Precision Measurements of (Net)-Proton Number Fluctuations in Au+Au Collisions at RHIC

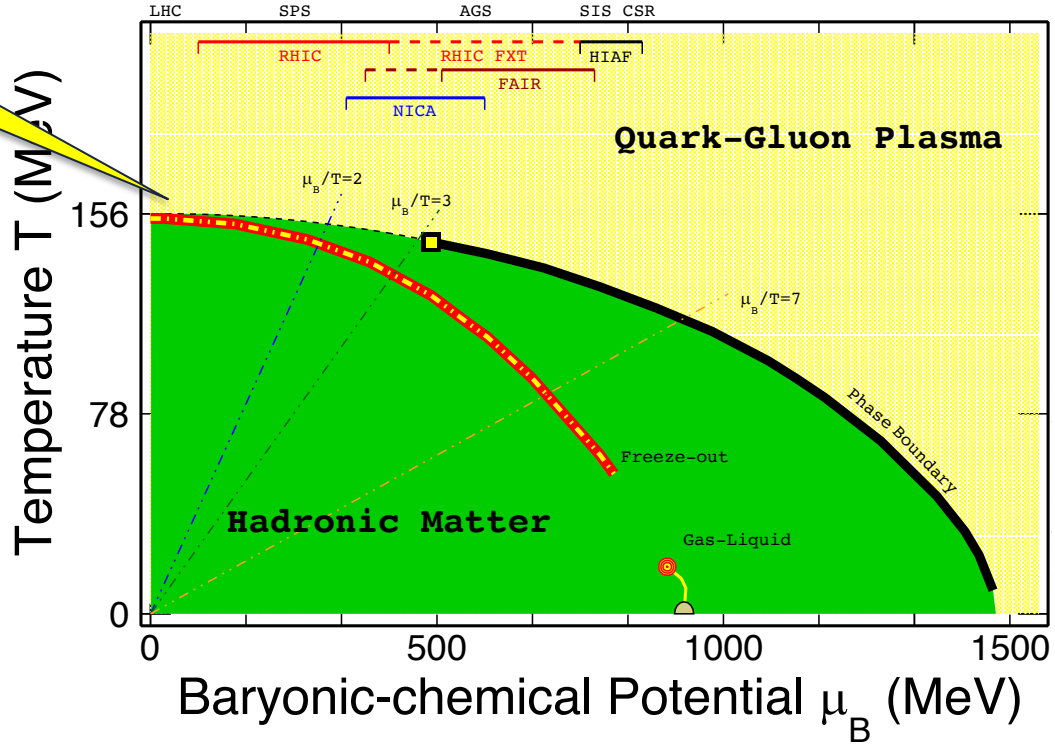
Nu Xu (LBNL)

Outline

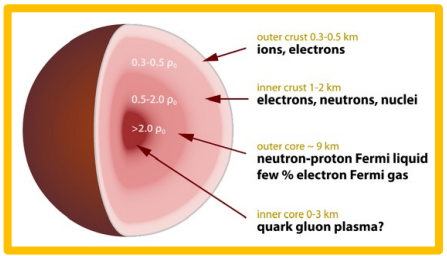
1) **Introduction**
2) Selected Recent Results
   - ➢ Collectivity
   - ➢ Baryon Correlations and Hyper-Nuclei Productions
   - ➢ Criticality from BES-II (collider)
3) Summary and Outlook

Nuclear Collisions and QCD Phase Diagram

Early Universe

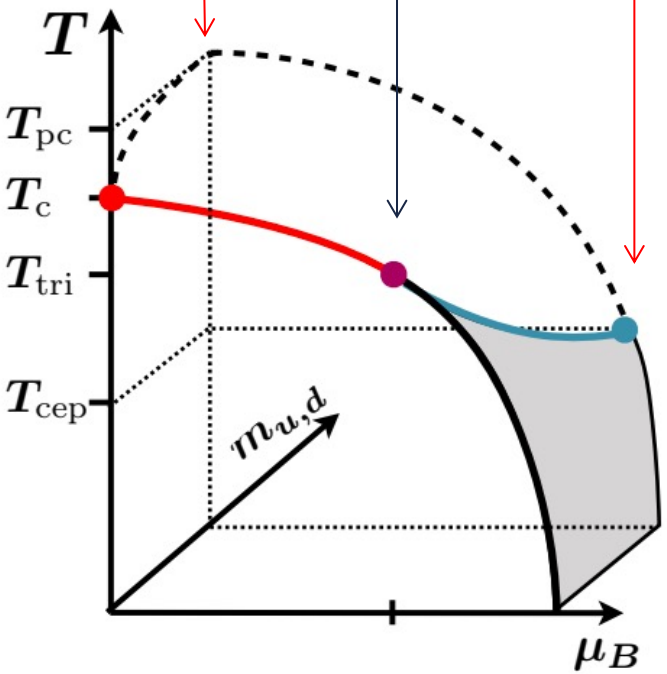


High baryon density: Inner structure of compact stars



1) RHIC BES: → search for 1st-order phase transition and **QCD critical point**;
2) Baryon interactions (*e.g.* $N-N$, $\Upsilon-N$) → inner structure of compact stars

LGT: QCD Phase Structure



F. Karsch *et al.*, 2020

1) QCD transition temperature:

$$T_{PC} = 156.5 \pm 1.5\ \text{MeV}$$

2) Chiral crossover line

$$T_{PC}(\mu_B) = T_{PC}^0 \left[1 - \kappa_2 \left(\frac{\mu_B}{T_{PC}^0}\right)^2 - \kappa_4 \left(\frac{\mu_B}{T_{PC}^0}\right)^4\right]$$

$$\kappa_2 = 0.012(4),\ \kappa_4 = 0.00(4)$$

3) Chiral transition temperature:

