Phases of baryonic matter

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ILGTI: TIFR

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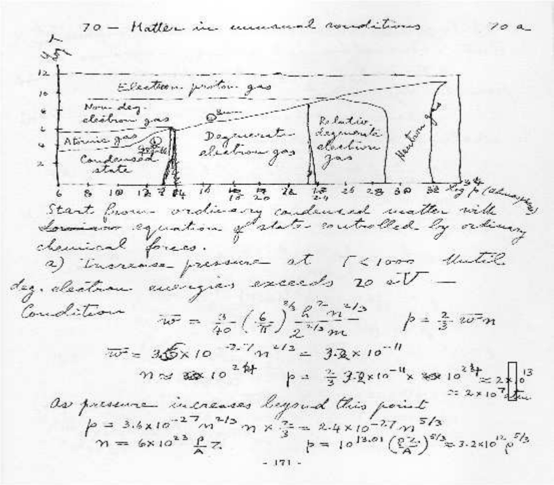
December 17, 2010

Outline

The forms of matter: an old quest



Enrico Fermi: notebooks

Extreme matter today

QCD: theory of strong interactions

SU(3) gauge theory of interacting quarks and gluons. Theory of gluons classically scale free, quantum corrections generate a scale: Λ_{QCD}.

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SU(3) gauge theory of interacting quarks and gluons. Theory of gluons classically scale free, quantum corrections generate a scale: Λ_{QCD}.

A theorist's reflex

Given Hamiltonian compute eigenstates, S-matrix elements: talk by Gottlieb, others.
Compute physics in a heat-bath: $Z(T,\mu) = \mathrm{Tr}\ \exp[-\beta(H-\mu B)]$.
Thermodynamics and phase transitions etc.

The experimental reflex

" We didn't have flint when when I was a kid, we had to rub two sticks together. "

The set of questions

Can experiment test any non-perturbative predictions of QCD?

In heavy-ion collisions QCD often enters indirectly: as the result of a long secondary computation such as hydro. Instead, can one get directly at QCD?

Can experiment test the existence of a critical point of QCD?

Do heavy-ion experiments have anything to say about the phase diagram? Or are they just dirtier versions of proton-proton collisions?

Outline

Background

Experiments test non-perturbative QCD in bulk

- Theoretical developments
- Observational tests

The phase diagram of QCD

- Symmetry arguments
- Dynamics: lattice results
- Signal of the critical point

Summary

Non-linear susceptibilities

Taylor expansion of the pressure in μ_B

$$P(T, \mu_B + \Delta\mu_B)/T^4 = \sum_n \frac{1}{n!} \left[\chi^{(n)}(T, \mu_B) T^{n-4}\right] \left(\frac{\Delta\mu_B}{T}\right)^n$$

has Taylor coefficients called non-linear susceptibilities (NLS).
When $\mu_B = 0$ they can be computed directly on the lattice, otherwise reconstructed from such computations.
(Gavai, SG: 2003, 2010)
Cumulants of the event-to-event distribution of baryon number are directly related to the NLS:

$$[B^2] = T^3 V \left(\frac{\chi^{(2)}}{T^2}\right), \quad [B^3] = T^3 V \left(\frac{\chi^{(3)}}{T}\right), \quad [B^4] = T^3 V \chi^{(4)}.$$

V unknown, can be removed by taking ratios.
(SG: 2009)

Tests and assumptions

$$m_1: \quad \frac{[B^3]}{[B^2]} = \frac{\chi^{(3)}(T,\mu_B)/T}{\chi^{(2)}(T,\mu_B)/T^2}$$

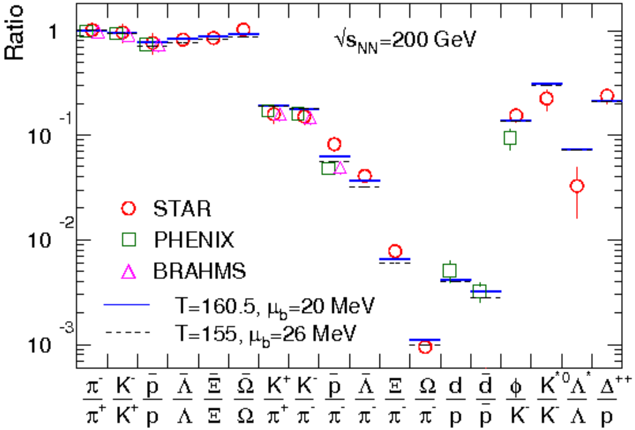
$$m_2: \quad \frac{[B^4]}{[B^2]} = \frac{\chi^{(4)}(T,\mu_B)}{\chi^{(2)}(T,\mu_B)/T^2}$$

$$m_3: \quad \frac{[B^4]}{[B^3]} = \frac{\chi^{(4)}(T,\mu_B)}{\chi^{(3)}(T,\mu_B)/T}$$

Also for cumulants of electric charge, Q, and strangeness, S.

