Study of the QCD Phase Structure in High-Energy Nuclear Collisions

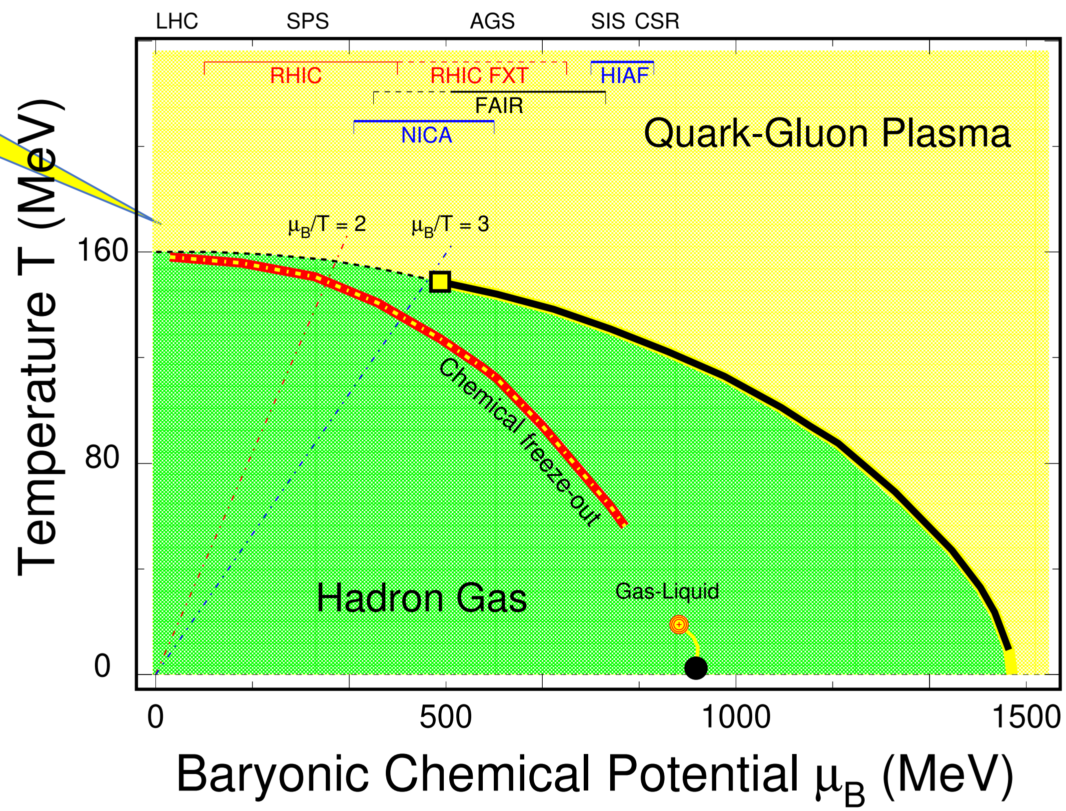
Nu Xu

Outline

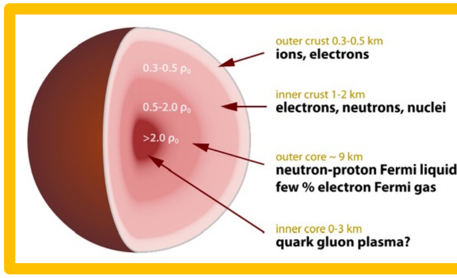
1) **Introduction**
2) Selected Recent Results
   - Collectivity and Baryon Correlation from FXT
   - Criticality from BES-II (collider)
3) Summary

Nuclear Collisions and QCD Phase Diagram

Early Universe

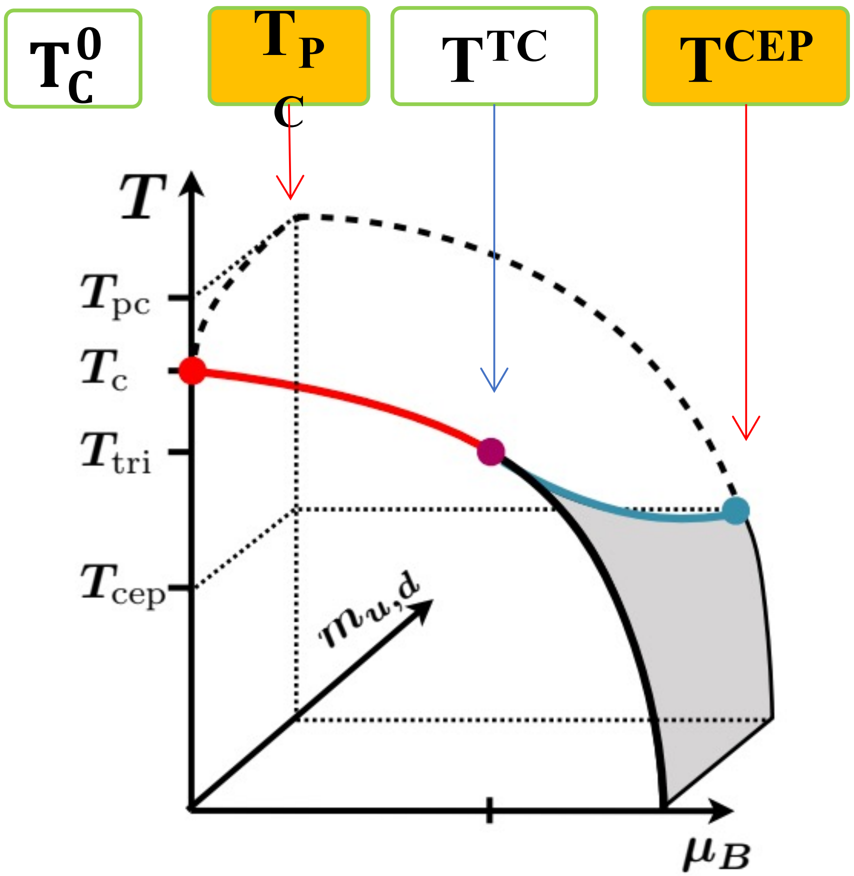


High baryon density: Inner structure of compact stars



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

LGT Calculation: 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)

Thermalization in Heavy-Ion Collisions

S. Gupta, **D. Mallick** *et al.* Phys. Lett. **B829**, (2022) 137021


Physics Letters B 829 (2022) 137021

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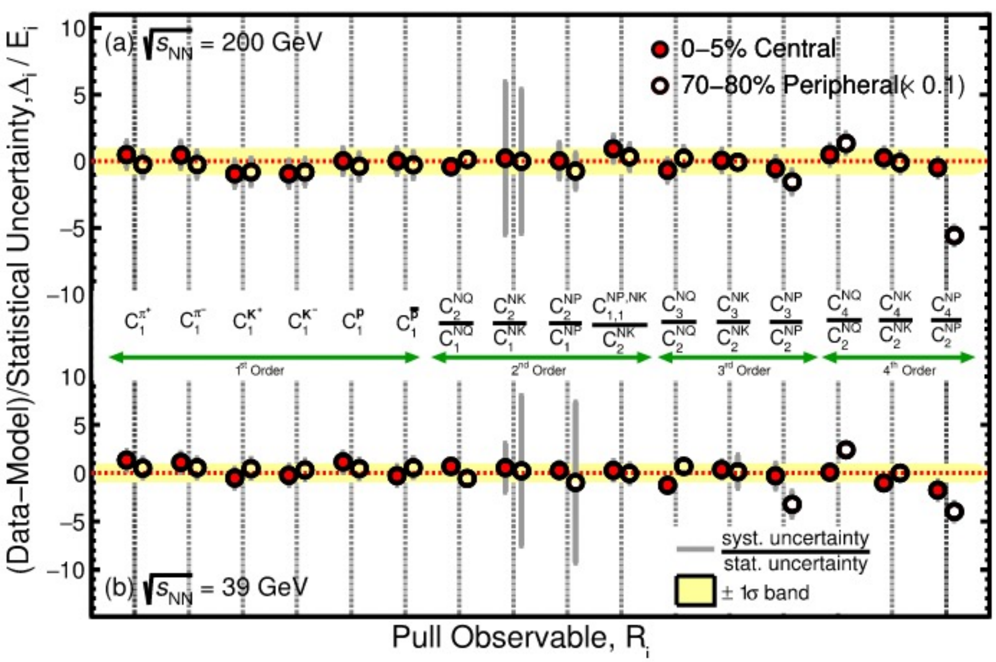
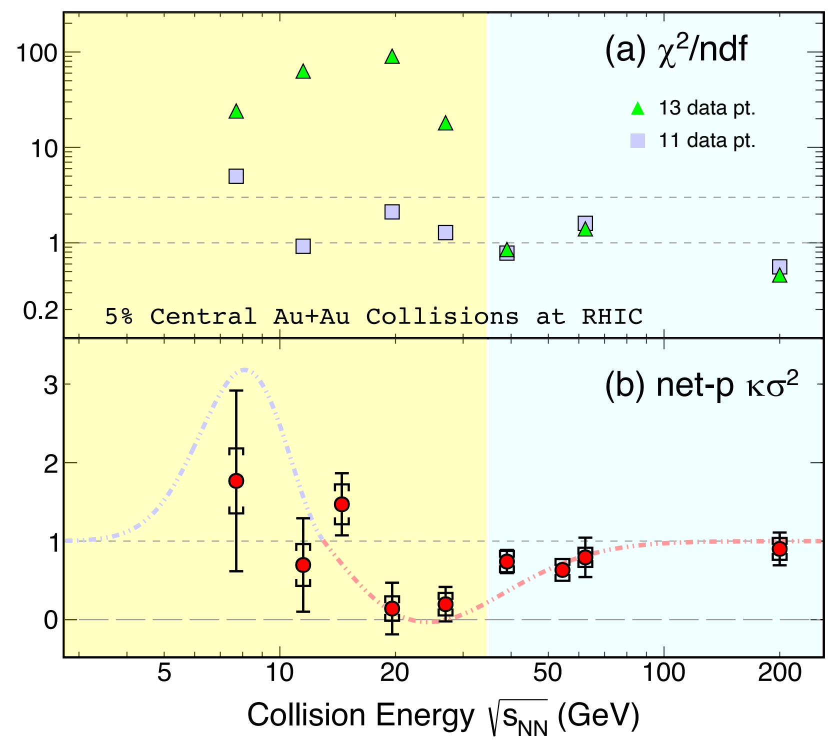
Limits of thermalization in relativistic heavy ion collisions

