Recent Results from RHIC BES Program

- Strange Meson Collectivity
- p High Moments

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Outline

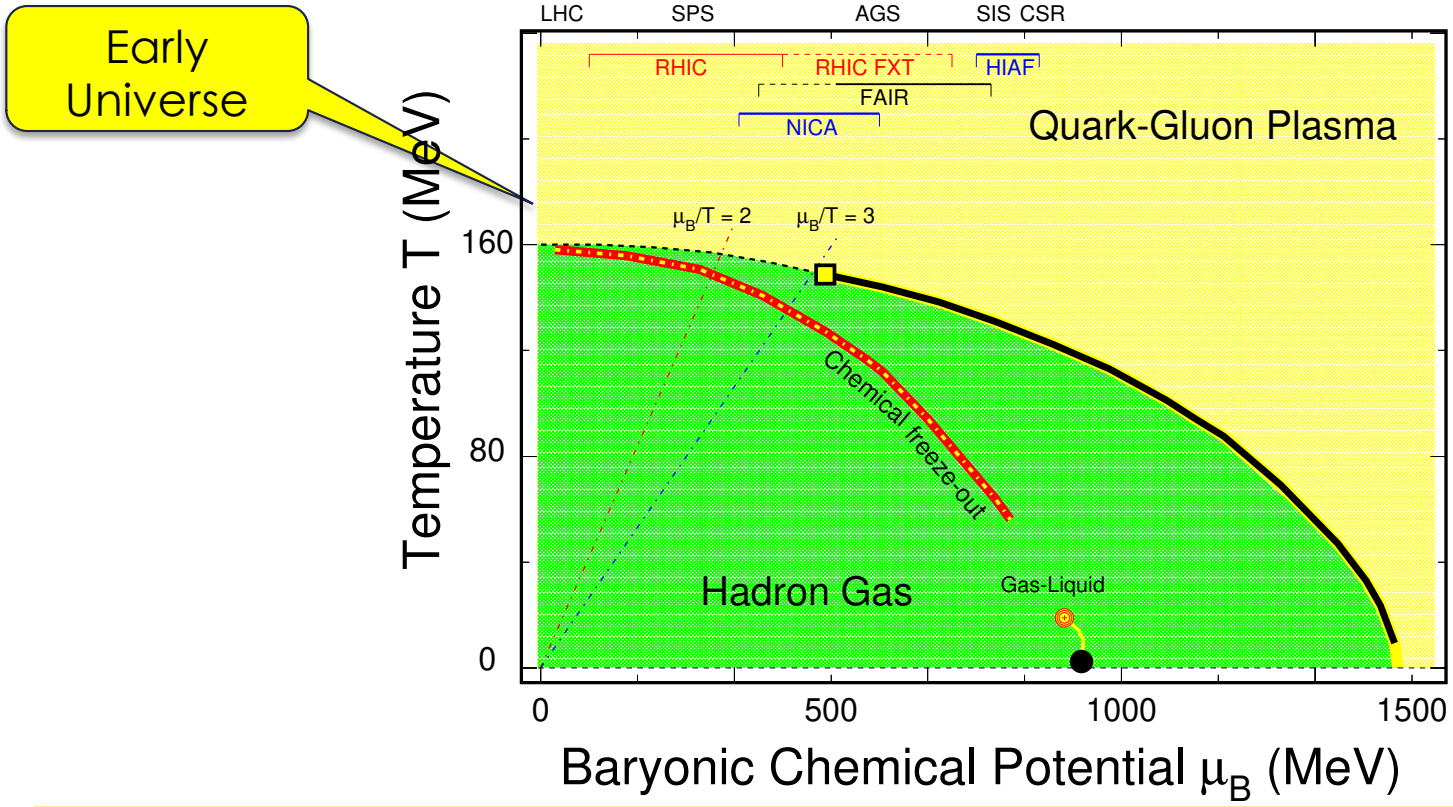
1) Introduction

2) Recent Results from STAR Experiment

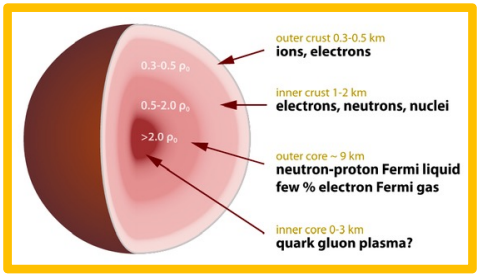
- Strange Meson Collectivity
- proton High Moments

3) Summary

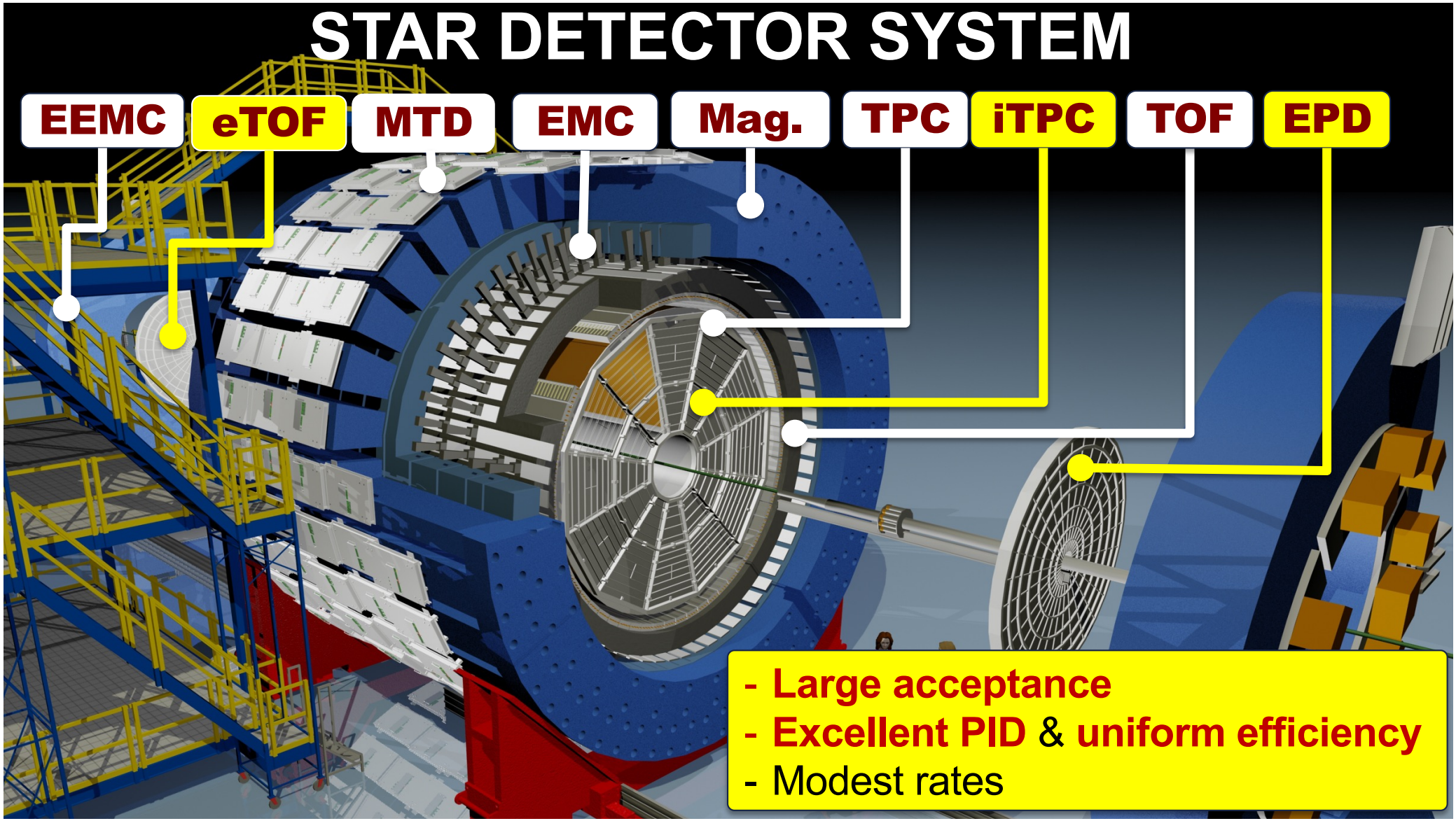
Nuclear Collisions and QCD Phase Diagram



