Theoretical Review of Dileptons from Heavy Ion Collisions

Hendrik van Hees

Texas A&M University

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1. QCD, Chiral Symmetry, and Dileptons
2. Hadronic Models in Medium
3. Models vs. Experiments
4. Sensitivities to QCD Matter
5. Conclusions
Dileptons and in-medium em. current correlation function

\[ \ell^- \ell^- q \bar{q} \rho / \omega \pi, \ldots, M, q_t \gtrless 1.5 \text{ GeV} \]

\[ \ell^+ \ell^- M, q_t \lesssim 1.5 \text{ GeV} \]

- **Dilepton emission rate** [McLerran, Toimela 85]

\[
\frac{dN_{e^+e^-}}{d^4x d^4q} = -g^{\mu\nu} \frac{\alpha_{\text{em}}^2}{3q^2 \pi^3} \text{Im} \left. \Pi^{(\text{em})}_{\mu\nu}(q) \right|_{q^2 = M_{e^+e^-}^2} f_B(q_0)
\]

\[
\Pi^{(\text{em})}_{\mu\nu}(q) = \int d^4x \exp(iq \cdot x) \Theta(x_0) \left\langle \left[ j^{(\text{em})}_\mu(x), j^{(\text{em})}_\nu(0) \right] \right\rangle_T
\]

- **\( \ell^+ \ell^- \) spectra \( \iff \) in-medium em. current-current correlator
- **Vector dominance \( \Rightarrow \) in-medium modifications of vector mesons!**
Chiral Symmetry Restoration

- light-quark sector of QCD: chiral symmetry
  - spontaneously broken in vacuum ($\langle \bar{q}q \rangle \neq 0$)
  - high temperature/density: restoration of chiral symmetry
- Lattice QCD: $T^\chi_c \approx T^\text{deconf}_c$

**Mechanism of chiral restoration?**
- “dropping masses”: $m_{\text{had}} \propto \langle \bar{\psi}\psi \rangle$
- “melting resonances”: broadening of spectra through medium effects

**Diagram:**
- Graph showing the spectral function with contributions from V and A transitions.
- Comparison of predicted and observed spectral functions.

**Legend:**
- $V[\tau \rightarrow 2n\pi \nu_\tau]$
- $A[\tau \rightarrow (2n+1)\pi \nu_\tau]$
- $\rho(770) + \text{cont.}$
- $a_1(1260) + \text{cont.}$

**Questions:**
- Dropping Masses?
- Melting Resonances?
Weinberg sum rules

\[ M_n = -\int_0^\infty \frac{ds}{\pi} s^n [\text{Im} \Pi_V(s) - \text{Im} \Pi_A(s)] \]

\[ M_{-2} = \frac{1}{3} f_\pi^2 \langle r_\pi^2 \rangle - F_A, \quad M_{-1} = f_\pi^2 \]

\[ M_0 = 0, \quad M_1 = c\alpha_s \langle (\bar{q}q)^2 \rangle \]

- theory connection of \textit{chiral symm. restoration} with dileptons in HICs
  - \( \Pi_V, \Pi_A \) from \textit{chiral hadronic model} at finite \( T, \mu_B \)
  - compare \( M_n(T, \mu_B) \) to \textit{IQCD} chiral order parameters at finite \( T \)
  - compare \( \Pi_V \) from \textit{hadronic model} to dileptons from HICs

- also QCD sum rules
  - relate \textit{current correlators} to \textit{condensates}
  - \textit{VMD} \( \leftrightarrow \) \textit{vector-meson spectral functions}

\[ \rho_N = \rho_0, \quad \kappa = 236 \]

\( \text{S. Leupold, W. Peters, U. Mosel} \)

\( \text{Nucl. Phys. A 628, 311 (1998)} \)
Hadronic many-body theory

- **pion-cloud modifications and baryonic/mesonic excitations**

[Chanfray et al, Herrmann et al, Ko et al, Rapp et al, Klingl et al, Post et al, Friman et al, ...]