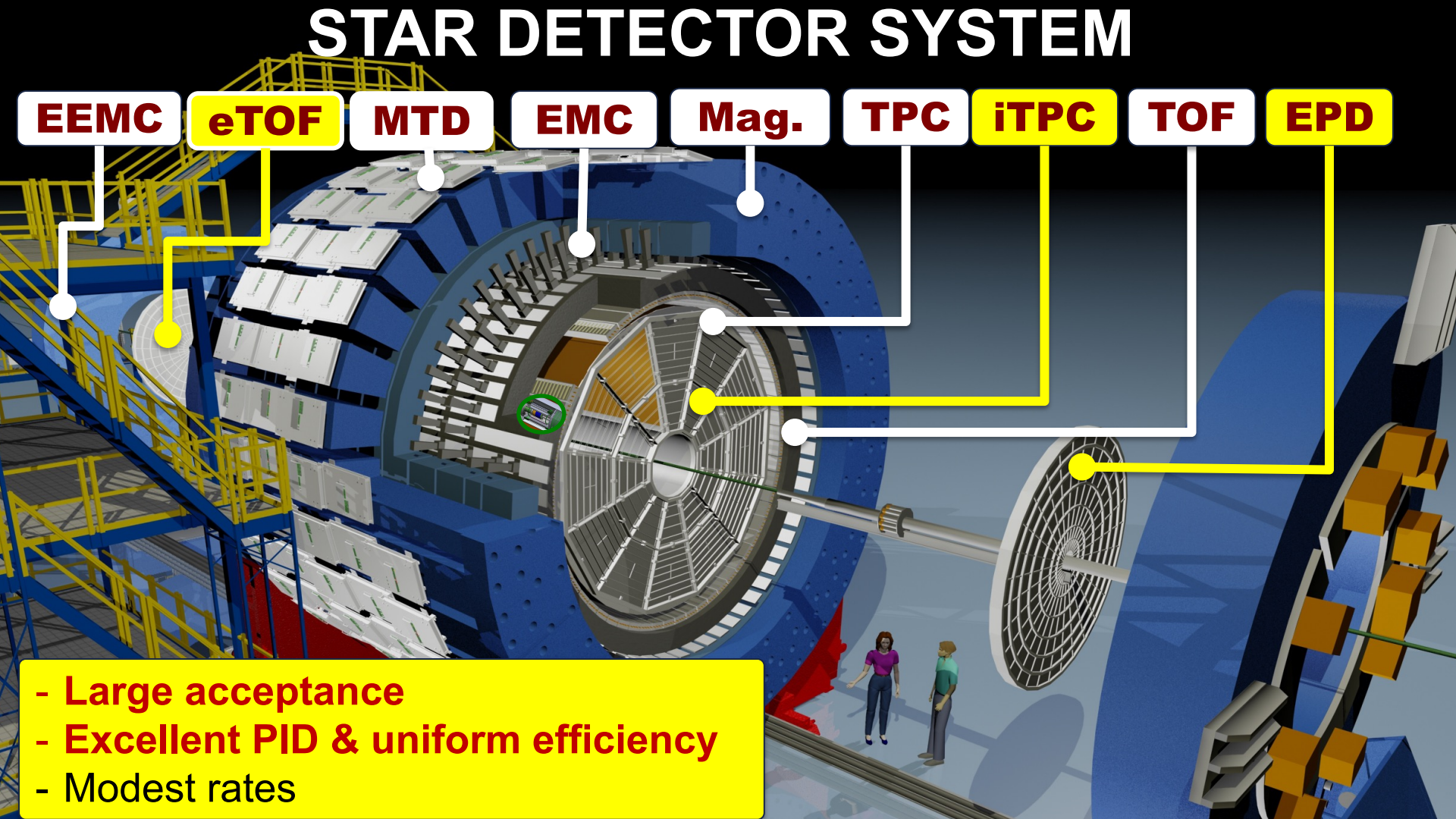
$$T_C = 132^{+3}_{-6}\ \text{MeV}$$

4) QCD critical end point:

$$T^{CEP} < T_C, \qquad \mu_B^{CEP} \gtrsim 3T_C$$

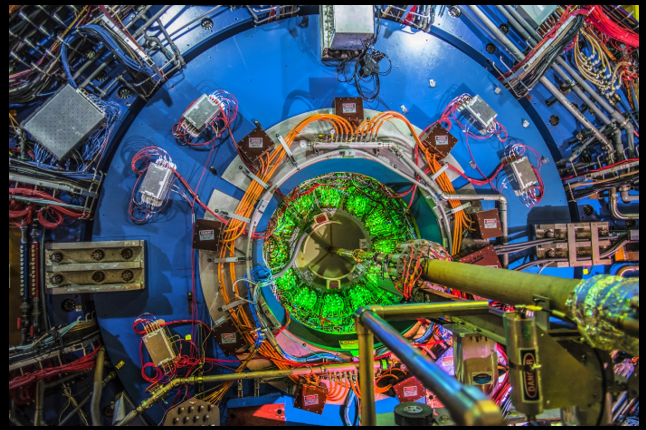
HotQCD: Phys.Lett.**B795**, 15(2019);
Phys. Rev. Lett. **123**, 062002(2019)

STAR DETECTOR SYSTEM



- **Large acceptance**
- **Excellent PID & uniform efficiency**
- Modest rates

Major Upgrades for BES-II



iTPC:
- Improves dE/dx
- Extends η coverage from 1.0 to 1.6
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019

