Exploring the QCD Phase Structure

Recent Results from RHIC BES-I

Nu Xu

Outline:

1) Introduction: QCD Phase Structure
2) STAR Detector System
3) RHIC BES-I Results
4) Summary and Outlook

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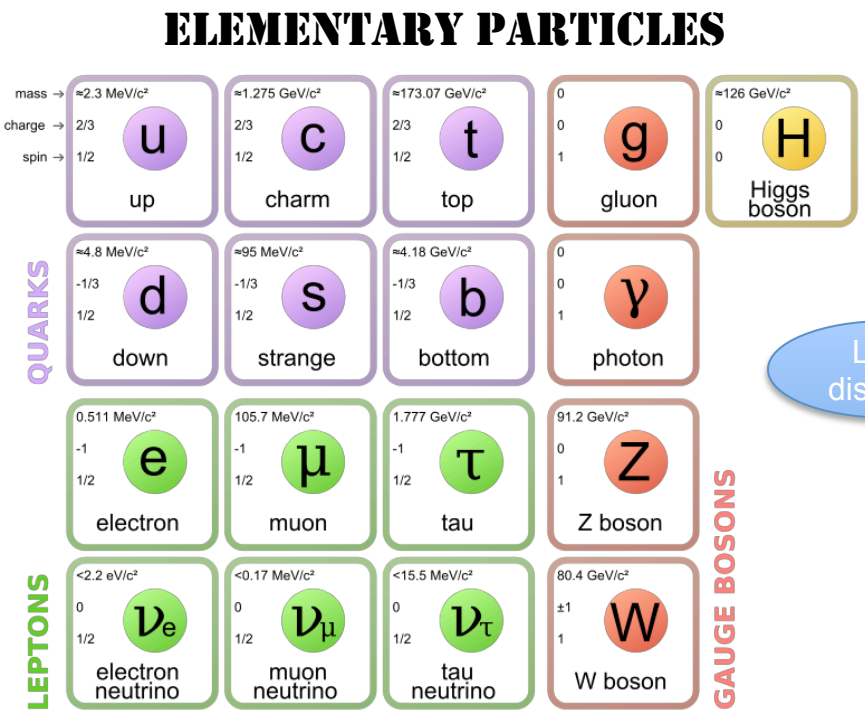
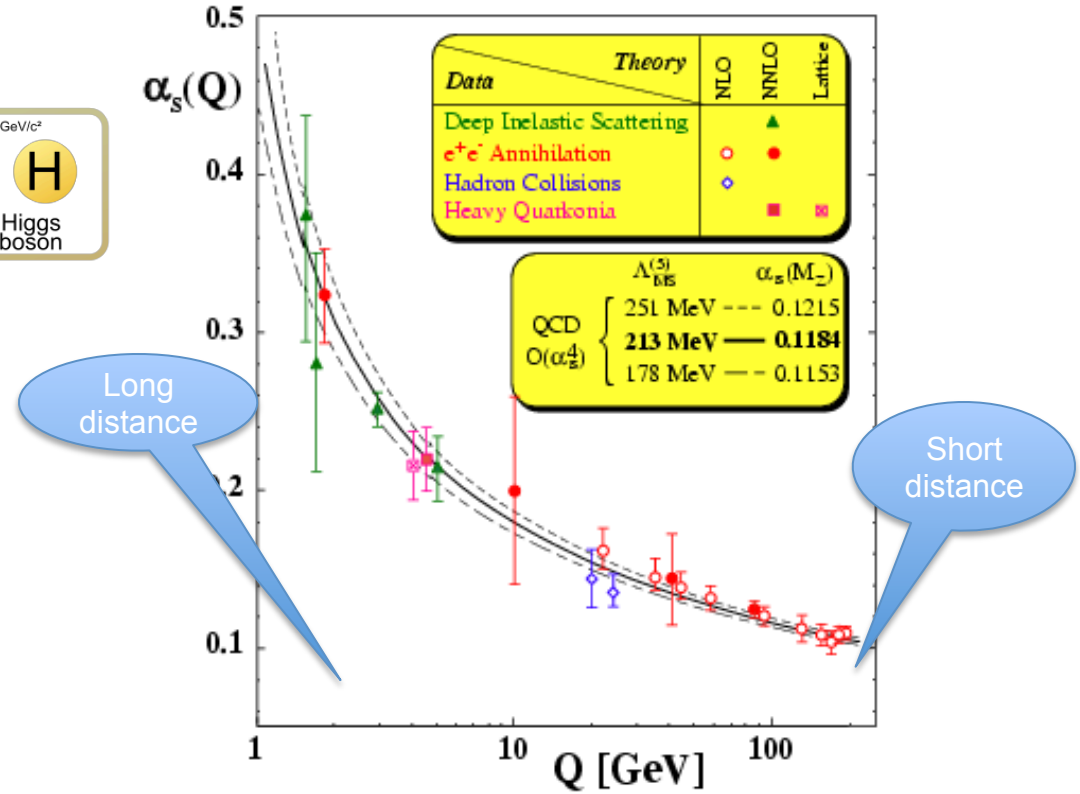
(2) *College of Physical Science & Technology, Central China Normal University, China*

QCD Emergent Properties





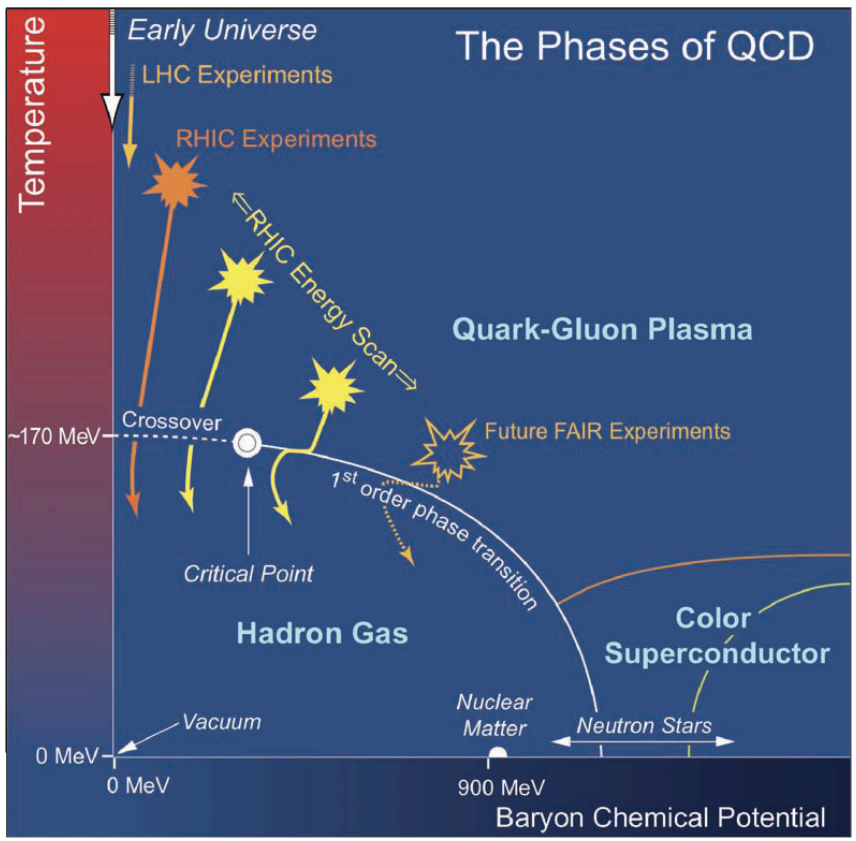
1) QCD is the basic theory for strong interaction. Its degrees of freedom are well defined at short distance.
2) Little is known regarding the dynamical structures of matter that made from ***q, g***. *E.g. the confinement*, *nucleon spin*, the ***QCD phase structure***... Large α_S and strong coupling – QCD at long distance.

