PHOTONS AS MESSENGERS OF THE NON-EQUILIBRIUM QUARK-GLUON PLASMA

Oscar Garcia-Montero
Fakultät für Physik
Universität Bielefeld
GARCIA@PHYSIK.UNI-BIELEFELD.DE
CONTENTS

- Photons and non-eq. effects
  - Early stages (Pre-eq)
    - Falling out of eq.: Hadronic Rescattering
- Photon Correlations
- Summary
MOTIVATION

- Heavy-Ion Collisions create an Isolated Quantum System which is
  - Initially far away from any equilibrium
  - Self-interacting
  - Expanding against the vacuum

A system battling to thermalize against all odds.
CAN WE PROBE THE ROLE OF Non-Eq DYNAMICS?
The Standard Model of Heavy Ion Collisions: A Hybrid Model

THE STANDARD MODEL OF HEAVY ION COLLISIONS: A HYBRID MODEL

HADRON GAS
SMASH
UrQMD

PRE-EQUILIBRIUM
AMY EKT
KøMPøST

QGP
VISH
MUSIC
vHLLE

Hadron Gas
Quark Gluon plasma

SYSTEM LOSES MEMORY!!

Anisotropy: $P_L/P_T$

$\alpha_s = 0$
$\alpha_s = 0.03$
$\alpha_s = 0.15$
$\alpha_s = 0.3$

Classical YM
Bottom-Up
Realistic coupling

SMASH
UrQMD

IP-Glasma

TRENTO

INITIAL CONDITIONS

THE STANDARD MODEL OF HEAVY ION COLLISIONS: A HYBRID MODEL

HADRON GAS
SMASH
UrQMD

PRE-EQUILIBRIUM
AMY EKT
KoMPoST

\[ \text{Hadamard Gas} \]

\[ \text{Quark Gluon Plasma} \]

\[ \text{System Loses Memory!!} \]

\[ \text{10} \]
\[ \text{100} \]
\[ \text{1000} \]

Rescaled occupancy: \( \frac{\alpha_s f}{\rho} \)

Anisotropy: \( \frac{P_T}{P_L} \)

\[ \alpha_s = 0 \]
\[ \alpha_s = 0.03 \]
\[ \alpha_s = 0.15 \]
\[ \alpha_s = 0.3 \]

Classical YM

Bottom-Up

Realistic

QCD

Initial Conditions

\[ 1 \]

\[ 3 \]

WHAT CAN WE USE TO PROBE THE ROLE OF Non-Eq DYNAMICS?
ELECTROMAGNETIC PROBES

- TBU: Photons and dilepton pairs
- No strong interactions
- Mean free path in medium > medium size
  - Photons escape, virtually unscathed

AS A CONSEQUENCE...

- Different sources through the evolution
- EMPs are particularly sensitive to the evolution of the system
- Direct Photons* are not produced in decays

Photons* = virtual photons, i.e. dilepton pairs also included in this notation
ELECTROMAGNETIC PROBES

- Photons* are not produced in decays
- No strong interactions
- Mean free path in medium > medium size
- Photons escape, virtually unscathed

AS A CONSEQUENCE...

- Different sources through the evolution
- EMPs are particularly sensitive to the evolution of the system

Direct Photons* are not produced in decays

Photons* = virtual photons, i.e. dilepton pairs also included in this notation
HOWEVER, EM probes are yet to be fully understood.

**DIRECT PHOTON PUZZLE**

"The inability to simultaneously describe both the photon yield and anisotropy."

\[
E \frac{dN}{d^3p} = \frac{1}{2\pi p_{\perp} \, dp_{\perp} \, dy} \left[ 1 + \sum_{n=1}^{\infty} v_n(p_{\perp}) \cos [n(\phi - \Psi_n)] \right]
\]

DIRECT EM PROBES

HOWEVER, electromagnetic probes are complicated

Since the yield is given by

\[ E \frac{dN}{d^3p} = \int_0^\infty E \frac{dN}{drd^3p} = \sum_i \int_{\tau_i}^{\tau_{i+1}} E \frac{dN_i}{drd^3p} \]

This entangles the yields originating in different stages

And the \( v_n \) even more (as it is a weighted avg.)

HOW TO DISENTANGLE A LONG EXPOSURE PICTURE?

Correlations.

