Recent Results from the 1st RHIC Beam Energy Scan

Nu Xu

Outline:

1) Introduction: RHIC BES-I Program
2) STAR Detector System
3) BES-I Results (selected) and BES-II
4) Summary

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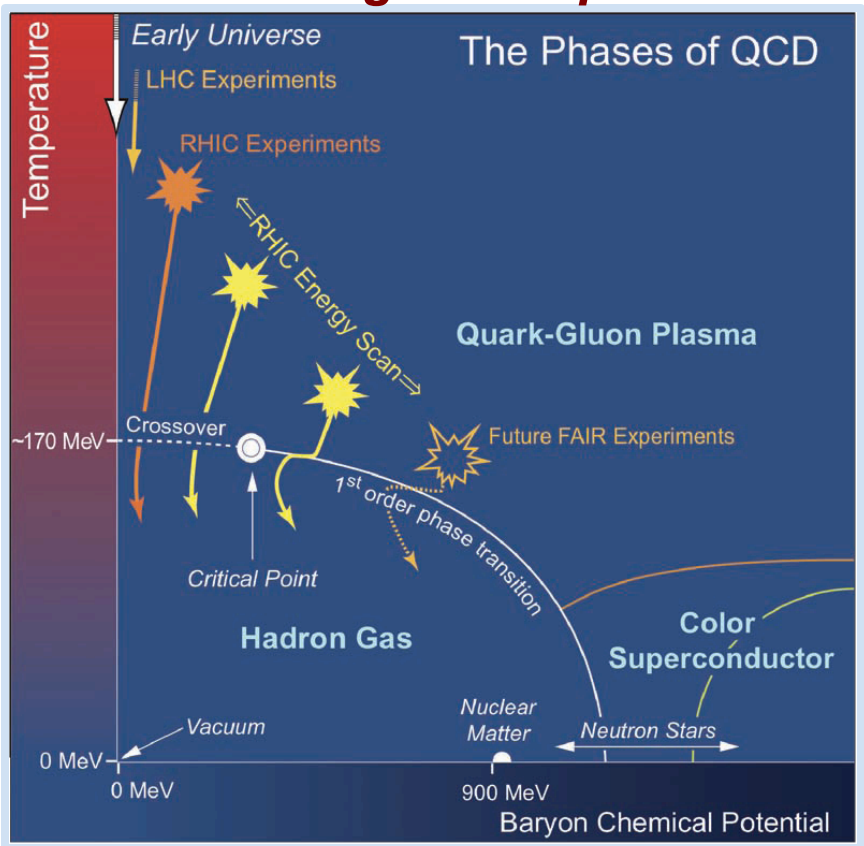
(2) *College of Physical Science & Technology, Central China Normal University, China*

Beam Energy Scan (I) at RHIC

QCD Emergent Properties



Study QCD Phase Structure

- Signals for onset of sQGP
- Signals for phase boundary
- Signals for critical point

Observables:

1st order phase transition

(1) Azimuthally HBT*

(2) Directed flow v_1*

Partonic vs. hadronic dof

(3) R_{AA}: N.M.F.

(4) Dynamical correlations*

(5) v_2 - NCQ scaling*

Critical point, correl. length

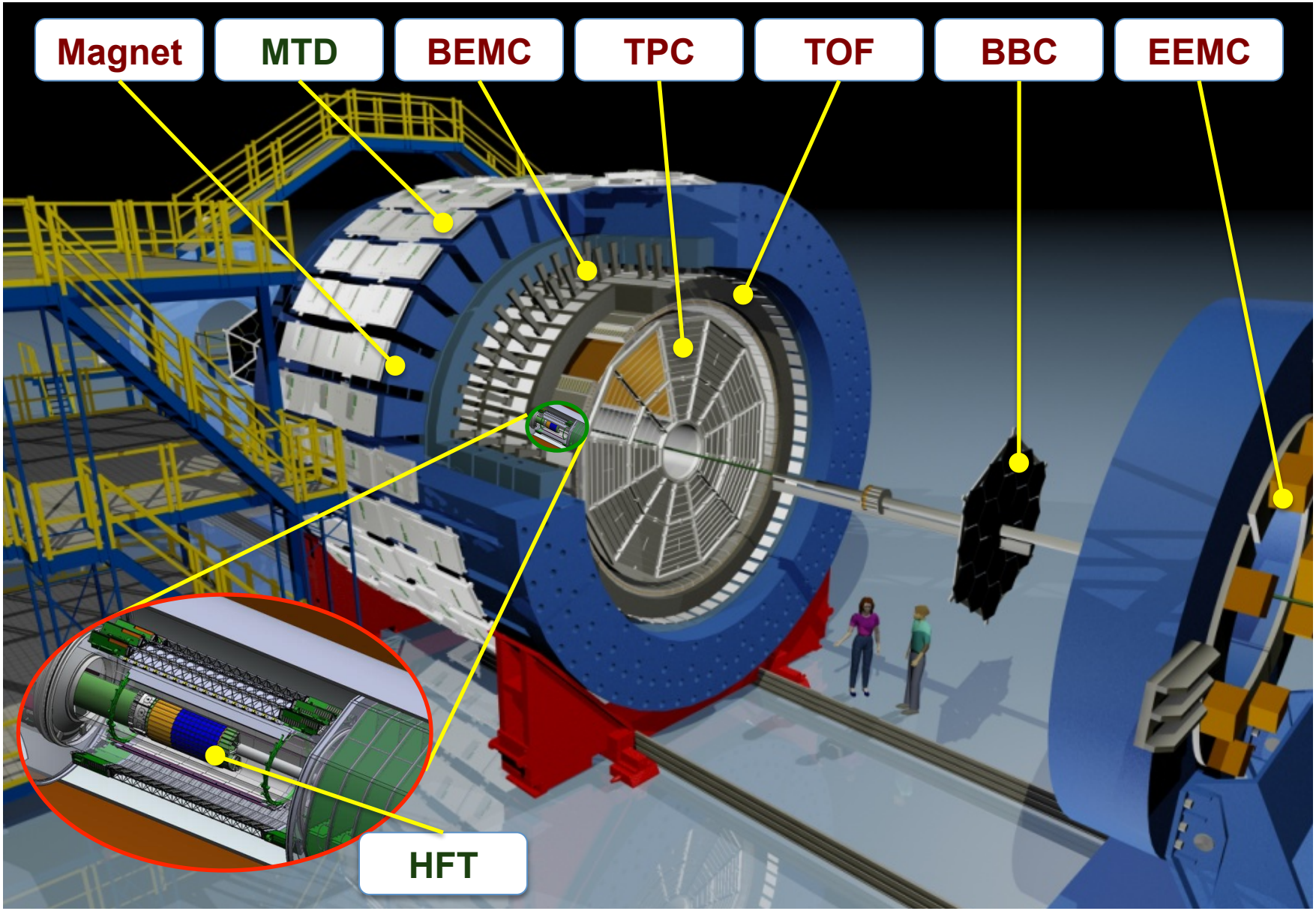
(6) Fluctuations*

(7) Di-lepton production

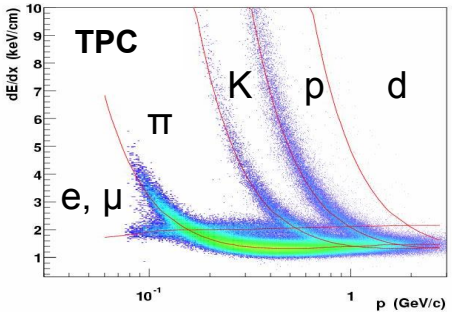
BES-I: $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39GeV

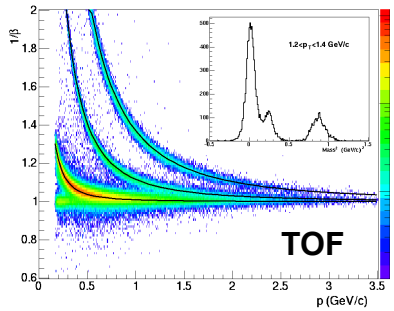
BES-I	Energy (GeV)	*μ_B (MeV)	Time (Week)	# of Events (Million)
2010	62.4	**50**	1	67
2010	39	**85**	1	130
2011	27	**140**	1.5	70
2011	19.6	**200**	1.5	36
2014	14.5	**~270**	3	21
2010	11.5	**320**	2	12
2010	7.7	**420**	4	4

STAR Experiment

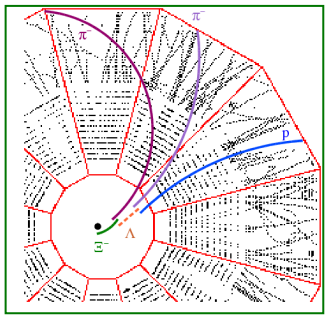


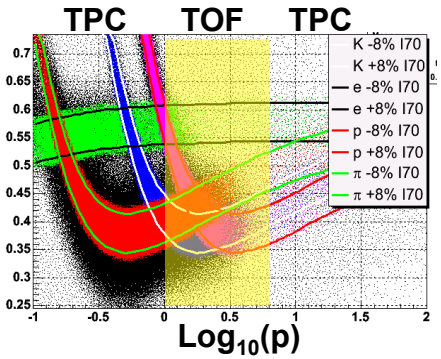
Particle Identification at STAR



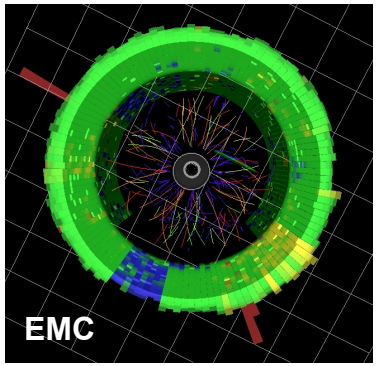


Charged hadrons

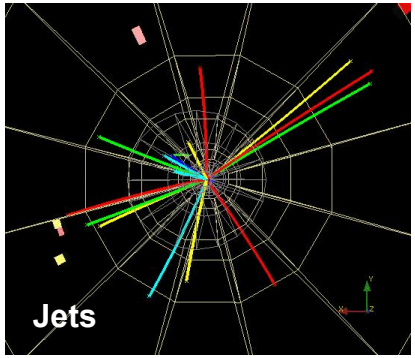




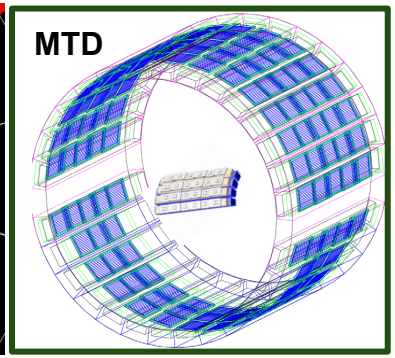
Hyperons & Hyper-nuclei



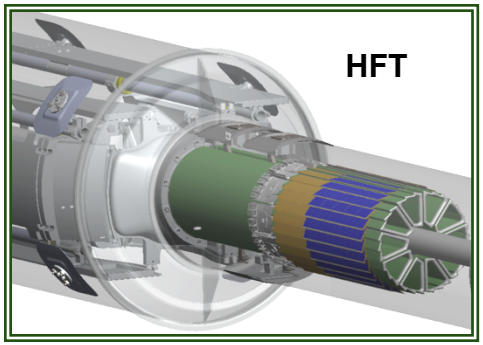
Neutral particles



Jets & Correlations



High p_T muons



Heavy-flavor hadrons

Multiple-fold correlations for the identified particles!

