Dileptons and Medium Effects in Heavy-Ion Collisions

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Thermalization ⇒ study the phase diagram:

- (highest) temperature of the matter
- chiral symmetry restoration (mass generation!)
- in-medium spectral properties below + above $T_c$

Inevitable consequences of QGP, link to lattice QCD
Outline

2.) Electromagnetic Emission and Chiral Symmetry
   - EM Thermal Rates
   - Axial-/Vector Correlators and Chiral Sum Rules

3.) Medium Effects and Thermal Dileptons
   - Vector Mesons in Medium: Hadronic Many-Body Theory
   - Experimental and Theoretical Constraints
   - Dilepton Rates: Hadronic vs. QGP

4.) Dileptons at SPS
   - CERES and NA60 Data
   - Interpretation + Open Issues

5.) Conclusions
2.) EM Emission Rates and Chiral Symmetry

E.M. Correlation Function:

\[ \Pi_{\text{em}}^{\mu\nu}(q) = -i \int d^4x e^{iqx} \left\langle j^{\mu}_{\text{em}}(x) j^{\nu}_{\text{em}}(0) \right\rangle_T \]

Emission Rates and Chiral Symmetry:

Emission Rates:

1. **Quark-Gluon Plasma**:
   - \( q\bar{q} \rightarrow e^+e^- \), ...
   - Mass and Temperature: \( M > 1.5\text{GeV} \), \( T > T_c \)

2. **Hot Dense Hadron Gas**:
   - \( \pi^+\pi^- \rightarrow e^+e^- \), ...
   - Mass and Temperature: \( M \leq 1\text{GeV} \), \( T \leq T_c \)

Radiation Sources:

- \( \frac{dN_{ee}}{d^4x d^4q} = -\frac{\alpha^2}{\pi^3 M^2} f^B(q_0,T) \) \( \text{Im} \Pi_{\text{em}}(M,q;\mu_B,T) \)
- \( \frac{dN_{\gamma}}{d^4x d^3q} = -\frac{\alpha}{\pi^2} f^B(q_0,T) \) \( \text{Im} \Pi_{\text{em}}(q_0=q;\mu_B,T) \)
2.2 Chiral Symmetry Breaking and Restoration

Splitting of “chiral partners” \( \rho - a_1(1260) \) \( \Rightarrow \) Chiral Symmetry Breaking

Axial-/Vector in Vacuum

\[ \text{V} [\tau \rightarrow 2n\pi \nu_\tau] \quad \text{A} [\tau \rightarrow (2n+1)\pi \nu_\tau] \]

\[ \rho(770) \quad \text{+ cont.} \quad a_1(1260) \quad \text{+ cont.} \]

\[ -\text{Im } \Pi_{em} \sim \left[ \text{Im } D_\rho + \text{Im } D_\omega /10 + \text{Im } D_\phi /5 \right] \]

Low-Mass Dilepton Rate:

\[ \frac{dN_{ee}}{d^4x d^4q} = -\frac{\alpha^2}{\pi^3 M^2} f^B(T) \text{Im } \Pi_{em} \sim \left[ \text{Im } D_\rho + \text{Im } D_\omega /10 + \text{Im } D_\phi /5 \right] \]

Axialvector Channel:

\( \pi^\pm \gamma \) invariant mass-spectra \( \sim \text{Im } D_{a_1}(M) \) ?!
2.3 Chiral Sum Rules and the $a_1(1260)$

- Energy-weighted moments of difference vector – axialvector:

$$I_0 = -\int \frac{ds}{\pi s^2} (\text{Im} \Pi_V - \text{Im} \Pi_A) = \frac{1}{3} f_\pi^2 \left\langle r_\pi^2 \right\rangle - F_A$$  
  \[\text{[Das et al '67]}\]

$$I_1(s_0) = -\int_0^{s_0} \frac{ds}{\pi s} (\text{Im} \Pi_V - \text{Im} \Pi_A) = f_\pi$$  
  \[\text{[Weinberg '67]}\]

$$I_2(s_0) = -\int_0^{s_0} \frac{ds}{\pi} (\text{Im} \Pi_V - \text{Im} \Pi_A) = 0$$

$$I_3 = -\int \frac{s ds}{\pi} (\text{Im} \Pi_V - \text{Im} \Pi_A) = c_\alpha_s \left\langle (\bar{q}q)^2 \right\rangle$$

- explicit link:
  \[V - A\] spectral fcts. (models) $\leftrightarrow$ order parameters (lattice QCD)

- extended to finite temperature  \[\text{[Kapusta+ Shuryak '93]}\]
3.1 Medium Effects I: Hadronic Many-Body Theory

[Chanfray et al, Herrmann et al, RR et al, Weise et al, Post et al, Eletsky et al, Oset et al, …]

