Exploring the Phase Diagram of QCD Matter with the RHIC Beam Energy Scan

Daniel Cebra (UC Davis)

Outline:

1) STAR Physics Program
2) Results from RHIC Beam Energy Scan I
3) Future Physics program

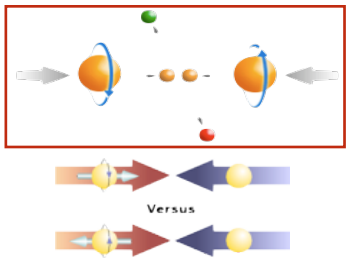
Professor Daniel Cebra

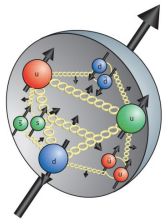
Future

Now

Past

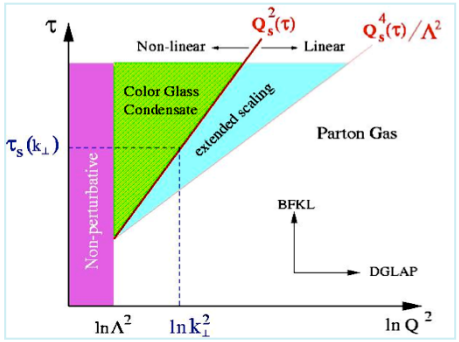
RHIC Physics Focus





Polarized *p+p* program

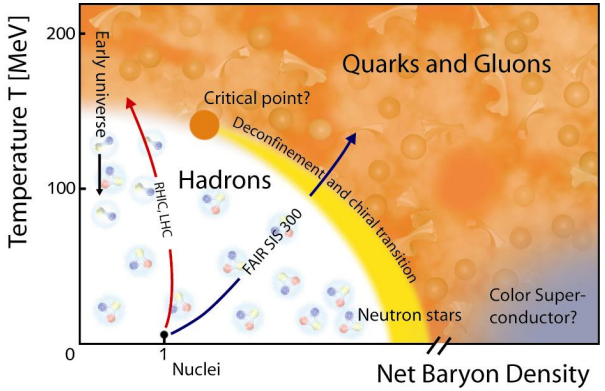
- Study ***proton intrinsic properties***



Forward program

- Study low-x properties, initial condition, search for ***CGC***
- Study elastic and inelastic processes in pp2pp

2020 -
eRHIC
(eSTAR)



1) At 200 GeV at RHIC

- Study ***medium properties, EoS***
- pQCD in hot and dense medium

2) RHIC beam energy scan (BES)

- Search for the ***QCD critical point***
- Chiral symmetry restoration

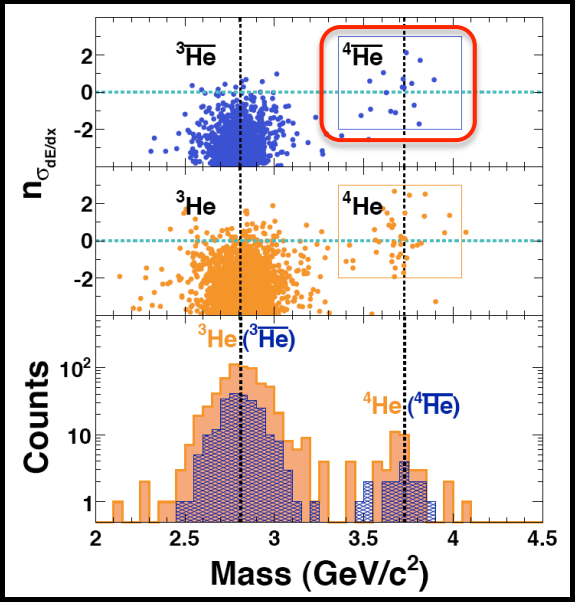
QGP and Antimatter Discoveries at RHIC

nature April, 2011

"Observation of the Antimatter Helium-4 Nucleus"

by ***STAR Collaboration***

Nature*, 473, 353(2011).*

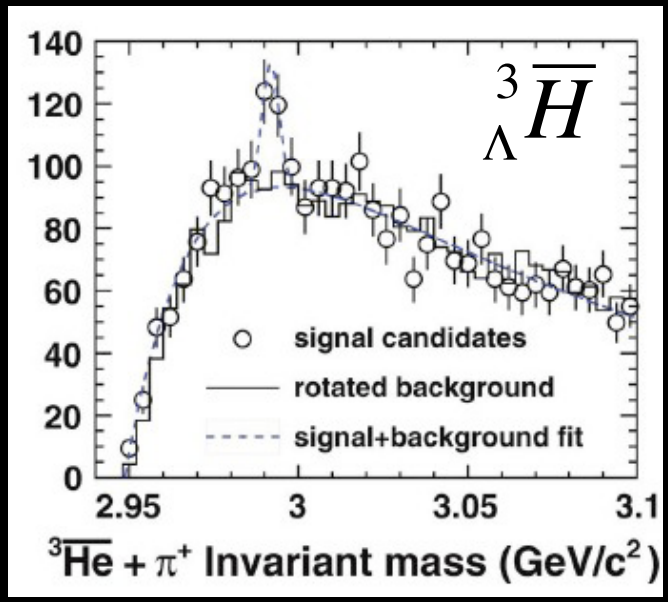


Science March, 2010

"Observation of an Antimatter Hypernucleus"

by ***STAR Collaboration***

Science*, 328, 58(2010).*



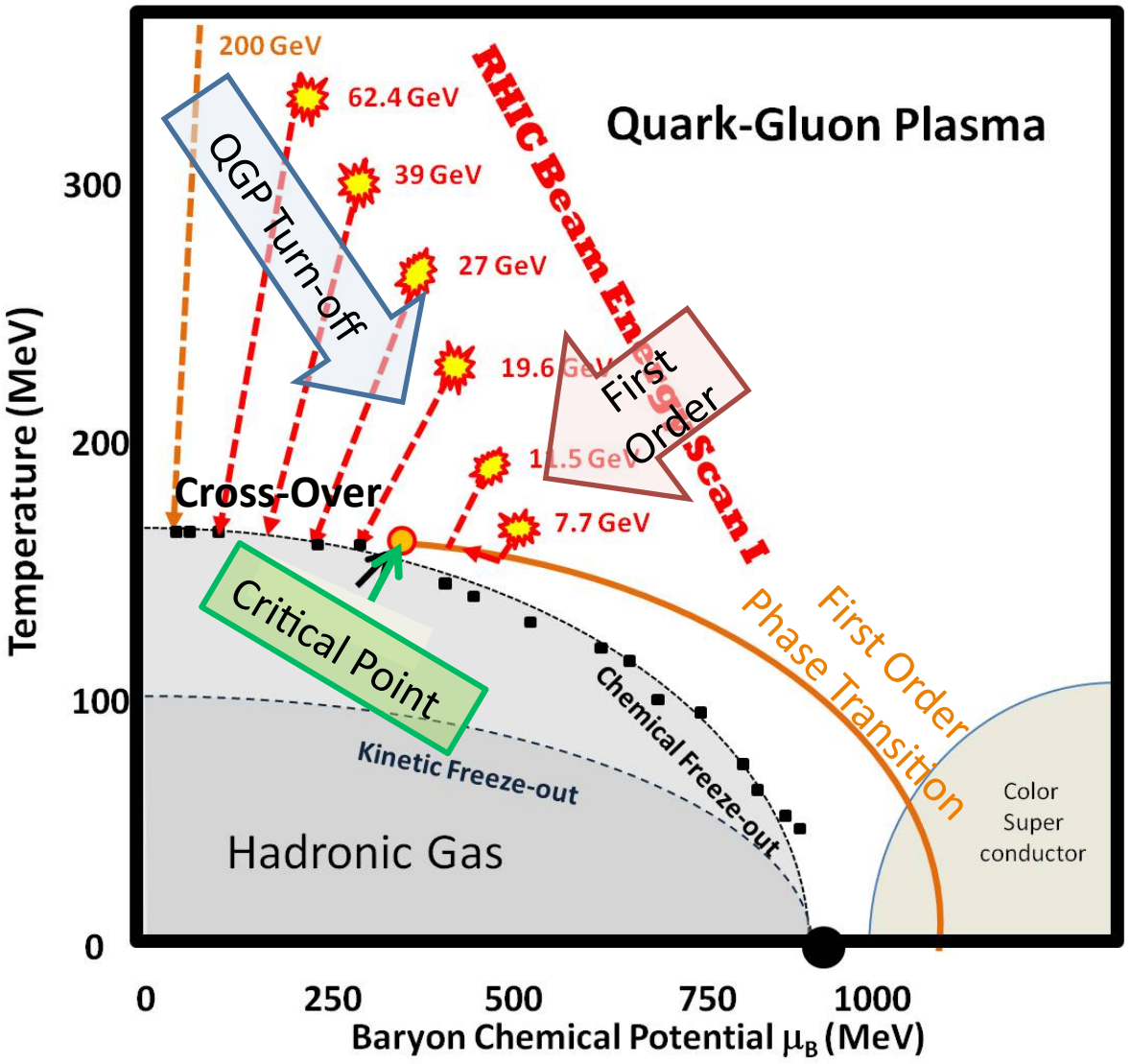
The RHIC Beam Energy Scan I

- We built RHIC to find the QGP.
  And we did it!

- But QGP is a new and complicated phase of matter. We have made huge progress in understanding its nature. At high energy, we expect a **cross-over** transition. At lower energy there should be a **first order** transition and a **critical point**.

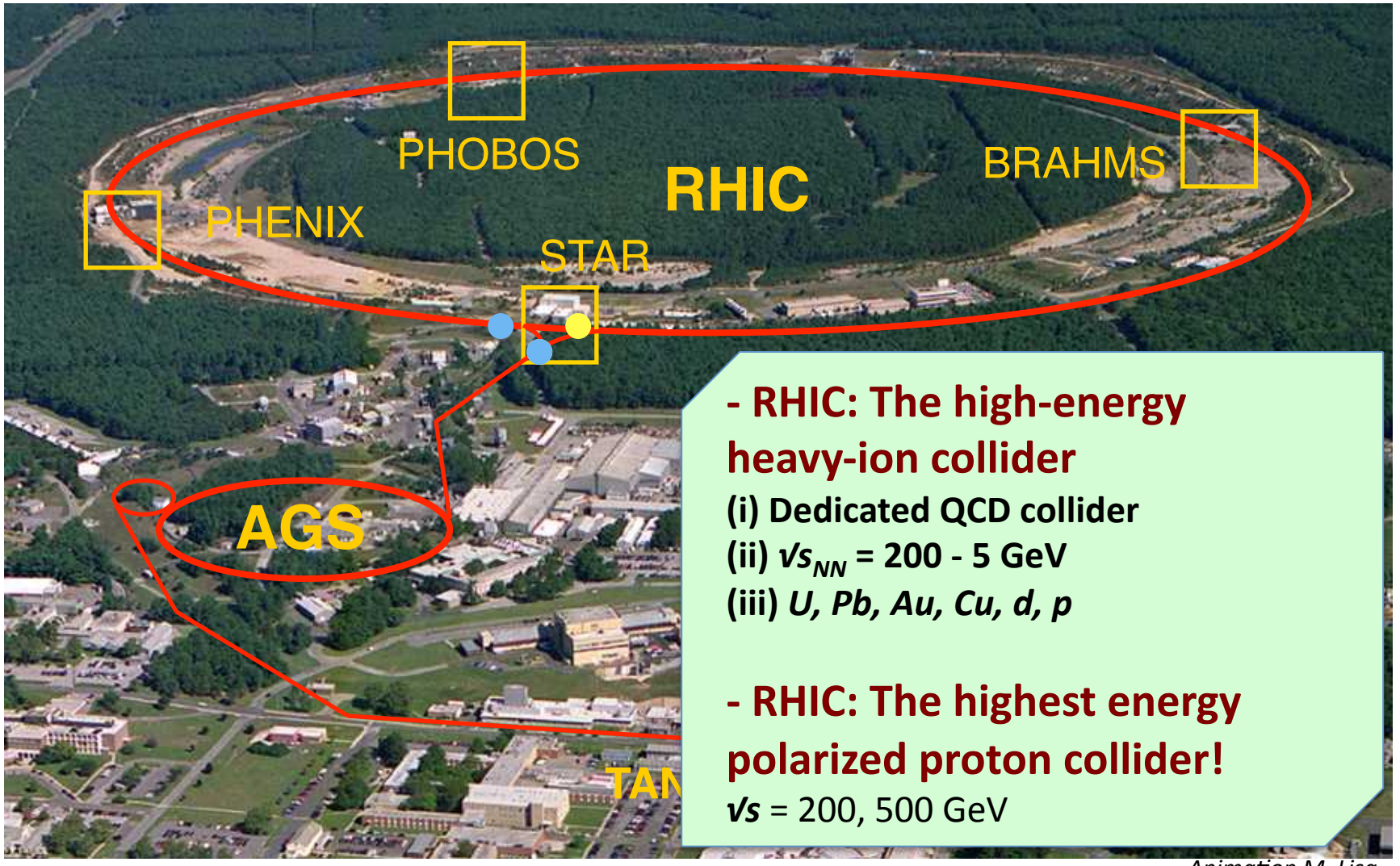
- To explore the structure of the QCD matter phase diagram we run a beam energy scan at RHIC

