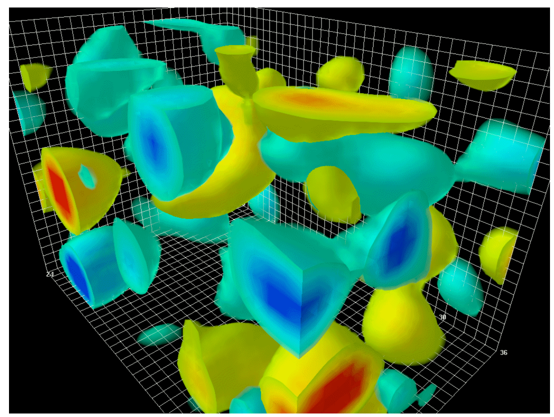
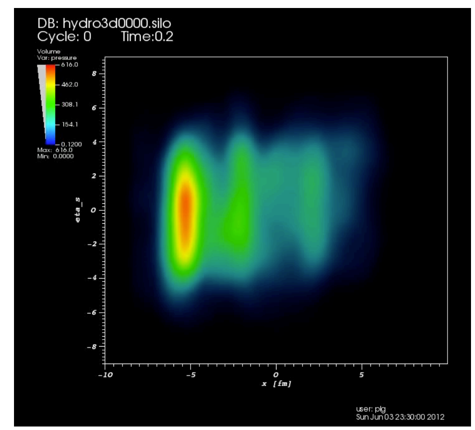
NSC³ Nuclear Science Computing Center at CCNU


丁亨通

2018年初设备进场:
理论峰值每秒一千万亿(10^{15})次浮点运算(1 PFlops/s)
500+500TB 存储

- 格点量子色动力学
- 硅像素实验室探测器模拟
- 高能实验数据分析
- 唯象、流体模拟计算
- 大数据、深度学习
- ……



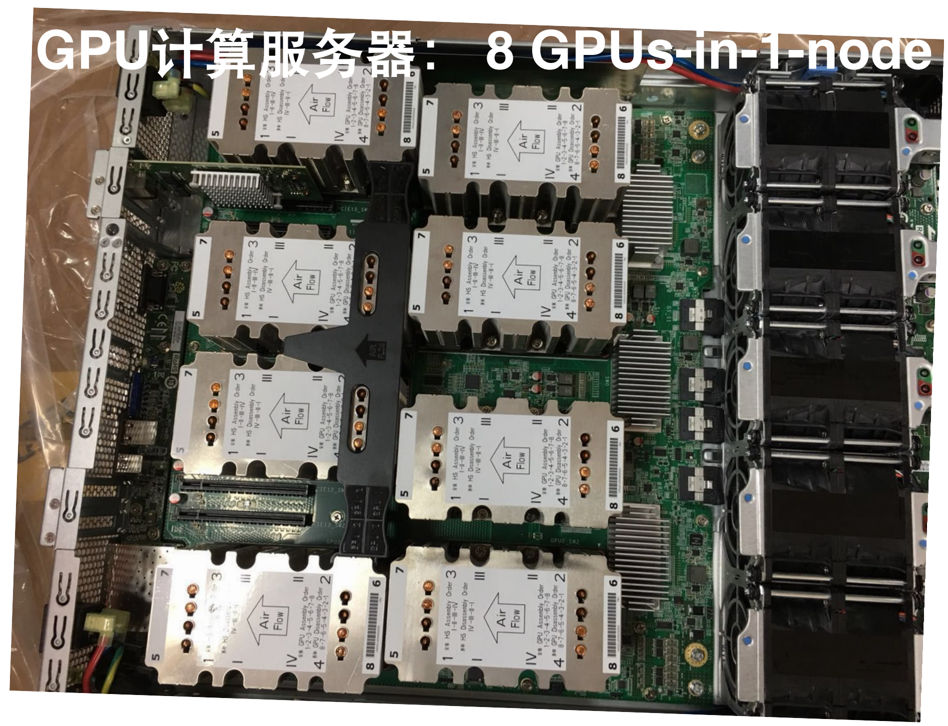


- 中科院近代物理研究所核物理专用GPU集群：0.8 PFlops (2016年)
- 德国Bielefeld大学格点量子色动力学专用GPU集群: 0.5 PFlops (2012年)


二楼会议室办公区


一楼机房内水冷空调


一楼机房内水冷机柜
Rittal - The System.