**ρ-Propagator:**
\[
D_\rho (M,q;\mu_B,T) = [M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]^{-1}
\]

**ρ-Selfenergies:**
\[
\Sigma_{\rho\pi\pi} = \rho \quad \Sigma_{\rho B,M} = \rho
\]

**Constraints:**
- vacuum decays: \( B,M \rightarrow \rho N, \rho \pi \)
- scattering data: \( \gamma N, \gamma A, \pi N \rightarrow \rho N \)

\[
\sigma_{\gamma A}^{abs}(q_0)/A \propto \text{Im} D_\rho(q_0=q)
\]

[Urban et al. '98]
3.1.2 $\rho(770)$ Spectral Function in Nuclear Matter

In-med $\pi$-cloud + $\rho$-$N \rightarrow B^*$ resonances

Relativist. $\rho$-$N \rightarrow B^*$ (low-density approx)

In-med $\pi$-cloud + $\rho$-$N \rightarrow N(1520)$

Constraints: $\gamma N$, $\gamma A$

$\pi N \rightarrow \rho N$ PWA

- good agreement: strong broadening + small mass-shift up
- constraints from (vacuum) data important quantitatively
3.1.3 QCD Sum Rules + \( \rho(770) \) in Nuclear Matter

Dispersion relation for correlator:

\[
\Pi_\alpha(Q^2)/Q^2 = \int_0^\infty ds \frac{\text{Im}\Pi_\alpha(s)}{s Q^2 + s}
\]

[Shifman, Vainshtein + Zakharov '79]

- **lhs:** OPE (spacelike \( Q^2 \)):
  
  \[
  \Pi_\rho = \frac{-1}{8\pi^2} \left[ (1 + \alpha_s) \ln \left( \frac{Q^2}{\Lambda^2} \right) + \frac{\pi^2}{3} \frac{\langle \alpha_s G^2 / \pi \rangle}{Q^4} \right. \\
  \left. - C \frac{\alpha_s \langle (\bar{q}q)^2 \rangle}{Q^6} \right] + \ldots \]

  4-quark condensate!

- **rhs:** hadronic model (\( s > 0 \)):

  \[
  \text{Im}\Pi_\rho(s) = \frac{m_\rho^4}{g_\rho^2} \text{Im}D_\rho(s) - \frac{s}{8\pi} \left( 1 + \frac{\alpha_s}{\pi} \right) \Theta(s - s_0)
  \]

\[\rho_N = \rho_0 \]
\[\kappa = 2.36\]

\[0.2\% \quad 1\%\]

[Leupold '98, Ruppert et al '05]
3.1.4 $\rho$-Meson Spectral Functions at SPS

- $\rho$-meson "melts" in hot and dense matter
- Baryon density $\rho_B$ more important than temperature
- Reasonable agreement between models
Model Comparison

- Vacuum
- $n_N=1/2$
- $n_N=1$
- $n_N=2$

[RR+Wambach '99]

[Eletsky et al. '01]

\[\text{Im } D_\rho (\text{MeV}^{-2})\]

\[T=150 \text{ MeV} \quad p=300 \text{ MeV/c}\]
3.2 Dilepton Emission Rate: Hadron Gas vs. QGP

- Hard-Thermal-Loop QGP rate enhanced over Born rate
- “matching” of HG and QGP in vicinity of $T_c$
- “Quark-Hadron Duality” ?!

Mathematical expression:

$$\frac{dR_{ee}}{dM^2} = \frac{c \alpha^2}{M^2} \int \frac{d^3q}{q_0} f^B(T) \text{Im} \Pi_{em}(M,q)$$

[Braaten, Pisarski + Yuan '90]
4.) Dilepton Spectra in Heavy-Ion Collisions

Thermal Emission:
\[
\frac{dN_{ee}^{\text{therm}}}{dM} = \int_{\tau_{0}}^{\tau_{f}} d\tau V_{FB}(\tau) \int \frac{M d^3q}{q_0} \frac{dR_{ee}^{\text{therm}}}{d^4q} (M,q;T,\mu_i) \text{ Acc}
\]

Pb-Pb Collisions: Trajectories in the Phase Diagram

- based on entropy (+baryon-number) conservation
- volume expansion: \( V_{FB}(\tau) = (z_0 + v_z \tau) \pi (R_\perp + 0.5a_\perp \tau^2)^2 \)
4.1 Pb-Au Collisions at SPS:  CERES/NA45

- QGP contribution small
- medium effects on $\rho$-meson!
- dropping mass or broadening?!
4.2 In-In at SPS: Dimuons from **NA60**

• excellent mass resolution and statistics

• for the first time, **dilepton excess spectra** could be extracted!

