QCD相变临界点及奇异双重子态的实验寻找

“重子数涨落与重子-重子相互作用：一场重子的狂欢盛宴”

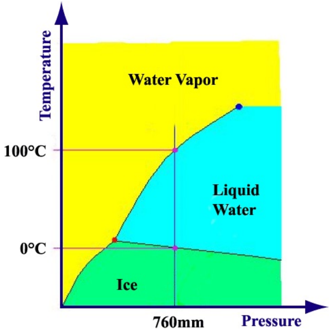
罗晓峰

华中师范大学

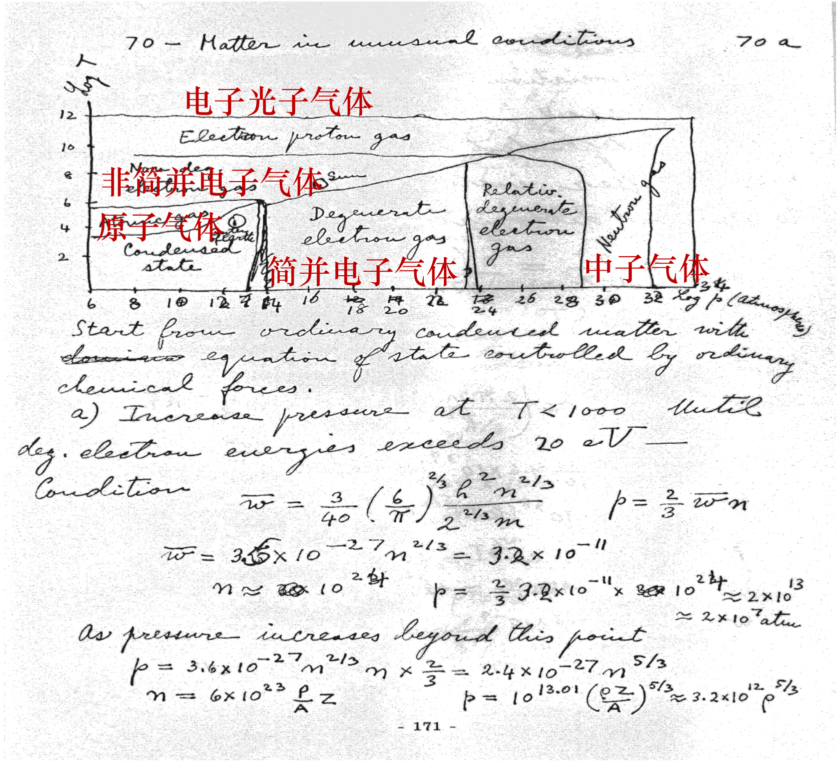
2026年4月25日

极端条件下的物质形态

E. Fermi



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



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

$\overline{w} = 3.6 \times 10^{-27} n^{2/3} = 3.2 \times 10^{-11}$

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

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

As pressure increases beyond this point

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

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

- 171 -

水

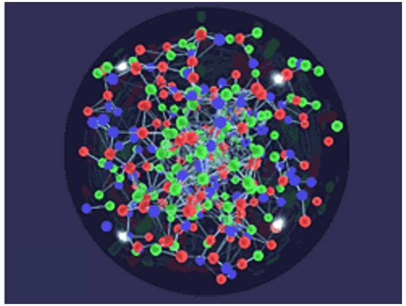
~ 10^2 °C

太阳

~ 10^7 °C

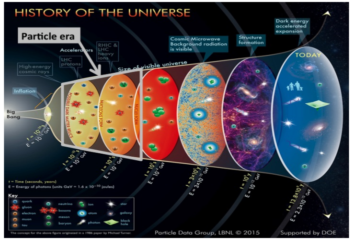
QGP

~ 10^{12} °C
(Early Universe)

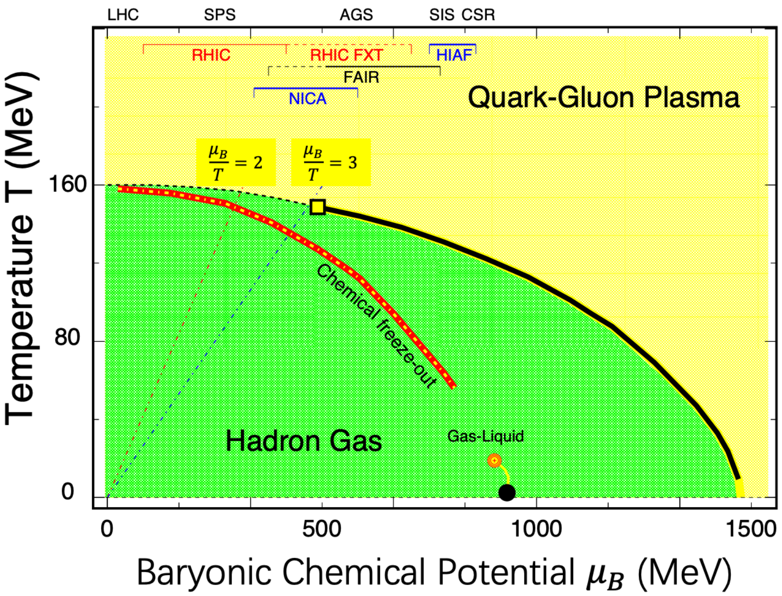


极端高温高密环境中的物质形态及相结构是什么？

QCD Phase Diagram



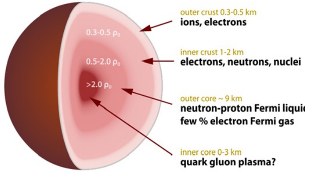
宇宙演化

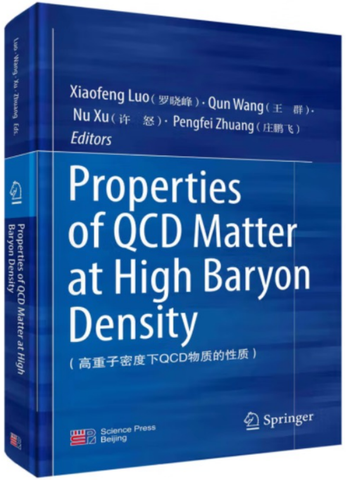


Lattice QCD : at $\mu_B = 0$, smooth crossover. T_c ~ 156 MeV
Large μ_B : 1^{st} order phase transition and QCD critical point ?

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




Xiaofeng Luo（罗晓峰）· Qun Wang（王　群）· Nu Xu（许　怒）· Pengfei Zhuang（庄鹏飞）
Editors
Properties of QCD Matter at High Baryon Density
（高重子密度下QCD物质的性质）
Science Press Beijing
Springer
Luo · Wang · Xu · Zhuang Eds.
Properties of QCD Matter at High Baryon Density

关键科学问题：高重子密度区是否存在QCD临界点?

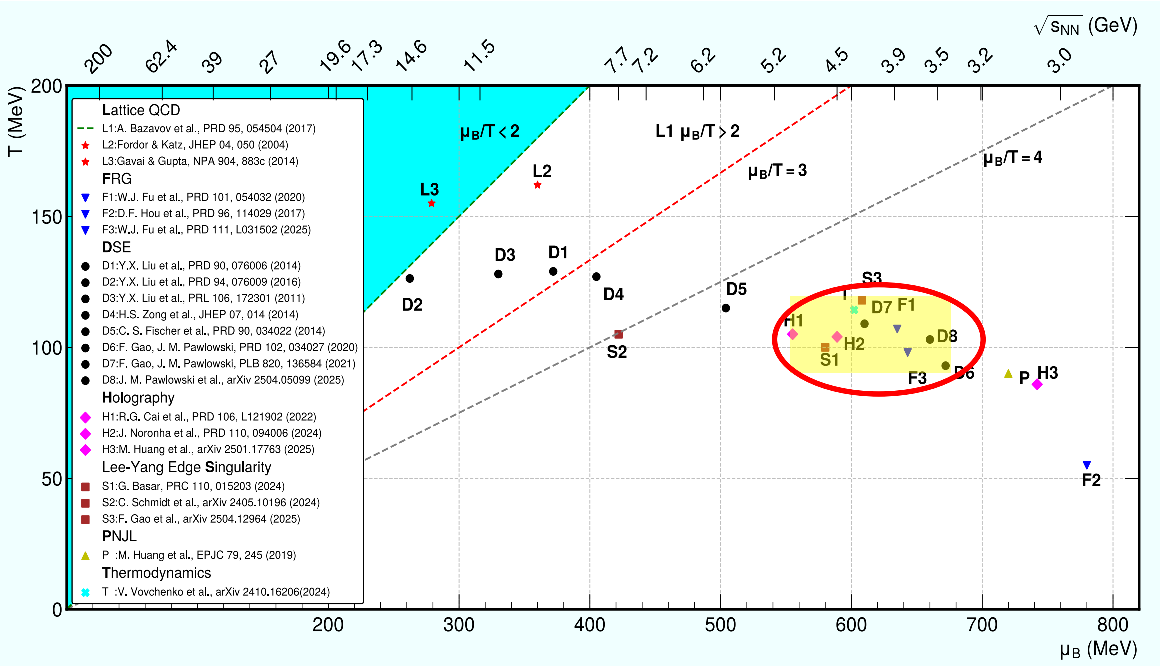
它是国际核物理领域待解决的关键科学问题之一，也是我国大科学装置强流离子加速器(HIAF)的一个主要物理目标(2025年在广东惠州建成)。

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

Theoretical Estimations (2004-2025)



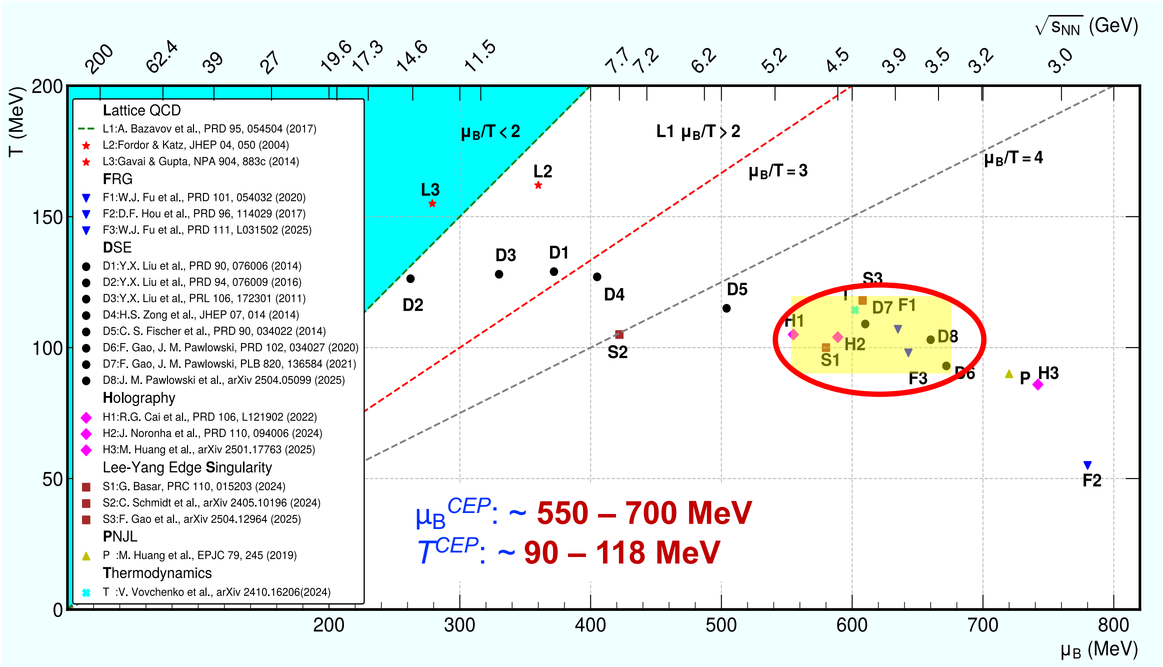
“Converge region”： μ_B^{CEP}: ~ **550 – 700 MeV**
T^{CEP}: ~ **90 – 118 MeV**

