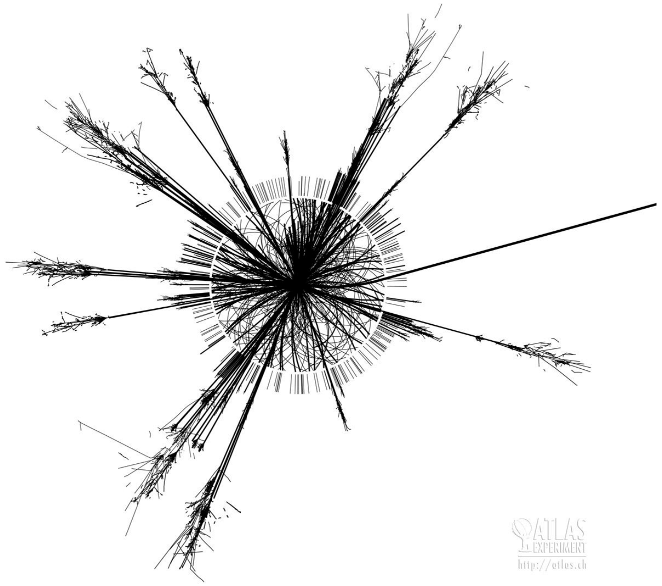

Jet quenching in expanding medium

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[in collaboration with

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8th International Conference on New Frontiers in Physics
(ICNFP 2019)

Outline of the talk

1. Experimental signatures vs theoretical **modelling** of jet quenching.
2. Medium induced gluon radiation and BDMPS-Z **formalism**.
3. **Scaling behavior** of the single emission gluon spectrum and gluon splitting rate for the static and Bjorken expanding mediums.
4. Kinematic rate equation.
5. Medium modified gluon splitting **rate** and gluon **spectrum** for the static, exponential and Bjorken evolving mediums.
6. The nuclear modification **factor** for the jet R_{AA} for the different medium profiles.
7. **Comparison** of the results with the ATLAS, LHC data.
8. Summary and discussions.

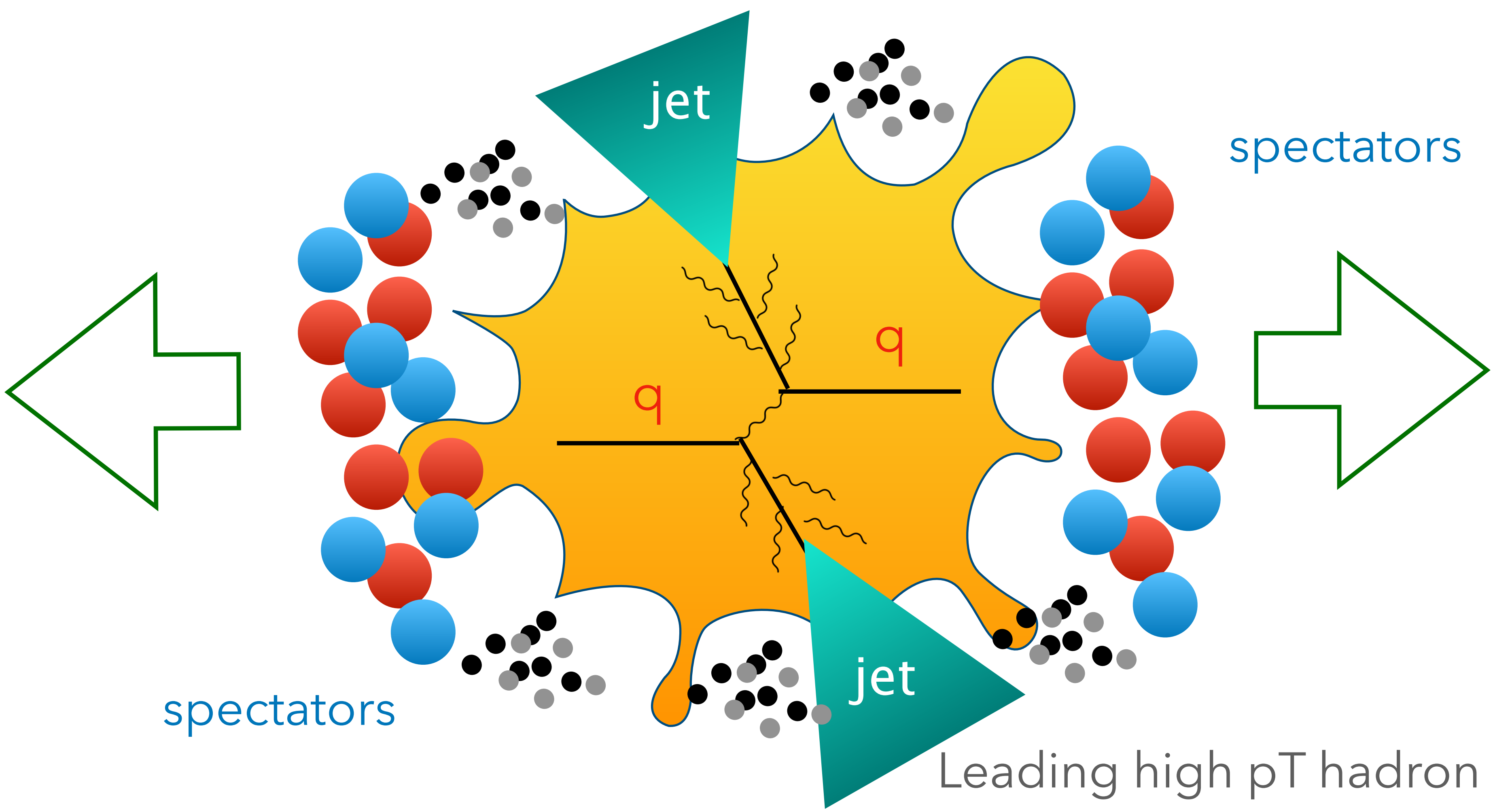
or in one sentence

Study medium induced cascade in an expanding medium
to calculate observables
and match with data from LHC
for jet quenching

Jet formation

• High energy partons, resulting from an initial hard scattering, will create a high energy collimated spray of particles → JETS

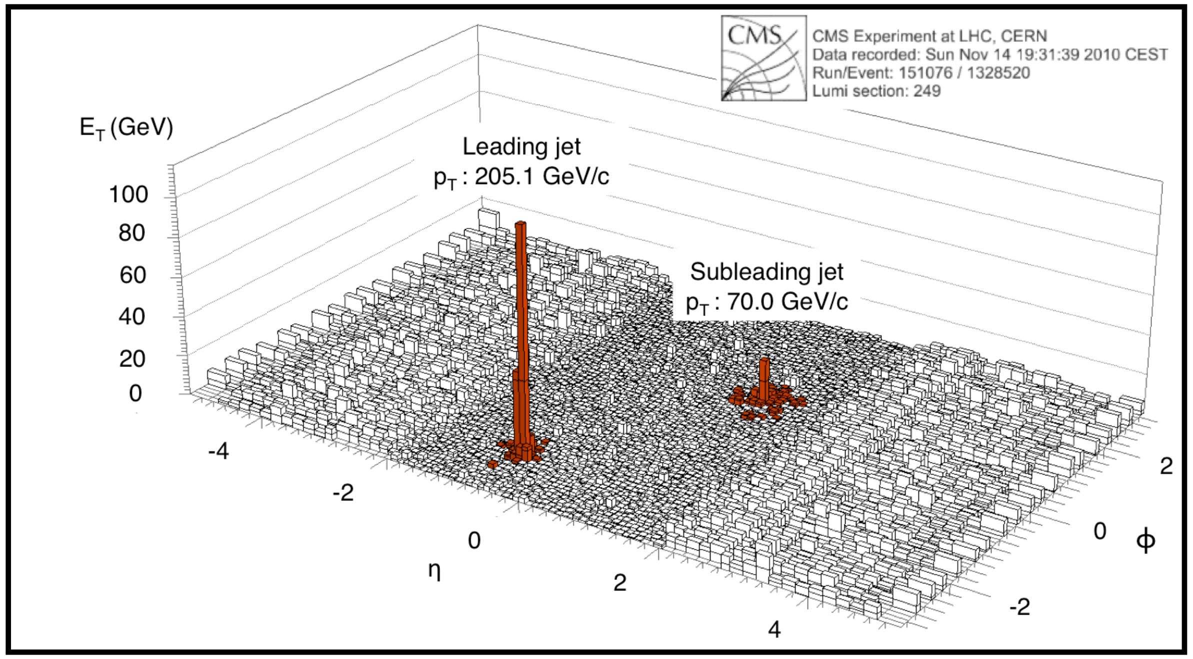
• Partons traveling through a dense color medium are expected to lose energy via medium induced gluon radiation, "jet quenching" and the magnitude of the energy loss depends on the gluon density of the medium.

