

Heavy Ions Collisions and the search for the Quark-Gluon Plasma

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1. QCD matter. The final state in HIC.
2. The first stages and before. The initial state in HIC.
3. Signals for the QGP formation.
4. Experimental/Theoretical status.
 - ⇒ RHIC
 - ⇒ LHC

0. What do heavy ion collisions do?

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Study QCD under extreme conditions

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→ High Temperatures

1. QCD matter

QCD is the theory of strong interactions.

⇒ It describes interactions between hadrons (p , π , ...)

↘ Asymptotic states.

↘ *Normal* conditions of temperature and density.

↘ Nuclear matter (us).

↘ Colorless objects.

QCD

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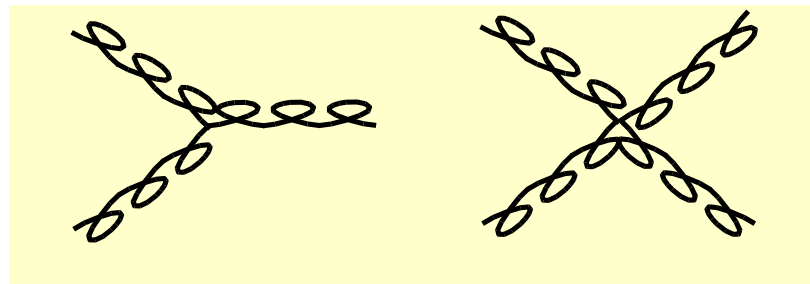
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⇒ Quarks and gluons in the Lagrangian

↘ Fundamental particles.

charge=+2/3	u (~ 5 MeV)	c (~ 1.5 GeV)	t (~ 175 GeV)
charge=-1/3	d (~ 10 MeV)	s (~ 100 MeV)	b (~ 5 GeV)

↘ Colorful objects. **color = charge of QCD** \longrightarrow **vector**
Similar to QED, but gluons can interact among themselves



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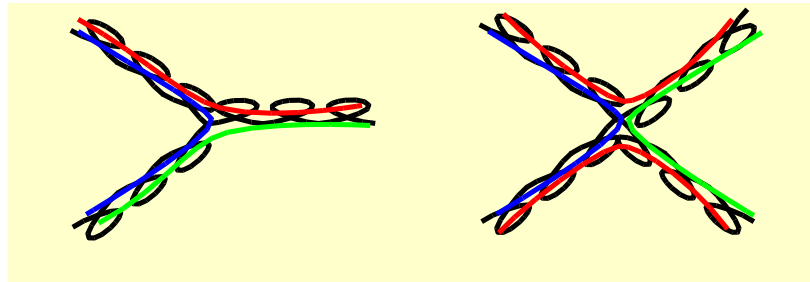
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↘ Gluons carry color charge \longrightarrow **This changes everything...**

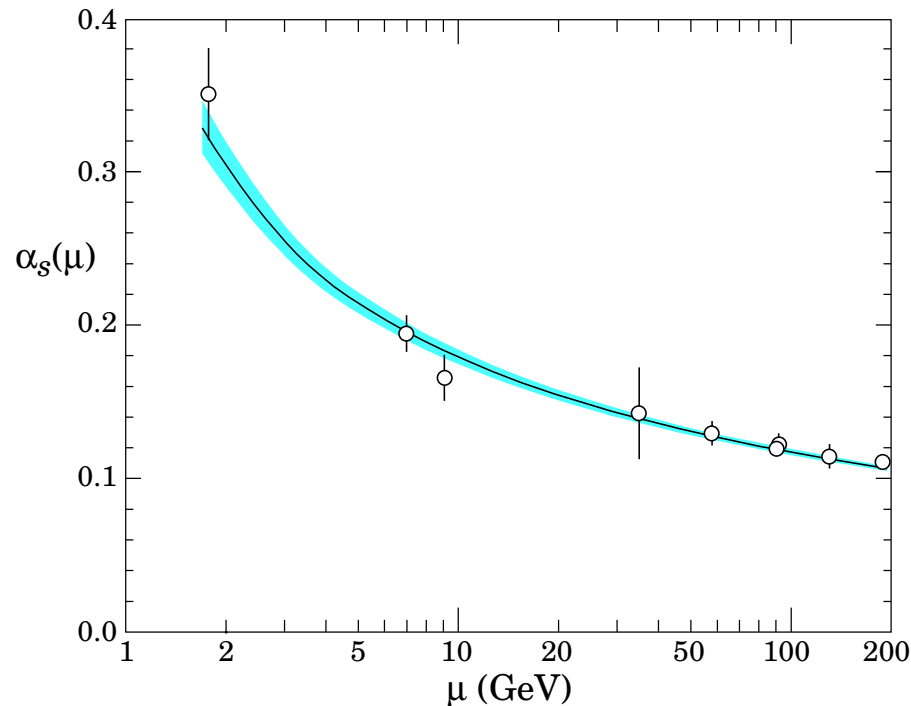
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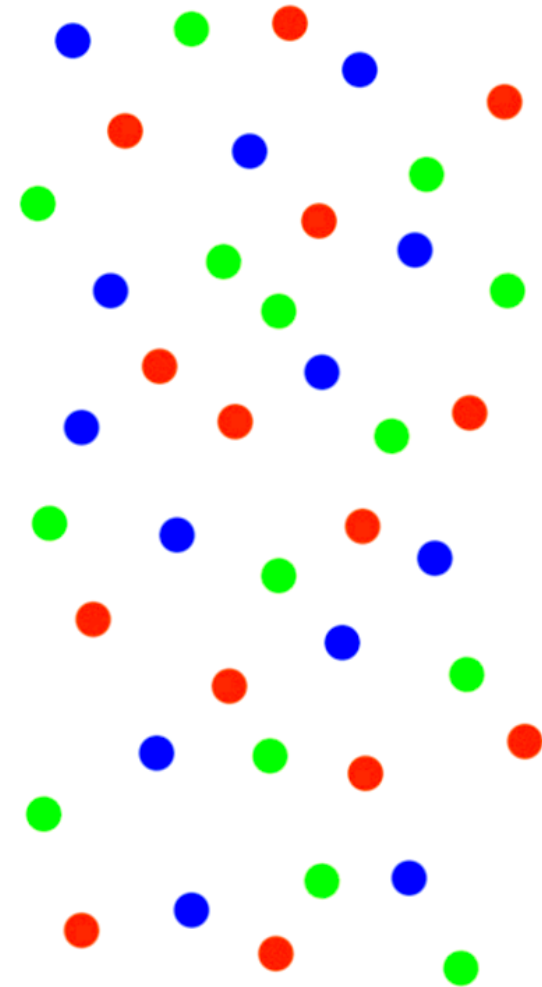
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- ⇒ Strength smaller at smaller distances: **Asymptotic freedom**.



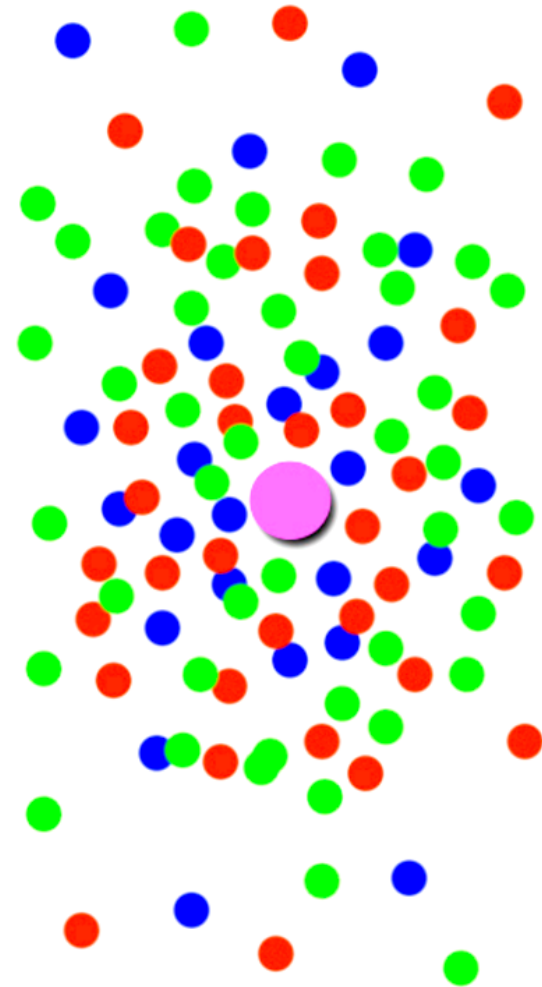
Picture

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(quarks or gluons disturb vacuum).



