κ_4/κ_1 consistent with UrQMD

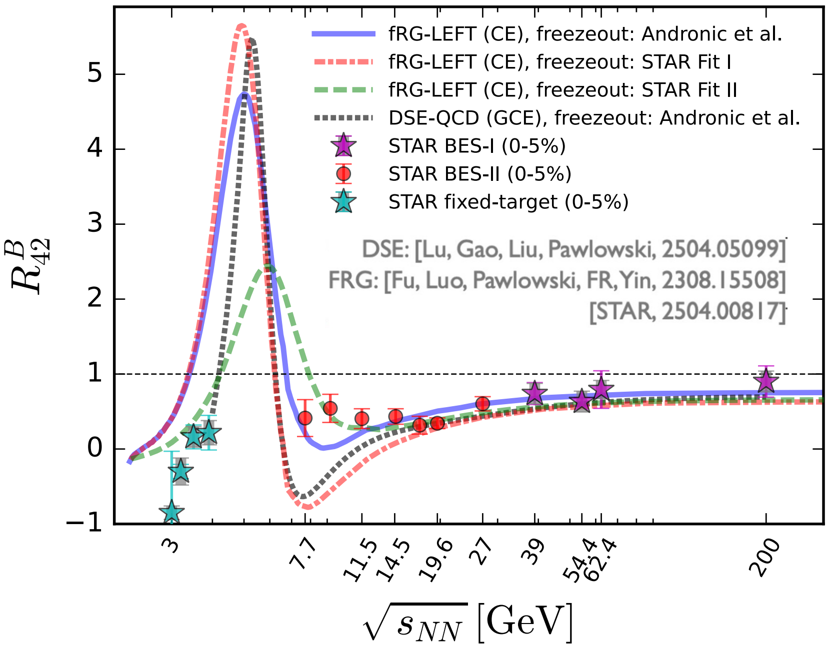
Z. Sweger, Yongcong Xu, Xin Zhang @ QM25

