STAR Experiment at RHIC

- High-Energy Nuclear Collisions and the QCD Phase Structure

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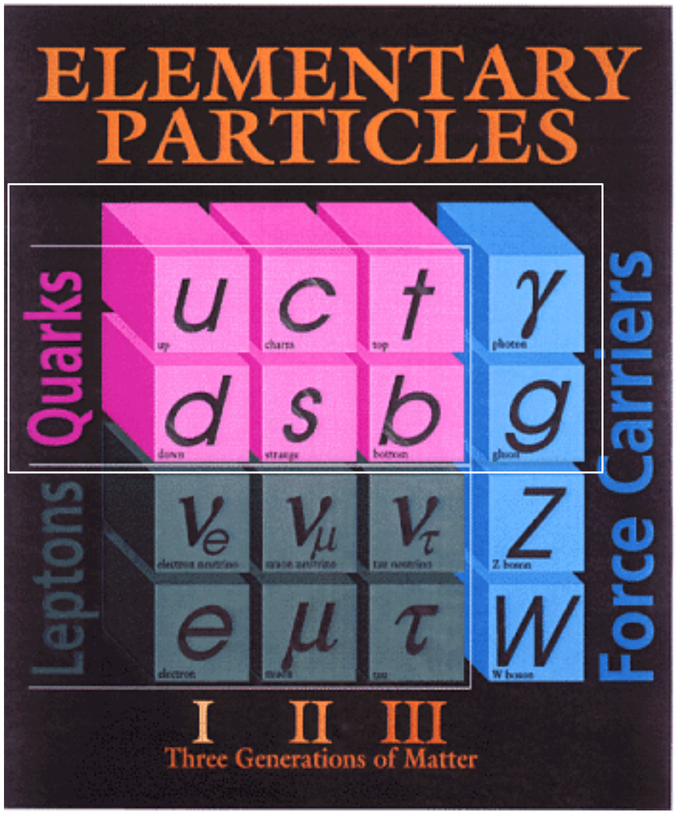
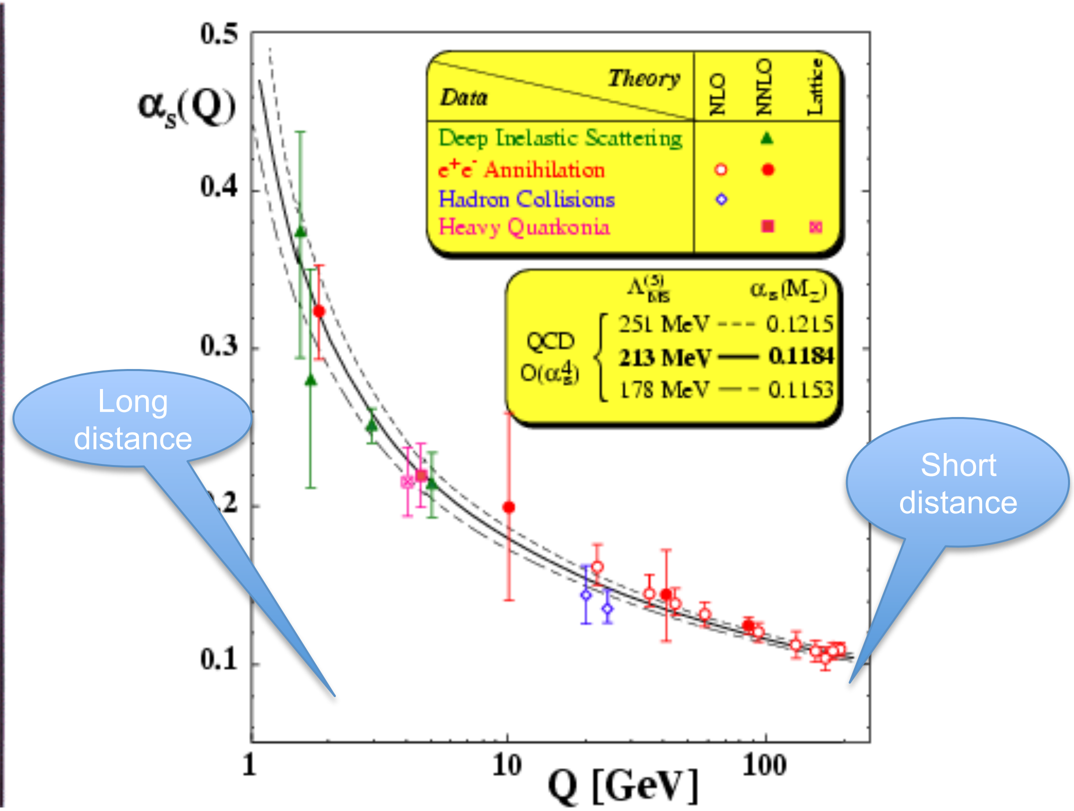
Many Thanks to the STAR Group at VECC!

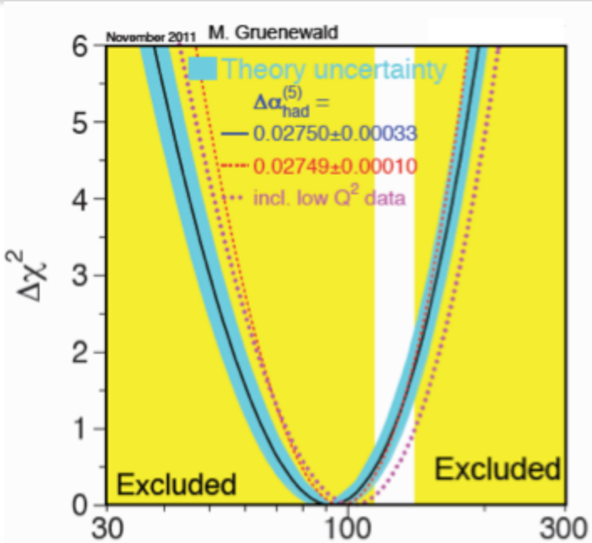
Quantum ChromoDynamics

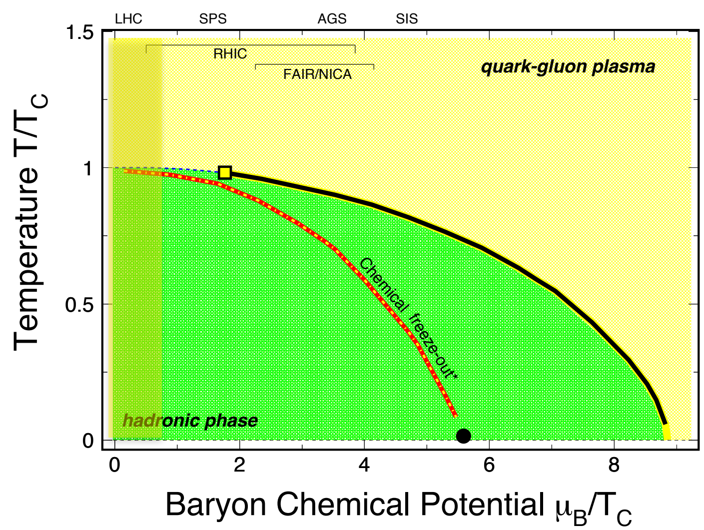




1) QCD is the basic theory for strong interaction. Its degrees of freedom are well defined at short distance.
2) Little is known regarding the dynamical structures of matter that made from ***q, g***. *E.g. the confinement*, *nucleon spin*, the ***QCD phase structure***... Large $\boldsymbol{\alpha_s}$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

QCD in Twenty-One Century





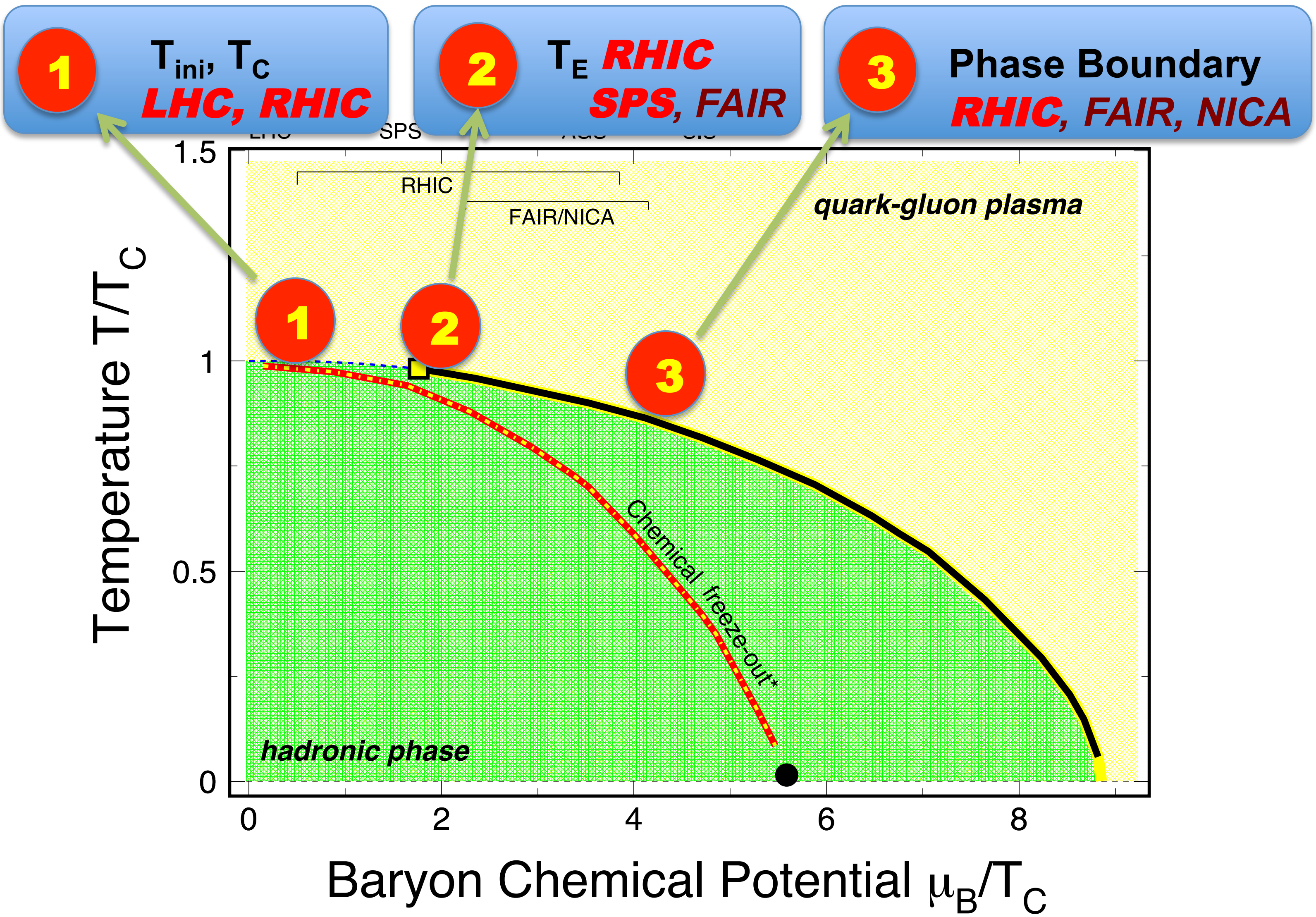
(1) Higgs Particle –

- Origin of Mass
- SM ➔ The *Theory*

(2) QCD Phase Structure –

- Critical point, phase boundaries
- Confinement
- χ_C symmetry
- Nucleon helicity structure
- …
- Non-linear QCD
- …
- String theory
- Emerging properties

The QCD Phase Diagram and High-Energy Nuclear Collisions



Outline

(1) Introduction

(2) Recent Results and RHIC Beam Energy Scan

(3) Near Future Plan(s)

(4) My Wish list

STAR Collaboration

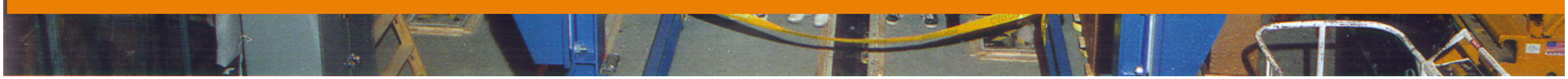
STAR Experiment at RHIC

(http://www.star.bnl.gov/)

Fundamental Science: particle physics, nuclear physics, astrophysics, cosmology, …

State of Art Technology: detector R&D, simulations, IT, computing, mass/fast data managing, …

- 550 scientists
- 53 institutes
- 12 countries
~ 150 PhD thesis completed since 2001