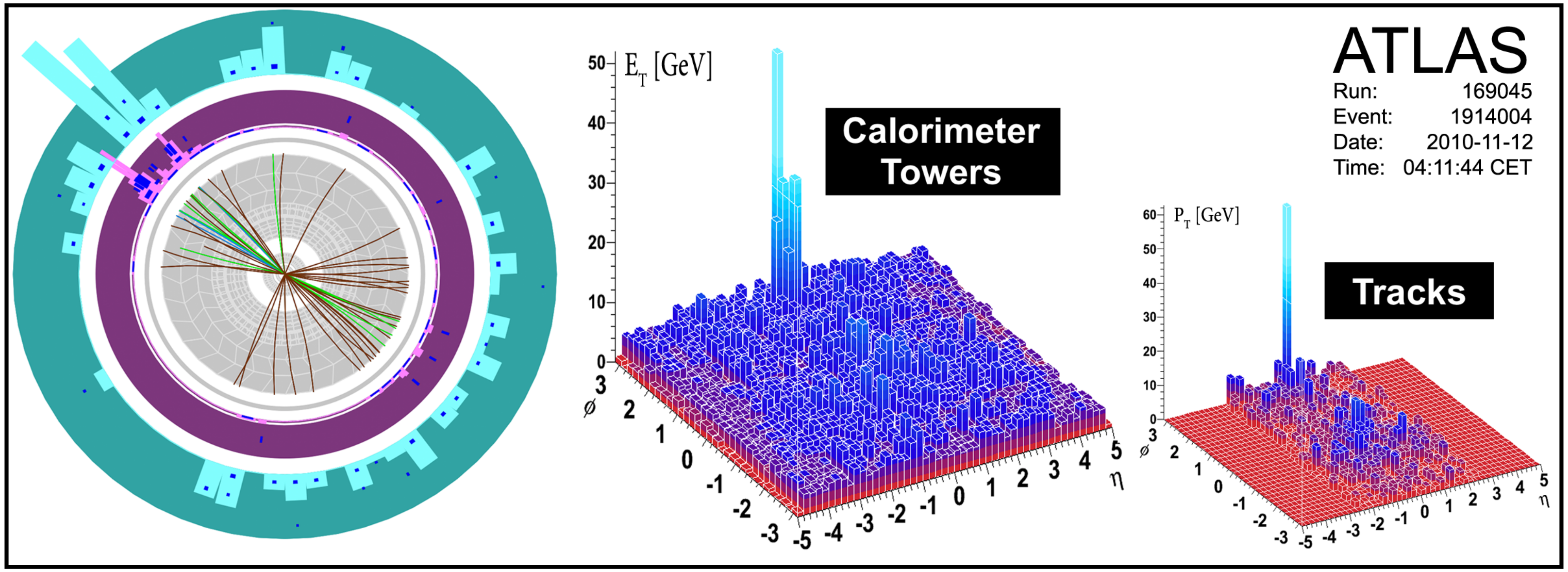


Experimental signatures from LHC

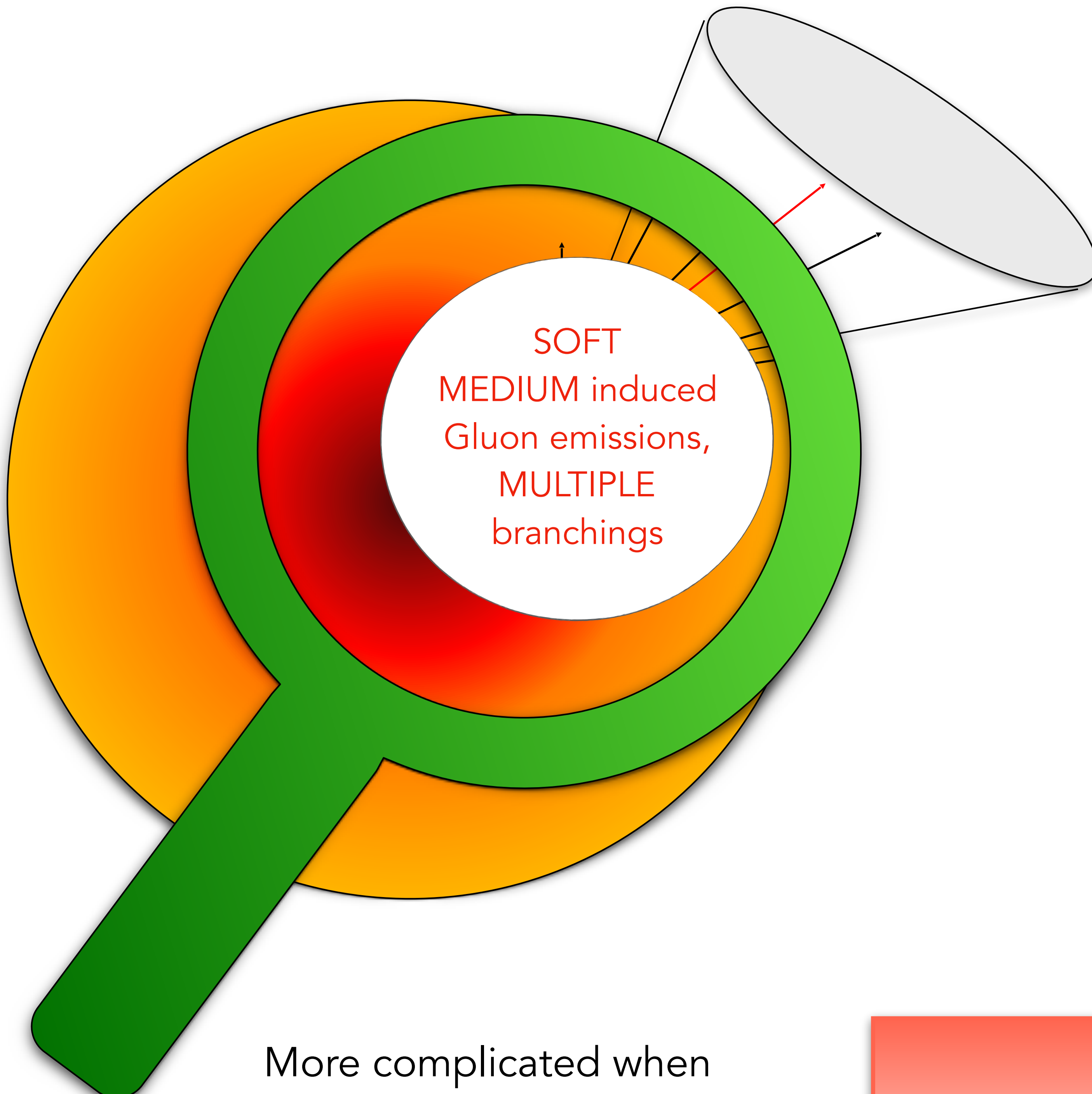
Questions we need to ask ?

- Di-jet asymmetry
- Missing energy linked to transportation of a majority of jet energy by soft particles towards large angles.
- Multiple branching at large angles.
- MC event generators: JEWEL, Q-Pythia etc.



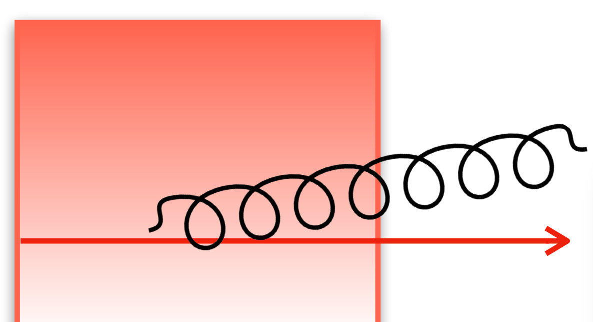


Let us frame the problem …



- Medium induced soft gluons controls energy transport at large angles.
- Offspring gluons carry away sizable amount of energy of parent gluons.
- Efficient way of energy transfer to medium.
- Repeated application of single gluon emission kernel to mimic multiple gluon emission

More complicated when getting more realistic: vacuum radiation, medium induced gluon radiation, expanding medium..



Q) Is parton splitting in vacuum same as in medium (expanding) ?

Medium induced gluon radiation

Inclusive energy distribution of an in- medium produced parton :

$$\omega\frac{dI}{d\omega} = \frac{\alpha_s\, C_R}{(2\pi)^2\,\omega^2}\, 2\mathrm{Re}\int_{\xi_0}^{\infty} dy_l \int_{y_l}^{\infty} d\bar{y}_l \int d\mathbf{u} \int_0^{\chi\omega} d\mathbf{k}_\perp\, e^{-i\mathbf{k}_\perp\cdot\mathbf{u}}\, e^{-\frac{1}{2}\int_{\bar{y}_l}^{\infty} d\xi\, n(\xi)\,\sigma(\mathbf{u})}\, \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial\mathbf{u}} \int_{\mathbf{y}=0}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)} \mathcal{D}\mathbf{r}\, \exp\left[i\int_{y_l}^{\bar{y}_l} d\xi\, \frac{\omega}{2}\left(\dot{\mathbf{r}}^2 - \frac{n(\xi)\sigma\,(\mathbf{r})}{i\,\omega}\right)\right]$$

$\chi \to \infty$ **or** $R \to \infty$ **"unconstrained"**

$\chi \to 1$ **"constrained" kinematics**

The expanding medium is characterised with the time/length dependent quenching factor,

$$\hat{q}(\xi) = \hat{q}_0\left(\frac{\xi_0}{\xi}\right)^{\alpha} \qquad\qquad \bar{\hat{q}} = \frac{2}{L^2}\int_{\xi_0}^{L+\xi_0} d\xi(\xi - \xi_0)\hat{q}(\xi)$$

For multiple scattering centres, the particle performs Brownian motion

$n(\xi)\sigma\ (r) \sim (1/2)\hat{q}(\xi) r^2$

Multiple soft scattering approximation

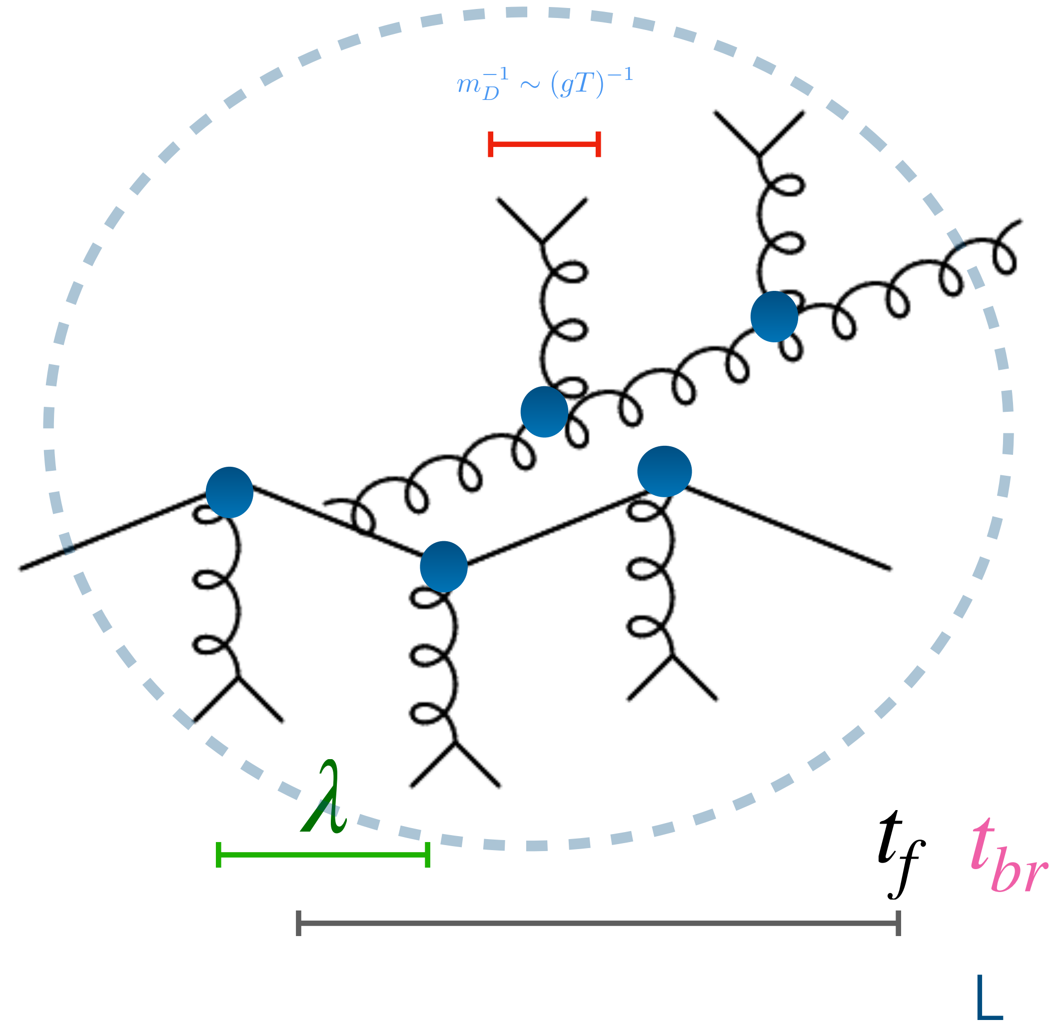
In medium radiation

- The BDMPS-Z spectrum (static medium) :

$$\lim_{R\to\infty} \omega \frac{dI^{(med)}}{d\omega} = \frac{2\alpha_s C_R}{\pi} \ln \left| \cos \left[(1+i) \sqrt{\frac{\omega_c}{2\omega}} \right] \right|$$

- The BDMPS-Z spectrum (static medium with soft gluons only) :

$$\lim_{R\to\infty} \omega \frac{dI}{d\omega} \simeq \frac{2\alpha_s C_R}{\pi} \sqrt{\frac{\omega_c}{2\,\omega}} \quad ; \qquad \omega < \omega_c$$



- Particles undergo diffusion in medium : Radiative process.
- Typical formation time of radiated gluon is (t_f).
- During this timescale, the gluon undergoes multiple kicks which causes an increase in its transverse momentum.
- The typical time for induced emission is the branching time (t_{br}) .

$$\left.\begin{aligned} \langle \boldsymbol{k}^2 \rangle &= \hat{q} t_{\mathrm{f}} \\ t_{\mathrm{f}} &\sim \frac{\omega}{\langle \boldsymbol{k}^2 \rangle} \end{aligned}\right\} \qquad \begin{aligned} k_{\mathrm{br}}^2 &= \sqrt{\hat{q}\omega} \\ t_{\mathrm{br}} &= \sqrt{\frac{\omega}{\hat{q}}} \end{aligned}$$

Gluon spectra for different mediums

- The Altarelli- Parisi splitting function for gluon splitting is,

$$P_{gg} = N_c \frac{(1+z(1-z))^2}{z(1-z)}$$

- The BDMPS-Z spectrum (static medium with soft gluons only) :

$$\frac{dI}{dz} = \frac{\alpha_s}{\pi} P(z) \sqrt{\frac{q_0}{p}} \kappa(z) L$$

- The BDMPS-Z spectrum (static medium) :

$$\frac{dI}{dz} = \frac{2\alpha_s}{\pi} P(z) \,\mathrm{Re} \ln[\cos(\Omega_0 L)] \qquad \Omega_0 L = \sqrt{\frac{-i}{2} \frac{\hat{q}_0}{p}} \kappa(z) L$$

Gluon spectra for different mediums

- Variables :

$$\Omega_0 L = \sqrt{\frac{-i}{2}\frac{\hat{q}_0}{p}}\kappa(z)L \qquad P_{gg} = N_c \frac{(1+z(1-z))^2}{z(1-z)}$$

