Study the QCD Phase Structure
in High-Energy Nuclear Collisions
- Limits on the experimental search for the CEP

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Many Thanks to the Organizers!

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Outline

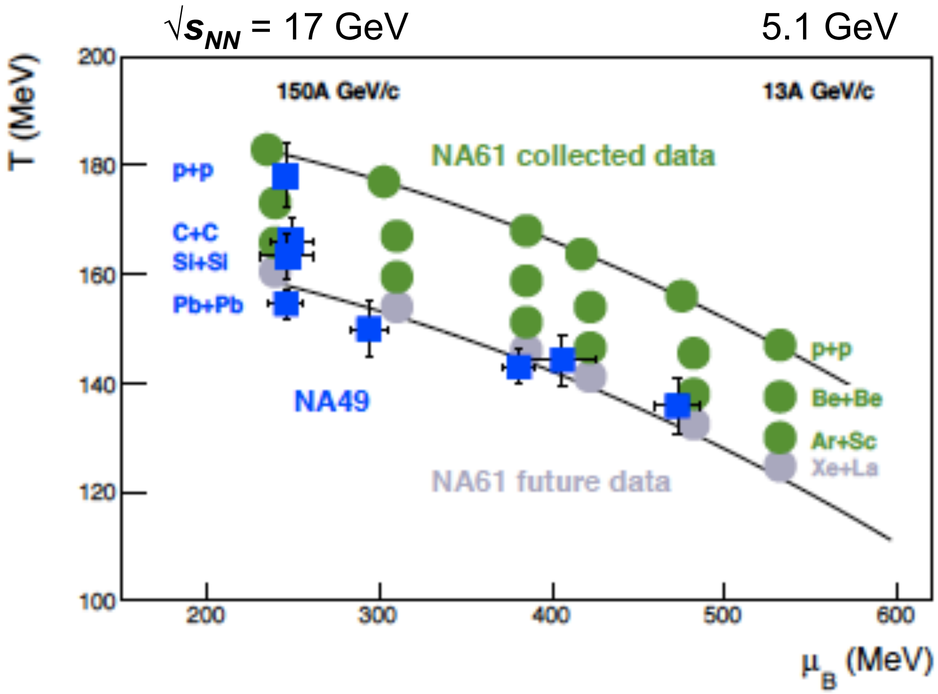
(1) Introduction

(2) Recent Results from BES-I at RHIC

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

(3) Summary and Outlook

NA49/NA61 Strategy and Status



1) Assume systems created in p+p to Pb+Pb at $\sqrt{s_{NN}}$ ~ 5-17 GeV collisions are ALL thermalized
2) Scan collision energy (5 < $\sqrt{s_{NN}}$ < 17 GeV, 550 < μ_B < 250 MeV) and initial system size (p+p to Pb+Pb) in order to alter the position of the freeze-out point relative to the phase-boundary

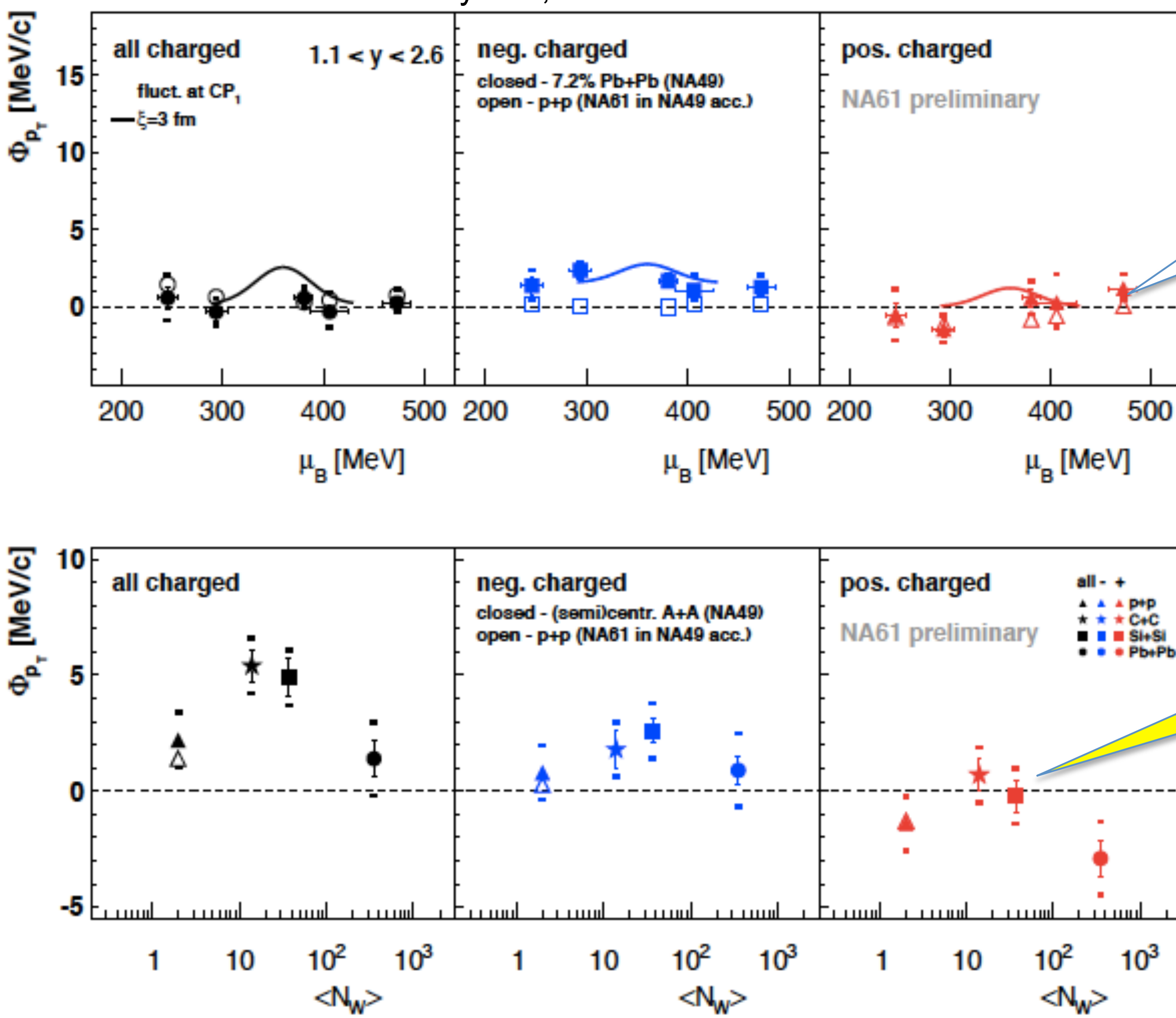
Review by M. Gazdzicki and P. Seyboth
arXiv: ***1506.08141***

The continuing search in nucleus-nucleus reactions for the maximum of fluctuations predicted for the critical point of strongly interacting matter has not yet turned up firm evidence in collisions of heavy nuclei either at the CERN SPS (central Pb+Pb collisions) or in the RHIC BES program (Au+Au collisions).

It is intriguing that both the fluctuations of quantities integrated over the full experimental acceptance (event multiplicity and transverse momentum) as well as the bin size dependence of the second factorial moment of pion and proton multiplicities in medium-sized Si+Si collisions at 158A GeV/c possibly suggest critical behaviour of the created matter.

NA49/NA61 Results

M. Gazdzicki and P. Seyboth, arXiv: ***1506.08141***



- Central Pb+Pb collisions (7.2%) vs. collision energy
- Flat strcture

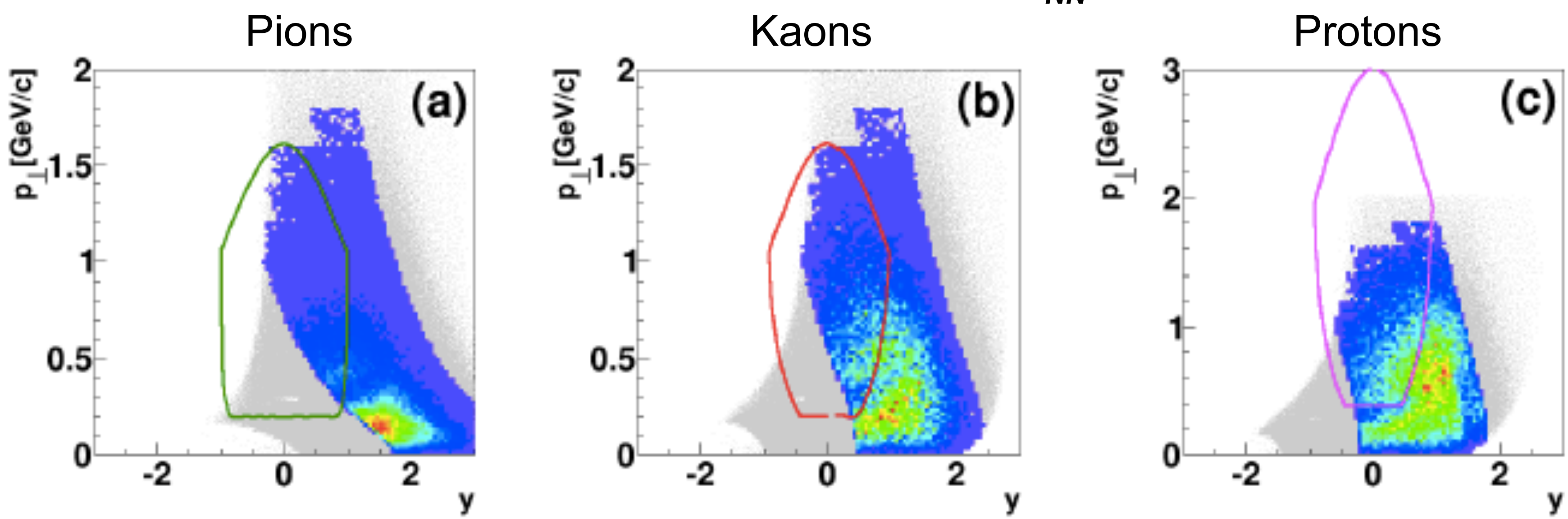
- Collision centrality dependence at 158 GeV/c.
- Peak around C+C, Si+Si collisions

Real critical behavior?