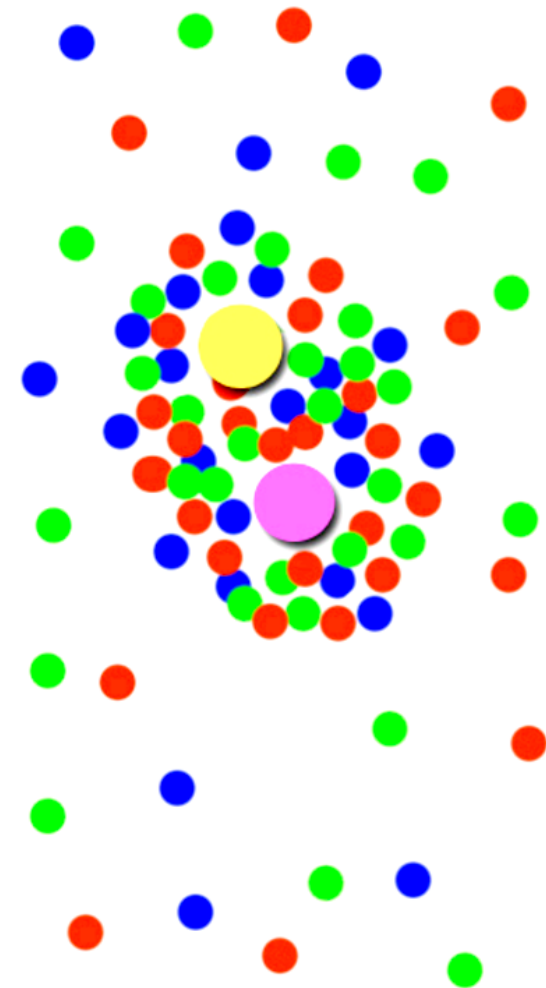
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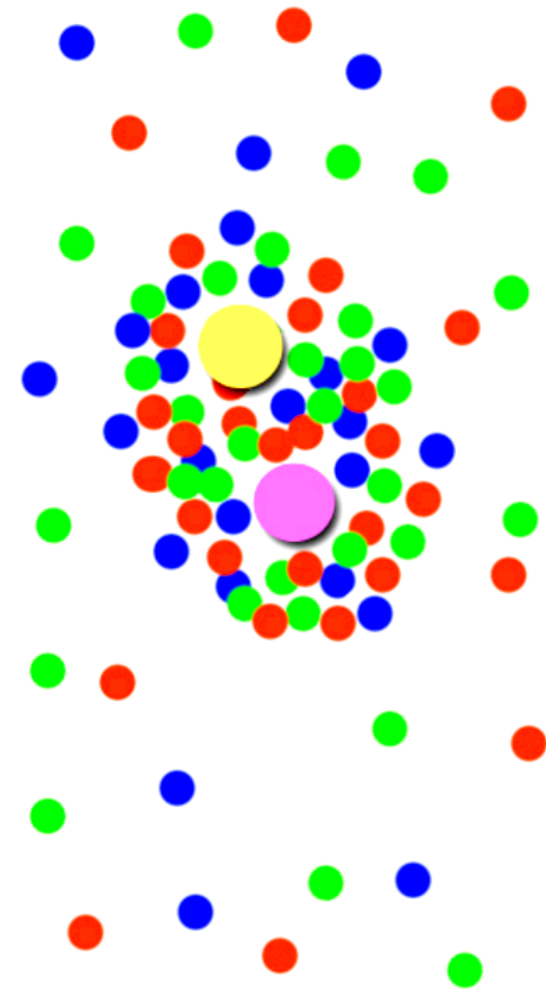
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- ⇒ colorless packages (hadrons) \implies **vacuum excitations.**



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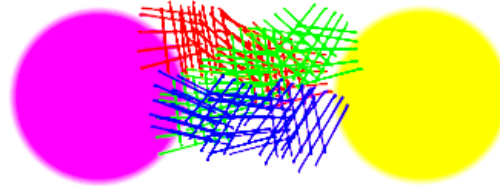
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- ⇒ masses:

	mass (GeV)	$\sum q_m$ (GeV)
p	~ 1	$2m_u + m_d \sim 0.03$
π	~ 0.13	$m_u + m_d \sim 0.02$



String Picture

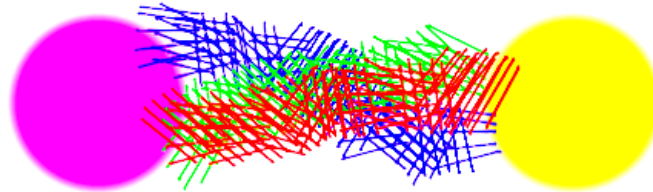
A way of visualizing a meson \longrightarrow a $q\bar{q}$ pair join together by a string



\Rightarrow Colorless object

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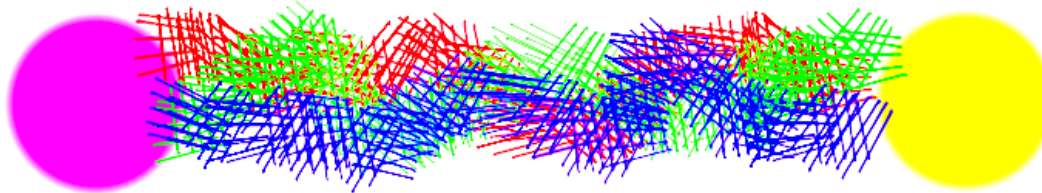
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\Rightarrow In the limit $m_q \rightarrow \infty$ the string cannot break (infinite energy)

Chiral Symmetry

In the absence of quark masses, the QCD Lagrangian splits into **two independent quark sectors**,

$$\mathcal{L}_{\text{QCD}} \equiv \mathcal{L}_{\text{gluons}} + i \bar{q}_L \gamma^\mu D_\mu q_L + i \bar{q}_R \gamma^\mu D_\mu q_R .$$

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- ⇒ However, **this symmetry is not observed.**
Solution: \mathcal{L}_{QCD} is invariant, but the vacuum $|0\rangle$ is not

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⇒ Symmetry breaking

Goldstone's theorem \implies massless bosons associated: **pions**.

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QCD phase diagram

Free quarks?

Asymptotic freedom: quarks and gluons interact weakly

⇒ @ small distances → increase density

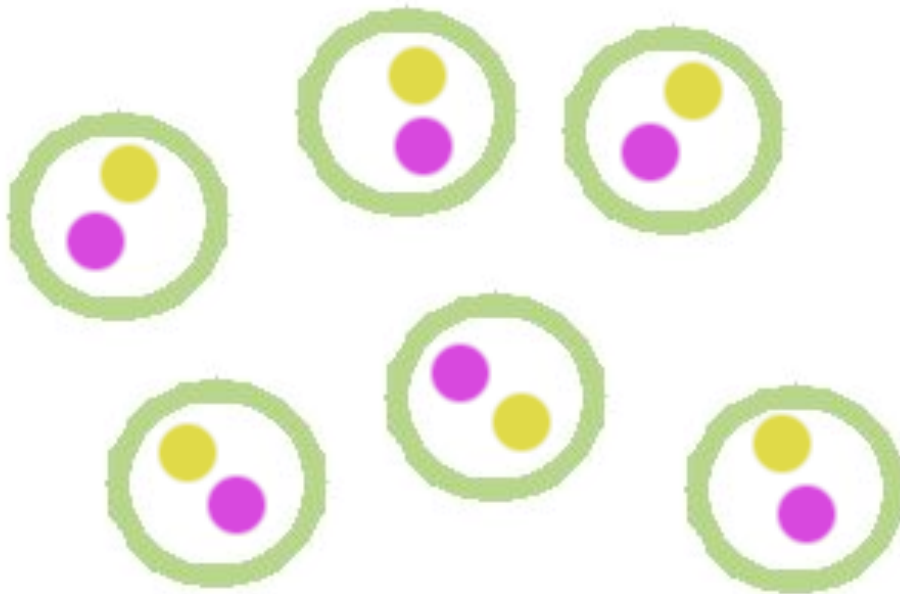
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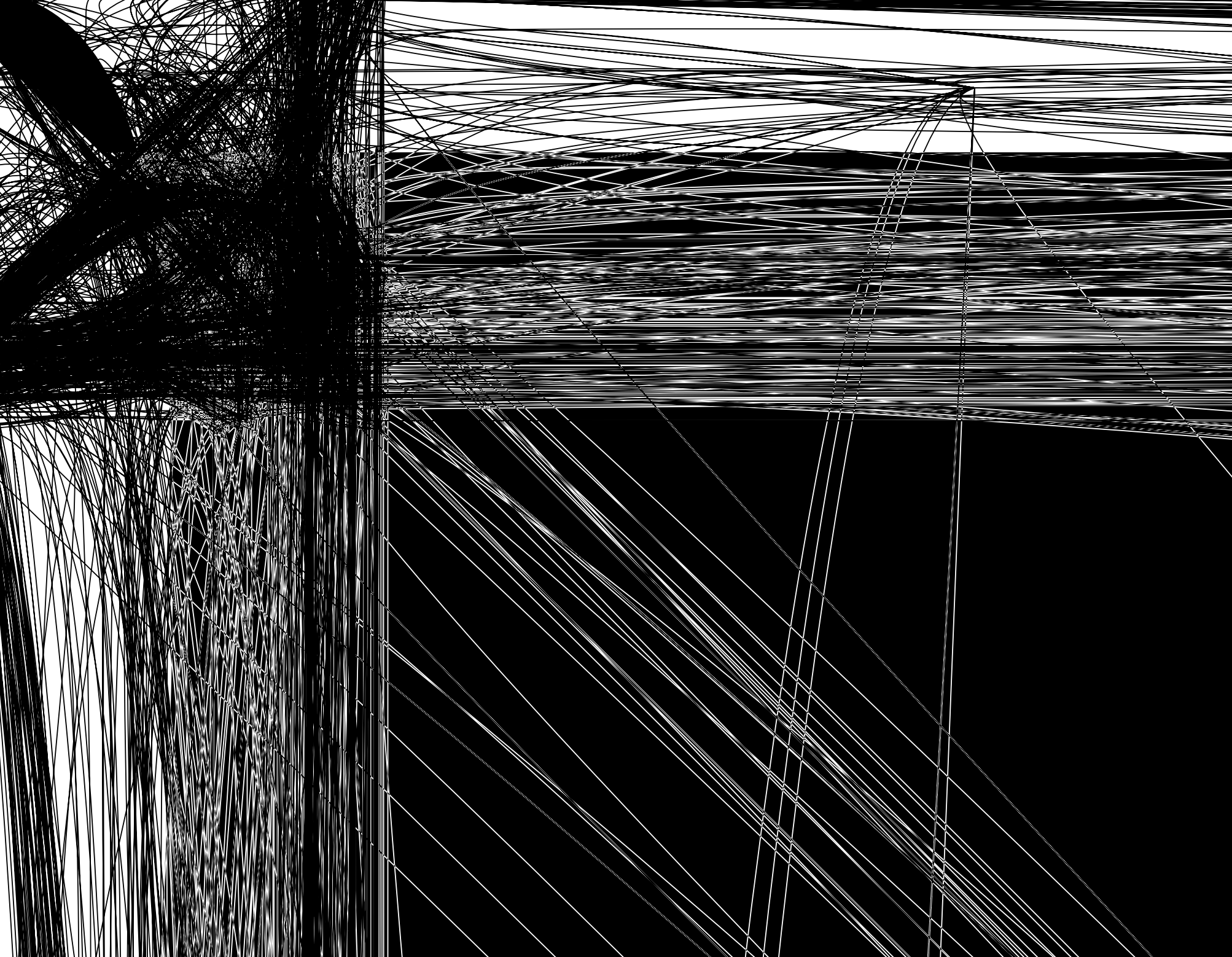
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- ⇒ In experiments of heavy ion collisions



