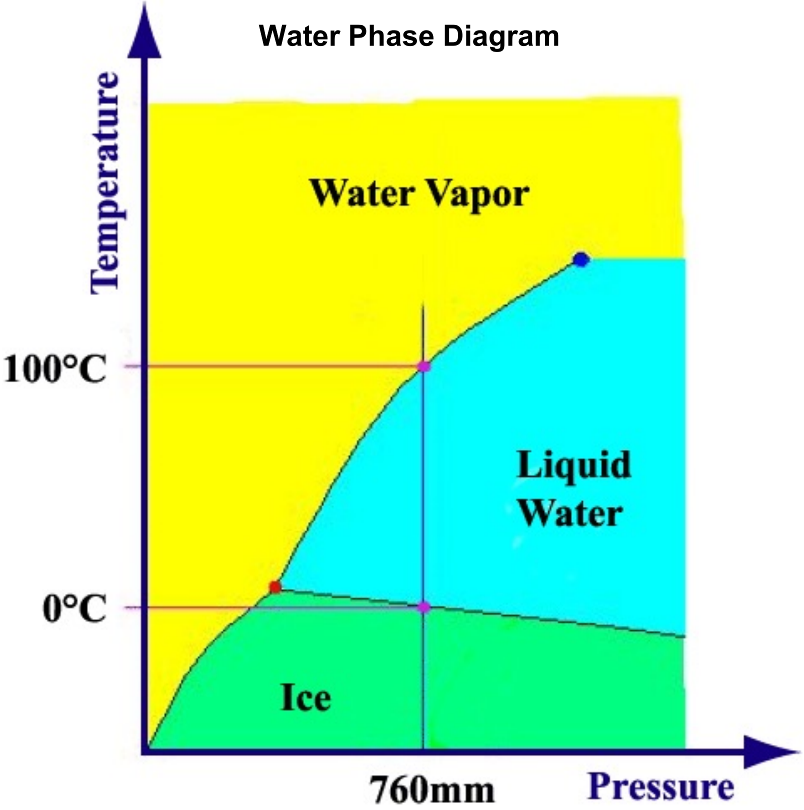
# Exploring the QCD Phase Diagram and Critical Point with Beam Energy Scan at RHIC

Xiaofeng Luo

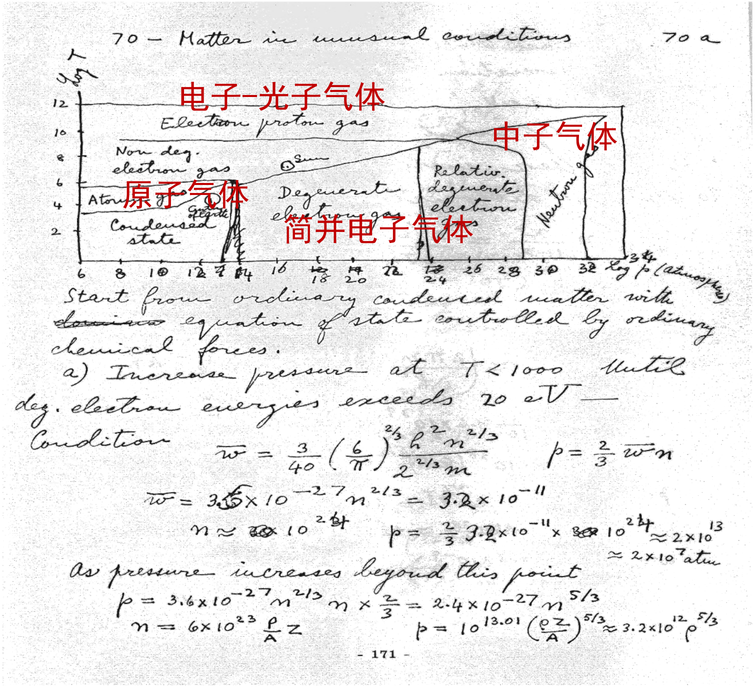
Central China Normal University
Dec. 10th, 2025

# Matters and Phase Transition in Extreme Condition

**Water Phase Diagram**




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




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

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

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

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

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

As pressure increases beyond this point

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

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

– 171 –

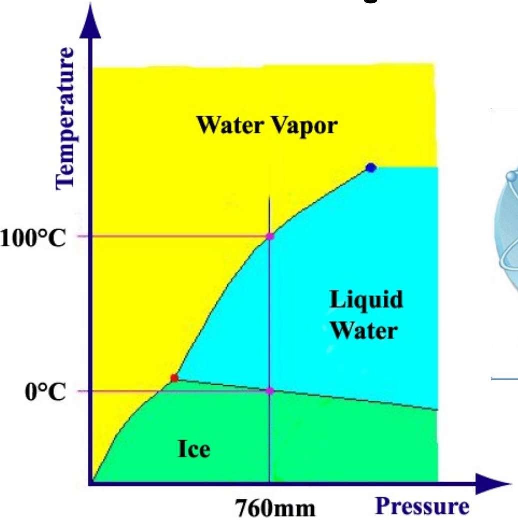
What are the states and phase structures of matter under extreme condition ?

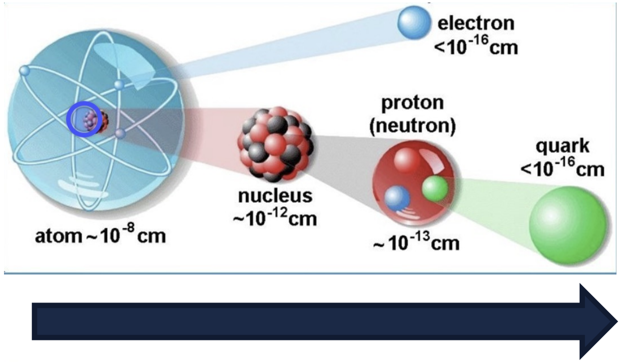
# QED/QCD Thermodynamics : More is Different

## QED

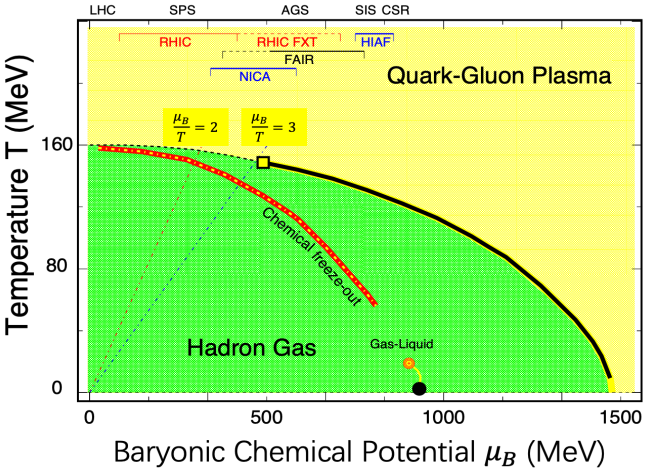
## QCD

### Water Phase Diagram




### QCD Phase Diagram




hundreds degrees Celsius (~100 ℃)

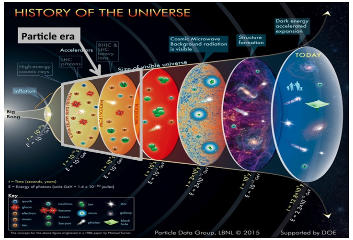
Trillions of degrees Celsius ($10^{12}$ ° C)

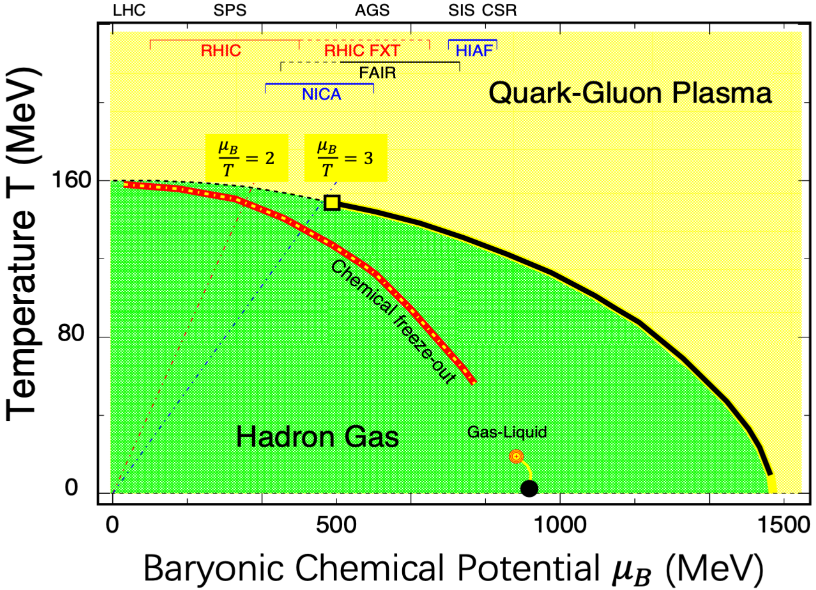
Fundamental DoF: Water molecules
Dominant interaction: electromagnetic

Fundamental DoF: quarks and gluons
Dominant interaction: strong interaction

# QCD Phase Diagram

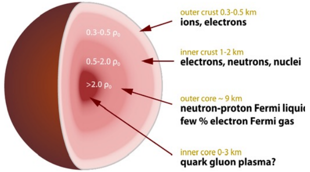
Emergent Properties of Strong Interactions, rich structure at high baryon density

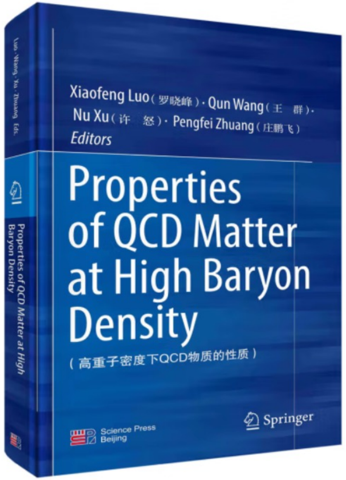



Lattice QCD : at $\mu_B = 0$, smooth crossover. $T_c$ ~ 156 MeV
Large $\mu_B$ : 1st order phase transition and QCD critical point ?

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).



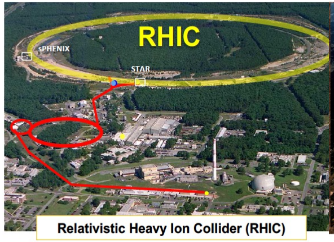

Key Physics : QCD phase structure and EoS of QCD matter at high baryon density.
(critical point and 1st order phase boundaries)

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

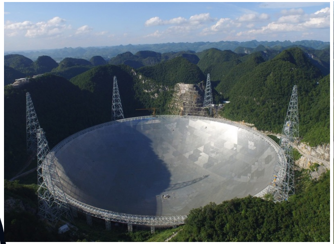
# “Multi-messenger”

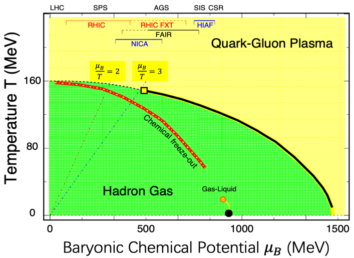
## Heavy-ion Experiment





## Astronomical Observations

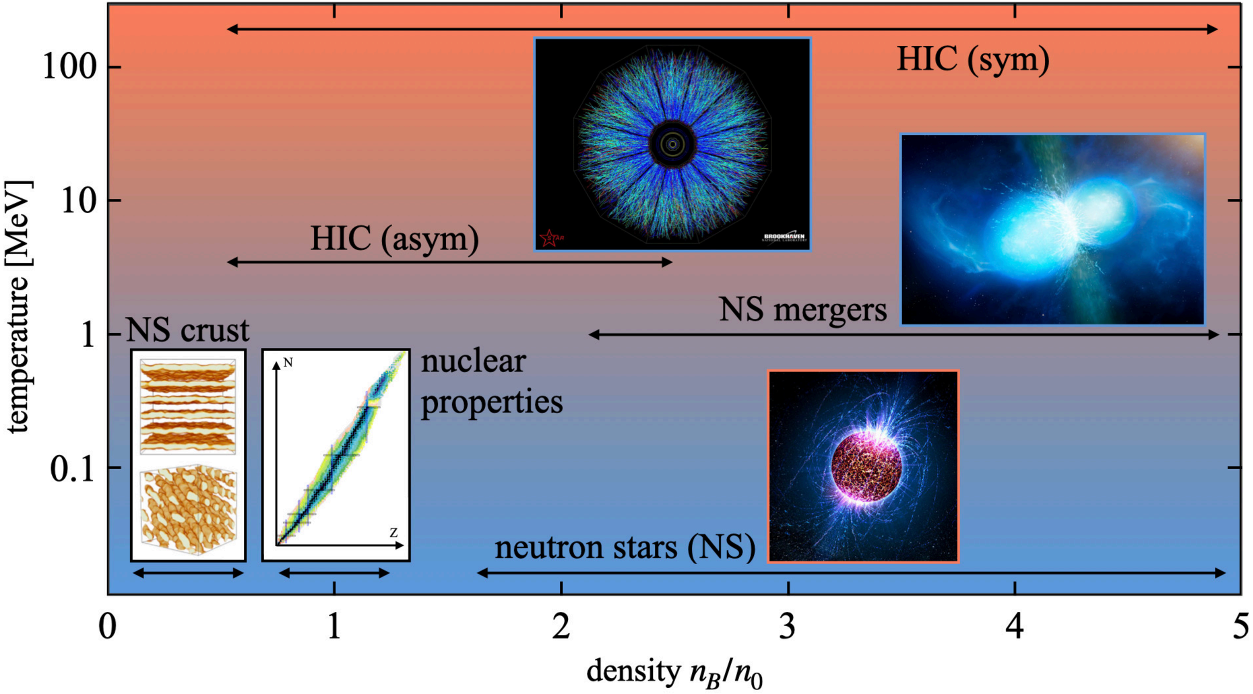




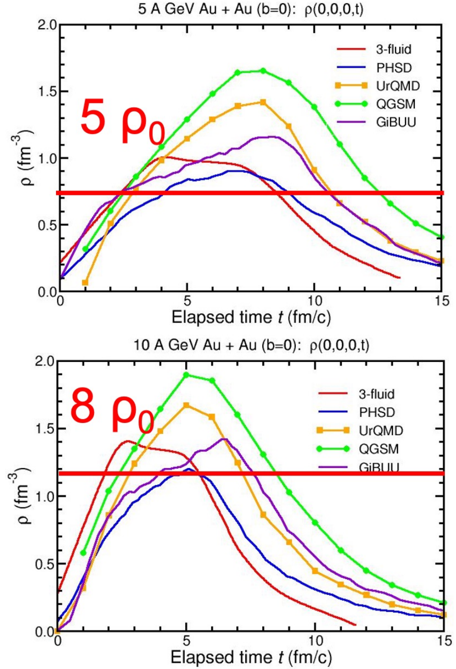

## Theory (Lattice QCD, FRG, DSE..)

# Dense Nuclear Matter

Agniezsk Sorensen, et al., arXiv : 2301.13253




**Baryon densities in central Au+Au collisions**




I. C. Arsene et al., Phys. Rev. C 75, 034902 (2007)

Heavy-ion collisions provide a unique and controlled experimental way to study the properties of nuclear matter at **high baryon density**.

