Sign-posting the phase diagram of QCD

Sourendu Gupta, Xiaofeng Luo, Bedanga Mohanty,
Hans-Georg Ritter, Nu Xu

TIFR Mumbai, CCNU Wuhan, VECC Kolkata, LBNL Berkeley, LBNL Berkeley

International Symposium on Multiparticle Dynamics 2011
TIFR Mumbai
September 26, 2011

Outline

Heavy-ion physics

Experimental observations

Many interesting new phenomena: jet quenching, elliptic flow, strange chemistry, fluctuations of conserved quantities ...

Heavy-ion physics

Experimental observations

Many interesting new phenomena: jet quenching, elliptic flow, strange chemistry, fluctuations of conserved quantities ...

Systematic understanding

Matter formed: characterized by T and μ. History of fireball described by hydrodynamics and diffusion. Small mean free paths.

Heavy-ion physics

Experimental observations

Many interesting new phenomena: jet quenching, elliptic flow, strange chemistry, fluctuations of conserved quantities ...

Systematic understanding

Matter formed: characterized by T and μ. History of fireball described by hydrodynamics and diffusion. Small mean free paths.

Theoretical underpinning

Does QCD describe this matter? Is there a new nonperturbative test of QCD?

Predictions from QCD

- Lagrangian has free parameters: cutoff a, quark masses $m_u \simeq m_d \ll \Lambda_{QCD}$, $m_s \simeq \Lambda_{QCD}$, $\cdots$
- Compute enough quantities from QCD: $m_\pi(a, m_{ud}, m_s, \cdots)$, $m_K(a, m_{ud}, m_s, \cdots)$, $f_K(a, m_{ud}, m_s, \cdots)$, $f_\pi(a, m_{ud}, m_s, \cdots)$, $m_\rho(a, m_{ud}, m_s, \cdots)$, $m_p(a, m_{ud}, m_s, \cdots)$, $T_c(a, m_{ud}, m_s, \cdots)$, $T_E(a, m_{ud}, m_s, \cdots)$, $\mu_E(a, m_{ud}, m_s, \cdots)$
- Fix the free parameters using some of the predictions. Then the remaining are scale-free predictions.

Predictions from QCD

- Lagrangian has free parameters: cutoff a, quark masses $m_u \simeq m_d \ll \Lambda_{QCD}$, $m_s \simeq \Lambda_{QCD}$, $\cdots$
- Compute enough quantities from QCD: $m_\pi(a, m_{ud}, m_s, \cdots)$, $m_K(a, m_{ud}, m_s, \cdots)$, $f_K(a, m_{ud}, m_s, \cdots)$, $f_\pi(a, m_{ud}, m_s, \cdots)$, $m_\rho(a, m_{ud}, m_s, \cdots)$, $m_p(a, m_{ud}, m_s, \cdots)$, $T_c(a, m_{ud}, m_s, \cdots)$, $T_E(a, m_{ud}, m_s, \cdots)$, $\mu_E(a, m_{ud}, m_s, \cdots)$
- Fix the free parameters using some of the predictions. Then the remaining are scale-free predictions.

Predictions from QCD

- Lagrangian has free parameters: cutoff a, quark masses $m_u \simeq m_d \ll \Lambda_{QCD}$, $m_s \simeq \Lambda_{QCD}$, $\cdots$
- Compute enough quantities from QCD: $m_\pi(a, m_{ud}, m_s, \cdots)$, $m_K(a, m_{ud}, m_s, \cdots)$, $f_K(a, m_{ud}, m_s, \cdots)$, $f_\pi(a, m_{ud}, m_s, \cdots)$, $m_p(a, m_{ud}, m_s, \cdots)$, $m_\rho(a, m_{ud}, m_s, \cdots)$, $T_c(a, m_{ud}, m_s, \cdots)$, $T_E(a, m_{ud}, m_s, \cdots)$, $\mu_E(a, m_{ud}, m_s, \cdots)$
- Fix the free parameters using some of the predictions. Then the remaining are scale-free predictions.

