STAR Results from RHIC Beam Energy Scan-I

Nu Xu[1,2]

Outline:

1) STAR Physics Program and Detector System
2) Selected Results from RHIC BES-I
3) Near Future Physics Program

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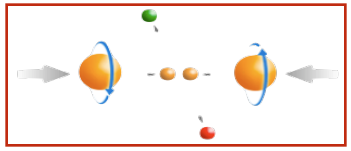
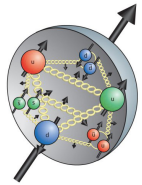
[2] *Nuclear Science Division, Lawrence Berkeley National Laboratory, USA*

STAR Collaboration

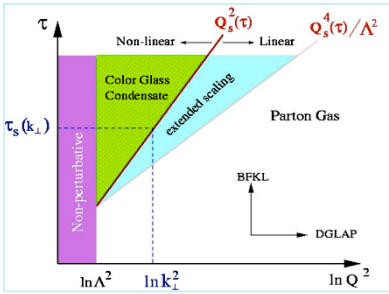
STAR Physics Focus





Polarized *p+p* Program

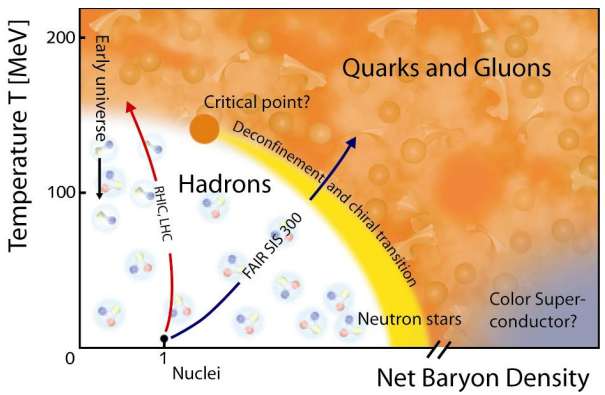
- ***proton intrinsic properties***



Small-x Physics Program

- Low-x properties, initial condition, ***CGC***
- Elastic and inelastic processes in pp2pp

STAR ***Decadal Plan*** + *2020 -* **eRHIC** (eSTAR)



1) At 200 GeV at RHIC

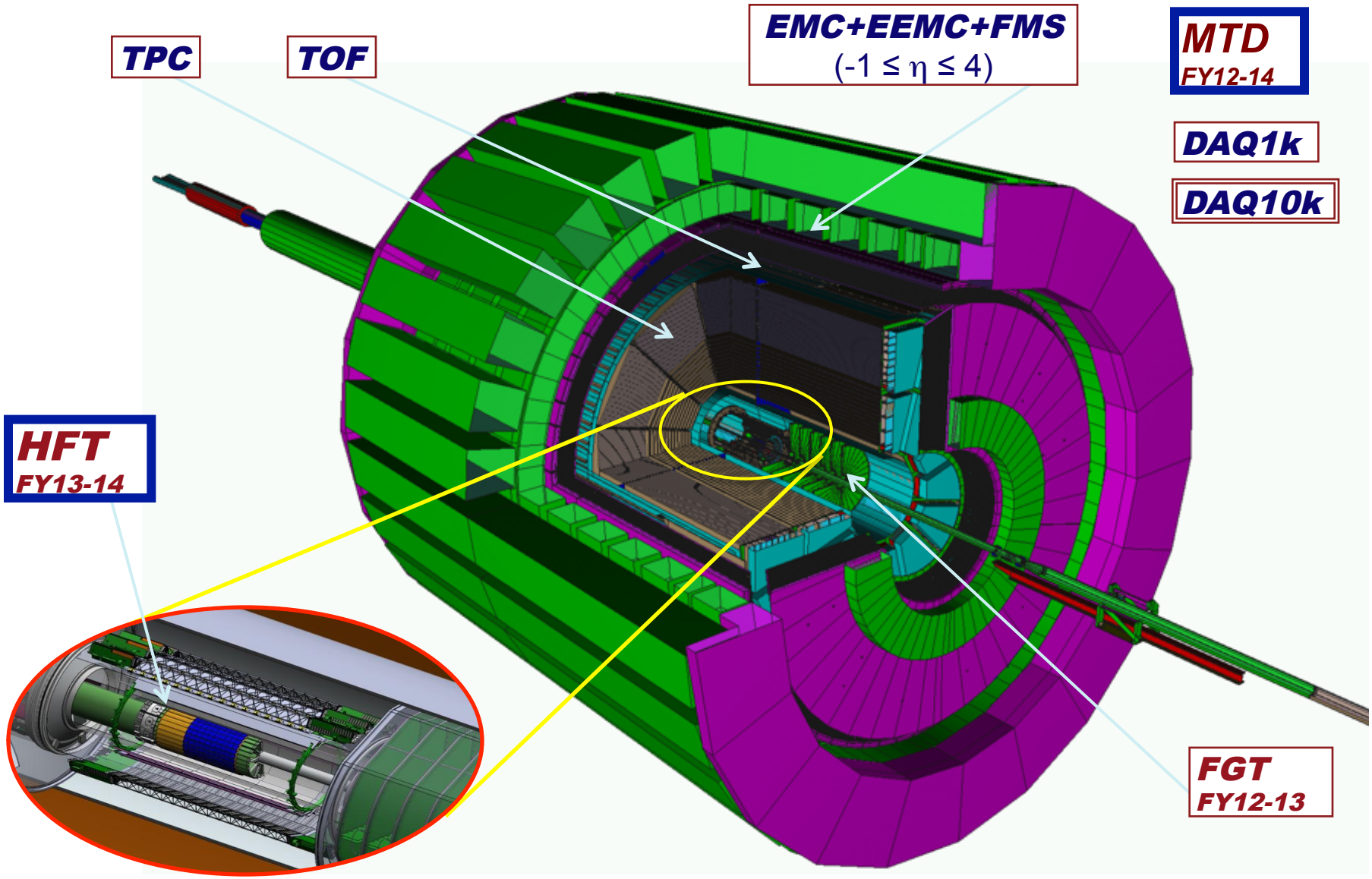
- ***Deconfinement**** & *medium properties, EoS*
- pQCD in hot and dense medium

2) RHIC Beam Energy Scan (BES-I)

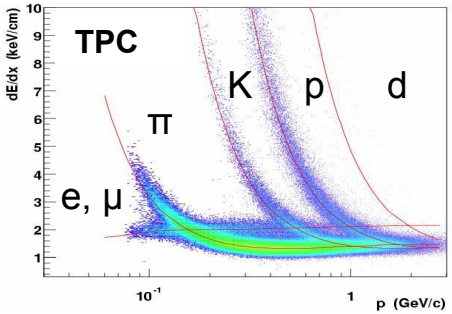
- ***QCD phase structure*:*** phase boundary & critical point
- ***Chiral symmetry restoration****

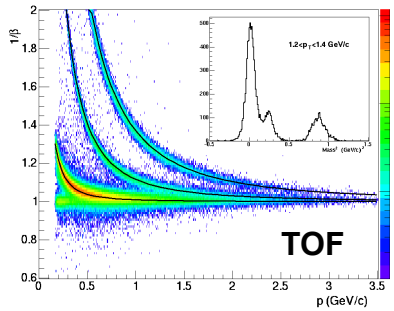
* Holy Grail for the physics of high-energy nuclear collisions

STAR Detectors *Fast and Full azimuthal particle identification*

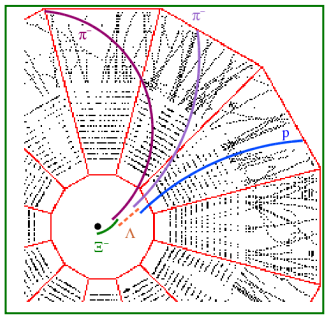


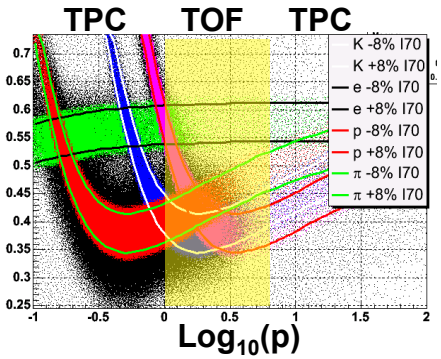
Particle Identification at STAR



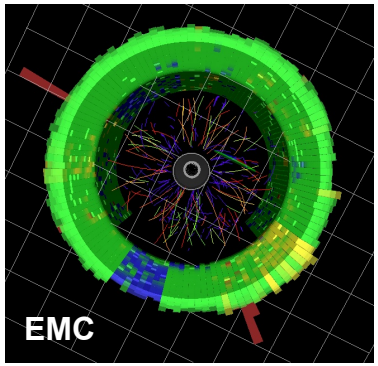


Charged hadrons

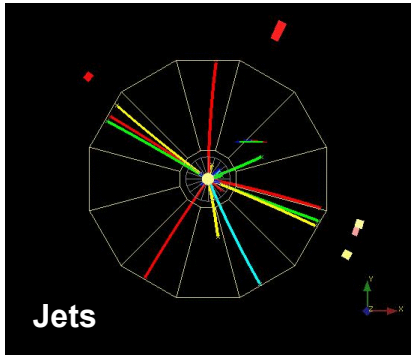




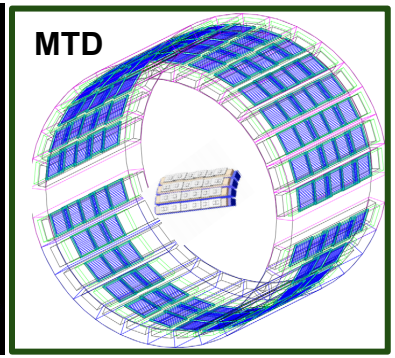
Hyperons & Hyper-nuclei



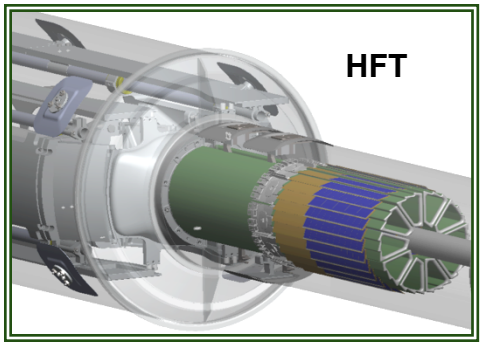
Neutral particles



Jets & Correlations



High p_T muons



Heavy-flavor hadrons

Multiple-fold correlations among 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**