GPU计算服务器： 8 GPUs-in-1-node

QCD Medium Properties at Finite Baryon Density

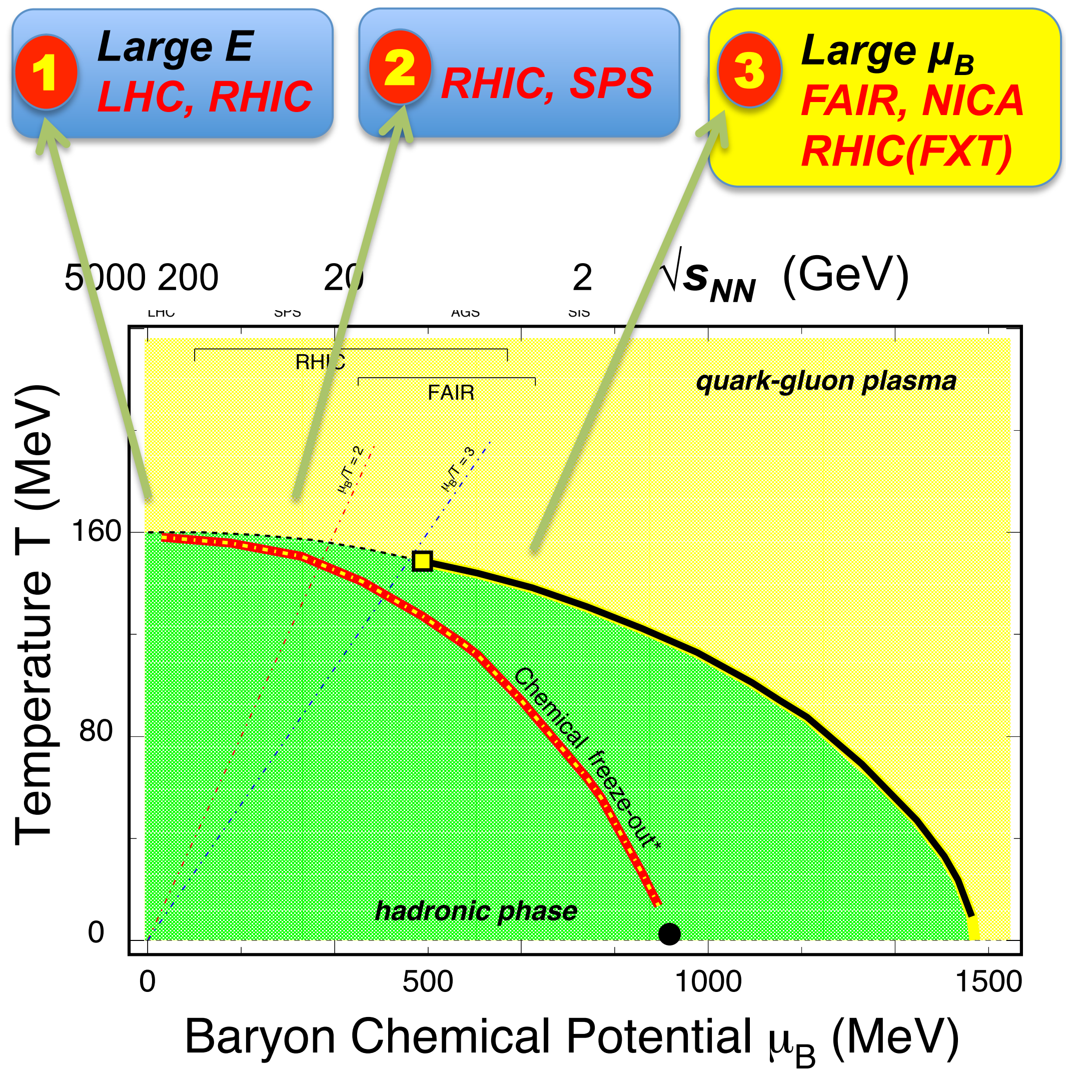
- BES in High-Energy Nuclear Collisions

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

The QCD Phase Diagram and the Beam Energy Scan



2000 – 2012 RHIC+LHC

Top energy program

Discovery of sQGP*

- QCD **Critical Point**
- Chiral effects

2010 – 2017: RHIC BES-I

7.7, 11.5, 14.5, 19.6, 27, 39, 54.4 GeV

2019 – 2020: RHIC BES-II

7.7, 11.5, 14.5, 19.6 GeV

FXT*: 4.5, 3.9, 3.6, 3.0 GeV

2022 – : RHIC+FAIR BES-III

Fixed-target programs

Outline

(1) Introduction

(2) Recent Results from BES-I at RHIC

i. Collectivity

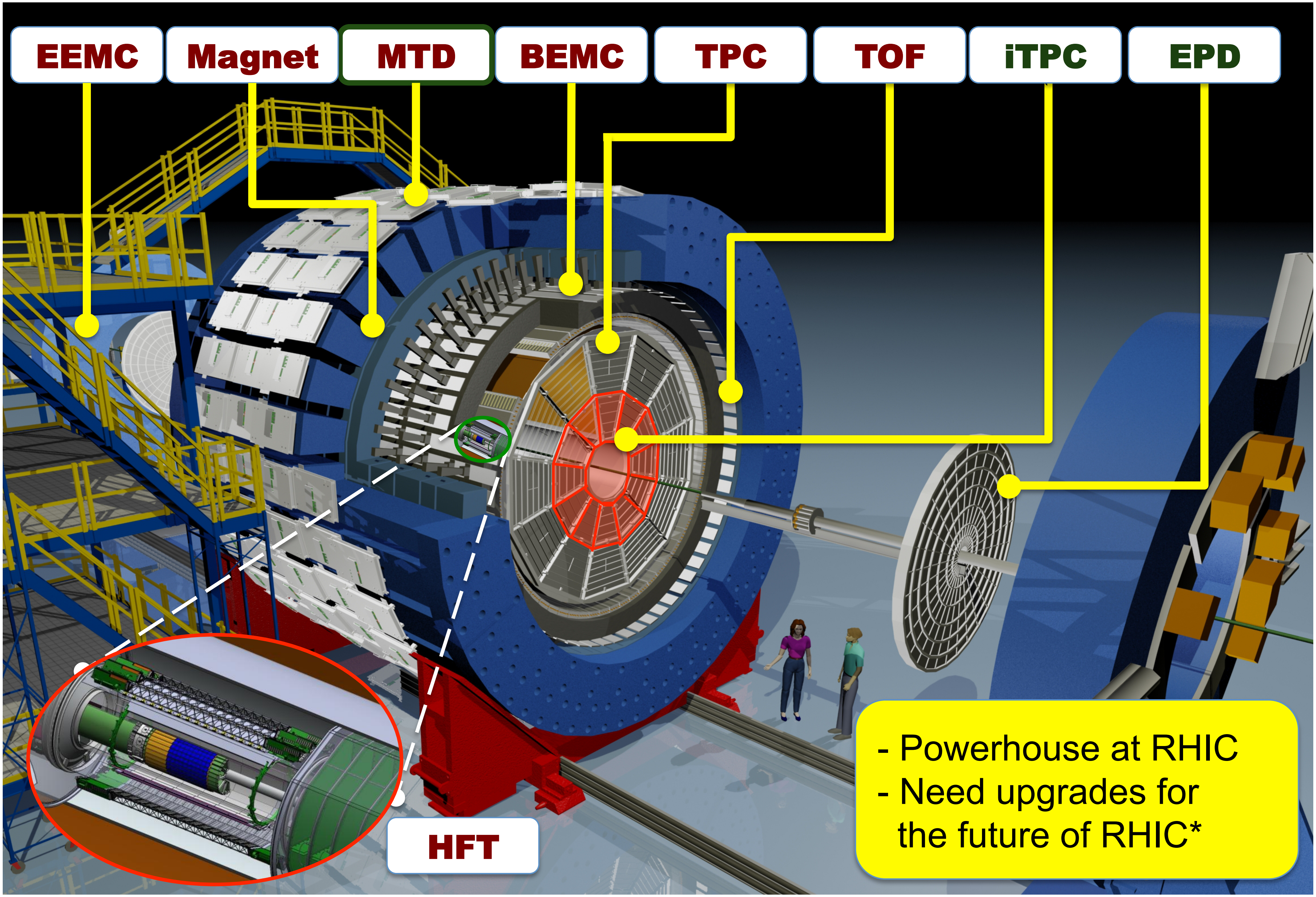
ii. Chirality

iii. Criticality

QCD Emergent Properties

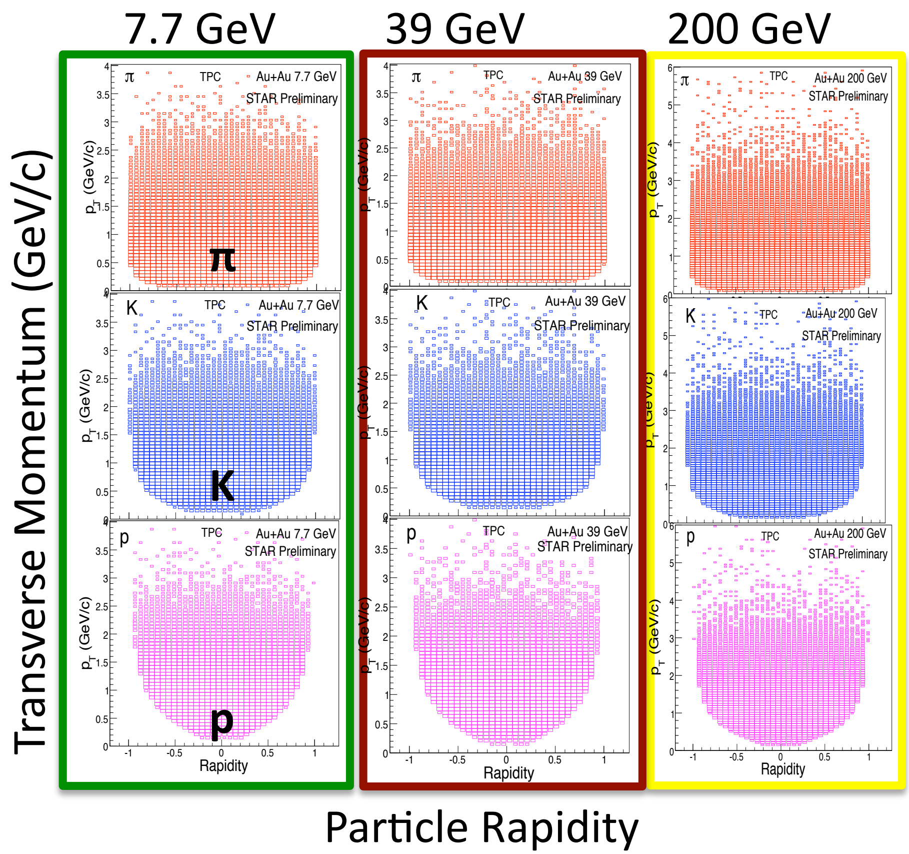
(3) BES-II and Beyond

STAR Detector System



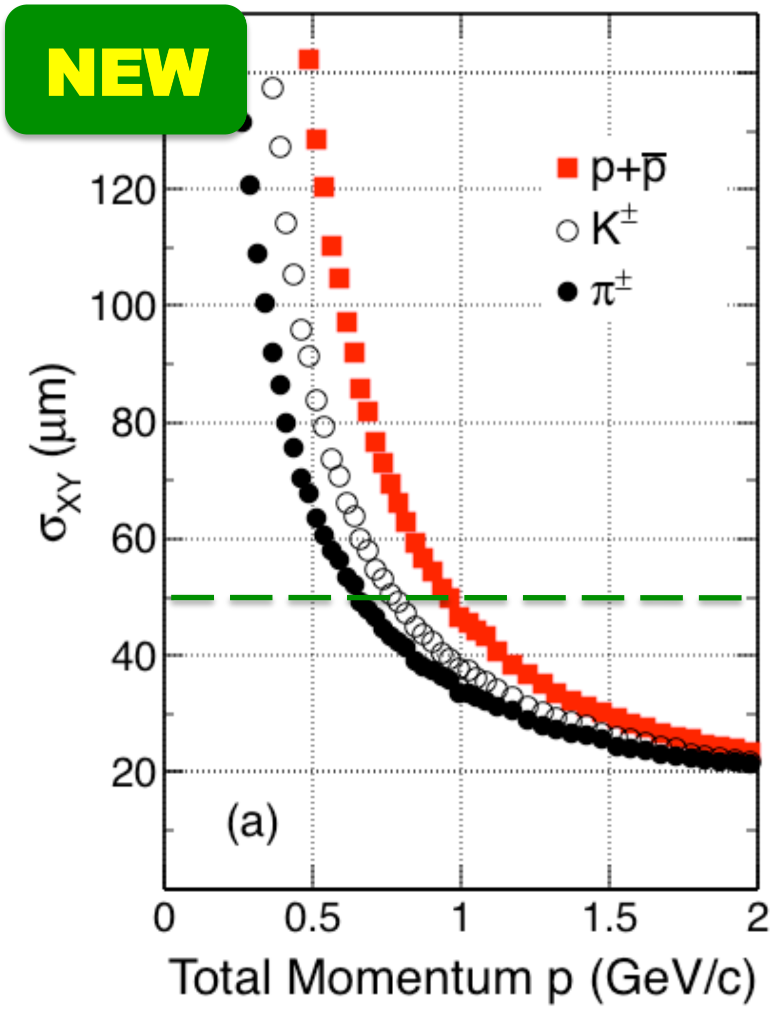
Data Sets for BES-I Program

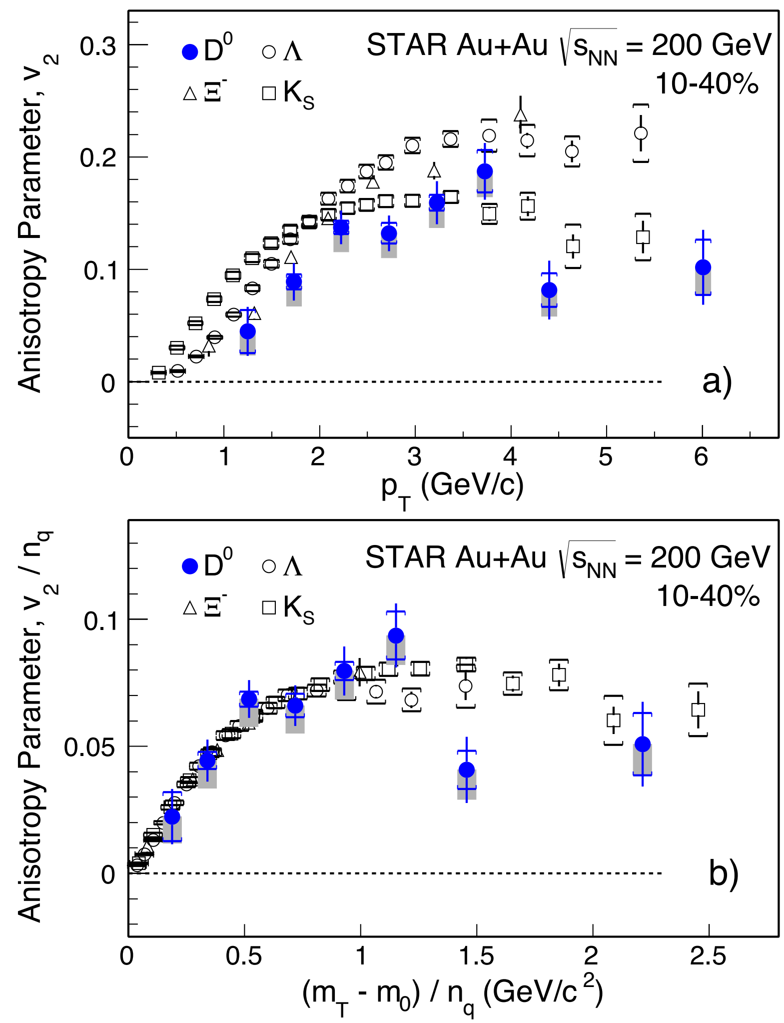
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
54.4	**1000**	**2017**
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010



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)



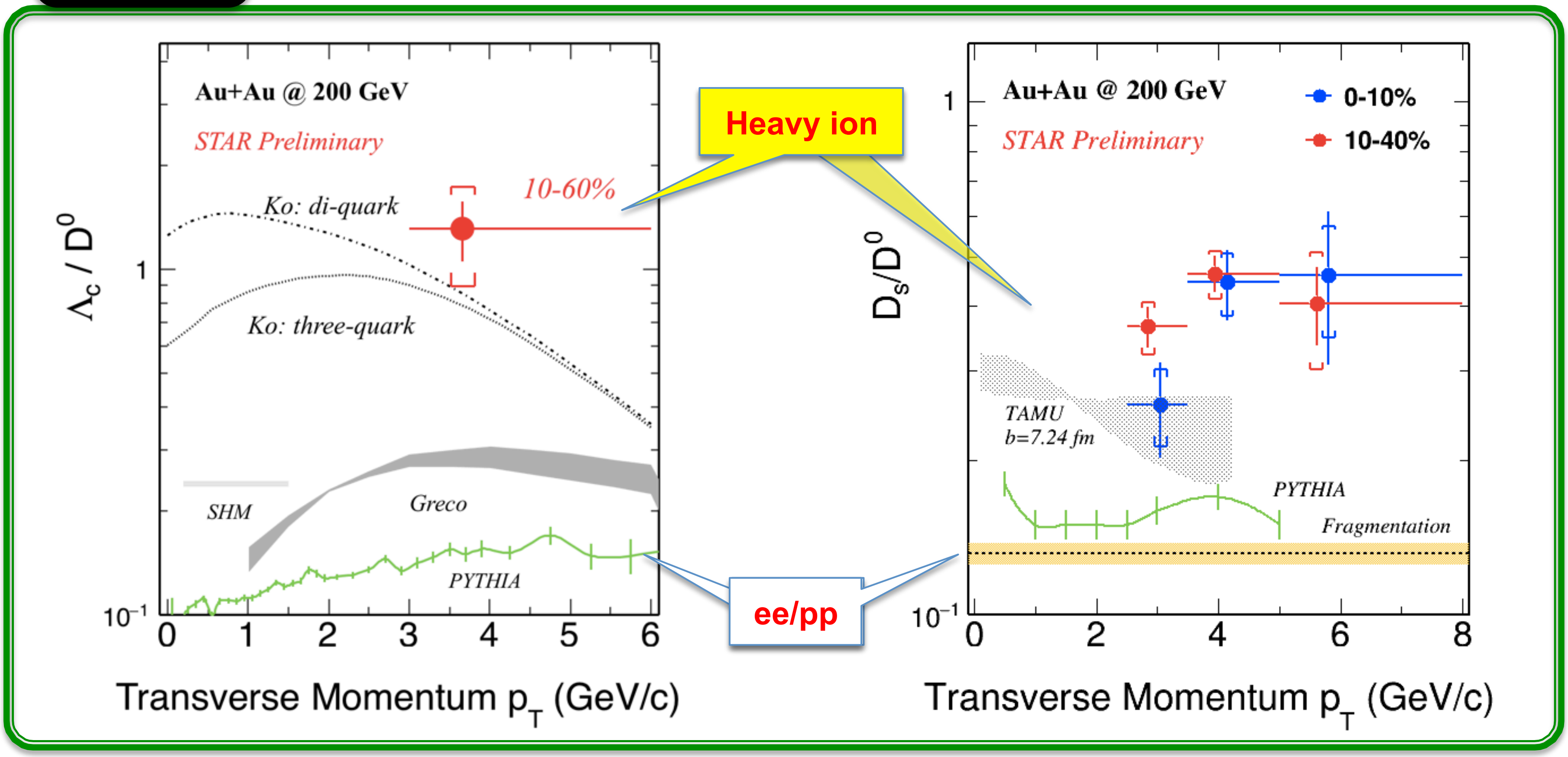


"These results suggest that charm quarks have achieved local thermal equilibrium with the medium created in such (200GeV Au+Au) collisions."

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

NEW

Λ_C/D^0 and D_s/D^0 Ratios



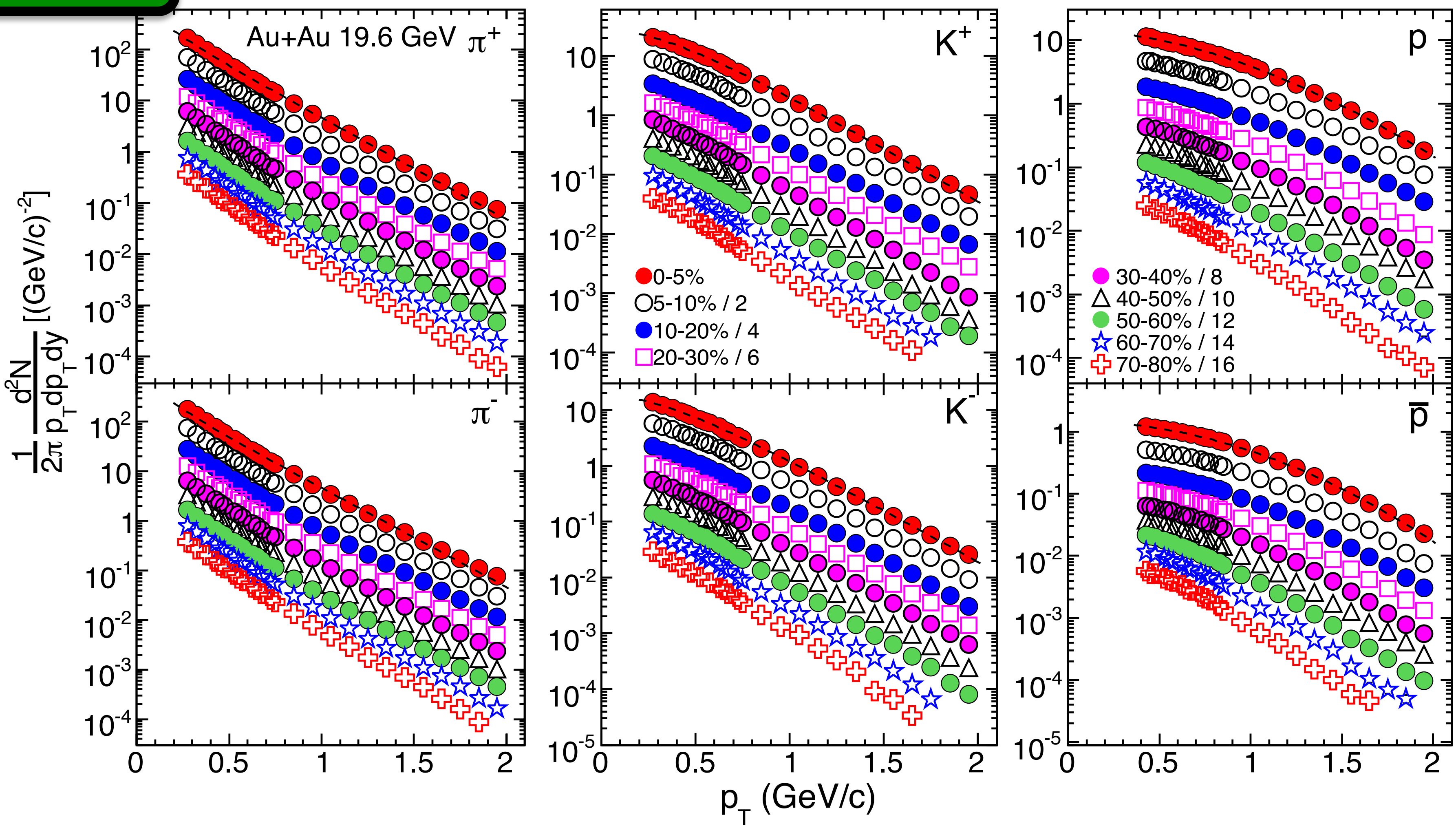
RHIC: Need more data on heavy quark hadron, both charm- and bottom-hadrons, in order to extract the properties of the QGP!

