Study the QCD Phase Structure at the *High Baryon Density*

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Outline:

1) Introduction
2) Selected results from RHIC BES-I
3) Selected day-I observables for CBM

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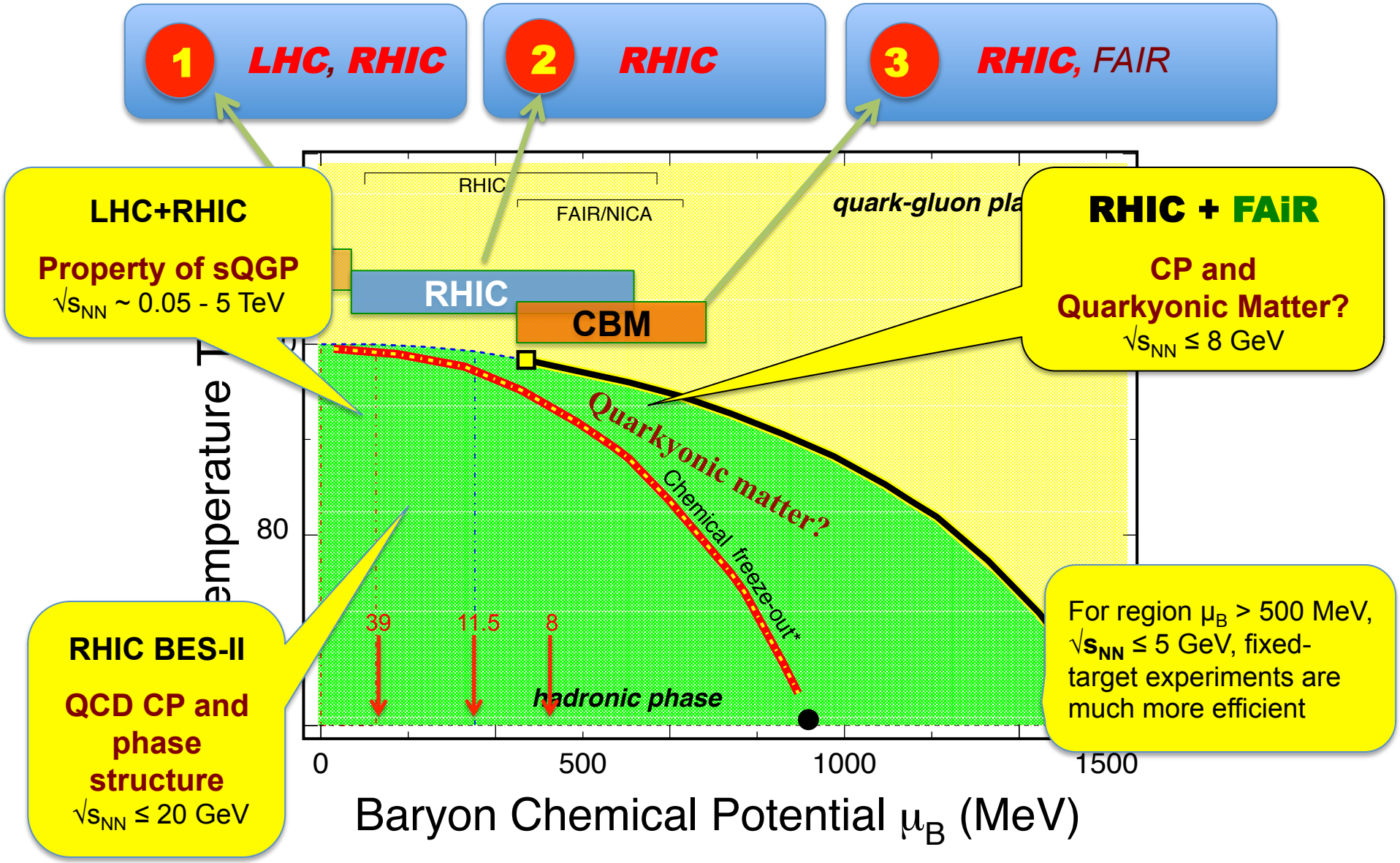
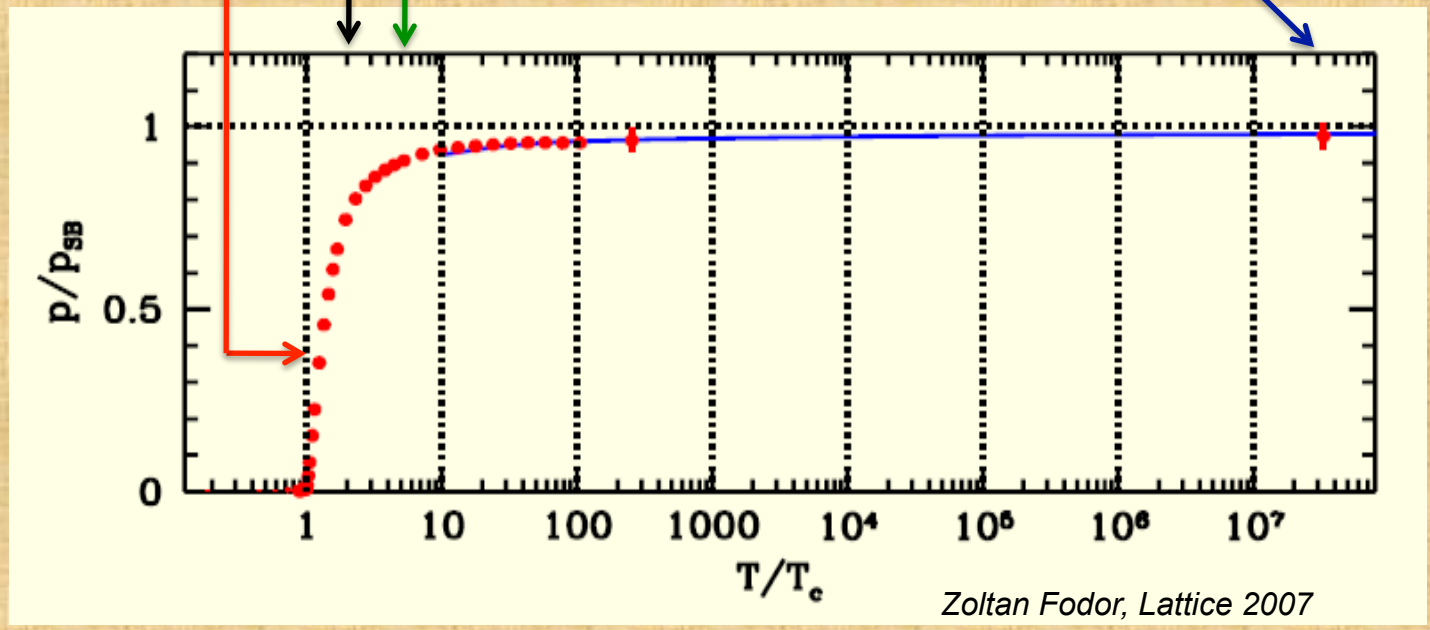
Exploring QCD Phase Structure

