Jet medium modifications

Carlota Andres

CPHT, École polytechnique

HP2023, Aschaffenburg, March 26 -31

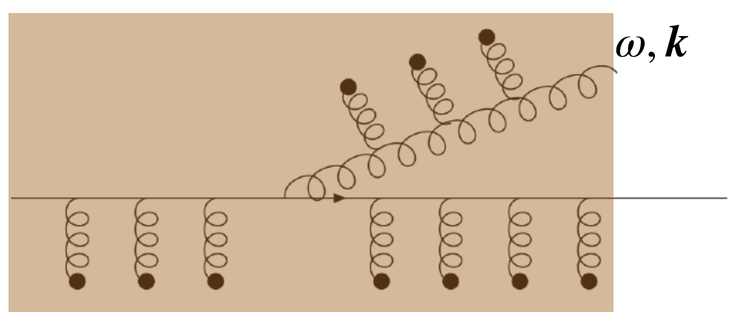
CPHT Centre de Physique Théorique

MARIE CURIE ACTIONS

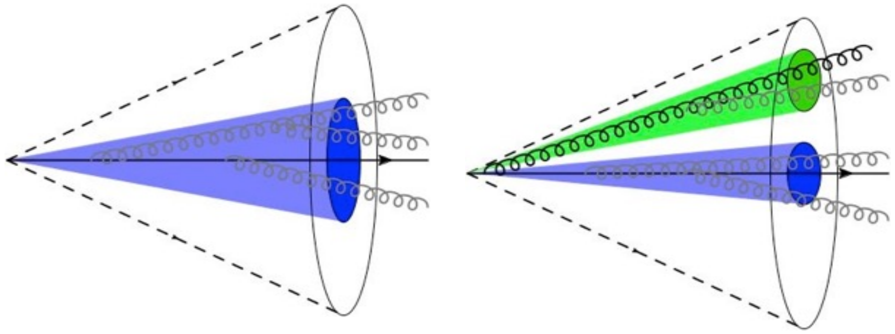
l'X ÉCOLE POLYTECHNIQUE

Jet modification in HI

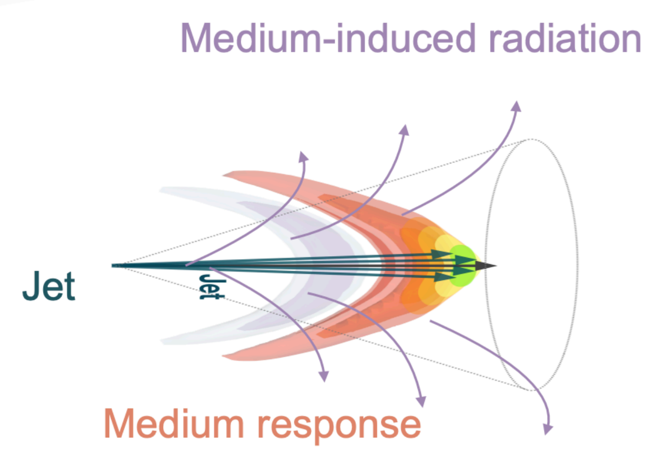
- **Medium-induced** energy loss
  - Out-of-cone energy loss
  - Jet and hadron suppression



- **Color coherence** effects Soto-Ontoso's talk Mon 17:05
  - Expected to modify the jet inner structure
  - Not yet unequivocally seen in observables



- **Medium response** Go's talk Mon 17:30
  - Medium recoils become part of the jet
  - Not yet unequivocally seen in observables



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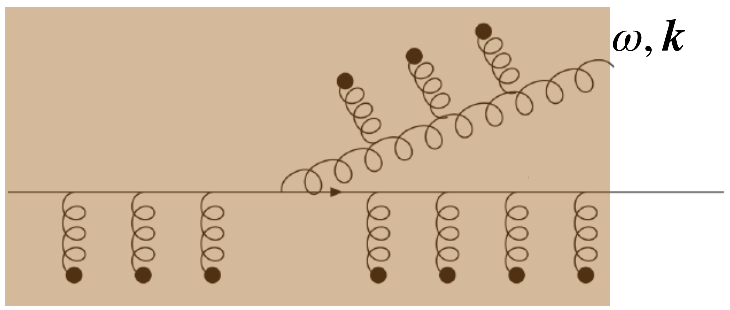

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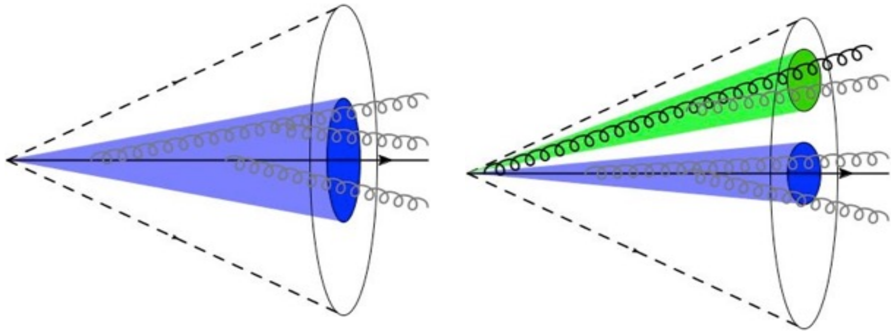

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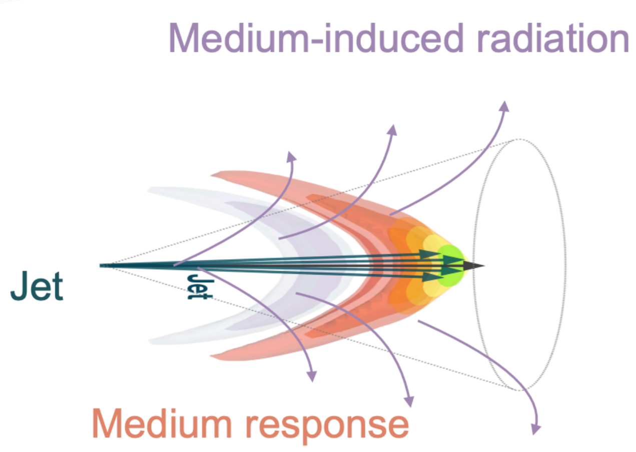
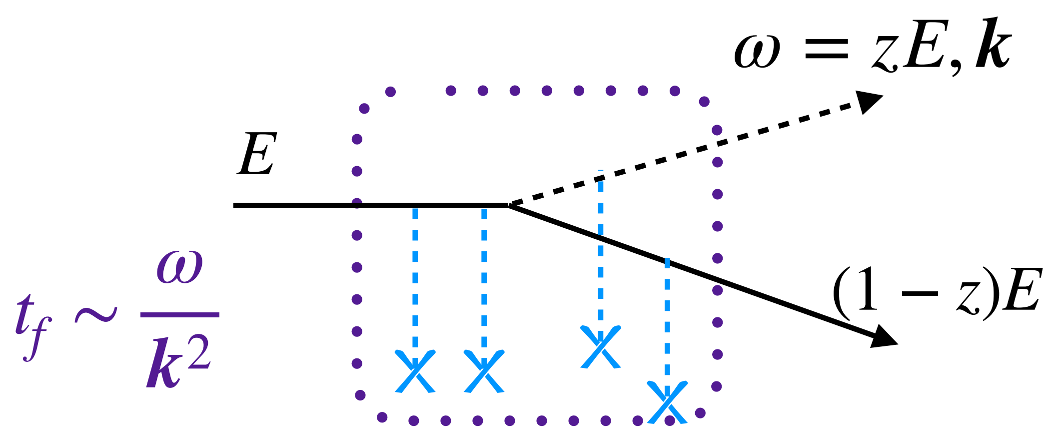


Medium-induced radiation

- During the formation time of the gluon **multiple scatterings** act **coherently**

LPM effect



Landau, Pomeranchuk, Migdal

Suppression of the spectrum for **large formation times**

- Resummation of multiple scatterings: **BDMPS-Z formalism**

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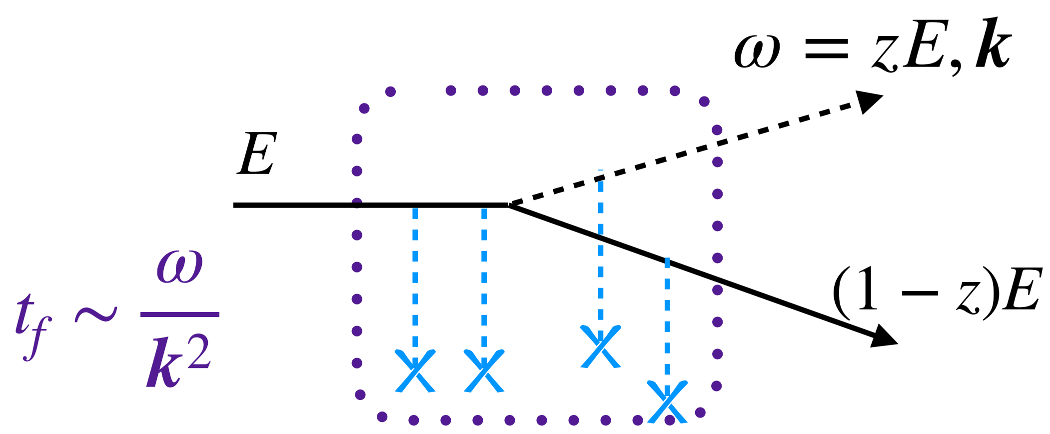

Landau, Pomeranchuk, Migdal

Suppression of the spectrum for **large formation times**

- Resummation of multiple scatterings: **BDMPS-Z formalism**
    - For energy loss calculations, we only need the soft limit ($z \ll 1$):

Formally : $E \to \infty, z \to 0 \quad (\omega = zE \text{ finite})$

Emission kernel — Broadening

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

Baier, Dokshitzer, Mueller, Peigné, Schiff (96)
Zakharov (97)

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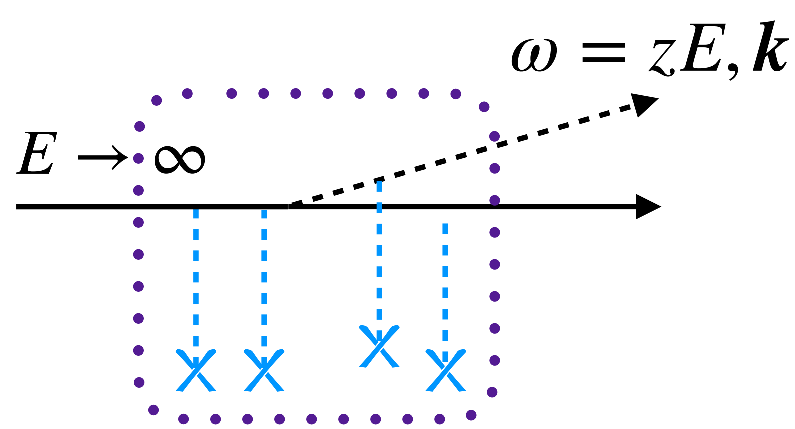
LPM effect

$t_f \sim \frac{\omega}{\boldsymbol{k}^2}$



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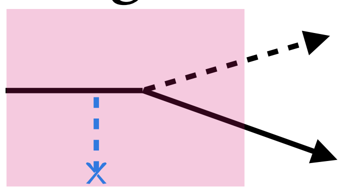
Medium-induced radiation

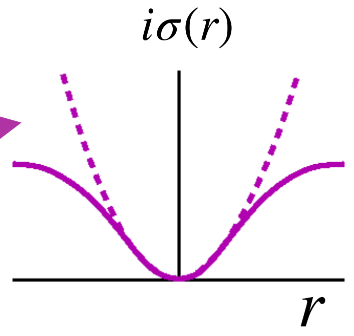
- In practice, solved for some approximations
  - **Opacity expansion** in the number of scatterings

    $N = 1$: GLV   Gyulassy, Levai, Vitev (2000)



  - **Harmonic oscillator (HO):** multiple soft scatterings (Gaussian approximation)

    $$n\sigma(r) \approx \frac{1}{2}\hat{q}r^2$$



  - **AMY:** infinite length medium   Arnold, Moore, Yaffe (2002)

- Recent approaches going beyond these approximations $V(\boldsymbol{q}) \propto \frac{1}{\boldsymbol{q}^4}$
  - **Improved opacity expansion** (IOE)

