High-Energy Nuclear Collisions and ***the QCD Phase Structure***

Nu Xu[1,2]

ATHIC2014
OSAKA
The 5th Asian Triangle Heavy Ion Conference 2014
In Osaka, Japan on August 5-8, 2014

Outline:

1) Introduction
2) Recent Results From BESI at RHIC
3) Outlook

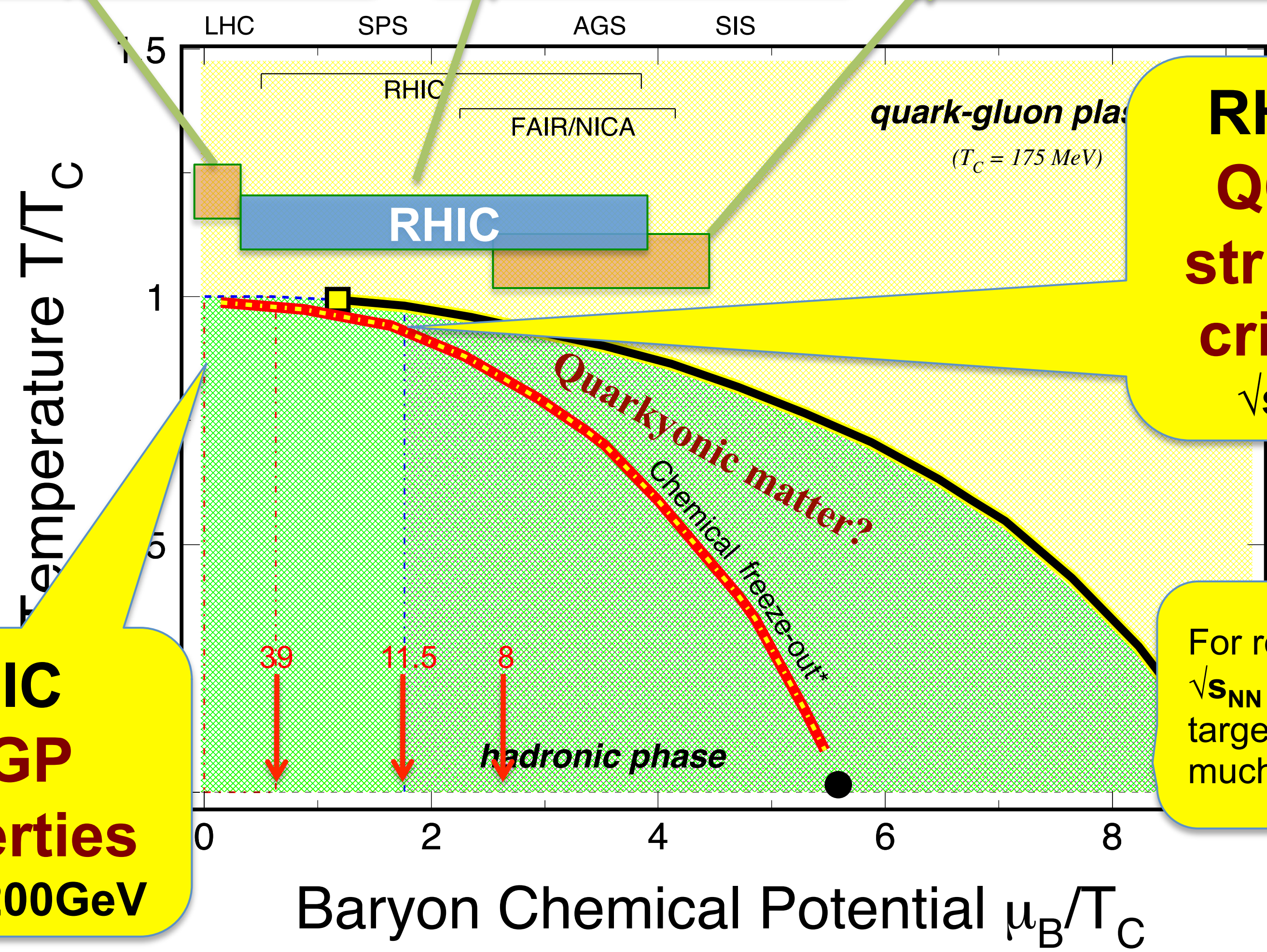
[1] College of Physical Science & Technology, Central China Normal University, China
[2] Nuclear Science Division, Lawrence Berkeley National Laboratory, USA

Exploring QCD Phase Structure

1 ***LHC, RHIC***

2 ***RHIC***

3 ***RHIC****, NICA, FAIR*



RHIC BES-II
QCD phase structure and critical point
$\sqrt{s_{NN}} \leq 20$ GeV

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

RHIC
sQGP properties
$\sqrt{s_{NN}} = 200$GeV

LHC, RHIC, FAIR

(I) 2000 - 2012: RHIC, LHC

1) sQGP: strongly coupled QGP, η/S =>0, ideal fluid.
2) At $\mu_B = 0$ smooth cross over.

(II) 2010 - 2014: RHIC BESI (20 ≤ μ_B ≤ 420 MeV, 200 ≥ $\sqrt{s_{NN}}$ ≥ 7.7 GeV)

1) $\sqrt{s_{NN}}$ ≤ 15 GeV, μ_B ≥ 300 MeV: Hadronic interactions become dominant.
2) Collectivity and fluctuation results hint phase transition. However, more data are needed to confirm. RHIC BESII and FAIR CBM.

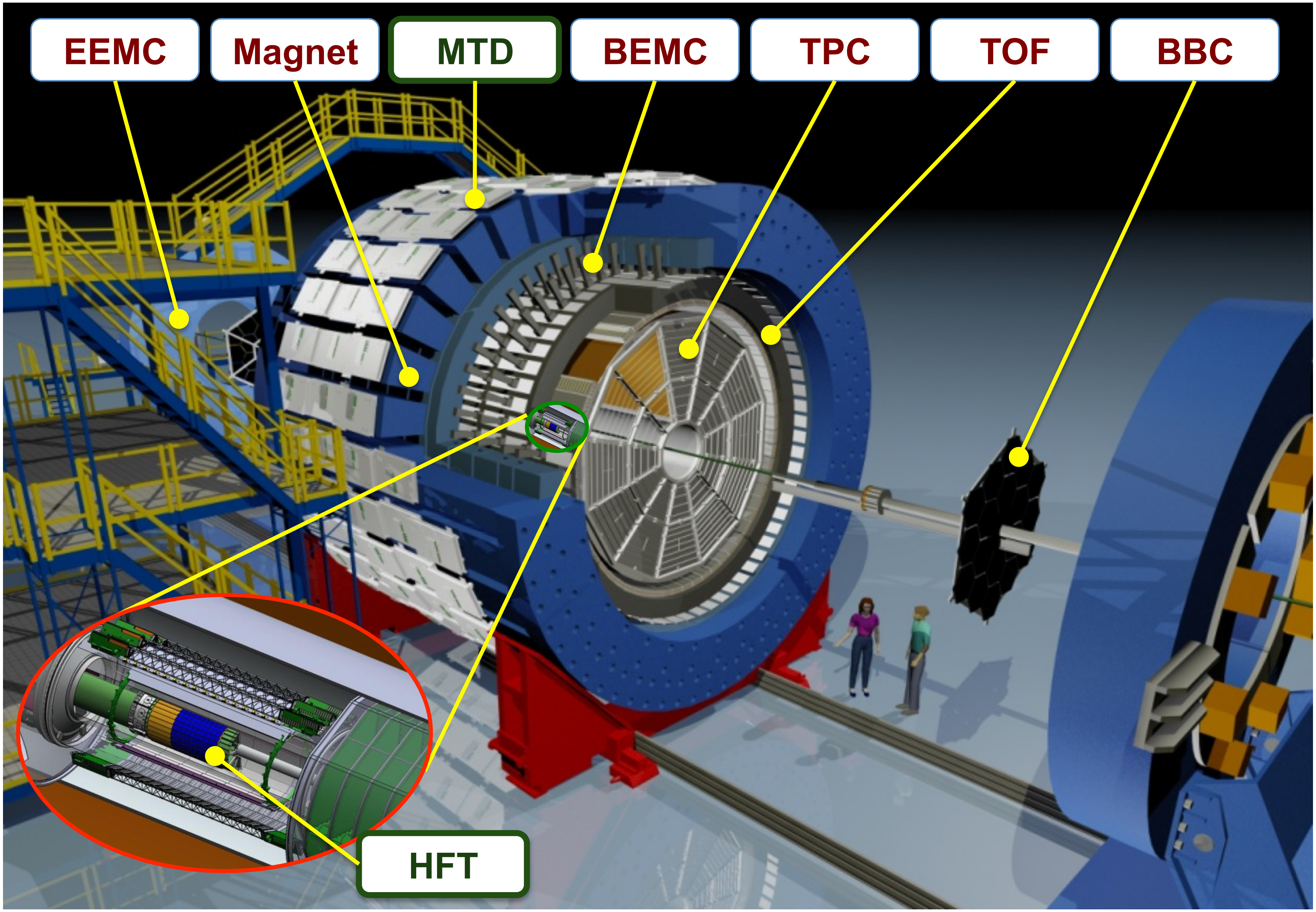
(III) 2018 and beyond:

Collider: RHIC BESII (7.7 < $\sqrt{s_{NN}}$ < 20 GeV, 420 ≥ μ_B ≥ 300 MeV)

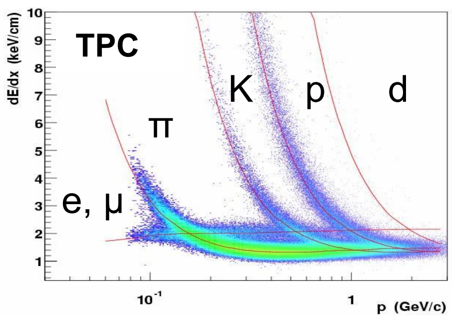
Fixed-target: FAIR CBM ($\sqrt{s_{NN}}$ ≤ 12 GeV, μ_B ≥ 300 MeV)

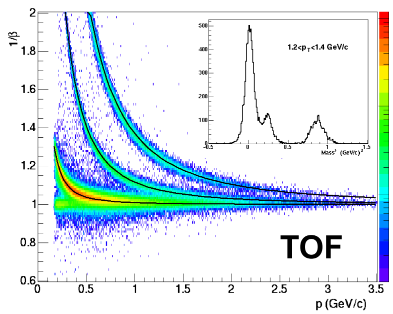
1) High luminosity, new detectors
2) Physics focus：Cp, Pb and Qm

STAR Detector System

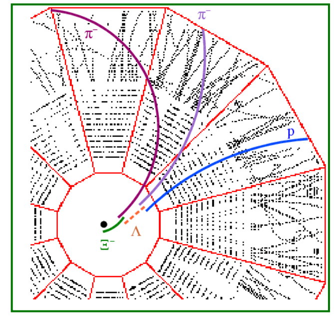


Particle Identification at STAR

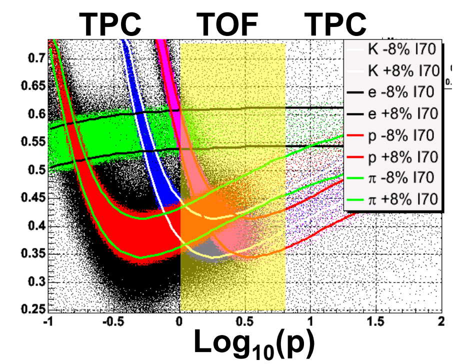


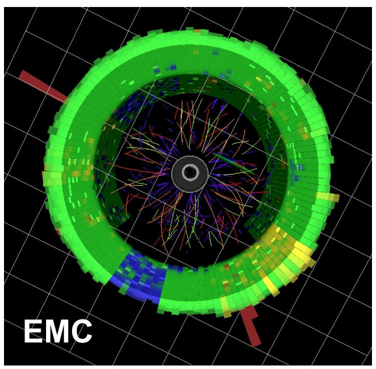


Charged hadrons

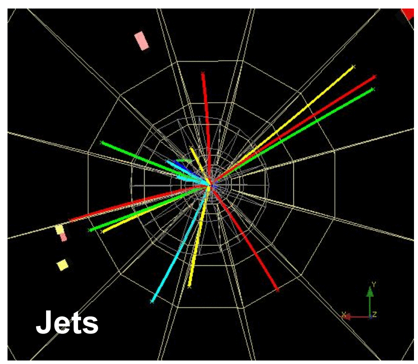


Hyperons & Hyper-nuclei

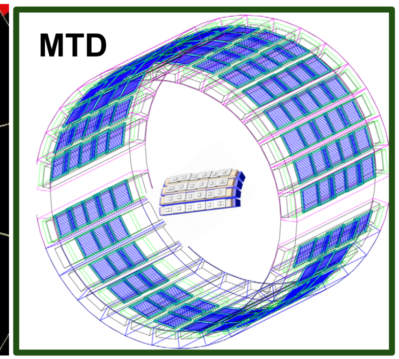




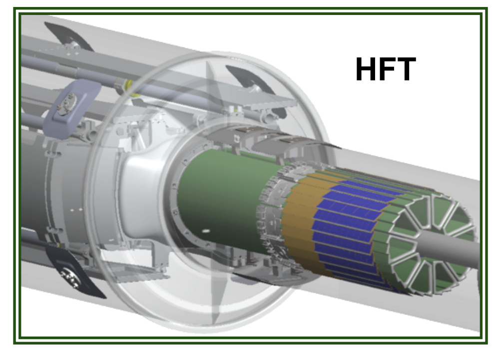
Neutral particles



Jets & Correlations



High p_T muons



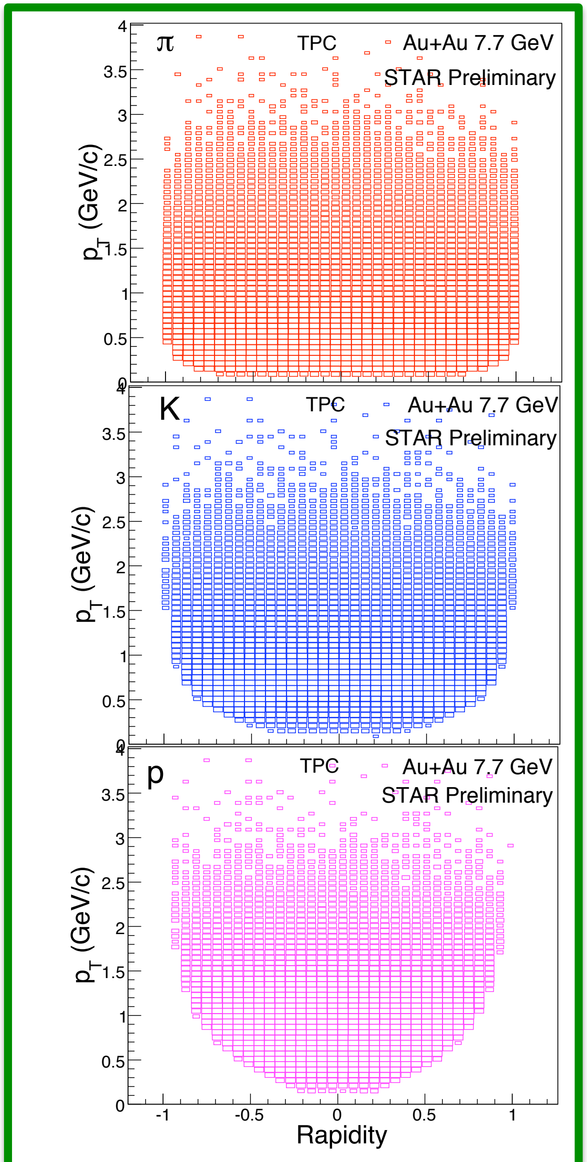
Heavy-flavor hadrons

Wide acceptance plus excellent particle identification

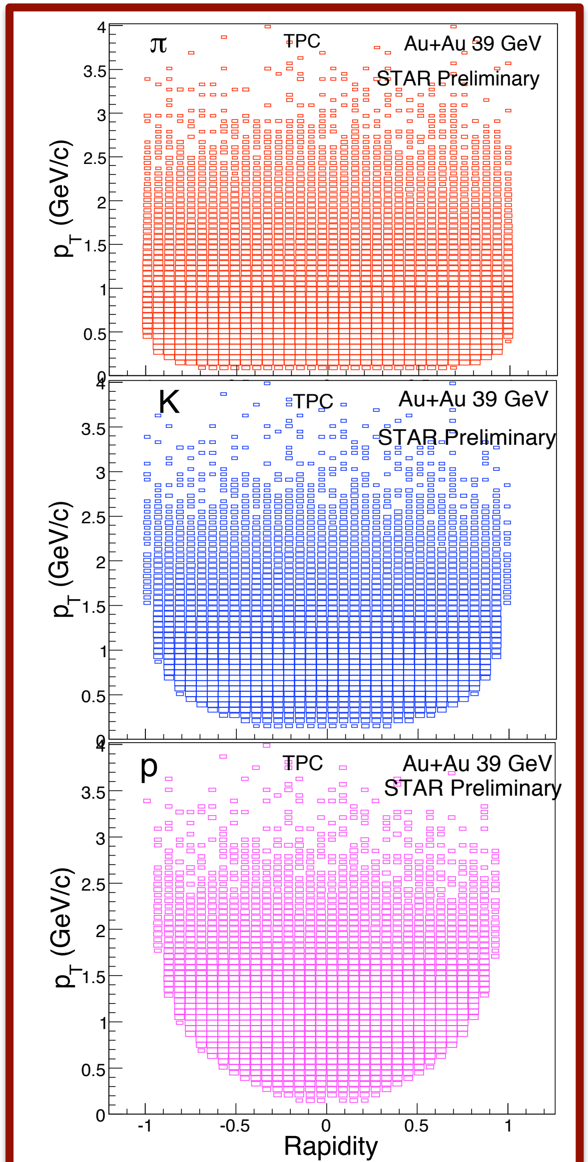
Multi-fold correlations for identified particles!

