Medium Induced Shower In An Expanding QCD Plasma

Ismail Soudi
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University of Jyväskylä, Department of Physics, P.O. Box 35, FI-40014 University of Jyväskylä, Finland.
Helsinki Institute of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland.
ismail.i.soudi@jyu.fi

Introduction

We apply the BDMPS-Z formalism, to derive medium-induced parton splitting rates within a Bjorken expanding QCD plasma. We investigate the impact of the medium expansion on the splitting rates and compare them with those in a static medium. Additionally, we examine the leading order in the opacity expansion and the harmonic oscillator solution, valid in the limits of small and large formation times, respectively.

Splitting Rates in Expanding Medium

Following [3], the splitting rate for $a \to bc$ $(P \to zP, (1-z)P)$ can be written as

$$\frac{d\Gamma^a_{bc}}{dz}(P,z,t) = \frac{g^2 T_0 P^a_{bc}(z)}{4\pi P^2 z^2 (1-z)^2} \mathrm{Re} \int_0^t d\Delta t \int_{\boldsymbol{p}} e^{-i\int_0^{\Delta t} du\, \delta E(u,\boldsymbol{p})} \psi_I(\boldsymbol{p}, \Delta t; t) \,,$$

Momentum broadening described using Hard Thermal Loop potential

$$C(t,\boldsymbol{p}) = \frac{C_R g^2 T(t) m_D^2(t)}{\boldsymbol{q}^2(\boldsymbol{q}^2 + m_D^2(t))} \,.$$

We consider a **Bjorken expanding** [2, 1] thermal medium with temperature $T(t) = T_0 \left(\frac{t_0}{t+t_0}\right)^{\alpha/3}$, where t_0 is the time the parton enters the medium and α the expansion exponent.

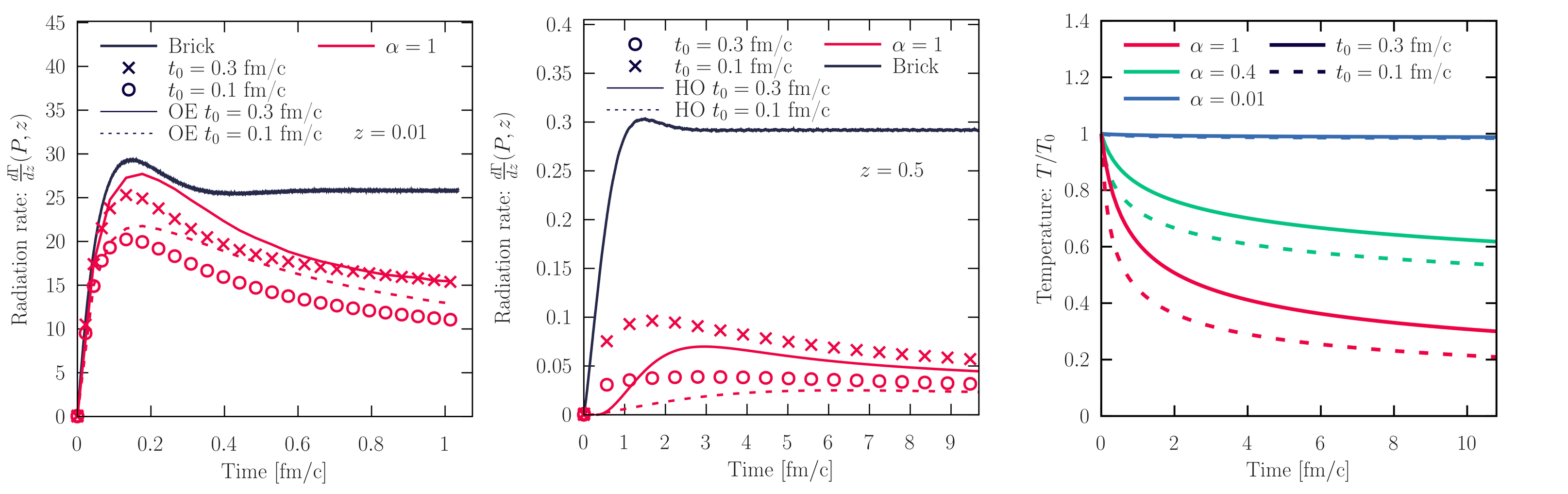

Figure 1: Rate of $P = 16$ GeV gluon splitting to a gluon (zP) with $z = 0.01$ (left) and $z = 0.5$ (right). Static medium in black lines, Bjorken expanding medium with $t_0 = 0.1$ fm/c or 0.3 fm/c using red circles or crosses respectively.

We compute the splitting of a $P = 16$ GeV gluon to a gluon with $z = 0.01$ and $z = 0.5$ in a static and Bjorken expanding medium with $T_0 = 0.2$ GeV.

