Search for the QCD Critical Point and Strange Dibaryon in Heavy-ion Collisions at RHIC

“with Baryon Fluctuations and Correlations”

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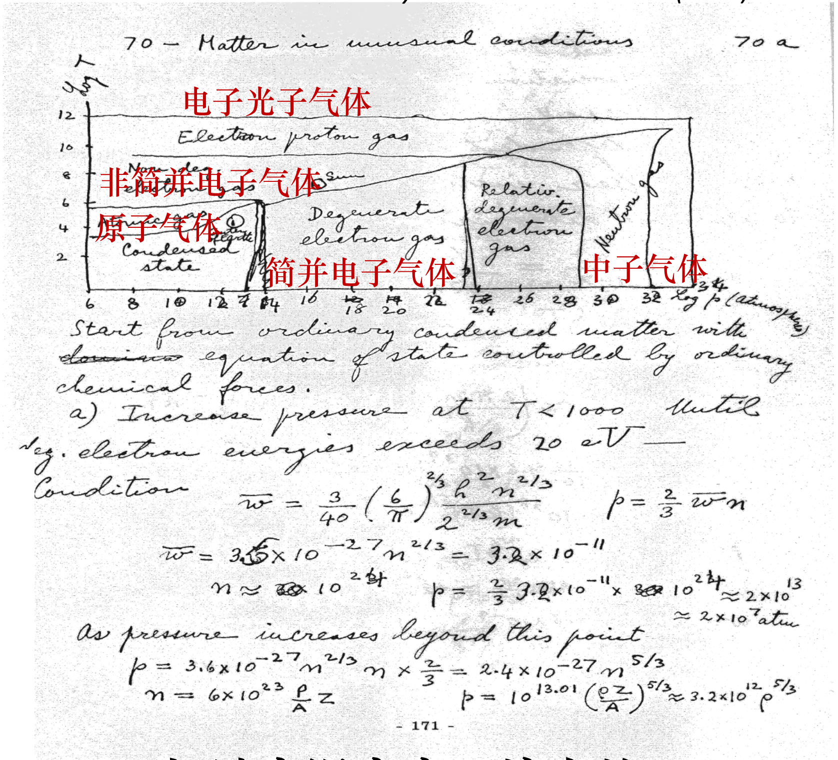
Central China Normal University

Aug. 20th , 2026

极端条件下的物质形态

E. Fermi

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



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

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

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

$$\overline{w} = 3.5\times10^{-27} n^{2/3} = 3.2\times10^{-11}$$

$$n \approx 10^{24} \qquad p = \frac{2}{3}\,3.2\times10^{-11}\times10^{24} \approx 2\times10^{13} \approx 2\times10^{7}\ \text{atm}$$

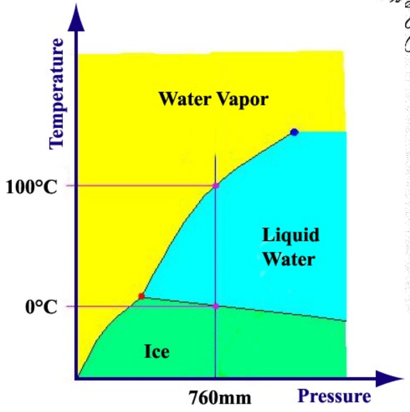
As pressure increases beyond this point

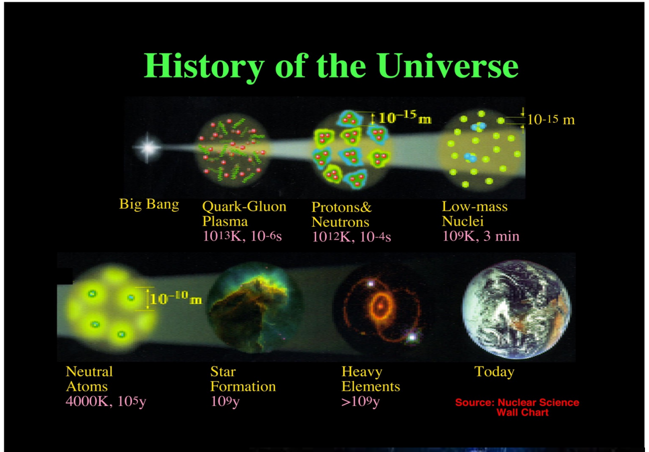
$$p = 3.6\times10^{-27} n^{2/3}\, n \times \frac{2}{3} = 2.4\times10^{-27} n^{5/3}$$

$$n = 6\times10^{23}\frac{\rho}{A}Z \qquad p = 10^{13.01}\left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2\times10^{12}\rho^{5/3}$$

- 171 -

Water Phase Diagram

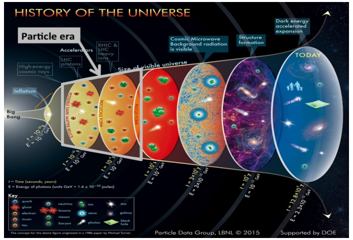




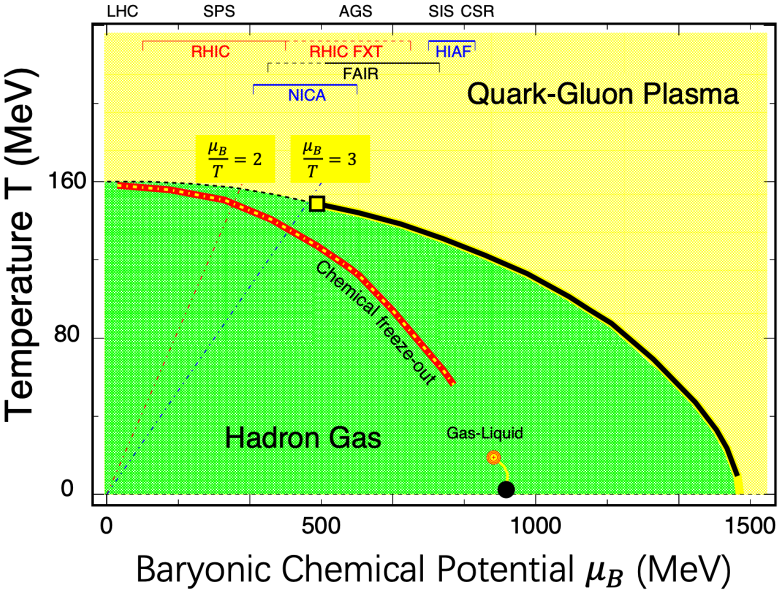
极端高温高密环境中的物质形态及相结构是什么？

1) **早期宇宙演化**
2) **致密星体状态方程**

QCD Phase Diagram



宇宙演化



Lattice QCD : at $\mu_B = 0$, smooth crossover. T_c ~ 156 MeV

Large μ_B : 1st order phase transition and QCD critical point ?

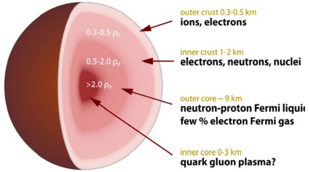
Y. Aoki et al., Nature 443, 675 (2006) ;

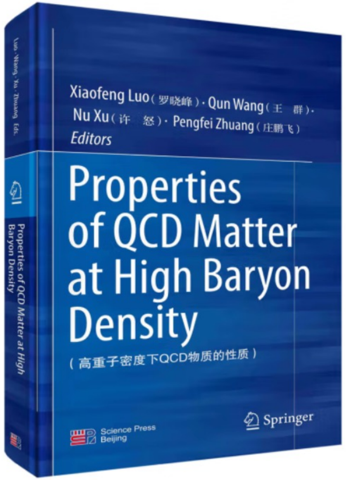
A. Bazavov et al (HotQCD), PRD 85, 054503 (2012).

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?

它是国际核物理领域待解决的关键科学问题之一，也是我国大科学装置强流离子加速器(HIAF)的一个主要物理目标(2025年在广东惠州建成)。

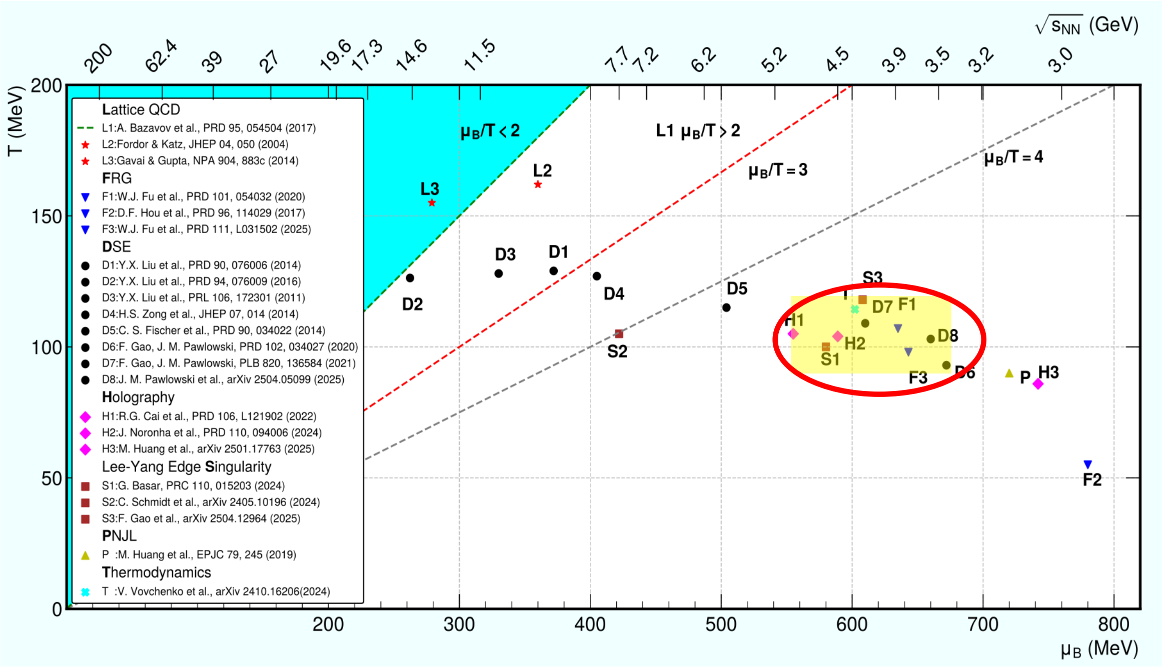
马余刚、许怒、刘峰，基于HIAF集群的QCD相结构研究，中国科学:物理学 力学 天文学,2020,50(11):124

赵红卫,从HIAF到CNUF, 现代物理学知识，第36卷(2024年), 第1期

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

Search for the QCD Critical Point

Theoretical Estimations (2004-2025)



"Converge region"

μ_B^{CEP}: ~ **600 – 700 MeV**

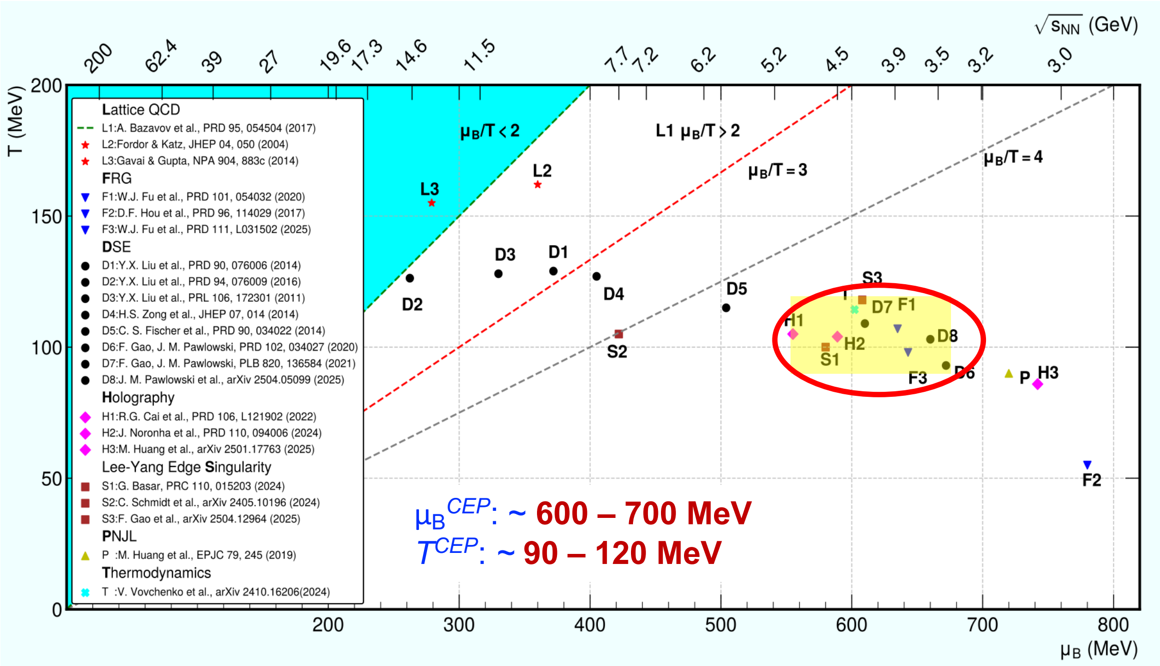
T^{CEP}: ~ **90 – 120 MeV**

Wei-jie Fu、Fei Gao、Mei Huang、Yuxin Liu et al.