1. Two sides of the equation equal if there is thermal equilibrium and no other sources of fluctuations.
2. Right hand side computed in the grand canonical ensemble (GCE). Can observations simulate a grand canonical ensemble? What T and μ_B?

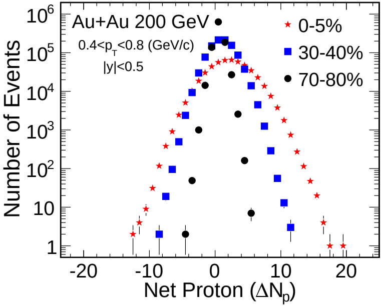
The fireball thermalizes



Chemical freeze out: $T = 160.5$ MeV, $\mu = 20$ MeV.

Andronic et al, nucl-th/0511071

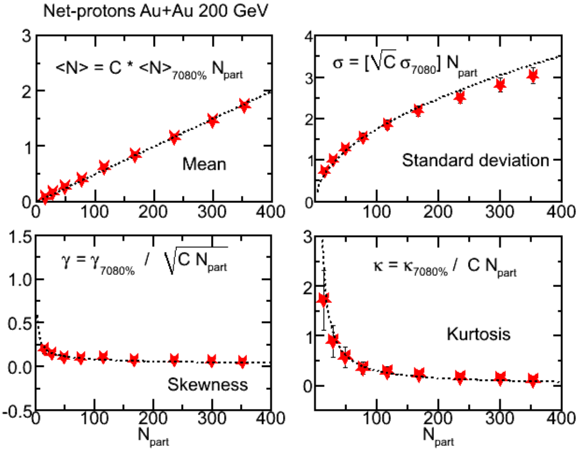
Event distributions of conserved charges



STAR, 1004.4959

- Fluctuations of conserved quantities are Gaussian: provided large volume and equilibrium
- Proton number a substitute for baryon number: how good?
- Is this Gaussian due (entirely or largely) to thermal fluctuations?

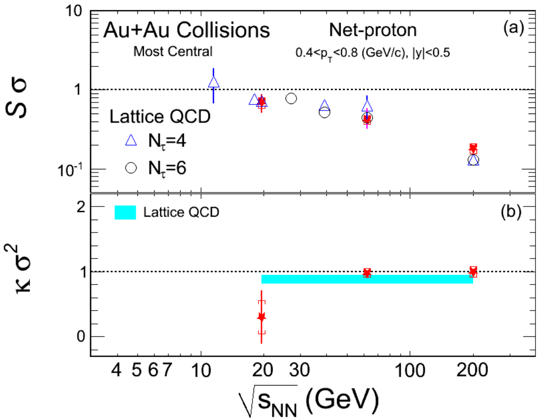
STAR measurements: 2009



$\ell \gg \xi$ $(K \ll 1)$ tested and found true.

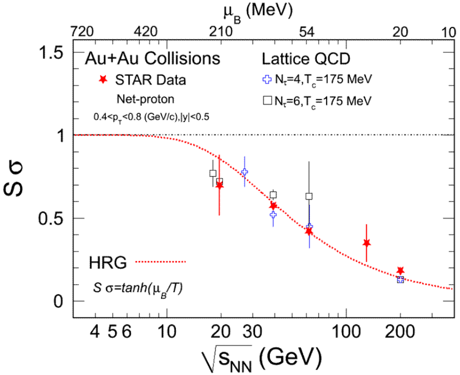
STAR Collaboration: QM 2009, Knoxville

STAR measurements: beginning 2010



First ever agreement between lattice and experiment for bulk matter! STAR Collaboration: 2010

STAR measurements: end 2010



Continuing agreement between bulk matter lattice and experiment!

STAR Collaboration: ICPAQGP, Goa, December 2010

Outline

How many flavours?

