Impact of pre-equilibrium dynamics on jet quenching observables

Marcos González Martínez
IGFAE, Universidade de Santiago de Compostela
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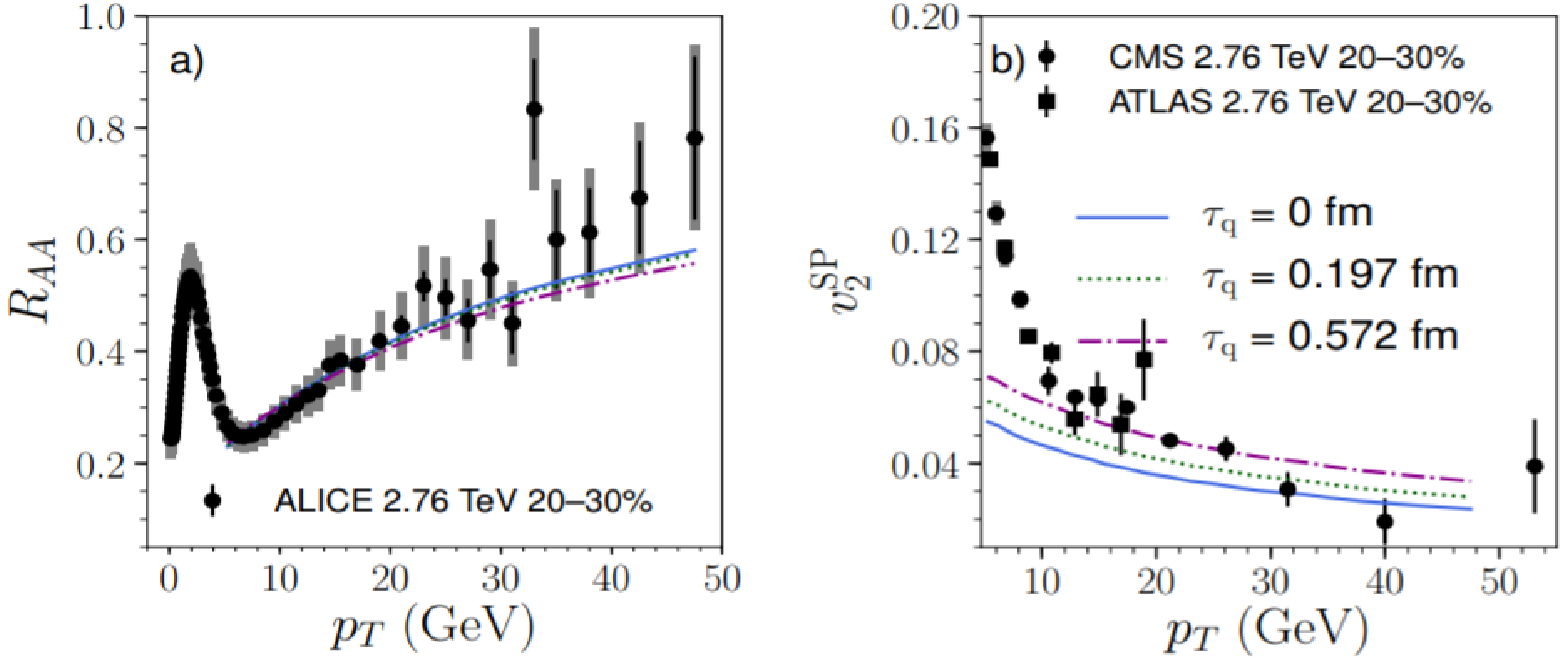
Carlota Andres, Liliana Apolinário, Fabio Dominguez, MGM,
Carlos A. Salgado: JHEP 03 (2023) 189

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

IGFAE Instituto Galego de Física de Altas Enerxías

Why study initial stages?

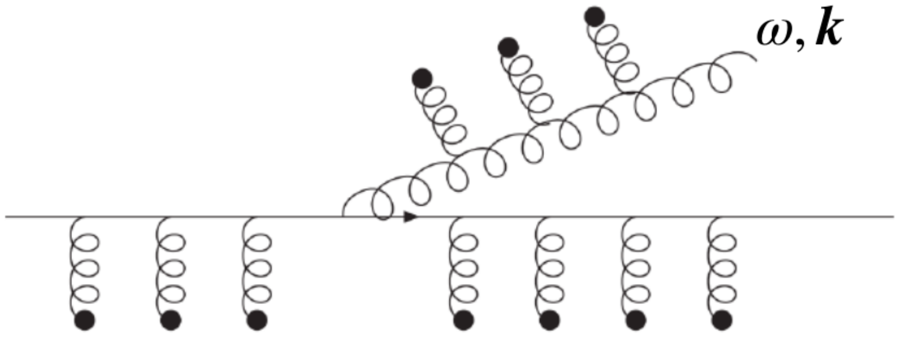


R_{AA} and high-p_t v_2 very sensitive to energy loss in the initial stages

Carlota Andres, Néstor Armesto, Harri Niemi, Risto Paatelainen, Carlos A. Salgado: PLB 2020 135318

Energy loss

- Jet quenching: partons interact with QGP and lose energy



- Two available analytical approximations
  - Harmonic oscillator: multiple soft scatterings
  - First opacity or GLV approximation: one single hard scattering

Medium-induced gluon spectrum

- Soft gluon emission spectrum off a hard parton (BDMPS-Z):

$$\omega \frac{dI}{d\omega d^2\boldsymbol{k}} = \frac{2\alpha_s C_R}{(2\pi)^2\omega^2} \mathrm{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{\boldsymbol{pq}} \boldsymbol{p}\cdot\boldsymbol{q}\, \widetilde{\mathcal{K}}(t',\boldsymbol{q};t,\boldsymbol{p})\mathcal{P}(\infty,\boldsymbol{k};t',\boldsymbol{q})$$

- Recently, new method with no approximations. Full solution obtained numerically by solving two differential equations

$$\partial_\tau \mathcal{P}(\tau,\boldsymbol{k};s,\boldsymbol{l}) = -\frac{1}{2}n(\tau)\int_{\boldsymbol{k}'} \sigma(\boldsymbol{k}-\boldsymbol{k}')\mathcal{P}(\tau,\boldsymbol{k}';s,\boldsymbol{l})$$