FRG : Wei-jie Fu, J. M. Pawlowski, and F. Rennecke, Phys. Rev. D 101, 054032 (2020)
Wei-jie Fu, Chuang Huang, Jan M. Pawlowski, Fabian Rennecke, Rui Wen, Shi Yin, 2603.13455

DSE : Fei Gao, J. M. Pawlowski, Phys. Lett. B 820, 136584 (2021)

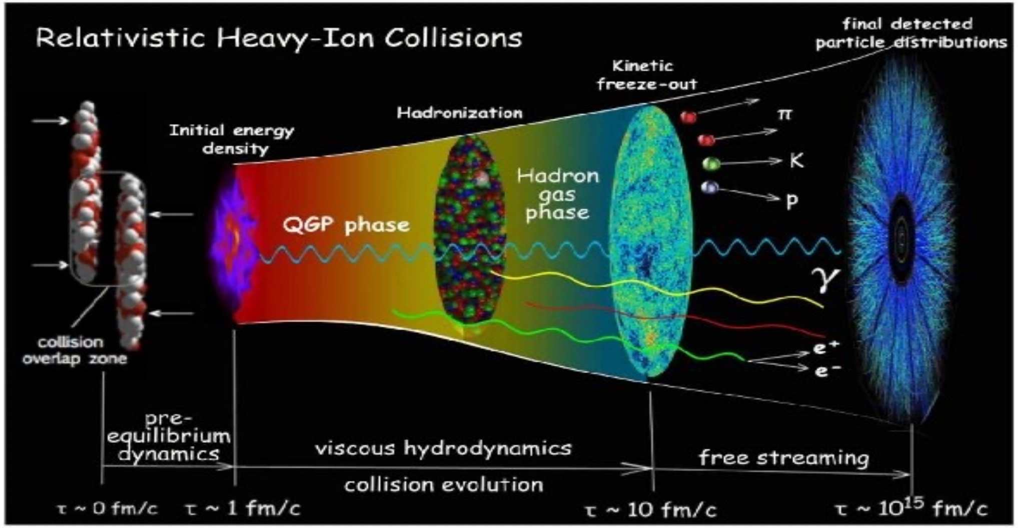
Theoretical Estimations (2004-2025)



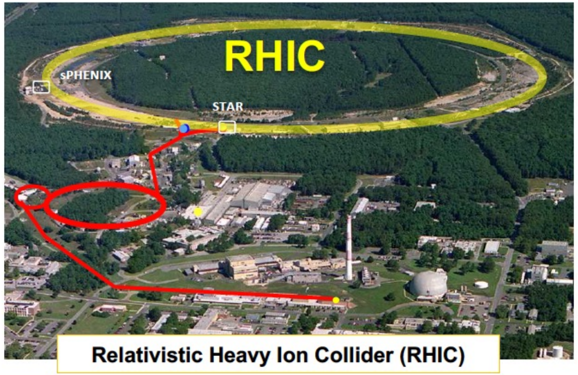
"…experimental measurements are essential to determine whether a QCD critical point exists." *2023 US Long Range Plan for Nuclear Science*

Y. Zhang, Z. Wang, X. Luo, N. Xu, arXiv : 2602.08356
Christian S. Fischer, Jan M. Pawlowski, arXiv : 2603.11135

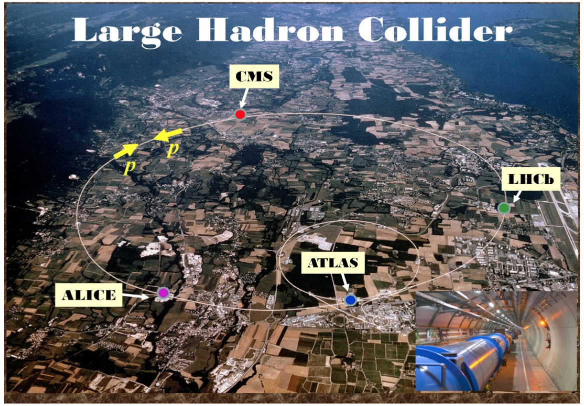
Relativistic Heavy-Ion Collisions



相对论重离子对撞机(RHIC)

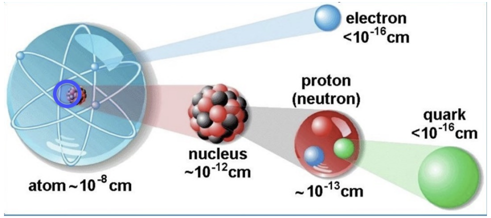


大型强子对撞机(LHC)



- Properties of QGP

强耦合低粘滞理想流体(夸克汤)
强电磁场、强涡旋场



- QCD Phase Structure

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

Relativistic "Minds" Collisions (战略研讨会)

Organizers: T. Ludlam, H. Ritter, G. Stephans, M. Gazdzicki, B. Friman, F. Videbaek, T. Satogata, K. Rajagopal, L. McLerran

March, 2006@BNL

Thursday, March 9

8:30 – 9:00	*Registration*	
Chair: T. Ludlam		
9:00 – 9:10	Welcome	T. Ludlam (10)
9:10 – 9:50	Introduction and overview	K. Rajagopal (35+5)
9:50 – 10:25	Lattice results on the QCD critical point	F. Karsch (30+5)
10:25	*Break (15)*	
10:40 – 11:05	Fluctuations at the critical point	M. Stephanov (20+5)
11:05 – 11:40	Experimental overview & prospects for RHIC	G. Roland (30+5)
11:40 – 12:15	RHIC machine considerations	T. Satogata (30+5)
12:15	*Lunch*	
Chair: George Stephans		
1:30 – 2:00	Excitation function – NA 49 results	P. Seyboth (25+5)
2:00 – 2:30	Excitation function—onset of deconfinement	E. Shuryak (25+5)
2:30 – 2:50	Soft mode of the QCD critical point	H. Fujii (15+5)
2:50 – 3:10	Baryon number fluctuation near the critical point	Y. Hatta (15+5)
3:10	*Break (15)*	
3:25 – 3:55	Hydro evolution near the QCD critical point	C. Nonaka (15+5)
3:55 – 4:25	Future prospects for the CERN SPS	M. Gazdzicki (25+5)
4:25 – 5:00	Experiments with PHENIX near the critical point	P. Steinberg (25+10)
5:00 – 5:35	Experiments with STAR near the critical point	T. Nayak (25+10)
6:15	*Reception and dinner*	

Friday, March 10

Chair: F. Videbaek		
8:30 – 9:30	Low energy operation of RHIC: AGS low energy extraction performance	 N. Tsoupas (15+5)
	Luminosity monitoring issues	A. Drees (15+5)
	Low energy electron cooling	A. Fedotov (15+5)
9:30 – 10:00	Energy dependence of temperature and baryochemical potential	K. Redlich (25+5)
10:00 – 10:25	Observable power laws at the QCD critical point	N. Antoniou (20+5)
10:25	*Break (15)*	
10:40– 11:10	The CBM experiment at FAIR	P. Senger (25+5)
11:10 – 11:35	Excitation function – experimental perspective	N. Xu (20+5))
11:35 – 12:00	Experience with CERES	H. Appelshauser (20+5)
12:00 – 12:25	Critical point at SPS energy?	R. Stock (20+5)
12:25	*Lunch*	
Chair: L. McLerran		
2:00 – 2:30	Lattice calculations at finite baryon potential	Z. Fodor (25+5)
2:30 – 3:00	Fluctuations and correlations	V. Koch (25+5)
3:00 – 3:25	Hadron production and phase changes	J. Rafelski (20+5)
3:25 – 3:45	Can we discover the first-order phase transition at RHIC?	J. Randrup (15+5)
3:45	*Break (15)*	
4:00 – 4:20	Signals of the first order phase transition	H. Stoecker (15+5)
4:20 – 5:30	Summary/discussion – prospects for experiments at RHIC	*Discussion Leaders :* H.-G. Ritter & T. Roser
5:30	*Adjourn*	

Following this meeting, the proposal to conduct a beam energy scan was formally submitted to the RHIC Program Advisory Committee (PAC).

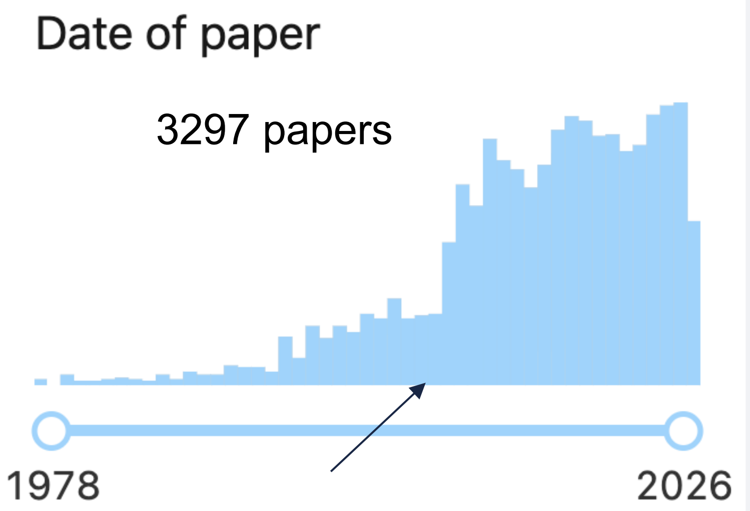
INT Workshop 2008-2b : The QCD Critical Point

Organizers: Volker Koch, Gunther Roland, Mikhail Stephanov

July 28, 2008	S. Gupta	"New results in QCD at finite μ"
July 29, 2008	M.P. Lombardo	"The QCD critical point at imaginary mu"
July 29, 2008	S. Ejiri	"Numerical study of the critical point in lattice QCD at high temperature and density"
July 30, 2008	K. Fukushima	"What can we learn from model studies on the chiral critical end-point?"
July 30, 2008	B. Klein	"Scaling and Finite-Size Scaling Analysis of Critical Behavior in Lattice QCD"
July 31, 2008	J. Braun	"Chiral Phase Boundary from Quark-Gluon Dynamics"
July 31, 2008	C. Ratti	"A quasiparticle model for QCD thermodynamics"
August 4, 2008	J. Verbaarschot	"Phase of the Fermion Determinant and the Phase Diagram of QCD"
August 5, 2008	R. Lacey	"The Role of Energy Scans at RHIC"
August 5, 2008	L. Ferroni	"Space and Phase Space saturation: a simple Bag-Model-inspired picture for a smooth transition to QGP"
August 6, 2008	M. Asakawa	"QCD Critical Point and its Effect on Physical Observables"
August 6, 2008	T. Hell	"Thermodynamics of a Nonlocal PNJL Model for Two and Three Flavors"
August 7, 2008	C. Miao	"QCD Equation of State and Fluctuations on the Lattice"
August 11, 2008	K. Rajagopal	"The Search for the QCD Critical Point Using Lattice QCD Calculations-Part I" Part 2
August 11, 2008	F. Karsch	"Lattice results on the QCD critical point"
August 11, 2008	J. Randrup	"Spinodal decomposition: A tool for seeing the phase transition?"
August 11, 2008	H. Caines	"STAR and the RHIC Energy Scan"
August 11, 2008	K. Homma	"Fluctuations and Search for the QCD Critical Point"
August 12, 2008	G. Stephans	"Experimental Exploration of the QCD Phase Diagram"
August 12, 2008	K.F. Liu	"Finite Density Phase Transition with Canonical Ensemble Approach"
August 12, 2008	C. Nonaka	"Hydrodynamic Expansion with the QCD Critical Point in Heavy Ion Collisions"
August 12, 2008	M. Mitrovski	"Energy and System Size Dependence of Hadron Production from NA49"
August 12, 2008	T. Schuster	"Energy and System Size Dependence of Fluctuations: NA49 results and NA61 plans"
August 12, 2008	G. Westfall	"K/pi Fluctuations and the Balance Function-Part 1" Part 2 Part 3
August 13, 2008	K. Redlich	"Charge Fluctuations and transport coefficients near CEP"
August 13, 2008	H. Fujii	"Spectral functions near the QCD critical point in chiral models"
August 13, 2008	R. Karabowicz	"The CBM Experiment"
August 13, 2008	P. Stankus	"Critical Point Scans at RHIC Full Energy"
August 14, 2008	L. McLerran	"The QCD Phase Diagram: The Large N Limit"
August 14, 2008	P. de Forcrand	"Towards a controlled lattice study of the QCD chiral critical point"
August 14, 2008	S. Roessner	"The interplay of flavour- and Polyakov-loop- degrees of freedom --- A PNJL model analysis"
August 14, 2008	J. Liao	"Magnetic Component of Strongly Coupled Quark Gluon Plasma & QCD Phase Diagram from E-M Duality Perspective"
August 14, 2008	H. Stoecker	"Cosmic matter in the Lab: FAiR=The International Facility for Antiproton and Ion Research"
August 15, 2008	R. Scharenberg	"STAR's measurement of long-Range forward backward multiplicity correlations in Heavy Ion central Au-Au collisions at $\sqrt{s}$=200 GeV"
August 15, 2008	D. Blaschke	"Nonlocal Chiral Quark Models & Critical (End-)Point"
August 18, 2008	C. Greiner	"Fast chemical equilibration of hadrons-the importance of multiparticle collisions in heavy ion reactions"
August 19, 2008	K. Mitsutani	"The possible quasi-particle picture of the quark near Tc and its effect on the dilepton production rate"
August 20, 2008	J-W. Chen	"Phase Transitions and the perfectness of Fluids"
August 21, 2008	M. Tachibana	"Spectral Continuity of Hadrons in Dense QCD"

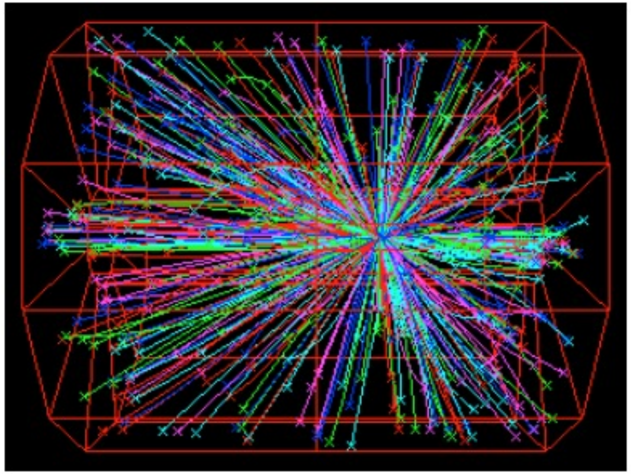
RHIC Ramping into the Era of Beam Energy Scan (2008-2010)

Search for the “QCD critical point” in Inspires



Find a “critical point”at 2008 !

