

# QCD Medium Properties at Finite Baryon Density

- BES in High-Energy Nuclear Collisions

Nu Xu<sup>(1,2)</sup>

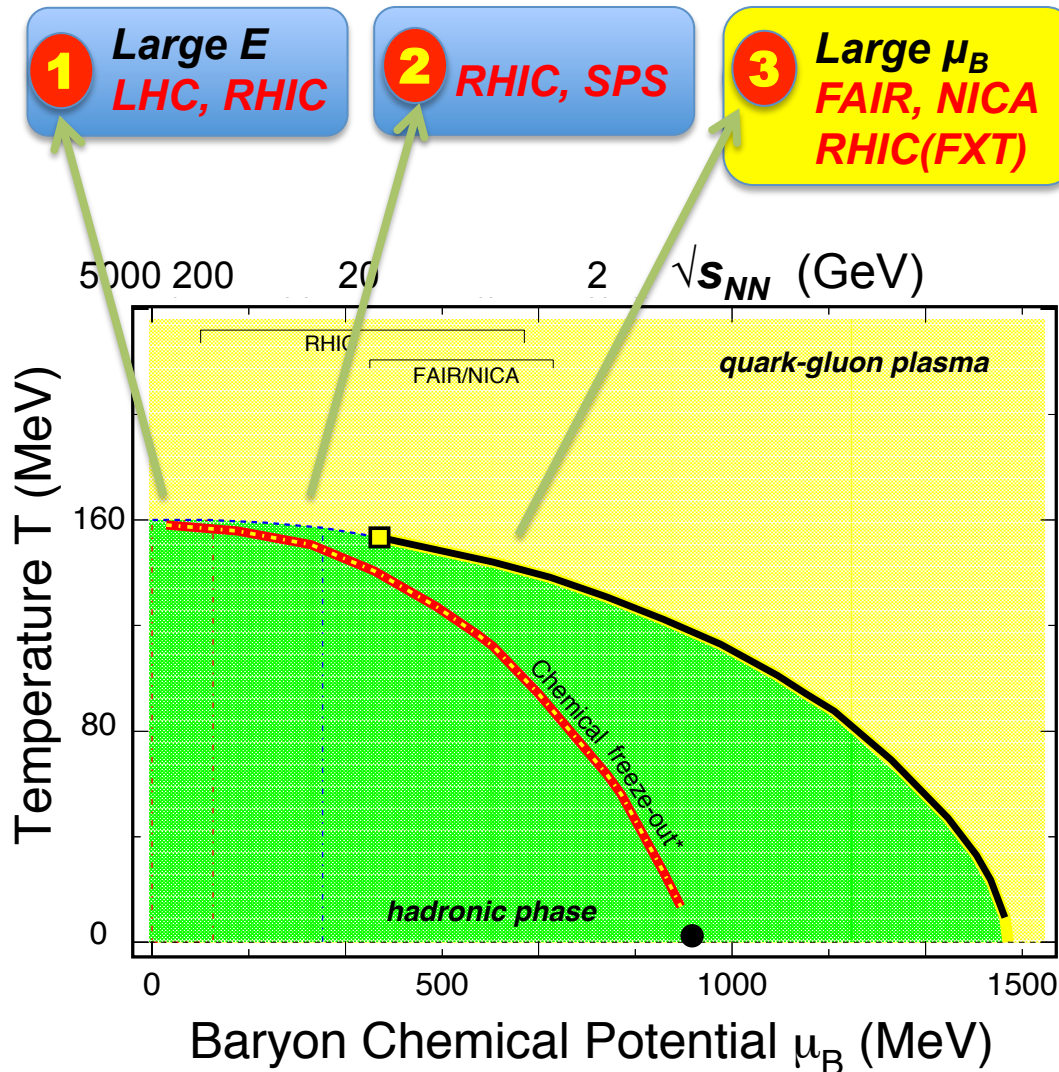
**Many thanks to the Organizers!**



*(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

## (1) Introduction

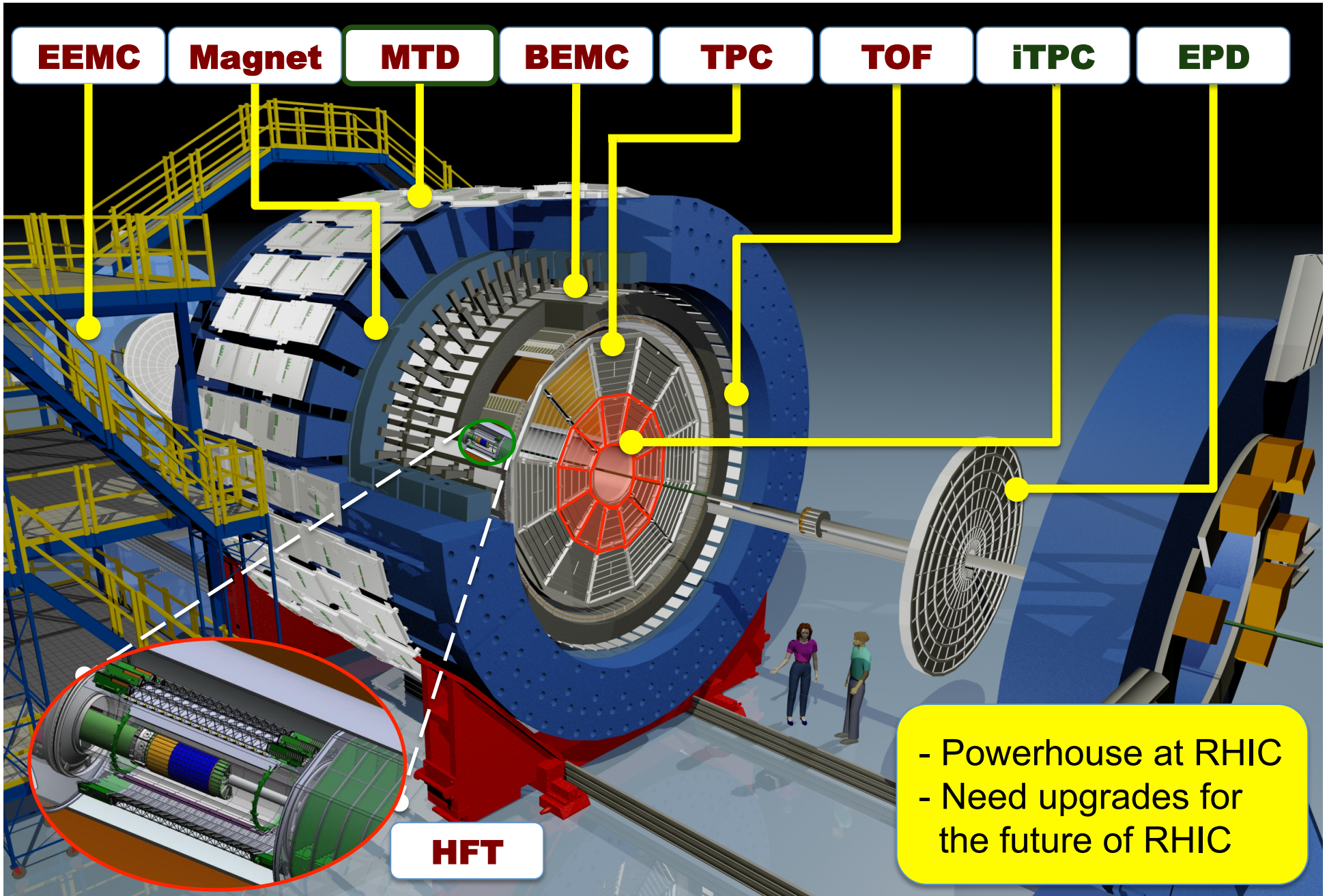
## (2) Recent Results from BES-I at RHIC

- i. Collectivity
- ii. Chirality
- iii. Criticality

**QCD  
Emergent  
Properties**

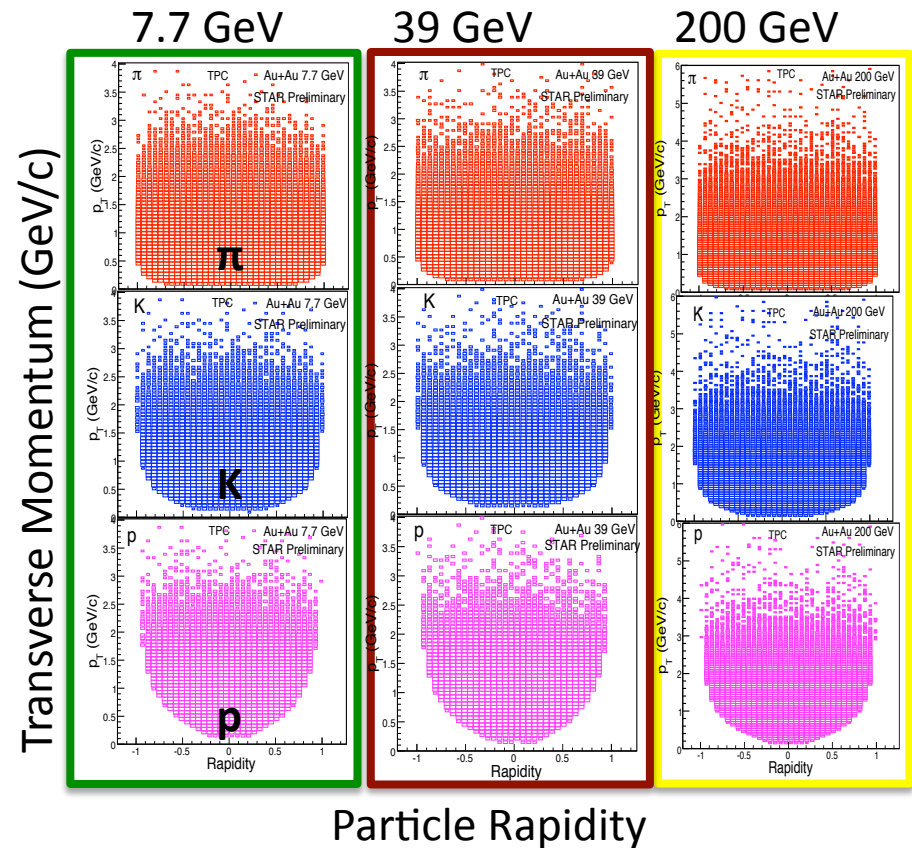
## (3) BES-II and Beyond

# STAR Detector System





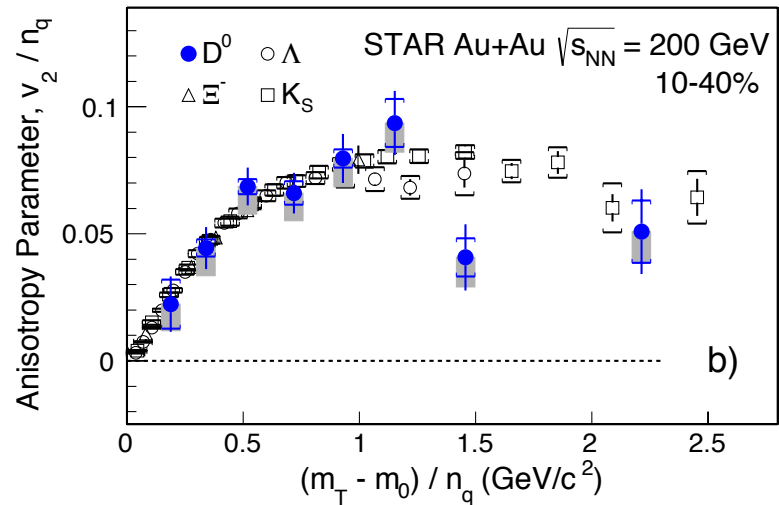
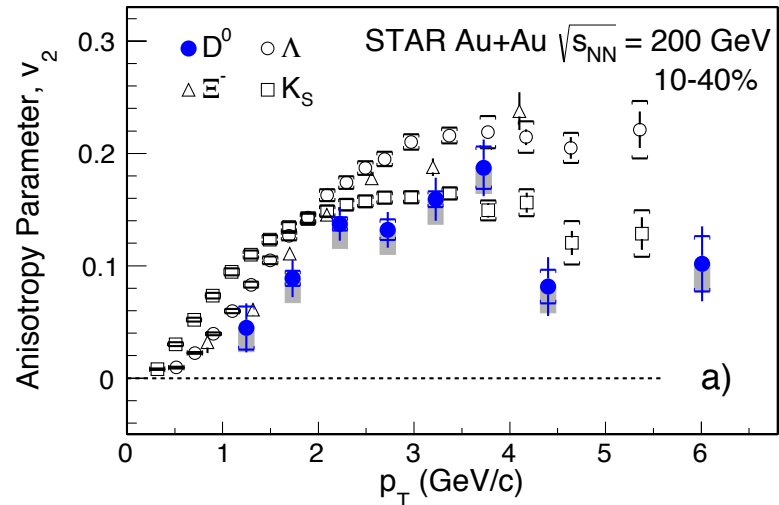
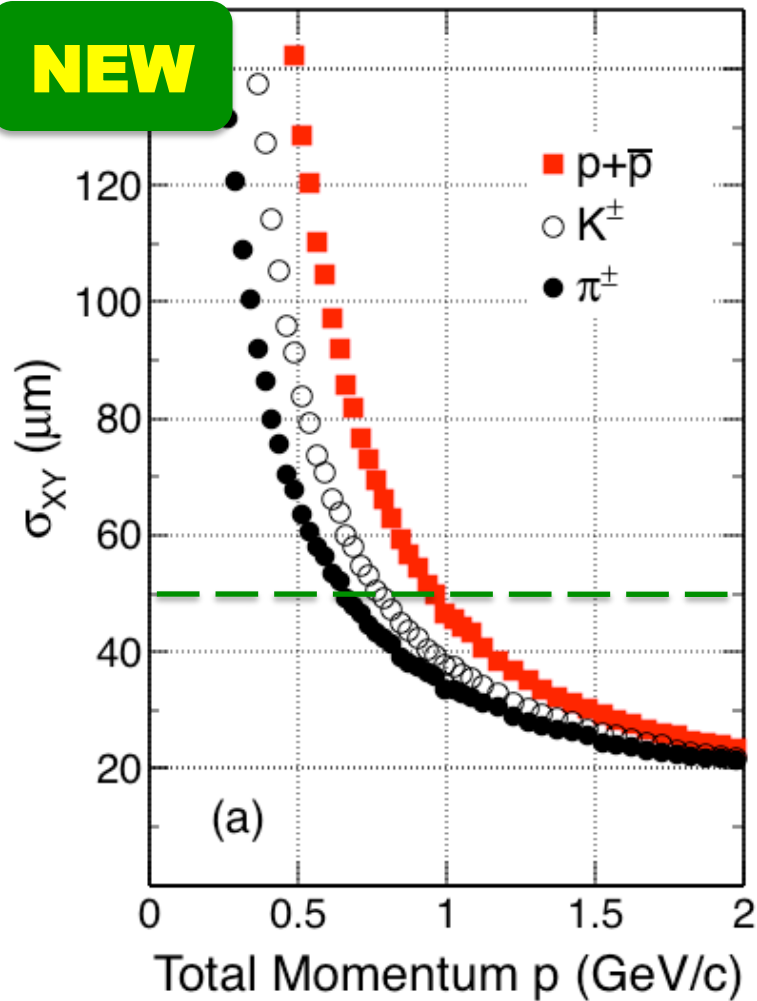
$\sqrt{s_{NN}}$ (GeV)	Events ( $10^6$ )	Year
200	350	2010
62.4	67	2010
<b>54.4</b>	<b>1000</b>	<b>2017</b>
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010