Heavy ions collisions: some history...

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In this model the multiplicity $\langle n \rangle$ is proportional to the entropy. Check that for an isentropic expansion, $\langle n \rangle \sim (\sqrt{s})^{1/2}$. [This is in rough agreement with data]

Comments about hydrodynamical models

- ⇒ The initial conditions are not fixed by the model.
- ⇒ They assume that thermodynamical equilibrium is reached almost instantaneously.
- ⇒ At large densities/temperatures, classical hydrodynamics should work. Present energies could, though, be far from this regime.
- ⇒ Hydrodynamical models, improved for initial conditions, viscosities, etc... are still used nowadays → a lot of phenomenology [pretty good agreement with data.]
- ⇒ Goal: to check the degree of thermalization of the system, measure its temperature, etc...

PbPb collisions @ LHC in Hydro

Evolution of the temperature with time

Simulations by V. Ruuskanen and H. Niemi.

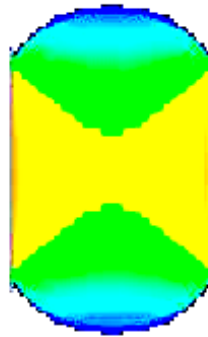


time: 3.0000

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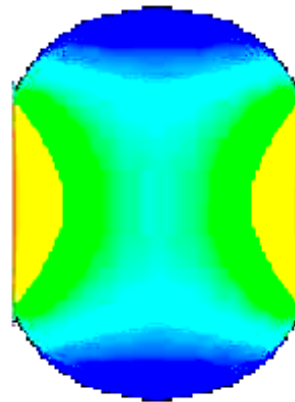


time: 7.0000

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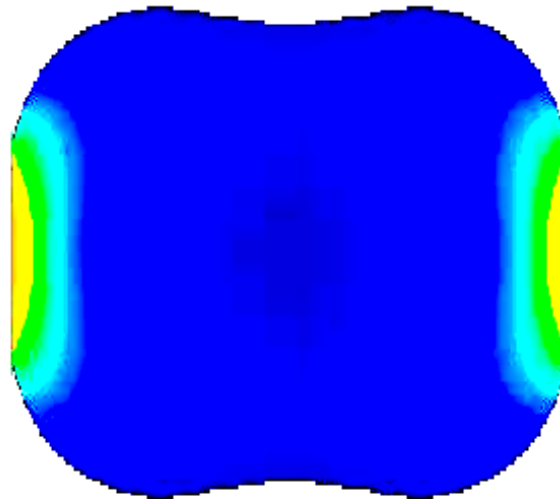
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time: 10.0000

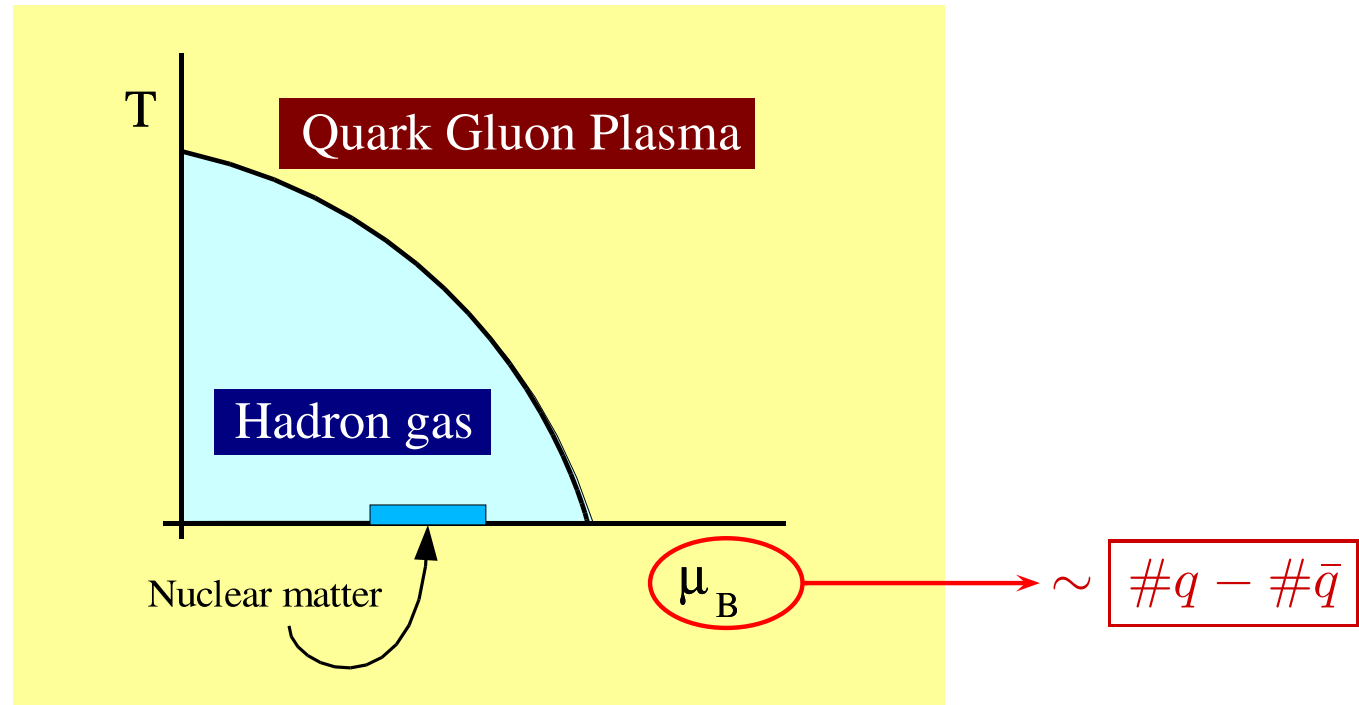
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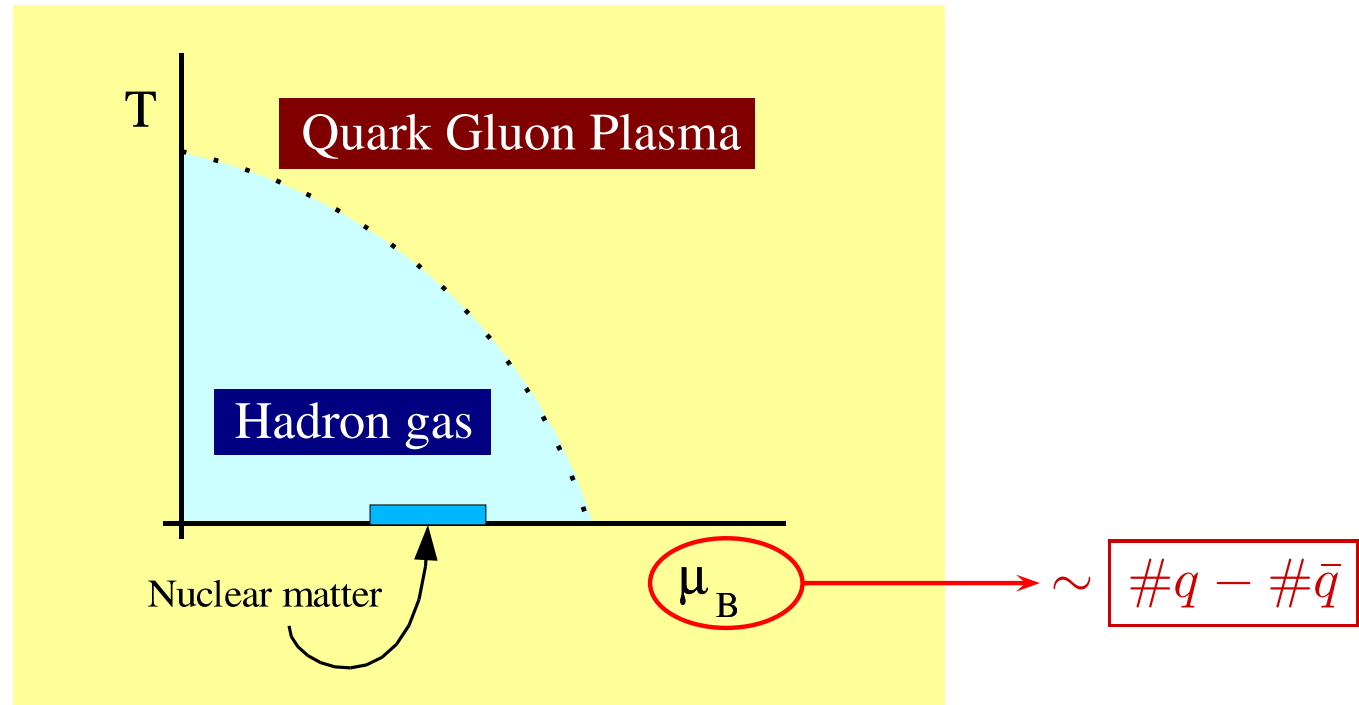
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QCD phase diagram



