Study the QCD Phase Structure
in High-Energy Nuclear Collisions

SN0493 and SN0598

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May Thanks to Organizers!

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Outline

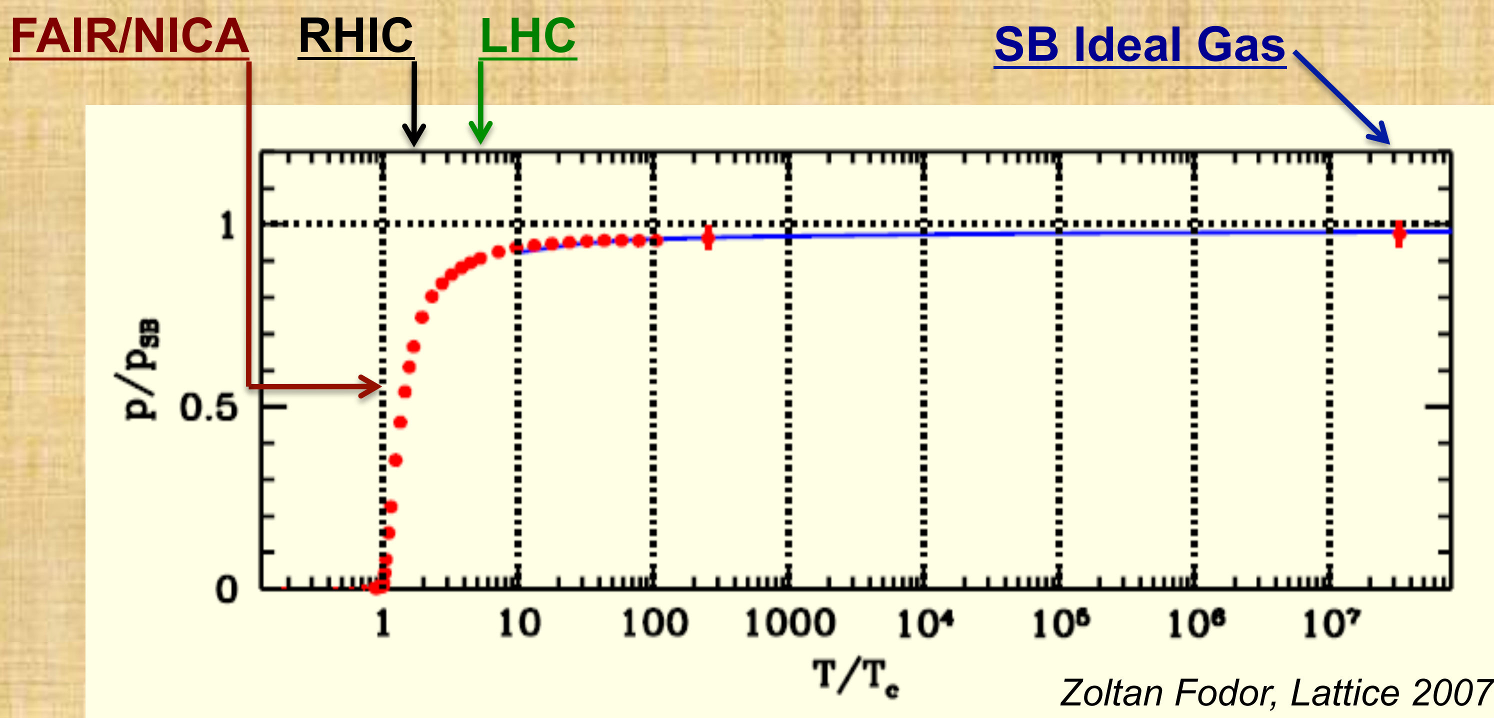
(1) Introduction

(2) Recent Results from BES-I

[i] Collectivity; [ii] Criticality; [iii] Chirality

(3) Physics Program in BES-II

QCD Thermodynamics

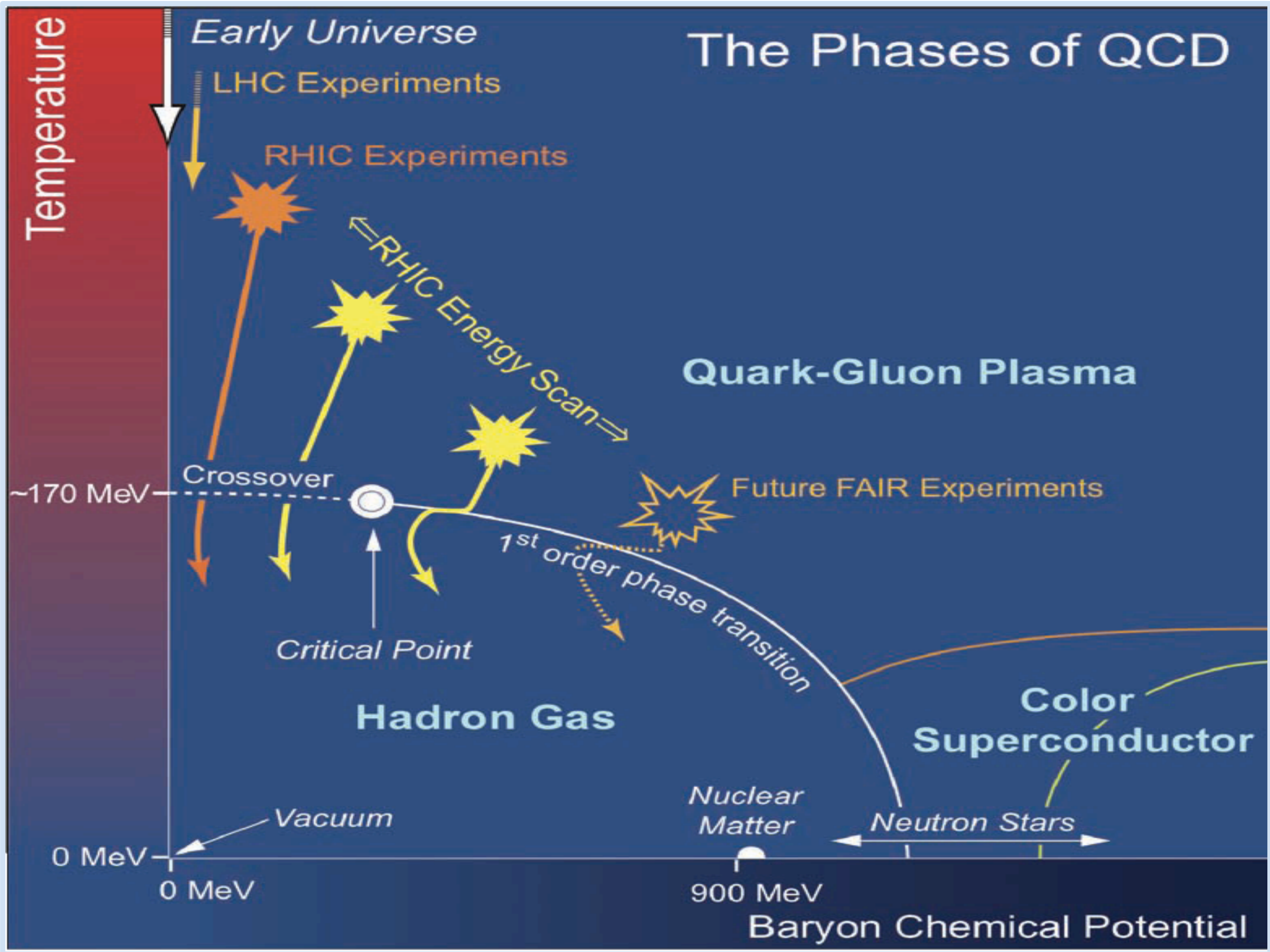


1) At $\mu_B = 0$: cross over transition, $140 < T_c < 160$ *MeV*

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

3) Thermalized, evolutions are similar for RHIC and LHC

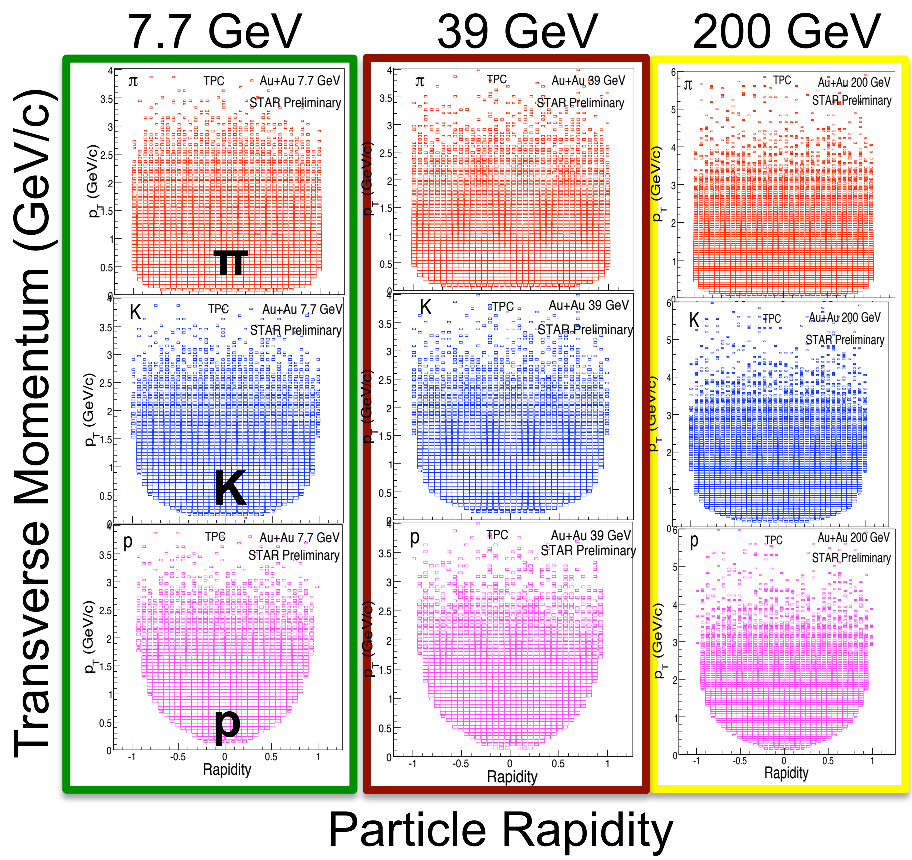
4) RHIC BES and FAIR/NICA: **large μ_B, rapid changes**



The Phases of QCD
Temperature
Early Universe
LHC Experiments
RHIC Experiments
⇐RHIC Energy Scan⇒
Quark-Gluon Plasma
Future FAIR Experiments
~170 MeV
Crossover
1st order phase transition
Critical Point
Hadron Gas
Color
Superconductor
Nuclear
Matter
Neutron Stars
Vacuum
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

