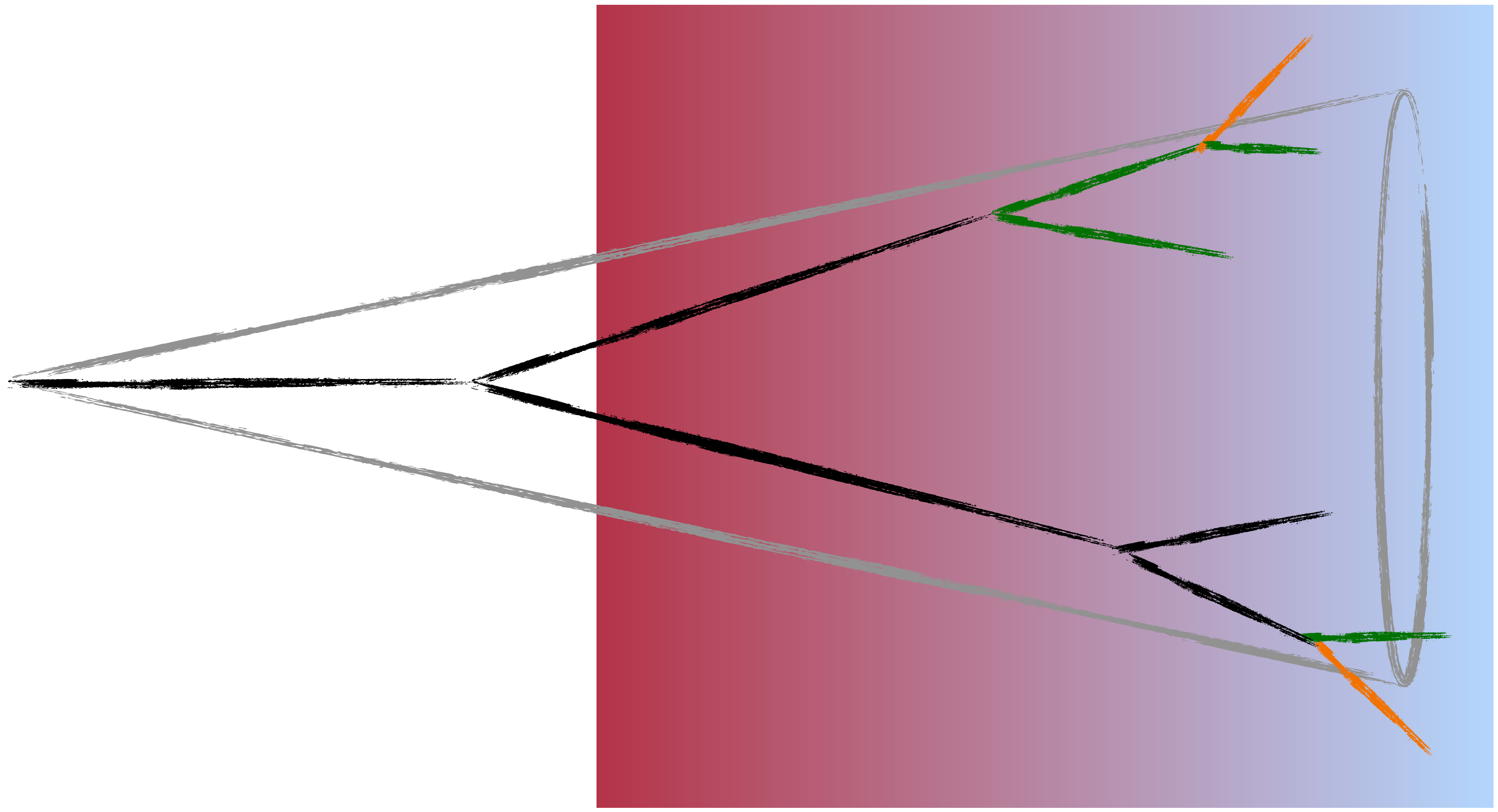
Recent advances on jet quenching



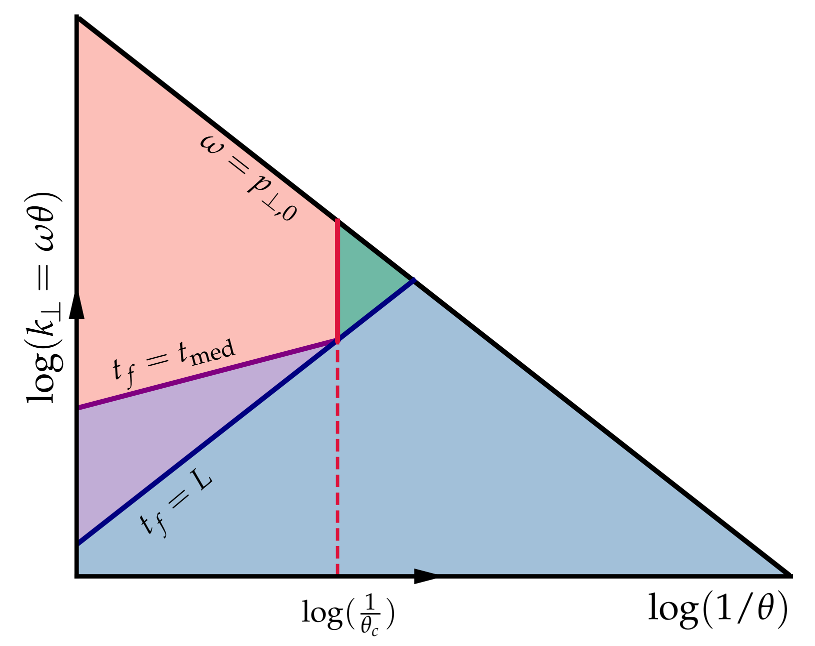
Alba Soto-Ontoso

9th Quarks and Nuclear Physics

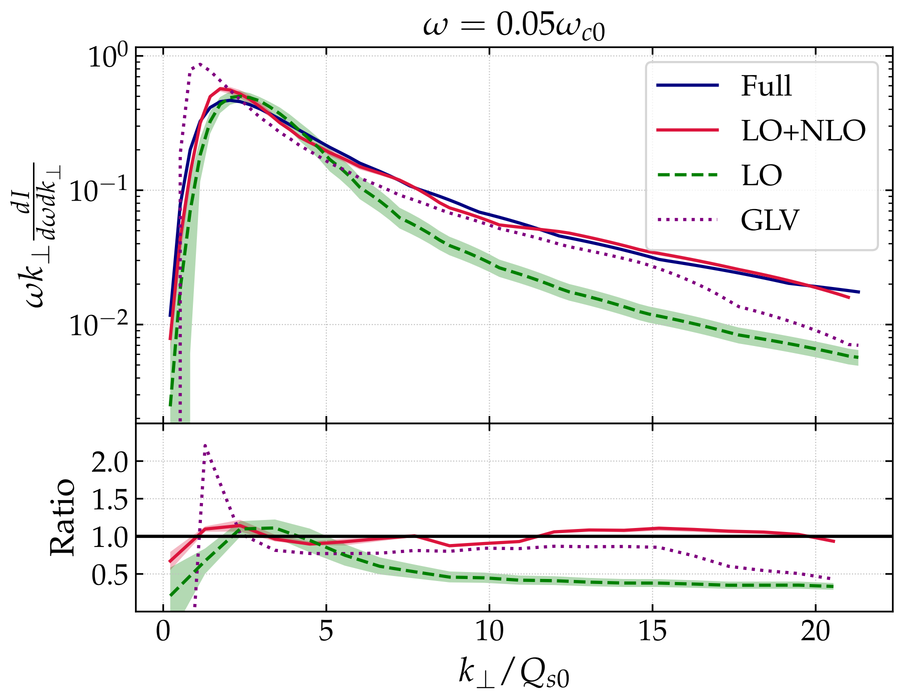
Online, 7th September, 2022

Outline

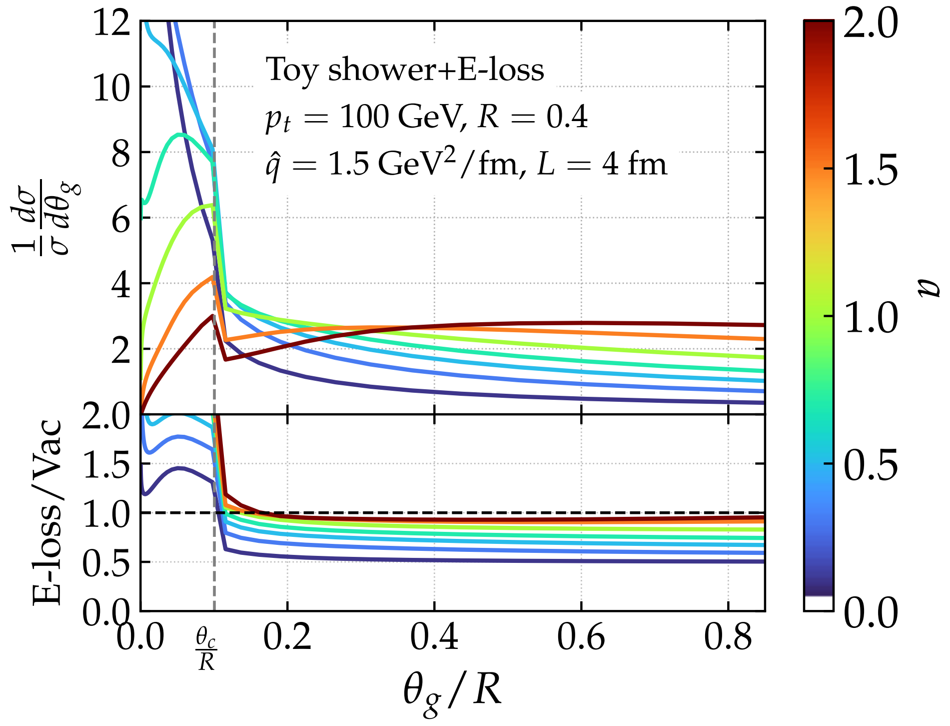
1 Radiation phase-space for jets in dense media



2 Medium-induced emissions spectrum



3 Jet substructure calculations

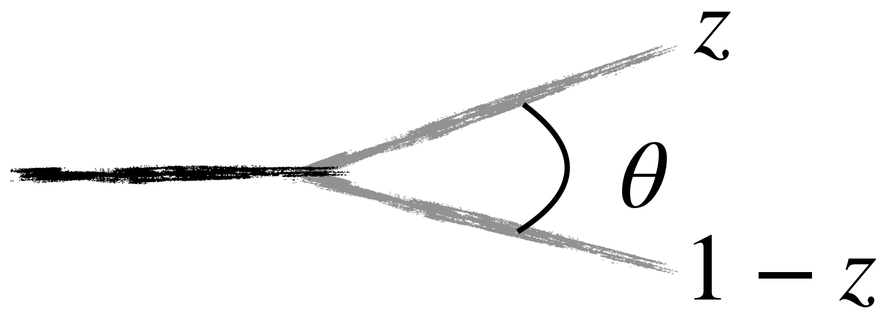


Focus of this talk is on the perturbative evolution of jets in the QGP

Phase-space for emissions in the medium at DLA

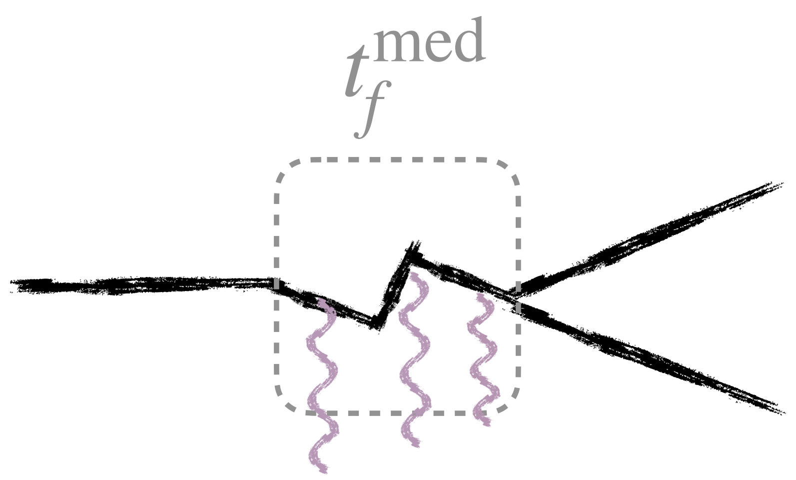
Jet evolution in the medium is a multi-scale process: $Q, T, \lambda_{\mathrm{QCD}}, \mu_D, \hat{q}\ldots$

vacuum splittings



$$t_f^{\mathrm{vac}} \approx (z\theta^2)^{-1} \quad \mathrm{d}P^{\mathrm{vac}} = \frac{\alpha_s C_i}{2\pi}\frac{\mathrm{d}z}{z}\frac{\mathrm{d}\theta}{\theta}$$

transverse momentum broadening



$$\langle k_{t,f} \rangle = \hat{q} t_f \to t_f^{\mathrm{med}} = \sqrt{\frac{2\omega}{\hat{q}}}$$