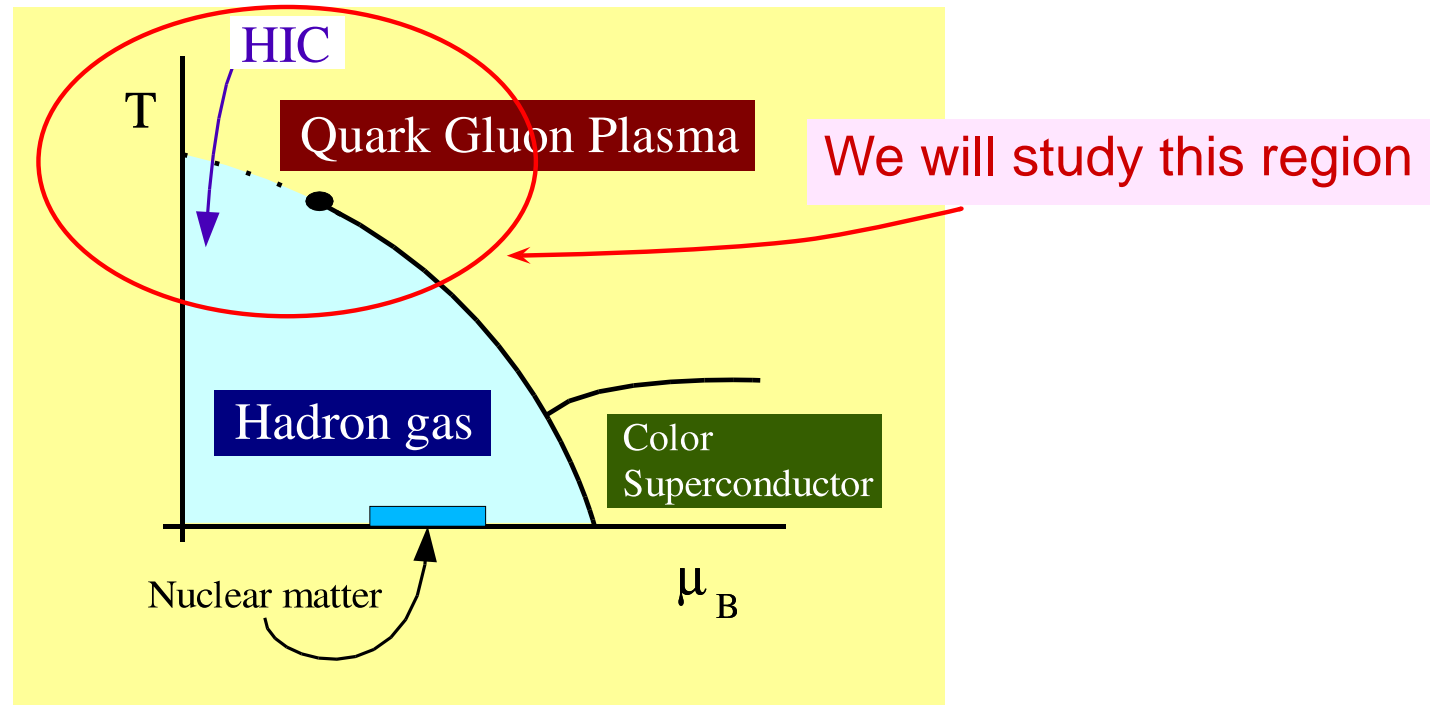
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- ⇒ First lattice calculations found a phase transition between ordinary matter and QGP.
- ⇒ Including quark masses maybe not a real phase transition
- ⇒ Present status: several different phases found recently.

QCD thermodynamics I

⇒ In the grand canonical ensemble, the thermodynamical properties are determined by the (grand) partition function

$$Z(T, V, \mu_i) = \text{Tr} \exp\left\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\right\}$$

where $k_B = 1$, H is the Hamiltonian and N_i and μ_i are conserved number operators and their corresponding chemical potentials.

⇒ The different thermodynamical quantities can be obtained from Z

$$P = T \frac{\partial \ln Z}{\partial V}, \quad S = \frac{\partial(T \ln Z)}{\partial T}, \quad N_i = T \frac{\partial \ln Z}{\partial \mu_i}$$

⇒ Expectation values can be computed as

$$\langle \mathcal{O} \rangle = \frac{\text{Tr} \mathcal{O} \exp\left\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\right\}}{\text{Tr} \exp\left\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\right\}}$$

QCD thermodynamics II

In order to obtain Z for a field theory with Lagrangian \mathcal{L} one normally makes the change $-it = 1/T$, with this, the action

$$iS \equiv i \int dt \mathcal{L} \longrightarrow S = - \int_0^{1/T} d\tau \mathcal{L}_E$$

and the grand canonical partition function can be written (for QCD) as

$$Z(T, V, \mu) = \int \mathcal{D}\bar{\psi} \mathcal{D}\psi \mathcal{D}A^\mu \exp\left\{- \int_0^{1/T} dx_0 \int_V d^3x (\mathcal{L}_E - \mu \mathcal{N})\right\},$$

where $\mathcal{N} \equiv \bar{\psi} \gamma_0 \psi$ is the number density operator associated to the conserved net quark (baryon) number.

Additionally, (anti)periodic boundary conditions in $[0, 1/T]$ are imposed for bosons (fermions)

$$A^\mu(0, \mathbf{x}) = A^\mu(1/T, \mathbf{x}), \quad \psi(0, \mathbf{x}) = -\psi(1/T, \mathbf{x})$$

QCD thermodynamics III

In order to solve these equations

⇒ Perturbative expansion

↗ $\alpha_S(T)$ small for large T → bad convergence, but some results obtained.

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⇒ Lattice QCD

↗ Discretization in $(1/T, V)$ space

↗ Contributions to Z are computed by random configurations of fields in the lattice

↗ Most of the results for $\mu = 0$, results for small μ only recently available.

First example: Equation of State (EoS)

Naïve estimation: Let's fix $\mu = 0$, the pressure of an ideal gas (of massless particles) is proportional to the number of d.o.f: $P \propto NT^4$. So,

$$P_{\pi} \propto 3 \times T^4; \quad P_{QGP} \propto (\underbrace{2 \times 2 \times 3}_{\text{quarks}} + \underbrace{2 \times 8}_{\text{gluons}}) \times T^4$$

So, one expects a **large difference** (factor ~ 10) between the two phases.

