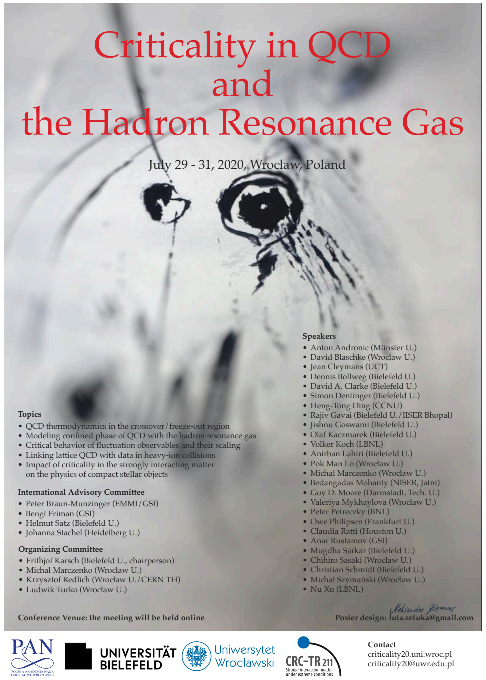
Search for the QCD Critical Point

- Selected Results from RHIC Beam Energy Scan Program

Nu Xu



Many thanks to Organizers!

Outline

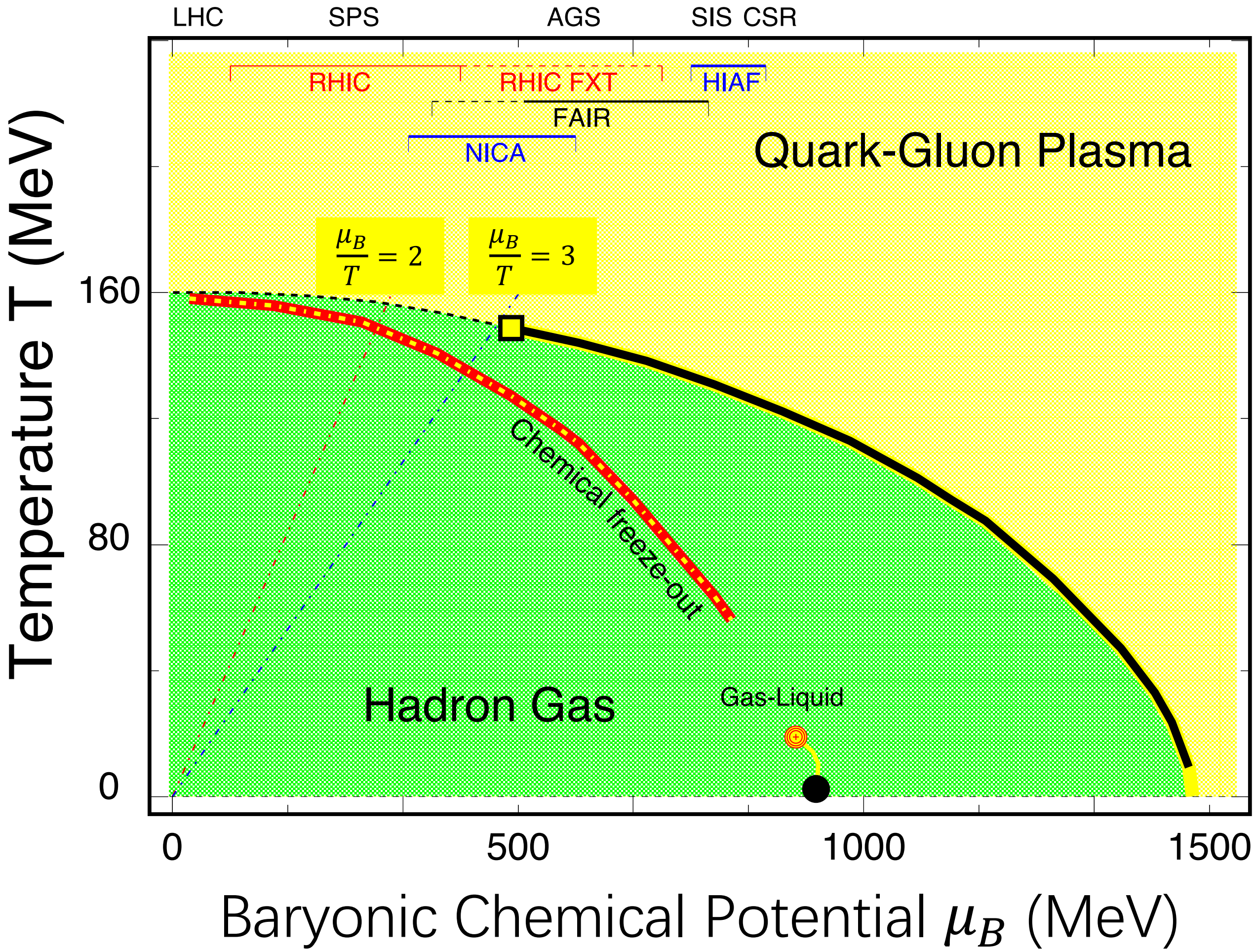
(1) Introduction

(2) Selected Results from RHIC BES-I

- Recent progresses
- Baryon number conservations, reference for high moments data
- Status of thermalization in high-energy nuclear collisions

(3) RHIC BES-II and Beyond

The QCD Phase Diagram

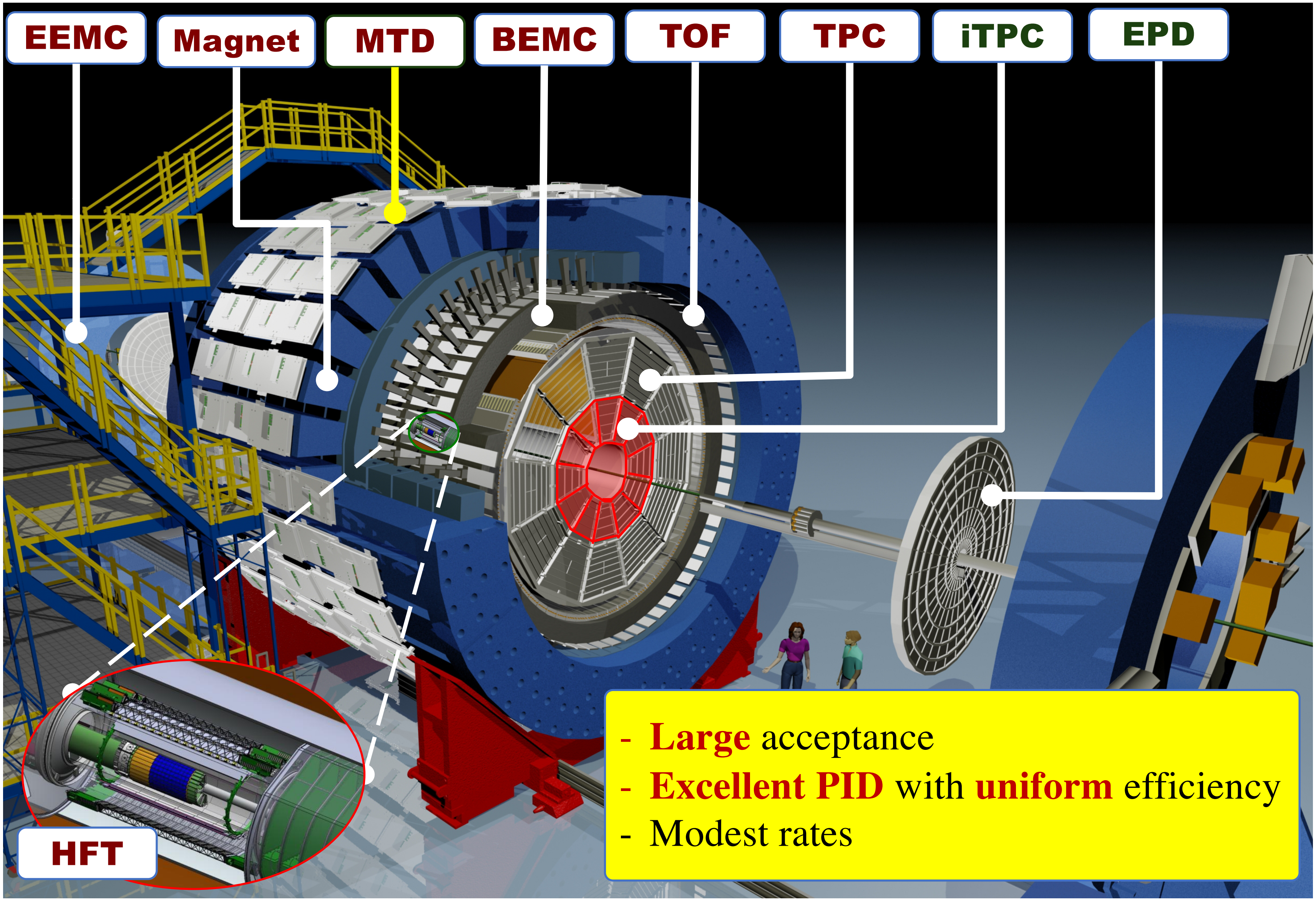


(1) Smooth crossover at vanishing baryon chemical potential, i.e. at high collision energy;