We’ll come back to this.
Recent advances in...

PHOTONS AS MESSENGERS OF EARLIER TIMES
**EARLY RADIATION: IS IT RELEVANT?**

- Pre-equilibrium photons are computed using approximated 2-to-2 kinetic rates
  \[
  E \frac{d^3 R}{d^3 p} = \frac{40}{9 \pi^2} \alpha_s \mathcal{L} f_q(p) \int \frac{d^3 p'}{(2\pi)^3} \frac{1}{p'} \left[ f_s(p') + f_q(p') \right]
  \]

- Space-time evolution to fold the rates with. Use the "bottom-up" thermalization scenario:
  1. Early times: 2-to-2 broadening \( 1 \ll \tau_Q \ll \alpha_s^{-3/2} \)
  2. Onset of thermalization: \( \alpha_s^{-3/2} \ll \tau_Q \ll \alpha_s^{-5/2} \)
  3. Mini-jet quenching \( \alpha_s^{-5/2} \ll \tau_Q \ll \alpha_s^{-13/5} \)

- Input: Gluon distributions from classical statistics
  Pheno. matching for the free parameters, i.e. \( Q_s \)

Caveat: pure "bottom-up" gives a long pre-equilibrium stage. These should be taken as largest
REFINEMENT: KINETIC THEORY

Pre-equilibrium photons are computed using approximated 2-to-2 kinetic rates

\[ E \frac{d^3R}{d^3p} = \frac{40}{9\pi^2}\alpha_s \mathcal{L} \int \frac{d^3p'}{(2\pi)^3} \frac{1}{p'} [f_g(p') + f_q(p')] \]

Distributions are computed in QCD Kinetic theory, using the Fokker-Planck diffusion approximation

\[ \left( \frac{\partial}{\partial t} + v \cdot \nabla_x \right) f_{g/q}(t, x, p) = -\nabla_p \cdot \mathcal{J}_{g/q} + S_{g/q} \]

ICs: \( f_g(t_0, p) = f_0 \theta \left( 1 - \frac{\sqrt{p_x^2 + p_z^2} \xi^2}{Q_s} \right) \) and \( f_q(t_0, x, p) = 0 \)

Pheno. matching to energy (multiplicities)

\[ \frac{dE}{d\eta} = 2N_c C_F A_T \frac{f_0 Q_s^3}{(2\pi)^3} \frac{1}{\xi} \mathcal{F}(\xi) \]

Gluon number suppressed by large \( Q_s \) Pre-eq. Photons relevant at lower energies.
**DI-LEPTON PRODUCTION IN HICS**

- Di-lepton ($e^+e^-/\mu^+\mu^-$) pairs with invariant mass $M \sim \text{few GeVs}$ produced during the initial state; late stage production is suppressed by $\exp(-M/T)$

- Do pre-equilibrium dileptons “out-shine” the Drell-Yann, decay spectra?
  - For some kinematic windows, it may be the case.

- New window into pre-equilibrium dynamics for $1\text{GeV} < M < 3\text{GeV}$ accessible with next generation of heavy-ion detectors (ALICE3, LHCb)
Falling out of equilibrium

RESCATTERING DURING THE HADRONIC STAGE
NEQ EFFECTS IN THE HADRONIC STAGE

- Hadronic observables are sensitive to end (hadronic) non-equilibrium effects. Are the photons produced also sensitive?

ICs

\( T_{\text{RENTO}} \)

(3+1) MUSIC IDEAL HYDRO

QGP

AFTERBURNER

SMASH

MODEL A:

THERMAL PHOTONS
\[ T > 150 \text{ MeV} \]

AFTERBURNER [microscopic] PHOTONS

MODEL B:

THERMAL PHOTONS
\[ T > 150 \text{ MeV} \] + THERMAL PHOTONS
\[ 150 > T > 120 \text{ MeV} \]

PHOTONS FROM HADRONIC RESCATTERING

Main contributions

\[ \pi \pi \pi \pi \]

Hydrodynamical - Thermal Rates

- Rates obtained from convolution of process amplitude and thermal distribution functions

QGP: AMY, JHEP 0112 (2001) 009

Transport - SMASH photons

- Non-equilibrium production of photons in hadronic matter
- Perturbative production - no backreaction
- Photons are sampled when underlying meson scattering happens


