Results from RHIC Beam Energy Scan-I

Nu Xu[1,2]

Outline:

1) Introduction
2) Selected Results from RHIC BES-I
3) Near Future Physics Programs at RHIC

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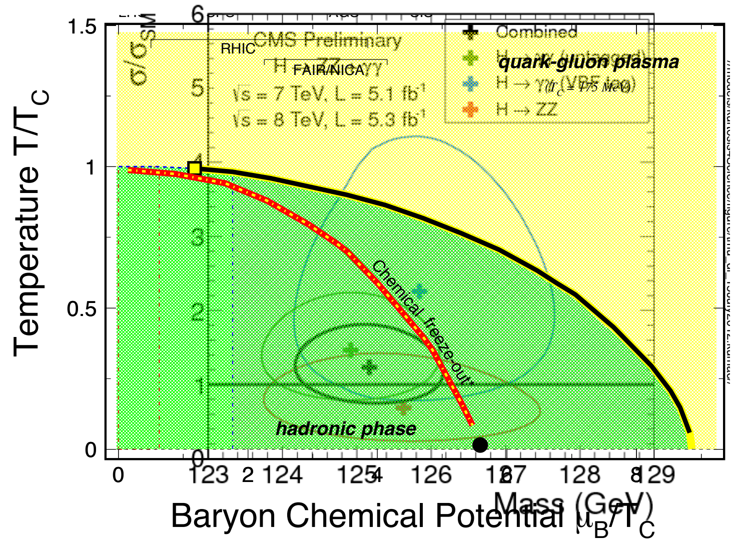
[2] Nuclear Science Division, Lawrence Berkeley National Laboratory, USA

QCD in the Twenty-First Century



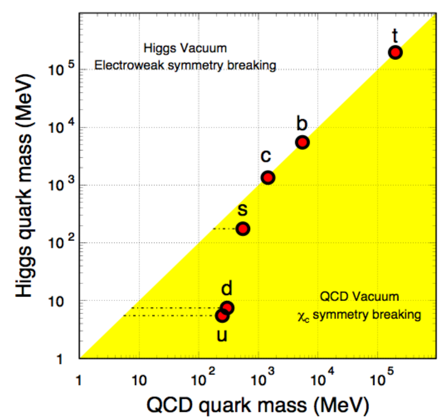
Emergent properties with QCD degrees of freedom!

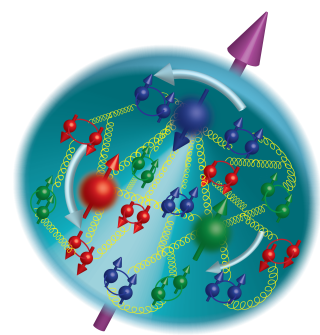
(1) Higgs (-like) Particle –

- **Origin of Mass**, **QCD dof**
- Standard Model ➔ The *Theory*

(2) QCD Emergent Properties:

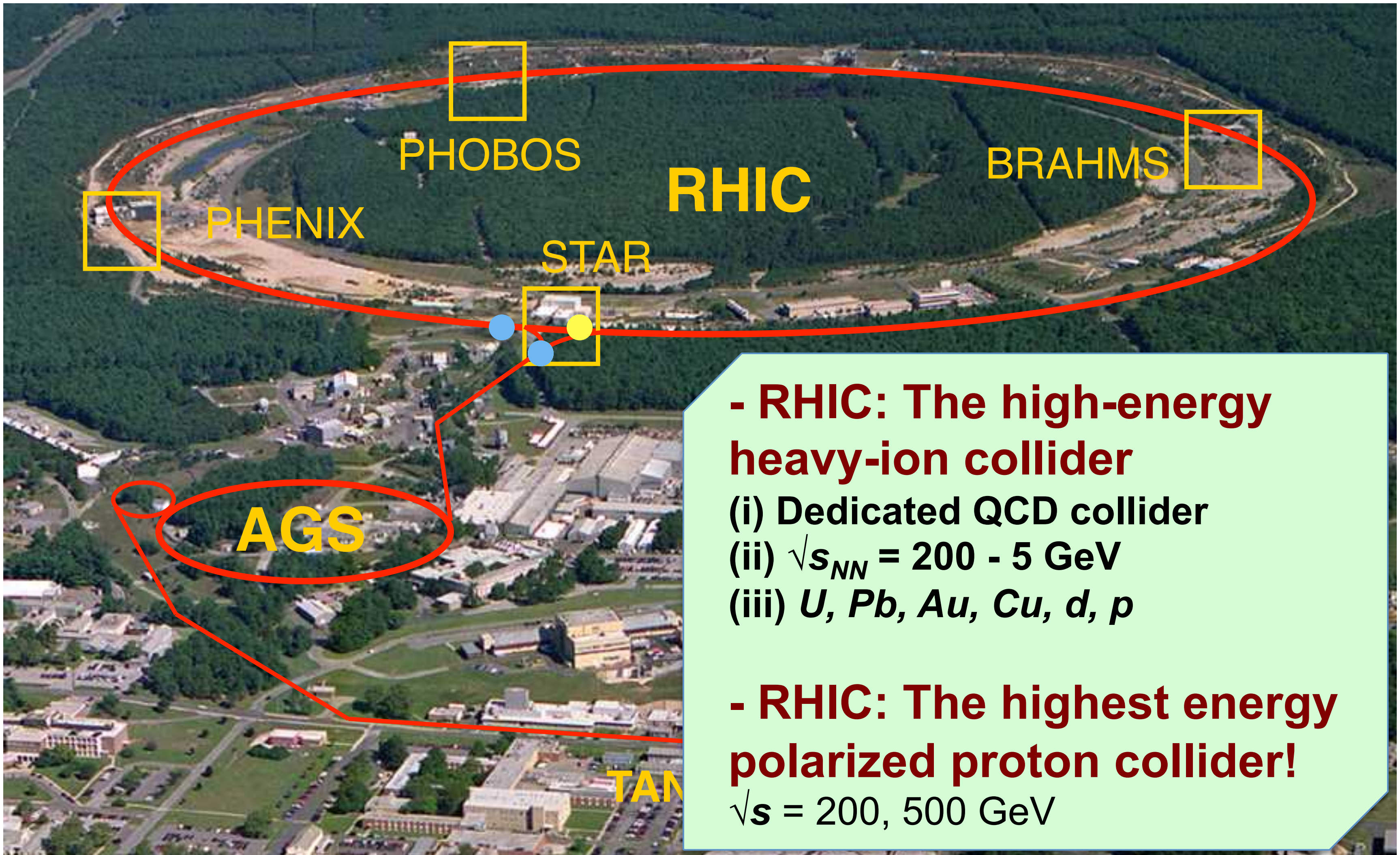
- Confinement
- χ_C symmetry
- QCD Phase Structure
- Nucleon helicity structure
- Non-linear QCD at small-x





Relativistic **H**eavy **I**on **C**ollider

Brookhaven National Laboratory (BNL), Upton, NY



- RHIC: The high-energy heavy-ion collider

(i) Dedicated QCD collider

(ii) $\sqrt{s_{NN}}$ = 200 - 5 GeV

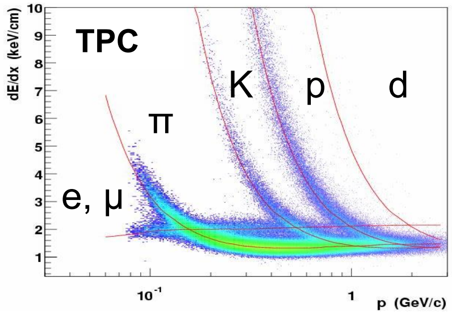
(iii) *U, Pb, Au, Cu, d, p*

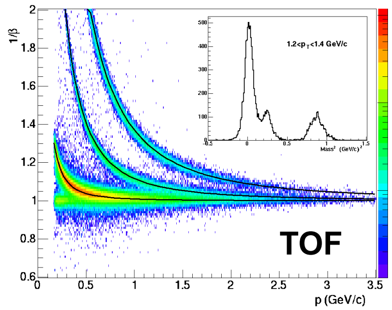
- RHIC: The highest energy polarized proton collider!

