TRONDMOHN FOUNDATION

UNIVERSITY OF BERGEN

The role of vacuum-like and medium-induced emissions in jet quenching

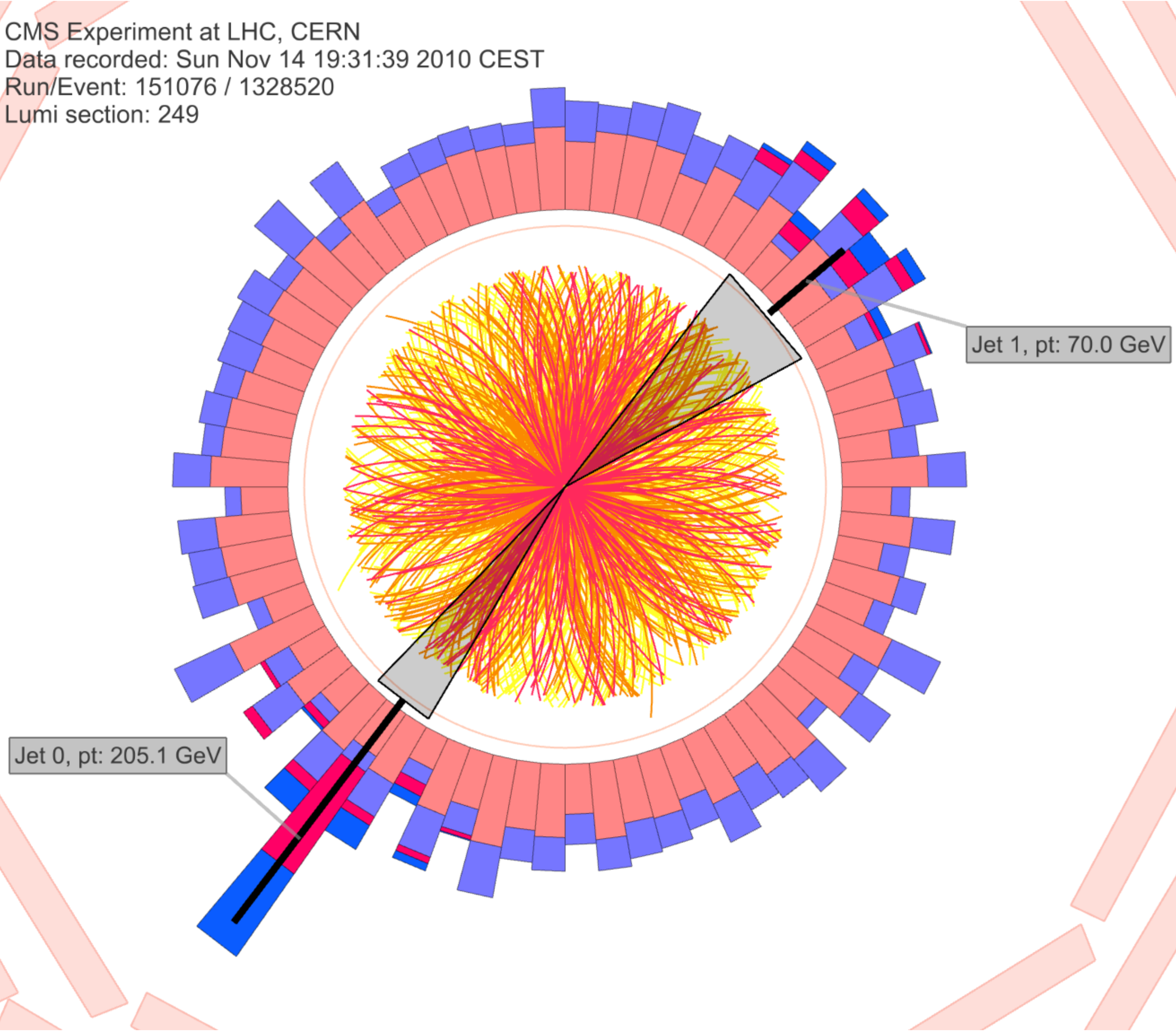
Konrad Tywoniuk

CFNS Workshop: Jet Physics: From RHIC/LHC to EIC, 29 June 2022 to 1 July 2022

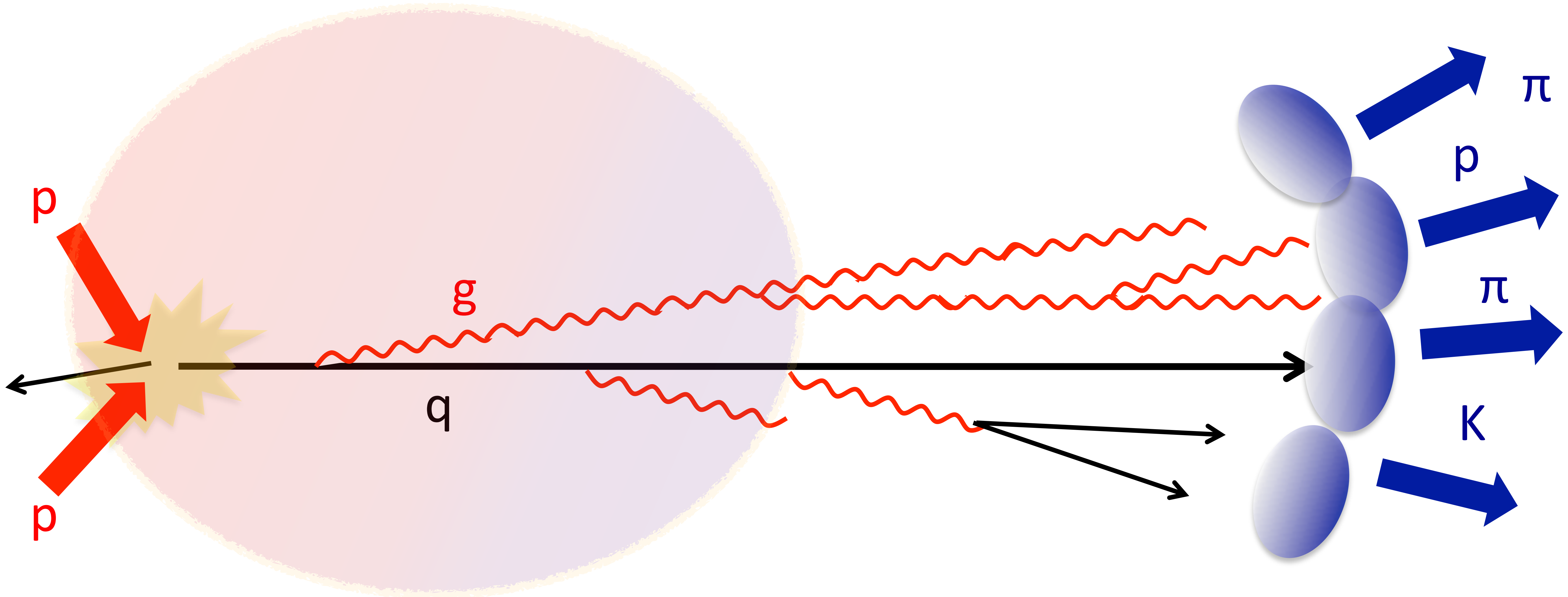
Jets in medium

Spacetime structure of QCD jets.

Sensitivity to properties of the quark-gluon plasma.



JET EVOLUTION IN THE MEDIUM



- Hard probes are processes occurring at higher energies and at shorter times than what is achievable in the QGP.
  - Includes production of heavy quarks, jets, heavy bosons etc.
- The "long distance" fragmentation of the jet takes place on similar timescales as the lifetime of the QGP.
- Sensitivity to jet transport parameter $\hat{q}$ (≈medium density + quantum corrections)

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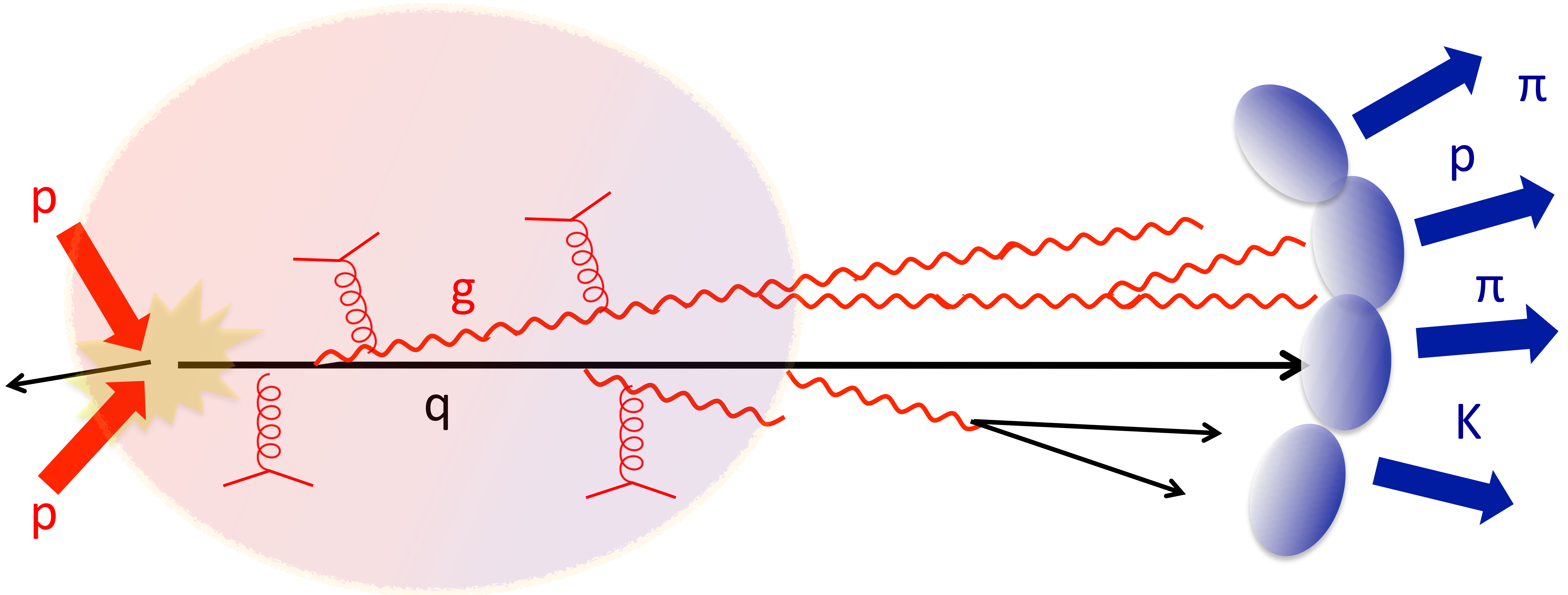

