Electromagnetic Probes in Heavy-Ion Collisions

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Outline

1. QCD, Chiral Symmetry, and Dileptons
2. Models vs. Experiments at SPS and RHIC
3. Conclusions and Outlook
Dileptons and in-medium em. current correlation function

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

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

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

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

- **\( \ell^+ \ell^- \) spectra ⇔ in-medium em. current-current correlator**
- **Vector dominance ⇒ 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: $T_c^\chi \simeq T_c^{deconf}$

Mechanism of chiral restoration?
- “dropping masses”: $m_{\text{had}} \propto \langle \bar{\psi}\psi \rangle$
- “melting resonances”: broadening of spectra through medium effects
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 ($\rho_B + \rho_{\bar{B}}$, not $\rho_B - \rho_{\bar{B}}$, relevant!)
    - different approaches consistent if constrained by data
      ($\gamma N, \gamma A, \pi N \to \rho N$)

  - Hendrik van Hees (JLU Gießen)
CERES vs. Hadronic many-body theory

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

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

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

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

- $\rho$, $\omega$, $\phi$ 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]
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!)
Intermediate mass region – QGP vs. hadron gas

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

[HvH, Rapp 07]
PHENIX $e^+e^-$-mass spectrum

- **RR**: hadronic many-body theory \([\text{Rapp 01, 02}]\) (for $N_{\text{part}} = 125$)
- **KD+IZ**: chiral reduction formalism \([\text{Dusling, Zahed 07}]\)
- **EB+WC**: Transport model (HSD) \([\text{E. L. Bratkovskaya, W. Cassing, O. Linnyk 08}]\)
- **LMR enhancement cannot be described!**

[T. Dahms (Thesis), arXiv:0810.3040]
Conclusions and Outlook

- **hadronic many-body theory**
  - broadening, small mass shifts of spectra (baryon effects prevalent)
  - hadron-parton duality of dilepton rates (QGP portion depends on $T_c$)

- **Heavy-ion collisions**
  - 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!

- **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]

- **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