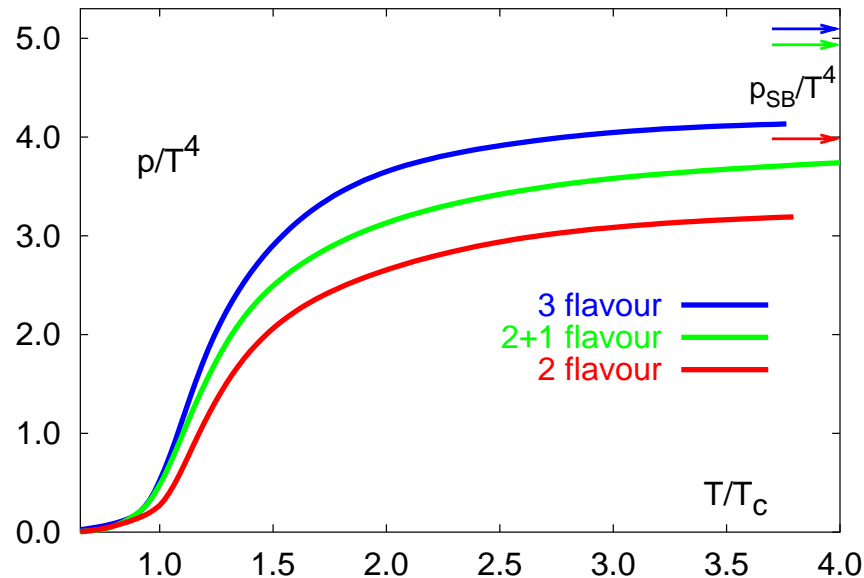
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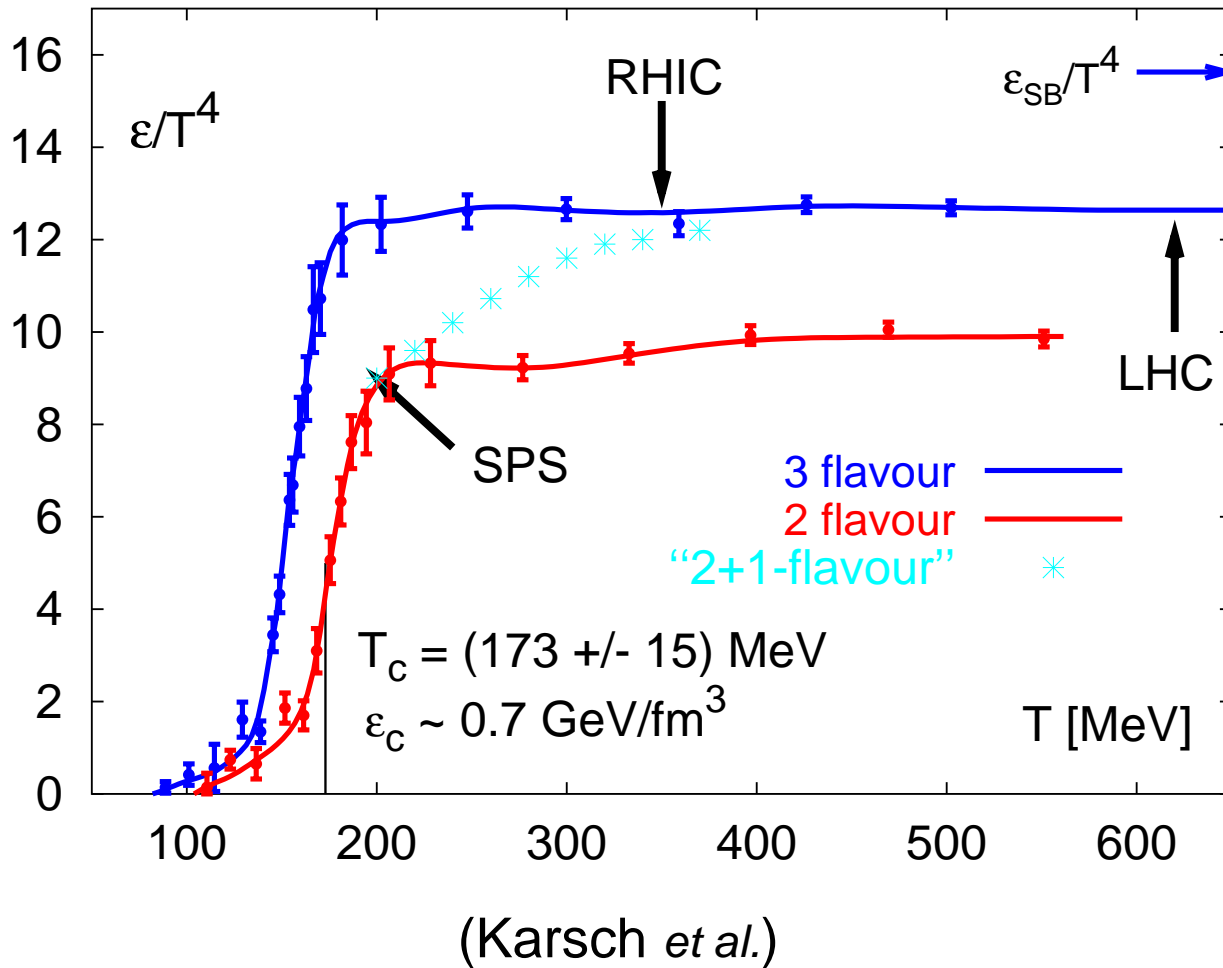
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Lattice results (Karsch *et al.*)



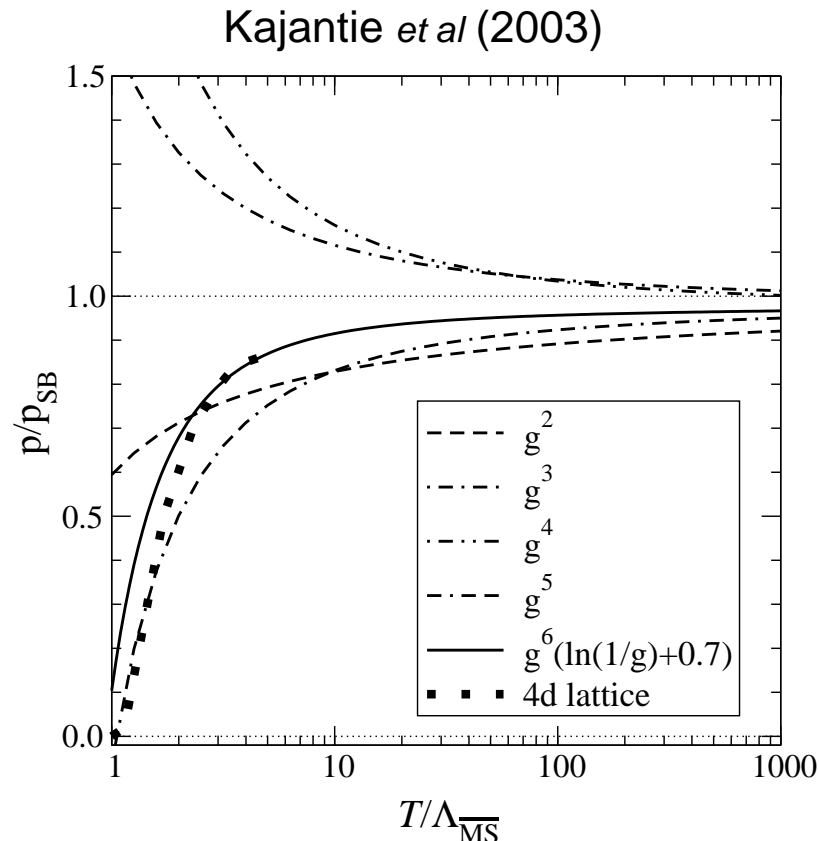
More EoS

In an ideal gas: $\epsilon_{SB} = 3P$



Perturbative calculations

Different orders in perturbation theory for the pressure (normalized to the Stefan-Boltzmann pressure) compared with lattice results.



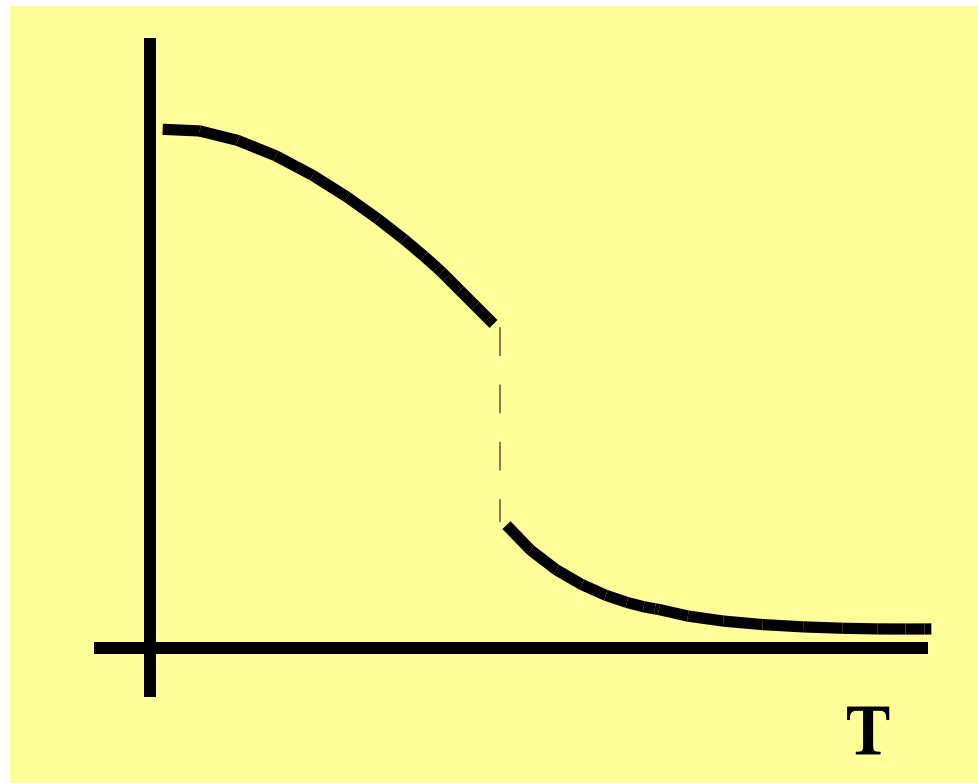
Convergence for very large T , problems for $T \sim T_c$.

