Thermal photons and dileptons

Theory

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Outline

1. Electromagnetic probes in heavy-ion collisions
   - Em. current correlation function and electromagnetic probes
   - Sources of dilepton emission in heavy-ion collisions
   - Sources of thermal photons in heavy-ion collisions

2. Application to heavy-ion collisions
   - Models for bulk-medium evolution
   - 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

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

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

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

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

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

\[
\Sigma_{\mu\nu} = G_{\rho} \]

\[
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Sources of dilepton emission in heavy-ion collisions

1. initial hard processes: Drell Yan

2. “core” ⇔ emission from thermal source \[\text{[McLerran, Toimela 1985]}\]

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

3. “corona” ⇔ emission from “primordial” mesons (jet-quenching)

4. after thermal freeze-out ⇔ emission from “freeze-out” mesons \[\text{[Cooper, Frye 1975]}\]

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

- HMBT for vector mesons [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, ...]
- ππ interactions and baryonic excitations

+ corresponding vertex corrections ⇔ 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

-Im $D_\rho$ ($\text{GeV}^{-2}$) vs. $M$ (GeV)

- $\rho(770)$

- $T=0$
- $T=120$ 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 $M$
In-medium spectral functions and baryon effects

-Im $D_\omega$ (GeV$^{-2}$) vs $M$ (GeV)

-Im $D_\omega$ (GeV$^{-2}$) vs $M$ (GeV)

$\omega(782)$

[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 $M$
**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]
Intermediate masses: hadronic “4π contributions”

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

- “4π contributions”: $\pi + \omega, a_1 \to \mu^+ + \mu^-$
- leading-order virial expansion for “four-pion piece”
- additional strength through “chiral mixing”
motivation: $q_T$ spectra too soft compared to NA60 data

thermal contributions not included in models so far

also for $\pi$, $a_1$
Dileptons from thermal QGP

- in QGP phase: $q\bar{q}$ annihilation
- HTL improved electromagnetic current correlator

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

- 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 γ rates

“quark-hadron duality”? 

Sources of thermal photons in heavy-ion collisions

- **QGP**: rates from [Arnold, Moore, Yaffe, JHEP 12, 009 (2001)]
  - $q\bar{q} \rightarrow \gamma g$, $qg \rightarrow \gamma q$

  ![Diagram of QGP rates](image)

  - 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

  ![Diagram of hadronic matter](image)

  - $\pi\rho a_1$, $\omega$-t-channel exchange

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Medium evolution
Thermal fireball

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

- **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:**
  - \( \mu_{N}^{\text{chem}} = 232 \text{ MeV} \)
  - hadron ratios fixed
    \( \Rightarrow \mu_N, \mu_\pi, \mu_K, \mu_\eta \) at fixed
  - \( s/\rho_B = 27 \)

- **thermal freezeout:**
  - \( (T_{\text{fo}}, \mu_{\pi}^{\text{fo}}) \approx (120, 80) \text{ MeV} \)
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)]

\[ T^\mu_\nu = (\epsilon + P_\perp)u^\mu u^\nu - P_\perp g^\mu_\nu - (P_\parallel - P_\perp)V^\mu V^\nu \]

- 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)

- $T_c = 170$ 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!

![Graph showing energy density and baryon density over time for In+In collisions at 158 AGeV.]
Coarse-grained transport (UrQMD)

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

![Longitudinal density profile at t=2fm / 5fm](image)

Longitudinal density profile at t=2fm / 5fm
In+In @ 158 AGeV

![Transversal density profile at t=2fm / 5fm](image)

Transversal density profile at t=2fm / 5fm
In+In @ 158 AGeV

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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

![Graph showing comparing different processes](image-url)
Dielectrons (SIS/HADES)
coarse-graining method works at low energies!

UrQMD-medium evolution + RW-QFT rates

\[ e^+ e^- \, M \text{ spectrum (SIS/HADES)} \]
\( e^+ e^- m_T \) spectra (SIS/HADES)

- dielectron spectra from \( \text{Ar} + \text{KCl}(1.76\text{AGeV}) \rightarrow e^+ e^- \) (SIS/HADES)
dielectron spectra from Ar + K Cl (1.76 A GeV) → e⁺e⁻ (SIS/HADES)
dielectron spectra from $\text{Ar} + \text{K Cl}(1.76\text{AGeV}) \rightarrow e^+e^-$ (SIS/HADES)
$e^+e^- m_T$ spectra (SIS/HADES)

- dielectron spectra from $\text{Ar} + \text{K Cl}(1.76\text{AGeV}) \rightarrow e^+e^-$ (SIS/HADES)
dielectron spectra from $\text{Ar} + \text{K Cl}(1.76\text{AGeV}) \to e^+e^-$ (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 ($dN_{\text{ch}}/dy = 120$)
$\mu^+\mu^-$ M spectra (SPS/NA60)

