High-Energy Nuclear Collisions & the QCD Phase Structure

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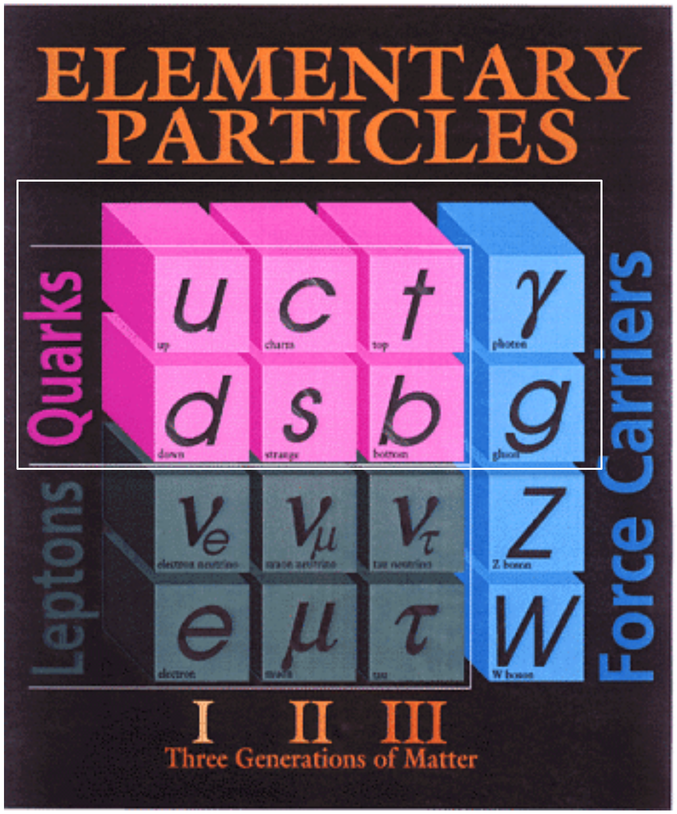
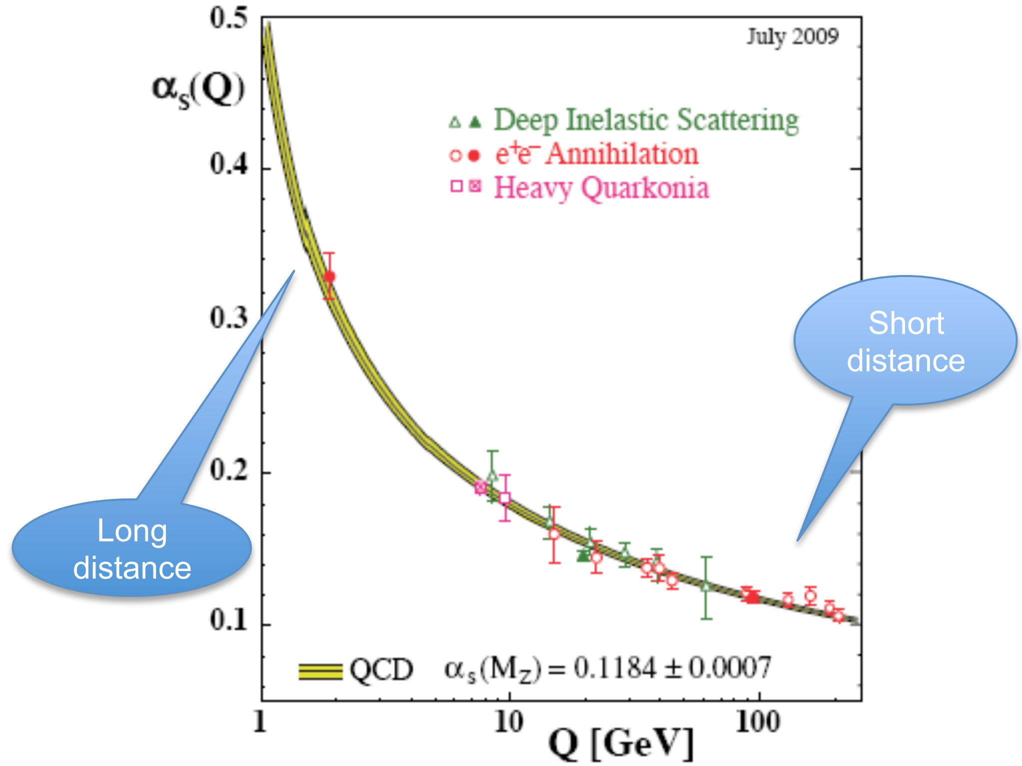
Many Thanks to the Organizers!

Quantum ChromoDynamics



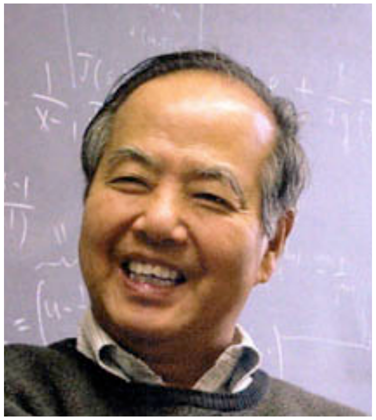


1) QCD is the basic theory for strong interaction. Its degrees of freedom, are well defined at short distance.
2) Little is known regarding the dynamical structures of matter that made from ***q, g***. *E.g. the confinement*, *nucleon spin*, the ***QCD phase structure***... Large α_s and strong coupling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

What Is the Problem ?

- The confinement:

Quarks are the basic building blocks of matter.
No free quarks are seen, confined within hadron:
$\Delta v_0 \sim 1\ fm^3$, $\rho_0 \sim 0.16\ fm^{-3}$, $\varepsilon_0 \sim 0.15\ GeV/fm^3$



T.D Lee, 1970

- Heavy ion collisions: Large, hot and dense system
phase structure

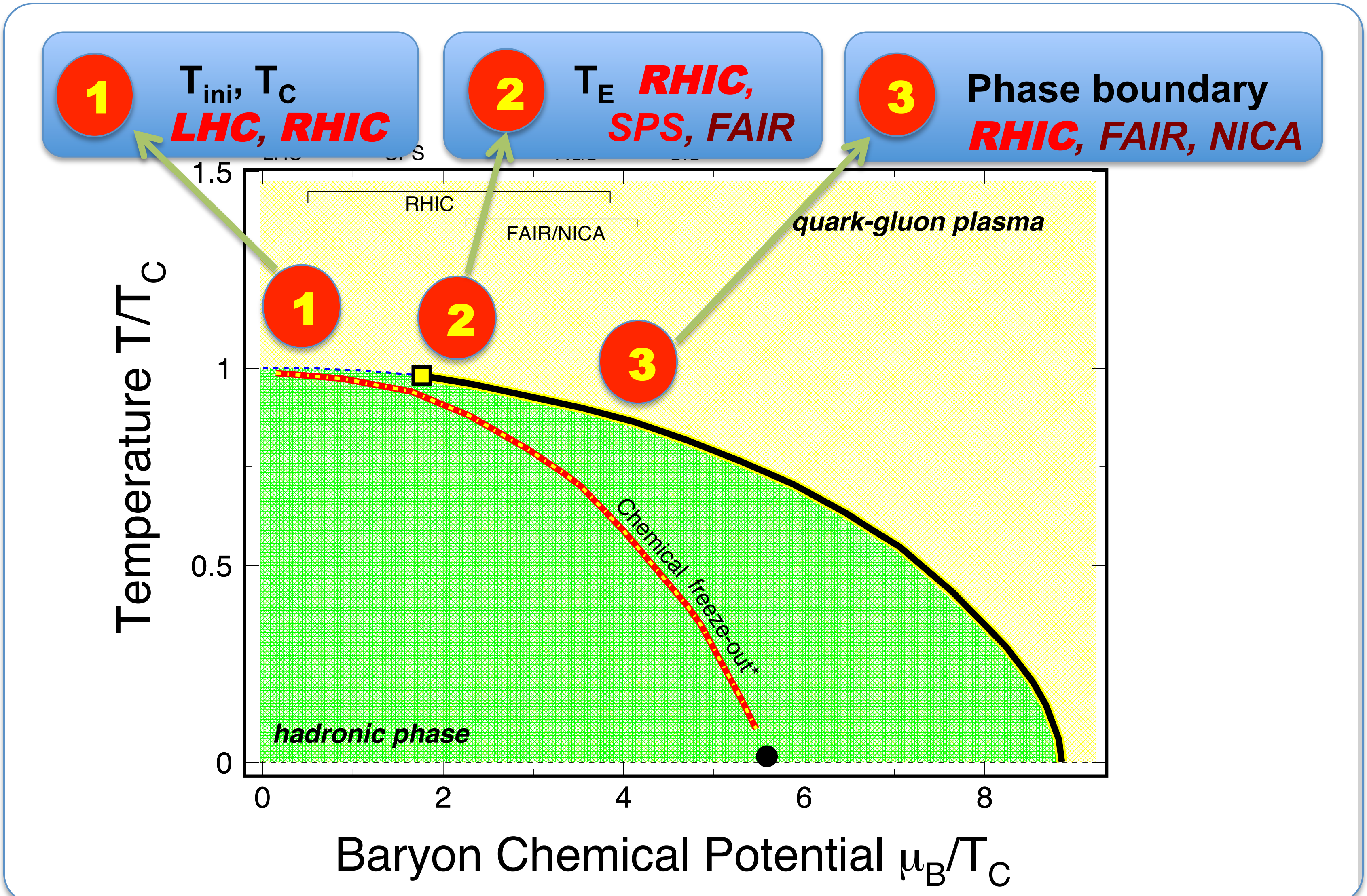
$\Delta v \sim 1000\ fm^3 = 1000\ v_0$
$\rho \gg 3\ fm^{-3} \sim 20\ \rho_0$
$\varepsilon \gg 3\ GeV/fm^3 \sim 20\ \varepsilon_0$
$\Longrightarrow$ **Quark Gluon Plasma (QGP)**

Quarks and gluons are ‘freely’ moving in a large volume
New form of ***matter with partonic degrees of freedom***

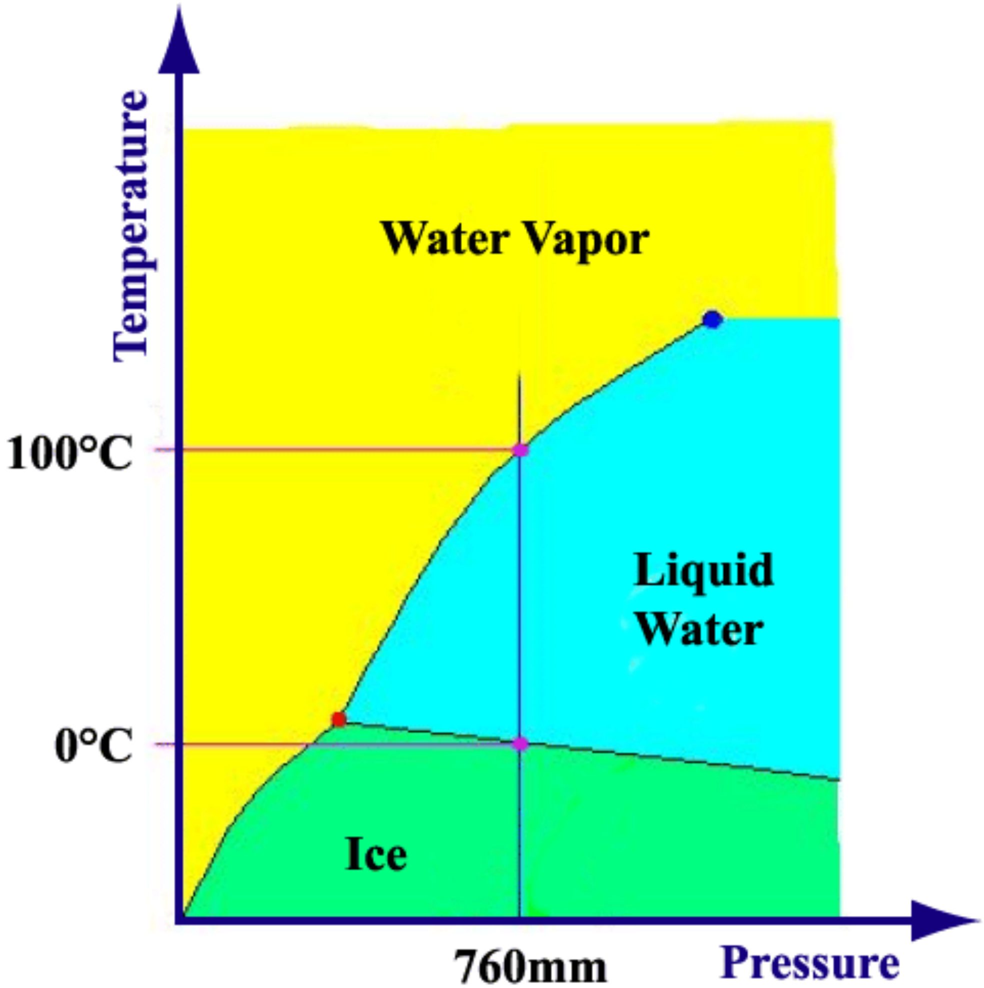
- Connection with other fields

cosmology, origin of the universe, evolution of the universe,
quantum statistics with partons, …

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.

