Recent Results from RHIC Beam Energy Scan-I

Nu Xu[1,2]

Outline:

1) Introduction

2) Selected results from BES-I at RHIC

3) Summary and outlook

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Exploring QCD Phase Structure

LHC+RHIC

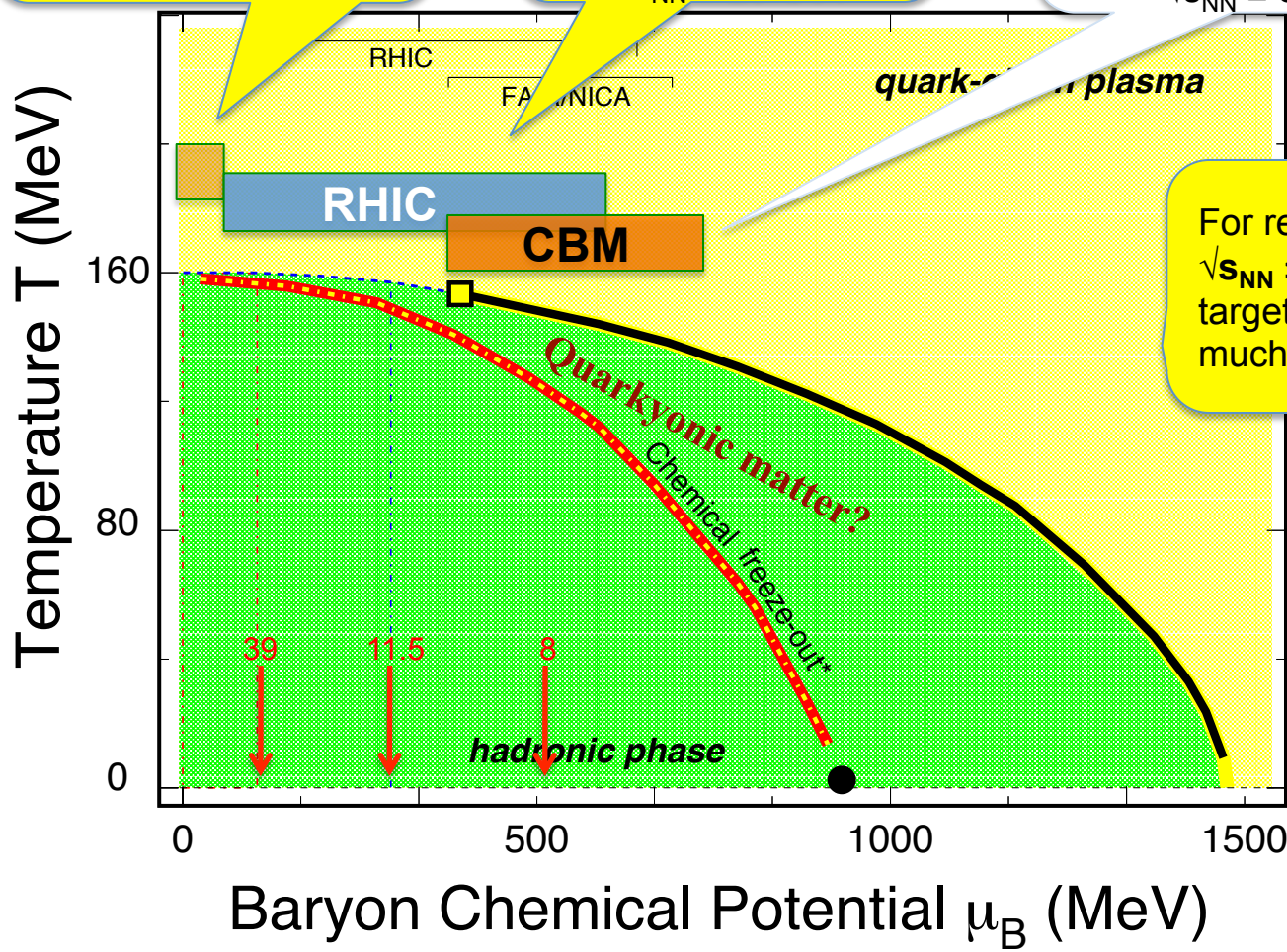
Property of sQGP
$\sqrt{s_{NN}}$ ~ 0.2 – 5.4 TeV