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

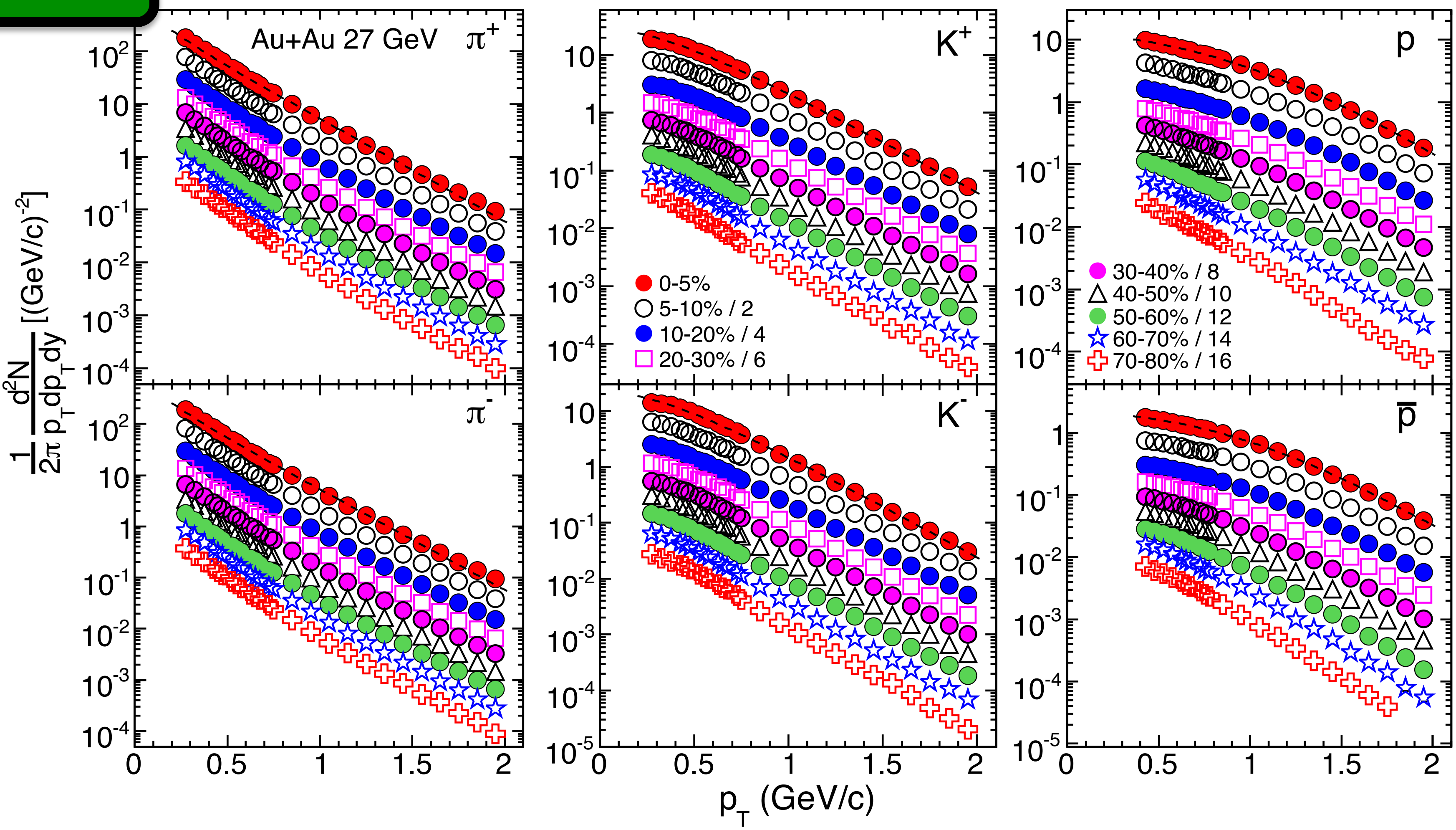


STAR: arXiv:1701.07065, PRC**96**, 44904(2017)

STAR: Hadron Spectra from BES-I

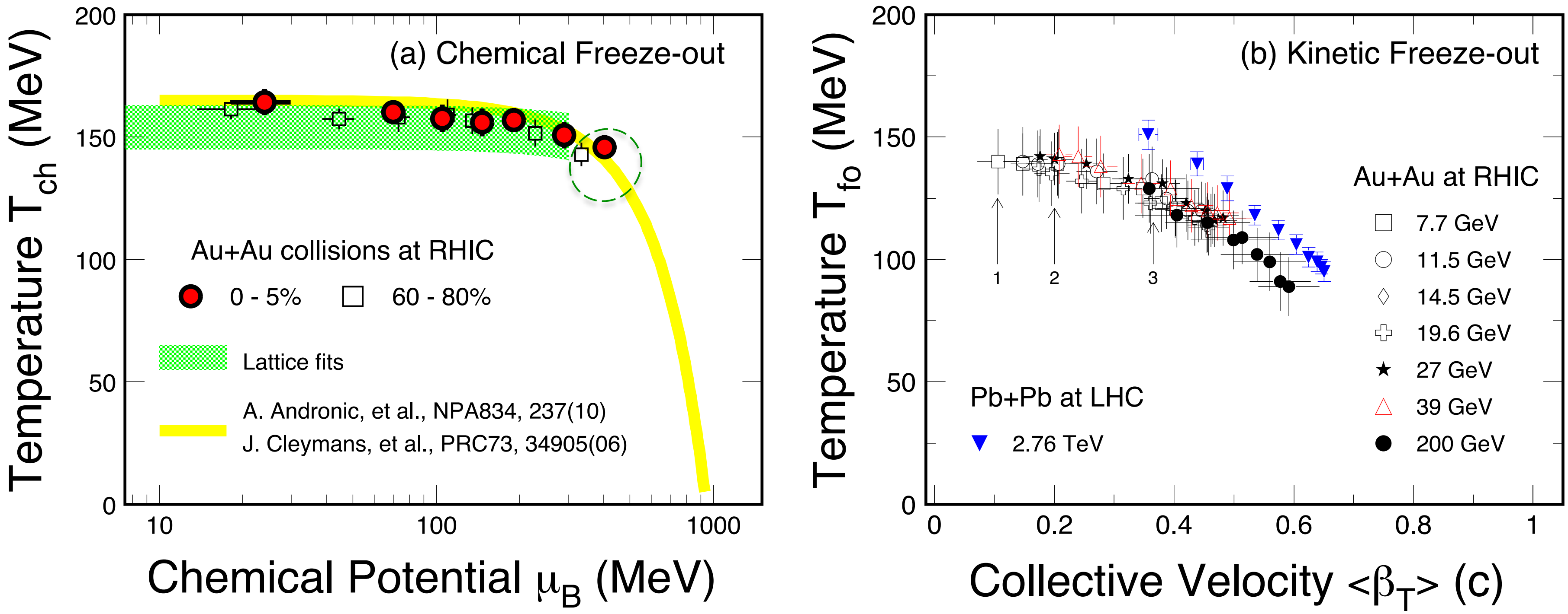
NEW

$\sqrt{s_{NN}}$ = 27 GeV Au+Au Collisions



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

Bulk Properties at Freeze-outs



Chemical Freeze-out: (GCE)

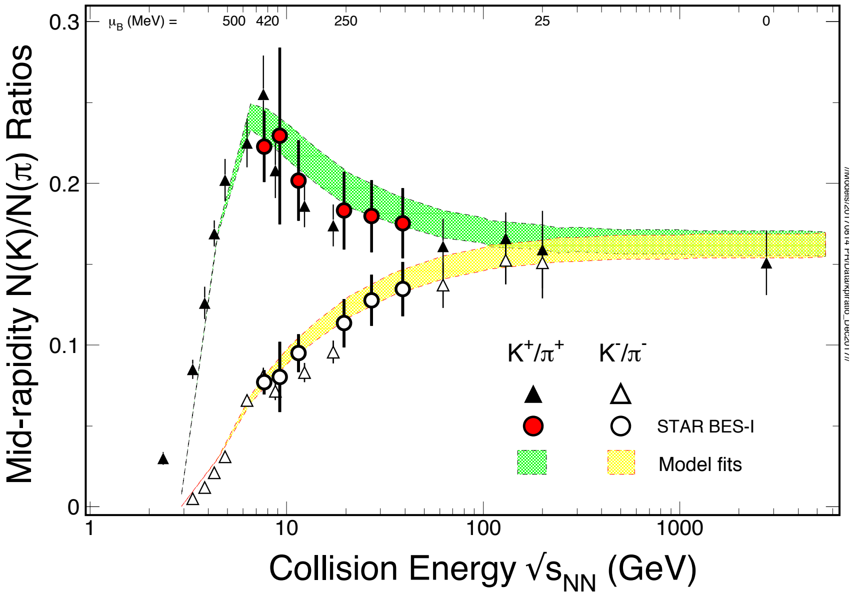
- Weak temperature dependence
- Centrality dependence μ_B!
- LGT calculations indicate the Critical Region around μ_B **~ 300 MeV?**

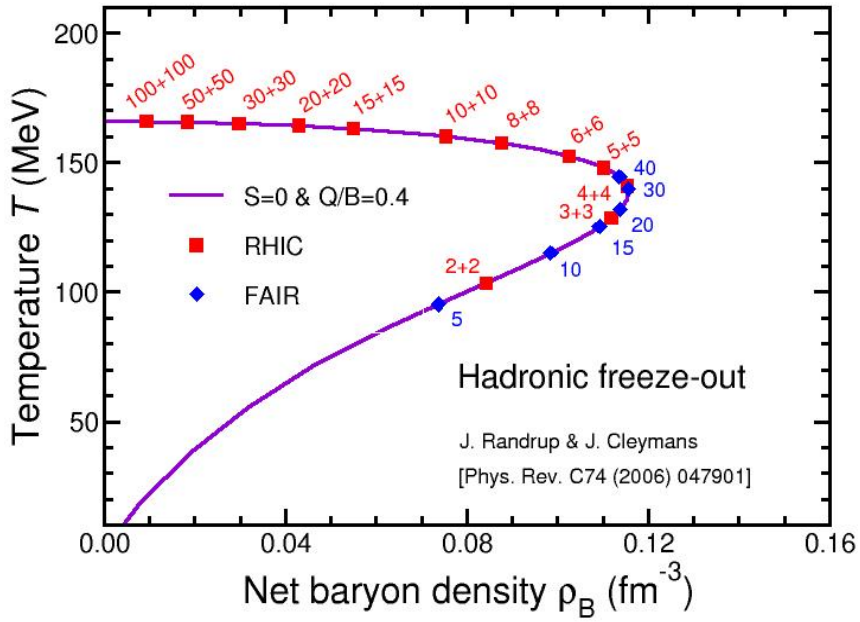
Kinetic Freeze-out:

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

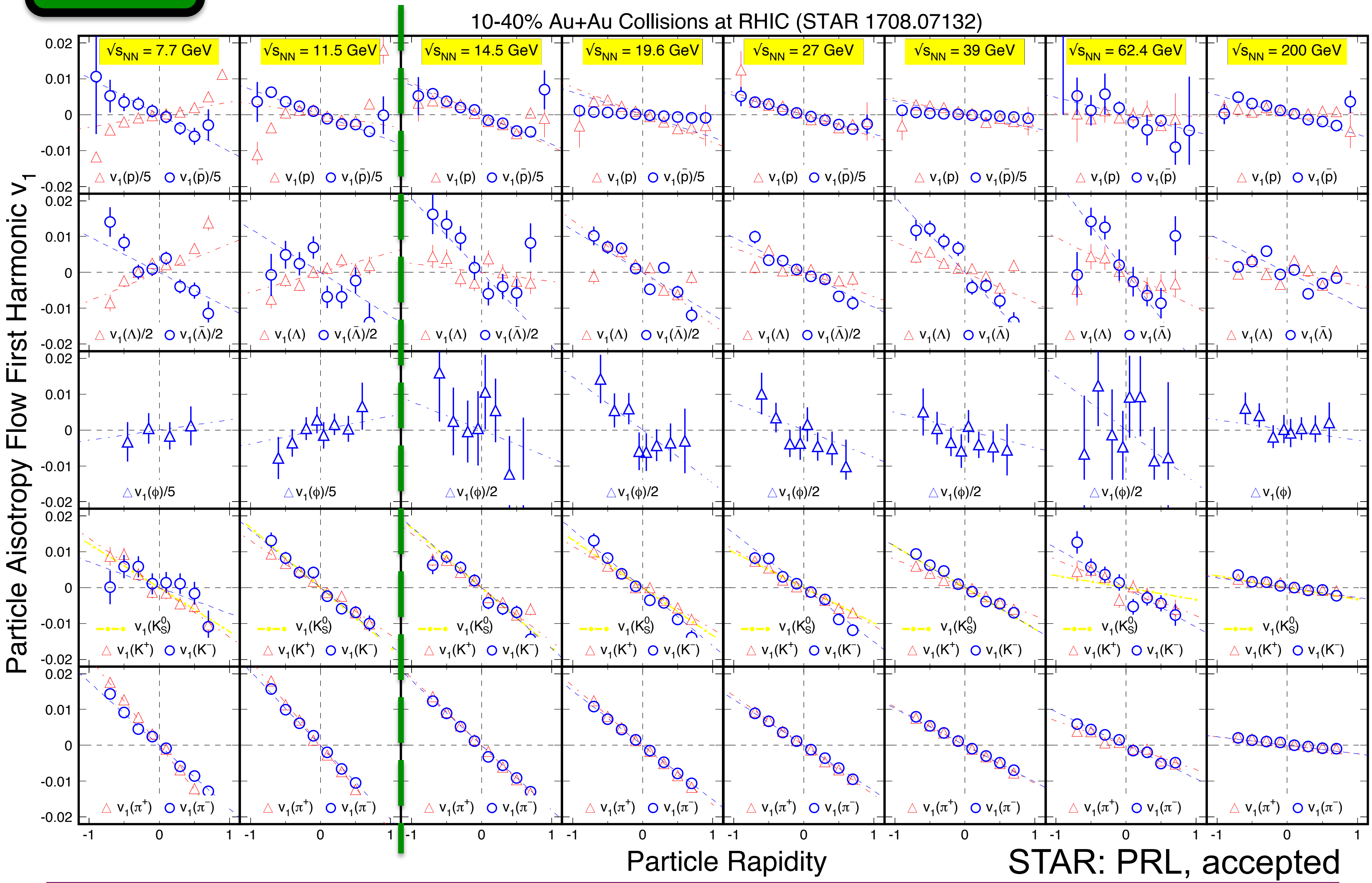
STAR: 1701.07065; PRC**96**, 44904(2017) . J. Randrup and J. Cleymans, PR**C74**, 047901(2006)