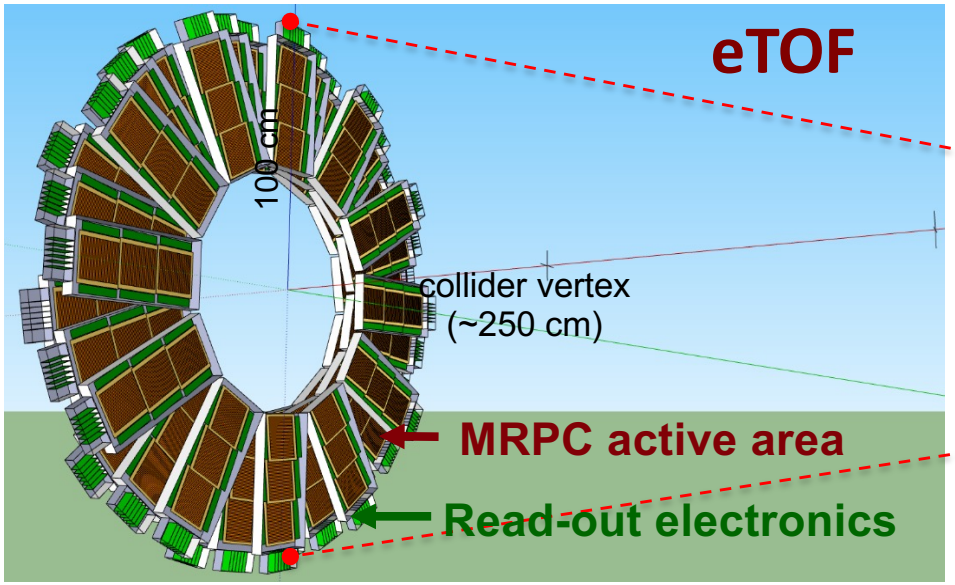
High baryon density: Inner structure of compact stars

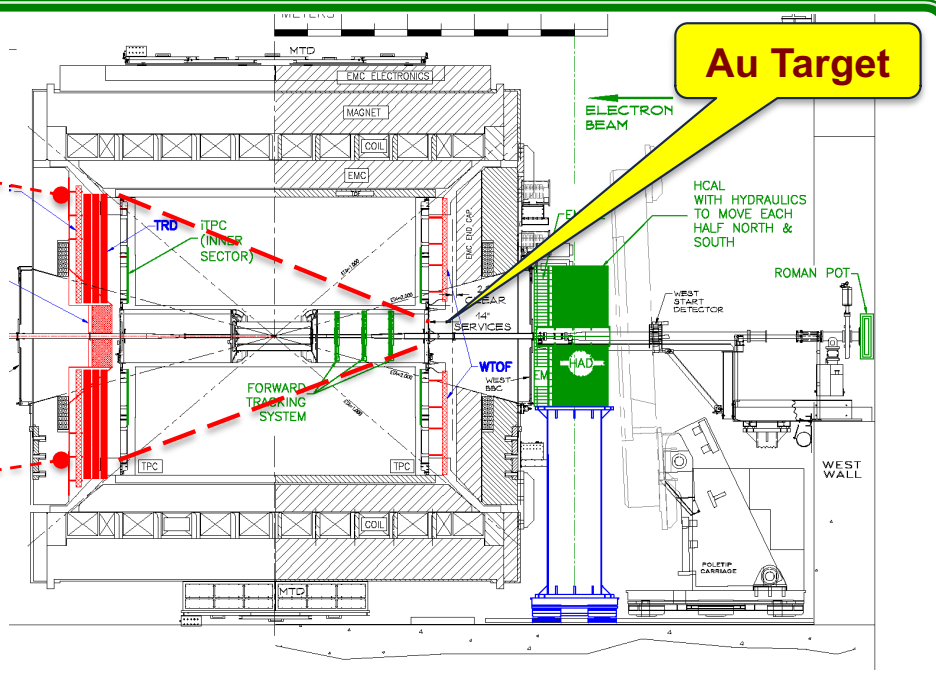


1) RHIC BES: → search for 1st-order phase transition and **QCD critical point**;
2) Study EOS at high baryon density


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

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

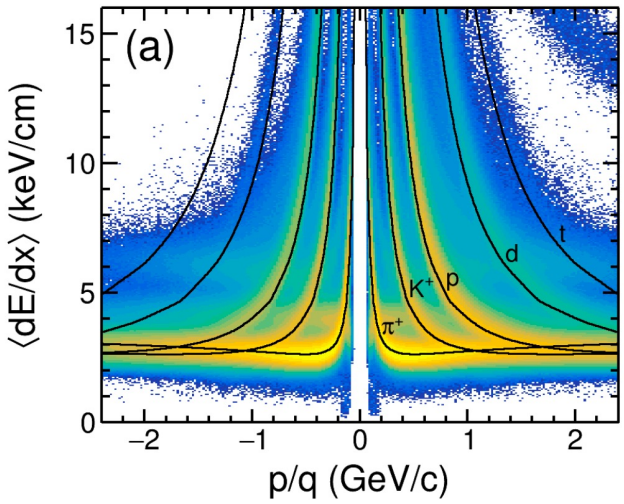
STAR BES-I and -II Data Sets

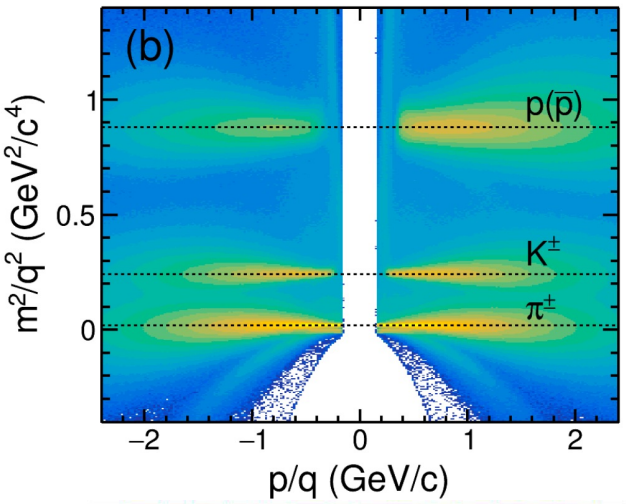
Au+Au Collisions at RHIC											
Collider Runs						**Fixed-Target Runs**					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	57 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M	420 MeV		Run-21	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

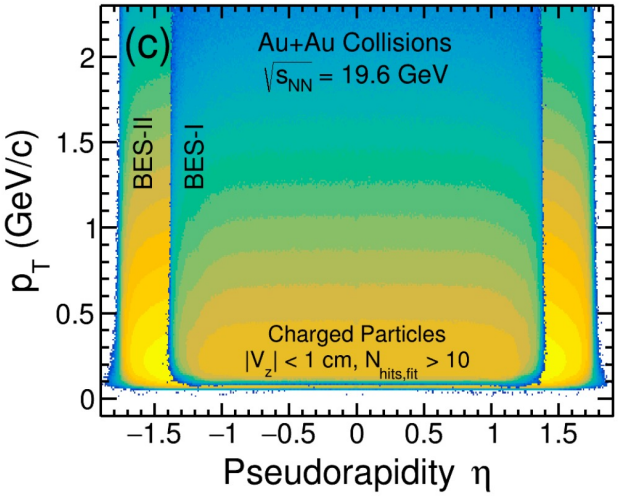
Most precise data to map the QCD phase diagram

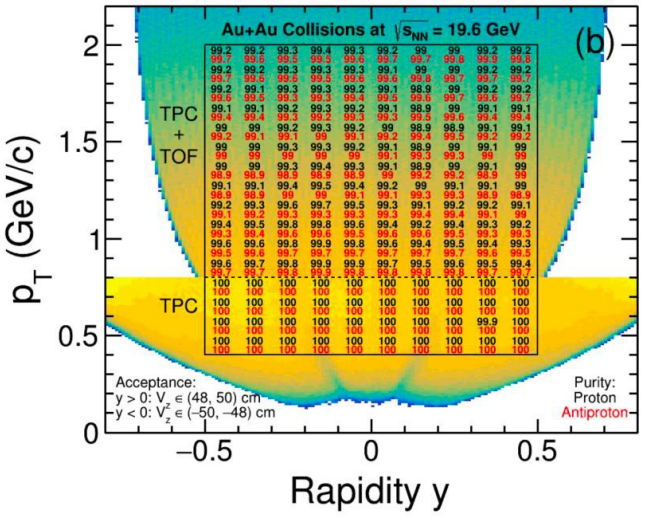
$$3 < \sqrt{s_{NN}} < 200 \text{ GeV}; \quad 760 > \mu_B > 25 \text{ MeV}$$