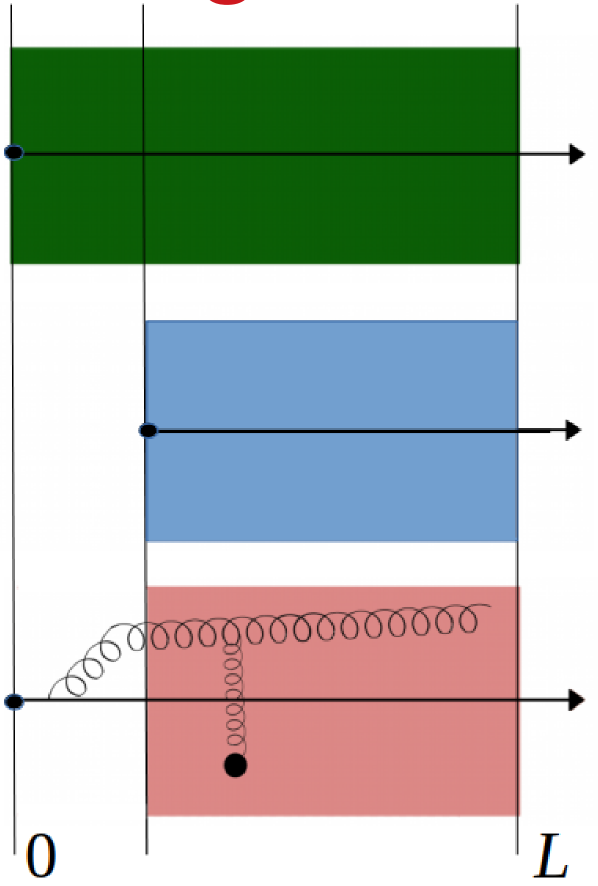
$$\partial_t \widetilde{\mathcal{K}}(s,\boldsymbol{q};t,\boldsymbol{p}) = \frac{i\boldsymbol{p}^2}{2\omega}\widetilde{\mathcal{K}}(s,\boldsymbol{q};t,\boldsymbol{p}) + \frac{1}{2}n(t)\int_{\boldsymbol{k}'} \sigma(\boldsymbol{k}'-\boldsymbol{p})\widetilde{\mathcal{K}}(s,\boldsymbol{q};t,\boldsymbol{k}')$$

Carlota Andres, Liliana Apolinario, Fabio Dominguez: JHEP 07 (2020) 114
Carlota Andres, Fabio Dominguez, MGM: JHEP 03 (2021) 102

Initial stages in medium production

τ_p parton production

τ_m medium hydrodynamization (starting time of the medium)



A) $\tau_p = \tau_m = 0$ — medium of size L (theory calculations)

B) $\tau_p = \tau_m > 0$ — medium of size $L - \tau_m$ (employed in phenomenology)

C) $\tau_m > \tau_p = 0$ — vacuum until τ_m and medium from τ_m to L (**new calculation**)

All the emissions are **medium induced**, pure vacuum already substracted

Some details of the calculation

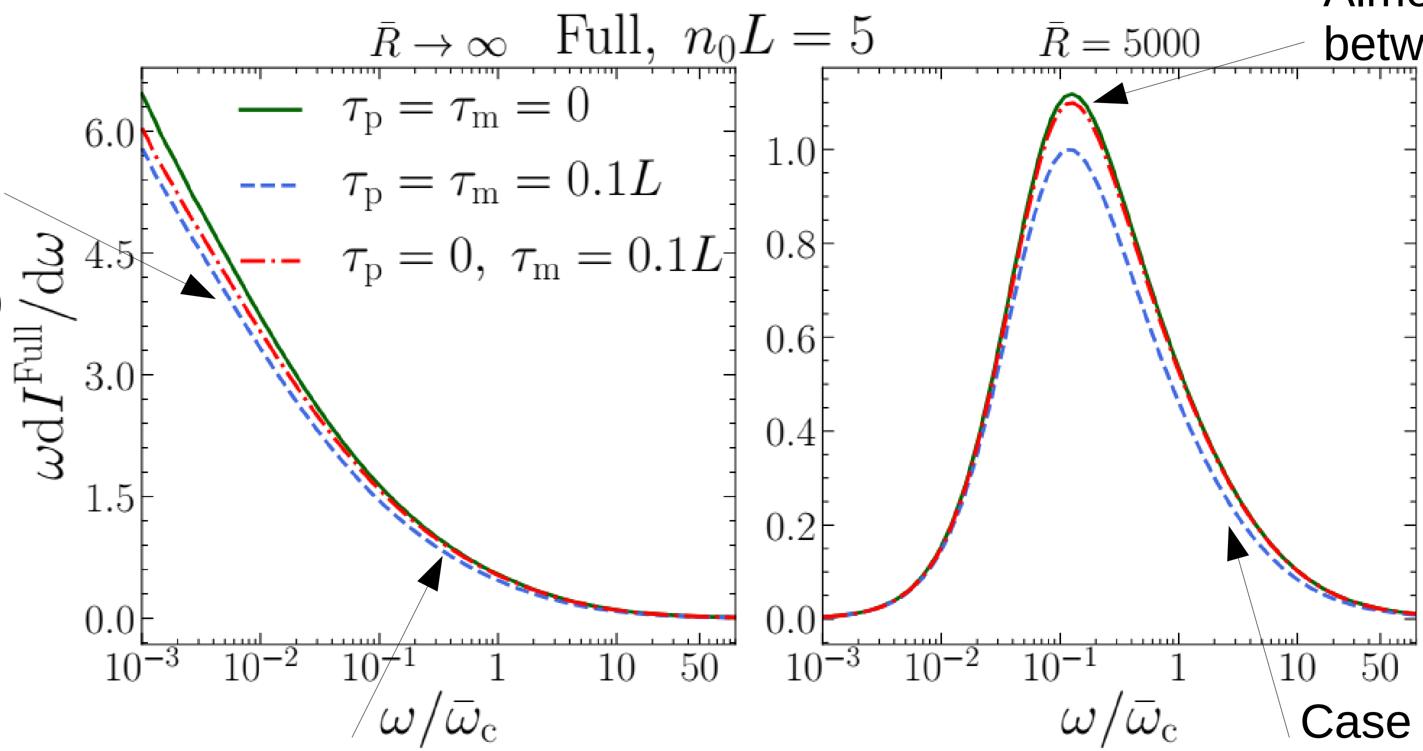
- Full spectrum: easy to perform numerical evaluation (we can use any density profile we want)
- Analytical approaches:
  - GLV: difference between cases A and C is the spectrum of case A for a medium of size τ_m, non trivial result! **New energy scale** $\bar{\omega}_{\rm m} \equiv \frac{1}{2}\mu^2\tau_{\rm m} = \bar{\omega}_c\frac{\tau_{\rm m}}{L}$
  - HO: smaller differences. **New energy scale** $\omega_{\rm m} \equiv \frac{1}{2}\hat{q}_0\tau_{\rm m}^2 = \omega_c\frac{\tau_{\rm m}^2}{L^2}$
- Initial stages effects specially **relevant for small gluon energies**, that is, for small gluon formation times. For large formation times initial stages are not relevant

$$\omega \frac{dI}{d\omega} = \int_0^{\omega} \omega \frac{dI}{d\omega d^2 k}$$

$$\bar{\omega}_c = \frac{1}{2}\mu^2 L$$

Results: full with small τ_m

$\overline{R}$: kinematical cut-off

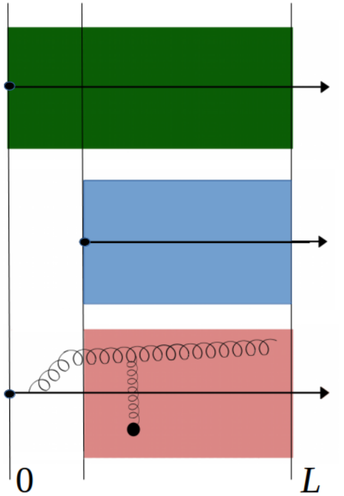


Almost no difference between A) and C)

