"BEST 2016" – Topical Workshop on Beam Energy Scan [https://indico.cern.ch/event/487447/]
Indiana University Bloomington, May 9 - 11, 2016

Study the QCD Phase Structure in High-Energy Nuclear Collisions

- Experimental Overview on Bulk Properties and the Search for Critical Point at BES

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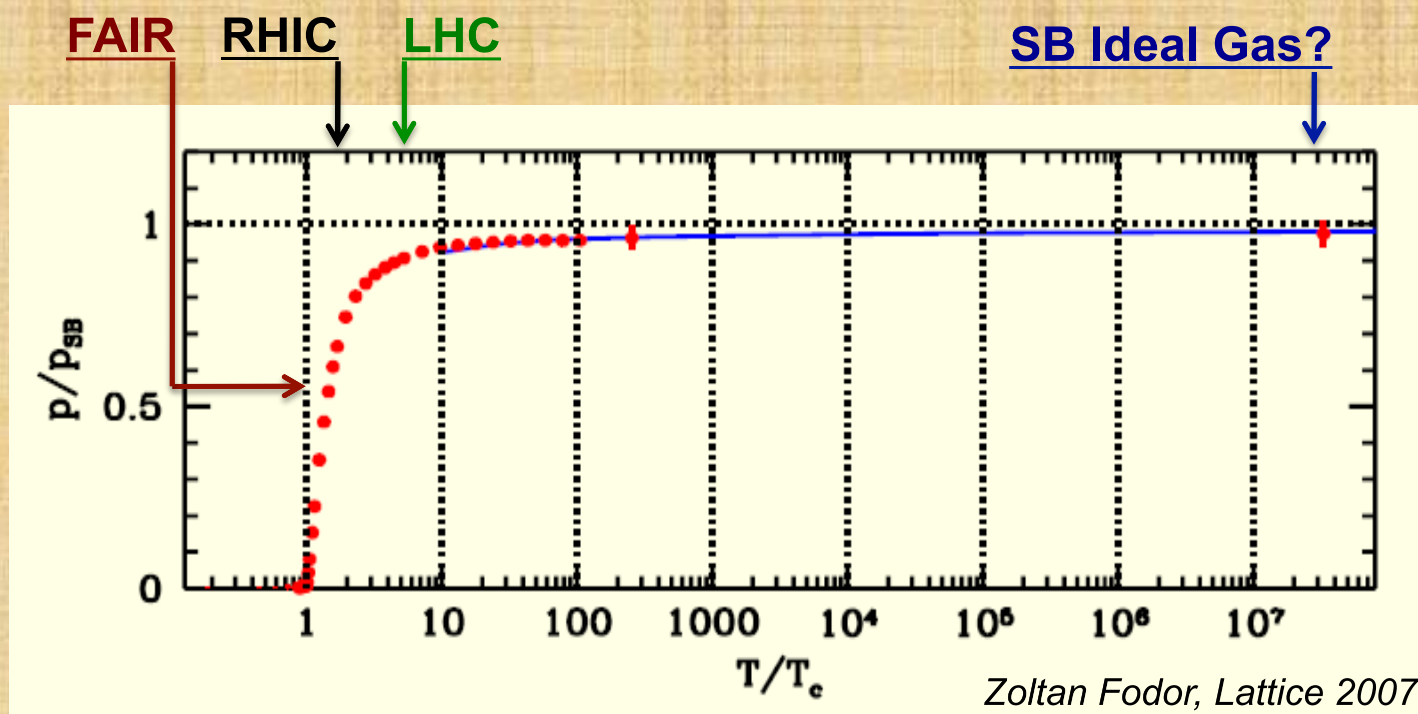
QCD Thermodynamics



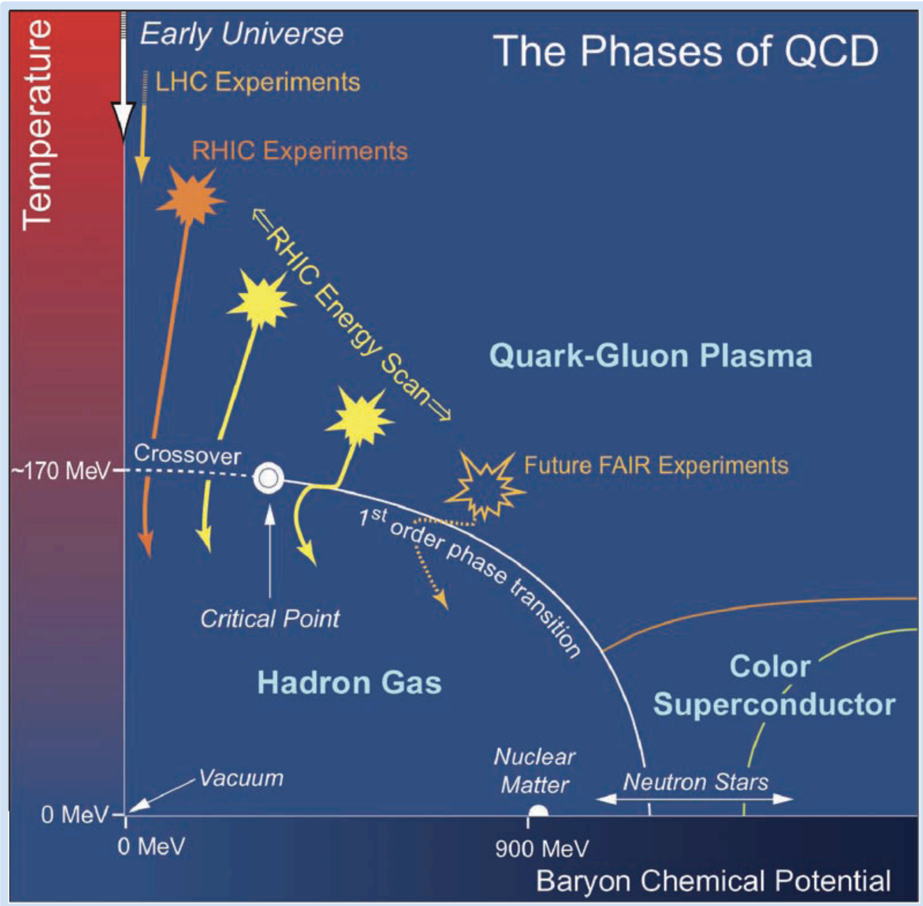
1) At $\mu_B = 0$: cross over transition, $140 < T_c < 160$ MeV

2) T_{ini}(LHC) ~ 2-3*T_{ini}(RHIC)

3) Thermalized: evolutions are similar for RHIC and LHC

4) RHIC **BES** & FAIR **CBM**: large μ_B, EOS changes rapidly

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 at AGS/FAIR

Outline

(1) Introduction

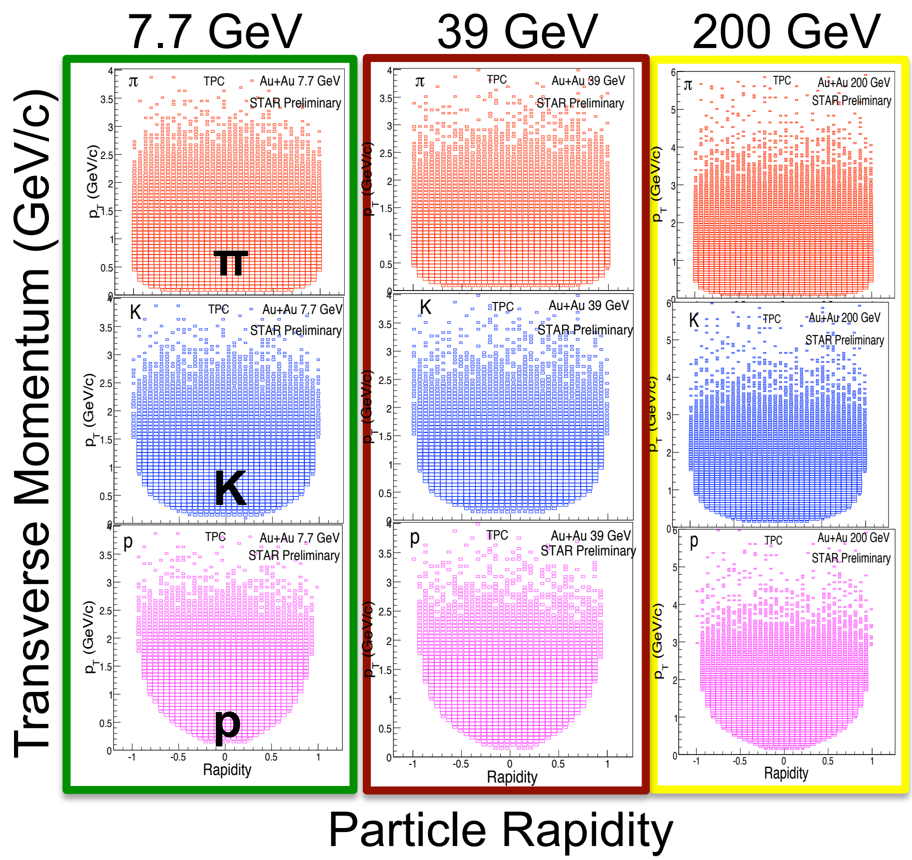
(2) Recent Results from BES-I

1) Collectivity; 2) Criticality; 3) Chirality

(3) Physics Programs in BES-II and Beyond

Data Sets at STAR

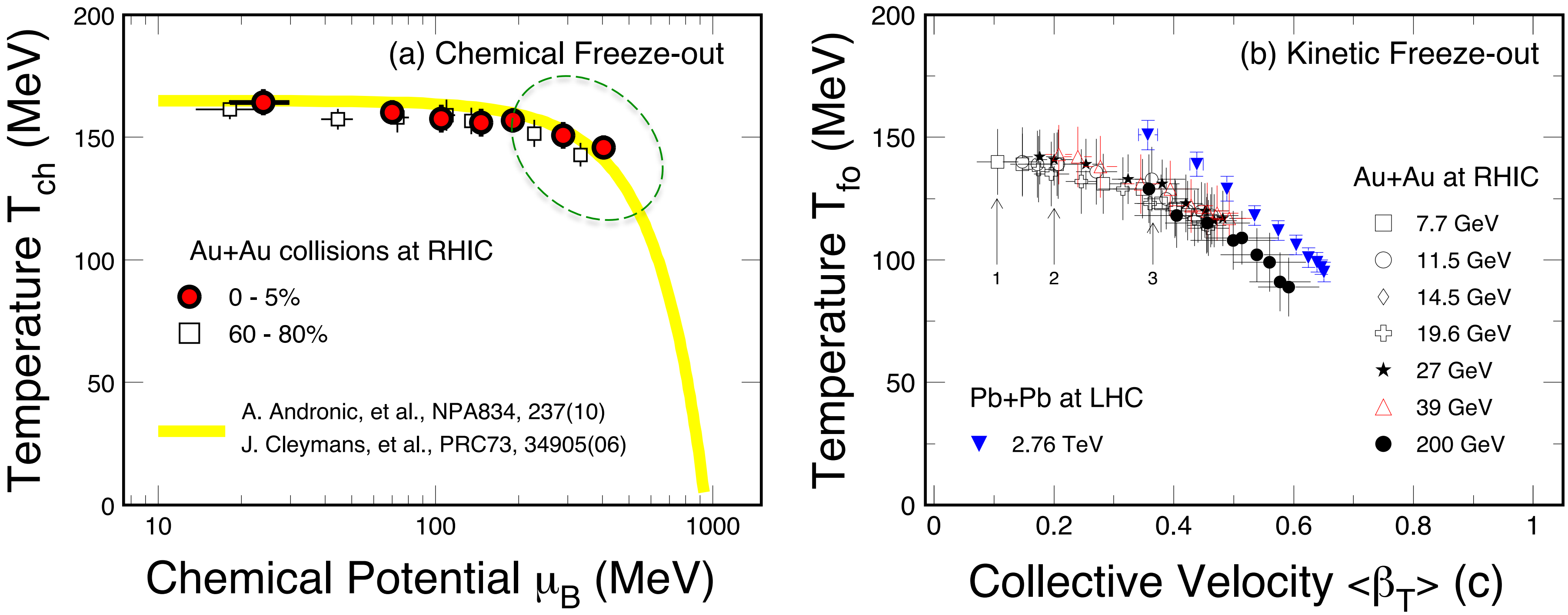
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	*μ_B (MeV)	*T_{CH} (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
39	39	2010	112	164
27	70	2011	156	162
19.6	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	316	152
7.7	4	2010	422	140