$\sqrt{s}$ = 200, 500 GeV

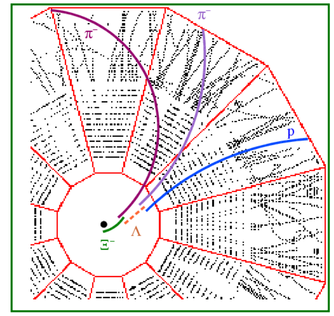
Animation M. Lisa

Particle Identification at STAR

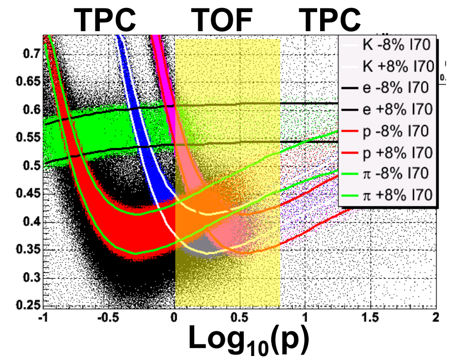


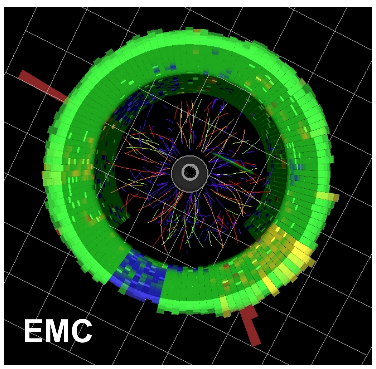


Charged hadrons

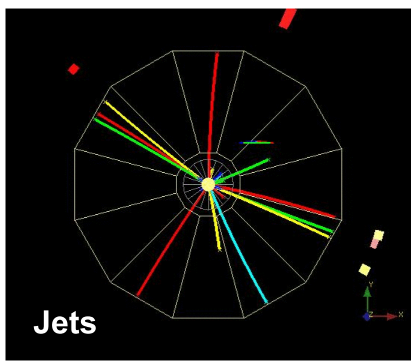


Hyperons & Hyper-nuclei

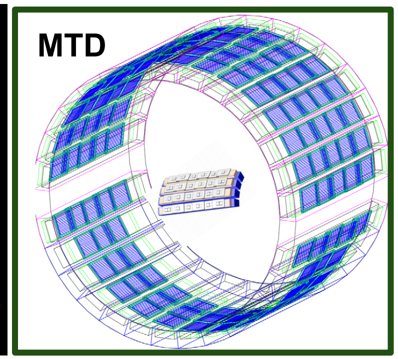




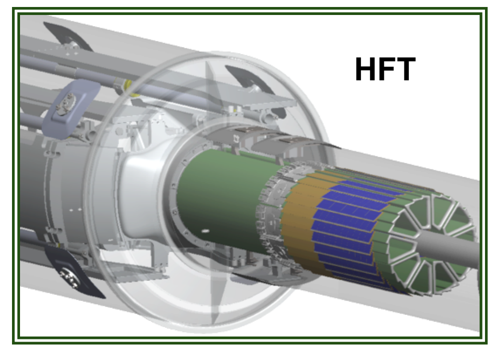
Neutral particles



Jets & Correlations



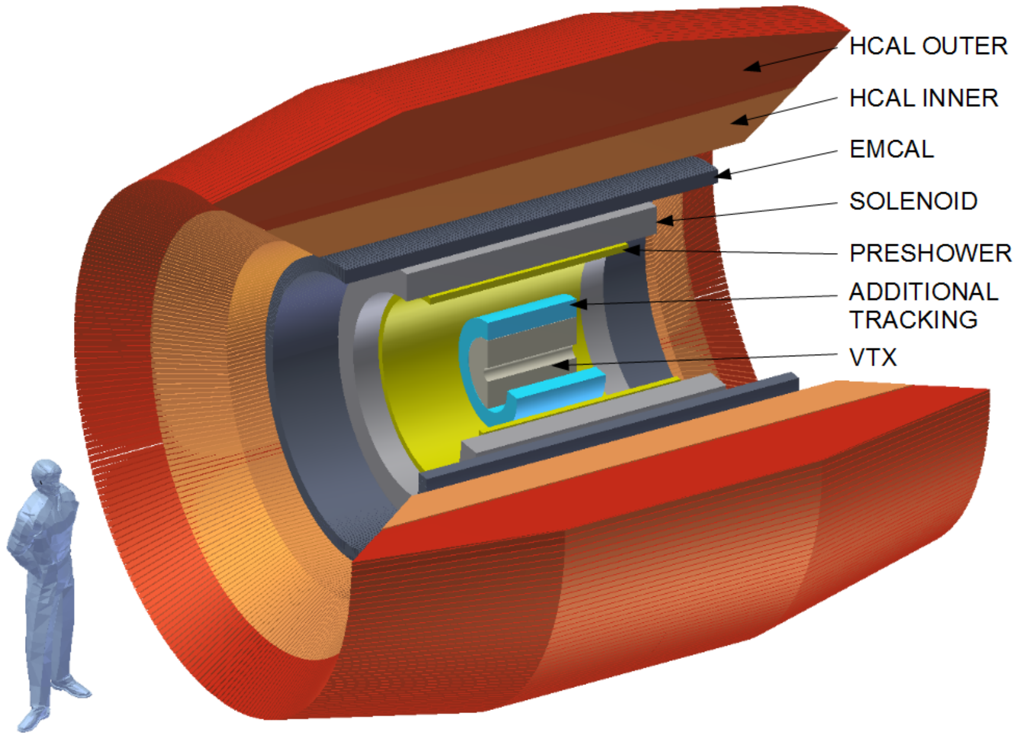
High p_T muons



Heavy-flavor hadrons

Multiple-fold correlations from identified particles!

sPHENIX: A Jet Detector at RHIC



Large acceptance

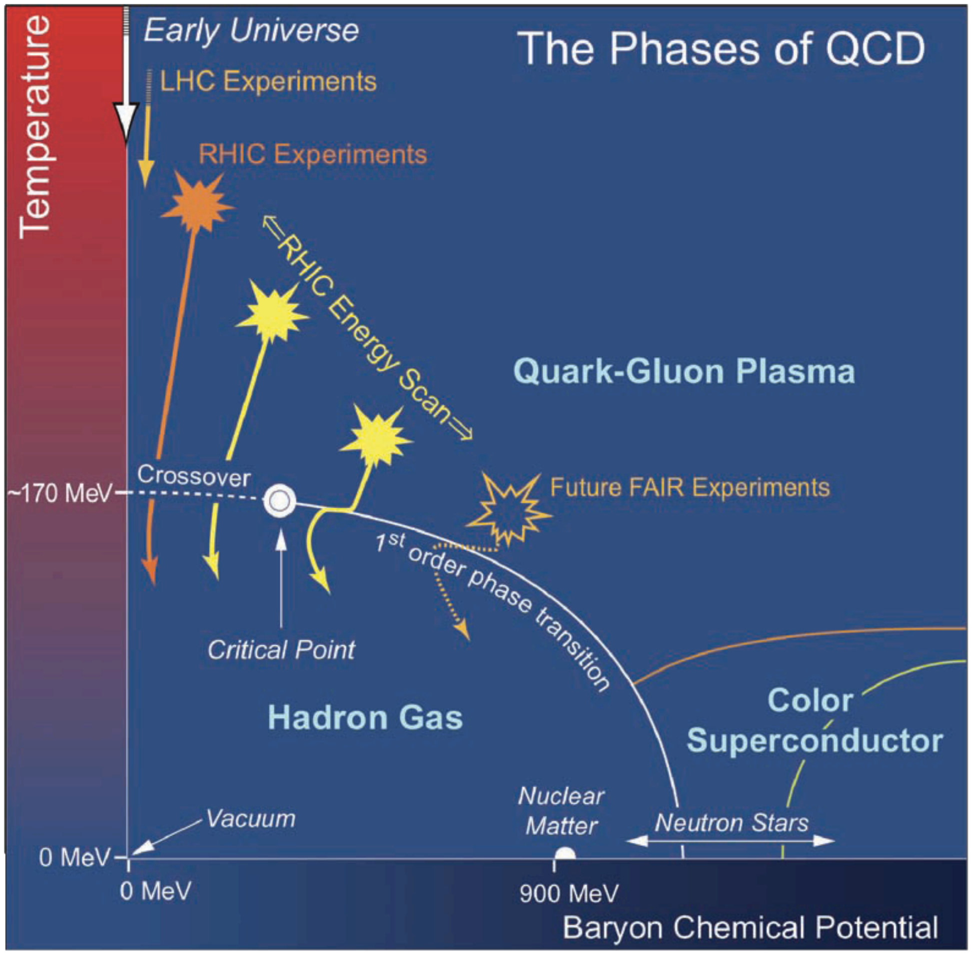
Jets and multiple correlations

➔ **sQGP properties at RHIC**

http://arxiv.org/abs/arXiv:1207.6378

Beam Energy Scan at RHIC

Study QCD Phase Structure
- Signals of phase boundary
- Signals for critical point



Observations:

(1) Azimuthally HBT
1st order phase transition

(2) Directed flow v_1
1st order phase transition

(3) Dynamical correlations
partonic vs. hadronic dof

(4) v_2 - NCQ scaling
partonic vs. hadronic dof

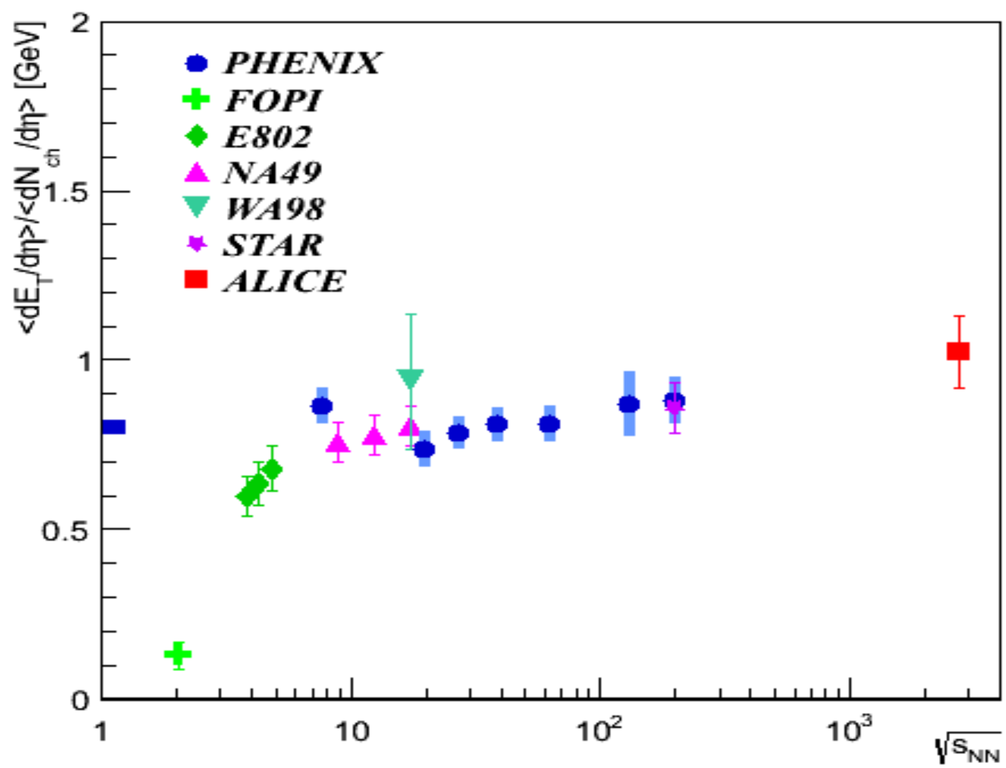
(5) Fluctuations
Critical point, correl. length

