QCD phase diagram

M. Stephanov

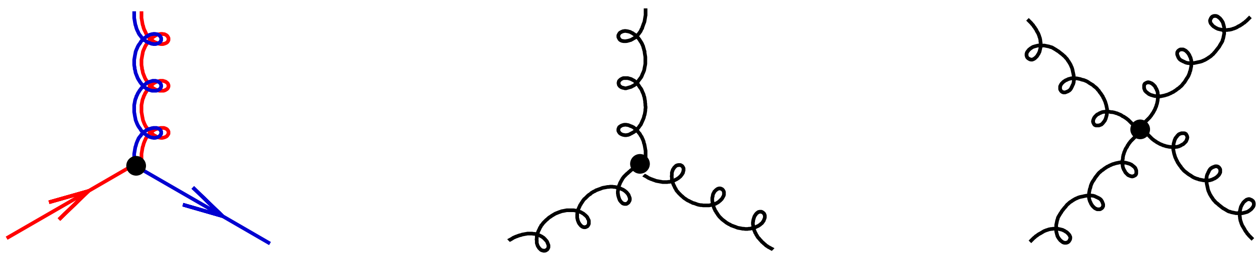
U. of Illinois at Chicago

RBRC 1999-2004

QCD – asymptotically free field theory

- At short distances – can see fundamental constituents.
- QCD is a quantum field theory:

$$S = \int d^4x \left[\sum_{f=1}^{N_f} \bar{q}_f \left(i\partial\!\!\!/ + gA\!\!\!/ - m_f \right) q_f \; - \frac{1}{2} \mathrm{Tr}\, F_{\mu\nu} F^{\mu\nu} \right];$$



- Predictive power: i.e., for every physical quantity it gives a recipe to calculate it.

  ... Whether we are ready to do the calculation is a different matter.

- Strongly interacting theory (confinement) — hadrons.
  QCD generates the mass as we know it.

QCD thermodynamics

- Applications:
  - Neutron stars (large density, low T)
  - Heavy-ion collisions (large T, large density)
- QCD allows first principle calculations
- Questions: phases, phase diagram, as function of T, μ_B, $\ldots$

QCD thermodynamics

- Applications:
  - Neutron stars (large density, low T)
  - Heavy-ion collisions (large T, large density)
- QCD allows first principle calculations
- Questions: phases, phase diagram, as function of T, μ_B, ...
- Early expectations $\Rightarrow$

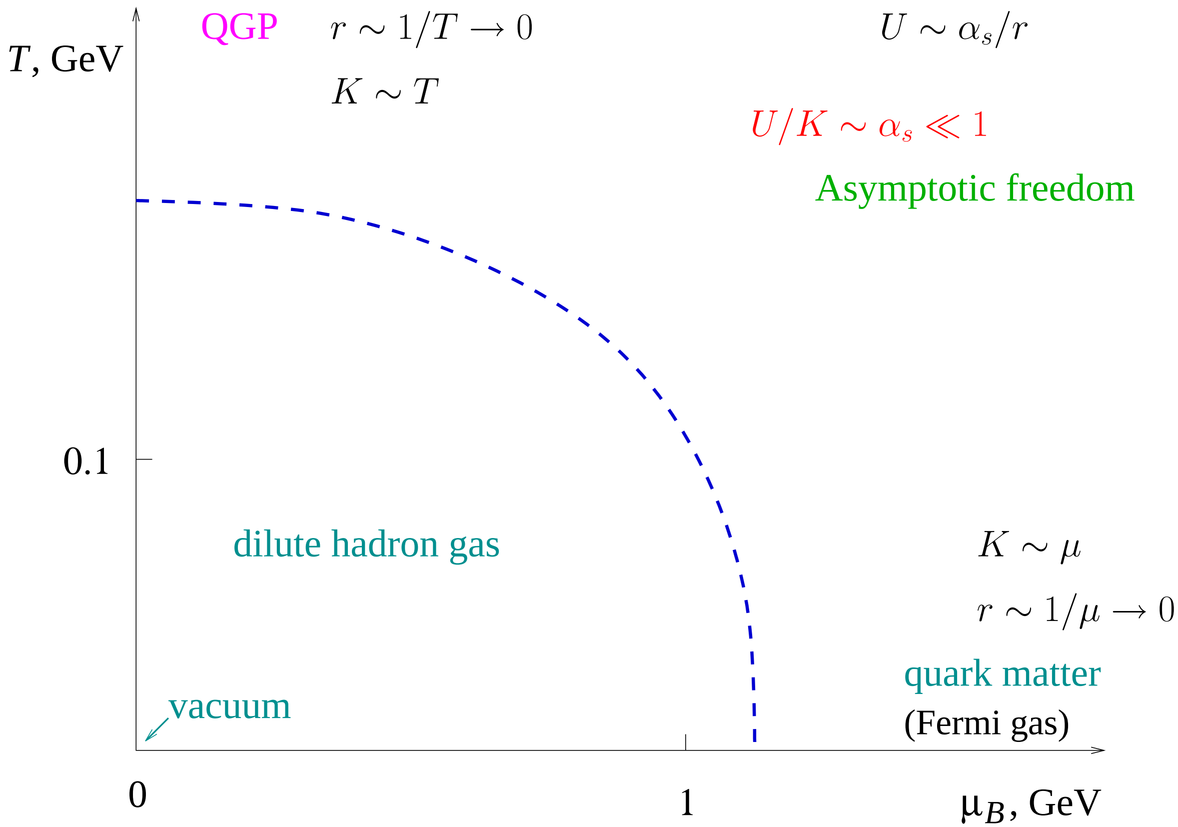
Natural scale:

