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

“with Baryon Fluctuations and Correlations”

Xiaofeng Luo (罗晓峰)

Central China Normal University

Oct. 19th, 2026





This C3NT Workshop for me belike….

This C3NT Workshop for me belike….



Outline

- **CEP and Strange-Dibaryon Search : the past, now and future**

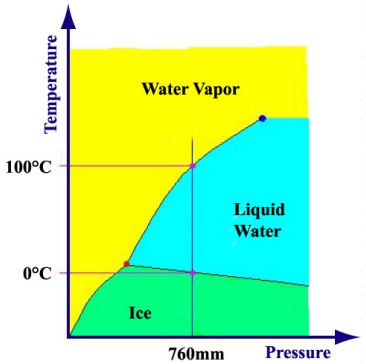
Disclaimer

- **Till today, the Hunting for the QCD Critical Point is still ongoing, new analysis results at FXT energies (3 – 5.2 GeV) will be reported in QM2027 (March, 2027).**
- **The STAR experimental results of H-dibaryon, will be reported at QM2027, NOT in this talk.**

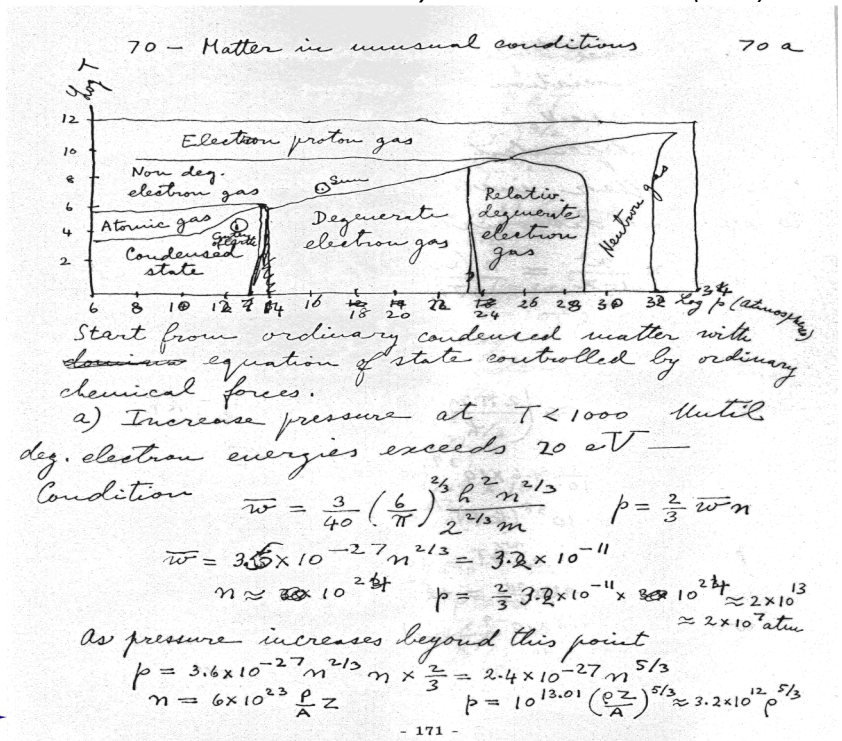
Matters Under Extreme Condition



E. Fermi



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



What are the states of matter and phase structure for the strongly interacting matter created in high-energy nuclear collisions?

Water

~ 10^2 °C



Sun

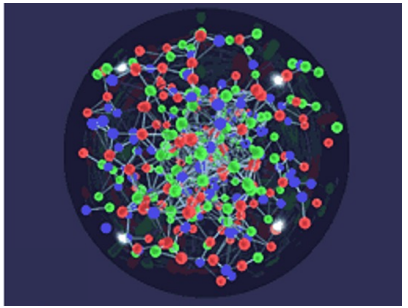
~ 10^7 °C



QGP

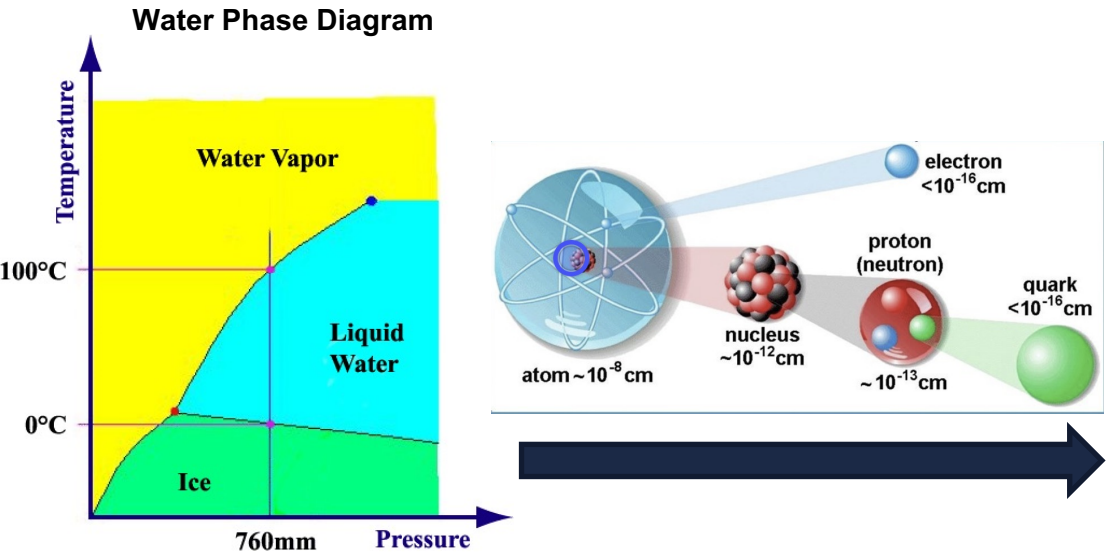
~ 10^{12} °C

(Early Universe)



QED/QCD Thermodynamics : More is Different

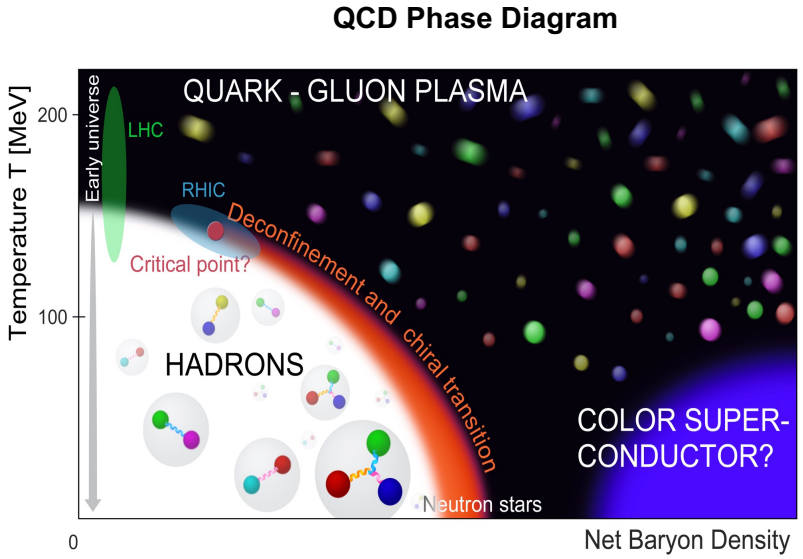
QED



hundreds degrees Celsius (~100 ℃)

Fundamental DoF: Water molecules
Dominant interaction: electromagnetic

QCD

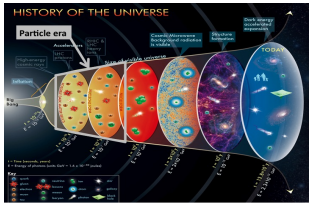


Trillions of degrees Celsius (10^{12} ° C)

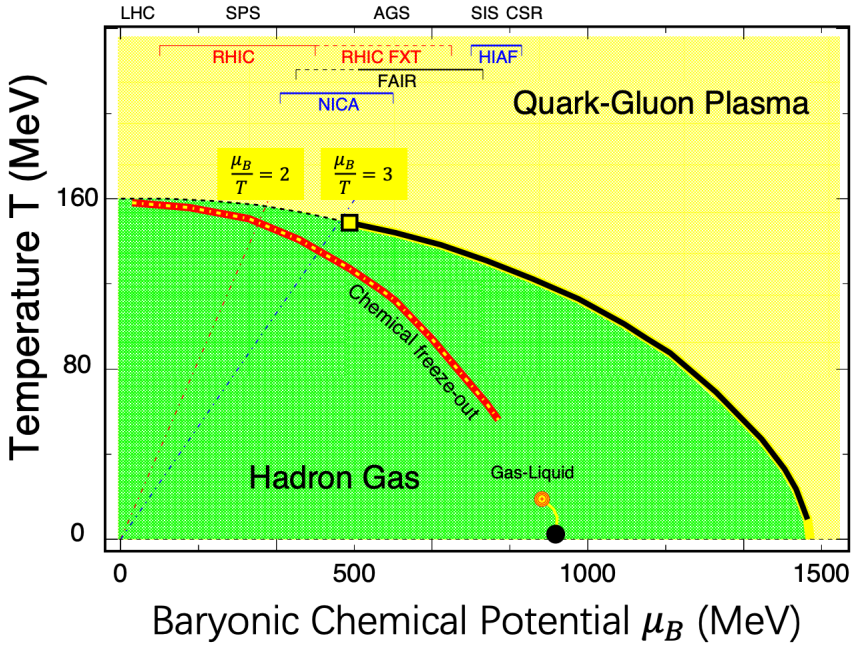
Fundamental DoF: quarks and gluons
Dominant interaction: strong interaction

QCD Phase Diagram

Condense matter physics of strong Interactions, rich structure at high baryon density



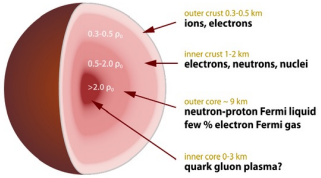
Evolution of the Universe

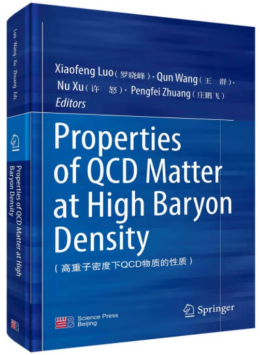


Lattice QCD : at $\mu_B = 0$, smooth crossover. T_c ~ 156 MeV

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).



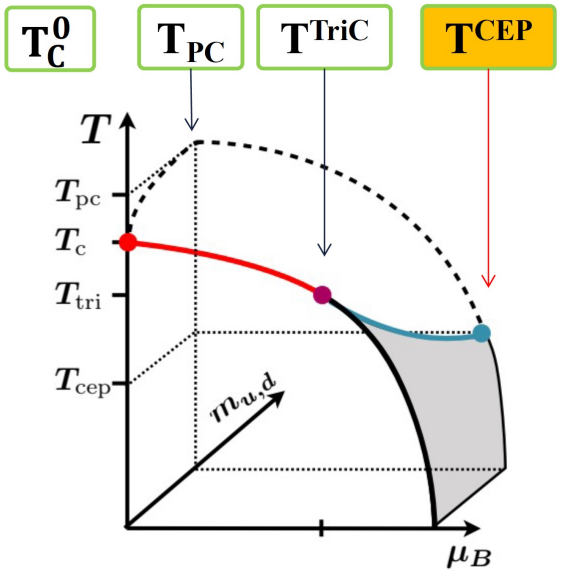


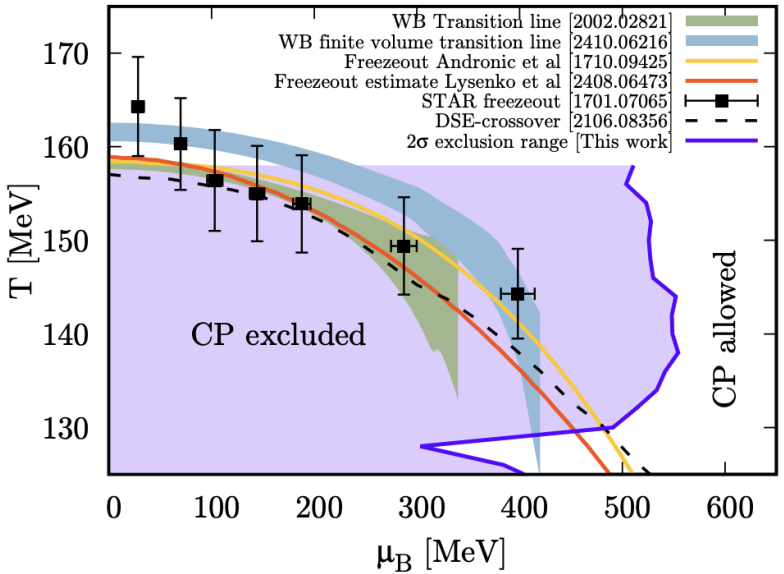
Key Physics : QCD phase structure and EoS of QCD matter at high baryon density. (critical point and 1st order phase boundaries)

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

Search for the QCD Critical Point

Location of CEP：Lattice QCD





QCD transition T：T_{PC} = 156.5 +/- 1.5 MeV

Chiral P.T.：T_C = 132(+3)(-6) MeV

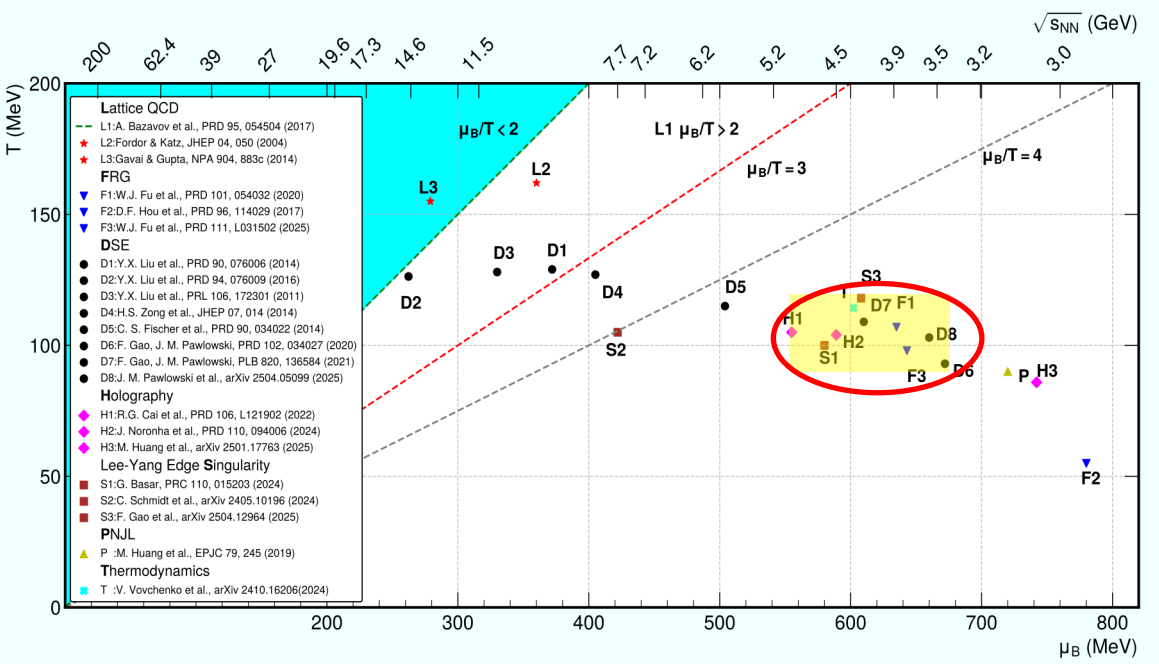
F. Karsch, Heng-Tong Ding et al. (HotQCD),
Phys. Lett. B 795, 15(2019)
Phys. Rev. Lett. 123, 062002(2019)