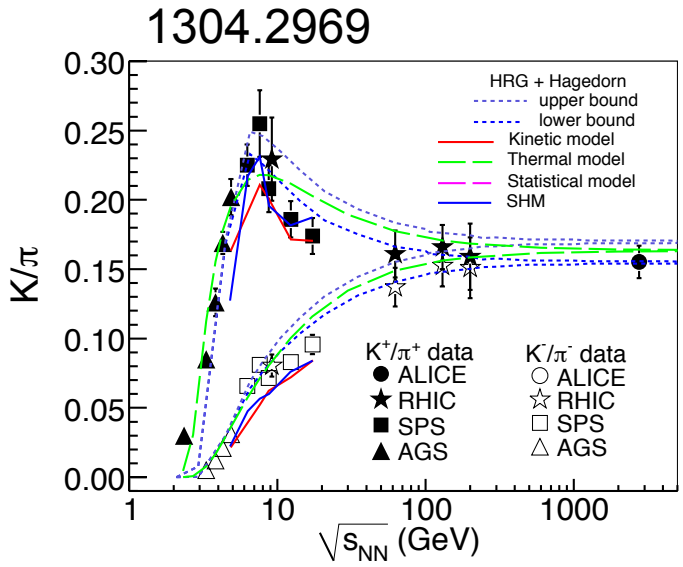


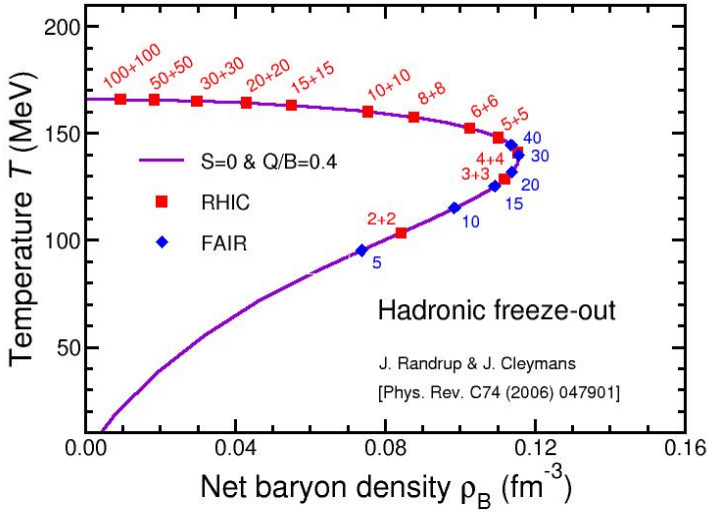
QCD Thermodynamics

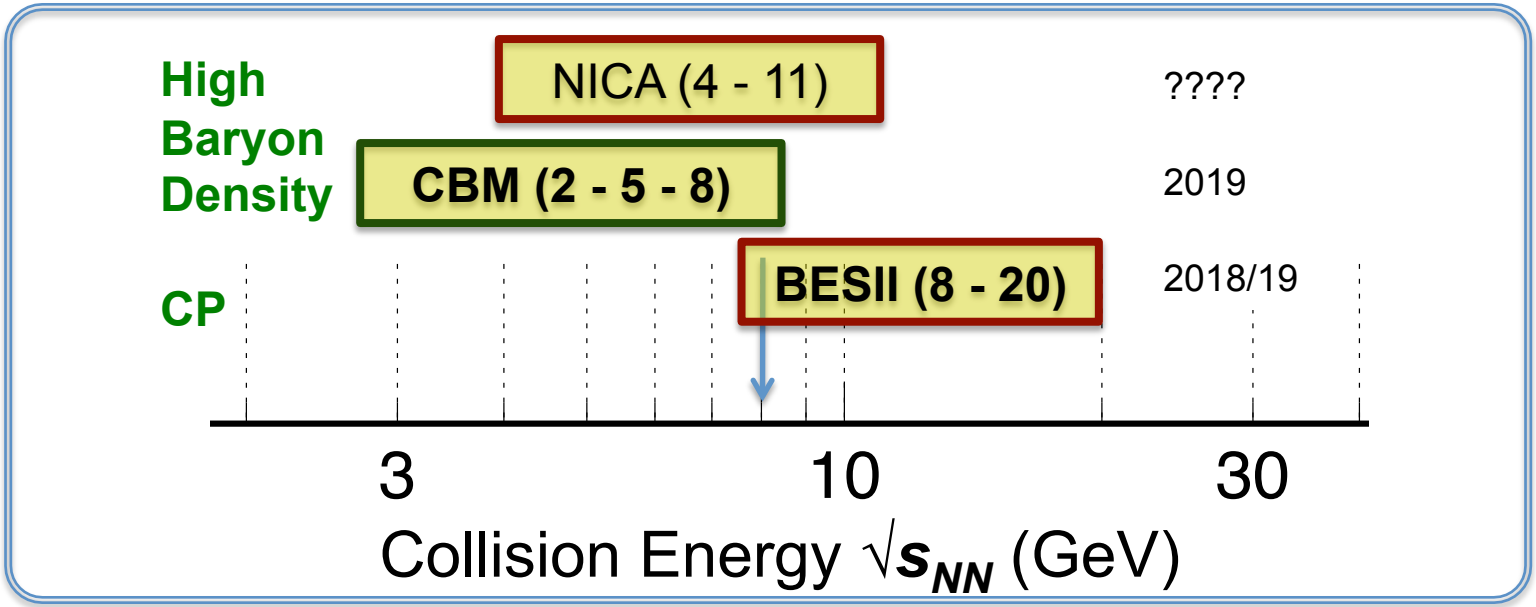


1) At $\mu_B = 0$: cross over transition, $150 < T_c < 200$ MeV
2) The SB ideal gas limit: $T/T_c \sim 10^7$
3) T_{ini}(LHC) ~ 2-3*T_{ini}(RHIC)
4) Thermodynamic evolutions are similar for RHIC and LHC

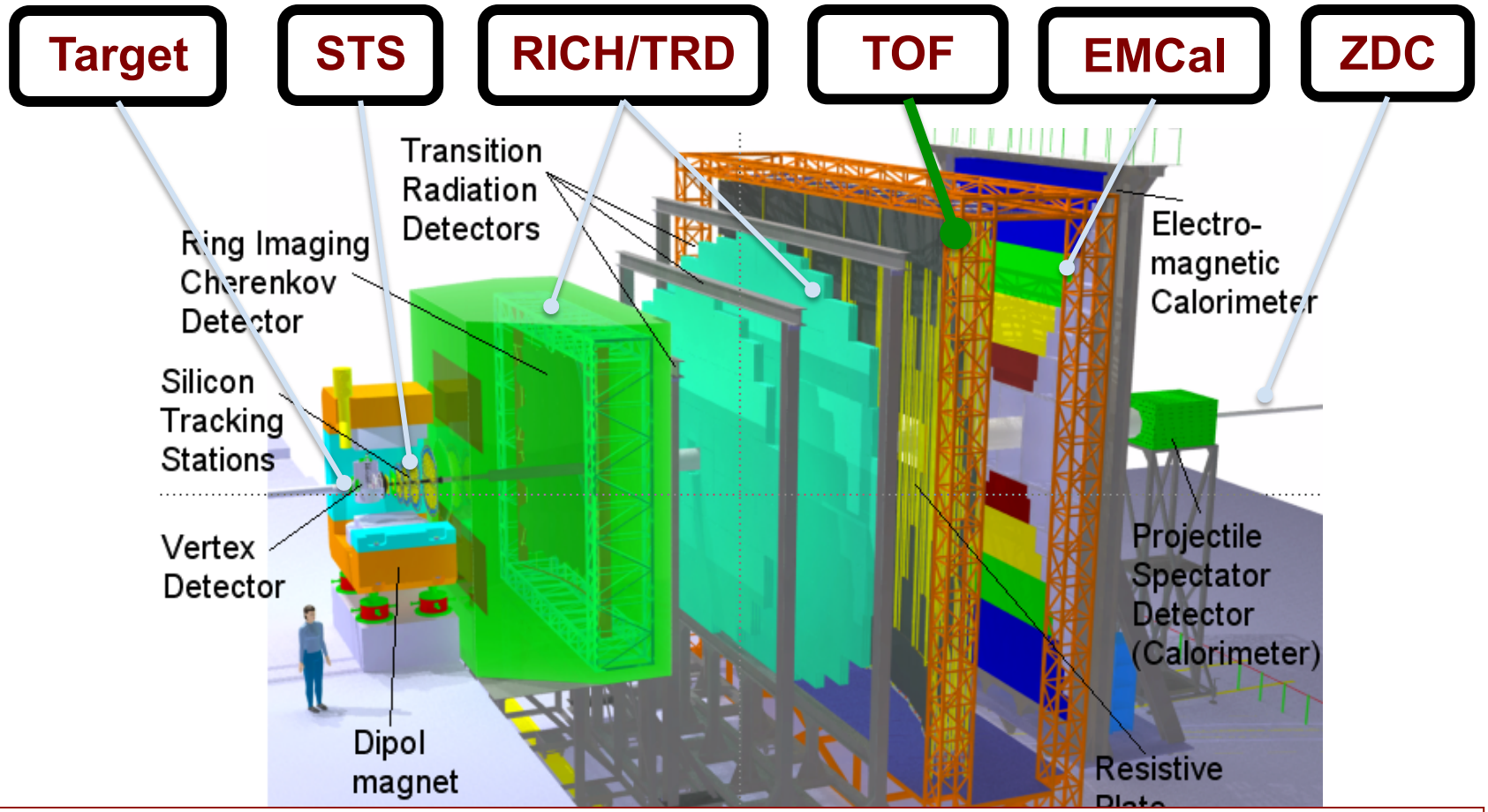
Baryon Density Peaks at ~ $\sqrt{s_{NN}}$ = 8 GeV