- 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 ( $v_2$ )

**NEW**

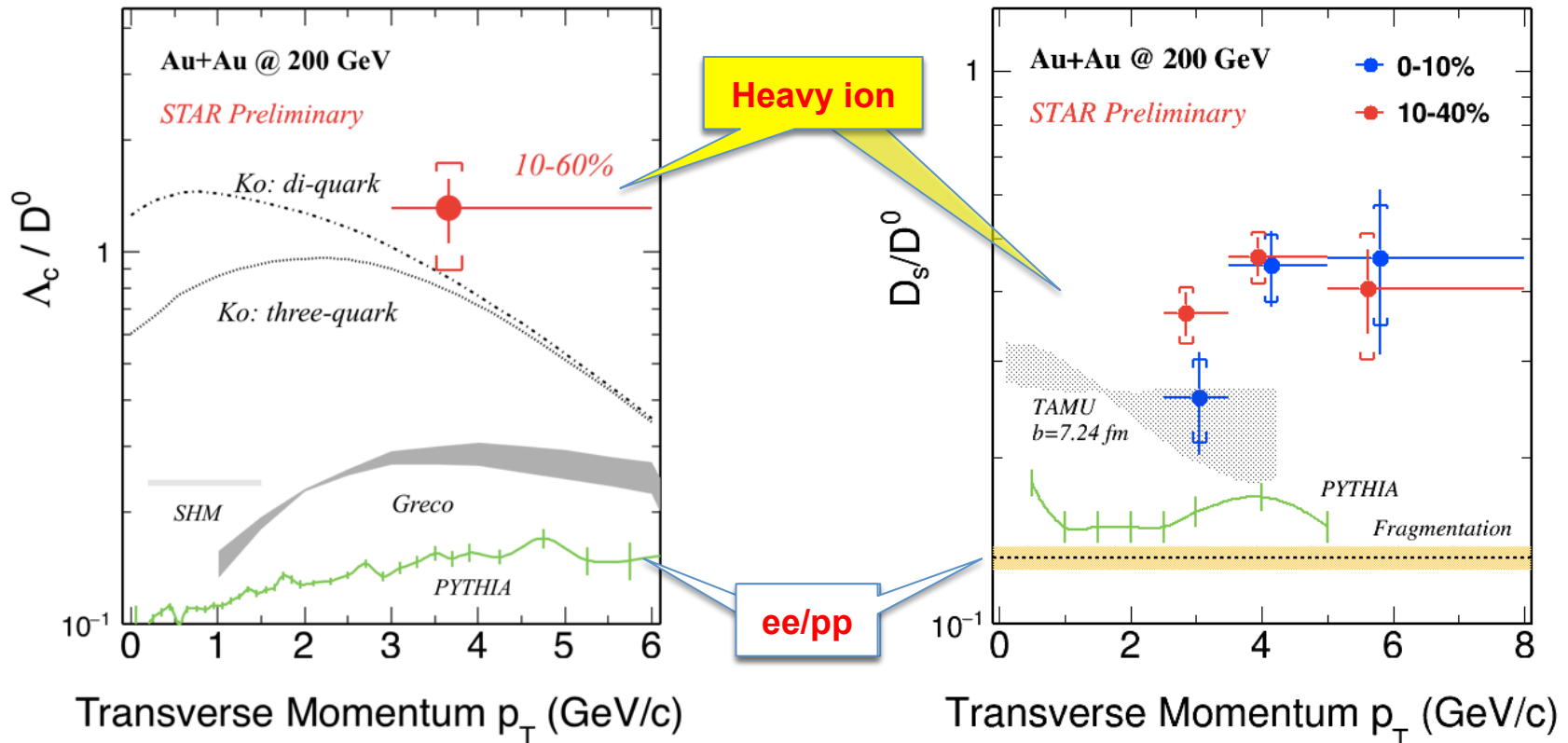


**“These results suggest that charm quarks have achieved local thermal equilibrium with the medium created in such (200GeV Au+Au) collisions.”**

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

**NEW**

# $\Lambda_c/D^0$ and $D_s/D^0$ Ratios

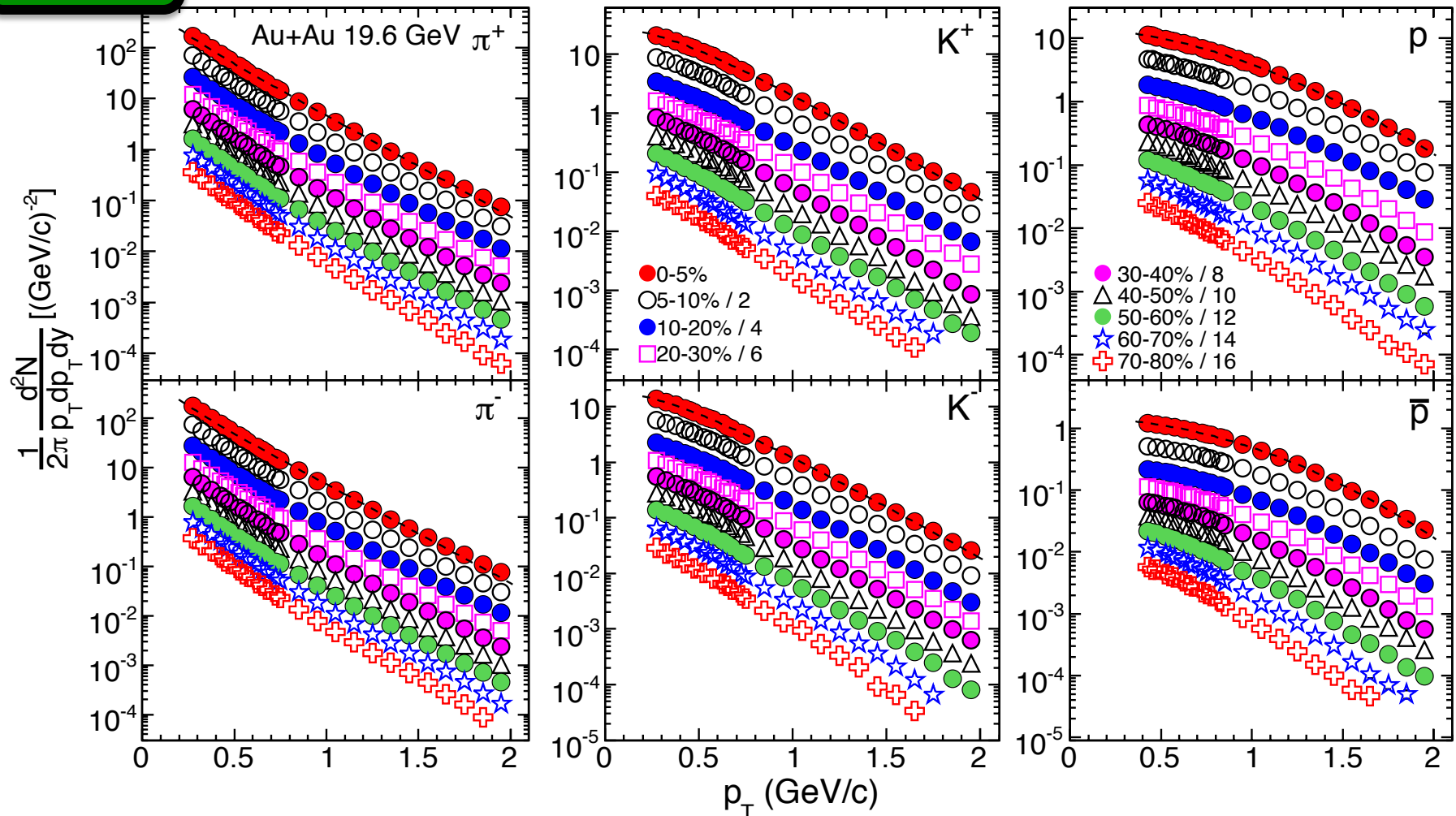


- 1) In HICs, the **ratios of  $\Lambda_c/D^0$  and  $D_s/D^0$  are much larger** than that from elementary collisions implying a different hadron production processes
- 2) HRG predicted an increase for both  $D_s/D^0$  and  $D^+/D^0$ , due to mass/T (i)
- 3) Sources: Charm conservation, strangeness enhancement and coalescence process for hadron production in heavy ion collisions!

STAR data: 1704.04364; (i) A. Andronic *et al.*, PLB**571**, 36(03); (ii) M. He *et al.*, PRL**110**, 112301(13); Y. Oh *et al.*, PRC**79**, 044905(09); S. Ghosh *et al.*, PRD**90**, 054018(14)

**NEW**

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

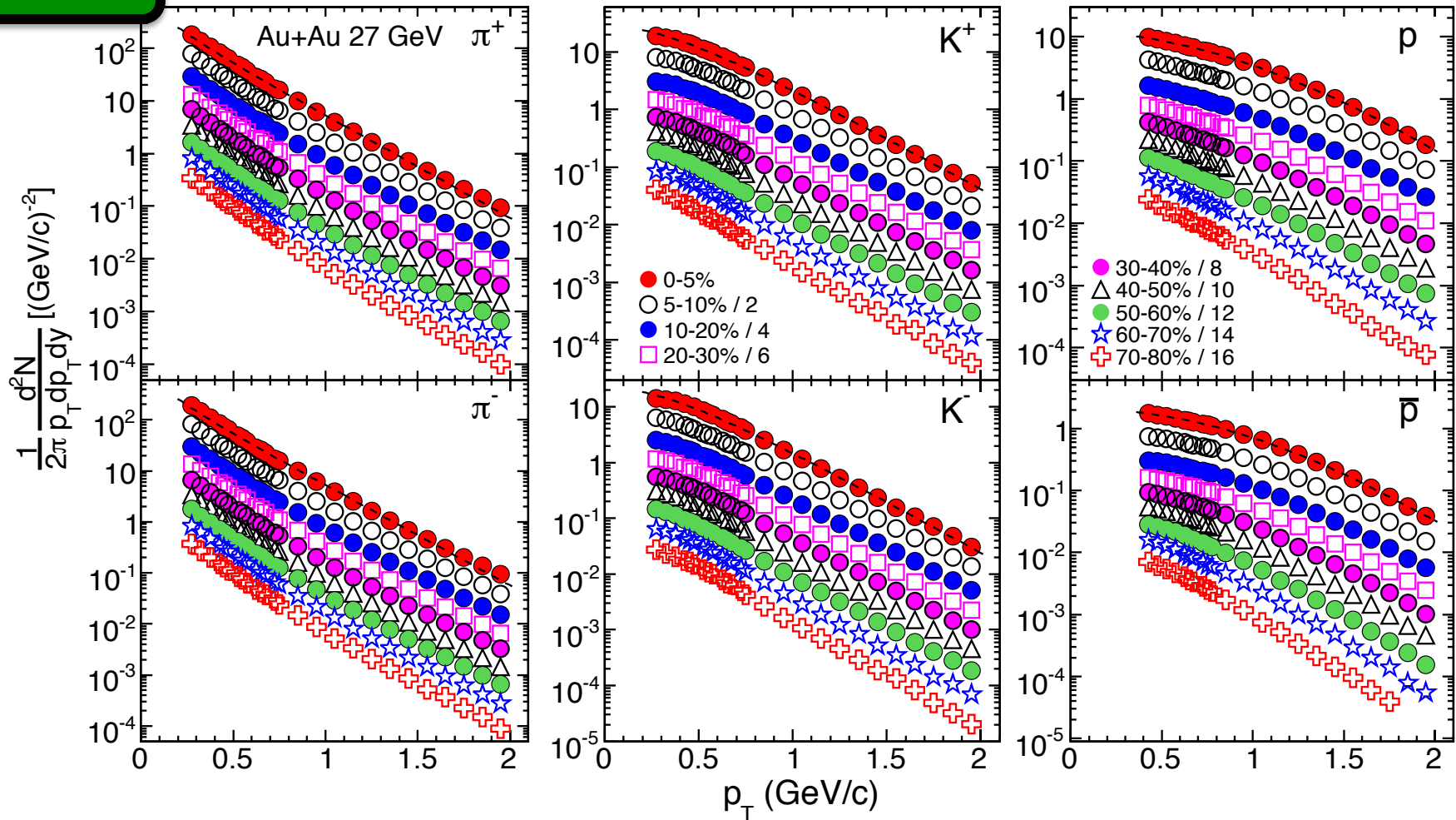


STAR: arXiv:1701.07065, to appear in PRC

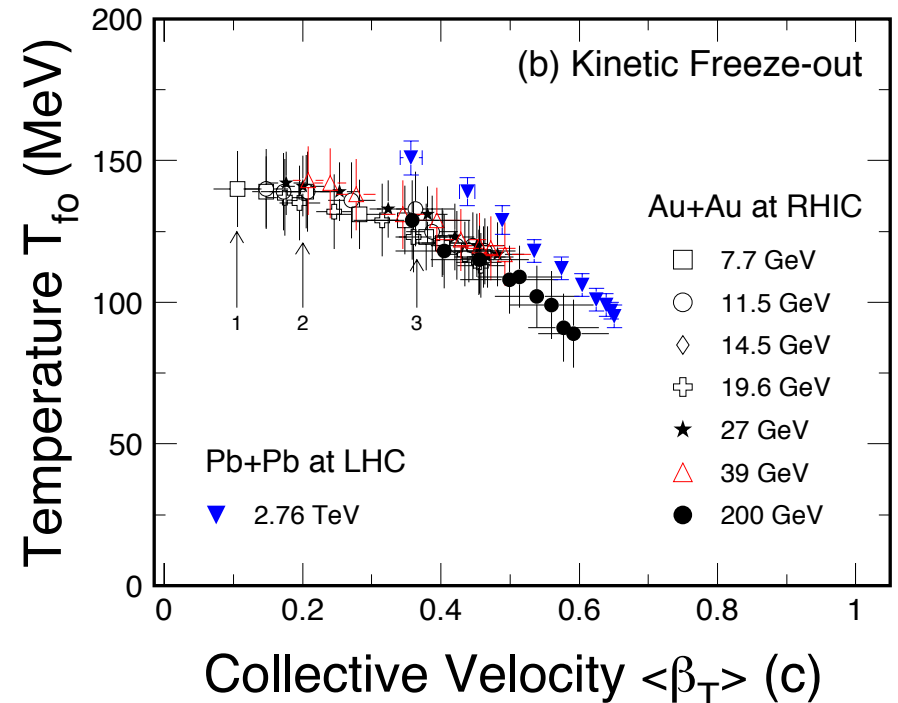
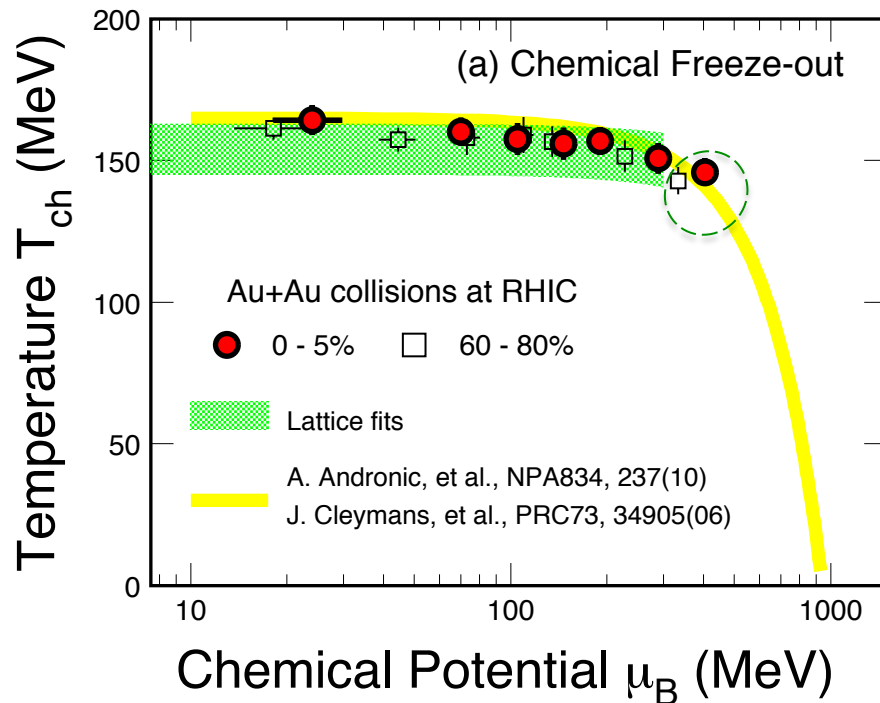