- **Three Goals of BES program:**
  - **Turn-off of QGP signatures**
  - **Find critical point**
  - **Search for phase boundary**



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

Brookhaven National Laboratory (BNL), Upton, NY

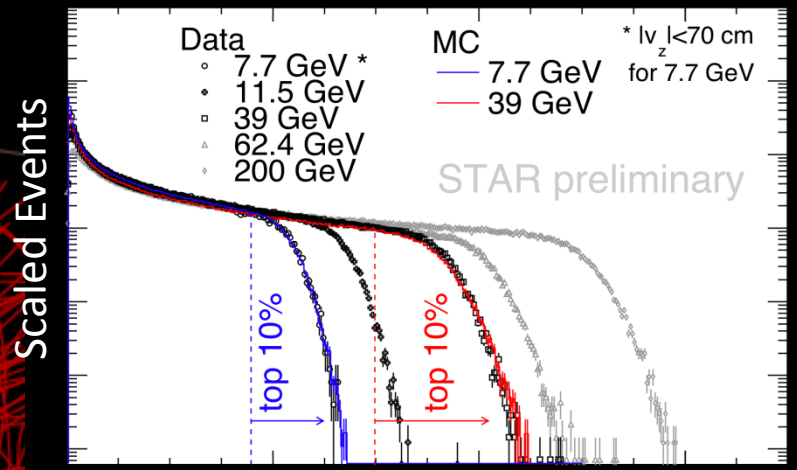


Animation M. Lisa


STAR Collaboration

STAR Experiment

Central Au+Au at 7.7 GeV

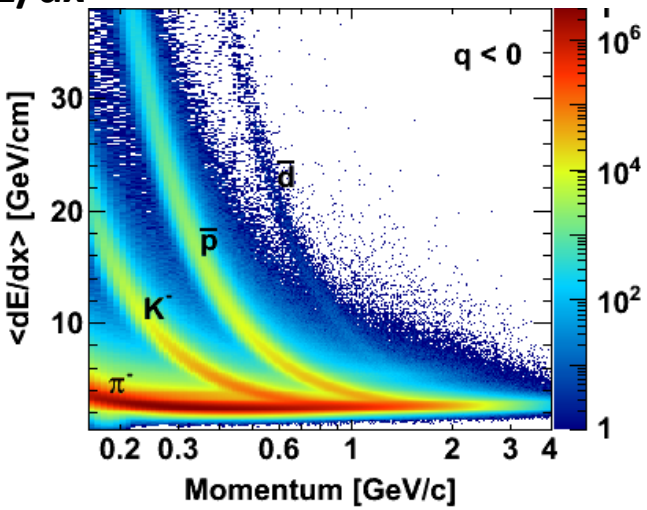


Detector performance generally improves with lower energies. Geometric acceptance remains the same, track density gets lower.

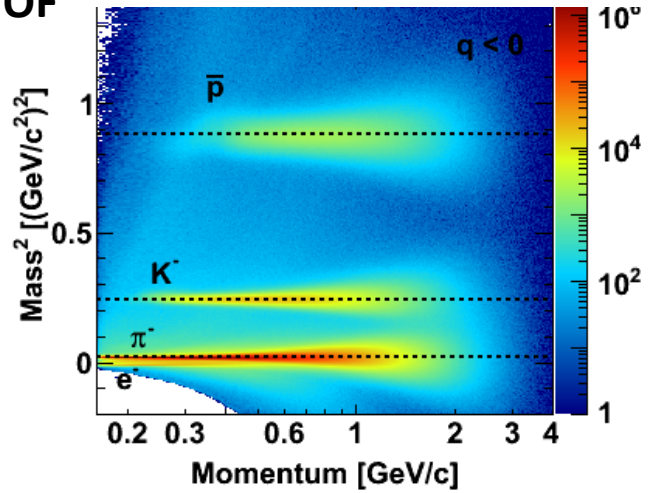
Triggering required effort, but was a solvable problem.

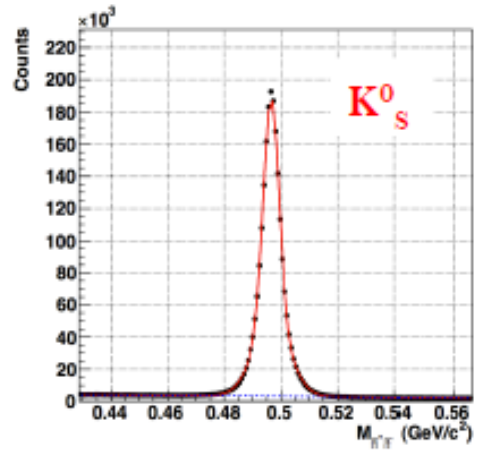
Particle Identification

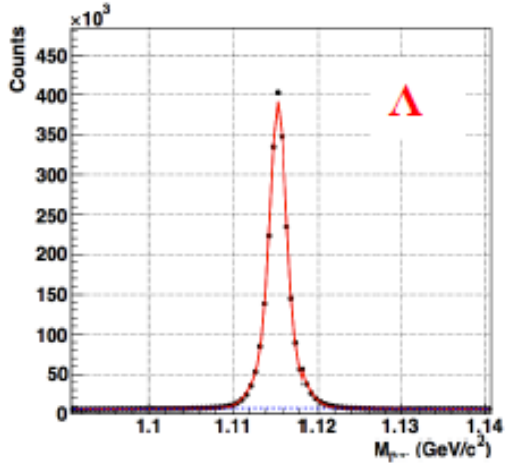
dE/dx

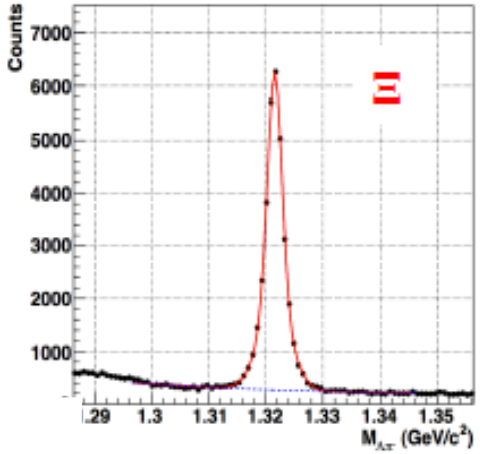


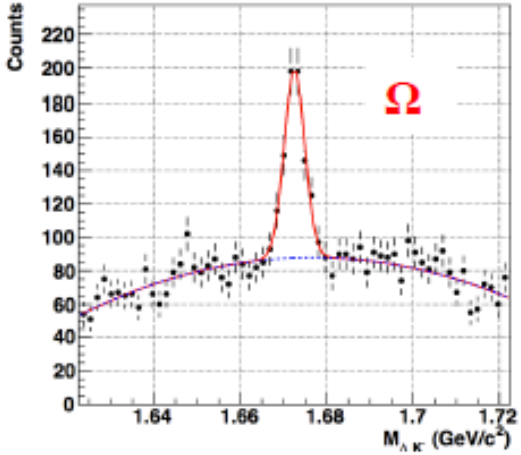
TOF





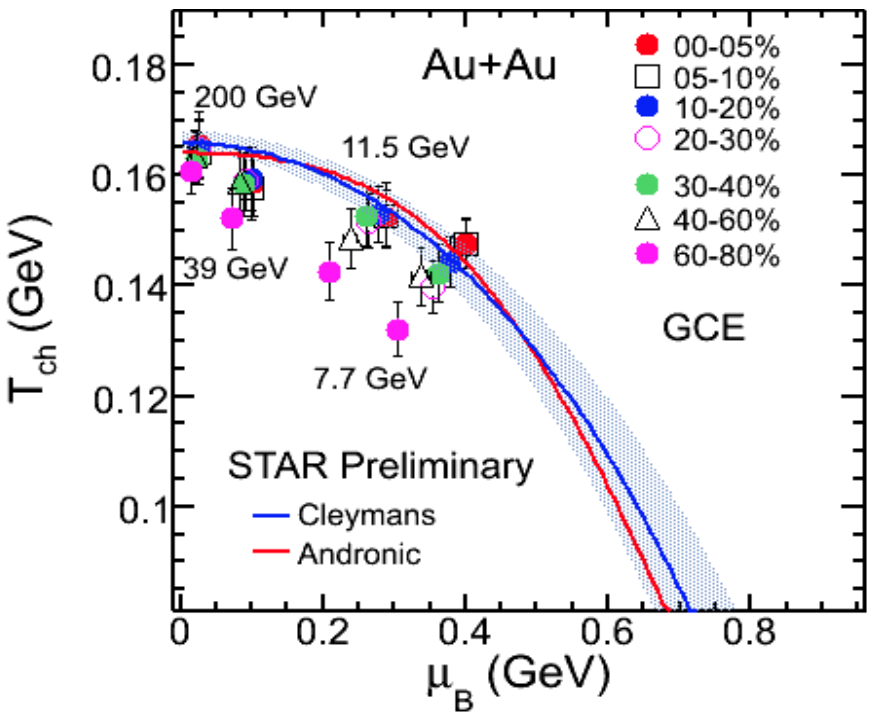


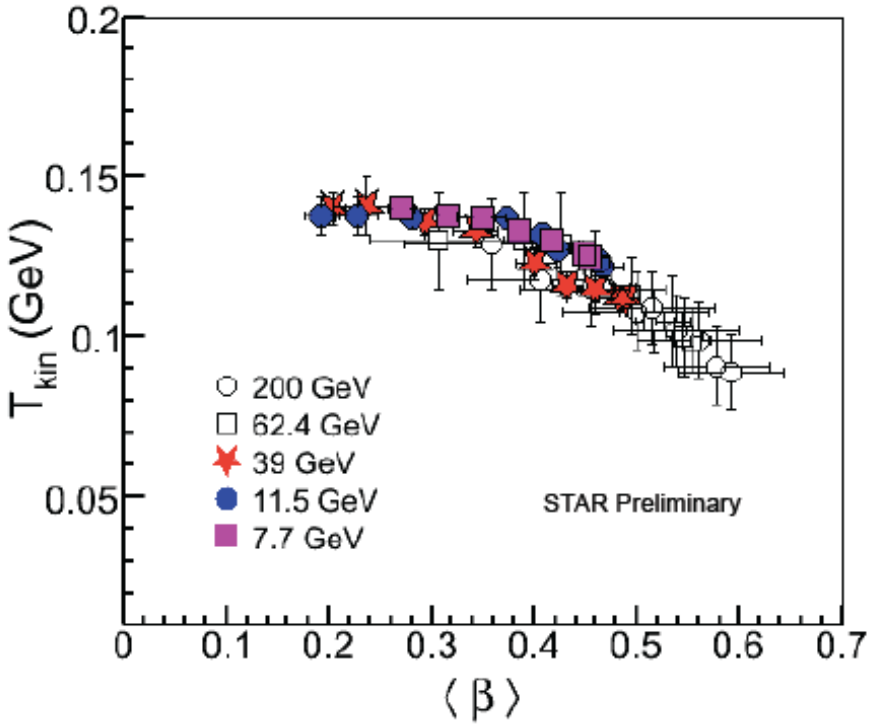




Invariant Mass

(1) Bulk Properties at Freeze-out





Chemical Freeze-out: (GCE)

