Study of the QCD Medium Properties at Finite Baryon Density

- Recent Results from the Beam Energy Scan at RHIC

Nu Xu[1,2]

Many Thanks to the Organizers!

[1] *College of Physical Science & Technology, Central China Normal University, China*
[2] *Nuclear Science Division, Lawrence Berkeley National Laboratory, USA*

Outline

(1) Introduction

(2) Recent Results from BES-I at RHIC

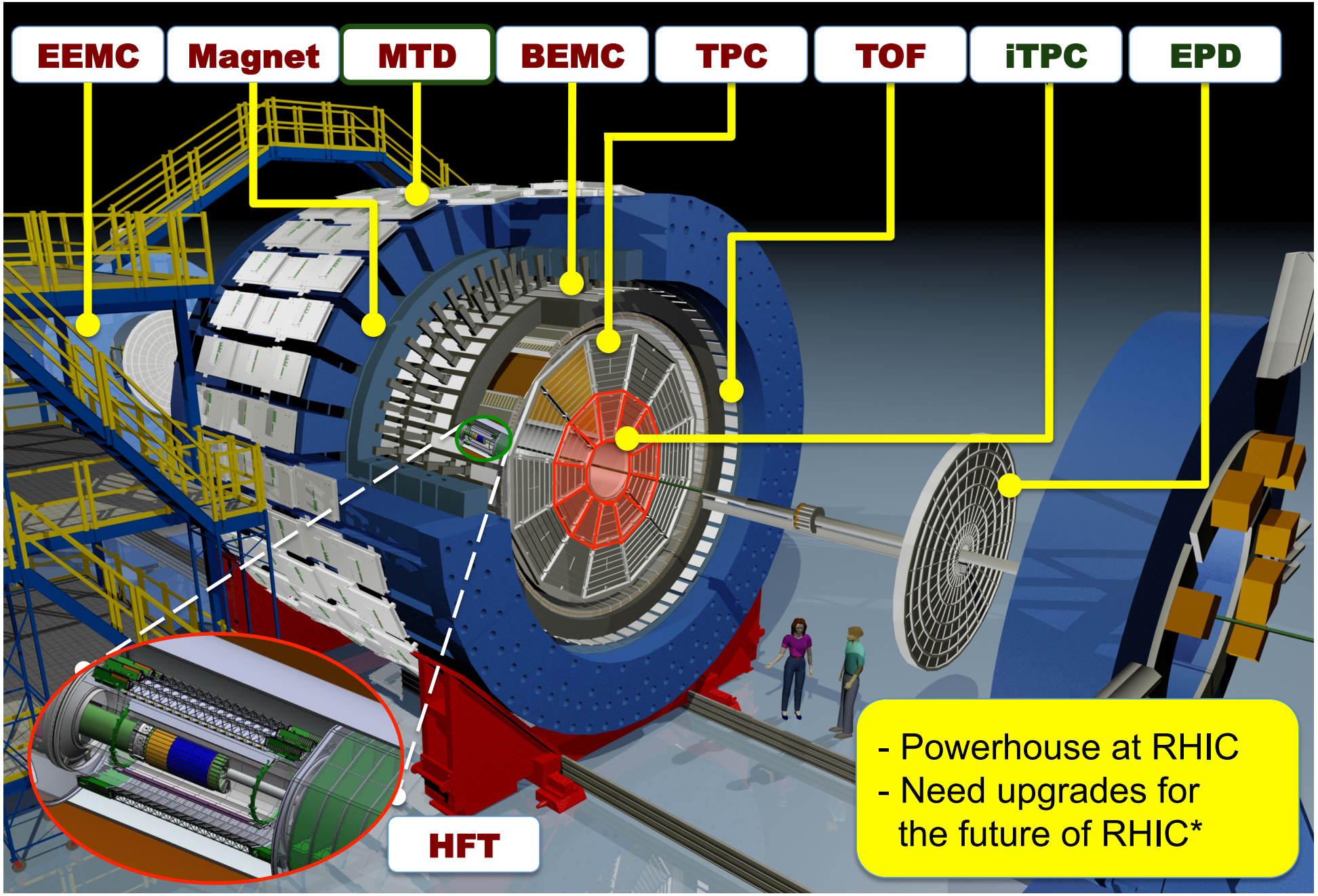
i. Collectivity

ii. Criticality

(3) BES-II and Beyond

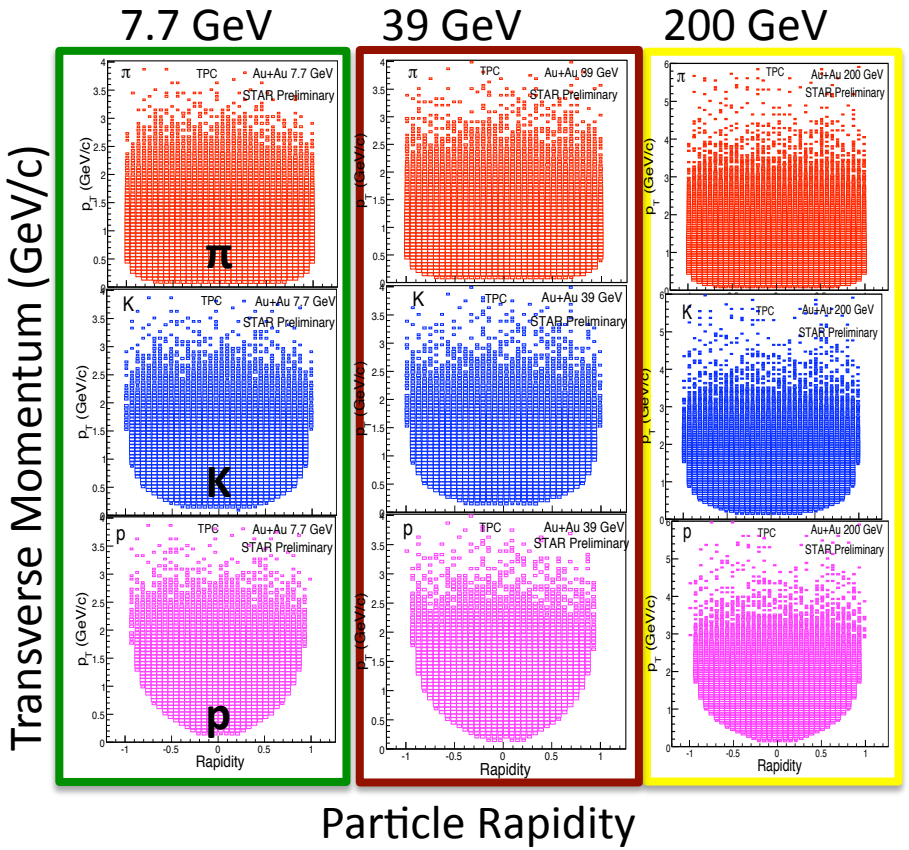
QCD Emergent Properties

STAR Detector System



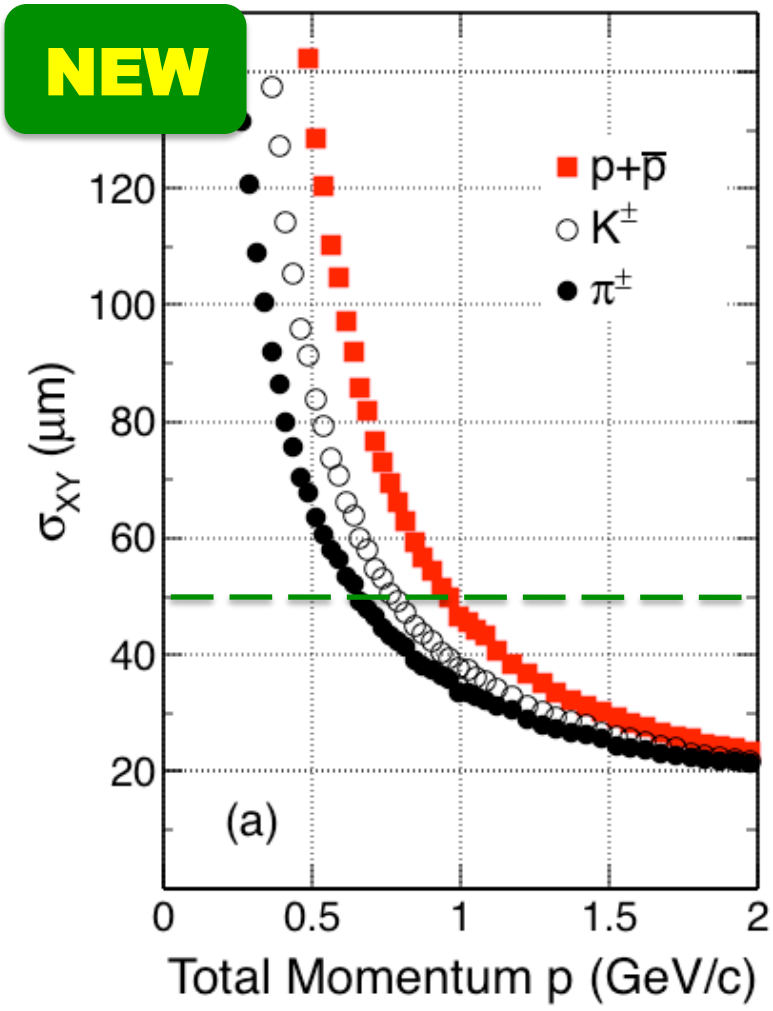
Data Sets for BES-I Program

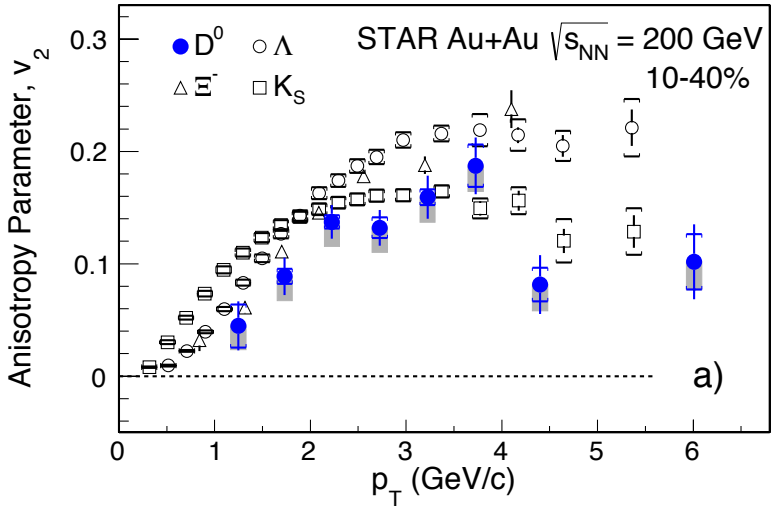
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
54.4	**1000**	**2017**
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010