The CBM Experiment

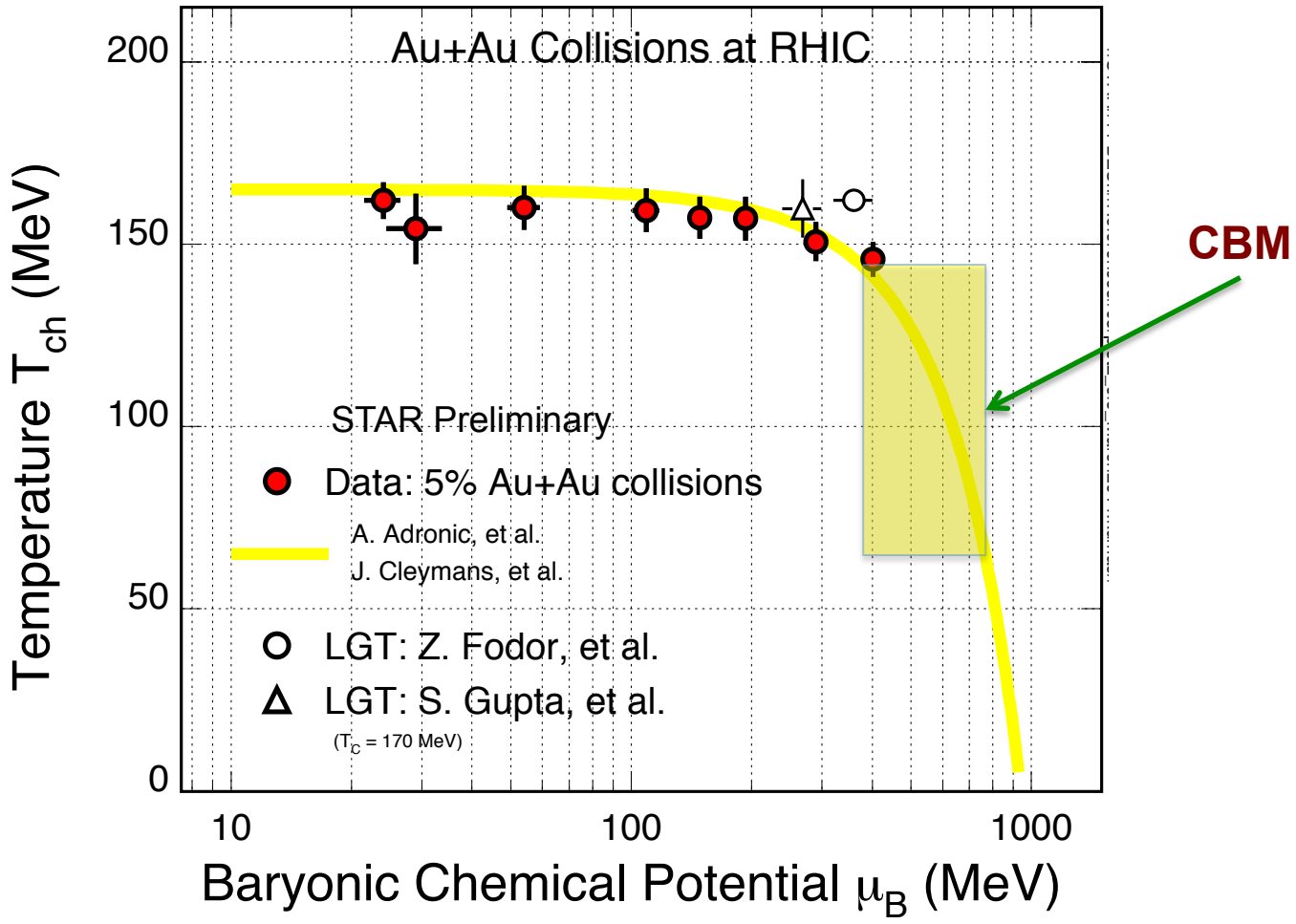


FAIR: the highest intensity accelerator complex in the 21st century

Precision measurements at high baryon density region for:

(i) dileptons (***e, μ***); (ii) high order baryon correlations; (iii) flavor productions (***s, c***)