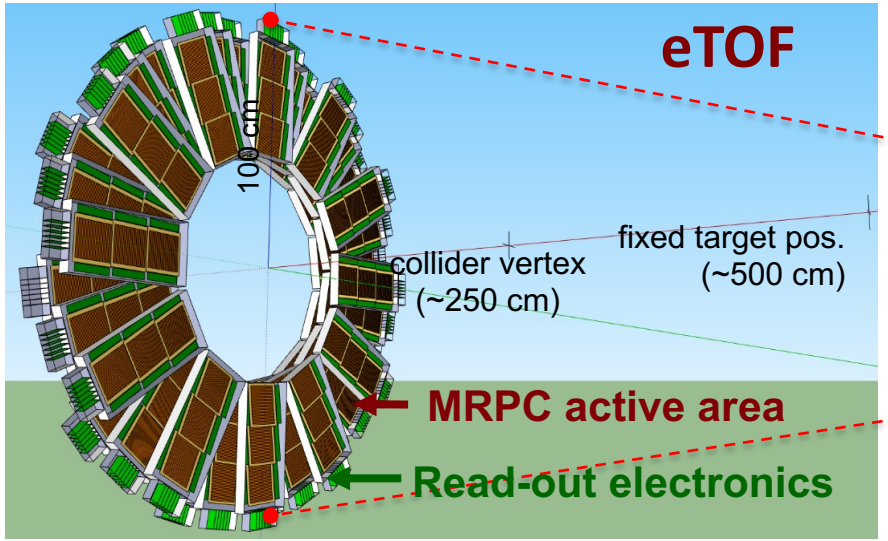
eTOF:
- Forward rapidity coverage
- PID at η = 0.9 to 1.6
- **Borrowed from CBM-FAIR**
- Ready in 2019

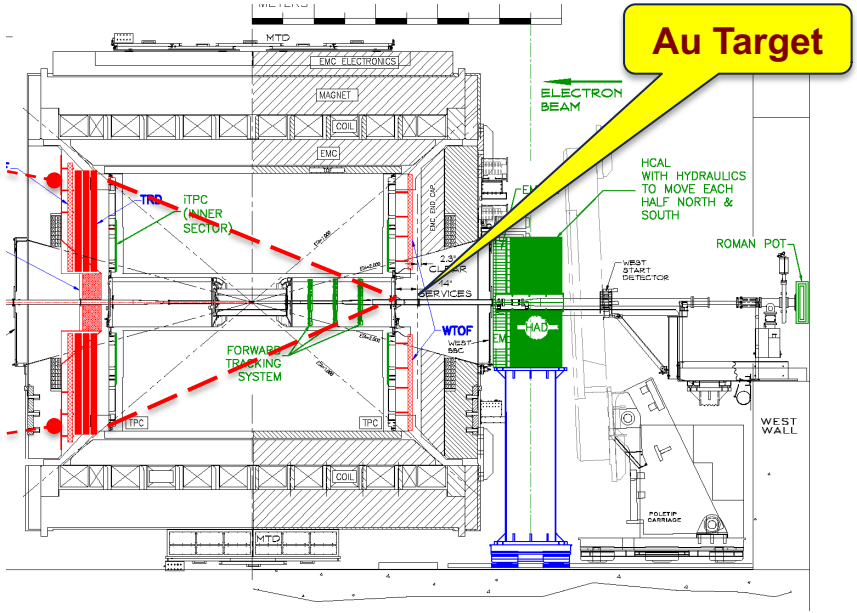
EPD:
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

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

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. NIM **A968,** 163970 (2020)

STAR Fixed Target Setup





CBM participates in RHIC BES-II in 2019 – 2021:

- Complementary to CBM program: $\sqrt{s_{NN}}$ = 3 - 7.2 GeV (**750 ≥ μ_B ≥ 420 MeV**)
- Strange-hadron, hyper-nuclei and fluctuation at the high baryon density region

STAR BES-I and BES-II Data Sets

Au+Au Collisions at RHIC

Collider Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19
2	62.4	46 M	75 MeV		Run-10
3	54.4	1200 M	85 MeV		Run-17
4	39	86 M	112 MeV		Run-10
5	27	585 M / **220**	156 MeV	3.36	Run-11, 18
6	19.6	595 M/ **270 M**	206 MeV	3.1	Run-11, 19
7	17.3	256 M / **116 M**	230 MeV		Run-21
8	14.6	340 M/ **145 M**	262 MeV		Run-14, 19
9	11.5	257 M/ **110 M**	316 MeV		Run-10, 20
10	9.2	160 M/ **78 M**	372 MeV		Run-10, 20
11	7.7	104 M / **45 M**	420 MeV		Run-21

Fixed-Target Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	4.5 (9.8)	110 M	590 MeV	1.52	Run-20
9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
12	**3.0** (3.85)	**260** + 2000 M	**760** MeV	-1.05	Run-18, 21

Most precise data to map the QCD phase diagram

$$3 < \sqrt{s_{NN}} < 200 \text{ GeV}; \quad 760 > \mu_B > 25 \text{ MeV}$$

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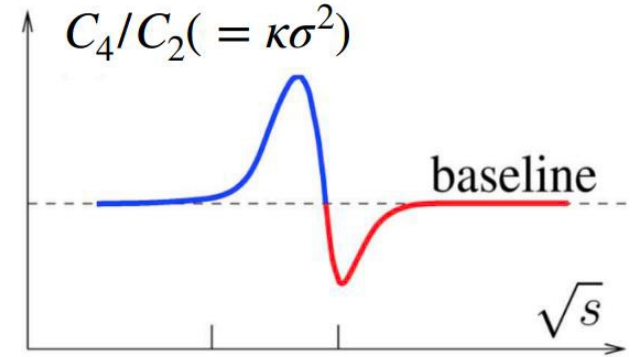
High Moments from BES-II