**NEW**

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



STAR: arXiv:1701.07065, to appear in PRC



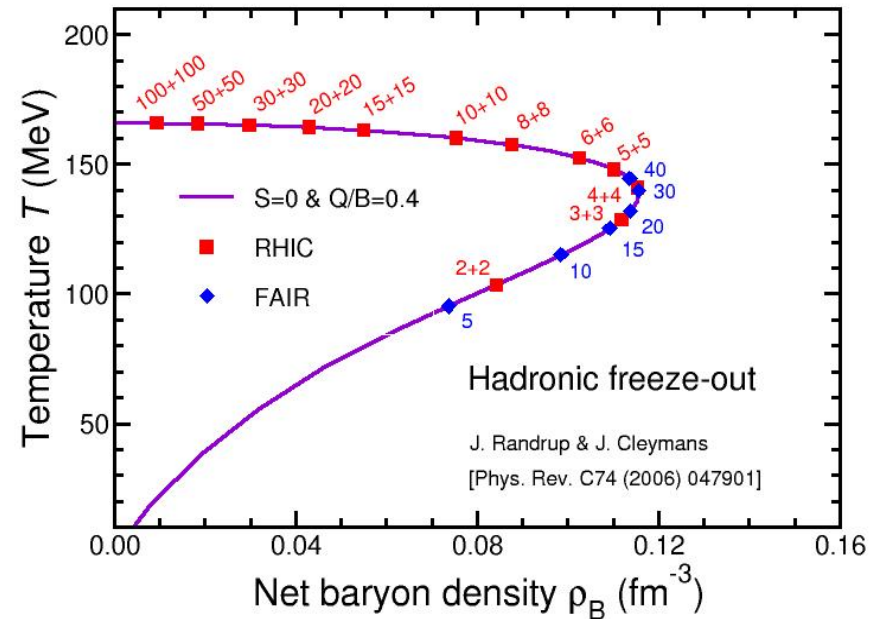
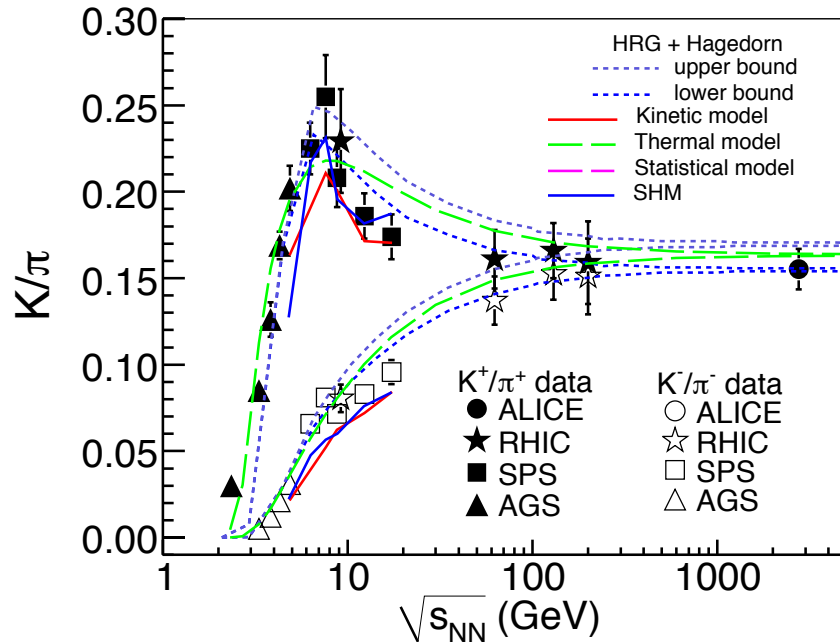
## Chemical Freeze-out: (GCE)

- Weak temperature dependence
- Centrality dependence  $\mu_B$ !
- LGT calculations indicate the Critical Region around  $\mu_B \sim 300$  MeV?

## Kinetic Freeze-out:

- Central collisions => lower value of  $T_{fo}$  and larger collectivity  $\beta_T$
- **Stronger collectivity at higher energy, even for peripheral collisions**

- ALICE: B.Abelev et al., PRL109, 252301(12); PRC88, 044910(2013).
- STAR: J. Adams, et al., NPA757, 102(05); STAR: 1701.07065
- S. Mukherjee: Private communications. August, 2012



- 1) The  $K^+/\pi$  ratio peaks at  $\sqrt{s_{NN}} \sim 8$  GeV,  
 $K/\pi$  ratio merges with  $K^+/\pi$  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: 1701.07065; J. Randrup and J. Cleymans, Phys. Rev. **C74**, 047901(2006)

