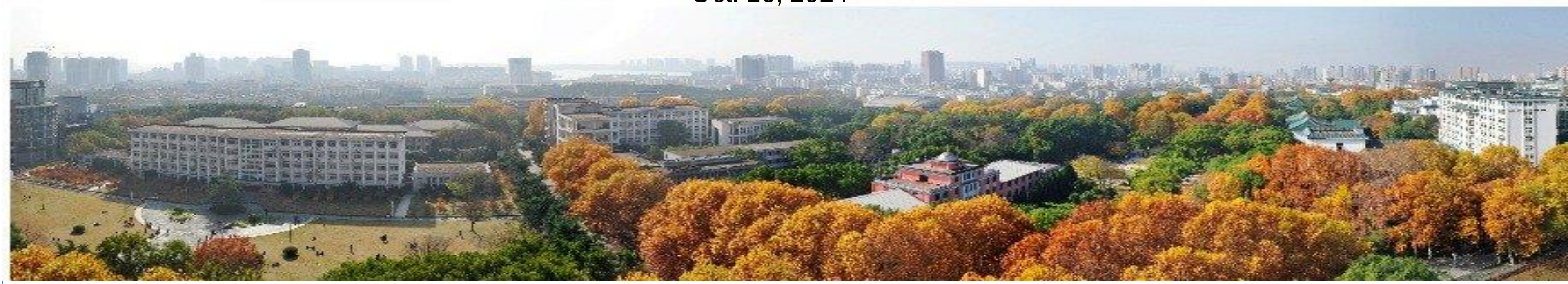
XIV MPD Collaboration Meeting

Study the QCD Phase Diagram with Beam Energy Scan at RHIC

Xiaofeng Luo (罗晓峰)

Central China Normal University

Oct. 16, 2024



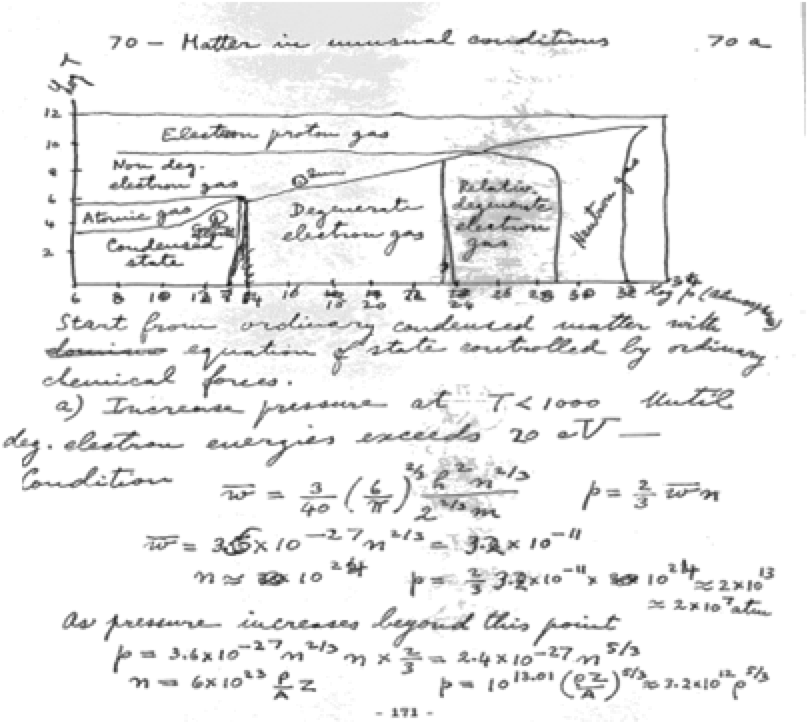
Outline

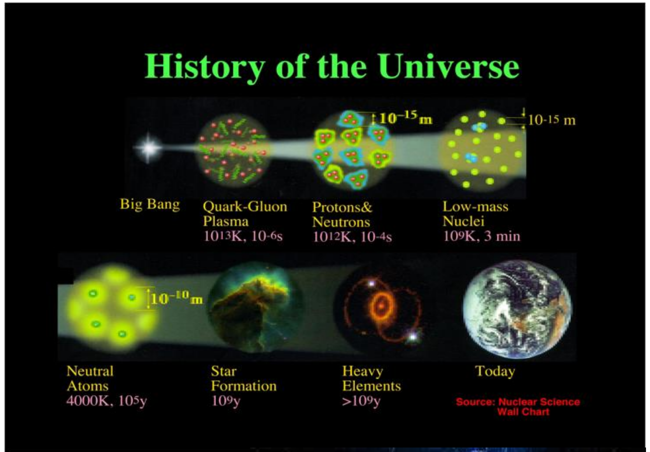
- Introduction
- Selected Results from RHIC Beam Energy Scan
  1) Net-Proton Fluctuations
  2) Baryon-Strangeness Correlations
  3) Yield Ratios of Light Nuclei
- Summary and Outlook

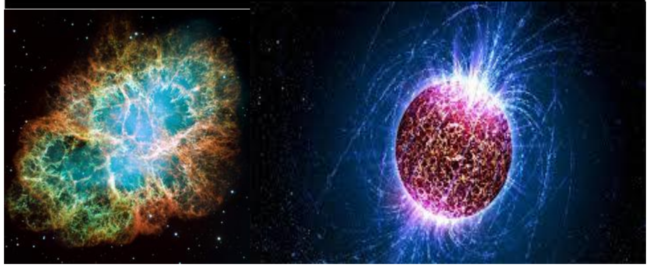
Matters in Extreme Condition

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

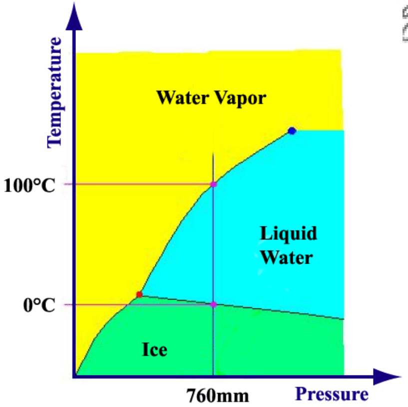
E. Fermi





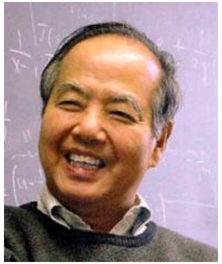


Water Phase Diagram

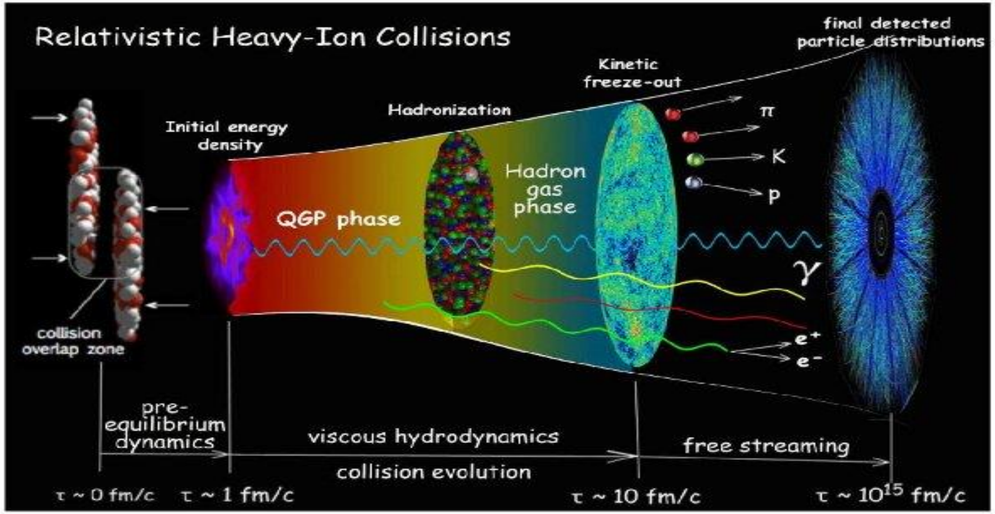


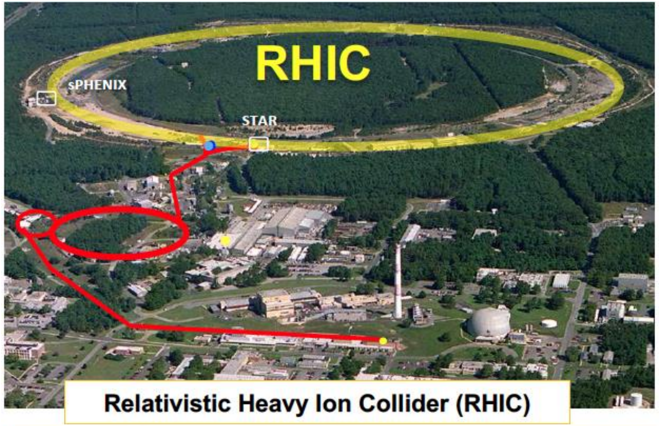
How to create extreme condition similar to early universe ?
What is the relevant degree of freedom and dominated interactions ?

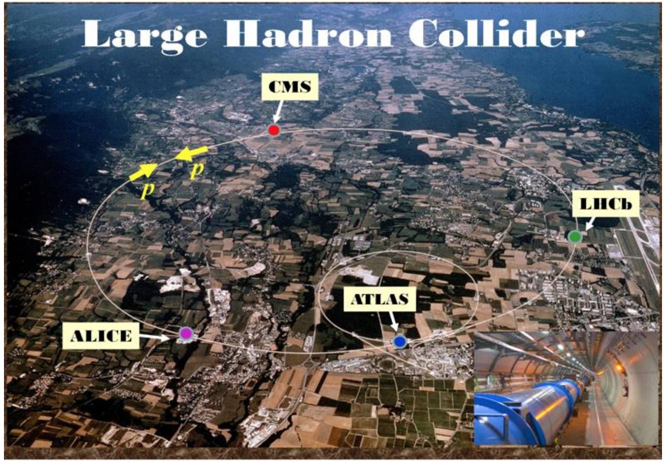
"Little Bang" and QGP



T.D. Lee
(1926-2024)







Relativistic Heavy-Ion Collisions

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

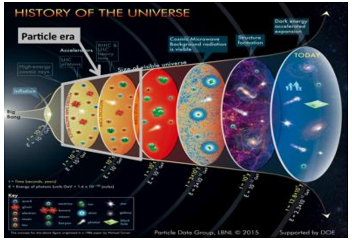
sQGP: Perfect liquid

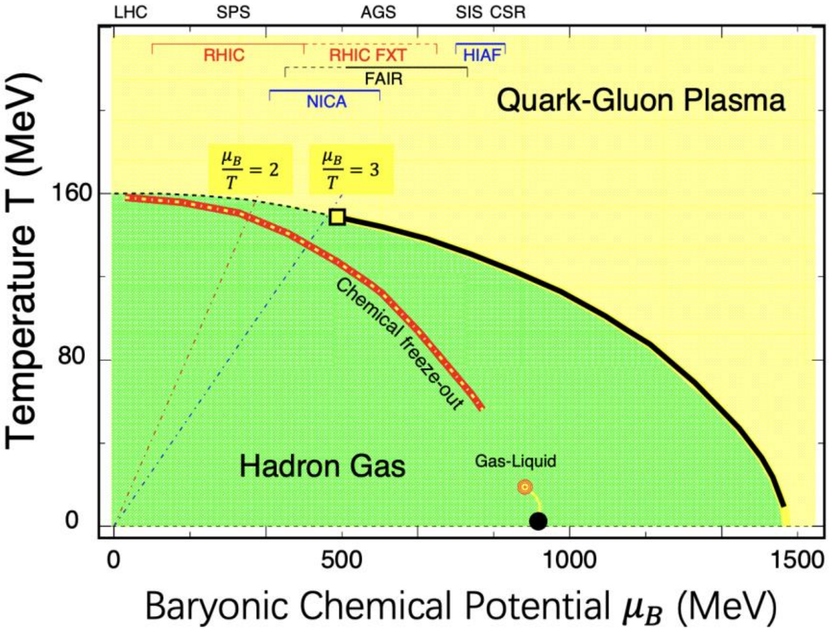
- Small eta/s ~ quantum limit
- Strong electromagnetic field
- Large vorticity

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

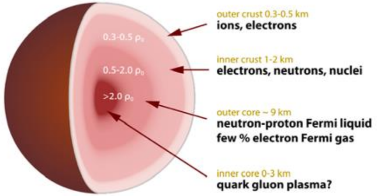




Lattice QCD : at $\mu_B = 0$, smooth crossover.