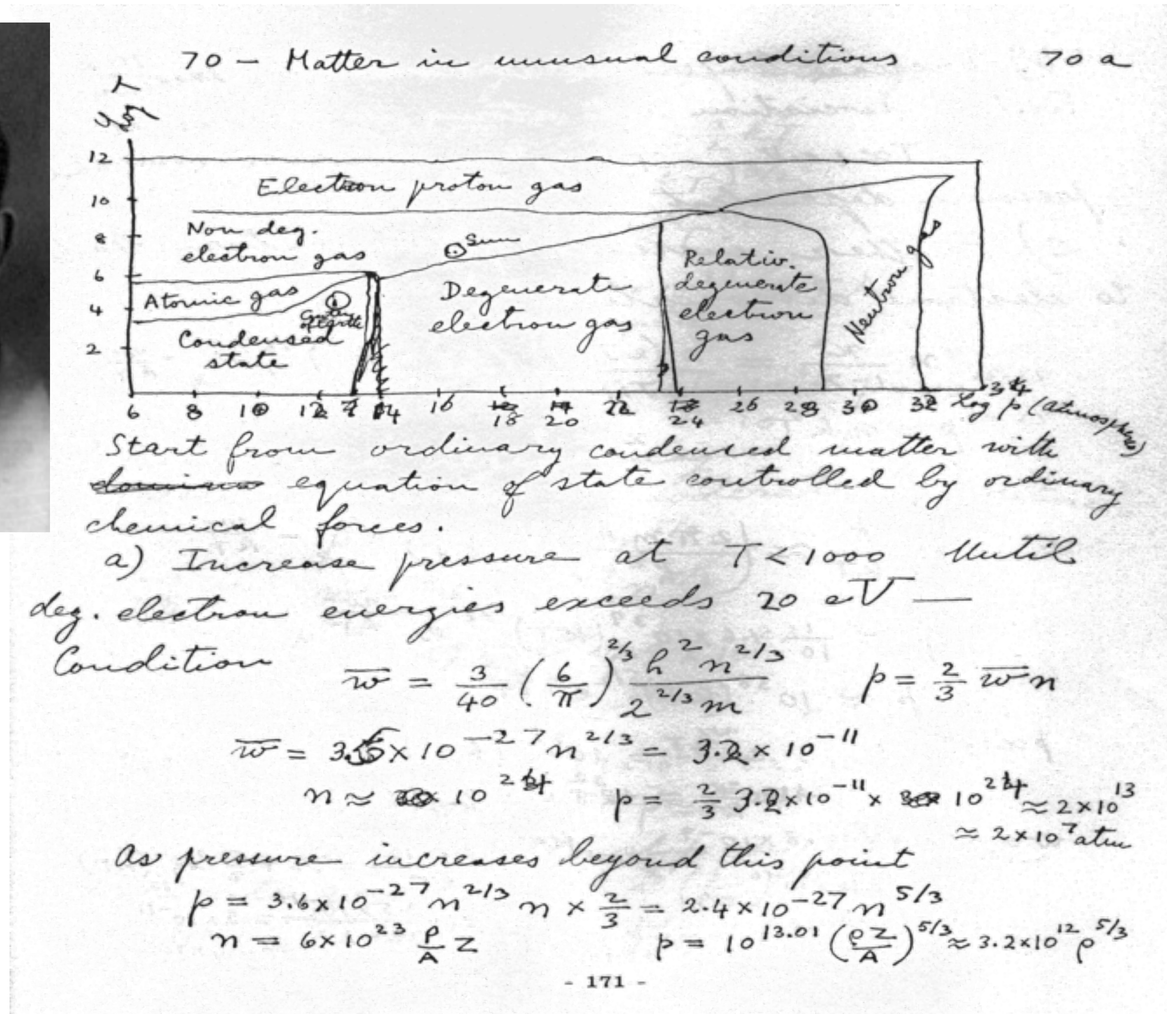
Water: H_2O

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

QCD Diagram (1953)

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

E. Fermi



70 — Matter in unusual conditions 70 a

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

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

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

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

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

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

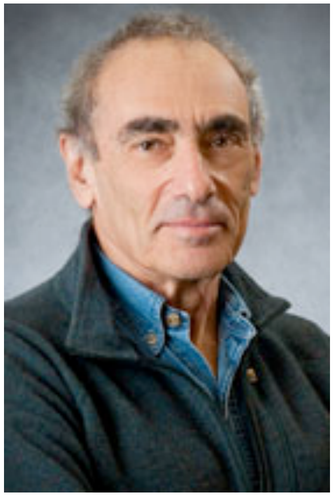
As pressure increases beyond this point

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

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

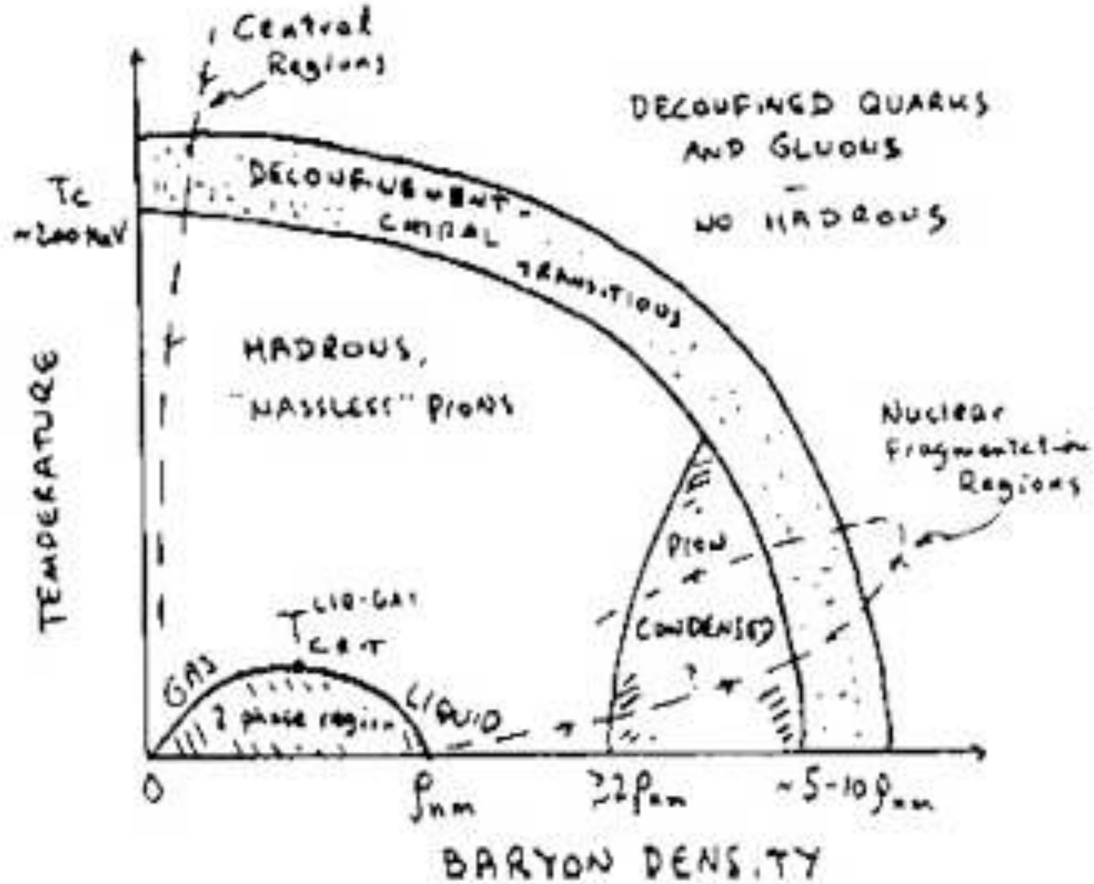
- 171 -

QCD Diagram (1983)

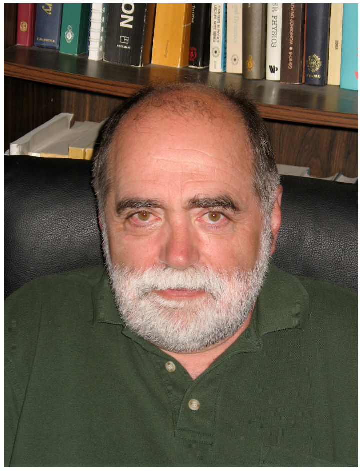


Gordon Baym

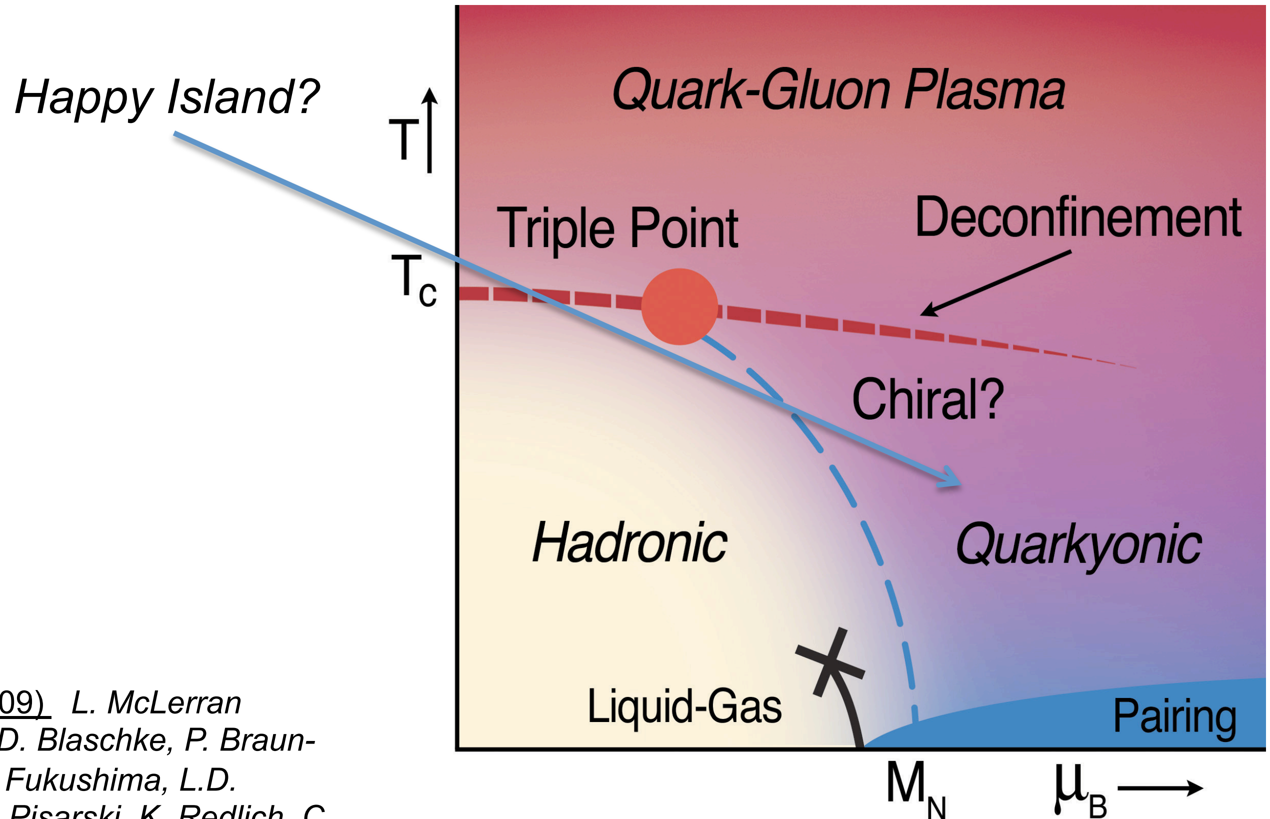
1983 US Long Range Plan - *by Gordon Baym*



QCD Diagram (2009)



Larry McLerran



nucl-th: 0907.4489, NPA830,709(09) *L. McLerran*
nucl-th 0911.4806: *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. Stach*

Systematic experimental measurements vs. (E_{beam}, A_{size}): extract **numbers** that related to the **QCD phase diagram**!

Outline

(1) Introduction

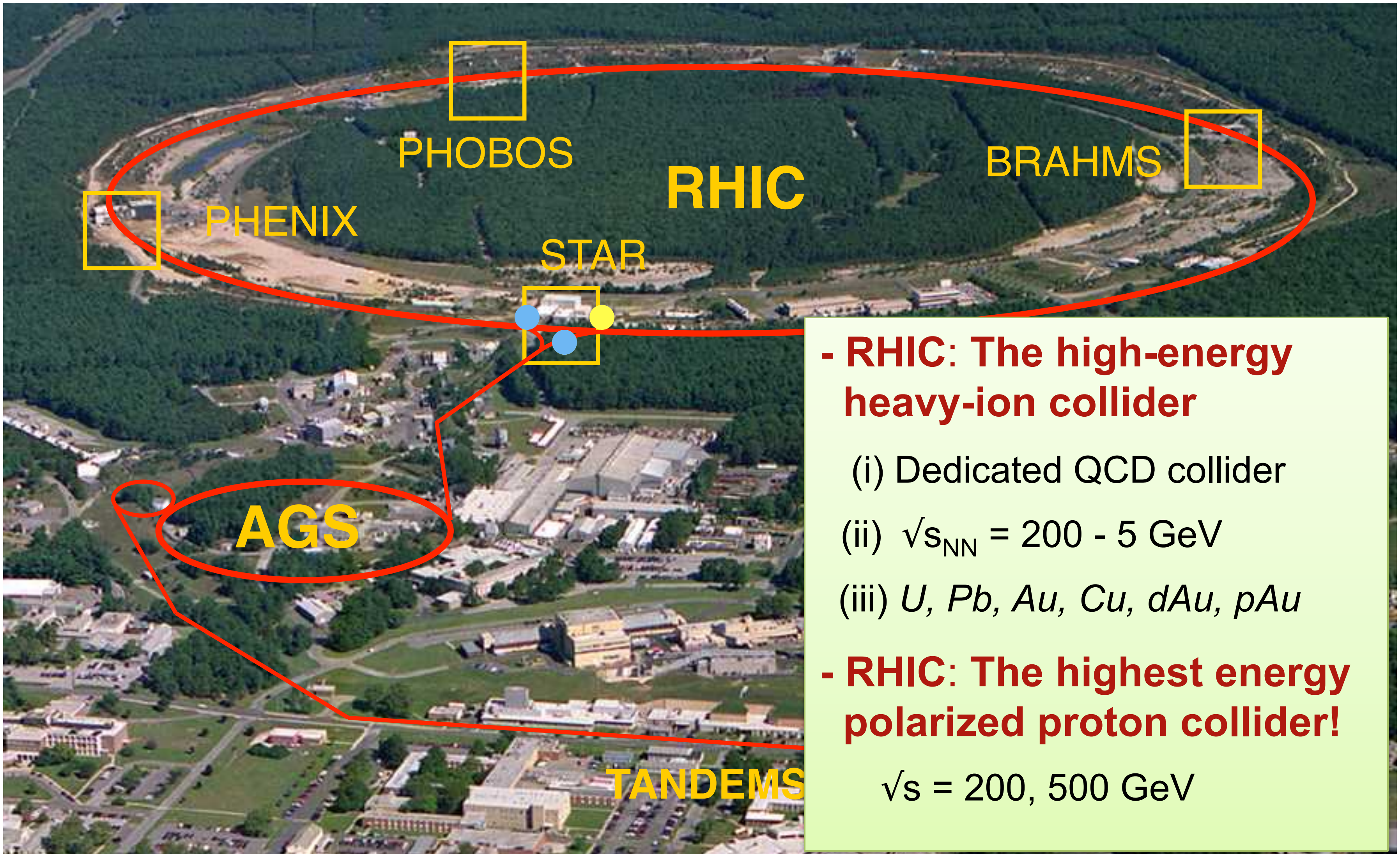
(2) Recent results from RHIC

(3) RHIC Beam Energy Scan

(4) Summary

Relativistic **H**eavy **I**on **C**ollider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