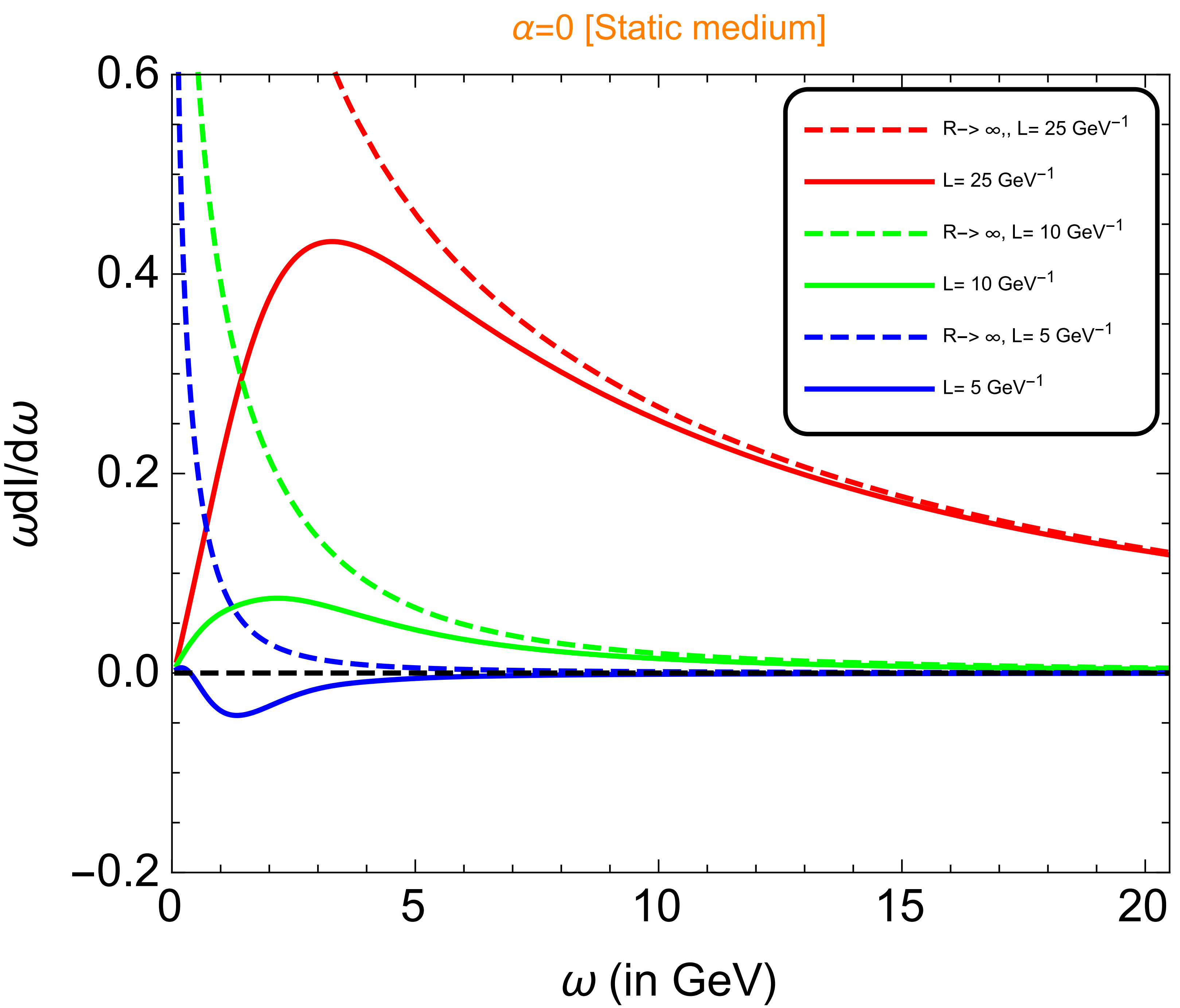
- The exponentially expanding medium :

$$\frac{dI}{dz} = \frac{2\alpha_s}{\pi} P(z) \,\mathrm{Re} \ln J_0(2\Omega_0 L)$$

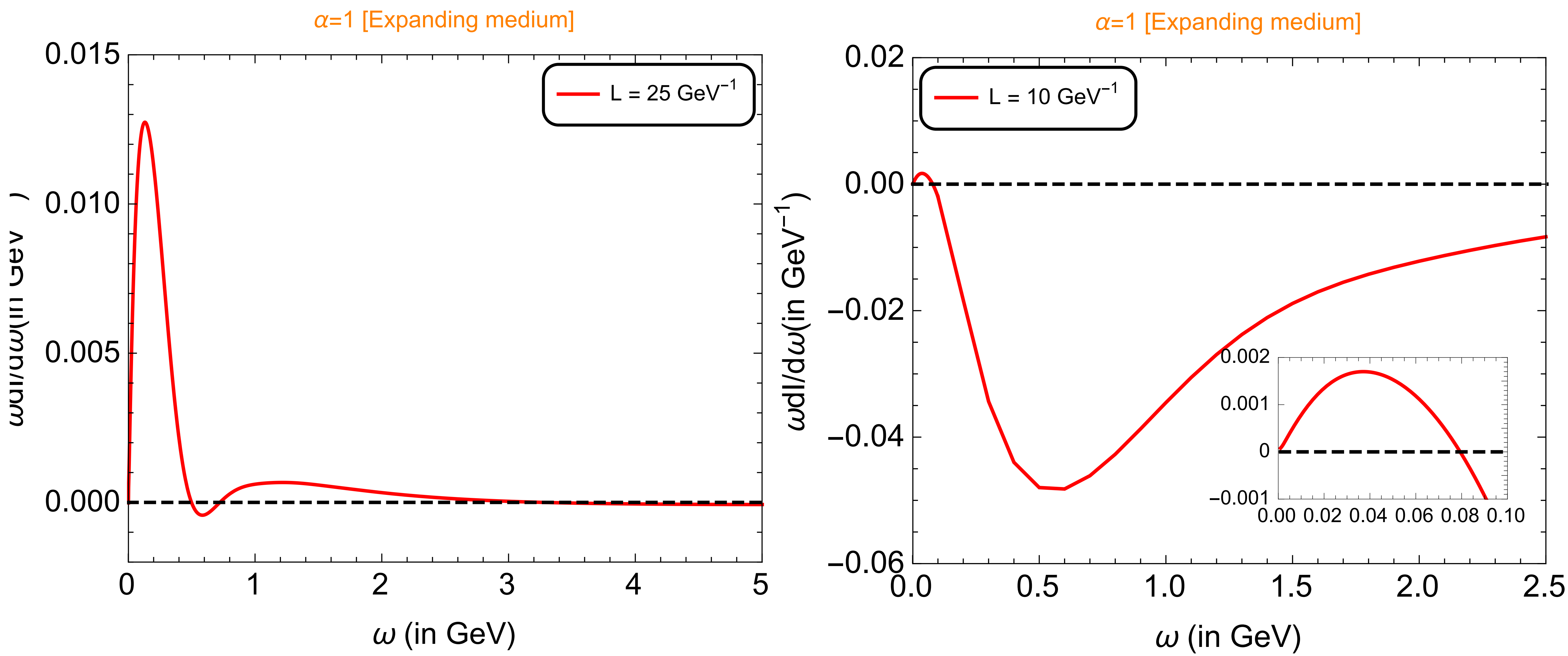
- The Bjorken expanding medium :

$$\frac{dI}{dz} = \frac{2\alpha_s}{\pi} P(z) \,\mathrm{Re} \ln \left[\left(\frac{t_0}{L+t_0} \right)^{1/2} \frac{J_1(z_0)Y_0(z_L) - Y_1(z_0)J_0(z_L)}{J_1(z_L)Y_0(z_L) - Y_1(z_L)J_0(z_L)} \right]$$

Gluon spectra for static medium

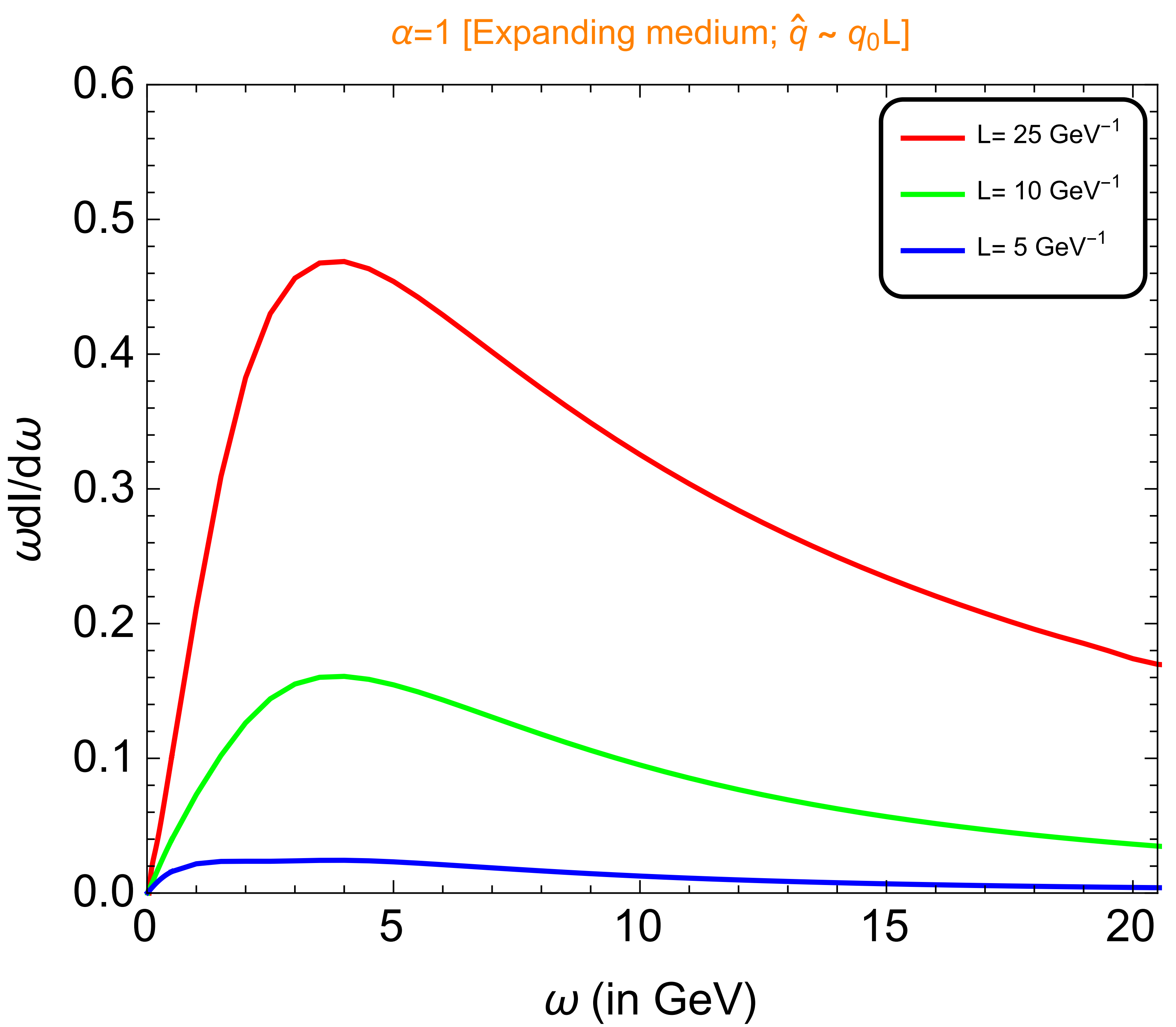


Gluon spectra for Bjorken expanding medium



When plotted with q^ as the expanding case (not scaled up), we observe the spectra to be negative for the expanding case at L < 2 fm