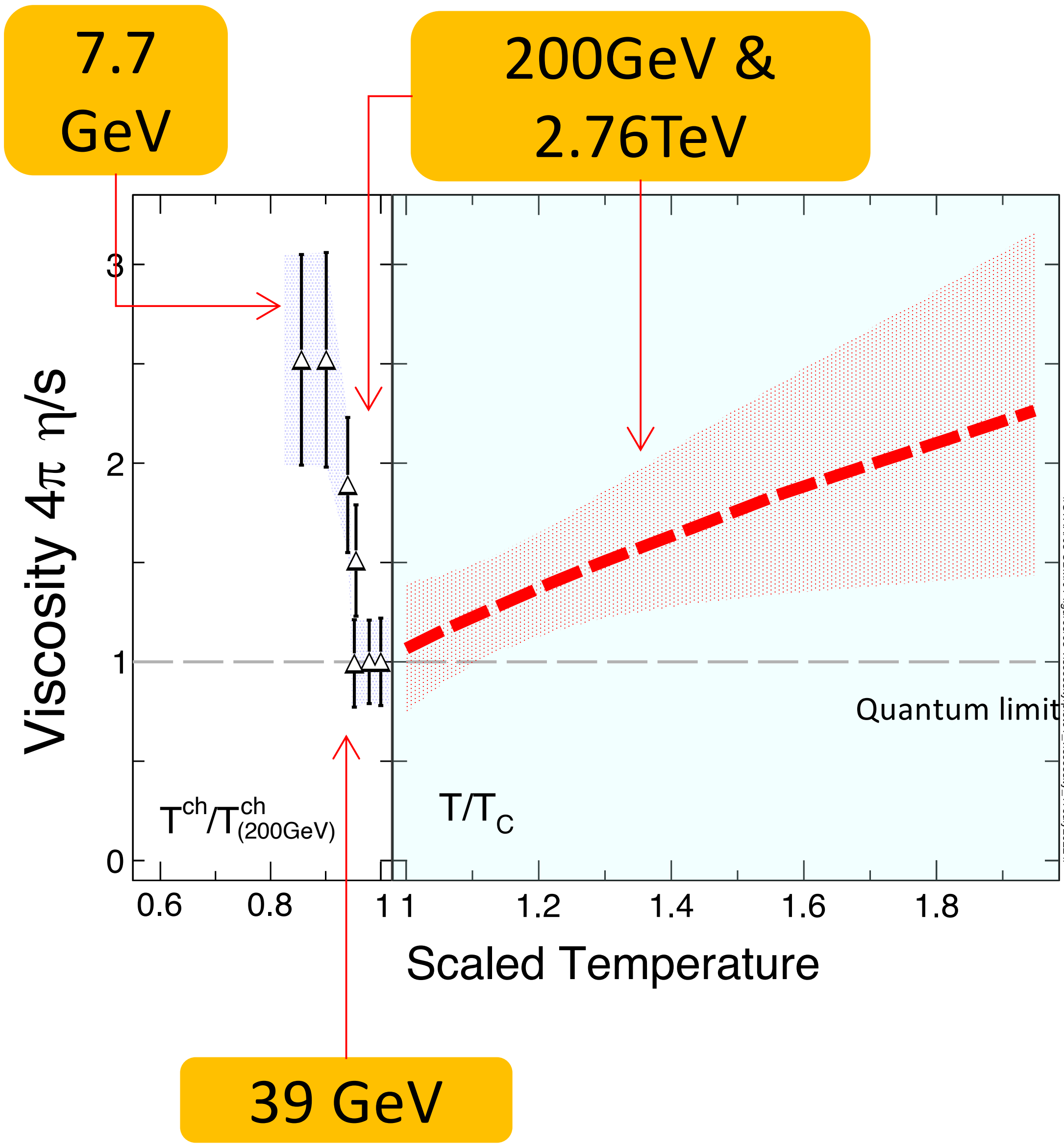
Sourendu Gupta [a], Debasish Mallick [b,c], Dipak Kumar Mishra [d], Bedangadas Mohanty [b,c,*], Nu Xu [e]

1) Test of the thermal model with high moments data: 4TH order;
2) Below 39 GeV, **data is not consistent with equilibrium.**





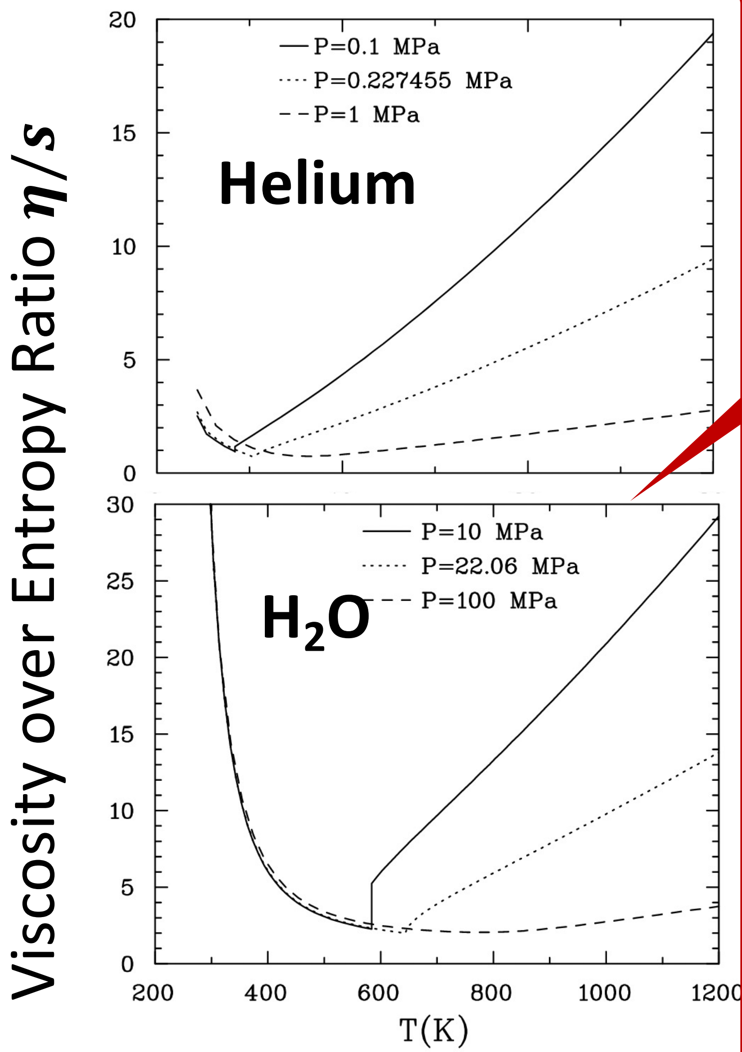
Equation of State for Strong Interaction



