Search for the QCD Critical Point in High-Energy Nuclear Collisions at RHIC

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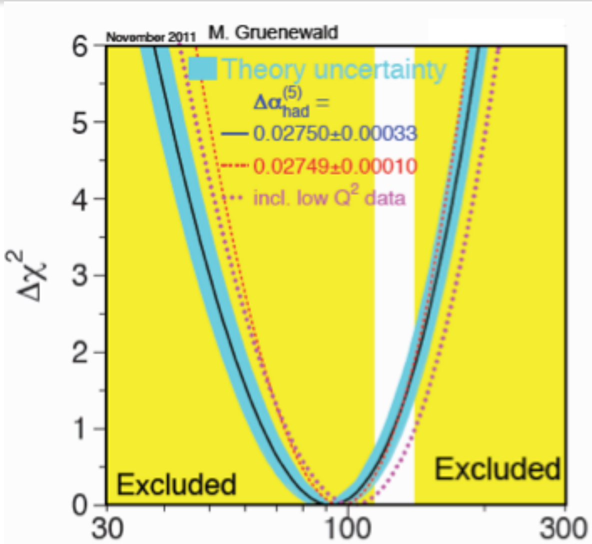
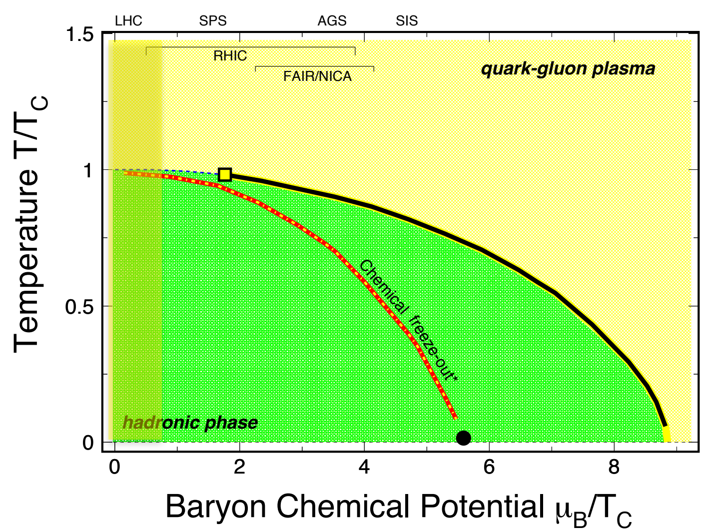
Many Thanks to the Organizers!

QCD in Twenty-One Century





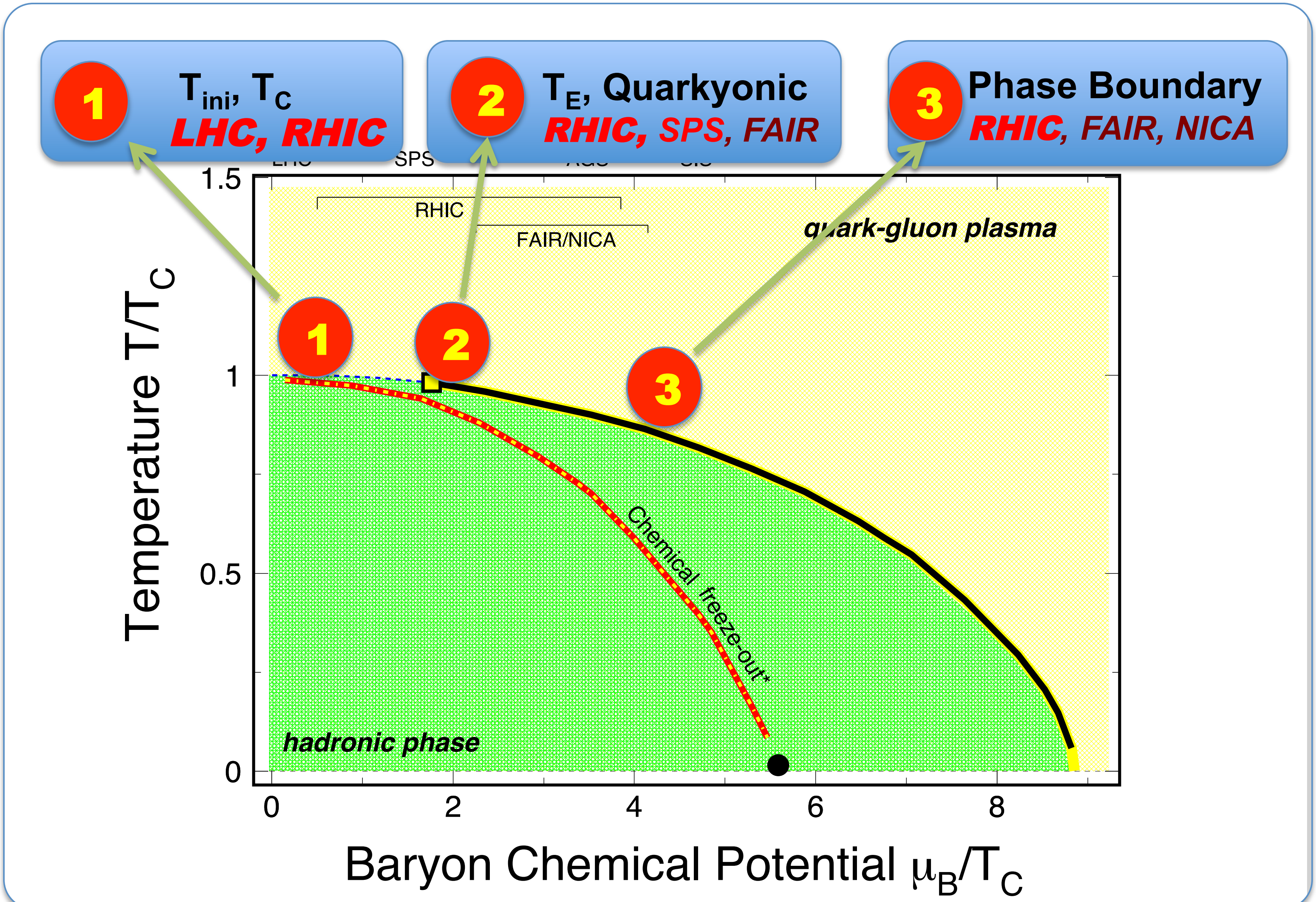
(1) Higgs Particle –

- Origin of Mass
- SM ➔ The *Theory*

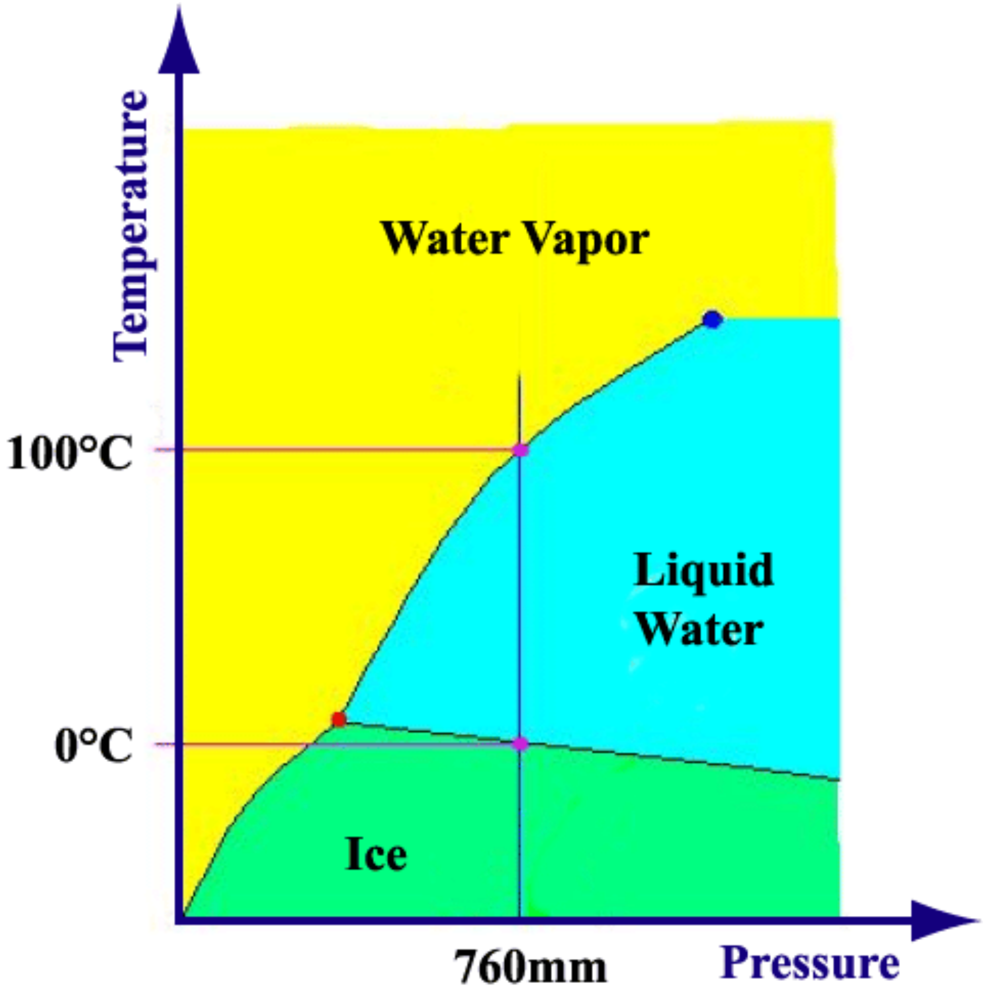
(2) QCD Phase Structure –

- Critical point, phase boundaries
- Confinement
- χ_C symmetry
- Nucleon helicity structure
- …
- Non-linear QCD at small-x
- …
- …
- Emerging properties

The QCD Phase Diagram and High-Energy Nuclear Collisions



Phase Diagram: Water



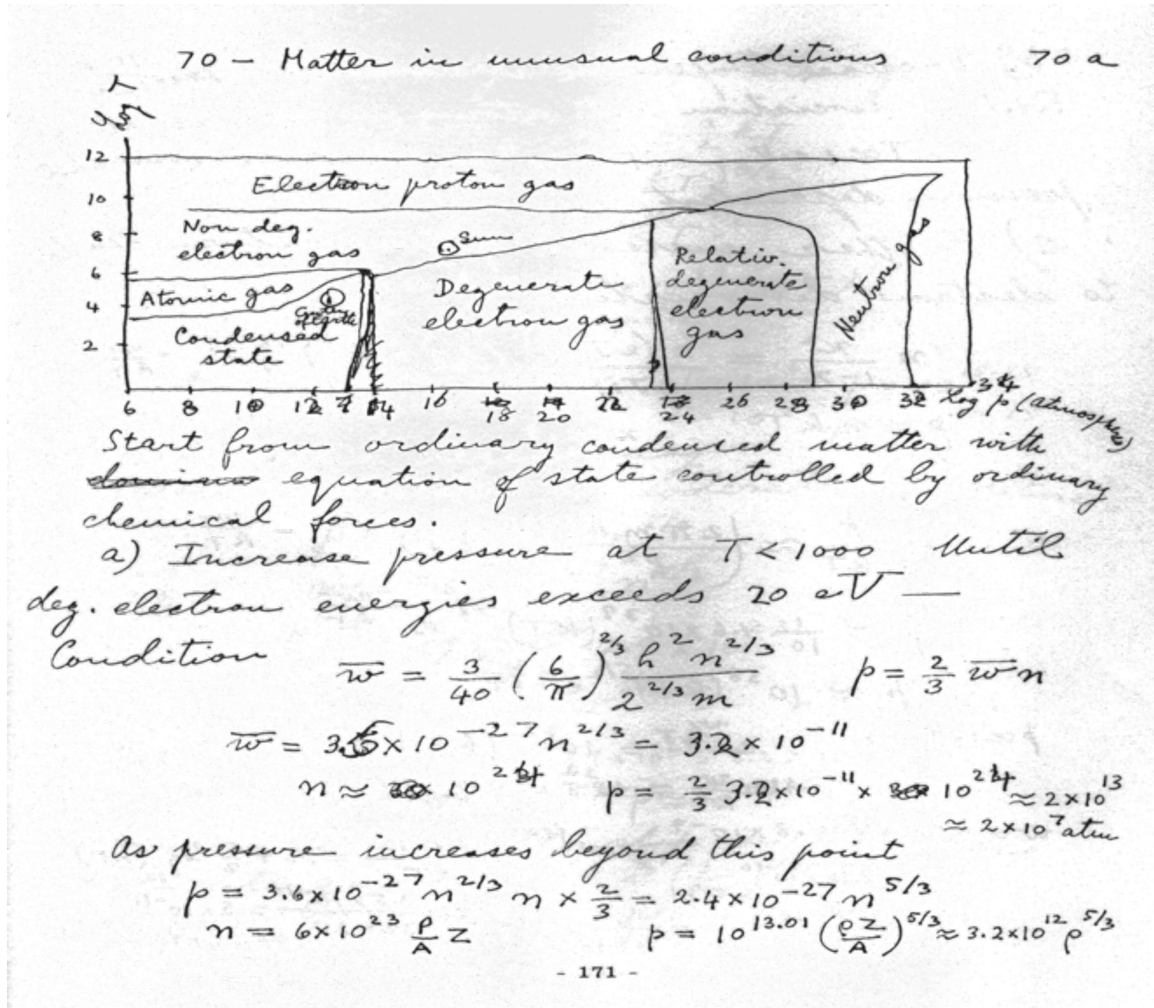
Phase diagram: A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

Water: H_2O

The QCD phase diagram: structure of matter with quark- and gluon-degrees (color degrees) of freedom.

