Study QCD Phase Diagram in High-Energy Nuclear Collisions

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Many Thanks to Organizers!

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Outline

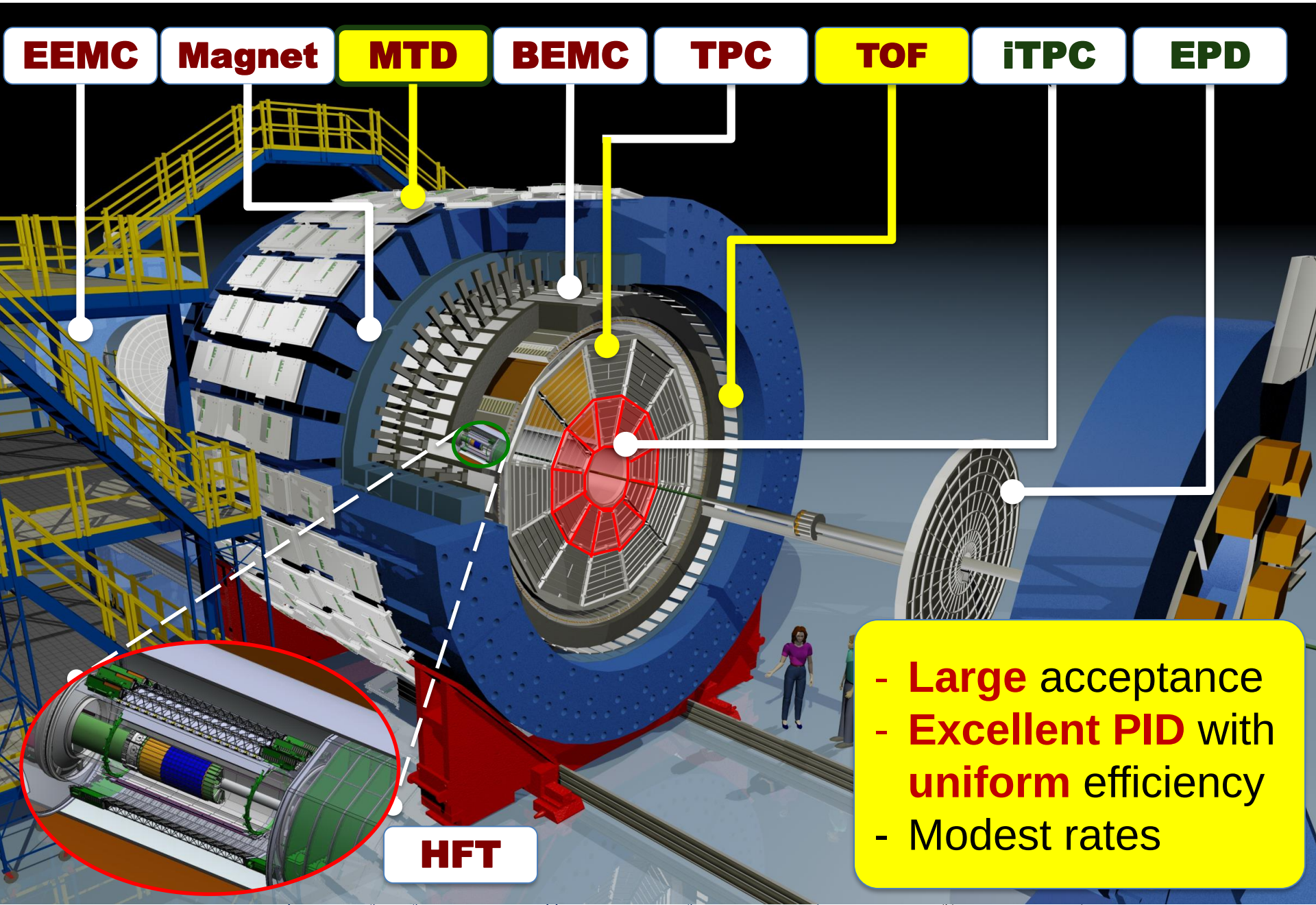
1) Introduction

2) Selected Results from BES-I

(i) **Collectivity**
(ii) Chirality
(iii) **Criticality**

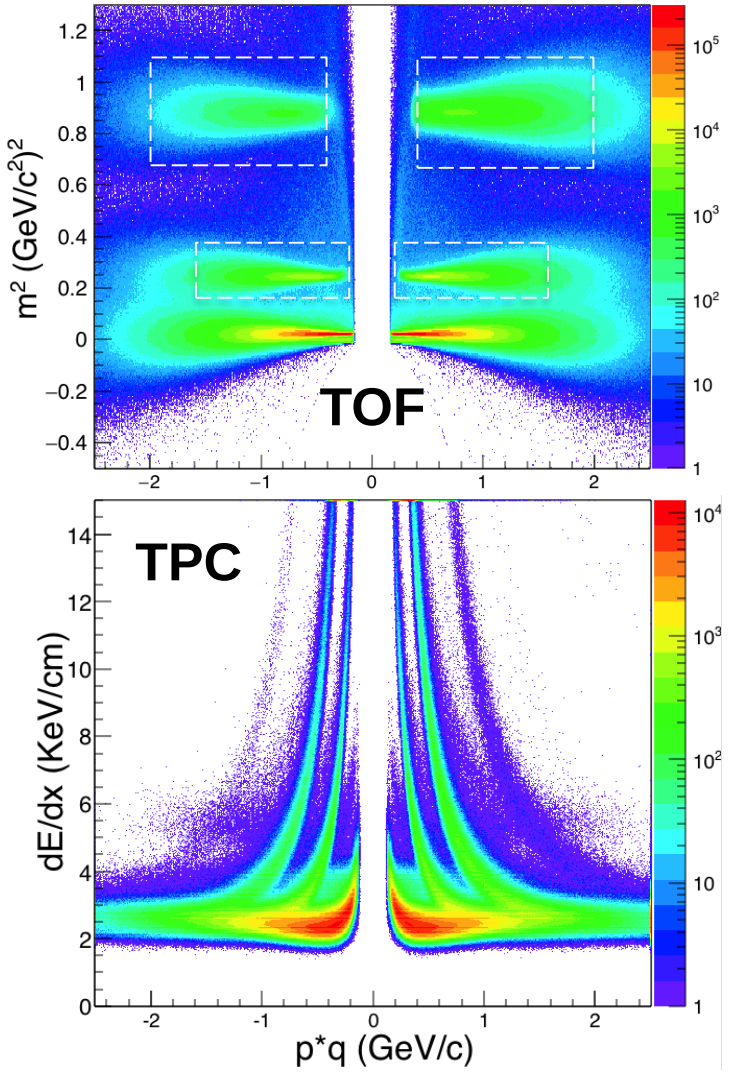
3) BES-II and Beyond

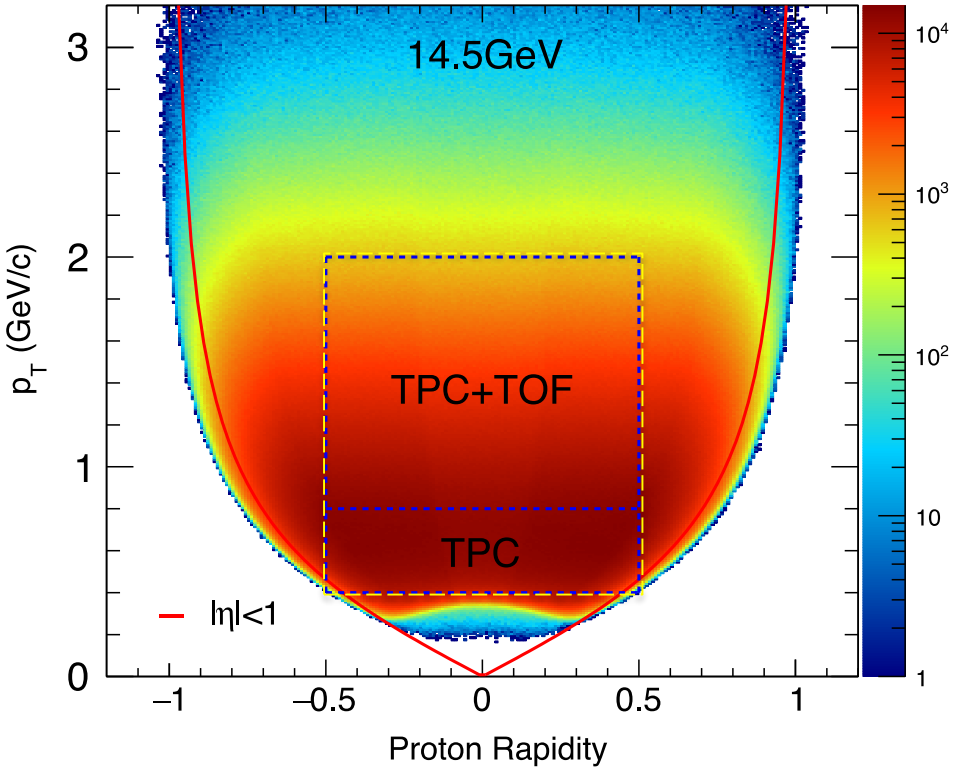
STAR Detector System



Proton Identification with TOF

Published net-proton results: Only TPC used for proton/anti-proton PID. TOF PID extends the phase space coverage.