STAR PID for (π, K, p)

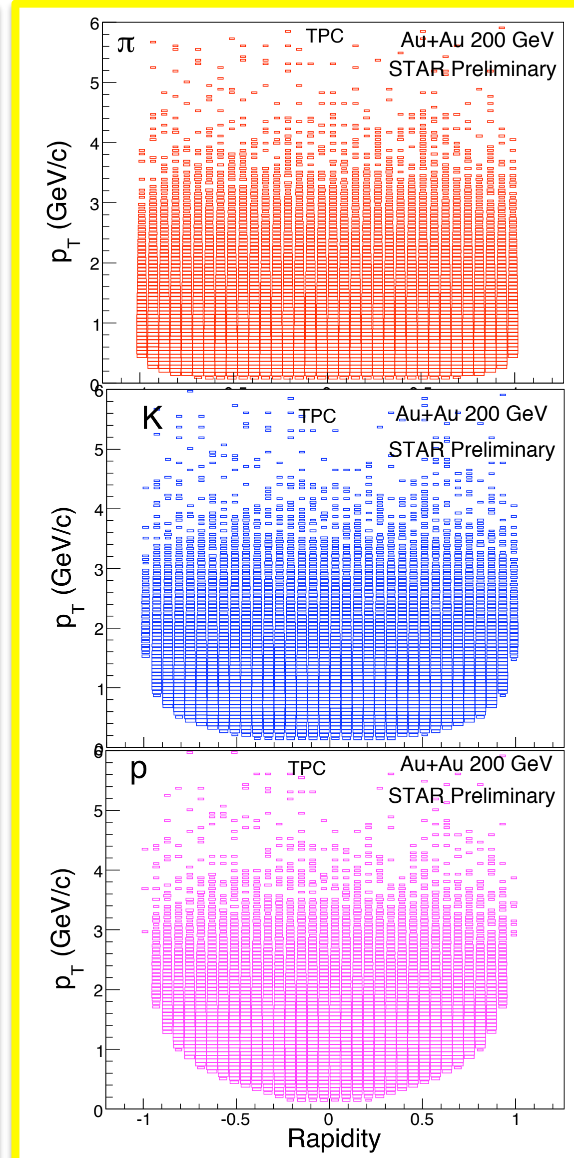
Au+Au at *7.7* GeV



Au+Au at *39* GeV

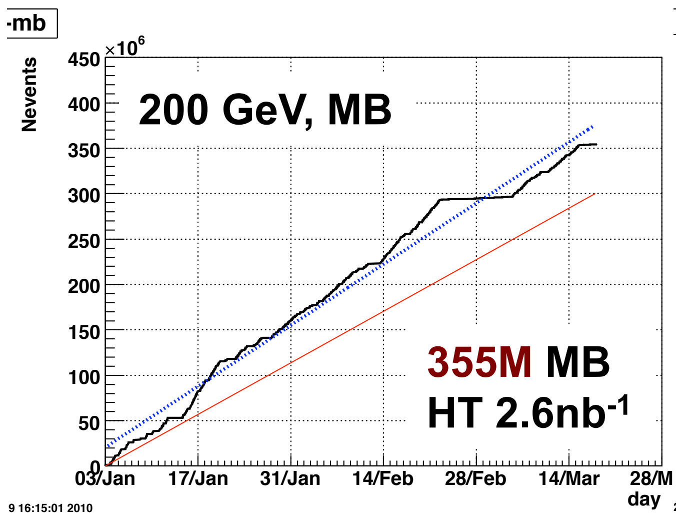


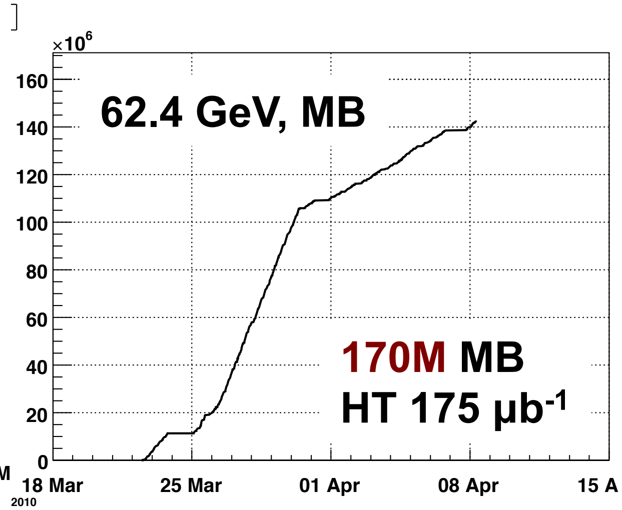
Au+Au at *200* GeV

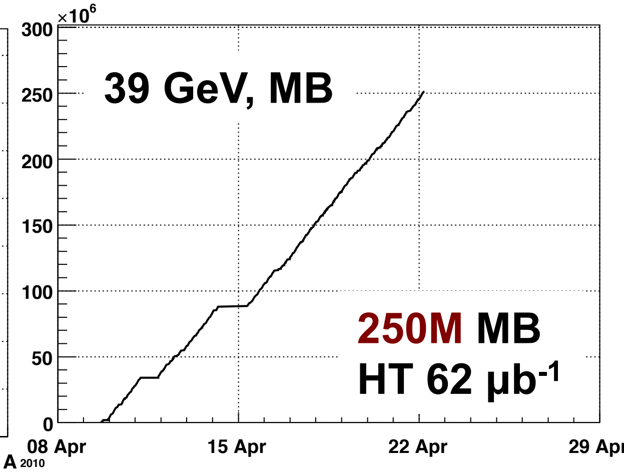


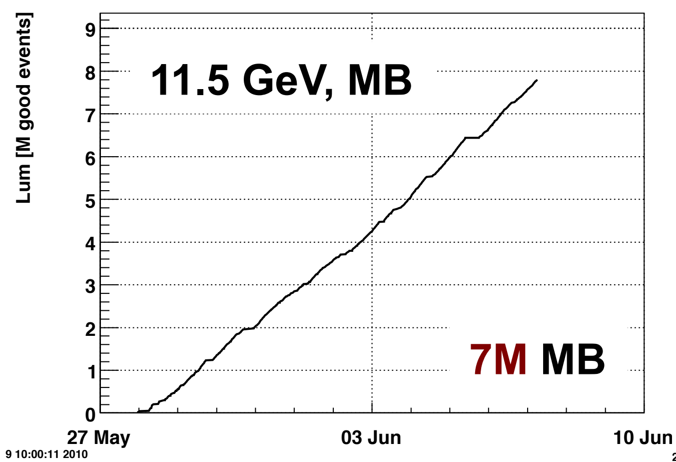
Run 10: 200, 62.4, 39, 11.5 7.7 GeV

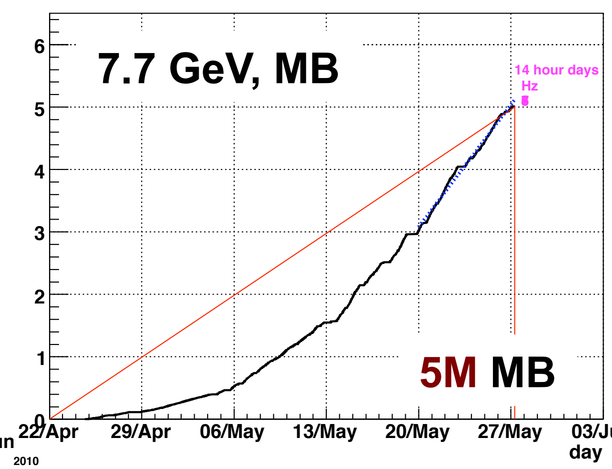
A great success, many thanks to CA-D!