E. Fermi: *"Notes on Thermodynamics and Statistics" (1953)*

E. Fermi



70 — Matter in unusual conditions 70 a

Start from ordinary condensed matter with equation of state controlled by ordinary chemical forces.

a) Increase pressure at T < 1000 until deg. electron energies exceeds 20 eV —

Condition $\overline{w} = \frac{3}{40}\left(\frac{6}{\pi}\right)^{2/3}\frac{h^2 n^{2/3}}{2^{2/3} m}$ $p = \frac{2}{3}\overline{w} n$

$\overline{w} = 3.5 \times 10^{-27} n^{2/3} = 3.2 \times 10^{-11}$

$n \approx 10^{24}$ $p = \frac{2}{3} 3.2 \times 10^{-11} \times 10^{24} \approx 2 \times 10^{13}$

$\approx 2 \times 10^{7}$ atm

As pressure increases beyond this point

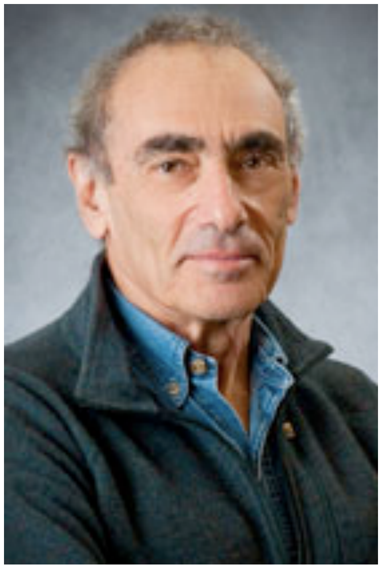
$p = 3.6 \times 10^{-27} n^{2/3} n \times \frac{2}{3} = 2.4 \times 10^{-27} n^{5/3}$

$n = 6 \times 10^{23} \frac{\rho}{A} Z$ $p = 10^{13.01}\left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2 \times 10^{12} \rho^{5/3}$

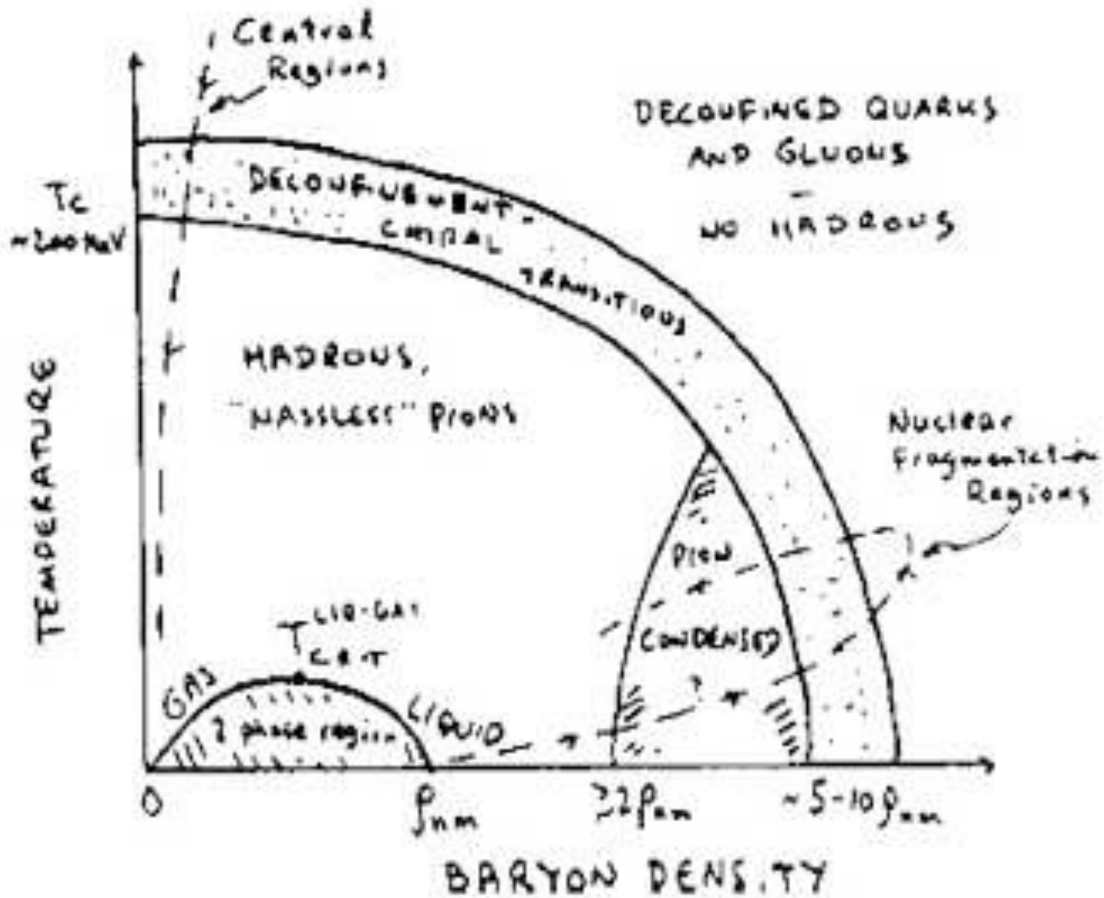
- 171 -

QCD Phase Diagram (1983)

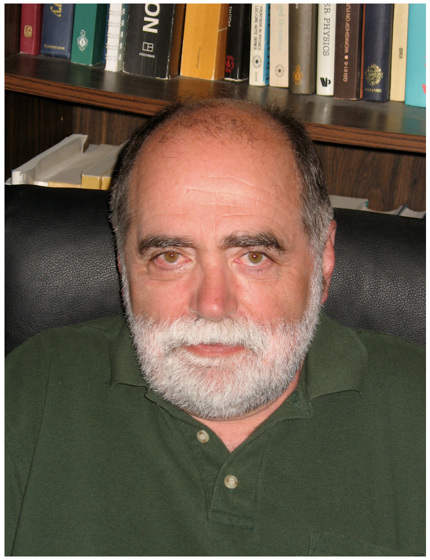
1983 US Long Range Plan *- by Gordon Baym*



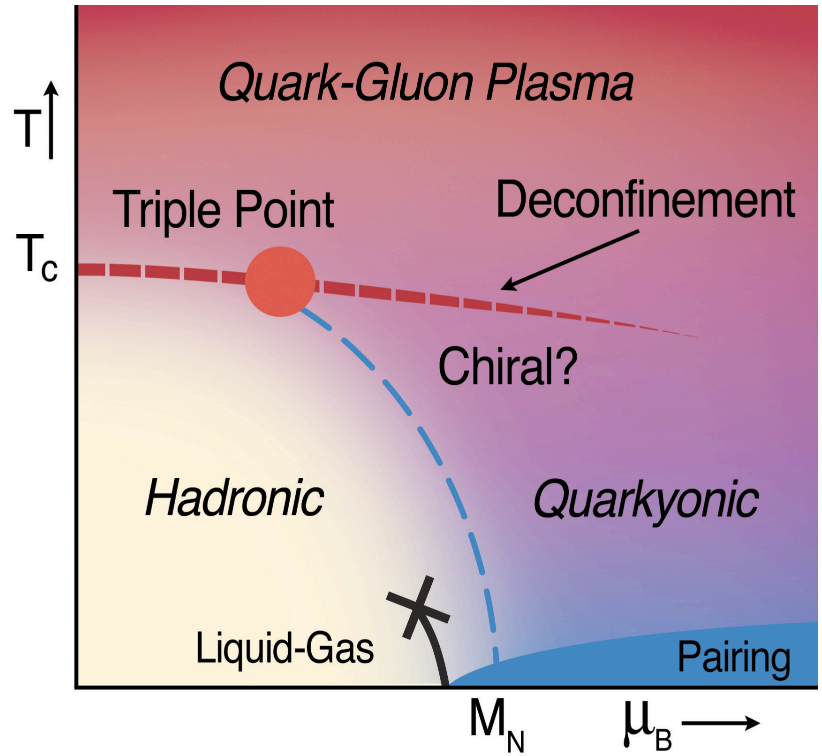
Gordon Baym



QCD Phase Diagram (2009)



Larry McLerran



nucl-th: 0907.4489, NPA830,709(09) ***L. McLerran***
nucl-th 0911.4806, NPA837,65(10): *A. Andronic,* ***D. Blaschke, P. Braun-Munzinger,***
J. Cleymans, K. Fukushima, ***L.D. McLerran****, H. Oeschler,*
R.D. Pisarski, ***K. Redlich****, C. Sasaki, H. Satz, and* ***J. Stachel***

Experiments: Systematic measurements (E_{beam}, A_{size}) : extract **numbers** that are related to the ***phase diagram***