- **RHIC: The high-energy heavy-ion collider**

  (i) Dedicated QCD collider

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

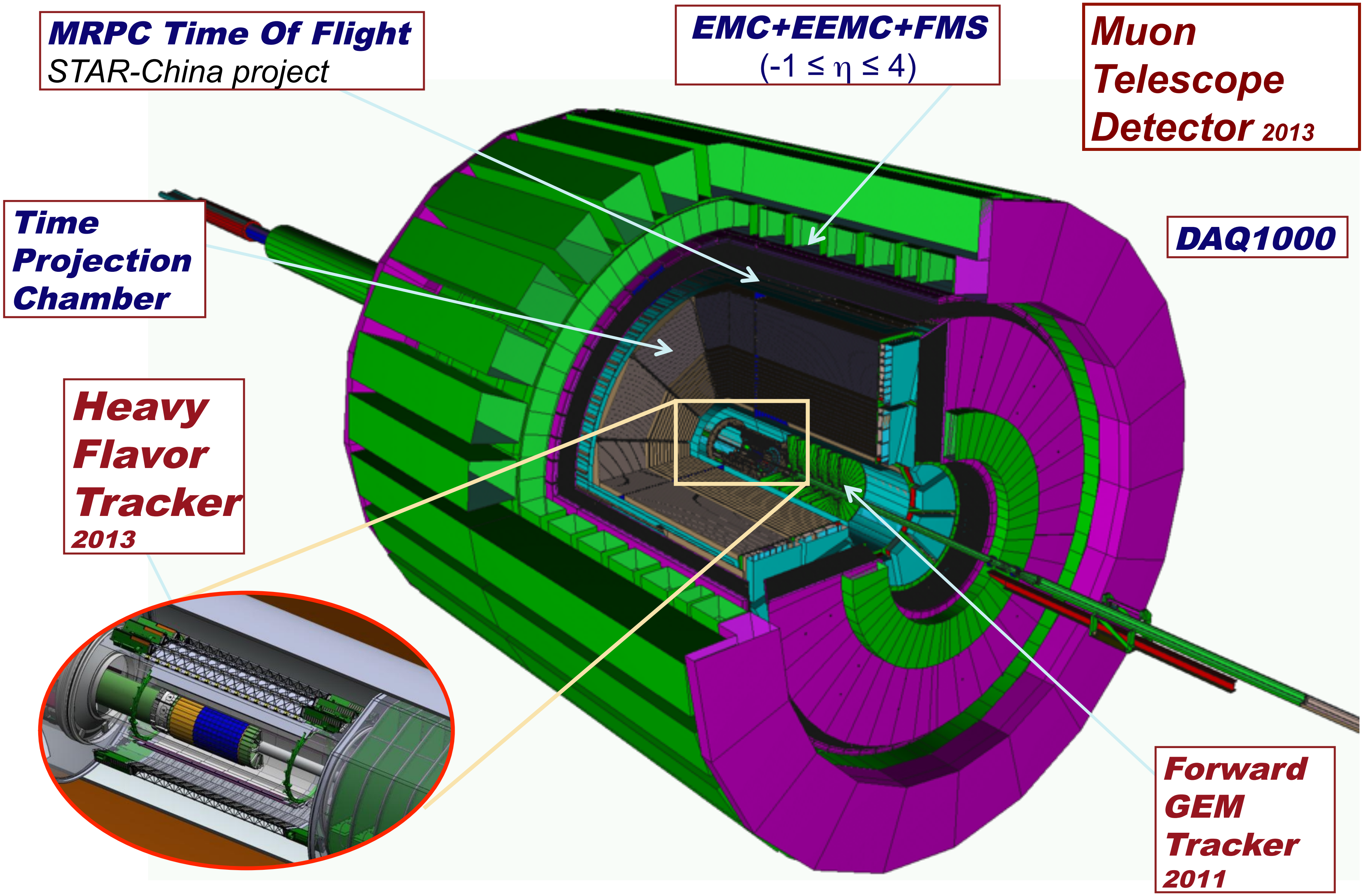
  (iii) *U, Pb, Au, Cu, dAu, pAu*

- **RHIC: The highest energy polarized proton collider!**

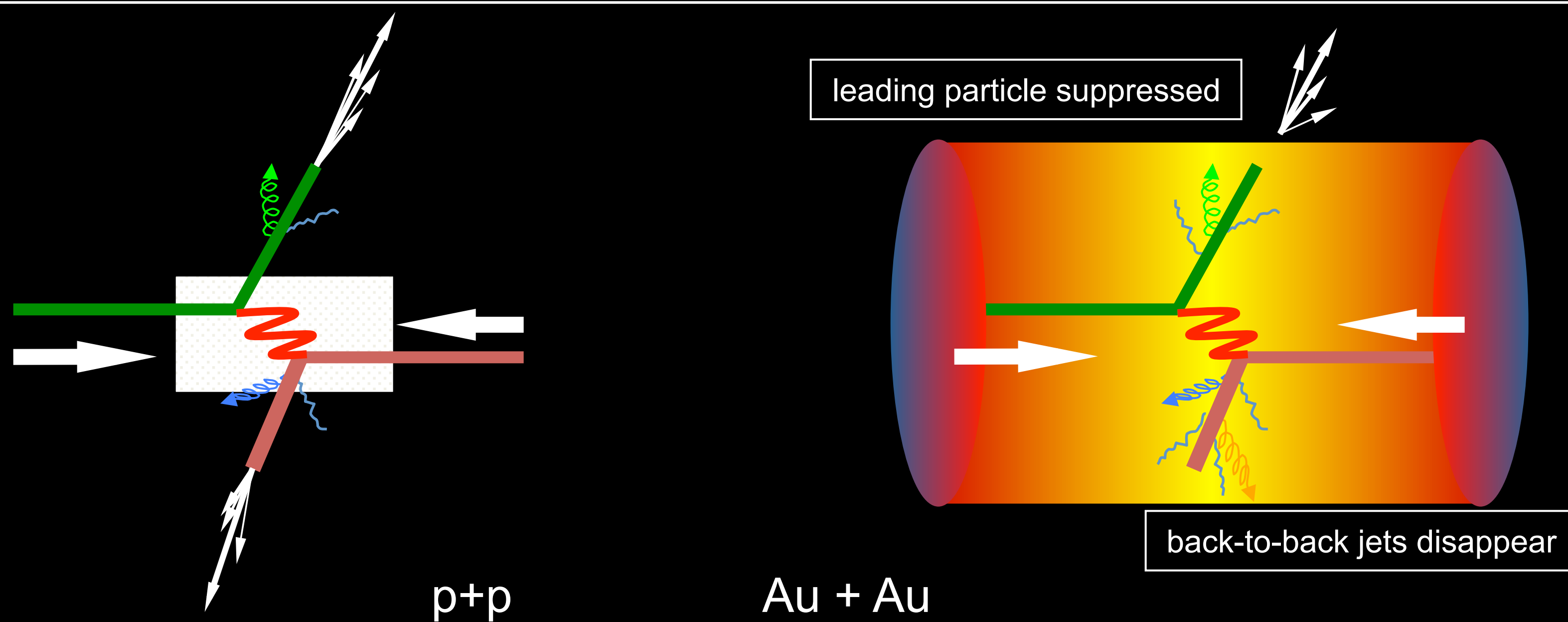
  $\sqrt{s}$ = 200, 500 GeV

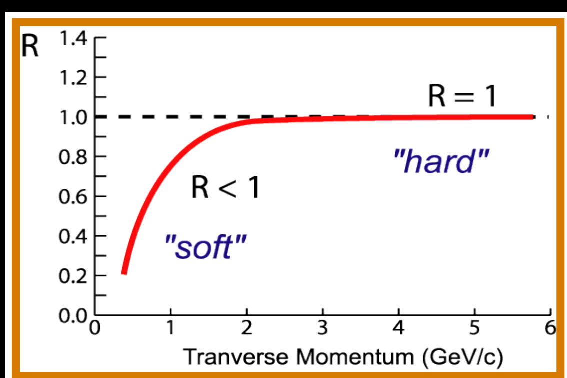
Animation M. Lisa

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



Energy Loss in A+A Collisions

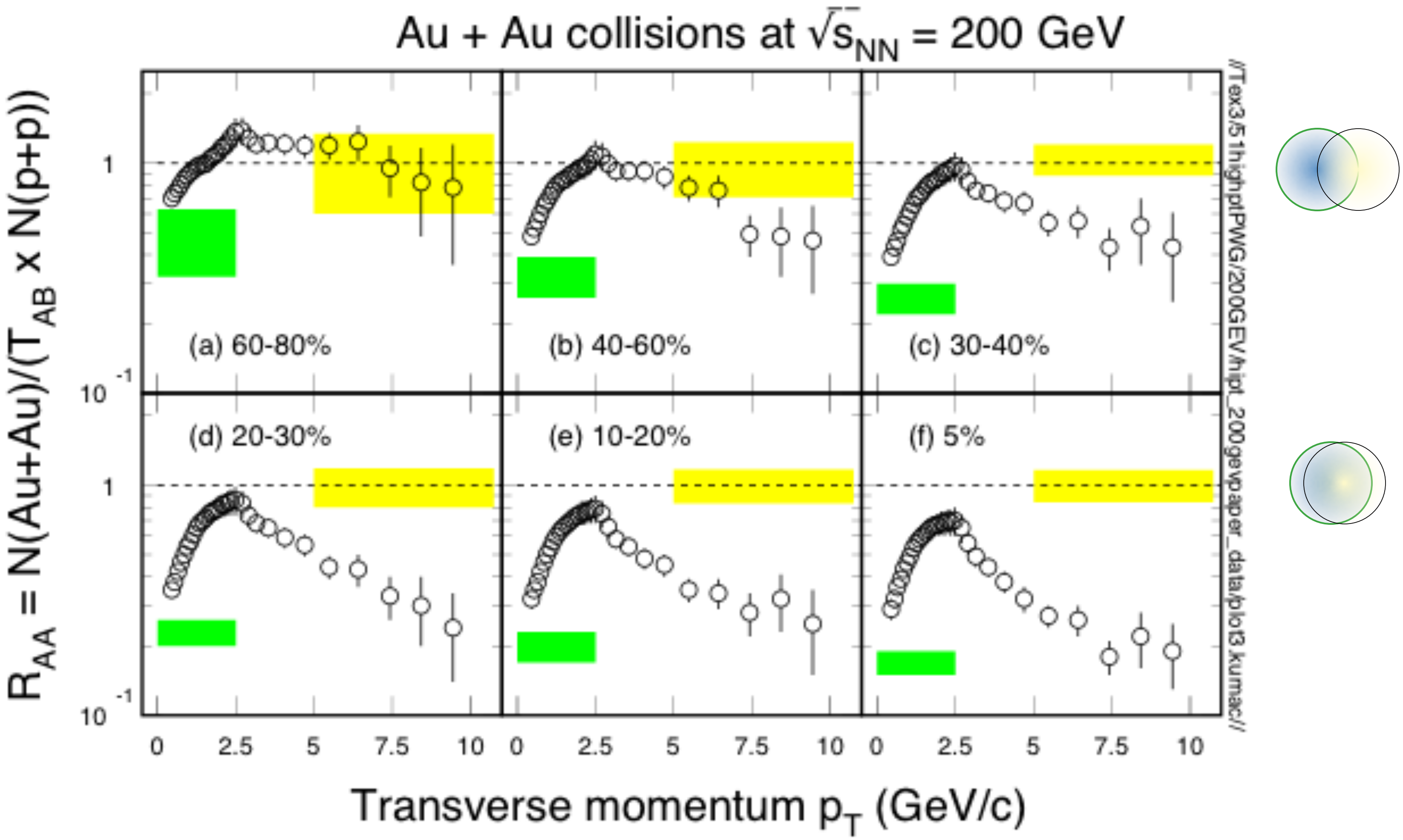




Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2\sigma^{AA}/dp_T dy}{d^2\sigma^{nn}/dp_T dy}$$