RHIC BES-II

QCD CP and phase structure
$\sqrt{s_{NN}} \leq 20$ GeV

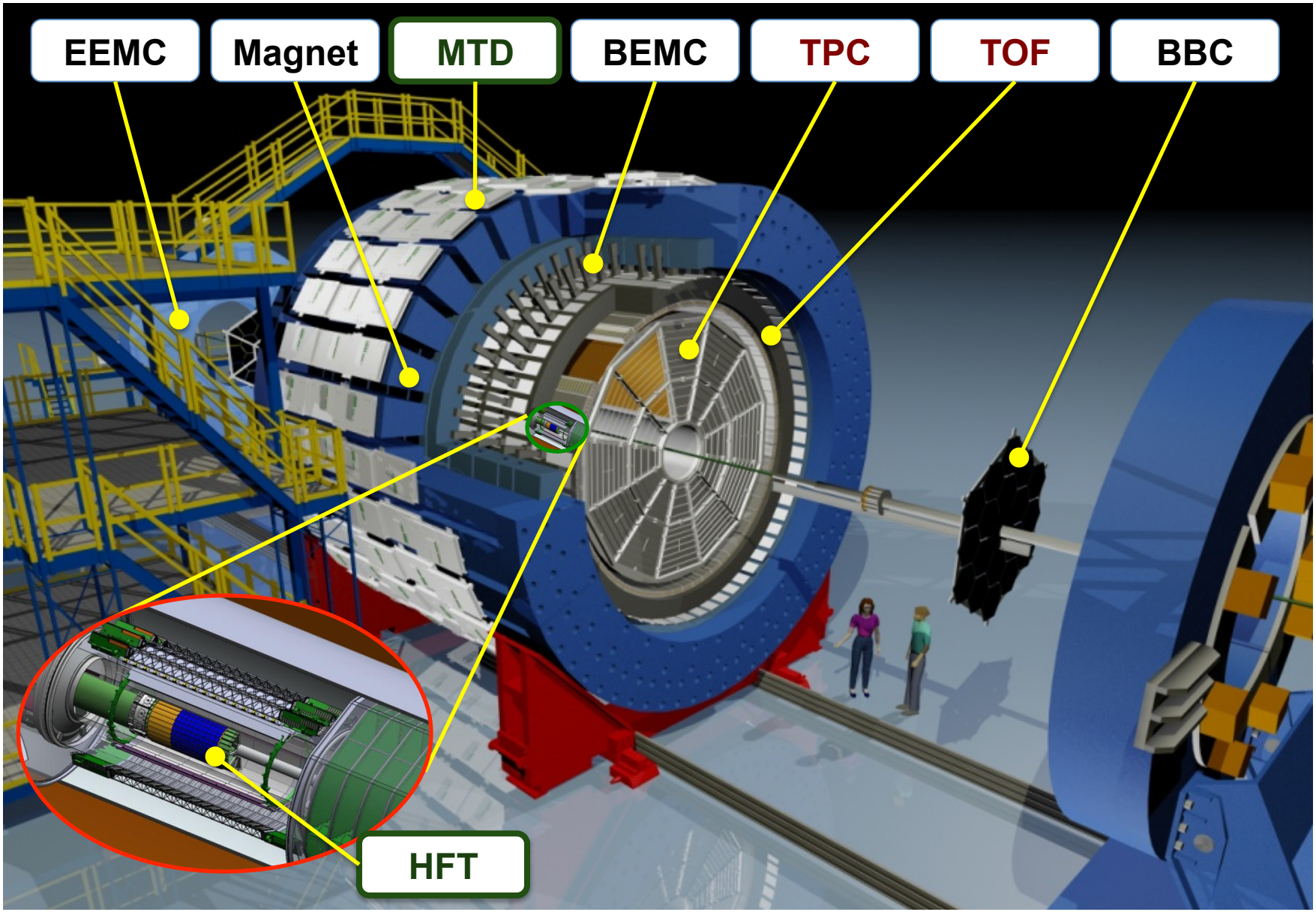
RHIC + FAiR

CP
Quarkyonic Matter?
$\sqrt{s_{NN}} \leq 8$ GeV



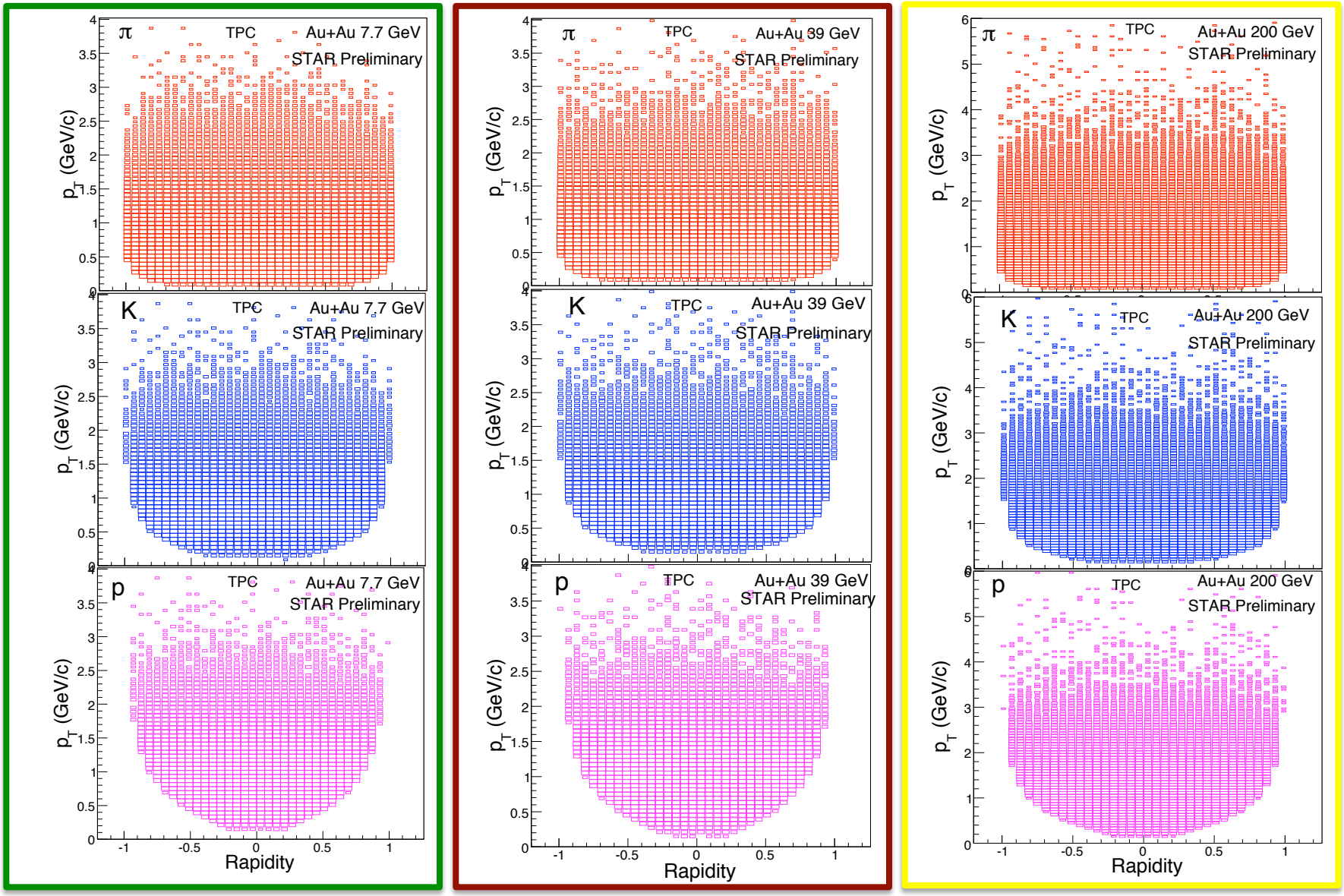
For region μ_B > 500 MeV, $\sqrt{s_{NN}} \leq 5$ GeV, fixed-target experiments are much more efficient

STAR Detector System

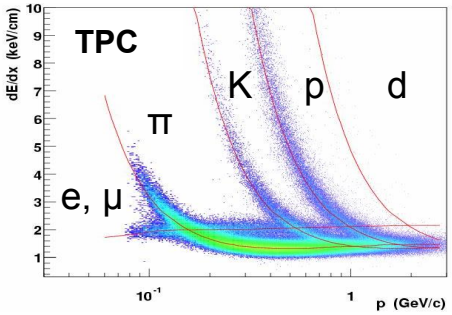


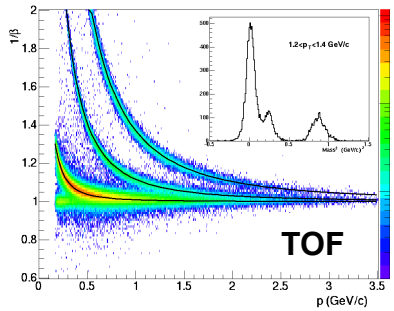
STAR PID for (π, K, p)

Au+Au at *7.7* GeV | **Au+Au at *39* GeV** | **Au+Au at *200* GeV**

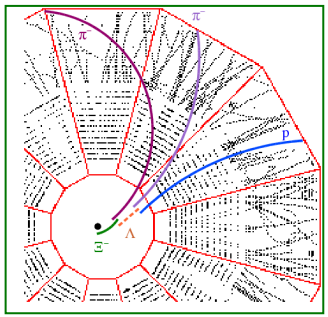


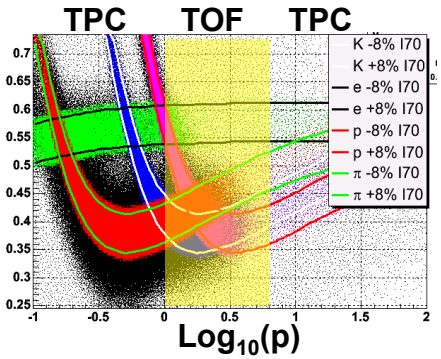
Particle Identification at STAR



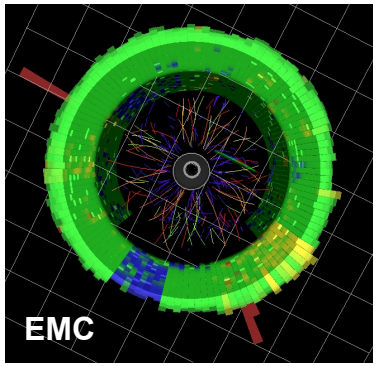


Charged hadrons

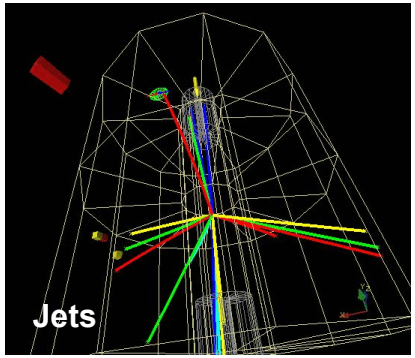




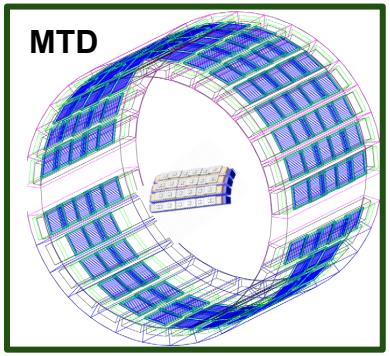
Hyperons & Hyper-nuclei



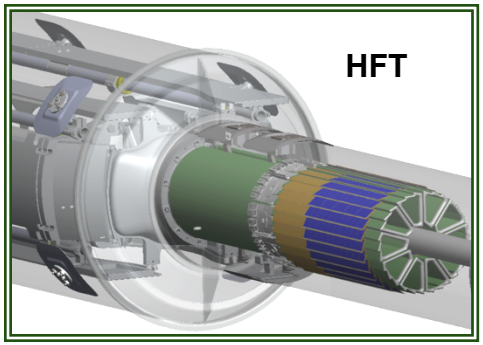
Neutral particles



Jets & Correlations



High p_T muons

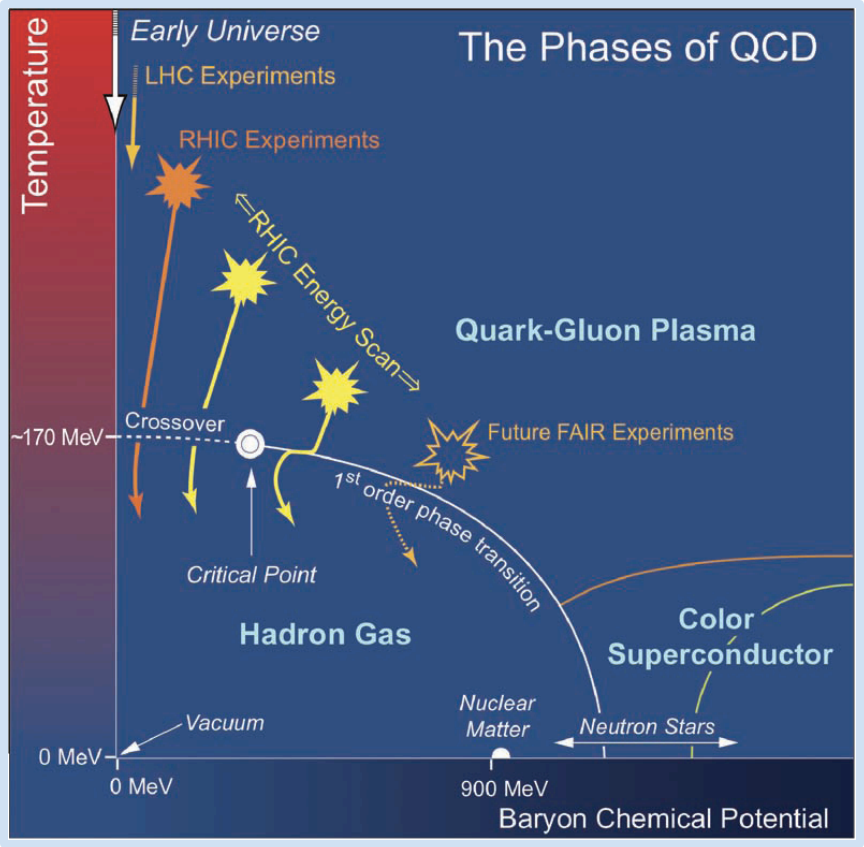


Heavy-flavor hadrons

Wide acceptance plus excellent particle identification

Multi-fold correlations for identified particles!

Beam Energy Scan-I at RHIC



Study QCD Phase Structure

- Onset of sQGP
- Phase boundary and critical point
- Chiral symmetry restoration

Observables:

1st order phase transition

(1) Azimuthally sensitive HBT

(2) Directed flow v_1

Partonic vs. hadronic dof

(3) R_{AA}: Nucl. Mod. Fact.