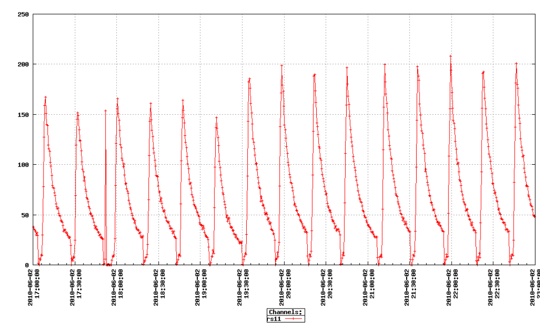








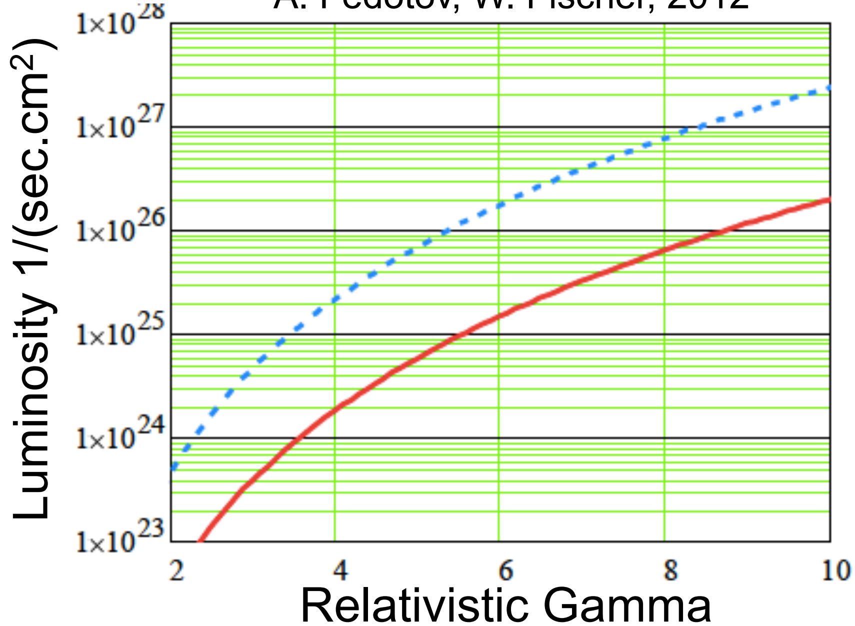




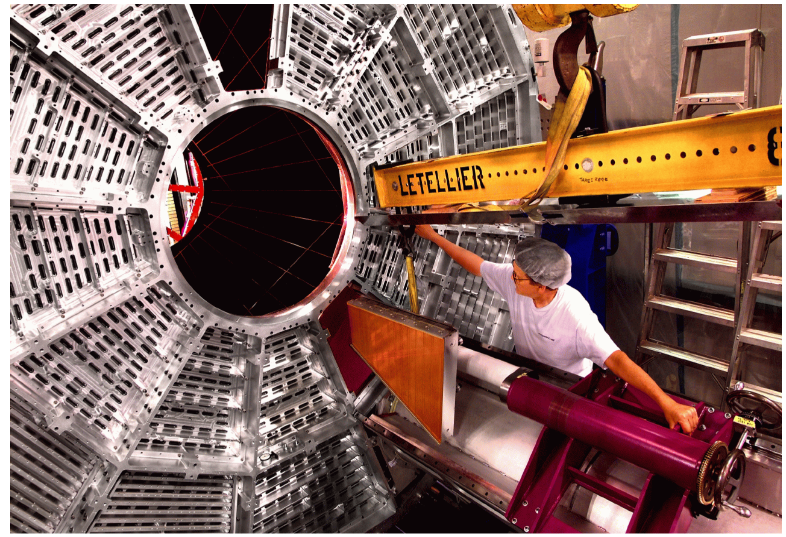
1) Successful run, all goals were reached or exceed
2) Many thanks to CA-D

BES-II: e-cooling, iTPC Upgrades

A. Fedotov, W. Fischer, 2012



$\sqrt{s_{NN}}$ (GeV)	~ 5	~ 20
Increasing factor	3-5	10



iTPC Upgrade: $|\eta| \leq 1.1$ ➔ **$|\eta| \leq 1.7$**

i) Crucial for BES-II

ii) Important for eSTAR

1) BES-II at $\sqrt{s_{NN}}$ < 20 GeV

2) RHIC e-cooling will provide increased luminosity ~ x3 - 10

3) STAR iTPC upgrade extend mid-rapidity coverage – beneficial to several crucial measurements

Facility for Antiproton and Ion Research: **FAIR**

Primary beam

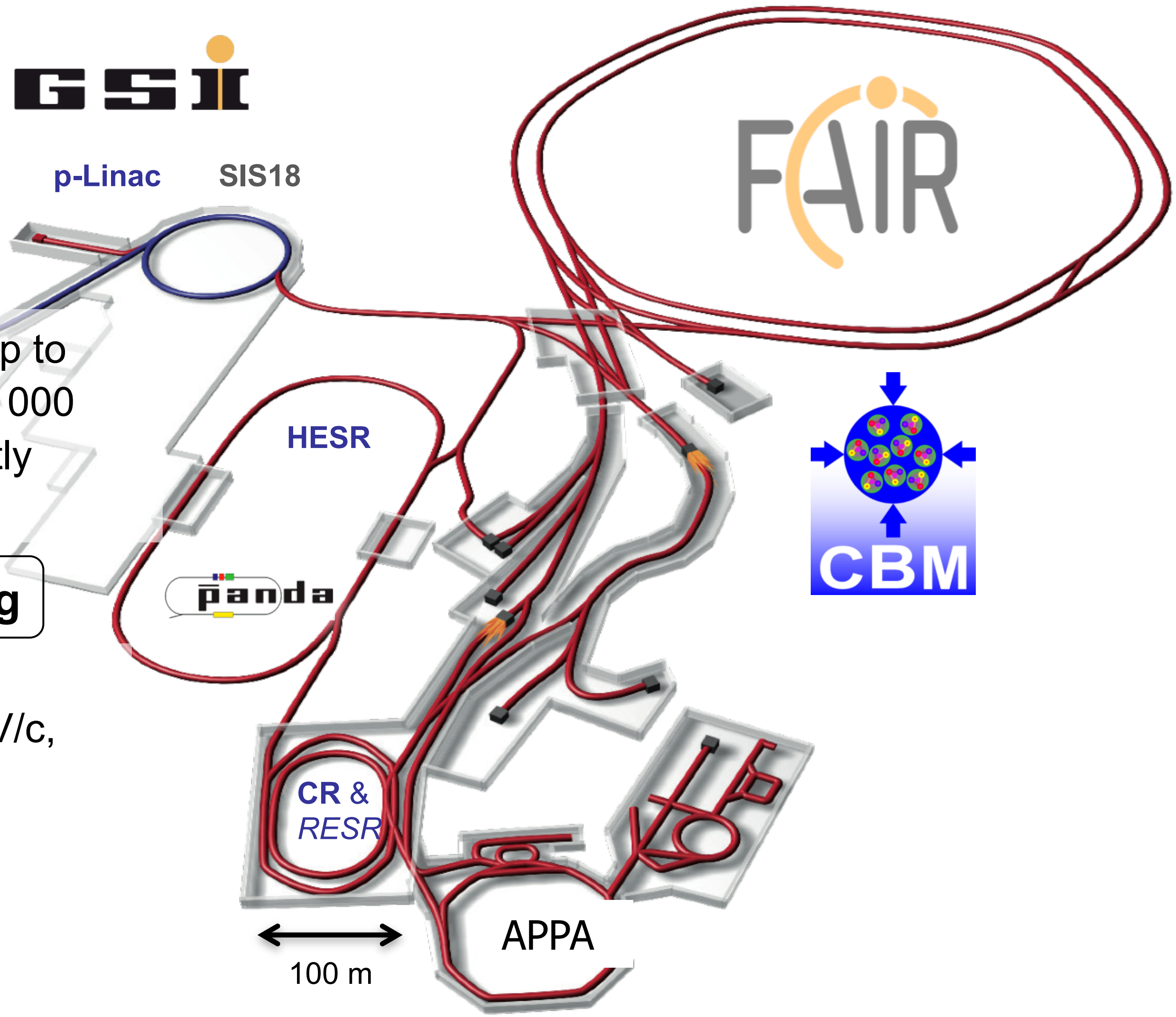
- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- **10^{10}/s $^{238}U^{73+}$** up to 35 GeV/u
- **3×10^{13}/s 30 GeV protons**

Secondary beam

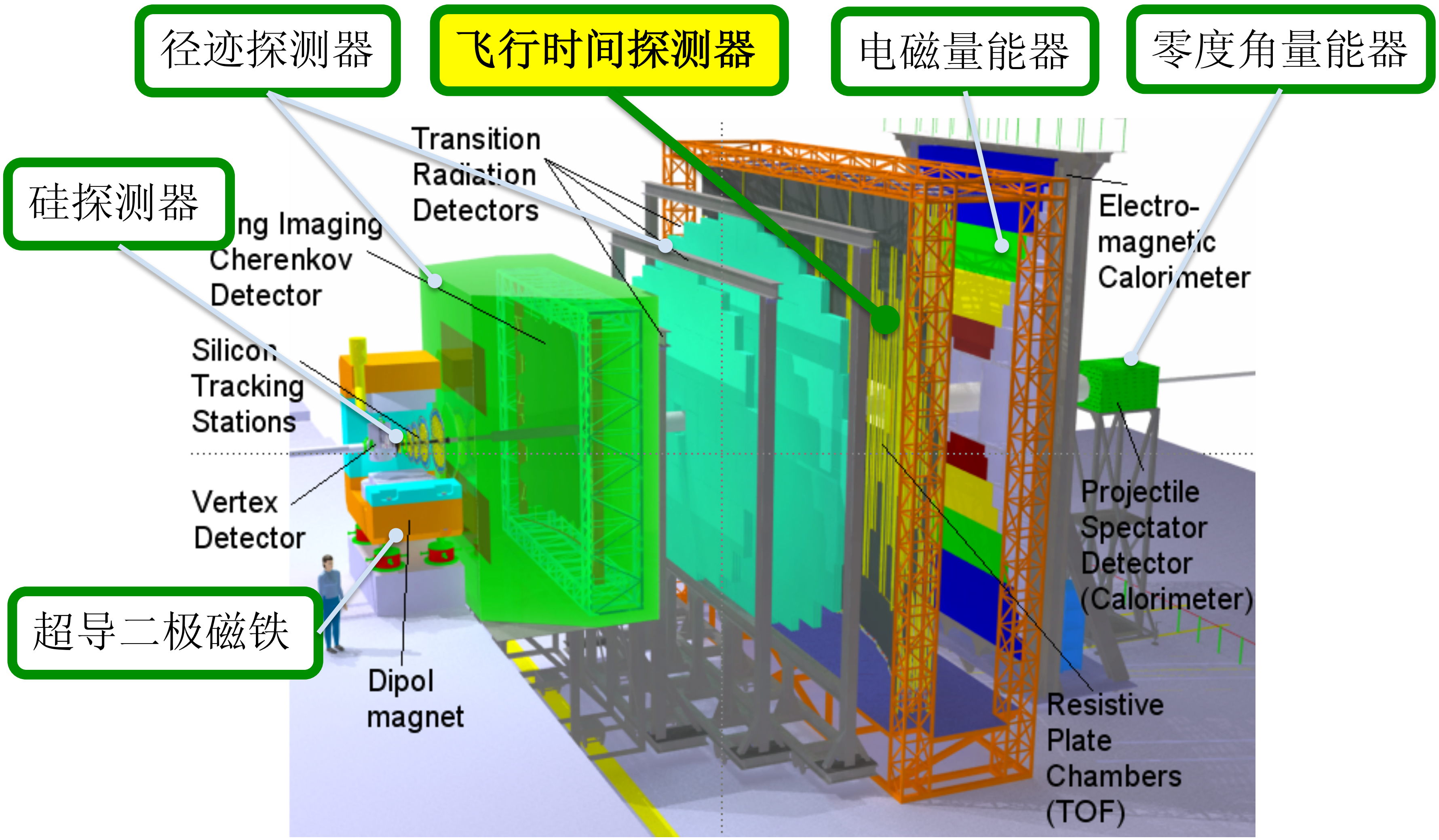
- range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently
- antiprotons 3 - 30 GeV