STAR Detector Configurations

	Period	Detectors	Physics
	2001-2010	**TPC**	*u, d, s*
	2010	TPC + TOF	*u, d, s + dilepton*
	2013	TPC + TOF + MTD	***u, d, s, c, b + dilepton***
	2014	TPC + TOF + MTD **+ HFT**	

➔ **STAR: Large coverage, excellent PID, fast DAQ**

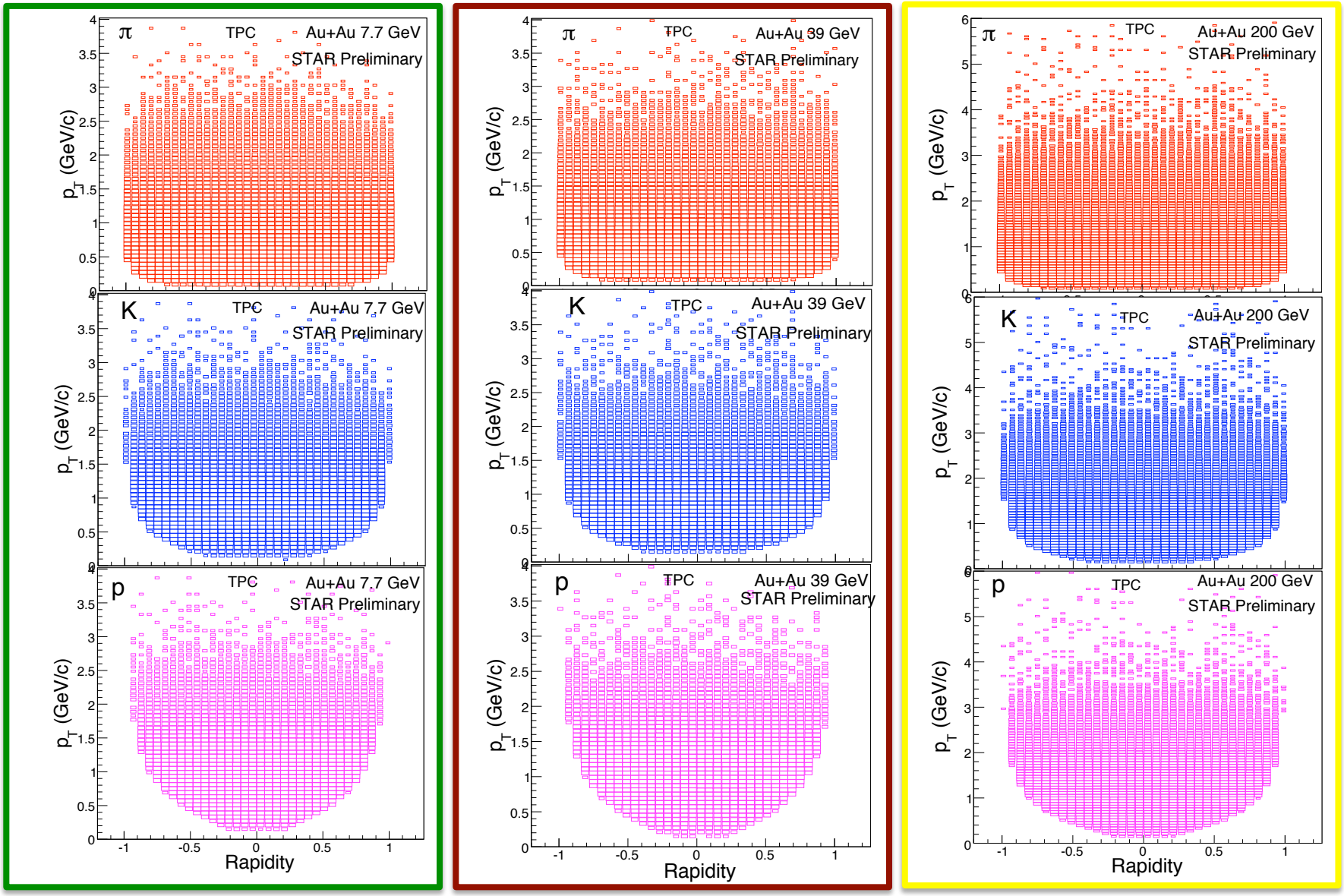
- detects nearly all particles produced at RHIC
- multiple fold correlation measurements
- **Probes: bulk, penetrating, and *bulk-penetrating***

➔ **STAR: Excellent mid-y collider experiment**

➔ **STAR: Expanding into forward rapidity regions**

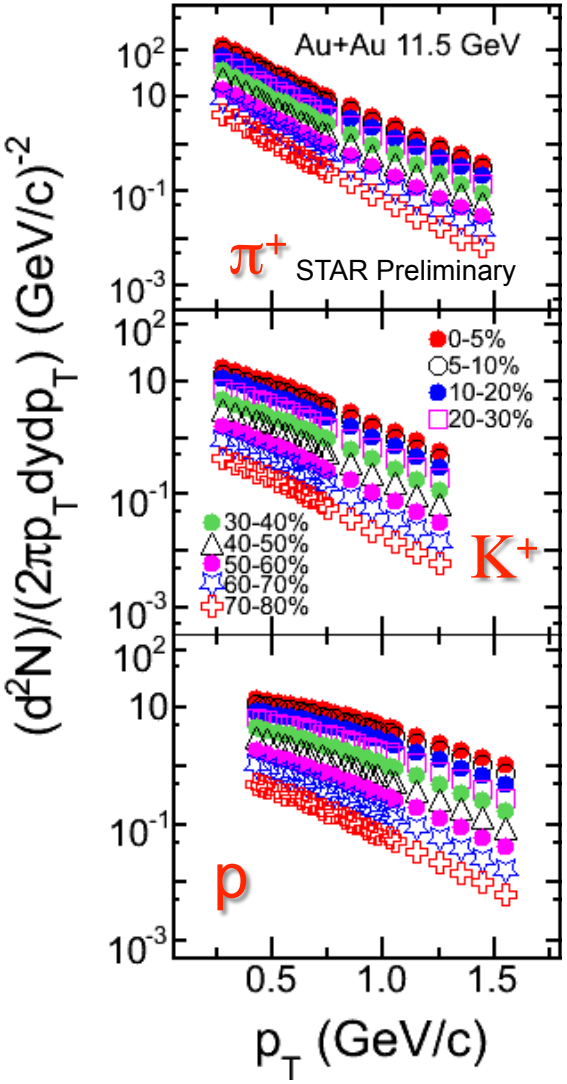
STAR PID for (π, K, p)

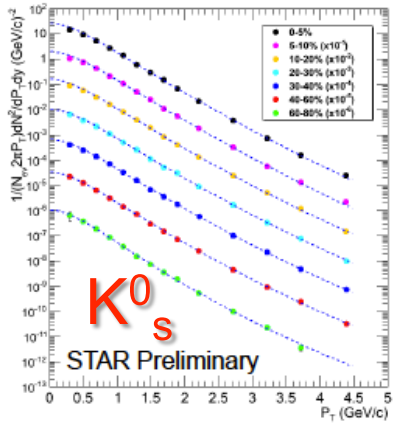
Au+Au at *7.7* GeV | **Au+Au at *39* GeV** | **Au+Au at *200* GeV**

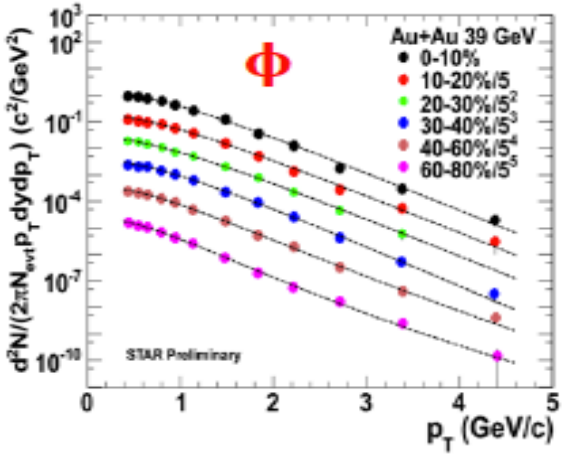


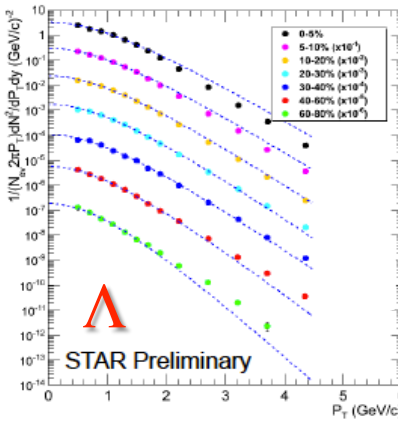
(1) Hadron Spectra

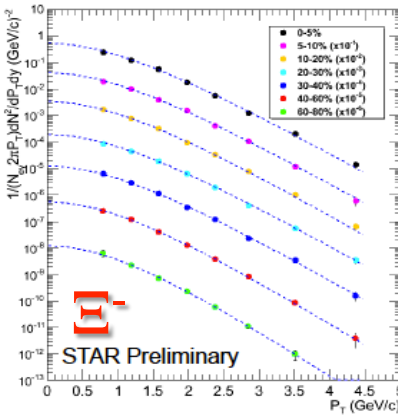
$\sqrt{s_{NN}}$ = *39* GeV Au+Au Collisions