1) Left-plot: Energy dependence of η/s extracted from light-flavor hadron v_2 and v_3. Right-plot: extracted from Bayesian fits to R_{AA} and v_2 at 200GeV collisions;
2) Both sides meet at the unity of the scaled temperature;
3) The values of η/s increase quickly below $\sqrt{s_{NN}} = 39$ GeV → QGP dominants in higher energies;
4) **Evidence of the QCD transition!**

1) L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL**97** (2006) 152303
2) X.Dong, Y.J. Lee & R.Rapp, ARNPS, **69** (2019) 417
3) J.E.Bernhard, J.S.Moreland & S. Bass, Nat. Phys. **15** (2015) 1113
4) I. Karpenko, P. Huovinen, H. Petersen, and M. Bleicher, Phys.Rev.**C91**, 064901 (2015).
5) G.Nijs, W.van der Schee, U. Gürsoy and R. Snellings, PRL**126**, (2021) 202301

Strongly-Interacting Low-Viscosity Matter

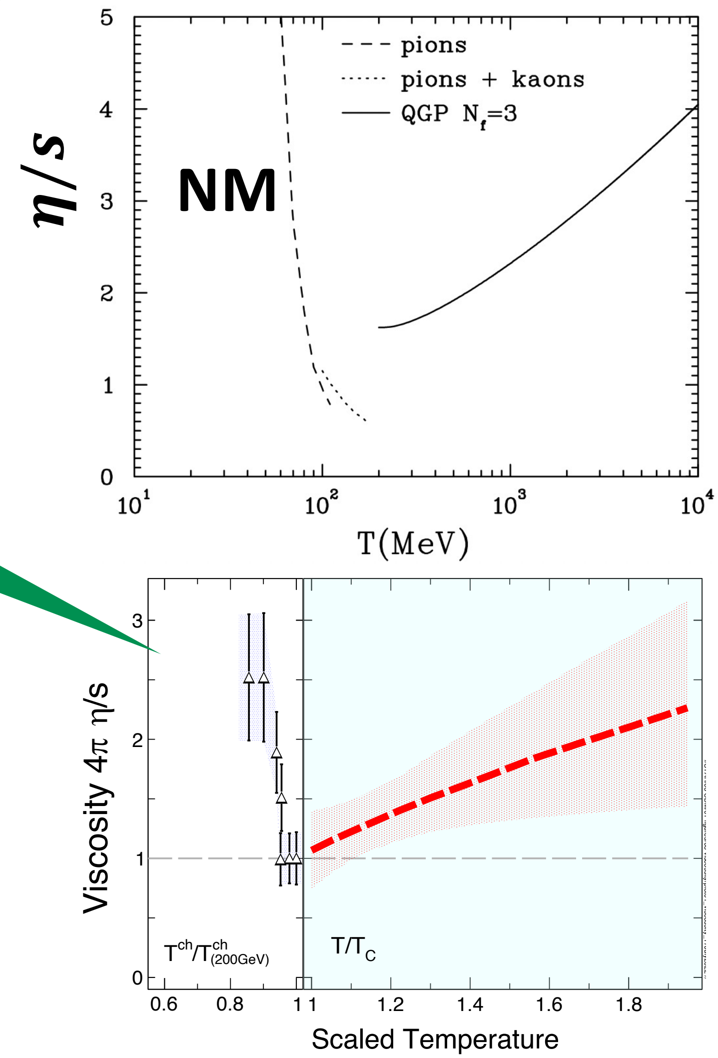


L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL**97** (2006) 152303

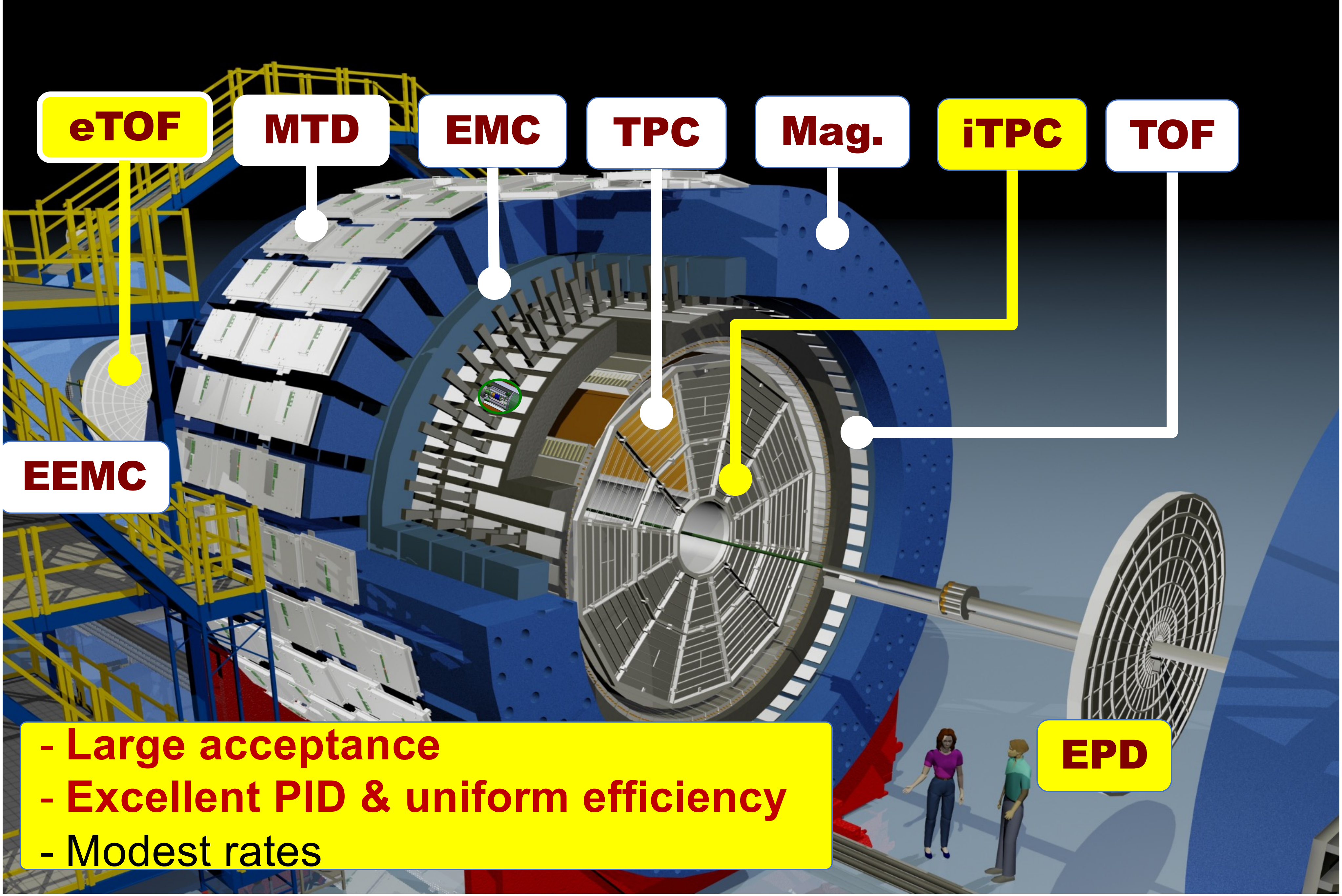
EM interaction
η/s ~ 1

Strong Interaction
η/s ~ 0.1

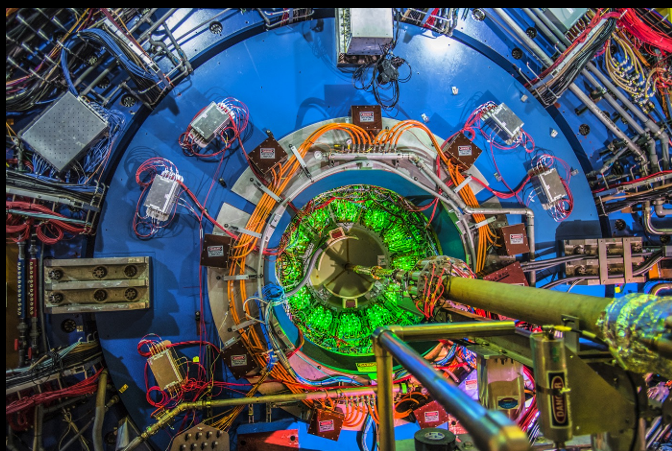
- QGP matter in $\sqrt{s_{NN}} \geq 39$ GeV collisions!
- Universal behavior for the QCD phase transition!

