New developments in studies of the QCD phase diagram, ECT*

Study the QCD Phase Structure with Beam Energy Scan at RHIC

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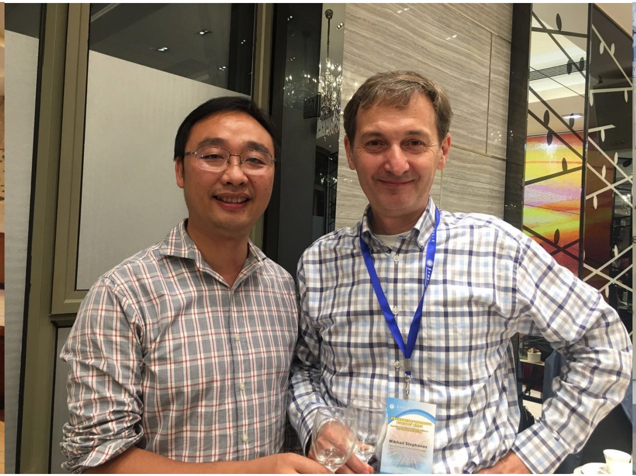
Central China Normal University

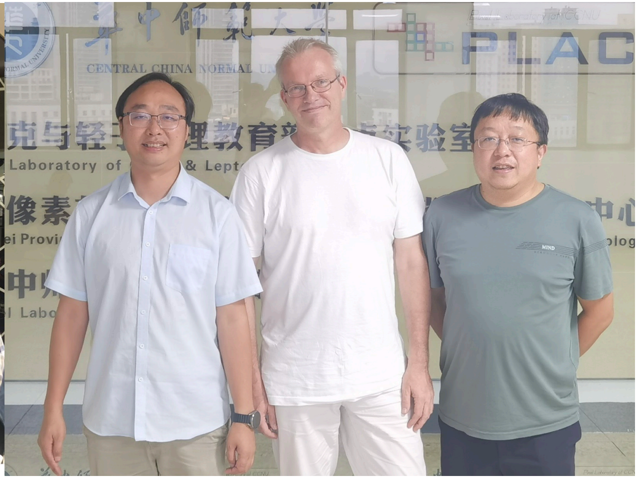
Sept. 9-13, 2024

Lattice or not-Lattice : That is a Question !?

2013 at Napa Valley



2017 at CCNU



2023 at CCNU

Discussion/collaboration between theorist and experimentalist are Very important !!

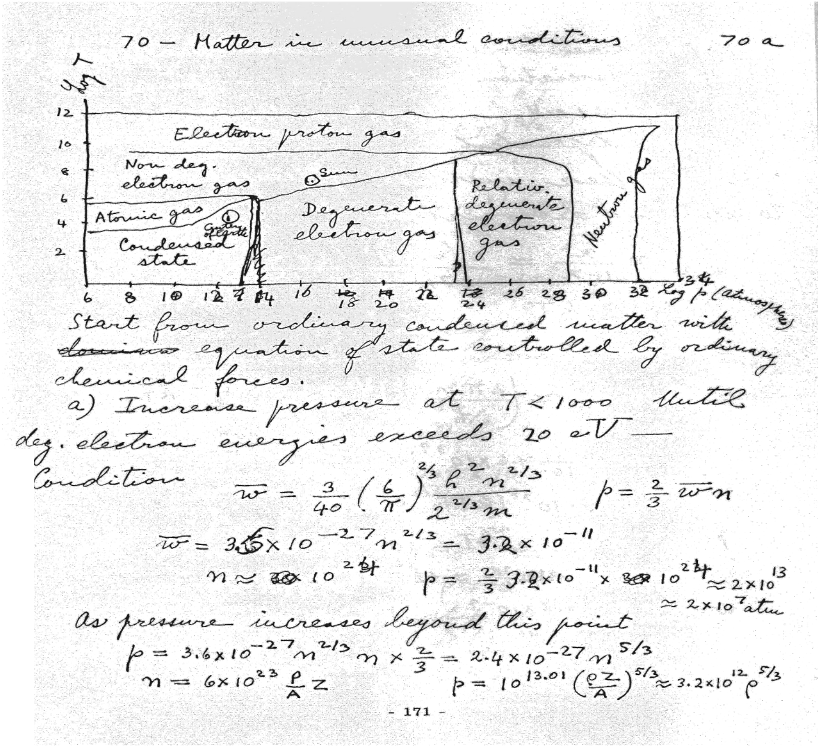
Outline

- Introduction
- Selected Results from RHIC Beam Energy Scan
  1) Net-Proton Fluctuations
  2) Baryon-Strangeness Correlations
  3) Light Nuclei Production
- Summary and Outlook

Matters in Extreme Condition

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

E. Fermi



70 — Matter in unusual conditions 70 a

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

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

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

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

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

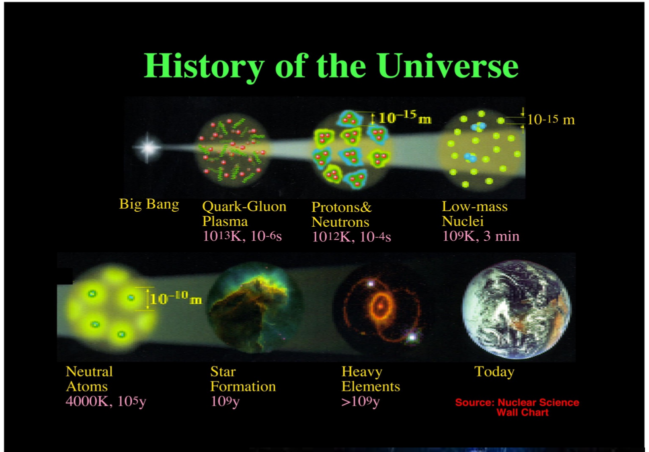
$$\approx 2\times10^{7}\ \text{atm}$$

As pressure increases beyond this point

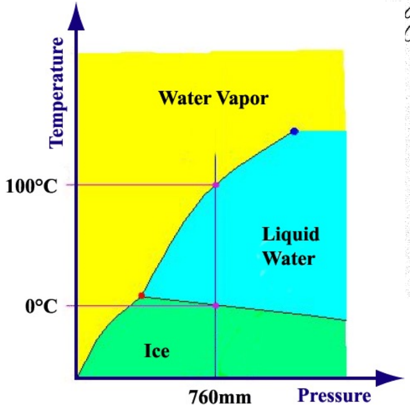
$$p = 3.6\times10^{-27} n^{2/3}\, n \times \frac{2}{3} = 2.4\times10^{-27} n^{5/3}$$

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

- 171 -

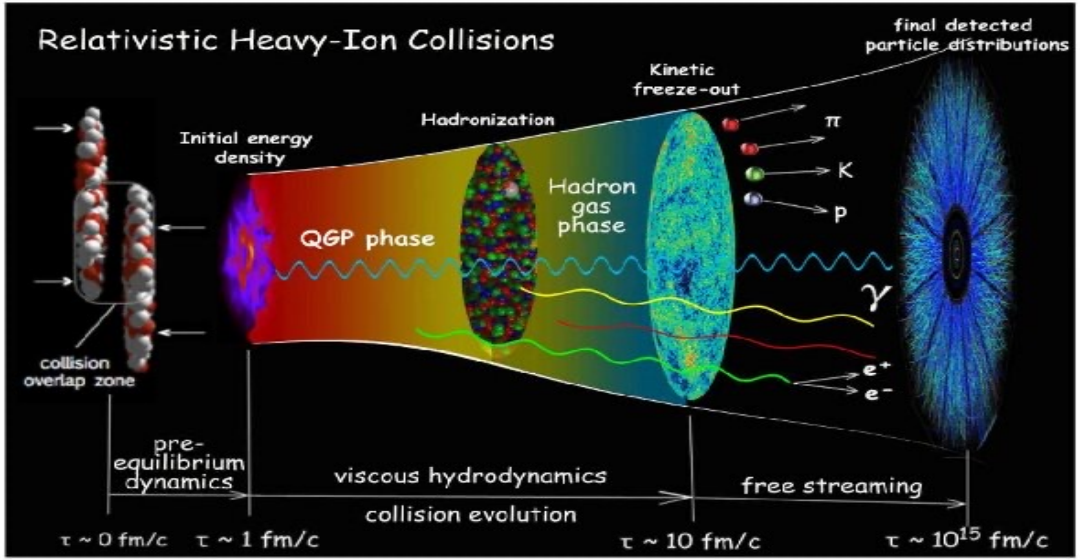


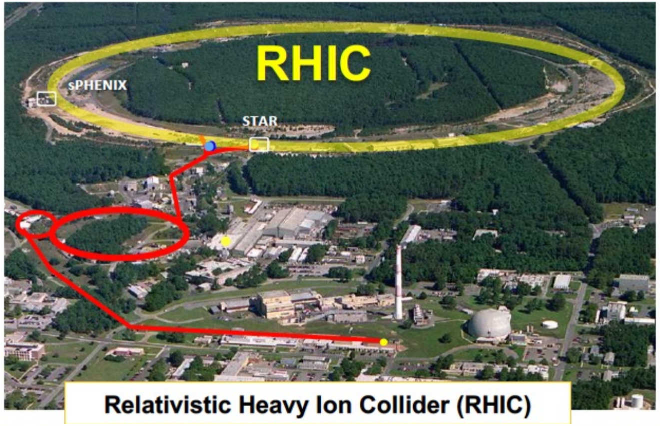
Water Phase Diagram

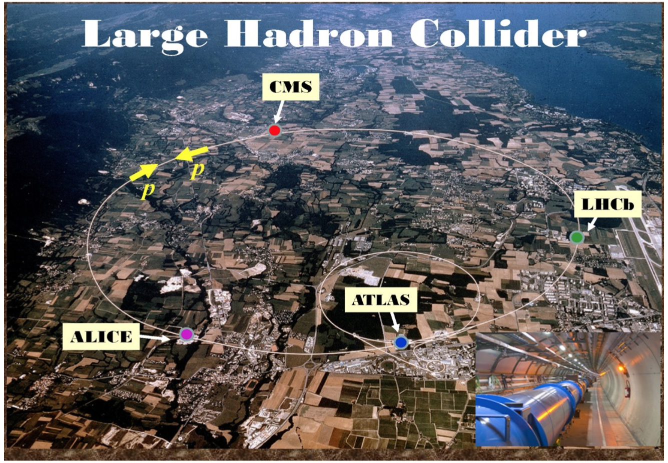


How to create extreme condition similar to early universe ?
What is the relevant degree of freedom and dominated interactions ?

Relativistic Heavy-Ion Collisions and QGP







- ➢ **Properties of Quark-Gluon Plasma (QGP)**
- ➢ **Phase structure of Strongly Interacting Matter**

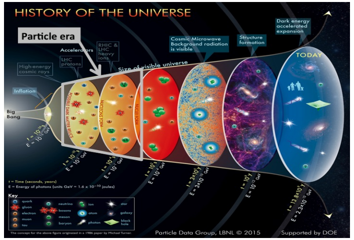
sQGP: Perfect liquid

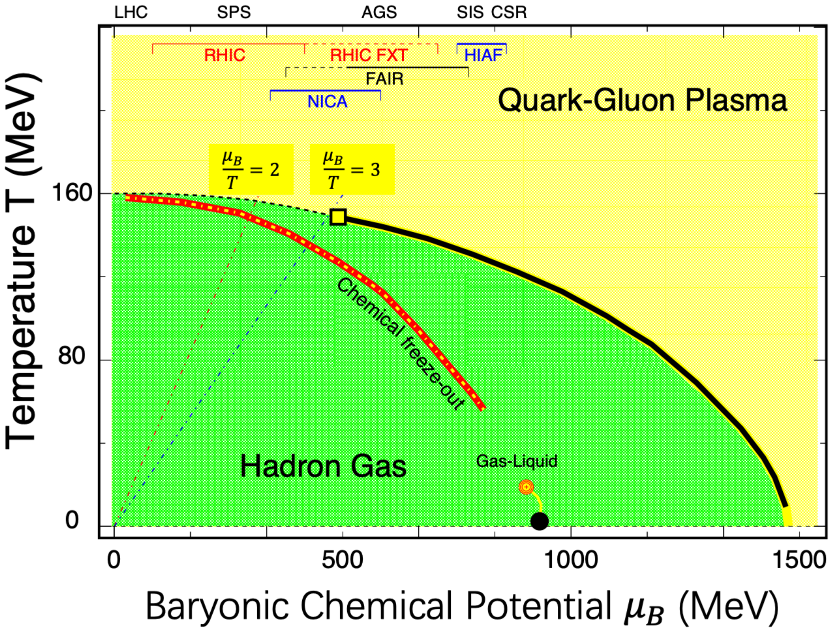
- Small eta/s ~ quantum limit
- Strong electromagnetic field
- Large vorticity

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

QCD Phase Diagram

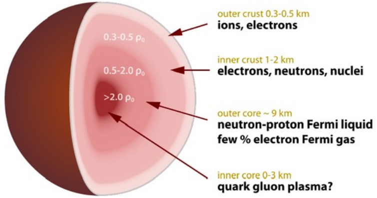
Emergent Properties of Strong Interactions, rich structure at high baryon density





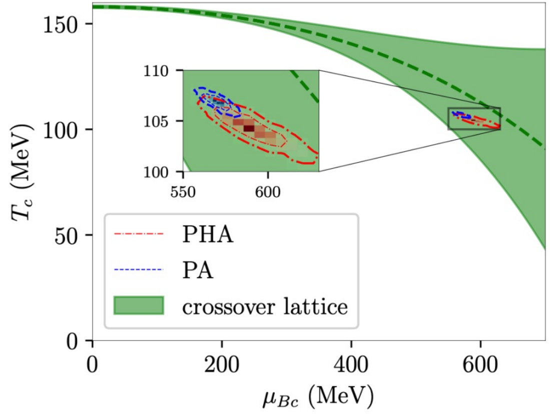
Lattice QCD : at $\mu_B = 0$, smooth crossover.
Large μ_B : 1st order phase transition and QCD critical point ?

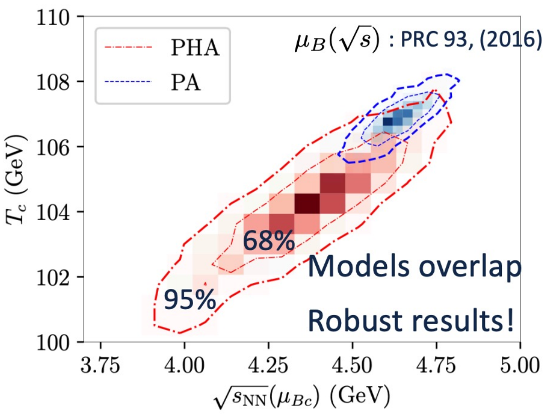
Y. Aoki et al., Nature 443, 675 (2006) ;
A. Bazavov et al (HotQCD), PRD 85, 054503 (2012).
K. Fukushima and C. Sasaki, Prog. Part. Nucl. Phys, 72, 99 (2013).
A. Bzdak et al., Phys. Rep. 853, 1 (2020).



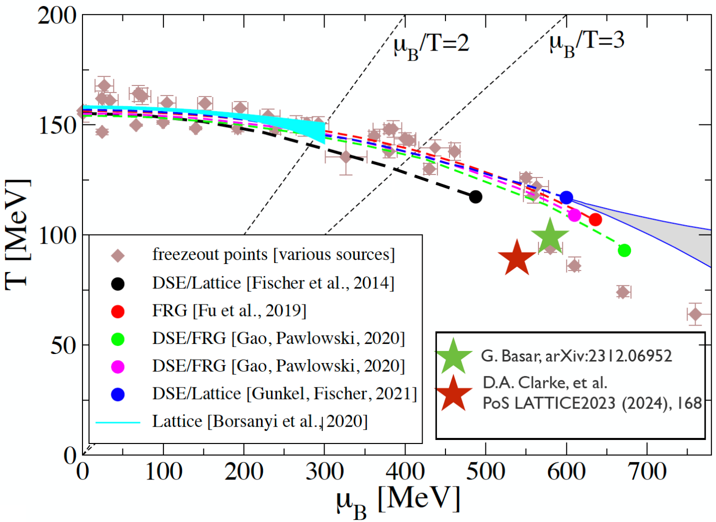
Q1 : Can we find the experimental signature of the smooth crossover ?
Q2 : Can we map out the 1st order phase boundary and find the QCD Critical Point ?
Q3 : What is the equation of state of the dense nuclear matter ?