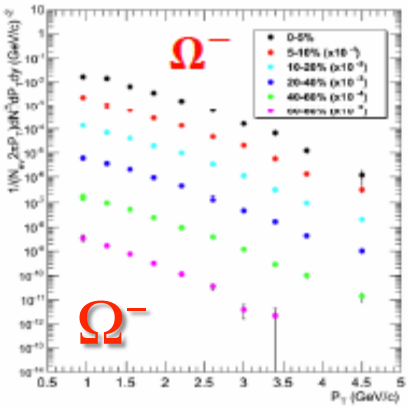




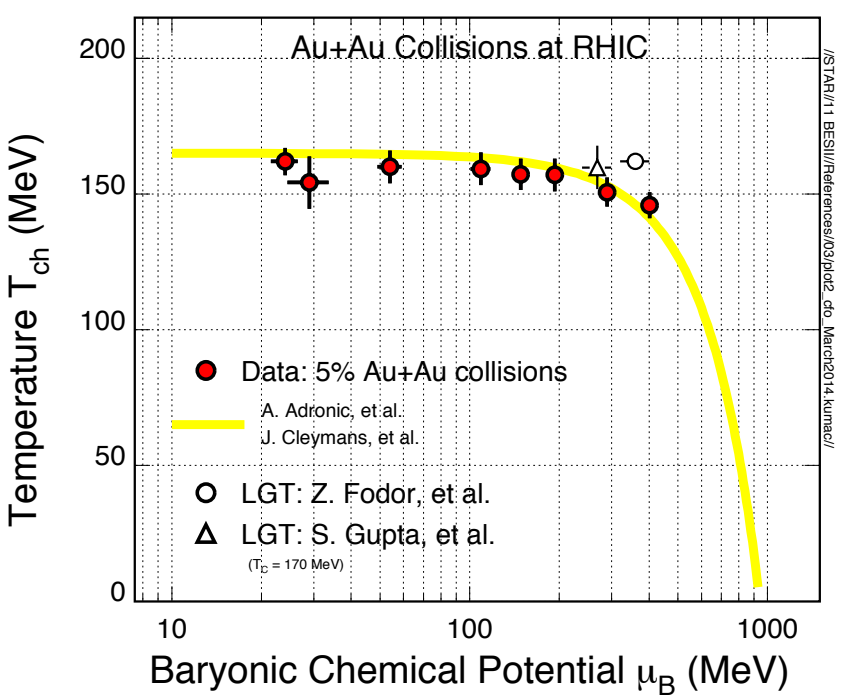


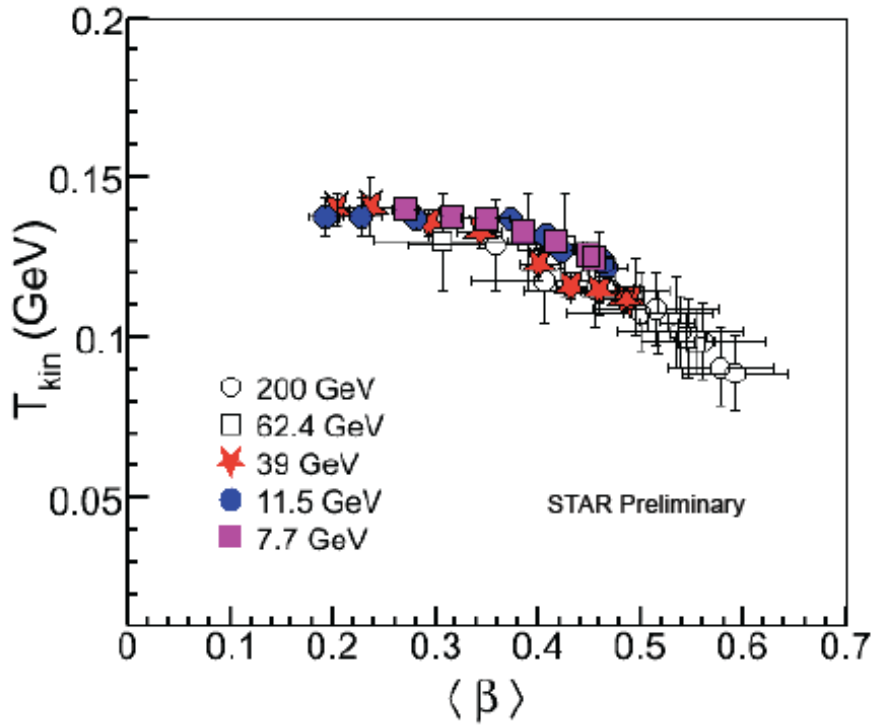






Bulk Properties at Freeze-out





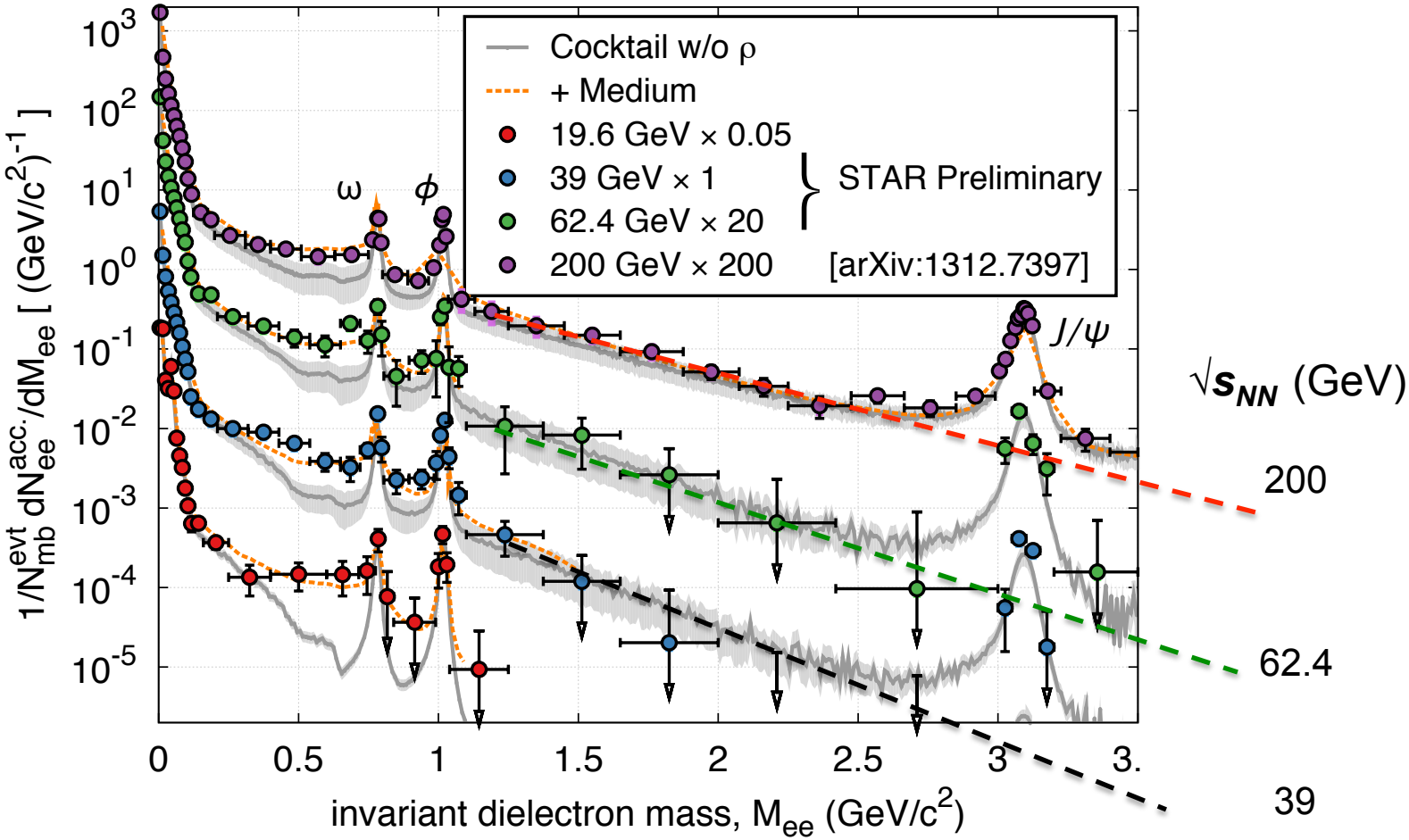
Chemical Freeze-out: (GCE)

- Central collisions => higher values of T_{ch} and μ_B!
- The effect is stronger at lower energy.

Kinetic Freeze-out:

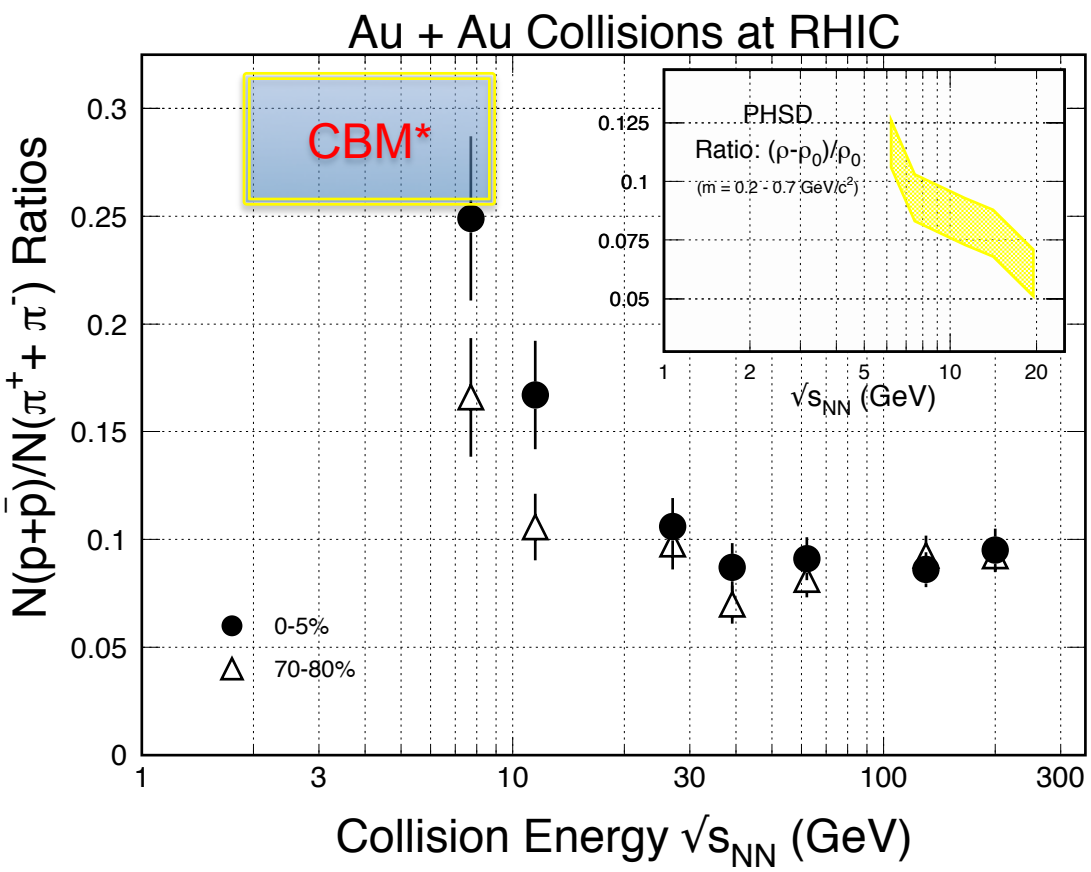
- Central collisions => lower value of T_{kin} and larger collectivity β
- Stronger collectivity at higher energy

(2) BES Dependence of Dielectrons



1) Low mass reg. ($M_{ee} \leq 1$GeV): no obvious energy dependence in the ratio of data/cooktail. At 19.6, the ratio is consistent with SPS results.
2) Intermediate mass reg. ($1 \leq M_{ee} \leq 3$GeV): clear energy dependence: => Correlated charm? Thermal radiation, ~exp($-M_{ee}/T$)?