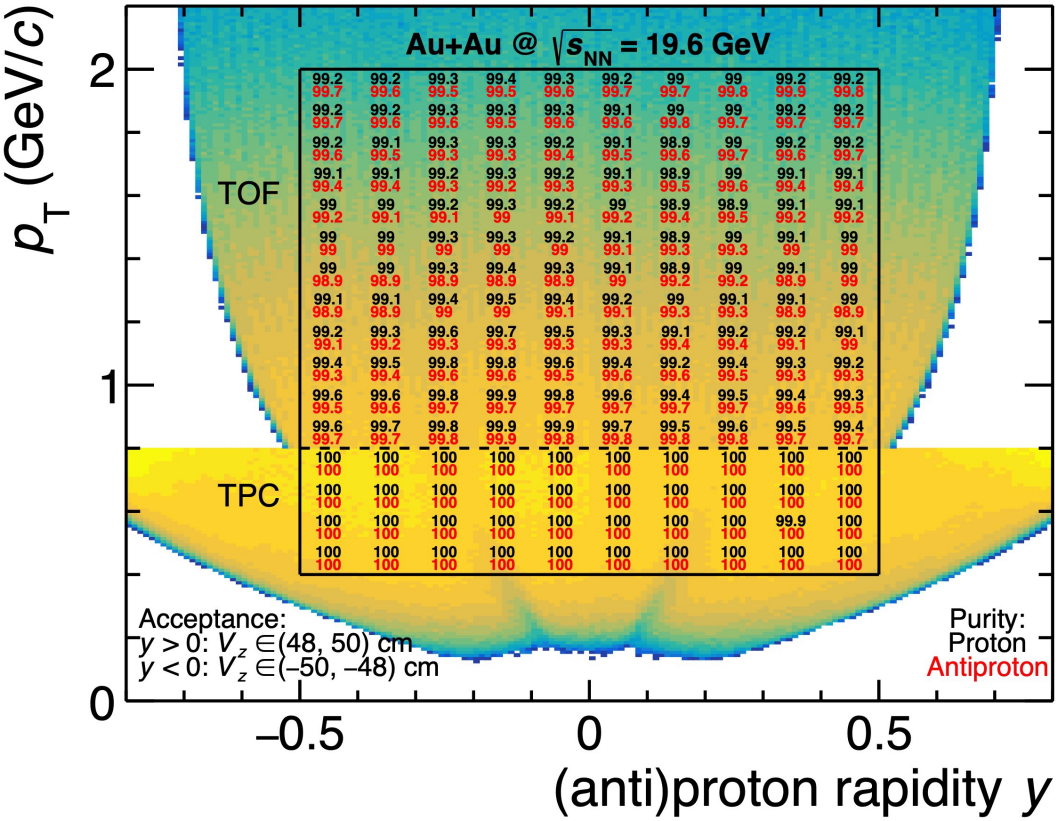
Precision Measurements of (Net-)Proton Number Fluctuations in Au+Au Collisions at RHIC (STAR Collaboration)



M. A. Stephanov, PRL 107 (2011) 052301

Signal for Critical Point:
Non-monotonical energy dependence

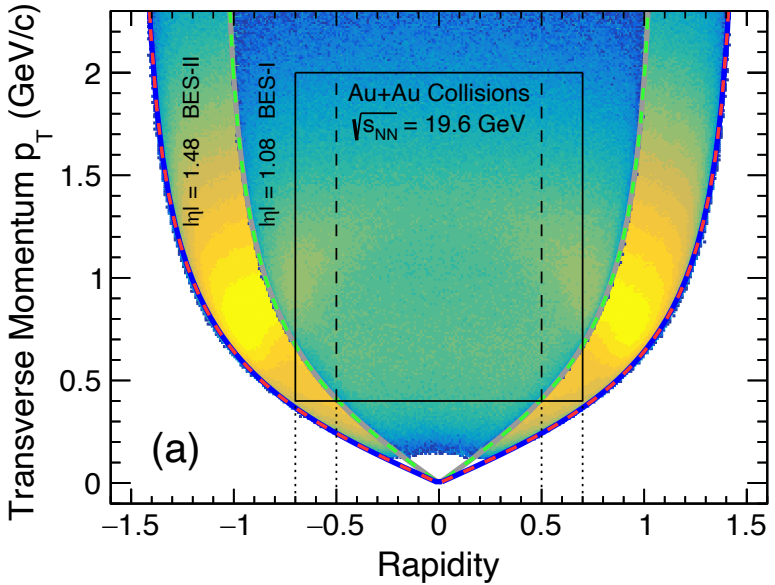
Proton Identification at BES-II

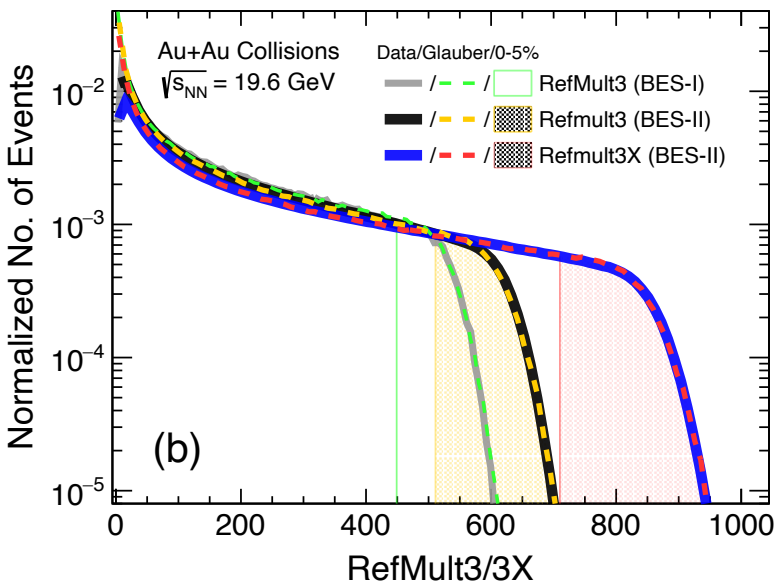


Detector	TPC	TPC+TOF
dE/dx	$\|n\sigma\| < 2$	
m^2 $(GeV/c^2)^2$	NA	0.6 – 1.2
p_T (GeV/c)	0.4 – 0.8	0.8 – 1.2
rapidity	$\|y\| < 0.5$	

