Thermal photons and dileptons

Theory

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1 Electromagnetic probes in heavy-ion collisions
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   - Sources of dilepton emission in heavy-ion collisions
   - Sources of thermal photons in heavy-ion collisions

2 Application to heavy-ion collisions
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   - Dielectrons (SIS/HADES) with S. Endres, M. Bleicher, R. Rapp
   - Dimuons (SPS/NA60) with S. Endres, M. Bleicher, R. Rapp
   - Direct Photons at RHIC and LHC with M. He, R. Rapp

3 Conclusions and Outlook
Em. current correlator $\ell^+\ell^-$ and $\gamma$ rates
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

\[
\begin{align*}
\pi^0, \eta \text{ Dalitz decays} \\
\frac{dN}{dy dm} \\
\rho/\omega \\
\Phi \\
\Psi
\end{align*}
\]

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

\[
\Pi^{<}_{\mu\nu}(q) = \int d^4 x \exp(i q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 f_B (q \cdot u) \text{Im} \Pi^{(\text{ret})}_{\mu\nu}(q)
\]

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

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

- \( u \): four-velocity of the fluid cell; \( p \cdot u = p_0^{\text{hb}} \) energy in “heat-bath frame”

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

- vector-meson dominance model:
Sources of dilepton emission in heavy-ion collisions

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

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

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

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

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

\[\begin{align*}
\pi & \quad \rho \quad \pi \\
B^*, a_1, K_1, & \quad N, K, \pi, \ldots
\end{align*}\]

- +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)
baryon effects important

- large contribution to broadening of the peak
- responsible for most of the strength at small $M$
baryon effects important
- large contribution to broadening of the peak
- responsible for most of the strength at small $M$
In-medium spectral functions and baryon effects

-Im D_φ (GeV^{-2})
M (GeV)
φ (1020)
T=0
T=120 MeV
T=150 MeV
T=175 MeV

[R. Rapp, J. Wambach 99]

- **baryon effects** important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M
Intermediate masses: hadronic “4π contributions”

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

- “4π 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

\[-i\Pi_{em,QGP} = \begin{array}{c}
\gamma^* \\
q
\end{array} \begin{array}{c}
\bar{q} \nonumber \\
\gamma^* \nonumber
\end{array}\]

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

“quark-hadron duality” around $T_c$
in-medium hadron gas matches with QGP
similar results also for $\gamma$ rates
“quark-hadron duality”?  

![Graph showing dilepton rates](image_url)

Sources of thermal photons in heavy-ion collisions

- **QGP**: rates from [Arnold, Moore, Yaffe, JHEP 12, 009 (2001)]
  - $q\bar{q} \rightarrow \gamma g, qg \rightarrow \gamma q$
  - resummation of soft-gluon bremsstrahlung contributions
  - Landau-Pomeranchuk-Migdal effect

- **hadronic matter** from [Turbide, Rapp, Gale, PRC 69, 014903 (2004); Rapp, Wambach EPJ A 6, 415 (1999)]
  - pion-cloud dressing + vector meson-baryon/meson interactions
  - $\pi \rho a_1, \omega$-t-channel exchange
Medium evolution
Thermal fireball

- **cylindrical fireball model:** \( V_{FB} = \pi (z_0 + v_{z0} t + \frac{a_z}{2} t^2) \left( \frac{a_{\perp}}{2} t^2 + r_0 \right)^2 \)

- **thermodynamics:**
  - isentropic expansion; \( S_{\text{tot}} \) fixed by \( N_{\text{ch}} \); \( T_c = T_{\text{chem}} = 175 \text{ MeV} \)
  - \( T > T_c \): 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:**
  - \( \mu_{\text{chem}}^N = 232 \text{ MeV} \)
  - hadron ratios fixed
    \( \Rightarrow \mu_N, \mu_\pi, \mu_K, \mu_\eta \) at fixed \( s/\rho_B = 27 \)

- **thermal freezeout:**
  \( (T_{fo}, \mu_{\pi}^{fo}) \simeq (120, 80) \text{ MeV} \)
Coarse-grained transport (UrQMD)

- Use ensemble of UrQMD runs with an equation of state
- Map evolution of medium to locally thermalized fluid cells
- Fit temperature, chemical potentials, flow-velocity field from anisotropic energy-momentum tensor [W. Florkowski et al, NPA 904-905, 803c (2013)]

\[ T^{\mu\nu} = (\varepsilon + P_\perp) u^\mu u^\nu - P_\perp g^{\mu\nu} - (P_\parallel - P_\perp) V^\mu V^\nu \]