FAIR SIS100 energies :
Temperature (T < 120 MeV)
Density ($\rho$ < ~ 8 $\rho_0$)
Reaction time : ~ $10^{-23}$ s

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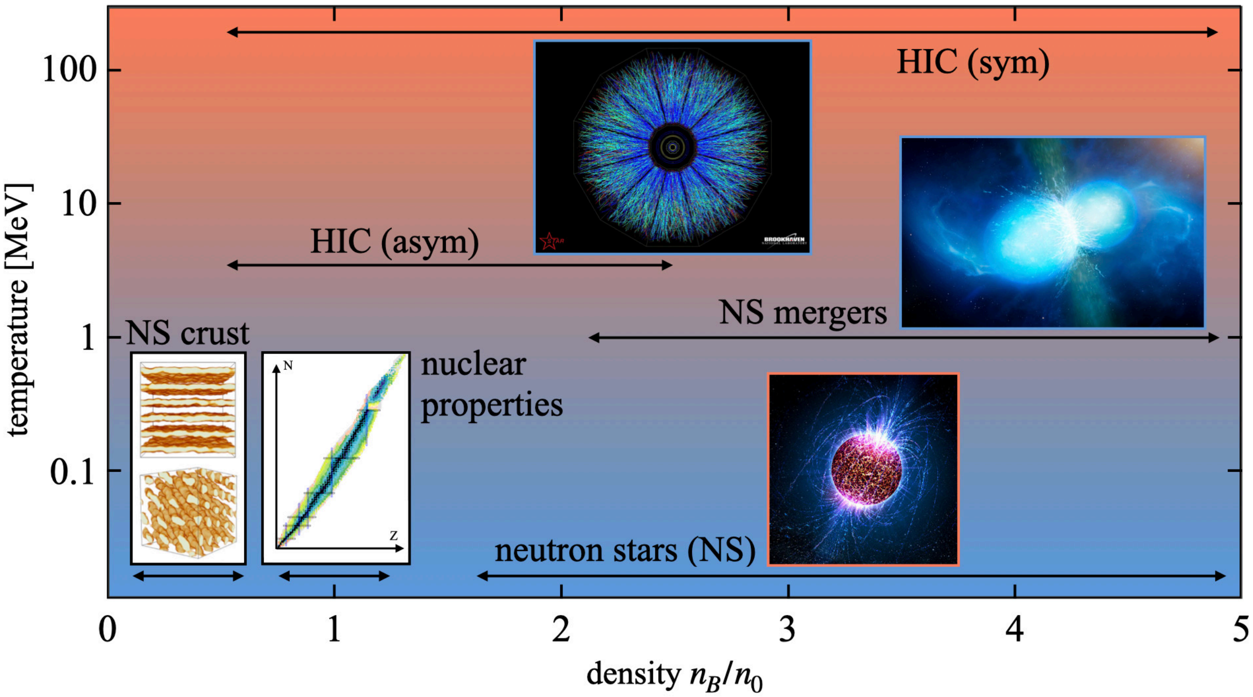
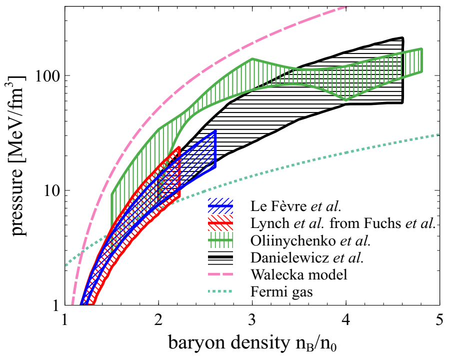
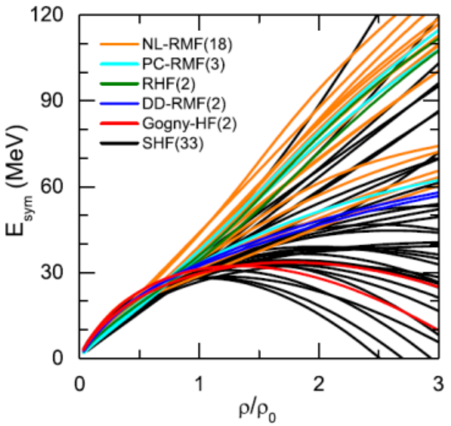
Agniezsk Sorensen, et al., arXiv : 2301.13253




B.A. Li, L.W. Chen, C.M. Ko
Phys. Rep. 464, 113(2008)

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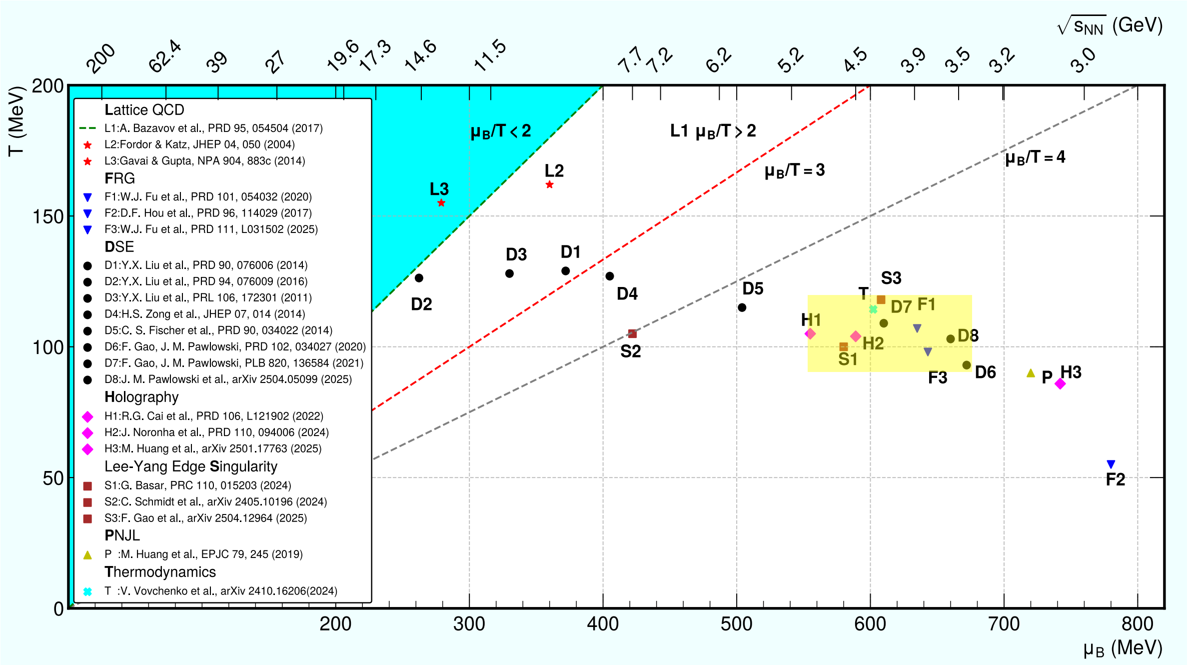
# Search for the QCD Critical Point

# Location of CEP : Theoretical Predictions/Estimations (2004-2025)




"**Focusing Region**" : $\mu_B^{CEP}$: ~ 550 – 700 MeV, $T^{CEP}$: ~ 90 – 118 MeV

FRG and DSE methods : **($T^{CEP}$, $\mu_B^{CEP}$ ) = (107, 635), (109, 610) MeV.**

Wei-jie Fu, J. M. Pawlowski, and F. Rennecke, Phys. Rev. D 101, 054032 (2020)
Fei Gao, J. M. Pawlowski, Phys. Lett. B 820, 136584 (2021)

# Relativistic "Minds" Collisions


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**

| | | |
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| 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) |
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| *12:15* | *Lunch* | |
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| 2:00 – 2:30 | Excitation function—onset of deconfinement | E. Shuryak (25+5) |
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| 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) |
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| *6:15* | *Reception and dinner* | |

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| | Luminosity monitoring issues | A. Drees (15+5) |
| | Low energy electron cooling | A. Fedotov (15+5) |
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Strategic workshop on the RHIC-STAR experiment: In 2005, RHIC released a white paper declaring the discovery of the sQGP, continuing RHIC operations required an urgent clarification of its next physics goals.

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## INT Workshop 2008-2b : The QCD Critical Point

Organizers: Volker Koch, Gunther Roland, Mikhail Stephanov

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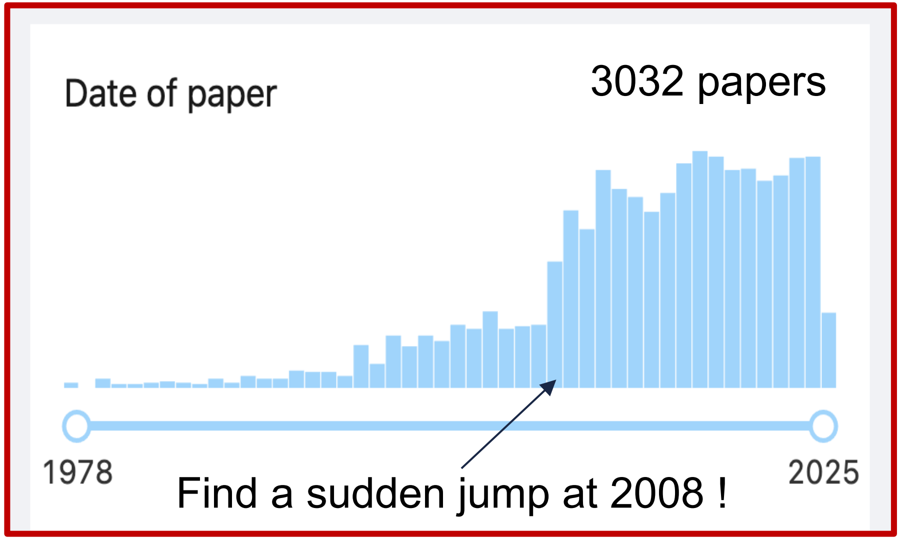
| July 28, 2008 | S. Gupta | "New results in QCD at finite $\mu$" |
| July 29, 2008 | M.P. Lombardo | "The QCD critical point at imaginary mu" |
| July 29, 2008 | S. Ejiri | "Numerical study of the critical point in lattice QCD at high temperature and density" |
| July 30, 2008 | K. Fukushima | "What 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"<br>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"<br>Part 2<br>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)

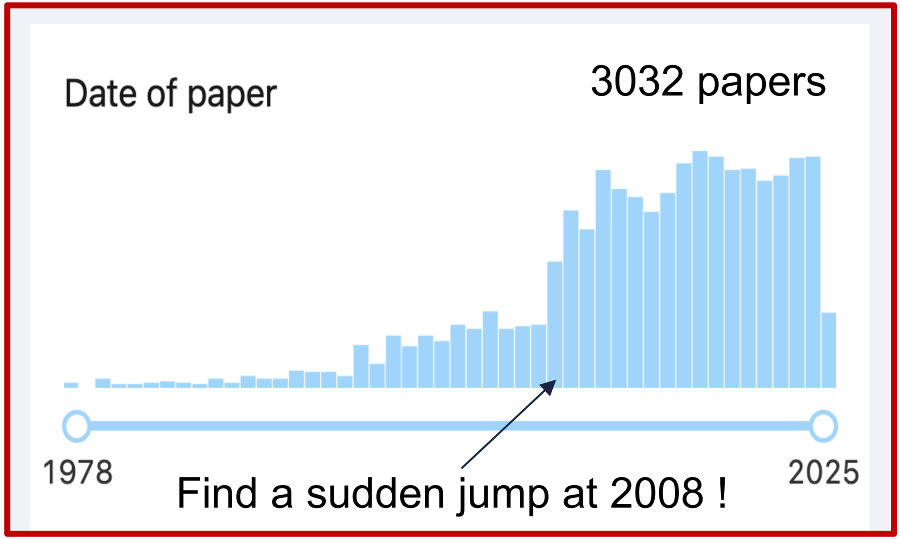
Search for the “QCD critical point” in Inspires
https://inspirehep.net/




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

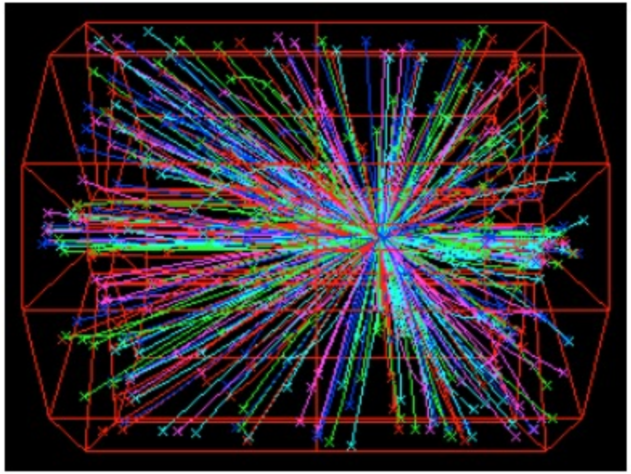
# RHIC Ramping into the Era of Beam Energy Scan (2008-2010)

Search for the "QCD critical point" in Inspires
https://inspirehep.net/




The "QCD critical point" related study jump into a 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.

# INT Workshop 2025-3a : The QCD Critical Point: Are We There Yet?

## The QCD Critical Point: Are We There Yet?

**October 27, 2025 - November 7, 2025**

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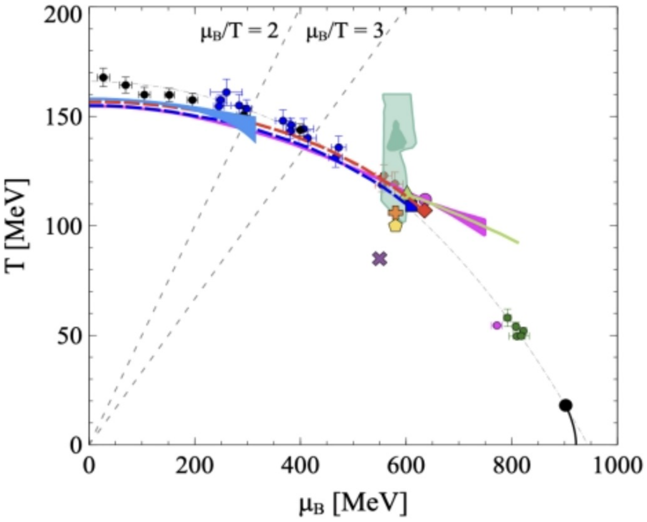
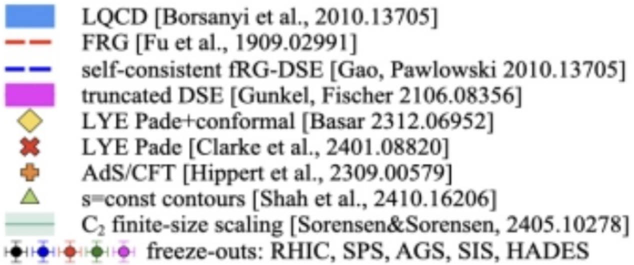
**INT-25-3a**



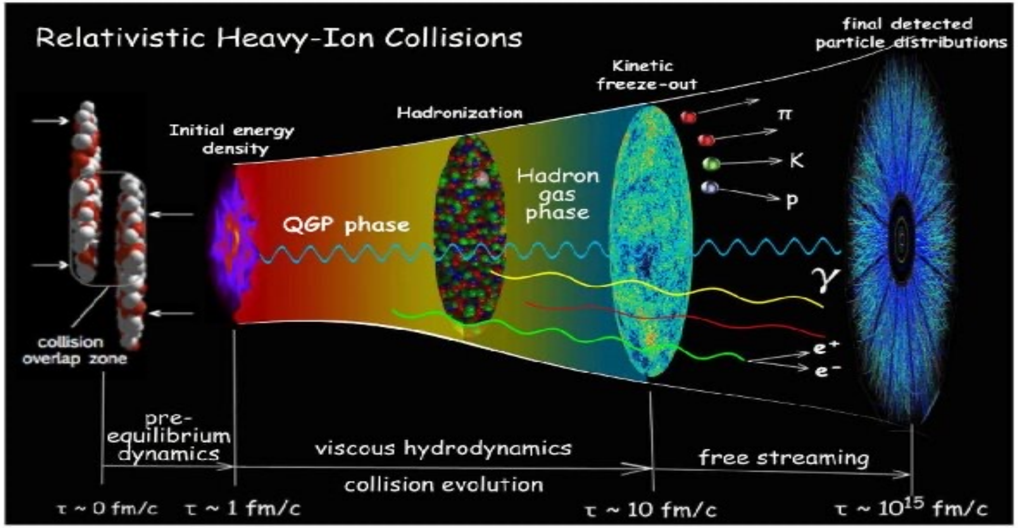

**VIEW SCHEDULE**

**PARTICIPANT LIST**

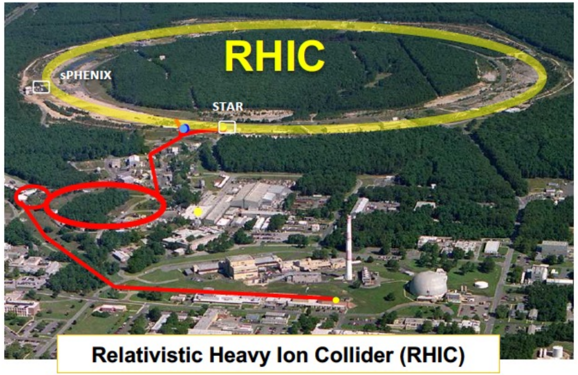
The priority application deadline for this program has passed

https://www.int.washington.edu/programs-and-workshops/25-3a

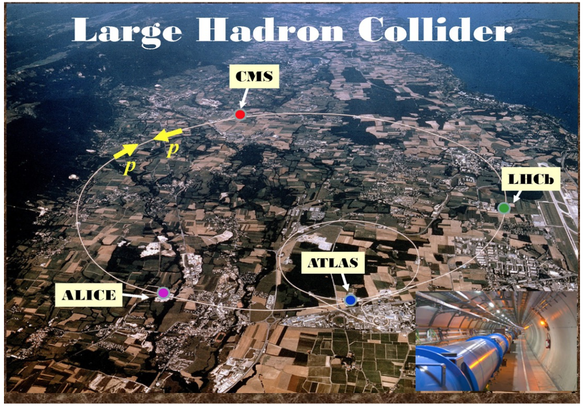
# Relativistic Heavy-Ion Collisions




相对论重离子对撞机(RHIC)

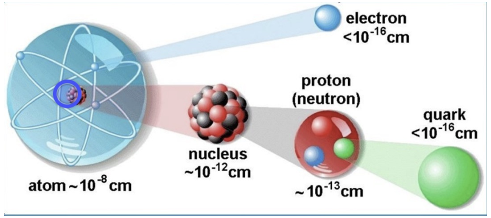



大型强子对撞机(LHC)



