Chiral spin symmetry and hot QCD

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T.D.Cohen, L.Ya.G., 2311.07333

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Symmetries of electric and magnetic interactions in electrodynamics

$$\begin{aligned} div\mathbf{E} &= 4\pi\rho \\ rot\mathbf{B} - \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} &= \frac{4\pi}{c}\mathbf{j} \\ rot\mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} &= 0 \\ div\mathbf{B} &= 0 \end{aligned}$$

How do we define **E** and **B** in a given Lorentz frame?

$$\mathbf{F} = q\mathbf{E} + q\frac{\mathbf{v}}{c} \times \mathbf{B}$$

Possible to measure directly **F** in electrodynamics but not possible in quantum chromodynamics. Is there another method to distinguish **E** and **B**? Yes!

Consider charges to be particles with $s = 1/2$. Two states: $\uparrow$ (spin up) and $\downarrow$ (spin down):

$$\begin{pmatrix} \uparrow \\ \downarrow \end{pmatrix}$$

Instead of spin-up and spin-down consider helicities (chiralities for massless particles):

$$R: \ \mathbf{s}\cdot\mathbf{p} > 0$$
$$L: \ \mathbf{s}\cdot\mathbf{p} < 0$$

$$\begin{pmatrix} R \\ L \end{pmatrix}$$

Consider a $SU(2)$ chiral spin transformation that mixes R and L:

$$\begin{pmatrix} R \\ L \end{pmatrix} \rightarrow \begin{pmatrix} R' \\ L' \end{pmatrix} = \exp\left(i\frac{\varepsilon^n \sigma^n}{2}\right)\begin{pmatrix} R \\ L \end{pmatrix}$$

What happens with the charge density ρ?

$$R'^{\dagger}R' + L'^{\dagger}L' = R^{\dagger}R + L^{\dagger}L$$

i.e.

$$\rho' = \rho$$

Charge density is invariant under the chiral spin transformation.

What happens with the current density $\mathbf{j} = \rho \mathbf{v}$?

Upon the chiral spin transformation $\mathbf{v}$ and $\mathbf{j}$ change.

$$\mathbf{F}_E = q\mathbf{E}$$

$$\mathbf{F}_B = \sim \mathbf{j} \times \mathbf{B}$$

Interaction of a charge with the electric field is invariant under the chiral spin transformation, while interaction of a current with the magnetic field is not.

We can distinguish the electric and magnetic fields by the chiral spin symmetry!

The electric part of the EM theory is more symmetric than the magnetic part!

$$\mathcal{L} = \mathcal{L}(\mathbf{E}, \mathbf{B}) - \rho\phi + \mathbf{j} \cdot \mathbf{A} + \textit{matter part}$$

Symmetries of quantum chromodynamics

The chromoelectric field is defined via interaction with the color charge

$$\mathbf{F} = Q^a \mathbf{E}^a; \qquad Q^a = \int d^3x \; q^\dagger(x) T^a q(x), \qquad a = 1, ..., 8$$

It is invariant under $SU(2)_{CS}$.

$q \to q' = \exp\left(i \frac{\varepsilon^n \Sigma^n}{2}\right) q, \qquad \Sigma = \{\gamma_k, -i\gamma_5\gamma_k, \gamma_5\}$

In a given Lorentz frame interaction of quarks with the electric part of the gluonic field is chiral spin invariant like in electrodynamics.

$SU(2)_{CS} \times SU(N_F) \subset SU(2N_F)$; $SU(2N_F)$ is also a symmetry of the color charge.

The color charge and electric part of the theory have a $SU(2N_F)$ symmetry that is larger than the chiral symmetry of QCD as a whole.

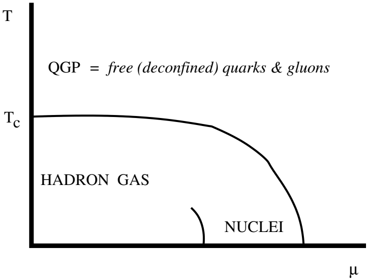
The fundamental vector of $SU(2N_F)$ at $N_F = 2$

$$\Psi = \begin{pmatrix} u_{\rm R} \\ u_{\rm L} \\ d_{\rm R} \\ d_{\rm L} \end{pmatrix}.$$

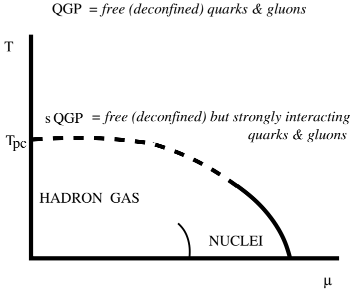
L.Ya.G., EPJA, 2015; L.Ya.G., M.Pak,PRD, 2015

Hot QCD. Before and after RHIC

What happens with hadrons in the medium upon increasing T?