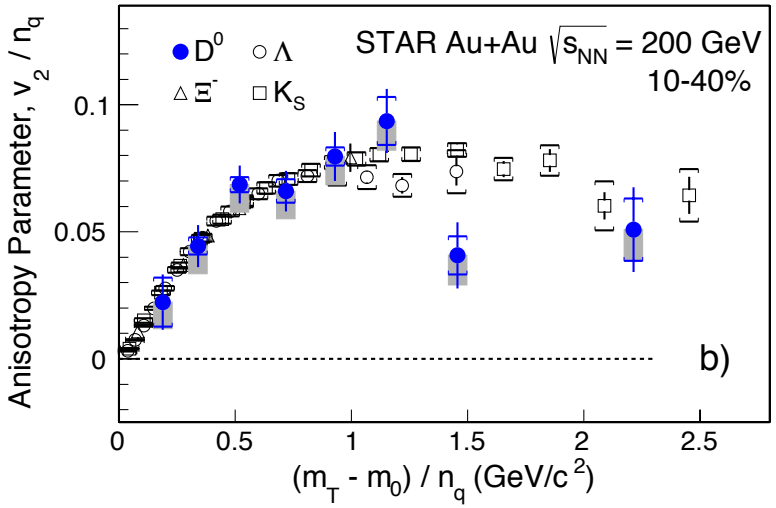


1) Largest data sets versus collision energy
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. Especially important for fluctuation analysis

STAR HFT Results: D^0 Collectivity (v_2)





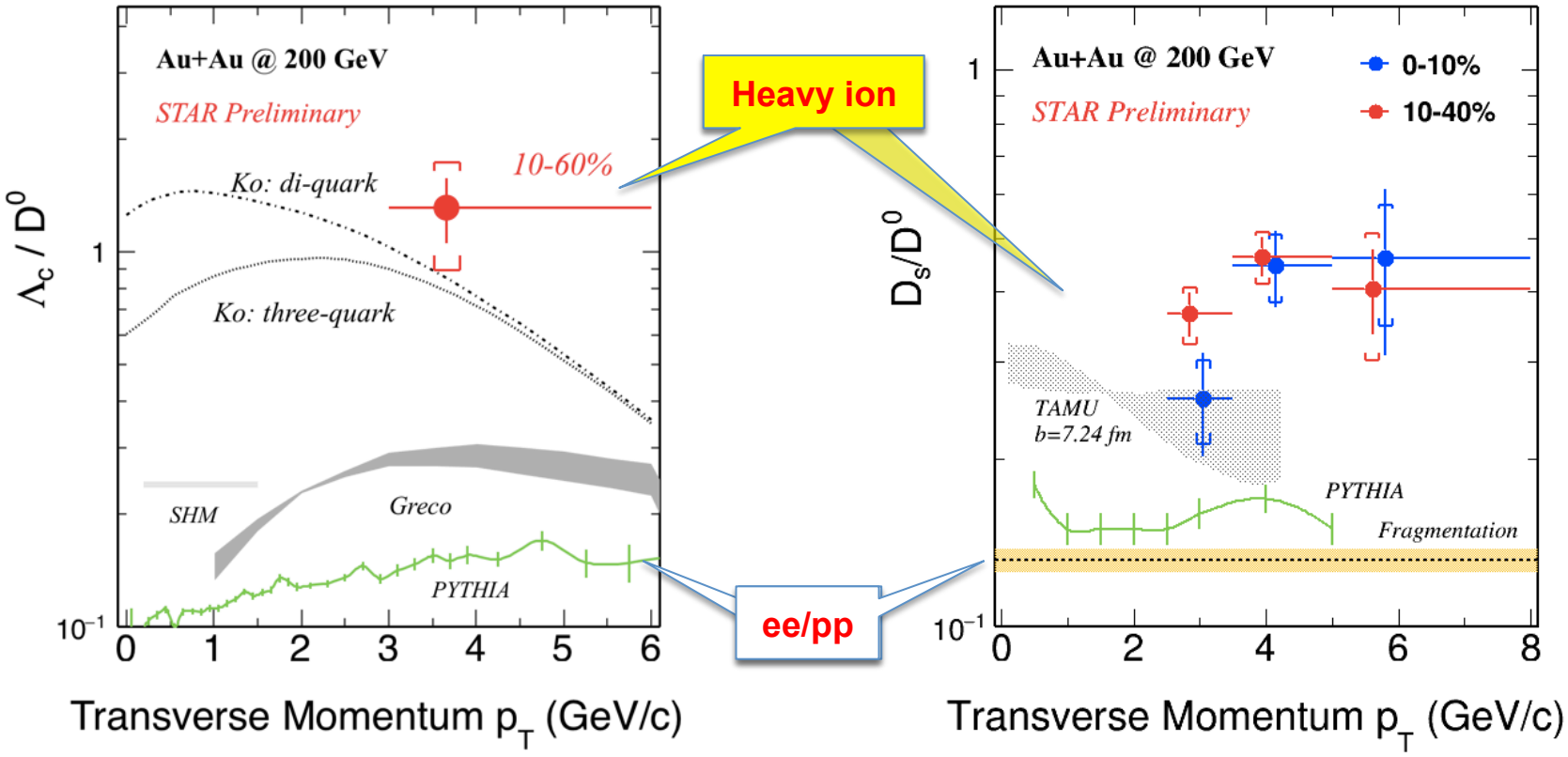


"These results suggest that charm quarks have achieved local thermal equilibrium with the medium created in such (200GeV Au+Au) collisions."

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

NEW

Λ_c/D^0 and D_s/D^0 Ratios



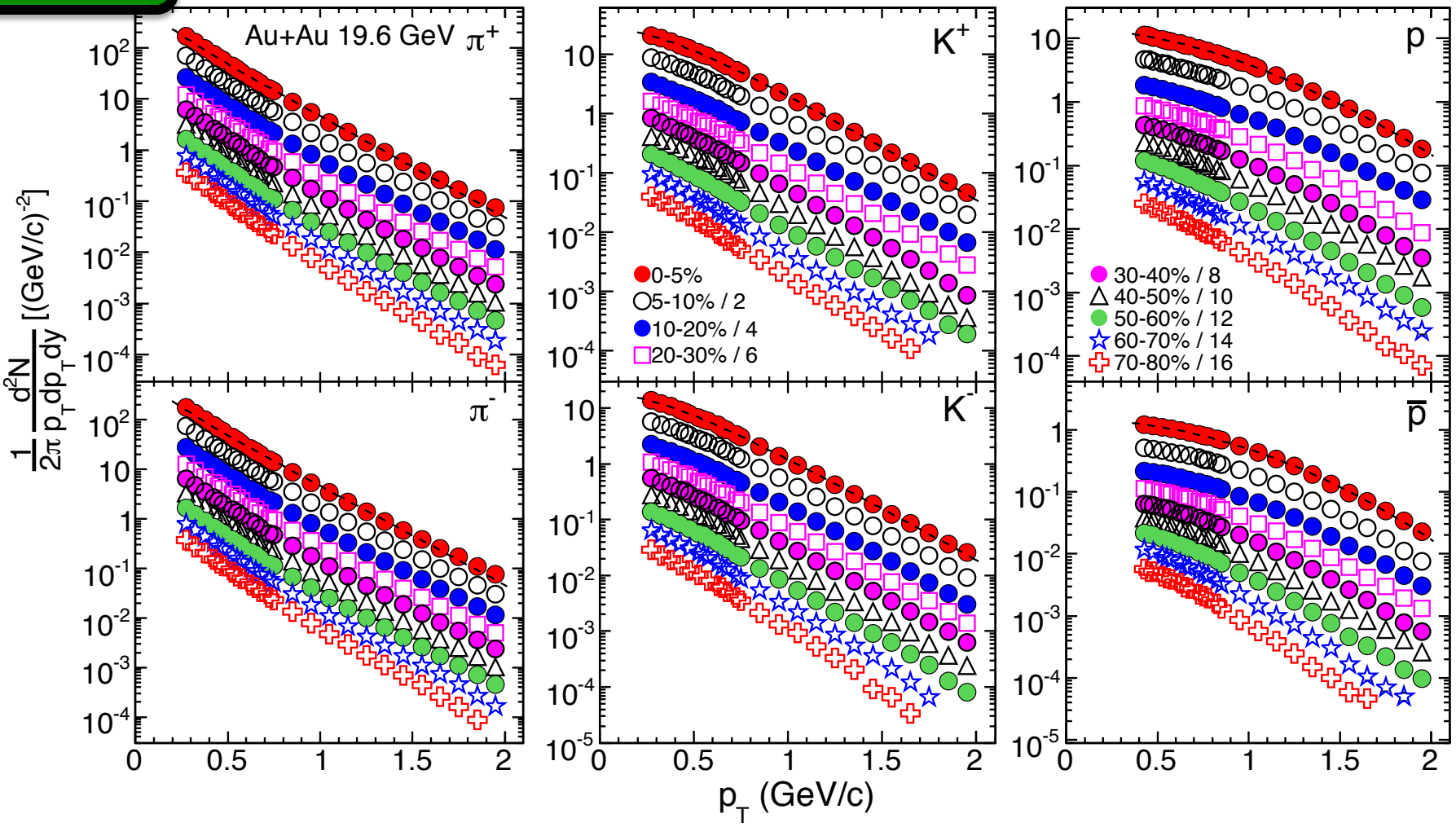
RHIC: Need more data on heavy quark hadron, both charm- and bottom-hadrons, in order to extract the properties of the QGP!