*The emergent properties of QCD matter*

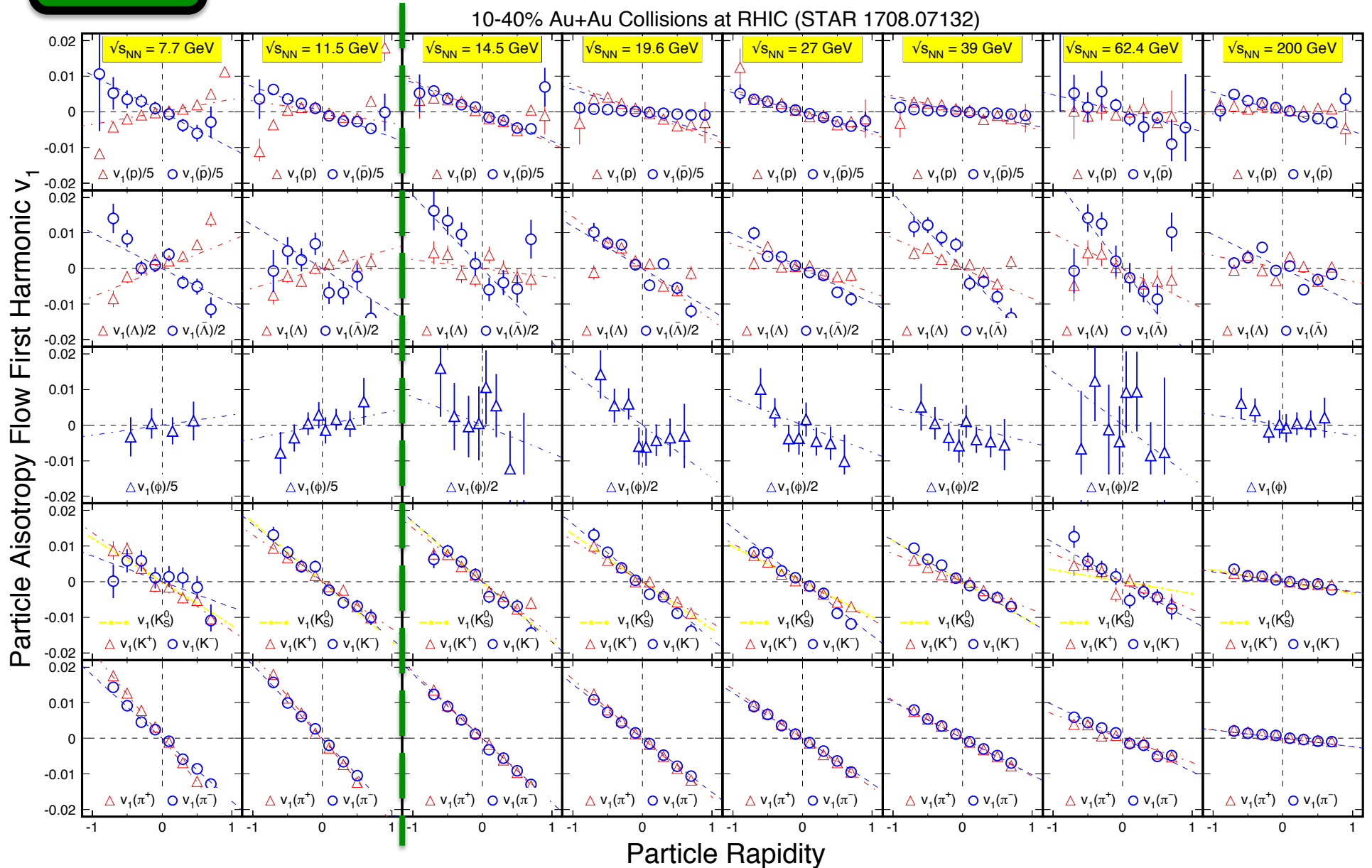
# Collectivity

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



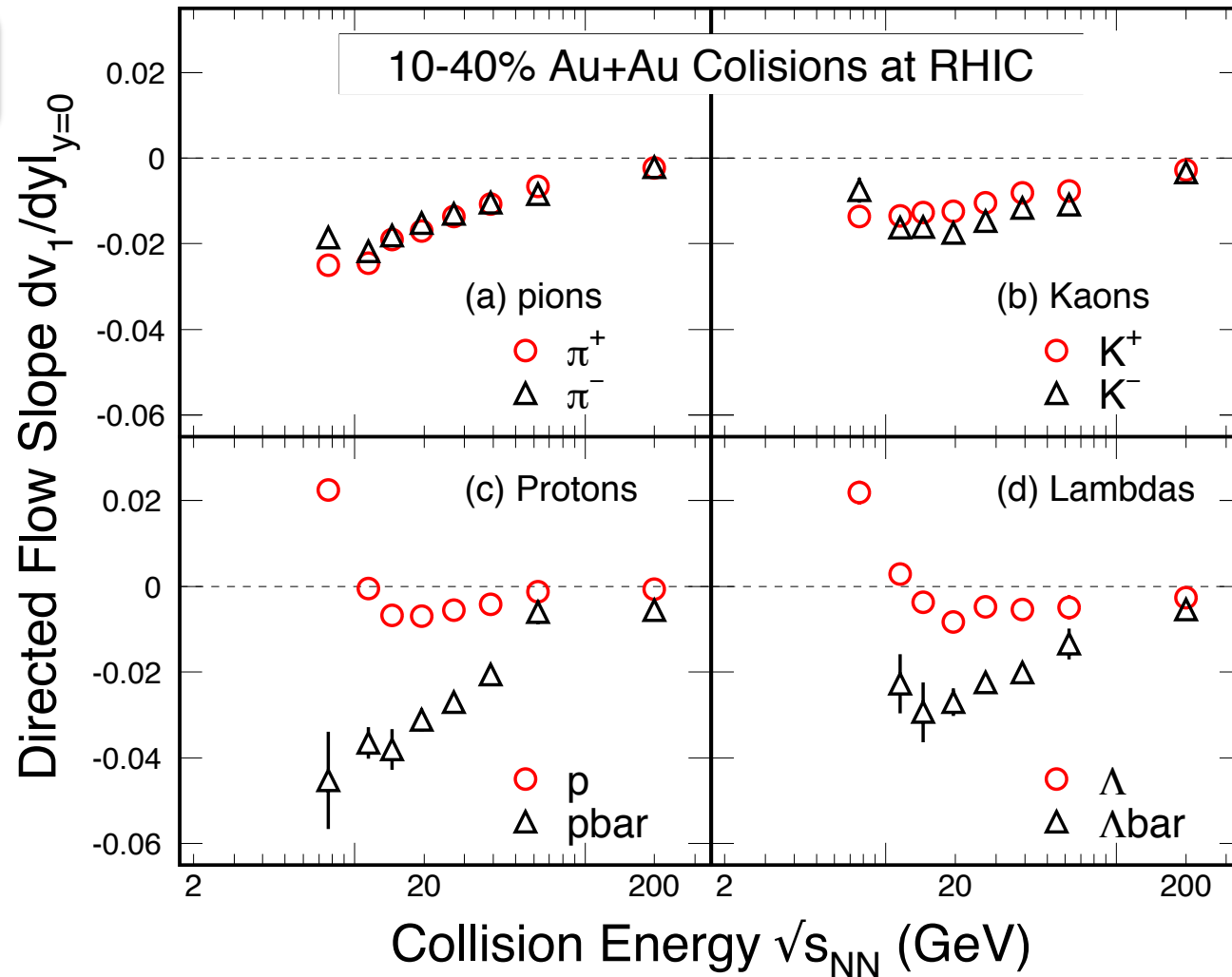
**NEW**

# $v_1$ versus Collision Energy



# $v_1$ versus Collision Energy

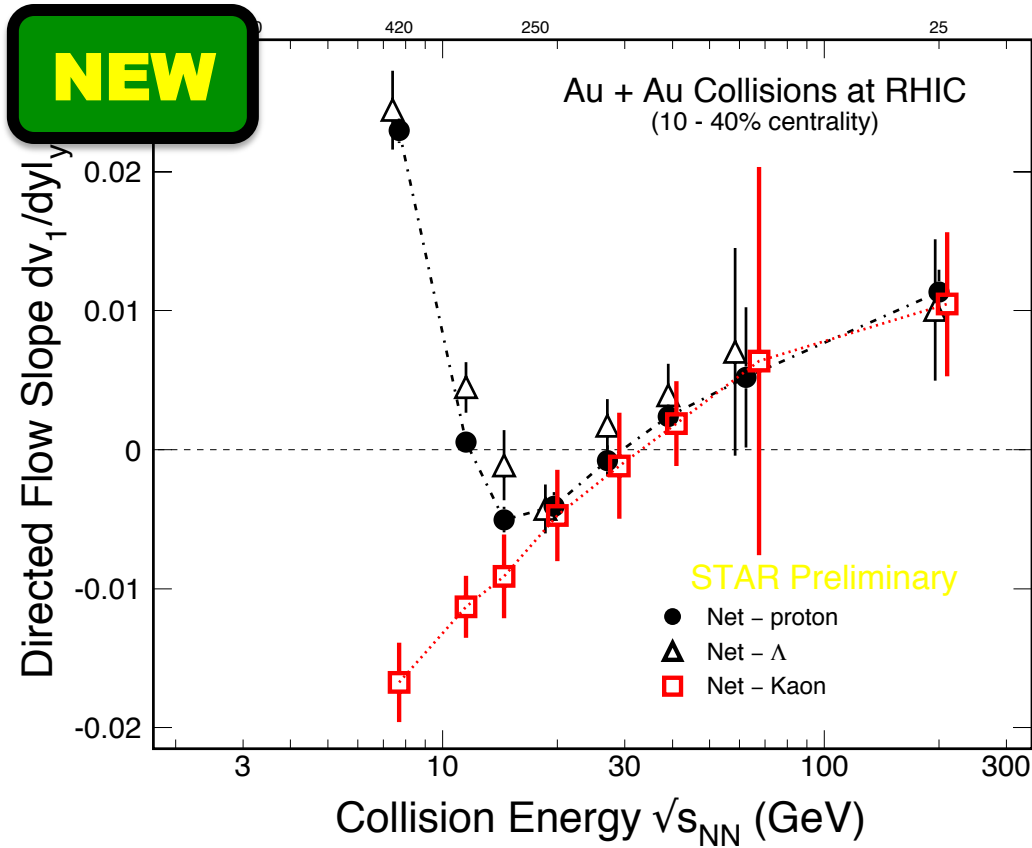
**NEW**



- 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

# $v_1$ vs. Energy: Softest Point?

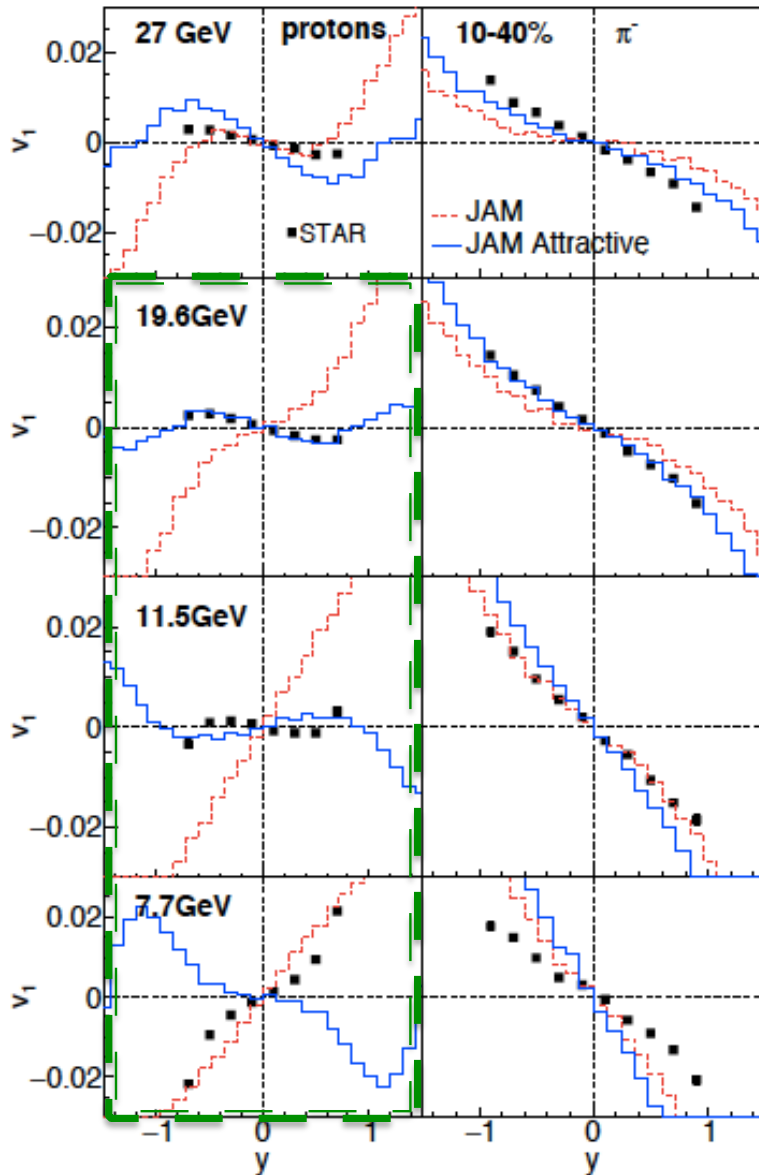


- 1) Minimum at  $\sqrt{s_{NN}} = 10$  GeV for net-proton and net- $\Lambda$ , but net-Kaon data continue decreasing as energy decreases
- 2) At low energy, or in the region where the net-baryon density is large, repulsive force is expected,  $v_1$  slope is large and positive!
- 3) Softest point only for baryons?
- 4) Need model to explain!

● STAR: PRL **112**, 162301(2014)  
 □▲ STAR: 1708.07132

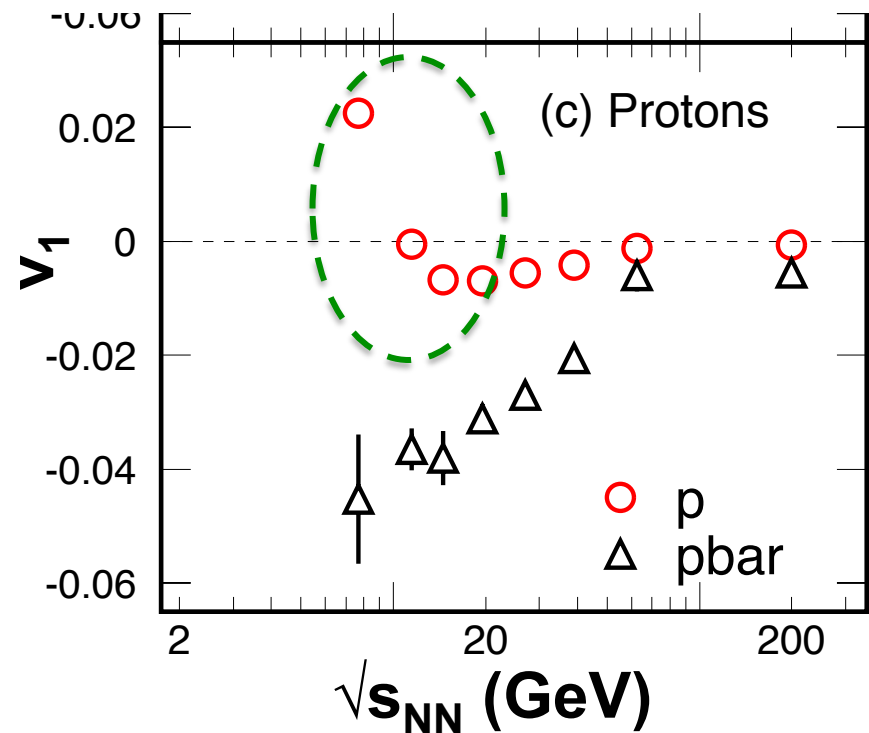
- M. Isse, A. Ohnishi et al, PR **C72**, 064908(05)  
 - Y. Nara, A. Ohnishi, H. Stoecker, PRC94, 034906(16), arXiv: **1601.07692**

# $v_1$ vs. Energy: Softest Point?

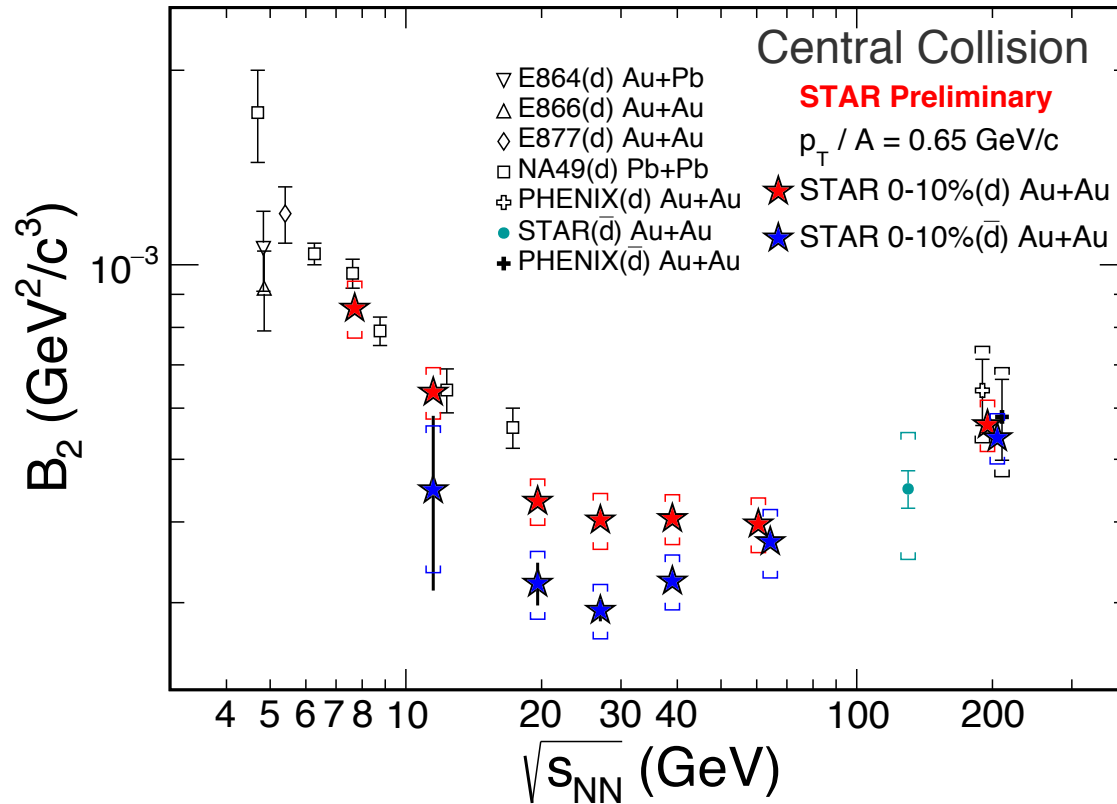


**“Attractive force”** →  
 Change of the EOS  
 ~ “softest point”

- Y. Nara, A. Ohnishi, H. Stoecker,  
 arXiv: [1601.07692](https://arxiv.org/abs/1601.07692) ; PRC94, 034906(2016)





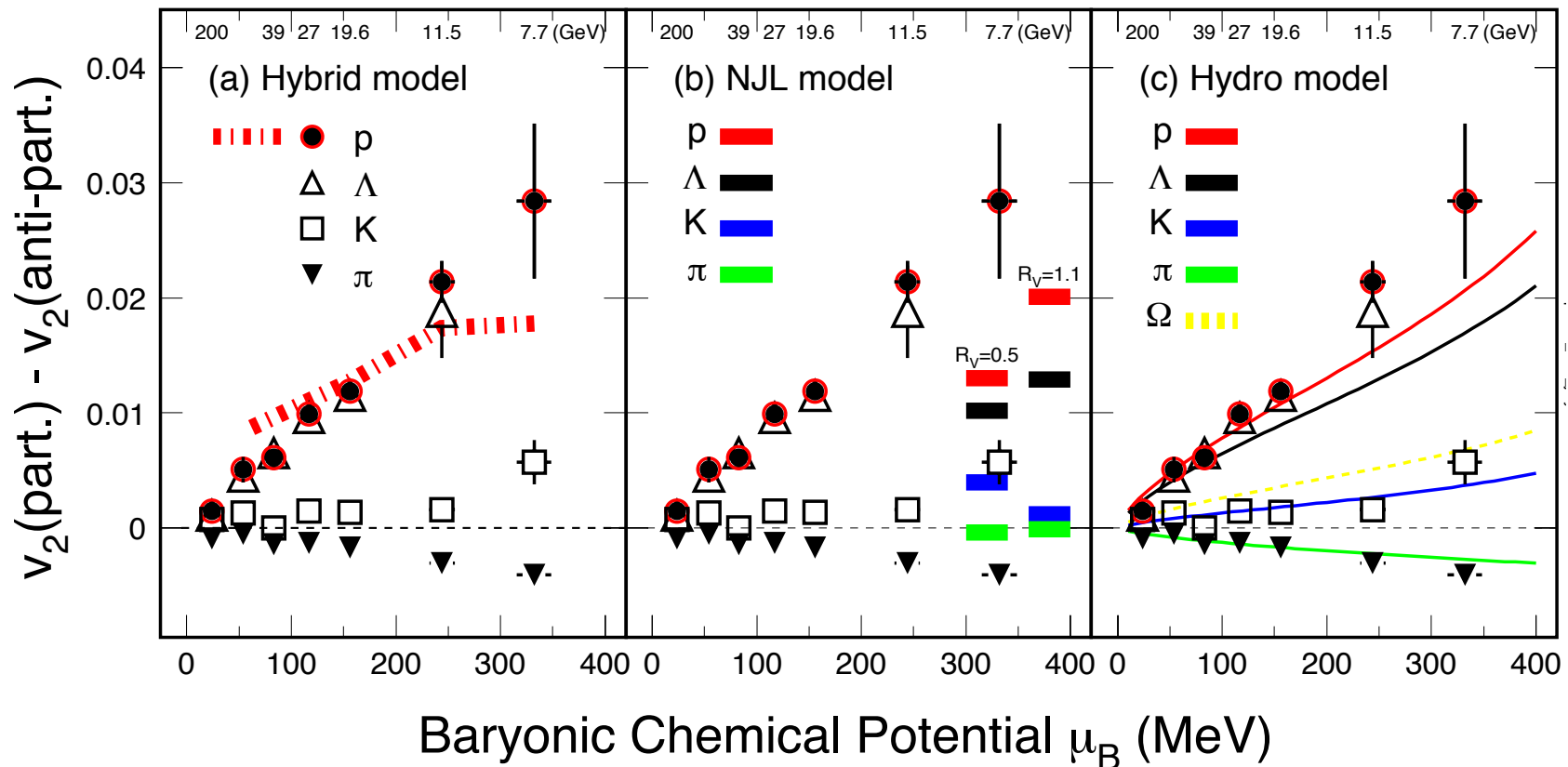


$B_2$ : Space-momentum correlation between nucleons at freeze-out

$$B_2 = 6\pi^3 \frac{m_d}{m_p^2} \frac{R_{np}}{V_f}$$

- 1)  $B_2$  of d higher than that of anti-d. Isospin effect not enough
- 2)  $B_2$  of both d and anti-d show minima around 20GeV

STAR Data: N. Yu *et al*, QM2015



(a) Hydro + Transport: Baryon results fit

[J. Steinheimer, et al. PR **C86**, 44902(13)]

(b) NJL model: Sensitive to vector-coupling, **CME**,  $\mu_B$  driven.