Understanding the Di-electrons

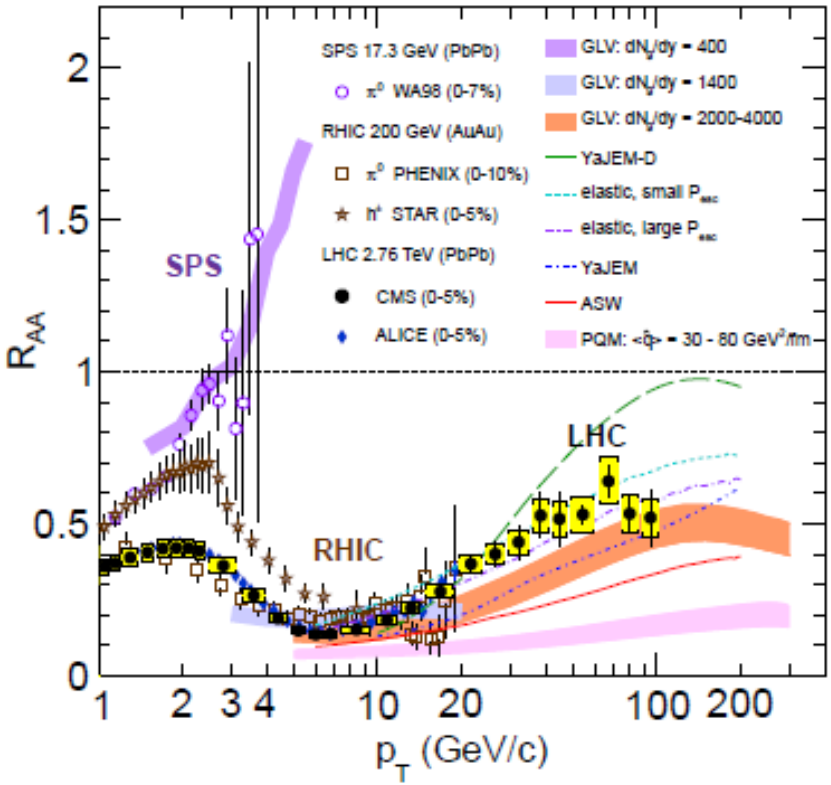


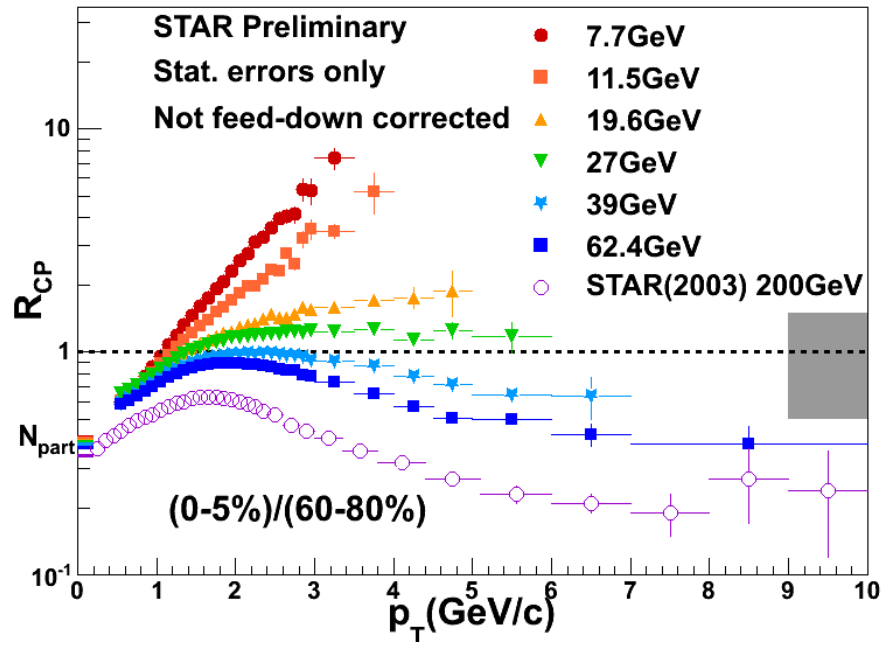
*CBM energy region: test the effect

1) With the in-medium broadened rho, model results* are consistent with experimental data ($m_{ee} \leq 1$ GeV/c^2) at $\sqrt{s_{NN}}$ = 200, 62.4, 39, 27 and 19.6GeV. (* driven by the baryon density in the medium)

2) In Au+Au collisions at 200GeV, the centrality and p_T dependence results on data/hadronic cocktails ($m_{ee} \leq 1$ GeV/c^2) understood with current model calculations

(3) BES Dependence of R_{AA}



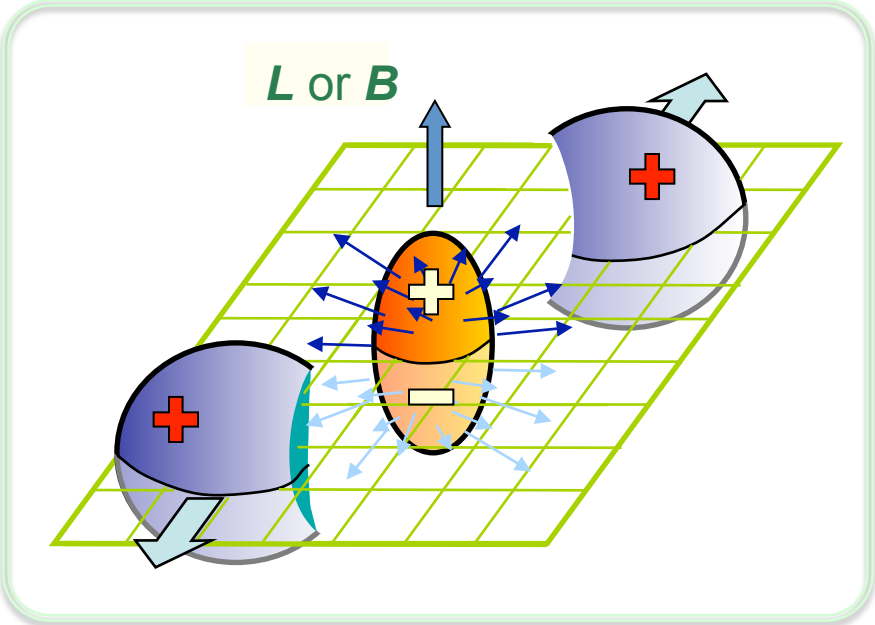


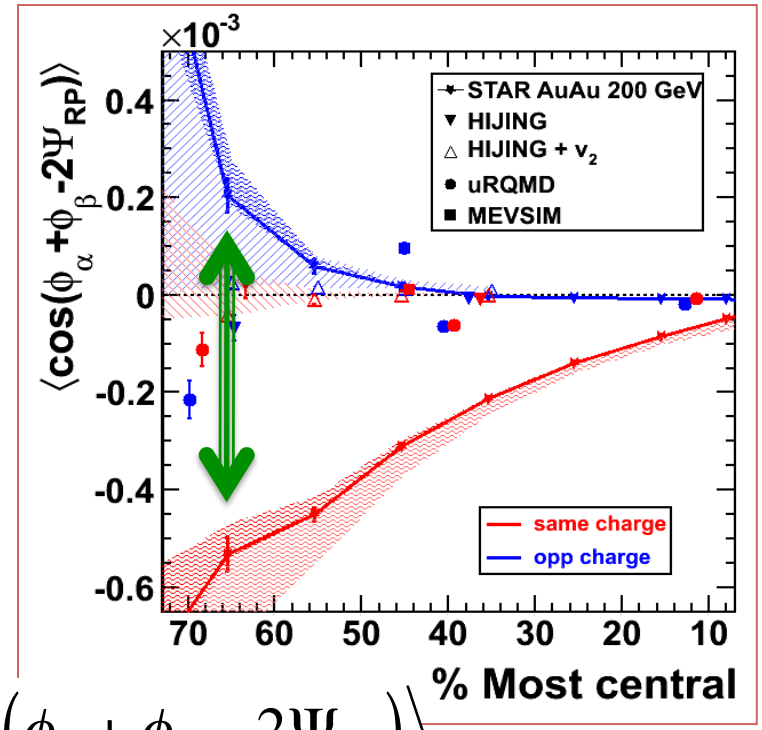
1) Suppression of high p_T hadrons: one of the key signatures for the formation of QGP in high-energy nuclear collisions

2) The **suppression is not observed** in low energy Au+Au collisions, especially for $\sqrt{s_{NN}} \leq 11.5$GeV

(4) Local Parity Violation

in High-Energy Nuclear Collisions





$$\left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{RP}\right)\right\rangle$$

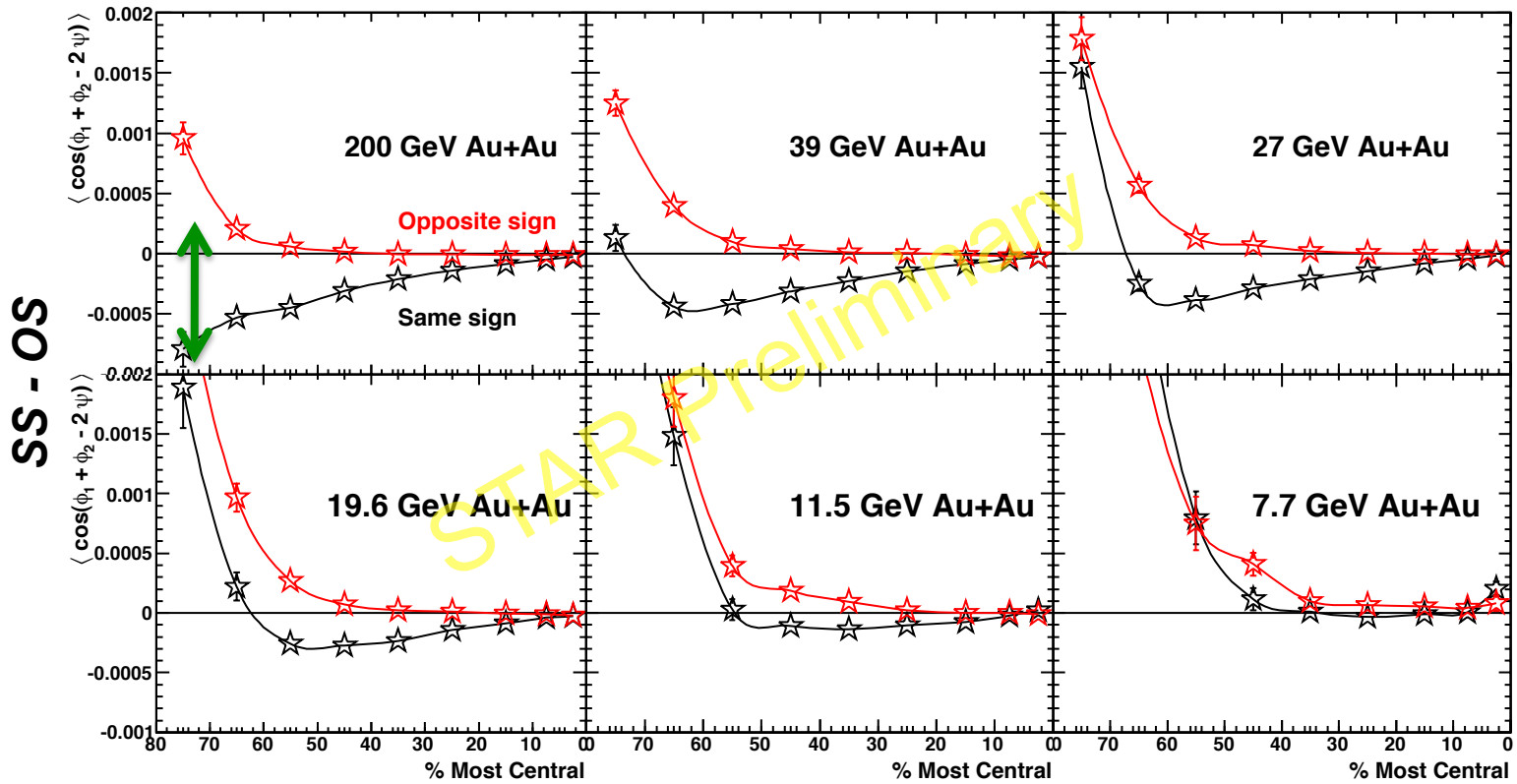
The separation between the same-charge and opposite-charge correlations.