STAR Detectors ***Fast*** *and* ***Full*** *azimuthal particle identification*

MRPC Time Of Flight

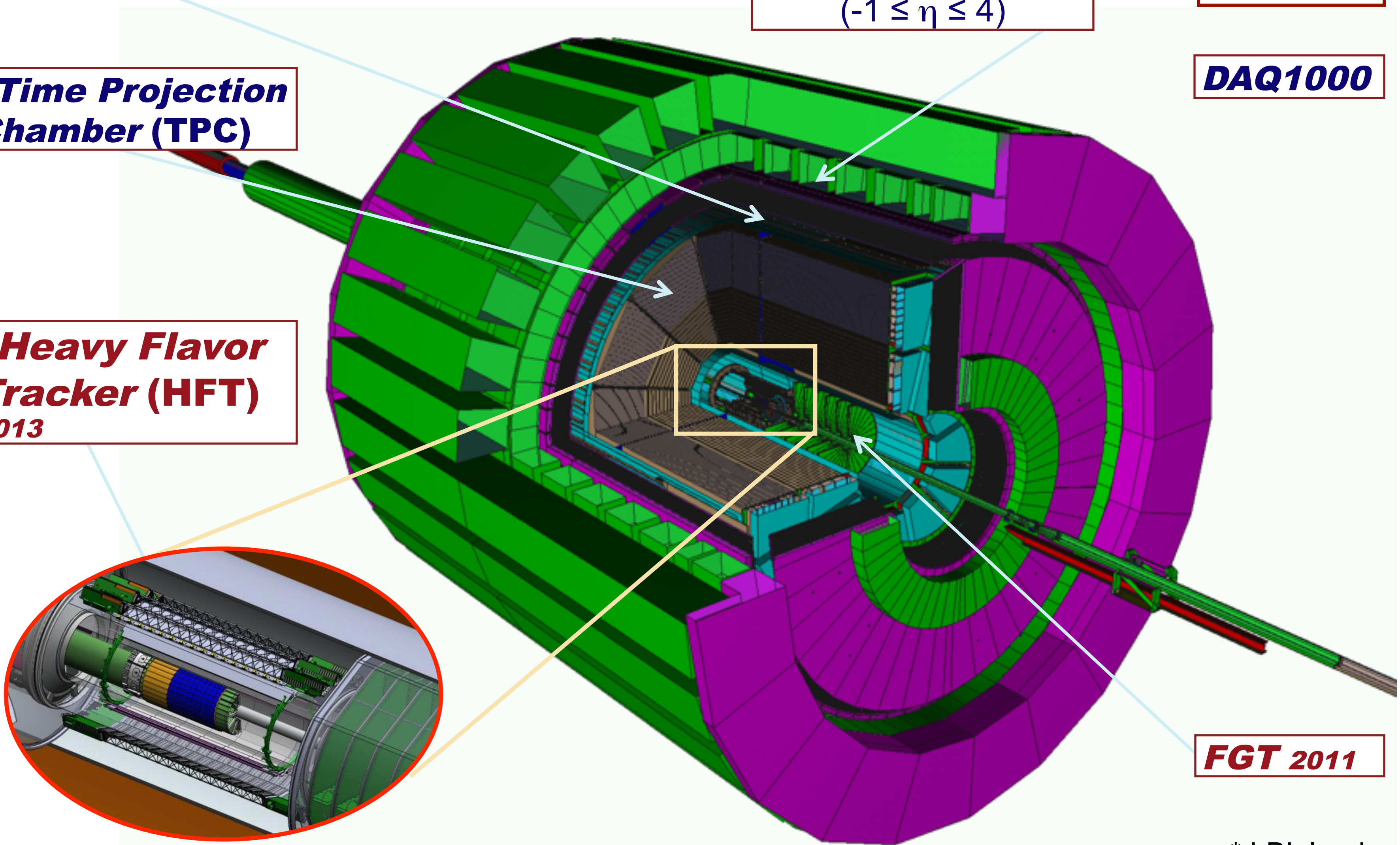
EMC+EEMC+FMS
$(-1 \leq \eta \leq 4)$

***MTD** 2013*

DAQ1000

****Time Projection Chamber*** **(TPC)**

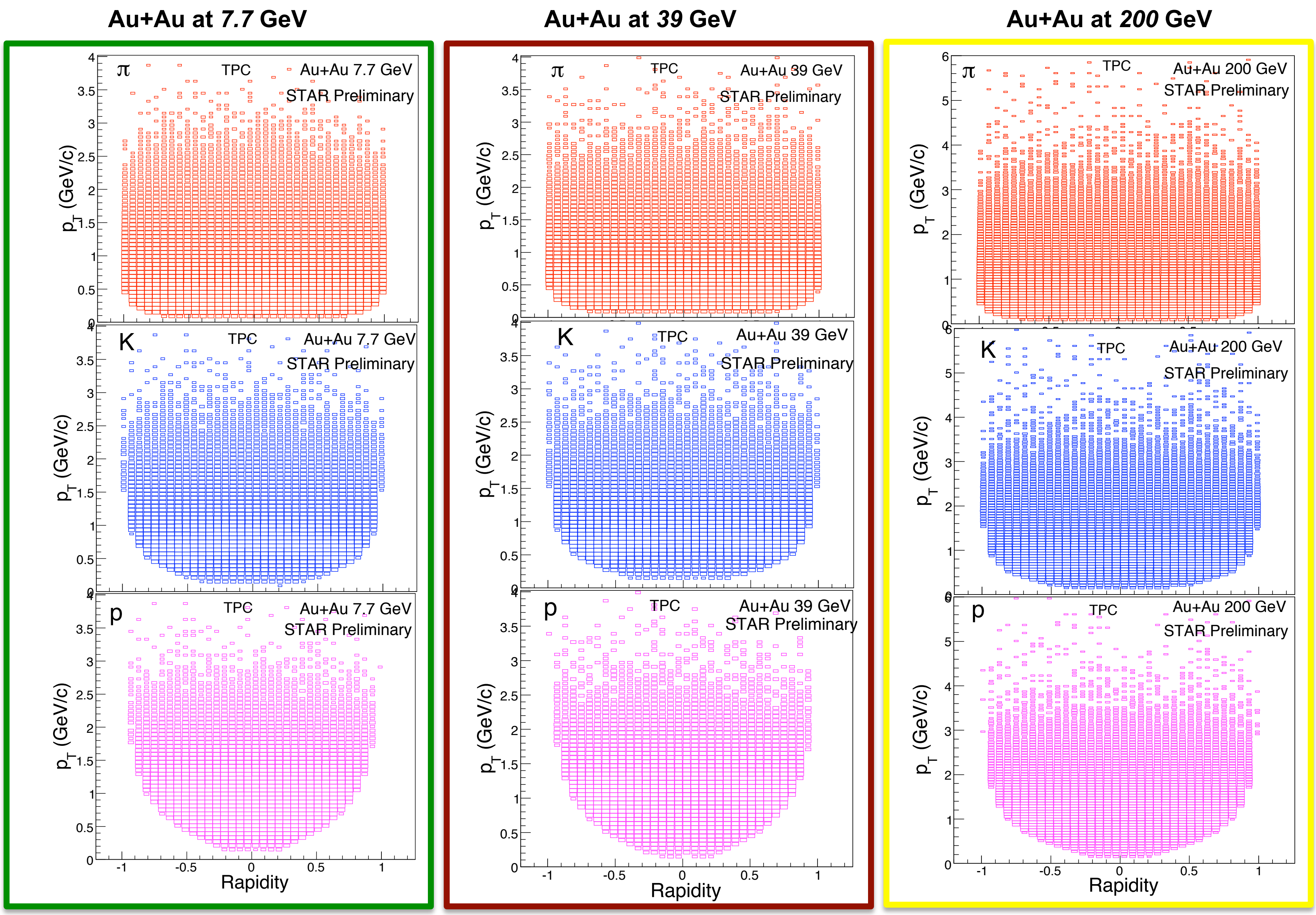
****Heavy Flavor Tracker*** **(HFT)**
2013



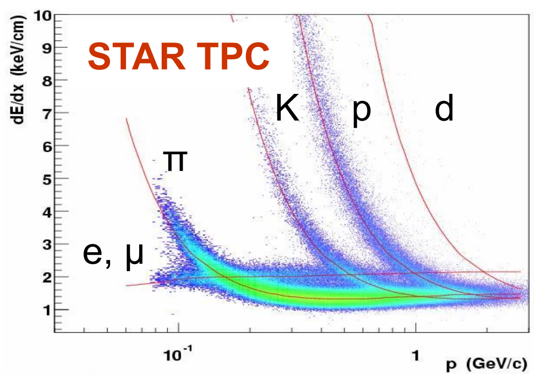
***FGT** 2011*

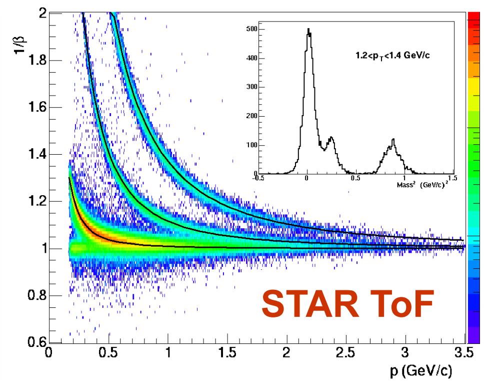
* LBL leads

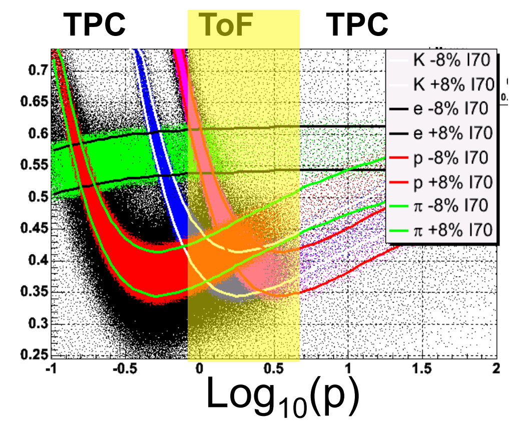
PID: ($\pi^{\pm}$, $K^{\pm}$, p) from Au+Au Collisions at 7.7, 39, 200 GeV

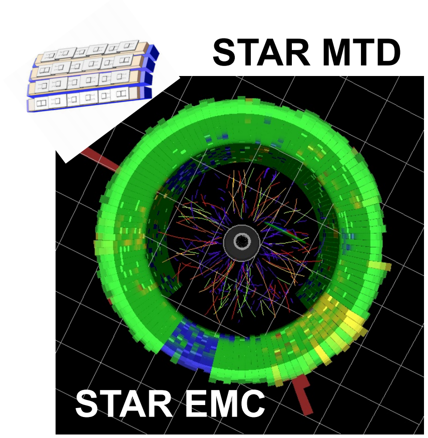


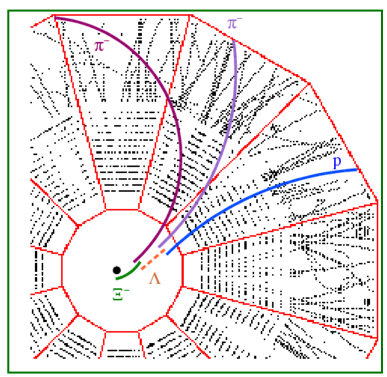
Particle Identification at STAR

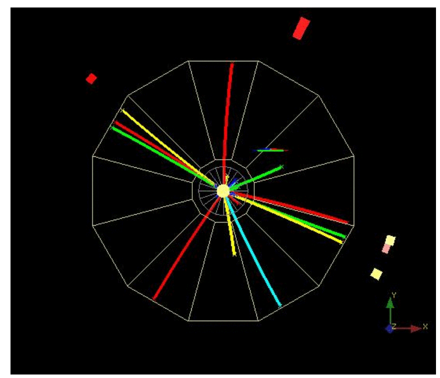


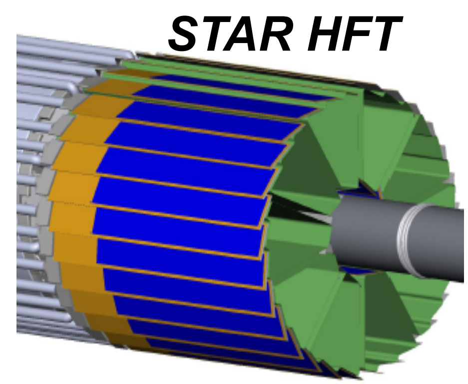








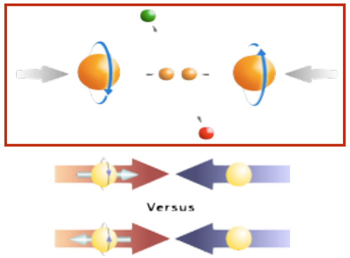


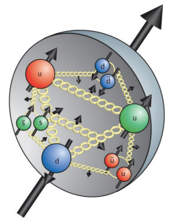


Neutral particles | **Strange hyperons** | **Jets** | **Heavy Quark Hadrons**

Multiple-fold correlations for both HI and Spin physics!

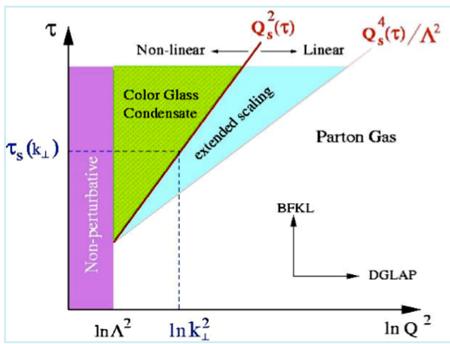
RHIC Physics Focus





Polarized *p+p* program

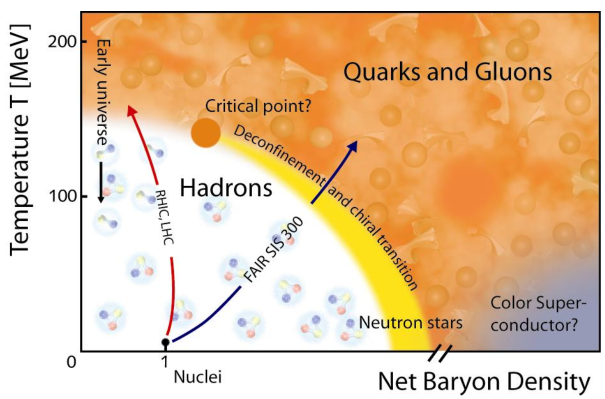
- Study ***proton intrinsic properties***



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

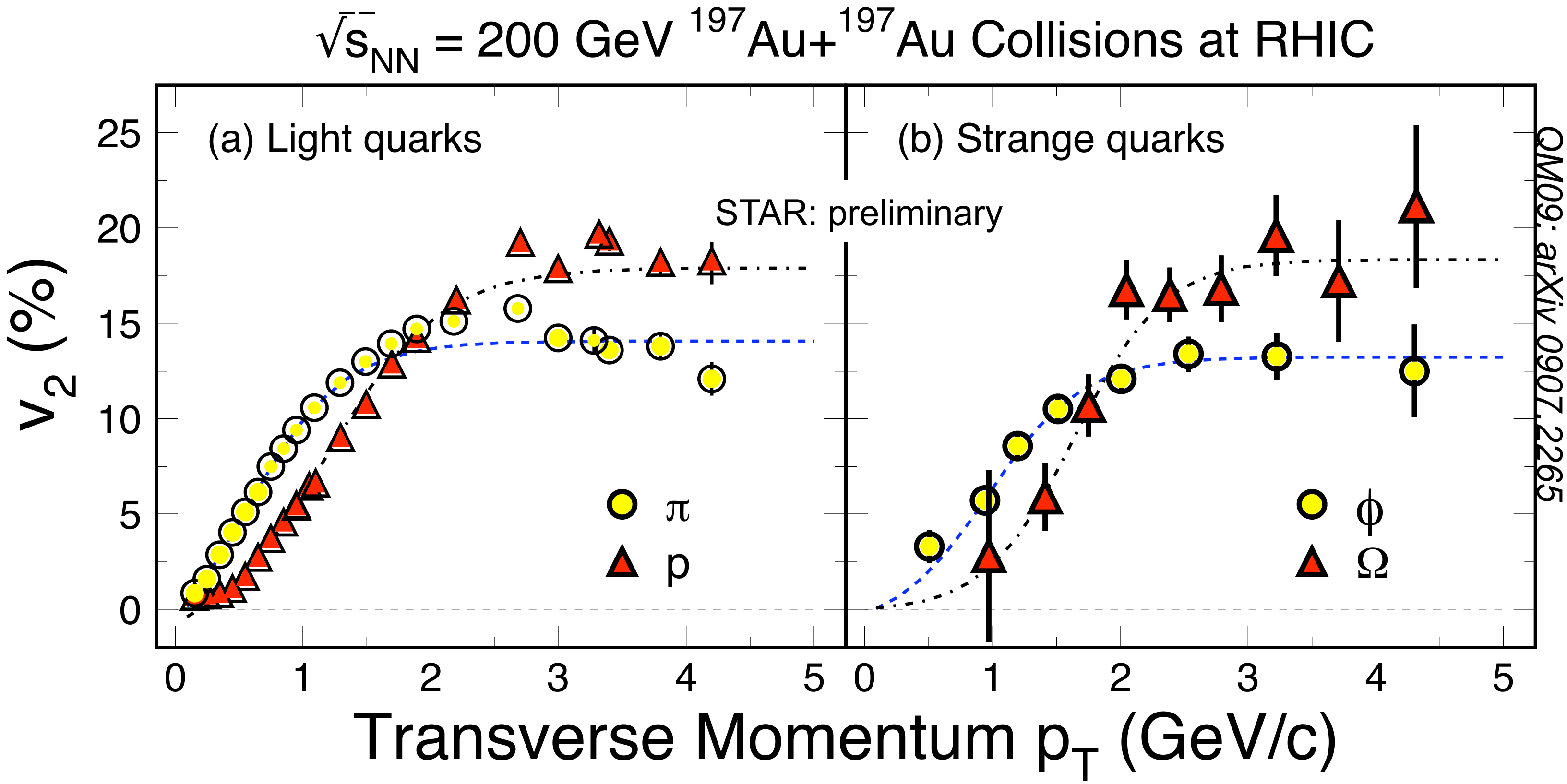
- Study ***medium properties, EoS***
- pQCD in hot and dense medium

2) RHIC beam energy scan (BES)