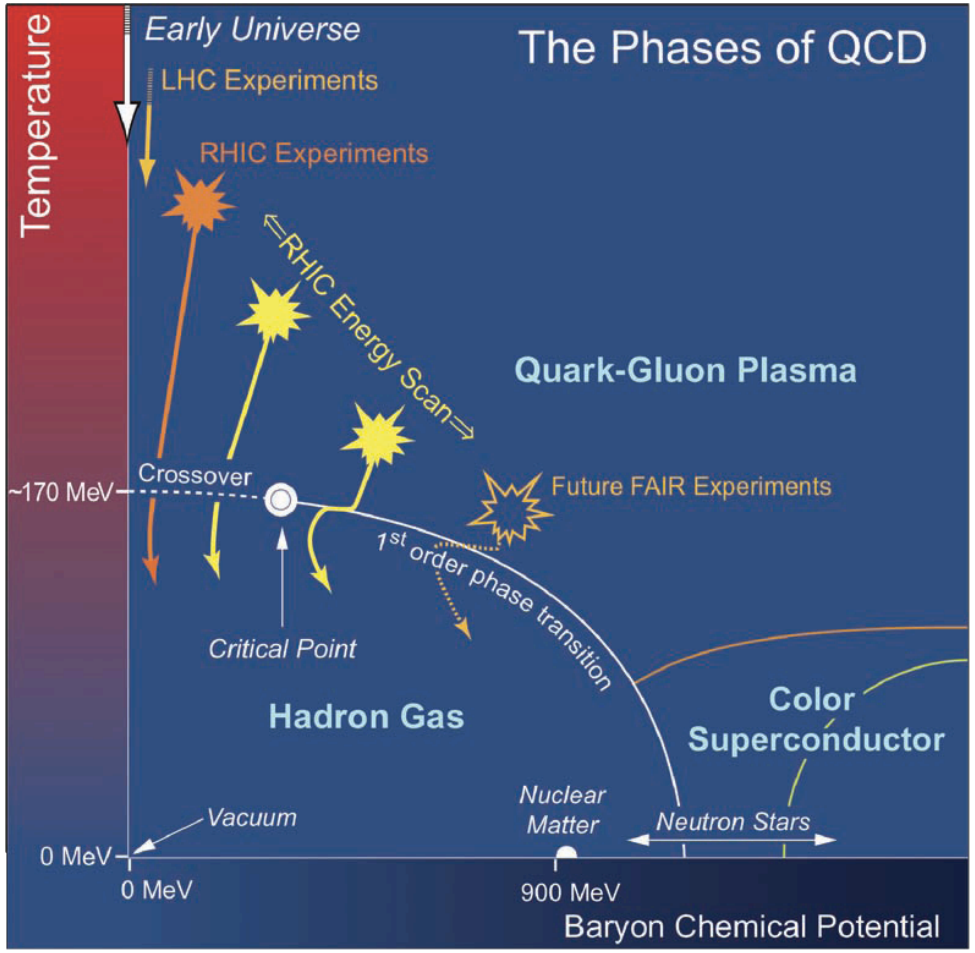
- detects nearly all particles produced at RHIC
- multiple fold correlation measurements
- **Probes: bulk, penetrating, and *bulk-penetrating***

➔ **STAR: Perfect Mid-y Collider Experiment**

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

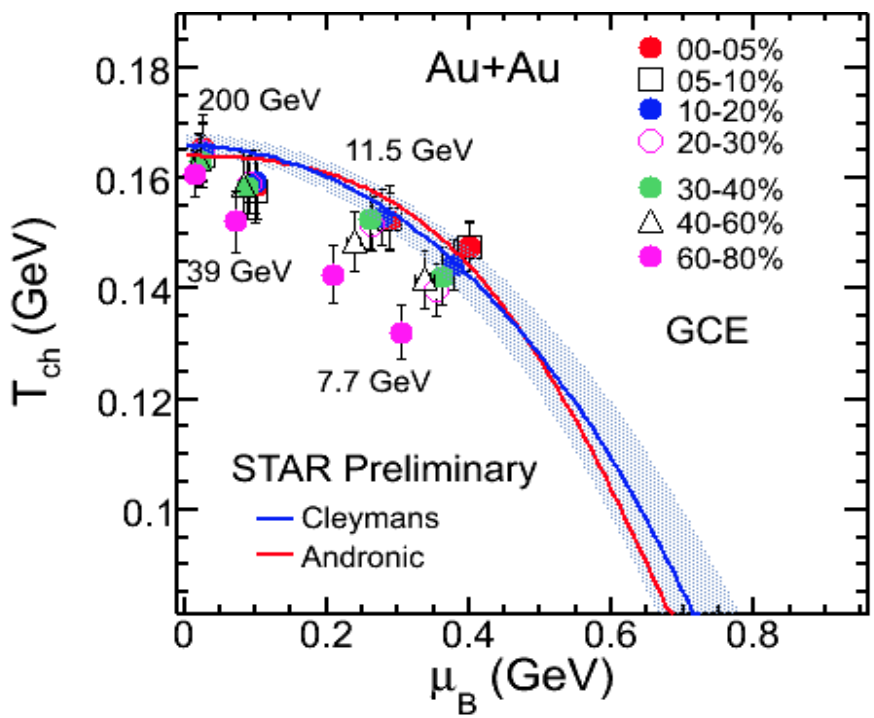
(4) v_2 - NCQ scaling
partonic vs. hadronic dof

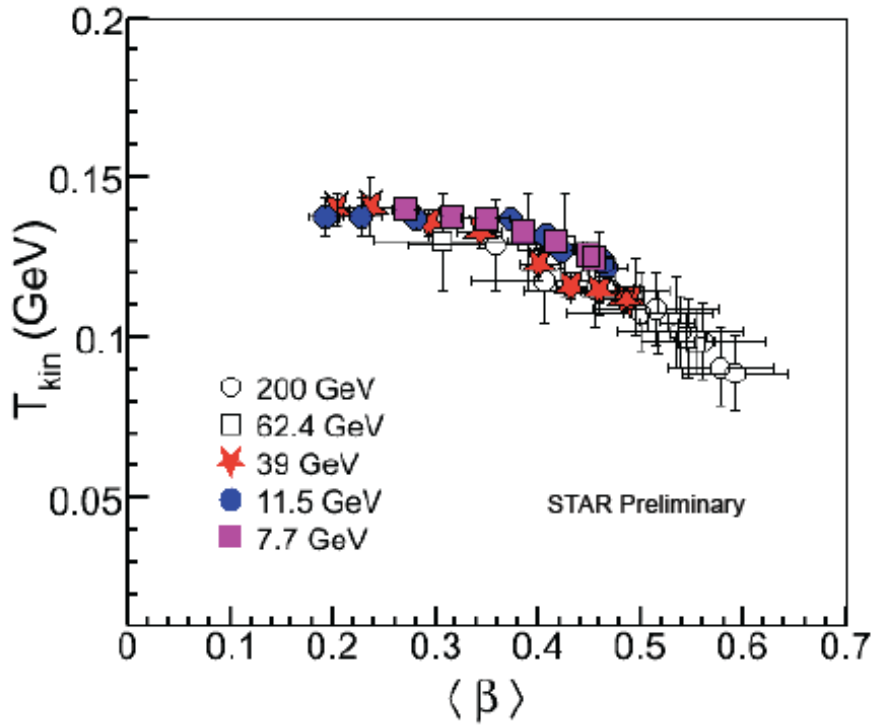
(5) Fluctuations
Critical point, correl. length

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

- arXiv:1007.2613

(1) Bulk Properties at Freeze-out





Chemical Freeze-out: (GCE)

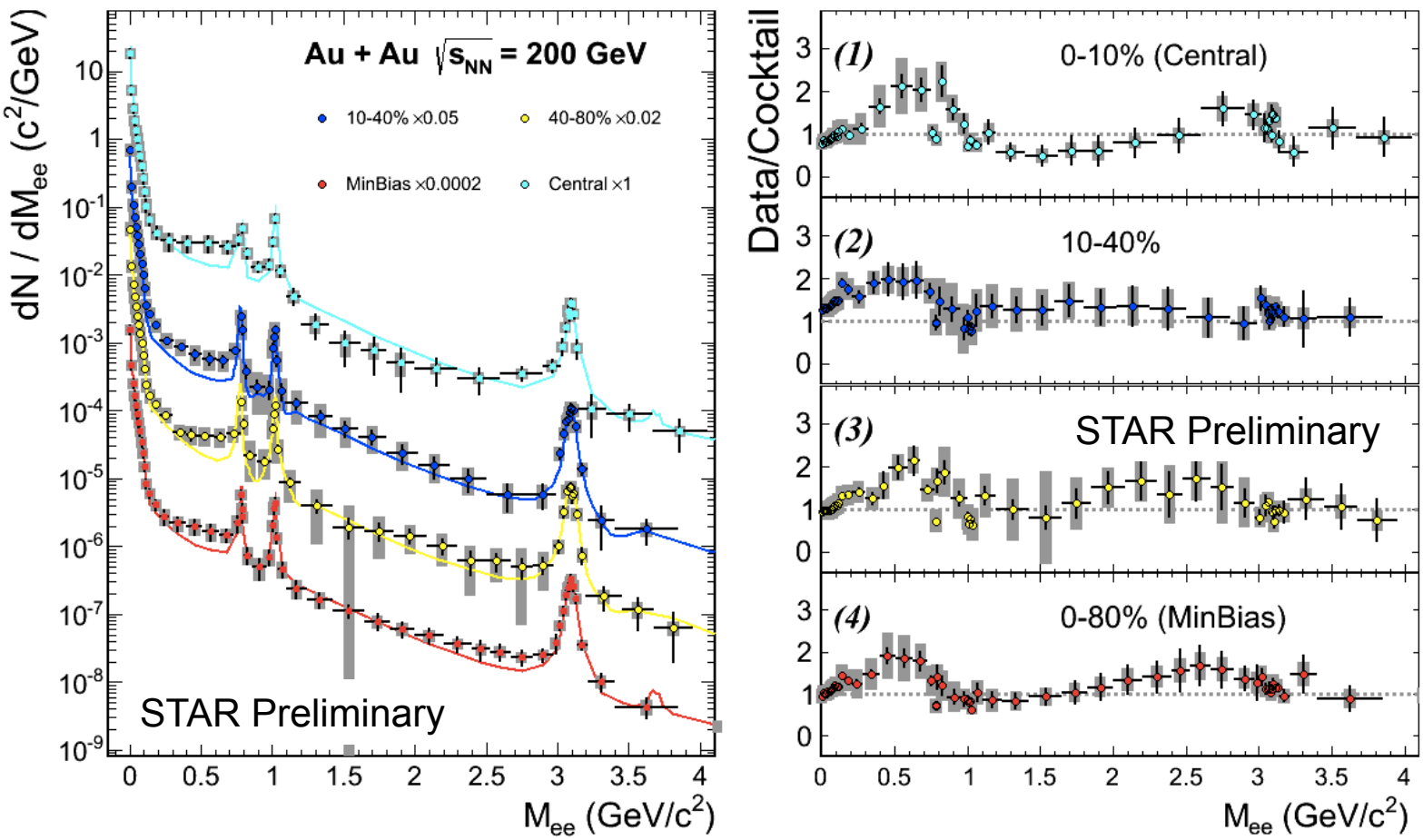
- Central collisions => higher values of T_{ch} and μ_B!
- The effect is stronger at lower energy.