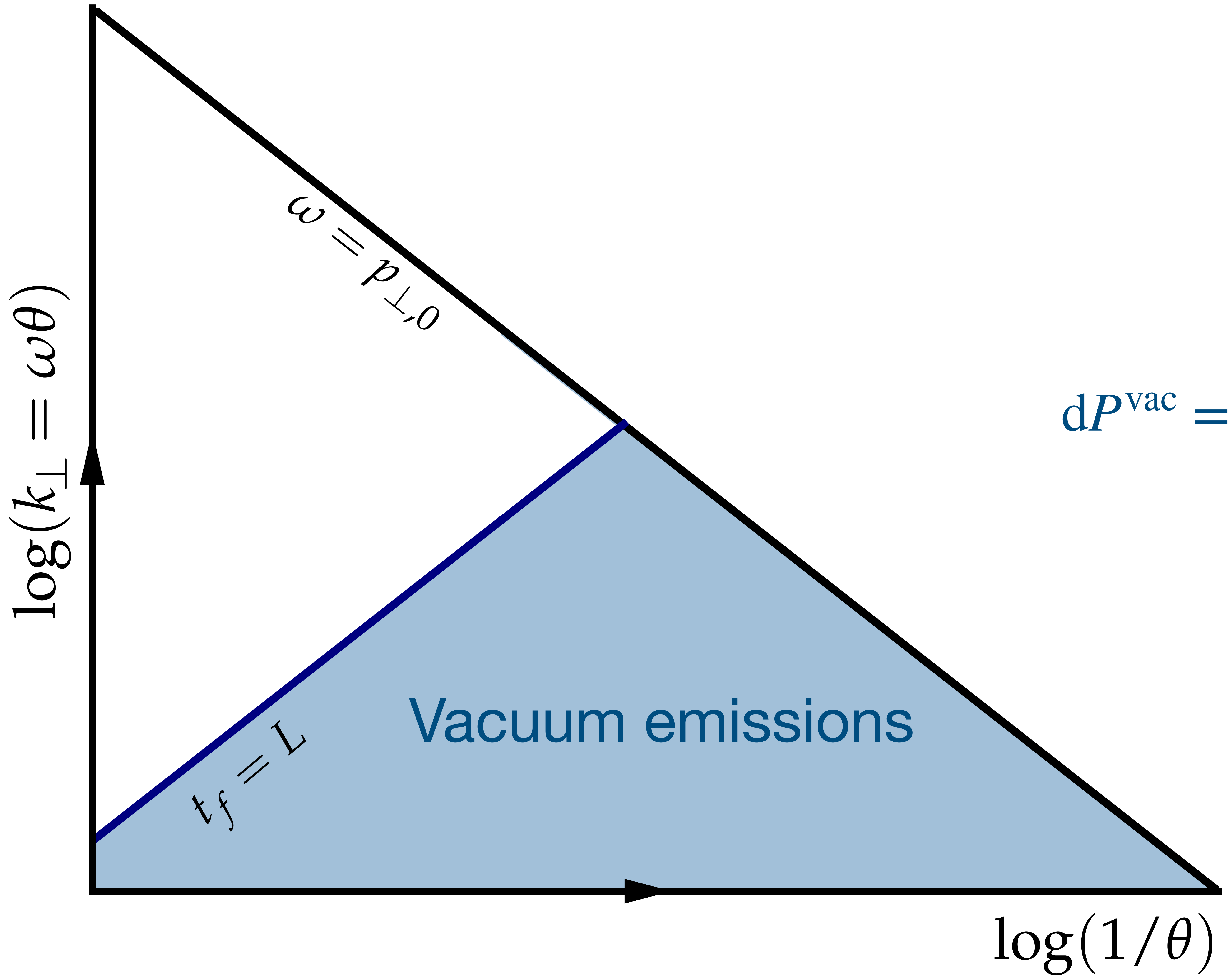
At double-log accuracy, in-medium, vacuum-like emissions must satisfy

[Caucal et al. PRL 120 (2018) 232001]

[Expanding media: Caucal et al. JHEP 04 (2021) 209]

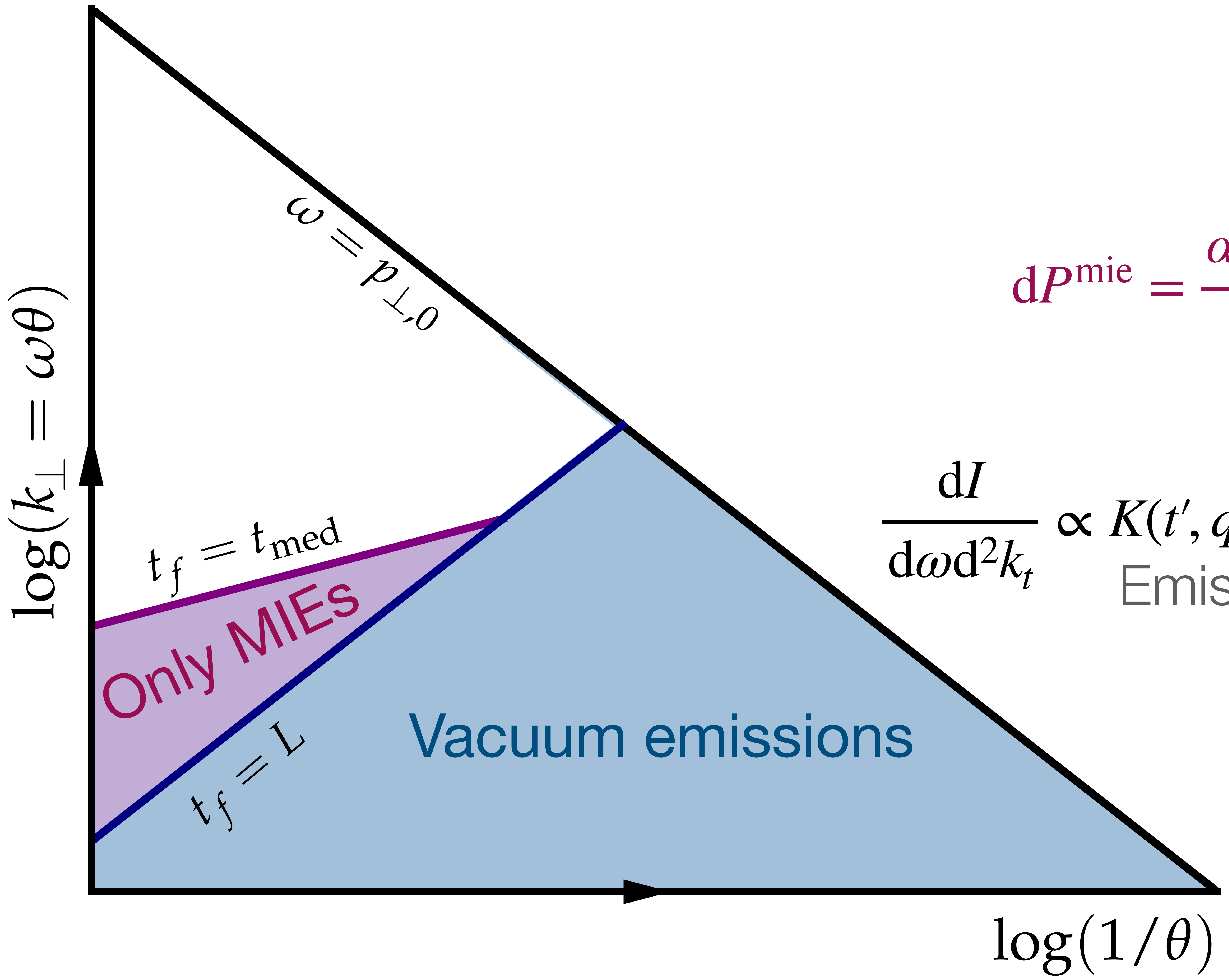
$$\boxed{t_f \ll t_f^{\mathrm{med}}}$$

Phase-space for emissions in the medium at DLA



$$\mathrm{d}P^{\mathrm{vac}} = \frac{\alpha_s C_i}{2\pi}\frac{\mathrm{d}z}{z}\frac{\mathrm{d}\theta}{\theta}$$

Phase-space for emissions in the medium at DLA

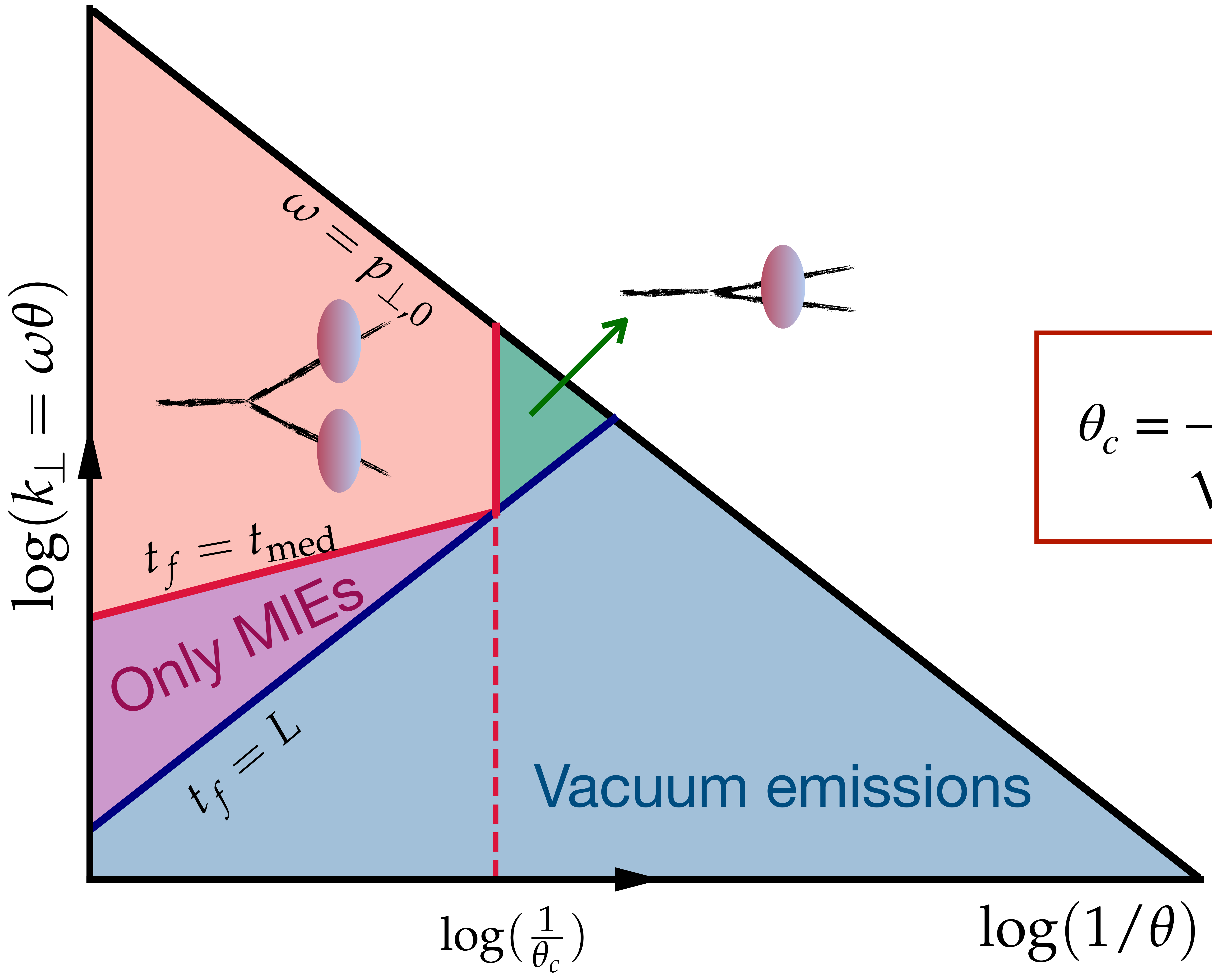


$$dP^{\rm mie} = \frac{\alpha_s^{\rm med} C_i}{2\pi} \frac{dI}{d\omega d^2k_t}$$

with

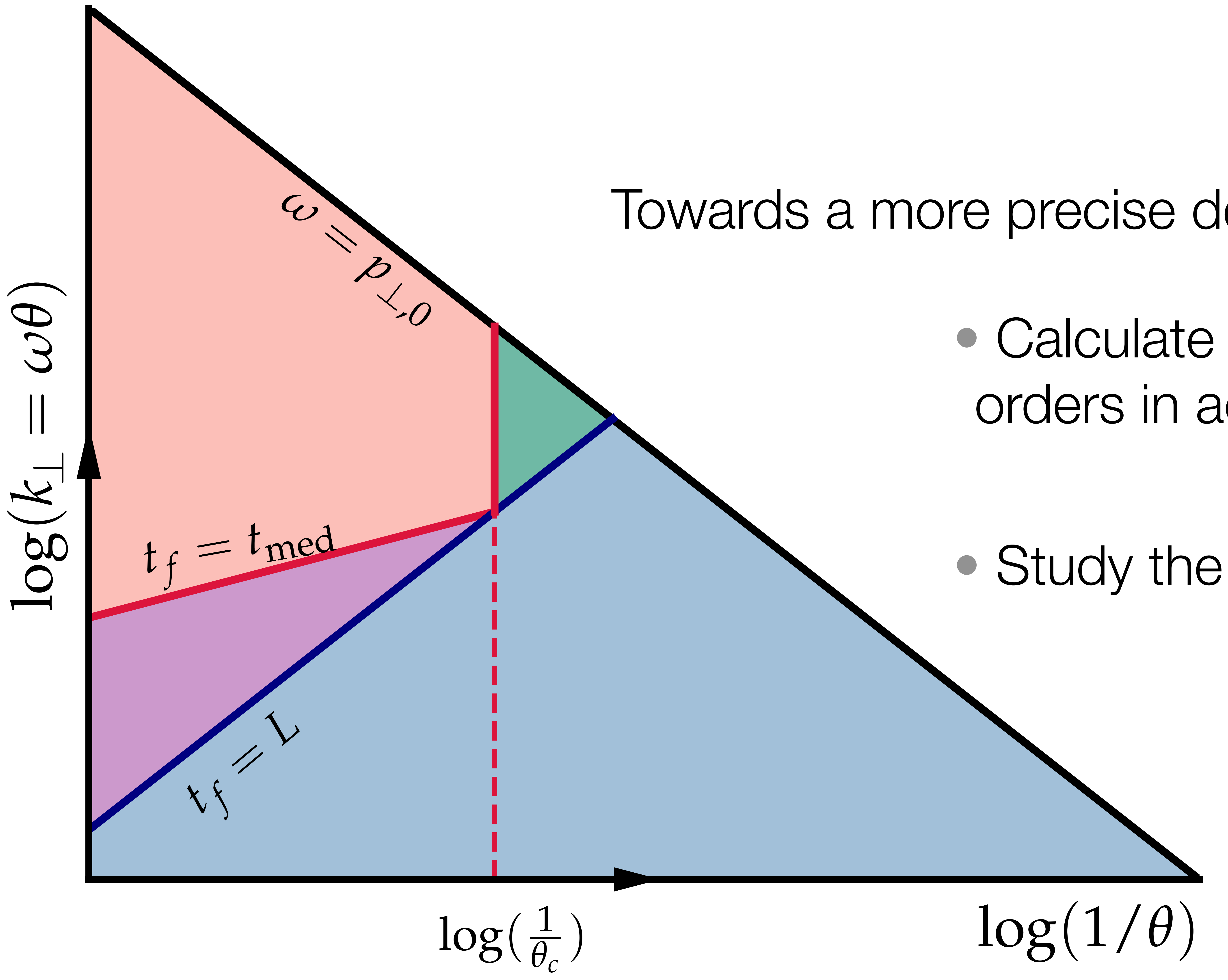
$$\frac{dI}{d\omega d^2k_t} \propto \underbrace{K(t', q; t, p)}_{\text{Emission}} \otimes \underbrace{P(\infty, k\ ;\ t', q)}_{\text{Broadening}}$$