Beam Energy Scan (I) at RHIC

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

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

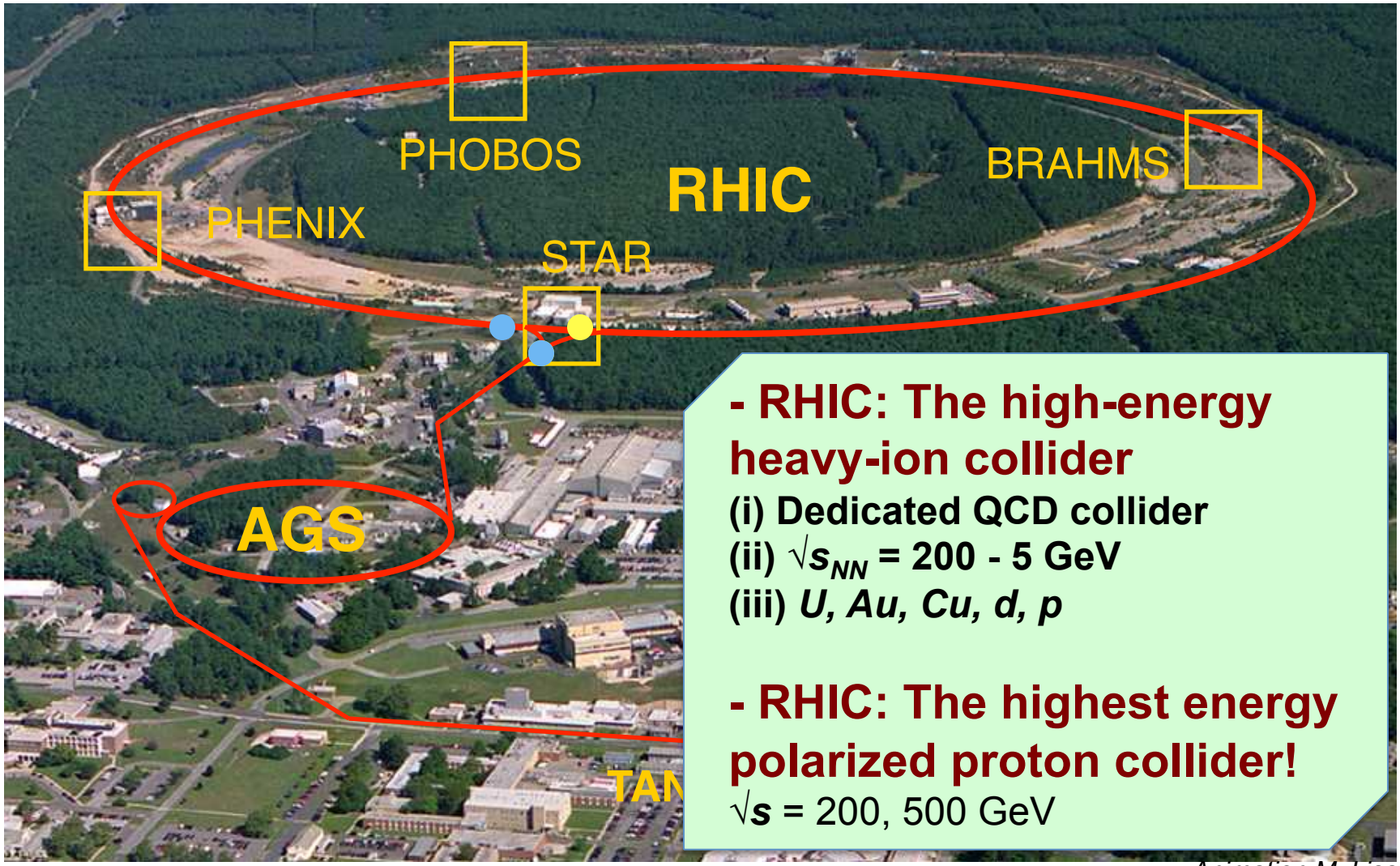
(6) Fluctuations

(7) Di-lepton production

- http://drupal.star.bnl.gov/STAR/starnotes /public/sn0493; arXiv:1007.2613

Relativistic Heavy Ion Collider

Brookhaven National Laboratory (BNL), Upton, NY



- RHIC: The high-energy heavy-ion collider

(i) Dedicated QCD collider

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

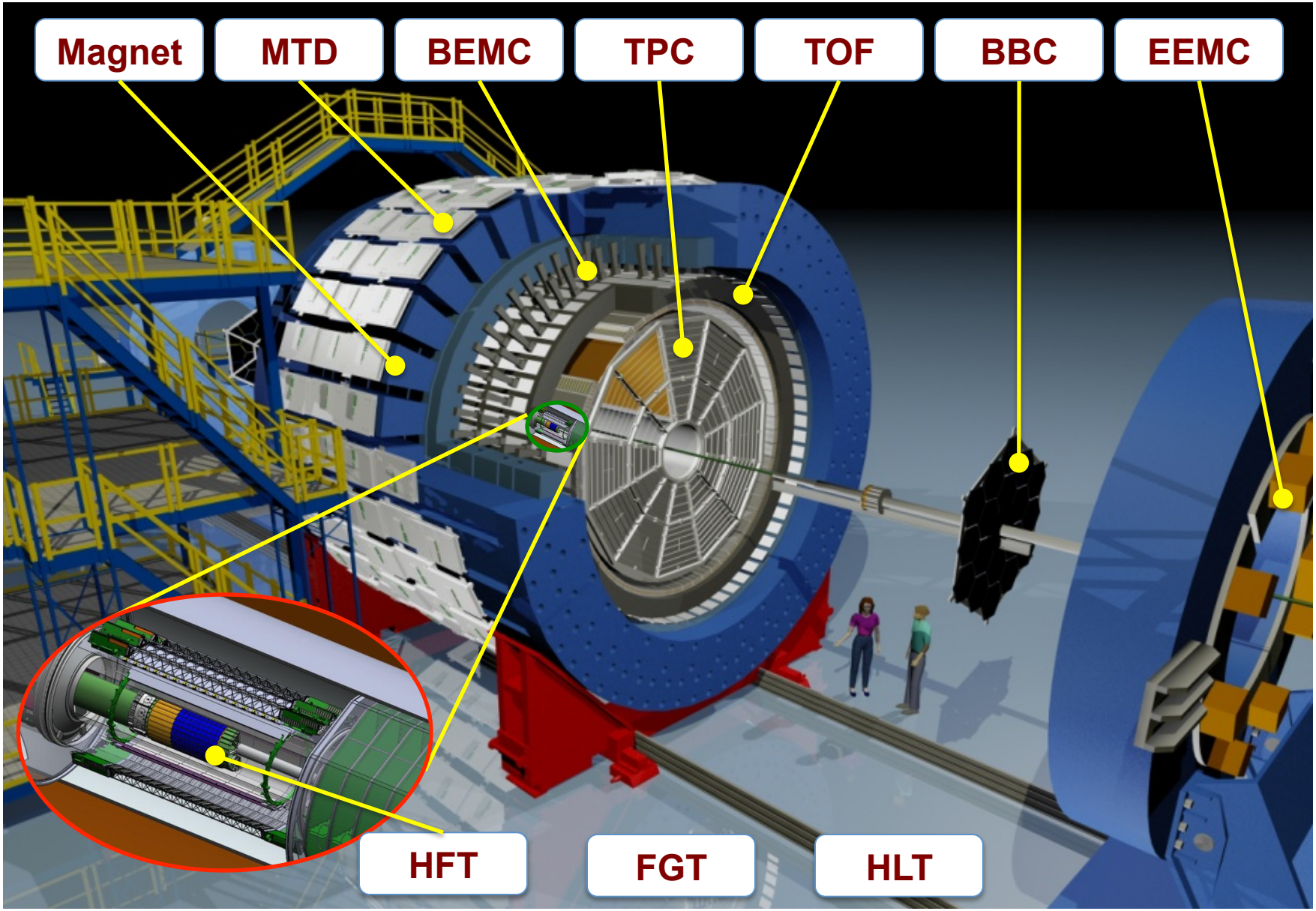
(iii) *U, Au, Cu, d, p*

- RHIC: The highest energy polarized proton collider!