Proton: PID, Acceptance and Purity









1) Cleaner proton PID with TPC and TOF, higher efficiency;
2) Wider acceptance and improved purity for both protons and anti-protons;
3) Wider acceptance for charged particles → important for determining collision centrality;
4) Overall systematic uncertainties in high moments measurements are also reduced by 20-30% depends on the order

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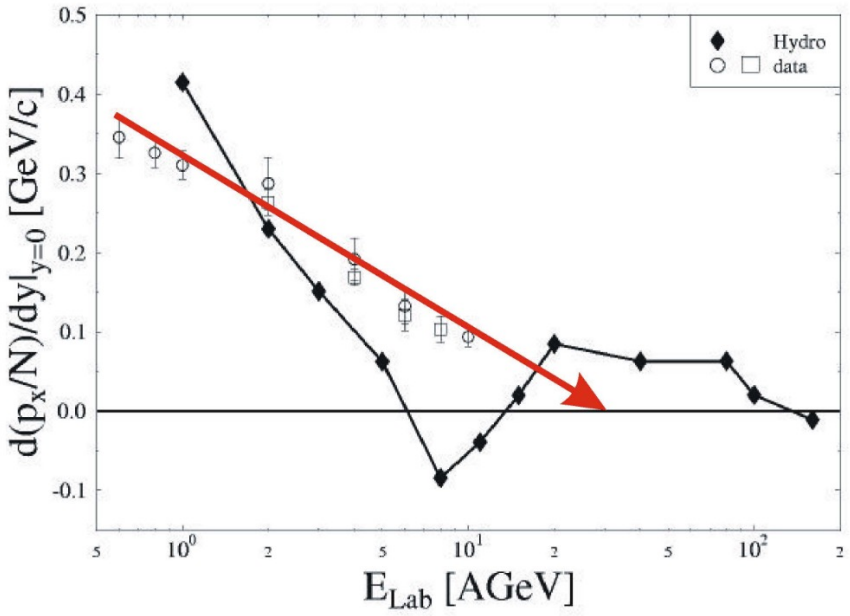
Collectivity

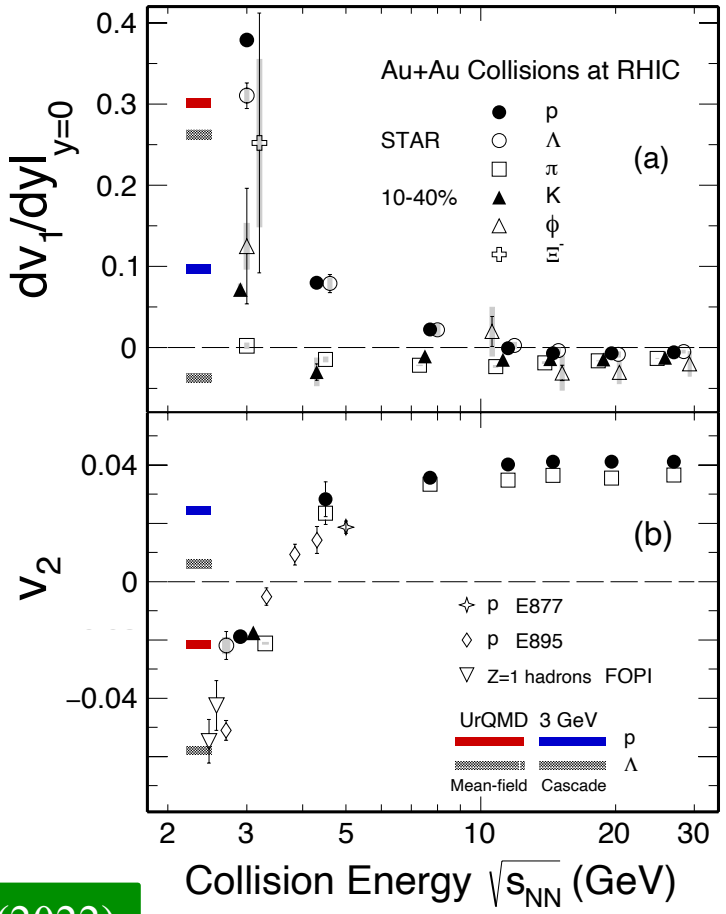
$$\partial_\mu[(\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu}] = 0$$
$$\partial_\mu[s\, u^\mu] = 0$$

$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left\{1 + \sum_{n=1}^{\infty} 2v_n(p_T)cos[n(\varphi - \Psi_R)]\right\}$$

- v_1 Directed flow;
- v_2 Elliptic flow;
- v_3 Triangle flow

“Collective Flow signals the Quark Gluon Plasma”



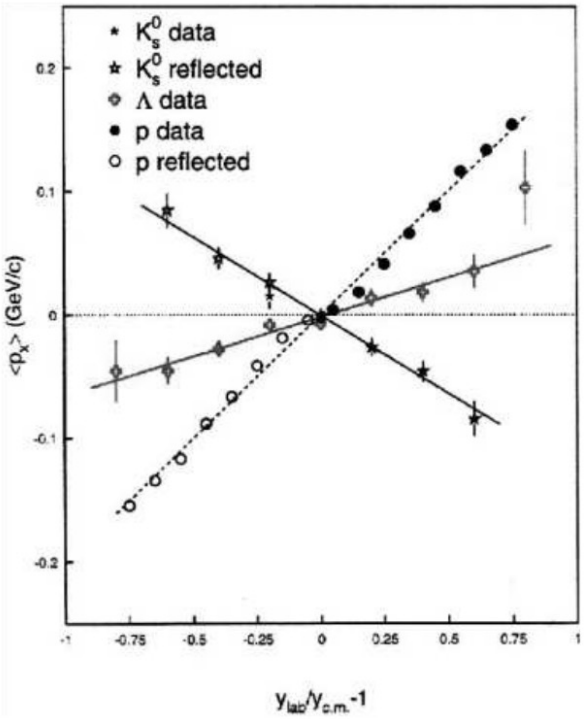


H. Stoecker, Nucl.Phys.A750, 121(2005)
D.H. Rischke et al. Acta Phys.Hung.A1, 209(1995)

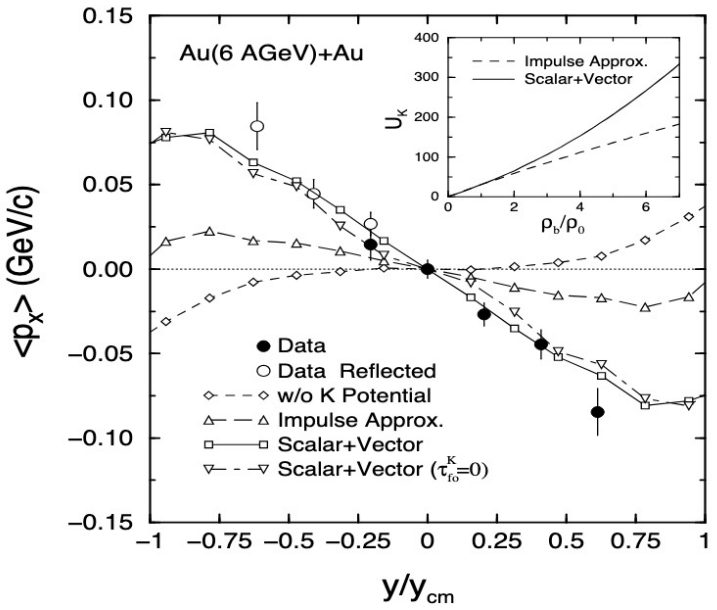
STAR: PLB**827**, 137003(2022)

Kaon Anti-Flow at High Baryon Density

E895: Phys.Rev.Lett. 85, 940 (2000)