Data Sets at STAR

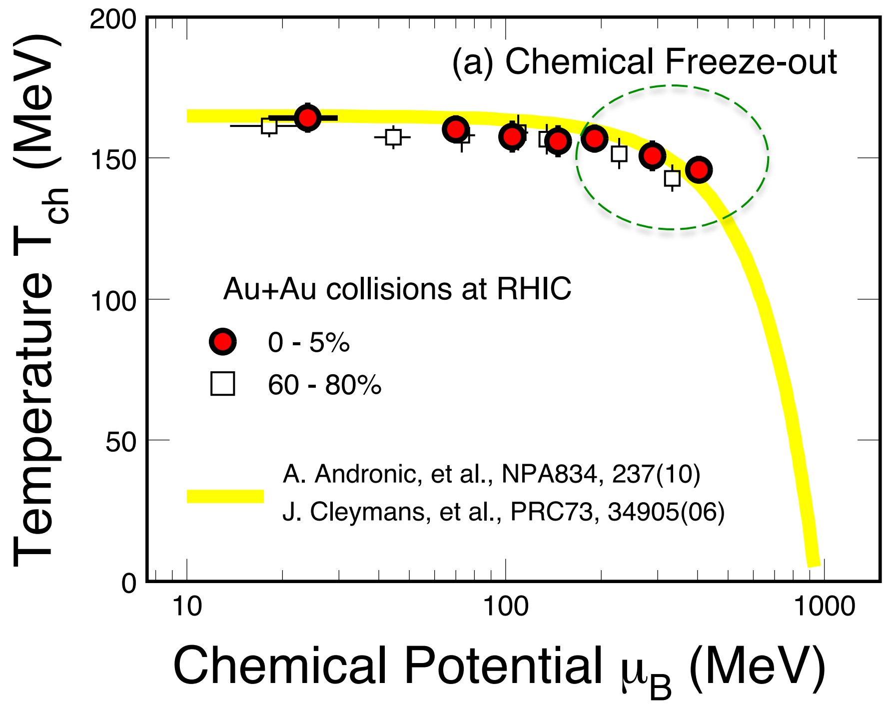
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	*μ_B (MeV)	*T_{CH} (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
39	39	2010	112	164
27	70	2011	156	162
19.6	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	316	152
7.7	4	2010	422	140

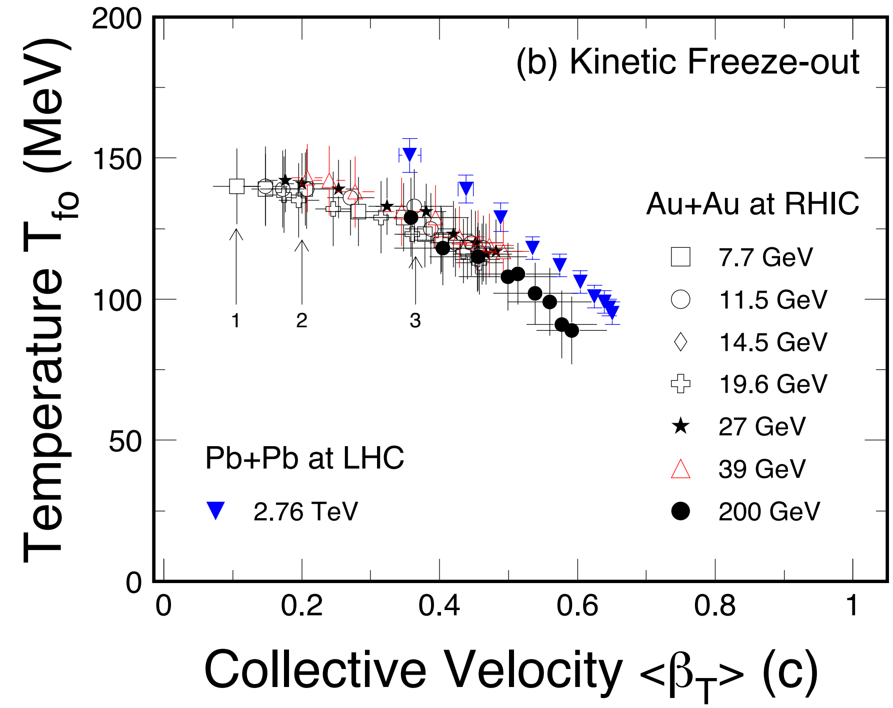


1) Largest data sets versus collision energy: **Many thanks to RHIC operation!**
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. Important for fluctuation analysis!

*(μ_B, T_{CH}) : J. Cleymans et al., PRC 73, 034905 (2006)
Talk by J. Thäder, at QM2015

Bulk Properties at Freeze-out





Chemical Freeze-out: (GCE)

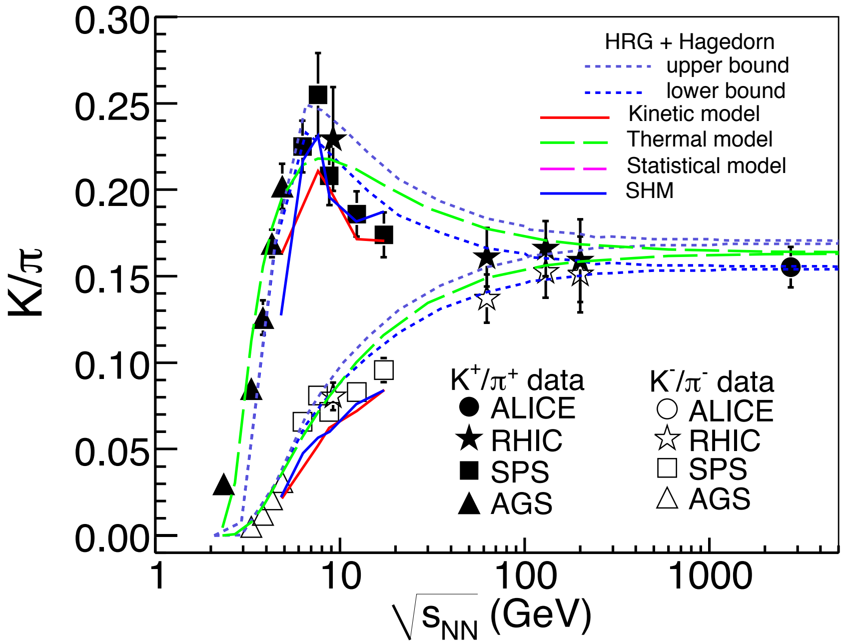
- Weak temperature dependence
- Centrality dependence μ_B!
- Lattice prediction on CP around μ_B ~ 300 – 400 MeV

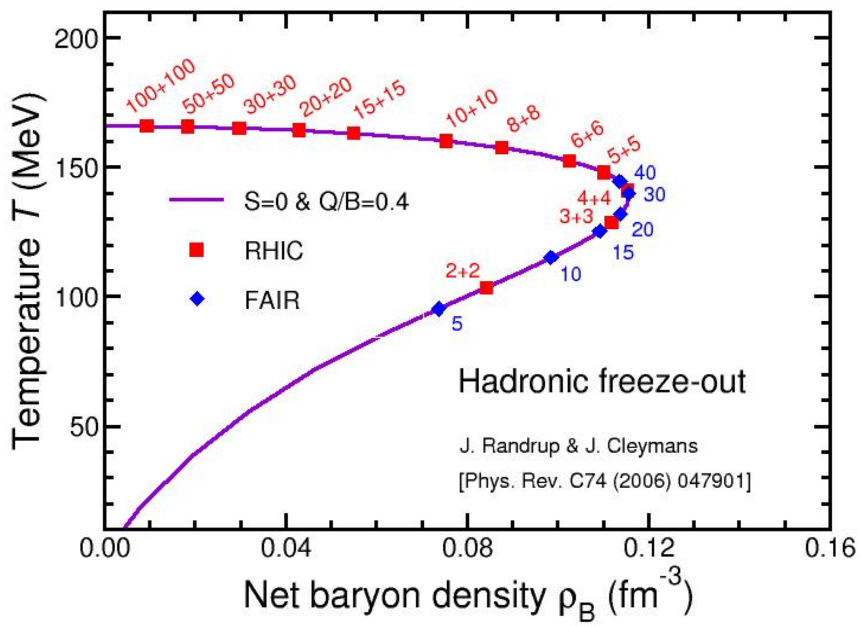
Kinetic Freeze-out:

- 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

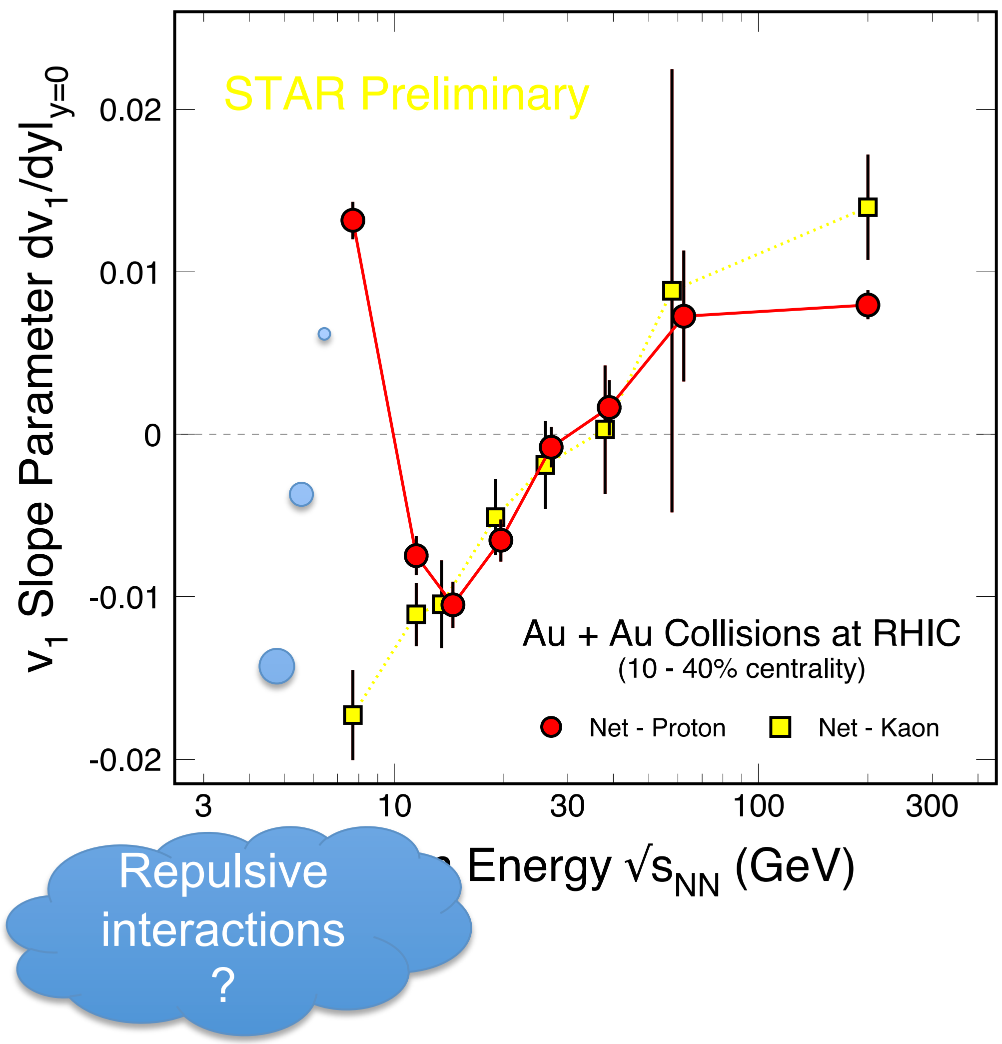




1) In heavy ion collisions $\mathbf{K^+/\pi}$ ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV, $\mathbf{K^-/\pi}$ ratio is a smooth and merges with $\mathbf{K^+/\pi}$ at higher collision energy
2) Model: **Baryon density peaks at at $\sqrt{s_{NN}}$ ~ 8 GeV**
3) At $\sqrt{s_{NN}}$ **>** 8 GeV, pair production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