1) Uniform acceptance for (anti-) protons |y|<0.5 with |Vz| < 50cm;
2) (anti-)protons identified using TPC dE/dx and TOF
3) Bin-by-bin purity > 99% in the full acceptance range and for all energies

BES-II: Centrality Determination



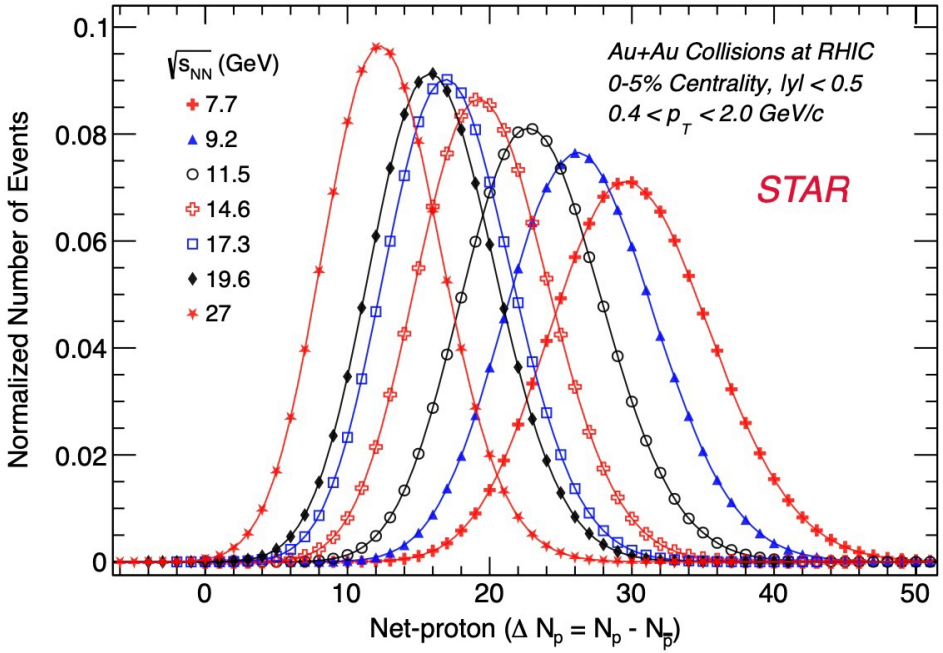


Reference multiplicity measurements **RefMult3**: *TPC measured charge particles except (anti-)protons*

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

Net-p from BES-II



1) Raw number distributions from BES-II: Uncorrected for detector efficiency;
2) Mean increases with decreasing collision energy: Effect of baryon stopping;
3) The increase in the width is due to the increase of proton numbers at lower energy

0-5%: C_4/C_2 improvement factor BES-II / BES-I			
7.7 GeV		19.6 GeV	
Stat.	Syst.	Stat.	Syst.
4.7	3.2	4.5	4
*Embedding statistics increased by a factor of 5!			

STAR: CPOD2024, SQM2024

Conserved Quantities (B, Q, S)

1) In strong interactions, baryons (B), charges (Q) and strangeness (S) are conserved;
2) Higher order moments/cumulants describe the shape of distributions and quantify fluctuations. They are sensitive to the correlation length ξ, phase structure;
3) Direct connection to theoretical calculations of susceptibilities.

Measured multiplicity N, $\langle \delta N \rangle = \mathbf{N} - \langle N \rangle$

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

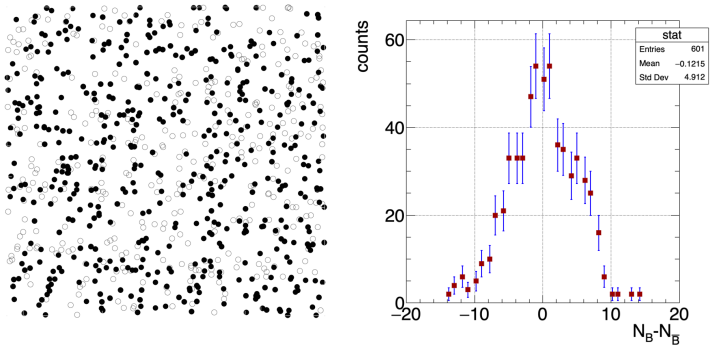
Moments, cumulants and susceptibilities:

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: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$