(4) **Charge separation**

(5) **v_2 - NCQ scaling**

Critical point, correl. length

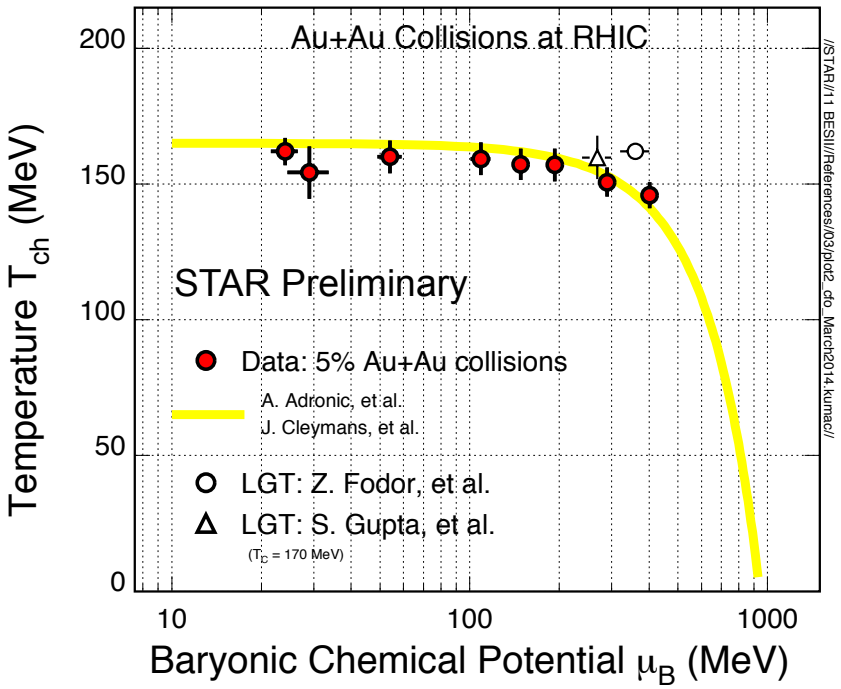
(6) **Fluctuations**

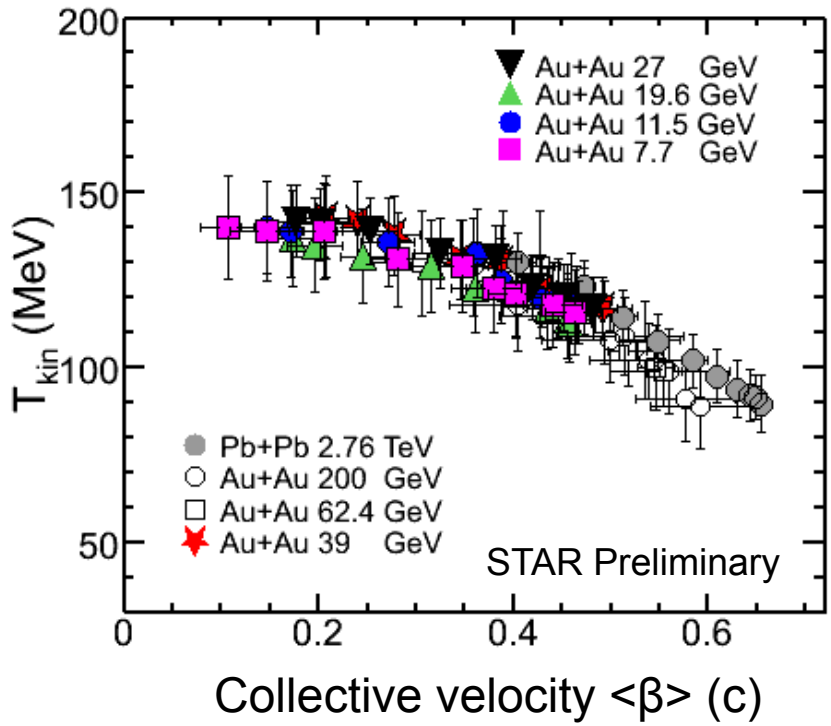
Chiral symmetry restoration

(7) Di-lepton production

BES-I: $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39GeV

Bulk Properties at Freeze-out





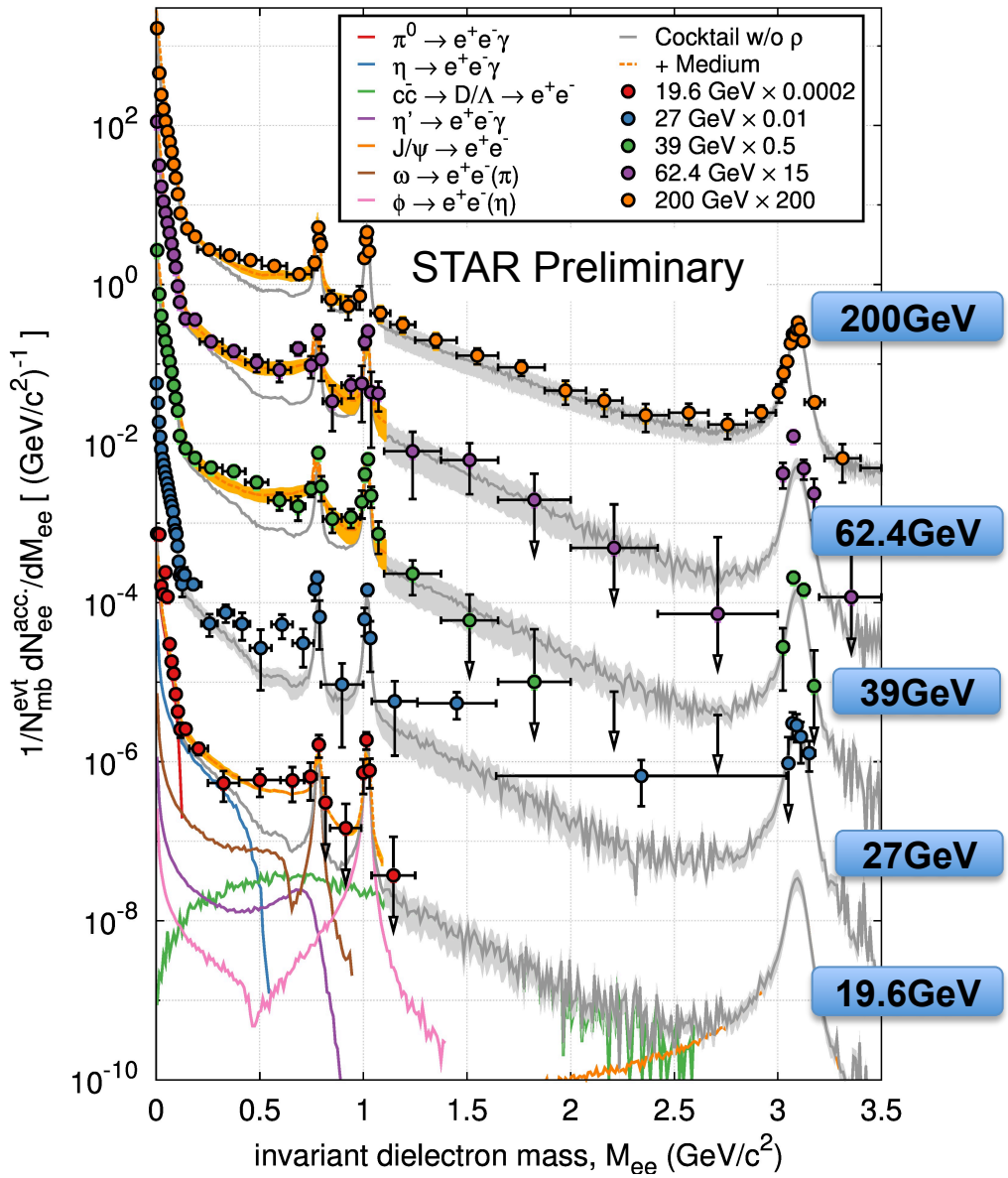
Chemical Freeze-out: (GCE)

- Central collisions
- BES-I: **$20 < \mu_B < 420$ MeV**
  T_{ch} variation is small
- Lattice CP prediction within reach(?)

Kinetic Freeze-out:

- Central collisions ➔ lower value of ***T_{kin}*** and larger collectivity ***β***
- Stronger collectivity at higher energy
- The freeze-out is local

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)

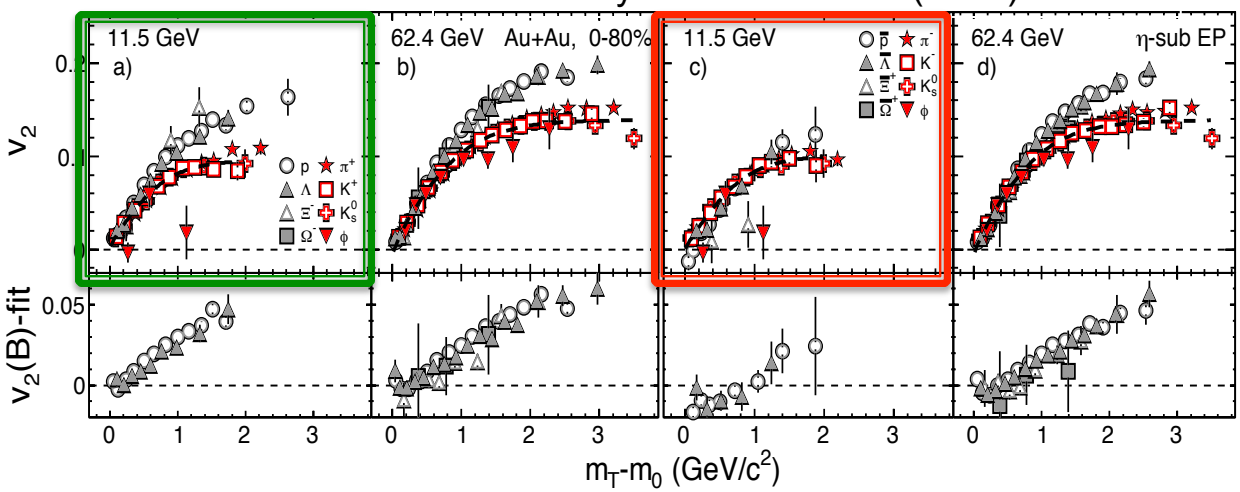
2) **$1 \leq M_{ee} \leq 3GeV/c^2$:** Thermal radiation: exp(**$-M_{ee}/T$**)? HFT: Charm contributions.