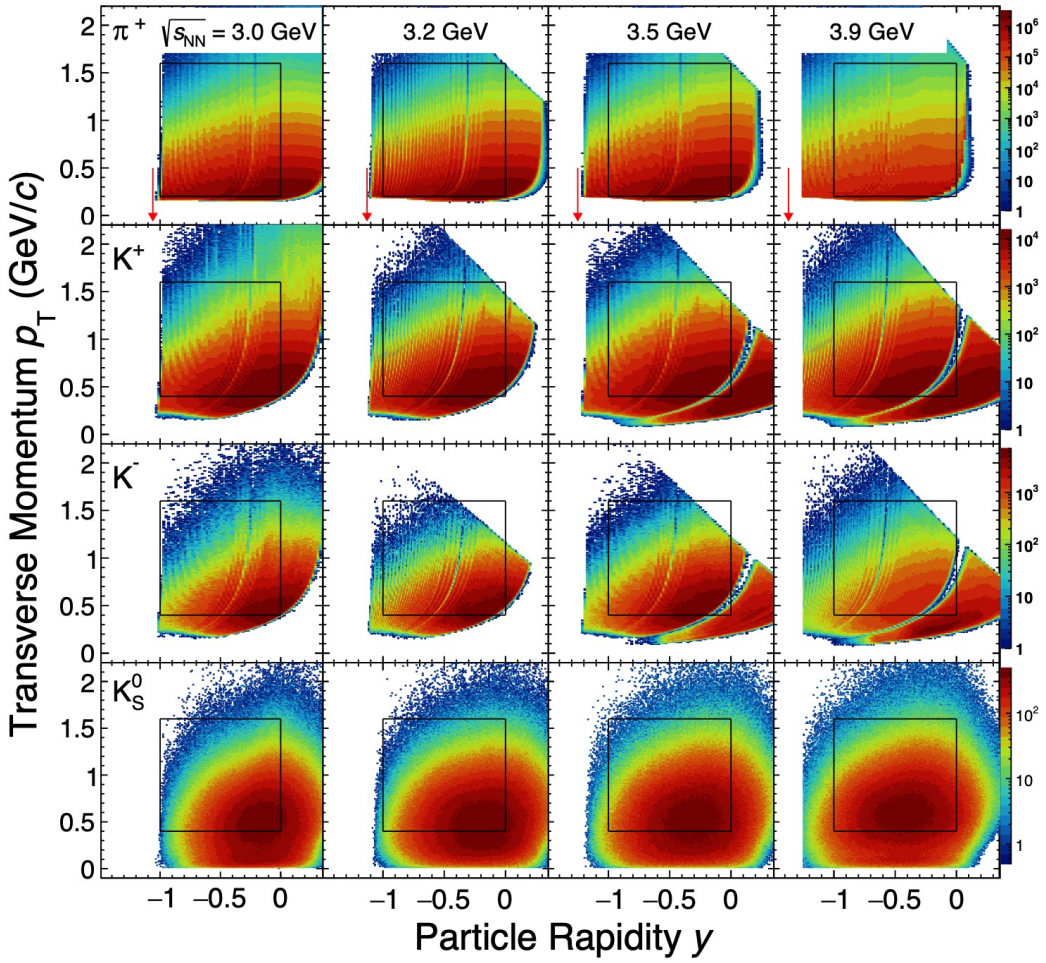
S. Pal, et al., Phys.Rev.C62, 061903 (2000)



1) Large anti-flow observed for K_S^0 by the E895 collaboration

2) Was attributed to a repulsive kaon potential

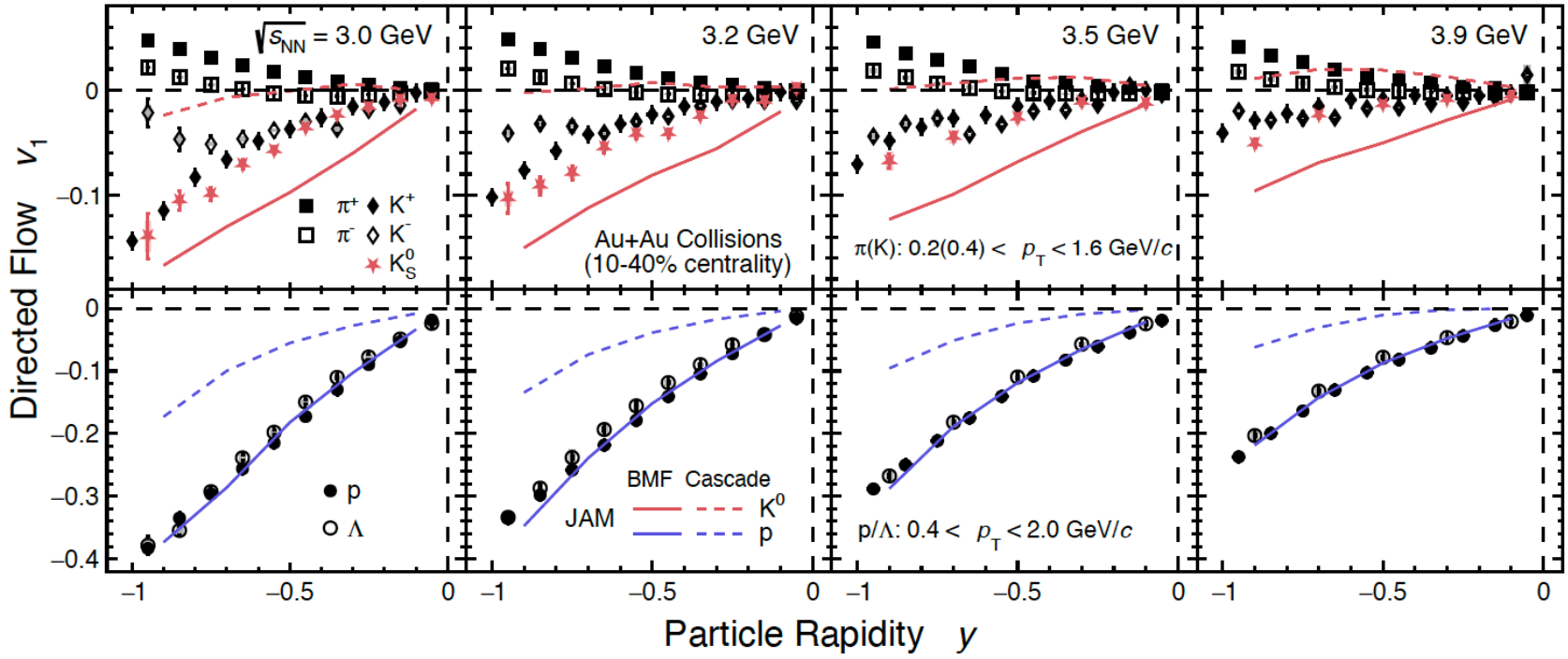
Kaon Anti-Flow at High Baryon Density



1) RHIC BESII data: 3.0, 3.2, 3.5 and 3.9 GeV Au+Au collisions;
2) STAR detector: wide acceptance for identified pions and Kaons;

Kaon Anti-Flow at High Baryon Density

STAR: 2503.23665 JAM2: Y. Nara, et al. Phys. Rev. C102, 024913 (2020)



1) Strong v_1 for protons and Λ observed;
2) Baryon mean field is needed to reproduce the observations for baryons;
3) Mesons' v_1 are weaker and its sign depends on p_T range

Kaon Anti-Flow at High Baryon Density

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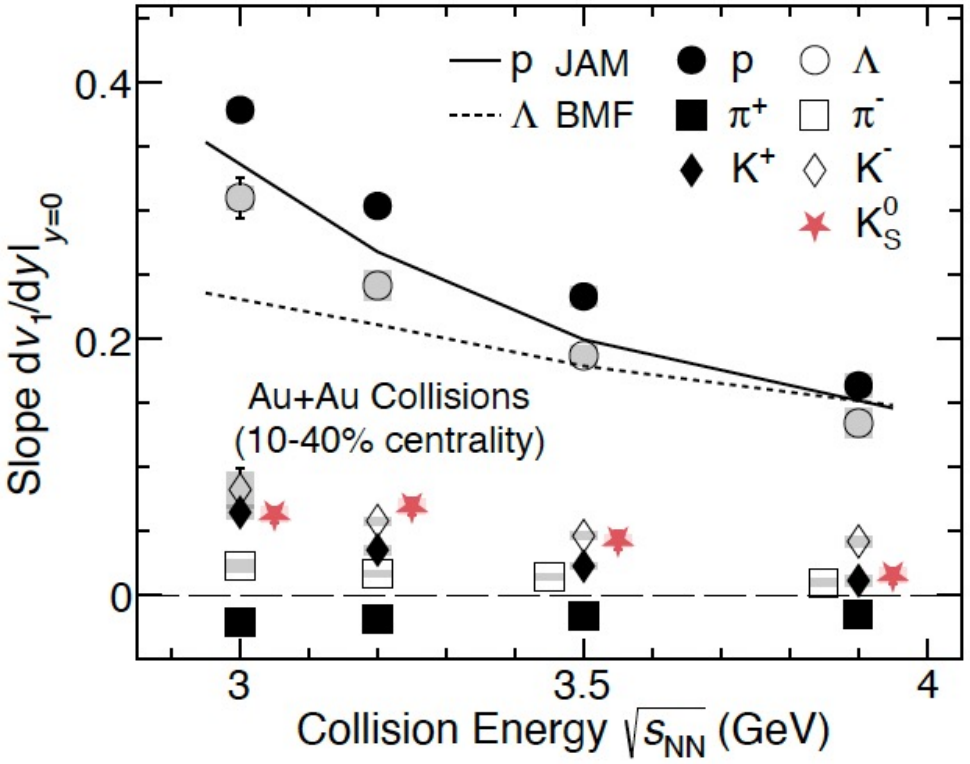