- substantial broadening of vector mesons with little mass shift!
  - baryon effects prevalent ($\rho_B + \rho_B$, not $\rho_B - \rho_B$, relevant!)
  - different approaches consistent if constrained by data
    ($\gamma N, \gamma A, \pi N \rightarrow \rho N$)
Hadronic models vs. lattice QCD

Dilepton Excitation Function in Central Au-Au ($N_{\text{part}}=330$)

Isovector Susceptibility

\[ \chi_q,I = \frac{\partial p}{\partial\mu_{q,I}}, \quad \mu_q = \mu_u + \mu_d, \quad \mu_I = \mu_u - \mu_d \]

- excitation function from top SPS to top RHIC energies:
  - little change in hadronic contribution [Rapp 02]
- IQCD: Smooth behavior of susceptibilities in $I = 1$ channel [Allton et al 04]
  - consistent with no mass shift in $I = 1$ channel
  - NB: $\chi_q (I = 0)$ shows peak at $T \rightarrow T_c$: signature of phase transition!
**ρ meson in hot hadronic matter**

- **EBEK:** [Eletsky, Belkacem, Ellis, Kapusta 01]
  - empirical $\rho + B/M$ scattering amplitudes
  - + Pomeron/Regge background
  - $T\rho$ approximation for finite-T effects
- **RW:** Hadronic many-body theory [Rapp, Wambach 99]
- **Somewhat different results**
  - more broadening and level repulsion:
    - in-med modifications of pion-cloud + $\rho BN$ interactions
Chiral approaches

- **Chiral reduction formalism** [Steele et al 96]
  - leading order in $\pi$ and $N$ density + chiral reduction formulas
  \[ \Rightarrow \text{in-medium current correlators in terms of vacuum correlators} \]
  - no Dyson resummation!

- **Hidden local symmetry** [Bando et al 85; Harada, Yamawaki 01,...]
  - Vector manifestation of chiral symmetry: $\rho_{\text{long}}$ chiral partner of $\pi$
  \[ \Rightarrow \text{dropping $\rho$ mass + violation of vector dominance ($T > T_{\text{flash}} = 0.7T_c$)} \]

- dilepton rates similar to more simple dropping mass models
Elementary reactions ($\gamma + A, \ p + A$)

- **Left:** JLaB $\gamma + A \rightarrow e^+ + e^-$ [CLAS Collab. 07]
  - Theory: Boltzmann Uehling Uhlenbeck (BUU) transport [Effenberger et al 00]
  - Good agreement: no mass shift, broadening of the $\rho$: $\Gamma_\rho \sim 220$ MeV
- **Right:** KEK $p + A \rightarrow e^+ + e^-$ [E325 Collaboration 07]
  - Fit to dropping-mass ansatz: $m^*/m = (1 - C \varrho/\varrho_0)$
  - $C = 0.092 \pm 0.002$, no broadening
  - Contradiction with JLab
  - $\rho/\omega$ ratio small; yield for $M > 0.85$ GeV?
HADES confirms DLS

Theory: transport model (HSD); coll. broadening + dropping mass
[Bratkovskaya, Cassing 07]

- moderate sensitivity to vector-meson medium effects!
- solution of DLS puzzle
  - improved $e^+e^-$ Bremsstrahlung [de Jong, Mosel 97; Kaptari, Kämpfer 06]
  - updated $\eta$- and $\Delta$-Dalitz contributions
CERES vs. Hadronic many-body theory

- Dilepton emission from thermal source
- thermal fireball evolution (isentropic QGP/MIX + hadron gas)

\[
\frac{dN_{\text{therm}}^{\ell\ell}}{dM} \propto - \int_{\text{FB}} d^4x \int \frac{d^3q}{Mq_0} \text{Im} \Pi^{(\text{em})}(q_0, \vec{q}) f_B(q_0) \text{Acc}
\]

- baryon effects essential!
  - many-body effects ⇔ very low-mass excess

[HvH, R. Rapp 07]
NA60 vs. Hadronic many-body theory + HR fireball

- $\rho$, $\omega$, $\phi$ multi-$\pi$, QGP, freeze-out + primordial $\rho$, Drell-Yan

### $M$ spectra
- Consistent with predicted broadening of $\rho$ meson
- $M < 1$ GeV: thermal $\rho$; $M > 1$ GeV: thermal multi-pion processes

### $m_t$ spectra
- $q_t < 1$ GeV: thermal radiation
- $q_t > 1$ GeV: freeze-out + hard primordial $\rho$, Drell-Yan

[HvH, Rapp 07]
NA 60 vs. Chiral reduction formalism + hydrodynamics

- low-mass + IMR spectrum described
- $\rho$: lack of broadening (due to low-density approximation)
- $q_T$ spectra: only thermal + freezeout, no primordial $\rho$

[Dusling, Teaney, Zahed 07]
NA60 vs. empirical spectral functions + RR fireball

- only thermal + freeze-out
- large QGP contribution
- sensitivity of spectral functions to data?!

