Recent Results from RHIC BES-I

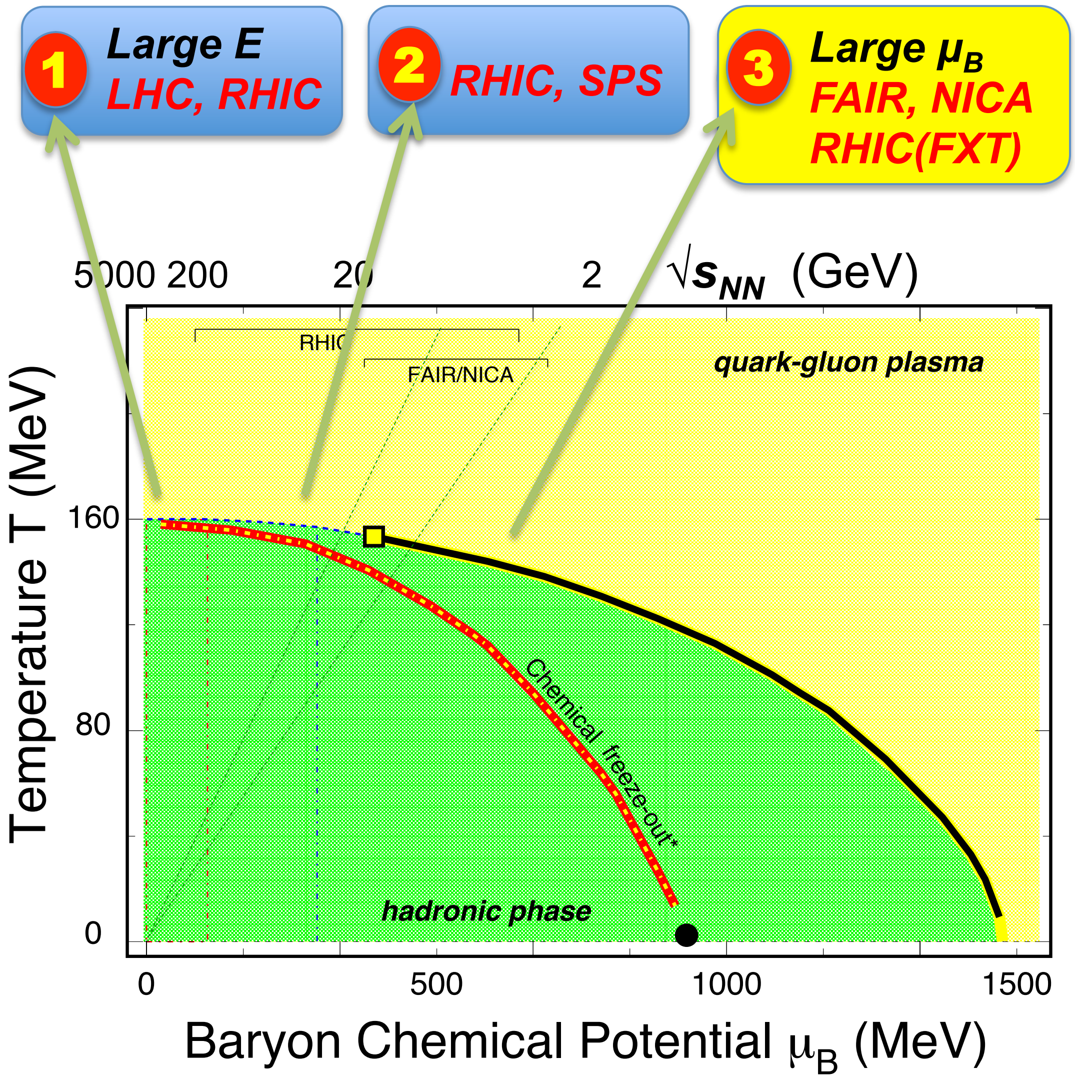
- QCD medium properties at finite baryon density

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

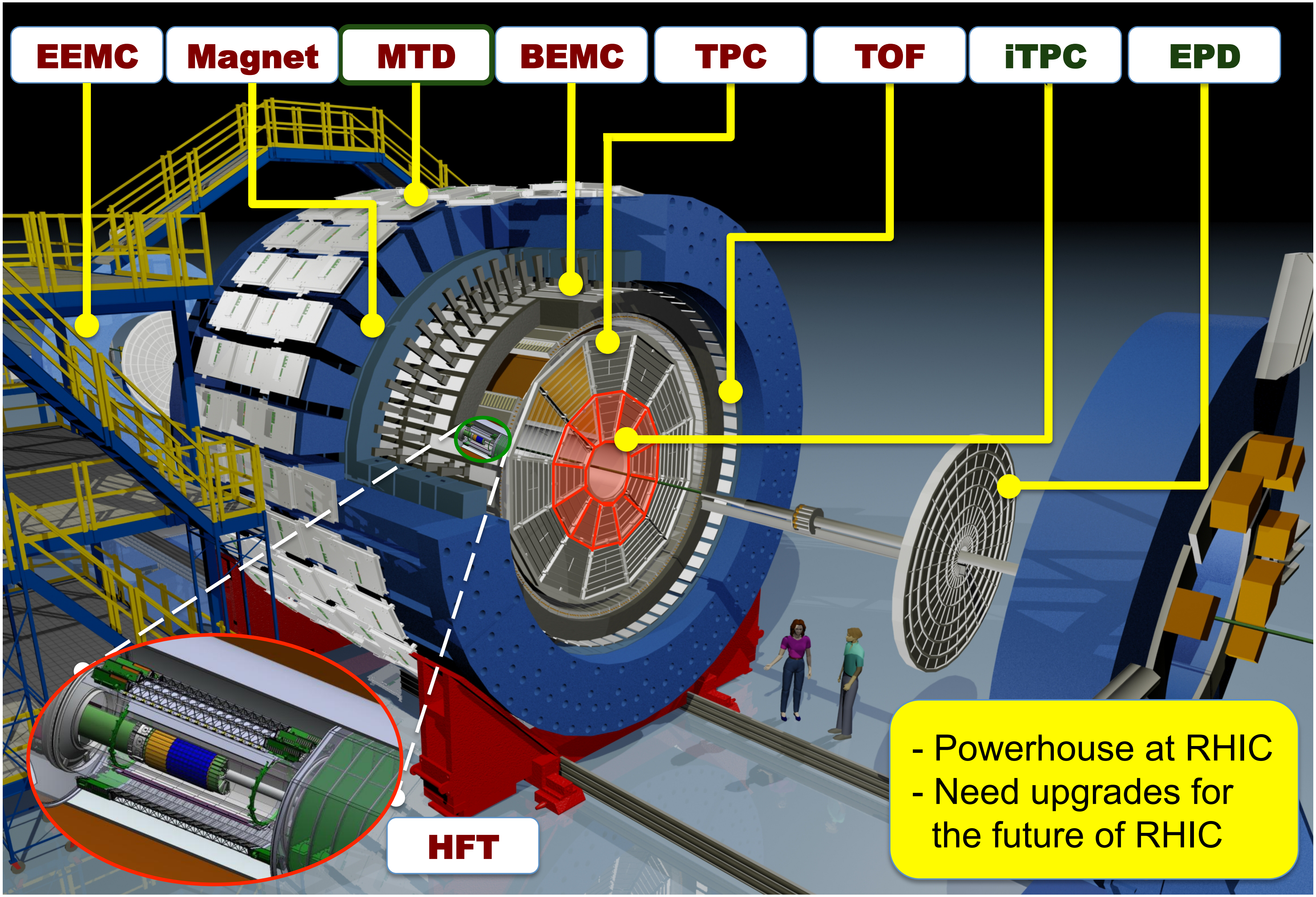
ii. Chirality

iii. Criticality

QCD Emergent Properties

(3) BES-II and Beyond

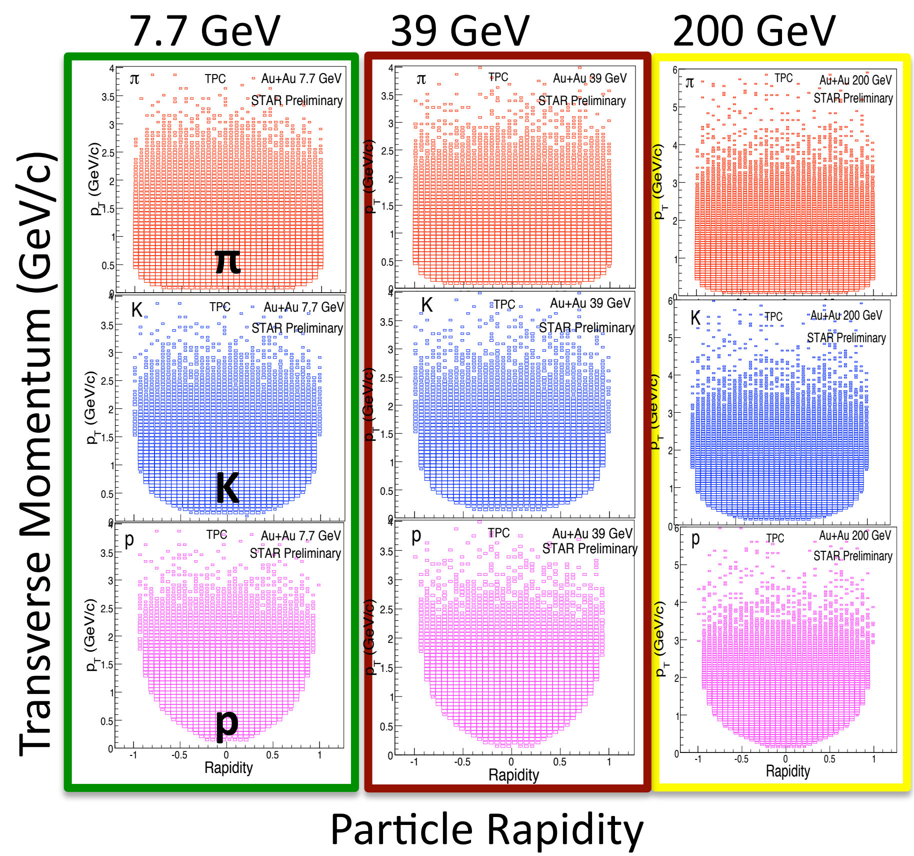
STAR Detector System



- Powerhouse at RHIC
- Need upgrades for the future of RHIC

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

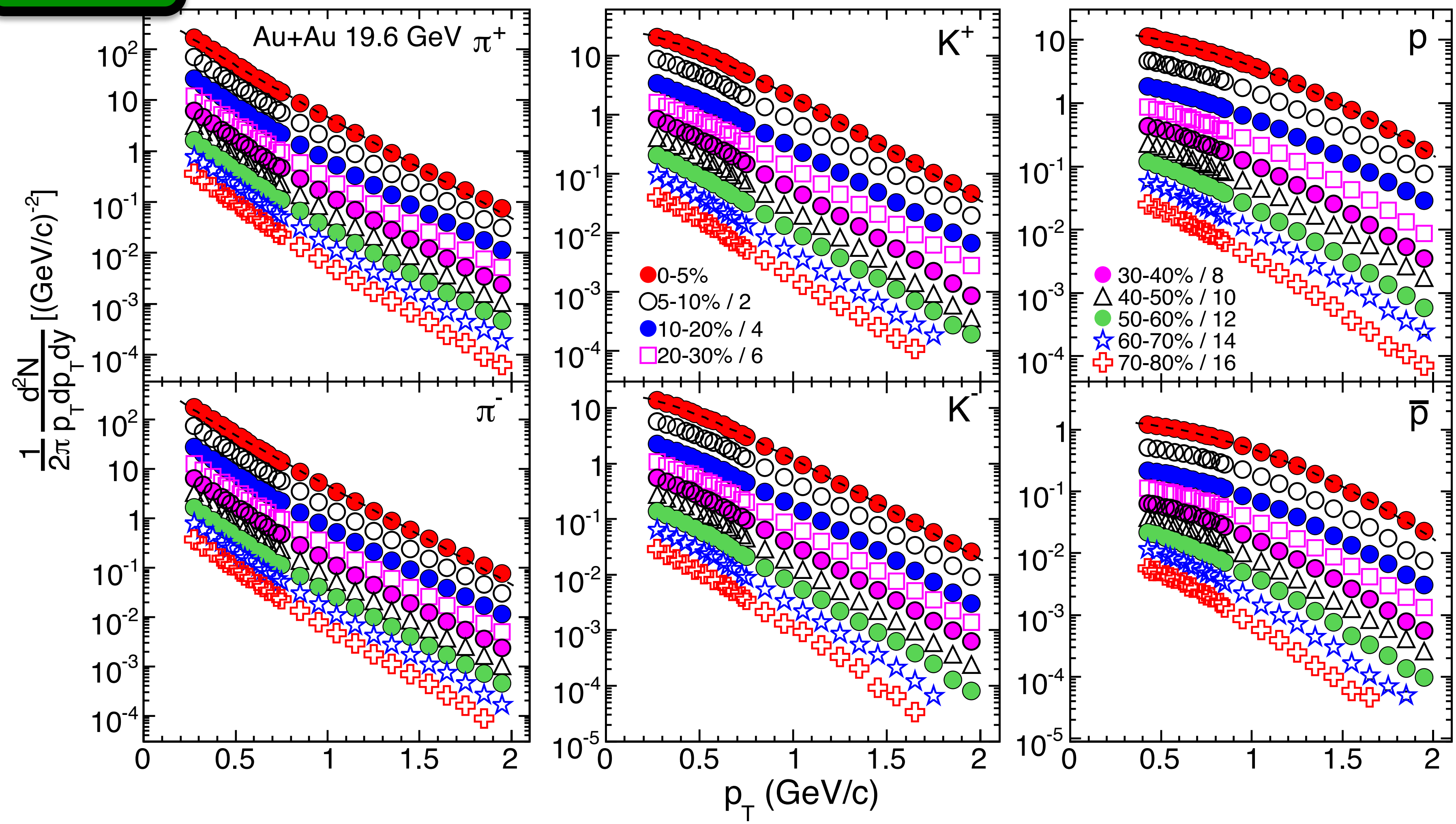


1) Largest data sets versus collision energy
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. Especially important for fluctuation analysis