S. Borsanyi, et al., Phys. Rev. D **112**, L111505 (2025)

CP Location：$\mu_B/T_c > 3$

If CP exist in the QCD phase diagram, it should be with μ_B > 450 MeV

Theoretical Estimations (2004-2025)

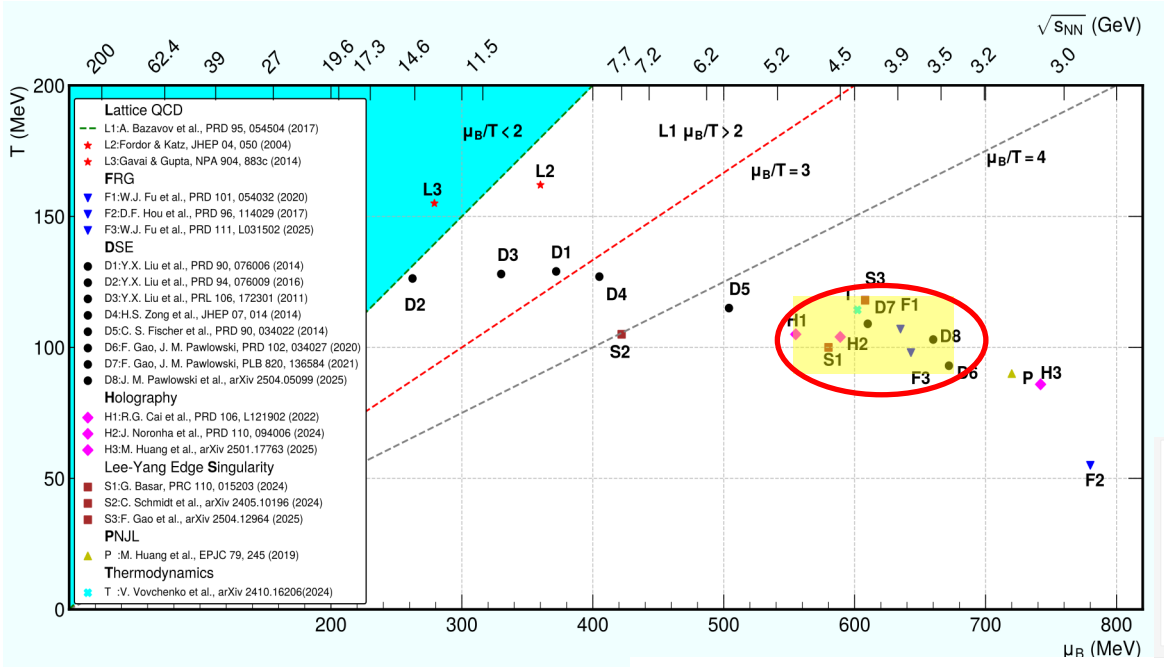


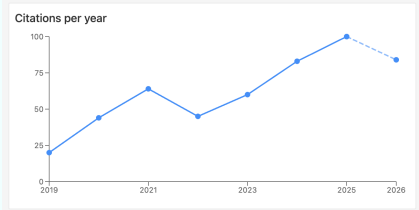
"Converge region" μ_B^{CEP}: ~ 600 – 700 MeV
T^{CEP}: ~ 90 – 120 MeV

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)





"Converge region"

μ_B^{CEP}: ~ 600 – 700 MeV

T^{CEP}: ~ 90 – 120 MeV

QCD phase structure at finite temperature and density

#44

Wei-jie Fu (Dalian U. Tech.), Jan M. Pawlowski (U. Heidelberg, ITP and Darmstadt, EMMI), Fabian Rennecke (Brookhaven) (Sep 6, 2019)

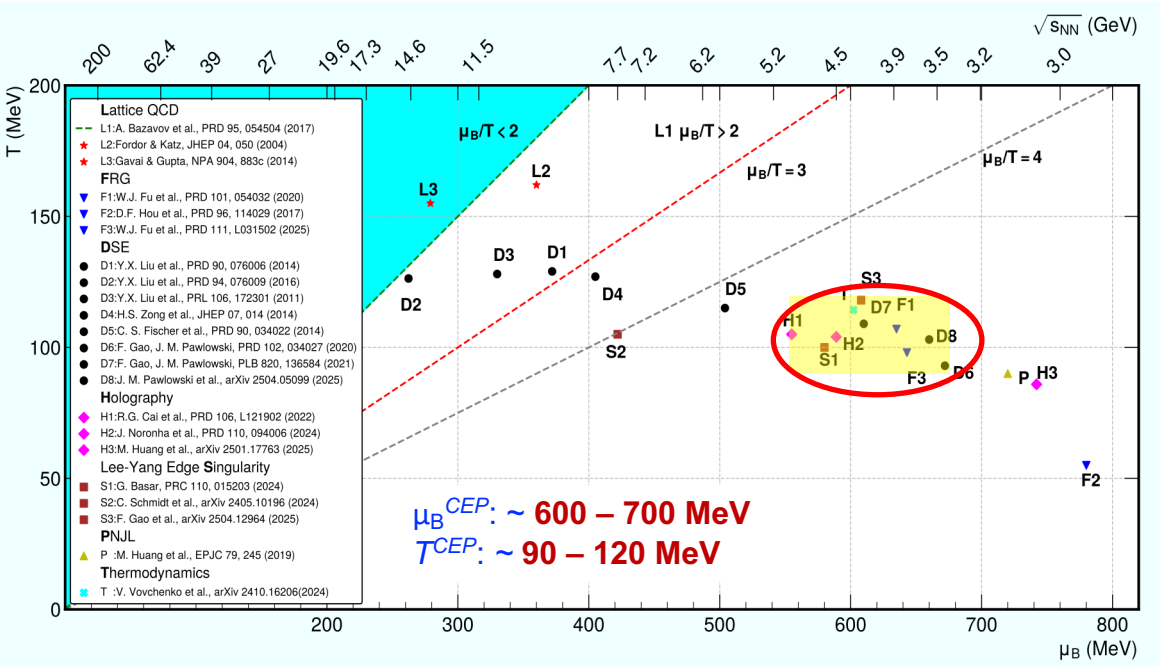
Published in: *Phys.Rev.D* 101 (2020) 5, 054032 • e-Print: 1909.02991 [hep-ph]

pdf DOI cite claim reference search 500 citations

FRG : Wei-jie Fu, J. M. Pawlowski, and F. Rennecke, Phys. Rev. D 101, 054032 (2020)
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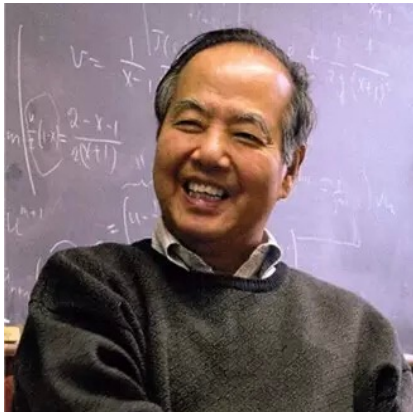
Theoretical Estimations (2004-2025)



"…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

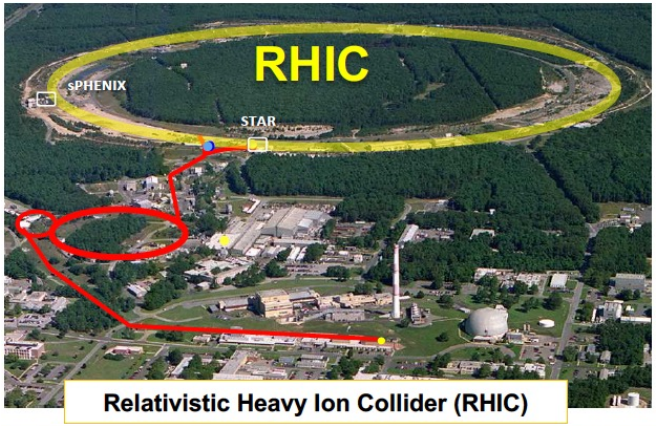


TD Lee

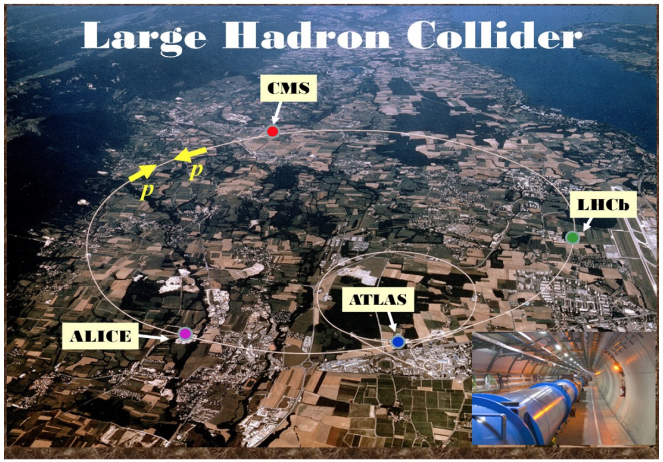


核子重如牛，对撞生新态

---李政道

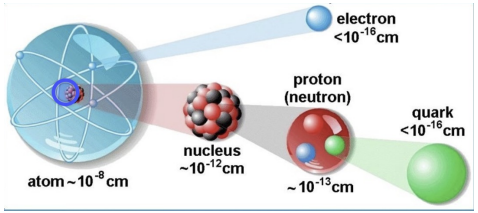


Relativistic Heavy Ion Collider (RHIC)



- Properties of sQGP

  Strongly coupled ideal fluid (quark soup),
  Viscosity : η/s ~1/4π



- QCD Phase Structure

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

Relativistic “Minds” Collisions (Strategy Workshop)



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

March, 2006@BNL

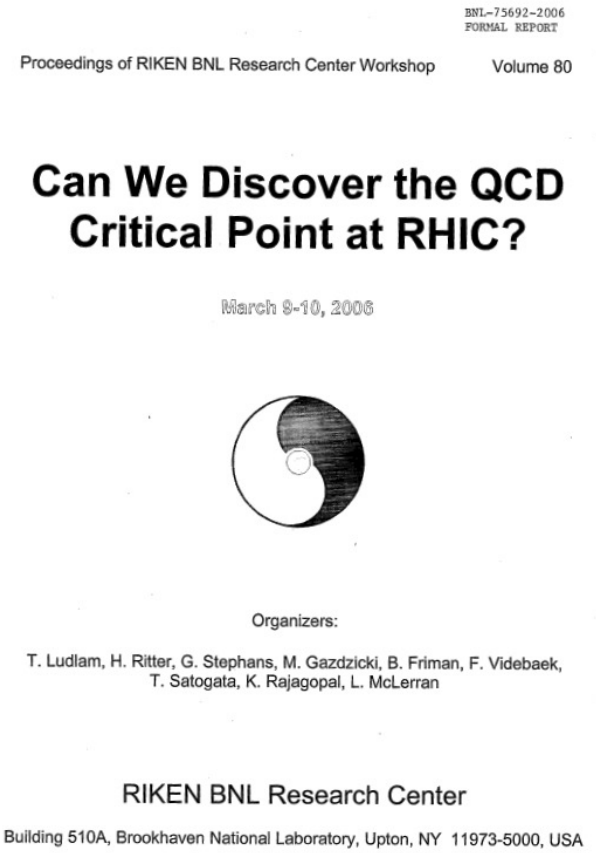
Thursday, March 9

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)
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3:25 – 3:45	Can we discover the first-order phase transition at RHIC?	J. Randrup (15+5)
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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).


BNL-75692-2006
FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 80

Can We Discover the QCD Critical Point at RHIC?

March 9-10, 2006

Organizers:

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

RIKEN BNL Research Center

Building 510A, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

CAN WE DISCOVER THE QCD CRITICAL POINT AT RHIC?



K. Rajagopal, MIT

Mapping the phase diagram. Finding the landmark that would go in any future book on QCD. Can RHIC do this?

Yes, IF:

- Accelerator & detector capabilities permit measurement of the event-by-event fluctuations of the hadronic observables I described, at a sequence of energies like that I described
- Nature is kind, and puts $\mu_B < 500$ MeV

If YES:

- The landmark discovered. Our map of the QCD phase diagram then anchored by experiment.
- Assuming reasonable progress in lattice QCD, quantitative comparison between theory & experiment for μ_B
- FAIR (and RHIC) can study the first order phase transition.

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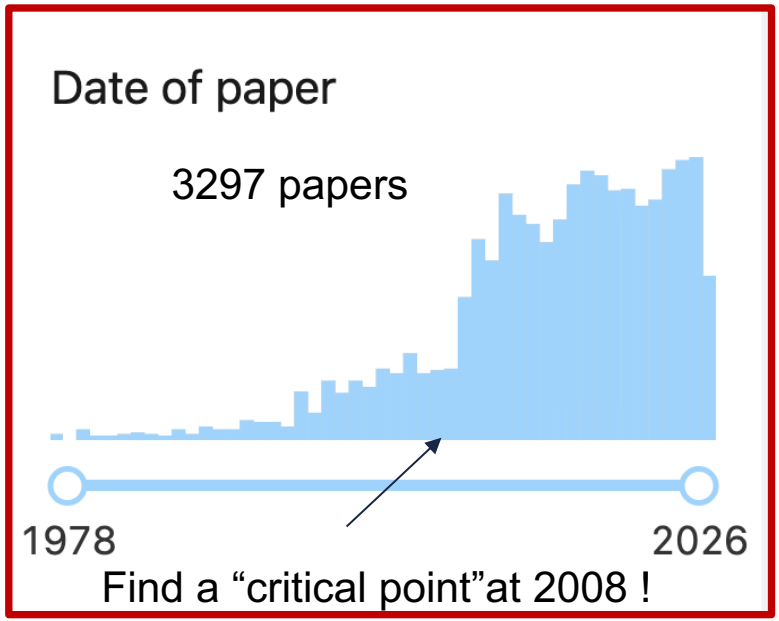
INT Workshop 2008-2b : The QCD Critical Point

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 √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"

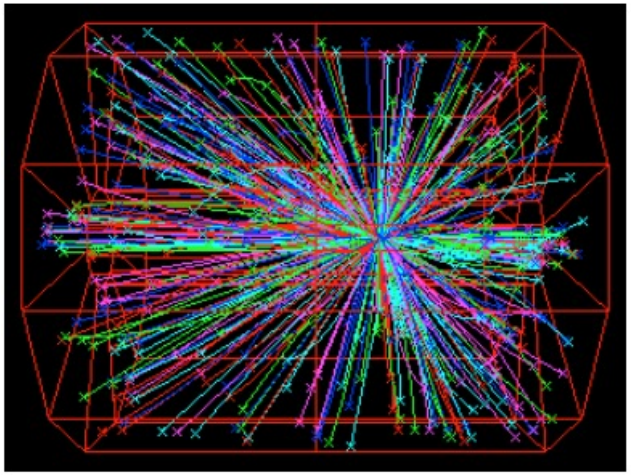
RHIC Ramping into the Era of Beam Energy Scan (2008-2010)

Search for the "QCD critical point" in Inspires



The "QCD critical point" related studies enter into highly productive level at 2008 !