- *http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493*

- *arXiv:1007.2613*

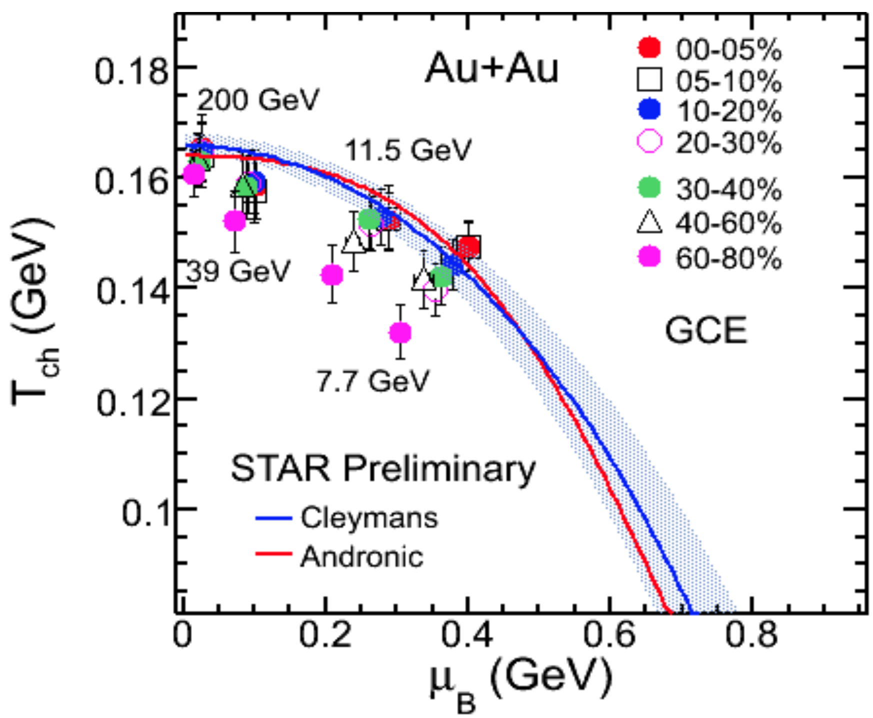
Energy Dependence of E_T/N_{ch}

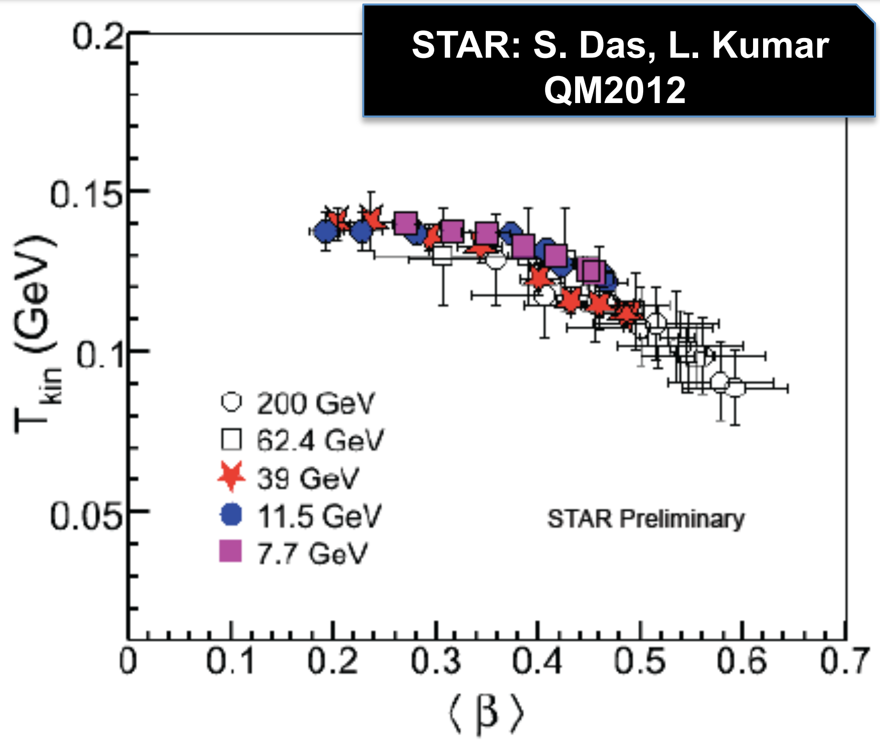
PHENIX: E. O'Brien, QM2012



E_T/N_{ch} shows a week energy dependence

Bulk Properties at Freeze-out





Chemical Freeze-out: (GCE)

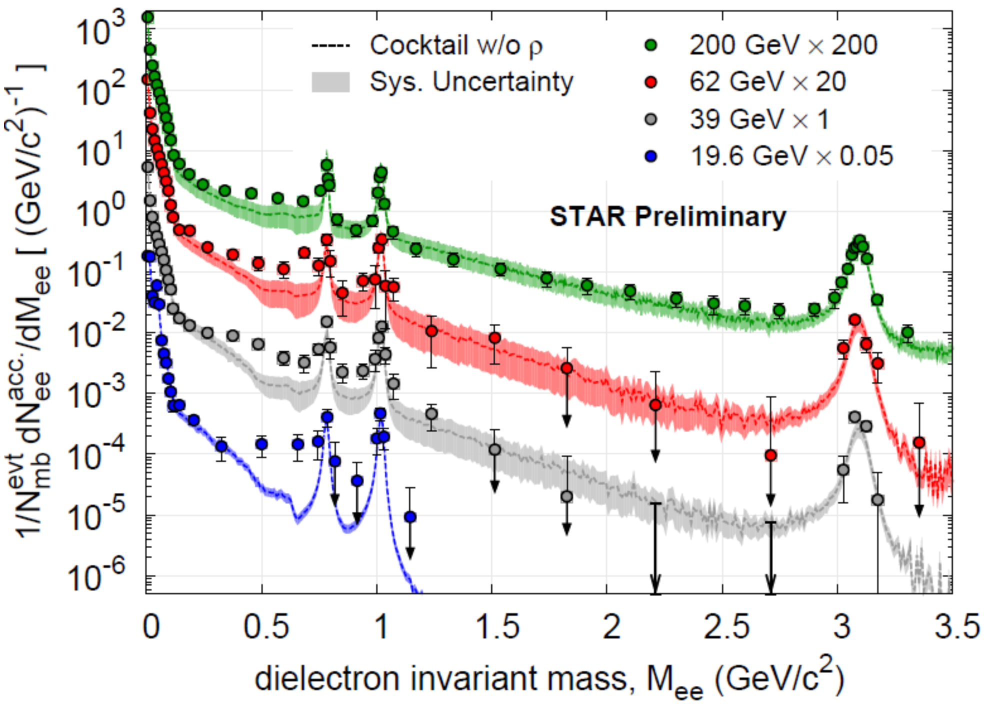
- Central collisions => higher values of T_{ch} and μ_B!
- The effect is stronger at lower energy.

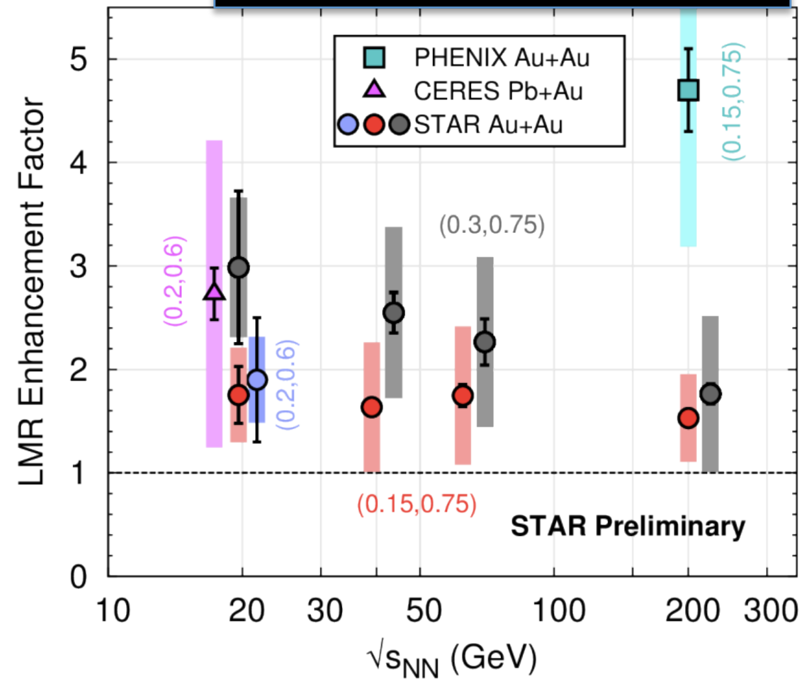
Kinetic Freeze-out:

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

Di-electrons: $\sqrt{s_{NN}}$ Dependence

STAR: B.C. Huang QM2012

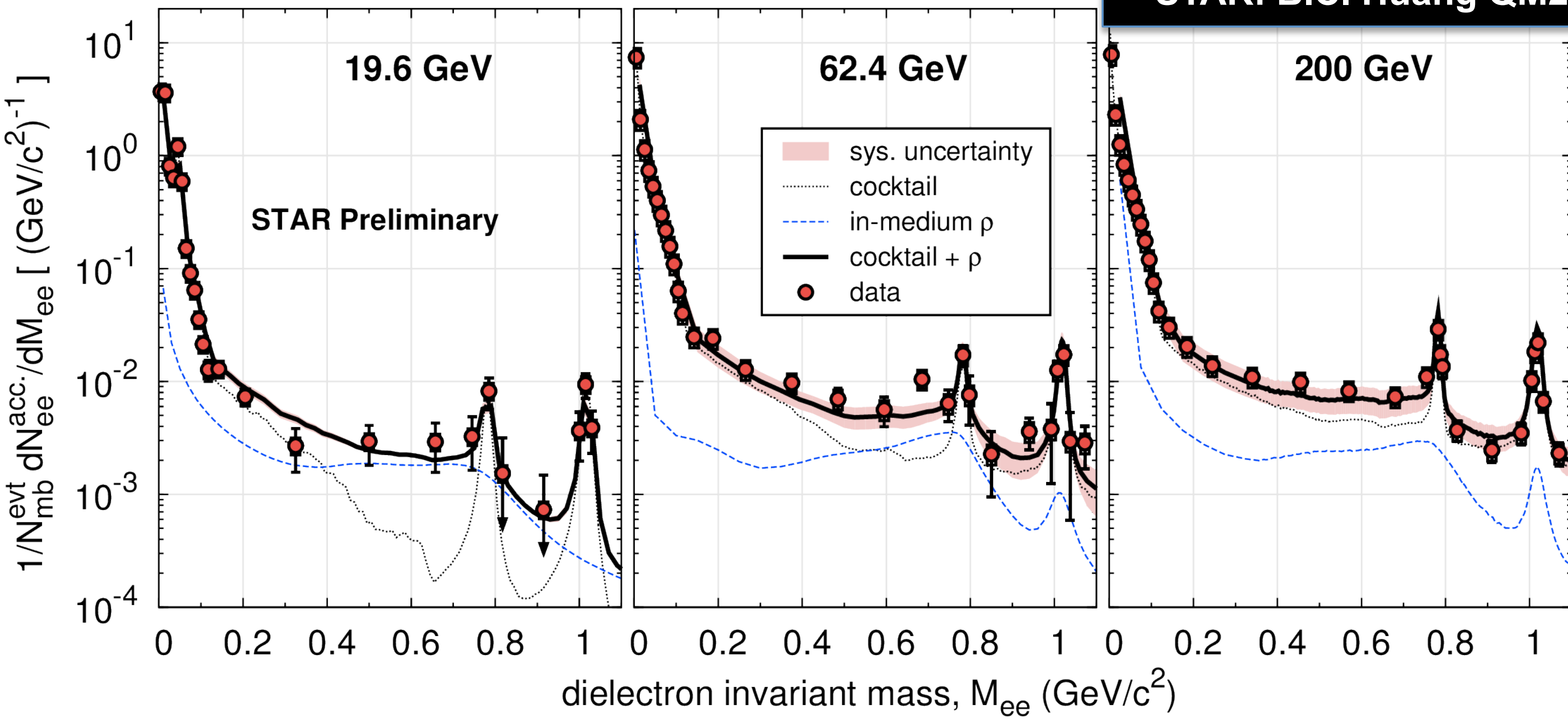




1) LMR enhancement vs. collision energy, mass cut dependence
2) Future Heavy Flavor Tracker and Muon Telescope Detector upgrades:
   - correlated charm contributions
   - extract direct radiation information

Di-electrons: Model Comparison

STAR: B.C. Huang QM2012

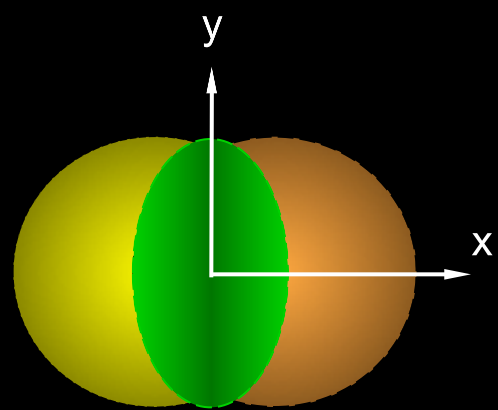


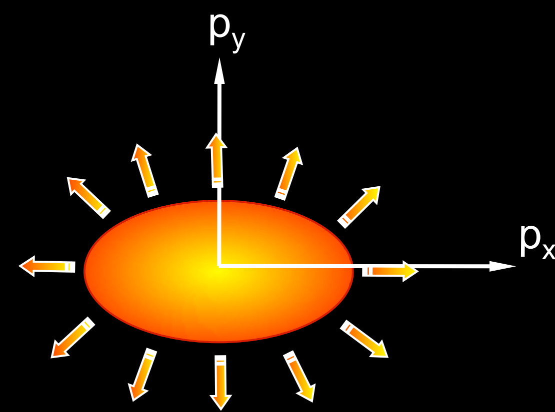
1) With in-medium broadened rho, model results are consistent with experimental data ($m_{ee} \leq 1$ GeV/c^2) at $\sqrt{s_{NN}}$ = 200, 62.4 and 19.6GeV