Search for the QCD Critical Point : To be Continued…

0-5% Au+Au Collisions at RHIC

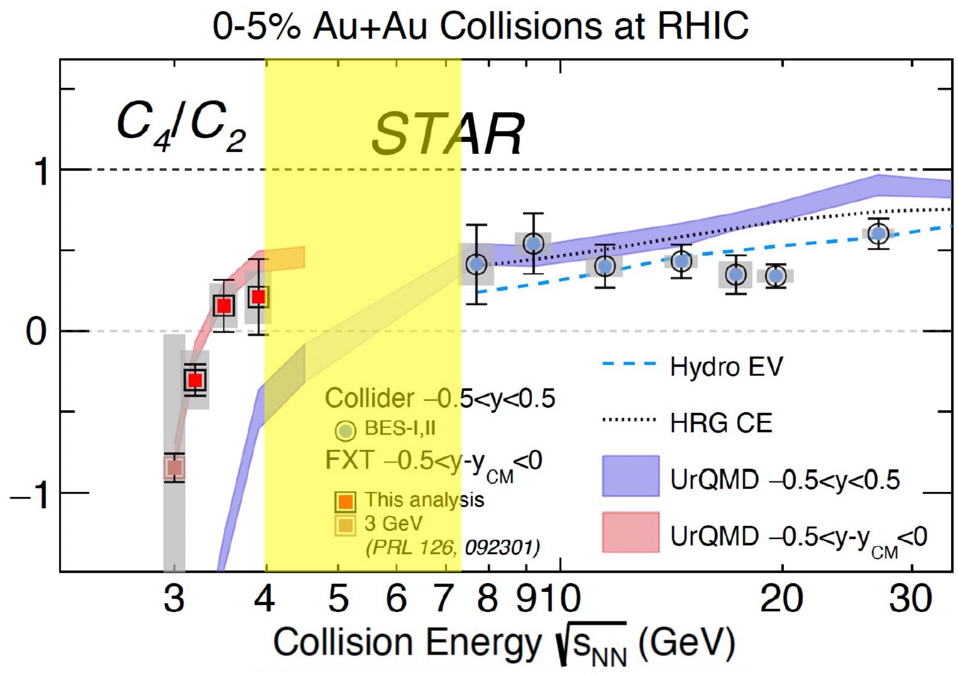


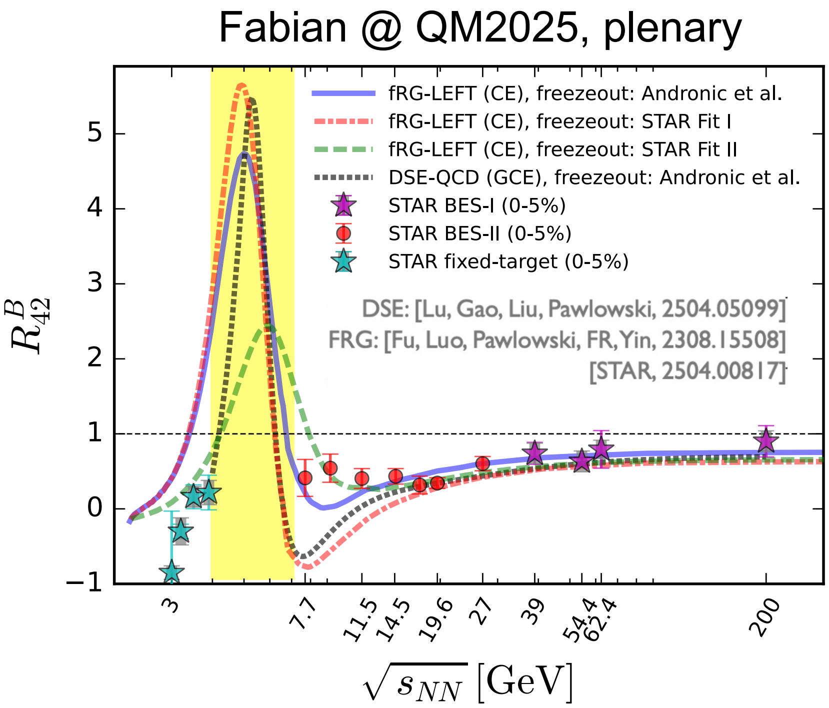
Fabian @ QM2025, plenary



- Experimental results between 4 – 8 GeV are crucial.
- Analysis of 4.5 GeV and 2 billion events from Run21 3 GeV are ongoing.

Search for the QCD Critical Point : To be Continued…

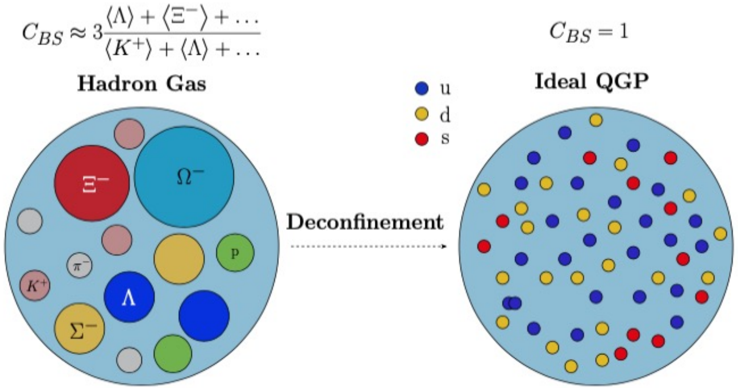




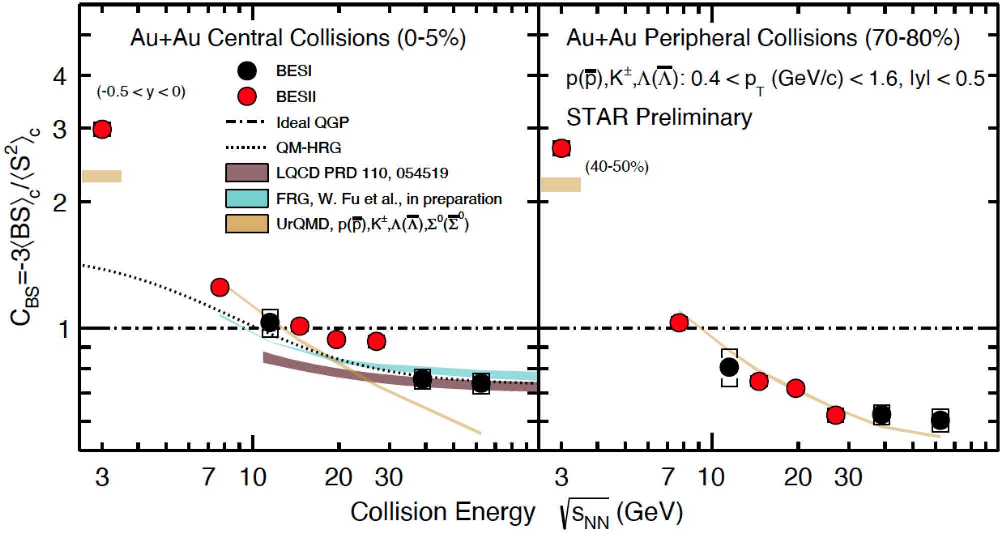
- Experimental results between 4 – 8 GeV are crucial.
- Analysis of 4.5 GeV and 2 billion events from Run21 3 GeV are ongoing.