Differences for small energies (small gluon formation times)

High energies: having vacuum or medium in initial stages gives the same result

Case B) (neglect initial stages) always smaller than the other two

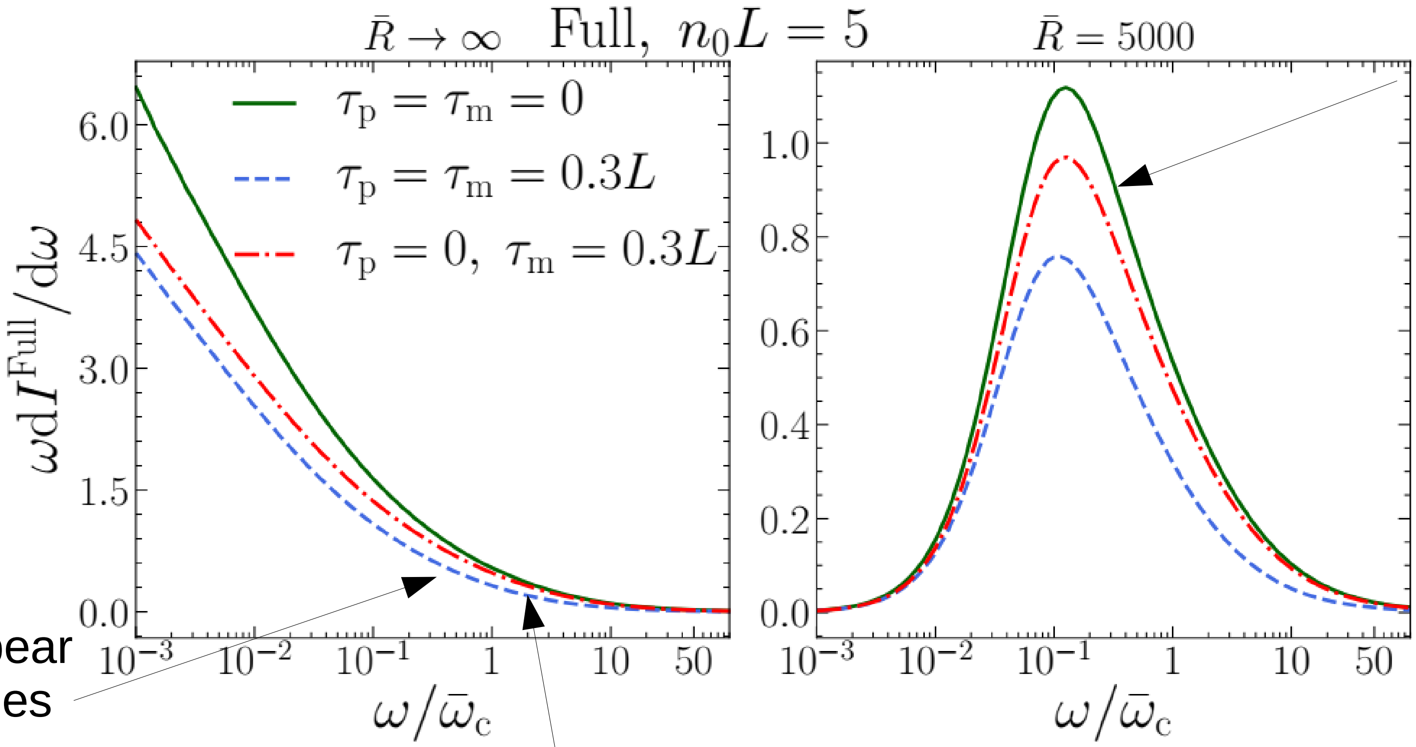


$$\omega\frac{dI}{d\omega} = \int_0^{\omega} \omega\frac{dI}{d\omega d^2k}$$

$\bar{R}$: kinematical cut-off

Results: full with big τ_m

$$\bar{\omega}_c = \frac{1}{2}\mu^2 L$$



Clear separation between cases

Differences appear at higher energies

High energy tail of A) and C) agrees

Azimuthal asymmetry estimation

- Energy loss quantified with quenching weighs (**independent emissions**)
- They are used to compute quenching factor (ratio of the partonic medium and vacuum spectra)

$$Q_i(p_T) = \frac{\mathrm{d}\sigma^{\mathrm{AA}}(p_T)/\mathrm{d}p_T}{\mathrm{d}\sigma^{\mathrm{pp}}(p_T)/\mathrm{d}p_T} = \int \mathrm{d}\epsilon \, P(\epsilon) \frac{\mathrm{d}\sigma^{\mathrm{pp}}(p_T+\epsilon)/\mathrm{d}p_T}{\mathrm{d}\sigma^{\mathrm{pp}}(p_T)/\mathrm{d}p_T}$$

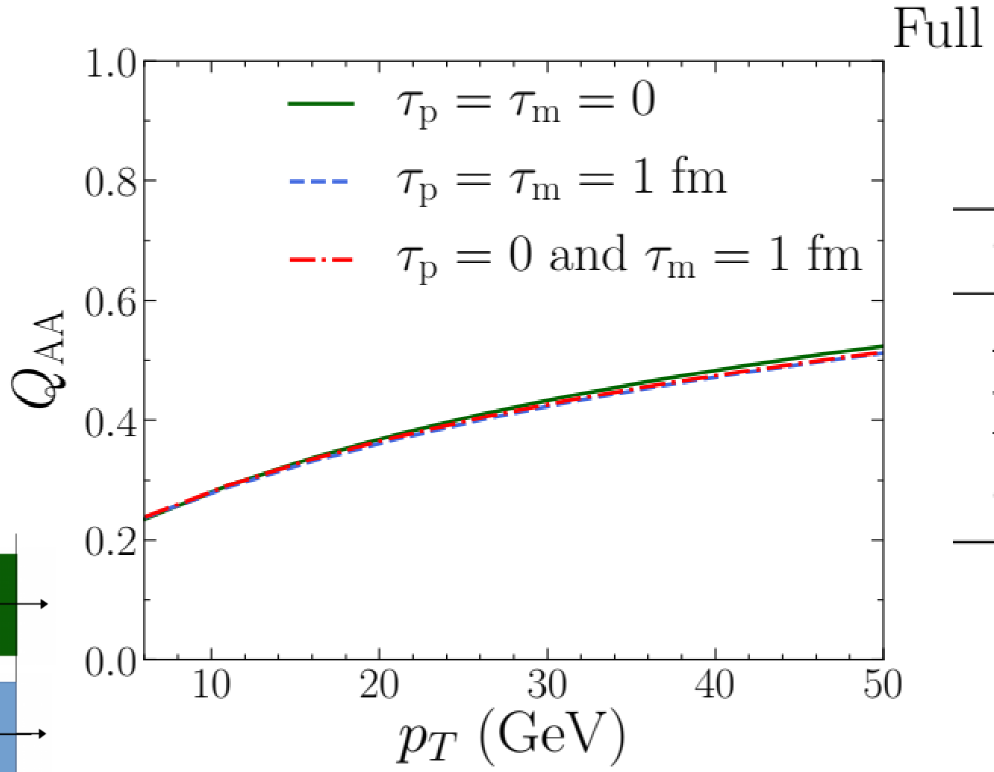
- Partonic spectrum given by power law $\mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}p_T \propto p_T^{-n}$
- Inclusive suppression of charged particles estimated as the average of the quenching factor along the in-plane and out-of-plane directions