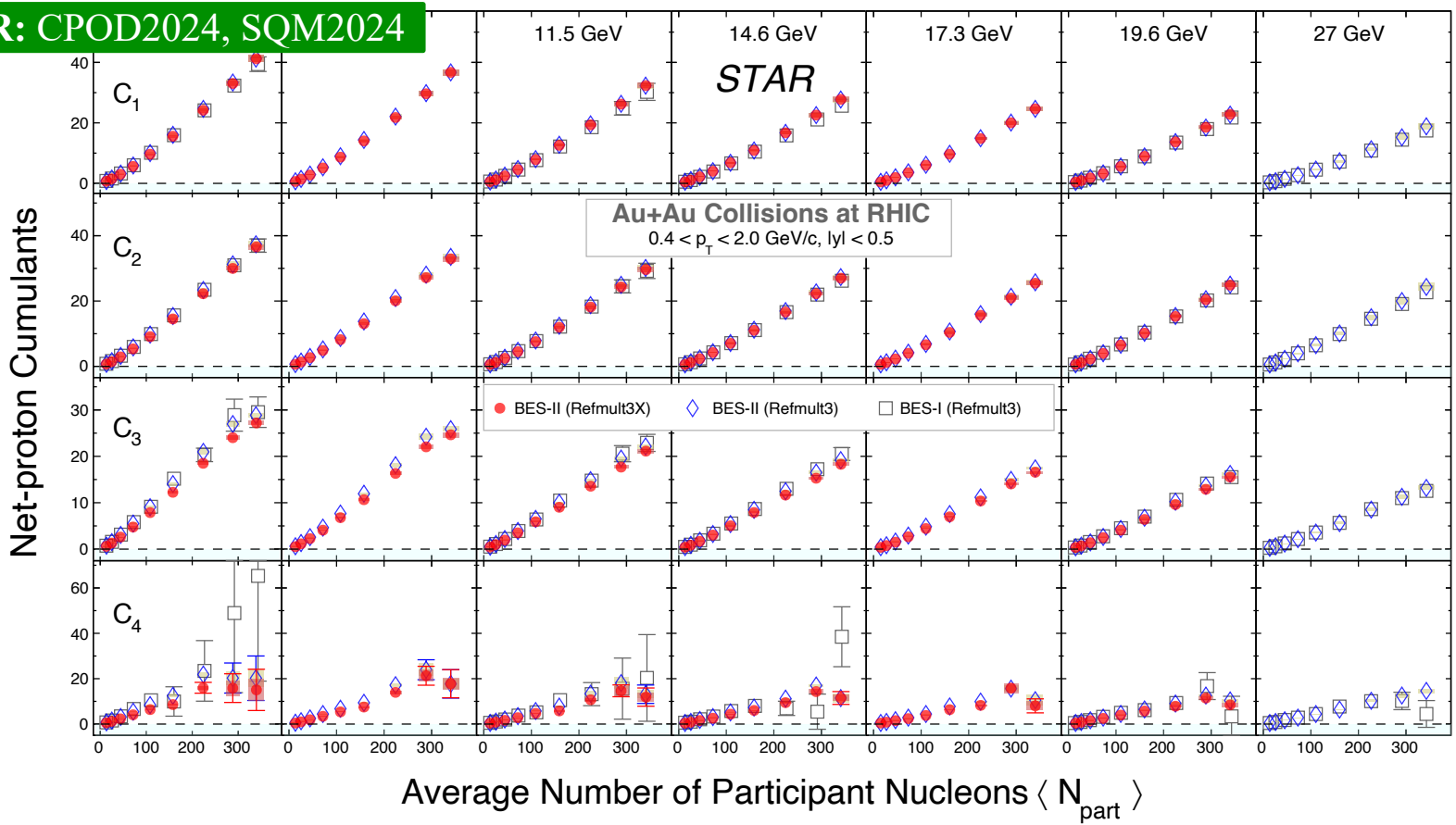
Animation: A.Rustamov



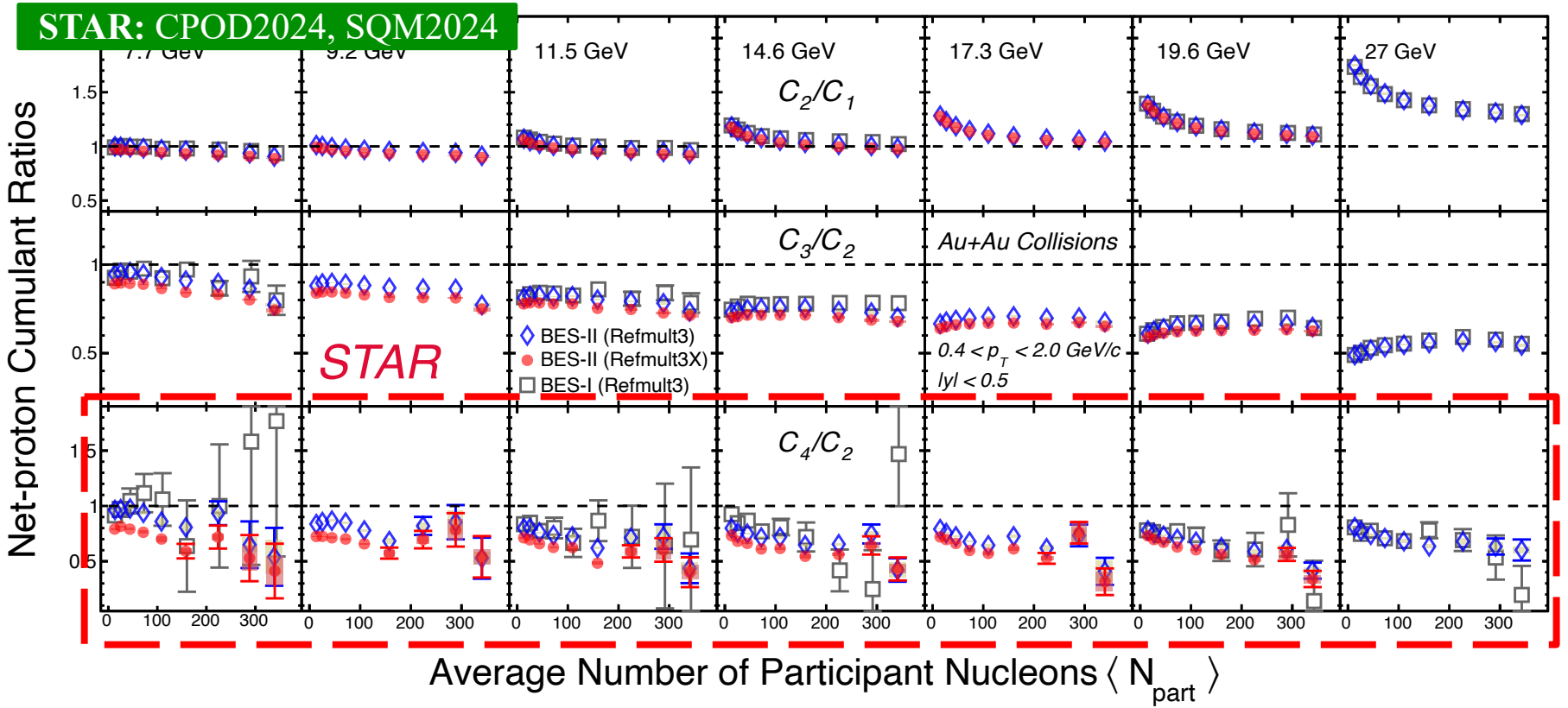
INT 2008-2b : The QCD Critical Point

Cumulants of Net-p from BES-II

STAR: CPOD2024, SQM2024

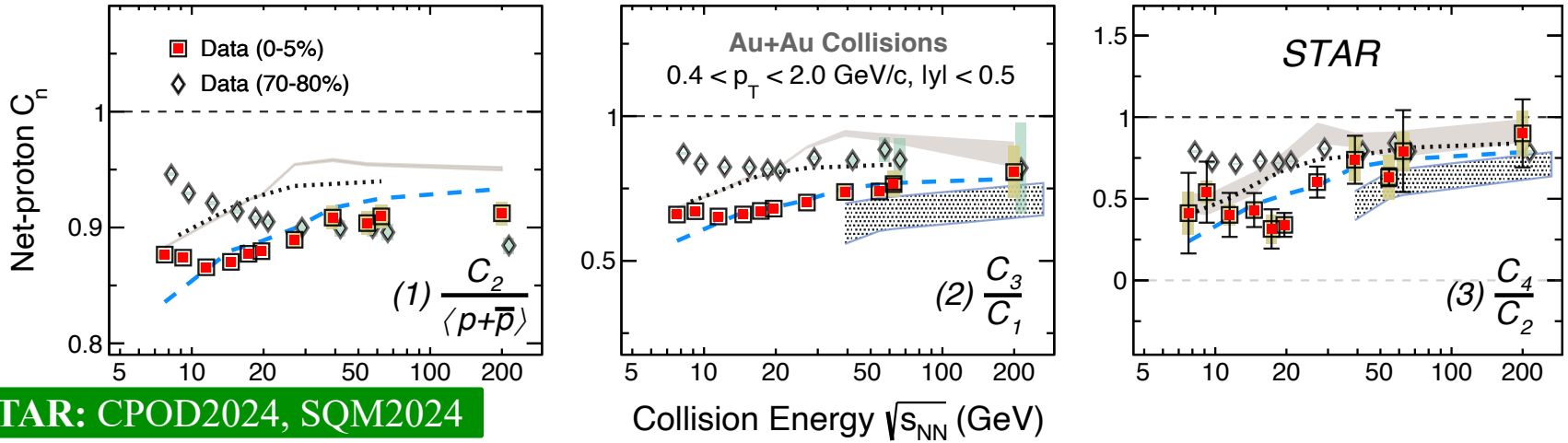


Net-p Cumulant Ratios



In 0-5% central collisions, values of C_4/C_2 are consistent among BES-I and BES-II