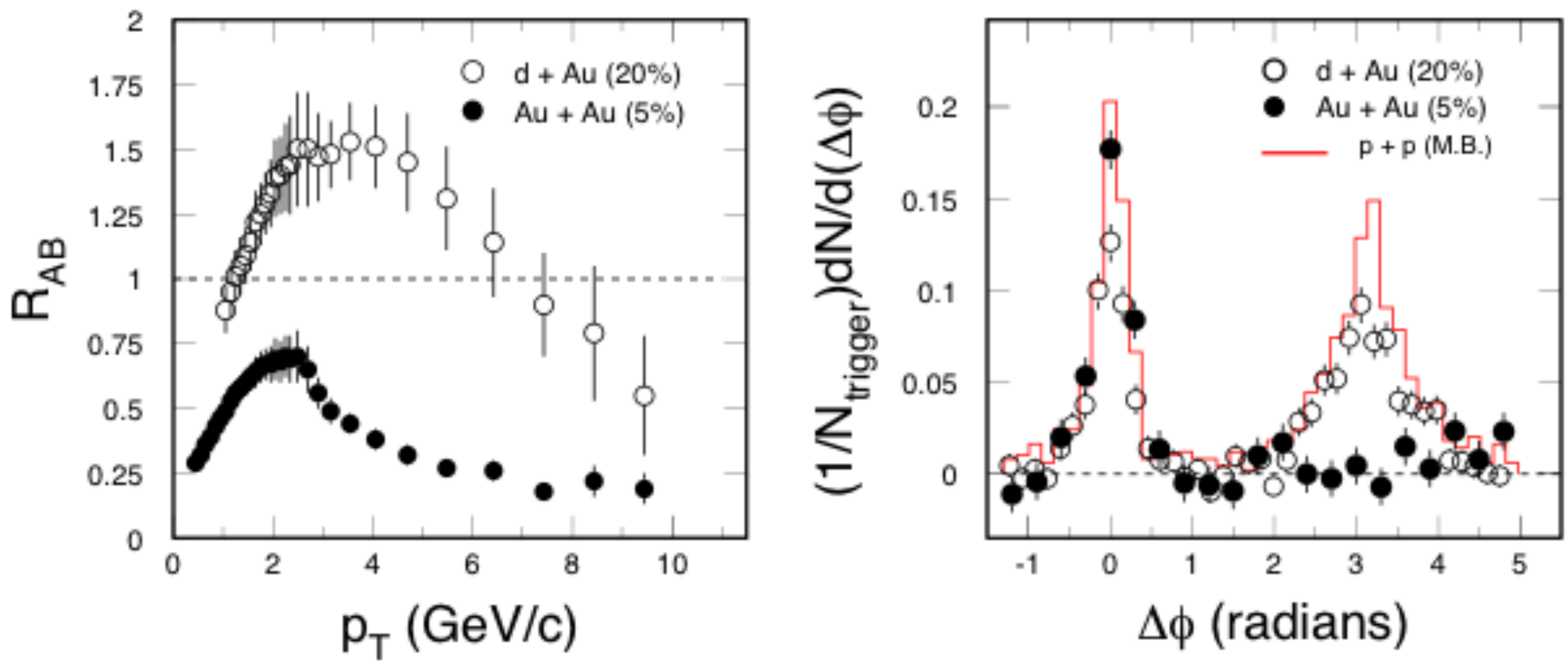
Hadron Suppression at RHIC



Hadron suppression in more central Au+Au collisions!

Partonic Energy Loss at RHIC

STAR: Nucl. Phys. ***A757***, 102(2005).

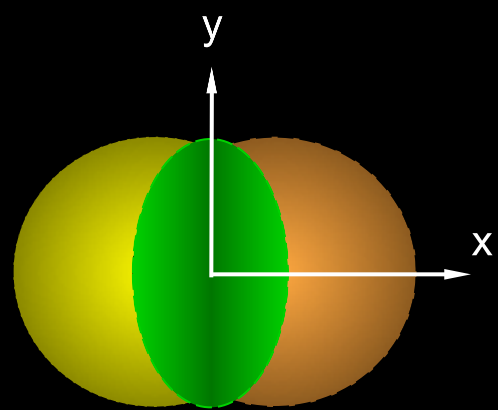


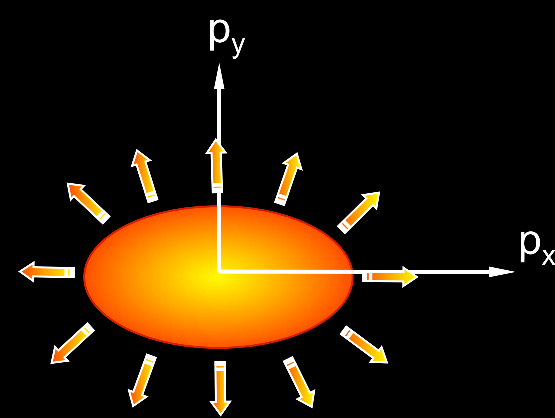
Central Au+Au collisions at $\sqrt{s_{NN}}$ = *200* GeV: light quark hadrons and the away-side jet in back-to-back 'jets' are suppressed. Major difference from p+p and d+Au collisions.

Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε_0

Anisotropy Parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy

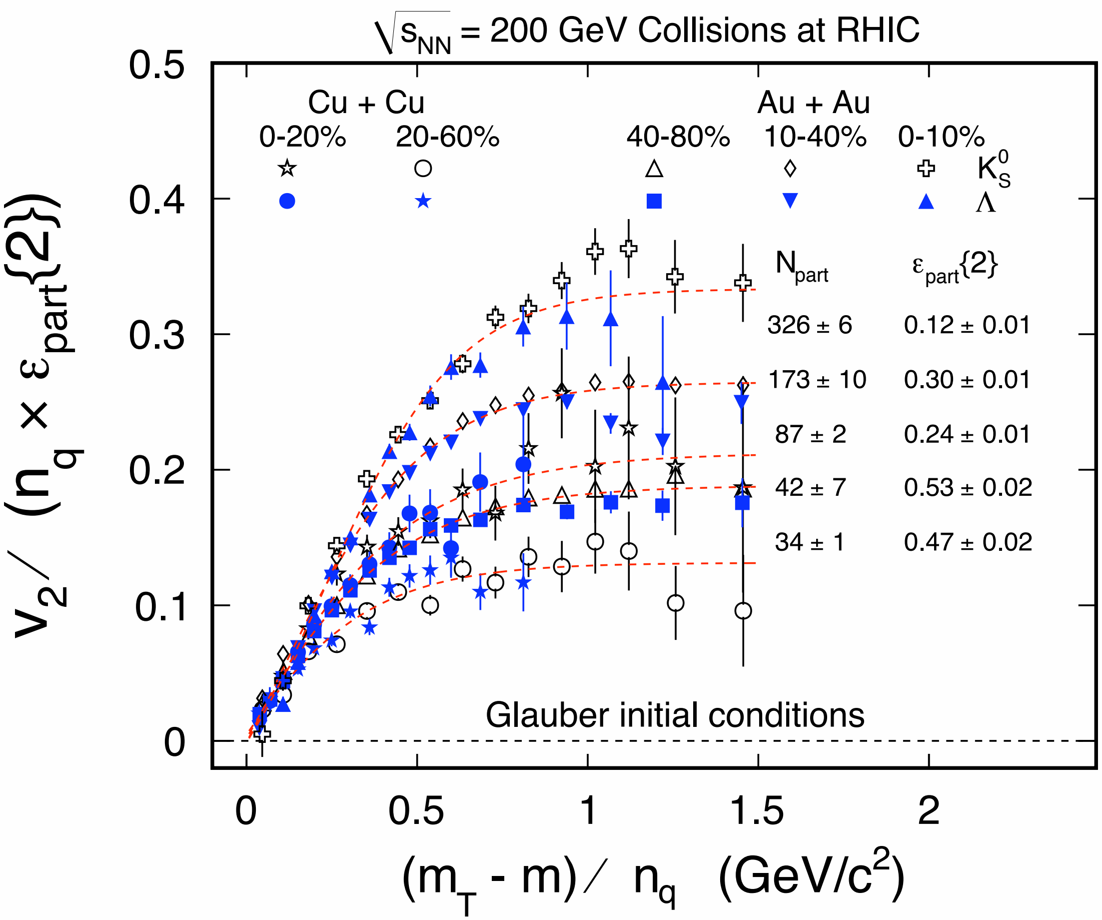




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \;\; \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

System Size Driven Collectivity

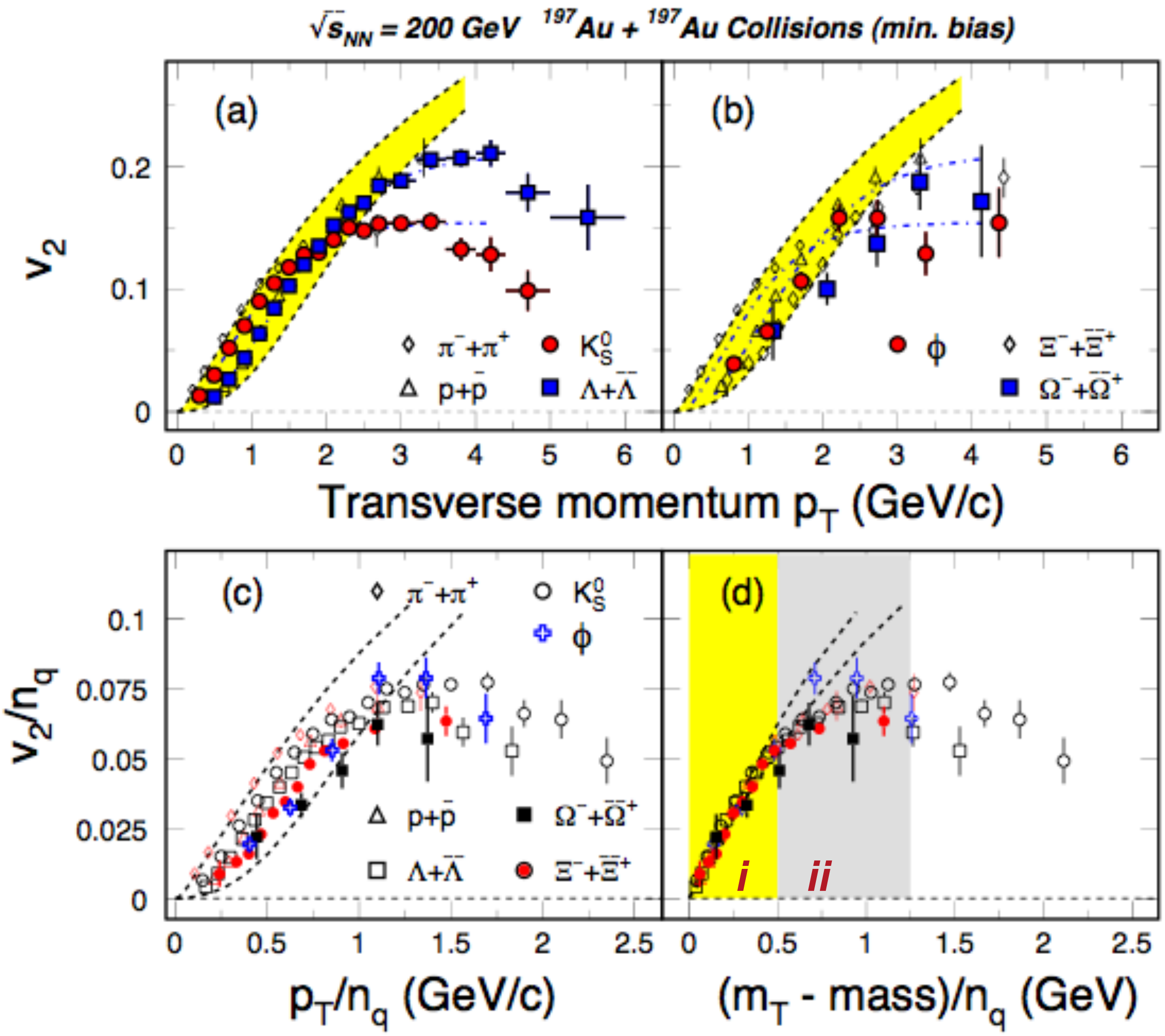


STAR: *PR**C81**,* 44902(10)