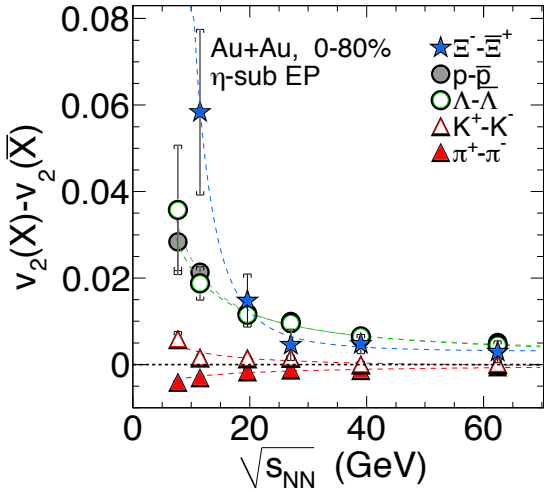
3) Higher statistics data are needed, **BES-II!**

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

Collectivity v_2 Measurements

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

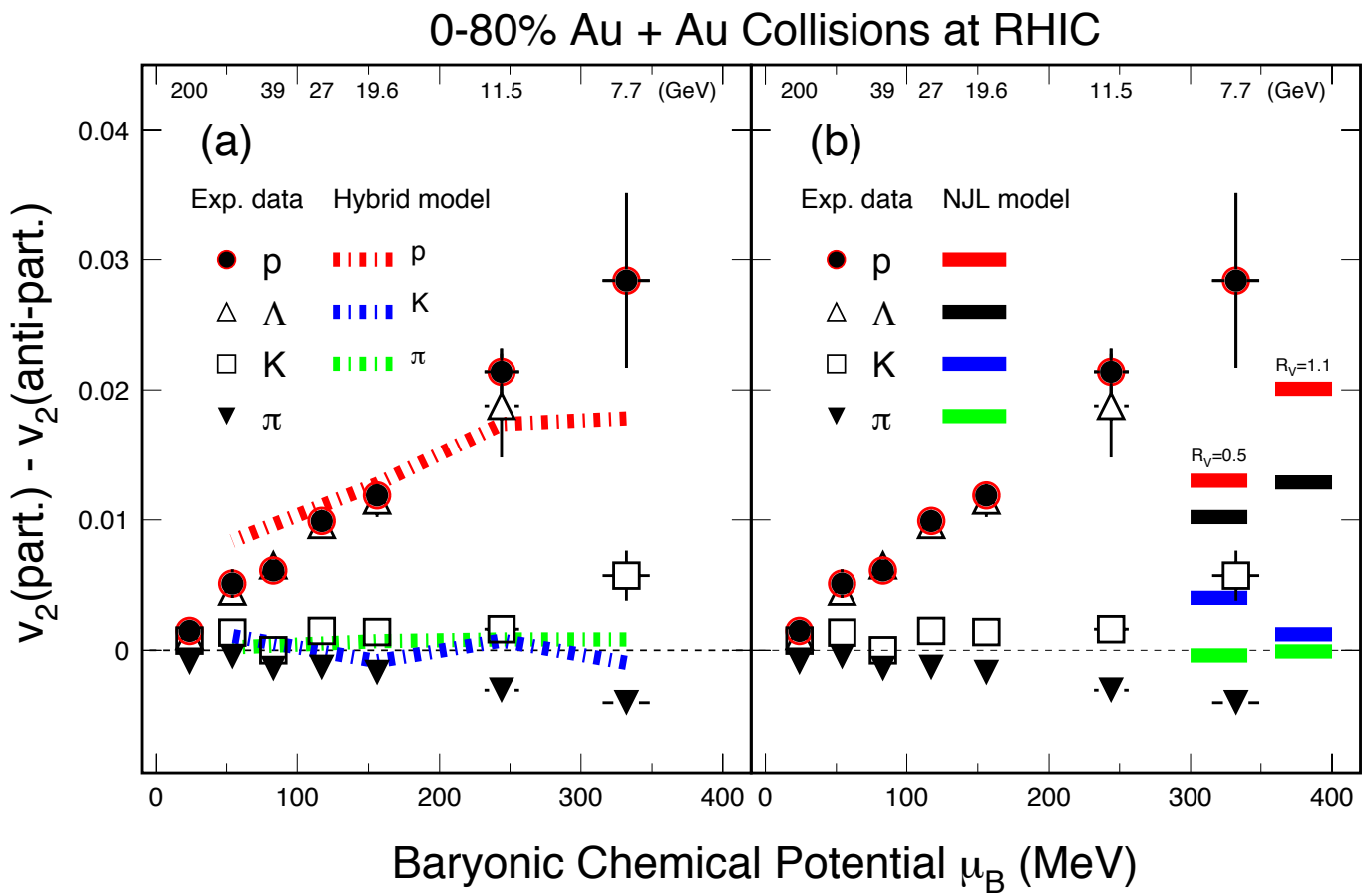




1) Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions

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

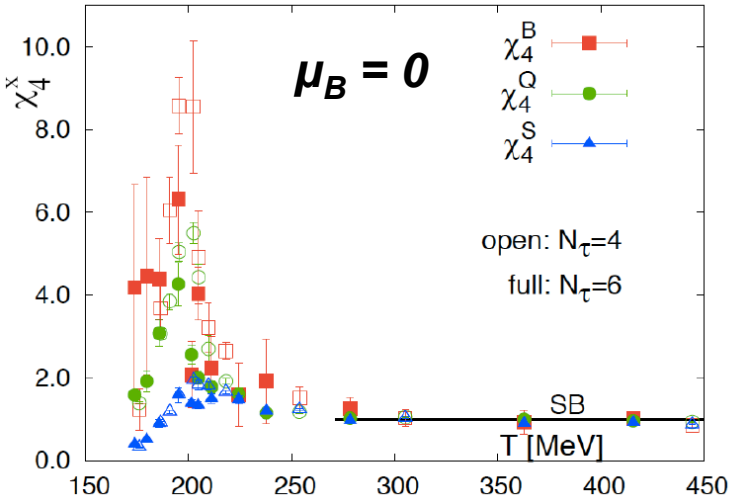


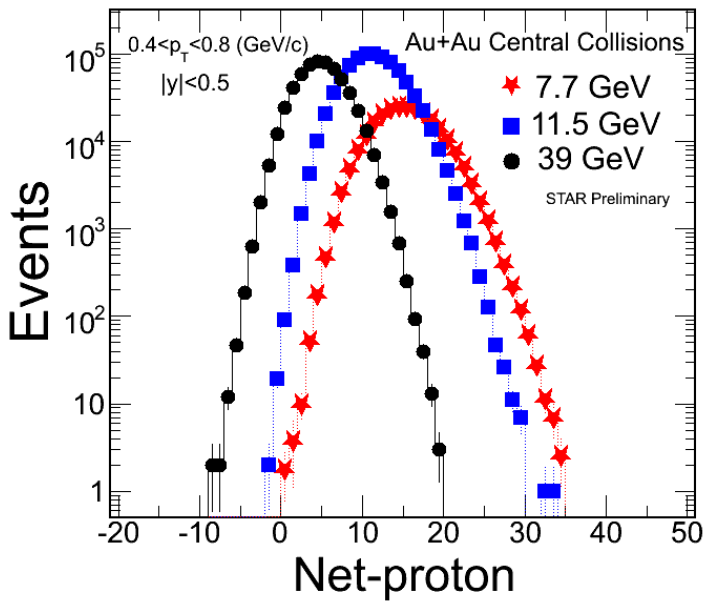
(a) Hydro + Transport: consistent with baryon data.