Cooling & Storage Ring

- radioactive beams
- 10^{11} antiprotons 1.5 - 15 GeV/c, stored and cooled



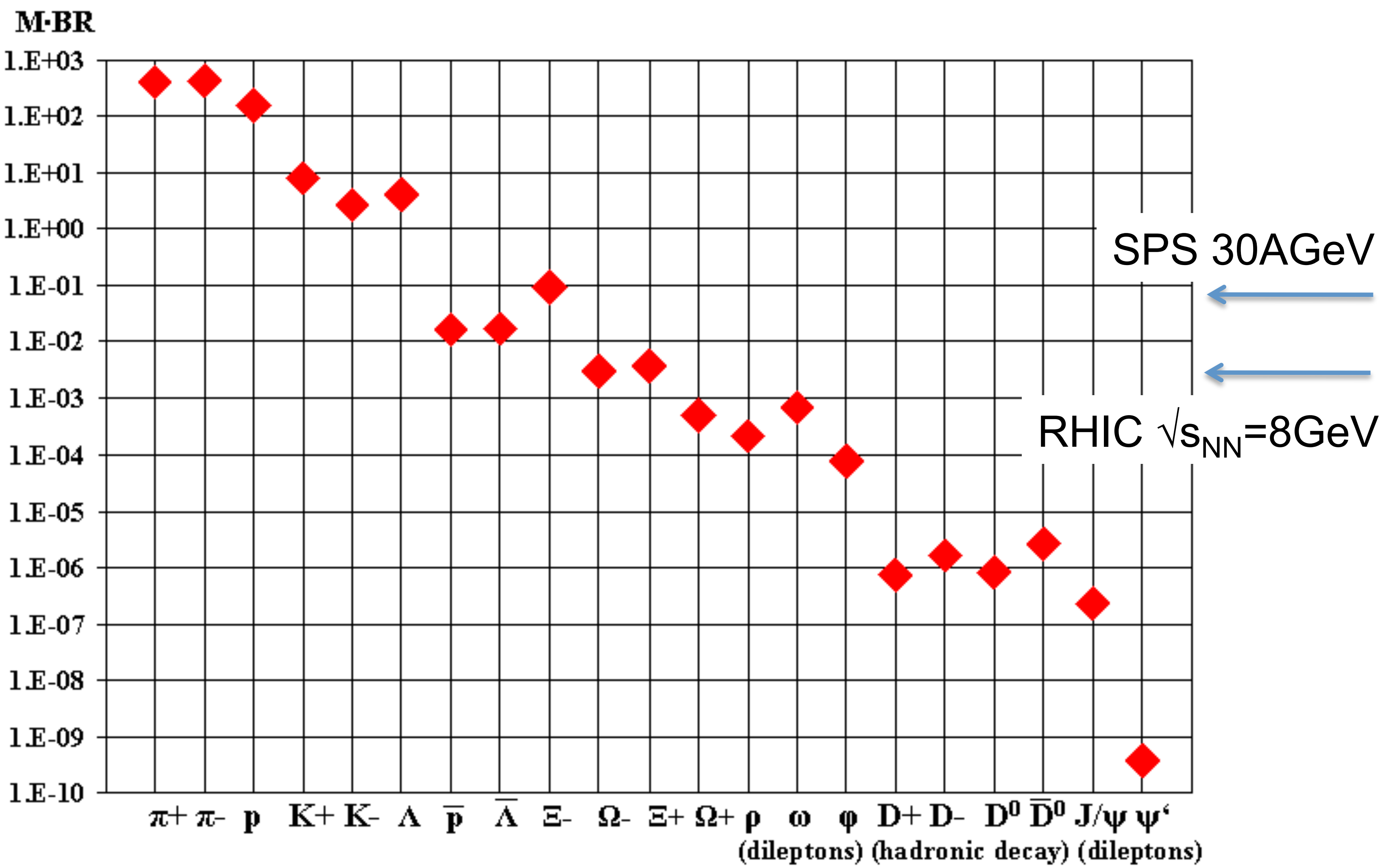
The Compressed Baryonic Matter Experiment: CBM



1) FAIR will provide the brightest HI beam starting 2018
2) High precision for the physics at high baryon density

Particle Production in 25 GeV Au+Au Collisions

(HSD and thermal model)



Future Direction

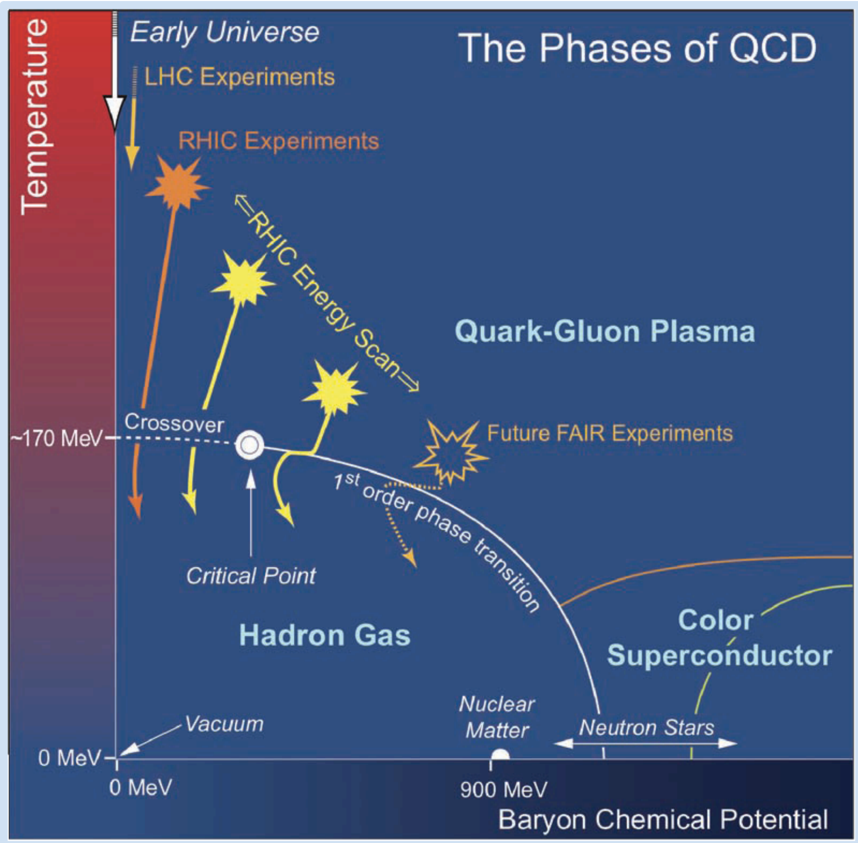
High luminosity

High precision

High baryon density

- origin of mass
- broken symmetry
- connection to cosmology
- …

Beam Energy Scan-I at RHIC



Study QCD Phase Structure
- Onset of sQGP
- Phase boundary and critical point
- Chrial symmetry restoration

Observables:

1st order phase transition
(1) Azimuthally sensitive HBT
(2) Directed flow v_1

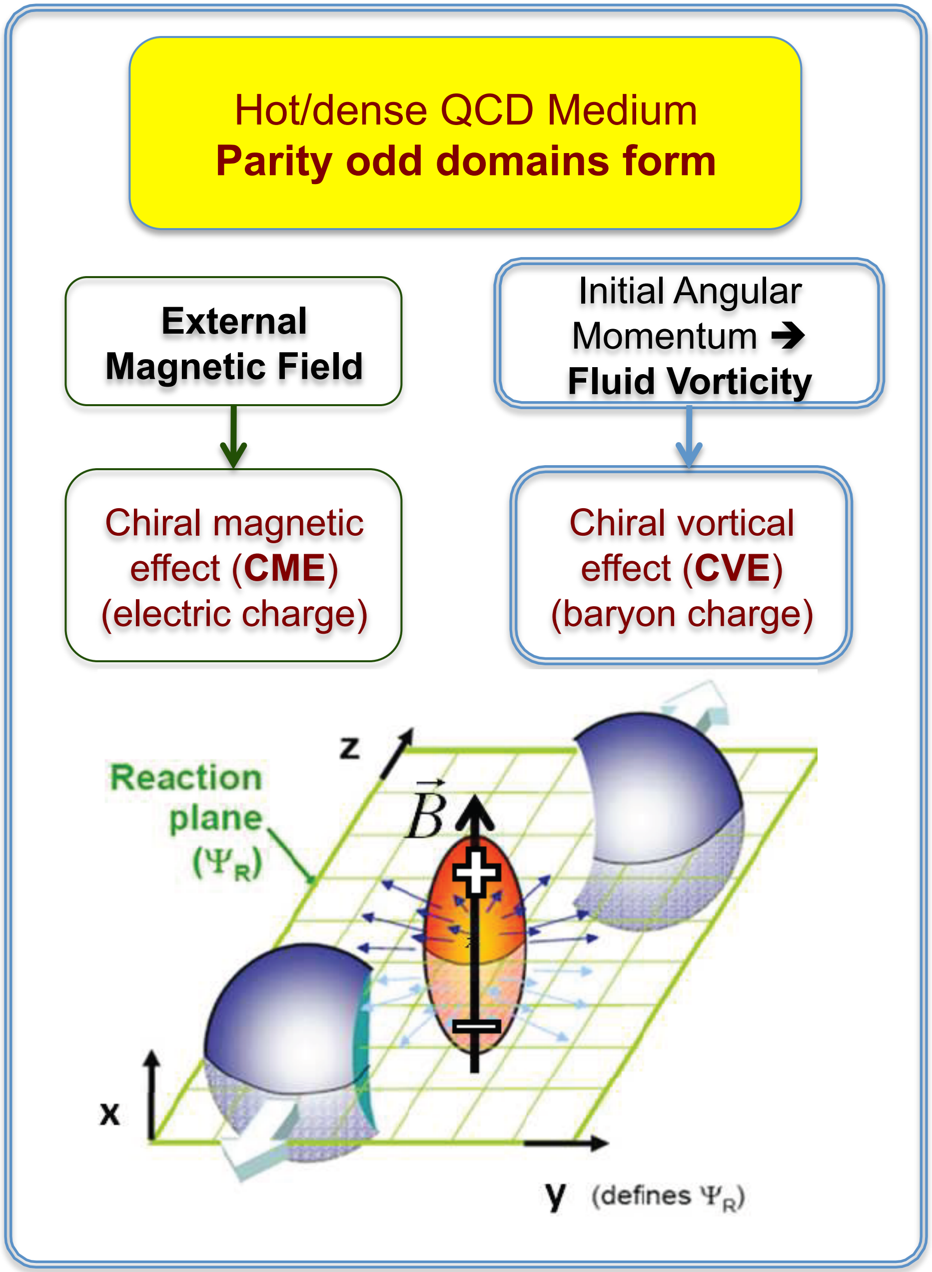
Partonic vs. hadronic dof
(3) R_{AA}: Nucl. Mod. Fact.
(4) Charge separation
(5) v_2 - NCQ scaling

Critical point, correl. length
(6) Fluctuations

Chiral symmetry restoration
(7) Di-lepton production

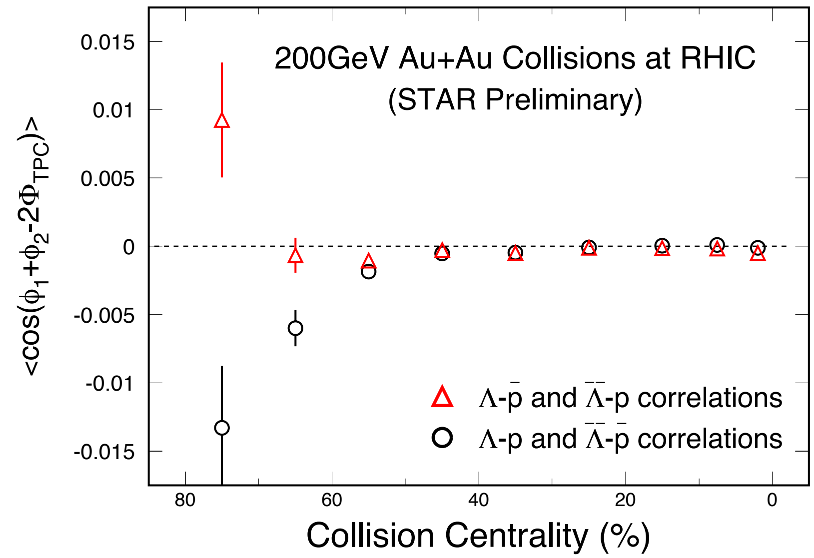
BES-I: $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39GeV

Study Global Chiral Effects at STAR



Chiral Vortical Effect

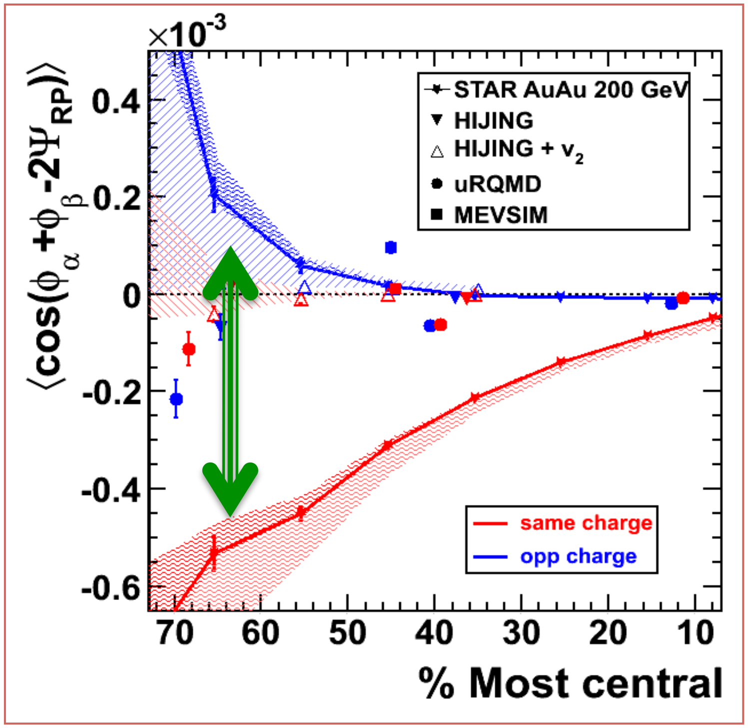
Λ-proton correlation measurement:



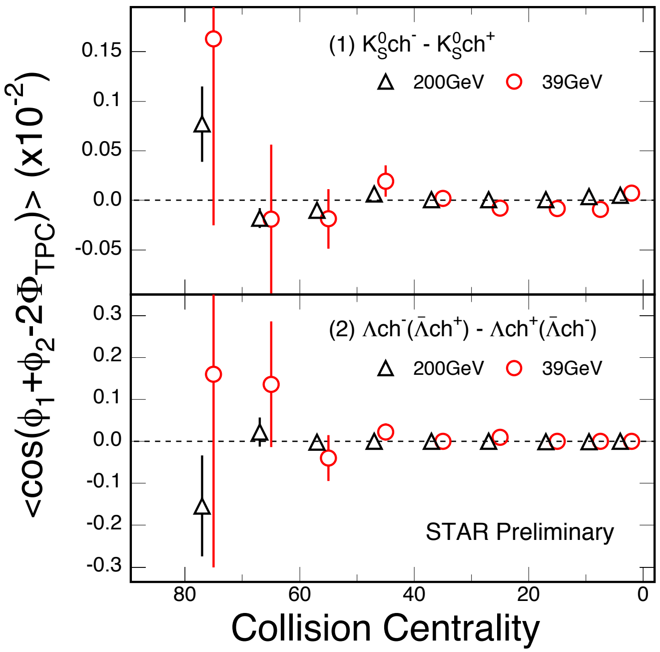
1) The opposite baryon number (Λ-pbar or Λbar-p) correlations (OB) are similar
2) The same baryon number (Λ-p or Λbar-pbar) correlations (SB) are lower than that of the OB, ***as expected from the CVE.***