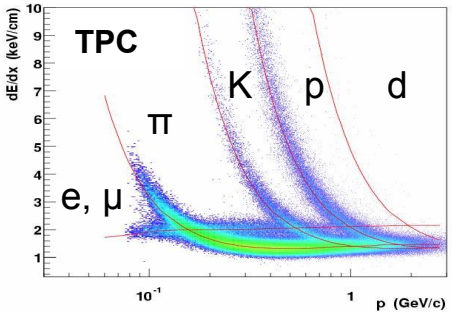
$\sqrt{s}$ = 200, 500 GeV

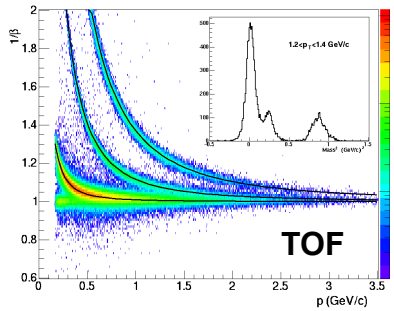
Animation M. Lisa

STAR Experiment

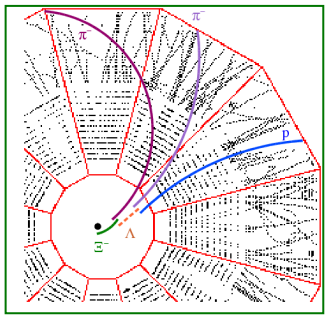


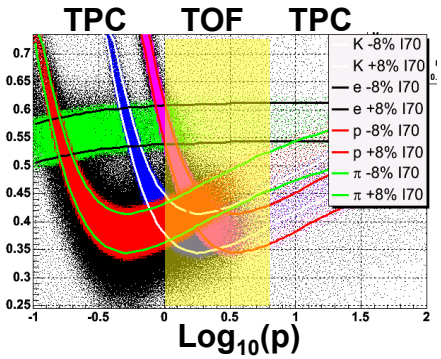
Particle Identification at STAR



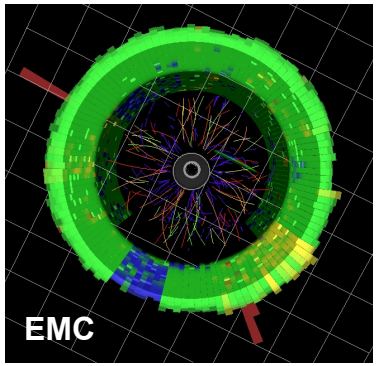


Charged hadrons

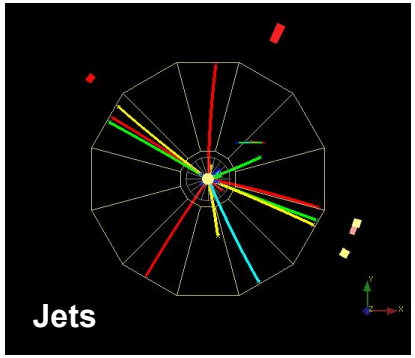




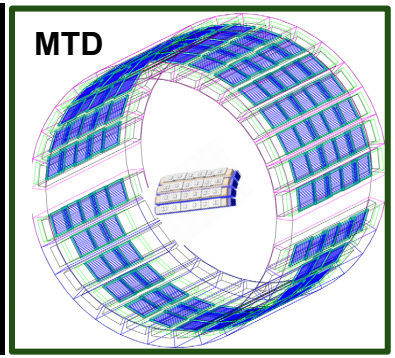
Hyperons & Hyper-nuclei



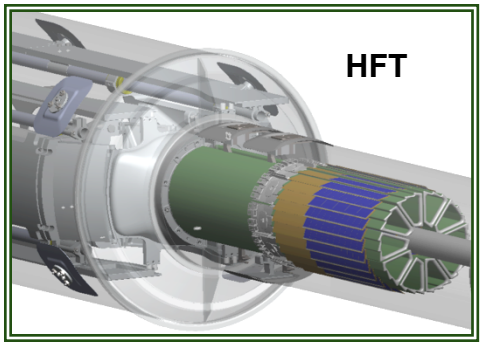
Neutral particles



Jets & Correlations



High p_T muons

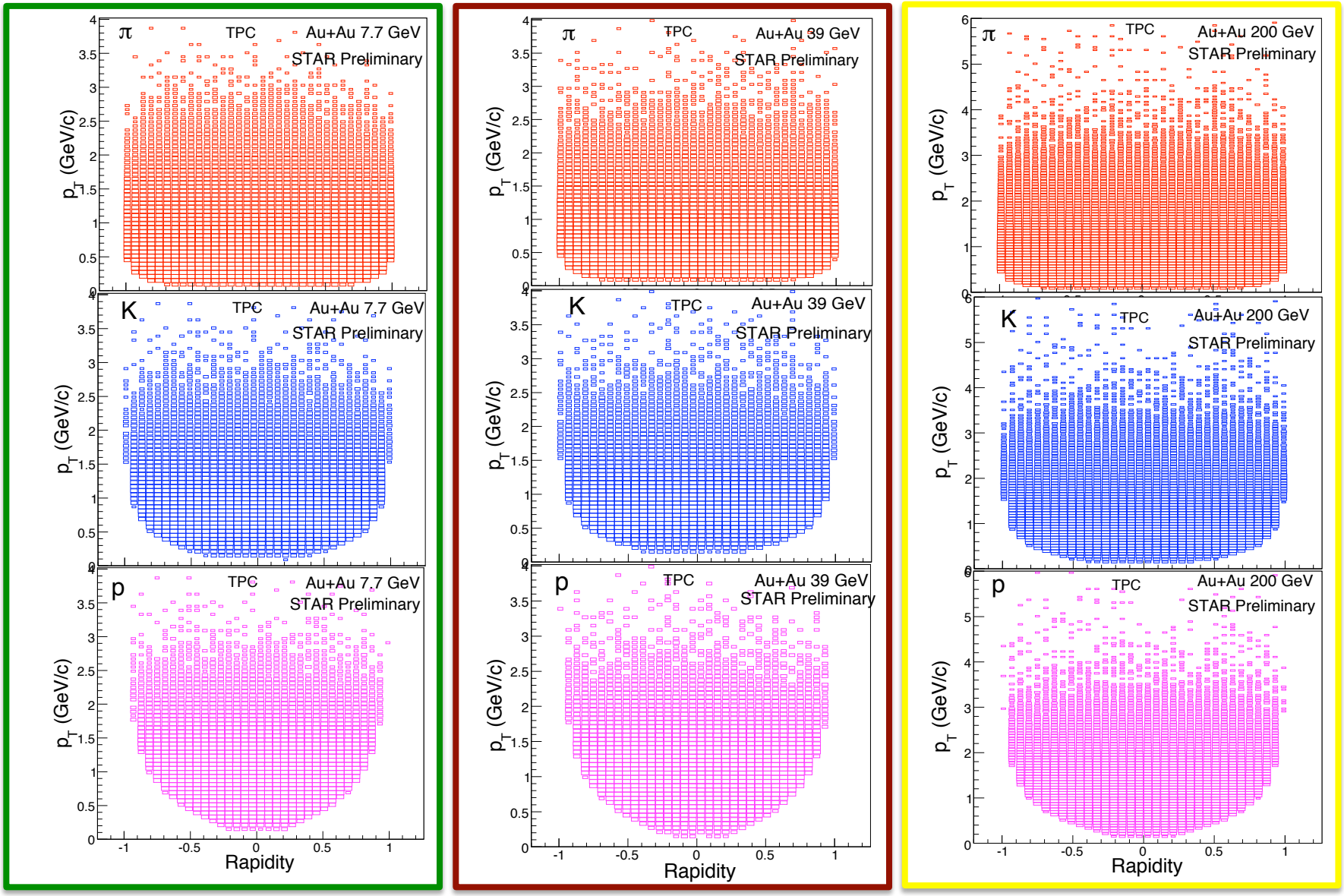


Heavy-flavor hadrons

Multiple-fold correlations for the identified particles!

STAR PID for (π, K, p)

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



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**

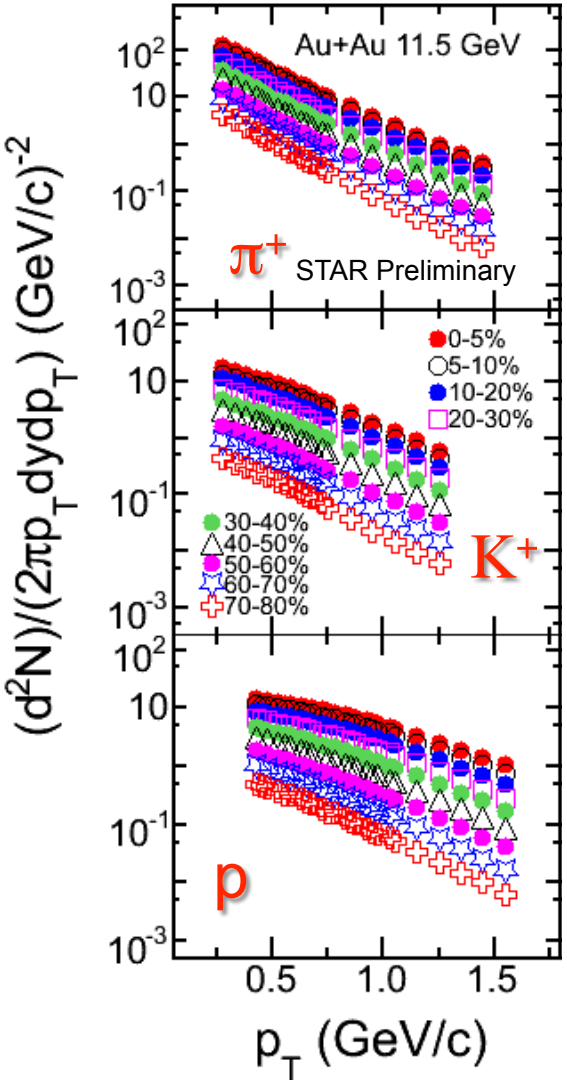
- detects nearly all particles produced at RHIC
- multiple fold correlation measurements
- **Probes: bulk, penetrating, and *bulk-penetrating***

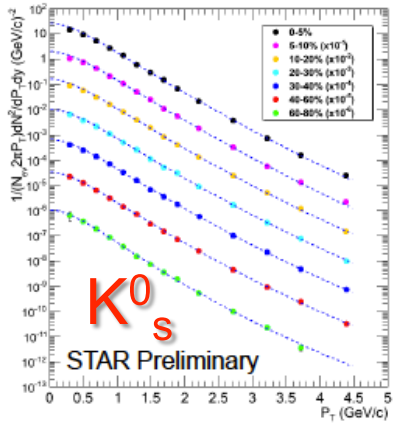
➔ **STAR: Perfect mid-y collider experiment**

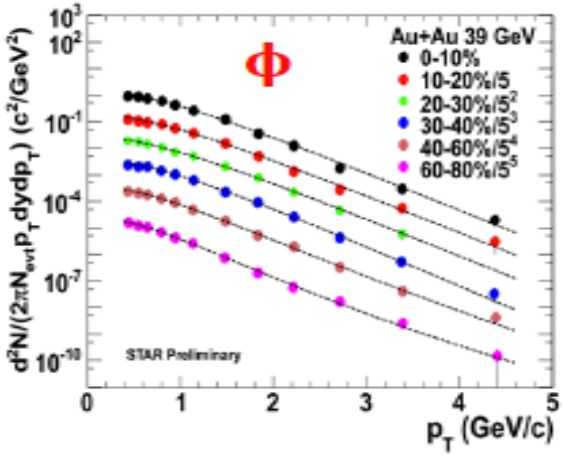
➔ **STAR: Expanding into forward rapidity regions**

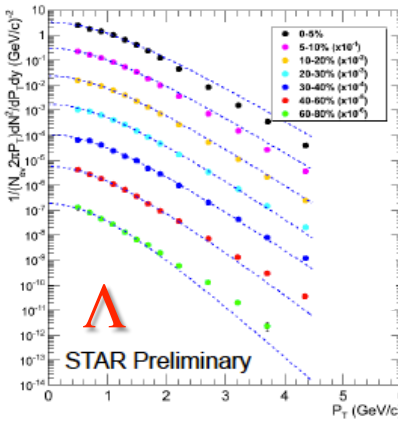
(1) Hadron Spectra

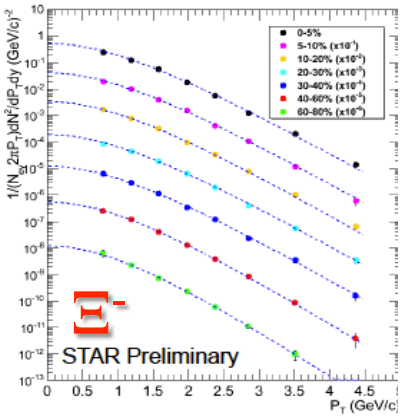
$\sqrt{s_{NN}}$ = *39* GeV Au+Au Collisions

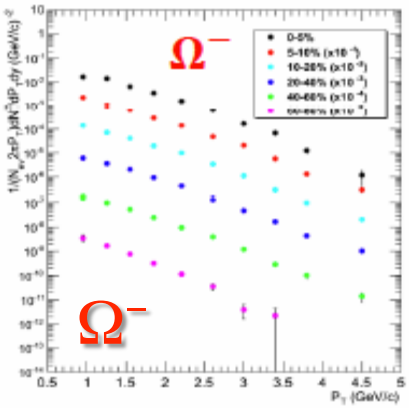




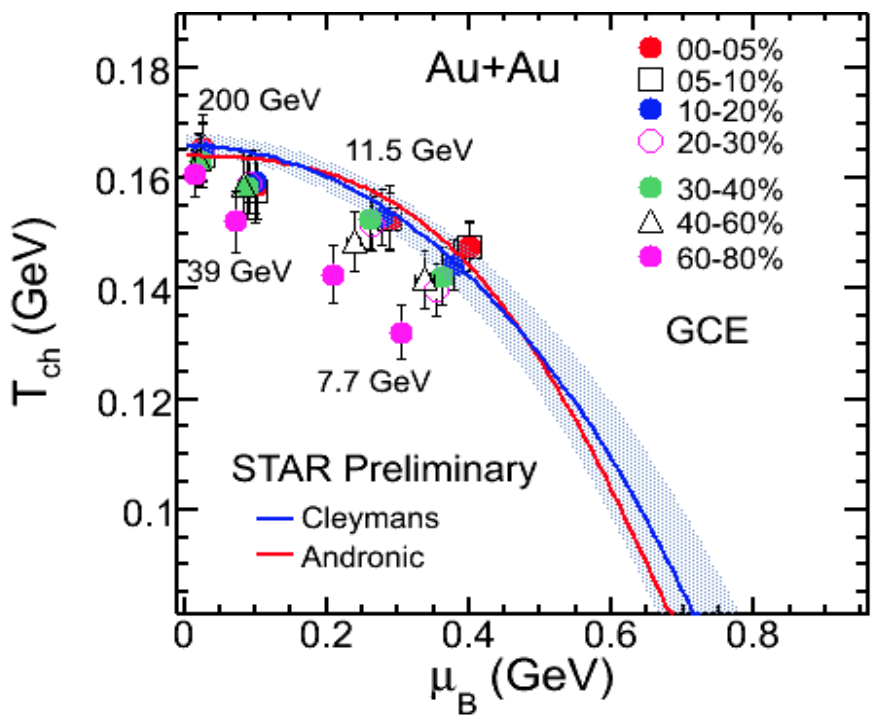


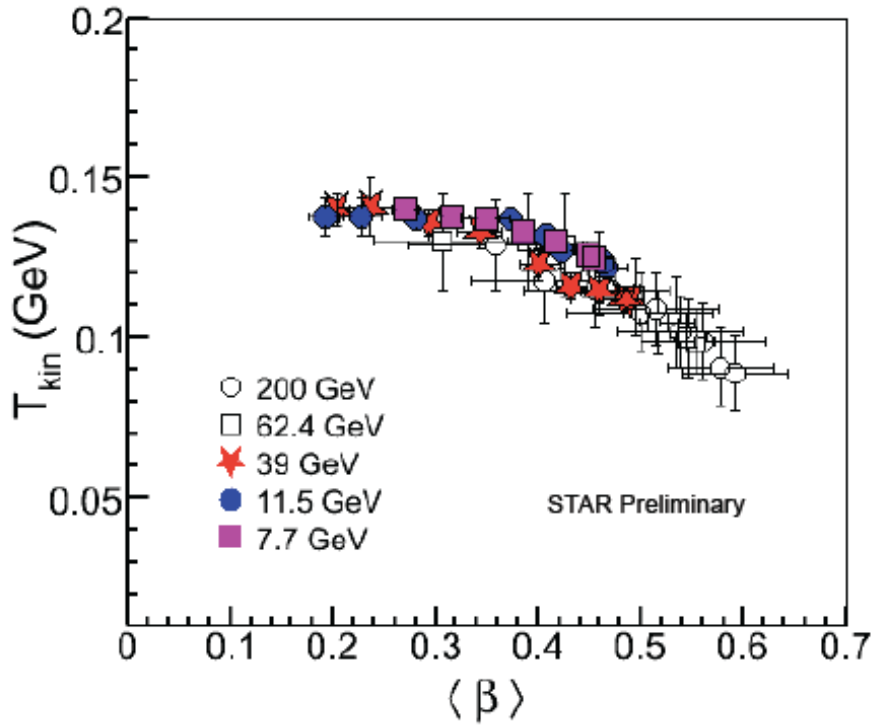






Bulk Properties at Freeze-out





Chemical Freeze-out: (GCE)