Energy Dependence of Cumulant Ratios

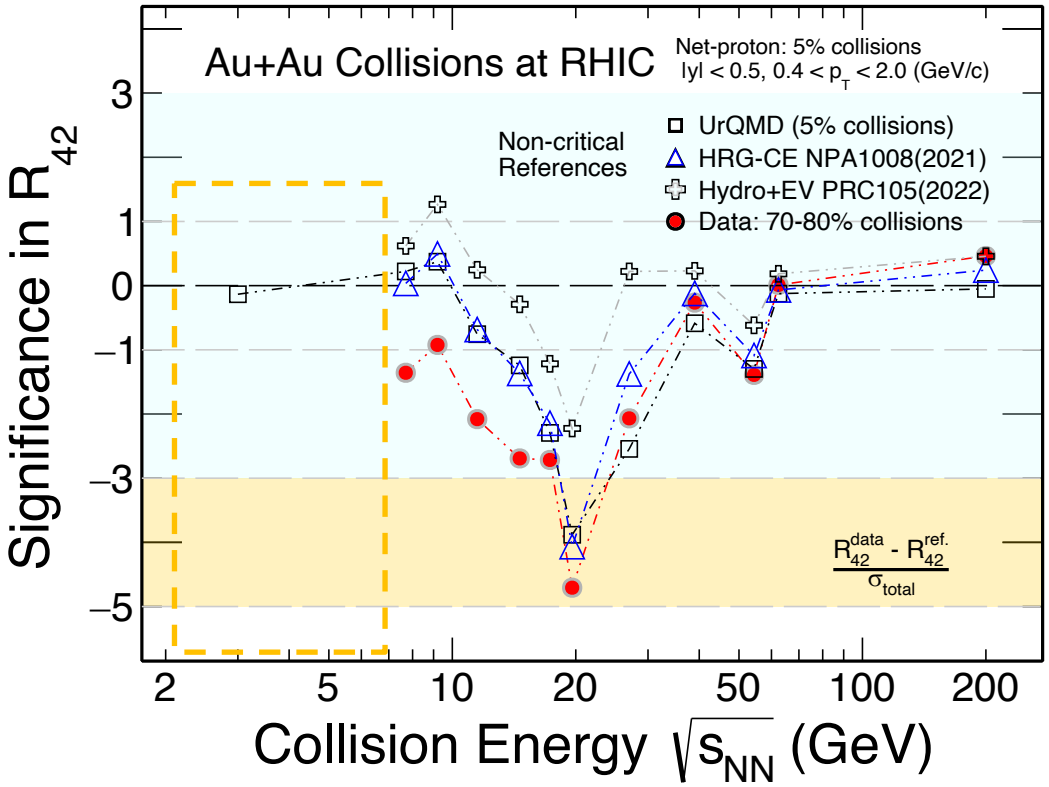


STAR: CPOD2024, SQM2024

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 collectivity. V. Vovchenko *et al.*, Phys. Rev. **C105**, 014904 (2022).
4) LQCD GCE: done for net-baryon A. Bazavov *et al.,* Phys. Rev. D101, 074502 (2020).