(2) 1st order phase transition and QCD critical point at finite baryon chemical potential. Lattice results suggest the region

$$\frac{\mu_B}{T} > 3$$

(3) RHIC BES+FXT program; NICA MPD, FAIR CBM/HADES, and HIAF CEE focus the finite/high baryon density region



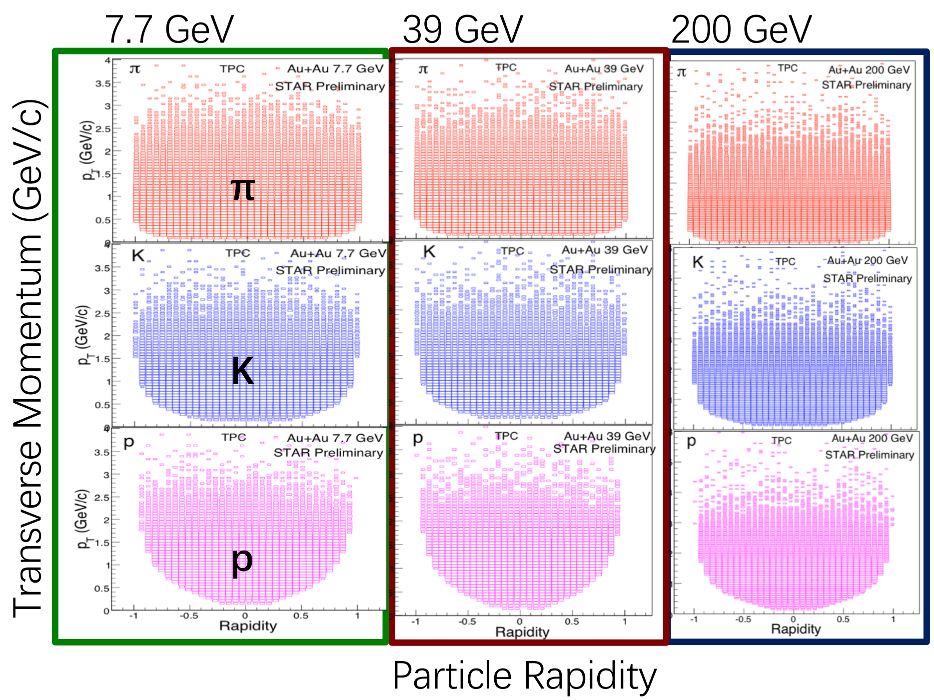
STAR

Detector

System

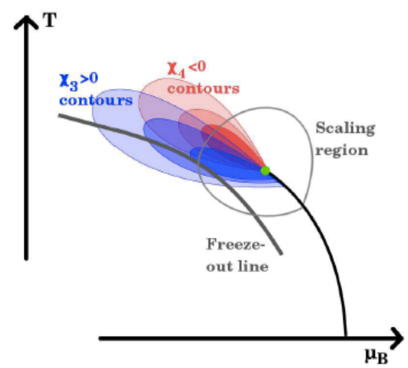
Data-sets for the BES-I Program

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.40	67	2010
54.4	1200	2017
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010

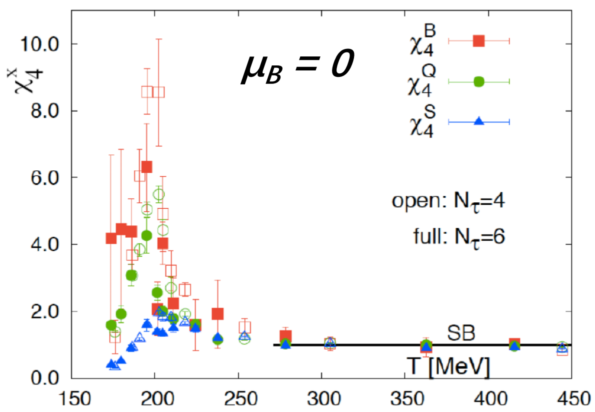


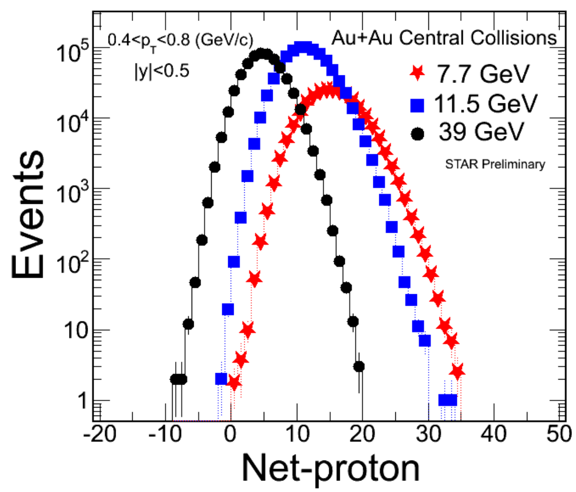
1) Largest data sets versus collision energy
2) STAR: Large and homogeneous acceptance, excellent particle identification.
   Especially important for fluctuation analysis

Criticality



High Moments





1) High moments of conserved quantum numbers: ***Q***, ***S***, ***B***, in high-energy nuclear collisions

2) Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \quad \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \quad \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

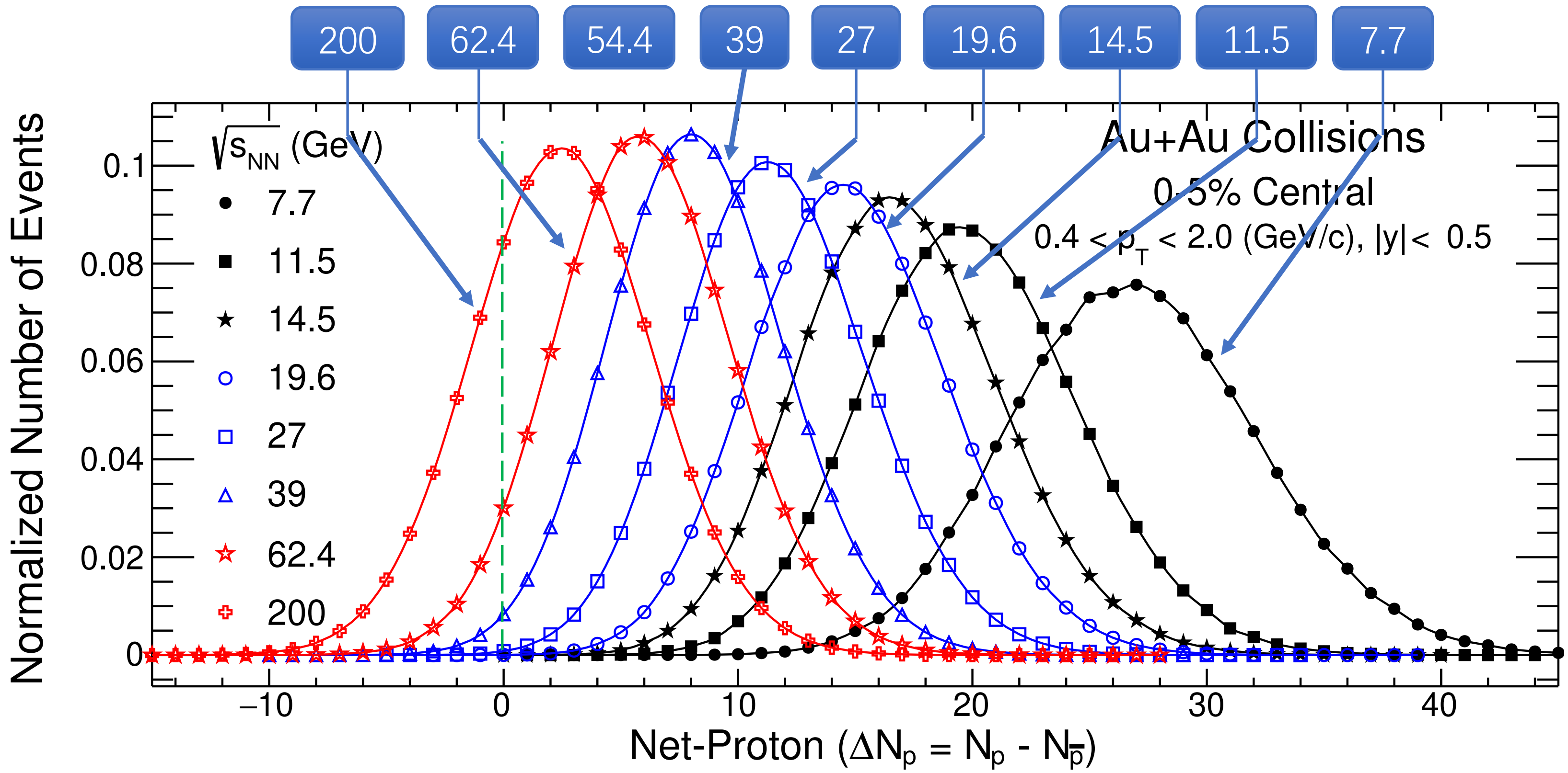
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