NA49/NA61 Acceptances

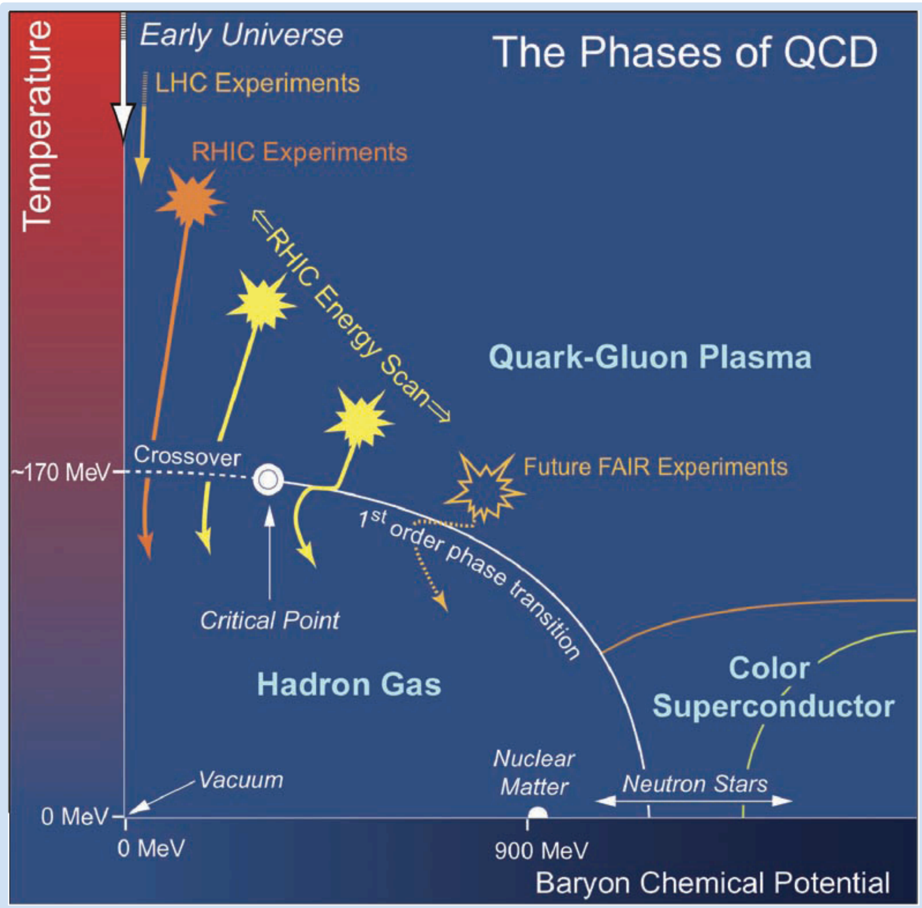
M. Gazdzicki and P. Seyboth, arXiv: ***1506.08141***

Pb+Pb Collisions at 30 GeV/u, $\sqrt{s_{NN}}$ = 7.6 GeV



1) In fixed target experiment, *particle identification* and *acceptance* (p_T, y) strongly depend on collision energy, particle mass
2) Systematic effects on the purity, volume fluctuation and acceptance ought be carefully studied

Beam Energy Scan at RHIC



2000 – 2010:

Top energy programs

Discovery of sQGP

2010 – 2014:

BES-I (7.7, 11.5, 14.5, 19.6, 27, 39 GeV)

- Phase boundary and CP
- Chiral symmetry

2019 – 2020:

BES-II $\sqrt{s_{NN}}$: 19.6, 14.5, 11.5, 7.7 GeV

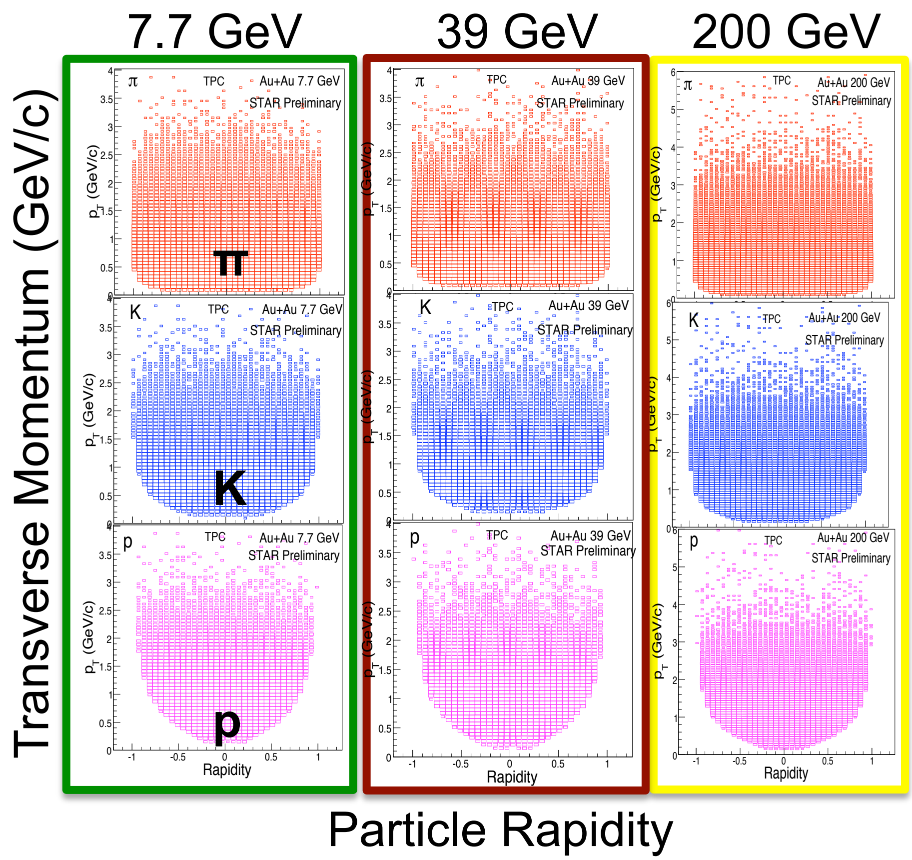
FXT*: $\sqrt{s_{NN}}$: 4.5, 3.9, 3.6, 3.0 GeV

2022 – 2025:

Fixed-target program

Data Sets at STAR

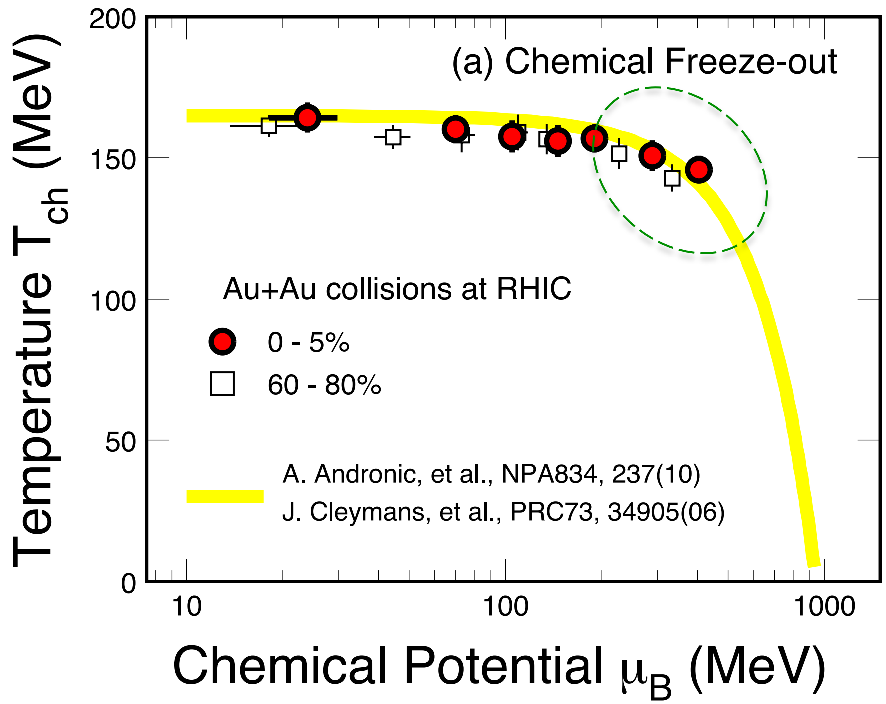
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	*μ_B (MeV)	*T_{CH} (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
39	39	2010	112	164
27	70	2011	156	162
19.6	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	316	152
7.7	4	2010	422	140

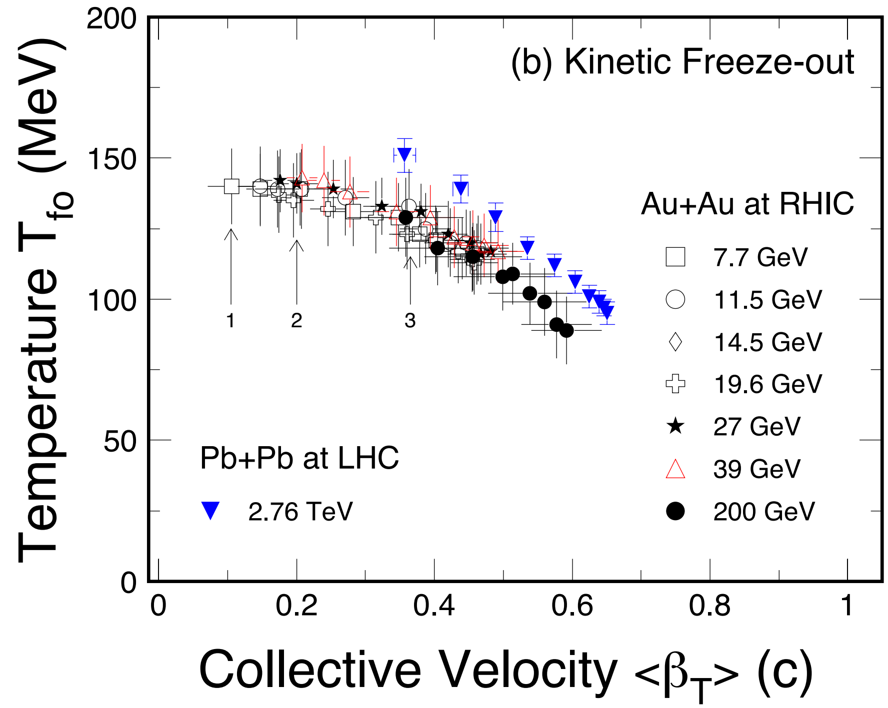


1) Largest data sets versus collision energy
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. Important for fluctuation analysis!