Phase transition: order parameters

In order to know if the change from a hadron gas to a QGP is a true phase transition or just a rapid crossover **order parameters are needed.**

Phase transition: order parameters

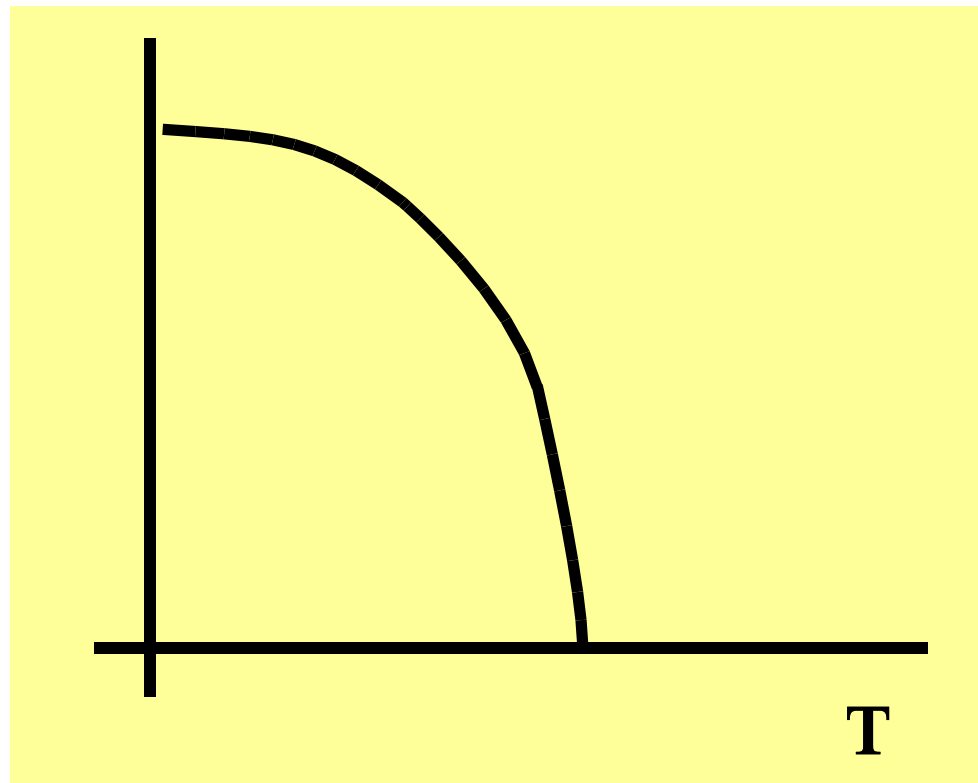
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First order: discontinuity in the order parameter.

Phase transition: order parameters

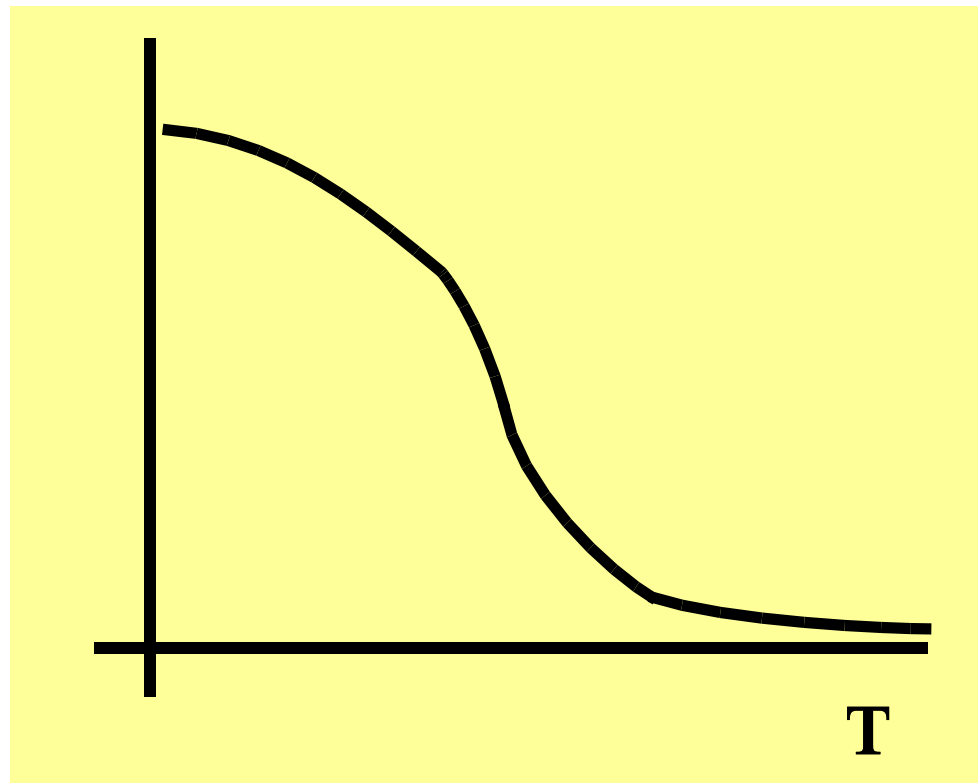
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Second order: discontinuity in the derivative.

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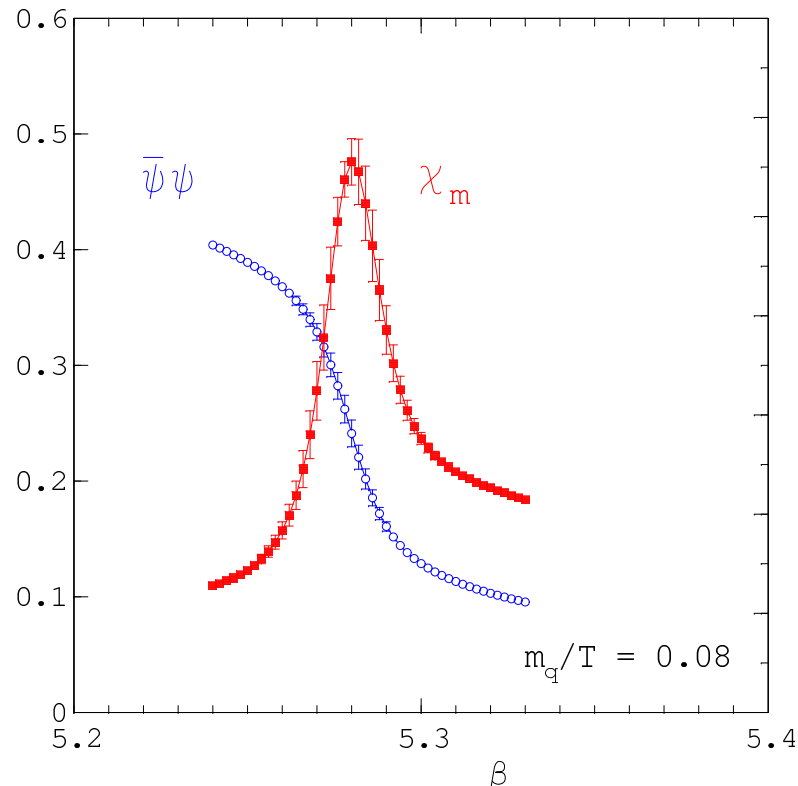
Crossover: Continuous function.

Order parameters in QCD I

[Let us fix $\mu = 0$].

⇒ Chiral symmetry restoration. For $m_q = 0$ the order parameter is the chiral condensate

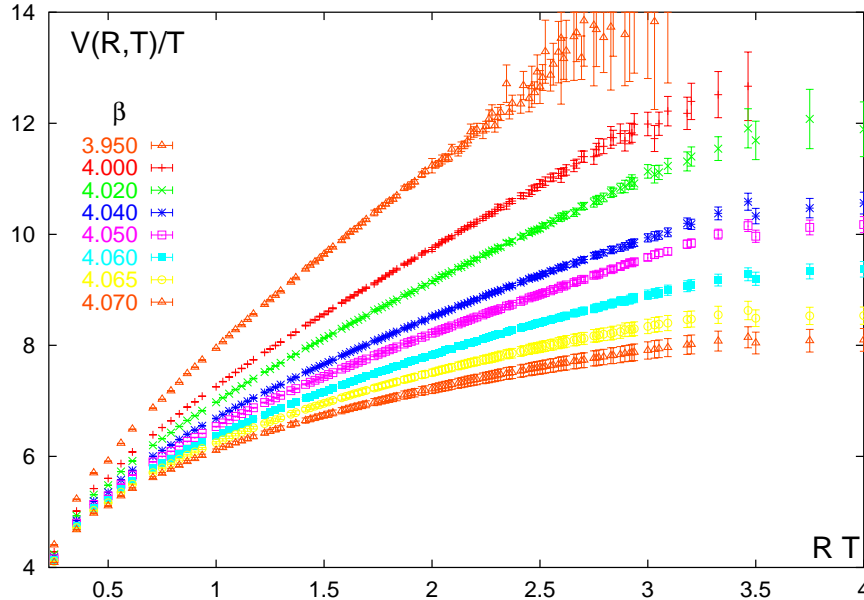
$$\langle 0 | \bar{q}_L q_R | 0 \rangle \neq 0 \quad \xrightarrow{T \rightarrow \infty} \quad \langle 0 | \bar{q}_L q_R | 0 \rangle = 0$$



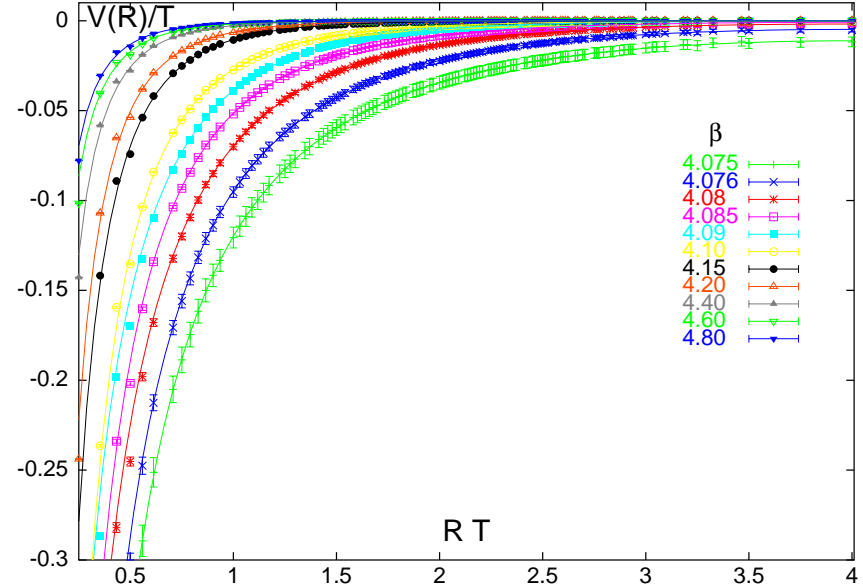
Order parameters in QCD II

⇒ Confinement. For $m_q = \infty$ we have seen that the potential is $V(r) \sim Kr$ for large distances → confinement.