    Semi-analytical expansion around the HO

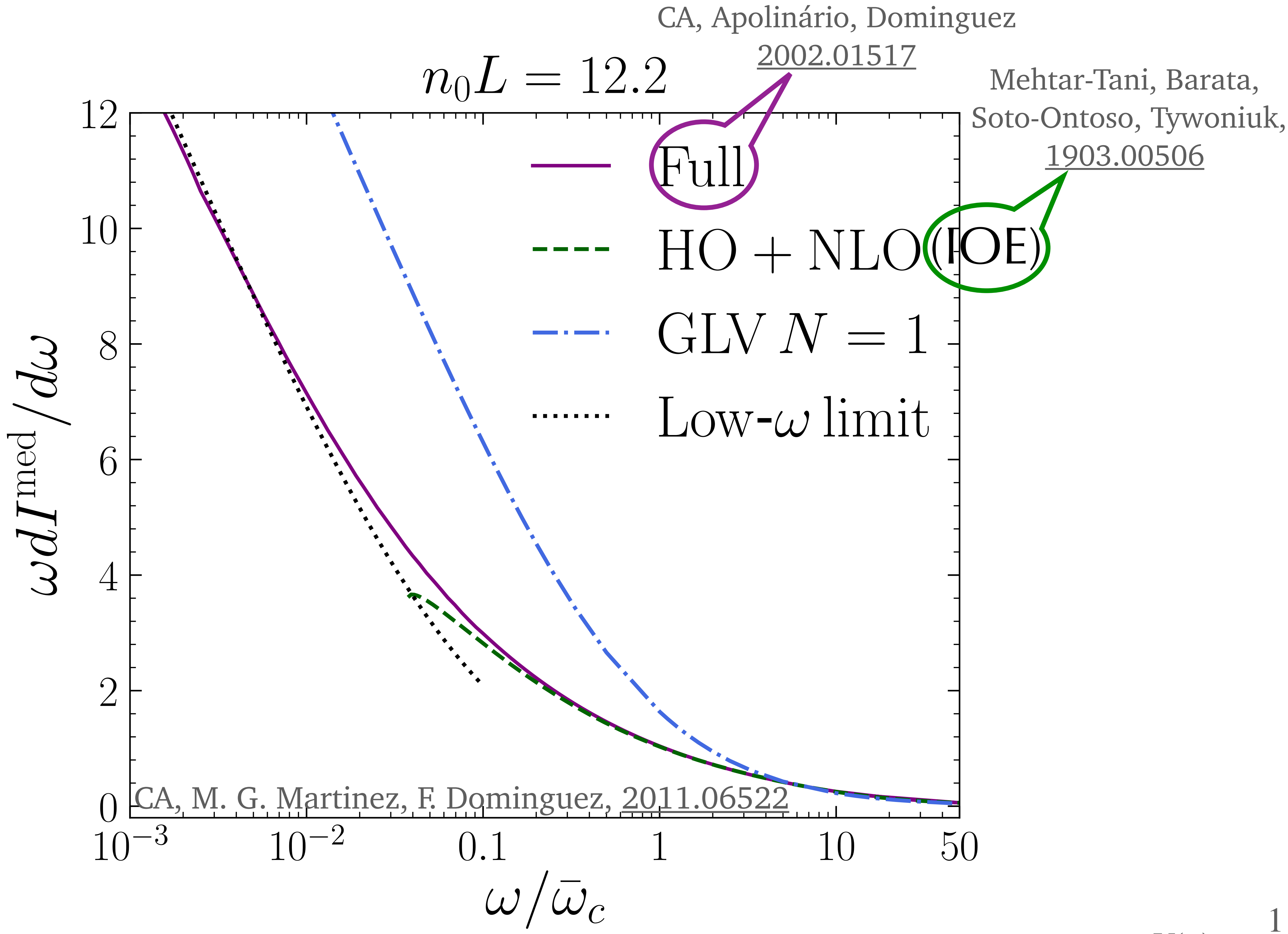
    Mehtar-Tani, Barata, Soto-Ontoso, Tywoniuk, 1903.00506, 2004.02323, 2106.07402
  - **Fully resummed spectrum** ($z \ll 1$)

    Kernel as a time dependent Schrödinger equation

    CA, Apolinario, Martinez, Dominguez, 2002.01517, 2011.06522

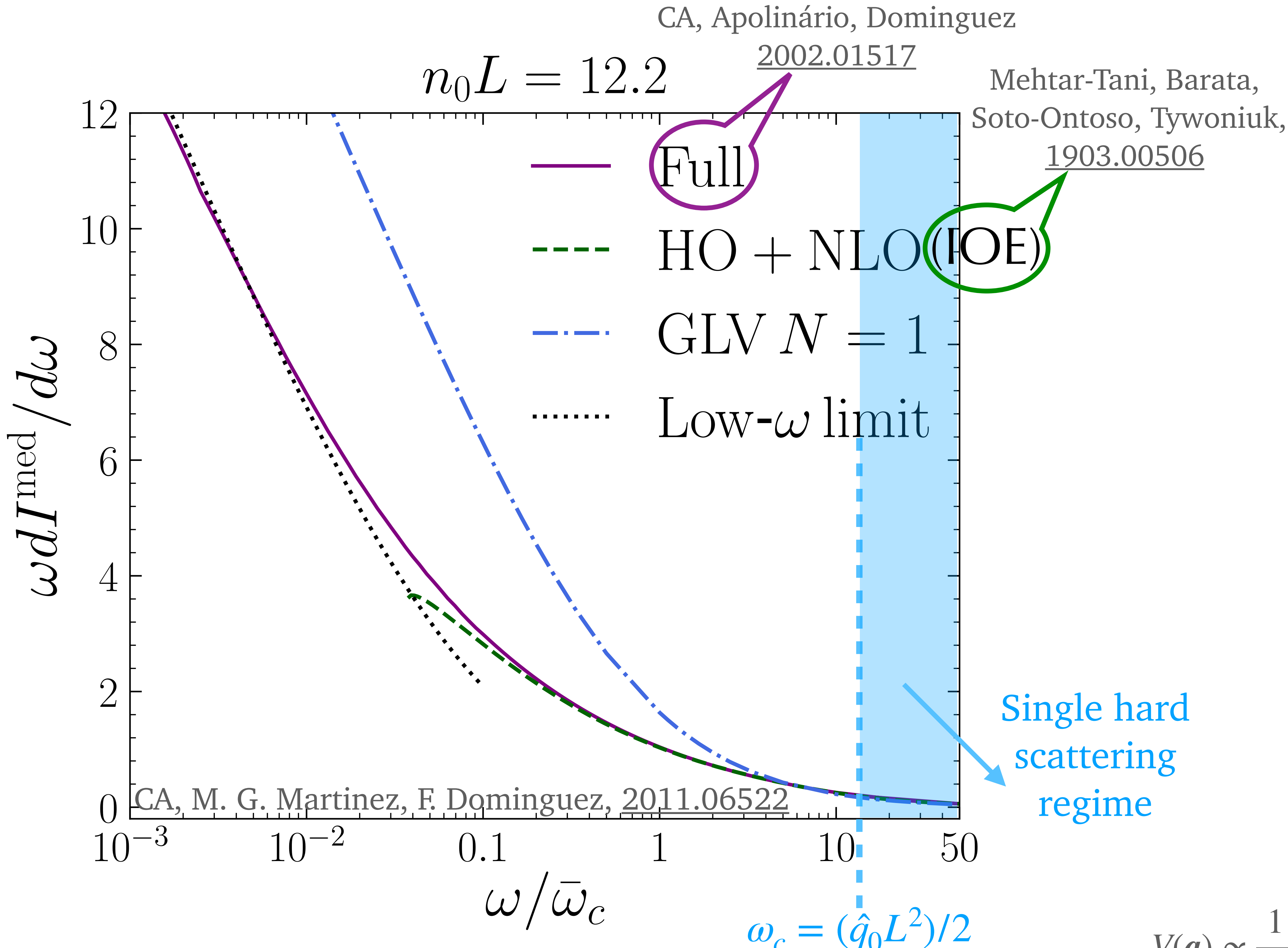
    Beyond the soft limit but integrated in k_T: Caron-Huot and Gale, 1006.2379

Medium-induced radiation



$V(\boldsymbol{q}) \propto \frac{1}{\boldsymbol{q}^4}$

Medium-induced radiation



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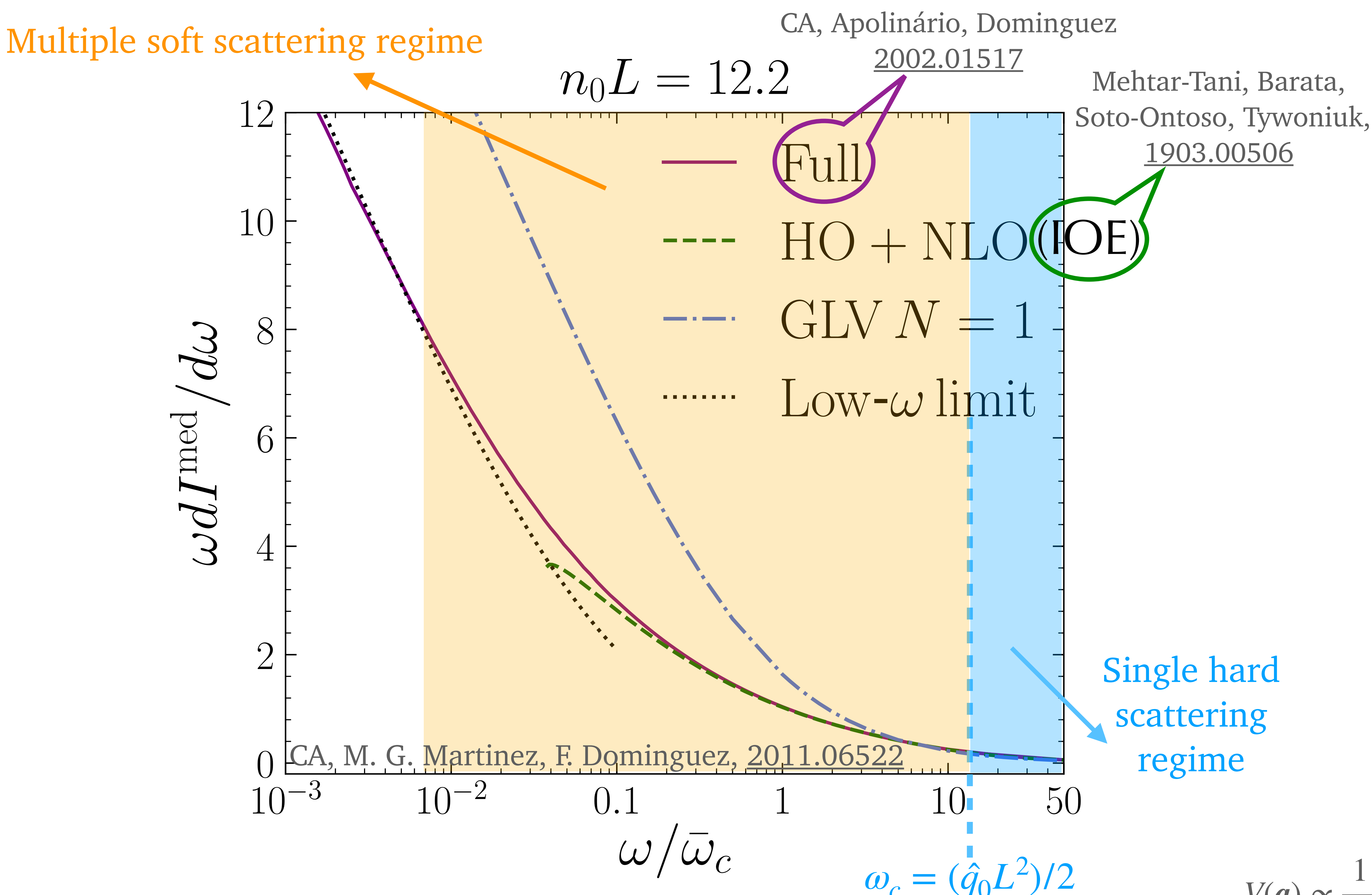

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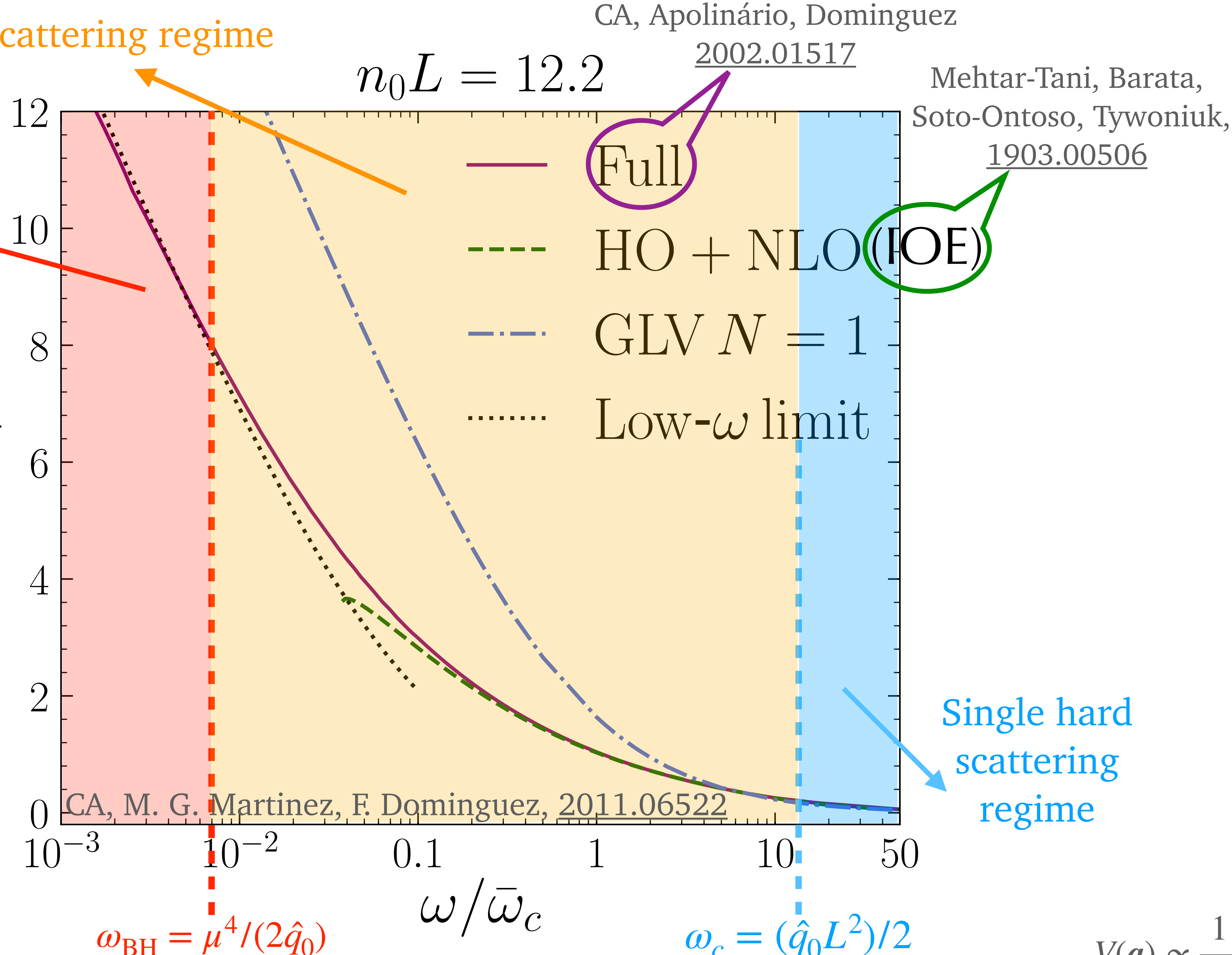


Not just a single hard scattering!