PRC**79**, 044905(09); S. Ghosh *et al.*, PRD**90**, 054018(14)

STAR: Hadron Spectra from BES-I

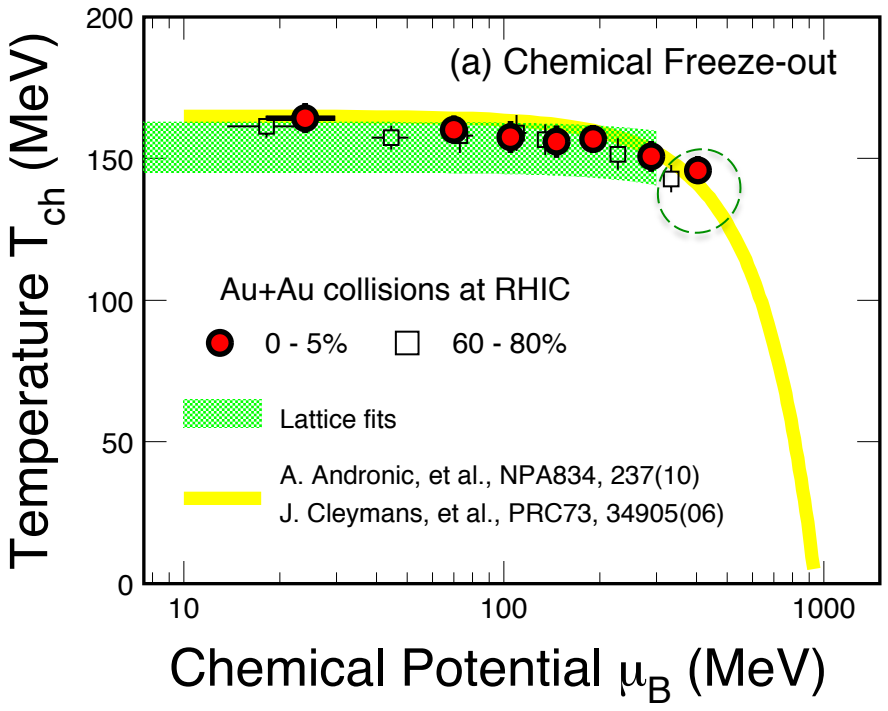
NEW

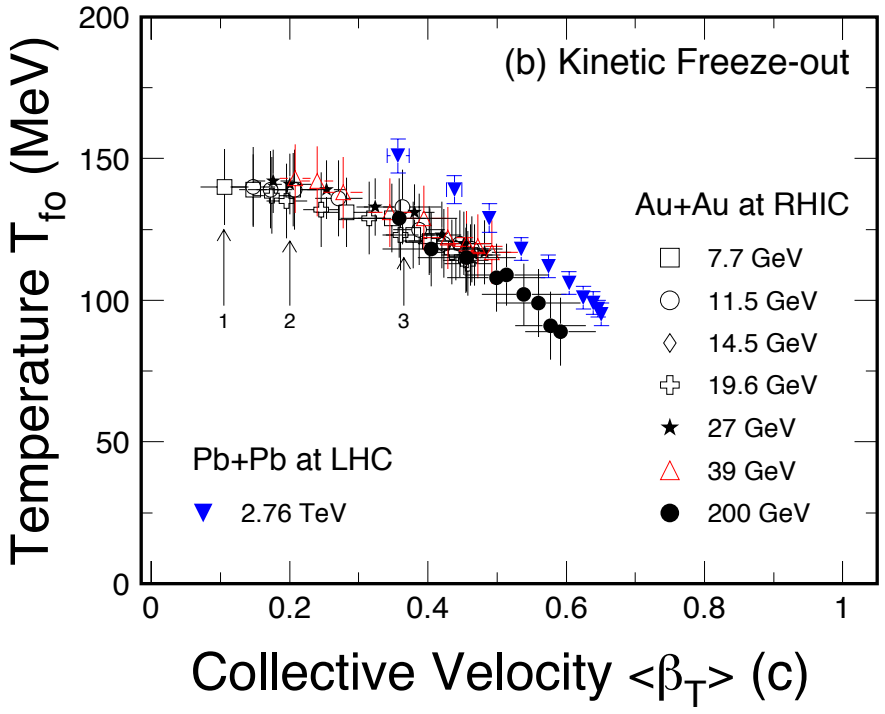
$\sqrt{s_{NN}}$ = *19.6* GeV Au+Au Collisions



STAR: arXiv:1701.07065, PRC**96**, 44904(2017)

Bulk Properties at Freeze-outs





Chemical Freeze-out: (GCE)

- Weak temperature dependence
- Centrality dependence μ_B!
- LGT calculations indicate the Critical Region around μ_B **~ 300 MeV?**

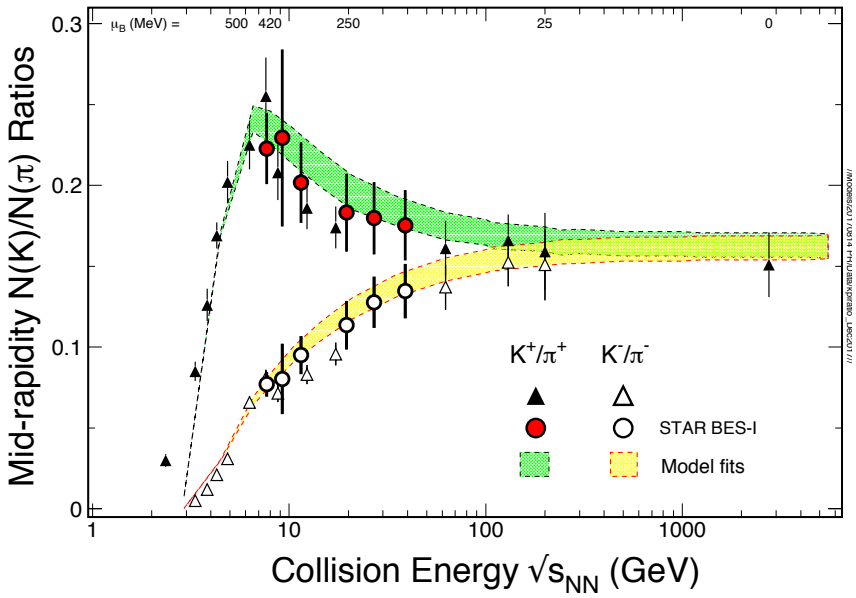
Kinetic Freeze-out:

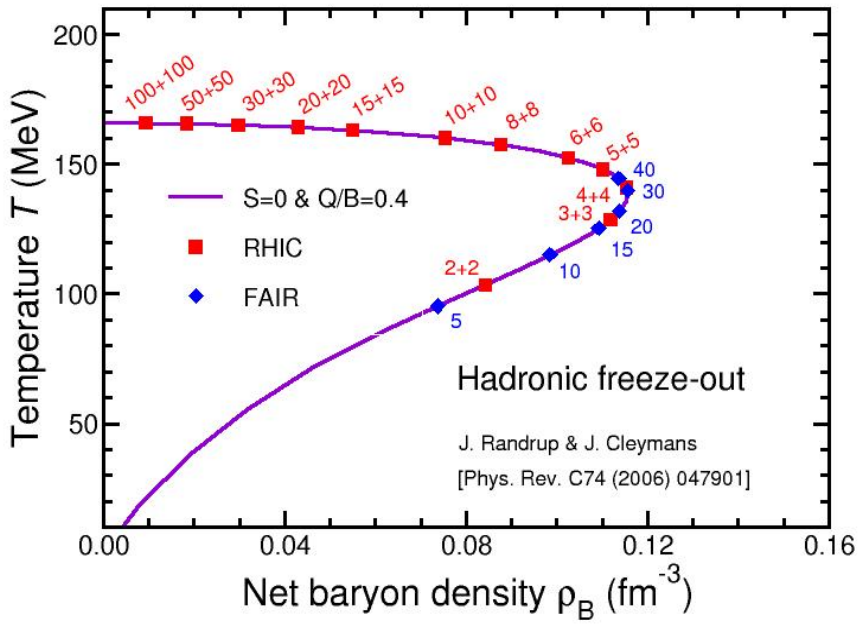
- Central collisions => lower value of T_{fo} and larger collectivity β_T

- **Stronger collectivity at higher energy, even for peripheral collisions**

- **ALICE**: B.Abelev et al., PRL**109**, 252301(12); PRC**88**, 044910(2013).
- **STAR**: J. Adams, et al., NPA**757**, 102(05); PRC**96**, 44904(2017) .
- S. Mukherjee: Private communications. August, 2012

K/π Ratios and Baryon Density





1) The **K^+/π** ratio peaks at **$\sqrt{s_{NN}} \sim 8$ GeV**, **K^-/π** ratio merges with **K^+/π** at higher collision energy
2) Model: **Baryon density peaks at $\sqrt{s_{NN}} \sim 8$ GeV**
3) At **$\sqrt{s_{NN}} > 8$ GeV, pair production becomes important**