L. Kumar, *et al.*1304.2969

Directed Flow v_1 Results



STAR: PRL**112**, 162301(2014)
Talk by P. Shanmuganathan at QM2015

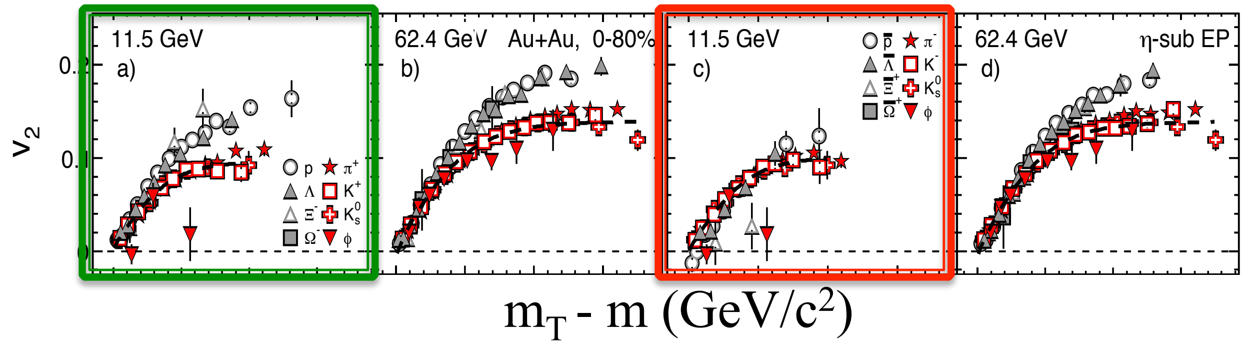
1) Mid-rapidity net-proton dv_1/dy published in 2014 by STAR, except the point at 14.5 GeV

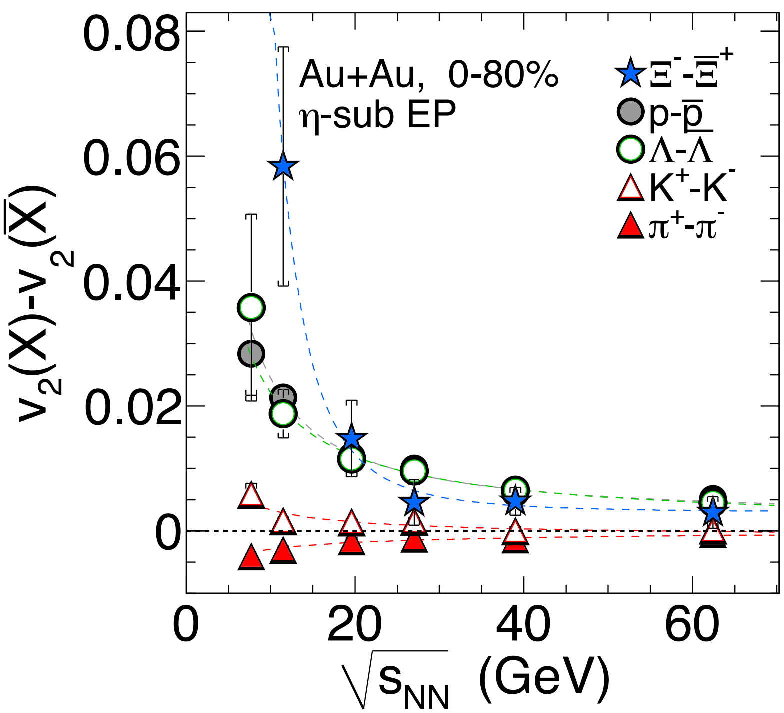
2) Minimum at $\sqrt{s_{NN}}$ = 14.5 GeV for net-proton, but net-Kaon data continue decreasing as energy decreases

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. Onishi et al, PRC72, 064908(05)

Collectivity $\boldsymbol{v_2}$ Measurements



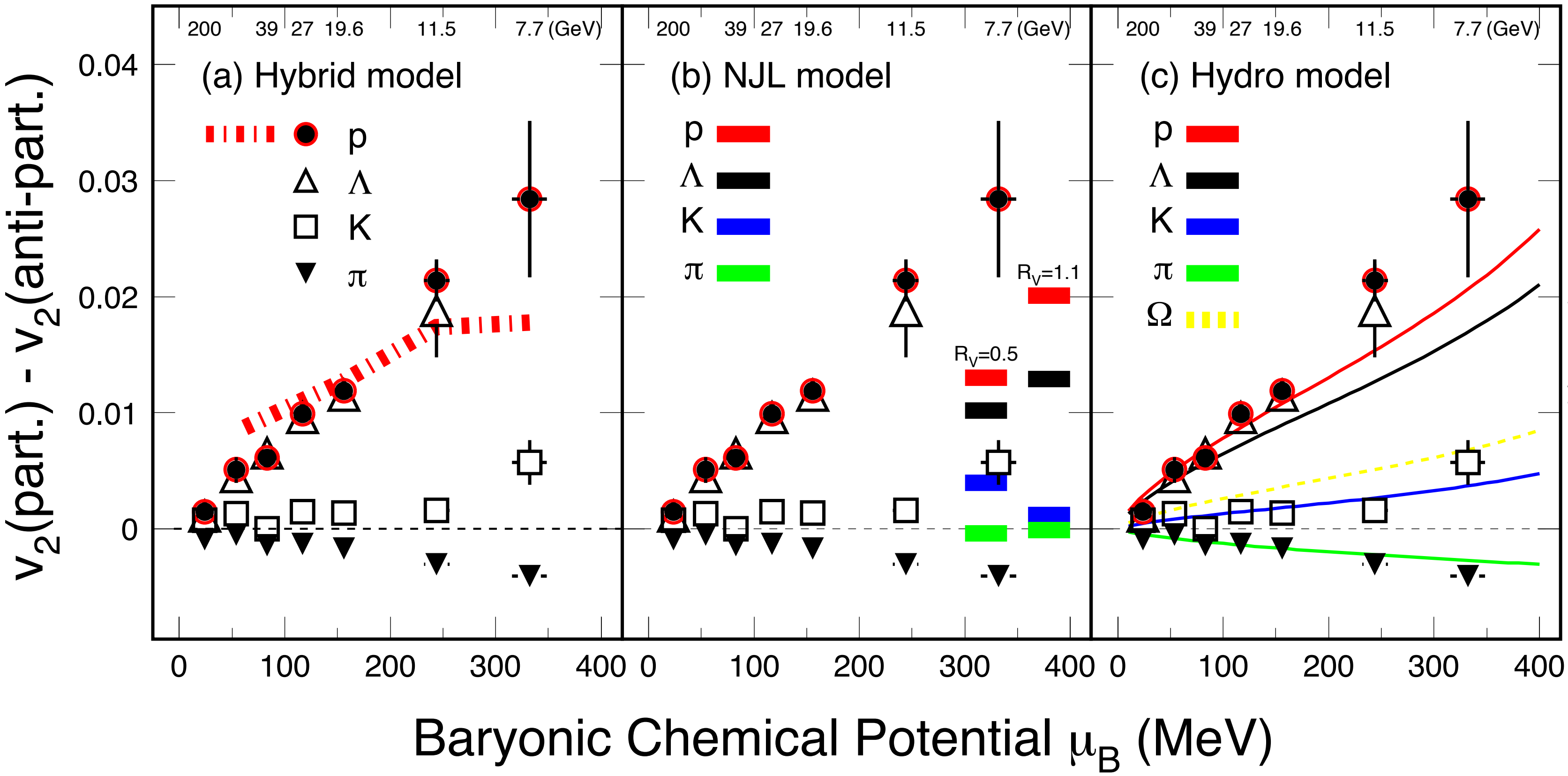


STAR: PR**110** (2013) 142301

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

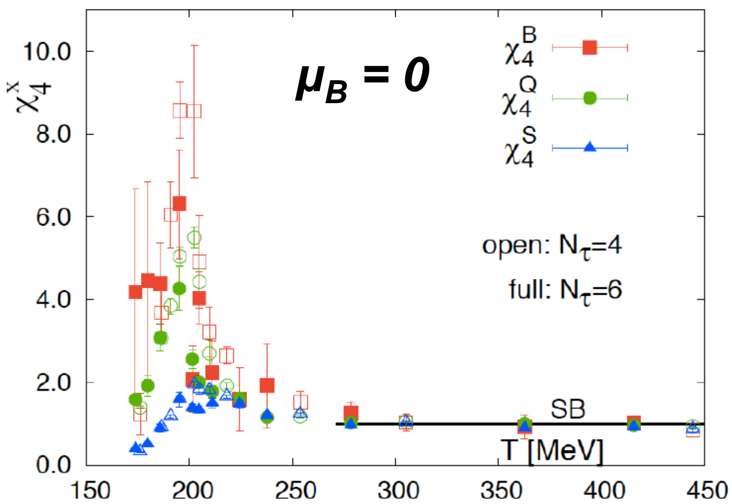


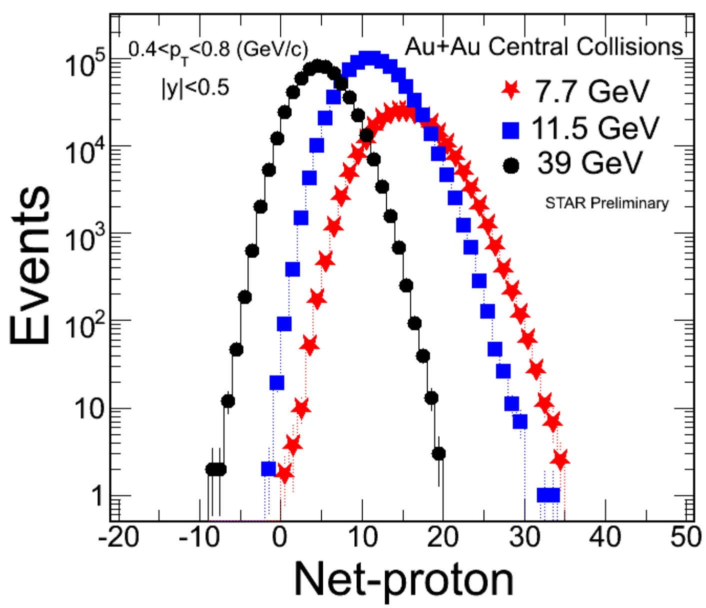
(a) Hydro + Transport: Baryon results fit [J. Steinheimer, et al. PRC86, 44902(13)]

(b) NJL model: Hadron splitting consistent. Sensitive to vector-coupling, **CME, μ_B** driven. [J. Xu, et al., PRL112.012301(14)]

(c) Pure Hydro solution with μ_B, viscosity: **Chemical potential μ_B** and **viscosity η/s** driven! [Hatta et al. arXiv:1502.05894//1505.04226//1507.04690]

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:

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

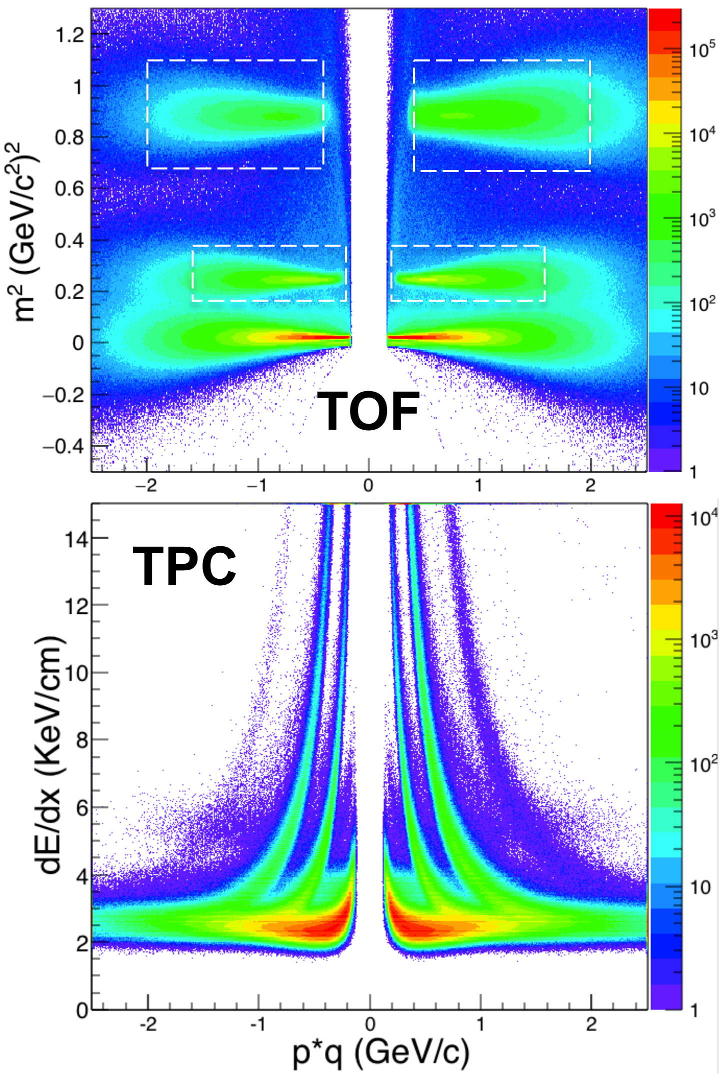
4) Extract susceptibilities and freeze-out temperature. An independent/important test of thermal equilibrium in heavy ion collisions.

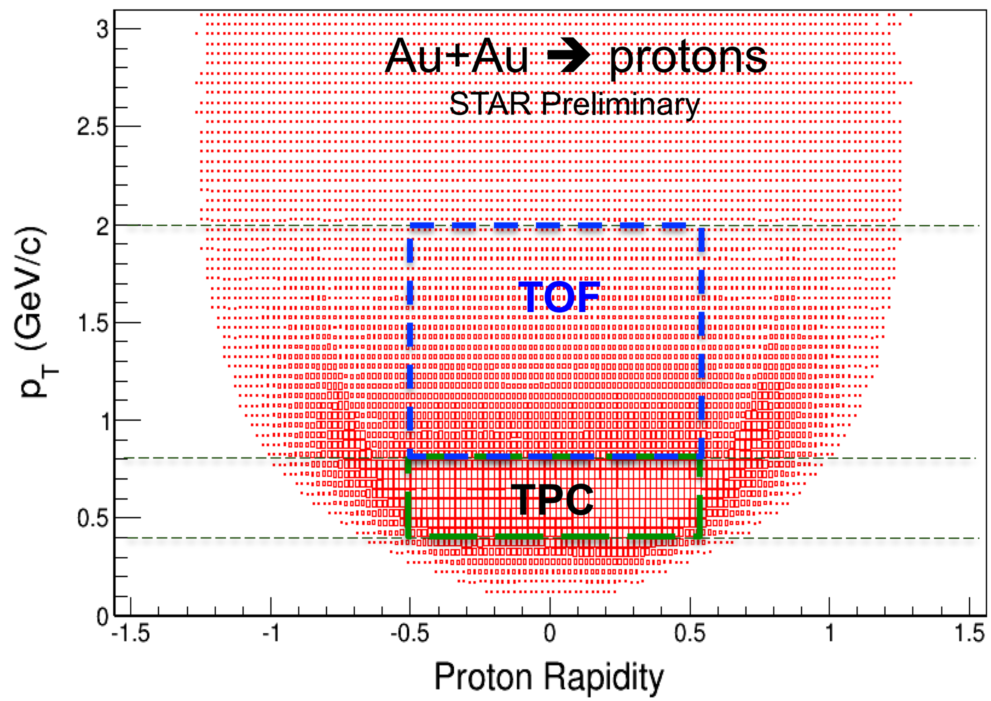
References:

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

Proton Identification with TOF

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





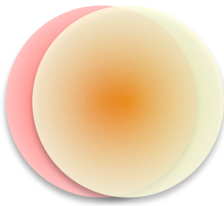
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

Efficiency corrections:

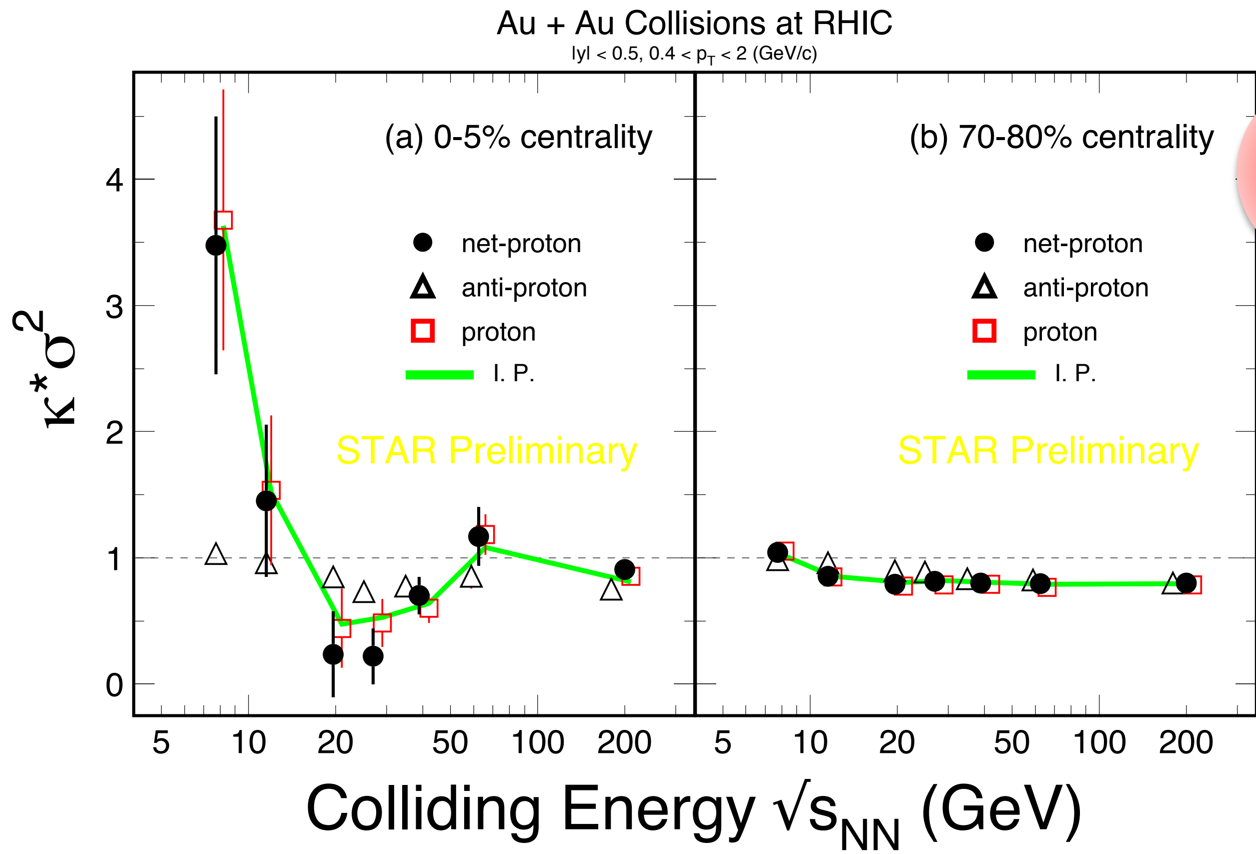
TPC ($0.4 \leq p_T \leq 0.8$ GeV/c): $\varepsilon_{TPC} \sim 0.8$

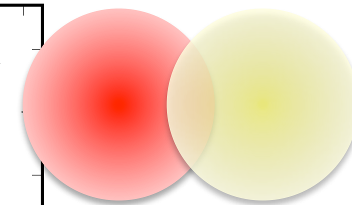
TPC+TOF ($0.8 \leq p_T \leq 2$ GeV/c): $\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$

Net-proton Higher Moment



central





peripheral

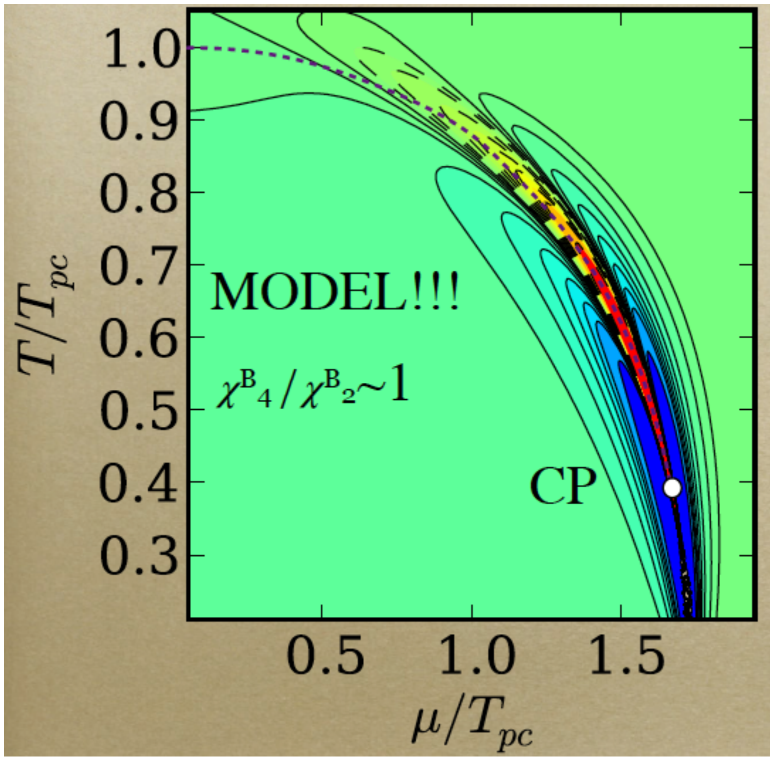
Net-proton results: All data show deviations below Poisson for $\kappa\sigma^2$ at all energies. Larger deviation at $\sqrt{s_{NN}}$ ~ 20 GeV.

Non-monotonic behavior in central collision! *X.F. Luo, CPOD2014, QM2015*

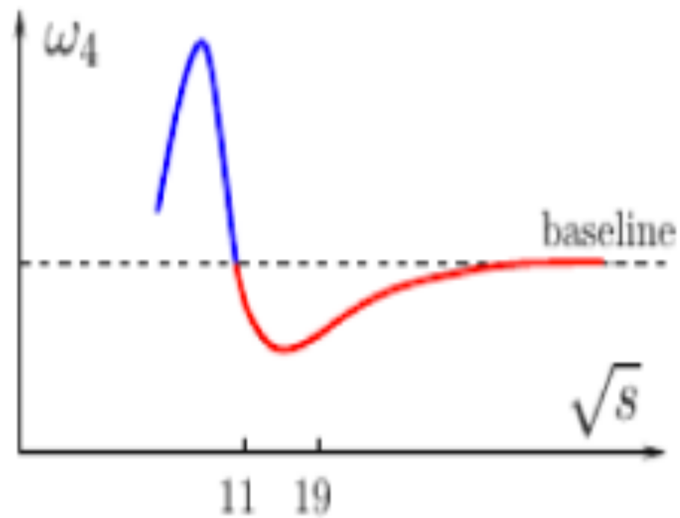
Question: What will happen at even lower collision energy?