Bulk Properties at Freeze-out

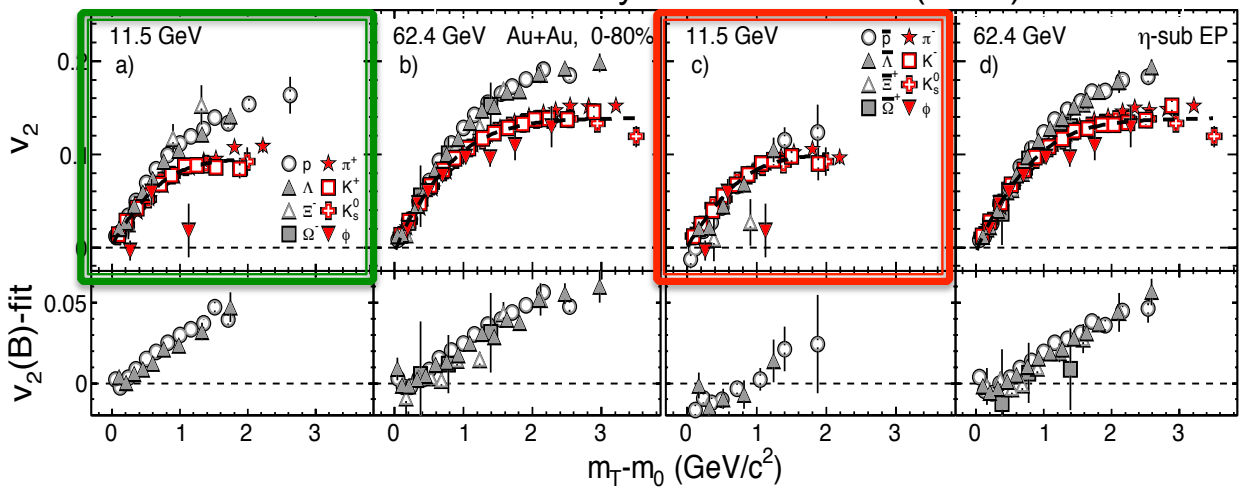


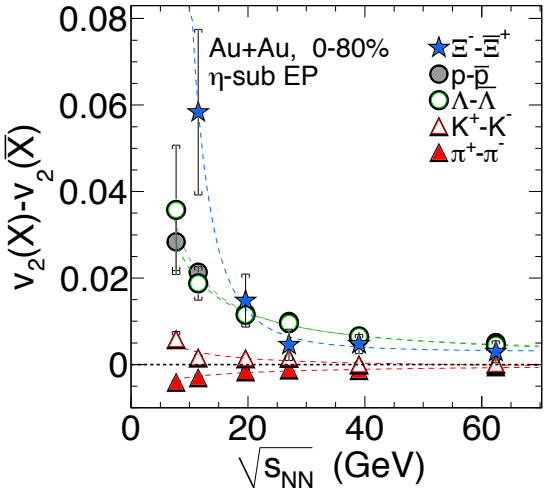
Chemical Freeze-out: (GCE)

- RHIC (20 ≤ μ_B ≤ 420 MeV): small temperature variation
- CBM (400 ≤ μ_B ≤ 750 MeV): temperature changes dramatically!

Collectivity v_2 Measurements

STAR: Phys. Rev. Lett. **110** (2013) 142301

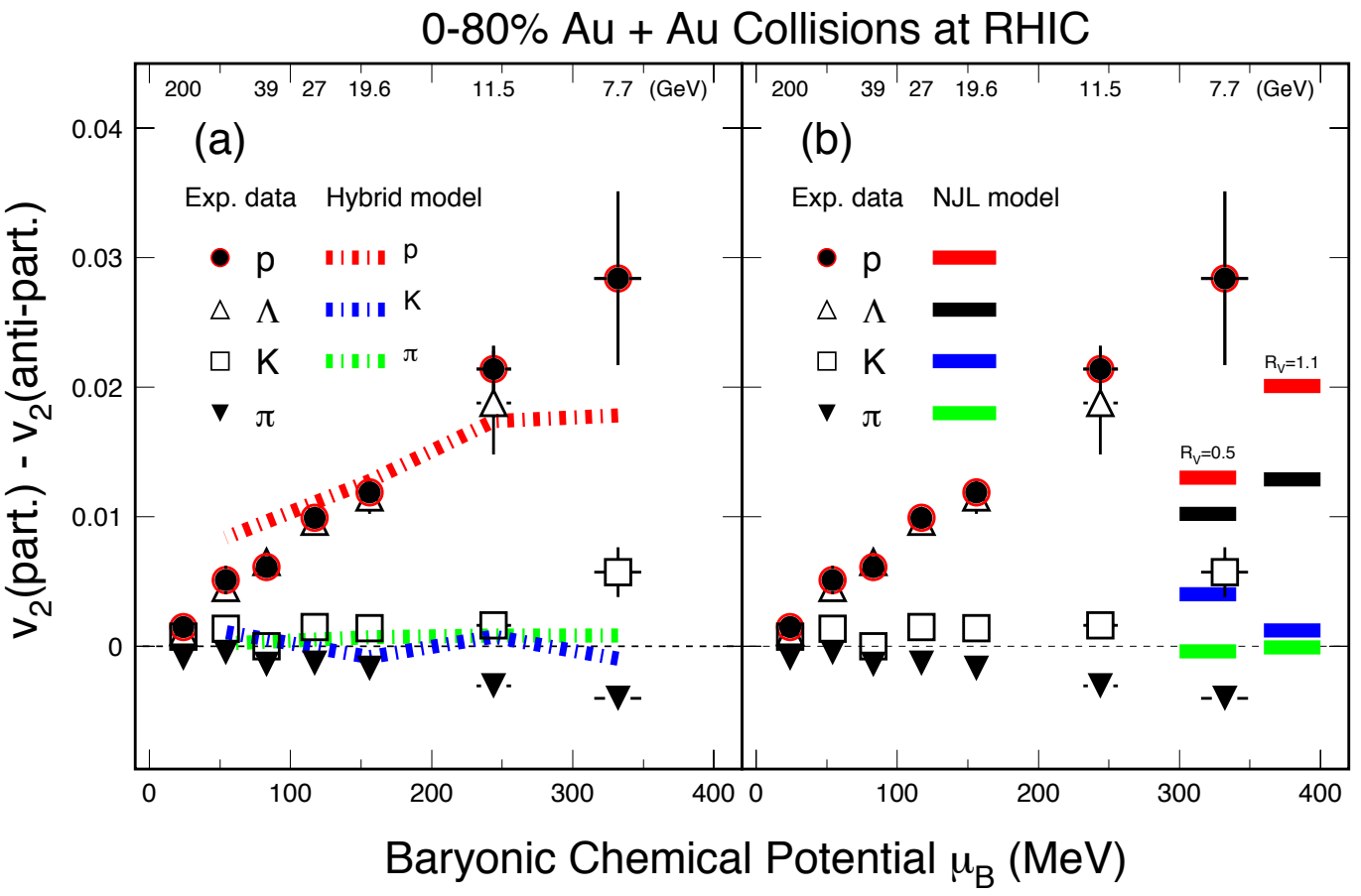




1) Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions

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

BES v_2 and Model Comparison



(a) Hydro + Transport: consistent with baryon data.

[J. Steinheimer, V. Koch, and M. Bleicher PRC86, 44902(13).]

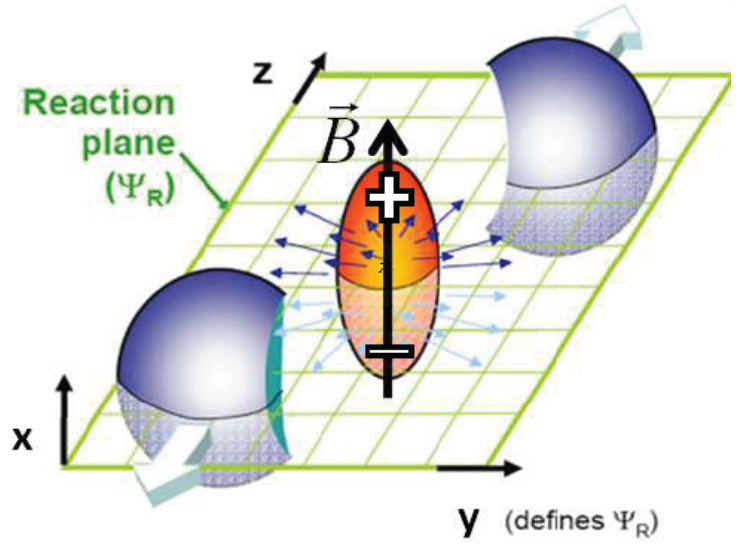
(b) NJL model: Hadron splitting consistent. Sensitive to vector-coupling, **CME, net-baryon density dependent.** [J. Xu, et al., arXiv:1308.1753/PRL112.012301]