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

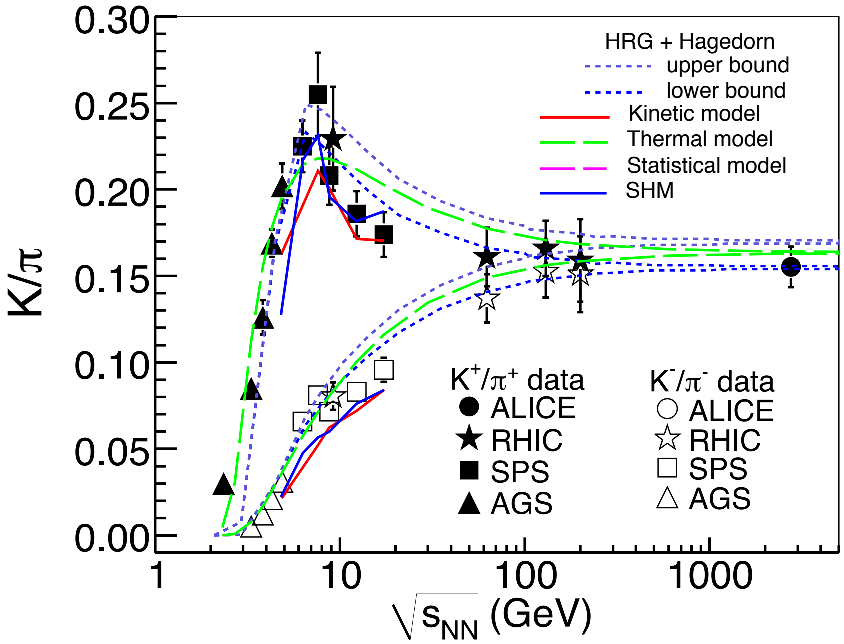


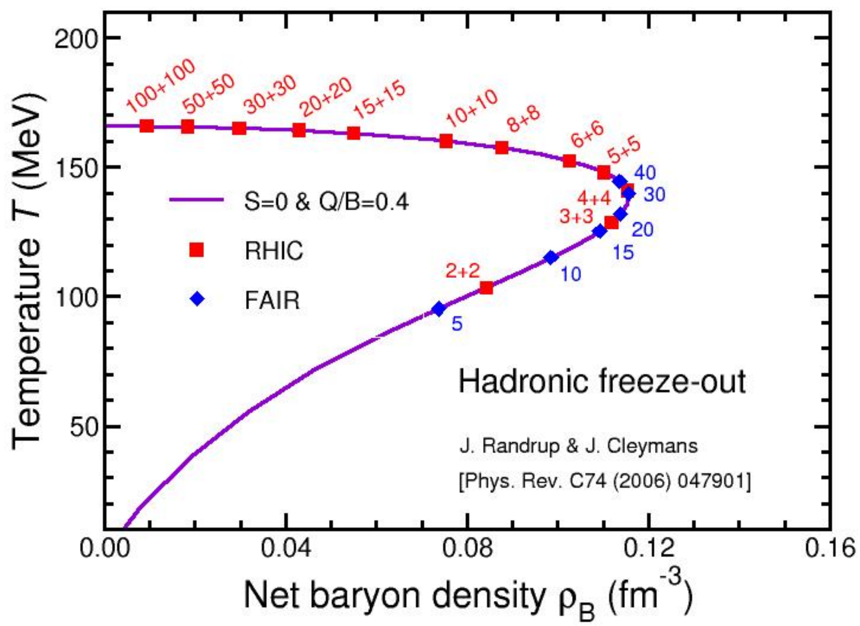
Chemical Freeze-out: (GCE)
- Weak temperature dependence
- Centrality dependence μ_B!
- Lattice prediction on CP around μ_B ~ 300 – 400 MeV

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

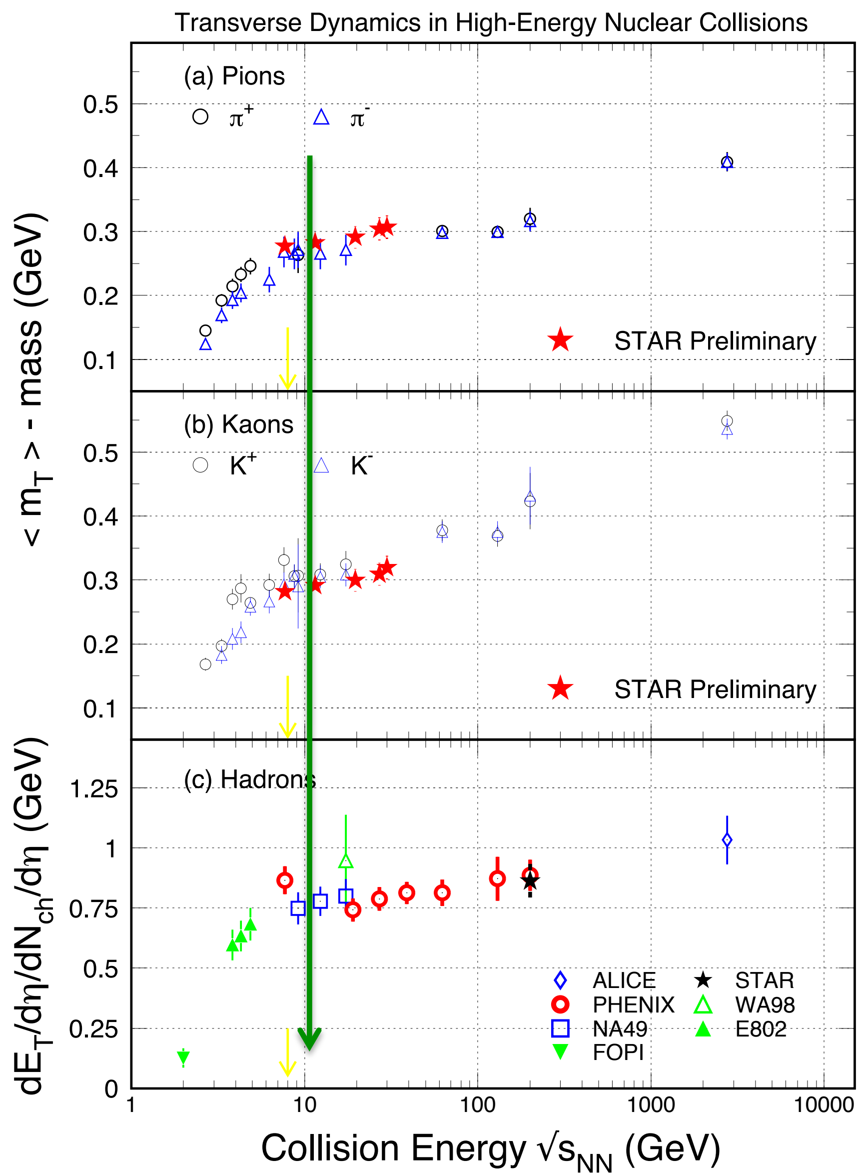




1) In heavy ion collisions **K^+/π** ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV, **K^-/π** ratio merges with **K^+/π** at higher collision energy
2) Model: Baryon density peaks at $\sqrt{s_{NN}}$ ~ 8 GeV
3) At $\sqrt{s_{NN}}$ **>** 8 GeV, pair production becomes important

L. Kumar, *et al.*1304.2969

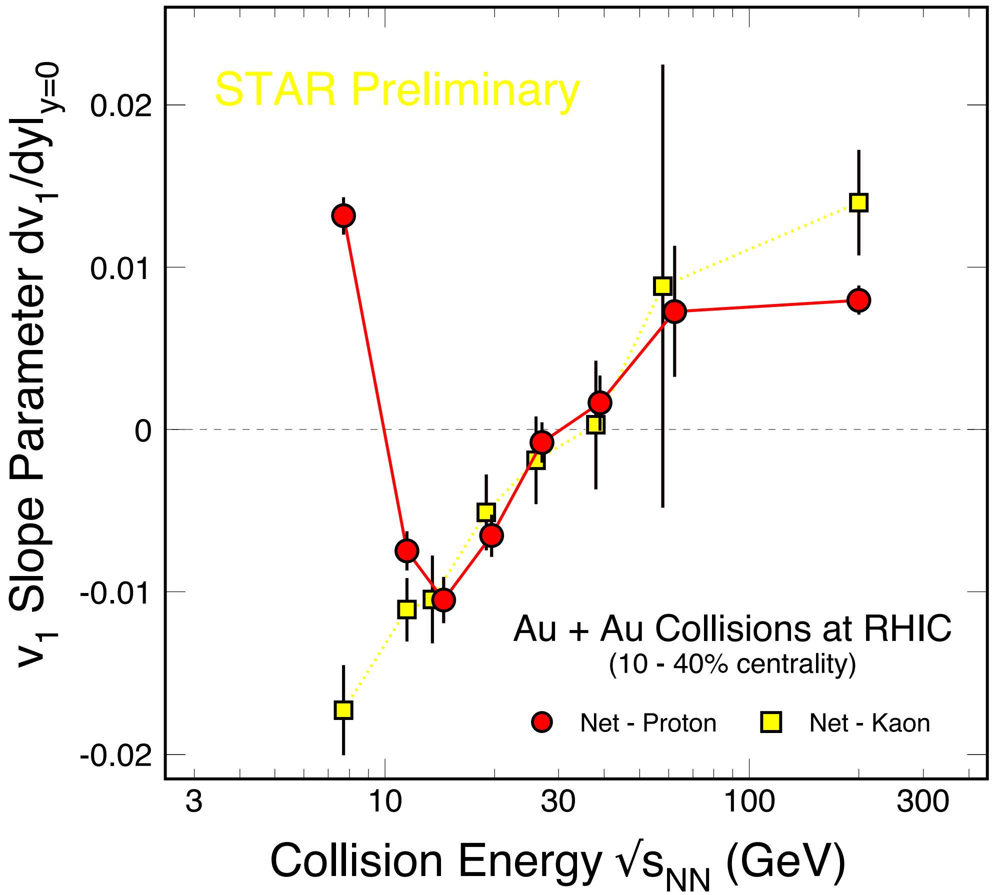
Transverse Energy per Particle



Transverse energy per particle increases versus collision energy, but a plateau appears at $\sqrt{s_{NN}}$ **~ 8-10 GeV!**

EOS change around 10 GeV?

Directed Flow v_1 Results



- STAR: PRL**112**, 162301(2014)
- STAR: QM2015

1) Mid-rapidity net-proton dv_1/dy published in 2014 by STAR, except the point at 14.5 GeV

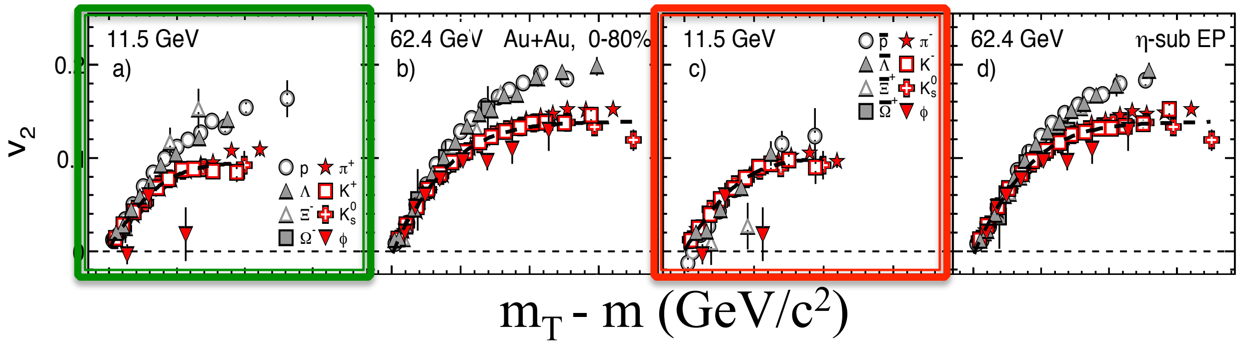
2) Minimum at $\sqrt{s_{NN}}$ = 14.5 GeV for net-proton, but net-Kaon data continue decreasing as energy decreases

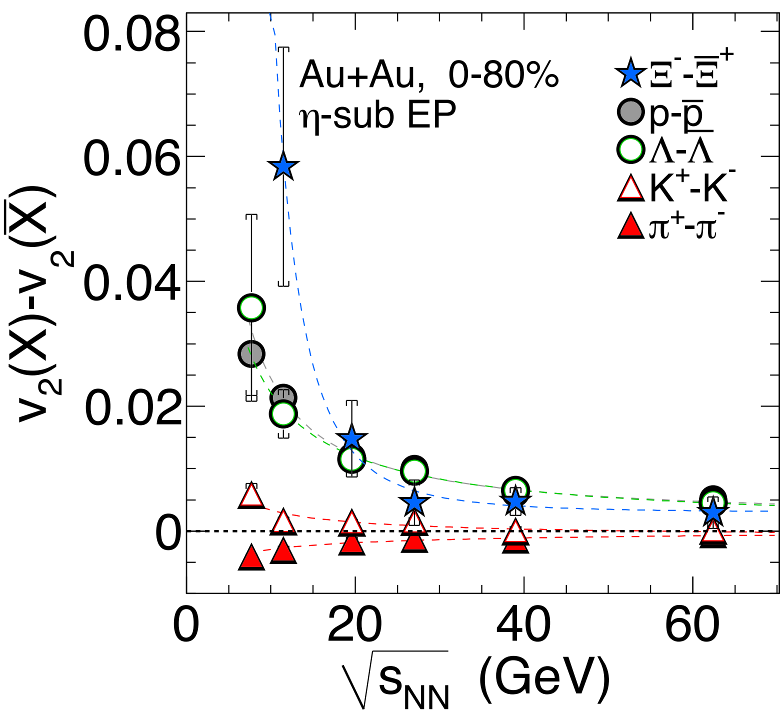
3) At low energy, or in the region where the net-baryon density is large, repulsive force is expected, v_1 slope is large and positive!