Kinetic Freeze-out:

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

STAR: S. Das, L. Kumar, QM2012

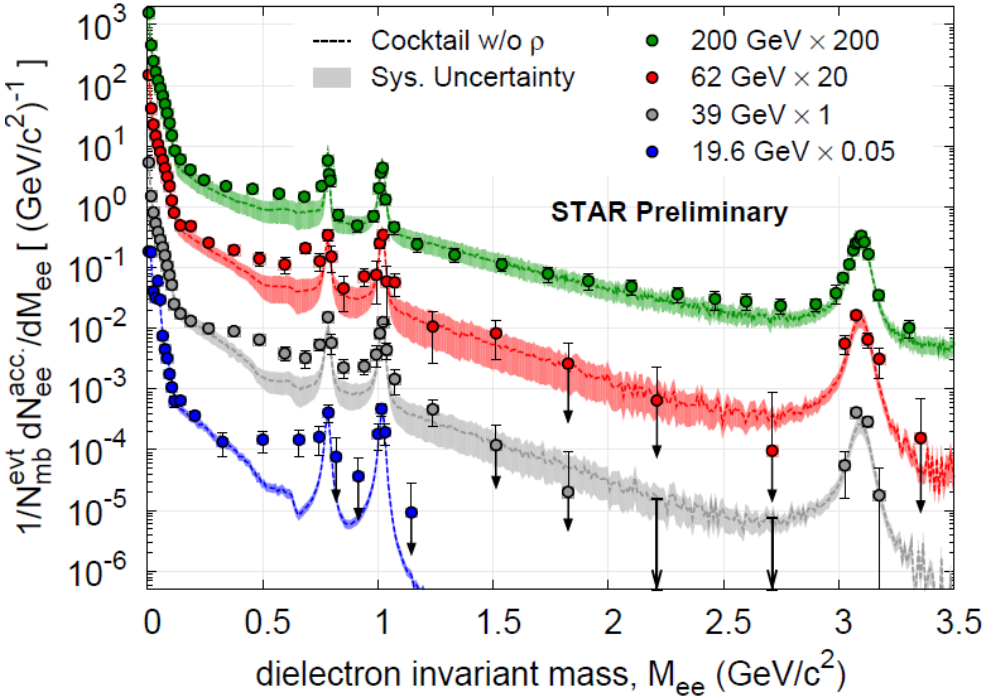
(2) Di-lepton Program at STAR

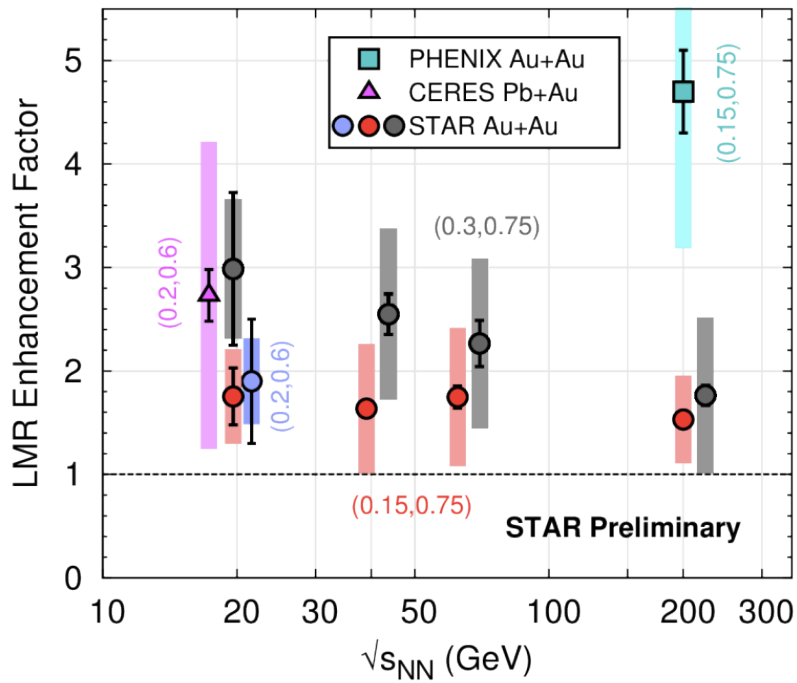


1) Large acceptance TPC & TOF => electron measurements
2) At $\sqrt{s_{NN}}$ = 200 GeV, LMR enhancement is flat vs. centrality
3) Future HFT/MTD upgrades: extract info on direct radiations

STAR: B.C. Huang, QM2012

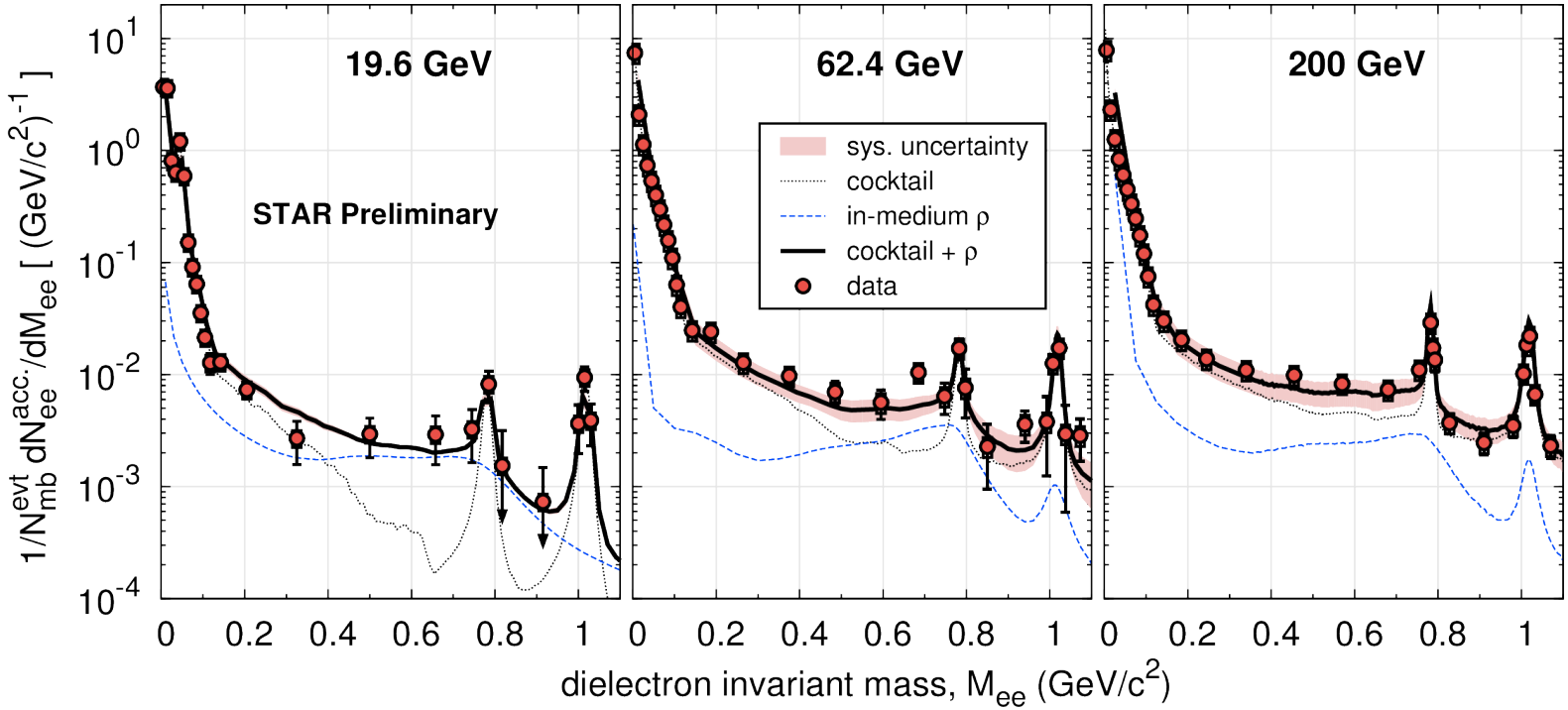
Di-electrons: $\sqrt{s_{NN}}$ Dependence





1) LMR enhancement is flat vs. collision energy at STAR
2) Future Heavy Flavor Tracker and Muon Telescope Detector upgrades:
   - correlated charm contributions
   - extract direct radiation information

Di-electrons: Model Comparison

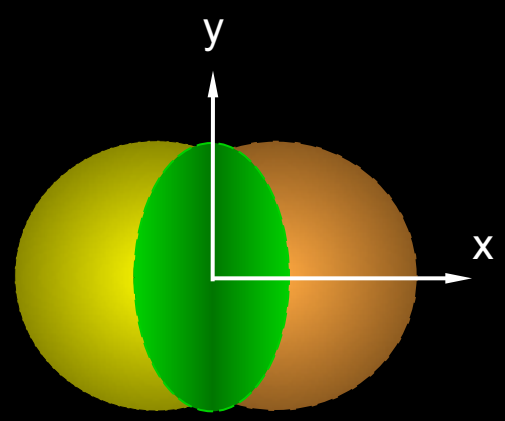


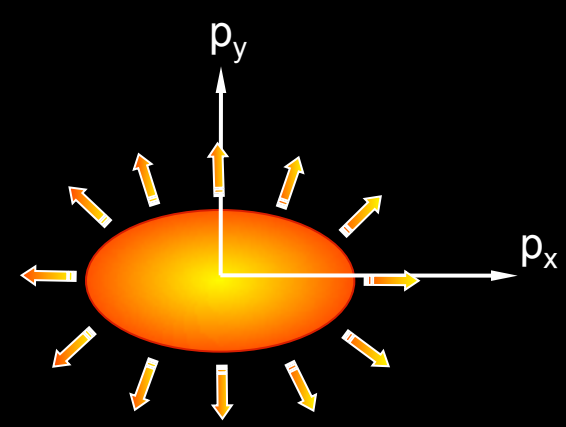
1) With in-medium broadened rho, model results are consistent experimental data ($m_{ee} \leq 1$ GeV/c^2) at $\sqrt{s_{NN}}$ = 200, 62.4 and 19.6GeV