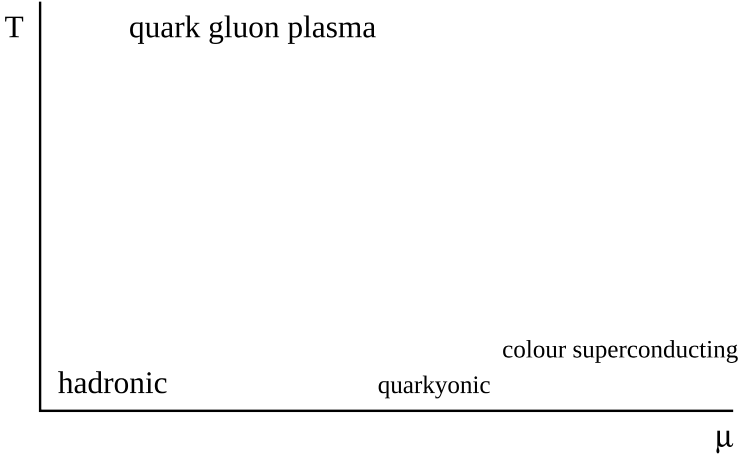
Predictions from QCD

- Lagrangian has free parameters: cutoff a, quark masses $m_u \simeq m_d \ll \Lambda_{QCD}$, $m_s \simeq \Lambda_{QCD}$, $\cdots$
- Compute enough quantities from QCD: $m_\pi(a, m_{ud}, m_s, \cdots)$, $m_K(a, m_{ud}, m_s, \cdots)$, $f_K(a, m_{ud}, m_s, \cdots)$, $f_\pi(a, m_{ud}, m_s, \cdots)$, $m_p(a, m_{ud}, m_s, \cdots)$, $m_\rho(a, m_{ud}, m_s, \cdots)$, $T_c(a, m_{ud}, m_s, \cdots)$, $T_E(a, m_{ud}, m_s, \cdots)$, $\mu_E(a, m_{ud}, m_s, \cdots)$
- Fix the free parameters using some of the predictions. Then the remaining are scale-free predictions.
- Take the cutoff to infinity. Difficult on the lattice; many technical devlopments on how to get continuum predictions from large a— add RG irrelevant terms to the action, choose scale setting appropriately.

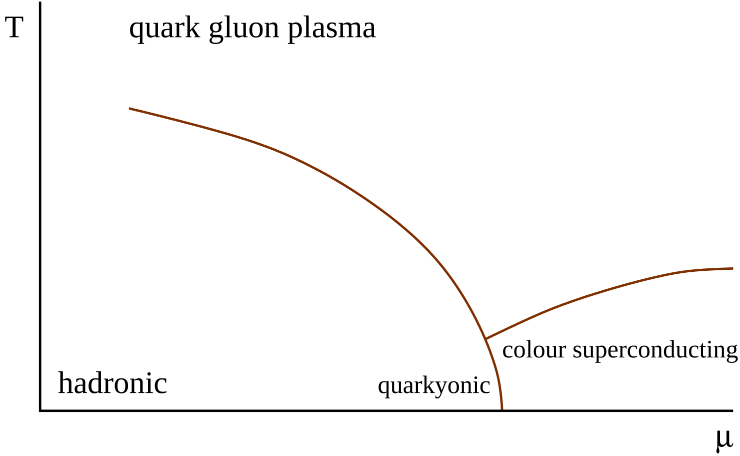
Predictions from QCD

- Lagrangian has free parameters: cutoff a, quark masses $m_u \simeq m_d \ll \Lambda_{QCD}$, $m_s \simeq \Lambda_{QCD}$, $\cdots$
- Compute enough quantities from QCD: $m_\pi(a, m_{ud}, m_s, \cdots)$, $m_K(a, m_{ud}, m_s, \cdots)$, $f_K(a, m_{ud}, m_s, \cdots)$, $f_\pi(a, m_{ud}, m_s, \cdots)$, $m_p(a, m_{ud}, m_s, \cdots)$, $m_\rho(a, m_{ud}, m_s, \cdots)$, $T_c(a, m_{ud}, m_s, \cdots)$, $T_E(a, m_{ud}, m_s, \cdots)$, $\mu_E(a, m_{ud}, m_s, \cdots)$
- Fix the free parameters using some of the predictions. Then the remaining are scale-free predictions.
- Take the cutoff to infinity. Difficult on the lattice; many technical devlopments on how to get continuum predictions from large a— add RG irrelevant terms to the action, choose scale setting appropriately.
- Most universal part of the solution: Moore's law