- M. Isse, A. Ohnishi et al, PR **C72**, 064908(05)

- Y. Nara, A. Ohnishi, H. Stoecker, arXiv: 1601.07692

Collectivity v_2 Measurements



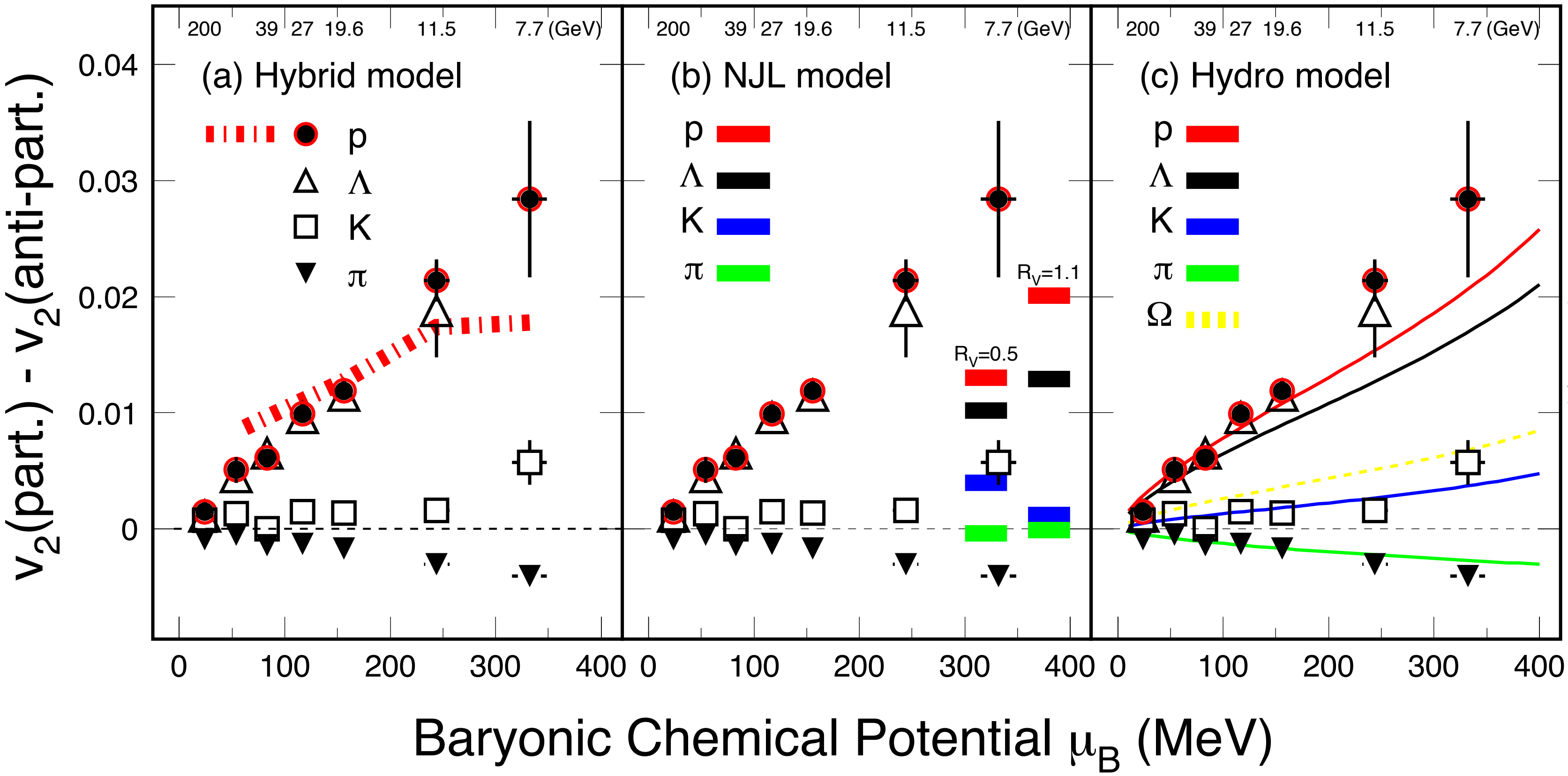


STAR: PR**110** (2013) 142301

1) Number of constituent quark (NCQ) **scaling** in v_2
=> **partonic collectivity**
=> ***deconfinement*** in high-energy nuclear collisions

2) At $\sqrt{s_{NN}}$ < 11.5 GeV, the universal **NCQ scaling in** v_2 **is broken,** consistent with hadronic interactions becoming dominant

BES v_2 and Model Comparison

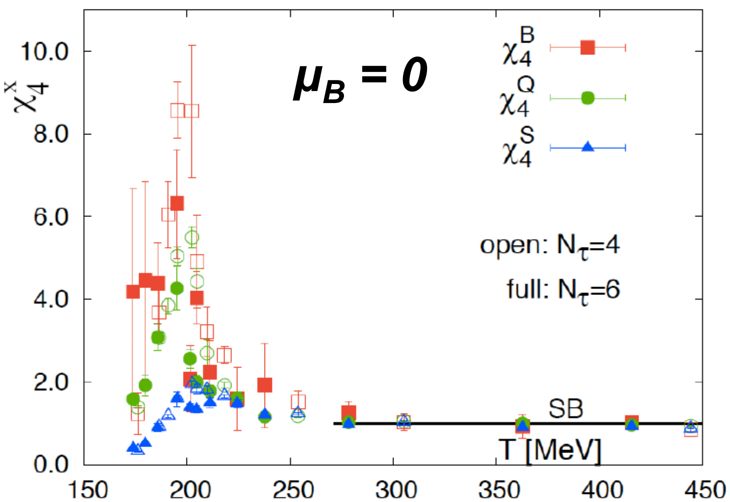


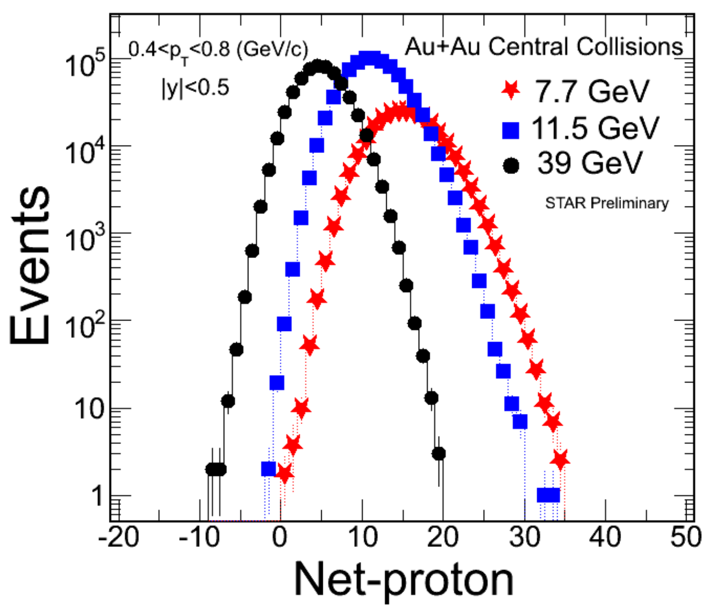
(a) Hydro + Transport: Baryon results fit [J. Steinheimer, et al. PR **C86**, 44902(13)]

(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





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:

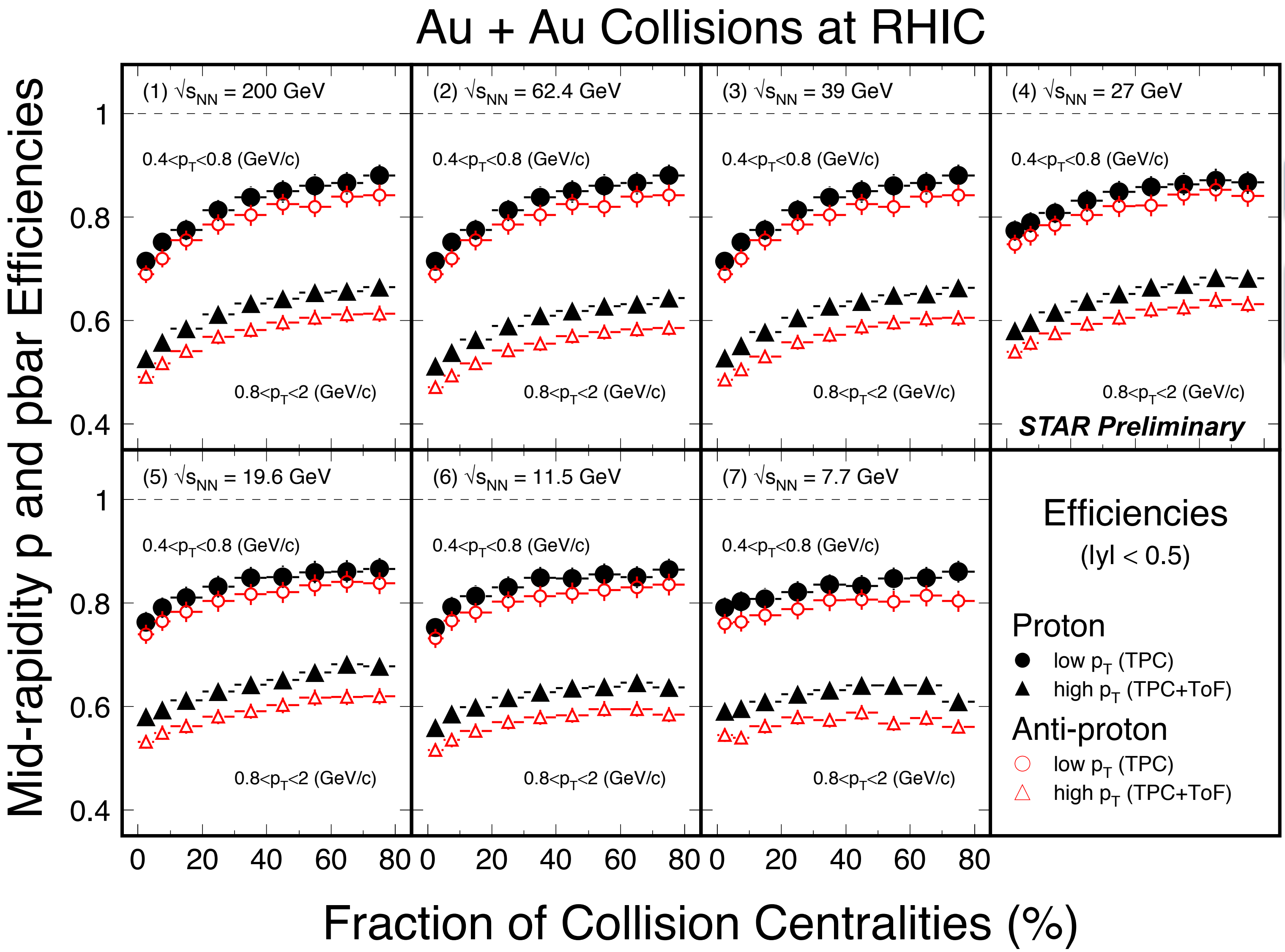
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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)