$$kT \sim \frac{\hbar c}{1\mathrm{fm}} = 0.2\ \mathrm{GeV}.$$

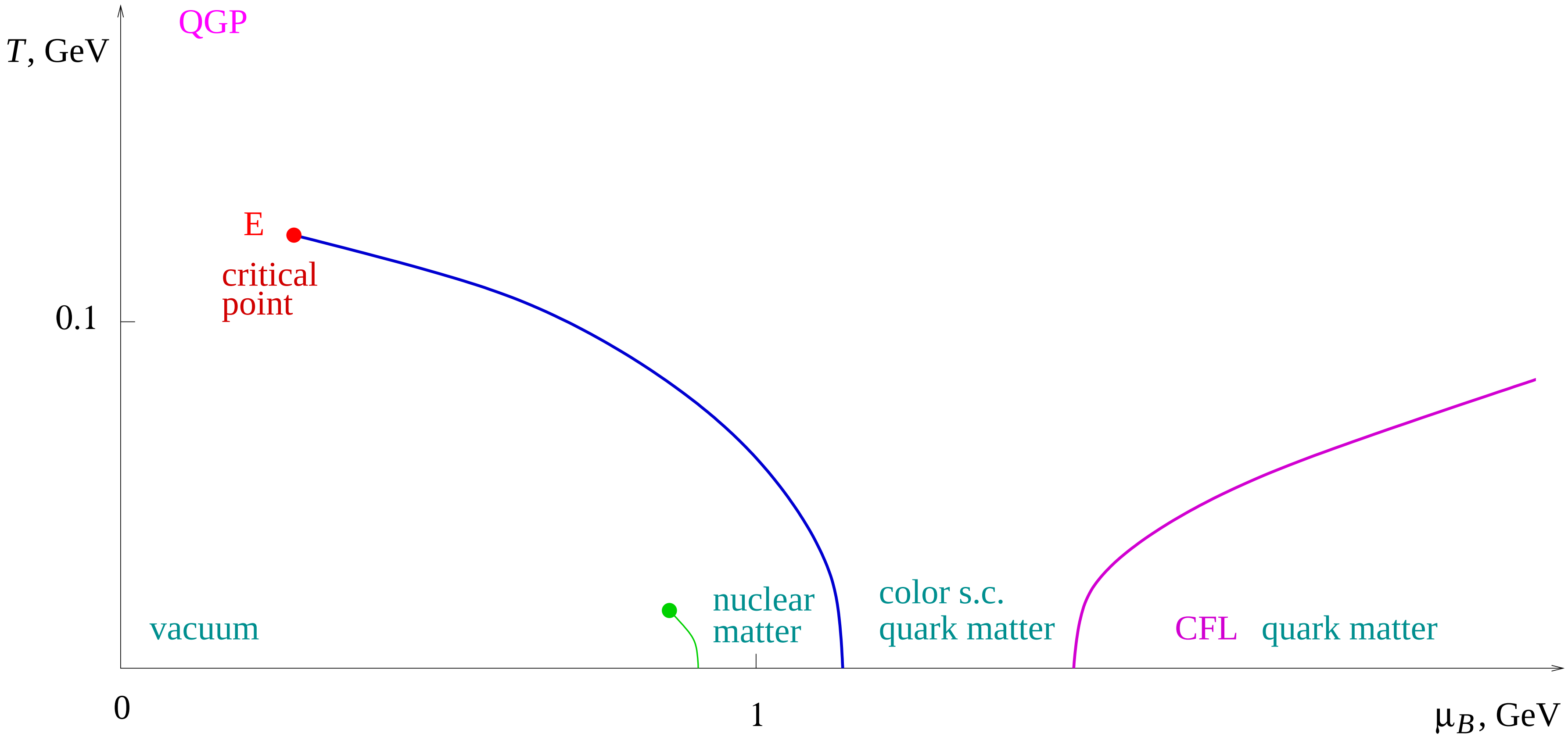
$$(T \sim 10^{12} K)$$

or

$$\rho_B \sim 1\mathrm{fm}^{-3}.$$

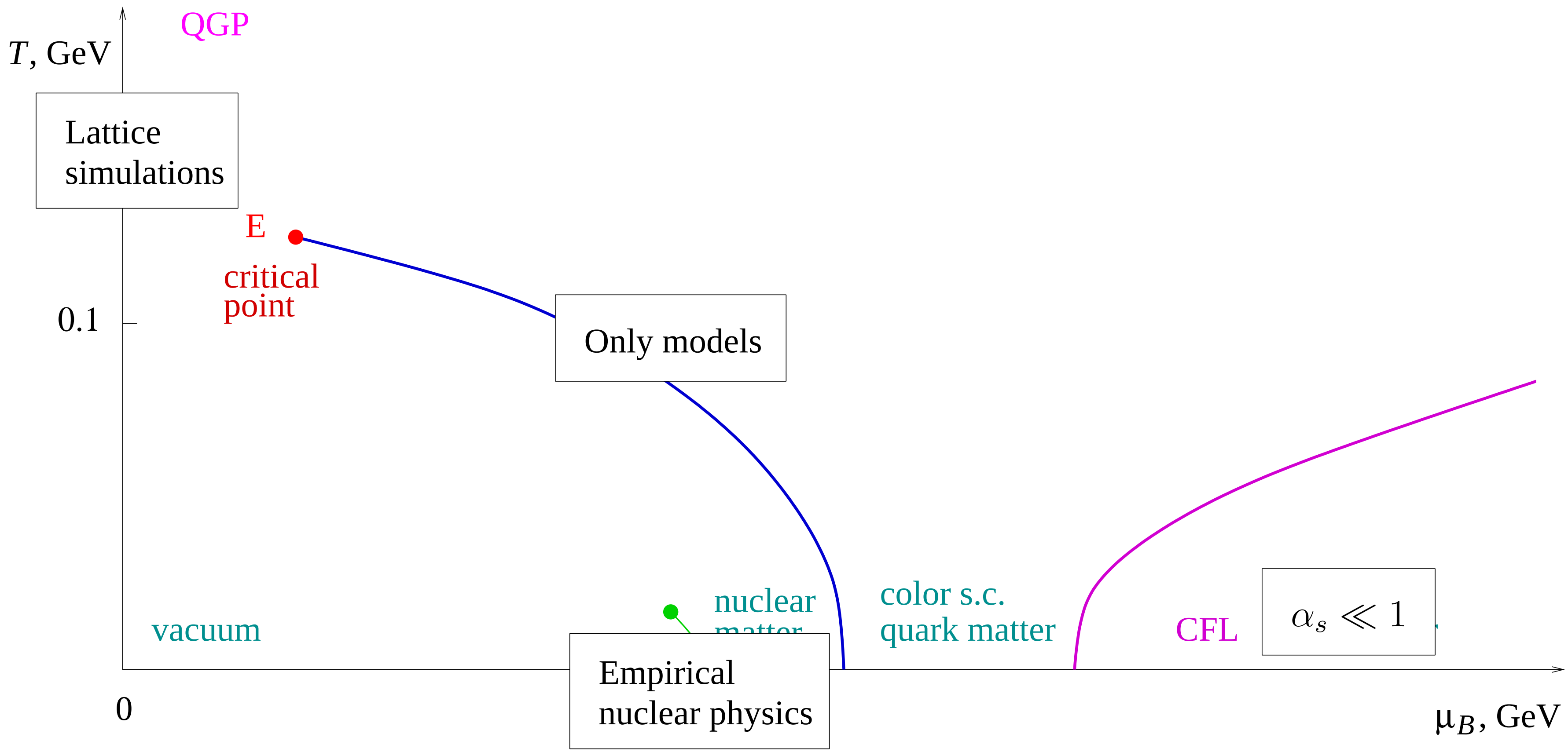


Contemporary view



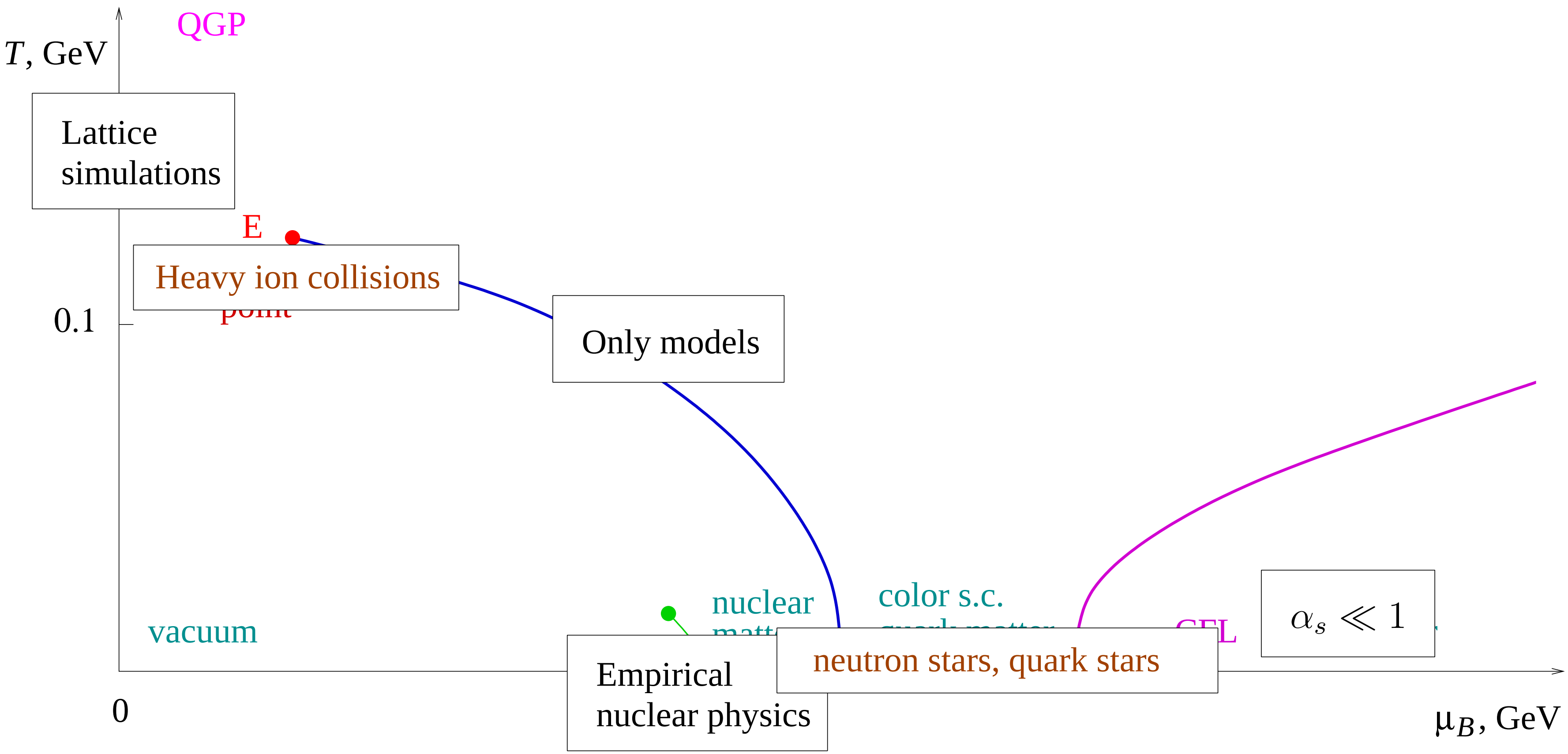
“Minimal” phase diagram