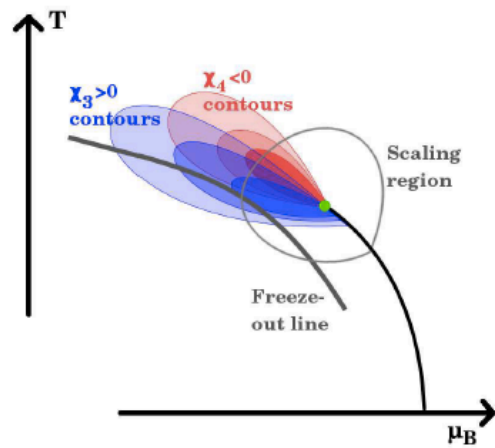
[J. Xu, et al., PRL**112**.012301(14)]

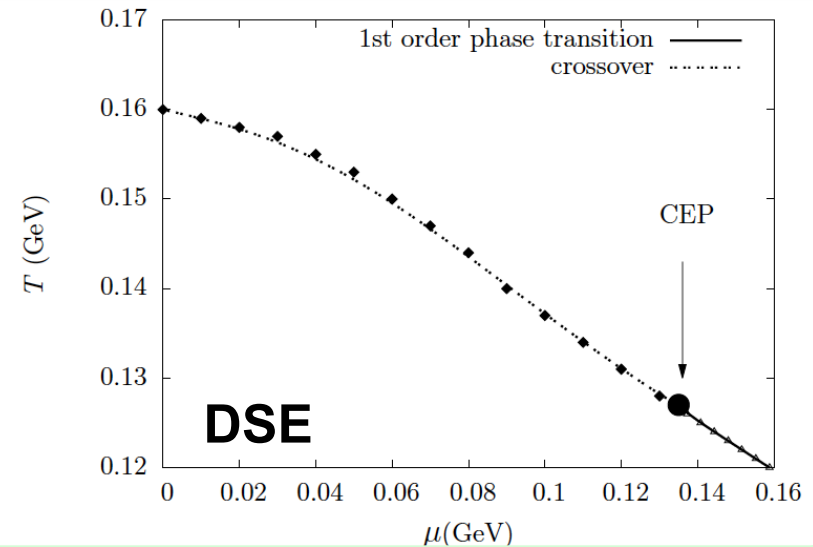
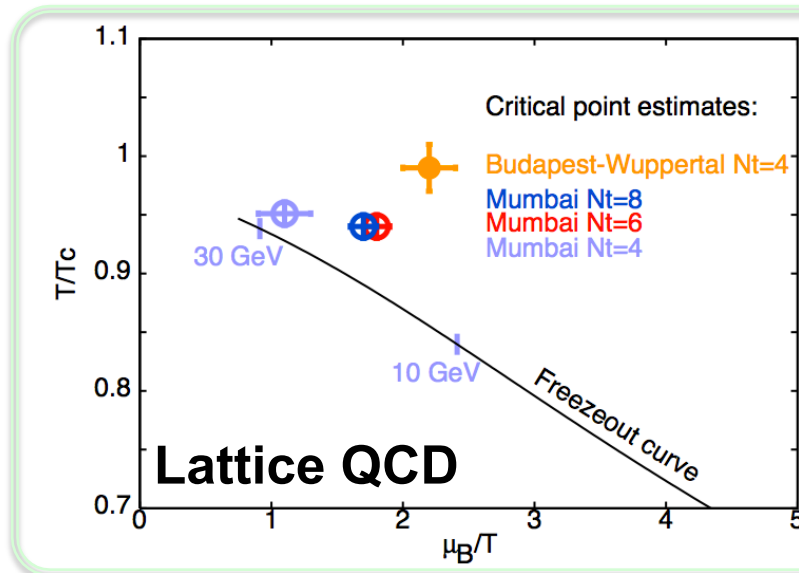
(c) Hydro solution: **Chemical potential  $\mu_B$**  and **viscosity  $\eta/s$**  driven!

[Hatta et al. PR **D91**, 085024(15); **D92**, 114010(15) //NP **A947**, 155(16)]

*The emergent properties of QCD matter*

# Criticality





## Lattice QCD:

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

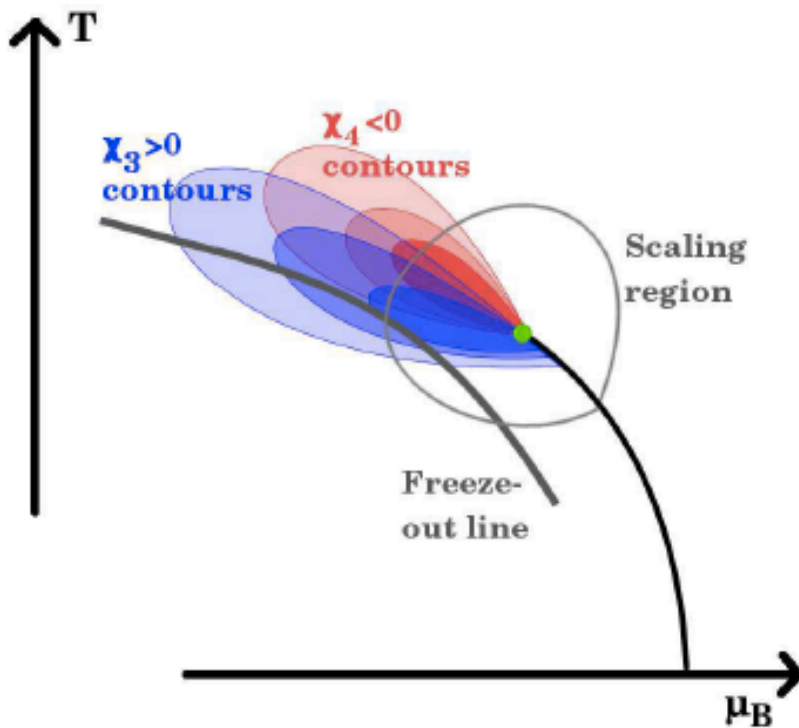
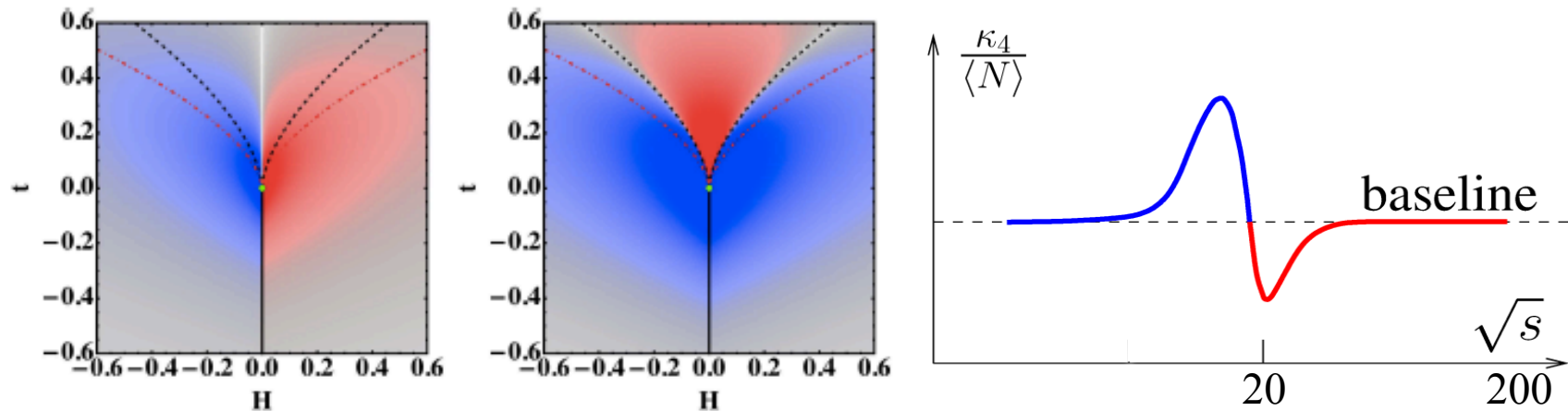
## DSE:

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

$$\mu_B^E = 300 \sim 504 \text{ MeV}, T_E = 115 \sim 162 \text{ MeV}, \mu_B^E / T_E > 2.5$$



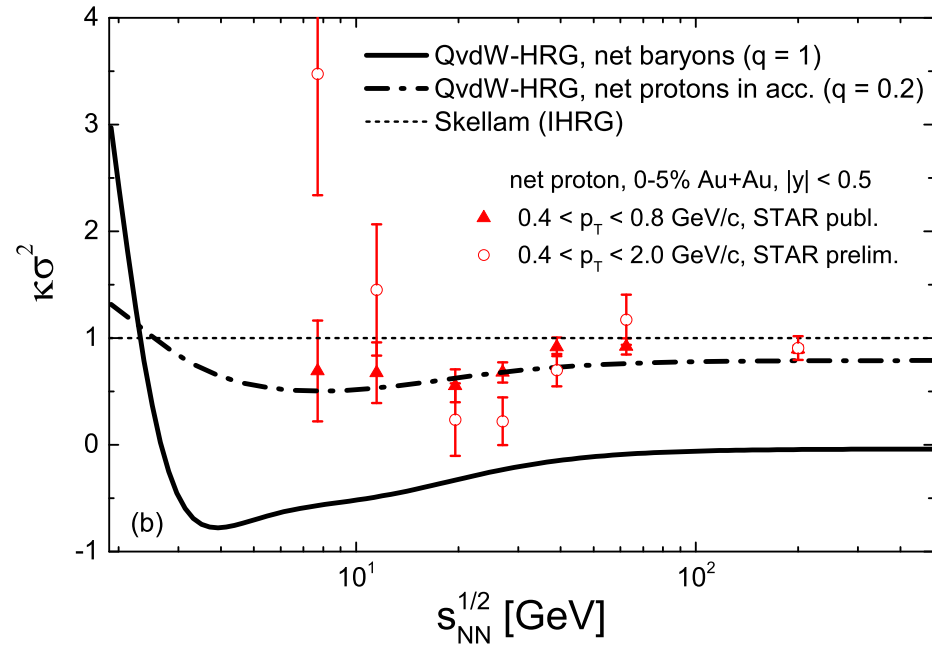
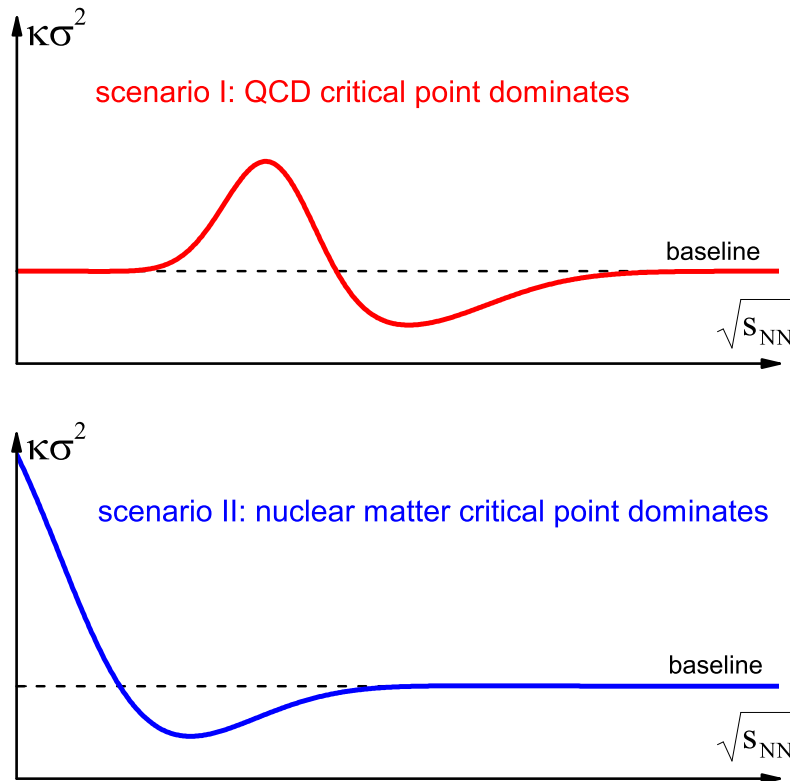
# Expectation from Model Calculations

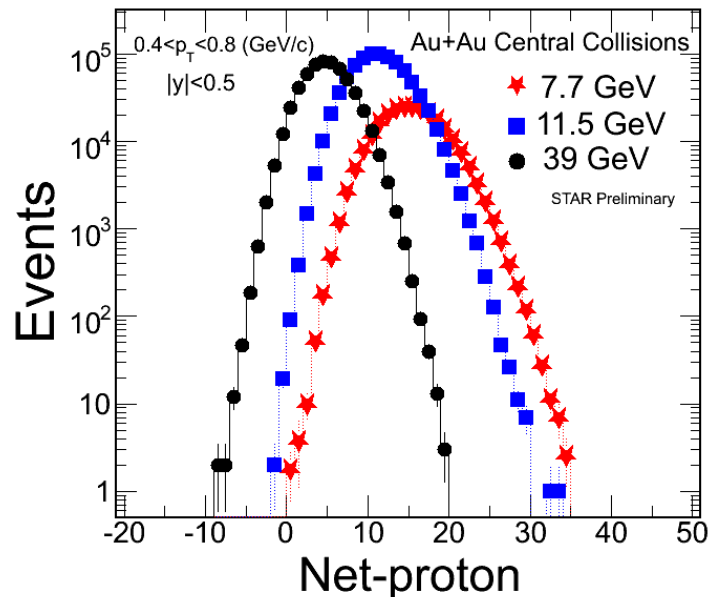
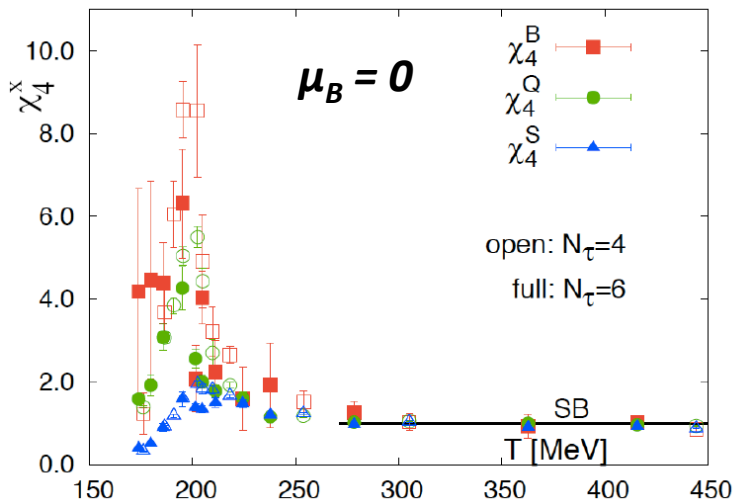


- Characteristic “Oscillating pattern” is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*
- Critical Region (CR)

- M. Stephanov, *PRL* **107**, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, arXiv: 1603.05198, Phys. Rev. **D93** (2016) 034037

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





1) Higher moments of conserved quantum numbers: **Q, S, B**, in high-energy nuclear collisions