[Ruppert et al 07]
HR fireball [HvH, Rapp 06, 07]

- thermal dileptons: agrees with hydro
- pions: need “primordial” hard comp.
  - low $p_T$: resonance decays
  - consistent with measured $R_A^{(\pi)}$

RR fireball [Ruppert, Renk 07]

- dileptons: harder than hydro
- pions: thermal only
Sensitivity II: Intermed. mass region – QGP vs. hadron gas

- **EoS-B**: $T_c = T_{chem} = 160$ MeV (large QGP part)
- **EoS-C**: $T_c = 190$ MeV, $T_{chem} = 160$ MeV (small QGP part)
- volume $\leftrightarrow T$: emission dominated by temperatures around $T_c$
  - (QGP vs. high-density hadronic phase)
- description of spectra comparable for different EoS

[HvH, Rapp 07]
Sensitivity III: Critical temperature and freeze-out

- **EoS-A**: $T_c = T_{\text{chem}} = 175$ MeV; **EoS-B**: $T_c = T_{\text{chem}} = 160$ MeV
- **EoS-C**: $T_c = 190$ MeV, $T_{\text{chem}} = 160$ MeV
  - norm depends on $t_{\text{fireball}}$ (kept fixed here)!
  - description of spectra comparable
  - reason for insensitivity to EoS and hadro-chemistry [HvH, Rapp 07]:
  - hadronic and partonic radiation "dual" for $T \sim T_c$
    - (pQCD: $\Pi_V \equiv \Pi_A \Rightarrow$ compatible with chiral symmetry restoration!)
PHENIX $e^+ e^-$-mass spectrum

min. bias 200A GeV Au+Au

Minimum Bias Au-Au Cocktail + Yield Data

hadronic many-body theory

[chiral reduction formalism

[central scaled by $N_{\text{part}}$]

LMR enhancement cannot be described!
Predictions: $e^+e^−-q_T$ spectra at RHIC

- theory: thermal [Rapp 08 (unpublished)]; hard contributions [Turbide et al 06]
- hard contributions (jet-thermal) take over for $q_T \gtrsim 3$ GeV
Conclusions and Outlook

- Models for vector ($\rho$) mesons in medium
  - hadronic many-body theory
    - broadening, small mass shifts of spectra (baryon effects prevalent)
    - hadron-parton duality of dilepton rates ($\text{QGP}$ portion depends on $T_c$)
  - chiral reduction formalism
    - low-density approximation, no broadening

- HLS+Vector Manifestation
  - dropping mass, no vector dominance near $T_c$

- Theory vs. Experiment
  - Elementary reactions
    - JLAB: BUU transport with broadening (with no mass shift)
    - KEK: Dropping-mass ansatz
  - Heavy-ion collisions
    - HADES (DLS): HSD transport; improved Bremsstrahlung and $\Delta$ Dalitz
    - CERES, NA60: Hadronic many-body theory robust due to duality involved mix of contributions at high $q_T$
    - PHENIX: Low-mass enhancement can not be described!
Conclusions and Outlook

- **Not covered in this talk: Thermal Photons**
  - Same em. correlator as for dileptons!
  - Hadronic many body theory: improvement in description of WA98 data
    - [Liu, Rapp 06]
  - Possibility to measure $T_{\text{initial}}$:
    \[
    \frac{dN_{\ell\ell}/dq_T}{dN_\gamma/dq_T}
    \]
    - [Alam et al 07]

- **Connection between chiral symmetry restoration and dilepton data**
  - hadronic chiral model at finite $T \Rightarrow \Pi_V$ and $\Pi_A$
  - confront $\Pi_V$ with dilepton data
  - check moments of $\Pi_V - \Pi_A$ with lQCD via Weinberg sum rules