4) Extract susceptibilities and freeze-out temperature: an independent and important test of thermal equilibrium in heavy ion collisions.

References:

- STAR: *PRL* **105**, 22303(10); *ibid*, **112**, 032302(14); arXiv: 2001.02852
- S. Ejiri, F. Karsch, K. Redlich, *PL* ***B633***, 275(06); M. Stephanov: *PRL* **102**, 032301(09) ; F. Karsch *et al., PL* ***B695***, 136(11); R.V. Gavai and S. Gupta, *PL* ***B696***, 459(11)
- A. Bazavov *et al.*, PRL **109**, 192302(12); V. Skokov *et al.*, PR**C88**, 034901(13); S. Borsanyi *et al.*, PRL **111**, 062005(13)
- PBM, A. Rustamov, J. Stachel, NP**A960**, 114(17); PBM et al., 2007.02463
- A. Bzdak, *et al.*, arXiv: 1906.00936, Physics Report, **853**, 1(2020)

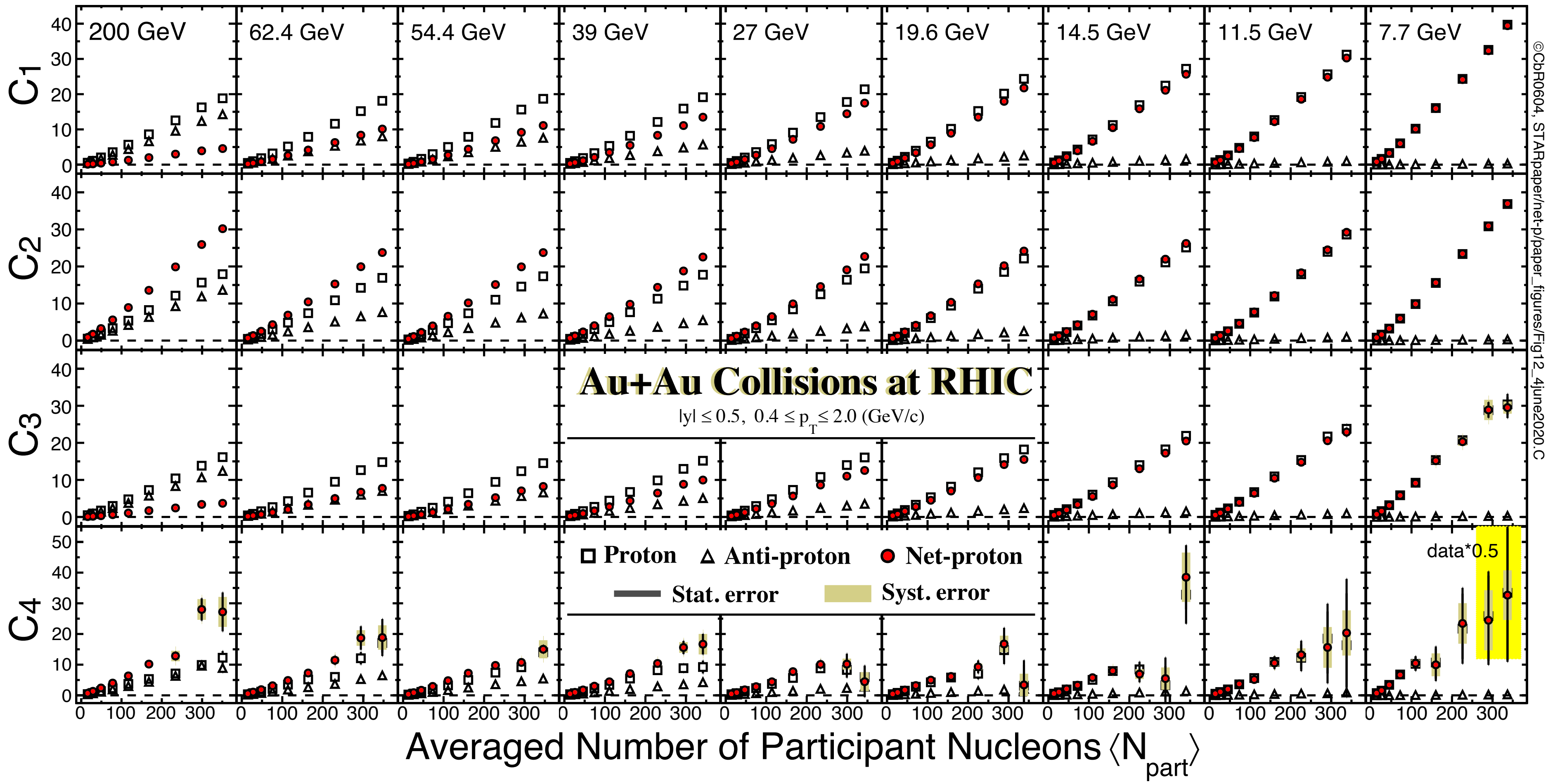
Collision Energy Dependence of net-protons



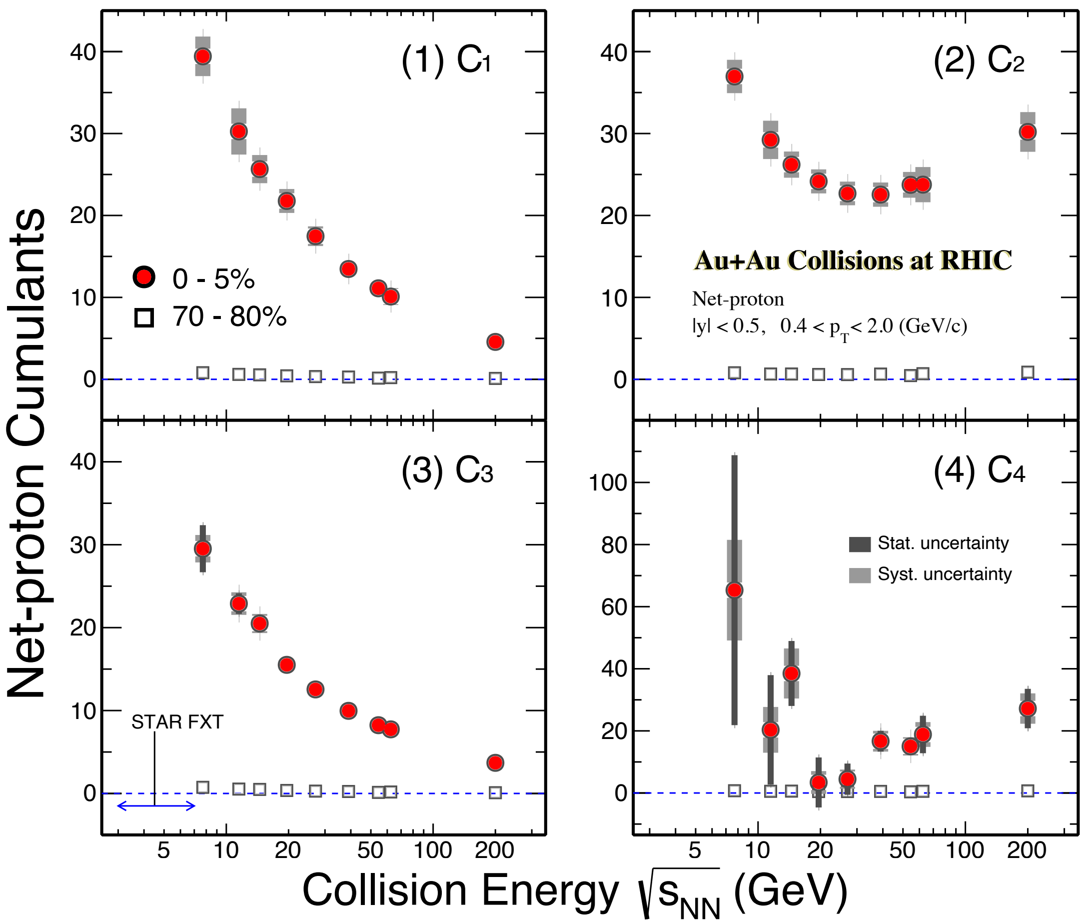
1) Net-proton distributions, top 5% central collisions, efficiency uncorrected
2) Value of mean and the width increase as energy decreases, effect of baryon stopping