In 2009, RHIC successfully conducted test runs of Au+Au collisions at 9.2 and 19.6 GeV.



Charged particle tracks from 9.2 GeV central collisions

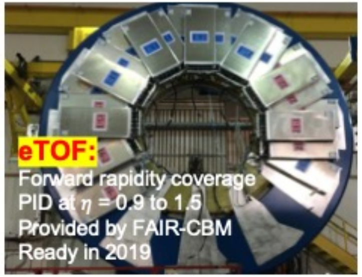
STAR, Phys. Rev. C 81, 024911 (2010)

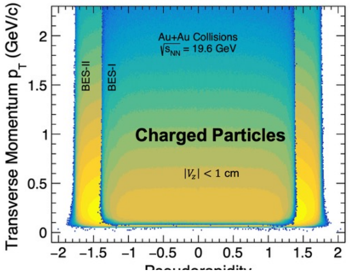
The “QCD critical point” related study jump into a highly productive level at 2008 !

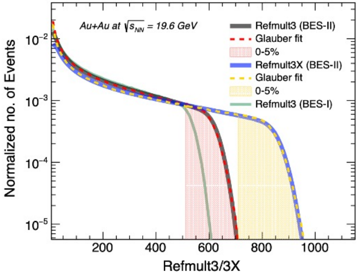
“RHIC White Paper for BES： STAR, arXiv:1007.2613”
It sounded the clarion call for RHIC to explore the QCD phase diagram and search for the QCD critical point, marking the beginning of the Beam Energy Scan era at RHIC.

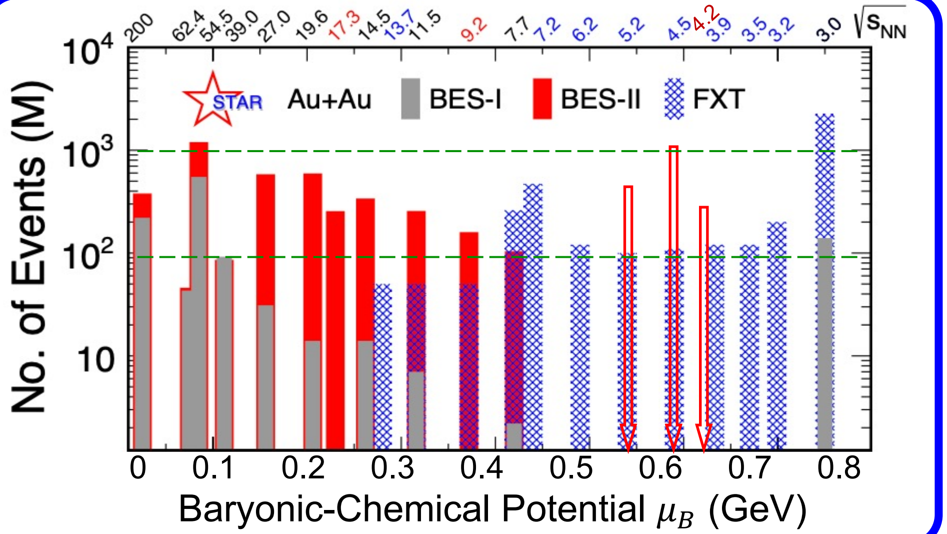
RHIC Beam Energy Scan Program (2010 – 2026)

Detector Upgrades BES-II









(1) Enlarge rapidity acceptance; (2) Improve particle identification; (3) Better centrality/event plane resolution

1) BES-I (2010 – 2014): 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, 200 GeV;

2) BES-II (2018 – 2026): 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, 4.2, 4.5**, 5.2, 6.2,…,13.7 GeV)

3) μ_B coverage : $25 < \mu_B < 750$ MeV

X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017)
Jinhui Chen, et al., Nucl. Sci. Tech. 35, 214 (2024)

Observables : Fluctuations of Conserved Quantities

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

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

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

- **Experimental Observables: Cumulants of Conserved Quantities Dis.**
  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: $C_{1,2,...}$
Factorial Cumulants: $\kappa_{1,2,...}$

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

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

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

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

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

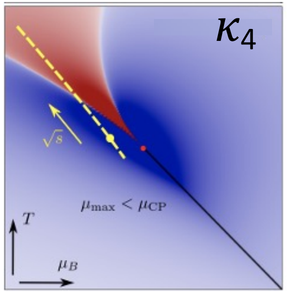
kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 = C_4 / C_2^2$

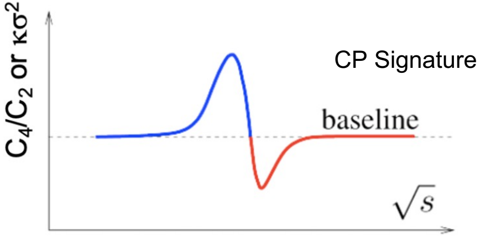
Moments, cumulants and susceptibilities:

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

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

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



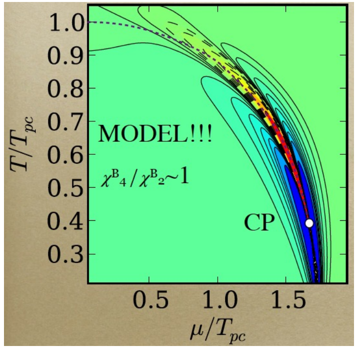


M. A. Stephanov, PRL 102 (2009) 032301

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)

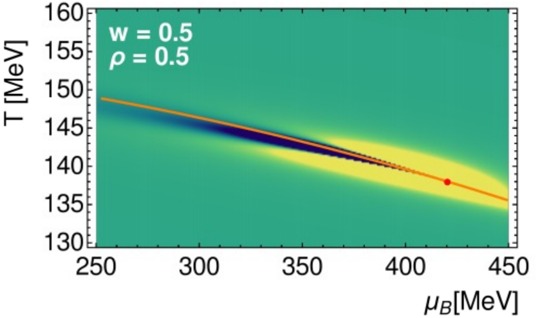
Critical Contributions to Fourth-order Fluctuations ($\kappa\sigma^2$)

PQM V. Skokov, QM2012



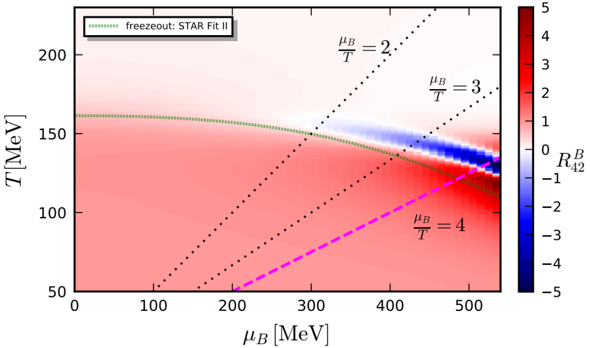
3D Ising Mapping

D. Mroczek et al, PRC 103, 034901 (2021)

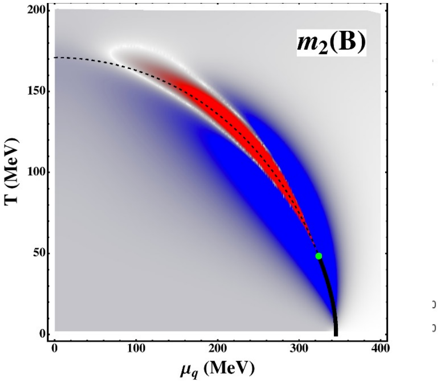


FRG

Wei-jie Fu, et al. PRD 104 (2021) 9, 094047



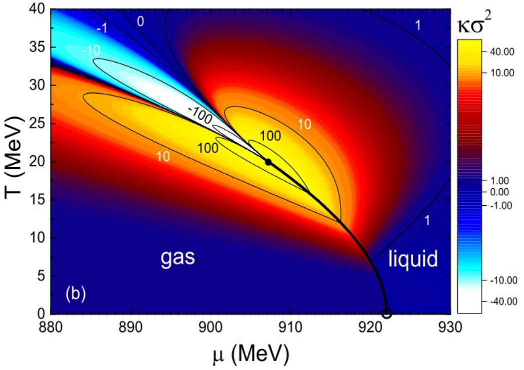
NJL



Jian Deng et al., PRD93, 034037 (2016)

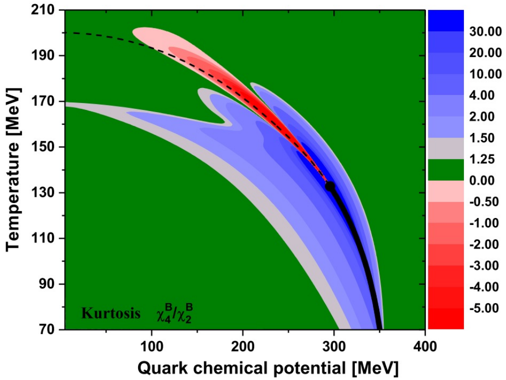
Symmetry and Universality

van der Waals (VDW)



Vovchenko et al., PRC92, 054901 (2015)

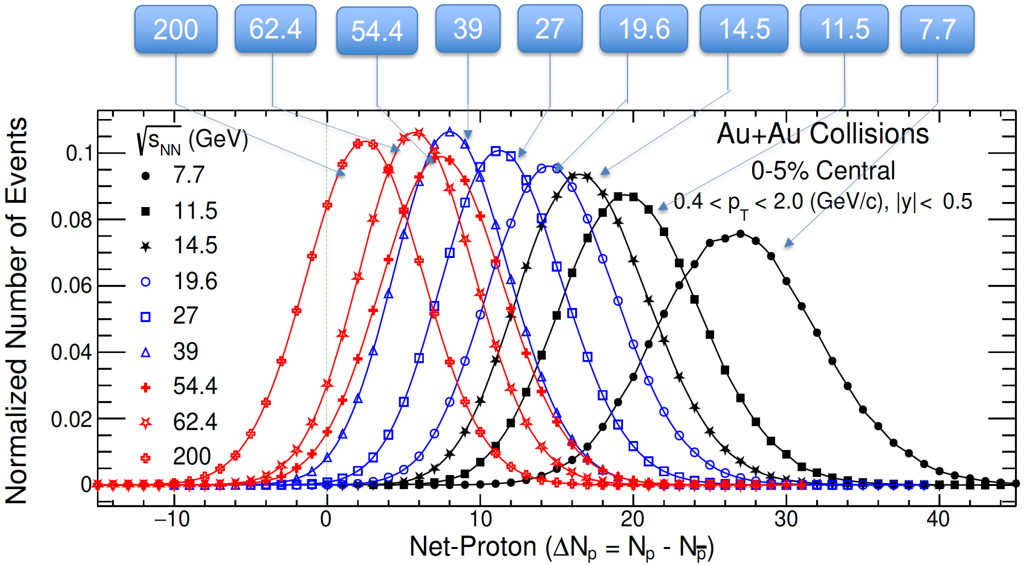
PNJL

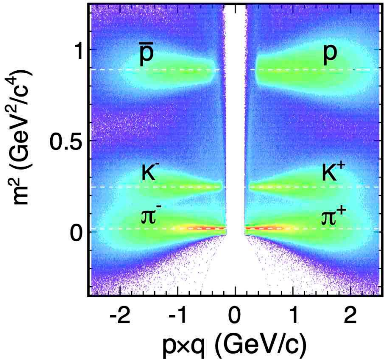


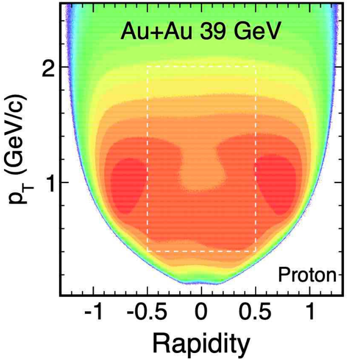
Guoyun Shao et al., EPJC 78, 138 (2018)

Mei Huang et al., EPJC 79, 245 (2019).