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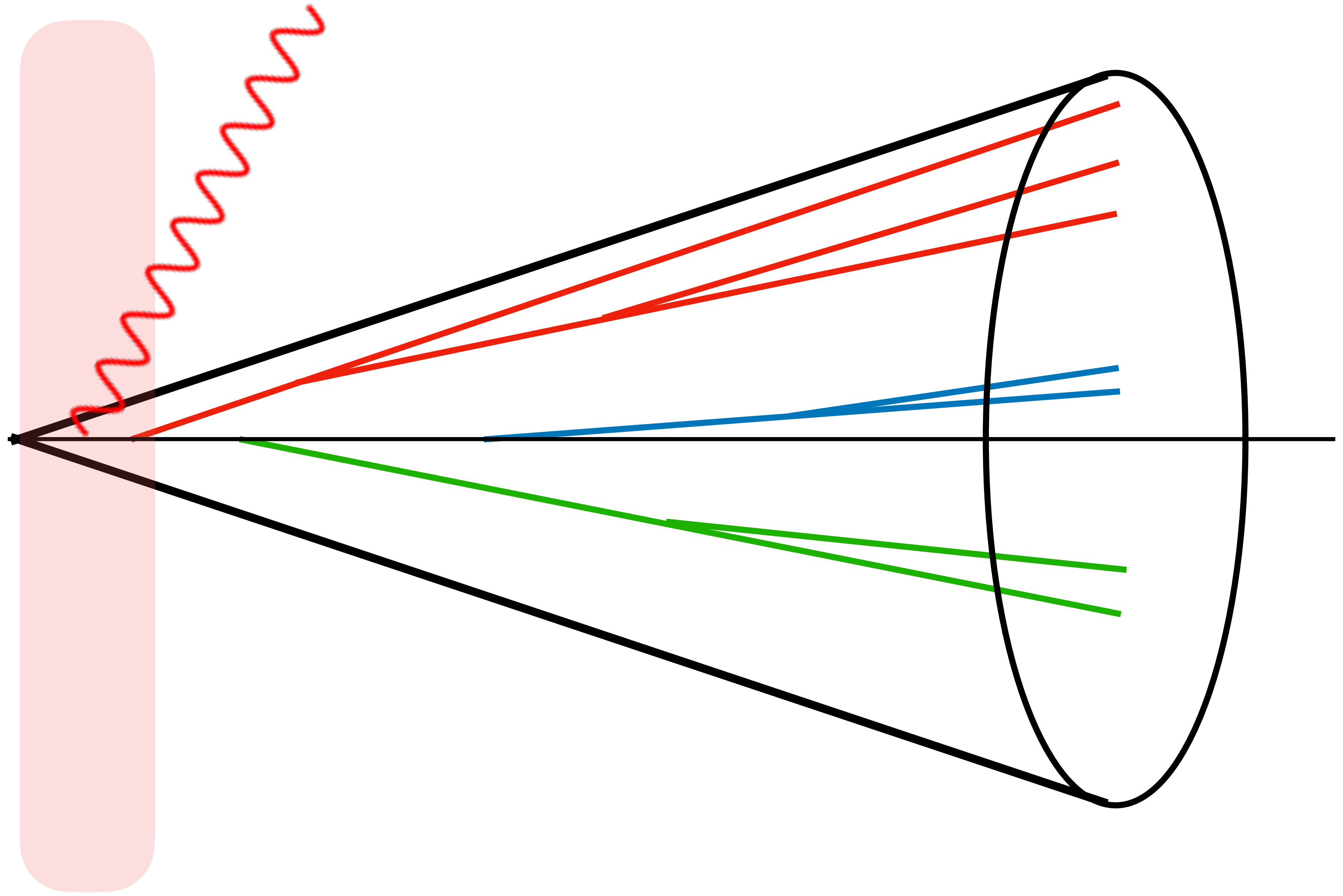
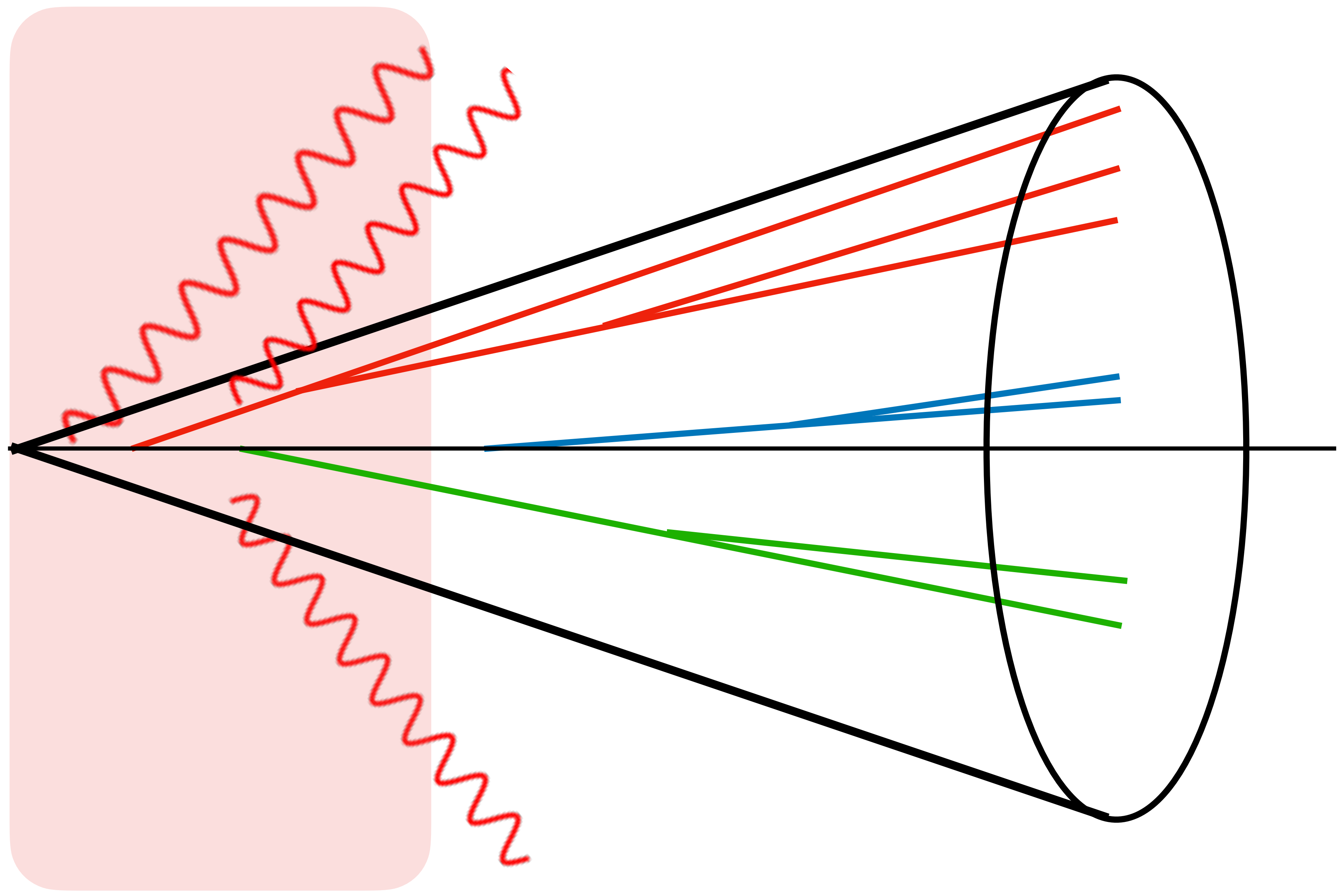
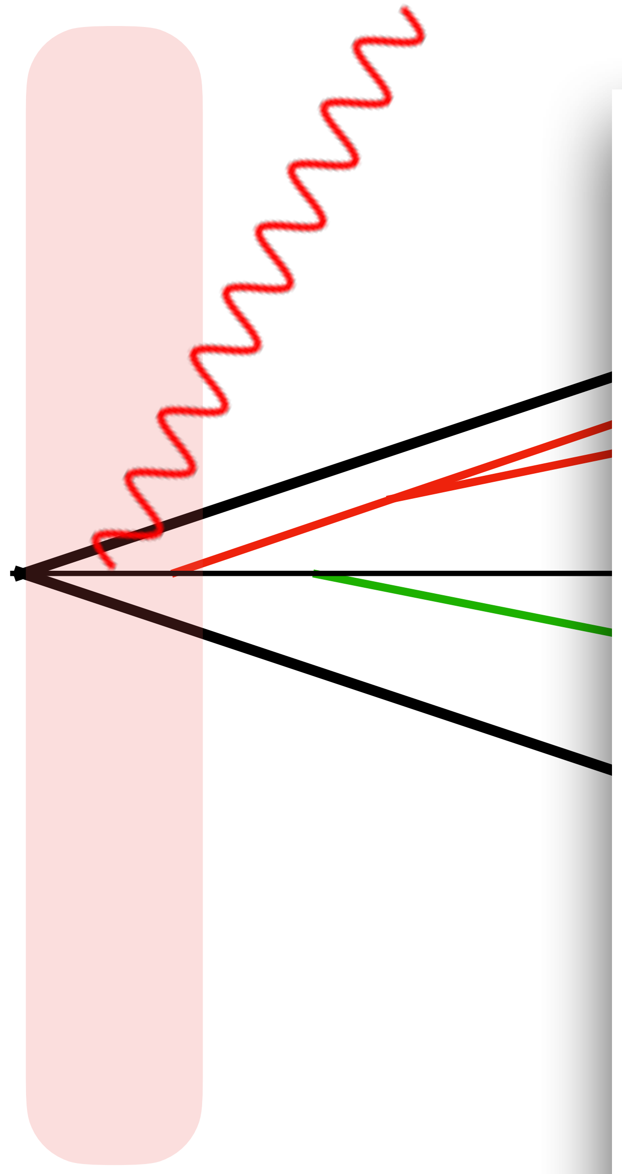
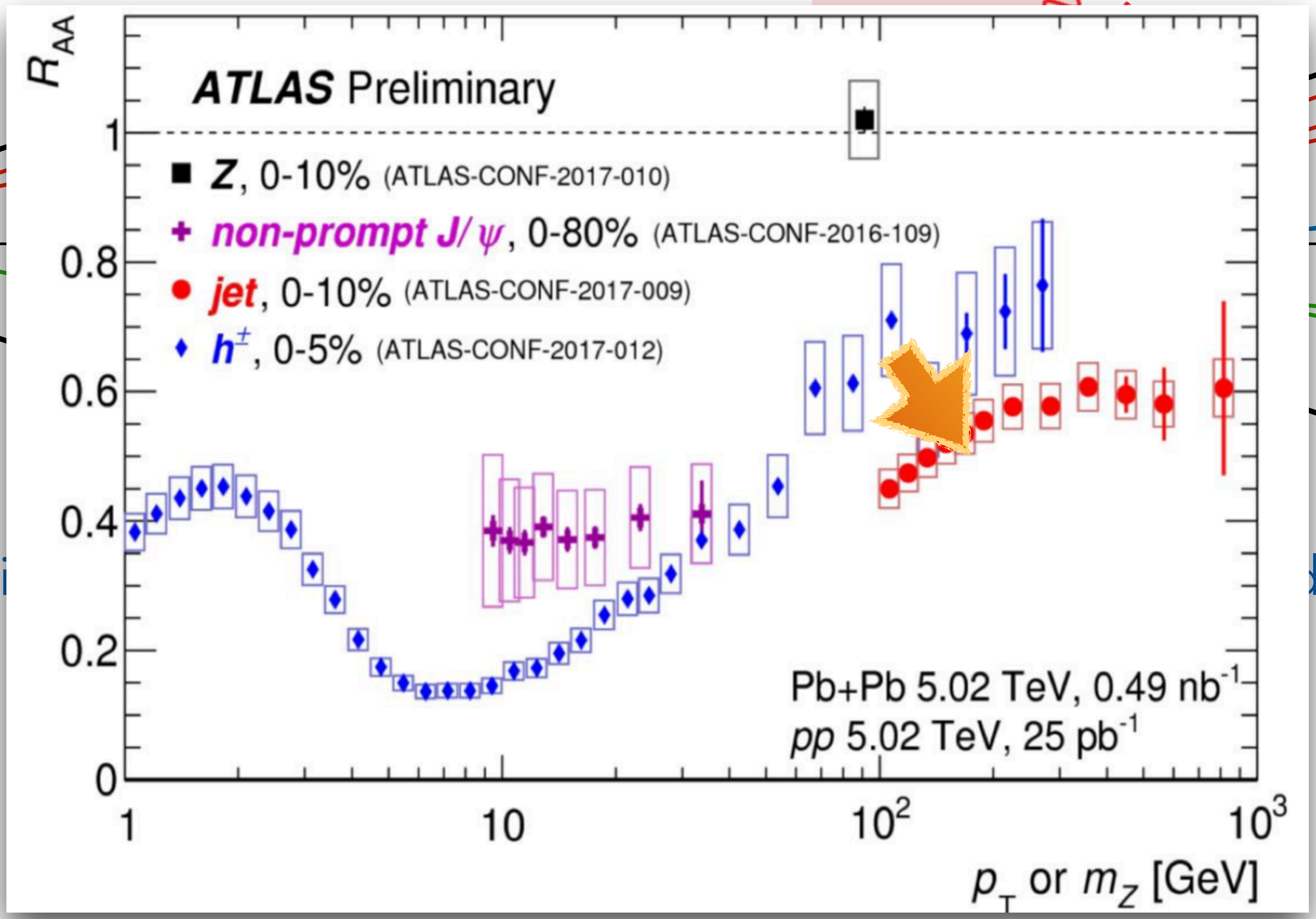


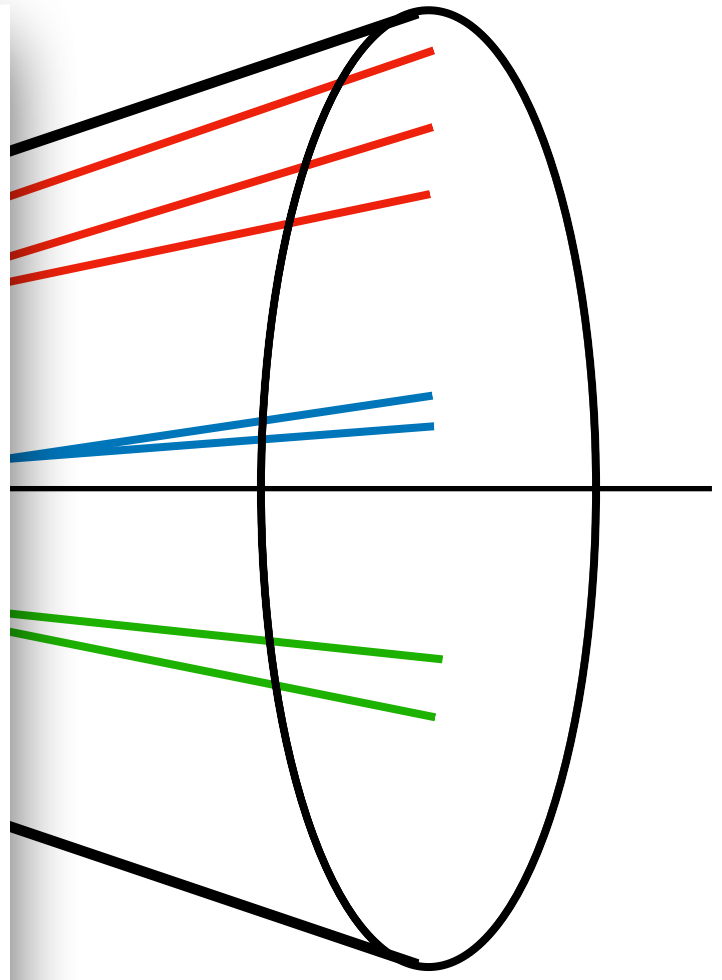
1 emitter (coherence)



n emitters (partial decoherence)