Phase-space for emissions in the medium at DLA



$$\boxed{\theta_c = \frac{2}{\sqrt{\hat{q}L^3}}}$$

Phase-space for emissions in the medium at DLA

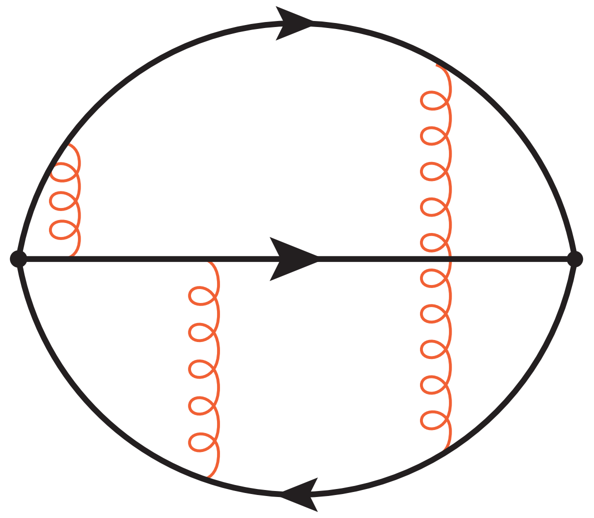


Towards a more precise description of phase-space:

- Calculate the boundaries at higher orders in accuracy
- Study the impact of hard scatterings

Fully differential medium-induced spectrum

$$(2\pi)^2\omega\frac{\mathrm{d}I}{\mathrm{d}\omega\mathrm{d}^2\mathbf{k}} \propto \frac{2\bar{\alpha}\pi}{\omega^2}\int_0^\infty \mathrm{d}t_2\int_0^{t_2}\mathrm{d}t_1\int_{\mathbf{x}} \mathrm{e}^{-i\mathbf{k}\cdot\mathbf{x}}\mathscr{P}(\mathbf{x},\infty;t_2)\partial_{\mathbf{x}}\cdot\partial_{\mathbf{y}}\mathscr{K}(\mathbf{x},t_2;\mathbf{y},t_1)_{\mathbf{y}=\mathbf{0}}$$ - vac

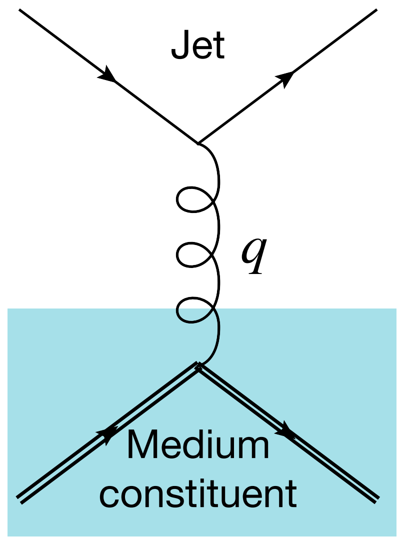


where the effective emission kernel $\mathscr{K}$ is solution of a 2+1D Schrodinger equation

$$\left[i\frac{\partial}{\partial t_2}+\frac{\partial^2}{2\omega}+iv(x_\perp)\right]\mathscr{K}(x_\perp,t_2,|y_\perp,t_1) = i\delta(x_\perp-y_\perp)\delta(t_2-t_1)$$

with the imaginary potential

$$v(x_\perp)\equiv C_R\int_q\left(1-\mathrm{e}^{iq_\perp\cdot x_\perp}\right)\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}q}$$



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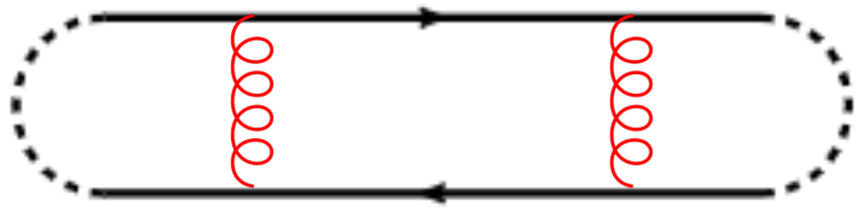
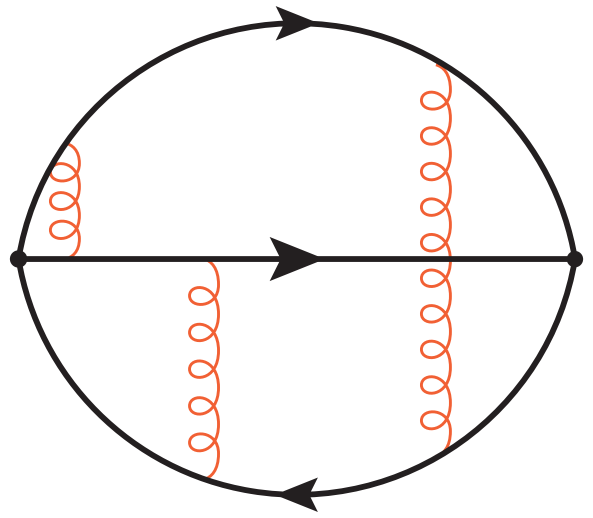
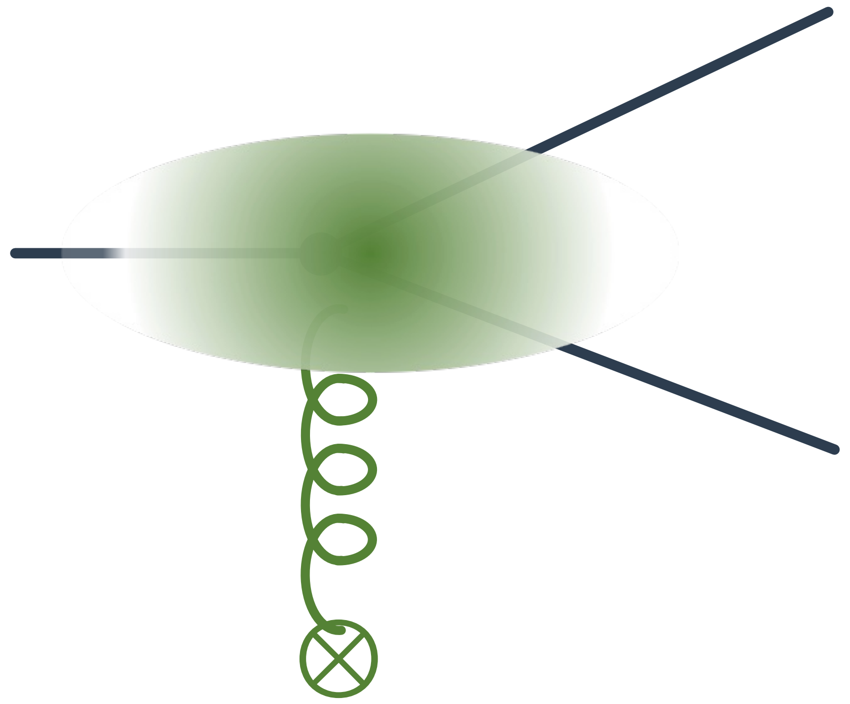




~~Traditional~~ strategies to solve this problem:

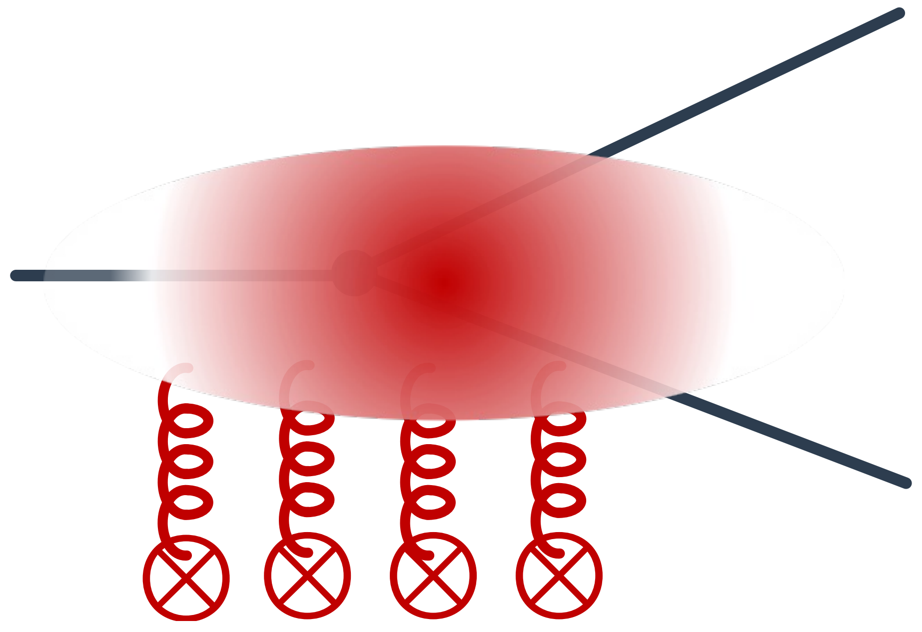
1 Opacity expansion

[Gyulassy, Levai, Vitev, PRL (2000)]
[Wiedemann NPB 588 (2000) 303-344]



2 Multiple, soft scattering approx

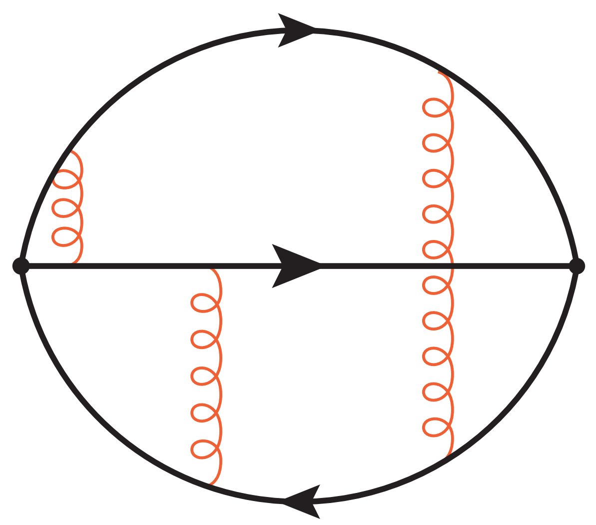
[BDMPS, NPB 483 (1997) 291-320]
[Zakharov, JETP Lett. 65 (1997) 615-620]



[Sketches courtesy of Adam Takacs]

Fully differential medium-induced spectrum

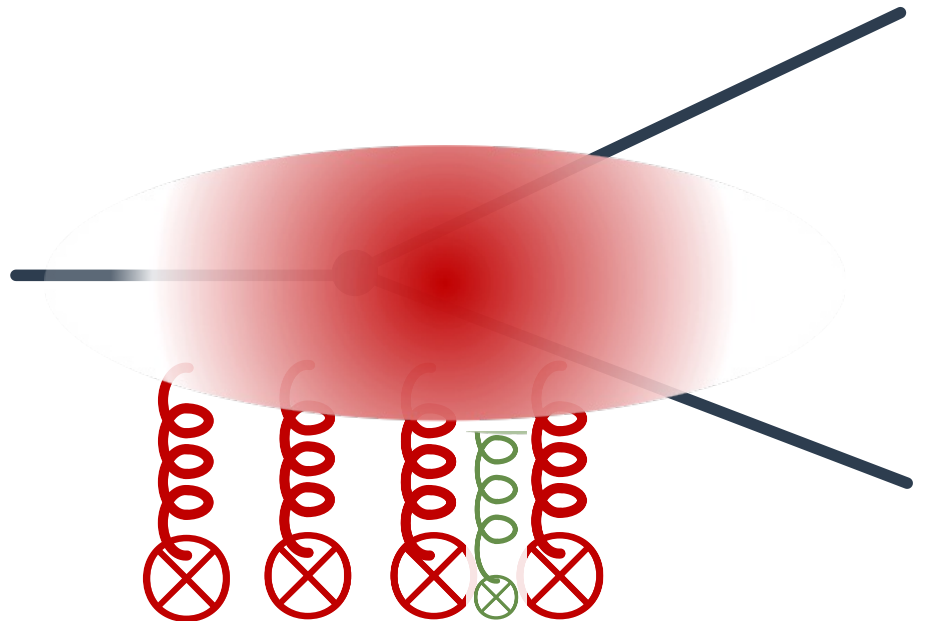
$$(2\pi)^2\omega\frac{\mathrm{d}I}{\mathrm{d}\omega\mathrm{d}^2\mathbf{k}} \propto \frac{2\bar{\alpha}\pi}{\omega^2}\int_0^\infty \mathrm{d}t_2\int_0^{t_2}\mathrm{d}t_1\int_{\mathbf{x}} \mathrm{e}^{-i\mathbf{k}\cdot\mathbf{x}}\mathscr{P}(\mathbf{x},\infty;t_2)\partial_{\mathbf{x}}\cdot\partial_{\mathbf{y}}\mathscr{K}(\mathbf{x},t_2;\mathbf{y},t_1)_{\mathbf{y}=\mathbf{0}} \text{ - vac}$$