Baryon-Strangeness Correlations

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



V. Koch, A. Majumder and J. Randrup, Phys. Rev. Lett. 95, 182301 (2005)



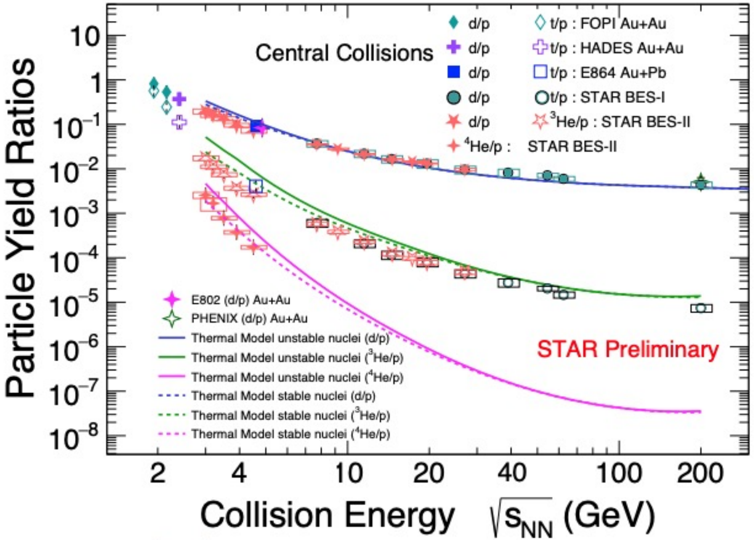
Hanwen Feng (STAR), QM25, Young Researcher Award
3 GeV: Yu Zhang (STAR), QM25 Poster ID 1020

- Central Collisions : C_{BS} consistent with FRG/LQCD at high energies (39, 62.4 GeV)
  While at 19.6 and 27 GeV, it deviates above from all calculations.
- Peripheral collisions: The energy dependence from 7.7 to 62.4 GeV can be described by UrQMD.
- Large value observed of C_{BS} at 3 GeV is consistent with baryon rich environment.

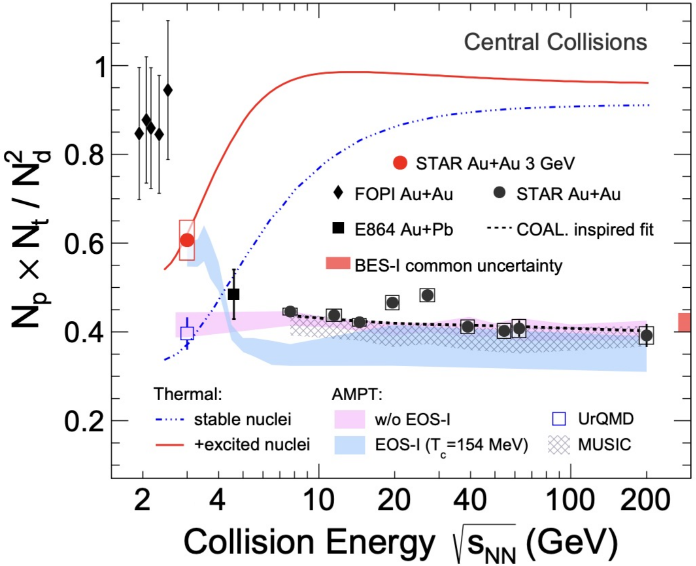
Light Nuclei Yield Ratios from BES-II (3 – 27 GeV)