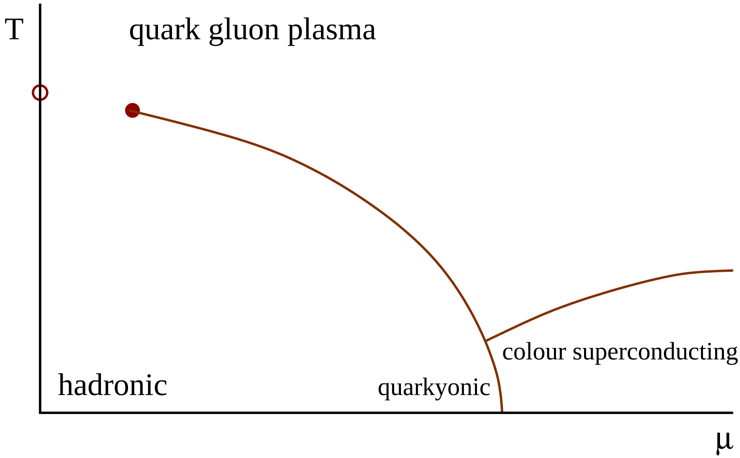
The phase diagram of QCD



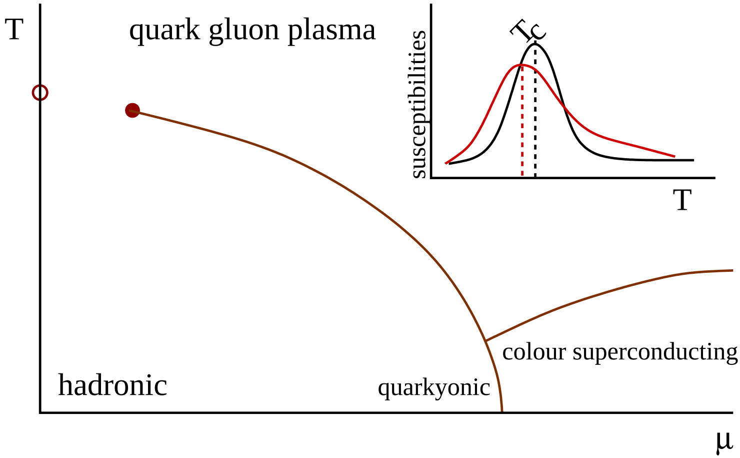
The phase diagram of QCD



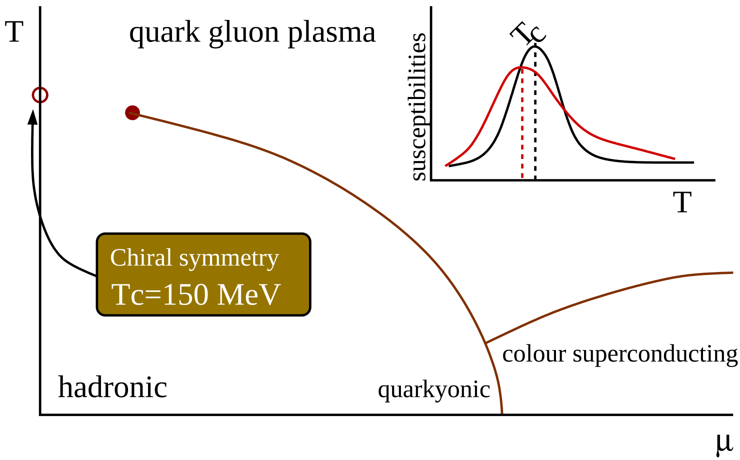
The phase diagram of QCD



The phase diagram of QCD

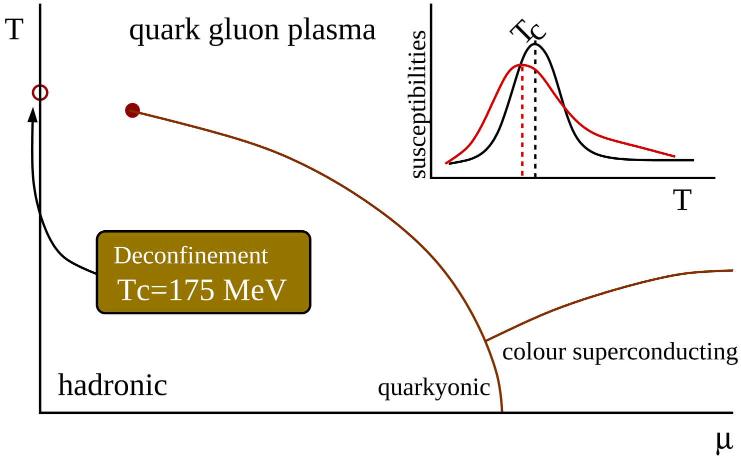


The phase diagram of QCD



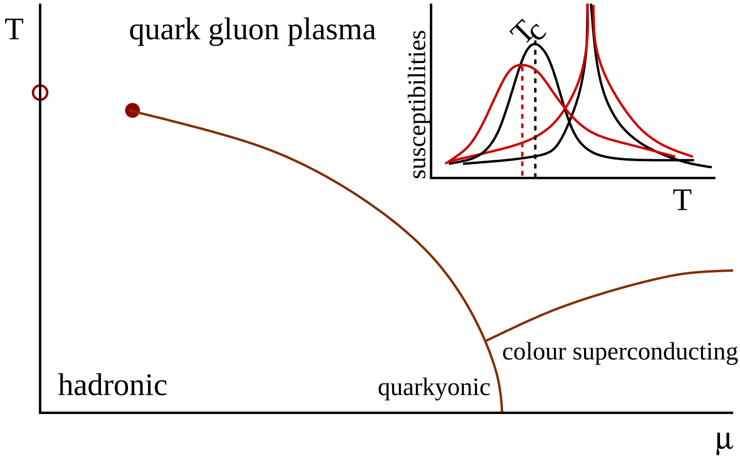
Y. Aoki *et al.*, Phys. Lett. B 643 (2006) 46