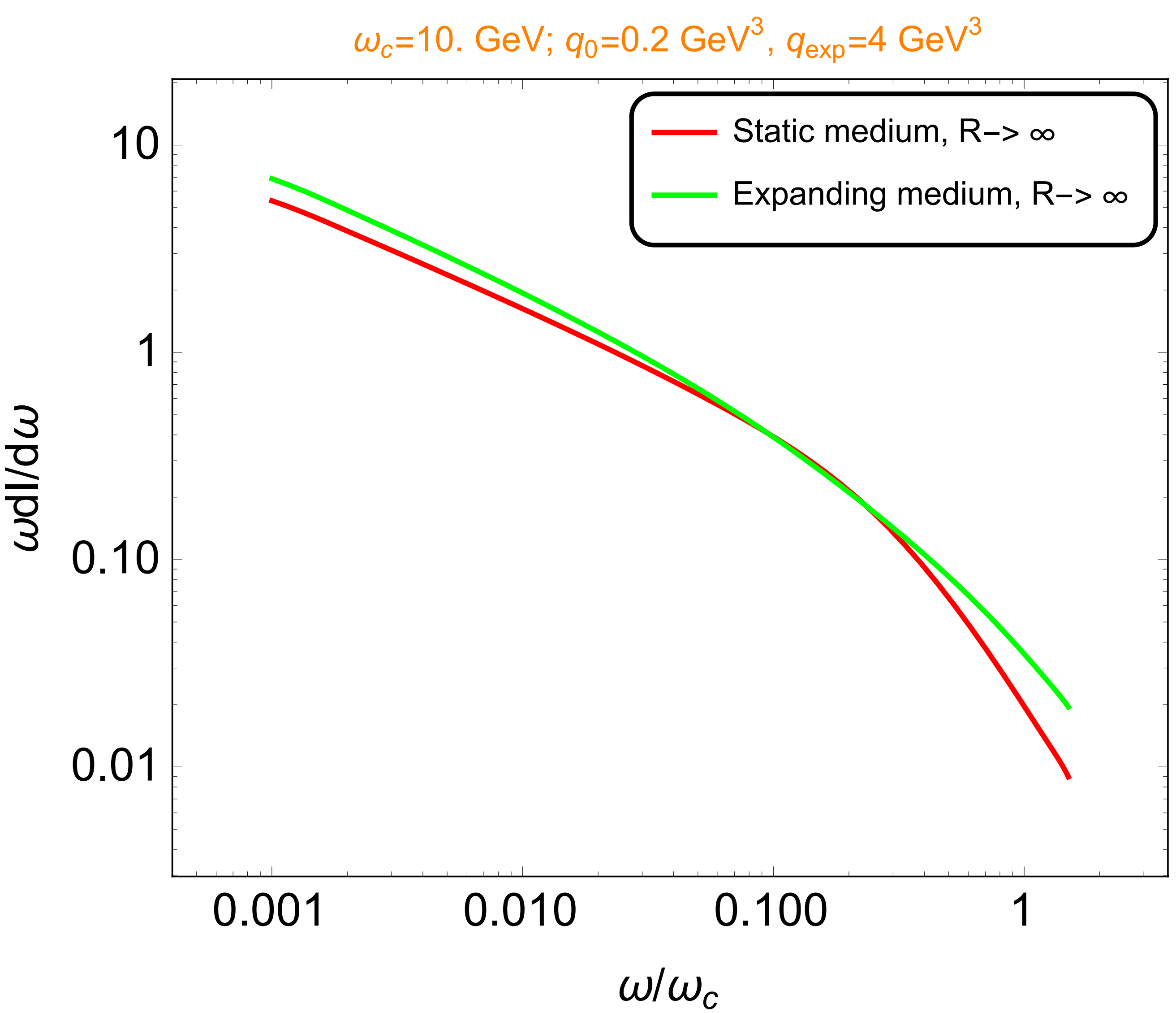
Scaling behavior for static and BJ expanding medium

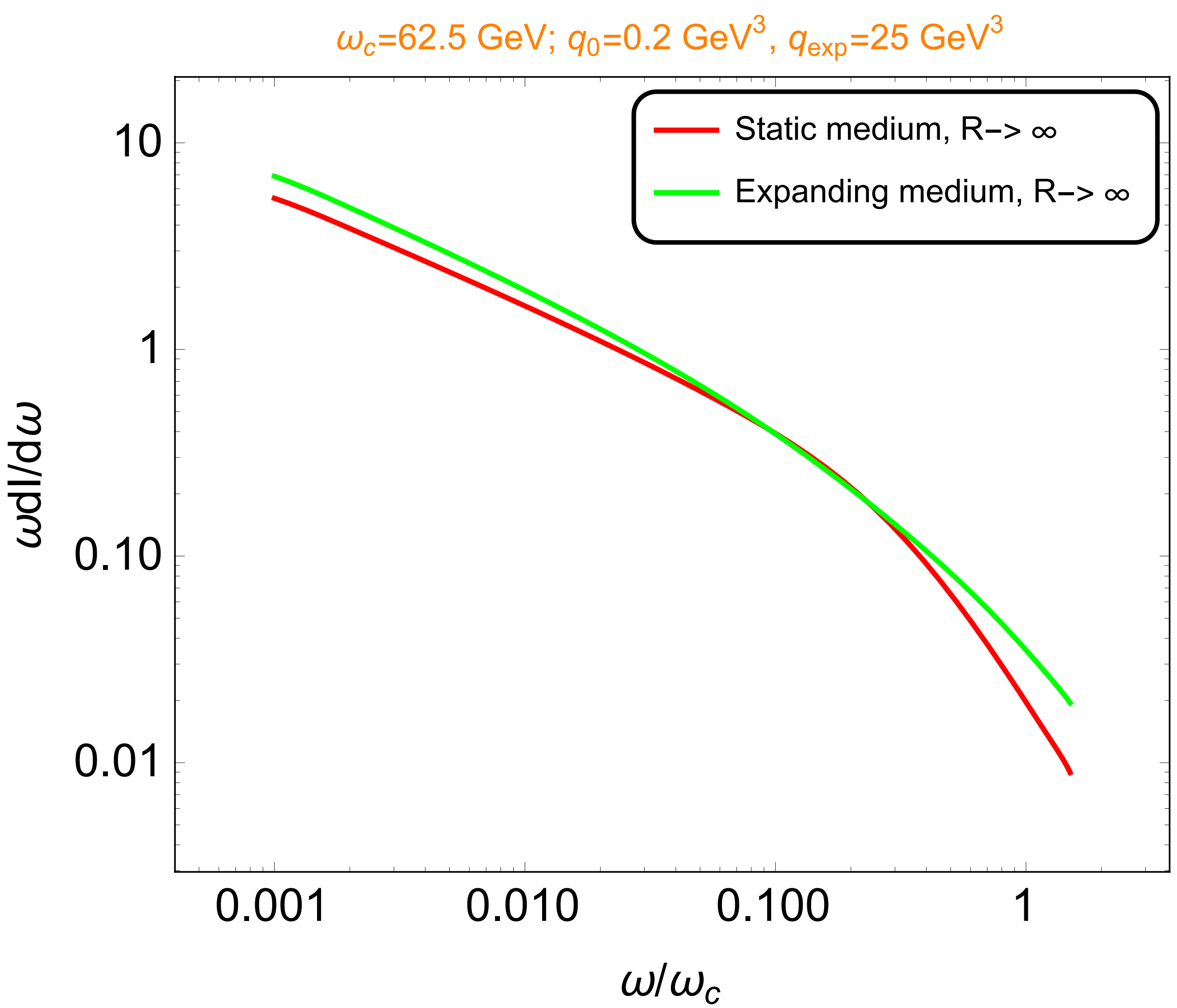


For scaled spectra, we observe the scaling behavior for Bjorken expanding case

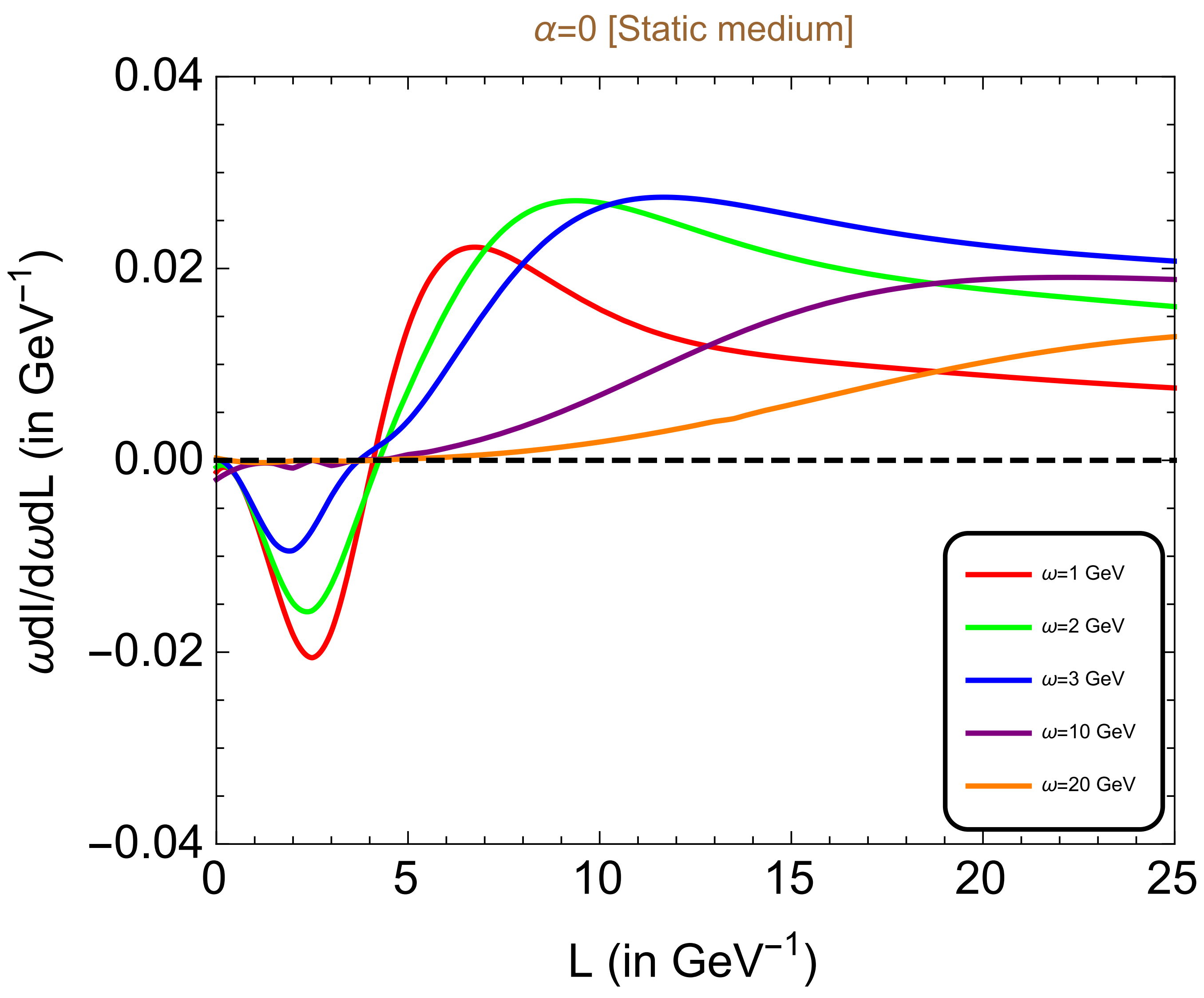
Scaling behaviour of the spectrum

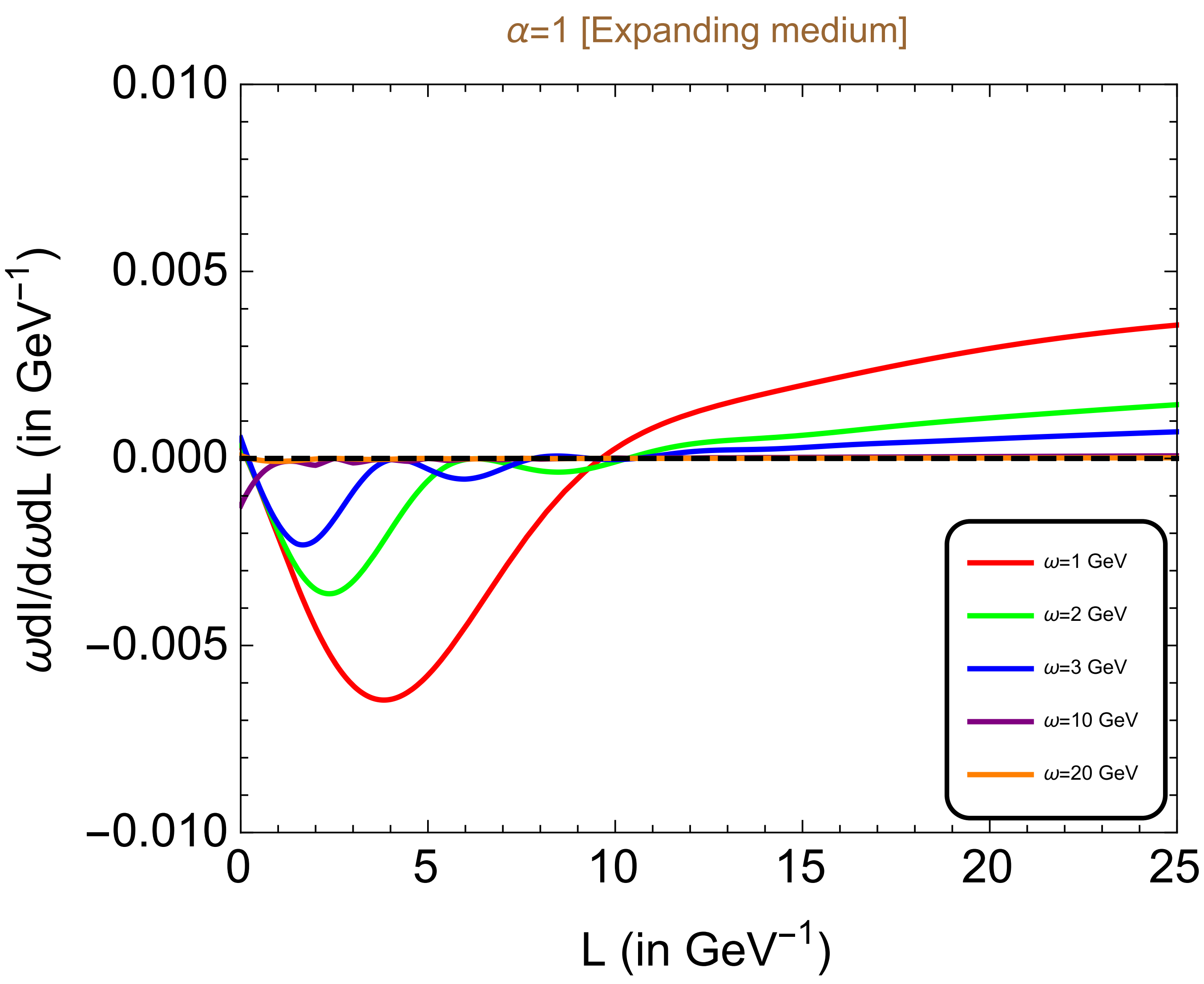
Spectra shows a scaling; Just increase q^ from static to expanding at same order of w_c