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

2) New Form of Matter at RHIC and Results from the Beam Energy Scan

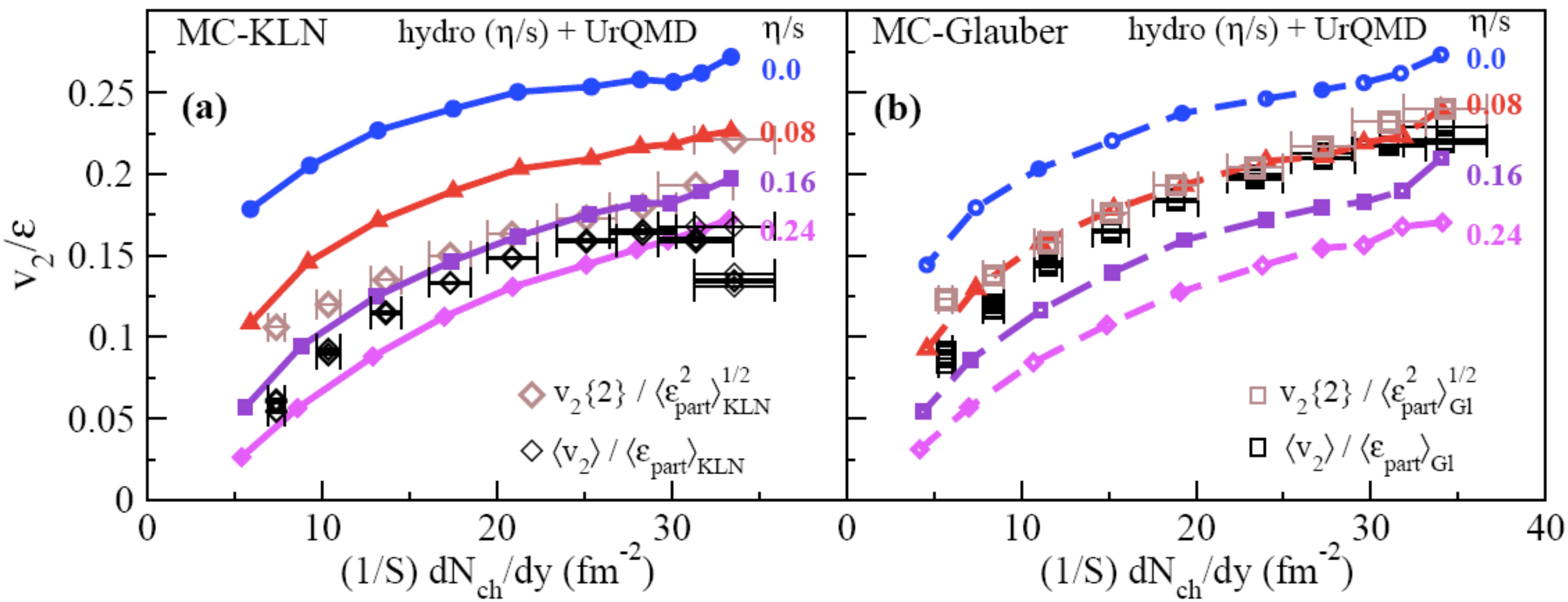
Partonic Collectivity at RHIC



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!***

Comparison with Model Results

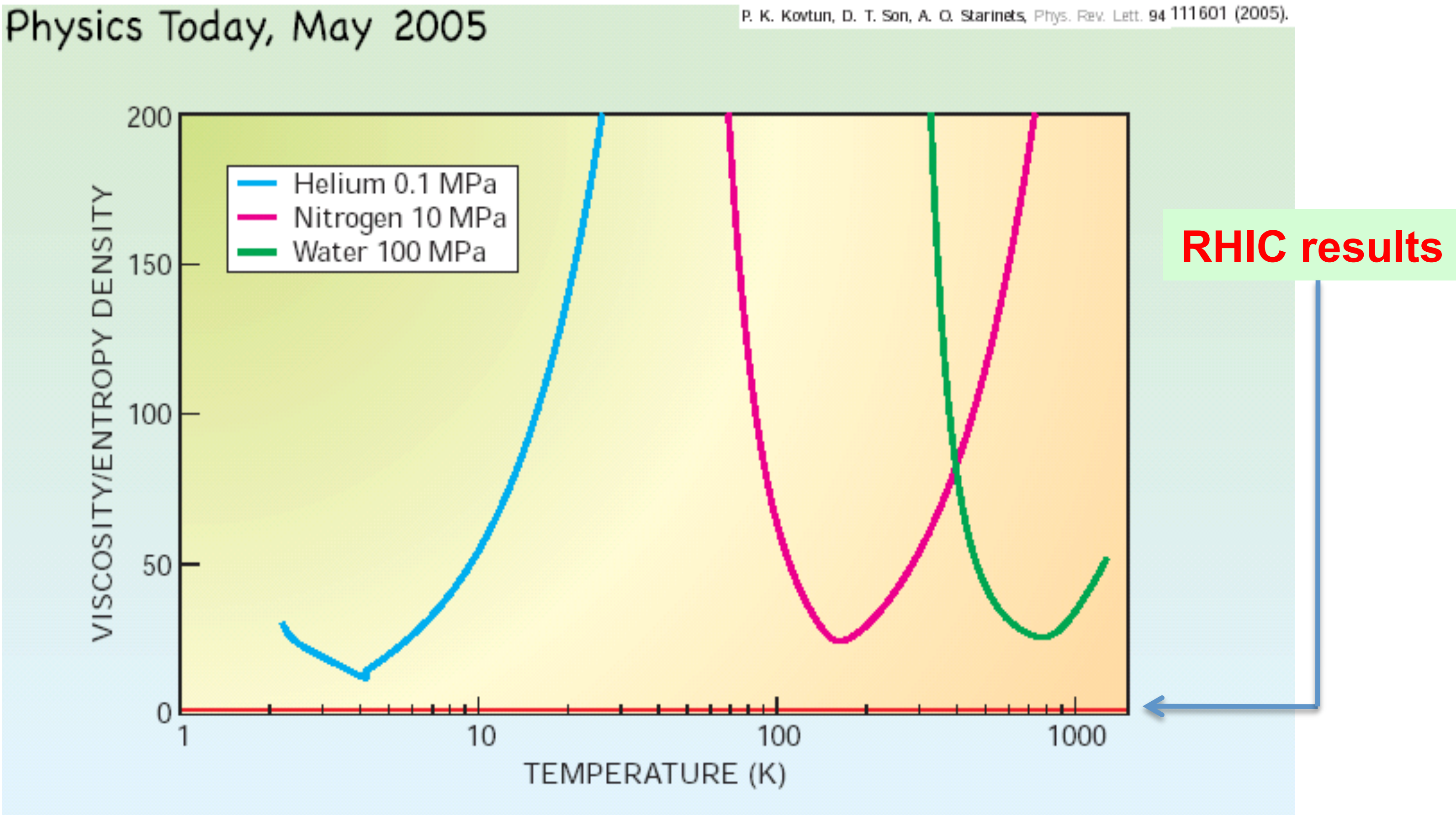


➔ ***Small value*** of specific viscosity over entropy ***η/s***

➔ Model uncertainty dominated by ***initial eccentricity ε***

Model: Song *et al. arXiv:1011.2783*

Low *η/s* for QCD Matter at RHIC



1) $\eta/s \geq 1/4\pi$

2) η/s(QCD matter) << η/s(QED matter)

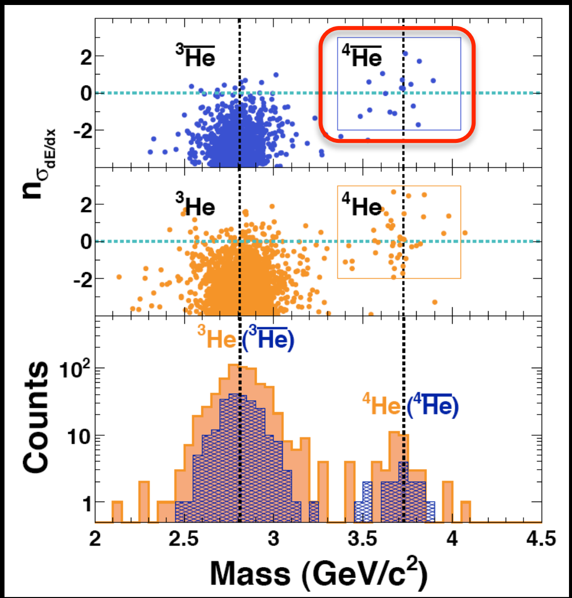
Antimatter Discoveries at RHIC

nature April, 2011

"Observation of the Antimatter Helium-4 Nucleus"

*by **STAR Collaboration***

***Nature**, 473, 353(2011).*

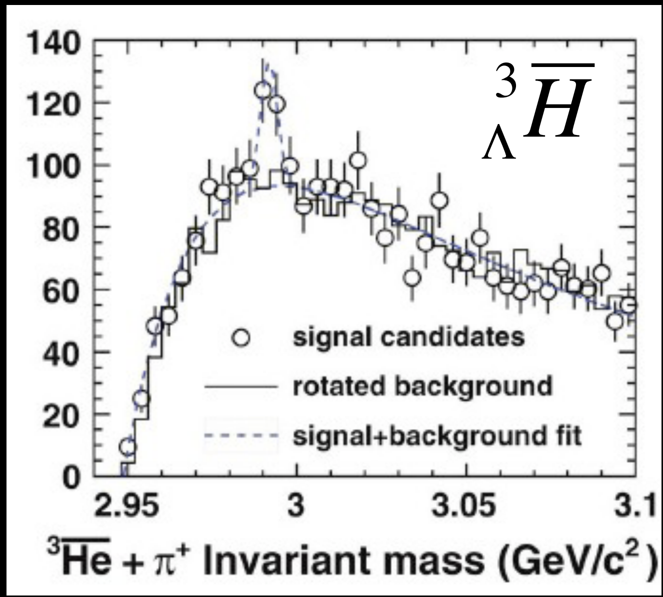


Science March, 2010

"Observation of an Antimatter Hypernucleus"

*by **STAR Collaboration***

***Science**, 328, 58(2010).*



$\bar{\alpha}$: Top-100 Physics in 2011

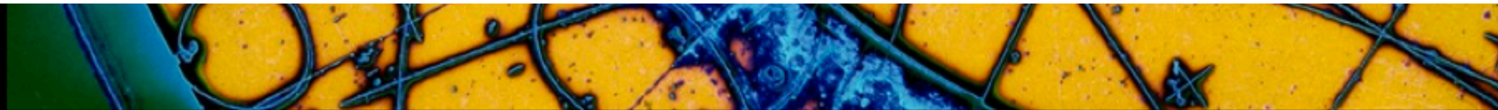


Image: CERN

The Top 10 Physics and Math Stories of 2011

1. **Faster than the Speed of Light:** Runaway subatomic particles seem to be breaking the cosmic speed limit. If the results hold up, physicists have some explaining to do.

14. **Astronomers Watch Black Hole Devour Star:** Researchers luck out, getting a front row seat for stellar annihilation.

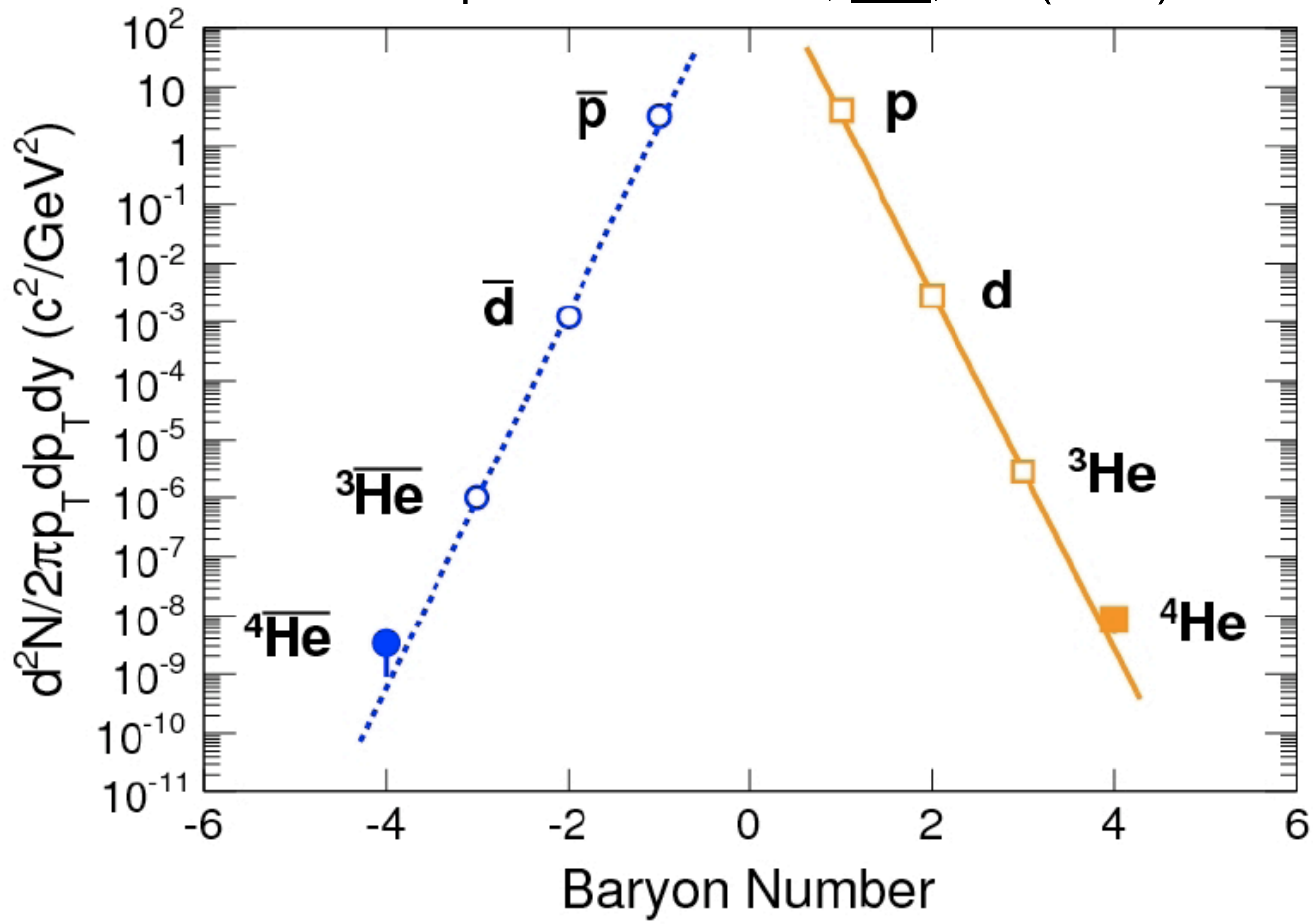
20. **Helium's Antimatter Twin Created:** Scientists catch particle only created once every 28 billion times nuclei are smashed together.