- Soft splitting $z \ll 0.5$:
  - Initial linear growth comparable between static and Bjorken expansion for full and OE rates.
  - Late time behavior suppressed in expanding medium.
  - Small t_0 leads to rapid temperature decrease, resulting in lower medium scales $\hat{q}$, increasing the formation time $(t_f \propto \frac{1}{\sqrt{\hat{q}}}) \Rightarrow$ failure of the opacity expansion.
- Hard splitting $z \simeq 0.5$:
  - More pronounced suppression of the splitting rate.
  - Early-time behavior of the HO solution significantly differs from the full rate.
  - Increased scale separation between hard parton P and medium T, resulting in deep LPM regime at late times.

Energy Cascade in Static Medium

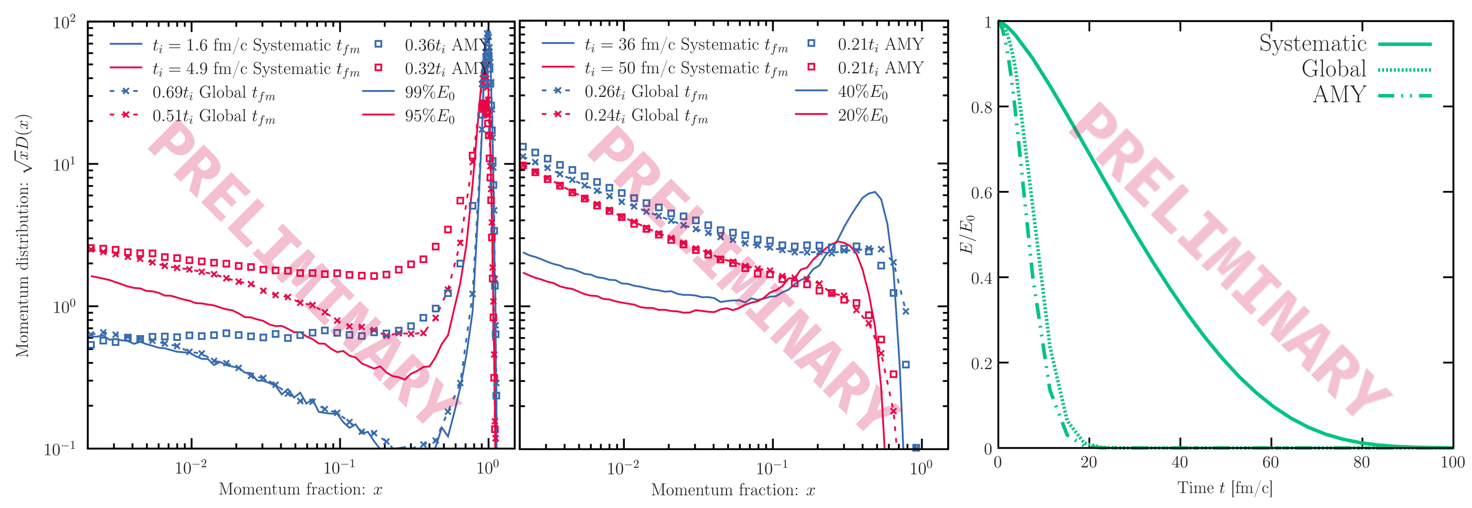

Figure 2: Evolution of gluon energy distribution in a static medium. Initial $P = 100$ GeV gluon traveling in a static medium $T = 0.2$ GeV, using systematic treatment of formation time (full lines), global formation time (dashedline-crosses) or AMY infinite medium (squares) at the same remaining energy.

We investigate the impact of systematic treatment of medium formation time of each splitting on the energy cascade in a static medium.

- Global formation time:

$$\partial_t D(x) = \int_0^1 dz \left[\frac{d\Gamma^a_{bc}}{dz}\left(\frac{x}{z}, z, \boldsymbol{t}\right) zD\left(\frac{x}{z}\right) - \frac{d\Gamma^a_{bc}}{dz}(x, z, \boldsymbol{t}) zD(x)\right]$$

- Systematic treatment of formation time:

$$\partial_t D(x) = \int_0^t ds \int_0^1 dz \left[\frac{d\Gamma^a_{bc}}{dz}\left(\frac{x}{z}, z, \boldsymbol{t-s}\right) zD\left(\frac{x}{z}\right) - \frac{d\Gamma^a_{bc}}{dz}(x, z, \boldsymbol{t-s}) zD(x)\right]$$

In Fig. 2, we show the evolution of a gluon $P = 100$ GeV energy distribution in a static medium with $T_0 = 0.2$ GeV.

- Early times: global formation time is comparable to the systematic treatment.
- The energy cascade is significantly delayed when using the systematic treatment of formation time.
- Late times: Global formation time similar to AMY infinite medium results.
- Hard splittings become more important when using the systematic treatment.

Conclusions

The medium expansion suppresses the splitting rates in a QCD medium. While the early-time behavior is well described by the OE expansion, the late time temperature decreases leads a large phase space for the deep LPM region. These rates are essential for understanding the in-medium QCD shower, where a systematic treatment of the formation time leads to significant delay of the energy cascade.

References

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Acknowledgements

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