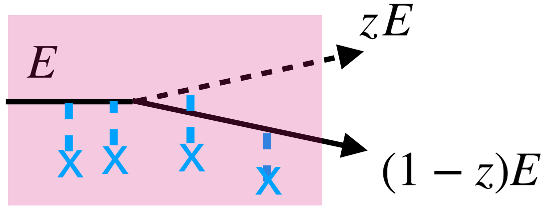
Generalized to the ROE

Isaksen, Takacs and Tywoniuk arXiv:2206.0281

Takacs' talk Thurs 9:00

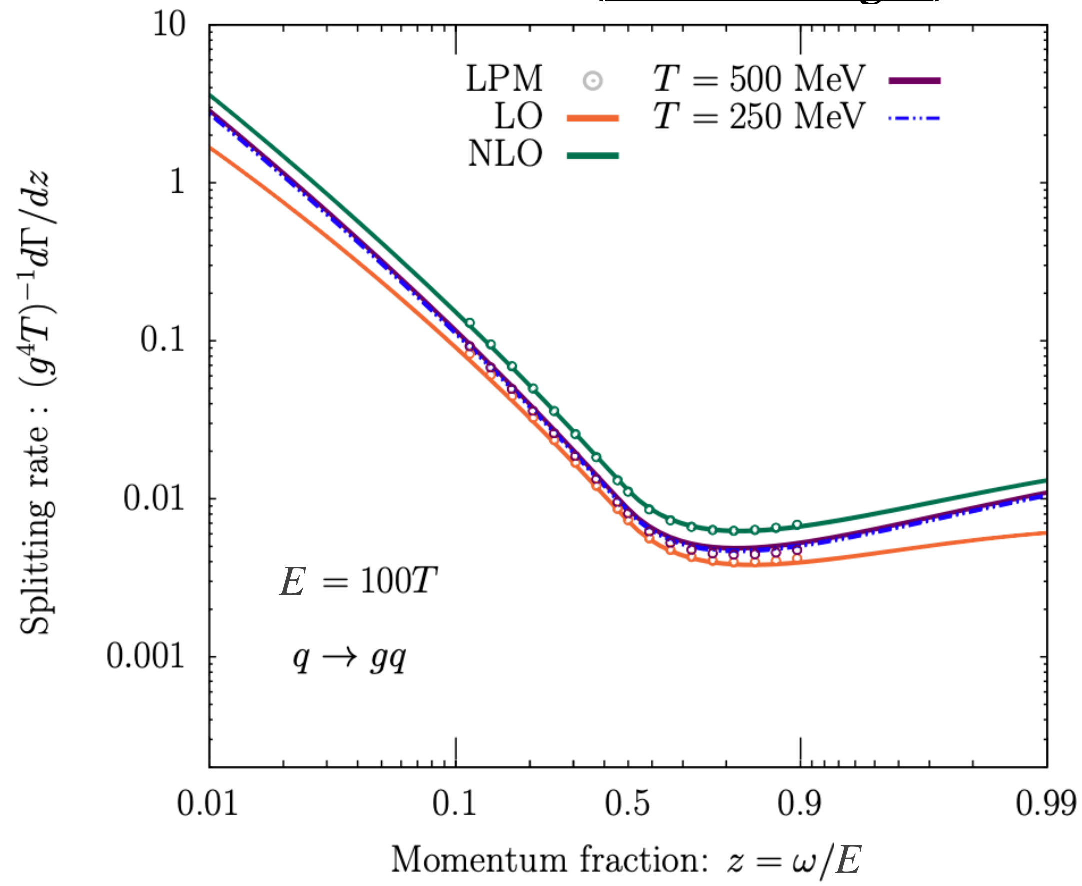
$V(\boldsymbol{q}) \propto \frac{1}{\boldsymbol{q}^4}$

Medium-induced radiation: non-perturbative potential



- Perturbative potential *(broadening kernel)* known at LO and NLO in pQCD Aurenche Gelis Zaraket (2002), Caron -Huot (2008)
- **Non-perturbative result** from EQCD Moore, Schlusser, 2009.06614 Ghiglieri's talk Tue 10:50
- Matching between the EQCD IR and the perturbative UV results
  Moore, Schlichting, Schlusser, Soudi, 2105.01679

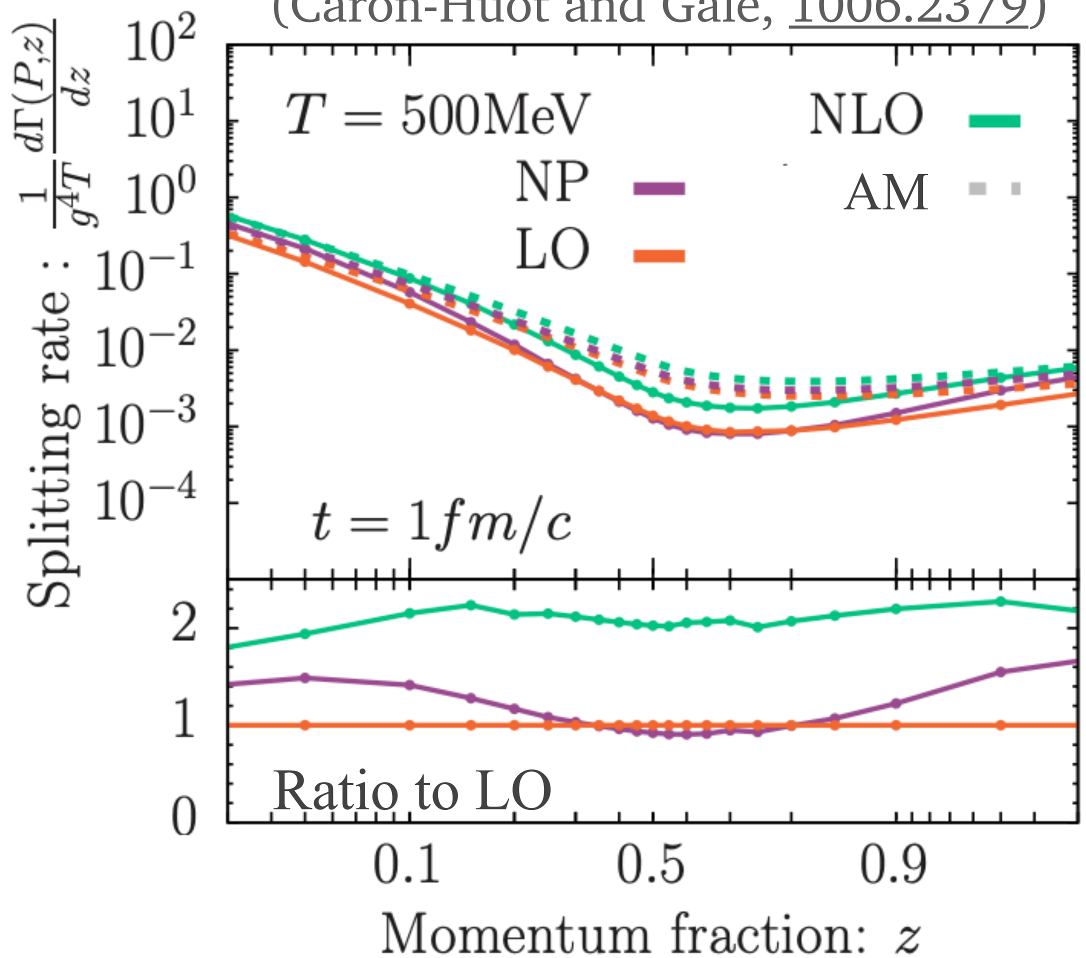
AMY rates (infinite length)



Moore, Schlichting, Schlusser, Soudi, 2105.01679

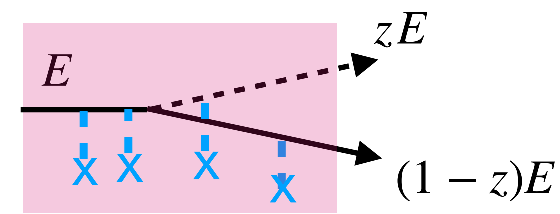
Finite length rates

(Caron-Huot and Gale, 1006.2379)



Schlichting, Soudi 2111.13731

Medium-induced radiation: non-perturbative potential



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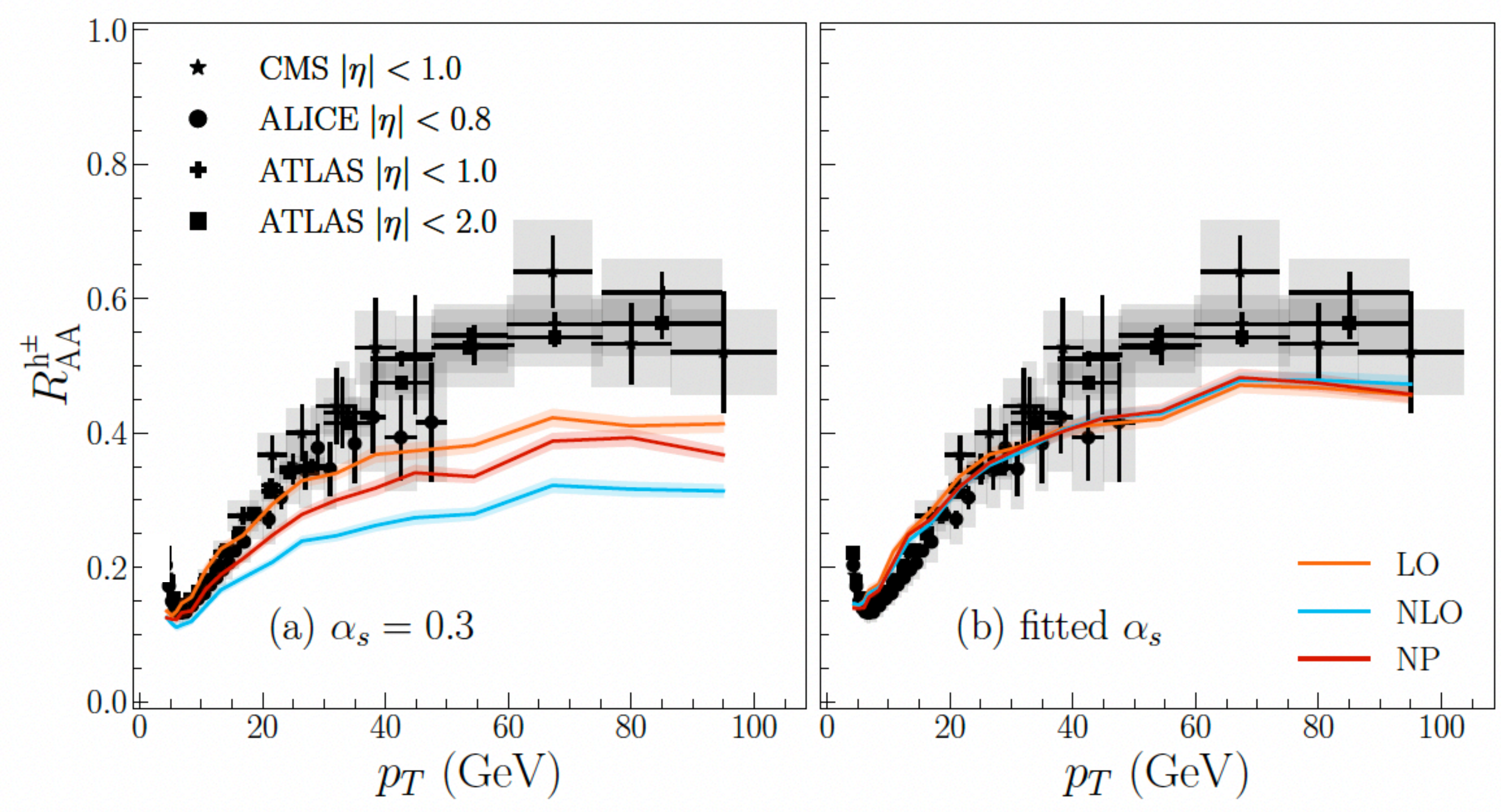


Rate Set	α_s
LO	0.280
NLO	0.242
NP	0.260

Yazdi, Shi, Jeon, Gale, 2206.05855

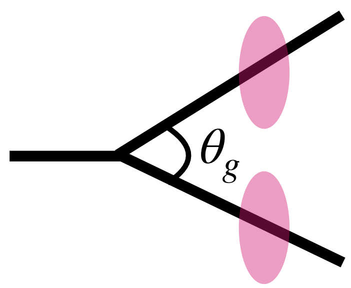
From energy loss to jet substructure

- Grooming techniques to isolate prongs corresponding to a hard splitting

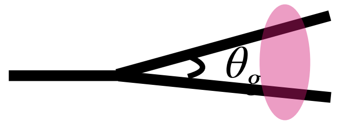
[ATLAS-CONF-2022-026]