Baryon conservations applied in all model calculations except LQCD!

Deviations from Non-CP Models



0-5% central collisions:

1) C_4/C_2 ratios: show minima at 19.6 GeV, **2-5σ effects**, depends on reference;

2) Future data from
(i) STAR FXT;
(ii) HADES at GSI and
(iii) CBM experiment at FAIR (2028) will cover the energy region $\sqrt{s_{NN}}$ = 2.4 – 4.9 GeV

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Summary

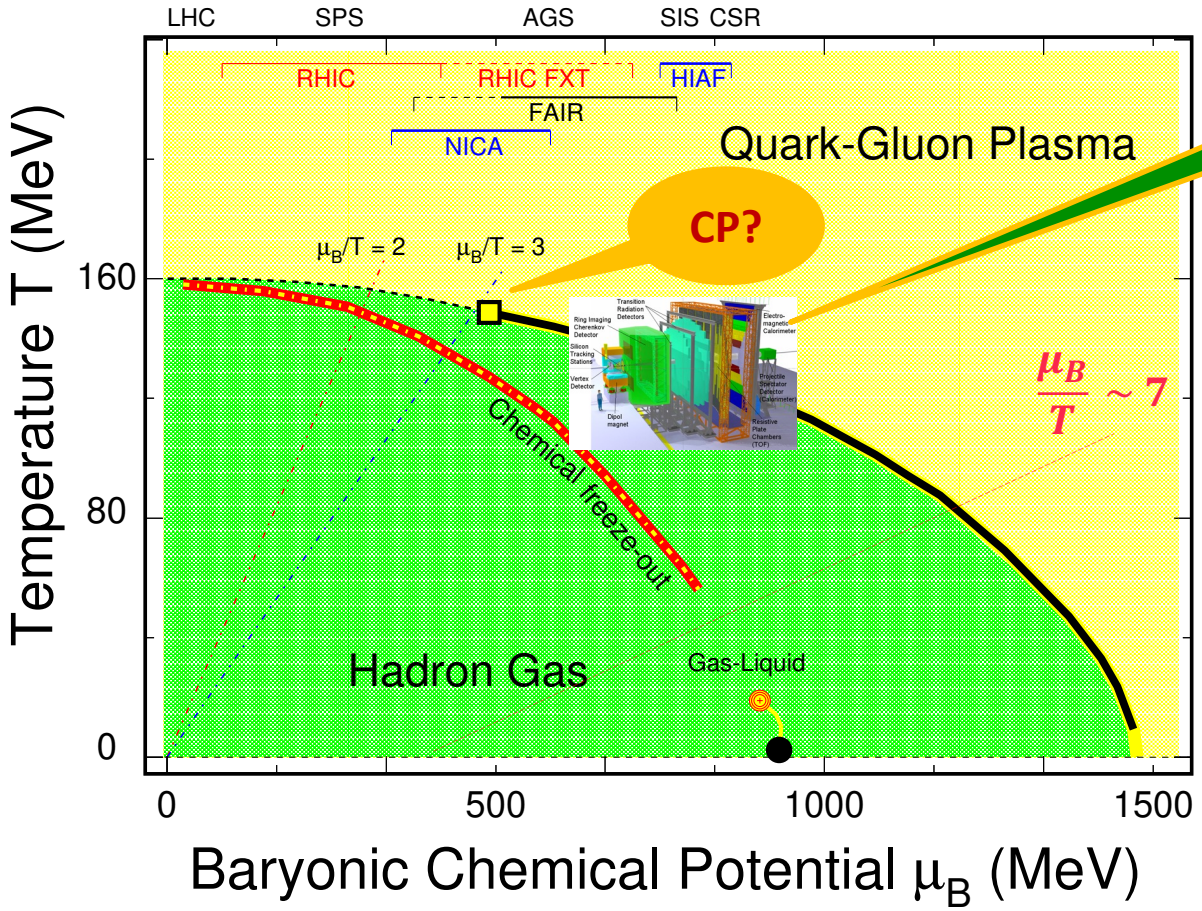
Search for QCD critical point:

- BES-II data offered high statistics, better acceptance, centrality resolution and systematic;
- Known model calculations **Do Not** reproduce the energy dependence ($\sqrt{s_{NN}}$ = 7.7 – 200 GeV)

Outlook:

(i) Transverse momentum p_T and rapidity scan;
(ii) Higher orders: C_5, and C_6 analysis;
(iii) Complete FXT data analysis at $\sqrt{s_{NN}}$ = 3 – 3.9 GeV

Future Physics Programs at High μ_B



CBM 2028

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

Acknowledgements:

RHIC and STAR Experiment

P. Braun-Munzinger, X. Dong, S. Esumi, F. Karsch, V. Koch, XF. Luo, B. Mohanty, ***A. Pandav***, A. Rustamov, K. Redlich, M. Stephanov, J. Stachel, J. Stroth, V. Vovchenko, ***Y. Zhang***

// BLUE: Theory // **RED**: Exp. //

Thank you for your attention!