Outline

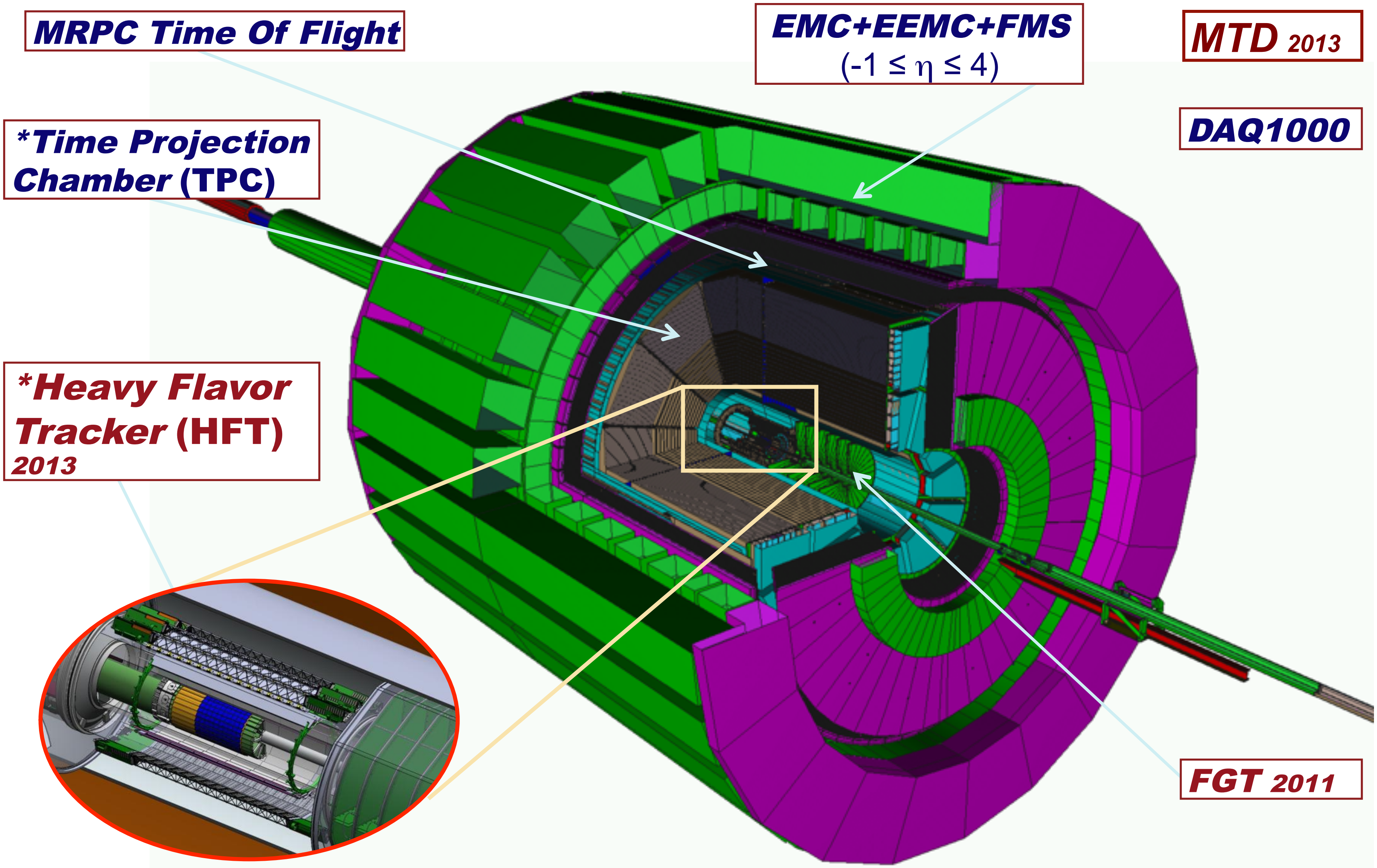
(1) Introduction

(2) Recent Results and
Beam Energy Scan at RHIC

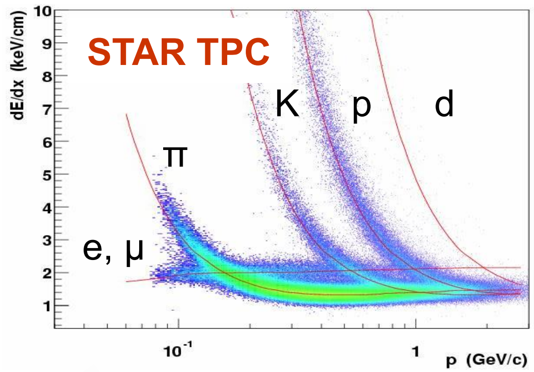
(3) Summary and Outlook

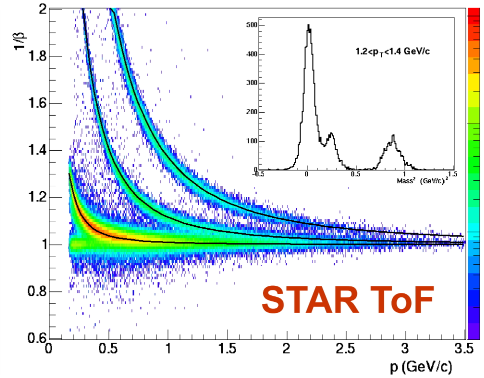
STAR Collaboration

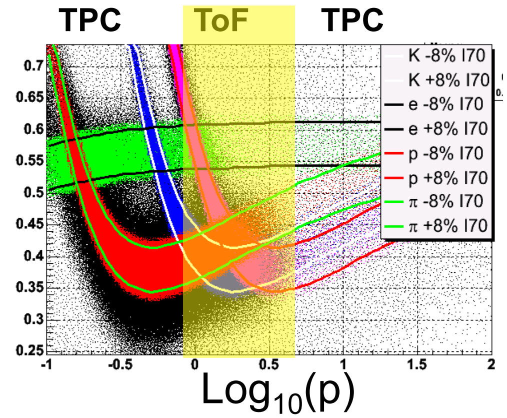
STAR Detectors *Fast* and *Full* azimuthal particle identification

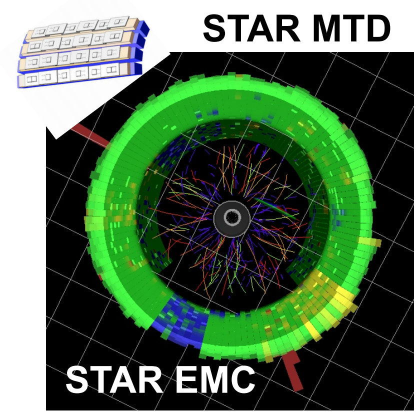


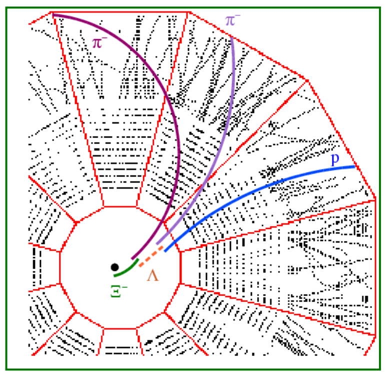
Particle Identification at STAR

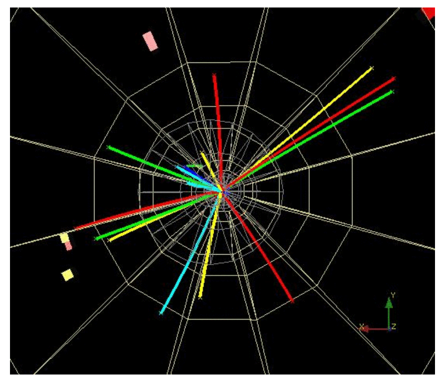


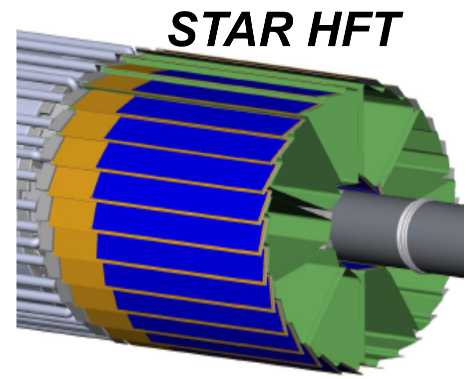








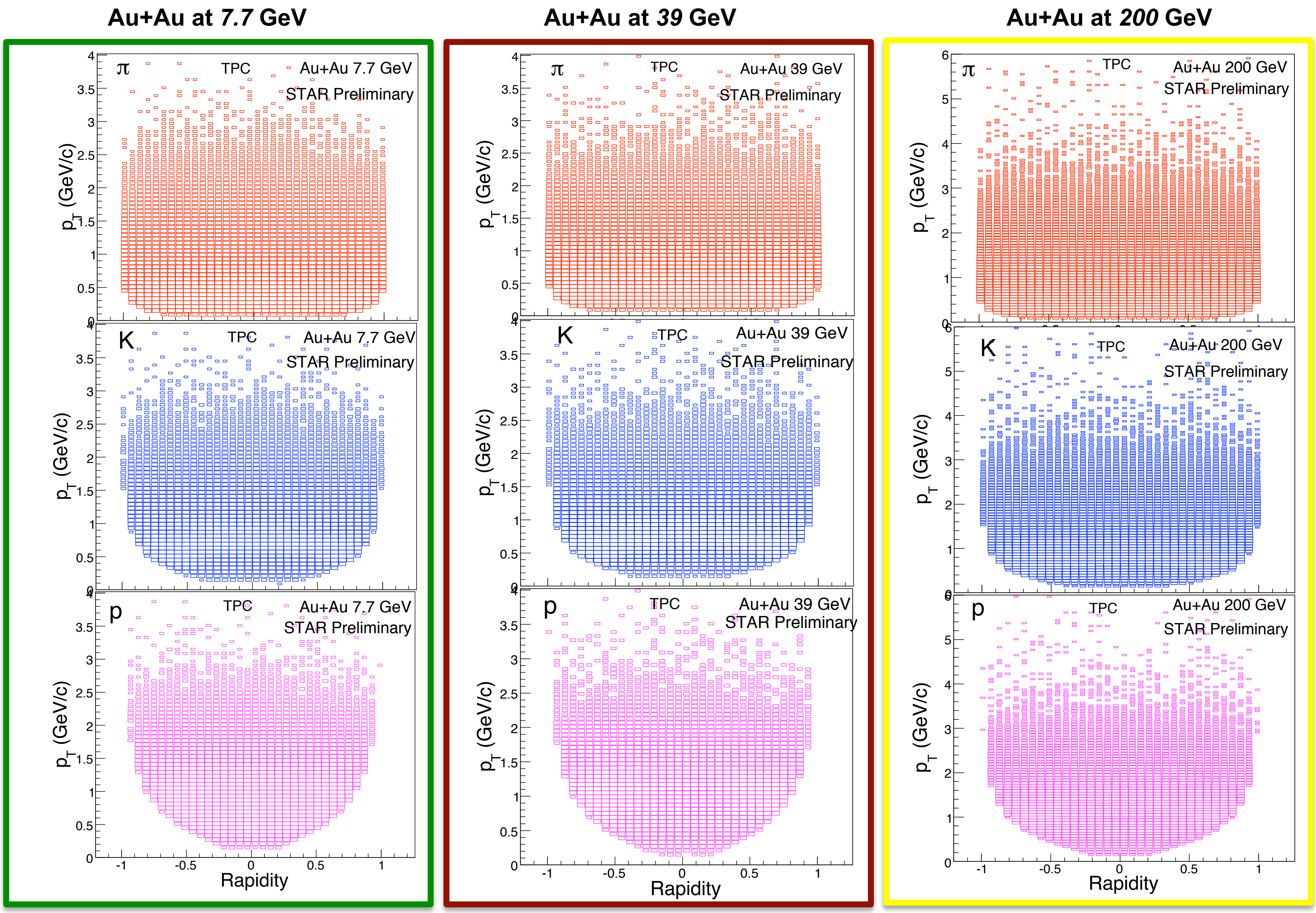




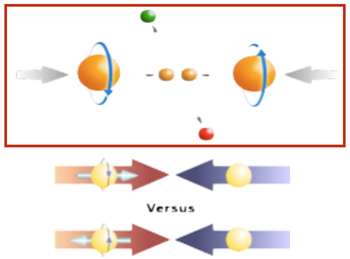
Neutral particles **Strange hyperons** **Jets** **Heavy Quark Hadrons**

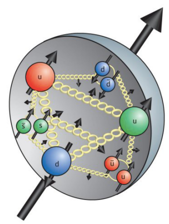
Multiple-fold correlations for both HI and Spin physics!

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

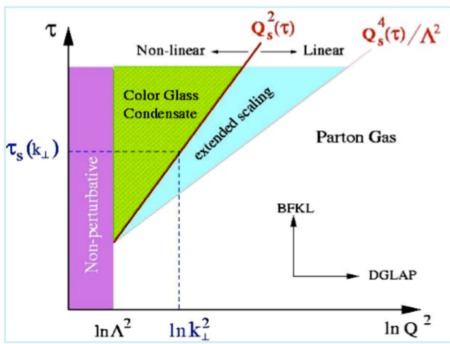


STAR Physics Focus



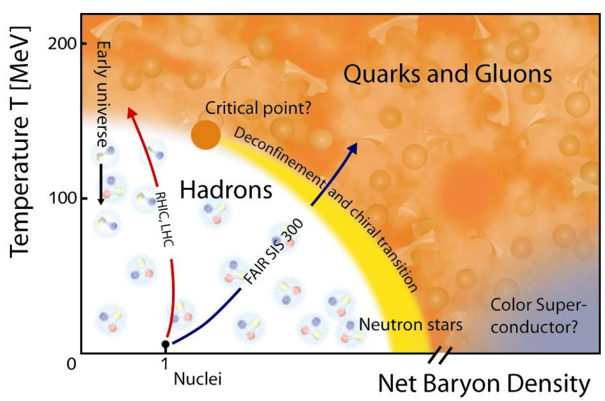


Polarized *p+p* program
- Study ***proton intrinsic properties***



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

2020 -
eRHIC
(eSTAR)

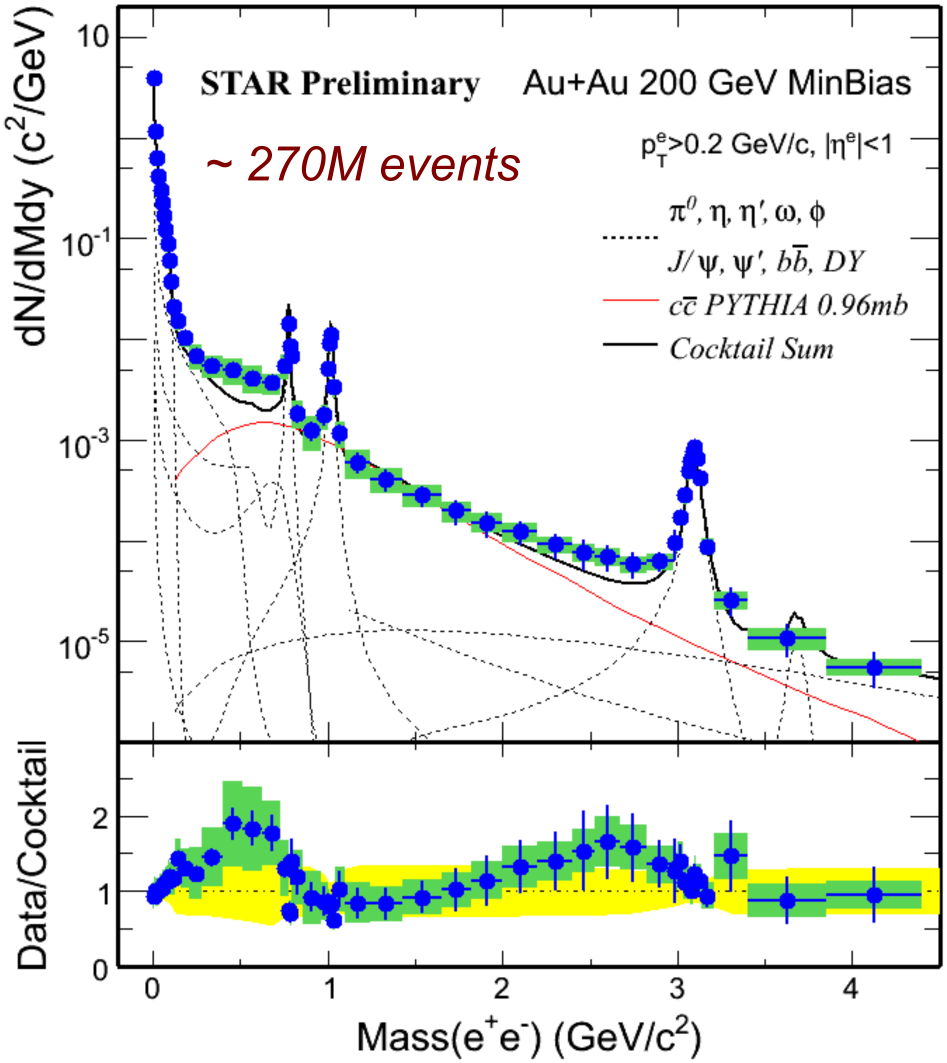


1) At 200 GeV at RHIC
- Study ***medium properties, EoS***
- pQCD in hot and dense medium