*(μ_B, T_{CH}) : J. Cleymans et al., PR **C73**, 034905 (2006)

Bulk Properties at Freeze-out





Chemical Freeze-out: (GCE)

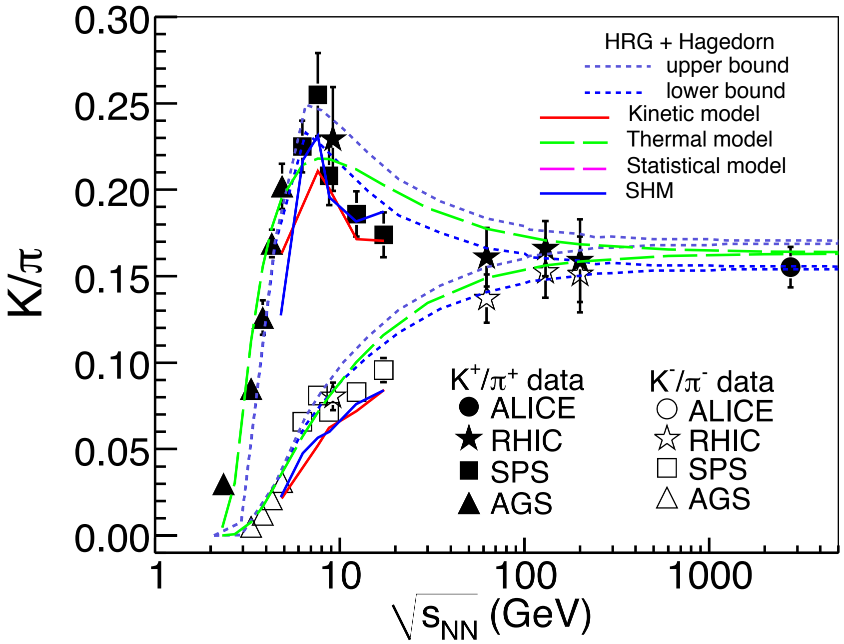
- Weak temperature dependence
- Centrality dependence μ_B!
- **CP about μ_B ~ *300* – 400 MeV?**

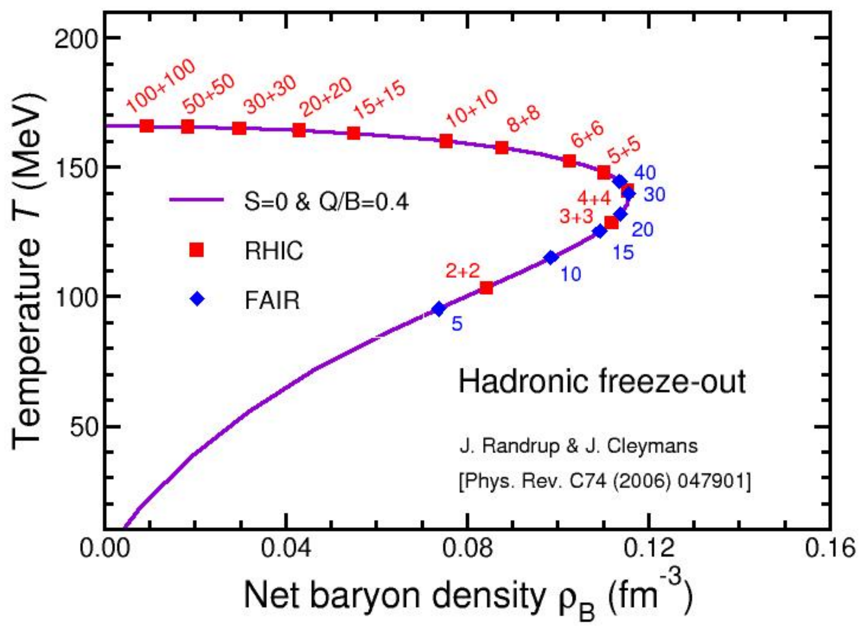
Kinetic Freeze-out:

- 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., PRL109, 252301(12); PRC88, 044910(2013).
STAR: J. Adams, et al., NPA757, 102(05); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14)

K^+/π Ratios and Baryon Density

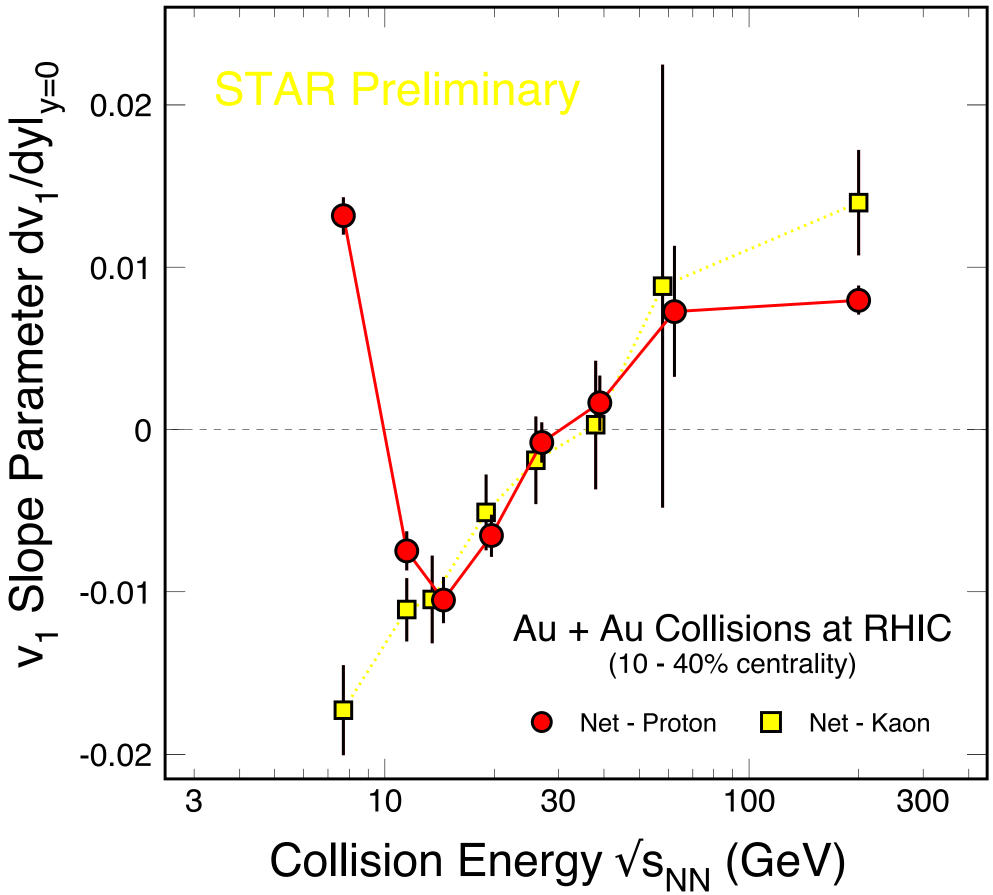




1) In heavy ion collisions $\mathbf{K^+/\pi}$ ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV, $\mathbf{K^-/\pi}$ ratio merges with $\mathbf{K^+/\pi}$ at higher collision energy
2) Model: Baryon density peaks at $\sqrt{s_{NN}}$ ~ 8 GeV
3) At $\sqrt{s_{NN}}$ **>** 8 GeV, pair production becomes important

L. Kumar, *et al.*1304.2969

The v_1 vs. Energy: Softest Point?

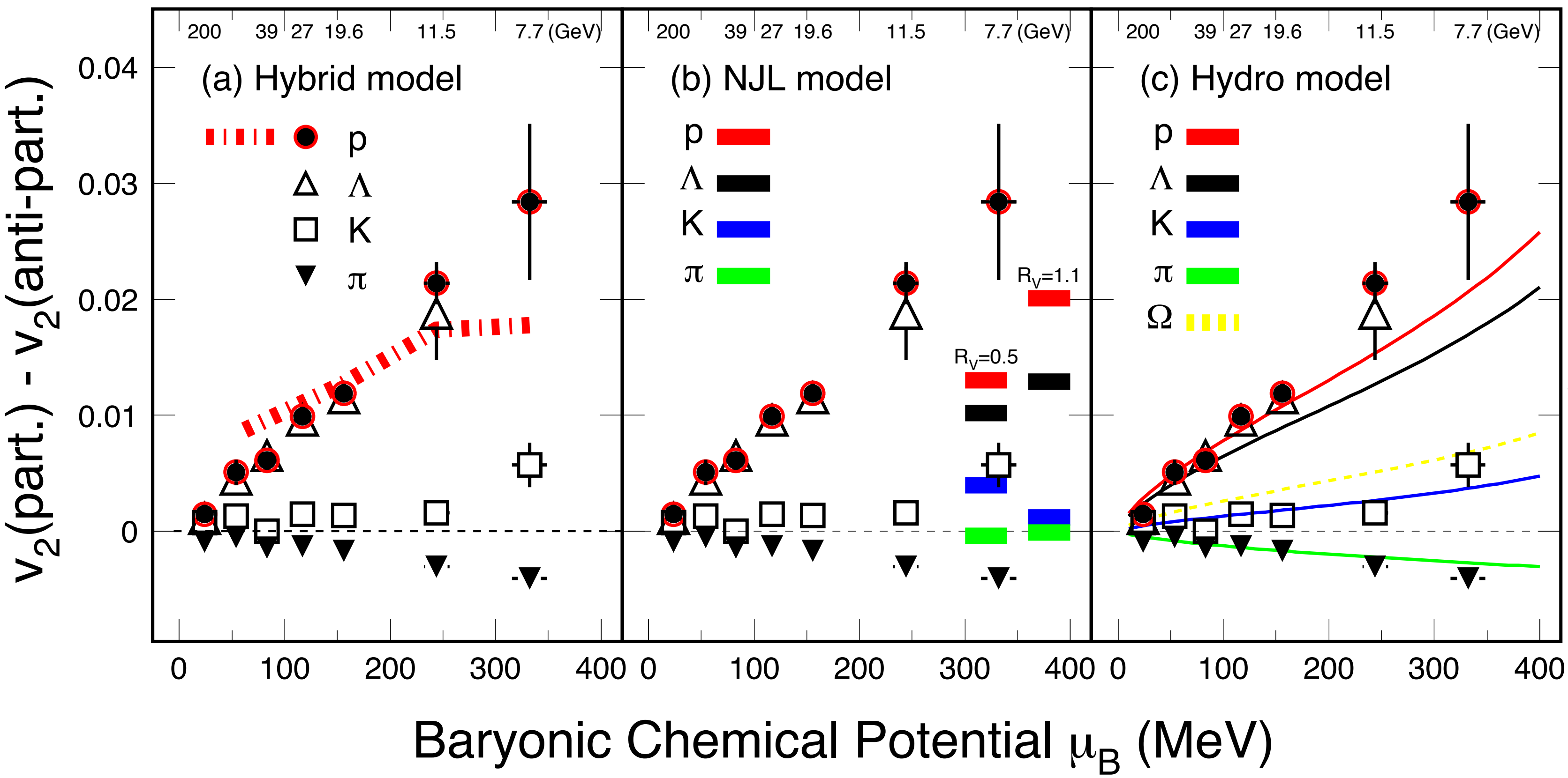


1) Mid-rapidity net-proton dv_1/dy published in 2014 by STAR, except the point at 14.5 GeV
2) Minimum at $\sqrt{s_{NN}}$ = 14.5 GeV for net-proton, but net-Kaon data continue decreasing as energy decreases
3) At low energy, or in the region where the net-baryon density is large, repulsive force is expected, v_1 slope is large and positive!
4) Softest point for baryons?