Efficiencies for Protons and Anti-protons

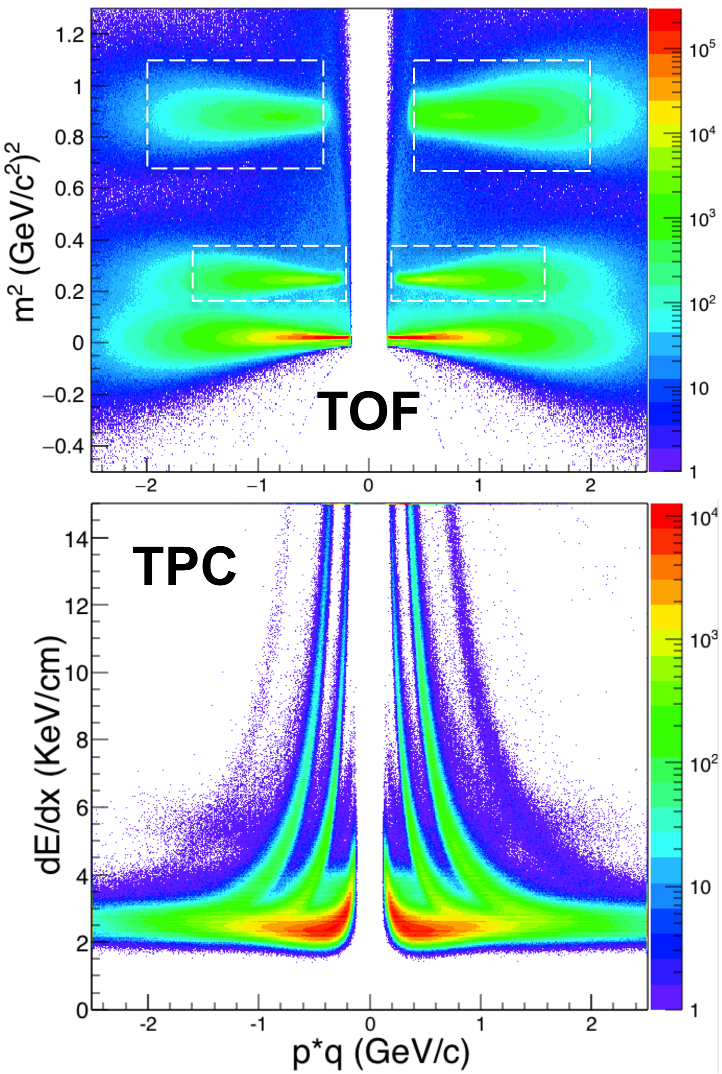


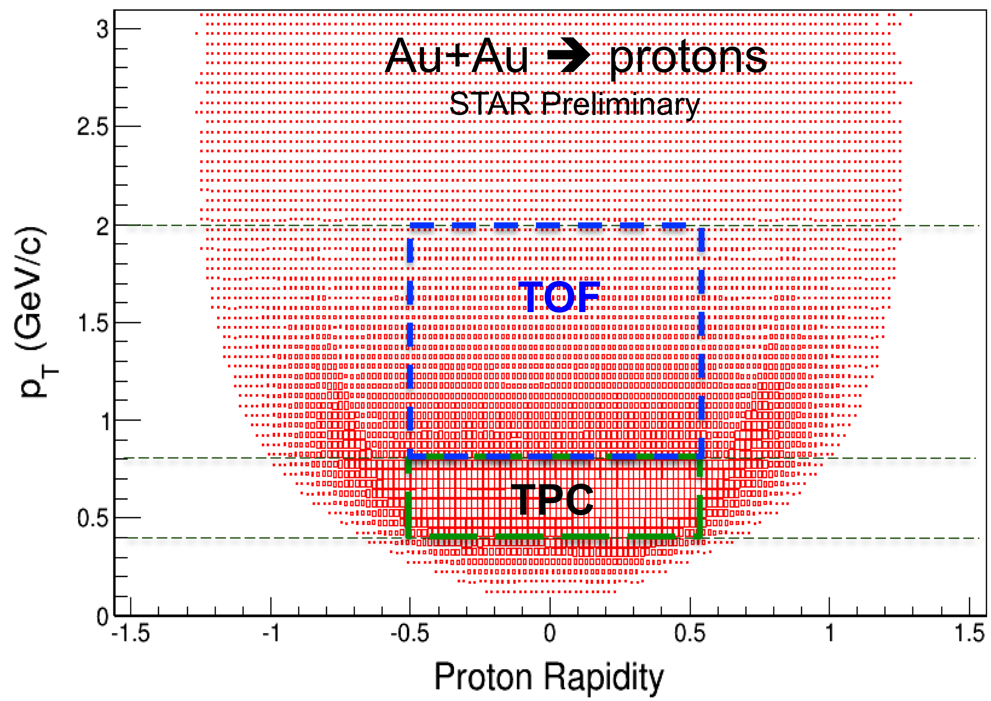
TPC

TPC + TOF

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

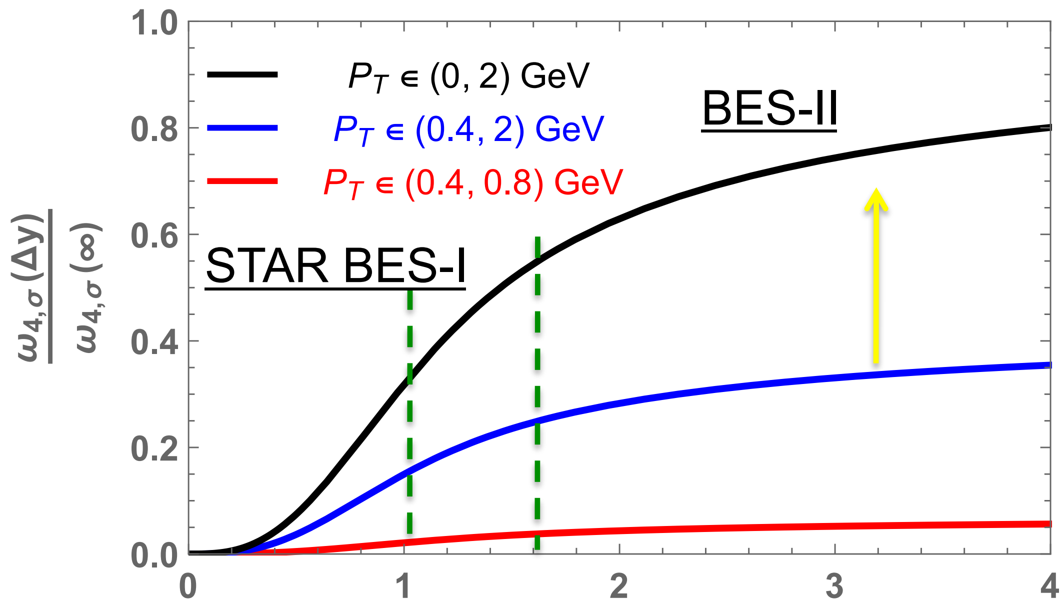
Efficiency corrections:

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): $\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$

Acceptance Matters

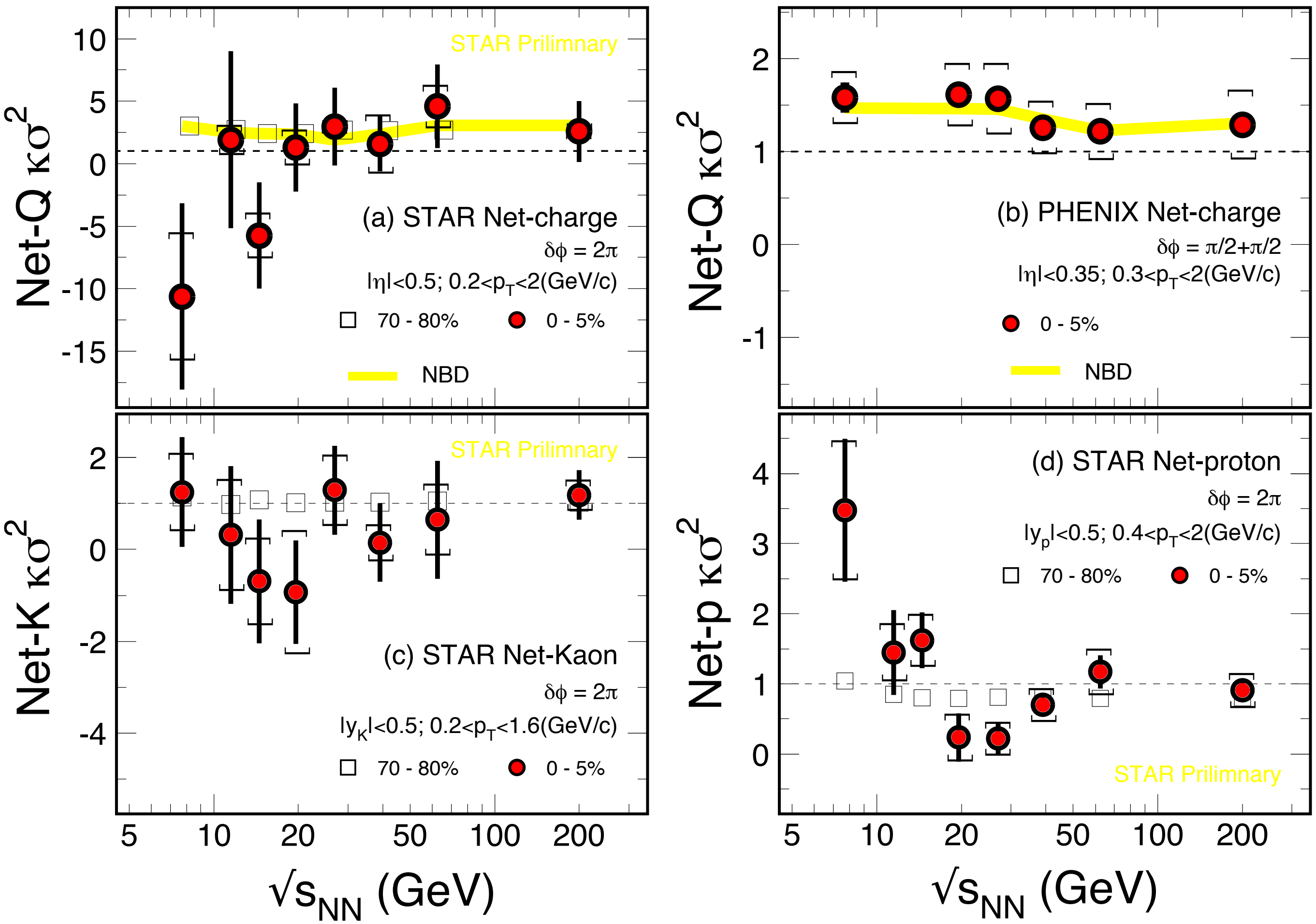
B. Ling, M. Stephanov, 1512.09125, Phys. Rev. **C93**, 034915(2016)



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

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

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



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

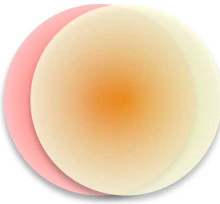
In STAR:

σ(Q) > σ(K) > σ(p)

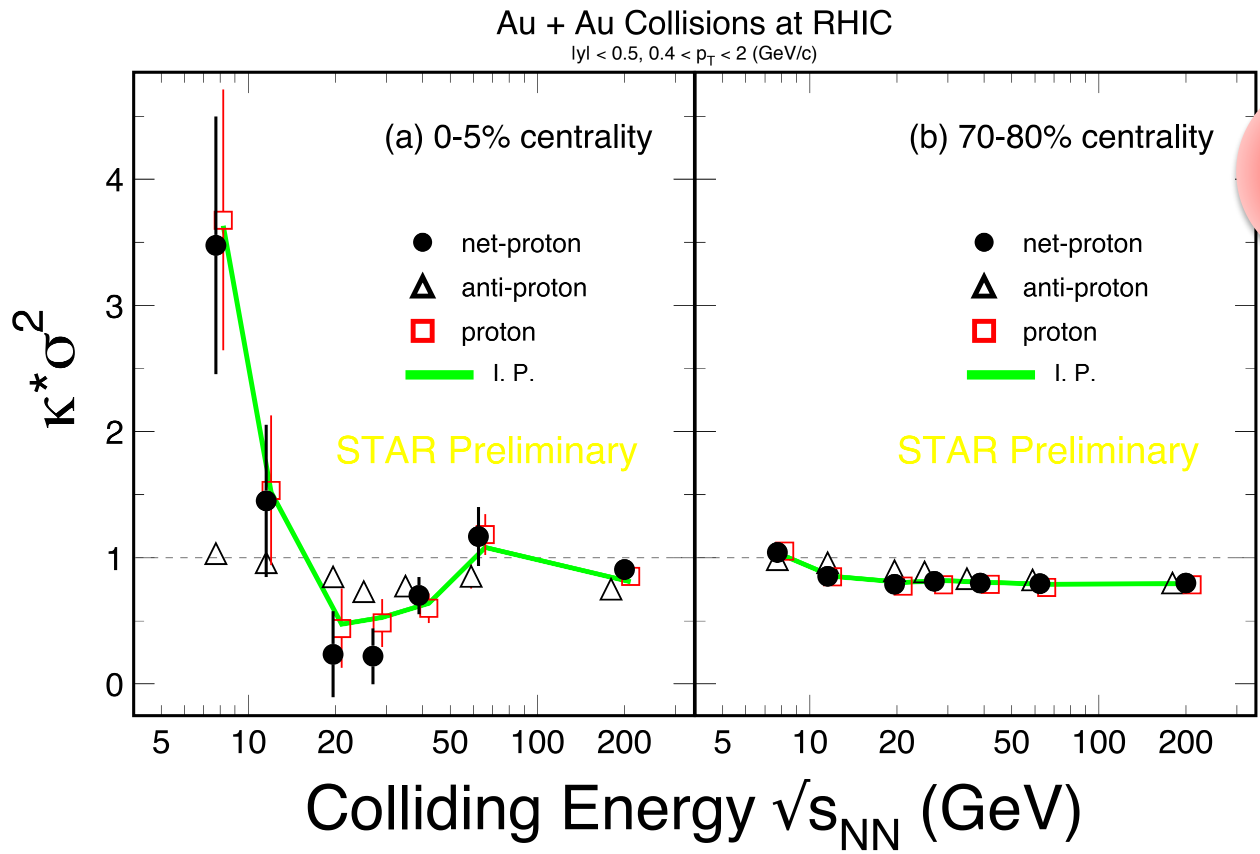
1) Higher moment of net-Q, net-Kaon, and net-proton measured at RHIC BES-I
2) Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions at $\sqrt{s_{NN}}$ < 27 GeV!