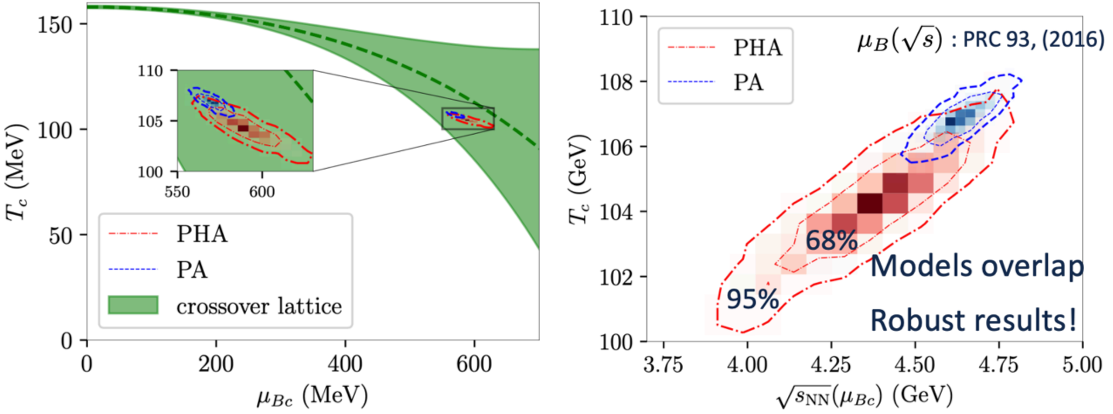
Large μ_B : 1st order phase transition and QCD critical point ?

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).

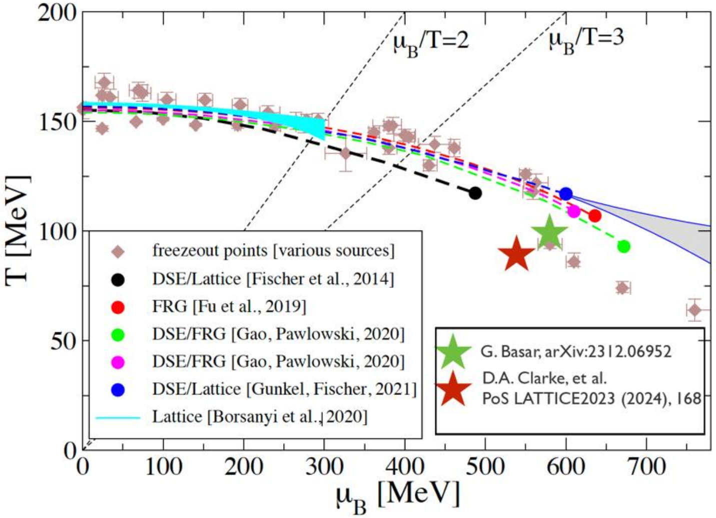


Q1 : Can we find the experimental signature of the smooth crossover ?
Q2 : Can we map out the 1st order phase boundary and find the QCD Critical Point ?
Q3 : What is the equation of state of the dense nuclear matter ?

Location of the QCD Critical Point : Theoretical Estimation/Prediction



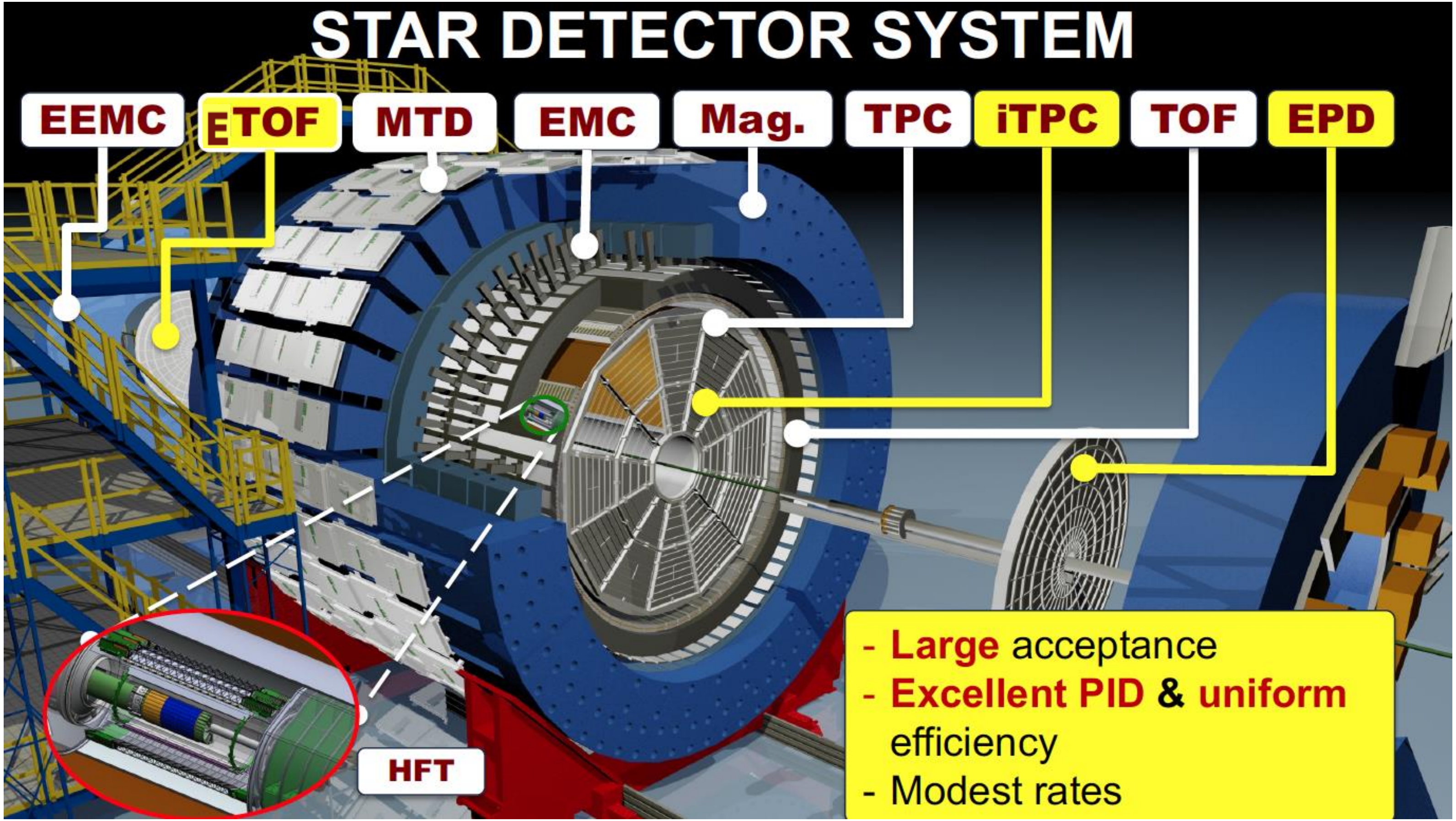
Holography+ Bayesian : Hippert et al., arXiv : 2309.00579



CPOD2024

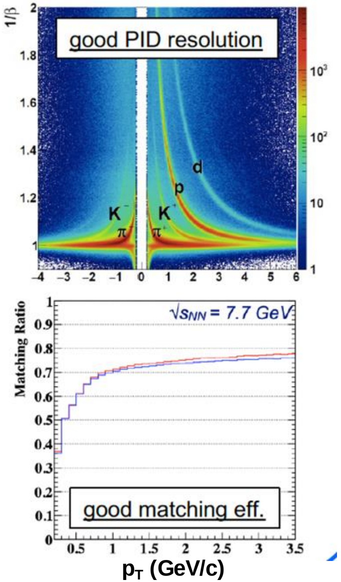
Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

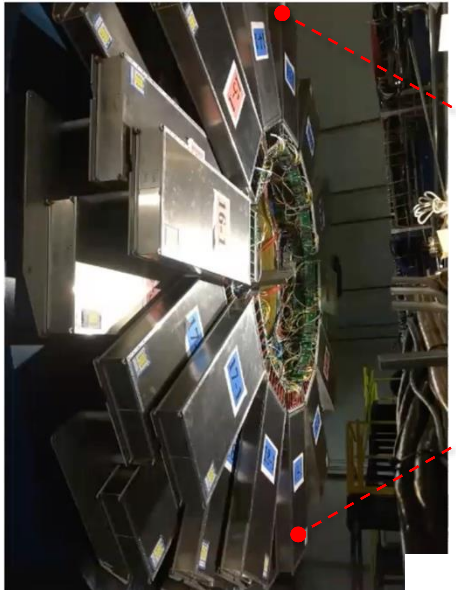
$(\mu_c, T_c) = (495 - 654, 100 - 119)$ MeV → $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

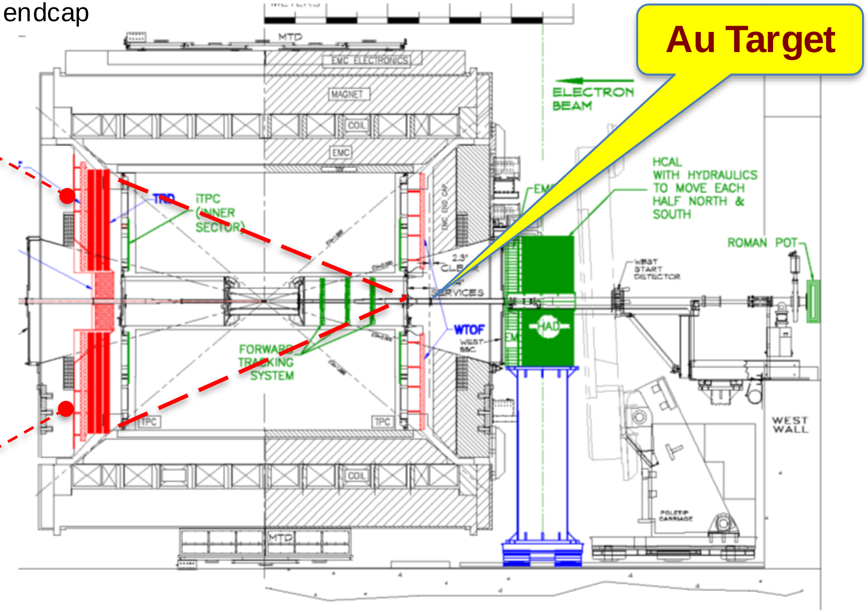

STAR DETECTOR SYSTEM
EEMC
ETOF
MTD
EMC
Mag.
TPC
iTPC
TOF
EPD
HFT
- Large acceptance
- Excellent PID & uniform efficiency
- Modest rates

STAR 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

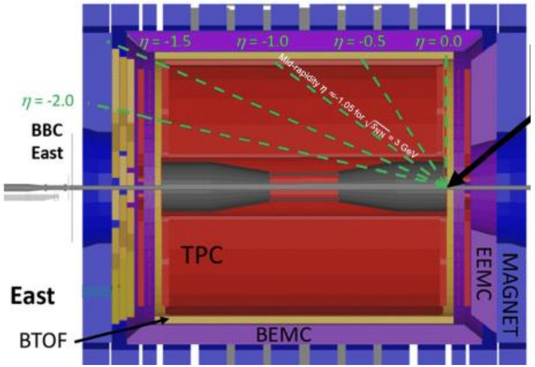
- Fixed-target Au+Au collisions : $\sqrt{s_{NN}}$ = 3 - 7.7 GeV (**750 ≥ μ_B ≥ 420 MeV**)
- Study the properties of QCD matter at high baryon density region

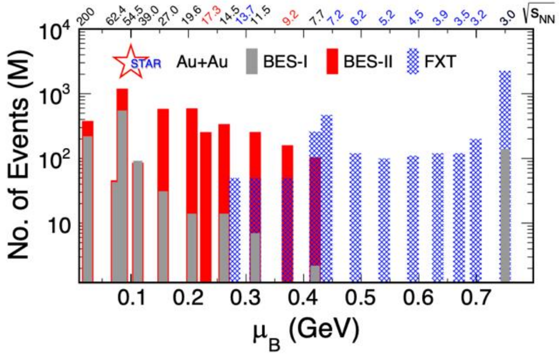
RHIC Beam Energy Scan (BES) Program (2010-2021)

Au+Au Collisions at RHIC （RHIC 金核-金核碰撞）

Collider Runns （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

STAR Fixed Target Mode

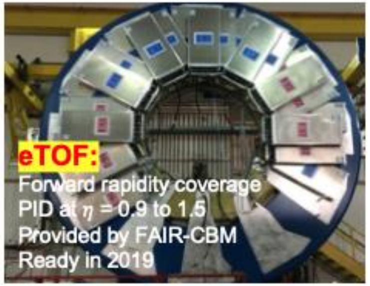




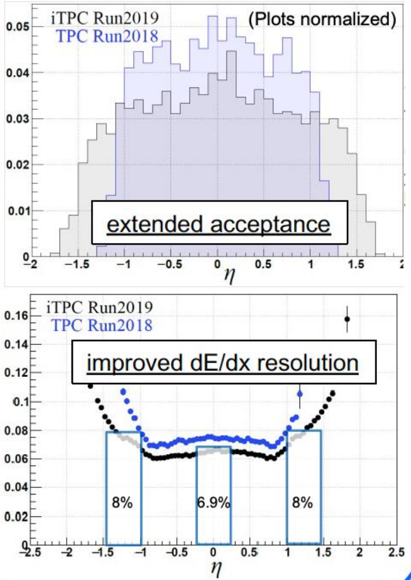
- ➢ Au+Au Collisions at 3 - 200 GeV (Collider + FXT)
- ➢ μ_B coverage : 25 < μ_B < 750 MeV

- ➢ 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)