STAR short paper: arXiv: 2001.02852

Net-proton Cumulants vs. Energy and Centrality



Energy Dependence of the Net-proton Cumulants

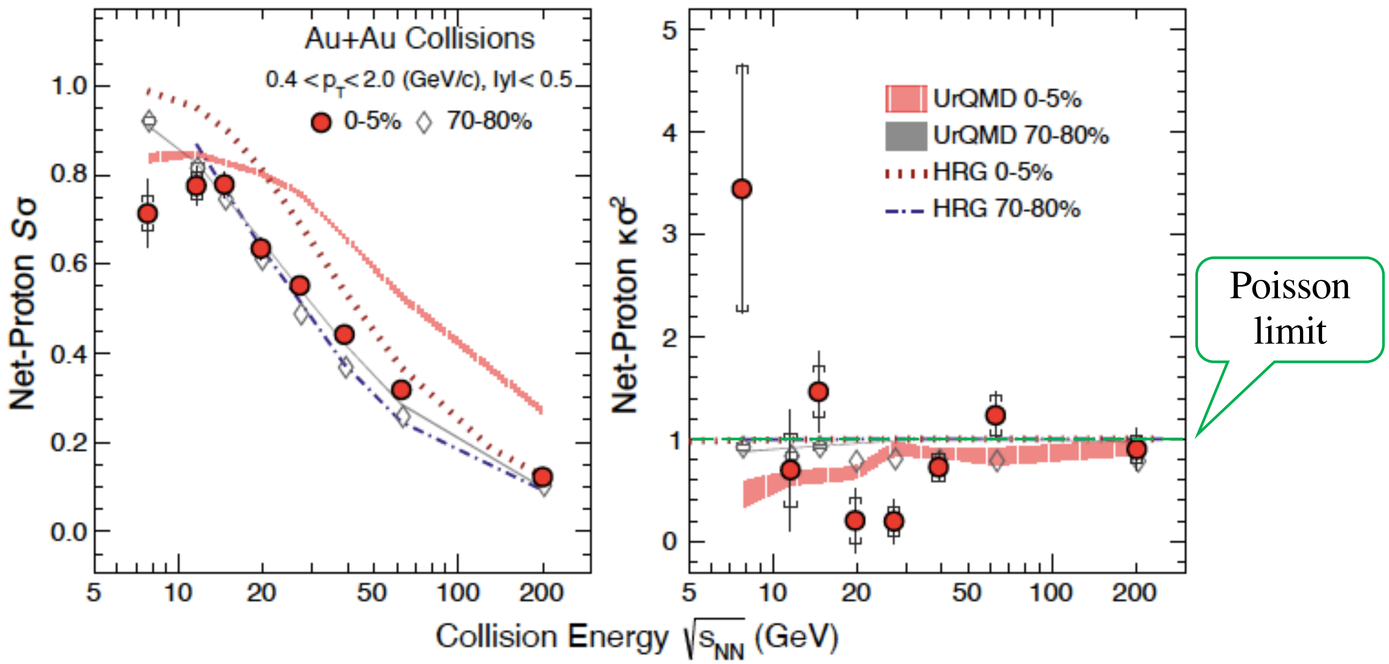


1) Cumulants of net-proton distributions from top 5% central and 70-80% peripheral collisions. Efficiency and acceptance corrections applied

2) Value of mean increase as energy decreases, effect of baryon stopping

STAR: arXiv: 2001.02852

Collision Energy Dependence: $s\sigma$ and $\kappa\sigma^2$

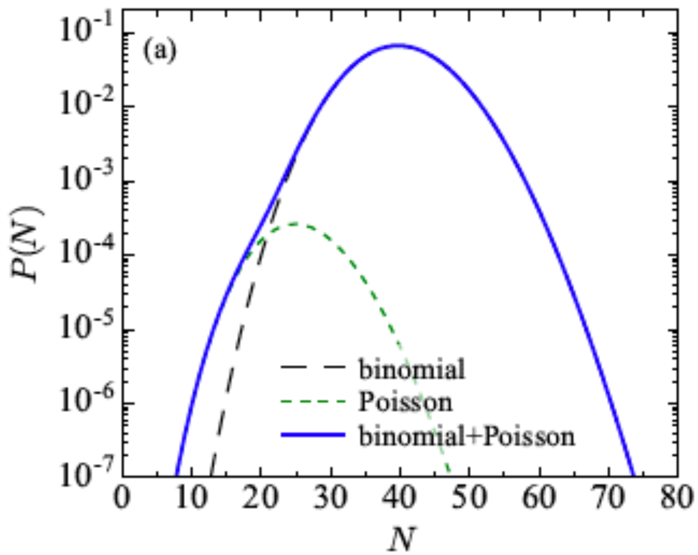


1) HRG and transport model predicted monotonical energy dependence: AMPT, JAM, UrQMD. Suppression at low energy due to conservation.
2) Net-proton 3rd and 4th orders: **deviate from the Poisson limit** in the most central collisions!
3) '**Attractive**' of protons at the 7.7 GeV collisions?