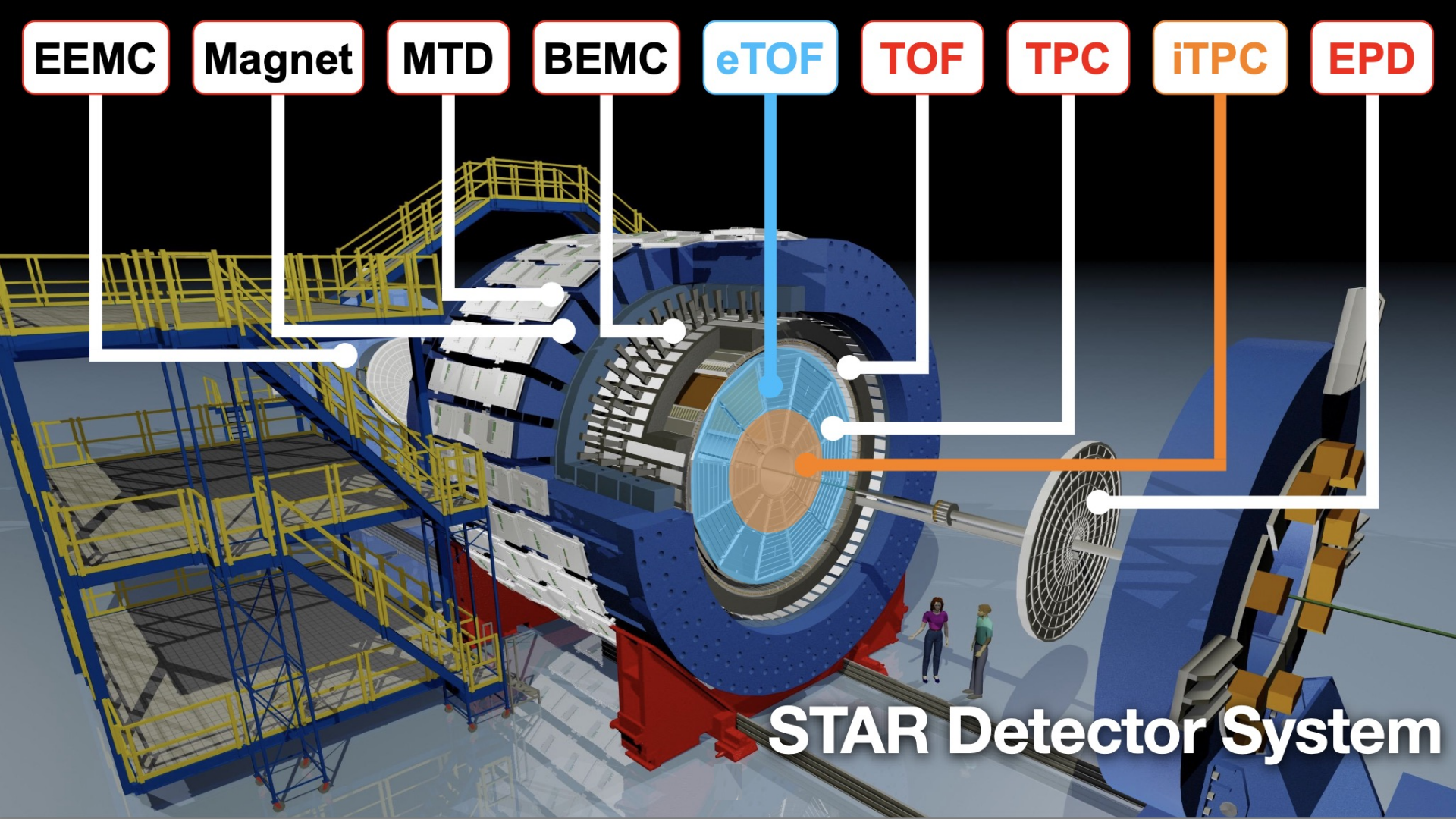
In 2009, RHIC successfully conducted test runs of Au+Au collisions at 9.2 and 19.6 GeV.



Charged particle tracks from 9.2 GeV central collisions

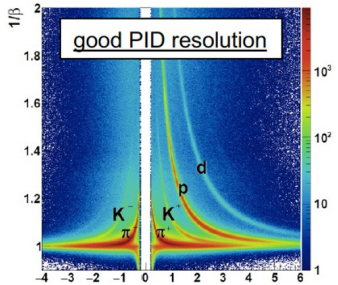
STAR, Phys. Rev. C 81, 024911 (2010)

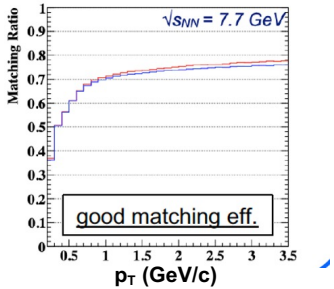
"RHIC White Paper for BES: STAR, arXiv:1007.2613"
It sounded the clarion call for RHIC to explore the QCD phase diagram and search for the QCD critical point, marking the beginning of the Beam Energy Scan era at RHIC.

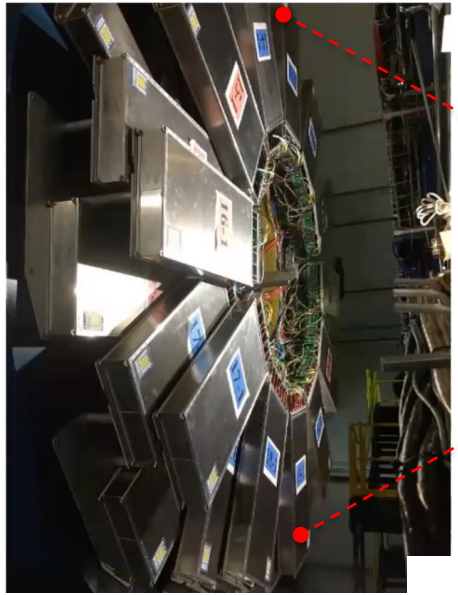

EEMC
Magnet
MTD
BEMC
eTOF
TOF
TPC
iTPC
EPD
STAR Detector System

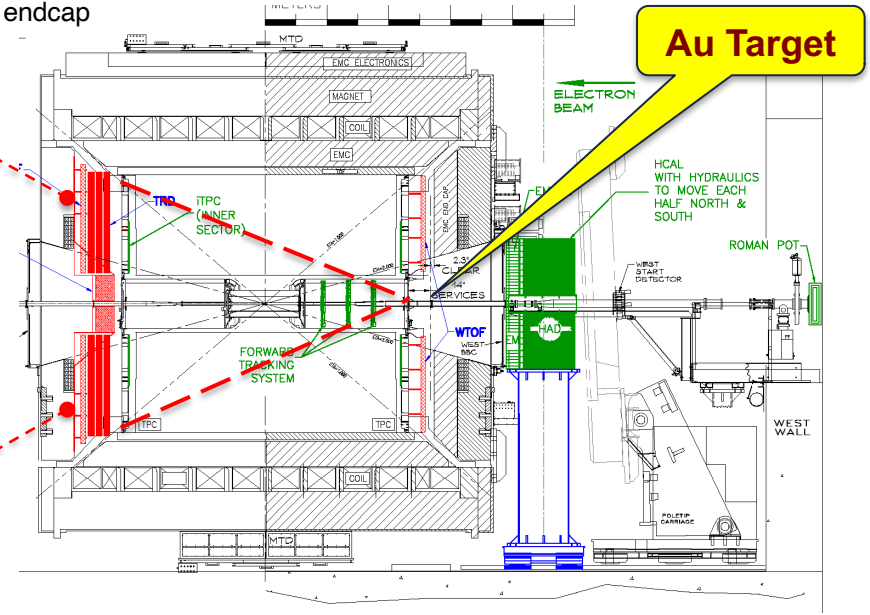
Fixed-Target Mode of the STAR Experiment

eTOF (2019+) 10% of the CBM TOF modules installed at STAR endcap









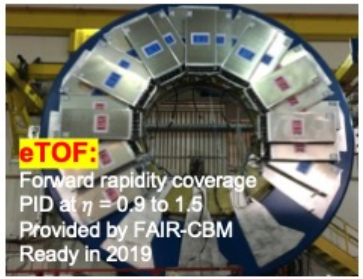
eTOF from CBM are installed at STAR endcap in RHIC BES-II

- 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

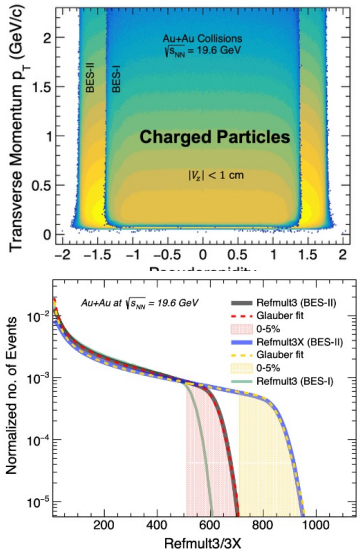
RHIC Beam Energy Scan Program (2010 – 2026)

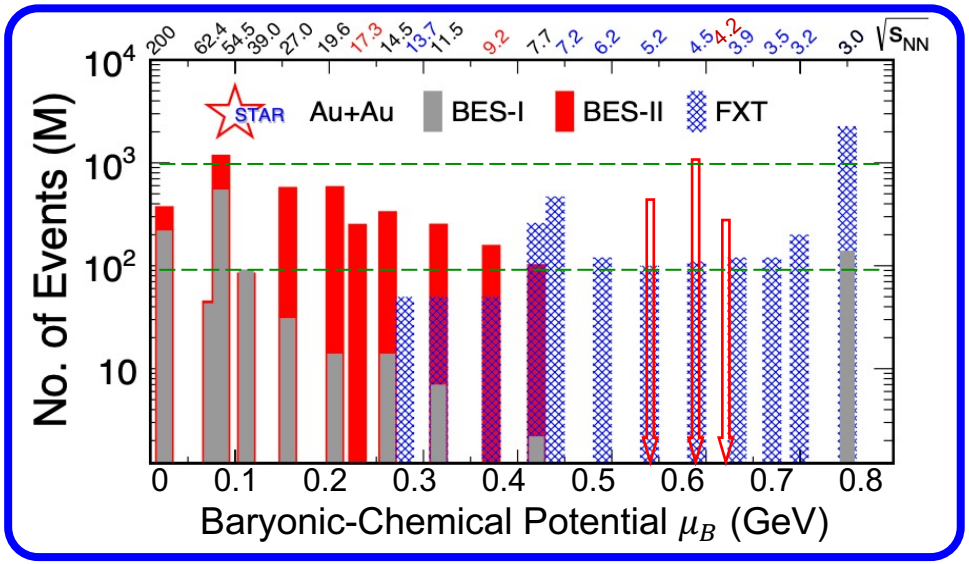
Detector Upgrades for BES-II











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

Caveats : Non-equilibrium, finite size/time effects

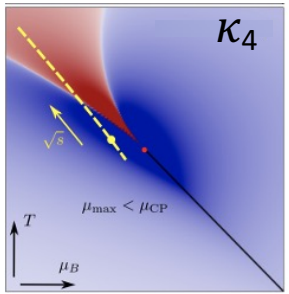
M. Asakawa, M. Kitazawa, B. Müller, PRC 101, 034913 (2020).
S Mukherjee, R. Venugopalan, Y Yin, PRL 117, 222301 (2016).
S. Wu, Z. Wu, H. Song, PRC 99, 064902 (2019).
S. Tang, S. Wu, H. Song, 108, 034901 (2023).

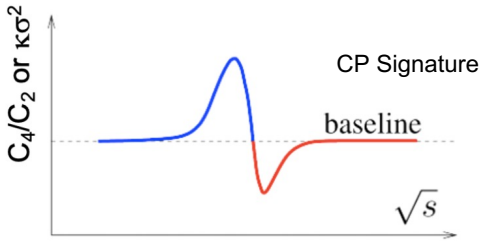
Measured multiplicity N, $\langle \delta N \rangle = N - \langle N \rangle$

mean:	M	$= \langle N \rangle$	$= C_1$
variance:	σ^2	$= \langle (\delta N)^2 \rangle$	$= C_2$
skewness:	S	$= \langle (\delta N)^3 \rangle / \sigma^3$	$= C_3/C_2^{3/2}$
kurtosis:	κ	$= \langle (\delta N)^4 \rangle / \sigma^4 - 3$	$= C_4/C_2^2$

Moments, cumulants and susceptibilities:

2nd order:	σ^2/M	$\equiv C_2/C_1$	$=$	χ_2/χ_1
3rd order:	Sσ	$\equiv C_3/C_2$	$=$	χ_3/χ_2
4th order:	$\kappa\sigma^2$	$\equiv C_4/C_2$	$=$	χ_4/χ_2

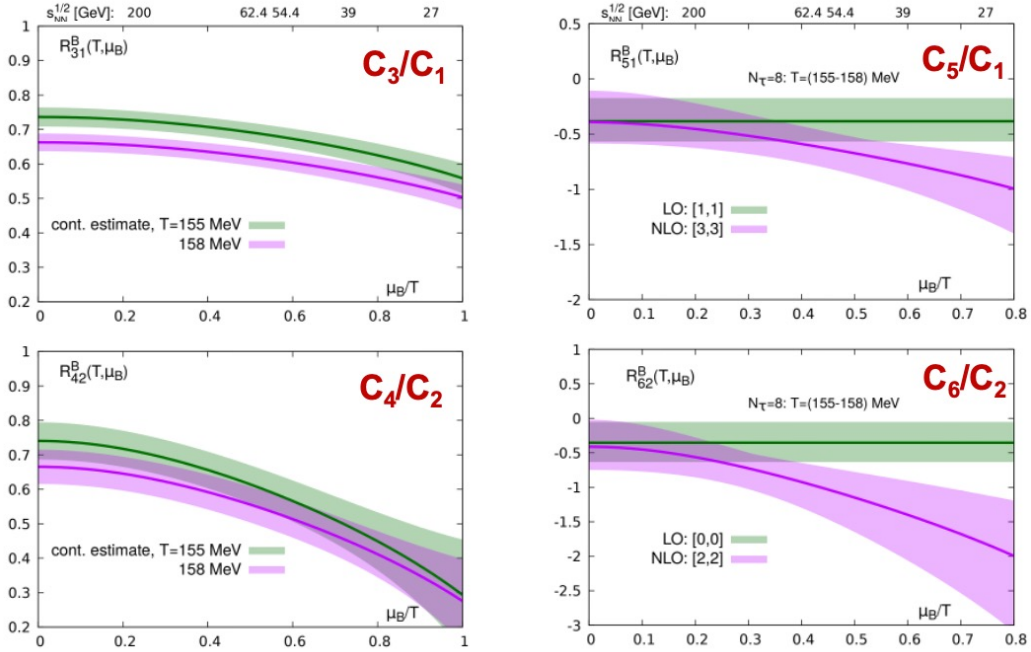




M. A. Stephanov, PRL 102 (2009) 032301

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)