Collectivity

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

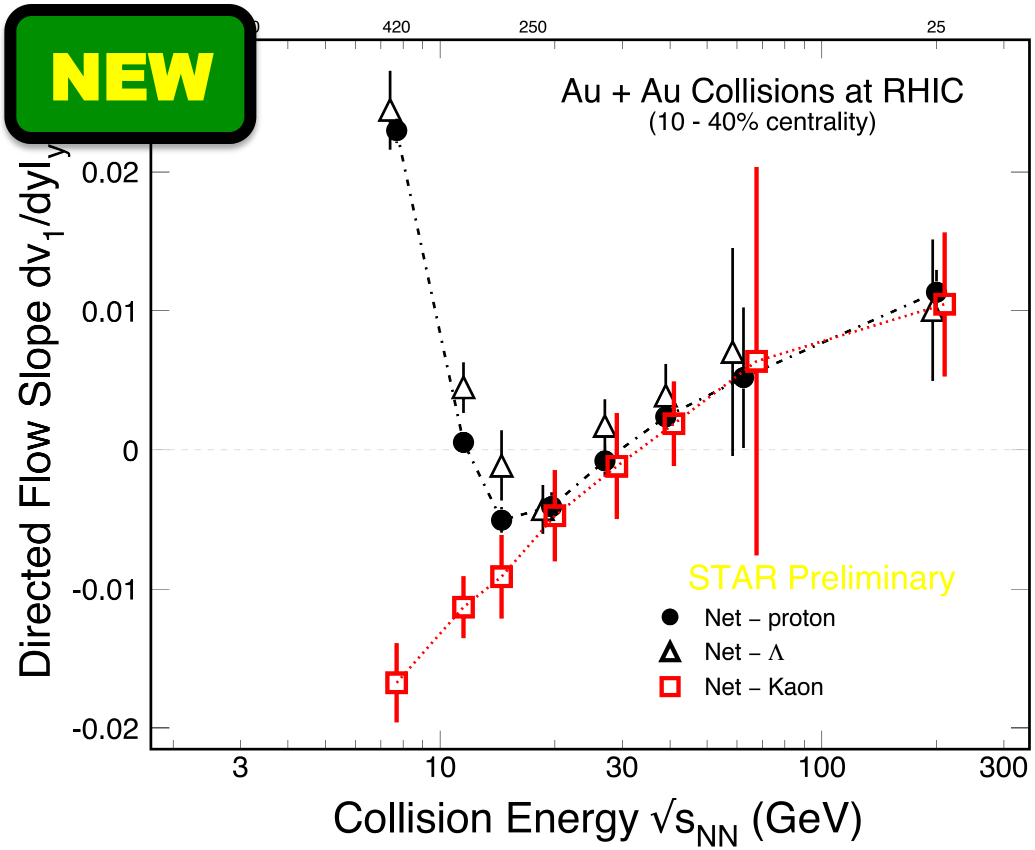
v_1 versus Collision Energy

NEW



STAR: PRL, accepted

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?

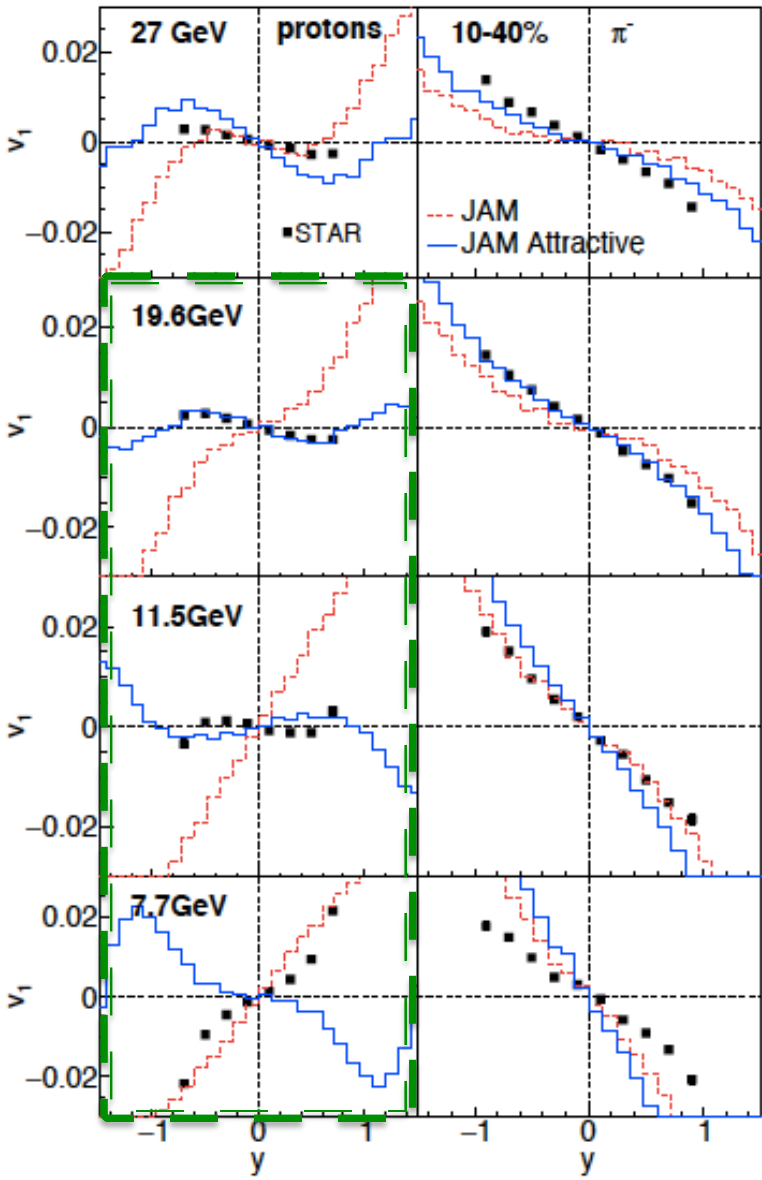
4) Need model to explain!

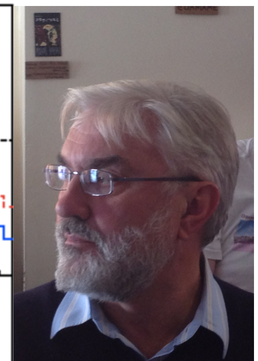
- M. Isse, A. Ohnishi et al, PR **C72**, 064908(05)
- Y. Nara, A. Ohnishi, H. Stoecker, PRC94, 034906(16), arXiv: **1601.07692**

● STAR: PRL**112**, 162301(2014)

□ △ STAR: 1708.07132; PRL, accepted

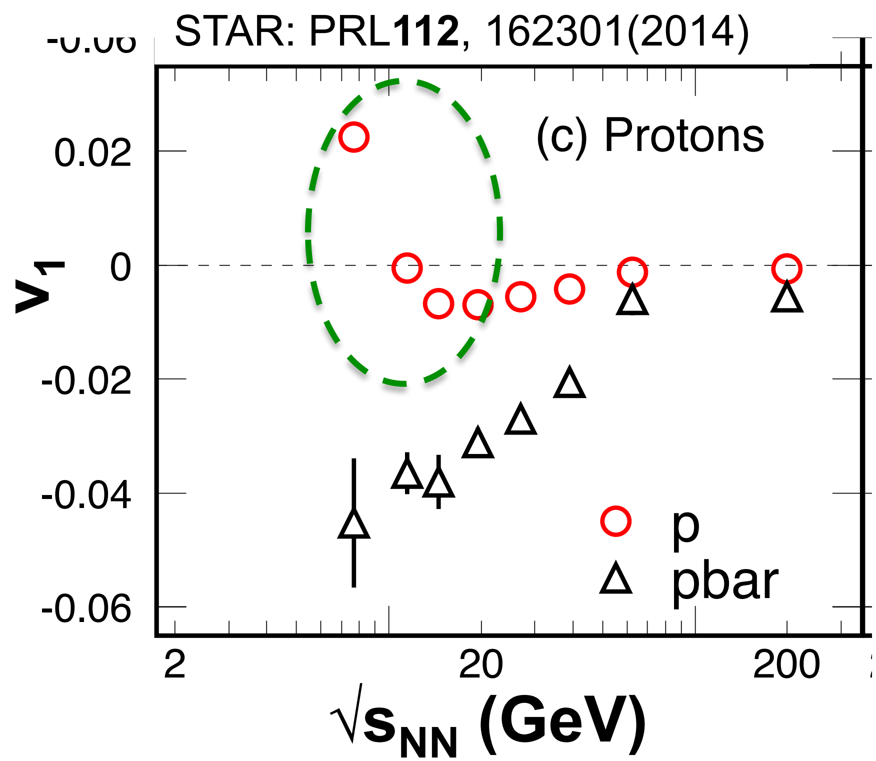
v_1 vs. Energy: Softest Point?



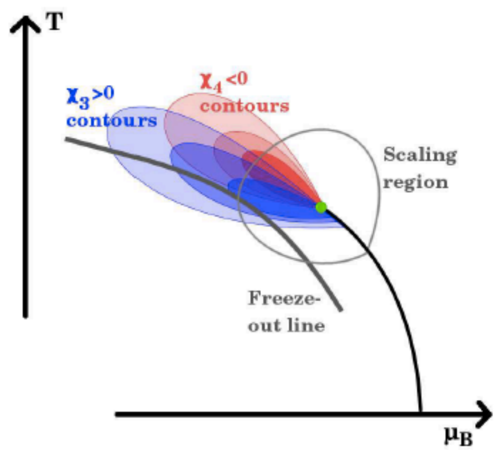


"Attractive force" ➔
Change of the EOS
~ "softest point"

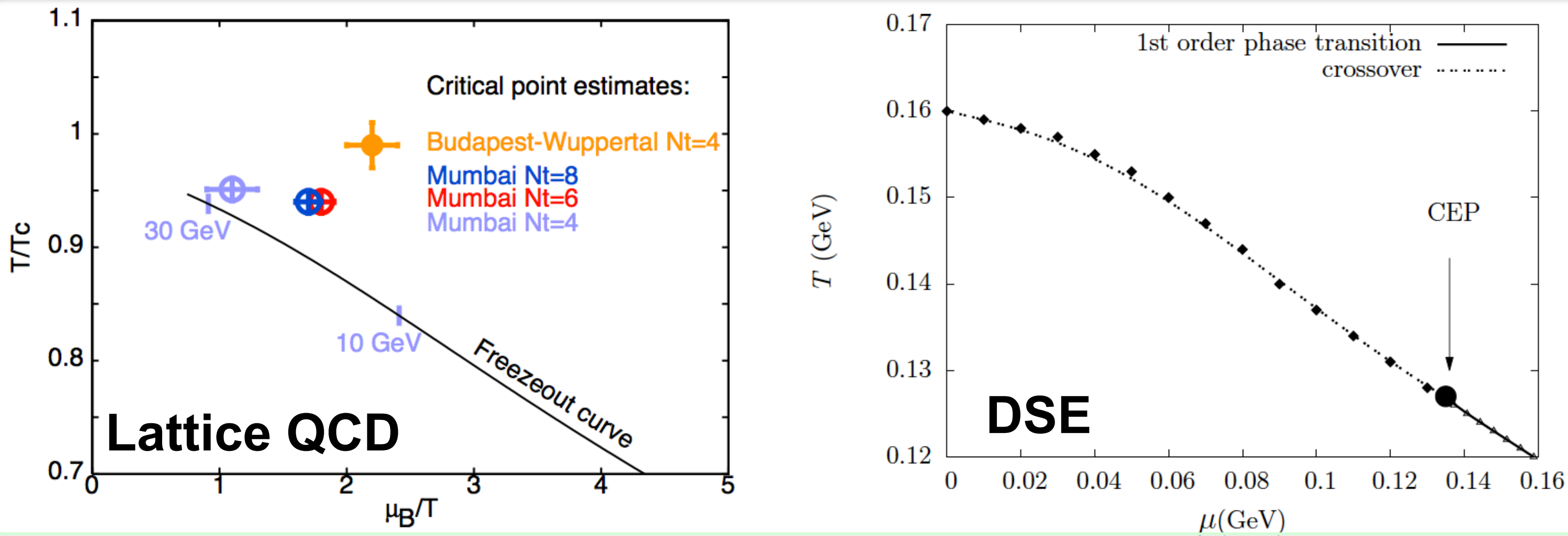
- Y. Nara, A. Ohnishi, H. Stoecker, arXiv: **1601.07692** ; PRC94, 034906(2016)



Criticality



Status on Predictions



Lattice QCD:

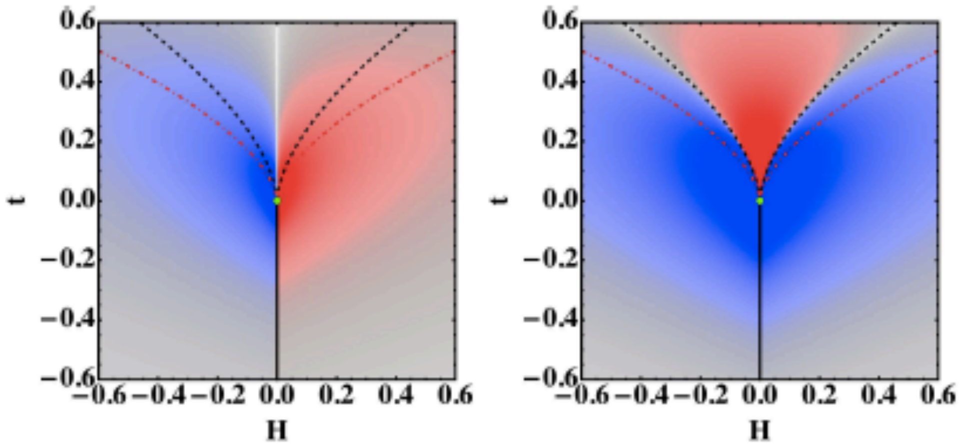
1) Fodor and Katz, JHEP 0404,050 (04)
   $(\mu^E_B, T_E) = (360, 162)$ MeV (Re.)
2) Gavai and Gupta, NPA 904, 883c (13)
   $(\mu^E_B, T_E) = (279, 155)$ MeV (Taylor)
3) F. Karsch ($\mu^E_B / T_E > 2$, CPOD2016)

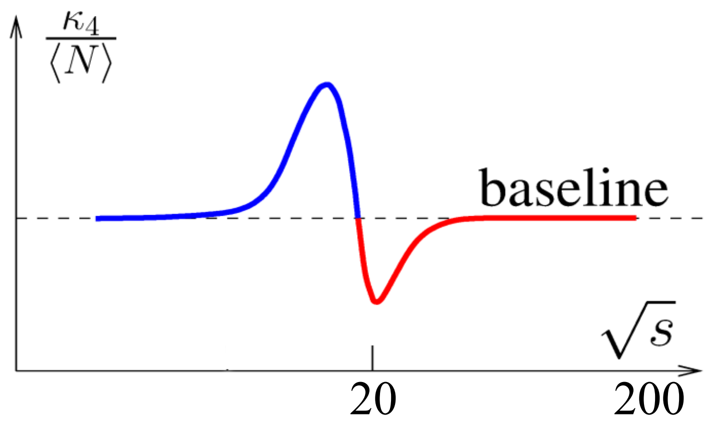
DSE:

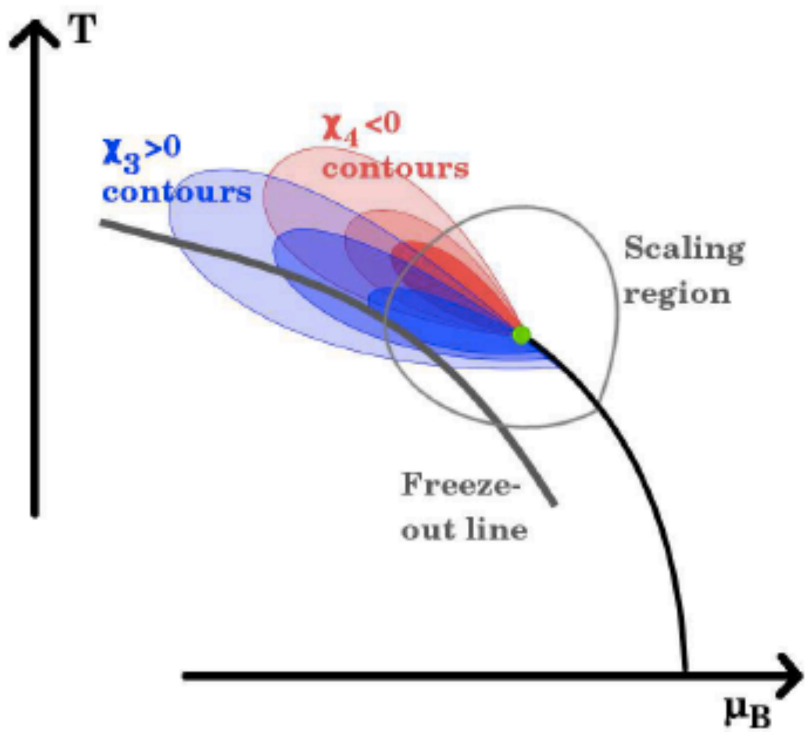
1) Y. X. Liu, et al., PRD90, 076006(14)
   $(\mu^E_B, T^E) = (372, 129)$ MeV
2) H.S. Zong et al., JHEP 07, 014(14)
   $(\mu^E_B, T_E) = (405, 127)$ MeV
3) C.S. Fischer et al., PRD90, 034022(14)
   $(\mu^E_B, T^E) = (504, 115)$ MeV

$\mu^E_B = 300 \sim 504$ MeV, $T_E = 115 \sim 162$ MeV, $\mu^E_B / T_E > 2.5$

Expectation from Model Calculations





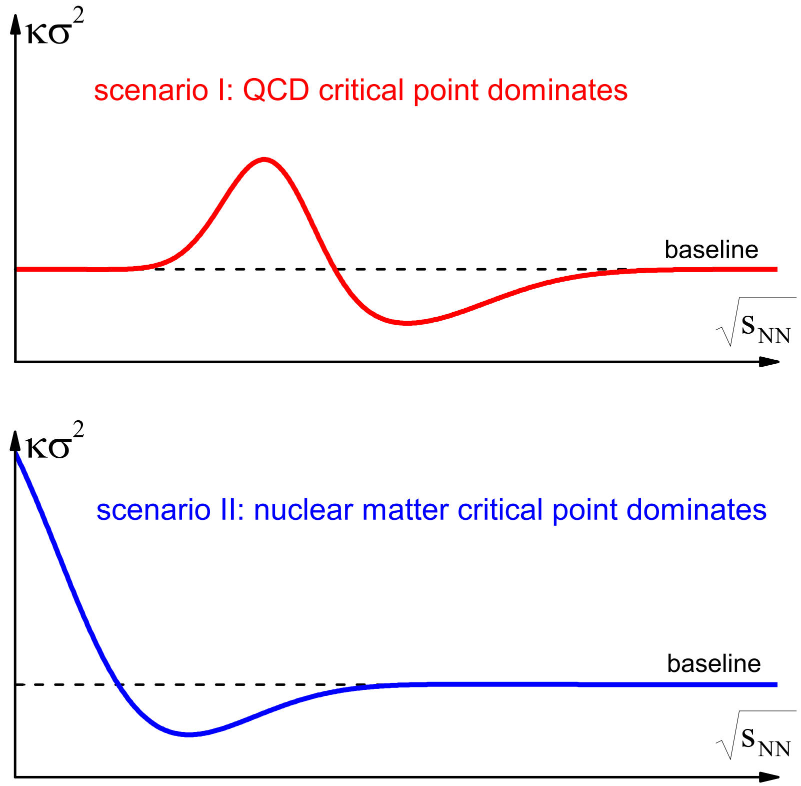


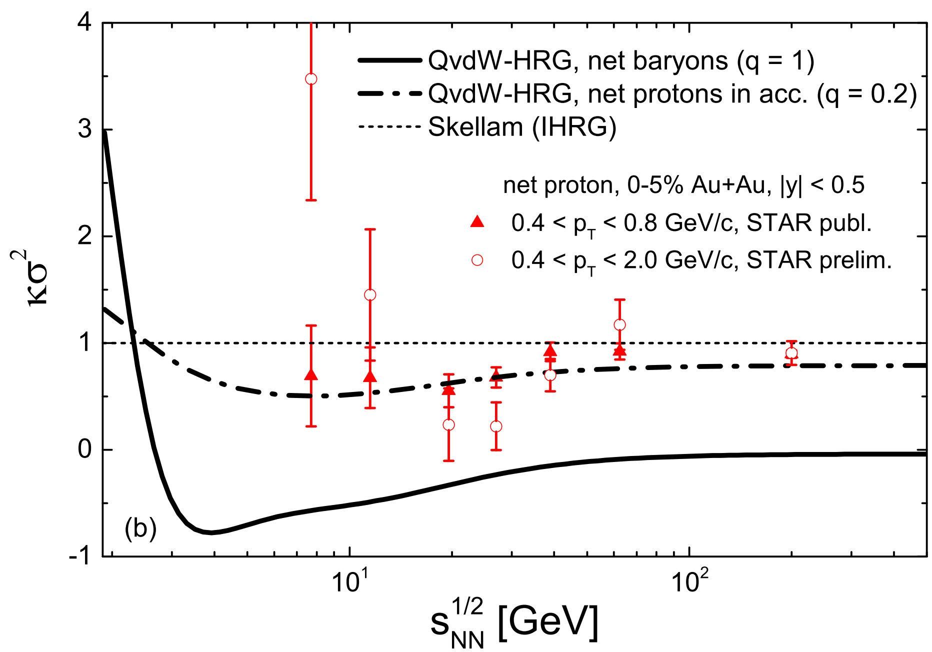
- Characteristic "Oscillating pattern" is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*
- Critical Region (CR)

- M. Stephanov, ***PRL107***, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, arXiv: 1603.05198, Phys. Rev. **D93** (2016) 034037

Model Expectation II

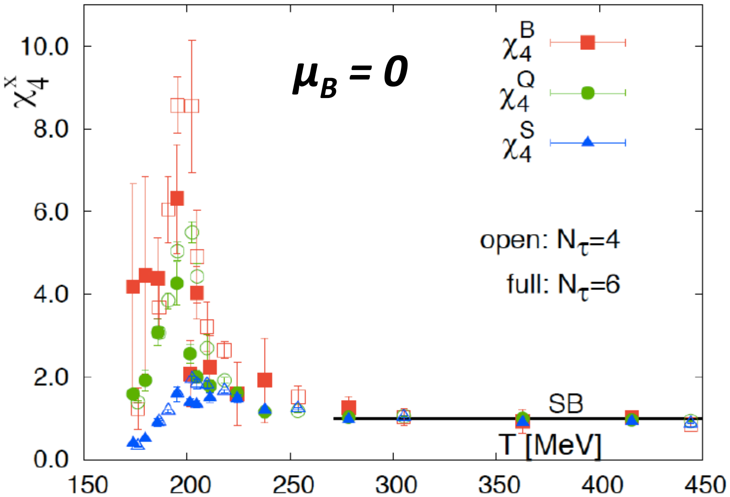
V. Vochenko, L.J. Jiang, M.I. Gorenstein and H. Stoecker 1711.07260

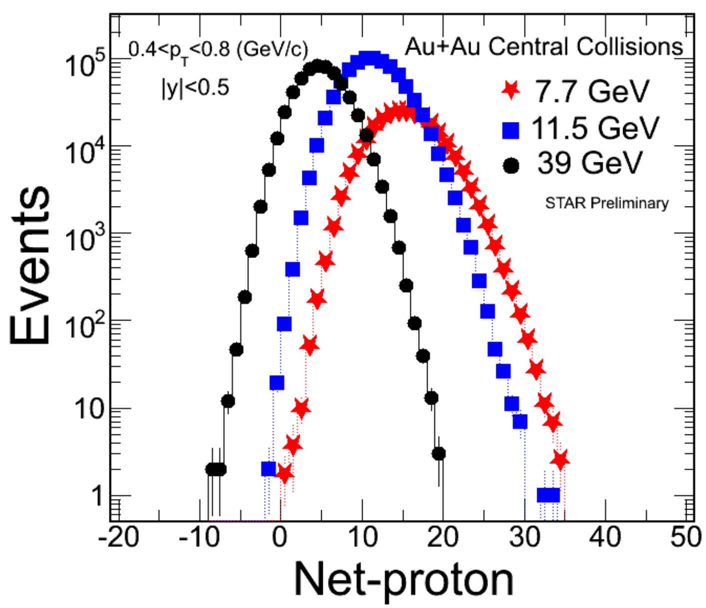




1) Both attractive and repulsive forces are needed to describe the criticality
2) This model might work for Liquid-gas CP, but will not work for QCD critical point due to wrong dof

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):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2,\ \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5},\ \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

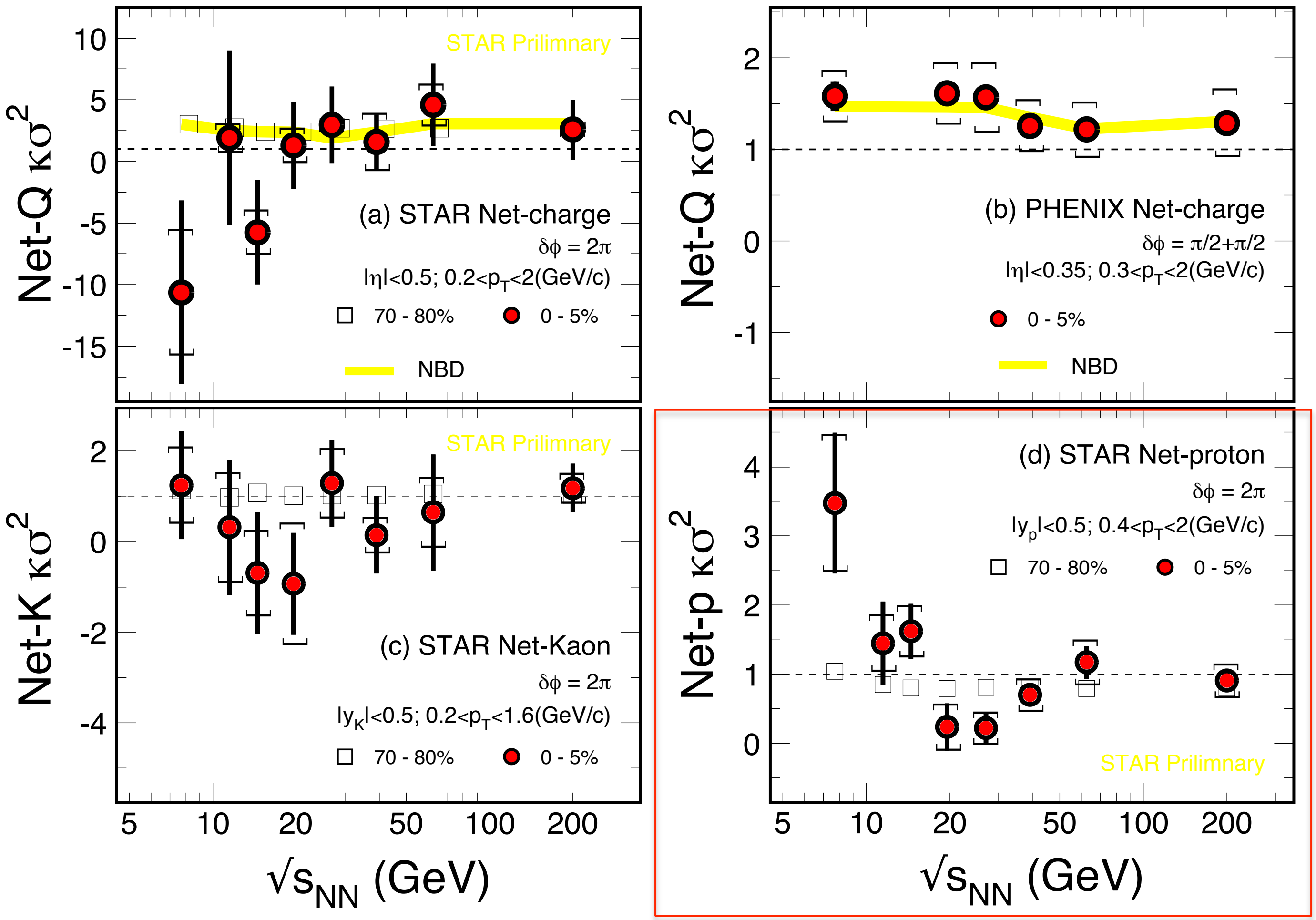
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

