Scale for the phase diagram of QCD

Sourendu Gupta

TIFR Mumbai

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Outline

The history of the universe

The symmetric universe

The broken symmetries of the standard model of particle physics visible to experiments today are expected not to have been broken in the early universe. The standard picture of cosmology involves multiple phase transitions in relativistic quantum matter as it cools from a hot beginning.

Symmetrizing a part of the universe

Not a single phase transition of relativistic quantum matter has been observed yet. Today there is the first possibility of observing such a phase transition in the laboratory.

Heavy-ion physics

Experimental observations

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Theoretical underpinning

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

Predictions from QCD: renormalization

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

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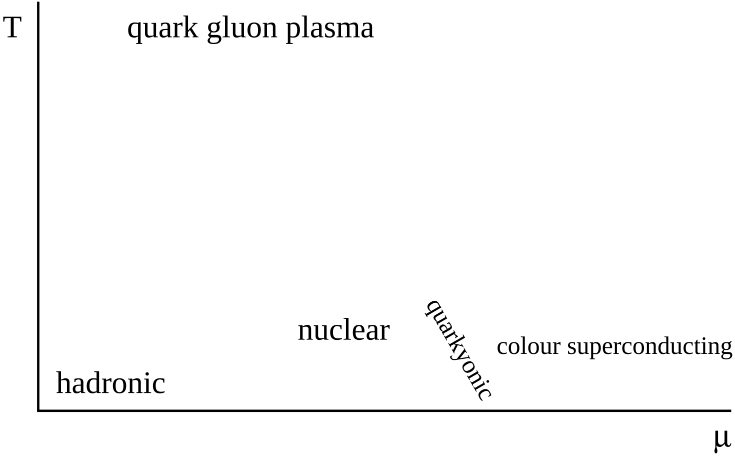
- Take the cutoff to infinity. Difficult on the lattice; many technical innovations on how to get stable predictions with small dependence on a.

The phase diagram of QCD



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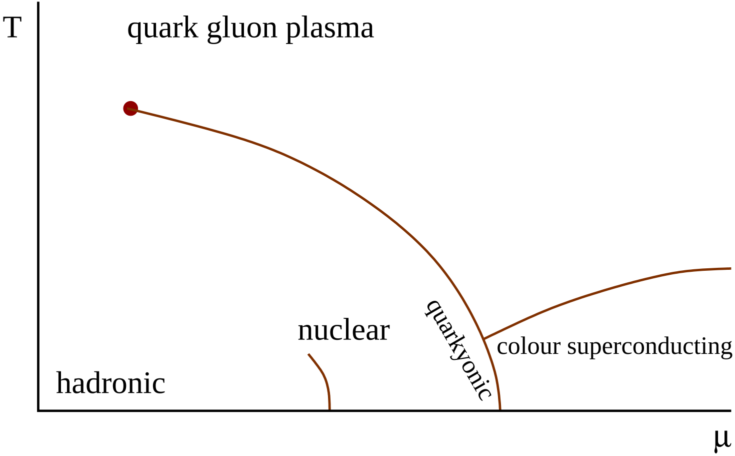

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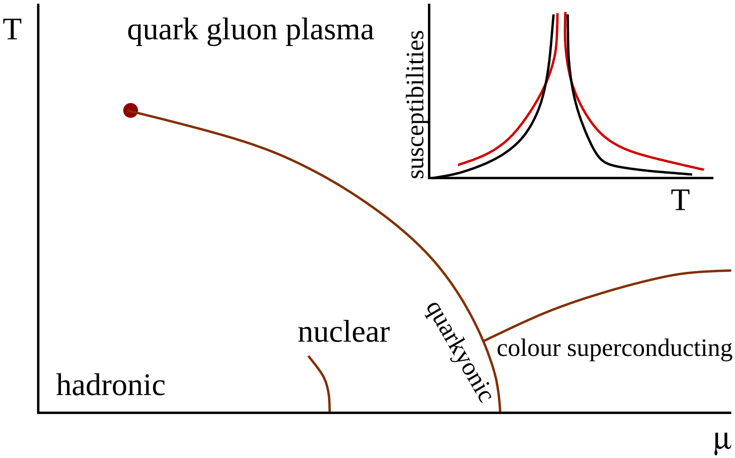