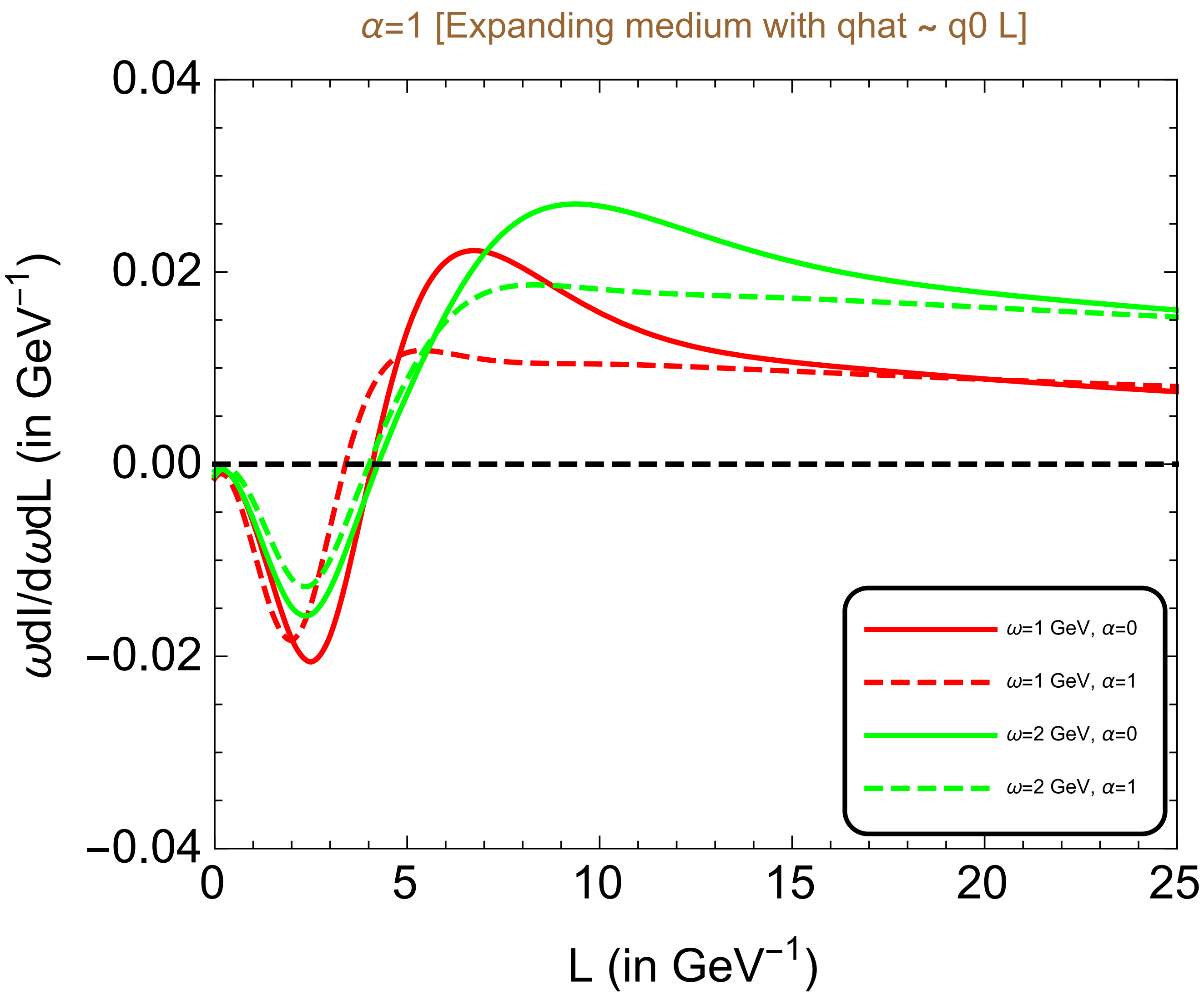
Splitting rate: Static vs Bjorken expanding medium

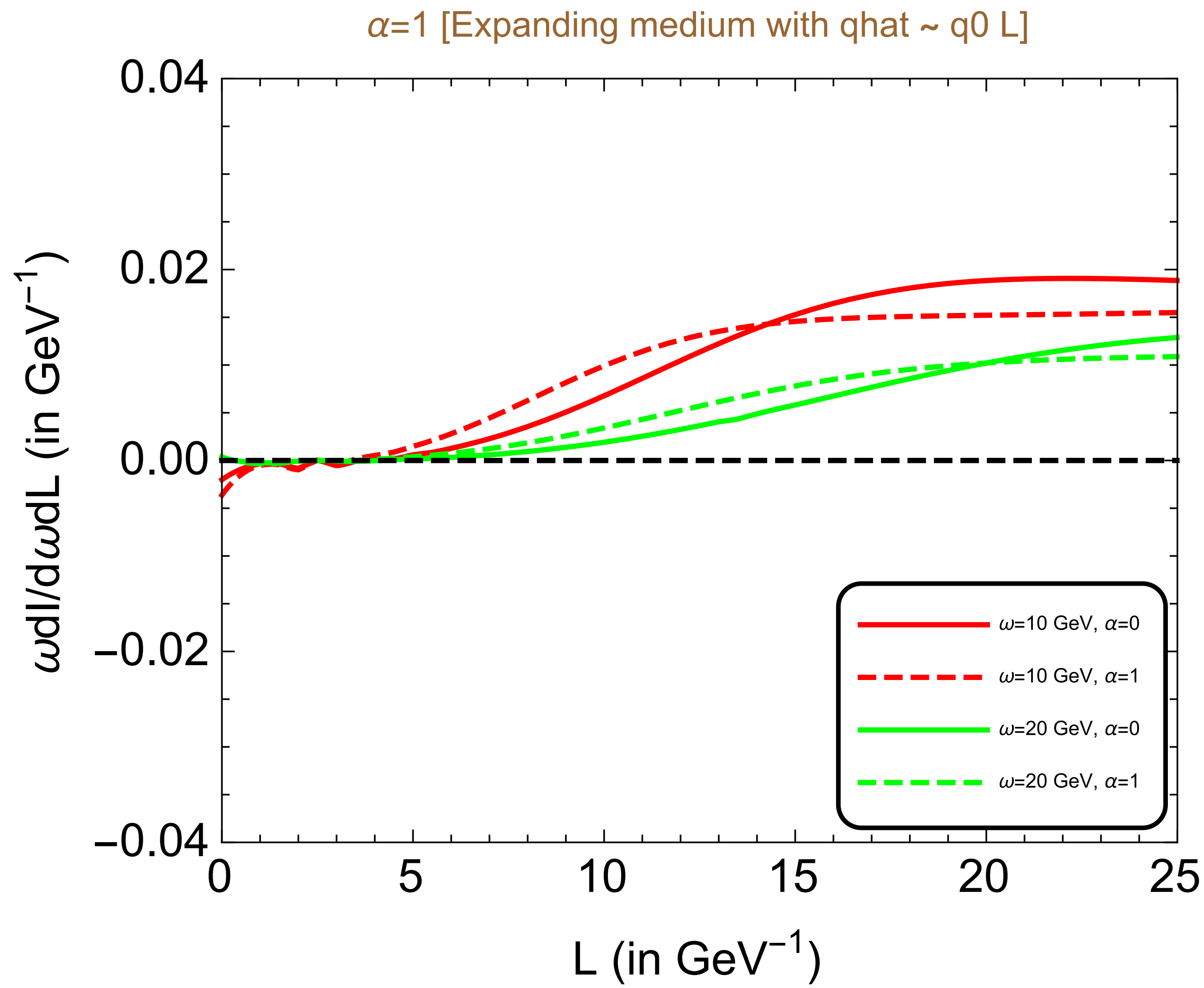




A comparison of the gluon splitting rates in a static medium with that of a Bjorken expanding medium in q^

Splitting rate: Static vs Bjorken expanding medium





A comparison of the gluon splitting rates in a static medium with that of a Bjorken expanding medium with scaling in q^

Kinematic rate equation

The kinematic evolution equation (GAIN + LOSS terms) :

$$\frac{\partial D(x,t)}{\partial L} = \int dz\, \hat{\mathcal{K}}(z,L) \left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z}, L\right) - \frac{z}{\sqrt{x}} D(x,L) \right]$$

We re -parametrize the equation in terms of a dimensionless variable **τ** ,

$$\tau \equiv \sqrt{\frac{\hat{q}_0}{p}} L$$

and arrive at the kinematic rate equation :

$$\frac{\partial D(x,t)}{\partial \tau} = \int dz\, \mathcal{K}(z,\tau|p) \left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z}, \tau\right) - \frac{z}{\sqrt{x}} D(x,\tau) \right]$$

where the gluon splitting rate is defined as :

$$\mathcal{K}(z,\tau|p) \equiv \sqrt{\frac{p}{\hat{q}_0}} \hat{\mathcal{K}}(z,L|p) = \sqrt{\frac{p}{\hat{q}_0}} \frac{dI}{dz dL}$$

Splitting rates for different mediums

- The BDMPS-Z spectrum (static medium with soft gluons only) :

$$\hat{\mathcal{K}}(z,\tau) = \frac{\alpha_s}{\pi} P(z)\kappa(z) \qquad \kappa(z) = \sqrt{[1-z(1-z)]/[z(1-z)]}$$

- The BDMPS-Z spectrum (static medium) :

$$\hat{\mathcal{K}}(z,\tau) = \frac{\alpha_s}{\pi} P(z)\kappa(z)\,\mathrm{Re}\left[(i-1)\tan\big((1-i)\kappa(z)\tau/2\big)\right]$$

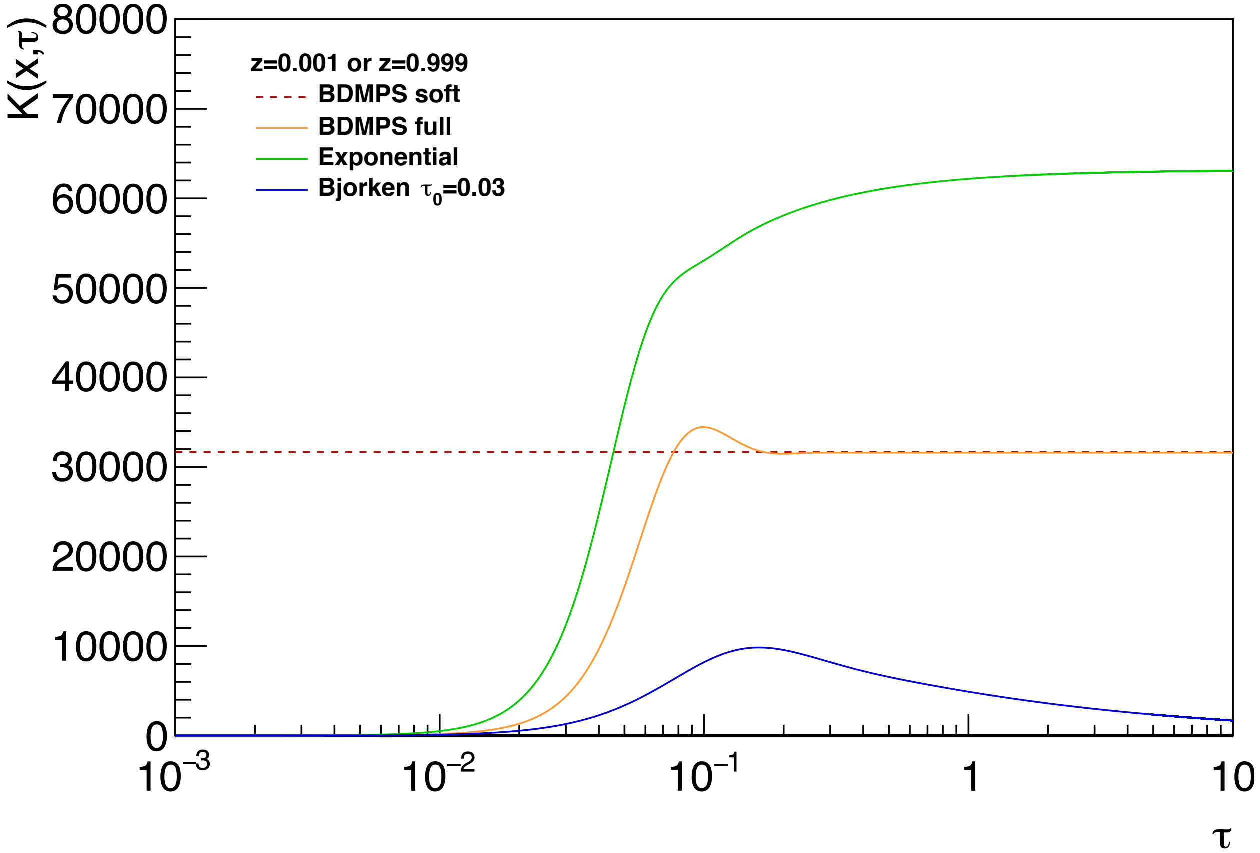
- The exponentially expanding medium :