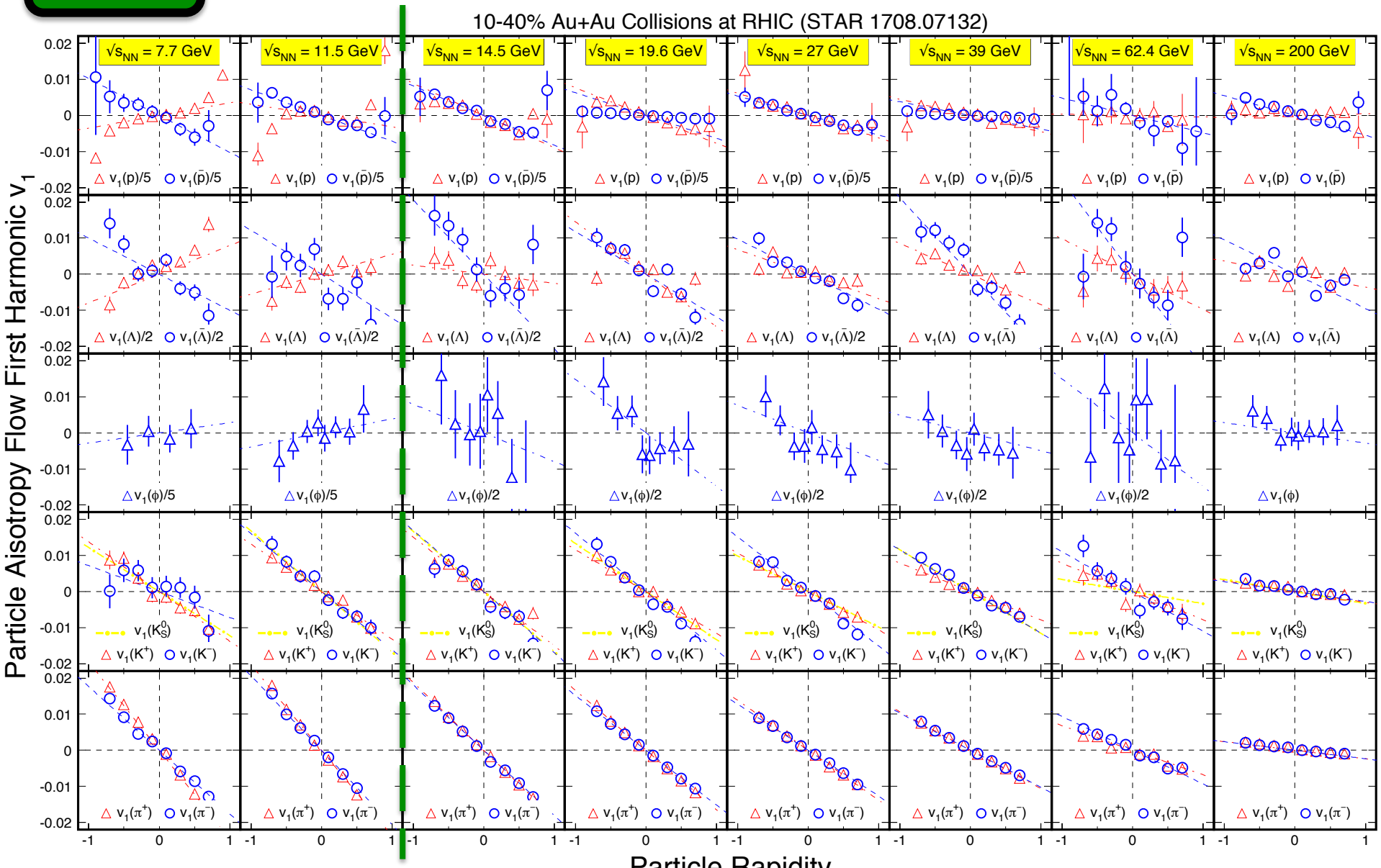
STAR: PRC**96**, 44904(17) . J. Randrup and J. Cleymans, PR**C74**, 047901(06); L. Kuma 2012

Collectivity

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

NEW

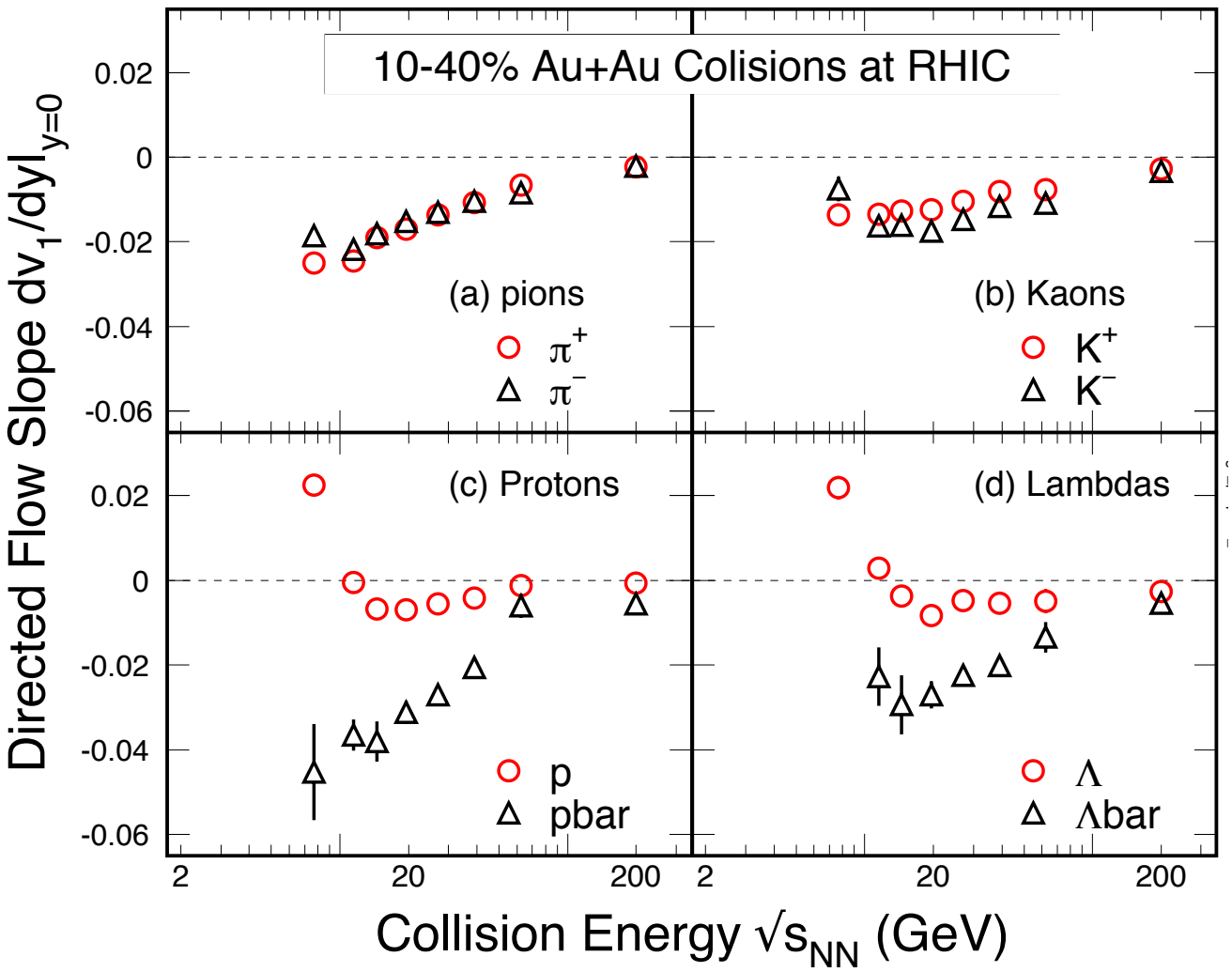
v_1 versus Collision Energy



STAR: PRL**120**, 062301(2018)

v_1 versus Collision Energy

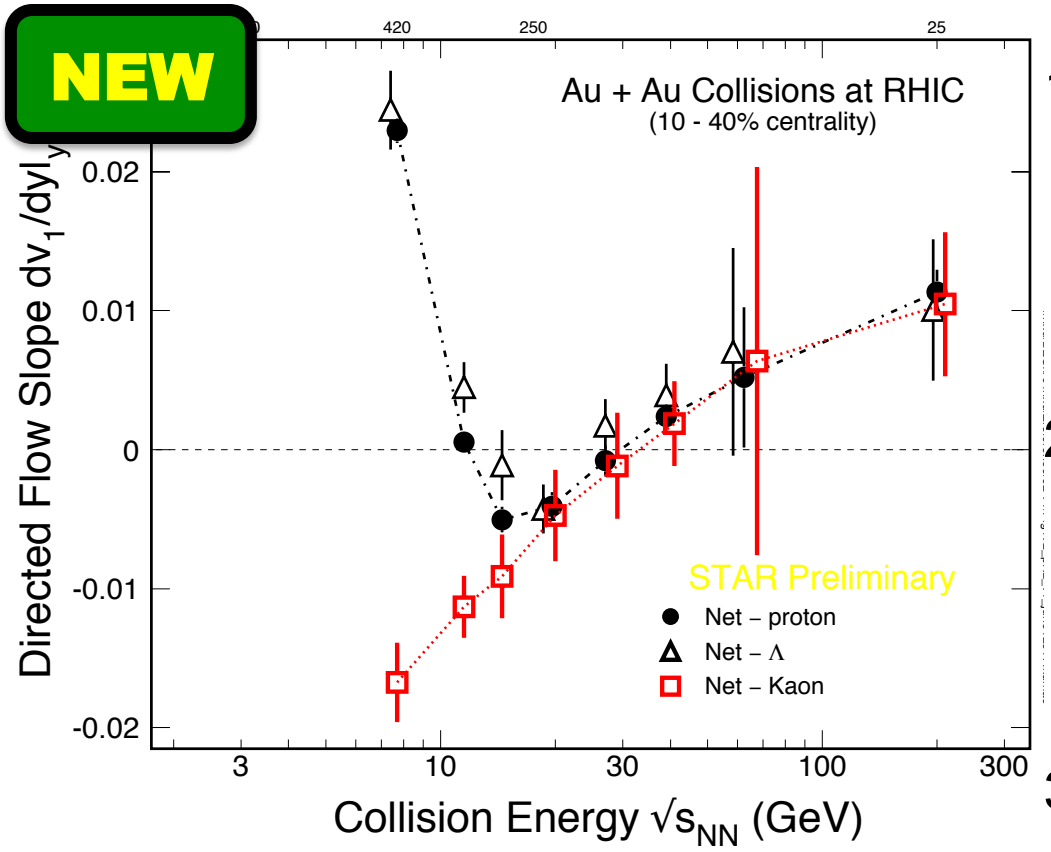
NEW



1) All produced hadrons mid-y v_1 slope < 0
2) At $\sqrt{s_{NN}}$ < 10 GeV, Baryons' v_1 becomes > 0

STAR: 1708.07132; PRL**120**, 062301 (2018)

v_1 vs. Energy: Softest Point?