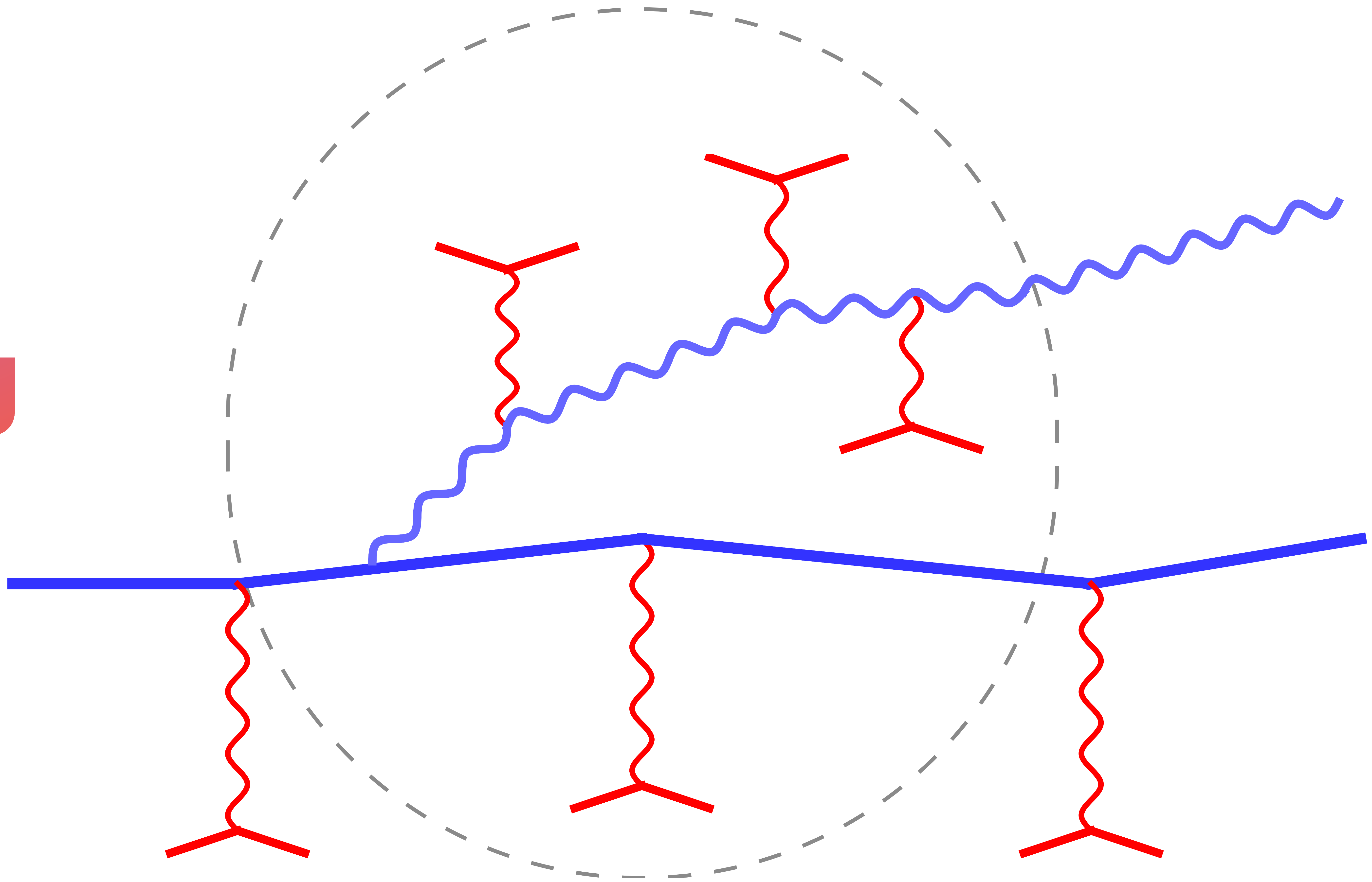




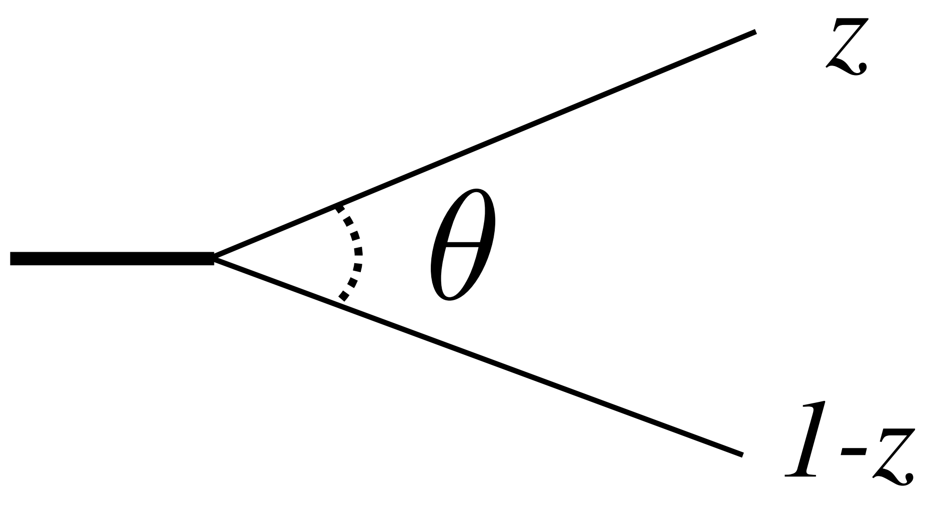
1 emi … decoherence)

1→2 parton splitting

Vacuum-like & medium-induced gluon radiation



PARTON SPLITTING IN VACUUM



Generic 1→2 splitting in QCD:

$$\mathrm{d}\Pi_{a\to bc} = \frac{\alpha_s}{\pi}\frac{\mathrm{d}\theta}{\theta} P_{ba}^{(c)}(z)\mathrm{d}z \approx \frac{2\alpha_s C_R}{\pi}\frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}z}{z}$$

Diverges for soft & collinear radiation!

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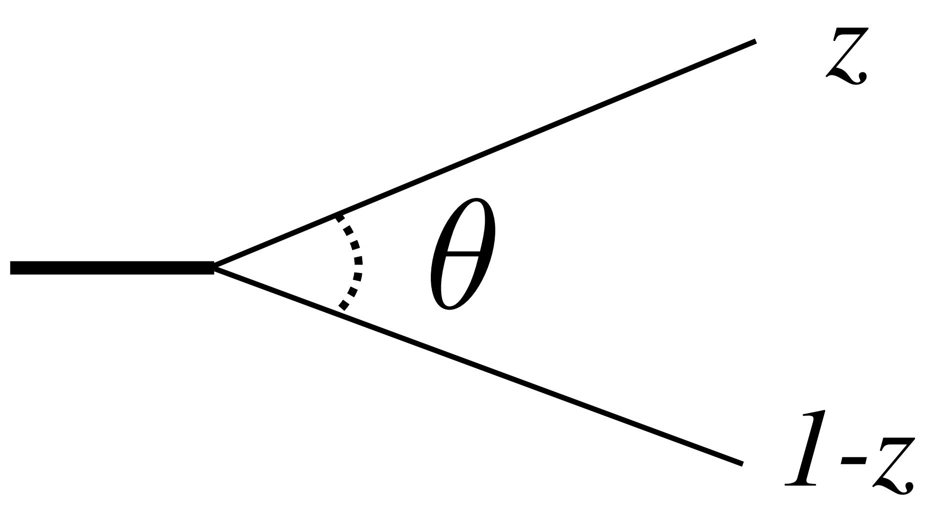

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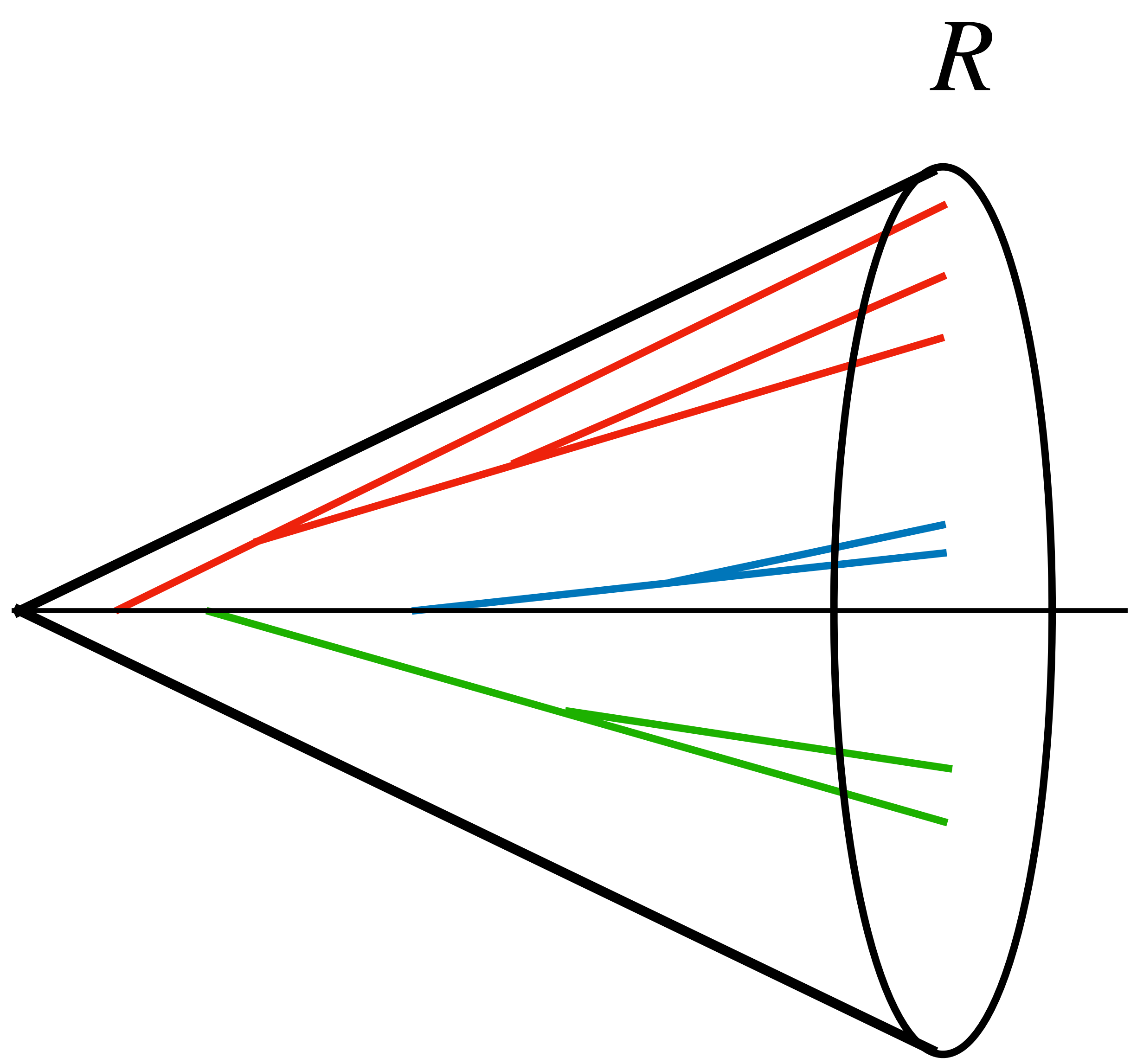


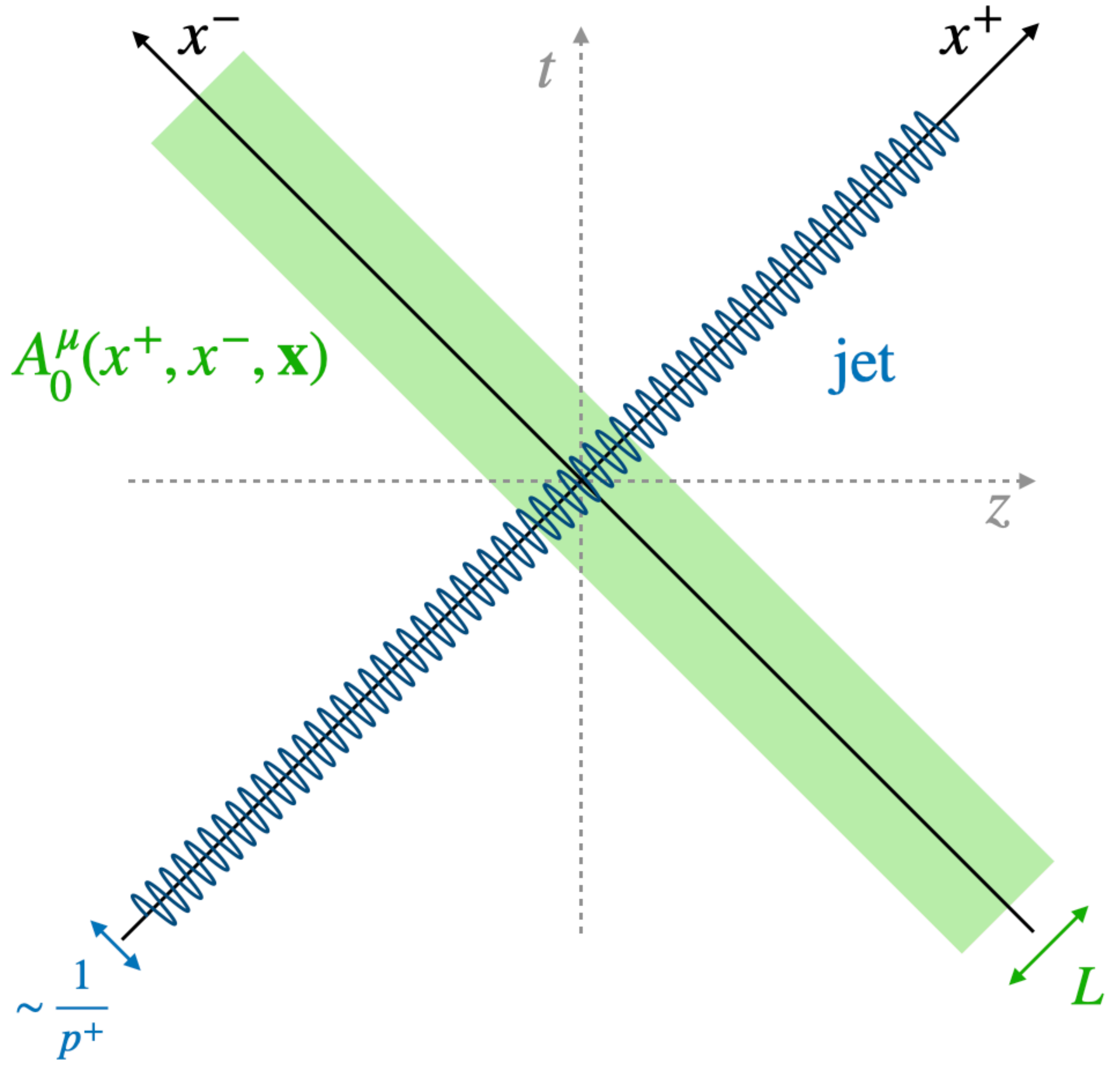
Large phase space for radiation compensates α_s!

$$\mathrm{Prob} = \frac{\alpha_s C_R}{\pi}\log^2\frac{p_T R}{\Lambda_{\mathrm{QCD}}} \gg 1$$

Need for resummation of collinear logarithms for final-state radiation.