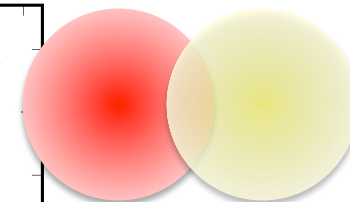
PHENIX: talk by P. Garg at QM2015; STAR: talk by J. Thäder and poster by J. Xu at QM2015

Net-proton Higher Moment



central





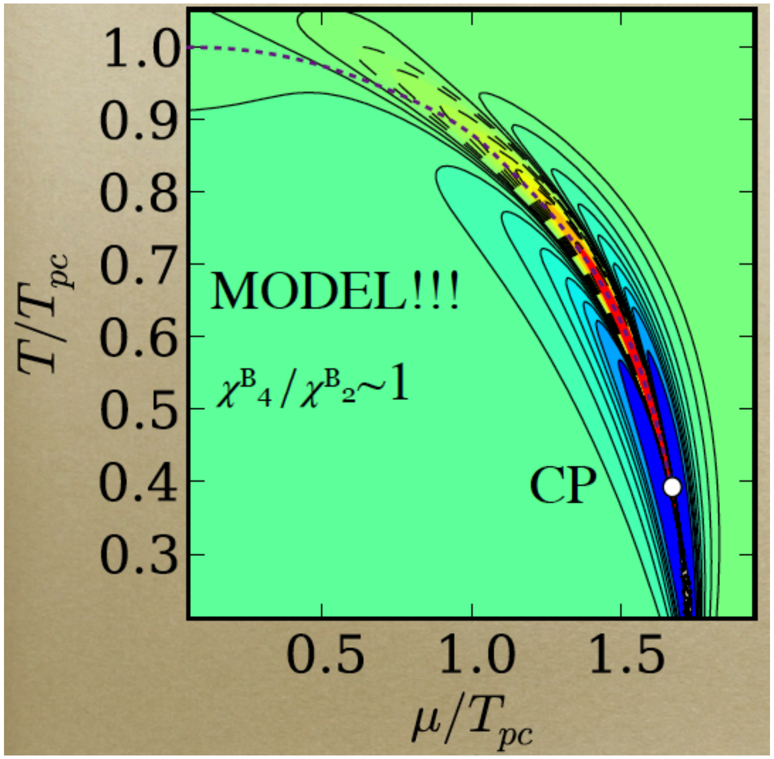
peripheral

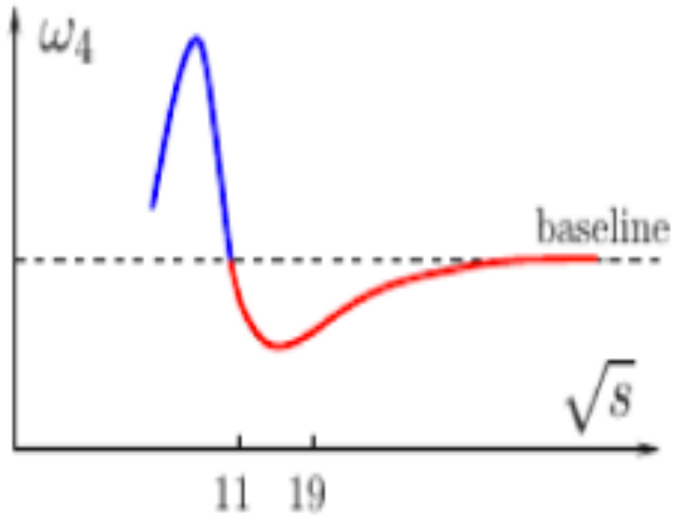
Net-proton results: All data show deviations below Poisson for $\kappa\sigma^2$ at all energies. Larger deviation at $\sqrt{s_{NN}}$ ~ 20 GeV.
Non-monotonic behavior in central collision!

X.F. Luo, CPOD2014, QM2015

Question: What will happen at even lower collision energy?

Expectation from Calculations





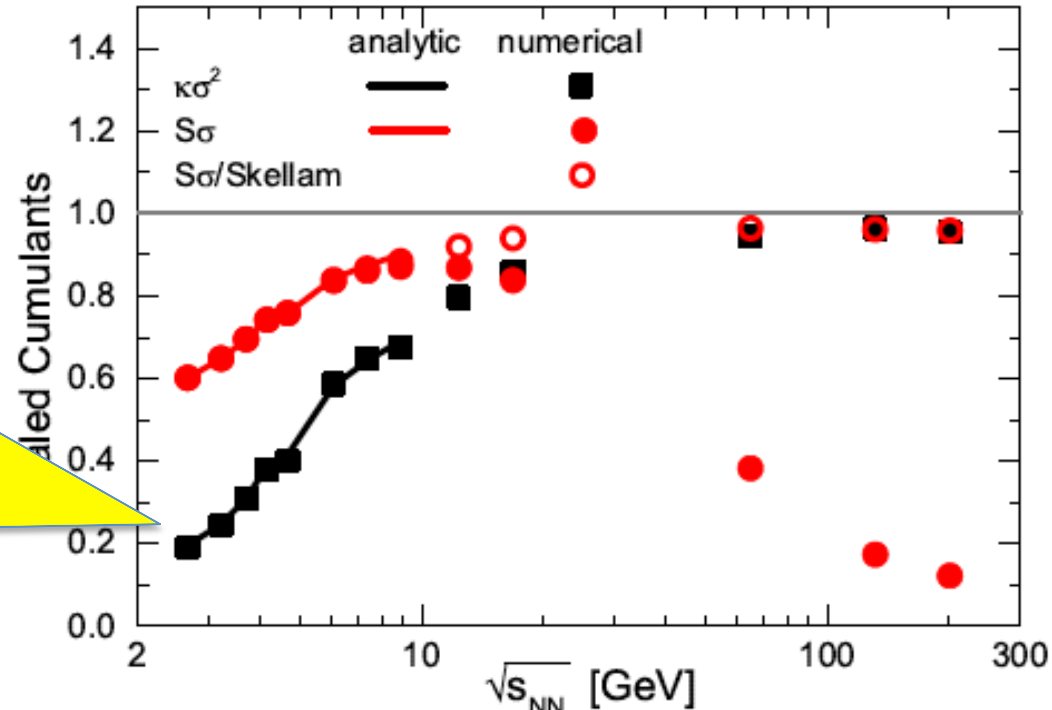
Characteristic "Oscillating pattern" is expected for a CP

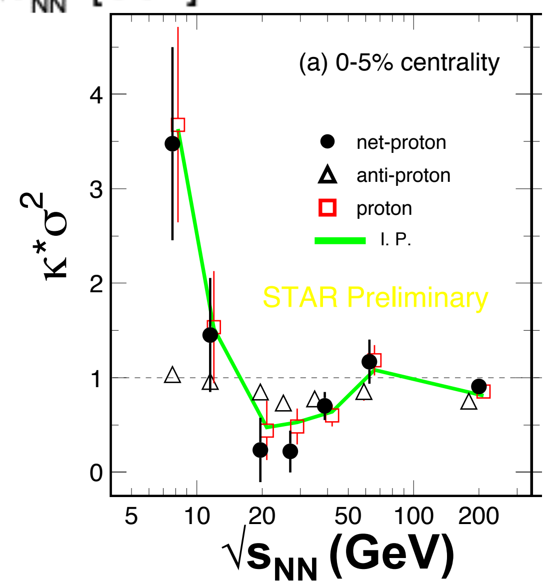
- M. Stephanov, ***PRL107***, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, arXiv: 1603.05198, Phys.Rev. **D93** (2016) 034037

Model Simulation Results

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

- Data: **$\kappa\sigma^2 > 1$!**
- Baryon conservations
- Mean-field
- Deuteron productions suppress the 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, accepted by NPA
4) P. Garg *et al.* Phys. Lett. **B726**, 691(13)
5) Mean-field effect (baryon): under study

The BES-II Program and Beyond

BES-II Upgrades

1) RHIC Electron Cooling:

- Luminosity increase by factors of 3-10 at $7<\sqrt{s_{NN}}<20$ GeV

2) STAR Inner TPC (iTPC):

- Extends rapidity coverage: $|y_p|$ from 0.5 to 0.8 ➔
  Crucial for QCD CP study
- Improved tracking efficiency and dE/dx ➔
  Important for di-electron measurements

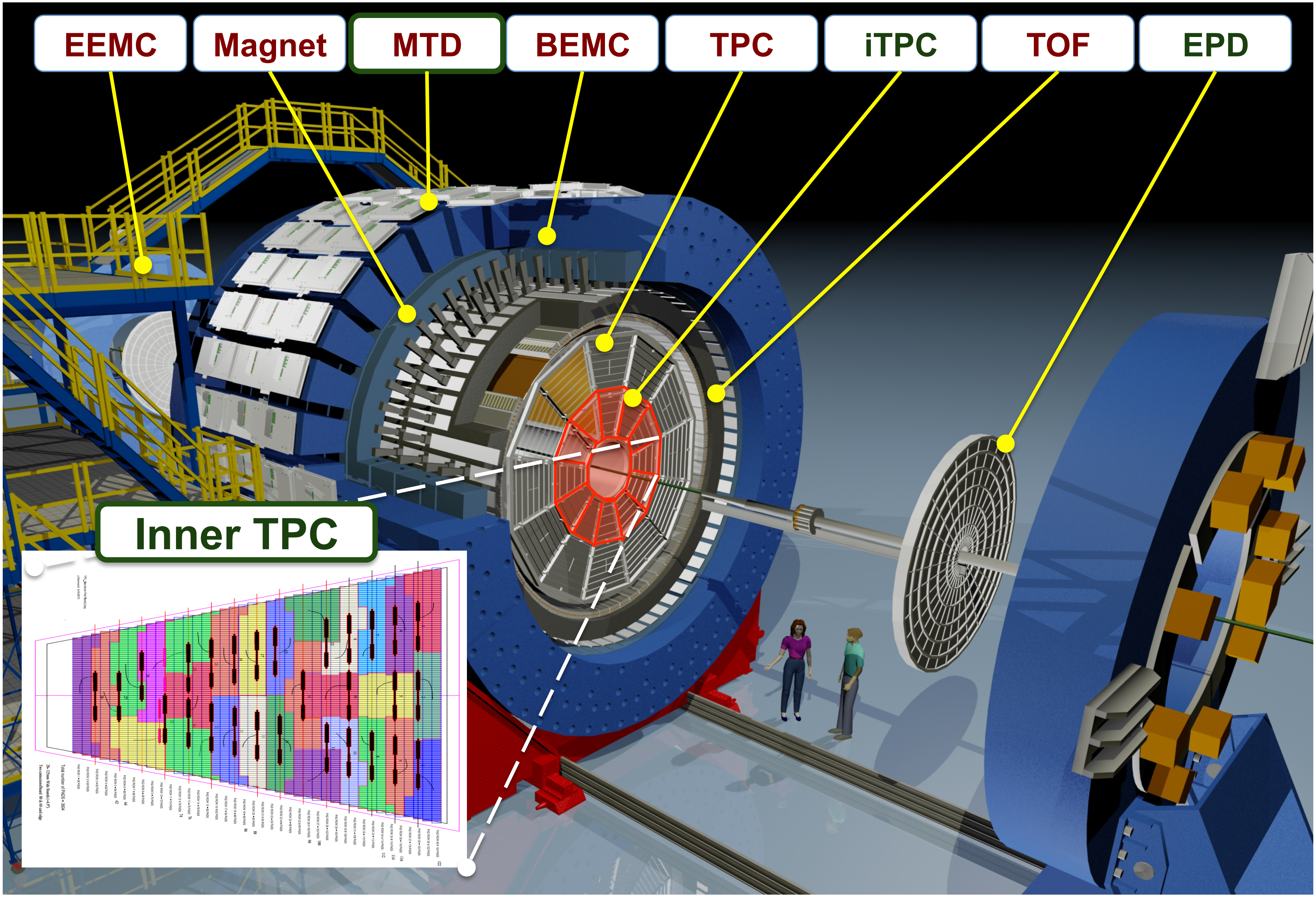
3) STAR Event Plane Detector (EPD):