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?

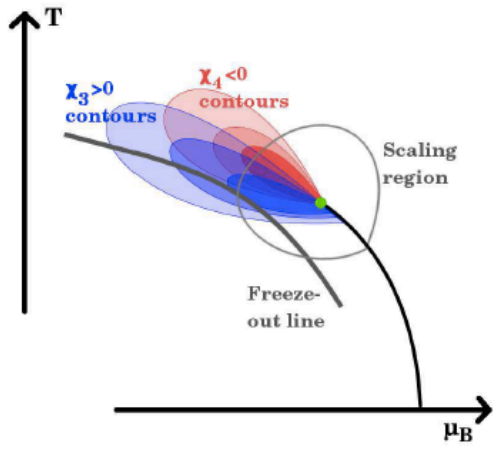
4) Need model to explain!

● STAR: PRL**112**, 162301(2014)

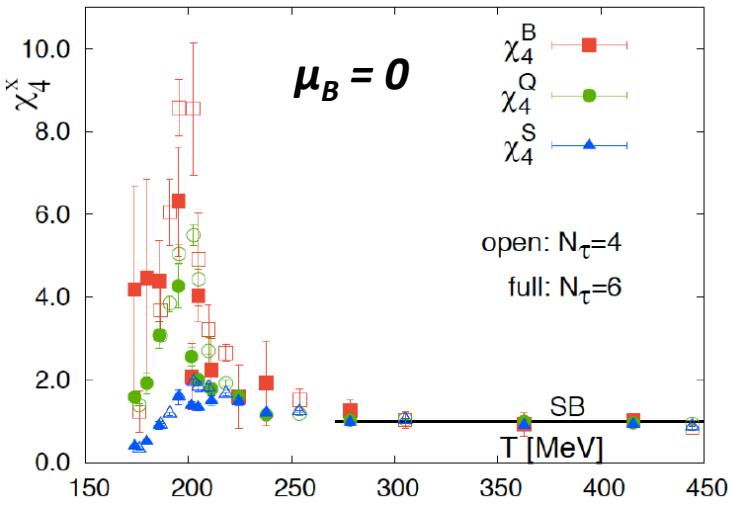
□△ STAR: 1708.07132
PRL**120**, 062301 (2018)

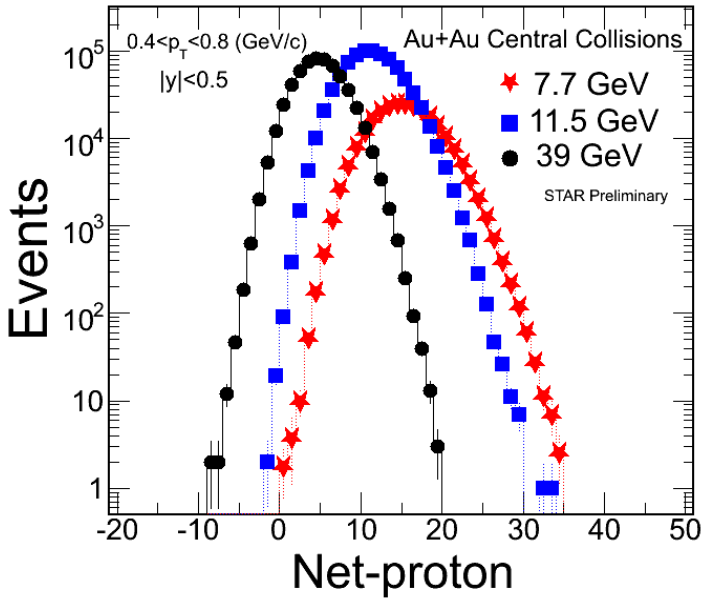
- M. Isse, A. Ohnishi et al, PR **C72**, 064908(05)
- Y. Nara, A. Ohnishi, H. Stoecker, PRC94, 034906(16), arXiv: **1601.07692**

Criticality



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:

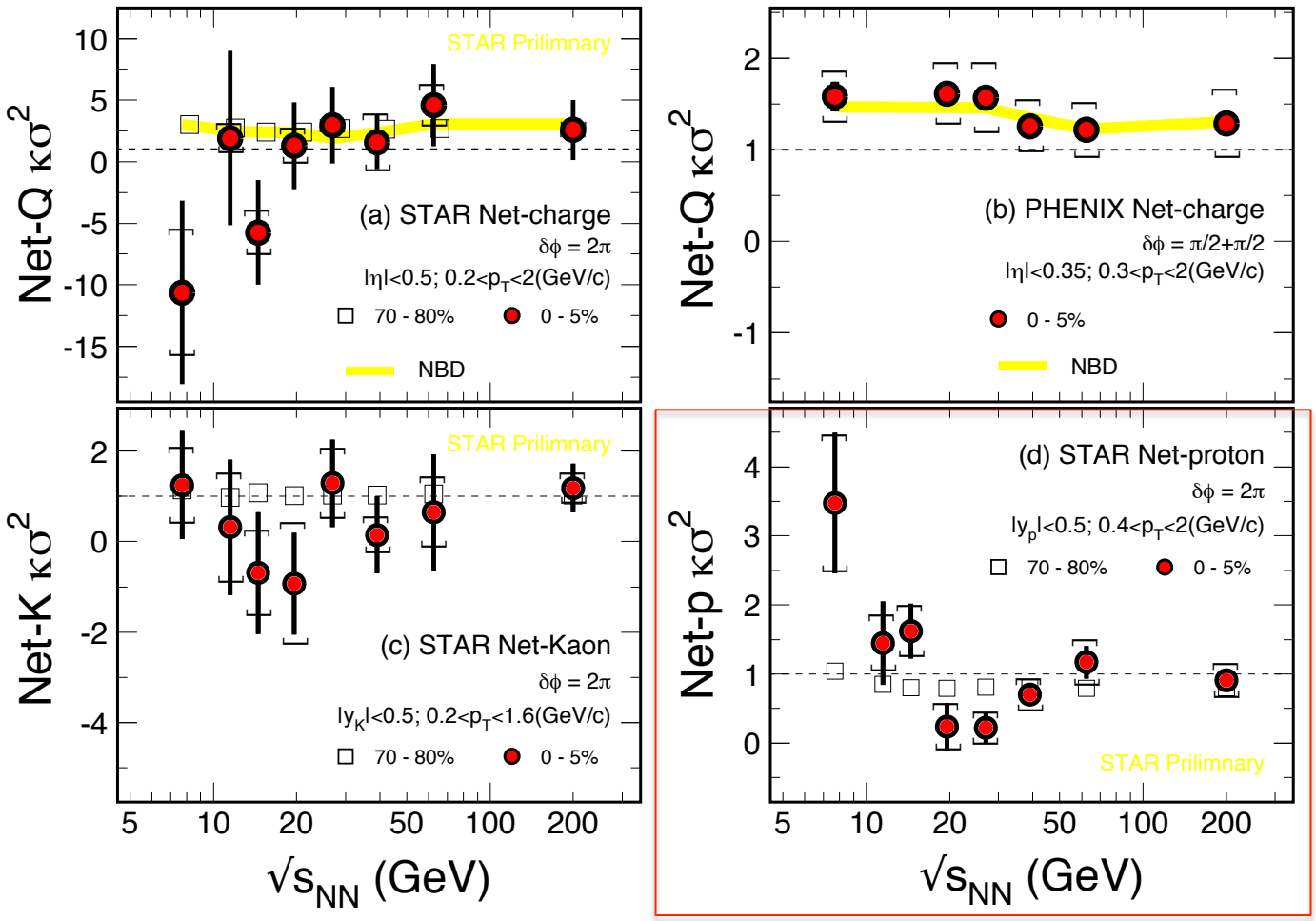
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

References:

- STAR: *PRL*<u>**105**</u>, 22303(10); *ibid*, <u>**112**</u>, 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

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



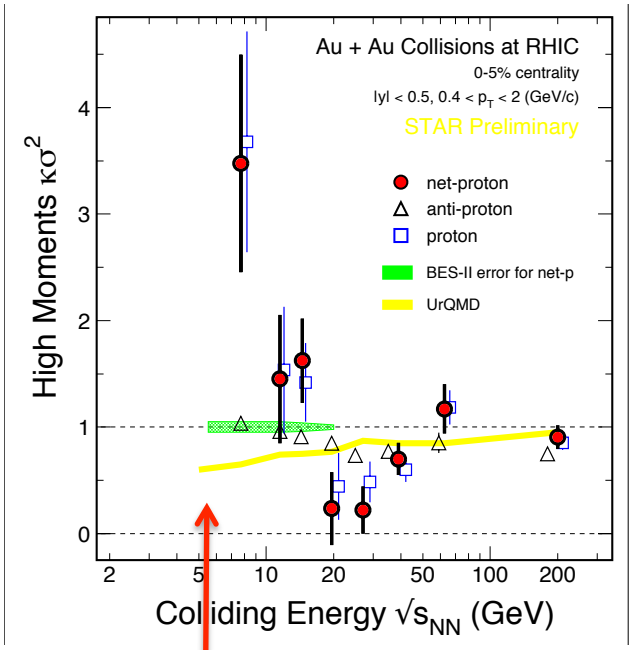
$$error(\kappa * \sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