Location of the QCD Critical Point : Theoretical Estimation/Prediction





Holography+ Bayesian : Hippert et al., arXiv : 2309.00579



CPOD2024

Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

(μ_c, T_c) = (495 - 654, 100 - 119) MeV → $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

Relativistic "Minds" Collisions (2006)

Critical Point: In 2005, RHIC released white paper: nucl-ex/0501009, sQGP has been found. Where does RHIC go from here? What is the important physics? How to highlight the importance of the STAR experiment?

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

Motivation & Plans： The workshop is motivated by a growing body of theoretical and experimental evidence that the critical point on the QCD phase diagram, if it exists, should appear on the QGP transition boundary at baryo-chemical potential ~100 - 500 MeV, corresponding to heavy ion collisions with c.m. energy in the range 5 - 50 GeV/u. Identifying and pinning down this point with experimental measurements would be a major step forward in the world-wide effort to determine the properties of QCD at high temperature and density.

Thursday, March 9

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

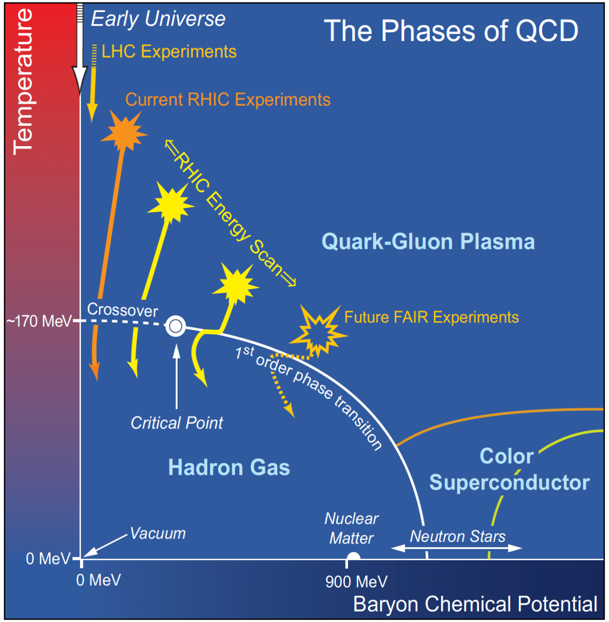
Friday, March 10

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

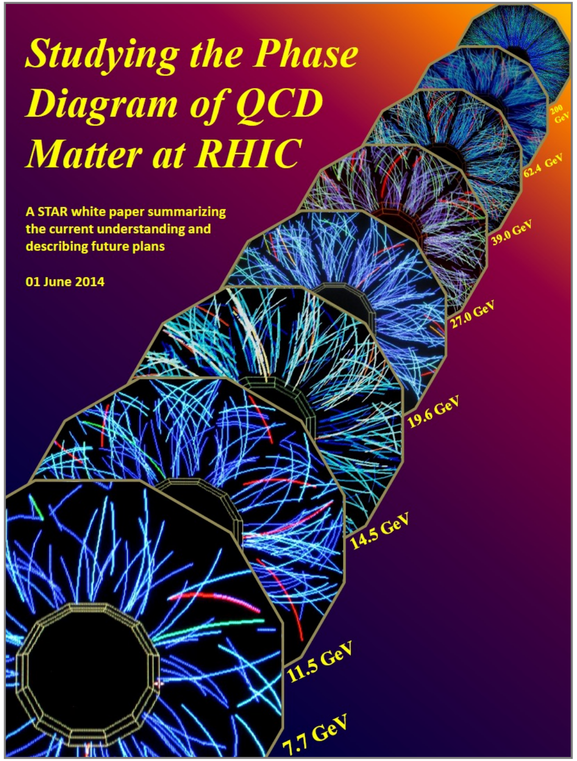
Build consensus in the field:
- Physical Importance
- Experimental Feasibility
- Sensitive observables

RHIC Beam Energy Scan Adventure

- BES first proposed to PAC 2006.
- STAR BES campaign formally started in 2010
- BES-II officially requested in 2014, starts 2019(18)



BES-II White Paper (2014)



Main Motivation:

- Looking for turning off QGP signals observed at RHIC top energy.
- Mapping out the crossover and/or 1st order QCD phase boundary
- Search for the signatures of possible QCD critical point.

STAR, arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

INT 2008-2b : The QCD Critical Point

Organizer: https://www.int.washington.edu/PROGRAMS/08-2b.html

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Mikhail Stephanov
University of Illinois at Chicago
misha@uic.edu

July 28, 2008	S. Gupta	"New results in QCD at finite μ"
July 29, 2008	M.P. Lombardo	"The QCD critical point at imaginary mu"
July 29, 2008	S. Ejiri	"Numerical study of the critical point in lattice QCD at high temperature and density"
July 30, 2008	K. Fukushima	"What can we learn from model studies on the chiral critical end-point?"
July 30, 2008	B. Klein	"Scaling and Finite-Size Scaling Analysis of Critical Behavior in Lattice QCD"
July 31, 2008	J. Braun	"Chiral Phase Boundary from Quark-Gluon Dynamics"
July 31, 2008	C. Ratti	"A quasiparticle model for QCD thermodynamics"
August 4, 2008	J. Verbaarschot	"Phase of the Fermion Determinant and the Phase Diagram of QCD"
August 5, 2008	R. Lacey	"The Role of Energy Scans at RHIC"
August 5, 2008	L. Ferroni	"Space and Phase Space saturation: a simple Bag-Model-inspired picture for a smooth transition to QGP"
August 6, 2008	M. Asakawa	"QCD Critical Point and its Effect on Physical Observables"
August 6, 2008	T. Hell	"Thermodynamics of a Nonlocal PNJL Model for Two and Three Flavors"
August 7, 2008	C. Miao	"QCD Equation of State and Fluctuations on the Lattice"
August 11, 2008	K. Rajagopal	"The Search for the QCD Critical Point Using Lattice QCD Calculations-Part I" Part 2
August 11, 2008	F. Karsch	"Lattice results on the QCD critical point"
August 11, 2008	J. Randrup	"Spinodal decomposition: A tool for seeing the phase transition?"
August 11, 2008	H. Caines	"STAR and the RHIC Energy Scan"
August 11, 2008	K. Homma	"Fluctuations and Search for the QCD Critical Point"
August 12, 2008	G. Stephans	"Experimental Exploration of the QCD Phase Diagram"
August 12, 2008	K.F. Liu	"Finite Density Phase Transition with Canonical Ensemble Approach"
August 12, 2008	C. Nonaka	"Hydrodynamic Expansion with the QCD Critical Point in Heavy Ion Collisions"
August 12, 2008	M. Mitrovski	"Energy and System Size Dependence of Hadron Production from NA49"
August 12, 2008	T. Schuster	"Energy and System Size Dependence of Fluctuations: NA49 results and NA61 plans"
August 12, 2008	G. Westfall	"K/pi Fluctuations and the Balance Function-Part 1" Part 2 Part 3

August 13, 2008	K. Redlich	"Charge Fluctuations and transport coefficients near CEP"
August 13, 2008	H. Fujii	"Spectral functions near the QCD critical point in chiral models"
August 13, 2008	R. Karabowicz	"The CBM Experiment"
August 13, 2008	P. Stankus	"Critical Point Scans at RHIC Full Energy"
August 14, 2008	L. McLerran	"The QCD Phase Diagram: The Large N Limit"
August 14, 2008	P. de Forcrand	"Towards a controlled lattice study of the QCD chiral critical point"
August 14, 2008	S. Roessner	"The interplay of flavour- and Polyakov-loop- degrees of freedom --- A PNJL model analysis"
August 14, 2008	J. Liao	"Magnetic Component of Strongly Coupled Quark Gluon Plasma & QCD Phase Diagram from E-M Duality Perspective"
August 14, 2008	H. Stoecker	"Cosmic matter in the Lab: FAiR=The International Facility for Antiproton and Ion Research"
August 15, 2008	R. Scharenberg	"STAR's measurement of long-Range forward backward multiplicity correlations in Heavy Ion central Au-Au collisions at $\sqrt{s}$=200 GeV"
August 15, 2008	D. Blaschke	"Nonlocal Chiral Quark Models & Critical (End-)Point"
August 18, 2008	C. Greiner	"Fast chemical equilibration of hadrons-the importance of multiparticle collisions in heavy ion reactions"
August 19, 2008	K. Mitsutani	"The possible quasi-particle picture of the quark near Tc and its effect on the dilepton production rate"
August 20, 2008	J-W. Chen	"Phase Transitions and the perfectness of Fluids"
August 21, 2008	M. Tachibana	"Spectral Continuity of Hadrons in Dense QCD"

https://www.int.washington.edu/talks/WorkShops/int_08_2b/

What is the sensitive experimental observable to search for CP ??

Higher-order fluctuations of Conserved Charge (B, Q, S)

Universality, the QCD critical / tricritical point and the quark number susceptibility #1
Yoshitaka Hatta (Kyoto U. and Wako, RIKEN), Takashi Ikeda (RIKEN BNL) (Oct, 2002)
Published in: *Phys.Rev.D* 67 (2003) 014028 • e-Print: hep-ph/0210284 [hep-ph]
pdf DOI cite 337 citations

Proton number fluctuation as a signal of the QCD critical endpoint #2
Y. Hatta (Kyoto U. and Wako, RIKEN), M.A. Stephanov (Illinois U., Chicago and RIKEN BNL) (Jan, 2003)
Published in: *Phys.Rev.Lett.* 91 (2003) 102003, *Phys.Rev.Lett.* 91 (2003) 129901 (erratum) • e-Print: hep-ph/0302002 [hep-ph]
pdf DOI cite 239 citations

Hadronic fluctuations at the QCD phase transition #1
S. Ejiri (Bielefeld U. and Tokyo U.), F. Karsch (Bielefeld U. and Brookhaven), K. Redlich (Wroclaw U. and CERN) (Sep, 2005)
Published in: *Phys.Lett.B* 633 (2006) 275-282 • e-Print: hep-ph/0509051 [hep-ph]
pdf links DOI cite 273 citations

Non-Gaussian fluctuations near the QCD critical point #7
M.A. Stephanov (Illinois U., Chicago) (Sep, 2008)
Published in: *Phys.Rev.Lett.* 102 (2009) 032301 • e-Print: 0809.3450 [hep-ph]
pdf DOI cite 527 citations

Third moments of conserved charges as probes of QCD phase structure #5
Masayuki Asakawa (Osaka U.), Shinji Ejiri (Brookhaven), Masakiyo Kitazawa (Osaka U.) (Apr, 2009)
Published in: *Phys.Rev.Lett.* 103 (2009) 262301 • e-Print: 0904.2089 [nucl-th]
pdf DOI cite 200 citations

Using Higher Moments of Fluctuations and their Ratios in the Search for the QCD Critical Point #24
Christiana Athanasiou (MIT), Krishna Rajagopal (MIT), Misha Stephanov (Illinois U., Chicago) (Jun, 2010)
Published in: *Phys.Rev.D* 82 (2010) 074008 • e-Print: 1006.4636 [hep-ph]
pdf DOI cite 148 citations

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2003
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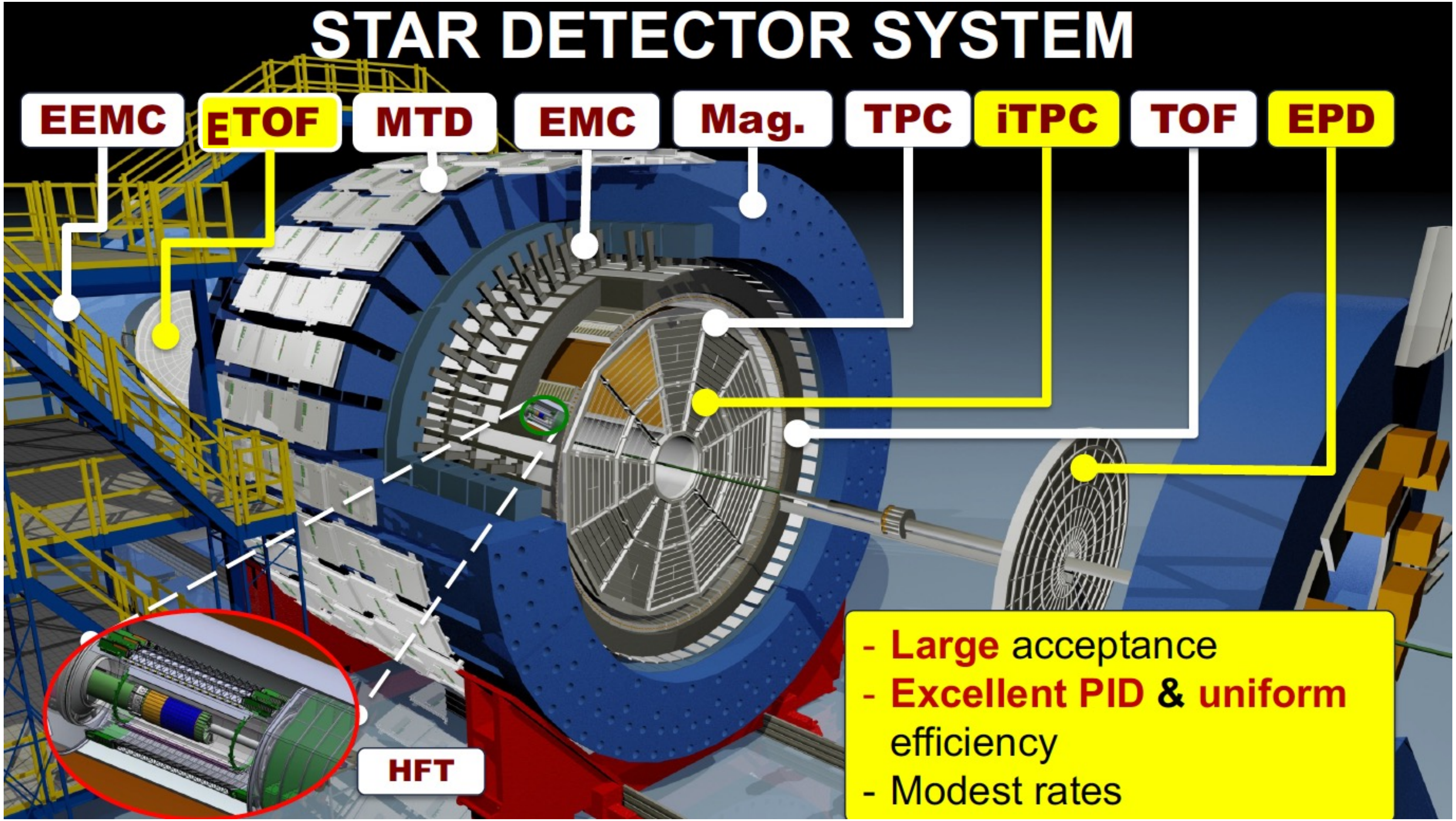
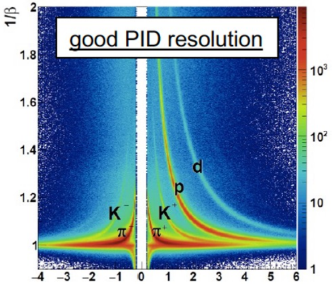
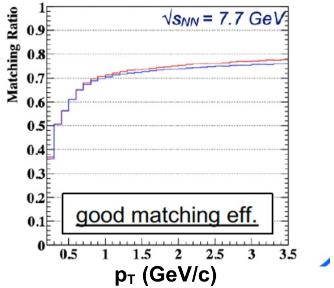

STAR DETECTOR SYSTEM
EEMC
ETOF
MTD
EMC
Mag.
TPC
iTPC
TOF
EPD
HFT
- Large acceptance
- Excellent PID & uniform efficiency
- Modest rates