- **Strong external EM field**
- ***De-confinement* and *Chiral symmetry restoration***

1) Parity-even observable: assumptions must be tested
2) BES dependence & UU coll. tests

- S. Voloshin, *PRC62*, 044901(00).
- STAR: *PR103*, 251601; PRC81, 054908(2009)

Dynamical Correlations

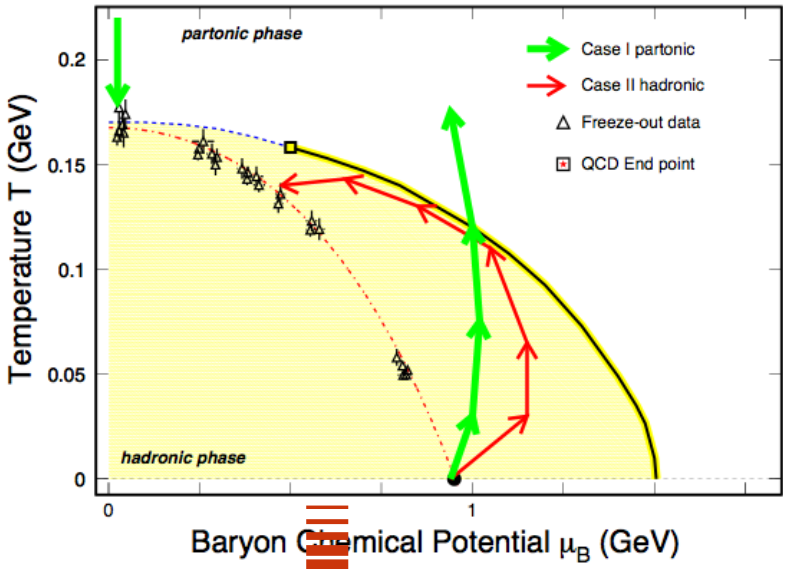


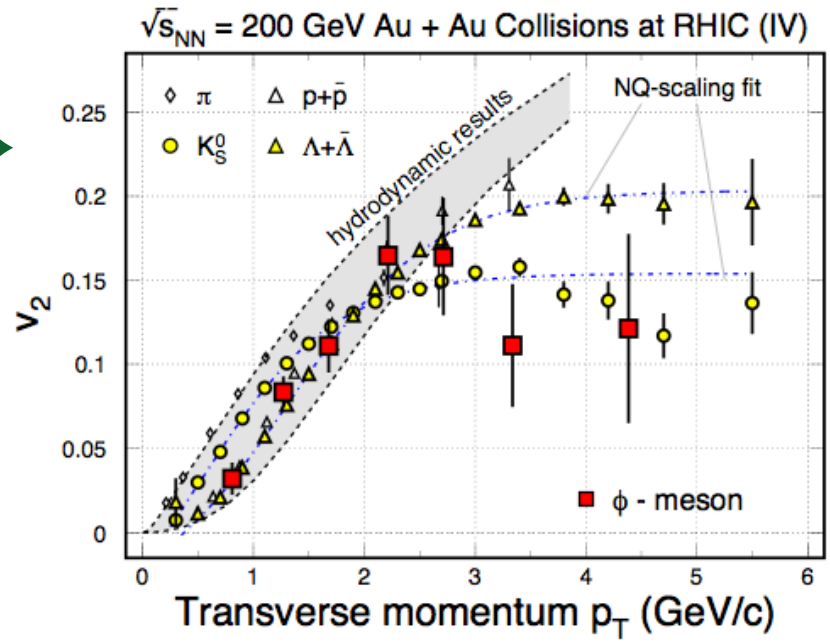
STAR: sub. to PRL, arXiv: 1404.1433

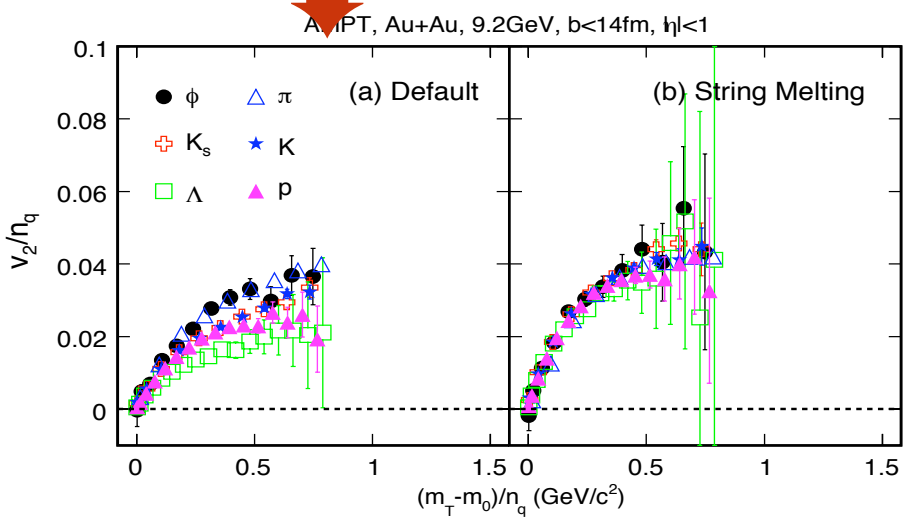
(1) Below $\sqrt{s_{NN}}$ = 11.5 GeV, the splitting between the same- and opposite-sign charge pairs (SS-OS) disappear

(2) If QGP is the source for the observed splitting at high-energy nuclear collisions ➔ hadronic interactions become dominant at $\sqrt{s_{NN}} \leq$ 11.5 GeV

(5) NCQ Scaling in v_2







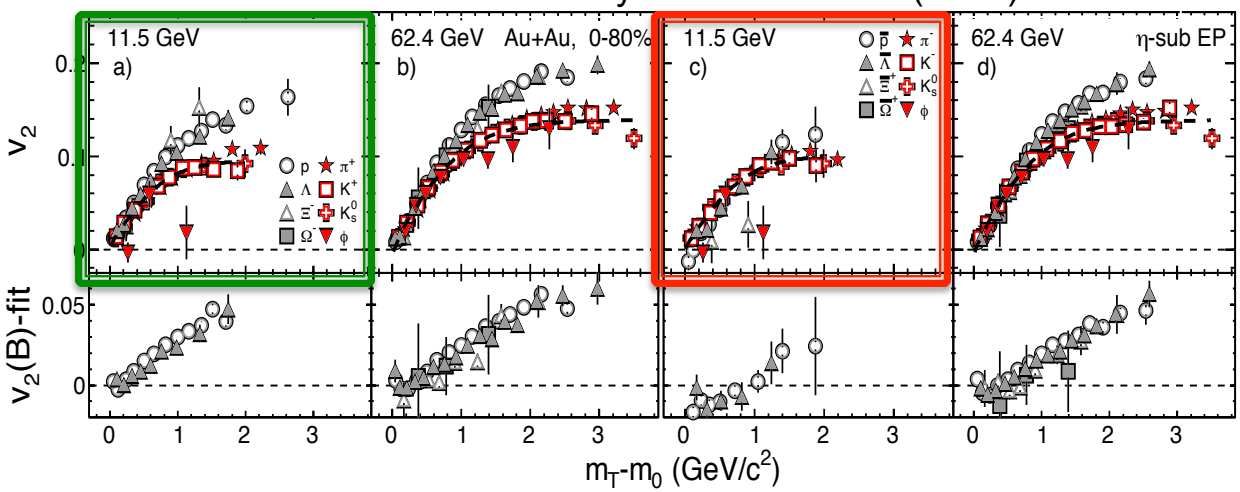
- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi,\ \pi\pi}$

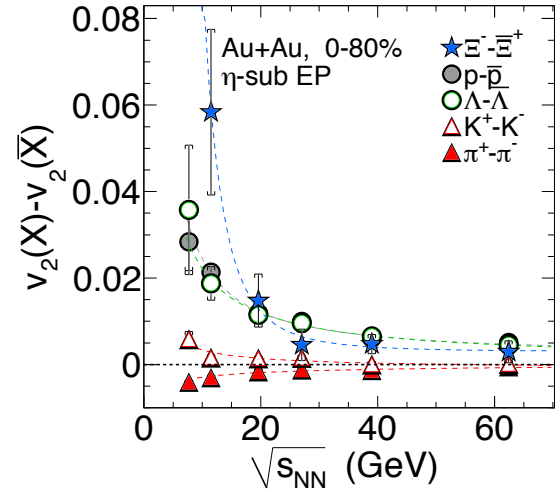
In the hadronic case, no number of quark scaling and the value of v_2 of φ will be small.