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



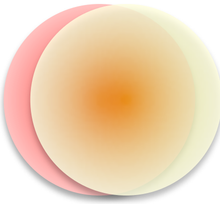
$$error(\kappa * \sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

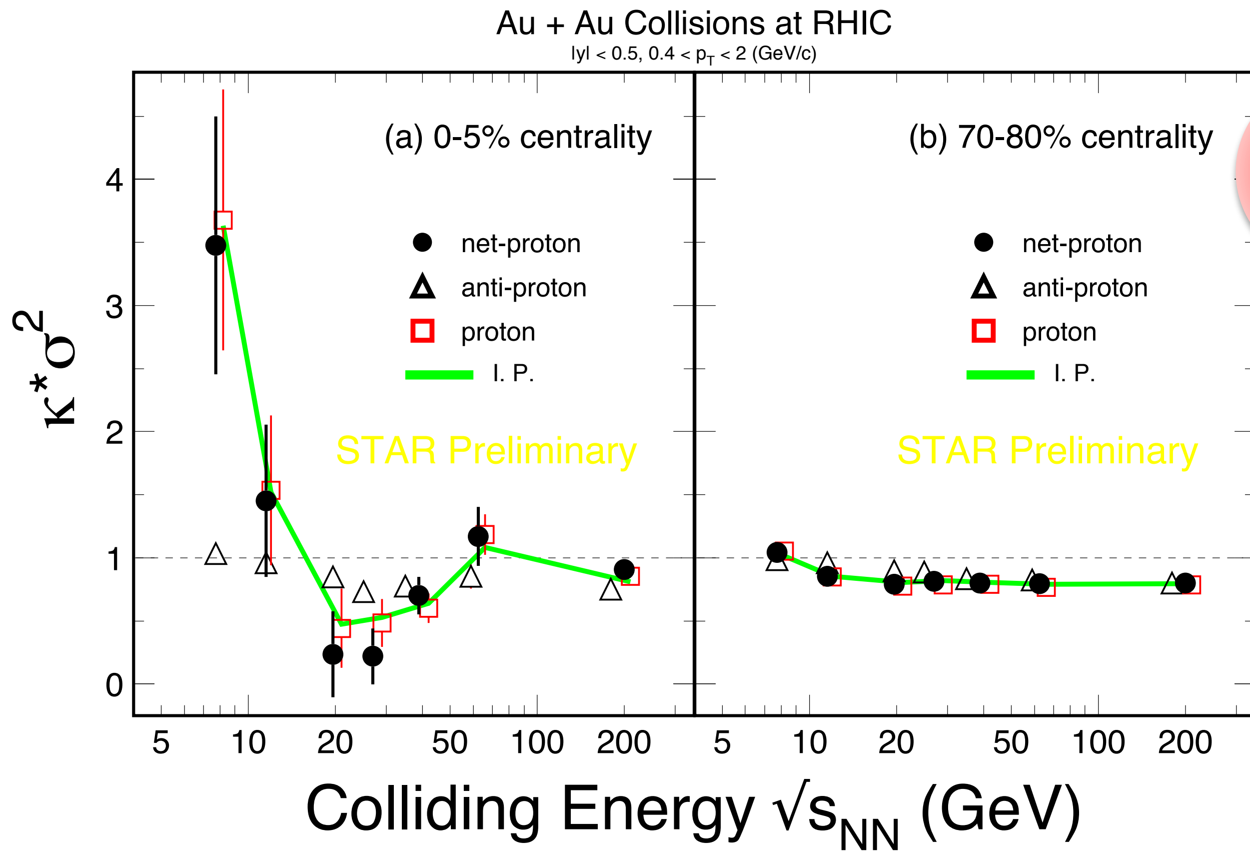
In STAR:

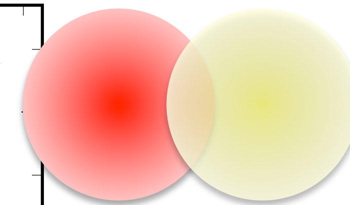
σ(Q) > σ(K) > σ(p)

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!

Net-proton Higher Moment



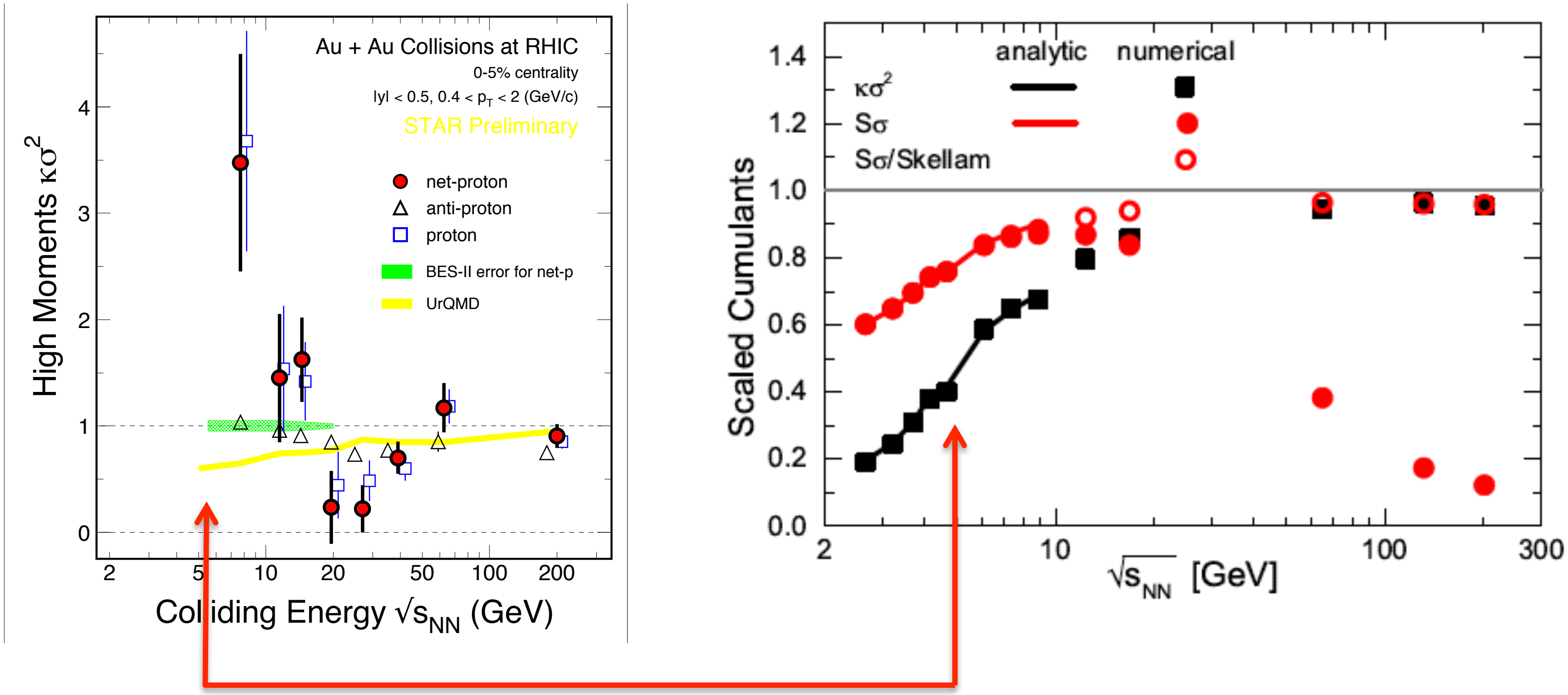




1) Flat energy dependence for 70-80% peripheral collisions
2) Non-monotonic behavior in the most central 0-5%, and 5-10% collisions. Net-p follow protons, especially at lower collision energies

STAR Data: *X.F. Luo, CPOD2014, QM2015*

No Model Reproduces the ‘Attraction’!



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

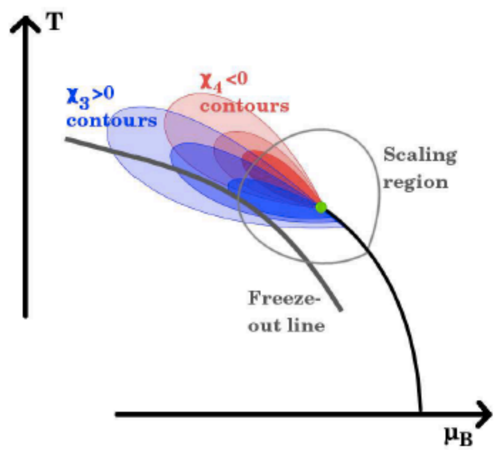
All models: ***suppress higher order net-proton fluctuations***

(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. Sokokov, Eur. Phys. J., **C77**, 288(2017) Interesting but unfinished, needs include dynamic effects in HIC.