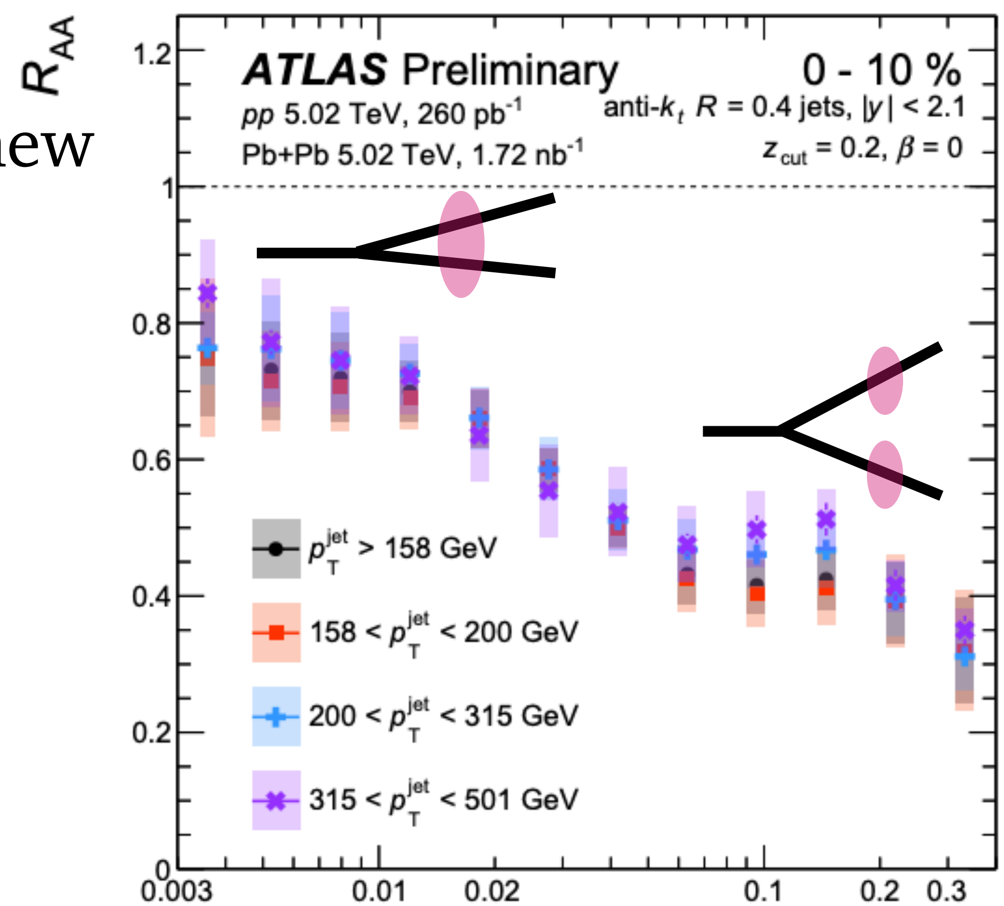
- The medium introduces a new resolution scale: θ_c

$\theta_g > \theta_c$

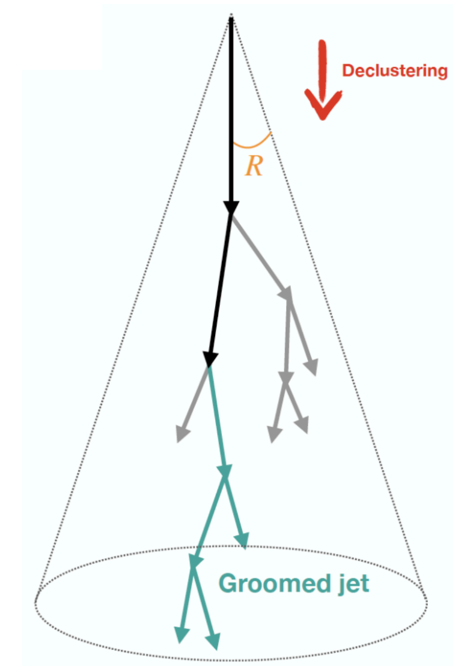


$\theta_g < \theta_c$





$r_g = \theta_g R$

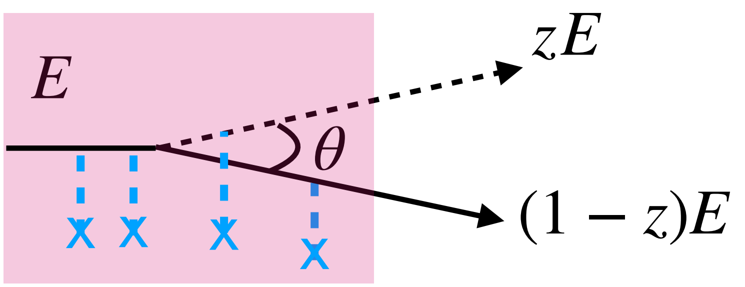


Sketch by Rey Torres

Soto-Ontoso's talk Mon 17:05

- Obtain θ_g and z_g distributions
  - Soft limit ($z \ll 1$) not that useful: $\frac{\mathrm{d}I^{\mathrm{med}}}{\mathrm{d}z\mathrm{d}\theta}$??

Beyond the soft limit



- **Complete (multiple scatterings)** medium-induced emission spectrum **keeping z** and **θ not available**

  until last Thursday! (See Isaksen's talk Tuesday 14:40) and slide 12 of this talk

- Two available approaches:

  - **Opacity expansion:**

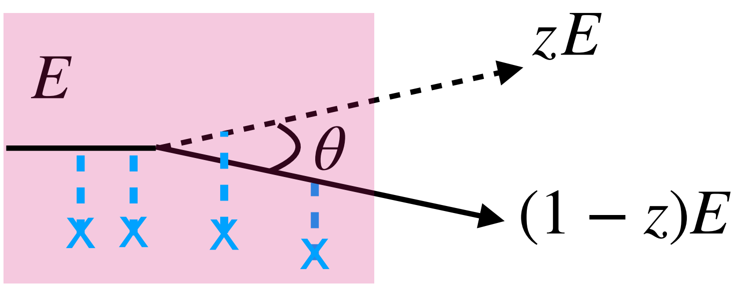
    See also Djordjevic's talk Tues 09:20

    - $N = 1$ result Ovanesyan, Vitev 1103.1074, 1109.5619
    - Highly complicated recursive relations to go to all orders Sievert, Vitev, 1807.03799
    - Some numerical results at $N = 1$ and $N = 2$ Sievert, Vitev, Yoon, 1903.06170
    - Unitarity issues can lead to negative cross sections

  - ***Tilted* Wilson lines:**

    - Assumes *semi-hard* splittings (z not too small) Dominguez, Milhano, Salgado, Tywoniuk, Vila, 1907.03653
    - All partons propagate along straight line trajectories Isaksen, Tywoniuk 2107.02542

Energy correlators

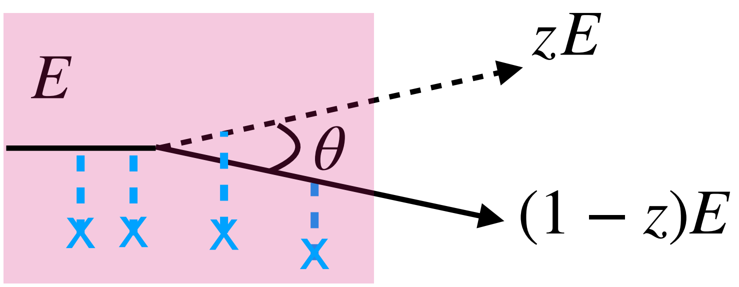


- **Two-point energy correlator** of a heavy-ion quark jet:

Proposed by CA, Dominguez, Elayavalli, Holguin, Marquet, Moult

$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta} = \frac{1}{\sigma_{qg}} \int \mathrm{d}z \, \frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}z\mathrm{d}\theta} \, z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

Energy correlators



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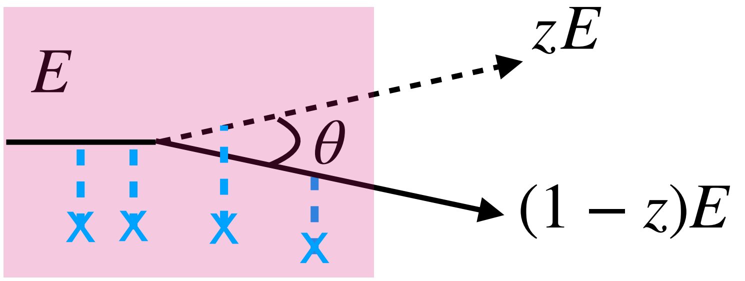
Inclusive

Energy correlators



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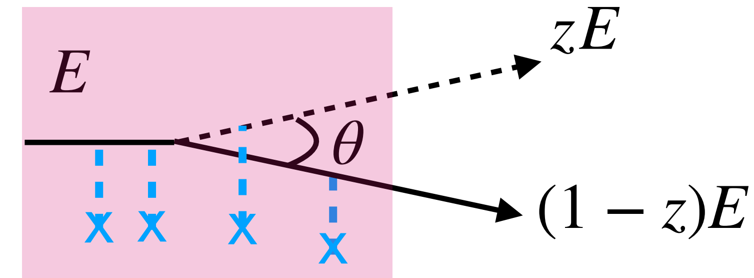
$$\frac{1}{\sigma_{qg}} \frac{d\sigma_{qg}^{\text{vac}}}{dz d\theta} = \frac{\alpha_s(\theta Q)}{\pi} C_F \frac{1+(1-z)^2}{z\theta} + \mathcal{O}\left(\alpha_s^2, \theta\right)$$

Inclusive medium-induced cross section differential in z and θ

Energy correlators



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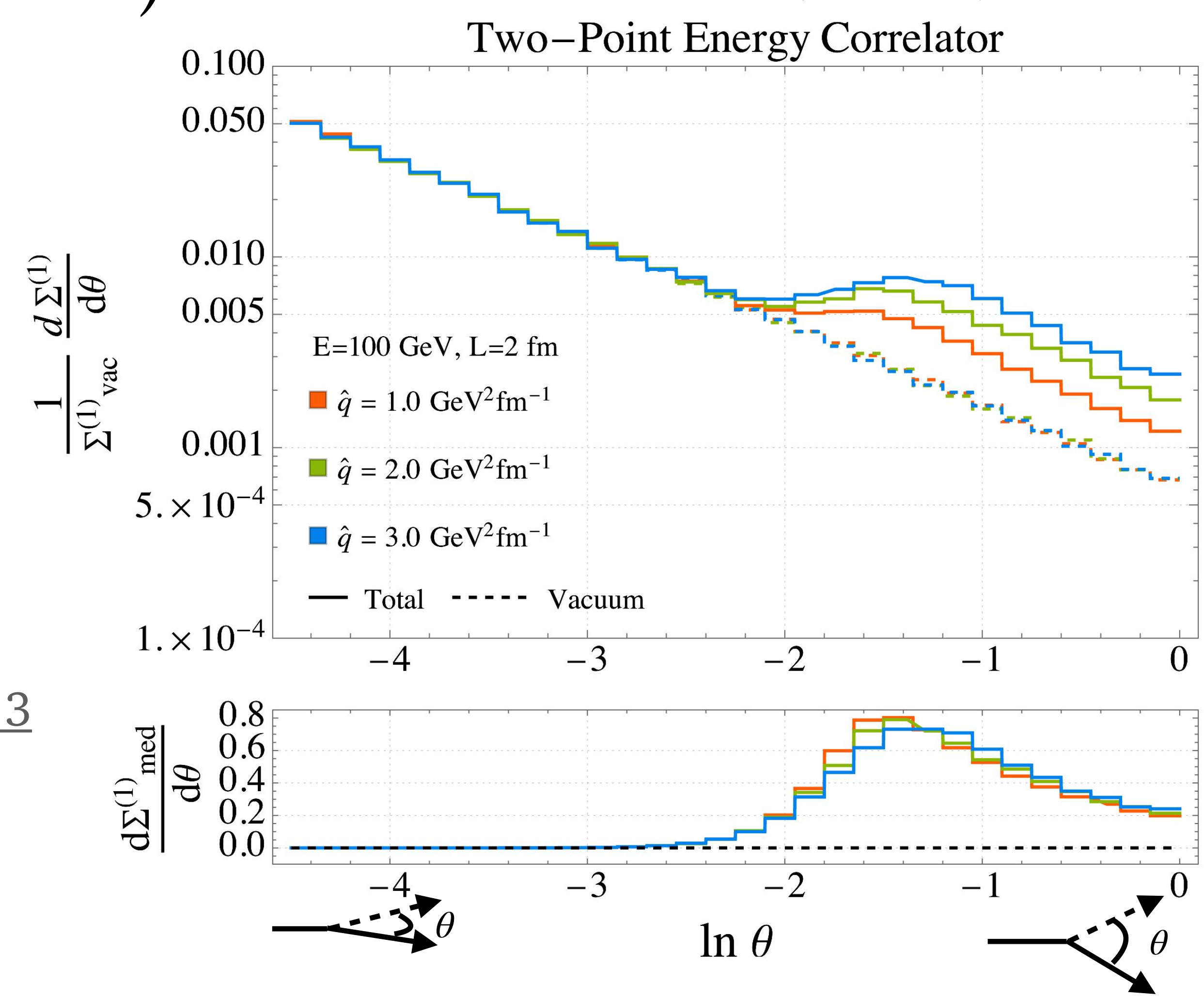


CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, 2209.11236

CA, Dominguez, Holguin, Marquet, Moult, 2303.03413

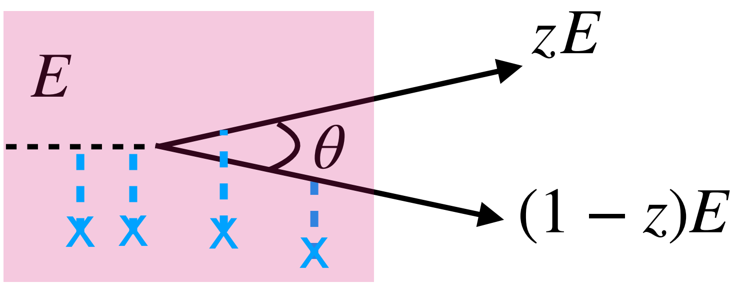
Dominguez's talk Wed 15:20

Holguin's talk Wed 11:50

Barata's talk Tues 12:10

Also experimental talks: Cruz-Torres for ALICE Tues 17:30, and Tamis for STAR Wed 11:30