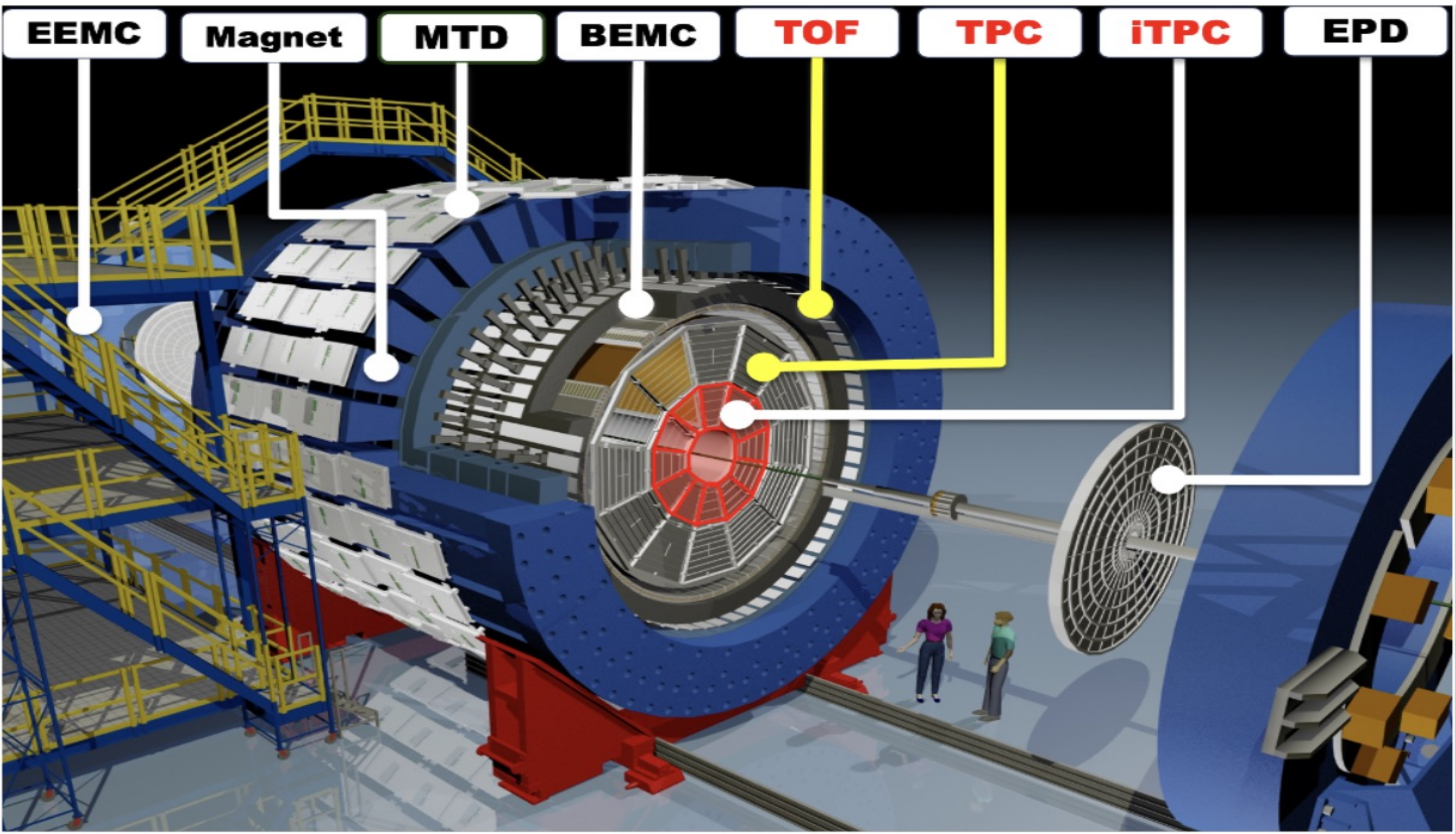

- Properties of QGP

**强耦合低粘滞理想流体(夸克汤)**
**强电磁场、强涡旋场**



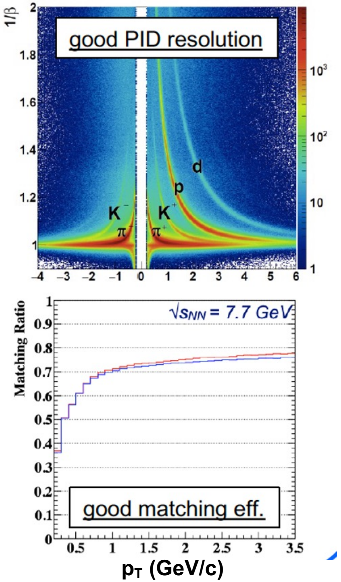

- QCD Phase Structure

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

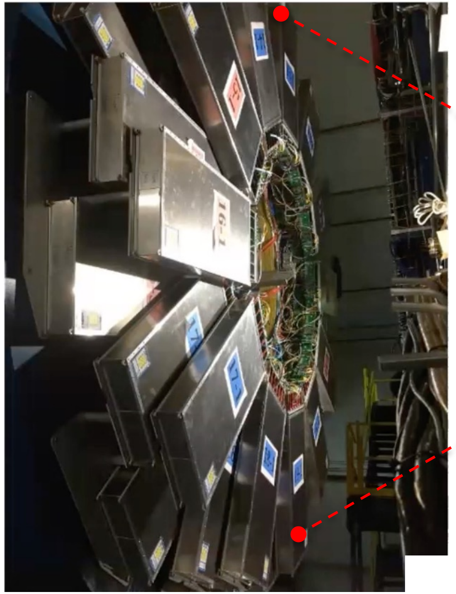

EEMC
Magnet
MTD
BEMC
TOF
TPC
iTPC
EPD

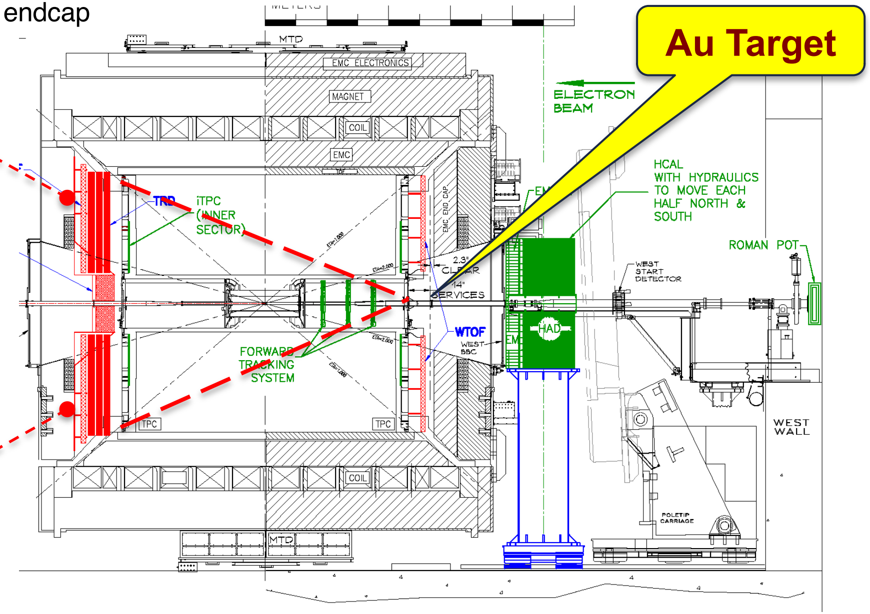
# STAR Experiment : Fixed-Target Mode

**eTOF (2019+)**




10% of the CBM TOF modules installed at STAR endcap

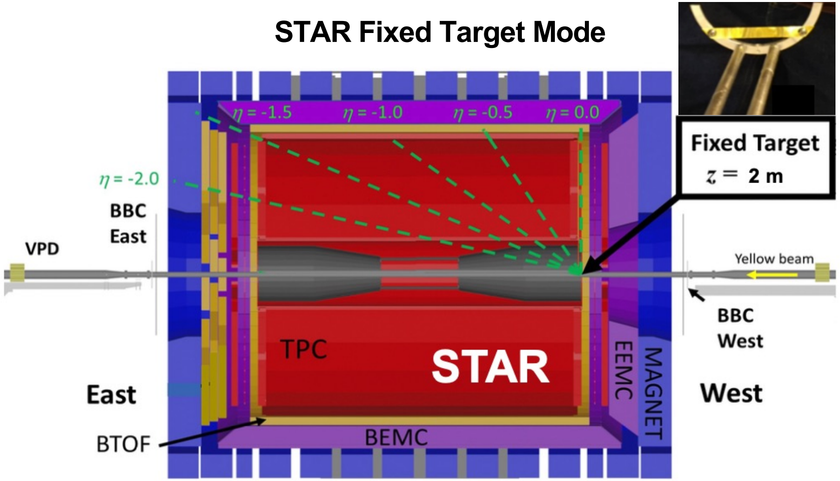


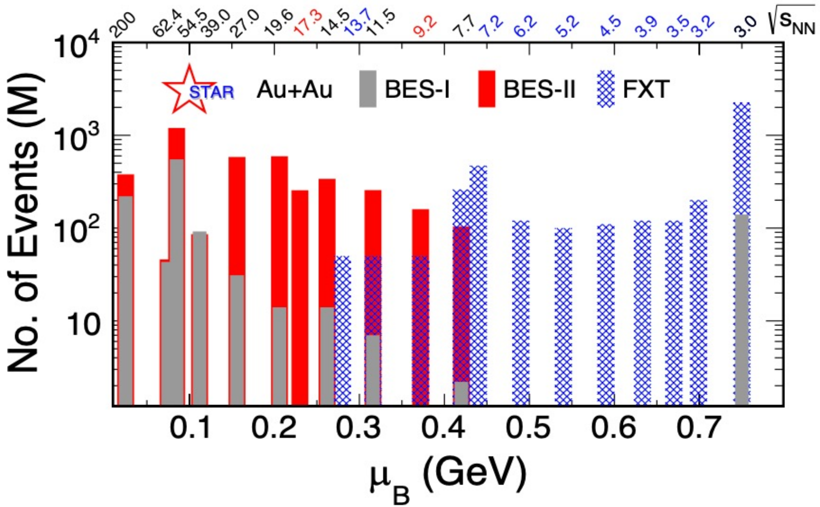



**eTOF from CBM are installed at STAR endcap in RHIC BES-II**

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

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




- ➢ BES-I (2010 – 2014): 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 GeV.

- ➢ BES-II (2018-2021): Collider mode (7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27 GeV),
  FXT mode: (**3.0, 3.2, 3.5, 3.9, 4.5**, 5.2, 6.2,…,13.7 GeV)

- ➢ $\mu_B$ coverage : $25 < \mu_B < 750$ MeV

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

# Observables: Cumulants of Conserved Quantities

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

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

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

- **Experimental Observables: Cumulants of Conserved Quantities**
  1) Sensitive to correlation length (ξ)
  2) Directly related to the susceptibility ratios

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

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

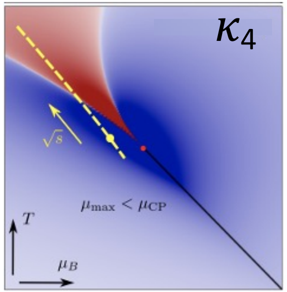
$$\kappa_1 = C_1 = \langle N \rangle,$$
$$\kappa_2 = -C_1 + C_2,$$
$$\kappa_3 = 2C_1 - 3C_2 + C_3,$$
$$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4,$$

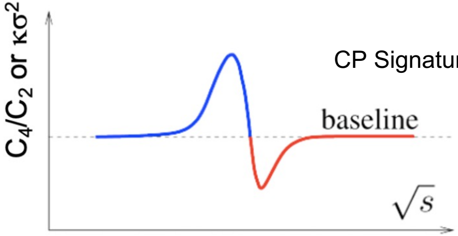
Measured multiplicity N, $\langle \delta N \rangle = N - \langle N \rangle$

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

Moments, cumulants and susceptibilities:

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



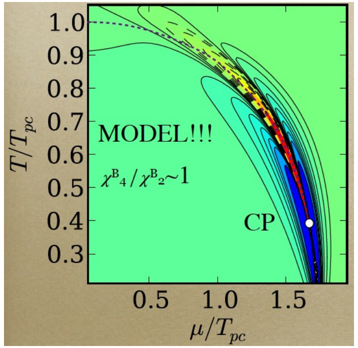




*M. A. Stephanov, PRL 102 (2009) 032301*

*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)*

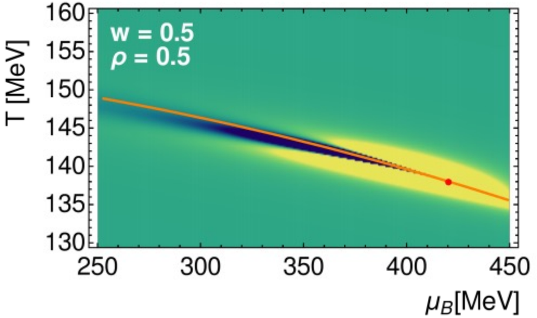
# Critical Contributions to Fourth-order Fluctuations ($\kappa\sigma^2$)

**PQM** V. Skokov, QM2012



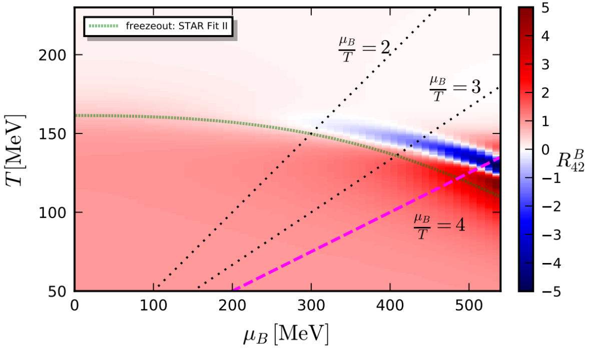

**3D Ising Mapping**

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



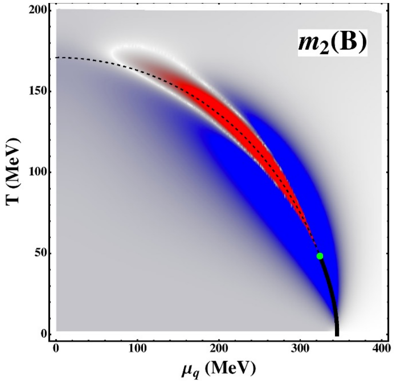

**FRG**

付伟杰等 PRD 104 (2021) 9, 094047



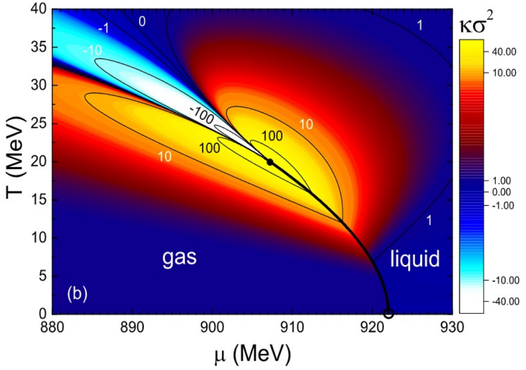

**Symmetry and Universality**

**NJL**



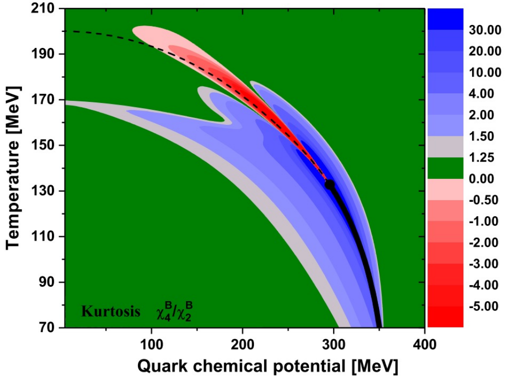

邓建等, PRD93, 034037 (2016)

**van der Waals (VDW)**




Vovchenko et al., PRC92, 054901 (2015)

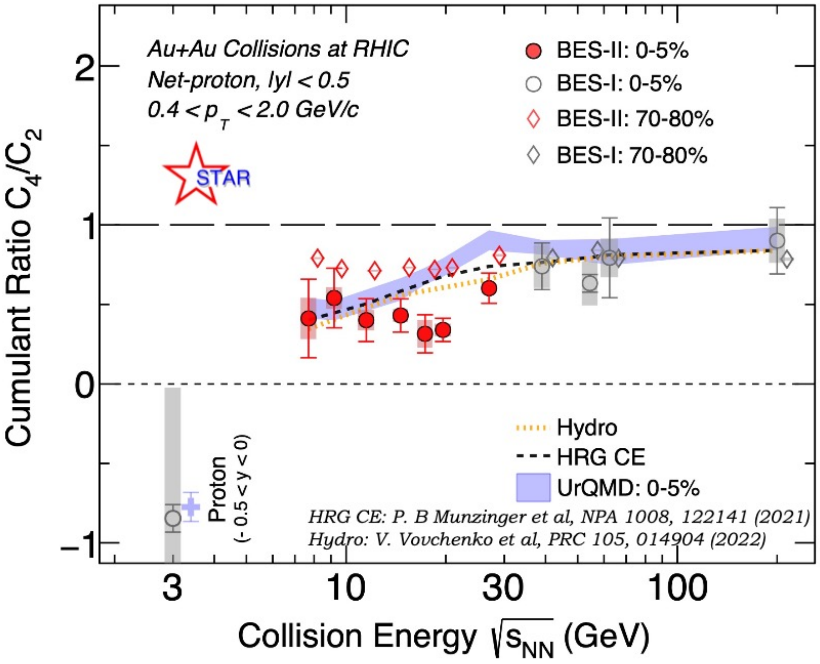
**PNJL**



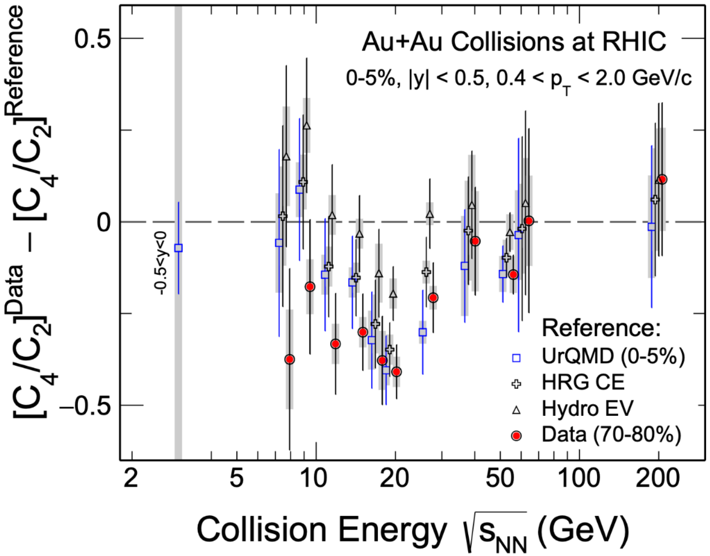

邵国运等, EPJC 78, 138 (2018)

李志宾、许坤、王昕扬、黄梅, EPJC 79, 245 (2019).