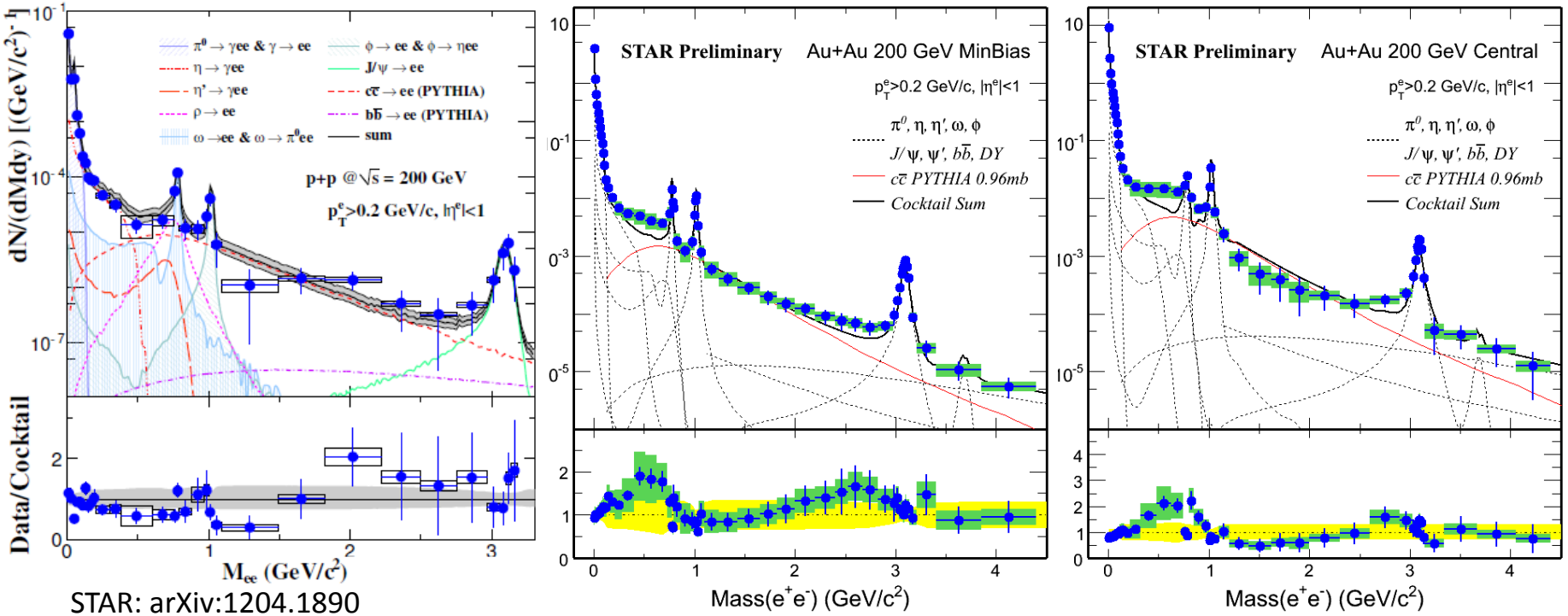
- Central collisions => higher values of T_{ch} and μ_B!
- The effect is stronger at lower energy.

Kinetic Freeze-out:

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

(2) Di-electron Production

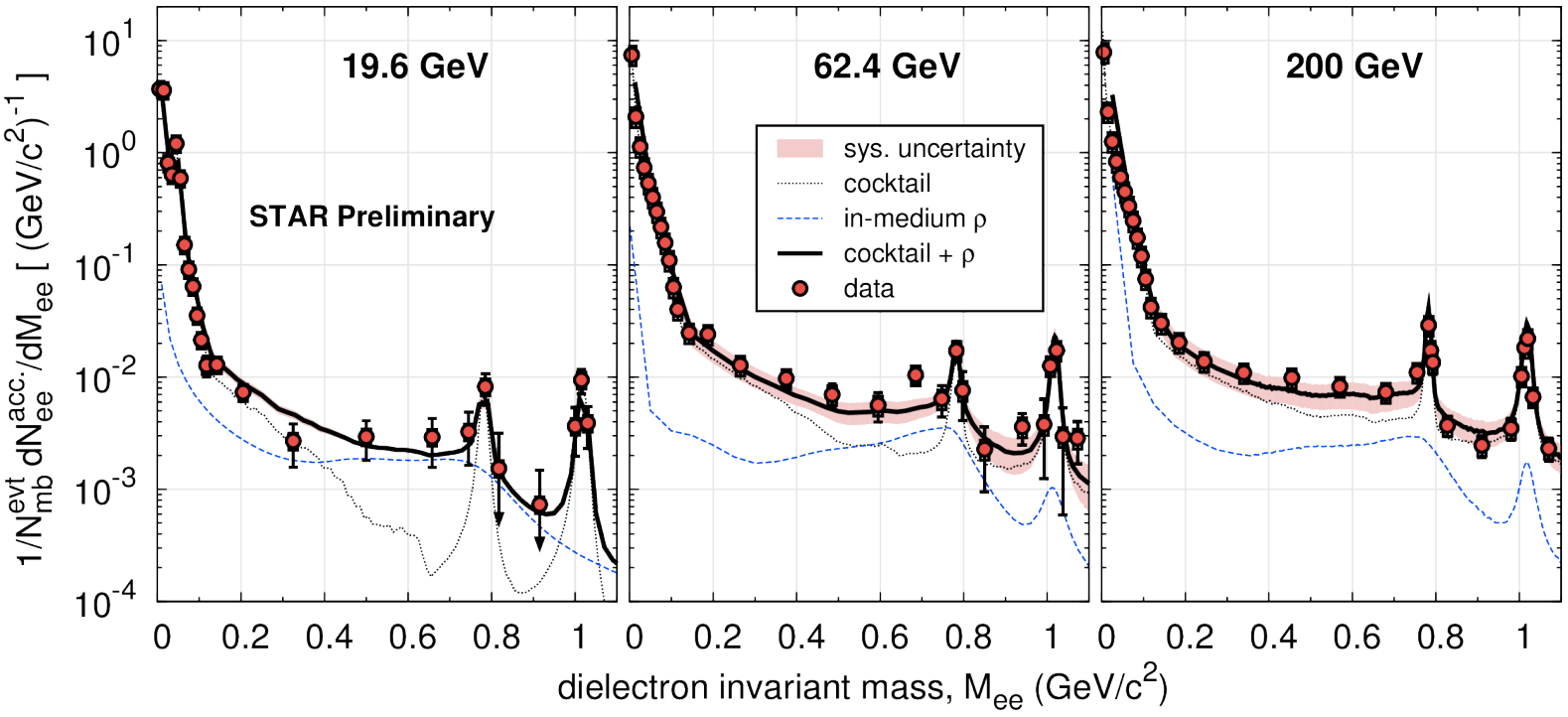
Vs = 200 GeV **p+p** **Au+Au MinBias** **Au+Au Central**



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.

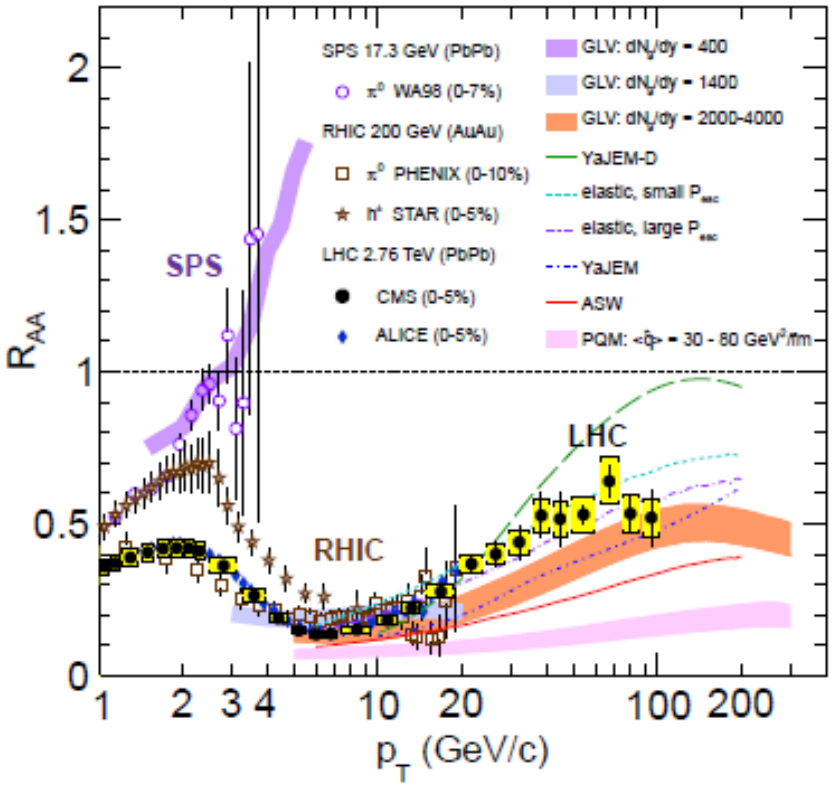
BES Dependence of Di-electrons

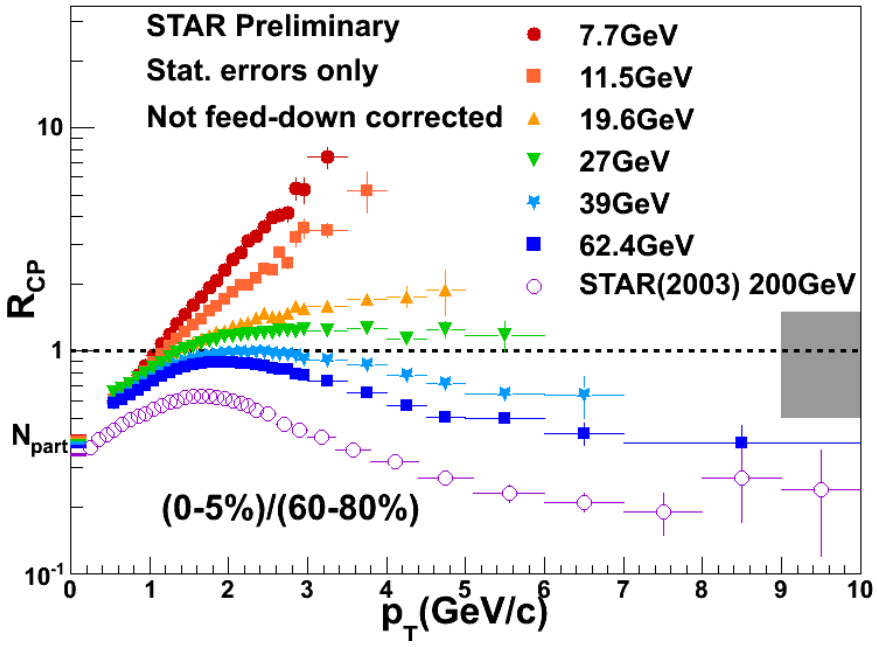


1) With in-medium broadened rho, model results are consistent with experimental data ($m_{ee} \leq 1$ GeV/c^2) at $\sqrt{s_{NN}}$ = 200, 62.4 and 19.6GeV