Chiral Effects

Hot/dense QCD Medium
Parity odd domains form

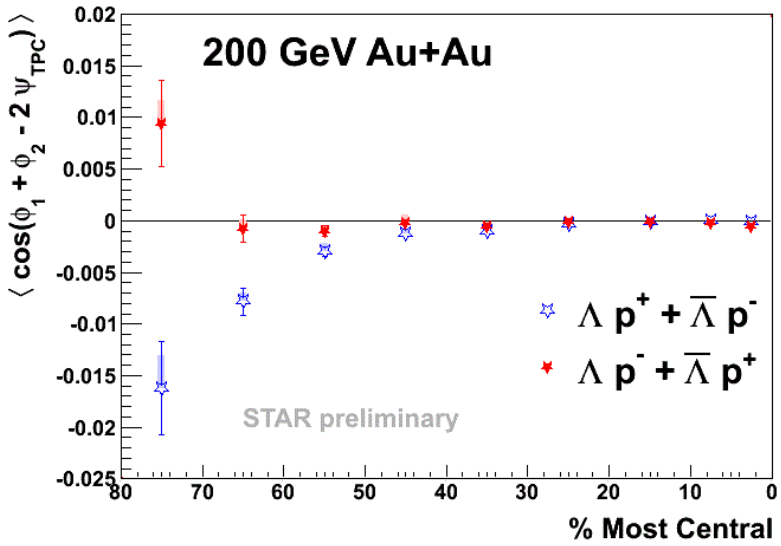
External Magnetic Field → Chiral magnetic effect (**CME**) (electric charge)

Initial Angular Momentum → **Fluid Vorticity** → Chiral vortical effect (**CVE**) (baryon charge)



Chiral Vortical Effect

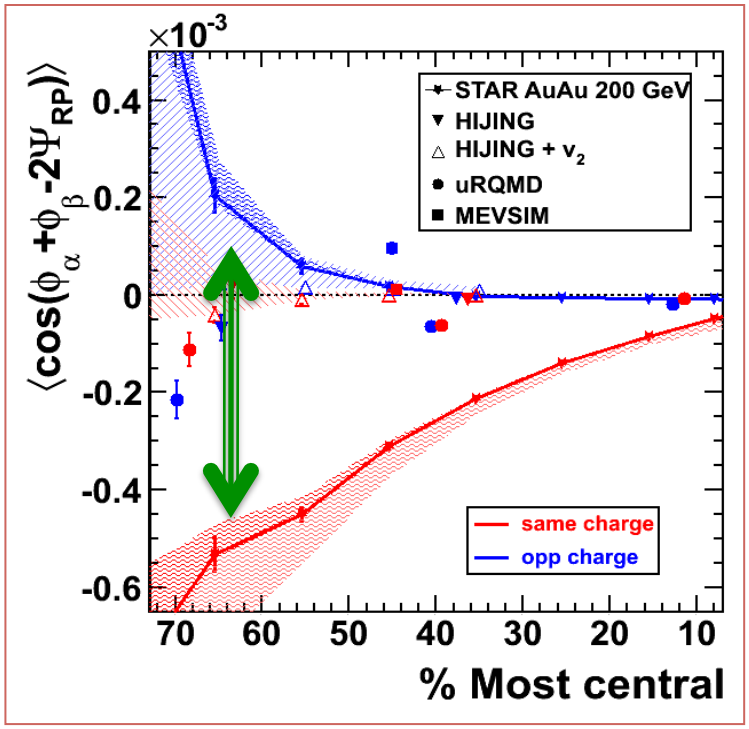
Λ-proton correlation measurement:



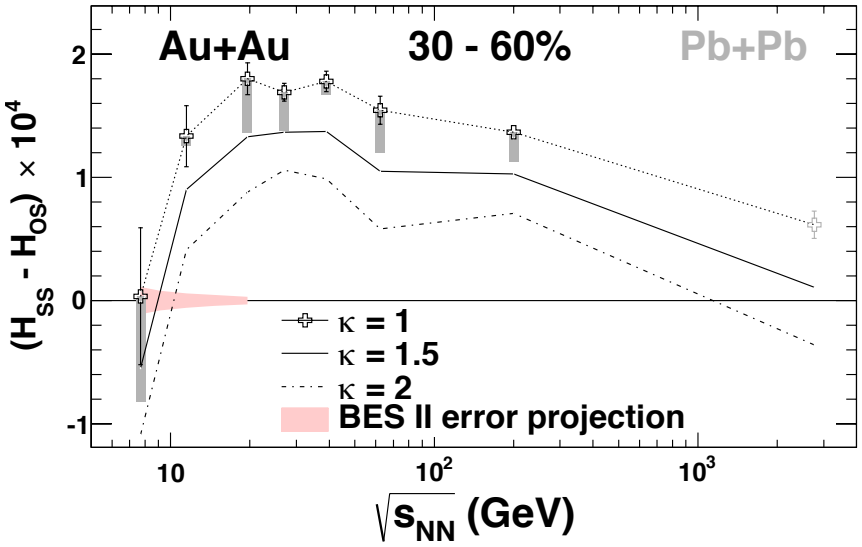
1) The opposite baryon number (Λ-pbar or Λbar-p) correlations (OB) are similar
2) The same baryon number (Λ-p or Λbar-pbar) correlations (SB) are lower than that of the OB, ***as expected from the CVE.***

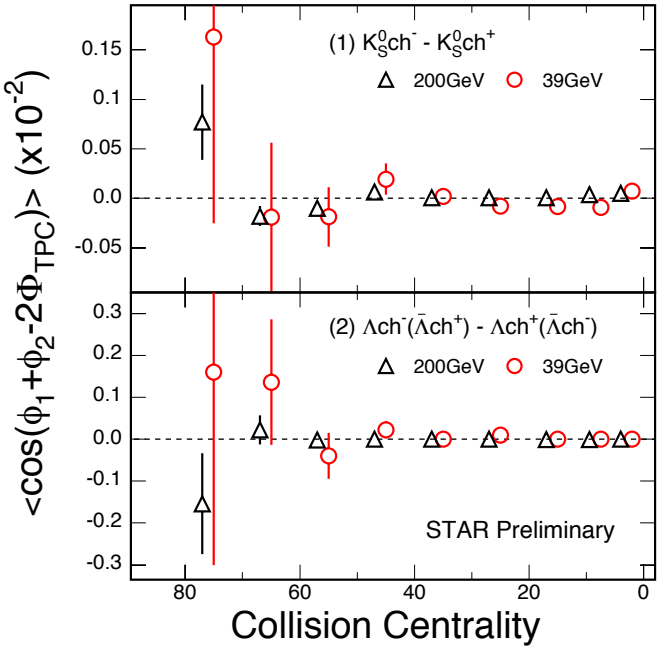
D. Kharzeev, D.T. Son, PRL106, 062301(11)
D. Kharzeev. PLB633, 260 (06)
D. Kharzeev, et al. NPA803, 227(08)