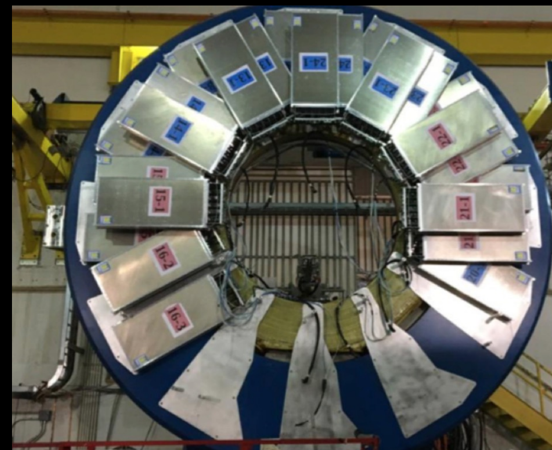


STAR DETECTOR SYSTEM



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

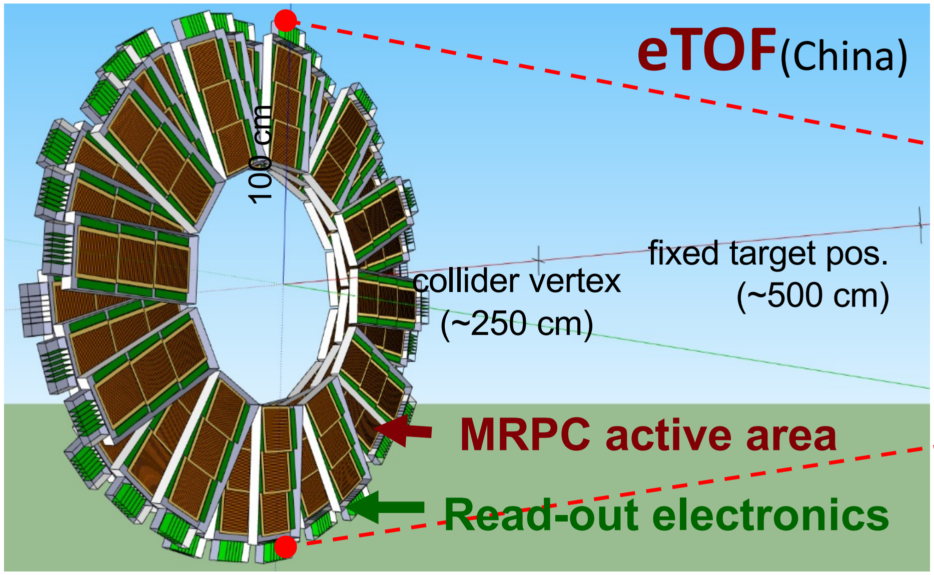
eTOF:
- Forward rapidity coverage
- PID at η = 0.9 to 1.6
- **Borrowed from CBM-FAIR**
- Ready in 2019

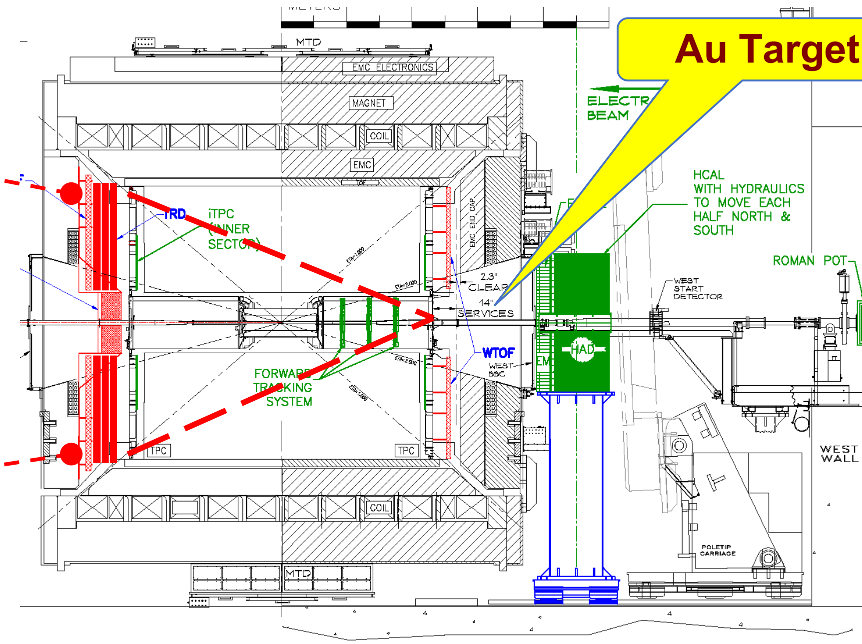
EPD:
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

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 (**760 ≥ 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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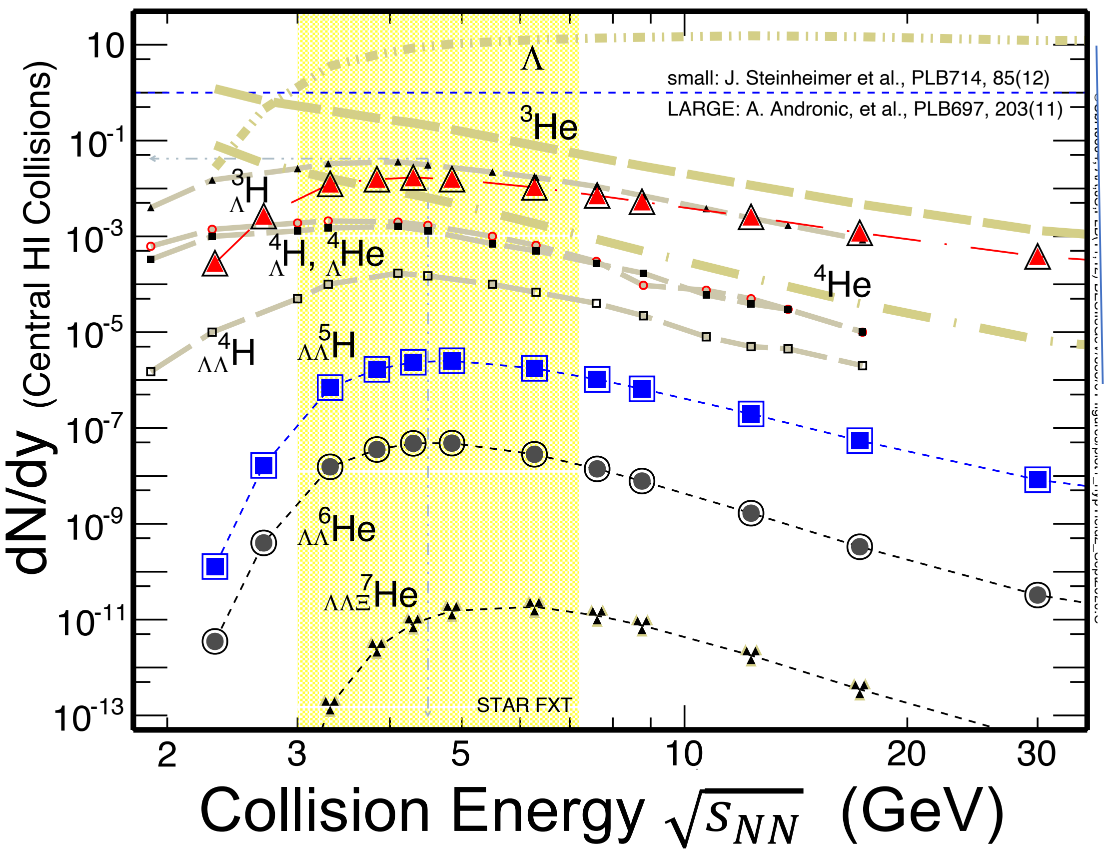
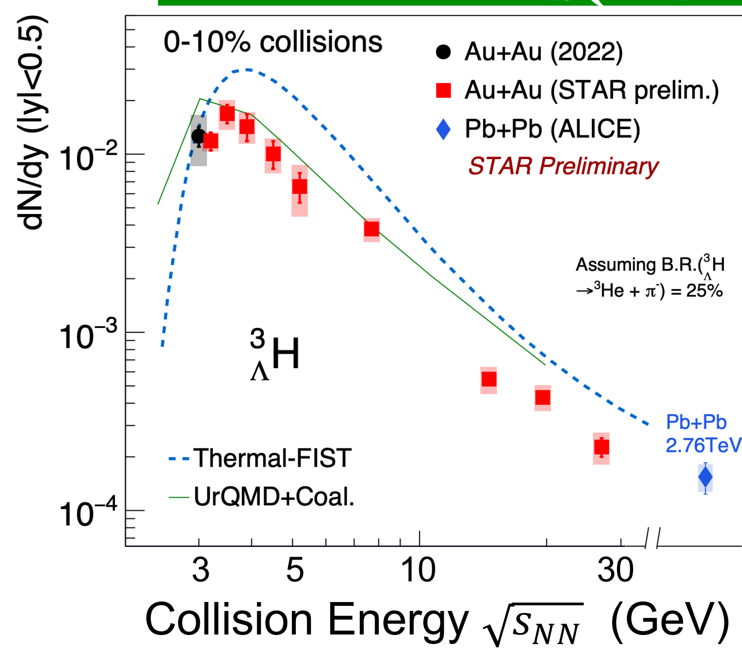
1) Introduction
2) **Selected Recent Results**
   - Collectivity and Baryon Correlation from FXT
   - Criticality from BES-II (collider)
3) Summary