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[Damjanovic et al. PRL ’06]

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• **quantitative theory?**
4.2.2 In-In at SPS: Theory vs. NA60

- predictions based $\rho$-spectral function of [RR+Wambach '99]
- uncertainty in fireball lifetime ($\pm 25\%$ norm.); or: infer $\tau_{FB} \approx 7\text{fm/c}$!
- relative strength of thermal sources fix

- good agreement with $\rho$ melting, including $p_t$ dependence [van Hees +RR '06]
4.2.3 Intermediate-Mass Region

- "$4\pi$" states dominate in the vacuum e.m. correlator above $M \approx 1.1\text{GeV}$

- **lower estimate:**
  use vacuum $4\pi$ correlator

- **upper estimate:**
  $O(T^2)$ medium effect $\rightarrow$
  "chiral V-A mixing": [Eletsky+Ioffe '90]

$$\Pi_V(q) = (1 - \varepsilon)\Pi_V^0(q) + \varepsilon\Pi_A^0(q)$$

with $\varepsilon(T_c) = \frac{1}{2}$

[van Hees+RR '06]
4.2.4 NA60 Data: Other $\rho$-Spectral Functions

- switch off medium modifications
- $T-$, $\rho_B-$ dependence of bare parameters: dropping mass

\[ \text{dropping mass} \quad \text{[Brown+Rho '91, Hatsuda+Lee '92]} \]

- free spectral function ruled out
- meson gas insufficient either
- dropping mass as used for CERES disfavored (free $\rho$ decays?)
4.2.5 (Some) Open Issues

- **Heavy-Ion Collisions** [NA60]
  - centrality dependence, free $\rho$’s (surface vs. volume)
  - sensitivity to fireball evolution
  - quantitative $\omega$ and $\phi$
  - thermal radiation at intermediate mass ($M=1.5-3$ GeV)
  - chiral restoration:
    - “duality” (hadron liquid $\rightarrow$ sQGP)
    - chiral sum rules
    - chiral mixing in the $M=1-1.5$ GeV region

- **Cold Nuclei** [CB/TAPS, KEK-E325]
  - dropping $\omega$-mass + broadening
  - dropping $\rho$-mass without broadening ?!
5.) Conclusions

- Strong medium effects in $l^+l^-$ spectra
- New level of precision in NA60 → model discrimination
- $\rho$-melting at $T_c$, no apparent mass shift
- Alternative models? (quality control)

- Chiral Restoration:
  - Direct (exp.): measure axialvector
  - Indirect (theo.): (1) effective model (constraints)
  (2) chiral sum rules (V-A moments) vs. lQCD
  (3) Compatibility with dilepton/photon data
- HADES, RHIC, LHC, SPS-09, CBM, ..., elementary reactions

In-medium V-meson spectroscopy has begun ...
3.3 Medium Effects II: Dropping Mass

Scale Invariance of $\mathcal{L}_{\text{QCD}} \rightarrow$ bare parameters change!? [Brown+Rho ’91, ’02]

$\langle \bar{q}q \rangle_T^{1/n} / \langle \bar{q}q \rangle_{\text{vac}}^{1/n} = f_\pi^*/f_\pi = m_N^*/m_N = m_\rho^*/m_\rho = \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right]^\alpha \left[ 1 - C \frac{\rho_B}{\rho_0} \right]$  

- density dependence: QCD sum rules: $C \approx 0.15$ [Hatsuda+ Lee ‘92]

- temperature dependence: $\alpha$
  quark condensate from chiral perturbation theory: $\langle \bar{q}q \rangle_T \approx \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right]^{1/3}$

- vector dominance coupling:
  $\text{Im} \Pi_\rho = \left( \frac{m_\rho^*}{g_\rho} \right)^4 \text{Im} D_\rho (m_\rho^*)$  
  (gauge invariance!)

\[ \text{Temperature evolution of chiral condensates} \]

ChPT+IAM [Pelaez ‘03]
3.) Medium Effects and Thermal Dileptons

3.1 Lattice QCD (QGP)

Dilepton Rate \( \sim \frac{\text{Im} \Pi(\omega, q=0)}{\omega^2} \)

EM Correlator \( \frac{\text{Im} \Pi(\omega, q)}{\omega^2} \)

- IQCD << pQCD at low mass (finite volume?)
- currently no thermal photons from lQCD
- vanishing electric conductivity!? but: [Gavai ’04]

[Bielefeld Group ’02, ’05]
3.4 In-Medium IV:
Vector Manifestation of Chiral Symmetry

- **Hidden Local Symmetry:** $\rho$-meson introduced as gauge boson, “Higgs” mechanism generates $\rho$-mass
- **Vacuum:** $\rho_L \leftrightarrow \pi$, good phenomenology (loop exp. $O(p/\Lambda_\chi, m_\rho/\Lambda_\chi, g)$)
- **In-Medium:** $T$-dep. $m_\rho^{(0)}$, $g_\rho$ matched to OPE (spacelike), $\Lambda_{\text{match}} < \Lambda_\chi$, Renormalization Group running $\rightarrow$ on-shell
  - dropping $\rho$-mass $\rightarrow 0$ (RG fixed point at $T_c$),
  - violation of vector dominance: $a = 2 \rightarrow 1$

\[ \gamma \quad \pi \quad \tilde{\sim} \quad \pi \quad \sim (a-2) \quad + \quad \sim a \]

- e.m. spectral function? matching HG-QGP: massless mesons?

