Photons and dileptons as probes of the hot and dense matter

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Photons as penetrating probes

Direct photons; real or virtual are penetrating probes for the bulk matter produced in hadronic collisions, as
- They do not interact strongly; - They have a large mean free path

Price: “Historians” of the heavy ion collision encode all sub-processes at all times.
⇒ Require models to describe the emission during the whole collision evolution

- Fire-balls
- Hydrodynamics
- Hydro+Transport
- (off-shell) Transport

Graphics from the slides by D. Srivastava.
I. PHSD - basic concepts

I. From hadrons to QGP:

- Initial A+A collisions – as in HSD:
  - string formation in primary NN collisions
  - string decay to pre-hadrons (B - baryons, m - mesons)

- Formation of QGP stage by dissolution of pre-hadrons
  (all new produced secondary hadrons)
  into massive colored quarks + mean-field energy

\[ B \rightarrow qqq, \quad m \rightarrow q\bar{q} \]

based on the Dynamical Quasi-Particle Model (DQPM) which defines
quark spectral functions, i.e. masses \( M_q(\varepsilon) \) and widths \( \Gamma_q(\varepsilon) \)

+ mean-field potential \( U_q \) at given \( \varepsilon \) – local energy density

(\( \varepsilon \) related by IQCD EoS to \( T \) - temperature in the local cell)

II. Partonic phase - QGP:

- quarks and gluons (= 'dynamical quasiparticles')
- with off-shell spectral functions (width, mass) defined by the DQPM
- in self-generated mean-field potential for quarks and gluons $U_q, U_g$ from the DQPM
- EoS of partonic phase: 'crossover' from lattice QCD (fitted by DQPM)
- (quasi-) elastic and inelastic parton-parton interactions:
  - using the effective cross sections from the DQPM
  - (quasi-) elastic collisions:
    $q + q \rightarrow q + q \quad g + q \rightarrow g + q$
    $q + \overline{q} \rightarrow q + \overline{q} \quad g + \overline{q} \rightarrow g + \overline{q}$
    $\overline{q} + \overline{q} \rightarrow \overline{q} + \overline{q} \quad g + g \rightarrow g + g$
  - inelastic collisions:
    (Breight-Wigner cross sections)
    $q + \overline{q} \rightarrow g \quad q + \overline{q} \rightarrow g + g$
    $g \rightarrow q + \overline{q} \quad g \rightarrow g + g$
    suppressed (<1%) due to the large mass of gluons
III. PHSD - basic concepts

III. Hadronization:

- Hadronization: based on DQPM

- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - 'strings' (strings act as 'doorway states' for hadrons)

\[ g \rightarrow q + \bar{q}, \quad q + \bar{q} \leftrightarrow \text{meson ('string')} \]
\[ q + q + q \leftrightarrow \text{baryon ('string')} \]

- Local covariant off-shell transition rate for q+q\bar{q} fusion

\[ \text{meson formation:} \]
\[ \frac{dN_{q+\bar{q} \rightarrow m}}{d^4x \ d^4p} = Tr_q Tr_{\bar{q}} \delta^4(p - p_q - p_{\bar{q}}) \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right) \delta(\text{flavor}, \text{color}) \]
\[ \cdot N_q(x_q, p_q) N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \cdot \omega_q \rho_q(p_q) \cdot \omega_{\bar{q}} \rho_{\bar{q}}(p_{\bar{q}}) \cdot |M_{qq\bar{q}}|^2 W_m(x_q - x_{\bar{q}}, p_q - p_{\bar{q}}) \]

- \(N_j(x,p)\) is the phase-space density of parton j at space-time position \(x\) and 4-momentum \(p\)
- \(W_m\) is the phase-space distribution of the formed 'pre-hadrons' (Gaussian in phase space)
- \(|M_{qq\bar{q}}|^2\) is the effective quark-antiquark interaction from the DQPM

IV. Hadronic phase: hadron-string interactions – off-shell HSD
Photons from the hot and dense medium

Photon sources in PHSD

1) From the QGP via partonic interactions:

- decays of mesons: \[ \pi \rightarrow \gamma + \gamma, \quad \eta \rightarrow \gamma + \gamma, \quad \omega \rightarrow \pi + \gamma \]
  \[ \eta' \rightarrow \rho + \gamma, \quad \phi \rightarrow \eta + \gamma, \quad a_1 \rightarrow \pi + \gamma \]

- secondary meson interactions: \[ \pi + \pi \rightarrow \rho + \gamma, \quad \rho + \pi \rightarrow \pi + \gamma \]
  using the off-shell extension of Kapusta et al. in PRD44 (1991) 2774

2) From hadronic sources

- Meson-meson and meson-baryon bremsstrahlung,
  \[ m+m \rightarrow m+m+\gamma, \quad m=\pi,\eta,\rho,\omega,K,K^*,... \]
  using the soft photon approximation, with an average elastic cross section of 10 mb.
  Caution: uncertain!