Baryon Number Fluctuations from Lattice QCD



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

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

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

Tylor expansion at small μ_B:

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

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

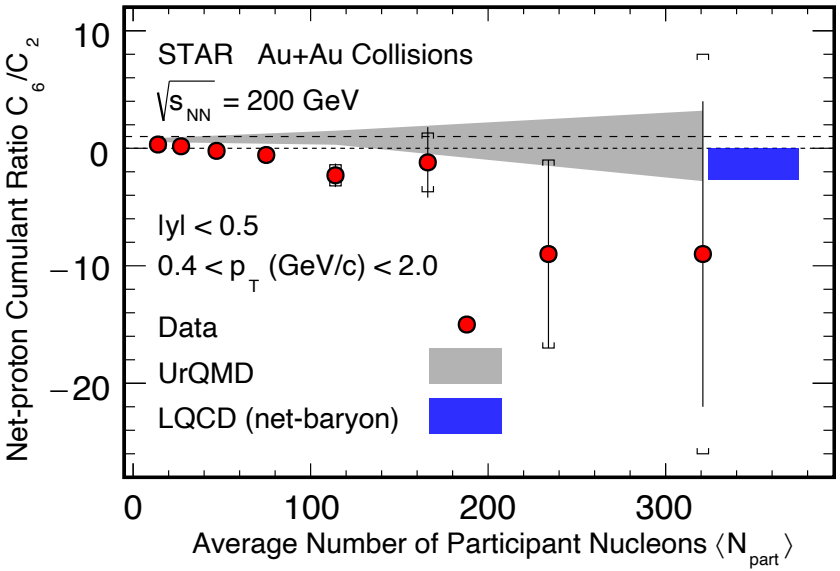
With $\mu_B/T < 1$, near the phase boundary:

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

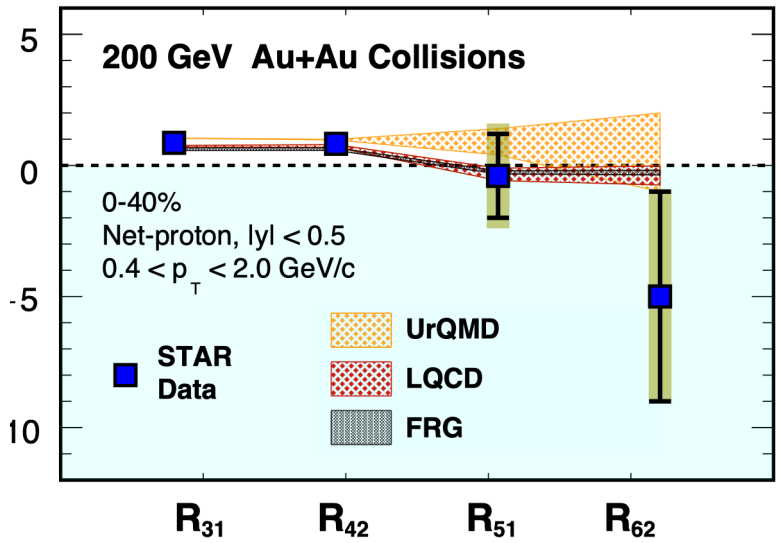
$$C_3/C_1 > C_4/C_2 > 0 > C_5/C_1 > C_6/C_2$$

A. Bazavov, H.-T. Ding, et al. (HotQCD),
Phys. Rev. D 96, 074510 (2017).
Phys. Rev. D 101, 074502 (2020).

Higher-order Net-Proton Number Fluctuations in Au+Au 200 GeV



STAR, Phys. Rev. Lett. 127, 262301 (2021)



STAR, Phys. Rev. Lett. 130, 082301 (2023)

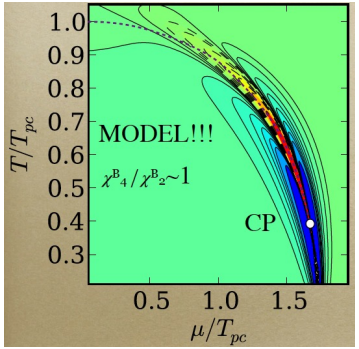
1. The sixth-order moment of the net proton number gradually becomes negative as the collision moves from the peripheral towards the central collisions.
2. A hierarchy from lower to higher order has been observed in central Au+Au collisions at 200 GeV.

The experimental results of Au+Au 200 GeV are consistent with the predictions of lattice QCD calculations regarding a smooth transition at small μ_B.

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

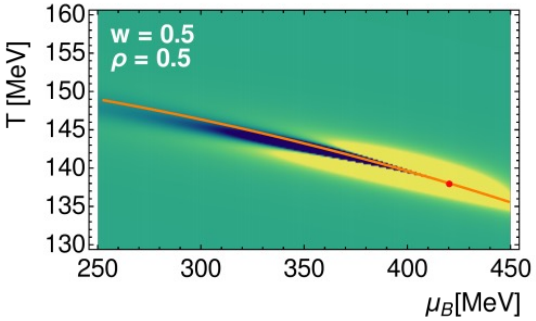
PQM

V. Skokov, QM2012



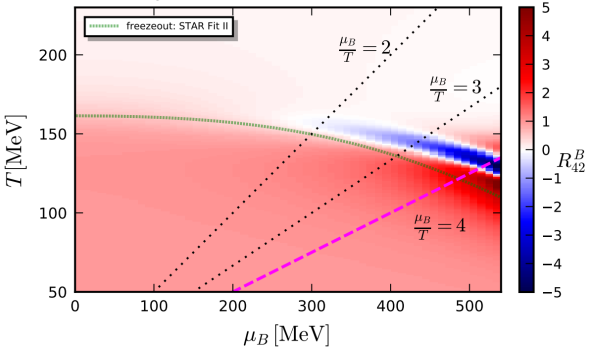
3D Ising Mapping

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



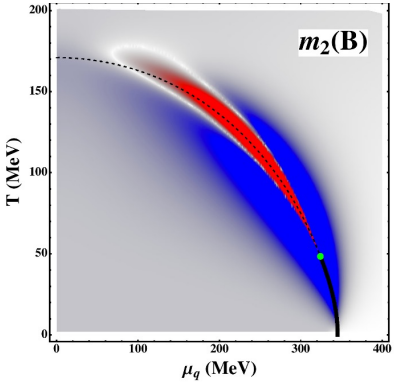
FRG

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



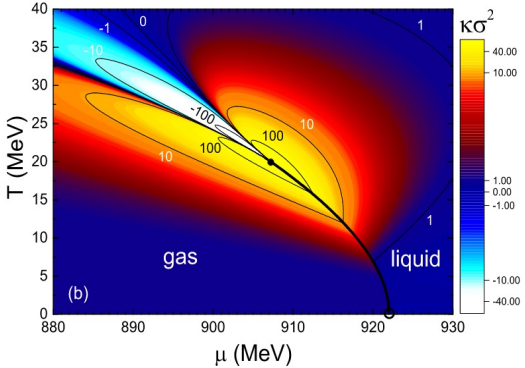
Symmetry and Universality

NJL



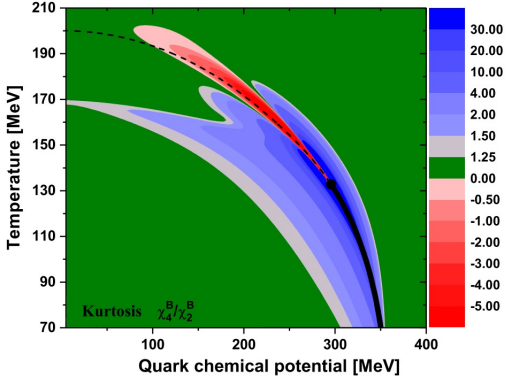
Jian Deng et al., PRD93, 034037 (2016)

van der Waals (VDW)



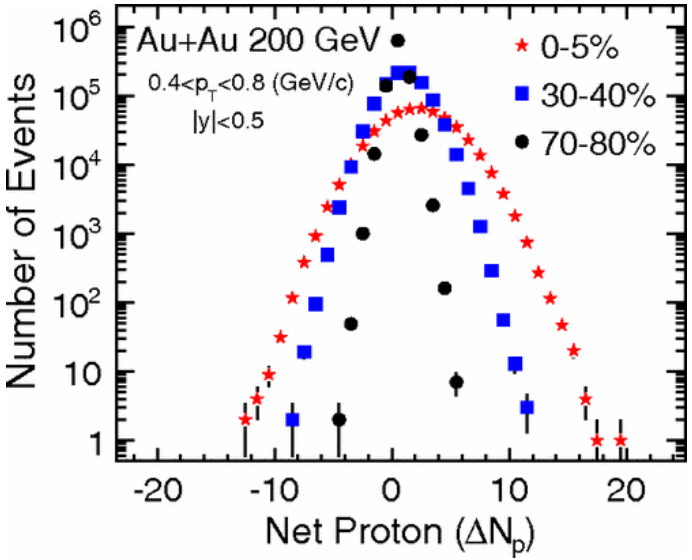
Vovchenko et al., PRC92, 054901 (2015)

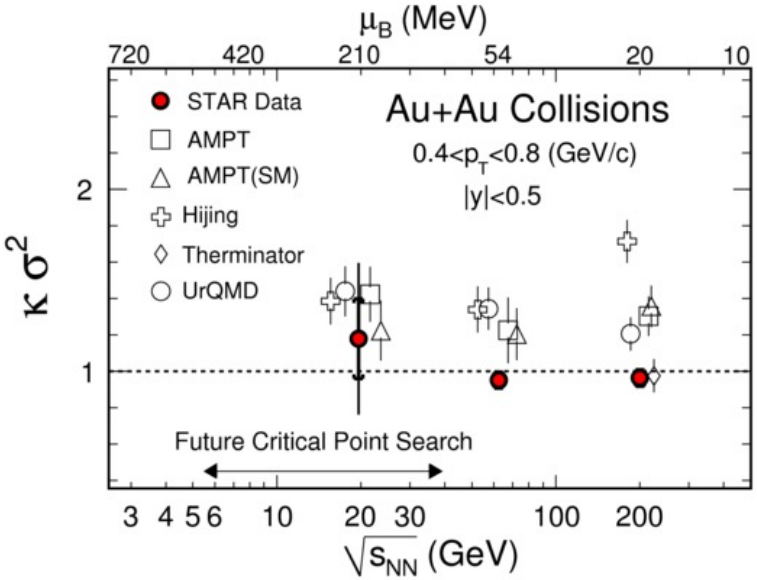
PNJL



Guoyun Shao et al., EPJC 78, 138 (2018)
Mei Huang et al., EPJC 79, 245 (2019).

Fluctuations of Conserved Charges at BES-I

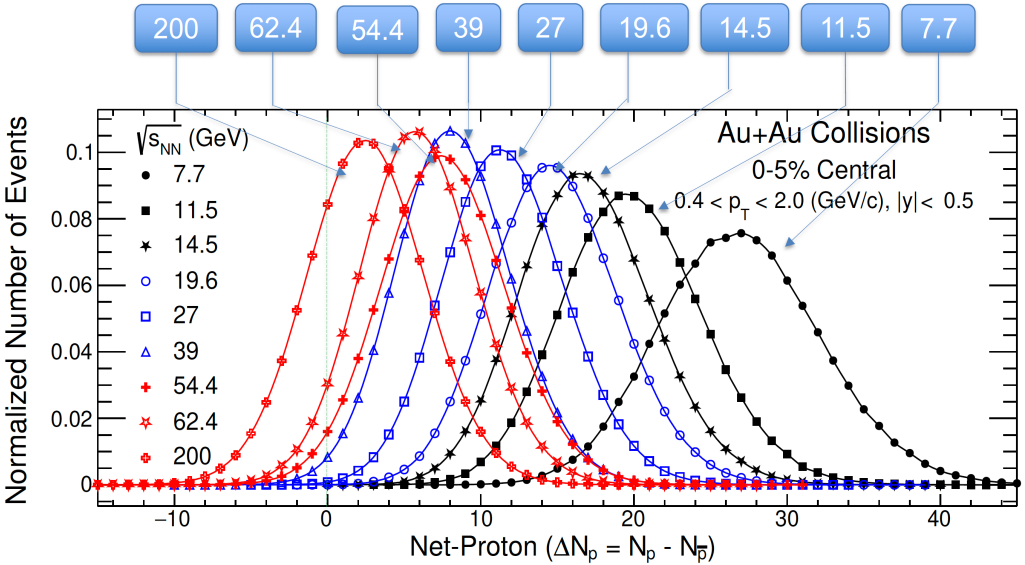


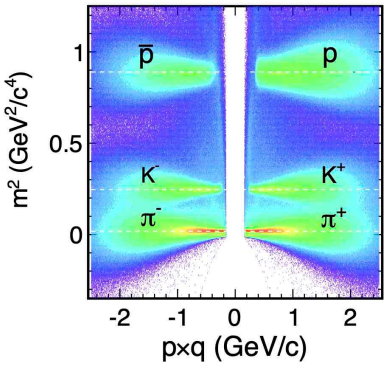


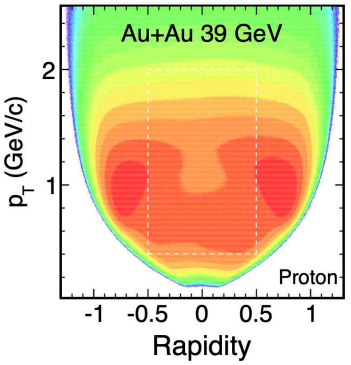
- First Measurement of High Order Net-Proton Fluctuations
- Verified the feasibility of the observable in heavy-ion experiment.