BES-II & Beyond

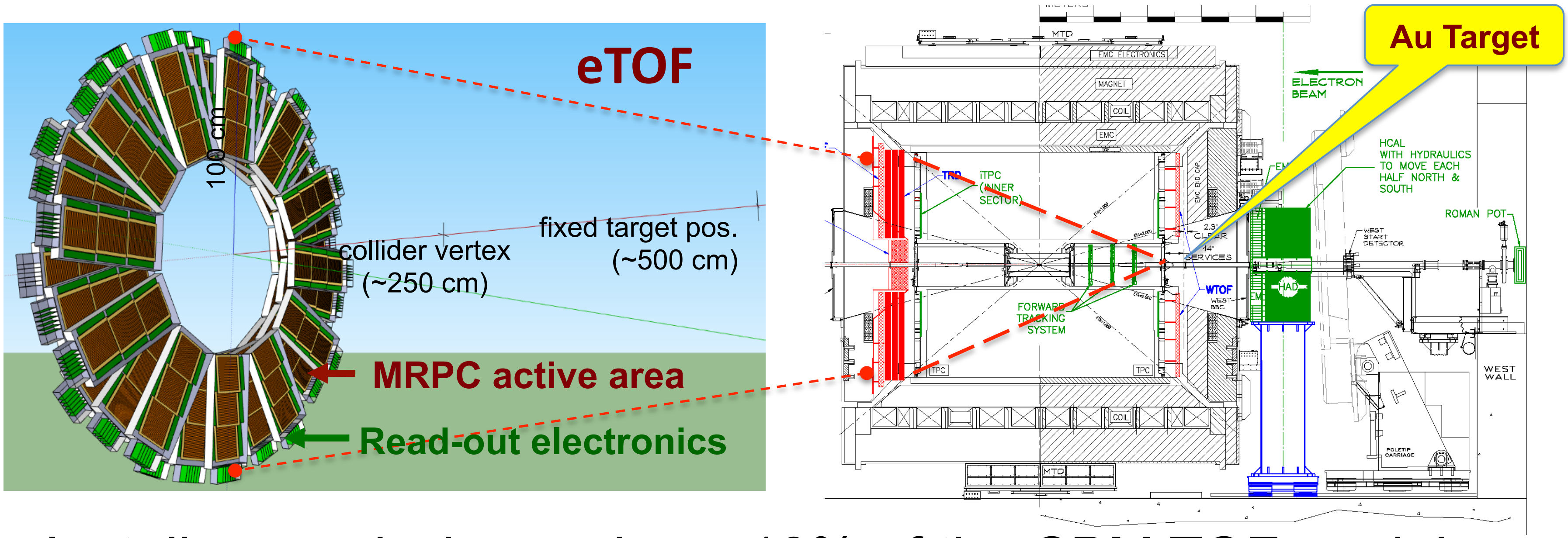


2019-2020: BES-II at RHIC

$\sqrt{s_{NN}}$ (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



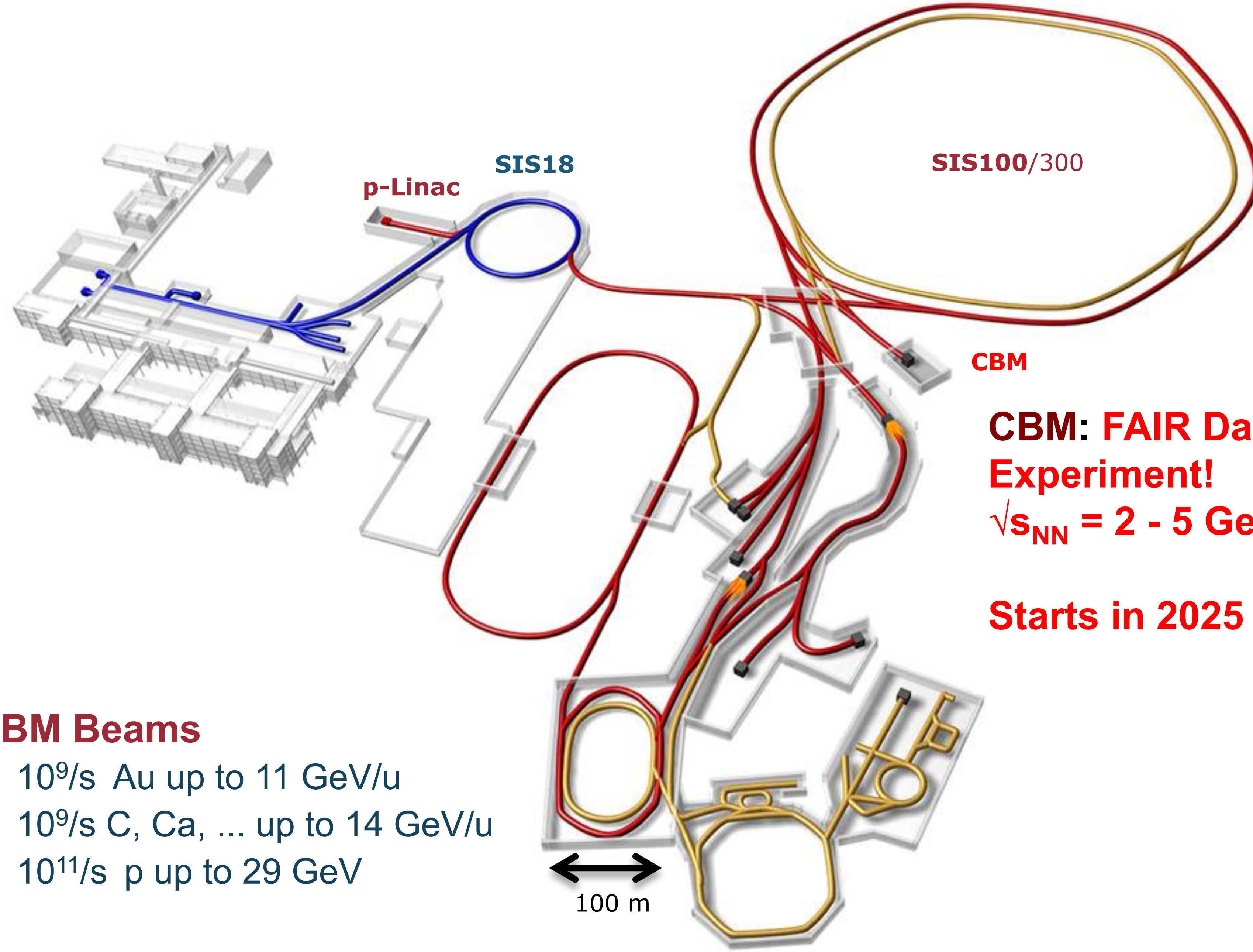
Install, commission and use 10% of the CBM TOF modules, including the read-out chains at STAR, starting in 2019

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

FAIR construction started, beam on target in 2025!

Facility for Antiproton & Ion Research: FAIR



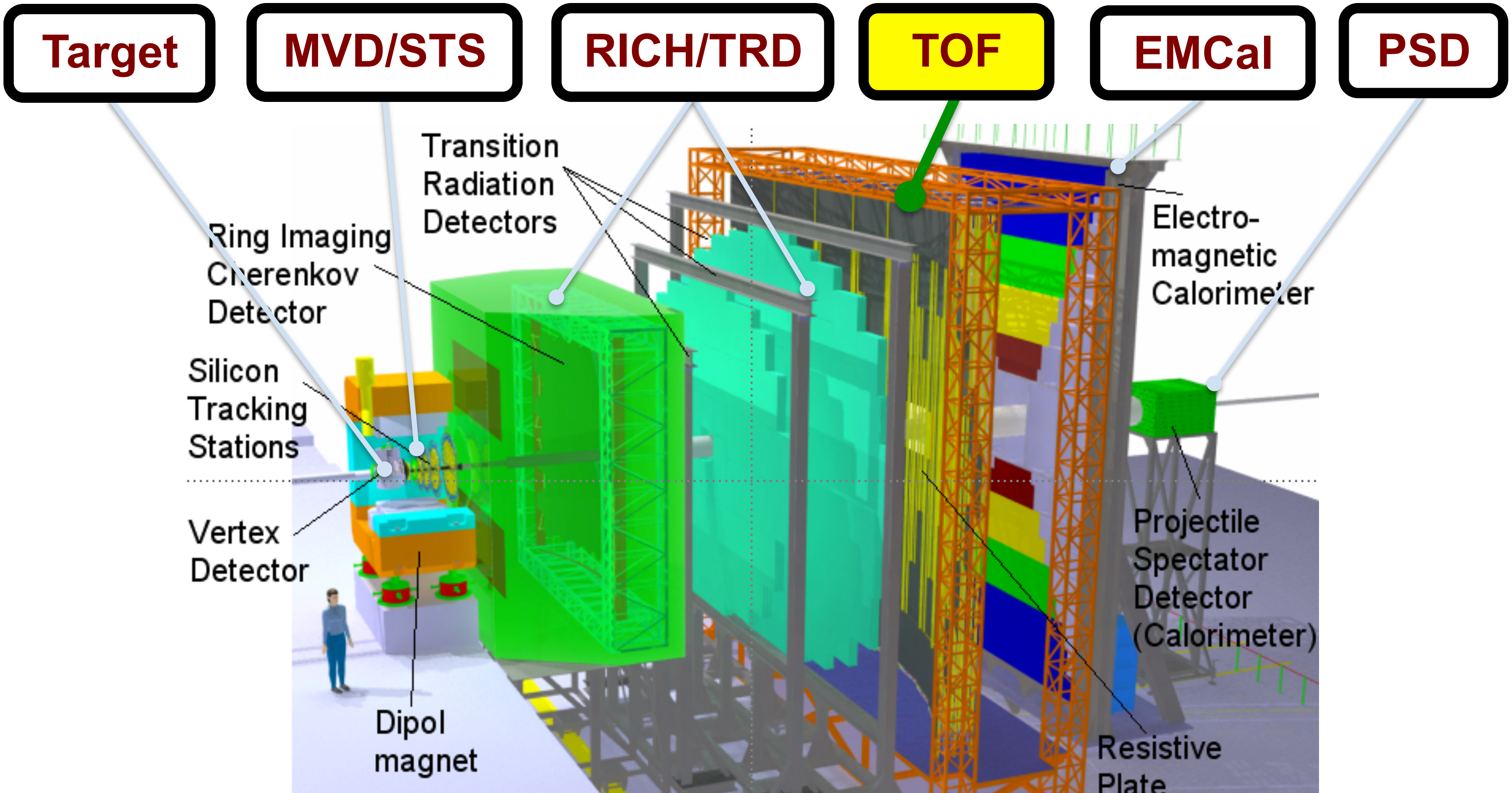
CBM: FAIR Day-1 Experiment!
$\sqrt{s_{NN}}$ = 2 - 5 GeV

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

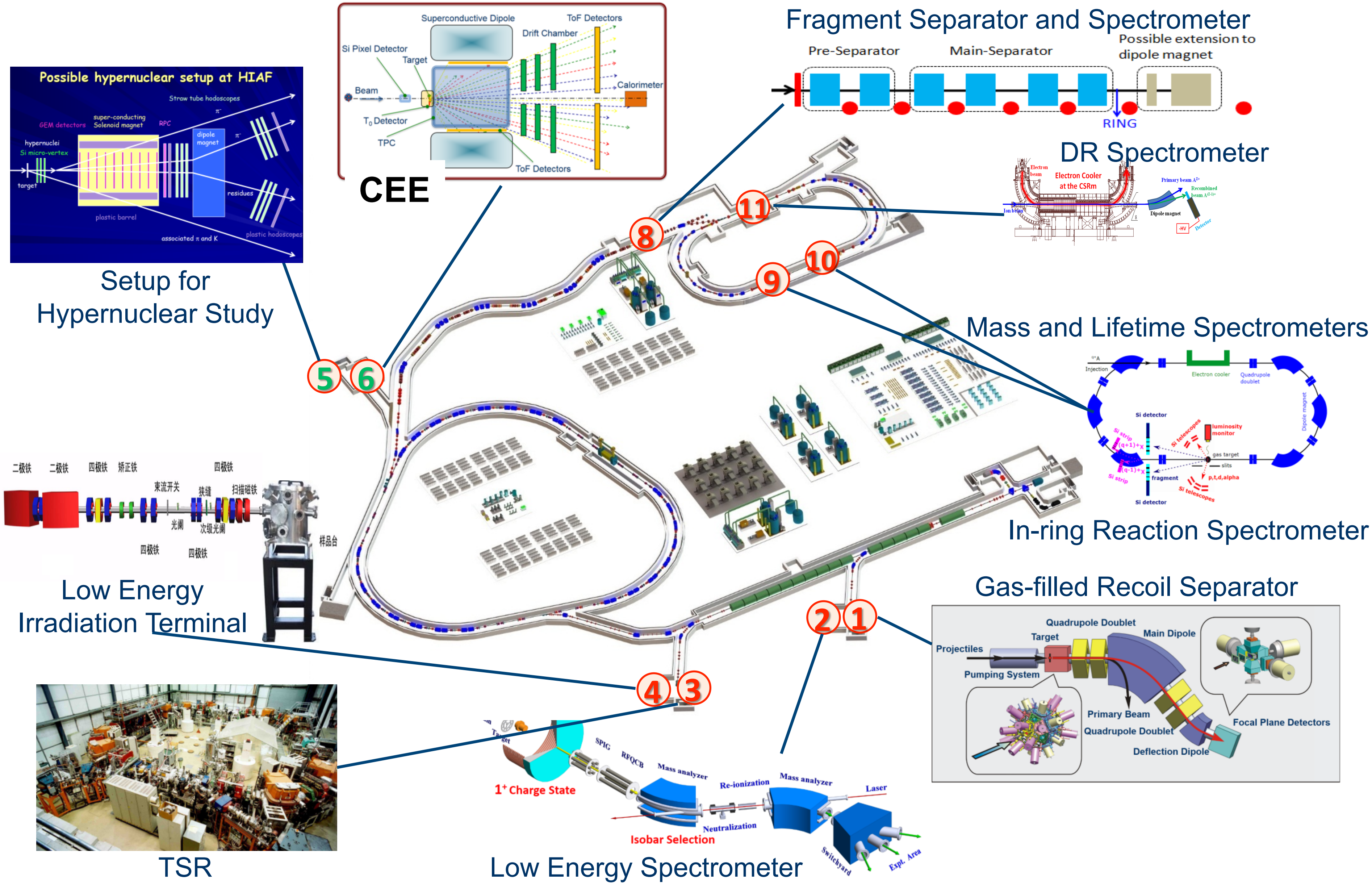


FAIR: One of the highest intensity accelerator complexes

Precision measurements at high baryon density region for:

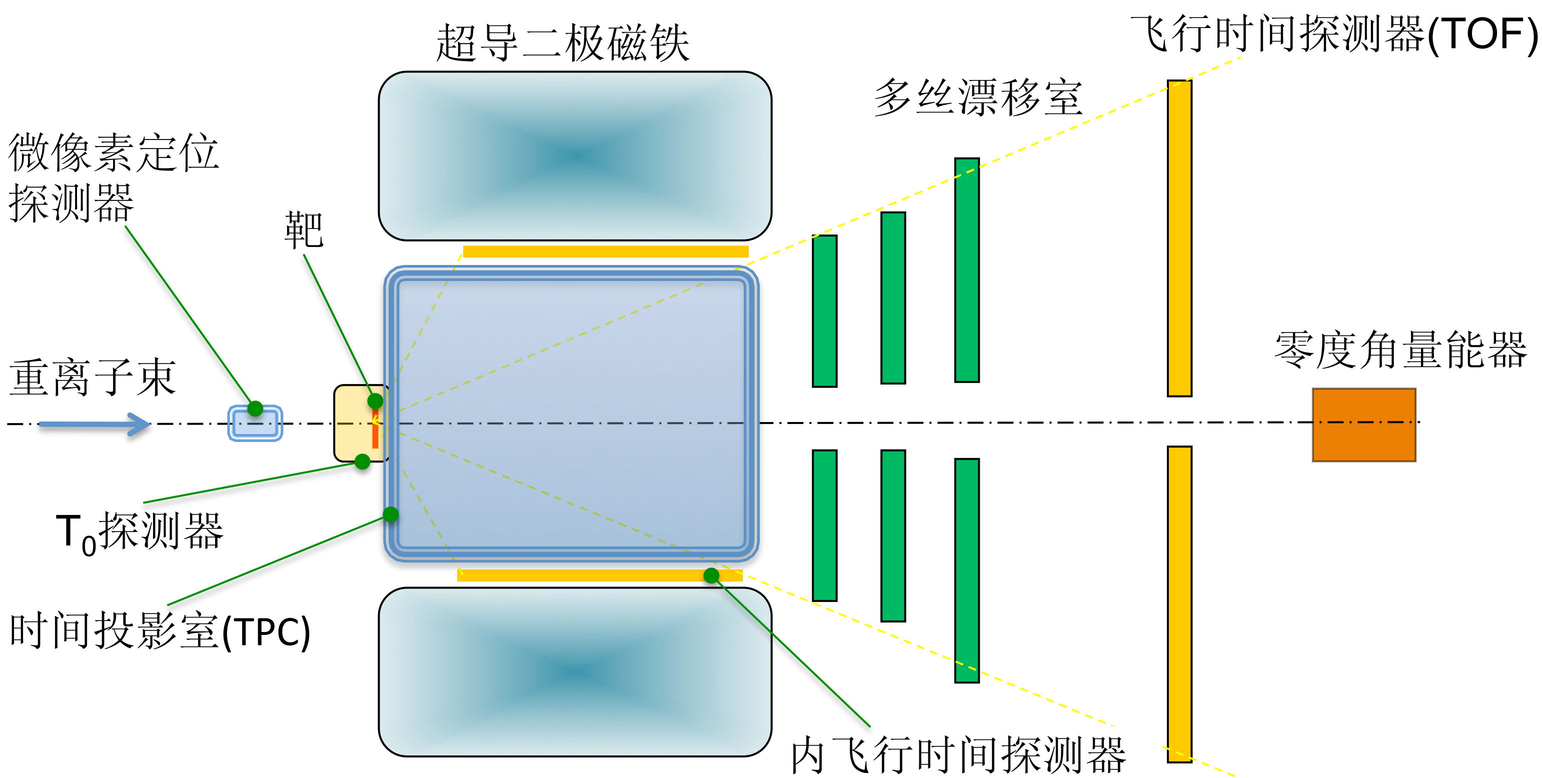
(i) Dileptons (***e, μ***); (ii) High order correlations; (iii) Flavor productions (***s, c***)