STAR FXT Program and High Baryon Density Region

A. Andronic *et al.* PL**B697**, 203(2011);
J. Steinheimer *et al.* PL**B714**, 85(2012)



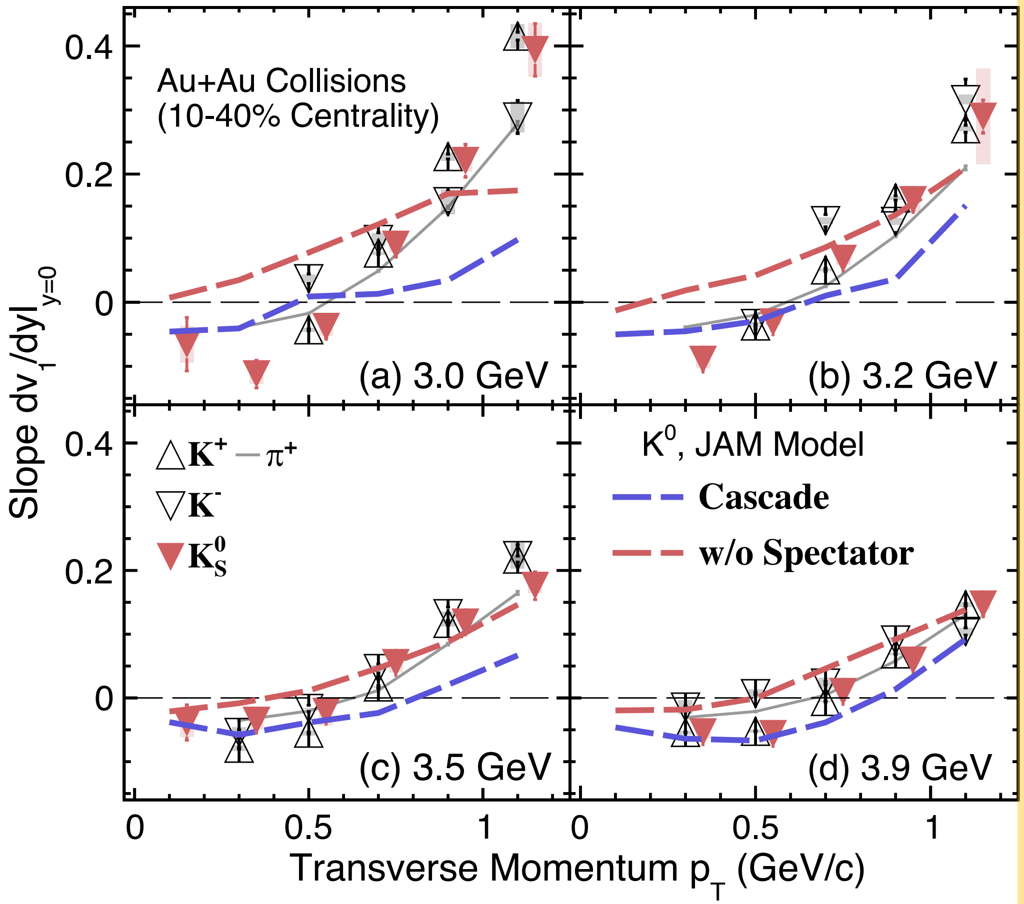
STAR: CPOD2024, SQM2024



1) Hypernucleus: ${}^{3}_{\Lambda}H$ yields versus energy: peaks at 3.2 GeV;
2) For $\sqrt{s_{NN}} < 10$ GeV, calculations from coalescence more consistent with data

Kaon Anti-Flow at High Baryon Density Region

STAR: CPOD2024, SQM2024



1) A systematic analysis of the p_T dependence of the neutral- and charged-Kaon v_1 from Au+Au collisions at $\sqrt{s_{NN}} = 3.0 - 3.9$ GeV;
2) At $p_T < 0.6$ GeV, all mid-rapidity v1 slopes are negative. Kaon potential was proposed to explain the data, ref.[1,2];
3) JAM model calculations suggest that spectator shadowing, similar to the case of elliptical v_2, plays important role for the negative v_1 slope parameter.

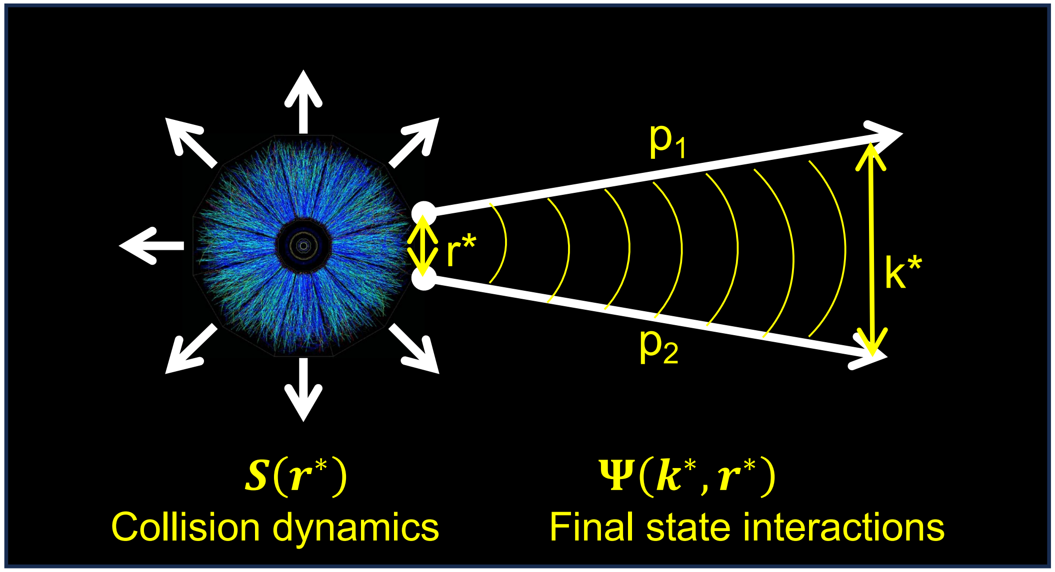
→ Spectator shadowing

→ **No Kaon potential is needed**

References:

(1) P. Chung *et al.* (E895), PRL **85**, 940(2000);
(2) G.-Q. Li, C. M. Ko, and B.-A. Li, PRL **74**, 235 (1995) and S. Pal, C. M. Ko, Z.-W. Lin, and B. Zhang, PR **C62**, 061903(2000)

Baryon Correlation Functions



STAR:

(1) Meson HBT: $\pi-\pi,\ \ K-K$;

(2) **Baryon Correlations:**

$p-p$	reference	
$p-\Lambda,\ p-\Xi^{-},\ p-\Omega$		*Y-N*
$p-\phi$		
$\Lambda-\Lambda$		*Y-Y*
$p-d,\ \ d-d$		*N-N-N*
$d-\Lambda$		*Y-N-N*