Collectivity: Driven by number of participants

More Analysis: How and when local equilibrium reached

Collectivity, De-confinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

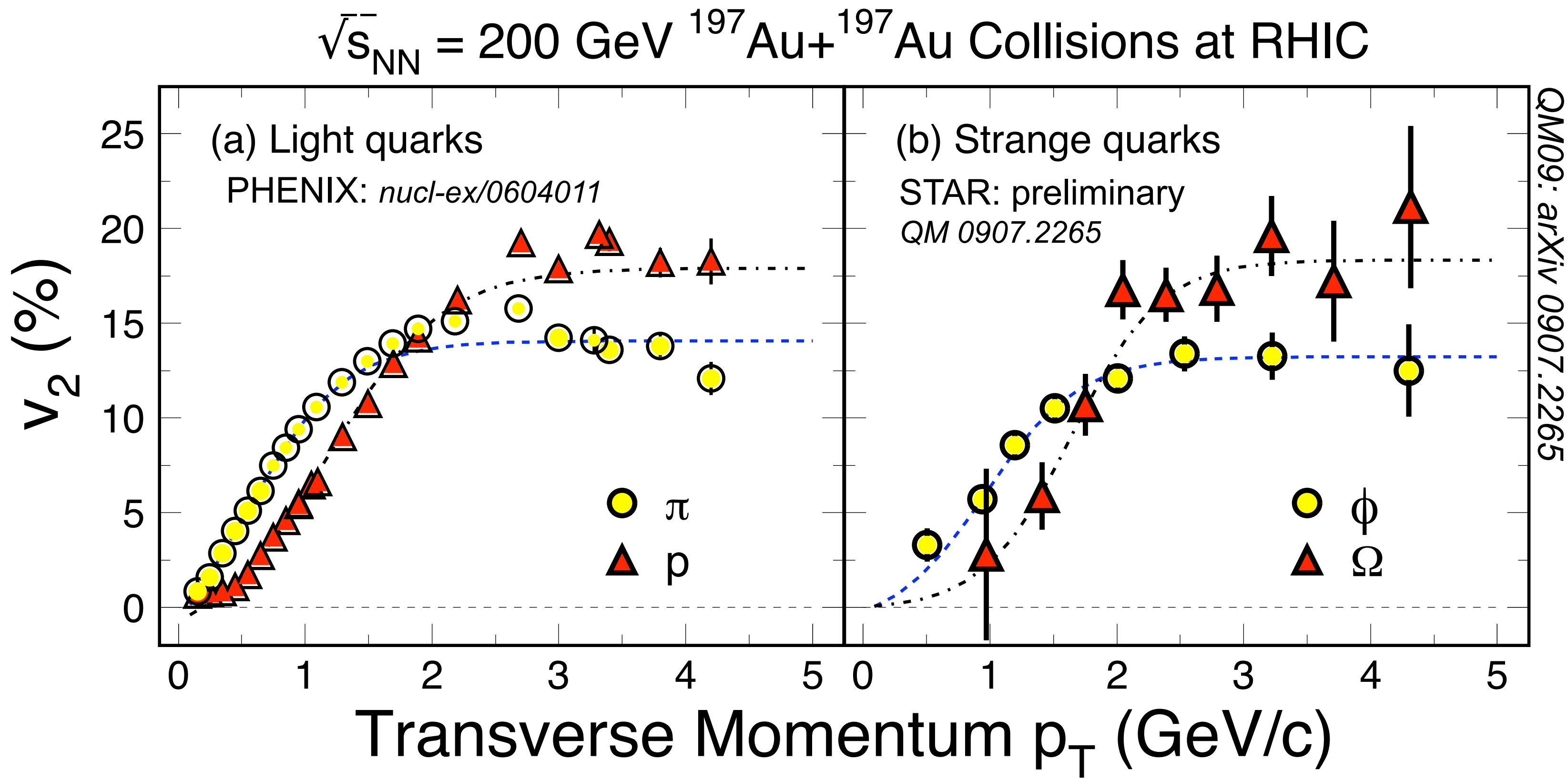
➪ **n_q-scaling**
novel hadronization process

➪ **Partonic flow**
De-confinement

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

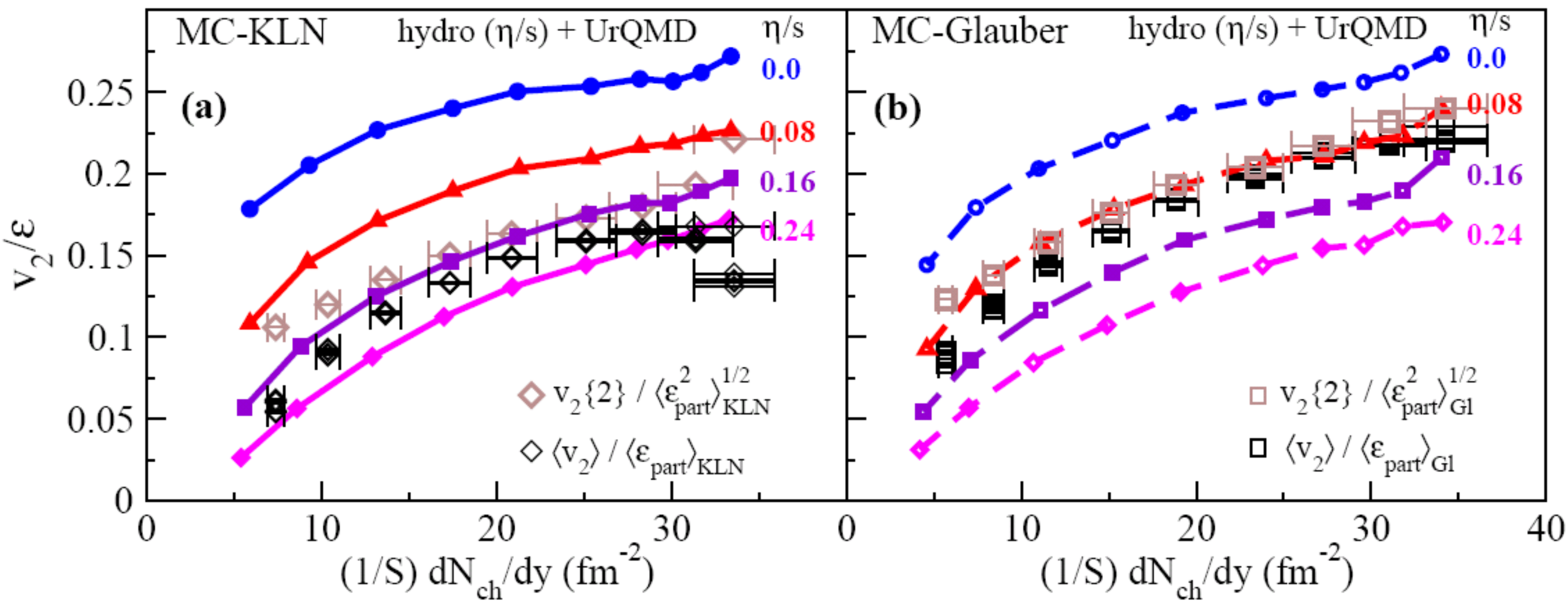
Partonic Collectivity at RHIC



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

➔ ***Collectivity developed at partonic stage!***
➔ ***De-confinement in Au+Au collisions at RHIC!***

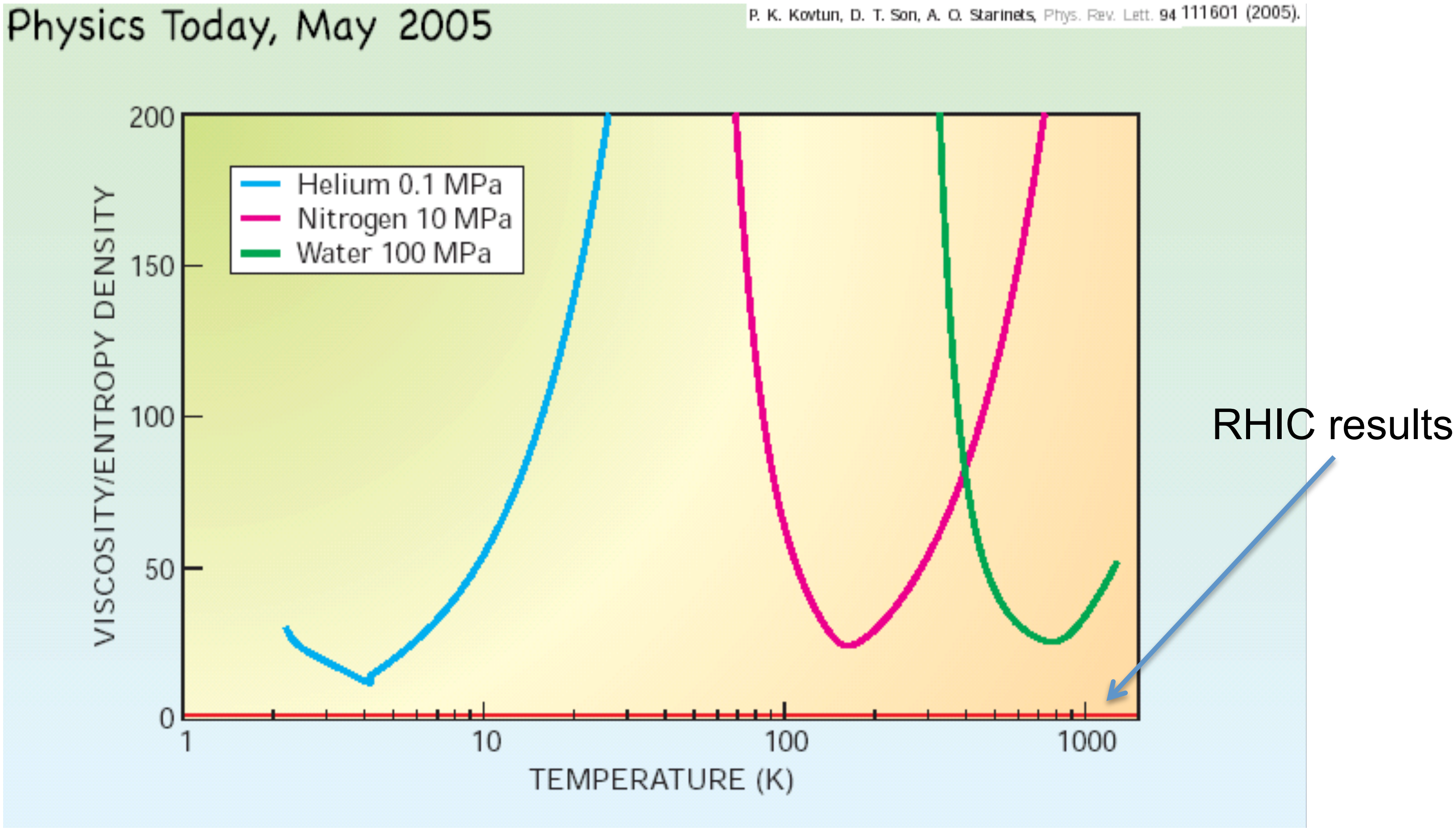
Hydrodynamic Model Comparison



- 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* at RHIC: "Perfect Liquid"



1) Nuclear matter: the viscosity/entropy ratio ≤ 1/4π, the ***quantum limit***.
2) "Strongly interaction matter, small ***η/s*** - *Perfect liquid*" at RHIC.

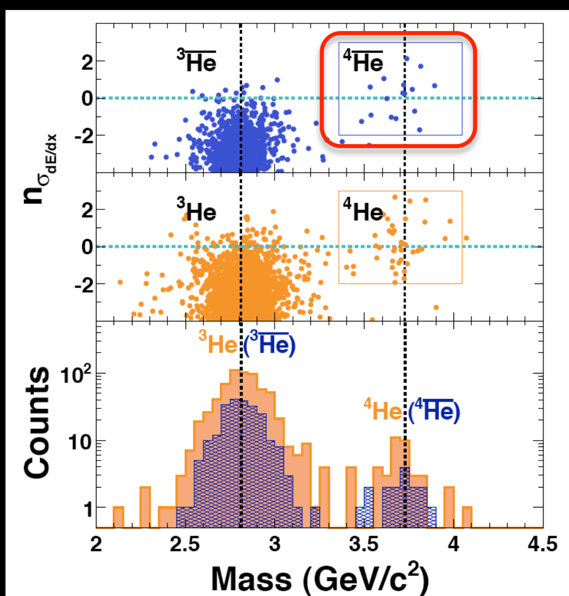
Antimatter Discoveries at RHIC

nature April, 2011

"Observation of the Antimatter Helium-4 Nucleus"

by ***STAR Collaboration***

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

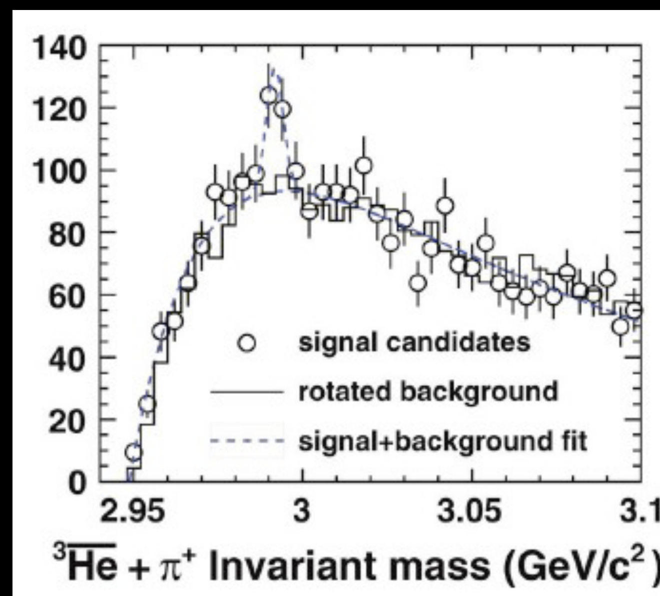


Science March, 2010

"Observation of an Antimatter Hypernucleus"

by ***STAR Collaboration***

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



Summary I

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

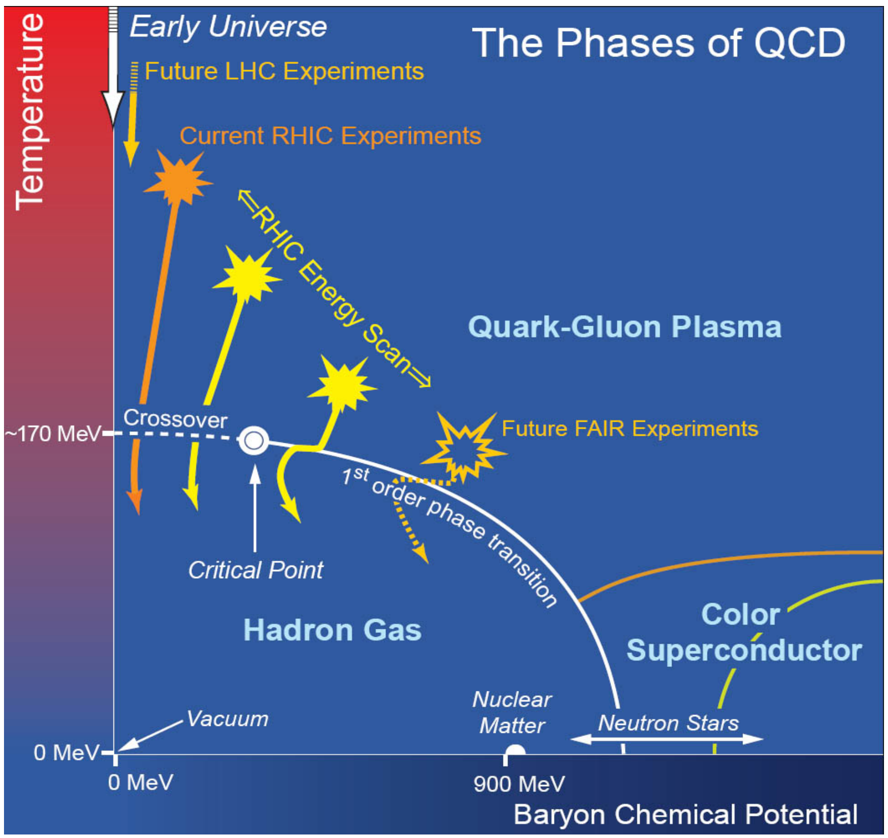
(2) The matter behavior like a ***quantum liquid*** with very small ***η/s***

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

What is the structure of the matter?