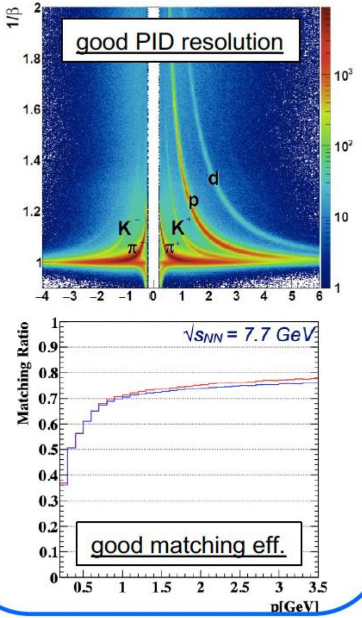
Detector Upgrade and Performance in BES-II



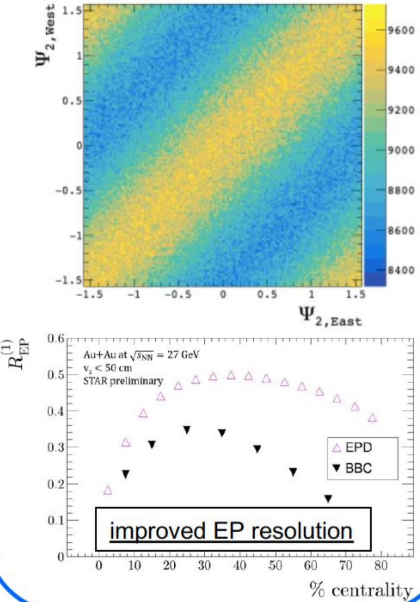
iTPC (2019+)



eTOF (2019+)



EPD (2018+)

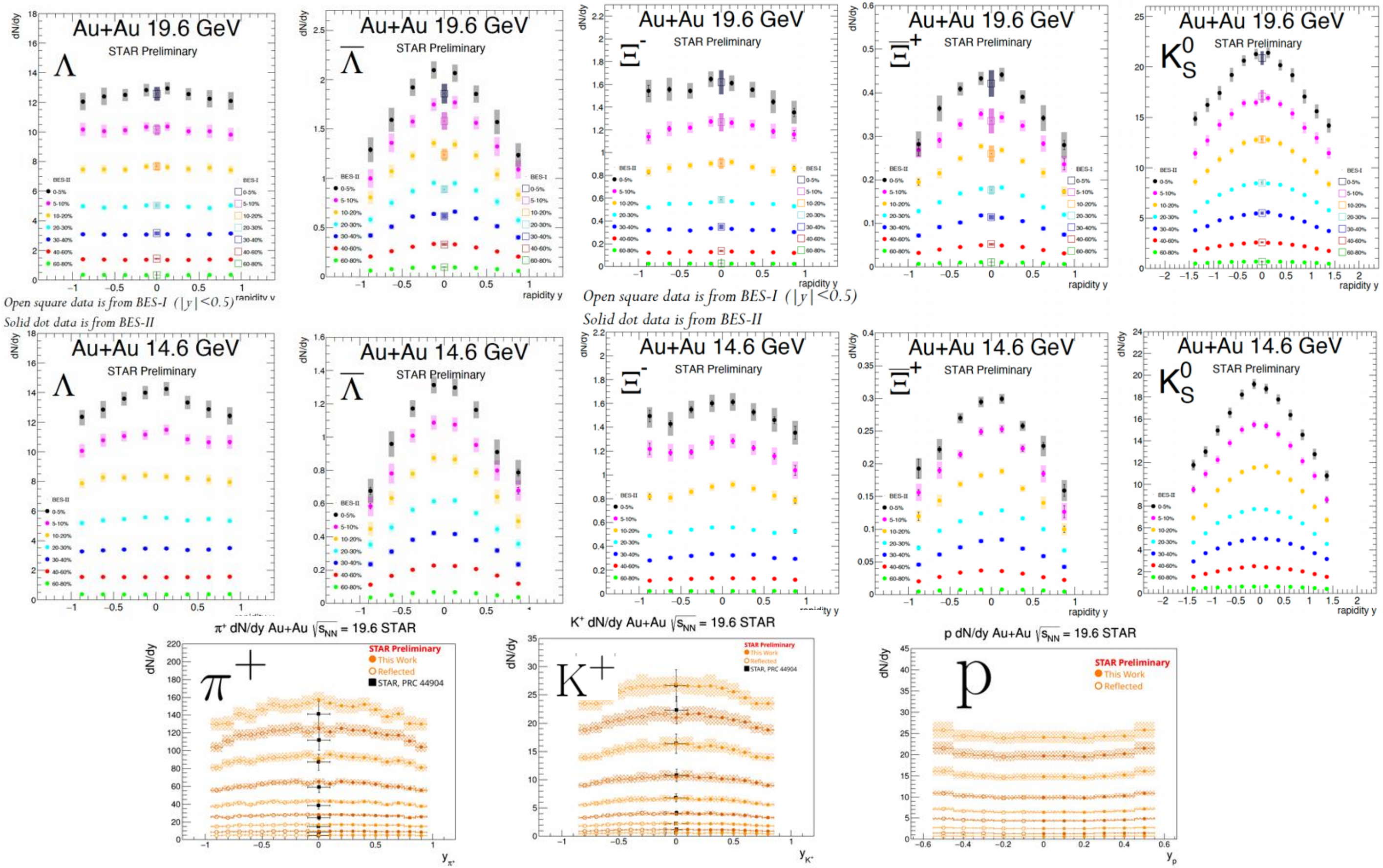


iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. Nucl. Instr. Meth. A 968, 163970 (2020)

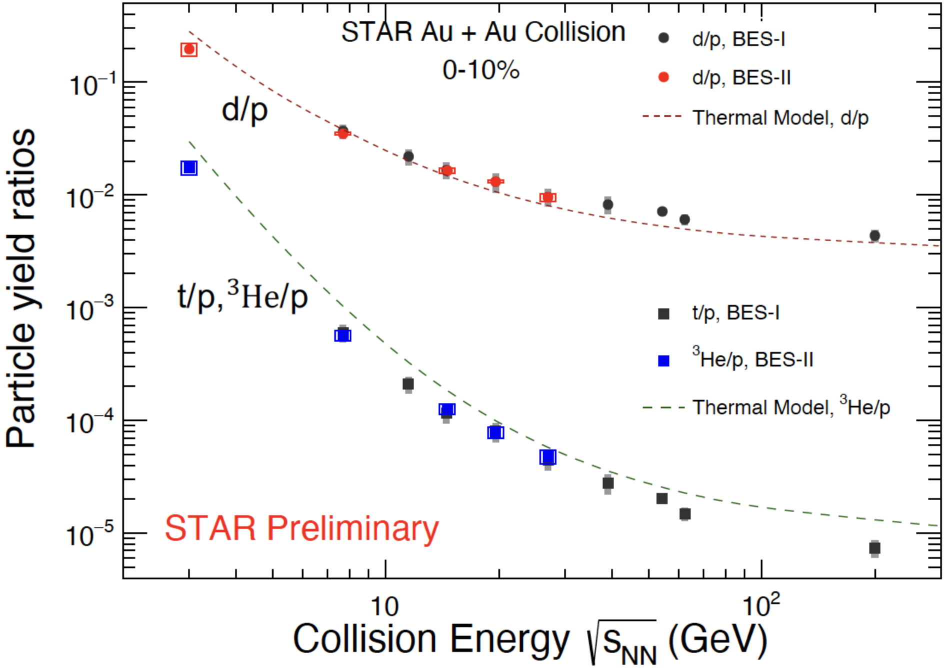
1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/event plane resolution

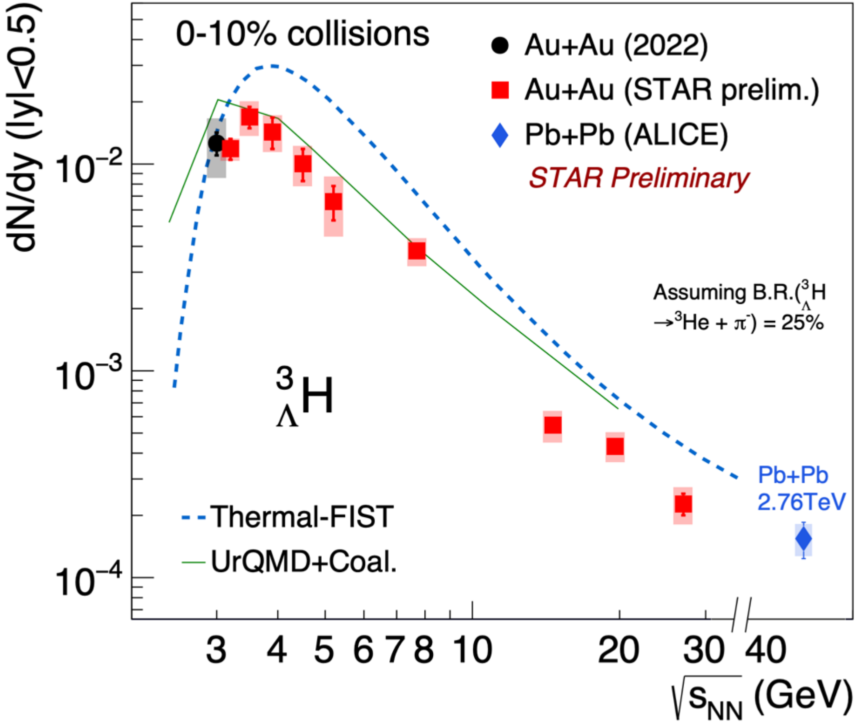
BES-II spectra (14.6, 19.6 GeV) : pi, k, p and strangeness

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:

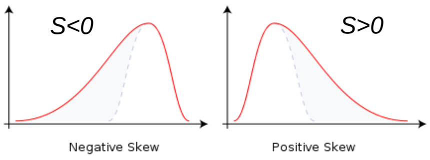
- 2nd order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$
- 3rd order: $S\sigma \equiv C_3/C_2 = \chi_3/\chi_2$
- 4th order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$

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

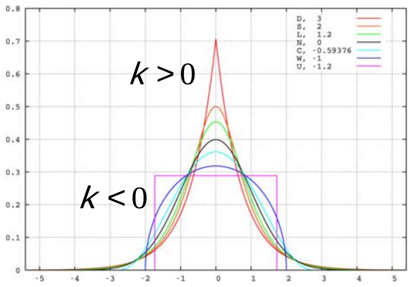
$$\langle (\delta N)^3 \rangle_c \approx \xi^{4.5}, \quad \langle (\delta N)^4 \rangle_c \approx \xi^7$$

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

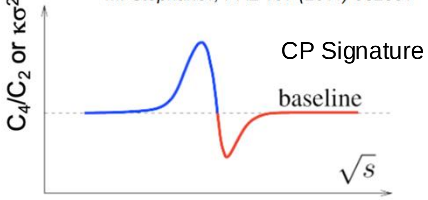
Skewness (S) → asymmetry



Kurtosis(K) → Sharpness



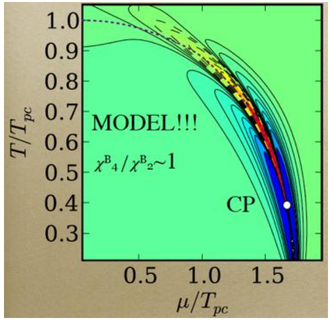
M. Stephanov, PRL 107 (2011) 052301



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)*

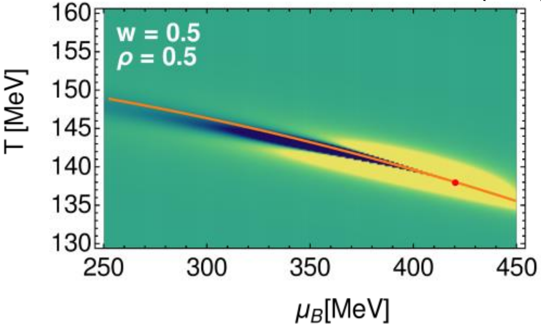
Critical Signal for the Fourth-order Fluctuations ($\kappa\sigma^2$)

PQM V. Skokov, QM2012



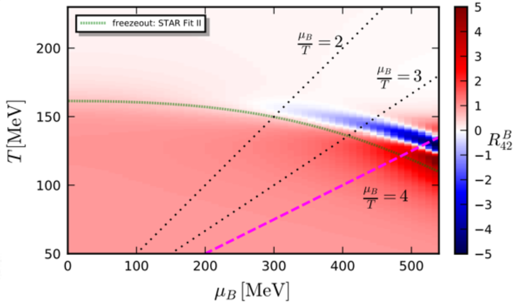
3D Ising Mapping

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

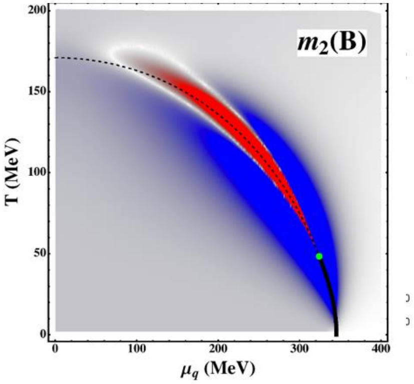


FRG

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

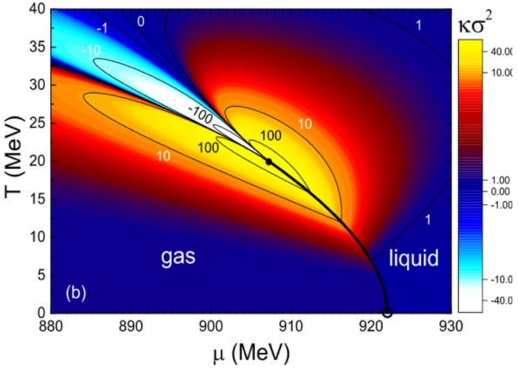


NJL



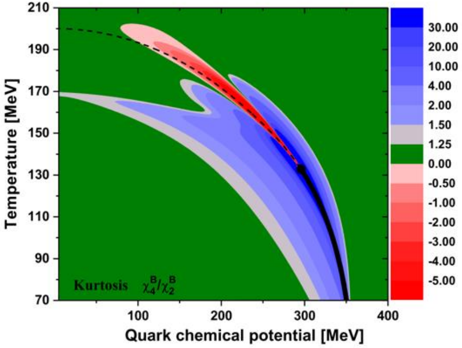
J. Deng, et al., PRD93, 034037 (2016)

van der Waals (VDW)