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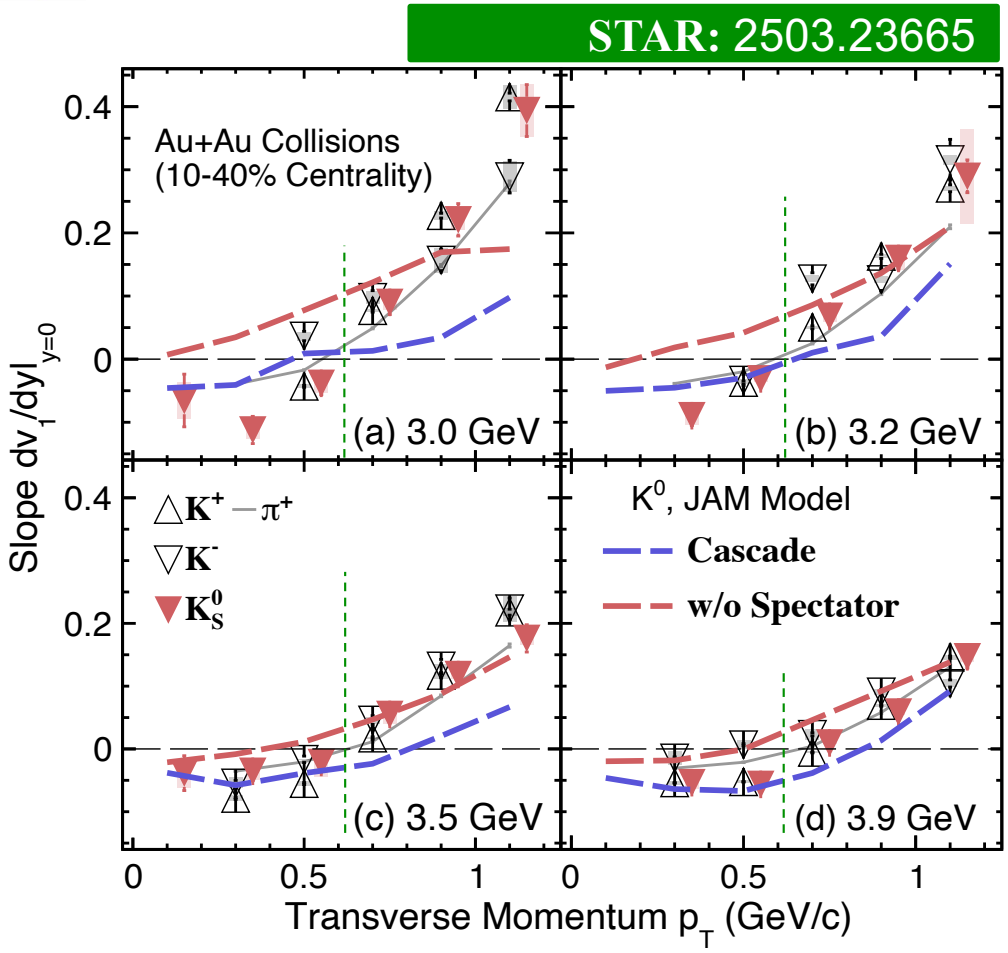
Kaon Anti-Flow at High Baryon Density



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.

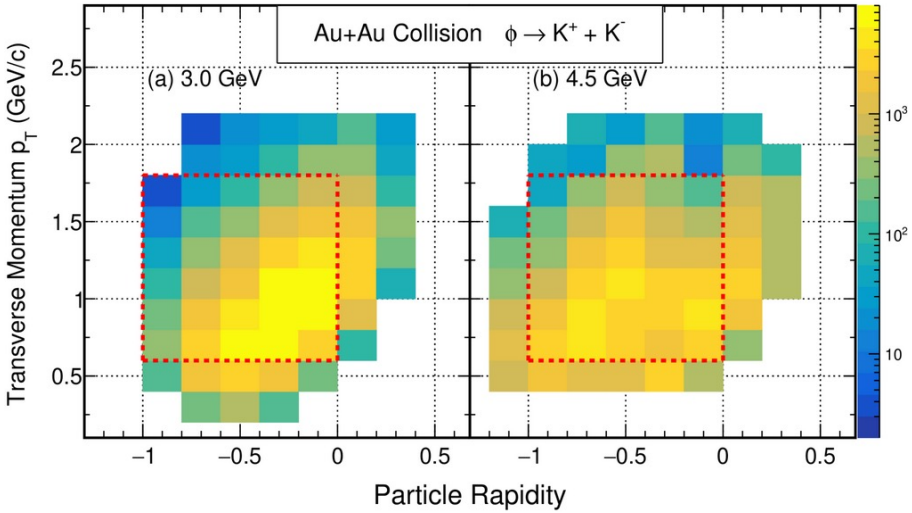
→ Spectator shadowing

→ 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)

ϕ-Meson Collectivity at High Baryon Density



Acceptance:

In the FXT region, ϕ-mesons are measured in $y_{target} < y < 0$ (mid-y) and $0.5 < p_T < 2.0$ GeV/c.

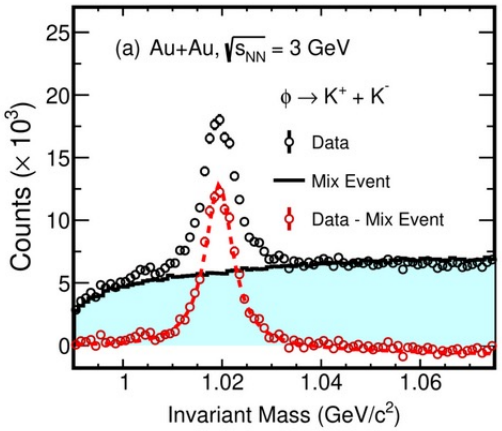
STAR: QM2025

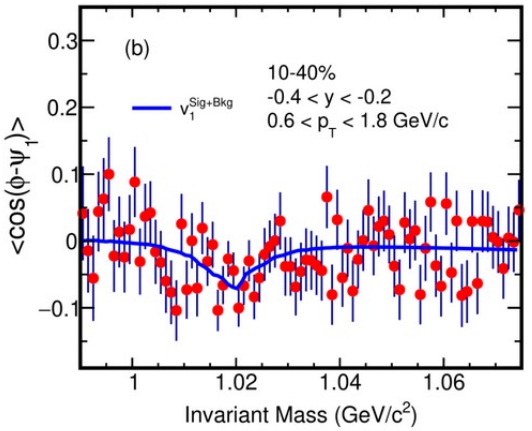
PID and extraction of ϕ v_1:

(i) $\phi \to K^+ + K^-$ (45% br)