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}



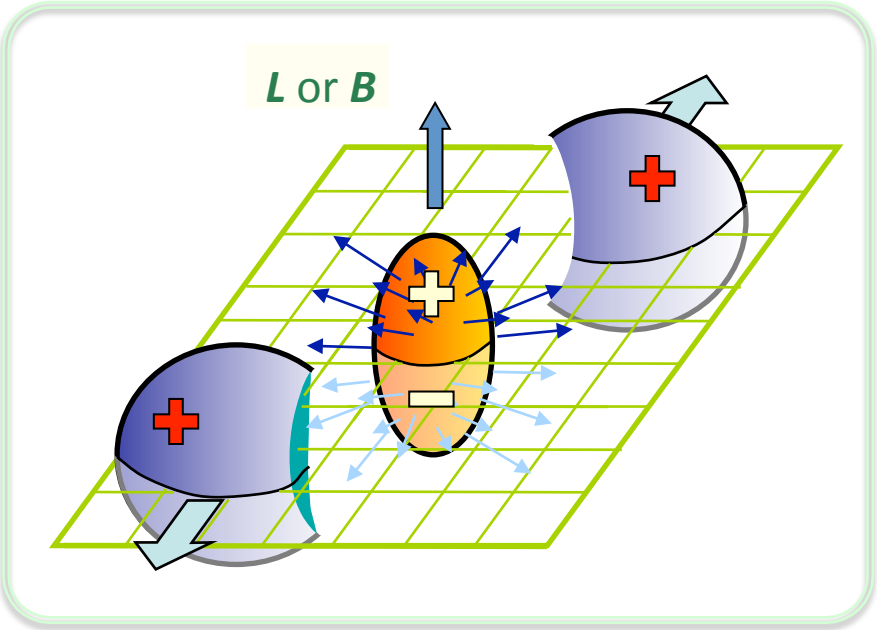


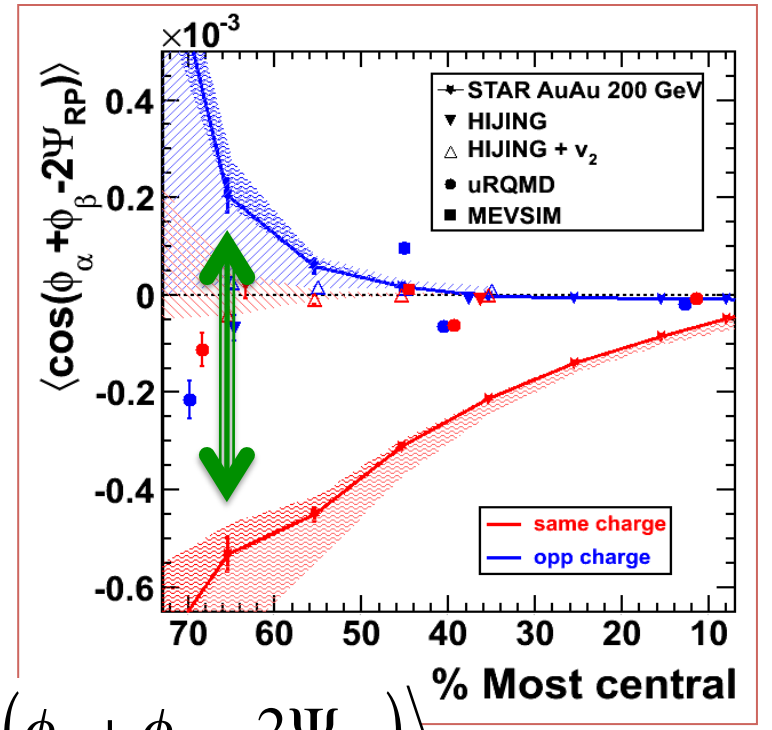
1) Suppression of high p_T hadrons: one of the key signatures for the formation of QGP in high-energy nuclear collisions

2) The **suppression 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





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

- Strong external EM field

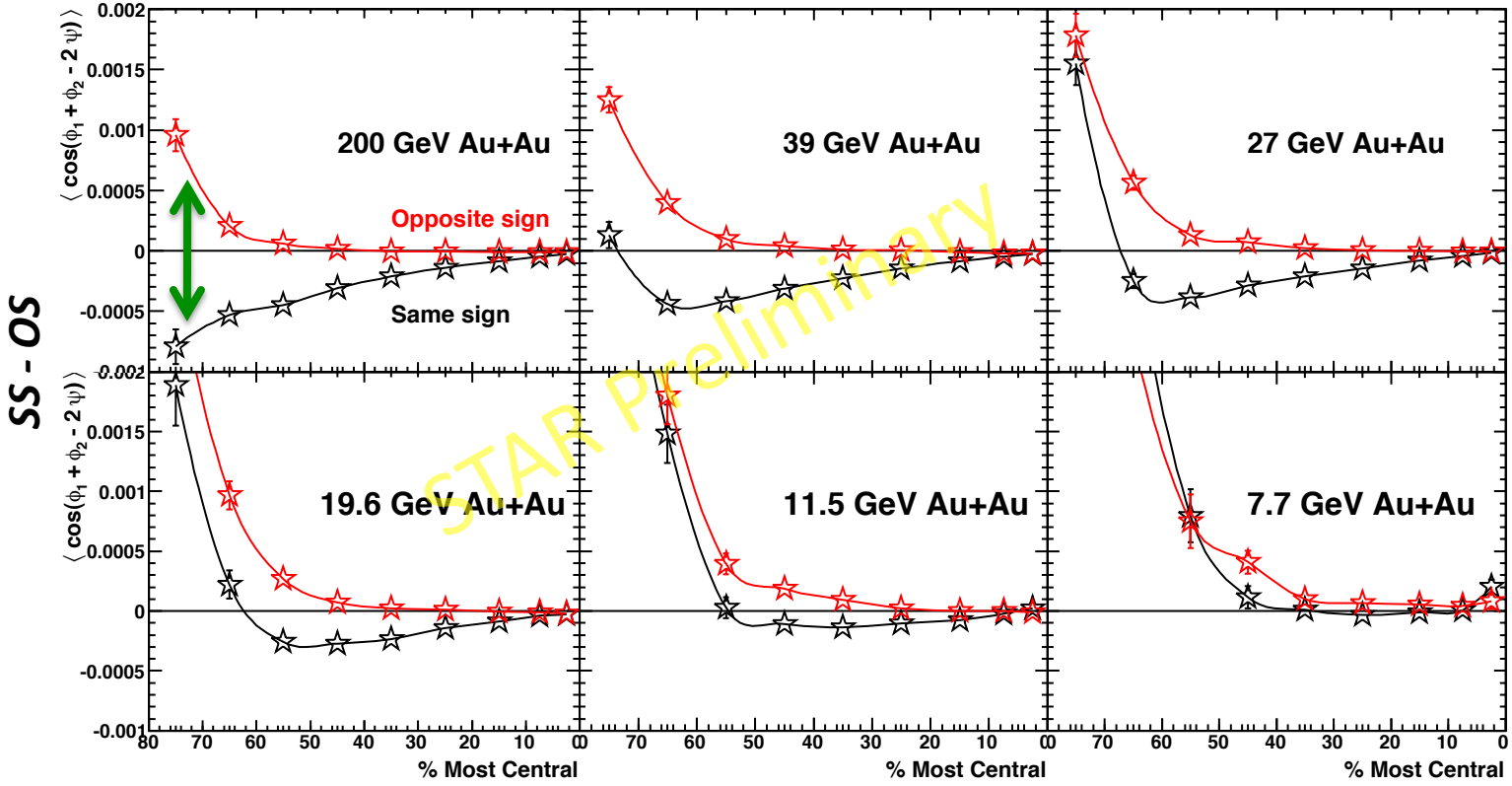
- *De-confinement* and *Chiral symmetry restoration*