FRG : Wei-jie Fu, J. M. Pawlowski, and F. Rennecke, Phys. Rev. D 101, 054032 (2020) [441 citations]
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) [179 citations]
Yi Lu, Fei Gao, Yu-Xin Liu, Jan M. Pawlowski, Phys. Rev. D 113, 054019(2026)

See Wei-jie Fu’s talk

Theoretical Estimations (2004-2025)



μ_B^{CEP}: ~ **550 – 700 MeV**

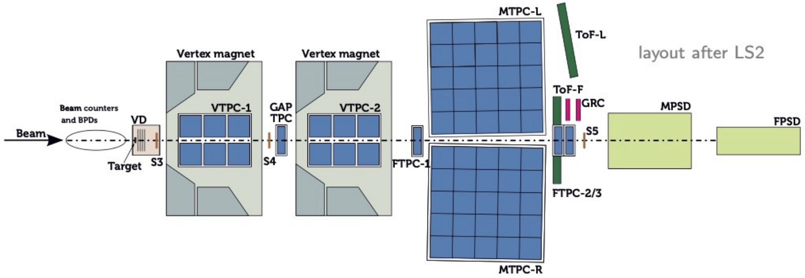
T^{CEP}: ~ **90 – 118 MeV**

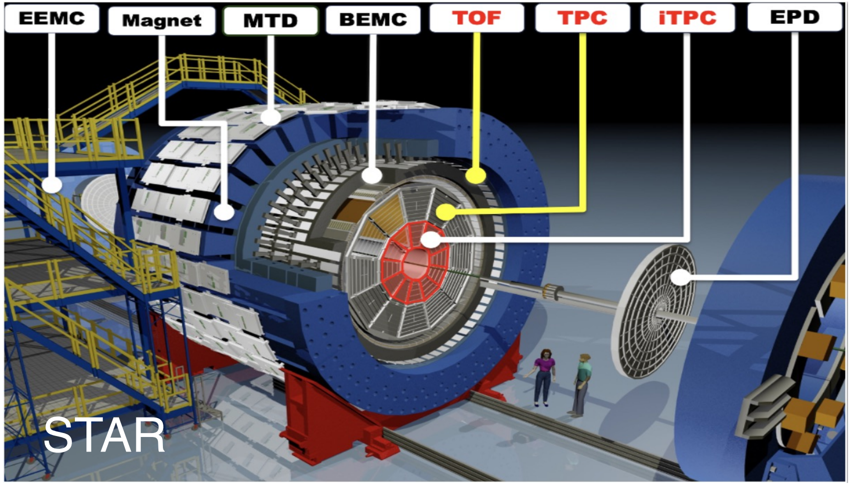
"…experimental measurements are essential to determine whether a QCD critical point exists." *2023 US Long Range Plan for Nuclear Science*

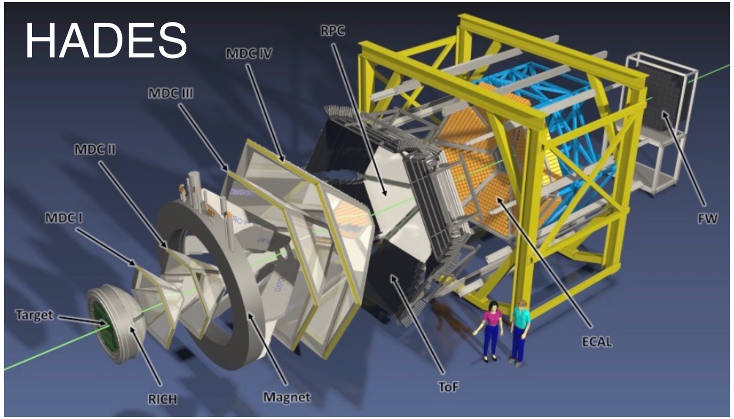
Y. Zhang, Z. Wang, X. Luo, N. Xu, arXiv : 2602.08356
Christian S. Fischer, Jan M. Pawlowski, arXiv : 2603.11135

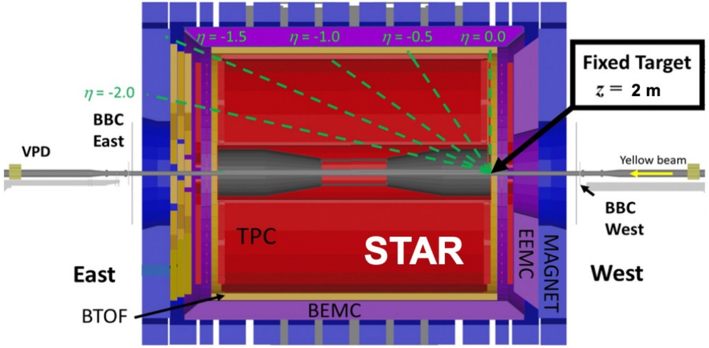
Search for QCD Critical Point in Heavy-ion Collisions Experiments

NA61/SHINE

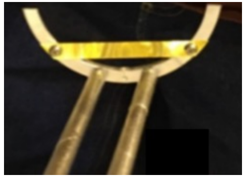








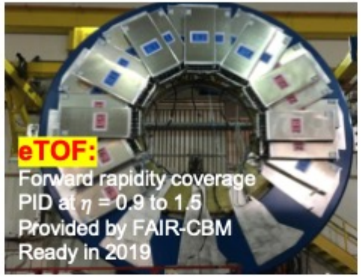
fixed target at STAR



RHIC Beam Energy Scan Program (2010 – 2026)

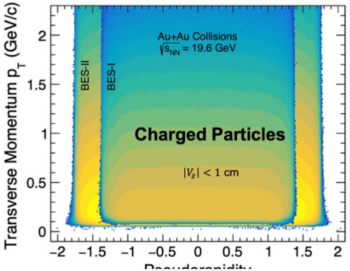
Detector Upgrades BES-II

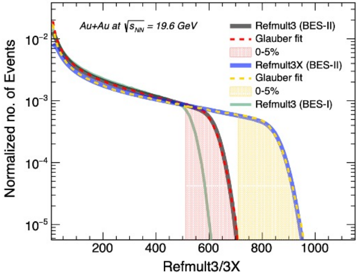
iTPC:
Improves dE/dx
Extends η coverage from 1.0 to 1.5
Lowers pT cut-in from 125 to 60 MeV/c
Ready in 2019

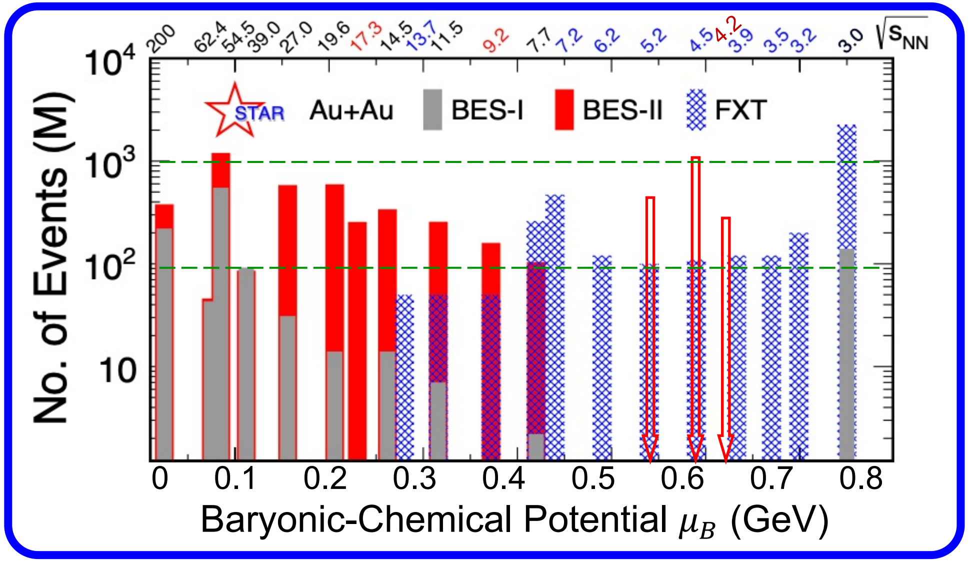


eTOF:
Forward rapidity coverage
PID at η = 0.9 to 1.5
Provided by FAIR-CBM
Ready in 2019

EPD:
Improves trigger
Better centrality & event plane measurements
Ready in 2018
Full EPD has been installed







(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 < μ_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

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

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: $C_{1,2,\ldots}$
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, $\langle \boldsymbol{\delta N} \rangle = \mathbf{N} - \langle \boldsymbol{N} \rangle$

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

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

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

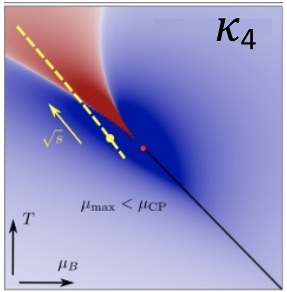
kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 = C_4 / C_2^2$

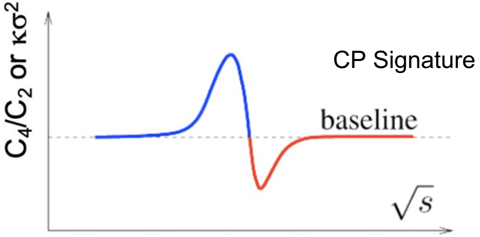
Moments, cumulants and susceptibilities:

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



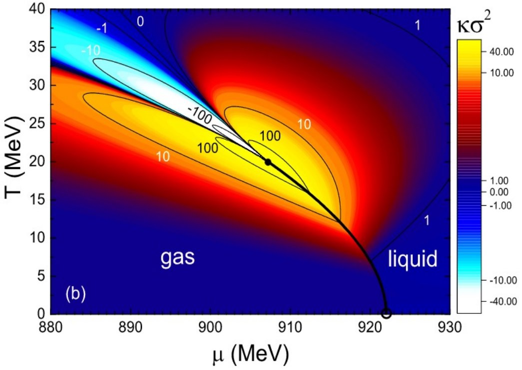


M. A. Stephanov, PRL 102 (2009) 032301

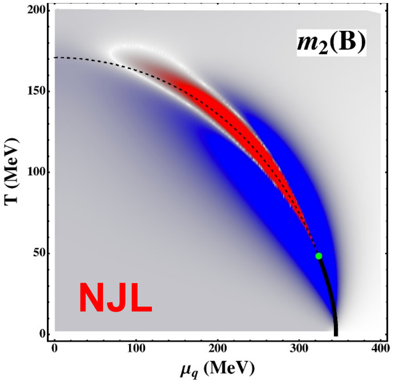
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009); 107, 052301 (2011). M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009). Cheng et al, PRD (2009) 074505. F. Karsch and K. Redlich , PLB 695, 136 (2011). B. Friman et al., EPJC 71 (2011) 1694. S. Gupta, et al., Science, 332, 1525(2012).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