Acceptance: $|y| \le 0.5$, $0.4 \le p_T \le 2$ GeV/c

Efficiency corrections:

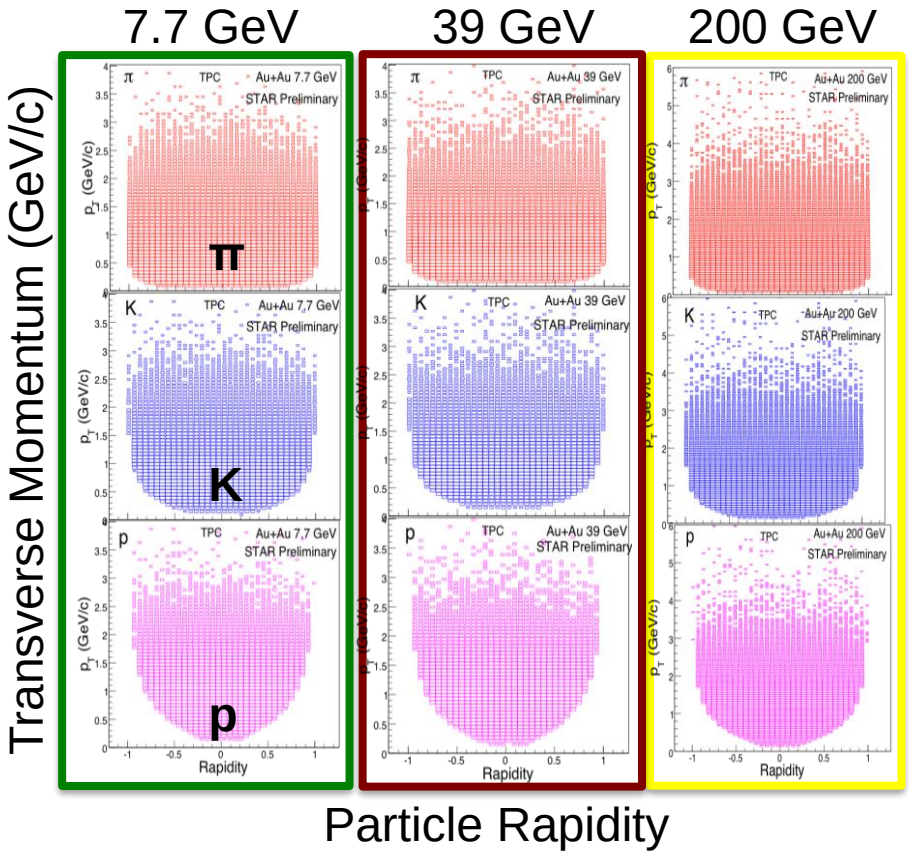
TPC ($0.4 \le p_T \le 0.8$ GeV/c): **$\varepsilon_{TPC} \sim 0.8$**

TPC+TOF ($0.8 \le p_T \le 2$ GeV/c): **$\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$**

20 years | STAR COLLABORATION

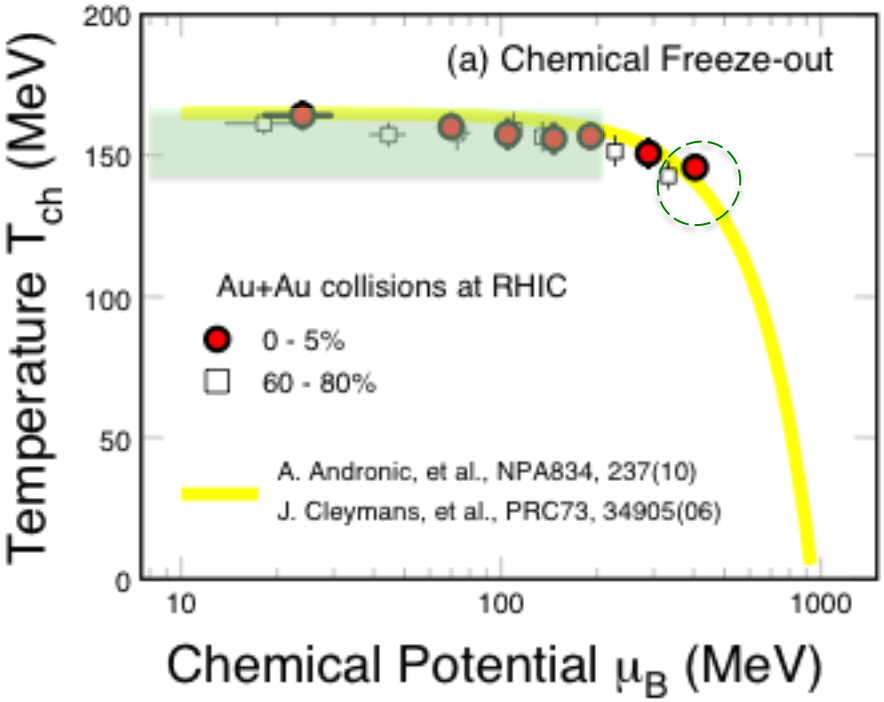
Data Sets for BES-I Program

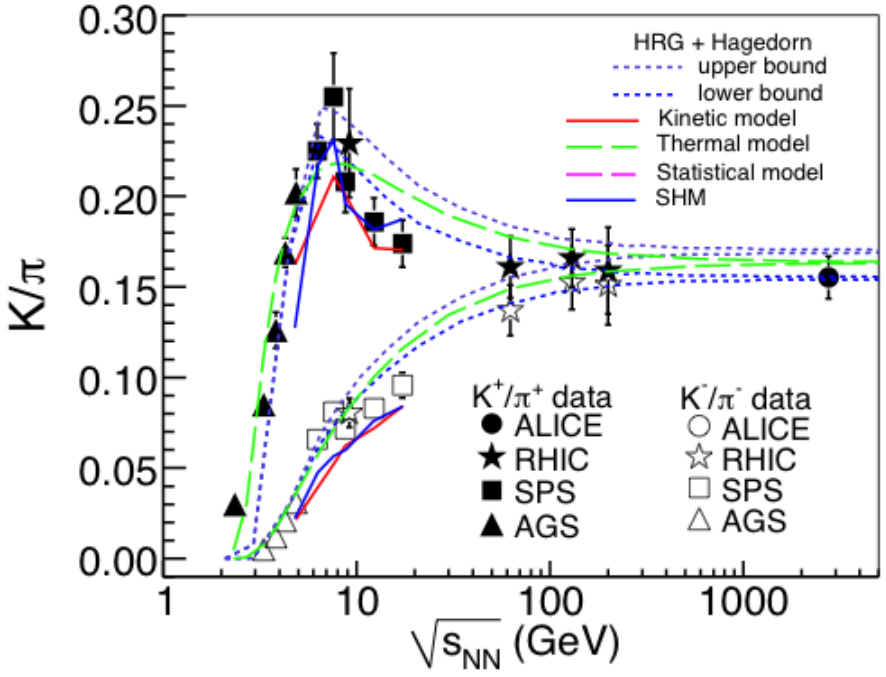
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
54.4	**1200**	**2017**
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010



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

Bulk Properties at Freeze-out





Chemical Freeze-out: (GCE)

- Weak temperature dependence
- Centrality dependence μ_B!
- LGT: **CP about $\mu_B \geq 500$ MeV?**

- The **K^+/π** ratio peaks at $\sqrt{s_{NN}} \sim 8$ GeV where model also predicted the peak of baryon density
- **HBDR**: ($\sqrt{s_{NN}} < 8$ GeV, $\mu_B \geq 420$ MeV)

- ALICE: B.Abelev et al., PRL109, 252301(12); PRC88, 044910(13).
- STAR: J. Adams, et al., NPA757, 102(05); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14)
- J. Randrup and J. Cleymans, Phys. Rev. **C74**, 047901(06)

Collectivity

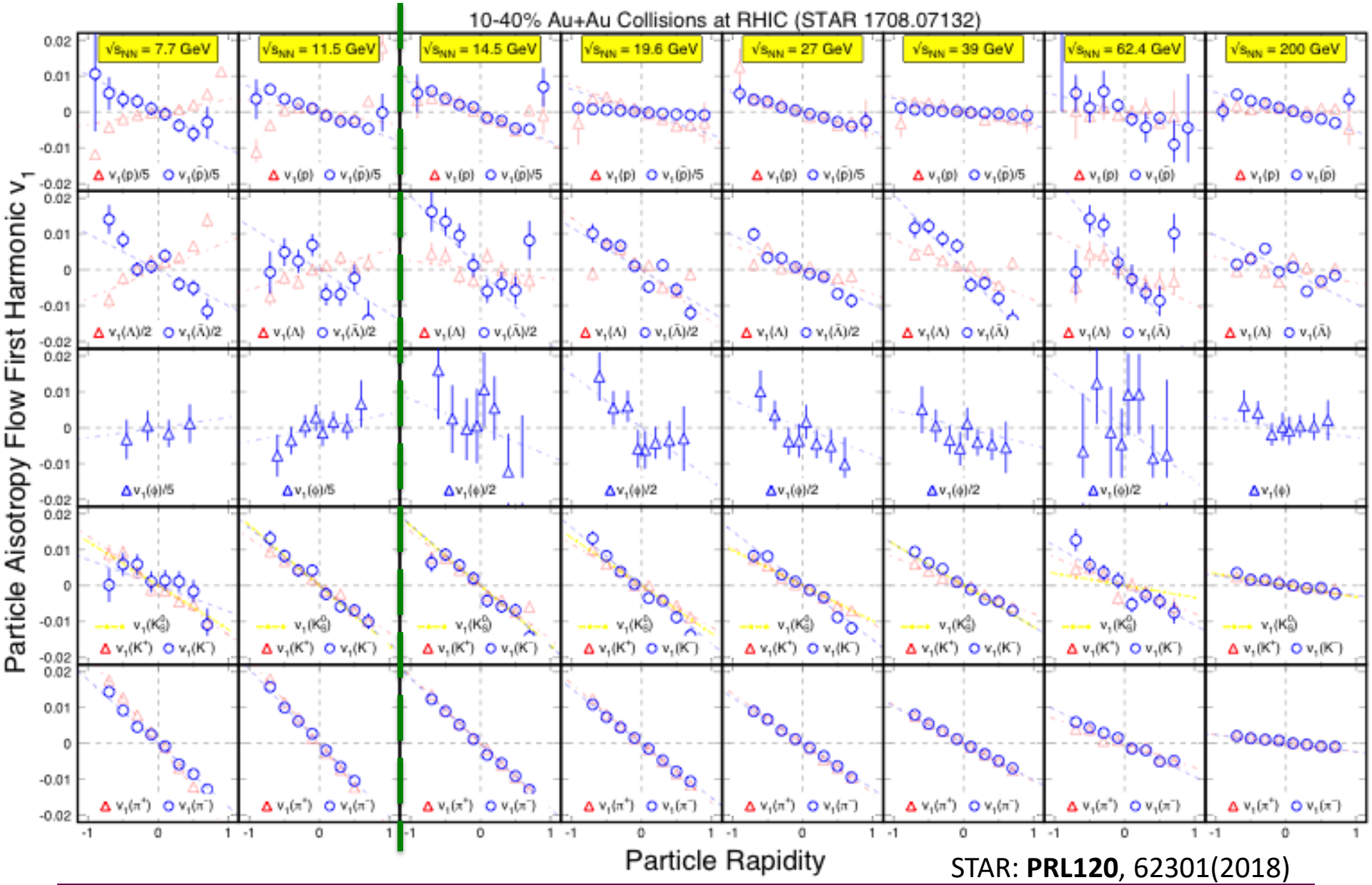
$$\partial_\mu [(\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu}] = 0$$
$$\partial_\mu [s\, u^\mu] = 0$$