- Extends pseudo-rapidity coverage to: $1.8< |\eta| <4.5$ ➔
  Trigger and event selection: multiplicity, event-plane

4) STAR End Cap TOF (eTOF) – (CBM-STAR):

- Extends PID to about $|\eta| < 1.5$ ➔
  Fixed-target program μ_B => 700 MeV

STAR Detector System

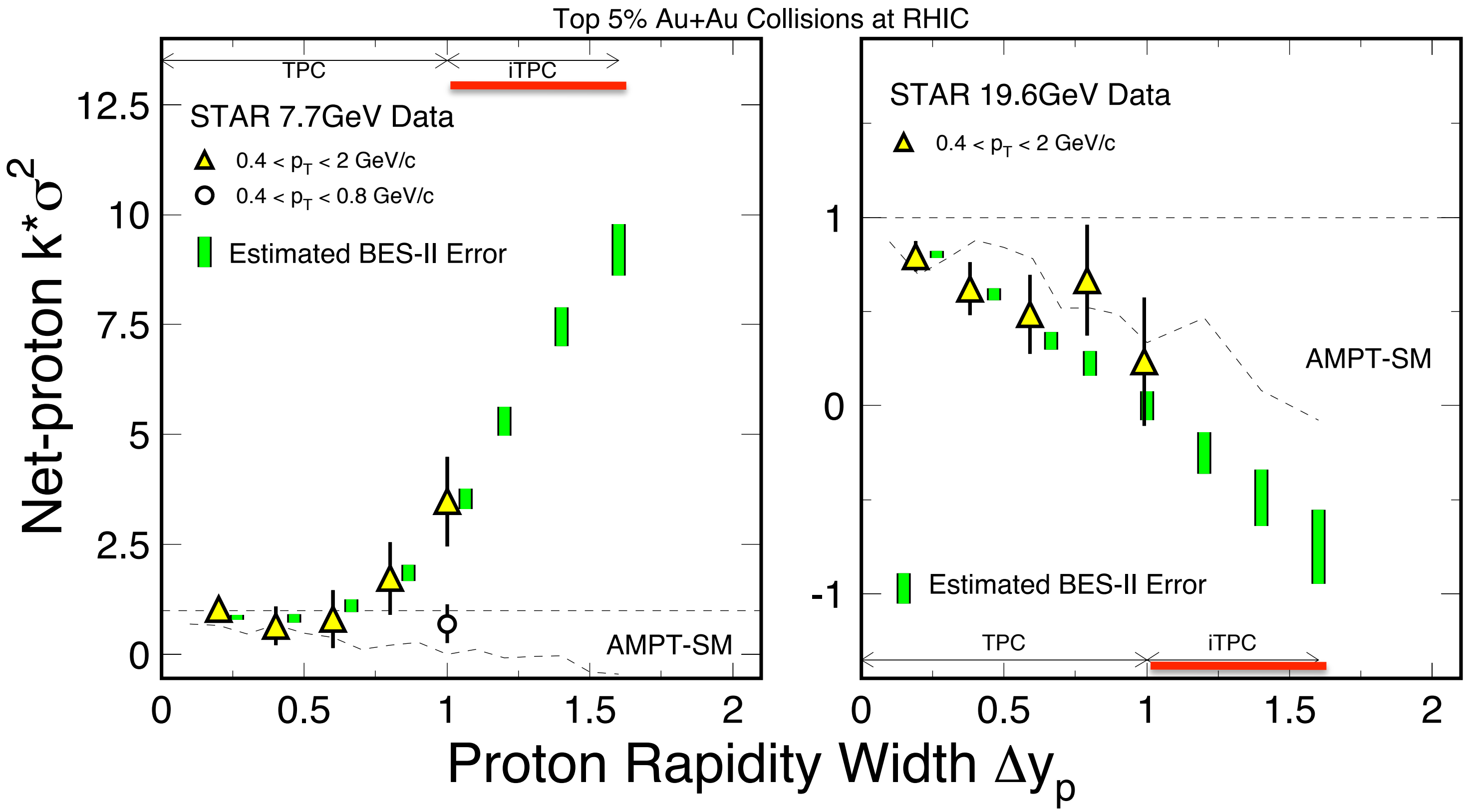


Event Statistics for BES at RHIC

$\sqrt{s_{NN}}$ (GeV)	# of Events (10^6)	BES-II / BES-I	Weeks	μ_B (MeV)	T_{CH} (MeV)	
200	350	2010		25	166	COLLIDER
62.4	67	2010		73	165	
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	
4.5		**2019-20**		~580	~110	FXT
3.9		**2019-20**		~630	~100	
3.6		**2019-20**		~680	~95	
3.0		**2019-20**		~730	~80	

Event statistics driven by QCD CP search and di-electron measurements

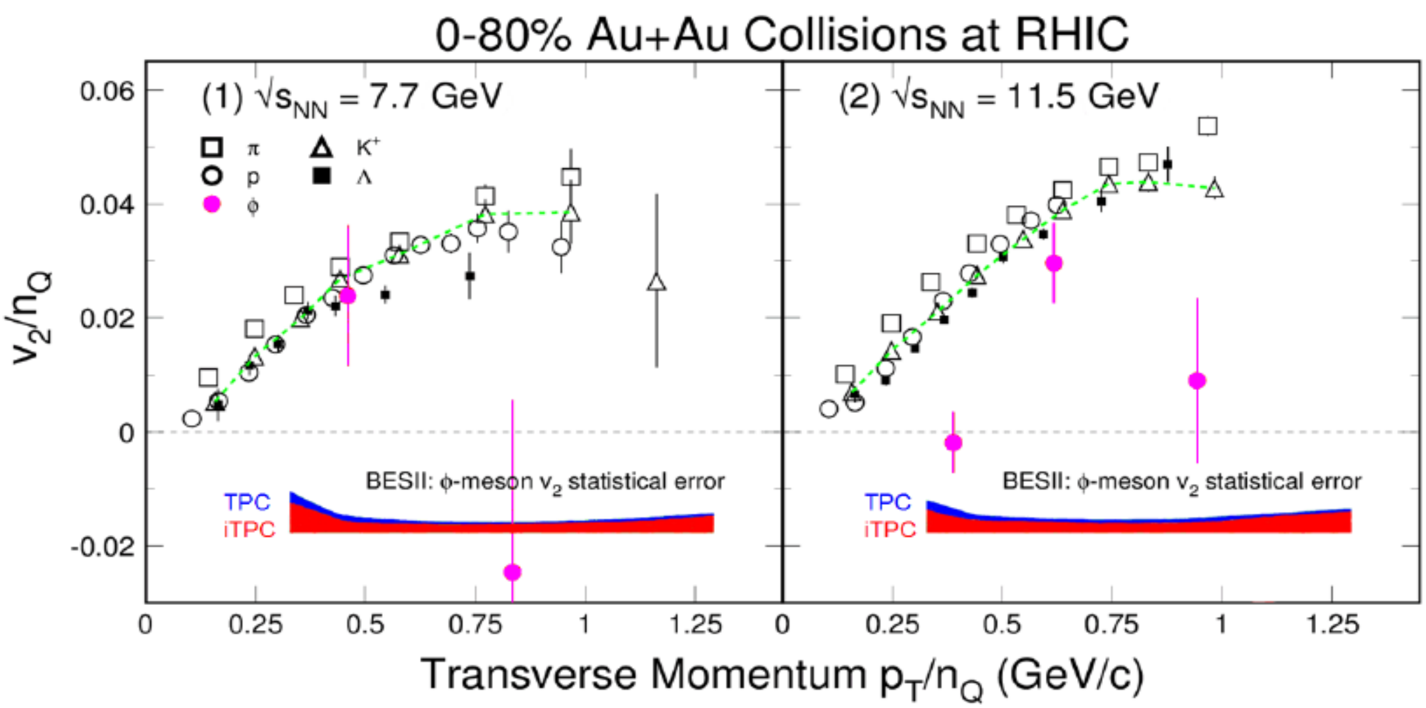
BES-II: Critical Point



1) iTPC extend the rapidity coverage to $\Delta y = 1.6$, allowing to studying kinematic acceptance for the CP (CR) search

2) Precision measurement of net-proton higher moments at high net-baryon region

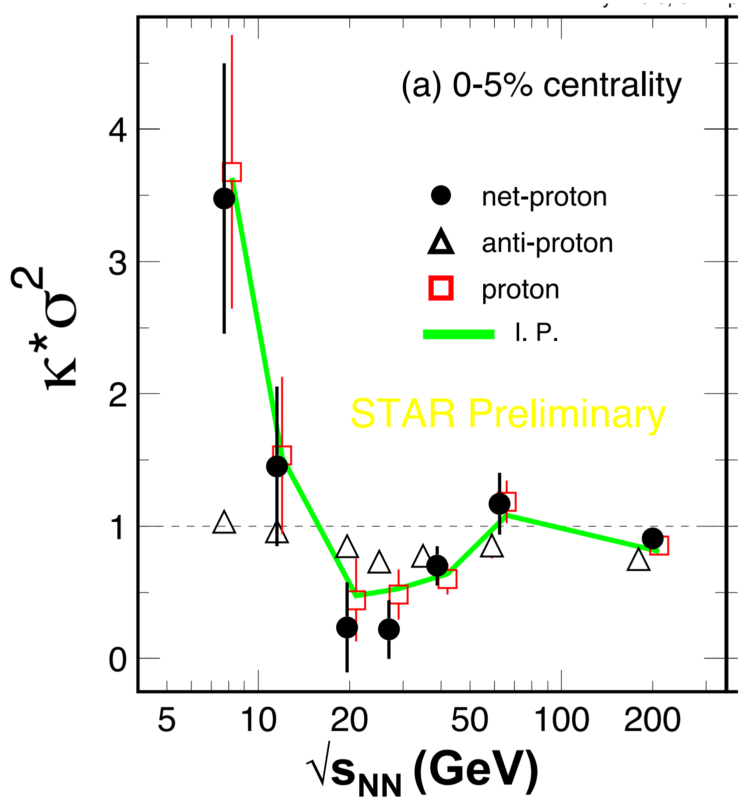
BES-II: Collectivity



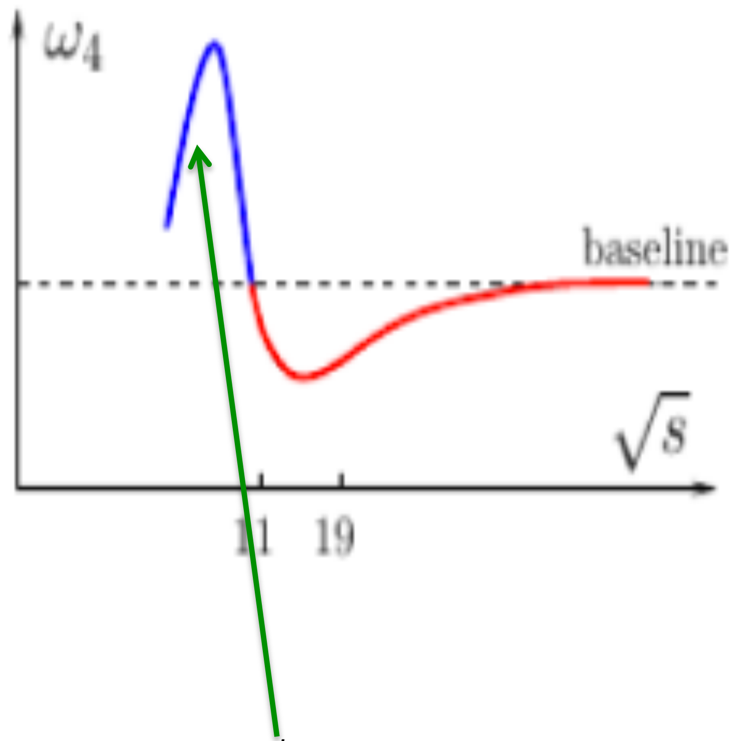
1) Strangeness: *penetrating probe* at high baryon region. Precision measurement for φ-meson v_2