~~Recent~~ developments in the fully differential spectrum

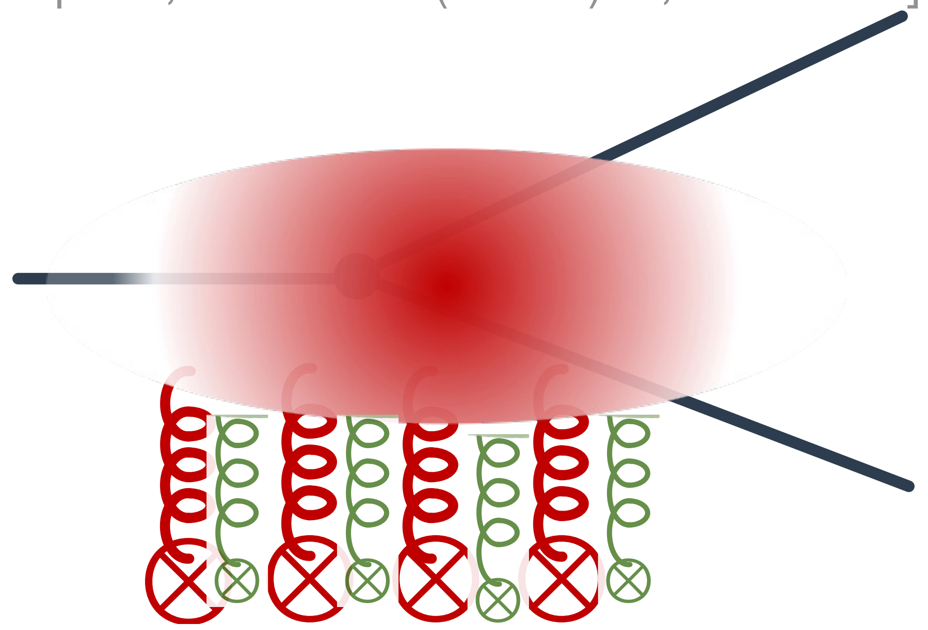
1 Improved opacity expansion

[Mehtar-Tani JHEP 07 (2019) 057]
[Mehtar-Tani, Tywoniuk JHEP 06 (2020) 187]

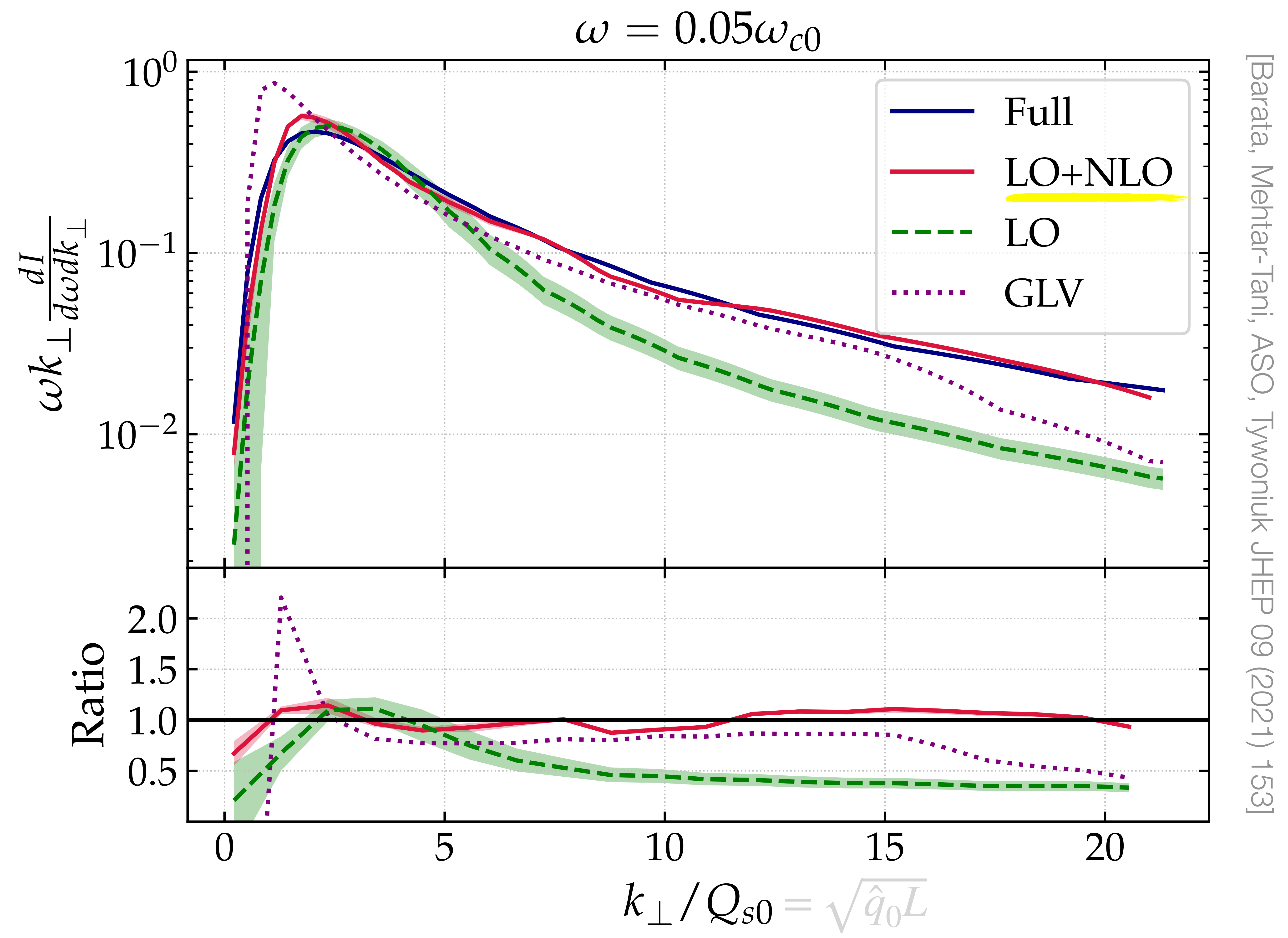


2 Numerical approaches

[Andres, Apolinario, Dominguez JHEP 07 (2020) 114]
[Andres, Dominguez, Gonzalez, JHEP 03 (2021) 102]
[Feal, Vazquez, PRD 98 (2018) 7, 074029]



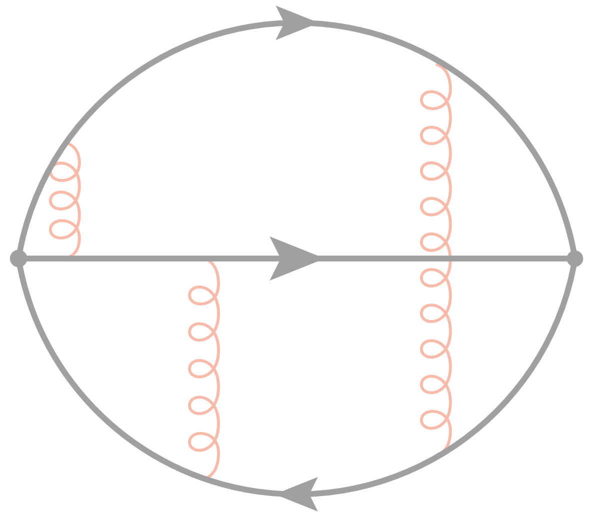
Fully differential medium-induced spectrum



Substantial progress in the determination of the medium-induced radiative kernel

Small detour: resummation vs non-perturbative ingredients

$$(2\pi)^2\omega\frac{\mathrm{d}I}{\mathrm{d}\omega\mathrm{d}^2\mathbf{k}} \propto \frac{2\bar{\alpha}\pi}{\omega^2}\int_0^\infty \mathrm{d}t_2 \int_0^{t_2}\mathrm{d}t_1 \int_{\mathbf{x}} \mathrm{e}^{-i\mathbf{k}\cdot\mathbf{x}}\mathcal{P}(\mathbf{x},\infty;t_2)\partial_{\mathbf{x}}\cdot\partial_{\mathbf{y}}\mathcal{K}(\mathbf{x},t_2;\mathbf{y},t_1)_{\mathbf{y}=\mathbf{0}} \text{ - vac}$$

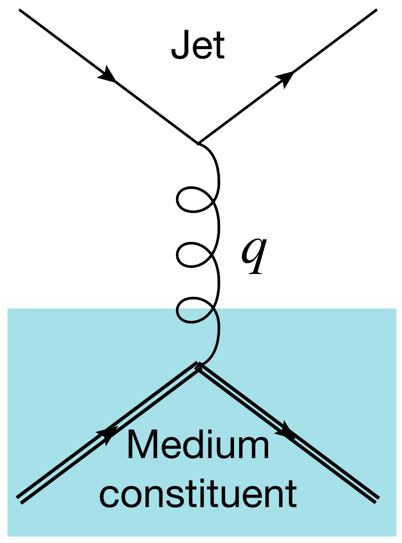


where the effective emission kernel $\mathcal{K}$ is solution of a 2+1D Schrodinger equation

$$\left[i\frac{\partial}{\partial t_2} + \frac{\partial^2}{2\omega} + iv(x_\perp)\right]\mathcal{K}(x_\perp, t_2, | y_\perp, t_1) = i\delta(x_\perp - y_\perp)\delta(t_2 - t_1)$$

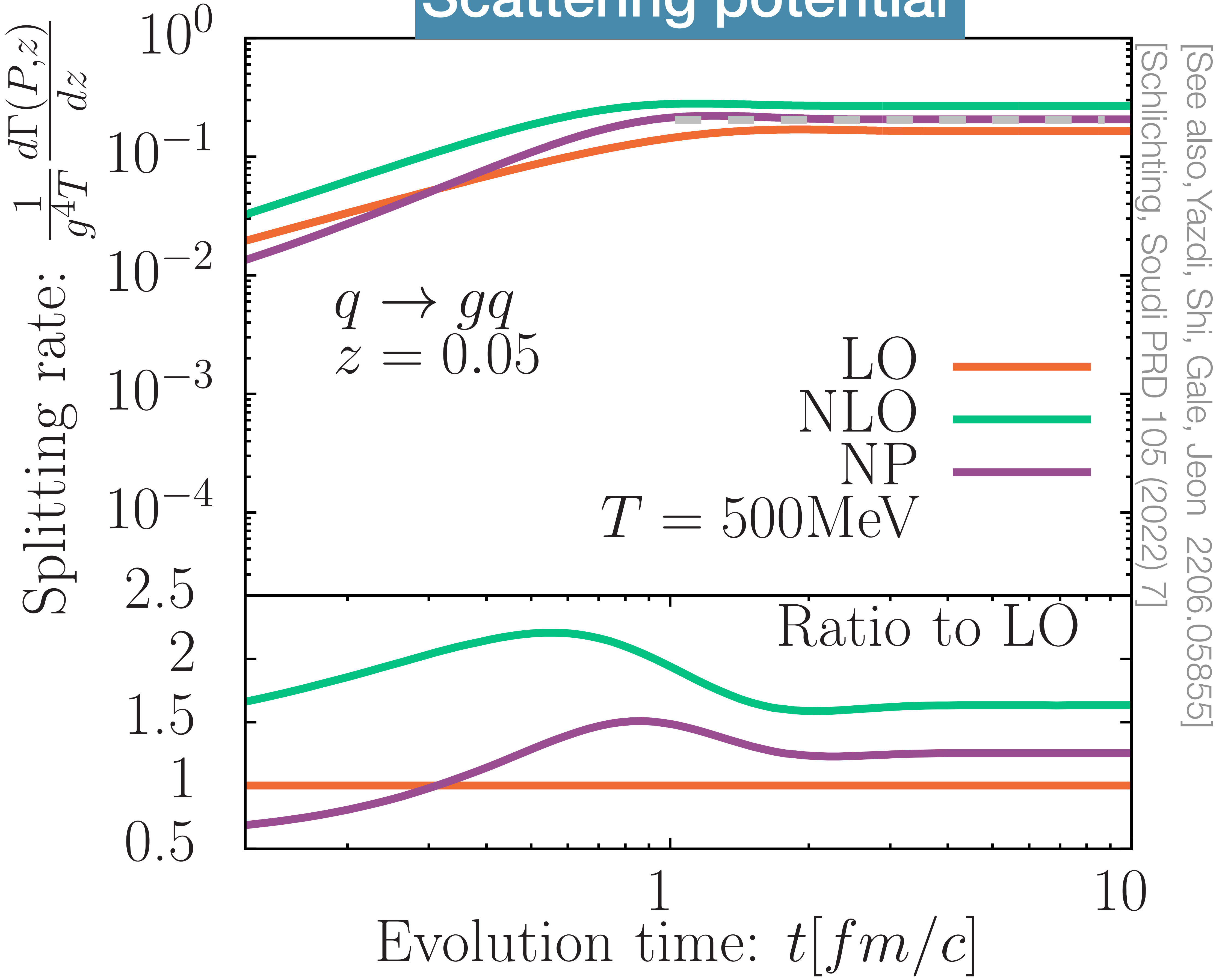
with the imaginary potential

$$v(x_\perp) \equiv C_R \int_q \left(1 - \mathrm{e}^{iq_\perp\cdot x_\perp}\right)\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}q}$$