PARTON PROPAGATION IN THE MEDIUM

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); Arnold, Moore, Yaffe (2003)
Barata, Milhano, Mehtar-Tani, Salgado, KT (in preparation)



Setup: light-cone perturbation theory in A^- background field ($A^+ = 0$ gauge).

Dressed (scalar) propagator:

$$(x|G_{\rm scal}|x_0) = (x|G_0|x_0) + 2p^+ \int_z (x|G_0|z)\, ig\mathcal{A}_0(z)\, (z|G_{\rm scal}|x_0)$$

Neglecting x^- dependence in the potential:

Conservation of large momentum component p^+.

$$(\boldsymbol{x}|\mathcal{G}(t,t_0)|\boldsymbol{x}_0) \equiv 2p^+ \int {\rm d}x^-\, {\rm e}^{ip^+(x-x_0)^-} (x|G_{\rm scal}|x_0)$$

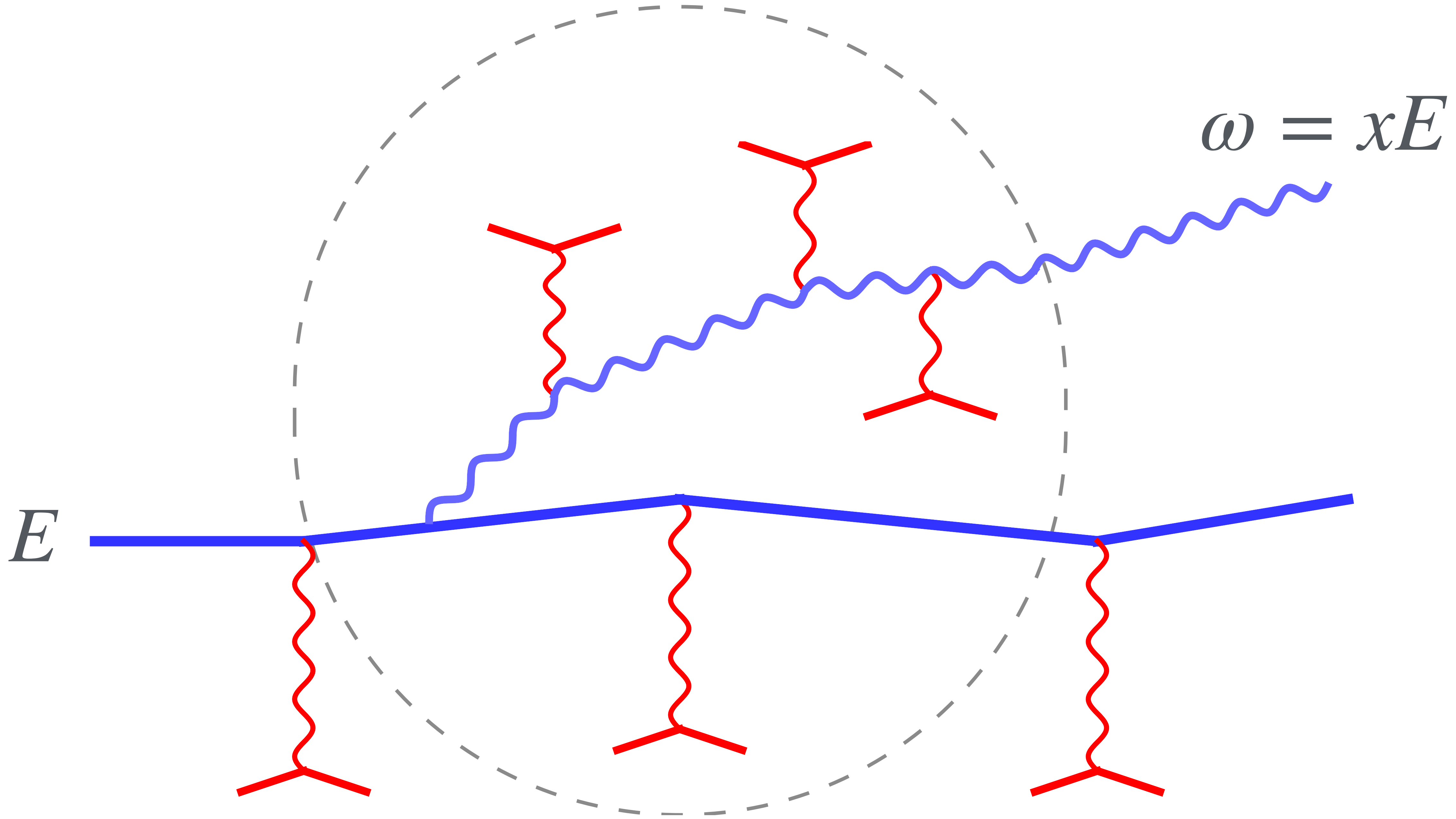
$$\left[i\frac{\partial}{\partial t} + \frac{\partial_\perp^2}{2p^+} + g\mathcal{A}_0(t,\boldsymbol{x})\right] (\boldsymbol{x}|\mathcal{G}(t,t_0)|\boldsymbol{x}_0) = i\delta(t-t_0)\delta(\boldsymbol{x}-\boldsymbol{x}_0)$$

2+1D time-dependent Schrödinger equation with $m = p^+$.

Medium-induced radiation

Momentum diffusion: $\langle k_\perp^2 \rangle = \hat{q} t$

- Many interactions occur during the formation of a soft gluon.
  - Interference between interactions leads to "shadowing".
  - LPM suppression of radiation.
- No collinear divergence!
- In QCD: formation time of gluons decrease with energy!

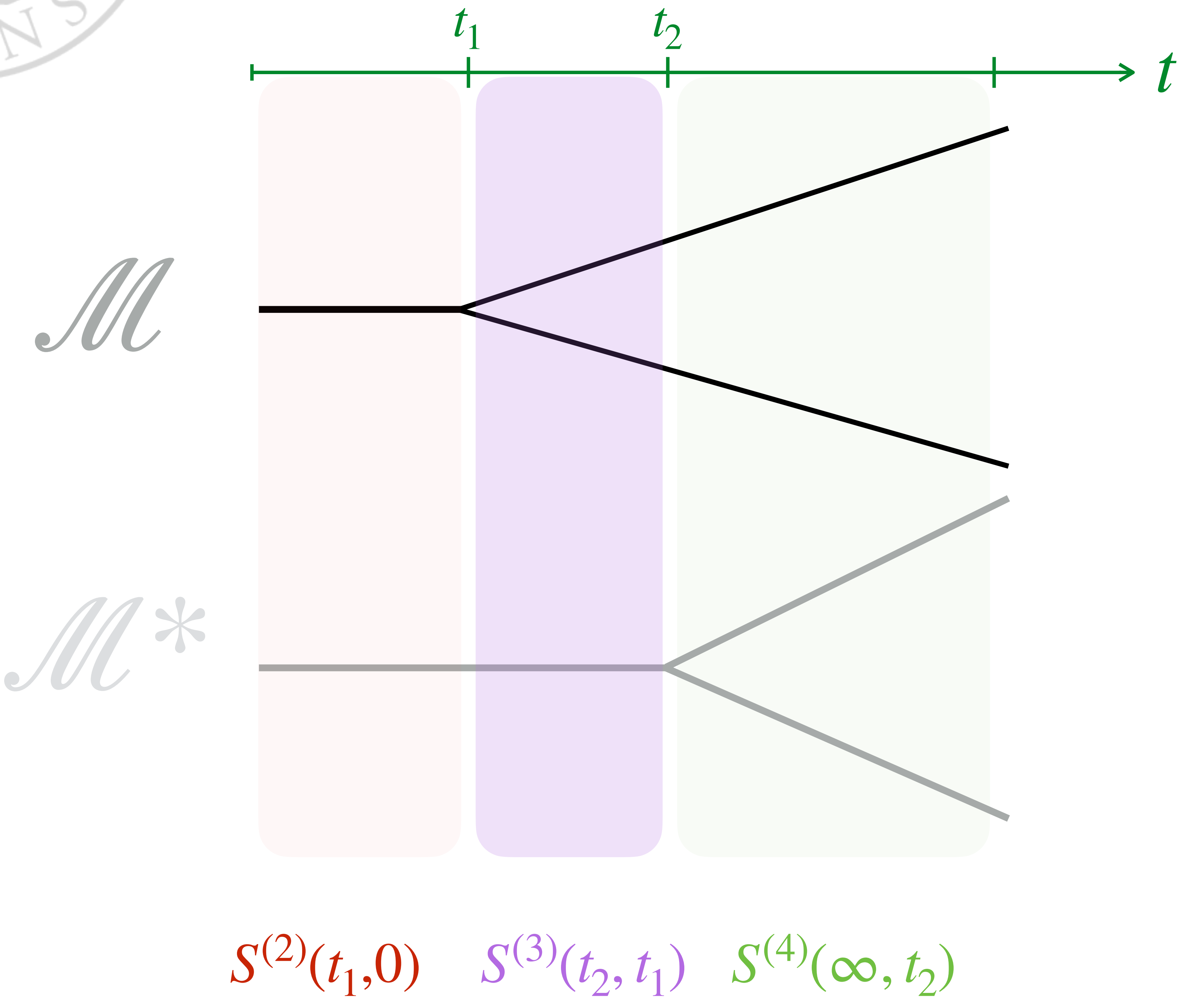


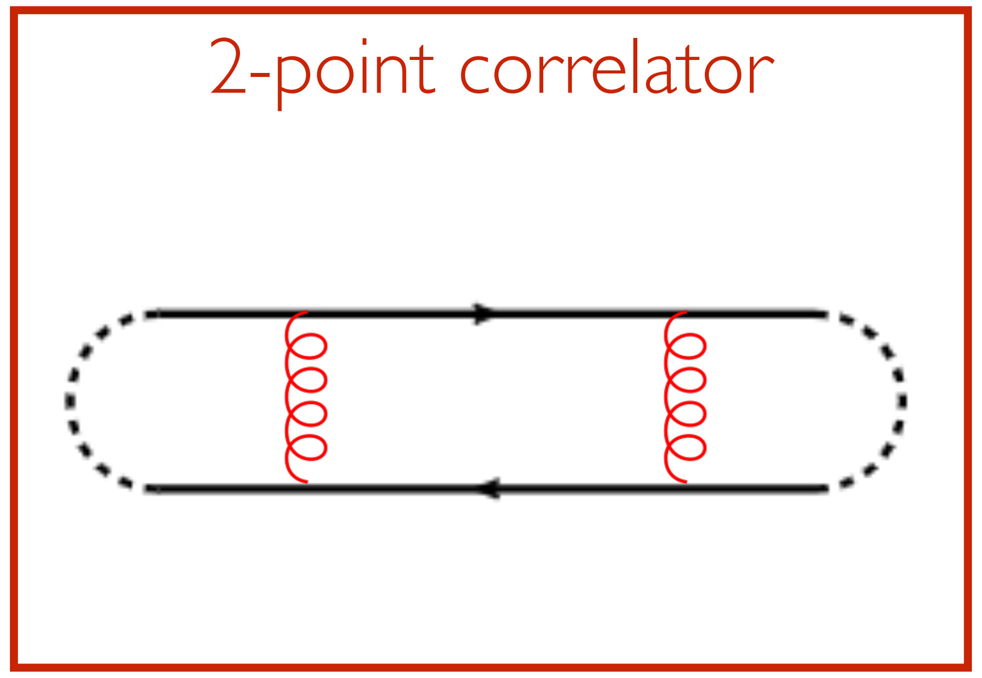
$$t_f = \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}}$$

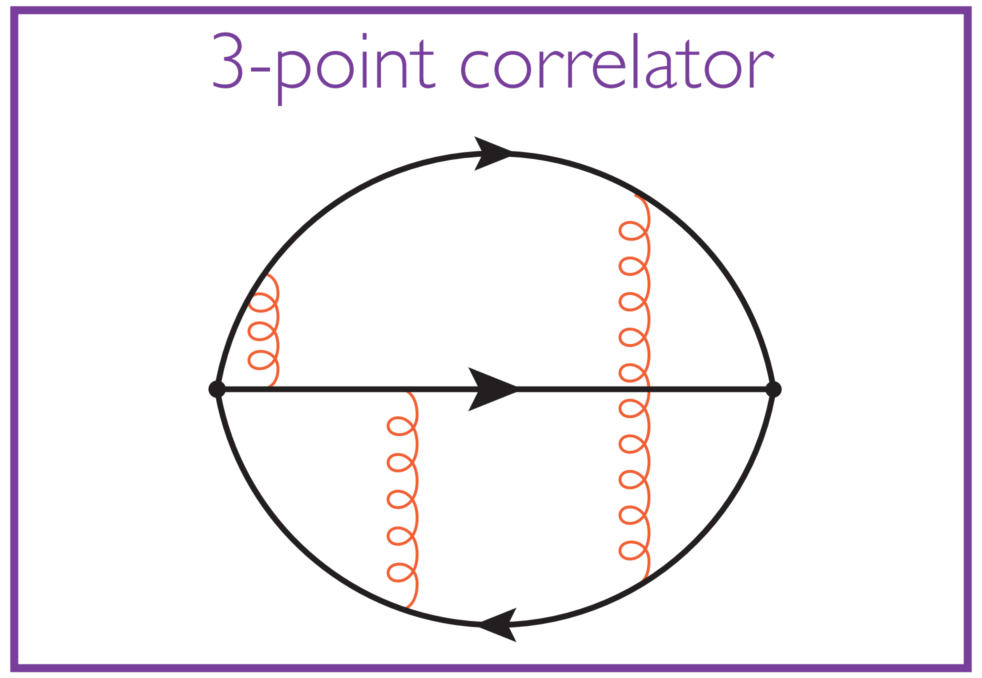
$$\omega \frac{dI}{d\omega} \sim \alpha_s C_R \frac{L}{\lambda} \to \alpha_s C_R \frac{L}{t_f}$$