STAR: Hadron Spectra from BES-I

NEW

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

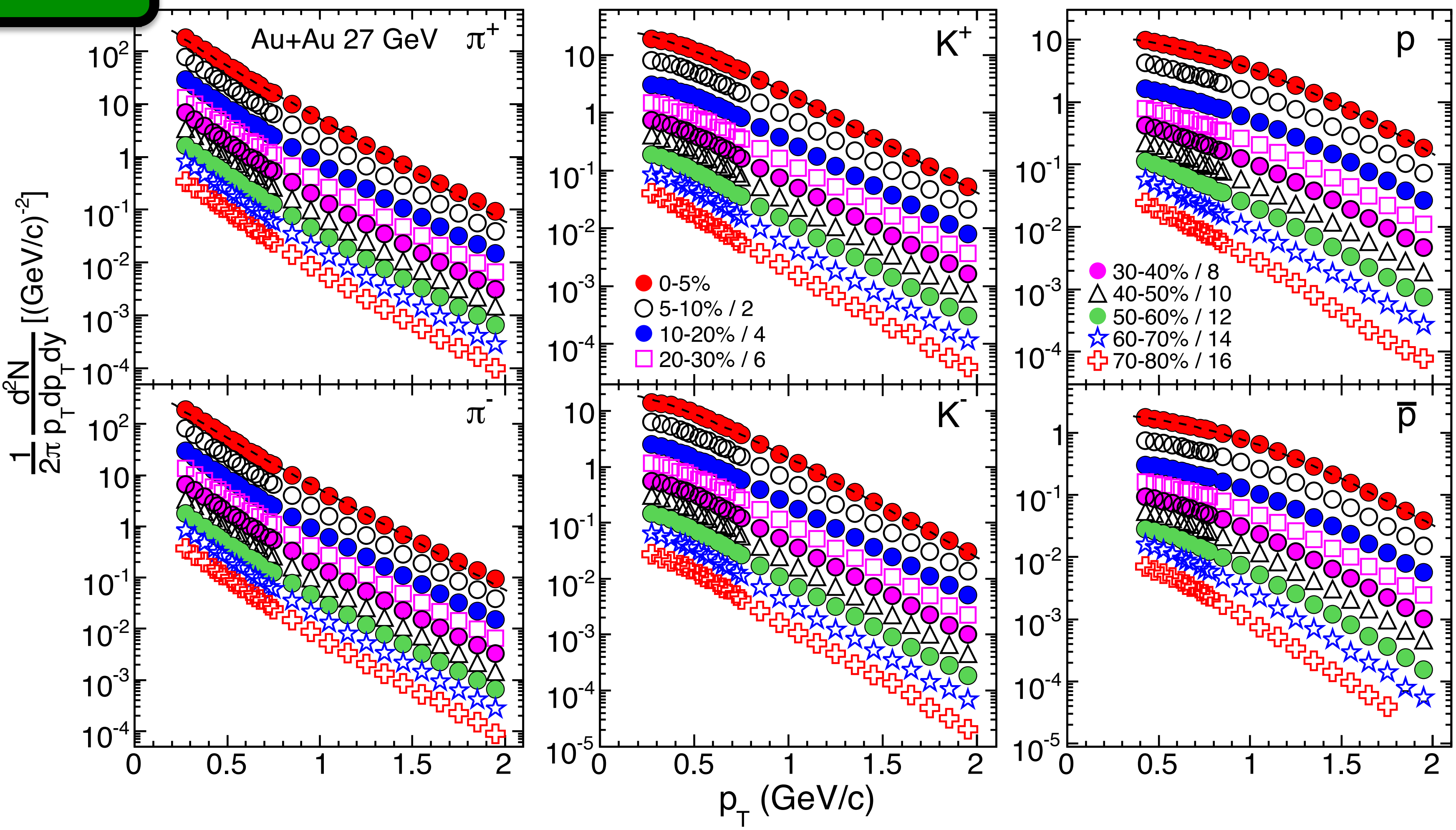


STAR: arXiv:1701.07065, PRC**96**, 44904(2017)

STAR: Hadron Spectra from BES-I

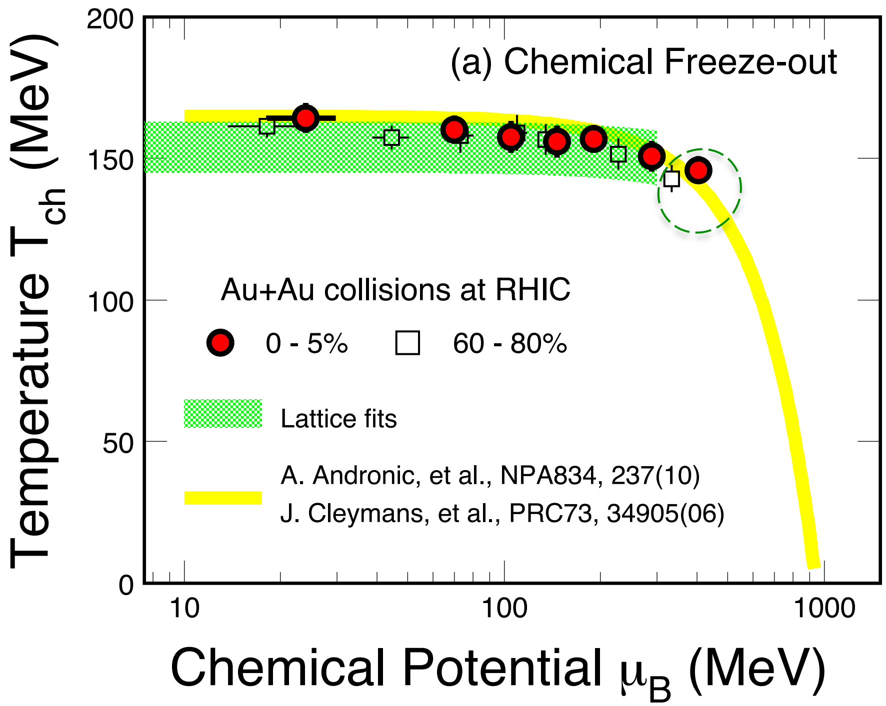
NEW

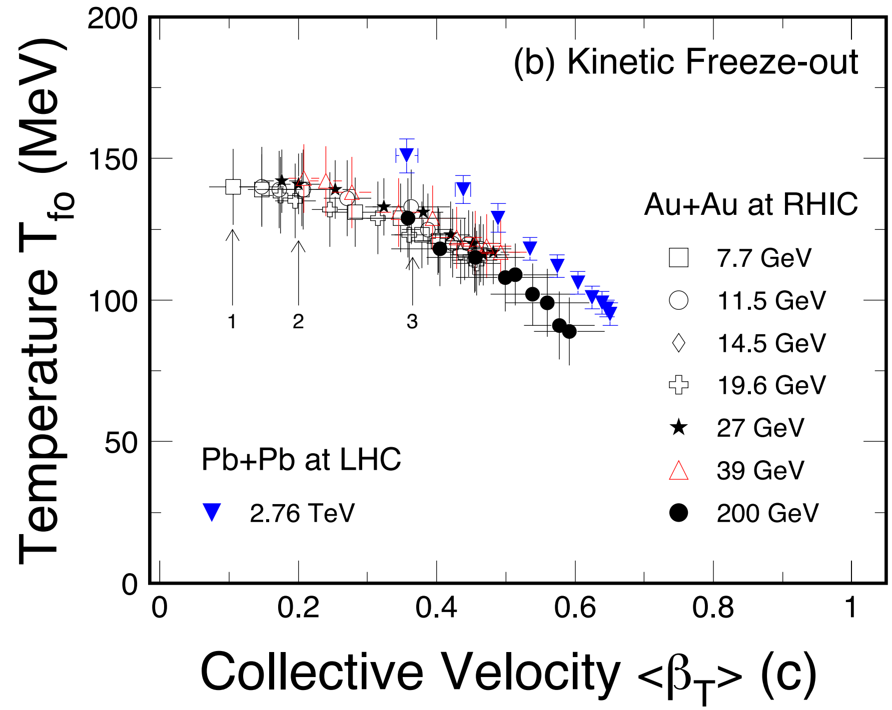
$\sqrt{s_{NN}}$ = 27 GeV Au+Au Collisions



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

Bulk Properties at Freeze-outs





Chemical Freeze-out: (GCE)

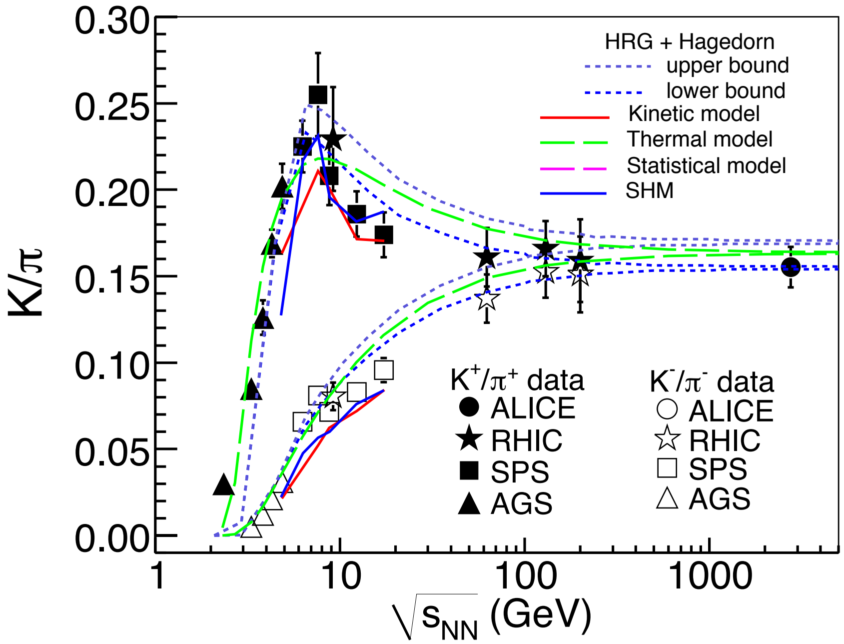
- Weak temperature dependence
- Centrality dependence μ_B!
- LGT calculations indicate the Critical Region around μ_B **~ 300 MeV?**

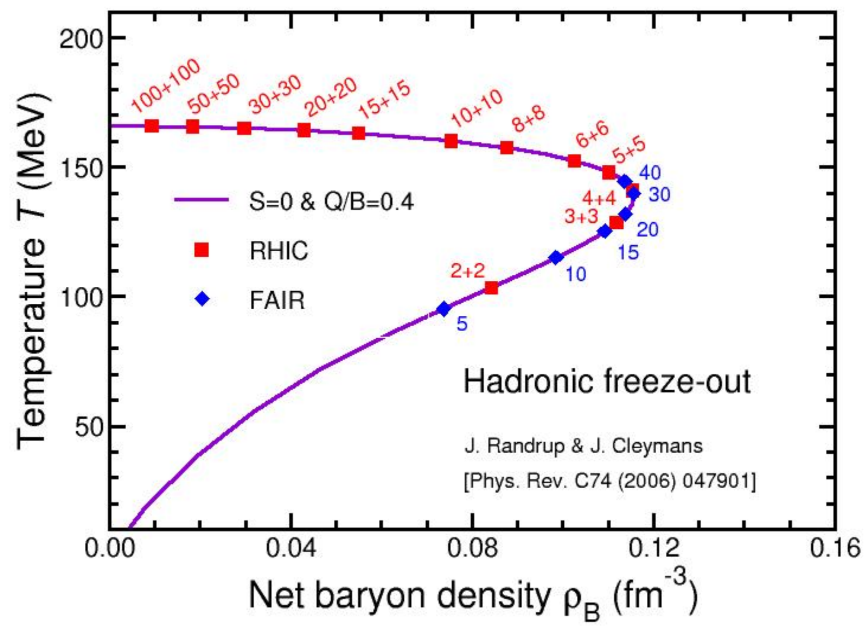
Kinetic Freeze-out:

- 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); **STAR**: 1701.07065
- S. Mukherjee: Private communications. August, 2012

K/π Ratios and Baryon Density

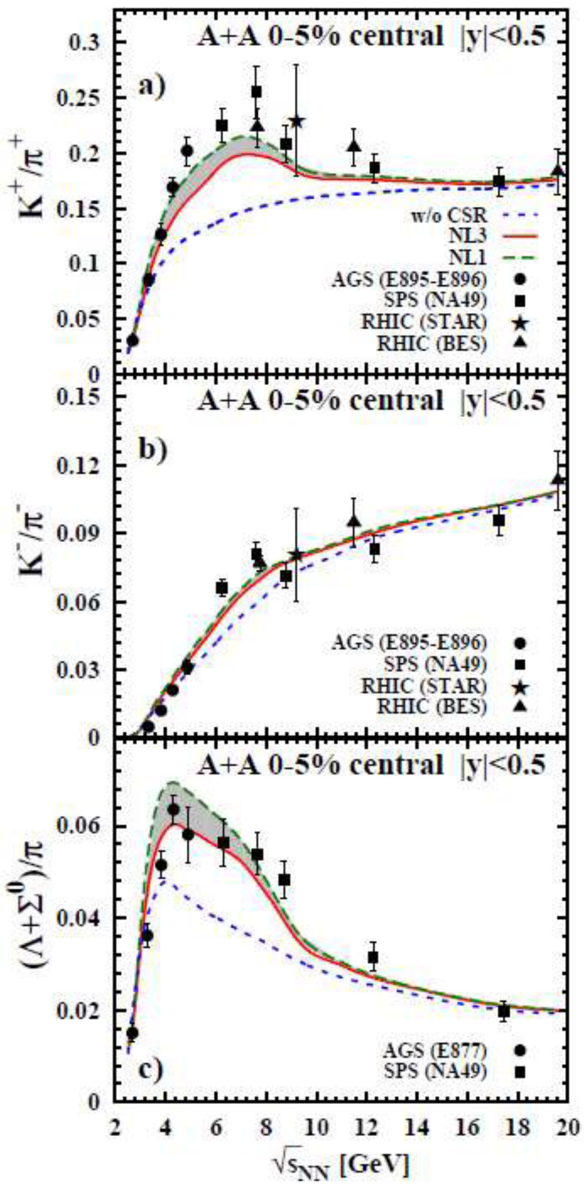




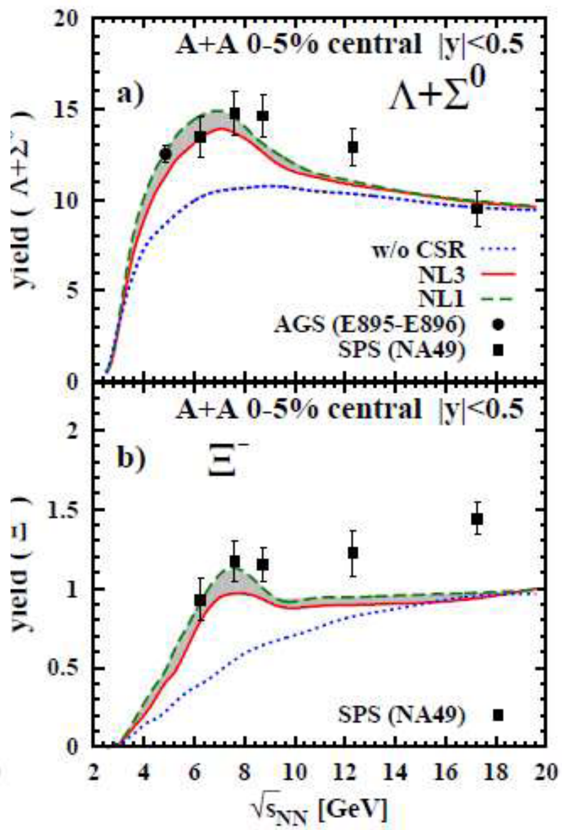
1) The **K^+/π** ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV,
   K^-/π ratio merges with **K^+/π** at higher collision energy
2) Model: **Baryon density peaks at $\sqrt{s_{NN}}$ ~ 8 GeV**
3) At **$\sqrt{s_{NN}}$ > 8 GeV,** pair production becomes important

STAR: 1701.07065; J. Randrup and J. Cleymans, Phys. Rev. **C74**, 047901(2006)

PHSD Results (A. Palmese *et al.* PRC**94**, 044912 (2016))



1) In hadronic phase, 'Chiral symmetry restoration' & strangeness exchanges lead to enhancement of the anti-s quarks hadrons around $\sqrt{s_{NN}}$ ~ 8GeV
2) All negatively charged anti-s-quark enhanced, but not the s-quark, why?
3) ϕ-meson production should be enhanced at the very same collision energy!



$$\gamma_S = \exp\left(-\pi \frac{m_s^2 - m_u^2}{2\sigma}\right)$$

$$\sigma \approx 0.17 GeV^2$$

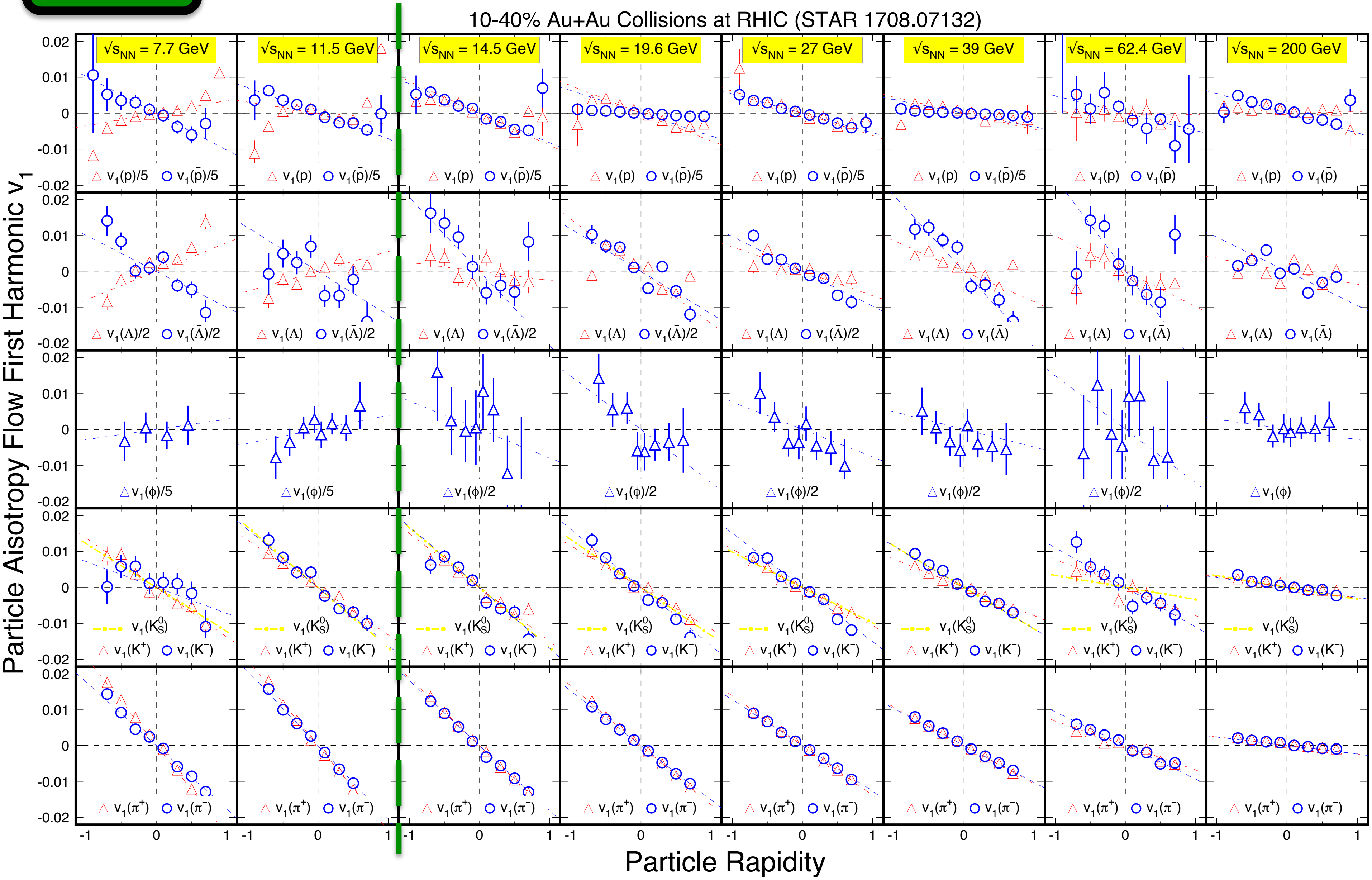
	hadron	quarks	Mass (MeV)
1	K^+	u^+s^-	493.7
2	K^-	u^-s^+	493.7
3	Λ	$u^+d^+s^-$	1115.7
4	Σ^0	$u^+d^+s^-$	1192.6
5	Ξ^-	$d^+s^-s^-$	1.321.3