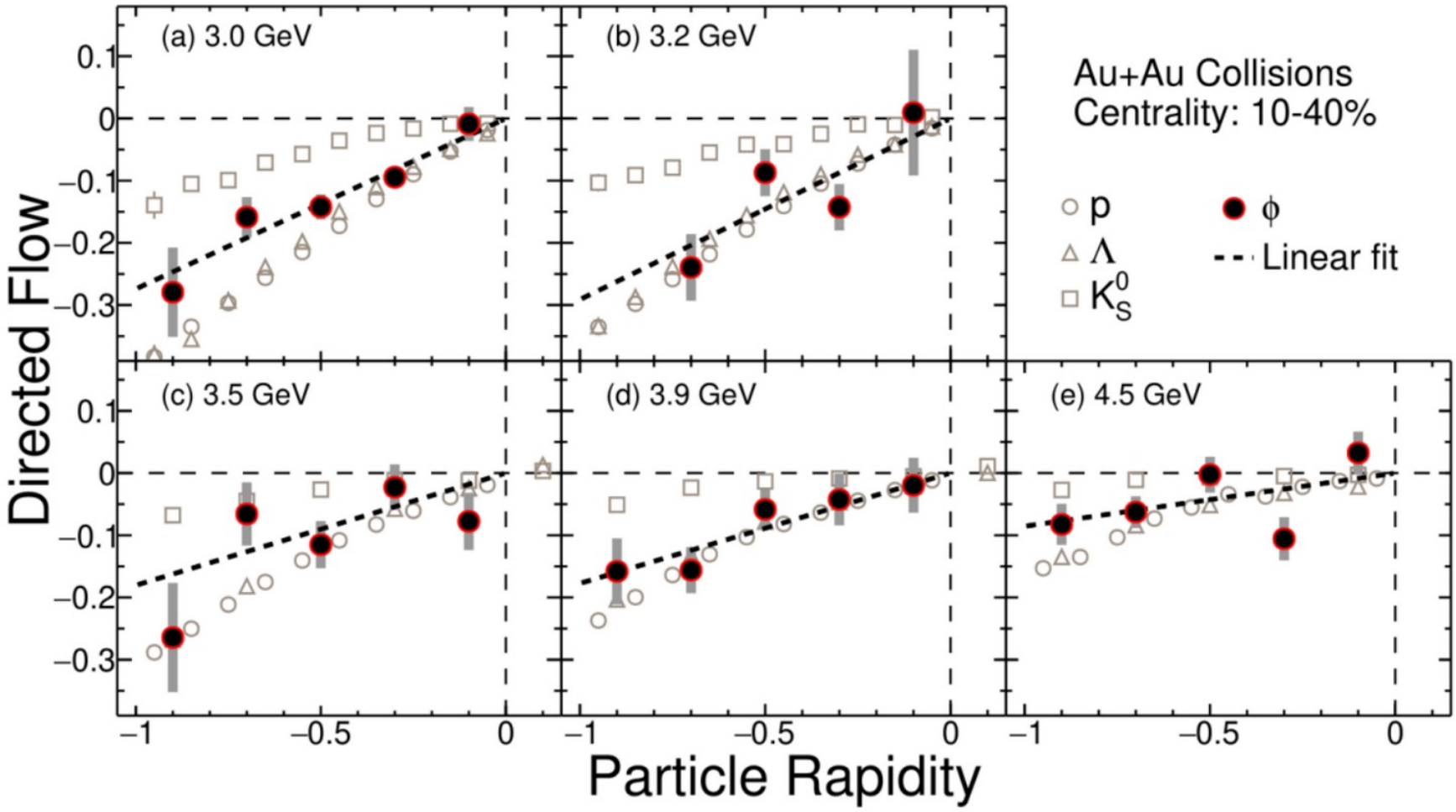
(ii) Inviant mass method:

$$v_1^{s+b} = \boldsymbol{v_1^s} \frac{s}{s+b} + v_1^b \frac{b}{s+b}$$

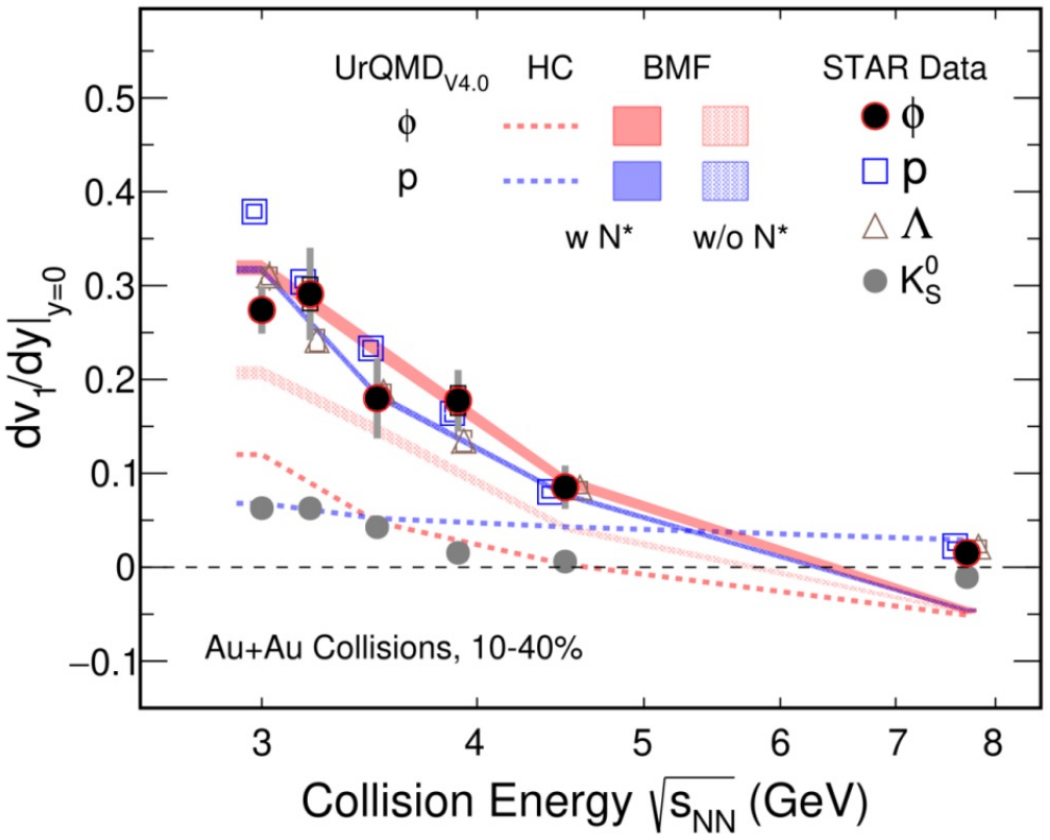




ϕ-Meson Collectivity at High Baryon Density



ϕ-Meson Collectivity at High Baryon Density



J. Steinheime and M. Bleicher, J.Phys.G43, 015104(2016)
J. Steinheime et al. Phys.Lett.B869, 139870(2025)

1) The ϕ-mesons show collectivity v_1 as strong as that of protons and Λ-baryon in mid-central Au+Au collisions at 3.0, 3.5, 3.9, 4.5 and 7.7 GeV, in the high baryon density region;

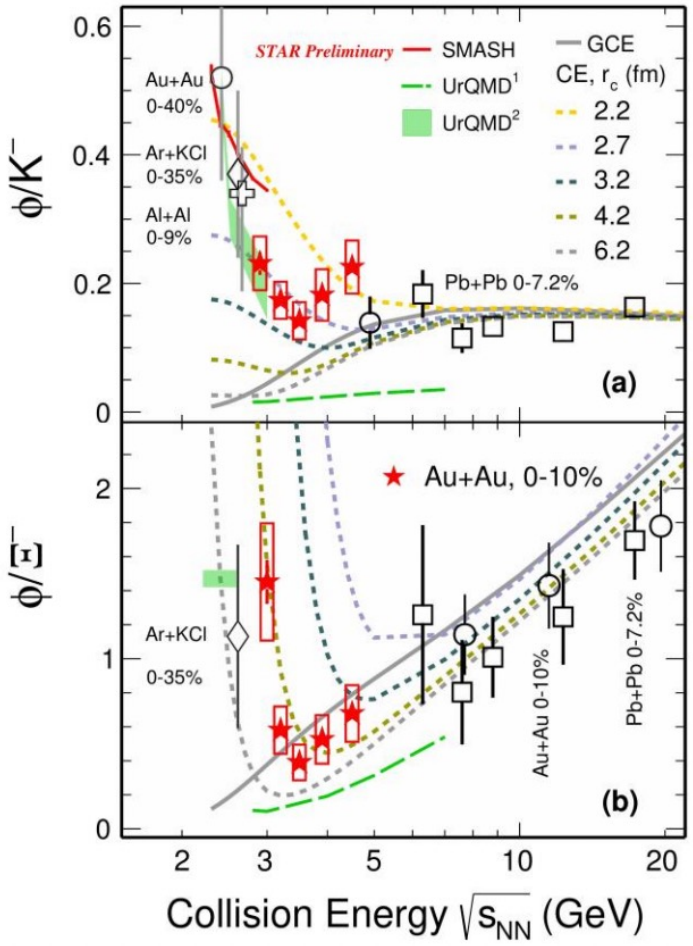
2) Transport model UrQMD (v4.0) calculations with high mass baryon resonances reproduce the energy dependence for ϕ-meson, proton and Λ;

$$N + N \rightarrow N^* + N \rightarrow N + \phi + N$$

3) A similar calculations also reproduce the ratios of ϕ/K^- and ϕ/Ξ^- at high density

4) How about Kaons?