The phase diagram of QCD



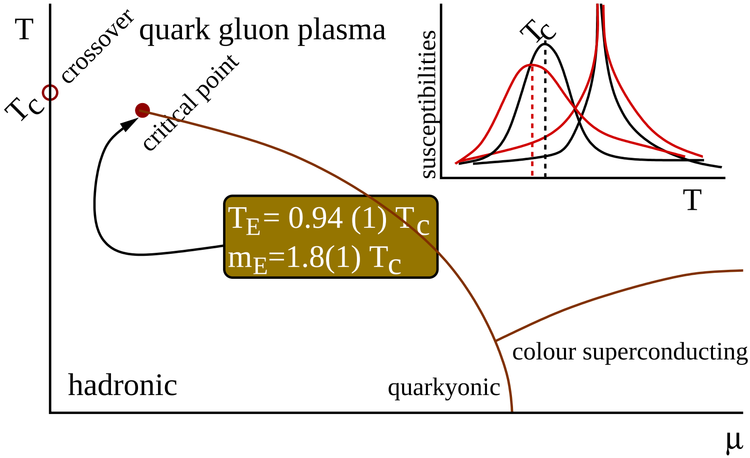
Y. Aoki *et al.*, Phys. Lett. B 643 (2006) 46

The phase diagram of QCD



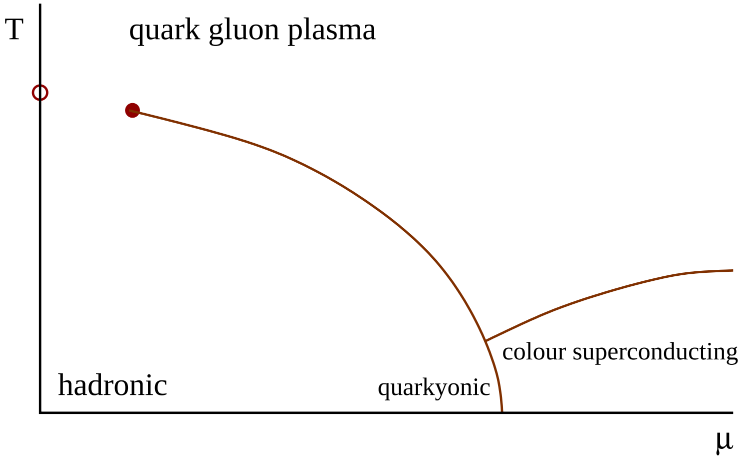
Gavai and Gupta, Phys. Rev. D 71 (2005) 110414, D 78 (2008) 114503

The phase diagram of QCD



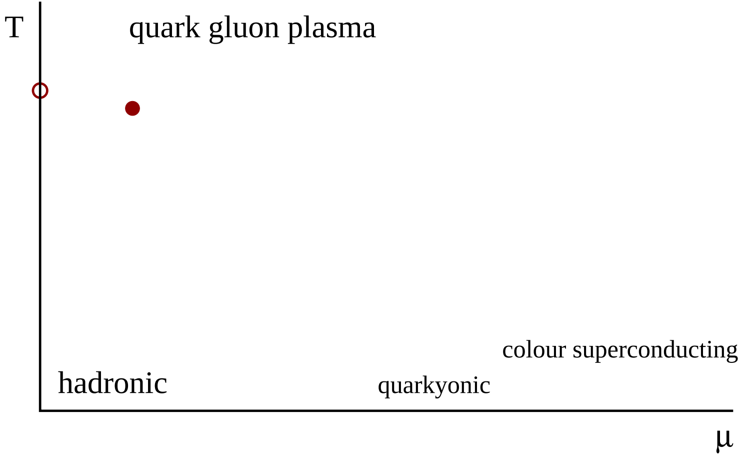
Gavai and Gupta, Phys. Rev. D 71 (2005) 110414, D 78 (2008) 114503