2) Sensitive to critical point ( $\xi$  correlation length):

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

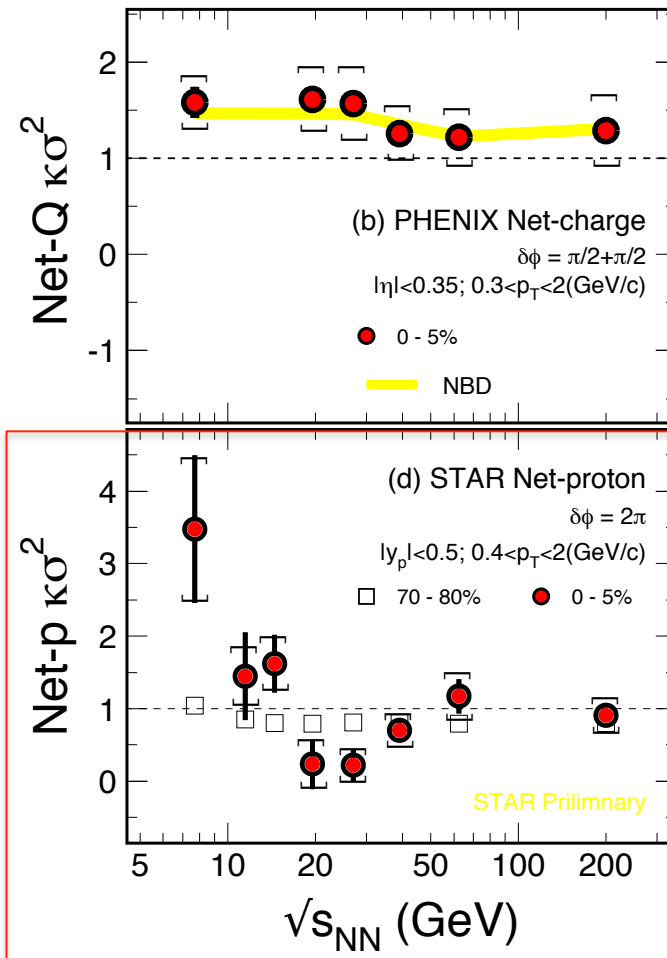
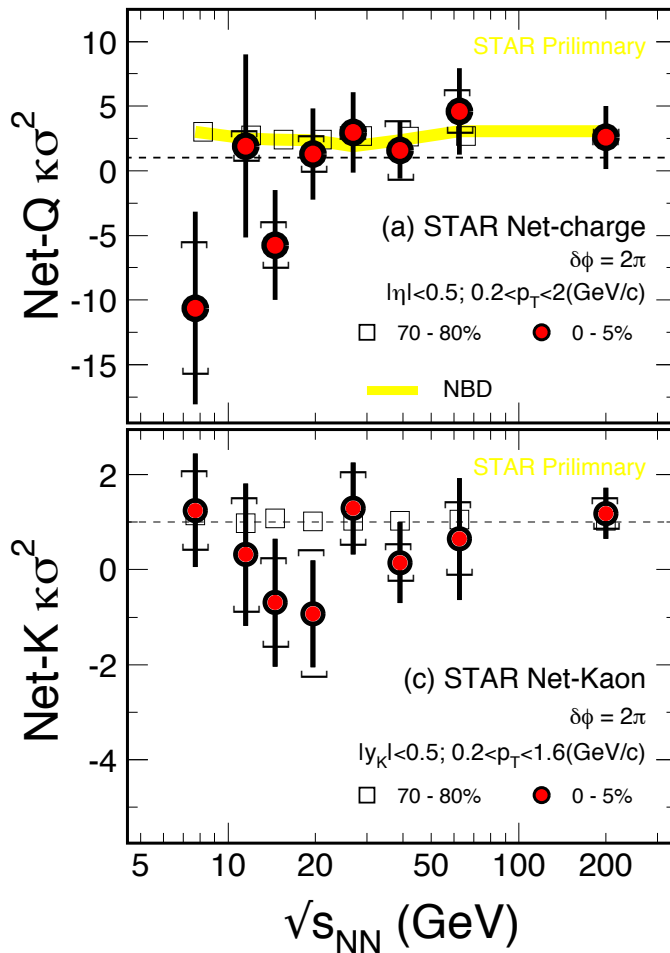
3) Direct comparison with calculations at any order:

$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \quad K\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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, *PLB***633**, 275(06) // M. Stephanov: *PRL***102**, 032301(09) // R.V. Gavai and S. Gupta, *PLB***696**, 459(11) // F. Karsch et al, *PLB***695**, 136(11),
- A. Bazavov et al., *PRL***109**, 192302(12) // S. Borsanyi et al., *PRL***111**, 062005(13) // V. Skokov et al., *PRC***88**, 034901(13)
- PBM, A. Rustamov, J. Stachel, arXiv:1612.00702



$$\text{error}(\kappa * \sigma^2) \propto$$

$$\frac{1}{\sqrt{N}} \frac{\sigma^2}{\epsilon^2}$$

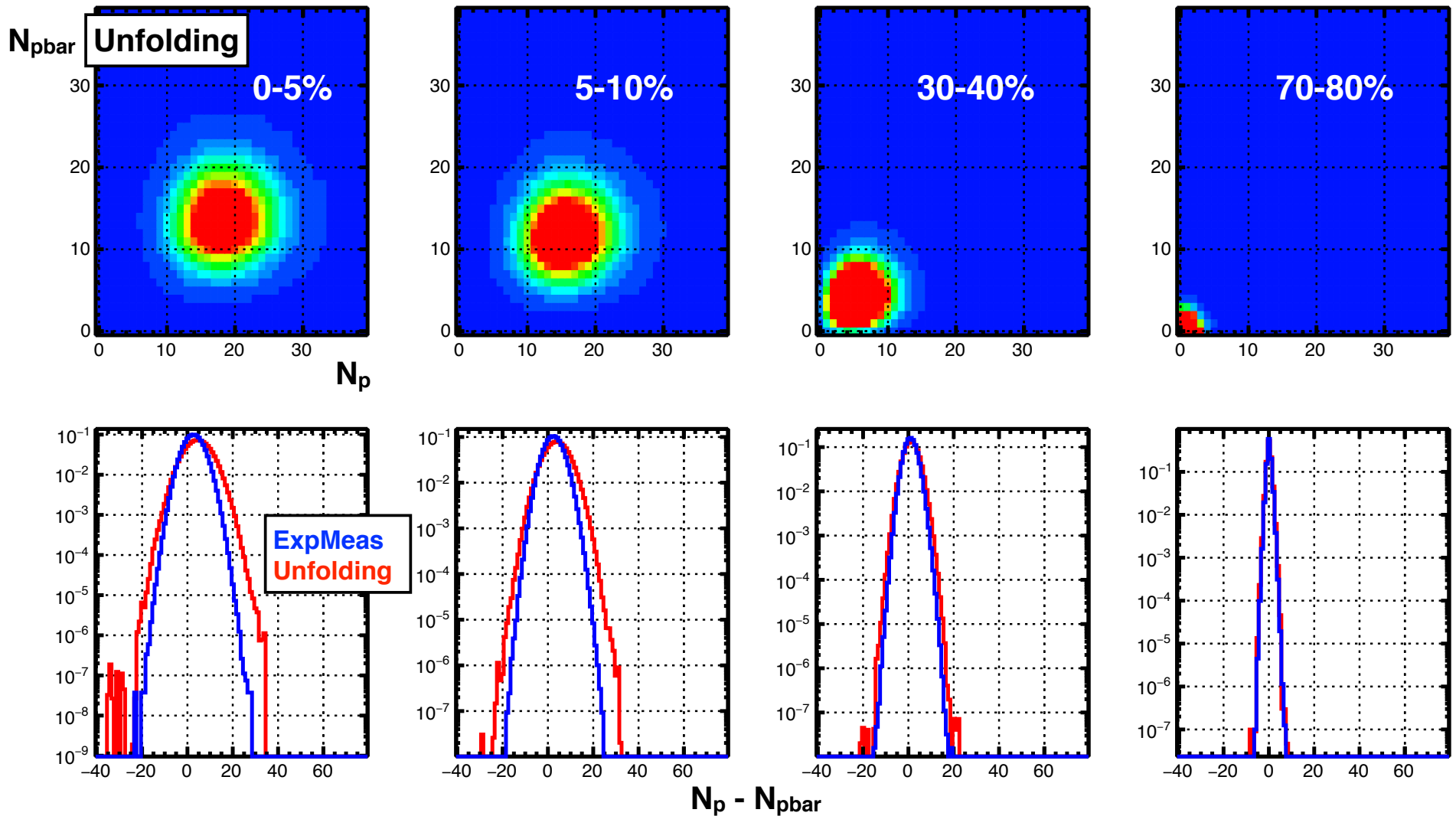
In STAR:

$$\sigma(Q) > \sigma(K) > \sigma(p)$$

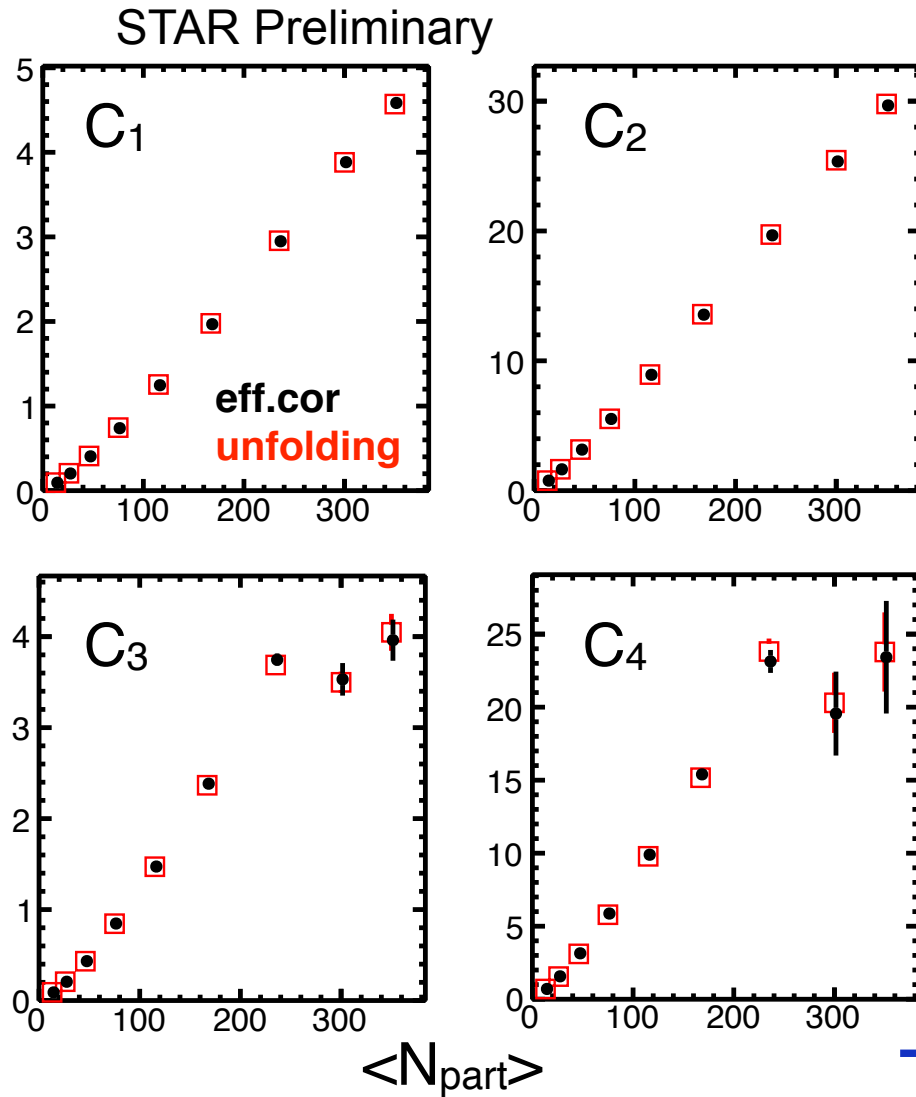
- 1) The results of net-Q and net-Kaon show flat energy dependence.
- 2) Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions starting at  $\sqrt{s_{NN}} < 27$  GeV!

# Unfolded distributions at $\sqrt{s_{NN}} = 200$ GeV

$\sqrt{s_{NN}} = 200$  GeV, net-proton,  $|y| < 0.5$ ,  $0.4 < p_T < 2.0$  (GeV/c),  
without CBWC nor VFC, binomial model, one RM unfolding with 30+100 iterations



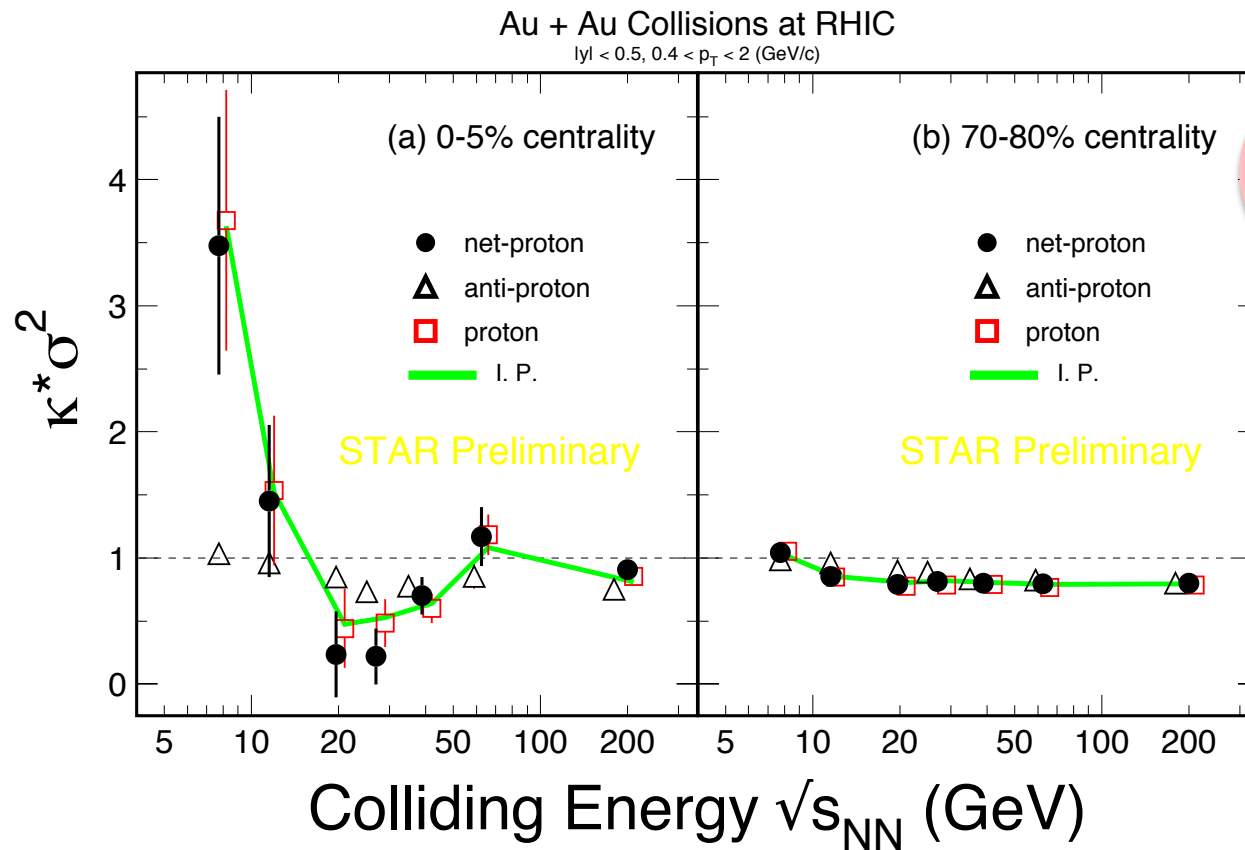
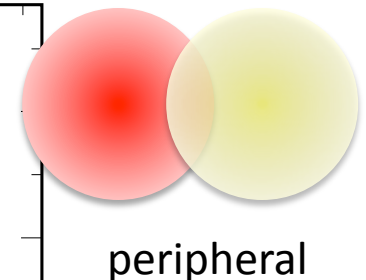
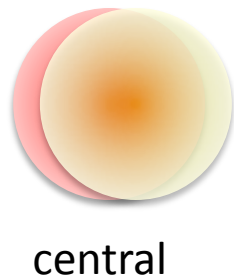
# Unfolding: $\sqrt{s_{NN}} = 200$ GeV Au+Au Collisions