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

van der Waals (VDW)



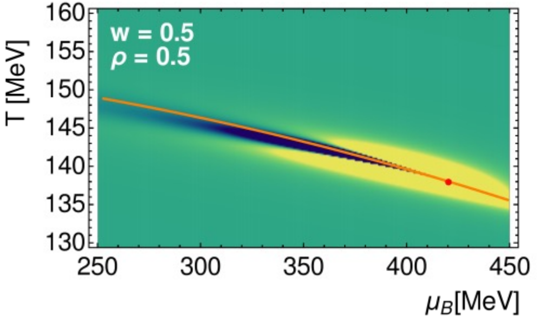
Vovchenko et al., PRC92, 054901 (2015)



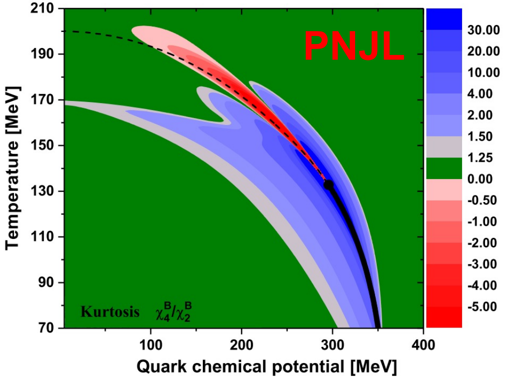
邓建等, PRD93, 034037 (2016)

3D Ising Mapping

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



Symmetry and Universality

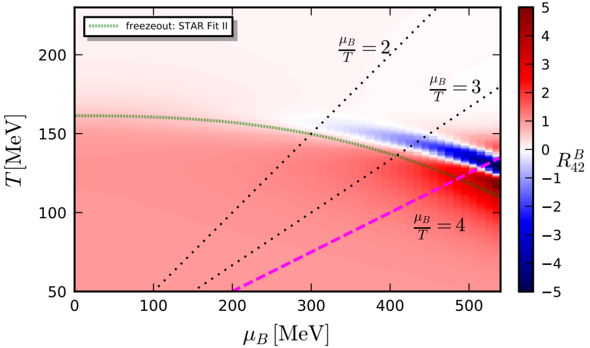


邵国运等, EPJC 78, 138 (2018)

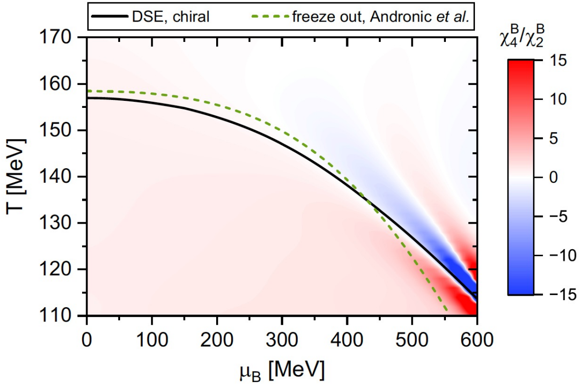
李志宾、许坤、王昕扬、黄梅, EPJC 79, 245 (2019).

FRG

付伟杰等 PRD 104 (2021) 9, 094047



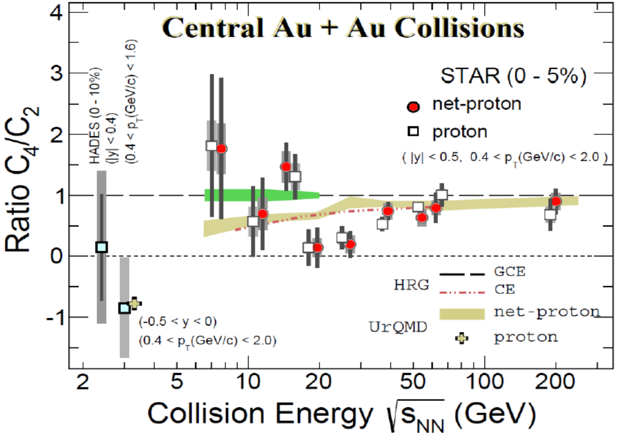
DSE



陆易、高飞、刘玉鑫等, PRD 113 (2026) , 054019

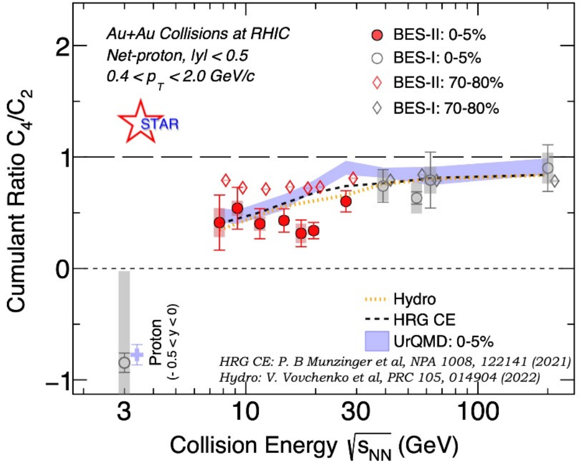
Net-Proton Fluctuations in BES-I and BES-II

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)

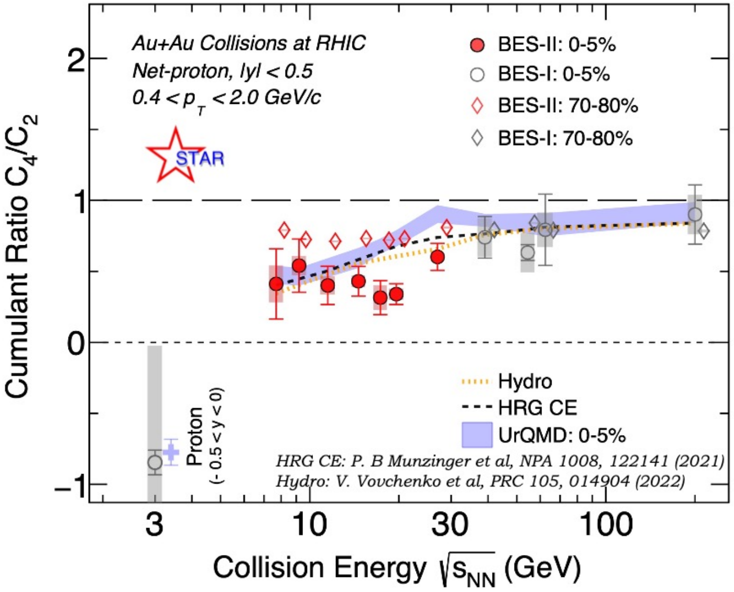


STAR: Phys. Rev. Lett. 128, 202303 (2022)
Phys. Rev. Lett. 126, 092301 (2021)
Phys. Rev. C 104, 024902 (2021)
Phys. Rev. C 107, 024908 (2023)
HADES: Phys. Rev. C 102, 024914 (2020)

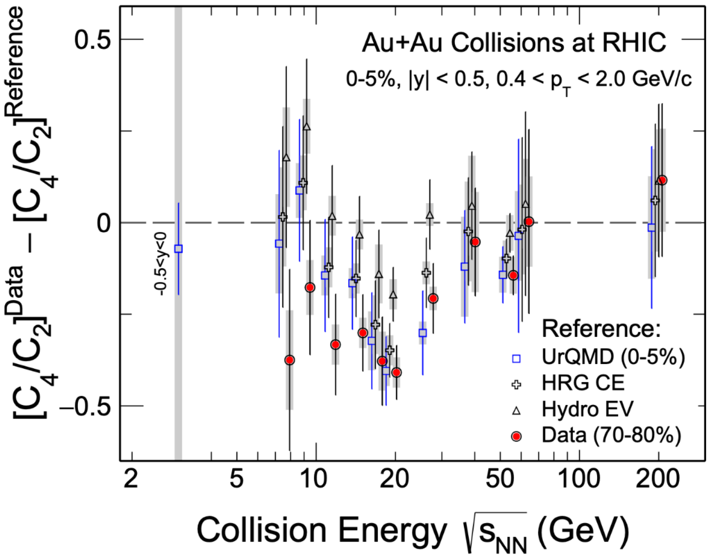
BES-II and BES-I results are consistent
BES-II : Better statistical precision
Larger Acceptance (| η |<1.6)
Better control on systematics

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]

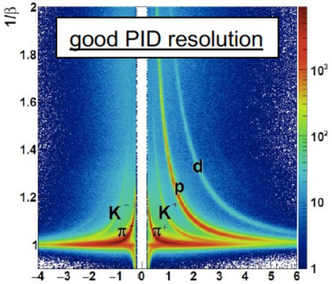
STAR: PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

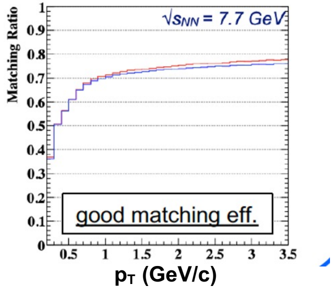
- 2-5σ deviations to non-CP baselines at 19.6 GeV
- Data from 3 – 7.7 GeV are crucial to establish the oscillation pattern of possible CP signal.