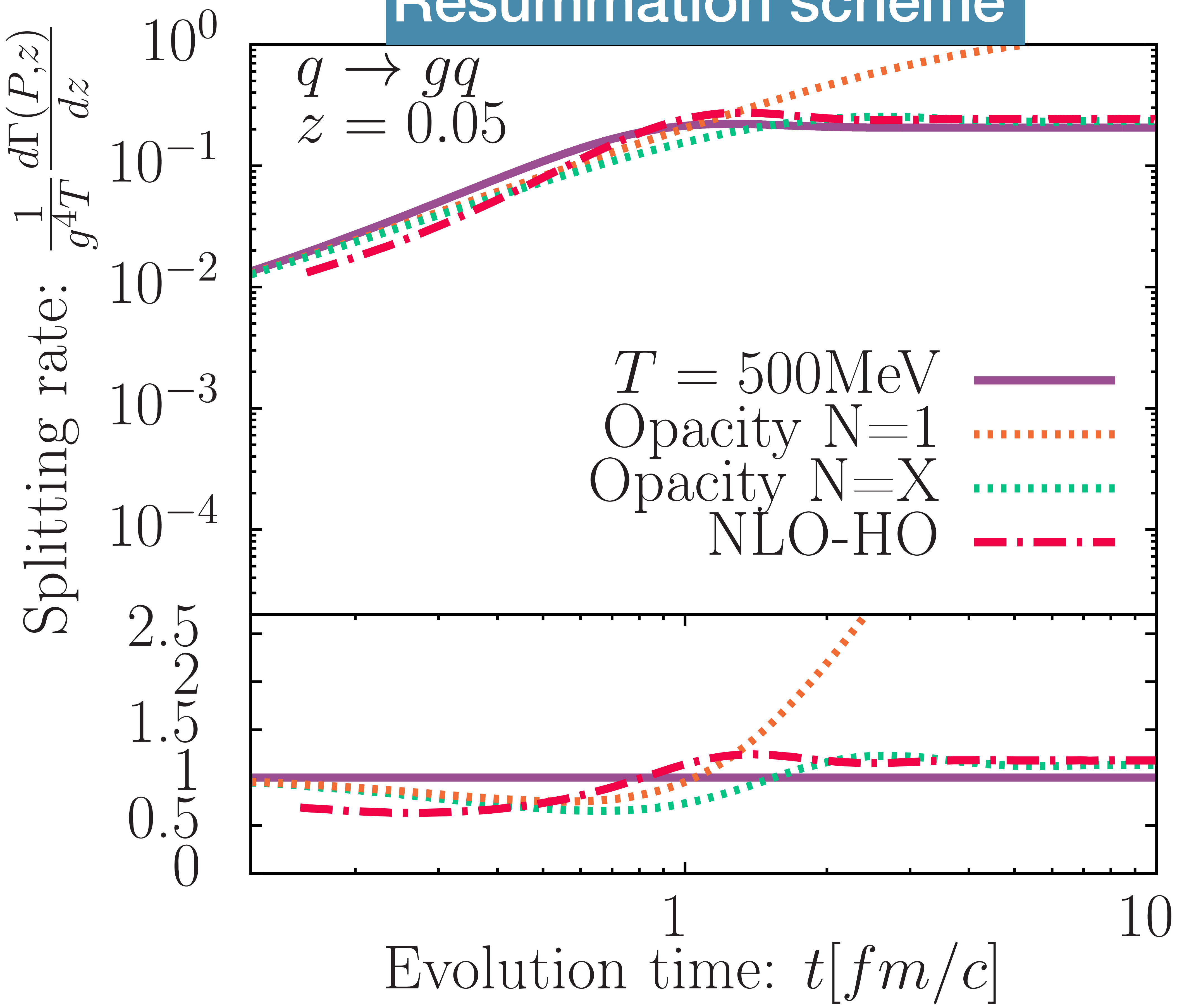


Small detour: resummation vs non-perturbative ingredients

Scattering potential



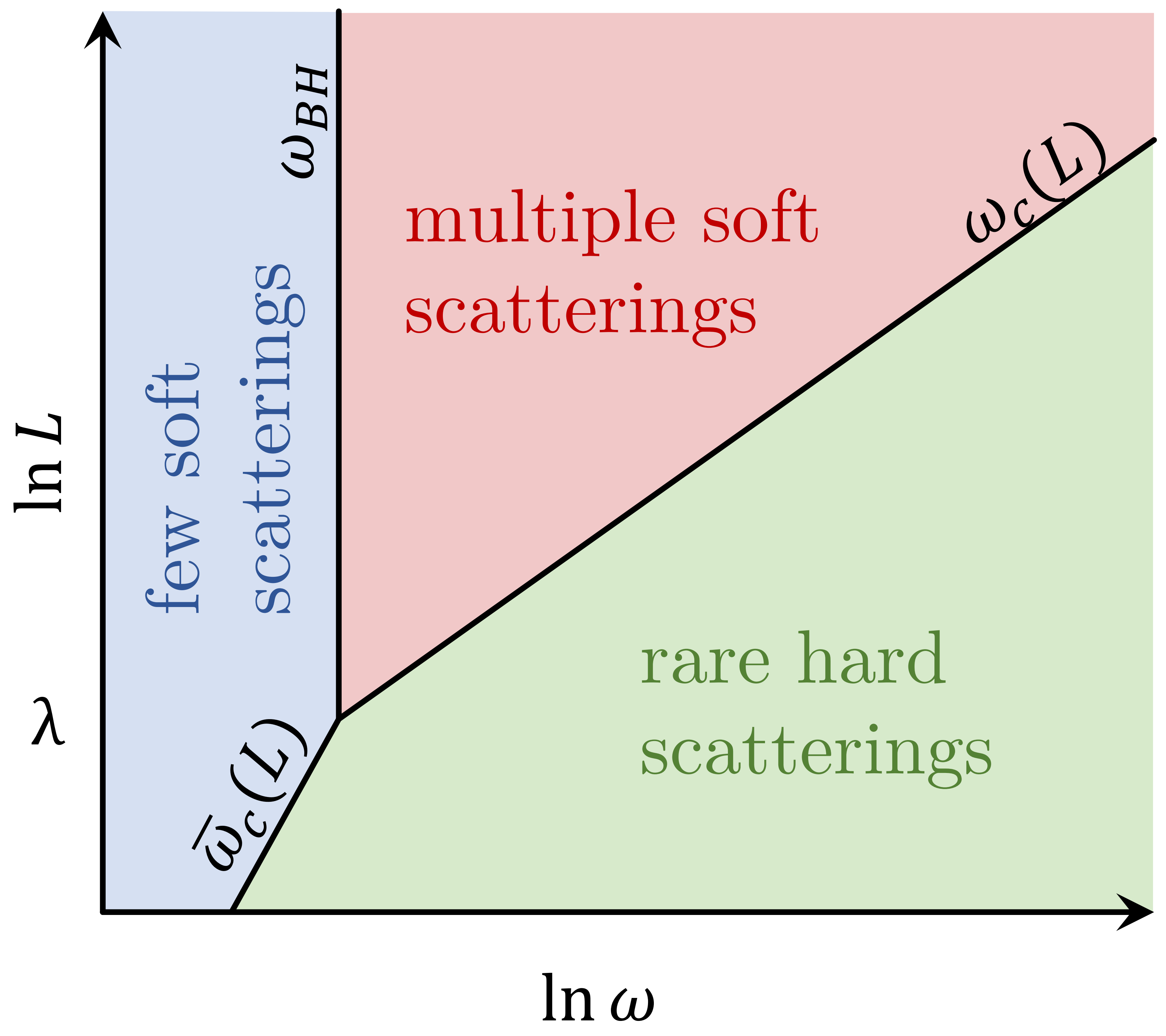
Resummation scheme

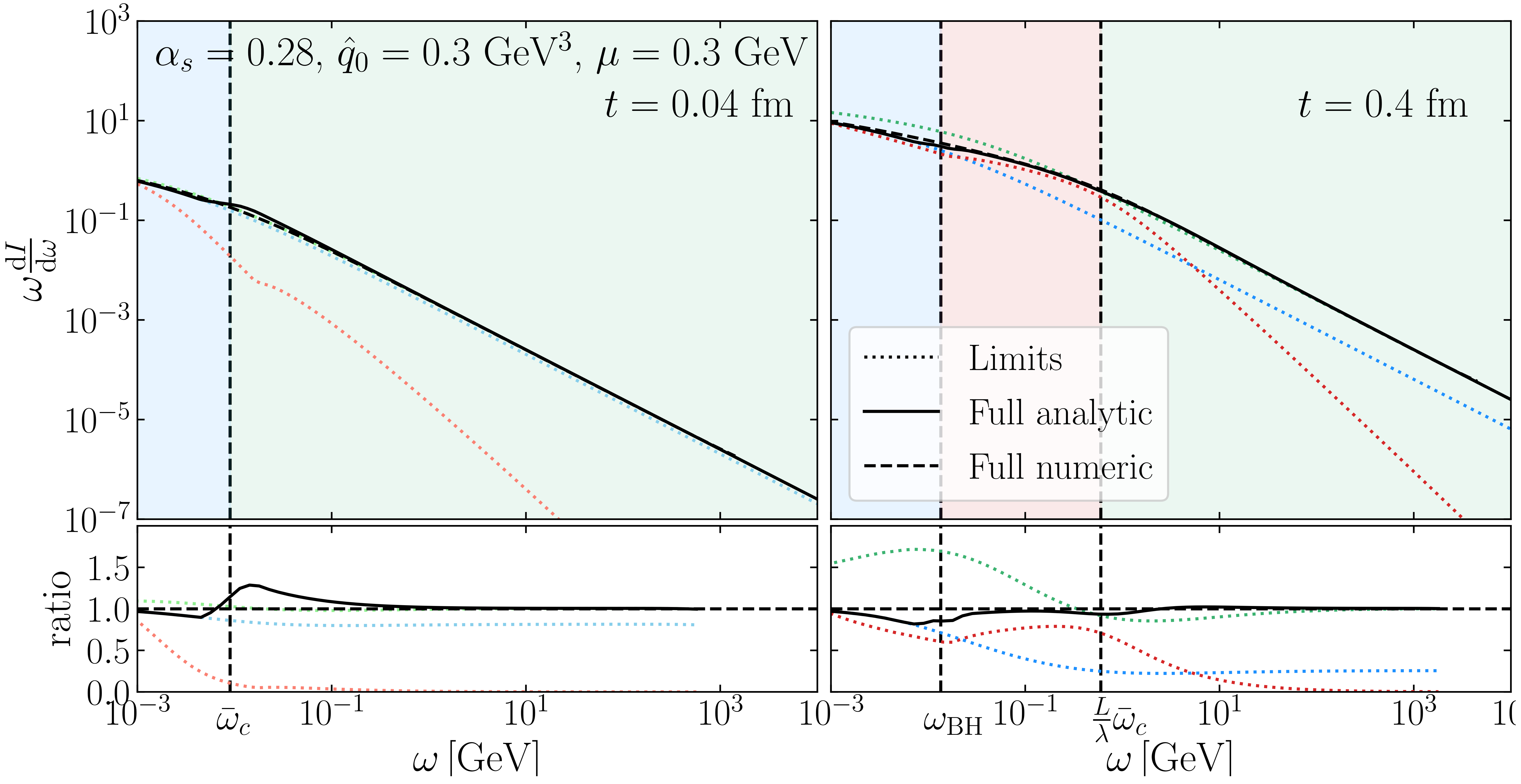


Scattering potential is the dominant uncertainty on splitting rates

Medium induced energy spectrum [Isaksen, Takacs, Tywoniuk 2206.02811]