CEE at HIAF (2023)



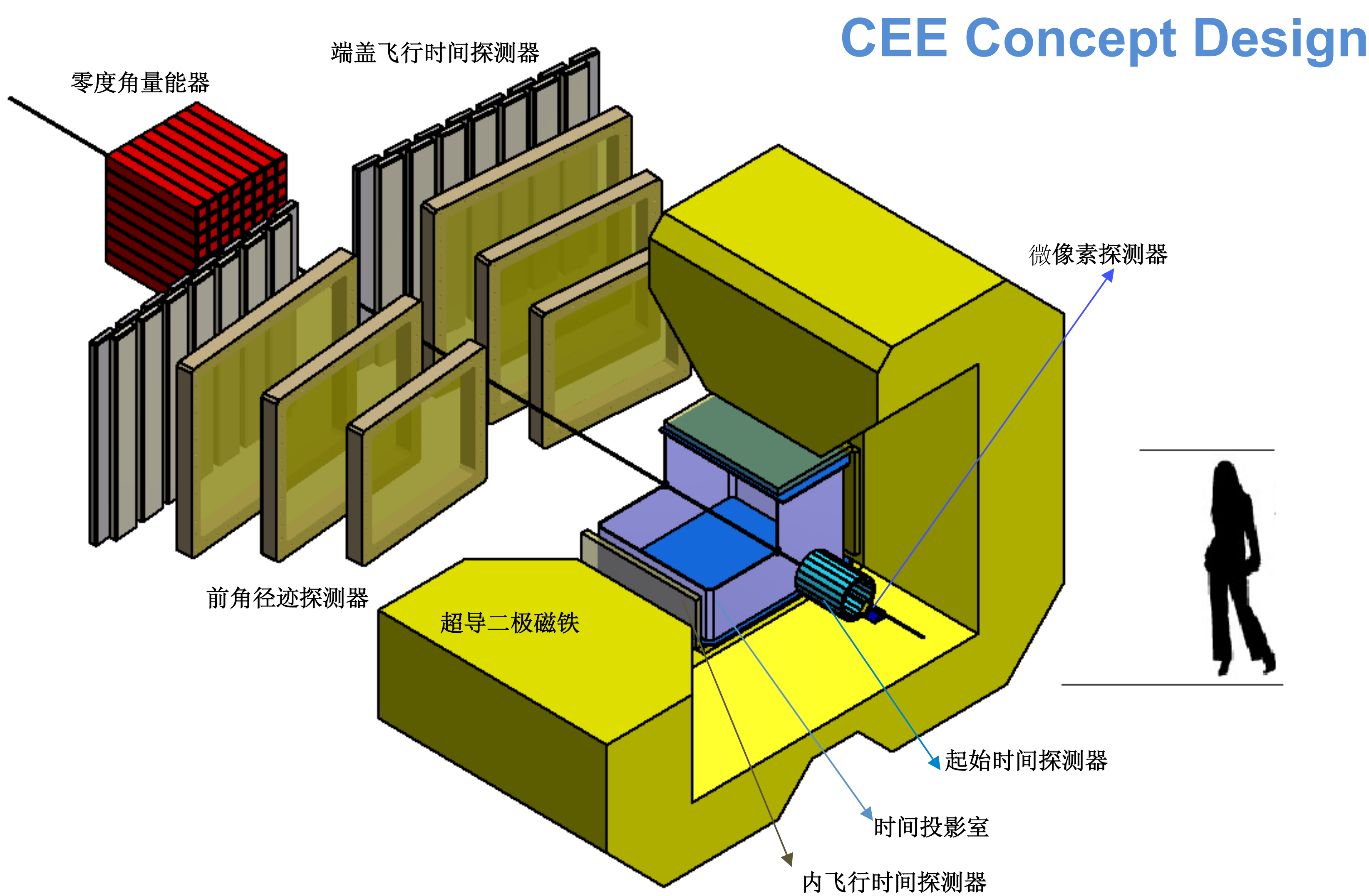
CEE 概念性设计

低温高密核物质测量谱仪（CEE）



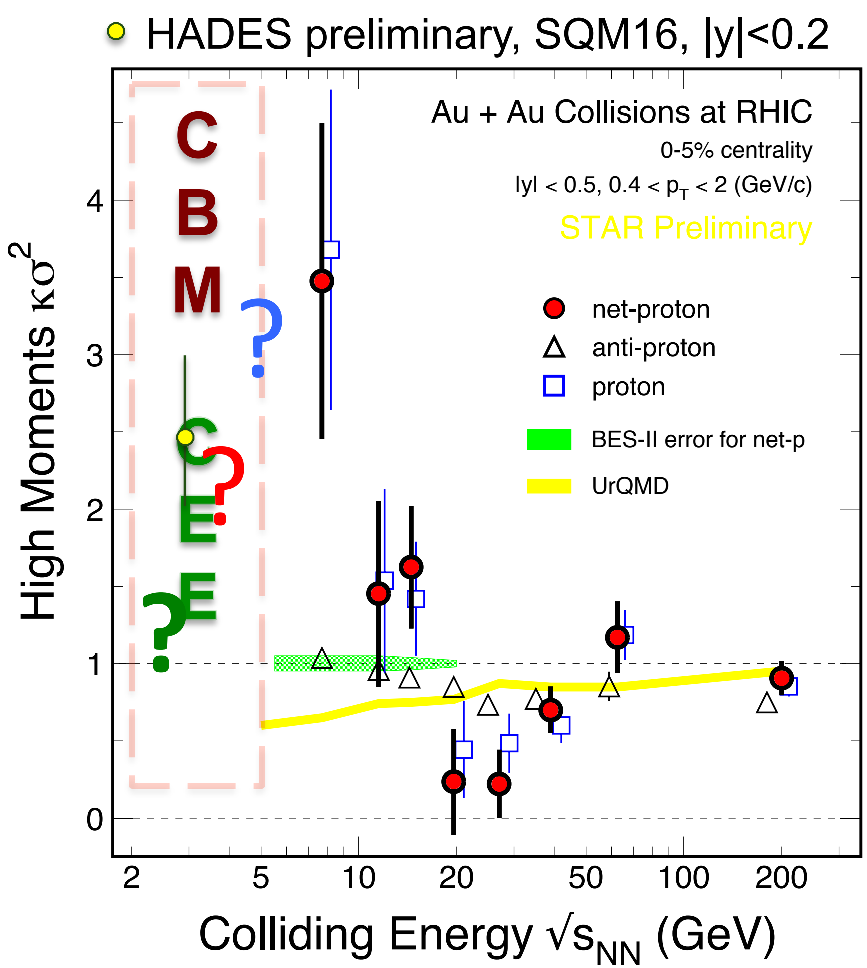
技术亮点: 1）微像素定位探测器（华中师范大学、中科院近代物理所）
2）高计数率高精度飞行时间探测器（清华大学、中国科学技术大学）
3）高精度三维径迹探测器（中科院上海应用物理所）
4）新型数据获取系统（中国科学技术大学）

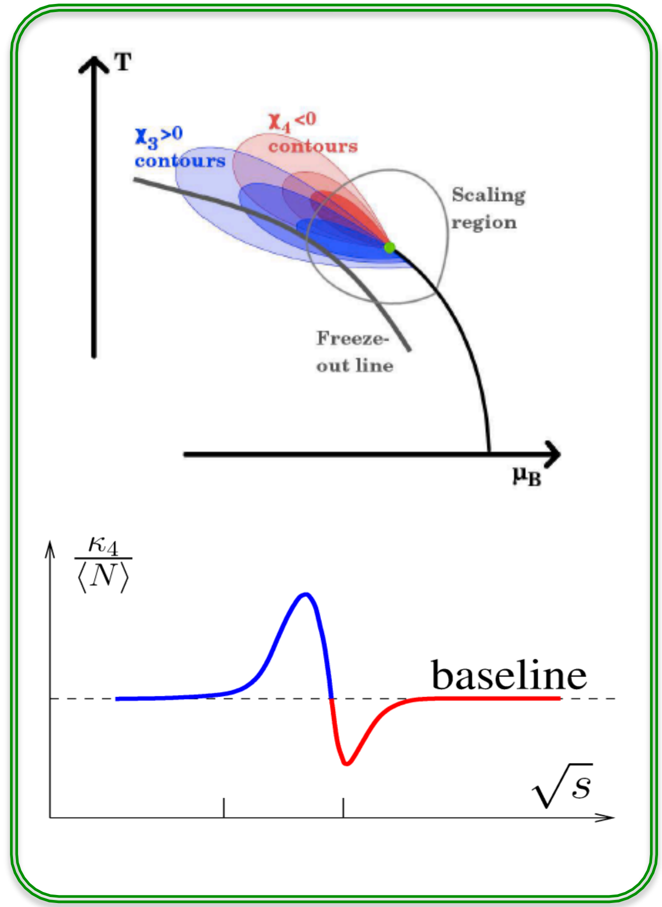
CEE 的总体设计



Observables: v_1/v_2/high-moment for light nuclei production and protons

Search for the QCD Critical Point

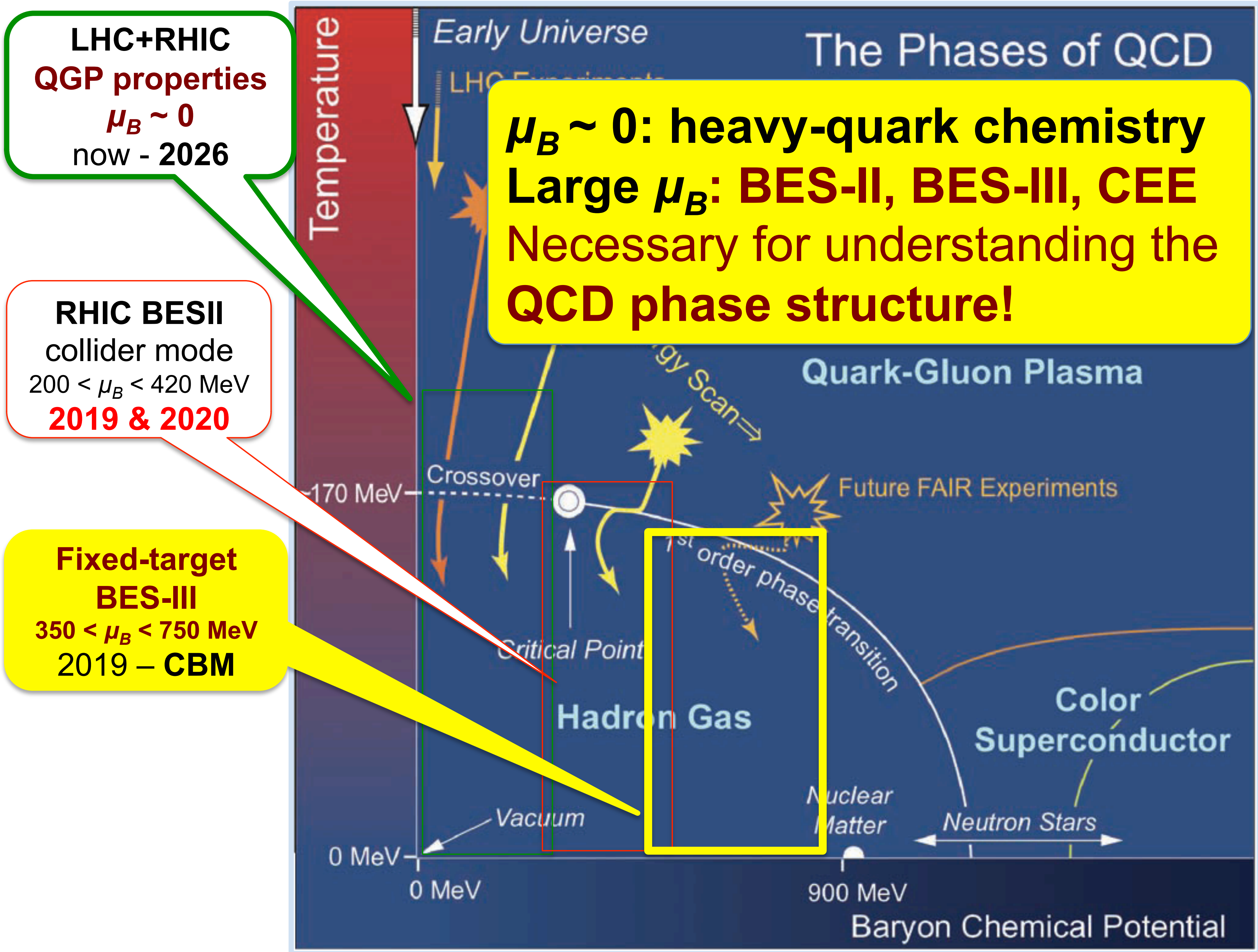




- RHIC BES-II: dramatically reduce the errors!
- CBM/RHIC FXT/CEE Experiments (**2.5 <** $\sqrt{s_{NN}}$ **< 8** GeV) :

Key region for Critical Point search

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



LHC+RHIC
QGP properties
$\mu_B \sim 0$
now - 2026
RHIC BESII
collider mode
$200 < \mu_B < 420$ MeV
2019 & 2020
Fixed-target
BES-III
$350 < \mu_B < 750$ MeV
2019 – CBM
Early Universe
The Phases of QCD
$\mu_B \sim 0$: heavy-quark chemistry
Large μ_B: BES-II, BES-III, CEE
Necessary for understanding the
QCD phase structure!
Temperature
Quark-Gluon Plasma
Crossover
170 MeV
Future FAIR Experiments
1st order phase transition
Critical Point
Hadron Gas
Color
Superconductor
Vacuum
Nuclear
Matter
Neutron Stars
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

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 // *XxYy*: project leader at CEE

Thanks for your attention!