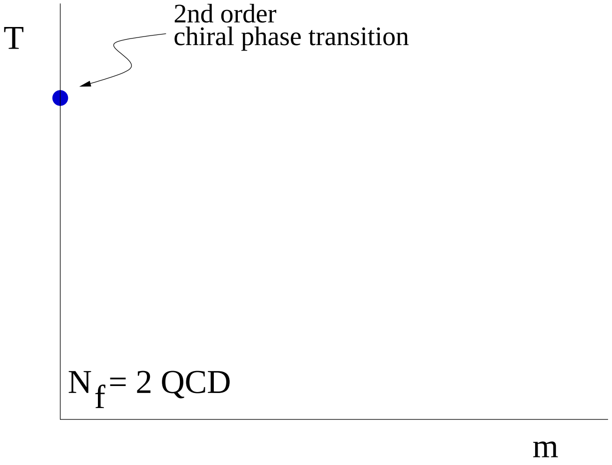
Scales of masses

In QCD two quarks are almost chiral: $m_{ud} \ll \Lambda_{QCD}$.
One quark is medium heavy: $m_s \simeq \Lambda_{QCD}$.
Three quarks decouple: $m_{cbt} \gg \Lambda_{QCD}$.

How light should m_s be to change the phase diagram?

If m_{uds} are simultaneously tuned from physical values then m_s must be decreased by factor of 6 or more. Endrodi etal, 0710.0988 (2007)
Similarly for $N_f = 3$. Karsch etal, hep-lat/0309121 (2004)
$N_f = 2$ phase diagram qualitatively fine.

The $T = 0$ phase diagram



Phase diagram plots singularities of free energy.

Pisarski and Wilczek, PR D 29, 338 (1984)

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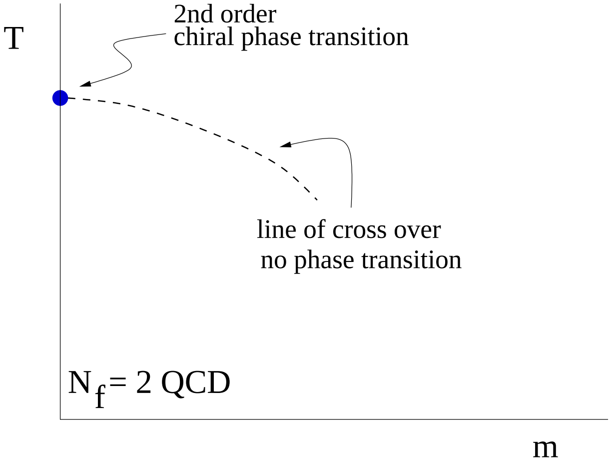

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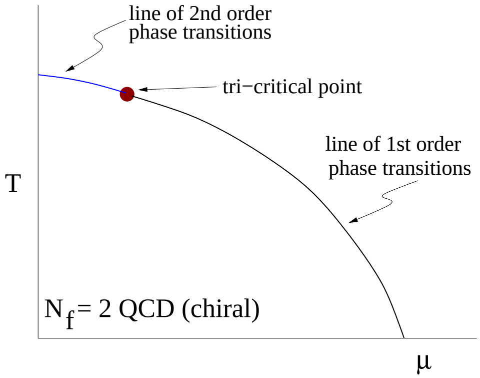
The extended phase diagram



Rajagopal, Stephanov, Shuryak 1998 and 1999

Other effects: anomaly, large-N counting, condensed phases?

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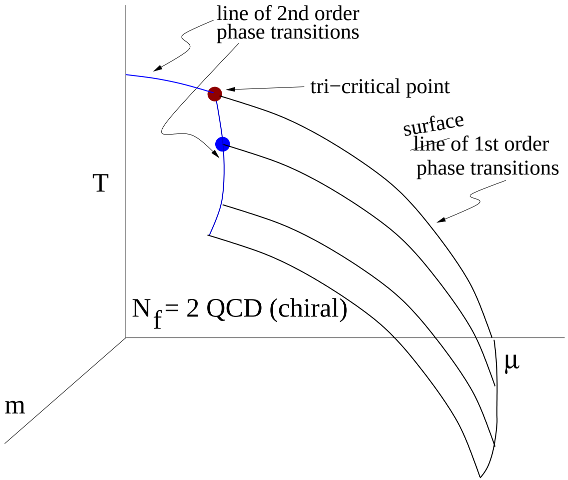