The phase diagram of QCD



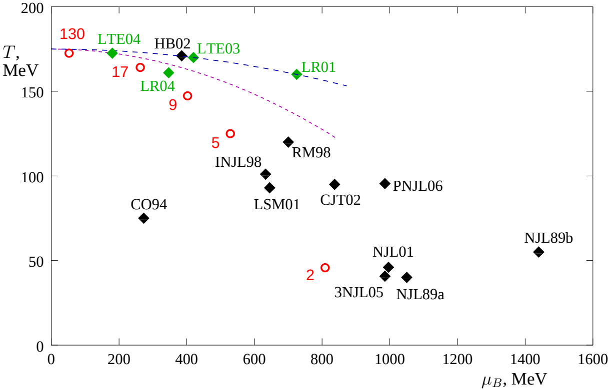
Gavai and Gupta, Phys. Rev. D 71 (2005) 110414, D 78 (2008) 114503

The phase diagram of QCD



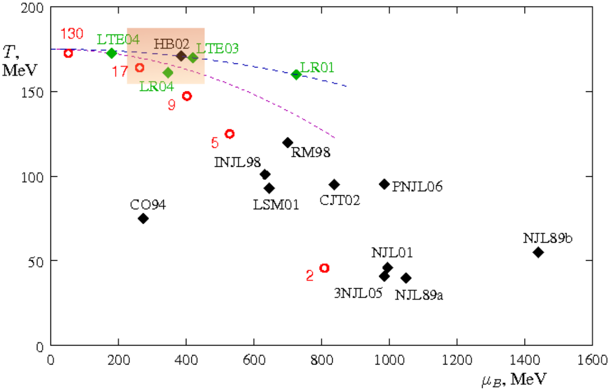
Gavai and Gupta, Phys. Rev. D 71 (2005) 110414, D 78 (2008) 114503

Improvement over time



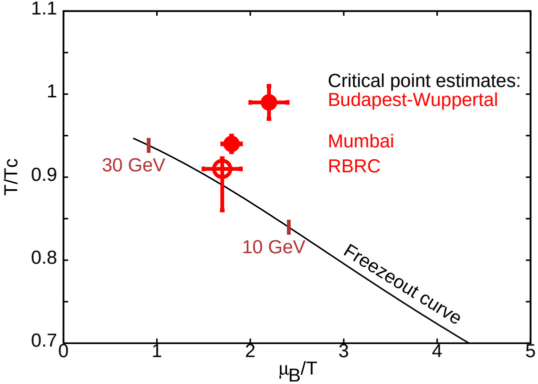
Compilations: Stephanov, Lattice 2006

Improvement over time



Compilations: Stephanov, Lattice 2006

Improvement over time



Compilations: SG, Quark Matter 2011

Outline

Fluctuations of conserved quantities

Observations

In a single heavy-ion collision, each conserved quantity (B, Q, S) is exactly constant when the full fireball is observed. In a small part of the fireball they fluctuate: from part to part and event to event.

Fluctuations of conserved quantities

Observations

In a single heavy-ion collision, each conserved quantity (B, Q, S) is exactly constant when the full fireball is observed. In a small part of the fireball they fluctuate: from part to part and event to event.

Thermodynamics

If $\xi^3 \ll V_{obs} \ll V_{fireball}$, then fluctuations can be explained in the grand canonical ensemble: energy and B, Q, S allowed to fluctuate in one part by exchange with rest of fireball (diffusion: transport).

Fluctuations of conserved quantities

Observations

In a single heavy-ion collision, each conserved quantity (B, Q, S) is exactly constant when the full fireball is observed. In a small part of the fireball they fluctuate: from part to part and event to event.

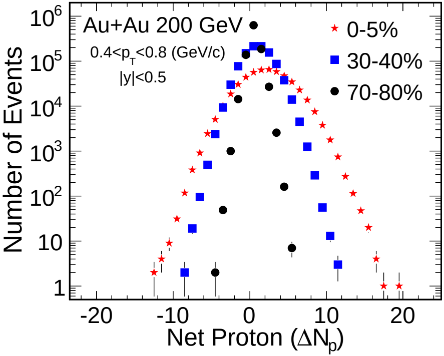
Thermodynamics

If $\xi^3 \ll V_{obs} \ll V_{fireball}$, then fluctuations can be explained in the grand canonical ensemble: energy and B, Q, S allowed to fluctuate in one part by exchange with rest of fireball (diffusion: transport).