[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]

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:

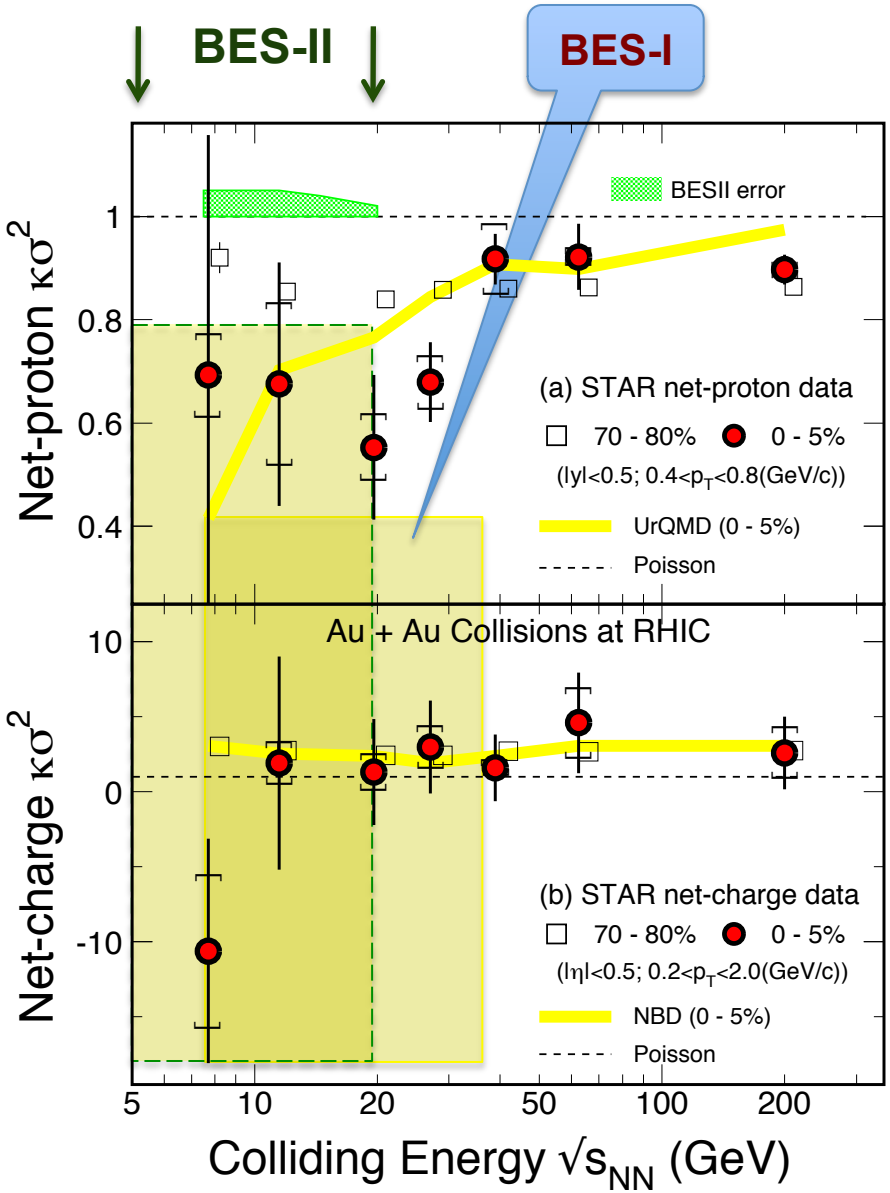
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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:

All data show deviations below Poisson for $\kappa\sigma^2$ at all energies.
Larger deviation at $\sqrt{s_{NN}} \sim 20$ GeV

Non-monotonic in data although UrQMD model shows monotonic

Comparing to LGT calculations

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

BES-II is needed:

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

More see Talk by B. Mohanty

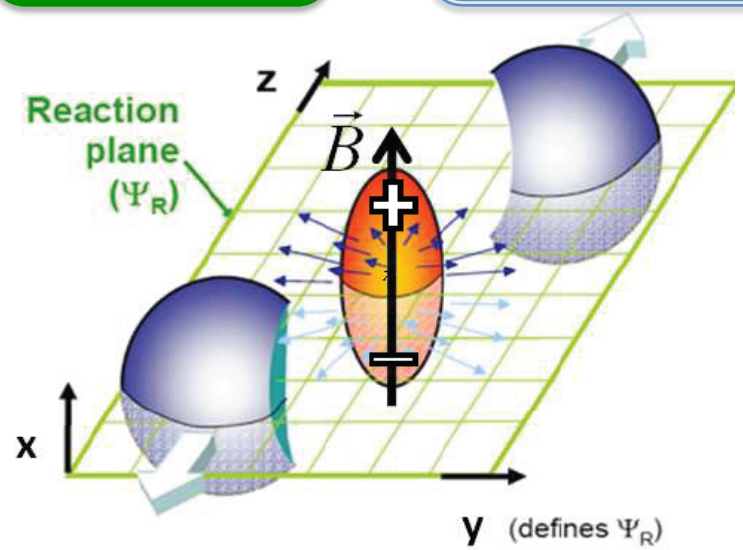
STAR: ***PRL112**, 32302(14) / arXiv: 1309.5681*
STAR: ***PRL113**,092301(14) / arXiv: 1402.1558*
P. Garg *et al, PLB726, 691(13)*

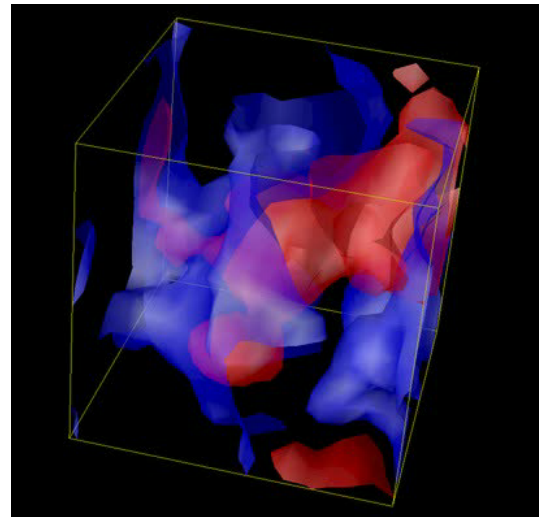
Study QCD Topological Structure

Hot/dense QCD Medium
Parity odd domains form

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

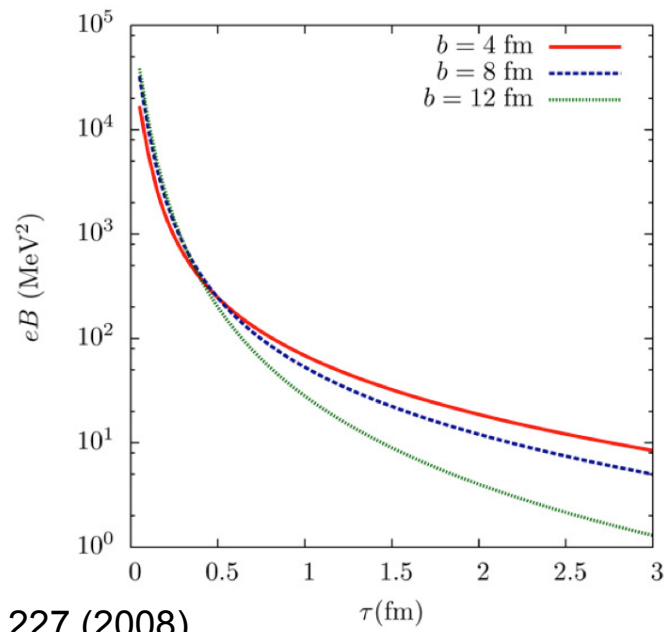
External Angular Momentum → Fluid Vorticity → Chiral vortical effect (**CVE**) (baryonic charge)





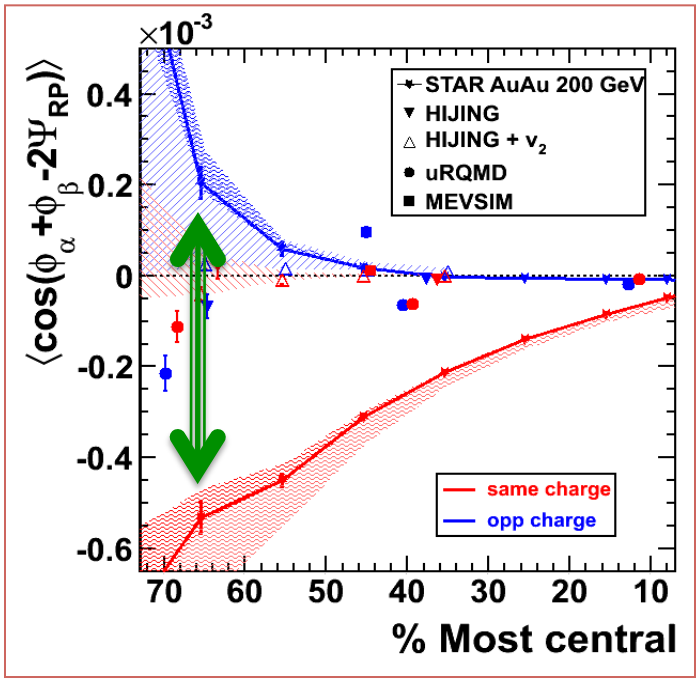
ITEP Lattice

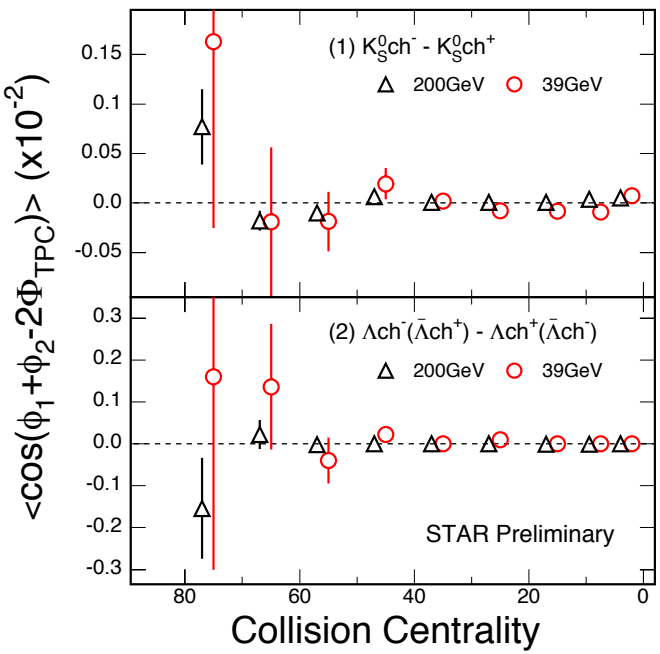
P. Buividovich et al., ***PRD80**, 054503(2009)*

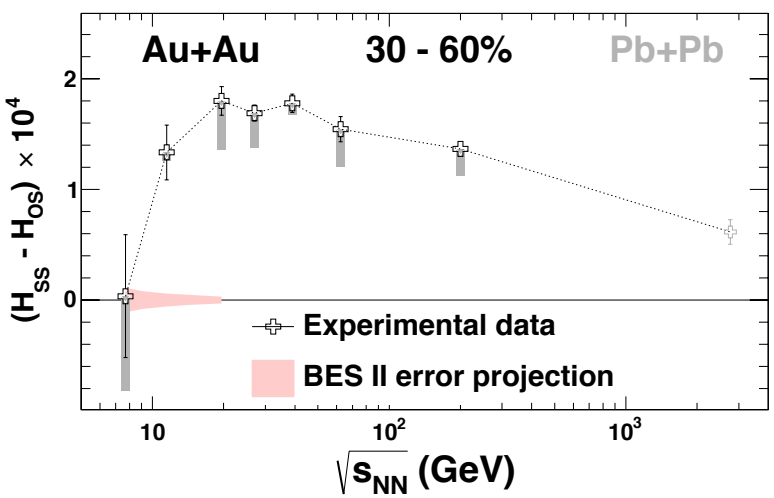


NPA 803, 227 (2008).