Discovery Magazine:

http://discovermagazine.com/photos/19-top-100-stories-of-2011

Light Nuclei Productions at RHIC

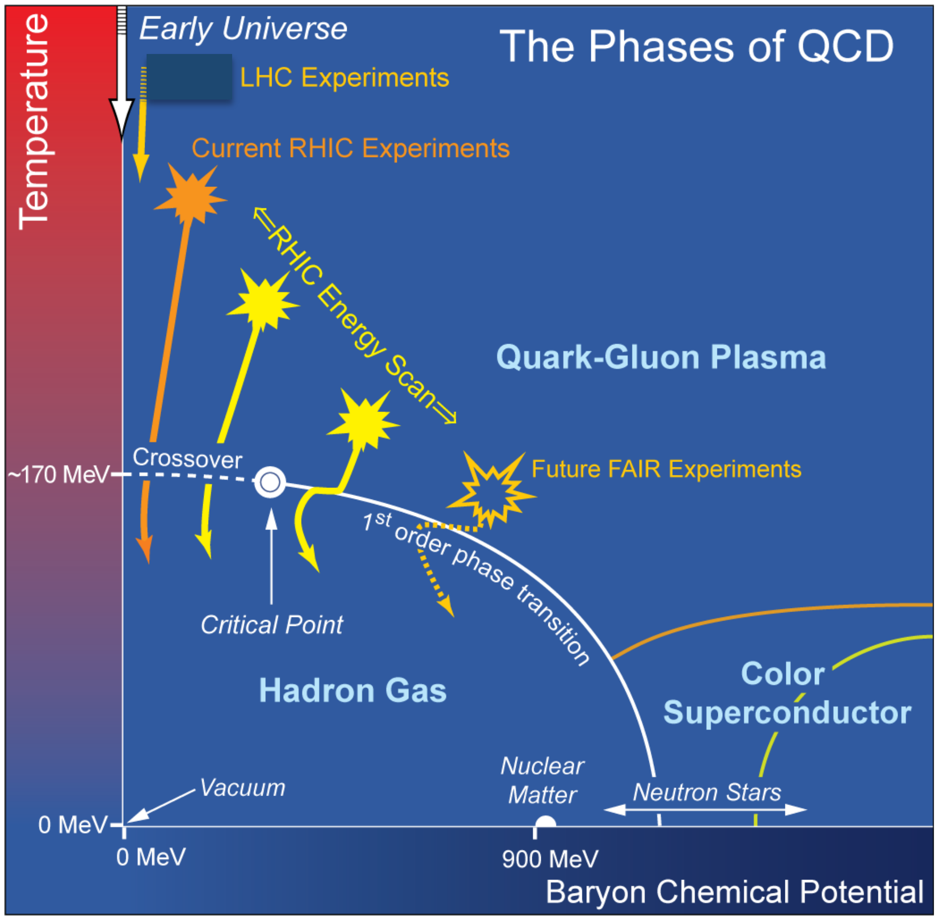
STAR Experiment: ***Nature***, **<u>473</u>**, 353(2011)



1) In high-energy nuclear collisions, **N(d) >> N(α)**:
   QGP ➔ (anti)light nuclei via coalescence
2) In the Universe, **N(d) << N(α): N(anti-α)?**

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

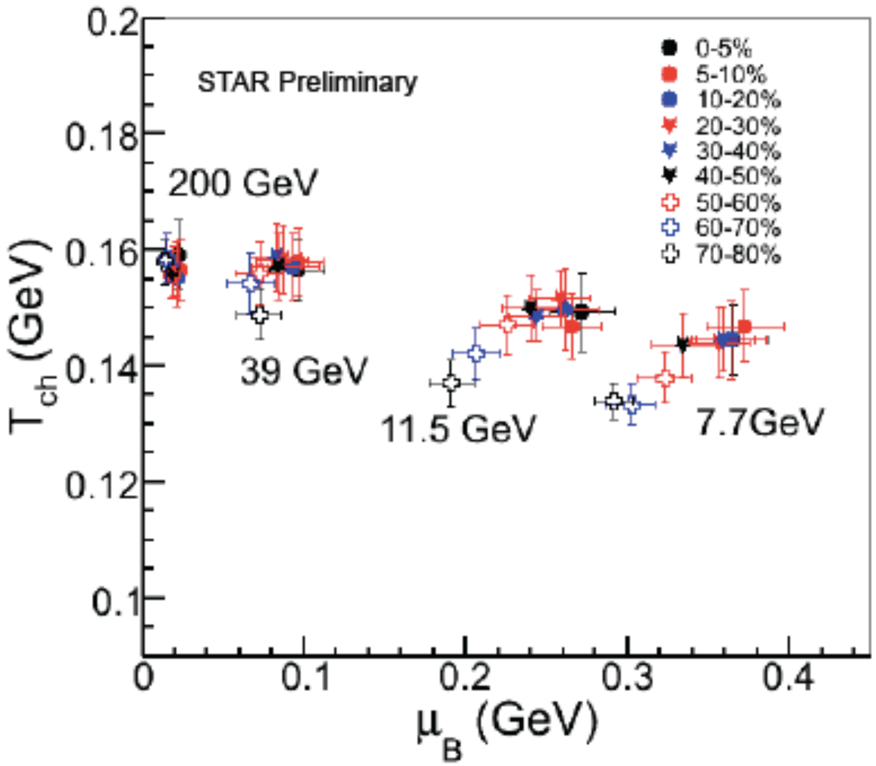
(4) v_2 - NCQ scaling:
partonic vs. hadronic dof

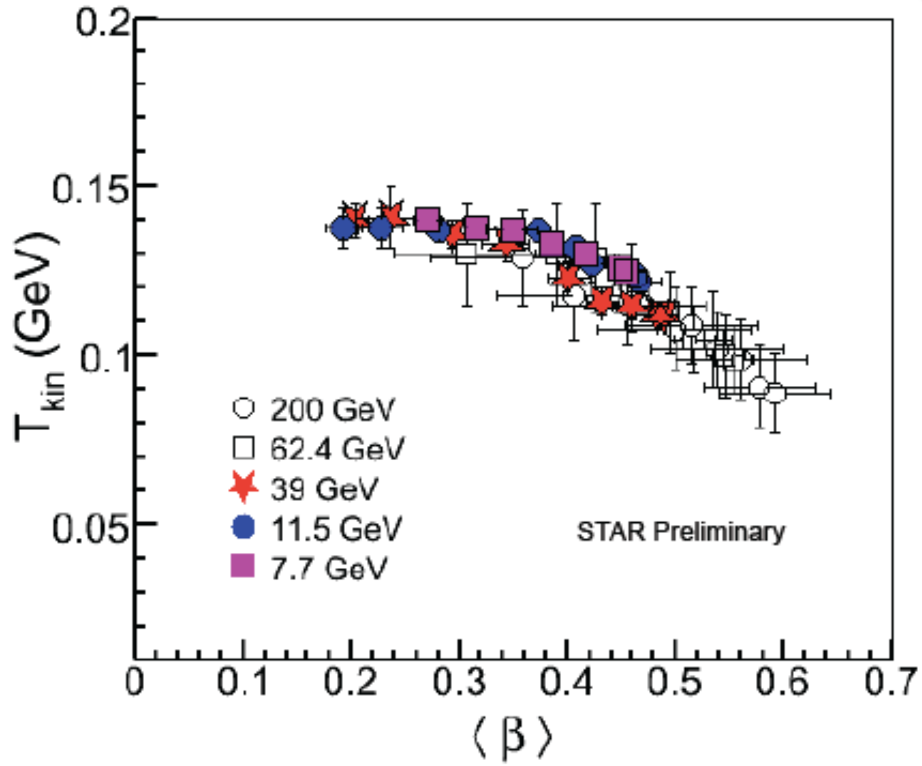
(5) Fluctuations:
Critical point, correl. length

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

- *arXiv:1007.2613*

Bulk Properties at Freeze-out





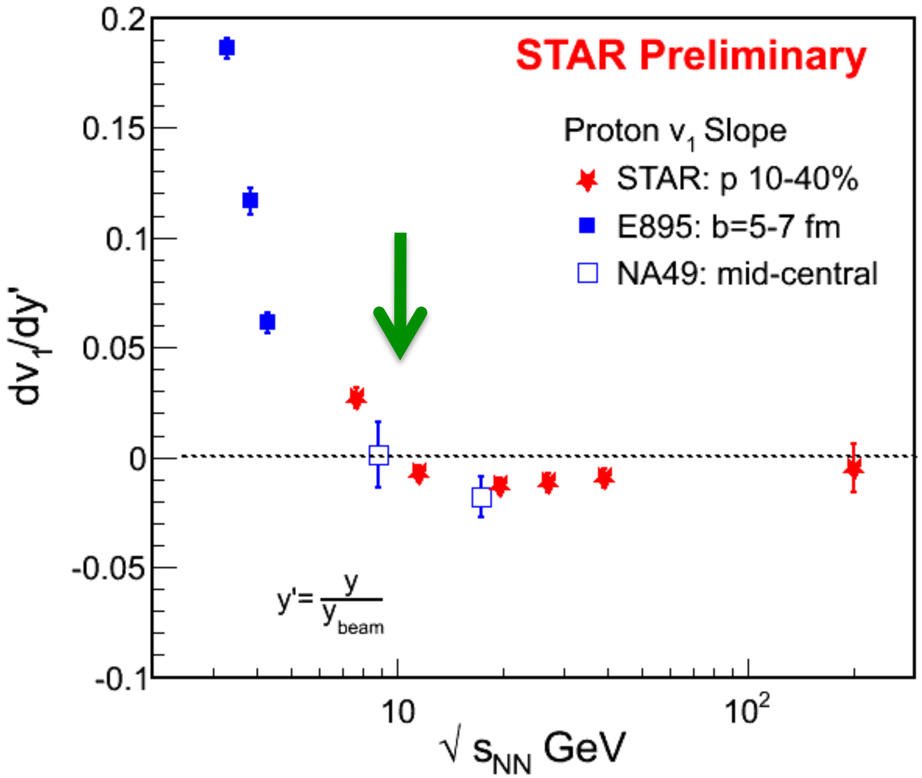
Chemical Freeze-out:

- 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
- Little energy dependence.

Mid-y v_1 slope vs. $\sqrt{s_{NN}}$



Mid-y v_1 is sensitive to:

- Nuclear stopping
- The mixture of initial and produced particles
- Equation of state (EOS)

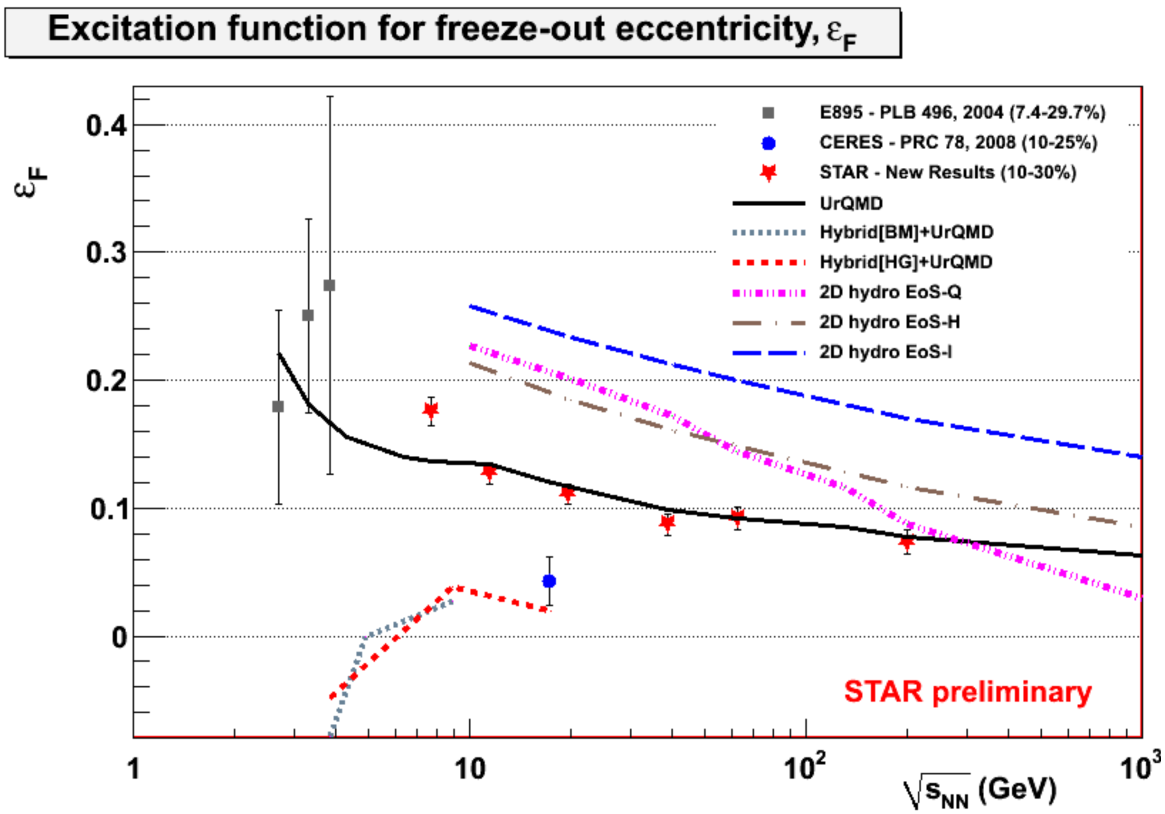
At low beam energy, initial nucleons are dominant, $v_1 > 0$, by definition

At higher beam energies, produced particles dominate the dynamics. Due to expansion, the sign of v_1 reverses

(1) The sign change occurs between $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV indicating significant change in the EOS around these beam energies

(2) Transport models can *NOT* reproduced the trend and change properly

Azimuthally Sensitive HBT vs. $\sqrt{s_{NN}}$



Freeze-out eccentricity w.r.t reaction plane:

$$\varepsilon_{f.o.} = 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

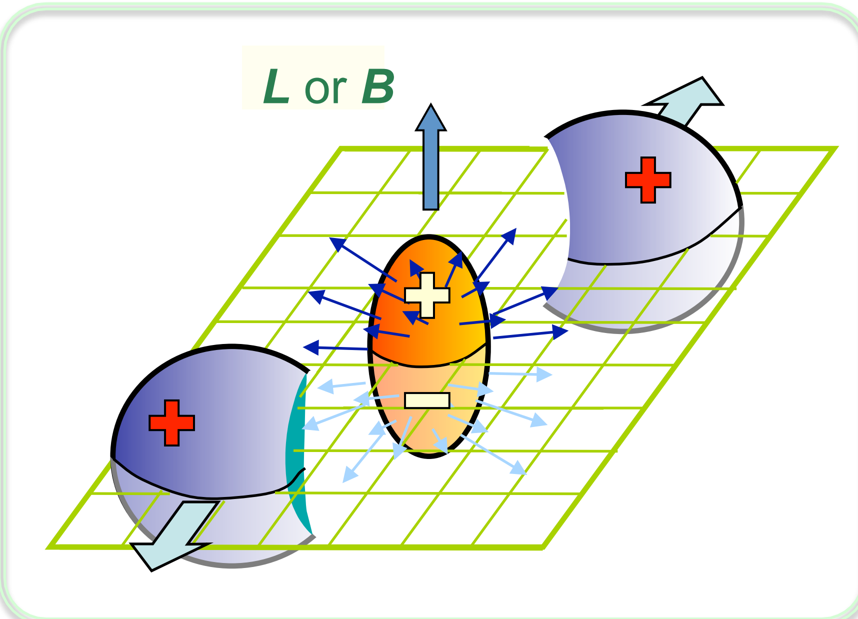
$$= \frac{R_Y^2 - R_X^2}{R_Y^2 + R_X^2}$$

E895: PLB 496 (2000) 1
CERES: PRC 78 (2008) 064901
STAR: PRL 93 (2004) 012301

From $\sqrt{s_{NN}}$ = 2.5 200 GeV, smooth trend observed for the freeze-out eccentricity $\varepsilon_{f.o.}$, as ***predicted*** by the transport model URQMD.