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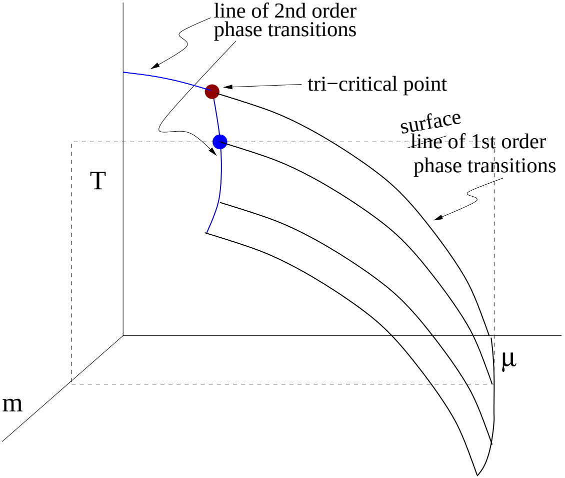

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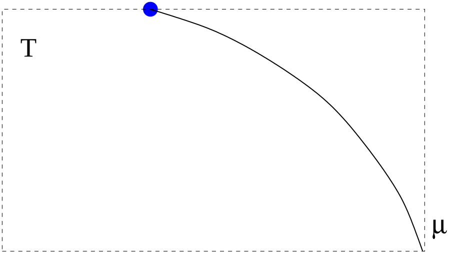

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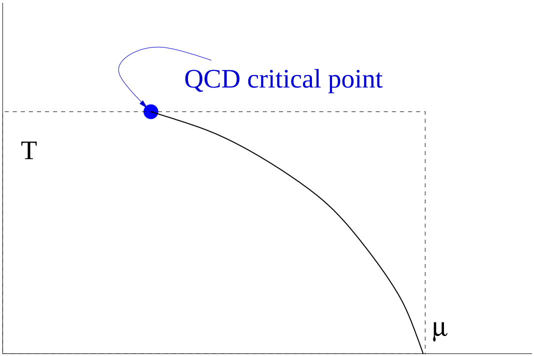

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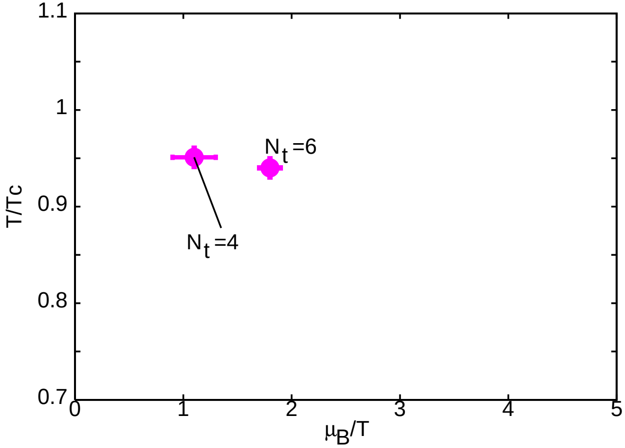
The critical point from lattice QCD



Staggered: $N_f = 2$, $m_\pi = 230$ MeV, $LT \geq 4$ Gavai, SG, 0806.2233
P4: $N_f = 2 + 1$, $m_\pi = 220$ MeV, $LT = 4$ Schmidt, 2010

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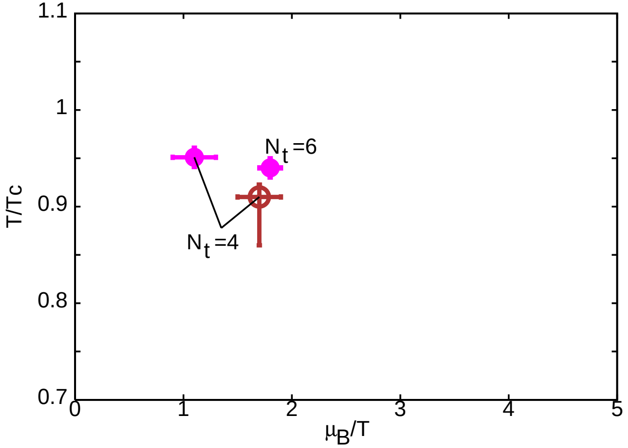

