Dileptons from heavy-ion collisions at SIS and FAIR/NICA energies

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Tel Aviv
March 28th 2017
Modelling of photon/dilepton emission

I. Emission rate from thermal field theory:

- **Photons:**
  \[
  \frac{d^3 R}{d^3 q} = - \frac{g_{\mu\nu}}{(2\pi)^3} \text{Im} \Pi^{\mu\nu}(q_0) = \mid q \mid f(q_0, T)
  \]

- **Dileptons:**
  \[
  \frac{d^3 R}{d^3 p_+ d^3 p_-} = \frac{2e^2}{(2\pi)^6} \frac{1}{q^4} L_{\mu\nu} \text{Im} \Pi^{\mu\nu}(q_0, \bar{q}) f(q_0, T)
  \]
  \(L_{\mu\nu}\) is the electromagnetic leptonic tensor

- **Bose distribution:**
  \[
  f(q_0, T) = \frac{1}{e^{q_0/T} - 1}
  \]

- **Hadron phase:** using VDM: \(\text{Im} \Pi \rightarrow \text{Im} D^\rho\) in-medium \(\rho\)-meson spectral function from many-body approach (cf. Rapp, Chanfrey, Wambach, NPA 617 (1997) 472)

- **Study of the in-medium properties of hadrons at high baryon density and T**

- **Restoration of chiral symmetry (\(\rho-a_1\)):**
  \(\text{Im} D^\rho \rightarrow\) chiral condensate (by Weinberg sum rules)
  (cf. Hohler, Rapp, arXiv:1311.2921)

- **Rates at \(q_0 \rightarrow 0\) are related to electric conductivity \(\sigma_0\)**
  \(\rightarrow\) Probe of electric properties of the QGP

  \[
  \frac{dR}{d^4 x d^3 q} \bigg|_{q_0 \rightarrow 0} = \frac{T}{4\pi^3} \sigma_0
  \]

  PHSD plot from Cassing et al., PRL 110 (2013) 182301; cf. also NJL: Marty et al., PRC87 (2013) 3, 034912
The in-medium rho-meson propagator

\[ D^{L,T}_{\rho}(q_0, q; \mu_B, T) = \frac{1}{M^2 - m^2_v - \Sigma^{L,T}_{\rho \pi \pi} - \Sigma^{L,T}_{\rho M} - \Sigma^{L,T}_{\rho B}} \]

depends on medium-dependent selfenergies that include modifications of the 2-pion decay, scatterings with baryons and mesons
cf. talk by Ralf
Modelling of the space-time evolution

a) Fit a fireball evolution to asymptotic particle spectra and integrate the microscopic dilepton rate in space-time over the fireball evolution; open question: is the assumption of thermal and chemical equilibrium justified?

b) Coarse-grained transport models: calculate energy-momentum tensor and charge current in local cells by averaging over many events:

\[ T^\mu{}^\nu = \int d^3 p \frac{p^\mu p^\nu}{p^0} f(\vec{x}, \vec{p}, t) = \frac{1}{\Delta V} \left\langle \sum_{i=1}^{N_p} \frac{p_i^\mu \cdot p_i^\nu}{p_i^0} \right\rangle, \]

\[ j_\mu = \int d^3 p \frac{p^\mu}{p^0} f_B(\vec{x}, \vec{p}, t) = \frac{1}{\Delta V} \left\langle \sum_{i=1}^{N_B} \pm \frac{p_i^\mu}{p_i^0} \right\rangle. \]

This defines a local ‘temperature‘ and chemical potential assuming chemical equilibrium; then integrate a microscopic dilepton rate in space-time

S. Endres et al., PRC 92 (2015) 014911
Large effect of a finite baryon density on the low-mass dilepton spectra!

Baryon-hole loops or meson-baryon scatterings drive the enhancement!