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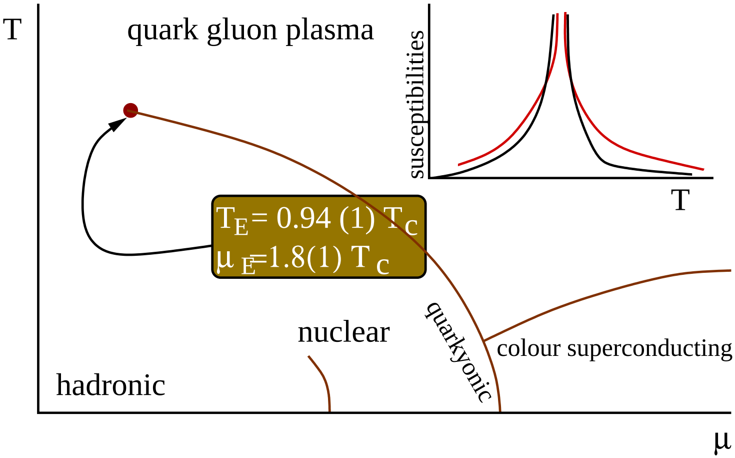

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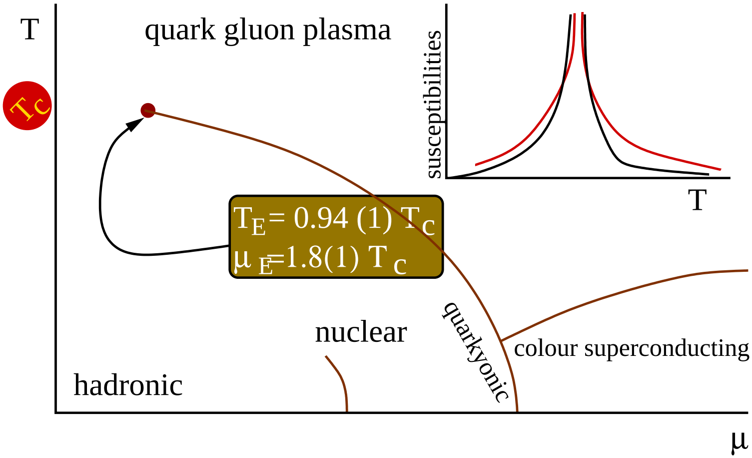

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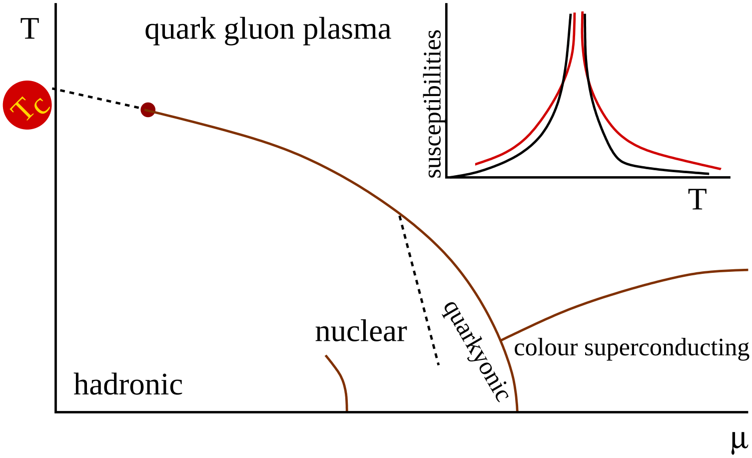

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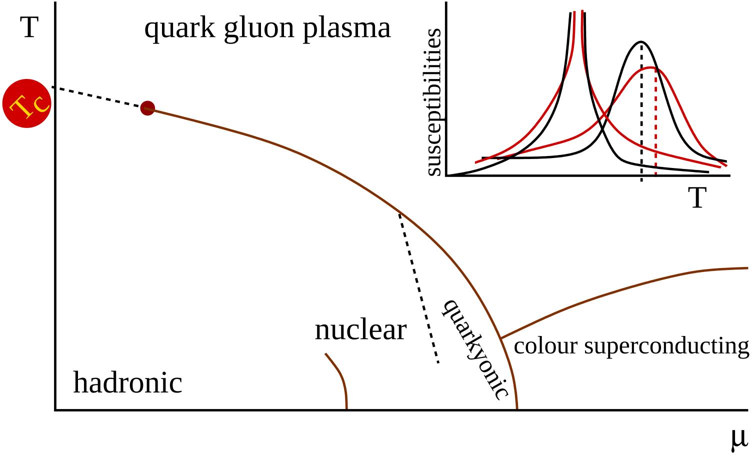

