The Dilepton Probe in Heavy-Ion Collisions

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Outline

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   - Chiral symmetry and dileptons
   - Thermal sources of dileptons
   - Non-thermal sources of dileptons

2. Comparison to Heavy-Ion data
   - Invariant-mass spectra
   - Sensitivity to $T_c$ and hadro-chemistry
   - IMR: Parton- or hadron-dominated source?

3. Conclusions and Outlook
Electromagnetic probes in heavy-ion collisions

- $\gamma, \ell^\pm$: no strong interactions
- Reflect whole “history” of collision:
  - From pre-equilibrium phase
  - From thermalized medium (QGP and hot/dense hadron gas)
  - From VM decays after thermal freeze-out

![Diagram showing various processes in heavy-ion collisions with Dalitz decays and dileptons](image)

Fig. by A. Drees
Electromagnetic probes and vector mesons

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

[L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

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

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

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

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

\[
\Sigma^\gamma_{\mu\nu} = G_\rho
\]

- derivable from partition sum \( Z(V, T, \mu, \Phi) \)!
Chiral symmetry

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

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

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

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

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

- V \([\tau \to 2n\pi \nu_\tau]\)
- A \([\tau \to (2n+1)\pi \nu_\tau]\)
- \(\rho(770) + \text{cont.}\)
- \(a_1(1260) + \text{cont.}\)
Hadronic many-body theory

- HMBT for vector mesons \([\text{Ko et al, Chanfray et al, Herrmann et al, Rapp et al, \ldots}]\)
- \(\pi\pi\) interactions and baryonic excitations

+ corresponding vertex corrections \(\Leftrightarrow\) gauge invariance
- 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)
In-medium spectral functions and baryon effects

- **baryon effects important**
  - large contribution to broadening of the peak
  - responsible for most of the strength at small $M$

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[R. Rapp, J. Wambach 99]
Dilepton rates: Hadron gas ↔ QGP

- in-medium hadron gas matches with QGP
- similar results also for $\gamma$ rates
- “quark-hadron duality”!?
- indirect evidence for chiral-symmetry restoration
Sources of dilepton emission in heavy-ion collisions

1. initial hard processes: Drell Yan
2. “core” ⇔ emission from thermal source [McLerran, Toimela 1985]

\[
\frac{1}{q_T} \frac{dN^{(\text{thermal})}}{dM dq_T} = \int d^4x \int dy \int M d\varphi \frac{dN^{(\text{thermal})}}{d^4xd^4q} \text{Acc}(M, q_T, y)
\]

3. “corona” ⇔ emission from “primordial” mesons (jet-quenching)
4. after thermal freeze-out ⇔ emission from “freeze-out” mesons [Cooper, Frye 1975]

\[
N^{(\text{fo})} = \int \frac{d^3q}{q_0} \int q_\mu d\sigma^\mu f_B(u_\mu q^\mu / T) \frac{\Gamma_{\text{meson} \rightarrow \ell^+ \ell^-}}{\Gamma_{\text{meson}}} \text{Acc}
\]

- additional factor \( \gamma = q_0/M \) compared to thermal emission
- physical reason
  - thermal source rate \( \propto \tau_{\text{med}} \frac{\Gamma_{\text{meson} \rightarrow \ell^+ \ell^-}}{\Gamma_{\text{meson}}} \)
  - decay of mesons after fo: rate \( \propto \frac{\Gamma_{\text{meson} \rightarrow \ell^+ \ell^-}}{\Gamma_{\text{meson}}} \)
- good agreement also for dielectron spectra in 158 GeV Pb-Au
- allows further check of low-mass tail from baryon effects down to $M \rightarrow 2m_e$
Dileptons in HICs

Importance of baryon effects

- Baryonic interactions important!
- In-medium broadening
- Low-mass tail!

\[
\frac{(1/N_{ch}) \, d^2 N_{\mu\mu}}{(dM \, d\eta) \, (20 \text{ MeV})^{-1}} \quad \text{vs.} \quad M \, (\text{GeV})
\]

\(T_c = T_{ch} = 175 \text{ MeV}, \, q = 0.1 \text{ c}^2/\text{fm}\)

\(\text{NA60} \quad \text{in-med} \rho \quad \text{QGP} \quad \text{prim} \rho \)

\(\text{FO} \rho \quad 4\pi \text{ mix} \quad \text{DY} \quad \phi \quad \omega \quad \omega - \text{t ex} \quad \text{total} \quad +\omega - \text{t ex} \)
Sensitivity to $T_c$ and hadro-chemistry

- recent lattice QCD: $T_c \approx 190$-200 MeV or $T_c \approx 150$-160 MeV?
- thermal-model fits to hadron ratios: $T_{\text{chem}} \approx 150$-160 MeV