Collectivity

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

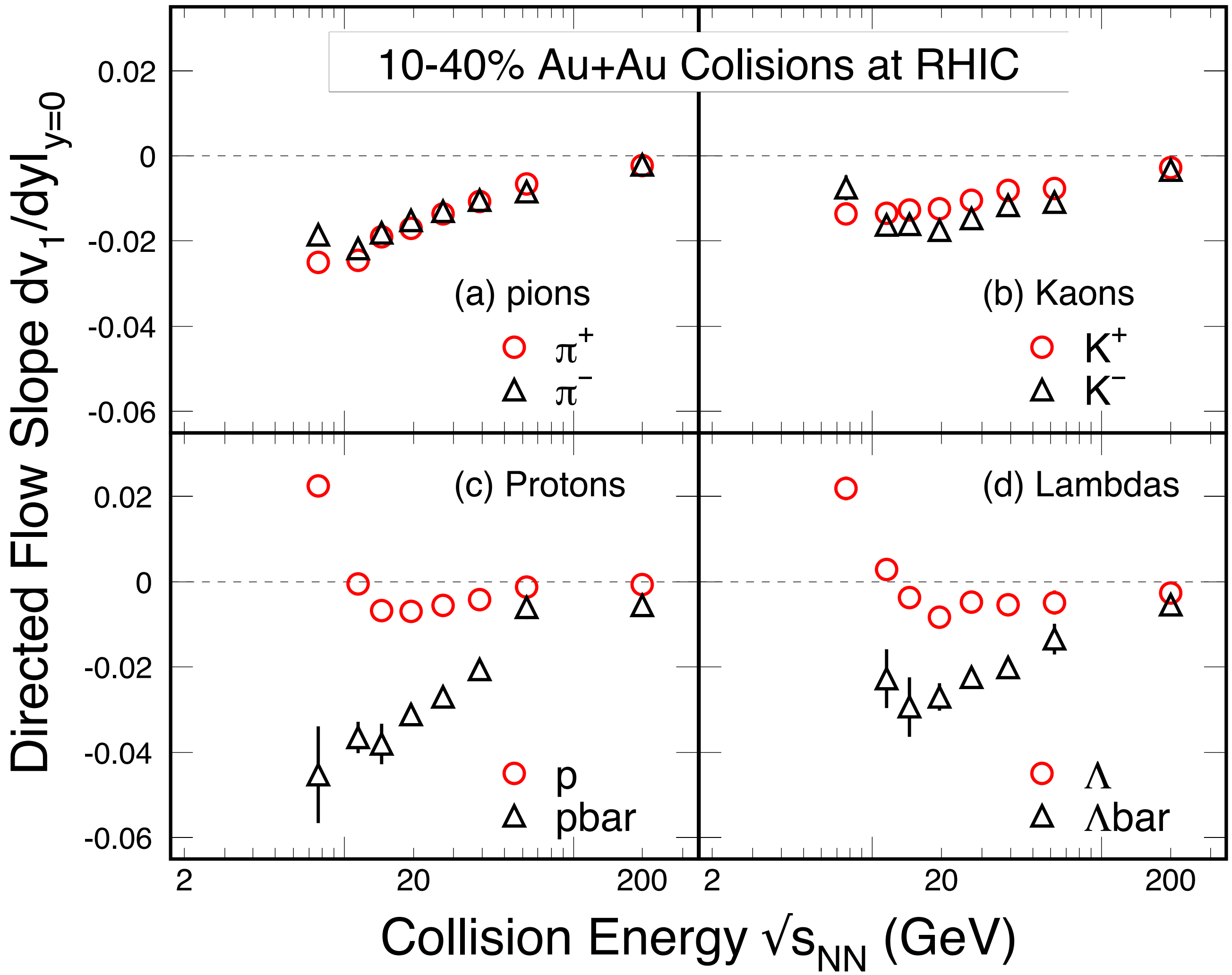
v_1 versus Collision Energy

NEW



v_1 versus Collision Energy

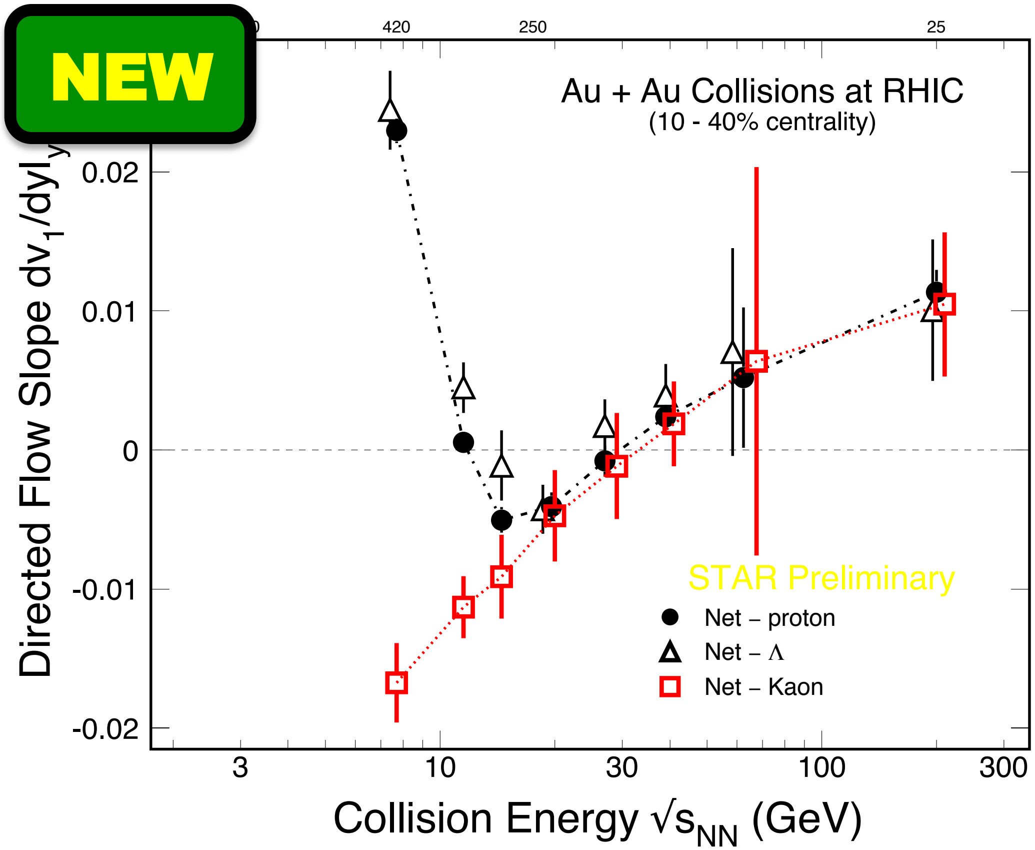
NEW



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-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!

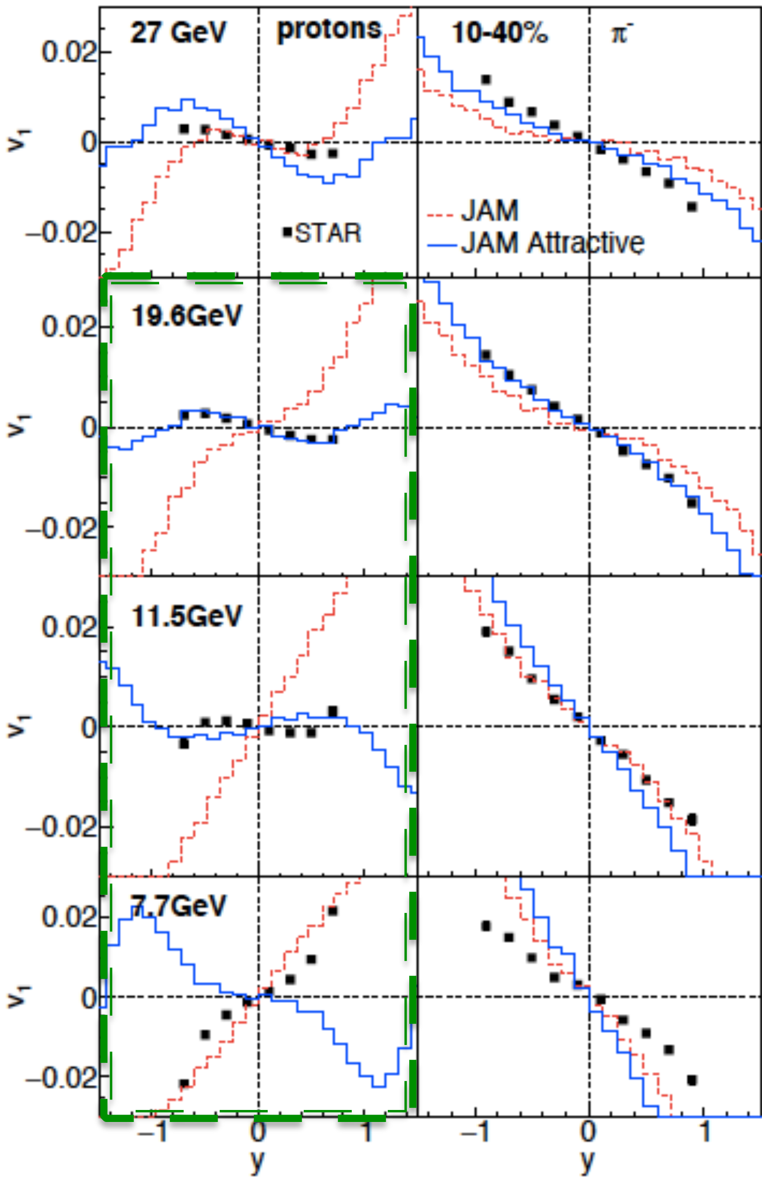
3) Softest point only for baryons?

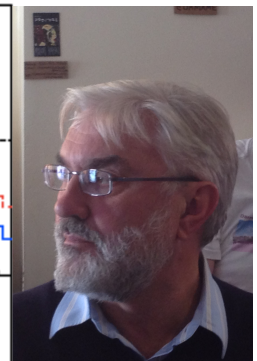
4) Need model to explain!

- 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)
□ Δ STAR: 1708.07132

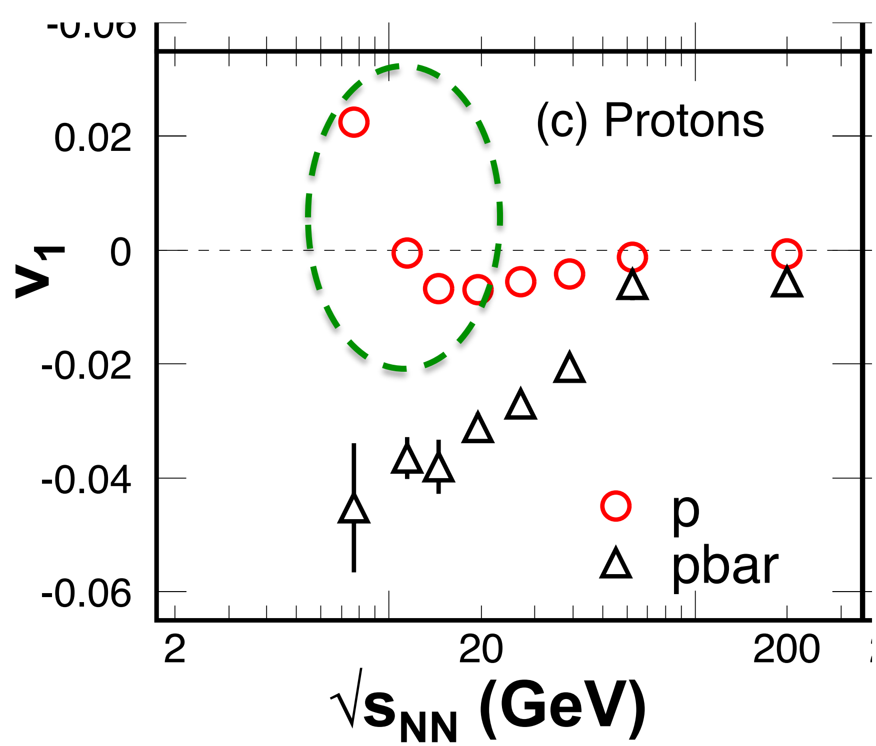
v_1 vs. Energy: Softest Point?



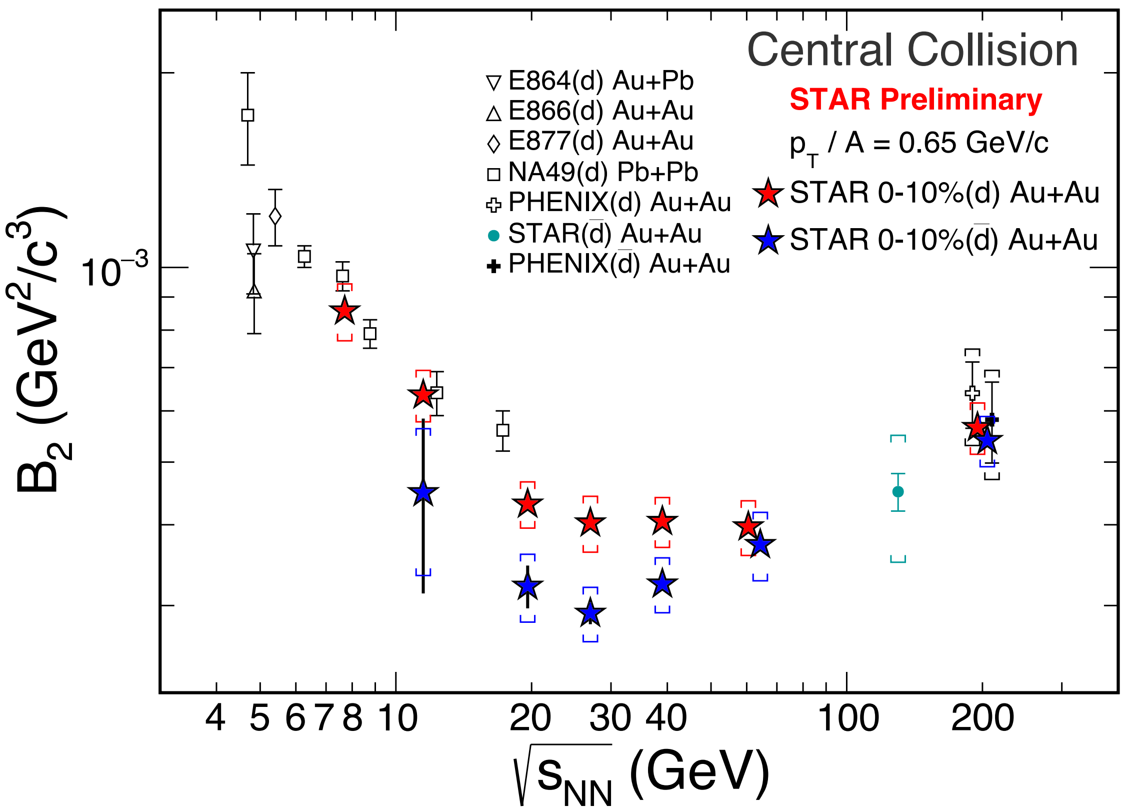


"Attractive force" → Change of the EOS ~ "softest point"

- Y. Nara, A. Ohnishi, H. Stoecker, arXiv: **1601.07692** ; PRC**94**, 034906(2016)