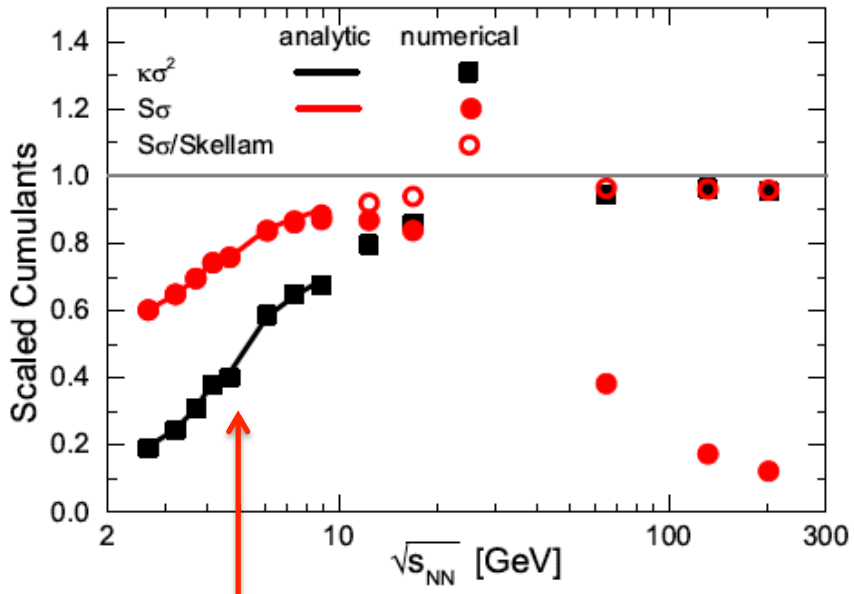
In STAR:

σ(Q) > σ(K) > σ(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!

No Model Reproduces the 'Attraction'!





At $\sqrt{s_{NN}} \leq 10$ GeV: Data: **$\kappa\sigma^2 > 1$!** Model: **$\kappa\sigma^2 < 1$!**

All models: ***suppress higher order net-proton fluctuations***

(UrQMD, AMPT, HRG and JAM do not reproduce data)

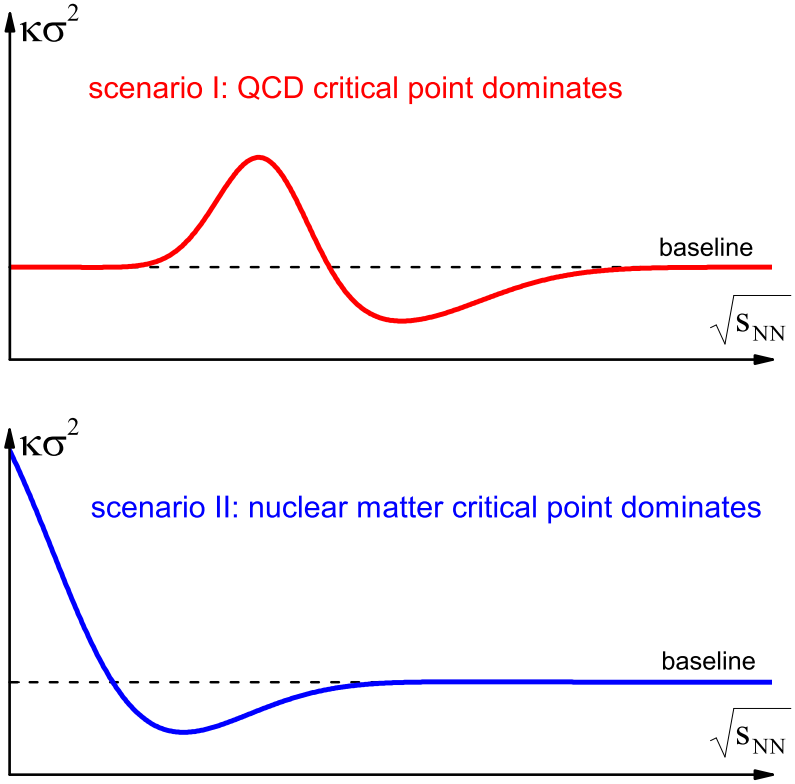
1) Z. Feckova, J. Steonheimer, B. Tomasik, M. Bleicher, 1510.05519, PR**C92**, 064908(15)
2) X.F. Luo *et al*, NP **A931**, 808(14); P.K. Netrakanti *et al.*, NP **A947**, 248(16); P. Garg *et al.* Phys. Lett. **B726**, 691(13)

3) Baryon mean-field (**attractive**): Shu He *et al.*, Phys. Lett. B**762**, 296(2016).

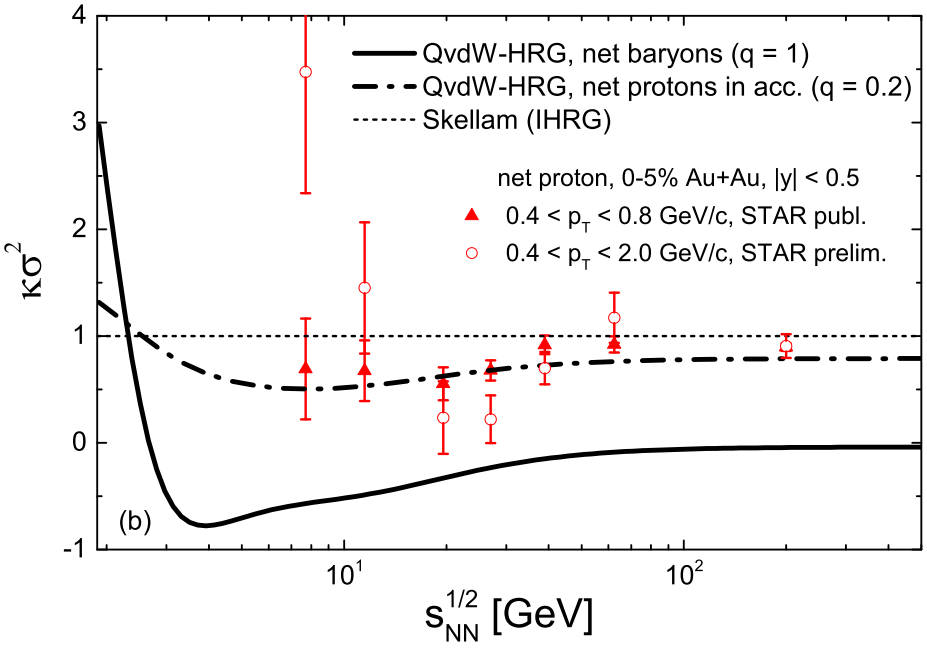
4) Proton clusters: A. Bzdak, V. Koch, V. Skokov, Eur. Phys. J., **C77**, 288(2017)

Interesting but unfinished, needs include dynamic effects.

Model Expectation II

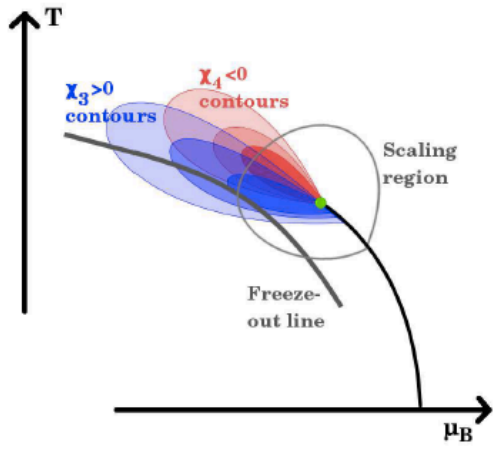


V. Vochenko, L.J. Jiang, M.I. Gorenstein and H. Stoecker 1711.07260



1) Both attractive and repulsive forces are needed to describe the criticality
2) This model might work for Liquid-gas CP, but will not work for QCD critical point due to wrong dof