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

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)

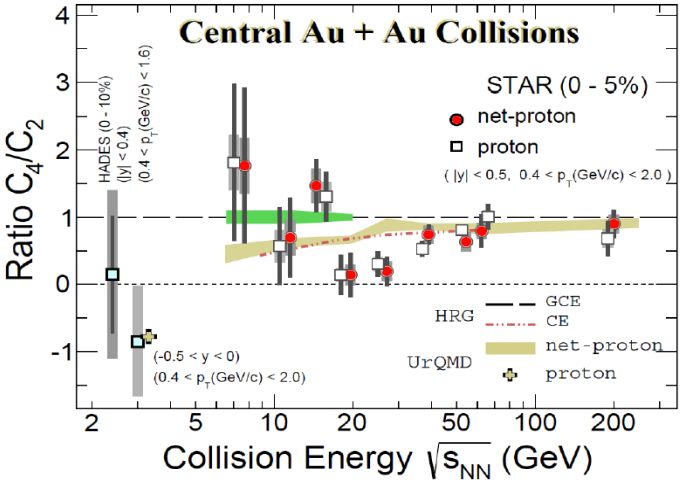
Stat. err: $C_r \propto \frac{\sigma^r}{\sqrt{N}}$

- **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

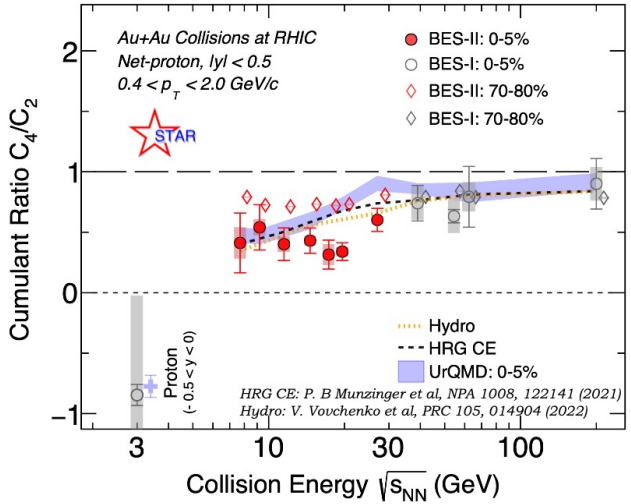
Net-Proton Fluctuations in BES-I and BES-II

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)

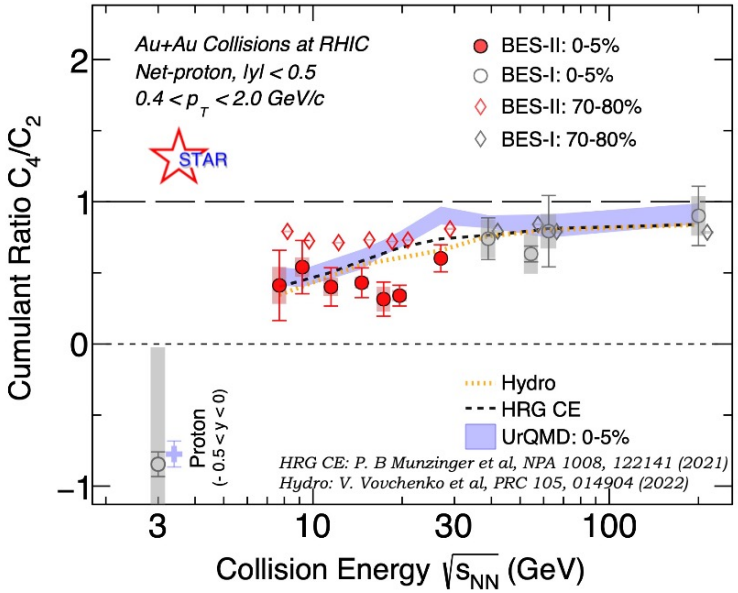


STAR: Phys. Rev. Lett. 105, 022302 (2010)
Phys. Rev. Lett. 112, 032302 (2014)
Phys. Rev. Lett. 126, 092301 (2021)
Phys. Rev. Lett. 128, 202303 (2022)
Phys. Rev. C 104, 024902 (2021)
Phys. Rev. C 107, 024908 (2023)
HADES: Phys. Rev. C 102, 024914 (2020)

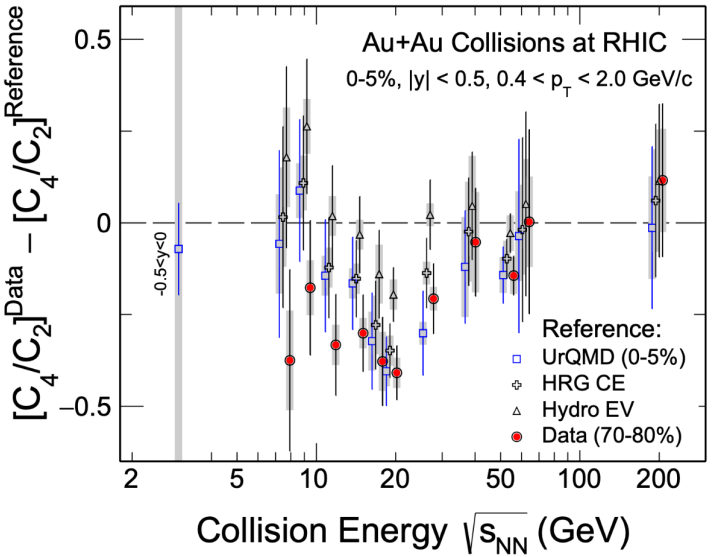
BES-II and BES-I results are consistent
BES-II : Better statistical precision
Larger Acceptance (| η |<1.6)
Better control on systematics

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

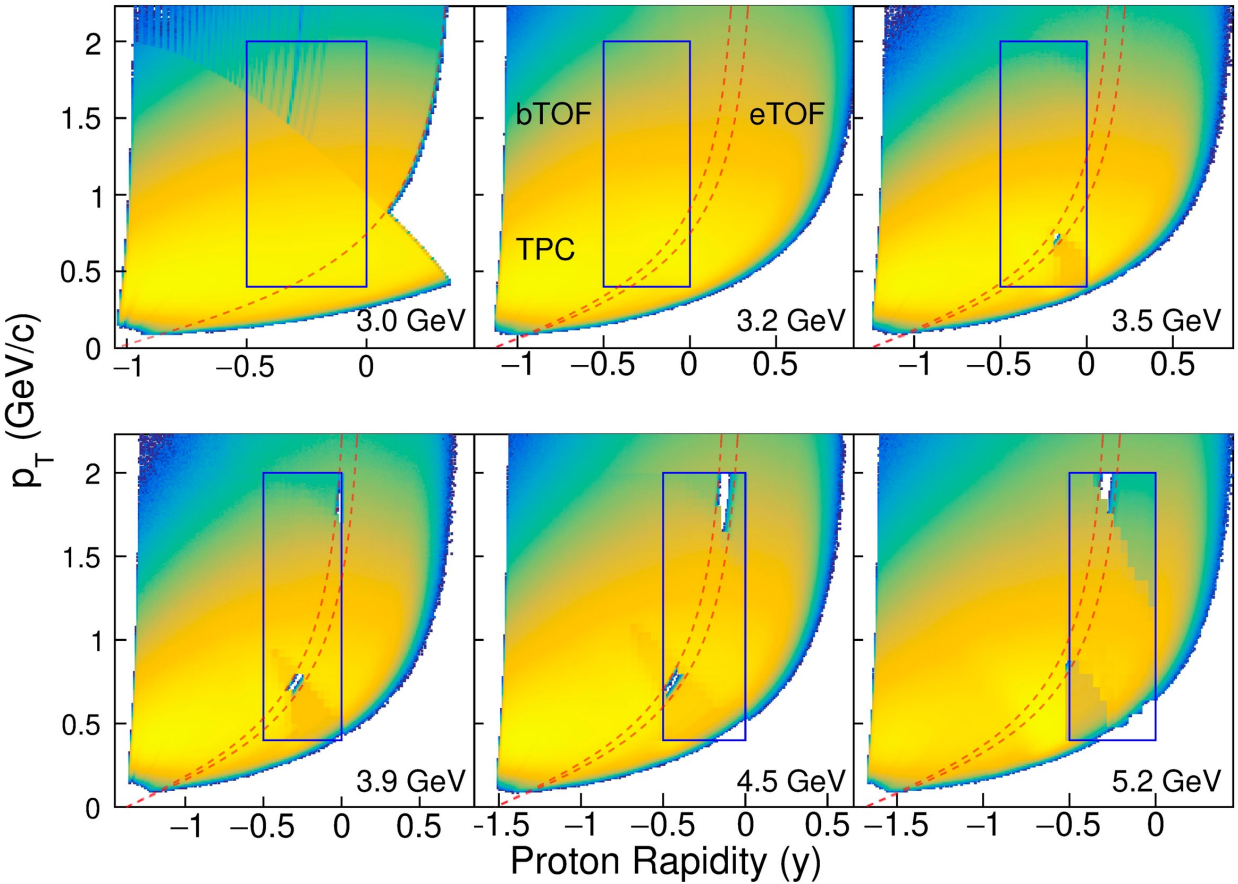


STAR : Phys. Rev. Lett. 135, 142301 (2025)
[Editor Suggestion, Featured in Physics]

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



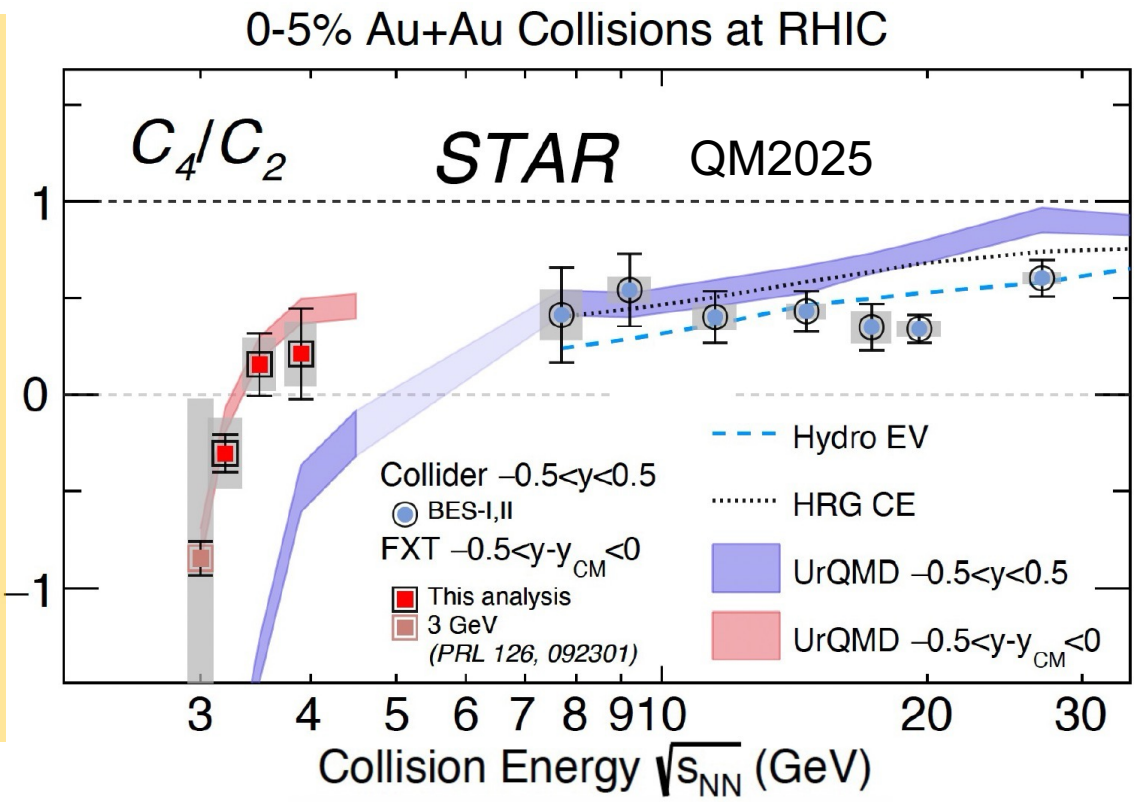
1) TPC, iTPC, bTOF, eTOF are used in the FXT program;

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

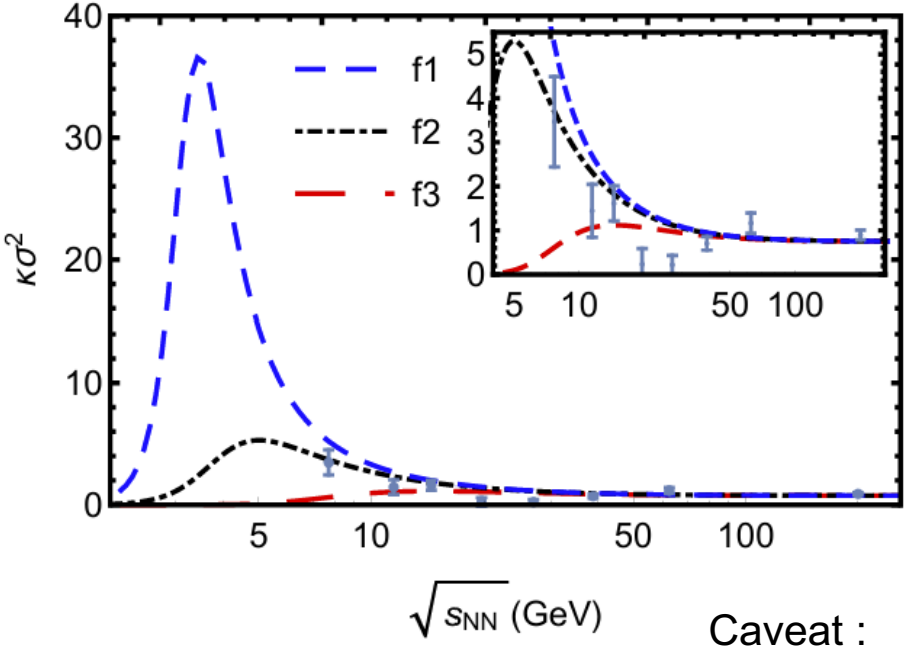
1) Collider mode: |y| <0.5
   FXT mode: -0.5 < y < 0.0
2) 3.0, 3.2, 3.5 and 3.9 GeV data were shown at QM2025
3) Data and UrQMD calculations are consistent for the FXT results. However, at the lowest energies, values of C_4/C_2 become negative: Centrality resolution issue



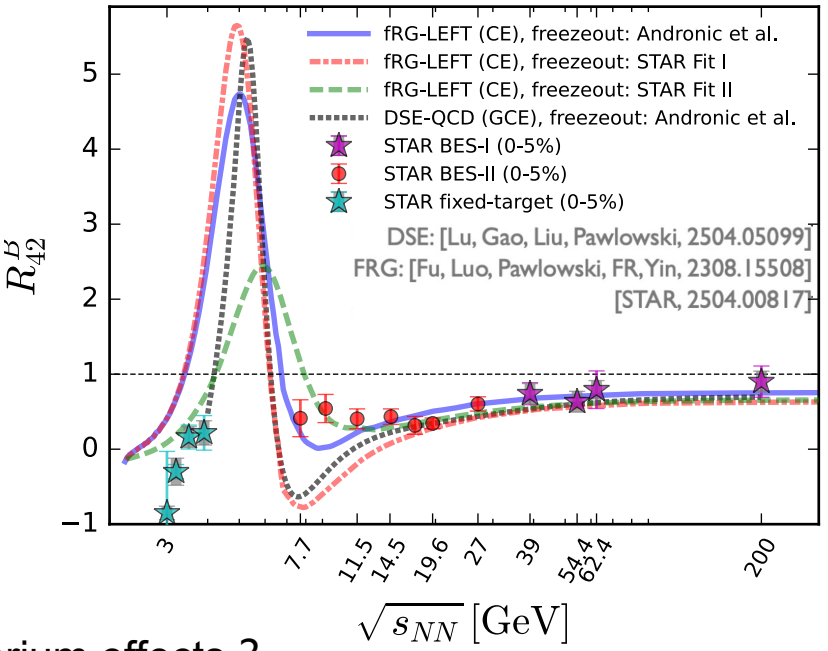
STAR 3GeV data (collected in 2018):
Phys. Rev. Lett. 128, 202303 (2022)
Phys.Rev. C107, 024908 (2023)