Comparison

Is the observed volume small compared to the volume of the fireball? Are observations in agreement with QCD thermodynamics?

Event-to-event fluctuations

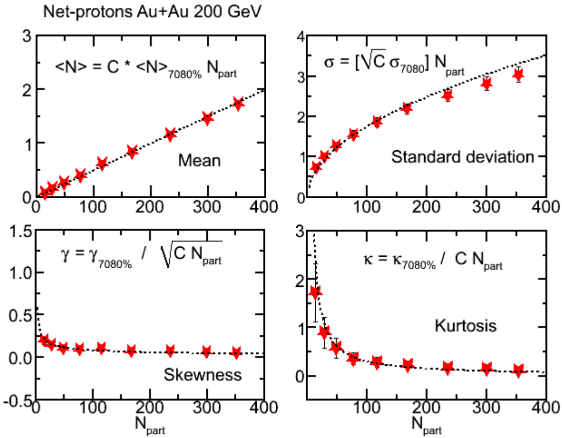


STAR arxiv:1004.4959

Central rapidity slice taken. p_T of 400–800 MeV. Important to check dependence on impact parameter. Protons observed: isospin fluctuations small.

Shape of distribution

STAR: QM 2009



Shape of distribution captured in cumulants $[B^n]$. Cumulants change with volume (proxy: N_{part}), and tends to Gaussian.

QCD predictions at finite μ_B

Make a MacLaurin expansion of the (dimensionless) pressure:

$$\frac{1}{T^4}P(T,\mu) = \sum_{n=0}^{\infty} T^{n-4}\chi_B^{(n)}(T,0)\frac{(\mu/T)^n}{n!},$$

measure each NLS at $\mu = 0$, sum series expansion to find NLS at any μ. Shape variables: $[B^n] = (VT^3)T^{n-4}\chi_B^{(n)}(t,\mu)$. Ratios of cumulants are state variables:

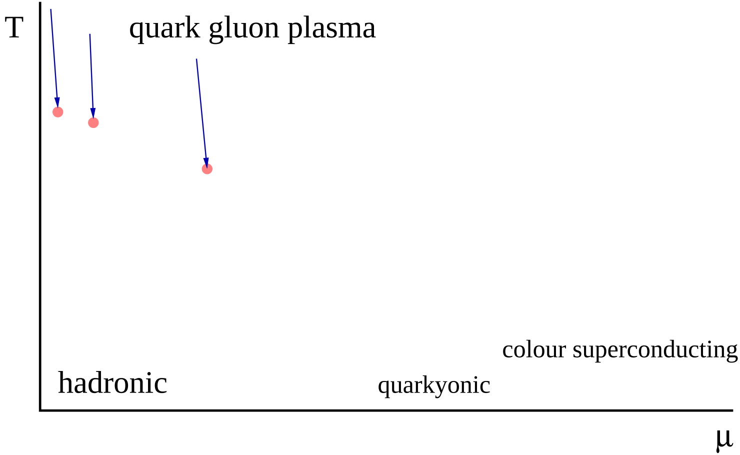
$$m_1: \quad \frac{[B^3]}{[B^4]} = \frac{T\chi_B^{(3)}}{\chi_B^{(2)}} = S\sigma$$

$$m_2: \quad \frac{[B^4]}{[B^2]} = \frac{T\chi_B^{(4)}}{\chi_B^{(2)}} = \kappa\sigma^2$$

$$m_3: \quad \frac{[B^4]}{[B^3]} = \frac{T\chi_B^{(4)}}{\chi_B^{(3)}} = \frac{\kappa\sigma}{S}$$