*** Thermalization is assumed!**

Collectivity v_2 Measurements

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

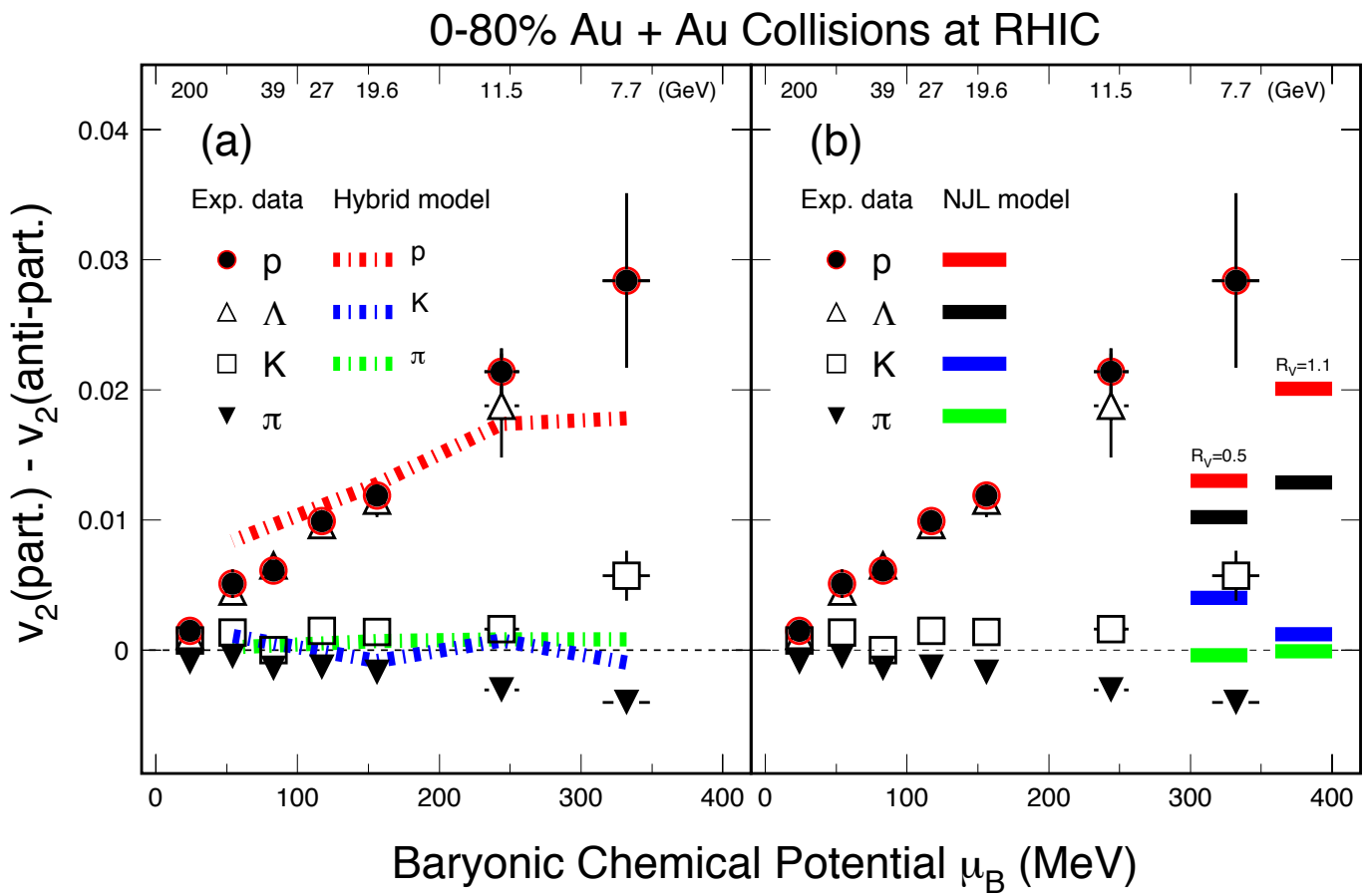




1) Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions

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

BES v_2 and Model Comparison



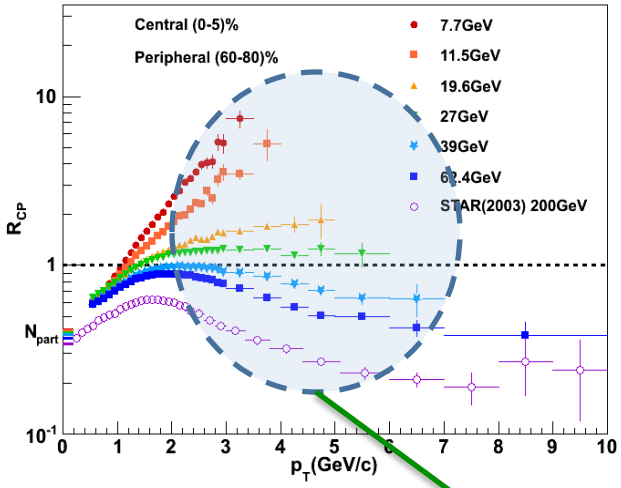
(a) Hydro + Transport: consistent with baryon data.

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

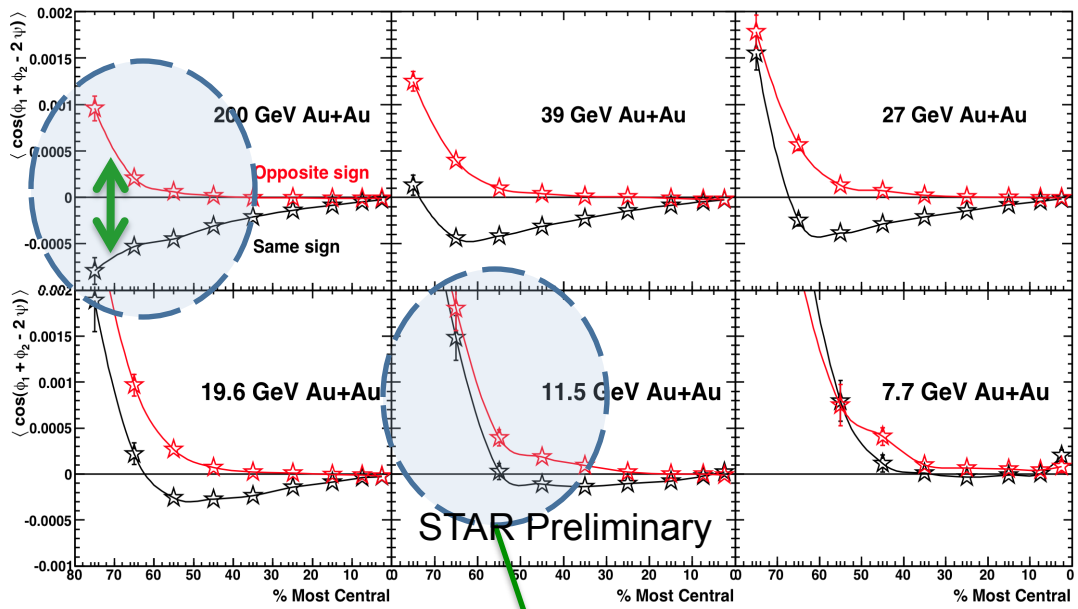
(b) NJL model: Hadron splitting consistent. Sensitive to vector-coupling, CME, net-baryon density dependent. [J. Xu, et al., arXiv:1308.1753/PRL112.012301]

Disappearance of QGP Signatures

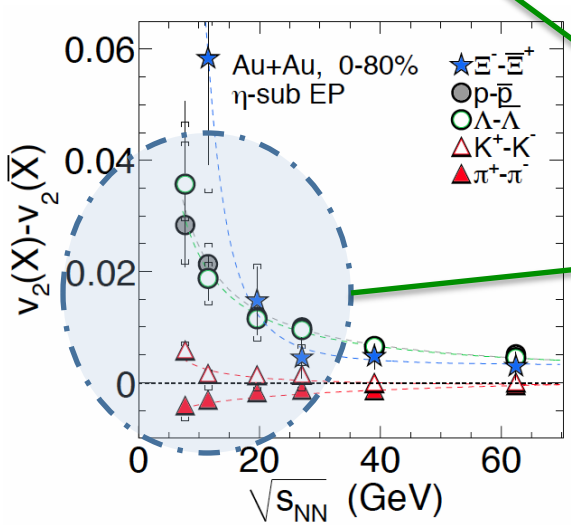
Parton energy loss



"Local Parity Violation"



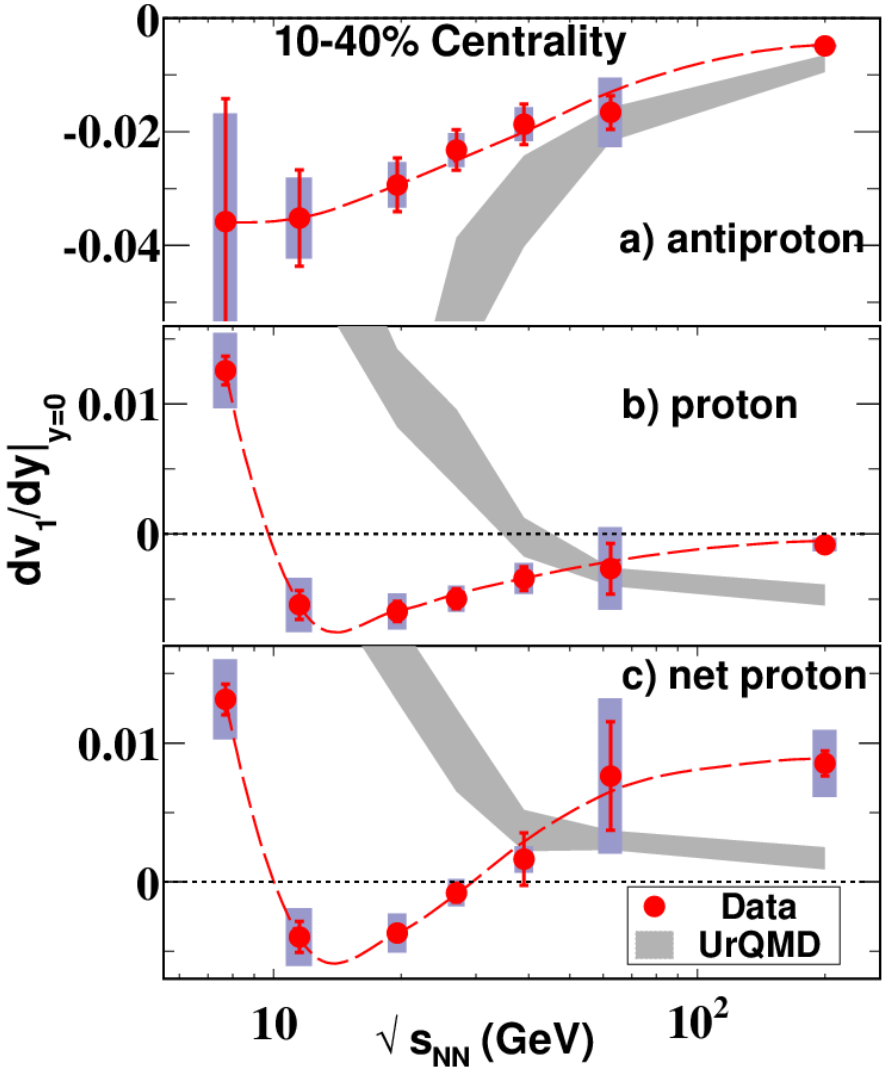
Partonic collectivity



sQGP key signatures

turned off at $\sqrt{s_{NN}}$ < 11.5 GeV!

(6) Direct Flow v_1: Soft Point

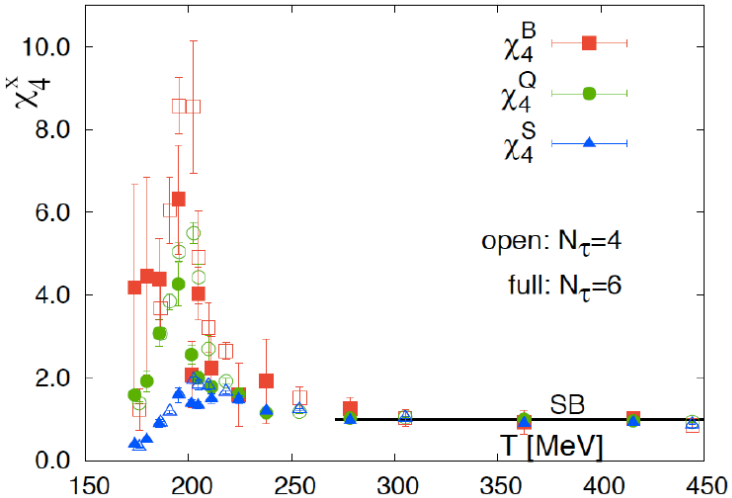


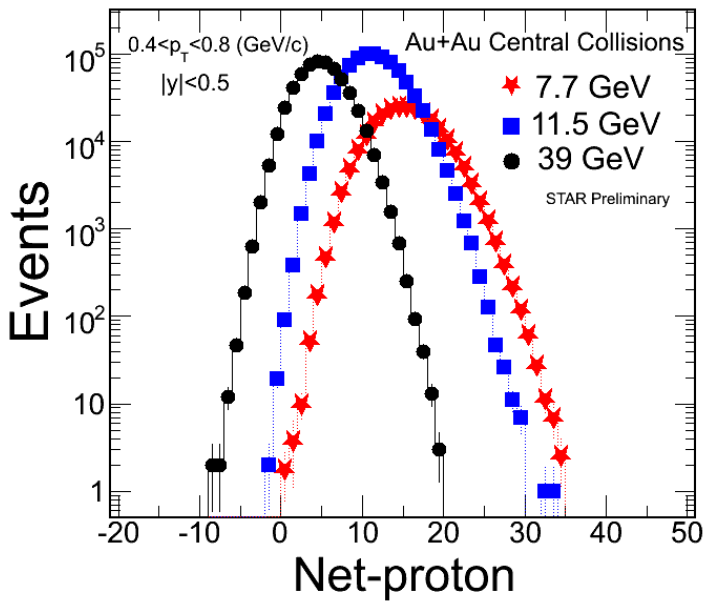
1) Net-proton slope changes sign twice between $\sqrt{s_{NN}}$ = 10 – 39 GeV

2) EOS soft point?