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

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August 20, 2014 25 / 35
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 ($dN_{\text{ch}}/dy = 120$)

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

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

![Graph showing dimuon spectra from In + In(158 AGeV) \( \rightarrow \mu^+ \mu^- \) (NA60) with min-bias data \( (dN_{\text{ch}}/dy = 120) \).]
$\mu^+ \mu^- \, M$ spectra (SPS/NA60)

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

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

In+In @ 158 AGeV
$dN_{ch}/dy = 120$, $0.6 < p_T < 0.8 \text{ GeV}$

- In-medium $\rho$
- QGP (Lat.)
- 4 pion
- Sum

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**μ⁺μ⁻ M spectra (SPS/NA60)**

- Dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60)
- Min-bias data (dN\(_{ch}/dy = 120\))

![Graph showing dimuon spectra from In + In(158 AGeV) → μ⁺μ⁻ (NA60) with min-bias data (dN\(_{ch}/dy = 120\)).](image)
\( \mu^+ \mu^- \) 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 $\text{In} + \text{In}(158\,\text{AGeV}) \to \mu^+\mu^-$ (NA60)
- min-bias data ($dN_{\text{ch}}/dy = 120$)

![Graph showing dimuon spectra from In + In(158 AGeV) to mu^+mu^- (NA60) with min-bias data (dN_{ch}/dy = 120).](image-url)
dimuon spectra from In + In (158 AGeV) → \(\mu^+\mu^-\) (NA60)
min-bias data (dN\text{ch}/dy = 120)
\( \mu^+\mu^- \) M spectra (SPS/NA60)

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

\[
\begin{align*}
\text{Invariant Mass } M & \text{ [GeV/c}^2] \\
0 & \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \quad 1.2 \quad 1.4
\end{align*}
\]

\[
\begin{align*}
\text{(d}N^2\text{)}/(\text{d}M\text{d}y) & \text{ [20 MeV]} \\
10^{-7} & \quad 10^{-8} \quad 10^{-9} \quad 10^{-10}
\end{align*}
\]
\( \mu^+ \mu^- \) M spectra (SPS/NA60)

- dimuon spectra from In + In (158 A GeV) \( \rightarrow \mu^+ \mu^- \) (NA60)
- min-bias data (d\(N_{ch}/dy = 120\))
\( \mu^+ \mu^- \) M 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 from In + In(158 AGeV) \( \rightarrow \mu^+ \mu^- \) (NA60)](image-url)
dimuon spectra from In + In (158 AGeV) → µ⁺µ⁻ (NA60)
min-bias data (dN_{ch}/dy = 120)
dimuon spectra from $\text{In} + \text{In}(158\text{AGeV}) \rightarrow \mu^+\mu^-$ (NA60)

min-bias data ($dN_{\text{ch}}/dy = 120$)

influence of baryon interactions in spectral function

from previous calculation with thermal-fireball parametrization (compatible with course-grained UrQMD)
**$\mu^+ \mu^-$ $m_T$ 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)

In-medium QGP (Lattice)

4 pion

Rapp Wambach SF

In+In @ 158 AGeV

HG-EoS + Lattice EoS

$\langle dN_{\text{ch}}/d\eta \rangle = 120$, $0.2 < M < 0.4 \text{ GeV}$
$\mu^+ \mu^- m_T$ spectra (SPS/NA60)

- Dimuon spectra from In + In (158 AGeV) $\rightarrow \mu^+ \mu^-$ (NA60)
- Min-bias data ($dN_{ch}/dy = 120$)
\( \mu^+ \mu^- m_T \) 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 $(\text{d}N_{\text{ch}}/\text{d}y = 120)$
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

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:


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Temperature vs. effective Slope

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

- blue-shift formula (Doppler effect) translates into

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

- 0-20% Au-Au, $y_l<0.35$
- Hadron gas
- QGP
- Primordial
- Total
- PHENIX

$0_0 \frac{dN}{d^3q} [\text{GeV}^{-2}]$

$q_T \text{ (GeV)}$

- 0-40% Pb-Pb, $y_l<0.75$

$0_0 \frac{dN}{d^3q} [\text{GeV}^{-2}]$

$q_T \text{ (GeV)}$
Direct photons: ideal hydro

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Thermal photons and dileptons
August 20, 2014 32 / 35
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 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)?
Conclusions and Outlook

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)
  \( \Rightarrow \) 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 \( \Rightarrow \) probable enhancement of rates due to non-perturbative enhanced cross sections around \( T_c \)??