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

● STAR: PRL**112**, 162301(2014)
■ STAR: QM2015

BES v_2 and Model Comparison



At large μ_B, low collision energies, the number of quark scaling in v_2 is broken

(a) Hydro + Transport: Baryon results fit [J. Steinheimer, et al. PR **C86**, 44902(13)]

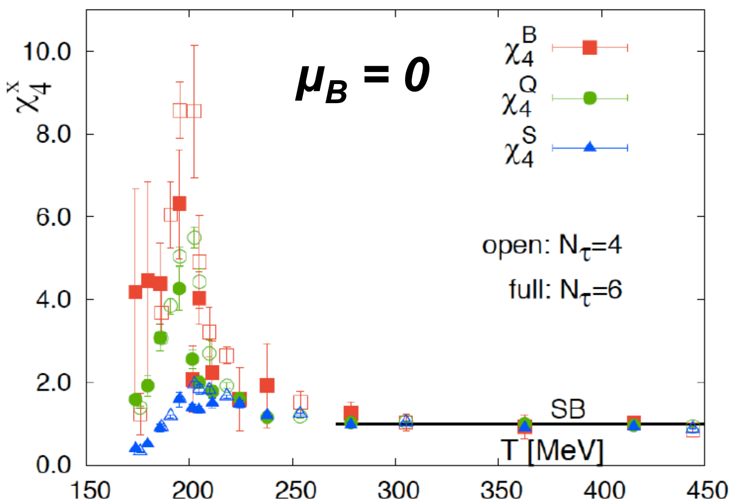
(b) NJL model: Sensitive to vector-coupling, **CME, μ_B** driven.

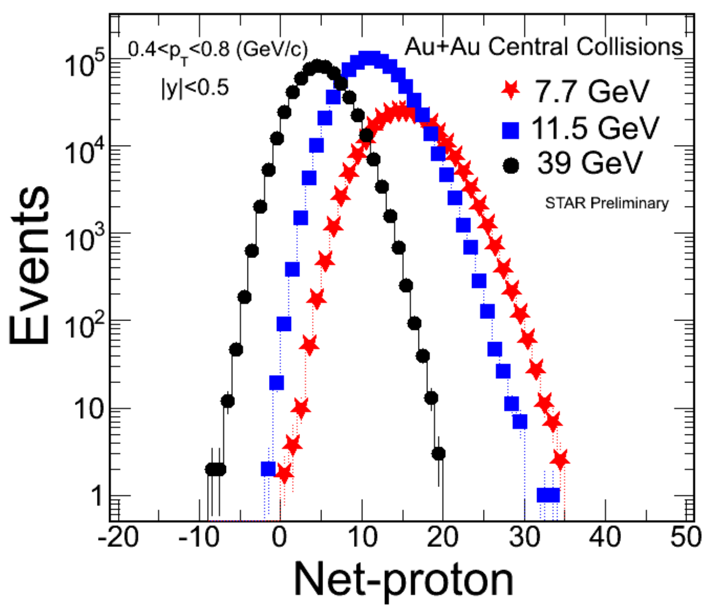
[J. Xu, et al., PRL**112**.012301(14)]

(c) Hydro solution: **Chemical potential μ_B** and **viscosity η/s** driven!

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

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:

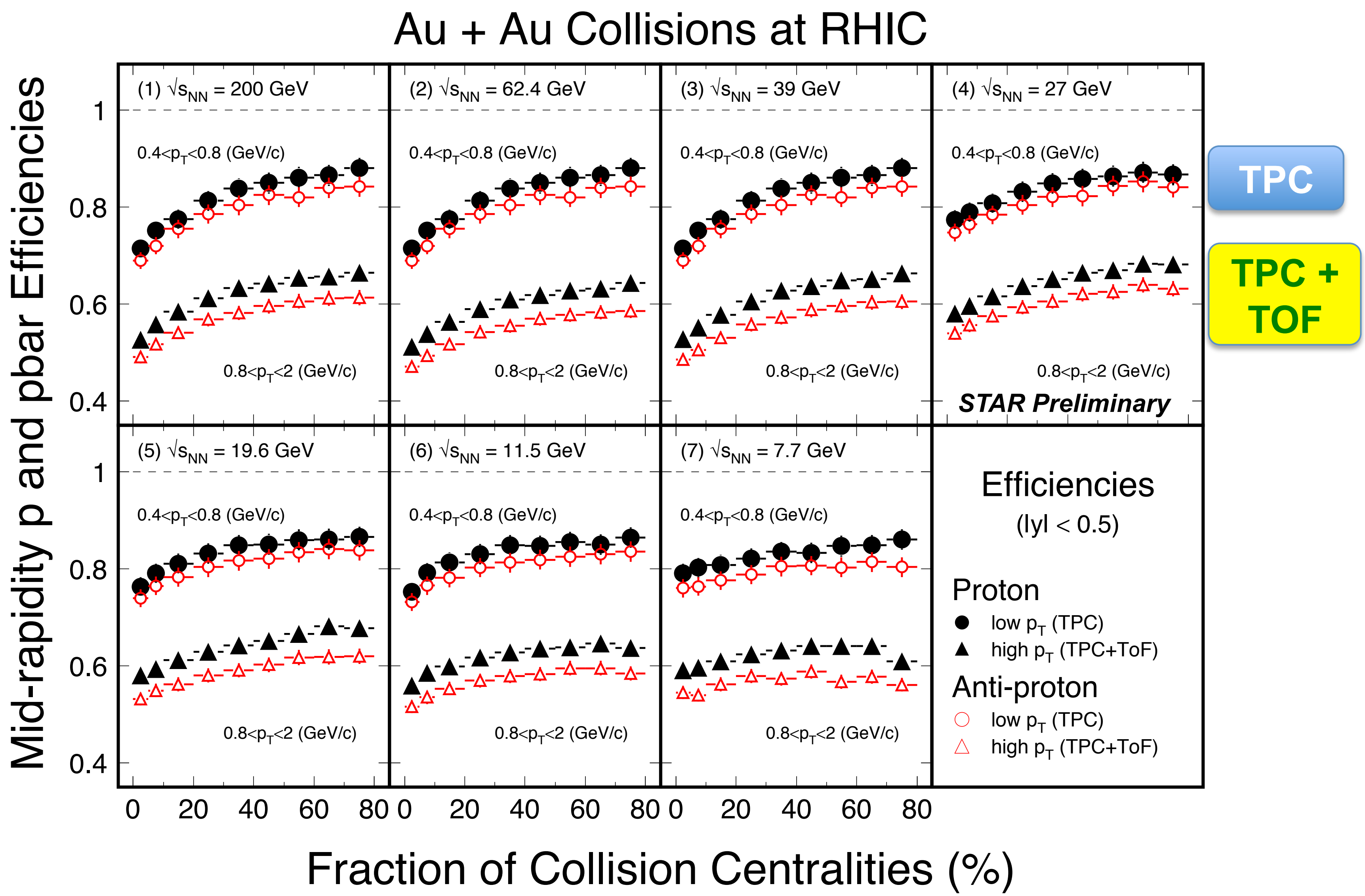
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

References:

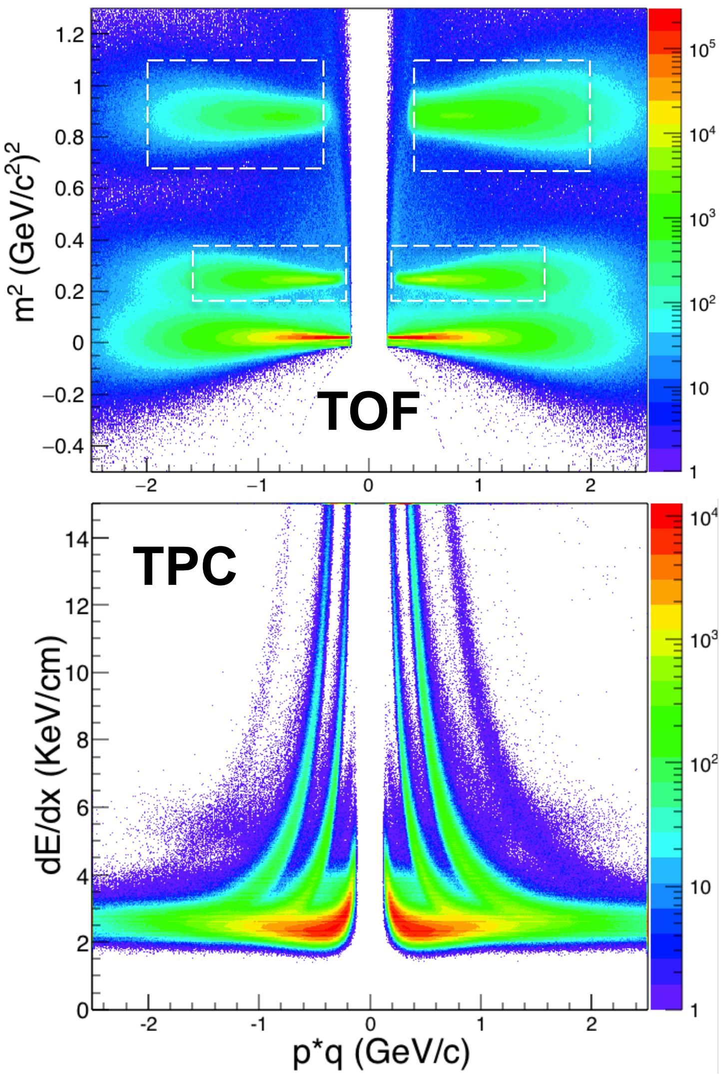
- STAR: *PRL* **105**, 22303(10); *ibid*, **112**, 032302(14)
- S. Ejiri, F. Karsch, K. Redlich, *PLB633*, 275(06) // M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB696*, 459(11) // F. Karsch et al, *PLB695*, 136(11),
- A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al.,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