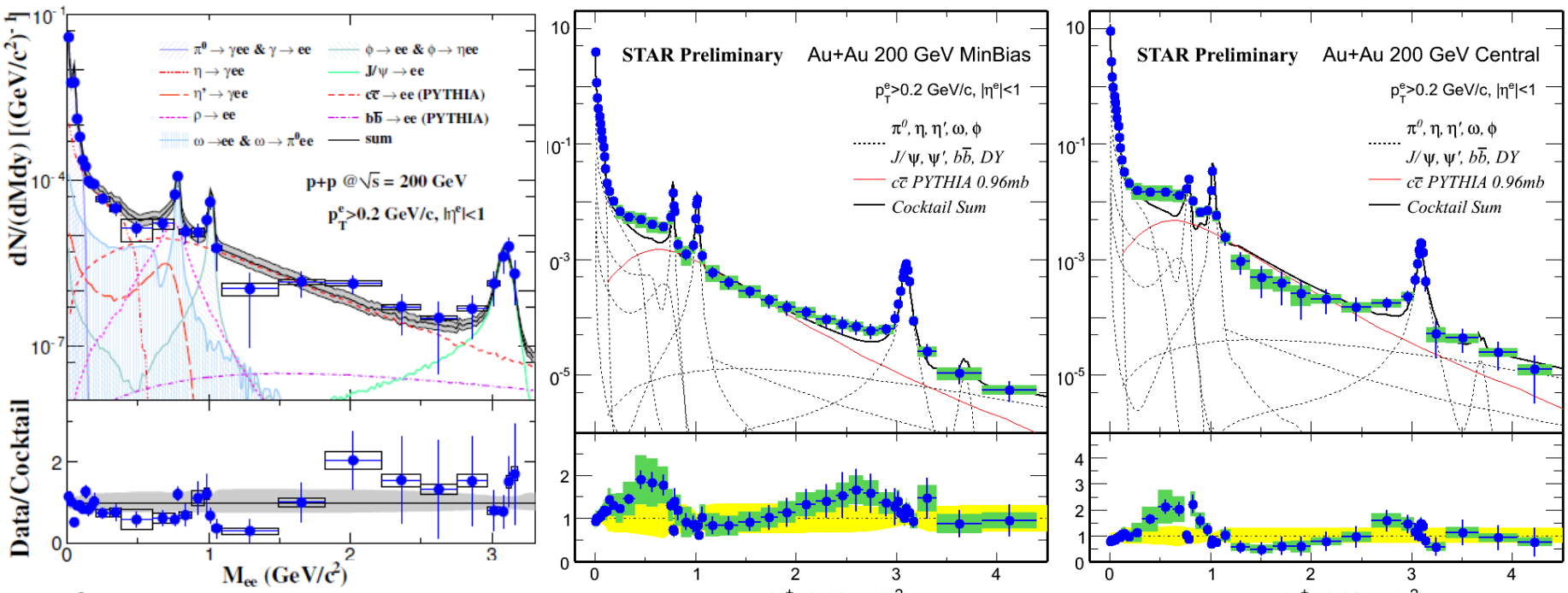
- Central collisions => higher values of T_{ch} and μ_B!
- The effect is stronger at lower energy.

Kinetic Freeze-out:

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

(2) Di-electron Production

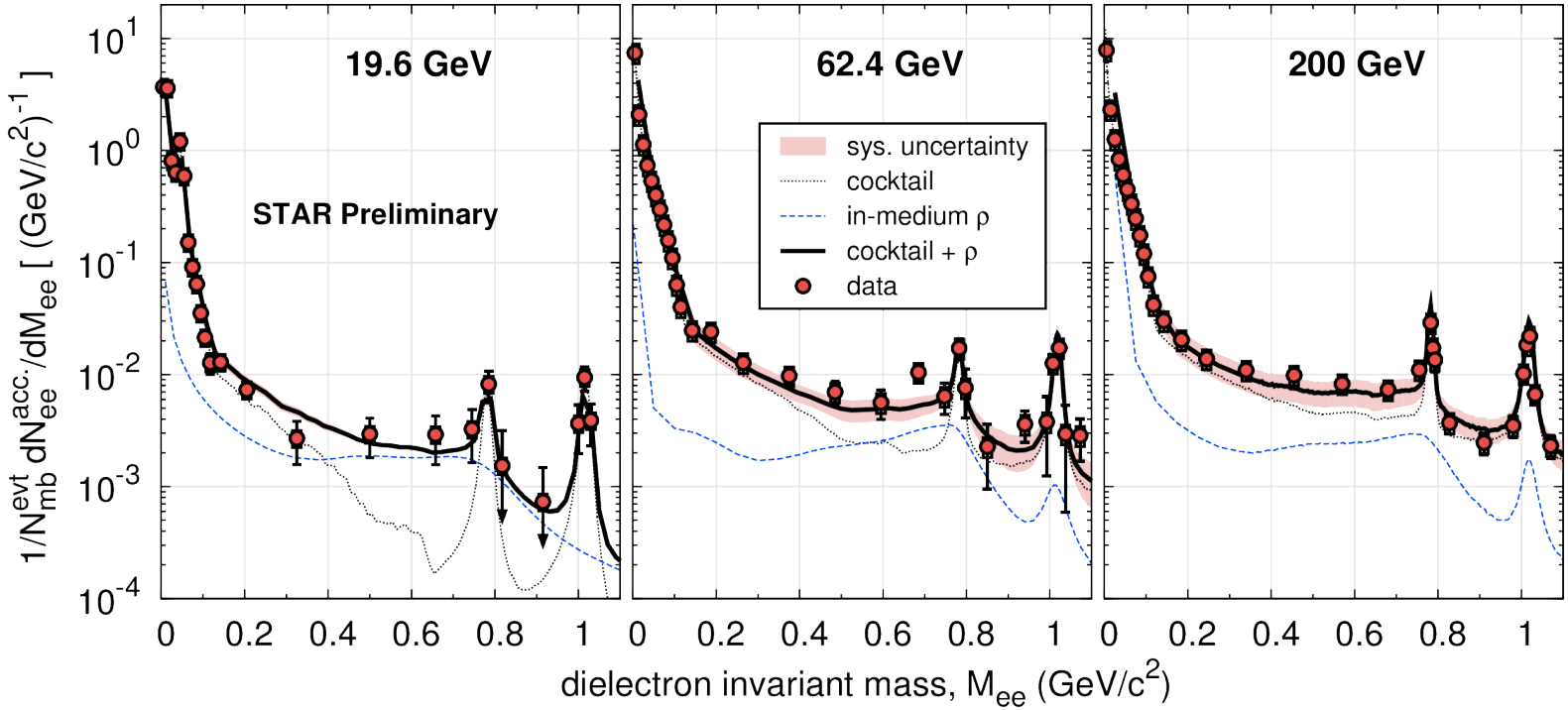
$\sqrt{s}$ = *200 GeV* **p+p** **Au+Au MinBias** **Au+Au Central**



STAR: arXiv:1204.1890

1) Direct radiation, penetrating-bulk probe, **great addition to STAR**!
2) Beam energy, p_T, centrality, mass dependence (8-10x more events): **R_{AA}, v_2, radial expansion, HBT, polarization, …**
3) HFT/MTD upgrades: key for the correlated charm contributions.