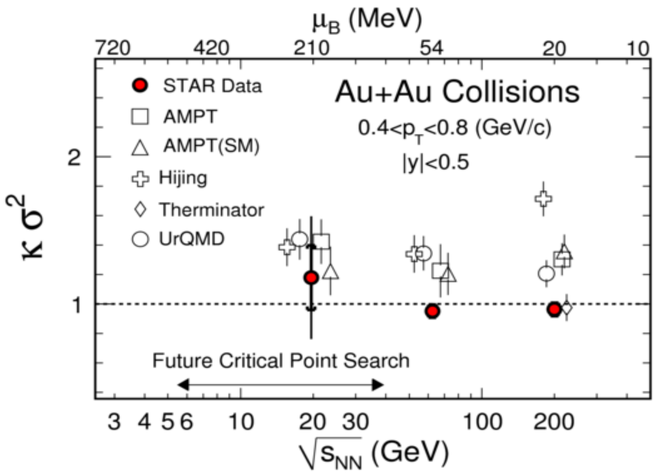
Vovchenko et al., PRC92, 054901 (2015)

PNJL



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

High Moments Measurements at STAR experiment

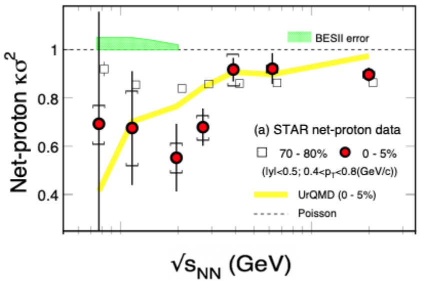


First measurement !

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

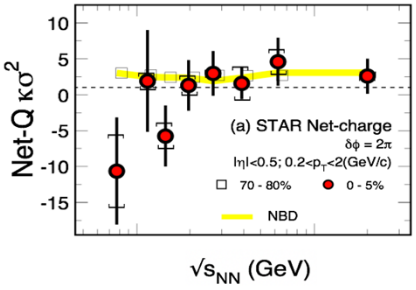
STAR, Phys. Rev. Lett. 105, 022302(2010).

Net-Proton



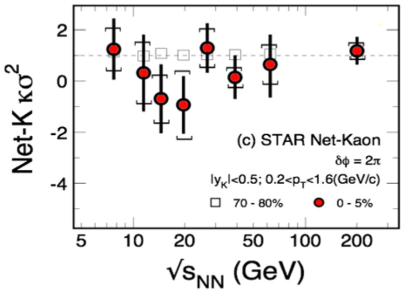
STAR, PRL 112, 032302 (2014).

Net-Charge



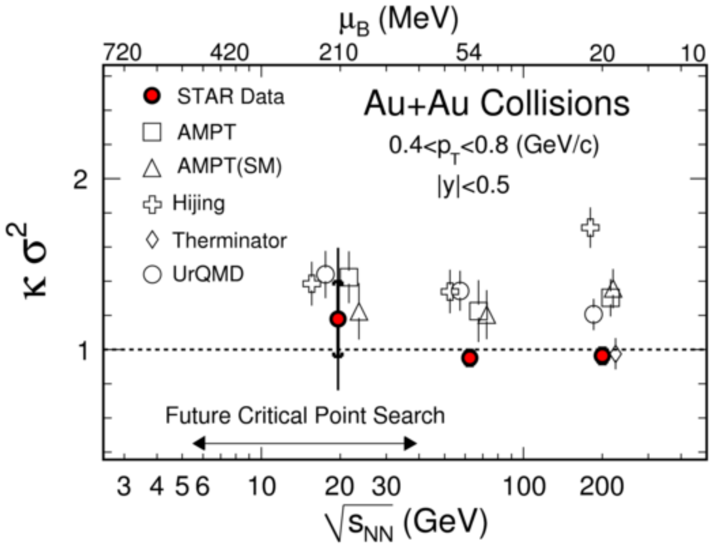
STAR, PRL113, 092301 (2014).

Net-Kaon

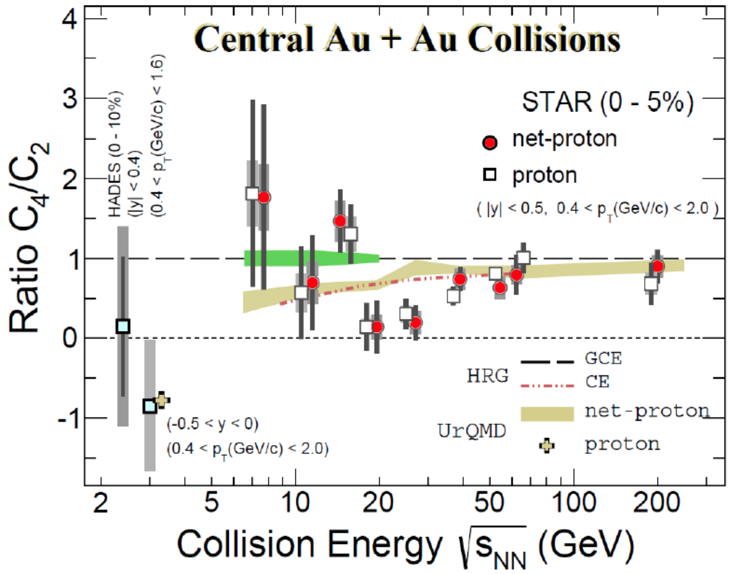


STAR, PLB 785, 551 (2018).

Higher Moments of Net-Proton Multiplicity Distributions



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

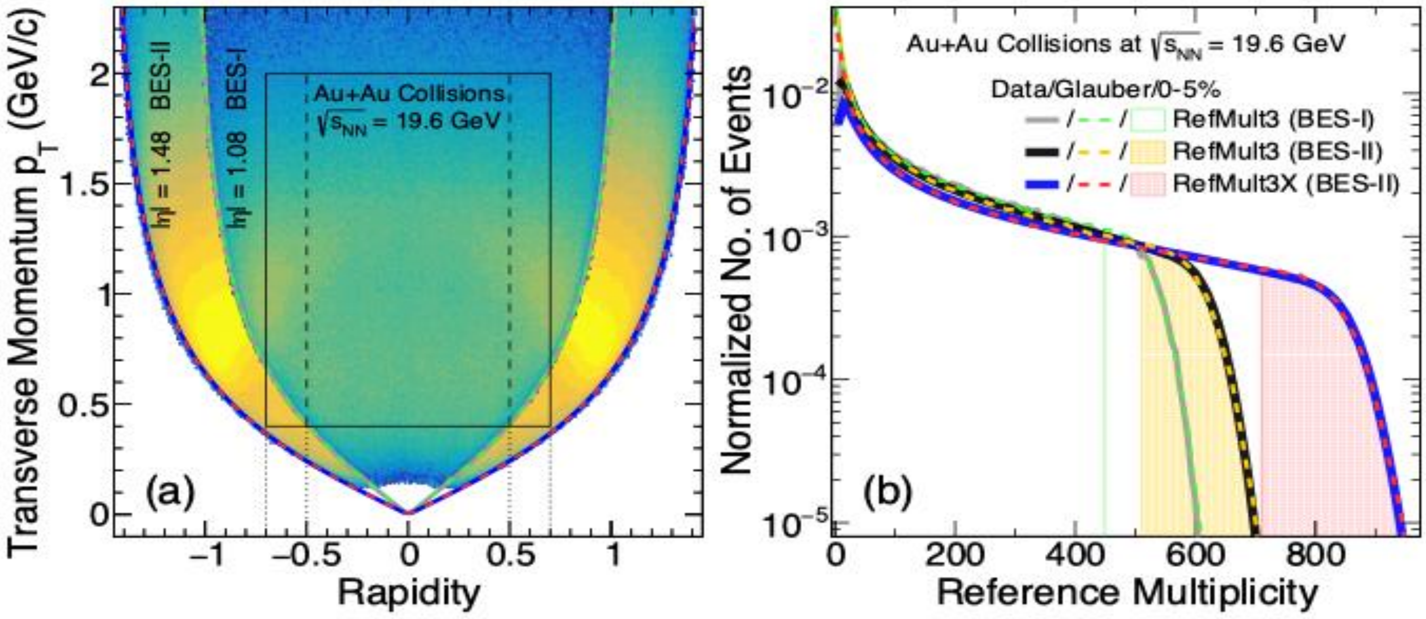


BES-I : Phys. Rev. Lett. 126, 092301 (2021)
Phys. Rev. C 104, 024902 (2021)
3 GeV: Phys. Rev. Lett. 128, 202303 (2022)
Phys. Rev. C 107, 024908 (2023)

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

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: **($|\eta|<1.0$)** for both BES-I and BES-II **2) RefMult3X:** **($|\eta|<1.6$)** for BES-II

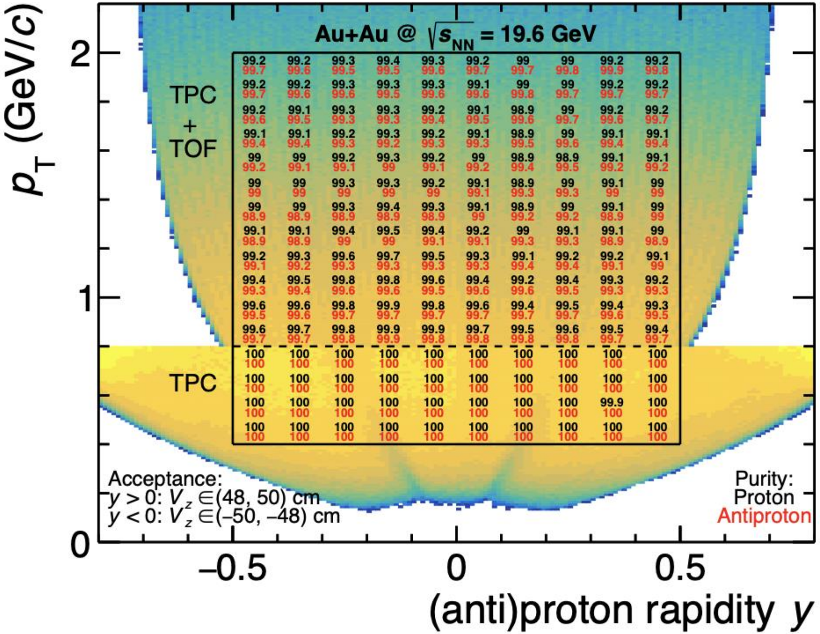
→ Larger acceptance → larger multiplicity → better centrality resolution

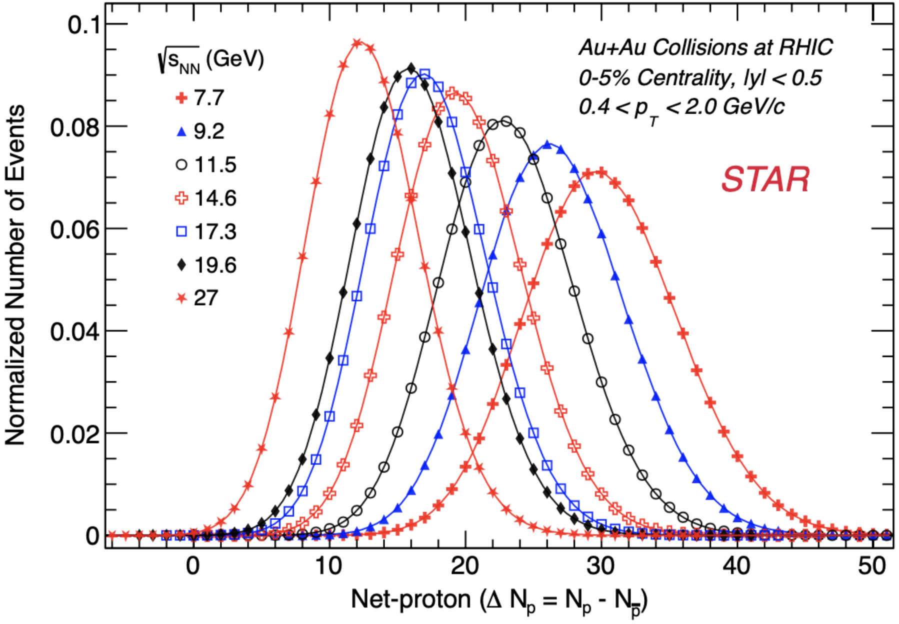
(Anti-)Proton Particle Identification and Net-Proton Distributions