Search for Local Parity Violation

in High Energy Nuclear Collisions



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

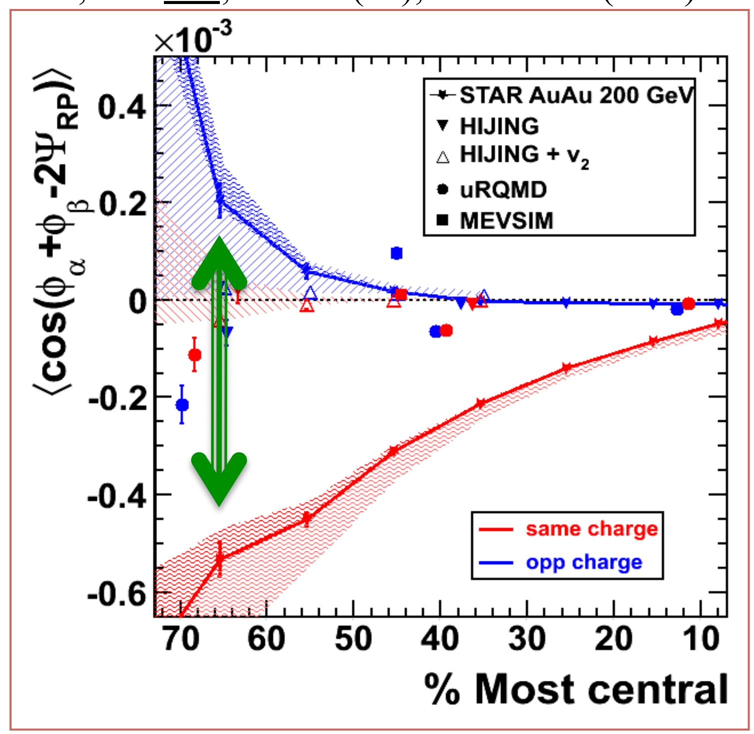
- **Strong external EM field**
- ***De-confinement* and *Chiral symmetry restoration***

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

Parity even observable

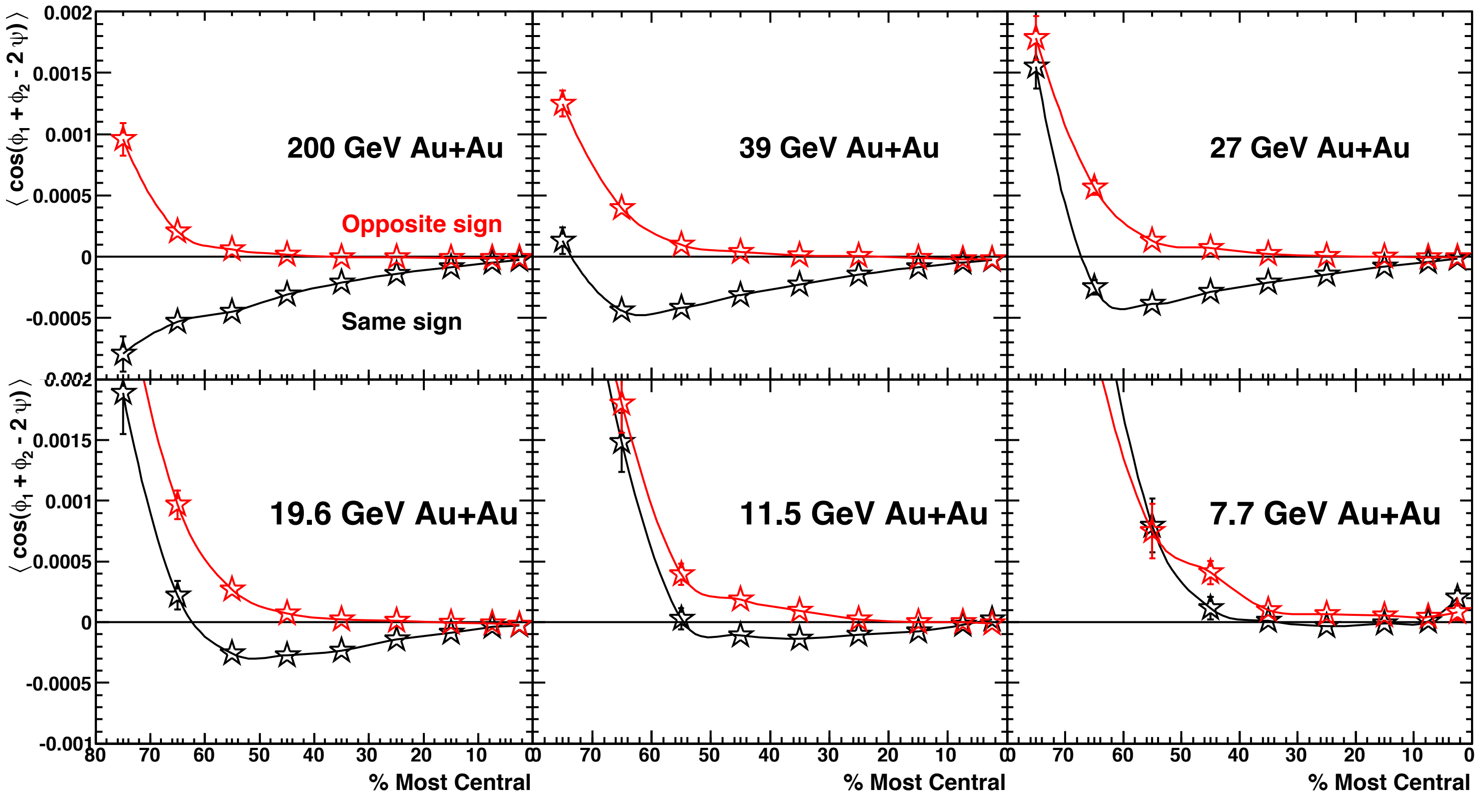
Voloshin, PR C62, 044901(00).

STAR; PRL**103**, 251601(09); 0909.1717 (PRC).



Future tests with Beam Energy Dependence & U+U collisions

Dynamical Correlations (I)

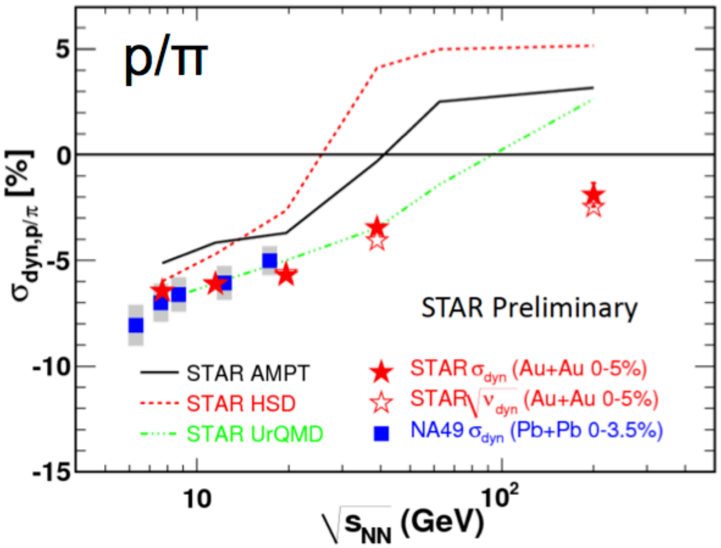


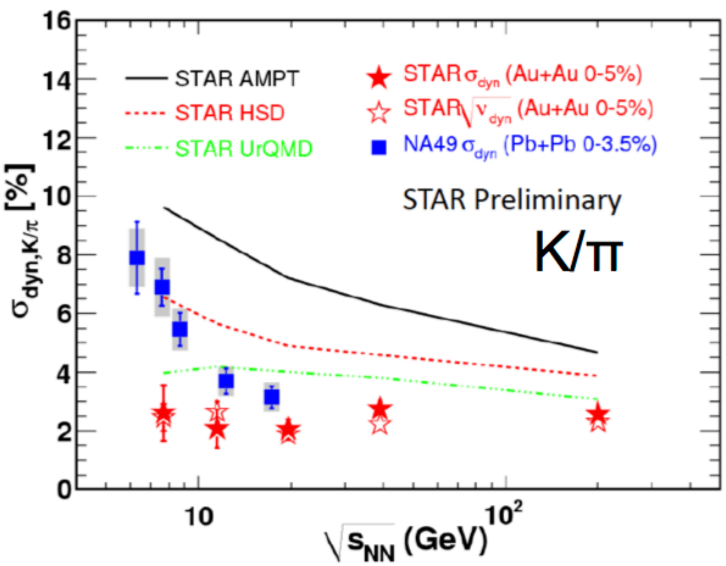
(1) Below $\sqrt{s_{NN}}$ = 11.5 GeV, the splitting between the same- and opposite-sign charge pairs disappeared

(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

Dynamical Correlations (II)

E-by-E PID Yield Ratios





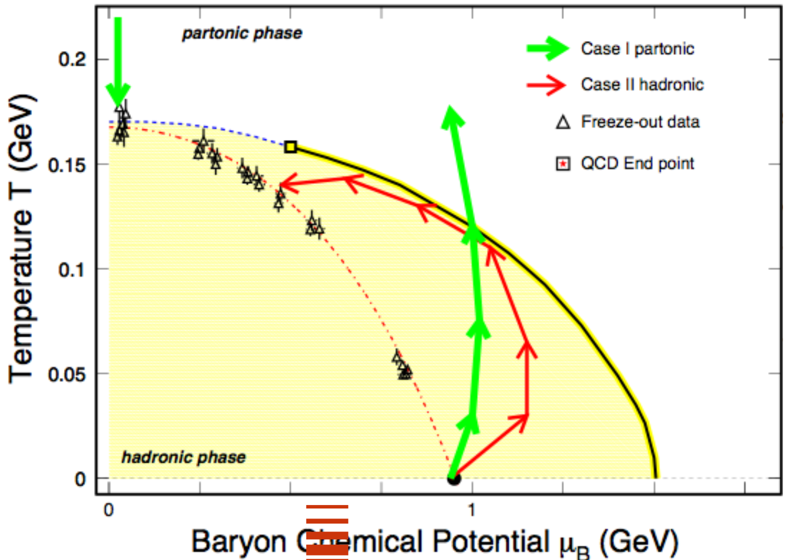
Au + Au collisions at RHIC

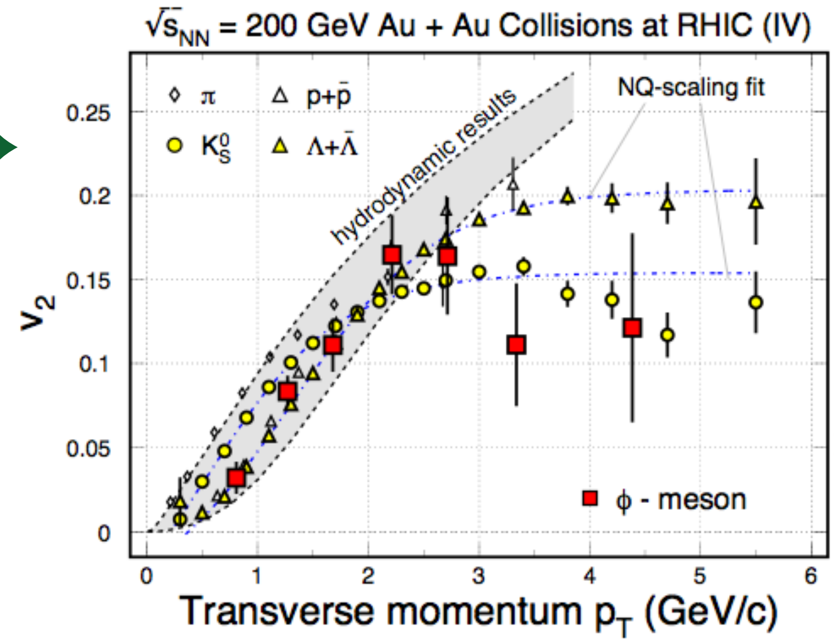
(1) Historical observable: Ratios of identified particle yields.

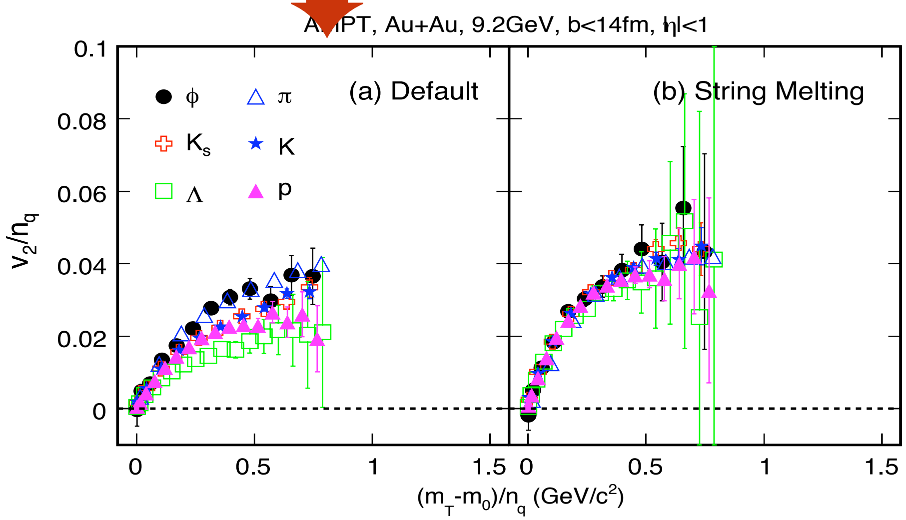
(2) In the observed energy range: $\sqrt{s_{NN}}$ = 7.7 - 200 GeV, both baryon/pion and Strangeness/pion ratios vary smoothly as predicted by the transport model URQMD.

(3) No strong enhancement in the strangeness ratio in new data.

Observable*: NCQ Scaling in v_2







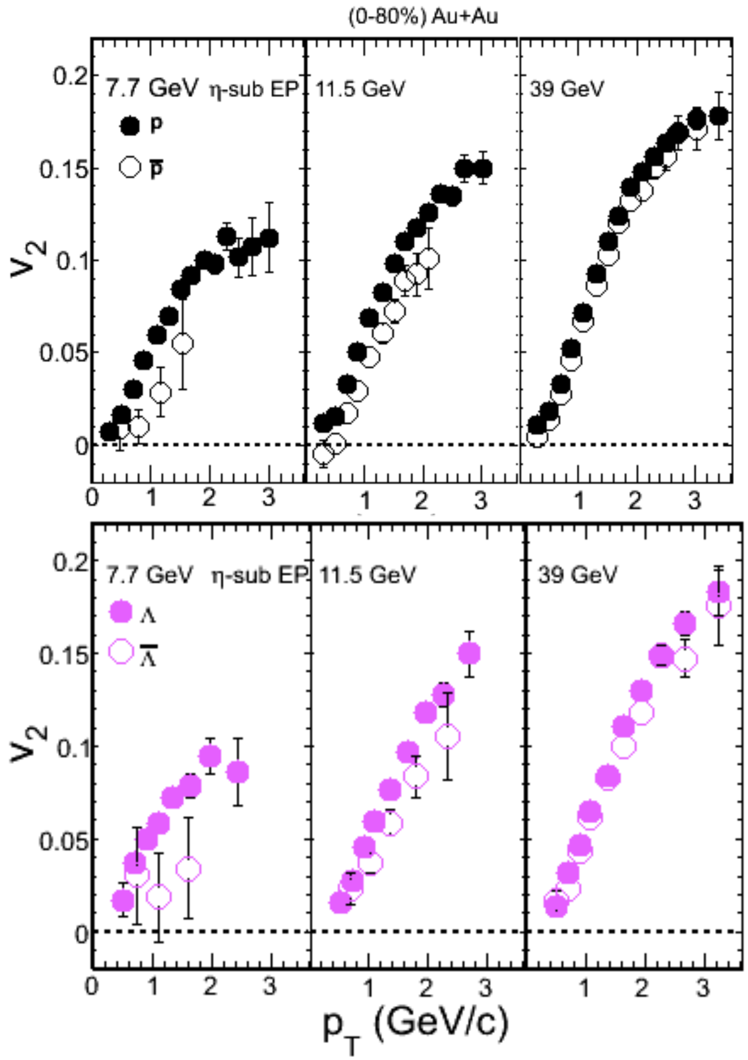
STAR Collaboration

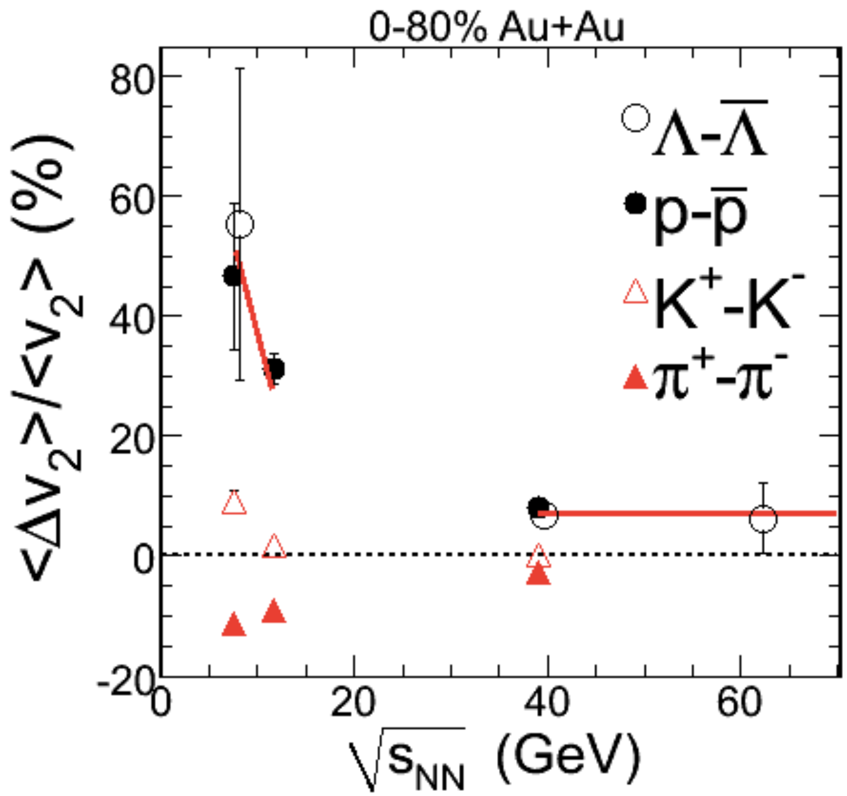
- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi,\ \pi\pi}$