Source

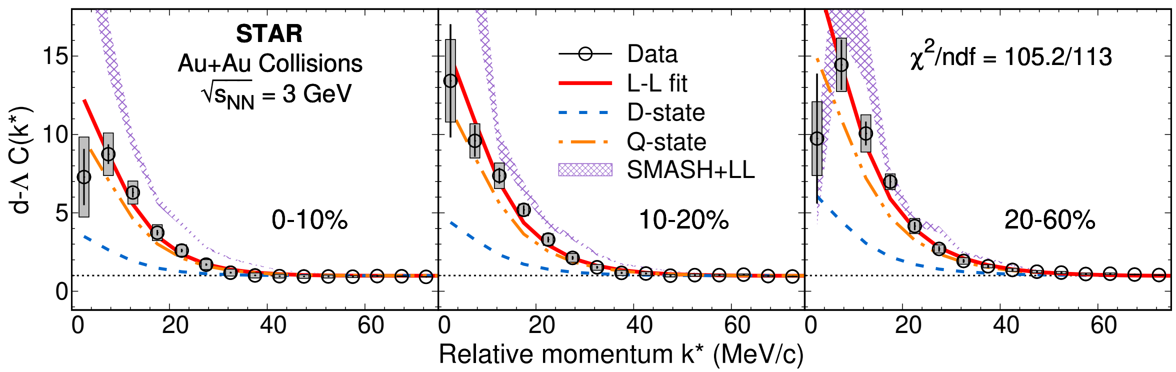
$$C_{the}(k^*) = \frac{1}{4\pi}\int \mathrm{d}^3 r^* S(r^*)|\Psi(r^*, k^*)|^2$$

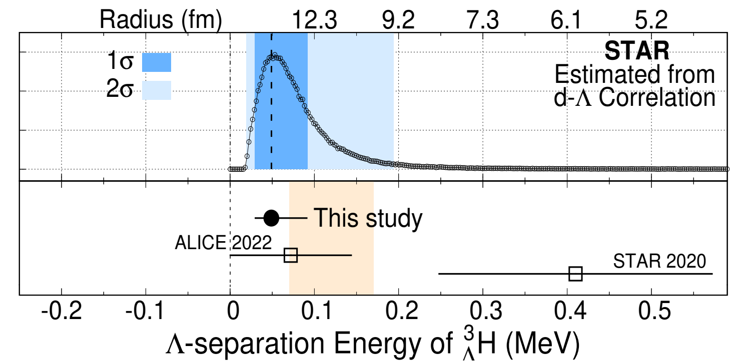
$$C_{exp}(k^*) = \lambda \frac{N_{same}(p_1, p_2)}{N(p_1)N(p_2)}$$

$$k^* = \frac{1}{2}|p_1^* - p_2^*|$$

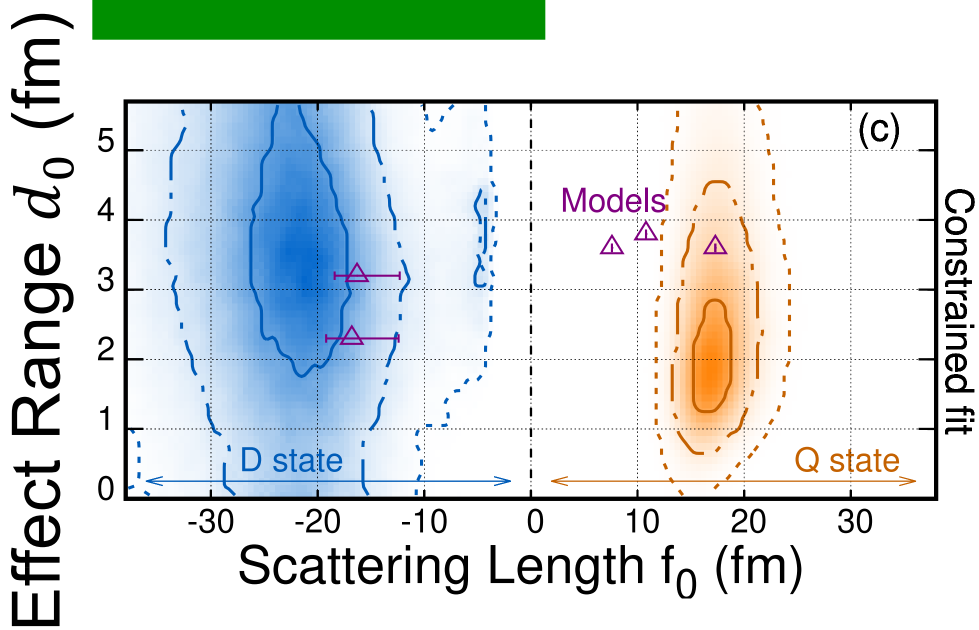
Final State Interactions:
(1) Quantum statistics; (2) Coulomb; (3) Strong interaction

$d - \Lambda$ Correlation Functions 3.0 GeV





STAR: CPOD2024



1) Centrality dependence of the $d - \Lambda$ correlation functions from 3.0 GeV Au+Au collisions;

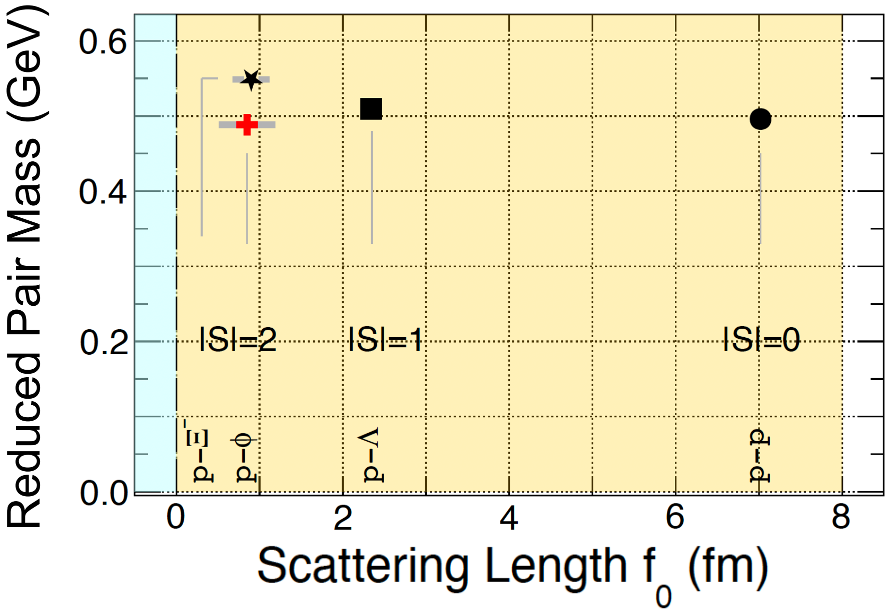
2) For the first time, spin dependent states, *D and Q*, identified experimentally!

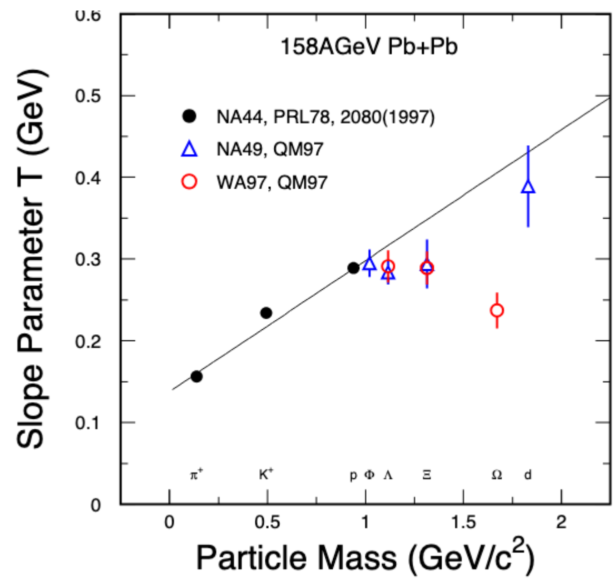
→ New window for studying 3-body interactions in the laboratory

References:

(1) J.M. Lattimer and M. Prakash, Science **304**, 536 (2004);
(2) M. Kohno and H. Kamada, arXiv:2406.13899;
(3) H. W. Hammer, Nucl. Phys. **A705**,173 (2002)

NY Correlations





H. van Hecke, H. Sorge NX, Phy.Rev.Lett. **81**, 5764(1998). *"Evidence of early multi-strange hadron freeze-out in high energy nuclear collisions"*

→ Rescatterings lead to collectivity

→ Collectivity is reduced as the strangeness content is increased

Hierarchy of strangeness content:

$$\boldsymbol{f_0(|s|=0) > f_0(|s|=1) > f_0(|s|=2) > 0}$$

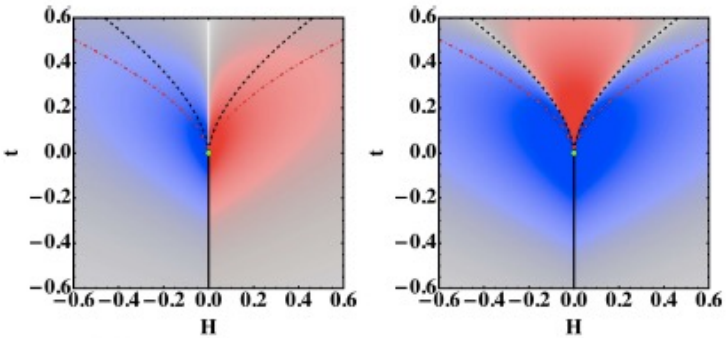
- ➢Interaction section is proportional to f_0^2, the observation implies that the strength of the interaction depends on strangeness;
- ➢Important for understanding EOS of the medium in nuclear collisions and compact stars; In case of $\boldsymbol{f_0 < 0}$, important for the search for di-baryons, such as $p\Omega^-$;
- ➢ Understand the strangeness hierarchy in QCD calculations?