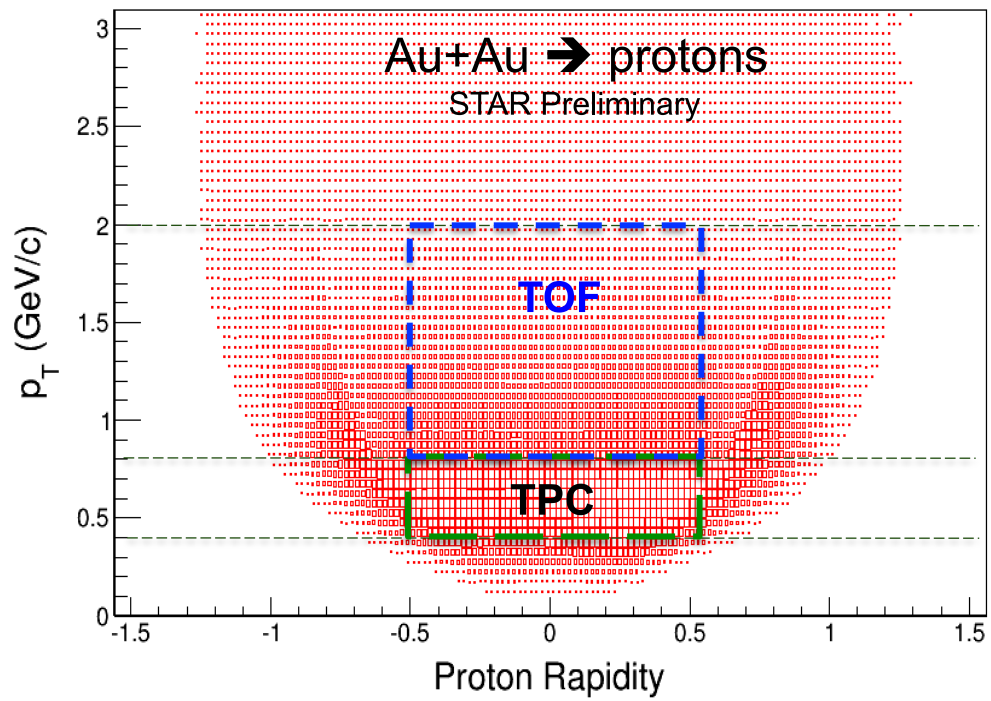
Efficiencies for Protons and Anti-protons



Proton Identification with TOF

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





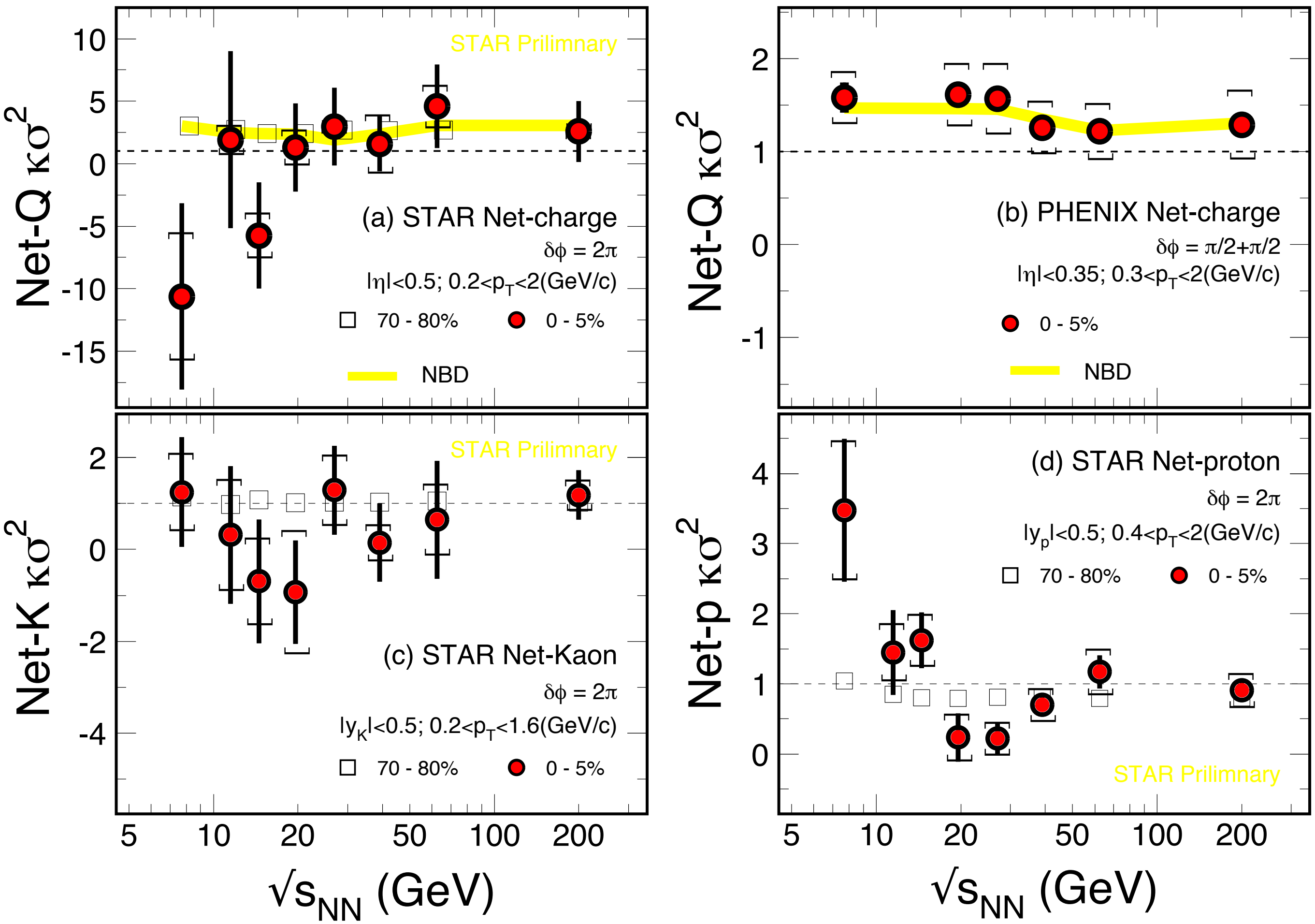
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

Efficiency corrections:

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

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

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



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

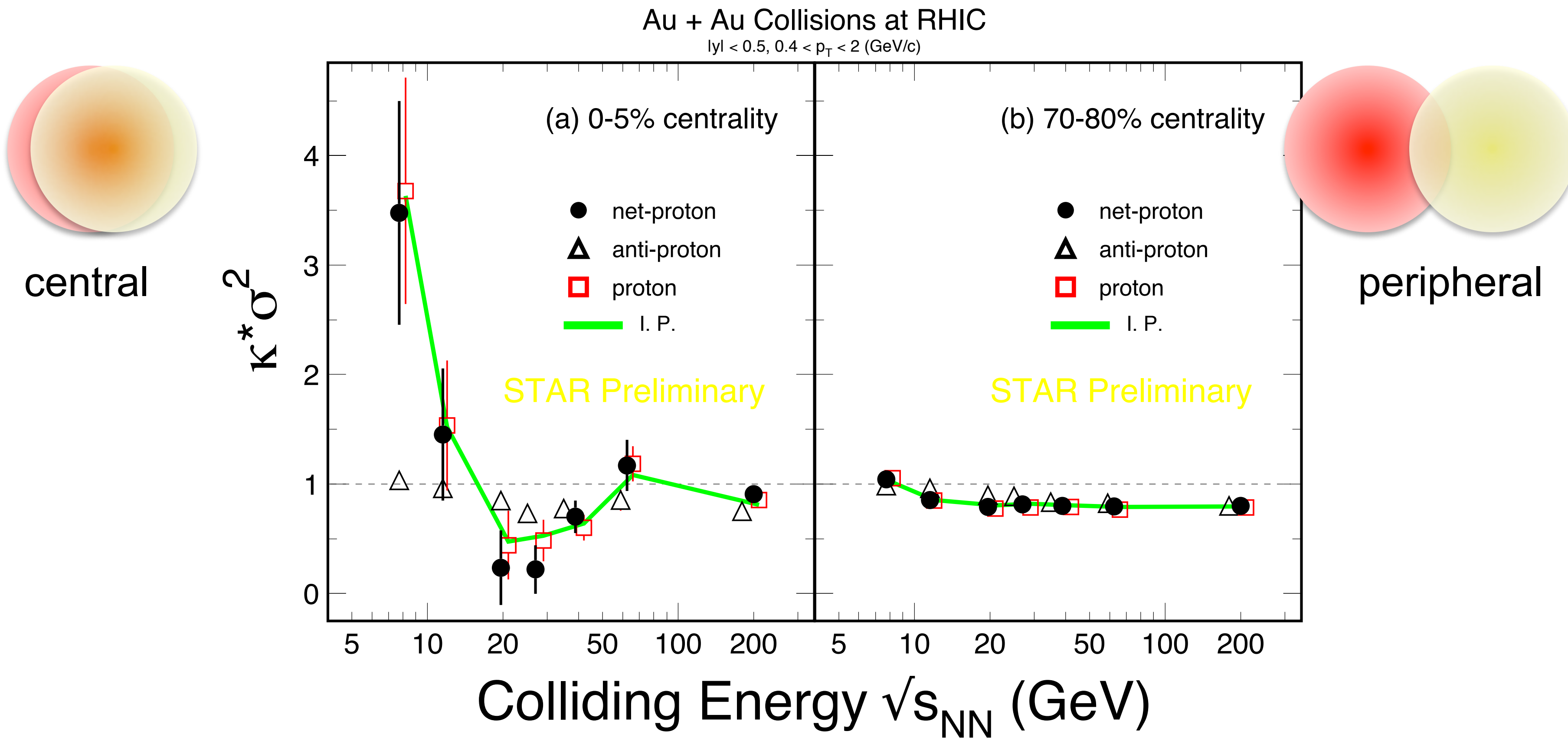
In STAR:

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!