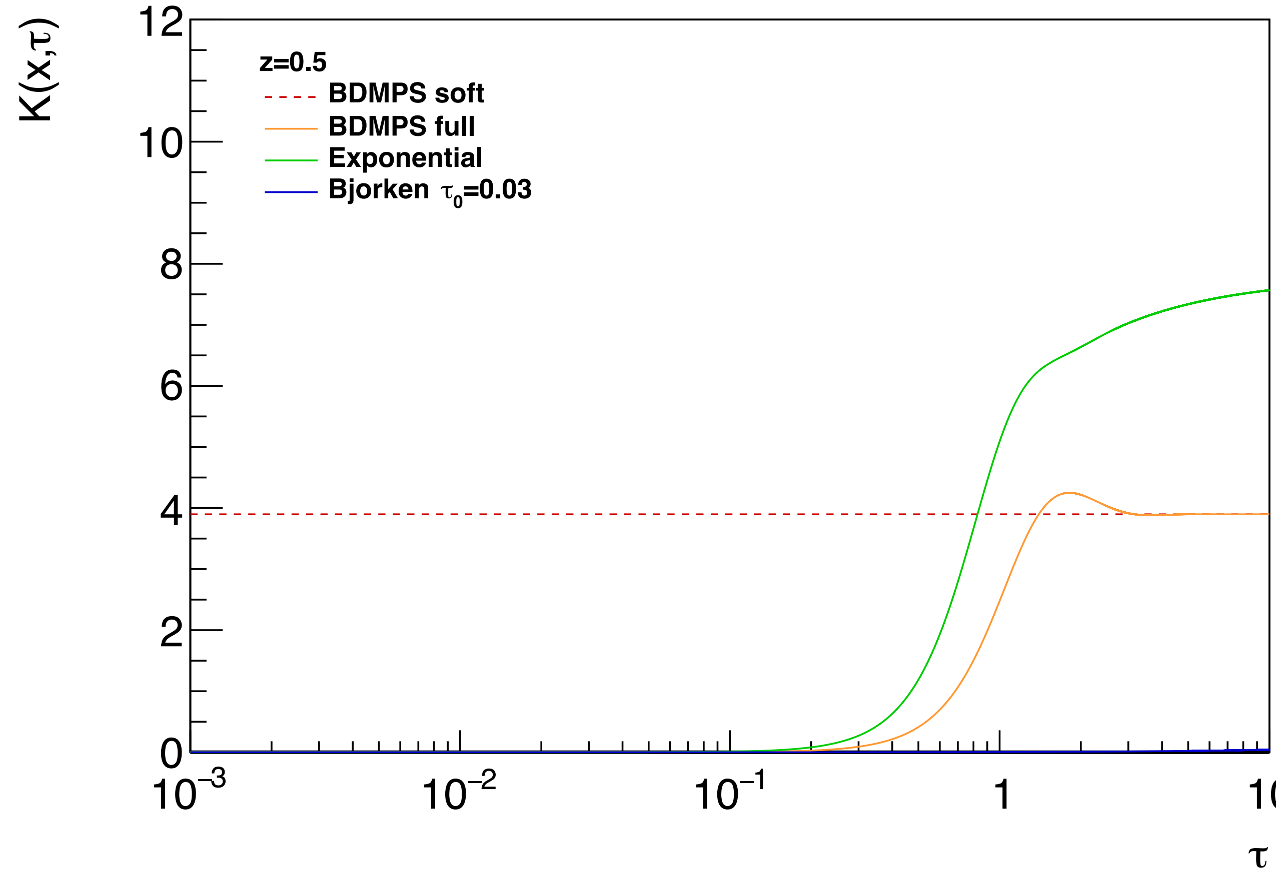
$$\mathcal{K}(z,\tau) = \frac{2\alpha_s}{\pi} P(z)\kappa(z)\,\mathrm{Re}\left[(i-1)\frac{J_1\big((1-i)\kappa(z)\tau\big)}{J_0\big((1-i)\kappa(z)\tau\big)}\right]$$

- The Bjorken expanding medium :

$$\mathcal{K}(z,\tau) = \frac{\alpha_s}{\pi} P(z)\kappa(z)\sqrt{\frac{\tau_0}{\tau+\tau_0}}\,\mathrm{Re}\left[(1-i)\frac{J_1(z_L)Y_1(z_0)-J_1(z_0)Y_1(z_L)}{J_1(z_0)Y_0(z_L)-J_0(z_L)Y_1(z_0)}\right]$$

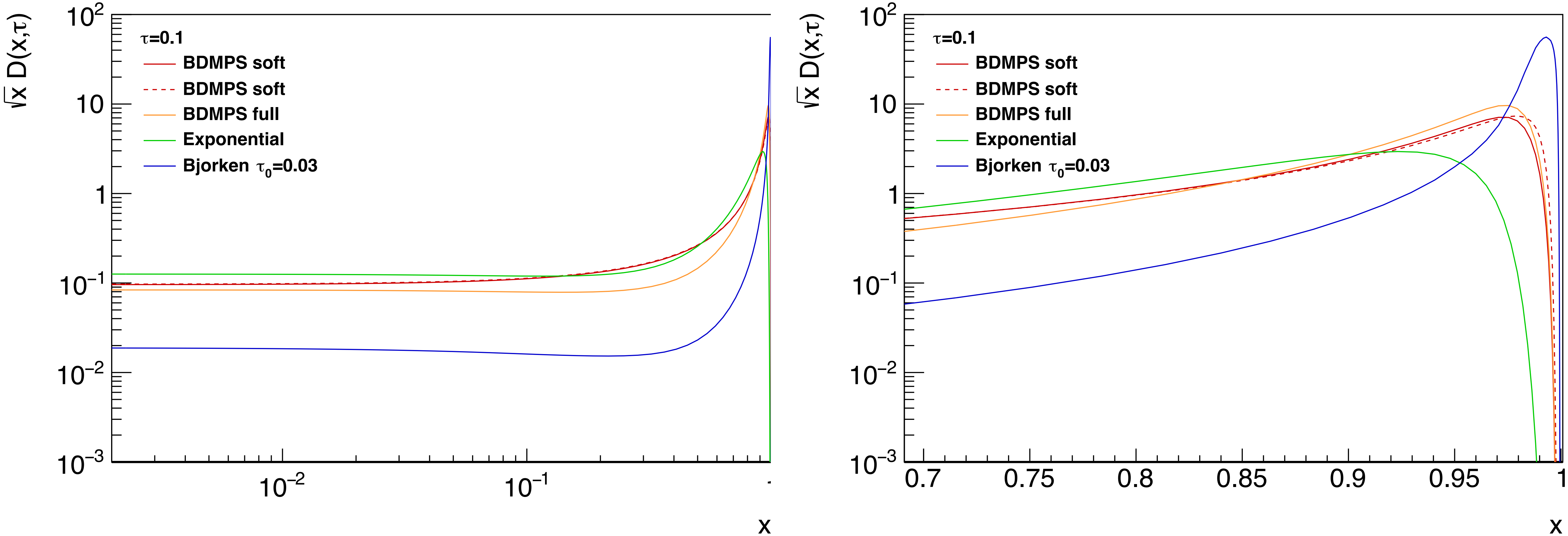
Medium modified splitting rate





- The BDMPS soft (w <w_c) has a constant splitting rate independent of the time of evolution of the plasma.
- The exponential and the Bjorken medium profile has the highest and the lowest rates respectively.
- The rates for all the profiles except the BDMPS soft are similar at very low evolution time or length of the medium.

Medium evolved gluon spectra

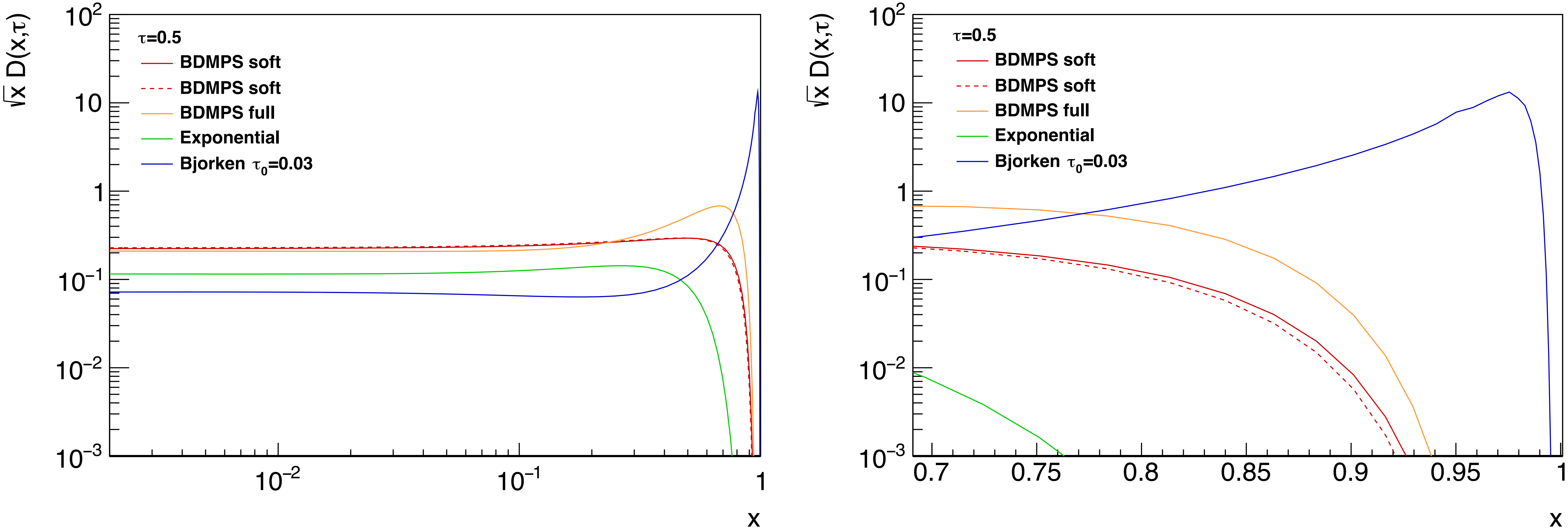


- The numerical value of the BDMPS soft is in close agreement with the analytical result.

$$D(x,\tau) = \frac{\tau}{\sqrt{x}(1-x)^{3/2}} \mathrm{e}^{-\pi \frac{\tau^2}{1-x}}$$