刘慧，26日上午

Liubing Chen, Yixuan Jin(STAR)@ QM25



The compound yield ratio is proposed to be sensitive to the neutron density fluctuations K. Sun et al. Phys.Lett.B 774 (2017) 103-107

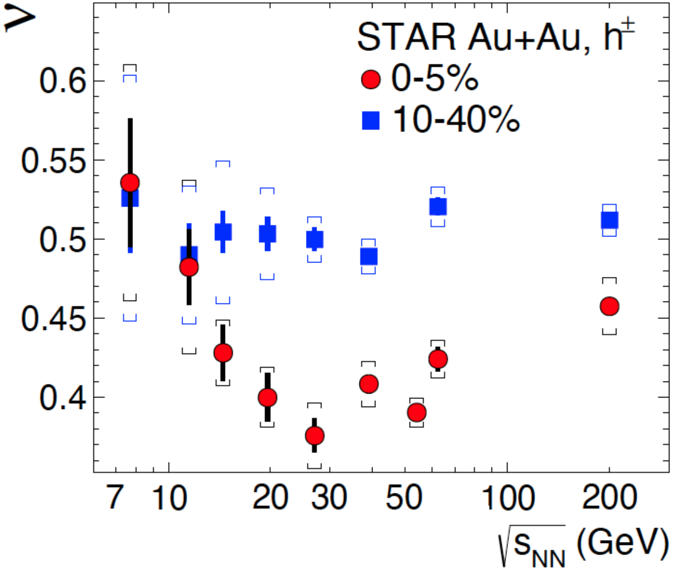


- Thermal model overestimate the light nuclei yield ratios for t/p and ^{3}He/p ratio, can be explained by the effect of hadronic re-scattering (K. Sun, et al., Nature Comm. 15,1074 (2004))
- Large increase is observed in compound yield ratio at low energies, which cannot be described by transport (UrQMD,AMPT) or hydro models.

STAR: Phys. Rev. Lett. 130, 202301 (2023)
Phys. Rev. C110, 054911 (2024)

Charged Hadrons Intermittency and p_T-p_T fluctuations

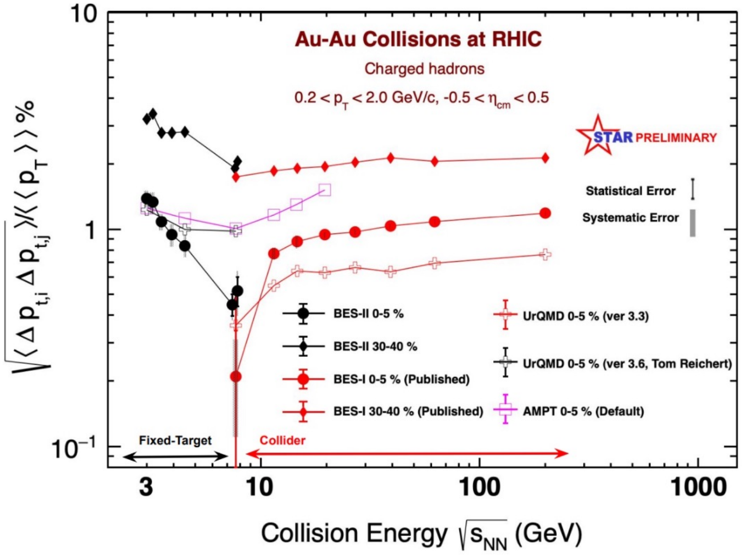
李治明，26日上午 Intermittency



STAR, Phys. Lett. B 845, 138165 (2023)

p_T-p_T fluctuations

$$< \Delta p_{t,i} \Delta p_{t,j} > = < (p_{t,i} - < p_t >)(p_{t,j} - < p_t >) >_{i \neq j}$$