PHENIX: talk by P. Garg at QM2015; STAR: talk by J. Thäder and poster by J. Xu at QM2015

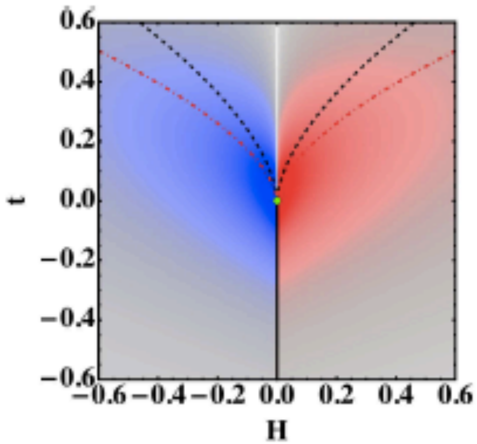
Net-proton Higher Moment

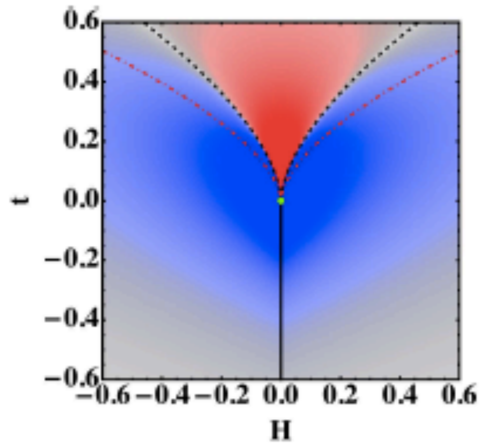


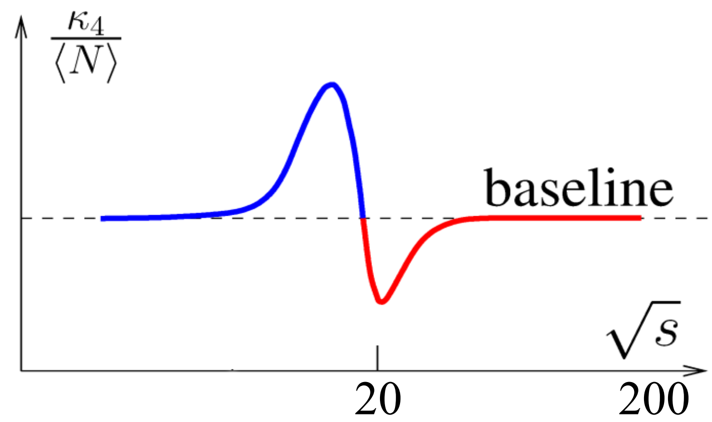
1) Flat energy dependence for 70-80% peripheral collisions
2) Non-monotonic behavior in the most central 0-5%, and 5-10% collisions. Net-p follow protons, especially at lower collision energies.
3) In the central 0-5% collisions, $\kappa\sigma^2 > 0$ at $\sqrt{s_{NN}}$ = 62.4, 11.5 and 7.7 GeV with a minimum at $\sqrt{s_{NN}} \sim 20$ GeV

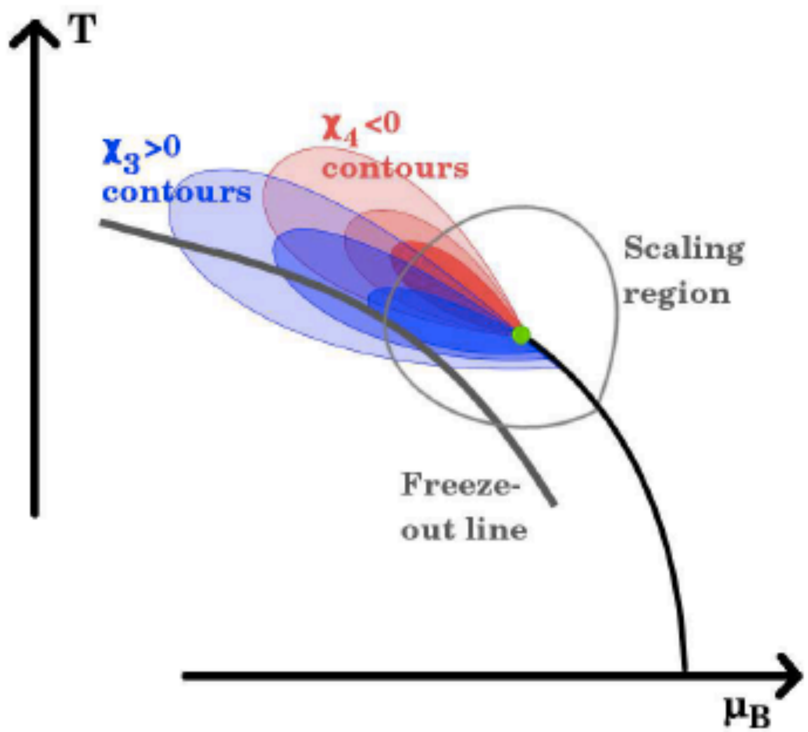
X.F. Luo, CPOD2014, QM2015

Expectation from Calculations





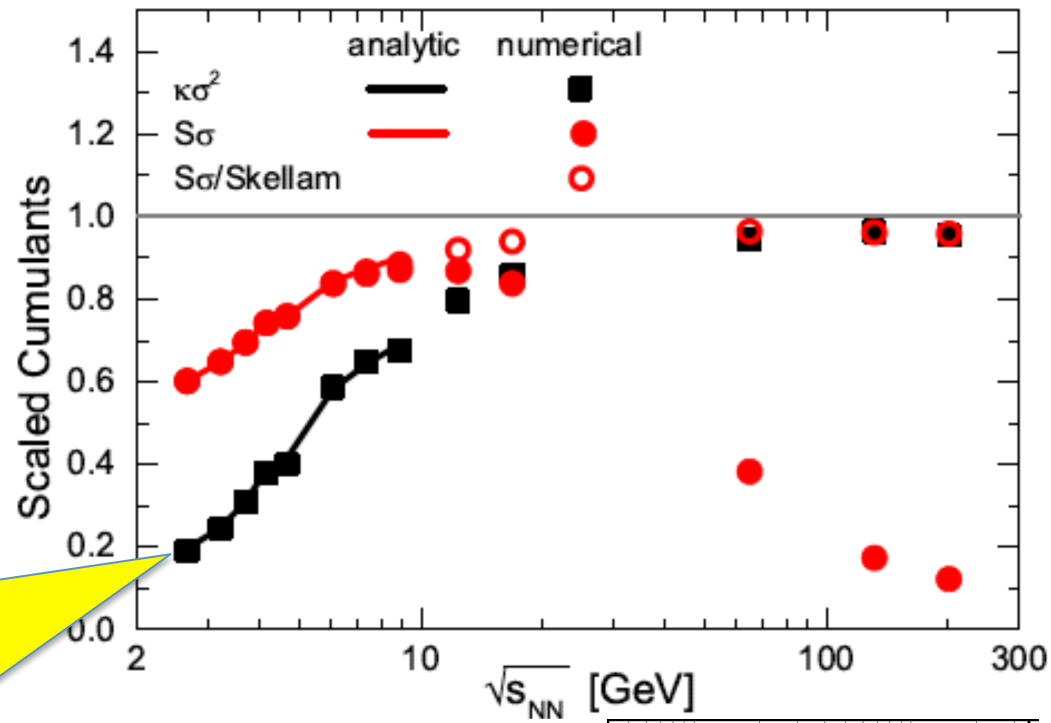




Characteristic "Oscillating pattern" is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*

- 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

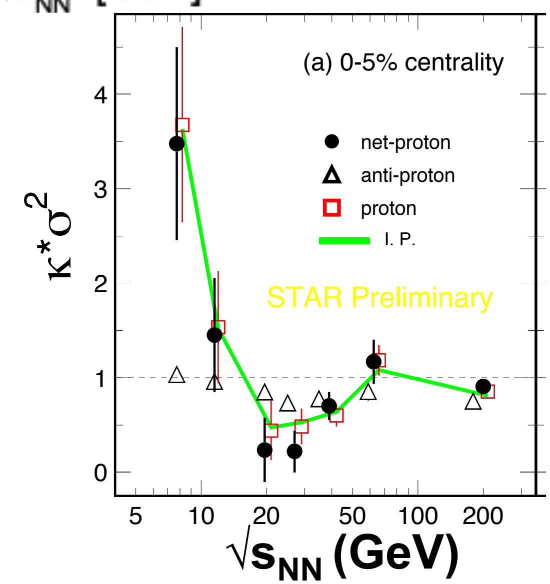
Model Simulation Results



At $\sqrt{s_{NN}} \leq 10$ GeV:

- Data: **$\kappa\sigma^2 > 1$!**
- Model: **$\kappa\sigma^2 < 1$!**
  - Baryon conservations
  - Mean-field
  - Deuteron productions

  All suppress higher order net-proton fluctuations

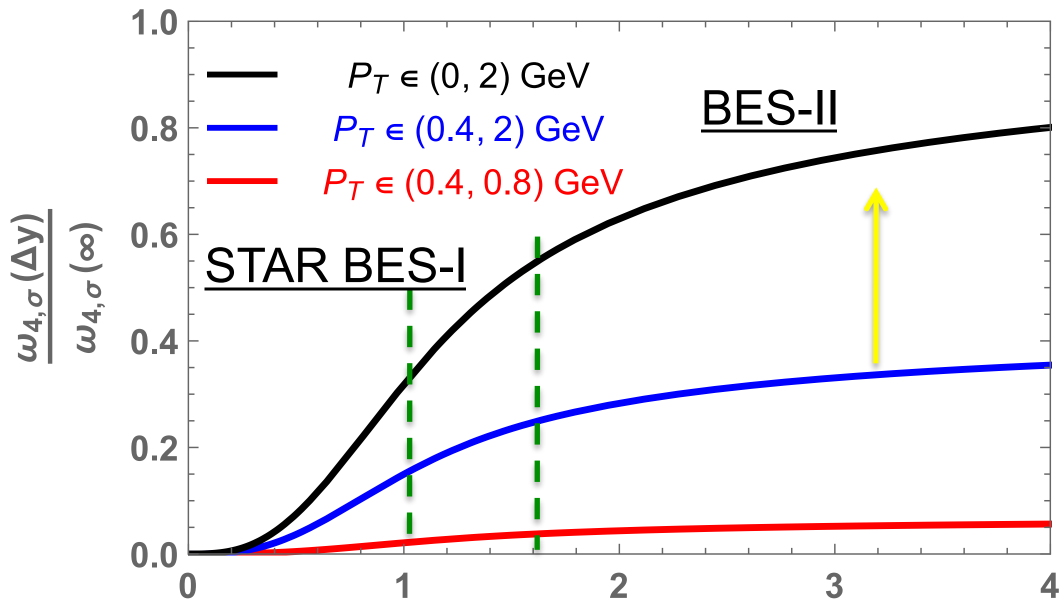


1) Z. Feckova, J. Steonheimer, B. Tomasik, M. Bleicher, 1510.05519, PR**C92**, 064908(15)
2) X.F. Luo *et al*, NP **A931**, 808(14)
3) P.K. Netrakanti *et al.* 1405.4617, NP **A947**, 248(16)
4) P. Garg *et al.* Phys. Lett. **B726**, 691(13)

5) Baryon mean-field effect (repulsive): also suppression in JEM.