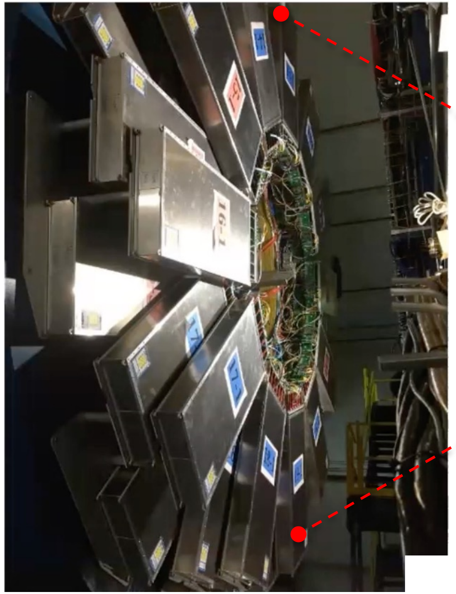
STAR Experiment : Fixed-Target Mode

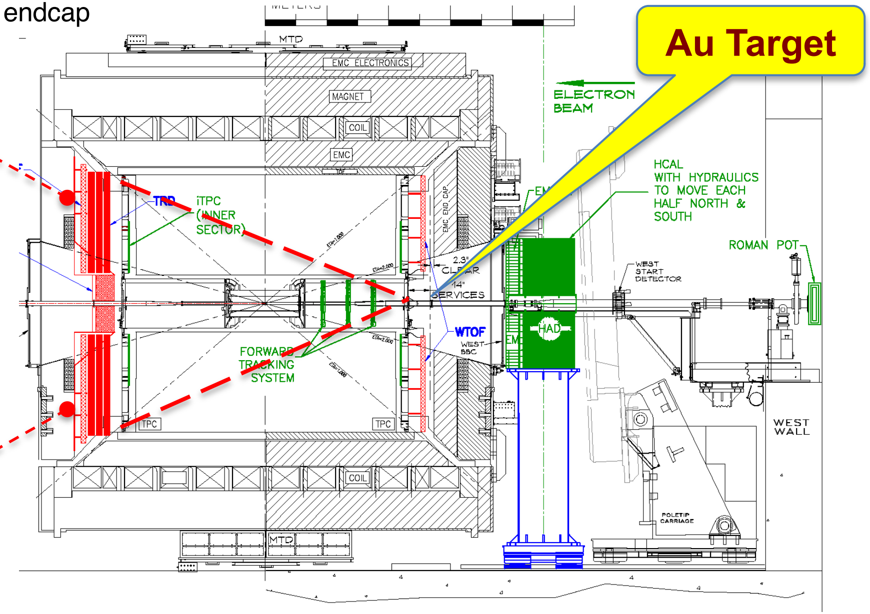
eTOF (2019+)

10% of the CBM TOF modules installed at STAR endcap







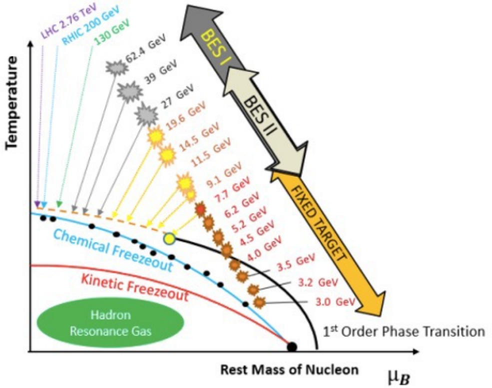


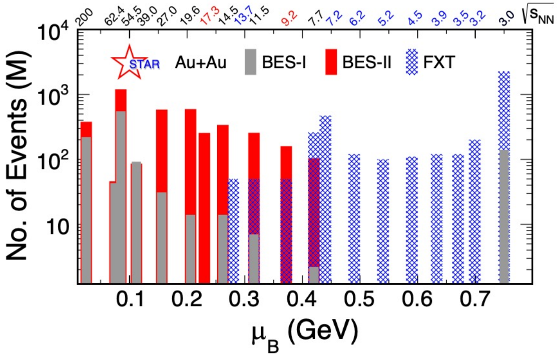
eTOF from CBM are installed at STAR endcap in RHIC BES-II

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

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

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

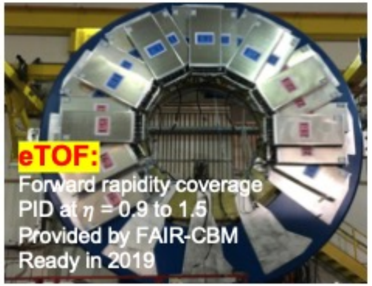


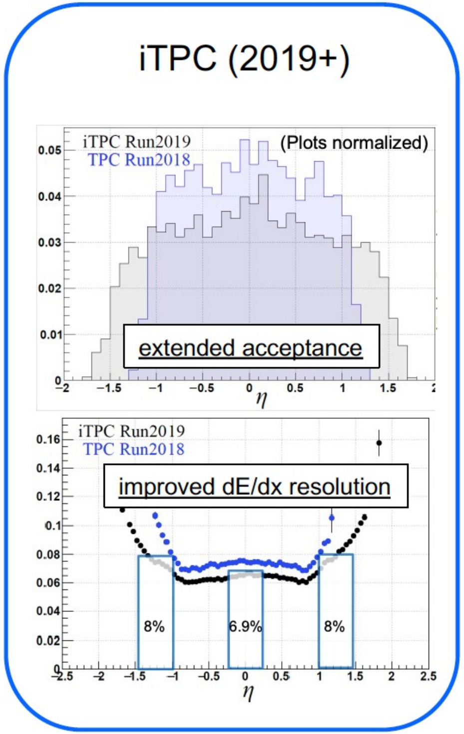


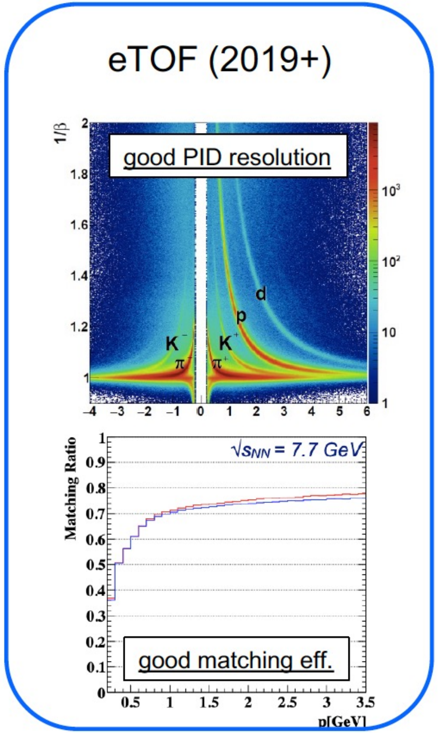
- ➢ Au+Au Collisions at 3 - 200 GeV (Collider + FXT)
- ➢ μ_B coverage : $25 < \mu_B < 750$ MeV

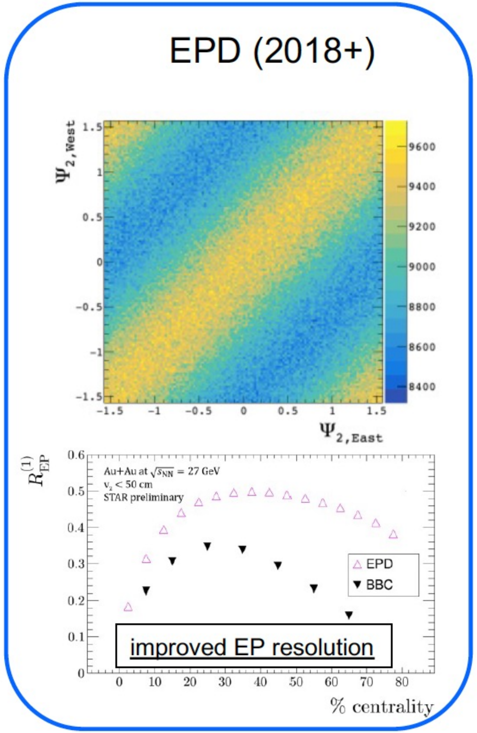
- ➢ x10-20 more statistics in BES-II compared to BES-I at collider energies
- ➢ BES-II: 8 collider energies (7.7 – 54.4GeV)
  12 FXT energies (3.0 - 13.7 GeV)

Detector Upgrade and Performance in BES-II







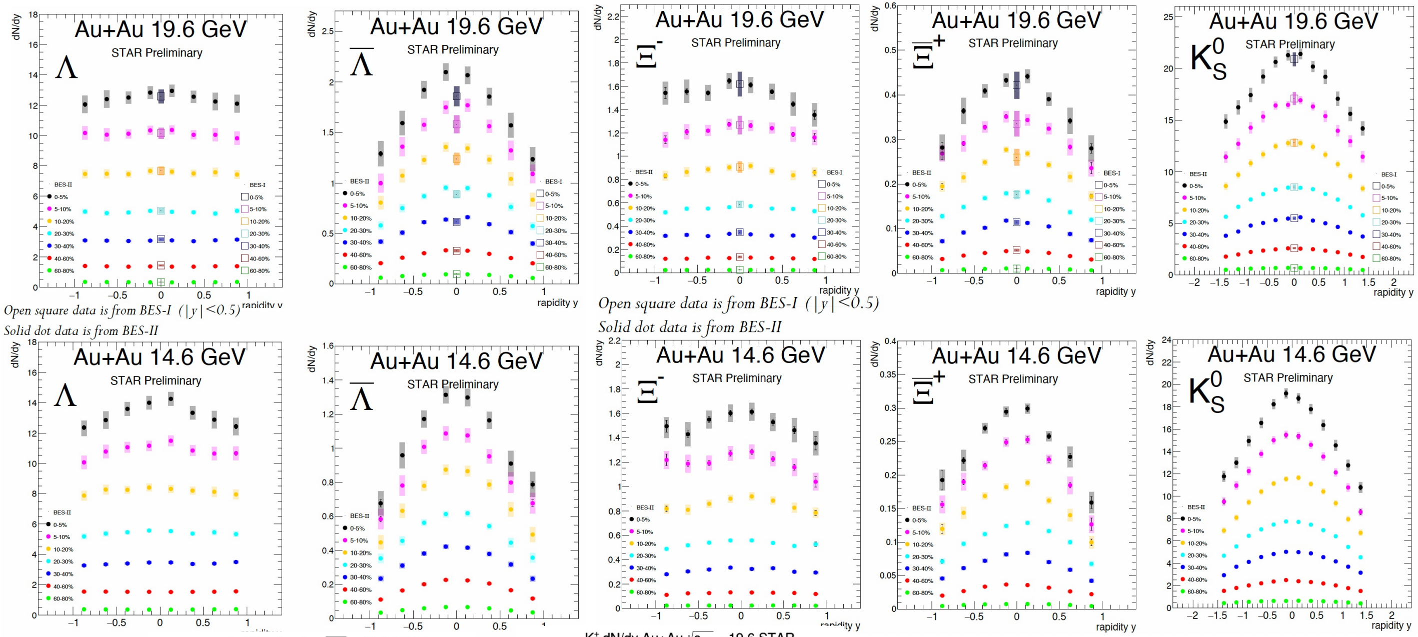


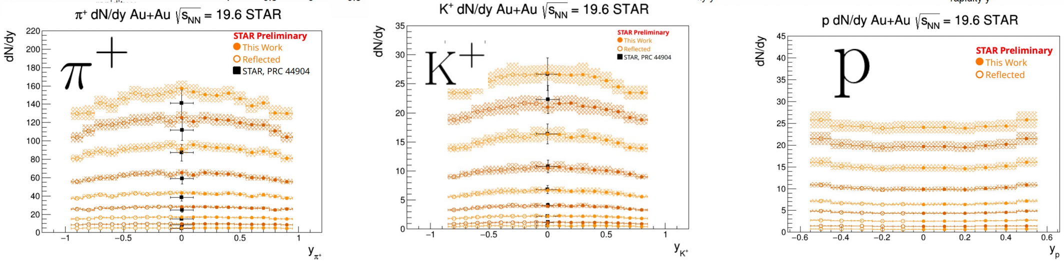
iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. Nucl. Instr. Meth. A 968, 163970 (2020)

1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/event plane resolution

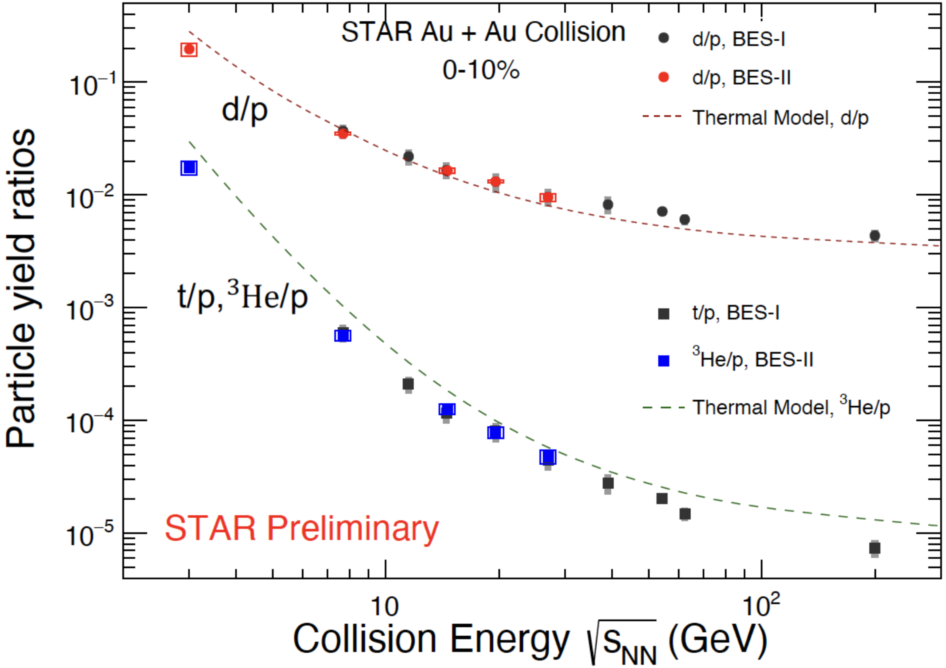
BES-II spectra (14.6, 19.6 GeV) : pi, k, p and strangeness

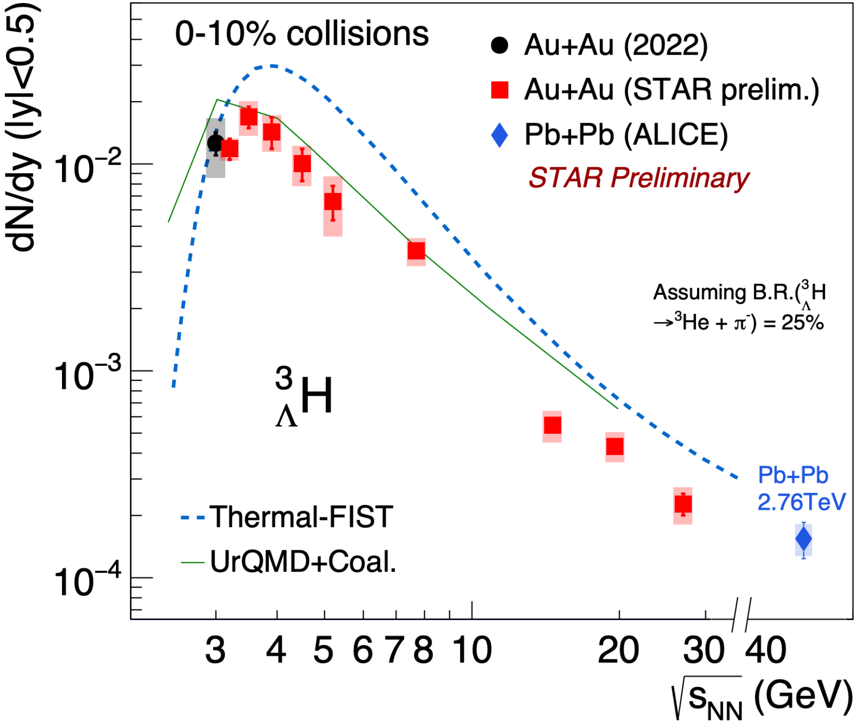
STAR, QM2023





Light and Hyper-nuclei Production in STAR BES-II





At high baryon density, light and hyper- nuclei are abundant

Observables: Higher Moments of Conserved Charge Distributions

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

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

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

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

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

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

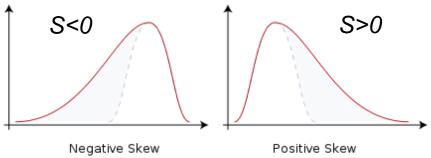
Moments, cumulants and susceptibilities:

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

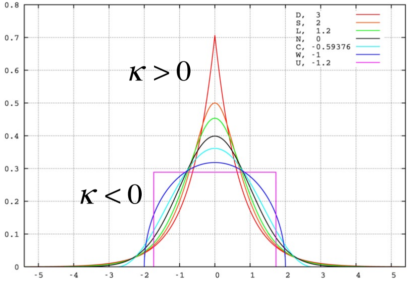
3^{rd} order: $S\sigma \equiv C_3/C_2 = \chi_3/\chi_2$

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

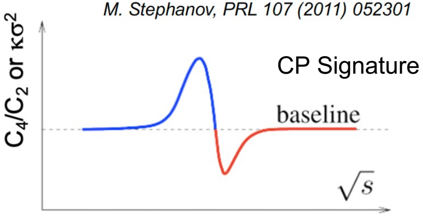
Skewness (S) → asymmetry



Kurtosis(κ) → Sharpness



M. Stephanov, PRL 107 (2011) 052301



1. Sensitive to correlation length (ξ)
2. Directly related to system susceptibility (χ)

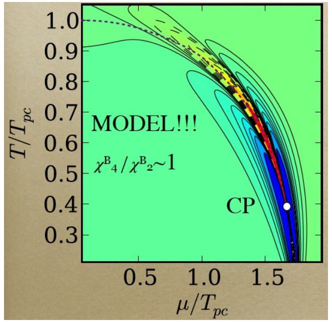
$$\langle (\delta N)^3 \rangle_c \approx \xi^{4.5}, \quad \langle (\delta N)^4 \rangle_c \approx \xi^7$$

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

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)*

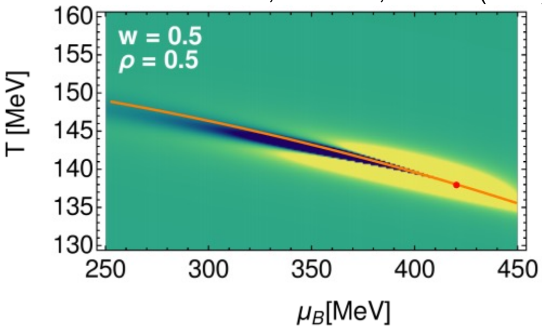
Critical Signal for the Fourth-order Fluctuations ($\kappa\sigma^2$)

PQM V. Skokov, QM2012



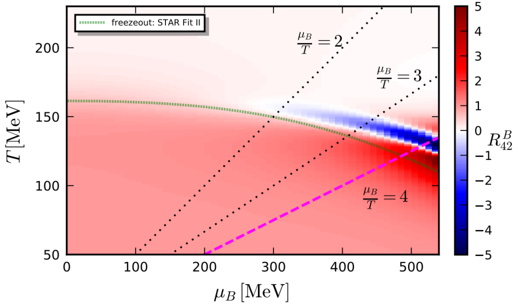
3D Ising Mapping

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

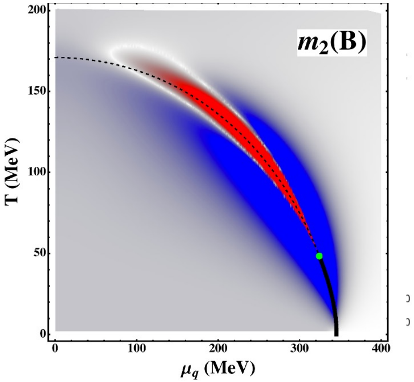


FRG

Weijie Fu, et al., PRD 104 (2021) 9, 094047

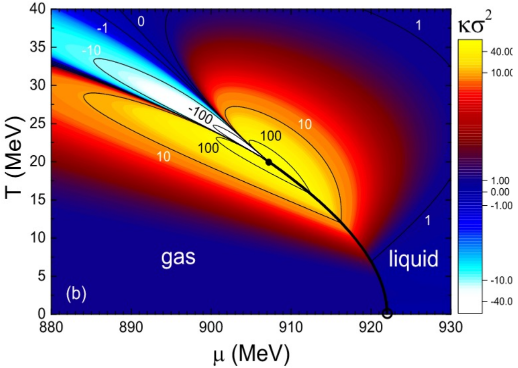


NJL



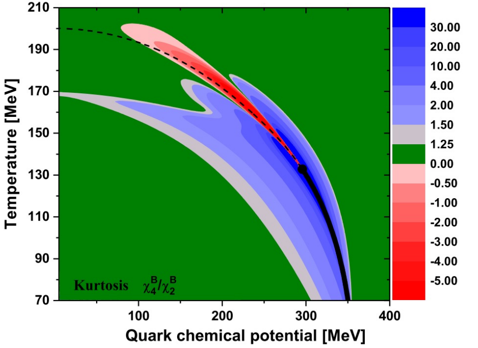
J. Deng, et al., PRD93, 034037 (2016)

van der Waals (VDW)



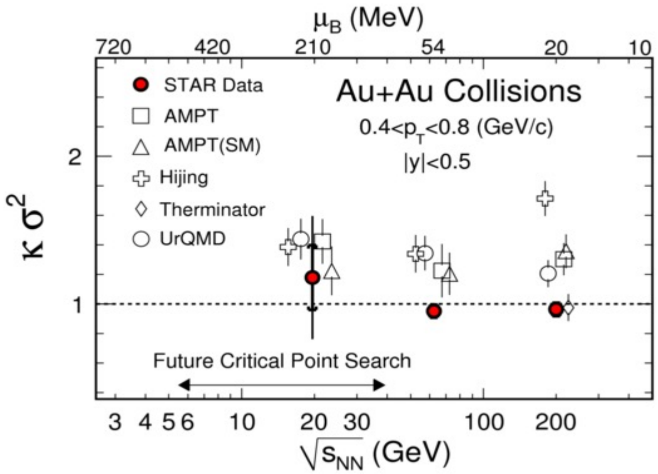
Vovchenko et al., PRC92, 054901 (2015)

PNJL



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

High Moments Measurements at STAR experiment

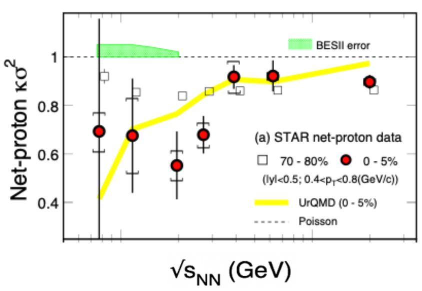


First measurement !

Verified the feasibility of the high moments observable in heavy-ion experiment.

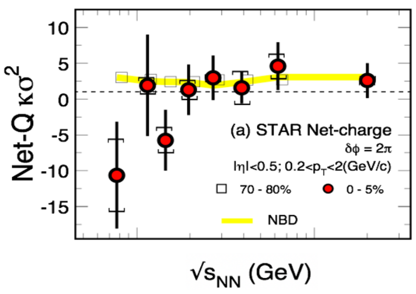
STAR, Phys. Rev. Lett. 105, 022302(2010).

Net-Proton



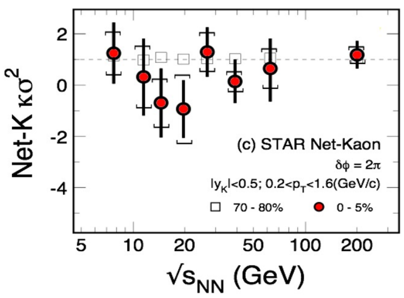
STAR, PRL 112, 032302 (2014).

Net-Charge



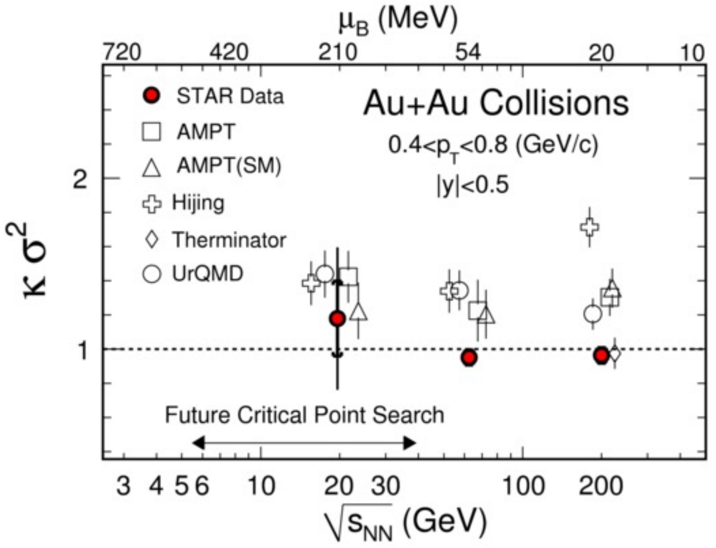
STAR, PRL113, 092301 (2014).

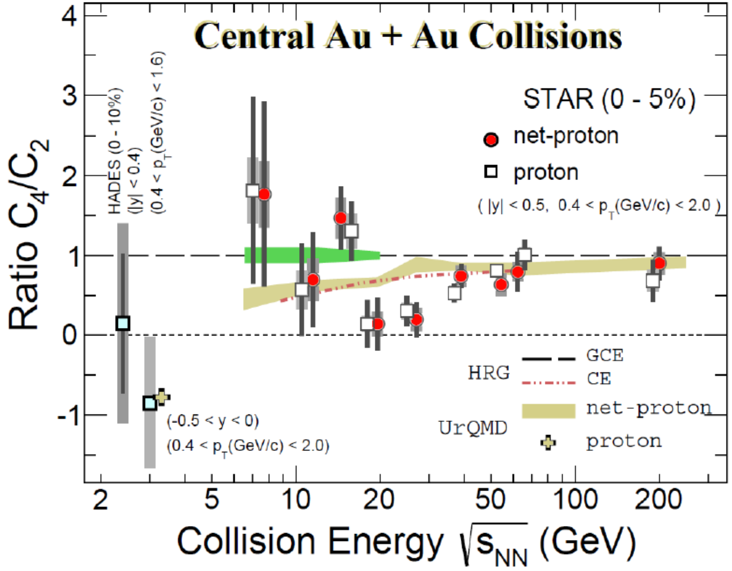
Net-Kaon



STAR, PLB 785, 551 (2018).

Higher Moments of Net-Proton Multiplicity Distributions





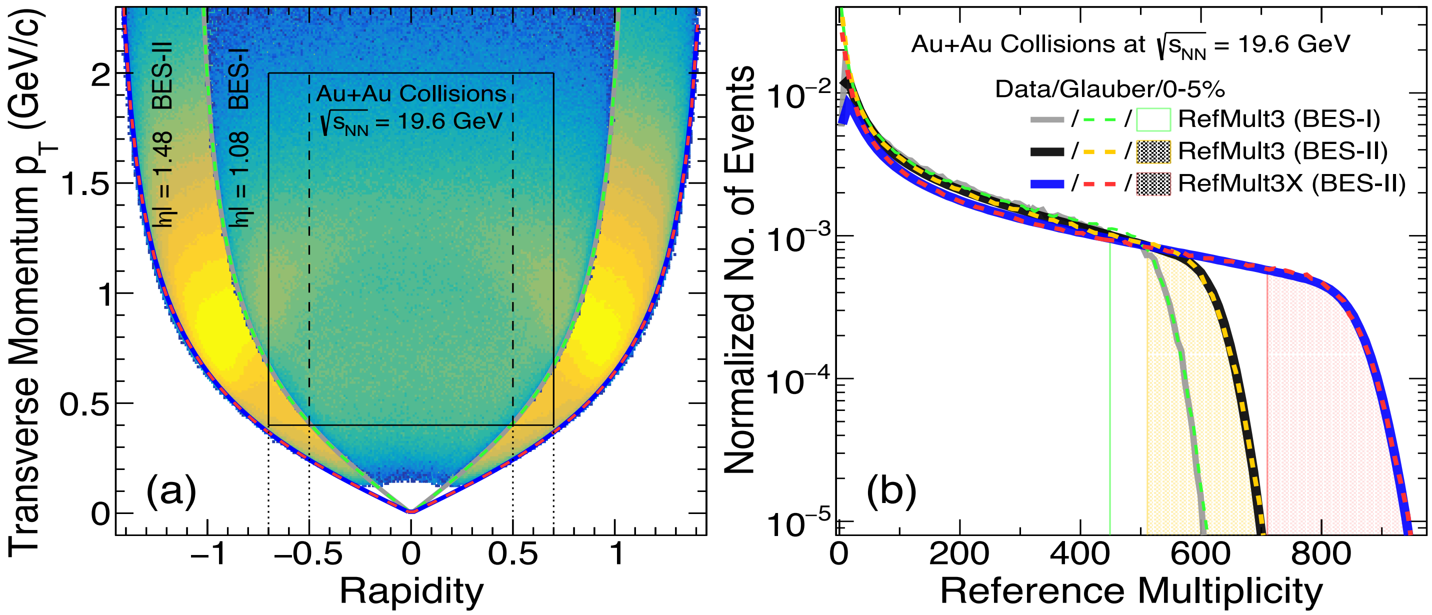
STAR, Phys. Rev. Lett. 105, 022302 (2010)

Verified the feasibility of the high moments observable in heavy-ion experiment.

BES-I : Phys. Rev. Lett. 126, 092301 (2021)
Phys. Rev. C 104, 024902 (2021)
3 GeV: Phys. Rev. Lett. 128, 202303 (2022)
Phys. Rev. C 107, 024908 (2023)

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

BES-II : Centrality Determination



1. Refmult3 : Multiplicity of charged particles except (anti-)protons is used for centrality determination (Avoid auto-correlation)

1) RefMult3: (| η |<1.0) for both BES-I and BES-II **2) RefMult3X: (| η |<1.6)** for BES-II

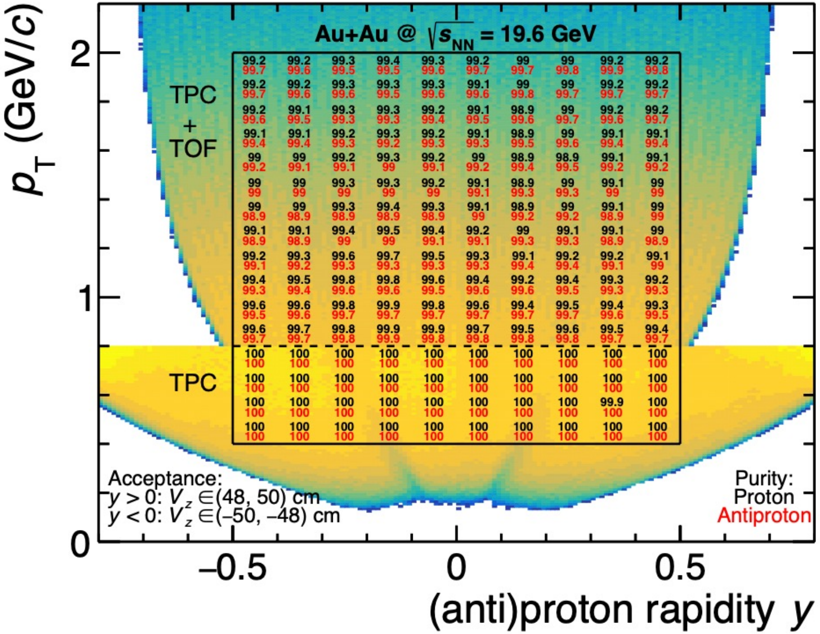
→ Larger acceptance → larger multiplicity → better centrality resolution