Beyond the soft limit: $g \to c\bar{c}$



- **Not divergent** for $z \to 0$. Need to go beyond the soft limit

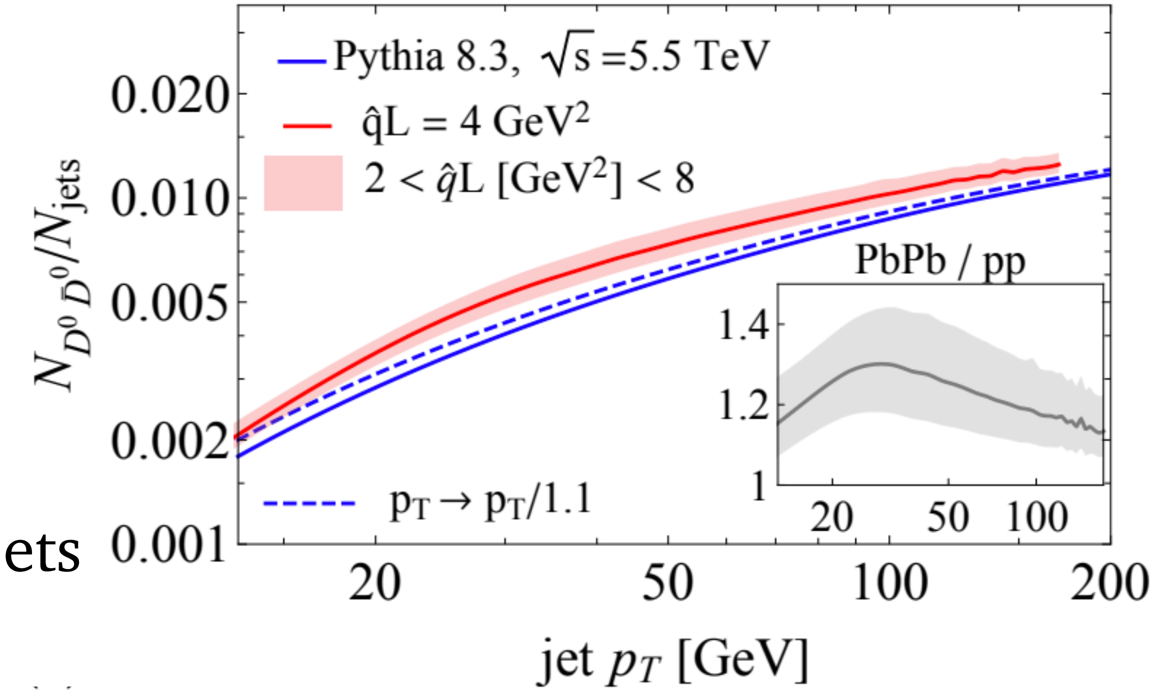
  Results with multiple scatterings but integrated in transverse momentum: Caron-Huot and Gale, 1006.2379

- **Keeping** both z and θ:
  - Opacity expansion results at $N = 1$ and $N = 2$ Sievert, Vitev, Yoon, 1903.06170
  - Results with **resummation of multiple scatterings** recently obtained in the large N_c limit and HO approximation

    (No need of the semi-hard approximation)

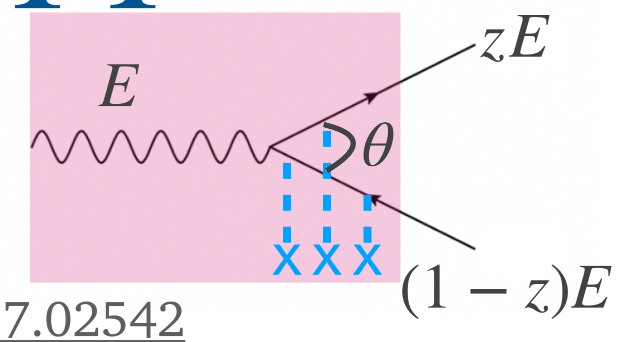
Attems, Brewer, Innocenti, Mazeliauskas, Park, van der Schee, Wiedemann, 2203.11241, 2209.13600

Brewer's talk Wed 12:10



Medium-enhanced production of $c\bar{c}$ pairs with jets

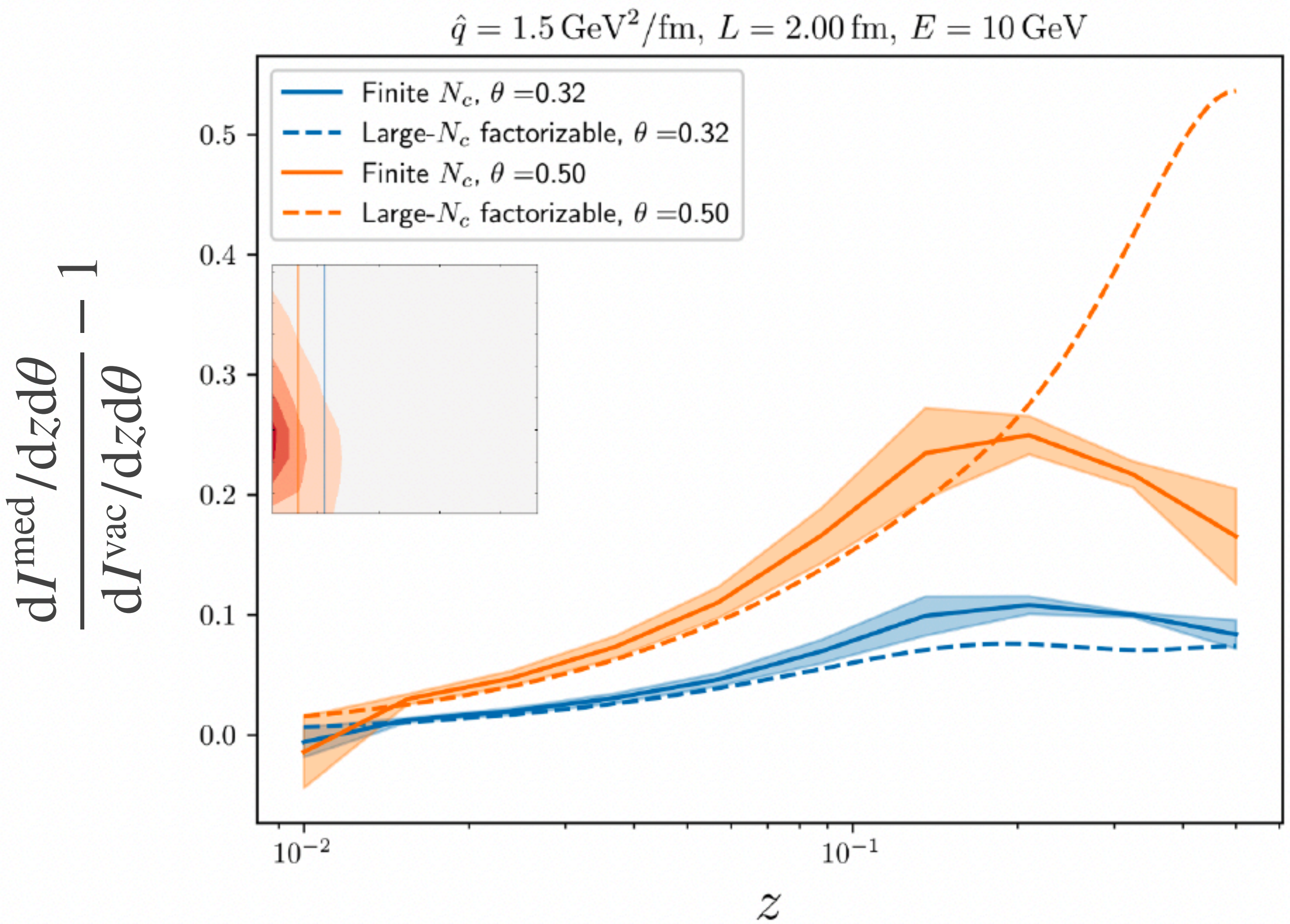
Beyond the soft limit: $\gamma \to q\bar{q}$



- Results with multiple scatterings in the ***semi-hard* approximation** available at large and finite N_c
  Dominguez, Milhano, Salgado, Tywoniuk, Vila, 1907.03653 Isaksen, Tywoniuk 2107.02542

- **Complete** (multiple scatterings) medium-induced emission spectrum **keeping** z and θ (Without using of the *semi-hard* approximation!!) Isaksen, Tywoniuk, 2303.12119
  (HO approximation)

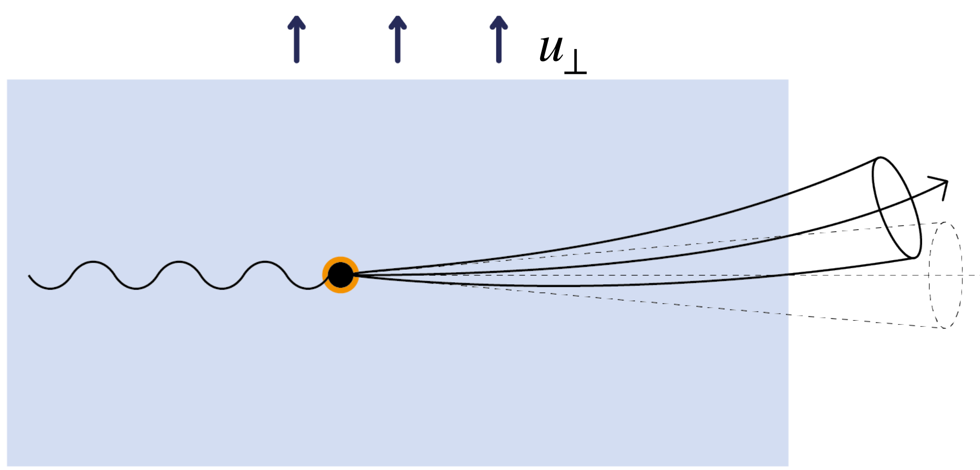
Isaksen's talk
Wed 14:40



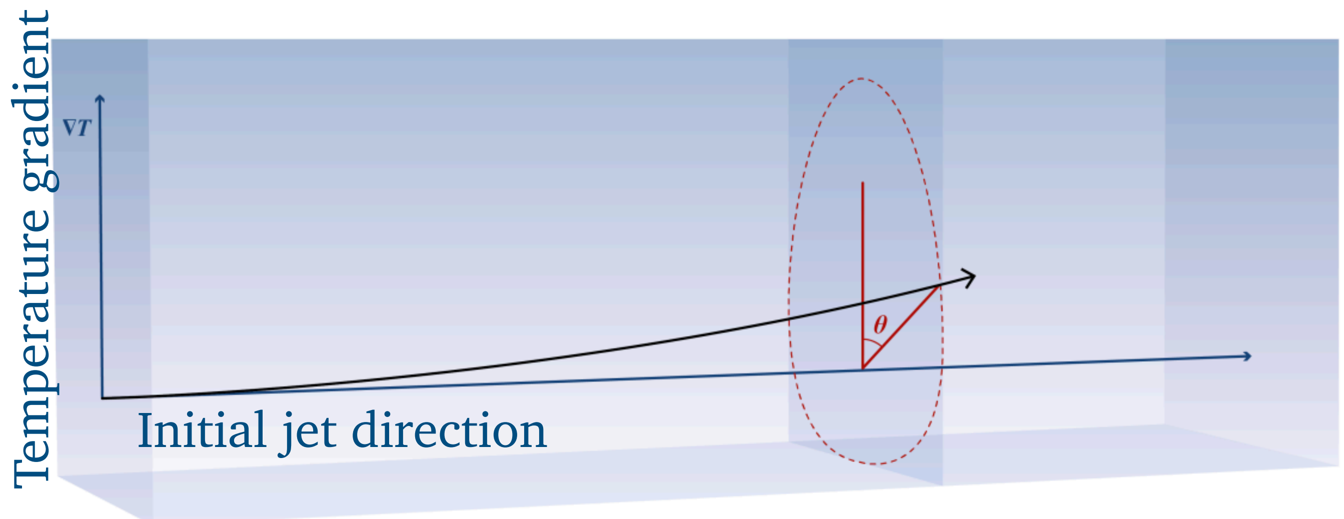
Isaksen, Tywoniuk, 2303.12119

Medium-induced radiation and transverse dynamics

- **Jets decouple** from the medium **transverse** dynamics in the **usual** (*eikonal*) **medium-induced approaches**



Uniform transverse flow



Transverse temperature gradients

- Need of **generalizing** the medium-induced formalisms to account for $\mathcal{O}(1/E)$ *(subeikonal)* terms

- **GLV emission spectrum** (and broadening) obtained: Sadofyev, Sievert, Vitev, 2104.09513
  - for transversely **flowing** matter
  - for transversely **inhomogeneous** matter

Sadofyev's talk
Wed 10:00

Medium-induced radiation and transverse dynamics

- **Broadening** with **multiple scatterings** obtained:
  - for transversely **flowing** matter CA, Dominguez, Sadofyev, Salgado, 2207.07141
  - for transversely **inhomogeneous** matter Barata, Sadofyev, Salgado, 2202.08847; Fu, Casalderrey-Solana, Wang, 2204.05323