- 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%**

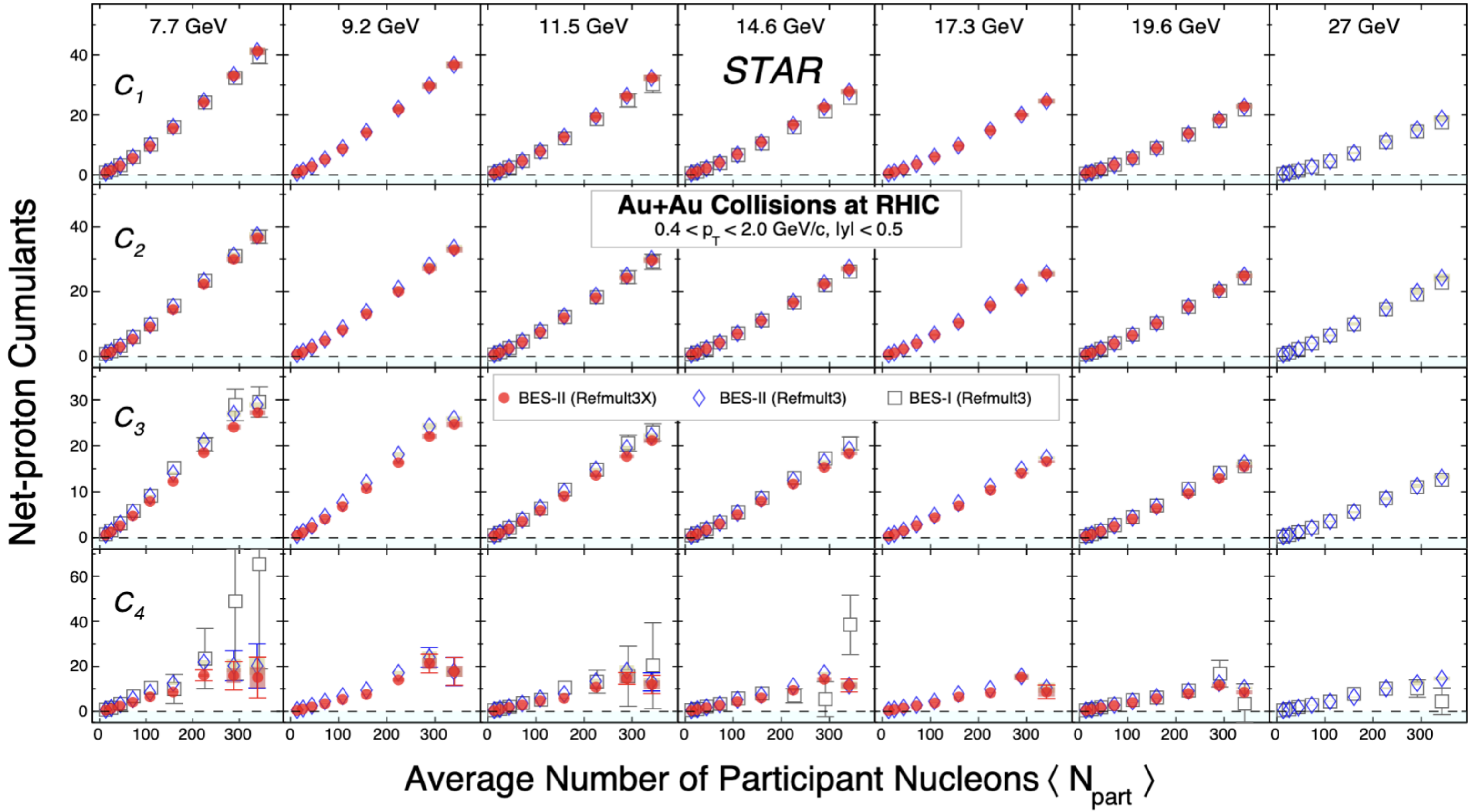
Stat. error $C_r \propto \frac{\sigma^r}{\sqrt{N}}$





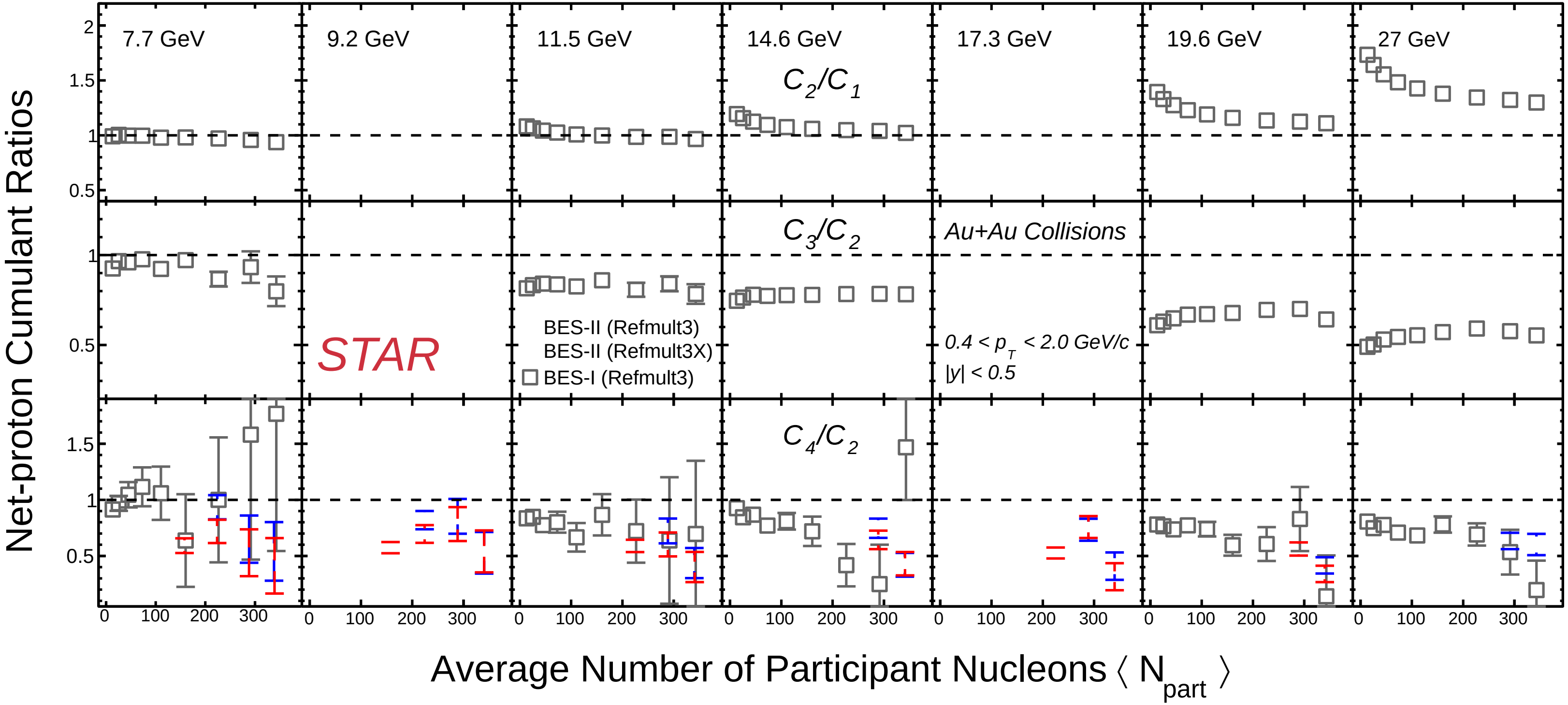
Centrality Dependence: Net-proton Cumulants

STAR: CPOD2024, SQM2024



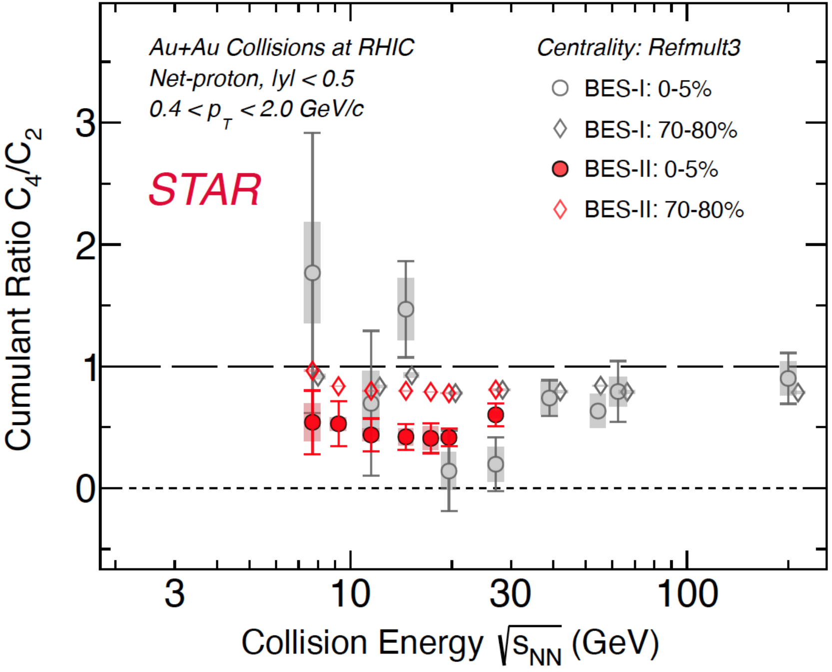
Centrality Dependence: Net-proton Cumulant Ratios

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%

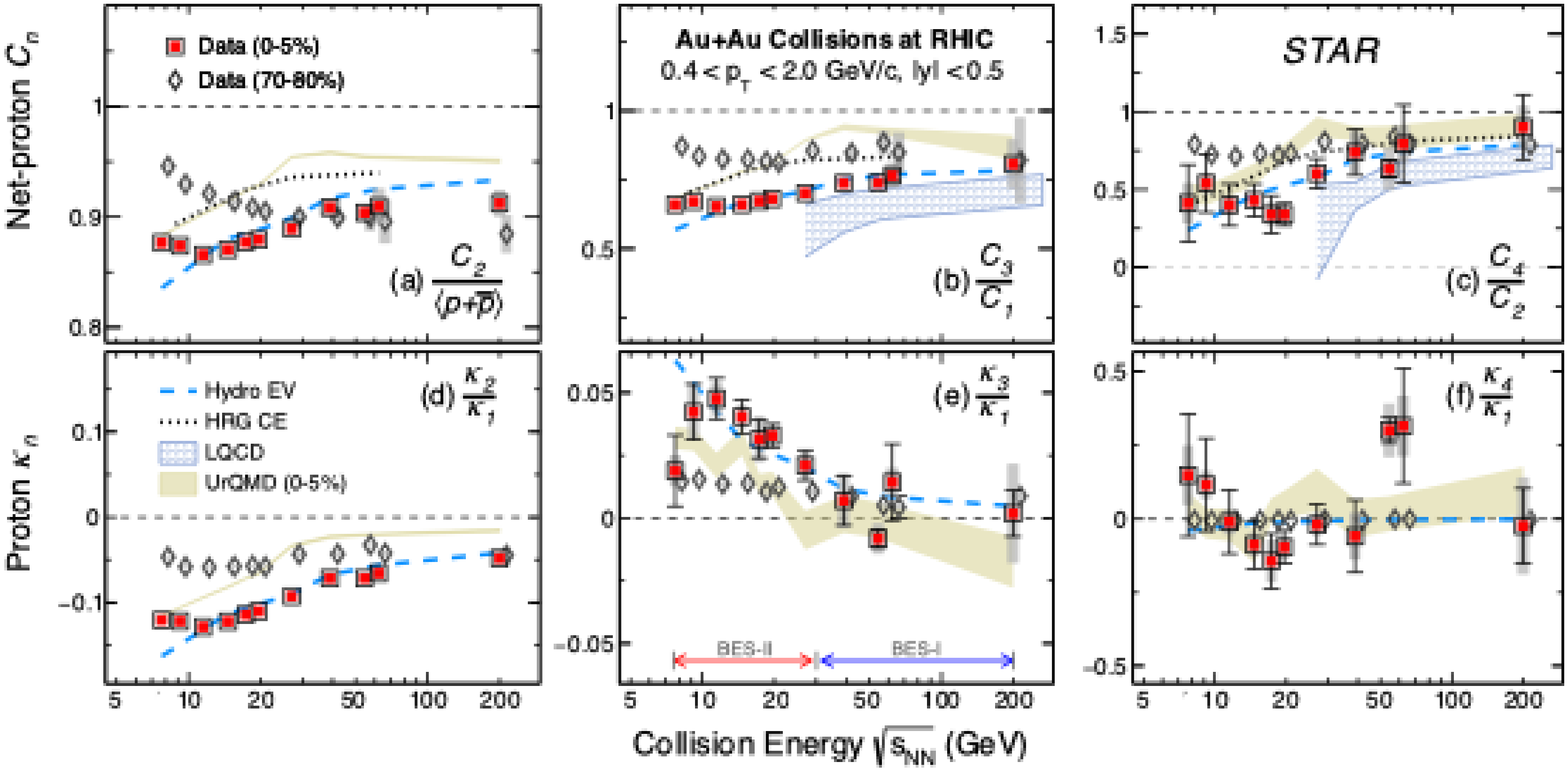
7.7 GeV		19.6 GeV	
stat. error	sys. error	stat. error	sys. error
4.7	3.2	4.5	4

BES-II and BES-I results are consistent !