- 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
  - $T_c \geq T \geq T_{\text{chem}}$: hadron gas in chemical equilibrium
- keep fireball parameters the same (including life time)
- mass spectra comparable to EoS-A ↔ slight enhancement of fireball lifetime
- in IMR QGP > multi-pion contribution
- higher hadronic temperatures ⇒ slightly harder $q_T$ spectra
- not enough to resolve discrepancy with data
- mass spectra comparable to EoS-A $\leftrightarrow$ slight reduction of fireball lifetime
- in IMR multi-pion $\gg$ QGP contribution
- higher hadronic temperatures + high-density hadronic phase $\Rightarrow$ harder $q_T$ spectra
- better agreement with data
Inverse-slope analysis

- to extract $T_{\text{eff}}$ fit to

$$\frac{1}{q_T} \frac{dN}{dq_T} = \frac{1}{m_T} \frac{dN}{dm_T} = C \exp \left( -\frac{m_T}{T_{\text{eff}}} \right)$$

- fit of theoretical $q_T$ spectra: $1 \, \text{GeV} < q_T < 1.8 \, \text{GeV}$

- standard fireball acceleration: too soft $q_T$ spectra
- lower $T_c$ in EoS-B and EoS-C helps (higher hadronic temperatures)
- NB: here, Drell Yan contribution taken out
- enhance fireball acceleration to $a_\perp = 0.1 c^2 / \text{fm}$
- effective at all stages of fireball evolution
- agreement in IMR not spoiled $\Leftrightarrow$ dominated from earlier stages
- EoS-B harder $\Leftrightarrow$ relative contribution of harder freeze-out $\rho$ decays vs. thermal $\rho$'s larger
EoS-B: QGP dominates over multi-pion radiation

- opposite in EoS-A and EoS-C
- multi-pion radiation dominantly from high-density hadronic phase

reason: \( dN_{ll}/dMdT \propto \text{Im} \Pi_{em}(M, T) \exp(-M/T) T^{-5.5} \)

- radiation maximal for \( T = T_{\text{max}} = M/5.5 \)
- hadronic and partonic radiation “dual” for \( T \sim T_c \)
  compatible with chiral-symmetry restoration!
- analysis of “cocktail”: hadron-$m_T$ spectra
- comparison to fireball evolution
- “sequential freeze-out” due to different coupling strength
M spectra (in $p_T$ slices)

- **EoS-A**: $T_c = T_{\text{ch}} = 175$ MeV
- **transverse acceleration**: $a_\perp = 0.1 c^2/\text{fm}$

- norm corrected by $\sim 3\%$ due to centrality correction
  (min-bias data: $\langle N_{\text{ch}} \rangle = 120$, calculation $N_{\text{ch}} = 140$)
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Conclusions and Outlook

- **dilepton spectra** ⇔ **in-medium em. current correlator**
- **model for dilepton sources**
  - radiation from **thermal sources**: QGP, $\rho$, $\omega$, $\phi$
  - $\rho$-decay after thermal freeze-out
  - decays of non-thermalized primordial $\rho$’s
  - Drell-Yan annihilation, correlated $D\bar{D}$ decays
- **invariant-mass spectra and medium effects**
  - excess yield dominated by radiation from **thermal sources**
  - baryons essential for **in-medium properties of vector mesons**
  - melting $\rho$ with little mass shift robust signal! (independent of $T_c$)
  - IMR well described by scenarios with radiation dominated either by QGP or **multi-pion processes** (depending on EoS)
    - Reason: mostly from thermal radiation around $160 \text{ MeV} \leq T \leq 190 \text{ MeV}$
    - “parton-hadron” duality of rates
    - compatible with chiral-symmetry restoration!
  - dimuons in In-In (NA60), Pb-Au (CERES/NA45), $\gamma$ in Pb-Pb (WA98)
Conclusions and Outlook

- fireball/freeze-out dynamics \(\Leftrightarrow m_T\) spectra and effective slopes
  - “non-thermal sources” important for \(q_T \gtrsim 1\) GeV
  - lower \(T_c\) \(\Rightarrow\) higher hadronic temperatures \(\Rightarrow\) harder \(q_T\) spectra
  - to describe measured effective slopes \(a_\perp = 0.085c^2/fm \rightarrow 0.1c^2/fm\)
  - off-equilibrium effects (viscous hydro)?

- Further developments
  - understand recent PHENIX results (large dilepton excess in LMR)
  - understand “DLS puzzle” (exp. confirmed by HADES)
    \(NN (np)!\) bremsstrahlung!
  - vector- should be complemented with axial-vector-spectral functions
    \((a_1\) as chiral partner of \(\rho\))
  - constrained with IQCD via in-medium Weinberg chiral sum rules
  - direct connection to chiral phase transition!