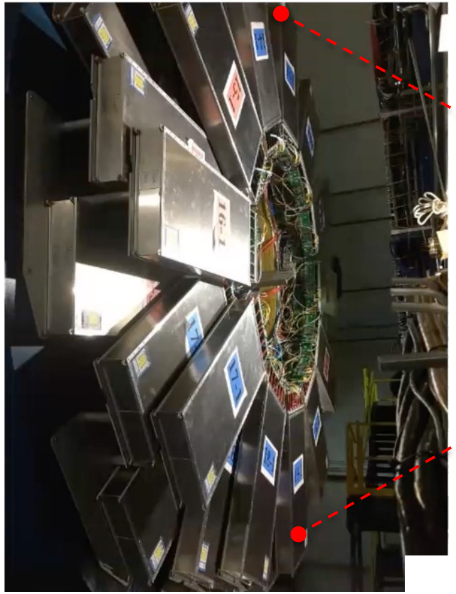
STAR Fixed-Target Setup

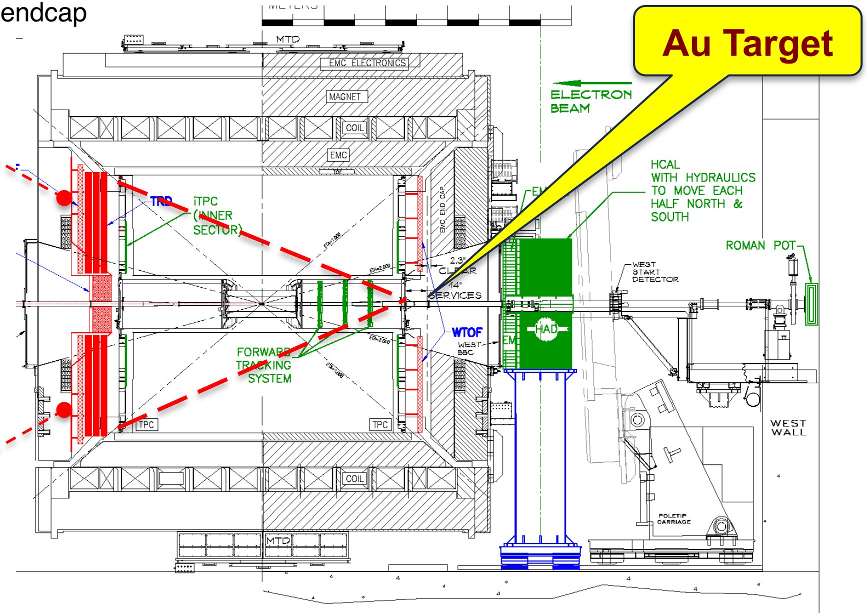
eTOF (2019+)

10% of the CBM TOF modules installed at STAR endcap





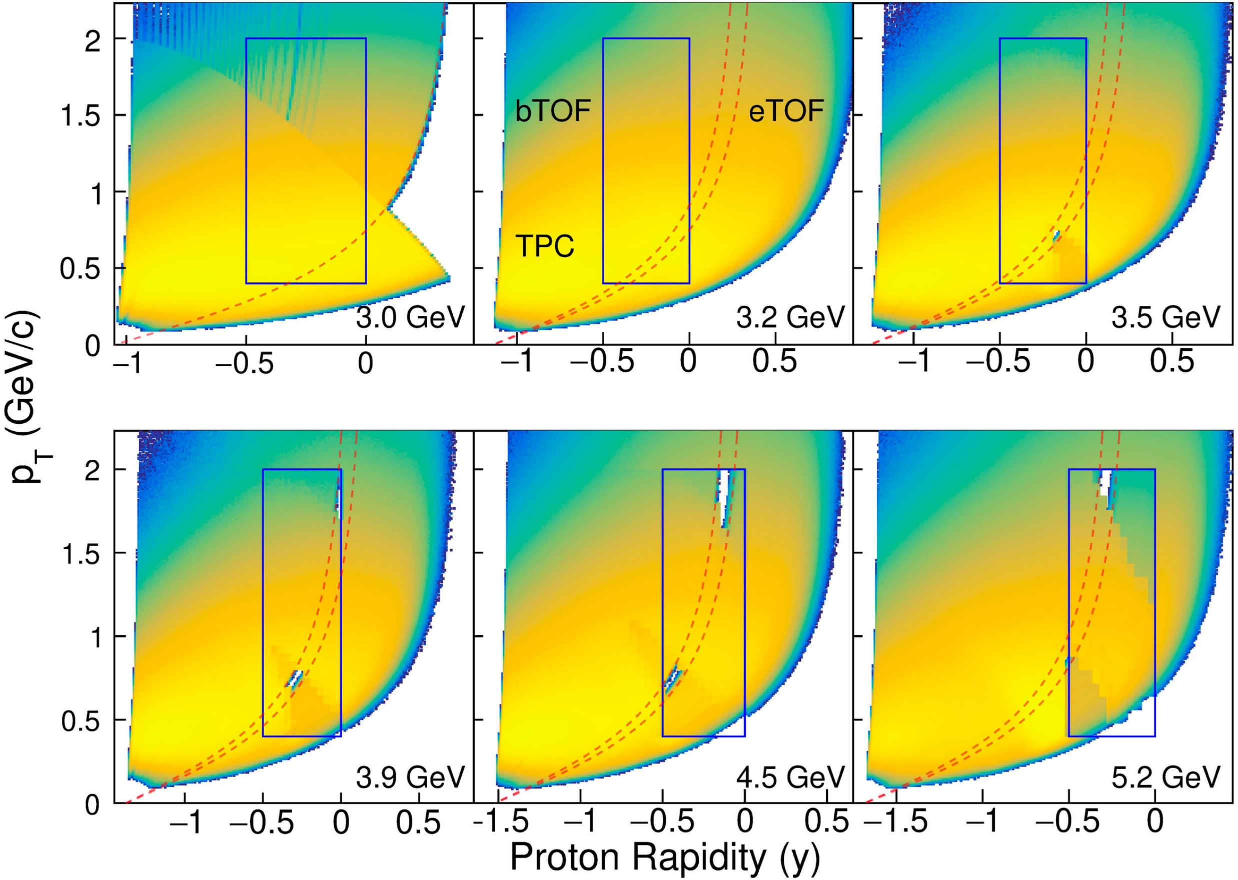




CBM participates in RHIC BES-II in 2019 – 2021:

- Fixed-target Au+Au collisions : $\sqrt{s_{NN}}$ = 3 - 7.7 GeV (**750 ≥ μ_B ≥ 420 MeV**)
- Study the properties of QCD matter at high baryon density region

Acceptance of Protons in FXT Program



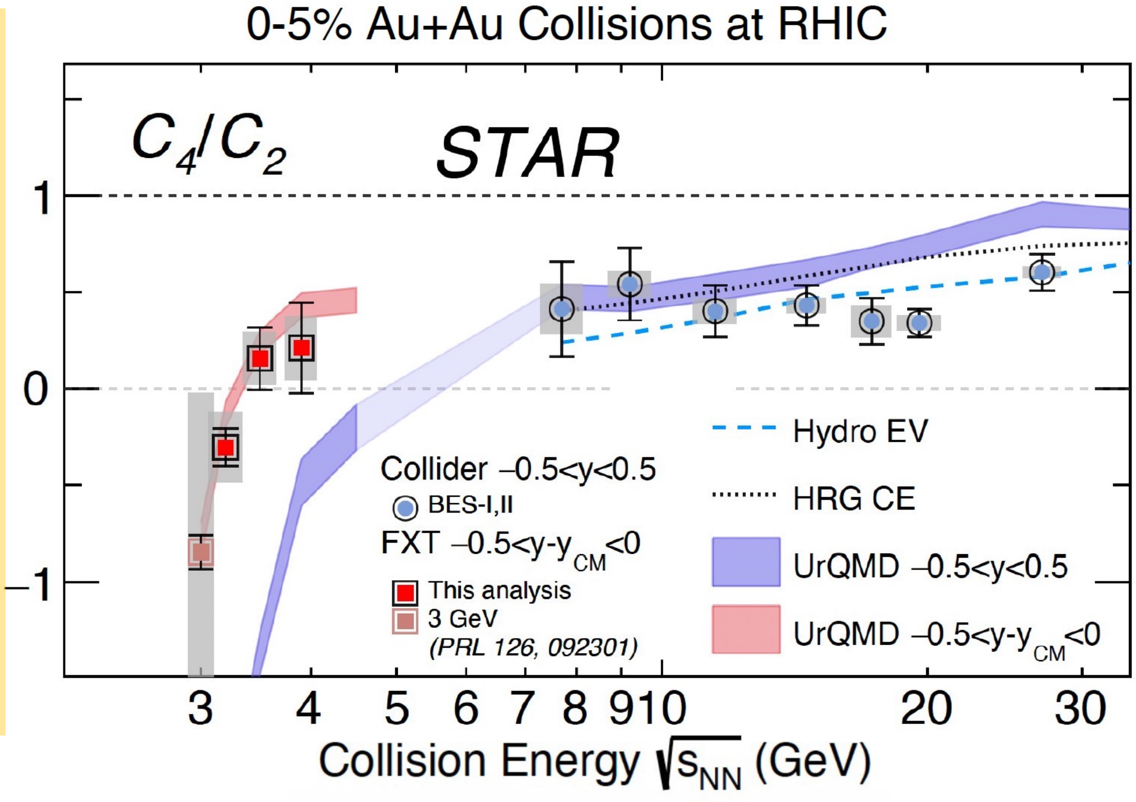
1) TPC, iTPC, bTOF, eTOF are used in the FXT program;

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



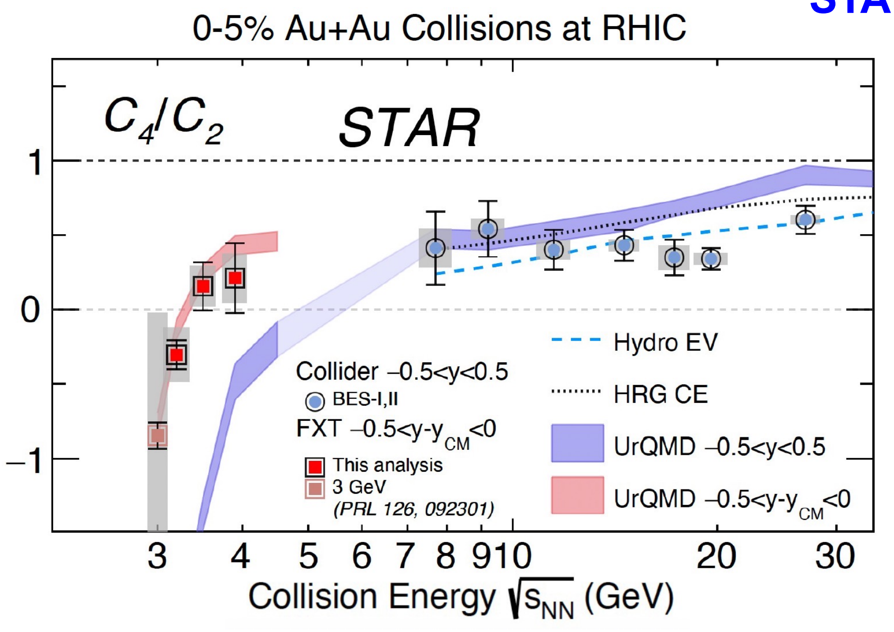
STAR 3 GeV data (collected in 2018):
Phys. Rev. Lett. 128, 202303 (2022)
Phys. Rev. C107, 024908 (2023)