2) Study the partonic vs. hadronic interactions

Net-proton Higher Moment



M. Stephanov, ***PRL107***, 052301(2011)

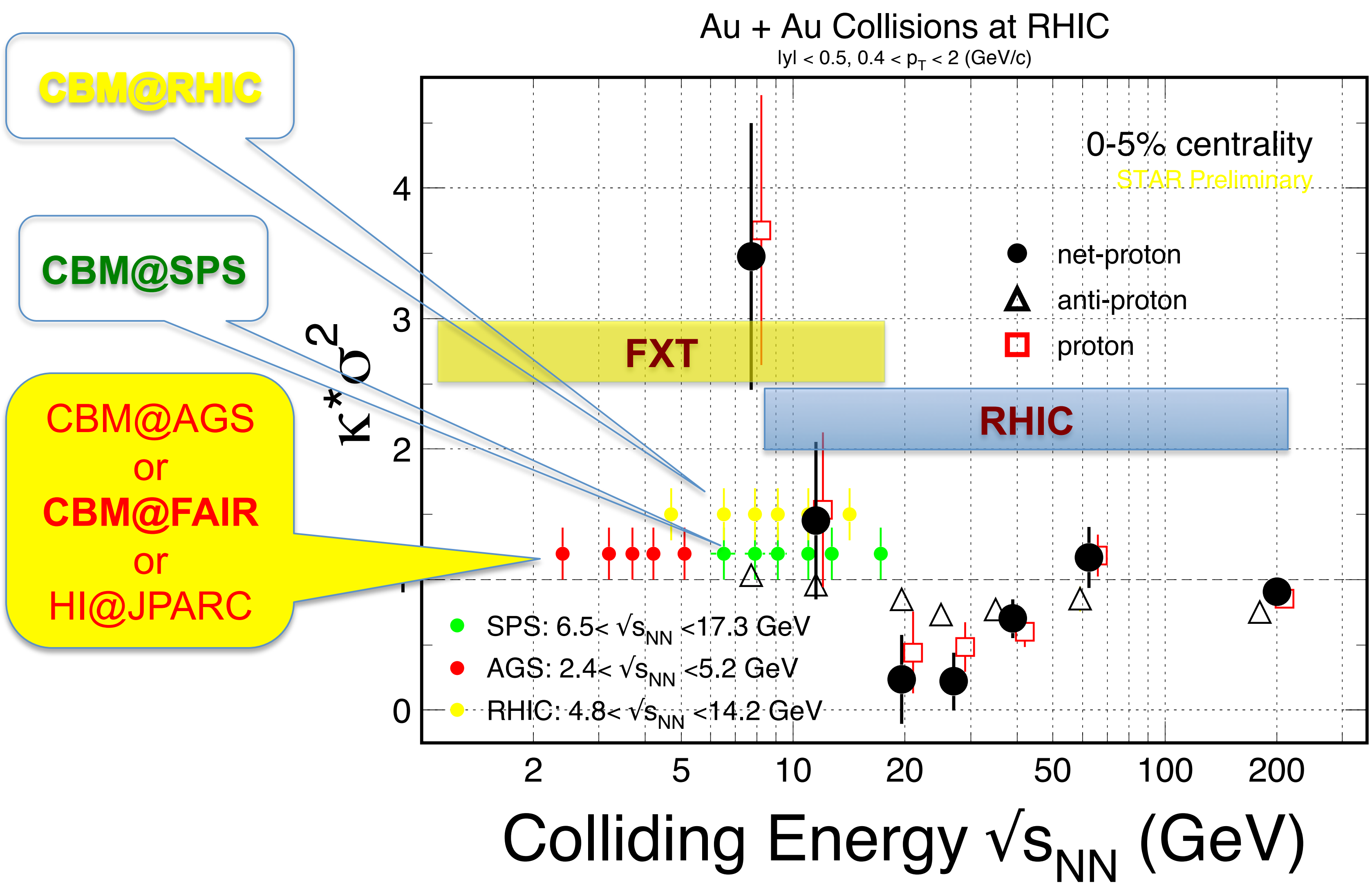


1) CEP=(μ_E=185, T_E=106)MeV => $\sqrt{s_{NN}}$ ~ 4 GeV

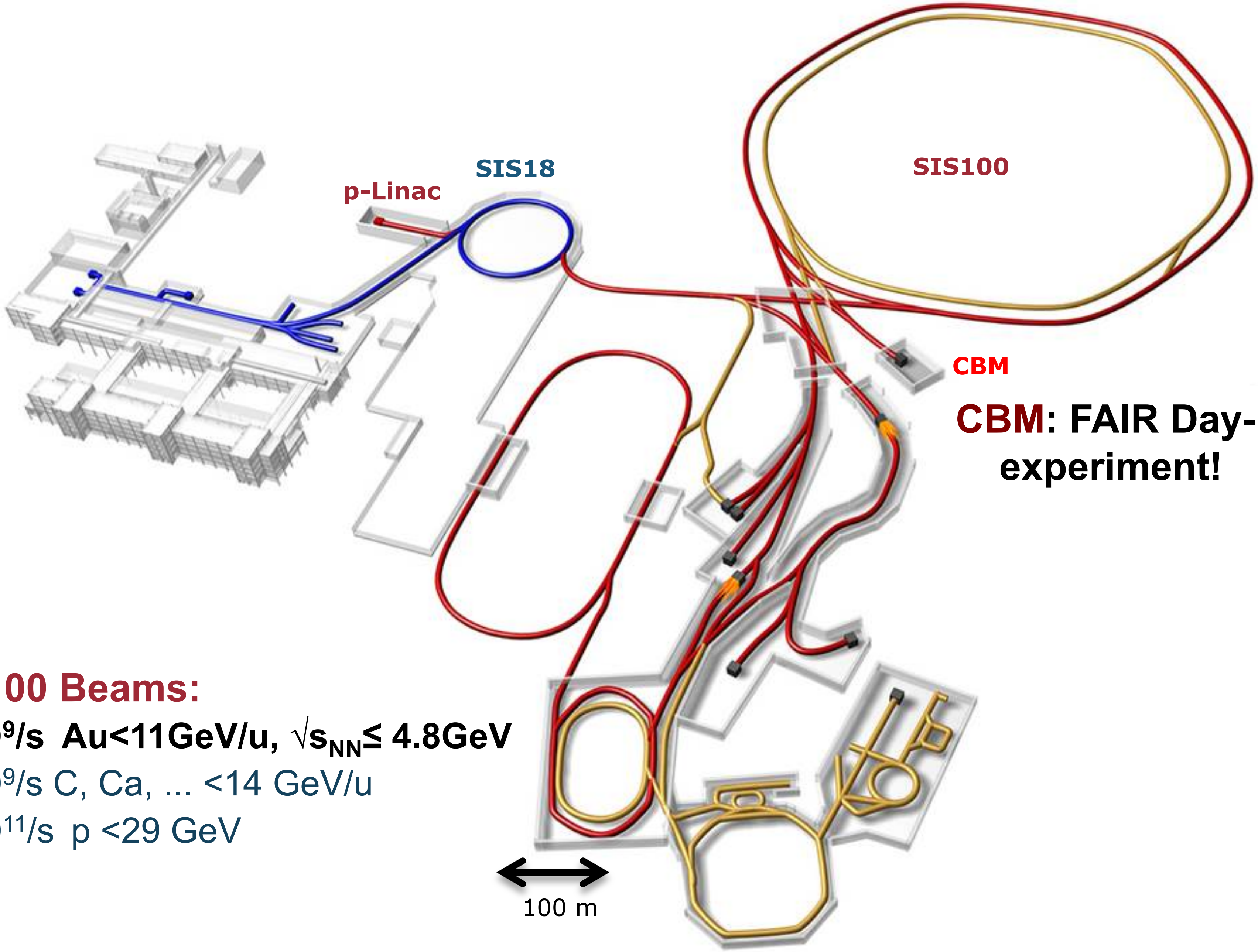
F. Gao, J. Chen, **Y.X. Liu**, S.X. Qin, **C.D. Roberts**, S. Schmidt, arXiv: 1507.00875

2) What will happen to net-proton $\kappa\sigma^2$ at higher baryon density region?

Fix-Target Experiments



Facility for Antiproton & Ion Research: FAIR

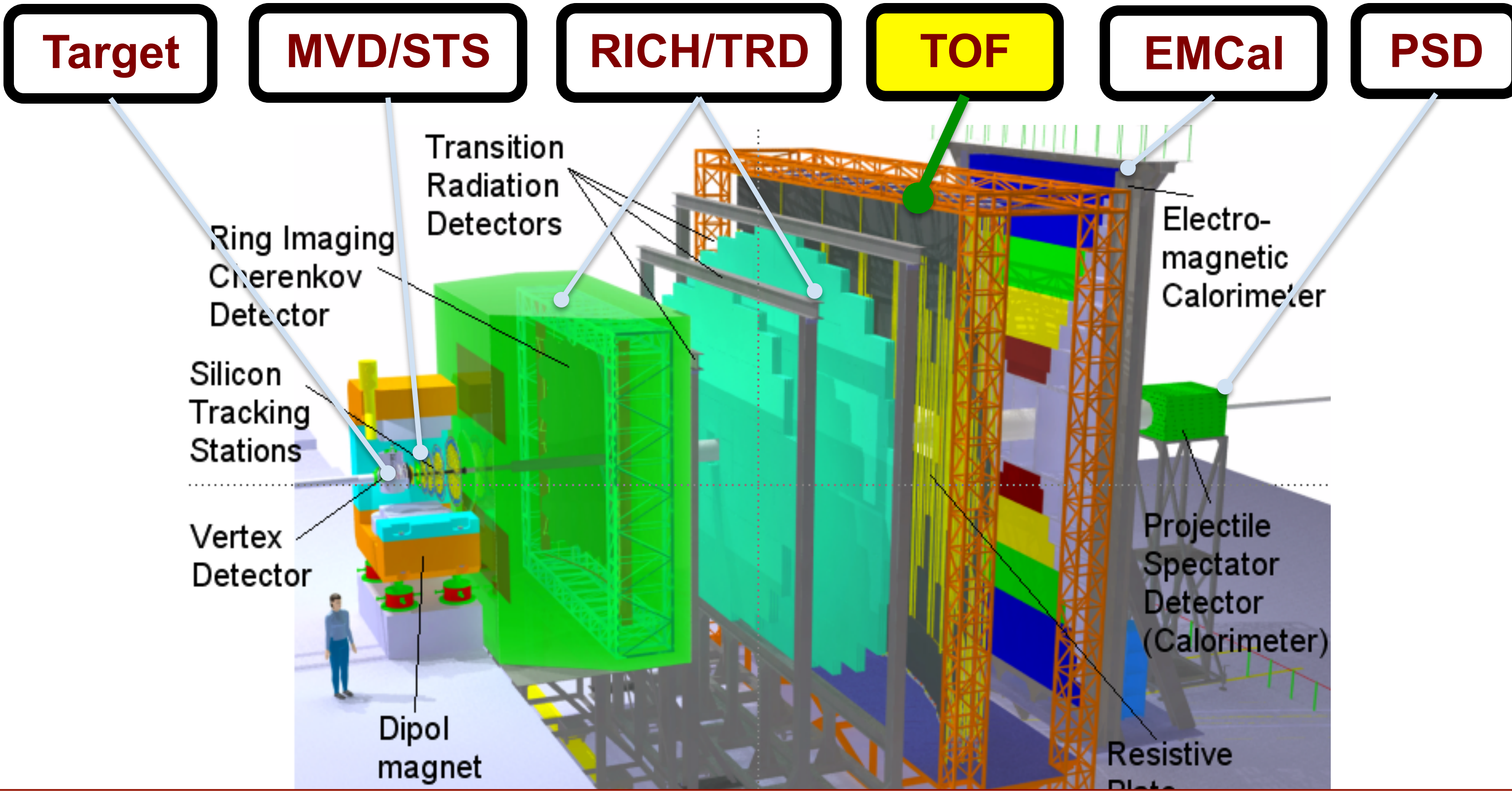


CBM: FAIR Day-1 experiment!