Analysis Details







- ➢ Centrality bin width correction (CBWC)
- ➢ Auto-correlation effect: new centrality definition
- ➢ Statistical uncertainty: Delta theorem / bootstrap
- ➢ Detector efficiency correction: Binomial model
- ➢ Pileup correction

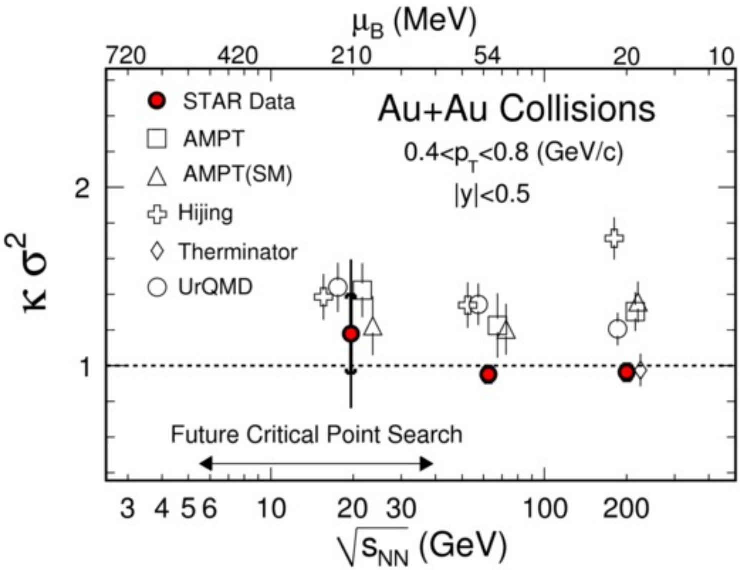
STAR, PRL 126, 092301 (2021)
STAR, PRC104, 024902 (2021)

Stat. err: $C_r \propto \dfrac{\sigma^r}{\sqrt{N}}$

- ➢ **Net-Proton:** $N_p - N_{\bar{p}}$
  (**proxy: Net-Baryon**)
- ➢ **Net-Charge:** $N_{Q^+} - N_{Q^-}$
- ➢ **Net-Kaon:** $N_{K^+} - N_{K^-}$
  (**proxy: Net-Strangeness**)

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

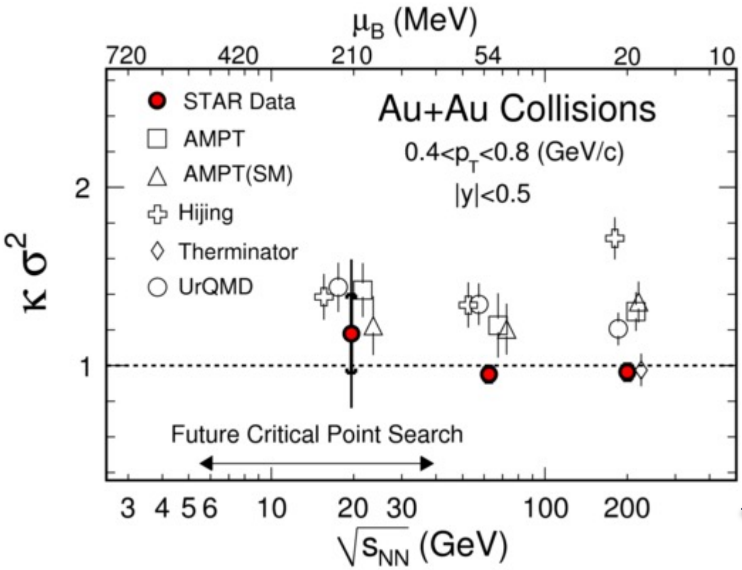
寻找QCD临界点：BES-I守恒荷分布的高阶矩测量



净质子数涨落的首次测量，
验证了该观测量的可行性

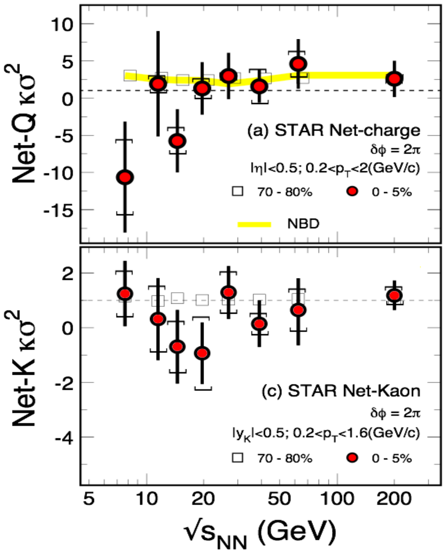
STAR, Phys. Rev. Lett. 105, 022302 (2010)

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)

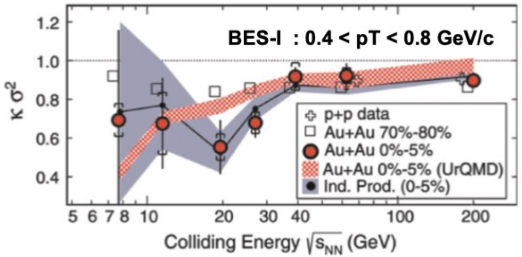


净电荷数涨落

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

净K介子数涨落

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

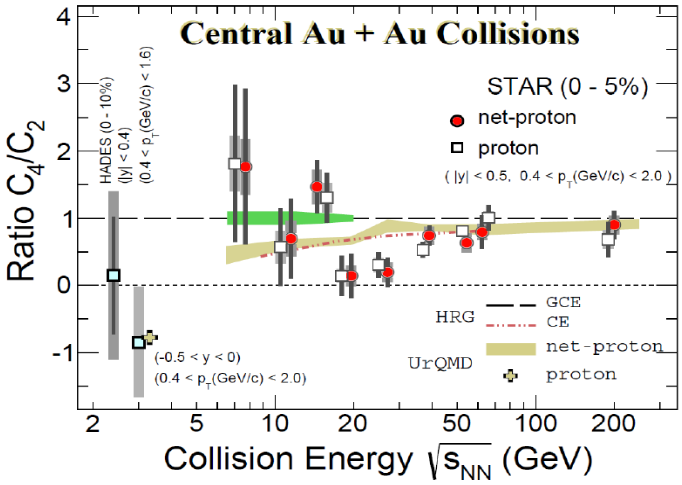


净质子数涨落

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

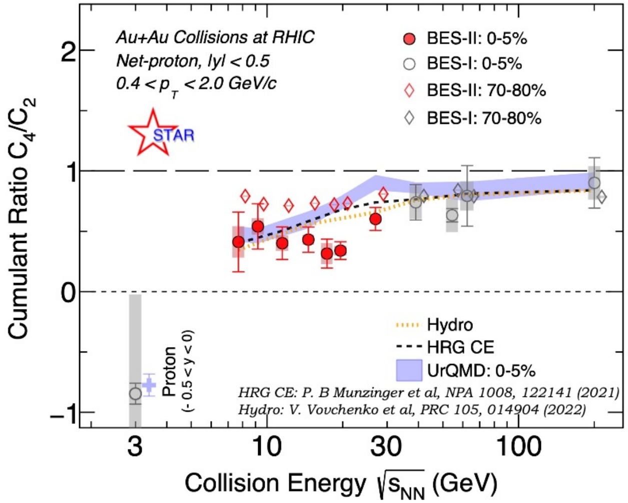
Net-Proton Fluctuations in BES-I and BES-II

BES-I (3 – 200 GeV)



$\sqrt{s_{NN}}$ (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**

BES-II (7.7 – 27 GeV)

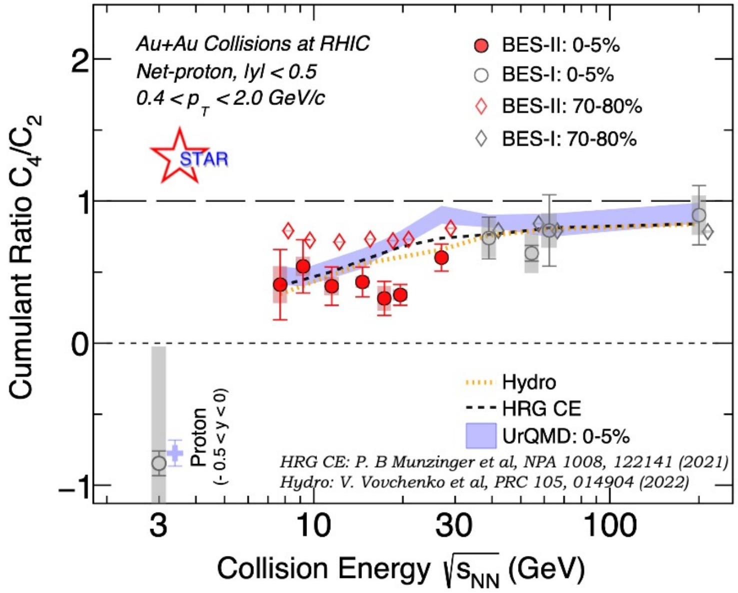


STAR: Phys. Rev. Lett. 105, 022302 (2010)
Phys. Rev. Lett. 112, 032302 (2014)
Phys. Rev. Lett. 126, 092301 (2021)
Phys. Rev. Lett. 128, 202303 (2022)
Phys. Rev. C 104, 024902 (2021)
Phys. Rev. C 107, 024908 (2023)
HADES: Phys. Rev. C 102, 024914 (2020)

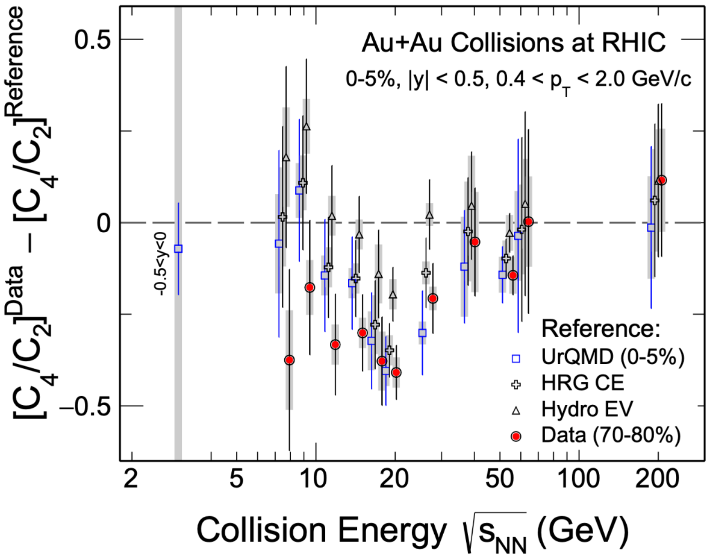
BES-II and BES-I results are consistent
BES-II : Better statistical precision
Larger Acceptance (| η |<1.6)
Better control on systematics

STAR : Phys. Rev. Lett. 135, 142301 (2025)
[Editor Suggestion, Featured in Physics]

Net-Proton Fluctuations in BES-II (7.7 – 27 GeV)



Comparing to non-CP baselines

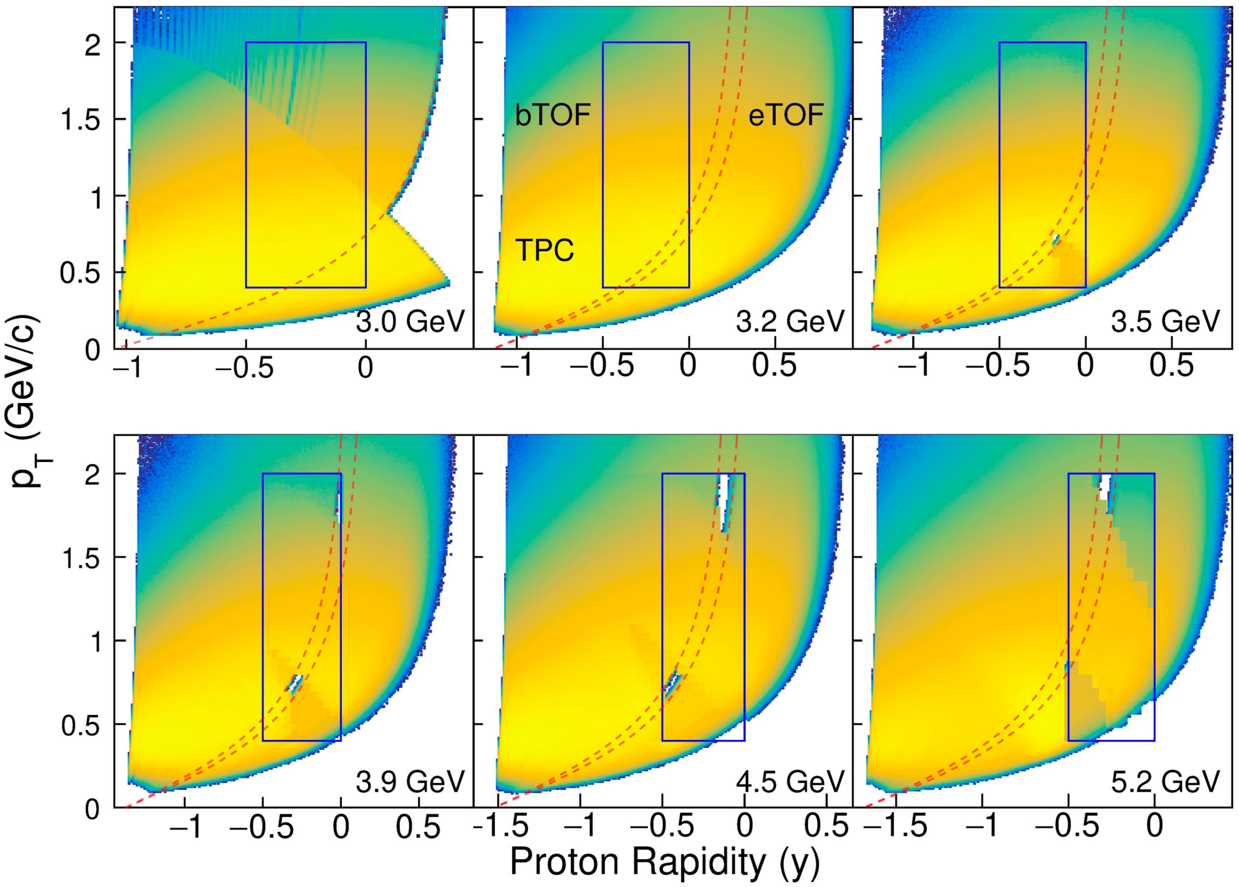


STAR : Phys. Rev. Lett. 135, 142301 (2025)
[Editor Suggestion, Featured in Physics]

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 3 – 7.7 GeV are crucial to establish the oscillation pattern of possible CP signal.