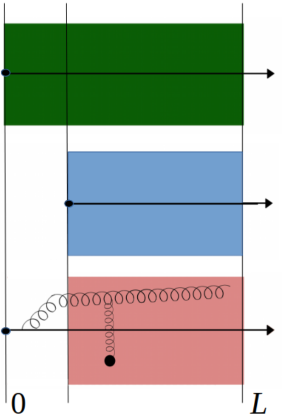
$$Q_{\mathrm{AA}}(p_T) = \frac{Q_q^{\mathrm{in}}(p_T) + Q_q^{\mathrm{out}}(p_T)}{2}$$

- High momentum azimuthal asymmetry approximated by

$$w_2 = \frac{1}{2} \frac{Q_q^{\mathrm{in}}(p_T) - Q_q^{\mathrm{out}}(p_T)}{Q_q^{\mathrm{in}}(p_T) + Q_q^{\mathrm{out}}(p_T)}$$

Azimuthal asymmetry: full spectrum

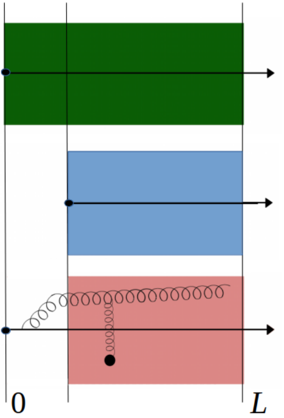


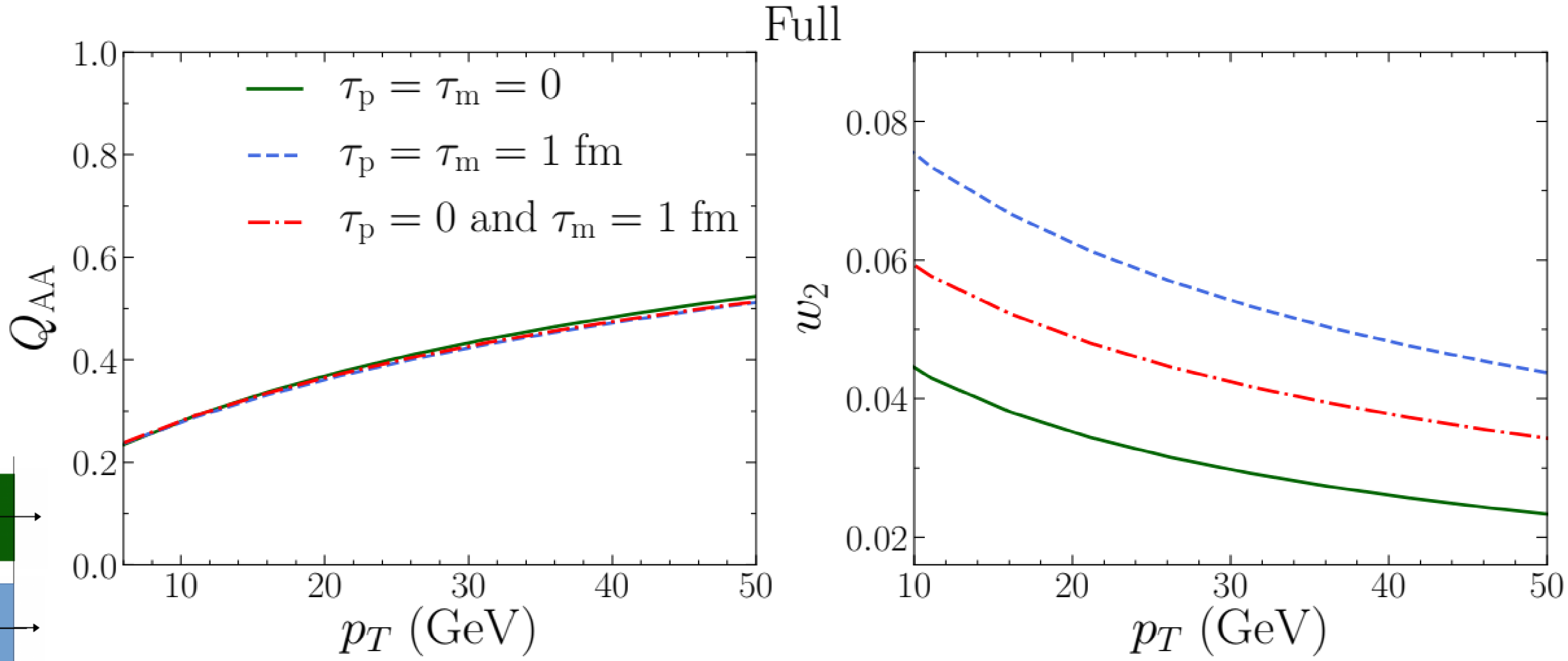


Fitting parameter results

Case	C_1
A: $\tau_p = \tau_m = 0\,\text{fm}$	2.2
B: $\tau_p = \tau_m = 1\,\text{fm}$	4.5
C: $\tau_p = 0$ and $\tau_m = 1\,\text{fm}$	2.5