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

Anisotropy Parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy

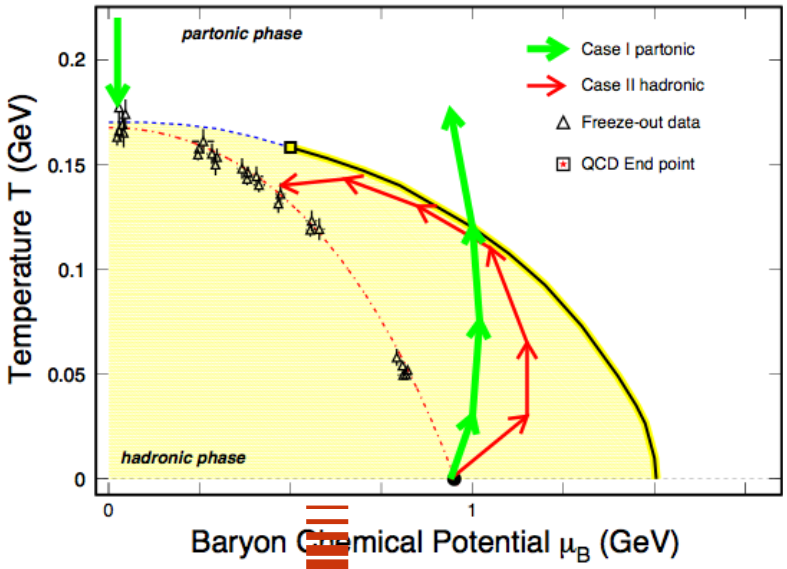


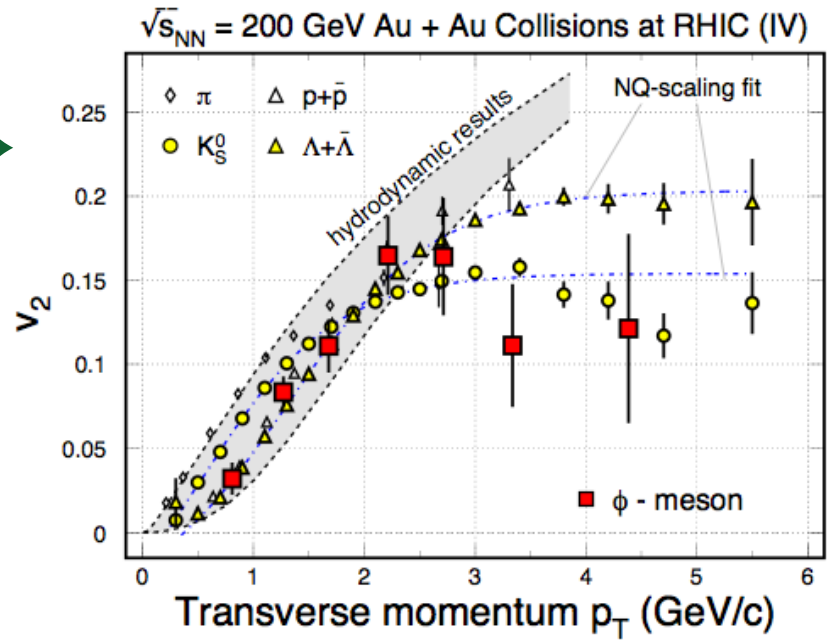


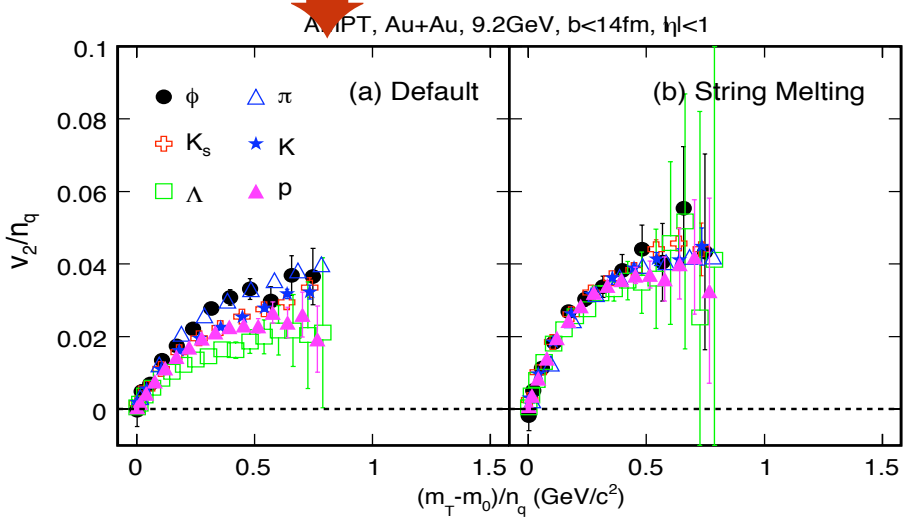
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \;\; \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