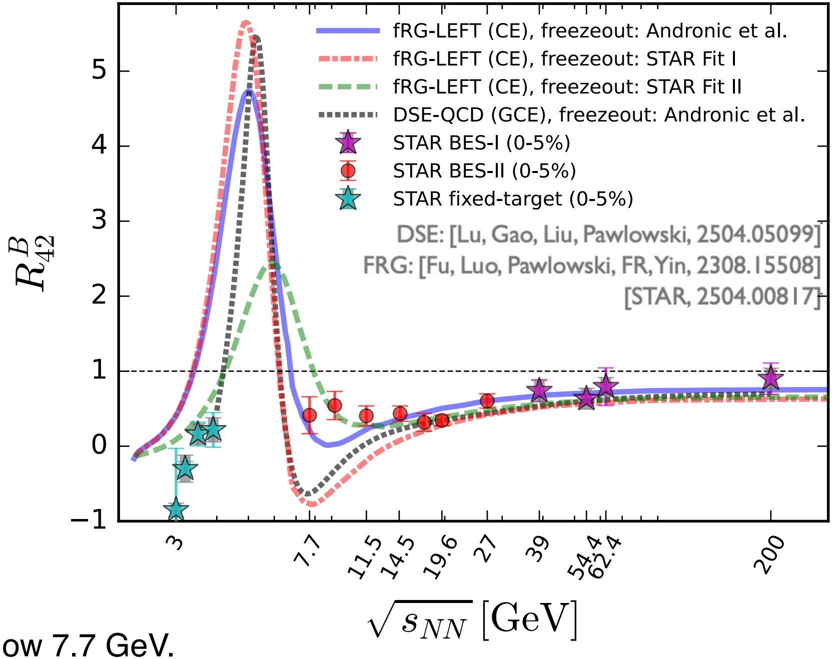
STAR, QM2025

Proton Number Fluctuations (C_4/C_2) from STAR FXT Program

STAR, QM2025

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



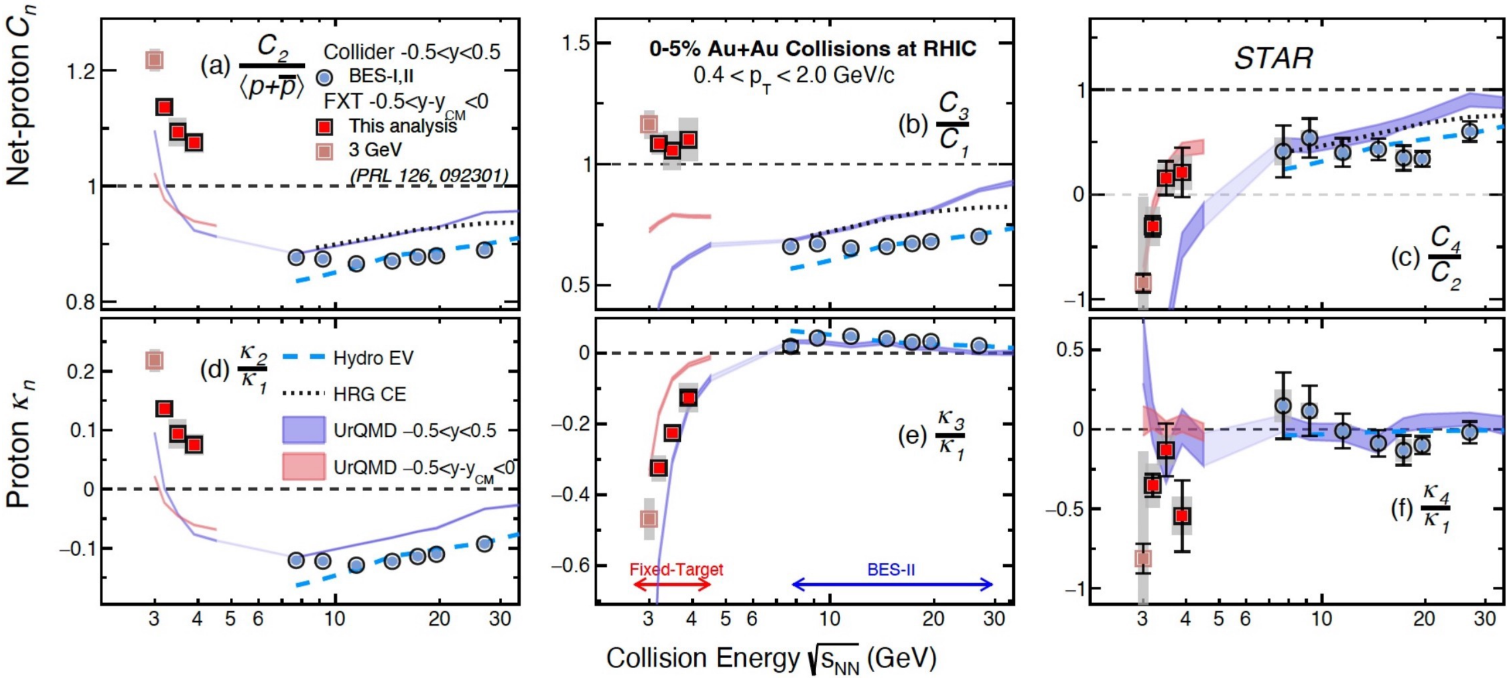


- ➢ Search for a maximum in data relative to non-CP baseline below 7.7 GeV.
- ➢ The STAR FXT results from 3, 3.2, 3.5 and 3.9 GeV are consistent with UrQMD calculations.
- ➢ Analysis of high statistics 3, 4.5 and 5.2 GeV from Run21 are ongoing.
  In addition，STAR took more data of 4.2, 4.5 and 5.2 GeV during Jan. 22-28, 2026.

Non-equilibrium effects ?

See Wei-jie Fu's talk

How about Lower Order Fluctuations ?



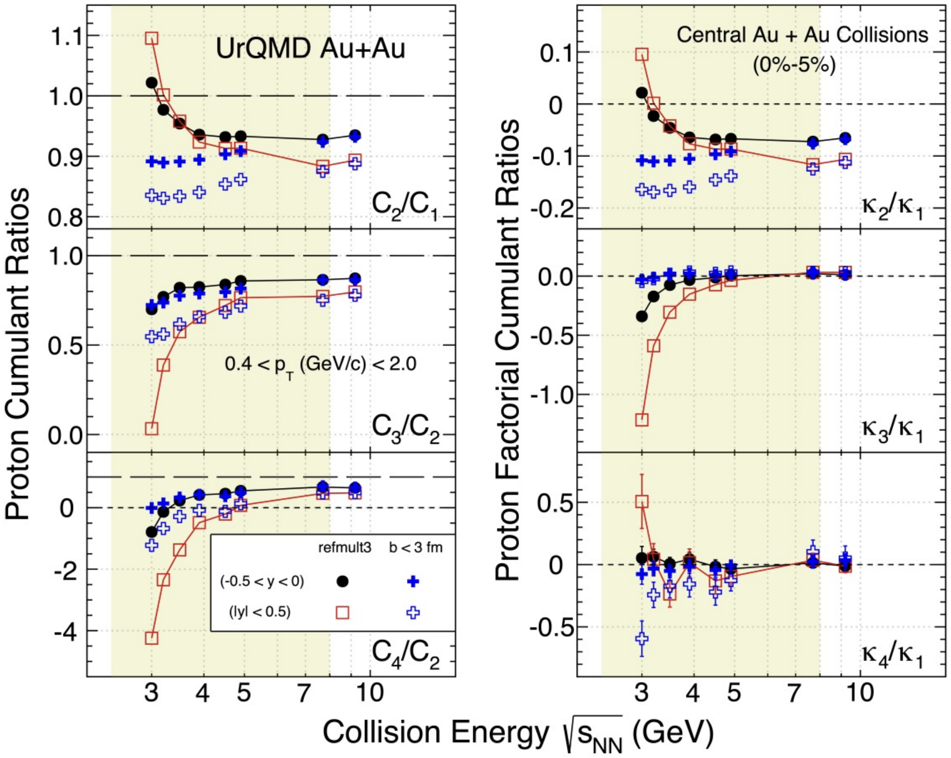
STAR, QM2025

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

UrQMD Simulations – I : Effects of Volume Fluctuations on Cumulants

Centrality Bin With Correction (CBWC) is applied.

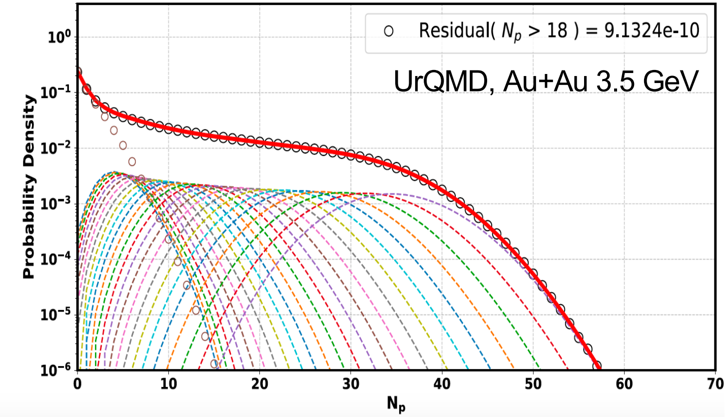


1) **Initial Volume Fluctuation**: The collision centrality is determined by charged particle multiplicities. Even in the same centrality bin, the collision volume varies event by event;
2) Simulations indicate that effects of the initial volume fluctuations becomes stronger at lower collision energies, which leads to the observed rapidly increase or decrease of κ_2/κ_1 and κ_3/κ_1;
3) At lower energies, as the centrality resolution becomes very poorer, initial volume fluctuations become more significant

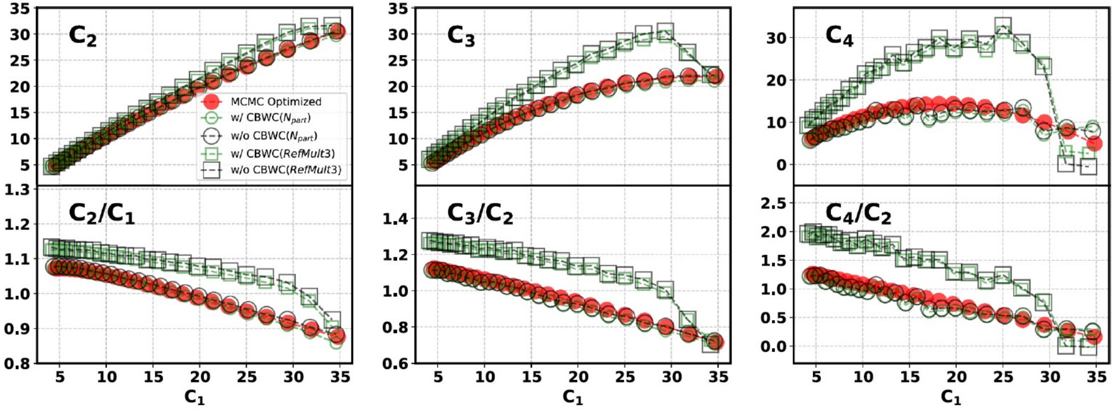
X. Zhang, Y. Zhang, XFL, N. Xu, Chin. Phys. C 50, 011003 (2026)

B. Friman, V. Koch, arXiv : 2511.11869

A New Approach



UrQMD, Au+Au 3.5 GeV



Centrality-Independent Genuine cumulant Analysis frRamework (CIGAR)

Edgeworth expansion :

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

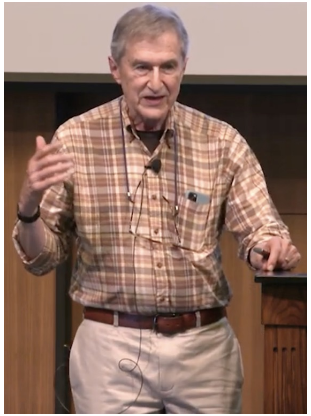
$$\sigma p(\sigma x) = Z(x)\left\{1 + \sum_{s=1}^{\infty}\left[\sigma^s \sum_{\{k_m\}} He_{s+2r}(x)\prod_{m=1}^{s}\frac{1}{k_m!}\left(\frac{S_m+2}{m+2}\right)^{k_m}\right]\right\}$$