2) RHIC beam energy scan (BES)
- Search for the ***QCD critical point***
- Chiral symmetry restoration

STAR Di-electron Program

Bulk-penetrating probe



1) Reasonable agreement between data and cocktail. ***No dramatic enhancement in the low mass region:***

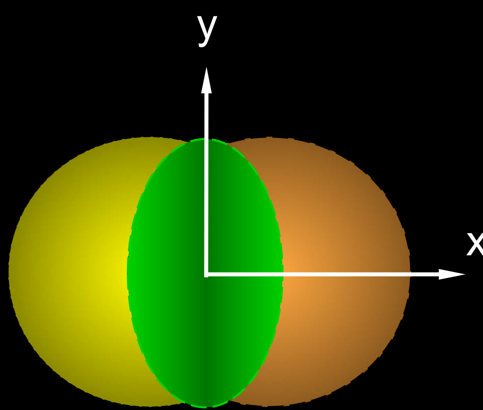
- *η, ω, J/ψ from PHENIX*
- *π^0, $(\pi^\pm)$ ϕ, from STAR*
- *ρ contribution not included*

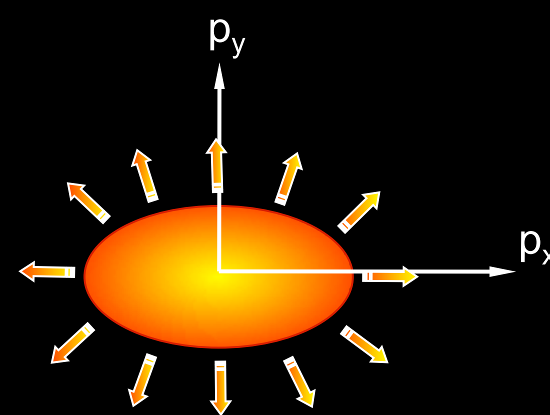
2) Topics – the centrality dependence of:

- slope parameter vs. mass
- $v_2(p_T)$ vs. mass
- $R_{AA}(p_T)$ vs. mass
- spin-alignment vs. mass

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

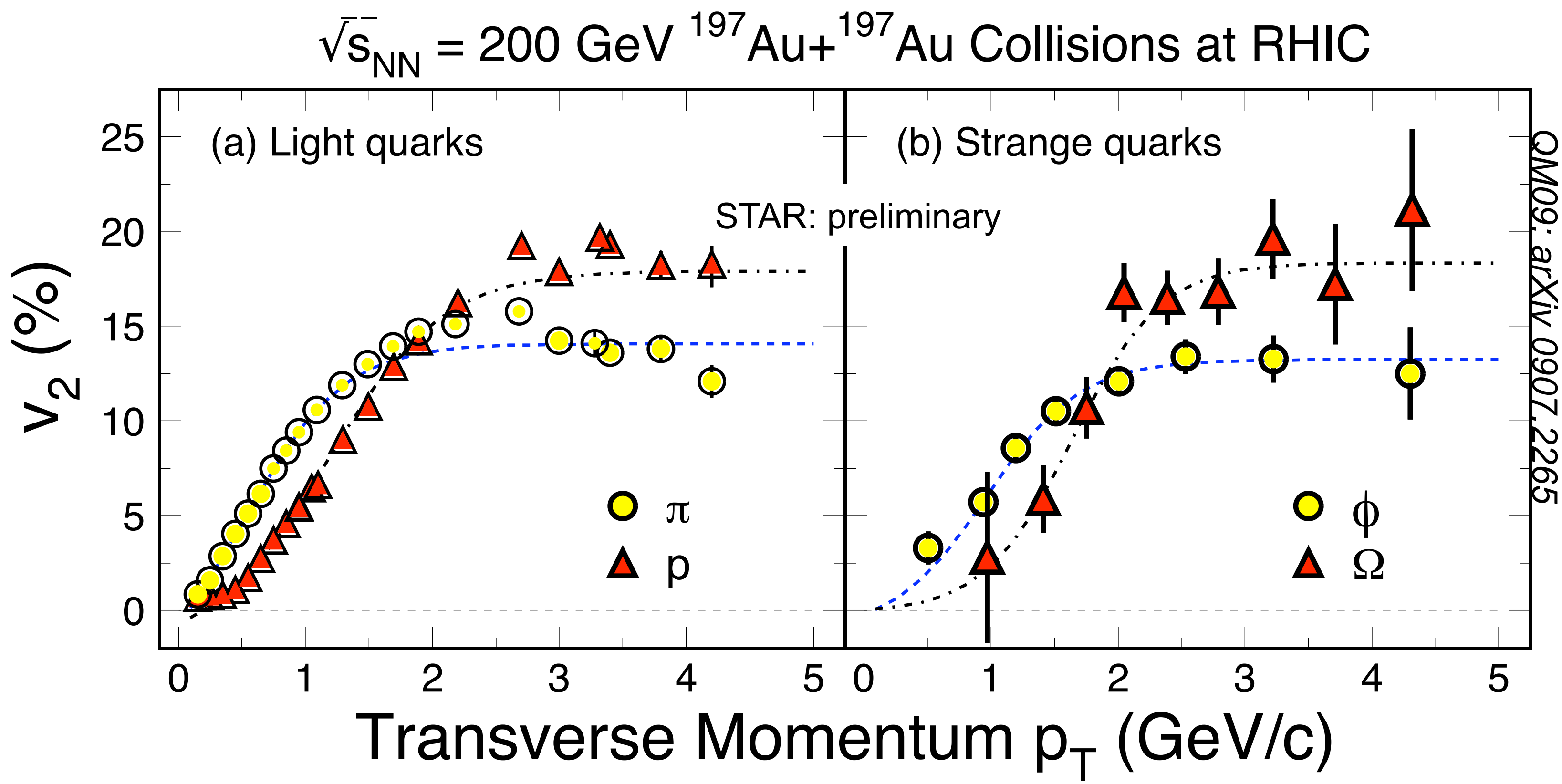




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

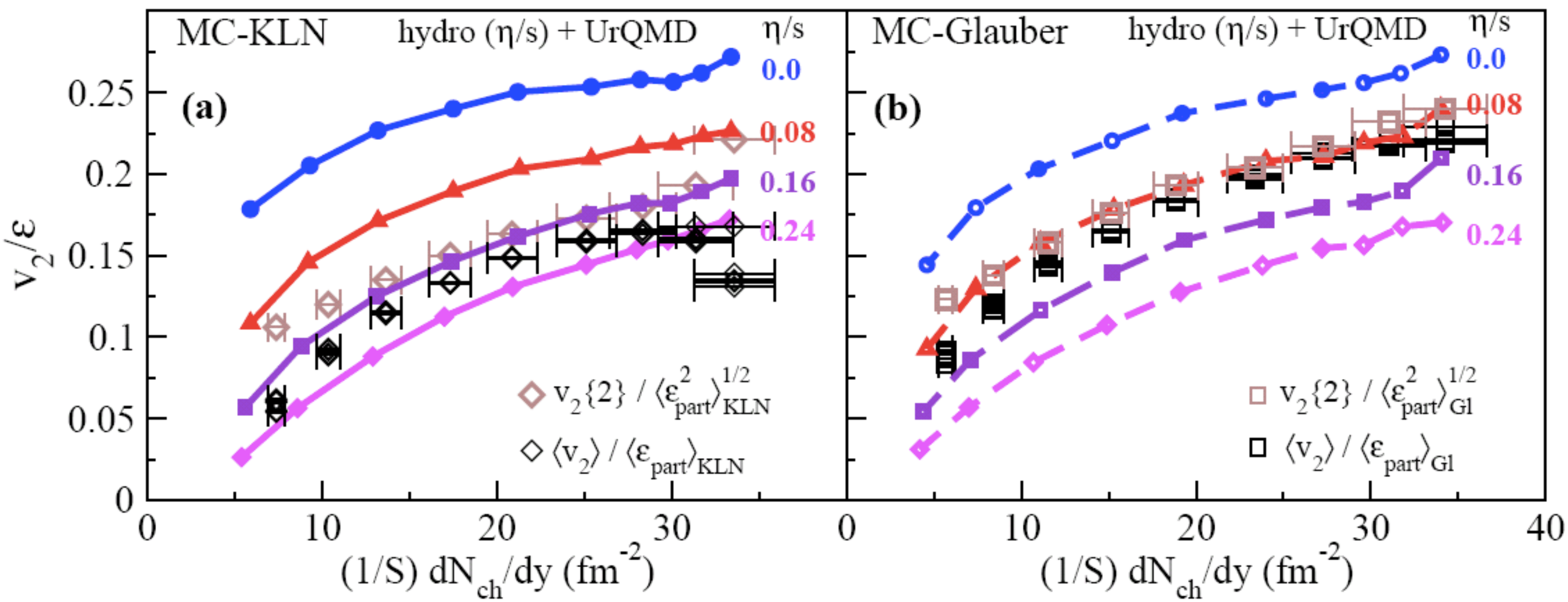
Partonic Collectivity at RHIC



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!***

Comparison with Model Results

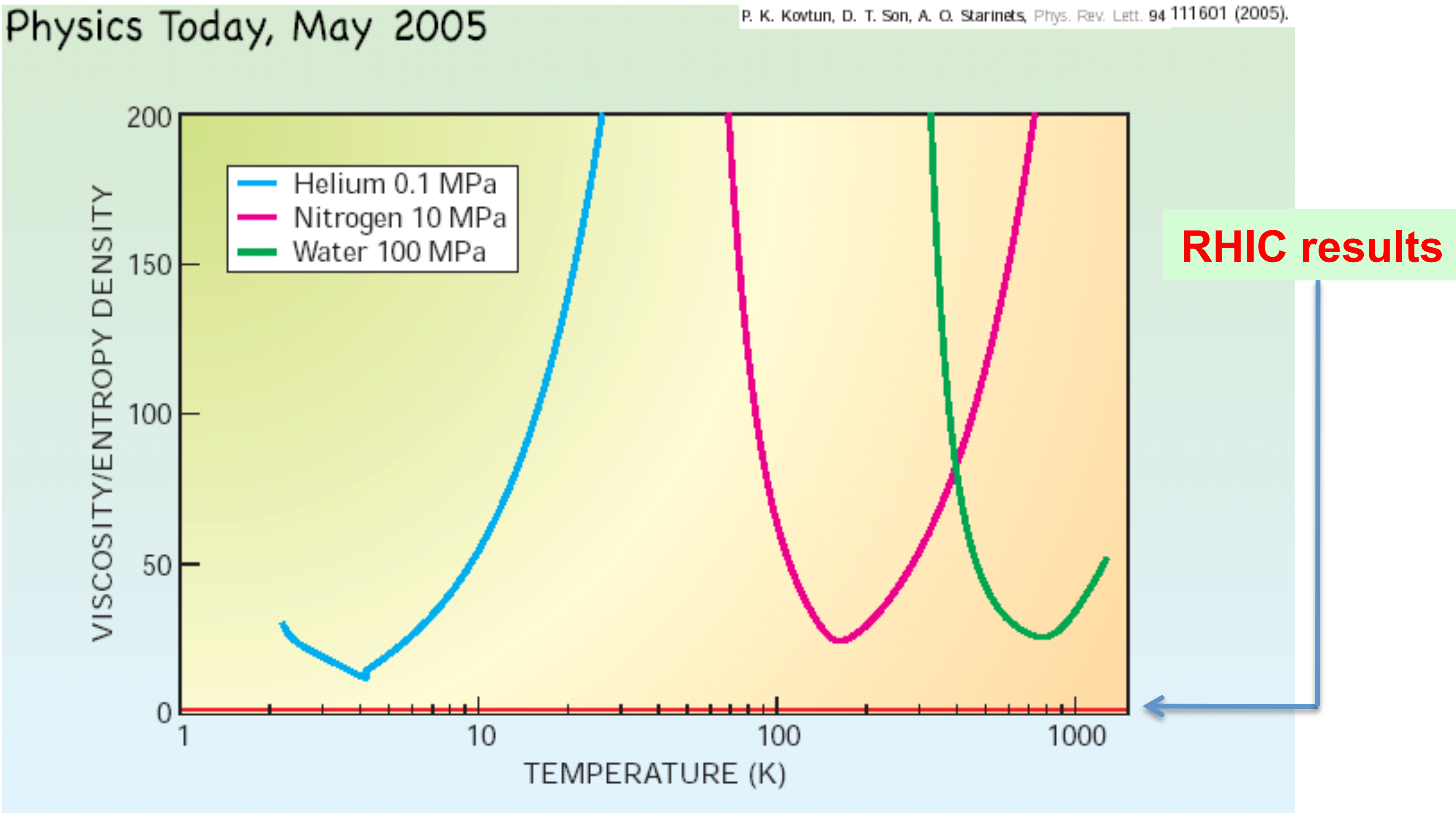


➔ ***Small value*** of specific viscosity over entropy ***η/s***

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

Model: Song *et al. arXiv:1011.2783*

Low *η/s* for QCD Matter at RHIC



1) ***η/s* ≥ *1/4π***

2) ***η/s***(QCD matter) < ***η/s***(QED matter)