(3) NCQ Scaling in v_2





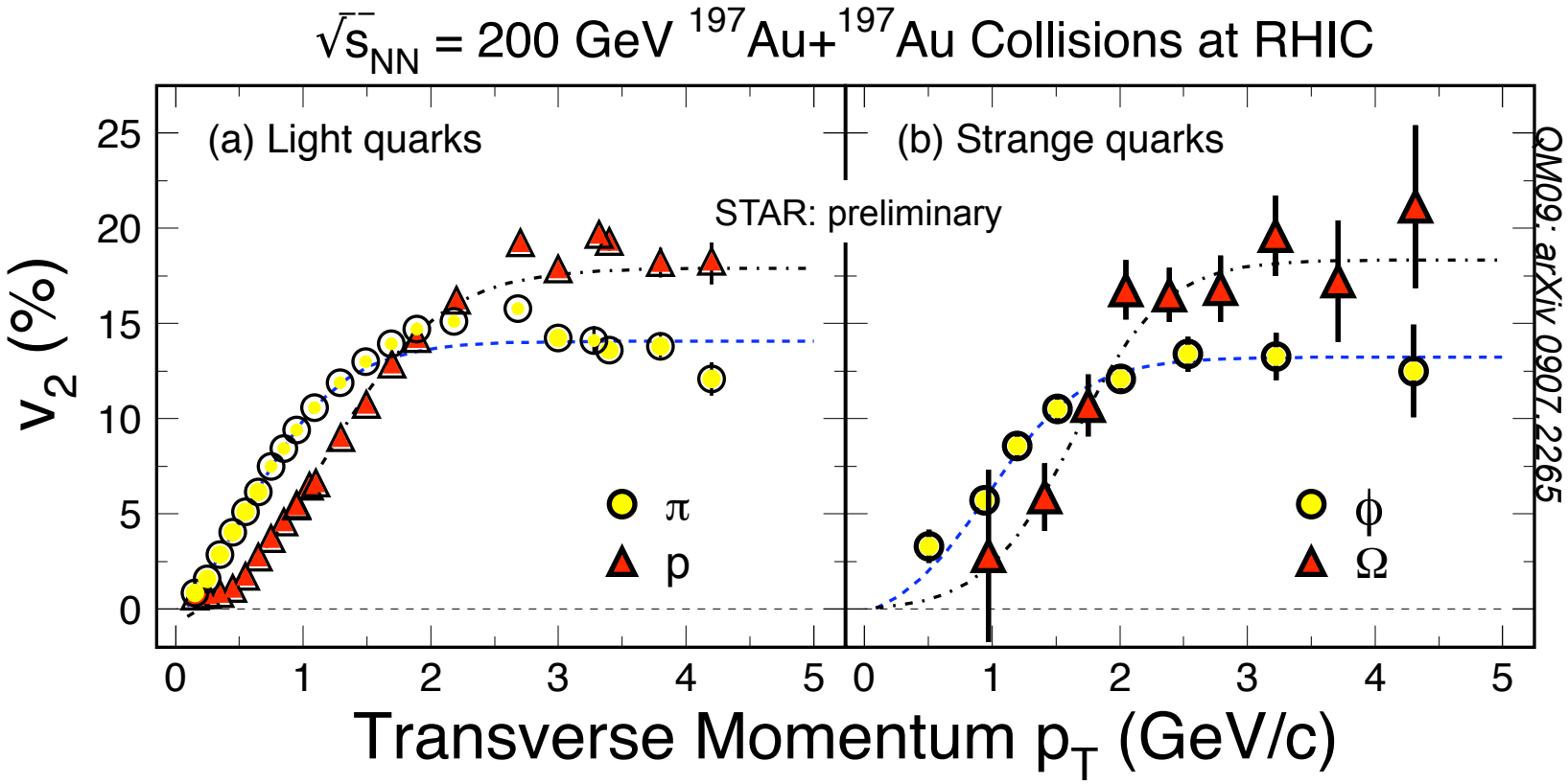


- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi,\ \pi\pi}$

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

*** Thermalization is assumed!**

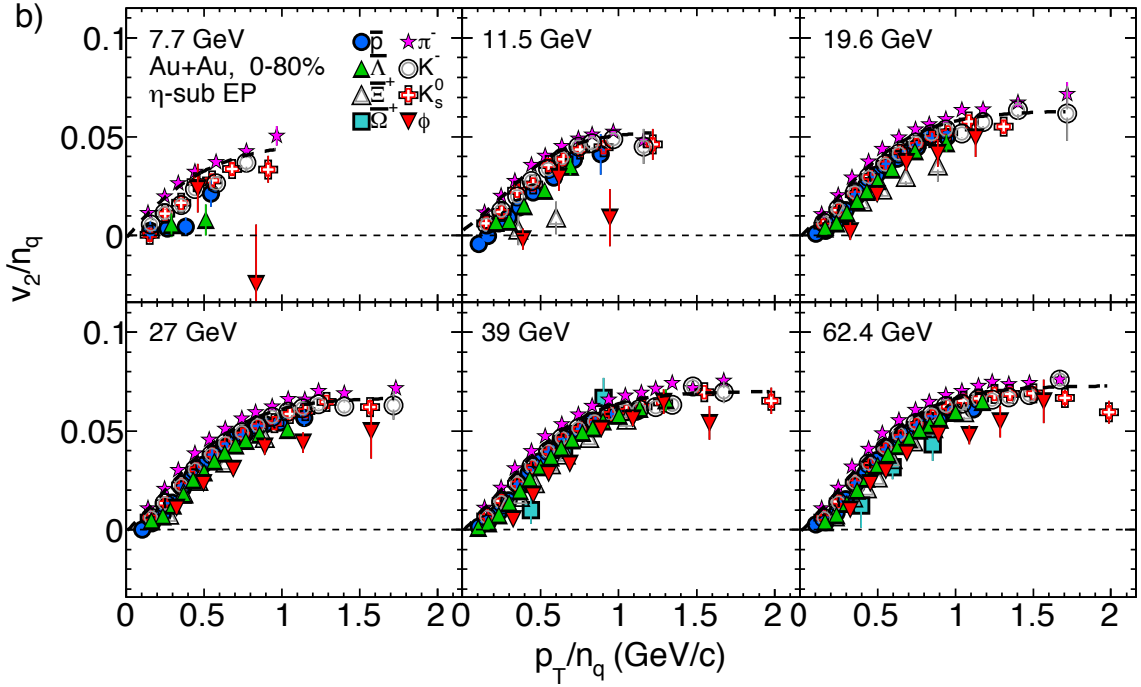
Partonic Collectivity at RHIC

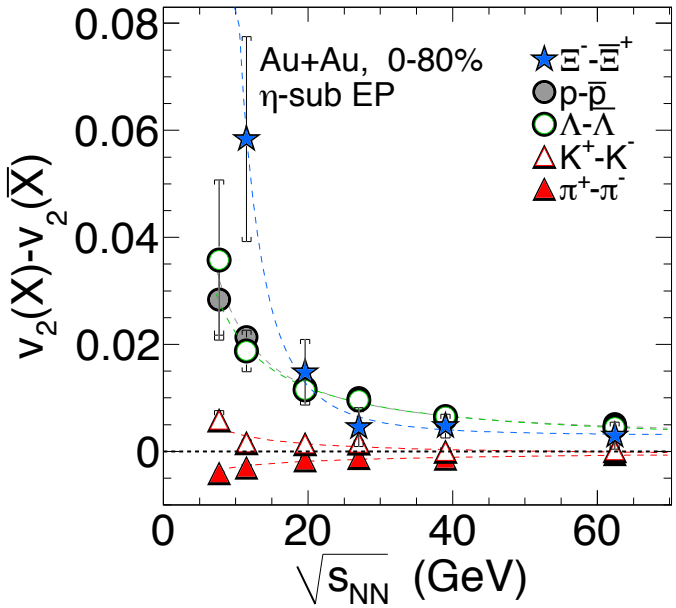


Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks scaling***

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

Collectivity v_2 Measurements



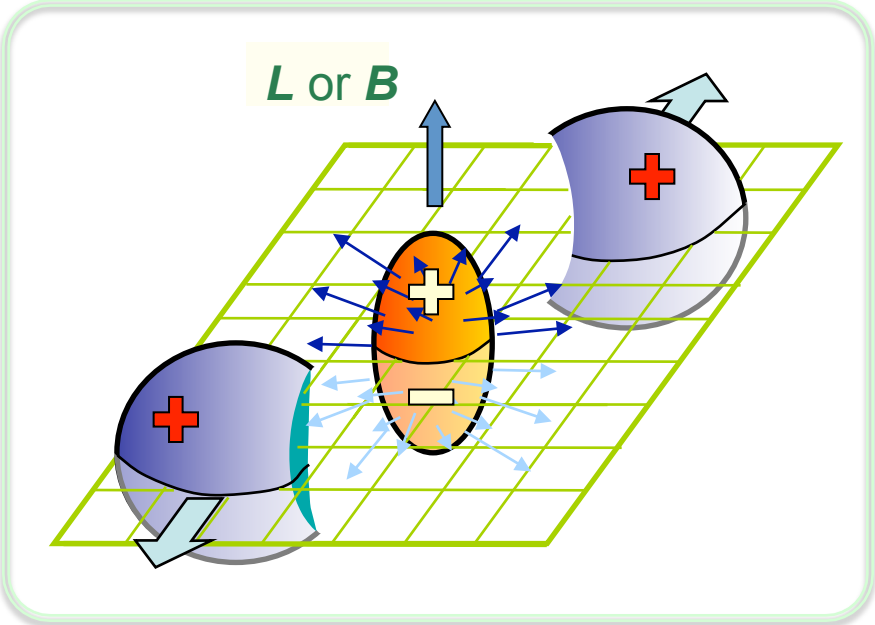


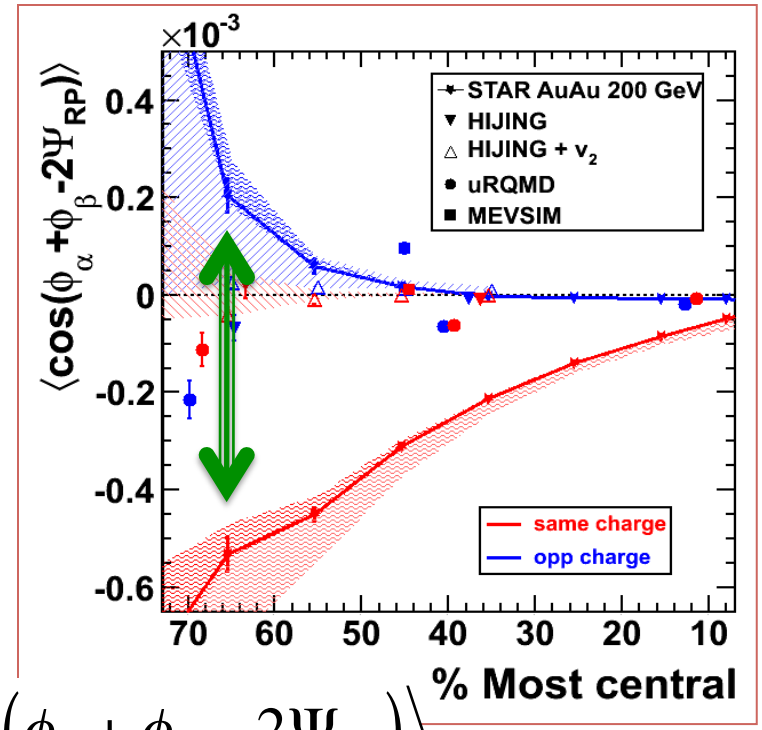
1) Systematic measurements of collectivities

2) Number of quark scaling is broken. Hadronic interactions become dominant, especially for $\sqrt{s_{NN}} < 11.5$ GeV

STAR: S.S. Shi, QM2012

(4) Search for Local Parity Violation in High Energy Nuclear Collisions





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

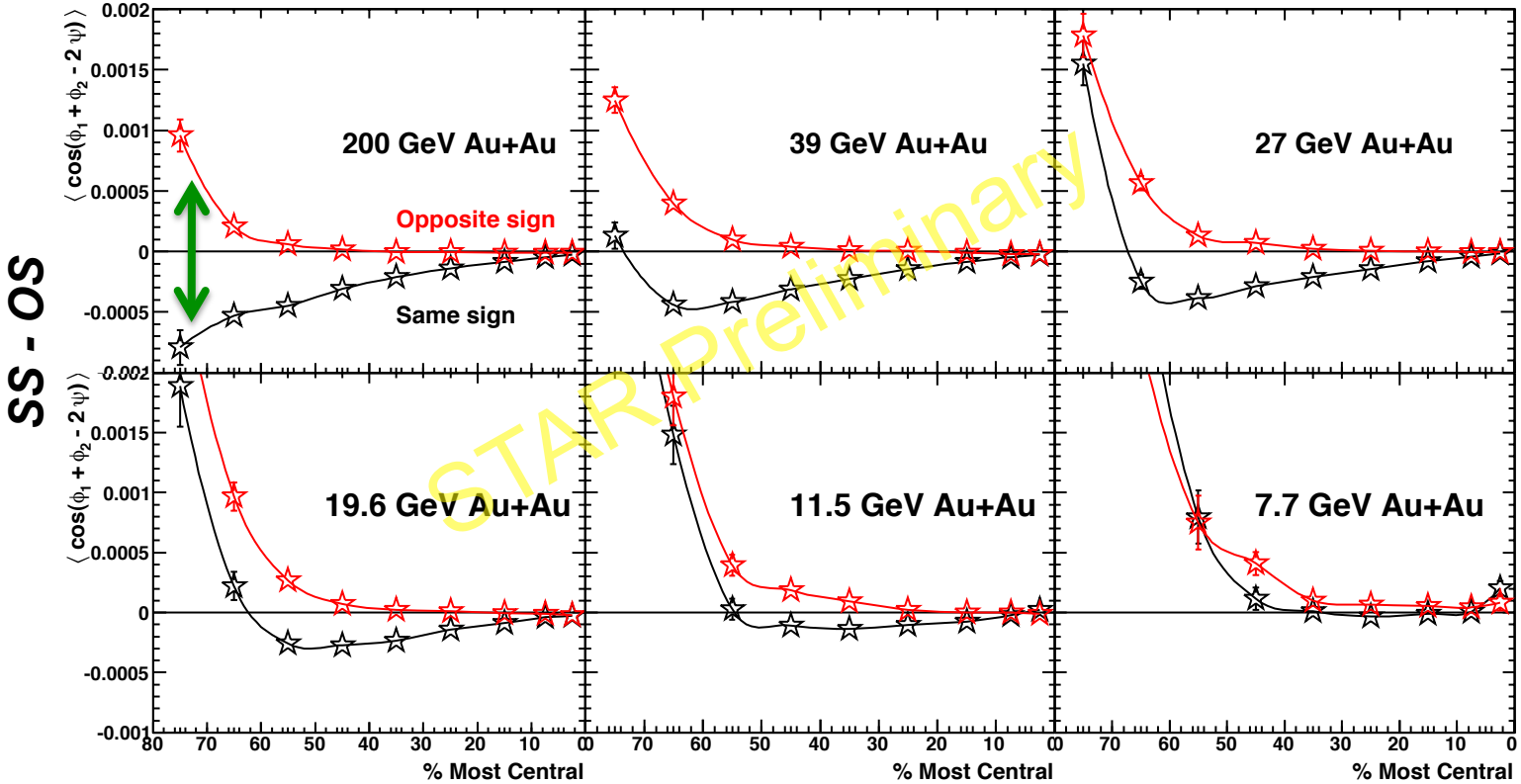
1) Parity-even observable, assumptions must be tested
2) Energy dependence & UU collisions

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

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

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

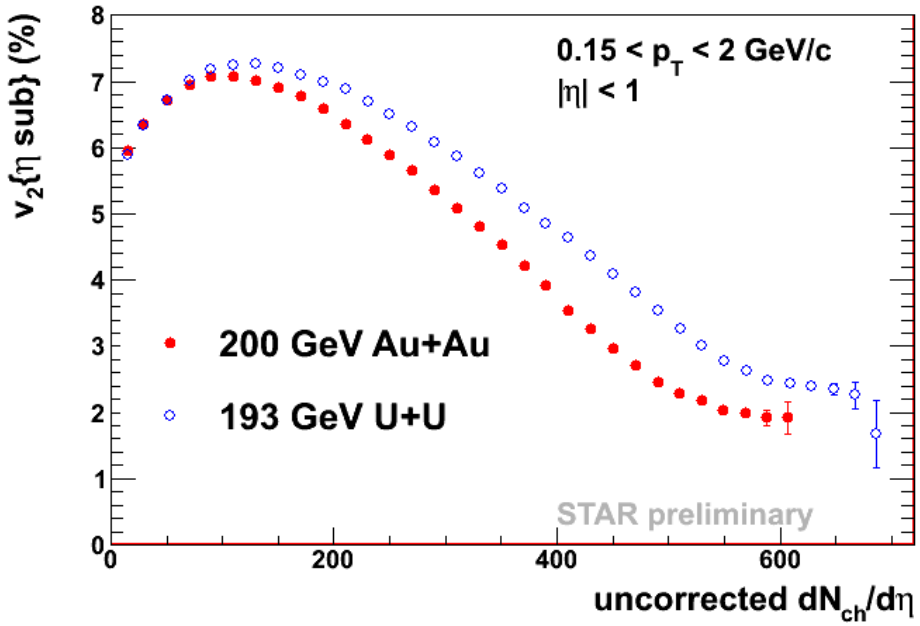
Dynamical Correlations

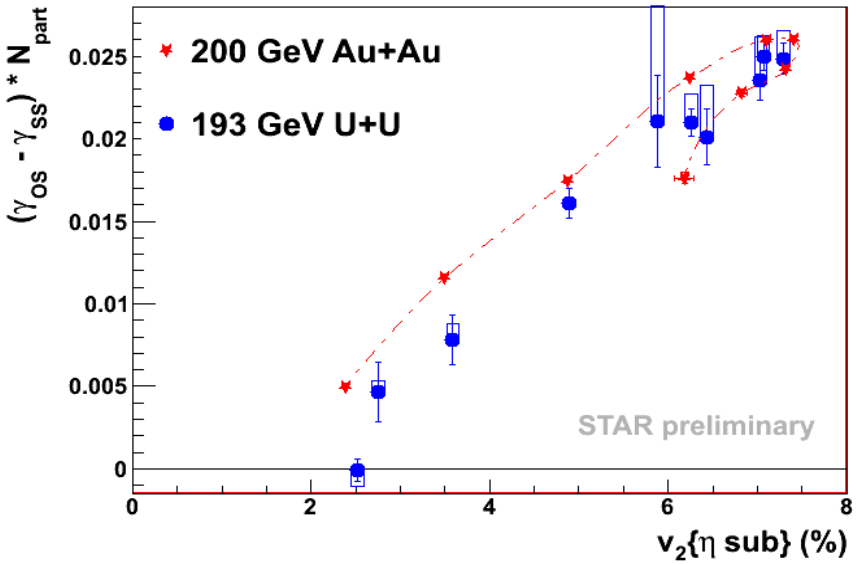


(1) Below $\sqrt{s_{NN}}$ = 11.5 GeV, the splitting between the same- and opposite-sign charge pairs (SS-OS) disappear

(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

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





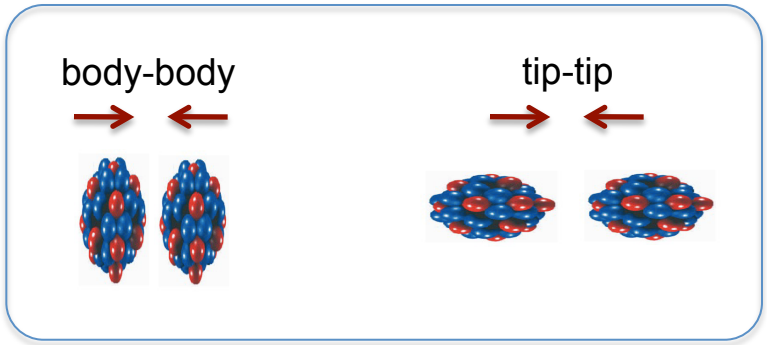
U+U Collisions:

(1) test CME with small external B-field

(2) test v_2 at 30% higher density

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

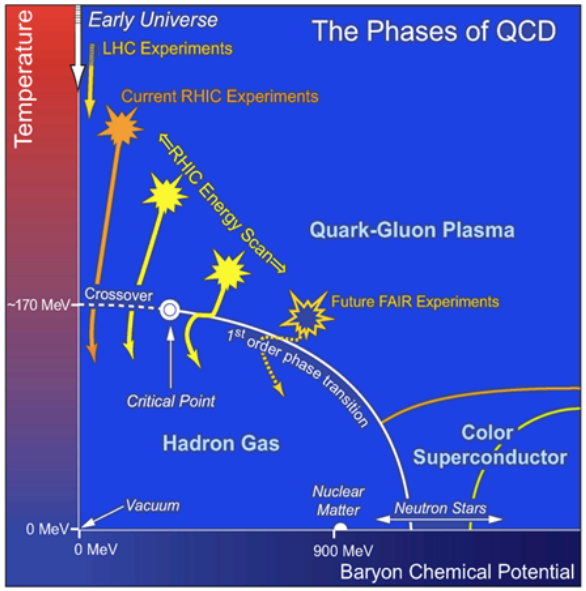
- STAR: G. Wang, QM2012

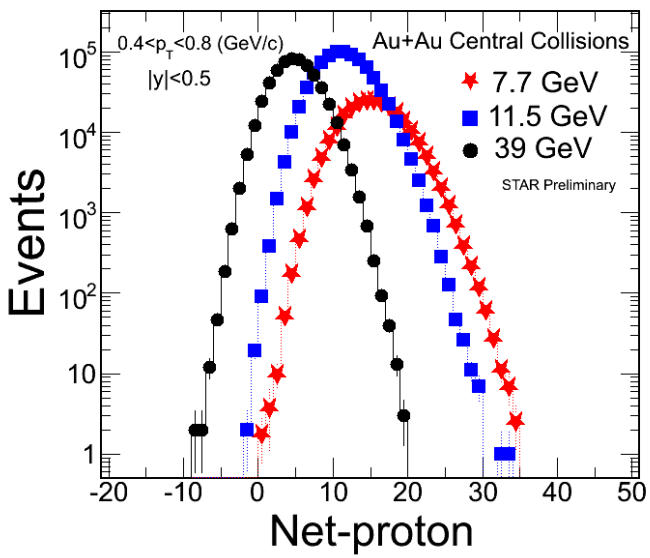


1) Comparing to Au+Au collisions, v_2 values are higher in U+U

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

(5) Net-protons Higher Moments





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

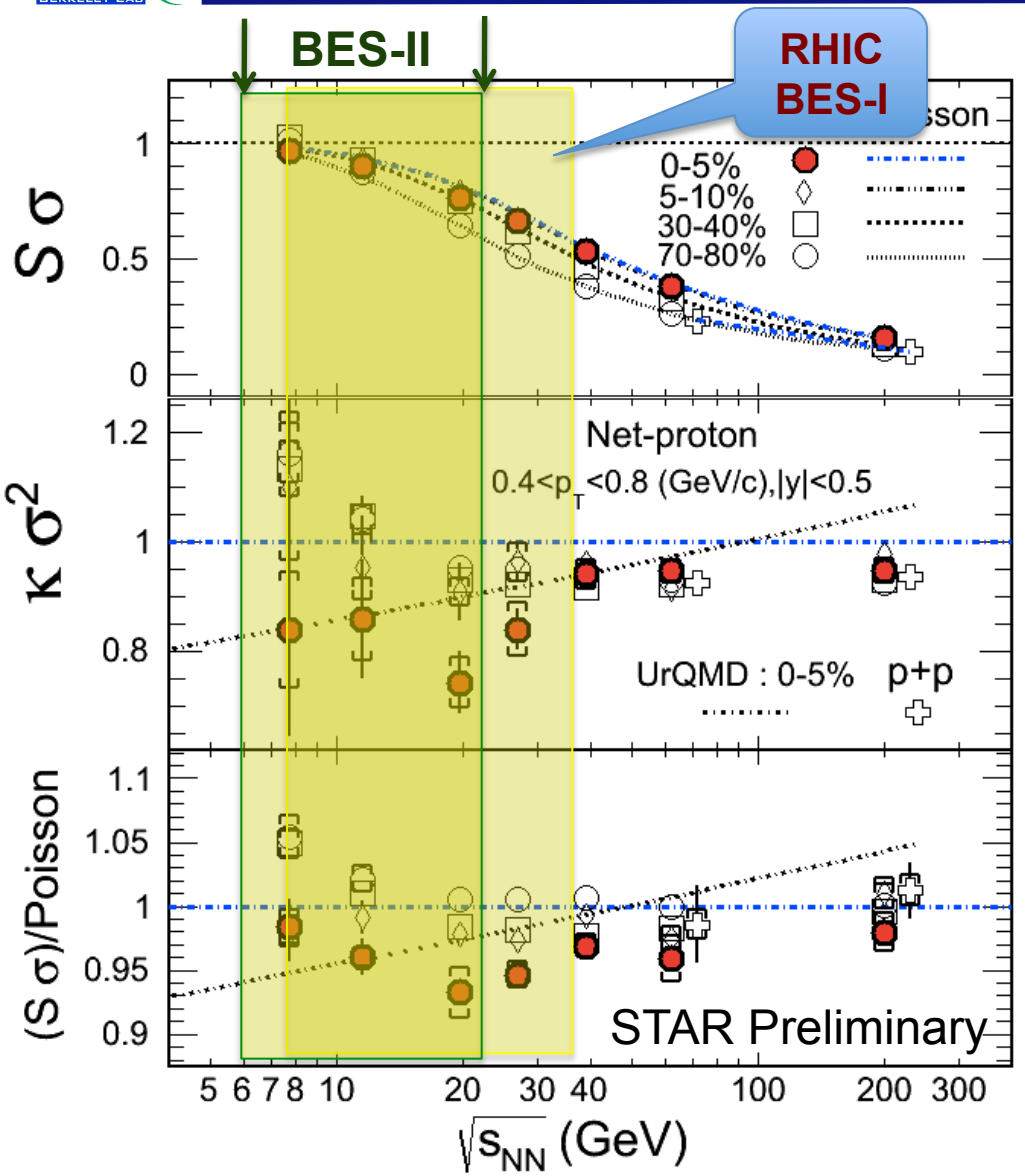
2) Sensitive to critical point (ξ correlation length):
$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \quad \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \quad \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with 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. Barvazov 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)

Net-proton Higher Moments



STAR net-proton results:

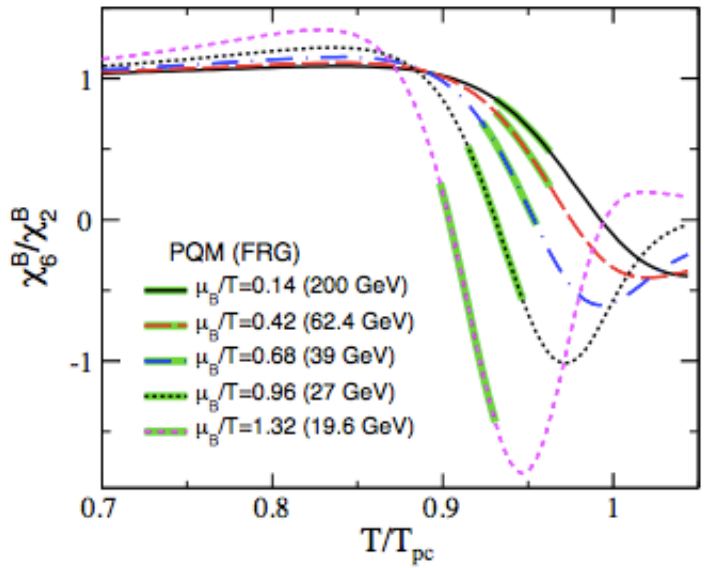
1) All data show deviations below Poisson beyond statistical and systematic errors in the 0-5% most central collisions for $\kappa\sigma^2$ and $S\sigma$ at all energies. Larger deviation at $\sqrt{s_{NN}} \sim 20$GeV.

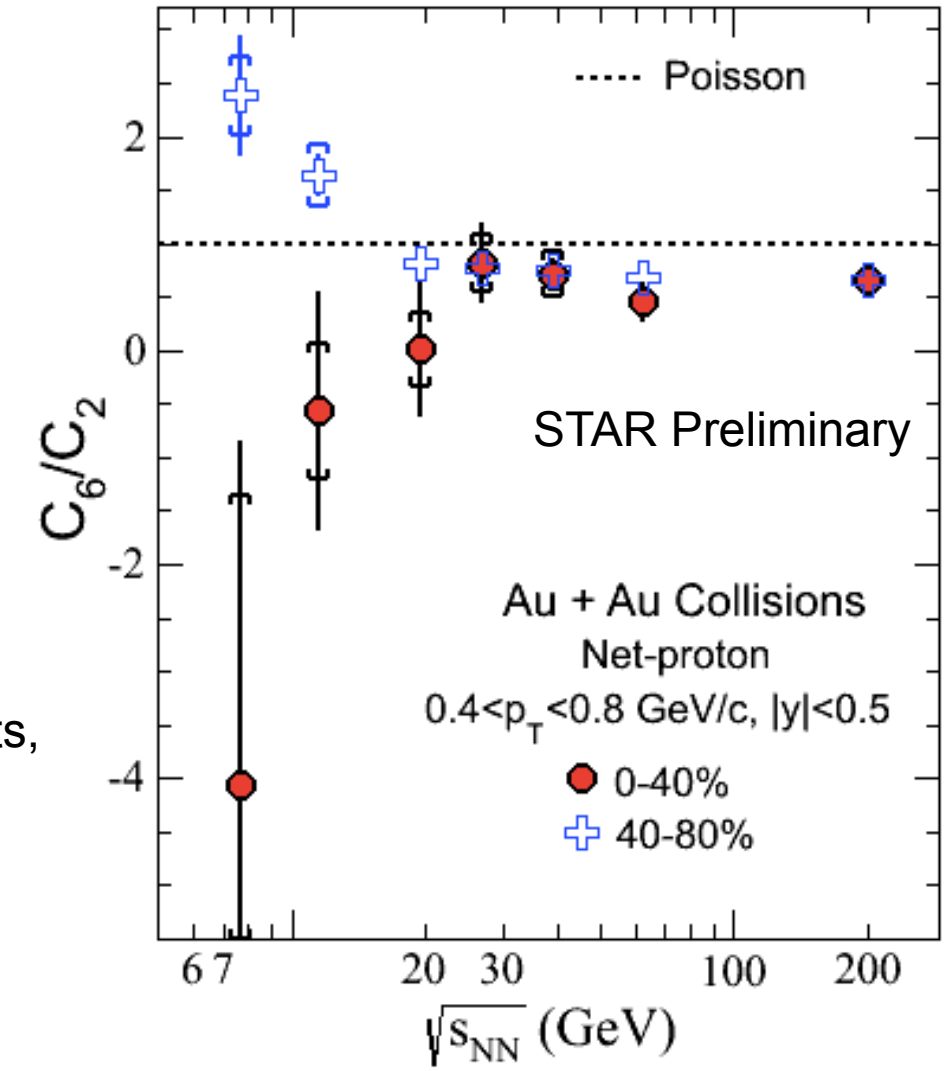
2) UrQMD model show monotonic behavior in the moment products.