Expectation from Models

V. Skokov, Quark Matter 2012

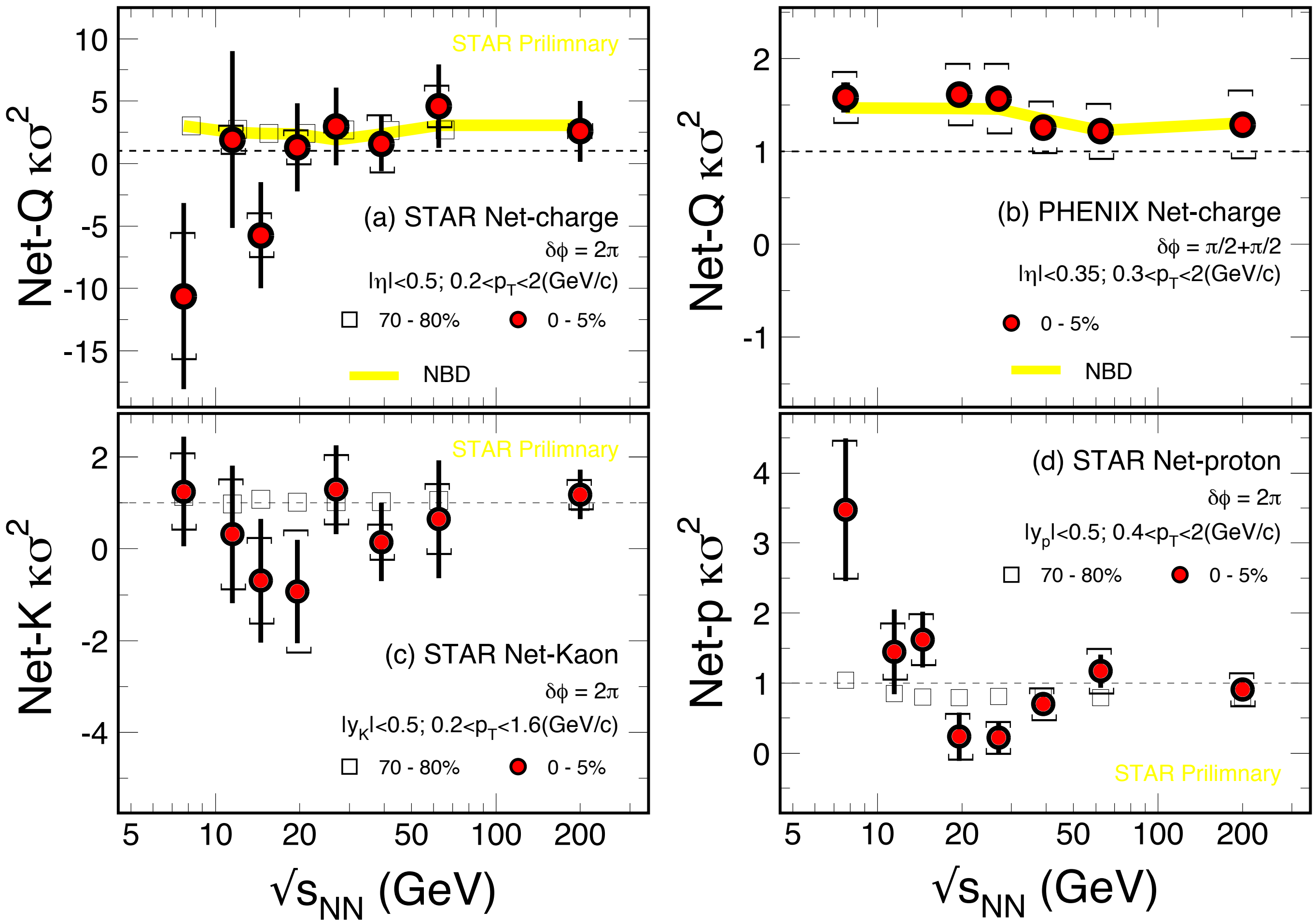


M. Stephanov, ***PRL107***, 052301(2011)



Characteristic "Oscillating pattern" is expected for CP.

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



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

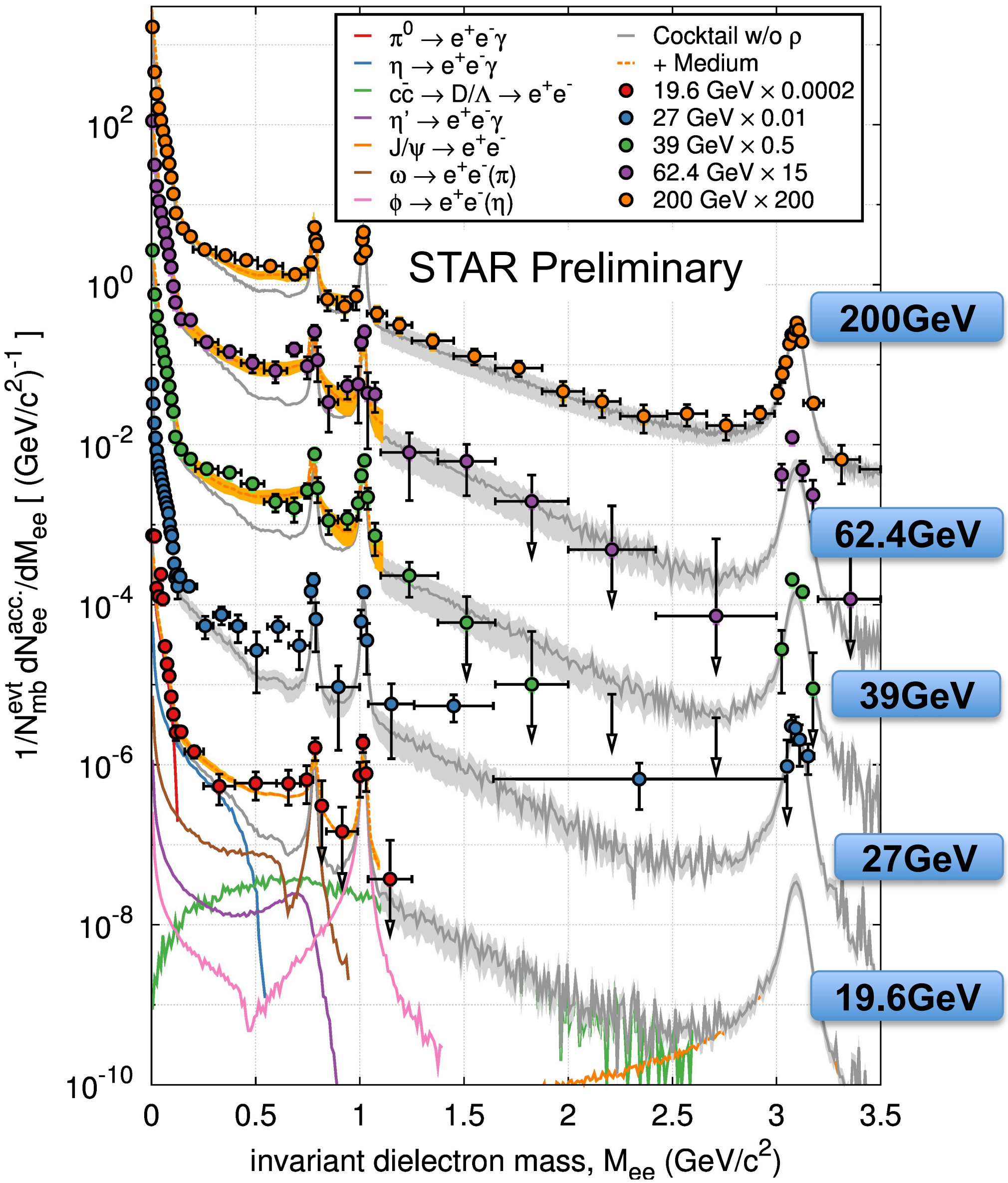
In STAR:

σ(Q) > σ(p) > σ(K)

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

Energy Dependence of Di-electrons



Bulk-penetrating probe:

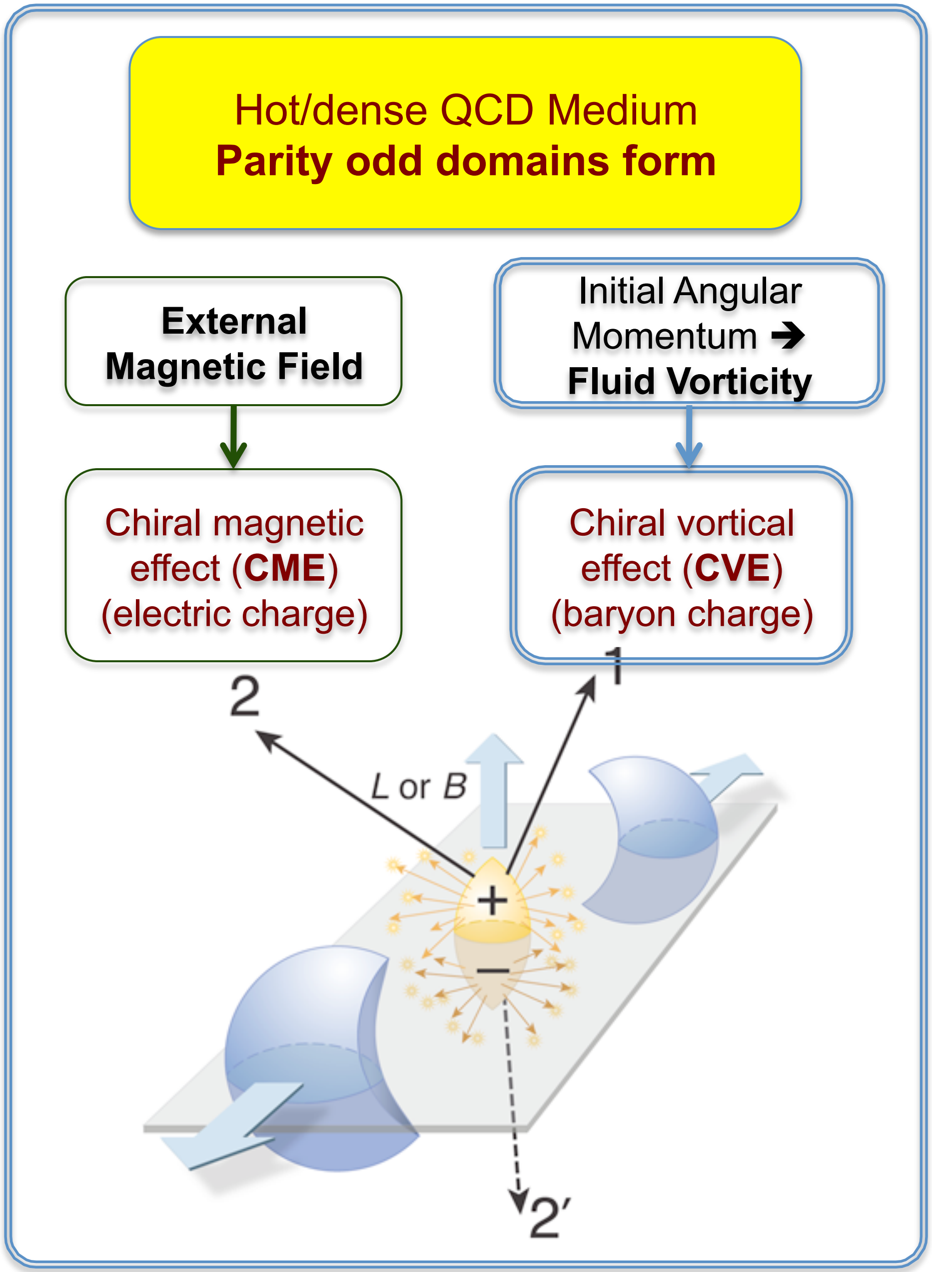
1) **$M_{ee} \leq 1 GeV/c^2$: In-medium broadened ρ**, model results* are consistent with exp. data. (* driven by the baryon density in the medium)