Energy Dependence of Deuterons



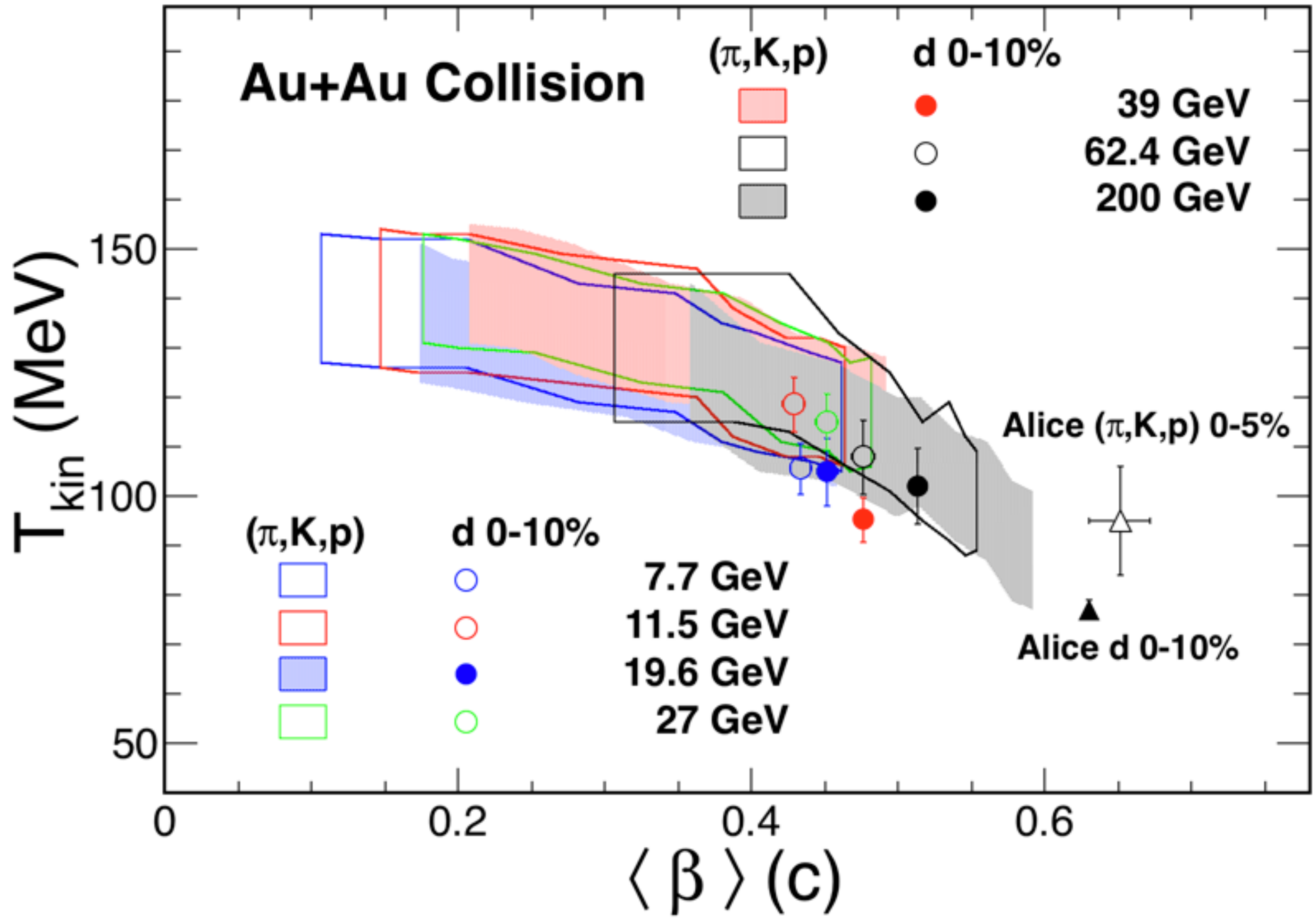
B_2: Space-momentum correlation between nucleons at freeze-out

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

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

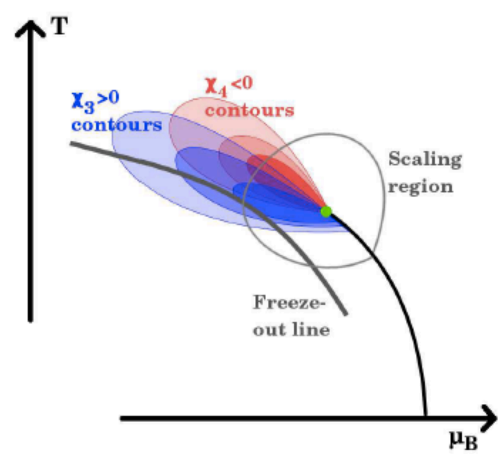
STAR Data: N. Yu *et al*, QM2015

Au+Au Collisions at RHIC

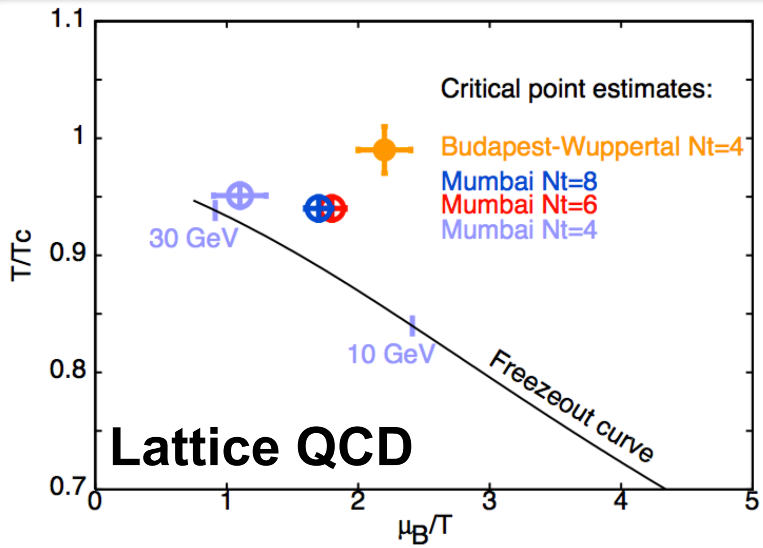


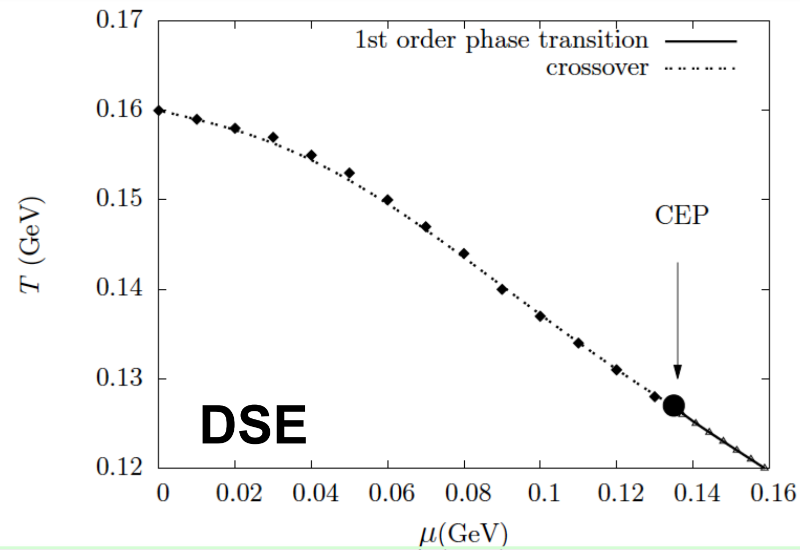
1) Blast-wave fit to (pion, Kaon and proton) and light-nuclei (d) transverse momentum spectra separately. Profile parameter n=1 used in all fits.
2) In the most central (0-10%) Au+Au collisions, light-nuclei kinetic freeze-out at a higher temperature and smaller collectivity parameters, compared to that of light hadrons.
3) When are light-nuclei produced in high-energy nuclear collisions?

Criticality



Status on Predictions





Lattice QCD:

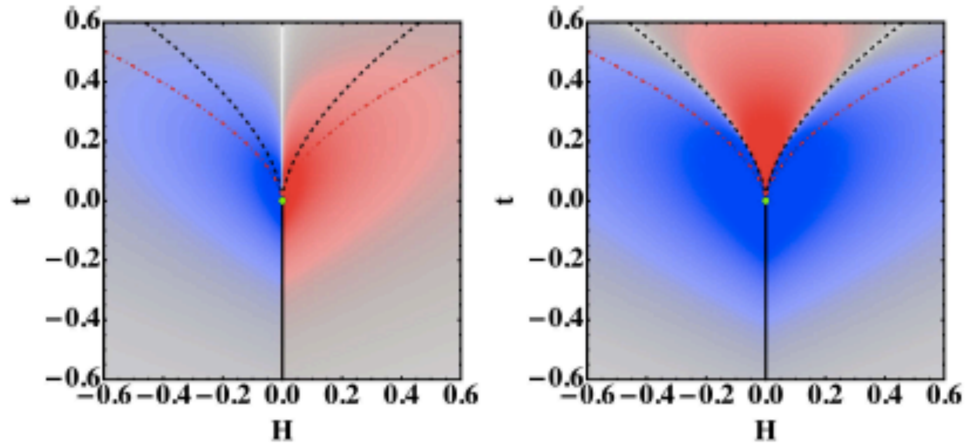
1) Fodor and Katz, JHEP 0404,050 (04)
   (μ^E_B, T_E)= (360, 162) MeV (Re.)
2) Gavai and Gupta, NPA 904, 883c (13)
   (μ^E_B, T_E)= (279, 155) MeV (Taylor)
3) F. Karsch (μ^E_B/ T_E >2, CPOD2016)

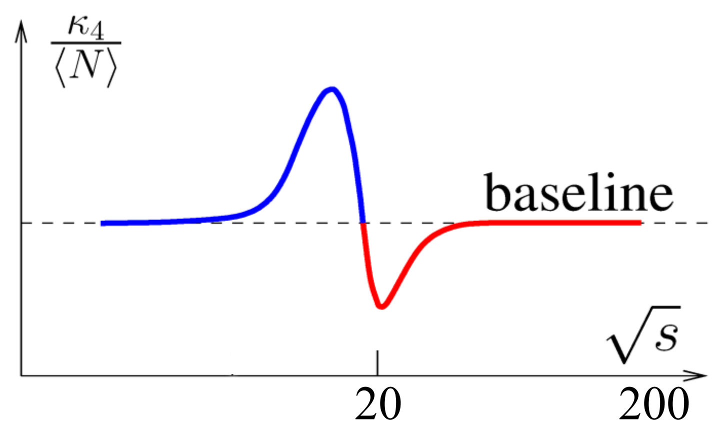
DSE:

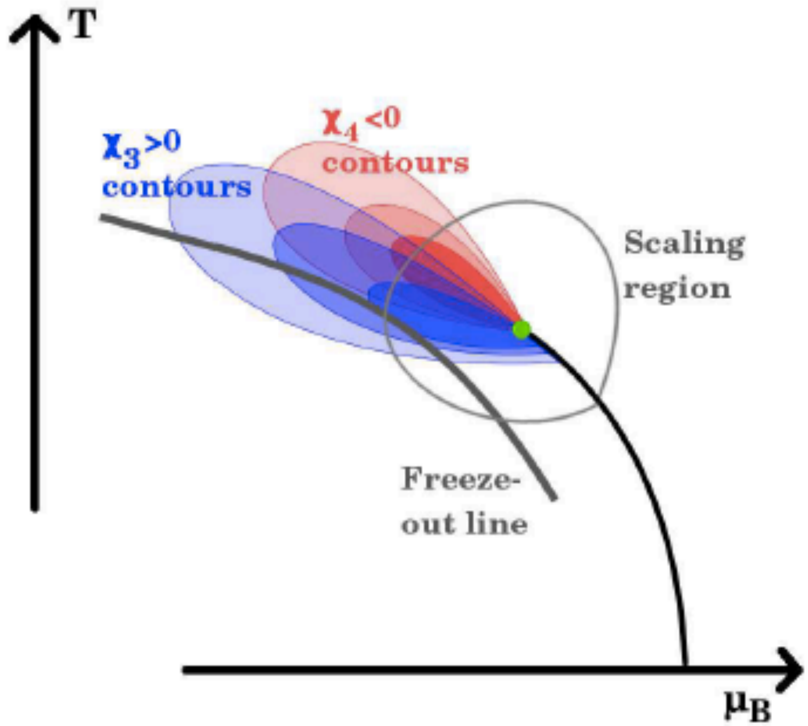
1) Y. X. Liu, et al., PRD90, 076006(14)
   (μ^E_B, T^E) = (372, 129) MeV
2) H.S. Zong et al., JHEP 07, 014(14)
   (μ^E_B, T_E)= (405, 127) MeV
3) C.S. Fischer et al., PRD90, 034022(14)
   (μ^E_B, T^E) = (504, 115) MeV