S. Endres et al., PRC 92 (2015) 014911
Modelling of photon/dilepton emission

II. Emission rate from relativistic kinetic theory:
(e.g. for $1+2 \rightarrow \gamma+3$)

\[
q_0 \frac{d^3 R}{d^3 q} = \int \frac{d^3 p_1}{2(2\pi)^3 E_1} \frac{d^3 p_2}{2(2\pi)^3 E_2} \frac{d^3 p_3}{2(2\pi)^3 E_3} (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - q) \\
\times |M|^2 \frac{f(E_1)f(E_2)[1 \pm f(E_3)]}{2(2\pi)^3}
\]

- $f(E)$ - distribution function
- $|M|$ – invariant scattering matrix element from microscopic models

- Modelling of hadronic elementary reactions:
  Chiral models, OBE models,… (Born-type diagrams)

- Problems:
  - very limited experimental information on mm, mB elementary reactions
  - Hadrons change their properties in the hot and dense medium:
    from vacuum cross sections to in-medium, i.e.
    from 'T-matrix' to 'G-matrix' approaches (many-body theory)

  E.g. : $\rho$-meson collisional broadening – important for dilepton studies!

Applicable also for non-equilibrium systems!
HSD coarse-grained with a microscopic dilepton rate

Only small differences between old on-shell transport (HSD) and coarse-grained microscopic spectra

What about a full off-shell quantum transport?
From SIS to LHC: from hadrons to partons

The goal: to study of the phase transition from hadronic to partonic matter and properties of the Quark-Gluon-Plasma on a microscopic level

→ need a consistent non-equilibrium transport approach on the level of propagators to incorporate dynamical spectral functions!

- with explicit parton-parton interactions (i.e. between quarks and gluons)
- explicit phase transition from hadronic to partonic degrees of freedom
- IQCD EoS for partonic phase (‘cross over’ at $\mu_q=0$)
- Transport theory for strongly interacting systems: off-shell Kadanoff-Baym equations for the Green-functions $S^<(x,p)$ in phase-space representation for the partonic and hadronic phase

Parton-Hadron-String-Dynamics (PHSD)

QGP phase is described by

Dynamical QuasiParticle Model (DQPM)


The Dynamical QuasiParticle Model (DQPM)

- Basic idea: interacting quasi-particles: massive quarks and gluons \((g, q, q_{\text{bar}})\) with Lorentzian spectral functions:

- fit to lattice (lQCD) results (e.g. entropy density) with 3 parameters

- T-dependent \(\alpha_s(T)\)

- Quasi-particle properties:
  - large width and mass for gluons and quarks

\[
\rho_i(\omega, T) = \frac{4\omega \Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2 \Gamma_i^2(T)} \quad (i = q, \bar{q}, g)
\]

- **DQPM** provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)

- **DQPM** gives transition rates for the formation of hadrons

\[
\mu_q = 0
\]

- IQCD: pure glue

- PHSD

DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Parton-Hadron-String-Dynamics (PHSD)

- **Initial A+A collisions – HSD:**
  \[ \text{N+N} \rightarrow \text{string formation} \rightarrow \text{decay to 'pre-hadrons'} \]

- **Formation of QGP stage if \( \varepsilon > \varepsilon_{\text{critical}} \):**
  - dissolution of pre-hadrons \( \rightarrow (\text{DQPM}) \rightarrow \)
  - massive quarks/gluons + mean-field potential \( U_q \)

- **Partonic stage – QGP :**
  - based on the Dynamical Quasi-Particle Model (DQPM)
  - **(quasi-) elastic collisions:**
    - \( q + q \rightarrow q + q \)
    - \( g + q \rightarrow g + q \)
    - \( q + \bar{q} \rightarrow q + \bar{q} \)
    - \( g + \bar{q} \rightarrow g + \bar{q} \)
    - \( \bar{q} + \bar{q} \rightarrow \bar{q} + \bar{q} \)
    - \( g + g \rightarrow g + g \)
  - **inelastic collisions:**
    - \( q + \bar{q} \rightarrow g + g \)
    - \( q + \bar{q} \rightarrow g + g \)
    - \( g \rightarrow q + \bar{q} + g \)
    - \( g \rightarrow g + g \)

