Pre-equilibrium photon production and the direct-photon puzzle

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The Role of Direct Photons in Heavy-Ion Physics

- Medium transparent to photons ($\lambda_{mfp} \approx 500$ fm)
- Produced over the entire duration of the collision
  - Test of space-time evolution, in particular of the hydro paradigm
- Experimental access to initial QGP temperature (?)

QGP photon rate $r_\gamma$ (lowest order):

$$E_\gamma \frac{dr_\gamma}{d^3p} \propto \alpha \alpha_s \, T^2 \exp\left(-\frac{E_\gamma}{T}\right) \log \left(\frac{E_\gamma T}{k_c^2}\right)$$

Total emission rate:

$$r_\gamma \propto T^4$$
Known and presumed photon sources

- **B field induced?**
- **Prompt (pQCD)**
- **Pre-equilibrium photons**
- **Direct Photons**
  - **Jet-medium interaction**
  - **Thermal**
  - **Hadronic bremsstrahlung**

- **Decay photons** ($\pi^0 \rightarrow \gamma \gamma$, $\eta \rightarrow \gamma \gamma$, $\omega \rightarrow \pi^0 \gamma$, ...)

Direct photons at $1 < p_T < 3$ GeV/c are hard to measure
(S/B ~ a few to 25%, depending on centrality and $p_T$)
The direct photon (flow) puzzle

- Around since Quark Matter 2011
- PHENIX: Data a challenge to theory
- Charles Gale: „Theory a challenge to the data“

It’s a challenge for models to simultaneously describe the yield and azimuthal anisotropy of direct photons

What’s actually so puzzling?

Elliptic flow gradually builds up with time:

- Expect large fraction of thermal photons from early times
- Expect bulk of hadrons to be produced at late times

R. Chatterjee, D. Srivastava

![Graph showing thermal photon production](image)

- Thermal Photons
  - Au+Au@200 AGeV
  - b=7 fm

- QM – Quark Matter
- HM – Hadronic Matter
- sum – QM + HM

- $v_2$ vs. $\tau_f$ (fm)
The direct-photon puzzle today: RHIC (yield & $v_2$)

Paquet et al., arXiv:1509.06738

- State-of-the-art hydro calculations
  - Shear and bulk viscosity
  - More realistic initial conditions
  - Event-by-event hydro
The direct-photon puzzle today: LHC (yield & $v_2$)

- Agreement within 1σ or so
  - Syst. uncertainties correlated in $p_T$
- Puzzle mostly with regard to RHIC data

Paquet et al., arXiv:1509.06738
Why is the puzzle interesting?

- **Space-time evolution not understood?**
  - “Standard model” of heavy-ion collisions based relativistic hydrodynamics
  - Works well for hadronic observables ($v_n$, HBT, …)
  - Why not for QGP photons?

- **Photon production in the QGP or the hadron gas not under control?**

- **Are we missing an important photon source?**

- **Paradigm shift regarding the role of photons as QGP messengers?**

We are missing something rather fundamental
The puzzle has triggered a lot of activity on the theory side. An incomplete list …

- Potentially underestimated late-stage photon sources
  - Meson-meson bremsstrahlung, meson-baryon bremsstrahlung
    [Linnyk, Bratkovskaya, et al., PHSD Transport model]
  - Enhanced photon production near $T_c$
    [van Hees, He, Rapp, arXiv:1404.2846]

- Mechanism leading to reduced photon production at the early stage (mostly addresses the $v_2$ problem)
  - Semi-QGP: Fewer photons from the QGP
  - Start hydro at later stage, up to 1.5 fm/c (“it takes some time before quarks appear”) [Fu-Ming Liu, Sheng-Xu Liu, arXiv:1212.6587]
  - Quasi-particle description of non-equilibrated quark-gluon system
    [Monnai, 1504.00406]

- Photon production related to initial magnetic field created by spectators
  - Conformal anomaly [Basar, Kharzeev, Skokov, PRL 109, 202303 (2012)]
  - Gauge/gravity duality [Muller, Wu, Yang, arXiv:1308.6568v3]
Pre-equilibrium photons

- Pre-equilibrium phase not well understood
  - Significant direct photon yield?
  - Pre-equilibrium flow?
  - BAMPS parton cascade (M. Greif, C. Greiner): not a large contribution(?)