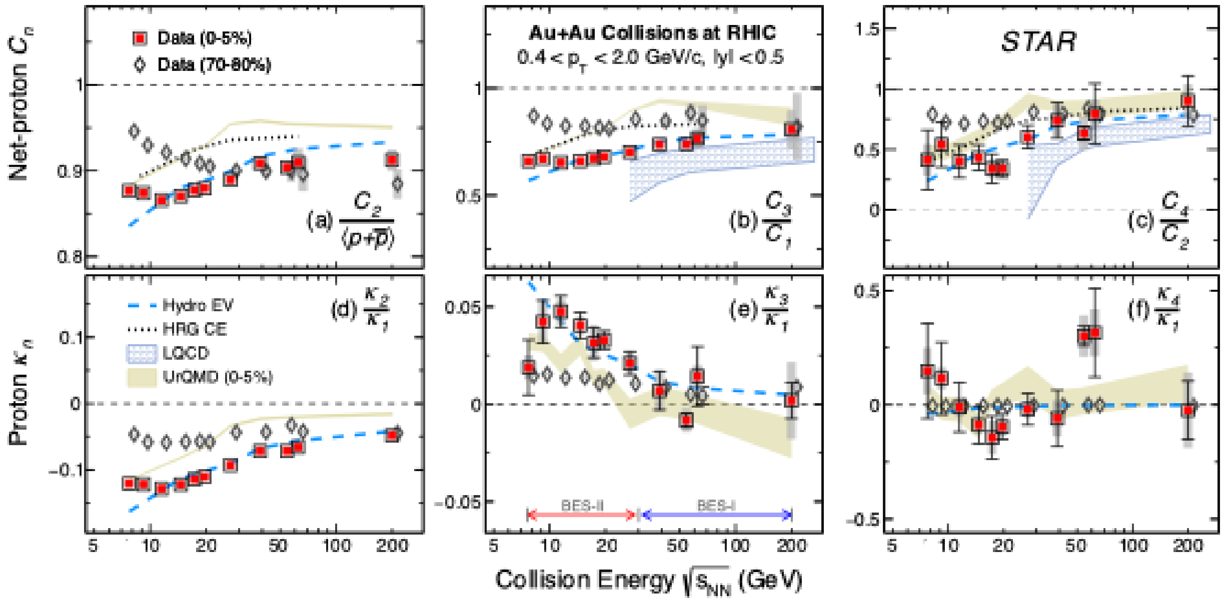
BES-II : Better statistical precision
Better control on systematics !

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);

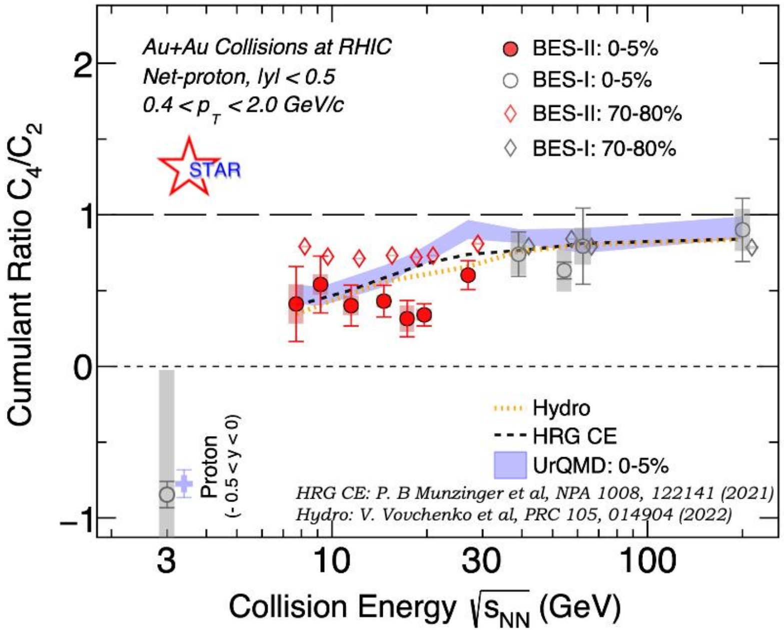
3) Hydro: HRG CE + EV, V. Vovchenko *et al.*, Phys. Rev. **C105**, 014904 (2022).

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

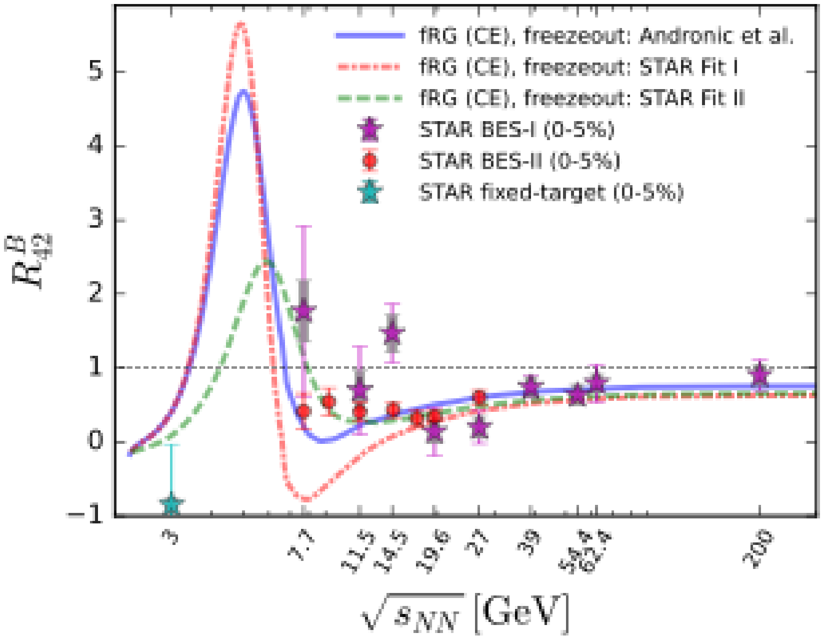
1. Baryon conservation in all model calculations
2. All proton factorial cumulant ratios show clear non-monotonic dependence
3. Lattice QCD describe the data up to 27 GeV.
4. Precise dynamical modelling is needed to fully understand the data.

Continue the Critical Point Search

STAR Measurement：Au+Au 3-200 GeV



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

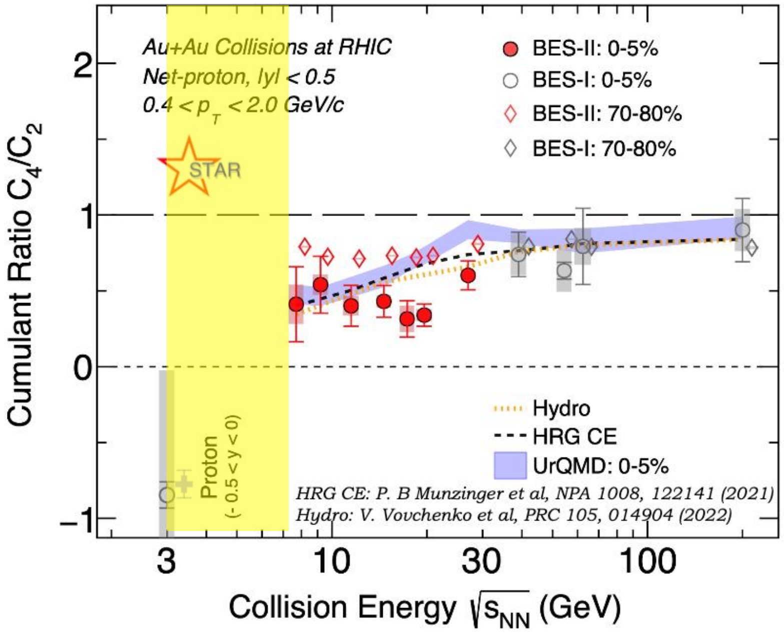


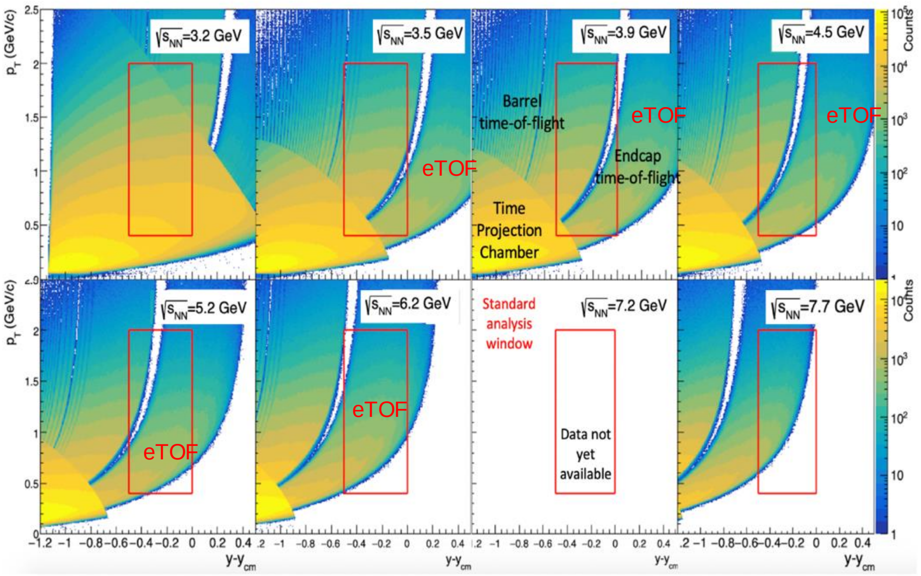
STAR: PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

Caveat : Non-equilibrium effect ? Need dynamical modelling.

Continue the Critical Point Search

STAR Measurement：Au+Au 3-200 GeV



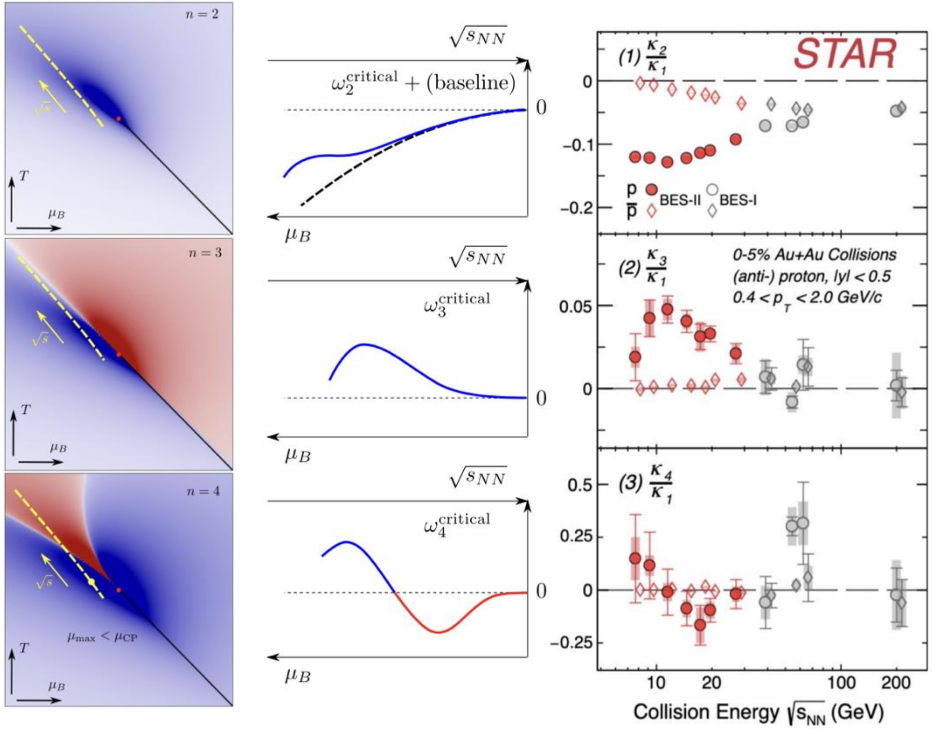


eTOF is crucial for mid-rapidity coverage at 3.5– 4.5 GeV

Energy gap between 3 and 7.7 GeV :
important for **Critical Point search ！**

NICA MPD : 4-11 GeV、CBM: 2.4-4.9 GeV

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



QCD critical point: recent developments

Mikhail Stephanov[1,2,*]