Acceptance of Protons in FXT Program



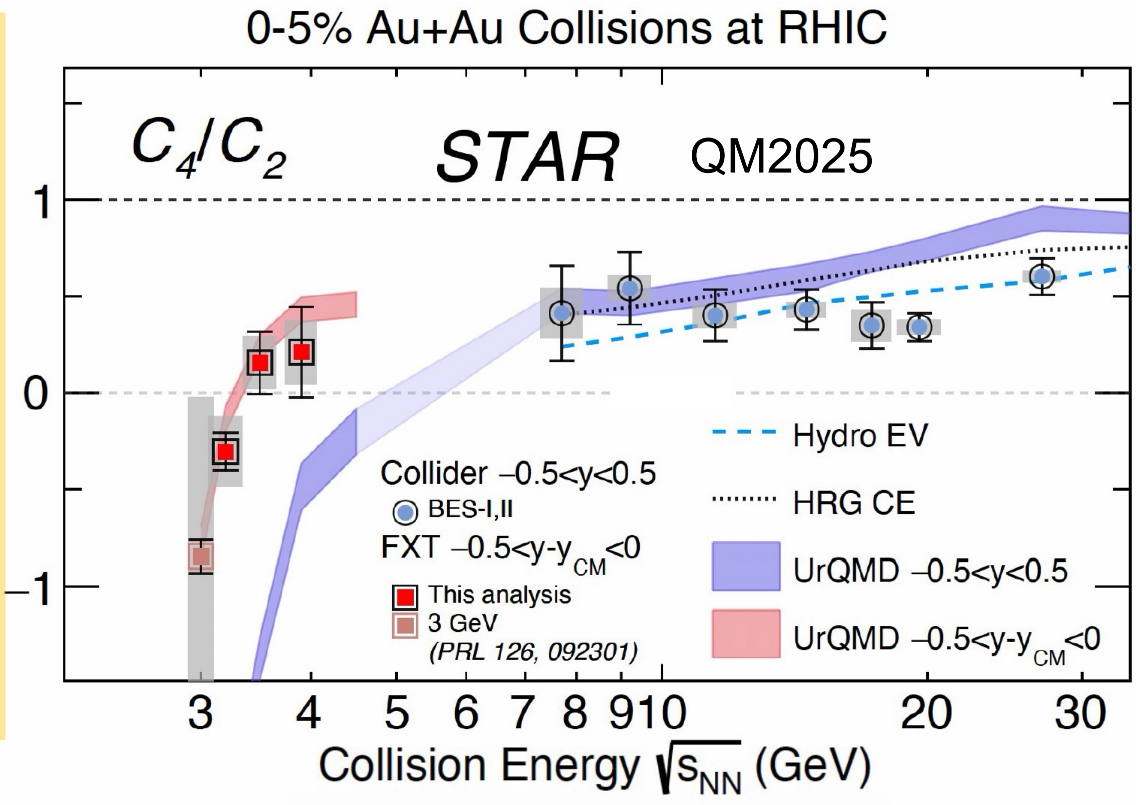
1) TPC, iTPC, bTOF, eTOF are used in the FXT program;

2) Lossing mid-y acceptance for energy higher than 4.5 GeV!

3) Analysis is focused on the mid-y region;

(Net-) Protons (C_4/C_2) from FXT Program

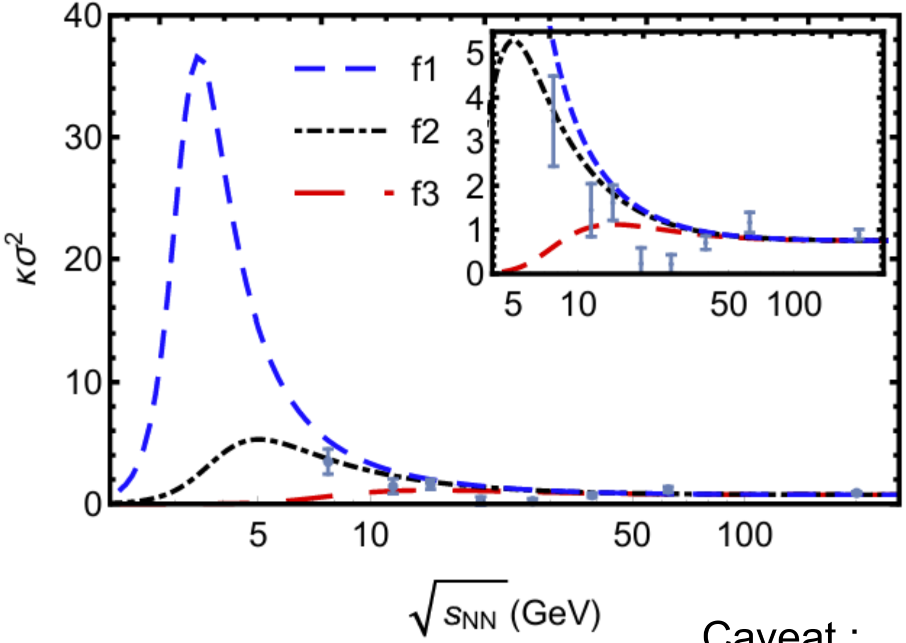
1) Collider mode: |y| <0.5
   FXT mode: -0.5 < y < 0.0
2) 3.0, 3.2, 3.5 and 3.9 GeV data were shown at QM2025
3) Data and UrQMD calculations are consistent for the FXT results. However, at the lowest energies, values of C_4/C_2 become negative: Centrality resolution issue



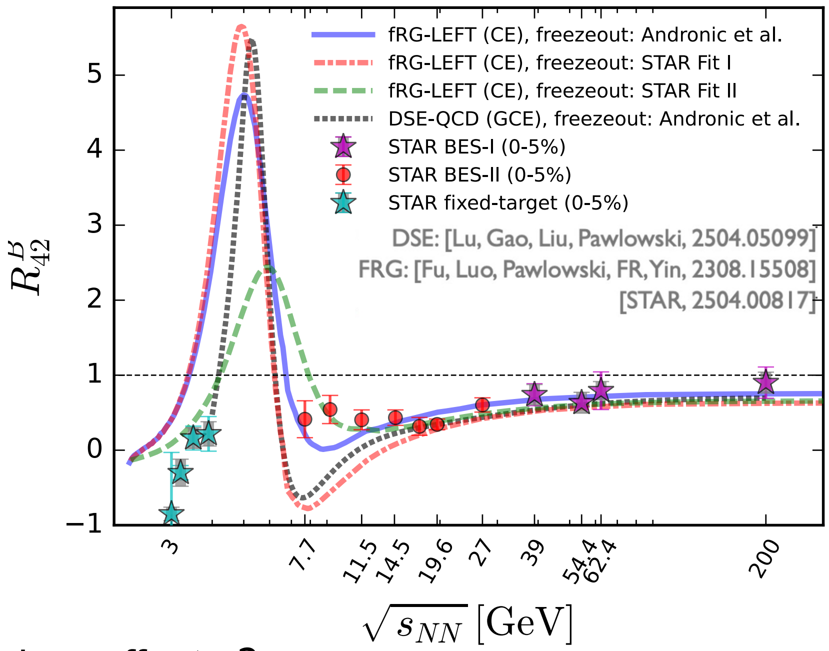
STAR 3GeV data (collected in 2018):
Phys. Rev. Lett. 128, 202303 (2022)
Phys.Rev. C107, 024908 (2023)

Baryon Number Fluctuations from Theory/Model Calculations

Mei Huang et al., Chin. Phys. C 42 (2018) 1, 013103



Fabian @ QM2025, plenary
Wei-jie Fu @ QPT2025, plenary

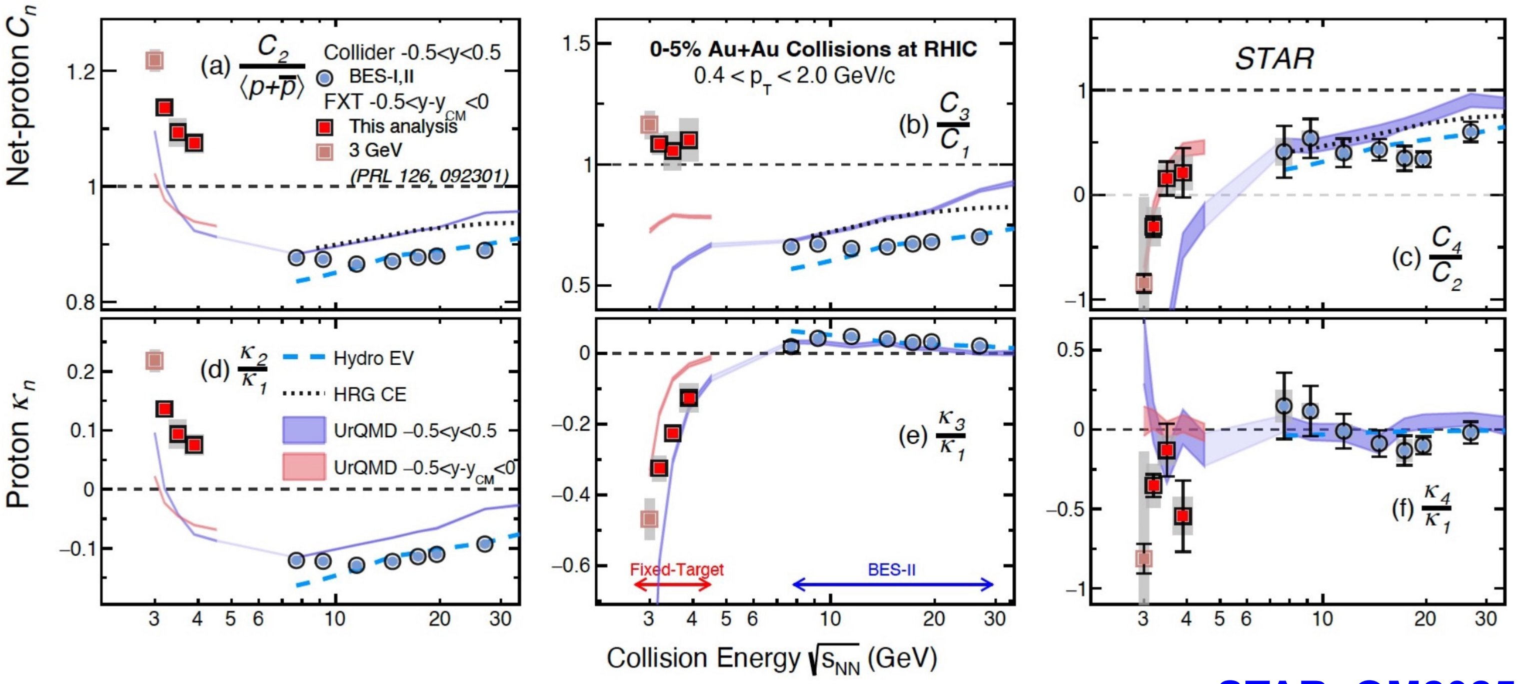


Caveat :
Non-equilibrium effects ?

See Weijie Fu's talk

- A peak structure caused by critical point around 3-5 GeV is predicted by different models
- STAR took high statistics data of 4.2, 4.5 and 5.2 GeV during Jan. 22-28, 2026.

How about Lower Order Fluctuations ?