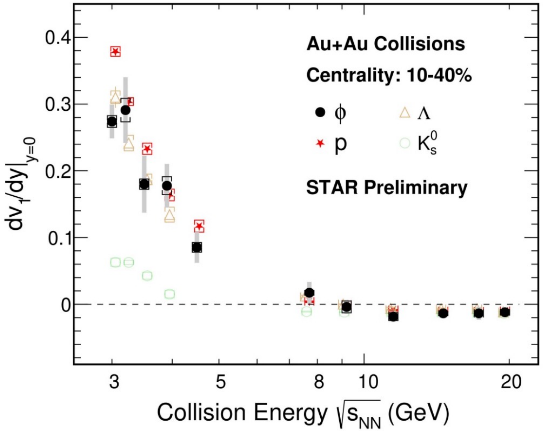


Rutik Manikandhan (STAR), QM25 Poster ID 774

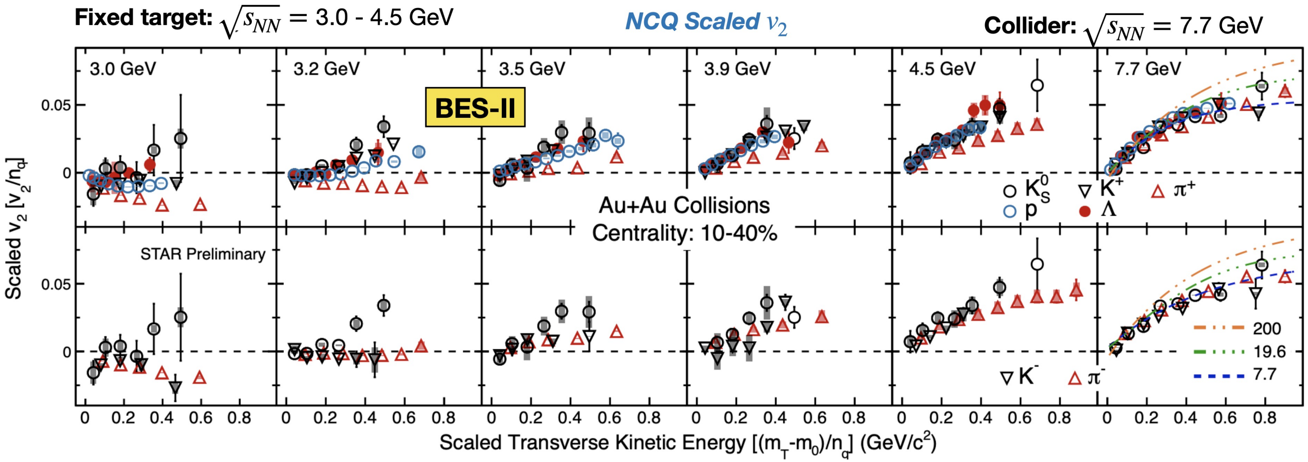
Non-monotonic energy dependences are observed in both charged particles Intermittency and p_T-p_T fluctuations.

Energy Dependence of Collective Flows (dv_1/dy, v_2) from BES-II

郑光裕 (STAR), QM25 Poster ID 696
Poster ID 171 @ this conference



v1(Φ) ~ v1(p) ~ v1(Λ)



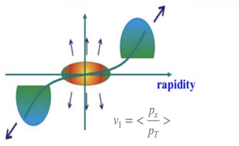
Hadronic interaction ⟶ Partonic collectivity

STAR, arXiv:2504.02531

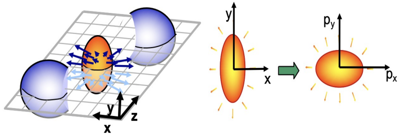
吴星，27日上午

- $\sqrt{s_{NN}}$ = 4.5- 7.7 GeV → sign change in Kaon v_1
- Sign change in ϕ v_1 and it follows baryons (p and Λ)

- For $\sqrt{s_{NN}} \geq$ 7.7 GeV →v_2 NCQ-scaling holds
- $\sqrt{s_{NN}}$ < 4.5 GeV → Gradual breaking of v_2 NCQ-scaling
- Dominance of *partonic* collectivity above 4.5 GeV



Directed flow (v_1): Sideward collective motion of produced particles



Elliptic flow (v_2): Initial spatial anisotropy leading to final momentum asymmetry of produced particles

Probe the EoS of QCD medium and understand the role of nuclear shadowing at high baryon density region.