ϕ-Meson Productions



At high baryon density, high mass baryon resonance N* is important for ϕ-meson production as well as its collectivity

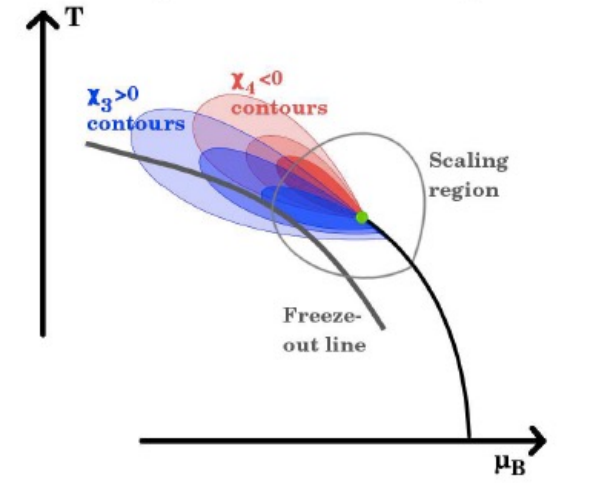
Any effects on like mesons?
Any effects on EOS?

J. Steinheime and M. Bleicher, J.Phys.G43, 015104(2016)
J. Steinheime et al. Phys.Lett.B869, 139870(2025)

STAR: Phys.Lett.B831, 137152 (2022)

The emergent properties of QCD matter

Criticality



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, $\langle \delta N \rangle = \mathrm{N} - \langle N \rangle$

mean: $\mathrm{M} = \langle \mathrm{N} \rangle = \mathrm{C}_1$

variance: $\sigma^2 = \langle (\delta \mathrm{N})^2 \rangle = \mathrm{C}_2$

skewness: $\mathrm{S} = \langle (\delta \mathrm{N})^3 \rangle / \sigma^3 = \mathrm{C}_3 / \mathrm{C}_2^{3/2}$

kurtosis: $\kappa = \langle (\delta \mathrm{N})^4 \rangle / \sigma^3 - 3 = \mathrm{C}_4 / \mathrm{C}_2^2$

Moments, cumulants and susceptibilities:

2^{nd} order: $\sigma^2/\mathrm{M} \equiv \mathrm{C}_2/\mathrm{C}_1 = \chi_2/\chi_1$

3^{rd} order: $\mathrm{S}\sigma \equiv \mathrm{C}_3/\mathrm{C}_2 = \chi_3/\chi_2$

4^{th} order: $\kappa\sigma^2 \equiv \mathrm{C}_4/\mathrm{C}_2 = \chi_4/\chi_2$

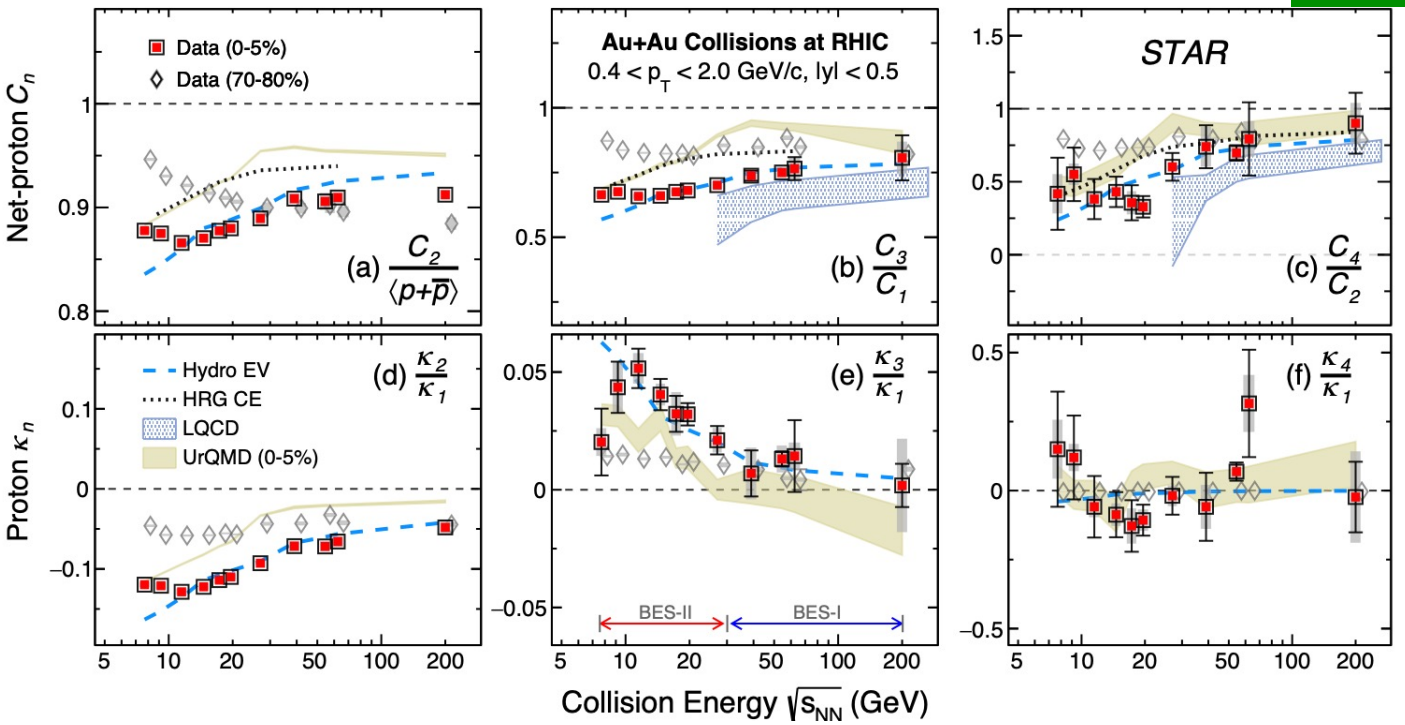
Factorial Cumulants (κ_i) measure irreducible multi-particle correlations:

$$\kappa_1 = C_1$$
$$\kappa_2 = -C_1 + C_2$$
$$\kappa_3 = 2C_1 - 3C_2 + C_3$$
$$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4$$

Energy Dependence (collider)

Au+Au Collisions at RHIC

STAR: PRL**135,** 142305(2025)



1) **UrQMD:** (hadronic transport calculations 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).

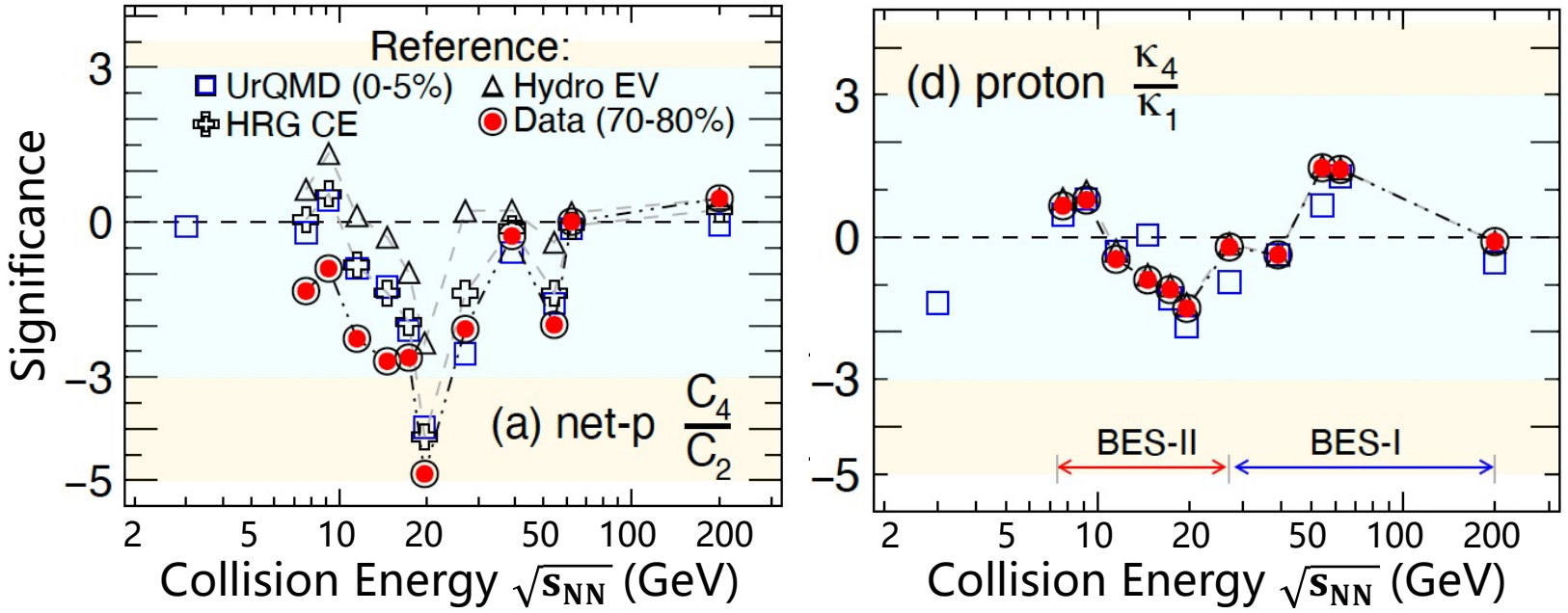
4) **LQCD: (**done for net-baryon) A. Bazavov *et al.,* Phys. Rev. D101, 074502 (2020). arXiv : 2407.09335