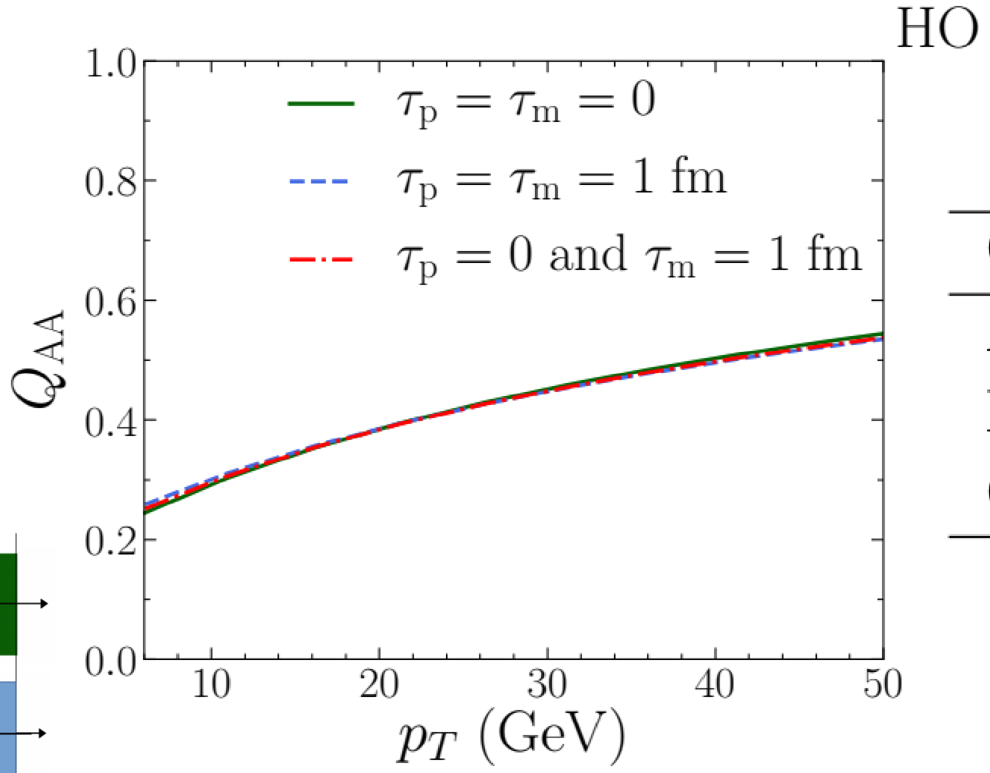
Azimuthal asymmetry: full spectrum





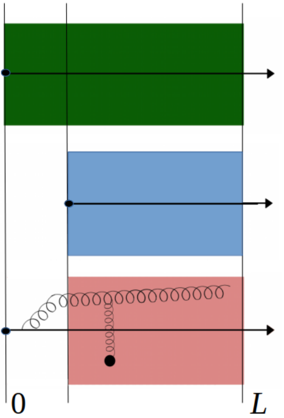
Combination of two observables is very sensitive to early stage scenario

Azimuthal asymmetry: HO

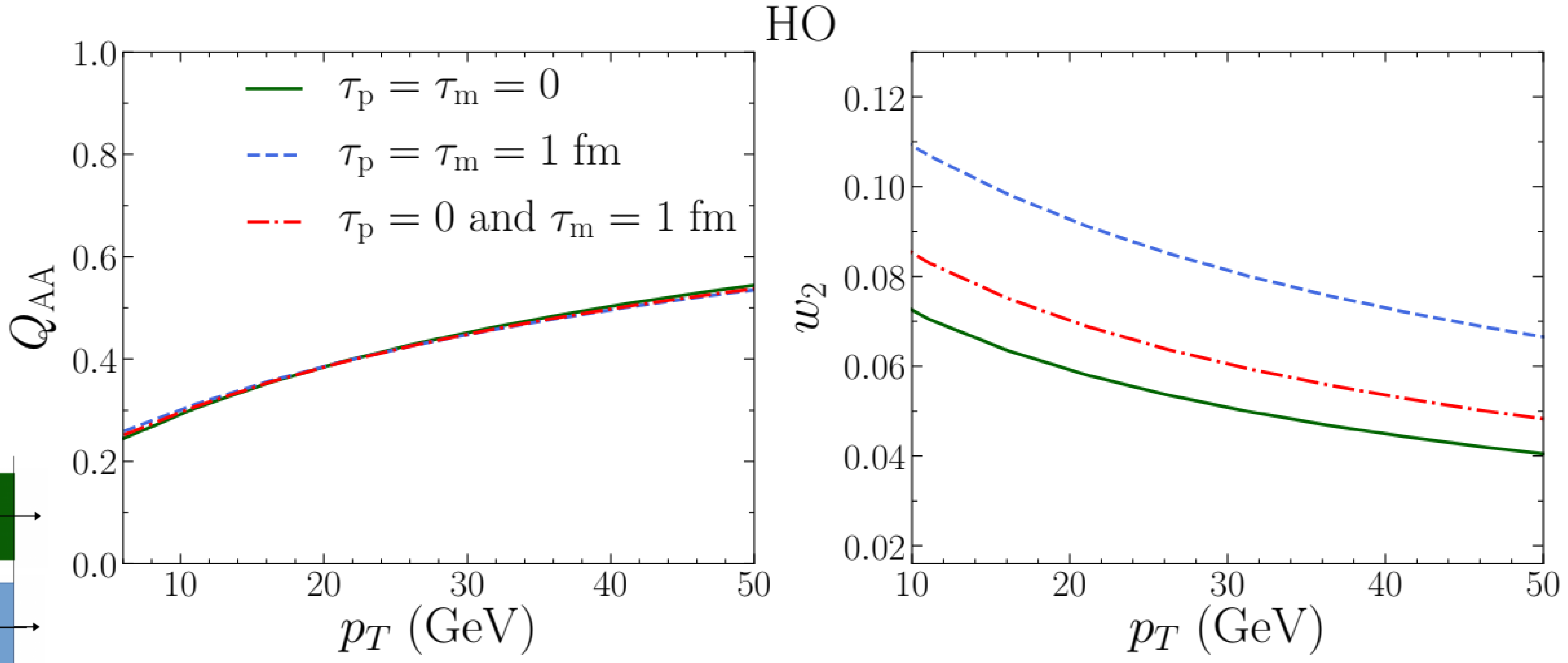


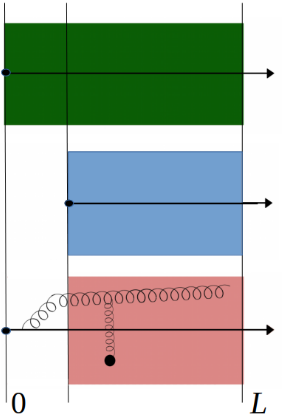
Fitting parameter results

Case	K_1
A: $\tau_p = \tau_m = 0\,\text{fm}$	1.5
B: $\tau_p = \tau_m = 1\,\text{fm}$	16
C: $\tau_p = 0$ and $\tau_m = 1\,\text{fm}$	8



Azimuthal asymmetry: HO





Combination of two observables is very sensitive to early stage scenario

Summary

- We computed the effects of initial stages in medium-induced radiation
- Small starting times of the medium: (almost) no difference between having or not having propagation before the start of the medium
- Large differences for big hydrodynamization times
- New energy scales determine the regions where initial stages are important
- We showed the importance of correctly accounting for the energy loss in the initial stages for the simultaneous description of the R_{AA} and high-p_t azimuthal asymmetry
- Full spectrum gives more robust results than HO

Thanks!