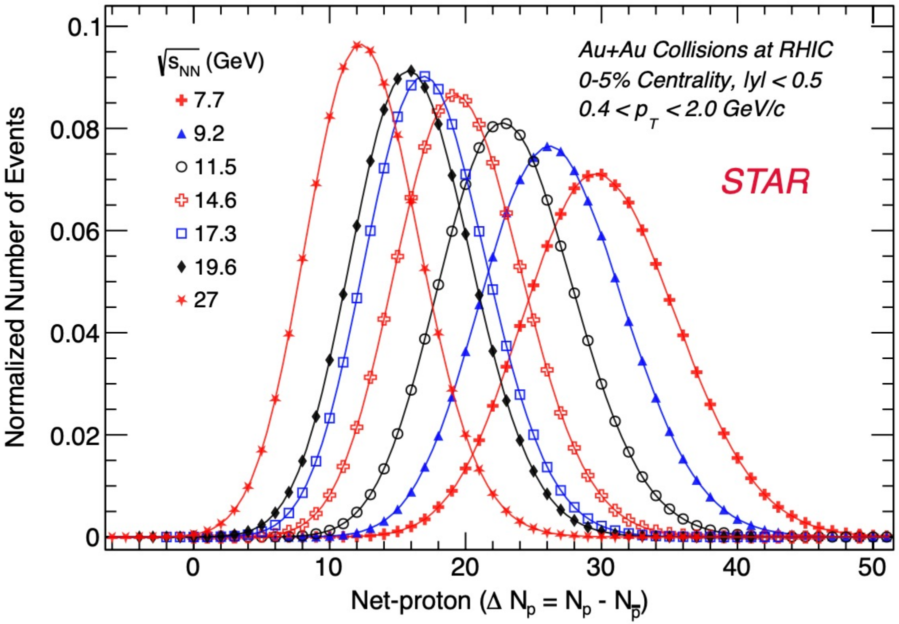
(Anti-)Proton Particle Identification and Net-Proton Distributions

- Identified protons in selected kinetic region are used for analysis:
  $0.4 < p_T < 2.0$ GeV/c and $|y| < 0.5$

✓ Bin-by-bin proton/antiproton purity > **99%**

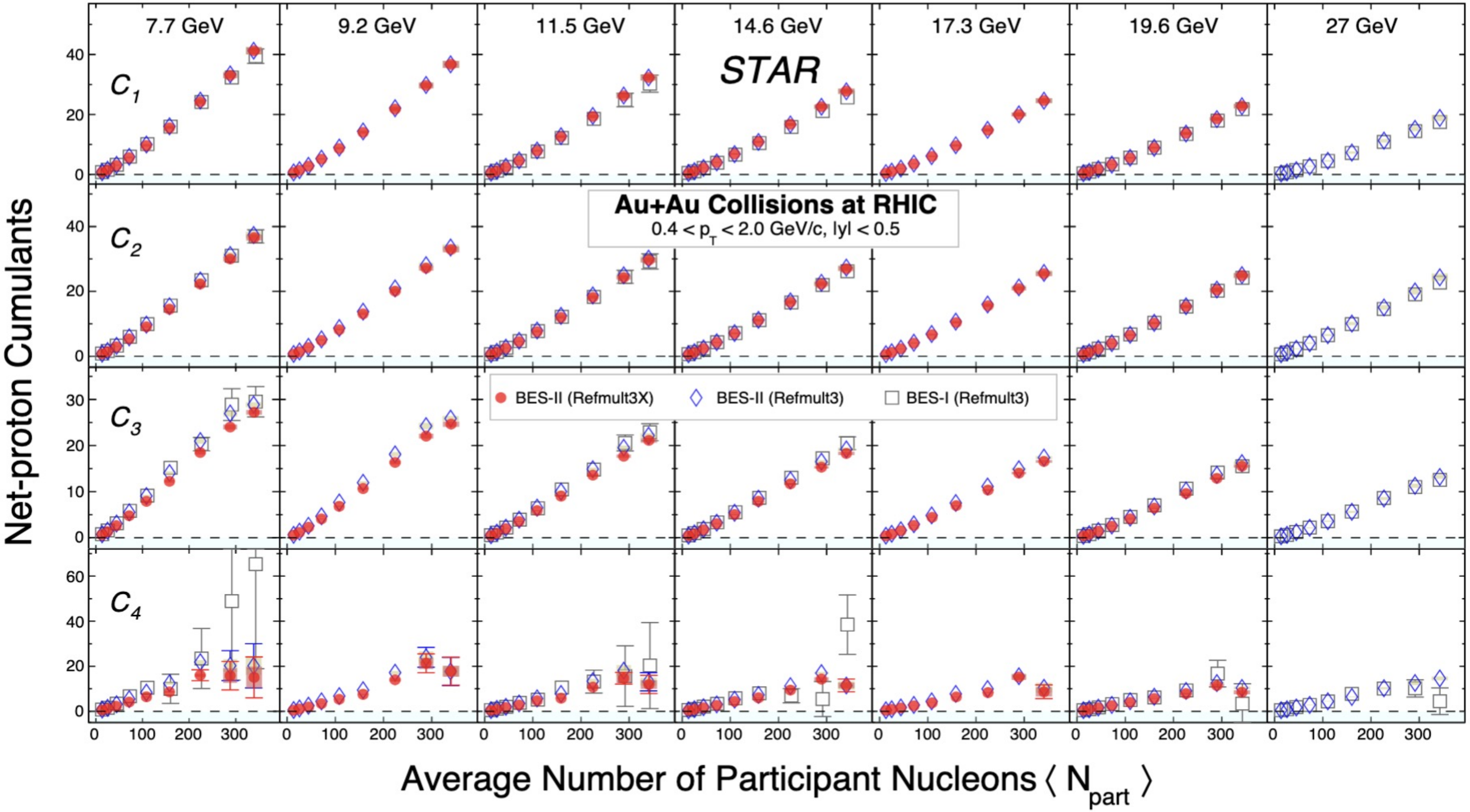
Stat. error $C_r \propto \frac{\sigma^r}{\sqrt{N}}$





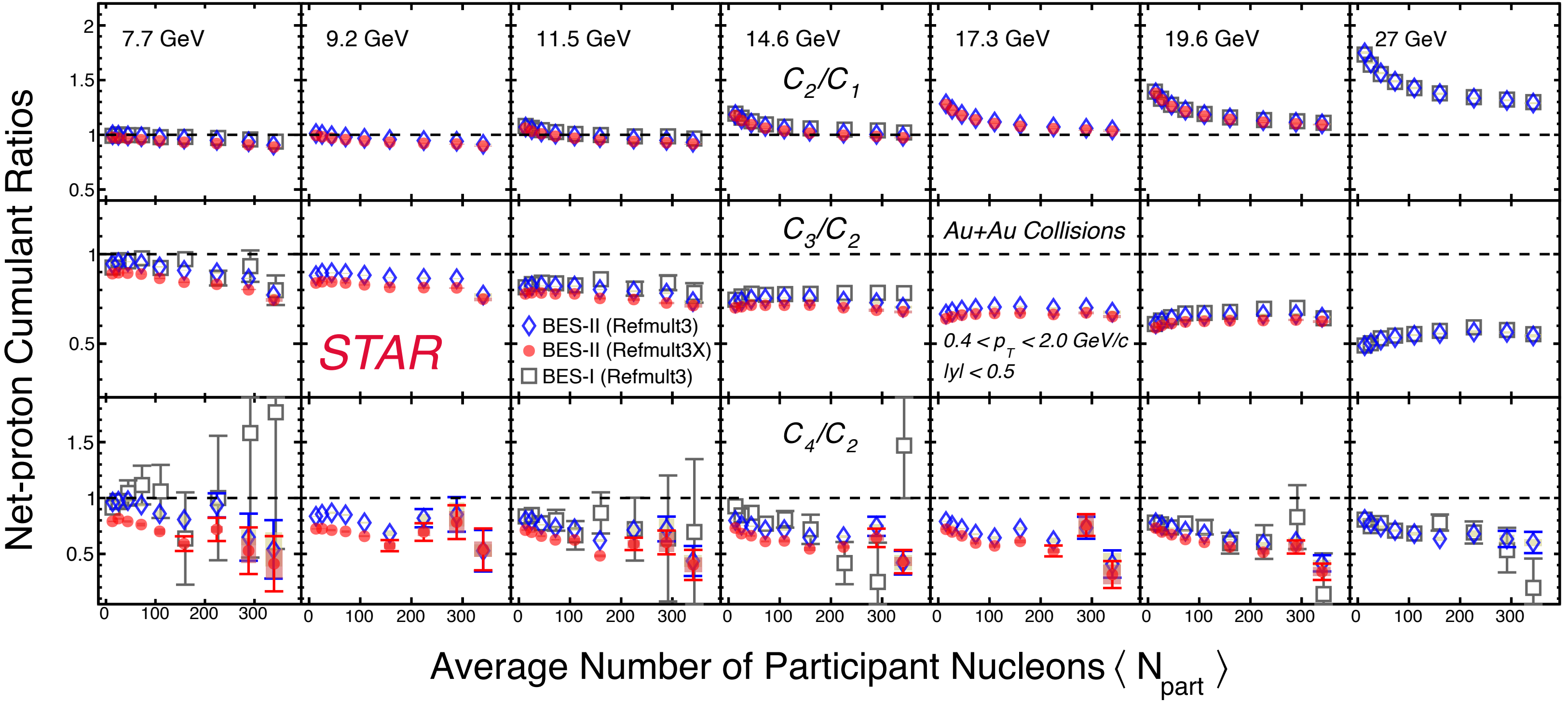
Centrality Dependence: Net-proton Cumulants

STAR: CPOD2024, SOM2024



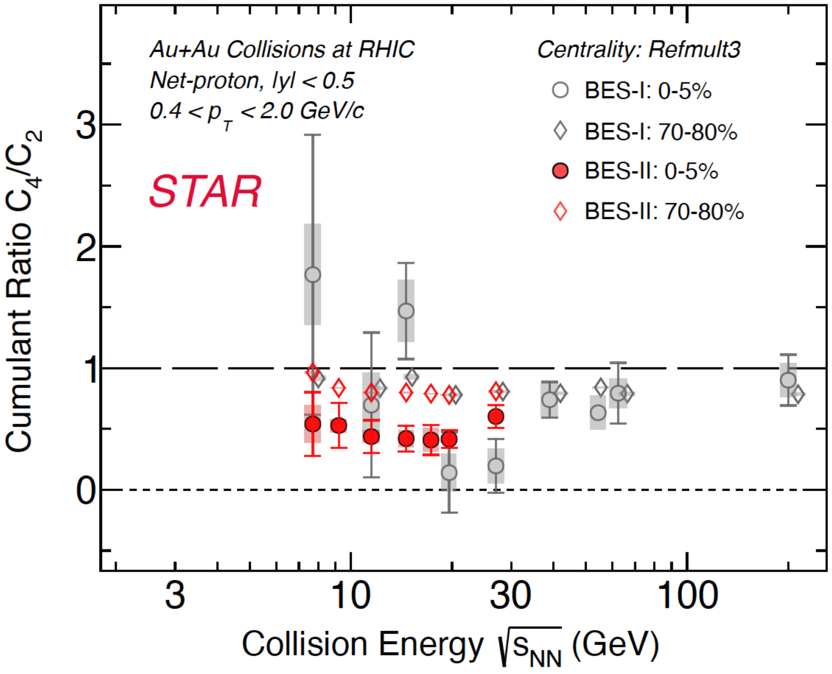
Centrality Dependence: Net-proton Cumulant Ratios

STAR: CPOD2024, SQM2024



1. Smooth variation across centrality and collision energy is seen from BES-II measurement;
2. For 0-5% most central collisions, weak effect of centrality resolution of C_4/C_2 is observed

Cumulant Ratios from BES-II and BES-I



STAR : CPOD2024, SQM2024

Events used for net-proton fluctuation studies

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

Deviation between BES-II and BES-I data

$\sqrt{s_{NN}}$ (GeV)	0-5%	70-80%
7.7	1.0σ	0.9σ
11.5	0.4σ	1.3σ
14.6	2.2σ	2.5σ
19.6	0.7σ	0.0σ
27	1.4σ	0.2σ

Reduction factor (BES-II vs. BES-I) in uncertainties on 0-5%

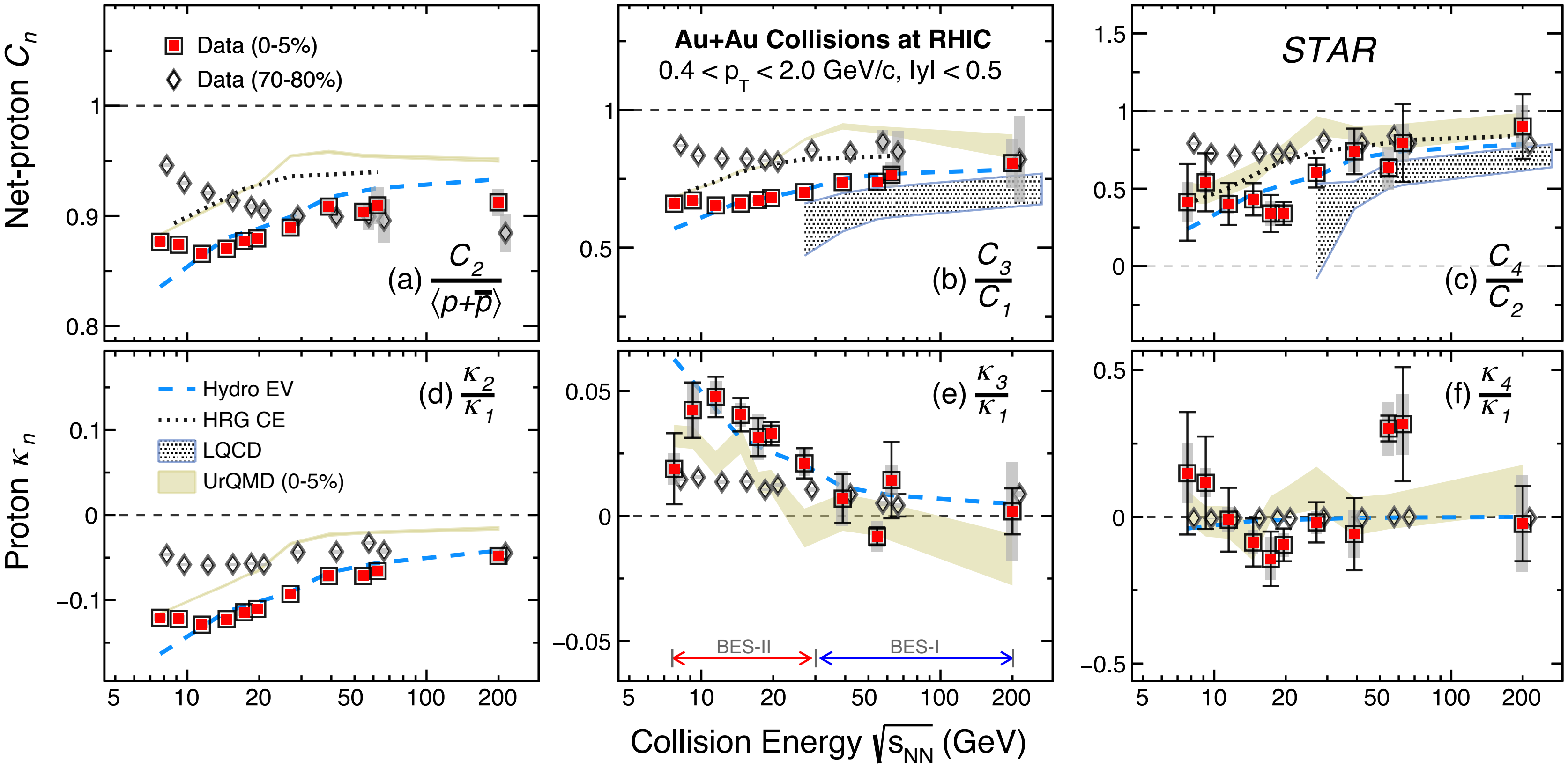
7.7 GeV		19.6 GeV	
stat. error	sys. error	stat. error	sys. error
4.7	3.2	4.5	4

BES-II and BES-I results are consistent !