- Thermal rates from partonic/hadronic QFT become applicable
- Here: extrapolated lattice QGP and Rapp-Wambach hadronic many-body theory
- Caveat: consistency between EoS, matter content of QFT model/UrQMD!
Coarse-grained transport (UrQMD)

- $T_c = 170 \text{ MeV}$; $T > T_c \Rightarrow$ lattice EoS; $T < T_c \Rightarrow$ HRG EoS
Coarse-grained transport (UrQMD)

- energy/baryon density $\Rightarrow T, \mu_B$ (for In+In @ SPS; NA60)
- central “fluid” cell!
Coarse-grained transport (UrQMD)

- temperature/density profiles (for In+In@SPS; NA60)

Longitudinal density profile at $t=2\text{fm} / 5\text{fm}$

Transversal density profile at $t=2\text{fm} / 5\text{fm}$
Parametrized Rapp-Wambach rates

- need rates as function of $T$, $\mu_B$, $\mu_\pi$, $\mu_K$
- parametrization of the microscopic rates necessary
- comparison for 20 AGeV Au Au collisions (min bias) [R. Rapp private commun.]
- pion-cloud effects not fully implemented $\Rightarrow$ some deviations in LMR
Dielectrons (SIS/HADES)
e^+e^- M spectrum (SIS/HADES)

- coarse-graining method works at low energies!
- UrQMD-medium evolution + RW-QFT rates

![Graph showing energy spectrum](attachment:image.png)

Ar + KCl @ 1.76 GeV

UrQMD (π + η + ω) and in-medium Spectral Function from Coarse-Graining (ρ)

For comparison:
- ρ with no baryon effects
dielectron spectra from Ar + K Cl(1.76 A GeV) $\rightarrow$ e$^+$e$^-$ (SIS/HADES)
dielectron spectra from Ar + K Cl(1.76 A GeV) → e^+ e^- (SIS/HADES)
e^+e^- m_T spectra (SIS/HADES)

- dielectron spectra from Ar + K Cl (1.76 A GeV) → e^+e^- (SIS/HADES)

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dielectron spectra from Ar + K Cl(1.76 AGeV) → e⁺e⁻ (SIS/HADES)
$e^+e^− m_T$ spectra (SIS/HADES)

- dielectron spectra from Ar + K Cl(1.76 AGeV) $→ e^+e^−$ (SIS/HADES)

![Graph showing dielectron spectra from Ar + K Cl(1.76 AGeV) $→ e^+e^−$ (SIS/HADES)]
Dimuons (SPS/NA60)
$\mu^+\mu^-$ M spectra (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158\text{AGeV}) \rightarrow \mu^+\mu^-$ (NA60)
- min-bias data ($dN_{\text{ch}}/dy = 120$)
dimuon spectra from $\text{In}+\text{In}(158\,\text{AGeV}) \rightarrow \mu^+\mu^-$ (NA60)
min-bias data ($dN_{\text{ch}}/dy = 120$)
higher IMR: provides averaged true temperature
(no blueshifts in the invariant-mass spectra!)
\( \mu^+ \mu^- \) M spectra (SPS/NA60)

- dimuon spectra from \( \text{In} + \text{In}(158 \text{AGeV}) \rightarrow \mu^+ \mu^- \) (NA60)
- min-bias data \( (dN_{\text{ch}}/dy = 120) \)

![Graph showing dimuon spectra from In + In at 158 AGeV](image)

\( \text{In+In @ 158 AGeV} \)

\(<dN_{\text{ch}}/dy>=120, \ p_T < 0.2 \text{ GeV} \)

- In-medium \( \rho \)
- QGP (Lattice)
- 4 pion
- Sum

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- dimuon spectra from $\text{In} + \text{In}(158\text{AGeV}) \rightarrow \mu^+\mu^-$ (NA60)
- min-bias data ($dN_{\text{ch}}/dy = 120$)
\( \mu^+ \mu^- \) M spectra (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) \( \rightarrow \mu^+ \mu^- \) (NA60)
- min-bias data \( (dN_{\text{ch}}/dy = 120) \)
dimuon spectra from $\text{In} + \text{In}(158\text{AGeV}) \rightarrow \mu^+\mu^-$ (NA60)
min-bias data ($dN_{\text{ch}}/dy = 120$)
$\mu^+\mu^-$ $M$ spectra (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158\text{AGeV}) \rightarrow \mu^+\mu^-$ (NA60)
- min-bias data ($dN_{\text{ch}}/dy = 120$)