Baryon Number Fluctuations from Theory/Model Calculations

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



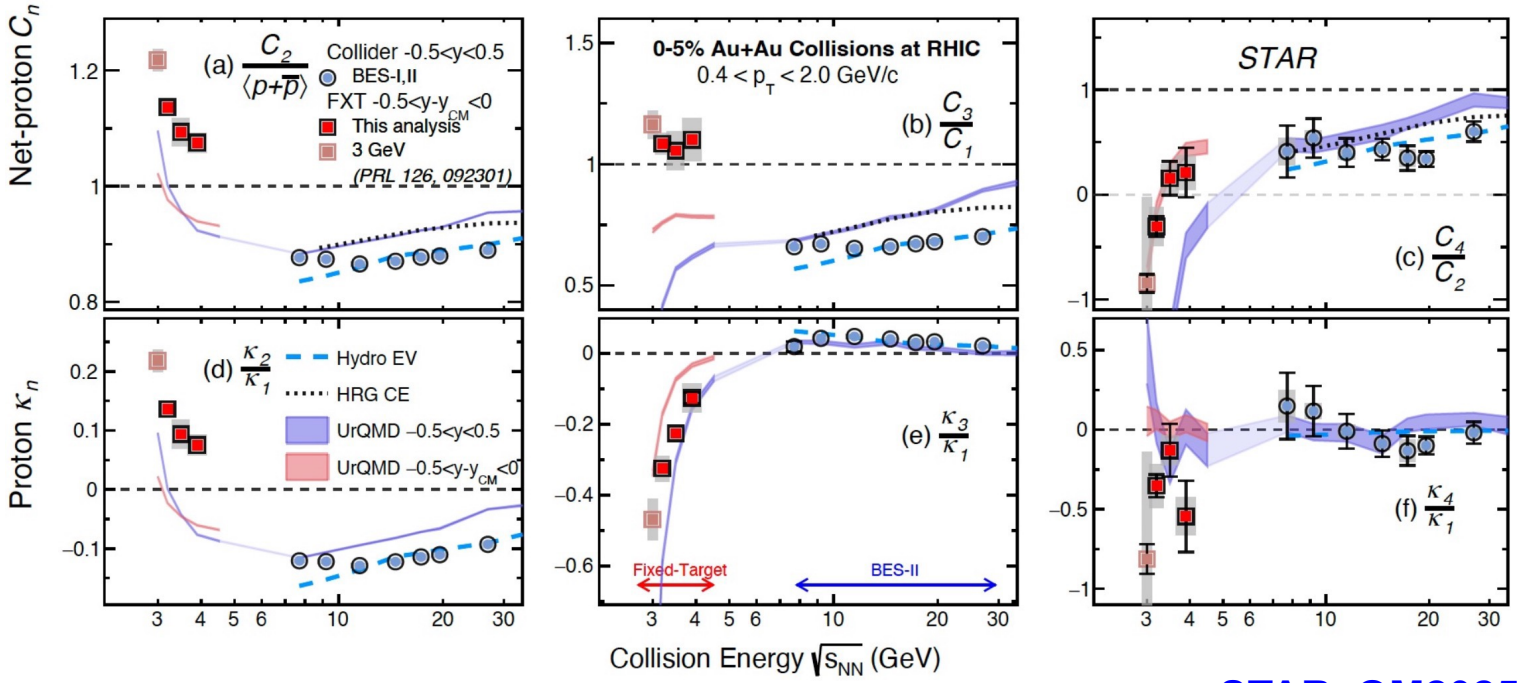
Fabian @ QM2025, plenary
Wei-jie Fu @ QPT2025, plenary



Caveat :
Non-equilibrium effects ?

- 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 ?

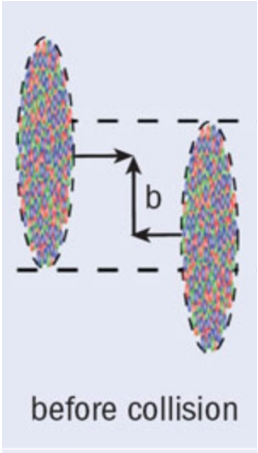


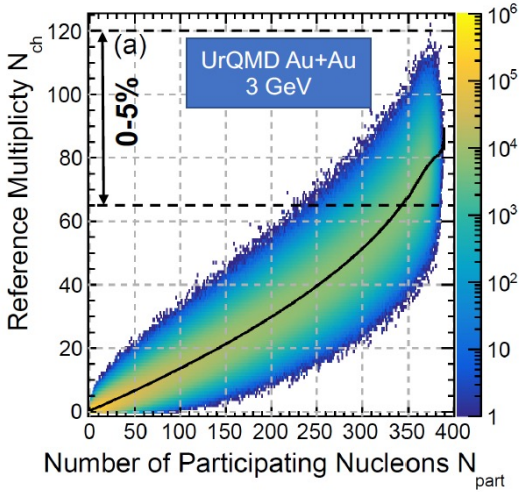
STAR, QM2025

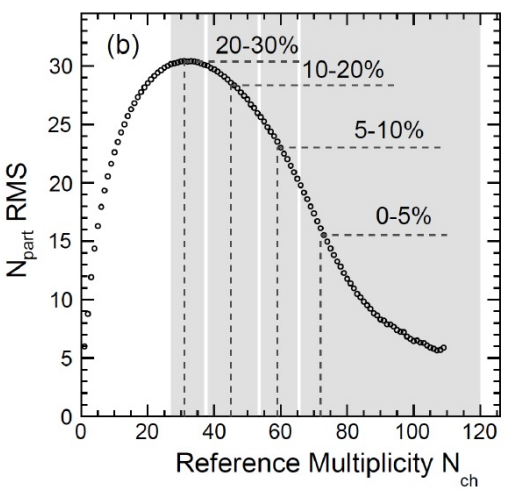
At 3.0 – 3.9 GeV central collisions (0-5%, -0.5<y<0):

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





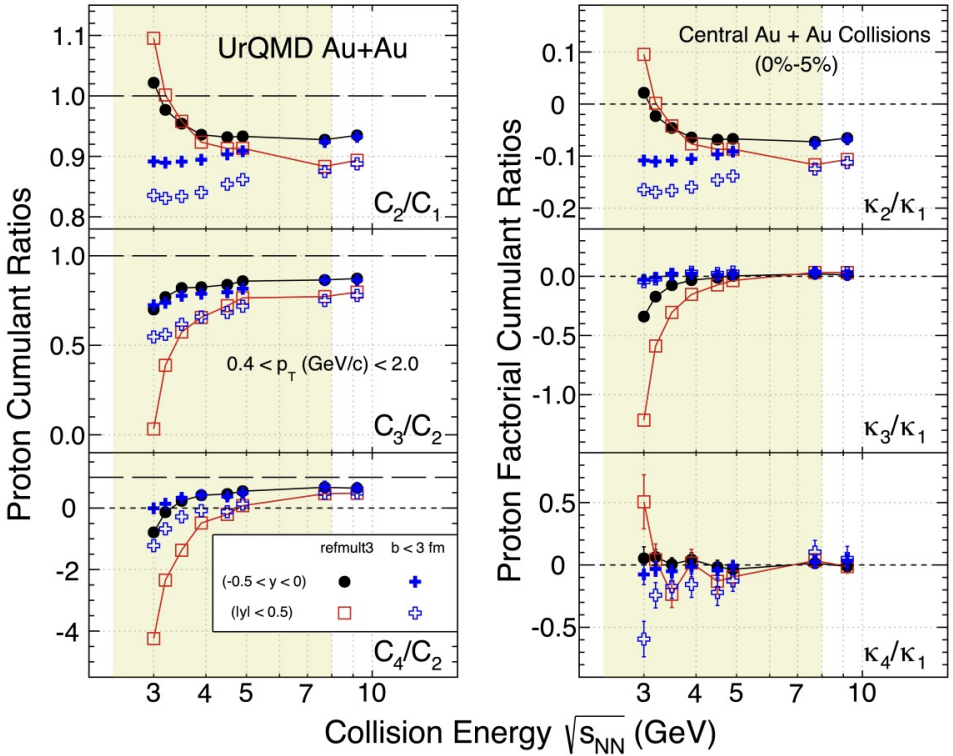


- Initial volume fluctuations are well known and large background for cumulant analysis, especially for low energies.

X. Luo, J. Xu, B. Mohanty, N. Xu, J. Phys. G40.105104 (2013),
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)

UrQMD Simulations : Effects of Volume Fluctuations on Cumulants

Centrality Bin With Correction (CBWC) is applied.

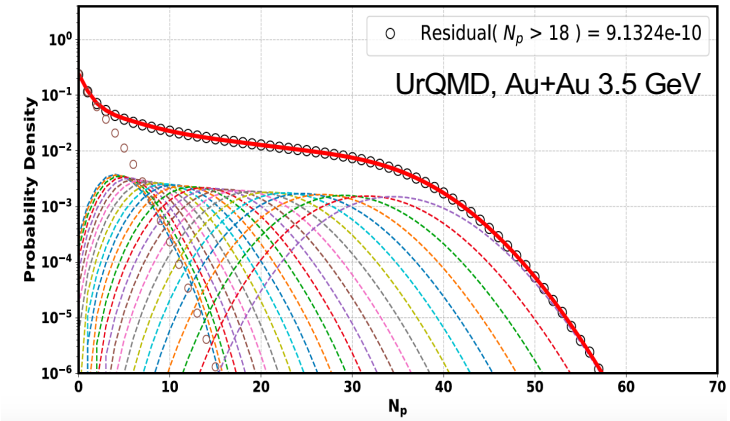


1) **Initial Volume Fluctuation**: The collision centrality is determined by charged particle multiplicities. Even in the same centrality bin, the collision volume varies event by event;
2) Simulations indicate that effects of the initial volume fluctuations becomes stronger at lower collision energies, 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

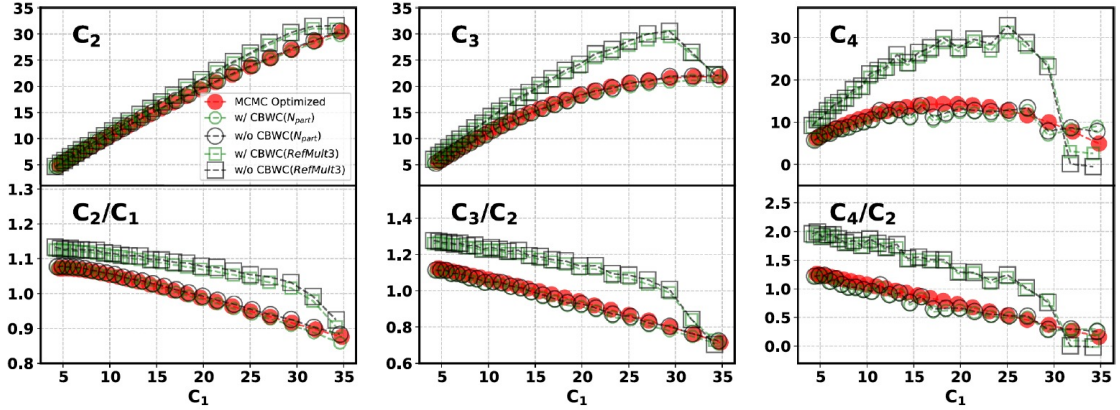
X. Zhang, Y. Zhang, XFL, N. Xu, Chin. Phys. C 50, 011003 (2026)

B. Friman, V. Koch, arXiv : 2511.11869

A New Approach (CIGAR) to Suppress VF



UrQMD, Au+Au 3.5 GeV



Centrality-Independent Genuine cumulant Analysis frRamework (CIGAR)

Edgeworth expansion :

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

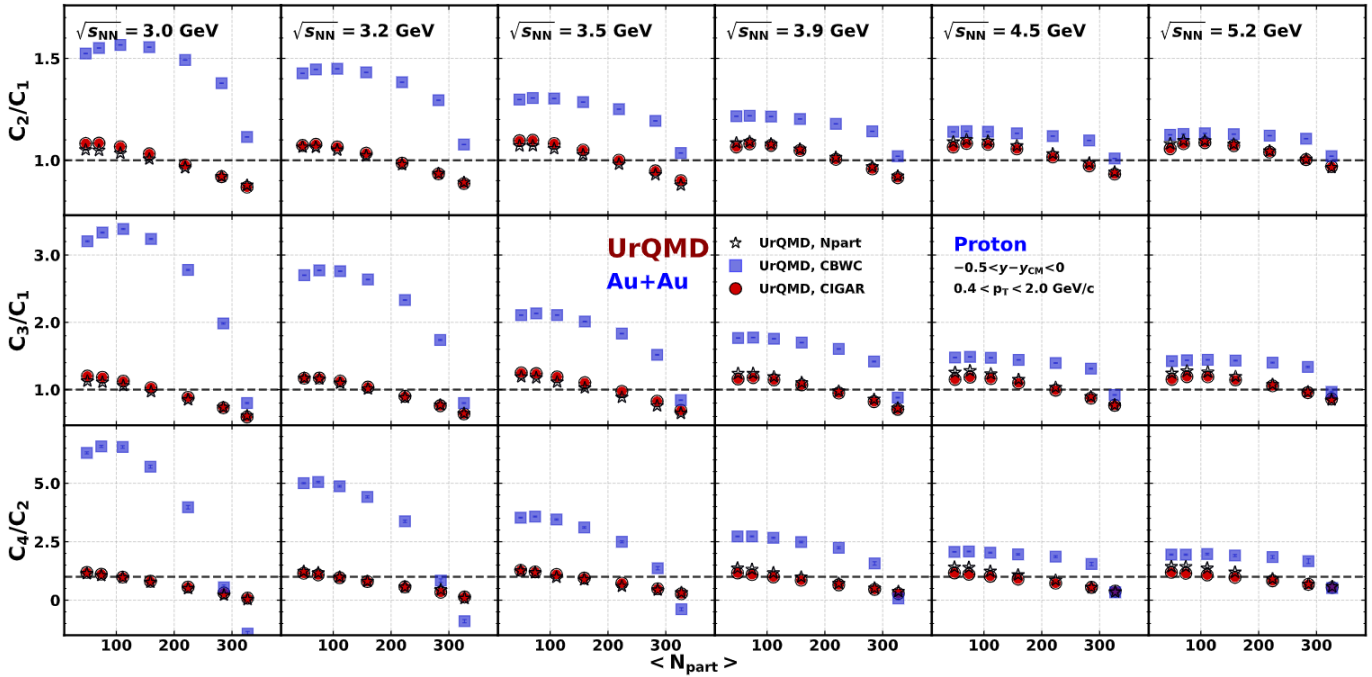
Z. Wang (汪朝辉), XFL, Phys. Lett. B 871, 139984 (2025)

Z. Wang (汪朝辉), CPOD 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) , which is applied to the STAR data analysis. New results at FXT energies will be presented at QM2027

UrQMD simulation : Methods Comparison at Low Energies



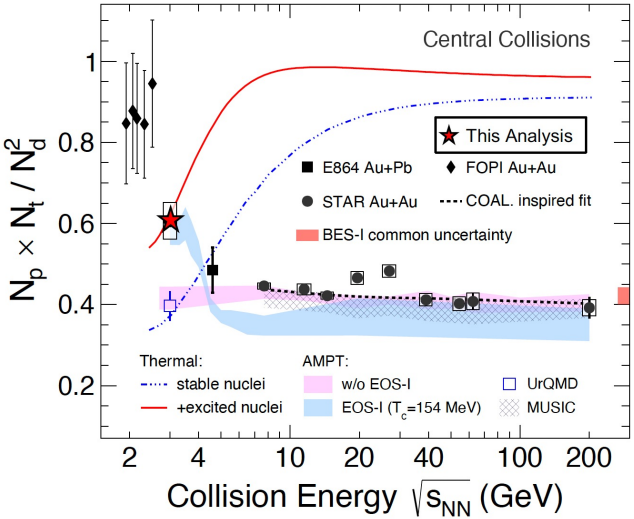
- At low energies, the CBWC method fails to suppress the volume fluctuation and the C4/C2 in central collisions become negative.

