Medium Modifications of Hadrons and Electromagnetic Probes

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Outline

QCD and Chiral Symmetry

Electromagnetic Probes

Challenges for experiment (and theory)
QCD and ("accidental") Symmetries

- Theory for strong interactions: QCD

\[ \mathcal{L}_{\text{QCD}} = -\frac{1}{4} F_{\mu\nu}^a F_{\mu\nu}^a + \bar{\psi}(i\gamma^\mu - \hat{M})\psi \]

- Particle content:
  - \( \psi \): Quarks, including flavor- and color degrees of freedom,
    \( \hat{M} = \text{diag}(m_u, m_d, m_s, \ldots) = \text{current quark masses} \)
  - \( A_\mu^a \): gluons, gauge bosons of SU(3)\text{color}
QCD and ("accidental") Symmetries

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- Symmetries
  - fundamental building block: local SU(3)_{color} symmetry
  - in light-quark sector: approximate chiral symmetry
  - chiral symmetry most important connection between QCD and effective hadronic models
Phenomenology from Chiral Symmetry

- In vacuum: Spontaneous breaking of chiral symmetry
- $\Rightarrow$ mass splitting of chiral partners

$\bar{q}q$-excitations of the QCD vacuum

- $\pi$ (140)
- $f_0$ (400-1200)
- $\rho$ (770)
- $\omega$ (782)
- $f_1$ (1285)
- $f_1$ (1420)
- $a_1$ (1260)

$P$-$S$, $V$-$A$ splitting in the physical vacuum

Graph showing $\text{Re} \Pi_{V,A}(\pi s)$ as a function of $s$ [GeV$^2$].

- $V$ [$\tau \rightarrow 2n\pi \nu_\tau$]
- $A$ [$\tau \rightarrow (2n+1)\pi \nu_\tau$]
- $\rho$ (770) + cont.
- $a_1$ (1260) + cont.
Phenomenology from Chiral Symmetry

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- ⇒ mass splitting of chiral partners

\[ \text{qq-excitations of the QCD vacuum} \]

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- \( a_1(1260) \)
- \( f_1(1285) \)
- \( f_1(1420) \)
- \( \phi (1020) \)

- **P-S, V-A splitting in the physical vacuum**

- **at high temperature/density**: restoration of chiral symmetry

- Lattice QCD: \( T^X_C \sim T^{\text{deconf}}_C \)
Finite Temperature/Density: Idealized Theory Picture

- **partition sum**: \( Z(V, T, \mu_q, \Phi) = \text{Tr}\{\exp[-(H[\Phi] - \mu_q N)/T]\} \)
Finite Temperature/Density: Idealized Theory Picture

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- partition sum: \( Z(V, T, \mu_q, \Phi) = \text{Tr}\{\exp[-(H[\Phi] - \mu_q N)/T]\} \)

Dynamical quantities → Imag. Time

T, \mu \rightarrow 0

analytic continuation

vacuum

Thermodyn. potentials
bulk properties
Why Electromagnetic Probes?

- $\gamma, \ell^\pm$: no strong interactions
- reflect whole "history" of collision
- chance to see chiral symm. rest. directly?

\[
\pi, \ldots, \rho/\omega, \gamma^*, \cdots, e^+, e^-, a_1
\]

Fig. by A. Drees
Why Electromagnetic Probes?

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\[
\pi, \ldots \quad \rho/\omega \quad \gamma^* \quad e^- \quad e^+ \quad a_1
\]

\[
\begin{align*}
\pi^0, \eta & \text{ Dalitz decays} \\
\rho/\omega & \\
\Phi & \\
\end{align*}
\]

\[
dN/(dy dm) \quad \rho/\omega \quad \Phi \quad \Psi \quad \psi' \quad \text{Drell–Yan}
\]

Fig. by A. Drees
Vector Mesons and electromagnetic Probes

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function

\[ J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f \]
Vector Mesons and electromagnetic Probes

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function
  
  \[ (J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f) \]

  \[ \Pi^{\leq}_\mu\nu(q) = \int d^4x \exp(iq \cdot x) \langle J_\mu(0) J_\nu(x) \rangle_T = -2f_B(q_0) \text{Im} \Pi^{(\text{ret})}_\mu\nu(q) \]

  \[ q_0 \frac{dN_\gamma}{d^4x d^3q} = \frac{\alpha_{\text{em}}}{2\pi^2} g^{\mu\nu} \text{Im} \Pi^{(\text{ret})}_\mu\nu(q) \bigg|_{q_0=|\vec{q}|} f_B(q_0) \]

  \[ \frac{dN_{e^+e^-}}{d^4x d^4k} = -g^{\mu\nu} \frac{\alpha^2}{3q^2\pi^3} \text{Im} \Pi^{(\text{ret})}_\mu\nu(q) \bigg|_{q^2=M_{e^+e^-}^2} f_B(q_0) \]