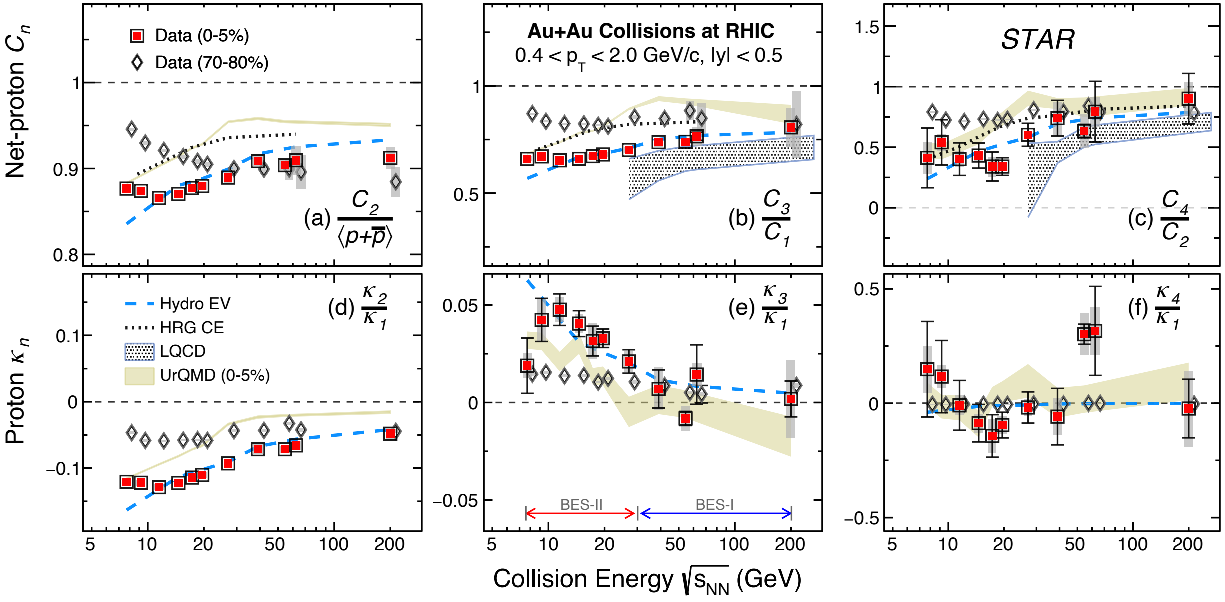
BES-II : Better statistical precision
Better control on systematics !

Energy Dependence and Model Comparison

STAR: CPOD2024, SQM2024



Energy Dependence and Model Comparison



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);

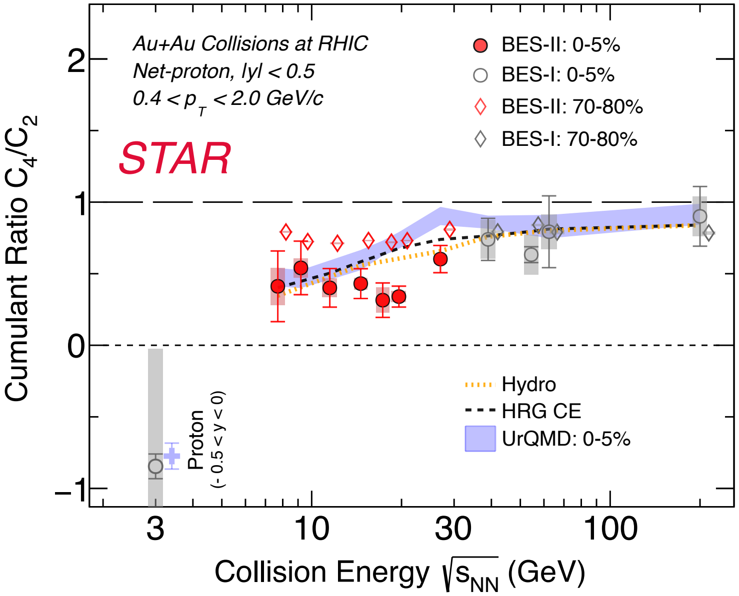
2) HRG CE: P.B. Munzinger *et al.* Nucl. Phys. **A1008**, 122141(2021);

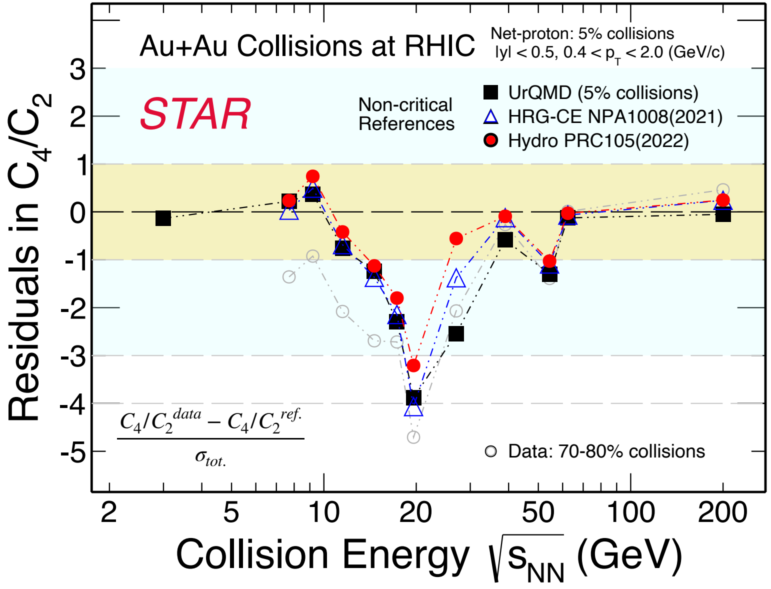
3) Hydro: HRG CE + EV, V. Vovchenko *et al.*, Phys. Rev. **C105**, 014904 (2022).

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

1. Baryon conservation in all model calculations
2. All proton factorial cumulant ratios show clear non-monotonic dependence
3. Lattice QCD describe the data up to 27 GeV.
4. Precise dynamical modelling is needed to fully understand the data.

Energy Dependence and Model Comparison

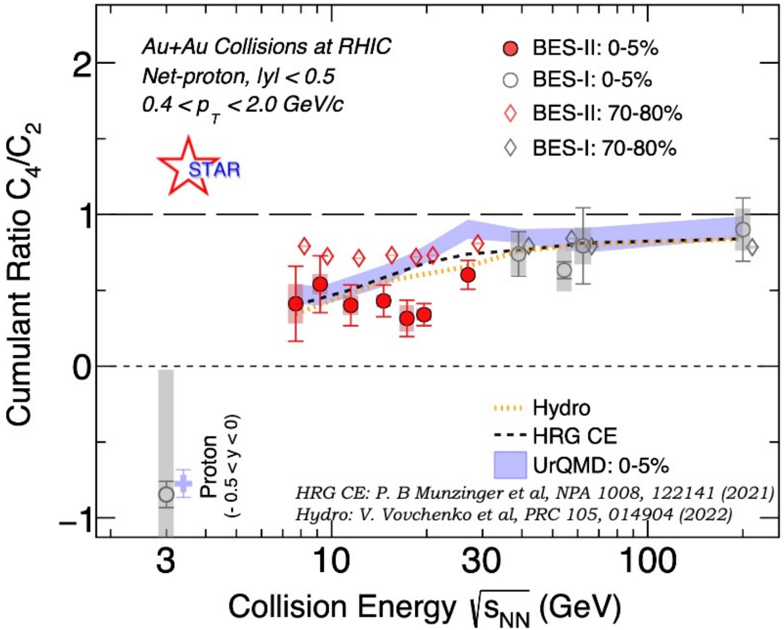




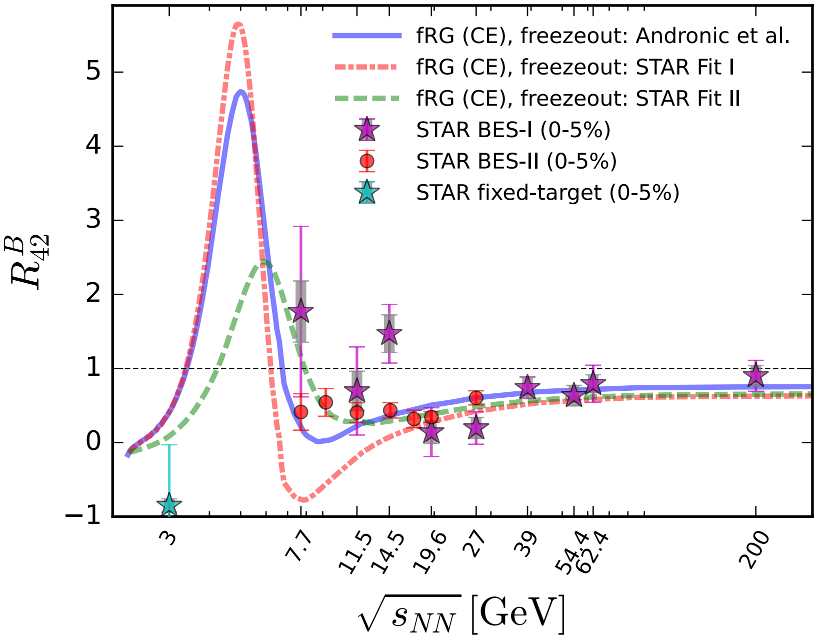
- Most central C_4/C_2 shows minimum around 20 GeV comparing to non-CP models and 70-80% collisions
  1) Maximum deviation: $3.2 - 4.7\sigma$ at 20 GeV ($1.3 - 2\sigma$ at BES-I)
  2) Overall deviation from $\sqrt{s_{NN}} = 7.7$ to 27 GeV: $1.9 - 5.4\sigma$ ($1.4 - 2.2\sigma$ at BES-I)

Continue the Critical Point Search

STAR Measurement：Au+Au 3-200 GeV



FRG: Wei-jie Fu, et al., arXiv : 2308.15508

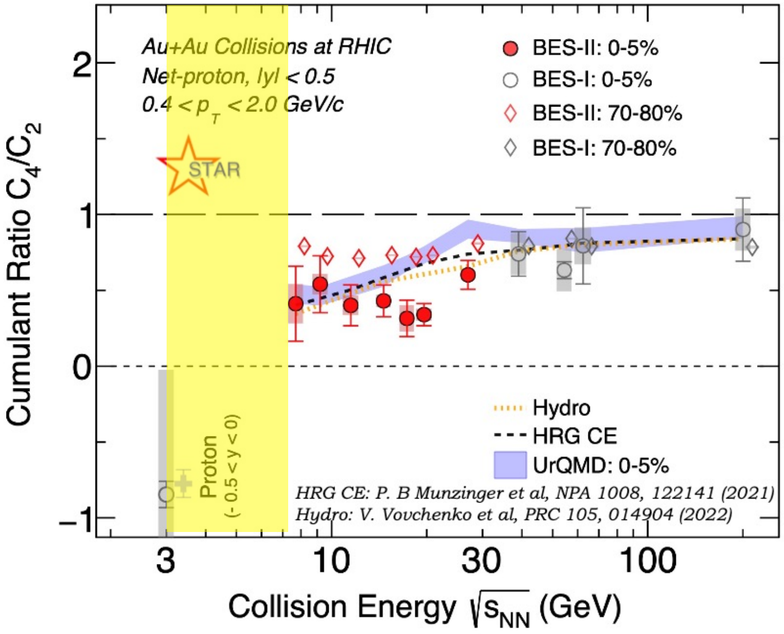


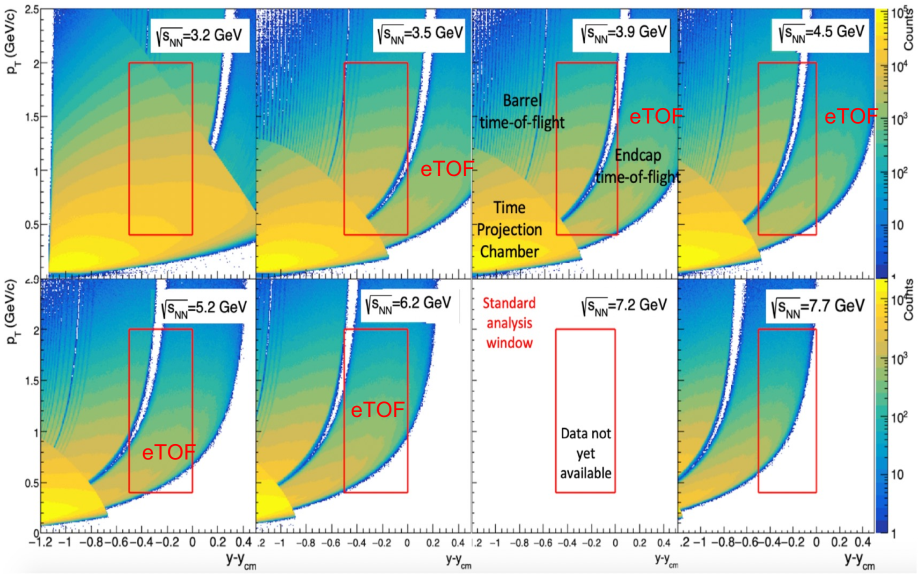
STAR: PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

Caveat : Non-equilibrium effect ? Need dynamical modelling.

Continue the Critical Point Search

STAR Measurement：Au+Au 3-200 GeV





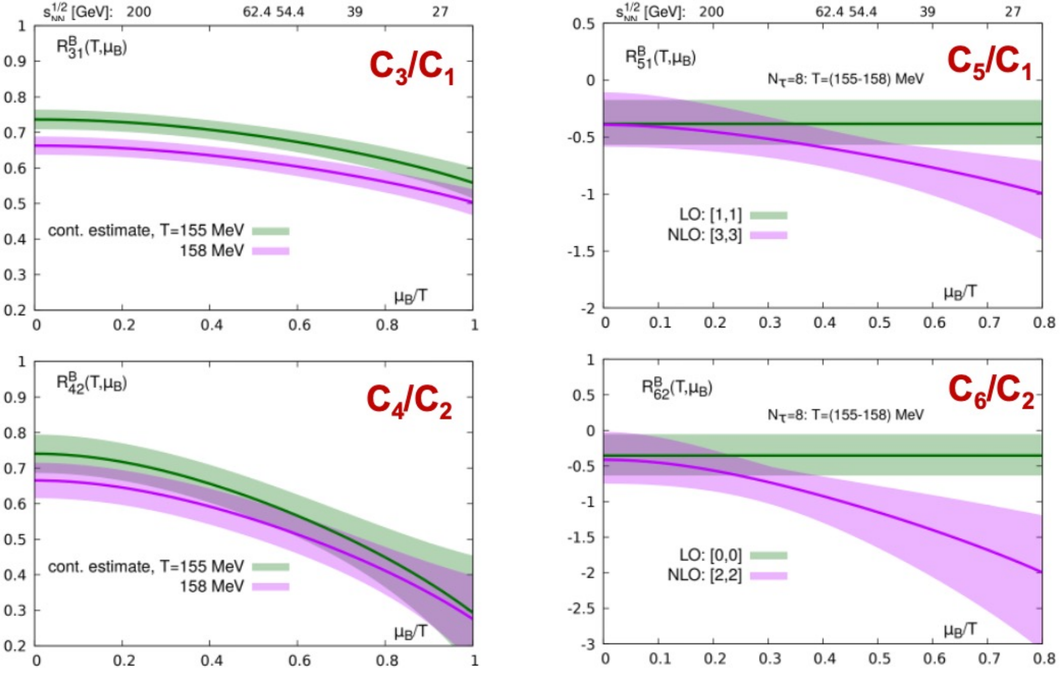
eTOF is crucial for mid-rapidity coverage at 3.5– 4.5 GeV

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

Two important things for future CP search :

- Experimental Results between 3 – 5 GeV
- Precise dynamical modeling and non-CP baselines

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:

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

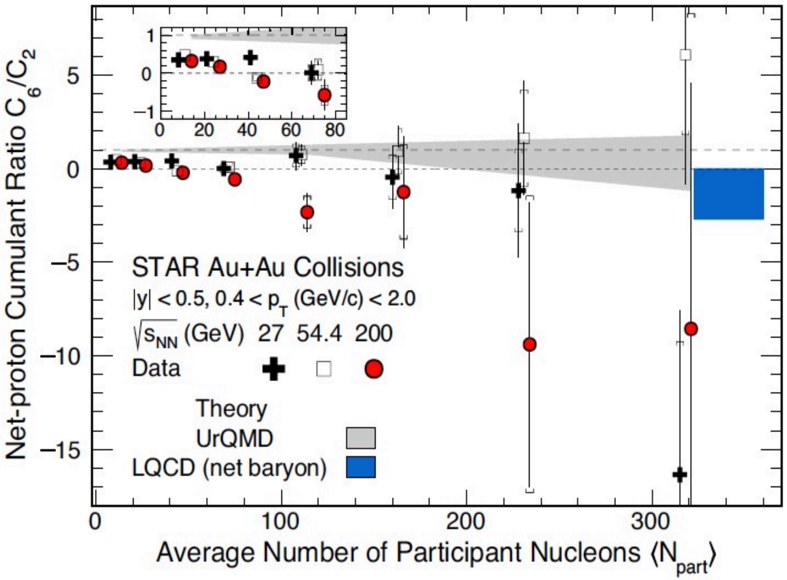
$$\chi^{BQS}_{ijk}(T) = \left.\frac{\partial^{(i+j+k)}P/T^4}{\partial\hat{\mu}^i_B\partial\hat{\mu}^j_Q\partial\hat{\mu}^k_S}\right|_{\vec{\mu}=0}$$