Beam Energy Scan at RHIC

Motivations: Study QCD phase structure
- Signals of phase boundary
- Signals for critical point



Observations:

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

(2) Dynamical correlations:
partonic vs. hadronic dof

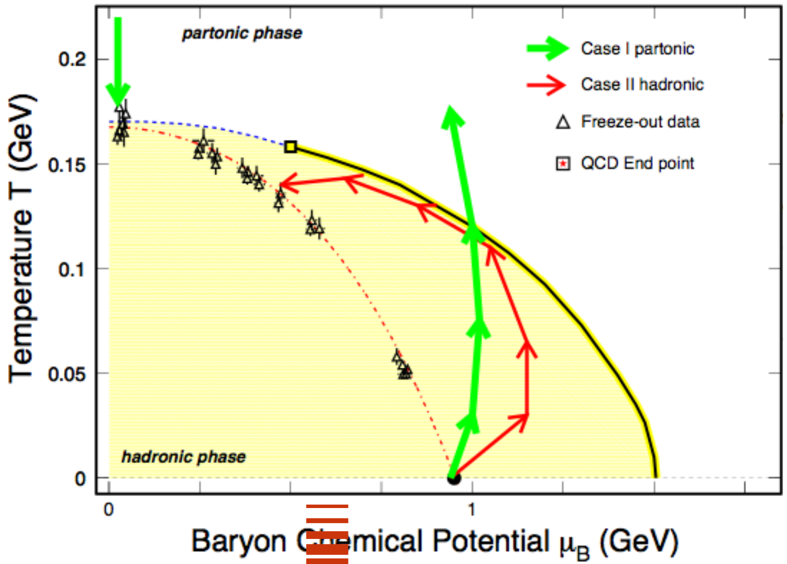
(3) Azimuthally HBT:
1st order phase transition

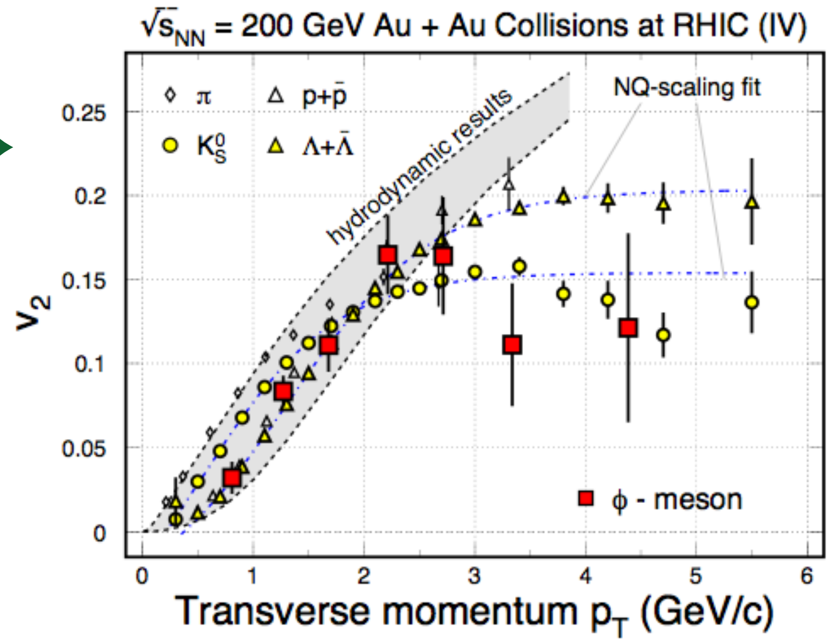
(4) Fluctuations:
Critical point, correl. length

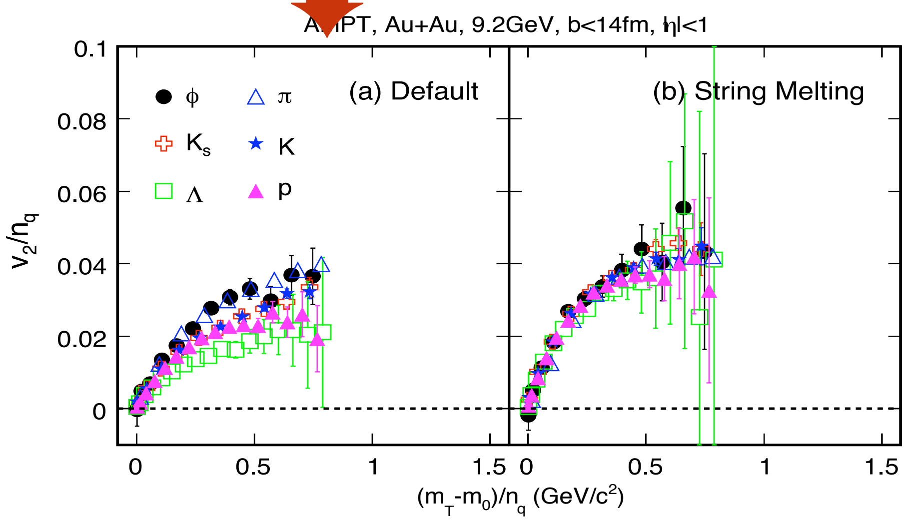
(5) Directed flow v_1
1st order phase transition

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

Observable*: NCQ Scaling in v_2







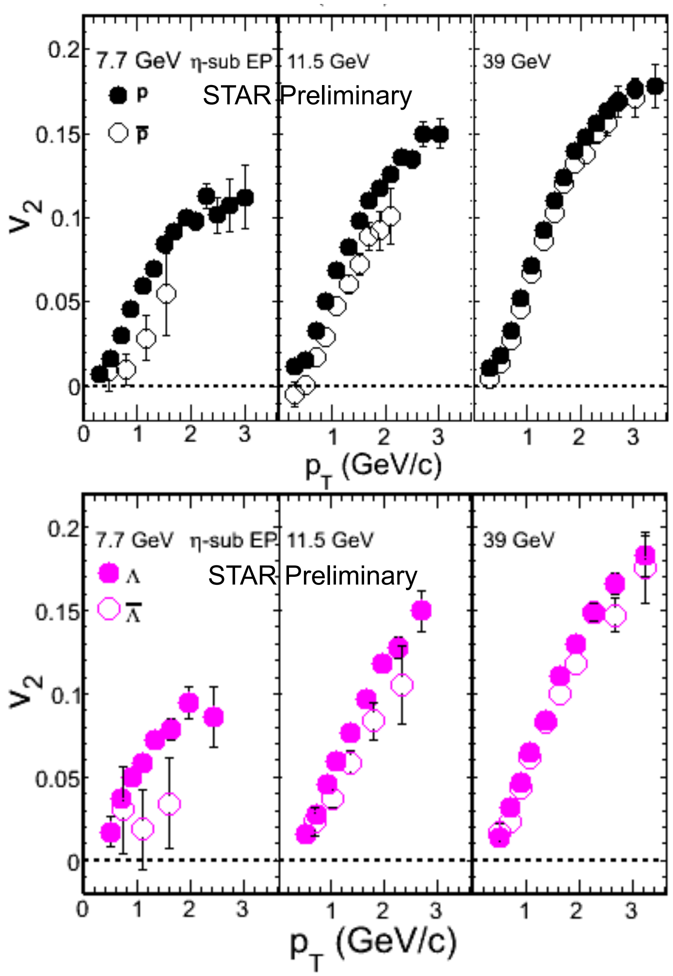
STAR Collaboration: F. Liu, S.S. Shi, K.J. Wu et al.

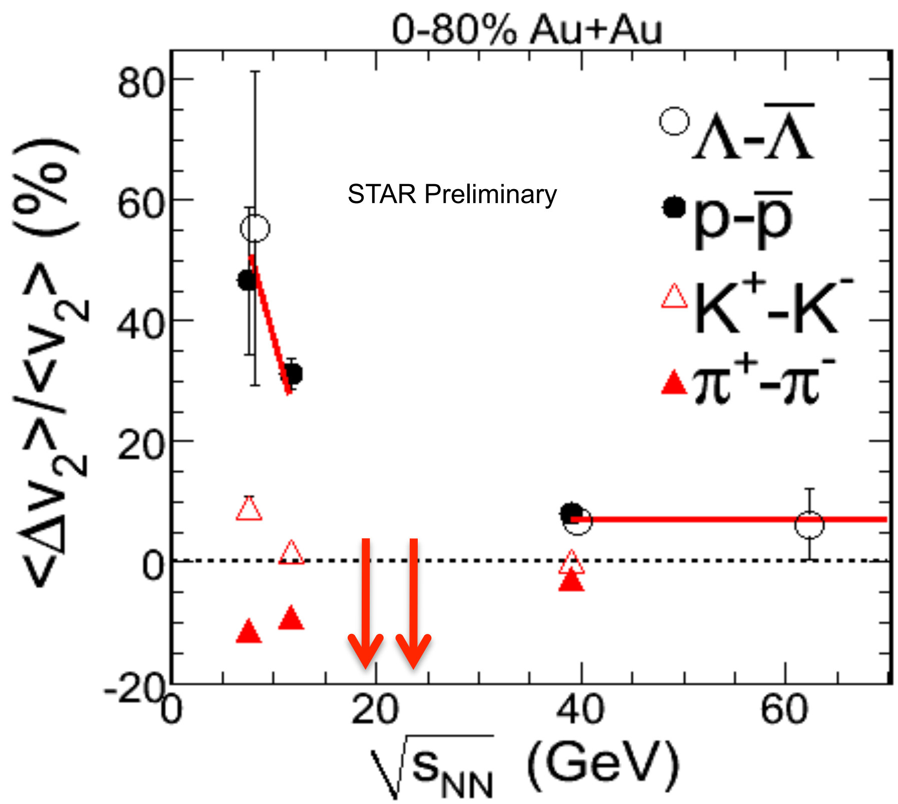
Disappearance of the v_2-NCQ scaling:

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. $\sqrt{s_{NN}}$

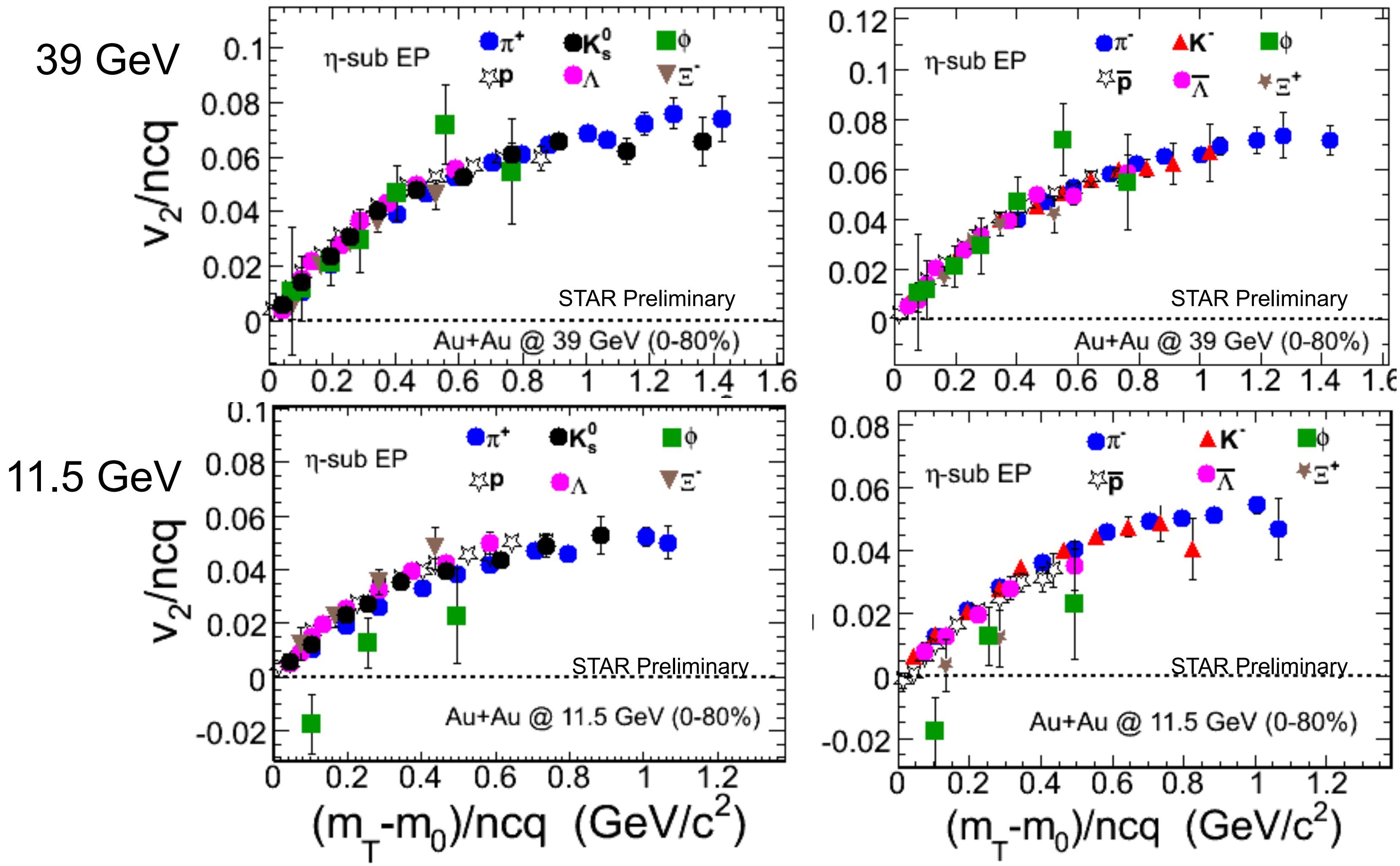




STAR: QM2011

Below $\sqrt{s_{NN}}$ = 11.5 GeV:
v_2(baryon) > v_2(anti-baryon) and $v_2(\pi^+) < v_2(\pi^-)$

v_2 Scaling vs. Beam Energy



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

STAR: QM2011

Summary II: v_2-NCQ-Scaling

1) Partonic collectivity in 200 GeV collisions
2) At $\sqrt{s_{NN}}$ = 11.5 GeV
   - v_2(baryon) > v_2(anti-baryon)
   - $v_2(\phi)$ < v_2(hadron)

   ➔ v_2-NCQ-scaling broken

   ➔ **[*hadronic*] < $\sqrt{s_{NN}}$ = 11.5 GeV**

   $\sqrt{s_{NN}}$ = 39 GeV < [*partonic*]

Where is the critical point?

