Medium Modifications of Hadrons and Chiral Symmetry

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QCD and Chiral Symmetry

Medium Modifications of the ∆

Electromagnetic Probes

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

- Theory for strong interactions: QCD

\[ \mathcal{L}_\text{QCD} = -\frac{1}{4} F^{\mu\nu}_a F^a_{\mu\nu} + \bar{\psi}(i\not{D} - \hat{M})\psi \]

- Particle content:
  - \( \psi \): Quarks, including flavor- and color degrees of freedom, \( \hat{M} = \text{diag}(m_u, m_d, m_s, \ldots) \) = current quark masses
  - \( A^a_{\mu} \): 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
  - ⇒ mass splitting of chiral partners

![Diagram showing energy levels of various particles](image)

- **qq-exitations of the QCD vacuum**

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

- **Lattice QCD**: $T_{\chi} \approx T_{\text{deconf}}$

- **Challenges for experiment (and theory)**
Phenomenology from Chiral Symmetry

- **In vacuum**: Spontaneous breaking of chiral symmetry
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  \[\text{qq-excitations of the QCD vacuum}\]

  \[
  \begin{align*}
  \pi (140) & \quad f_0 (400-1200) \\
  \rho (770) & \quad \omega (782) \\
  a_1 (1260) & \quad f_1 (1285) \\
  f_1 (1420) & \quad \phi (1020)
  \end{align*}
  \]

  \[P-S, V-A\text{ splitting in the physical vacuum}\]

- **at high temperature/density**: restoration of chiral symmetry
- **Lattice QCD**: \(T^\chi_c \sim T^\text{deconf}_c\)
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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\[ Z[V, T, \mu, \Phi] \]

- Dynamical quantities
- Thermodynamic potentials
  - bulk properties
- analytic continuation
- vacuum

\( T, \mu \to 0 \)
Medium Modifications of the $\Delta$

- Nucleon and $\Delta$ in hot/dense matter
- photo absorption on nuclei
- $\pi N$ invariant-mass spectra

Form factors

$F_{\text{mono}}(|\vec{k}|) = \frac{2}{\Lambda^2 + |\vec{k}|^2}$ (s- and p-waves)

$F_{\text{dip}}(|\vec{k}|) = \frac{4}{(2\Lambda^2 + |\vec{k}|^2)}$ (d-waves)
Medium Modifications of the $\Delta$

- Nucleon and $\Delta$ in hot/dense matter
- Photo absorption on nuclei
- $\pi N$ invariant-mass spectra
- Hadronic model: $N$, $\pi$, $\Delta (1232)$, higher resonances
- Pions fully relativistic, baryons anti-particle poles neglected
- $\pi N \Delta$ vertex: $p$ wave
- $\pi N B^*$ vertices: lowest angular momentum coupling

Form factors

- $F_{\text{mono}}(|\vec{k}|) = \Lambda^2 / (\Lambda^2 + \vec{k}^2)$ (s- and p-waves)
- $F_{\text{dip}}(|\vec{k}|) = [2\Lambda^2 / (2\Lambda^2 + \vec{k}^2)]^2$ (d waves)
Hadronic model in the vacuum

\[ \pi N \] scattering phase shift

Model fit
\[ f_{\pi N \Delta} = 3.3, \quad \Lambda_\pi = 290 \text{ MeV} \]

Data (Arndt et al)

\[ B^* \Delta/N_\pi \] vertex ↔ partial decay widths

e.g. \[ N^*(1440) \] (s wave),
\[ N^*(1520) \] (s+d waves), …
Medium modifications of the pion and the nucleon

- Pions: $\pi\pi$-interactions, nucleon- and $\Delta$-hole excitations

- Nucleons: $\pi N$ and $\pi B$, $B=\Delta(1232)$, $N^*(1440)$, $N^*(1535)$, $\Delta^*(1600)$, $\Delta^*(1620)$

- Coupling constants fitted to partial decay widths $B \to \pi N$
Medium modifications of the $\Delta$

- Diagram as in vacuum with dressed $\pi$- and $N$ propagators
- Vertex corrections: same resummed Migdal loops as for the $\pi$
- 4-fermion vertices: same Migdal parameters as for the pion

$B' = \Delta(1232), N^*(1440), N^*(1520), \Delta^*(1600), \Delta^*(1620), N^*(1700), \Delta^*(1700)$
Cold nuclear matter

- photo absorption on the nucleon

Graph showing the relationship between $k_{\gamma}$ (GeV) and $\sigma_{\gamma}$ (µb) with data points and a model curve.
Cold nuclear matter

- photo absorption on nuclei

![Graph showing photo absorption on nuclei with different densities and materials.](image-url)
Hot nuclear matter (RHIC)

\[ \Delta m \sim (17 \pm 7) \text{ MeV}, \quad \Delta \Gamma \sim (45 \pm 14) \text{ MeV} \]

Courtesy: Patricia Fachini
Hot nuclear matter (RHIC)

$\Delta (1232)$ Spectral Function at RHIC

$\Delta m \sim 7$ MeV, $\Delta \Gamma \sim 67$ MeV

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Why Electromagnetic Probes?