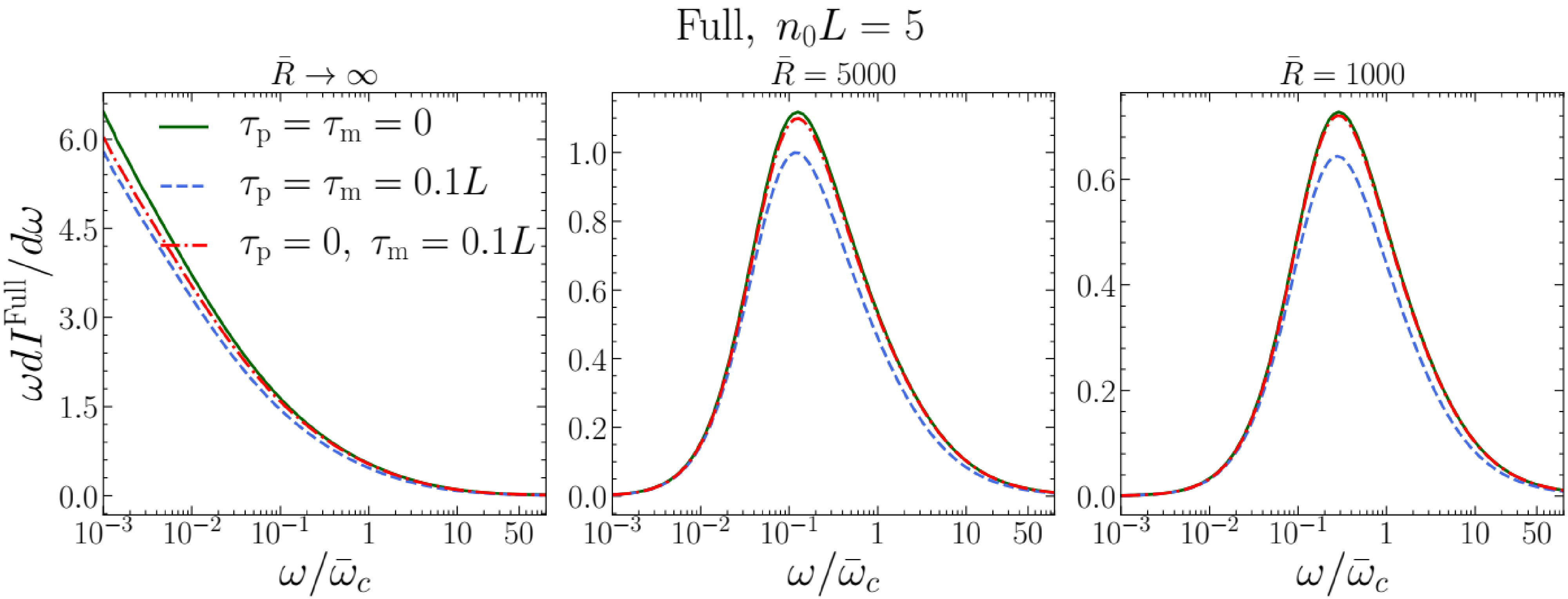
Back up

$$\omega \frac{dI}{d\omega} = \int_0^{\omega} \omega \frac{dI}{d\omega d^2 k}$$

Results full spectrum 1

$$\bar{\omega}_c = \frac{1}{2}\mu^2 L$$

$\overline{R}$: kinematical cut-off

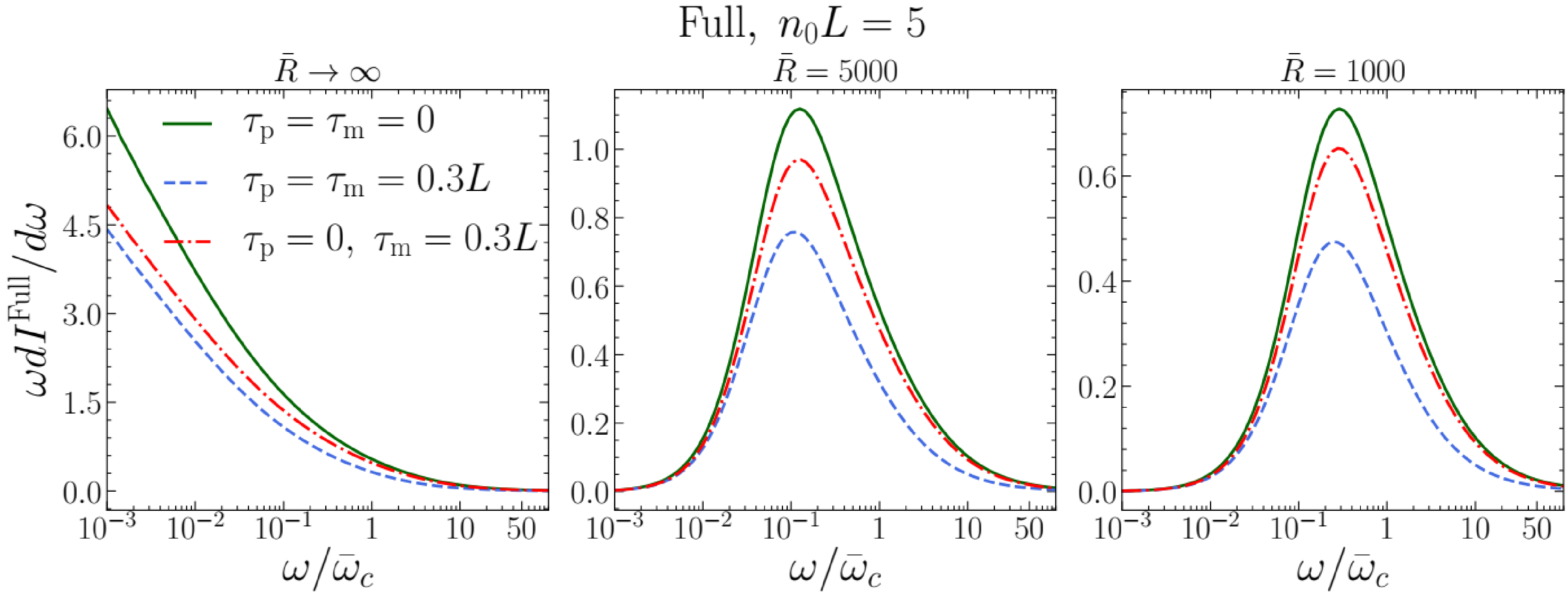


$$\omega\frac{dI}{d\omega} = \int_0^{\omega} \omega \frac{dI}{d\omega d^2k}$$

Results full spectrum 2

$$\bar{\omega}_c = \frac{1}{2}\mu^2 L$$

$\overline{R}$: kinematical cut-off

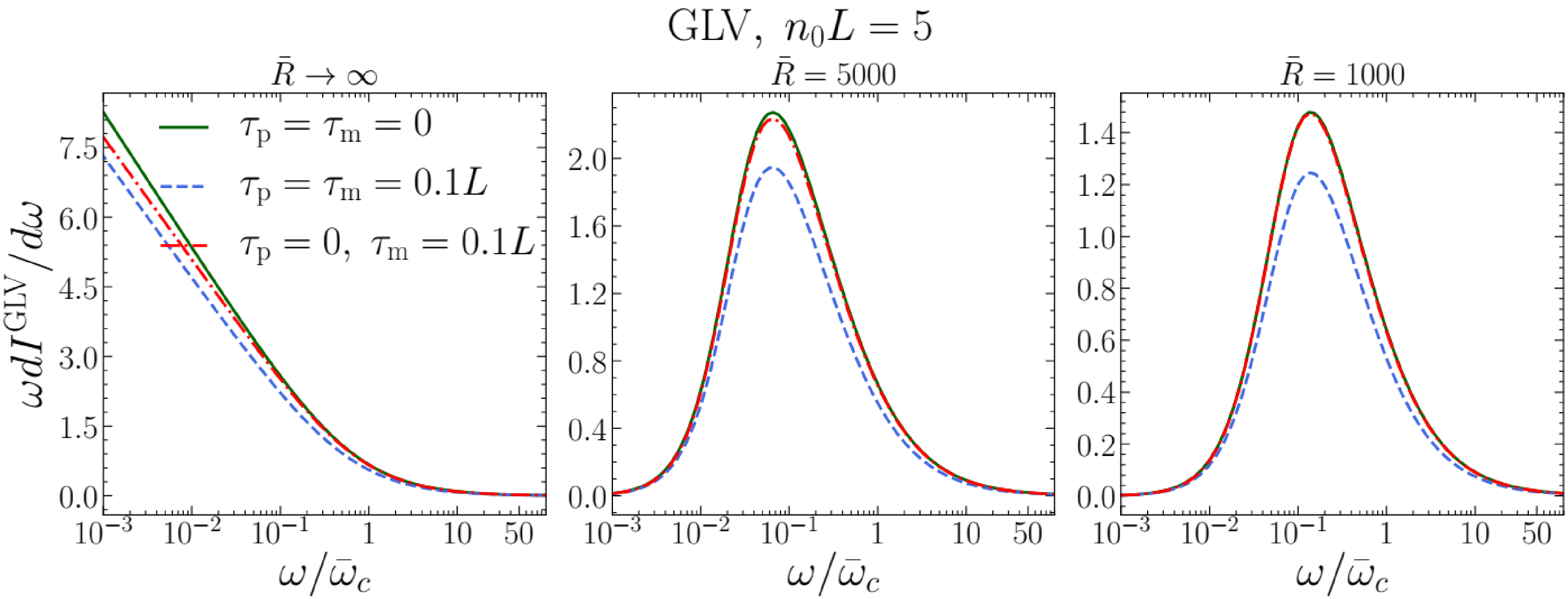


$$\omega\frac{dI}{d\omega} = \int_0^{\omega} \omega\frac{dI}{d\omega d^2k}$$

Results GLV 1