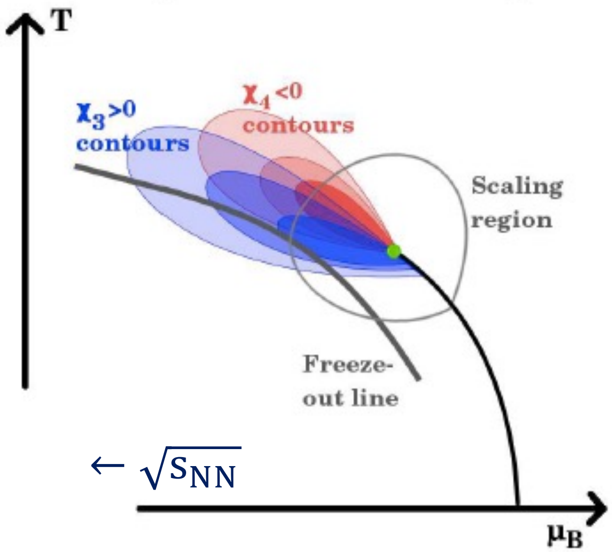
High Moments from BES-II

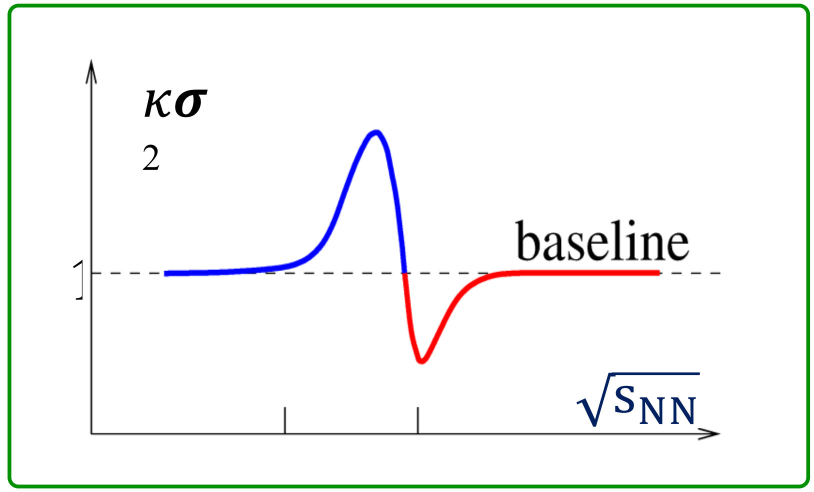
Precision Measurements of (Net-)Proton Number Fluctuations in Au+Au Collisions at RHIC (STAR Collaboration)

A. Pamdav's talk

Expectations for Models







- Characteristic "Oscillating pattern" is expected for the QCD critical point but the exact shape depends on the location of freeze-out with respect to the location of CP;
- Critical Region (CR)

- M. Stephanov, PRL**107**, 052301(2011) - V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, Phys. Rev. **D93** (2016) 034037

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

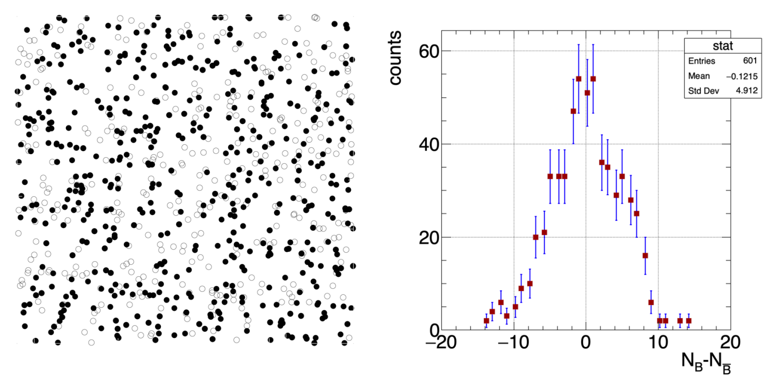
Moments, cumulants and susceptibilities:

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

Animation: Anar Rustamov



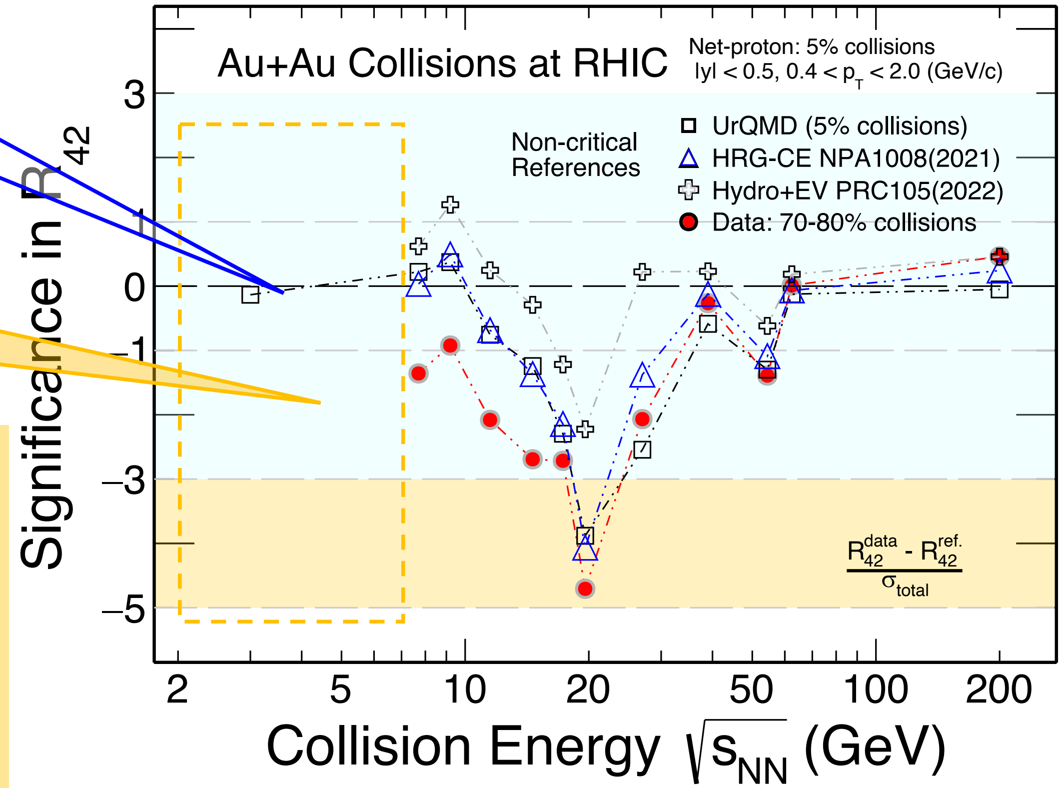
INT 2008-2b : "*The QCD Critical Point*"

F. Gross *et al.* 2212.11107: "*50 Years of QCD*"

Summary: Fluctuations

STAR FXT
HADES
CBM
(2028)

*Predictions on CP at 650 MeV ~ 4 GeV



"In summary, … Dynamic model calculations including the criticality is needed in order to understand the results from BES-II. On the experiment side, data between $\sqrt{s_{NN}}$ = 3.0 and 8.0 GeV is needed in order to search for the signals of QCD critical point and the 1st-order phase boundary."