BEFORE RHIC



AFTER RHIC

The chiral restoration crossover is observed at $T = 120 - 180$ MeV with the pseudocritical temperature at $T_{ch} \sim 155$ MeV.

We need objective information about degrees of freedom. Can be obtained in computer simulations on the lattice.

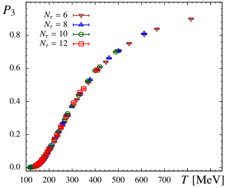


Figure: P. Petreczky and H.-P. Schadler, 2015.

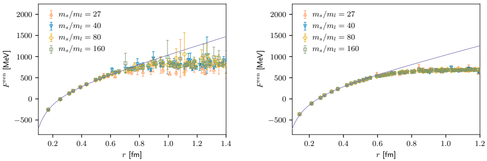


Figure: Left: $T = 141$ MeV; right: $T = 166$ MeV.
D. A. Clarke, O. Kaczmarek, F. Karsch, A. Lahiri, 2019.

There is no evidence that above T_{ch} QCD is in deconfined regime!

Correlation functions

The most detailed information about QCD is encoded in correlation functions

$$C_\Gamma(t,x,y,z) = \langle O_\Gamma(t,x,y,z)\, O_\Gamma(0,\mathbf{0})^\dagger \rangle \ .$$

They carry the full spectral information $\rho_\Gamma(\omega,\mathbf{p})$

$$C_\Gamma(t,\mathbf{p}) = \int_0^\infty \frac{d\omega}{2\pi}\, K(t,\omega)\rho_\Gamma(\omega,\mathbf{p}), \quad K(t,\omega) = \frac{\cosh(\omega(t-1/2T))}{\sinh(\omega/2T)} \ .$$

The spatial and temporal correlators are defined as

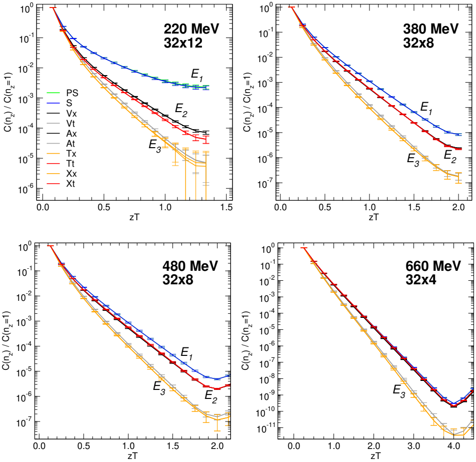
$$C_\Gamma^s(z) = \sum_{x,y,t} C_\Gamma(t,x,y,z) \ ,$$

$$C_\Gamma^t(t) = \sum_{x,y,z} C_\Gamma(t,x,y,z) \ .$$

Spatial correlators above T_{ch}

C. Rohrhofer, Y. Aoki, G. Cossu, H. Fukaya, C. Gattringer, L.Ya.G., S. Hashimoto, C.B. Lang, S. Prelovsek , 2017 - 2019

$N_f = 2$ QCD with the chirally symmetric Dirac operator.



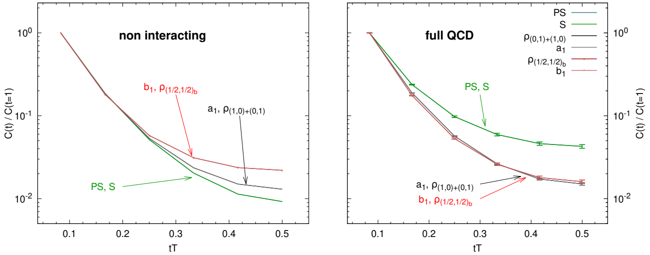
$E1$ - $U(1)_A$ symmetry; $E2$ - chiral spin and $SU(4)$ symmetries; $E3$ consistent with both chiral symmetry and chiral spin ($SU(4)$) symmetry.