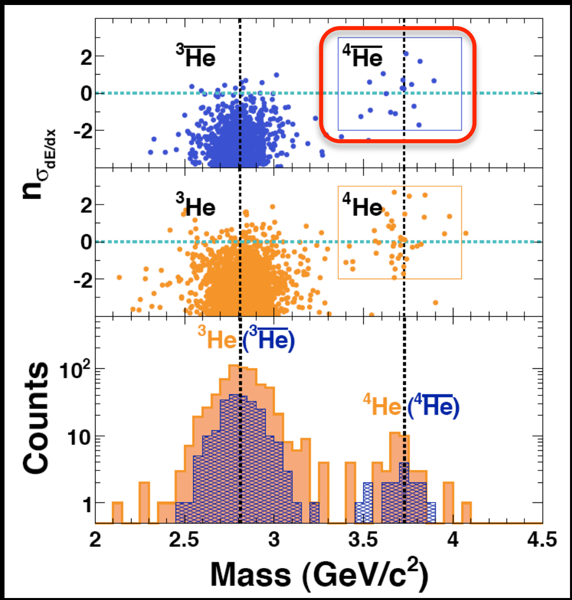
Antimatter Discoveries at RHIC

nature April, 2011

"Observation of the Antimatter Helium-4 Nucleus"

by ***STAR Collaboration***

Nature*, 473, 353(2011).*

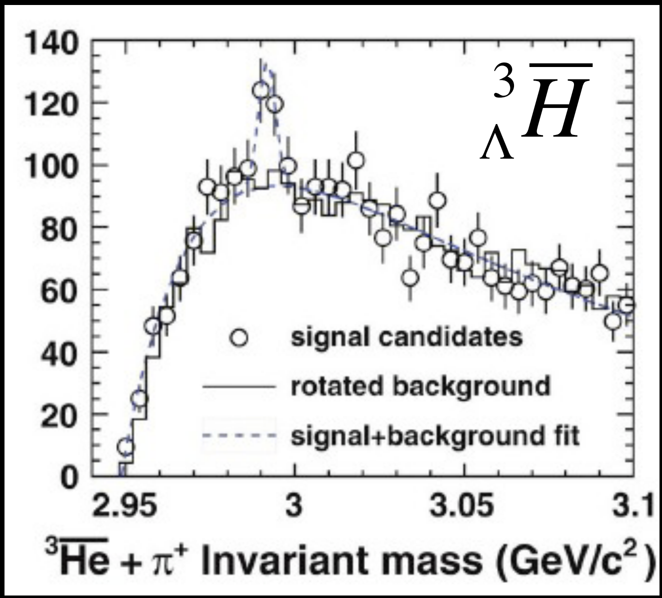


Science March, 2010

"Observation of an Antimatter Hypernucleus"

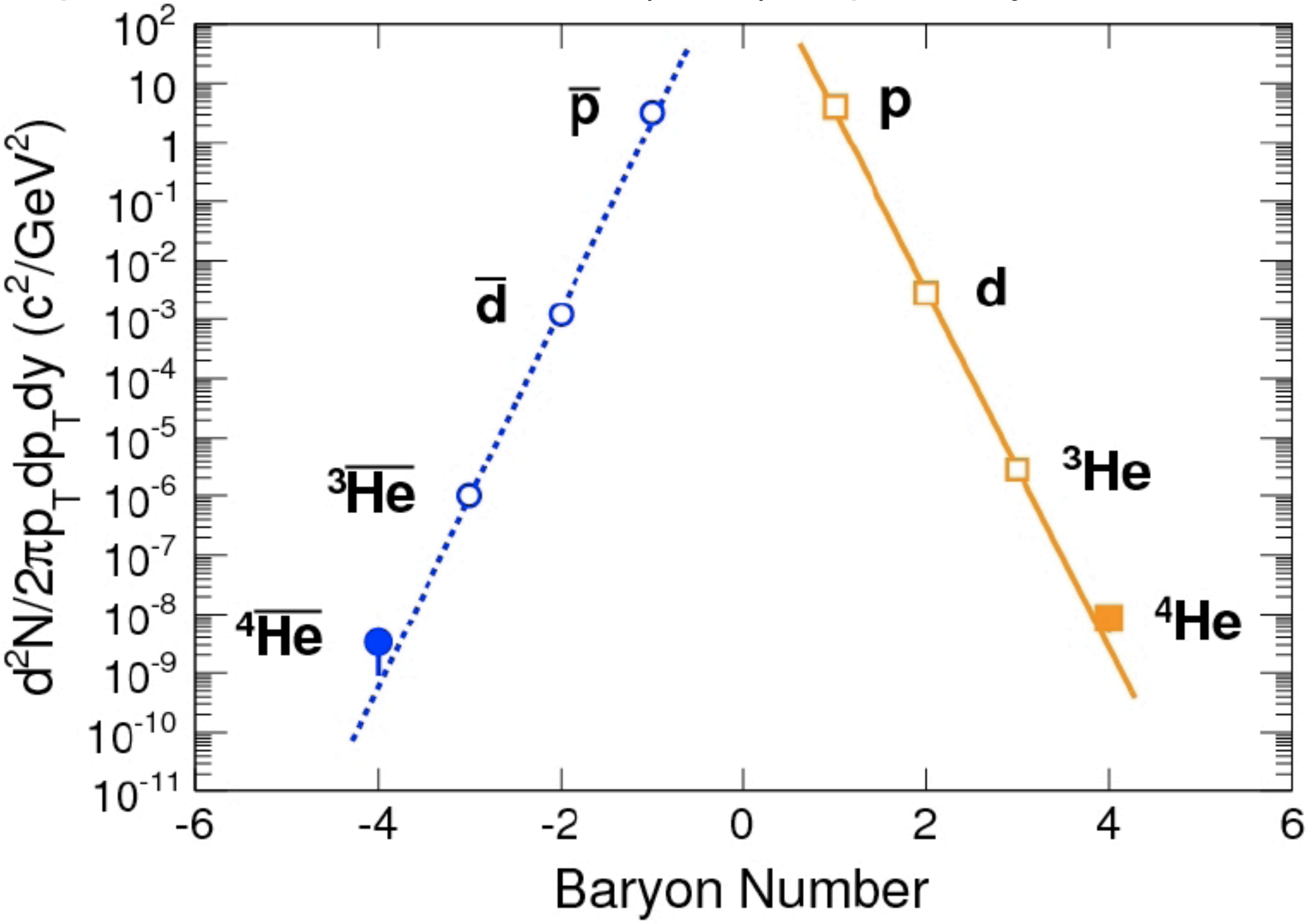
by ***STAR Collaboration***

Science*, 328, 58(2010).*



Light Nuclei Productions at RHIC

STAR Experiment: ***Nature***, **473**, 353(2011), Top 100 by ***Discover Magazine***

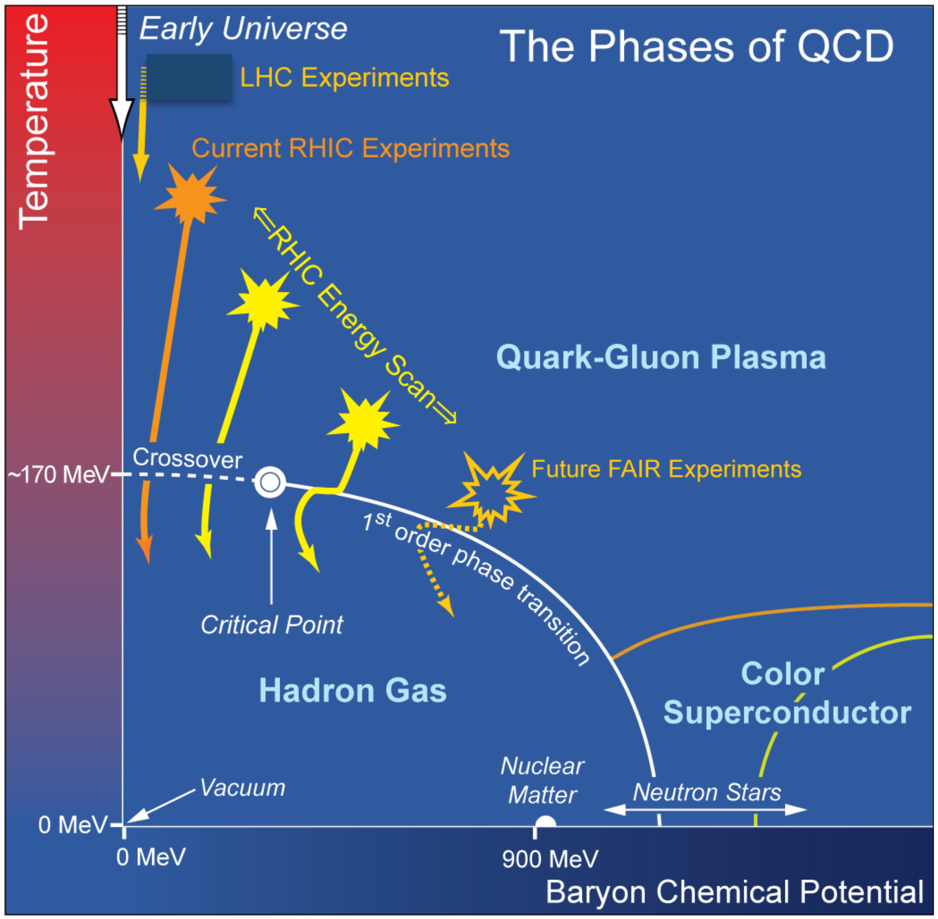


1) In high-energy nuclear collisions, **N(d) >> N(α)**:
   QGP ➔ (anti)light nuclei via coalescence
2) In the Universe, **N(d) << N(α): N(anti-α)?**

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

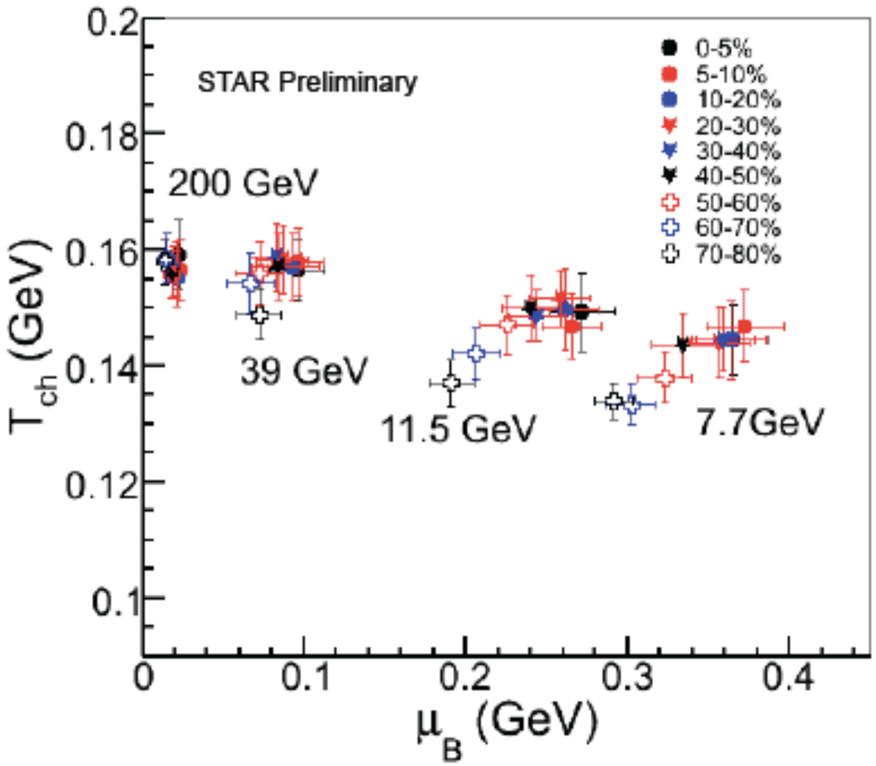
(4) v_2 - NCQ scaling
partonic vs. hadronic dof

