Electromagnetic spectra at the CERN-SPS

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Electromagnetic probes in heavy-ion collisions
- Vector mesons and electromagnetic probes
- Sources of dilepton emission in heavy-ion collisions

Comparison to NA 60 data
- Invariant-mass spectra
- $m_T$ spectra

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 hadron gas
  - from VM decays after thermal freezeout

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

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

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

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

- \( u \): four-velocity of the fluid cell; \( p \cdot u = p_0^{\text{hb}} \) energy in “heat-bath frame”
- to lowest order in \( \alpha \): \( e^2 \Pi_{\mu\nu} \simeq \Sigma_{\mu\nu}^{(\gamma)} \)
- vector-meson dominance model:

\[
\Sigma_{\mu\nu}^{(\gamma)} = G_\rho
\]
Sources of dilepton emission in heavy-ion collisions

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

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

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

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

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

\[\begin{align*}
\rho & \quad \pi \\
\pi & \quad \rho
\end{align*}\]

\[\begin{align*}
\rho & \quad \pi \\
\pi & \quad \rho
\end{align*}\]

\[\begin{align*}
\rho & \quad B^*, a_1, K_1, ...
\end{align*}\]

\[\begin{align*}
\rho & \quad N, K, \pi, ...
\end{align*}\]

+ 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 $M$

[R. Rapp, J. Wambach 99]
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Intermediate masses: hadronic “$4\pi$ contributions”

- e.m. current-current correlator $\Leftrightarrow \tau \rightarrow 2n\pi$

- “$4\pi$ contributions”: $\pi + \omega, a_1 \rightarrow \mu^+ + \mu^-$
- leading-order virial expansion for “four-pion piece”
- additional strength through “chiral mixing”
Radiation from thermal sources: Meson t-channel exchange

- motivation: $q_T$ spectra too soft compared to NA60 data
- thermal contributions not included in models so far

- also for $\pi, a_1$
in QGP phase: $q\bar{q}$ annihilation

HTL improved electromagnetic current correlator

or electromagnetic current correlator from the lattice [H.-T. Ding, A. Francis et al (Bielefeld) 2011] (extrapolated to finite $q$)

“quark-hadron duality” around $T_c$
cylindrical fireball model: \( V_{FB} = \pi (z_0 + v_{z0} t + \frac{a_z}{2} t^2) \left( \frac{a_z}{2} t^2 + r_0 \right)^2 \)

thermodynamics:

- isentropic expansion; \( S_{\text{tot}} \) fixed by \( N_{\text{ch}} \); \( T_c = T_{\text{chem}} = 175 \) MeV
- \( T > T_c \): QGP; lattice equation of state
- continuous cross-over (no 1st-order mixed state!)
- \( T < T_c \): hadron-resonance gas

\[ \Rightarrow T(t), \mu_{\text{baryon,meson}}(t) \]

chemical freezeout:

- \( \mu^\text{chem}_N = 232 \) MeV
- hadron ratios fixed
  \[ \Rightarrow \mu_N, \mu_\pi, \mu_K, \mu_\eta \] at fixed \( s/\rho_B = 27 \)

thermal freezeout:

\( (T_{fo}, \mu^\text{fo}_\pi) \approx (120, 80) \) MeV
Fireball evolution

- comparison 1st-order EoS (EoS-A) vs. lattice EoS (EoS-L)
- in both $T_c = T_{ch} = 175$ MeV
- EoS-A: $t_{\text{form}} = 1$ fm/$c$, $r_0 = 4.6$ fm, $z_0 = 1.8$ fm $\Rightarrow$ $T_{\text{initial}} = 195$ MeV
- EoS-L: $t_{\text{form}} = 0.67$ fm/$c$, $r_0 = 4.0$ fm, $z_0 = 1.2$ $\Rightarrow$ $T_{\text{initial}} = 245$ MeV

![Graph showing the evolution of temperature with time for EoS-L and EoS-a]
M spectra (in $p_T$ slices)

- norm corrected by $\sim 3\%$ due to centrality correction
  (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)
M spectra (in $p_T$ slices)

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M spectra (in $p_T$ slices)

- norm corrected by $\sim 3\%$ due to centrality correction
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![Graph showing M spectra with various theoretical predictions and experimental data.](image)
M spectra (in $p_T$ slices)

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M spectra (in $p_T$ slices)

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

\begin{itemize}
  \item \text{NA60}
  \item in-med $\rho$
  \item QGP
  \item prim $\rho$
  \item FO $\rho$
  \item 4$\pi$ mix
  \item DY
  \item $\phi$
  \item $\omega$
  \item $\omega$-t ex
  \item total
  \item +$\omega$-t ex
\end{itemize}

$T_c = T_{ch} = 175$ MeV, EoS-L, $a_t = 0.1$ $c^2$/fm

\begin{equation}
(1/N_{ch}) d^2N_{\mu\mu} / (dM d\eta) (20 \text{ MeV})^{-1}
\end{equation}

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M spectra (in $p_T$ slices)

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

\[ M \text{ spectra (in } p_T \text{ slices)} \]

\[ \text{norm corrected by } \sim 3\% \text{ due to centrality correction} \]

\[ \langle N_{ch} \rangle = 120, \text{ calculation } N_{ch} = 140 \]
M spectra (in $p_T$ slices)

- norm corrected by $\sim 3\%$ due to centrality correction
  (min-bias data: $\langle N_{ch} \rangle = 120$, calculation $N_{ch} = 140$)
M spectra (in $p_T$ slices)

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

\[ T_c = T_{\text{ch}} = 175 \text{ MeV}, \text{ EoS-L, } a_t = 0.1 \text{ c}^2/\text{fm} \]

\[ 1.2 \text{ GeV} < q_t < 1.4 \text{ GeV} \]