→ Studying the potential → order parameter.



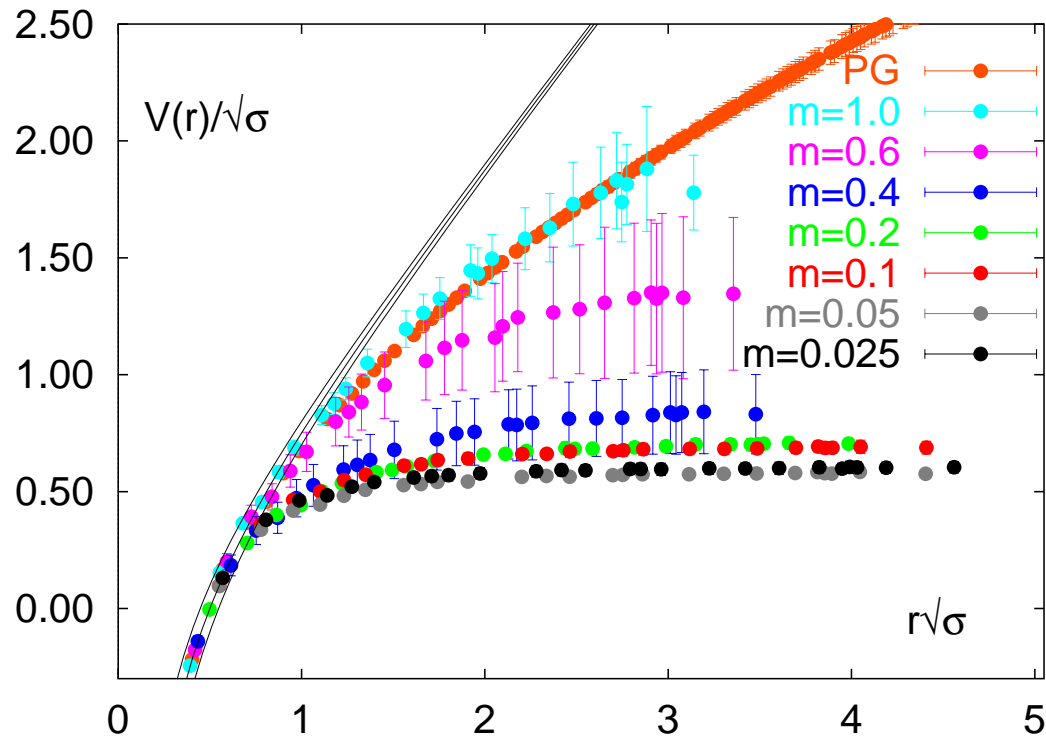
$T < T_c$



$T > T_c$

However...

When masses are taken into account ($m_q < \infty$)



$$T < T_c$$

The potential is screened even below T_c .
[Light $\bar{q}q$ pair creation breaks the string]

Influence of the quark masses ($\mu = 0$)

Two order parameters:

⇒ $m_q = 0 \longrightarrow$ Chiral condensate

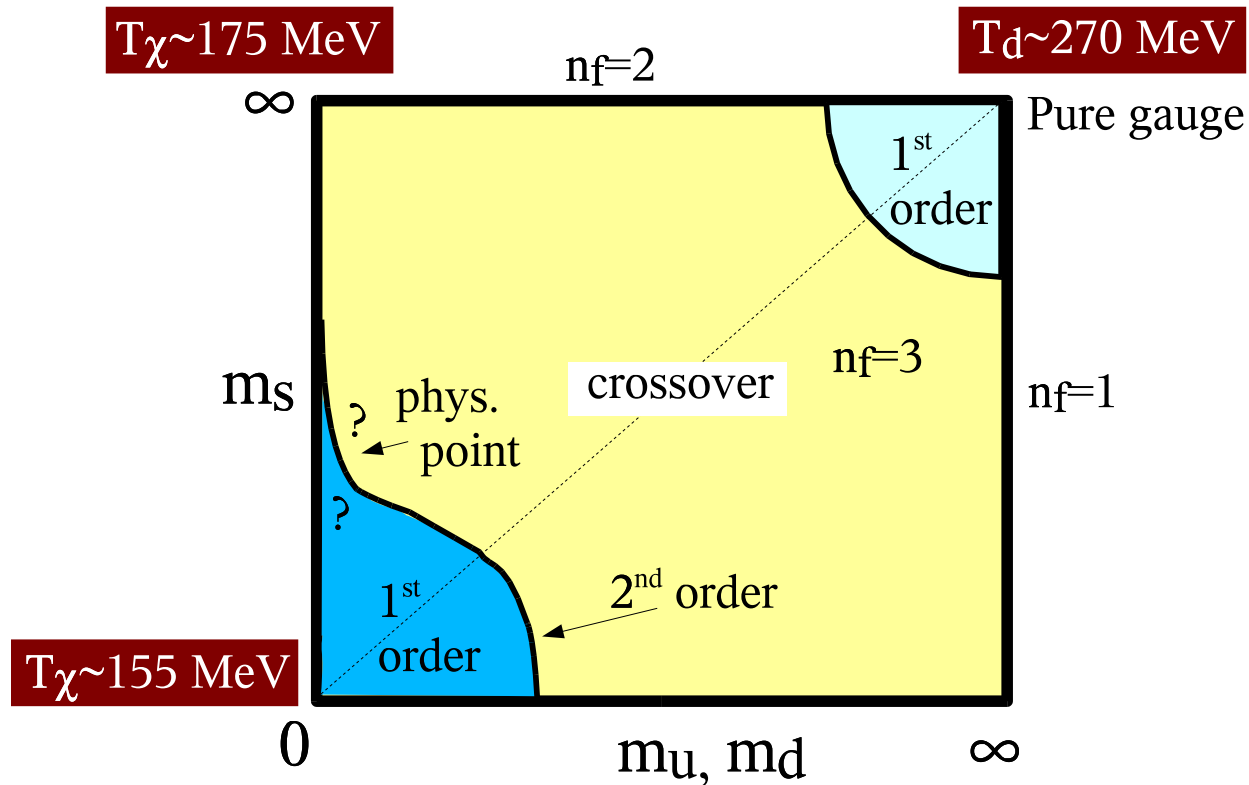
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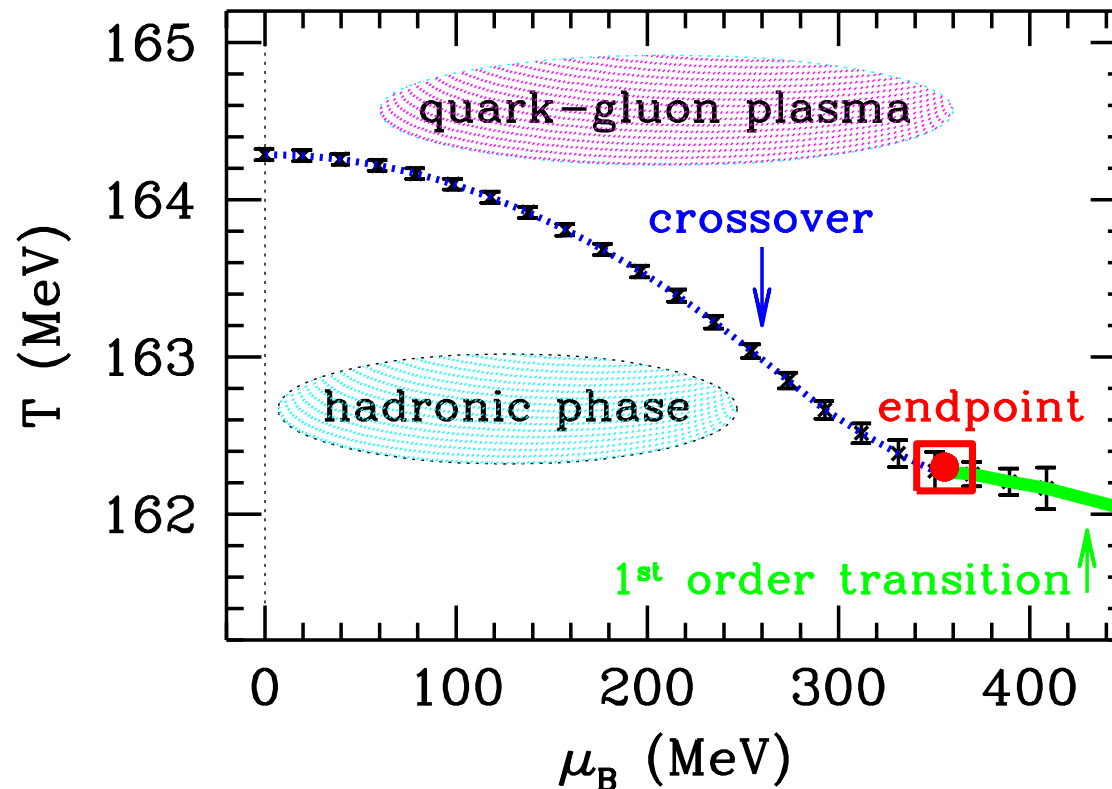


For physical masses, most likely **crossover**.