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

*** Thermalization is assumed!**

Particle and Anti-particle v_2 vs. $\sqrt{s_{NN}}$



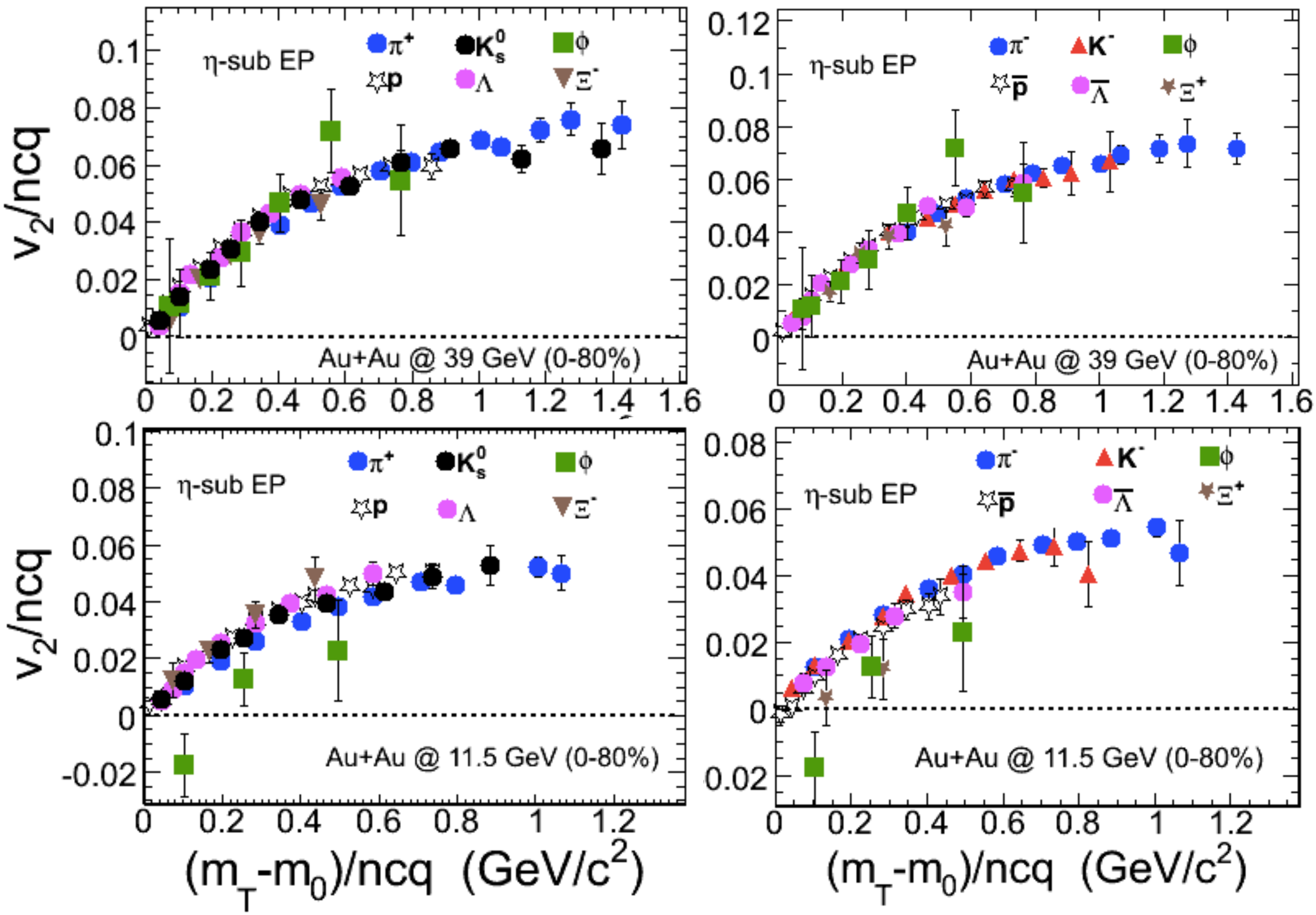


At $\sqrt{s_{NN}} \leq$ *11.5 GeV:*
- v_2(baryon) > v_2(anti-baryon)
- v_2(π^+) < v_2(π^-)
- v_2(K^-) < v_2(K^+)

STAR: Quark Matter 2011

Hadronic interactions are dominant

ϕ-meson v_2



The φ v_2 falls off trend from other hadrons at 11.5 GeV

Susceptibilities and Moments

Thermodynamic function:

$$\frac{p}{T^4} = \frac{1}{\pi^2} \sum_i d_i (m_i / T)^2 K_2(m_i / T) \cosh[(B_i \mu_B + S_i \mu_S + Q_i \mu_Q)/T]$$

The susceptibility: $T^{n-4}\chi_q^{(n)} = \frac{1}{T^4} \frac{\partial^n}{\partial\left(\mu_q / T\right)^n} P\left(\frac{T}{T_C}, \frac{\mu_q}{T}\right)\Big|_{T/T_C}, \qquad q = B,Q,S$

Conserved Quantum Number

$$\chi_q^{(1)} = \frac{1}{VT^3}\left\langle \delta N_q \right\rangle$$

$$\chi_q^{(2)} = \frac{1}{VT^3}\left\langle \left(\delta N_q\right)^2 \right\rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3}\left\langle \left(\delta N_q\right)^3 \right\rangle$$

$$\chi_q^{(4)} = \frac{1}{VT^3}\left(\left\langle \left(\delta N_q\right)^4 \right\rangle - 3\left\langle \left(\delta N_q\right)^2 \right\rangle^2\right)$$

$$\frac{T^2\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2$$

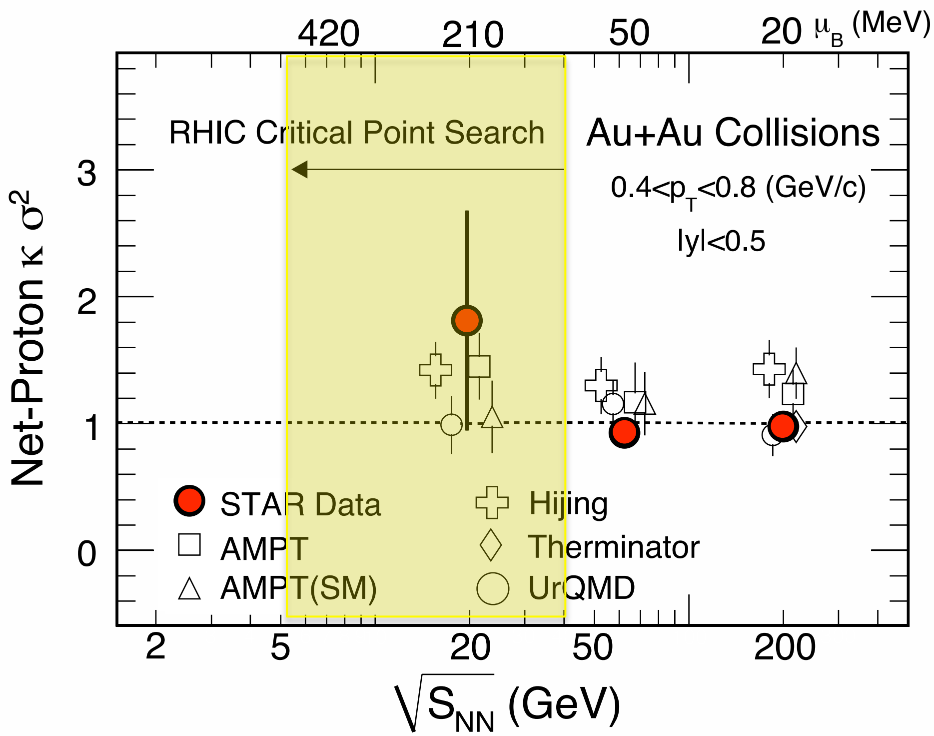
$$\frac{T\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma$$

Thermodynamic function ⇔ Susceptibility ⇔ Moments

Model calculations, *e.g.* LGT, HRG ⇔ Measurements

First Results on High Moments

STAR: *PRL*, ***105***, *22302(2010)*



Energy Scan in Au+Au collisions:

Run 10: 7.7, 11.5, 39 GeV
Run 11: 19.6, 27 GeV

1) Centrality averaged events. In this analysis, effects of volume and detecting efficiencies are all canceled out.

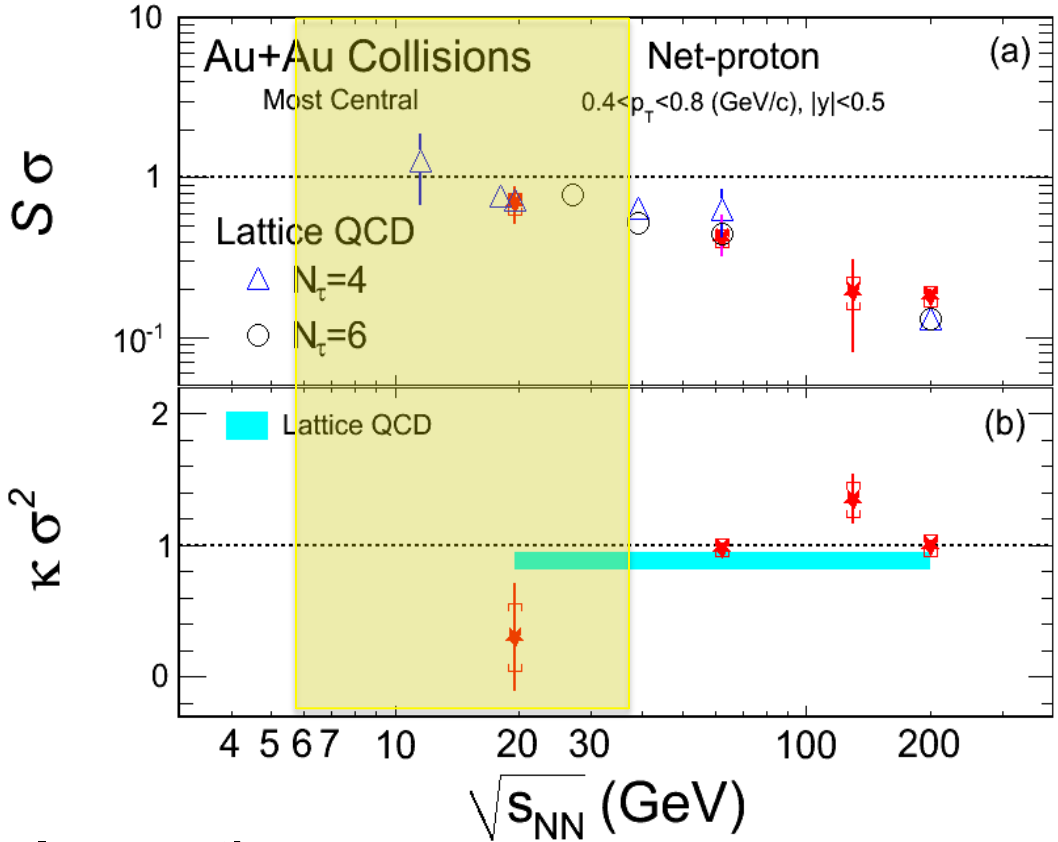
2) ALL transport model results values are higher than unity, except the Theminator result at 200GeV. LGT predicted values around 0.8-0.9, due to finite chemical potential effect.

3) Test of thermalization with higher moments.

4) **Critical point effect**: non-monotonic dependence on collision energy.

- STAR: PRL105, 22302(2010).
- F. Karsch and K. Redlich, arXiv:1007.2581

Comparing with LGT Results



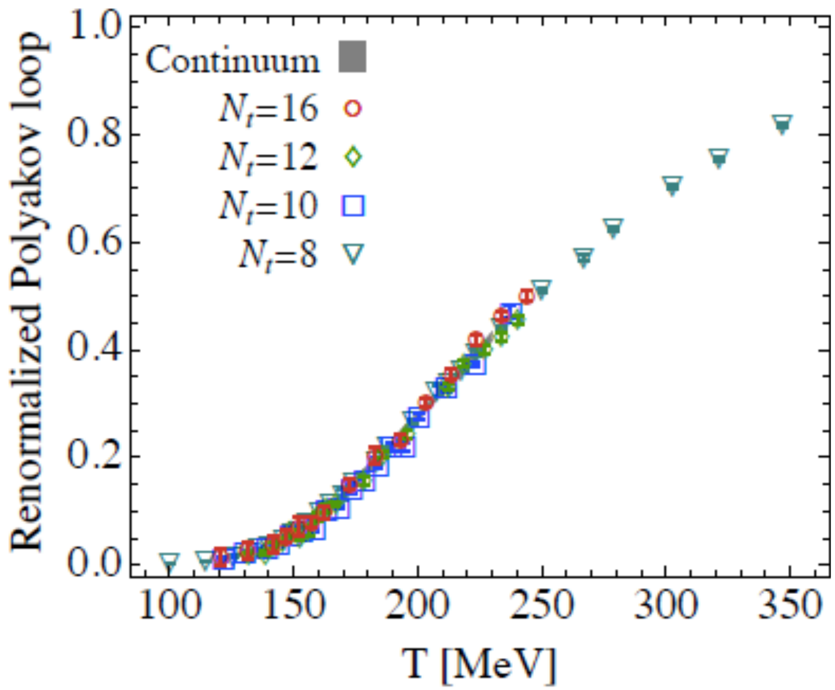
References:
- STAR, *PRL105, 22303(10)*
- R.V. Gavai and S. Gupta: *PLB696, 459(11)*
- S. Gupta *et al*, *Science, 332, 1525(2011)*

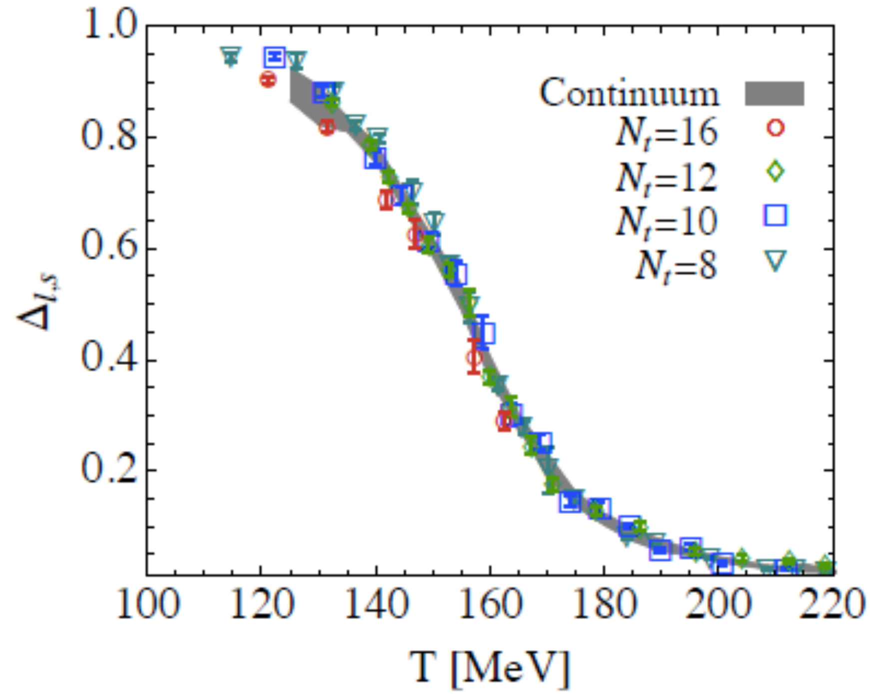
Assumptions:

(a) Freeze-out temperature is close to LGT T_C
(b) Thermal equilibrium reached in central collisions
(c) Taylor expansions, at $\mu_B \neq 0$, on LGT results are valid

➔ **Lattice results are consistent with data for 60 < $\sqrt{s_{NN}}$ < 200 GeV**
➔ **$T_C = 175^{+1}_{-7}$** (MeV)

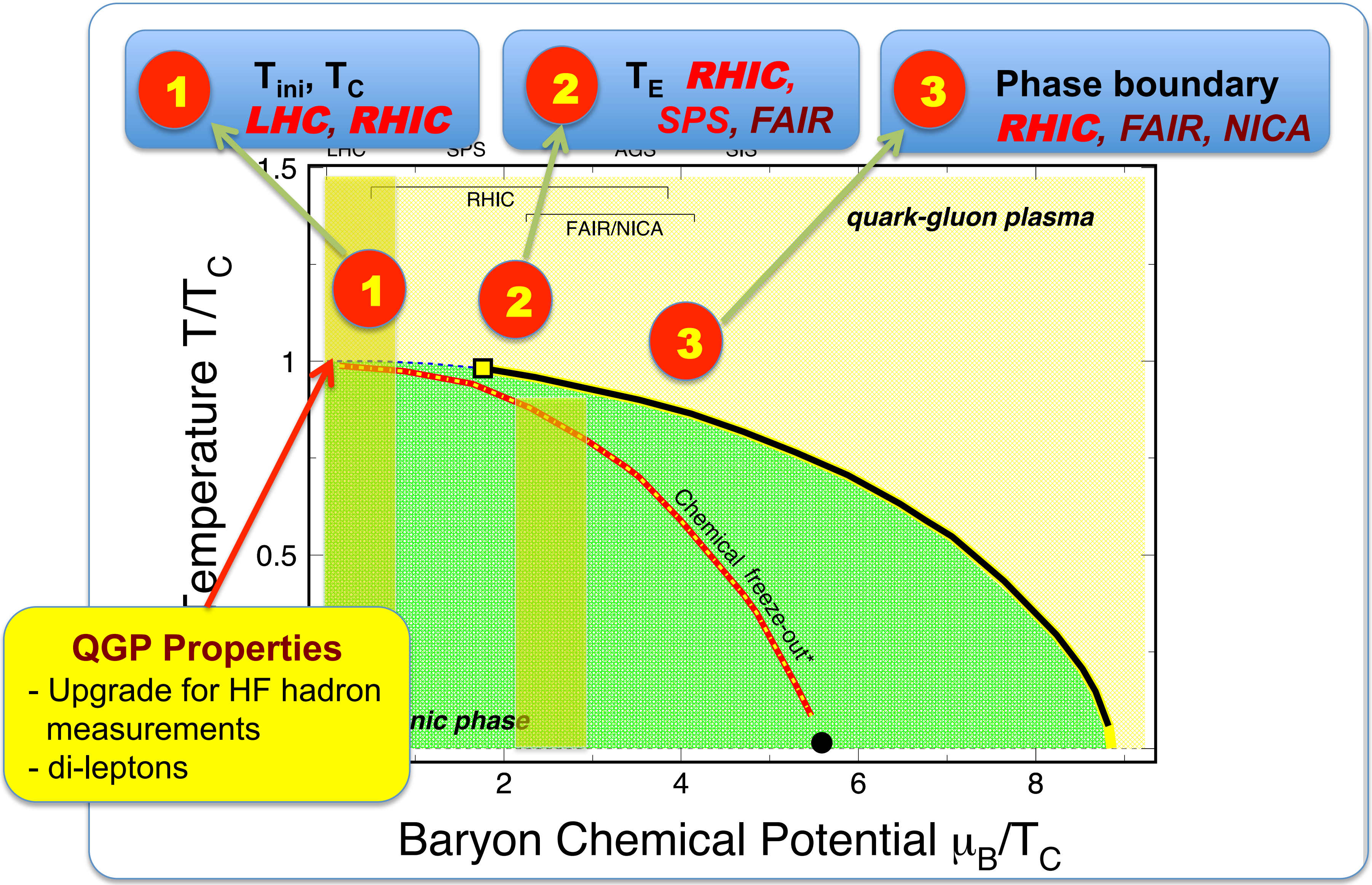
Lattice: Phase Transition Temperature





Action	Temperature
Polyakov Loop	**T_C^{conf} ~ 170 MeV**
Chiral Operator	**T_C^{Chiral} ~ 160 MeV**
RHIC Data	**T_C^{Exp} ~ 175^{+1}_{-7} MeV**
	(T_{CH}^{Exp} ~ 160±5 MeV)

Outlook: (7.7, 11.5, 15.5, 19.6, 27, 39,62, 200 GeV)



Summary

(1) In high-energy nuclear collisions, hot and dense ***matter, with partonic degrees of*** **freedom and collectivity, has been formed**

(2) The matter behavior like a ***quantum liquid with*** small ***η/s***

(3) Partonic matter ➔ **antimatter**: ${}^{3}_{\Lambda}\overline{H},\ {}^{4}\overline{He}$

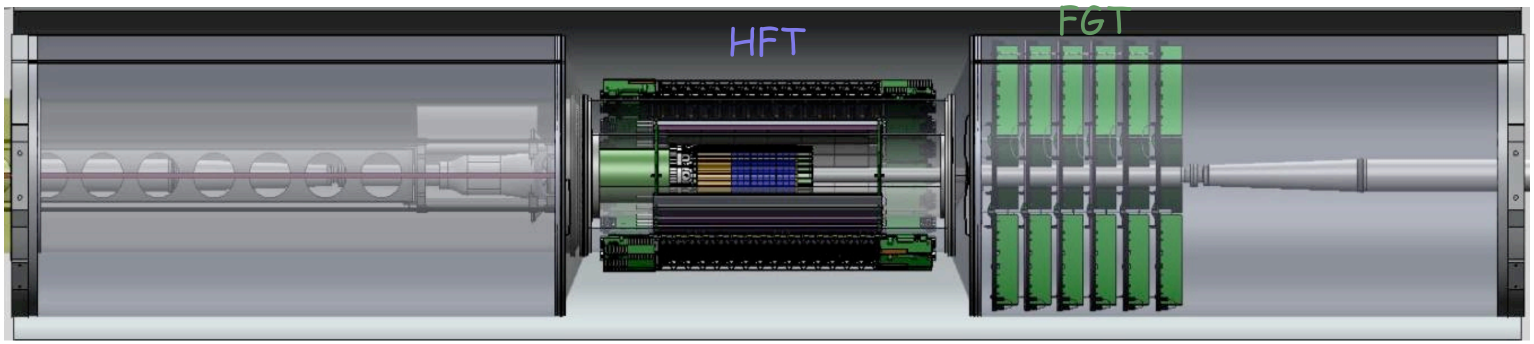
(4) **[partonic] <** $\boldsymbol{\mu_B}$ ***~110–320*** **(MeV) < [hadronic]**

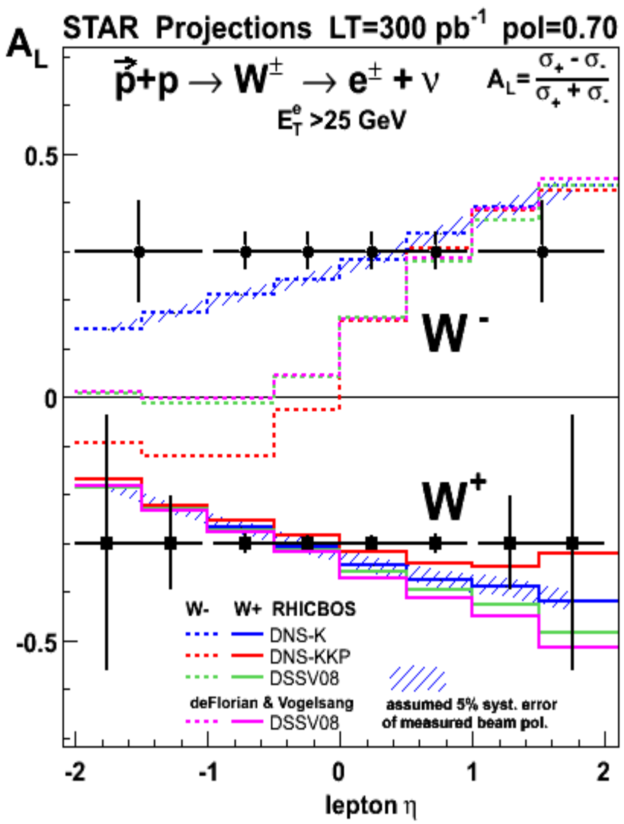
(5) Net-proton distributions are consistent with LGT results. QCD Scale: $\boldsymbol{T_C = 175^{+1}_{-7}}$ **(MeV)**

Future Activities

(1) 2012 - 2016: FGT, HFT, and MTD
(2) 2016 - 2022: Decadal Plan, eSTAR
(3) Beyond: eRHIC

Forward GEM Tracker



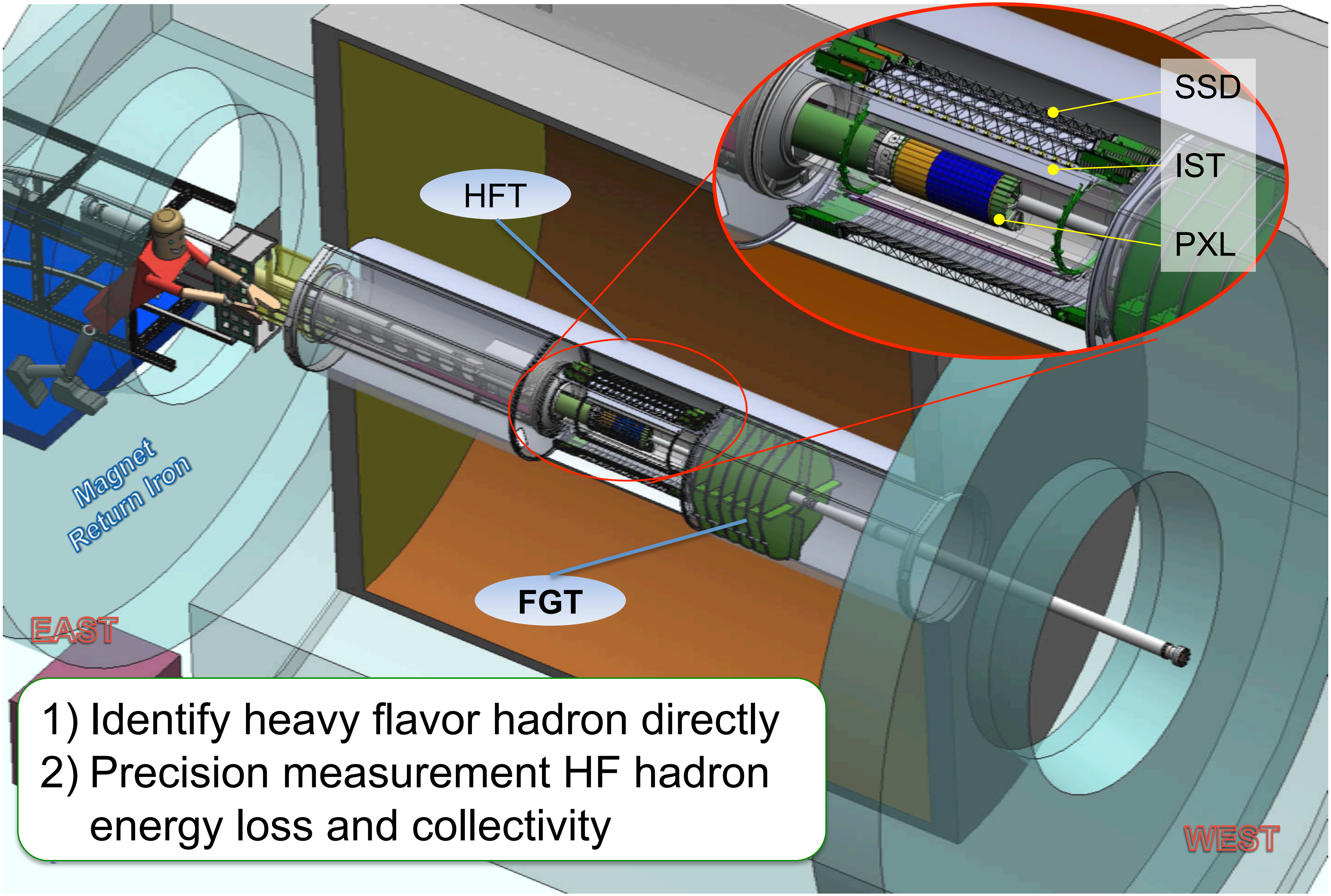


1) FGT: RHIC CP project
2) Six light-weight triple-GEM disks
3) New mechanical support structure
4) Planned installation: Summer 2011

1) Full charge-sign discrimination at high-p_T
2) Design polarization performance of **70% or better** to collect at least $300pb^{-1}$
3) **Ready* for Run 12!**

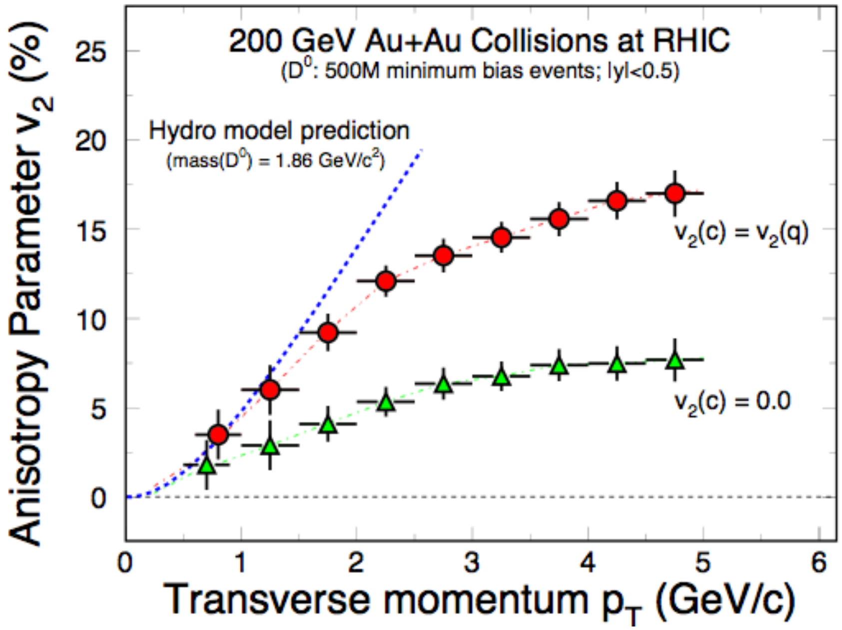
*** minimal configuration**

Outlook: Heavy Flavor Tracker at STAR



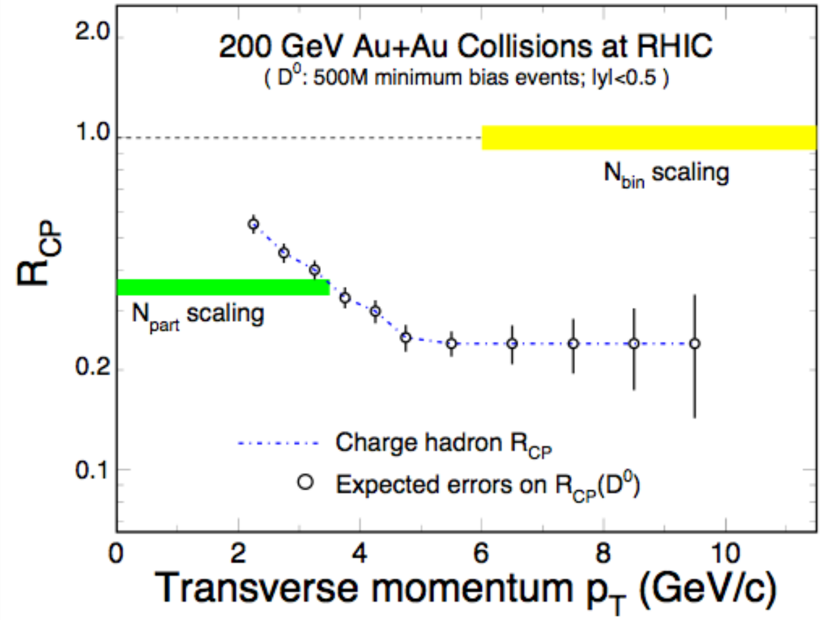
1) Identify heavy flavor hadron directly
2) Precision measurement HF hadron energy loss and collectivity