Charge Separation wrt Event Plane (**CME**)







CME disappears: with neutral hadrons:

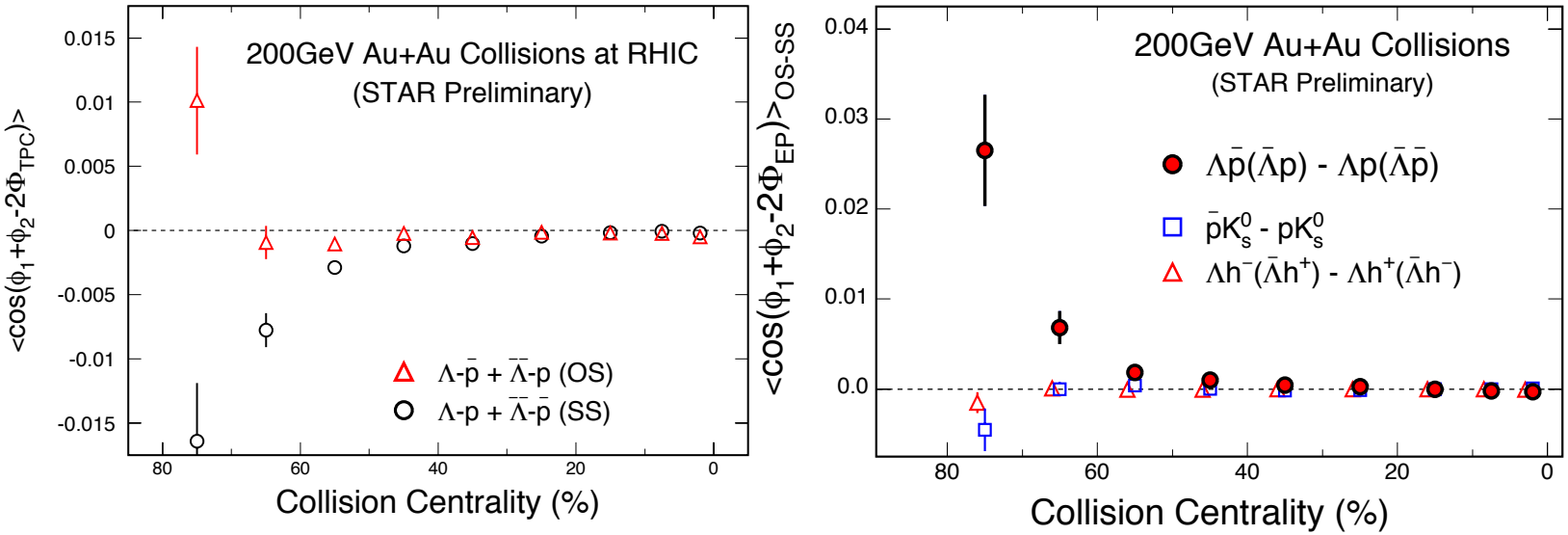
At low energy, no csr, no CME:

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

STAR: ***PRL103***, *251601(09)*
PRL113, *052302(14)*/arXiv: 1404.1433
D. Kharzeev. PLB633, 260 (06)
D. Kharzeev, et al. NPA803, 227(08)

Baryon Separation wrt Event Plane (CVE)

Λ-proton correlation: Λ contains the same B-charge as p but no e-charge



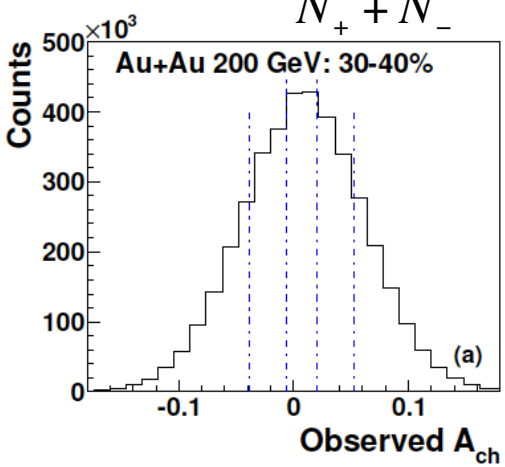
1) The opposite baryon-charge correlations (OS) are similar, ~ zero. But the same baryon-charge correlations (SS) are lower than that of the OS. The difference OS-SS is non-zero, ***baryon-charge separation***, as expected from the CVE
2) Neither p-K_0 nor Λ-charge hadron correlations show any separation effect, consistent with CVE

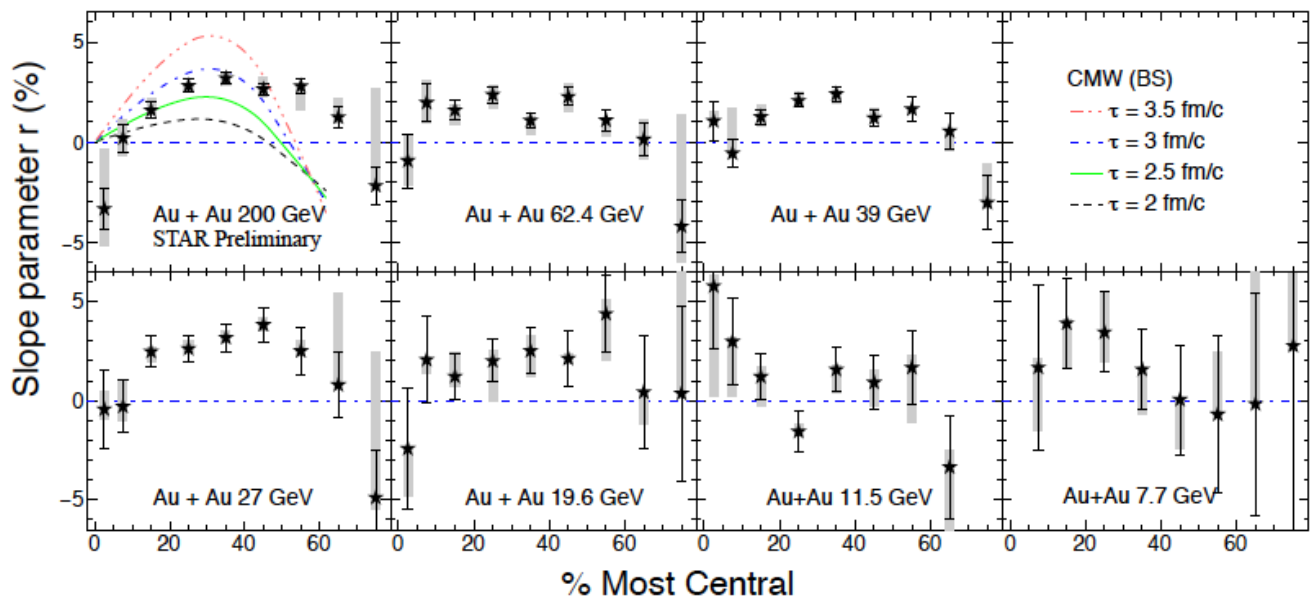
STAR: F. Zhao, DQM2014 Proceedings
Kharzeev, D.T. Son, PRL106, 062301(11); D. Kharzeev. PLB633, 260 (06); D. Kharzeev, et al. NPA803, 227(08)

Charged Pion v_2 Separation (**CMW**)

$$j_A = \frac{N_c\, e}{2\pi^2}\mu_V B \quad \Leftrightarrow \quad j_V = \frac{N_c\, e}{2\pi^2}\mu_A B \quad \Rightarrow \quad \frac{dN_\pm}{d\varphi} \approx 1 + 2\left[v_2 \mp A_{ch}\frac{q_e}{\rho_e}\right]\cos(2\varphi)$$