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

– Ψ_R event-plane angle

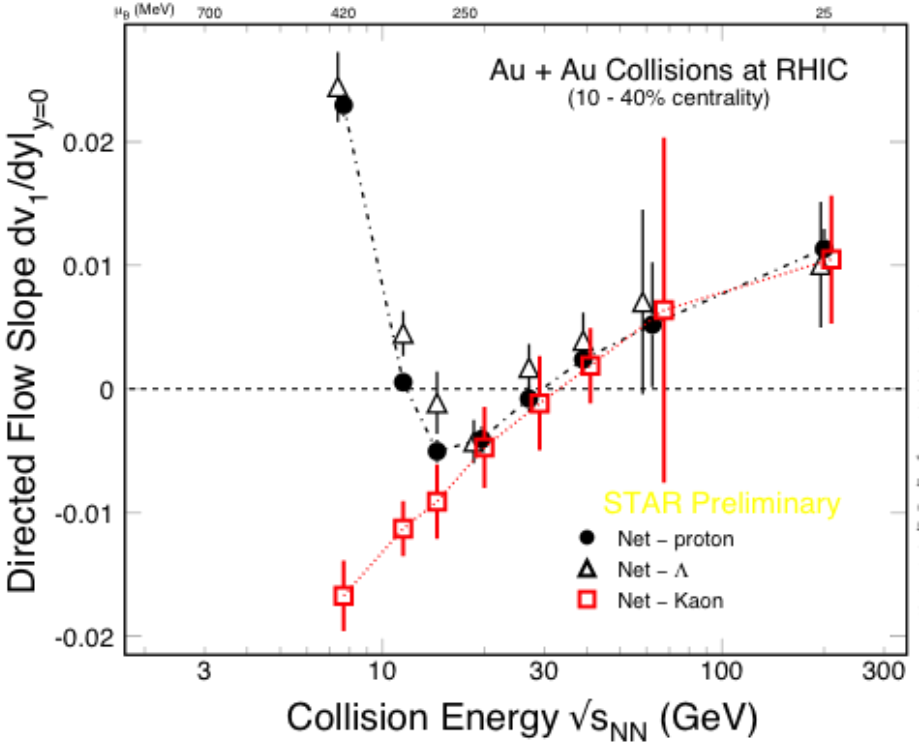
– v_1 Directed flow; – v_2 Elliptic flow; – v_3 Triangle flow

v_1 versus Collision Energy



STAR: **PRL120**, 62301(2018)

v_1 vs. Energy: Softest Point?



STAR: PRL**112**, 162301(2014)
STAR: PRL**120**, 62301(2018)

1) Minimum at $\sqrt{s_{NN}}$ = 10 GeV for net-proton and net-Λ, but net-Kaon data continue decreasing as energy decreases

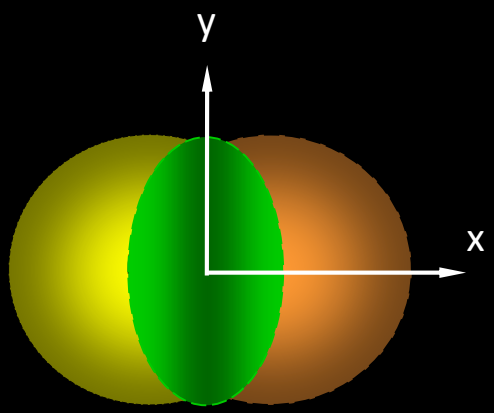
2) At low energy, or in the region where the net-baryon density is large, ***repulsive force*** is expected, v_1 slope is large and positive!

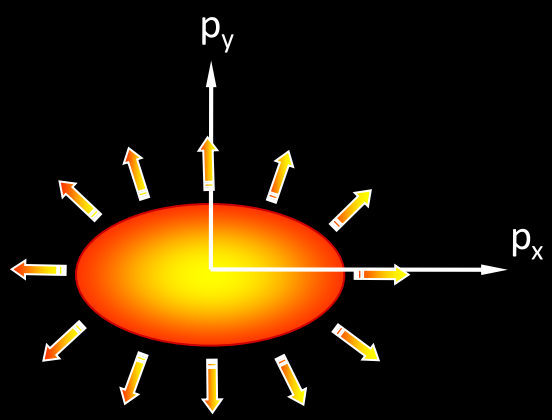
3) Softest point only for baryons?

- M. Isse, A. Ohnishi et al, PR **C72**, 064908(05)
- Y. Nara, A. Ohnishi, H. Stoecker, PRC94, 034906(16), arXiv: **1601.07692**

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇩ momentum-space-anisotropy

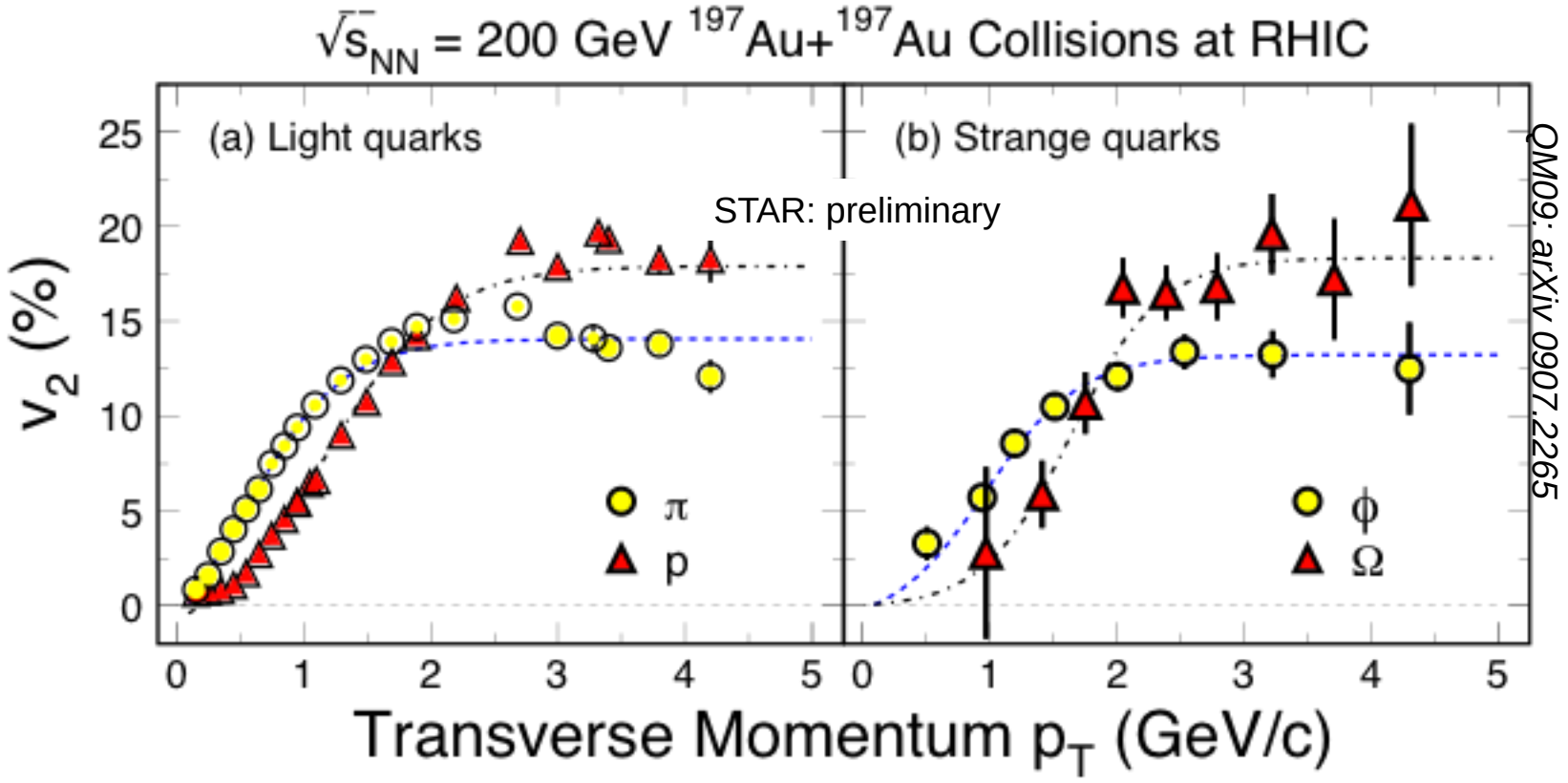




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Partonic Collectivity at RHIC