  Wang&Luo, Phys. Lett. B 871, 139984 (2025)

- The results from CIGAR method converge to the Npart-based centrality results, indicating the new method can effectively suppress volume fluctuations.

Other Possible Observables for CEP Search

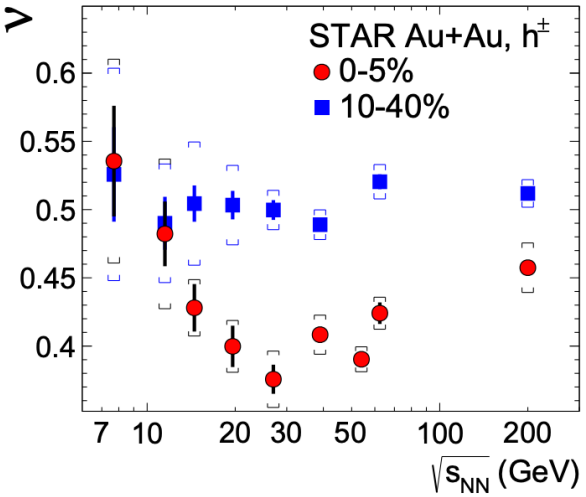
Light Nuclei Production



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

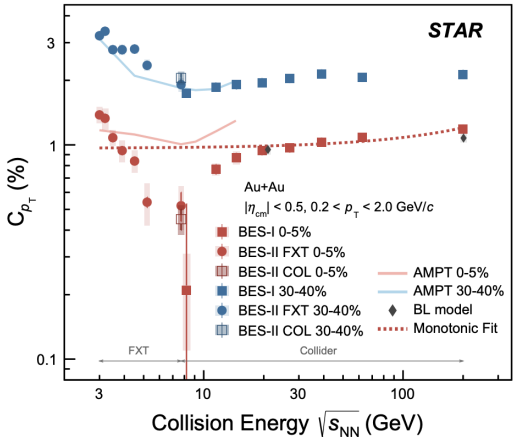
STAR: Phys. Rev. Lett 130, 202301 (2023)

Intermittency of Charged Particles



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

Transverse Momentum Correlations



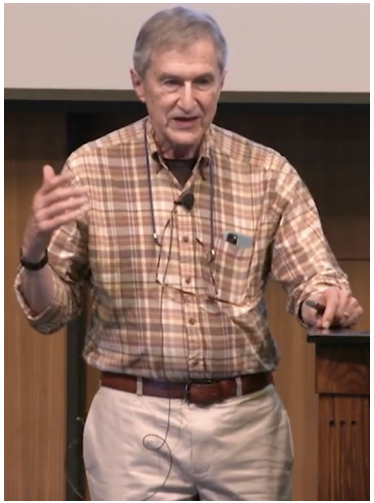
STAR, Phys. Rev. Lett. 137, 132301 (2026)

BES-II results are under collaboration review

Search for the Strange Dibaryon

A state with six quarks and non-zero strangeness

H-Dibaryon (S = -2)



(1946-)

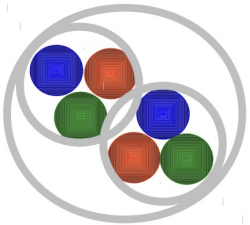
1977年，Jaffe predicted dihyperonn (H) : deeply bound ΛΛ system (uuddss), (J=0, S= -2, m~2150 MeV), 81 MeV below ΛΛ mass the. (2231)。

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)

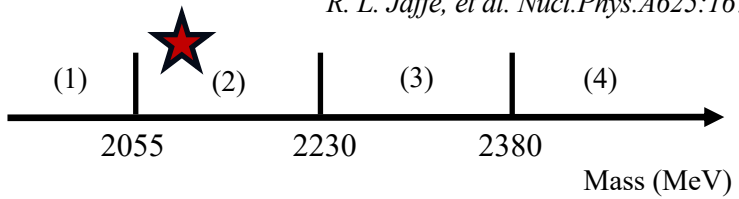


Over the more than 40 years that followed. multiple experimental groups have attempted to find it, such as the J-PARC E42 experiment in Japan, the RHIC-STAR/AGS experiments in the United States, and the LHC-ALICE/SPS experiments in Europe, etc, still elusive.

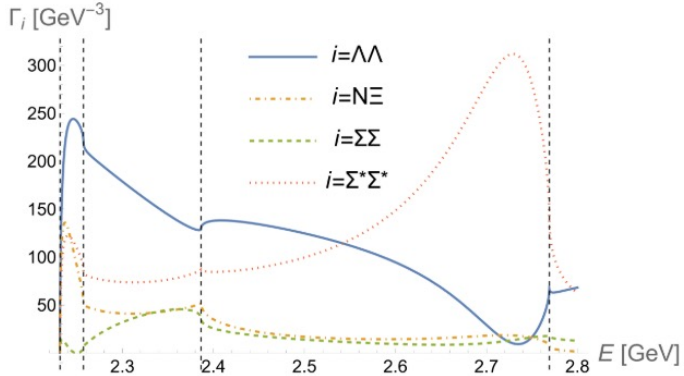
Review： H. Clement, Progress in Particle and Nuclear Physics 93, 195 (2017)

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

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

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

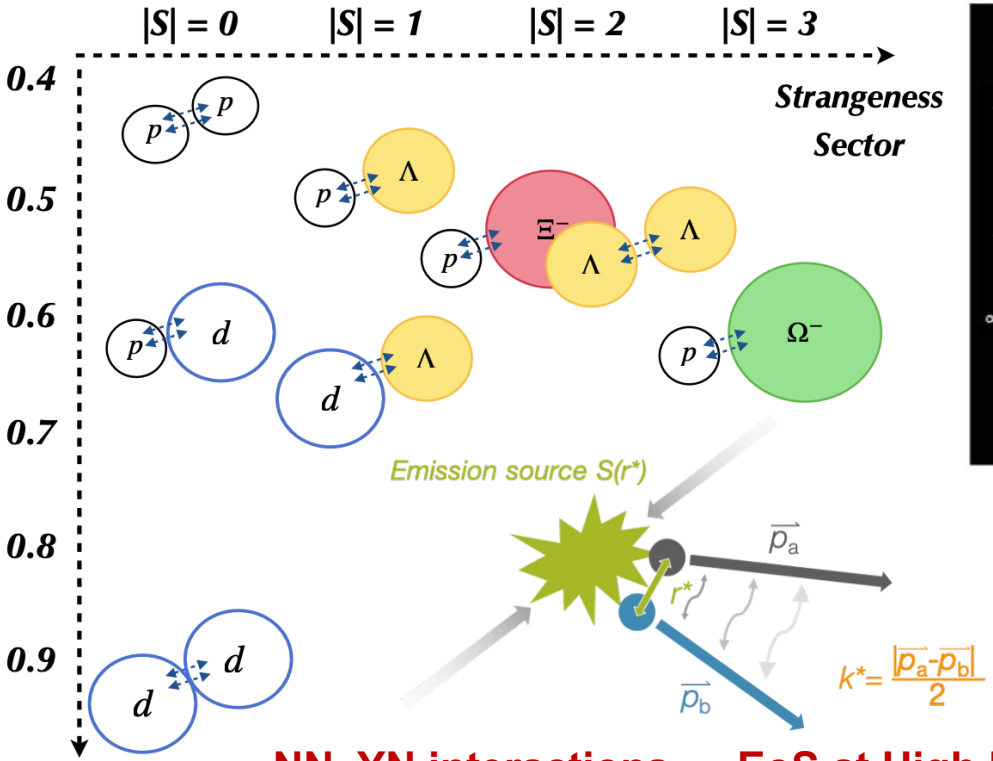
H. Pang, J. Ping, F. Wang, T. Goldman, E. Zhao, PRC-69-065207 (2004);
H. Pang, J. Ping, L. Chen, F. Wang, T. Goldman, PRC-70-035201 (2004);
M. Chen, H. Huang, J. Ping, F. Wang, PRC-83-015202 (2011);
H. Huang, J. Ping, F. Wang, PRC-92-065202 (2015)

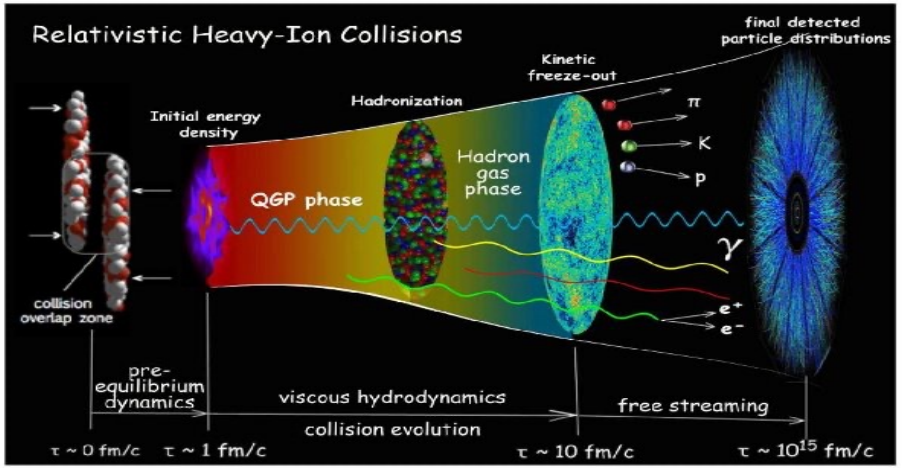
ΩΩ

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



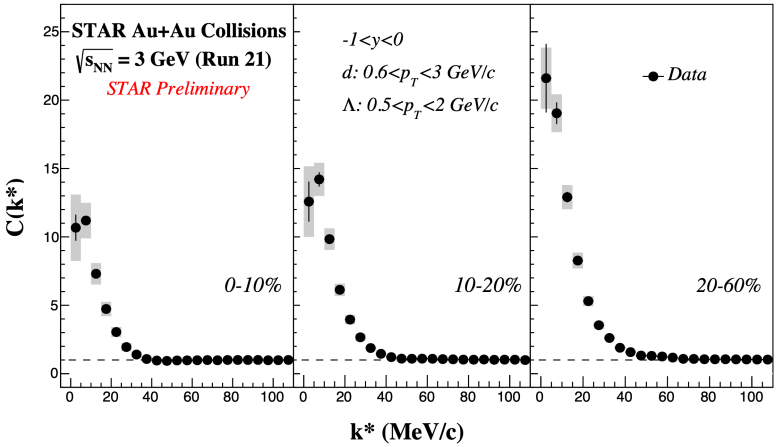


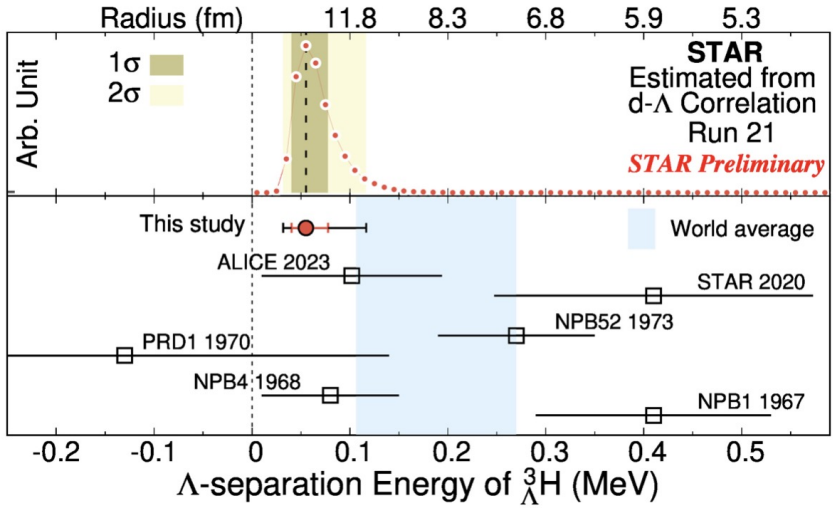
Heavy-ion collisions produce a large number of nucleons and hyperons, making it an ideal setting for studying the properties of strong interactions.

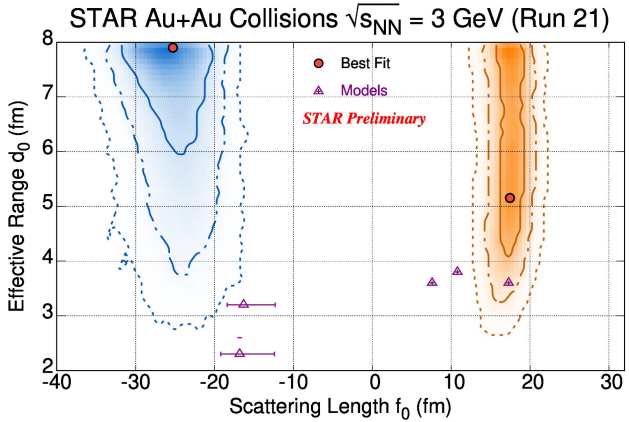
NN, YN interactions : EoS at High Baryon Density

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

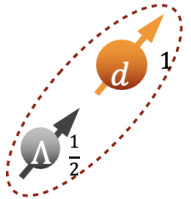
First Observation of deuteron – Λ Correlations







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

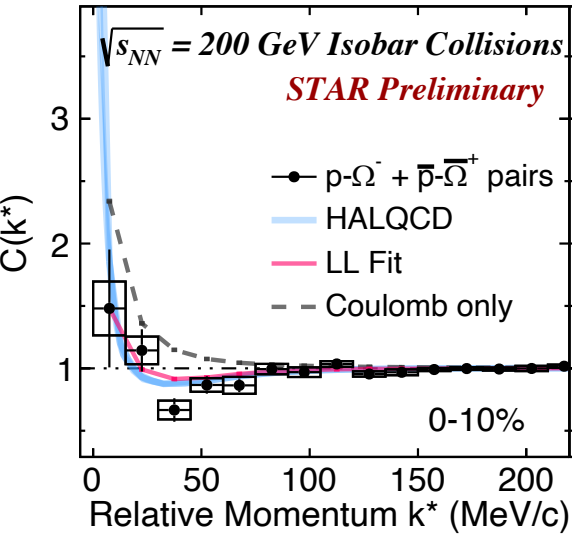


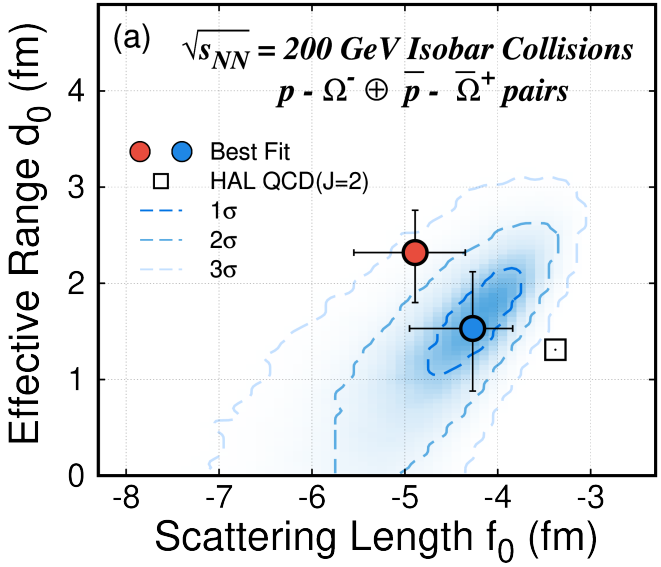
$$^3_\Lambda\mathrm{H}\ B_\Lambda = 0.06^{+0.06}_{-0.03}\ \text{(MeV) @ 95\% CL}$$