$$A_{ch} = \frac{N_+ - N_-}{N_+ + N_-}$$



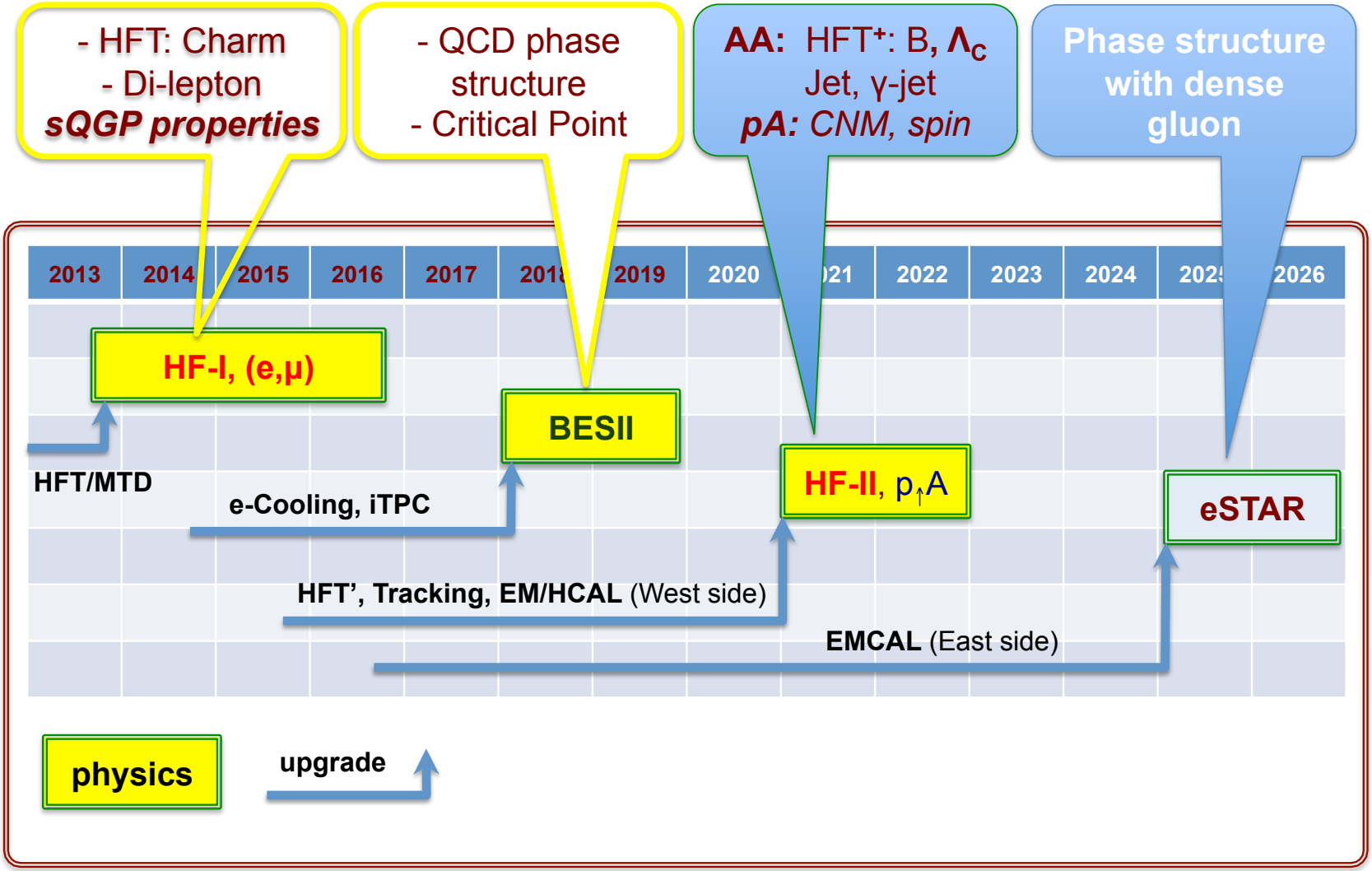


1) The centrality dependence of difference between $v_2(\pi^+)$ and $v_2(\pi^-)$ vs. charge asymmetry is observed for Au+Au/U+U collisions at $\sqrt{s_{NN}} \geq 27$ GeV, as expected by CMV model predictions. Large statistics data needed for $\sqrt{s_{NN}} \leq 20$ GeV

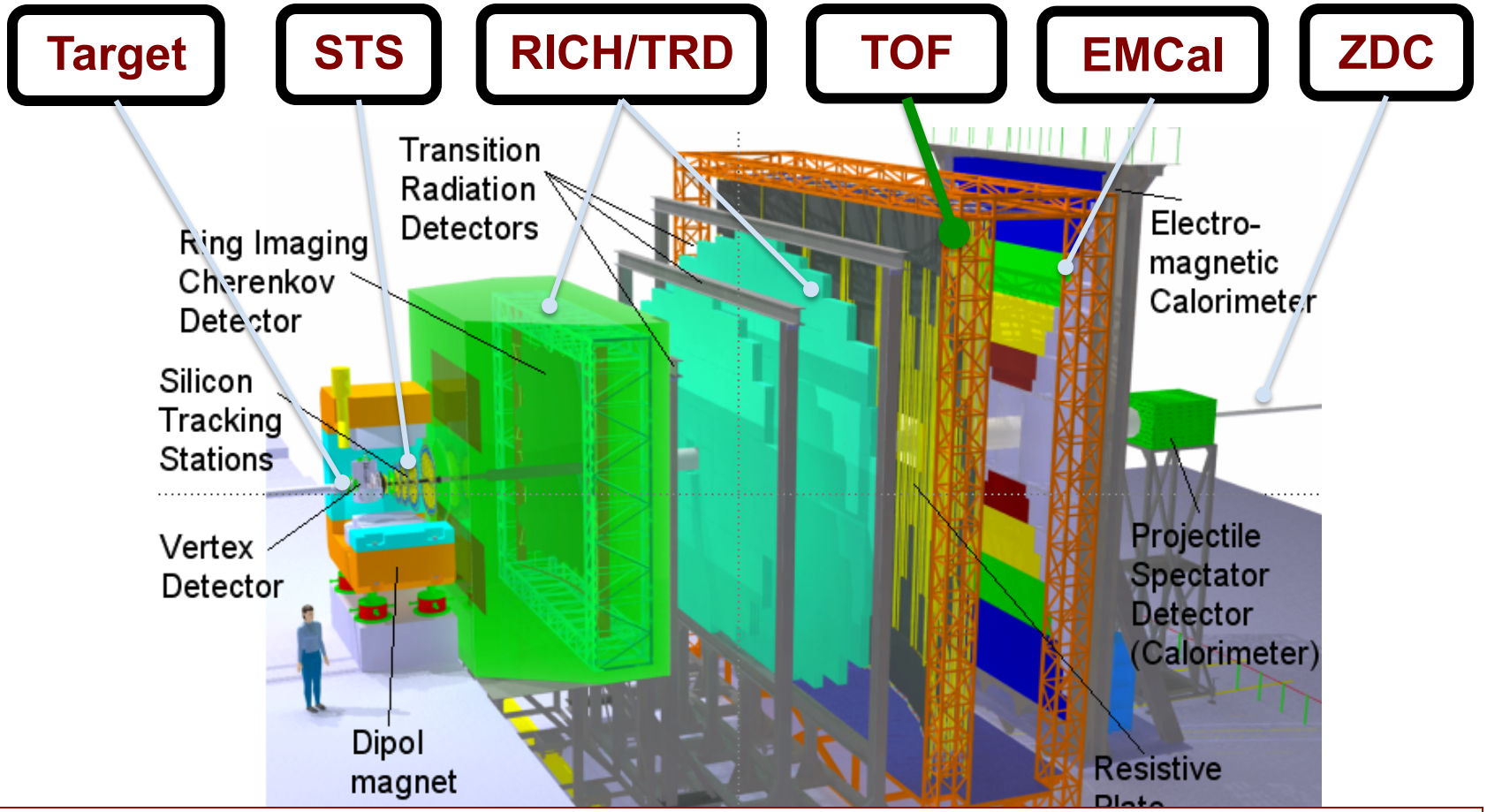
2) Note for CMW, unlike CME, CVE., the quantum effect is not required a prior.