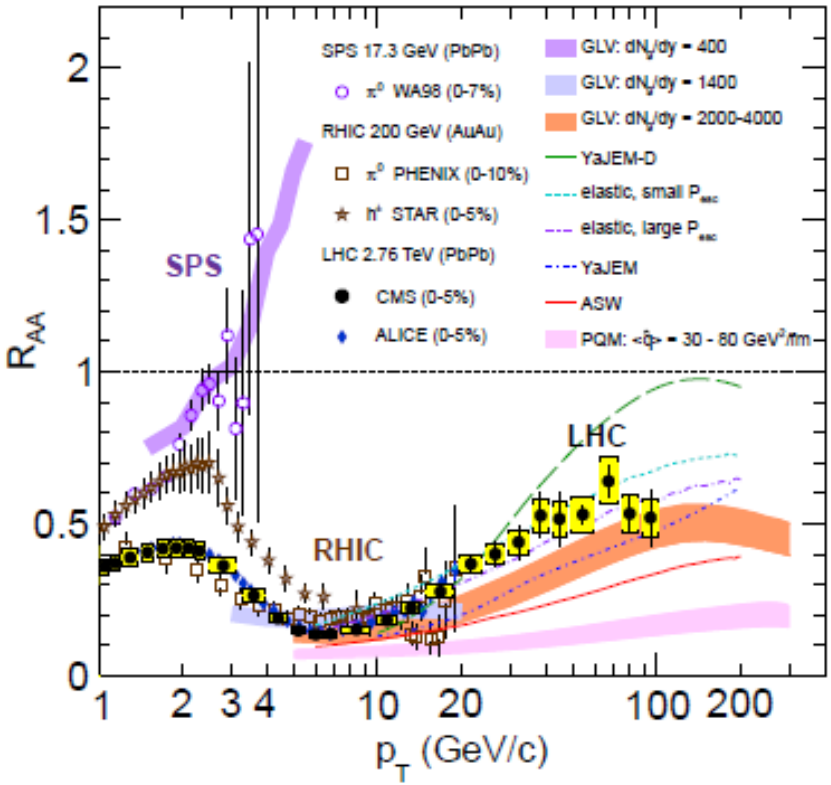
BES Dependence of Di-electrons

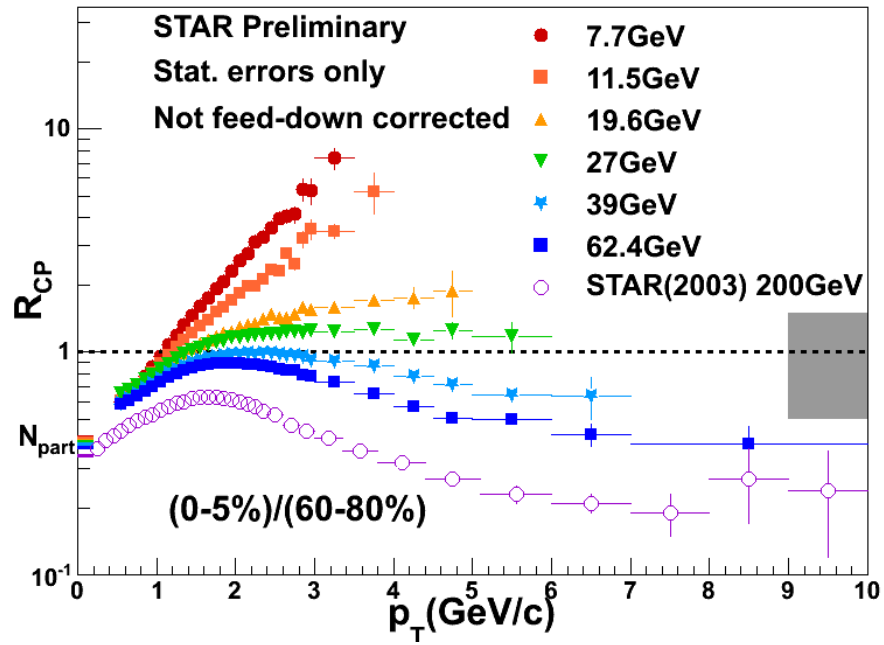


1) With in-medium broadened rho, model results are consistent with experimental data ($m_{ee} \leq 1$ GeV/c^2) at $\sqrt{s_{NN}}$ = 200, 62.4 and 19.6GeV

2) 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}



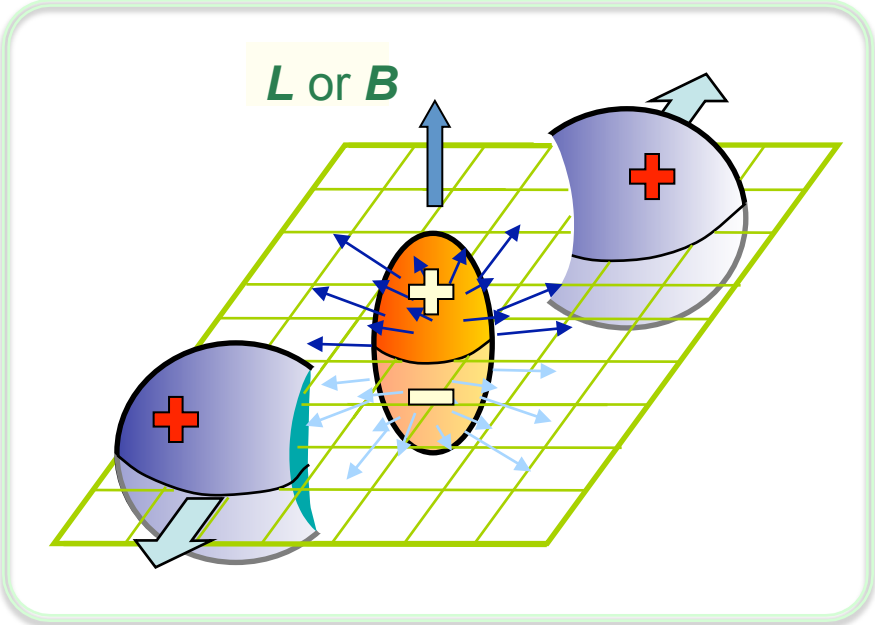


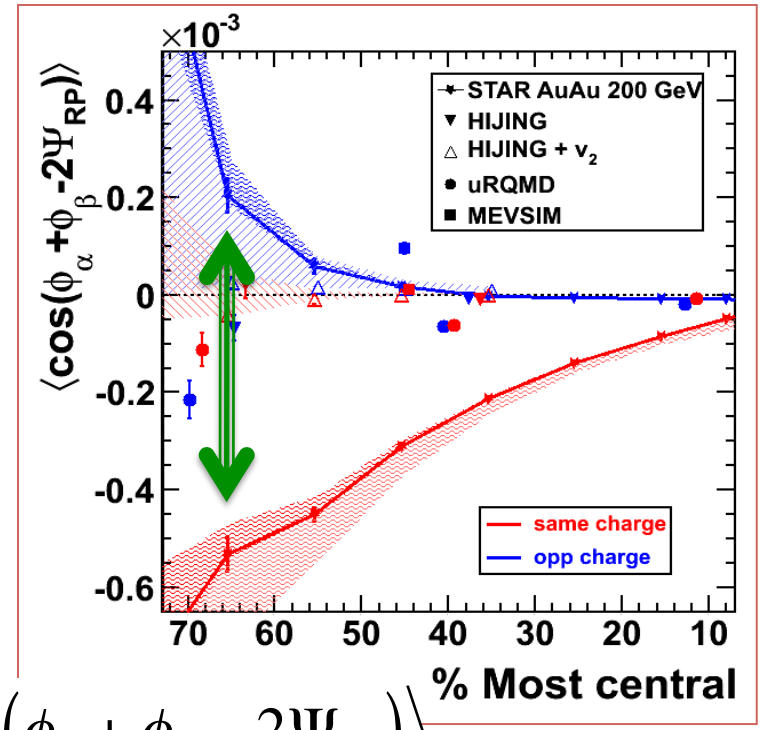
1) Suppression of high p_T hadrons: one of the key signatures for the formation of QGP in high-energy nuclear collisions

2) The **suppression was 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





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

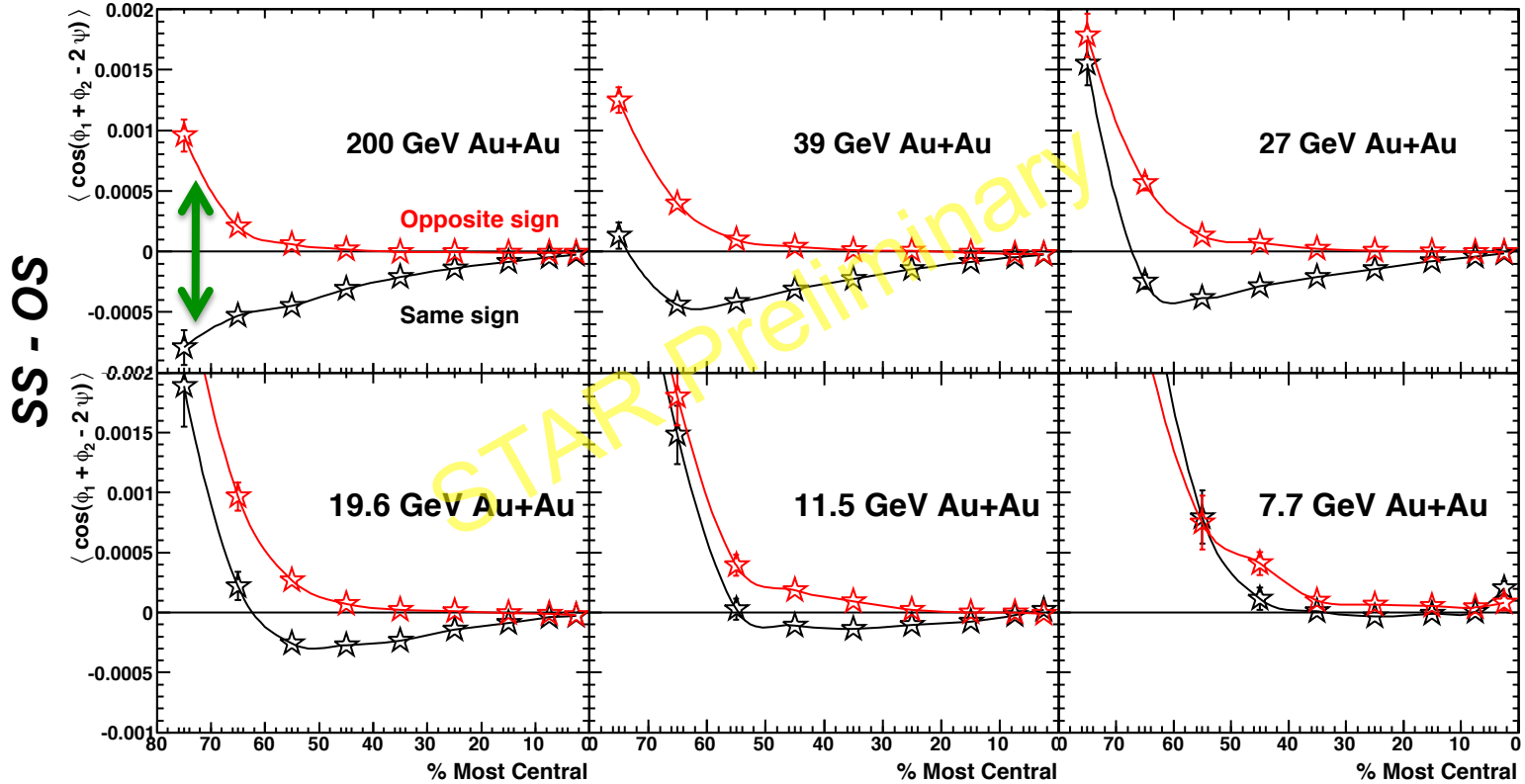
The separation between the same-charge and opposite-charge correlations.