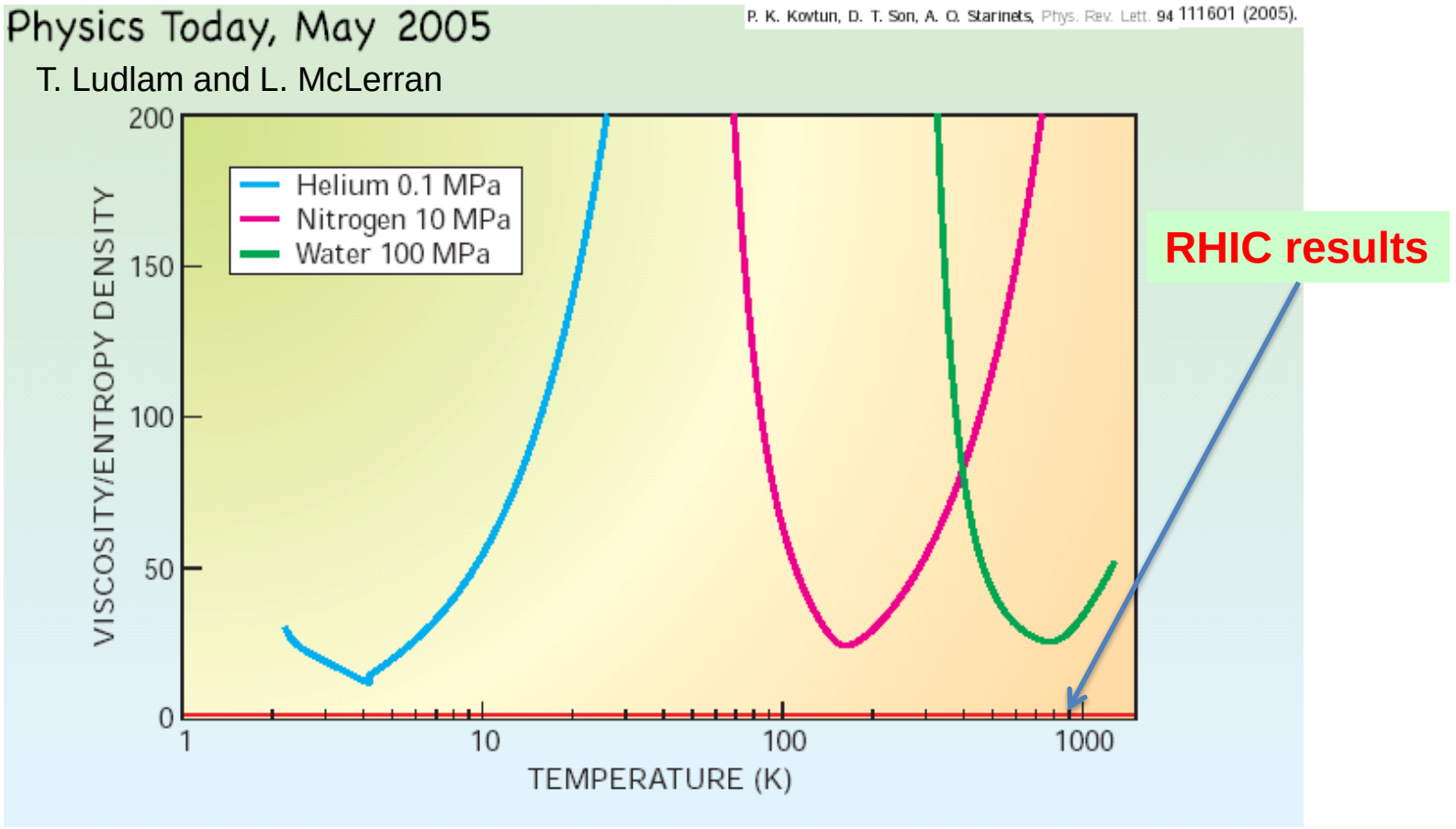


Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks scaling (NCQ)***

➔ ***Partonic Collectivity, necessary for QGP!***

➔ ***De-confinement in Au+Au collisions at RHIC!***

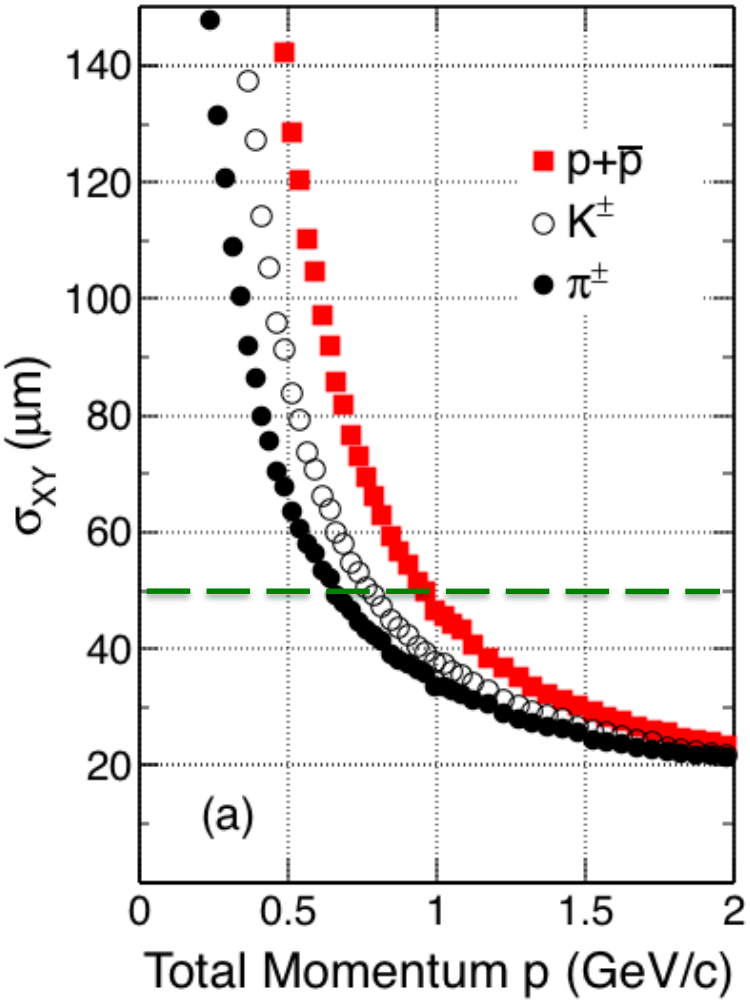
Low η/s for QCD Matter at RHIC

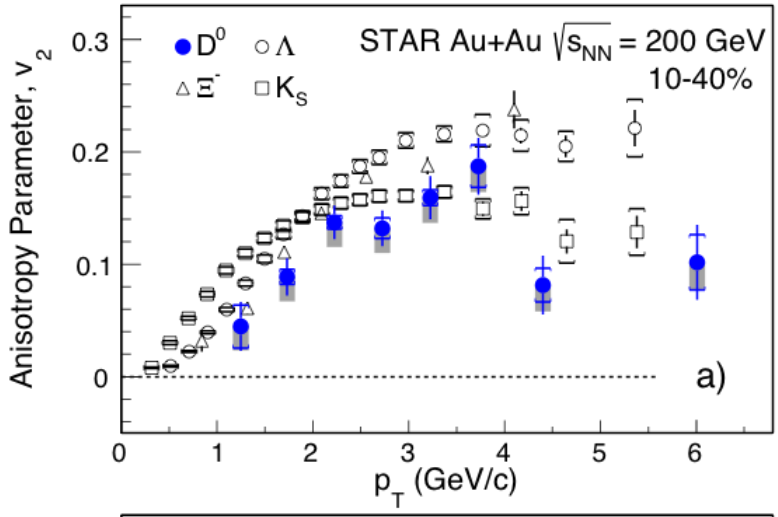


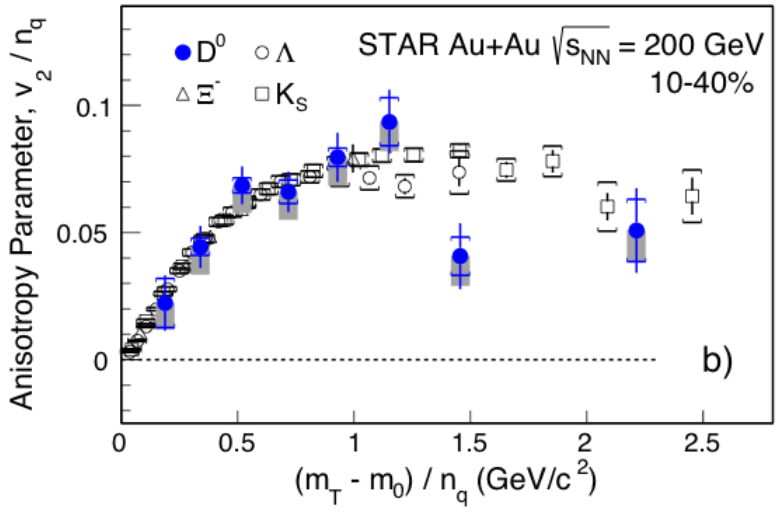
1) $\eta/s \geq 1/4\pi$, *'perfect liquid'*

2) η/s(QCD matter) << η/s(QED matter)

STAR HFT Results: D^0 Collectivity (v_2)



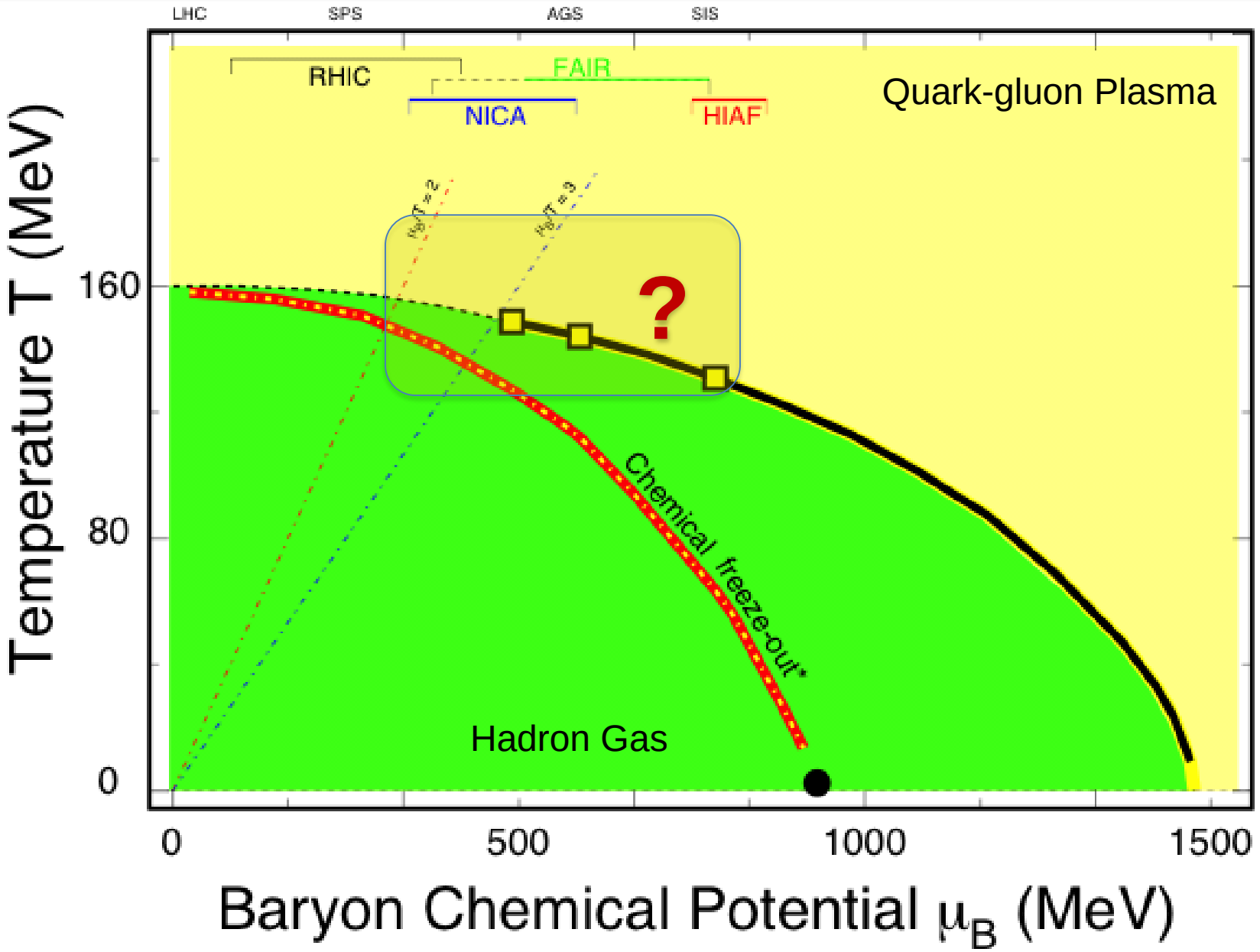




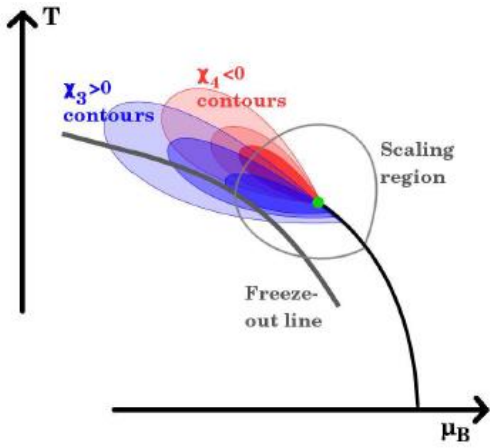
"These results suggest that charm quarks have achieved **local thermal equilibrium** with the medium created in such (200GeV Au+Au) collisions."