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

![Diagram showing electromagnetic probes and their interactions with hadrons.](image)
Why Electromagnetic Probes?

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- reflect whole “history” of collision
- chance to see chiral symm. rest. directly?

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

\[ (J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f) \]

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

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

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

- 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

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

Ward-Takahashi Identities from chiral symmetry

\[ f_2^\pi = -\int_0^\infty dp_0 \pi p_0^2 \left[ \text{Im} \Pi_{V}(p_0,0) - \text{Im} \Pi_{A}(p_0,0) \right] \]

\[ = -\int_0^\infty dp_0 \pi \left[ \text{Im} \Pi_{V}(p_0,0) - \text{Im} \Pi_{A}(p_0,0) \right] - \pi^2 \alpha_s \langle O^{\chi_{SB}} \rangle \]

↑ spectral functions of vector (e.g. \(\rho\)) and axial vector (e.g. \(a_1\)) directly related to order parameters of chiral symmetry

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Medium Modifications of Hadrons and Chiral Symmetry
Vector Mesons and Chiral Symmetry

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

\[
\Pi^{\mu\nu}_{V/A}(p) := \int d^4x \exp(iax) \left\langle J^\nu_{V/A}(0) J^\mu_{V/A}(x) \right\rangle_{\text{ret}}
\]

- **Ward-Takahashi Identities** from chiral symmetry \(\Rightarrow\) **Weinberg-sum rules**

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

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

- **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

-Im $\Pi_{V,A} / (\pi s)$ [dim.-less]

- $V [\tau \rightarrow 2n\pi \nu_\tau]$
- $A [\tau \rightarrow (2n+1)\pi \nu_\tau]$
- $\rho(770)$ + cont.
- $a_1(1260)$ + cont.
Vector Mesons and chiral symmetry

-Im $\Pi_{V,A}/(\pi s)$ [dim.-less]

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Mass Spectral Function

Dropping Masses?

Melting Resonances?
Models

- different models with chiral symmetry: equivalent only on shell ("low-energy theorems")
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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 models + many-body techniques to assess medium modifications of vector mesons
Models

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

\[ B^*, a_1, K_1, ..., \]
\[ N, K, \pi, ... \]
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Medium Modifications of the $\Delta$
Electromagnetic Probes
Challenges for experiment (and theory)

Models

- Phenomenological hadronic models [Chanfray et al, Herrmann et al, Rapp et al, ...] for vector mesons
- $\pi \pi$ 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)
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.]
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Dilepton rates at SpS

35% Central Pb(158AGeV)+Au

$\langle N_{ch}\rangle = 250$

- CERES '95+'96
- $p_t > 0.2\text{GeV}$
- $2.1<\eta<2.65$
- $\Theta_{ee} > 35\text{mrad}$

$\frac{d^2N_{ee}/d\eta dM}{dN_{ch}/d\eta}$

10^{-8} to 10^{-4}

Cocktail

QGP

Spectral Function

"a_1"

"$\rho$"

Dropping Masses?

Melting Resonances?

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Medium Modifications of Hadrons and Chiral Symmetry
New NA60 Dimuon Data

- $2\pi$ contributions + $\rho B$ interactions from Rapp + Wambach ’99
- Intermediate mass range: Mixing of $\Pi_V$ with $\Pi_A$
  (Dey, Eletsky, Ioffe ’90)

\[
\Pi_V^{(T)} = (1 - \epsilon)\Pi_V + \epsilon\Pi_A,
\epsilon = \frac{1}{2} \frac{n_\pi(T, \mu_\pi)}{n_\pi(T_c, 0)}
\]

- Fireball model $\Rightarrow$ time evolution
- Absolute normalization!
- Good overall agreement with data
- Room for $\omega$ and $\phi$?
- “Corona $\rho$’s”?
New NA60 Dimuon Data

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

- Same absolute normalization!
New NA60 Dimuon Data

- Chiral reduction formalism (Steele, Yamagishi, Zahed ’96)
- based on chiral symmetry and Veltman-Bell master equations
- virial expansion $\Leftrightarrow$ medium modifications from vacuum correlators (restricted to low $\pi/B$ densities)
QCD and Chiral Symmetry
Medium Modifications of the $\Delta$
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Challenges for experiment (and theory)

**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?
underestimates medium effects on the $\rho$
(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

- 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 variations with momenta (q) and transverse (q_t) scales for Central Pb–Pb collisions at a center-of-mass energy of 17.3 AGeV. The graph compares different theoretical models: Hadron Gas, QGP (T_0=205 MeV), pQCD (Δk^2=0.2), and their sum. The data from WA98 within the rapidity range 2.35<y<2.95 is also plotted.]

- ππ → ρ → ππγ not enough to explain enhancement
- New development (Liu/Rapp work in progress): πK → K* → πKγ
- Consistency with dileptons
Challenges for Theory

- Need a fully *chiral* model

- 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”