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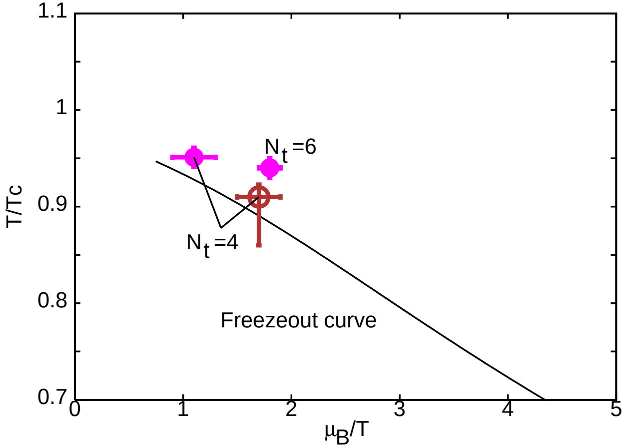

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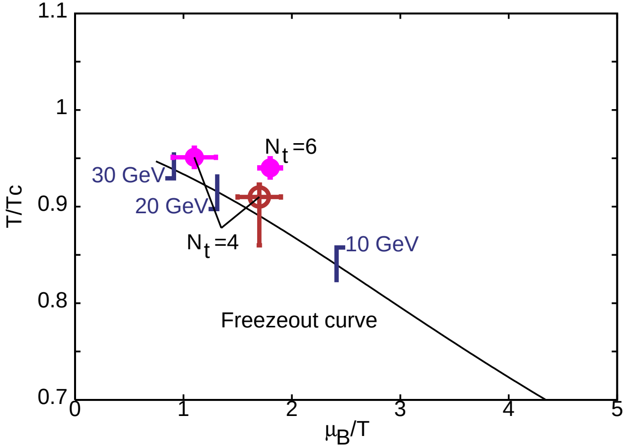

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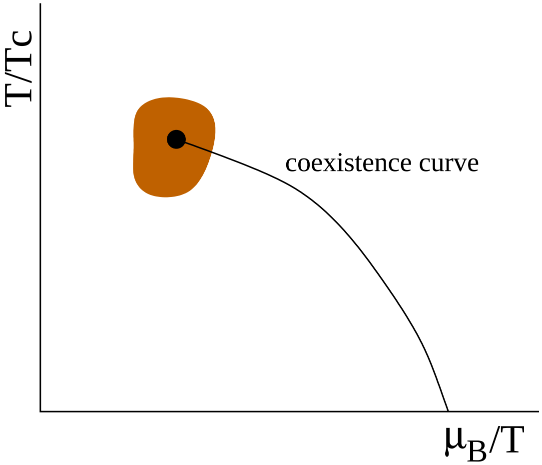
How to find the critical point: be lucky!



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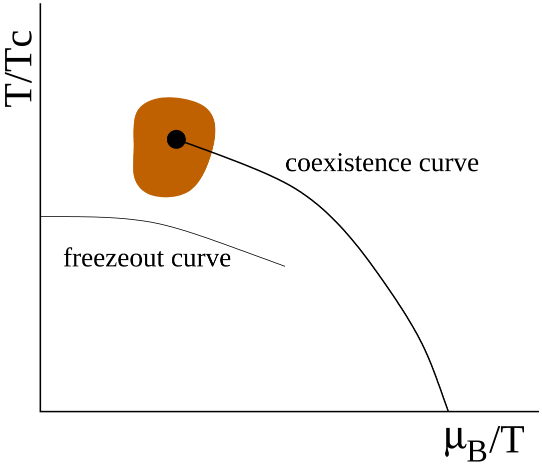

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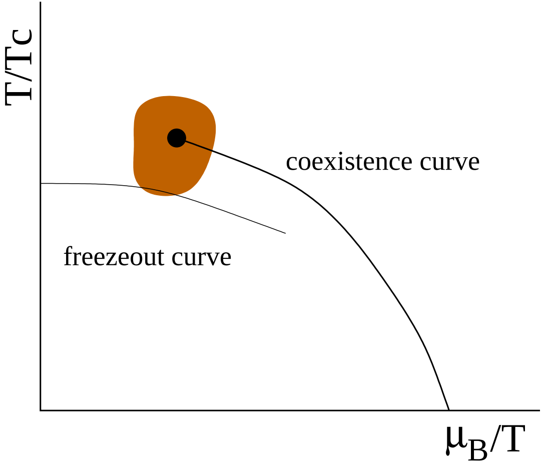