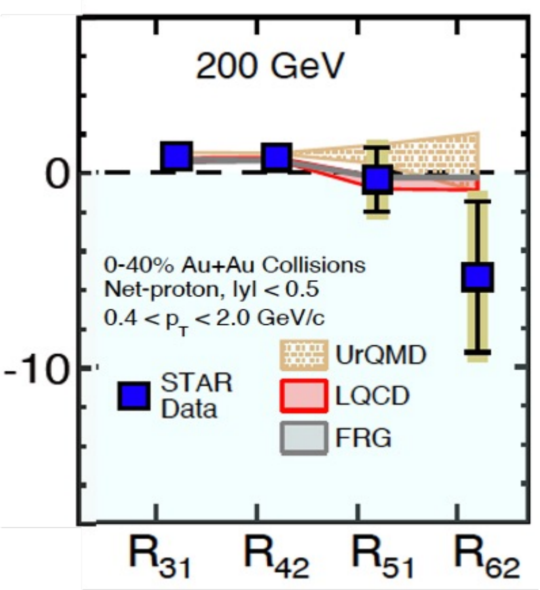
Two features：1) Ordering of cumulant ratios, 2) Negative in fifth and sixth order fluctuations

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

A. Bazavov, D. Bollweg, H.-T. Ding, et al. (HotQCD), Phys. Rev. D 101, 074502 (2020);

Higher-Order Net-Proton Fluctuations



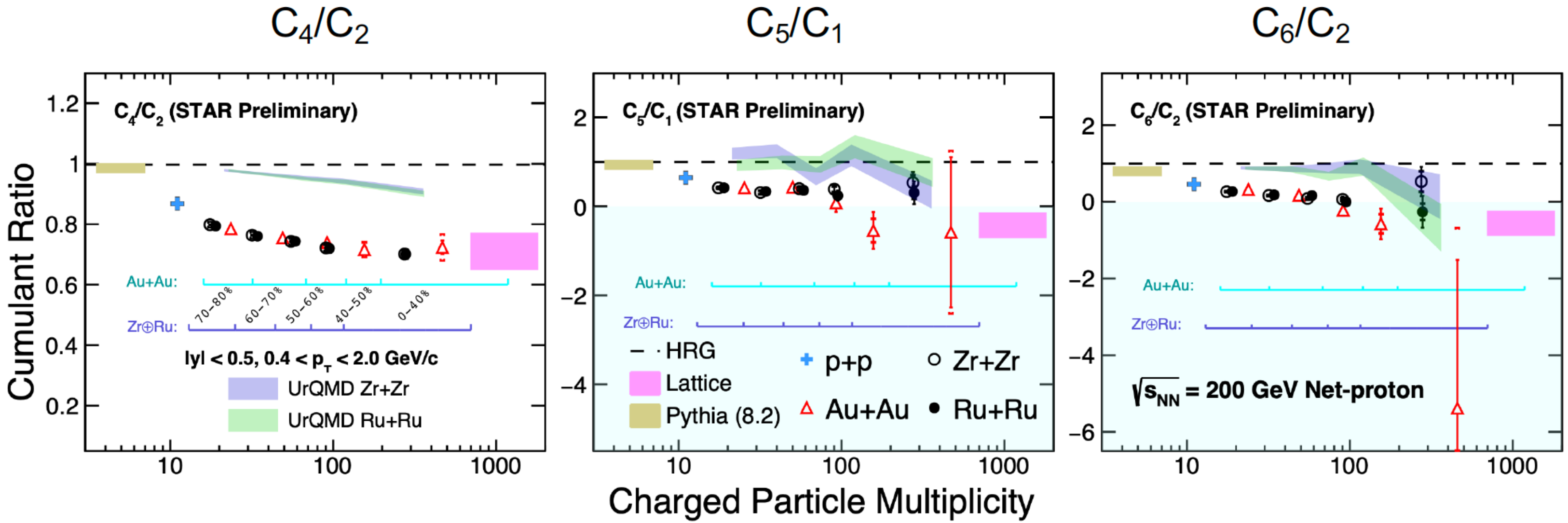


Consistent with Lattice QCD :

1) The sixth-order net-proton fluctuations progressively become negative values from peripheral to central collisions
2) Ordering from lower to higher orders in central collisions.
3) Analysis of BES-II data is ongoing

STAR : PRL 127, 262301 (2021).
STAR : PRL 130, 082301 (2023).

C_5/C_1 and C_6/C_2 : System Size Dependence



200 GeV : p+p, Ru+Ru, Zr+Zr and Au+Au

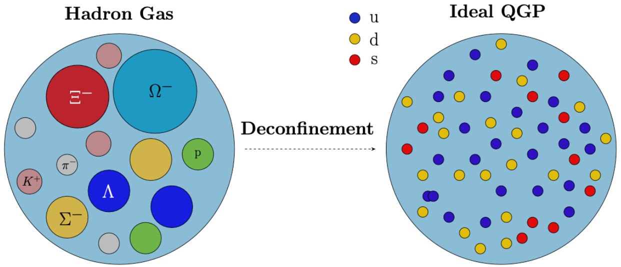
p+p : STAR, arXiv : 2311.00934(accepted by PLB)

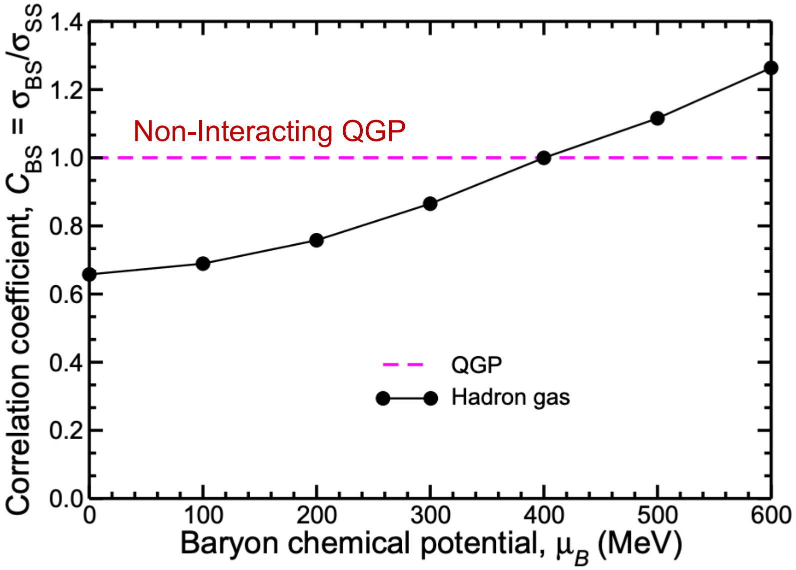
200 GeV Au+Au: PRC 104 (2021) 024902; PRL 126.092301 (2021), PRL 127, 262301 (2021).

- Cumulant ratios (up to C6) of net-proton from p+p, Au+Au and isobar data, systematic decreasing trend with multiplicity, approaching LQCD calculations

- Most central Au+Au collision results become consistent with Lattice QCD calculation for the formation of thermalized QCD matter and smooth crossover transition.

Baryon-Strangeness Correlations : Theory





$$C_{BS} = -3\chi^{11}_{BS}/\chi^2_S = -3\frac{< BS > - < B >< S >}{< S >^2}$$

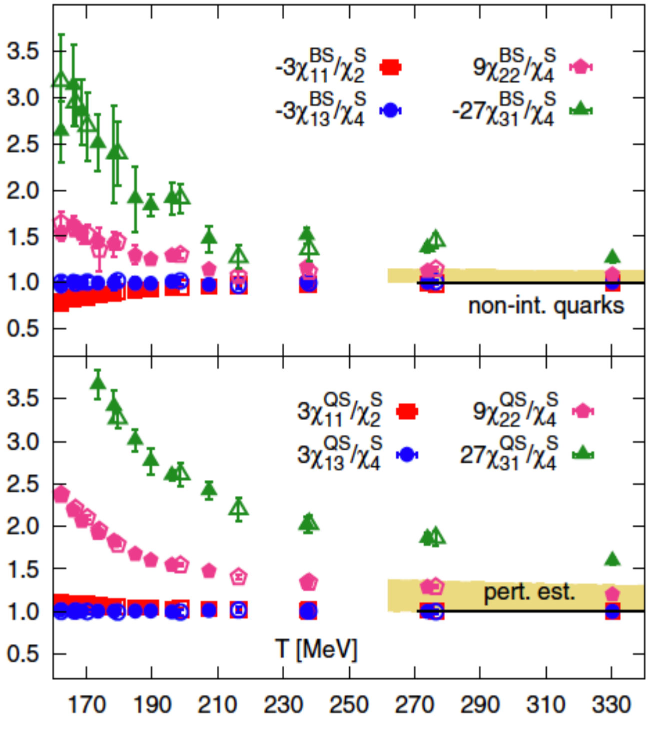
- **Ideal QGP**: $B = \frac{1}{3}(\mathrm{u} + d + s)$
  if quarks are uncorrelated
  $\chi_{BS} = -\frac{1}{3}\chi_s{}^2 \quad \rightarrow \quad C_{BS} = 1$

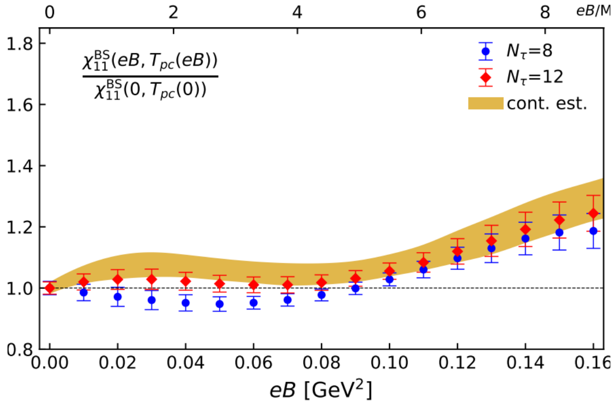
- **Hadronic Matter :**
  Only include Lambda : $C_{BS} = 3$
  Adding more strange meson make C_{BS} smaller (high energy)

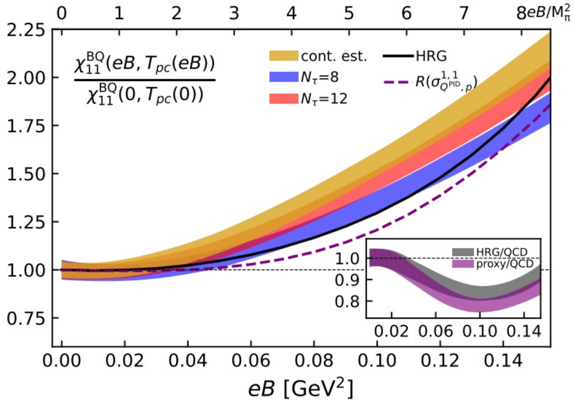
V. Koch, et al., PRL95, 182301 (2005).

- Sensitive to the degree of freedom of strongly interacting matter
- Used to search for the onset of deconfinement

Baryon-Strangeness or Baryon-Charge Correlations : Lattice QCD







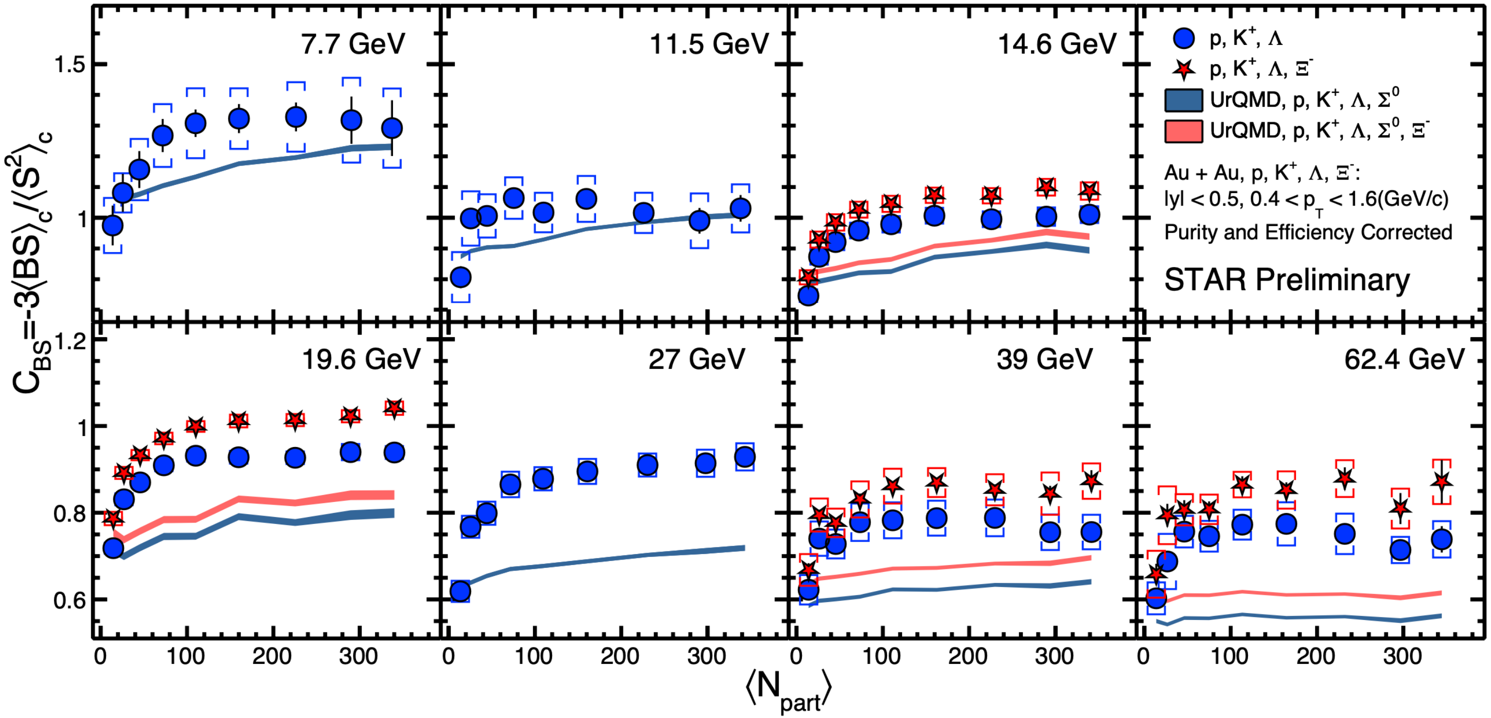
H.-T. Ding, et al., EPJA 57,202 (2021)
H.-T. Ding, et al., Phys. Rev. Lett.132.201903 (2024)