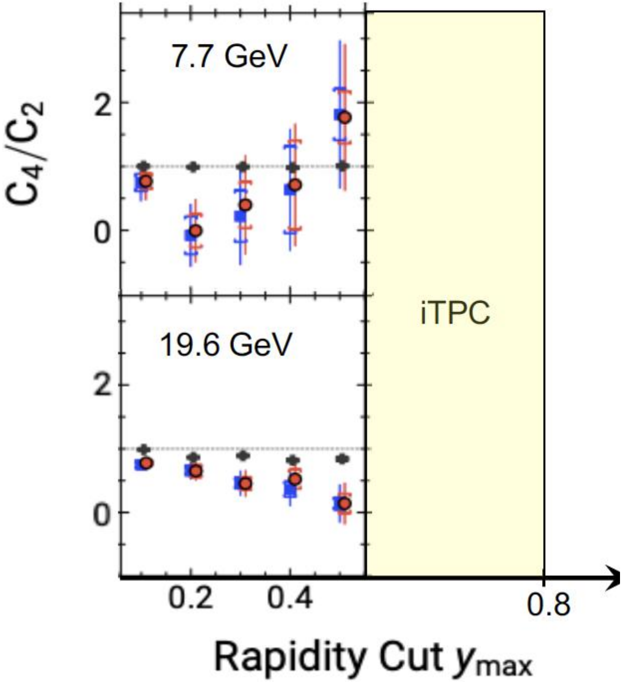
[1]Department of Physics, University of Illinois, Chicago, Illinois 60607, USA
[2]Kadanoff Center for Theoretical Physics, University of Chicago, Chicago, Illinois 60637, USA

"The release of the BES-II data by STAR represents a major step towards uncovering the structure of the QCD phase diagram. It is remarkable that the non-monotonic features of the data are in qualitative agreement with the expectations from equilibrium thermodynamics near the QCD critical point, if one assumes such a point is located at $\mu_B \gtrsim 420$ MeV. Such a location of the critical point would be consistent with recent estimates from various theoretical approaches….."

arXiv : 2410.02861

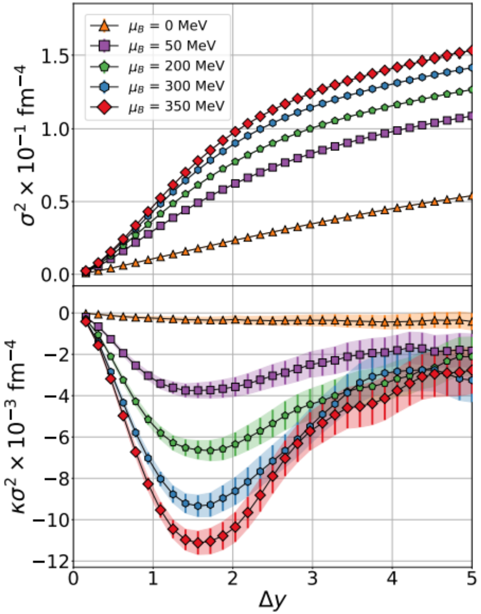
Rapidity dependence around CEP

STAR, PRC 104 (2021) 024902

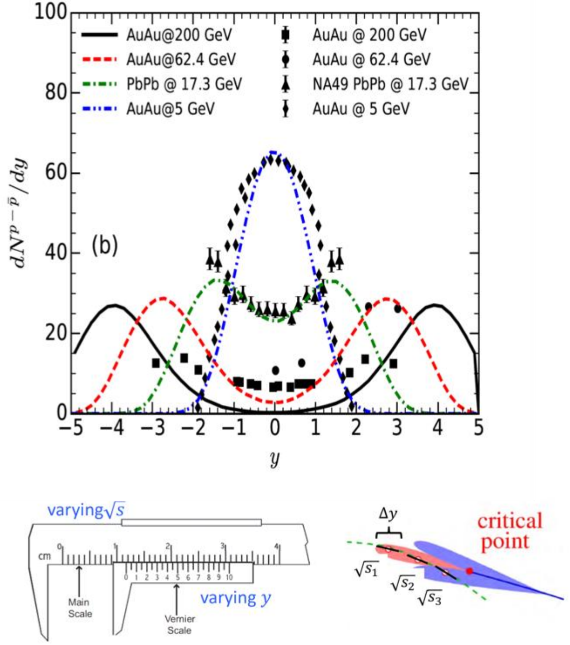


Rapidity coverages at STAR BES-II

Collider: $|y|<y_{max}$=0.8, FXT: -1.0<y<0.5 @ 3 GeV, NICA : $|y|<y_{max}$= 1.5



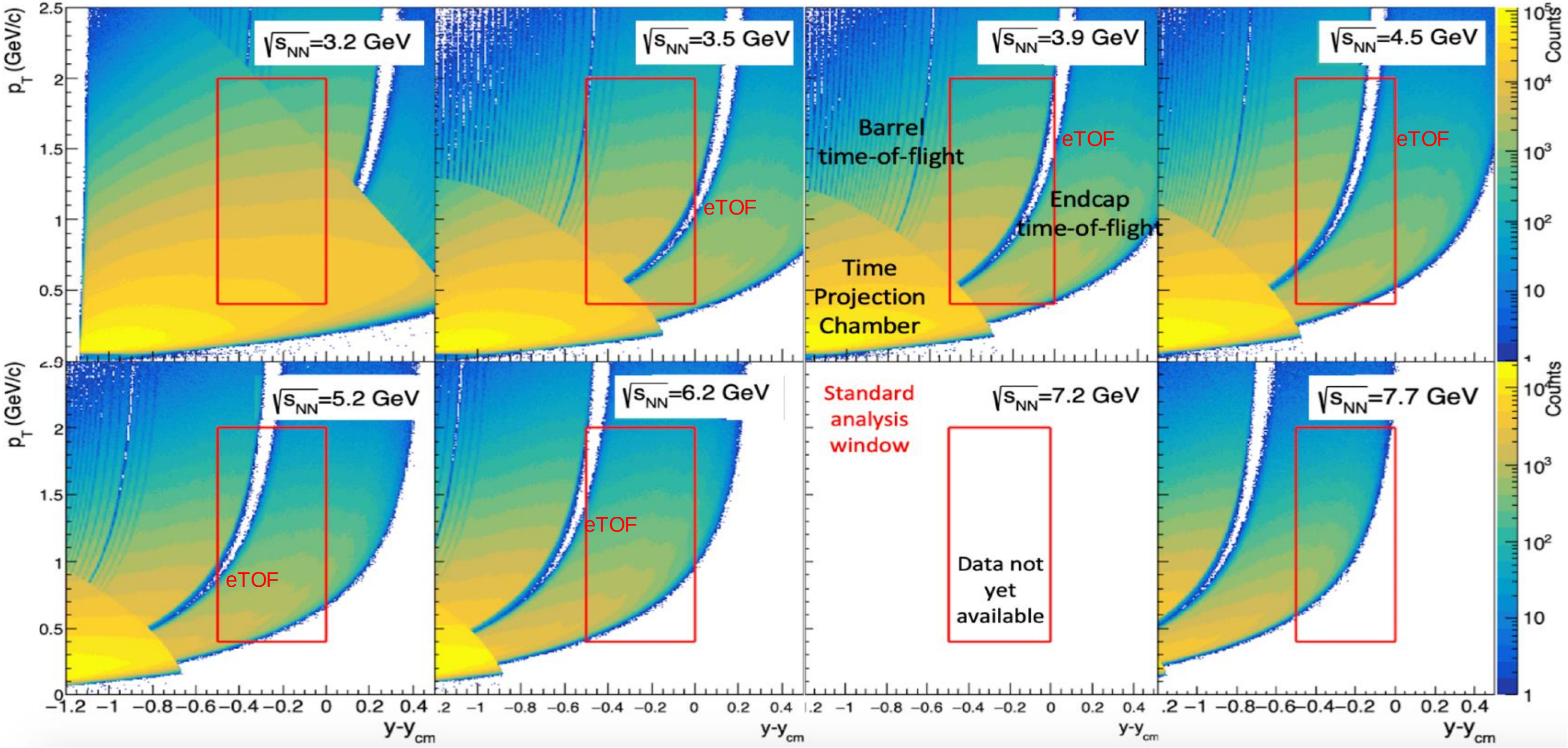
G. Pihan et al., Phys. Rev. C 107, 014908 (2023)



J. Brewer et al., Phys. Rev. C 98, 061901 (2018)

J. Li, et al., arXiv 2311.11374

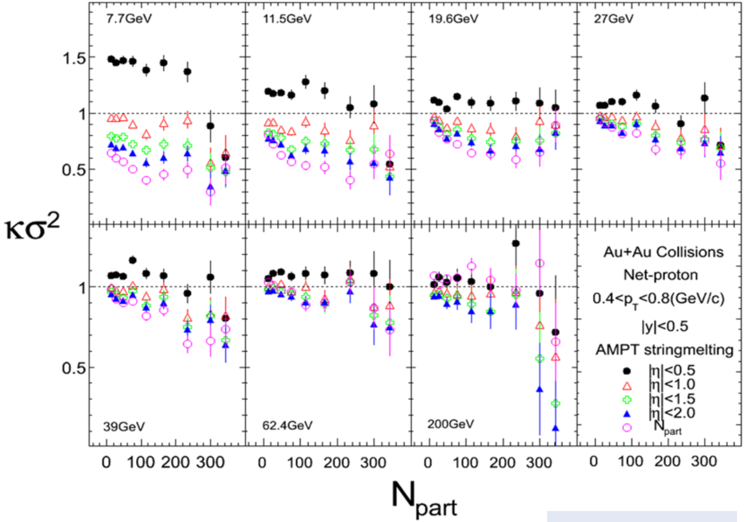
Challenges for fluctuation analysis in FXT energies： Acceptance

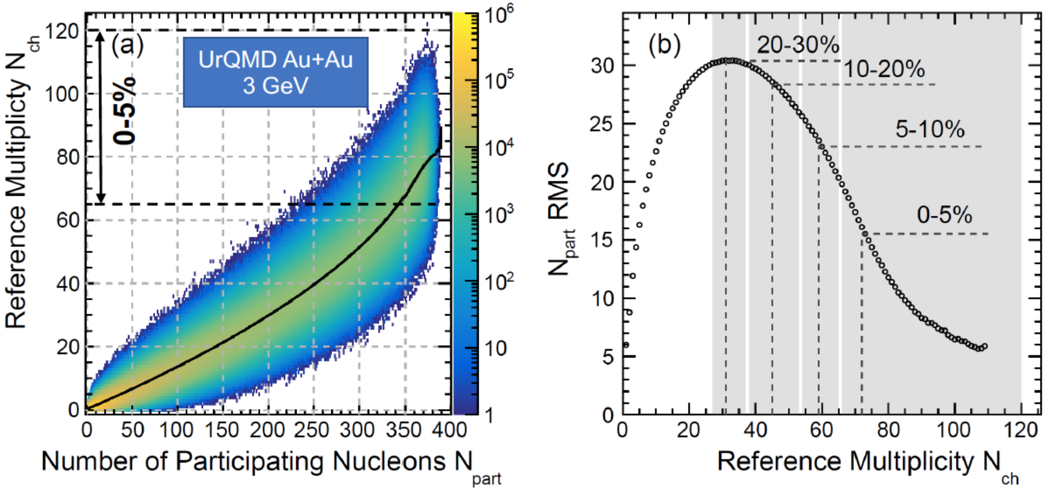


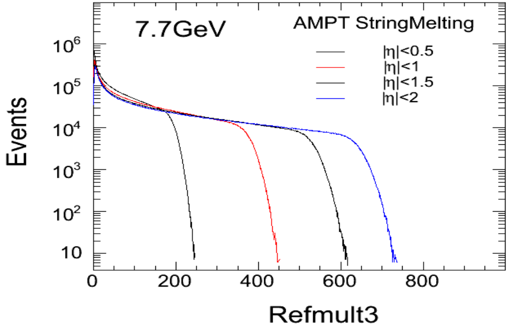
eTOF is crucial for mid-rapidity coverage at 3.5– 4.5 GeV,
But still half rapidity: (-0.5, 0)

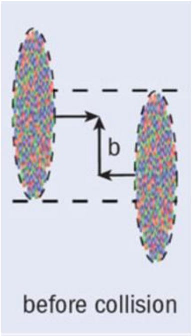
NICA has advantage of large acceptance！

Challenges for fluctuation analysis in FXT energies: Initial Volume Fluctuations、Pile-up









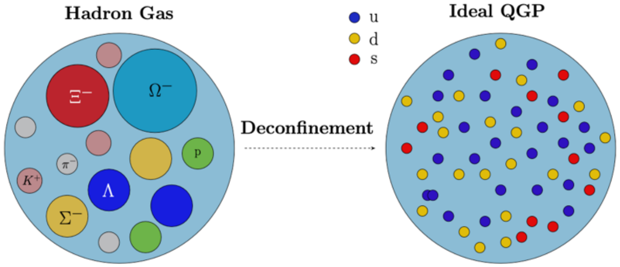
- Initial Volume/Npart Fluctuations are originated from the many-body quantum and dynamical process of heavy-ion collisions.