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

- STAR: X.F. Luo, QM2012

Net-proton Higher Moments





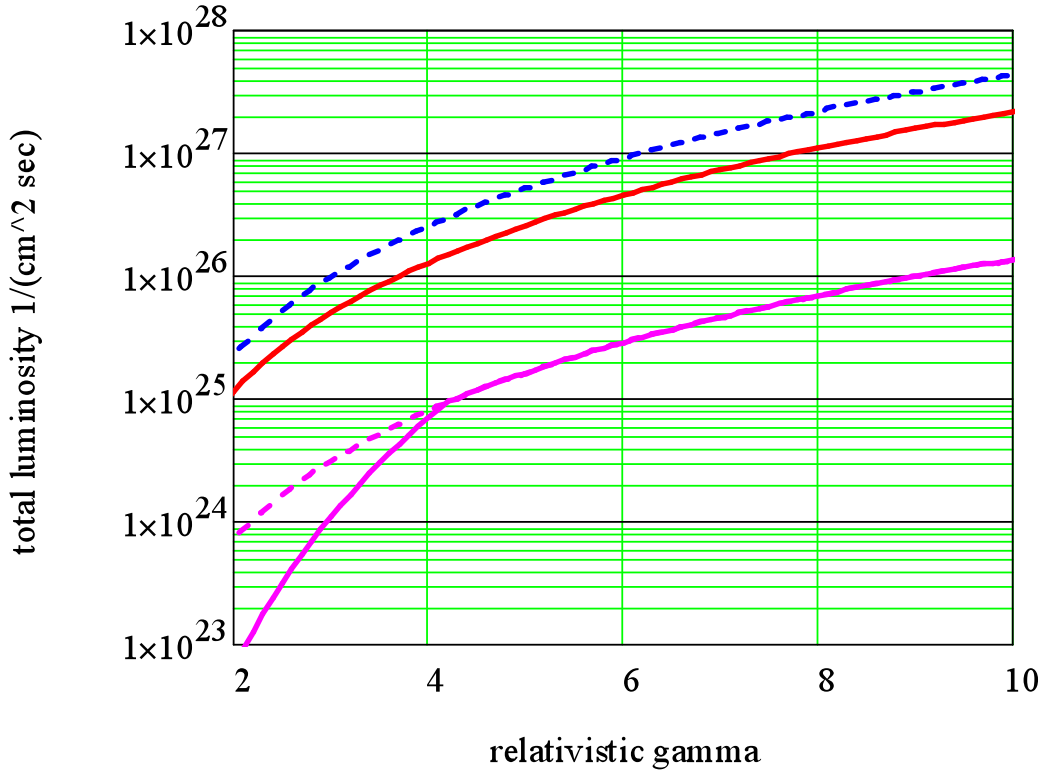
1) Higher sensitivity expected from higher order moments
2) STAR first net-proton C_6/C_2 results, wide centrality bins
3) More data needed especially for collisions below 20 GeV

- B. Friman, F. Karsch, K. Redlich, V. Sokokov, Eur. Phys. J. C71 1694(2011).
- STAR: L.Z. Chen, QM2012

e-cooling at RHIC for BES-II

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

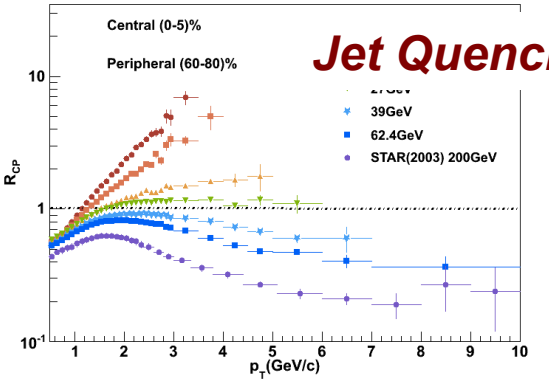
Fermi Lab Pelletron



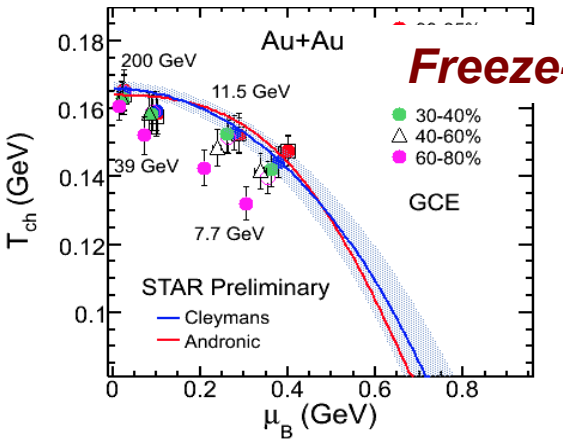
$\sqrt{s_{NN}}$ (GeV)	~ 5	~ 20
Increasing factor*	3-5	10

- Requested to install the e-cooling device in FY13
- BES-II data taking in 2015 - 2017

