Hadrons in the Extreme QCD Matter

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Space-like and time-like electromagnetic baryonic excitations

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Why hadrons in QCD matter?

Mass without mass

- massless gauge theories are
  - scale invariant: \( \mathcal{L}(\Lambda x) = \mathcal{L}(x) \)
  - chirally symmetric:
    \[
    U(N)_L \times U(N)_R \sim SU(N)_V \times SU(N)_A \times U(1)_B \times U(1)_A
    \]

- both symmetries are broken
  - scale invariance broken by quantum effects \( \rightarrow \Lambda_{\text{QCD}} \)
  - \( \chi_{\text{sym}} \) broken by the Golstone mechanism \( \rightarrow \langle \bar{q}q \rangle \neq 0 \)
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Mass of the nucleon

$$M_N = \langle N | \frac{\beta g}{2g} G^a_{\mu \nu} G_a^{\mu \nu} + m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s | N \rangle / 2M_N = m_0 + \Sigma$$
Why hadrons in QCD matter?

QCD Matter

\[ T \]

\[ \mu_B \]

- Quark Gluon Plasma
- Hadron Gas
- ~155 MeV
- CEP

Nuclei
Why hadrons in QCD matter?

QCD Matter

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Why hadrons in QCD matter?

**QCD Matter**

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Why hadrons in QCD matter?

- broken symmetries get restored in the medium
- what are the mechanisms for hadronization?
- doubling of parity partners?
Why hadrons in QCD matter?

QCD Matter

► symmetries get restored in the medium
► mechanisms for hadronization
► doubling of parity partners?
Heavy-ion collisions and photons

as compared to the size of the fireball photons have a long mean free path

→ leave the interaction zone undisturbed

E. Feinberg 1976, E. Shuryak 1978
e^+e^- - annihilation in the vacuum

\[ R = \frac{\sigma(e^+e^- \rightarrow \text{Hadronen})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

Invariante Masse (GeV)

Daten
u, d, s Quarks
\( \omega/\rho \)
\( \phi \)
Vector-meson selfenergies (HMT)

\[ D_{\nu}^{\mu} = (M^2 - m_V^2 - \Sigma^L_V(\omega, q))^{-1} P_L^{\mu\nu} + (M^2 - m_V^2 - \Sigma^T_V(\omega, q))^{-1} P_T^{\mu\nu} \]

\( \rho \)-meson selfenergy:

\[ \Sigma^{L/T}_\rho = \Sigma^{L/T}_{\rho \pi \pi} + \Sigma^{L/T}_{\rho M} + \Sigma^{L/T}_{\rho B} \]

vertex corrections from dressed pions:
Dilepton data HADES and NA60

Ar+KCl $\sqrt{s_{NN}}=2.61$ GeV
0~34%

1/2(n+pp), $\eta$ subtrahiert

In+In $\sqrt{s_{NN}}=17.2$ GeV

$T_i = 235$ MeV
$T_c = 170$ MeV

1/2(n+pp), $\eta$ subtrahiert

1/N^2 dN_{cor}/dM_{ee} (GeV/c^2)^{-1}

Dimuon invariante Masse $M_{\mu\mu}$ (GeV/c^2)

Dimuonausbeute dN/dM_{\mu\mu} (20 MeV)^{-1}
Functional Renormalization Group

partition function: (scalar field \( \phi(x) \))

\[
Z[j] = e^{W[j]} = \int [\mathcal{D}\phi] \ e^{-S[\phi] + \int d^4 x \ \phi(x)j(x)}
\]

effective action: (Legendre transform of \( W \))

\[
\Gamma[\varphi] = -W[j] + \int d^4 x \ \varphi(x)j(x); \quad \varphi(x) \equiv \langle \phi(x) \rangle
\]

stationarity condition and thermodynamic potential:

\[
\frac{\delta \Gamma[\varphi]}{\delta \varphi} \bigg|_{\varphi=\varphi_0} = 0; \quad \rightarrow \quad \Omega(T; \mu_i) = \frac{T}{V} \Gamma[\varphi_0]
\]

Wilsonian coarse graining:

\[
\phi(x) = \phi_{q \leq k}(x) + \phi_{q > k}(x)
\]

\[
\rightarrow \quad Z[j] = \int [\mathcal{D}\phi_{q \leq k}] \int [\mathcal{D}\phi_{q > k}] \ e^{-S[\phi] + \int d^4 x \ \phi j} ; \quad \lim_{k \to 0} Z_k[j] = Z[j]
\]

= \[Z_k[j]\]
Functional Renormalization Group

**Flow equation** for $\Gamma_k$ including bosons and fermions:

$$\partial_k \Gamma_k = \text{Tr} \int_q \left( \frac{1}{2} G_{\varphi,k}(q) R_{\varphi,k}(q) - G_{\psi,k}(q) R_{\psi,k}(q) \right)$$

$$G_{\varphi,k}(q) = \left[ \Gamma_k^{(2)}[\varphi] + R_{\varphi,k}(q) \right]^{-1}$$

$$G_{\psi,k}(q) = \left[ \Gamma_k^{(2)}[\psi] + R_{\psi,k}(q) \right]^{-1}$$

$$\Gamma_k^{(2)}[\varphi] = \frac{\delta^2 \Gamma_k[\varphi]}{\delta \varphi^2}; \quad \Gamma_k^{(2)}[\psi] = \frac{\delta^2 \Gamma_k[\varphi]}{\delta \psi \delta \bar{\psi}}$$

$$\partial_k \Gamma_k = \frac{1}{2} \left( \begin{array}{c} R_k^1 \\ \vdots \\ R_k^4 \end{array} \right)$$
Momentum flow of the effective action
Flow of the $\sigma$ and $\pi$ spectral functions in vacuum
Phase diagram of the Quark-Meson Model

- chiral order parameter $\sigma_0$ decreases towards higher $T$ and $\mu$
- a crossover is observed at $T \approx 175$ MeV and $\mu = 0$
- critical endpoint (CEP) at $\mu \approx 292$ MeV and $T \approx 10$ MeV
- vacuum: $\sigma_0 = 93.5$ MeV, $m_\pi = 138$ MeV, $m_\sigma = 509$ MeV, $m_q = 299$ MeV
\( \sigma \text{- and } \pi \text{ spectral function for finite } T \text{ at } \mu = 0 \)
$\sigma$ spectral function with increasing $T$ at $\mu = 0$
$\pi$ spectral function with increasing $T$ at $\mu = 0$