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

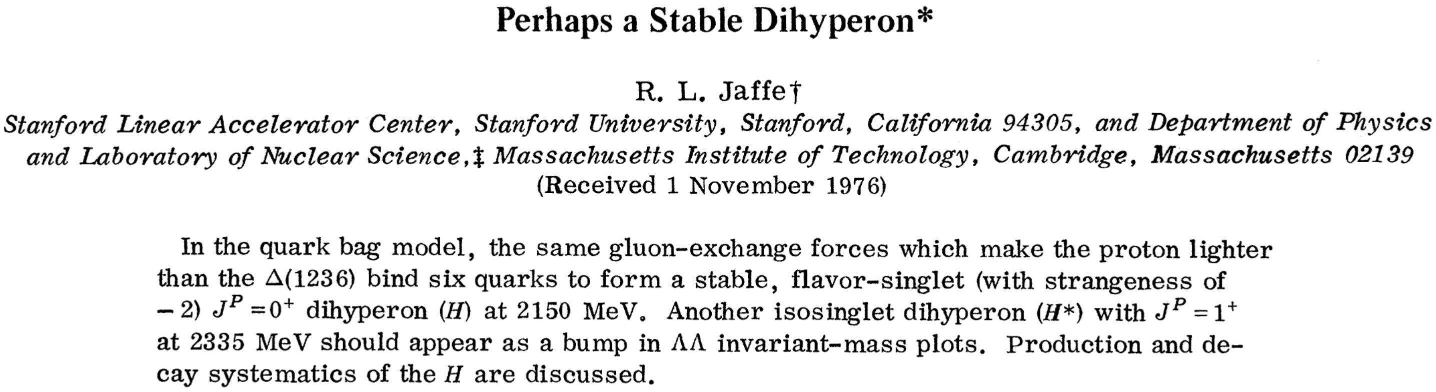
- ➢ Using Edgeworth Expansion to reconstruct the proton number distribution with cumulant as parameters
- ➢ New Method (CIGAR) has been verified to effectively suppress the volume fluctuations.

Stay Tune !!

奇异双重子态的预言和寻找



(1946-)
2023年在MIT，
“50 years of QCD”

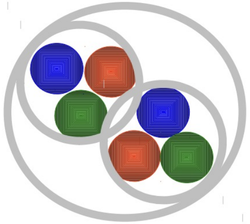


Perhaps a Stable Dihyperon*

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 $\Delta(1236)$ 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 $\Lambda\Lambda$ invariant-mass plots. Production and decay systematics of the H are discussed.

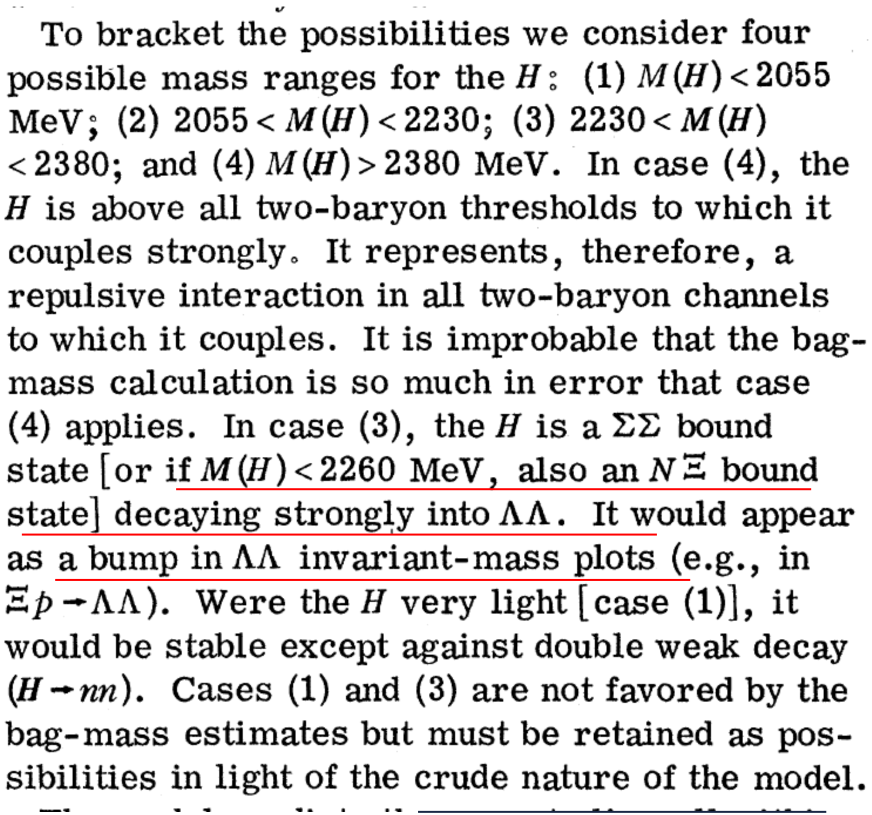
R. L. Jaffe, Phys. Rev. Lett. 38, 617 (1977)



1977年，Jaffe基于夸克袋模型预言 dihyperonn (H)：deeply bound ΛΛ system (uuddss), (J=0, S= -2, m~2150 MeV), 81 MeV below ΛΛ阈值(2231)。

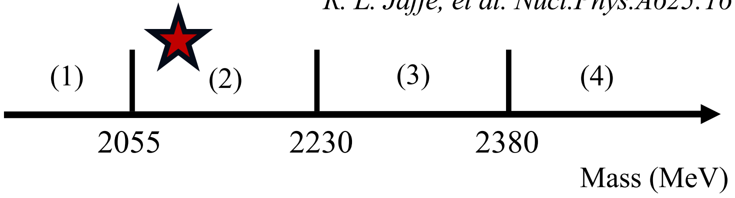
之后的40多年间，理论及实验寻找H-dibaryon的热潮从未间断。多个实验组尝试寻找，如日本JPARC E42实验，美国RHIC-STAR/AGS实验，欧洲LHC-ALICE/SPS实验等等。

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

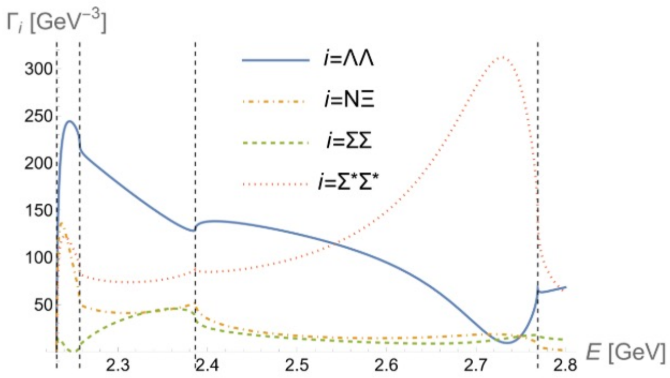


To bracket the possibilities we consider four possible mass ranges for the H: (1) $M(H) < 2055$ MeV; (2) $2055 < M(H) < 2230$; (3) $2230 < M(H) < 2380$; and (4) $M(H) > 2380$ MeV. In case (4), the H is above all two-baryon thresholds to which it couples strongly. It represents, therefore, a repulsive 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.

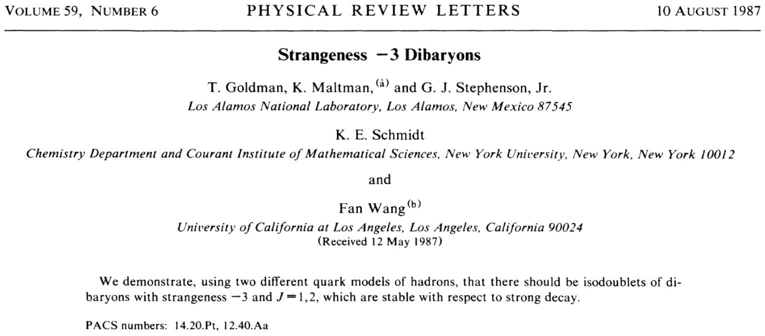


胡陶然,郭奉坤, arXiv:2601.14922

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)

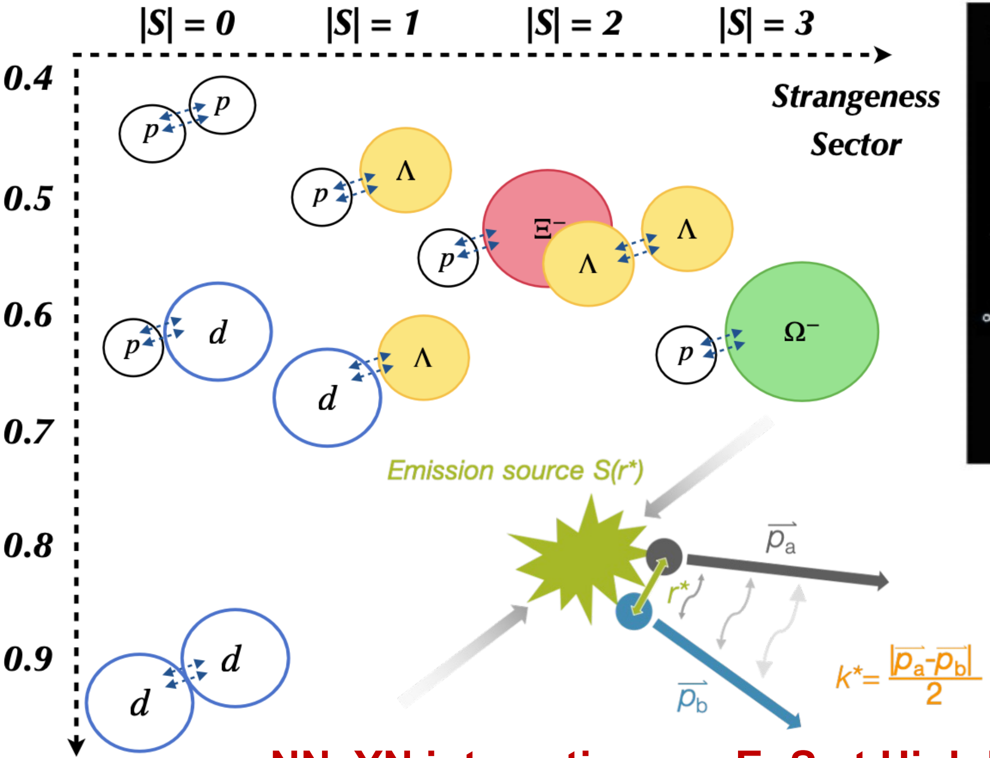
H. Pang, J. Ping, F. Wang, T. Goldman, E. Zhao, PRC-69-065207 (2004);
H. Pang, J. Ping, L. Chen, F. Wang, T. Goldman, PRC-70-035201 (2004);
M. Chen, H. Huang, J. Ping, F. Wang, PRC-83-015202 (2011);
H. Huang, J. Ping, F. Wang, PRC-92-065202 (2015)