2) Open issues:
   - charm contributions in the model calculations
   - transverse spectra
   - consistency between IMR and LMR

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

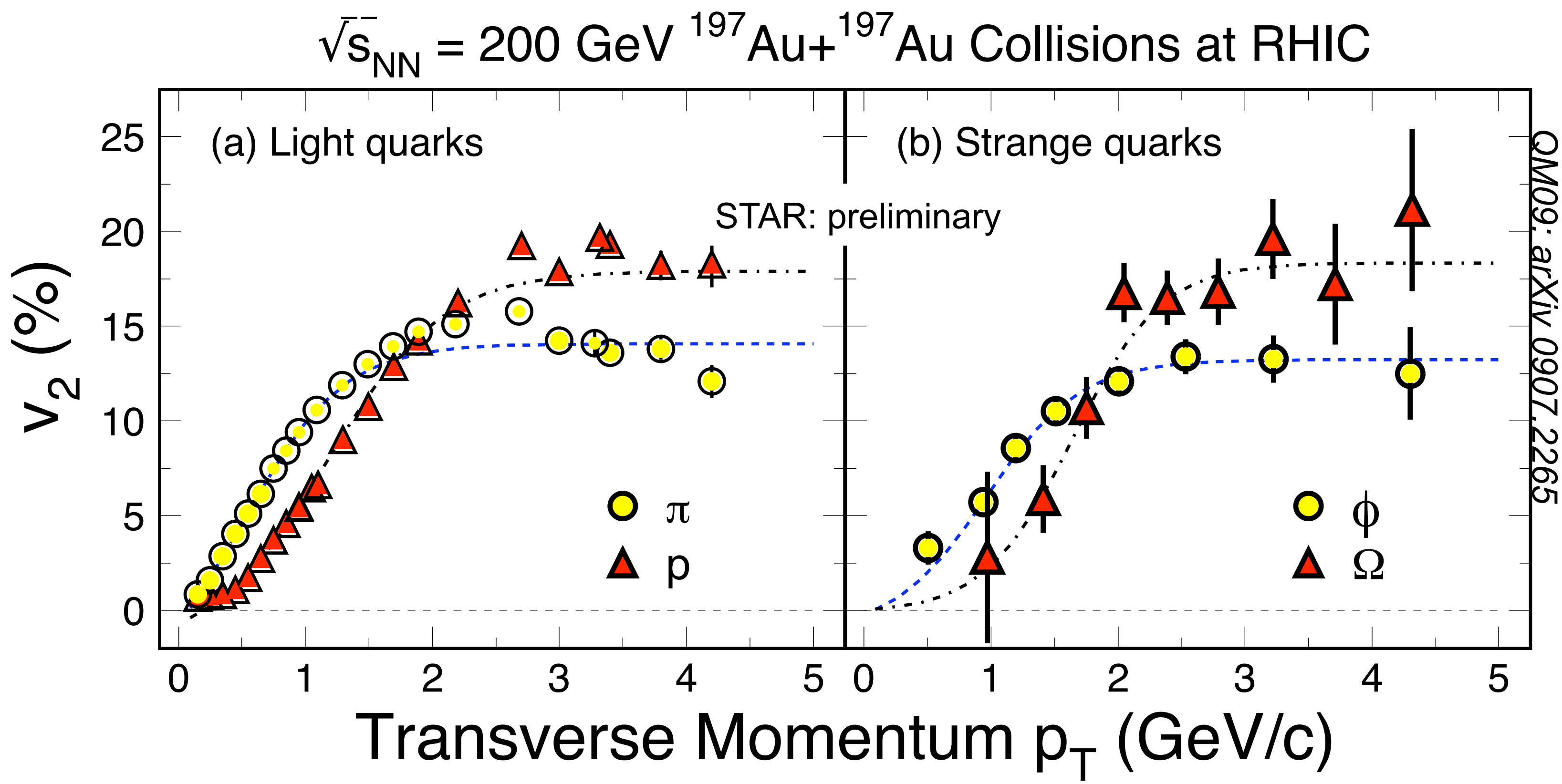




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \;\; \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

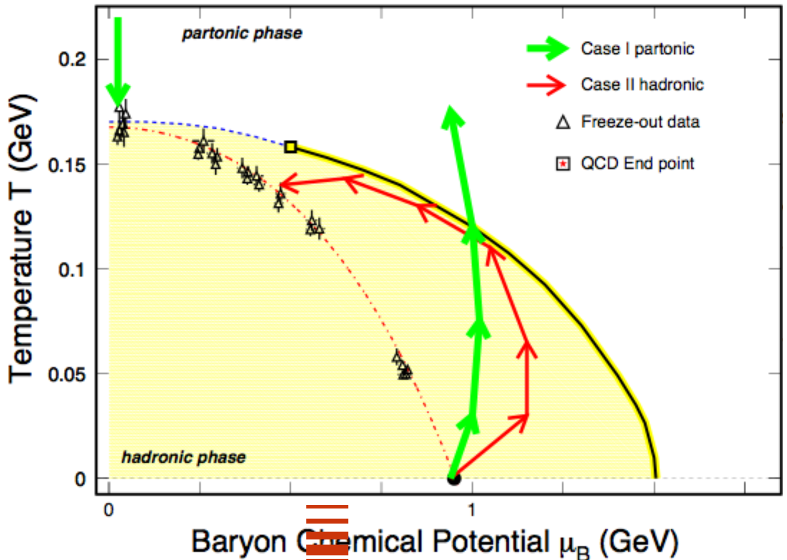
Partonic Collectivity at RHIC

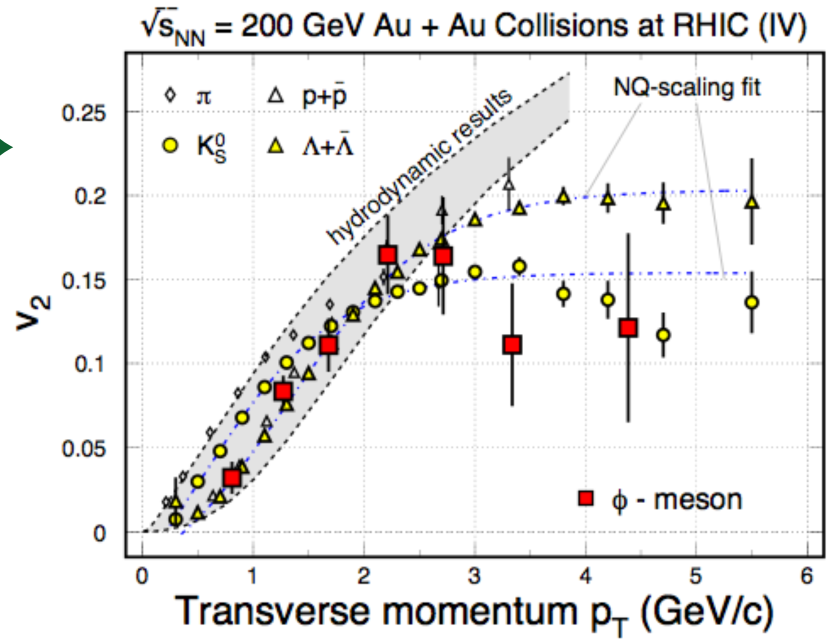


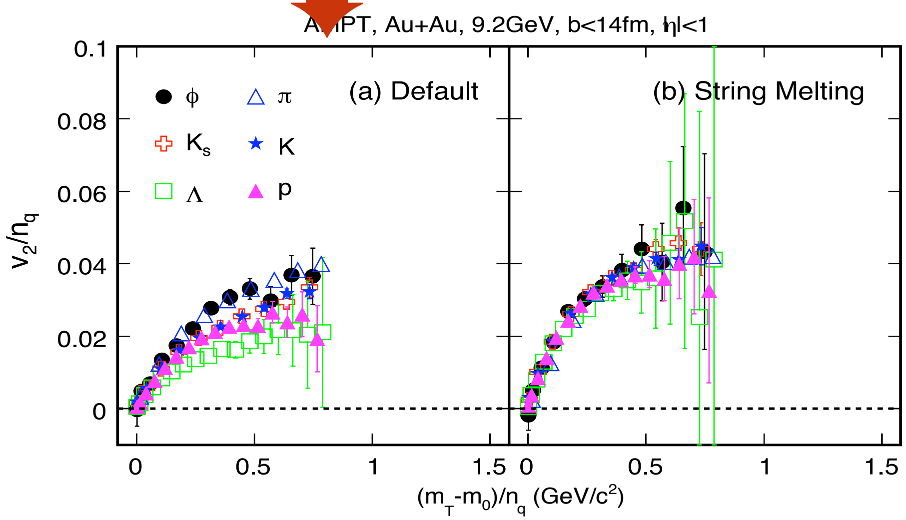
Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks scaling***

➔ ***Partonic Collectivity, necessary for QGP!***
➔ ***De-confinement in Au+Au collisions at RHIC!***

NCQ Scaling in v_2





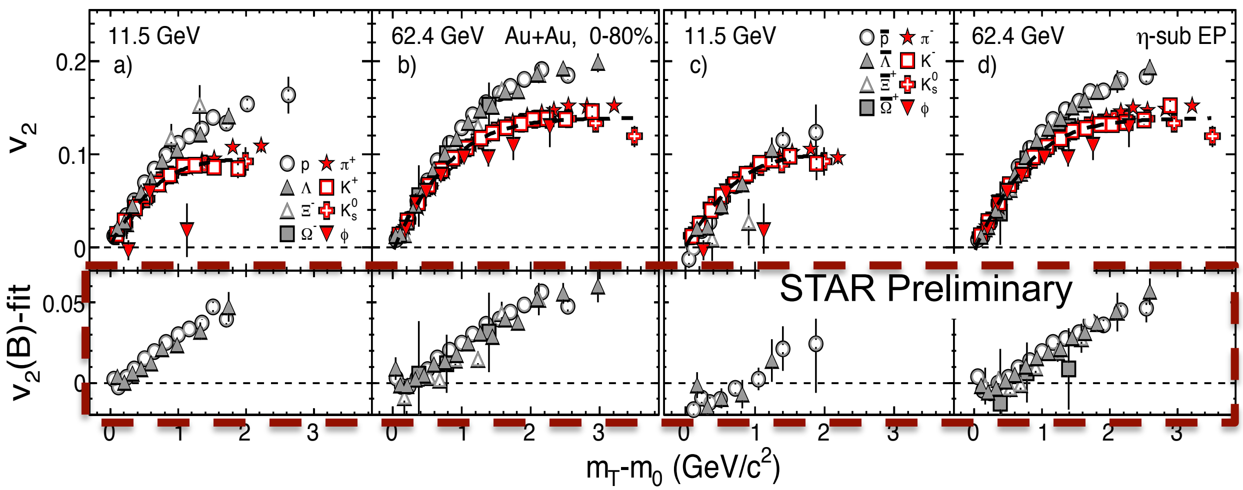


- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi,\, \pi\pi}$

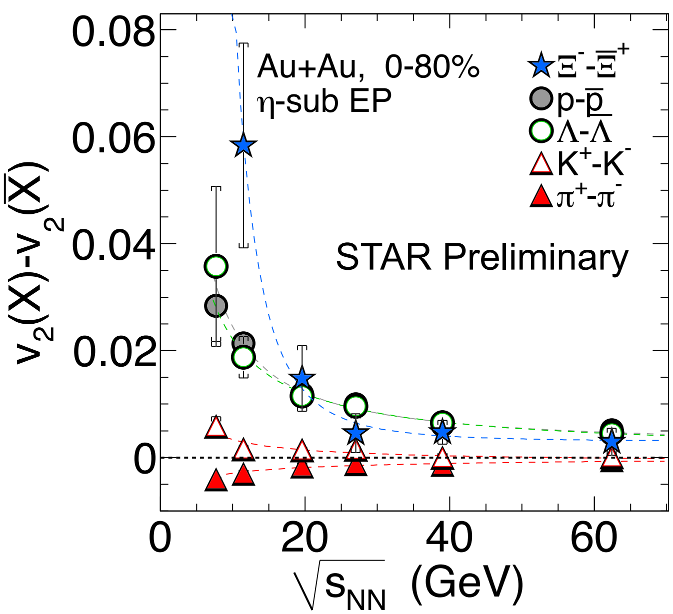
In the hadronic case, no number of quark scaling and the value of v_2 of φ will be small.