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

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

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

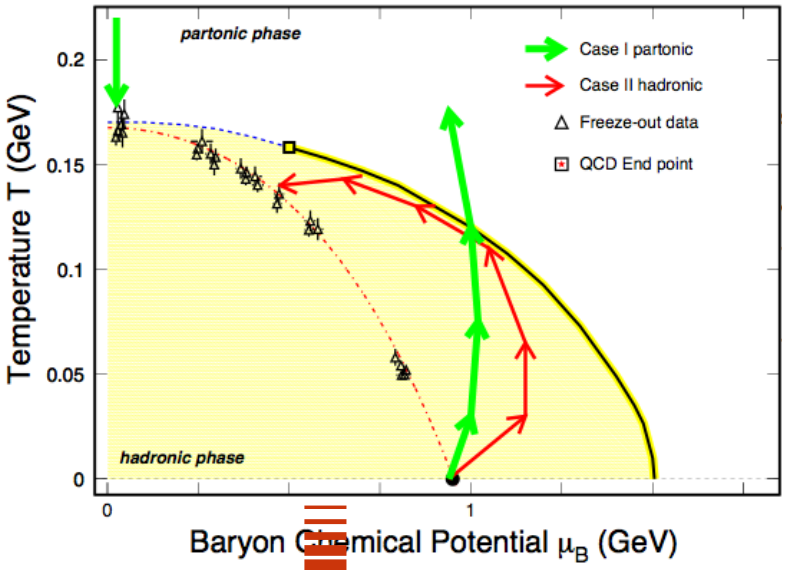
Dynamical Correlations

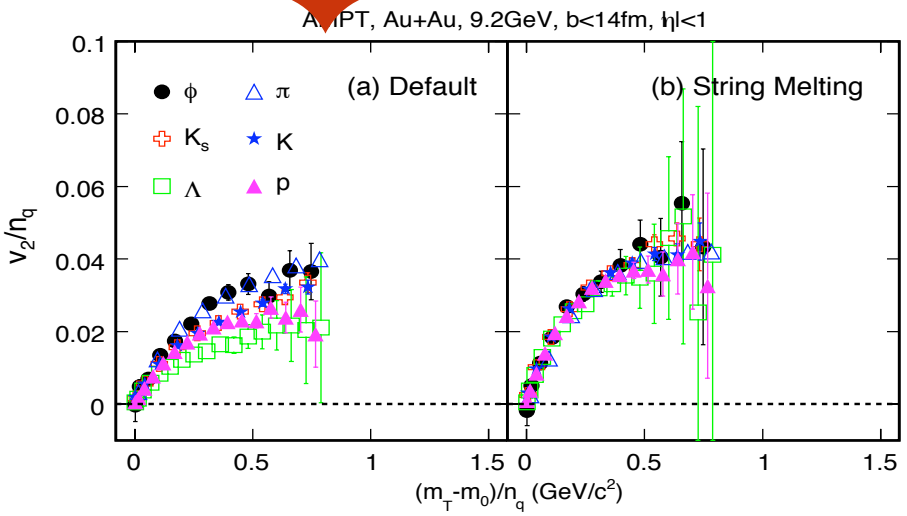


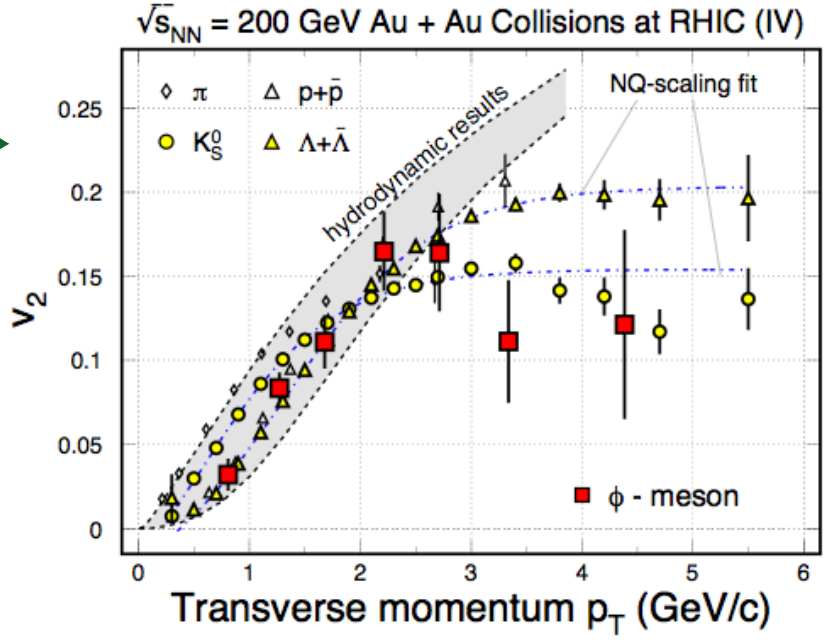
(1) Below $\sqrt{s_{NN}}$ = 11.5 GeV, the splitting between the same- and opposite-sign charge pairs (SS-OS) disappear

(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) Collectivity: NCQ Scaling in v_2







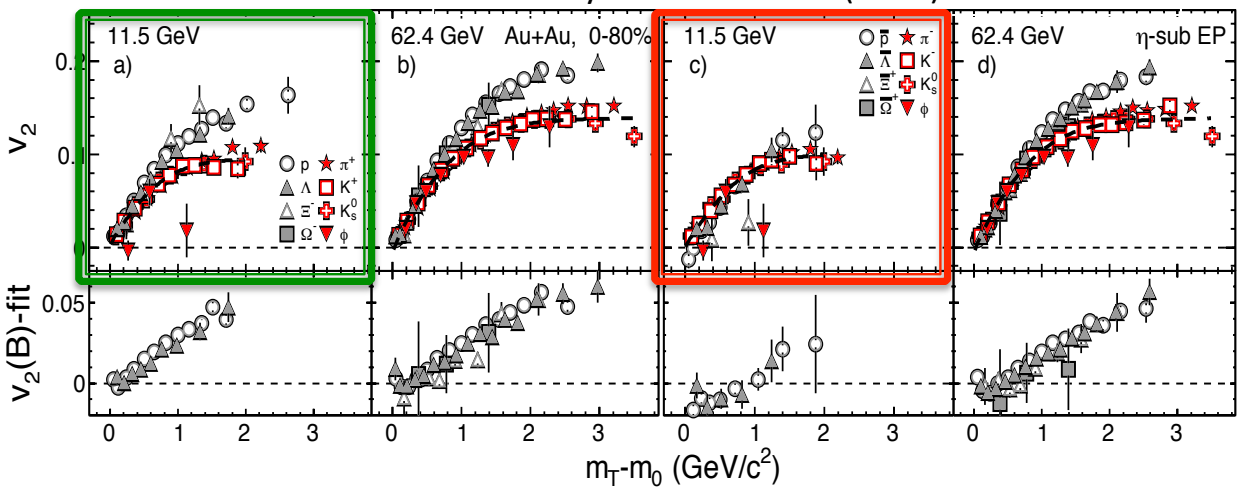
- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ ϕ not K^+K^- ⇨ ϕ
- $\sigma_{\phi h} << \sigma_{p\pi,\ \pi\pi}$

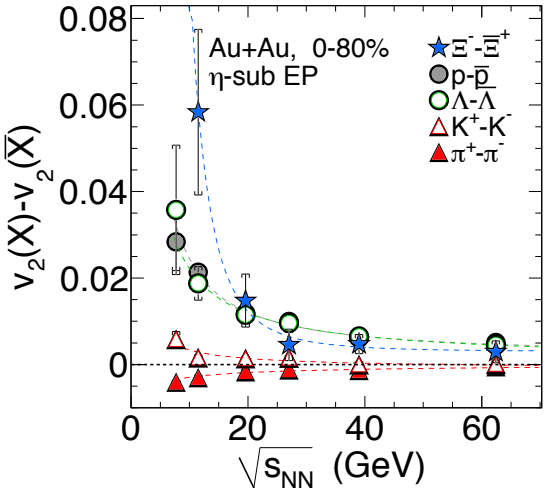
In the hadronic case, no number of quark scaling and the value of v_2 of ϕ will be small.

*** Thermalization is assumed!**

Collectivity v_2 Measurements

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

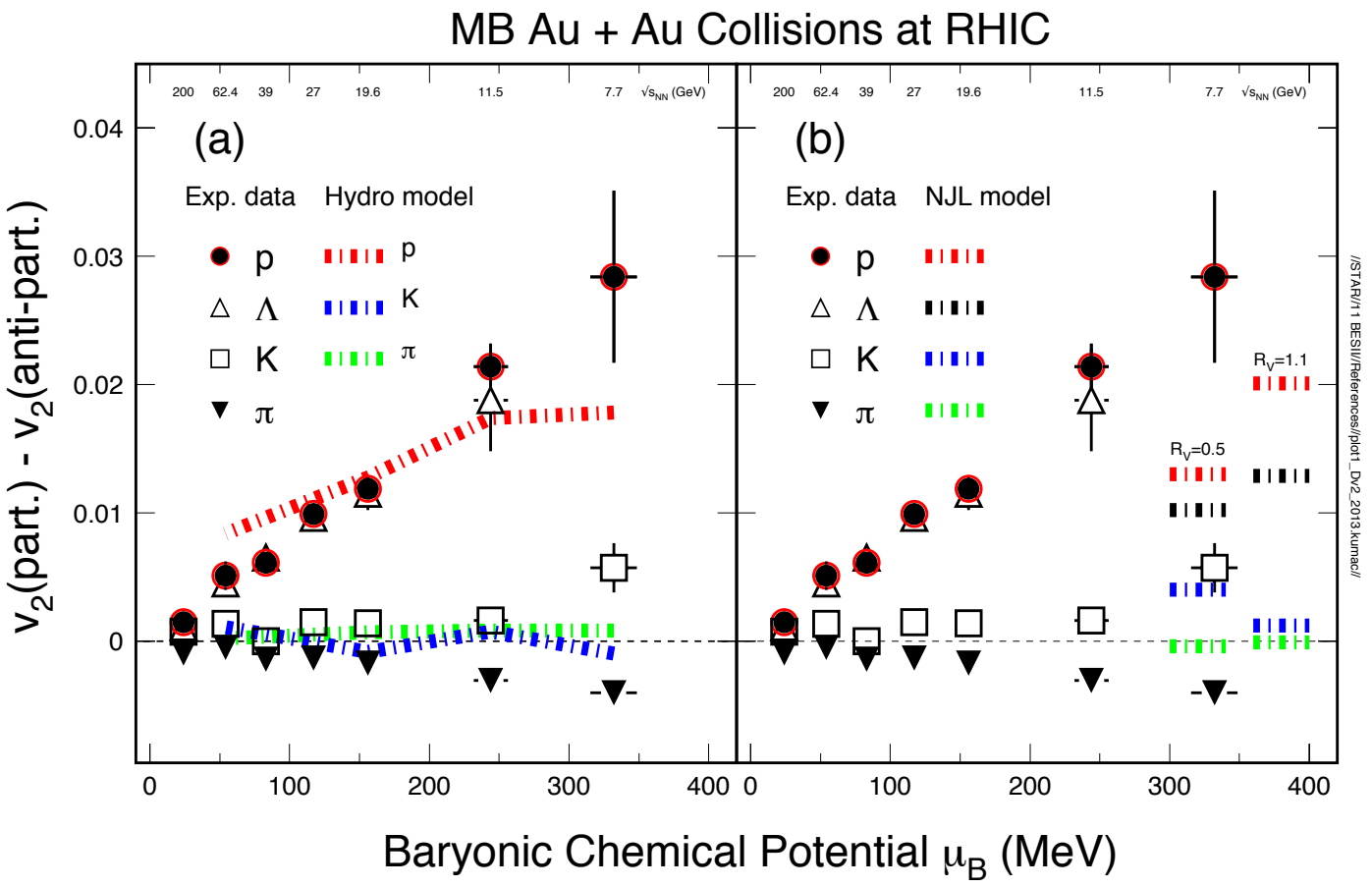




1) Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions

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

NCQ-Scaling and Phase Diagram

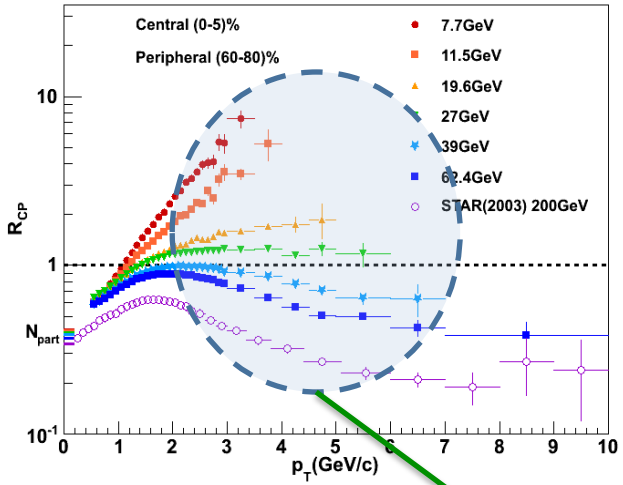


1) v_2 difference between particle and anti-particle related to vector coupling
2) The vector density is sensitive to baryon density