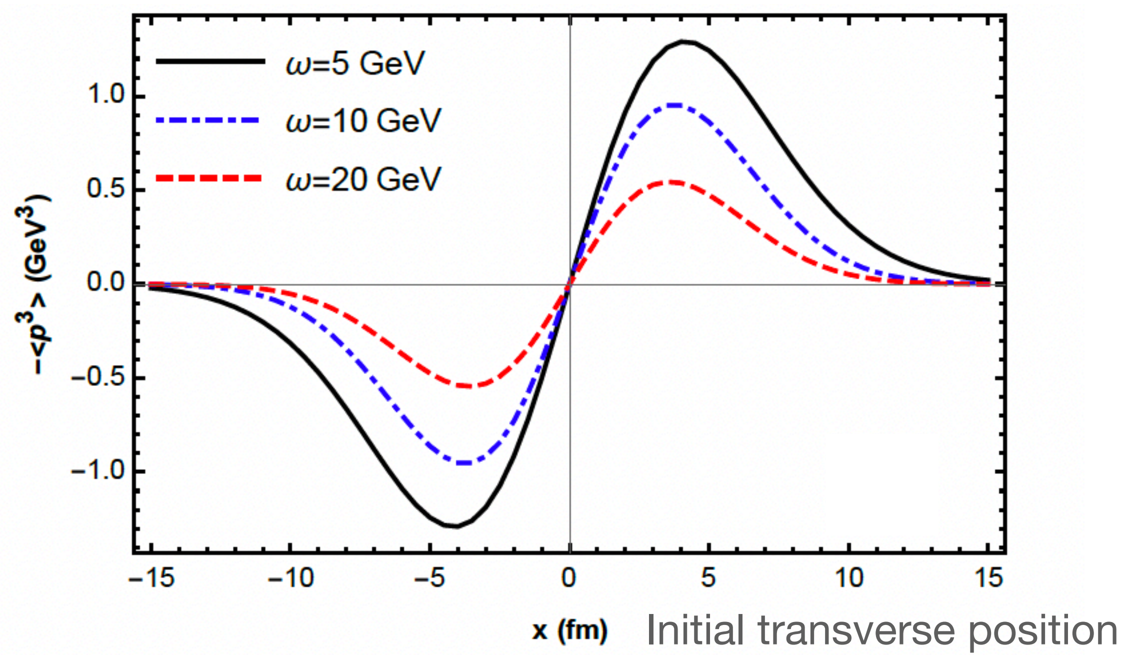
Sadofyev's talk Wed 10:00

See also Barata, Sadofyev, Wang 2210.06519

See also Mayo López's poster

Transverse inhomogeneities

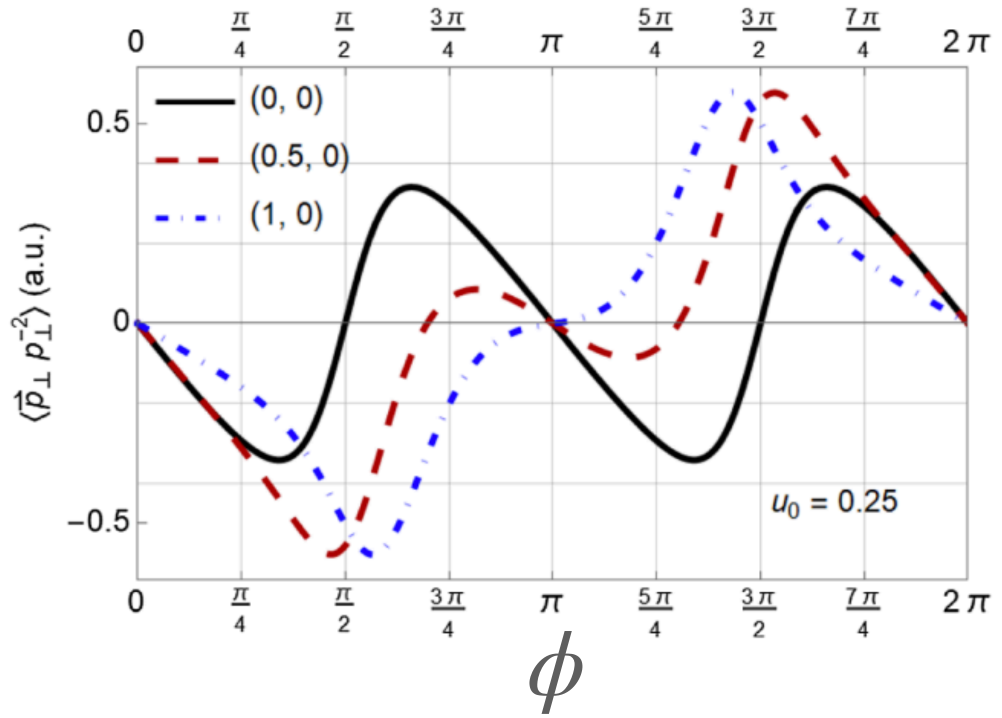
Fu, Casalderrey-Solana, Wang, 2204.05323



Xin-Nian Wang's talk Tue 10:00

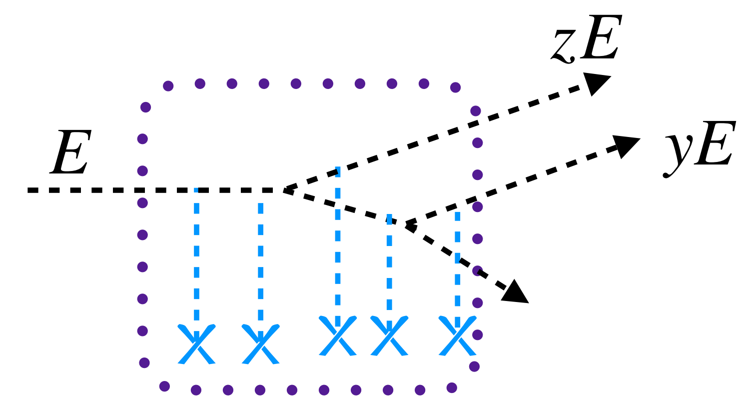
Transverse flow (single scattering)

Antiporda, Bahder, Rahman, Sievert, 2110.03590



Multiple splittings

- **Overlapping effects** among **multiple splittings?**

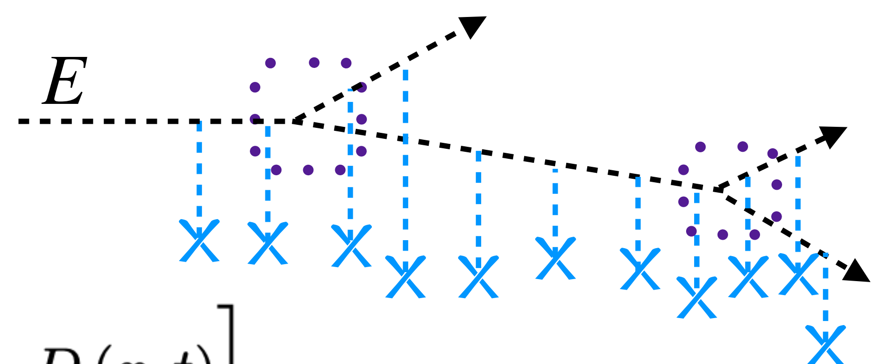


Extremely hard calculation performed for $g \rightarrow ggg$
(on-shell emitter, infinite, static medium, large N_c, HO)

Seems to be a **small effect for gluon showers**. **Parton showers** seem to be **safe**!

Arnold, Iqbal, Chang, Gorda, Rase, Elgeadwy (2015-2022) 2212.08086, 2302.10215

- **Independent medium-induced splittings**



Jeon, Moore (2003) Blaizot, Dominguez, Iancu, Mehtar-Tani (2014)

$$\frac{\partial}{\partial t}D(x,t) = \frac{1}{t_*}\int \mathrm{d}z\,\mathcal{K}(z)\left[\sqrt{\frac{z}{x}}D\left(\frac{x}{z},t\right) - \frac{z}{\sqrt{x}}D\left(x,t\right)\right]$$ **BDIM**

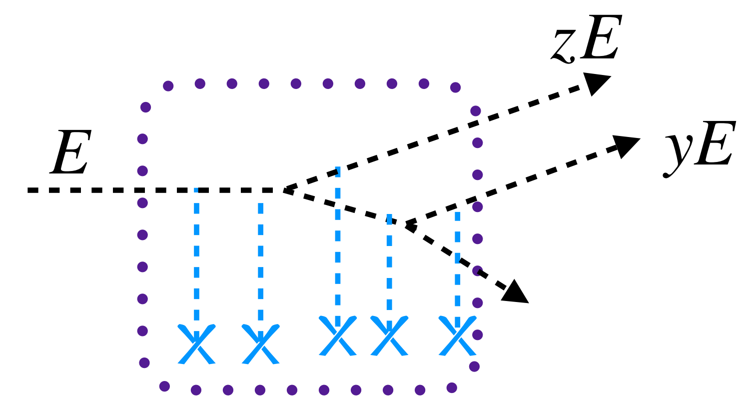
$$t_* = \alpha\sqrt{\frac{E}{\hat{q}}}$$

$$\frac{\partial}{\partial t}D(x,\boldsymbol{k},t) = \frac{1}{t_*}\int \mathrm{d}z\,\mathcal{K}(z)\left[\frac{1}{z^2}\sqrt{\frac{z}{x}}D\left(\frac{x}{z},\frac{\boldsymbol{k}}{z},t\right) - \frac{z}{\sqrt{x}}D\left(x,\boldsymbol{k},t\right)\right] + \int_{\boldsymbol{q}}\mathcal{C}(\boldsymbol{q})D(x,\boldsymbol{k}-\boldsymbol{q},t)$$

*Neglecting any momentum transfer during the formation time of the splittings

Multiple splittings

- **Overlapping effects** among **multiple splittings?**



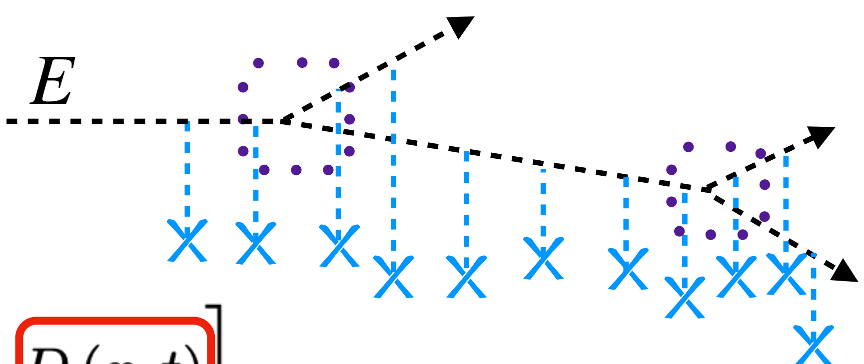
Extremely hard calculation performed for $g \to ggg$
(on-shell emitter, infinite, static medium, large N_c, HO)

Seems to be a **small effect for gluon showers**. **Parton showers** seem to be **safe**!

Arnold, Iqbal, Chang, Gorda, Rase, Elgeadwy (2015-2022) 2212.08086, 2302.10215

- **Independent medium-induced splittings**

Jeon, Moore (2003) Blaizot, Dominguez, Iancu, Mehtar-Tani (2014)



$$\frac{\partial}{\partial t} D(x,t) = \frac{1}{t_*} \int \mathrm{d}z\, \mathcal{K}(z) \left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z}, t\right) - \frac{z}{\sqrt{x}} D(x,t) \right]$$ **BDIM**

Inclusive gluon distribution — Gain term — Loss term

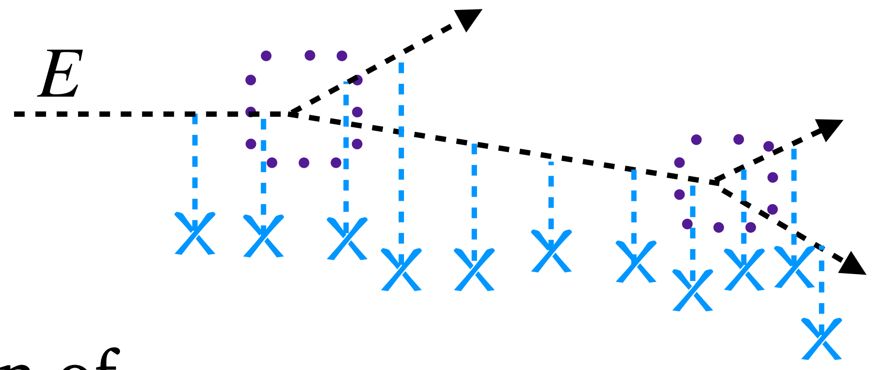
$t_* = \alpha \sqrt{\frac{E}{\hat{q}}}$

Broadening

$$\frac{\partial}{\partial t} D(x, \boldsymbol{k}, t) = \frac{1}{t_*} \int \mathrm{d}z\, \mathcal{K}(z) \left[\frac{1}{z^2} \sqrt{\frac{z}{x}} D\left(\frac{x}{z}, \frac{\boldsymbol{k}}{z}, t\right) - \frac{z}{\sqrt{x}} D(x, \boldsymbol{k}, t) \right] + \int_{\boldsymbol{q}} \mathcal{C}(\boldsymbol{q}) D(x, \boldsymbol{k} - \boldsymbol{q}, t)$$

*Neglecting any momentum transfer during the formation time of the splittings

Multiple splittings



- Generalization of BDMI to account for the transmission of **polarization** in an **anisotropic** medium (Static medium, HO, $\hat{q}$ constant but $\hat{q}_y \neq \hat{q}_z$)

  Polarization is found to be created and washed out at each step of the branching

  Hauksson, Iancu 2303.03914

- **Energy** and **angular profile** of the **medium-induced** cascade
  - **Kinetic theory** approach: linearized Boltzmann equation (Static medium, AMY radiation rates)

    Energy distribution: Soudi, Schlichting 2008.04928

    Angular distribution: Mehtar-Tani, Soudi, Schlichting, 2209.10569

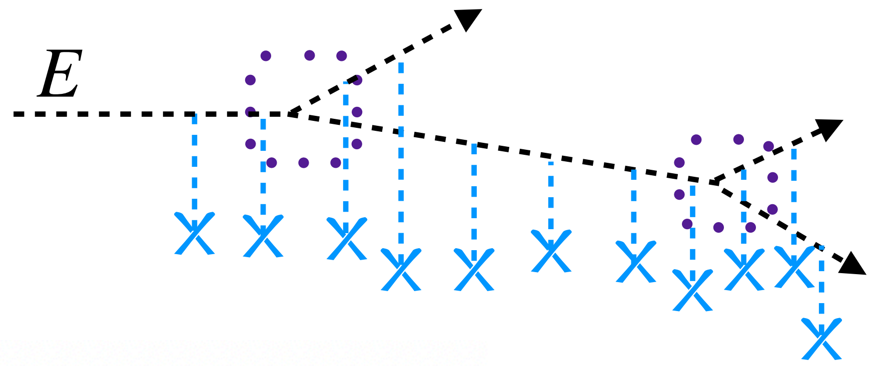
  - Solving **BDMI** equations for **longitudinally expanding media** (HO)