Charge Separation wrt Event Plane



STAR: submitted to PRL, arXiv: 1404.1433



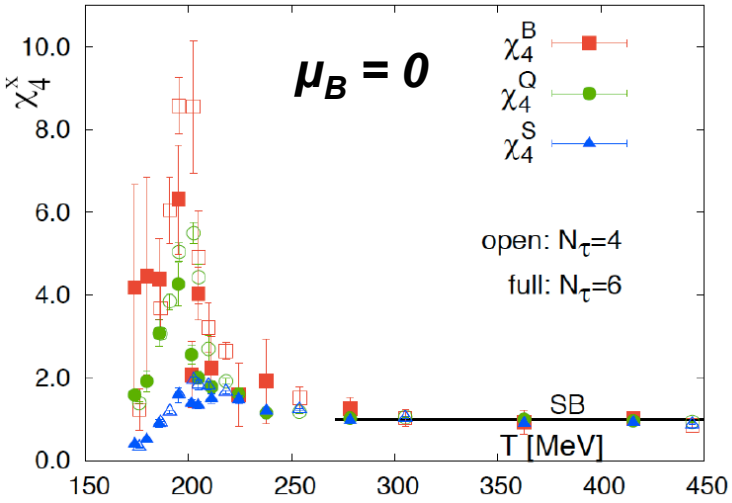


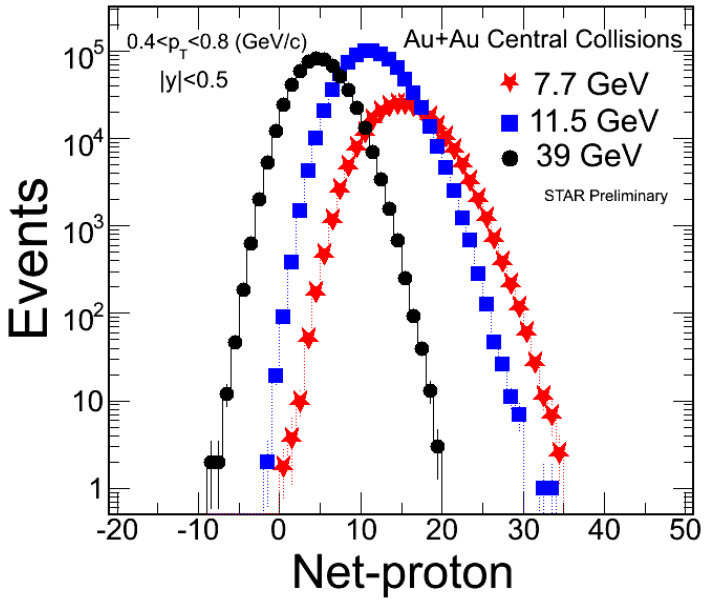
LPV(CME) disappears: with neutral hadrons:

LPV(CME) disappears at low energy:
➔hadronic interactions become dominant at $\sqrt{s_{NN}} \leq 11.5$ GeV

STAR: PRL. 103, 251601(09)
D. Kharzeev. PLB633, 260 (06)
D. Kharzeev, et al. NPA803, 227(08)

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:

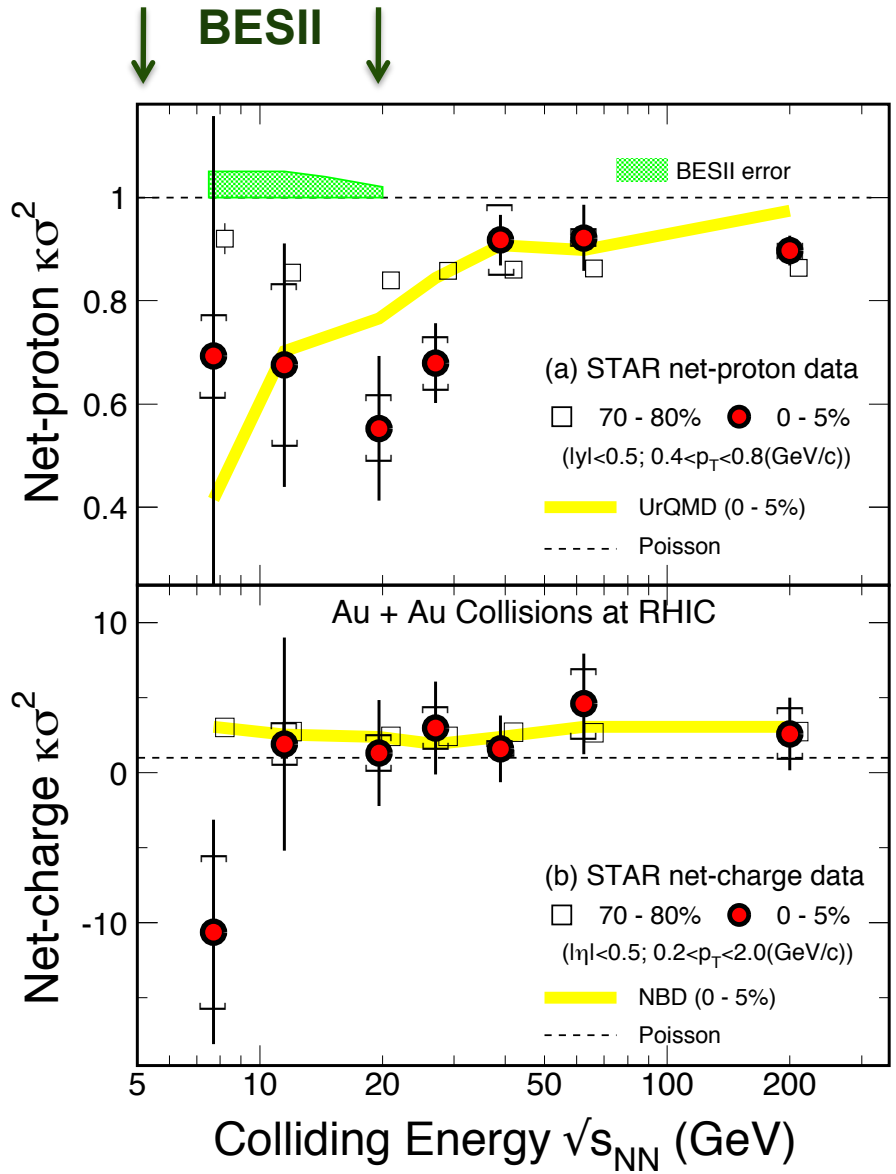
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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)

Higher Moments Results



Net-proton results:

1) All data show deviations below Poisson for $\kappa\sigma^2$ at all energies. Larger deviation at $\sqrt{s_{NN}}$~20GeV
2) UrQMD model shows monotonic behavior in the moment products

*STAR: **PRL112**, 32302(14)/arXiv: 1309.5681*

Net-charge results:

1) No non-monotonic behavior
2) More affected by the resonance decays

STAR: arXiv: 1402.1558
P. Garg et al, PLB726, 691(13)