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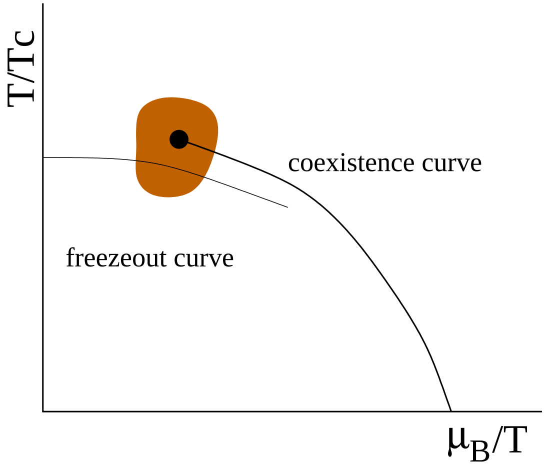
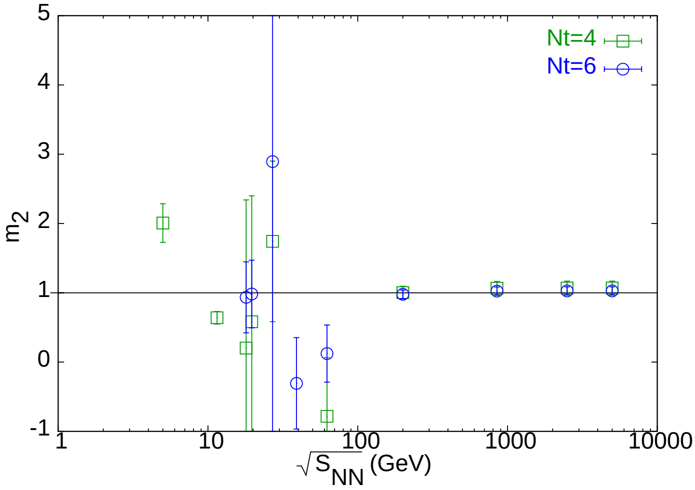


Observables



Gavai, SG: 2010

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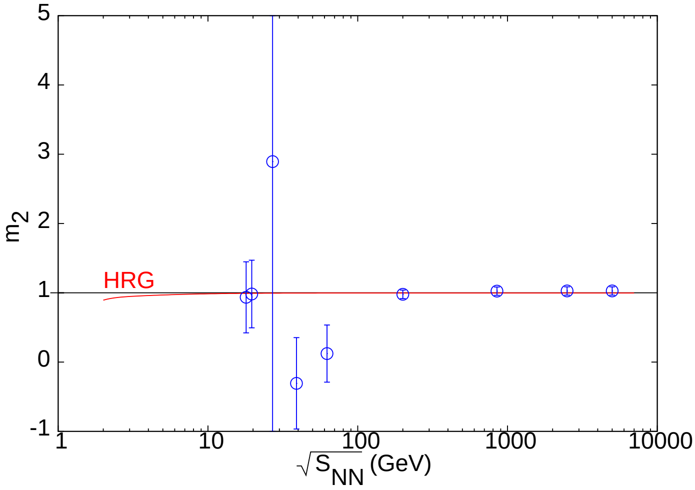

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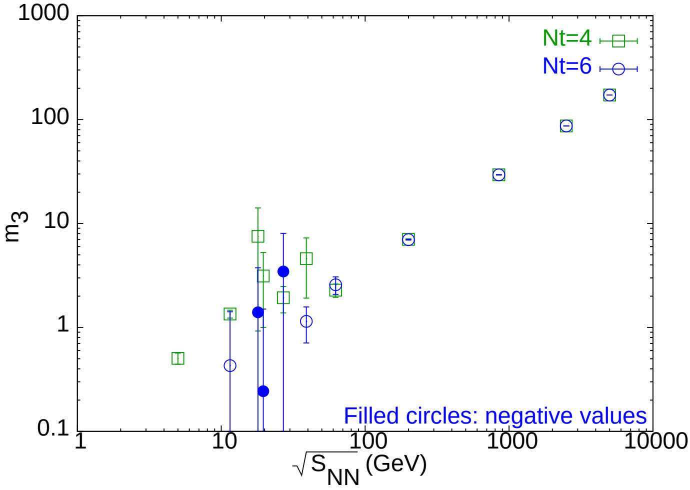