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

Expectation from Model Calculations



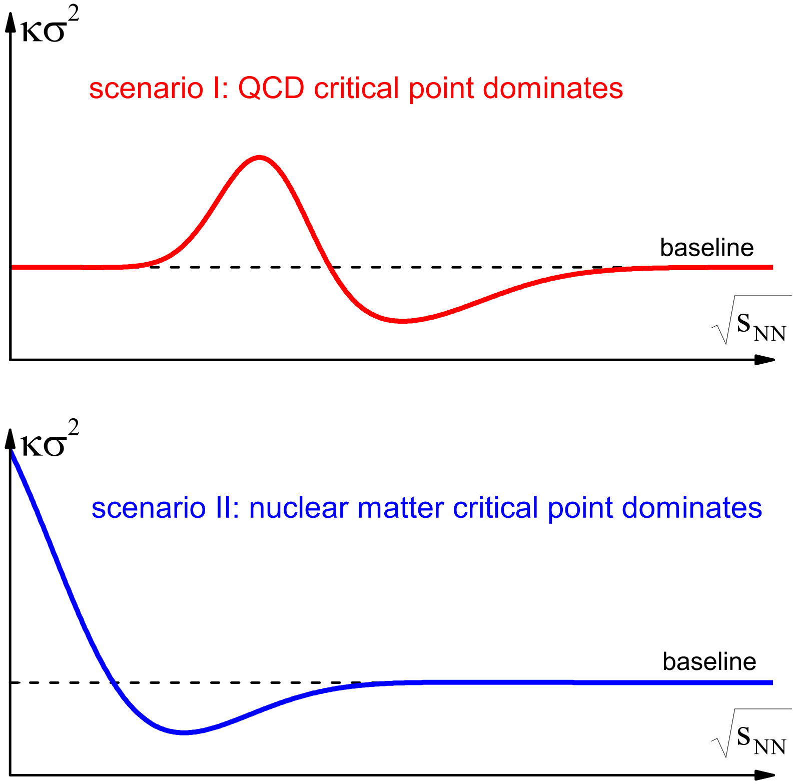




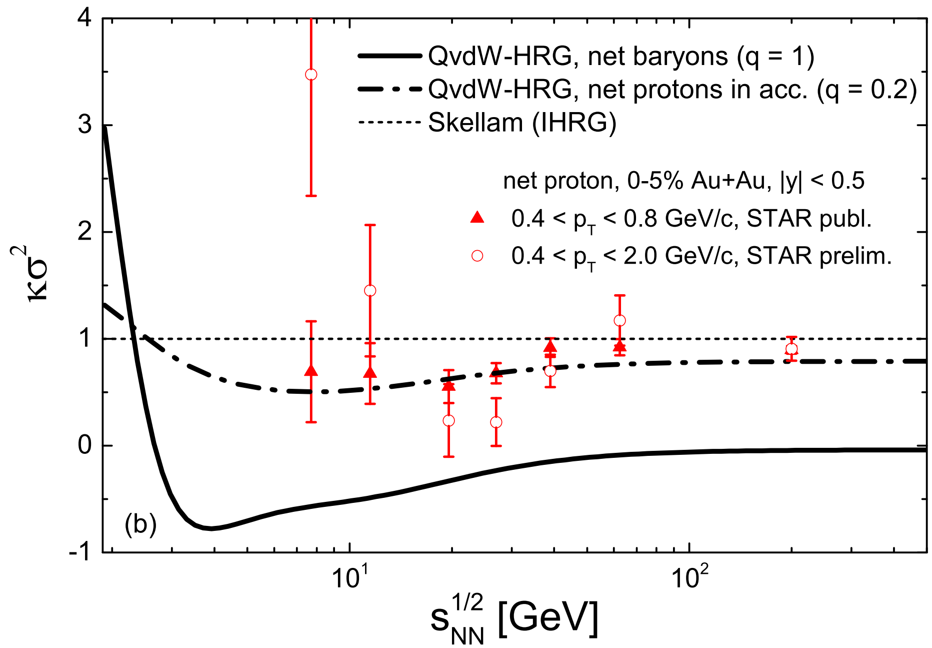
- Characteristic “Oscillating pattern” is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*
- Critical Region (CR)

- 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

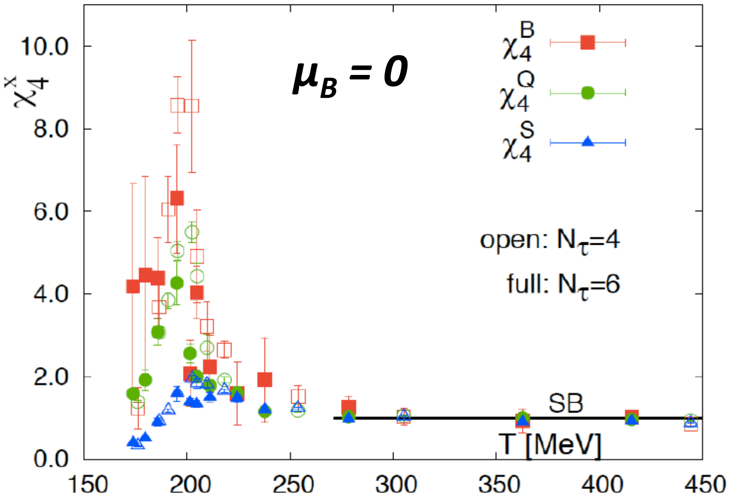
Expectation from Model Calculations!

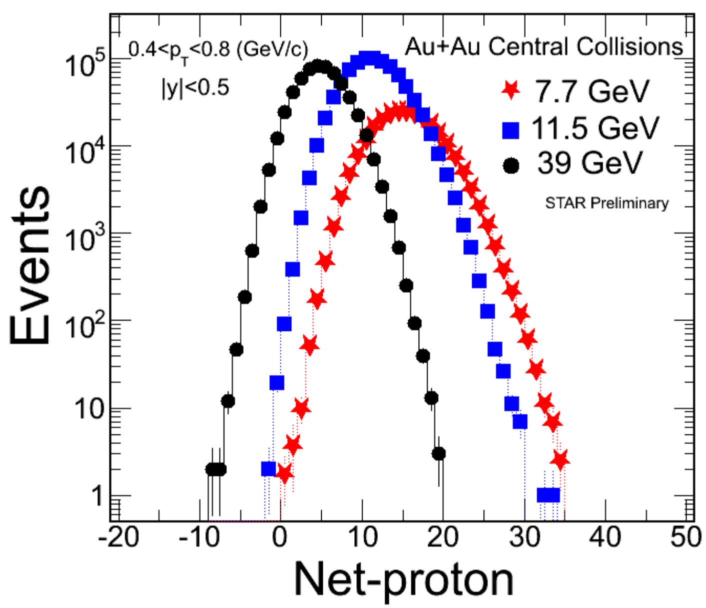


V. Vochenko, L.J. Jiang, M.I. Gorenstein and H. Stoecker   1711.07260



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:

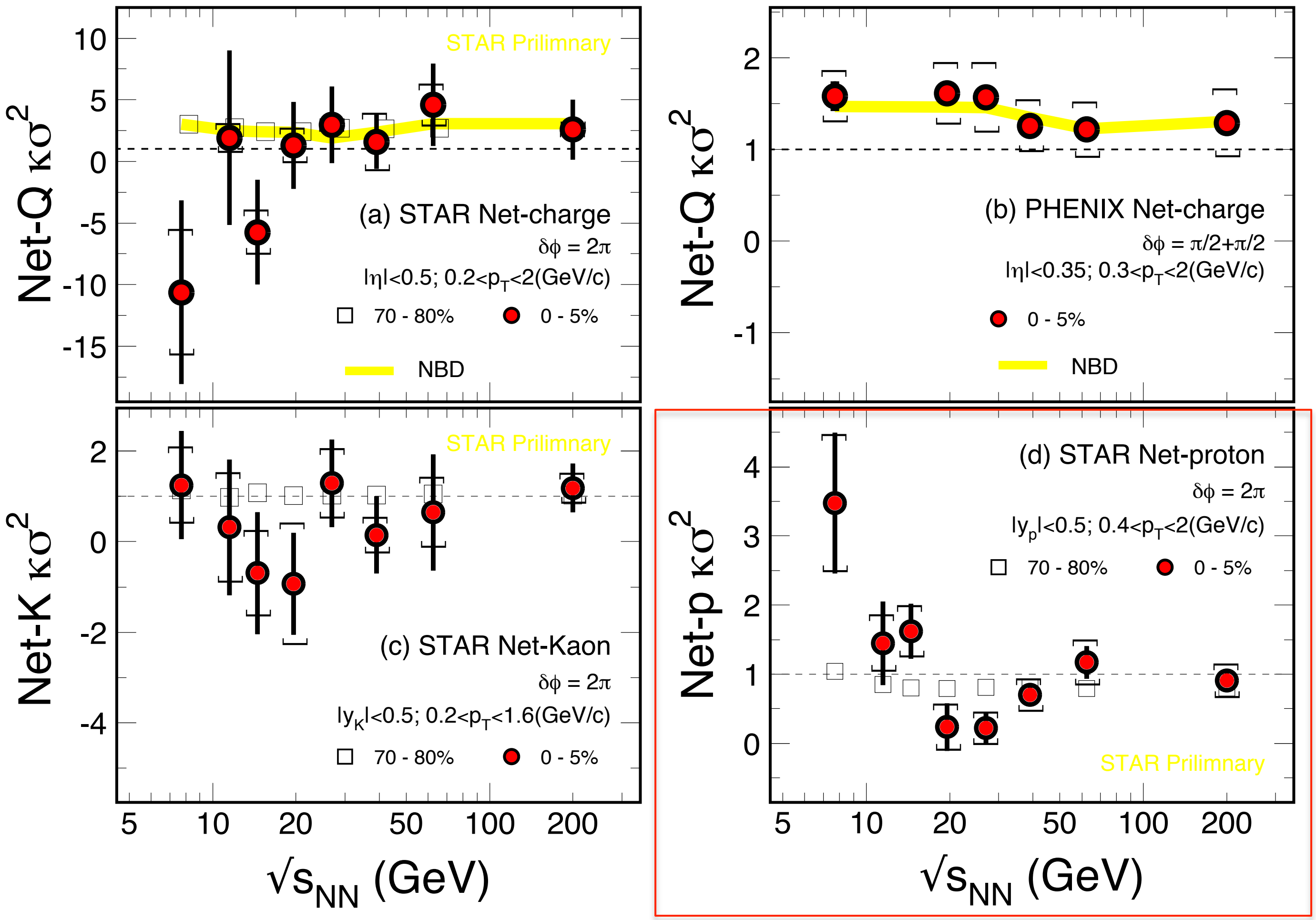
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

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



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

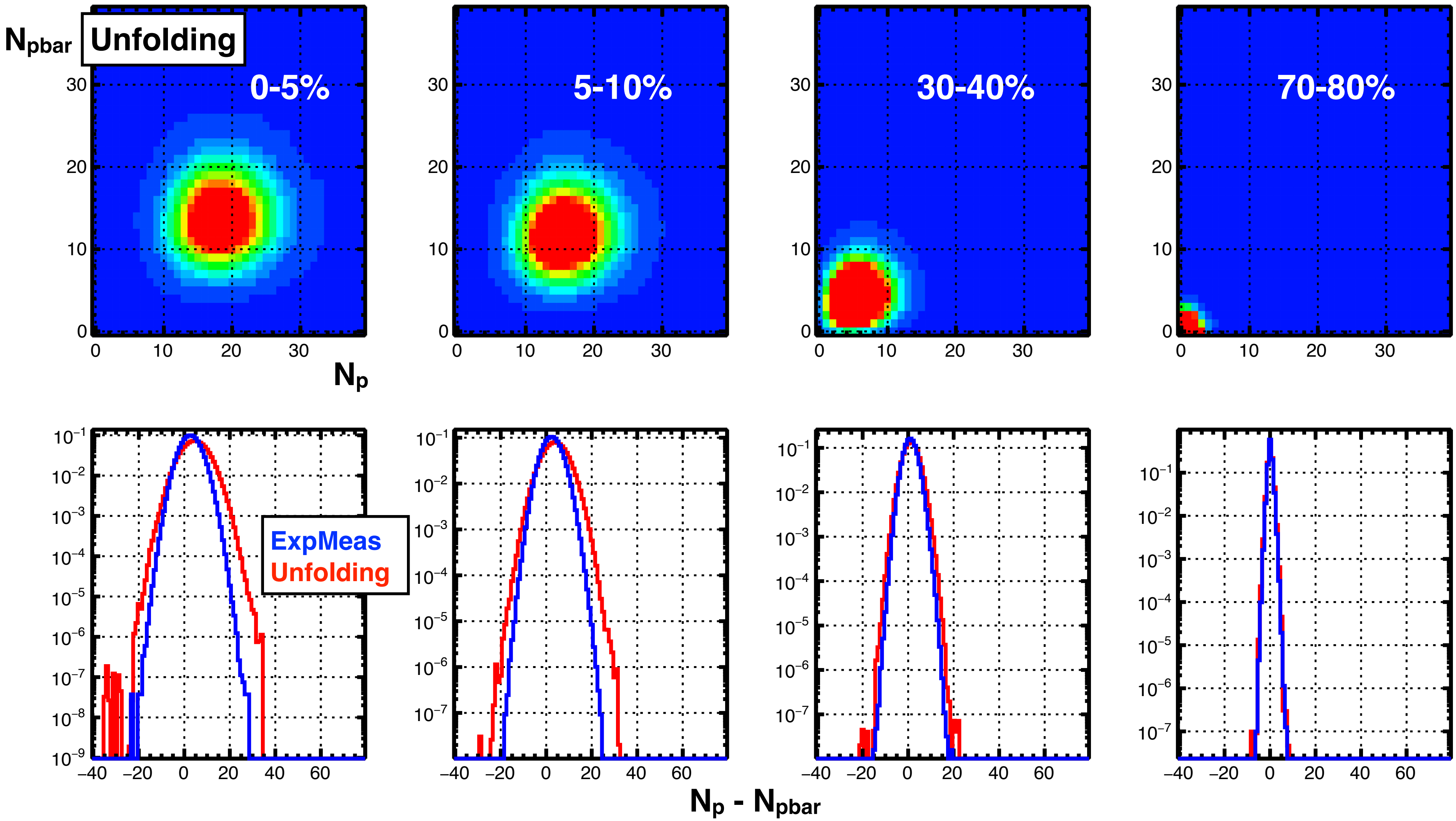
In STAR:

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!