1) Higher order are more sensitive to QCD phase transition

2) Baryon-charge correlation is sensitive to the magnetic effect

A. Bazavov, H.-T. Ding, et al. (HotQCD) Phys. Rev. Lett. 111, 082301 (2013).

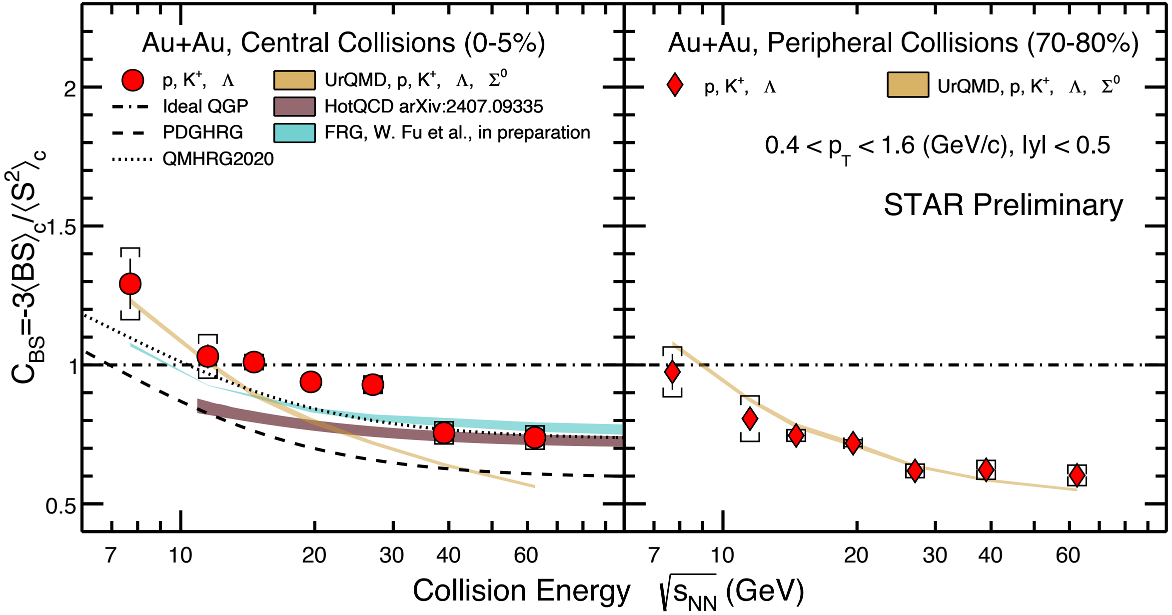
Centrality Dependence of C_{BS}

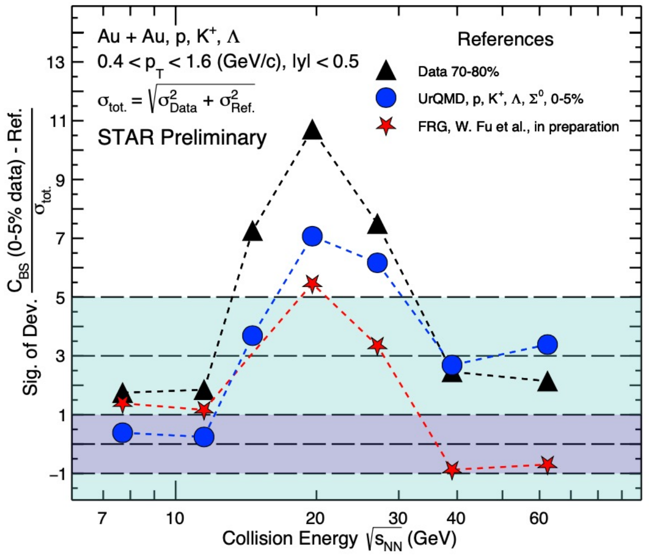


- Data of 14.6 and 19.6 GeV are from BES-II, other energies are from BES-I
- UrQMD can describe the centrality dependence of 7.7 GeV, 11.5 GeV, qualitatively and quantitatively, while it underestimates the higher energy.

STAR, CPOD2024

Energy Dependence of C_{BS} and Model Comparison

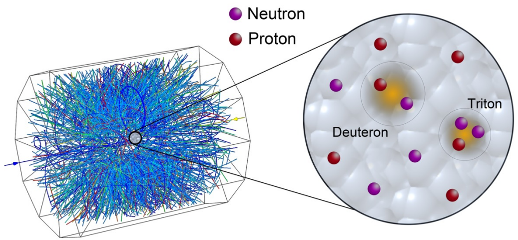


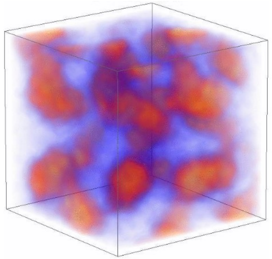


STAR, CPOD2024

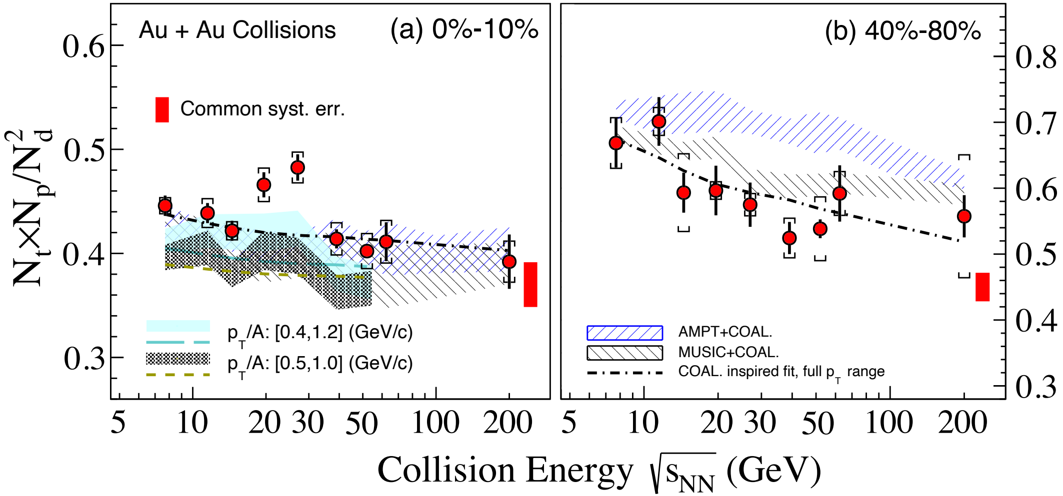
- ➢ Peripheral collisions (70-80%) can be well described by UrQMD;
- ➢ For central collisions:
  1) At high energy is consistent with FRG and LQCD, 7.7 and 11.5 GeV are reproduced by UrQMD
  2) Largest deviation is found at 19.6 GeV, which is more than 5σ
- ➢ Analysis of BES-II data (both collider and FXT) and BQ correlation are ongoing.

Yield Ratio of Light Nuclei from BES-I





Yield ratios of light nuclei are related to nucleon density fluctuations and can be used to search for the QCD critical point.



Coalescence picture：

$$N_d = \frac{3}{2^{1/2}}\left(\frac{2\pi}{m_0 T_{eff}}\right)^{3/2} N_p \langle n \rangle (1 + C_{np})$$

$$N_t = \frac{3^{\frac{3}{2}}}{4}\left(\frac{2\pi}{m_0 T_{eff}}\right)^{3} N_p \langle n \rangle^2 (1 + \Delta n + 2C_{np})$$

$$N_t \times N_p / N_d^2 = g(1 + \Delta n)$$

K.J. Sun, L.W. Chen, C.M. Ko, J. Pu, and Z.B. Xu, Phys. Lett. B 781, 499 (2018)

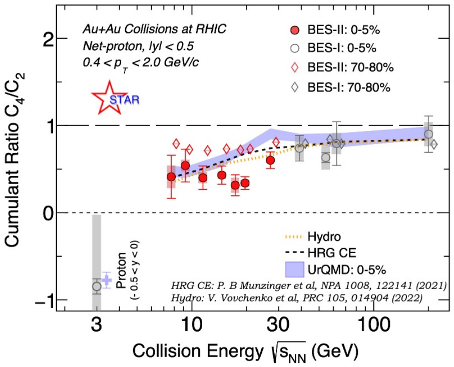
- Non-monotonic behavior observed in 0-10% central Au+Au collisions around 19.6 and 27 GeV with 4.1σ significance (combined) deviated from coalescence baseline.
- Analysis of BES-II data (both collider and FXT) are ongoing.

STAR, SQM2024

3 GeV, arXiv : 2311.11020
STAR: Phys. Rev. Lett. 130, 202301 (2023)

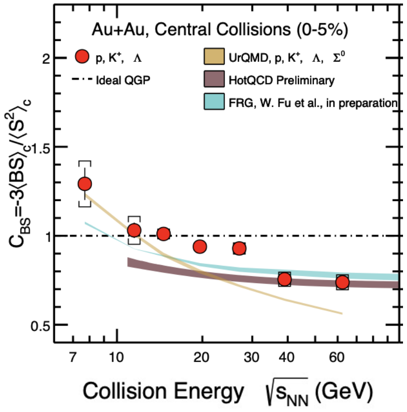
Summary and Outlook

Net-Proton Fluctuations



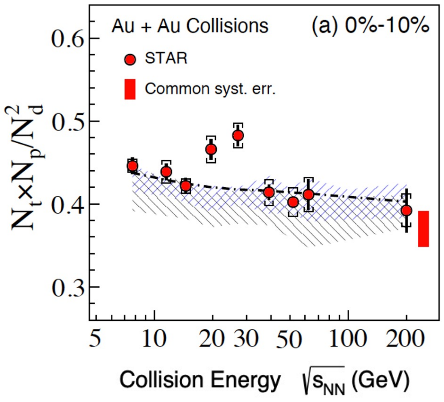
STAR, CPOD2024, SQM2024

BS correlations



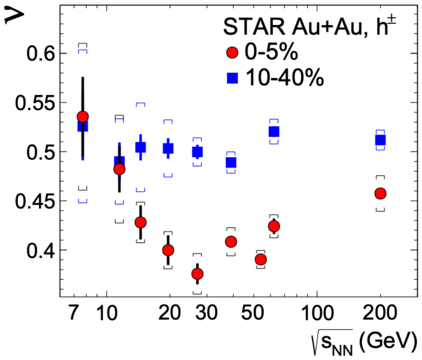
STAR, CPOD2024

Yield Ratio of Light Nuclei

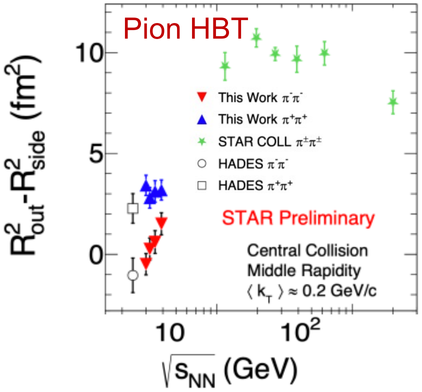


STAR: PRL130, 202301 (2023)

Intermittency



STAR, PLB 845, 138165 (2023)

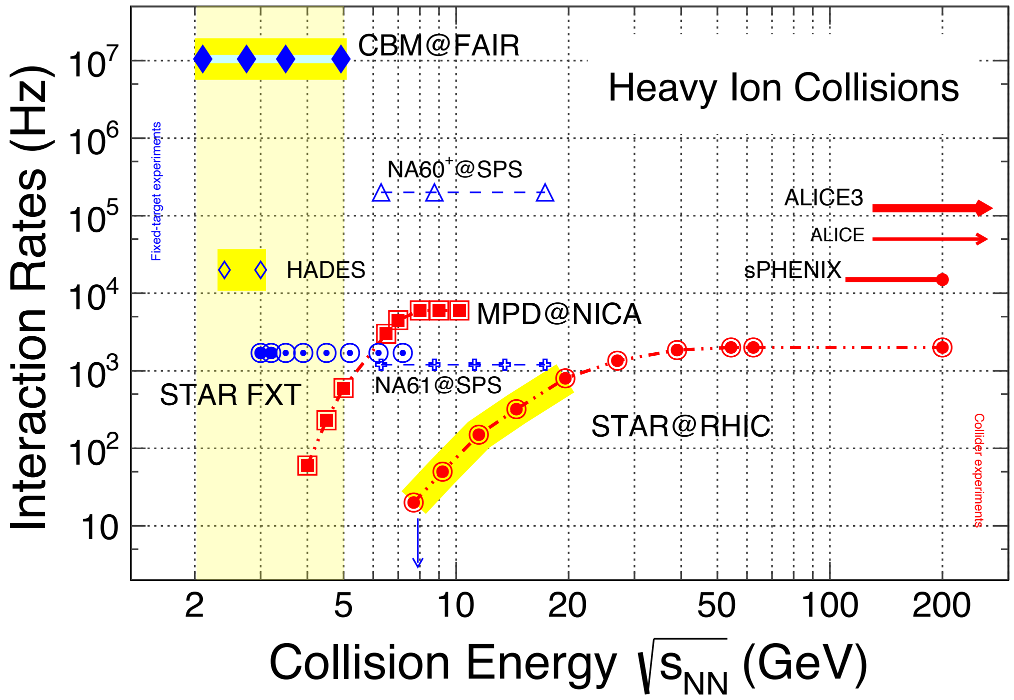


BES-II : high statistics, better acceptance and systematics

1. *Understand the reason lead to the deviations around 20 GeV*
2. *Continue to search for QCD critical point between 3 – 20 GeV*
3. *Need reliable dynamical modeling and non-CP baselines*

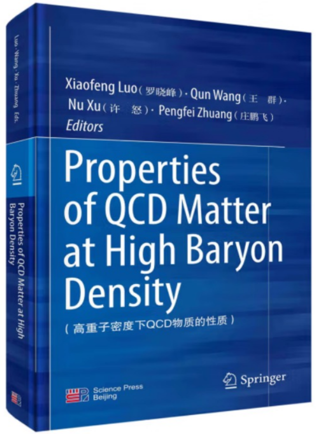
Summary and Outlook

Rich physics at high baryon density : QCD phase structure, EoS etc.



Future High Baryon Density Frontier:

- FAIR/CBM (2.4 - 4.9 GeV)
- HIAF/CEE (2.1– 4.5 GeV)
- NICA/MPD (4 - 11 GeV)



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

International Workshop on Physics at High Baryon Density (PHD2024)

https://indico.ihep.ac.cn/event/22462/ Nov. 1-4, 2024@CCNU

International Workshop on Physics at High Baryon Density (PHD2024, 第一届高重子密度物理国际研讨会)

Nov 1 – 4, 2024
Asia/Shanghai timezone

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- Confirmed Speaker
- Local Organizing Committee

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

高能核核碰撞中产生的高重子密度物质蕴含着丰富的物理，对研究强相互作用相结构、宇宙和致密星体演化以及理解极端条件下核物质性质具有重要意义。随着未来国内外重离子大科学装置（德国FAIR/CBM、中国HIAF/CEE、俄罗斯NICA/MPD）的相继建成，高重子密度物理领域正成为国际物理研究的前沿热点。在这一背景下，系统分析和总结已有研究进展并规划未来发展路线，培养和储备高重子密度物理研究的人才队伍, 集聚国内外顶尖科学家的智慧显得尤为必要和重要。因此，我们决定发起"高重子密度物理研讨会"系列会议 (计划每年举办一次，以研讨会搭配更聚焦的小型专题讨论会形式)，旨在为国内外科研人员搭建起高水平的学术交流平台，共同探讨高重子密度区物理的挑战和机遇。同时我们将与国内外核物理理论中心紧密合作，为推动我国高重子密度物理相关研究走向国际前沿打下坚实基础。

第一届高重子密度物理研讨会于2024年11月1日-4日在华中师范大学召开，1号报到，2-4号会议。会议不收取注册费，会议报告为邀请报告。

The high baryon density matter produced in high-energy nuclear-nuclear collisions harbors rich physics, which is of great importance for exploring the phase structure of strong interactions, the evolution of the universe and compact stars, and understanding the properties of nuclear matter under extreme conditions. With the upcoming completion of major heavy-ion facilities around the world (FAIR/CBM in Germany, HIAF/CEE in China, NICA/MPD in Russia), the field of high baryon density physics is becoming a frontier hotspot in international physics research. Against this background, it is particularly necessary and important to systematically analyze and summarize existing research progress, plan future development paths, cultivate and reserve talent teams for high baryon density physics research, and gather the wisdom of top scientists. Therefore, we have decided to launch a series of "Workshop on Physics at High Baryon Density" (planned to be held annually, in the form of seminars combined with more focused small-scale topical discussions), aiming to build a high-level academic exchange platform for researchers worldwide to jointly explore the challenges and opportunities of high baryon density physics. At the same time, we will work closely with domestic and international nuclear physics theory centers to lay a solid foundation for high baryon density physics research.

The first workshop on physics at high baryon density will be held at Central China Normal University from Nov. 1 to 4, 2024, with registration on the Nov. 1st and the meeting time from the Nov. 2nd to the 4th. No registration fee will be charged. The talks are by invitation only.

Welcome to PHD2024@CCNU ！

Physics Topics :

1) QCD Phase Structure at High Baryon Density
2) Nuclear Matter at High Density and Equation of State
3) Dynamical Evolution of Heavy-ion Collisions
4) Nuclear Matter Under Extreme External Fields
5) Hadron Properties in Nuclear Medium
6) Nuclear Physics in Compact Stars

Local Organizing Committee:

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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)

Thank you for your attention !