    Energy distribution: Adhya, Spousta, Salgado, Tywoniuk, 2106.02592

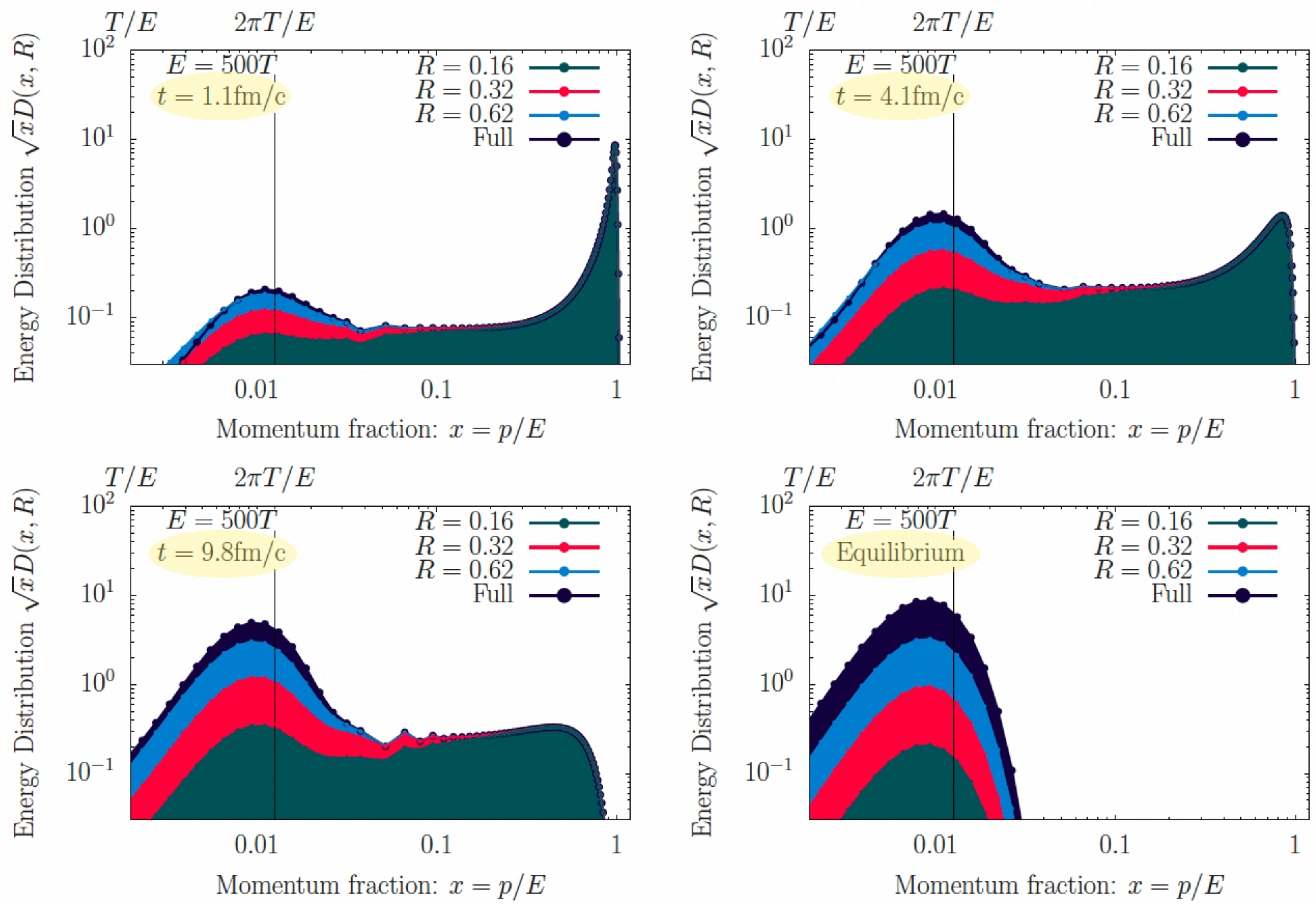
    Angular distribution: Adhya, Kutak, laczek, Rohrmoser, Tywoniuk, 2211.15803

    Adhya's poster

Multiple splittings



Mehtar-Tani, Soudi, Schlichting, 2209.10569



Out-of-cone energy loss via **medium-induced radiation**, followed by **elastic scatterings** of soft fragments pushing the distribution to **large angles** and thermalization

Jet quenching in the initial stages?

- **Jet quenching** is the only QGP signature **not** (yet?) **observed** in **small systems**
- In small systems the **initial stages** (IS) are specially important

Understanding jet quenching in the initial stages becomes crucial!

- Usually, jet quenching analyses neglect energy loss in the IS, but some observables have been found sensitive to the IS

  CA, Armesto, Niemi, Paatelainen, Salgado, arXiv:1902.03231

  Stojku, Auvinen, Djordjevic, Huovinenm, Djordjevic, arXiv:2008.08987

  Gonzalez-Martinez's Wed 14:20

- Many new developments in the computation of the **broadening in the pre-hydro stages**
  - In the Glasma phase: Ipp, Müller, Schuh, arXiv:2001.10001, arXiv:2009.14206

    Carrington, Czajka, Mrówczynski, arXiv:2112.06812, arXiv:2202.00357

    Avramescu, Baran, Greco, Ipp, Müller, Ruggieri, 2303.05599 Avramescu's talk Tues 12:10
  - Between the Glasma and hydro phases with Kinetic theory

    Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron, 2303.12595

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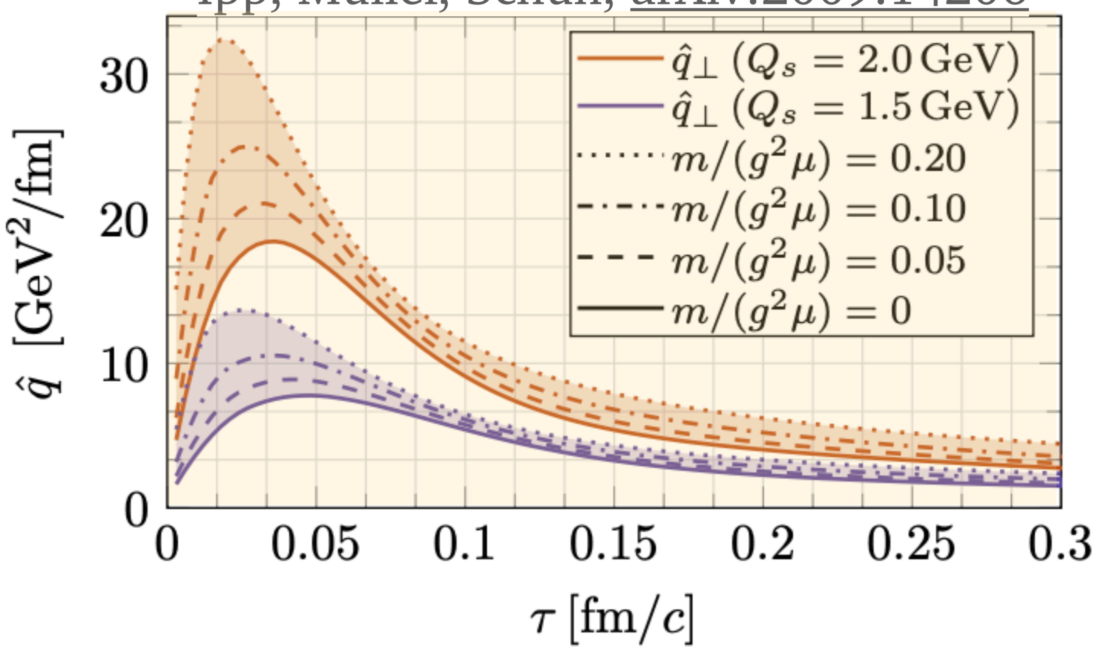
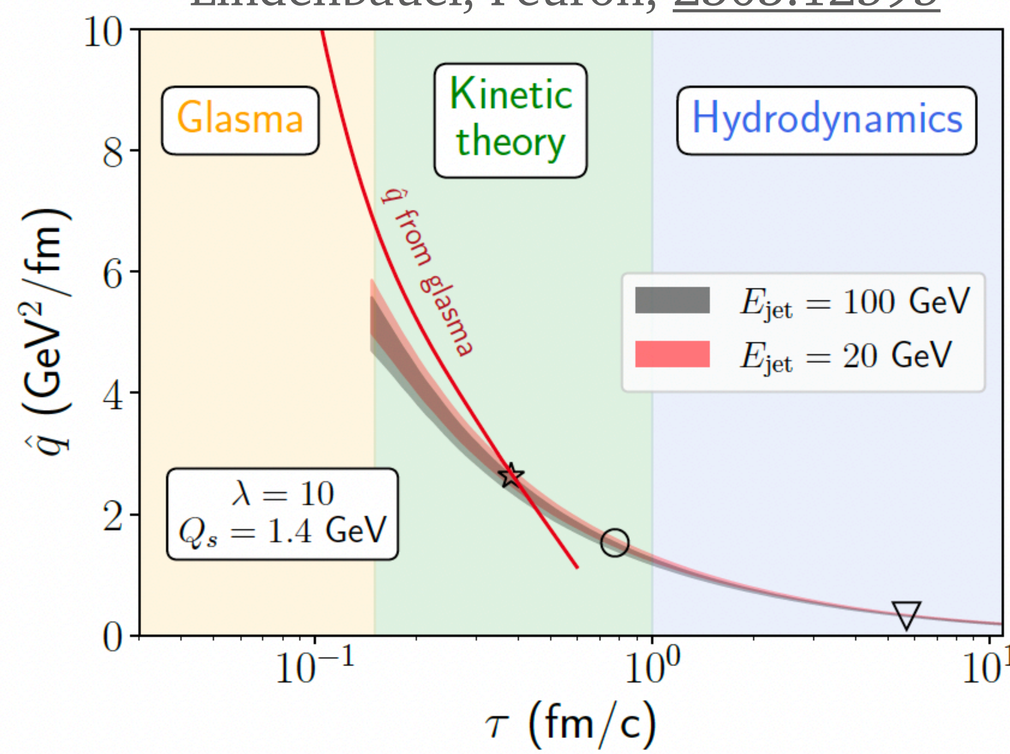
Glasma
Ipp, Müller, Schuh, arXiv:2009.14206



Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron, 2303.12595



$\hat{q}$ relatively large!

Summary

- Many new developments in the theory of **medium-induced radiation**
    - **Improved analytical** approximations and **numerical solutions** for the emission spectrum in the soft limit ($z \ll 1$)
    - **Non-perturbative** determination of the potential (broadening kernel)
    - Results **beyond the soft limit keeping the angle**:
        - Opacity expansion
        - Semi-hard approximation for multiple scatterings
        - **First complete** results with **multiple scatterings**
    - Calculations coupling the jet to the **medium's transverse dynamics**
- **Overlapping effects** between multiple emissions in gluon showers found to be **small** (with caveats)
- Calculations of the **broadening** in the **pre-hydrodynamics** stages

Thank you!

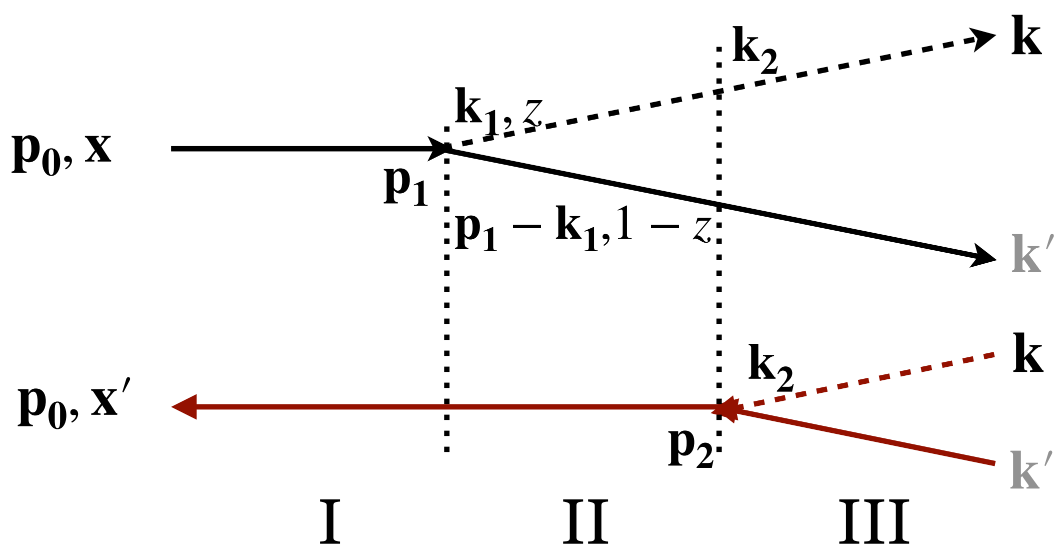
Beyond the soft approximation

- The emitted gluon carries a fraction of energy z of the energy of the parent quark

$$z\frac{dI}{dzd^2\boldsymbol{k}} = \frac{\alpha_s P_{g\leftarrow q}(z)}{(2\pi)^2 z(1-z)^2E^2}\,\mathrm{Re}\int_0^\infty dt' \int_0^{t'} dt \int_{\boldsymbol{p}_1\boldsymbol{p}_2\boldsymbol{k}_1\boldsymbol{k}_2} \mathcal{P}_q(t,\boldsymbol{p}_1;0,\boldsymbol{p}_0)$$
$$\times\,(\boldsymbol{k}_1 - z\boldsymbol{p}_1)\cdot(\boldsymbol{k}_2 - z\boldsymbol{p}_2)\;\widetilde{\mathcal{K}}^{(3)}(t',\boldsymbol{k}_2 - z\boldsymbol{p}_2; t, \boldsymbol{k}_1 - z\boldsymbol{p}_1; \boldsymbol{p}_2 - \boldsymbol{p}_1)$$
$$\times\,\mathcal{P}_g(\infty,\boldsymbol{k};t',\boldsymbol{k}_2)$$