Contemporary view



“Minimal” phase diagram

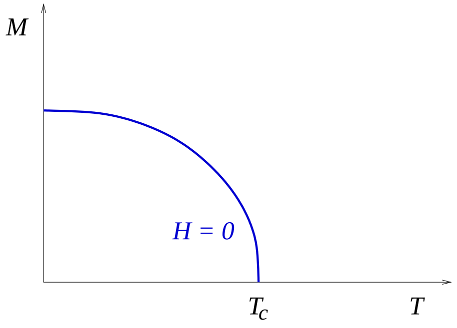
Contemporary view

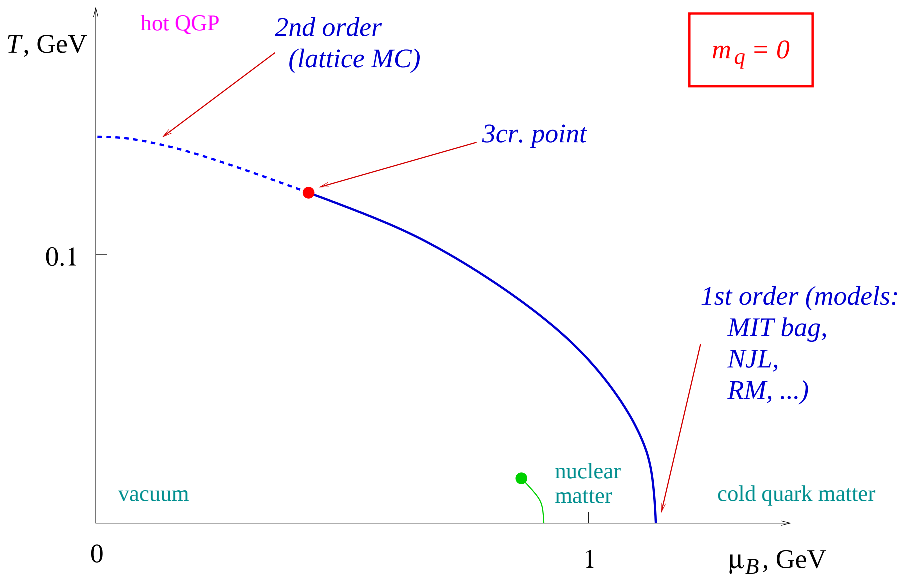


“Minimal” phase diagram

Role of chiral symmetry and $m_q \neq 0$

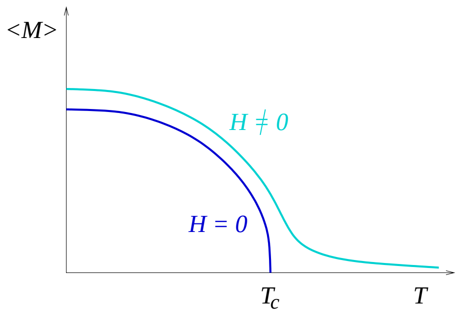
Ferromagnet



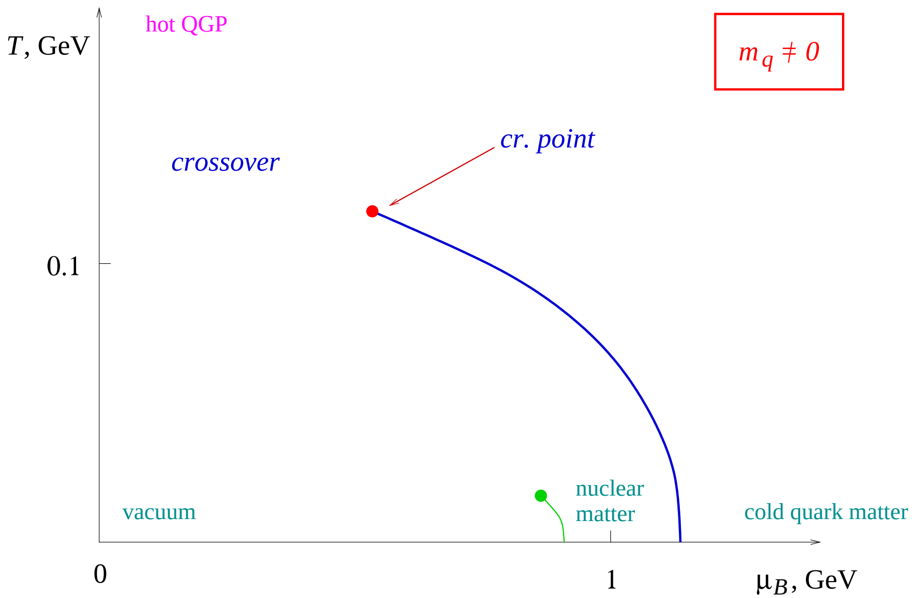