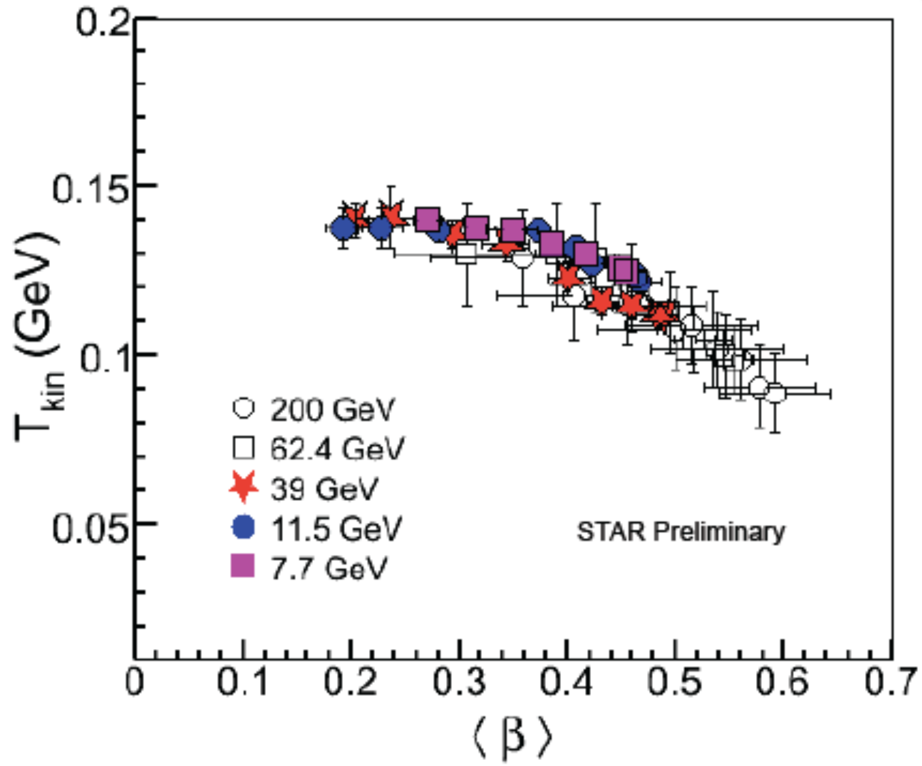
(5) Fluctuations
Critical point, correl. length

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

- *arXiv:1007.2613*

Bulk Properties at Freeze-out





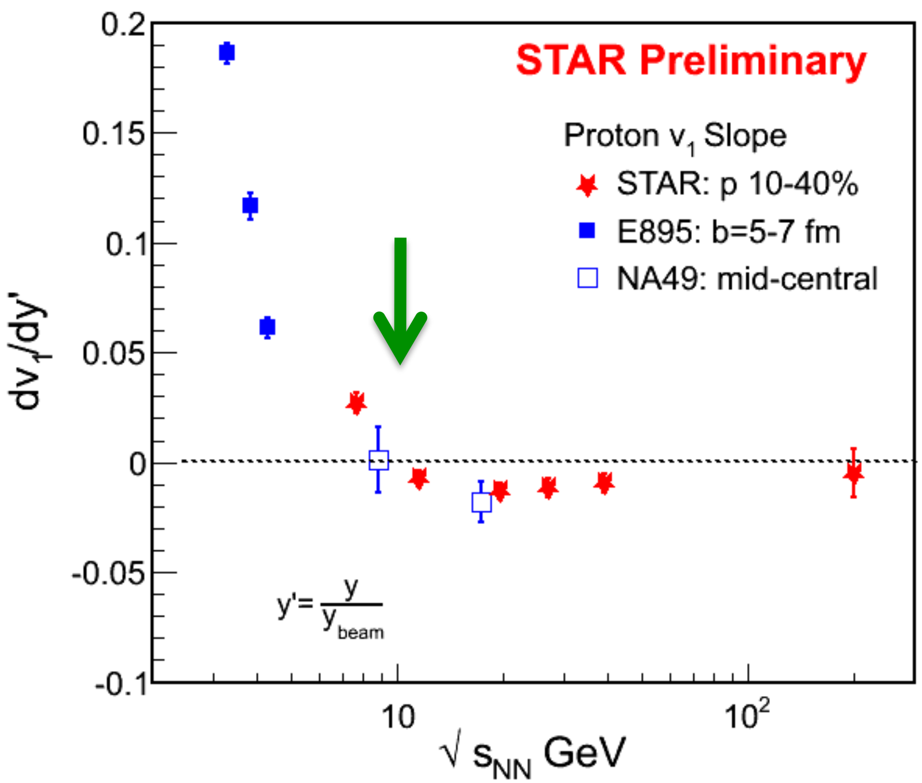
Chemical Freeze-out:

- 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

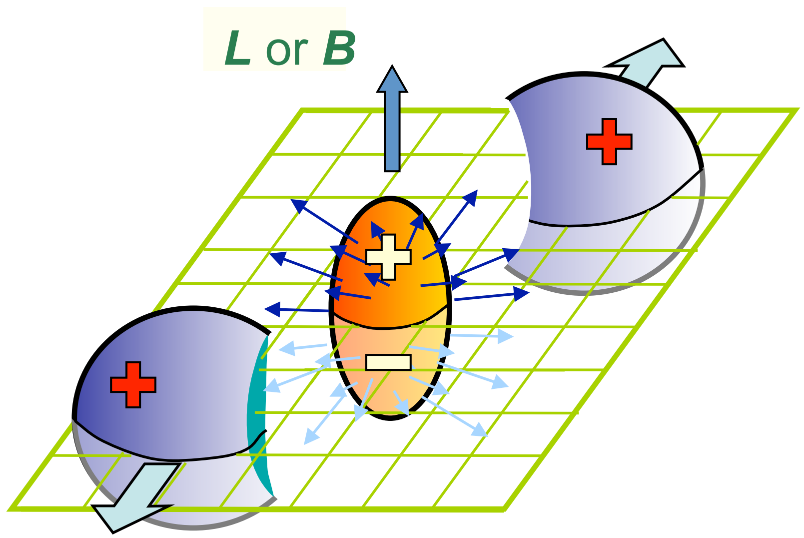
At higher beam energies, produced particles dominate the dynamics. Due to expansion, the sign of v_1 reverses

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

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

Search for Local Parity Violation

in High Energy Nuclear Collisions

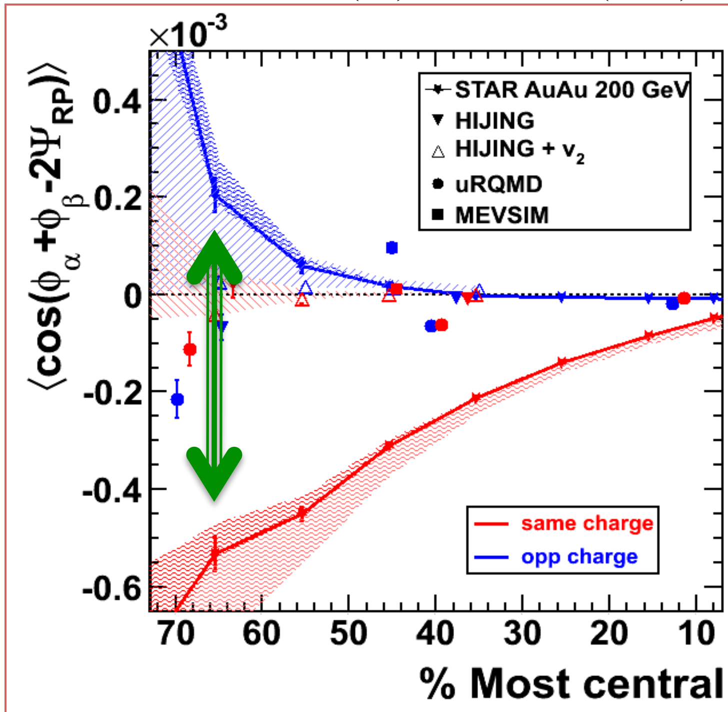


$$\left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{RP}\right)\right\rangle$$

Parity even observable

Voloshin, PR C62, 044901(00).

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

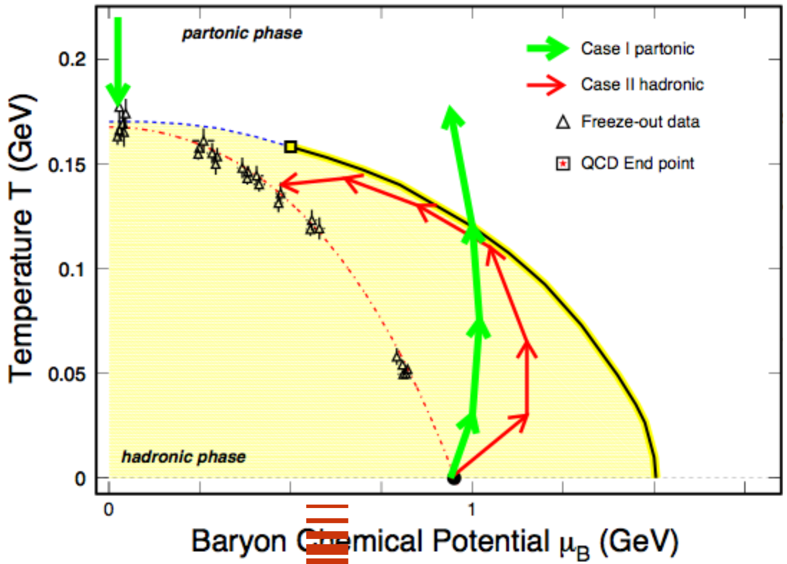


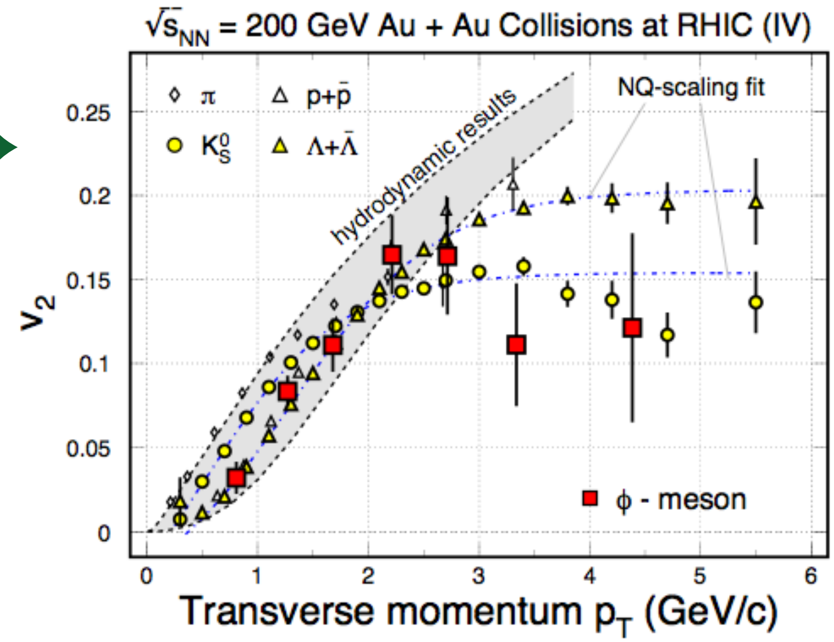
The separation between the same-charge and opposite-charge correlations.

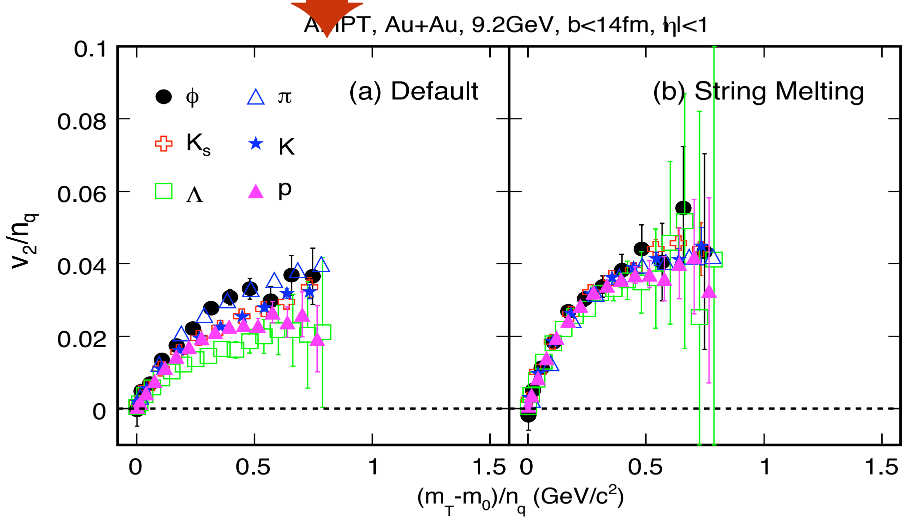
- **Strong external EM field**
- ***De-confinement* and *Chiral symmetry restoration***