BES-II & Beyond

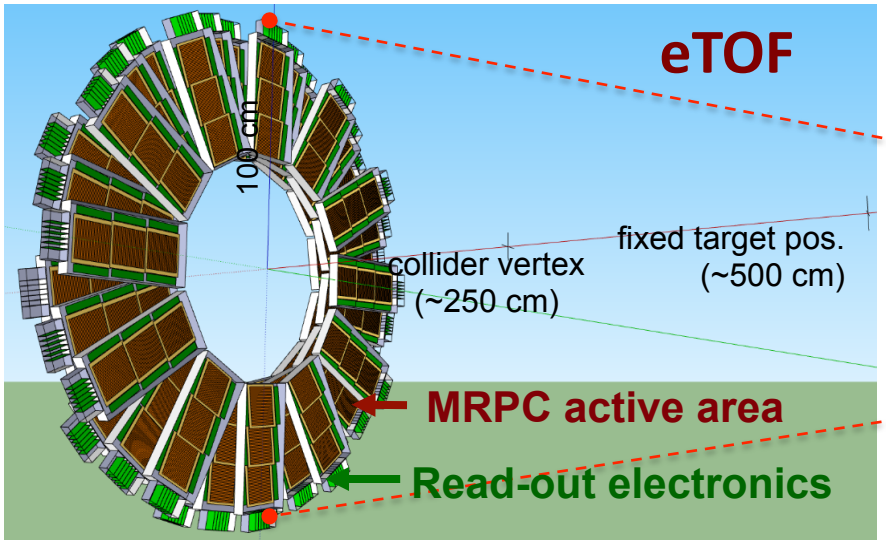


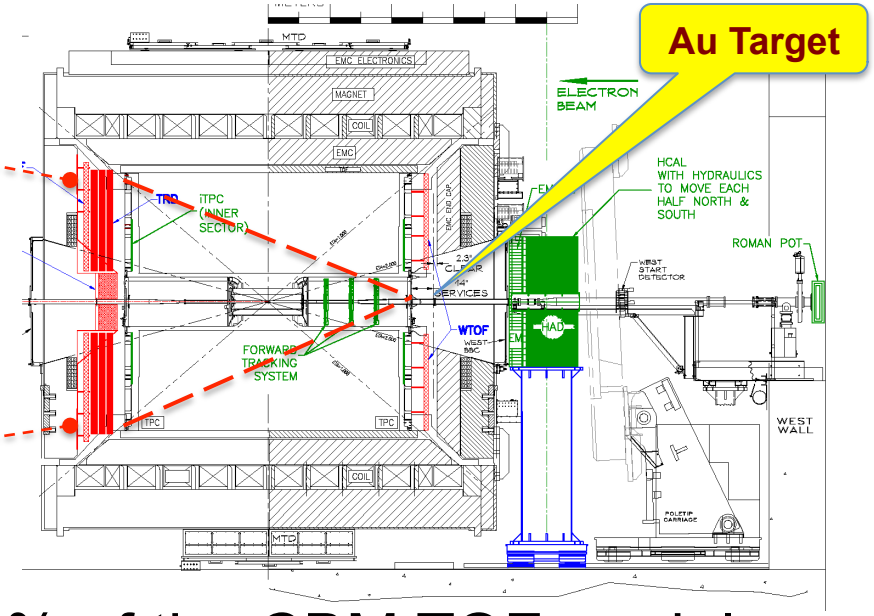
2019-2020: BES-II at RHIC

$\sqrt{s_{NN}}$ (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**			
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-20** / 2011	**3**	206	160
14.5	**300** / 20	**2019-20** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-20** / 2010	**5**	315	152
9.2	**160** / 0.3	**2019-20** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-20** / 2010	**14**	420	140

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

CBM Phase-0 Exp: eTOF at STAR



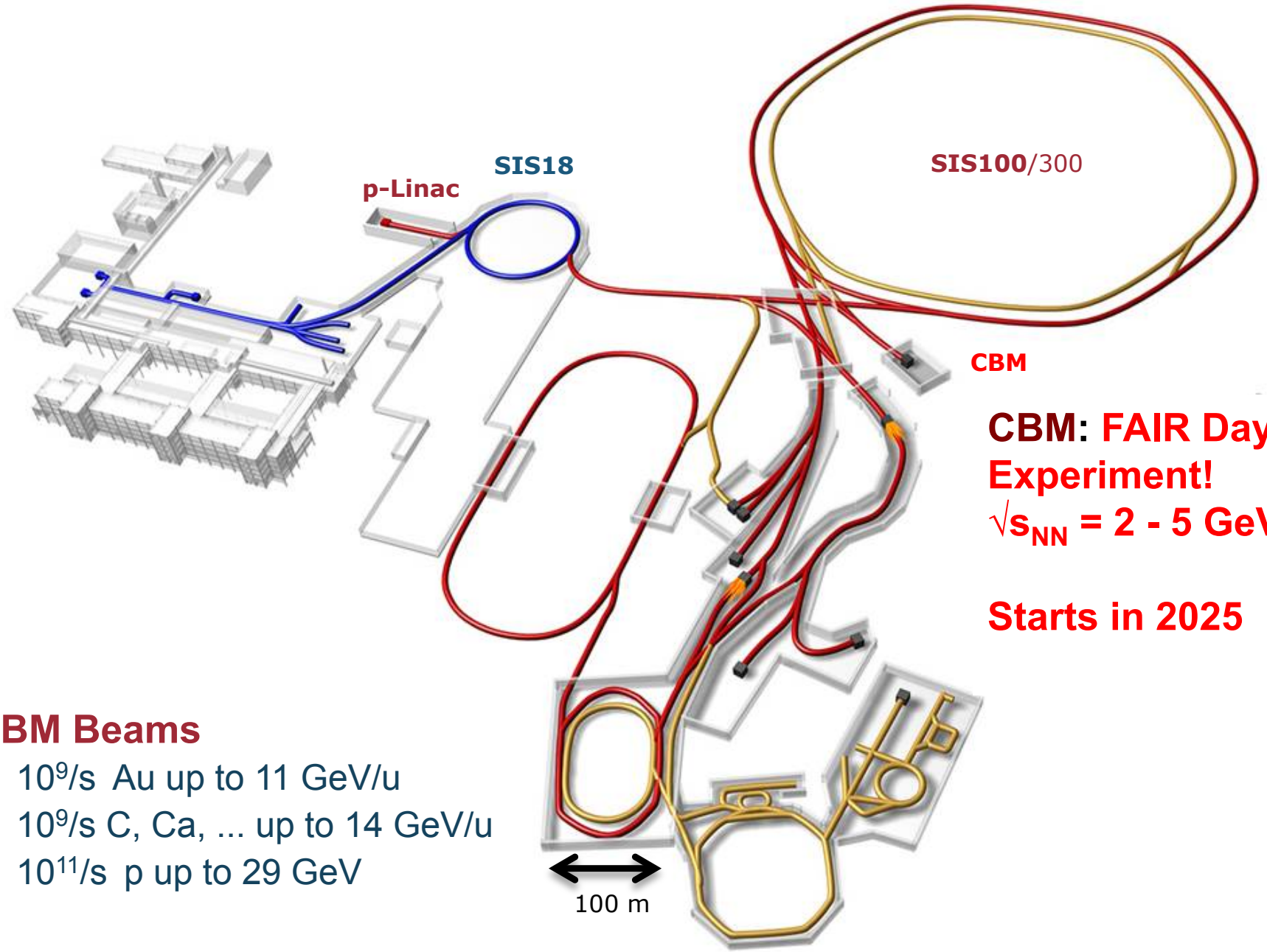


Install, commission and use 10% of the CBM TOF modules, including the read-out chains at STAR, starting in 2019

CBM participating in RHIC Beam Energy BES-II in 2019-2020:

- Complementary to part of CBM's physics program:
  $\sqrt{s_{NN}}$ = **3**, **3.6**, **3.9**, **4,5**, 7.7 GeV (**750 ≥ μ_B ≥ 420 MeV**)
  especially for ***B-*** & ***s-hadrons*** production and fluctuations

Facility for Antiproton & Ion Research: **FAIR**



CBM: FAIR Day-1 Experiment!