Role of chiral symmetry and $m_q \neq 0$

Ferromagnet at $H \neq 0$:



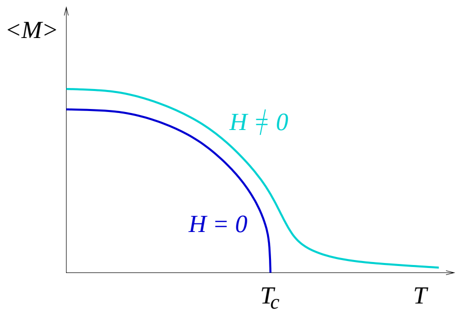
no phase transition, but crossover



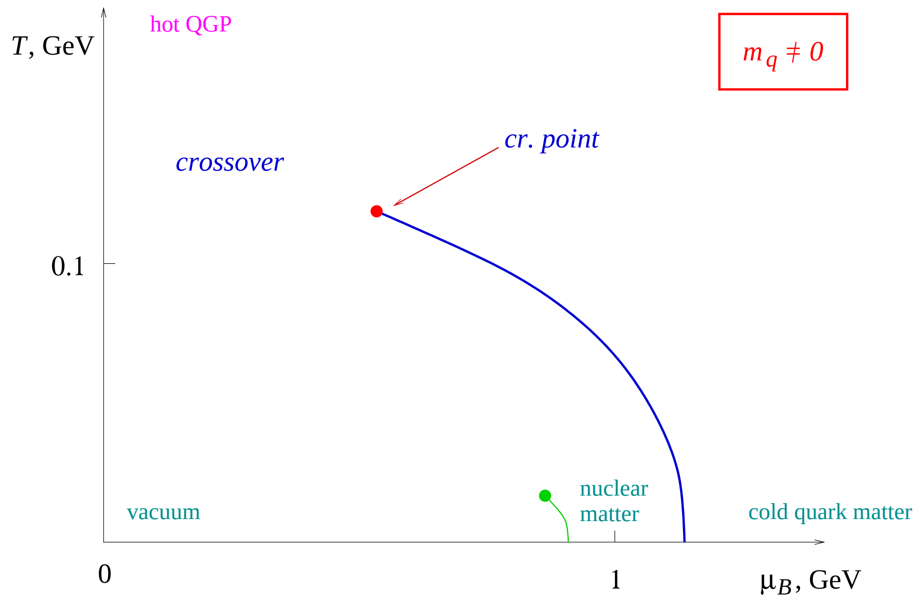
- Why all phases (can be) connected? Because $\nexists$ order parameters: no chiral symmetry ($m_q \neq 0$);
  ...