STAR: Phys. Rev. Lett. **118**, 212301(2017)

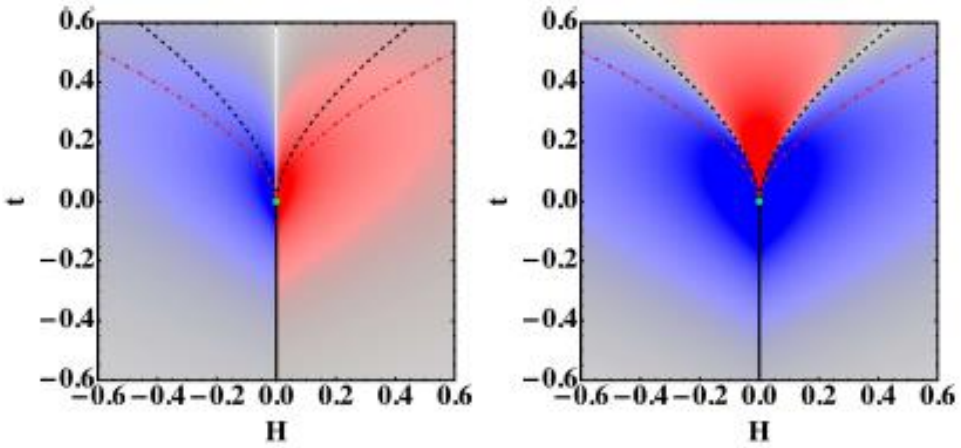
QCD Phase Structure

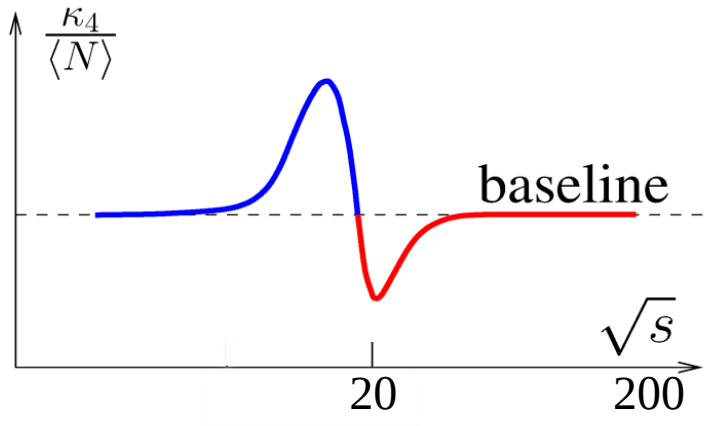


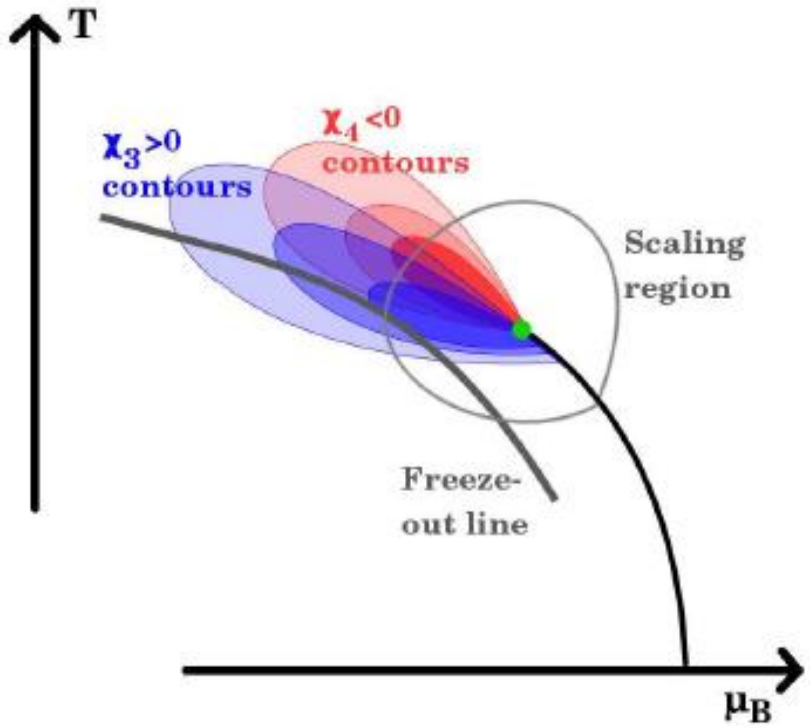
Criticality



Expectation from Model Calculations



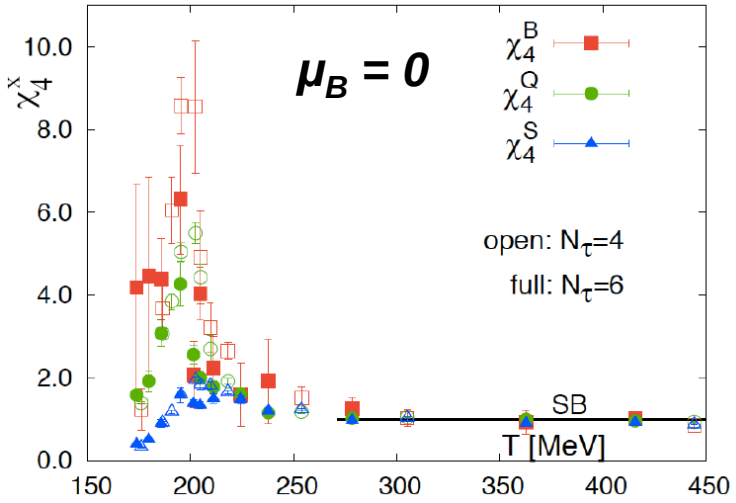


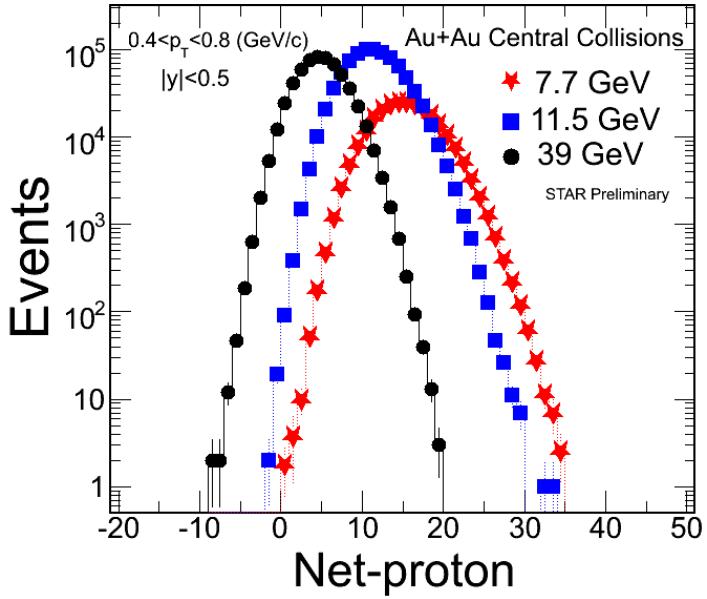


- Characteristic “Oscillating pattern” is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*
- Critical Region (CR)

- M. Stephanov, ***PRL107***, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, Phys. Rev. **D93** (2016) 034037

Higher Moments and Criticality





1) Higher 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:

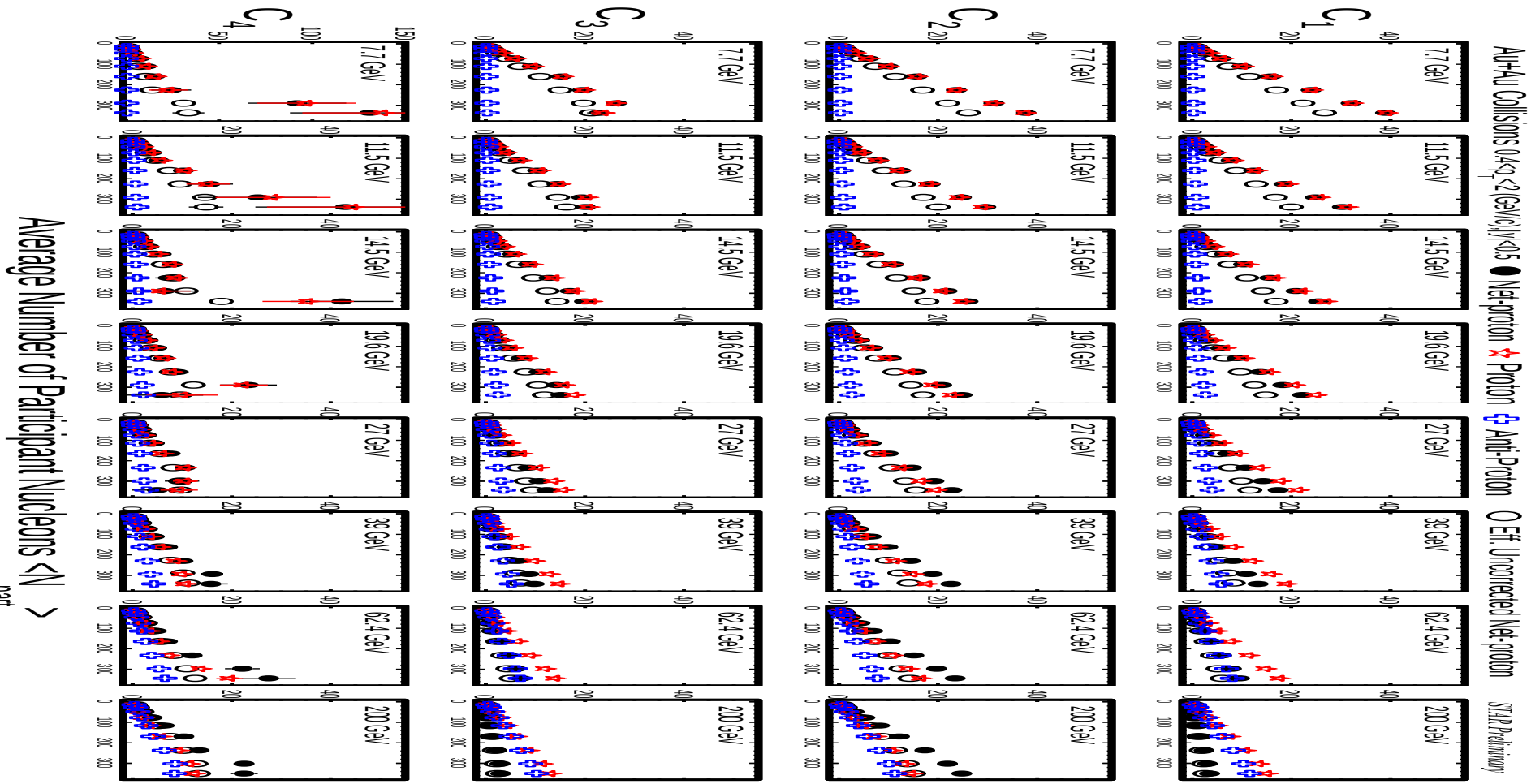
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