- to lowest order in \( \alpha \): \( e^2 \Pi_\mu\nu \simeq \Sigma^{(\gamma)}_\mu\nu \)

- derivable from partition sum \( Z(V, T, \mu, \Phi) \)!
Vector Mesons and chiral symmetry

- Vector and axial-vector mesons ↔ correlators of the respective currents

\[
\Pi_{V/A}^{\mu\nu}(p) := \int d^4x \exp(ipx) \left\langle J_{V/A}^\nu(0) J_{V/A}^\mu(x) \right\rangle_{\text{ret}}
\]
Vector Mesons and chiral symmetry

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- Ward-Takahashi Identities from chiral symmetry ⇒ Weinberg-sum rules

\[ f_\pi^2 = - \int_0^\infty \frac{dp_0^2}{\pi p_0^2} \left[ \text{Im} \Pi_V(p_0,0) - \text{Im} \Pi_A(p_0,0) \right] \]

\[ -\frac{\pi}{2} \alpha_s \langle \mathcal{O}_{\chi SB} \rangle = - \int_0^\infty \frac{dp_0^2}{\pi} \left[ \text{Im} \Pi_V(p_0,0) - \text{Im} \Pi_A(p_0,0) \right] \]

- Spectral functions of vector (e.g. \( \rho \)) and axial vector (e.g. \( a_1 \)) directly related to order parameters of chiral symmetry!
Vector Mesons and chiral symmetry

- $\text{Im} \Pi_{V,A}/(\pi s)$ [dim.-less]
  - $V [\tau \rightarrow 2n\pi \nu_\tau]$ (filled dots)
  - $A [\tau \rightarrow (2n+1)\pi \nu_\tau]$ (open squares)
  - $\rho(770)$ + cont. (green line)
  - $a_1(1260)$ + cont. (cyan line)
Vector Mesons and chiral symmetry

\[ \text{Spectral Function} \]

- \( \rho \) (770) + cont.
- \( a_1 \) (1260) + cont.

\[ \text{Dropping Masses?} \]

\[ \text{Melting Resonances?} \]
different models with chiral symmetry: equivalent only on shell ("low-energy theorems")
Models

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- model-independent conclusions only in low-temperature/density limit (chiral perturbation theory) or from lattice-QCD calculations
Models

- different models with chiral symmetry: equivalent only on shell ("low-energy theorems")
- model-independent conclusions only in low-temperature/density limit (chiral perturbation theory) or from lattice-QCD calculations
- use phenomenological hadronic many-body theory (HMBT) to assess medium modifications of vector mesons
Models

- Phenomenological HMBT [Chanfray et al, Herrmann et al, Rapp et al, ...] for vector mesons
- $\pi\pi$ interactions and baryonic excitations
Models

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- $\pi\pi$ interactions and baryonic excitations

- Baryon (resonances) important, even at RHIC with low net baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)
The meson sector (vacuum)

- most important for $\rho$-meson: pions

\[ |F_\pi(q^2)|^2 \]

\[ q^2 \text{ [GeV}^2\text{]} \]

\[ M_{\pi\pi} \text{ [GeV]} \]

\[ \delta_{11} \text{ [deg.]} \]
The meson sector (matter)

- Pions dressed with $N$-hole-, $\Delta$-hole bubbles
- Ward-Takahashi vertex corrections mandatory!
The meson sector (contributions from higher resonances)
The baryon sector (vacuum)

- $P = 1$-baryons: $p$-wave coupling to $\rho$: $N(939), \Delta(1232), N(1720), \Delta(1905)$
- $P = -1$-baryons: $s$-wave coupling to $\rho$: $N(1520), \Delta(1620), \Delta(1700)$
Photoabsorption on nucleons and nuclei

\[ \sigma (\mu b) \]

\[ q_0 (\text{MeV}) \]

\[ 0 \quad 200 \quad 400 \quad 600 \]

\[ \text{full bkgd} \quad \text{1/3 bkgd} \]
Photoabsorption on nucleons and nuclei

![Graph showing photoabsorption on nucleons and nuclei with q₀ (MeV) on the x-axis and σ (µb) on the y-axis. Two separate plots are shown side by side. The left plot compares full bkgd and 1/3 bkgd with experimental data, while the right plot shows the same comparison with different scales for q₀ (MeV) and σ (µb).]
Dilepton rates: Hadron gas ↔ QGP

- In-medium hadron gas matches with QGP
- Similar results also for $\gamma$ rates
- "quark-hadron duality"?
- Does it work with chiral model?
- Hidden local symm. + baryons? [Harada, Yamawaki et al.]
Dilepton rates at SpS

35% Central Pb(158A GeV)+Au

\[
\frac{d^2N}{d\eta dM} / \frac{dN_{ch}}{d\eta} \quad [100\text{MeV}]^{-1}
\]

Cocktail
QGP

\[
0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2
M_{ee} \quad [\text{GeV}]
\]

\[
10^{-8} \quad 10^{-7} \quad 10^{-6} \quad 10^{-5} \quad 10^{-4}
(d^2N_{ee}/d\eta dM) / (dN_{ch}/d\eta)
\]

CERES '95+'96
free \pi\pi
in-med. \pi\pi + QGP
drop \rho-mass + QGP

\[
<\text{N}_{ch}>=250
\]

\[
p_t>0.2\text{GeV}
\]

\[
2.1<\eta<2.65
\]

\[
\Theta_{ee}>35\text{mrad}
\]

Dropping Masses?