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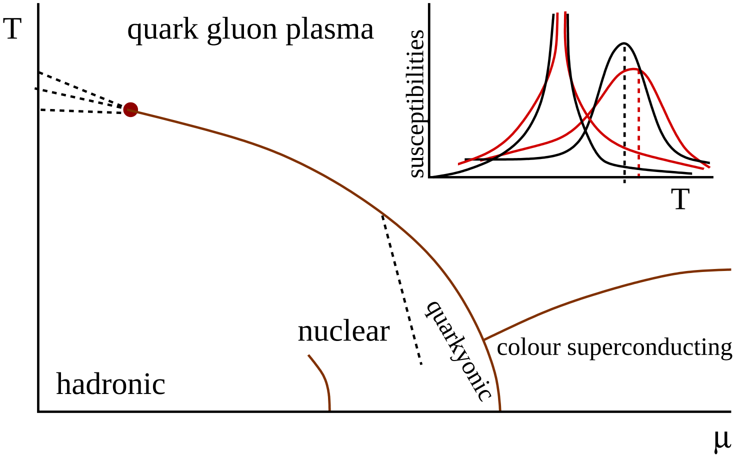

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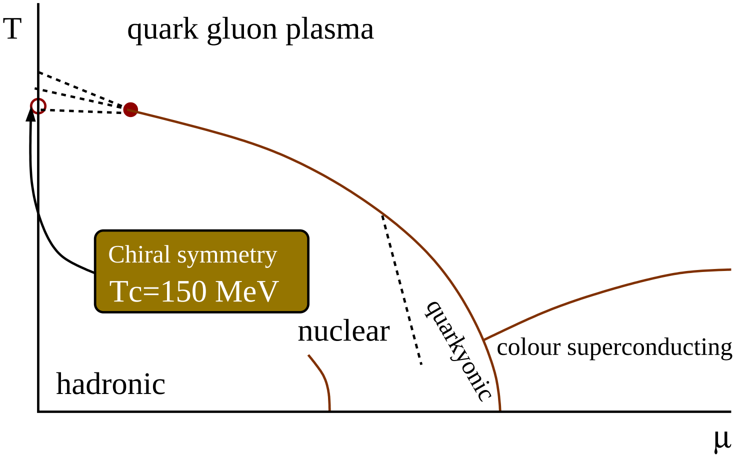

Y. Aoki *et al.*, Phys. Lett. B 643 (2006) 46

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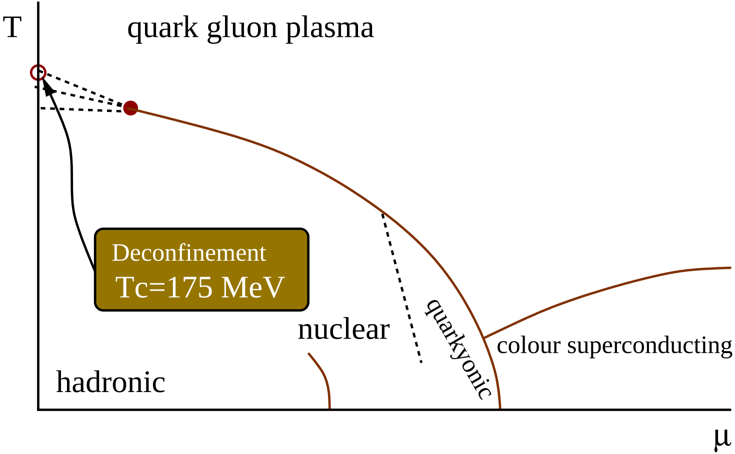

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Outline

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.

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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).

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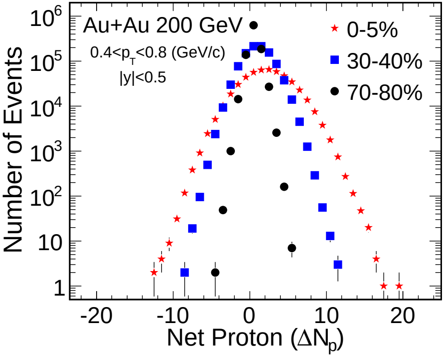
Comparison

Is $\xi^3 \ll V_{obs}$: central limit theorem? Is $V_{obs} \ll V_{fireball}$: are observations in agreement with QCD GCE thermodynamics?