Role of chiral symmetry and $m_q \neq 0$

Ferromagnet at $H \neq 0$:

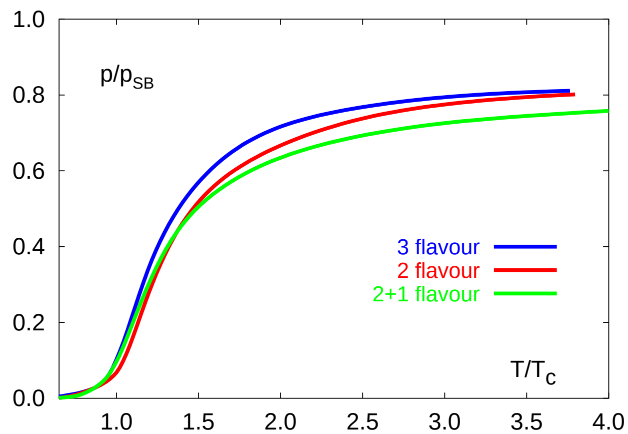


no phase transition, but crossover



- Why all phases (can be) connected? Because ∄ order parameters: no chiral symmetry ($m_q \neq 0$); . . .

- No phase boundary does not mean same physics: (compare water-vapor, gas-plasma)

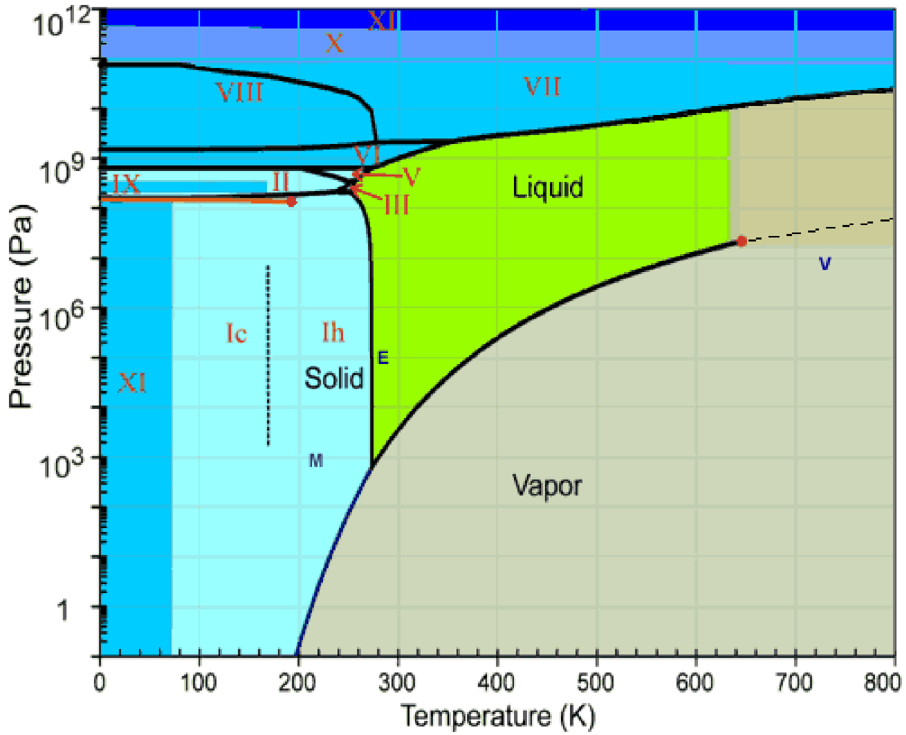


(Bielefeld)

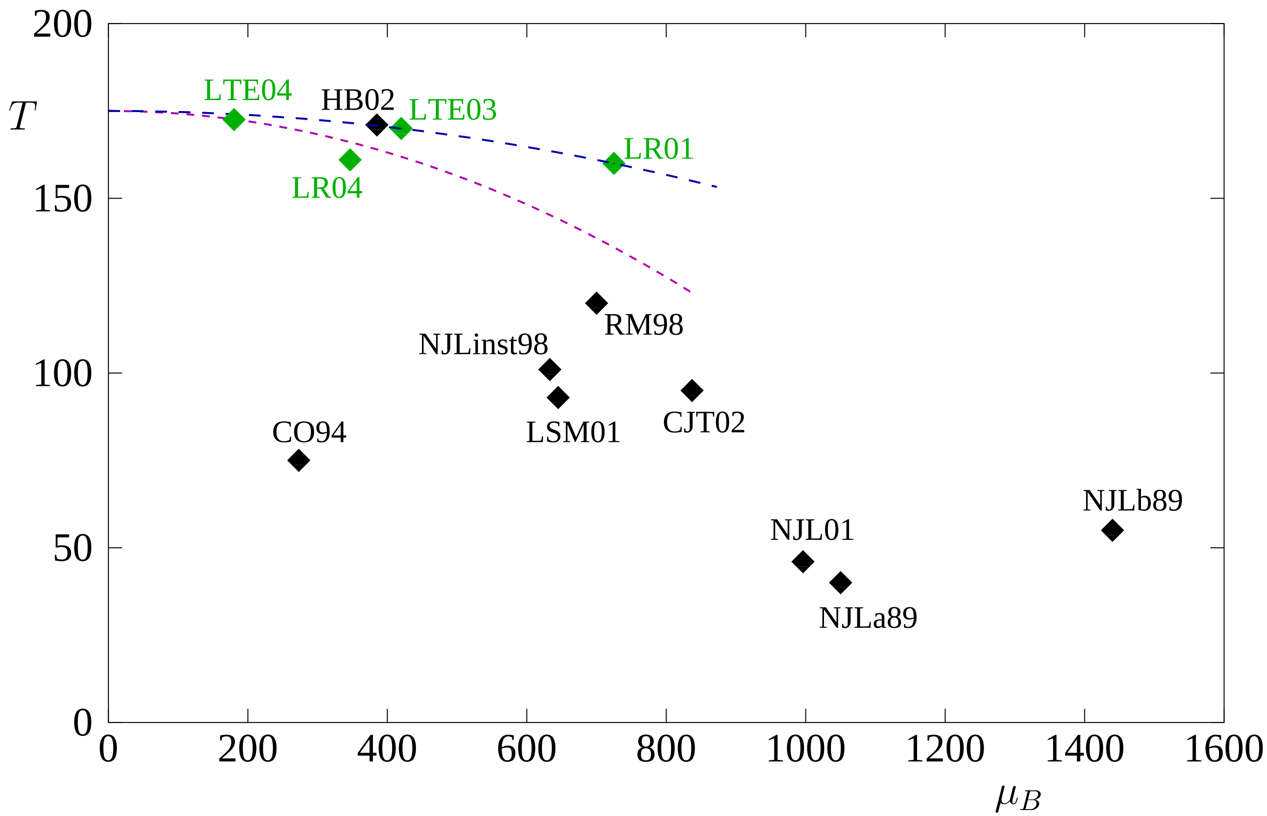
Critical point in known liquids

Critical point $\exists$ in many liquids (critical opalescence).