Future tests with Beam Energy dependence & U+U collisions

Observable*: NCQ Scaling in v_2





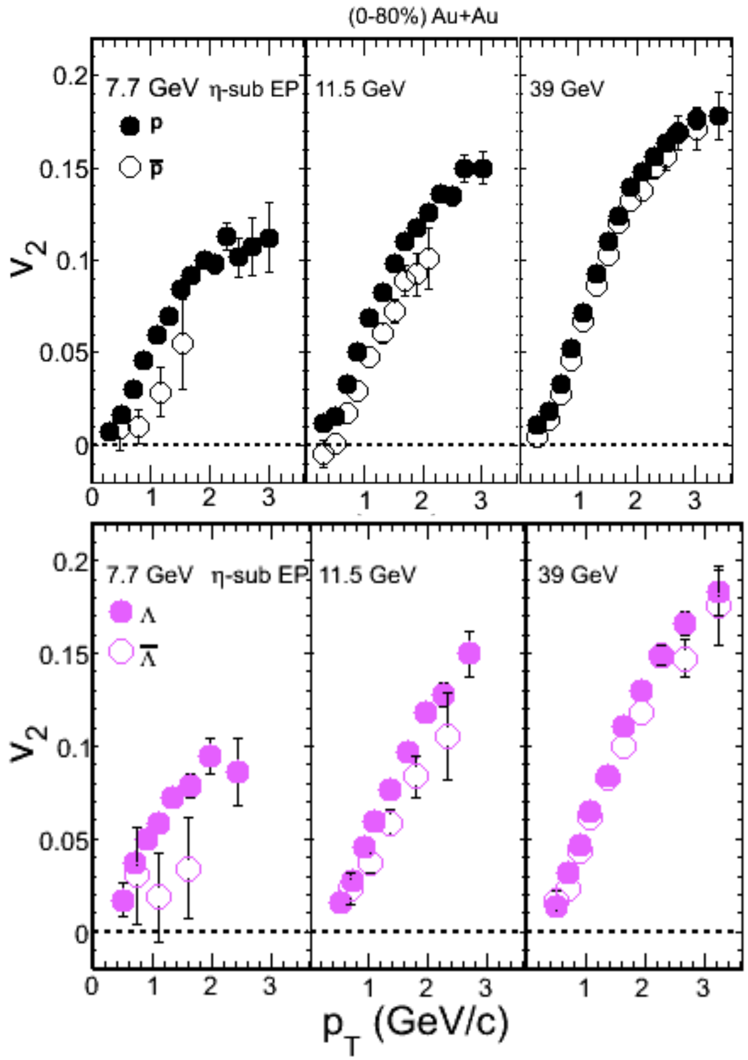


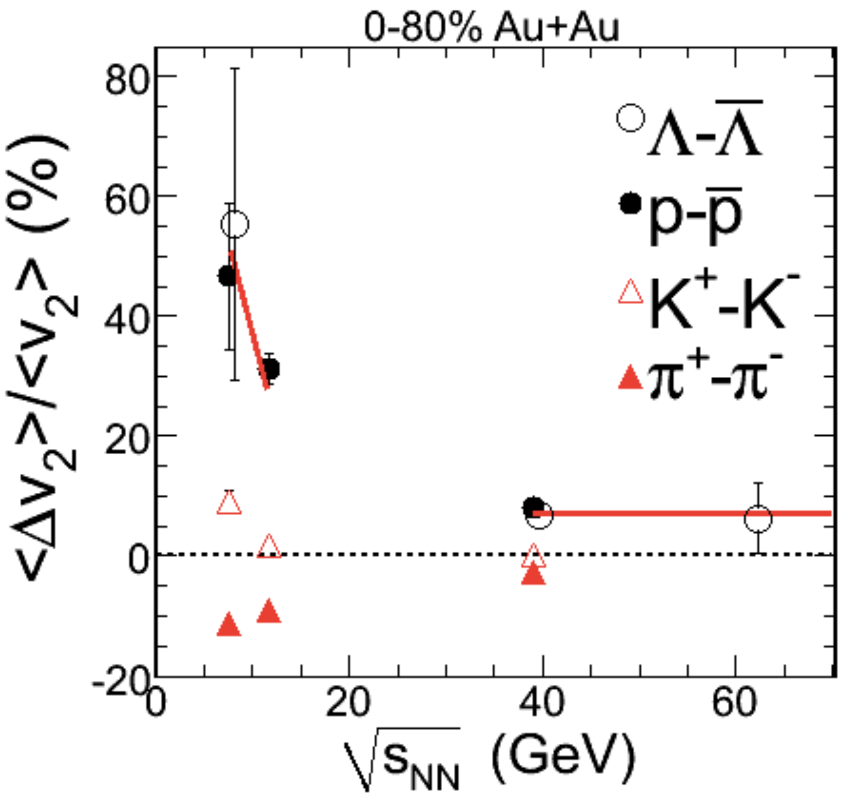
- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi, \pi\pi}$

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

*** Thermalization is assumed!**

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





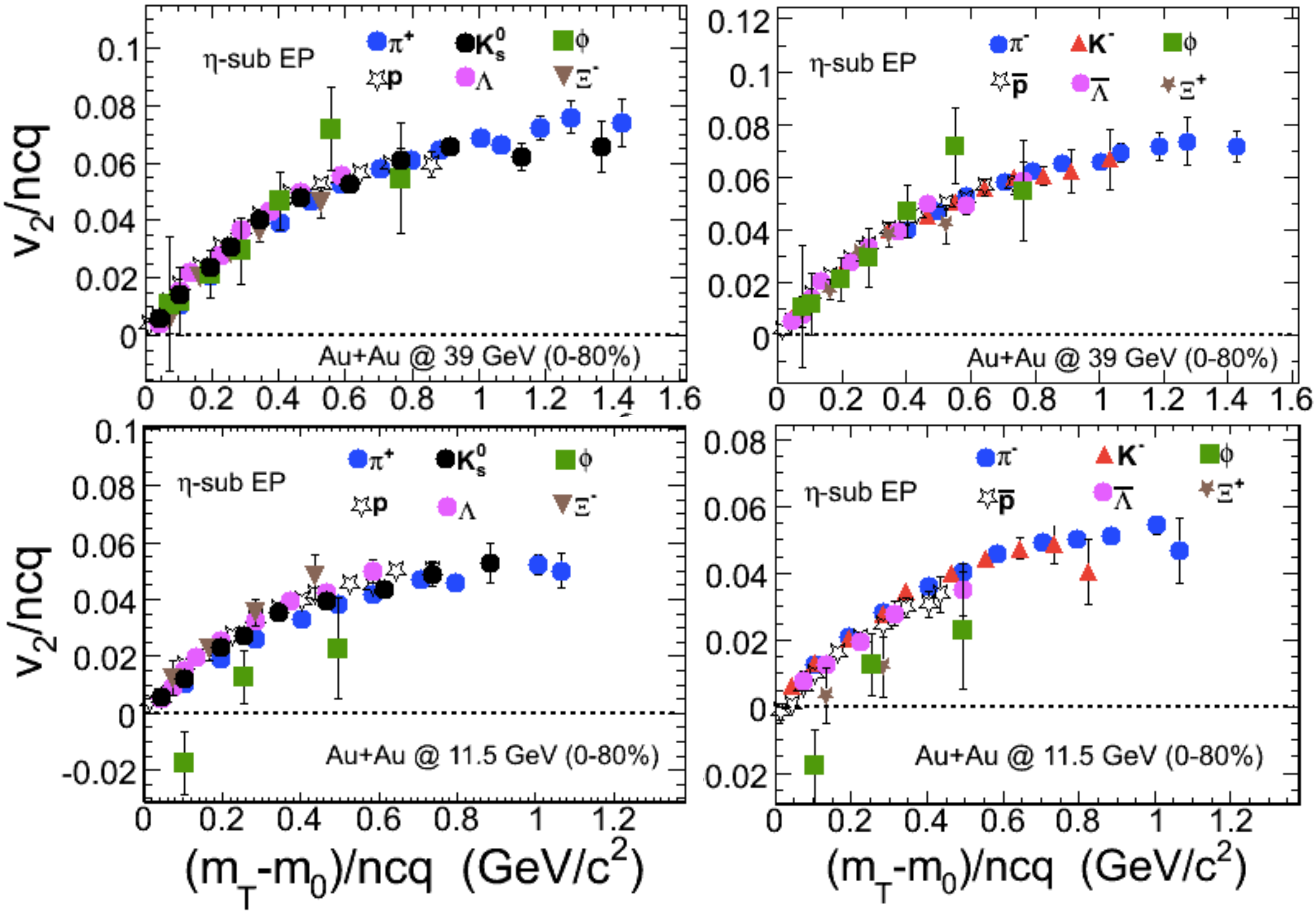
At $\sqrt{s_{NN}} \leq$ *11.5 GeV:*

- v_2(baryon) > v_2(anti-baryon)
- $v_2(\pi^+) < v_2(\pi^-)$
- $v_2(K^-) < v_2(K^+)$

STAR: Quark Matter 2011

Hadronic interactions are dominant

Sign Dependence and ϕ-meson v_2



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

-The v_2-scaling holds for hadrons with same charge (?)

"*Effects of Hadronic Potential*" by Xu, Chen, Ko, Lin, 1201.3391

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

Conserved Quantum Number

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

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

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

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

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

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

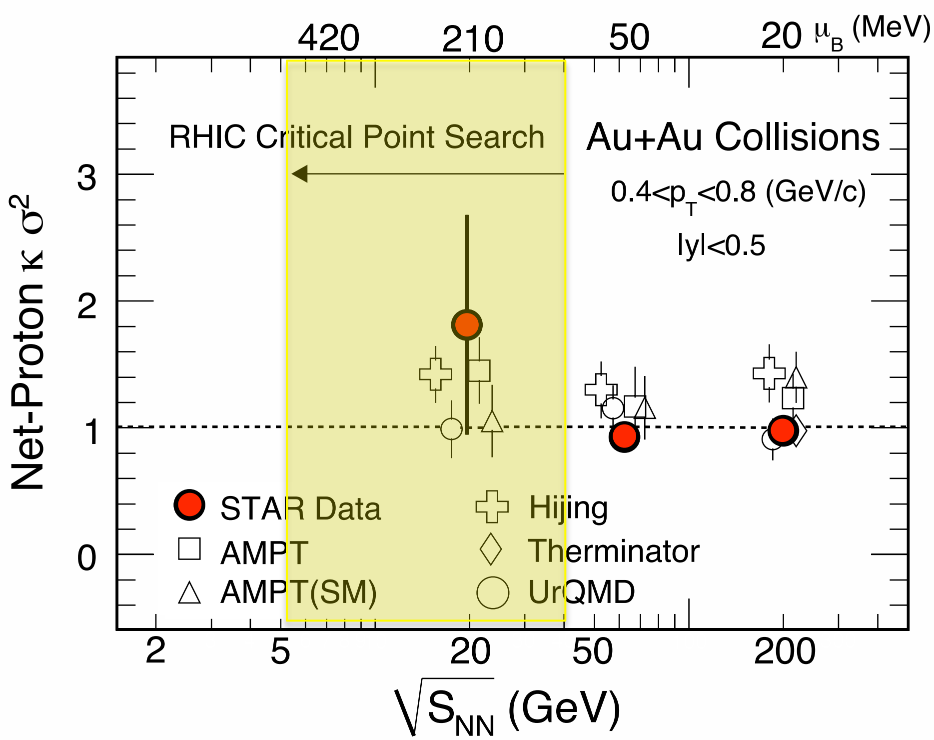
S. Gupta, F. Karsch, V. Koch
K. Redlich, M. Stephanov …

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.

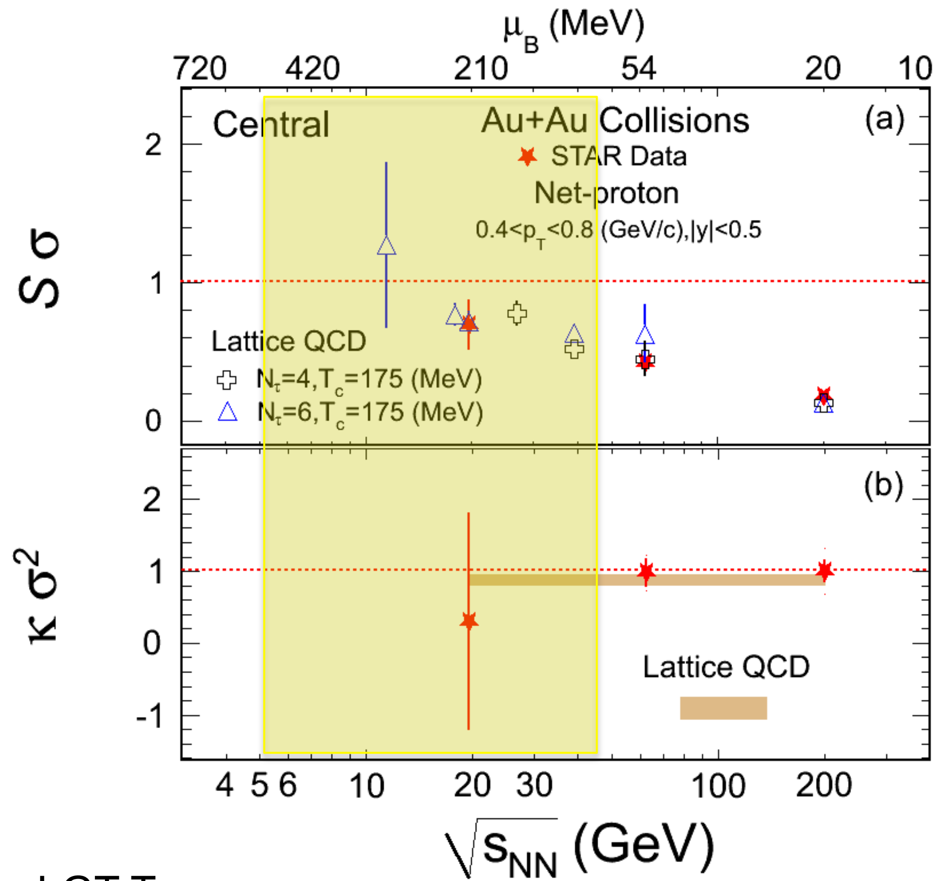
2) Most transport model results values are higher than unity, except the Theminator result at 200GeV. LGT predicted values around 0.8-0.9.