References:

- STAR: *PRL* **105**, 22303(10); *ibid*, **112**, 032302(14)
- S. Ejiri, F. Karsch, K. Redlich, *PLB633*, 275(06) // M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB696*, 459(11) // F. Karsch et al, *PLB695*, 136(11),
- A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // V. Skokov et al., PRC88, 034901(13)
- PBM, A. Rustamov, J. Stachel, arXiv:1612.00702, NPA960, 114(17)

Energy Dependence of Net-p

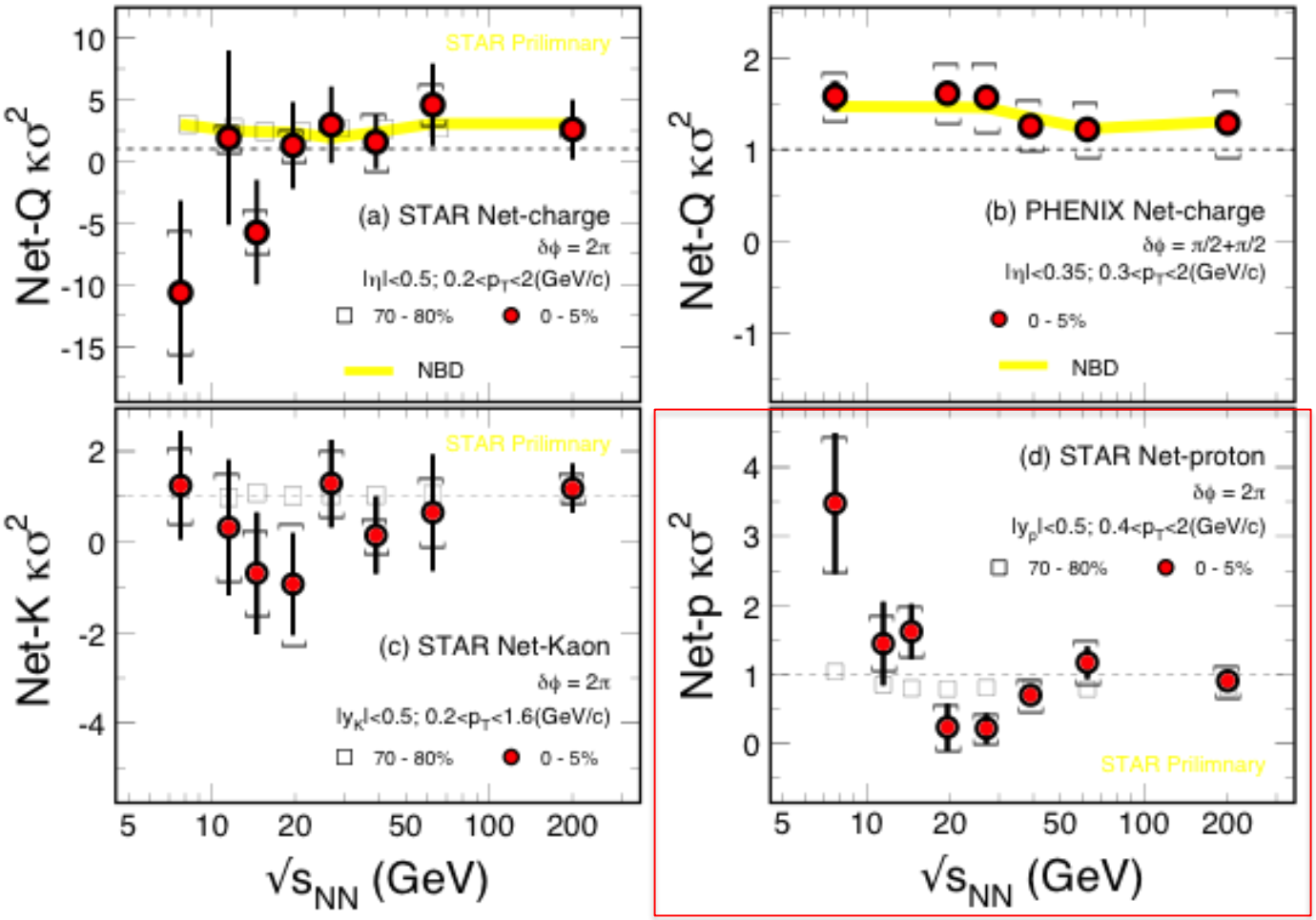


STAR data:

(0-5%) Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, 200 GeV

net-p |y|<0.5, p_T: 0.4 – 2.0 GeV/c

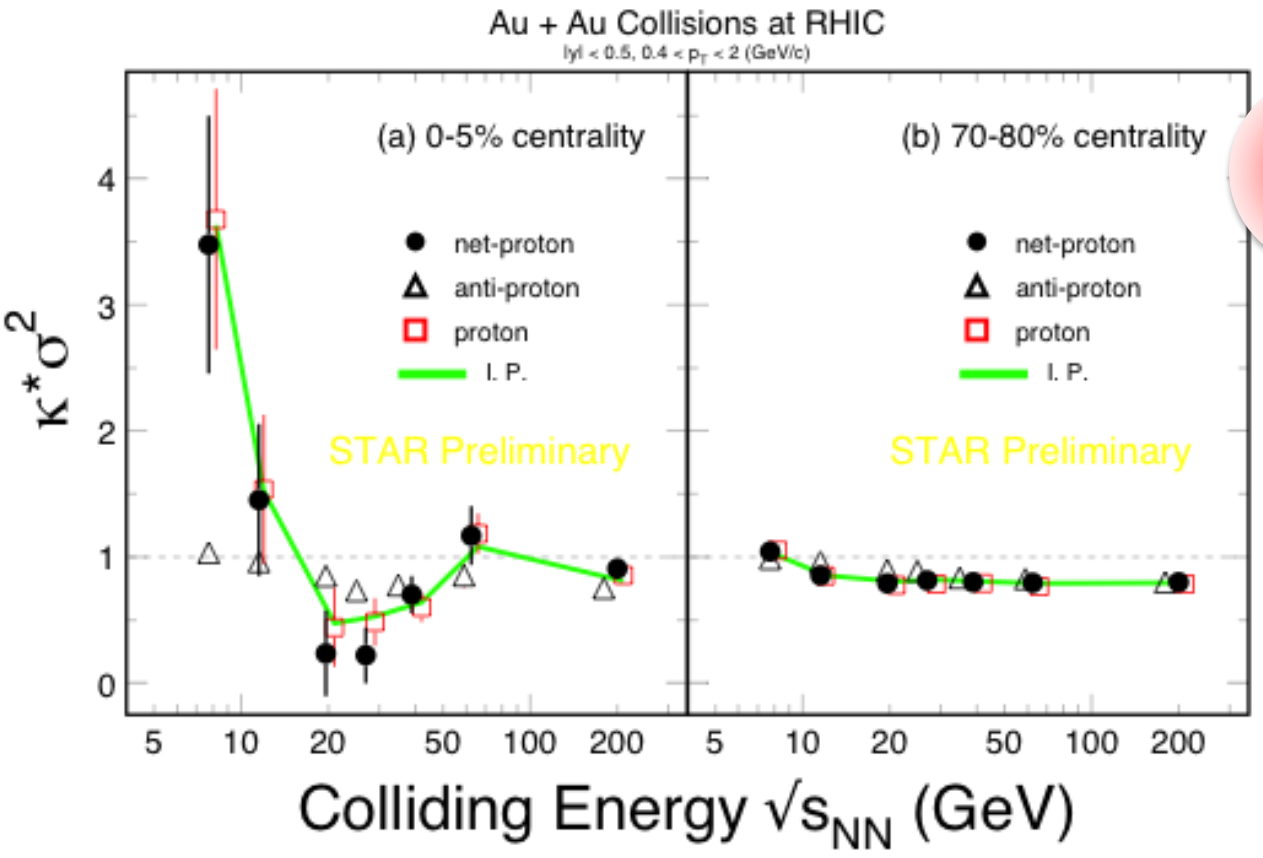
Higher Moments of Net-Q, -K, -p



1) The results of net-Q and net-Kaon show flat energy dependence
2) Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions starting at $\sqrt{s_{NN}}$ < 27 GeV!

Net-proton Higher Moment

central



peripheral

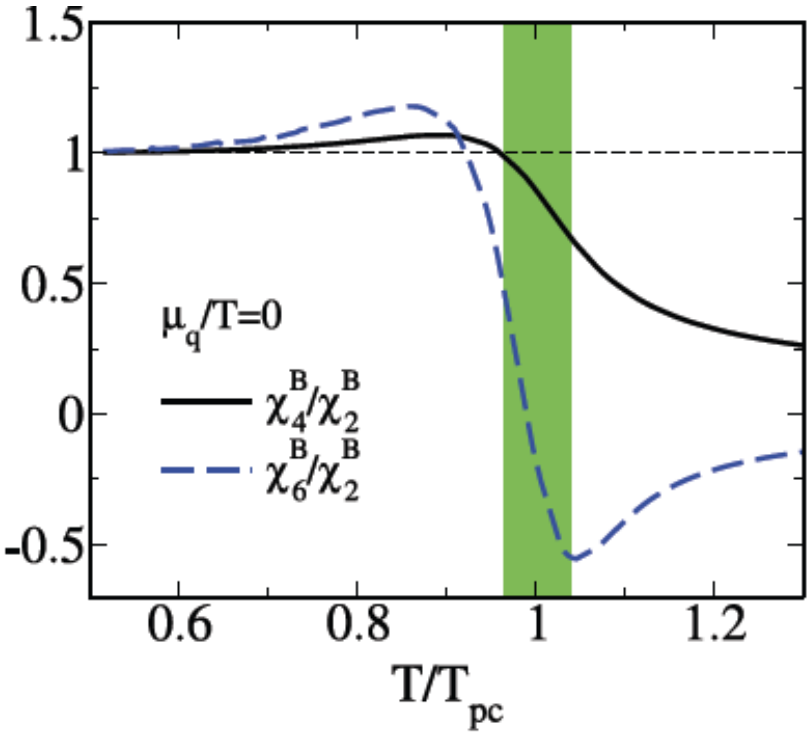
1) Non-monotonic in the most central 0-5% collisions
2) Attractive enhancement at $\sqrt{s_{NN}} < 20$GeV!