Finite (small) baryochemical potential

The order of the transition depends on μ .

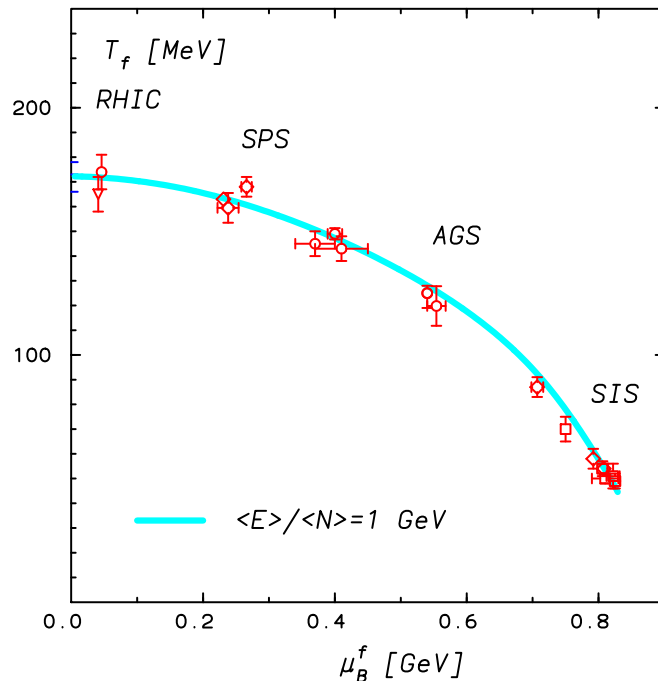
Recent results from Lattice [Fodor *et al* (2004)]



Critical point: crossover/first order phase transition

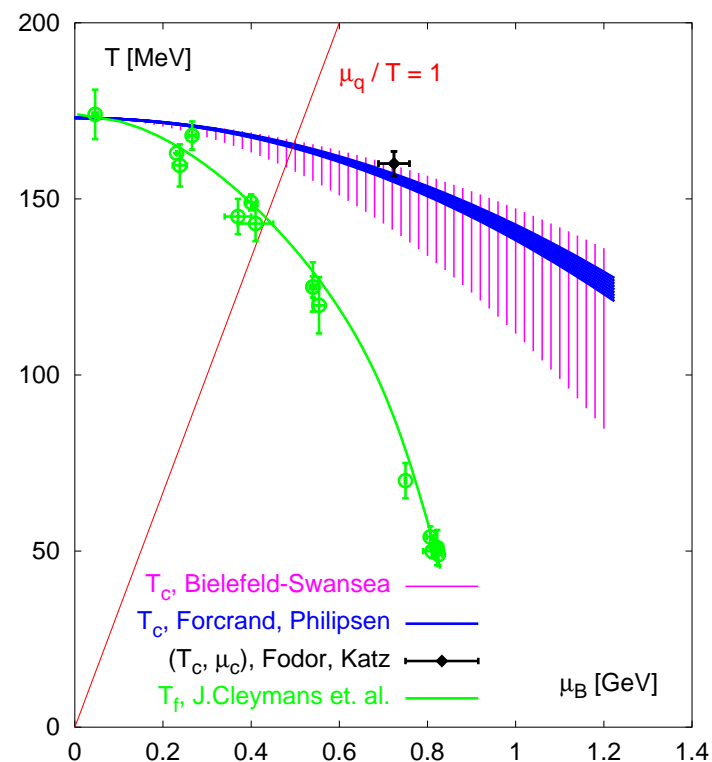
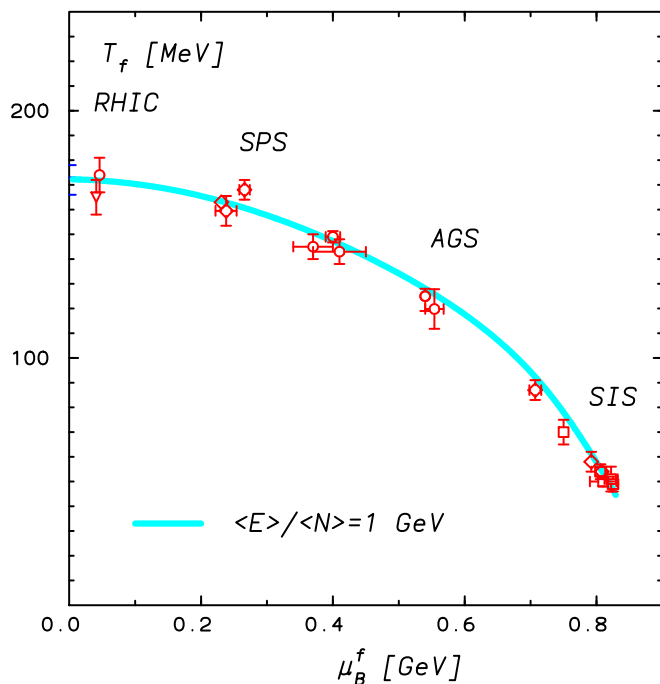
Where are the HIC??

Statistical models (ideas based on ideal gases of hadrons) obtain μ_B and T for the different experiments through particle composition:



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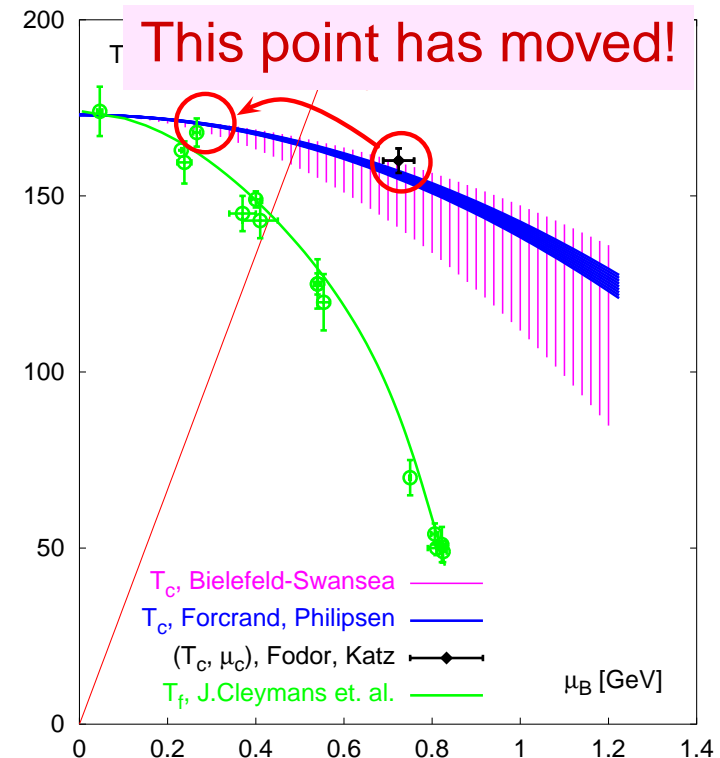
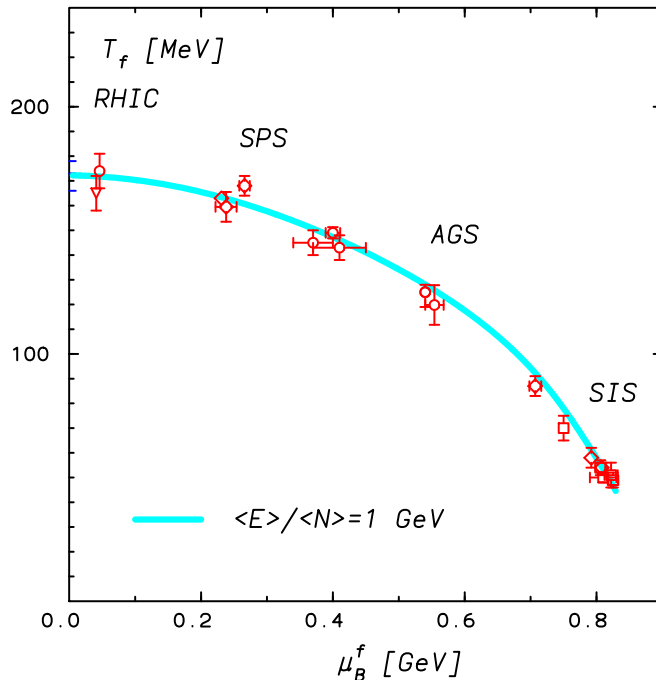
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[Model dependent]

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⇒ Heavy ion collisions experiments attempt to study this region.