Melting Resonances?
QCD and Chiral Symmetry
Electromagnetic Probes
Challenges for experiment (and theory)

New NA60 Dimuon Data

- intermediate mass range: Mixing of $\Pi_V$ with $\Pi_A$
  (Dey, Eletsky, Ioffe '90)

\[
\Pi_V^{(T)} = (1 - \epsilon) \Pi_V + \epsilon \Pi_A,
\]

\[
\epsilon = \frac{1}{2} \frac{T_\pi(T, \mu_\pi)}{T_\pi(T_c, 0)} \propto \rho
\]

- Fireball model $\Rightarrow$ time evolution
- absolute normalization!
- good overall agreement with data
- sensitive to $\omega$ and $\phi$!
- $\omega$: similar model as for $\rho$
- $\phi$: less well known; width assumed $\approx 80$ MeV

(hep-ph/0603084)
New NA60 Dimuon Data

- $2\pi$ contributions + $\rho B$ interactions from Rapp+Wambach ’99
- intermediate mass range: Mixing of $\Pi_V$ with $\Pi_A$

$$\Pi_V^{(T)} = (1 - \epsilon)\Pi_V + \epsilon\Pi_A, \quad \epsilon = \frac{1}{2} \frac{T_\pi(T, \mu_\pi)}{T_\pi(T_C, 0)}$$

- same absolute normalization!
- “Corona effect” for high $p_T$?
New NA60 Dimuon Data

- Chiral reduction formalism (Steele, Yamagishi, Zahed ’96)
- based on chiral symmetry and Veltman-Bell master equations
- virial expansion $\iff$ medium modifications from vacuum correlators (restricted to low $\pi/B$ densities)

---

Graphs showing the Imaginary part of the $\Pi_{VA}$ correlator and the fit including $\Delta(1230)$, $N^*(1520)$, $N^*(1720)$. Fits and pn average shown.
New NA60 Dimuon Data

- Underestimates medium effects on the $\rho$ (due to low-density approximation? No broadening!)
- Intermediate masses: mixing less pronounced
- Indication of chiral restoration?
New NA60 Dimuon Data

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  (due to low-density approximation? No broadening!)
- Intermediate masses: Less effect of mixing
- Indication of chiral restoration?
New NA60 Dimuon Data (semicentral)

Challenges for experiment (and theory)

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Medium Modifications of Hadrons and Electromagnetic Probes
Challenges for Experiment

- Direct signature for chiral restoration: spectra for $\rho$ and $a_1$ mesons degenerate
- $\pi^{\pm}\gamma$ invariant mass spectrum $\leftrightarrow a_1$ spectral function

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\(\omega\)-spectral function from CBELSA/TAPS
Challenges for Experiment

- Photon rate

![Graph showing photon rate](image)

- $\pi\pi \rightarrow \rho \rightarrow \pi\pi\gamma$ not enough to explain enhancement
- New development (Liu/Rapp work in progress):
  $\pi K \rightarrow K^* \rightarrow \pi K\gamma$
- Consistency with dileptons
Challenges for Theory

- Need a fully **chiral** model

\[
\begin{align*}
\pi & \overset{\pi_s}{\longrightarrow} \sigma \\
\pi_p & \overset{\rho_s}{\longrightarrow} \rho \\
\rho & \overset{\pi_s}{\longrightarrow} a_1 \\
N^{1/2^+} & \overset{\pi_s}{\longrightarrow} N(1535)^{1/2^-} \\
\Delta^{3/2^+} & \overset{\pi_s}{\longrightarrow} N(1520)^{3/2^-} \\
& \quad \text{or} \\
\rho & \overset{\pi_s}{\longrightarrow} a_1 \\
\end{align*}
\]

- How to treat **(axial-) vector mesons** (gauge model?)

- Approximation scheme for both **dynamical properties** (spectral functions) and **thermodynamic bulk properties** (phase diagram)?
Conclusions

- chiral symmetry: important feature to connect QCD ↔ hadronic effective models
- important property of (s)QGP: How is chiral symmetry restored?
- electromagnetic probes may provide most direct insight
  - invariant-mass spectra for chiral partners: here $\rho$ and $a_1$
  - low-energy photons ↔ dileptons (puzzle?)
- a lot to do also for theory
  - consistent chiral scheme for hadrons
  - self-consistent treatment of (axial-) vector particles
  - equation of state including in-medium modifications vs. statistical models with “free hadron properties”