New resummation scheme relevant for dilute media and/or very soft frequencies

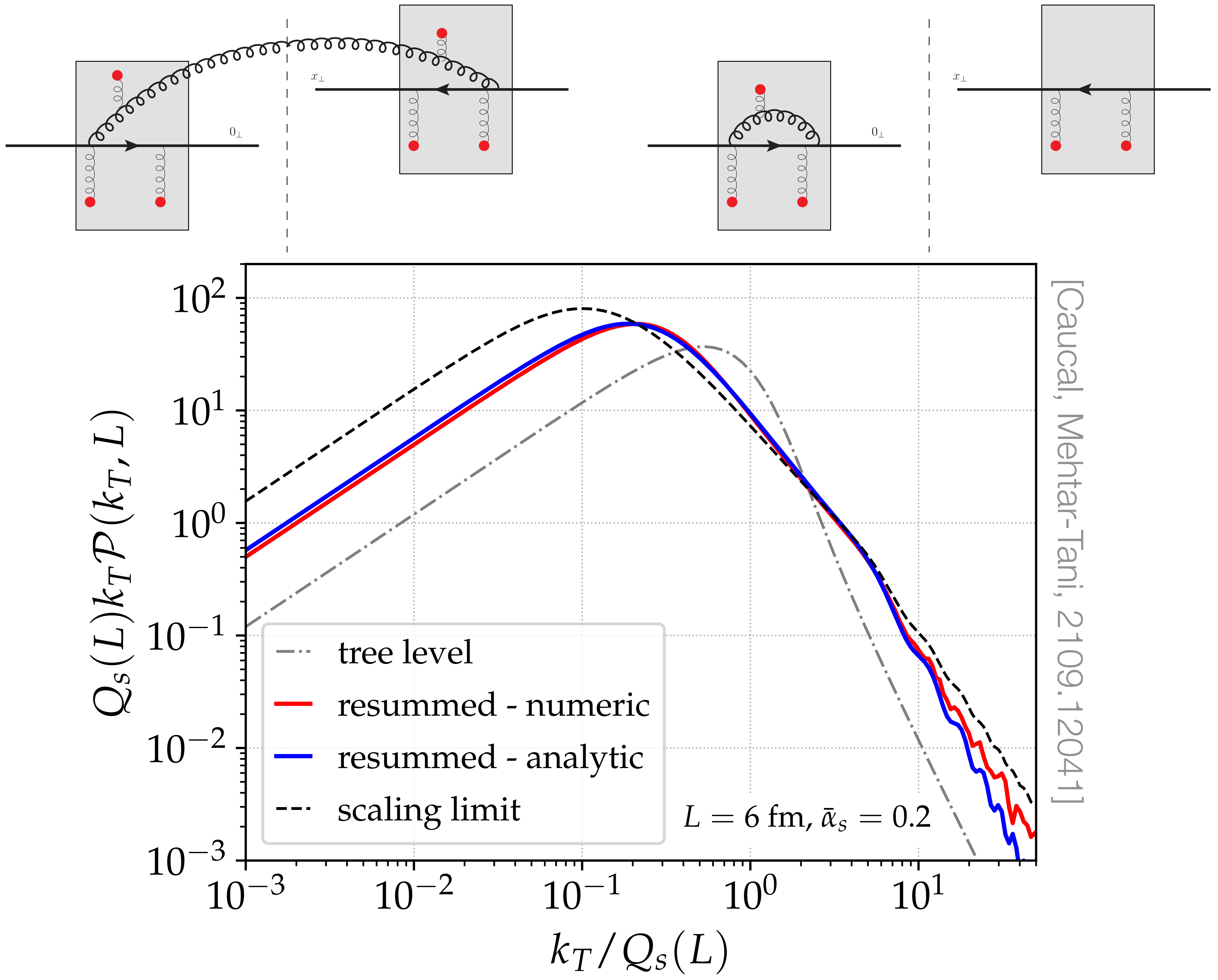




Full analytic control over the entire phase-space. To-do: add angular dependence

Transverse momentum broadening See João's talk

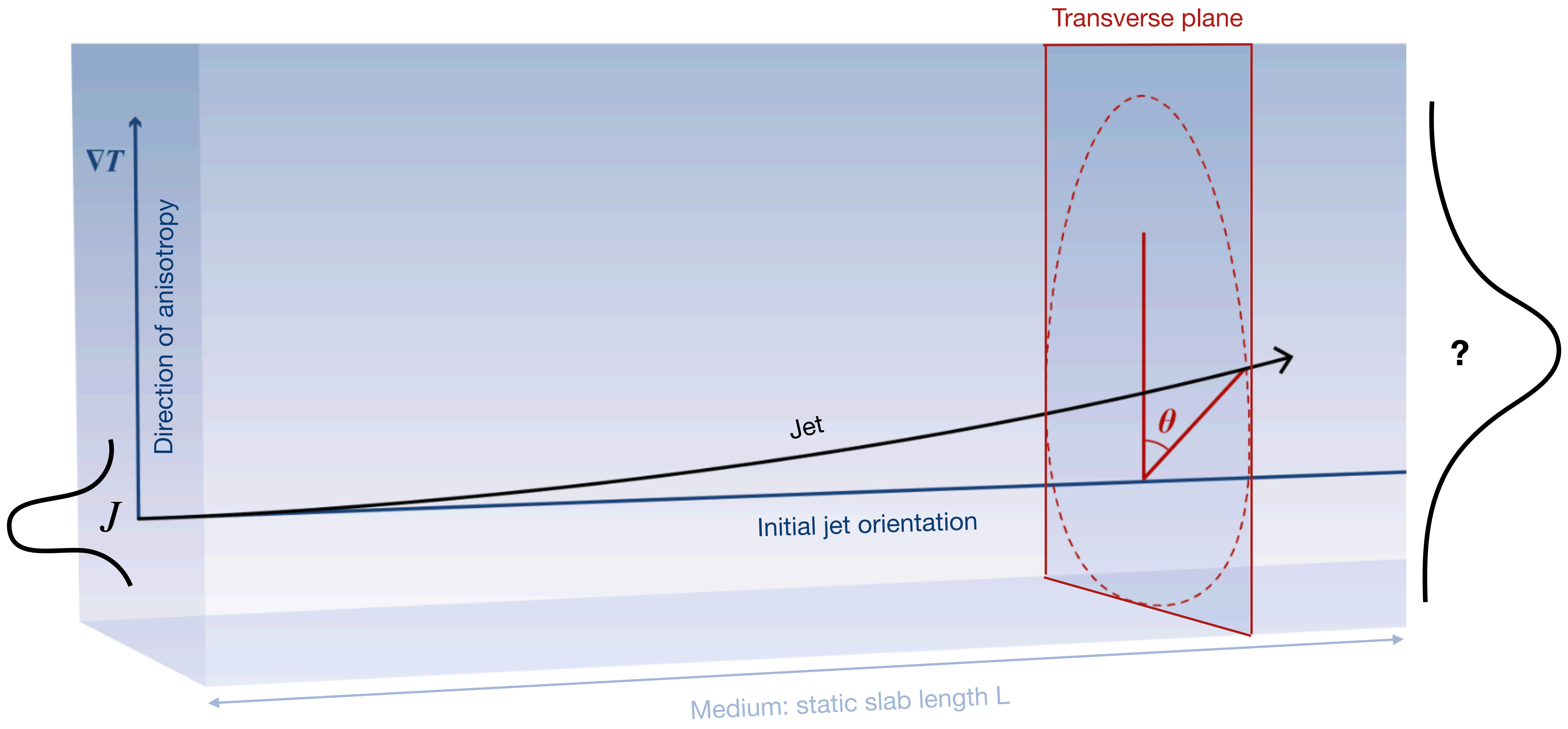
1 Quantum corrections



[Caucal, Mehtar-Tani, 2109.12041]

[See also Ghiglieri, Weitz 2207.08842]

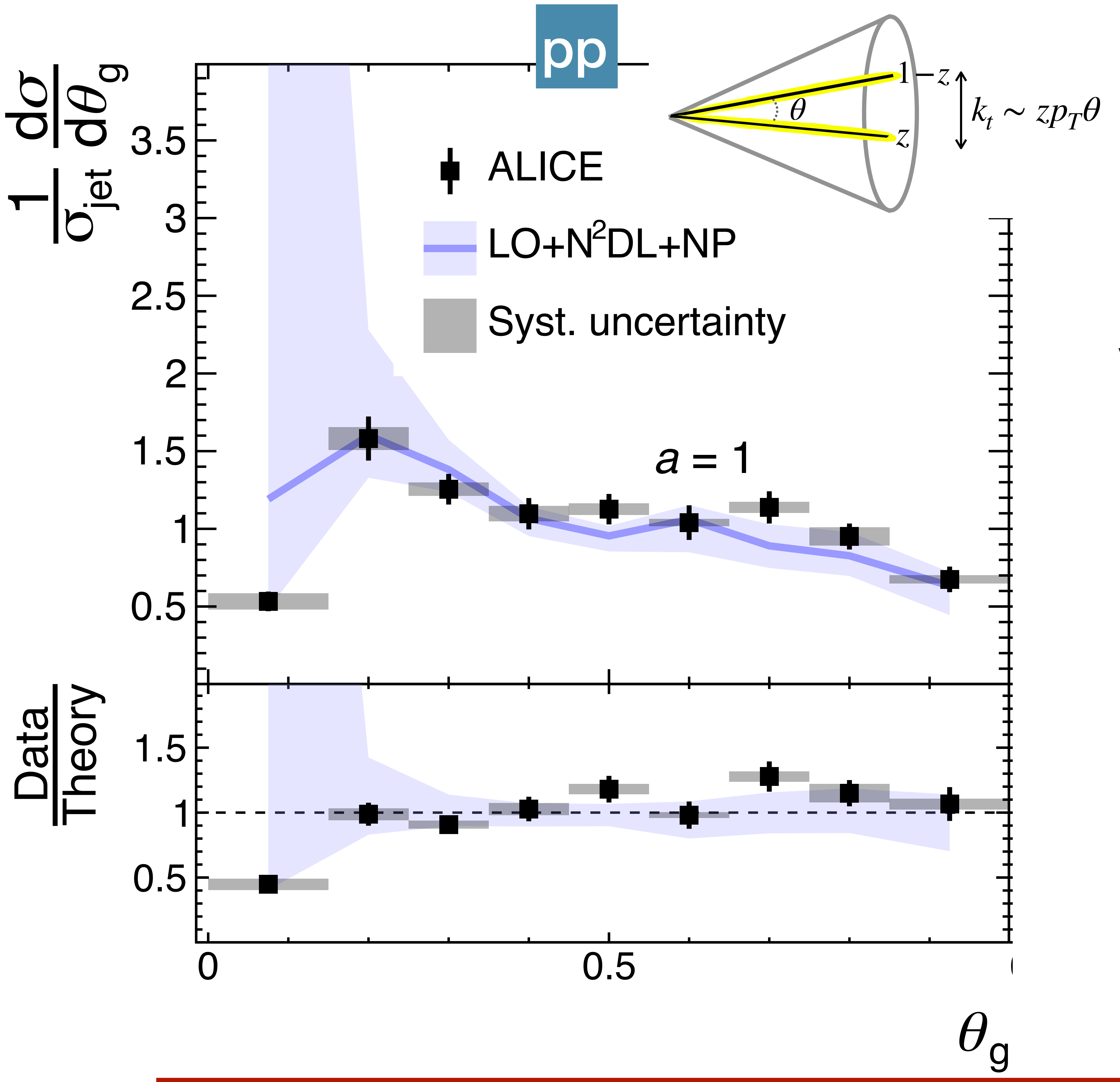
2 Inhomogeneous media

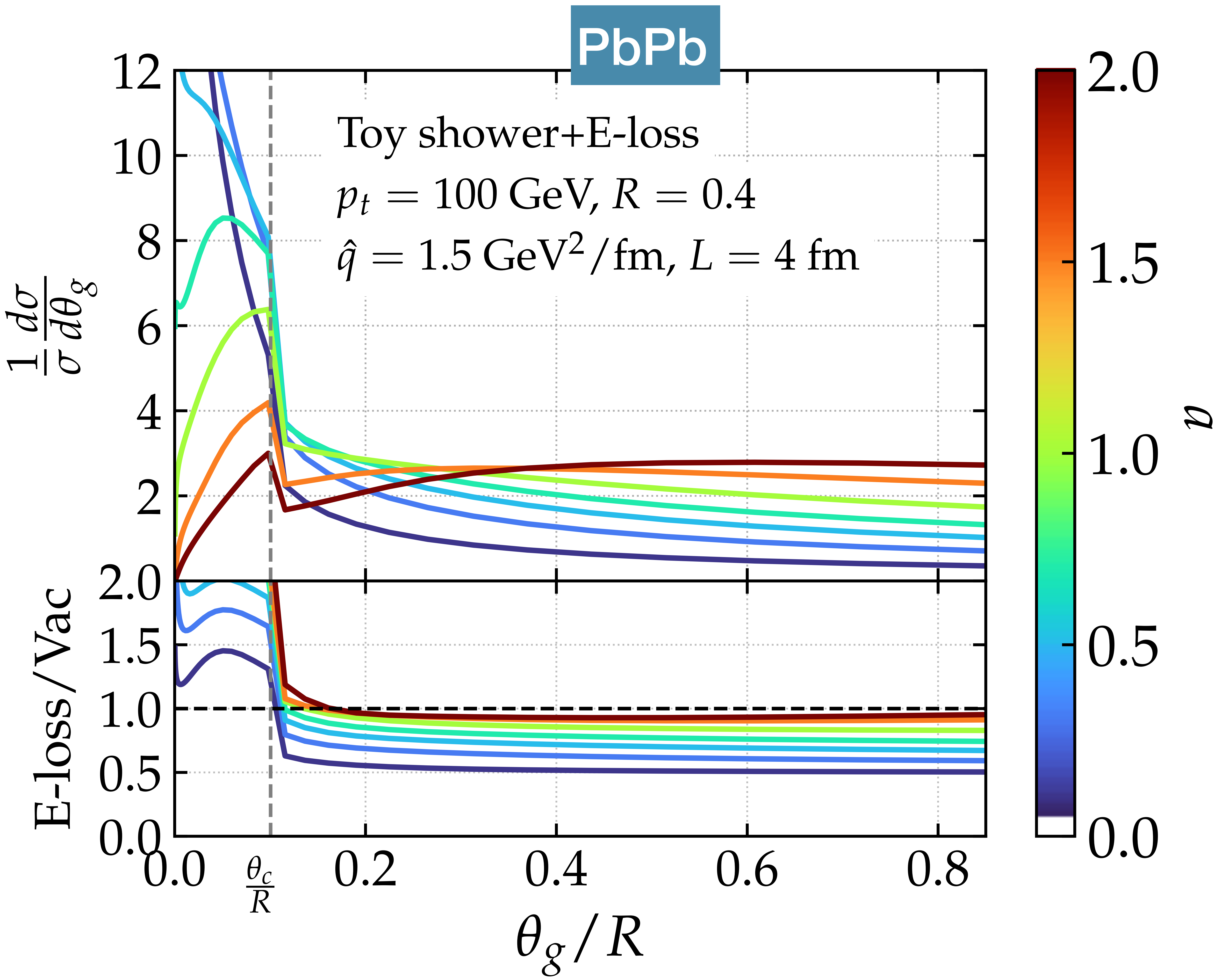


[Sadofyev, Sievert, Vitev, PRD 104 (2021) 9, 094044]
[Barata, Sadofyev, Salgado PRD 105 (2022) 11, 114010]
[Fu, Casalderrey-Solana, Wang 2204.05323]
[Andres, Dominguez, Sadofyev, Salgado 2207.07141]

Jet substructure calculations: status

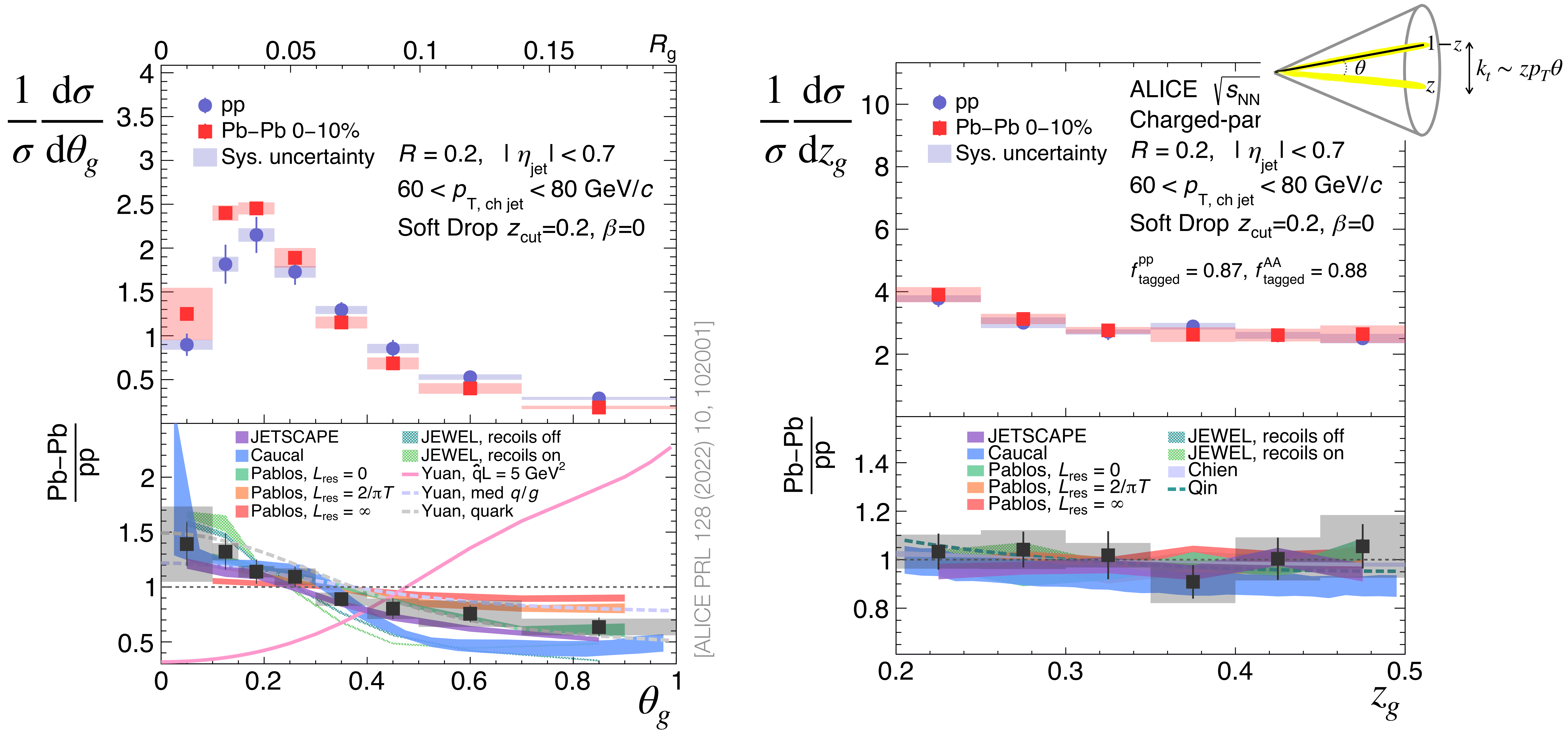
[Caucal, ASO, Takacs JHEP 07 (2021) 020]
[Caucal, ASO, Takacs PRD 105 (2022) 11, 114046]