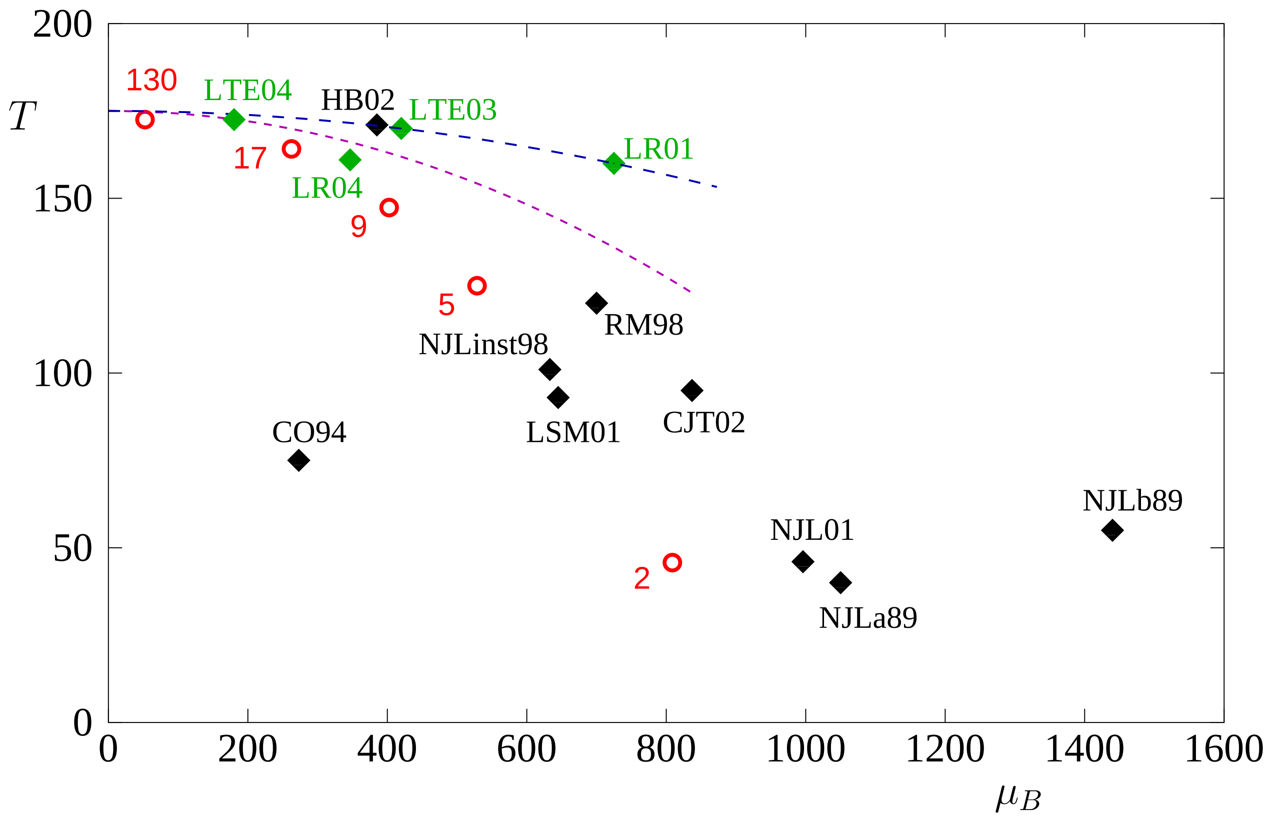
Water:



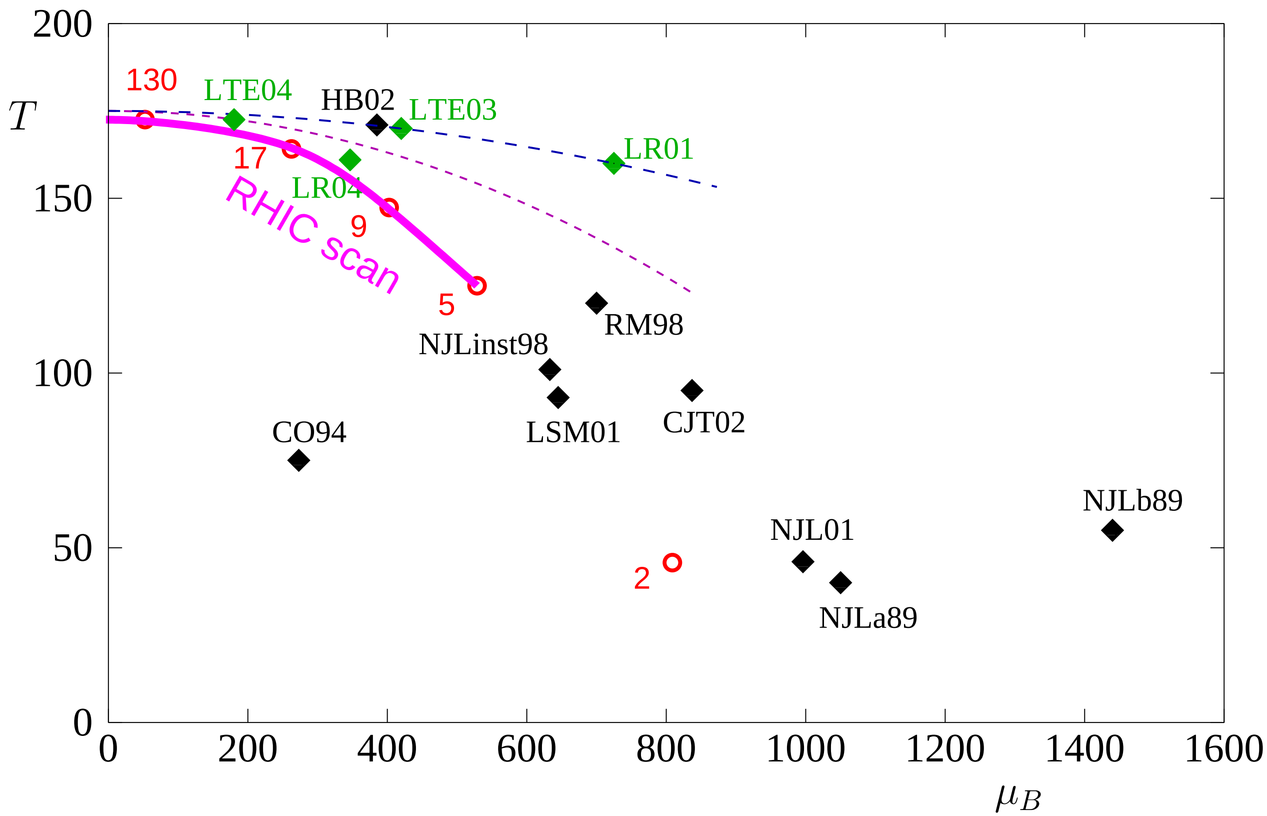
Locating the QCD critical point



Locating the QCD critical point



Locating the QCD critical point

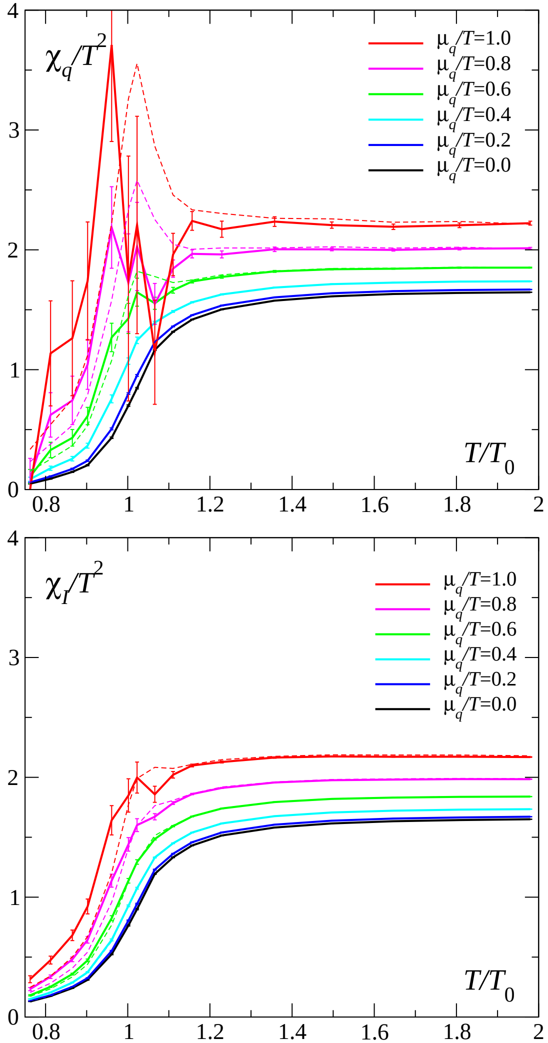


Experiments can scan the phase diagram by changing $\sqrt{s}$: RHIC.

Signatures: event-by-event fluctuations.

Susceptibilities diverge $\Rightarrow$ fluctuations grow towards the critical point.

Critical point on the lattice

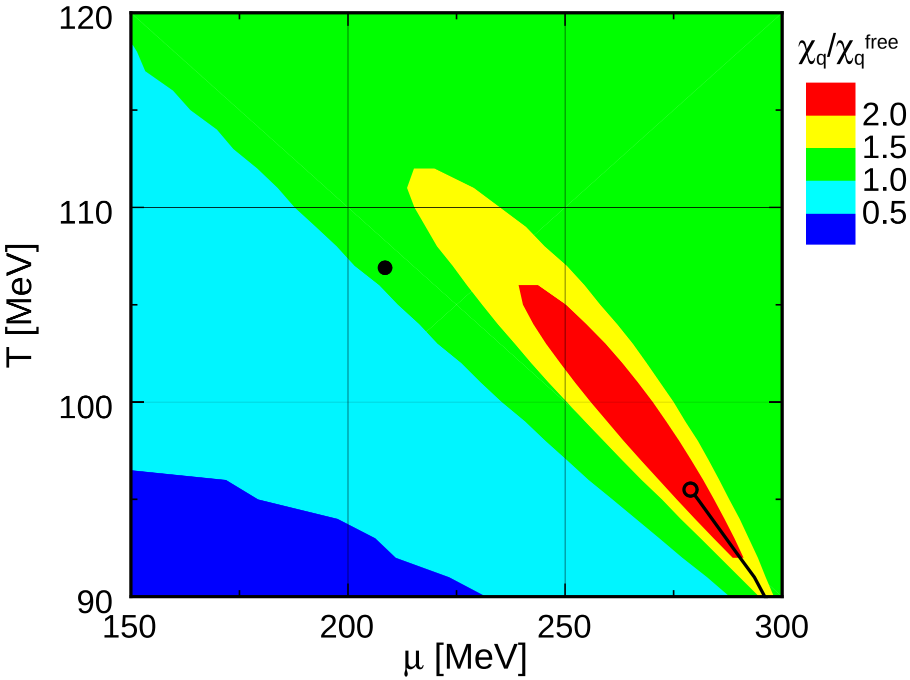


Allton, *et al*: peak in χ_B, but not in χ_I

Several approaches:

- Reweighting: Fodor-Katz
  - 2001: $\mu_B \sim 725$ MeV
  - 2004: $\mu_B \sim 360$ MeV (smaller m_q and V)
- Taylor expansion: Bielefeld-Swansea (to μ^6)
  - 2003: $\mu_B \sim$ 420 MeV
  - 2005: 300 MeV $\lesssim \mu_B \lesssim$ 500 MeV
- Taylor expansion: Gavai-Gupta (to μ^8)
  - $\mu_B \sim 180$ MeV (more precisely > 180 MeV)
- Imaginary μ: Philipsen-deForcrand, Lombardo, *et al*
  - Sensitive to m_s, perhaps $\mu_B \gg$ 300 MeV
- Fixed density: deForcrand, Kratochvila
  - ? ($N_f = 4$, small volumes)

Shape and size of singular region



(from Hatta, Ikeda)

Important for experimental scan:

We only need to hit the ‘petal’. Maximum ξ is anyway limited by finite τ to $\xi \sim 2-3$ fm, hence $\chi/\chi_0 \sim 4-9$.