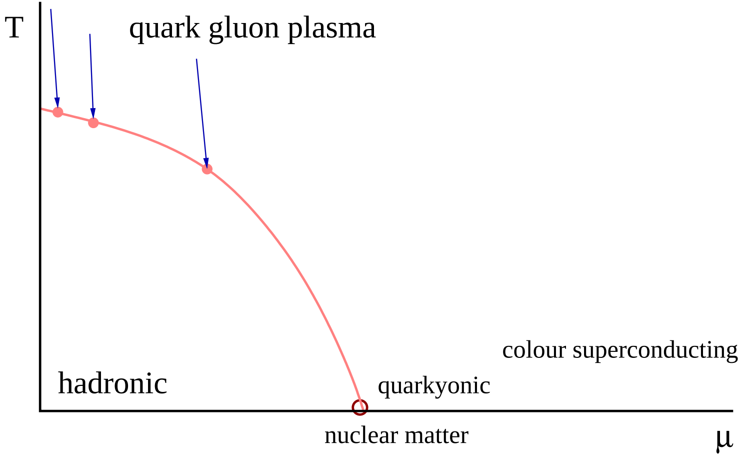
SG, 2009

The freezeout curve



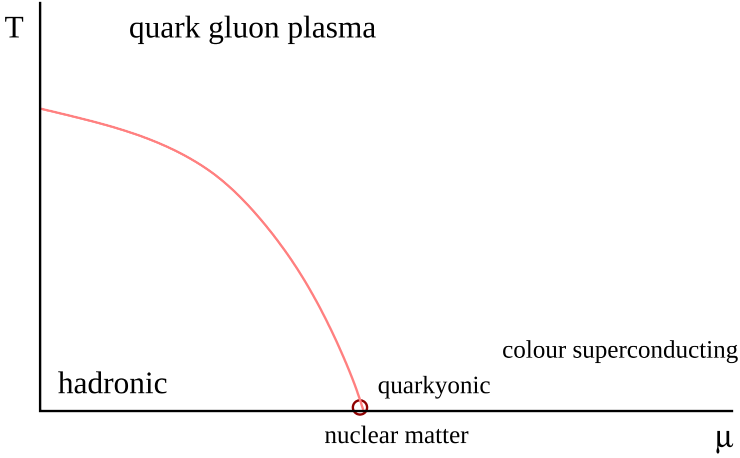
Hadron gas models: Hagedorn, Braun-Munzinger, Stachel, Cleymans, Redlich, Becattini

The freezeout curve



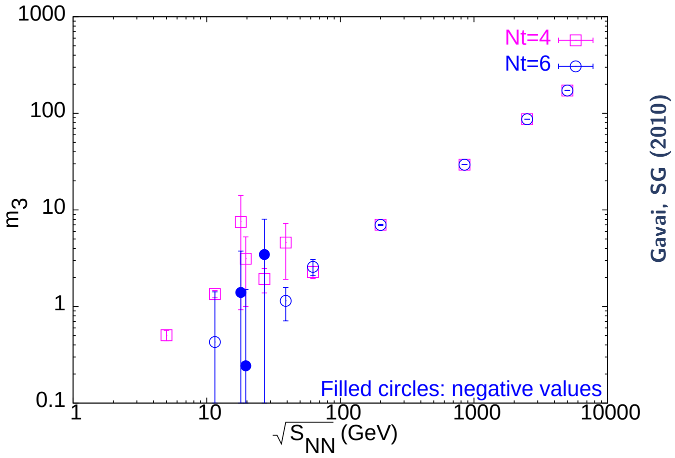
Hadron gas models: Hagedorn, Braun-Munzinger, Stachel, Cleymans, Redlich, Becattini

The freezeout curve



Hadron gas models: Hagedorn, Braun-Munzinger, Stachel, Cleymans, Redlich, Becattini