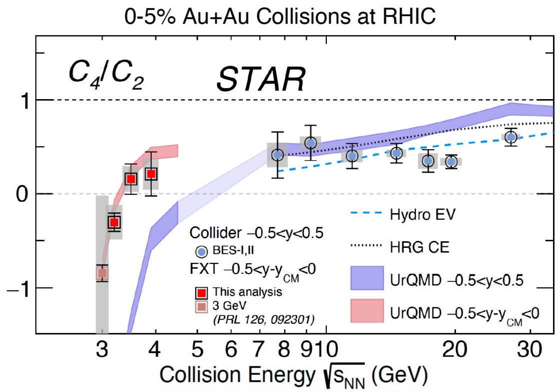
Summary and Outlook

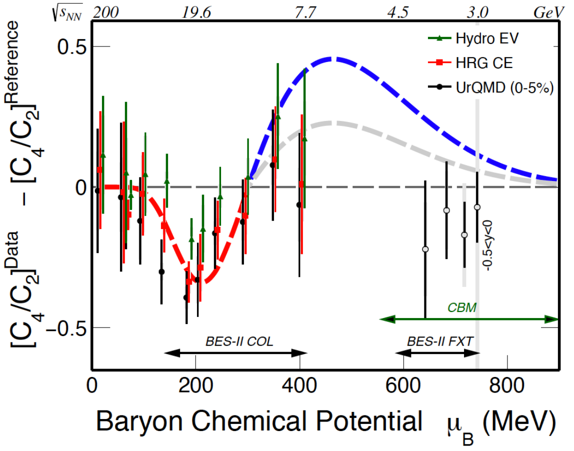
- STAR reported precision measurement of (net-) proton fluctuations in Au+Au collisions from BES-II including 3.2-3.9 GeV (FXT) and 7.7-27 GeV(Collider).
  -better statistics, systematics and centrality resolution.

- Collider energies : for net-proton C_4/C_2 in central collisions, deviations of 2-5σ are observed w.r.t non-CP reference (model or peripheral data) at 19.6 GeV.

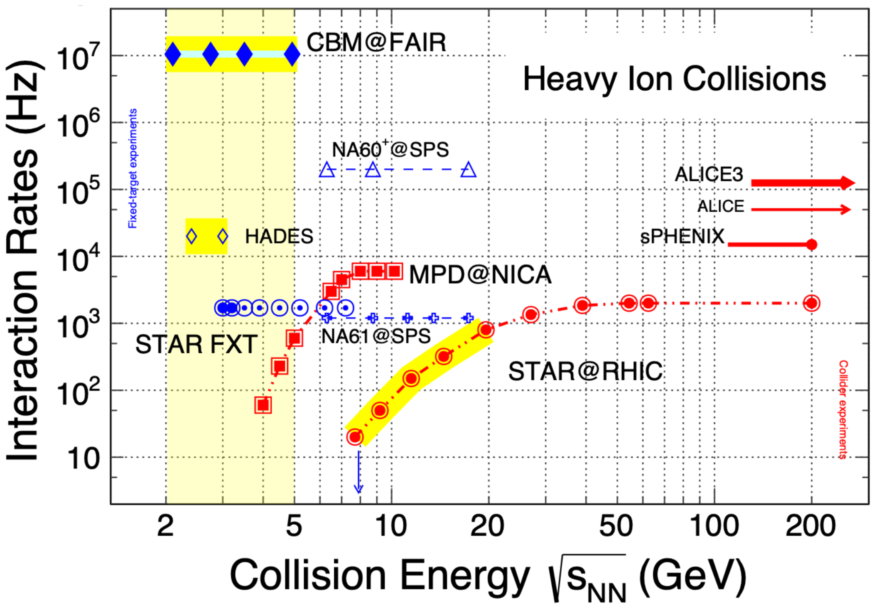
- FXT energies : proton C_4/C_2 in central collisions are consistent with UrQMD calculations at 3.0 – 3.9 GeV. Analysis of 4.5 GeV and high statistics 3 GeV data (2 Billion events) are ongoing.

- More observables: BS correlations, intermittency, light nuclei, flow, p_T-p_T fluctuations.