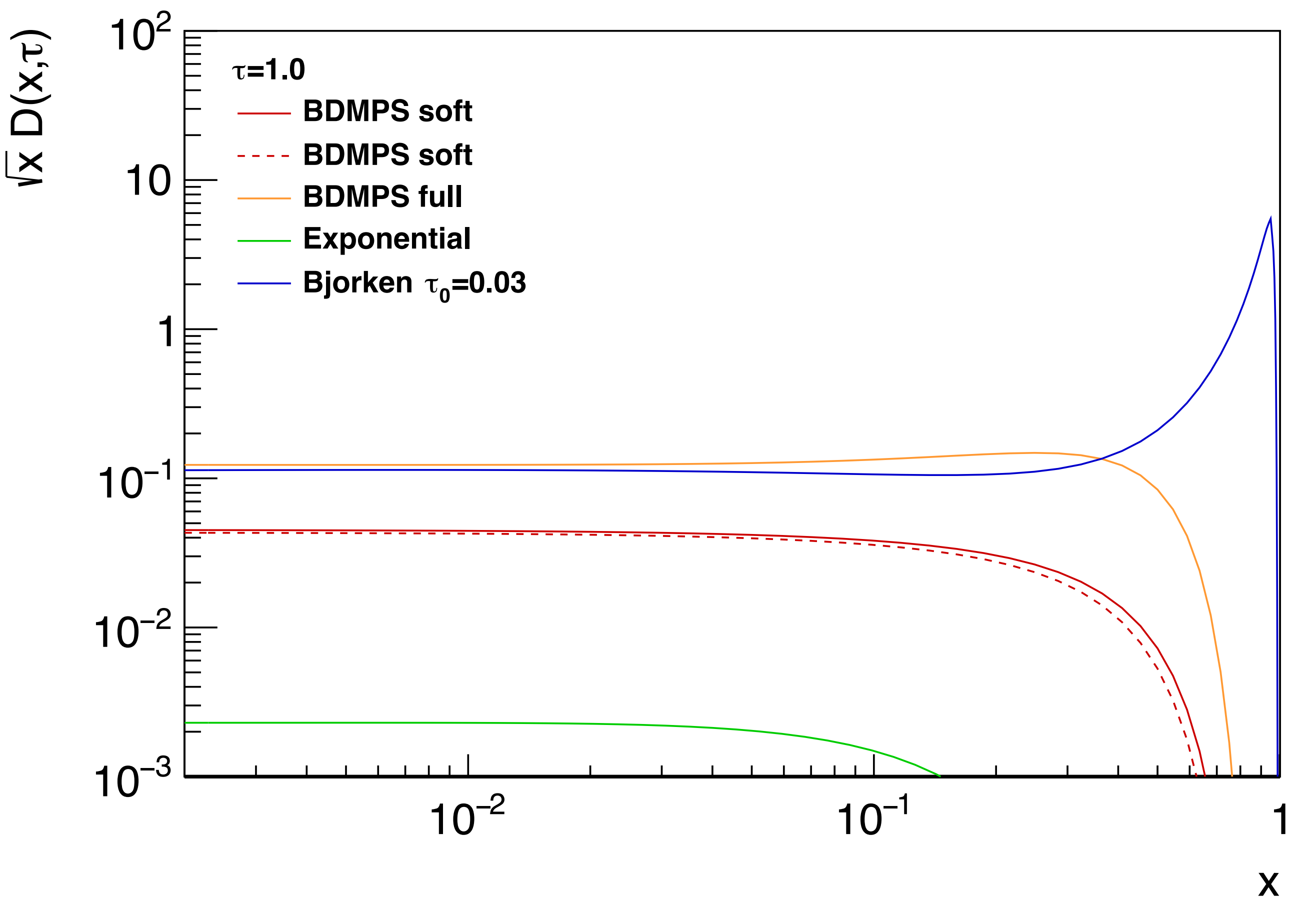
- The small-x (left) and high-x (right) dependence of the medium-induced gluon distribution D(x,τ) for τ = 0.1.

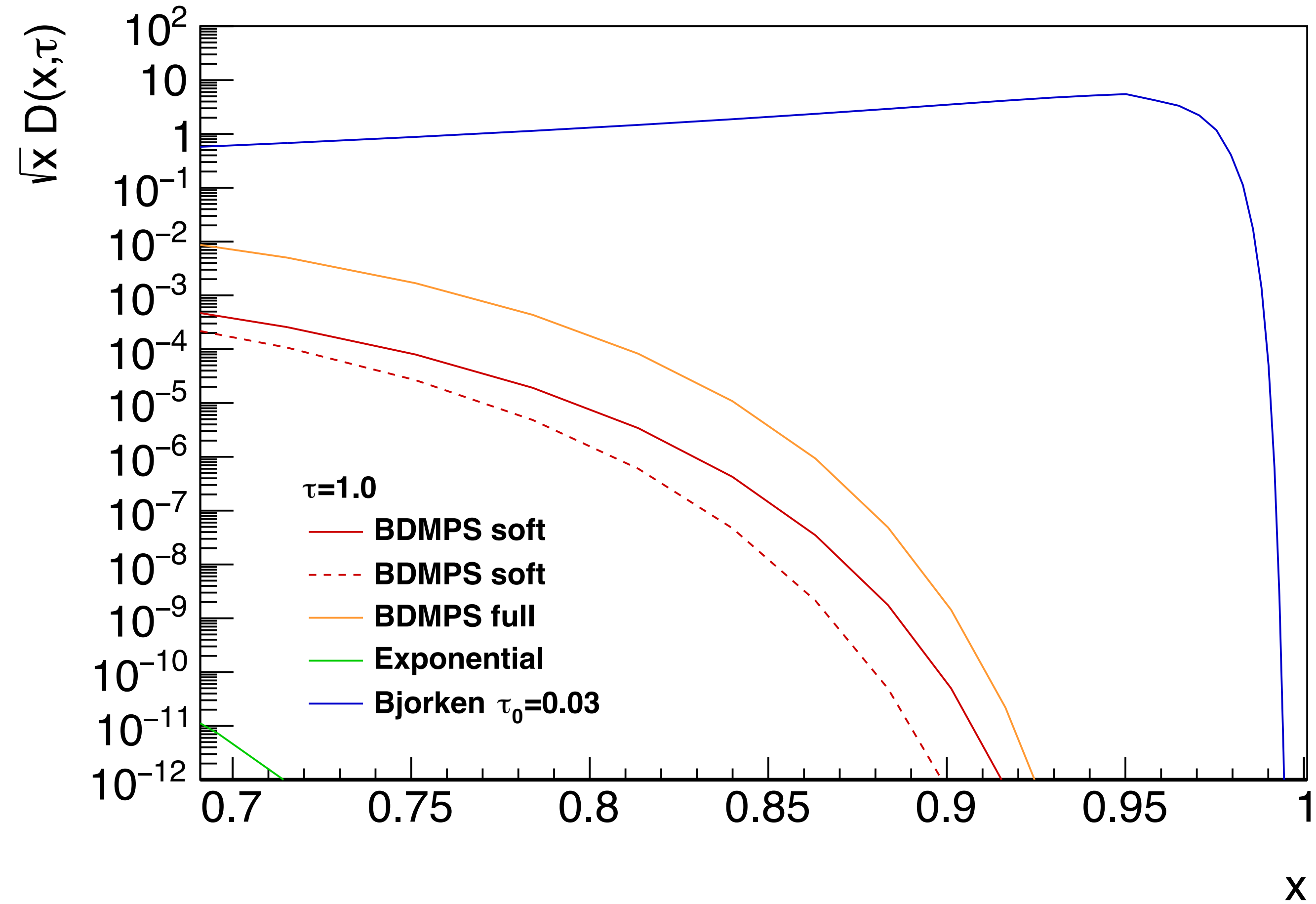
Medium evolved gluon spectra



- The numerical value of the BDMPS soft is in close agreement with the analytical result.
- The small-x (left) and high-x (right) dependence of the medium-induced gluon distribution D(x,τ) for τ = 0.5.

Medium evolved gluon spectra





- The numerical value of the BDMPS soft is in close agreement with the analytical result.
- The small-x (left) and high-x (right) dependence of the medium-induced gluon distribution D(x,τ) for τ = 1.0.
- The results of the spectra are consistent with the rates of the individual medium profiles.

Moments of the distribution and R_{AA}

Considering the formula for the parton spectrum at high-p_T ,

$$\frac{d\sigma_{\rm AA}}{dp_T} = \int dp'_T \int_0^1 \frac{dx}{x}\, \delta(p_T - xp'_T) D\left(x, \tau \equiv \sqrt{\hat{q}/p'_T}\right) \frac{d\sigma_0}{dp'_T}$$

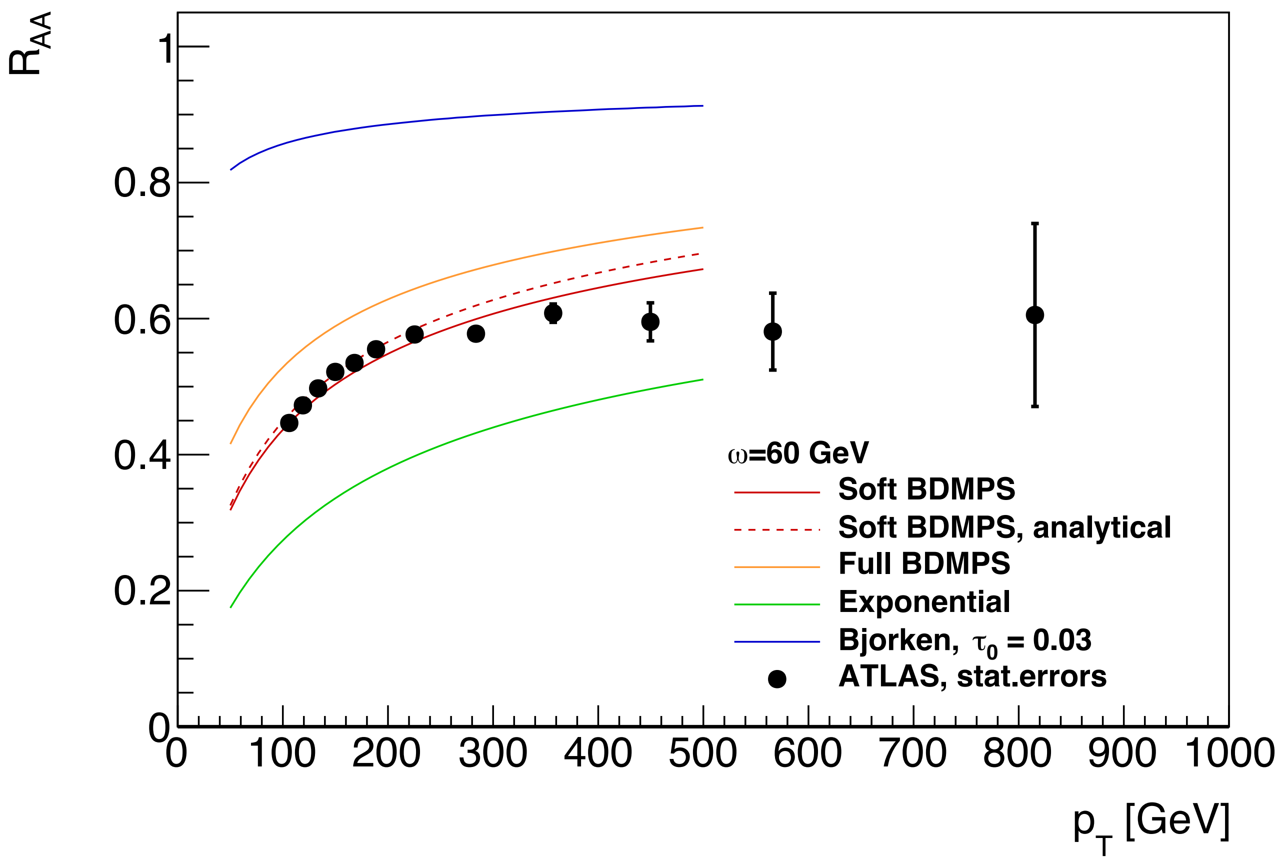
We assume that we have a steeply falling hard spectrum, with N = 5.6,