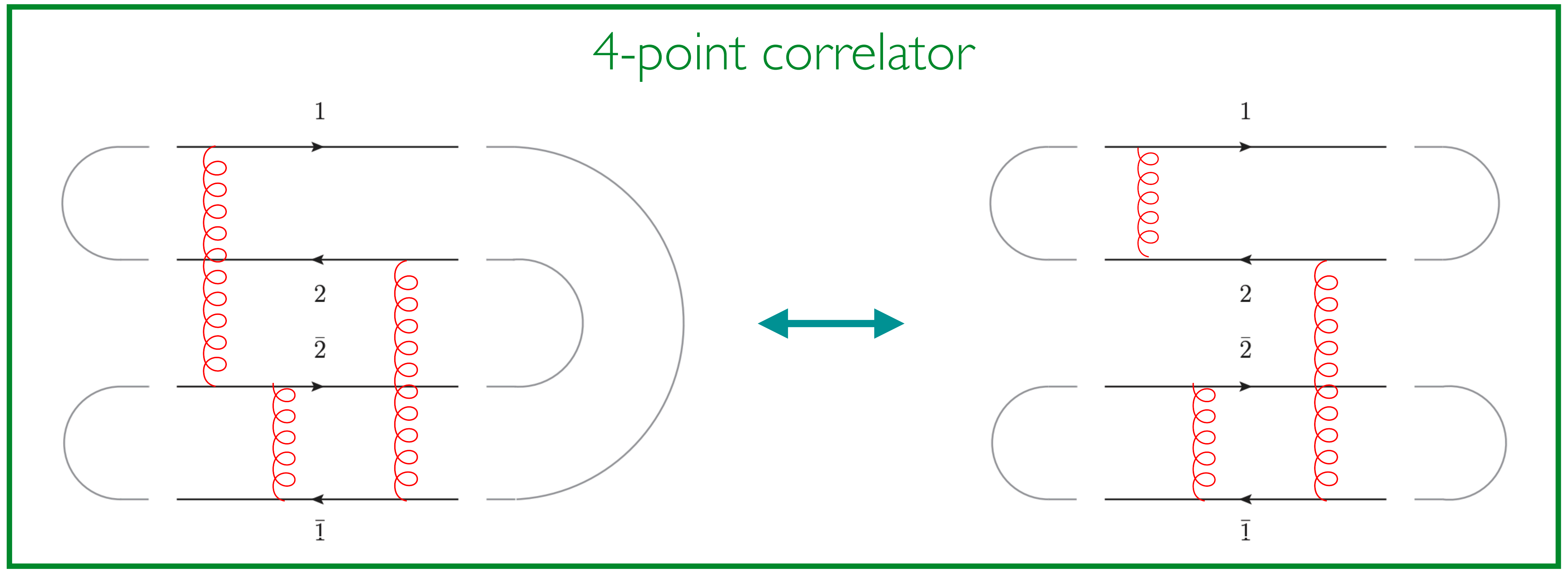
Parton splitting

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996) (Arnold, Moore, Yaffe (2003))
Blaizot, Dominguez, Iancu, Mehtar-Tani (2010)





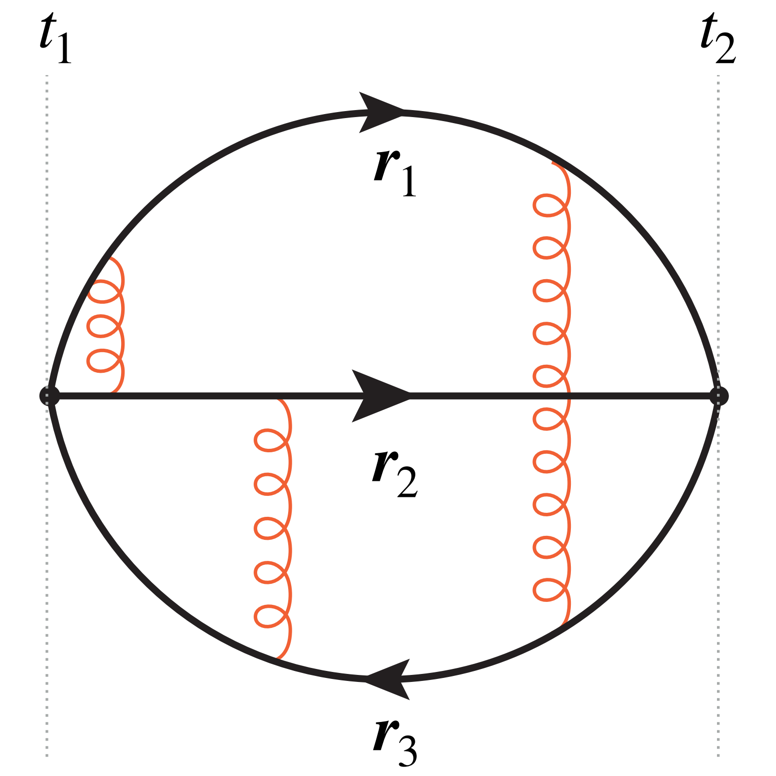




- n-body correlators of dressed propagators resum medium interactions evaluated in the background of fluctuating medium.

THREE-POINT CORRELATOR

$$\mathcal{K}(\boldsymbol{x},t_2;\boldsymbol{y},t_1)=\int_{\boldsymbol{r}(t_1)=\boldsymbol{y}}^{\boldsymbol{r}(t_2)=\boldsymbol{x}}\mathcal{D}\boldsymbol{r}\,\exp\left\{i\int_{t_1}^{t_2}\mathrm{d}s\left[\frac{\omega}{2}\dot{\boldsymbol{r}}^2+iv(\boldsymbol{r},s)\right]\right\}$$



Resumming 3-body interactions via potential:

(Including real and virtual exchanges.)

$$v(t,\boldsymbol{x})=\gamma(t,0)-\gamma(t,\boldsymbol{x})=\int_{\boldsymbol{q}}\frac{\mathrm{d}^2\sigma_{\mathrm{el}}}{\mathrm{d}\boldsymbol{q}^2}\left(1-\mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right)$$

$$\simeq\frac{1}{4}\hat{q}_0\boldsymbol{x}^2\ln\frac{1}{\boldsymbol{x}^2\mu_*^2}+\mathcal{O}(\boldsymbol{x}^4\mu_*^2)$$

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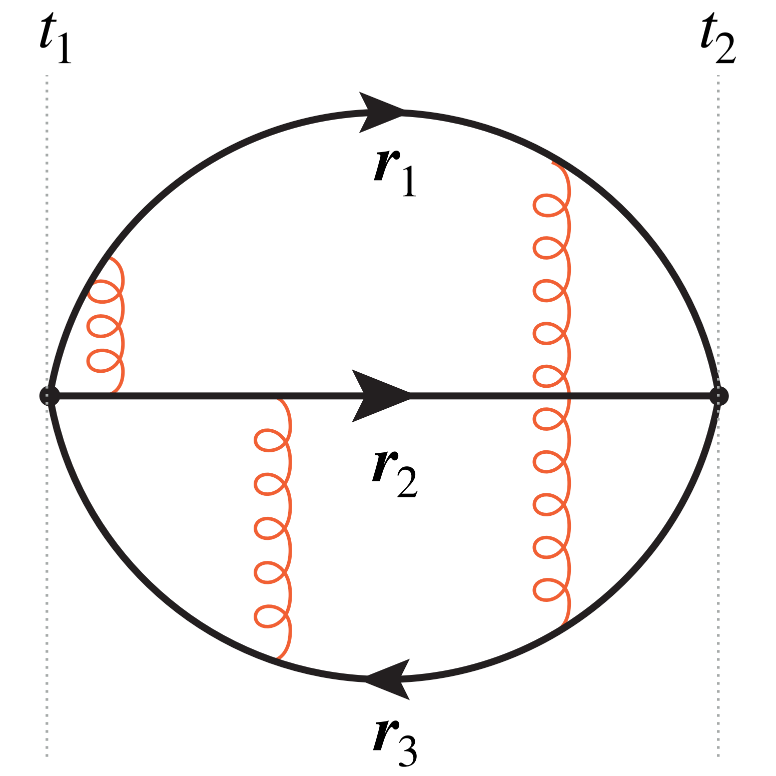

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First term is universal/perturbative.
Harmonic oscillator (up to a log).

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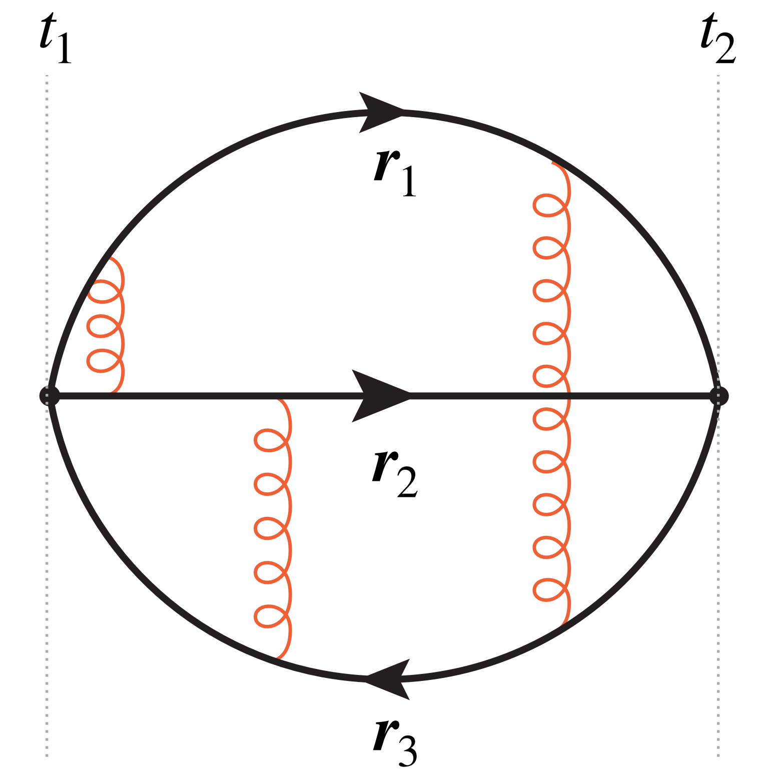

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"Bare" jet transport coefficient

$$\hat{q}_0 = 4\pi \alpha_s^2 N_c n_0 = \frac{\mu^2}{\lambda}$$

Three-point correlator

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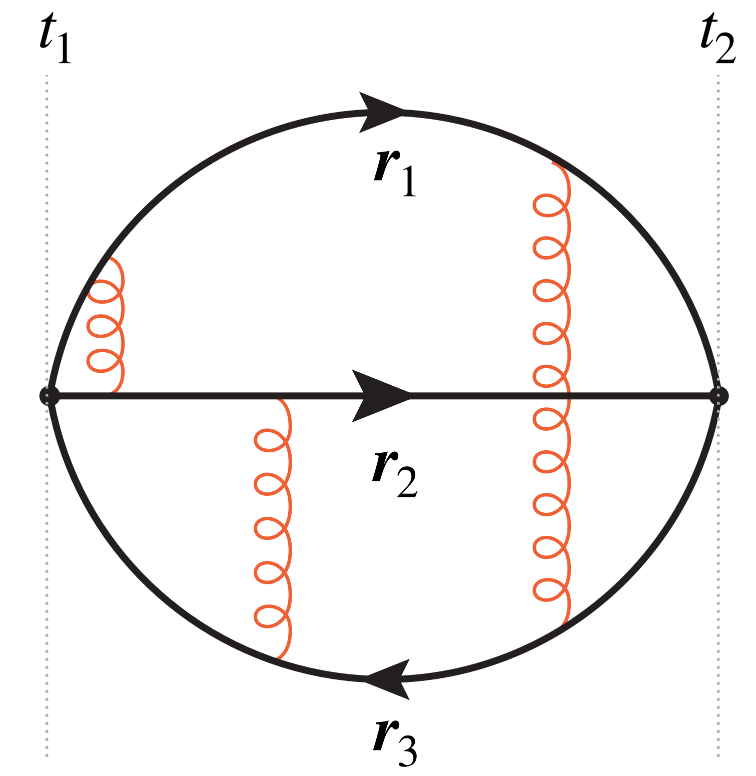