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

\[ + \omega^{-t} \text{ ex} \]

\[ \text{total} \]

\[ \text{+} \omega^{-t} \text{ ex} \]
M spectra (in $p_T$ slices)

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

![Graph showing M spectra (in $p_T$ slices) with various decay channels and theoretical models.]
M spectra (in $p_T$ slices)

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

1.6 GeV $< q_t < 1.8$ GeV

$T_c = T_{ch} = 175$ MeV, EoS-L, $a_t = 0.1 \text{ c}^2/\text{fm}$

$(1/N_{ch}) \frac{d^2 N_{\mu\mu}}{dM \, d\eta} (20 \text{ MeV})^{-1}$

$M$ (GeV)

$+\omega^{-t \, \text{ex}}$

$\omega^{-t \, \text{ex}}$

$\omega$

$\phi$

$4\pi \text{ mix}$

$\text{DY}$

$\text{FO $\rho$}$

$\text{prim $\rho$}$

$\text{QGP}$

$\text{in-med $\rho$}$

$\text{NA60}$

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M spectra (in $p_T$ slices)

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

\[ T_c = T_{ch} = 175 \text{ MeV, EoS-L, } a_t = 0.1 \text{ } c^2/\text{fm} \]

\[ 1.8 \text{ GeV} < q_t < 2.0 \text{ GeV} \]

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

\[ M \text{ (GeV)} \]

\[ + \omega -t \text{ ex} \]

\[ \omega -t \text{ ex} \]

\[ \omega \phi \text{ DY} \]

\[ 4\pi \text{ mix} \]

\[ \text{FO } \rho \]

\[ \text{prim } \rho \]

\[ \text{in-med } \rho \]

\[ \text{QGP} \]

\[ \text{NA60} \]

\[ 10^{-9} \]

\[ 10^{-8} \]

\[ 10^{-7} \]

\[ 10^{-6} \]

\[ 10^{-5} \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ 1.2 \]

\[ 1.4 \]

\[ 1.8 \text{ GeV} < q_t < 2.0 \text{ GeV} \]

\[ T_c = T_{ch} = 175 \text{ MeV, EoS-L, } a_t = 0.1 \text{ } c^2/\text{fm} \]

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

\[ M \text{ (GeV)} \]
M spectra (in $p_T$ slices)

- norm corrected by $\sim 3\%$ due to centrality correction
  (min-bias data: $\langle N_{\text{ch}} \rangle = 120$, calculation $N_{\text{ch}} = 140$)
M spectra (in $p_T$ slices)

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

\[ T_c = T_{ch} = 175 \text{ MeV}, \text{ EoS-L}, a_t = 0.1 \text{ c}^2/\text{fm} \]
\[ 2.2 \text{ GeV} < q_t < 2.4 \text{ GeV} \]

\[ \frac{(1/N_{ch}) d^2 N_{\mu\mu}}{(dM d\eta)} (20 \text{ MeV})^{-1} \]

\[ M (\text{GeV}) \]

\[ +\omega -t \ ex \]

\[ \omega -t \ ex \]

\[ \omega \]

\[ \phi \]

\[ 4\pi \text{ mix} \]

\[ \text{DY} \]

\[ \text{FO} \]

\[ \rho \]

\[ \text{prim} \rho \]

\[ \text{QGP} \]

\[ \text{in-med} \rho \]

\[ \text{NA60} \]
The higher-mass region

- DY subtracted in data
- theory a bit low $\Rightarrow$ need longer QGP phase $\Rightarrow$ somewhat smaller formation time
Importance of baryon effects

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

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

\[M \, (\text{GeV})\]

\[q_T\]

\[T_c = T_{ch} = 175 \, \text{MeV}, \, a_t = 0.1 \, \text{c}^2/\text{fm}\]
$m_T$ spectra

![Graph showing $m_T$ spectra with labeled regions and theoretical predictions.](image)

- $0.2 \text{ GeV} < M < 0.4 \text{ GeV}$ (*6)
- $0.4 \text{ GeV} < M < 0.6 \text{ GeV}$ (*3)
- $0.6 \text{ GeV} < M < 0.9 \text{ GeV}$
- $1.0 \text{ GeV} < M < 1.4 \text{ GeV}$

Theory

Semicentral In-In

$T_c = T_{ch} = 175 \text{ MeV}$, $a_t = 0.1 \text{ c}^2/\text{fm}$
Conclusions and Outlook

- **dilepton spectra** ⇔ **in-medium em. current correlator**
- models 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
- 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
  - 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!
  - here: lattice EoS ⇒ QGP dominates over hadronic in the IMR
- dimuons in In-In (NA60), Pb-Au (CERES/NA45), $\gamma$ AA at SPS, RHIC, LHC ⇒ Charles Gale’s talk on Thursday
Conclusions and Outlook

- More realistic medium evolution
  - use transport model for medium evolution
  - dilemma: consistent implementation of in-medium em. current correlators?
  - pragmatic solutions:
    - use transport-hydro-hybrid approach: for UrQMD+Shasta 3D hydro
      ⇒ [Elvira Santini et al 2010/11]; use thermal rates in hydro; “shining” in UrQMD “afterburner”
    - new approach: “coarse-grained transport” ⇒ find energy + baryon density (“Eckhart frame”)
      ⇒ EoS. gives $(T, \mu_B) + \mu_\pi, \mu_K$; use again thermal rates in coarse-grained fluid cells
      ⇒ Stephan Endres’s talk on Thursday!

- Further theoretical developments
  - vector- should be complemented with axial-vector-spectral functions
    $(a_1$ as chiral partner of $\rho$)
  - constrained with lQCD via in-medium Weinberg chiral sum rules
  - direct connection to chiral phase transition!
    ⇒ Paul Hohler’s talk today!