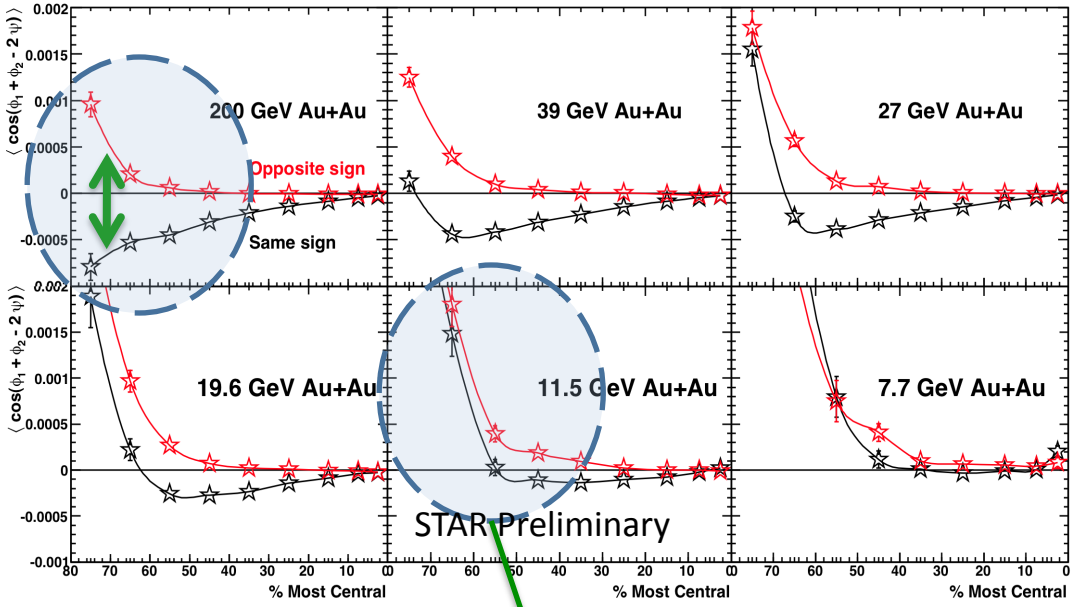
- *J. Xu, Song, Ko & Li, PRL, (2014)*

Disappearance of QGP Signatures

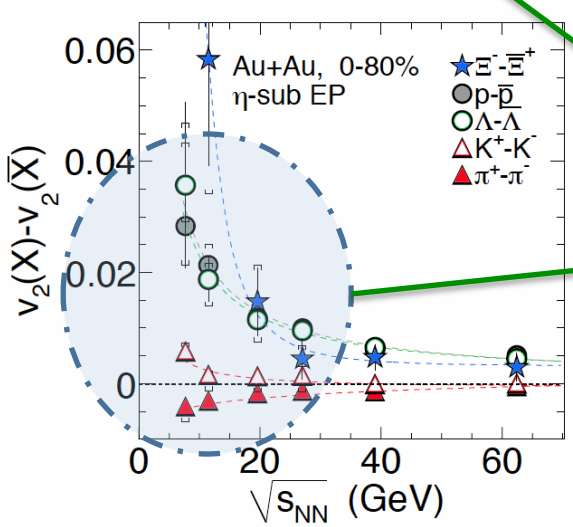
Parton energy loss



"Local Parity Violation"



Partonic collectivity

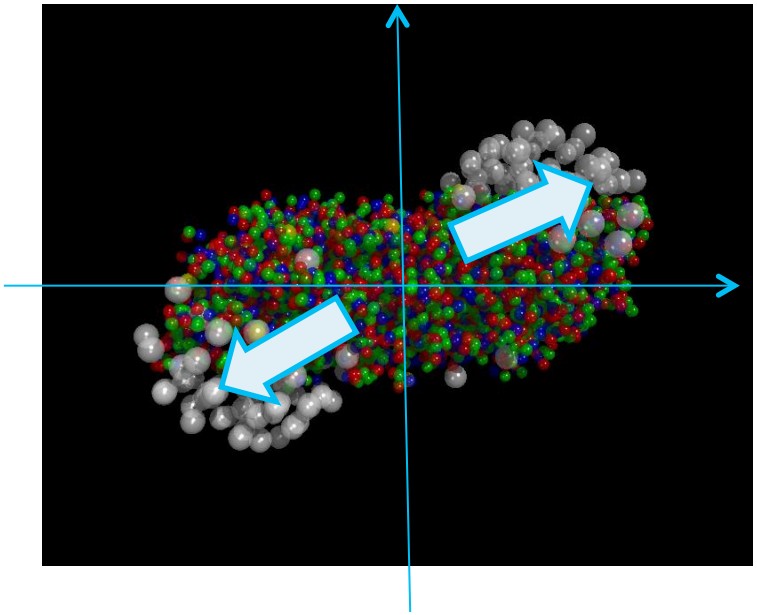


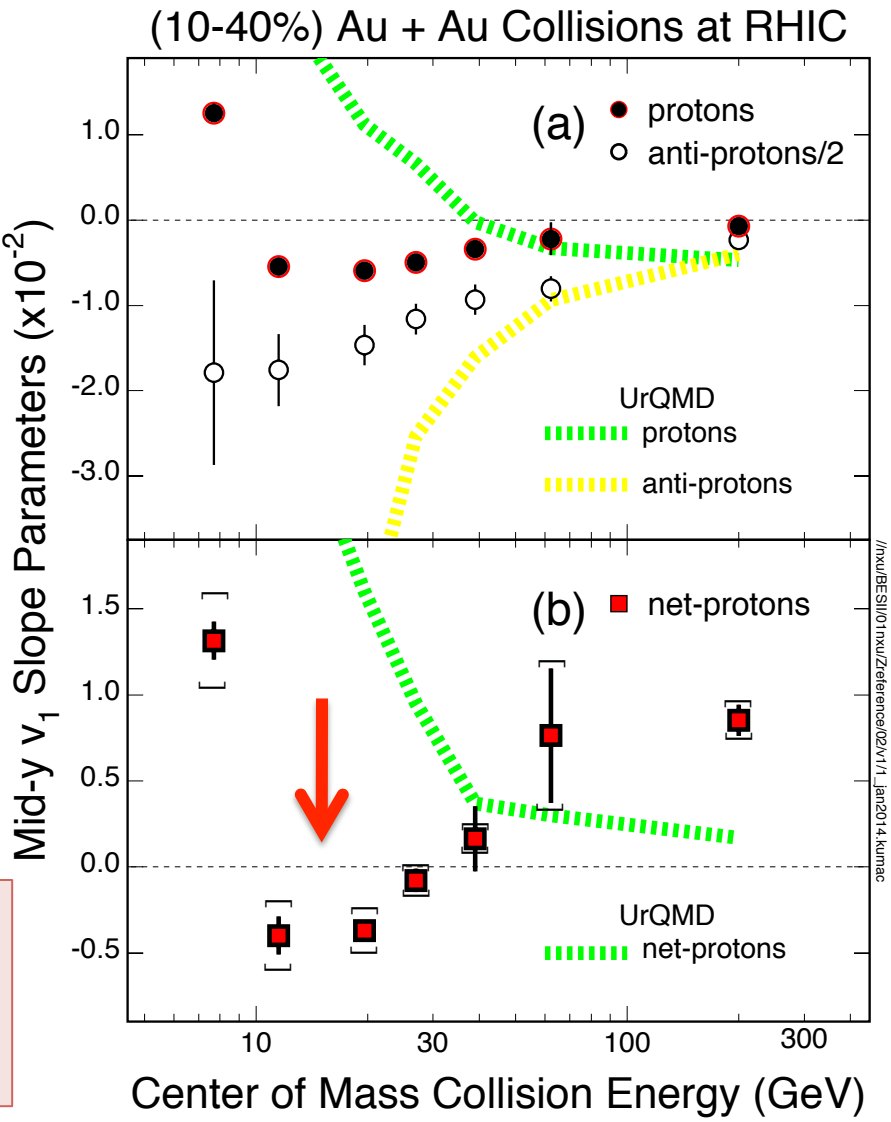
sQGP key signatures

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

(6) Collectivity: Directed Flow v_1

Directed flow is a measure of the compressive recoil of the nucleons



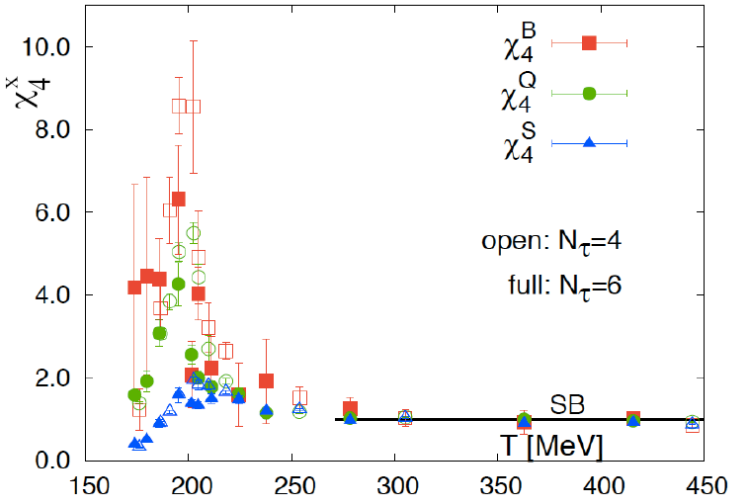


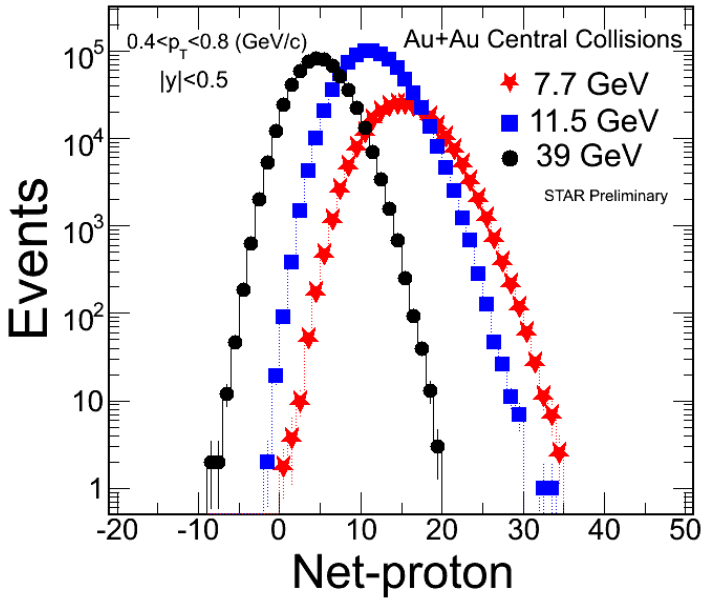
•First order phase transition is characterized by unstable coexistence region.

• v_1 is a manifestation of early pressure in the system

• We see a minimum of the v_1 signal. ➔ ***Suggestive***

(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 calculation at any order:

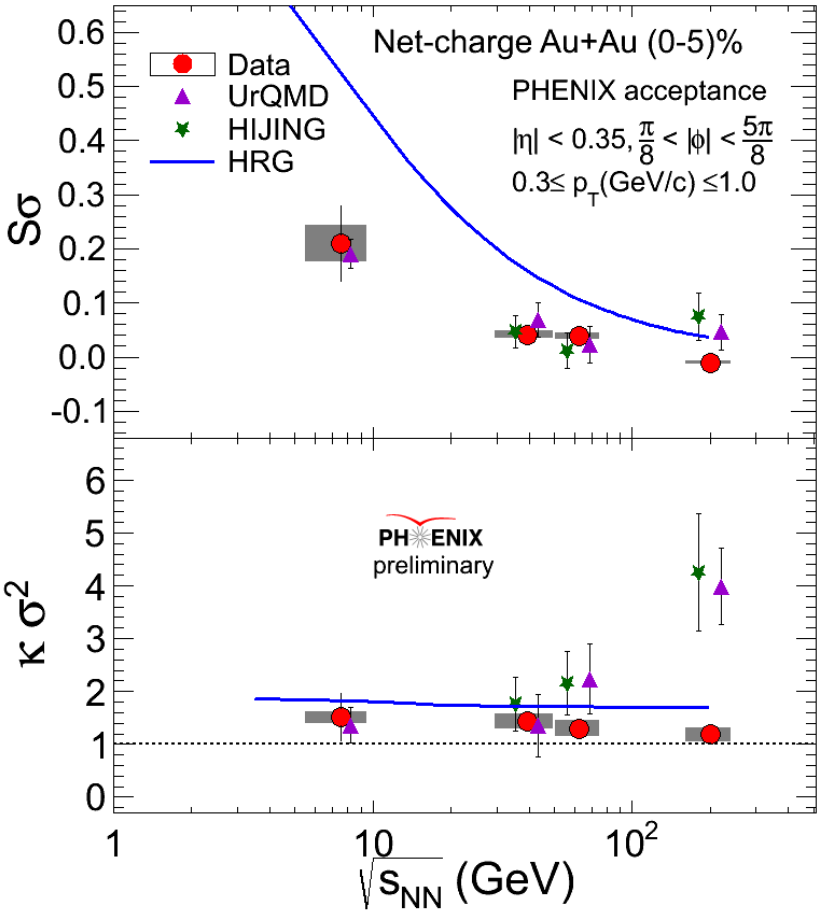
$$S*\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa*\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