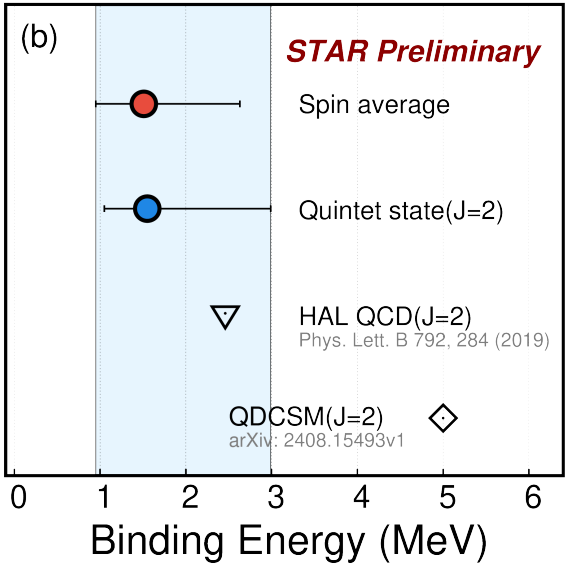
Extracted physical parameters:
f_0 (D) = −25.3±3.3 fm
f_0 (Q) = 17.5±1.6 fm

Xialei Jiang (STAR), QM2025
STAR, Phys. Rev. Lett. 136, 242303 (2026)

p-Ω^- Correlation Function (S = -3)







Kehao Zhang (STAR), QM2025

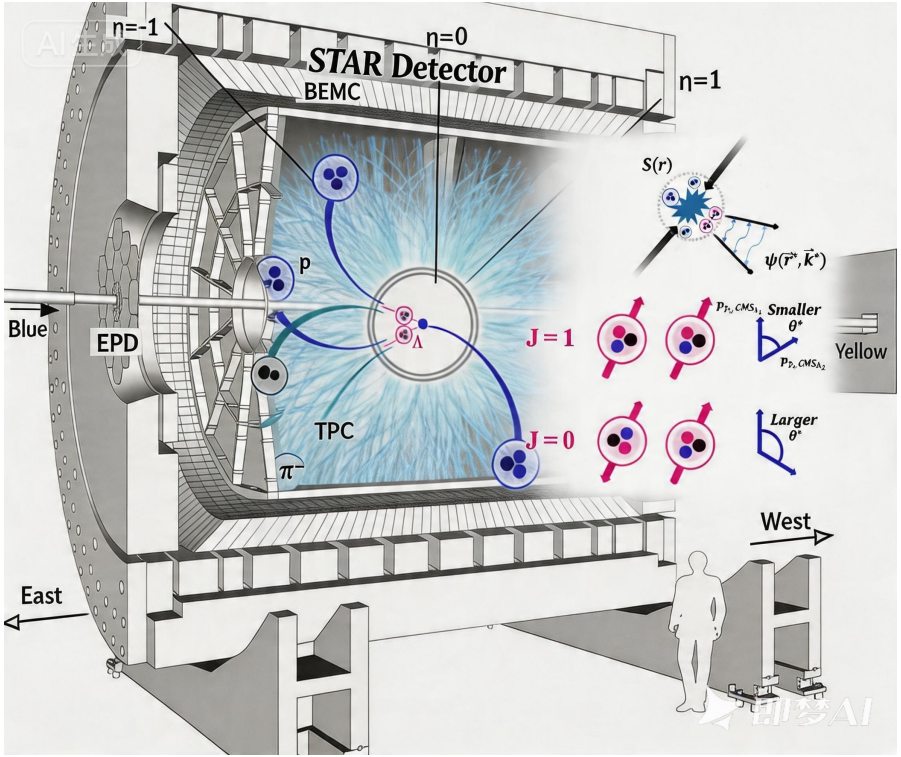
	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.89^{+0.54}_{-0.66}$	$-4.27^{+0.43}_{-0.68}$	-3.38
d_0 (fm)	$2.32^{+0.44}_{-0.52}$	$1.53^{+0.54}_{-0.66}$	1.31
BE (MeV)	$1.51^{+1.12}_{-0.56}$	$1.55^{+1.44}_{-0.50}$	2.27

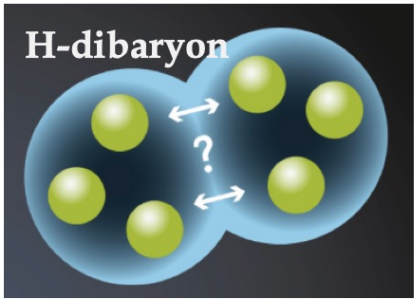
I. First experimental constraints in heavy-ion collisions of strong interaction parameters in p-Ω^- pair

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 at STAR



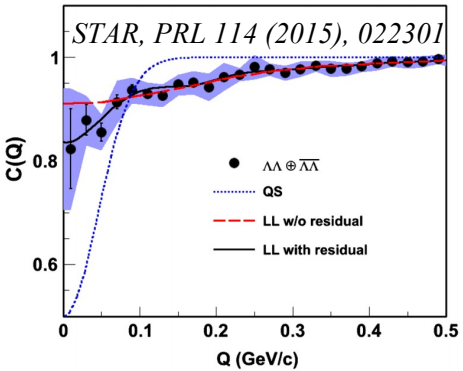


Possible channel:

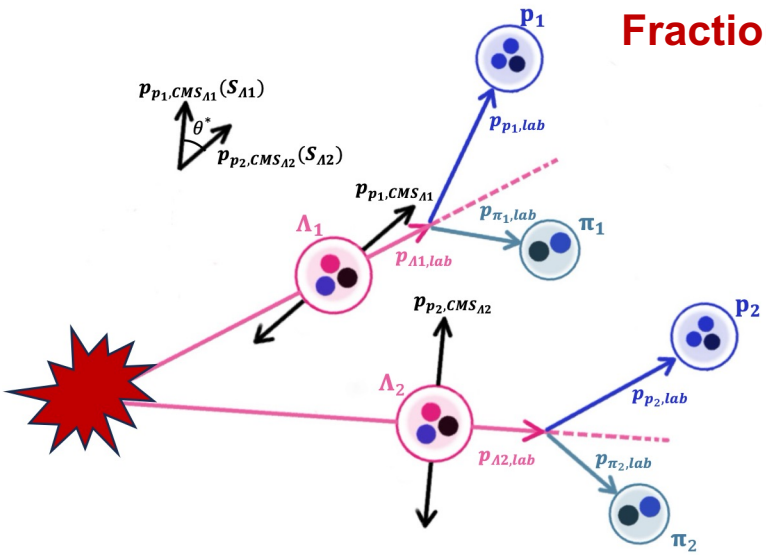
H-dibaryon $\Leftrightarrow p + \Xi$

H-dibaryon $\Leftrightarrow \Lambda + \Lambda$

H (J=0) -> Λ+Λ



H-Dibaryon Searches with Spin Femtoscopy Method

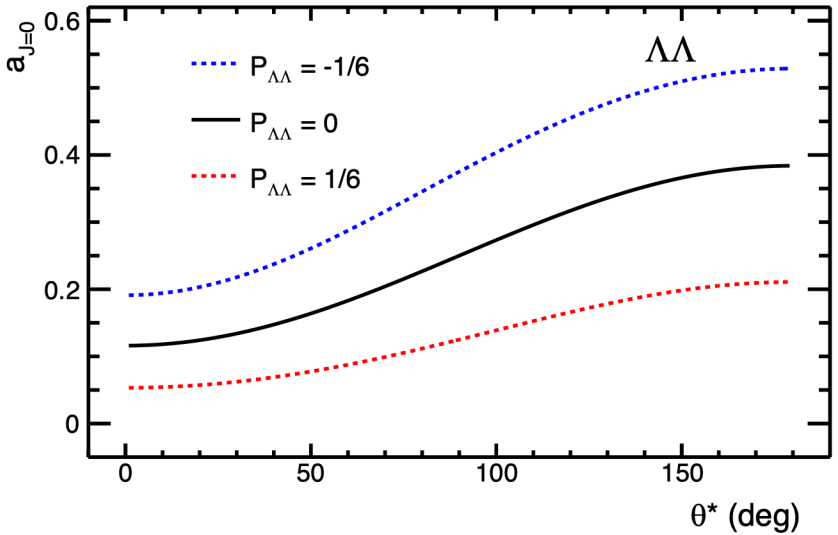


Λ rest frame

Self-analyze of Λ weak decay

Fraction of J=0 ΛΛ state :

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



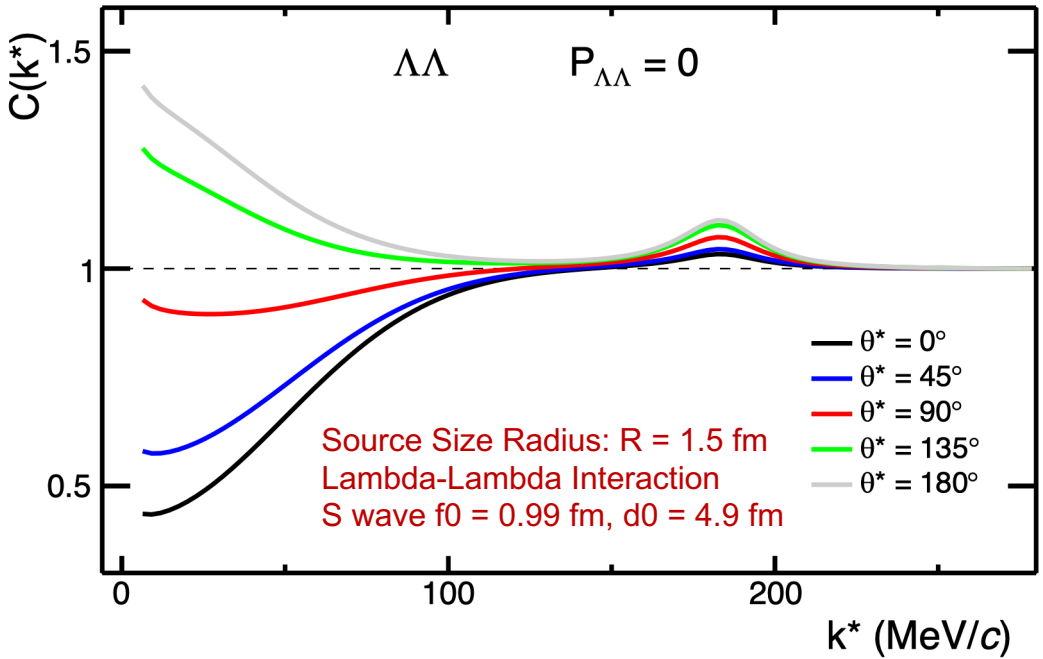
K. Zhang, X. Wang, XFL, arXiv: 2607.00413

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
assume :
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:

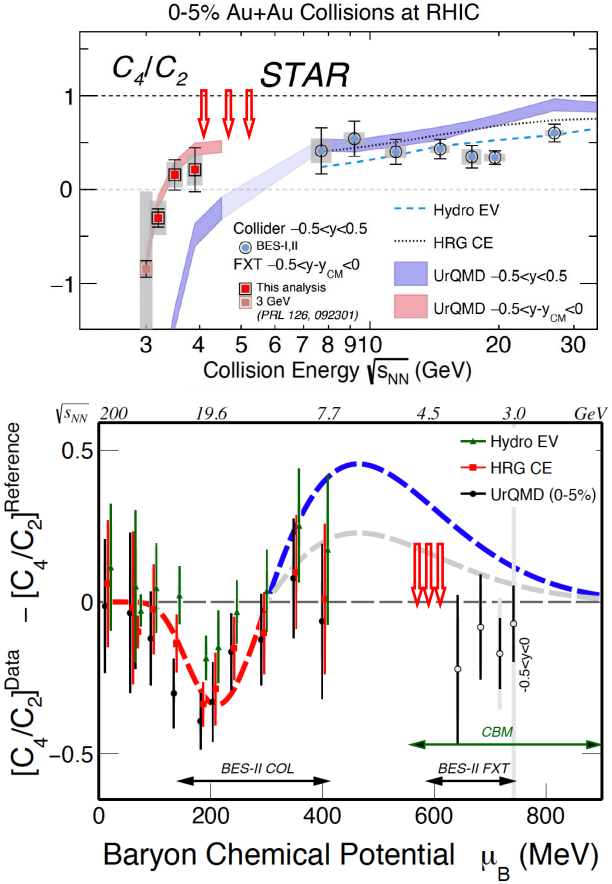
  Collider energies: for net-proton C_4/C_2 in central collisions, deviations of 2-5σ are observed w.r.t non-CP reference at 19.6 GeV

  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 suppress the initial volume fluctuation. Reanalyzing all data sets including 4.2, 4.5 and 5.2 GeV Au+Au collisions is under way;

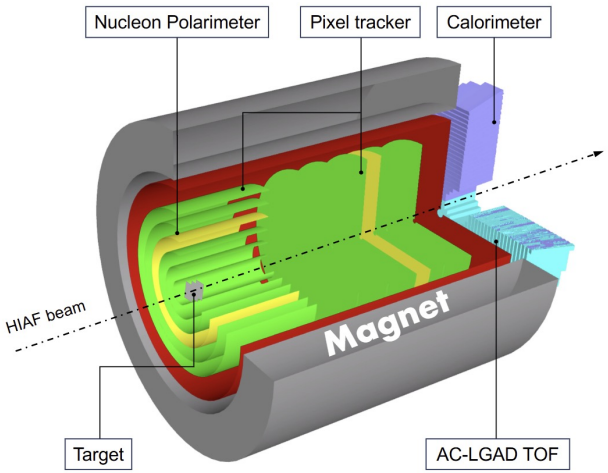
- Modeling with dynamical effects including critical fluctuations and non-equilibrium effects are crucial to understand the experimental data

- 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

The 3rd International Workshop on Physics at High Baryon Density (PHD2026, 第三届高重子密度物理国际研讨会)

Nov 10 – 13, 2026
Crowne Plaza Xinghai, Dalian, China
Asia/Shanghai timezone

https://indico.ihep.ac.cn/event/29146/

Enter your search term

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:

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Weijie Fu (Dalian University of Technology, co-Chair)
Defu Hou (Central China Normal University)
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)

Welcome to PHD2026 in Dalian!



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 !