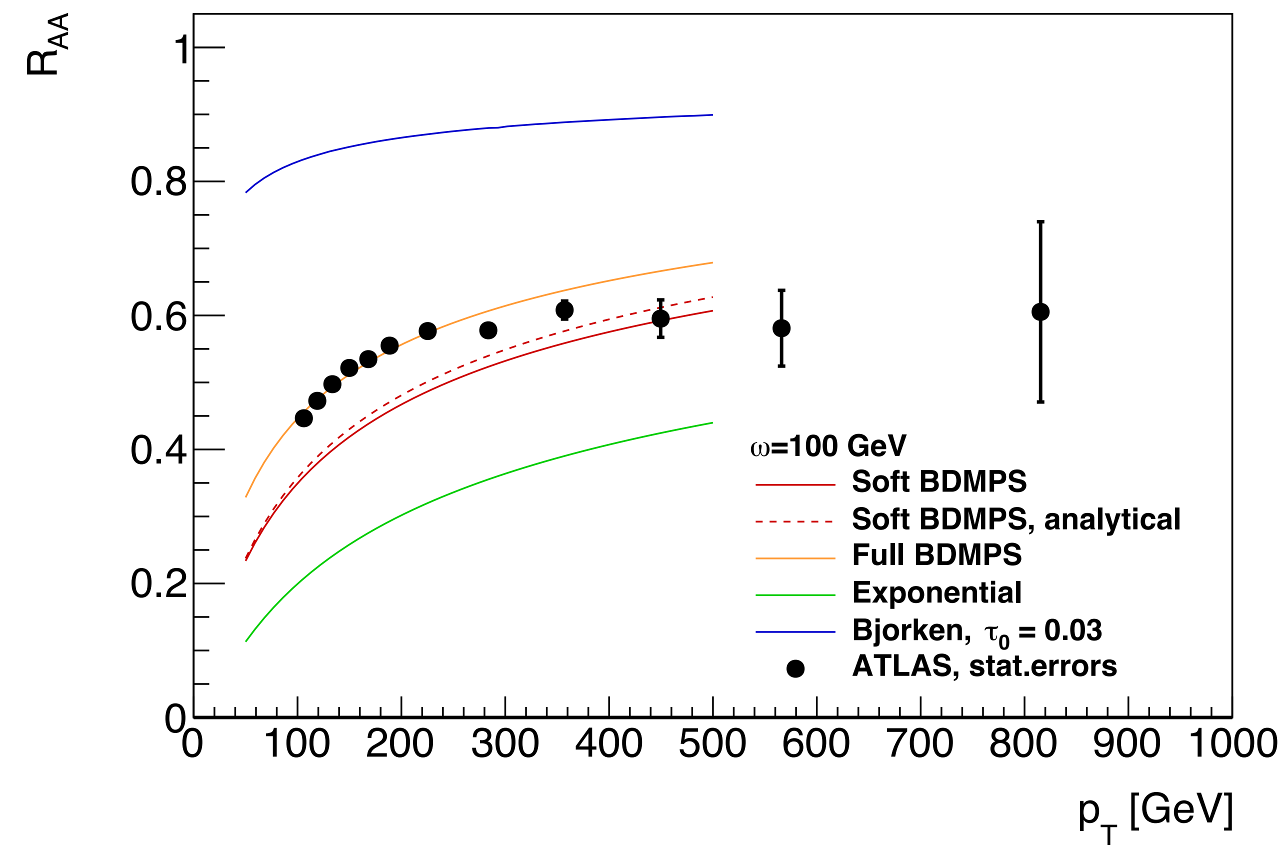
$$d\sigma_0/dp_T \propto p_T^{-N}$$

The jet suppression factor Q (p_T) = $d\sigma_{AA}/dp_T$ /$d\sigma_0/dp_T$, is simply ,

$$Q(p_T) = \int_0^1 dx\, x^{N-2} D(x, \sqrt{x}\tau)$$

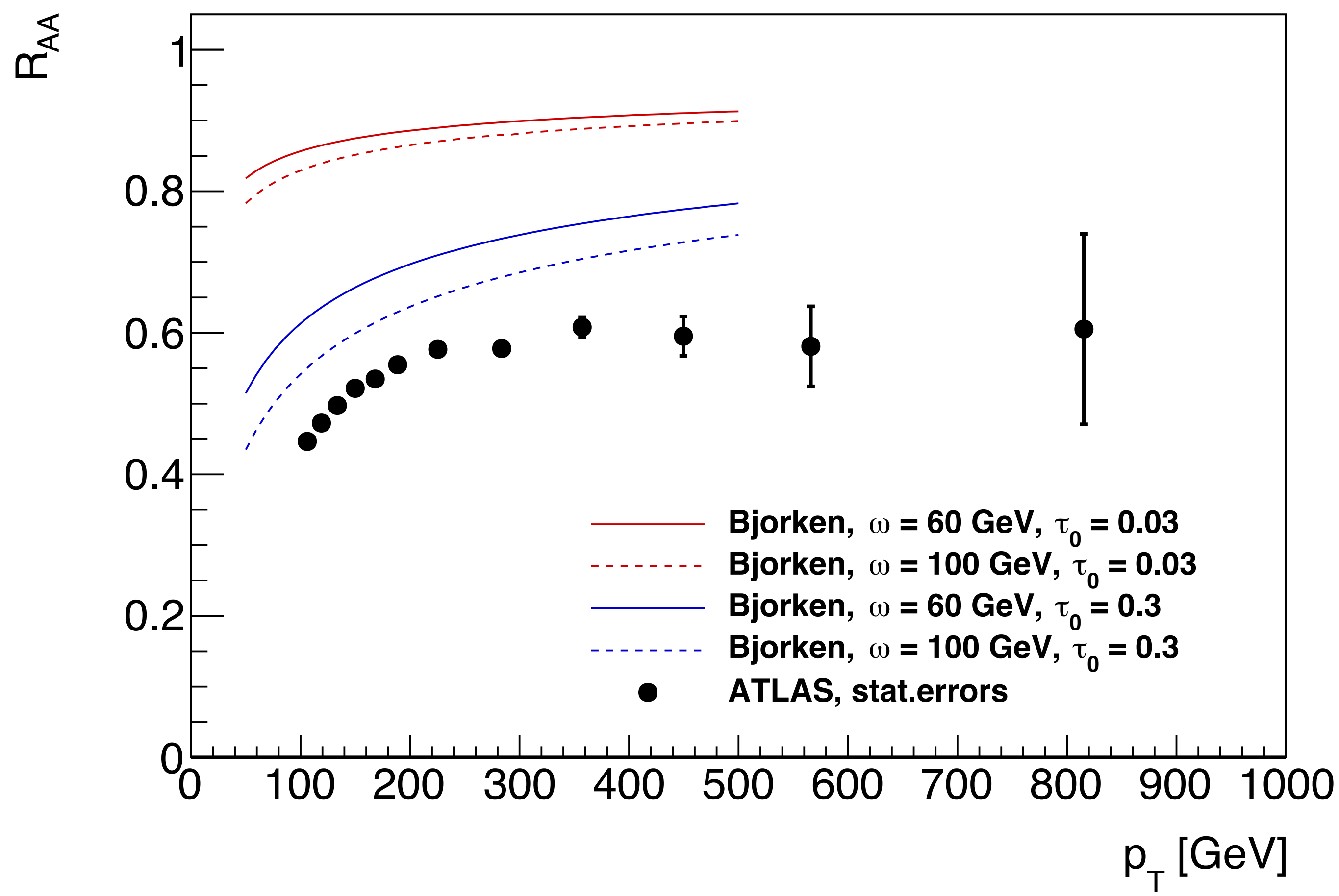
Theory vs. Experiment : Jet R_{AA}





- The nuclear suppression factor with n = 5.6 for a fixed power law spectrum.
- The numerical value of the BDMPS (soft) is in close agreement with the analytical result.
- The Bjorken expanding medium has the least quenching.
- The exponential medium has maximum quenching.

Jet R_{AA} for Bjorken profile

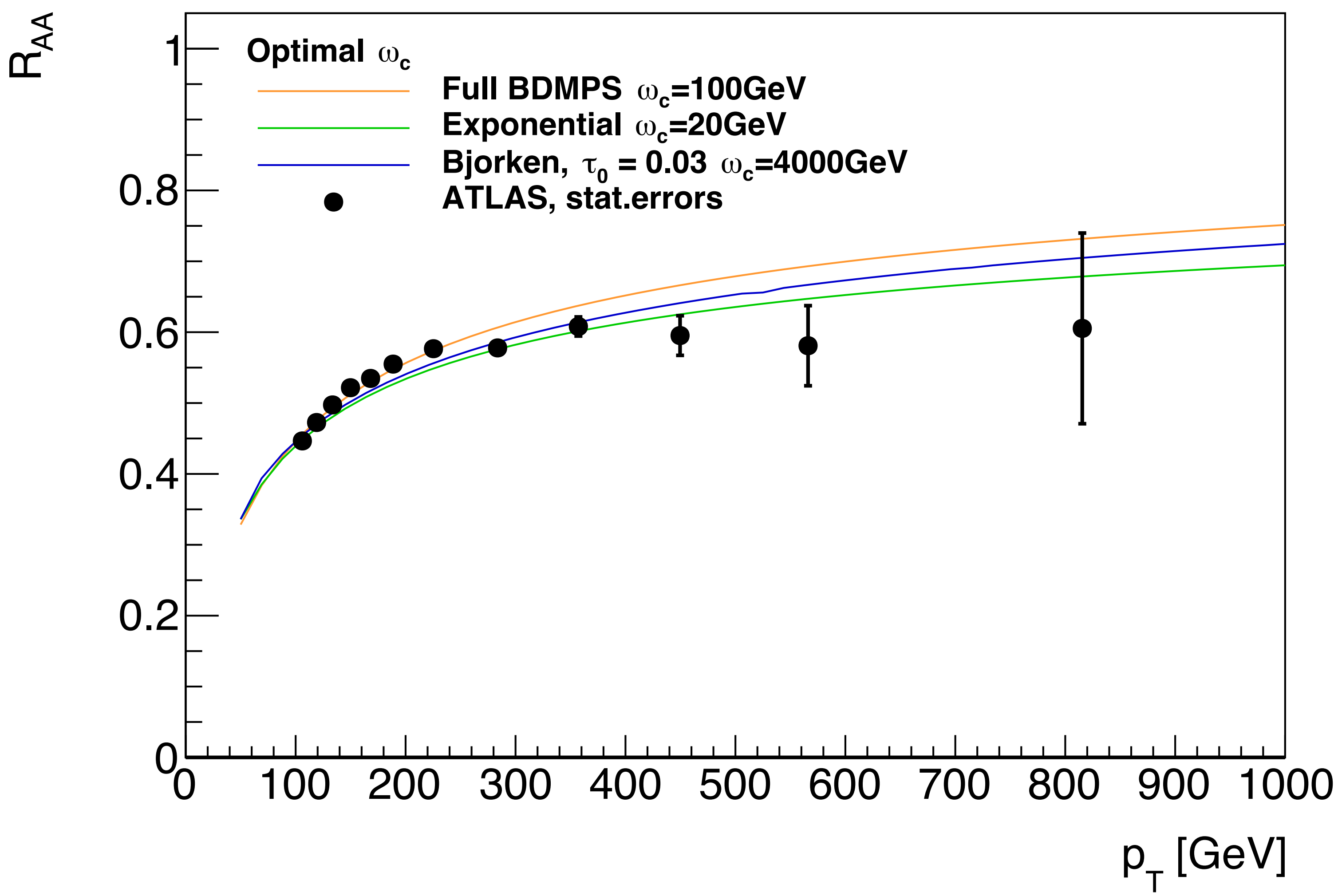


- As the initial time at which the Bjorken medium starts evolving becomes higher, we observe higher quenching by the medium.
- The medium acts like a static medium if we increase the initial time of the Bjorken expansion.

Jet R_{AA} for re-scaled profiles

Can we re-scale our profiles by some constant factor for the quenching ?

Jet R_{AA} for re-scaled profiles



$$\bar{\hat{q}} = \frac{2}{L^2}\int_{\xi_0}^{L+\xi_0} d\xi(\xi - \xi_0)\hat{q}(\xi)$$

$\langle q \rangle^{BDMPS} = 0.2\ \mathrm{GeV}^3$

$\langle q \rangle^{expo} = 0.105\ \mathrm{GeV}^3$

$\langle q \rangle^{BJ} = 0.01\ \mathrm{GeV}^3$

- The nuclear suppression factor R_{AA} for a power-law spectrum with fixed n = 5.6 with minimisation and scaling up the q^.
- The medium evolved spectra with the time dependent splitting imposes newer insights into the quenching mechanism of the jets in the medium. The re-scaling of the quenching factor is able to characterize the different medium profiles effectively.
- However, simply re-scaling the quenching factor is not enough; evolution equation plays a role too !

Summary and discussions

- The medium-evolved gluon spectra and splitting rates are systematically calculated using the kinetic rate equation for all the medium profiles.

- A study of the distinctive features of the spectra at low and high momentum fractions of radiated gluons are provided.

- We provide a calculation of the jet R_{AA} which quantifies a sensitivity of the inclusive jet suppression on the way the medium expands.

- Finally, we compare the predicted jet R_{AA} with the experimental data from ATLAS, LHC and confirm the scaling behavior of the quenching.

- Going beyond energy loss: medium-modified intra-jet and out-of-jet distribution of particles.

- Generalizing to more complicated medium models (implementation of hot spots).

  ==> Can we develop analytical insights for a rate that depends on local medium properties ?

References

- **Theoretical formalisms**

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- **Figures from experiment**

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" Let us look forward to exciting times ahead..."

Thank you