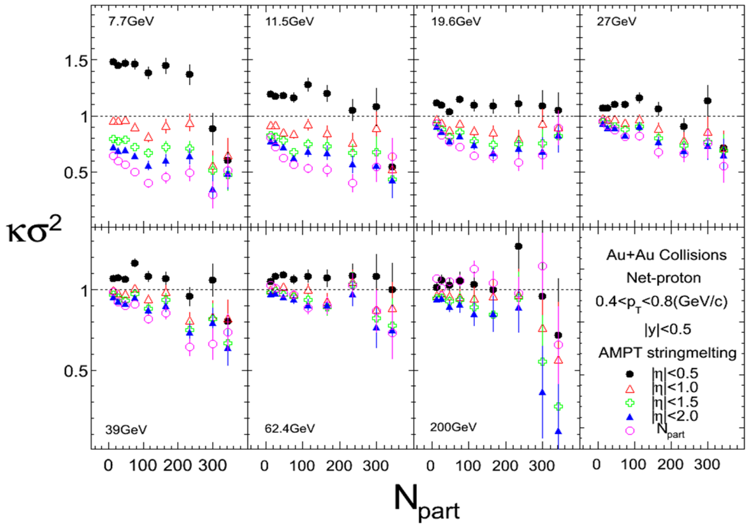


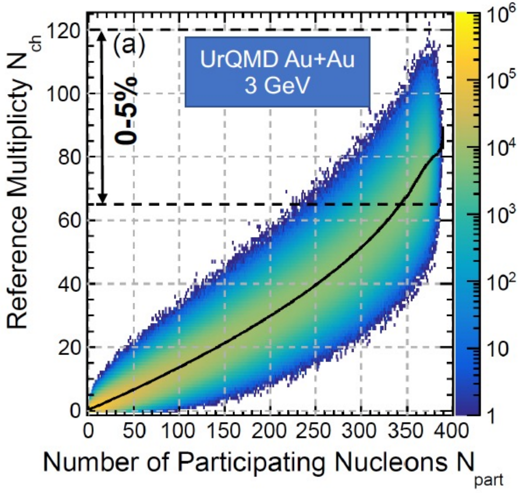
STAR, QM2025

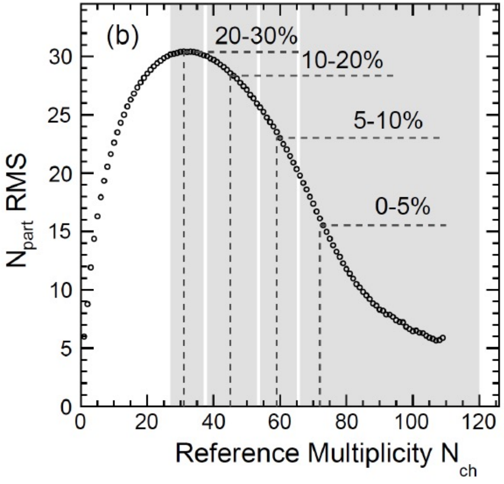
At 3.0 – 3.9 GeV central collisions (0-5%, -0.5<y<0):

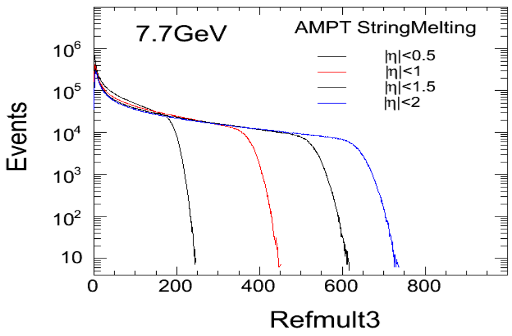
1) Change of trends and increase above unity for 2nd and 3rd order cumulants;
2) Deviations from UrQMD model calculations is seen

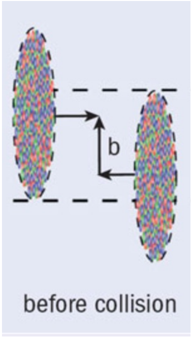
Challenges for fluctuation analysis in FXT energies：Initial Volume Fluctuations











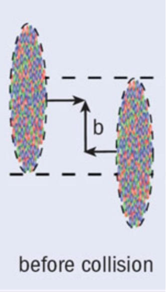
- Initial volume fluctuations are well known and largest background for cumulant analysis, especially for low energies.

STAR, Phys. Rev. C 107, 024908 (2023)
P. Braun-Munzinger , A. Rustamov, J. Stachel, Nucl. Phys. A 960,114 (2017)
Arghya Chatterjee et al., Phys. Rev. C 101, 034902 (2020)
Y. Zhang, Y. Huang, T. Nonaka, X. Luo, Nucl. Inst. Meth. A 1026(2022)166246

References

[1] Z. Pengfei, L. Lianshou
Multiplicity moments and nuclear geometry in relativistic heavy-ion collisions
Phys. Rev. D, 42 (1990), pp. 848-852
View in Scopus ↗ Google Scholar ↗

How to isolate the initial volume fluctuations from true signal ?



- Multiplicity N arise from independent Source, such as participant nucleon (Np).

$$N = \sum_{i=1}^{N_p} n_i$$

n_i is the multiplicity from i^{th} source.

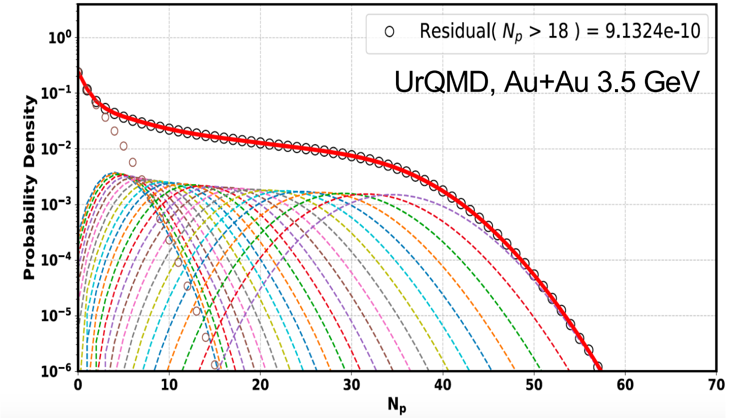
- Multiplicity Fluctuations:

$$\frac{\sigma_N^2}{M_N} = \frac{\sigma_n^2}{M_n} + <n> \frac{\sigma_{N_p}^2}{M_{N_p}}$$

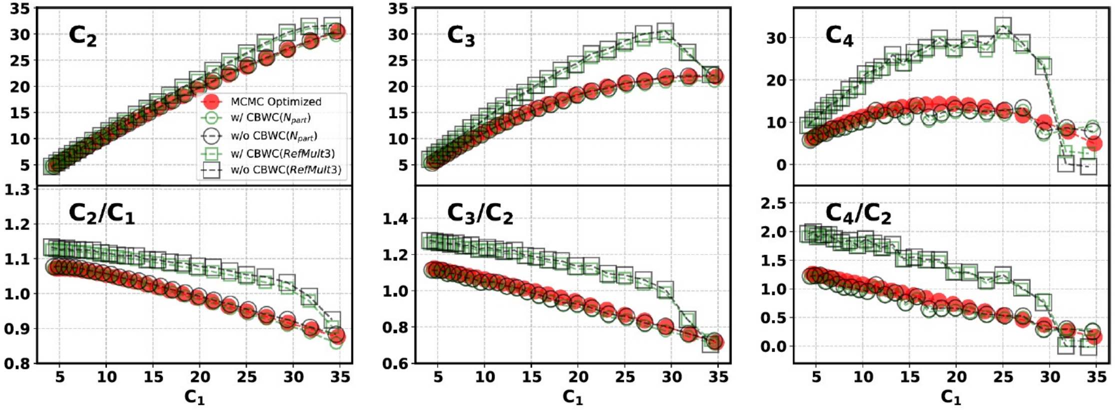
Independent Emission Source Models

V. Skokov et al, PRC 88, 034911 (2013)
P. Braun-Munzinger et al, NPA 960,114 (2017)

A New Approach to Suppress VF



UrQMD, Au+Au 3.5 GeV



Edgeworth expansion :

Centrality-Independent Genuine cumulant Analysis frRamework (CIGAR)

$$\sigma p(\sigma x) = Z(x)\left\{1 + \sum_{s=1}^{\infty}\left[\sigma^s \sum_{\{k_m\}} He_{s+2r}(x) \prod_{m=1}^{s} \frac{1}{k_m!}\left(\frac{S_m+2}{m+2}\right)^{k_m}\right]\right\}$$

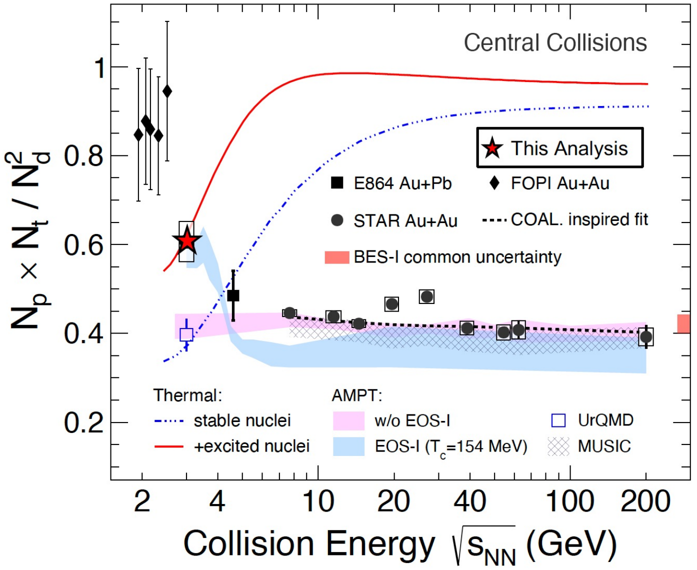
Zhaohui Wang, XFL, Phys. Lett. B 871, 139984 (2025)

where Chebyshev-Hermite polynomials H_{e_n} is defined as: $H_{e_n}(x) = (-1)^n exp(x^2/2)\frac{d^n}{dx^n}exp(-x^2/2)$

- Using Edgeworth Expansion to reconstruct the proton number distribution with cumulant as parameters
- New Method (CIGAR) has been verified to effectively suppress the volume fluctuations (VF).

其他QCD临界点观测量

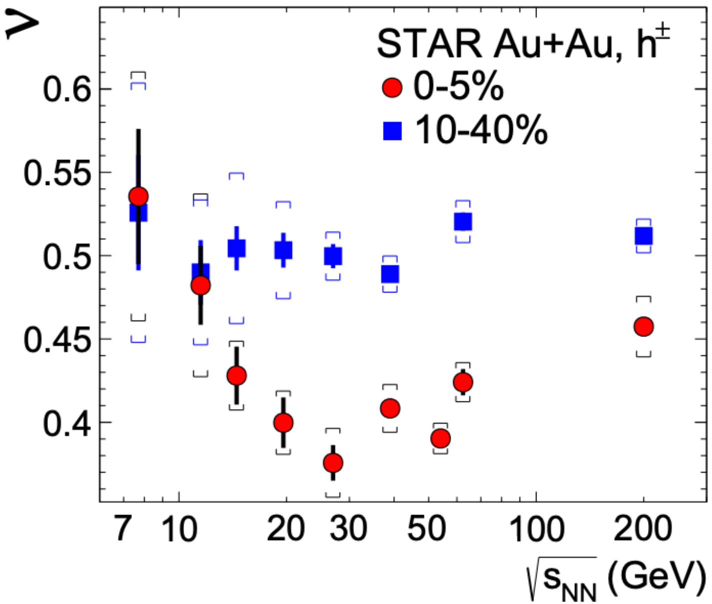
Light Nuclei Production



STAR, Phys. Rev. C 110, 054911 (2024)

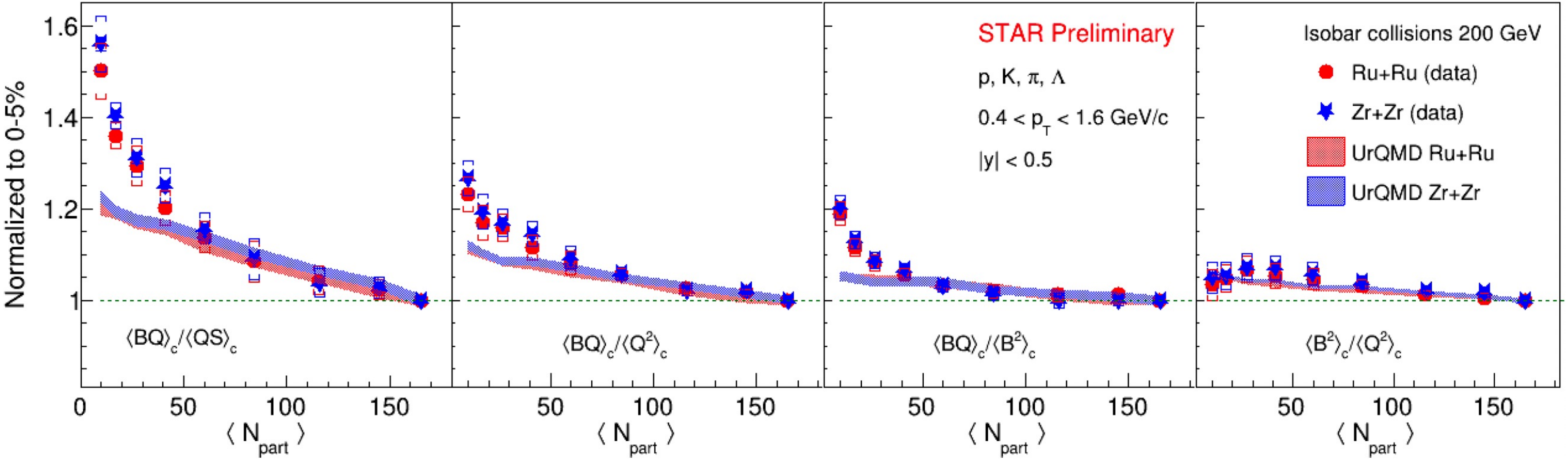
STAR: Phys. Rev. Lett 130, 202301 (2023)