- 1) Unfolding method established
- 2) Embedding used to generate the response matrix
- 3) Final results will follow soon

From T. Nonaka and S. Esumi

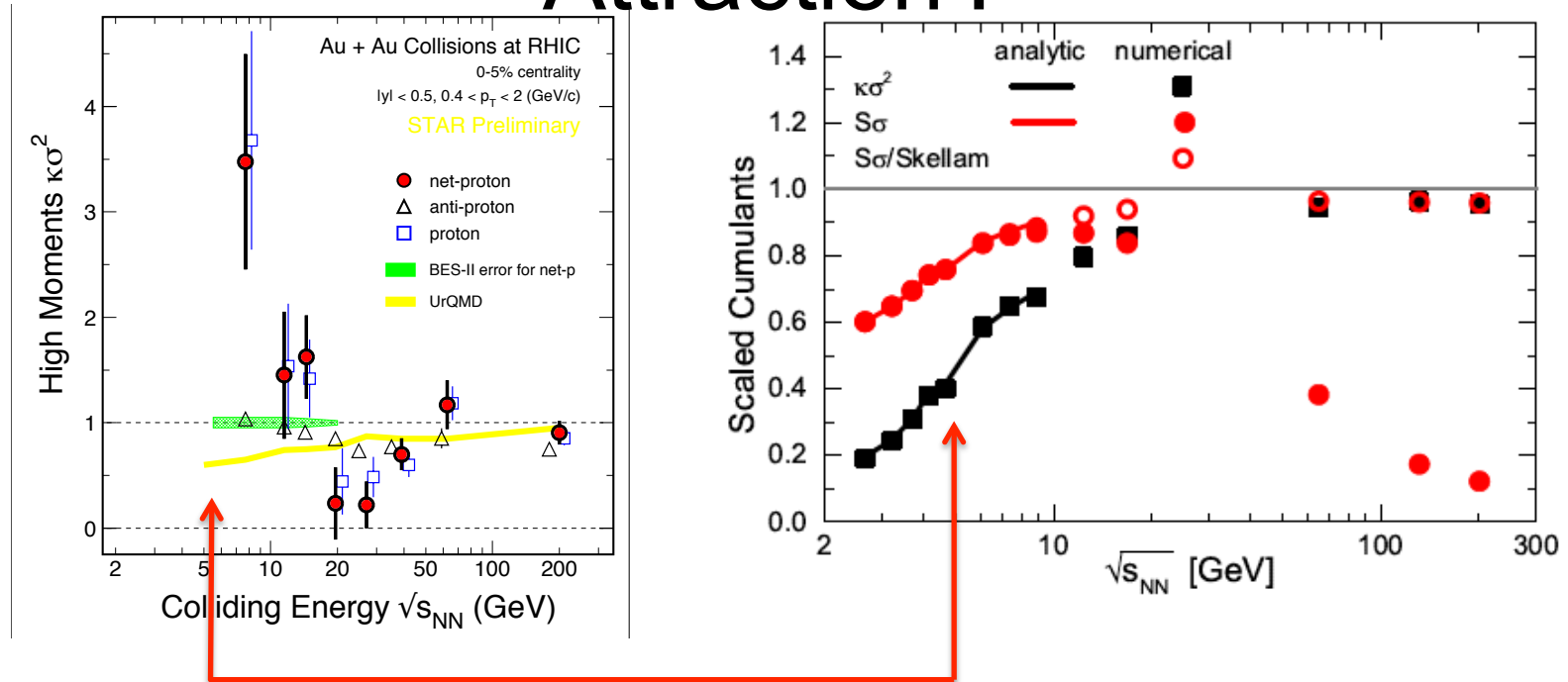




- 1) Flat energy dependence for 70-80% peripheral collisions
- 2) Non-monotonic behavior in the most central 0-5%, and 5-10% collisions. Net-p follow protons, especially at lower collision energies

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

# No Model Reproduces the 'Attraction'!



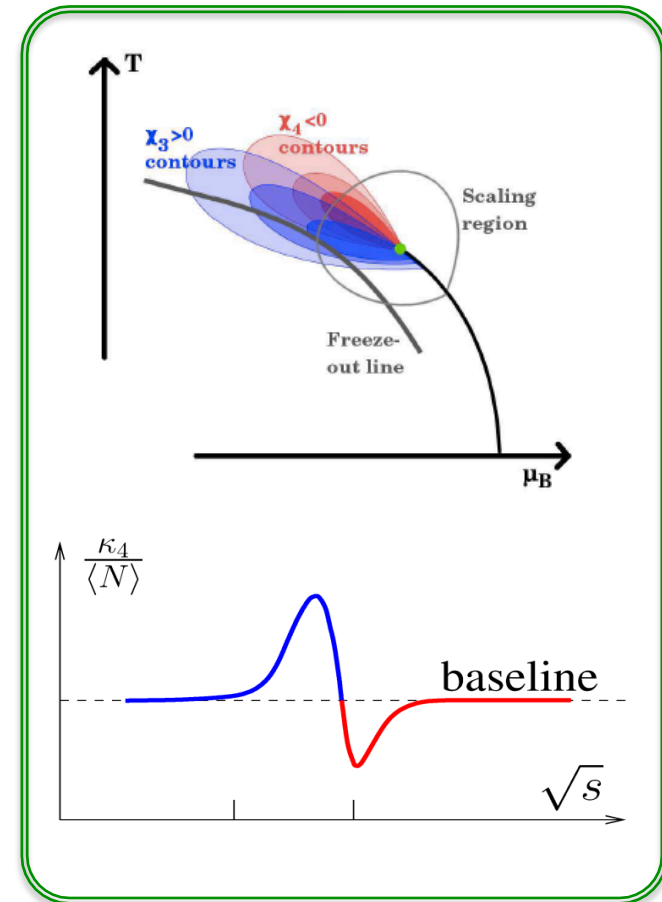
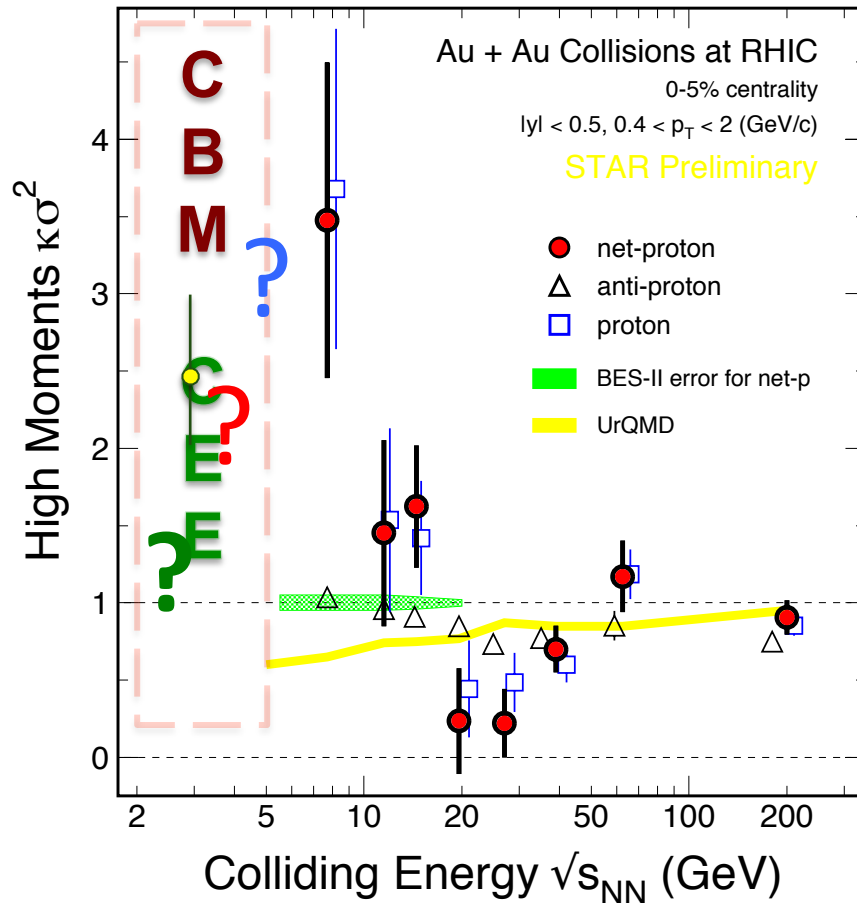
At  $\sqrt{s_{NN}} \leq 10$  GeV: **Data:  $\kappa\sigma^2 > 1!$  Model:  $\kappa\sigma^2 < 1!$**

**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, [PRC92](#), 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. [B762](#), 296(2016).
- 4) **Proton clusters**: A. Bzdak, V. Koch, V. Sokolov, Eur. Phys. J., [C77](#), 288(2017)  
Interesting but unfinished, needs include dynamic effects in HIC.