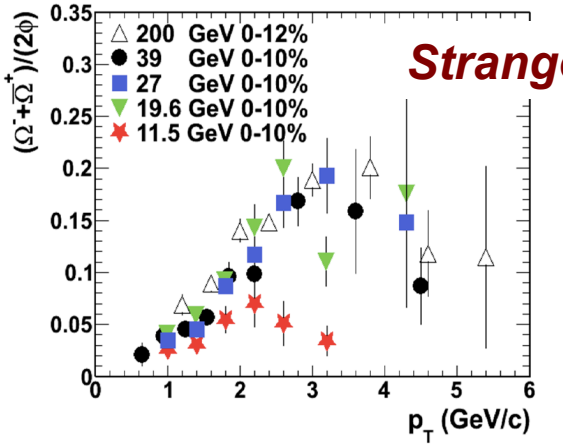
RHIC Beam Energy Scan-I



Jet Quenching



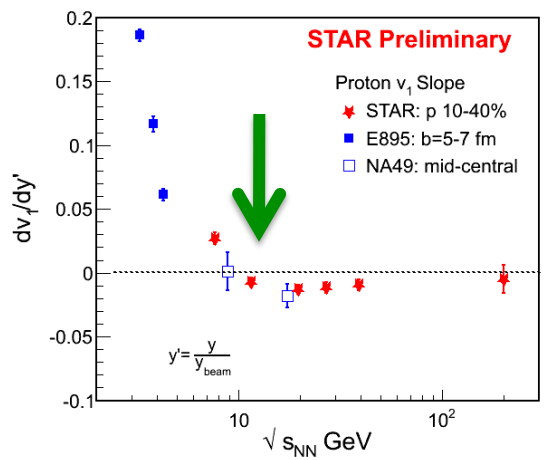
Freeze-out



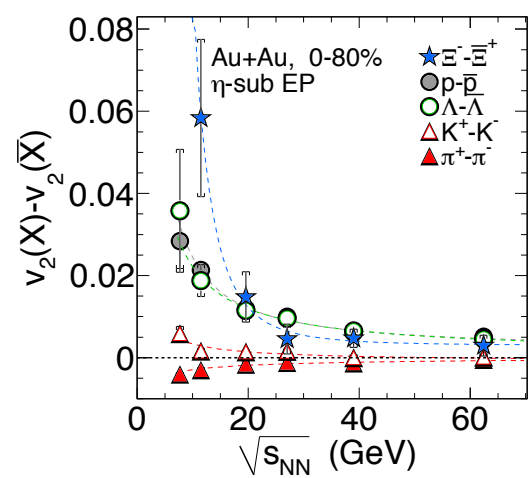
Strangeness

$\sqrt{s_{NN}}$ (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		

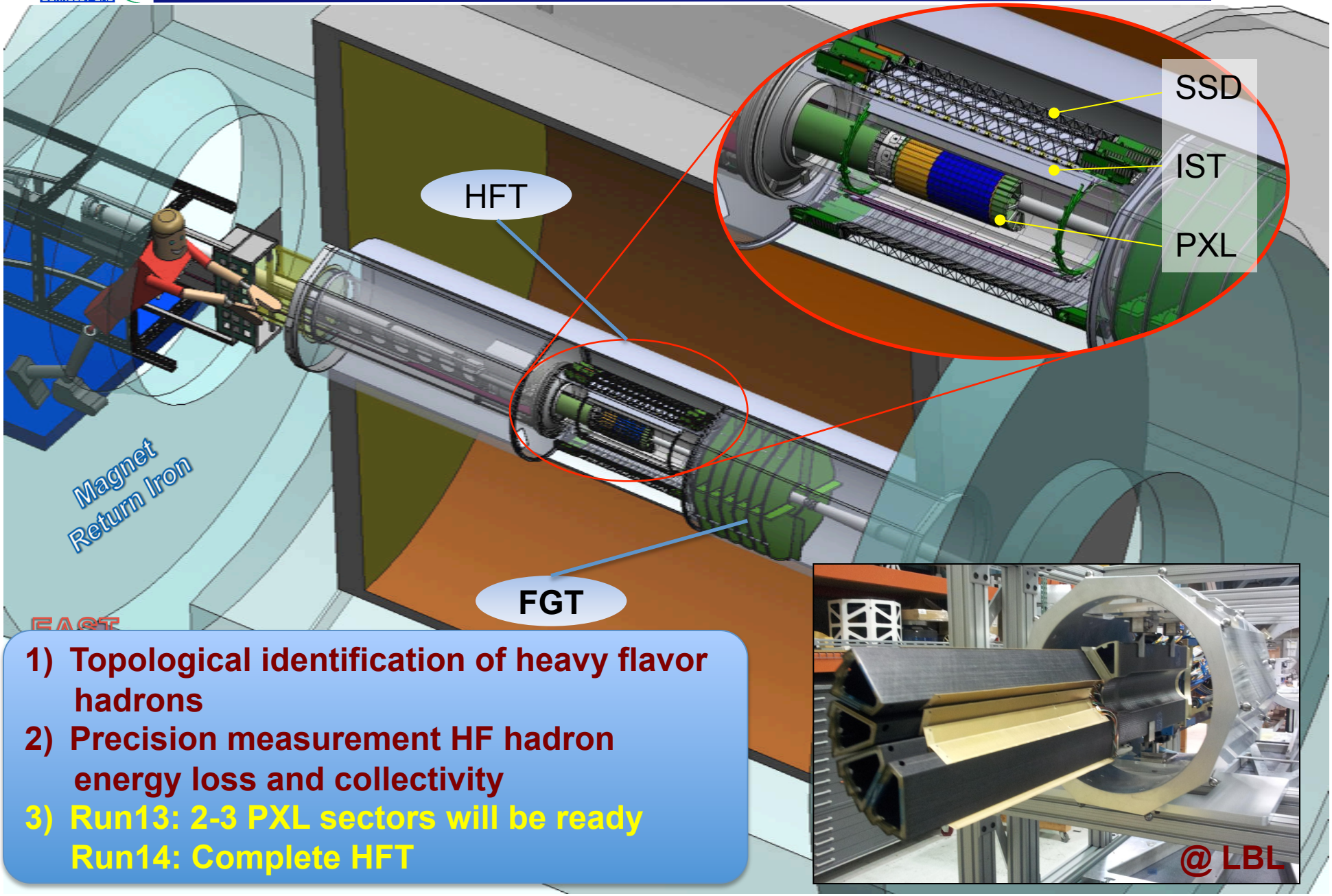
Directed Flow v_1



Elliptic Flow v_2

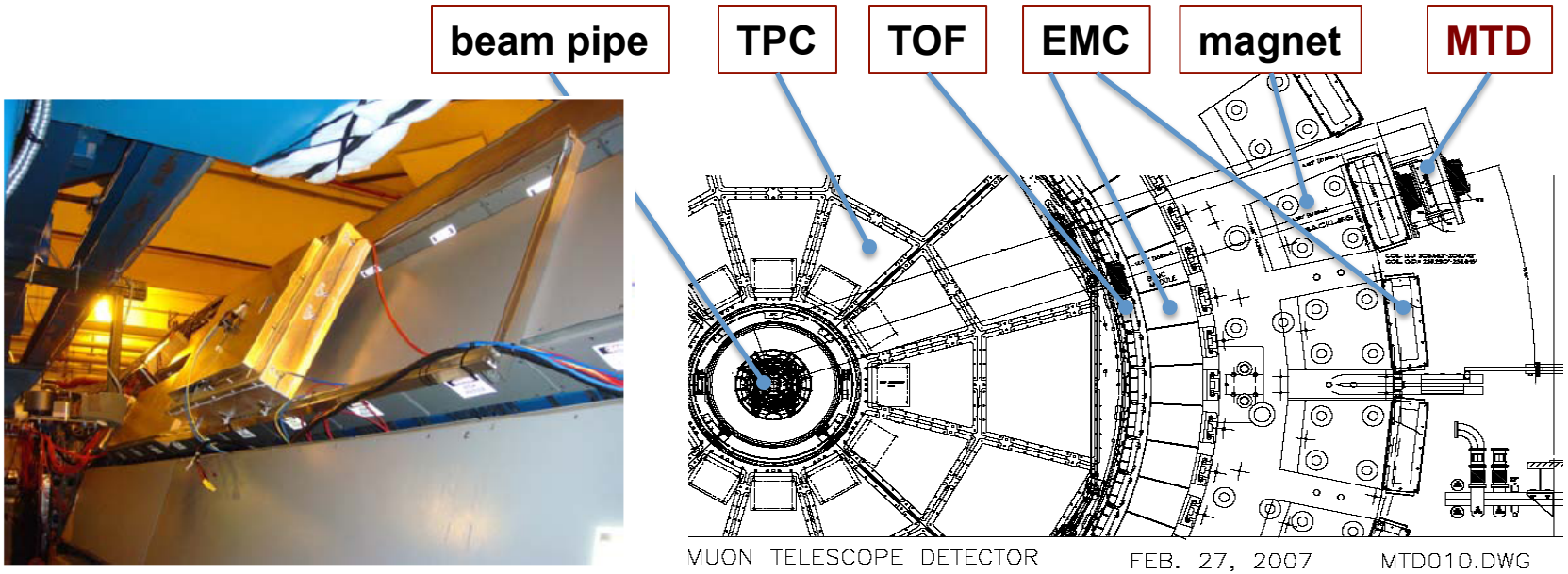


Heavy Flavor Tracker at STAR



1) Topological identification of heavy flavor hadrons
2) Precision measurement HF hadron energy loss and collectivity
3) Run13: 2-3 PXL sectors will be ready
   Run14: Complete HFT

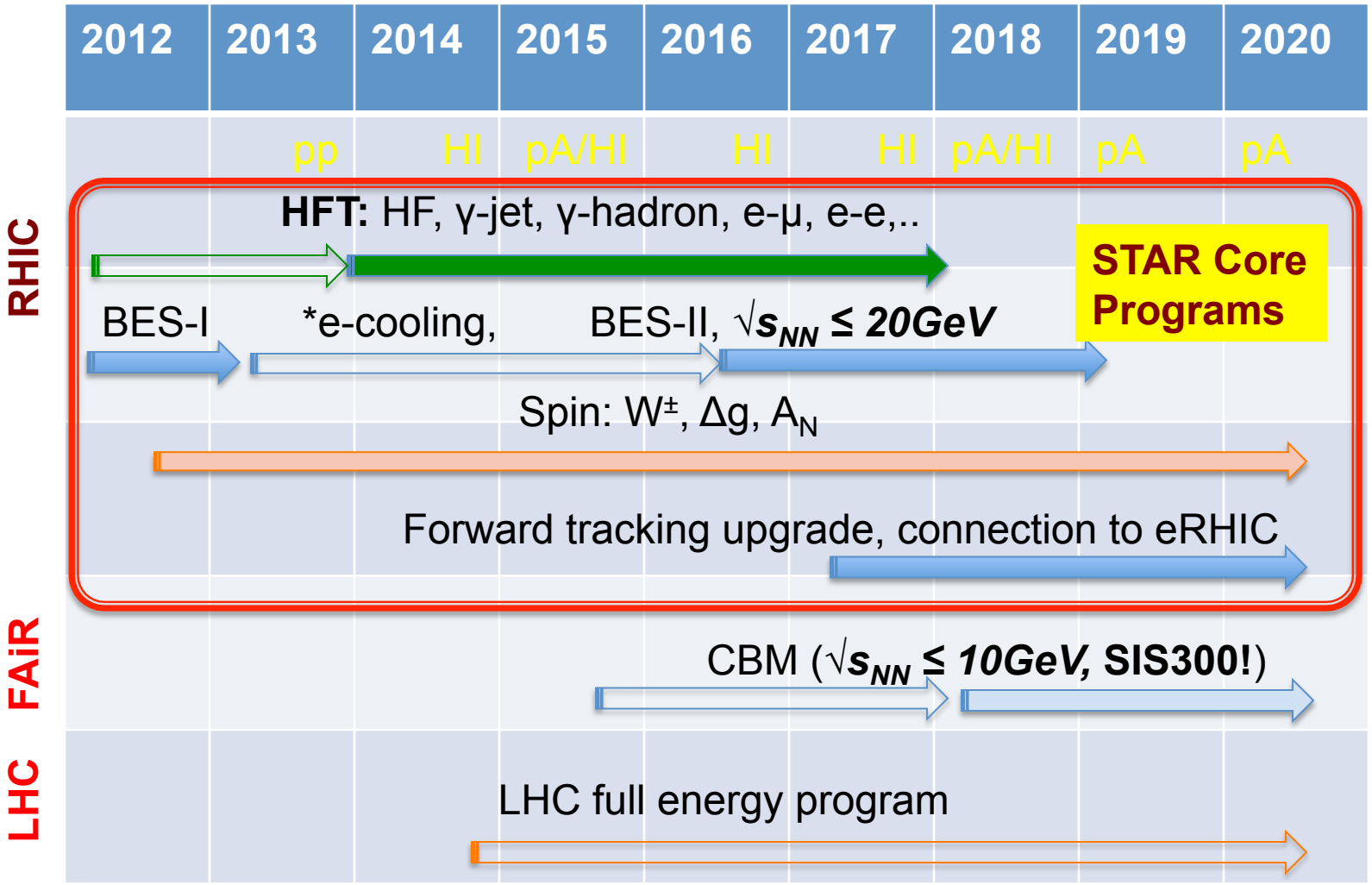
Muon Telescope Detector at STAR



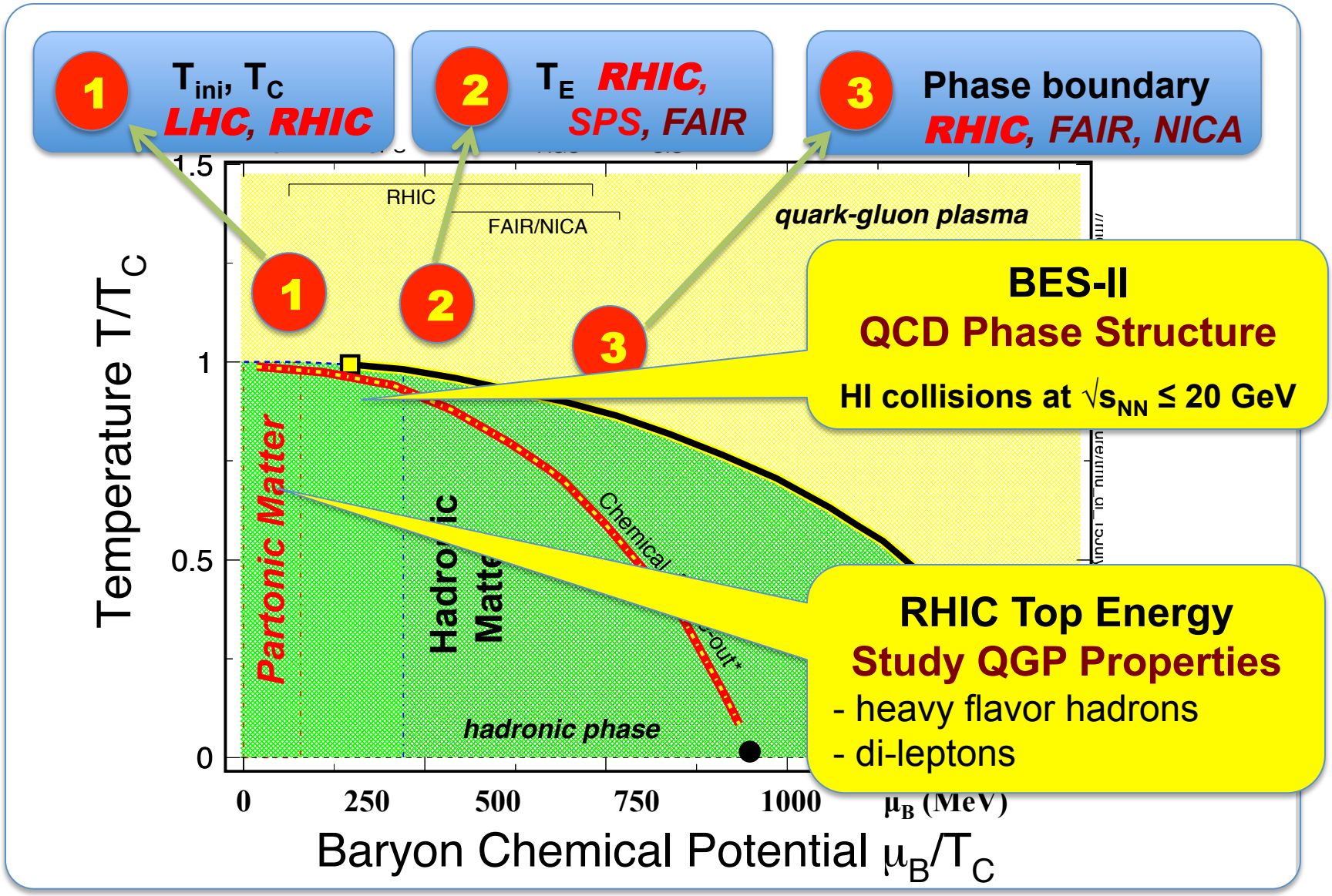
Muon Telescope Detector (MTD) at STAR:

1) MRPC technology; μ_ε ~ 36%; cover ~45% azimuthally and |y| < 0.5
2) TPC+TOF+MTD: muon/hadron enhancement factor ~ $10^{2\text{-}3}$
3) For high p_T muon trigger, heavy quarkonia, B→J/Ψ+X, dileptons, …
4) China-India-STAR collaboration
5) **Run14**: MTD will be fully ready

Study QCD Phase Structure



Exploring the QCD Phase Structure



Summary

1) BES Program:

- Partonic dominant: $\sqrt{s_{NN}}$ **> 39 GeV** ($\mu_B \leq$ 100MeV)
  Hadronic dominant: $\sqrt{s_{NN}}$ **≤ 11.5 GeV** ($\mu_B \geq$ 330MeV)
- High statistics data for energy region $\sqrt{s_{NN}}$ **≤** 20 GeV, needs e-cooling at RHIC

2) Heavy Flavor and Di-lepton Programs:

STAR HFT+MTD upgrades ready by summer of 2013

Unique opportunities for exploring QCD phase structure at RHIC