# Recall : Net-Proton Fluctuation in BES-II (7.7–27 GeV)




Comparing to non-CP baselines

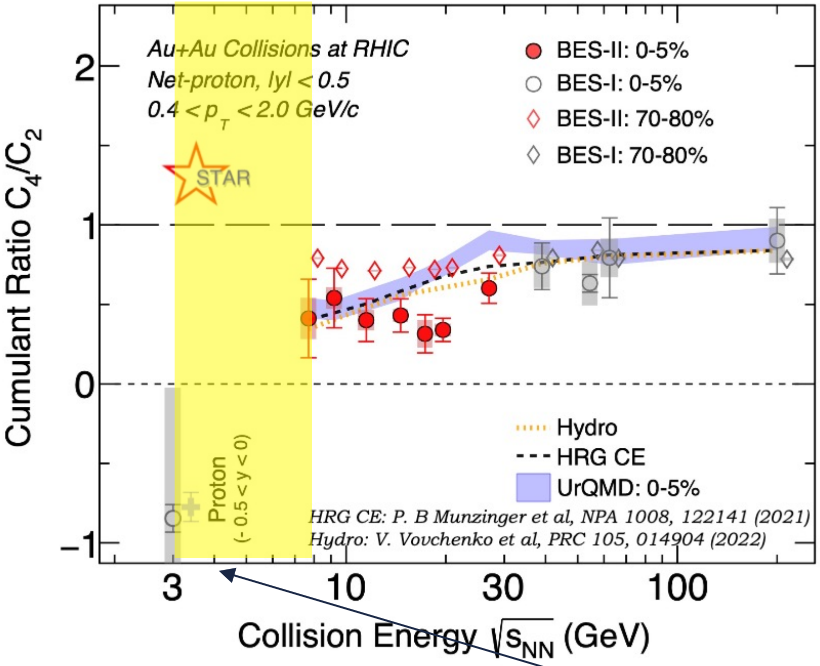



STAR: Phys. Rev. Lett. **135**, 142301 (2025) [Editor Suggestion]

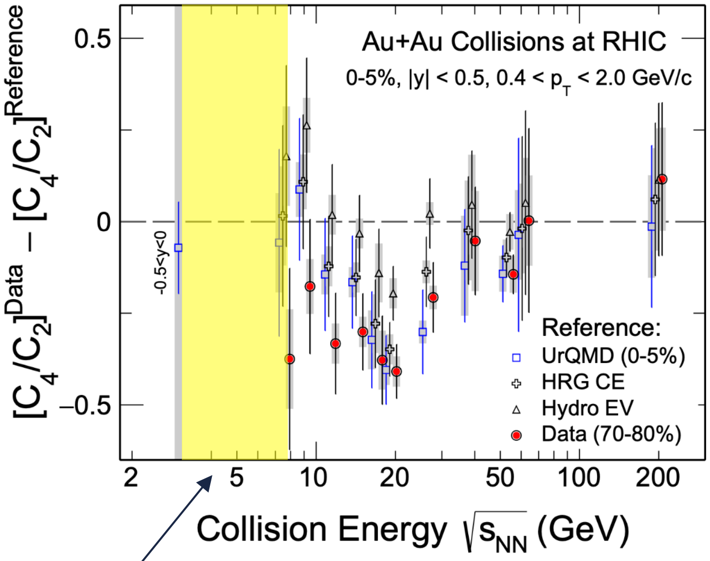
**STAR:** PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
**HADES:** PRC102, 024914(2020)

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

# Recall : Net-Proton Fluctuation in BES-II (7.7–27 GeV)




Comparing to non-CP baselines

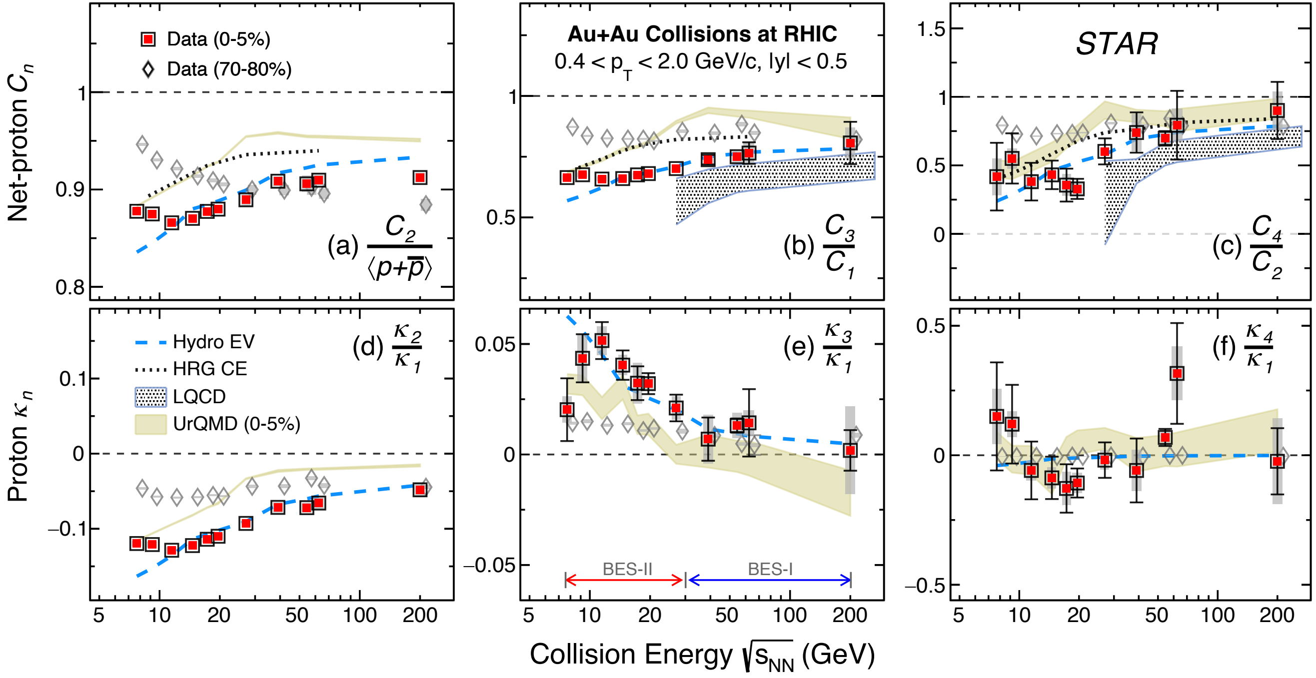



STAR: Phys. Rev. Lett. **135**, 142301 (2025)
[Editor Suggestion]

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

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

# Energy Dependence of (factorial) Cumulant Ratios




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

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

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

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

1) All cumulant ratios deviate below Poisson baseline (unity). $C_4/C_2$ shows deviation at ~ 20 GeV w.r.t non-CP references (models and peripheral data) 2 – 5$\sigma$.
2) Negative $\kappa_2$, positive $\kappa_3$; $\kappa_4/\kappa_1$ consistent with Poisson baseline at zero within uncertainties
3) Lattice QCD (net-baryon) describe the data up to 27 GeV.

STAR: Phys. Rev. Lett. **135**, 142301 (2025)

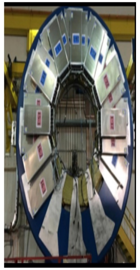
# Proton Number Fluctuations from STAR Fixed-Target Program

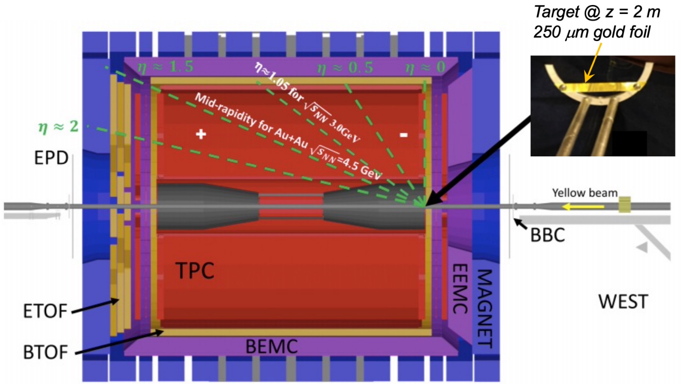
3.2, 3.5, 3.9 GeV：

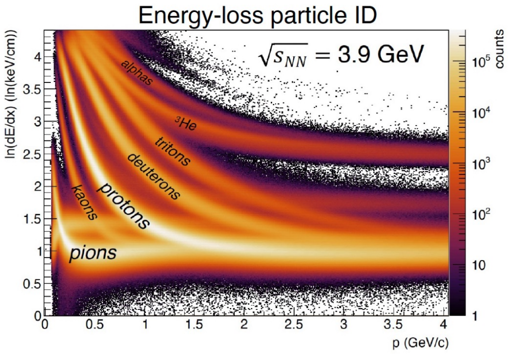
Data Set Details

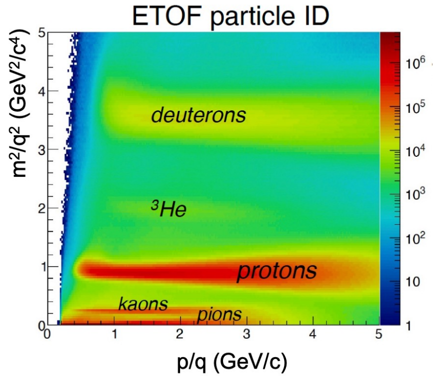
| Nominal $\sqrt{s_{NN}}$ (GeV) | Precision $\sqrt{s_{NN}}$ (GeV) | Beam Energy (GeV) | # Good Events | CoM Rapidity | Chemical Pot. $\mu_B$ (MeV) |
|---|---|---|---|---|---|
| 3.2 | 3.208 | 4.593 | 201M | 1.139 | 697 |
| 3.5 | 3.531 | 5.761 | 116M | 1.254 | 666 |
| 3.9 | 3.918 | 7.309 | 117M | 1.375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

Particle Identification





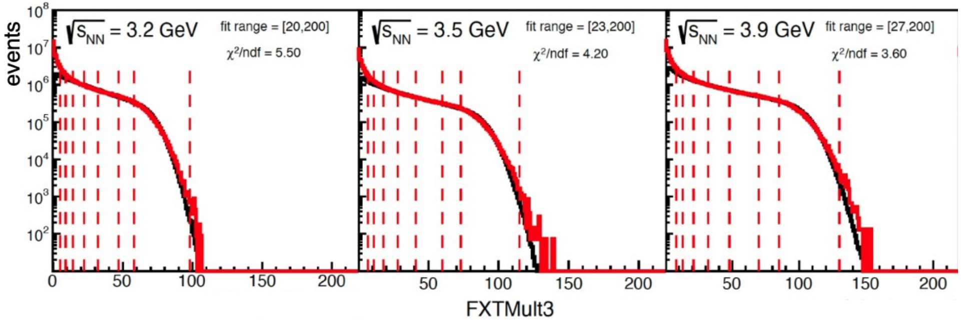



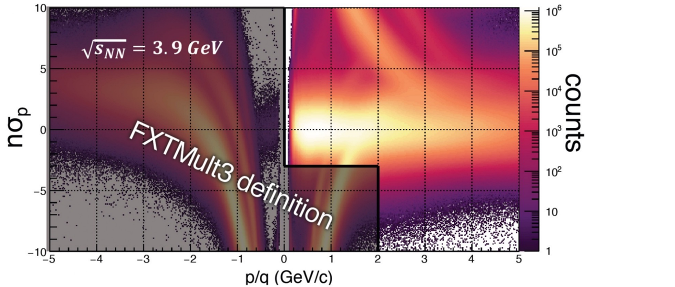




- ETOF provided by CBM-FAIR, crucial for PID at BES-II, especially for the FXT program
- Good detector performance (timing resolution, matching efficiency, stability)

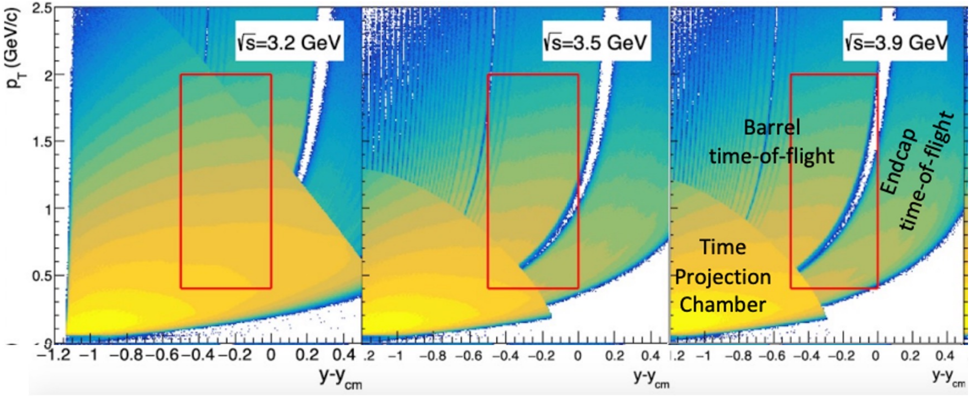
Z. Sweger, Yongcong Xu, Xin Zhang @ QM25

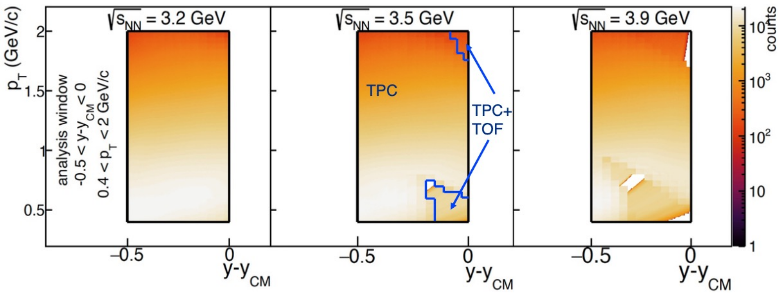
# Proton Acceptance and Identification




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



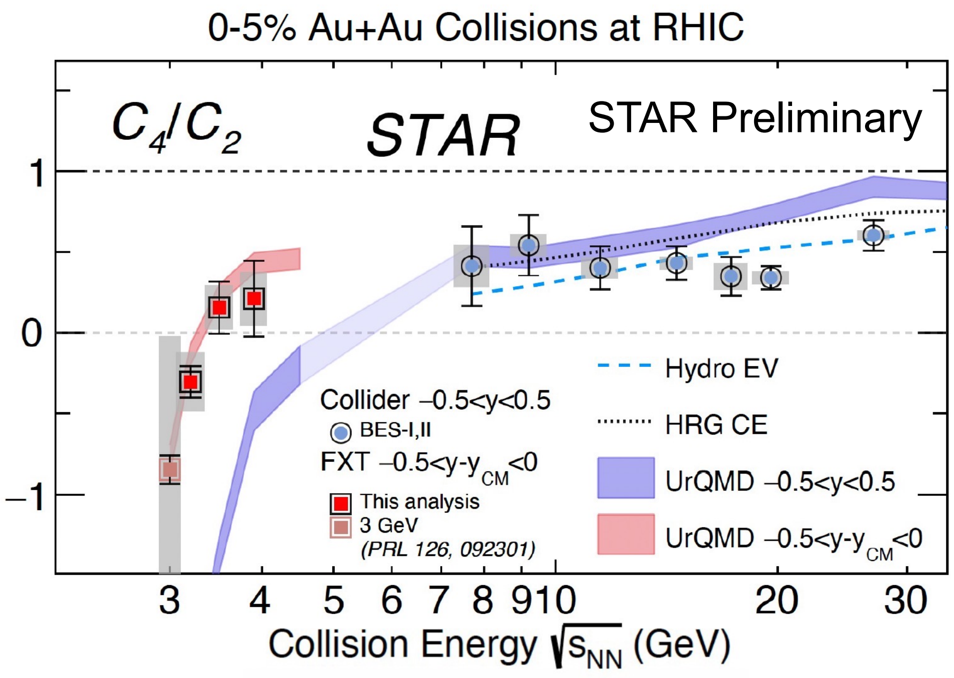

Slow TPC/Fast TOF PID + Pile-up = Fast/Slow miss match -> Will distort cumulant measurement

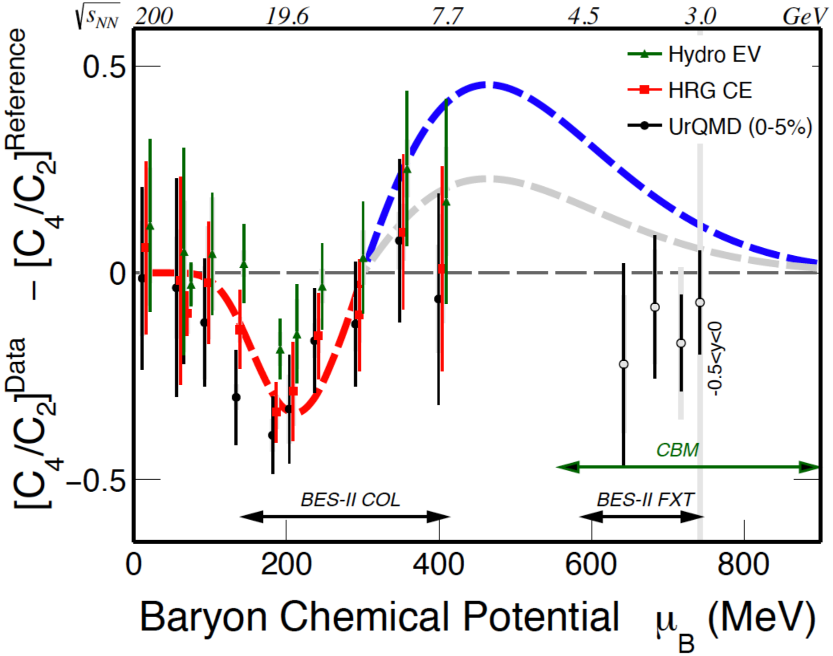
Conventional PID method for Proton :
TPC PID at low $p$
TPC+TOF at high $p$
-> Acceptance gap.