[Harada, Yamawaki et al., '01]
4.2 Recent Advances at SPS: Power of Precision

NA60 Data vs. Model Predictions [RR+Wambach '99; RR'03]

- \( \rho \)-meson "melting" supported (baryons!)
- dropping mass (as used to explain CERES data) ruled out
- open issues:
  1. \( M > 0.9\,\text{GeV} \) (\( 4\pi \to \mu^+\mu^- \) !?)
  2. normalization: 0.6 \( (p_t < 0.5\,\text{GeV}) \), 0.8 (all \( p_t \)), \( \sim 2 \) \( (p_t > 1\,\text{GeV}) \)
  3. other models (vector manifestation, chiral virial approach, ...)
4.2.2 Modified Fireball and Absolute Normalization

• $\rho$-spectral function unchanged since [RR+Wambach '99]

• expanding fireball, fixed $S (\leftrightarrow N_{ch})$: $V_{FB}(\tau) = (z_0 + v_z \tau) \pi (R_{\perp 0} + 0.5a_\perp \tau^2)^2$

  Increase $a_\perp \Rightarrow$ reduced lifetime ($\tau = 9 \rightarrow 6 \text{fm}/c$), increased $v_\perp = 0.4 \rightarrow 0.5c$

• reasonable agreement with absolute normalization, but …

• too little yield at high $p_t$; “free $\rho$”? $\omega$? check central …
Revival Attempts for Dropping $\rho$-Mass

E.g., [Skokov+Toneev ‘05]

$\varepsilon > 1\text{GeVfm}^{-3} \approx \varepsilon_c$ for $\Delta \tau = 8\text{ fm/c}?!$

Bjorken regime: $\tau_{FB} = 0.5\text{ fm/c}?!$

- Not compatible with gauge invariance (no $m_\rho^*$ in VDM)
- acceptance?
$M \geq 1\text{GeV}$ in NA60

[H. van Hess + RR, in prep.]

- combination of $4\pi + \text{QGP} + \text{charm}$?!
- (beware: schematic acceptance)
4.2.5 Chiral Virial Approach vs. NA60 (central)

[Steele, Yamagishi + Zahed ’99]

[implementation van Hees + RR ’05]
5.) Electromagnetic Probes

5.1.1 Thermal Photons I : SPS

Expanding Fireball + pQCD

WA98 “Low-\(q_t\) Anomaly”

\[ \text{WQA98 Data} \quad 2.35 < y < 2.95 \]

- \(pQCD+Cronin\) at \(q_t > 1.6\text{GeV}\)
  \(\Rightarrow T_0=205\text{MeV}\) suff., HG dom.

\[ \text{[Turbide,RR+Gale’04]} \]

- addtl meson-Bremsstrahlung
  \(\pi\pi \rightarrow \pi\pi\gamma\) \(\pi K \rightarrow \pi K\gamma\)
  substantial at low \(q_t\)

\[ \text{[Liu+RR’05]} \]
5.1.2 Thermal Photons II: RHIC

- thermal radiation $q_t < 3\text{GeV}$ ?!
- QGP window $1.5 < q_t < 3\text{GeV}$ ?!

- also: $\gamma$-radiation off jets
- shrinks QGP window $q_t < 2\text{GeV}$ ?!

[Gale, Fries, Turbide, Srivastava ’04]
5.3.1 RHIC: Vector Mesons in Medium

Hadronic Many-Body Theory

- Baryon effects important even at $\rho_{B,\text{net}} = 0$:
  sensitive to $\rho_{B,\text{tot}} = \rho_B + \rho_{\bar{B}}$, most pronounced at low $M$

- $\phi$ more robust $\leftrightarrow$ OZI
Dilepton Emission Rates

\[ [\bar{q}q \rightarrow ee] [\bar{q}q + O(\alpha_s)] \]

\[ dR_{ee} / dM_{ee} \text{ [fm}^{-4} \text{ GeV}^{-2}] \]

T=180MeV

in-med HG \approx in-med QGP!
Quark-Hadron Duality ?!
5.3.2 Dileptons II: RHIC

- low mass: thermal! (mostly in-medium $\rho$)
- connection to Chiral Restoration: $a_1(1260) \rightarrow \pi\gamma, 3\pi$
- int. mass: QGP (resonances?) vs. $c\bar{c} \rightarrow e^+e^-X$ (softening?)