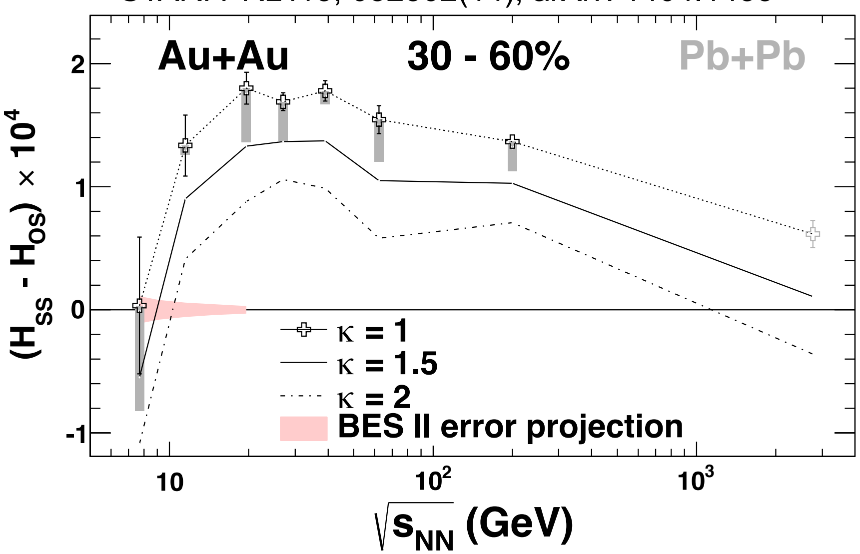
D. Kharzeev, D.T. Son, PRL106, 062301(11)
D. Kharzeev. PLB633, 260 (06)
D. Kharzeev, et al. NPA803, 227(08)
J.F. Liao, arXiv: 1401.2500, IAS

Charge Separation wrt Event Plane



STAR: PRL113, 052302(14), arXiv: 1404.1433





LPV(CME) disappears: with neutral hadrons:

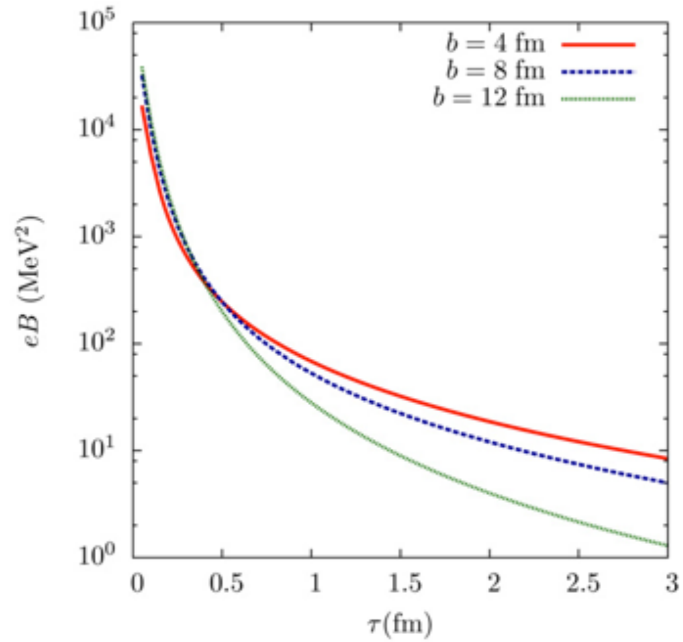
LPV(CME) disappears at low energy:

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

STAR: PRL. 103, 251601(09); 113, 052302(14)
D. Kharzeev. PLB633, 260 (06)
D. Kharzeev, et al. NPA803, 227(08)

Time Scales

(a) CME:



External magnetic field:

$\tau_B = 2R/\gamma = 0.1 - 0.2$ fm/c

Partonic process:

$\tau_p = 1/m_q = 1$ - few fm/c

Hadronic process:

$\tau_h = 1/m_h = 0.2 - 1$ fm/c

(b) CVE:

External angular momentum conserved!

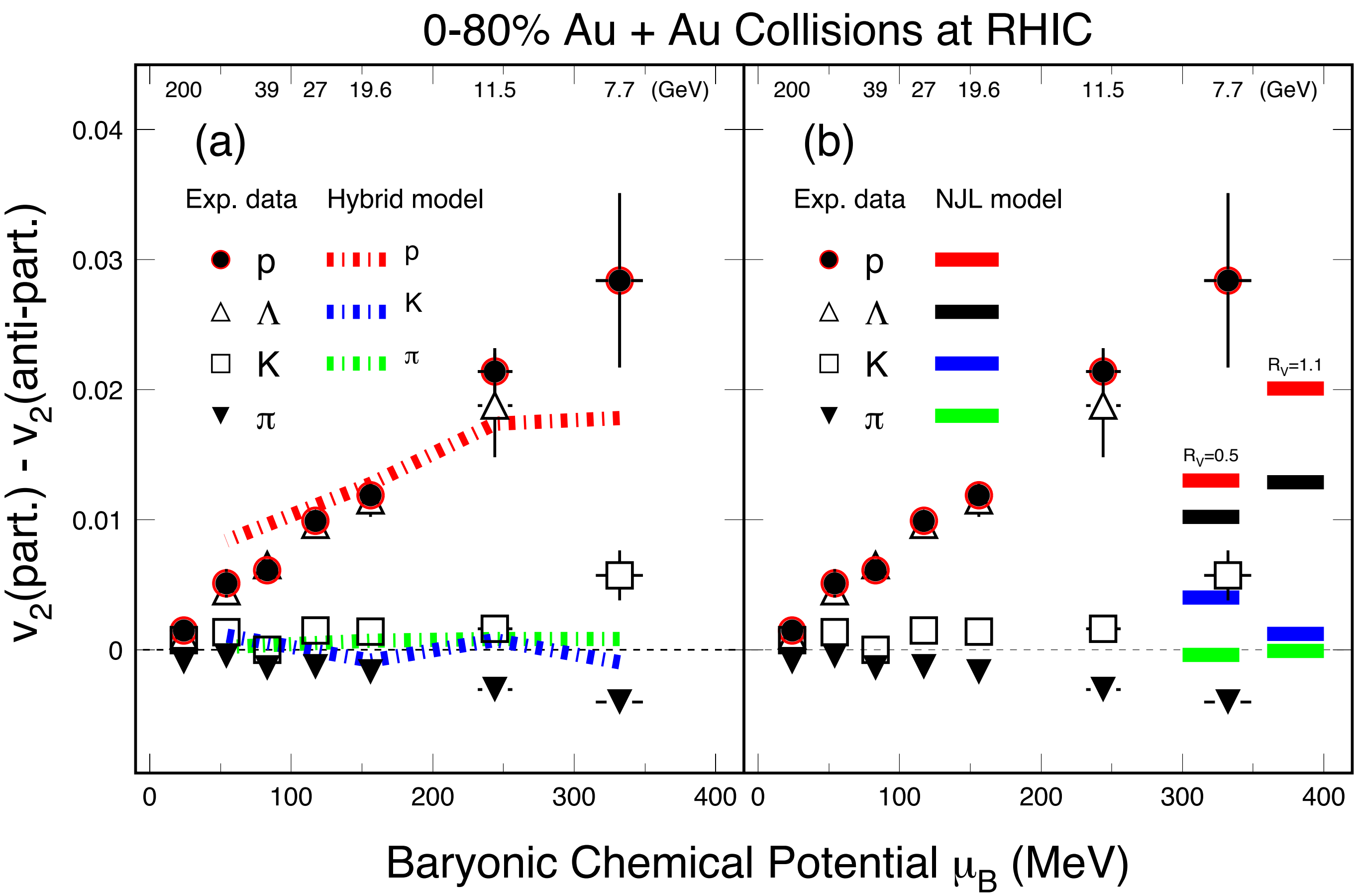
More important at high baryon region?

Understanding the Global Chiral Effect

- untested QCD basic property

- **CME vs. CVE?**
- **Partonic vs. hadronic?**
- **Quantitative predictions?**
- **Other physics backgrounds?**

BES v_2 and Model Comparison

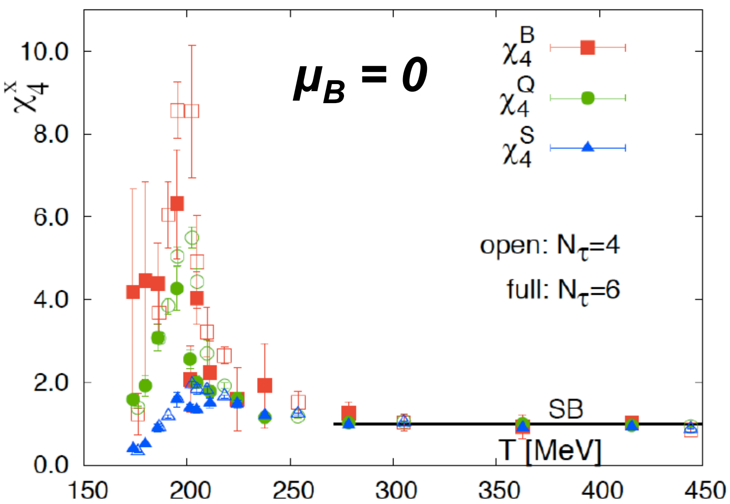


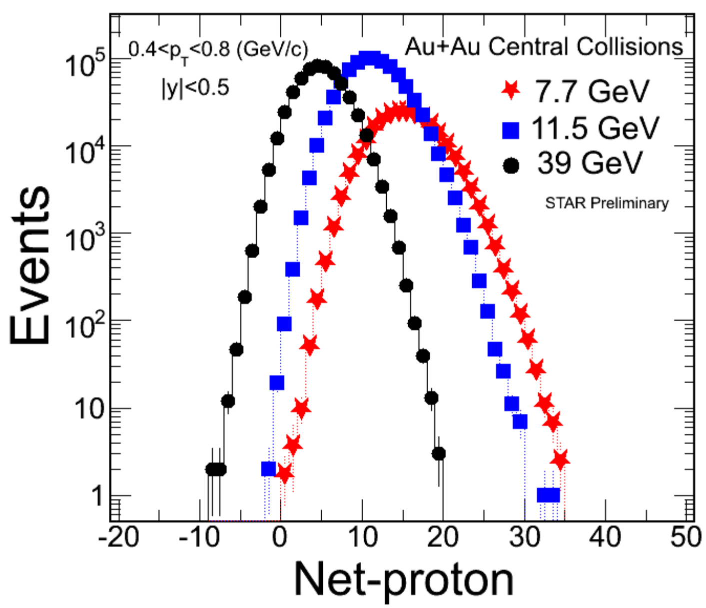
(a) Hydro + Transport: consistent with baryon data.