![Graph showing dimuon spectra](image-url)
\(\mu^+\mu^-\) M spectra (SPS/NA60)

- dimuon spectra from In + In (158 AGeV) \(\rightarrow\) \(\mu^+\mu^-\) (NA60)
- min-bias data (\(dN_{ch}/dy = 120\))
\( \mu^+ \mu^- \) M spectra (SPS/NA60)

- dimuon spectra from \( \text{In} + \text{In}(158 \text{ AGeV}) \rightarrow \mu^+ \mu^- \) (NA60)
- min-bias data (d\( N_{\text{ch}}/d\eta = 120 \))
**μ⁺μ⁻** M spectra (SPS/NA60)

- dimuon spectra from \( \text{In} + \text{In} (158 \text{ AGeV}) \rightarrow \mu^+ \mu^- \) (NA60)
- min-bias data (\(dN_{\text{ch}}/dy = 120\))

![Graph](image-url)

**Legend**:
- In-medium \(\rho\)
- QGP (Lat.)
- 4 pion
- Sum

**In+In @ 158 AGeV**

\(<dN_{\text{ch}}/dy>=120, \ 1.4 < p_T < 1.6 \text{ GeV}\)
dimuon spectra from $\text{In} + \text{In}(158\text{AGeV}) \rightarrow \mu^+\mu^-$ (NA60)

min-bias data ($dN_{\text{ch}}/dy = 120$)
\( \mu^+ \mu^- \) \( M \) spectra (SPS/NA60)

- dimuon spectra from \( \text{In} + \text{In}(158 \, \text{AGeV}) \rightarrow \mu^+ \mu^- \) (NA60)
- min-bias data \((dN_{\text{ch}}/dy = 120)\)

\[
\begin{array}{c}
\text{In+In @ 158 AGeV} \\
<\!dn_{\text{ch}}/dy\!>=120, \; 1.8 < p_T < 2.0 \, \text{GeV}
\end{array}
\]
dimuon spectra from In + In (158 A GeV) → $\mu^+\mu^-$ (NA60)
min-bias data ($dN_{ch}/dy = 120$)
\( \mu^+ \mu^- \) M spectra (SPS/NA60)

- dimuon spectra from \( \text{In} + \text{In}(158\text{AGeV}) \rightarrow \mu^+ \mu^- \) (NA60)
- min-bias data \((dN_{\text{ch}}/dy = 120)\)

![Graph showing dimuon spectra from In+In with different models: In-medium \(\rho\), QGP (Lat.), 4 pion, and Sum.](image)

- \( \text{In+In \@ 158 AGeV} \)
- \(<dN_{\text{ch}}/dy>=120, \ 2.2 < p_T < 2.4 \text{ GeV}\)
**$\mu^+\mu^-$ $M$ spectra (SPS/NA60)**

- dimuon spectra from $\text{In} + \text{In}(158\text{AGeV}) \rightarrow \mu^+\mu^- \ (\text{NA60})$
- min-bias data ($dN_{\text{ch}}/dy = 120$)
- influence of baryon interactions in spectral function
- from previous calculation with thermal-fireball parametrization (compatible with course-grained UrQMD)

![Graph](image.png)

- $T_c = T_{\text{ch}} = 175 \text{ MeV}$, $a_t = 0.1 \text{ c}^2/\text{fm}$
\( \mu^+ \mu^- m_T \) spectra (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) → \( \mu^+ \mu^- \) (NA60)
- min-bias data (d\(N_{\text{ch}}/dy = 120\))
\( \mu^+ \mu^- \) \( m_T \) spectra (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) \( \rightarrow \mu^+ \mu^- \) (NA60)
- min-bias data \((dN_{ch}/dy = 120)\)

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\( \mu^+ \mu^- m_T \) spectra (SPS/NA60)

- dimuon spectra from In + In(158 A GeV) → \( \mu^+ \mu^- \) (NA60)
- min-bias data (dN\(_{\text{ch}}\)/dy = 120)

In-medium QGP (Lattice)

4 pion Sum

Rapp Wambach SF

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Thermal photons and dileptons

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\( \mu^+ \mu^- \ m_T \) spectra (SPS/NA60)

- dimuon spectra from In + In(158 AGeV) \( \rightarrow \mu^+ \mu^- \) (NA60)
- min-bias data \((dN_{ch}/dy = 120)\)

![Graph showing dimuon spectra](image-url)
Direct Photons at RHIC and LHC
fitted to measured $p_T$ spectra and $v_2$; multi-strange hadrons: fo at $T_c$!