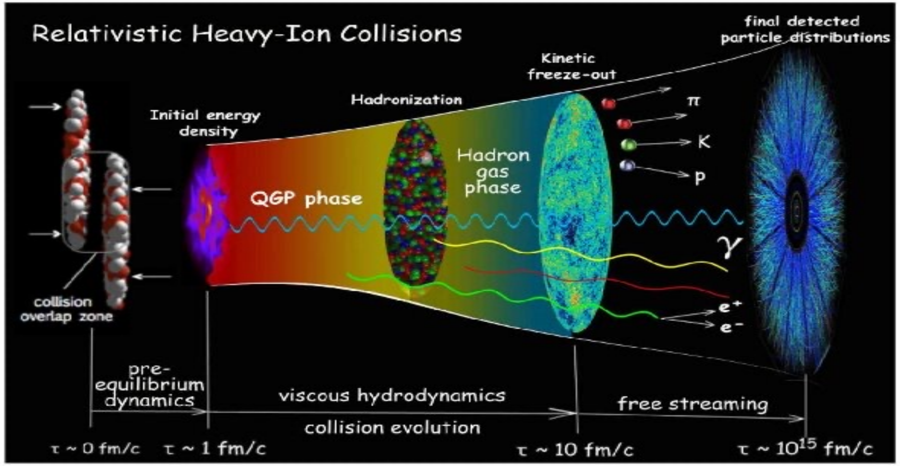
ΩΩ

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



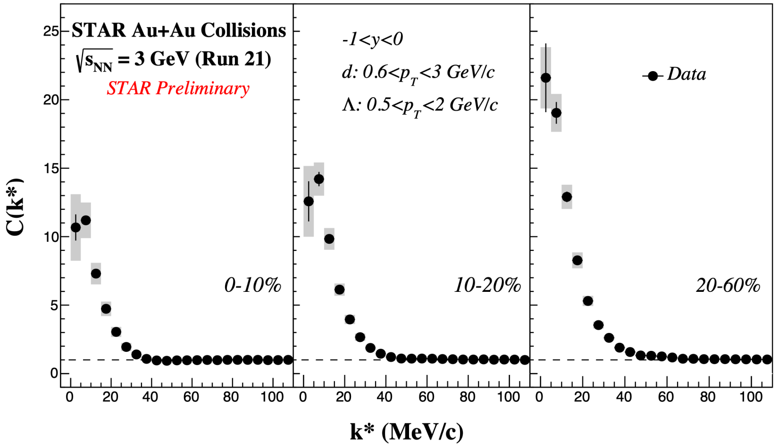


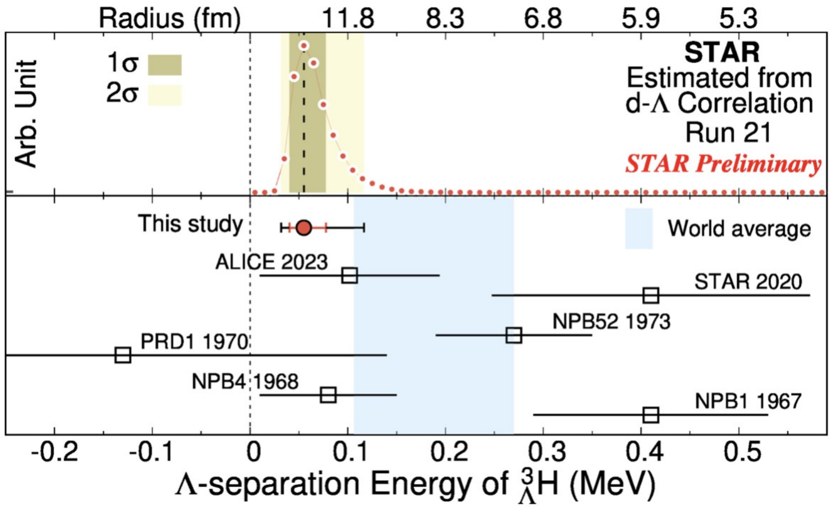
Heavy-ion collisions produce a large number of nucleons and hyperons, making it an ideal setting for studying the properties of strong interactions.

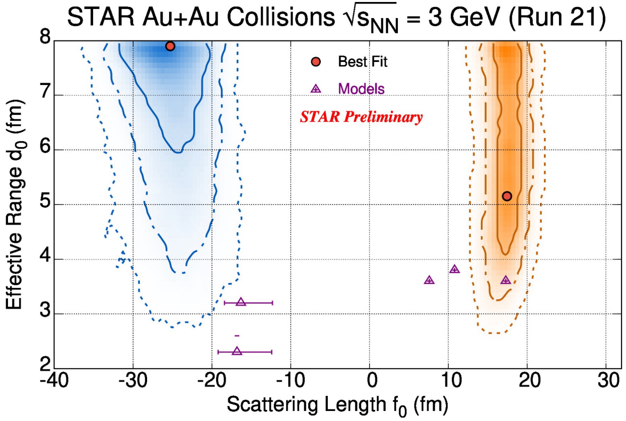
NN, YN interactions： EoS at High Baryon Density

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

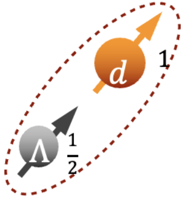
$d-\Lambda$ Correlation functions at 3.0 GeV (Run21)







1) The most accurate results of binding energy and radius of $^{3}_{\Lambda}\mathrm{H}$.
Open a new way to constrain $^{3}_{\Lambda}\mathrm{H}$ properties.

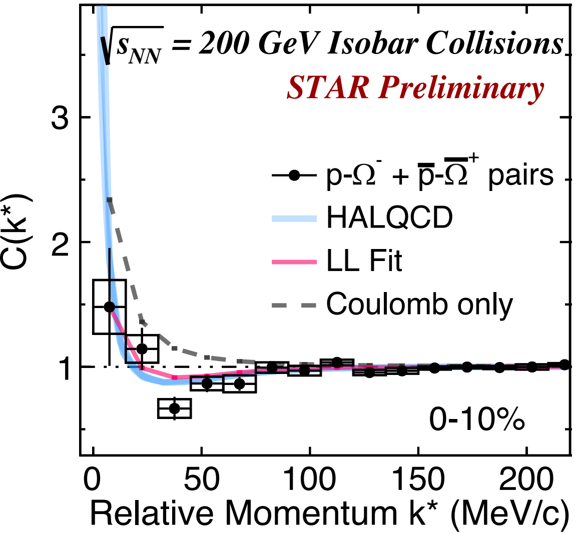


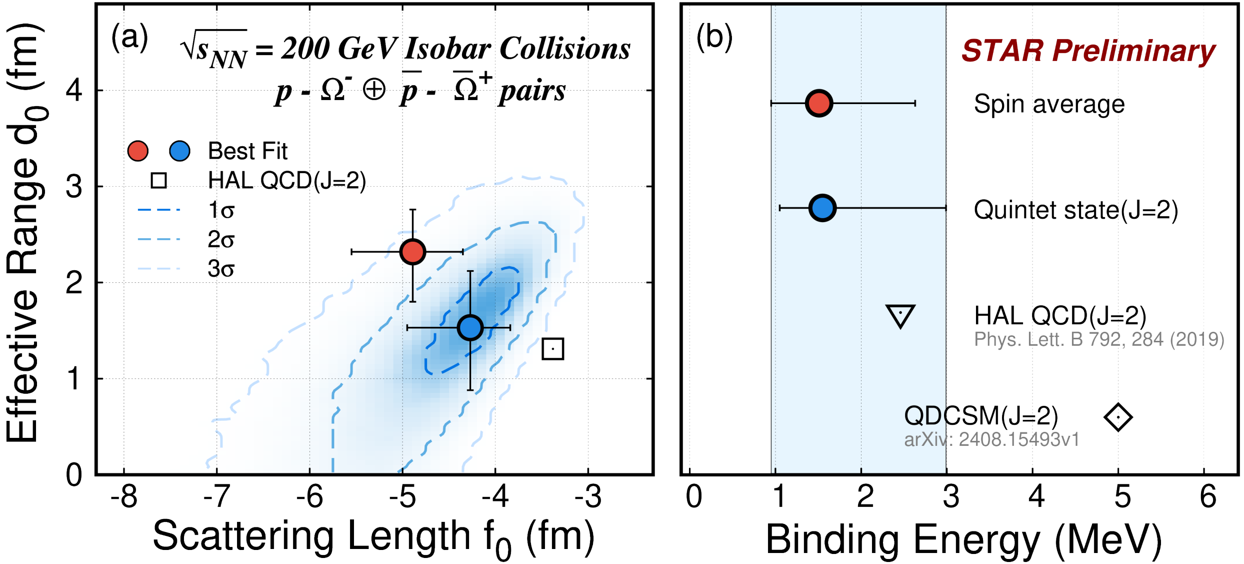
$$^{3}_{\Lambda}\mathrm{H}\ B_{\Lambda} = 0.06^{+0.06}_{-0.03} \text{ (MeV) @ 95\% CL}$$

Extracted physical parameters:
f_0 (D) = −25.3±3.3 fm
f_0 (Q) = 17.5±1.6 fm

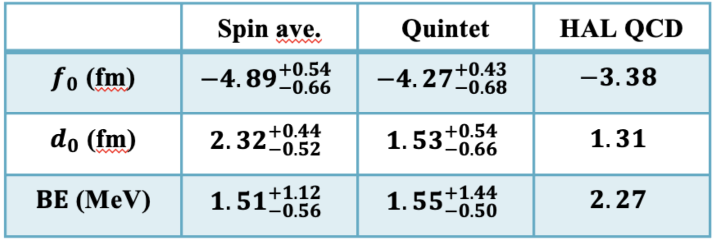
Xialei Jiang (STAR), QM2025
STAR, arXiv: 2511.15493 (PRL in press)

p-Ω^- Correlation Function (|S|=3)





Kehao Zhang (STAR), QM2025



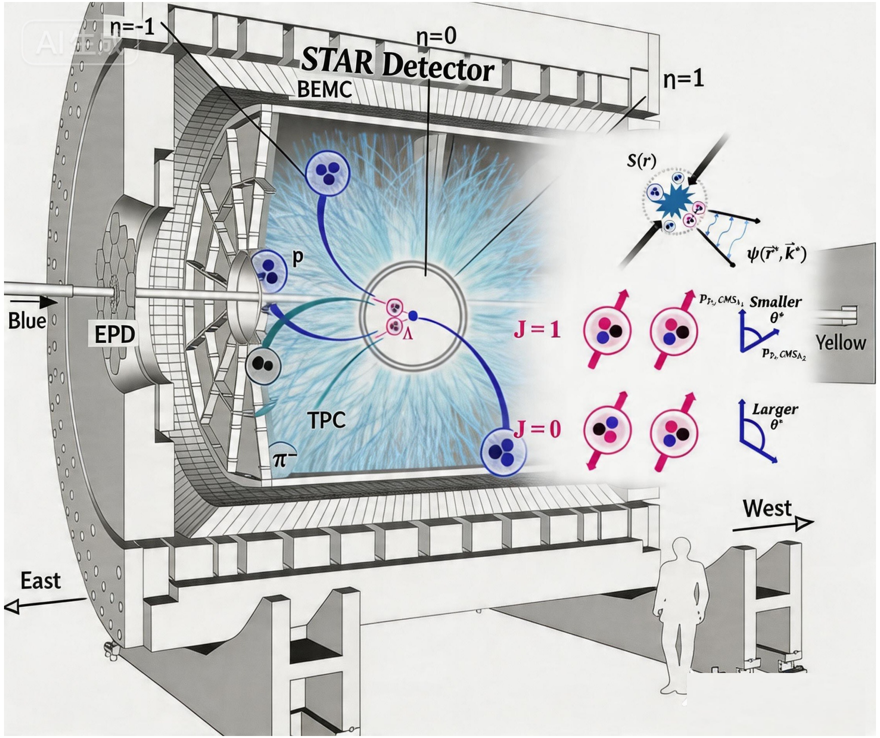
	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.89^{+0.54}_{-0.66}$	$-4.27^{+0.43}_{-0.68}$	-3.38
d_0 (fm)	$2.32^{+0.44}_{-0.52}$	$1.53^{+0.54}_{-0.66}$	1.31
BE (MeV)	$1.51^{+1.12}_{-0.56}$	$1.55^{+1.44}_{-0.50}$	2.27