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

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

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

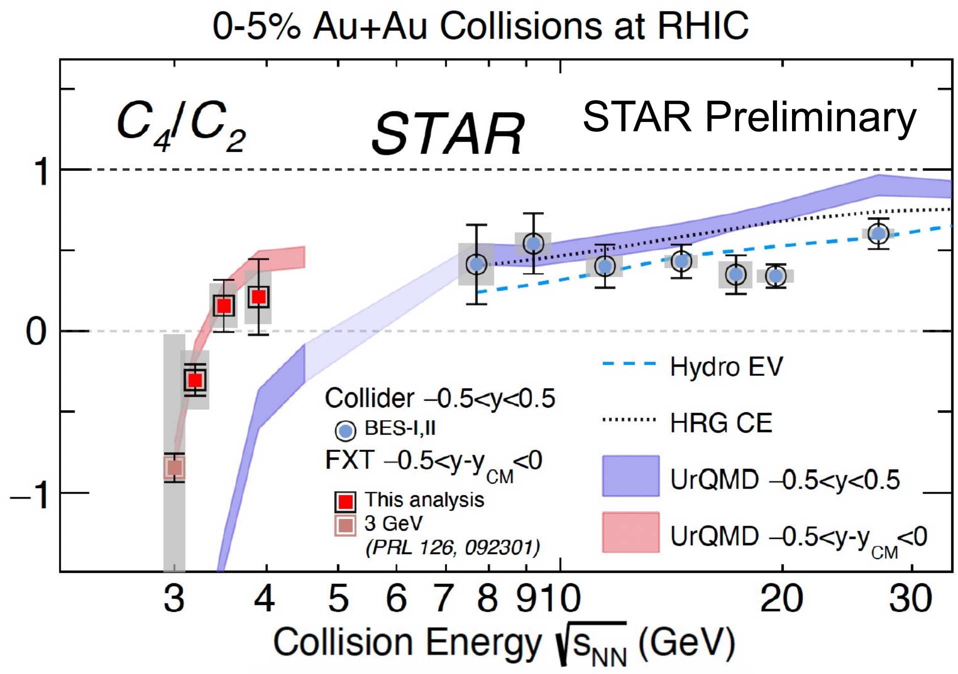


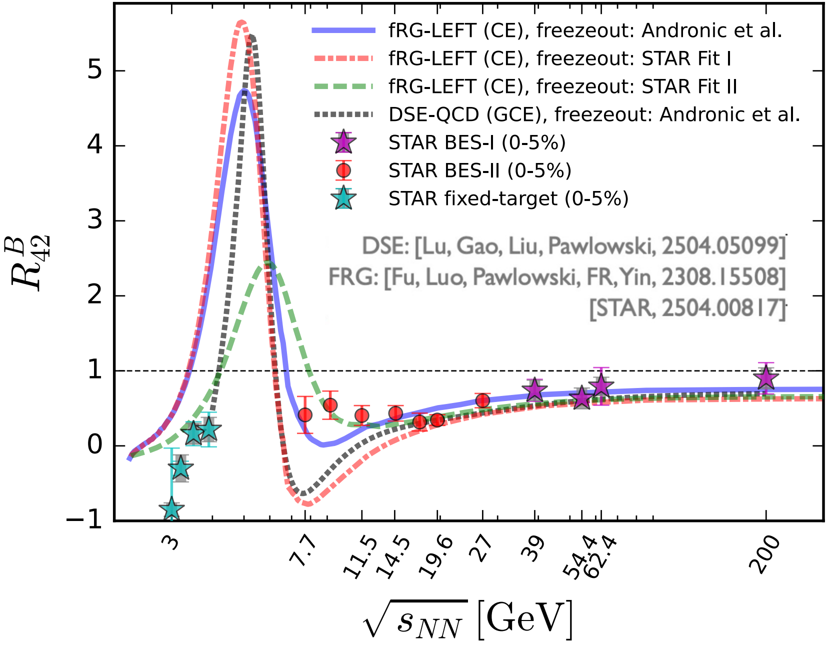

固定靶能量点: 3.0, 3.2, 3.5, 3.9 GeV初步结果

Z. Sweger, Yongcong Xu, Xin Zhang @ QM25

# Search for the QCD Critical Point : To be Continued…



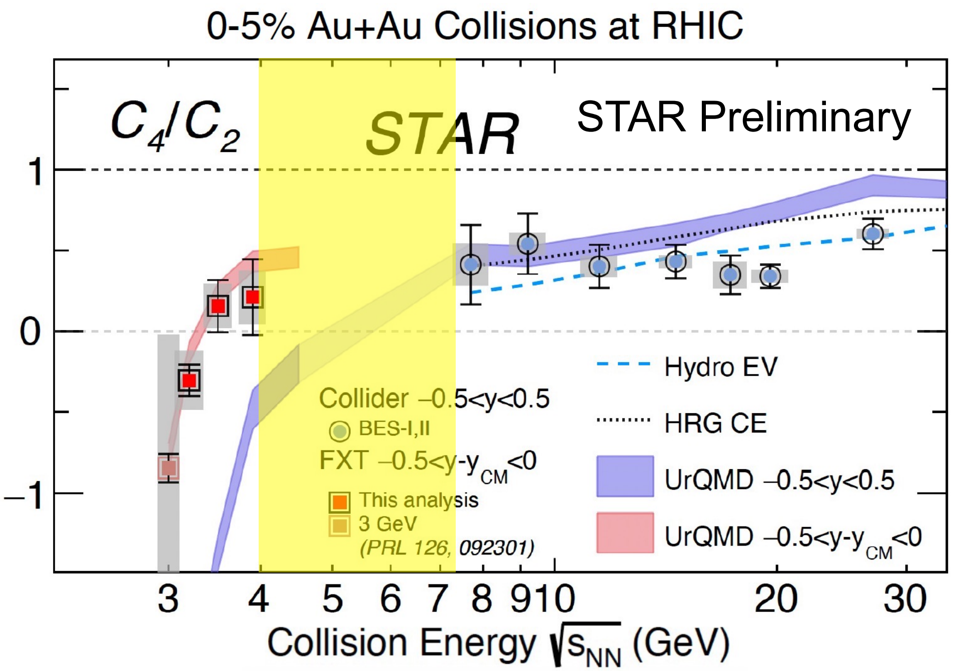

Fabian @ QM2025, plenary
Wei-jie Fu @ QPT2025, plenary

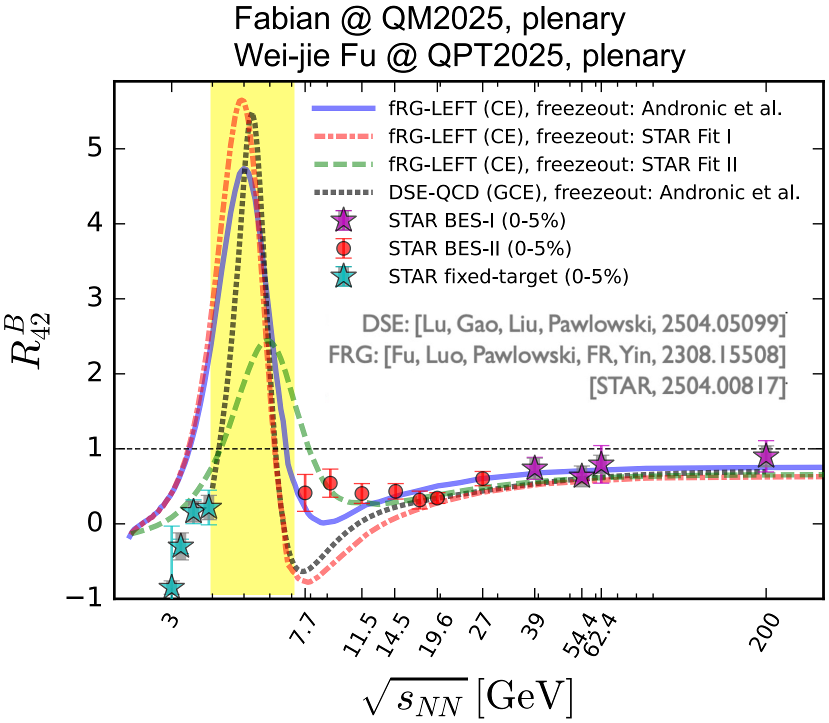



非平衡效应的影响？ Baryon vs. Proton ?

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

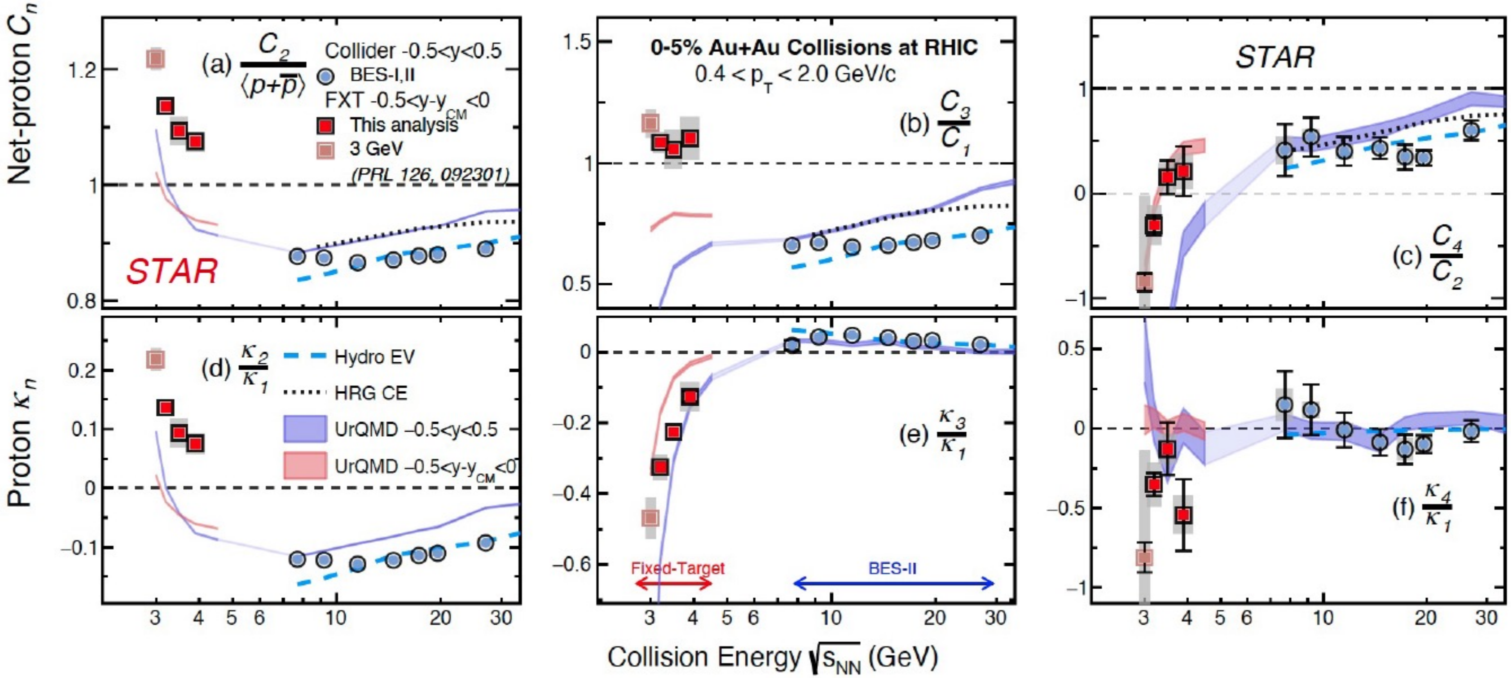
# Search for the QCD Critical Point : To be Continued…




- Experimental results between 4 – 8 GeV are crucial.   非平衡效应的影响?  Baryon vs. Proton ?
- Analysis of 4.5 GeV and 2 billion events from Run21 3 GeV are ongoing.
  In STAR, we are also pushing for taking more data of 4.2 and 4.5 GeV.

# Energy Dependence of (Factorial) Cumulant Ratios



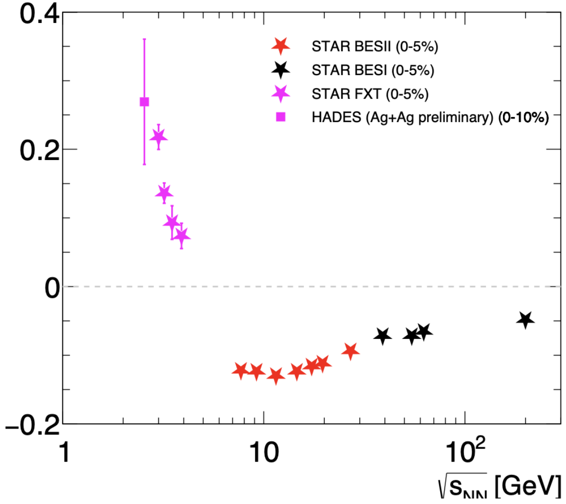

At 3.0 – 3.9 GeV central collisions (0-5%, -0.5<y<0):

1) UrQMD describe the trends of the data
2) Proton (factorial) cumulants at 2$^{nd}$ and 3$^{rd}$ order deviates from UrQMD
3) Proton $C_4/C_2$, $\kappa_4/\kappa_1$ consistent with UrQMD

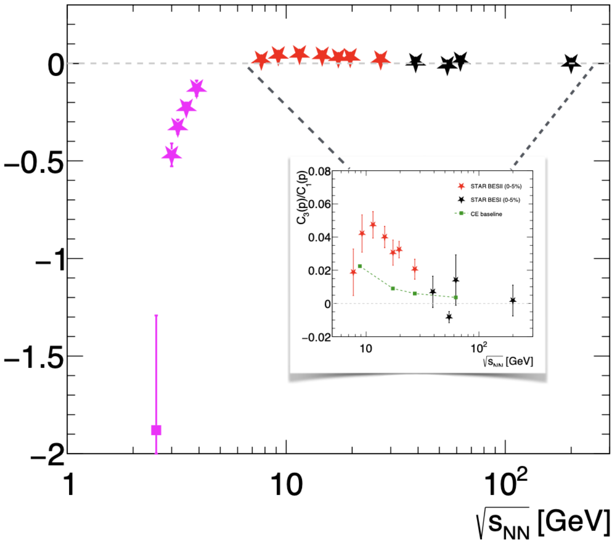
Z. Sweger, Yongcong Xu, Xin Zhang @ QM25

# Proton Factorial Cumulants : STAR vs. HADES

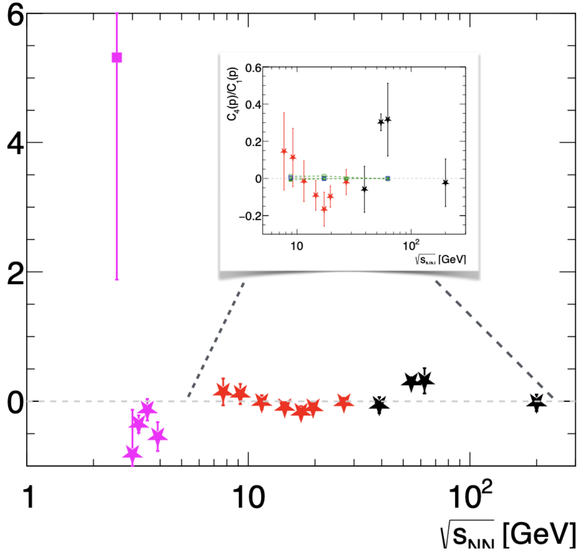
$K_2/K_1$




$K_3/K_1$




$K_4/K_1$




**STAR 、 HADES,** Quark Matter 25

**STAR FXT:** Au-Au, $\langle N_W \rangle \approx 320$:

$-0.5 < y < 0$

$0.4 < p_t < 2$ GeV/c

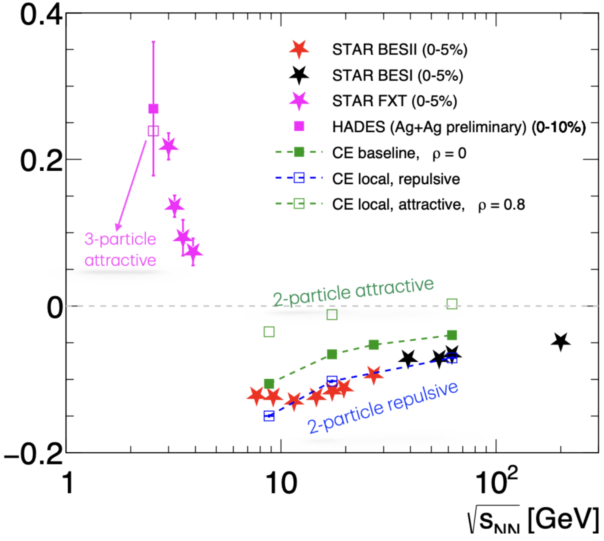
**HADES:** Ag-Ag, $\langle N_W \rangle \approx 170$