STAR: 1401.3043
Accepted by PRL

(7) Higher Moments





1) High moments for 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:

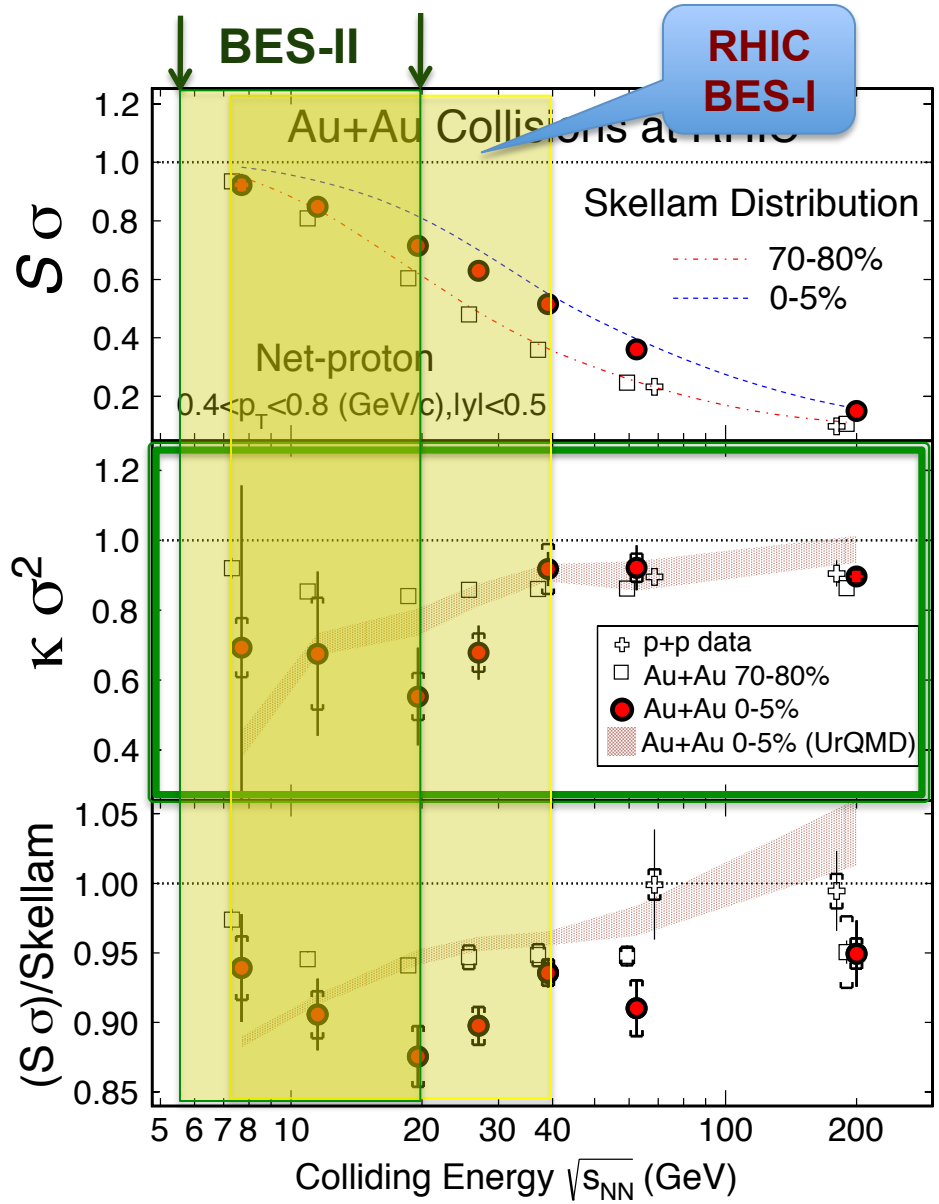
$$S * \sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa * \sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

References:

- A. Bazavov et al. *1208.1220* (NLOTE) // STAR: *PRL*105, 22303(2010) // M. Stephanov: *PRL*102, 032301(2009) // R.V. Gavai and S. Gupta, *PLB696*, 459(2011) // S. Gupta, et al., *Science,* 332, 1525(2011) // F. Karsch et al, *PLB695*, 136(2011) // S.Ejiri etal, PLB633, 275(06) // M. Cheng et al, *PRD79*, 074505(2009) // Y. Hatta, et al, *PRL91*, 102003(2003)

Net-proton Higher Moments



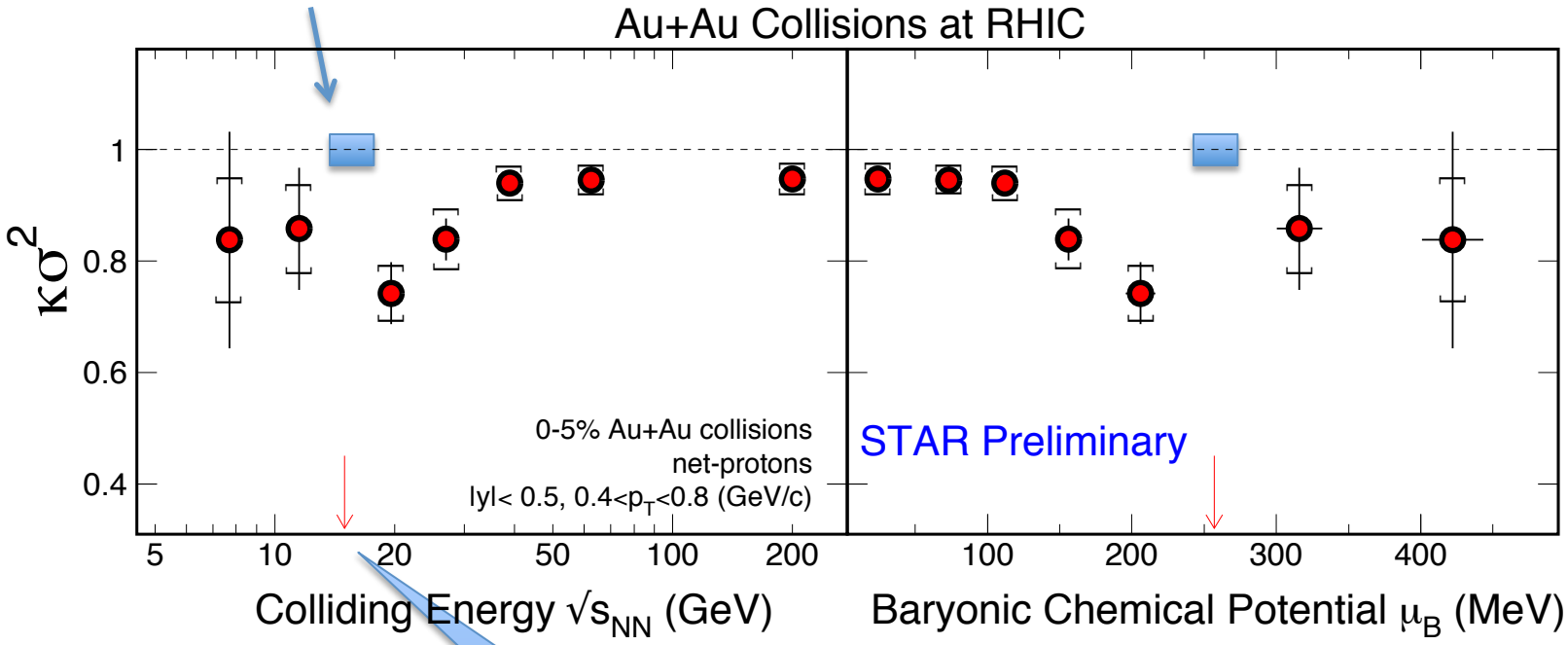
STAR net-proton results:

1) All data show deviations below Poisson beyond statistical and systematic errors in the 0-5% most central collisions for $\kappa\sigma^2$ and $S\sigma$ at all energies. Larger deviation at $\sqrt{s_{NN}}$ ~ 20GeV
2) Independent p and pbar production reproduces the observed energy dependence of $\kappa\sigma^2$ and $S\sigma$
3) UrQMD model show monotonic behavior in the moment products
4) Higher statistics needed for collisions at $\sqrt{s_{NN}}$ < *20 GeV.* **BES-II is needed**.

STAR: ***PRL, 112****, 32302(14) / arXiv: 1309.5681*

Net-proton Higher Moment

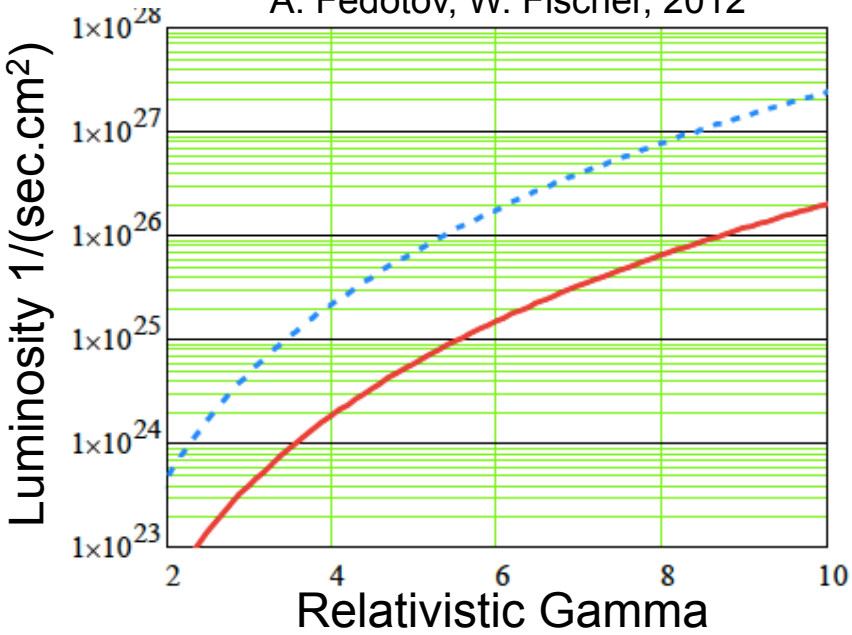
Expected statistical error from Run 14



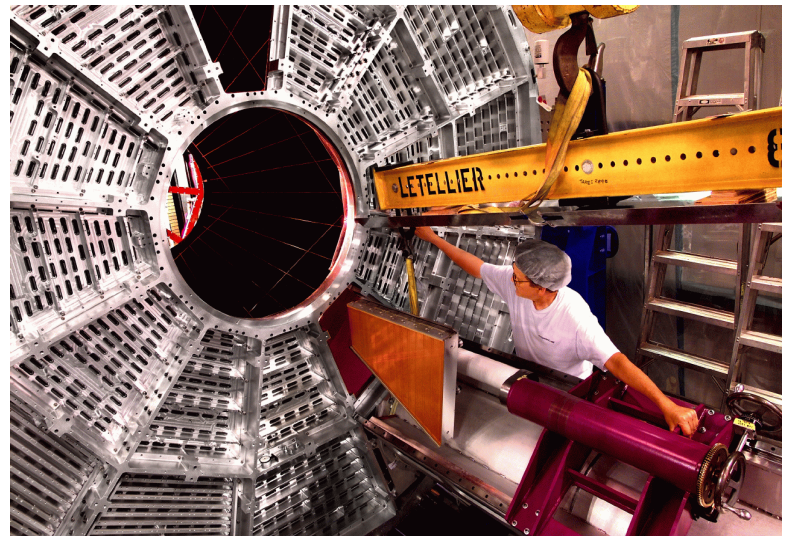
$\sqrt{s_{NN}}$ = 14.6GeV
21M events

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

Beam Energy Scan at RHIC

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BES-II (Year)	Energy (GeV)	*μ_B (MeV)	Time (Week)	# of Events (Million)
2018 - 2019	20 - 5	200 - ~ 500	35	700 - 100