- **Hadronization (based on DQPM):**
  - \( g \rightarrow q + \bar{q}, \quad q + \bar{q} \leftrightarrow \text{meson (or 'string')} \)
  - \( q + q + q \leftrightarrow \text{baryon (or 'string')} \)

- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

QGP in equilibrium: Transport properties at finite \((T, \mu_q)\): \(\eta/s\)

Infinite hot/dense matter = PHSD in a box:

Shear viscosity \(\eta/s\) at finite \((T, \mu_q)\)

IQCD:

\[
\frac{T_c(\mu_q)}{T_c(\mu_q=0)} = \sqrt{1 - \alpha \mu_q^2} \approx 1 - \alpha/2 \mu_q^2 + \ldots
\]

QGP in PHSD = strongly-interacting partonic system

\(\eta/s\): \(\mu_q=0 \Rightarrow\) finite \(\mu_q\): smooth increase as a function of \((T, \mu_q)\)

Transport properties at finite \((T, \mu_q)\): \(\sigma_e/T\)

**PHSD in a box:**
Electric conductivity \(\sigma_e/T\) at finite \(T\)

*W. Cassing et al., PRL 110(2013)182301*

- the QCD matter even at \(T \sim T_c\) is a much better electric conductor than Cu or Ag (at room temperature) by a factor of 500!

**Electric conductivity \(\sigma_e/T\) at finite \((T, \mu_q)\)**

*H. Berrehrah et al. arXiv:1412.1017*

\[
\sigma_e/T : \mu_q=0 \rightarrow \text{finite } \mu_q: \text{smooth increase as a function of } (T, \mu_q)
\]

- **Photon emission:** rates at \(q_0 \rightarrow 0\) are related to electric conductivity \(\sigma_0\)

\[
q_0 \frac{dR}{d^4xd^3q_{q_0 \rightarrow 0}} = \frac{T}{4\pi^3} \sigma_0
\]

\(\sigma_0 \rightarrow \text{Probe of electric properties of the QGP}\)
Dilepton sources

- from the QGP via partonic (q,qbar, g) interactions:

- from hadronic sources:
  - direct decay of vector mesons (ρ,ω,φ,J/Ψ,Ψ′)
  - Dalitz decay of mesons and baryons (π₀,η,Δ,...)
  - correlated D+Dbar pairs
  - radiation from multi-meson reactions (π+π+, π+ρ, π+ω, ρ+ρ , π+a₁) - $4\pi$°

Advantage of dileptons: additional „degree of freedom“ ($M$) allows to disentangle various sources
Dileptons at SIS energies - HADES

- HADES: dilepton yield $dN/dM$ scaled with the number of pions $N_{\pi 0}$

- Dominant hadronic sources at $M > m_\pi$:
  - $\eta, \Delta$ Dalitz decays
  - NN bremsstrahlung
  - direct $\rho$ decay

- $\rho$ meson = strongly interacting resonance
  - strong collisional broadening of the $\rho$ width

- In-medium effects are more pronounced for heavy systems such as Ar+KCl than C+C
- The peak at $M \sim 0.78$ GeV relates to $\omega/\rho$ mesons decaying in vacuum

Dileptons at SIS energies: A+A vs. N+N

- ratio of AA/NN spectra (scaled by $N_{\pi\pi}$) after subtracted $\eta$ contribution

Strong enhancement of dilepton yield in A+A vs. NN is reproduced by HSD and IQMD for C+C at 1.0, 2.0 A GeV and Ar+KCl at 1.75 A GeV

Two contributions to the enhancement of dilepton yield in A+A vs. NN

1) the pN bremsstrahlung which scales with the number of collisions and not with the number of participants, i.e. pions;

2) the multiple Δ regeneration – dilepton emission from intermediate Δ’s which are part of the reaction cycles Δ→πN; πN→Δ and NN→NΔ; NΔ→NN

Enhancement of dilepton yield in A+A vs. NN increases with the system size!
Dileptons at SIS (HADES): Au+Au

CPOD-2016:
HADES preliminary: Au+Au, 1.23 A GeV

- HSD predictions (2013)

- Strong in-medium enhancement of dilepton yield in Au+Au vs. NN
  ➔ related to Δ regeneration!