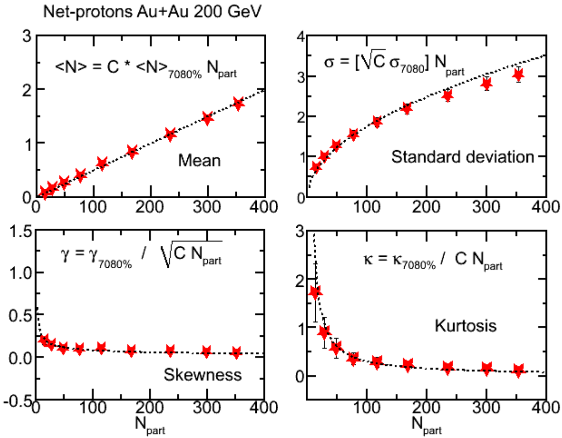
Event-to-event fluctuations



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.

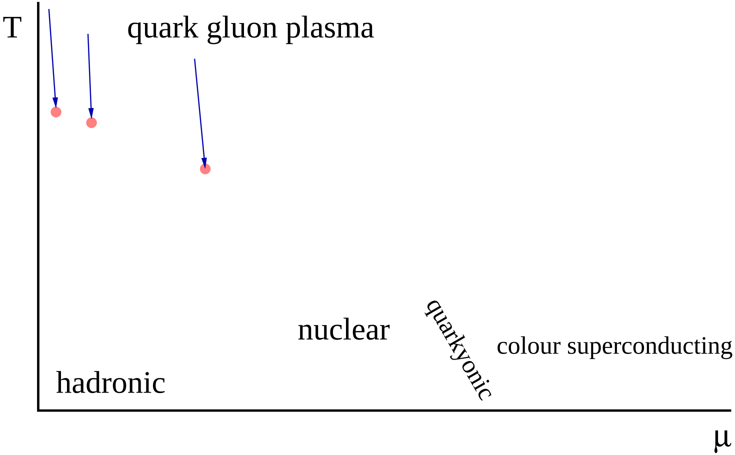
Shape of distribution



STAR: QM 2009

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

The freezeout curve



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

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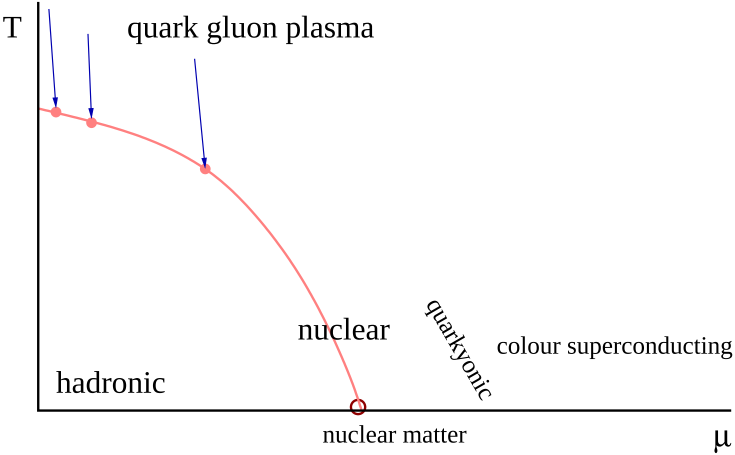

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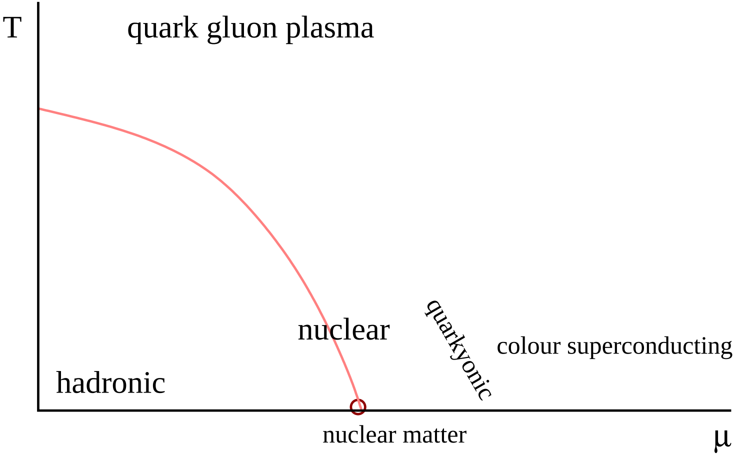

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QCD predictions at finite μ_B

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:

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

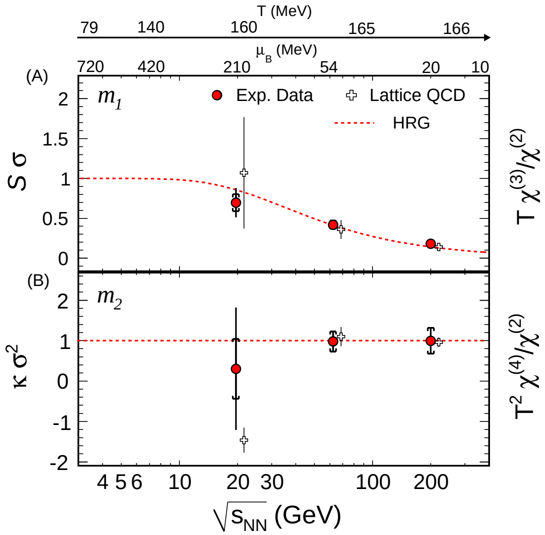
$$m_2: \quad \frac{[B^4]}{[B^2]} = \frac{T\chi_B^{(4)}}{\chi_B^{(2)}} = \kappa\sigma^2$$

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

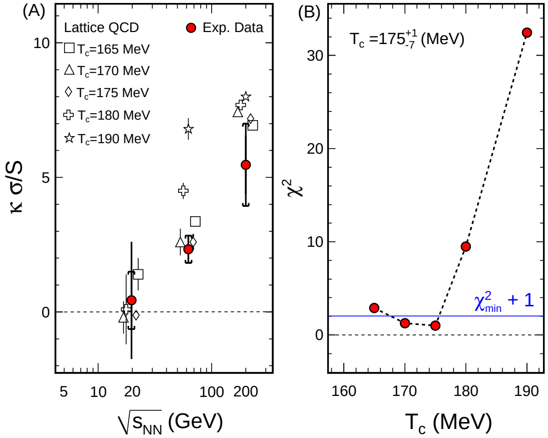
SG, 2009

Outline

Checking the match



Tuning lattice scale to match data



GLMRX, Science, 332 (2011) 1525

Outcome

Thermalization

1 parameter tuning makes thermodynamic predictions agree with data for 2 ratios at 3 energies. Indicates thermalization of the fireball at freezeout: not only mean chemistry but chemical fluctuations consistent with thermal.

T_c

Comparison of lattice and data along the freezeout curve gives

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

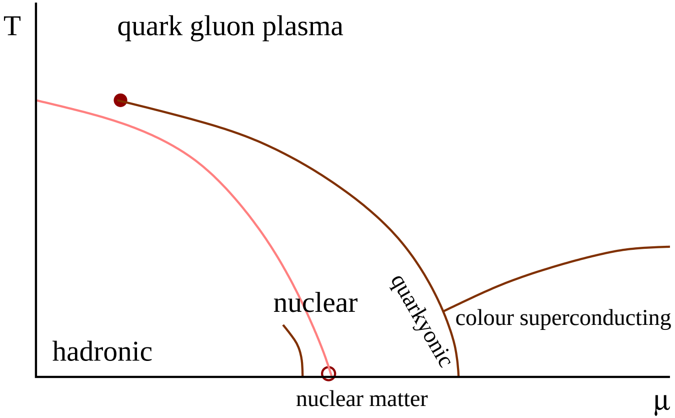
in agreement with other scale settings on the lattice. Indicates that non-perturbative phenomena in single hadron physics and strong interaction thermodynamics are mutually consistent through QCD.

Outline

Near term: control systematics

1. Is the fireball volume large enough? **Koch: 2011**
2. How short are microscopic length scales? **Padmanath *et al.*: 2011**
3. How important are isospin fluctuations? **STAR: 2010, Kitazawa and Asakawa: 2011**
4. Are volume fluctuations important? **STAR: 2010**
5. Do chemistry fluctuations freeze out with mean chemistry? Peclet length scale **Bhalerao and SG: 2009; SG: 2011, Karsch: 2011**
6. How important are finite lattice spacing artifacts? **Gavai and SG: 2010, HotQCD: ongoing**
7. How good is the series expansion in μ? **York and Moore: 2011**
8. How sensitive are the results to m_{ud} and m_s? **Gavai and SG: 2008**

Short term: search for the critical point



In the critical region $\xi^3 \simeq V_{fireball}$ and (1) Gaussian statistics fails (2) non-monotonically with scan energy, (3) QCD predictions does not agree with data.

Long term: a new science

1. Quantitative understanding of the initial state: increase the observed volume: watch crossover from thermal fluctuations to initial fluctuations.
2. Understand thermalization and transport: look at the region away from the peak of the fluctuations; tails of distributions thermalized slowly. High-order cumulants are good tools provided the experiment has the luminosity.
3. Use penetrating probes to look back directly at the early stages of the fireball: understand thermalization and transport. Penetrating probes interact weakly; need high luminosity.
4. If transport and initial state under control then one can ask about the equation of state.