X.F. Luo, CPOD2014, QM2015

C_6/C_2

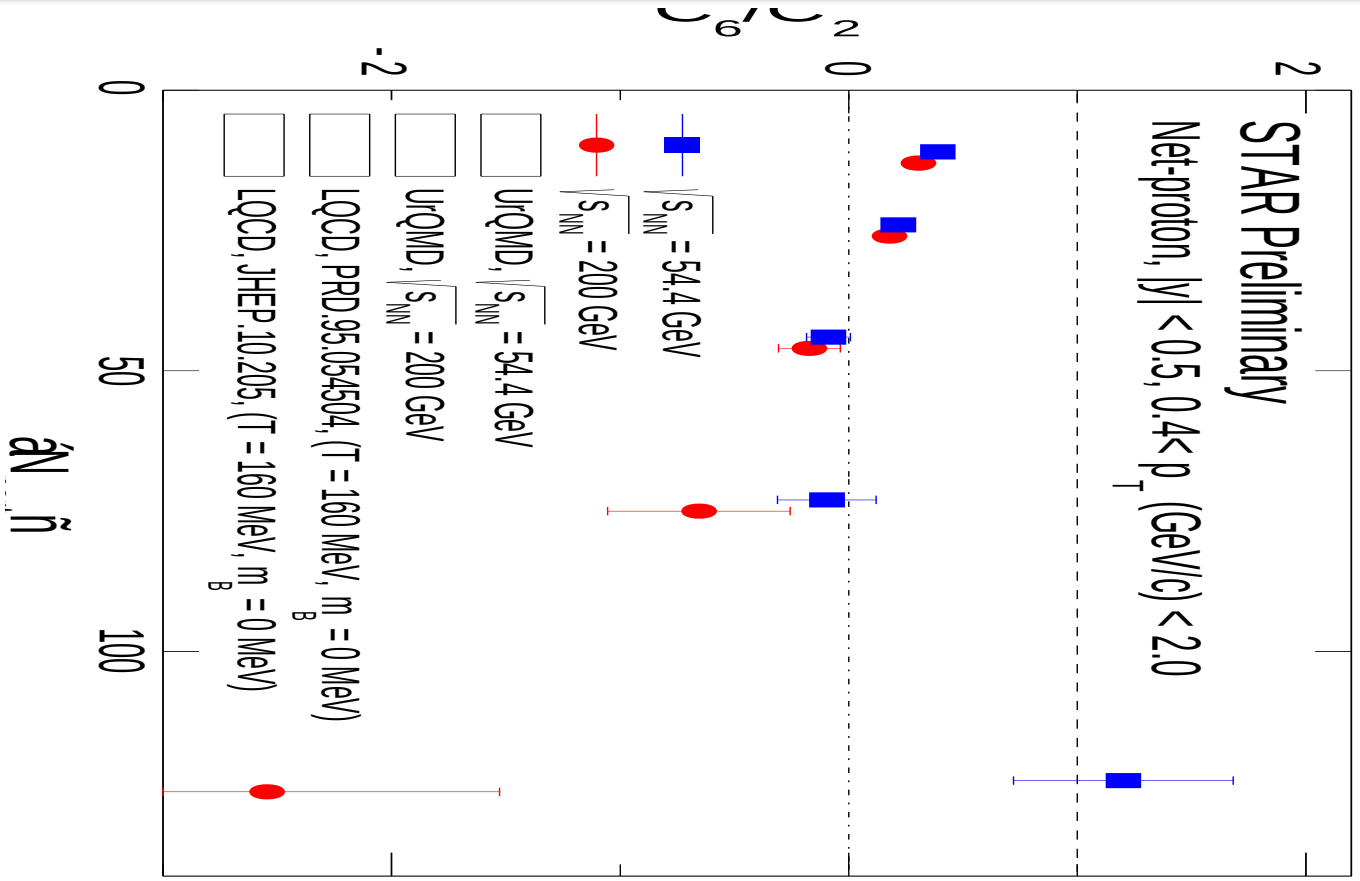
- QUESTION:

  at $\mu_B \sim 0$, sign for smooth crossover?



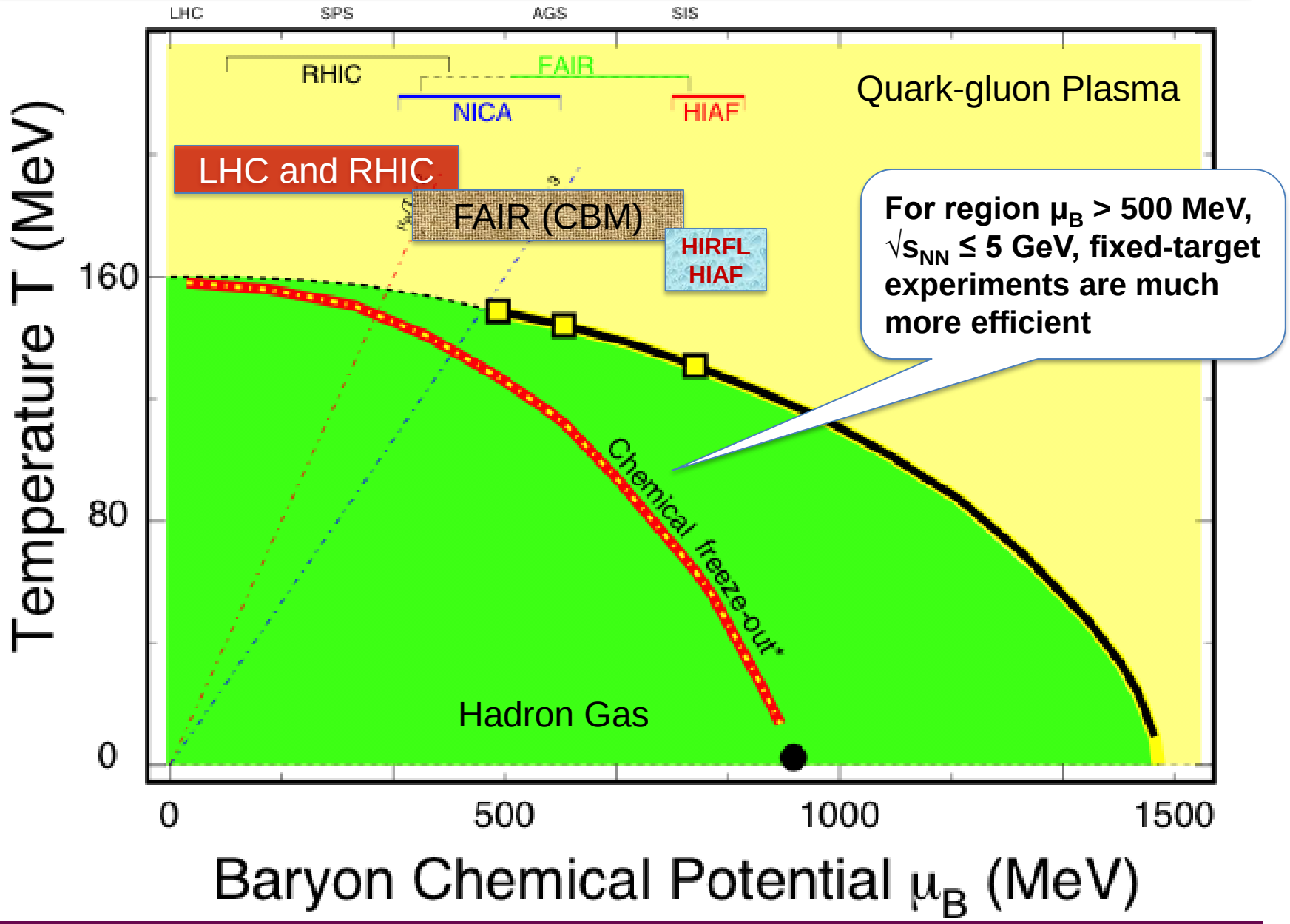
Reference: *B. Friman et al, Eur. Phys. J. C 71:1694(2011)*

C_6/C_2

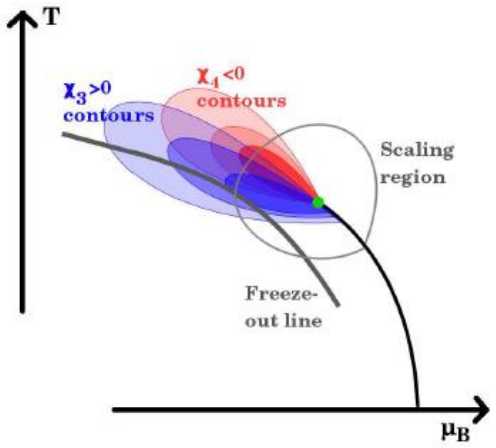


- In central collisions, the ratios of **C6/C2>0 and < 0 for 54.4 and 200GeV**, respectively
- LQCD predictions are consistent with 200GeV central result, not trivial!
- This is qualitatively consistent with the PQM model prediction while UrQMD shows C6/C2>0 for all collisions. LQCD predictions are consistent