$-0.4 < y < 0.4$

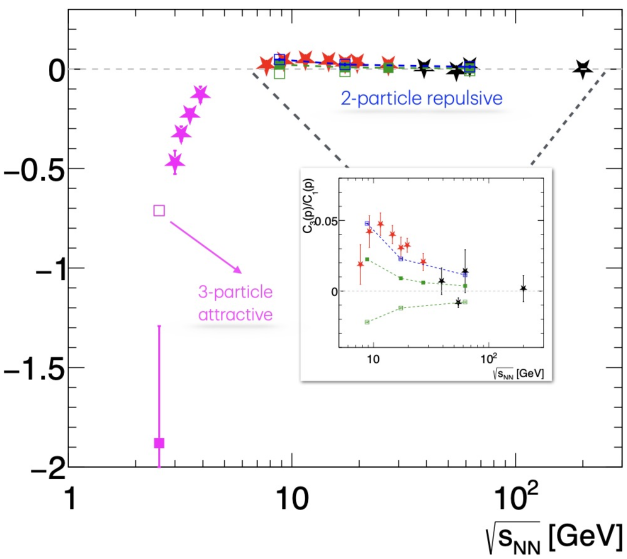
$0.4 < p_t < 1.6$ GeV/c

# Proton Factorial Cumulants : STAR vs. HADES

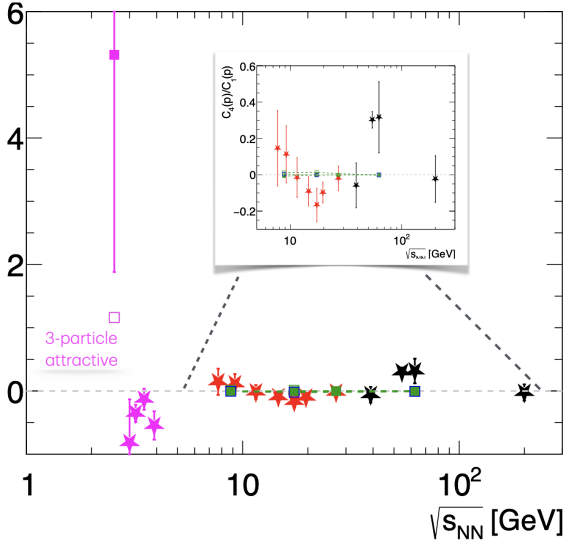
$K_2/K_1$




$K_3/K_1$




$K_4/K_1$

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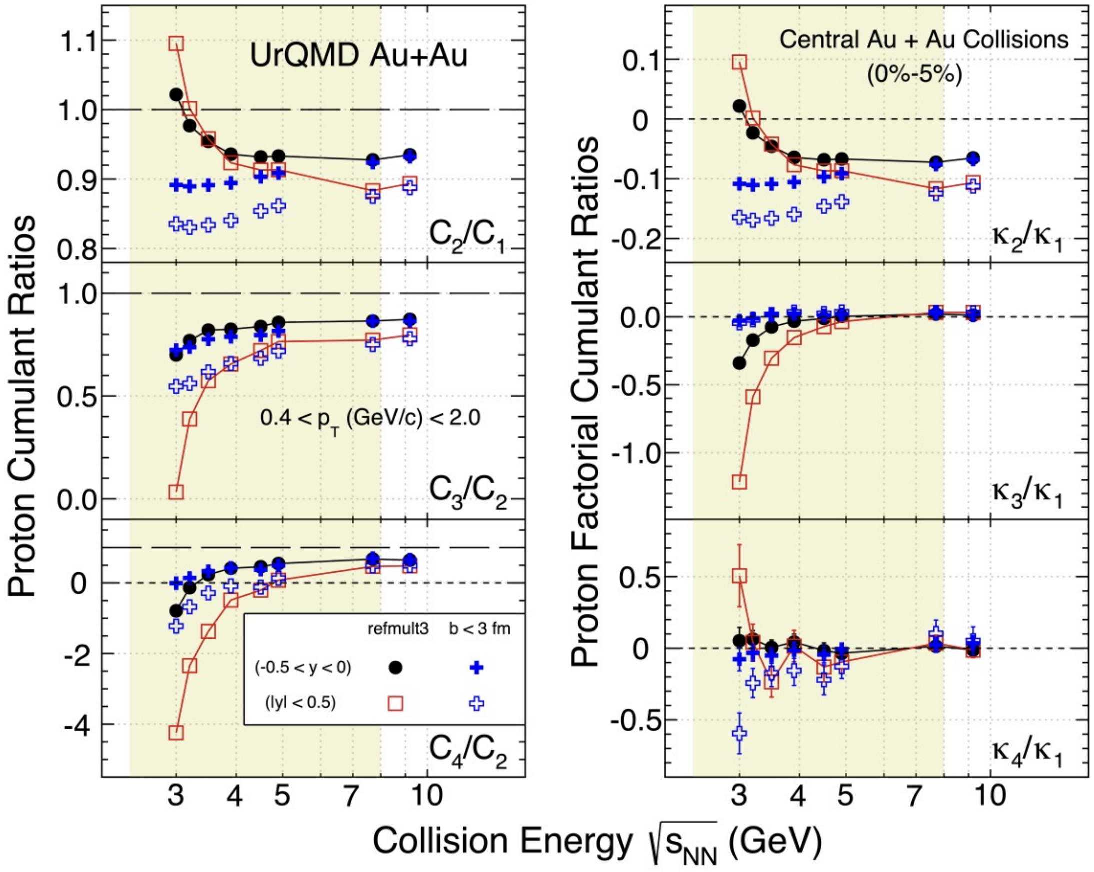
$-0.4 < y < 0.4$

$0.4 < p_t < 1.6$ GeV/c

Changing from repulsive to attractive force between protons at different energies : Sign of phase transition ?

P. Braun-Munzinger, B. Friman, K. Redlich, A. Rustamov, J. Stachel, NPA 1008 (2021) 122141
P. Braun-Munzinger, K. Redlich, A. Rustamov, J. Stachel, JHEP 08 (2024) 113
B. Friman, A. Rustamov, K. Redlich (in preparation)

# UrQMD Simulations : Effects of Volume Fluctuations and BNC



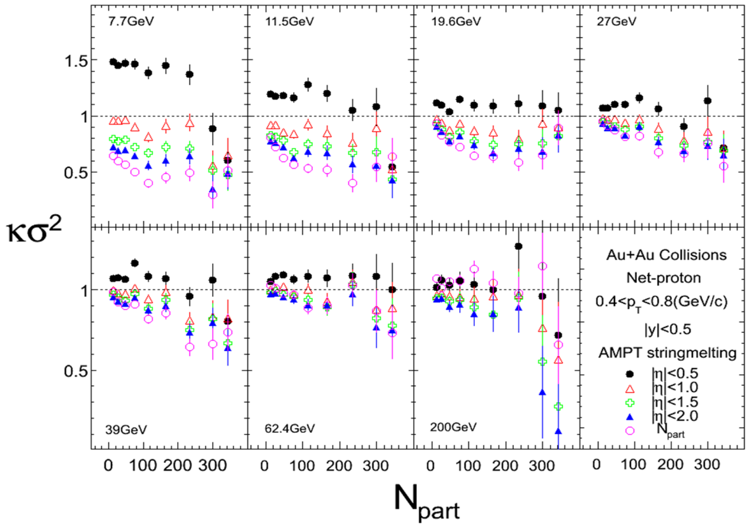

- Baryon number conservation (BNC) and Volume Fluctuations (VF) are included in UrQMD simulations
- The simulation shows that the effects of volume fluctuations are strong at low energies, which can cause rapidly increase or decrease of K2/K1 and K3/K1.

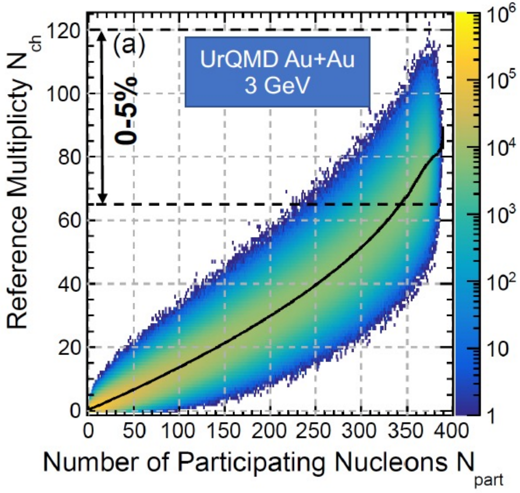
  Xin Zhang, Yu Zhang, XFL, Nu Xu, Chin. Phys. C 50,011003 (2026)

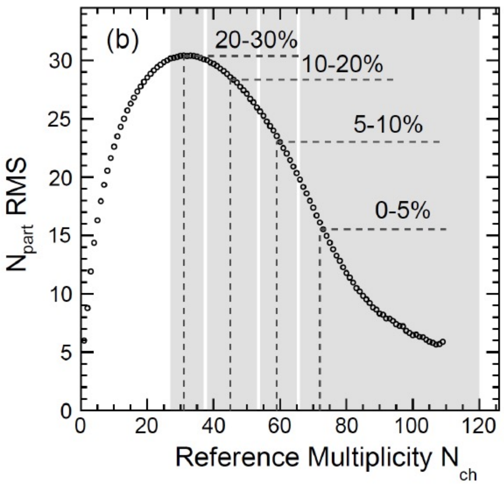
- New Methods are developed to eliminate VF at low energies.

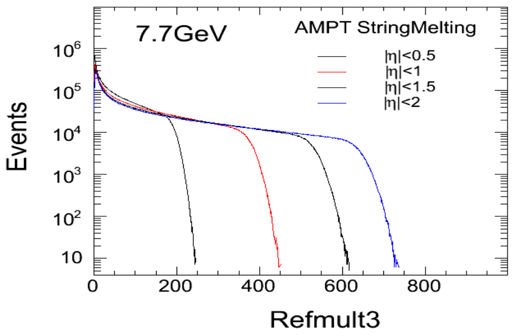
  A Centrality-independent Framework: Zhaohui Wang and XFL, Physics Letters B 871, 139984 (2025)

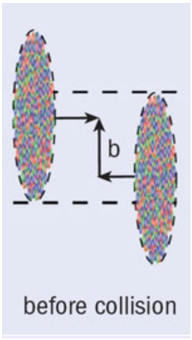
# Challenges for fluctuation analysis in FXT energies：Initial Volume Fluctuations



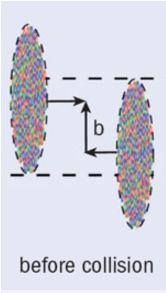




- Initial volume fluctuations are well known and largest background for cumulant analysis, especially for low energies.

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 ↗




Independent Emission Source Models

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

How to isolate the initial volume fluctuations from true signal ?

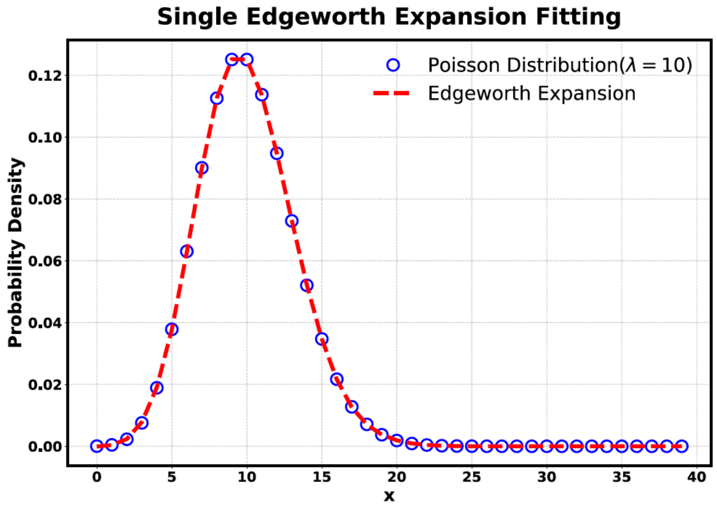
- Multiplicity N arise from independent Source, such as participant nucleon (Np).

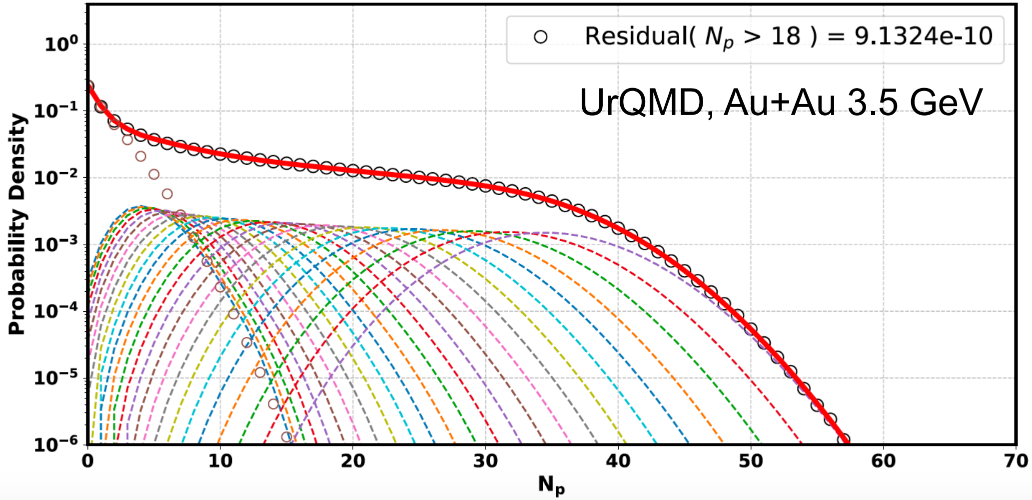
$$N = \sum_{i=1}^{N_p} n_i$$

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

- Multiplicity Fluctuations:

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



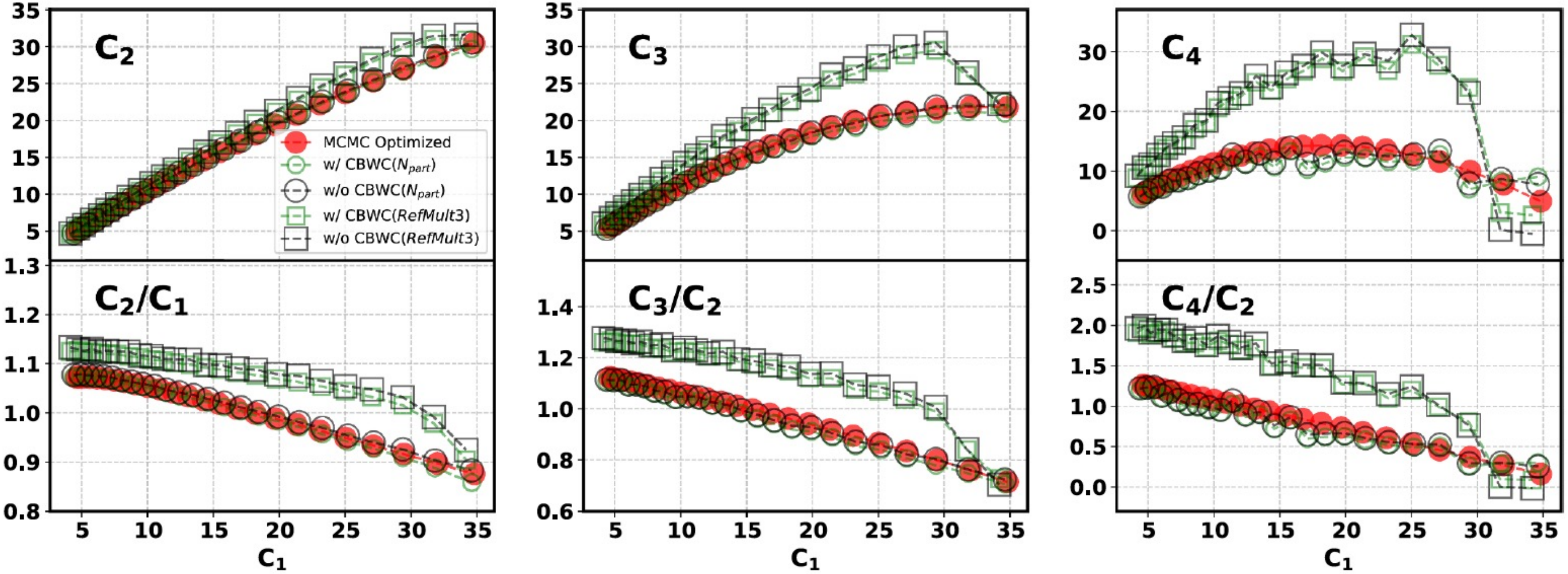




Edgeworth expansion :

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

Chebyshev-Hermite polynomials $He$

UrQMD, Au+Au 3.5 GeV

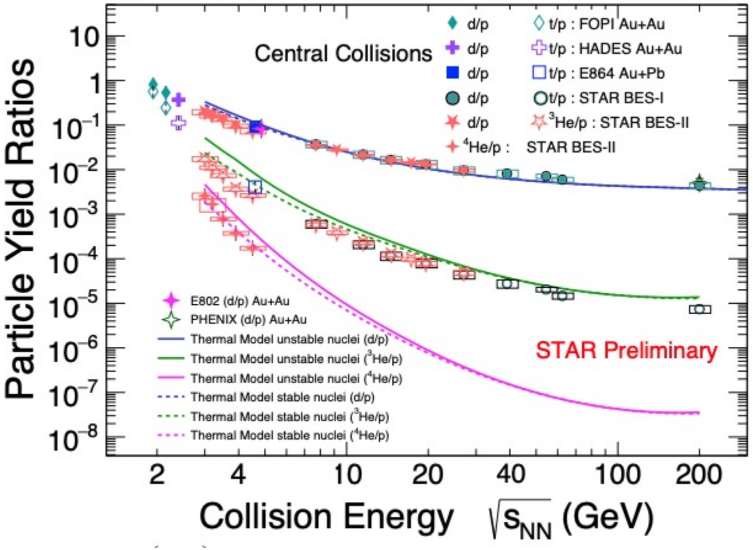



Data Analysis with this new method is underway.