*** Thermalization is assumed!**

Collectivity v_2 Measurements



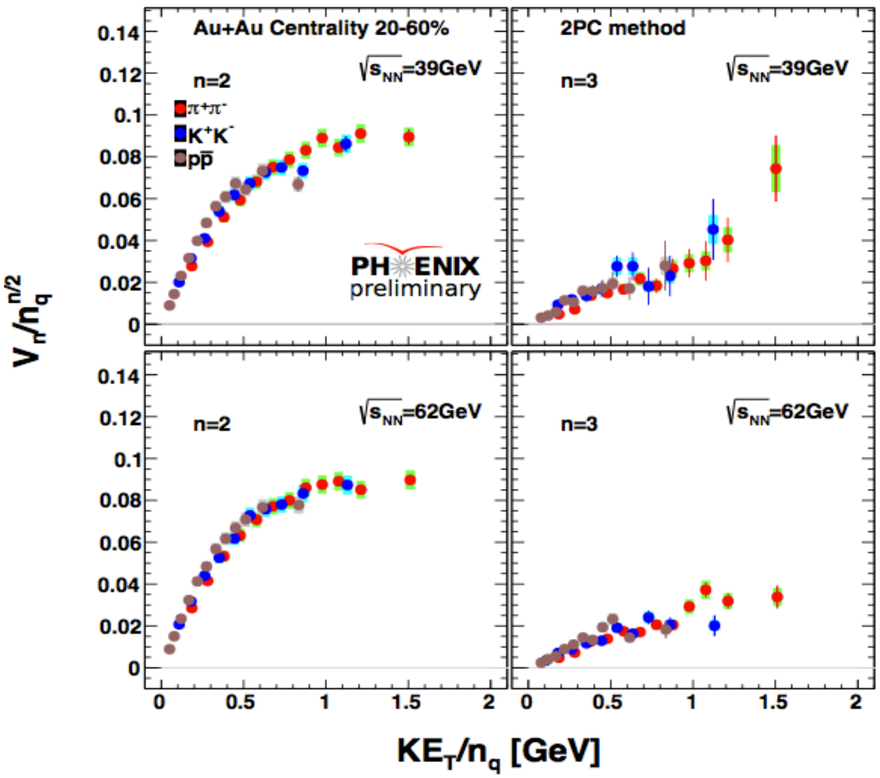
STAR: Nasim MD, S.S. Shi QM2012



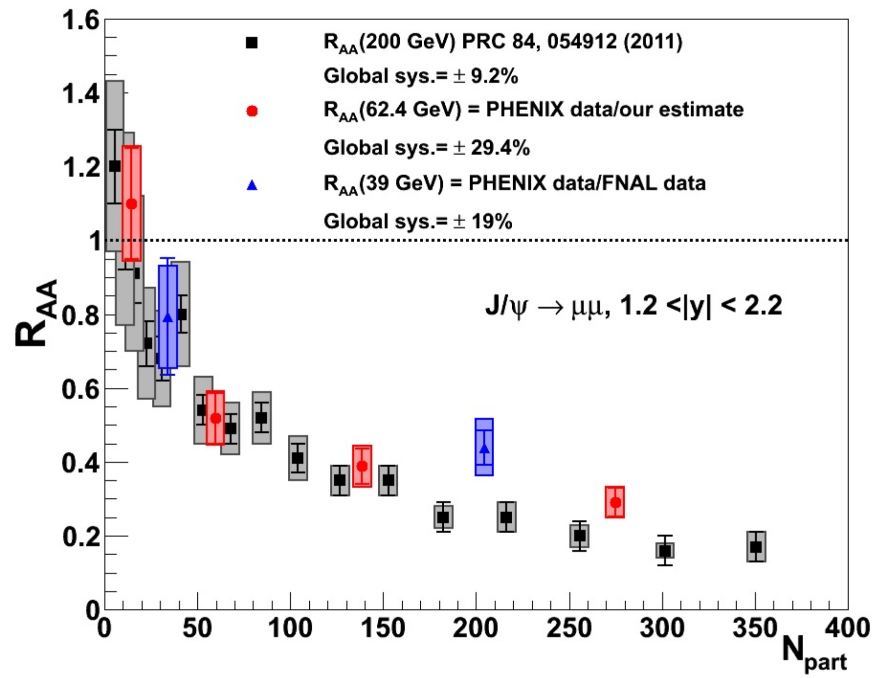
1) Systematic measurements of collectivities

2) At lower beam energies, the number of quark scaling is broken. Hadronic interactions become dominant, especially for $\sqrt{s_{NN}}$ < 11.5 GeV

NCQ Scaling of v_2/v_3 & J/ψ R_{AA}



PHENIX: E. O'Brien, QM2012

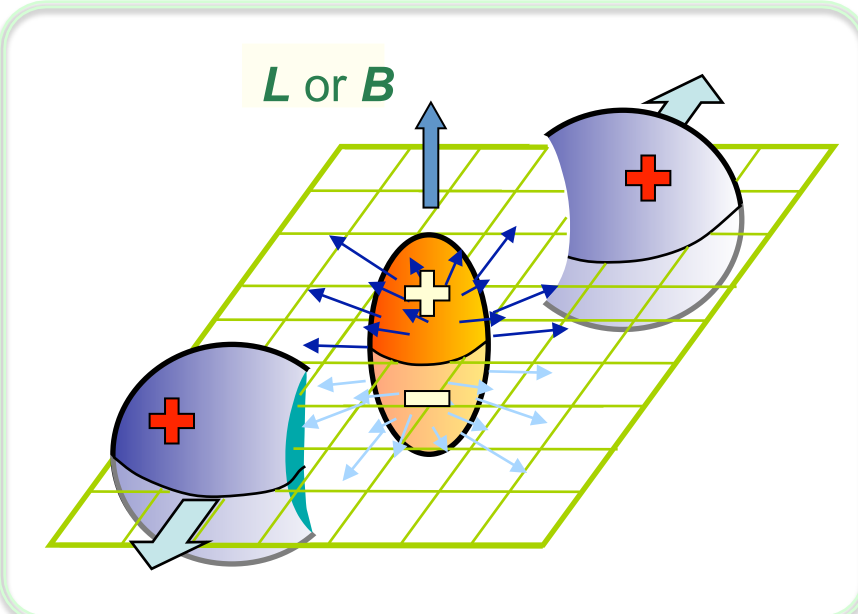


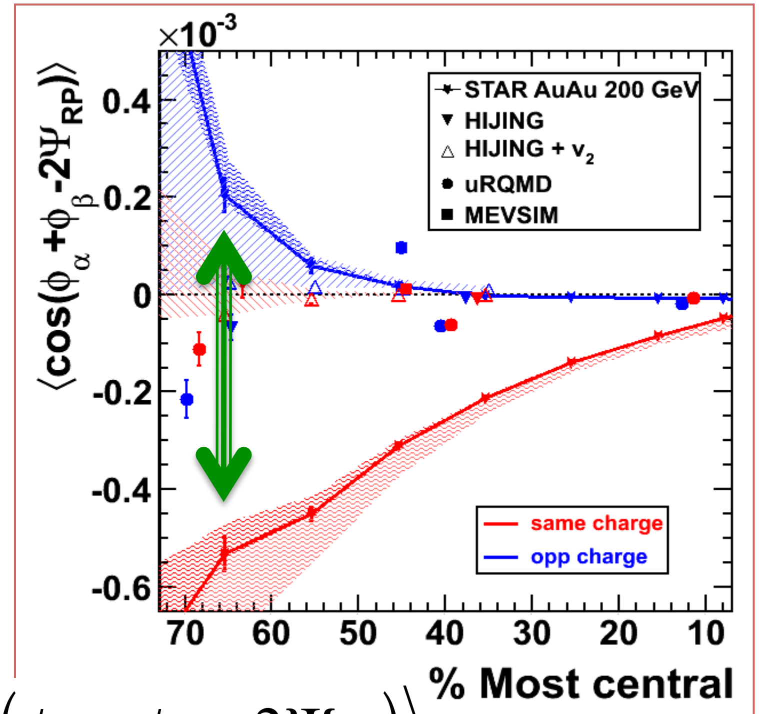
$\sqrt{s_{NN}} \geq 39$ GeV, measured v_i (i=2,3) and J/ψ R_{AA} show no energy dependence

➔ Partonic interaction and sQGP dominant for collisions at $\sqrt{s_{NN}} \geq 39$ GeV

Search for 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.