STAR: arXiv: 2001.02852

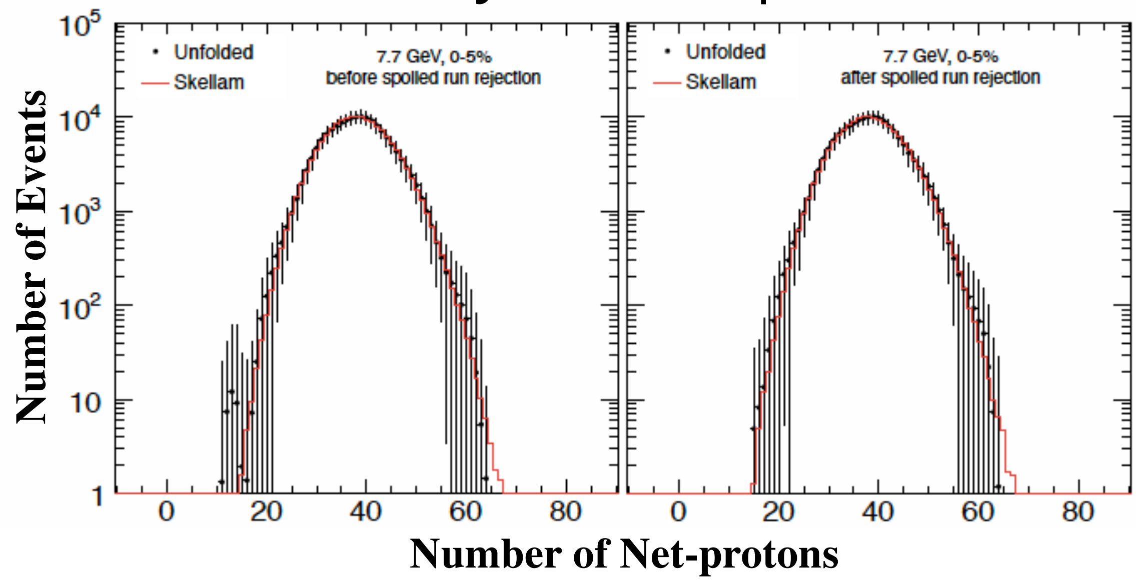
"Phase Boundary" vs. Spoiled Events

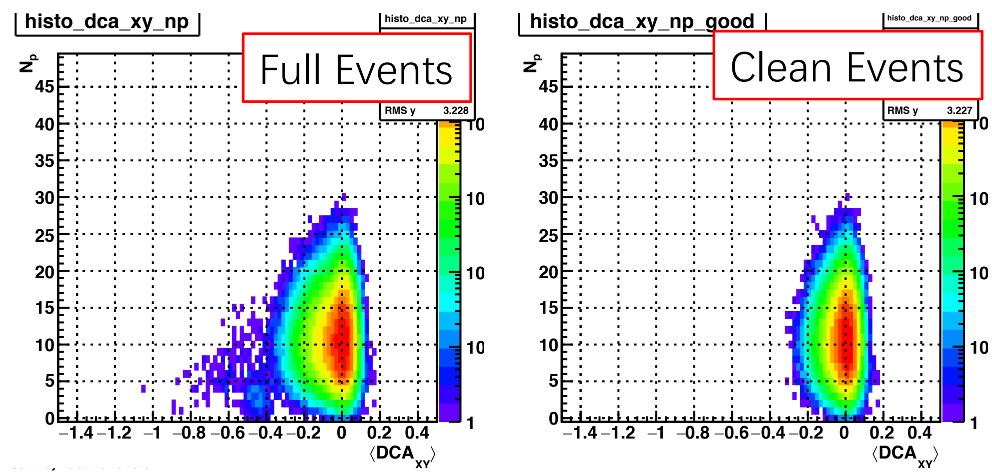
- STAR: arXiv: 2001.02852
- A. Bzdak, V. Koch, D. Oliinychenkov, and J. Steinheimer, Phys. Rev. **C98**, 054901(2018).



Given the fit, we can also predict the factorial cumulants, C_2, C_5, C_6 and we obtain:

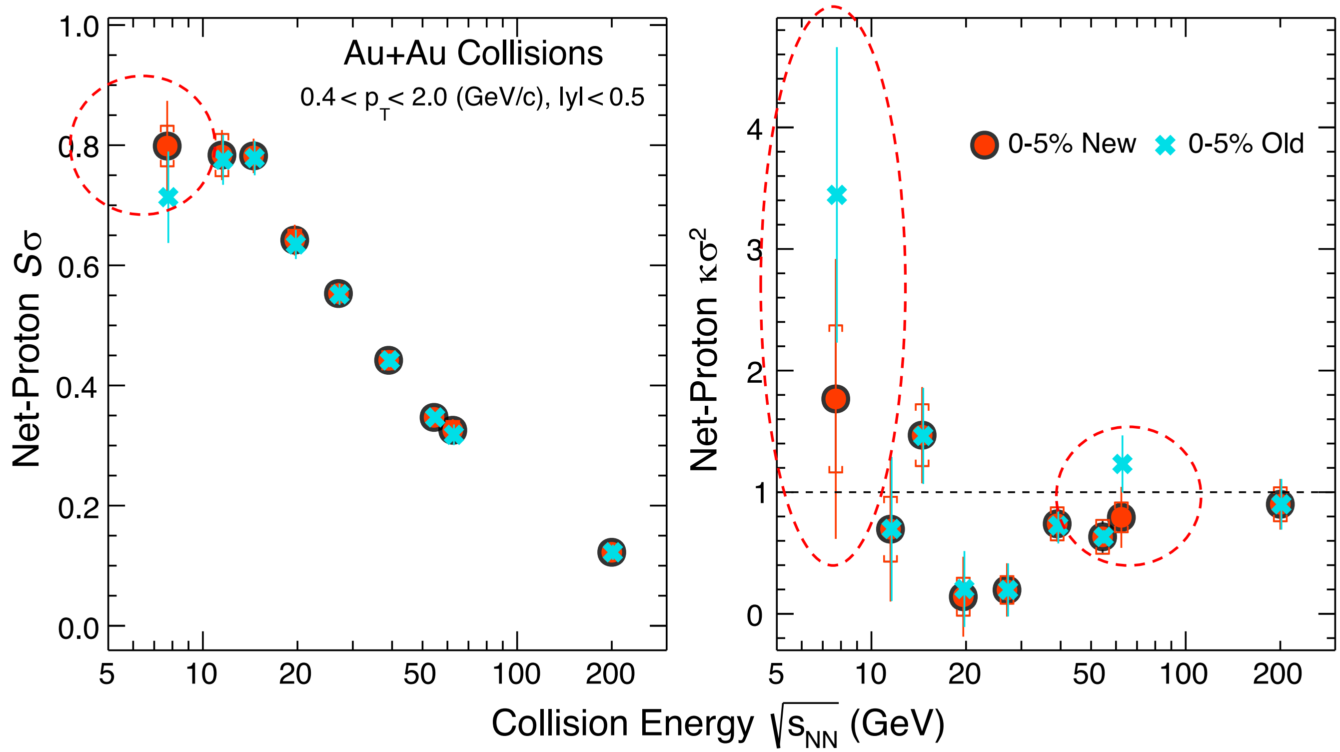
$$C_2 \approx -3.85,$$
$$C_5 \approx -2645,$$
$$C_6 \approx 40900,$$





- For the 7.7 GeV collisions, after cleaning up the spoiled events, the 2[nd] bump is gone, C5 becomes close to zero;
- We made scan of the DCA_{XY} vs. run number for all collisions. All systematic uncertainties are also re-evaluated

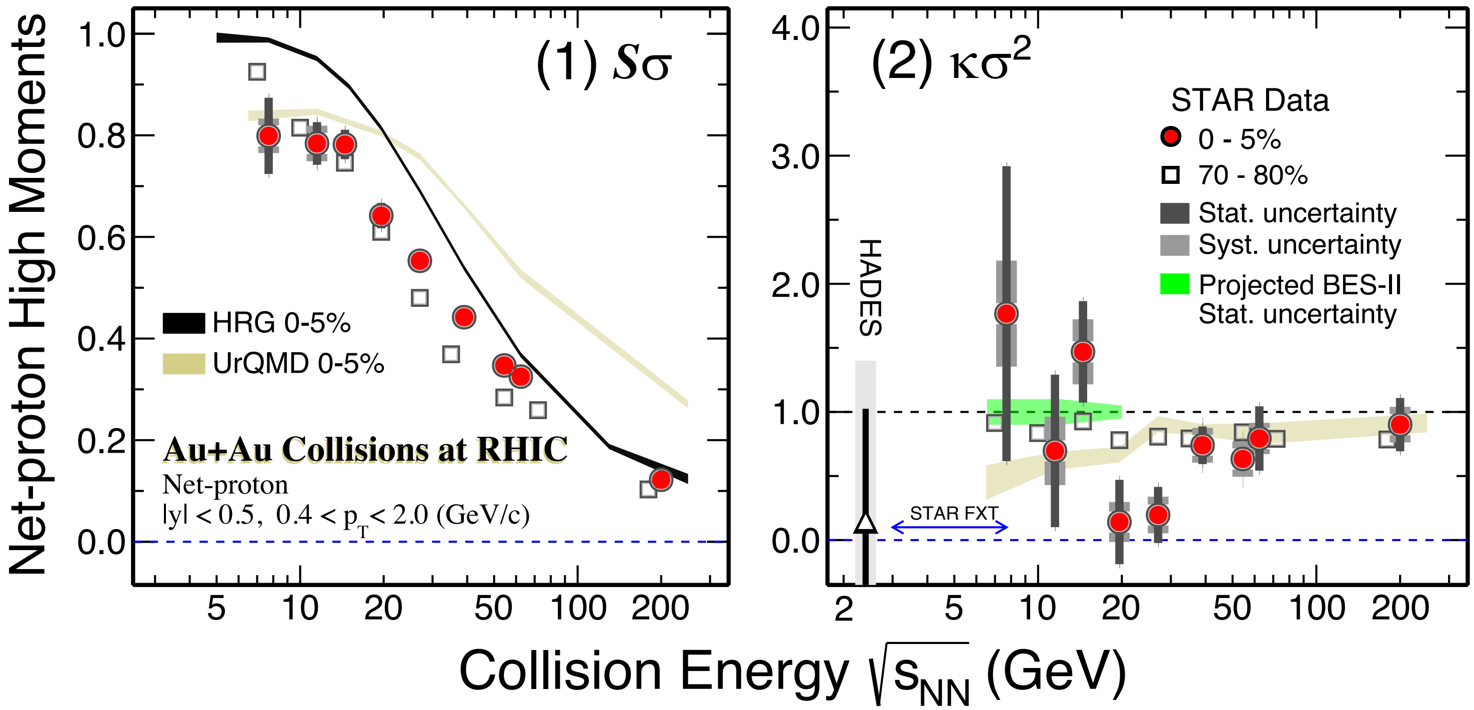
Removing the Spoiled Events



All within statistical uncertainties, the largest changes are seen in central Au+Au collisions:

- 7.7 GeV C_3/C_2 and C_4/C_2
- 62.4 GeV C_4/C_2

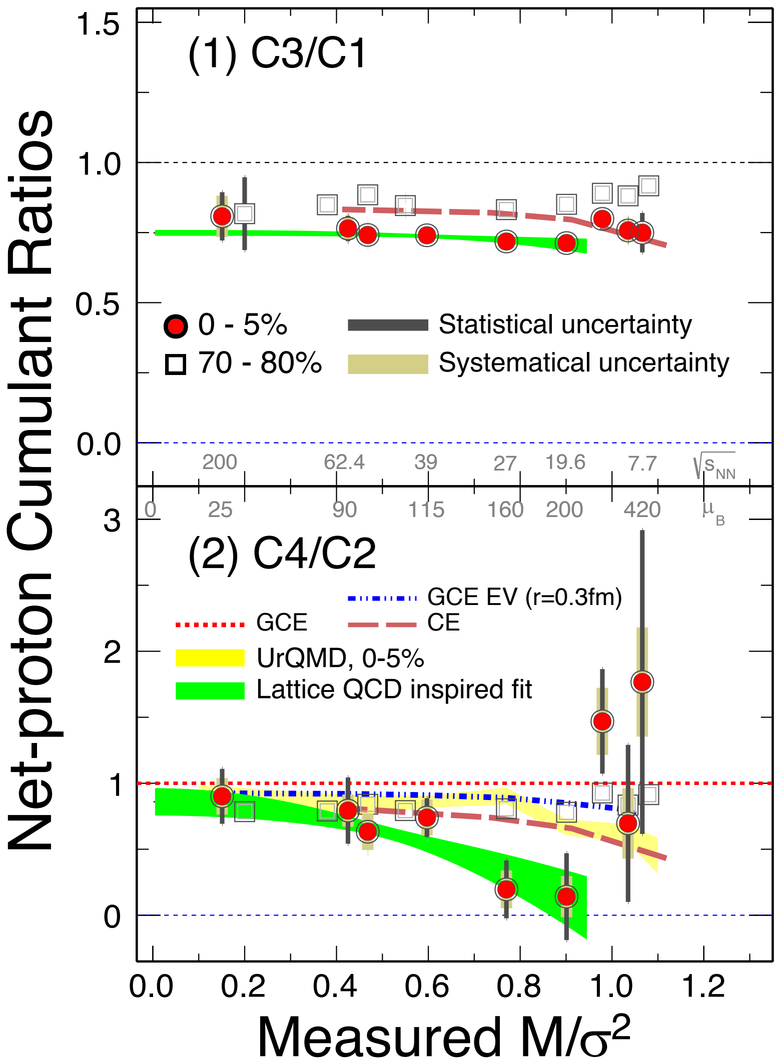
Collision Energy Dependence: $s\sigma$ and $\kappa\sigma^2$



1) HRG and transport model predicted monotonical energy dependence: AMPT, JAM, UrQMD. Suppression at low energy due to conservation.
2) Net-proton 3rd and 4th orders: **deviate from the Poisson limit** in the most central collisions!
3) '**Attractive**' of protons at the 7.7 GeV collisions?

HADES: 2002.08701

STAR: arXiv: 2001.02852 (resubmitted)



Reference for the Data

1) Frithjof, at finite baryon density, LGT calculations suggested:

$$\frac{C_3}{C_1} \propto \left(\frac{C_1}{C_2}\right)^{-3} = \left(\frac{M}{\sigma^2}\right)^{-3} \qquad \frac{C_4}{C_2} \propto \left(\frac{C_1}{C_2}\right)^{-2} = \left(\frac{M}{\sigma^2}\right)^{-2}$$

T_{pc} = 156.5±1.5 MeV at $\mu_B = 0$;

2) PBM et al. argued baryon number nonservation, i.e. the Canonical Ensemble (**CE**) for describing the system;

3) All transport model results [3] are all consistent with the CE [2] calculations (at least for C_4/C_2);

4) Excluded volume approach [4] also leads to suppression at high baryon region, argued the density effect

Proper reference for the data?

- STAR Data: arXiv: 2001.02852 (re-submitted)

[1] F. Karsch, Talk at INT Workshop, May 2020
[2] P. Braun-Munzinger et al., arXiv: 2007.02463
[3] For example, S. He et al., Phys. Lett. **B762**, 296(2016)
[4] For example, J.H. Fu, Phys. Lett. **B722**, 144(2013)

Compare to Predictions: χ^2 fitting

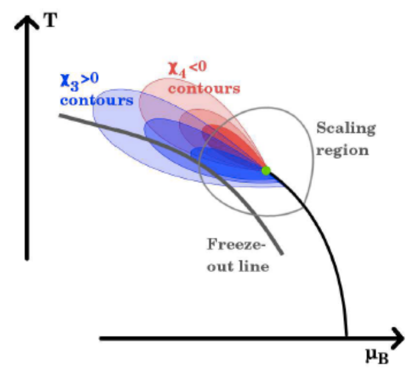
Top 0 - 5% Au + Au Collisions at RHIC					
Energy Range	Cumulant Ratios	HRG GCE	HRG CE [2]	HRG EV [4] (r = 0.5 fm)	UrQMD [3]
7.7 – 27 GeV	C_2/C_1	< 0.001	< 0.001	< 0.001	< 0.001
	C_3/C_2	< 0.001	$7.54e^{-3}$	< 0.001	< 0.001
	C_4/C_2	$5.53e^{-3}$	$4.50e^{-3}$	$1.45e^{-2}$	$2.21e^{-3}$
7.7 – 62.4 GeV	C_2/C_1	< 0.001	< 0.001	< 0.001	< 0.001
	C_3/C_2	< 0.001	< 0.001	< 0.001	< 0.001
	C_4/C_2	< 0.001	$1.28e^{-1}$	$1.07e^{-2}$	$5.77e^{-3}$