- Wide in μ_B, slim in T. (Note scale: $\mu_B : T \sim 15 : 1$.)
- $\chi/\chi_0 > 2.5$ in the interval $\Delta\mu_B \sim 150$ MeV;
- $\chi/\chi_0 > 4$ — $\Delta\mu_B = ?$
- Lattice?

Magnitude of the effect

Scaling and universality of critical phenomena: $\chi \sim \xi^{\rm power}$ $\quad (\text{power} \approx 2)$.

How big can ξ grow?

Limited by:

- Finite size of the system $\xi < 6$ fm.
- Finite *time*: $\tau \sim 10$ fm.

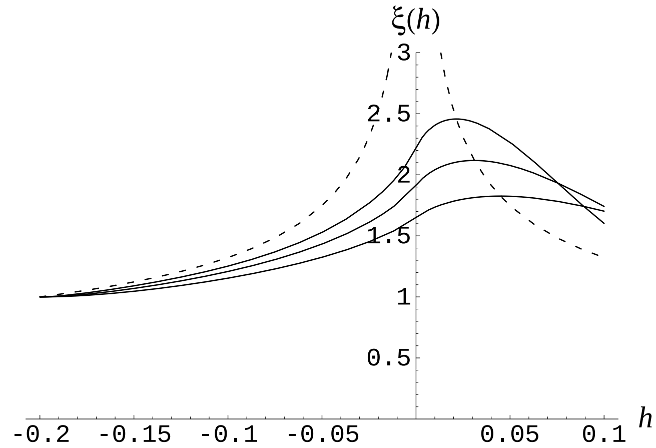
$$\xi \sim \tau^{1/z}$$

$z > 1$ – dynamical critical exponent.

Dynamic universality class of liquid-gas phase transition, i.e., $z \approx 3$:

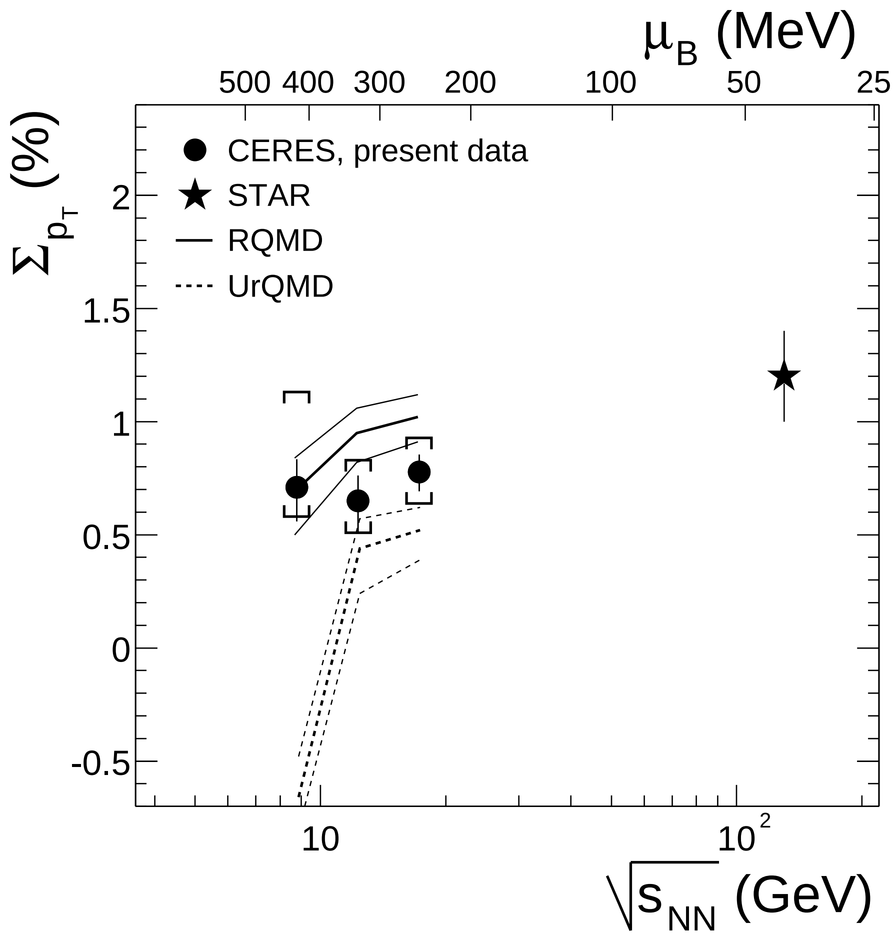
- Critical mode – diffusive: $\omega \sim iDq^2$,
- $D = \dfrac{\lambda_B}{\chi_B} \sim \xi^{-1} \to 0 \qquad 2 + 1 = 3.$

(Son, MS, PRD70:056001,2004)



(Berdnikov, Rajagopal, PRD61:105017,2000)

Data (example): p_T fluctuations (CERES)



Near the critical point (for CERES acceptance) one expects:

$$\sim 2\% \times \left(\frac{G}{300\ \mathrm{MeV}}\right)^2 \left(\frac{\xi_\sigma}{3\ \mathrm{fm}}\right)^2$$

$(\xi_\sigma = 1/m_\sigma)$

Signal one is looking for:
non-monotonic dependence on $\sqrt{s}$.

Also: low transverse momenta (thermal, soft)), $p_T < 3T \sim 500$ MeV – where critical point correlations are (cf. CERES data – $p_T < 1.5$ GeV).

Current status and summary notes

- Phase diagram of QCD at nonzero baryon density is under active theoretical investigation: much progress in lattice calculations.

  Still a lot to be done to narrow down the prediction for the critical point.

- Heavy ion collision experiments can discover the critical point by observing non-monotonous signatures.

- Needed:
  - Accelerator with variable $\sqrt{s}$ to scan phase diagram
  - Detector with sufficient acceptance and p.id. at $p_T \lesssim 500$ MeV to
    - measure fluctuations (of mean p_T, ratios, etc.);
    - measure μ_B, T of freezeout.

- RHIC is the ideal machine to do this