Blaizot, Dominguez, Iancu, Mehtar-Tani arXiv:1209.4585

Apolinario, Armesto, Milhano, Salgado arXiv:1407.0599



Beyond the soft approximation

- The emitted gluon carries a fraction of energy z of the energy of the parent quark

$$z\frac{dI}{dzd^2\boldsymbol{k}} = \frac{\alpha_s P_{g\leftarrow q}(z)}{(2\pi)^2 z(1-z)^2E^2}\,\mathrm{Re}\int_0^\infty dt'\int_0^{t'}dt\int_{\boldsymbol{p}_1\boldsymbol{p}_2\boldsymbol{k}_1\boldsymbol{k}_2}\mathcal{P}_q(t,\boldsymbol{p}_1;0,\boldsymbol{p}_0)$$
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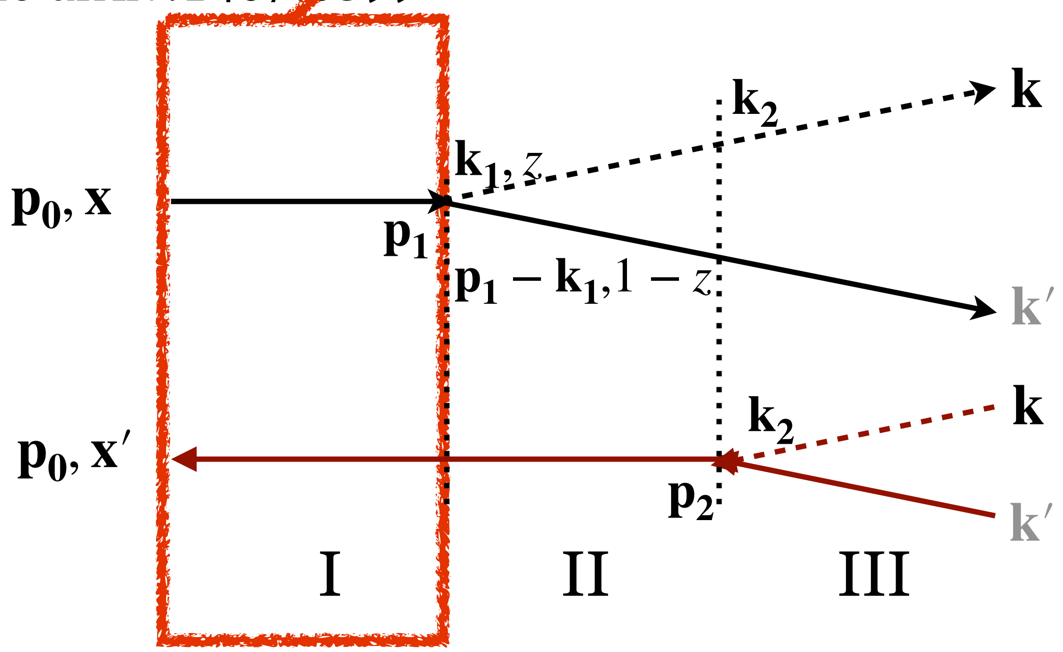

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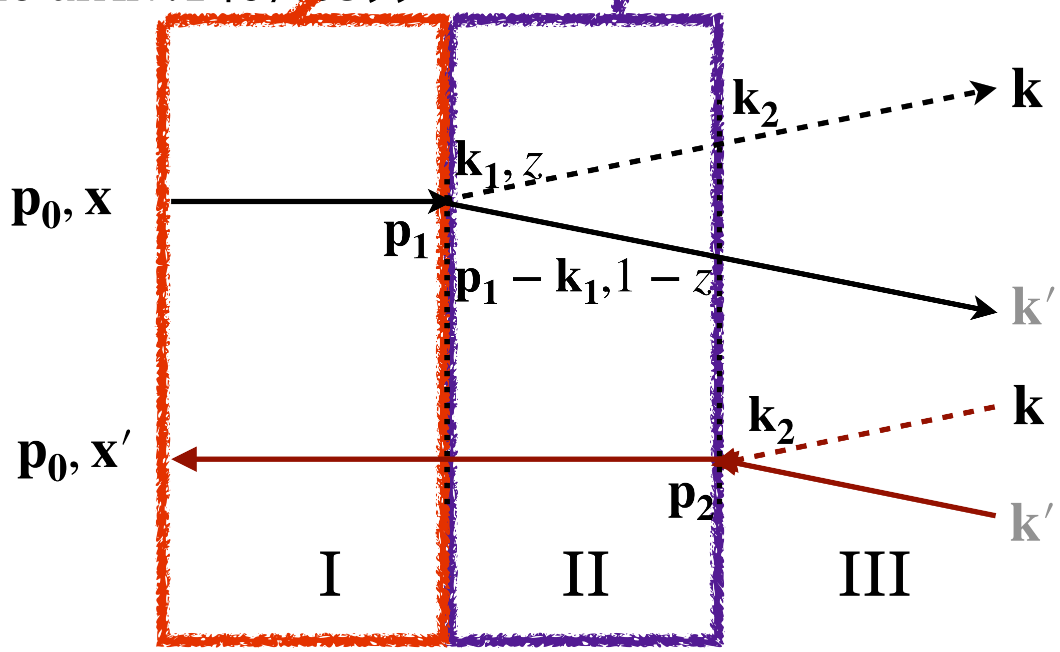

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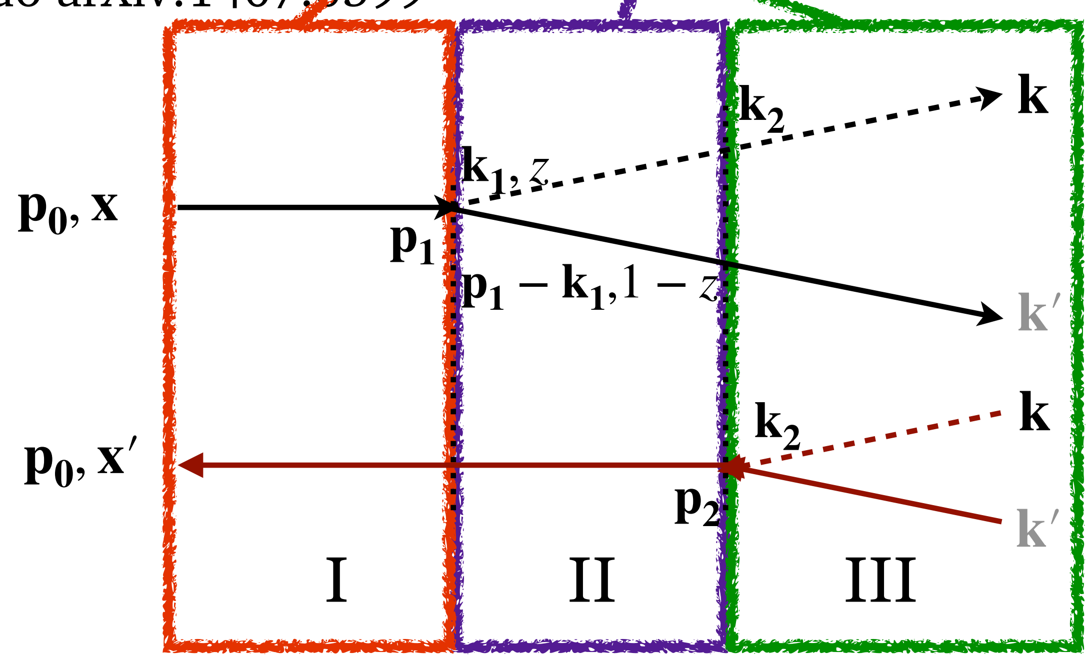
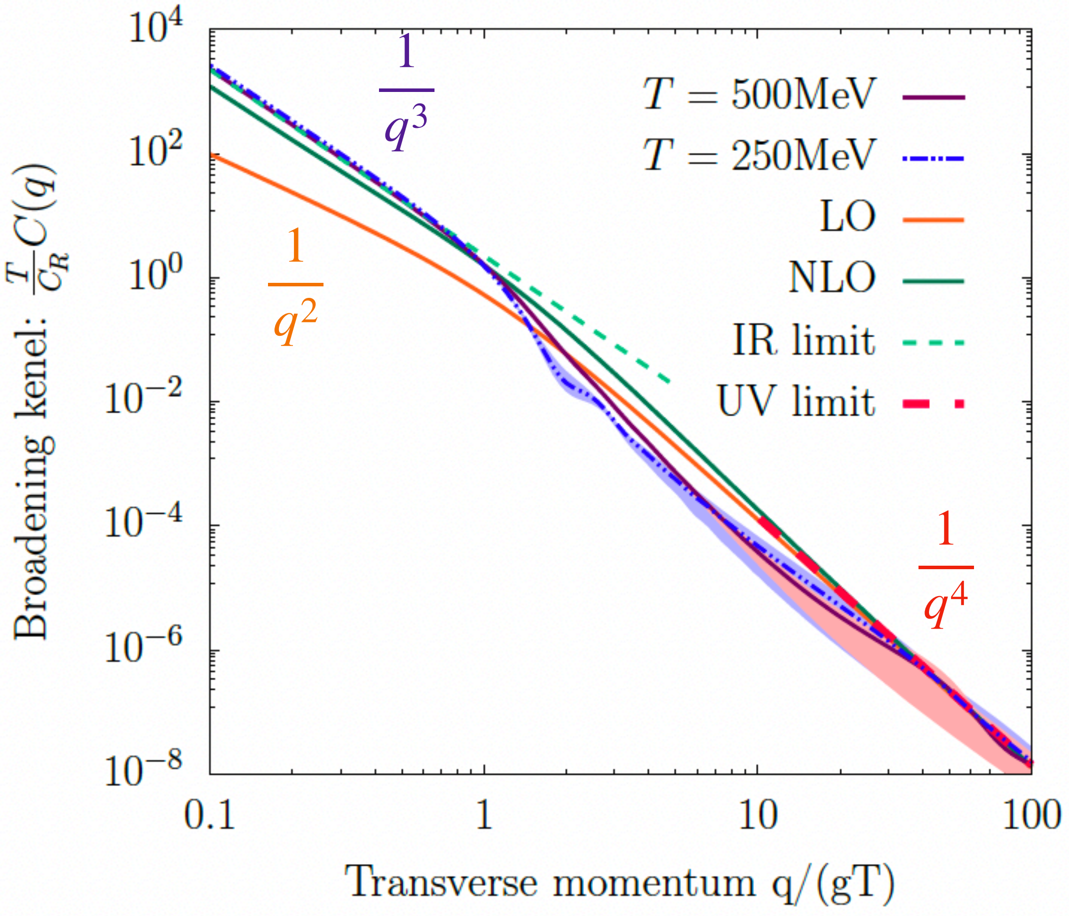
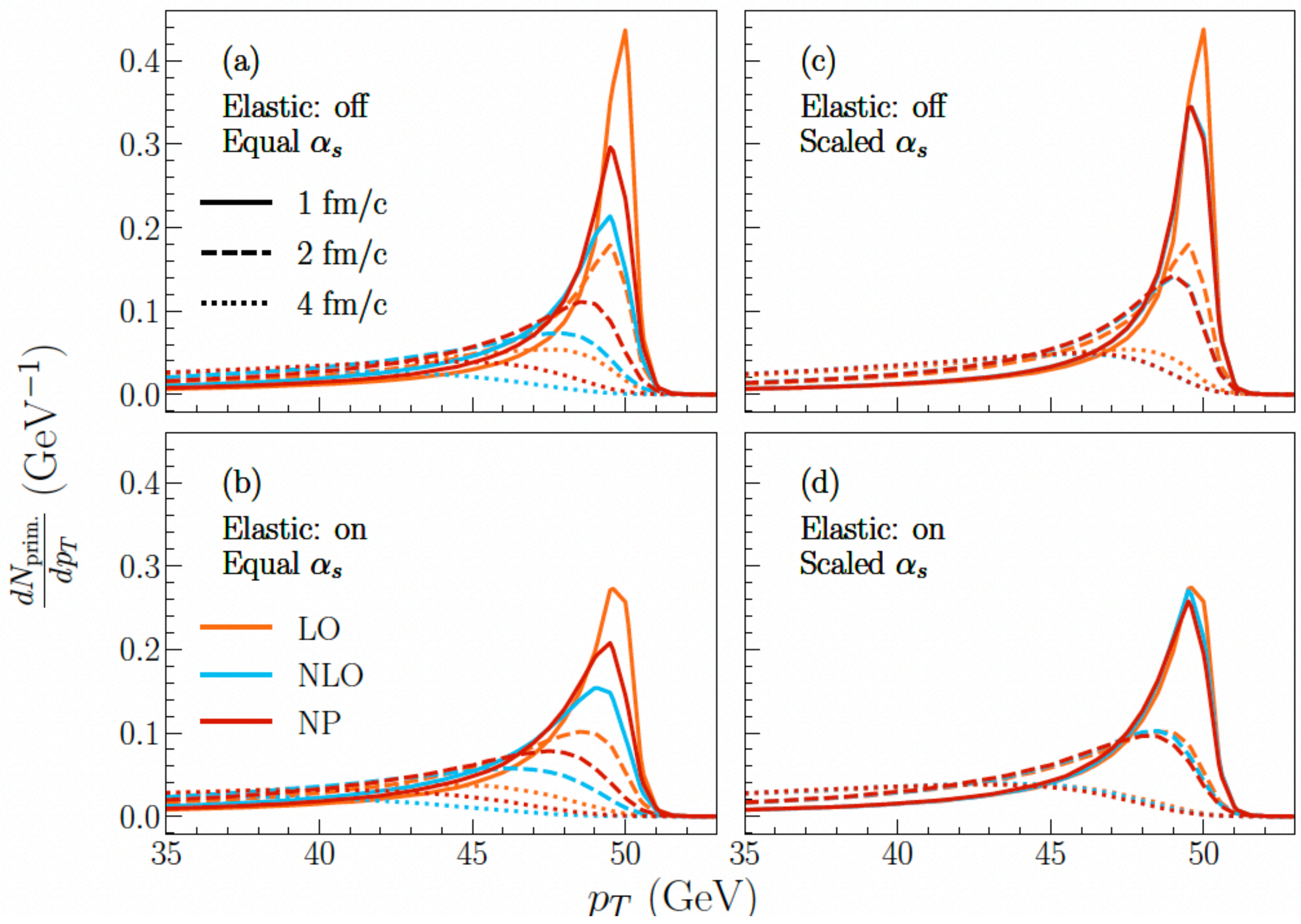


Non-perturbative potential



Schlichting, Soudi 2111.13731

$E = 50\,\text{GeV}, T = 300\,\text{MeV}$



Yazdi, Shi, Jeon, Gale, 2206.05855