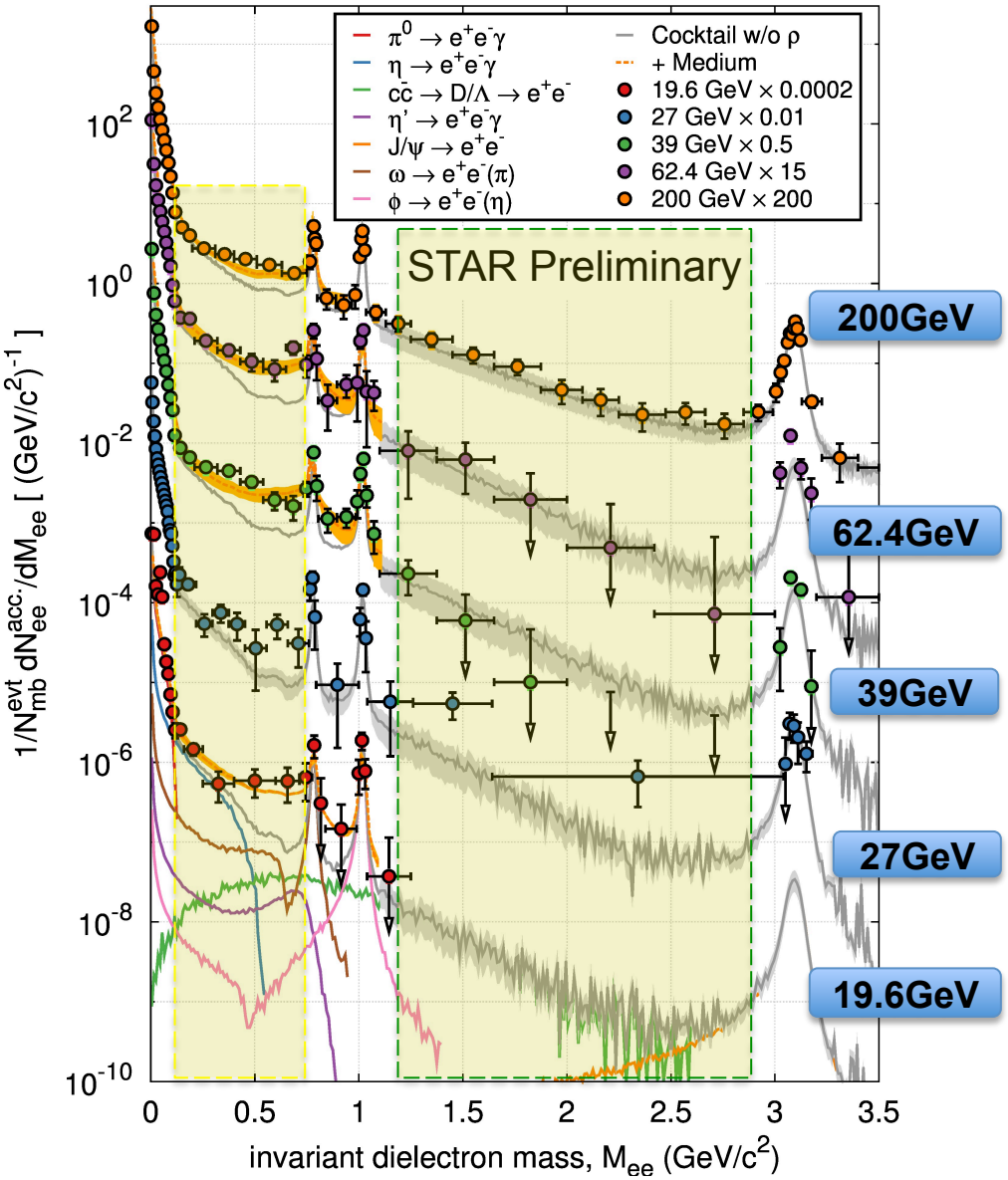
BESII is needed:

Higher statistics needed for collisions at $\sqrt{s_{NN}} < 20$ GeV

Comparing to LGT calculations

T_f = 146 ± 6 MeV , $\sqrt{s_{NN}}$ > 39 GeV

Energy Dependence of Di-electrons



Bulk-penetrating probe:

1) **$M_{ee} \leq 1GeV/c^2$:** In-medium broadened ρ, model results* are consistent with exp. data. At 200GeV, the enhancement is in the order of **1.77±0.11 ±0.24±0.33** within $0.3<M_{ee}<0.7GeV/c^2$) (* driven by the baryon density in the medium)

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

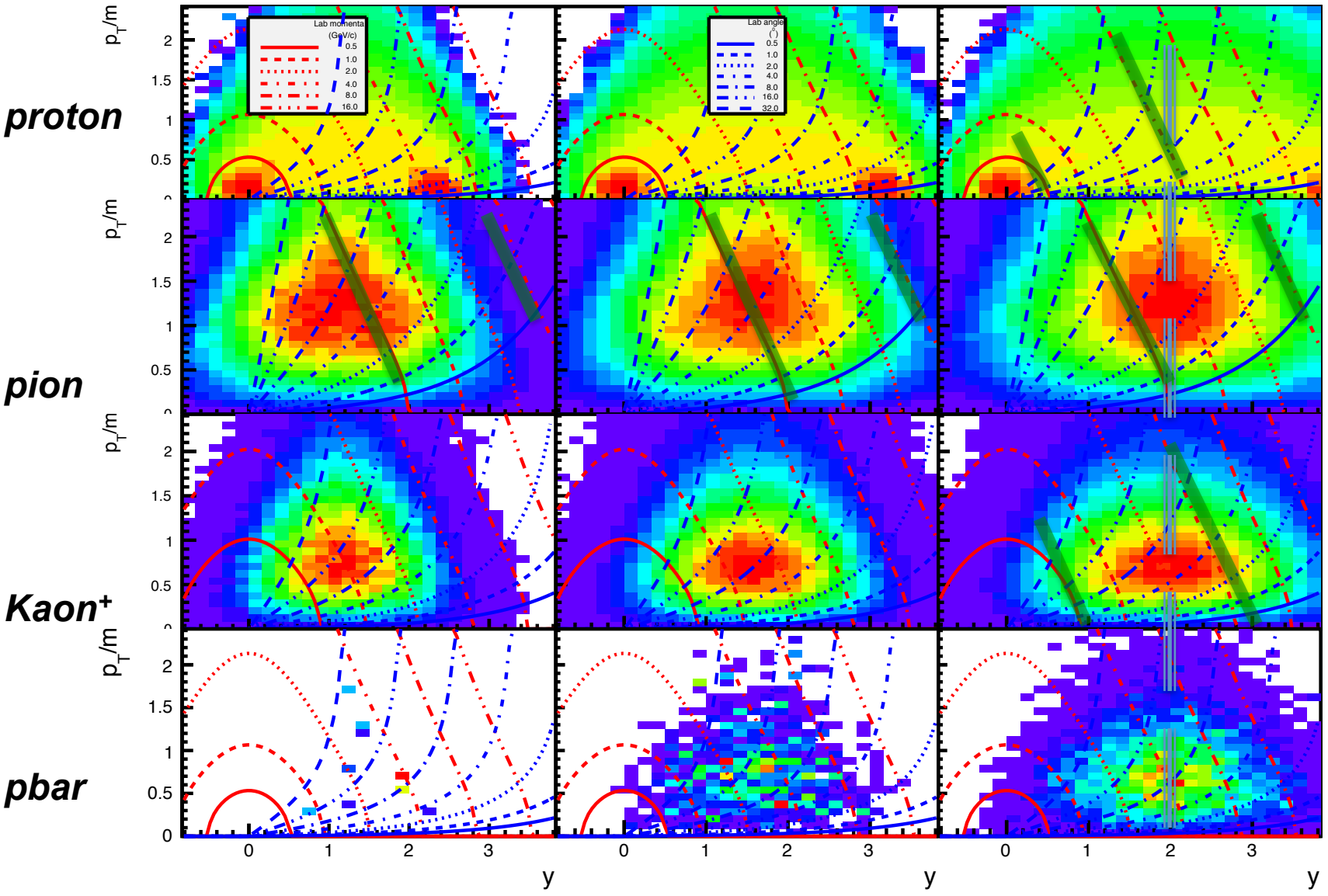
3) High statistics data are needed, **BESII!**

- STAR: (200GeV data) sub. to PRL. 1312.7397
- R. Rapp: PoS CPOD13, 008(2013)
- O. Linnyk et al, PRC85, 024910(12)