Z. Wang, XFL, Physics Letters B 871, 139984 (2025)

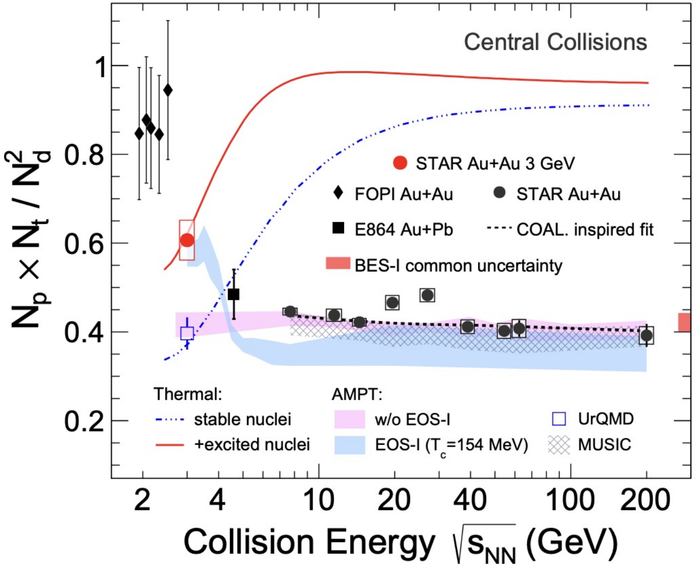
# Light Nuclei Yield Ratios from BES-II (3 – 27 GeV)

Yixuan Jin (STAR, Best Poster Award)@ QM25




The compound yield ratio is proposed to be sensitive to the neutron density fluctuations

K. Sun et al. Phys.Lett.B 774 (2017) 103-107




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

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

# Dense Nuclear Equation of State

NN, YN, NNN, YNN, two body or three body interactions

1. Hypernuclei Production、Directed flow
2. Femtoscopy correlations
3. Other observables.

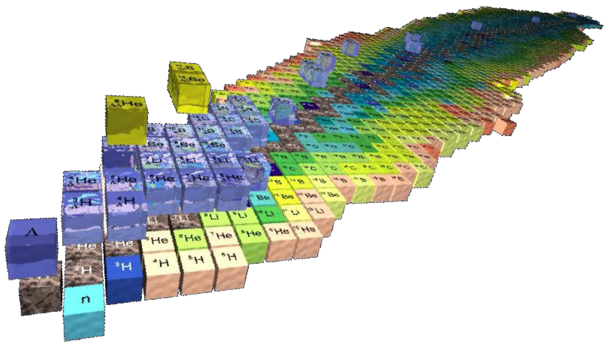
# Hyper-Nuclei Production

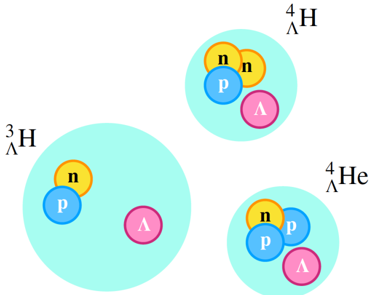
PRL**114**, 092301(2015), HYP2018, 1512.06832, 1711.07521

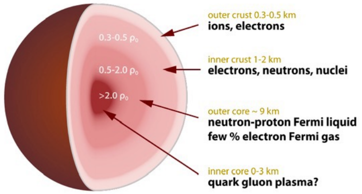
*S=-2*

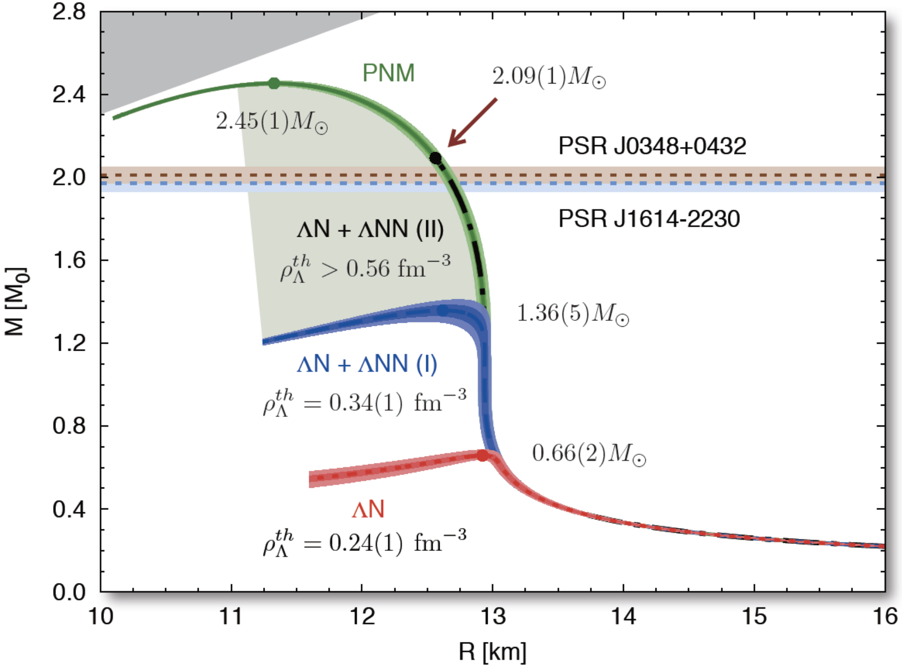
*S=-1*

*S=-0*





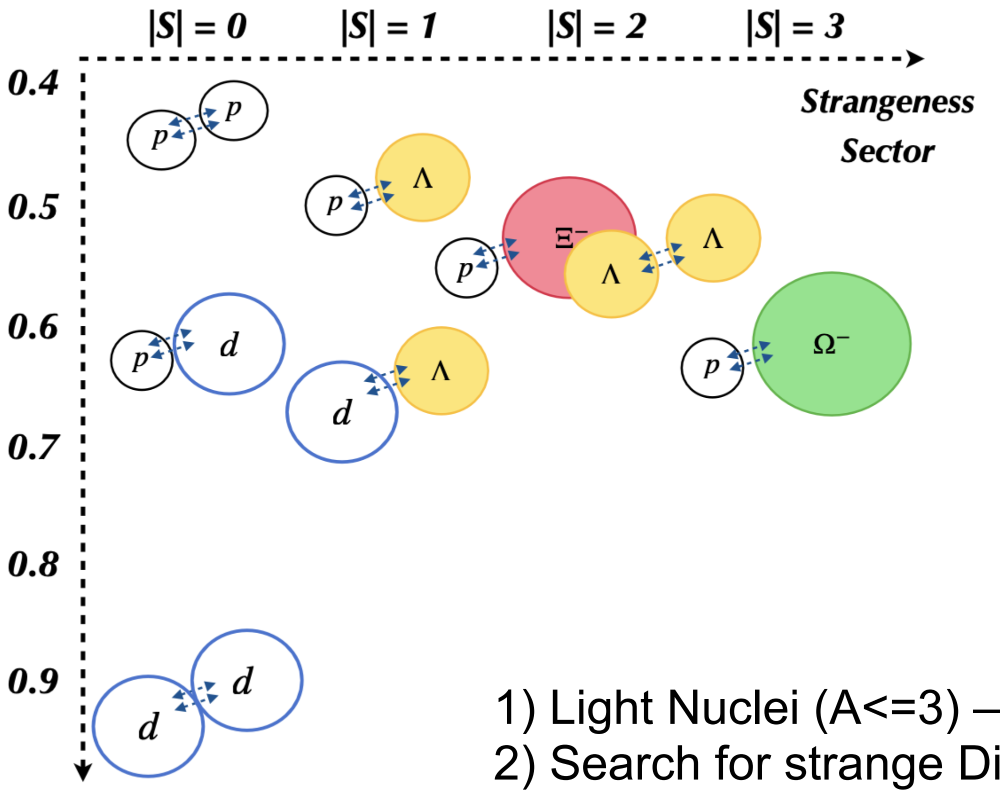



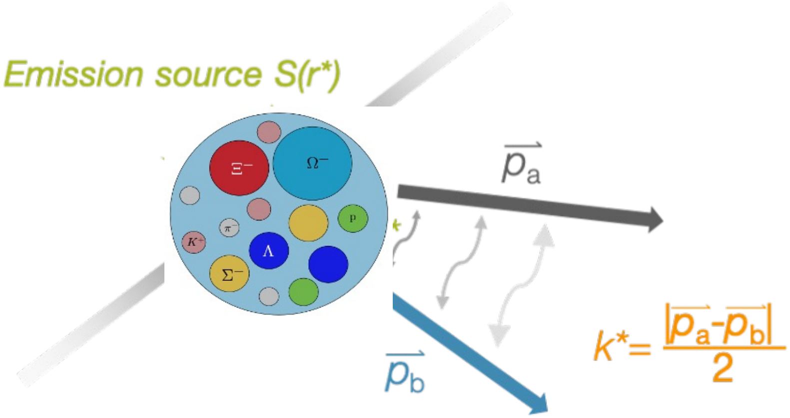




➢ Hyper-nuclei provide access to the hyperon–nucleon interactions: NY, YNN,

: Key to understand the EoS at high baryon density and inner structure of neutron star.

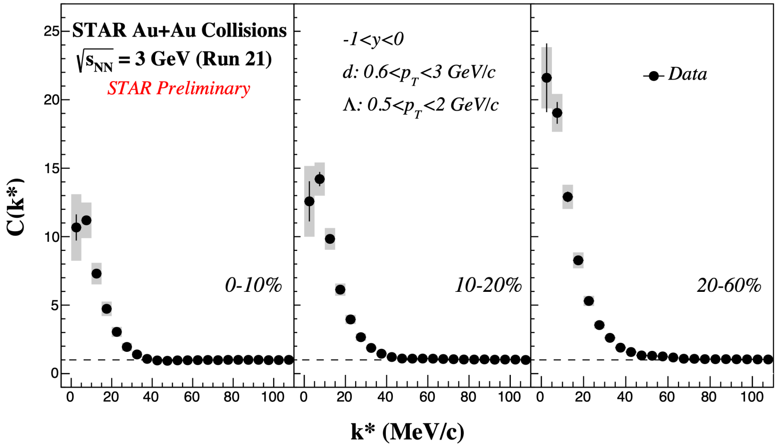
# Two-particle femtoscopy correlations : NN and YN Interactions

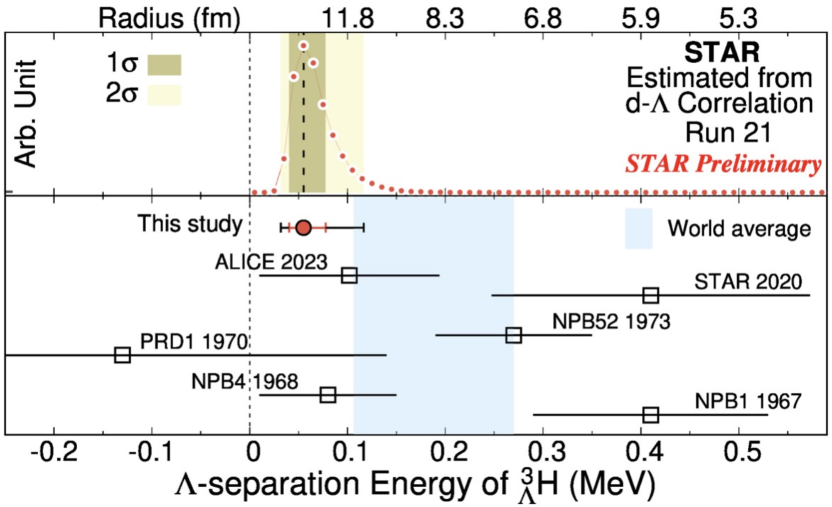


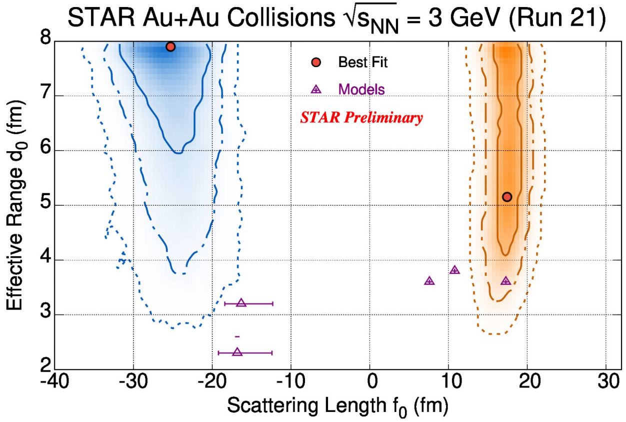




1) Light Nuclei (A<=3) – Lambda at Au+Au 3 GeV
2) Search for strange Di-baryon in isobar collisions 200 GeV

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

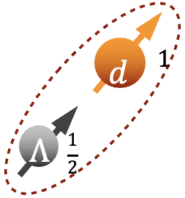



1) The most accurate results of binding energy and radius of $^3_\Lambda$H.
Open a new way to constrain $^3_\Lambda$H properties.

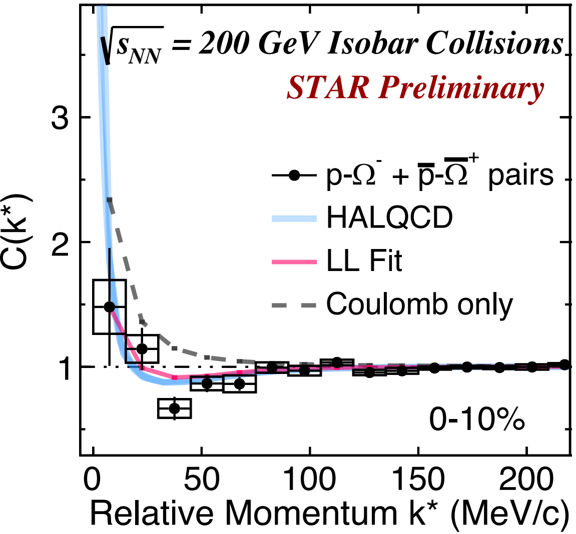
$$^3_\Lambda\mathrm{H}\ B_\Lambda = 0.06^{+0.06}_{-0.03}$$ (MeV) @ 95% CL

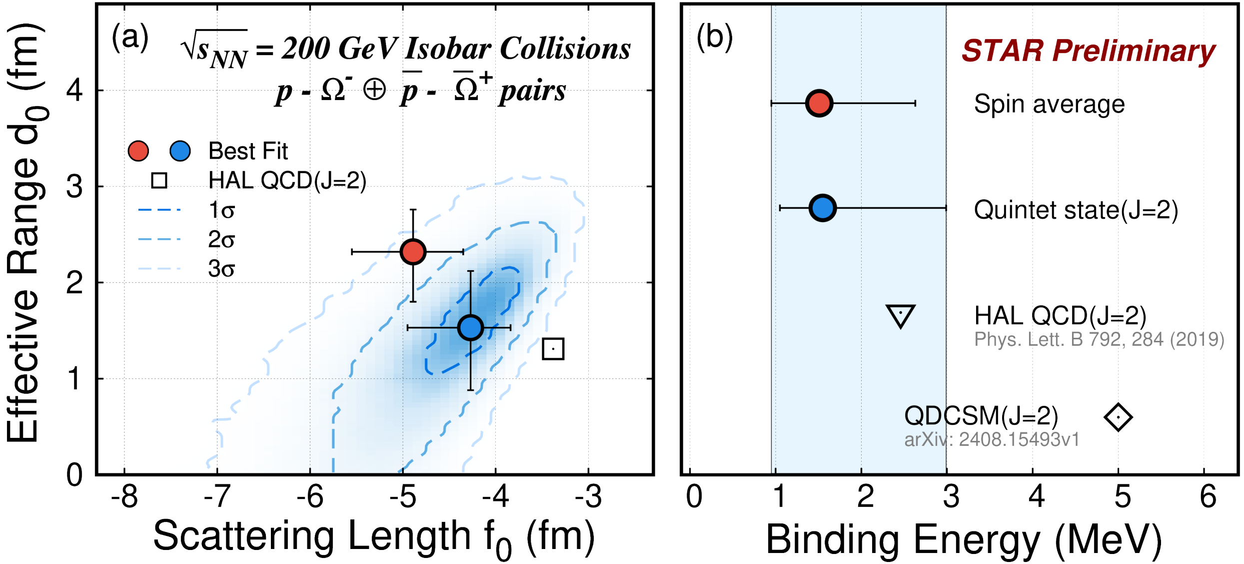



Extracted physical parameters:
$f_0$ (D) = −25.3±3.3 fm
$f_0$ (Q) = 17.5±1.6 fm

STAR : Xialei Jiang, QM2025

# p-$\Omega^-$ Correlation Function ( |S|=3 )




STAR: Kehao Zhang, QM2025

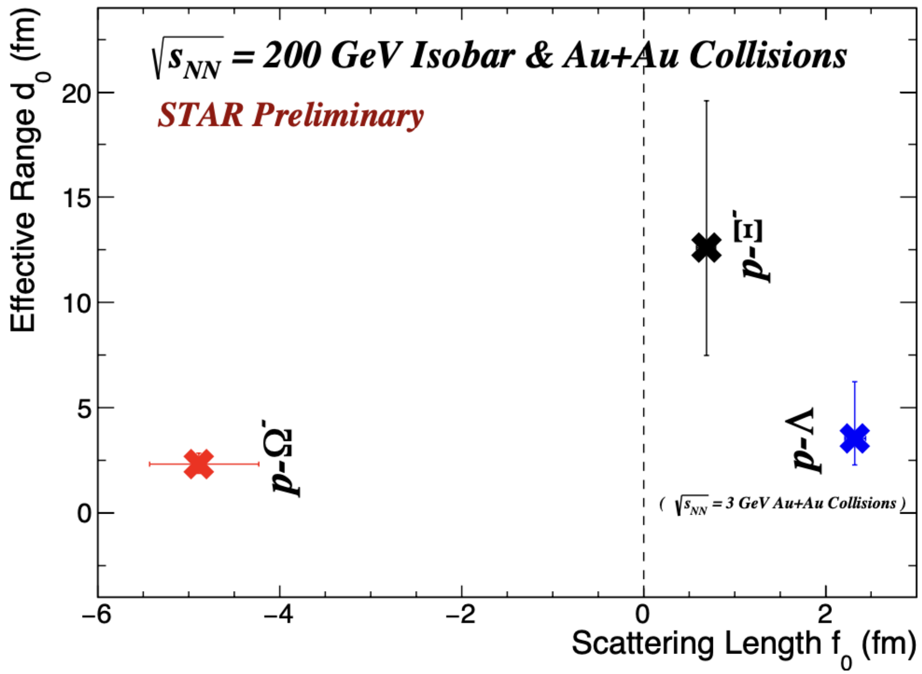
| | Spin ave. | Quintet | HAL QCD |
|---|---|---|---|
| $f_0$ (fm) | $-4.89^{+0.54}_{-0.66}$ | $-4.27^{+0.43}_{-0.68}$ | $-3.38$ |
| $d_0$ (fm) | $2.32^{+0.44}_{-0.52}$ | $1.53^{+0.54}_{-0.66}$ | $1.31$ |
| BE (MeV) | $1.51^{+1.12}_{-0.56}$ | $1.55^{+1.44}_{-0.50}$ | $2.27$ |