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

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

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

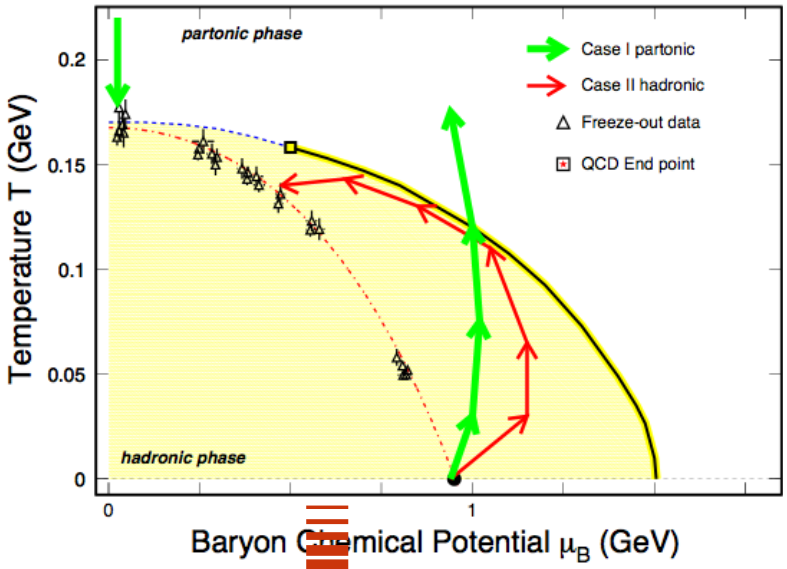
Dynamical Correlations

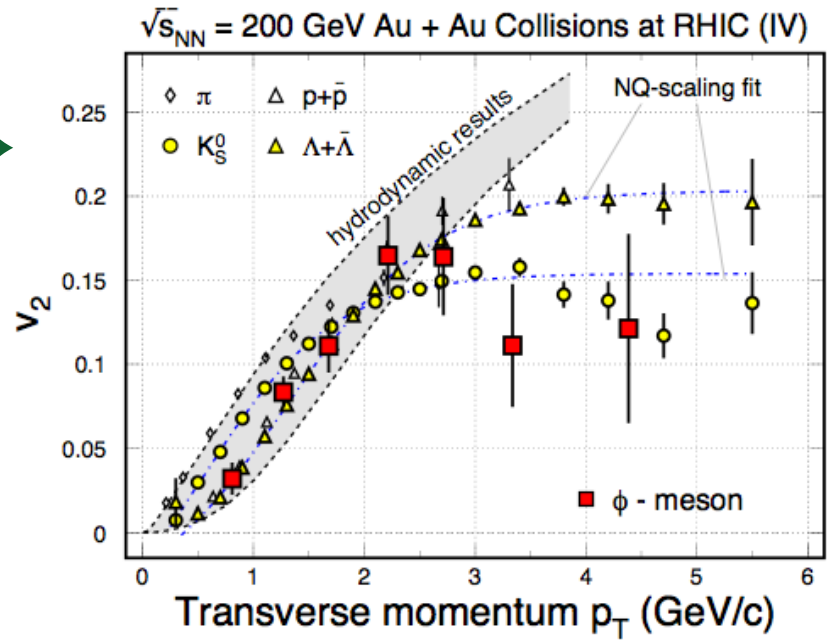


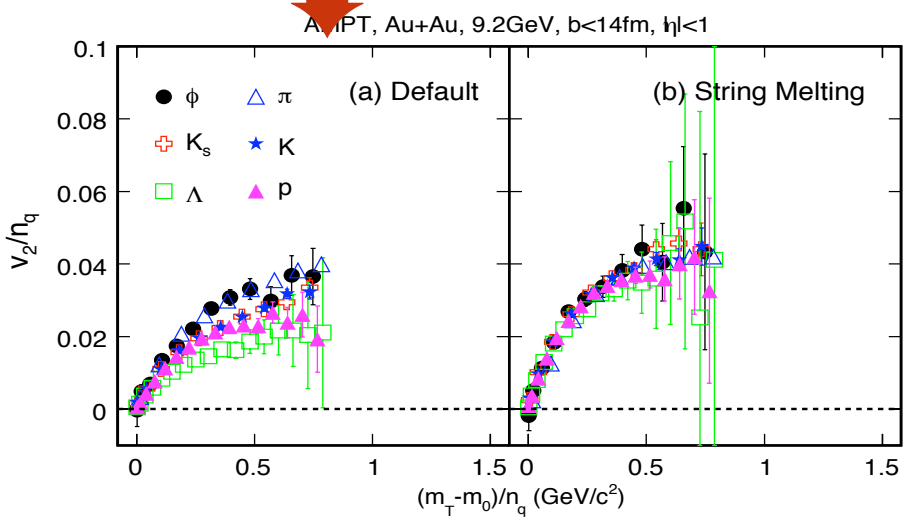
(1) Below $\sqrt{s_{NN}}$ = 11.5 GeV, the splitting between the same- and opposite-sign charge pairs (SS-OS) disappear

(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







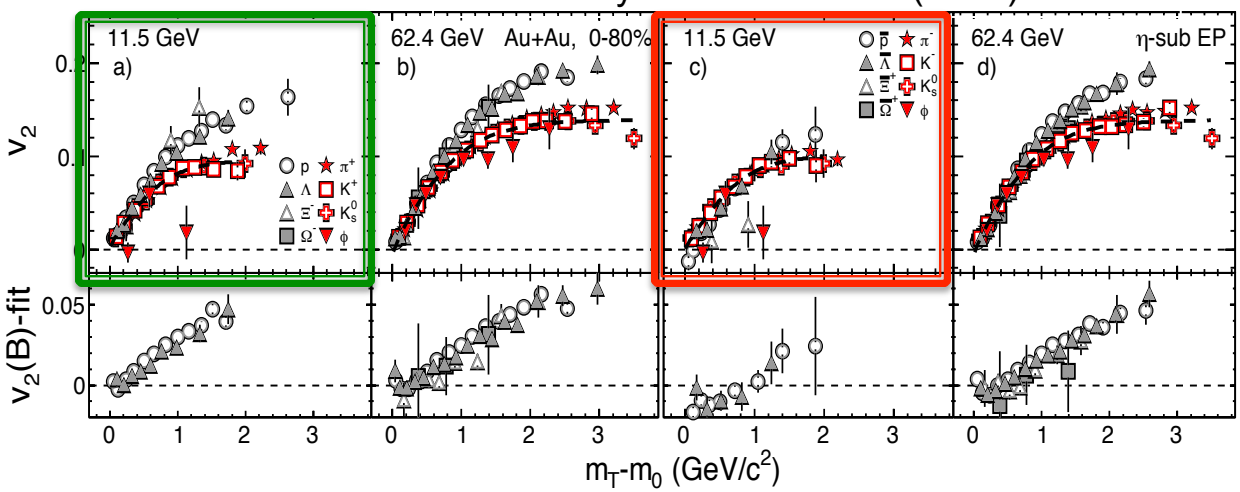
- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi,\ \pi\pi}$

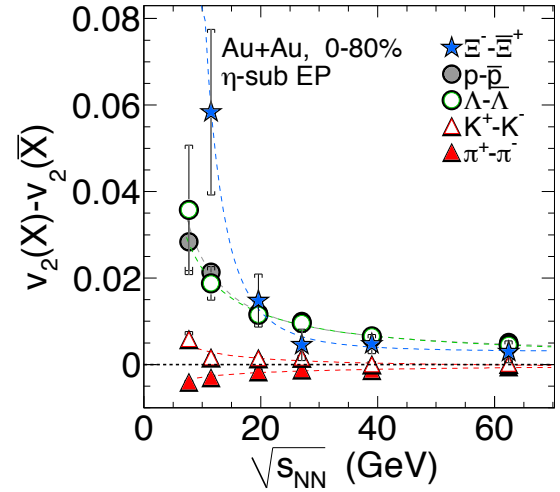
In the hadronic case, no number of quark scaling and the value of v_2 of φ will be small.

*** Thermalization is assumed!**

Collectivity v_2 Measurements

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



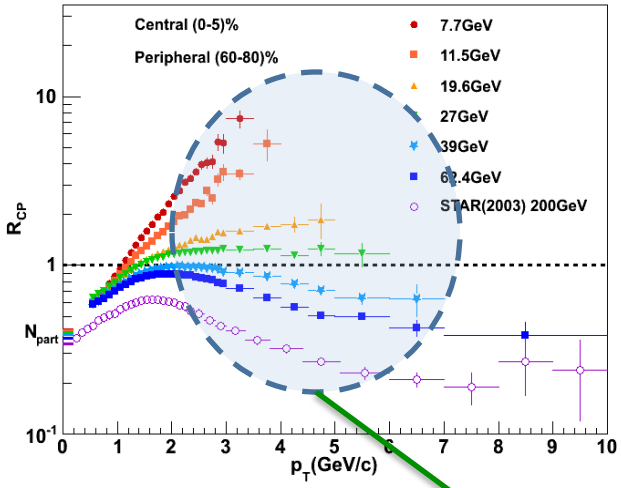


1) Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions

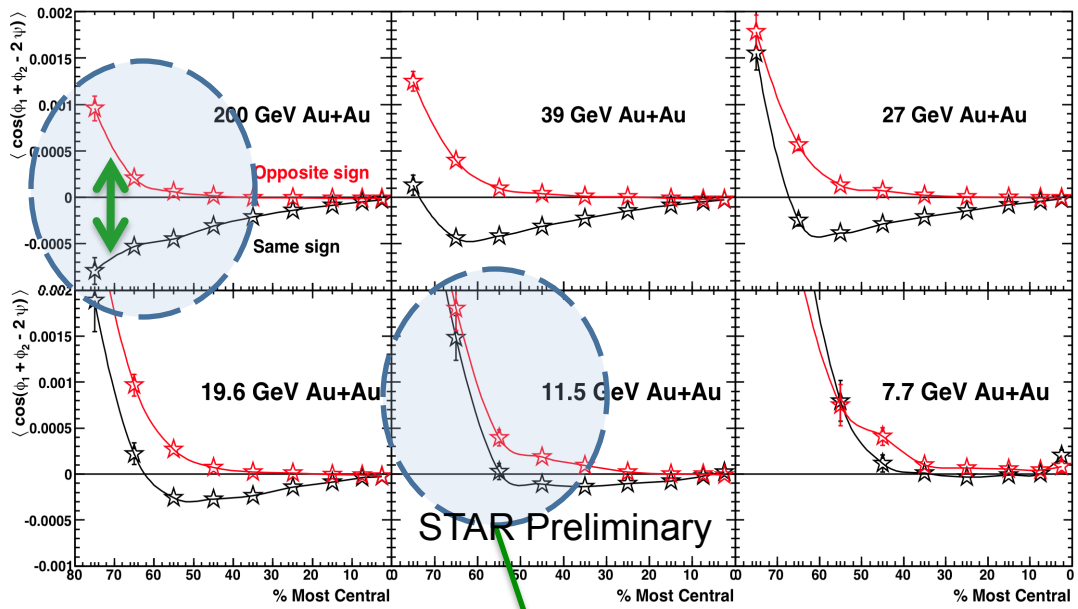
2) At $\sqrt{s_{NN}}$ < 11.5 GeV, the v_2 **NCQ scaling is broken** indicating hadronic interactions become dominant.