HFT: Charm Hadron v_2 and R_{AA}



- 200 GeV Au+Au m.b. collisions (500M events).
- Charm hadron collectivity ⇨ drag/diffusion constants ⇨

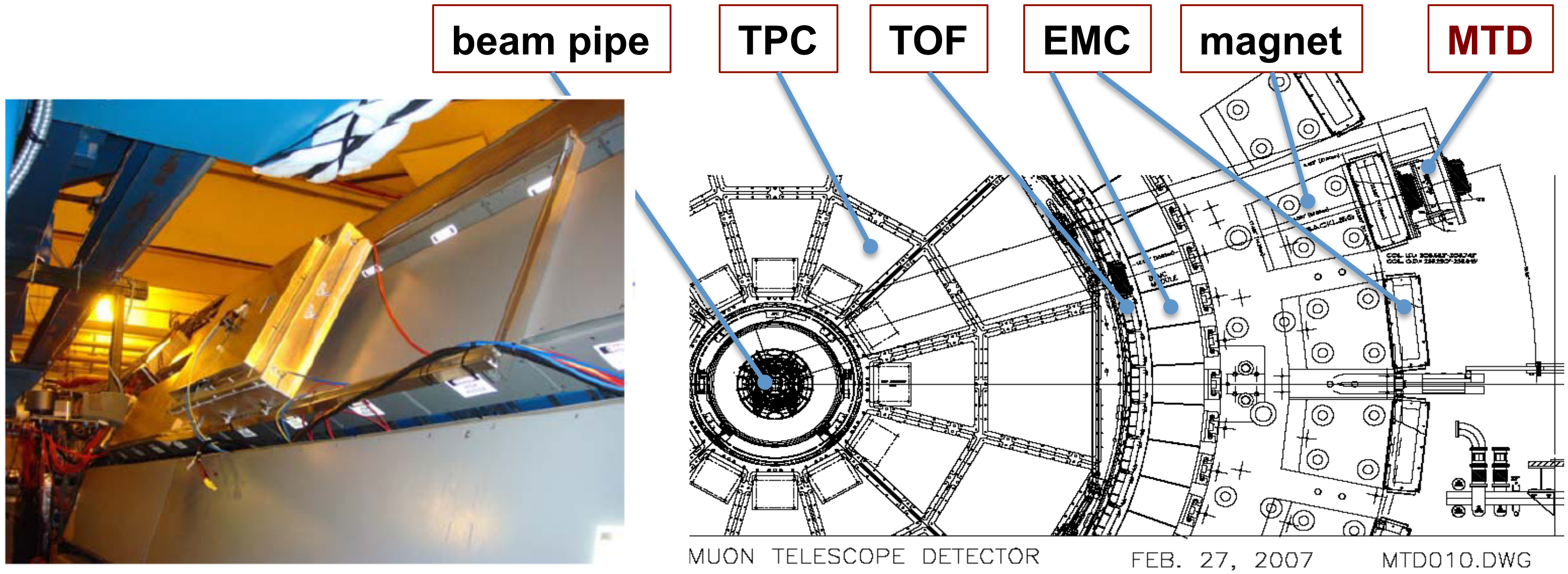
- Medium properties!
- Light quark thermalization!



- 200 GeV Au+Au m.b. collisions (|y|<0.5 500M events)
- Charm hadron R_{AA} ⇨

- Energy loss mechanism!
- QCD in dense medium!

STAR: Muon Telescope Detector



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, light vector mesons, B→J/Ψ+X
4) China-India-STAR collaboration: approved by DOE and China + India
5) **Run 13**: 50% MTD will be ready

Key Upgrades

1) **FGT**: fully funded, ready for Run12.
   - W-physics, sea quark contributions to proton spin

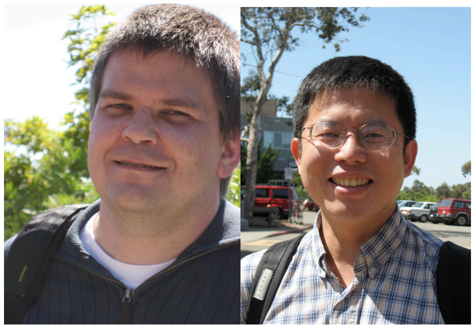
2) **HFT**: CD1 done. CD2/3 done, will be ready for Run 14.
   - Heavy quark collectivity, light quark thermalization

3) **MTD:** approved by BNL, China, India (15%) funds secured.
   - Excited quarkonia states, trigger for rare processes

4) **eSTAR** task force established. An important step toward EIC.

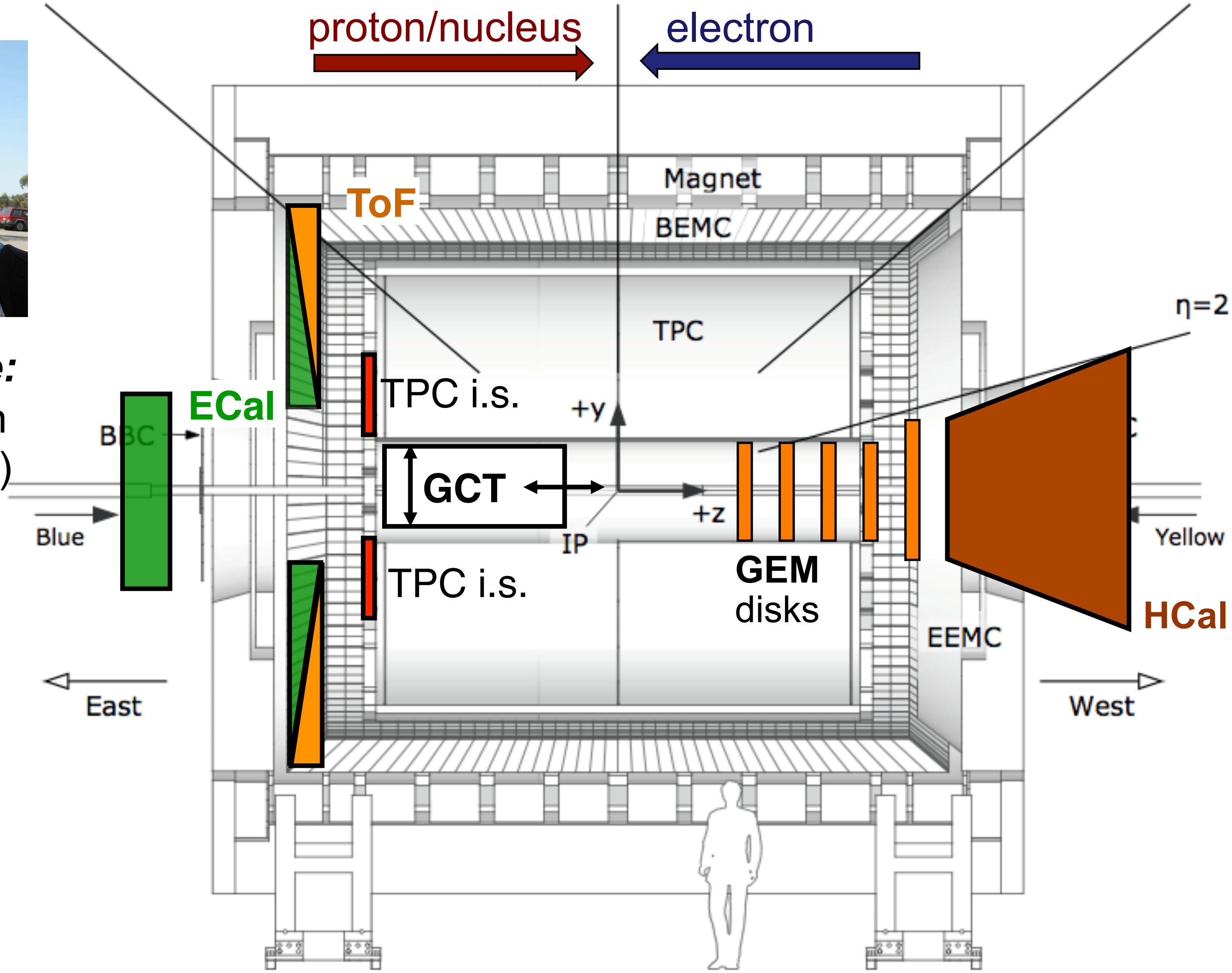
(1) Forward Spaghetti Calorimeter (UCLA)	April 2011	approved
(2) Forward TOF/TRD (BNL/USTC/VECC)	November 2011	
(3) BBC Polarimetry (ANL)	November 2011	
(4) Crystal BSO Calorimeter (USTC)	November 2011	

From *STAR* to *eSTAR*



eSTAR Task Force:
- Ernst Sichtermann
- Zhangbu Xu (BNL)

- Detector R&D
- Science cases



Summary and Outlook

1) **STAR at RHIC**: Dedicated facility for studying matter with QCD degrees of freedom:

- Properties of QGP

- Sea quark and gluon contributions to proton helicity structure

- QCD critical point, phase boundary

2) Future: EIC (eRHIC, 2022 - …)

- Partonic structures of nucleon and nuclei

- Understanding the dynamical evolution from cold nuclear matter to hot QGP

Phase Structures of QCD Matter

Nu's Wish List for Local STAR Groups:

1) More students for STAR data analysis and R&D for future upgrades

2) Publish PMD data collected in the RHIC BES program, search for possible signature of χ_C-transition in high-energy nuclear collisions.

RHIC Run 12

21 week case:

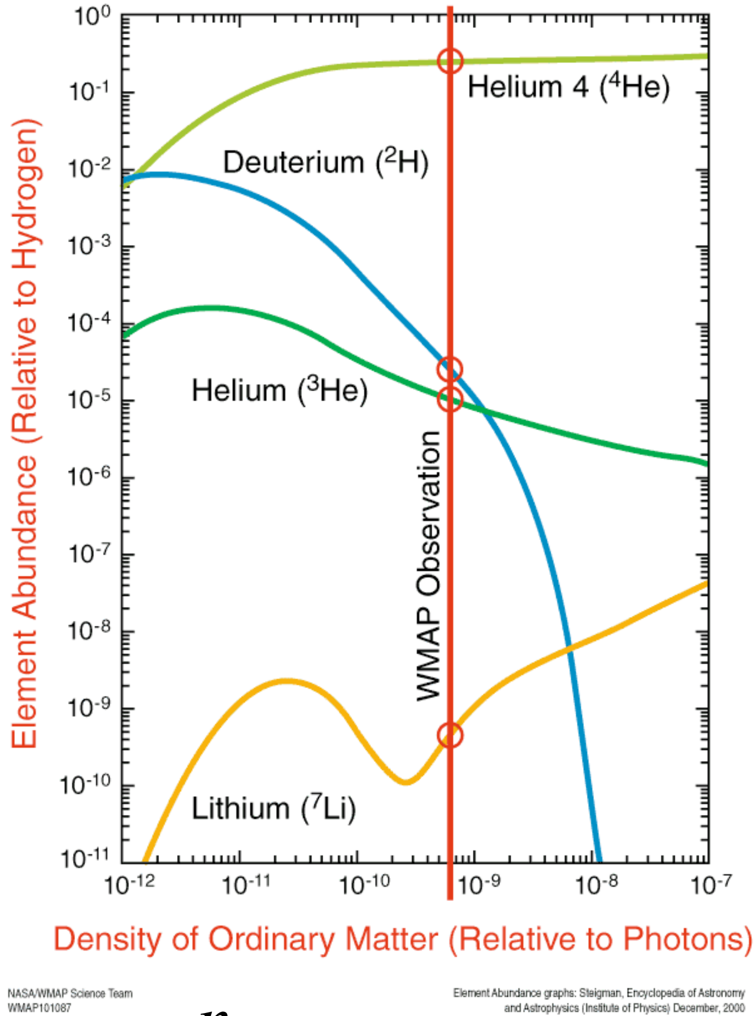
Cool down:	January 17, 2012
Shift	end of January
1) 200 GeV p+p	4 weeks
2) 500 GeV p+p	7 weeks
3) 200 GeV Cu+Au	5 weeks
Or 193 GeV U+U	4 weeks
Or 15.5 GeV Au+Au	2.5 weeks

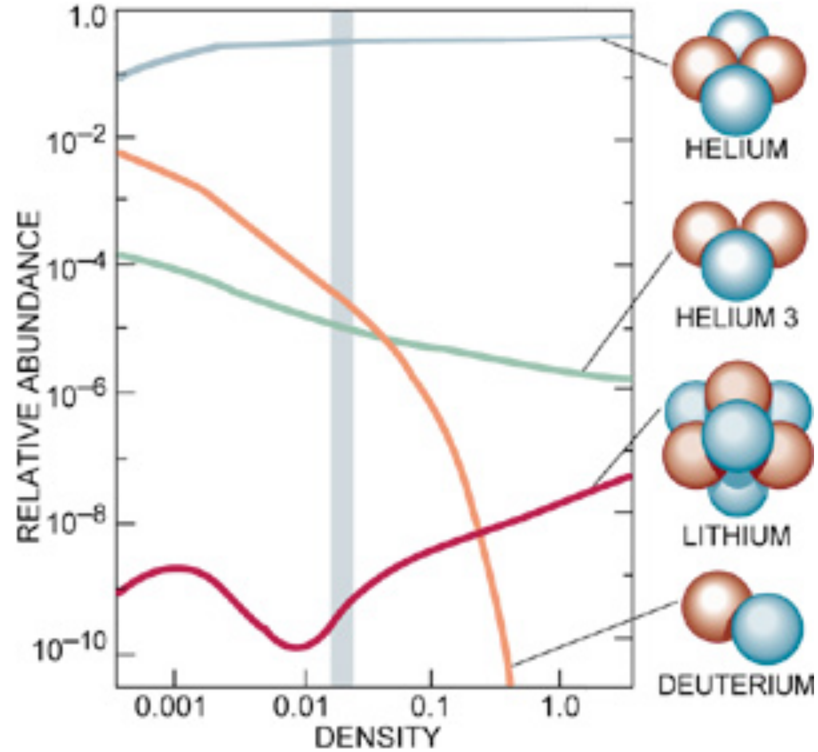
STAR is/will be ready.
In advance, thank you for participate in STAR data taking

Many Thanks to the Organizers!

Nu Xu

Atomic Nuclei Formation





$$\frac{n_B}{n_\gamma} \approx 10^{-9}$$