- can be achieved with (ideal) hydro

[He, Fries, Rapp, PRC 85, 044911 (2012); HvH, He, Rapp arXiv: 1404.2846 [nucl-th]]

- important for “sufficient” photon $v_2$:
  - rapid buildup of $v_2$
  - (nearly) full $v_2$ at end of mixed phase
  - consistent with CQN scaling for multi-strange and other hadrons!
RHIC:

[PHENIX $\pi^+$ (av. 0-20%) vs. $p$ (av 0-20%)]

[PHENIX $\pi^-$ + $K^-$ (0-20%)]

[STAR $\phi$ (av. 0-20%)]

[STAR $\phi$ (0-80%) vs. $p$ (0-5%)]

blue-shift formula (Doppler effect) translates into

\[ T_{\text{eff}} \simeq T \sqrt{\frac{1 + \langle v_T \rangle}{1 - \langle v_T \rangle}}, \quad v_T : \text{transverse fluid flow} \]

measured slope indicates emission from source around \( T_c \)
Direct photons: fireball

0-20% Au-Au, \( y_t < 0.35 \) hadron gas

- QGP
- primordial
- total
- PHENIX

\( q_0 \frac{dN}{d^3q} \) (GeV^2)

\( q_T \) (GeV)

0-40% Pb-Pb, \( y_t < 0.75 \)

\( q_0 \frac{dN}{d^3q} \) (GeV^2)

\( q_T \) [GeV]

PHENIX dir \( \gamma \) (BBC)

- total
- total-2
- thermal \( \gamma \)

ALICE prelim.

- total
- thermal \( \gamma \)
Direct photons: ideal hydro

\[ q_0 \frac{dN}{d^3q} (\text{GeV}^2) \]

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

\[ q_0 \frac{dN}{d^3q} (\text{GeV}^2) \]

\[ q_T \text{ [GeV]} \]

PHENIX dir $\gamma$ (BBC)
- total
- total-2
- thermal $\gamma$

lattice EoS

ALICE prelim.
- total
- thermal $\gamma$
Direct photons: enhanced rates

- Assume enhancement of baseline rates by factor of 2
- Augmented up to factor of 3 for $140 \text{ MeV} < T < 200 \text{ MeV}$
Conclusions and Outlook

- **General ideas**
  - em. probes ⇔ in-medium em. current-correlation function
  - dual rates around $T_c$ (compatible with $\chi$ symmetry restoration)
    ⇒ see Paul Hohler’s talk
  - medium modifications of $\rho$, $\omega$, $\phi$
  - importance of baryon-resonance interactions

- **Application to dileptons in HICs**
  - need realistic bulk-medium evolution
  - thermal fireball, (ideal) hydrodynamics
  - new: coarse-grained transport
  - applicable also at low collision energies
  - allows use of thermal-QFT models for em. current-correlation functions
  - successful description at HADES, SPS, and RHIC (STAR)
  - consistent description of $M$ and $m_T$ spectra!
  - **Outlook**: effective slope of $M$ spectra in higher IMR
    $(1.5 \text{ GeV} < M < M_{J/\psi})$ provides $\langle T \rangle$
  - applied in beam-energy scan at RHIC and FAIR ⇒ signature of phase transition?
  - signature of cross-over vs. 1st order (or even critical endpoint)?
Application to photons in HICs

- so far: bulk evolution with elliptic thermal fireball and hydro
direct-photon “$v_2$ puzzle”
dominated from fireball temperatures around $T_c$ (remnant of latent heat)

⇒ Early build-up of elliptic flow
compatible with early freeze-out of multi-strange hadrons
can be achieved with fireball parametrization or choice of appropriate hydro-initial conditions (initial flow)
still yield missing ⇒ probable enhancement of rates due to non-perturbative enhanced cross sections around $T_c$?!?