Out-of-Equilibrium Photon Production in the Late Stages of Relativistic Heavy-Ion Collisions


Motivation
- Direct photons are clean probes created throughout the collision and free of final state effects.
- Current mismatch with data (“Direct Photon Puzzle”) may be fixable via inclusion of non-equilibrium effects.

How does microscopic hadronic rescattering during the late stage affect the results?

First full hybrid calculation for photon production at high beam energies

Late time non-equilibrium effects are significant for anisotropy generation

Photons from Hadronic Transport
- Non-equilibrium production of photons in hadronic matter
  - Microscopic scattering and production using the SMASH transport code.
- Photons are sampled when underlying meson scattering happens
  - Perturbative production - no backreaction
- Kinematic properties are sampled from differential cross-sections
  - Using U(1) symmetric Chiral Perturbation Theory

Main contributions: meson-bremstrahlung and 2-to-2 scattering processes

Results
- Computed yield and anisotropy of photons. For $v_2$ we used $v_2(p_T) = \langle p_x^2 - p_y^2 \rangle / \langle p_T^2 \rangle$
- Photon anisotropies are measured relative to the hadronic event plane

A tale of two setups

Initial Conditions
- MUSIC (3+1) + IDEAL HYDRO
- Details: Au+Au @ $\sqrt{s} = 200$ GeV + Pb+Pb @ $\sqrt{s} = 2.76$ TeV

QGP evolution
- $T_{ENTO} - AVERAGE ICS$
- Details: $b=5$ fm - 10-20%

Hadronic Stage
- Afterburner: non-equilibrium evolution
- MUSIC (3+1)
- Hadronic stage is hydrodynamical

Non-trivial to resolve the discrepancies in the photon observables

Approach could be further improved by new channels (Kaon, Baryonic, ...)

Interested? Read the paper!
Simulating Many Accelerated Strongly-interacting Hadrons

Hadronic transport approach

Includes hadrons with masses up to ~ 2 GeV

Particles propagate and collide on the basis of physical cross sections

Effective solution to Boltzmann equation: $p_\mu \partial^\mu f + m \partial_p (F^\mu f)^\mu = C[f]$

Successfully studied bulk properties, as well as dilepton and strangeness production

Steinberg et al, Phys.Rev.C 99 (2019) 6, 064908

Steinberg et al, arXiv: 1912.09895

This work: SMASH 1.8
https://smash-transport.github.io
https://doi.org/10.5281/zenodo.3484711

Newest version -> SMASH 2.1.4
PHOTONS FROM HADRONIC TRANSPORT

Get differential and total cross section from the Chiral Lagrangian

Use $\frac{d\sigma}{dt}$ and $\frac{d\sigma}{dt} d\Omega$ (depending on end-state kinematics) to sample the direction and momentum of photons

**MESON BREMSSTRAHLUNG**

Photon production from pion 2-to-3 process.
Mediated by $\sigma, \rho$, and $f$ resonances

**BENCHMARK: COMPARISON TO THERMAL RATES**

**SMASH** setup: thermal matter with periodic box

Compute Thermal photon rates: 4-volume density of photons

Fair agreement to known parametrizations


AMY, JHEP 0112 (2001) 009

**2-TO-2 SCATTERINGS**

Photon production from $\rho$/pion 2-to-2 scattering processes


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**AMY, JHEP 0112 (2001) 009**
HYDRO VS. TRANSPORT

Comparison
Photons from SMASH (transport) vs. MUSIC (Hydro, Hadronic)

Hydro Photons produced using thermal rates:

Note: Total is a weighted average!

NON-EQUILIBRIUM EFFECTS ENHANCE PHOTON ANISOTROPIES