Thermal dilepton rates in lattice QCD

Dileptons from dynamical off-shell quark and gluon interactions, LO and NLO in the coupling


- Quantitative agreement of DQPM, lattice QCD and HTL

Lessons from SPS: NA60

- **Dilepton invariant mass spectra:**
  - PHSD: Linnyk et al, PRC 84 (2011) 054917
  - Hybrid-UrQMD: Santini et al., PRC84 (2011) 014901

- **Message from SPS: (based on NA60 and CERES data)**
  1. **Low mass spectra** - evidence for the in-medium broadening of \(\rho\)-mesons
  2. **Intermediate mass spectra above 1 GeV** - dominated by partonic radiation
  3. **The rise and fall of \(T_{\text{eff}}\)** – evidence for the thermal QGP radiation
  4. **Isotropic angular distribution** – indication for a thermal origin of dimuons

- **Inverse slope parameter \(T_{\text{eff}}\):**
  - Spectrum from QGP is softer than from hadronic phase since the QGP emission occurs dominantly before the collective radial flow has developed
Dileptons at RHIC: STAR data vs model predictions

Centrality dependence of dilepton yield

Message: STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP

Excess in low mass region, min. bias

Models:
- Fireball model – R. Rapp
- PHSD

Low masses:
- collisional broadening of ρ

Intermediate masses:
- QGP dominant

PRC 92 (2015) 024912
Dileptons from RHIC BES: STAR

Message:
- BES-STAR data show a constant low mass excess (scaled with $N(\pi^0)$) within the measured energy range.
- PHSD: excess increasing with decreasing energy due to a longer $\rho$-propagation in the high baryon density phase.
- Good perspectives for future experiments – CBM(FAIR) / MPD(NICA)
Dileptons at FAIR/NICA energies: predictions

Au+Au, $s^{1/2}=19$ GeV, $b=2$ fm, $|y|<1$

Au+Au, $s^{1/2}=11$ GeV, $b=2$ fm, $|y|<1$

Au+Au, $s^{1/2}=9$ GeV, $b=2$ fm, $|y|<1$

Au+Au, $s^{1/2}=7.7$ GeV, $b=2$ fm, $|y|<1$

PHSD:
- sum
- $D/\bar{D}$
- $q + \bar{q} \rightarrow e^+e^-$

$M$ [GeV/c$^2$]

$\frac{dN}{dM}$ [1/(GeV/c$^2$)]
Messages from dilepton data

- **Low dilepton masses:**
  - Dilepton spectra show sizeable changes due to the in-medium effects – modification of the properties of vector mesons (as collisional broadening) - which are observed experimentally
  - In-medium effects can be observed at all energies from SIS to LHC

- **Intermediate dilepton masses at FAIR/NICA:**
  - The QGP (qbar-q) dominates for M>1.2 GeV
  - Fraction of QGP dominant over D/D_bar

**Outlook:**
* experimental energy scan
* experimental measurements of dilepton’s higher flow harmonics $v_n$
Thanks to: PHSD group (2016)

FIAS & GSI
Elena Bratkovskaya
Taesoo Song
Pierre Moreau
Andrej Ilner

Giessen University
Wolfgang Cassing
Olena Linnyk
Thorsten Steinert
Alessia Palmese
Eduard Seifert

External Collaborations

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Barcelona University:
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Angel Ramos

Duke University:
Steffen Bass
Marlene Nahrgang
Non-equilibrium dynamics: description of A+A with PHSD

PHSD: highlights

PHSD provides a good description of 'bulk' observables (y-, pT-distributions, flow coefficients $v_n$, ...) from SIS to LHC