Day-I Observables at CBM

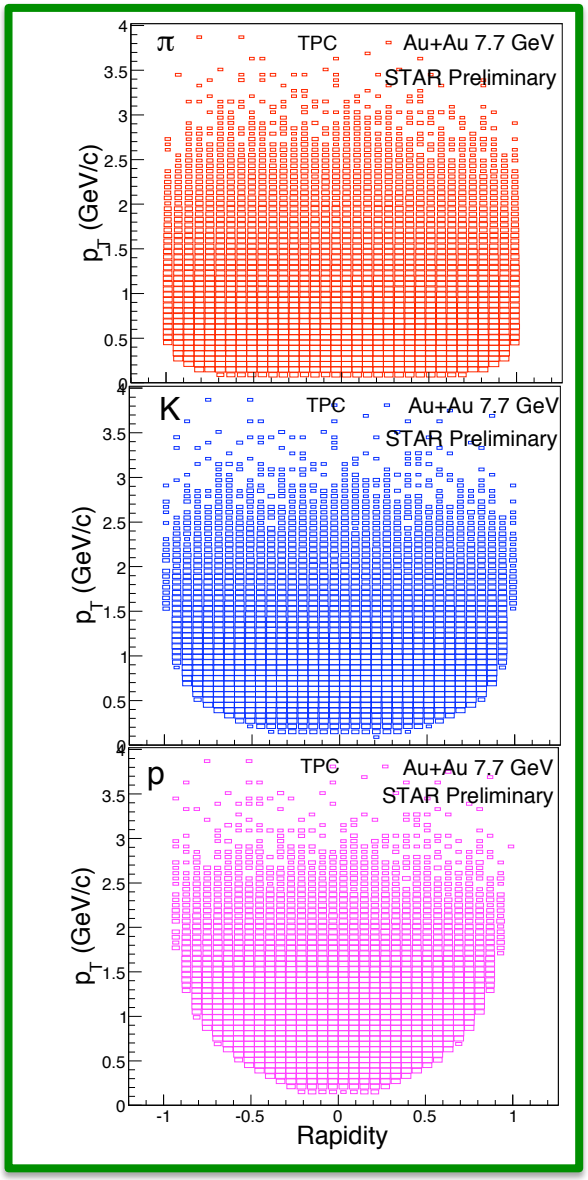
- Hadron spectra and anisotropies: π, K, p, Φ, Λ, Ξ, Ω
  - Freeze-out property
  - Phase boundary
- Baryon/strangeness correlations: κ(net-Q, net-p, net-s)
  - Critical point, phase boundary
  - Global Chiral effect
- Dilepton spectra $m_{ll}(b, p_T, A)$
  - Chiral property, quarkyonic matter
- Exotics, …

Phase Space vs. Acceptance

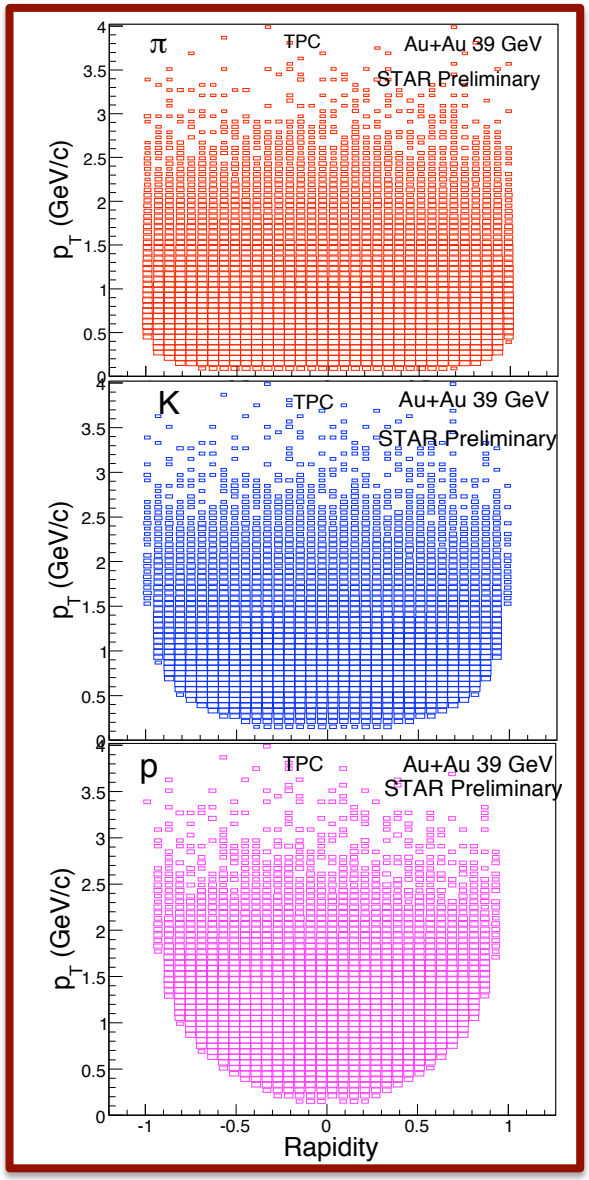


STAR PID for (π, K, p)

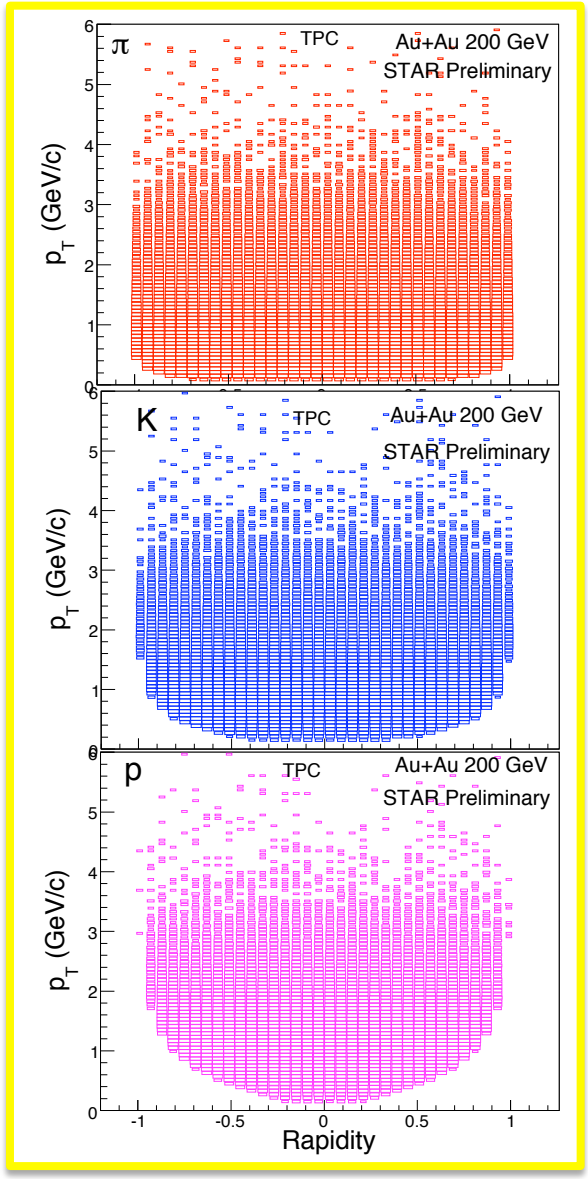
Au+Au at *7.7* GeV



Au+Au at *39* GeV



Au+Au at *200* GeV



Exploring QCD Phase Structure