Intermittency of Charged Particles



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

Cross-Correlation Between B, Q, S



Changfeng Li and Hanwen Feng, SQM 2026

- The cumulant ratios increase more rapidly than UrQMD from central to peripheral
- In peripheral collisions, the peripheral-to-central ratios follow the order

磁场效应?? H.-T. Ding et al, PRL 111, 114522 (2025)

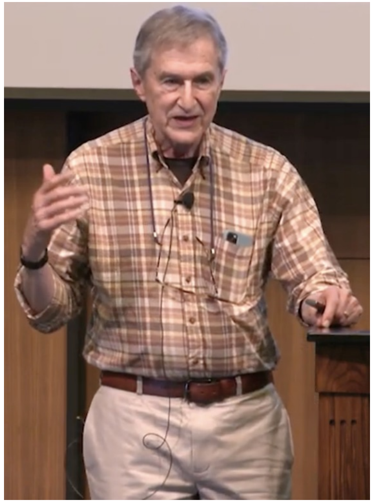
$$\frac{\langle BQ\rangle_c}{\langle QS\rangle_c} > \frac{\langle BQ\rangle_c}{\langle Q^2\rangle_c} > \frac{\langle BQ\rangle_c}{\langle B^2\rangle_c} > \frac{\langle B^2\rangle_c}{\langle Q^2\rangle_c}$$

Need more theoretical/model inputs to understand the data

Search for the Strange Dibaryon

A state with six quarks and at least one strange quark

H-Dibaryon (S = -2)



1977年，Jaffe predicted dihyperonn (H) : deeply bound ΛΛ system (uuddss), (J=0, S= -2, m~2150 MeV), 81 MeV below ΛΛ mass the. (2231)

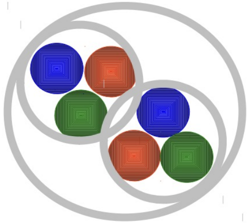
(1946-)

Perhaps a Stable Dihyperon*

R. L. Jaffe†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Department of Physics and Laboratory of Nuclear Science,‡ Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 1 November 1976)

In the quark bag model, the same gluon-exchange forces which make the proton lighter than the Δ(1236) bind six quarks to form a stable, flavor-singlet (with strangeness of −2) $J^P = 0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H^*) with $J^P = 1^+$ at 2335 MeV should appear as a bump in ΛΛ invariant-mass plots. Production and decay systematics of the H are discussed.

R. L. Jaffe, Phys. Rev. Lett. 38, 617 (1977)

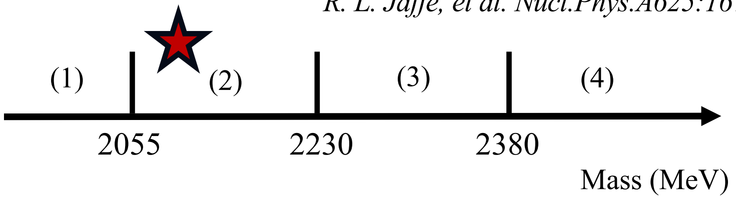


Over the more than 40 years that followed. multiple experimental groups have attempted to find it, such as the J-PARC E42 experiment in Japan, the RHIC-STAR/AGS experiments in the United States, and the LHC-ALICE/SPS experiments in Europe, etc, still elusive.

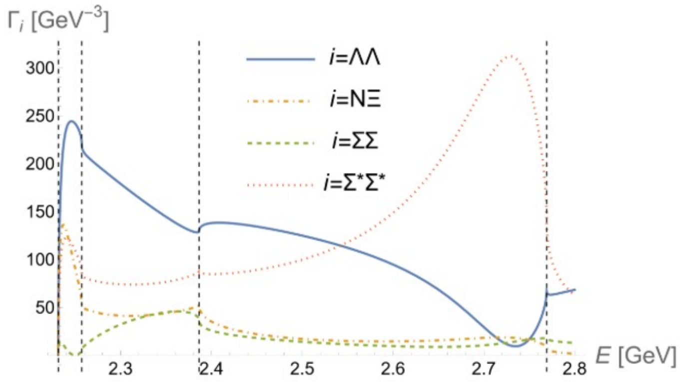
Review： H. Clement, Progress in Particle and Nuclear Physics 93, 195 (2017)

To bracket the possibilities we consider four possible mass ranges for the H: (1) $M(H)<2055$ MeV; (2) $2055<M(H)<2230$; (3) $2230<M(H)<2380$; and (4) $M(H)>2380$ MeV. In case (4), the H is above all two-baryon thresholds to which it couples strongly. It represents, therefore, a repulsive interaction in all two-baryon channels to which it couples. It is improbable that the bag-mass calculation is so much in error that case (4) applies. In case (3), the H is a $\Sigma\Sigma$ bound state [or if $M(H)<2260$ MeV, also an $N\Xi$ bound state] decaying strongly into $\Lambda\Lambda$. It would appear as a bump in $\Lambda\Lambda$ invariant-mass plots (e.g., in $\Xi p\to\Lambda\Lambda$). Were the H very light [case (1)], it would be stable except against double weak decay ($H\to nn$). Cases (1) and (3) are not favored by the bag-mass estimates but must be retained as possibilities in light of the crude nature of the model.

R. L. Jaffe, Phys. Rev. Lett. 38, 617 (1977)
R. L. Jaffe, et al. Nucl.Phys.A625:167-191 (1997)



The $\Lambda\Lambda$, $N\Xi$, $\Sigma\Sigma$, and $\Sigma^*\Sigma^*$systems are coupled, and their interplay governs the structure of possible dibaryon states and near-threshold phenomena.



T. R. Hu and F. K. Guo, arXiv:2601.14922

Strangeness -3 NΩ and Strangeness -6 ΩΩ Dibaryons

NΩ

MIT bag model: in 1987 MIT bag model predicted NΩ dibaryon which is stable with respect to strong decay

VOLUME 59, NUMBER 6 PHYSICAL REVIEW LETTERS 10 AUGUST 1987

Strangeness −3 Dibaryons

T. Goldman, K. Maltman,[a] and G. J. Stephenson, Jr.
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

K. E. Schmidt
Chemistry Department and Courant Institute of Mathematical Sciences, New York University, New York, New York 10012

and

Fan Wang[b]
University of California at Los Angeles, Los Angeles, California 90024
(Received 12 May 1987)

We demonstrate, using two different quark models of hadrons, that there should be isodoublets of dibaryons with strangeness −3 and $J = 1,2$, which are stable with respect to strong decay.

PACS numbers: 14.20.Pt, 12.40.Aa

Quark-Delocalization color-screeing model (QDCSM) and chiral quark model (ChQM)

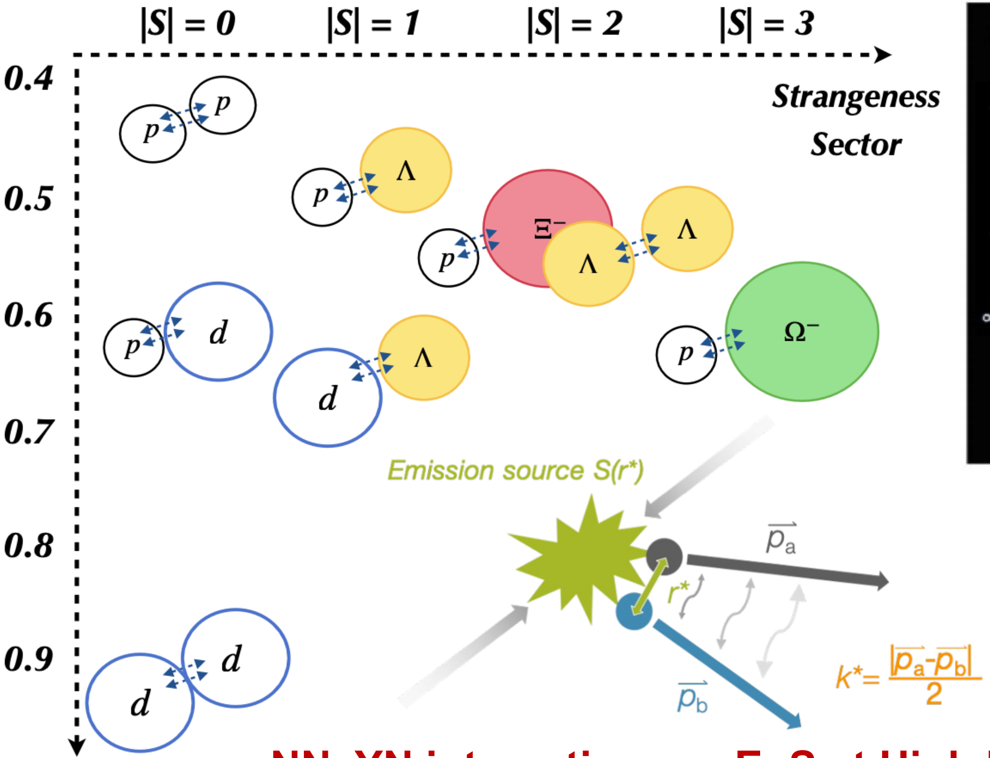
H. Pang, J. Ping, F. Wang, T. Goldman, E. Zhao, PRC-69-065207 (2004);
H. Pang, J. Ping, L. Chen, F. Wang, T. Goldman, PRC-70-035201 (2004);
M. Chen, H. Huang, J. Ping, F. Wang, PRC-83-015202 (2011);
H. Huang, J. Ping, F. Wang, PRC-92-065202 (2015)

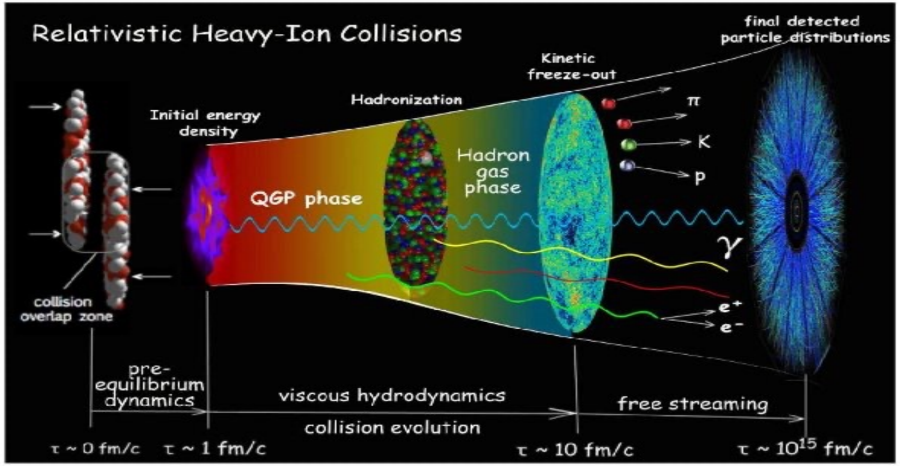
ΩΩ

Binding energy 100 MeV, lifetime 2 times of free Omega's
More likely a six-quark particle with large binding energy and short relative distance (RMS=0.84 fm) between two Omegas

Z. Y. Zhang et al., NPA625, 59 (1997); PRC61, 065204 (2000)

Femtoscopy correlations： NN and YN Interactions



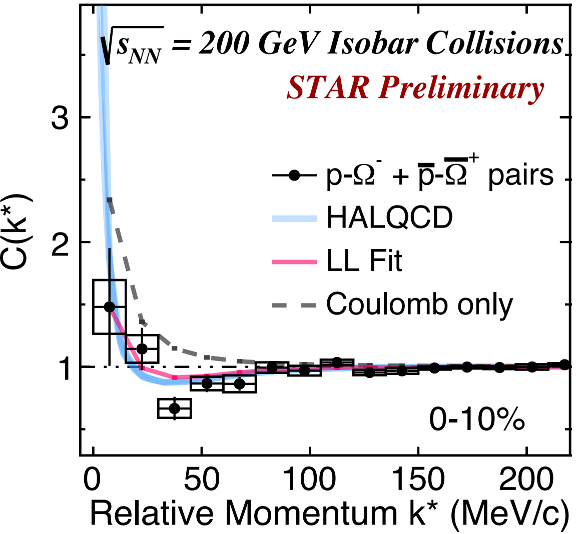


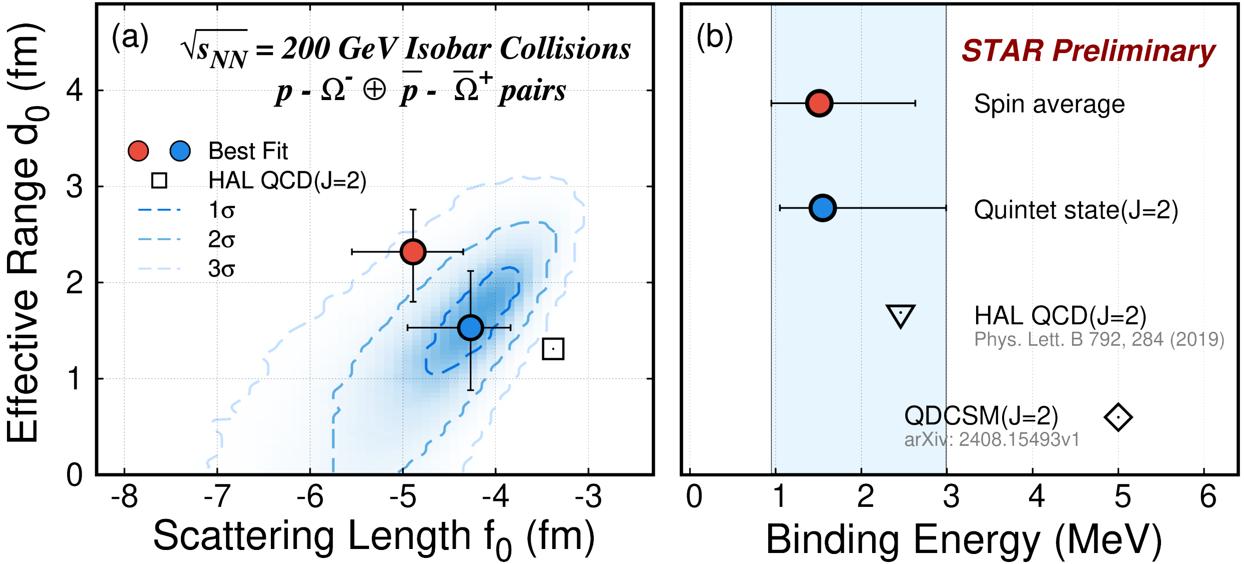
Heavy-ion collisions produce a large number of nucleons and hyperons, making it an ideal setting for studying the properties of strong interactions.