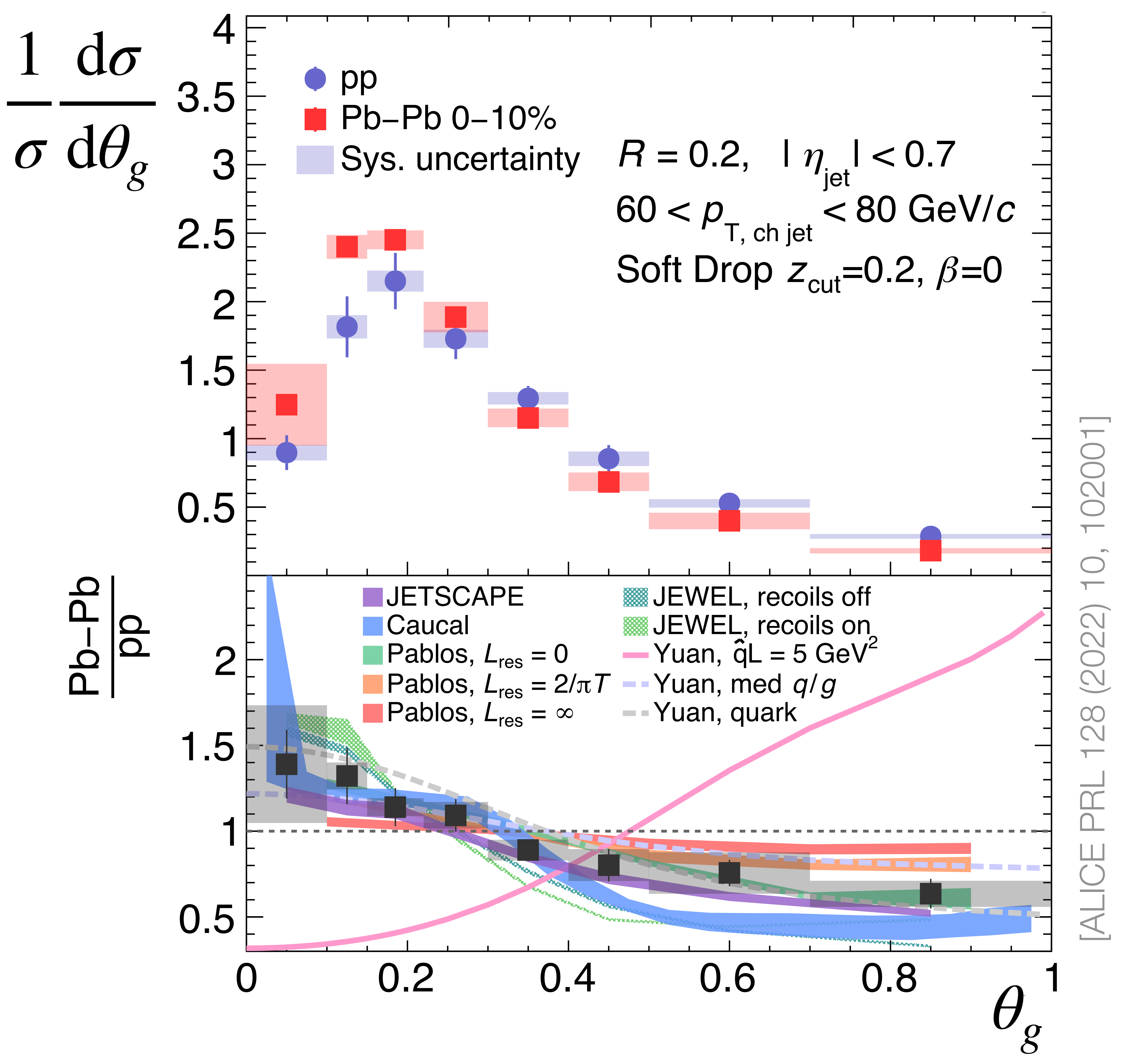
Jet substructure calculations in the medium are still in their infancy

Jet substructure measurements: status



Sizeable narrowing of the jet core observed in data

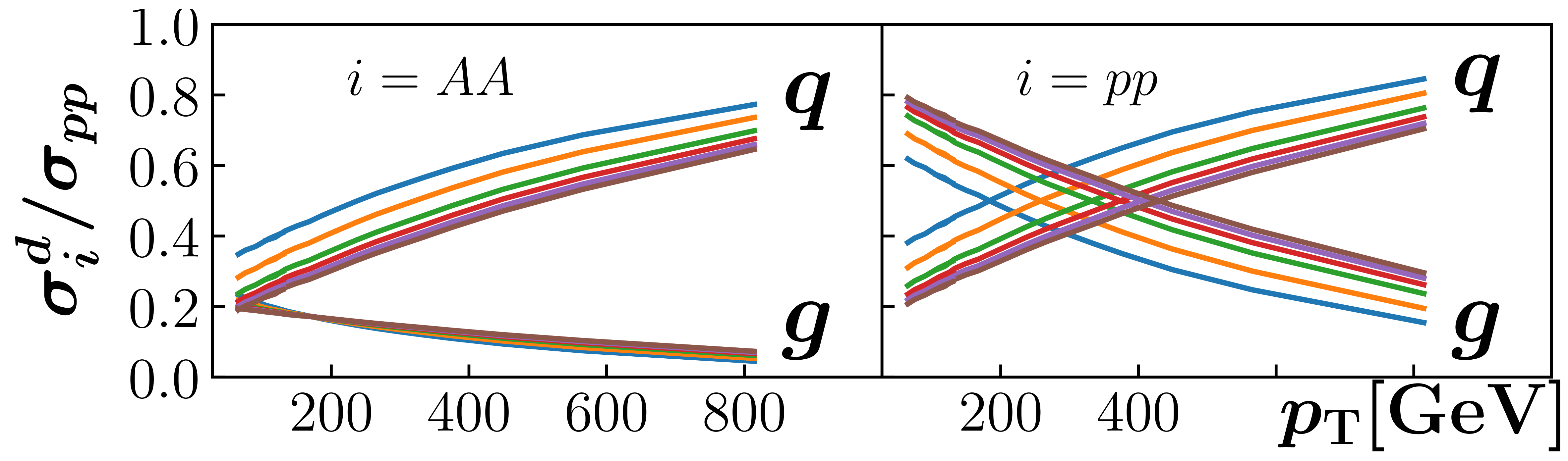
Interpretation of jet narrowing



Yuan, med q/g [PLB 808 (2020) 135634]

$$\frac{1}{\sigma}\frac{d\sigma}{d\theta_g}\Big|_{AA} = f_q \frac{1}{\sigma}\frac{d\sigma}{d\theta_g}\Big|_{pp} + f_g \frac{1}{\sigma}\frac{d\sigma}{d\theta_g}\Big|_{pp}$$

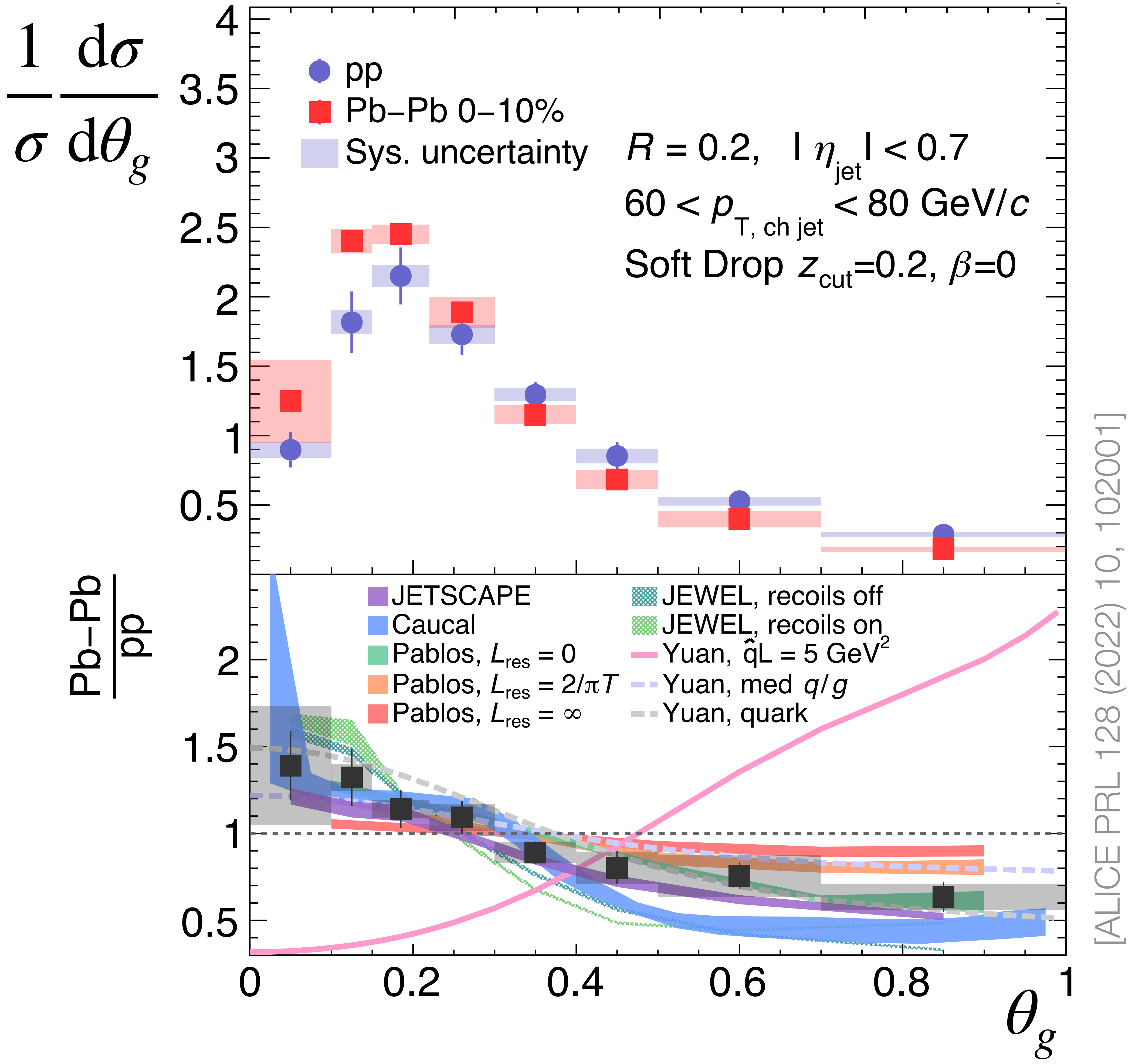
with $f_{q,g}$ as determined from a global fit to R_{AA}