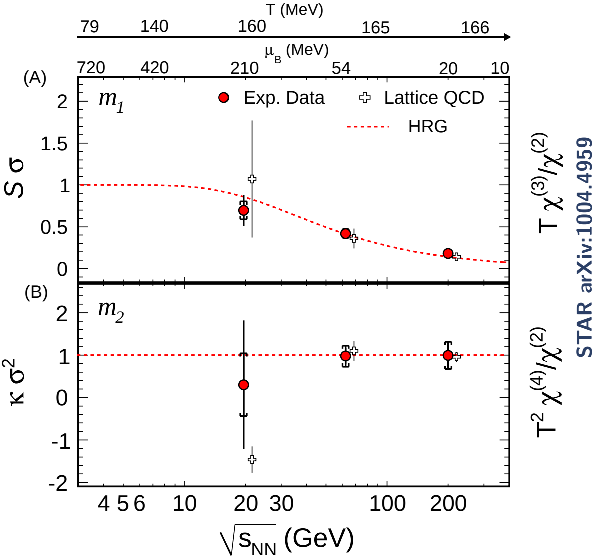
Predictions along the freezeout curve



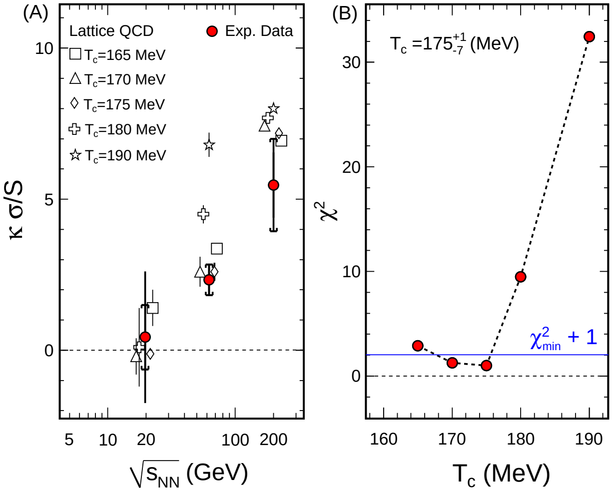
Lattice predictions along the freezeout curve of HRG models using $T_c = 170$ MeV.

Outline

Checking the match



Tuning lattice scale to match data



Science, 332 (2011) 1525

Conclusions

Thermalization

1 parameter tuning makes thermodynamic predictions agree with data for 2 ratios at 3 energies. Indicates thermalization of the fireball at freezeout.

T_c

Comparison of lattice and data along the freezeout curve gives

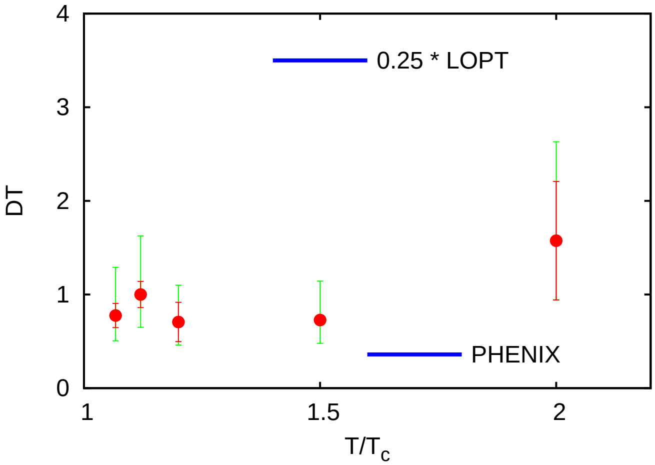
$$T_c = 175^{+1}_{-7}\ \mathrm{MeV},$$

in agreement with other scale settings on the lattice. Indicates that non-perturbative phenomena in single hadron physics and strong interaction thermodynamics are mutually consistent through QCD.

Systematics

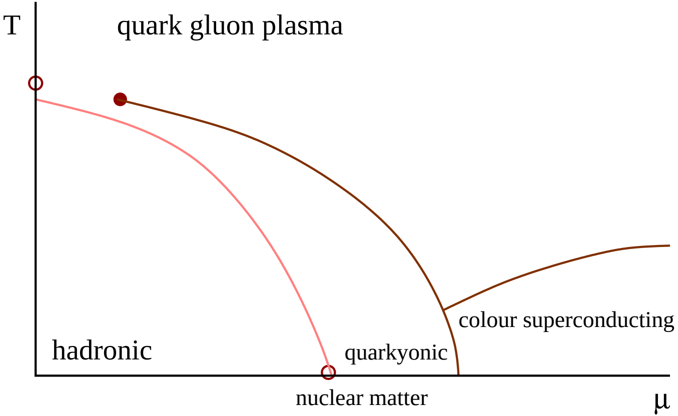
1. How important are isospin fluctuations?
   STAR 2010, Kitazawa and Asakawa 2011
2. Is diffusion quantitatively under control?
   Banerjee, Datta, Gavai, Majumdar 2011
3. Are volume fluctuations important?
   STAR 2010
4. How accurately is the freezeout curve known?
5. Do chemistry and fluctuations freeze out at the same time?
6. How important are finite lattice spacing artifacts?
   Redlich and Karsch 2011, Gavai and SG 2010
7. How good is the series expansion in μ?
   York and Moore 2011
8. How good is the resummation of the series?
9. How sensitive are the results to m_{ud} and m_s?
   Gavai and SG 2008

First lattice results on heavy-quark diffusion



Banerjee, Datta, Gavai, Majumdar 2011

Search for the critical point



Near a critical point system departs from equilibrium. If the critical point lies near the freezeout curve, then (1) Gaussian statistics will fail and (2) QCD predictions will not agree with data.