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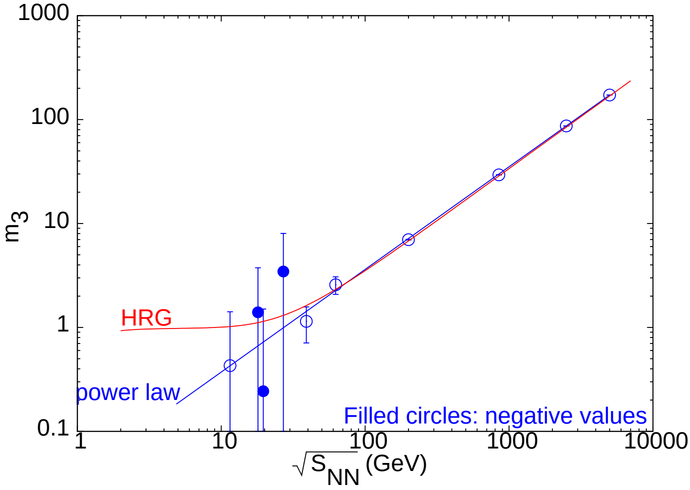

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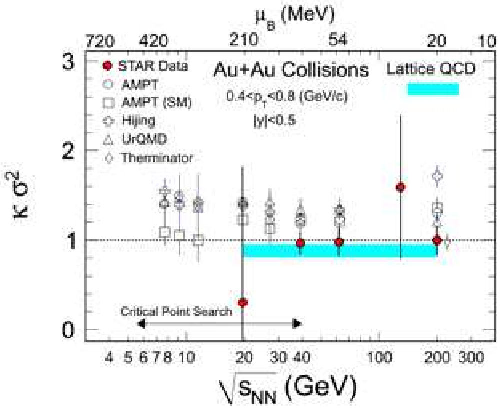
New STAR data



Intriguing structure in m_2: not predicted by models which have no critical point. See also PNJL: Deb (parallel session)

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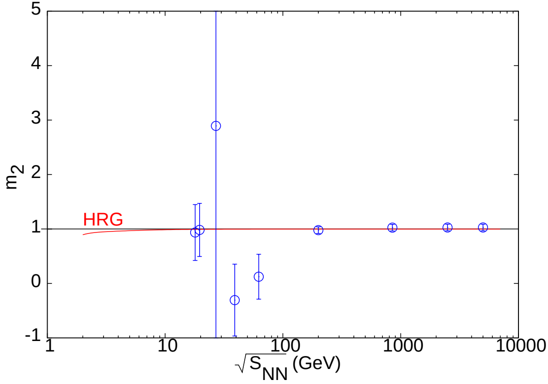

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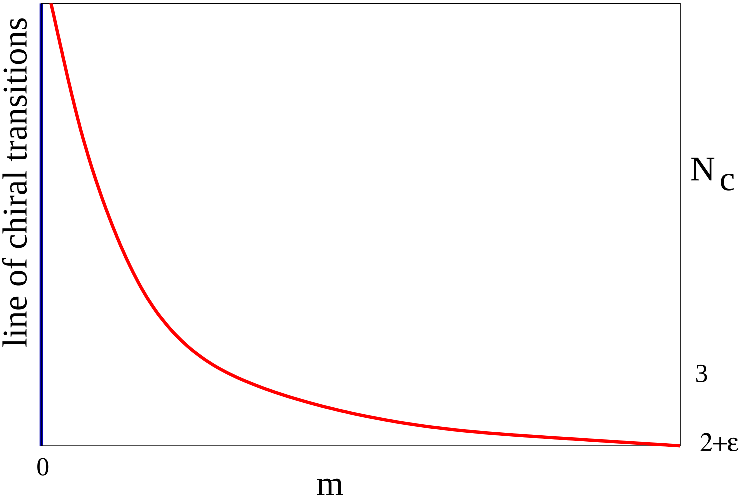
Outline

The sign problem in QCD can be evaded

1. The strange quark is heavy; light quarks determine the shape of the phase diagram. The cross over temperature now under control: $T_c \simeq 170$ MeV. SU(2) flavour symmetry breaking unlikely to change T_c.
2. Lattice determines series expansion of pressure; indicates a critical point in QCD. Lattice spacing effects under reasonable control. Physical quantities can be found be resumming the series expansion (*e.g.*, Padé approximants).
3. First direct comparison of lattice results with experimental data done; good agreement. A landmark in the field: good evidence for thermalization.
4. A step-by-step analysis suggested for critical point: failure of CLT scaling, fluctuations not frozen at chemical freezeout, evidence for non-monotonic behaviour of $m_{1,2,3}$ near this point.