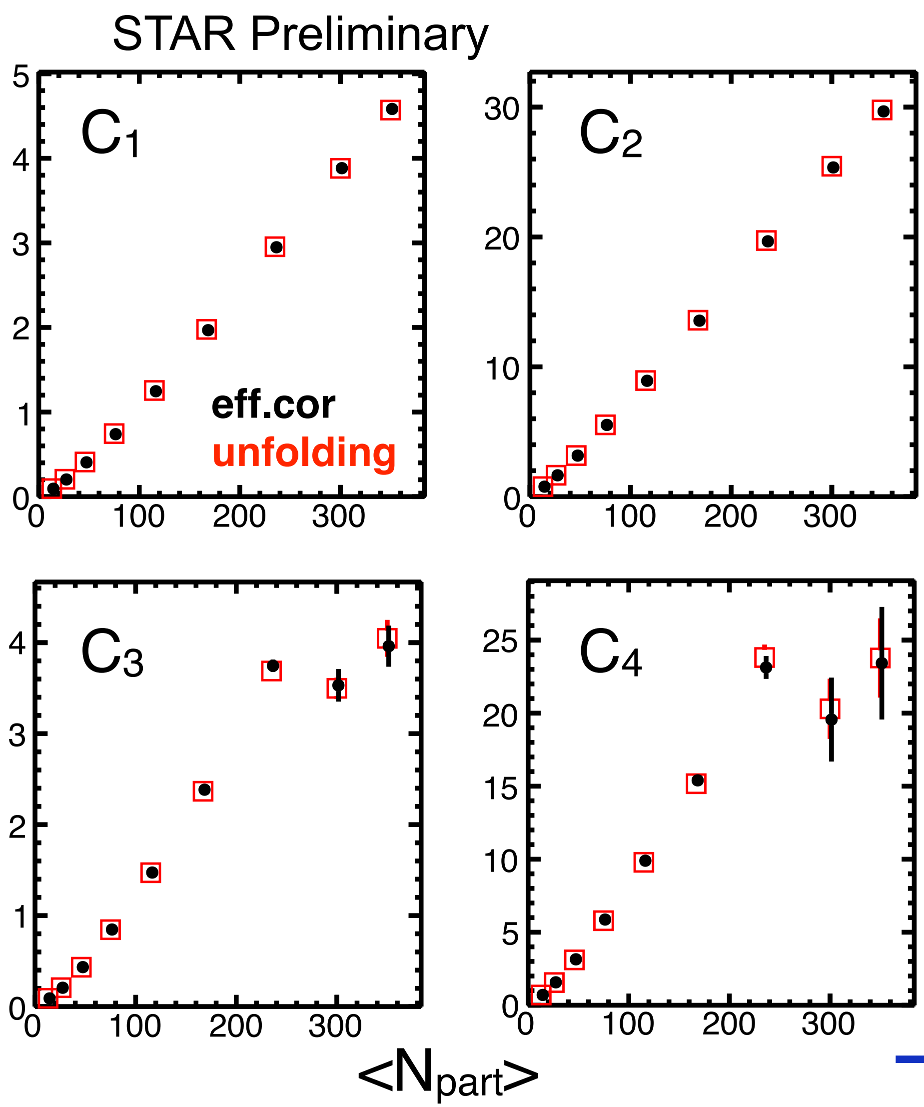
Unfolded distributions at $\sqrt{s_{NN}}$ = 200 GeV

$\sqrt{s_{NN}}$ = 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



T. Nonaka and S. Esumi *et al.*

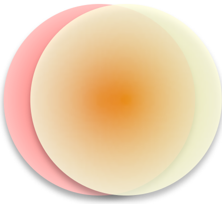
Unfolding: $\sqrt{s_{NN}}$ = 200 GeV Au+Au Collisions



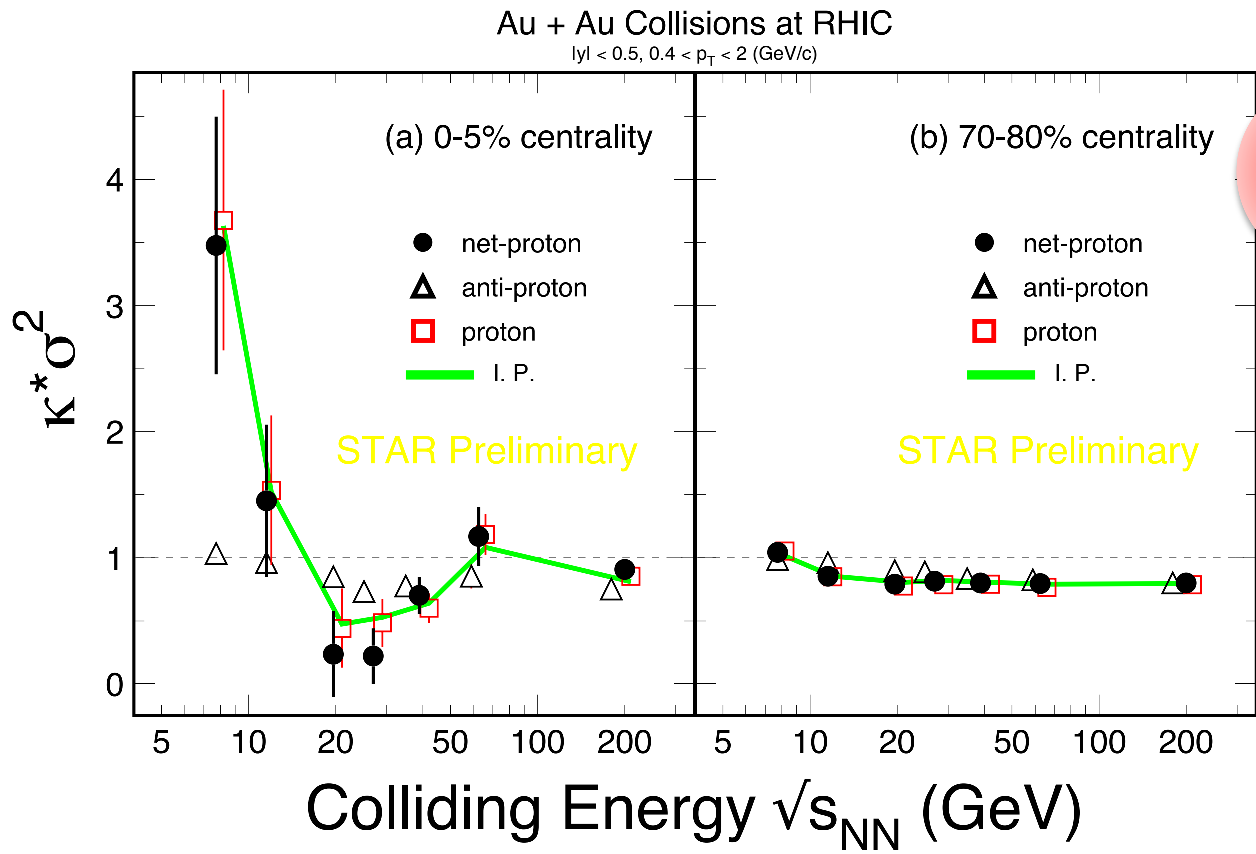
1) Unfolding method established
2) Embedding used to generate the response matrix
3) Final results will follow soon