1) The energy dependence is reproduced by most calculations at high energy;
2) Deviations appear below $\sqrt{s_{NN}} < 35$ GeV

Significances at the 4TH Orders

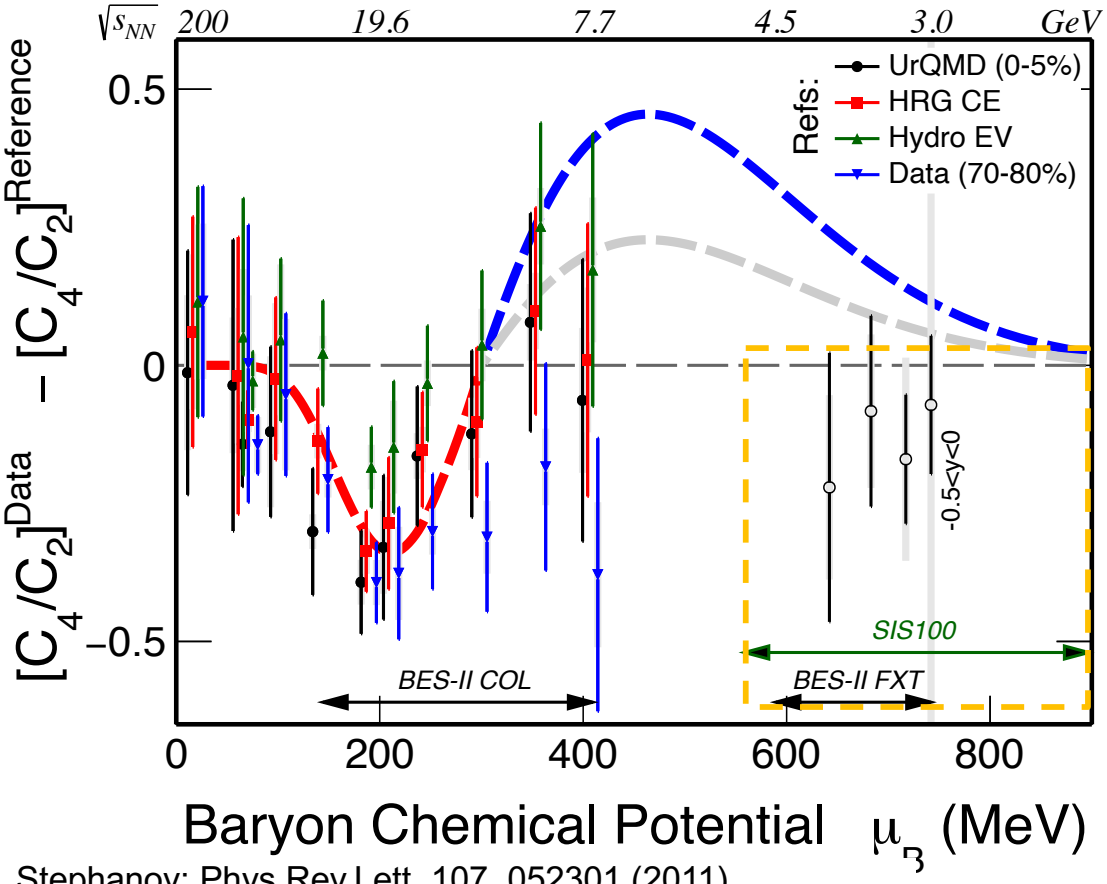
STAR: PRL**135,** 142305(2025)

0-5% Au+Au Collisions at RHIC



Significant deviations from non-critical references are observed!

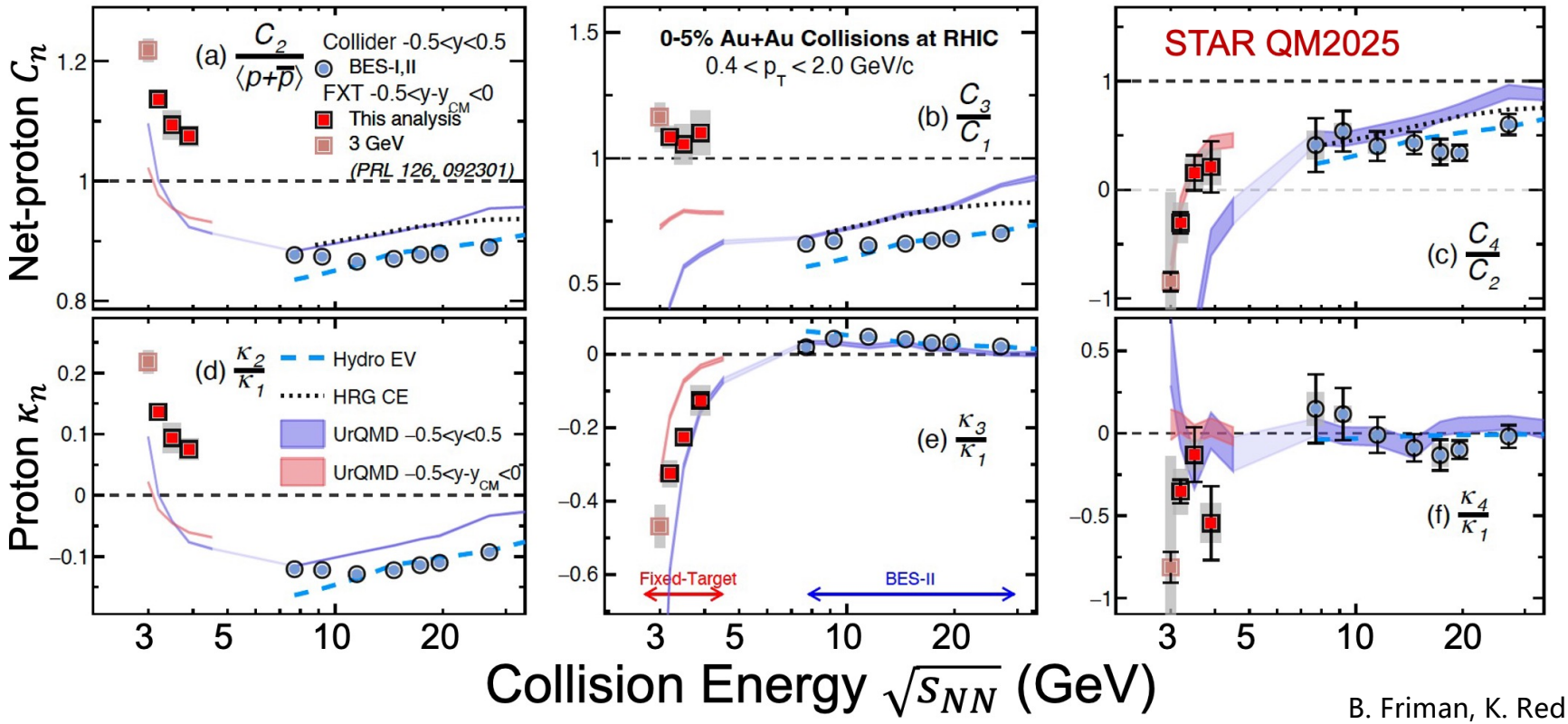
Search for the QCD CEP



M. Stephanov: Phys.Rev.Lett. 107, 052301 (2011)
P. Braun-Munzinger et al. Nucl.Phys. A1008, 122141 (2021)

1) Experimental data between 3.5 – 8 GeV are crucial;
2) CBM at FAIR will play important role for the search of QCD critical point

Energy Dependence (collider+FXT)



B. Friman, K. Redlich, and A. Rustamov 2508.18879

1) Results from FXT region show different trends from collider mode;
2) Dominant at high energy, the repulsive interactions seem not sufficient for $\sqrt{s_{NN}} < 10$ GeV

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3) Questions:

a) High mass N*: why no effects on light meson like pions, Kaons? Effects on EOS?

b) At high density, do we expect attractive interactions among baryons?

Acknowledgements:

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

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

Thank you for your attention!