Thermal rates and conductivity

- **off-shell dynamical quasiparticle quark and gluon interaction**
- **lattice QCD**
  - Ding et al, PRD83 (2011) 034504
- **Hard Thermal Loops**
  - Braaten, Pisarski, NP B337 (1990) 569

**Thermal rate**

\[
\frac{dW}{d\omega d^3p} = \frac{5\alpha^2}{54\pi^3} \frac{1}{\omega^2(e^{\omega/T} - 1)} \rho_V(\omega, \vec{p}, T)
\]

**Electric conductivity**

\[
\sigma = \frac{C_{em}}{6} \lim_{\omega \to 0} \frac{\rho_{ii}(\omega, \vec{p} = 0, T)}{\omega T}
\]


- \( P=0 \)
Photons from SPS to LHC: direct photon flow puzzle

Figure 3. Direct-photon $e_{\gamma}^{\text{dir}}$ in 0-40% Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [8].

EMMI Rapid Reaction Task Force
Direct-Photon Flow Puzzle
February 24-28, 2014, GSI, Darmstadt, Germany
Photon $v_2$ puzzle

Strong elliptic flow of photons ($v_2(\gamma^{\text{dir}}) \sim v_2(\pi)$) seen by PHENIX is surprising, if the origin would be the QGP! Variety of models: $v_2(\gamma^{\text{dir}}) \ll v_2(\pi)$

QGP radiation occurs at early time when flow is not yet developed!

PHSD: photon spectra at RHIC: QGP vs. HG?

- Direct photon spectrum (min. bias)

\[ dN/dp_T \propto 1/p_T \]

Au+Au, \( s_{NN}^{1/2} = 200 \text{ GeV}, \) MB, \(|y|<0.35\)

PHENIX, PRL 104, 132301

PHSD:
- QGP gives up to \( \sim 50\% \) of direct photon yield below 2 GeV/c

<table>
<thead>
<tr>
<th>Model</th>
<th>PHSD</th>
<th>PHENIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hadrons</td>
<td>260 ± 20</td>
<td>200 ± 20</td>
</tr>
<tr>
<td>Total</td>
<td>220 ± 20</td>
<td>233 ± 14 ± 19</td>
</tr>
</tbody>
</table>

Linnyk et al., PRC88 (2013)
034904; PRC 89 (2014) 034908

- Sizeable contribution from hadronic sources
  - meson-meson (mm) and meson-Baryon (mB) bremsstrahlung

mm and mB bremsstrahlung channels can not be subtracted experimentally
Are the direct photons a barometer of the QGP?

- Do we see the **QGP pressure** in $v_2(\gamma)$ if the photon productions is **dominated by hadronic sources**?

1) $v_2(\gamma^{\text{incl}}) = v_2(\pi^0)$ - inclusive photons mainly come from $\pi^0$ decays
   - HSD (without QGP) underestimates $v_2$ of hadrons and inclusive photons by a factor of 2, whereas the PHSD model with QGP is consistent with exp. data

   ➔ **The QGP causes the strong elliptic flow of photons indirectly**, by enhancing the $v_2$ of final hadrons due to the partonic interactions

**Direct photons** (inclusive(=total) – decay):

2) $v_2(\gamma^{\text{dir}})$ of **direct photons** in PHSD underestimates the PHENIX data:
   - $v_2(\gamma^{QGP})$ is very small, but QGP contribution is up to 50% of total yield ➔ lowering flow

   ➔ **PHSD**: $v_2(\gamma^{\text{dir}})$ comes from **mm and mB bremsstrahlung**!