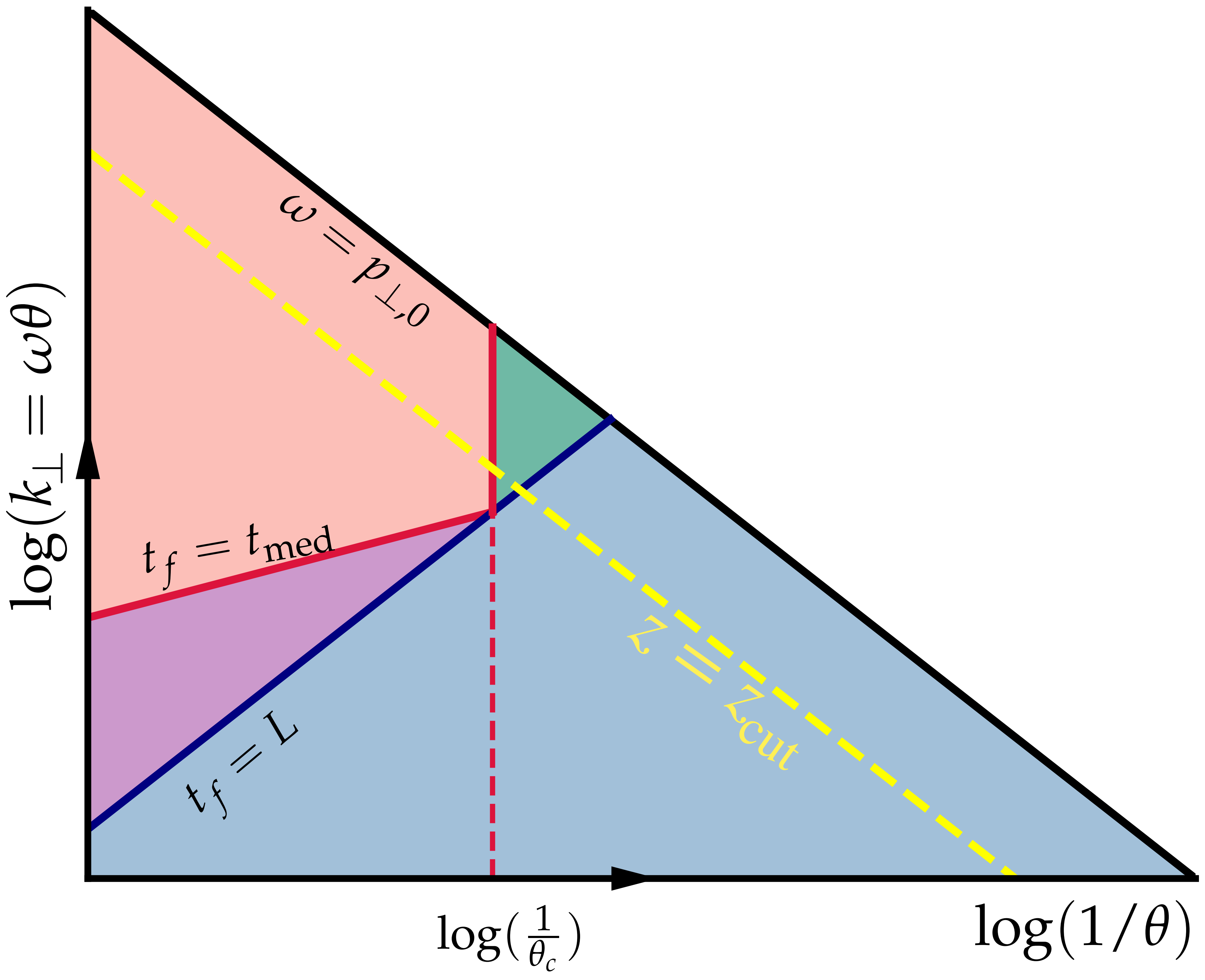
[PRL(2019) 25, 252301]

Narrowing is a result of bias towards quark jets in PbPb

Interpretation of jet narrowing

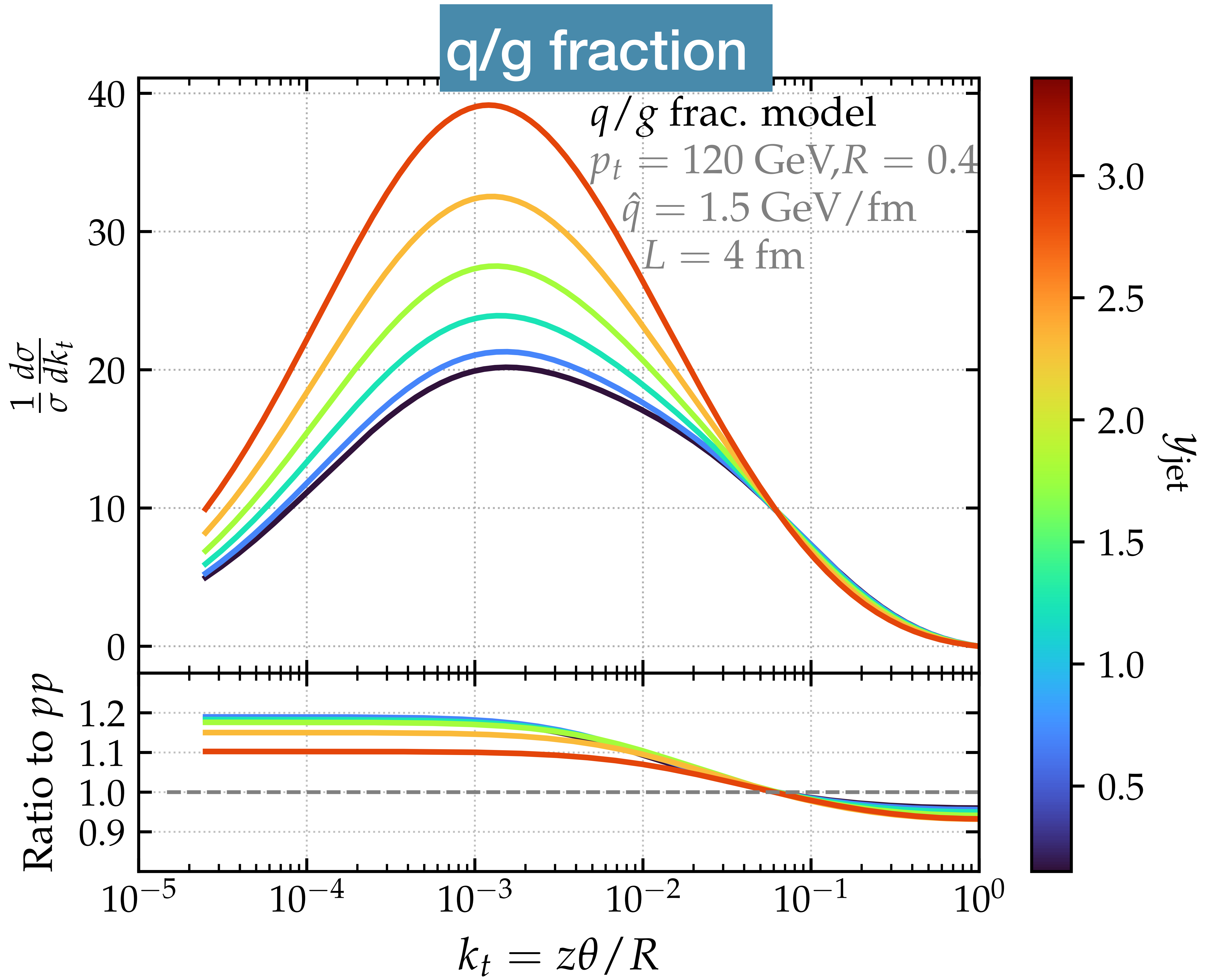


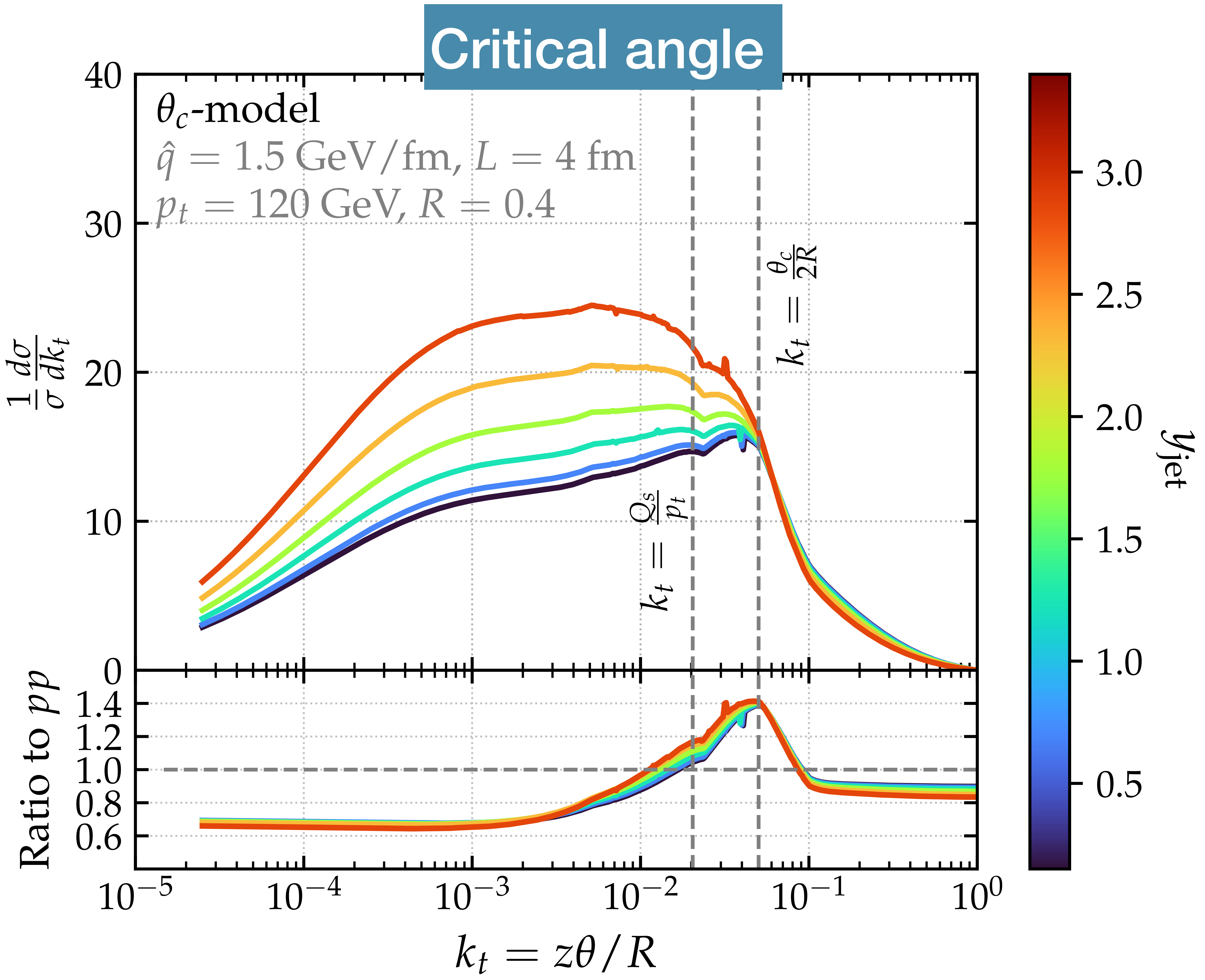
Caucal [PRL 120 (2018) 232001]



Narrowing driven by filtering due to critical angle

Pushing forward jet substructure measurements [Pablos, ASO to appear]



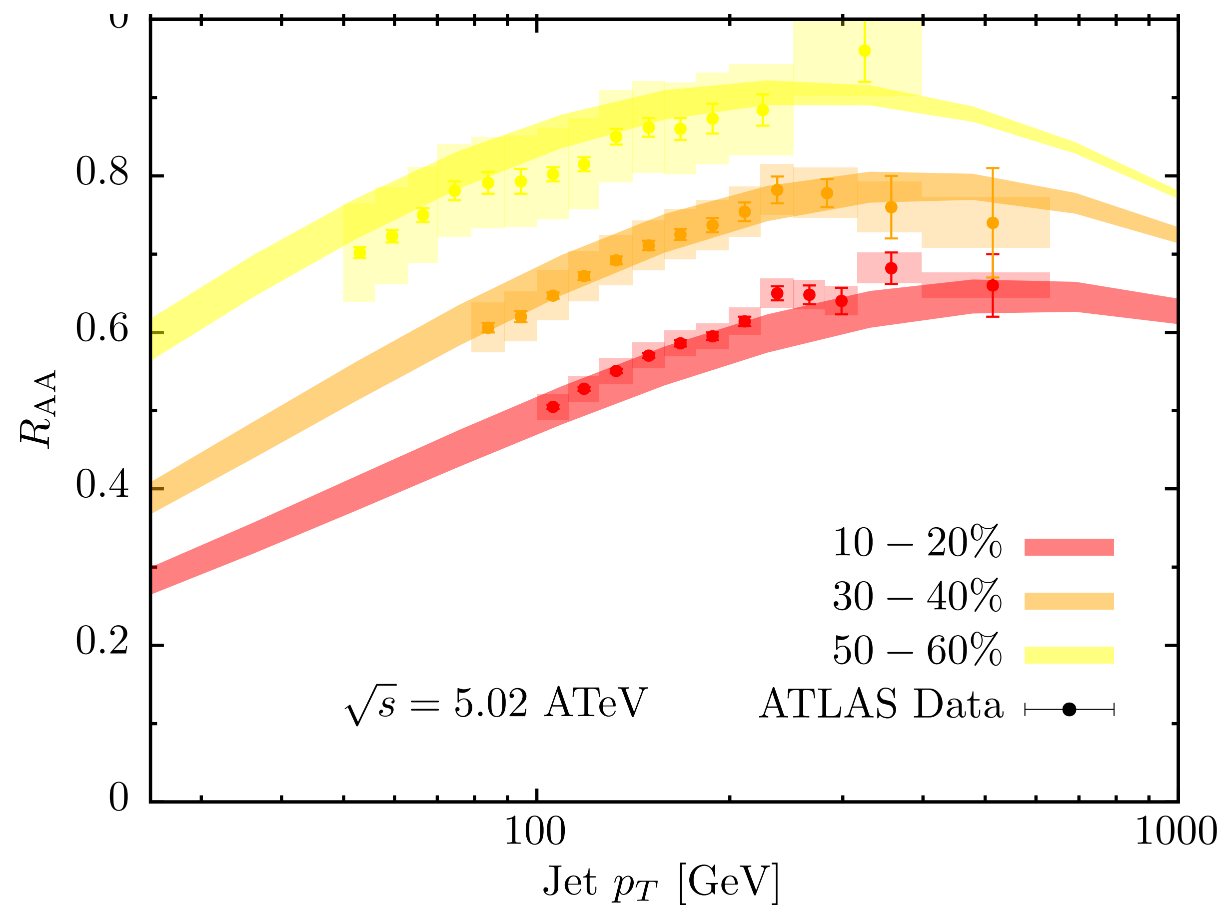


Substructure measurements at forward rapidities have a huge discriminating power

Conclusions and outlook

- Outstanding progress in jet quenching theory during the last 5 years
- However, pheno calculations are mostly based on multiple, soft approximation

Exception:



[Mehtar-Tani, Pablos, Tywoniuk PRL 127 (2021) 25, 252301]

- Jet substructure theory in heavy-ion collisions is at the dawn of a new era
- Extension to heavy-quarks for dead-cone searches/medium-enhanced production [Attems et al 2203.11241]
- Ultimately, analytical tools should become building blocks of Monte Carlo generators