Summary and Outlook



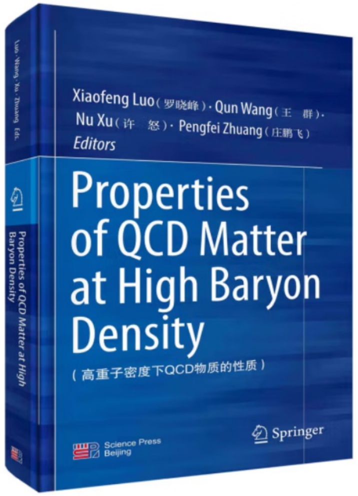
Rich Physics at High Baryon Density

- Critical point and phase boundary;
- Nuclear matter EOS at high baryon density;
- Y-N interactions, inner structure of compact stars. etc. (Observation of Strange Di-baryon, Kehao Zhang(STAR)@QM25

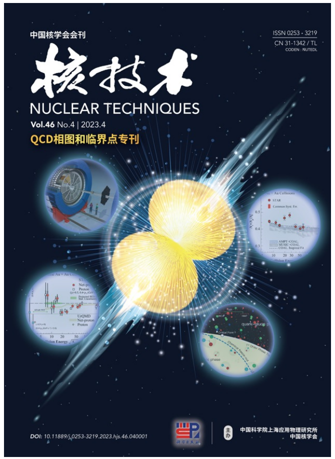
Future High Baryon Density Experiments:

- FAIR/CBM (2.4 - 4.9 GeV)
- HIAF-HNS/CEE (2.1– 4.5 GeV)
- NICA/MPD (4 - 11 GeV)
- JPARC-HI (2-6.2 GeV)

高重子密度下QCD物质的性质 (2022)



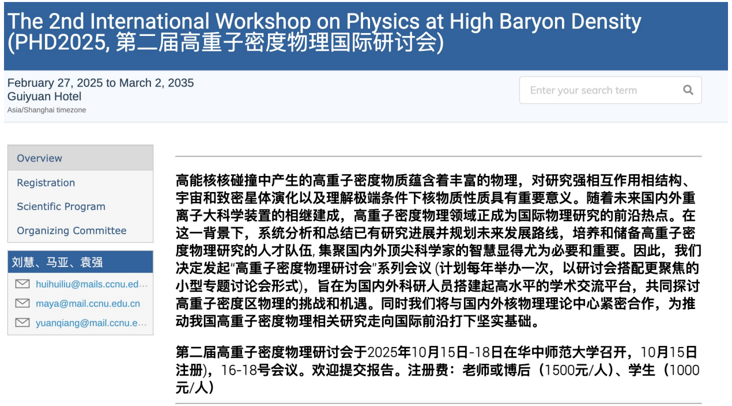
核技术“QCD相图和临界点专刊”(2023)



The 2nd International Workshop on Physics at High Baryon Density (PHD2025)

期待金秋十月相聚华师桂子山！ Oct. 16-18, 2025@CCNU

https://indico.ihep.ac.cn/event/25334/


The 2nd International Workshop on Physics at High Baryon Density (PHD2025, 第二届高重子密度物理国际研讨会)

February 27, 2025 to March 2, 2035
Guiyuan Hotel
Asia/Shanghai timezone

Enter your search term

Overview
Registration
Scientific Program
Organizing Committee

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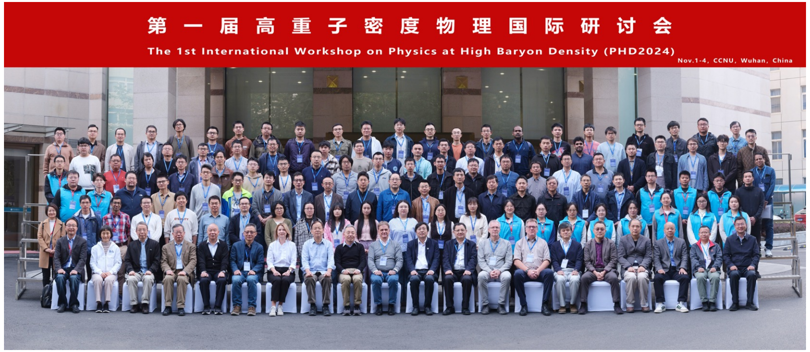
maya@mail.ccnu.edu.cn
yuanqiang@mail.ccnu.e...

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。

第二届高重子密度物理研讨会于2025年10月15日-18日在华中师范大学召开，10月15日注册），16-18号会议。欢迎提交报告。注册费：老师或博后（1500元/人）、学生（1000元/人）



Welcome to PHD2025@CCNU ！

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)
Weijie Fu (Dalian University of Technology)
Sophia Han (T.D. Lee Institute, Shanghai Jiao Tong University)
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)

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STAR Collaboration and Theory Colleagues

Thank you for your attention!