PHSD: Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908
Centrality dependence of the thermal photon yield

scaling of thermal photon yield vs centrality: 
\[ \frac{dN}{dy} \sim N_{\text{part}}^a \] with \( a \sim 1.48 \pm 0.08 \)

('Thermal' photon yield = direct photons - pQCD)

PHSD predictions:
- Hadronic channels scale as \( \sim N_{\text{part}}^{1.5} \)
- Partonic channels scale as \( \sim N_{\text{part}}^{1.75} \)

\[ \frac{dN}{dy}(0.4 < p_T < 5 \text{ GeV/c}) \]


- PHSD: scaling of the thermal photon yield with \( N_{\text{part}}^a \) with \( a \sim 1.5 \)
- similar results from viscous hydro:
  \((2+1)d \text{ VISH2+1: } a(\text{HG}) \sim 1.46, a(\text{QGP}) \sim 2, a(\text{total}) \sim 1.7\)
Centrality dependence of the direct photon yield

from talk by S. Mizuno at QM'2014

PHENIX data - arXiv:1405.3940

PHSD predictions:

- PHSD approximately reproduces the centrality dependence
- mm and mB bremsstrahlung is dominant at peripheral collisions

! Warning: large uncertainties in the Bremsstrahlung channels in the present PHSD results
**Hadronic sources** dominate at low $p_T$

**High $p_T$**: dominated by thermal photons from QGP

E. Bratkovskaya, S.M. Kiselev, and G.B. Sharkov, PR C78 (2008) 034905
Photon spectra at SPS

Updated HSD (2014) including meson-baryon bremsstrahlung

direct $\gamma$: Pb+Pb, 160A GeV, 10% central, $2.35 < \eta < 2.95$

HSD: no medium effects

- HSD: meson-meson and meson-baryon bremsstrahlung using SPA
- But bremsstrahlung rates are uncertain

EMMI Rapid Reaction Task Force 'Direct Photon Flow Puzzle', 24-28 February 2014, GSI Darmstadt
Meson-meson Bremsstrahlung at SPS within SPA


**Soft Photon Approximation:**

\[ m_1 + m_2 \rightarrow m_1 + m_2 + \gamma \]

\[
q_0 \frac{d^3 \sigma^\gamma}{d^3 q} = \frac{\alpha}{4\pi} \frac{\bar{\sigma}(s)}{q_0^2}
\]

\[
\bar{\sigma}(s) = \frac{s - (M_1 + M_2)^2}{2M_1^2} \sigma(s),
\]

\( \sigma(s) \) – elastic meson-meson cross section

\[ m_1 + m_2 \rightarrow m_1 + m_2 \]

- ???

- Taken \( \sigma(s) = 10 \text{ mb} \) for ALL \( m_1 + m_2 \) channels!
- No isospin factors!

\[ \Rightarrow \text{Needs to be improved!} \]

E. Bratkovskaya, S.M. Kiselev, and G.B. Sharkov, PR C78 (2008) 034905
mm bremsstrahlung beyond SPA


- \( \pi\pi \rightarrow \pi\pi\gamma, \pi K \rightarrow \pi K\gamma \) bremsstrahlung:

the photon yield within an effective chiral hadronic model including electromagnetic interaction via \( U_{em}(1) \) gauge is larger than using SPA!

![Graph showing the rate for \( \pi\pi \rightarrow \pi\pi\gamma \)]
Photons from PHSD at LHC

- Is the considerable elliptic flow of direct photons at the LHC also of hadronic origin as for RHIC?!

- The photon elliptic flow at LHC is lower than at RHIC due to a larger relative QGP contribution / longer QGP phase.

⇒ **LHC (similar to RHIC):** hadronic photons dominate spectra and $v_2$
Towards the solution of the $v_2$ puzzle

- Is hadronic bremsstrahlung a ‘solution’?

Other scenarios:

- Early-time magnetic field effects?

- Glasma effects?
  (L. McLerran, B. Schenke, arXiv: 1403.7462)

- Pseudo-Critical Enhancement of thermal photons near $T_C$?
  (H. van Hees, M. He, R. Rapp, arXiv:1404.2846)

- ???
The photons produced in the QGP contribute up to 50% to the spectrum, but have small $v_2$.

The measured direct photon elliptic flow $v_2$ – comparable to that of hadrons – is attributed mainly to intermediate hadronic scattering channels.

Hadronic channels scale as $N_{\text{part}}^{1.5}$ (as seen by PHENIX). Partonic channels scale as $N_{\text{part}}^{1.75}$.

More sound theoretical understanding of bremsstrahlung by mesons and baryons is needed.
Outlook

- Reducing the uncertainties in the bremsstrahlung rates (beyond SPA).
- Direct photon spectra at low $p_T$, incorporating the LPM effect microscopically.
- Combining the pieces: electric conductivity, photon production, dilepton production.
- Elliptic flow of dileptons vs mass: disentangling the QGP and hadronic contributions to the dilepton spectra.
- Dileptons at lower collision energies: Beam energy scan, FAIR.