$$\bar{\omega}_c = \frac{1}{2}\mu^2 L$$

$\overline{R}$: kinematical cut-off

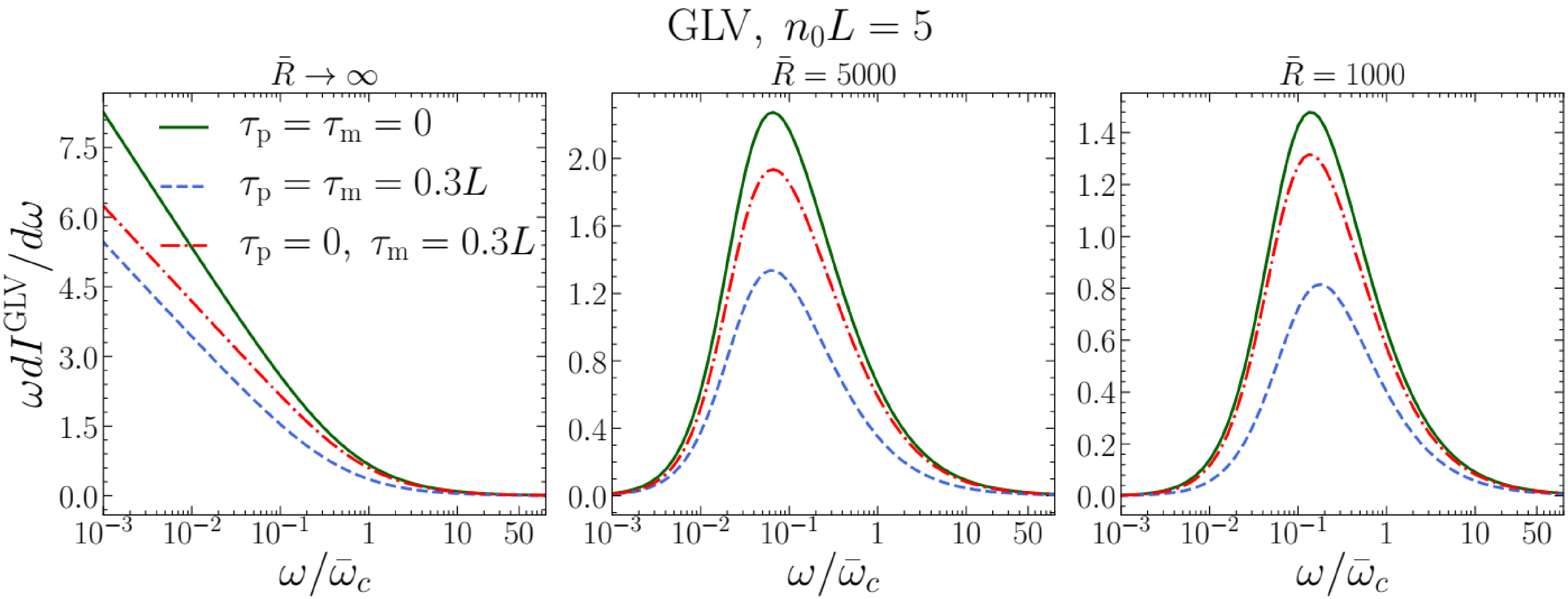


$$\omega \frac{dI}{d\omega} = \int_0^{\omega} \omega \frac{dI}{d\omega d^2 k}$$

$$\bar{\omega}_c = \frac{1}{2}\mu^2 L$$

Results GLV 2

$\overline{R}$: kinematical cut-off

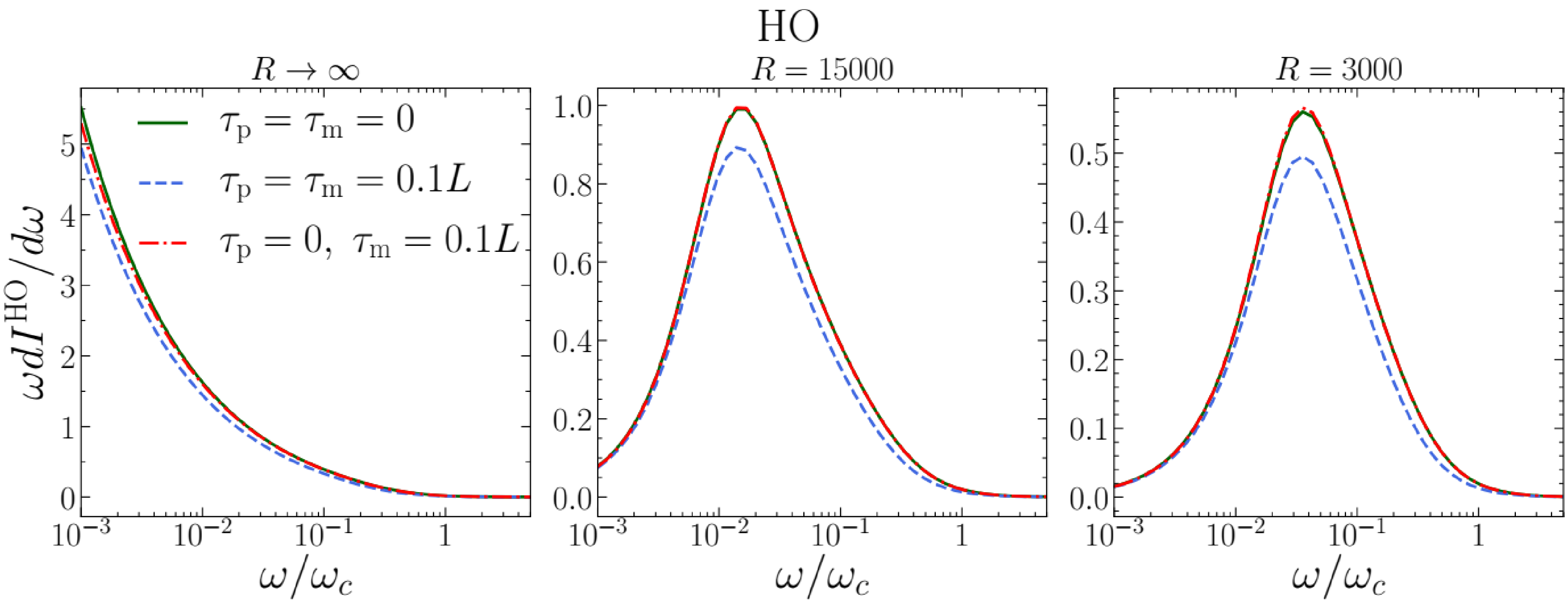


$$\omega \frac{dI}{d\omega} = \int_0^{\omega} \omega \frac{dI}{d\omega d^2 k}$$

R: kinematical cut-off

Results HO 1

$$\omega_c = \frac{1}{2}\hat{q}_0 L^2$$

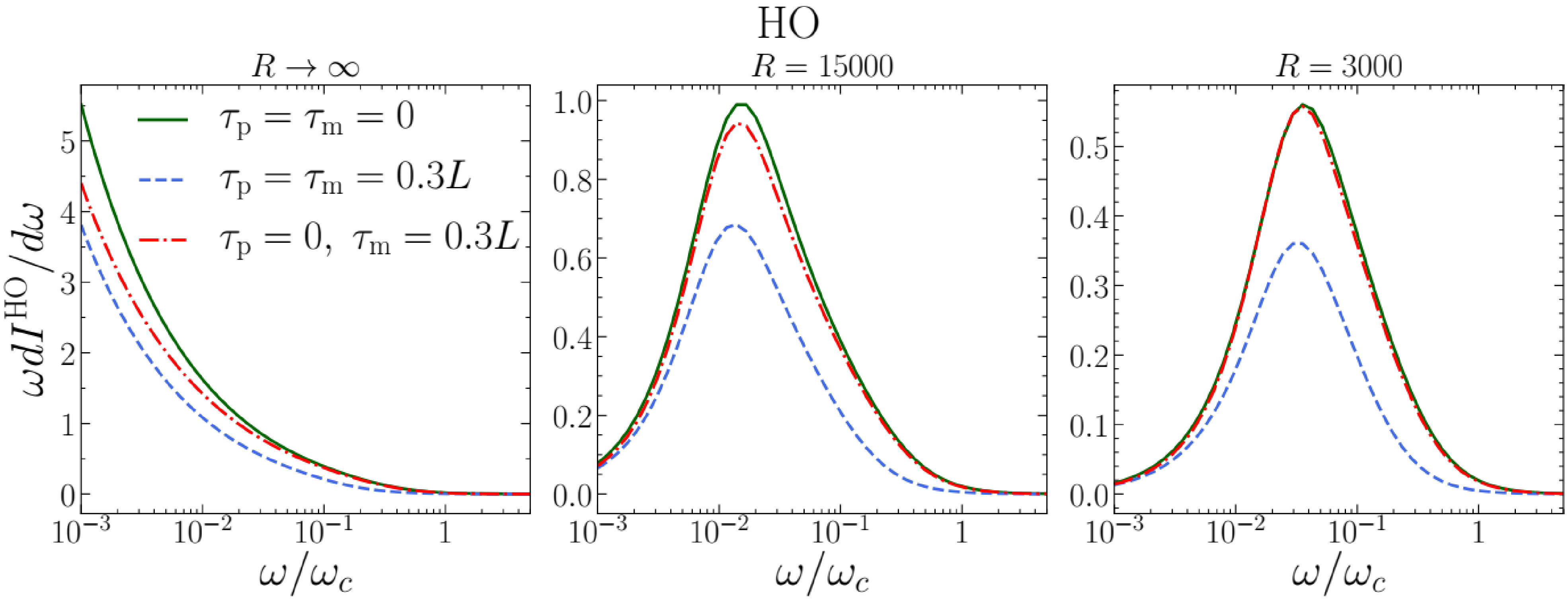


$$\omega \frac{dI}{d\omega} = \int_0^{\omega} \omega \frac{dI}{d\omega d^2 k}$$

R: kinematical cut-off

Results HO 2

$$\omega_c = \frac{1}{2}\hat{q}_0 L^2$$



Azimuthal asymmetry estimation II

We fit $Q_{\rm AA}$ to data using both full result and HO

Full	HO
$n(\xi) = C_1\,T(\xi)\,, \quad \text{and} \quad \mu^2(\xi) = \frac{6\pi\alpha_s}{e} T^2(\xi)$	$\hat{q}(\xi) = K_1\,T^3(\xi)$ $T(\xi) = T_0 \left(\frac{\xi_0}{\xi + \xi_0}\right)^c$
Temperature directly from hydro	
Fitting $Q_{\rm AA}$ to data fixes the constant	First fit T to hydro, then fit K_1

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Different initial stages give different results: dependence on treatment of early times