Acceptance Matters

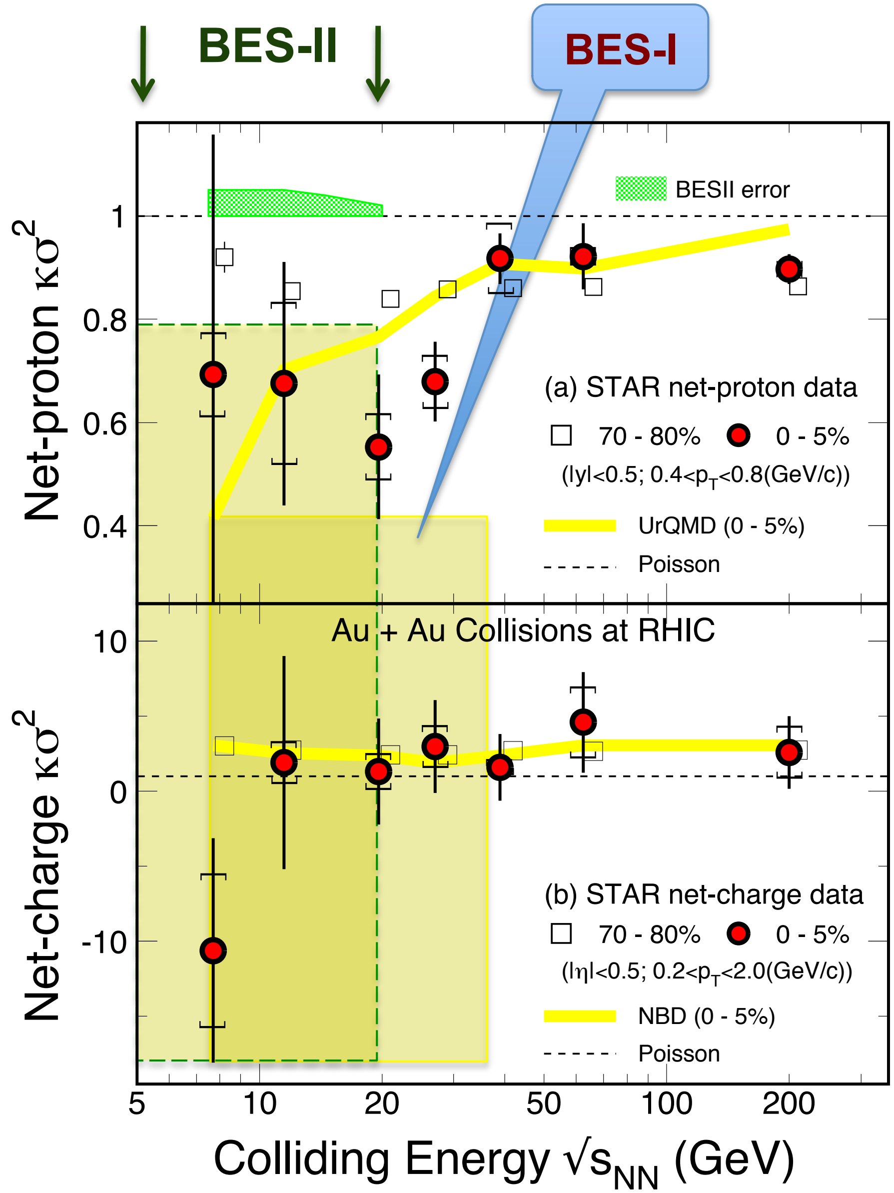
B. Ling, M. Stephanov, 1512.09125, Phys. Rev. **C93**, 034915(2016)

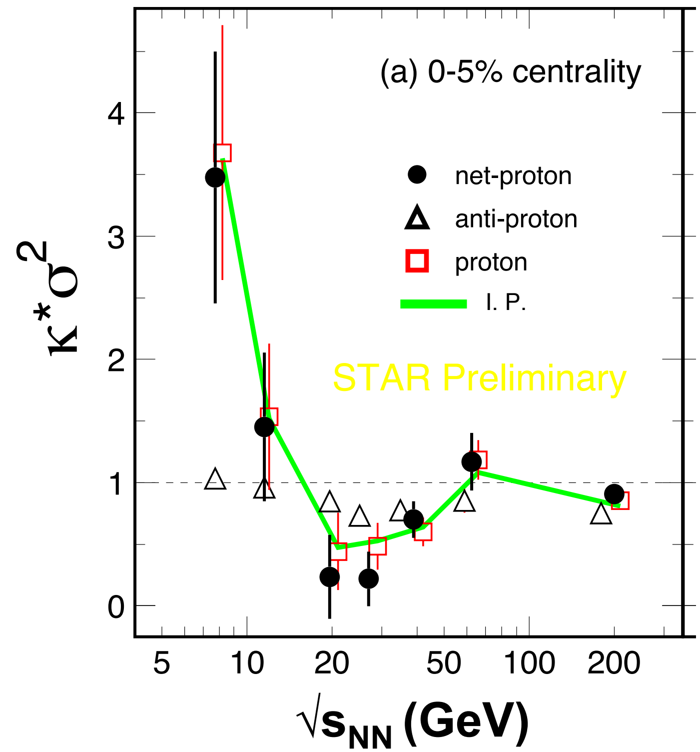


$$\kappa_4[M] = \underbrace{\langle M \rangle}_{\text{Poisson}} + \kappa_4[\sigma_V] \times g^4 \underbrace{\left(\bigcirc \right)^4}_{\sim M^4} + \ldots \propto \begin{cases} M^4 & \textbf{Critical} \\ \langle M \rangle & \text{Non-critical} \end{cases}$$

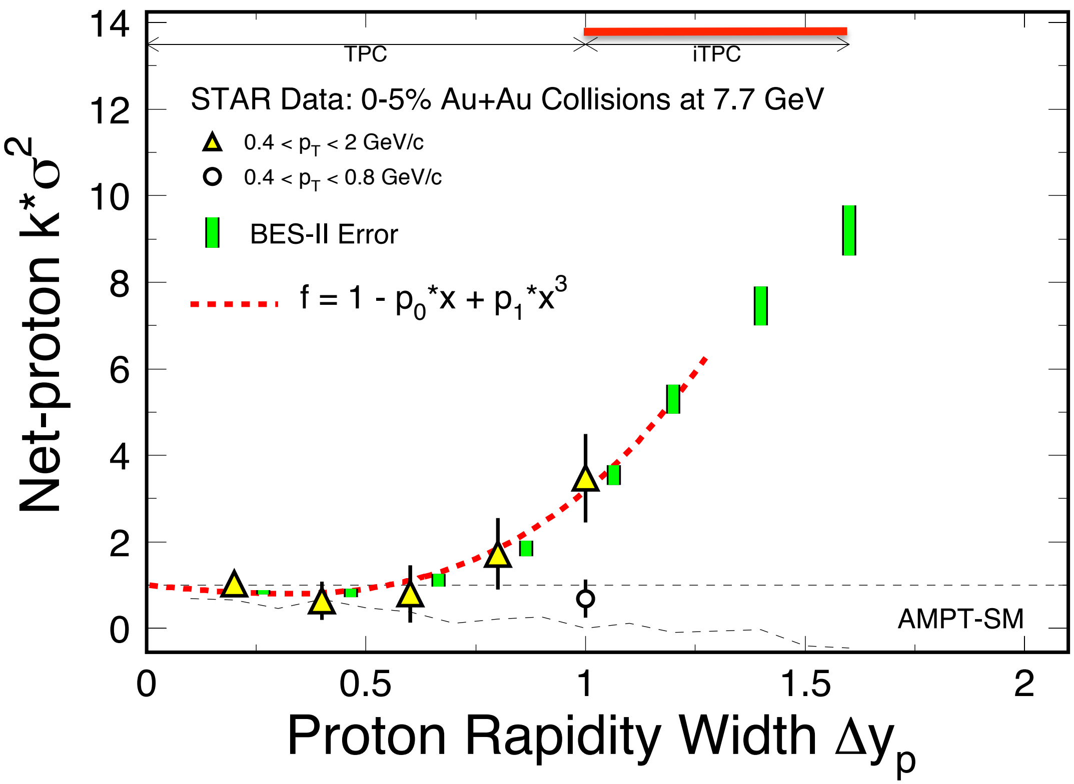
1) Acceptance is important!
2) Low p_T of protons is more important than wider rapidity.
   Fixed-target experiment is more advantageous