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

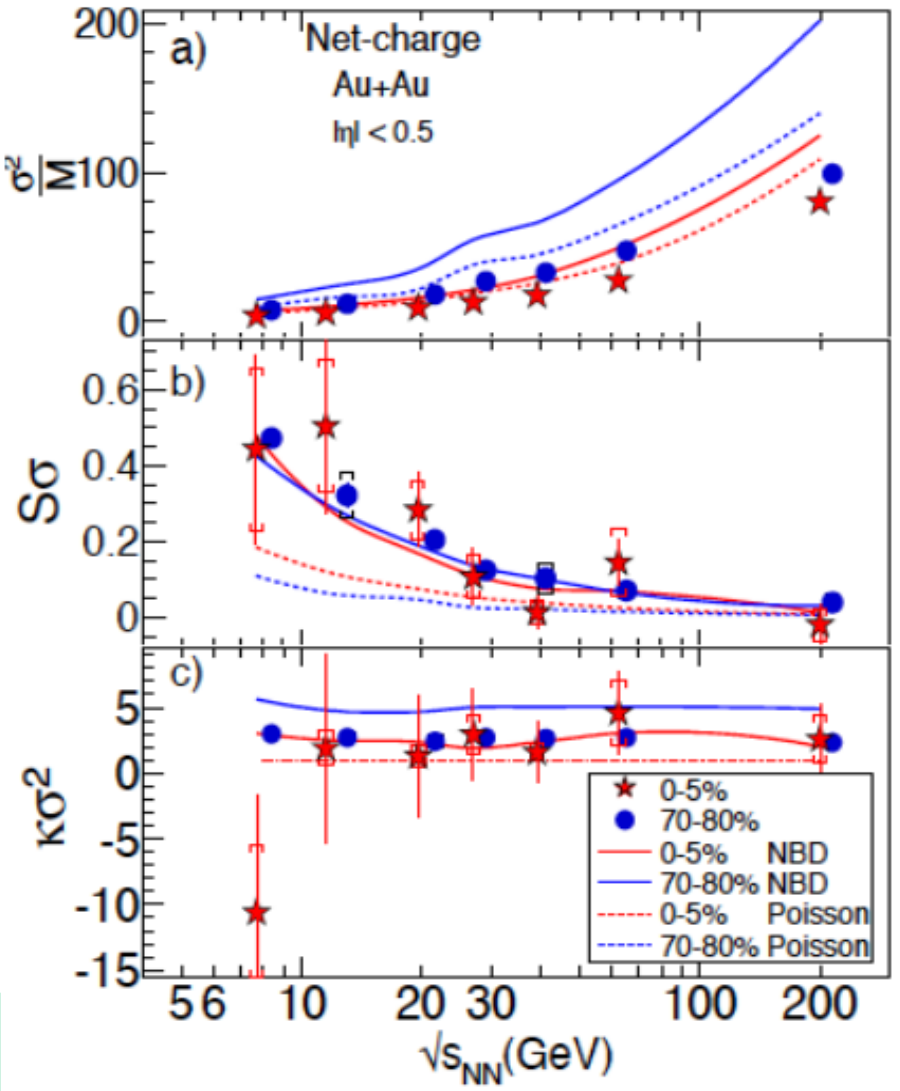
References:

- 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-Q Higher Moments at RHIC

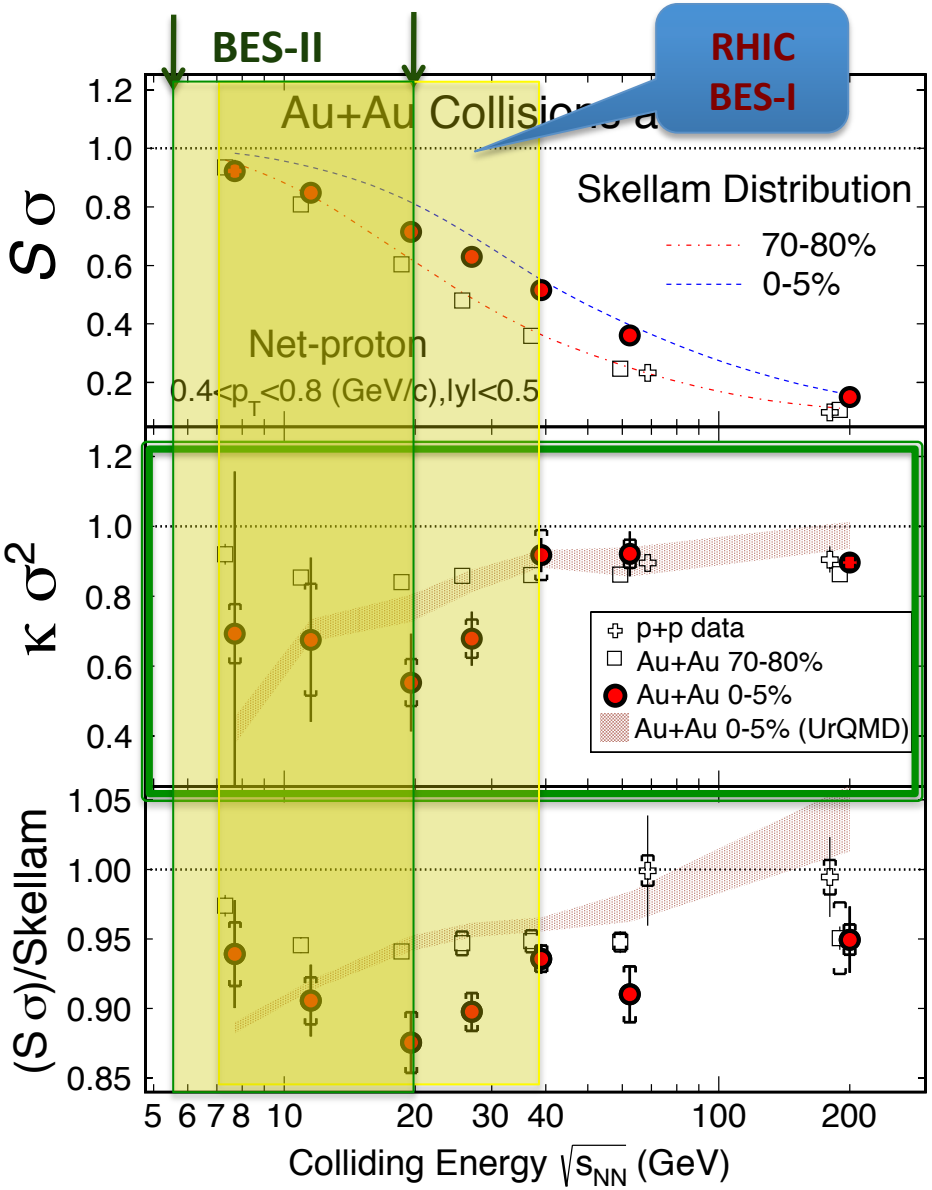


Acceptance and Efficiency correlations are needed



STAR Results: T. Nayak *et al.*

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 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.* **BES-II is needed**.

STAR: 1309.5681, PRL accepted

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**

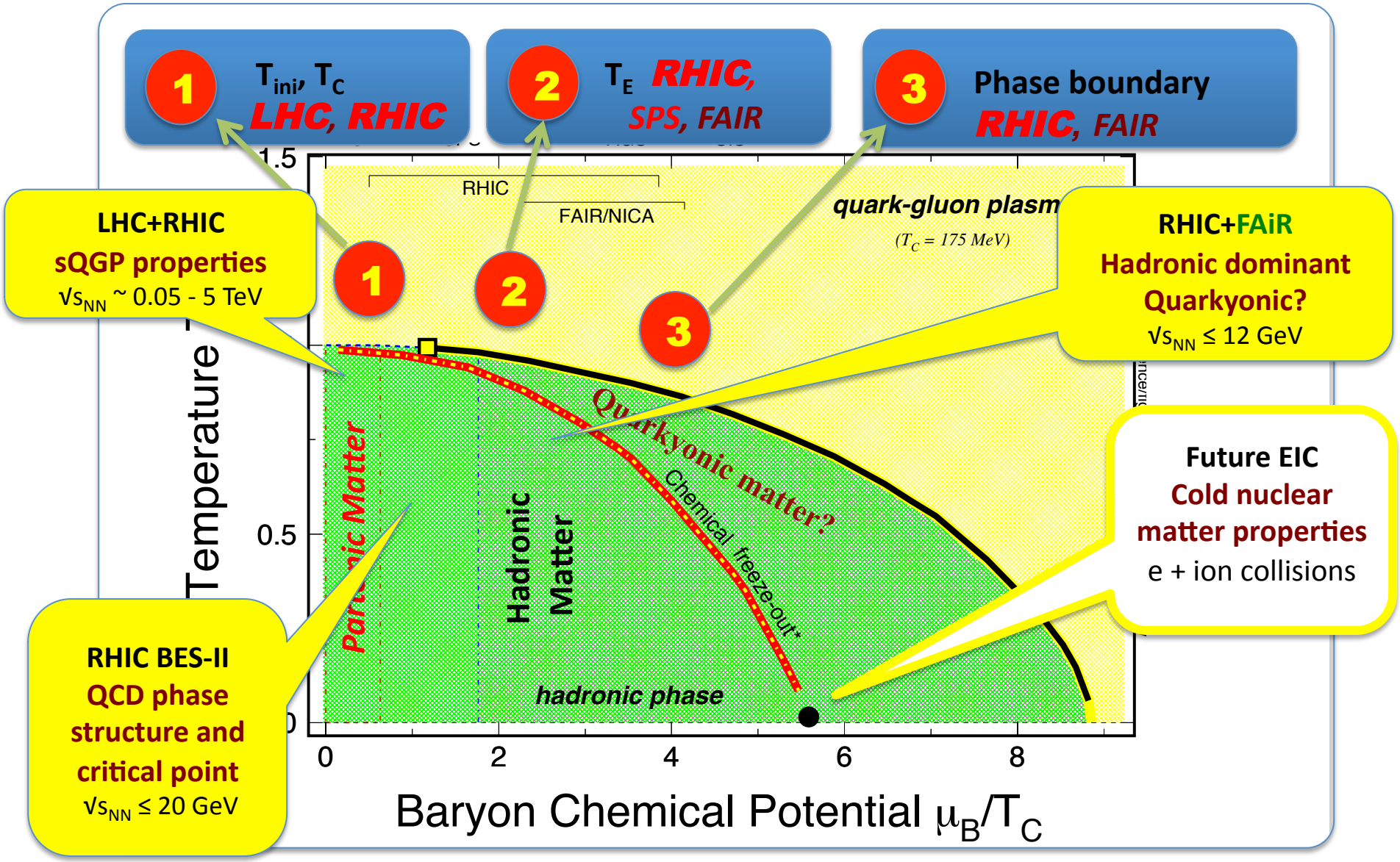
(2) RHIC BES-I:

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

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

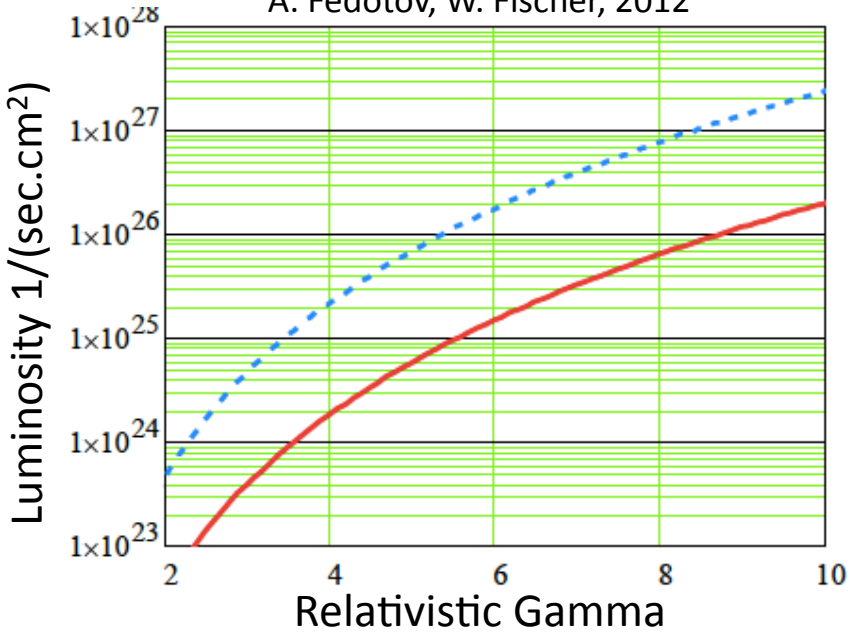
(3) RHIC BES-II: focus at $\sqrt{s_{NN}} \leq 20$ GeV region with higher luminosity (x10) + iTPC: Run18 (2017)

Exploring QCD Phase Structure

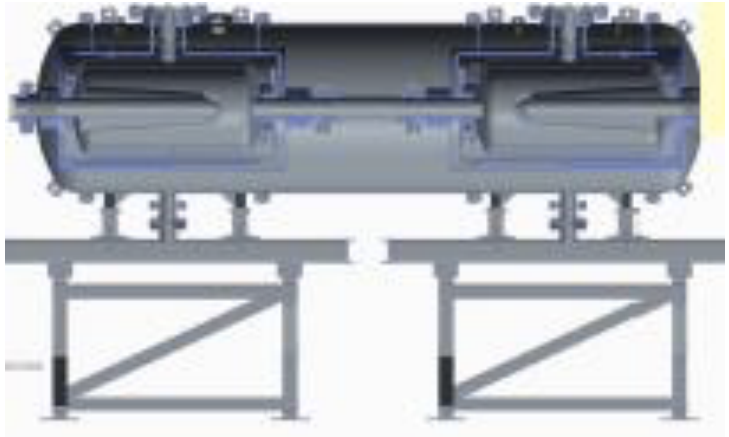


e-cooling at RHIC for BES-II

A. Fedotov, W. Fischer, 2012

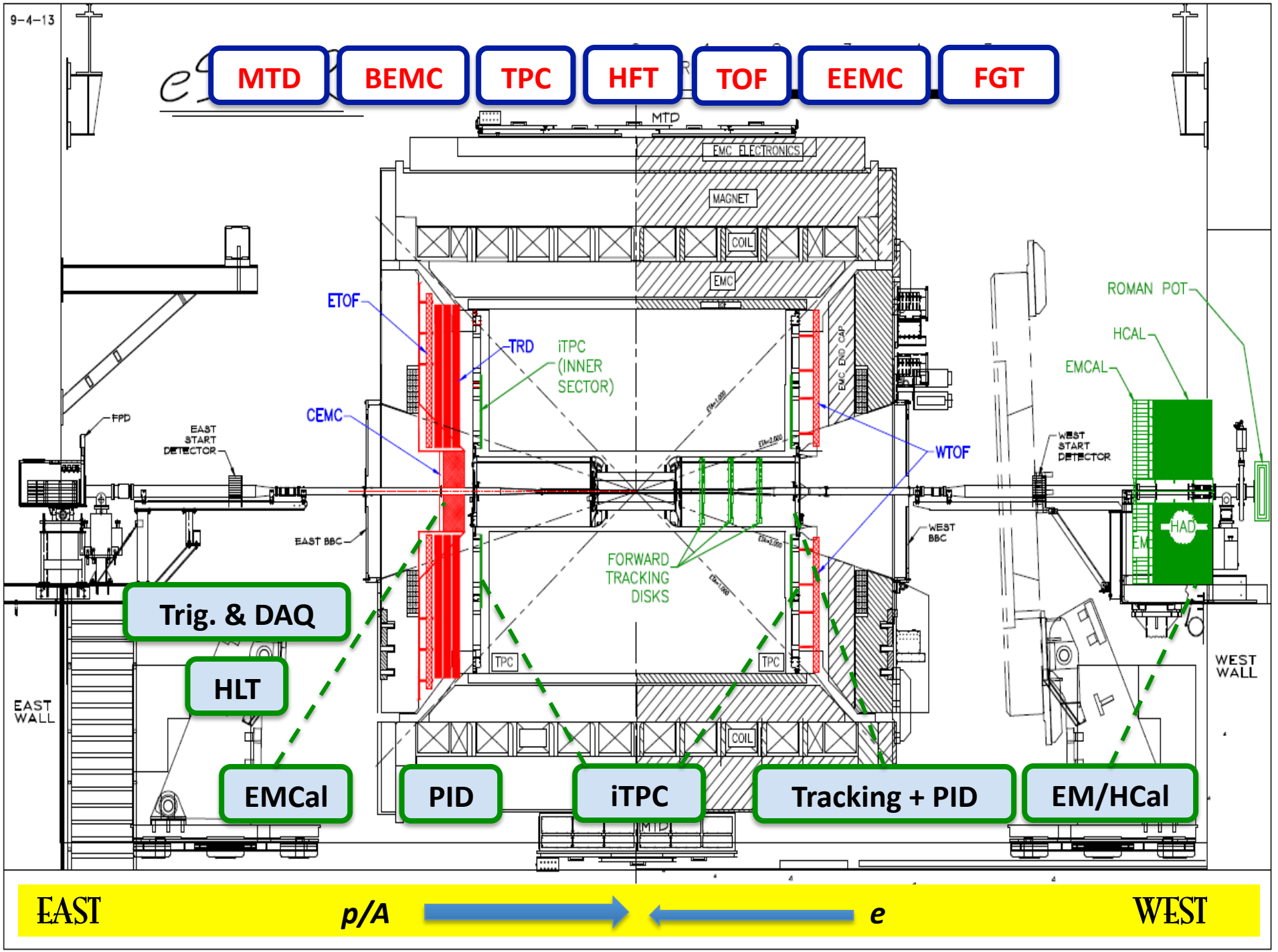


SRF Gun

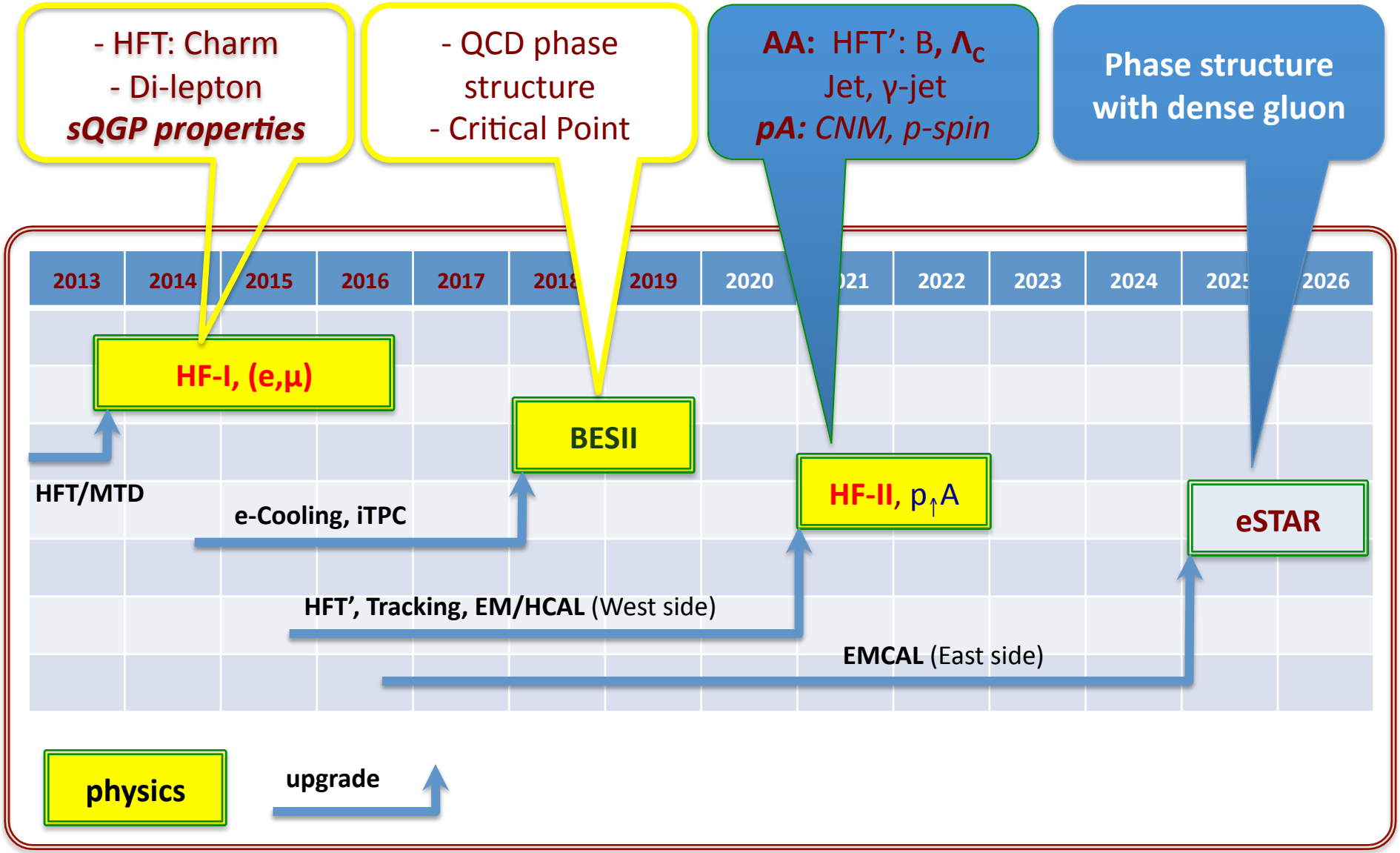


$\sqrt{s_{NN}}$ (GeV)	~ 5	~ 20
Increasing factor*	3-5	10

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


MTD
BEMC
TPC
HFT
TOF
EEMC
FGT
9-4-13
MTD
EMC ELECTRONICS
MAGNET
COIL
EMC
ETOF
TRD
iTPC
(INNER
SECTOR)
CEMC
EMC END CAP
ROMAN POT
HCAL
EMCAL
FPD
EAST
START
DETECTOR
WTOF
WEST
START
DETECTOR
EAST BBC
WEST
BBC
FORWARD
TRACKING
DISKS
HAD
EM
TPC
TPC
EAST
WALL
WEST
WALL
COIL
MTD
Trig. & DAQ
HLT
EMCal
PID
iTPC
Tracking + PID
EM/HCal
EAST
p/A
e
WEST

STAR: Future Plans



Thank you!