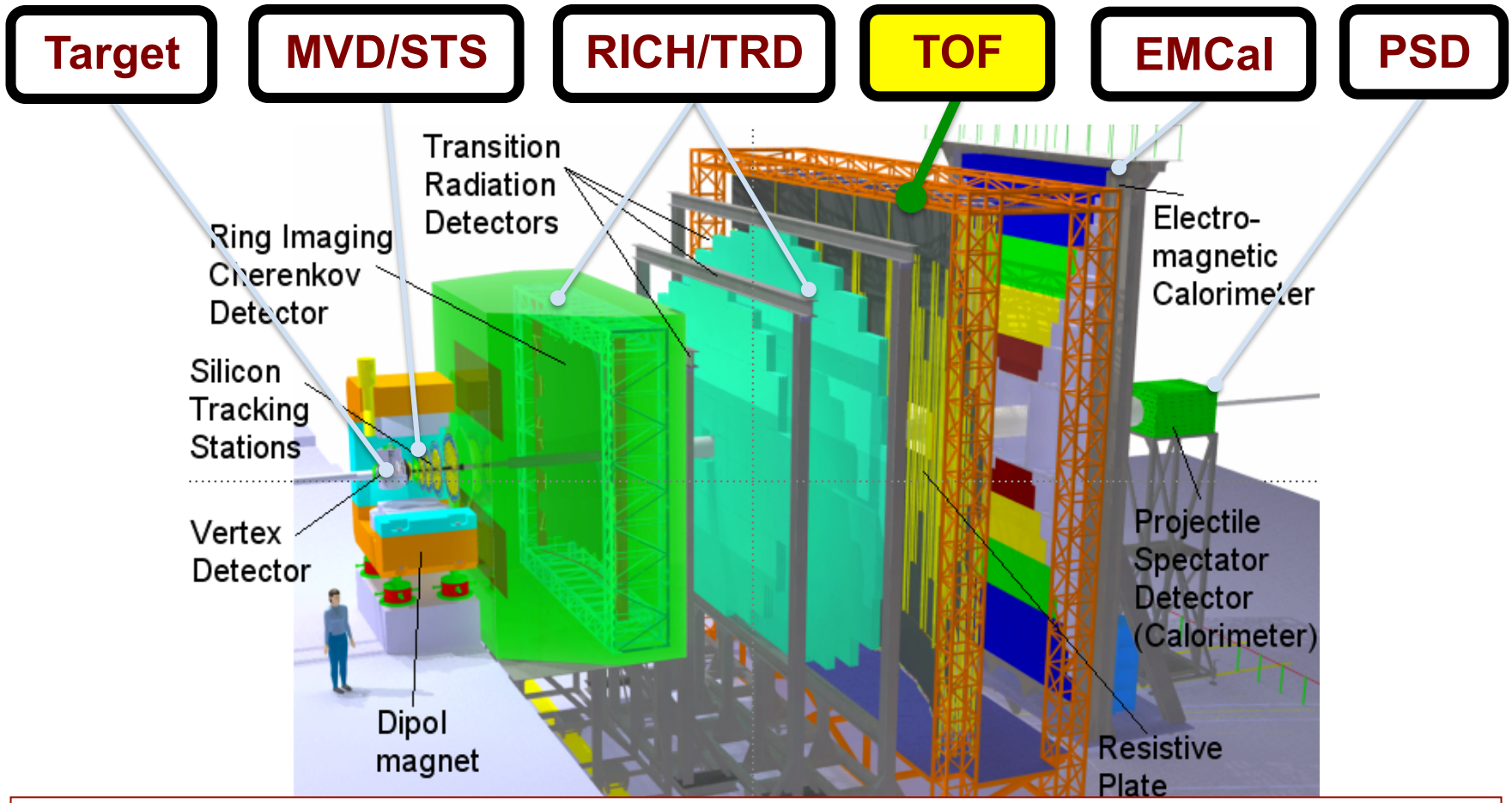
$\sqrt{s_{NN}}$ = 2 - 5 GeV

Starts in 2025

CBM Beams

- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

CBM Experiment at FAIR

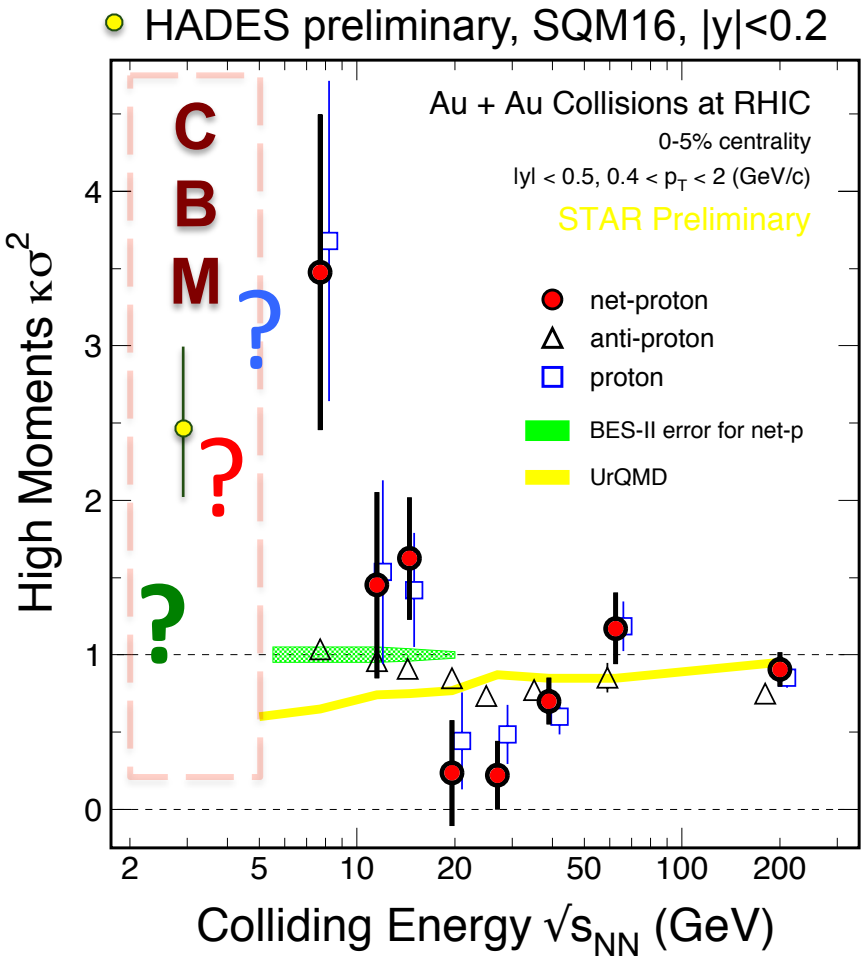


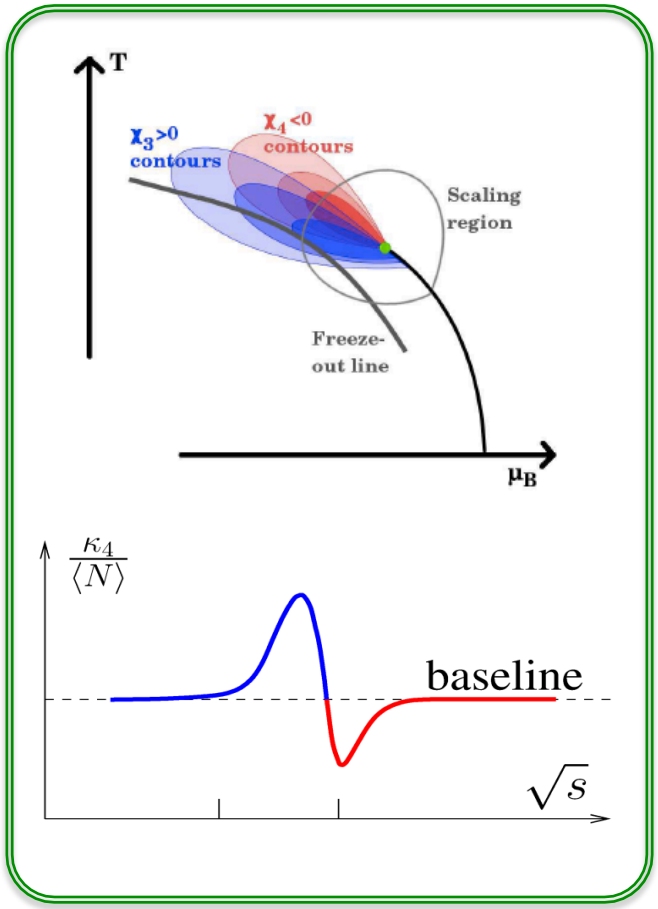
FAIR: One of the highest intensity accelerator complexes

Precision measurements at high baryon density region for:

(i) Dileptons (***e, μ***); (ii) High order correlations; (iii) Flavor productions (***s, c***)

Search for the QCD Critical Point





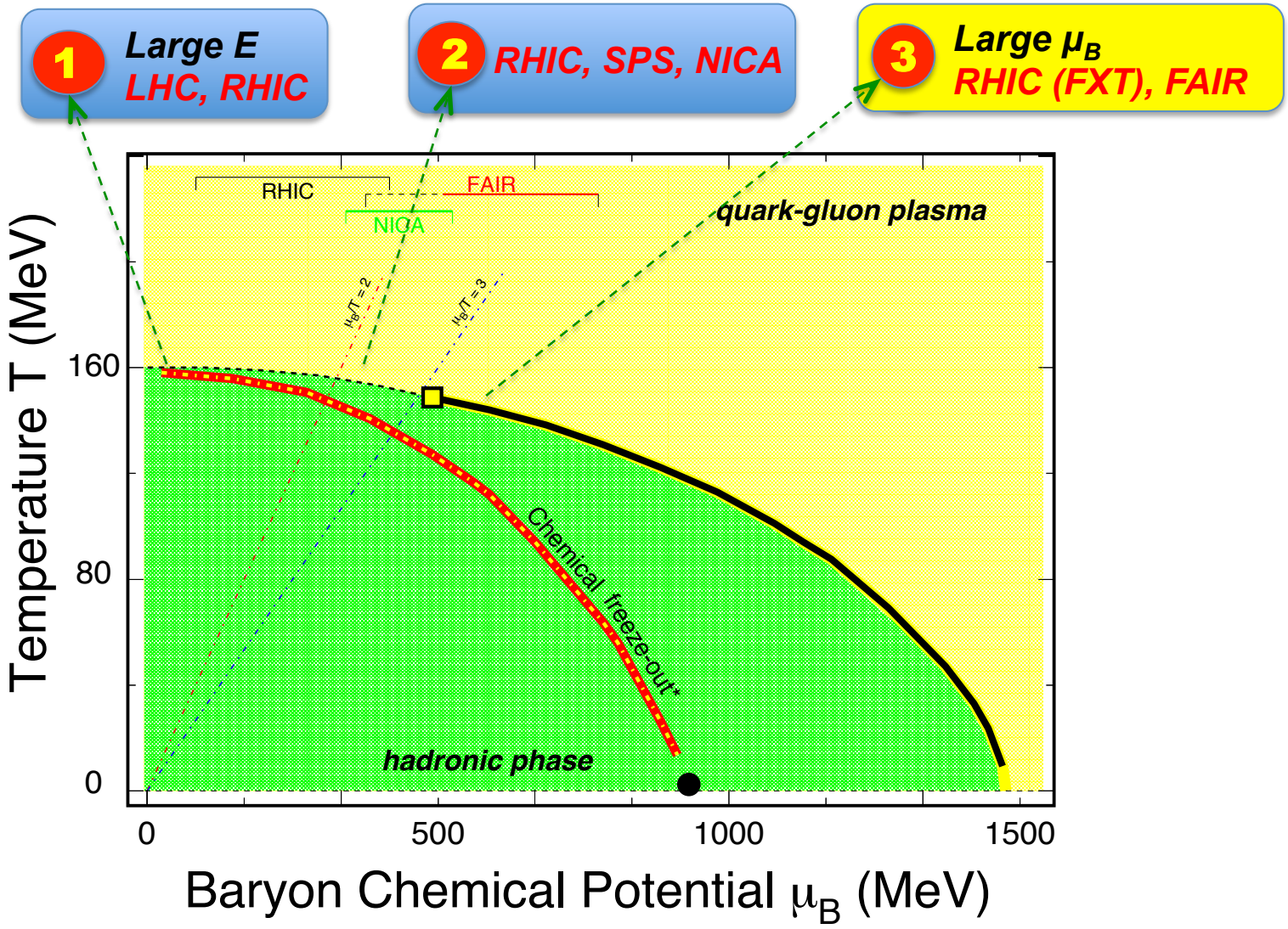
- RHIC BES-II: dramatically reduce the errors!
- CBM/RHIC FXT Experiments (**2.5 < $\sqrt{s_{NN}}$ < 8** GeV) :

  Key region for Critical Point search

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

Map the QCD Phase Diagram

2019 – 2020: 7.7, 11.5, 14.5, 19.6 GeV (FXT*: 4.5, 3.9, 3.6, 3.0 GeV)
2023 - : NICA (4 – 11 GeV)
2025 - : CBM + others



Acknowledgements

P. Braun-Munzinger, X. Dong, S. Esumi, S. Gupta, XG. Huang, F. Karsch, V. Koch, JF. Liao, *F. Liu*, *F. Lu*, 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

Thanks for your attention!