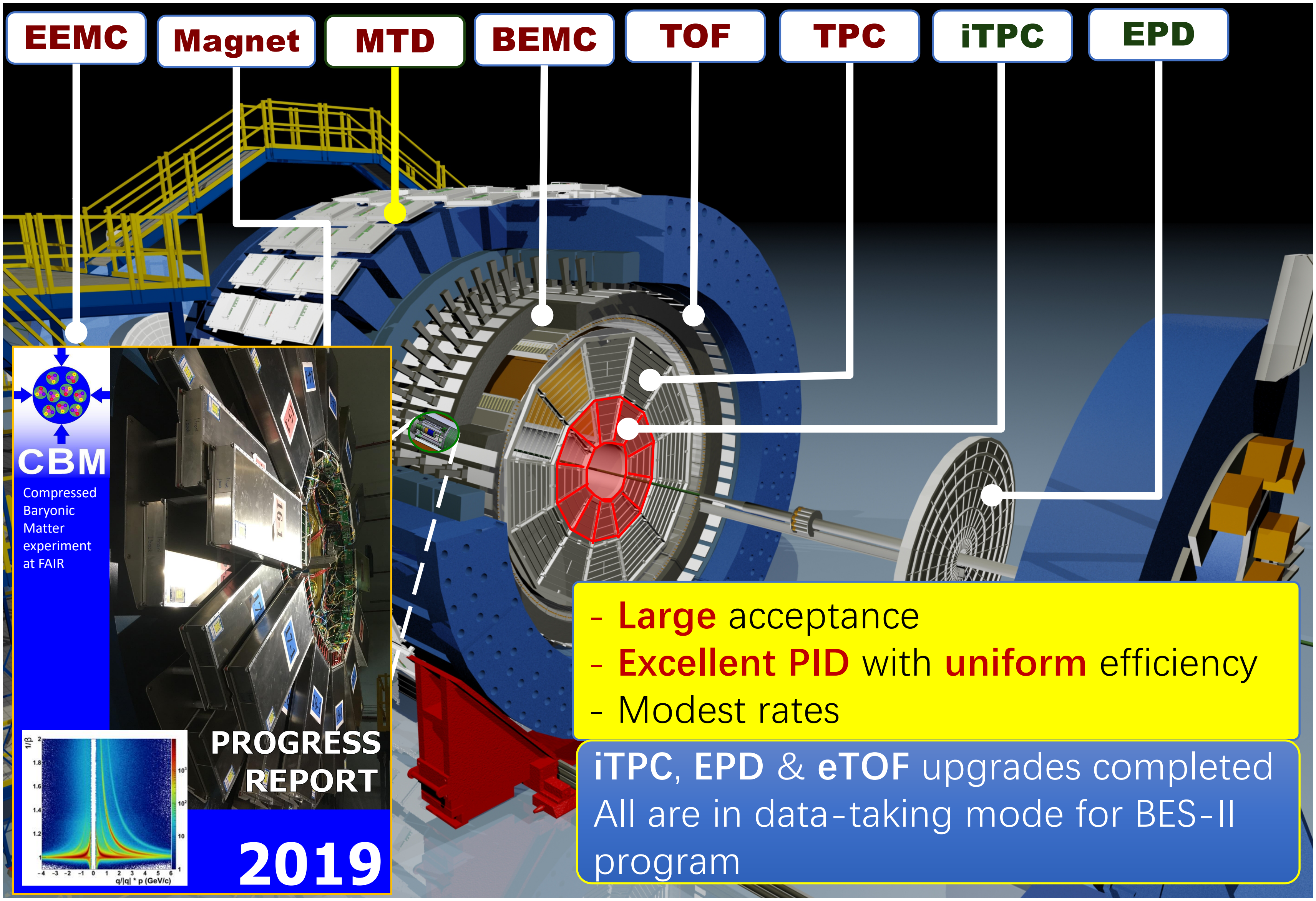
- Models predicted monotonical energy dependence. Statistically do not agree with data, especially at finite baryon density region
- Statistical analysis → non-monotonical energy dependence, see B. Mohanty talk

[2] P. Braun-Munzinger et al., arXiv: 2007.02463; [3] S. He et al., Phys. Lett. **B762**, 296(2016)
[4] J.H. Fu, Phys. Lett. **B722**, 144(2013); A. Bhattacharyya et al., Phys. Rev. **C90**, 034909(2014) and private communications

Emergent properties of the QCD matter

BES-II & Beyond





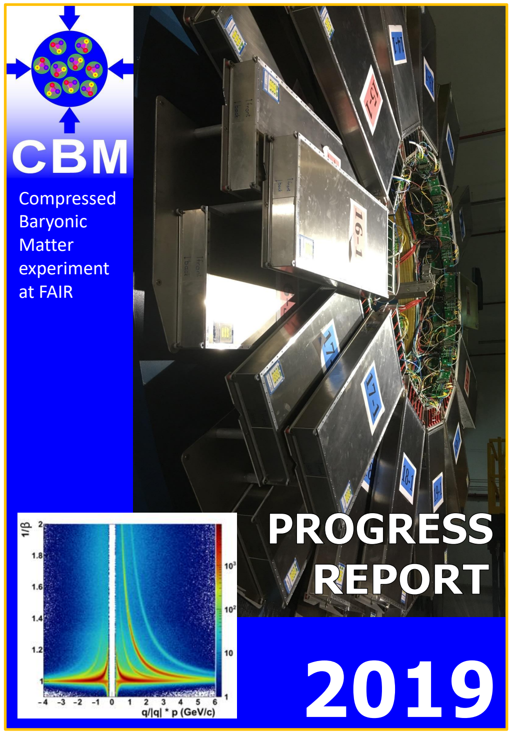
STAR Detector System

BES–II at RHIC: 2019 - 2021

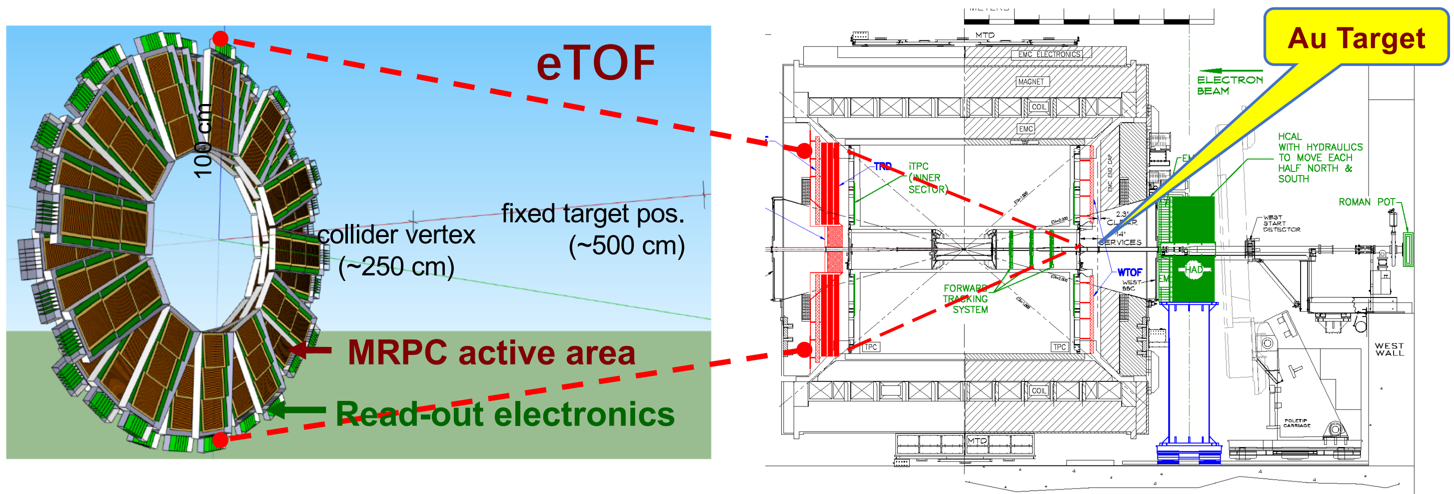
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks
200	350	2010	
62.4	67	2010	
54.4	1200	2017	
39	39	2010	
27	70 / 1500	2011 / 2018	
19.6	**400** / 36	**2019** / 2011	**3**
14.5	**300** / 20	**2019** / 2014	**2.5**
11.5	**230** / 12	**2020** / 2010	**5**
9.2	**160** / 0.3	**2020** / 2008	**9.5**
7.7	**100** / 4	**2021** / 2010	**14**
7.2	150	2016 - 2019	**< 1**
…			
3.0	250		**3**

BES-II Program:

- Precisely map the QCD phase diagram
  200 < μ_B < 420MeV
- The FXT program extends the baryon density to
  μ_B < 750MeV (3GeV)
- Important energy range for hyper-nuclei studies, connecting to the inner dynamics of compact stars