$SU(2)_{CS}$ and $SU(4)$ symmetries persist up to $T \sim 500$ MeV.

Temporal correlators above T_{ch}

C. Rohrhofer, Y. Aoki, L.Ya.G., S. Hashimoto, 2020

$N_F = 2$ QCD at $T = 220$ MeV

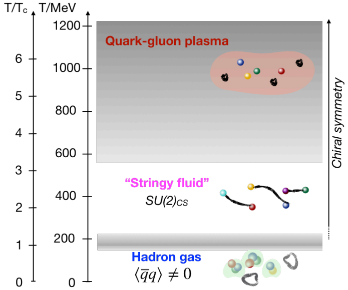


Free quarks: $SU(2)_L \times SU(2)_R$ and $U(1)_A$ multiplets.

Full QCD at $T = 220$ MeV: $U(1)_A$, $SU(2)_L \times SU(2)_R$, $SU(2)_{CS}$ and $SU(2N_F)$ multiplets.

Above T_{ch} QCD is approximately $SU(2)_{CS}$ and $SU(4)$ symmetric.

Three regimes of QCD



$0 - T_{ch}$ - Hadron Gas (broken chiral symmetry);

$T_{ch} - 3T_{ch}$ - Stringy Fluid (chiral, $SU(2)_{CS}$ and $SU(4)$ symmetries; electric confinement)

Stringy fluid is mostly populated with $J = 0, 1$ states. It is a densely packed system of "mesons" that interact strongly. Quark interchanges between "mesons" are significant.

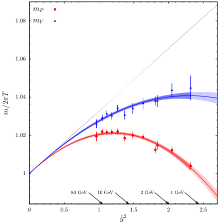
$T > 3T_{ch}$ - a smooth approach to QGP (chiral symmetry)

Screening masses and stringy fluid. L.Ya.G., O. Philipsen, R. Pisarski, 2022

$$e^{pV/T} = Z = \mathrm{Tr}(e^{-aHN_\tau}) = \mathrm{Tr}(e^{-aH_z N_z}) = \sum_{n_z} e^{-E_{n_z} N_z} ,$$

QGP - (quasi)parton dynamics drives observables.

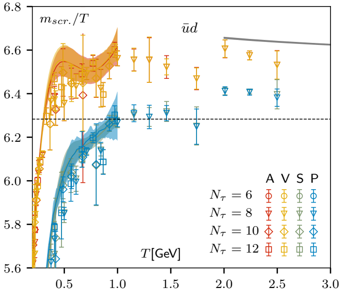
Lattice at $T \sim 1$ - 160 GeV (M.D. Brida et al, 2022) :

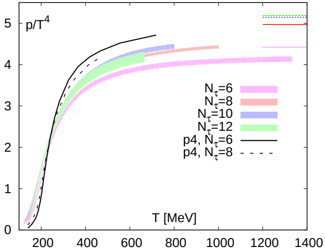


$$\frac{m_{PS}}{2\pi T} = 1 + p_2\, \hat{g}^2(T) + p_3\, \hat{g}^3(T) + p_4\, \hat{g}^4(T) ,$$

$$\frac{m_V}{2\pi T} = \frac{m_{PS}}{2\pi T} + s_4\, \hat{g}^4(T) ,$$

From A. Bazavov et al, 2018,2019:

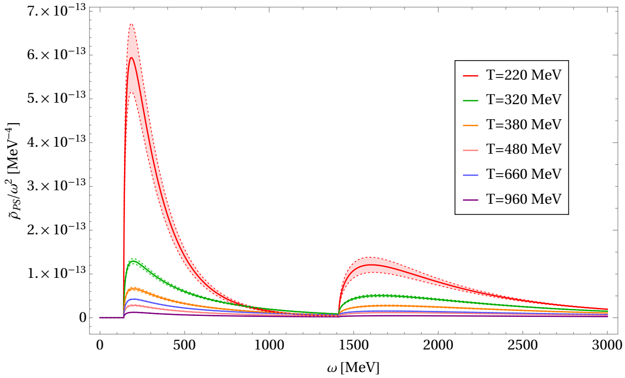




An independent demonstration of the existence of a temperature window $T_{ch} < T < 3T_{ch}$, in which chiral symmetry is restored but the dynamics is inconsistent with a (quasi)partonic description.