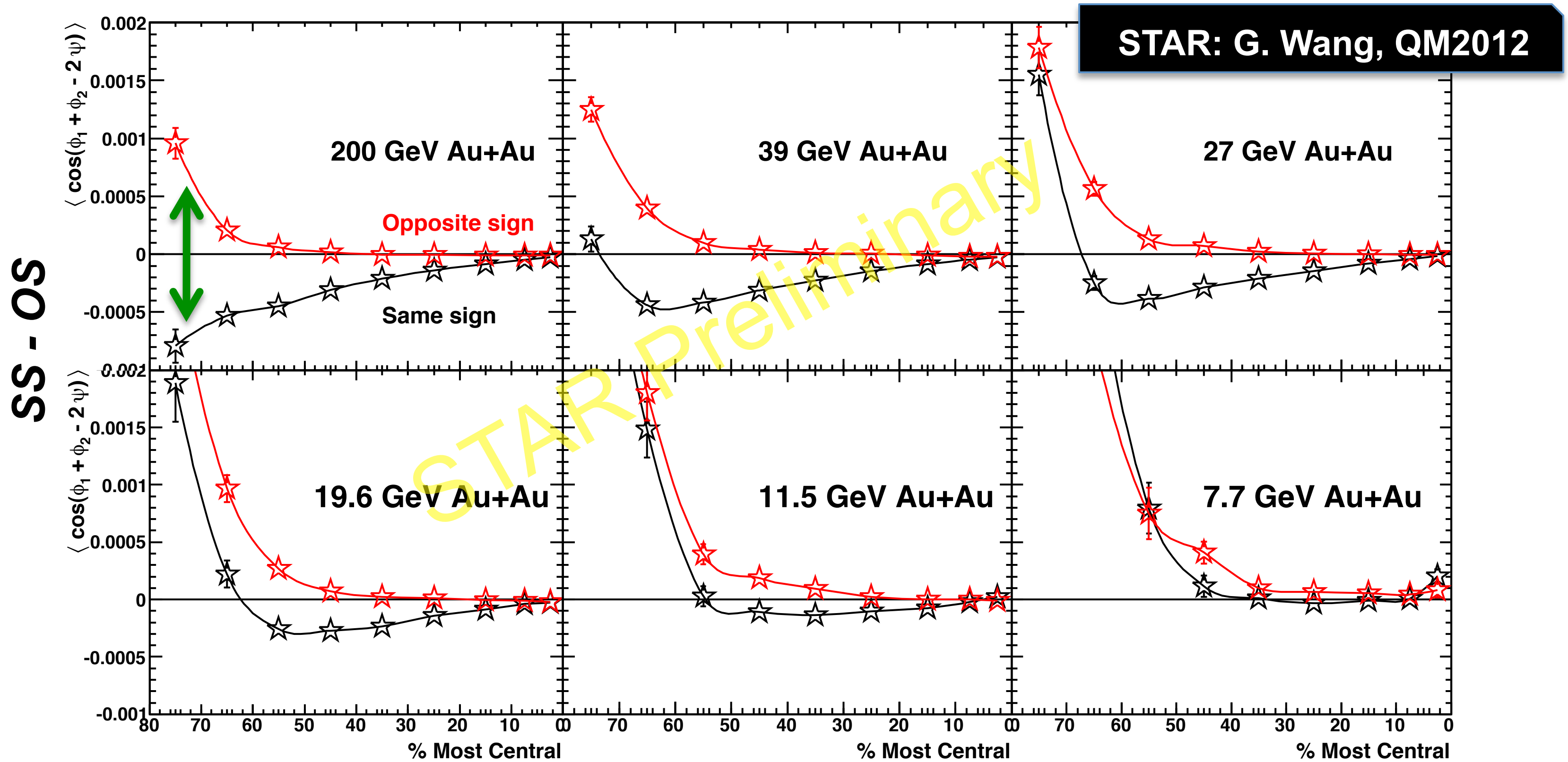
- Strong external EM field

- *De-confinement* and *Chiral symmetry restoration*

1) Parity-even observable, assumptions must be tested
2) Energy dependence & UU collisions

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

Dynamical Correlations vs. $\sqrt{s_{NN}}$

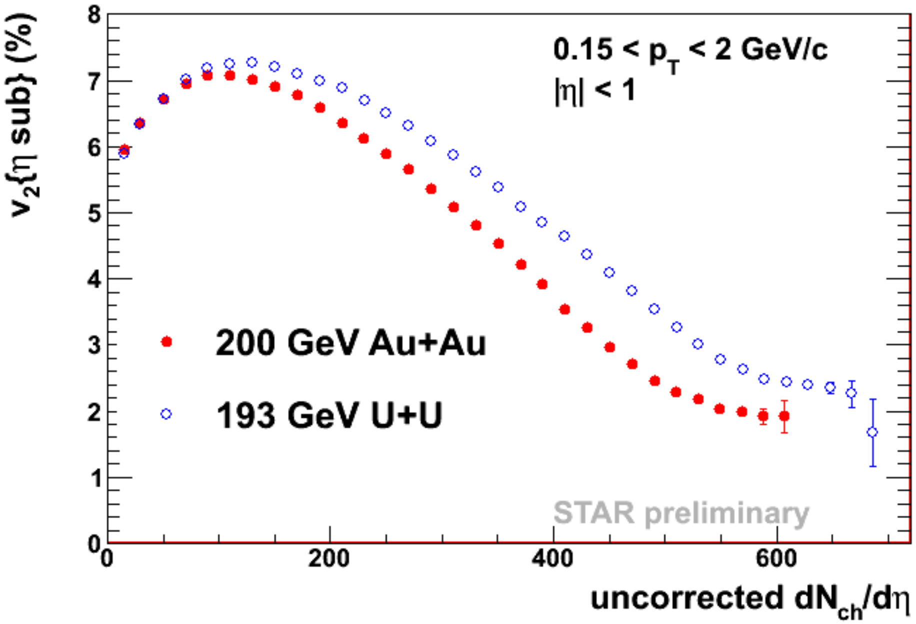


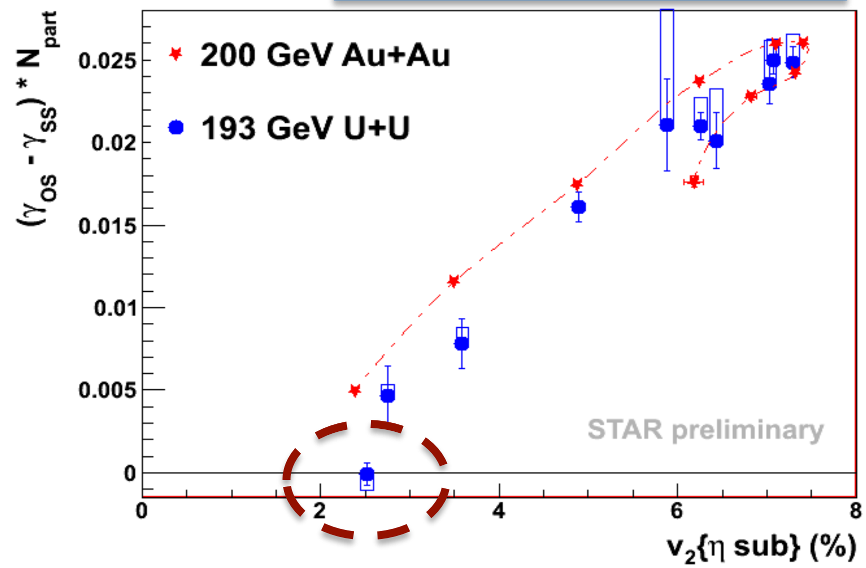
(1) Below $\sqrt{s_{NN}}$ = 11.5 GeV, the splitting between the same- and opposite-sign charge pairs (SS-OS) disappear

(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

$\sqrt{s_{NN}}$ = 193GeV U+U Collisions

STAR: G. Wang, QM2012



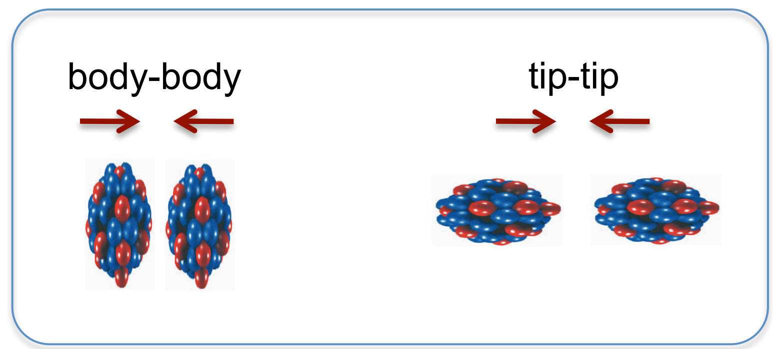


U+U Collisions:

(1) test CME with small external B-field

(2) test v_2 at 30% higher density

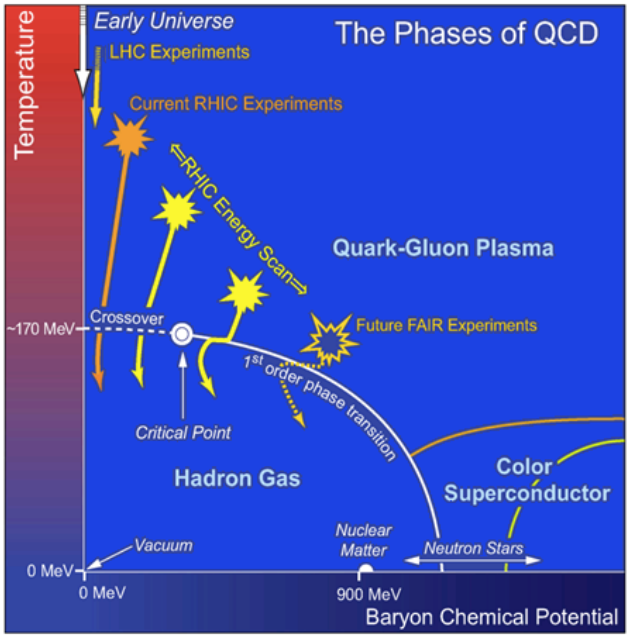
(3) test path-length dependence of R_{AA}

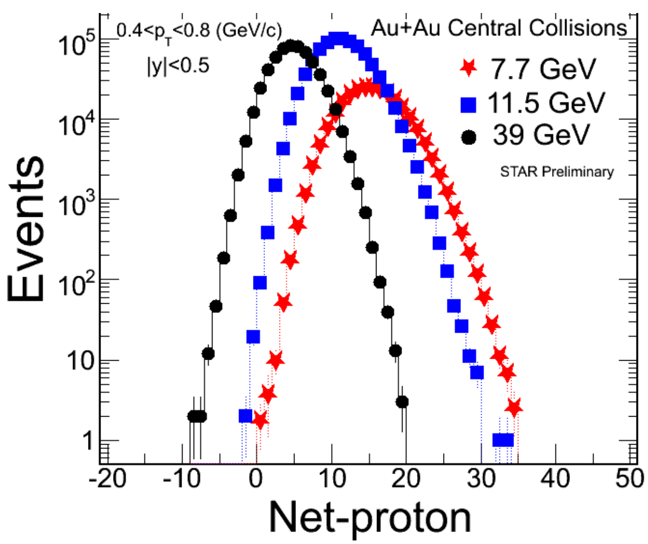


1) Comparing to Au+Au collisions, v_2 values are higher in U+U

2) **At 1% most central collisions, v_2 is found to be finite & SS-OS=0!**

Higher Moments





1) High moments for conserved quantum numbers: ***Q, S, B***, in high-energy nuclear collisions