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, PLB695, 136(2011)

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

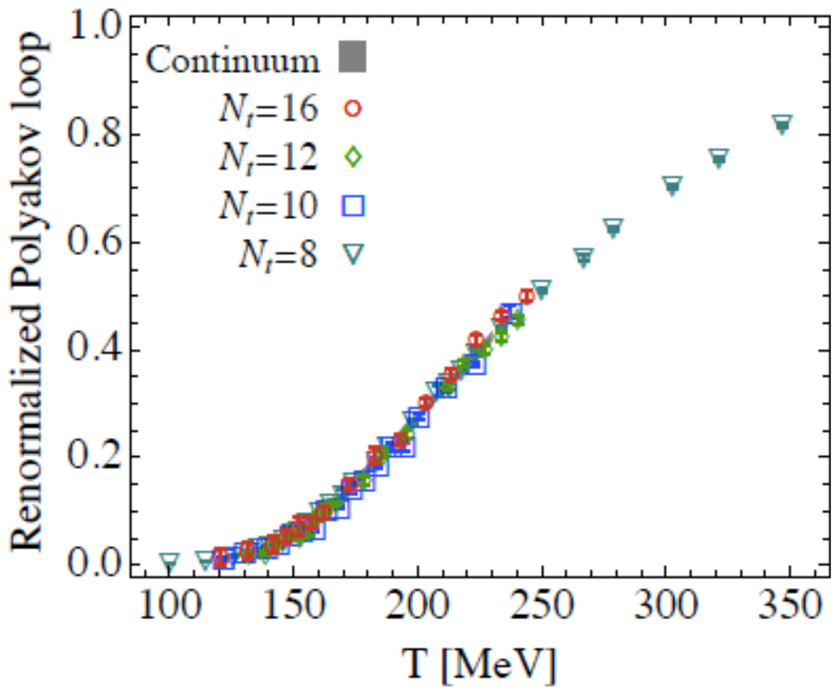
(b) Thermal equilibrium reached in central collisions

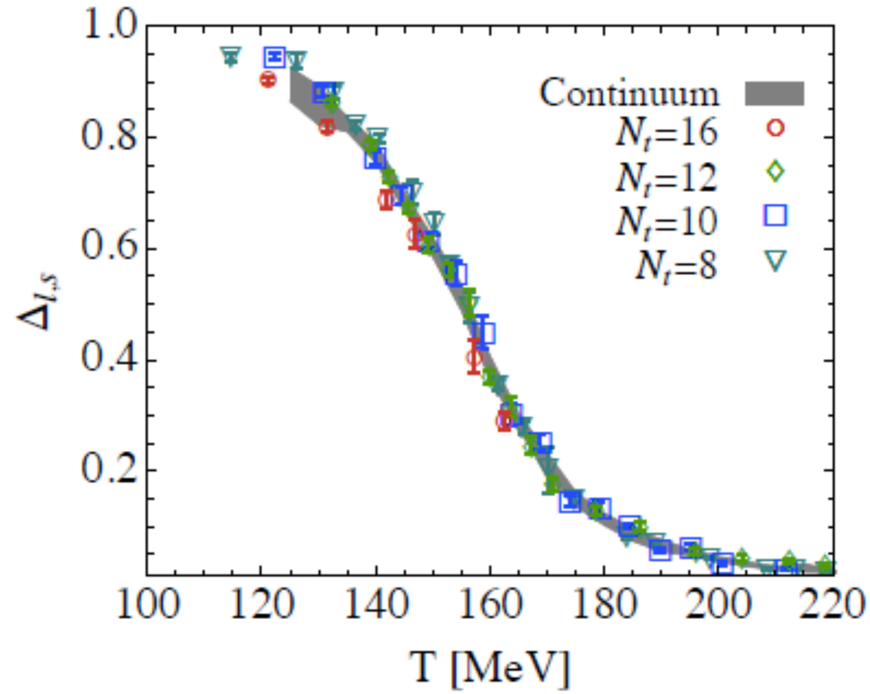
(c) Taylor expansions, at $\mu_B \neq 0$, on LGT results are valid

➔ **Lattice results are consistent with data for 20 < $\sqrt{s_{NN}}$ < 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} ~ 155 MeV
RHIC Data	T_C^{Exp} ~ 175^{+1}_{-7} MeV
	(T_{CH}^{Exp} ~ 160±5 MeV)

Summary

(1) In $\sqrt{s_{NN}}$ = 200GeV Au+Au collisions, hot and dense ***matter, with partonic degrees of*** **freedom and collectivity, has been formed**

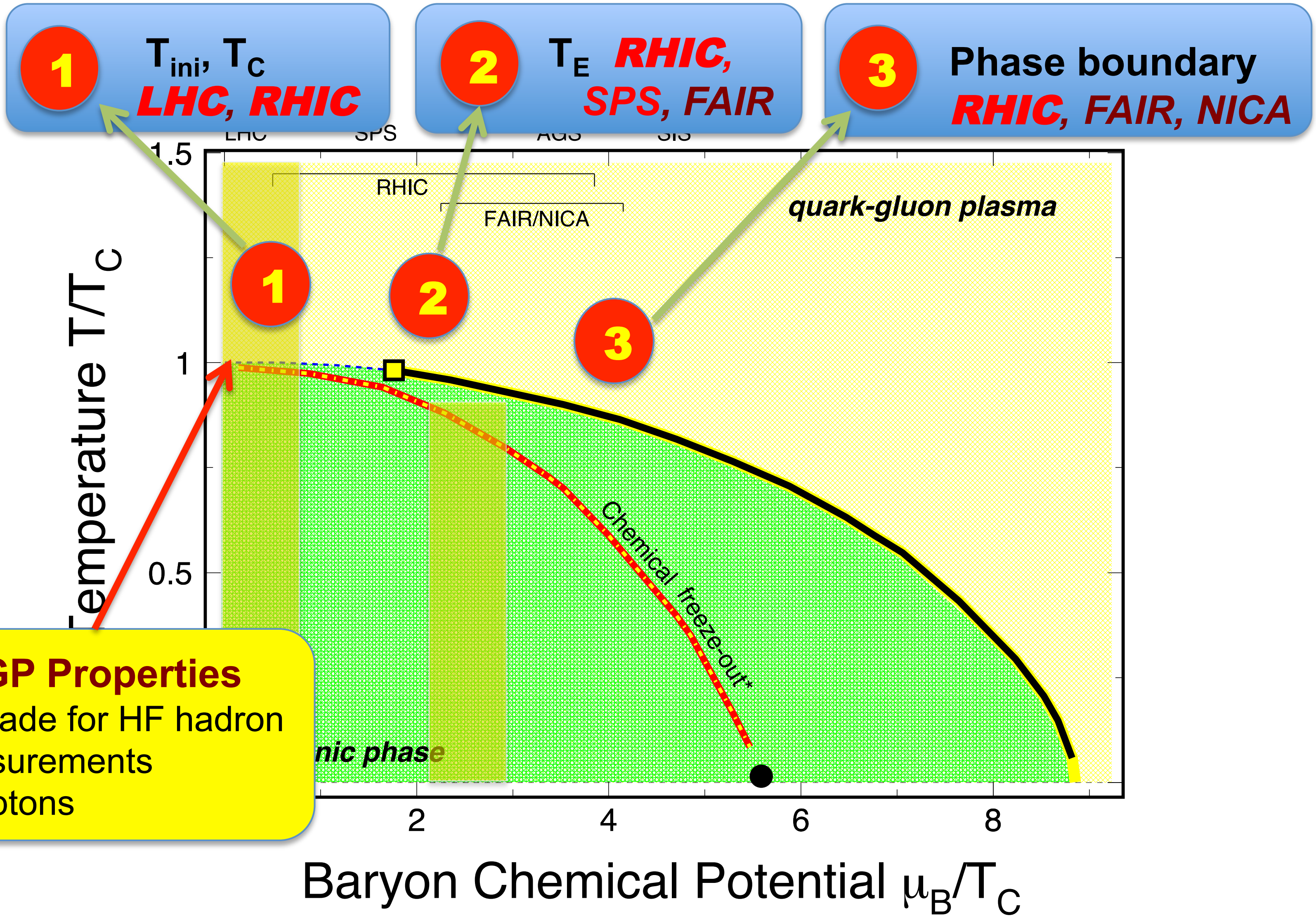
(2) The matter behavior like a ***quantum liquid with*** small ***η/s***

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

(4) **[partonic] <** ***μ_B ~110–320*** **(MeV) < [hadronic]**

(5) Within errors, the net-proton distributions are consistent with LGT results.

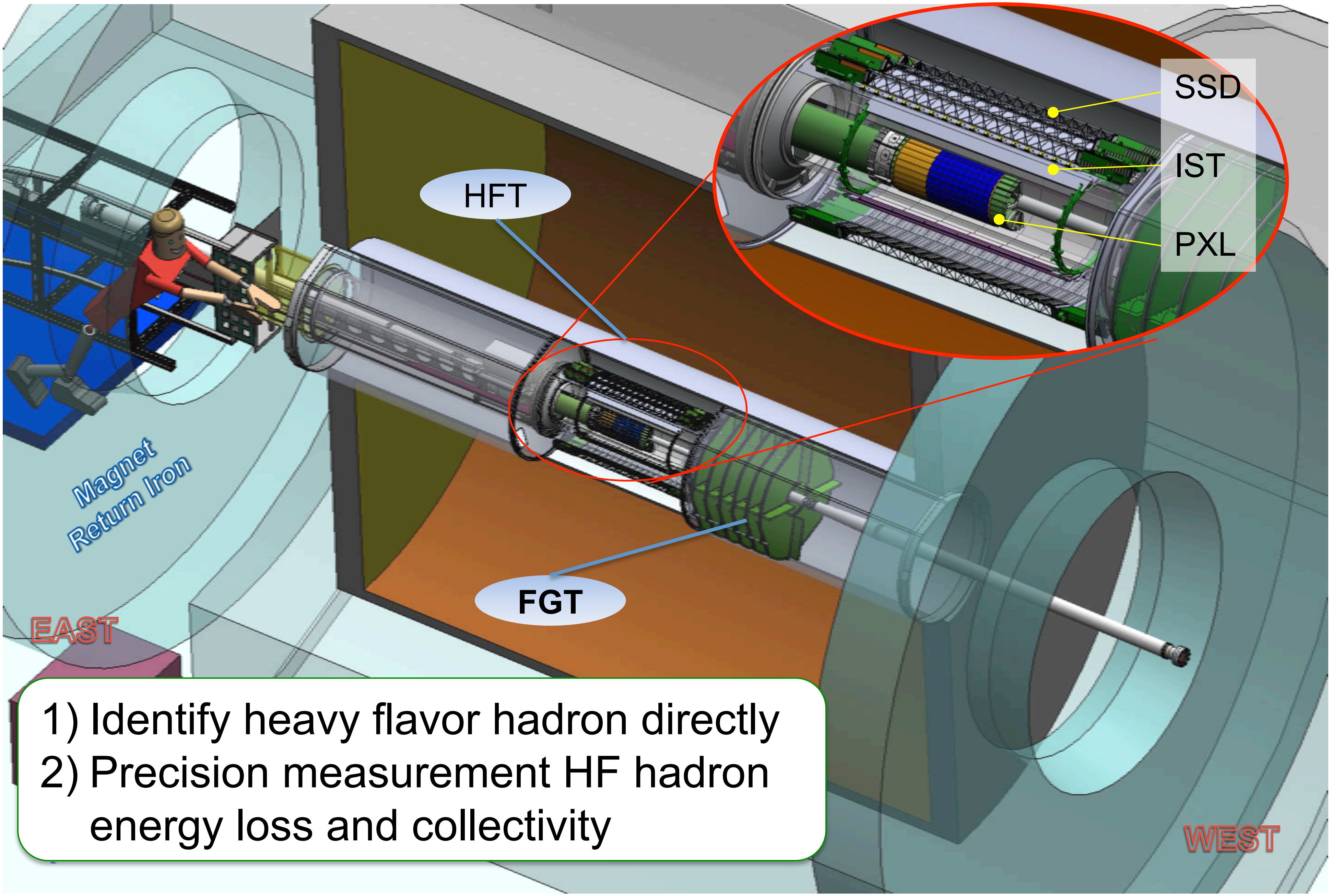
Outlook: (7.7, 11.5, 15.5, 19.6, 27, 39,62, 200 GeV)



QGP Properties

- Upgrade for HF hadron measurements
- di-leptons

Outlook: Heavy Flavor Tracker at STAR



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

Many Thanks to the Organizers!

Nu Xu