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

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

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

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

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

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

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

Thermodynamic function ⇔ Susceptibility ⇔ Moments, Observable

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

Correlations, Susceptibilities
Higher Moments

$$\delta N = N - \langle N \rangle$$

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \qquad \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}$$

$$\left\langle (\delta N)^4 \right\rangle - 3\left\langle (\delta N)^2 \right\rangle^2 \approx \xi^7$$

M. A. Stephanov, PRL. ***102,*** *032301 (09)*

$$S = \frac{\left\langle (\delta N)^3 \right\rangle}{\left\langle (\delta N)^2 \right\rangle^{3/2}}$$

$$\kappa = \frac{\left\langle (\delta N)^4 \right\rangle - 3\left\langle (\delta N)^2 \right\rangle^2}{\left\langle (\delta N)^2 \right\rangle^2}$$

R.V. Gavai and S. Gupta: 1001.2796.
F. Karsch and K. Redlich, arXiv:1007.2581

Skewness: Symmetry of the correlation function.

Kurtosis: Peakness of the correlation function. *Connection to thermodynamics,* χ_X.

Higher order correlations are correspond to higher power of the correlation length of the system: **more sensitive to critical phenomena**.

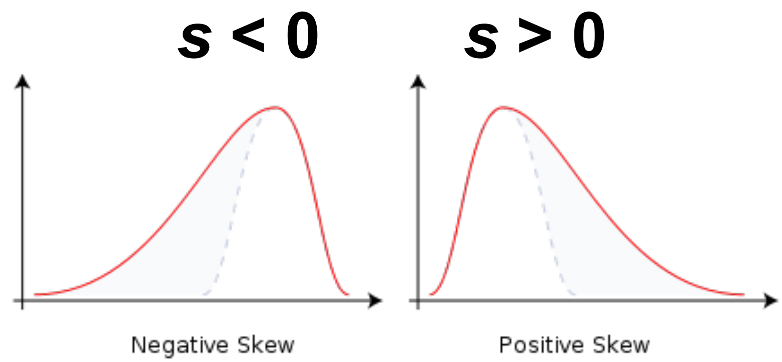
S & ***K*** observables:
total charge, total protons,
net-p, net-Q

Non-Gaussian Fluctuations

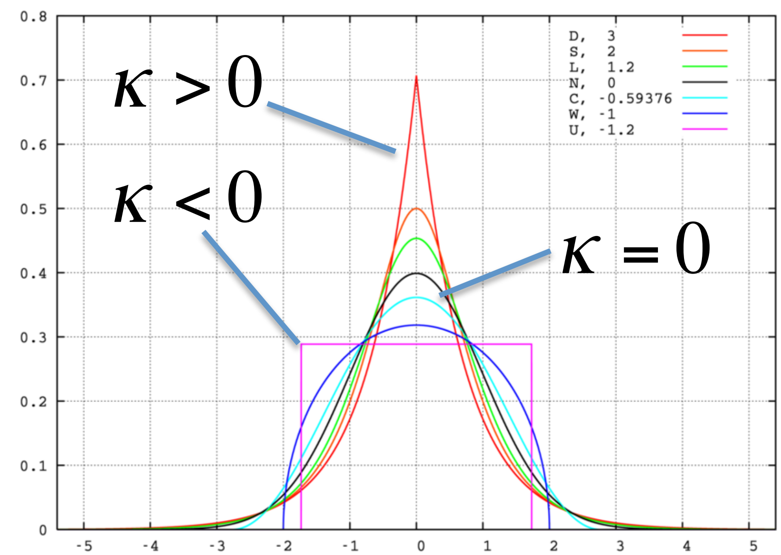
N: event by event multiplicity distribution

$$m = \langle N \rangle \qquad s = \frac{\left\langle \left(N - \langle N \rangle\right)^3 \right\rangle}{\sigma^3}$$

$$\sigma = \sqrt{\left\langle \left(N - \langle N \rangle\right)^2 \right\rangle} \qquad \kappa = \frac{\left\langle \left(N - \langle N \rangle\right)^4 \right\rangle}{\sigma^4} - 3$$

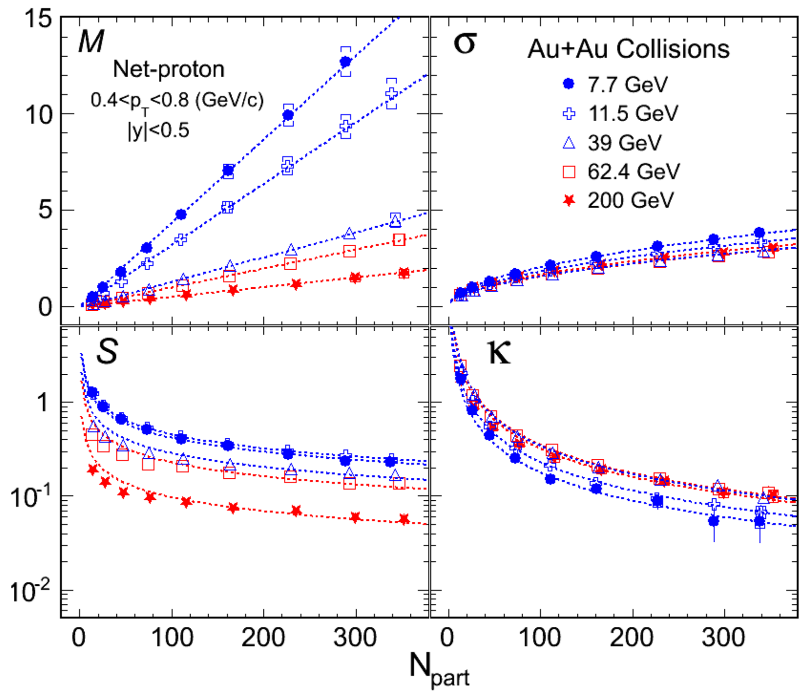


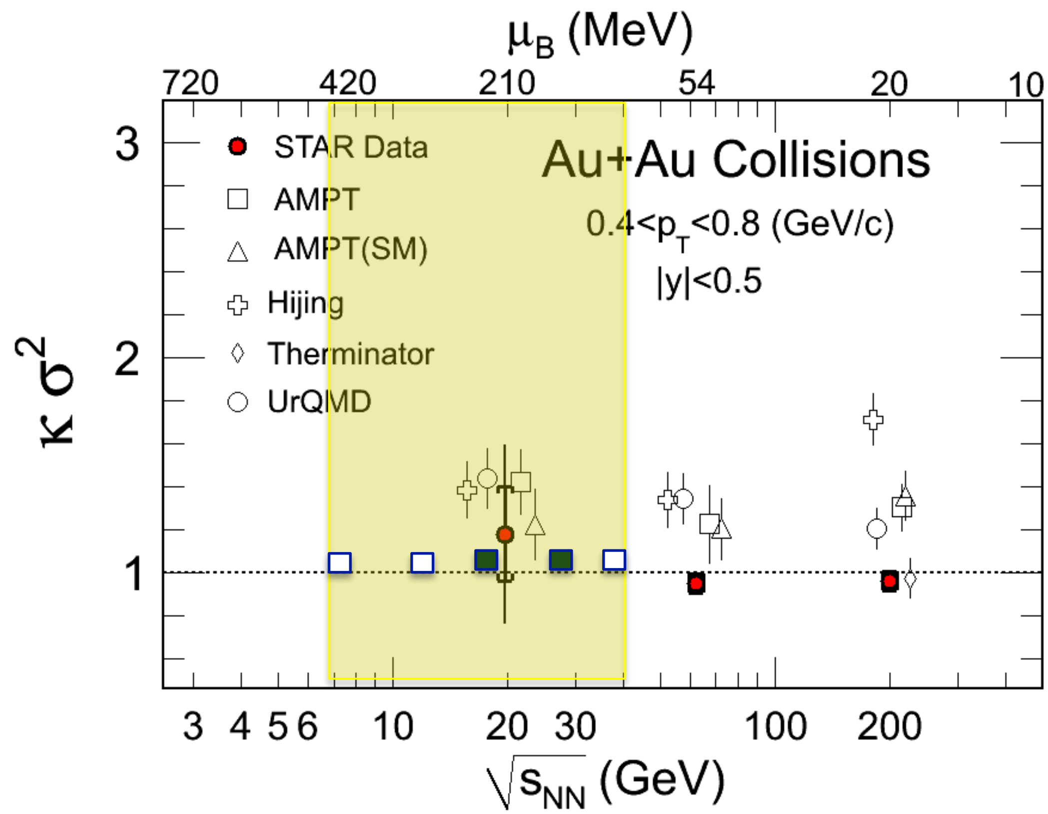
For a Gaussian distribution, the *skewness* and *kurtosis* are all zero.
Ideal probe of the non-Gaussian fluctuations at critical point.



Net-proton Higher Moments

STAR: 1004.4959, **PRL105**, 22303(2010)





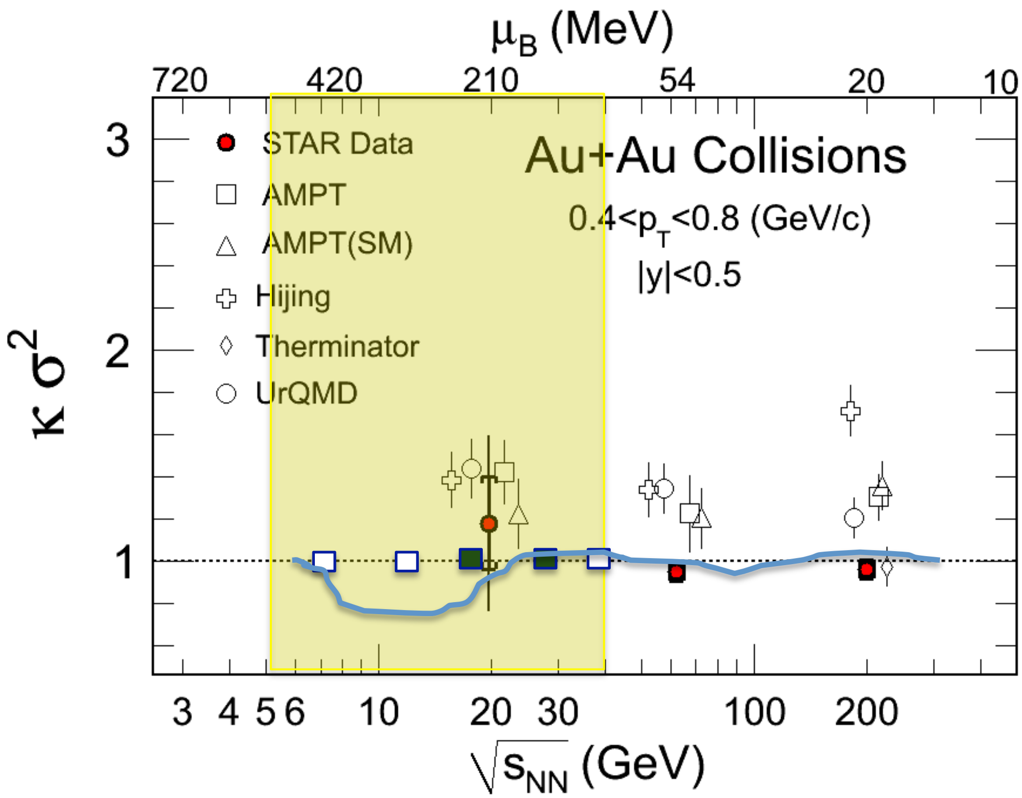
Energy Scan in Au+Au collision :

Run 10: 7.7, 11.5, 39 GeV

Run 11: 19.6, 27 GeV

Few Remarks

STAR: PRL105,22302(2010)



Energy scan in Au+Au collision :

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

1) The data is from 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.