Higher Moments Results





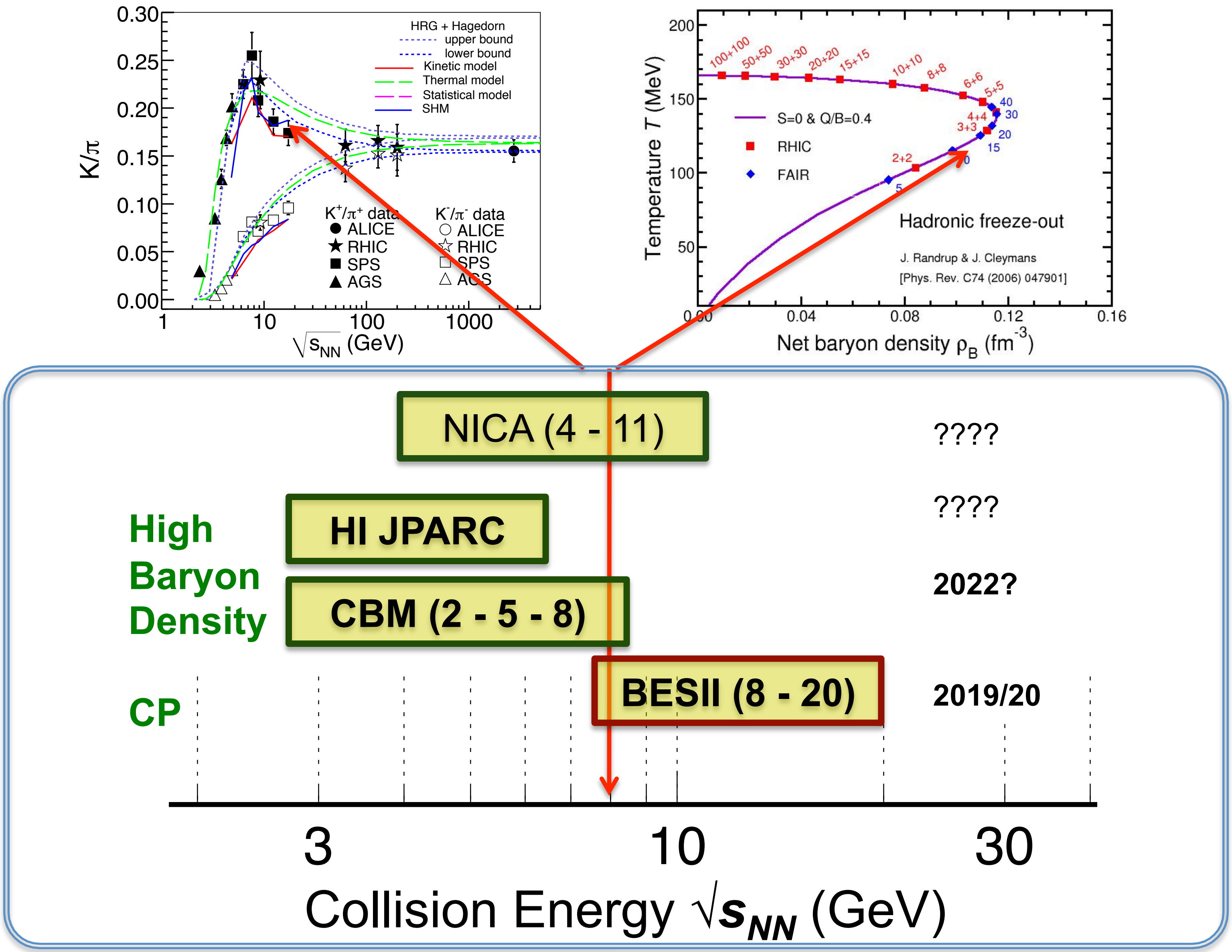
BES-II: Larger Acceptance



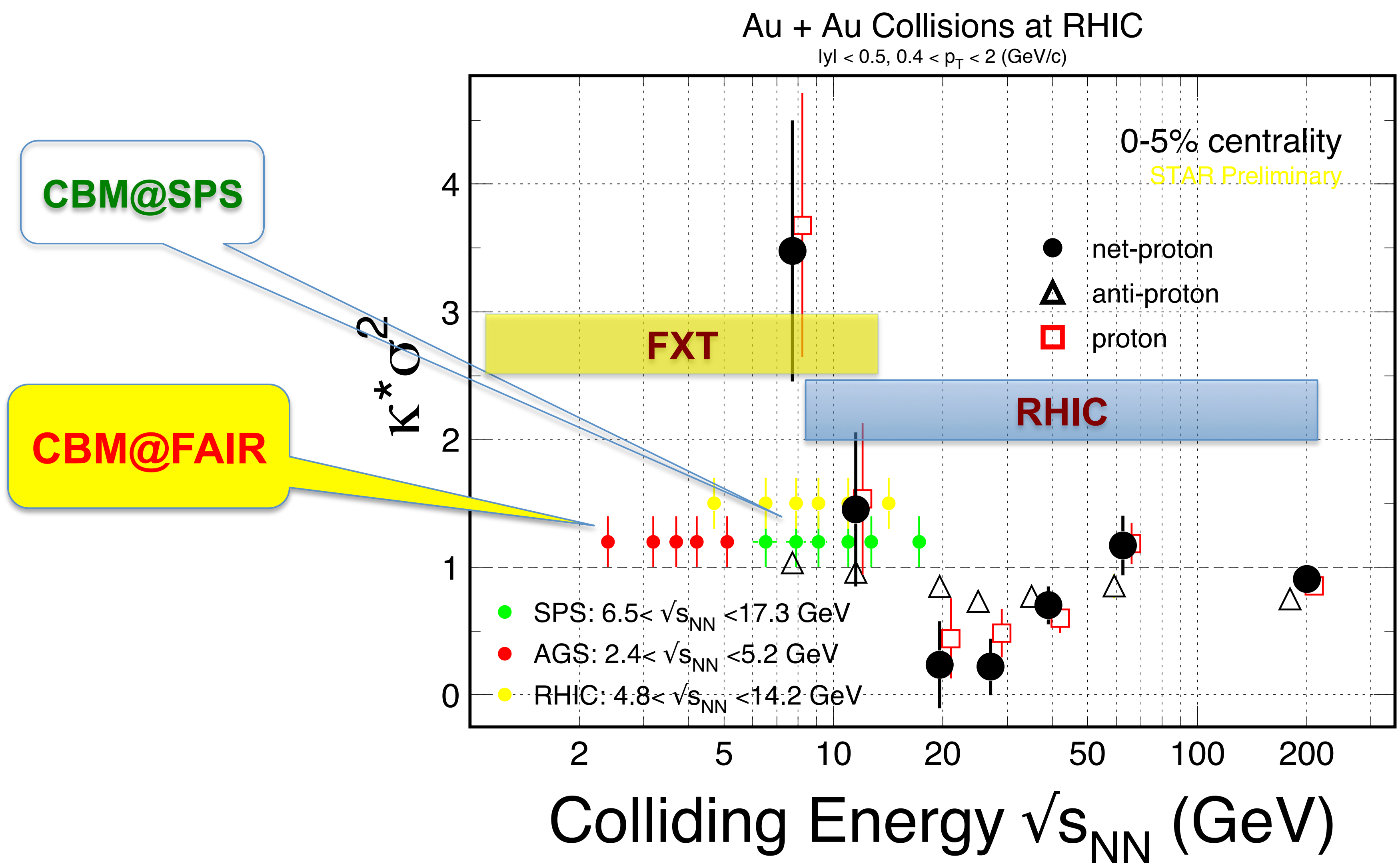
1) BES-I results: Poisson + Baryon conservation + v^3, criticality?

2) BES-II: iTPC extend the rapidity coverage to Δy = 1.6, allowing to studying kinematic dependence and precision measurement of higher moments

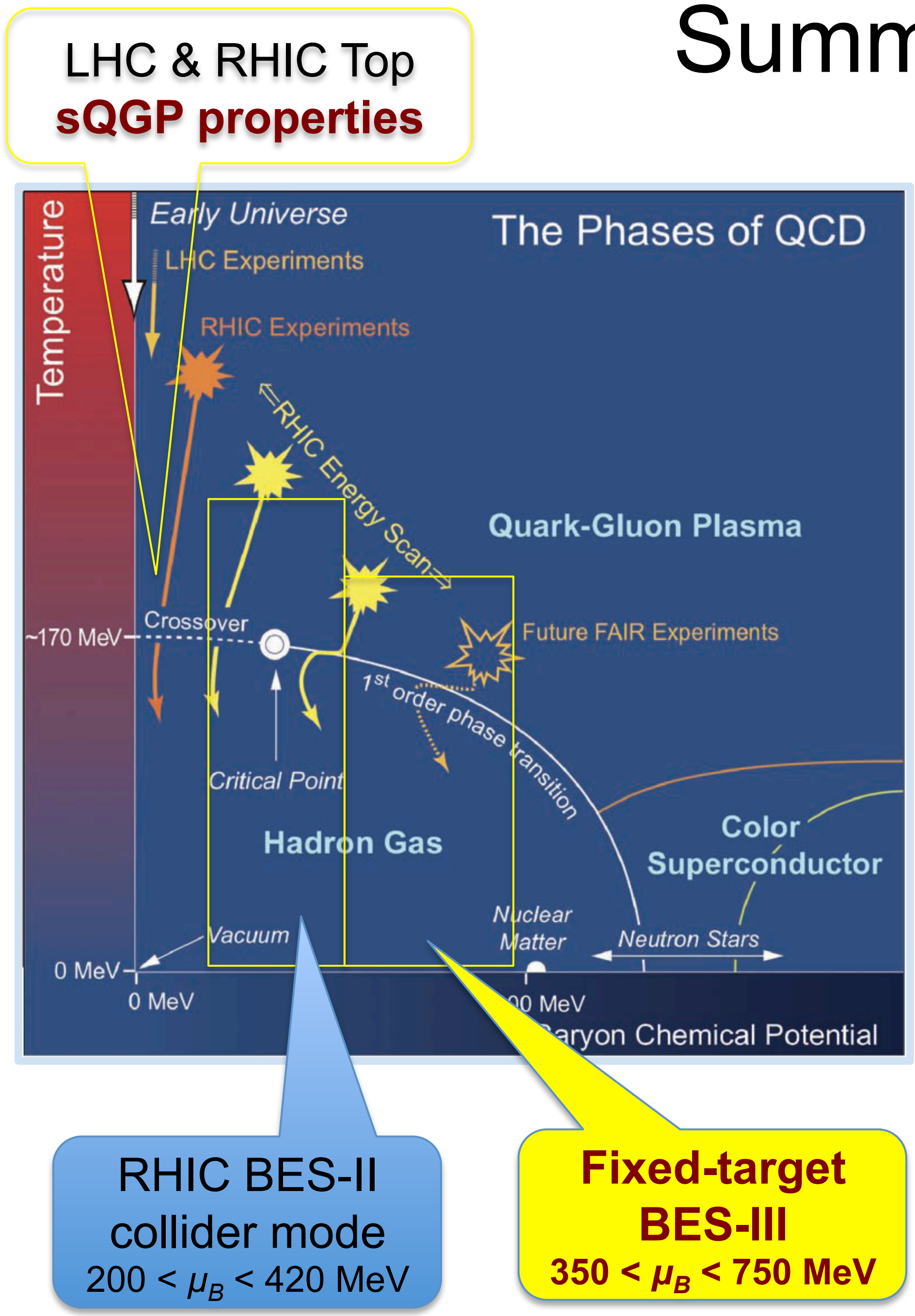
Baryon Density



BES-III: Fix-Target Experiments



Summary and Outlook



BES-I at RHIC:

Non-monotonic energy dependence

Power-law behavior: v^3 for $k*\sigma^2$

BES-II at RHIC: (200 < μ_B < 420 MeV)

- Larger acceptance in rapidity
- Larger statistics
- Better understanding of systematics

Possible new discovers are:

- QCD critical point (*partial*)
- Chiral effects: CVE, CME, …
- The ϕ-meson v_2

Longer Future: fixed-target experiment (FXT) at extreme large net-baryon density, 350 < μ_B < 750 MeV (8 < $\sqrt{s_{NN}}$ < 2 GeV)

FXT, the **Beam Energy Scan Three** needed for

QCD Critical Point!

Many Thanks to the CPOD2016 Organizers

Best Wishes to K!