Disappearance of QGP Signatures

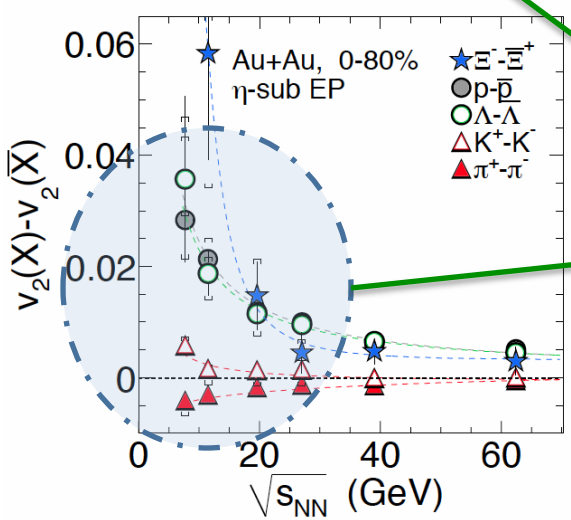
Parton energy loss



"Local Parity Violation"



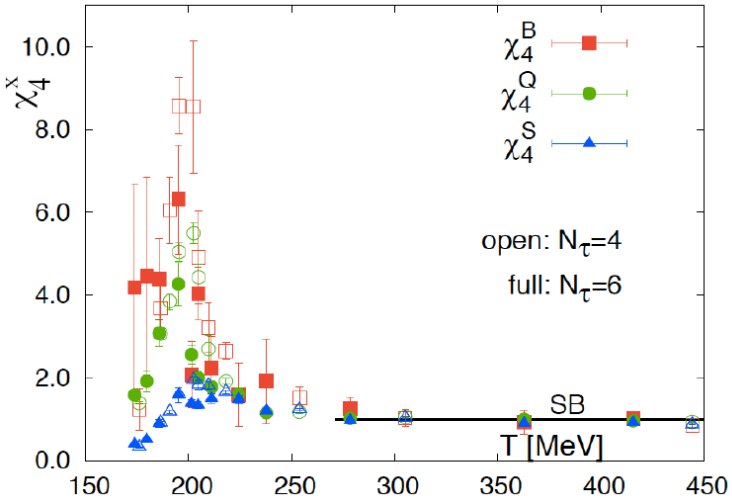
Partonic collectivity

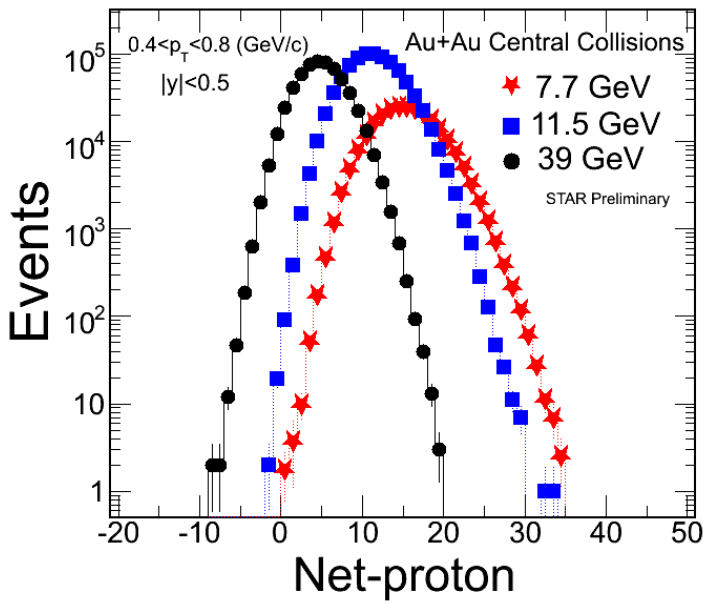


sQGP key signatures

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

(6) 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 calculation at any order:

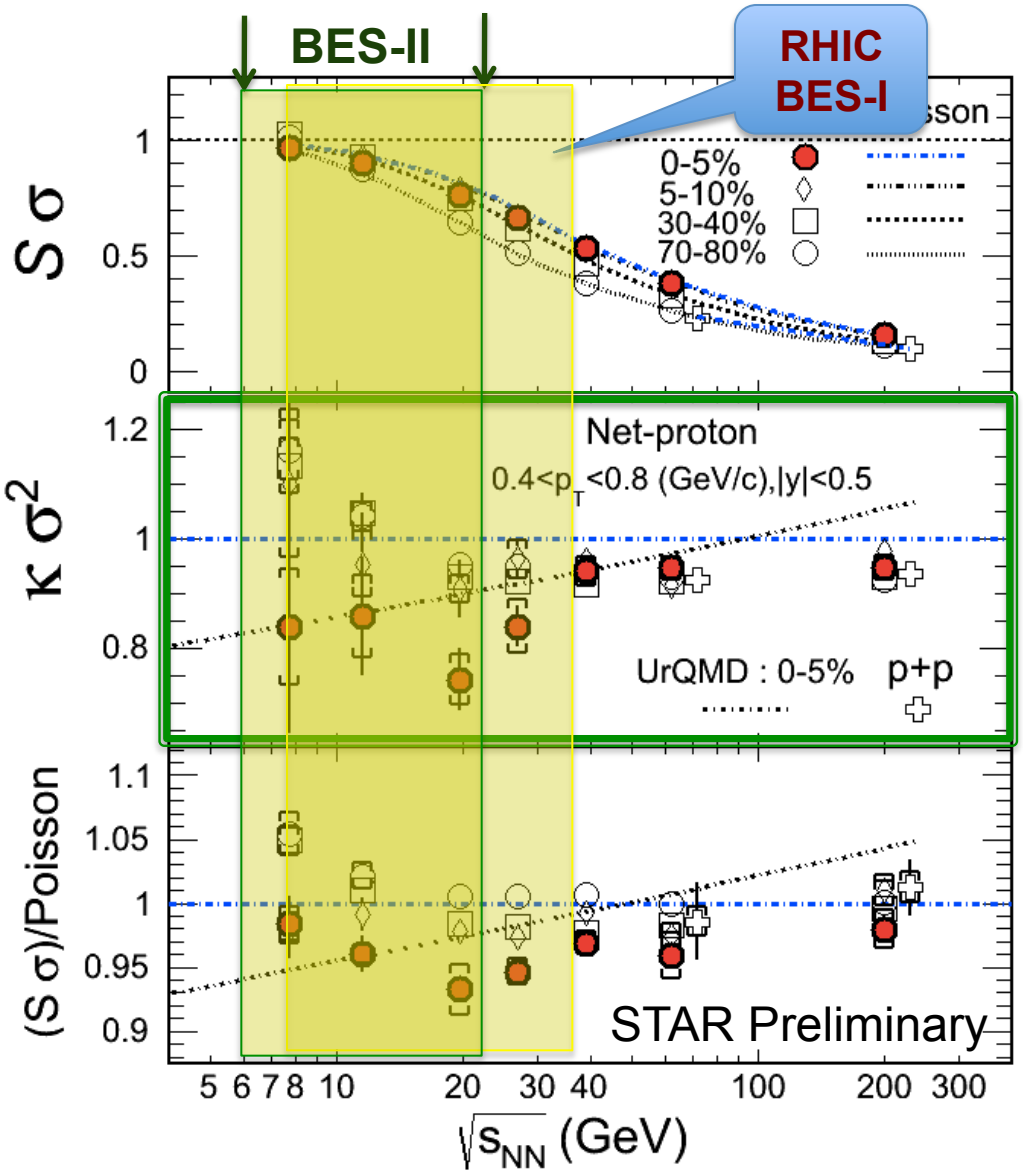
$$S * \sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa * \sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

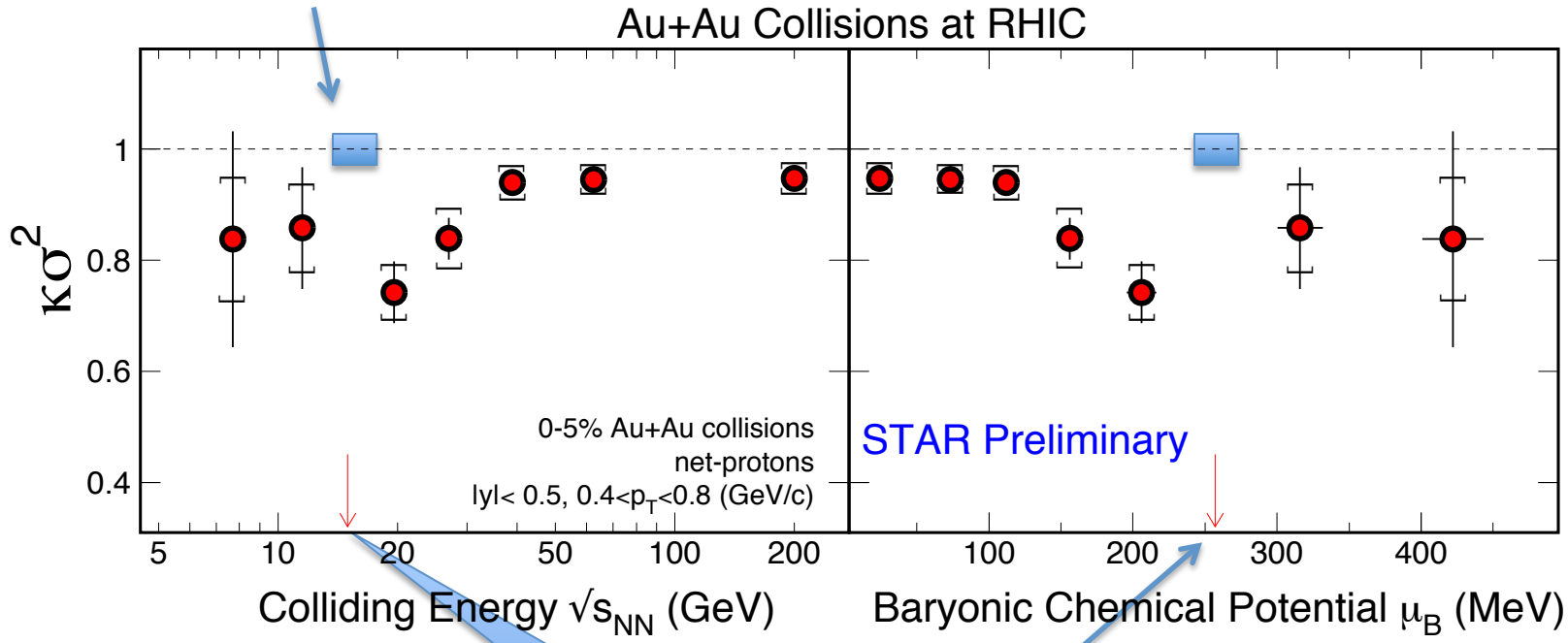


STAR net-proton results:

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 $\sqrt{s_{NN}} \sim 20$GeV
2) Independent p and pbar production also reproduce 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.*