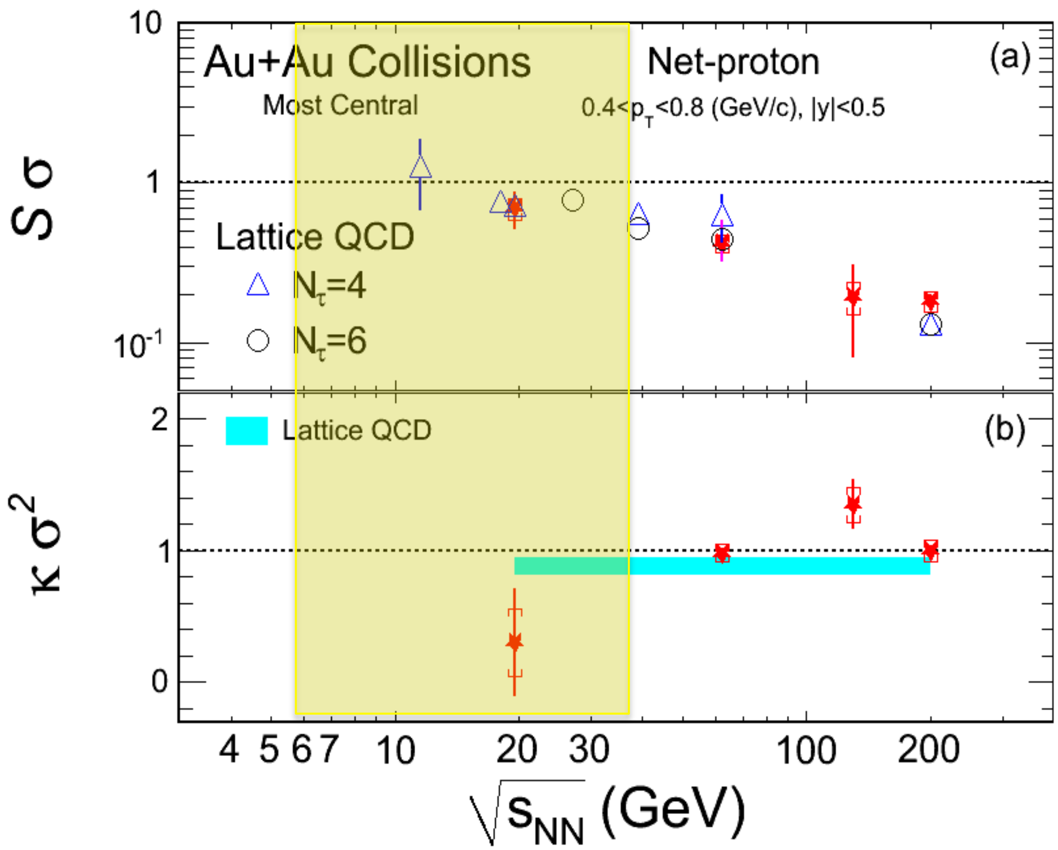
4) Critical point effect: non-monotonical dependence on collision energy.

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

Thermalization in HI Collisions?

All HI results from are consistent with the thermal model predictions, except the elementary p+p collisions.

Comparing with LGT Results



References:

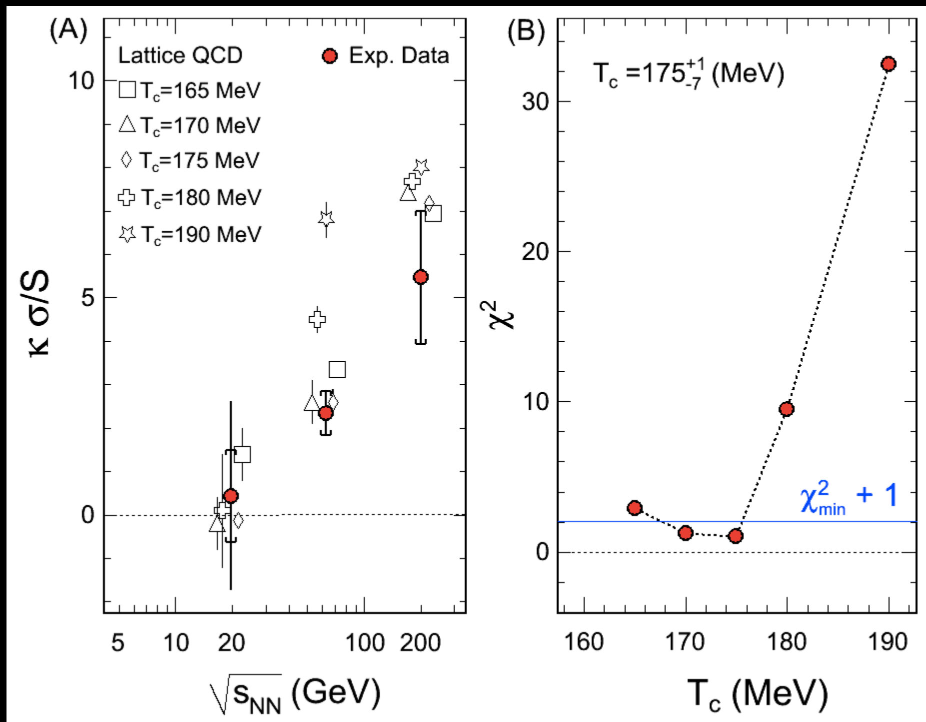
- STAR, *PRL105, 22303(10)*
- F. Karsch and K. Redlich, *PLB695, 136(11)*
- R.V. Gavai and S. Gupta: *PLB696, 459(11)*

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

Scale of Hot/Dense Matter on LGT



Science AAAS

June, 2011

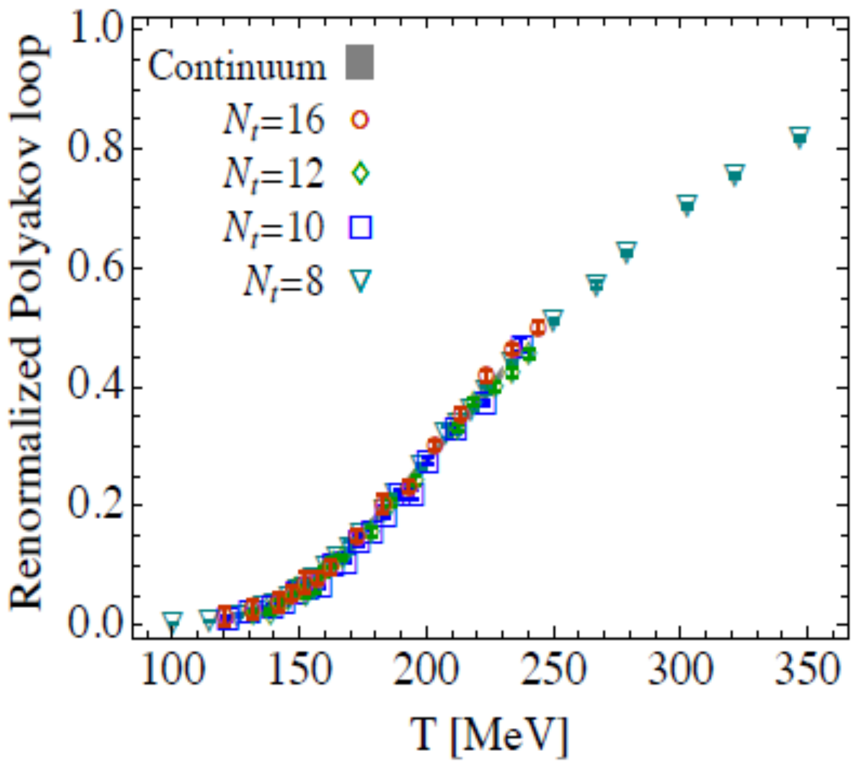
"Scale for the Phase Diagram of Quantum Chromodynamics"

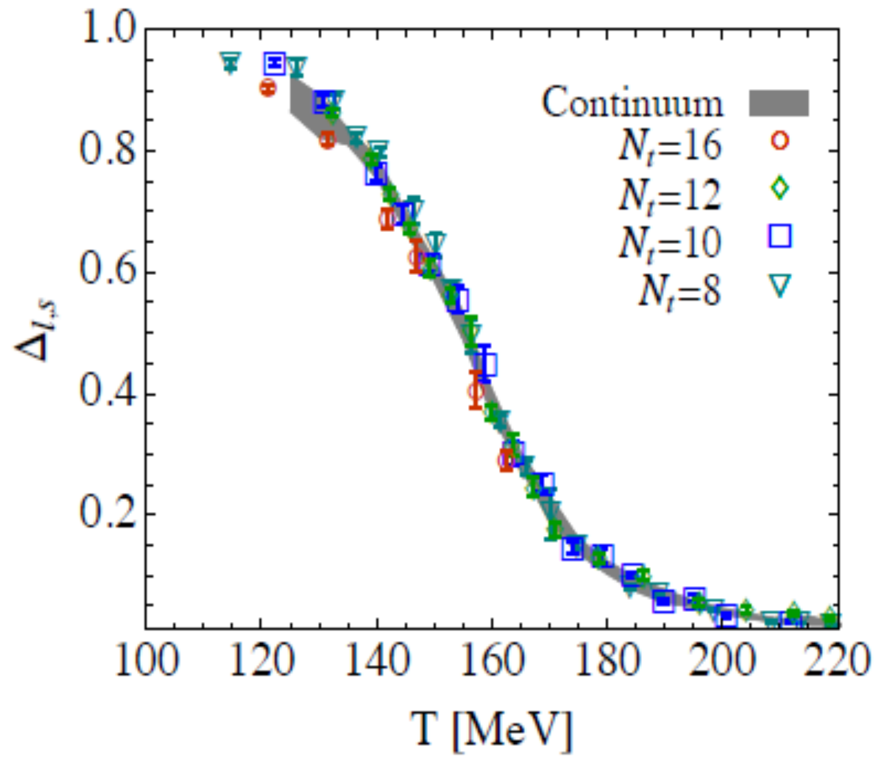
Science, 332, 1525(2011)

1) In central collisions at RHIC, the high moments measurements are consistent with thermal equilibrium assumption
2) Scale of LGT, determined with the data, is***: T_C=175+1-7*** (MeV)

STAR, ***PRL****105, 22303(2010);* F. Karsch and K. Redlich, ***PLB****695, 136(2011);* R.V. Gavai and S. Gupta: ***PLB****696, 459(2011);* S. Gupta, X.F. Luo, B. Mohanty, H.G. Ritter, NX*, **Science**, 332, 1525(2011)*

Lattice-QCD: Phase Transitions





T_c^{conf} ~170 MeV

T_c^{chiral} ~150MeV

Summary

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

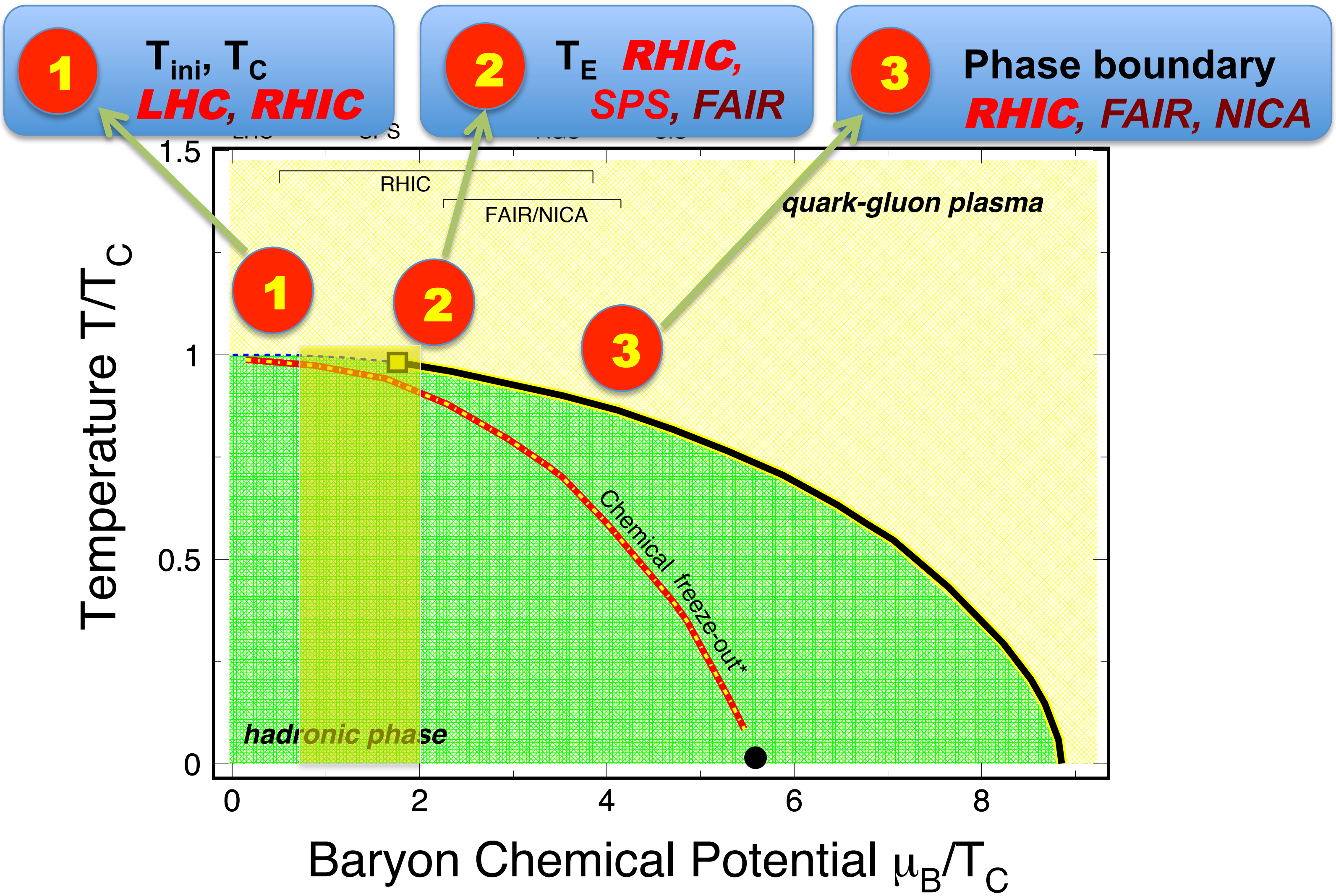
(2) The matter behavior like a ***quantum liquid*** with very small ***η/s***

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

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

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

Summary & Outlook



Many Thanks to the Organizers!

STAR Collaboration