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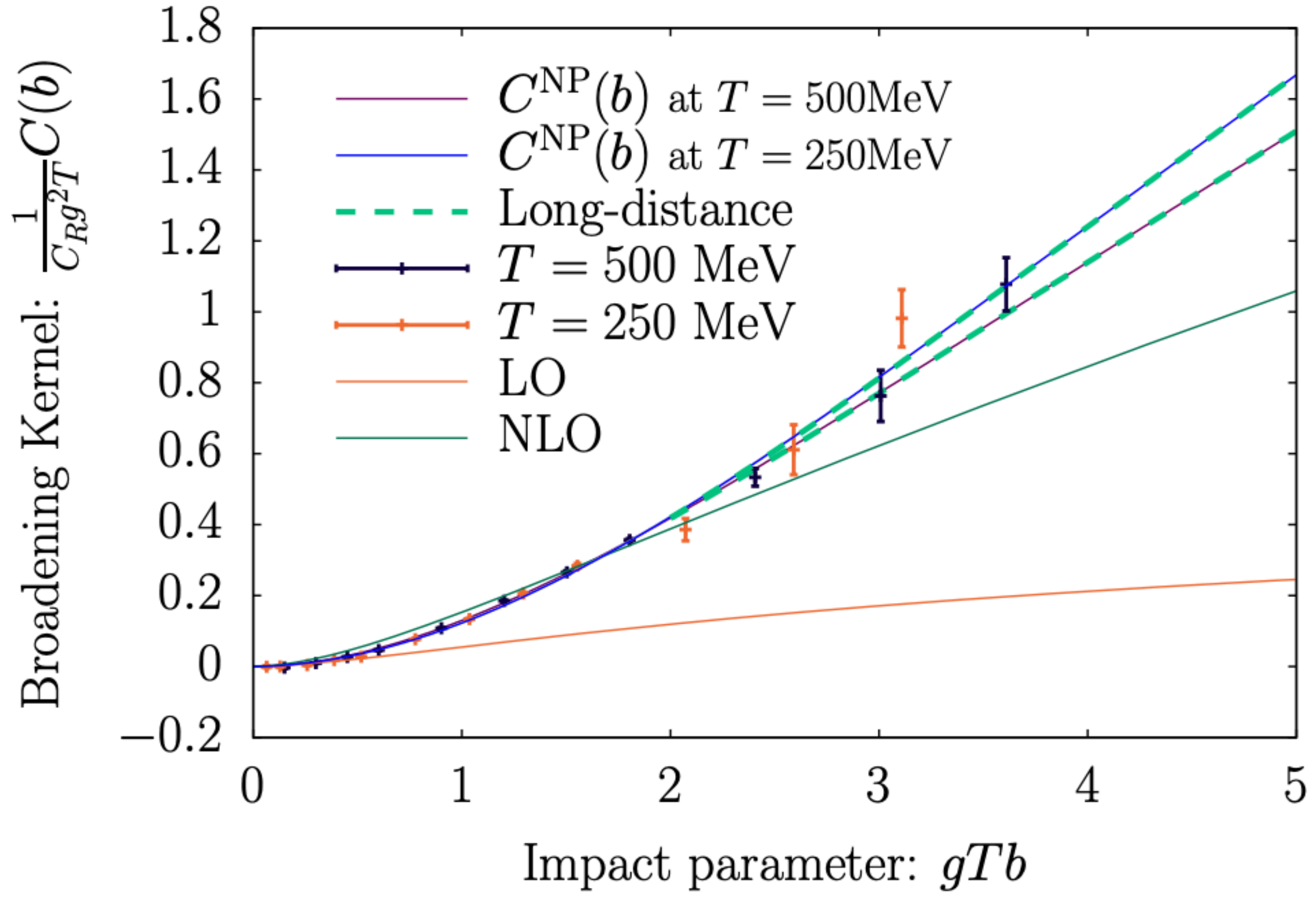
Non-perturbative contributions from EQCD



Schlichting, Soudi 2111.13731

"Bare" jet transport coefficient

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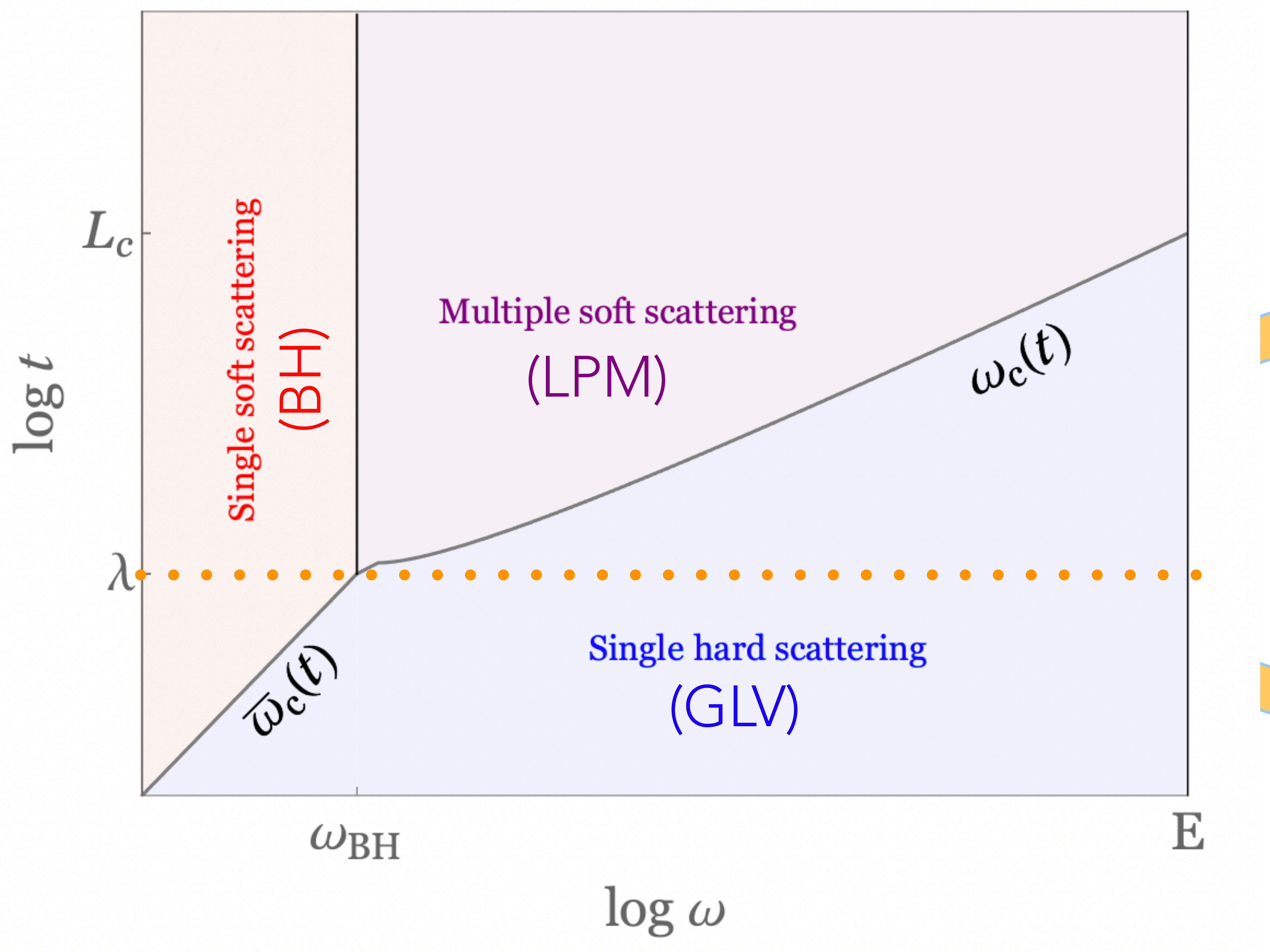
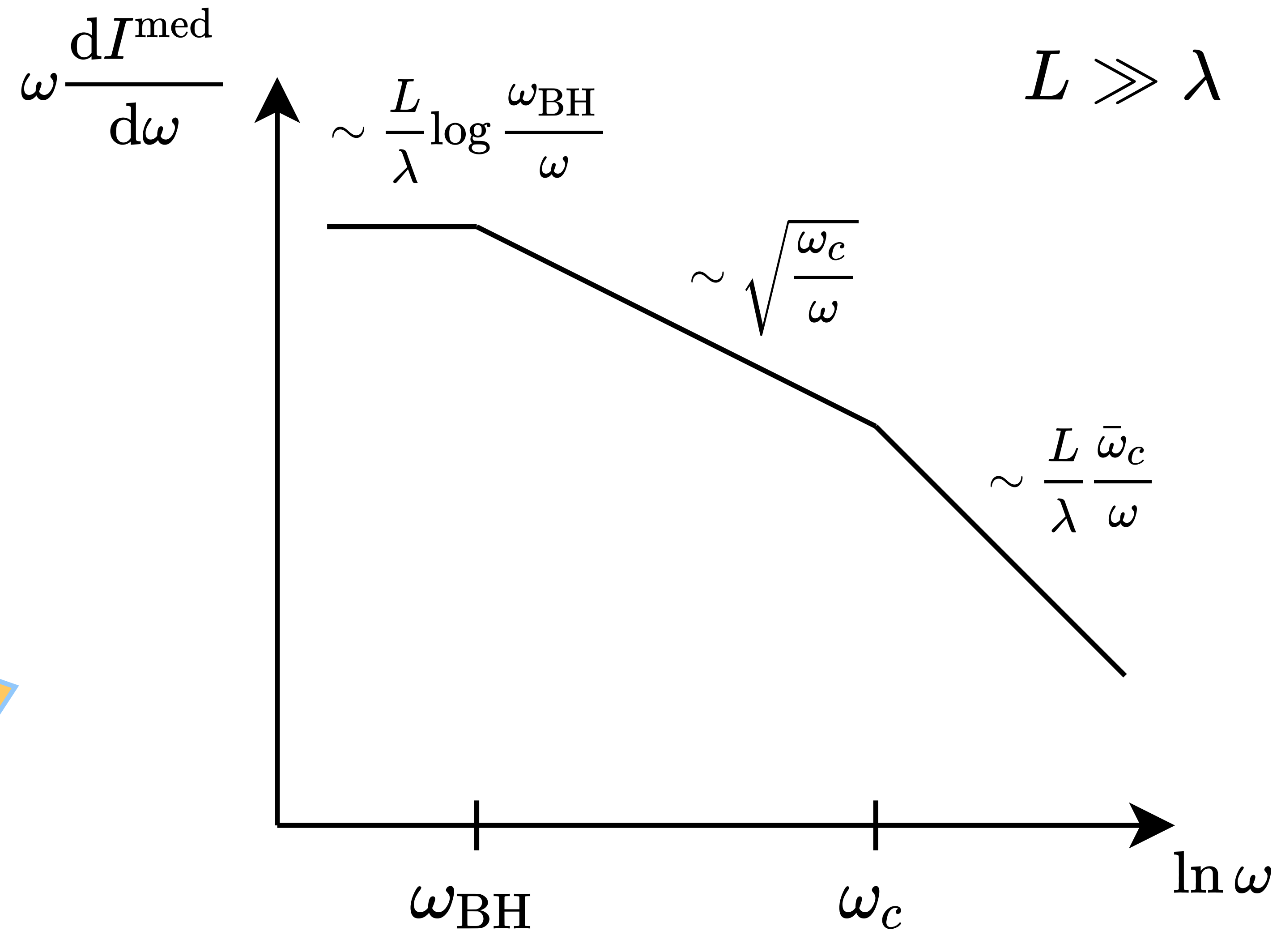
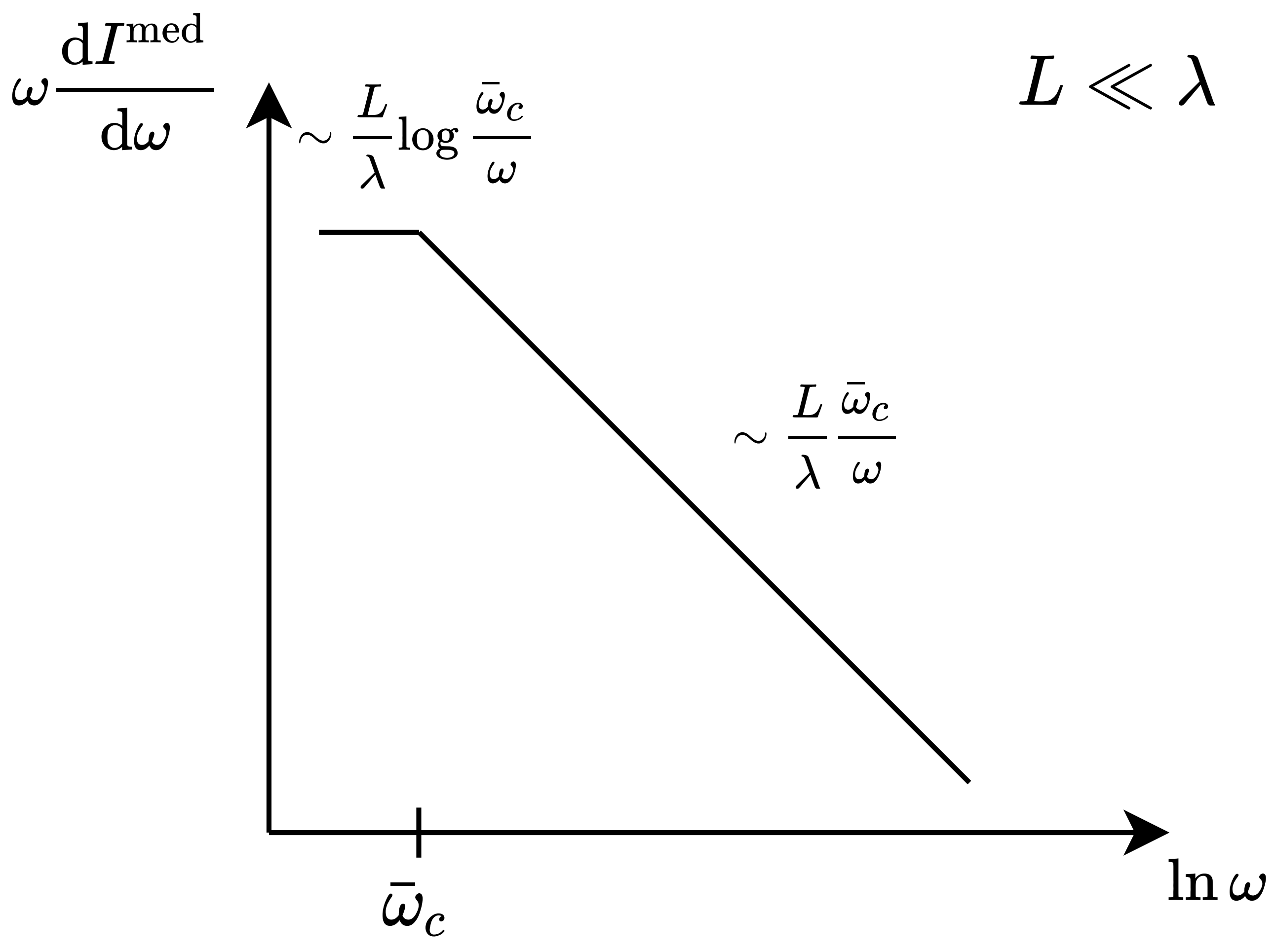
FEATURES OF THE SPECTRUM

Isaksen, Takacs, KT 2206.02811 [hep-ph]

Analytic control in full phase space!