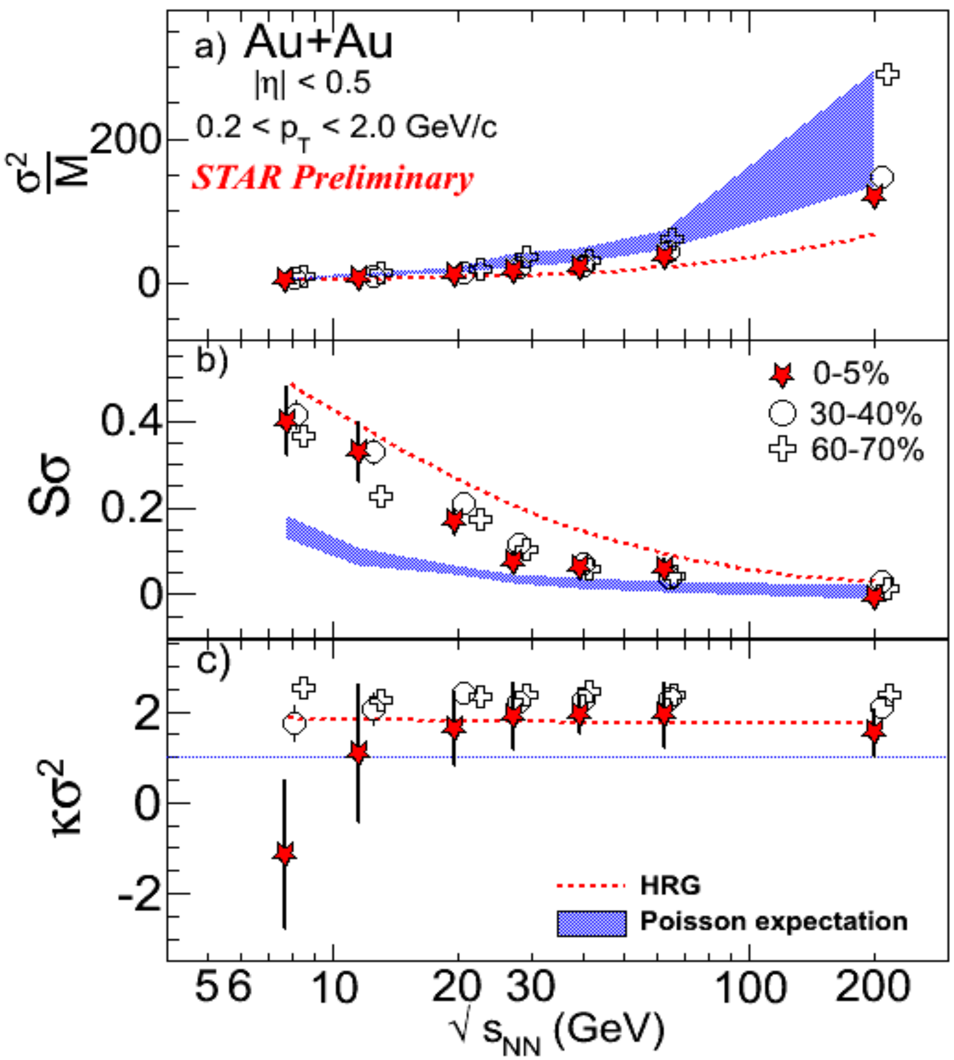
2) Sensitive to critical point (ξ correlation length):
$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \ \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \ \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with Lattice results:
$$S*\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa*\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

- A. Bazavov et al. *1208.1220* (NLOTE)
- STAR Experiment: *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)
- M.Cheng et al, *PRD79*, 074505(2009)
- Y. Hatta, et al, *PRL91*, 102003(2003)

Higher Moment: Net-charge



STAR: D. McDonald, QM2012

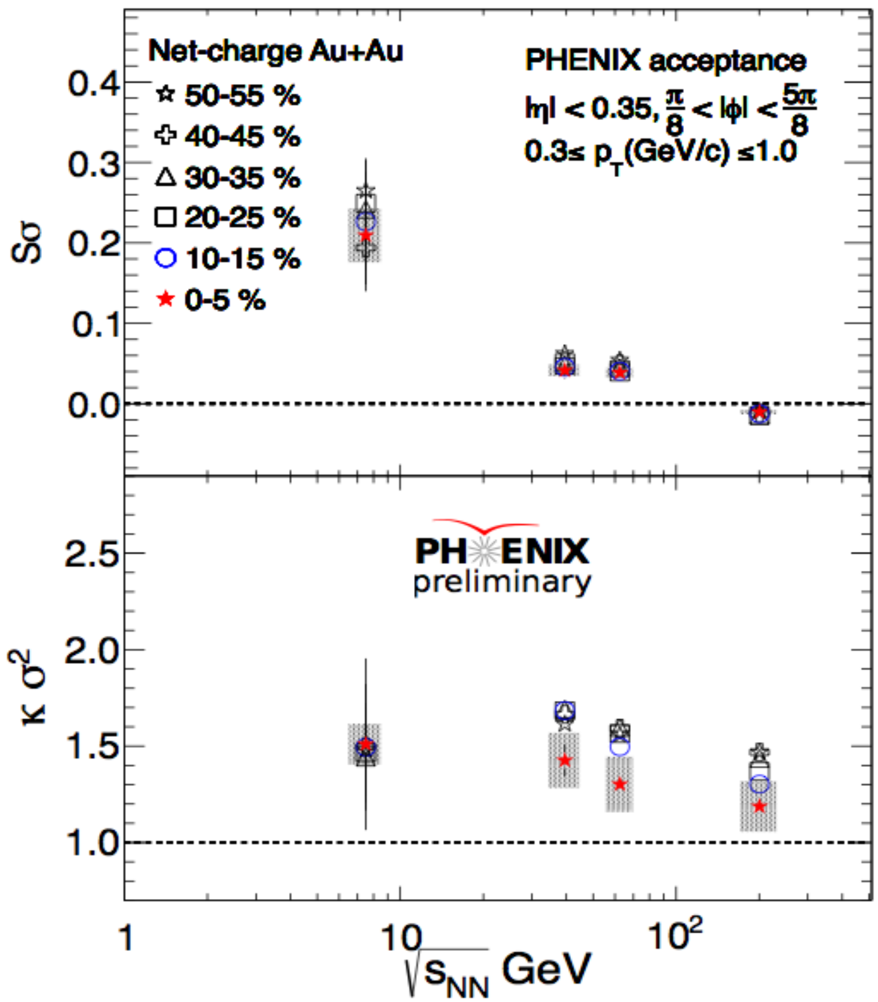
1) Preliminary net-charge results: efficiency, decay, … effects under study

2) Higher statistics data needed below 20 GeV

- HRG Model: K. Redlich et al, private communications

Higher Moments for Net Charge

PHENIX: E. O'Brien, QM2012



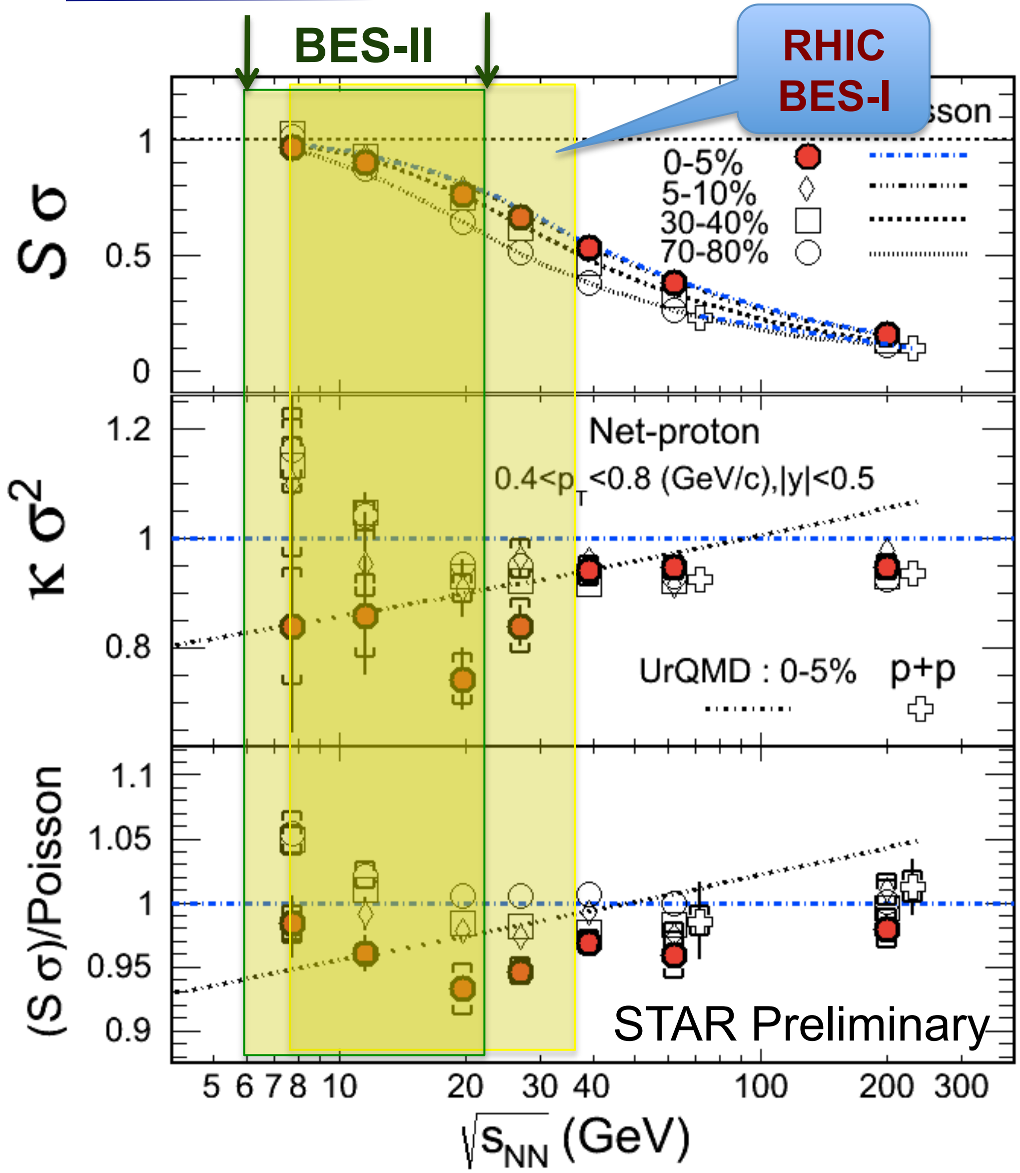
1) Neither K nor S vary with centrality at 7.7, 39, 62.4 and 200 GeV

2) Kurtosis vs. energy is flat within errors

3) Skewness tracks UrQMD prediction

4) Analysis of data sets from $\sqrt{s_{NN}}$ = 19.6, 27 GeV still to be completed