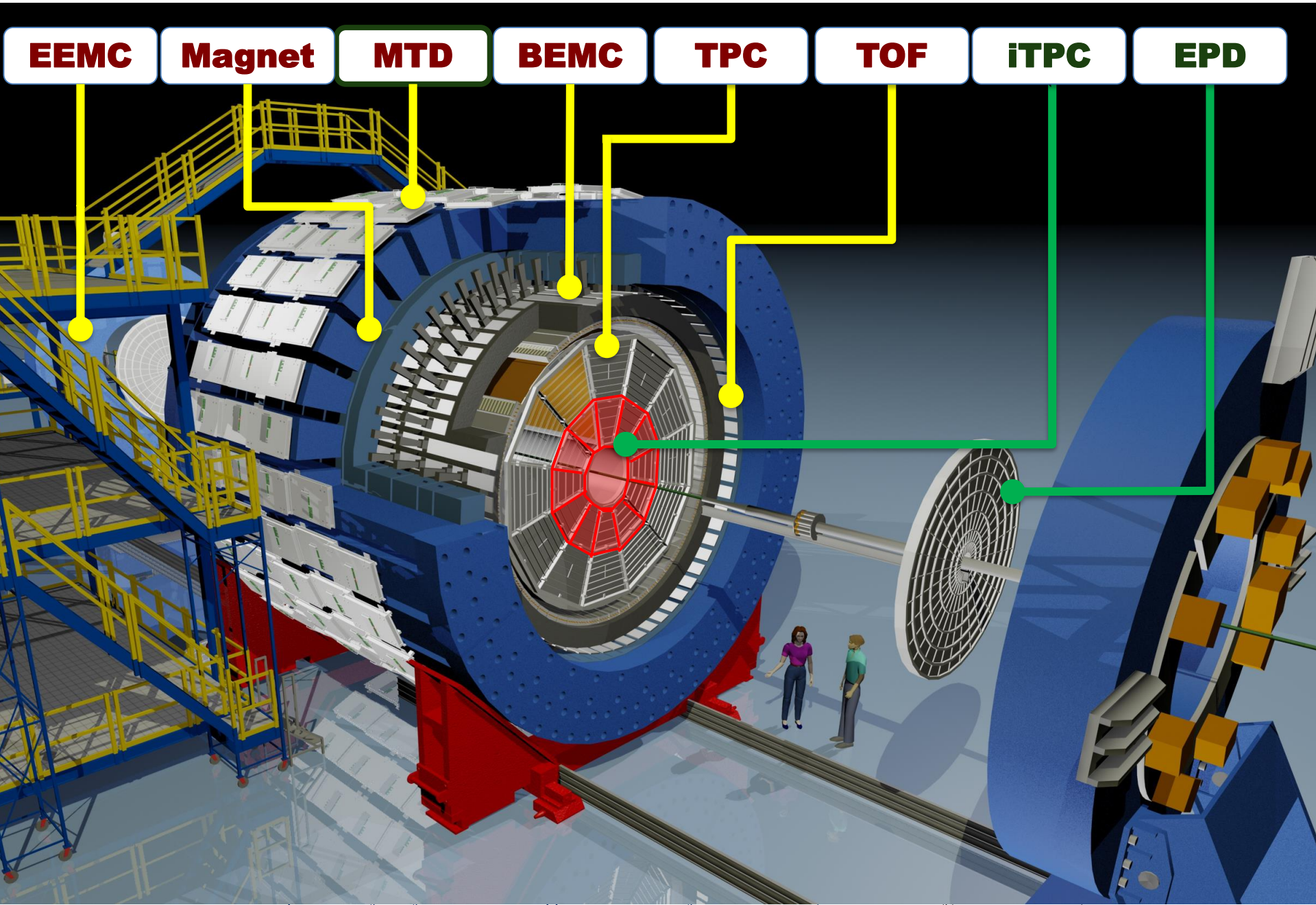
QCD Phase Structure



BES-II & Beyond



STAR Detector System

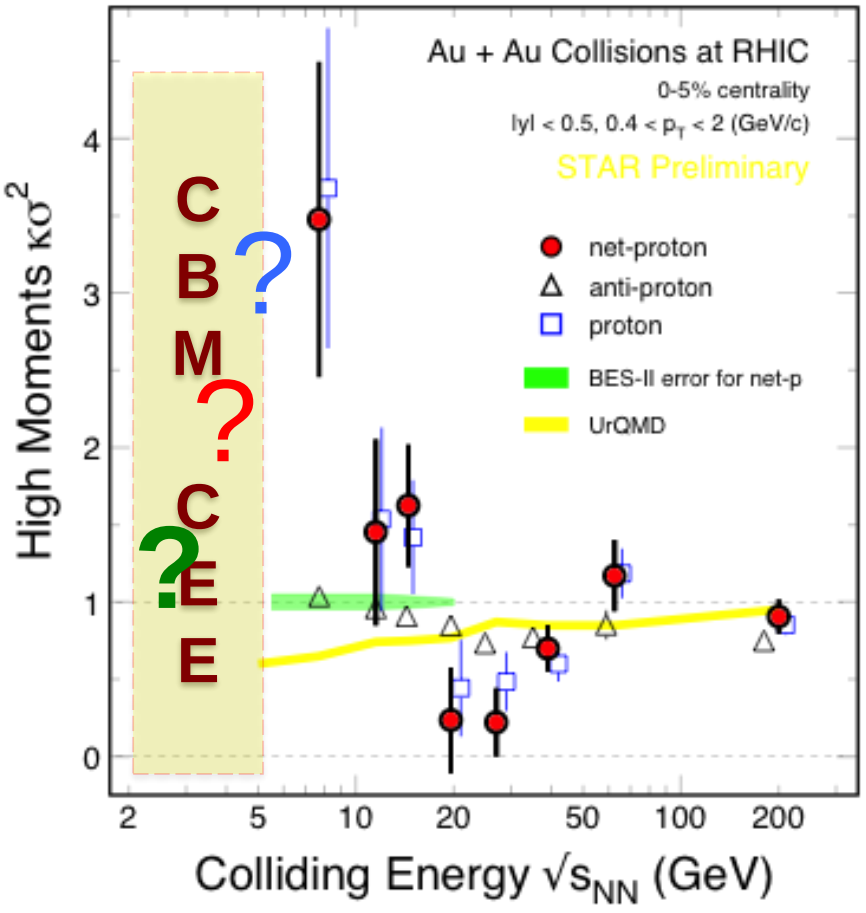


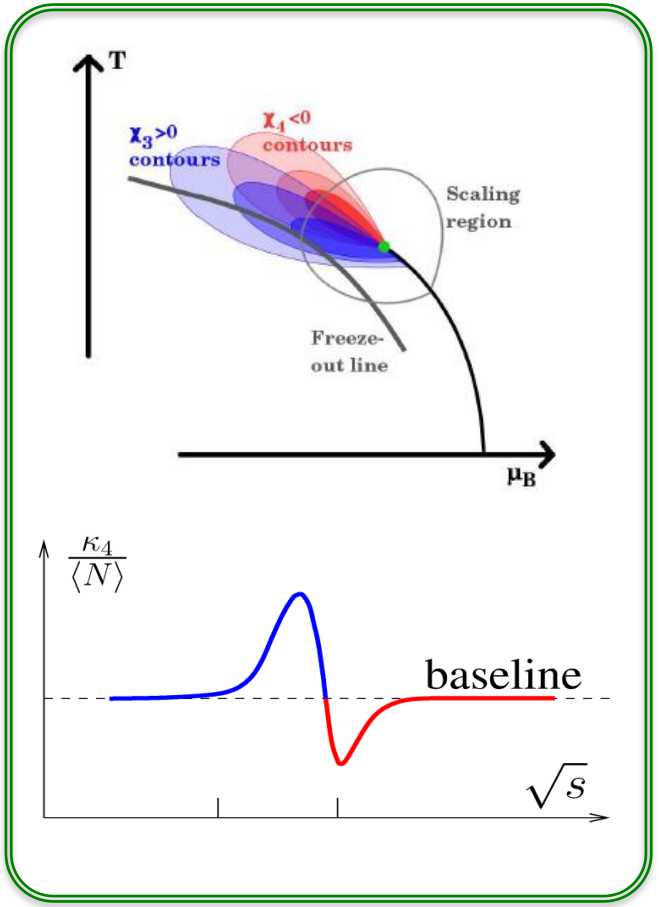
2019 - 2021: BES-II at RHIC

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
54.4	1200	2017		90	
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-21** / 2011	**3**	206	160
14.5	**300** / 20	**2019-21** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-21** / 2010	**5**	315	152
9.2	**160** / 0.3	**2019-21** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-21** / 2010	**14**	420	140

Precision measurements: map the QCD phase diagram **$200 < \mu_B < 420$MeV**

QCD Critical Point



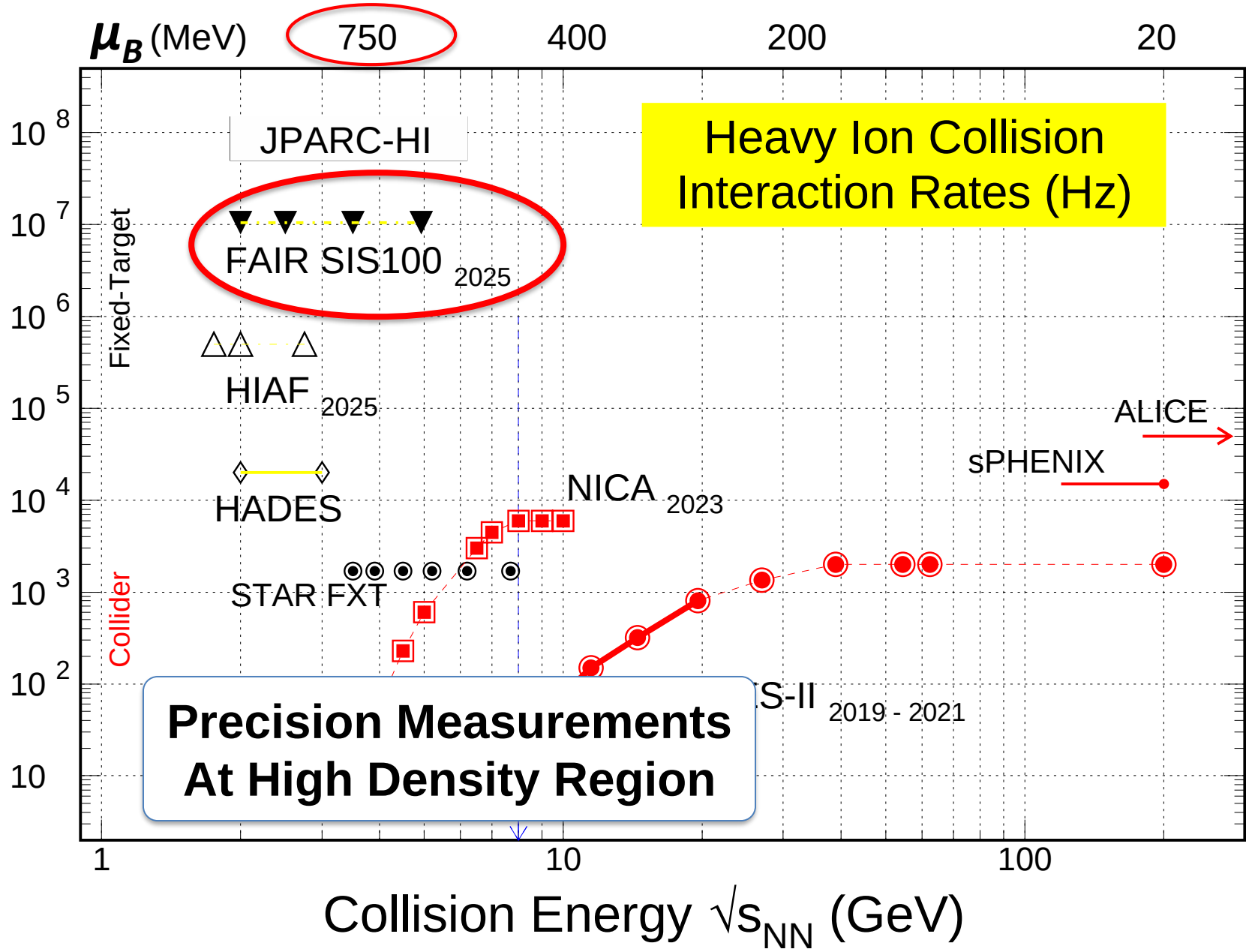


- RHIC BES-II: dramatically reduce the errors!
- CBM Experiments (**2.5 < √s_{NN} < 8** GeV) :

  Key region for Critical Point search

STAR Data: X.F. Luo *et al*, CPOD2014, QM2015; PRL**112** (2014) 32302

Future Facilities for Heavy Ion Collisions



Acknowledgements

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

// BLUE: Theory // **RED**: Exp., high moment //

Thank you for your attention!