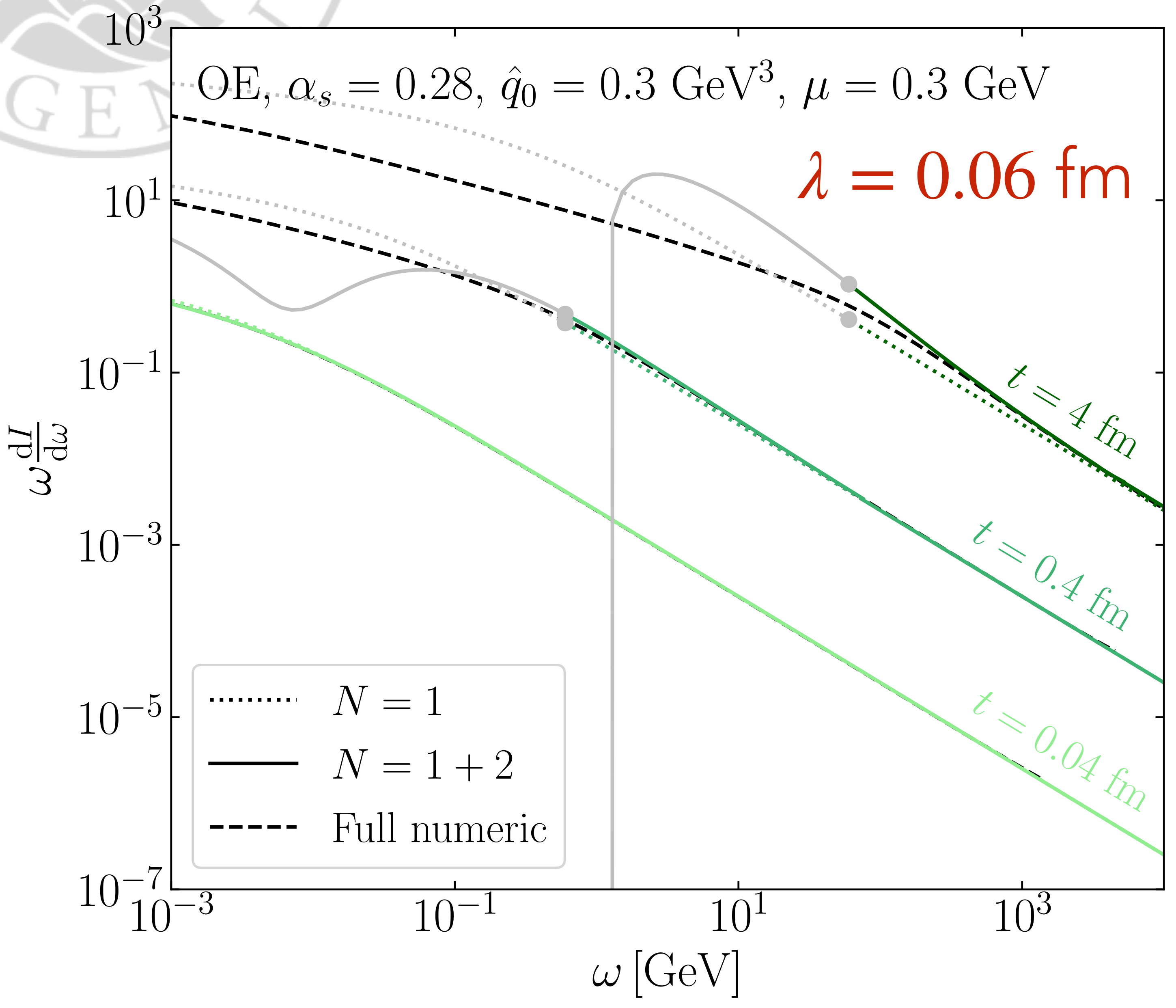






RESUMMATION SCHEMES

Numerical comparison to Andres, Dominguez, Gonzalez Martinez 2011.06522



Opacity expansion:

Direct expansion around vacuum in terms of L/λ, truncated at $\mathcal{O}(L/\lambda)$ (called N=1 or GLV approximation).

Converges in dilute medium & hard regime.

$$\bar{\omega}_c(t) = \frac{1}{2}\mu^2 t$$

Wiedemann (2000); Gyulassy, Levai, Vitev (2001)

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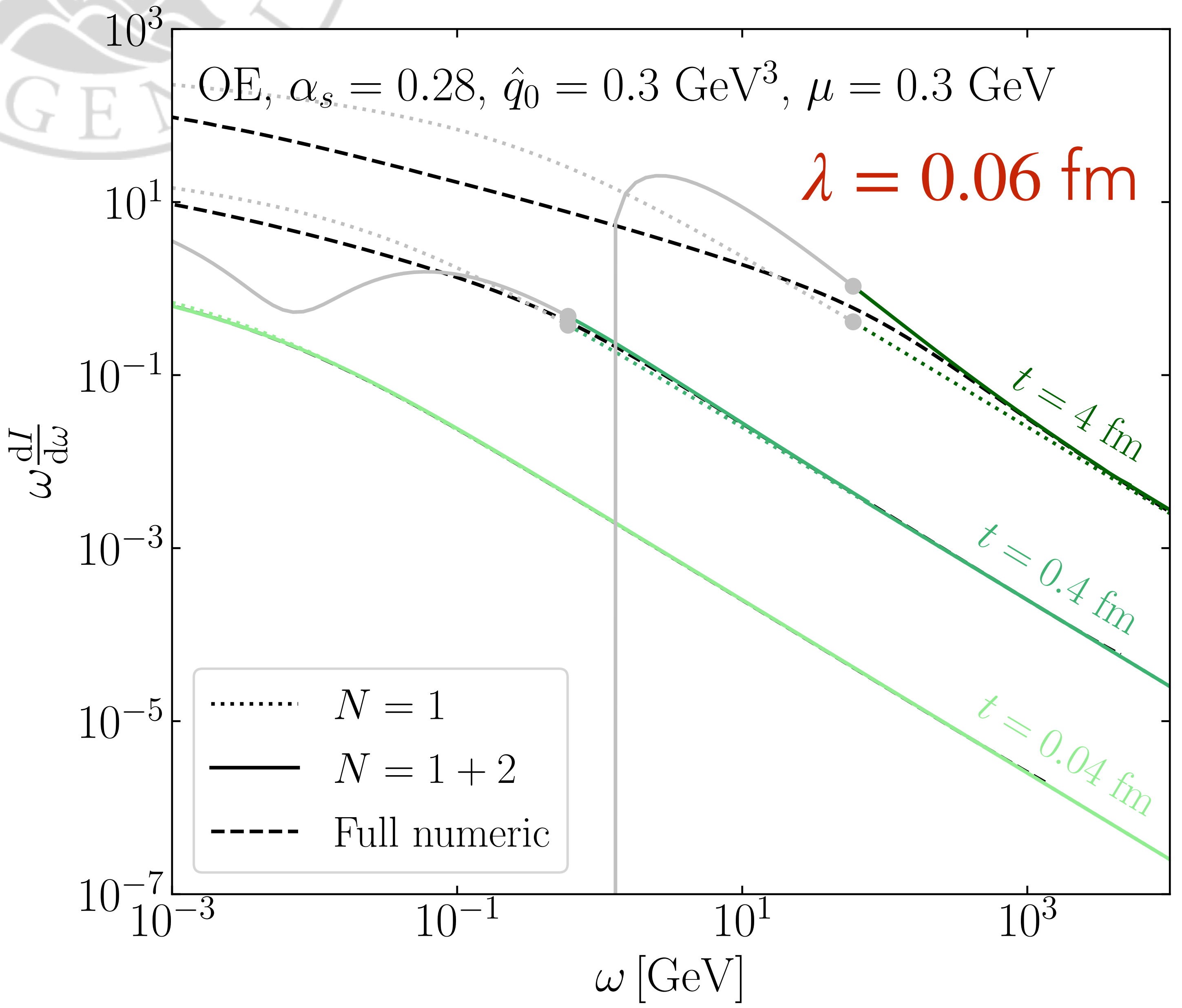

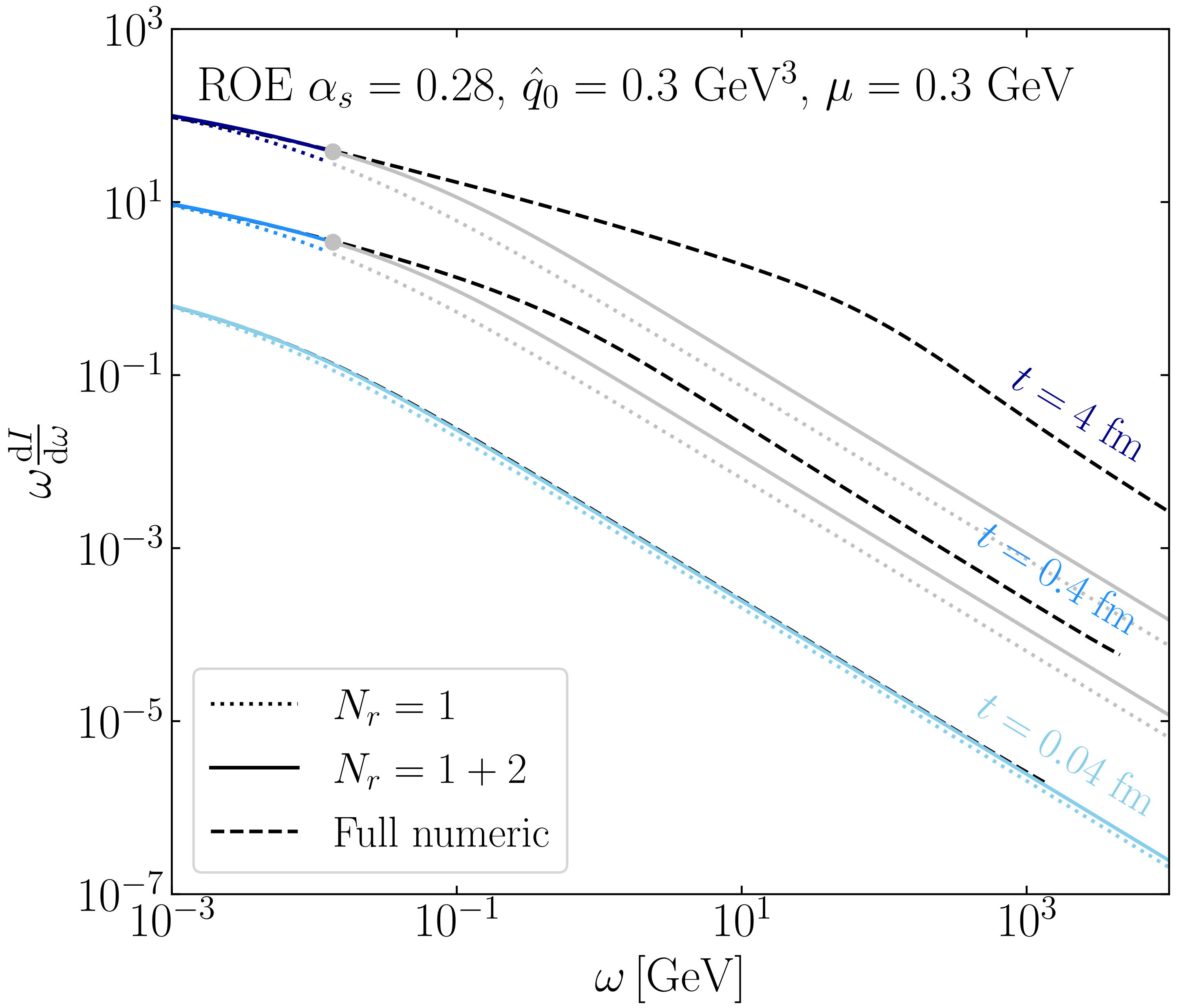

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Sensitivity to the mean free path.

Converges in the soft regime.

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Isaksen, Takacs, KT 2206.02811 [hep-ph]

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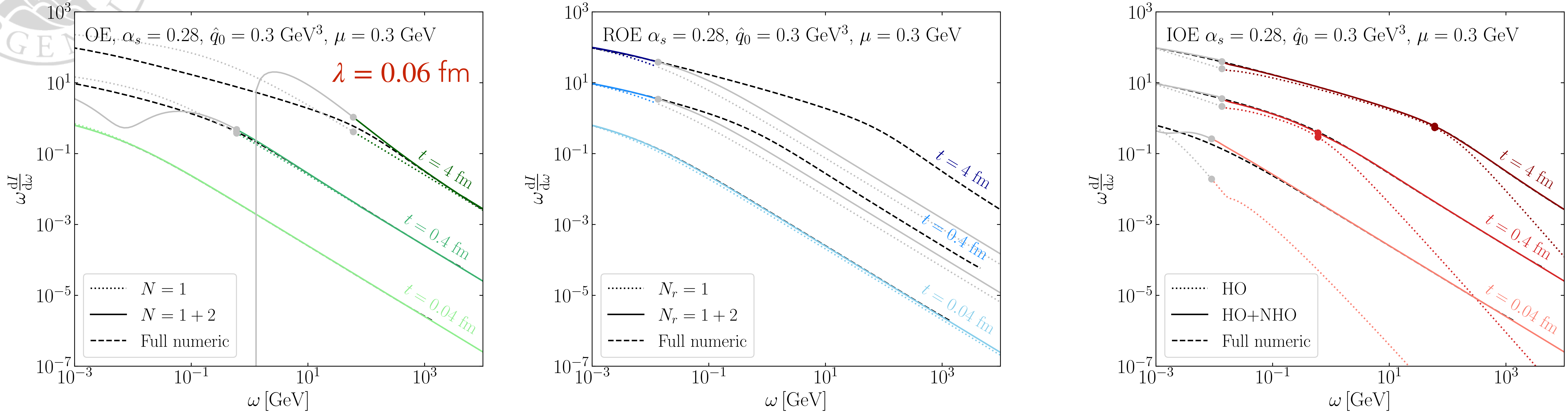

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Isaksen, Takacs, KT 2206.02811 [hep-ph]

Improved opacity expansion:

Expansion of rare, hard scattering on top of the harmonic oscillator solution.