Net-proton Higher Moments



STAR: X.F. Luo, QM2012

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 $\sqrt{s_{NN}} \sim 20$GeV

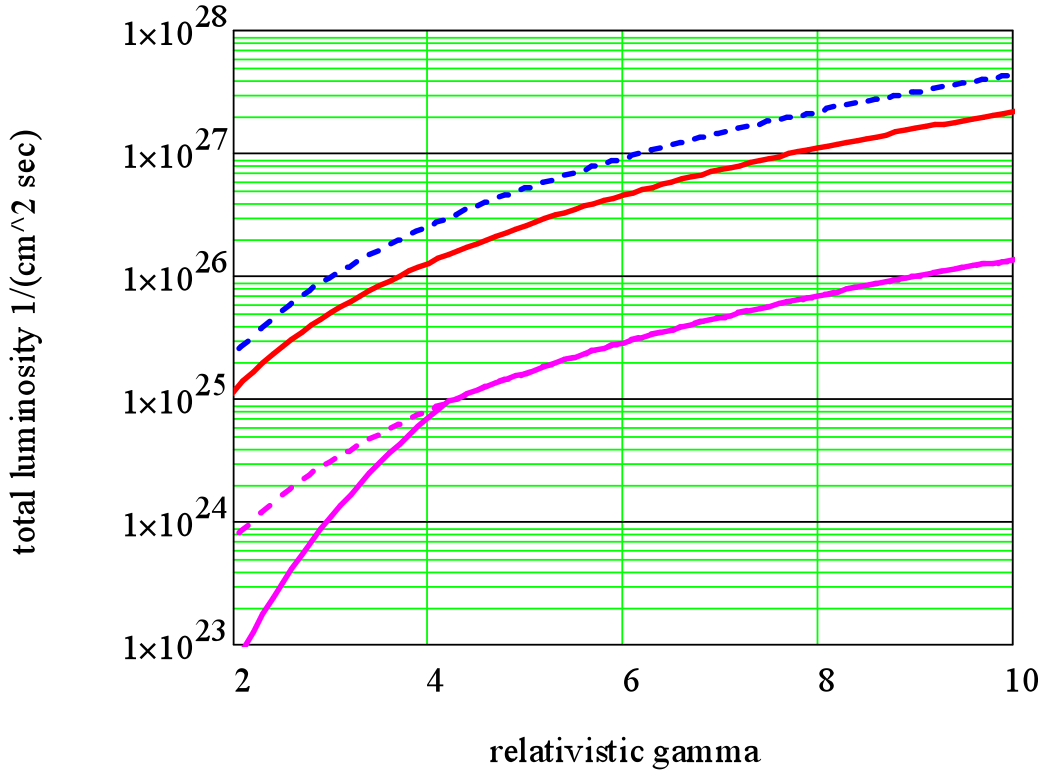
2) UrQMD model show monotonic behavior

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

e-cooling at RHIC for BES-II

A. Fedotov, W. Fischer, private discussions, 2012.

Fermi Lab Pelletron

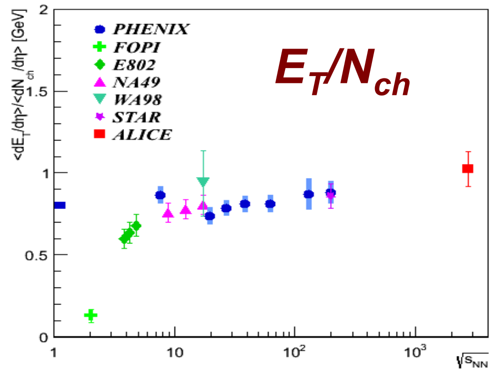


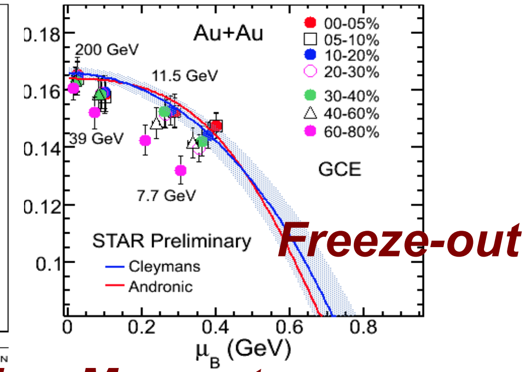
$\sqrt{s_{NN}}$ (GeV)	~ 5	~ 20
Increasing factor*	3-5	10

- Requested to install the e-cooling device
- BES-II data taking in 2016 - 2017

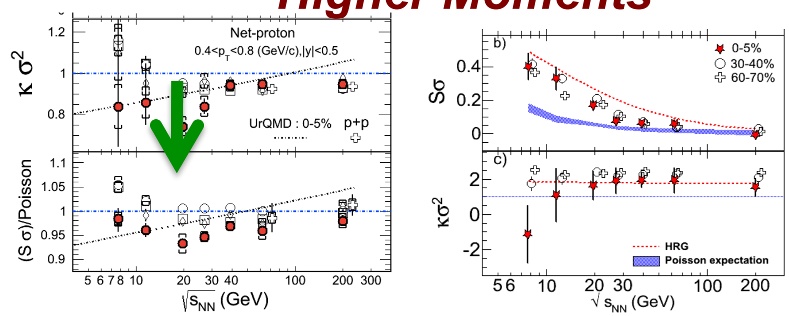
RHIC Beam Energy Scan-I

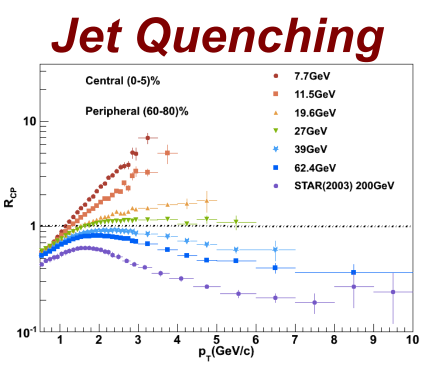
$\sqrt{s_{NN}}$ (GeV)	μ_{B*} (MeV)	Events(10^6)
39	112	130
27	156	70
19.6	206	36
11.5	316	12
7.7	420	5
5	550	--
* for central collisions		

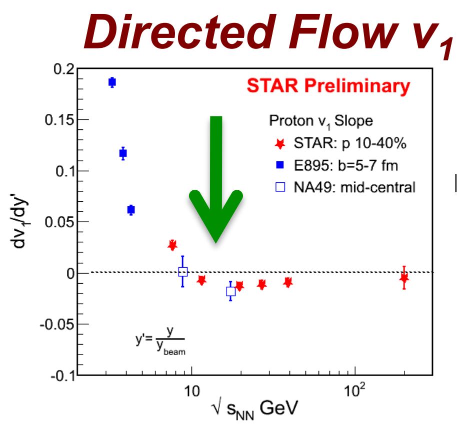


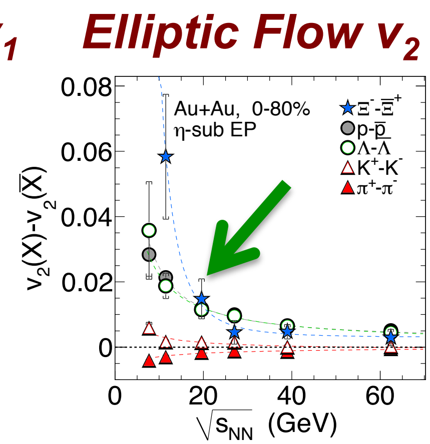


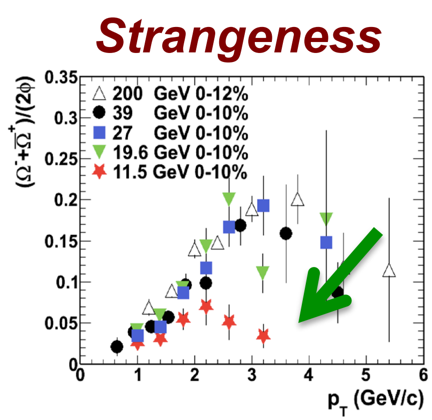
Higher Moments





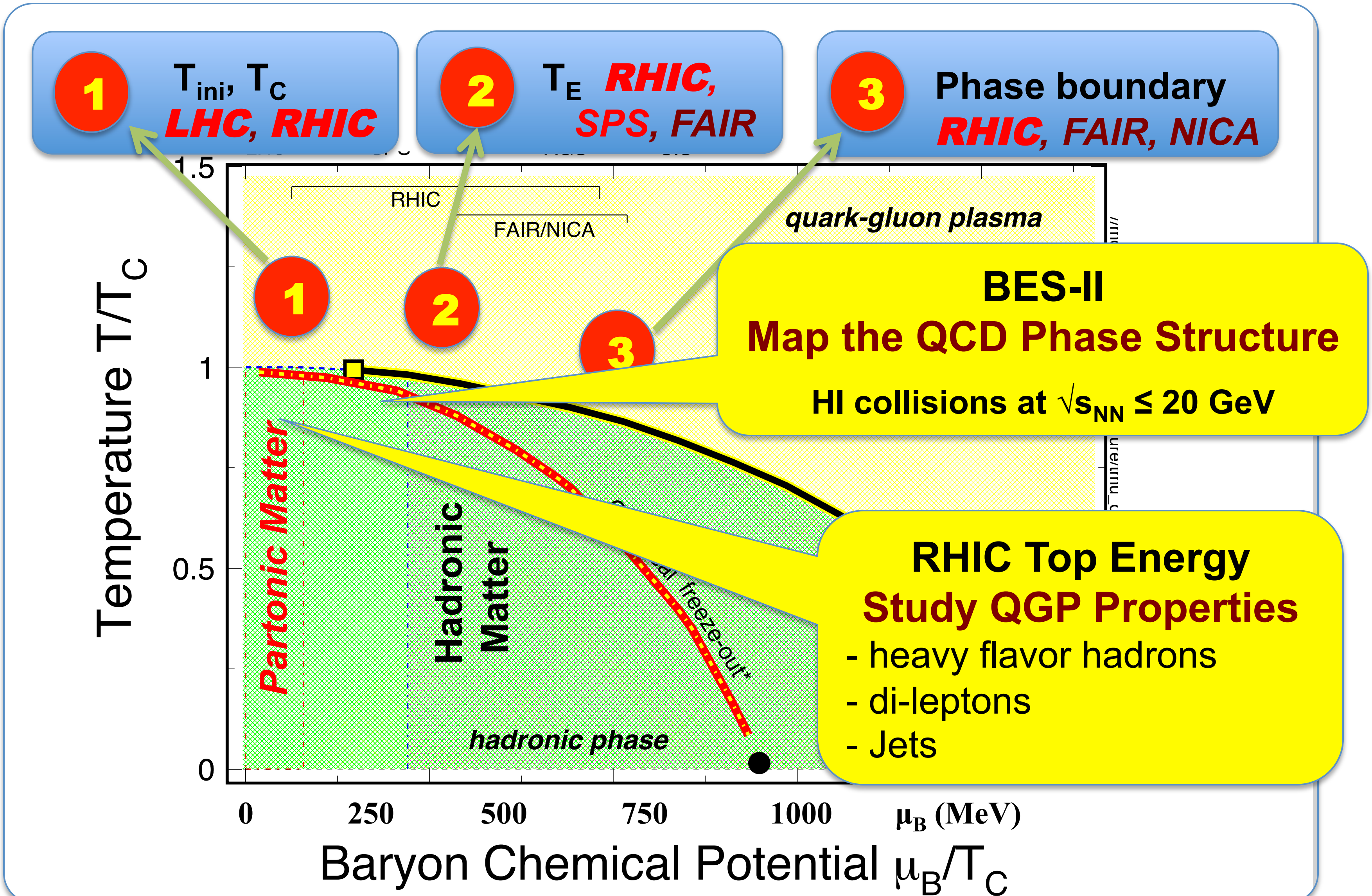






Changes at $\sqrt{s_{NN}}$ < 20 GeV, calls for higher statistics data!

Exploring the QCD Phase Structure



Summary

1) BES-I Program:

- Partonic QGP dominant: $\sqrt{s_{NN}}$ **> 39 GeV**
  Hadronic interactions become dominant: $\sqrt{s_{NN}}$ **≤ 11.5 GeV**

- High statistics data for energy region $\sqrt{s_{NN}}$ ≤ 20 GeV,
  needs e-cooling at RHIC => BES-II

2) Jets, Heavy Flavor and Di-lepton Programs:

PHENXI: sPHENIX, full jets reconstruction, ready by 2018
STAR: HFT+MTD upgrades, ready by summer of 2014

RHIC provides unique opportunities for exploring matter with QCD degrees of freedom in the coming decade!