Have another N? No thanks



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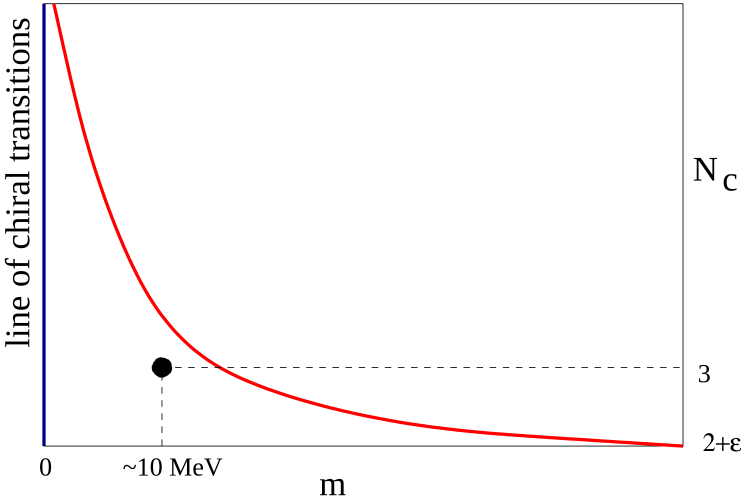

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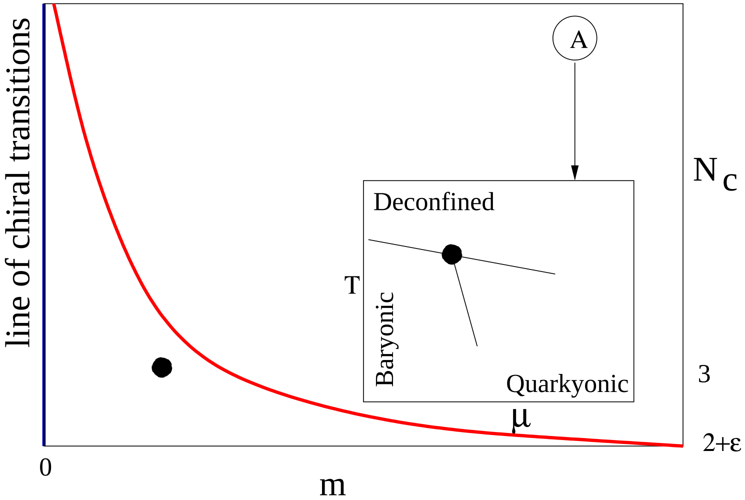

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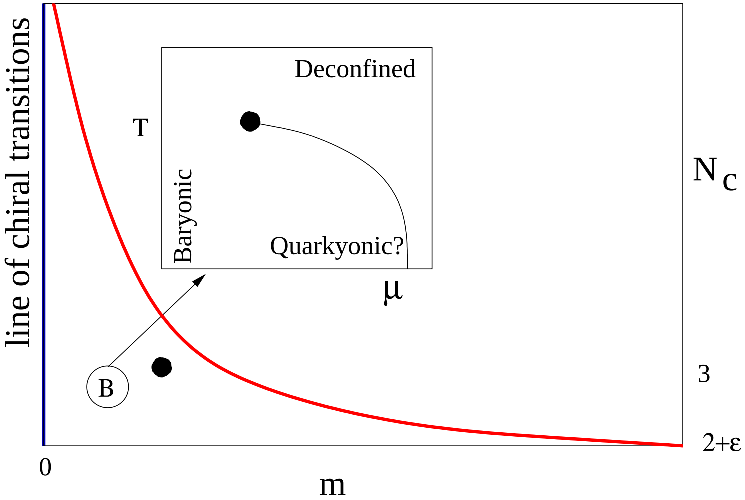
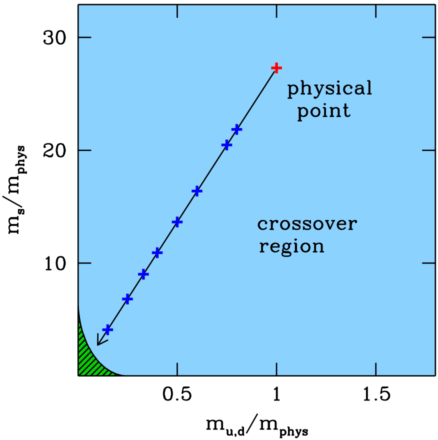


Lattice results for the Columbia Plot



In $N_f = 2+1$:

$$m_\pi^{crit} \begin{cases} = 0.07 m_\pi & (N_t = 4) \\ < 0.12 m_\pi & (N_t = 6) \end{cases}$$

Endrodi etal, 0710.0988 (2007)

Similarly for $N_f = 3$.

Karsch etal, hep-lat/0309121 (2004)