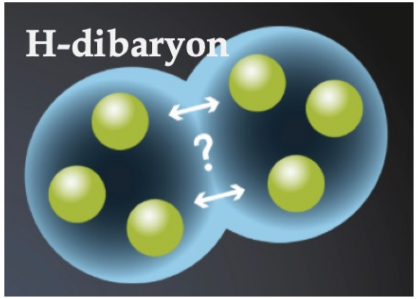
I. First experimental constraints in heavy-ion collisions of strong interaction parameters in p-Ω^- pair

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

☐ **First experimental evidence of Strange Dibaryon**

H-Dibaryon Searchs at STAR





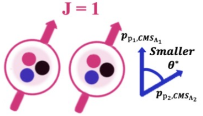
Possible channel:

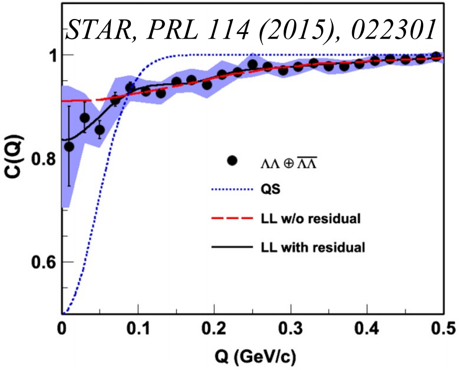
H-dibaryon ⇔ $p + \Xi$

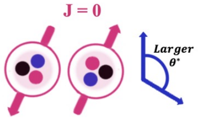
H-dibaryon ⇔ $\Lambda + \Lambda$

H -> Λ+Λ

利用Λ自相似衰变行为挑选
衰变末态ΛΛ系统的自旋！







Analysis of high stat. Isobar data finished Paper proposal soon.

Summary and Outlook

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

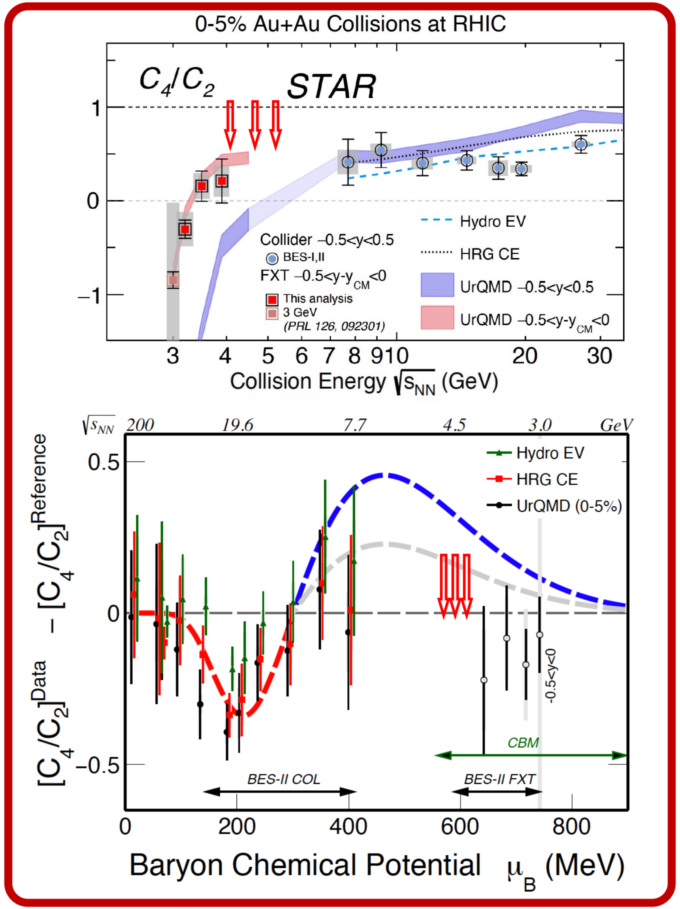
  Collider energies: for net-proton C_4/C_2 in central collisions, deviations of 2-5σ are observed w.r.t non-CP reference at 19.6 GeV

  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

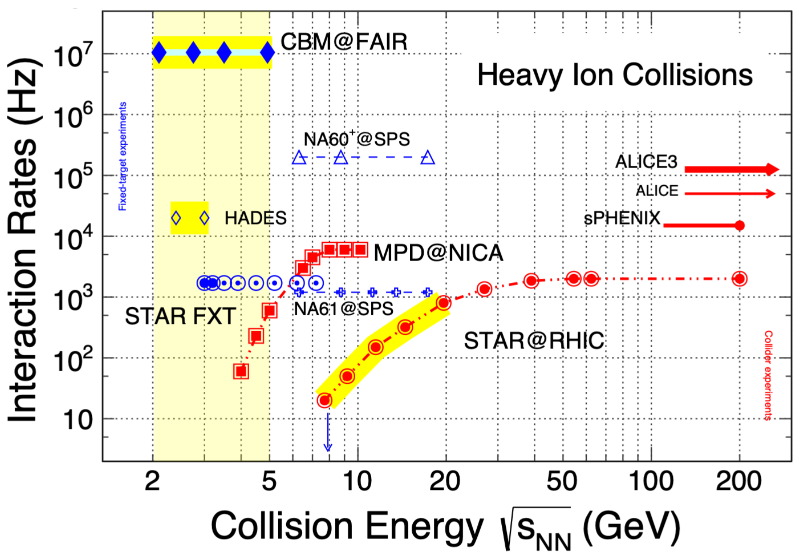
- STAR is working on a new analysis framework to determine the collision centrality, to suppress the initial volume fluctuation. Reanalyzing all data sets including 4.2, 4.5 and 5.2 GeV Au+Au collisions is under way;

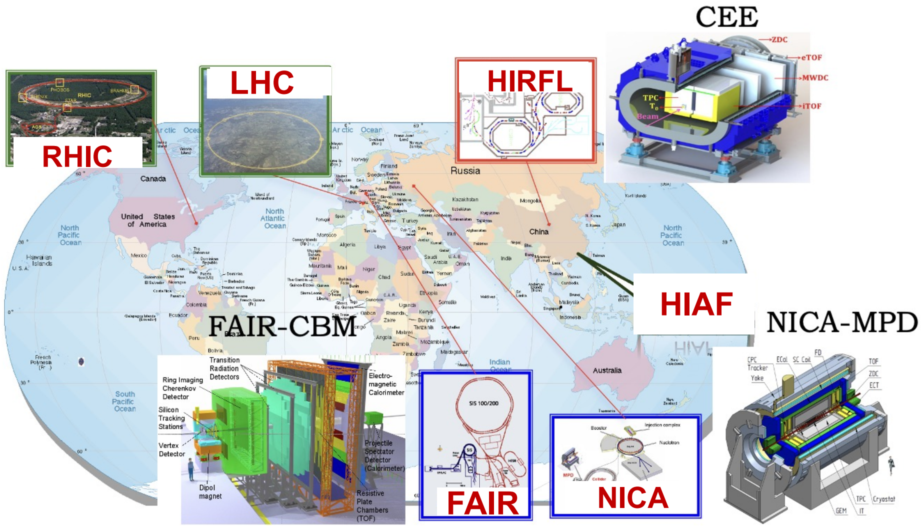
- Modeling with dynamical effects including critical fluctuations and non-equilibrium effects are crucial to understand the experimental data

Both CEP and Strange Dibaryon Search are ongoing !!



Summary and Outlook





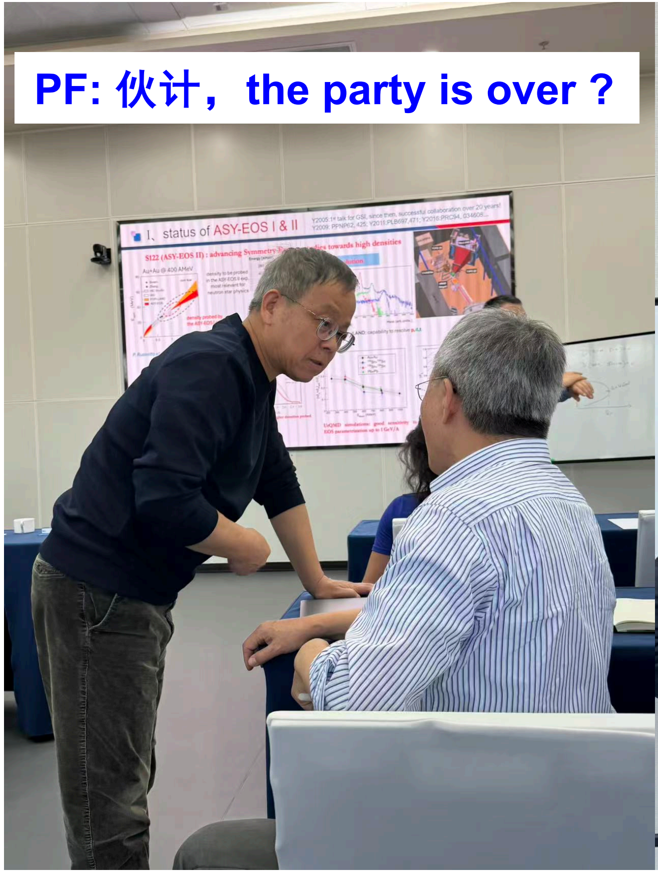
Future Low Energy Heavy-ion Experiments :

- FAIR-CBM (2.4 - 4.9 GeV, 2028 -)
- CSR-CEE (2.1 GeV, 2026-)
- HIAF-U/H-NS (2.1- 4.5 GeV, 203?)
- NICA-MPD (4 - 11 GeV, 2027 -)
- JPARC-HI (2-5 GeV, planning)

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.

PF: 伙计，the party is over ?



NU: Come to Huizhou, the party just begin !

International Conference on Nucleus-Nucleus Collisions (NN2027)

co-Chairs: Xiaofeng Luo[1] and Bing Guo[2]

[1]Central China Normal University
[2]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!