Jet-medium photons as a probe of early time dynamics and parton energy loss mechanisms

Rouzbeh Modarresi-Yazdi
Shuzhe Shi
Charles Gale
Sangyong Jeon

1McGill University
2Stony Brook University

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Introduction

- Jet energy loss in QGP medium
  - well-established signal of QGP existence
  - can study the properties of QGP medium
- Several approaches to jet-quenching reproducing data across many systems
- Photons: complementary probes with $\lambda_{\text{mfp}}$ larger than the medium size
- In this talk
  1. First dynamical calculation of jet-medium photons, compared with data
  2. Photons as potential probes of jet-energy loss
- Specific models to consider
  1. MARTINI (Schenke et al. Phys. Rev. C 80 (2009))
  2. CUJET (Xu et al. JHEP 08 (2014) 063)
MARTINI and CUJET

MARTINI:
▶ Solves rate equation
\[
\frac{dP(p)}{dt} = \int_k \left( P(p + k) \frac{d\Gamma_{AMY}(p + k, k)}{dk} - P(p) \frac{d\Gamma_{AMY}(p, k)}{dk} \right)
\] (1)

▶ Radiative energy loss: all orders in opacity expansion

CUJET:
\[
\frac{dP(p)}{dt} = \int_{k > 0} P(p) \frac{d\Gamma_{DGLV}(p, k)}{dk}
\] (2)

▶ Leading order in opacity expansion, explicit formation time dependence

Both:
▶ Collisional energy loss on the same footing as radiation
▶ LPM effect addressed in both
Event Generation

Figure 1: Flow of Physical information
Event Generation: A Modular Adventure

Jet creation from hard scattering
Viscous hydrodynamic background
High virtuality medium shower
Low virtuality medium shower
Parton list
Hadronization, decays
Lund Model, Pythia
Jet Clustering

JETSCAPE
(Putschke et al. arXiv:1903.07706)

Pythia 8.243

MATTER

CUJET
JHEP 03 (2014)
Or
MARTINI

VISH(2+1)D

Temperature, Fluid velocity

Figure 2: Workflow for event generation
Charged Hadron $R_{AA}$

- $\eta/s = 0.08$
- MC-Glauber initial condition

$\eta/s = 0.08$

$MC-Glauber$ initial condition

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$\eta/s = 0.08$

$MC-Glauber$ initial condition

Figure 3: Charged Hadron $R_{AA}$, central
Charged Hadron $R_{AA}$

Good agreement for semi-central events

\[
Pb+Pb \sqrt{s} = 2.76 \text{ ATeV}
\]

Figure 4: Charged Hadron $R_{AA}$, semi-central
Jet $R_{AA}$

Similarly for jets, good agreement at very central...

**Figure 5: Jet $R_{AA}$, central**
Jet $R_{AA}$

... and semi-central events

$P b + P b \sqrt{s} = 2.76$ ATeV, $|\eta_J| < 2.0$

$R = 0.4$, Anti-$k_T$

Figure 6: Jet $R_{AA}$, semi-central
Photons in HIC

- **Photon Sources**
  - Photon Sources
  - Photon Sources

- **Photons**
  - Photons
  - Photons

- **Initial Hard Scattering**
  - Prompt Photons (ex: $q\bar{q} \rightarrow \gamma g$)

- **Pre-Equilibrium Phase**
  - Pre-Equilibrium Photons (ex: $q_{\text{pre-eq}}\bar{q}_{\text{pre-eq}} \rightarrow \gamma g$)

- **Quark-Gluon Plasma Phase**
  - Thermal Photons (ex: $\pi^+\pi^- \rightarrow \rho^0\gamma$)

- **Hadron Gas Phase**
  - Thermal Photons (ex: $\pi^+\pi^- \rightarrow \rho^0\gamma$)

- **Freeze Out**
  - Decay Photons
    - (ex: $\pi^0 \rightarrow \gamma\gamma$)