RHIC
e-cooling

STAR
iTPC, RPD

High statistics requirement driven by di-lepton and high-moment measurement

Summary

(1) In high-energy nuclear collisions, $\sqrt{s_{NN}} \geq 200$ GeV, hot and dense ***matter, with partonic degrees of* freedom and collectivity, has been formed**

(2) RHIC BES-I:

[partonic] < μ_B ~ *110* (MeV) ($\sqrt{s_{NN}} \geq 39$ GeV)

[hadronic] > μ_B ~ *320* (MeV) ($\sqrt{s_{NN}} \leq 11.5$ GeV)

(3) RHIC BES-II: focus at $\sqrt{s_{NN}} \leq 20$ GeV region with higher luminosity (x10) + detector upgrade iTPC: Run18 (2017)

Exploring QCD Phase Structure

1 T_{ini}, T_C ***LHC, RHIC***

2 T_E ***RHIC, NICA***

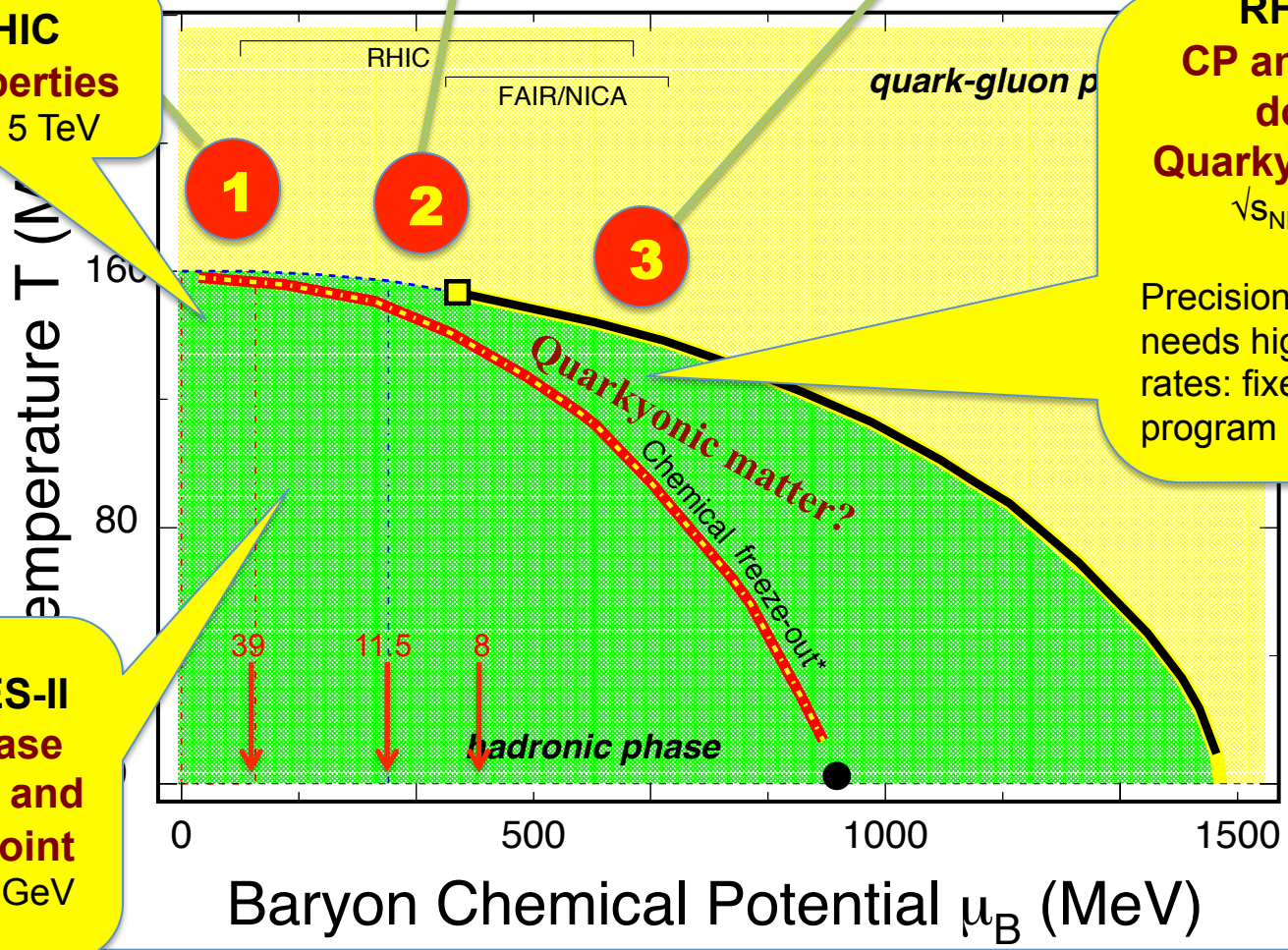
3 **Phase boundary** *NICA, FAIR*

LHC+RHIC
sQGP properties
$\sqrt{s_{NN}}$ ~ 0.2 - 5 TeV

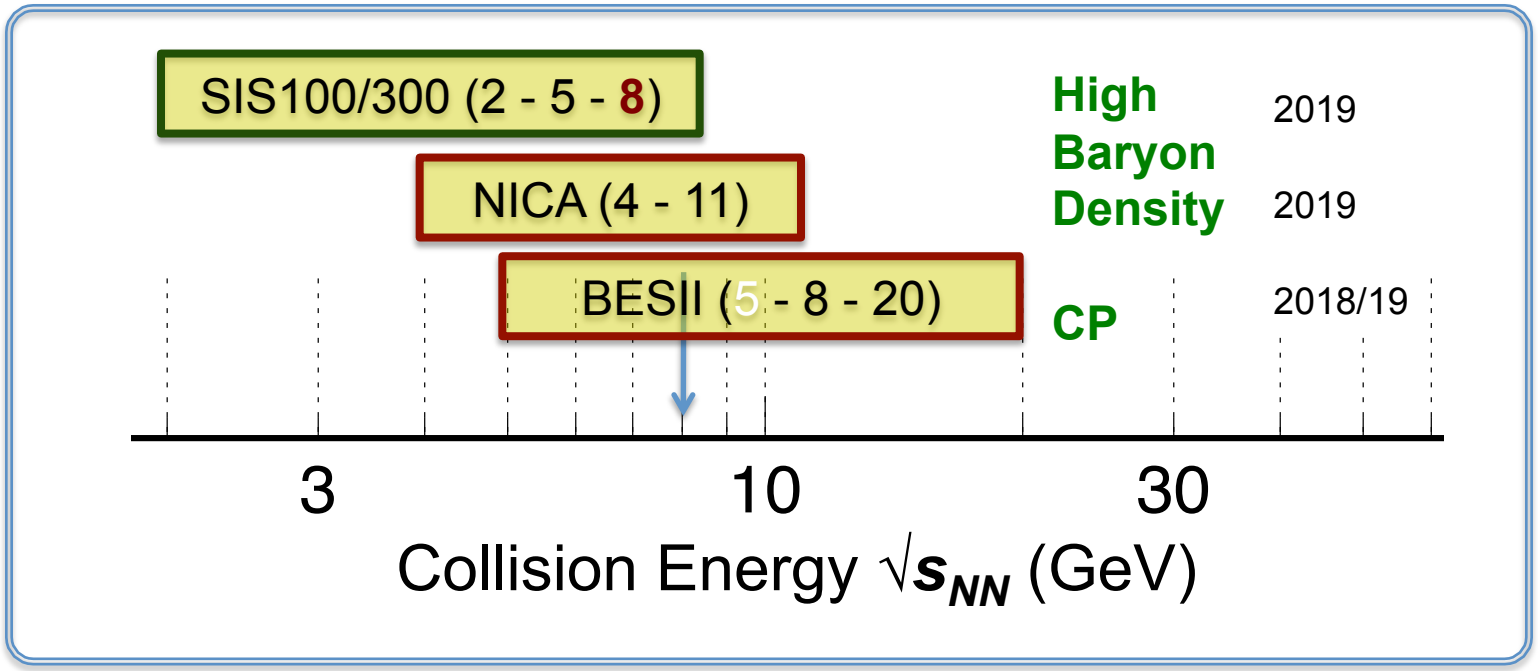
RHIC, FAiR
CP and Hadronic dominant
Quarkyonic Matter?
$\sqrt{s_{NN}} \leq 12$ GeV

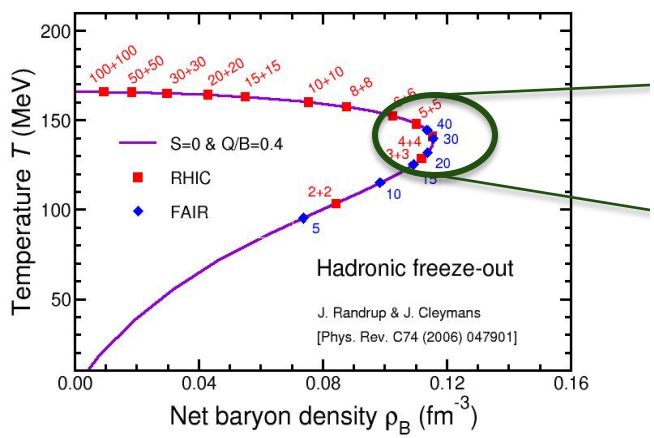
Precision measurements needs high collision rates: fixed target program more advantage

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



QCD Phase Structure at High Baryon Density





SIS300++ is important:

1) Baryon density peaks at ~ $\sqrt{s_{NN}}$ = 8 GeV
2) di-e & di-μ simultaneously ➔ **Chiral property**
3) Baryon/strangeness and correlations ➔ **CP, Quarkyonic matter**
4) Collectivity, exotics, …