SIS100 Beams:

- **10^9/s Au<11GeV/u, $\sqrt{s_{NN}} \leq$ 4.8GeV**
- 10^9/s C, Ca, ... <14 GeV/u
- 10^{11}/s p <29 GeV

CBM Experiment at FAIR

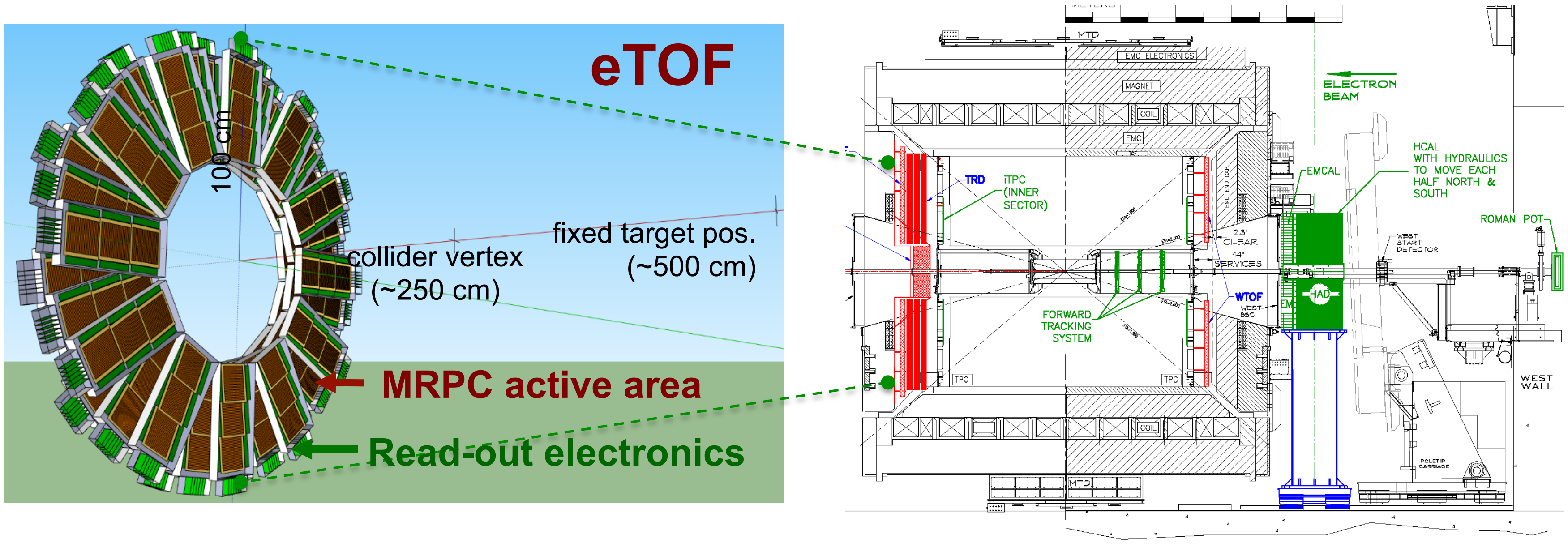


FAIR: One of the highest intensity accelerator complex in the 21st century

Precision measurements at high baryon density region for:

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

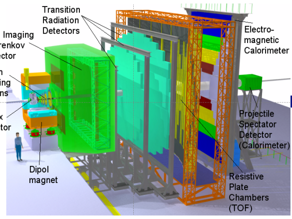
CBM Phase-0 Exp: eTOF at STAR



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

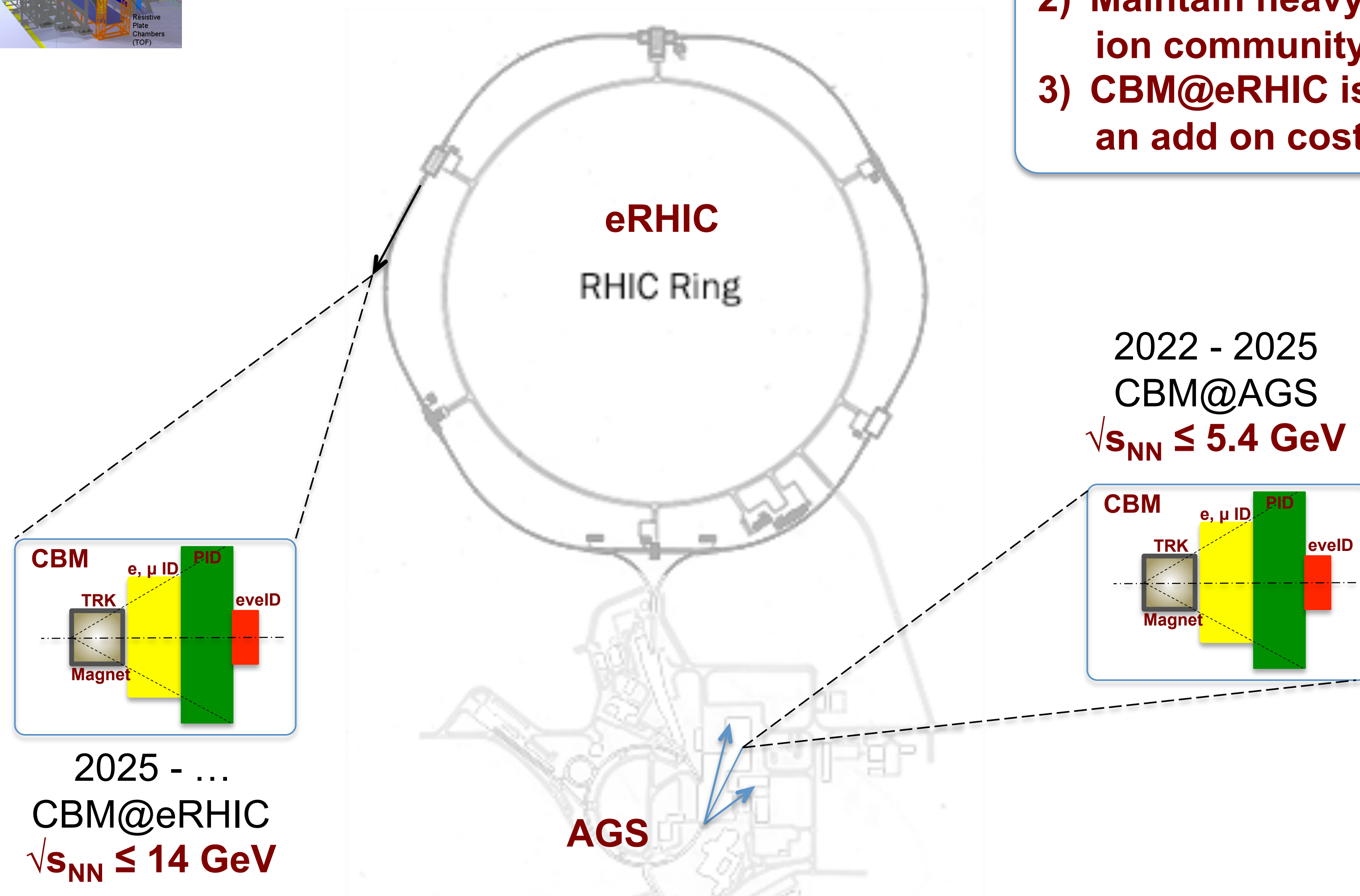
CBM participating in RHIC Beam Energy BES-II in 2019-2020:

- Complementary to part of CBM's physics program: $\sqrt{s_{NN}}$ = **3**, **3.6**, **3.9**, **4,5**, 7.7 GeV especially for the physics of ***B-*** & ***s-***production and fluctuations
- Operating of ~30 CBM TOF modules and electronics (~10 m^2, 10k channels)
- Experiencing with detector system, online calibration and monitoring tools
- Developing analysis strategies for particle identification and efficiency extraction



BES-III: CBM@BNL

1) **Study QCD phase structure**
2) **Maintain heavy ion community**
3) **CBM@eRHIC is an add on cost**

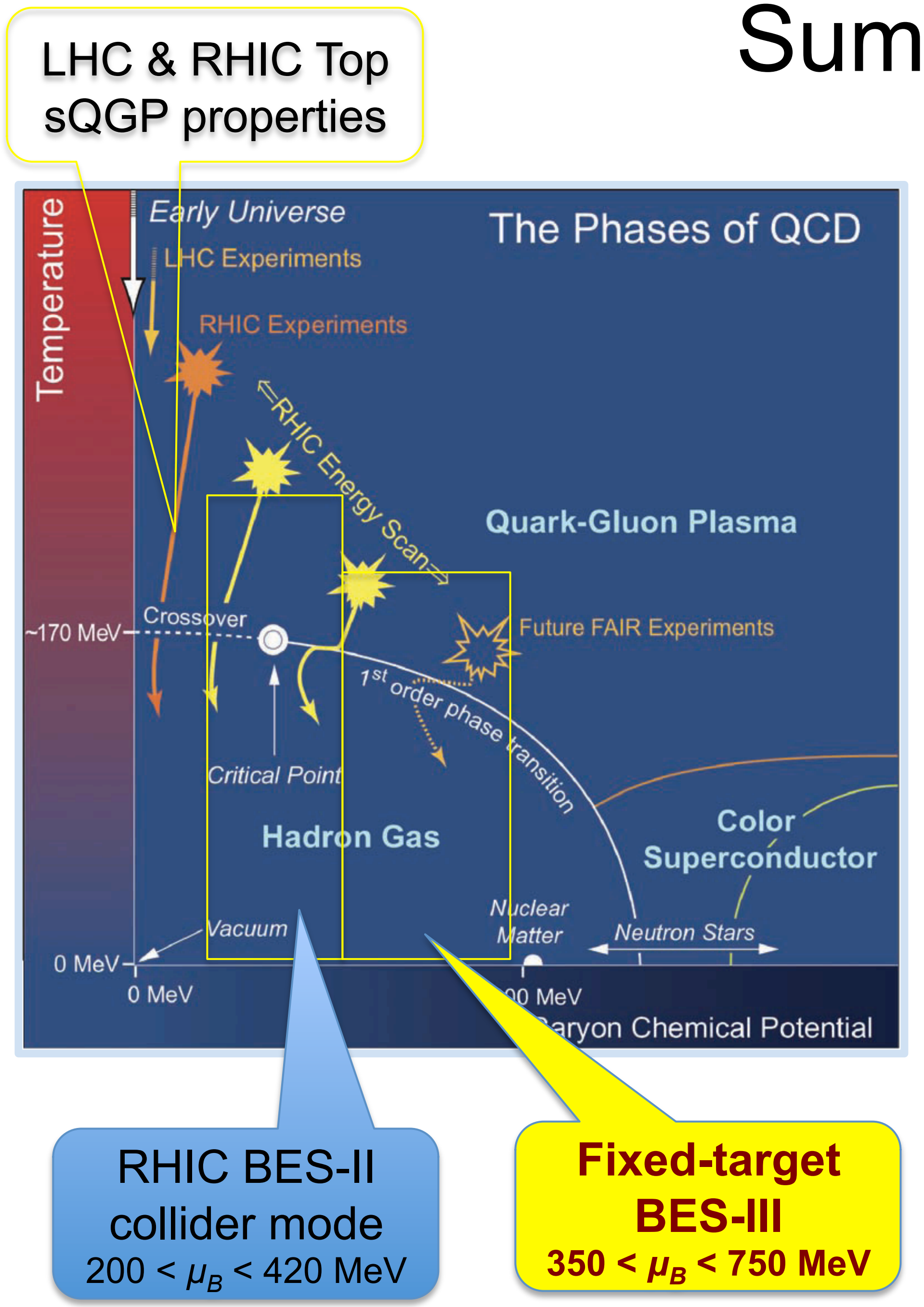


Challenges

1) Experiment:
   - Effects of acceptance
   - Effects of tracking, PID efficiencies
   - Collider vs. FXT (**BES-III**)
   - …

2) Theory: (observable)
   - Mean fields: Baryons, strangeness, …
   - Criticality at finite baryon density in transport, LGT
   - Chiral effects:
   - …

Summary



RHIC e-cooling and iTPC upgrades bring BES-II as a **new era** for studying the QCD phase structure at high net-baryon region (200 < μ_B < 420 MeV) with unprecedented precision and coverage. Possible new discovers are:

1) QCD critical point (*partial*)
2) Chiral effects
3) ϕ-meson v_2

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

Need FXT program, **BES-III,** for

QCD Critical Point!

Many Thanks to the BEST Organizers!!!