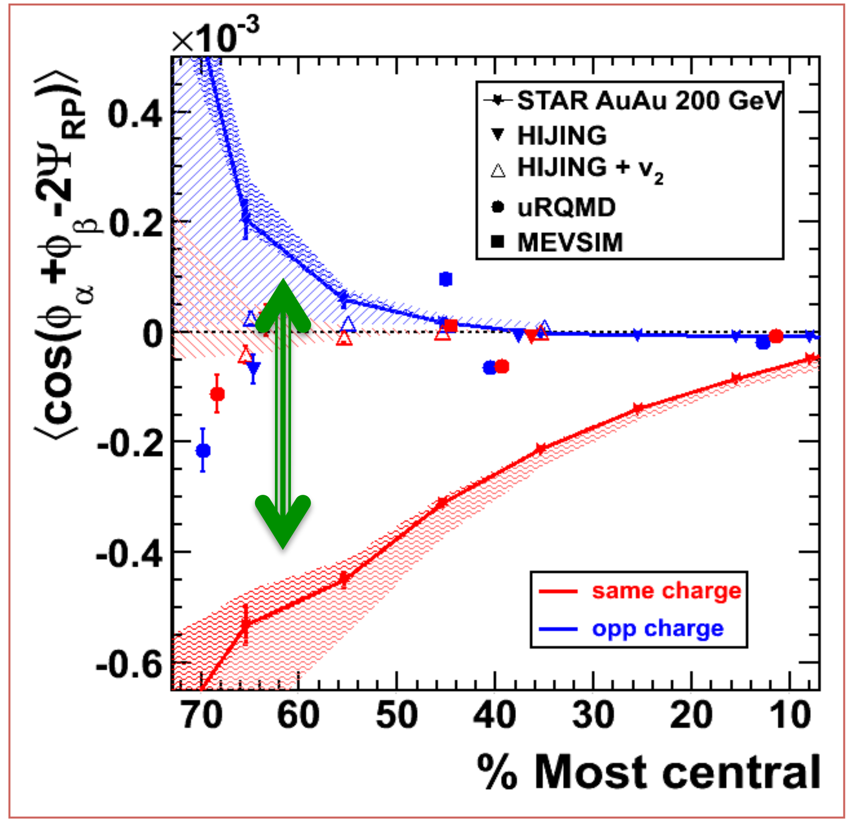
2) **$1 \leq M_{ee} \leq 3 GeV/c^2$:** Thermal radiation: $\exp(-M_{ee}/T)$? HFT: Charm contributions.

3) High statistics data are needed, **BES-II!**

- STAR: PRL113, 22301(14); arXiv:1312.7397
- R. Rapp: PoS CPOD13, 008(2013)
- O. Linnyk et al, PRC85, 024910(12)

Study Chiral Effects (Global)

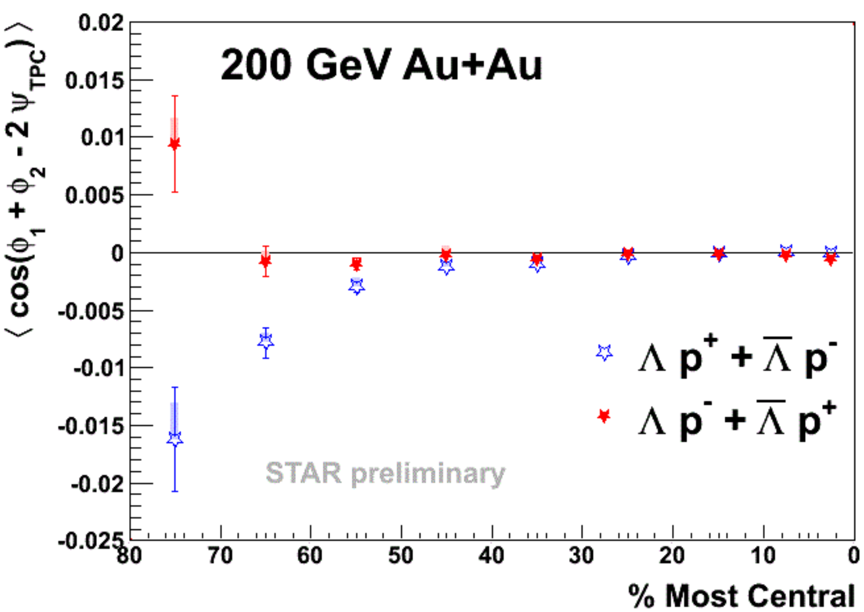


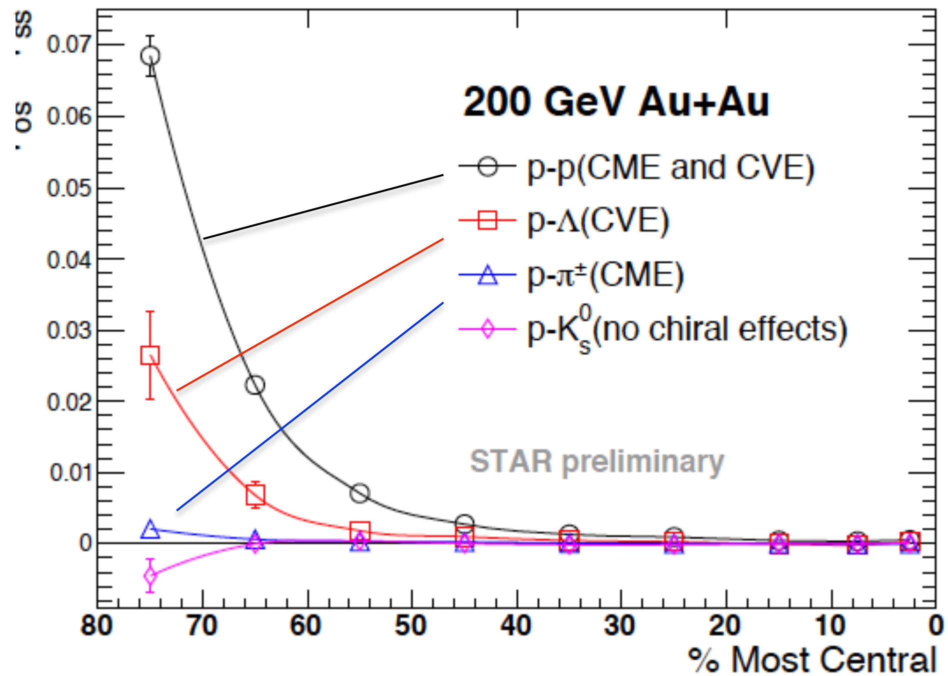


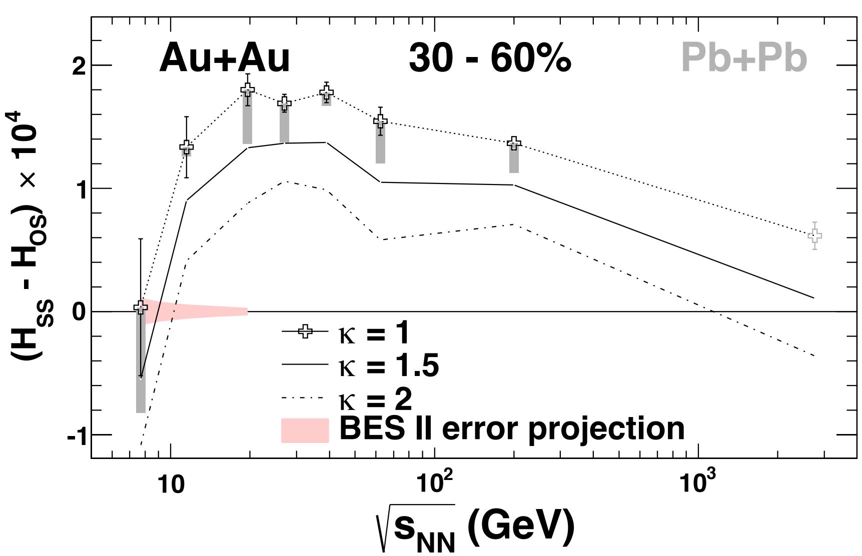
Charge pair correlation results are consistent with CME effect in non-central Au+Au collisions

STAR: F. Zhao, NPA931, c746(14)
PRL. 103, 251601(09) ; 113, 52302(14)
D. Kharzeev, D.T. Son, PRL106, 062301(11)
D. Kharzeev. PLB633, 260 (06)
D. Kharzeev, et al. NPA803, 227(08)

Charge Separation wrt Event Plane







1) **CVE**
2) **Global Chiral effect hierarchy:**
3) **LPV(CME) disappears at low energy:**

➔ hadronic interactions become dominant at $\sqrt{s_{NN}} \leq 11.5$ GeV

STAR: PRL. 103, 251601(09) ; 113, 52302(14)
Q.Y. Shou, NPA931, c758(14); F. Zhao, NPA931, c746(14)
L.W. Wen, poster at QM2015
D. Kharzeev. PLB633, 260 (06)
D. Kharzeev, et al. NPA803, 227(08)

The BES-II Program at RHIC

BES II Related Upgrades

1) RHIC Electron Cooling:

- Luminosity increase by factors of 3-10 for $5<\sqrt{s_{NN}}<20$ GeV

2) 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

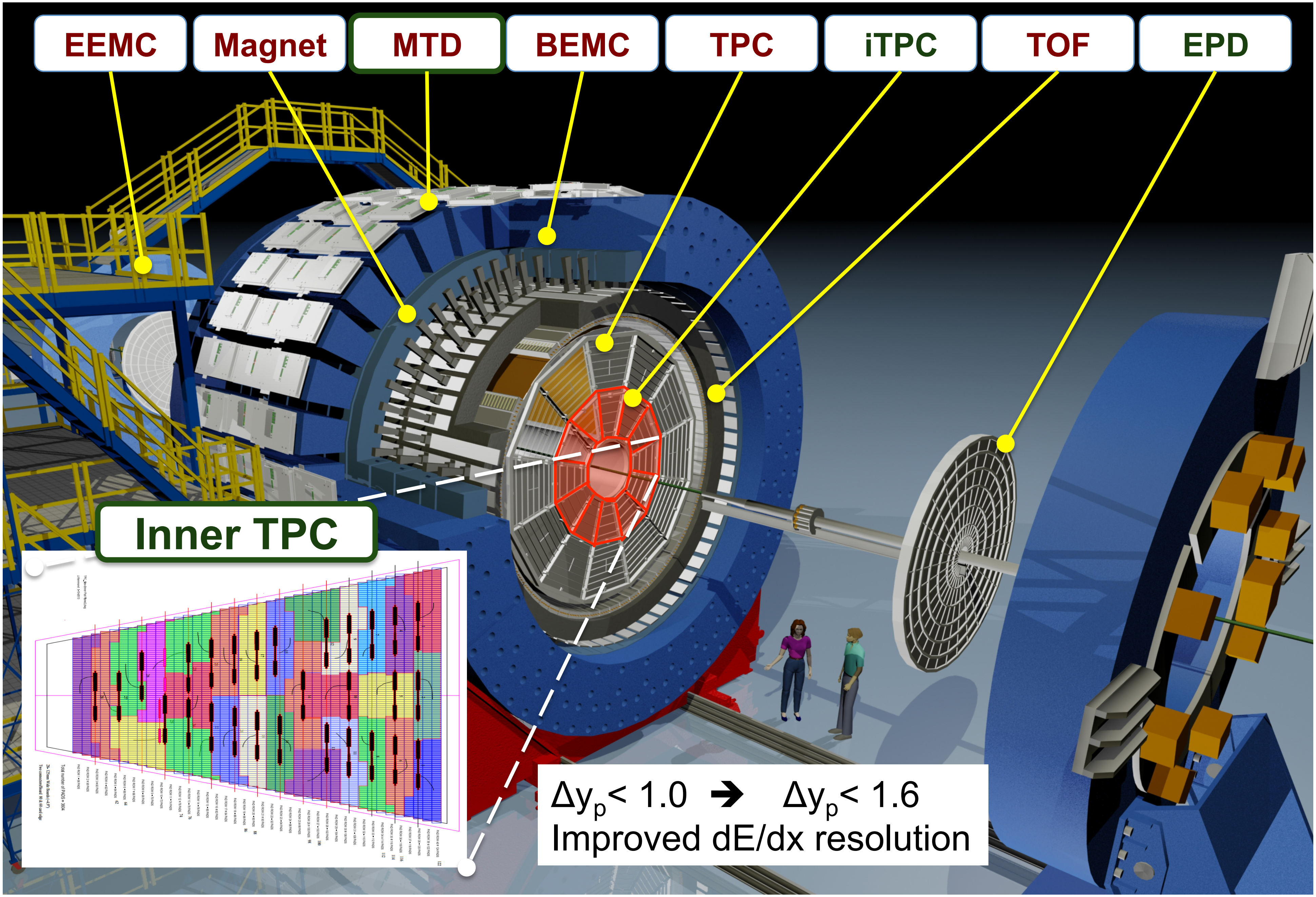
3) Event Plane Detector (EPD):

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

4) End Cap TOF (eTOF) – (CBM-STAR):

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

STAR Detector System

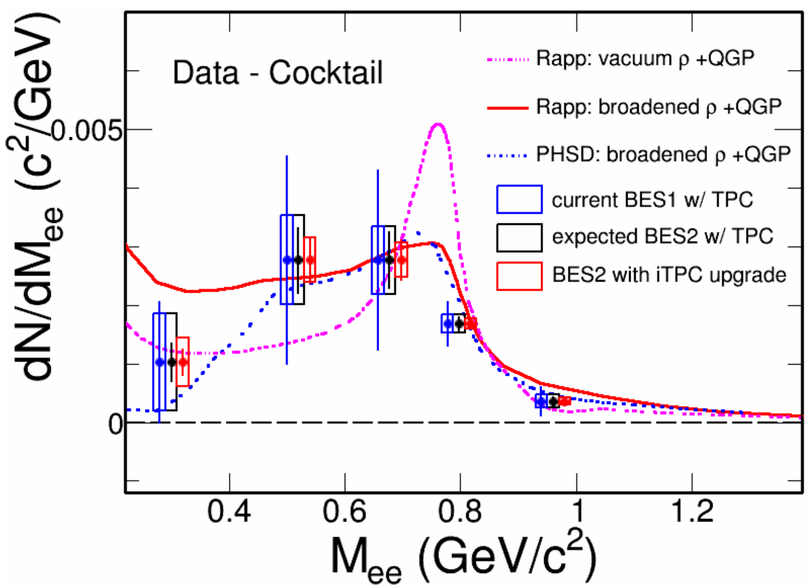


Event Statistics for BES II at RHIC

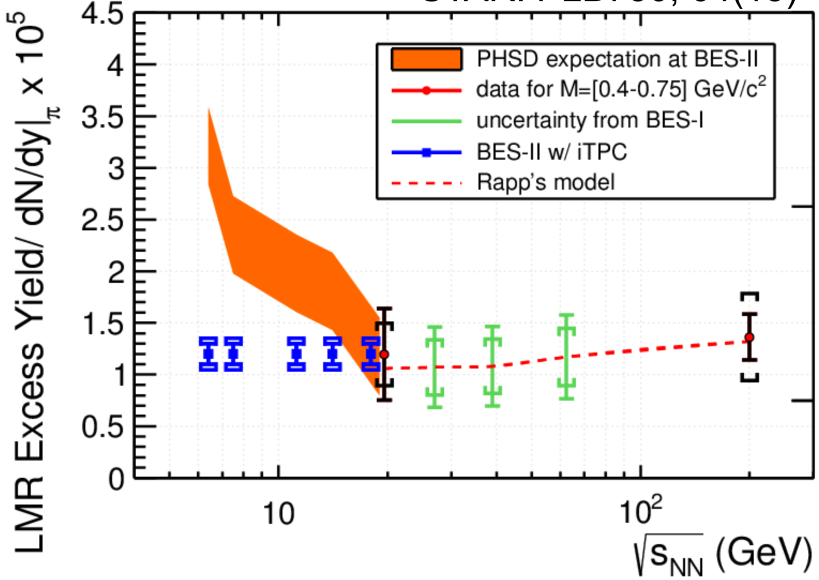
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-20** / 2011	**3**	206	160
14.5	**300** / 20	**2019-20** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-20** / 2010	**5**	315	152
9.2	**160** / 0.03	**2019-20** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-20** / 2010	**14**	420	140

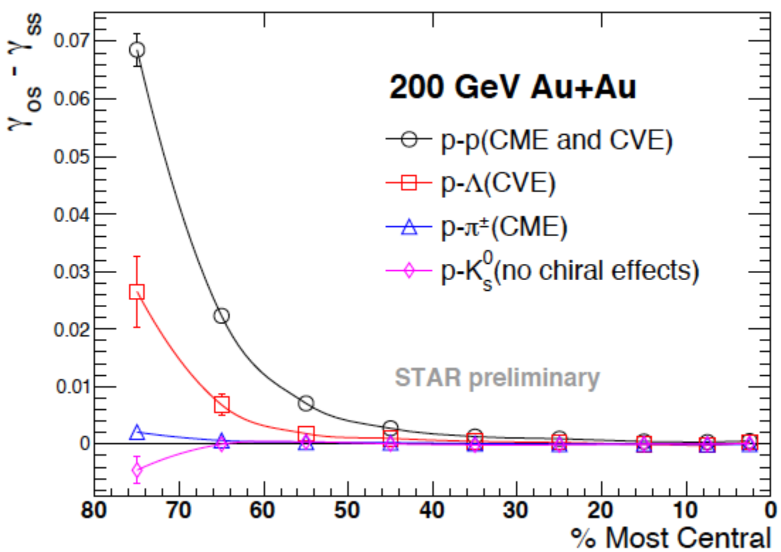
1) Event statistics driven by QCD CP search and di-electron measurements

BES-II: Chiral Properties



STAR: PLB750, 64(15)



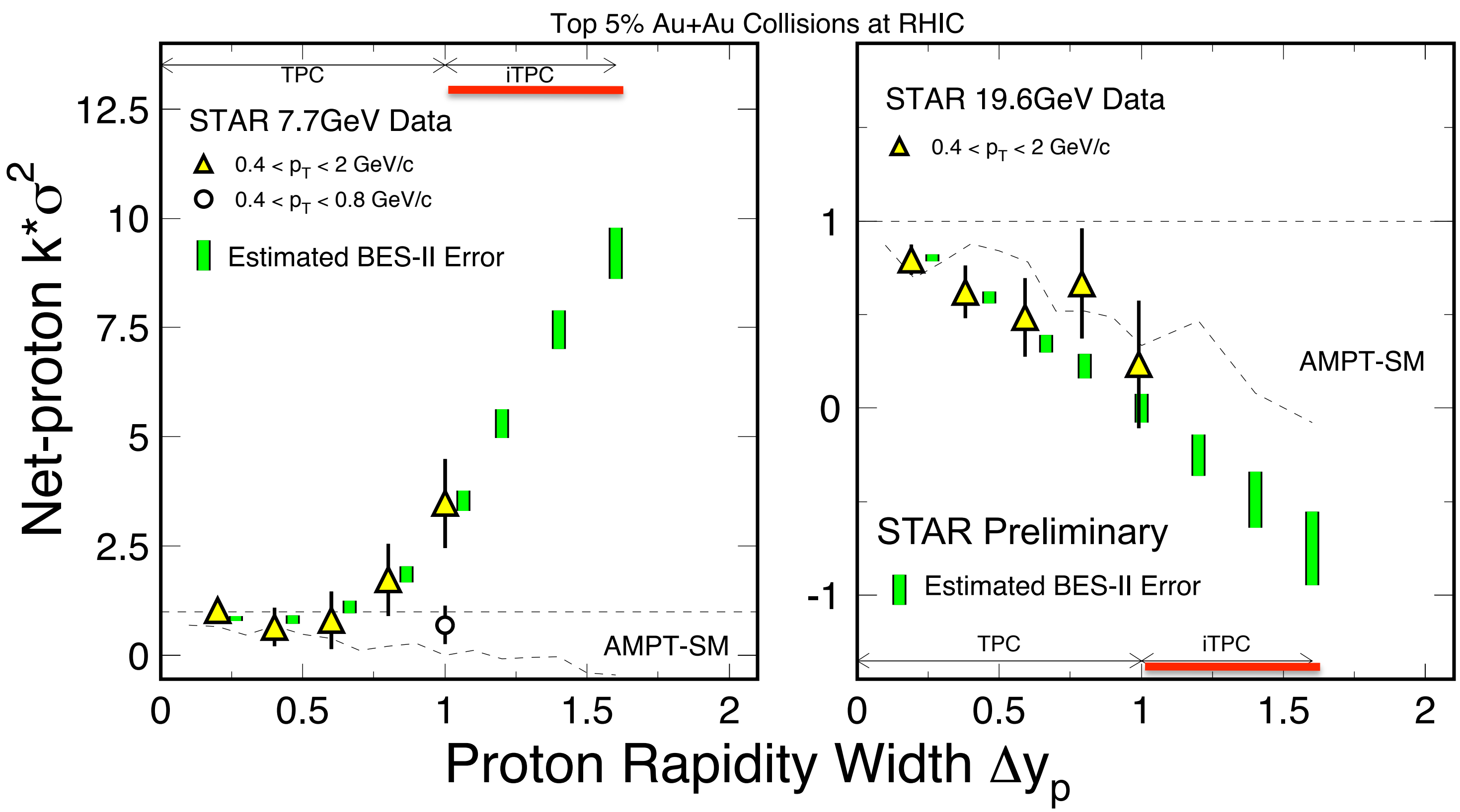


High net-baryon region:

1) Precision measurements on di-electron distributions

2) Global Chiral properties with identified hadrons

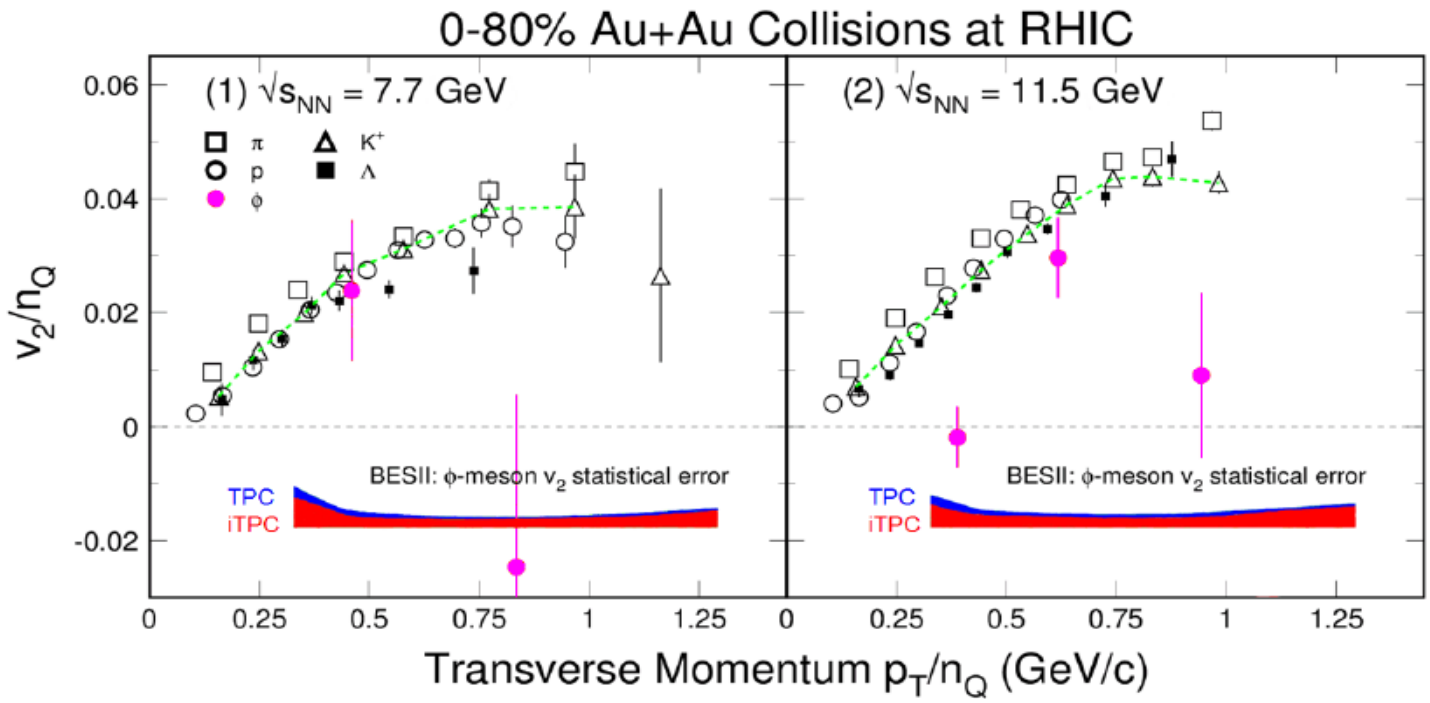
BES-II: Critical Point



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

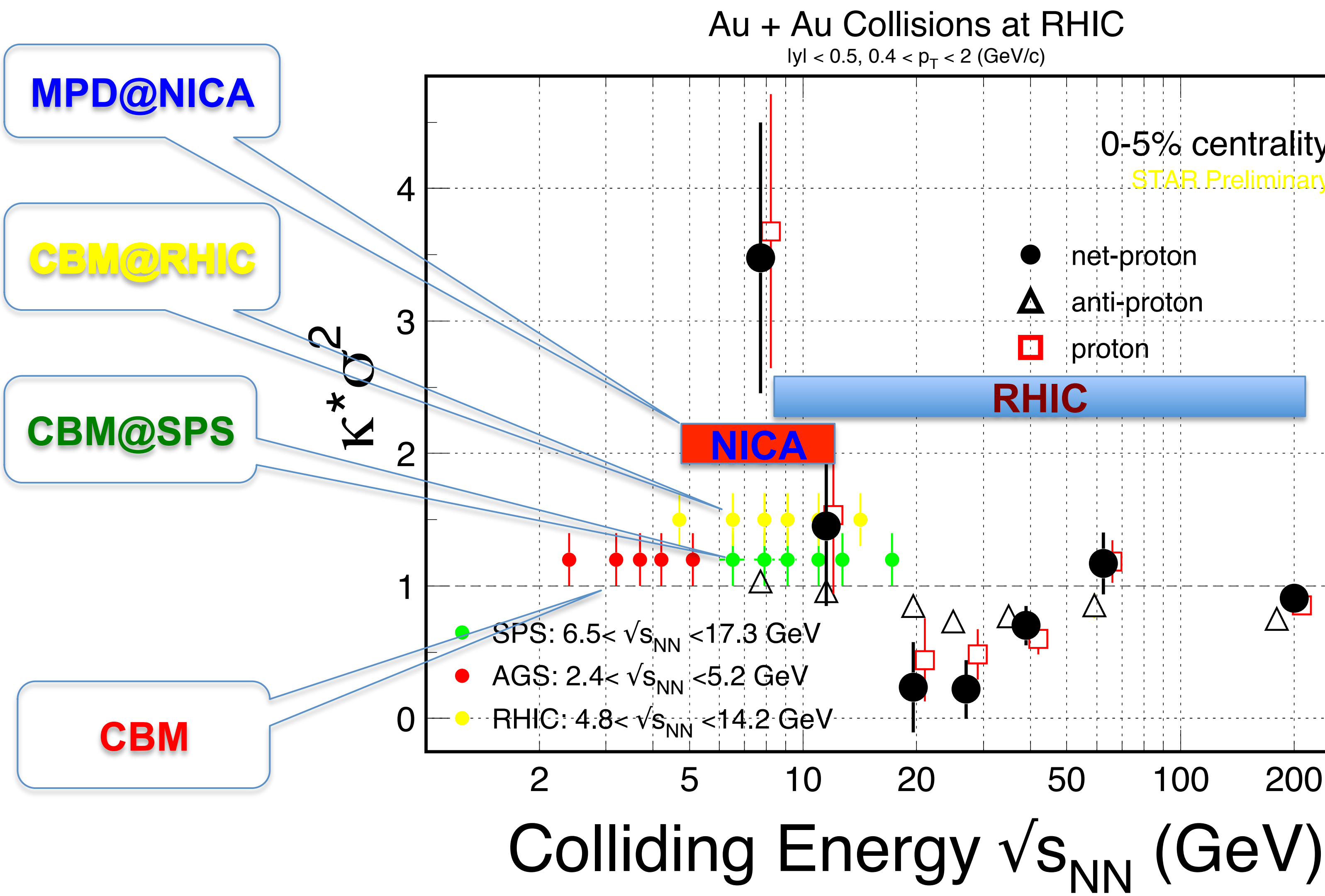
BES-II: Collectivity



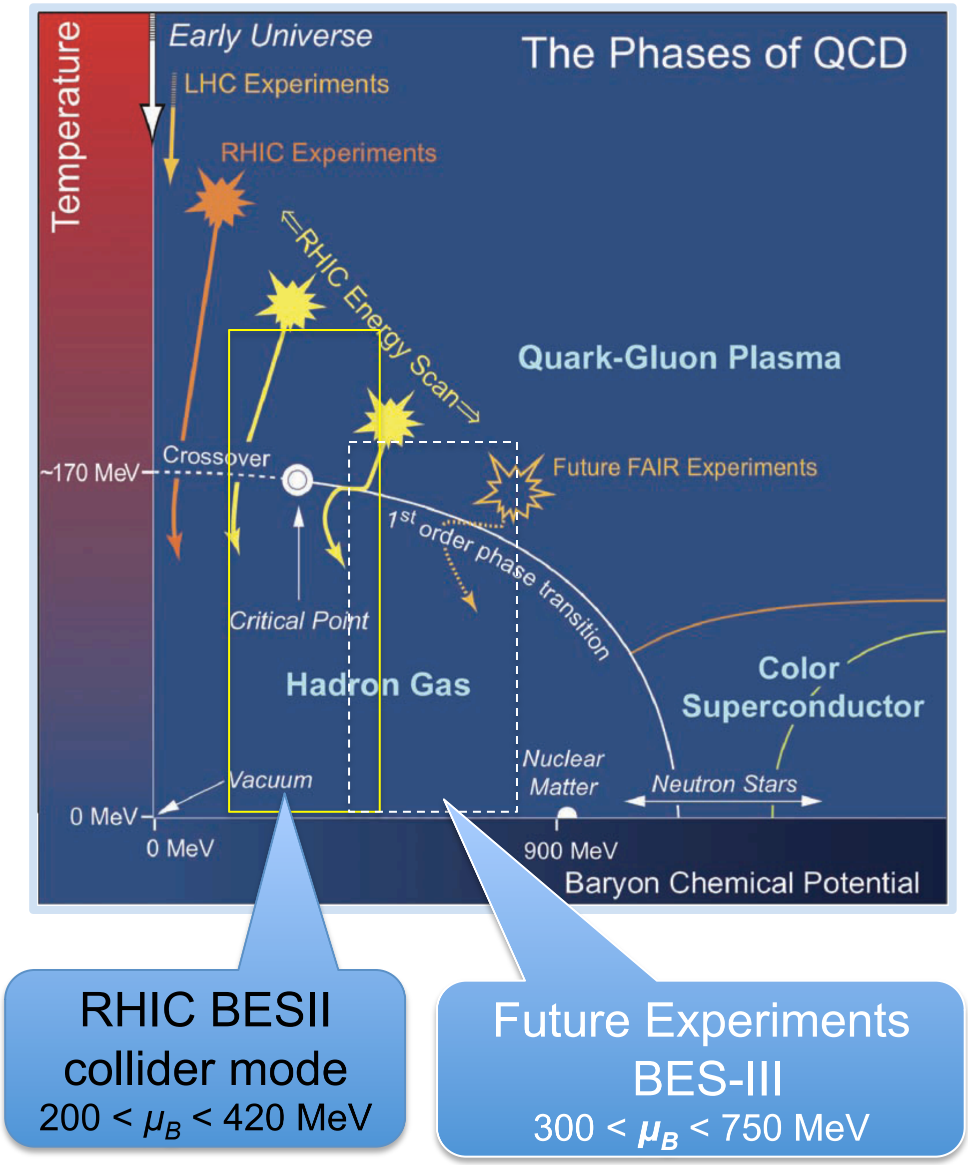
1) Precision measurement for φ-meson v_2

2) Study the partonic vs. hadronic interactions in the high net-baron region

Future Experiments



Summary



2019-2020: RHIC e-cooling and iTPC upgrades bring BES-II: 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) The QCD critical point (region) and phase boundary
2) Properties with Chiral symmetry

2020 and beyond: fixed-target experiments at large net-baryon density: 300 < μ_B < 750 MeV (12 < $\sqrt{s_{NN}}$ < 3 GeV)

Thank You!