NN, YN interactions： EoS at High Baryon Density

1) Light Nuclei (A<=3) – Lambda at Au+Au 3 GeV
2) Search for strange Di-baryon in isobar collisions 200 GeV

p-Ω^- Correlation Function (S = -3)





Kehao Zhang (STAR), QM2025

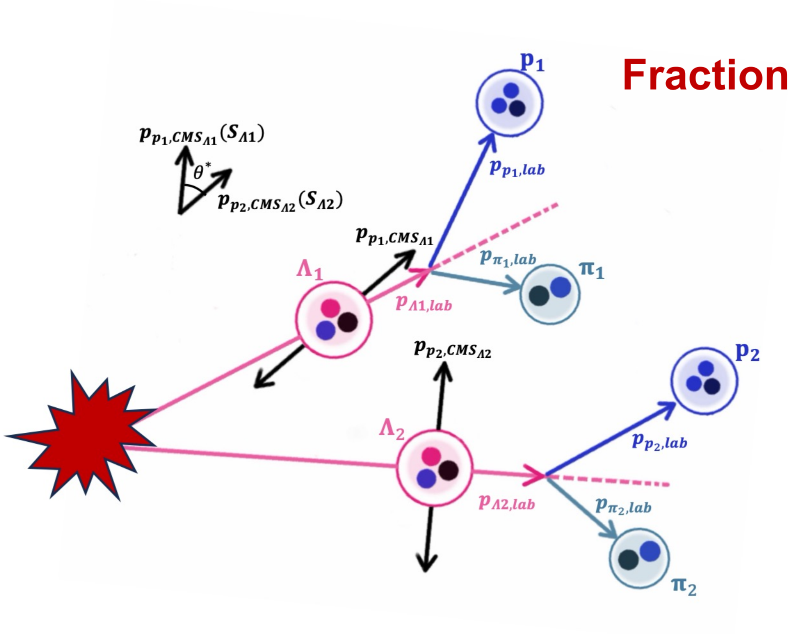
	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.89^{+0.54}_{-0.66}$	$-4.27^{+0.43}_{-0.68}$	-3.38
d_0 (fm)	$2.32^{+0.44}_{-0.52}$	$1.53^{+0.54}_{-0.66}$	1.31
BE (MeV)	$1.51^{+1.12}_{-0.56}$	$1.55^{+1.44}_{-0.50}$	2.27

I. First experimental constraints in heavy-ion collisions of strong interaction parameters in p-Ω^- pair

II. Extracted negative f_0 ($|f_0| > 2d_0$) by Spin average method and Quintet method

- **First experimental evidence of Strange Dibaryon**

H-Dibaryon Searches : Spin Selection Method

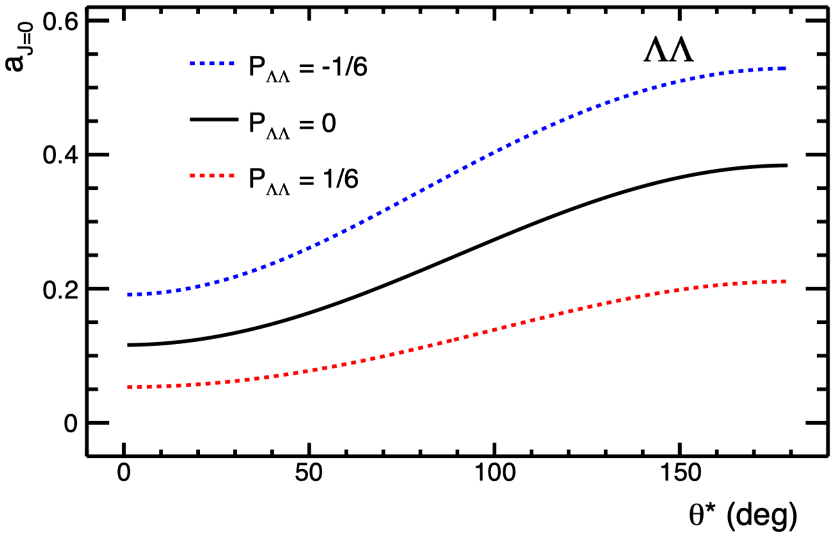


Λ rest frame

Self-analyze of Λ weak decay

Fraction of J=0 ΛΛ state :

$$a_{J=0}(\theta^*, P_{\Lambda\Lambda}) = \frac{1}{1+\frac{(1+P_{\Lambda\Lambda})(3+\alpha_\Lambda^2\cos\theta^*)}{(1-3P_{\Lambda\Lambda})(1-\alpha_\Lambda^2\cos\theta^*)}}$$



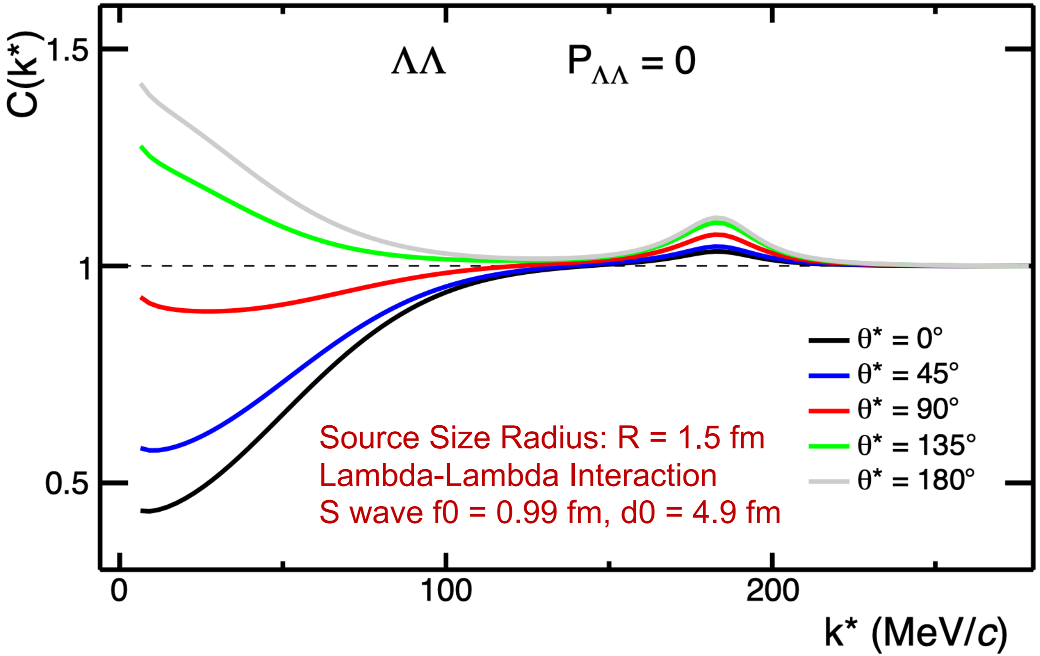
K. Zhang, X. Wang, XFL, arXiv: 2607.00413

H -> Λ+Λ (J=0)

One can enrich the fraction of total spin with J = 0 ΛΛ states by selecting the opening angle between two protons decayed from Λ.

Simulation with Lednicky–Lyuboshits (LL) model

$$C(k^*, \theta^*, P_{\Lambda\Lambda}) = a_{J=0}(\theta^*, P_{\Lambda\Lambda}) C_{J=0}(k^*) + (1 - a_{J=0}(\theta^*, P_{\Lambda\Lambda}))\, C_{J=1}(k^*)$$



1. **Gaussion Emission Source**
2. **Input H-dibaryon signal**

Breit–Wigner function

Mass: 30 MeV above **ΛΛ** Threshold,

Width: 15 MeV

The H-dibaryon signal is expected to be more pronounced at large θ^* range.

Data analysis ongoing, stay tune….

K. Zhang, X. Wang, XFL, arXiv: 2607.00413

Summary and Outlook

- Critical Point : STAR reported precision measurement of (net-)proton fluctuations in Au+Au collisions from BES-II:

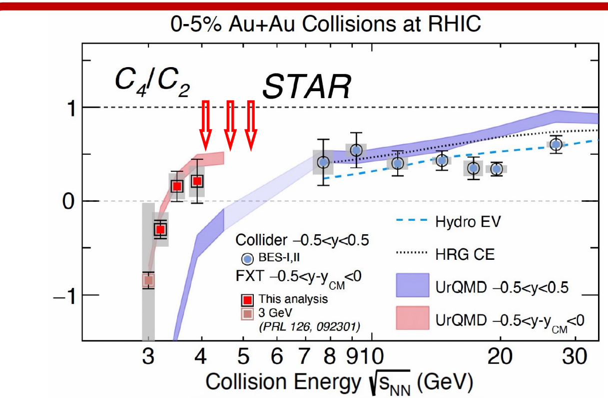
  Collider energies: for net-proton C_4/C_2 in central collisions, deviations of $2\text{-}5\sigma$ are observed w.r.t non-CP reference at 19.6 GeV

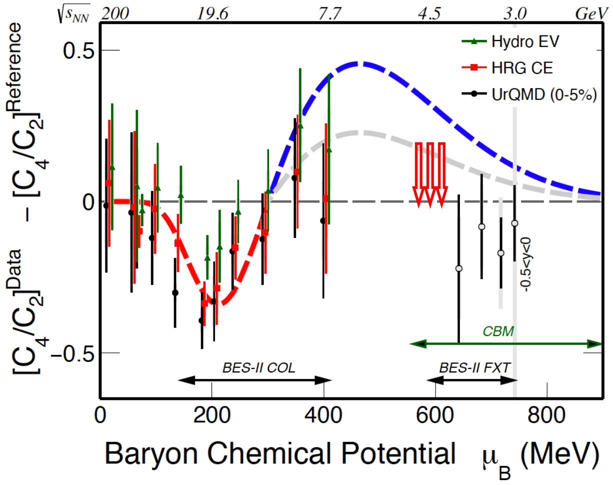
  FXT energies: proton C_4/C_2 in central collisions are consistent with UrQMD calculations at 3.0 – 3.9 GeV while low orders changing trends and deviate from the transport model calculations

- STAR is working on a new analysis framework to suppress the initial volume fluctuation. Reanalyzing all data sets including 4.2, 4.5 and 5.2 GeV Au+Au collisions is under way;

- Modeling with dynamical effects including critical fluctuations and non-equilibrium effects are crucial to understand the experimental data

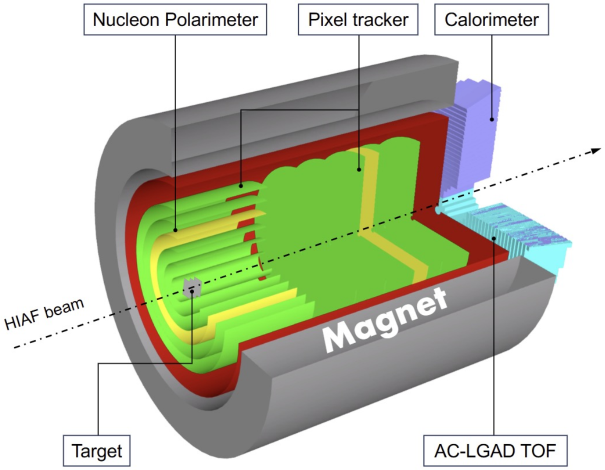
- Search for Strange Dibaryon with Baryon Correlations





Summary and Outlook

Hyperon-Nucleon Spectrometer (H-NS)



H-NS White Paper： 2606.06553 (2030-)

Future Low Energy Heavy-ion Experiments :

- FAIR-CBM (2.4 - 4.9 GeV, 2029 -)
- CSR-CEE (2.1 GeV, 2026-)
- HIAF-U/H-NS (2.1- 4.5 GeV, 2030 -)
- NICA-MPD (4 - 11 GeV, 2027 -)

Key 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.
- Spin dependent hadronic physics

International Conference on Nucleus-Nucleus Collisions (NN2027)

Joint hosted by
Central China Normal University
China Institute of Atomic Energy

Wuhan, China
Oct. 10 - 15, 2027

Many Thanks to:

Members of STAR Collaboration and Theory Colleagues

Thank you for your attention !