Computed yield and anisotropy of photons

Checked hadronic observables

**EQUILIBRIUM VS NON-EQUILIBRIUM**

**SOME TECHNICAL DETAILS**

Average (smooth) ICs for $b = 5$ fm

Transition Temperature $T = 150$

- Checked hadronic observables
- Comparison: Model A vs. Model B
- Computed yield and anisotropy of photons
  \[ v_2(p_\perp) = \frac{\langle p_\perp^2 - p_\parallel^2 \rangle}{\langle p_\perp^2 \rangle} \]
- Photon anisotropies are measured relative to the hadronic event plane

**NON-EQUILIBRIUM EFFECTS ENHANCE PHOTON ANISOTROPIES**
QGP VS. HADRONIC MATTER

HADRONIC STAGE IS RELEVANT! NON-EQ. EFFECTS SHOULD BE ACCOUNTED FOR.
Extracting the Information: FEMTOSCOPY
- Originally used to measure the size of astronomical light sources
  i.e. Cassiopeia A and Cygnus A

- How? $\delta x \delta p \gg 2\pi \hbar$ Photons behave classically
  $\delta x \delta p \lesssim 2\pi \hbar$ Photons behave quantum

- Quantum effects start at
  $$\delta x_{\text{max}} \sim 2R$$
  $$q^* = \frac{\pi \hbar}{R}$$

- Pair variables
  $$K^\mu = (K^0, K_1, 0, K^z)$$
  $$q^{\mu} = (q^0, q_0, q_s, q_l)$$
A tale of two sources

Far-from-equilibrium Photons
- Bottom-up—like evolution + matching
- Pre-equilibrium photons are computed using kinetic rates, Phys. Rev. C69 (2004) 014903
- Pre-equilibrium photons are computed using kinetic rates, OGM. Ann. Phys. 443 (2022) 168984

\[ E \frac{dN}{d^4X d^3p} = \frac{40}{9\pi^2} \alpha s L f_\pi(p) (l_\pi + l_q) \]

Pseudo-Critical Enhancement
- Phenomenological model.

\[ E \frac{dN_{\text{enh}}}{d^4X d^3p} \equiv h(T) E \frac{dN_{\text{thermal}}}{d^4X d^3p} \quad \text{and} \]

\[ h(T) = 1 + h_0 \exp \left\{ -\frac{(T - T_{pc})^2}{c^2} \right\} \]
A tale of two sources

Far-from-equilibrium Photons

- Bottom-up–like evolution + matching
- Pre-equilibrium photons are computed using kinetic rates , Phys.Rev. C95 (2017) no.5, 054904
OGM. Annals Phys. 443 (2022) 168984

\[ E \frac{dN}{d^4Xd^3p} = \frac{40}{9\pi^2} \alpha \alpha s \mathcal{L} f_q(p) (l_g + l_q) \]

Pseudo-Critical Enhancement

- Phenomenological model.
- At hadronization, non-perturbative rise in partonic cross-sections (Nucl. Phys. A933, 256 (2015))

\[ E \frac{dN_{enh}}{d^4Xd^3p} \equiv h(T) E \frac{dN_{thermal}}{d^4Xd^3p} \quad \text{and} \]

\[ h(T) = 1 + h_0 \exp \left\{ -\frac{(T - T_{pc})^2}{\sigma^2} \right\} \]

*JHEP 12, 009 (2001)
The HBT-Radii

\[ \langle q_i q_j \rangle = \int d^3 q q_i q_j g(q; K) \equiv \frac{1}{2} (R^{-1})_{ij} \]

\[ g(q; K) \equiv \frac{C(q, K) - 1}{\int d^3 q [C(q, K) - 1]} \]

Longitudinal direction affected the most by the inclusion of the sources.

Early-times production reduces effective radii, while late times increase it.

Are these differences enough to measure it?
SUMMARY

- Electromagnetic probes produced throughout space-time evolution of HICs; escape collision unscathed as they do not interact strongly with the QGP

- EM probes are carry sensitive information about the initial and early stages, which we can use to learn about the early evolution of the medium

- Late time non-equilibrium effects are significant for anisotropy generation

- Non-trivial to resolve the discrepancies in the photon observables

- Photon HBT can be the tool we use to cross-compare different models of photon production