- **Jet-Medium**
  - Jet-Medium (ex: $q_t\bar{q}_t \rightarrow \gamma g$)

- **From jet propagation**

**R. Modarresi-Yazdi (McGill)**

Jet-Med. Photons and Jet-Energy Loss

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Photons from Jet-Medium Interactions

- Two main photon production channels available to a jet in QGP
  1. Jet-Bremsstrahlung: kicks from the medium impart virtuality which is radiated as a photon
  2. Jet-Conversion: very soft exchanges with the medium “convert” a fermion jet to a photon which inherits its energy and momentum

(a) Sample Bremsstrahlung Diagram

(b) Sample Conversion Diagram
Jet-Medium Photons

- Similar to other radiative/collisional energy loss channels, jet medium photons are computed by

\[ f_\gamma(k) = \int d^4x \ d^3p \ P_j(p, x, t) \frac{d\Gamma(p, k)}{d^3p \ d^3k} \]  

- **MARTINI**: Bremsstrahlung rates have been computed within AMY-McGill and tabulated (Schenke et al. Phys. Rev. C 80 (2009))

- **CUJET**: No bremsstrahlung photons (work in progress)
Conversion Photons

- Can convert to photons via (at LO in $\alpha_s$)
  1. QCD Compton Scattering
  2. $q\bar{q}$ Annihilation
- Both have a t-channel, dominated by small momentum transfers
- Conversion: assume all the contribution comes from that region of phase-space
- In that limit:
  \[
  \frac{d\Gamma}{d^3p\,d^3k}(p, k) = e_f^2 \frac{2\pi \alpha_s}{3} \frac{T}{p} \left[ \frac{1}{2} \ln \frac{2pT}{m_q^2} - 0.36149 \right] \delta^{(3)}(p - k)
  \]
  (4)
- Conversion photon spectrum: directly proportional to parton spectrum!
Photon Results

Photon Yield: MARTINI

- Prompts: dominant as $p_T$ increases
- Medium sources lose significance beyond $p_T \approx 5$ GeV
- 12% (Conv.) + 18%(Brem.) = 30% of total yield for $p_T \in [5, 10]$ GeV
- (Prompt, Pre-Eq, Thermal) from C. Gale et al. (Phys. Rev. C 105 (2022) 1, 014909)

Figure 8: Photon yield, separated by channel
Jet-Medium Photons: MARTINI

- Compare total photon spectrum with & without jet-medium contribution
- Pre-Eq. Photons of dashed line from J. Churchill et al. (Phys.Rev.C 103 (2021) 2, 024904)
- Jet-Medium: nearly 30% of photon yield at intermediate $p_T$

![Graph showing photon yield with and without jet-medium photons]

Figure 9: Photon yield with and without jet-medium photons

$Pb+Pb \sqrt{s} = 2.76$ ATeV, $|\eta| < 0.8$, 20-40%
Conversion Photons: Comparison

▶ Spectra:
(Pre-Eq + Thermal + Prompt + (conv. or conv.) + Brem)

▶ ≈ 5% difference at most central collision: entirely due to jet-conv.

Figure 10: Semi-total photon spectra
Conclusion & Outlook

▶ Presented the first dynamical calculation of jet-medium photons with realistic jet distribution, realistic hydro background
▶ Jet-medium $\gamma$ contribute significantly: $\sim 30\%$ of total yield for intermediate $p_T$
▶ Jet-Conversion Photons: directly proportional to underlying jet distribution, dependent on jet-energy loss mechanisms.
▶ Added CUJET into JETSCAPE: allowing for fair comparison between CUJET and MARTINI
▶ Setting the stage for a multi-messenger comparison of (any) energy loss mechanisms
  ■ Introduce bremsstrahlung photons to CUJET
  ■ Extend the work to $\sqrt{s_{NN}} = 5.02$ TeV, RHIC Energies
  ■ More observables (ex: Jet-Medium photon $v_2$)