Net-proton Higher Moment

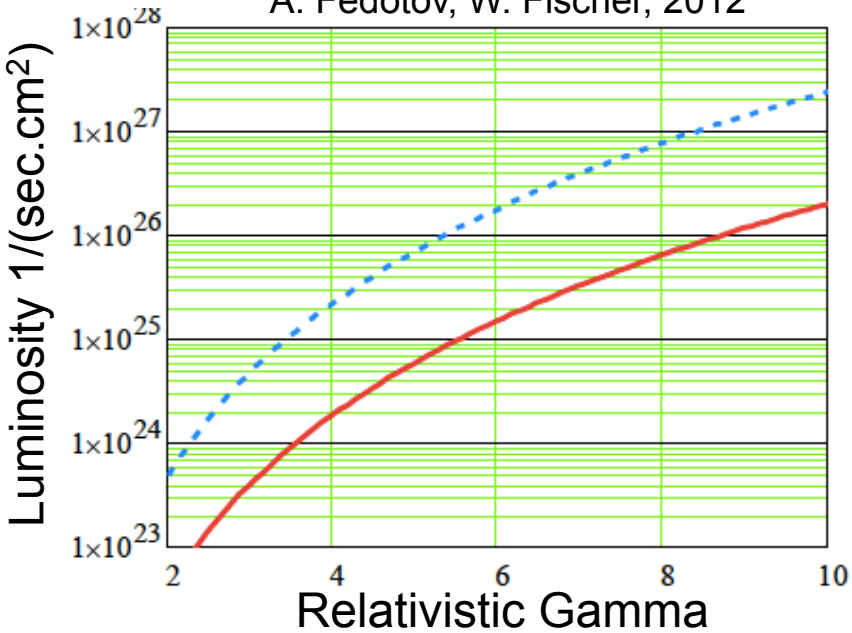
Expected statistical error from Run 14



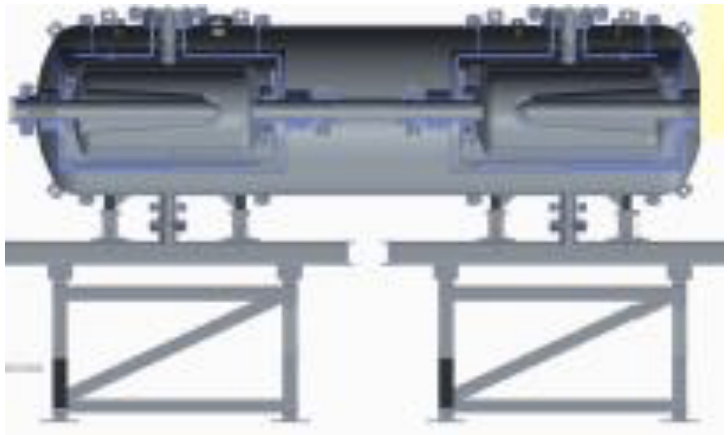
$\sqrt{s_{NN}}$ = 15GeV

e-cooling at RHIC for BES-II

A. Fedotov, W. Fischer, 2012



SRF Gun



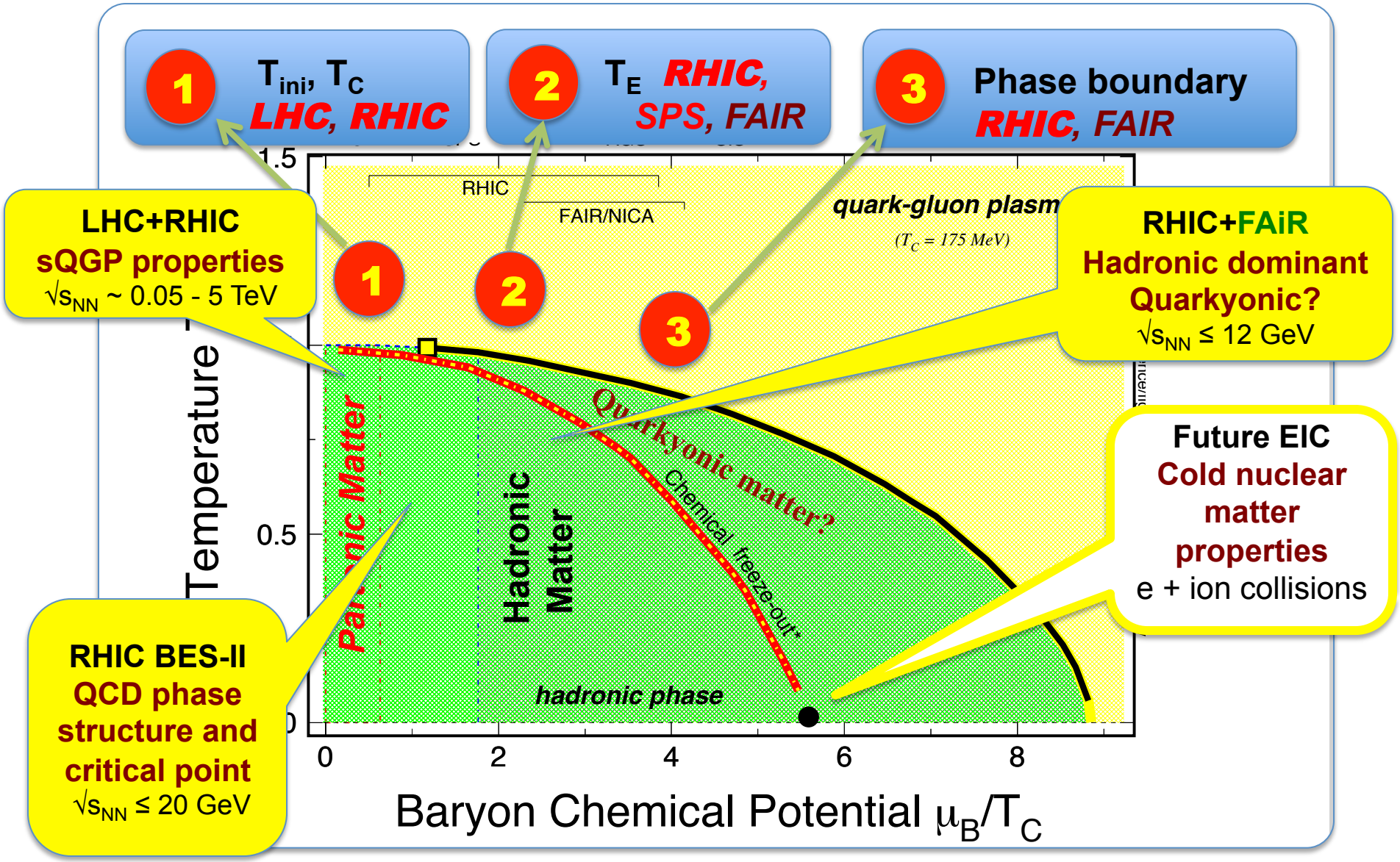
$\sqrt{s_{NN}}$ (GeV)	~ 5	~ 20
Increasing factor*	3-5	10

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

Exploring QCD Phase Structure



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)

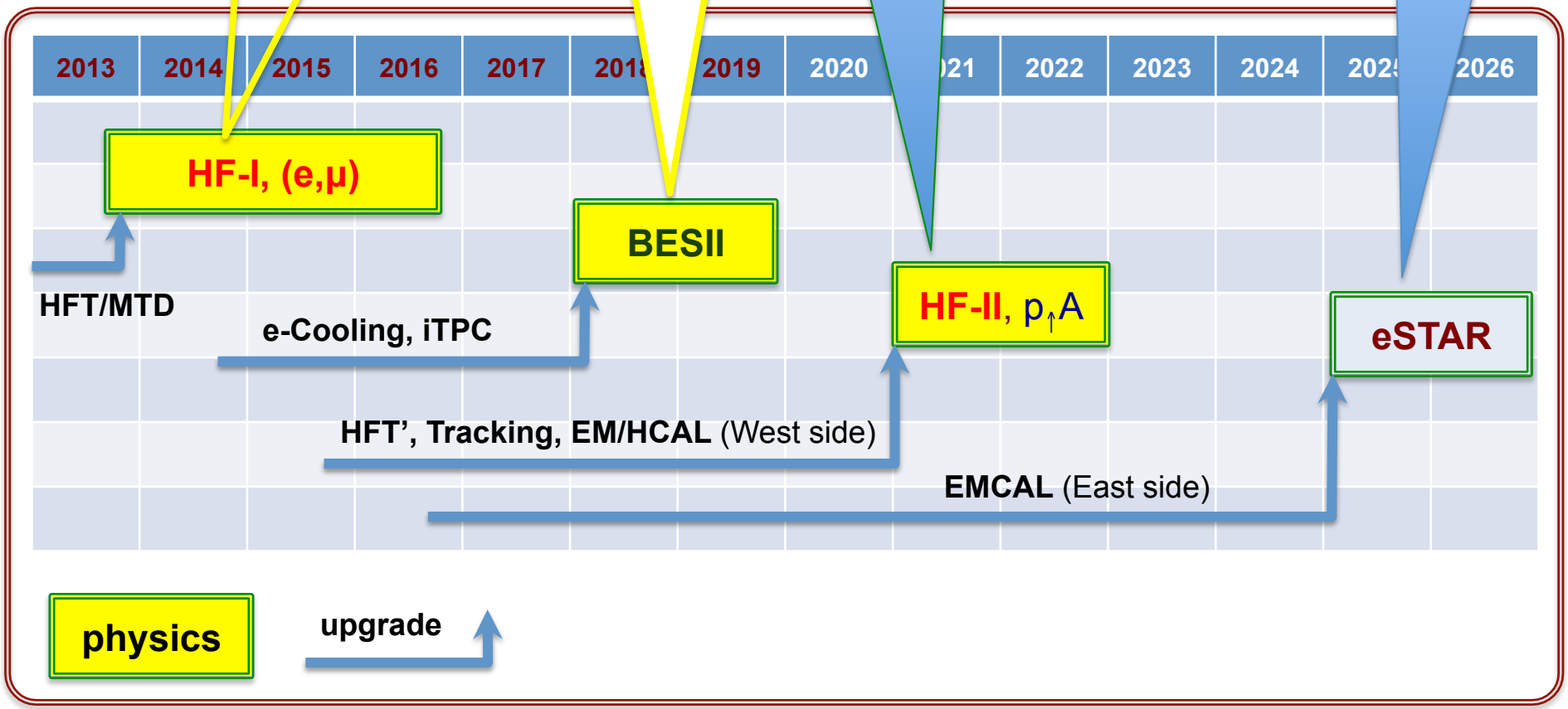
[hadronic] > μ_B ~ *320* (MeV) ($\sqrt{s_{NN}} \leq 11.5$ GeV)

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

STAR: Upgrade Plan

- HFT: Charm
- Di-lepton
sQGP properties

- QCD phase structure
- Critical Point

AA: HFT': B, Λ_c
Jet, γ-jet
pA: *CNM, p-spin*

Phase structure with dense gluon