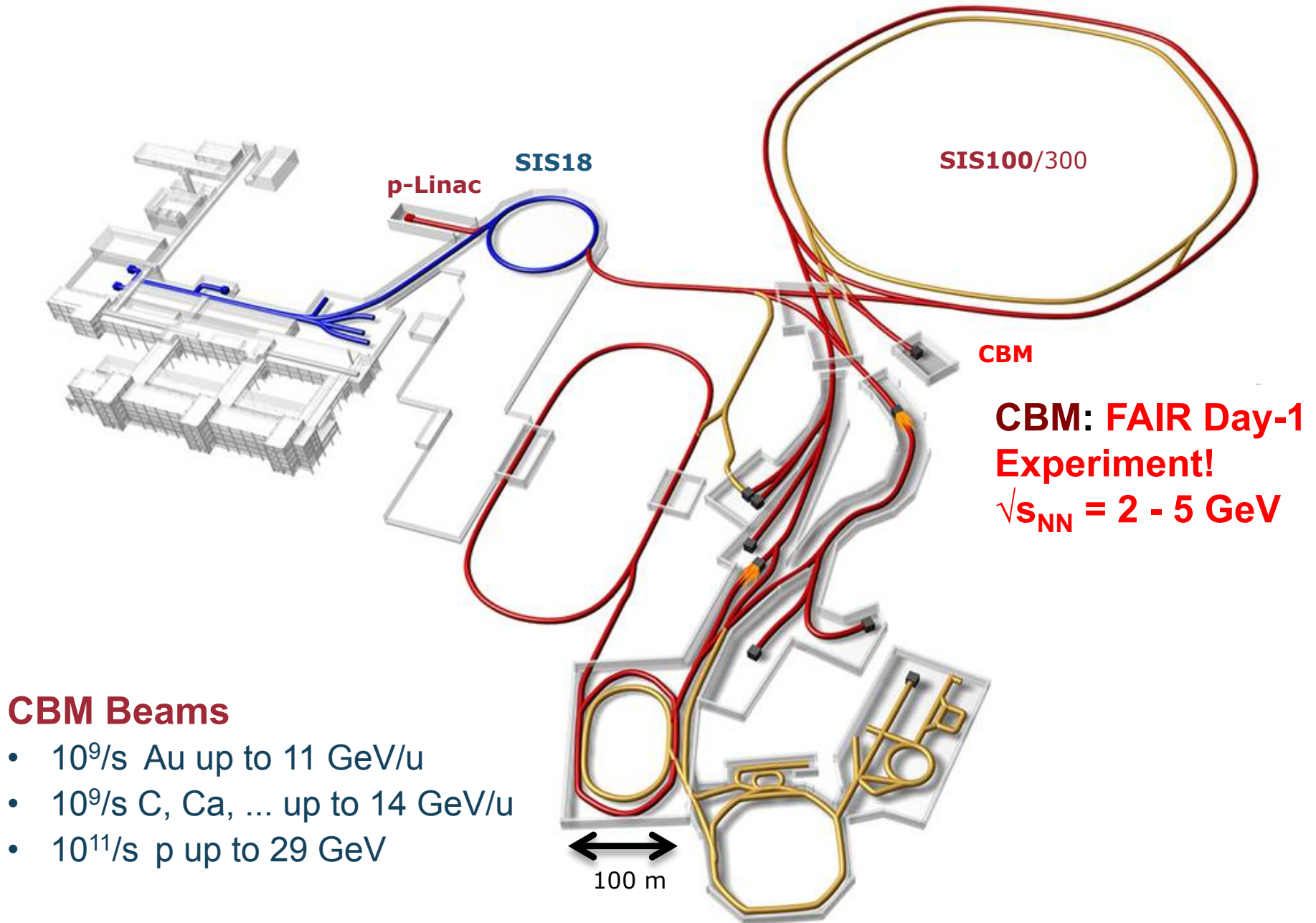
# Search for the QCD Critical Point

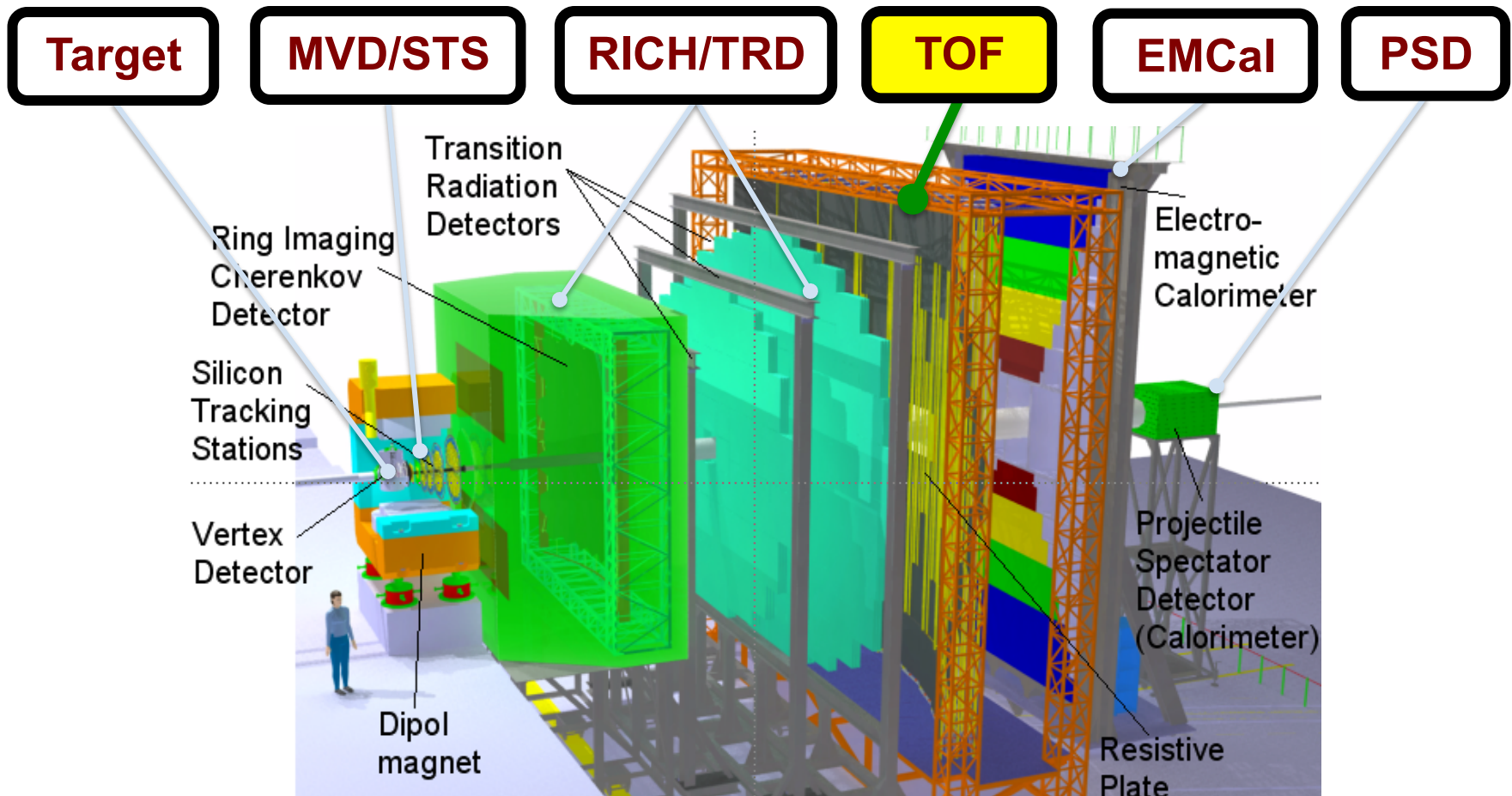
- HADES preliminary, SQM16,  $|y| < 0.2$



- RHIC BES-II: dramatically reduce the errors!
- CBM/RHIC FXT/HADES Experiments ( $2.5 < \sqrt{s}_{NN} < 8$  GeV):  
**Key region for Critical Point search**

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



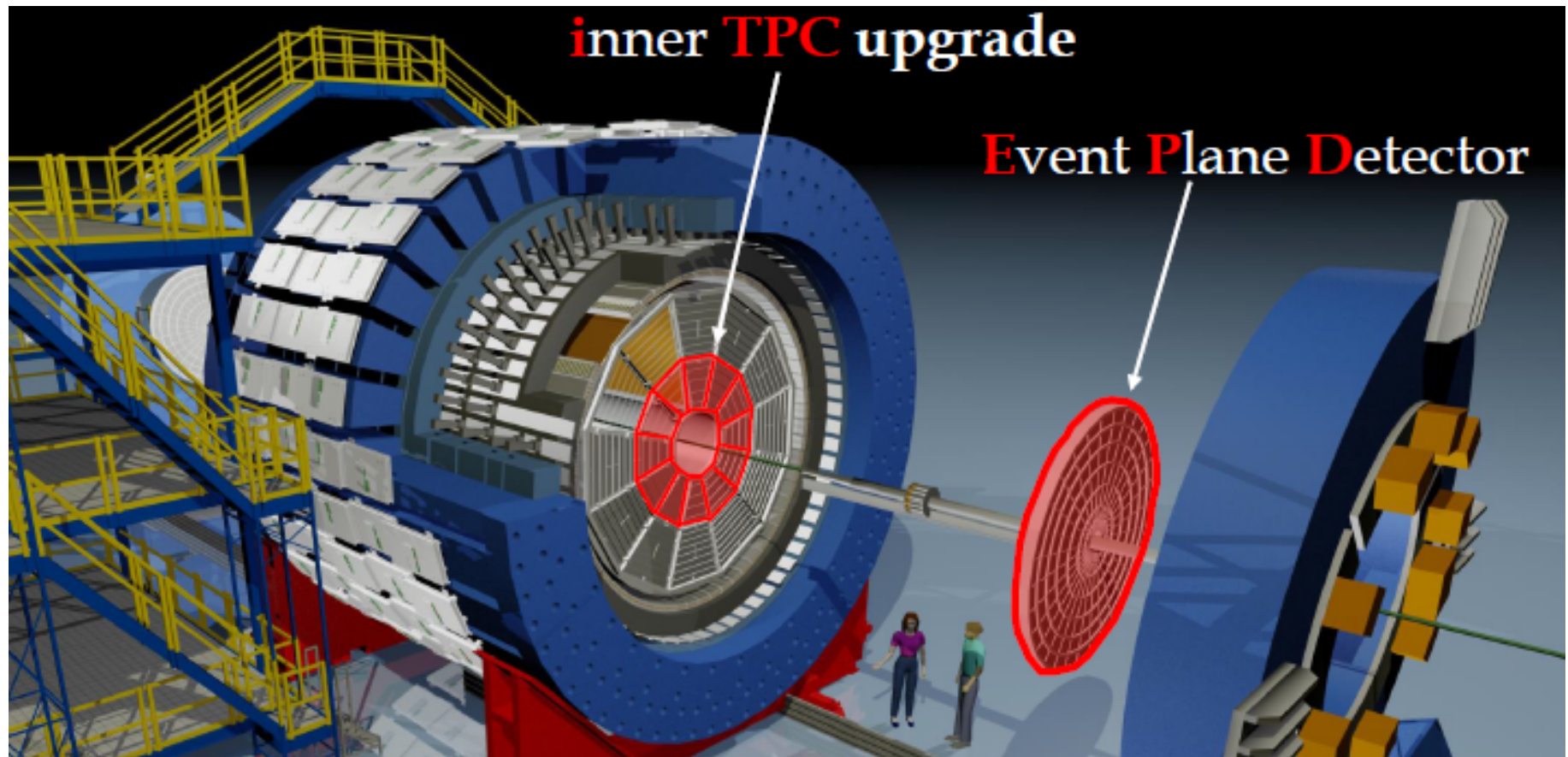


**FAIR:** One of the highest intensity accelerator complexes

**Precision measurements** at high baryon density region for:

- (i) Dileptons ( $e, \mu$ ); (ii) High order correlations; (iii) Flavor productions ( $s, c$ )





- 1) Enlarge rapidity acceptance
- 2) Improve particle identification
- 3) Enhance event plane resolution

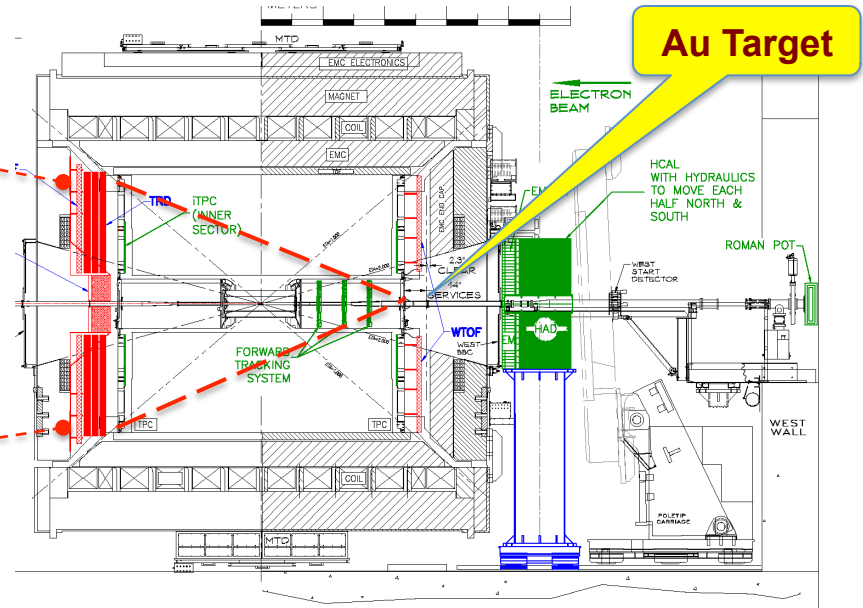
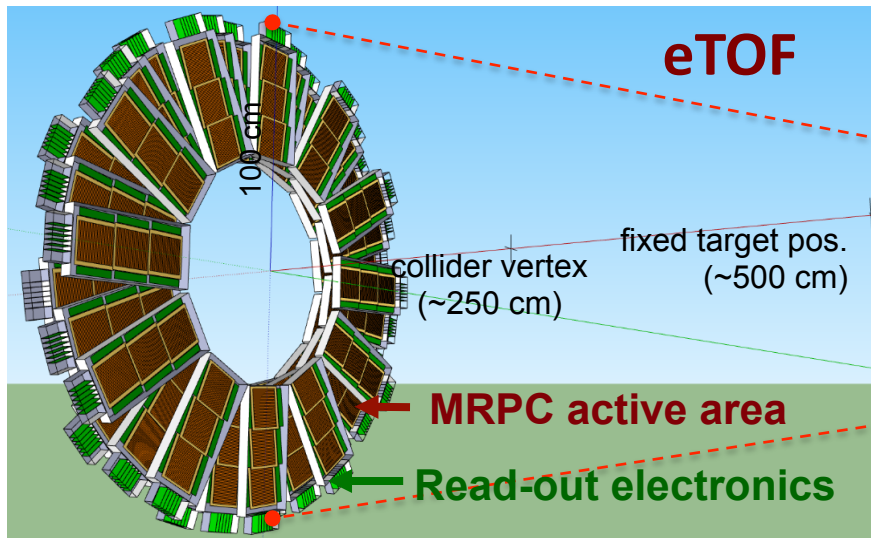
**iTPC, EPD, eTOF**  
**Dedicated two runs at**  
**RHIC: 2019 & 2020**



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

Precision measurements, map the QCD  
phase diagram  **$200 < \mu_B < 420 \text{ MeV}$**

# 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:**

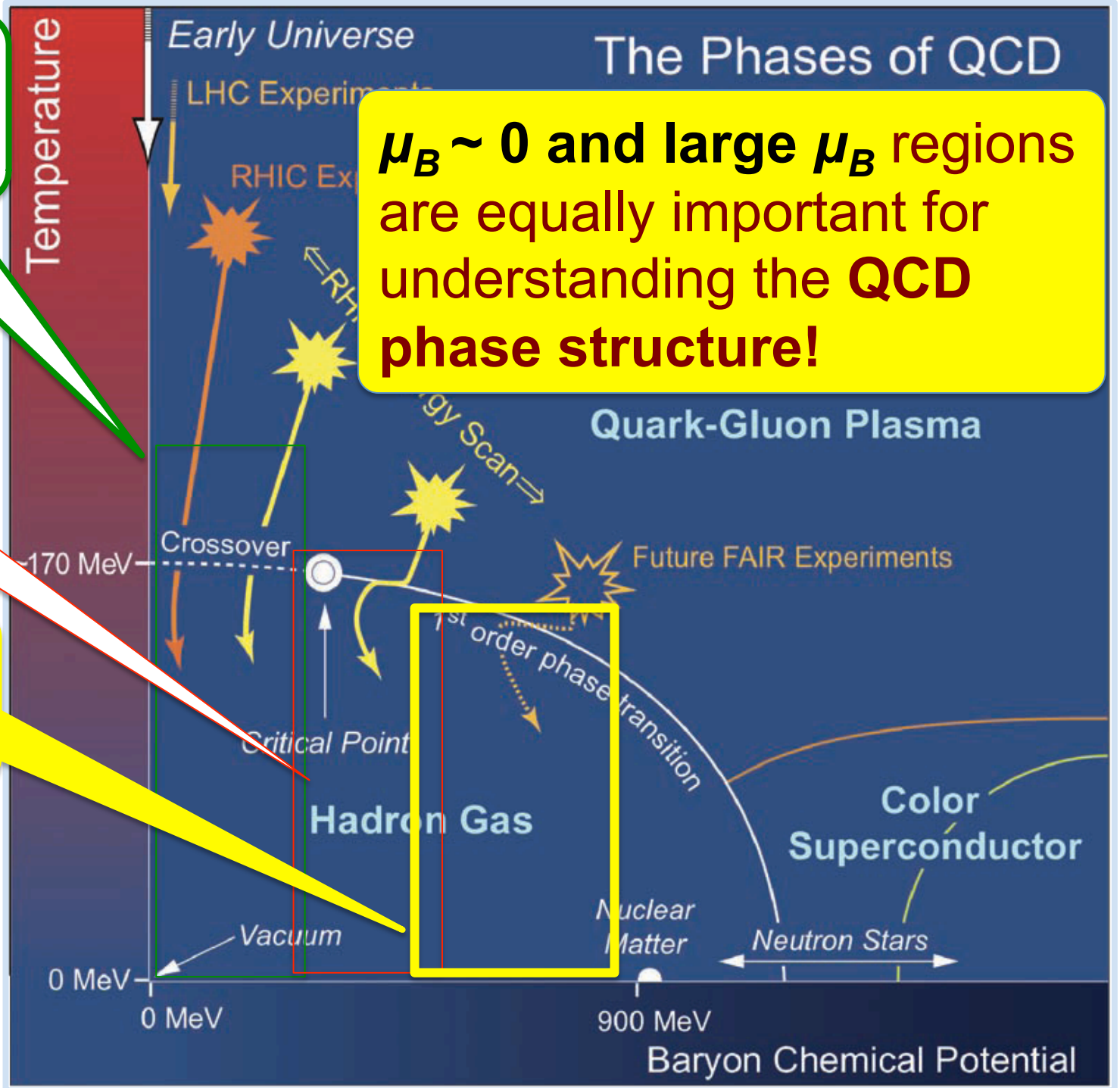
- Complementary to part of CBM's physics program:

$\sqrt{s_{NN}} = 3, 3.6, 3.9, 4.5, 7.7$  GeV ( $750 \geq \mu_B \geq 420$  MeV)

especially for ***B-*** & ***s-hadrons*** production and fluctuations

**FAIR construction started, beam on target in 2025!**

# The Phases of QCD



$\mu_B \sim 0$  and large  $\mu_B$  regions are equally important for understanding the **QCD phase structure!**

**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**

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