- Large parton momenta, but small space-time volume

![Event-averaged space-time volume as a function of the temperature](Paquet et al., arXiv:1509.06738)
What about the experimental side?

\[ R_\gamma = \frac{\gamma_{\text{incl}}}{\gamma_{\text{dec}}} = 1 + \frac{\gamma_{\text{dir}}}{\gamma_{\text{dec}}} \]

- Two independent methods at RHIC in agreement
  - Virtual photon method
    - Measure dileptons at \( m_{ee} \gtrsim m_\pi \)
    - Extrapolate to \( m = 0 \) (real photons)
  - External conversions
- Lower \( R_\gamma \) would solve yield and \( v_2 \) puzzle

\[
\begin{align*}
v_2^{\gamma,\text{dec}} &= (1 + \varepsilon) v_2^{\gamma,\text{incl}} \\
v_2^{\gamma,\text{dir}} &= v_2^{\gamma,\text{incl}} \left(1 - \frac{\varepsilon}{R_\gamma - 1}\right)
\end{align*}
\]

→ Next step: better modeling of \( \gamma_{\text{dec}} \) background

“A theory is something nobody believes, except the person who made it. An experiment is something everybody believes, except the person who made it.” A. Einstein
Next step:
Decay photon cocktail including effects of radial flow

- Experimental uncertainties on $\eta$ and $\omega$ $p_T$ spectra currently too large to be useful in the decay-photon cocktail
- Improvement over $m_T$ scaling: $\eta/\pi^0$ and $\omega/\pi^0$ from hydro modeling

$m_T$ scaling:
shape of particle spectra universal as a function of $m_T$

$$m_T = \sqrt{p_T^2 + m^2}$$
Do low $p_T$ direct photons mostly come from the early or the later stage of the collision?

→ Experimental approach: direct-photon HBT
Direct-photon Hanbury Brown-Twiss correlations

Correlation function:
\[ C_2 = \frac{P(k_1, k_2)}{P(k_1)P(k_2)} \]

\[ q = k_1 - k_2, \quad K = (k_1 + k_2)/2 \]

\[ P(k) = \int d^4x S(x, k) \equiv \int d^4x \frac{dN_\gamma(x, k)}{d^4x d^3k} \]

\[ C(q) = 1 + \lambda \exp(-R^2 Q_{inv}^2), \quad \lambda = \frac{1}{2} \text{ for a completely chaotic photon source} \]

In the presence of decay photons
\[ \lambda = \frac{1}{2} \left( \frac{N_{\gamma}^{\text{direct}}}{N_{\gamma}^{\text{total}}} \right)^2 = \frac{1}{2} \left( 1 + 1/R_\gamma \right)^2 \]

Two major motivations for direct-photon HBT
- Information on source size and emission duration
- Tool to measure direct photon at low \( p_T \)

Experimentally very challenging! Actively explored by ALICE …
Photon HBT and emission time

\[ C = 1 + \frac{1}{2} \exp\left[-(q_{\text{out}}^2 R_{\text{out}}^2 + q_{\text{side}}^2 R_{\text{side}}^2 + q_{\text{long}}^2 R_{\text{long}}^2)/2\right] \]

\[ q_{\text{long}} = |k_{1,z} - k_{2,z}| \]
\[ q_{\text{out}} = q_T \cdot K_T / K_T \]
\[ q_{\text{side}} = |q_T - q_{\text{out}} K_T / K_T| \]

- Example of a photon HBT calculation
  - Hydro + parton cascade
  - Lot’s of photons from pre-equilibrium phase in this model (\( \tau \approx 0.3 \text{ fm/c} \))
- Longitudinal correlation radius
  \( R_{\text{long}} \approx 1.6 \text{ fm} \) much smaller than \( R_{\text{out}} \) and \( R_{\text{side}} \)
  - Reflects early emission time of the bulk of the photons in this model
To be studied: Experimental sensitivity to early/late production of direct photons

- Calculation of correlation function using a hydro code

\[ C(q, K) = 1 + \frac{1}{2} \frac{|\int d^4x S(x, K)e^{iq\cdot x}|^2}{\int d^4x S(x, K + \frac{q}{2}) \int d^4y S(y, K - \frac{q}{2})} \]

- Add extra photons at early / late times and study change of correlation function, especially \( R_{\text{long}} \)

- Consider experimental limitations in terms of statistics, resolution, etc.
The only published experimental result on direct-photon HBT in A-A collisions: WA98 at the CERN SPS

Low $p_T$ direct-photon yields not easily explained by models
Summary

- Direct photon puzzle
  - Yield
  - $v_2$

- Solution to the direct-photon puzzle could be both and the experimental or on theory side

- Pre-equilibrium photons: Largely unexplored territory

- Photon HBT might help solve the puzzle:
  Early or late production of direct photos?
Extra slides
What’s actually puzzling?

Elliptic flow gradually builds up with time:

Expect large fraction of thermal photons from early times

Expect bulk of hadrons to be produced at late times

\[ v_2(\tau)/v_2(\tau_f) \]

\[ \tau \text{ (fm)} \]

\[ 0 \]

\[ 2 \]

\[ 4 \]

\[ 6 \]

\[ 8 \]

\[ 10 \]

\[ 12 \]

R. Chatterjee, arXiv:0901.3270