STAR, Phys. Rev. C 107, 024908 (2023)
P. Braun-Munzinger , A. Rustamov, J. Stachel, Nucl. Phys. A 960,114 (2017)
Arghya Chatterjee et al., Chinese Physics C 45, 064003 (2021)

- Pile-up effect

Y. Zhang, Y. Huang, T. Nonaka, X. Luo, Nucl. Inst. Meth. A 1026(2022)166246

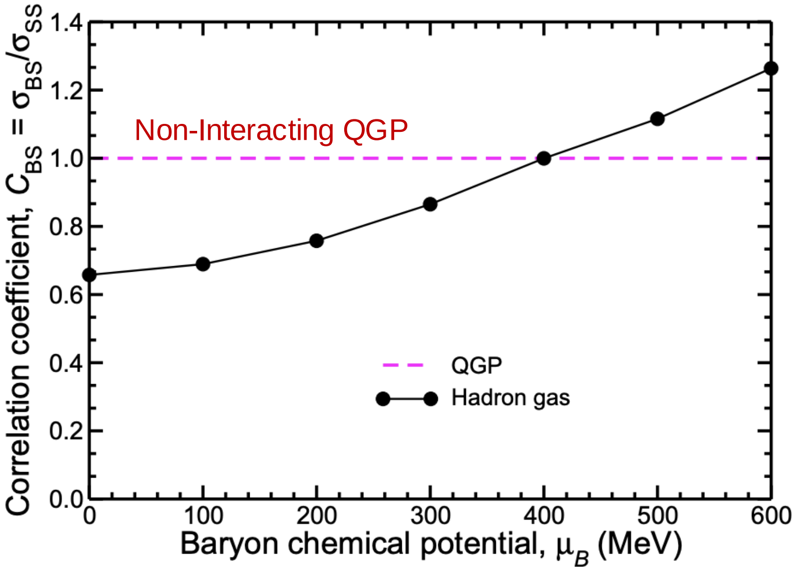
Baryon-Strangeness Correlations : Theory



$$C_{BS} = -3\chi_{BS}^{11}/\chi_S^2 = -3\frac{< BS > - < B >< S >}{< S >^2}$$

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

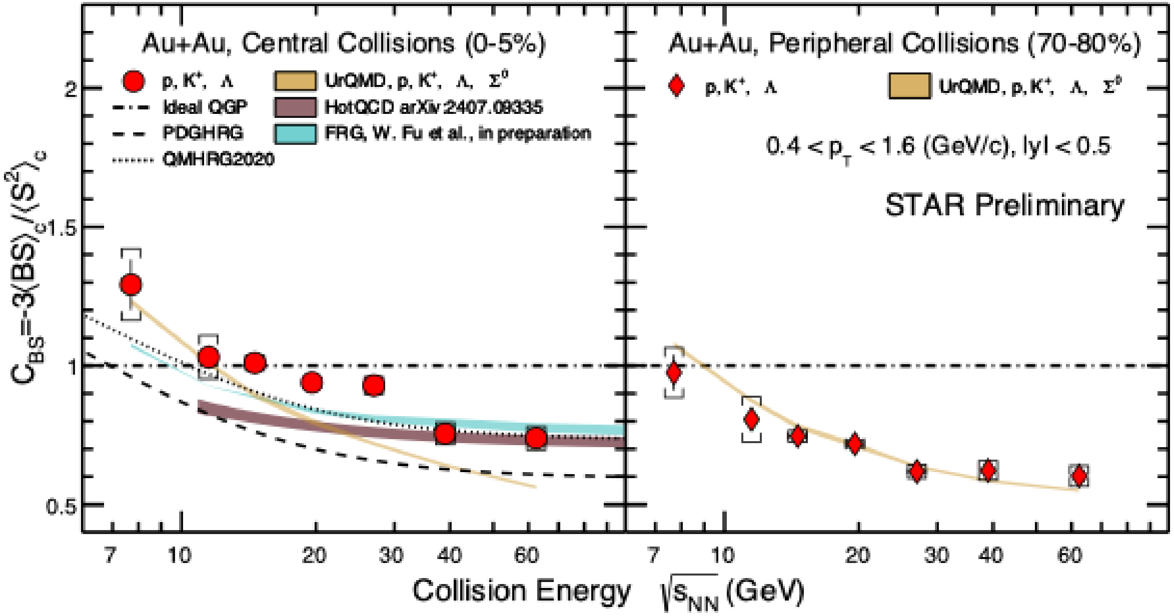
- **Hadronic Matter :**
  Only include Lambda : $C_{BS} = 3$
  Adding more strange meson make C_{BS} smaller (high energy)

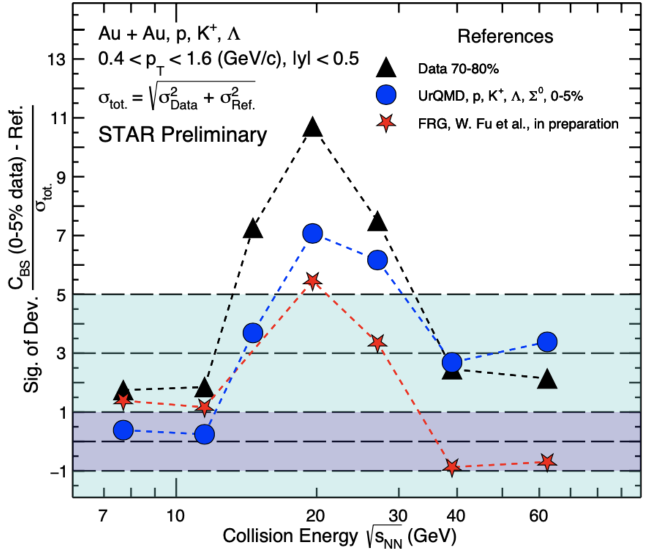


V. Koch, et al., PRL95, 182301 (2005).

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

Energy Dependence of C_{BS} and Model Comparison

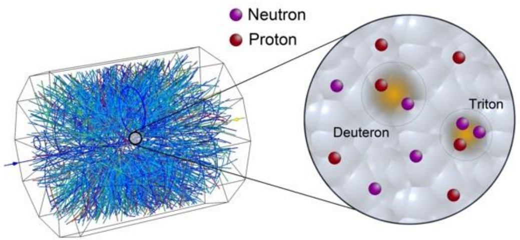


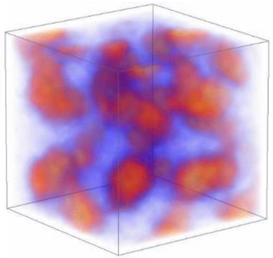


STAR, CPOD2024

- ➢ 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





Coalescence picture:

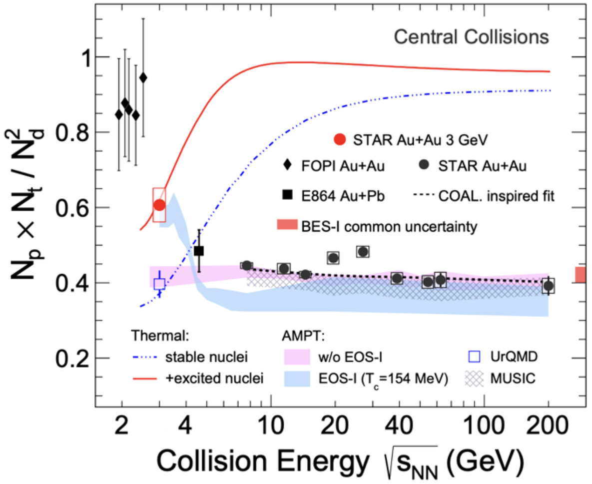
$$N_d = \frac{3}{2^{1/2}}\left(\frac{2\pi}{m_0 T_{eff}}\right)^{3/2} N_p \langle n \rangle (1 + C_{np})$$

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

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

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

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.

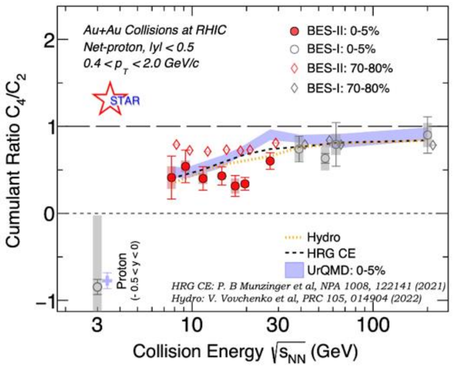
- Analysis of BES-II data (both collider and FXT) are ongoing.

STAR, SQM2024

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

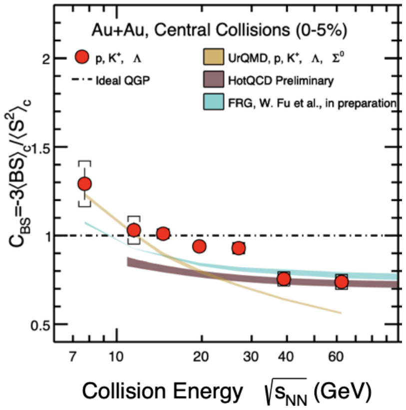
Summary and Outlook

Net-Proton Fluctuations



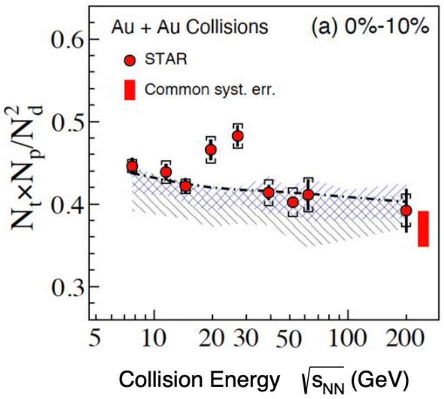
STAR, CPOD2024, SQM2024

BS correlations



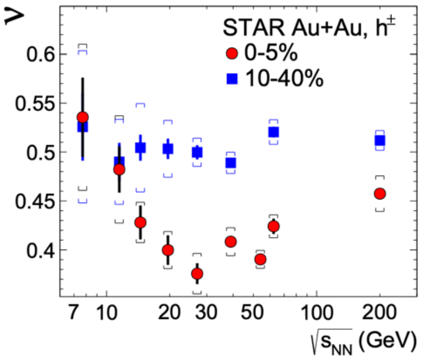
STAR, CPOD2024

Yield Ratio of Light Nuclei

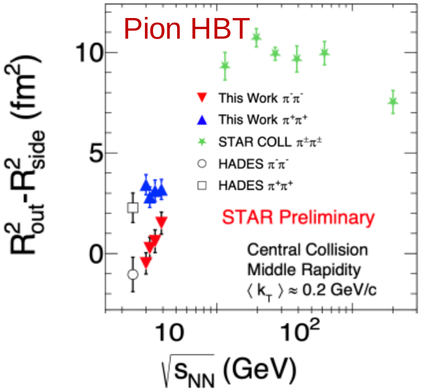


STAR: PRL130, 202301 (2023)

Intermittency



STAR, PLB 845, 138165 (2023)

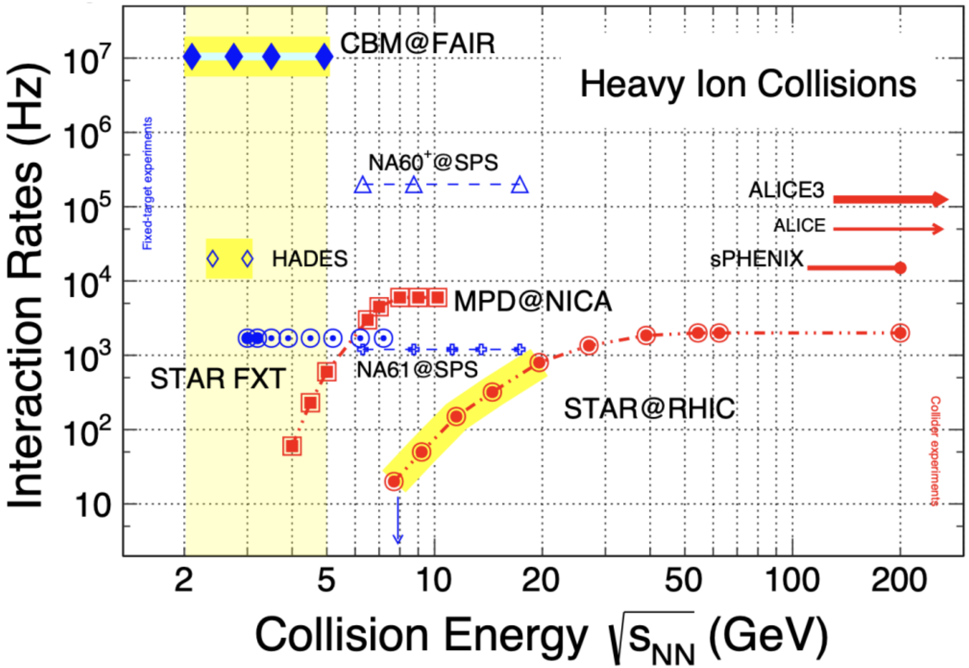


BES-II : high statistics, better acceptance and systematics

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

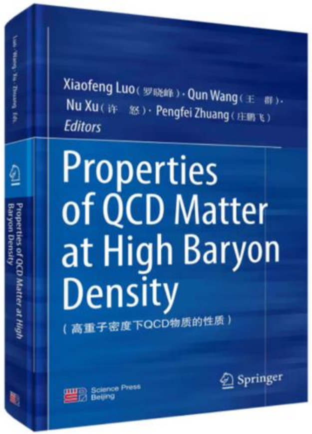
Rich physics at high baryon density : QCD phase structure, EoS etc.



Conduct FXT experiment at NICA !!

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

Thank you for your attention !