[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:

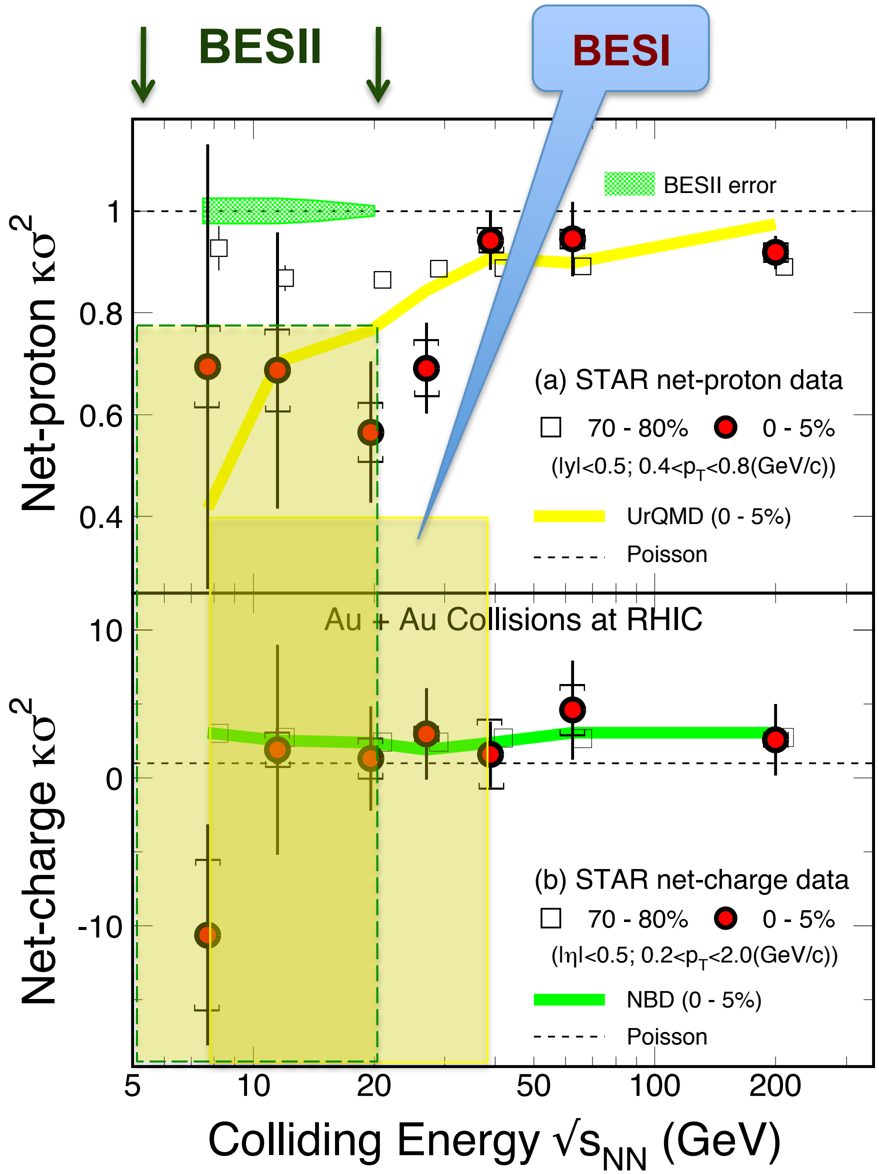
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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:

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

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

Net-charge results:

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

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

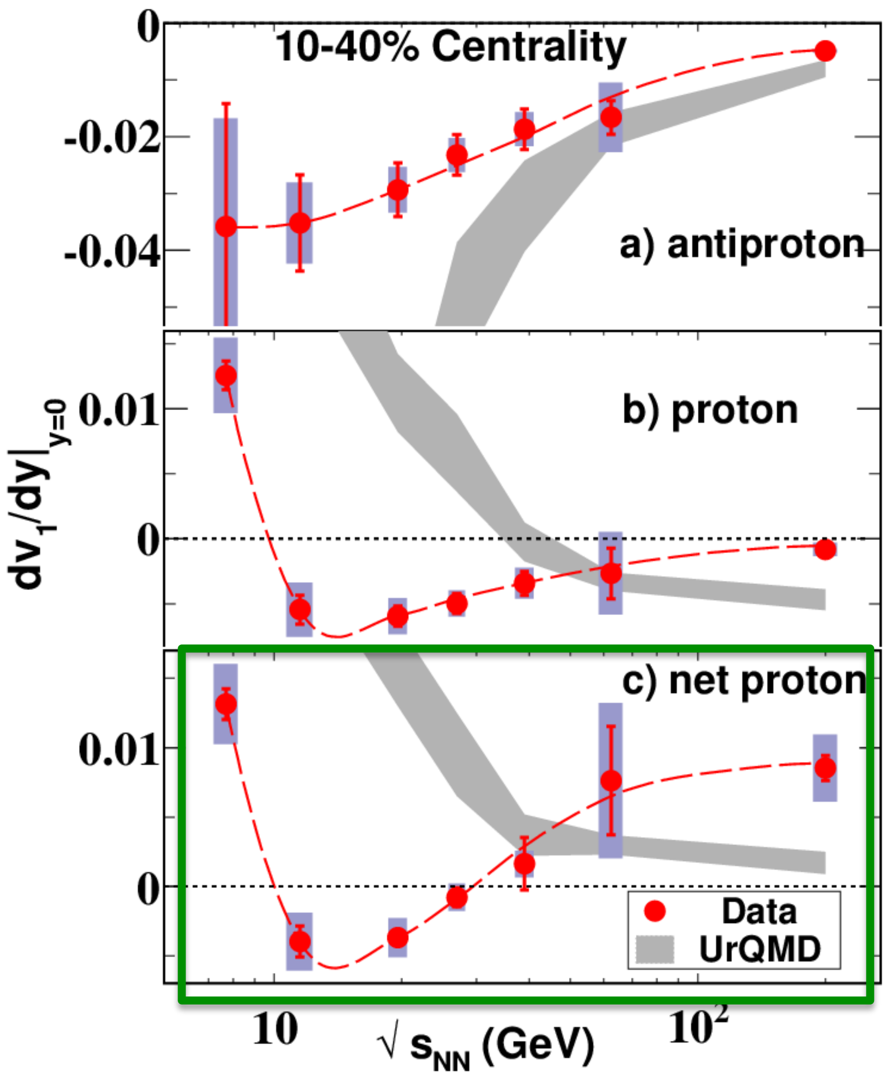
BESII needed:

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

Future measurements:

- Wider kinematic region
- Lighter symmetric systems - central collisions Si+Si, Cu+Cu, …

Directed Flow v_1: Softest Point?



1) Net-proton slope changes sign twice between $\sqrt{s_{NN}}$ = 7 – 39 GeV

2) EOS softest point?

3) Model calculations yet to reproduce the observation

4) BESII improvement:
   - improved reaction plane determination
   - systematic centrality dependence analysis
   - ***Connection to EOS?***

STAR: *PRL**112**, 162301(2014)/aiXiv:1401.3043*
[1] D.H. Rischke et al. HIP1, 309(1995)
[2] H. Stoecker, NPA750, 121(2005)
[3] J. Steinheimer et al., arXiv:1402.7236
[4] P. Konchakovski et al., arXiv:1404.2765

LHC, RHIC, FAIR

(I) 2000 - 2012: RHIC, LHC

1) sQGP: strongly coupled QGP, η/S =>0, ideal fluid.
2) At $\mu_B = 0$ smooth cross over.

It is time to discover the QCD critical point!

"The landmark in the QCD phase diagram."

more data are needed to confirm: RHIC BESII and FAIR CBM.

(III) 2018 and beyond:

Collider: RHIC BESII ($7.7 < \sqrt{s_{NN}} < 20$ GeV, $420 \geq \mu_B \geq 300$ MeV)

Fixed-target: FAIR CBM ($\sqrt{s_{NN}} \leqslant 12$ GeV, $\mu_B \geq 300$ MeV)

1) High luminosity, new detectors
2) Physics focus：Cp, Pb and Qm