Future: More events for $\sqrt{s_{NN}} \leq 20$ GeV

STAR: Upgrade Plan



The CBM Experiment at FAIR

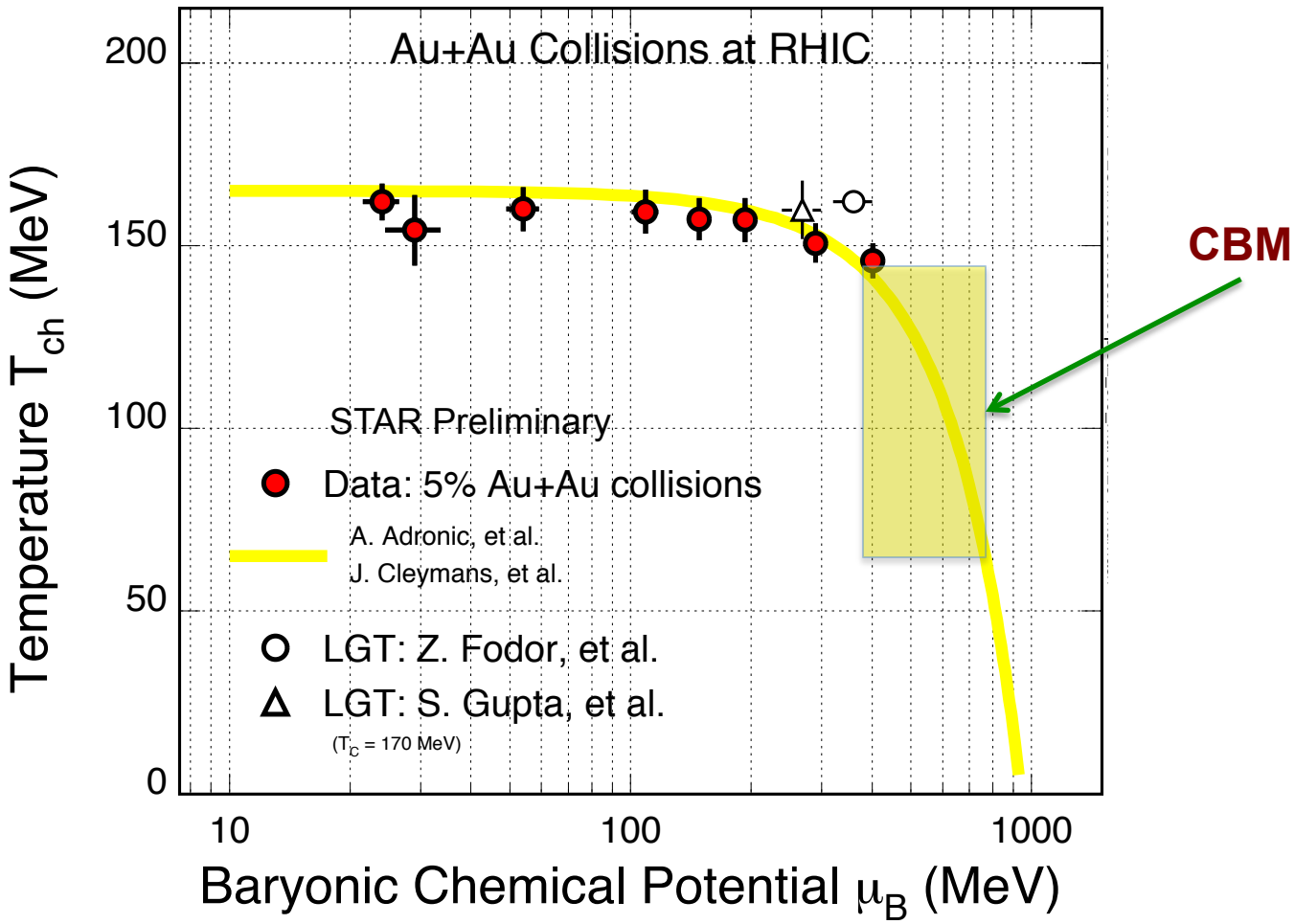


FAIR: the highest intensity accelerator complex in the 21st century

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

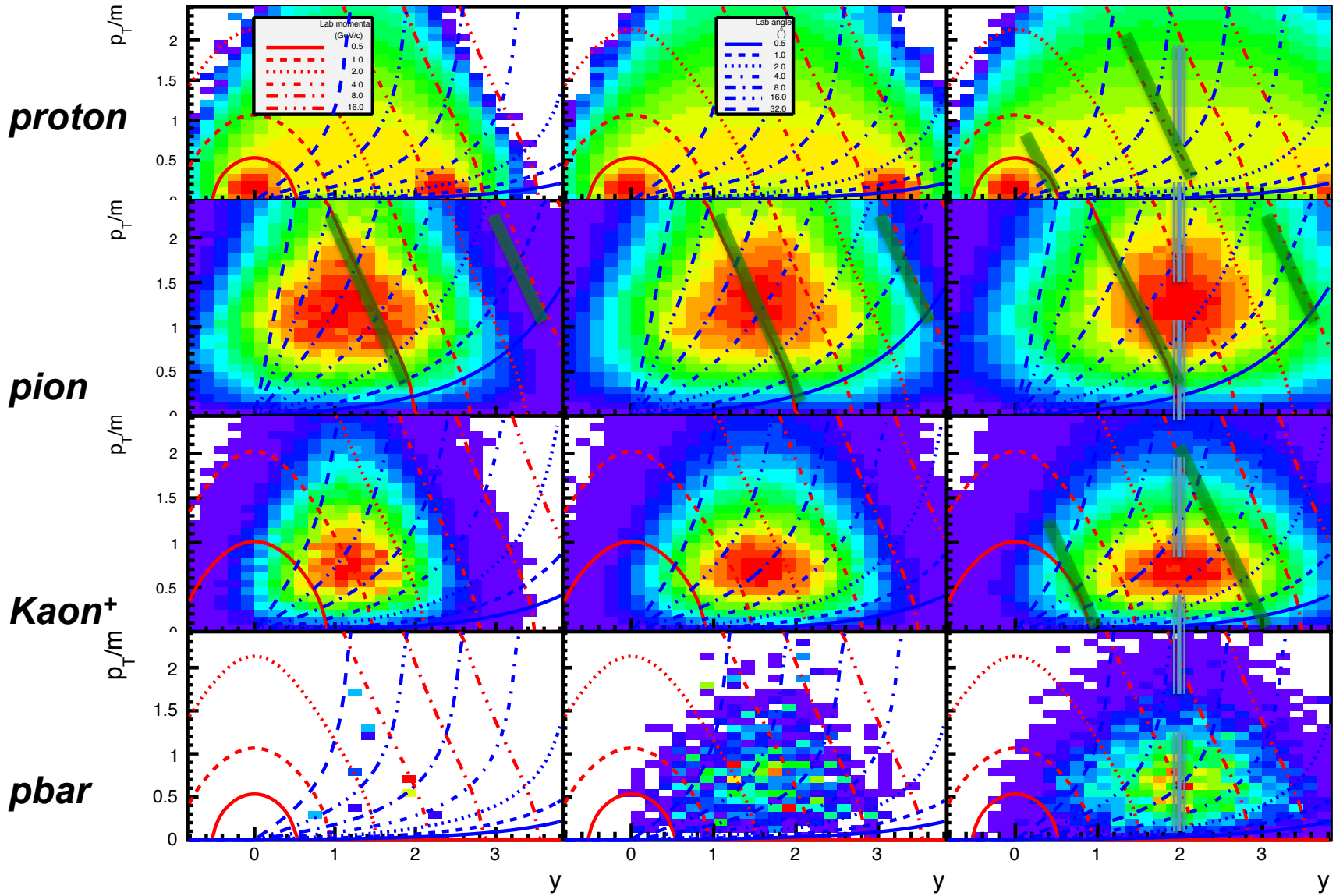


Chemical Freeze-out: (GCE)

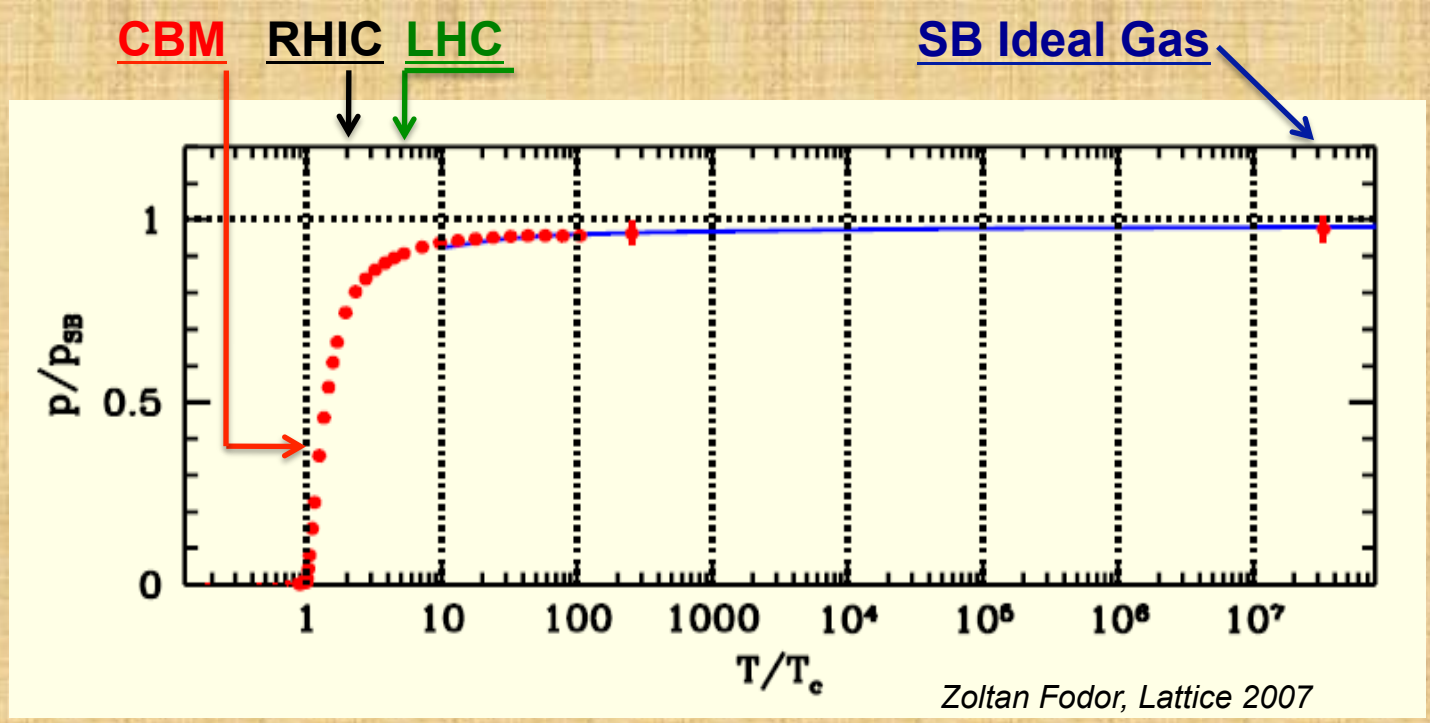
- RHIC (20 ≤ μ_B ≤ 420 MeV): small temperature variation
- CBM (400 ≤ μ_B ≤ 750 MeV): temperature changes dramatically!

Phase Space vs. Acceptance

Beam E/A ($\sqrt{s_{NN}}$) = 4 (3.05) GeV 10 (4.54) GeV 25 (6.98) GeV



QCD Thermodynamics



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

Future Focus

1) It is evident that the structure changes around $\sqrt{s_{NN}} \leq 20$ GeV: net-p Kurtosis, CME/CVE/CMW, ...

2) Need more focused theoretical efforts: **QCD critical point** and **Chiral related effects** - understand how QCD works!

3) Go to **higher baryon density region**, search for new phase structure, Quarkyonic Matter, …

Past Discoveries
2000 – 2015
QGP at $\mu_B \sim 0$

Future:
QCD phase structure
at $\mu_B \geq 300$ MeV

Happy Birthday!