CBM Phase-0 Exp: eTOF at STAR

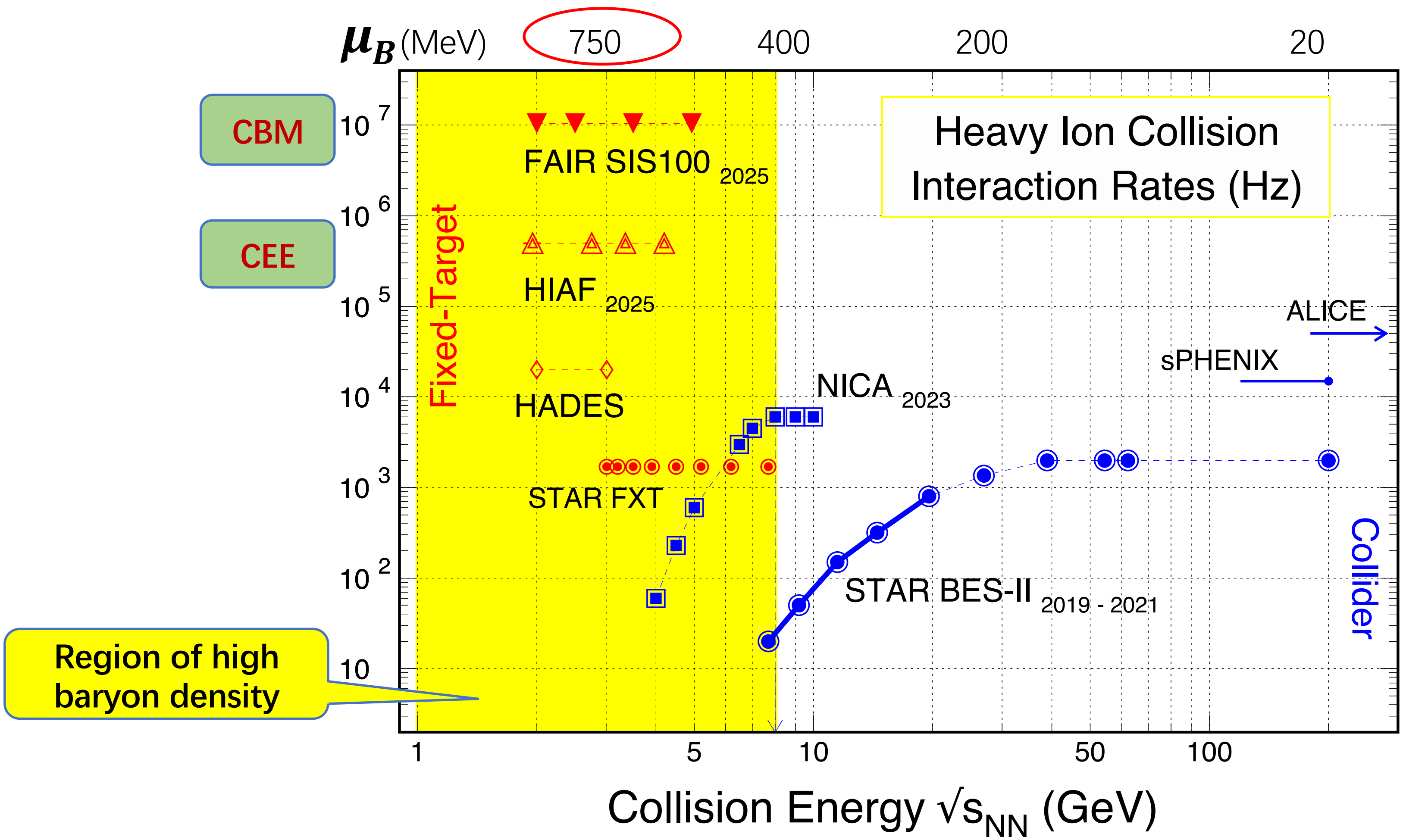


Install, commission and use 10% of the CBM TOF modules, including the read-out chains at STAR, started to work in 2019

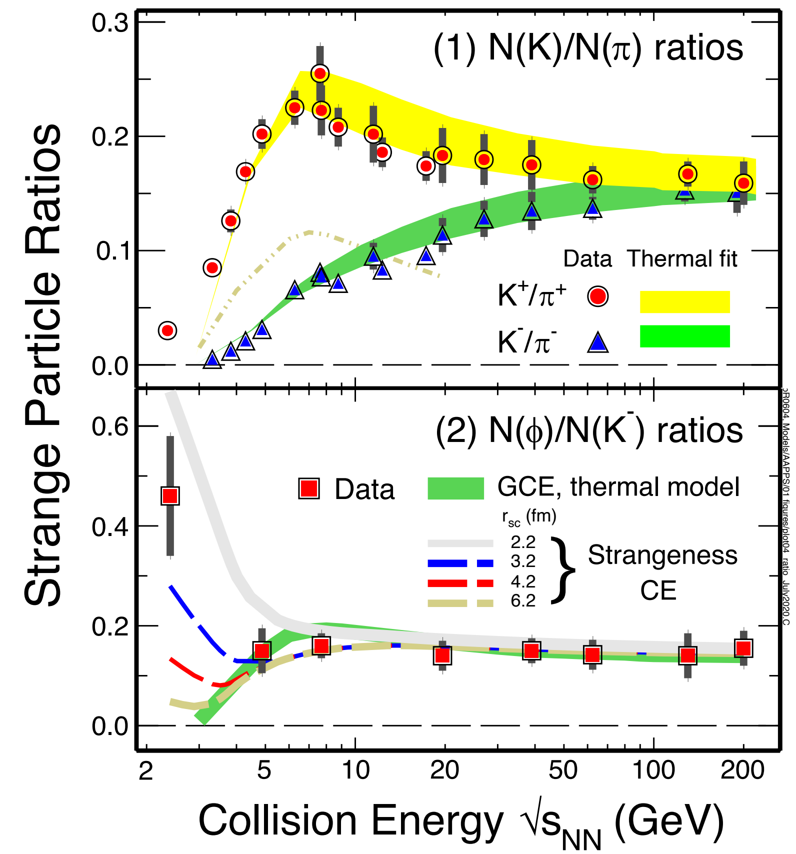
CBM participating in RHIC Beam Energy BES-II in 2019-2021:

- Complementary to part of CBM physics program: **Phase-0 CBM**
  $\sqrt{s_{NN}}$ = 3 - 7.2 GeV (**750 ≥ μ_B ≥ 420 MeV**)
  especially for the study of strangeness-hadrons, hyper-nuclei production and baryon-correlations

Future Facilities for Heavy Ion Collisions

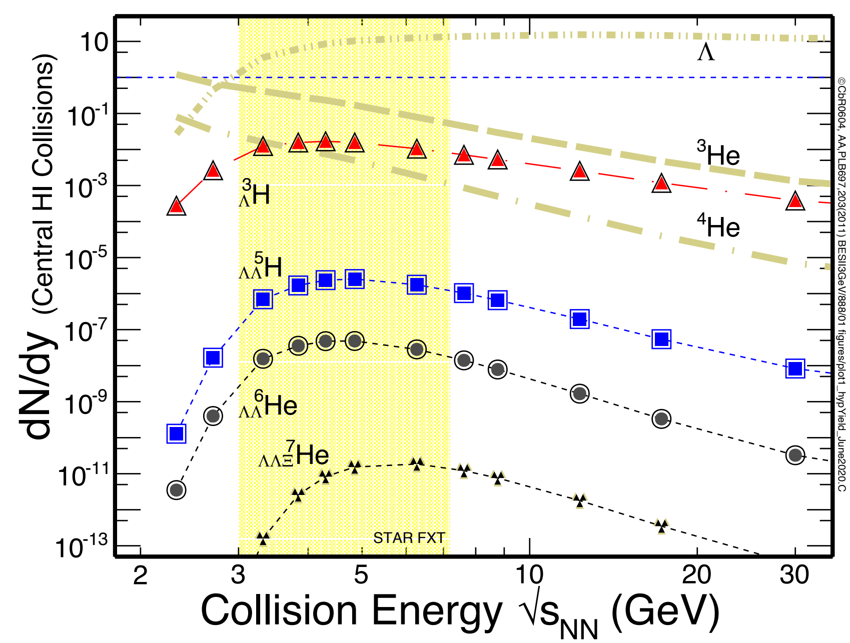


At High Baryon Density



At high baryon density region, canonical effect becomes important. **ϕ/K^- ratio** is a sensitive observable.

[1] K. Redlich, private communication, 2004



Hyper-Nuclei factory: 3-7 GeV region. Interactions of N-Λ, Λ−Λ and inner dynamics of dense stars could be studied.

[2] A. Andronic et al., Phys. Lett. **B697**, 203(2011)

Summary & Remarks

1) STAR BES-I has completed successfully. BES-II is well underway. The focus is in the region of 7.7 – 19.6 GeV in collider mode and the FXT mode will extend the energy down to 3 GeV ($\mu_B \geq 700\text{MeV}$);

2) High order cumulant is a powerful tool: require clean and efficient detecting system, thin targets* (FXT), and high event statistics. It should be applied to collisions at both high and low collision energy regions;

3) At high baryon density, canonical effect becomes important.

Acknowledgements

P. Braun-Munzinger, X. Dong, S. Esumi, S. Gupta, HZ. Huang, XG. Huang, F. Karsch, V. Koch, JF. Liao, F. Liu, XF. Luo, D. Mallick*, D. Kumar Mishra*, B. Mohanty, S. Mukherjee, T. Nonaka, A. Pandav*, K. Redlich, HG. Ritter, M. Shao, SS. Shi, M. Stephanov, J. Stroth, XM. Sun, ZY. Sun, Y. Wang, ZG. Xiao, N. Yu, L. Zhao, Y. Zhang*, PF. Zhuang

Thanks for your attention!