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

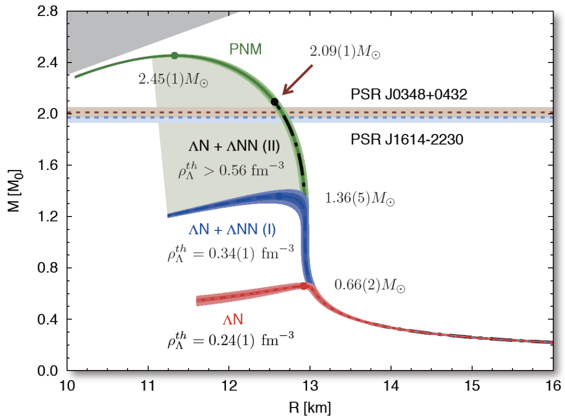
II. Extracted negative $f_0$ ( $|f_0| > 2d_0$) by Spin average method and Quintet method

- **First experimental evidence of Strange Dibaryon**

# Strong Interaction Parameters




STAR: Kehao Zhang, QM2025

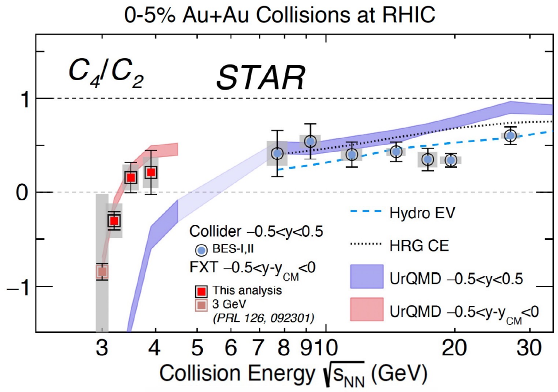



- Extracted negative $f_0$ in p-$\Omega^-$ pair -> Support the formation of bound state
- Interaction section is proportional to $f_0^2$, the observation implies that the strength of the interaction depends on strangeness;

These parameters provide important experimental input for studying the equation of state of dense nuclear matter and the internal structure of neutron stars.

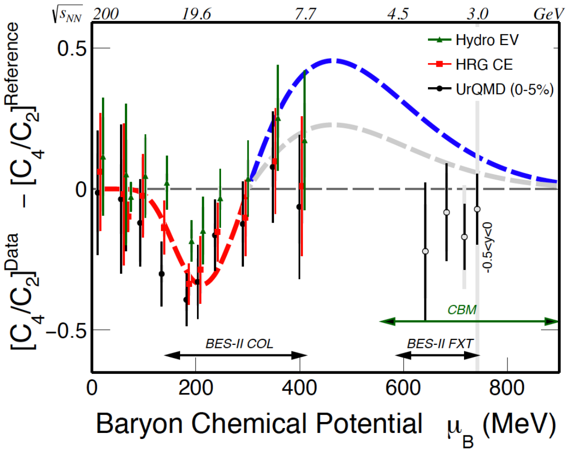
# Summary and Outlook

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




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

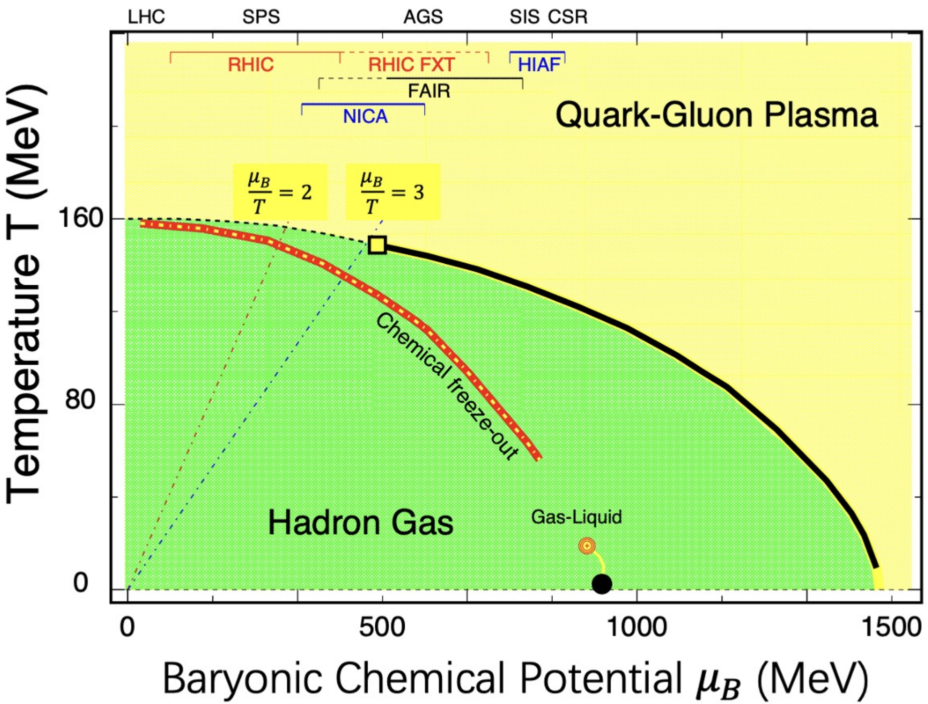
- FXT energies : proton $C_4/C_2$ in central collisions are consistent with UrQMD calculations at 3.0 – 3.9 GeV. Analysis of 4.5 GeV and high statistics 3 GeV data (2 Billion events) are ongoing.

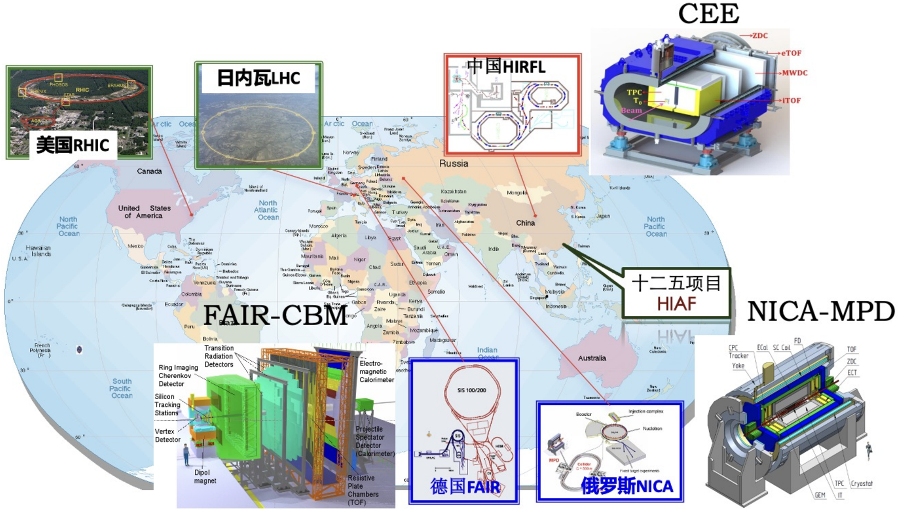



- New analysis framework has been built to eliminate volume fluctuations, which is crucial at FXT energies.

Dynamical modeling for HIC is important to understand the experimental data.

# Summary and Outlook




Physics at High Baryon Density

HIAF/CEE/H-NS: 2.1-4.5 GeV, NICA MPD : 4-11 GeV
FAIR/CBM: 2.4-4.9 GeV, JPARC-HI: 2-5 GeV (planning)

- Critical point and phase boundary;
- Nuclear matter EOS at high baryon density;
- Y-N interactions, inner structure of compact stars.

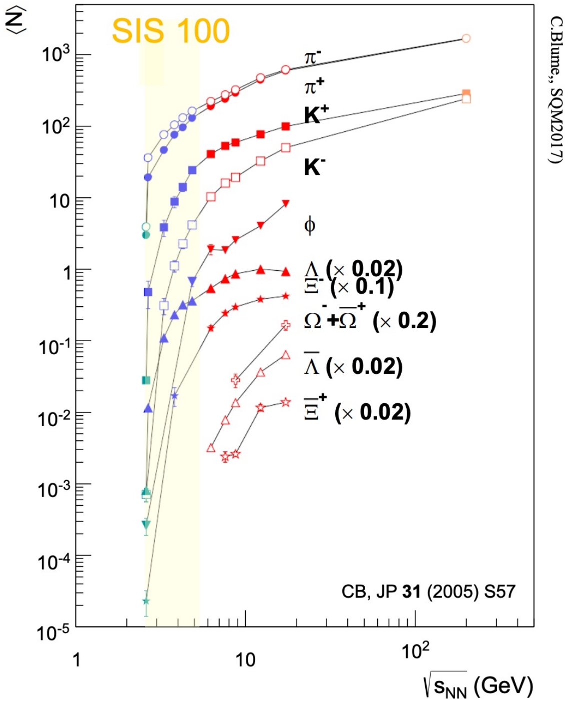
Many Thanks to:

Daniel Cebra, Xin Dong, ShinIchi Esumi, *Yige Huang*, Feng Liu, Bedanga Mohanty, *Bappaditya Mondal*, *Ashish Pandav*, *Zarchary Sweger, Fan Si*, *Zhaohui Wang,* Nu Xu, *Yongcong Xu,* Yifei Zhang, *Xin Zhang, Yu Zhang*

STAR Collaboration and Theory Colleagues

# Thank you for your attention!

# Sub-threshold multi-strange hyperon production




Blume/Markert PPNP66 (2011)
HADES PLB778 (2018); PLB793 (2019)

Sensitive to nuclear matter equation of state due to multistep production.

Strange and charmed particle production thresholds in pp - collisions

| reaction | $\sqrt{s}$ (GeV) | $T_{lab}$(GeV) |
|---|---|---|
| $pp \to K^+\Lambda p$ | 2.548 | 1.6 |
| $pp \to K^+K^-pp$ | 2.864 | 2.5 |
| $pp \to K^+K^+\Xi^-p$ | 3.247 | 3.7 |
| $pp \to K^+K^+K^+\Omega^-n$ | 4.092 | 7.0 |
| $pp \to \Lambda\bar{\Lambda}pp$ | 4.108 | 7.1 |
| $pp \to \Xi^-\bar{\Xi}^+pp$ | 4.520 | 9.0 |
| $pp \to \Omega^-\bar{\Omega}^+pp$ | 5.222 | 12.7 |
| $pp \to J/\Psi\, pp$ | 4.973 | 12.2 |

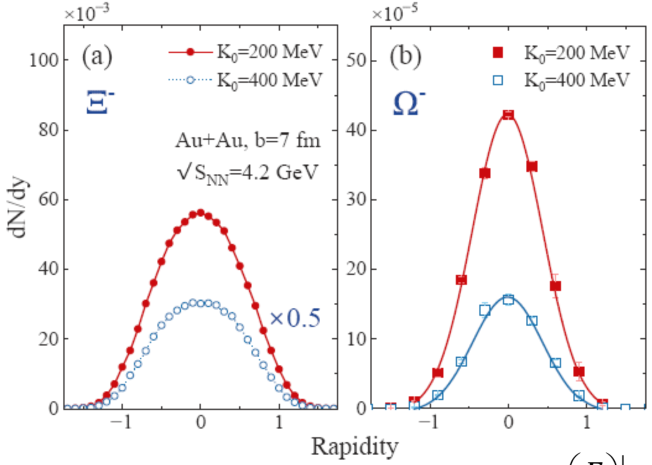
Hyperon production via multiple collisions

1. $pp \to K^+\Lambda^0 p$, $pp \to K^+K^-pp$,
2. $p\Lambda^0 \to K^+\Xi^- p$, $\pi\Lambda^0 \to K^+\Xi^-\pi$, $\Lambda^0\Lambda^0 \to \Xi^- p$, $\Lambda^0 K^- \to \Xi^-\pi^0$
3. $\Lambda^0\Xi^- \to \Omega^- n$, $\Xi^- K^- \to \Omega^-\pi^-$

Antihyperons

1. $\Lambda^0 K^+ \to \Xi^+\pi^0$,
2. $\Xi^+ K^+ \to \Omega^+\pi^+$.


Zhi-Ming Wu, Gao-Chan Yong, Phys. Rev. C 109, 054903 (2024)



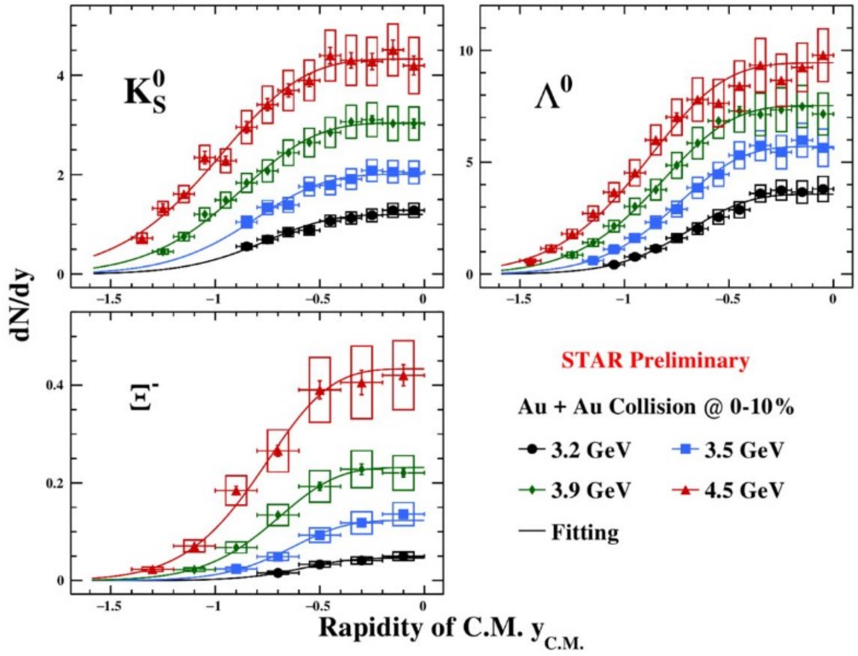

Compressibility: $K_0 = 9\rho^2 \left.\frac{d^2\left(\frac{E}{A}\right)}{d\rho^2}\right|_{\rho_0}$

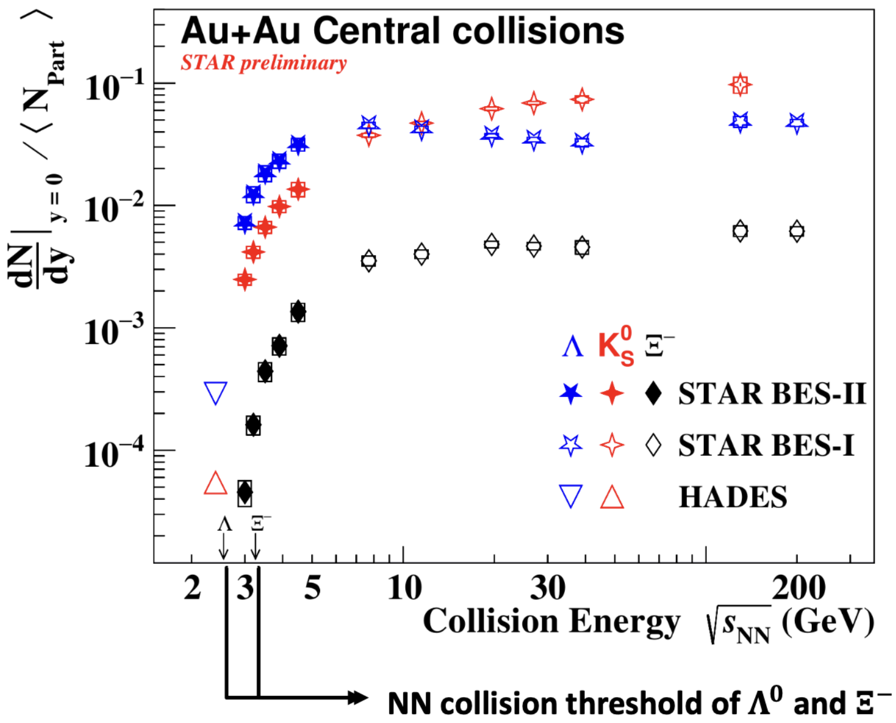
$$E(\rho,\delta) = E_0(\rho) + E_{sym}(\rho)\cdot\delta^2$$

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_0}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + \frac{Z_0}{24}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^4,$$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho}{\rho_0}-1\right) + \frac{K_{sym}}{18}\left(\frac{\rho}{\rho_0}-1\right)^2 + \frac{J_{sym}}{162}\left(\frac{\rho}{\rho_0}-1\right)^3 + \mathcal{O}\left[\left(\frac{\rho}{\rho_0}-1\right)^4\right]$$

# Strangeness Production at STAR BES




Comprehensive measurement of strangeness production at different energies from 3 to 4.5 GeV

PLB831,137152 (2022)，JHEP 10, 139 (2024)