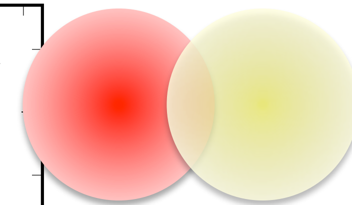
From T. Nonaka and S. Esumi

Net-proton Higher Moment



central



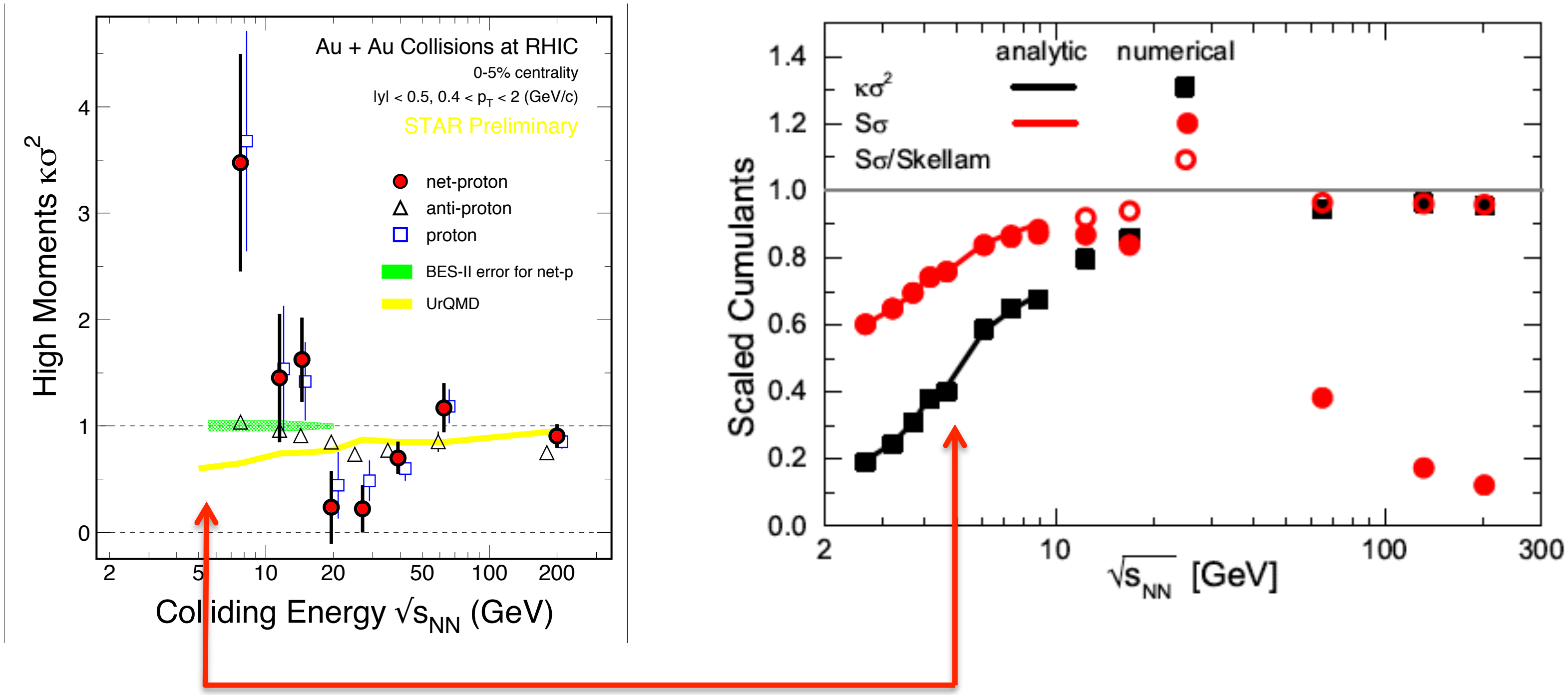


peripheral

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: **$\kappa\sigma^2 < 1$!**

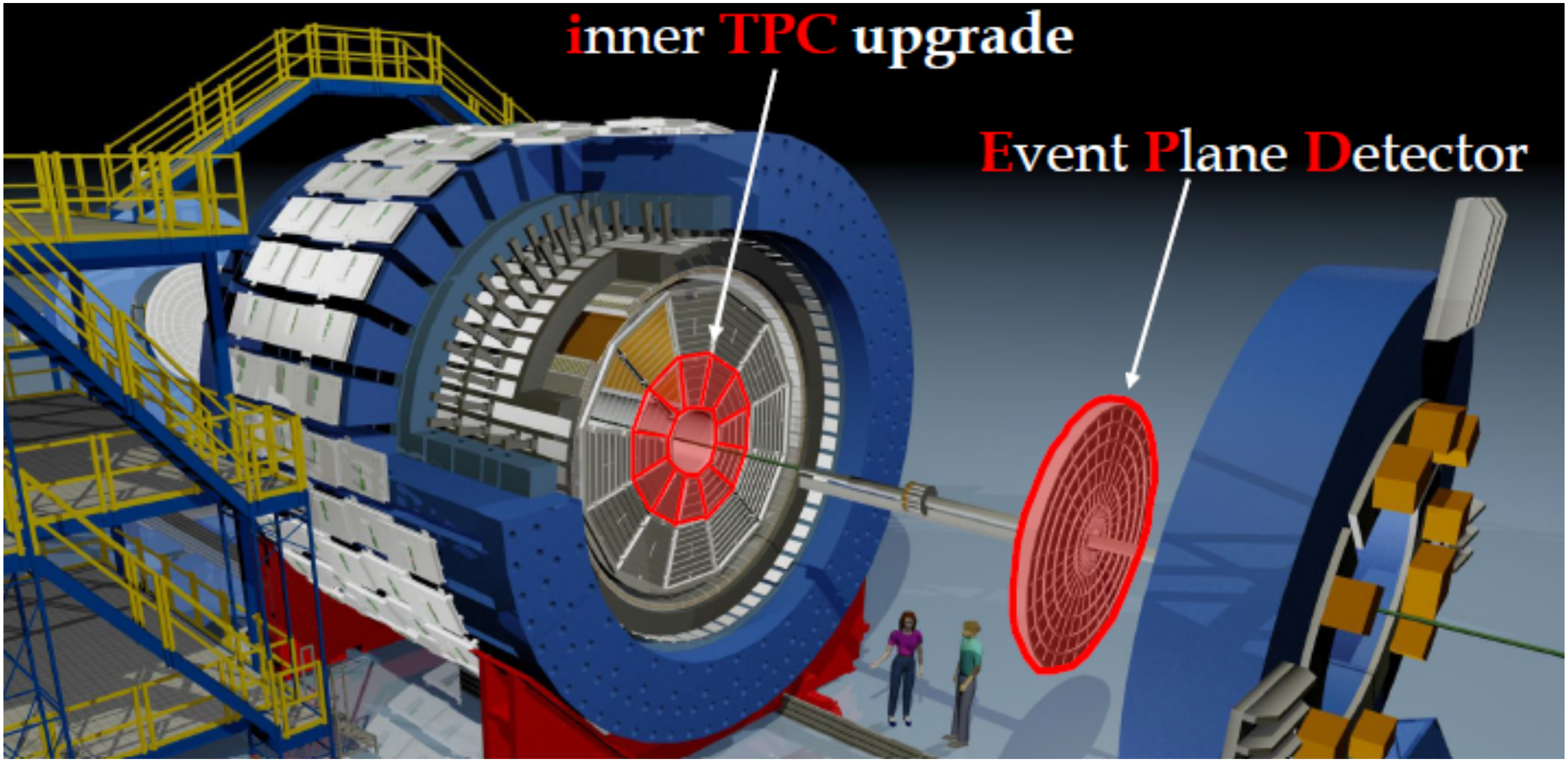
*All models: **suppress higher order net-proton fluctuations***

(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.

STAR Upgrades for BES Phase-II



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

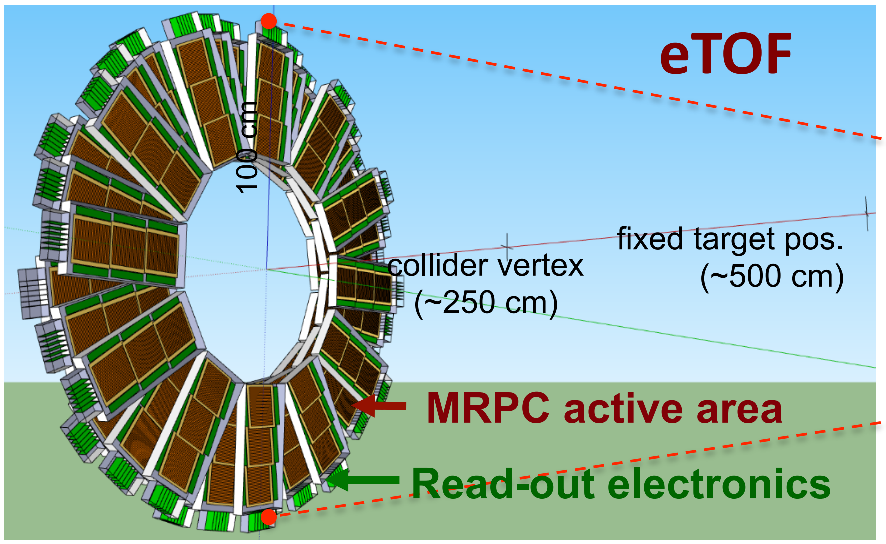
iTPC, EPD, eTOF
Dedicated two runs at RHIC: 2019 & 2020

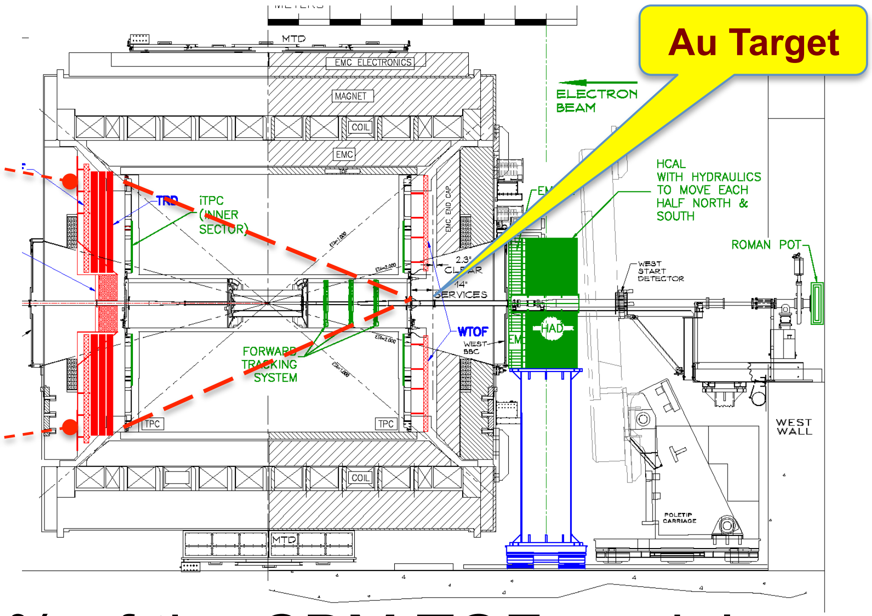
2019-2020: BES-II at RHIC

$\sqrt{s_{NN}}$ (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





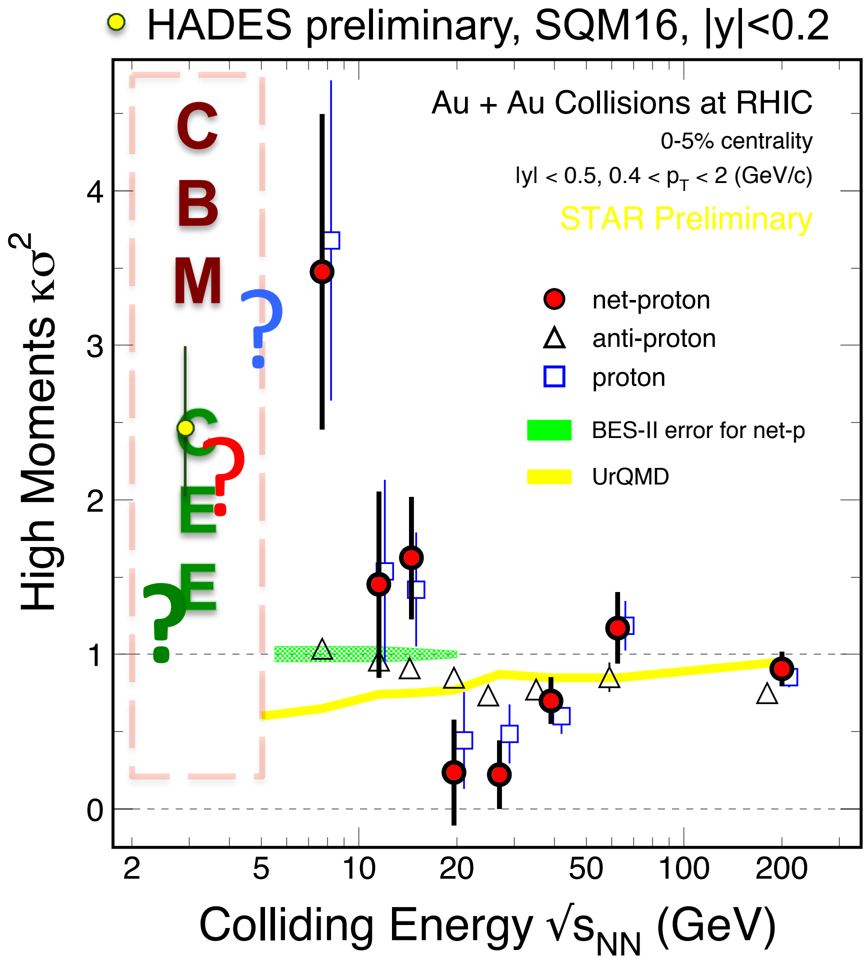
Install, commission and use 10% of the CBM TOF modules, including the read-out chains at STAR, starting in 2019

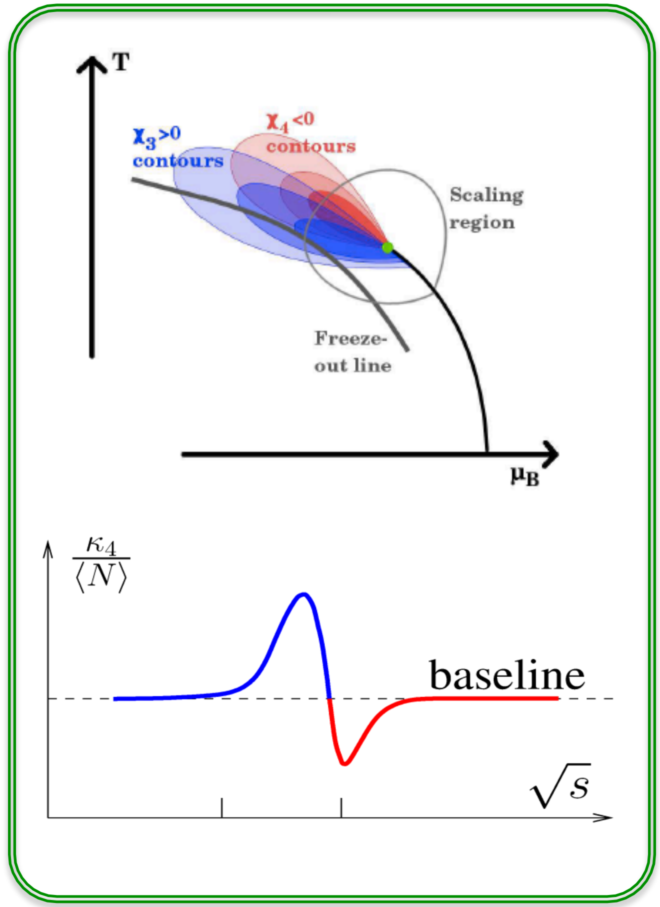
CBM participating in RHIC Beam Energy BES-II in 2019-2020:

- 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!

Search for the QCD Critical Point





- 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

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

Summary

1) At the mid-baryon density region, μ_B > 250 MeV ($\sqrt{s_{NN}}$ **< 20** GeV), interesting behaviors observed in Collectivity (Chirality) and Criticality!
2) High statistic data at high baryon regions needed: RHIC STAR BES-II, NICA, CBM, J-PARC(?).
3) At μ_B ~ 0 MeV, the high-energy limit, more data needed for the experimental evidence of the 'smooth-crossover'.

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