1) M. Hippert, *et al.*, 2309.00579; X. An *et al.*, NP **A1017** (2022) 122343;
2) W.J. Fu, *et al.*, 2308.15508; F. Gao *et al.*, PR **D104**, (2021) 054022

Outline

1) Introduction
2) Selected Recent Results
   - Collectivity and Baryon Correlation from FXT
   - Criticality from BES-II (collider)
3) **Summary and Outlook**

Summary

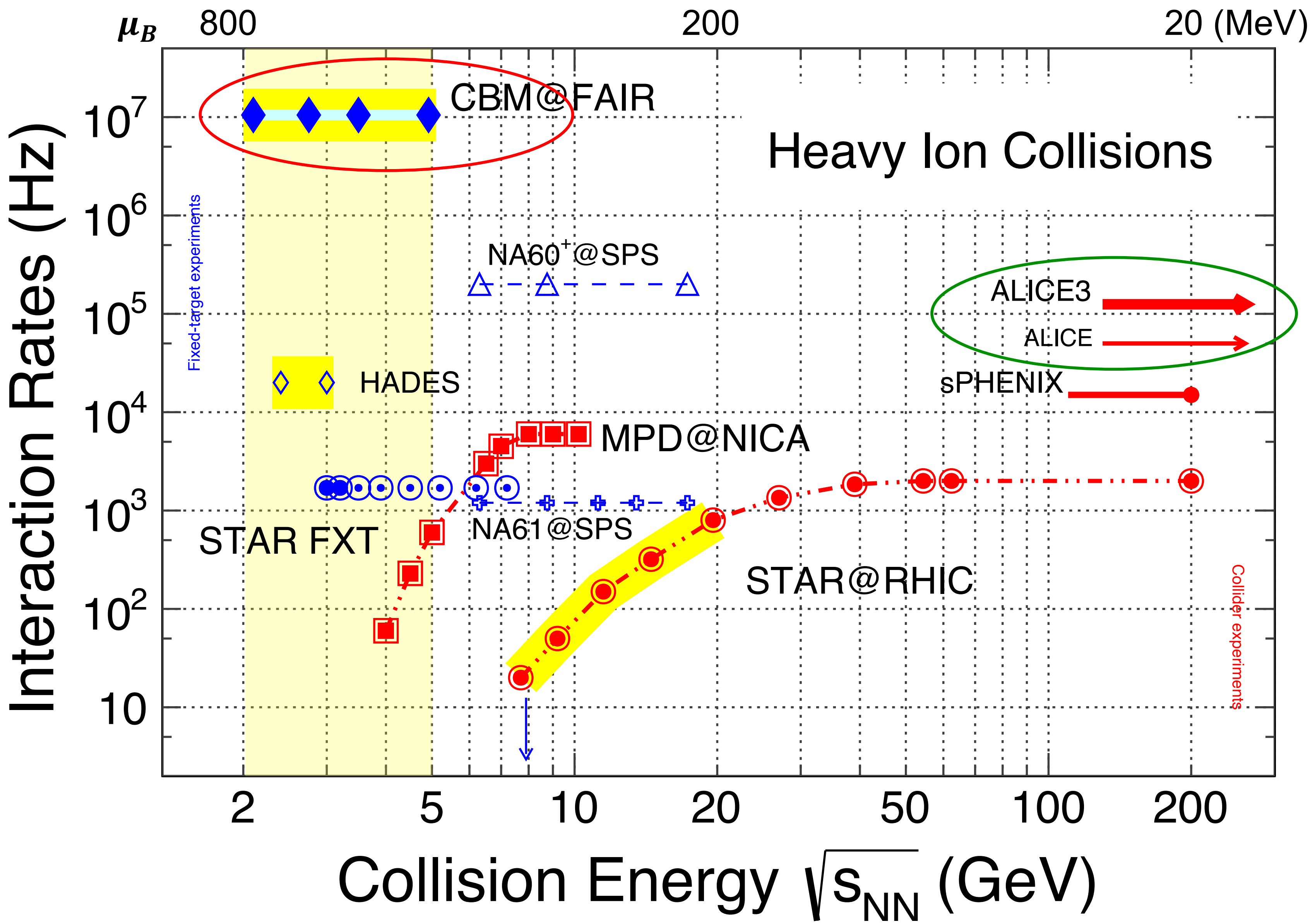
1) Rich physics at large μ_B region:

- Strangeness and EOS;
- Hypernuclei production;
- Baryon correlations;
- …

2) QCD critical point:

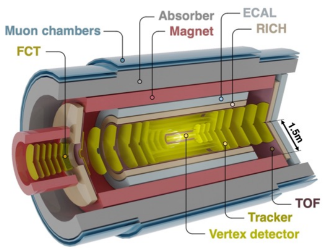
- BES-II data offered high statistics, better acceptance, centrality resolution and systematic;
- Will do (i) p_T and rapidity scan; (ii) C_5, and C_6 analysis; (iii) complete the FXT data ($\sqrt{s_{NN}}$ = 3 – 3.9 GeV)

Future High Rates Experiments

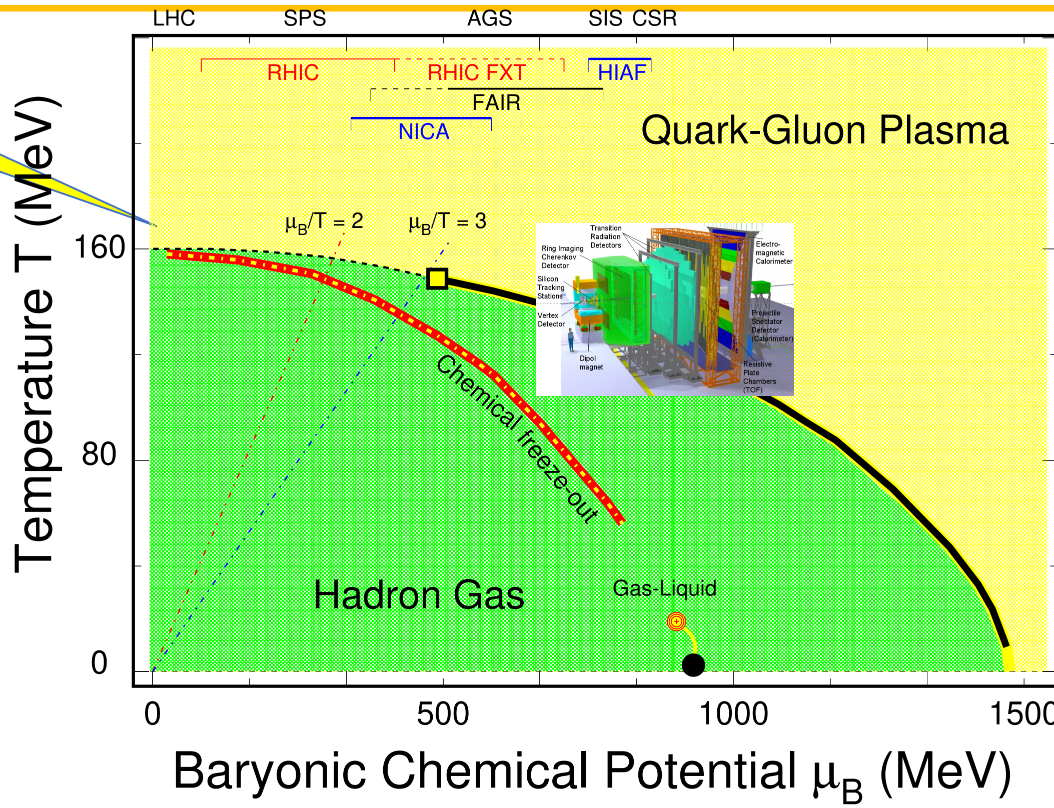


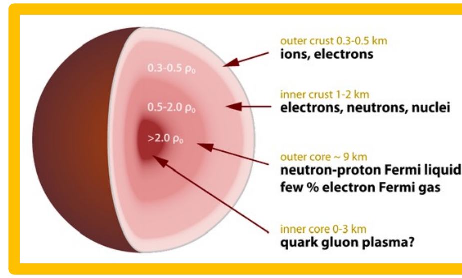
Nuclear Collisions and QCD Phase Diagram

Early Universe



- High order baryon fluctuation;
- 3D di-lepton spectra (collision centrality, pair mass and p_T)





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

1) Property of QGP, smooth crossover transition at $\mu_B = 0$;

2) Search for 1st-order phase transition and **QCD critical point**;

3) Baryon interactions (*e.g.* $N - N$, $Y - N$) → inner structure of compact stars

Many Thanks to Organizers!

Acknowledgements:

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!