π spectral function

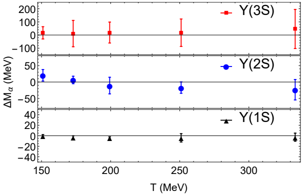
From spatial correlators via generalised Lehmann representation to spectral functions; P. Lowdon and O. Philipsen, 2022

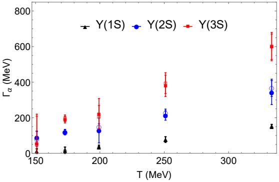


Existence of a pion state and its first radial excitations above T_{ch}. A clear demonstration that above T_{ch} the degrees of freedom are hadron-like.

Bottomonium above T_{ch}. R. Larsen et al, 2020

Mass shifts with respect to zero temperature and widths:



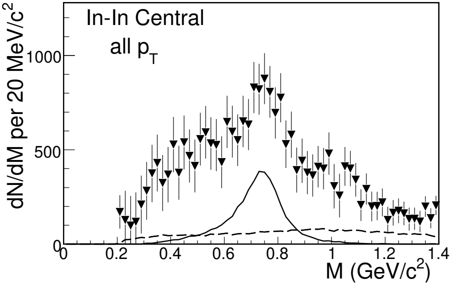


A clear demonstration that above T_{ch} the degrees of freedom are hadron-like.

15. ρ IS SEEN ABOVE T_{ch}

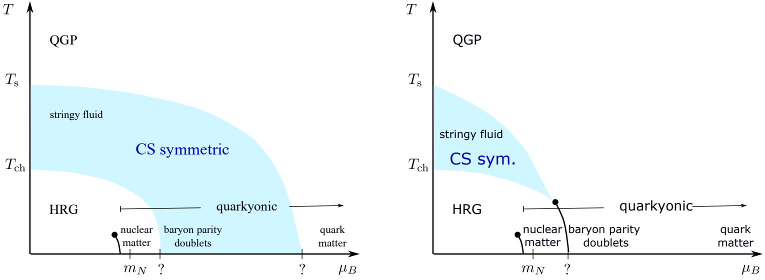
CERN SPS: R. Arnaldi et al, PRL 96 (2006) 162302

We report on a precision measurement of low-mass muon pairs in 158 AGeV indium-indium collisions at the CERN SPS. A significant excess of pairs is observed above the yield expected from neutral meson decays. The unprecedented sample size of 360000 dimuons and the good mass resolution of about 2% allow us to isolate the excess by subtraction of the decay sources. The shape of the resulting mass spectrum is consistent with a dominant contribution from $\pi+\pi- \rightarrow \rho \rightarrow \mu+\mu-$ annihilation. The associated space time averaged ρ spectral function shows a strong broadening, but essentially no shift in mass. This may rule out theoretical models linking hadron masses directly to the chiral condensate.

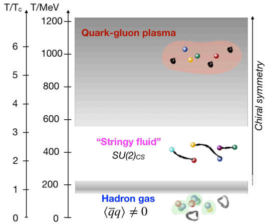


Independent T measurement by the black-body radiation: $T = 205 \pm 12$ MeV

Chiral spin symmetric band. L.Ya.G., O. Philipsen, R. Pisarski, 2022



Large Nc QCD phase diagram. T.D. Cohen, L.Ya.G., 2311.07333



In combined large N_c and chiral limit three regimes connected by smooth crossovers might become distinct phases separated by phase transitions:

$$\epsilon_{\rm HG} \sim N_c^0 \ , \ \ P_{\rm HG} \sim N_c^0 \ , \ s_{\rm HG} \sim N_c^0 \ ,$$

$$\epsilon_{\rm str} \sim N_c^1 \ , \ \ P_{\rm str} \sim N_c^1 \ , \ s_{\rm str} \sim N_c^1 \ .$$

$$\epsilon_{\rm QGP} \sim N_c^2 \ , \ \ P_{\rm QGP} \sim N_c^2 \ , \ s_{\rm QGP} \sim N_c^2 \ .$$

$T_{ch} \sim 130$ MeV; $T_d \sim 300$ MeV