Scale dependence of transport coefficient.

Converges in dense media above ω_{BH}.

$$\omega_c(t) = \frac{1}{2}\hat{q}t^2$$

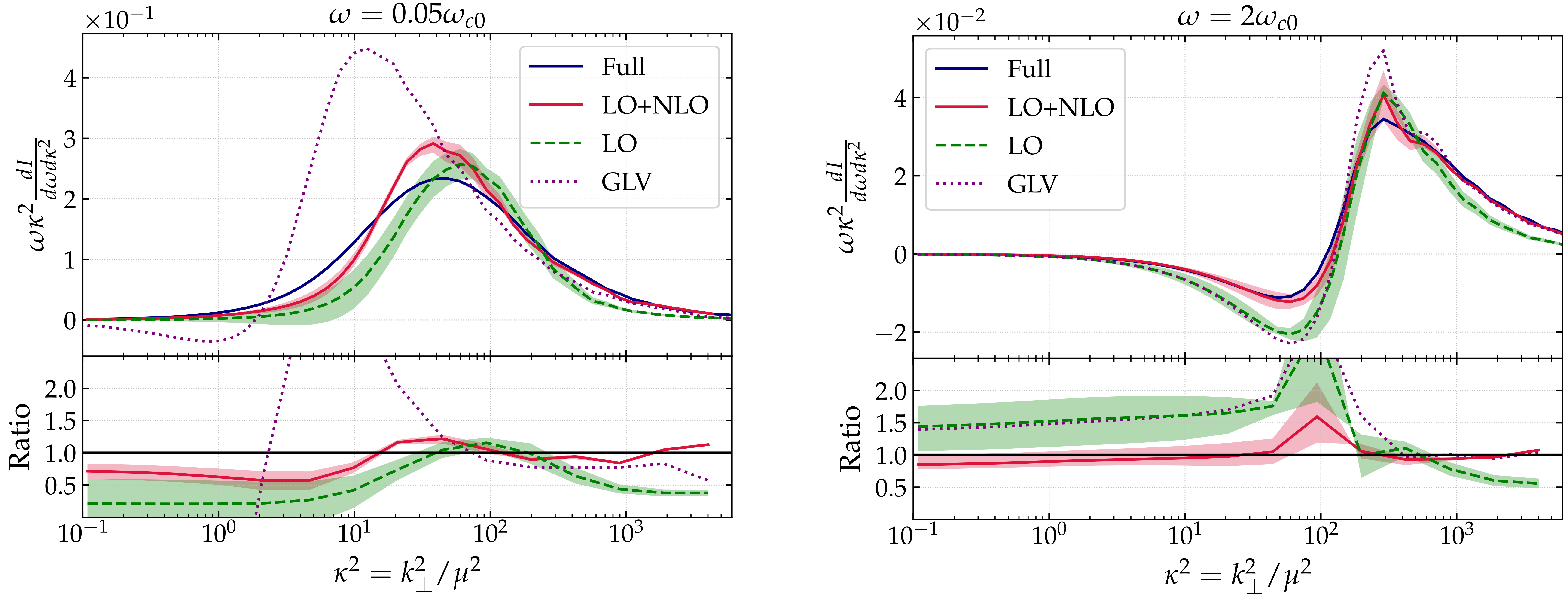
Mehtar-Tani 1903.00506; Mehtar-Tani, Tywoniuk 1910.02032; Mehtar-Tani, Barata 2004.02323

FULLY DOUBLE-DIFFERENTIAL SPECTRUM

Mehtar-Tani 1903.00506; Mehtar-Tani, Tywoniuk 1910.02032; Mehtar-Tani, Barata 2004.02323
Barata, Mehtar-Tani, Soto-Ontoso, KT 2106.07402
Numerical comparison to Andres, Dominguez, Gonzalez Martinez 2011.06522

$$(2\pi)^2\omega\frac{\mathrm{d}I}{\mathrm{d}\omega\mathrm{d}^2\boldsymbol{k}} = \frac{2\alpha_s C_R}{\omega^2}\mathrm{Re}\int_0^\infty \mathrm{d}t_2\int_0^{t_2}\mathrm{d}t_1\int_{\boldsymbol{x}} \mathrm{e}^{-i\boldsymbol{k}\cdot\boldsymbol{x}}\mathcal{P}(\boldsymbol{x};\infty,t_2)\partial_{\boldsymbol{x}}\cdot\partial_{\boldsymbol{y}}\mathcal{K}(\boldsymbol{x},t_2;\boldsymbol{y},t_1)_{\boldsymbol{y}=0} - (\mathrm{vac.})$$

Improved opacity expansion



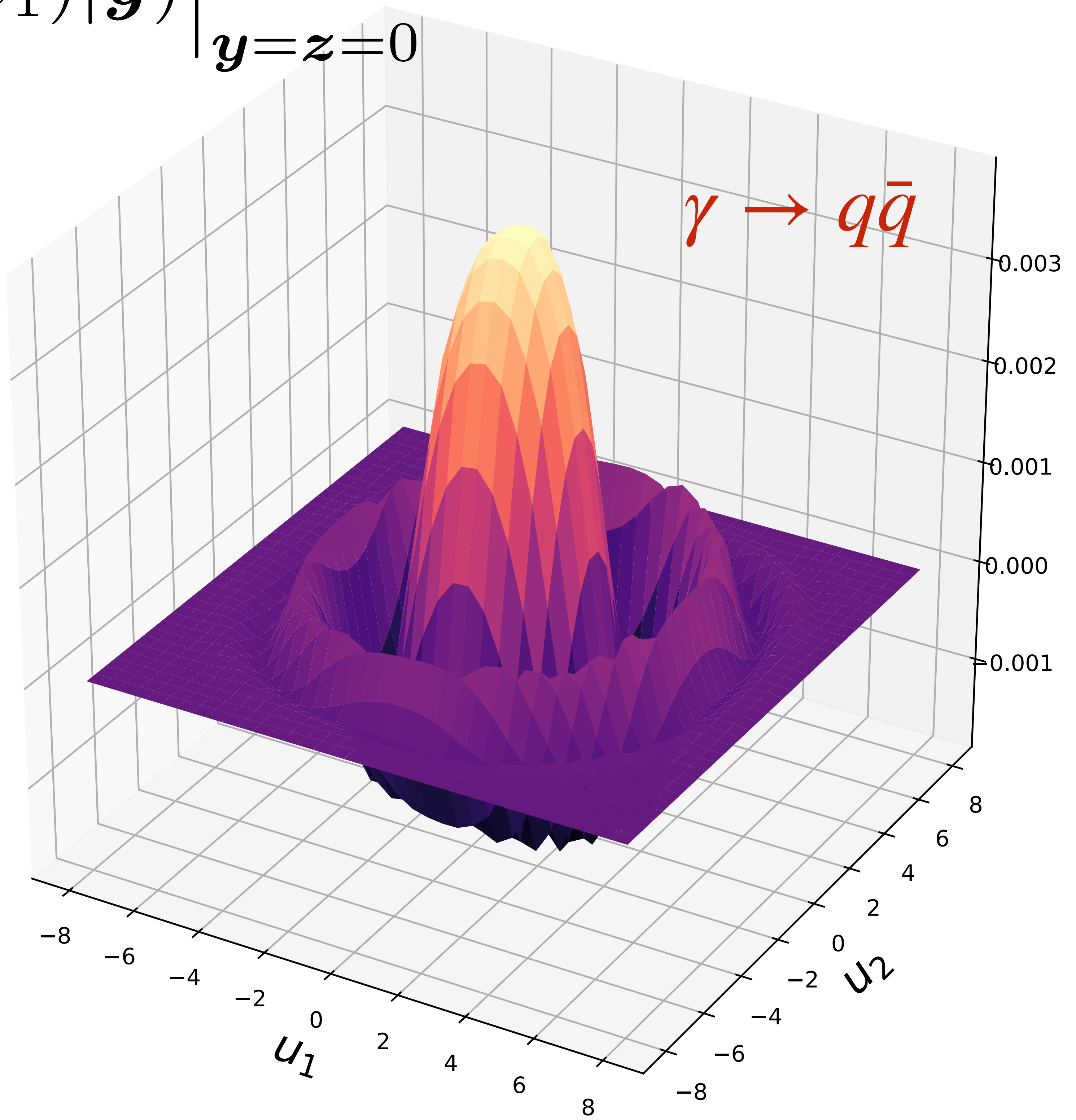
Other numerical solutions:
Zakharov hep-ph/0410321; Caron-Huot, Gale 1006.2379; Feal, Vazquez 1811.01591; Ke, Xu and Bass 1810.08177; Feal, Salgado, Vazquez 1911.01309; Andres, Apolinario, Dominguez 2002.01517

In-medium splitting function

Dominguez, Isaksen, KT (in preparation)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z\,\mathrm{d}^2\boldsymbol{k}} = \frac{g^2\,P(z)}{2(2\pi)^3[z(1-z)E]^2}\,\mathrm{Re}\int_0^\infty \mathrm{d}t_1 \int_{t_1}^\infty \mathrm{d}t_2 \int_{\boldsymbol{x},\boldsymbol{u},\bar{\boldsymbol{u}}} \mathrm{e}^{-i(\boldsymbol{u}-\bar{\boldsymbol{u}})\cdot\boldsymbol{k}}$$
$$\times\ \partial_{\boldsymbol{y}}\cdot\partial_{\boldsymbol{z}}(\boldsymbol{u};\bar{\boldsymbol{u}}|\tilde{S}^{(4)}(L,t_2)|\boldsymbol{x};\boldsymbol{z})(\boldsymbol{x}|\tilde{S}^{(3)}(t_2,t_1)|\boldsymbol{y})\Big|_{\boldsymbol{y}=\boldsymbol{z}=0}$$

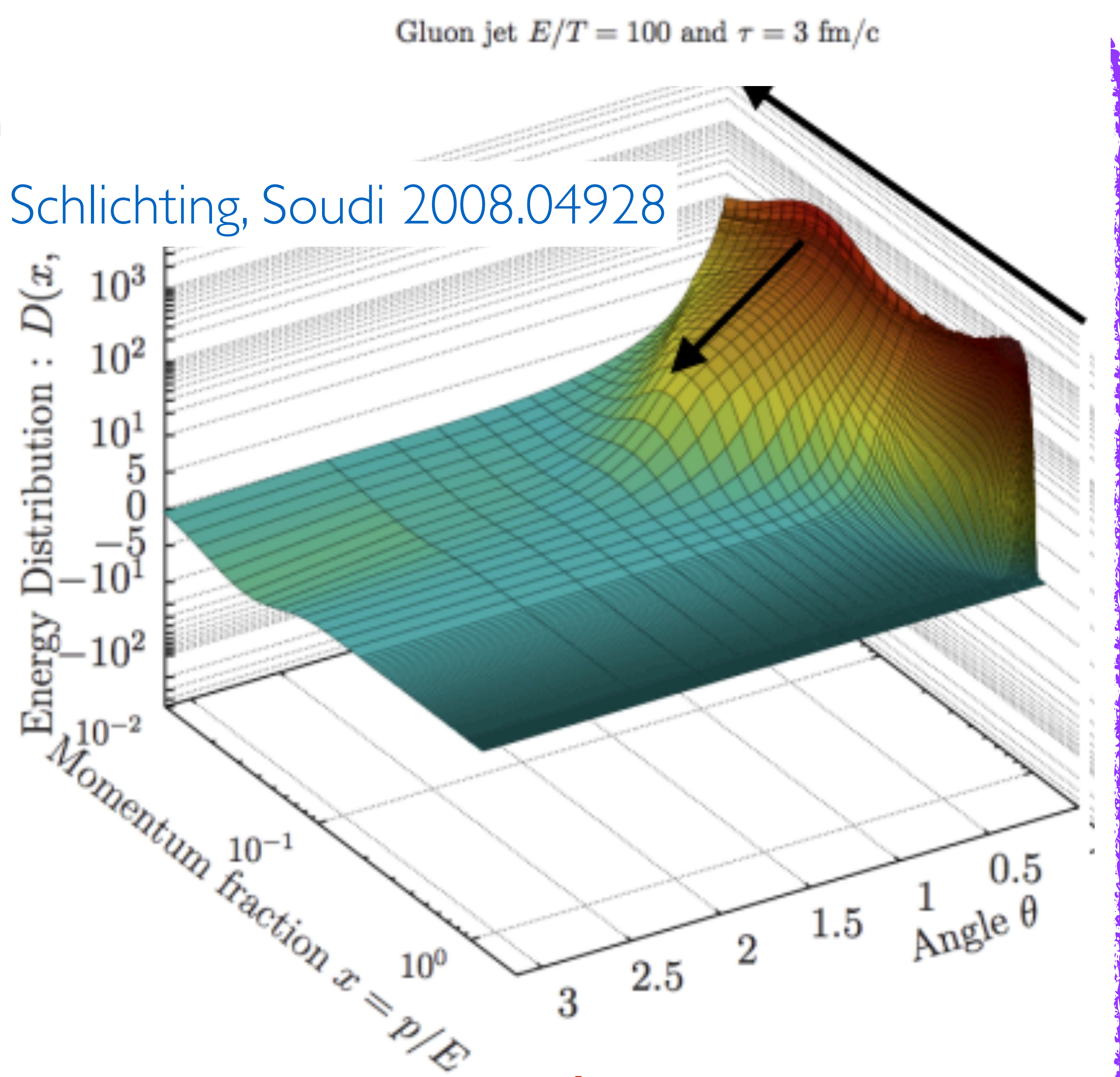
- beyond large-Nc: two-body dynamics in the 4-point correlator
- toward full precision calculation of splitting dynamics for all splitting processes



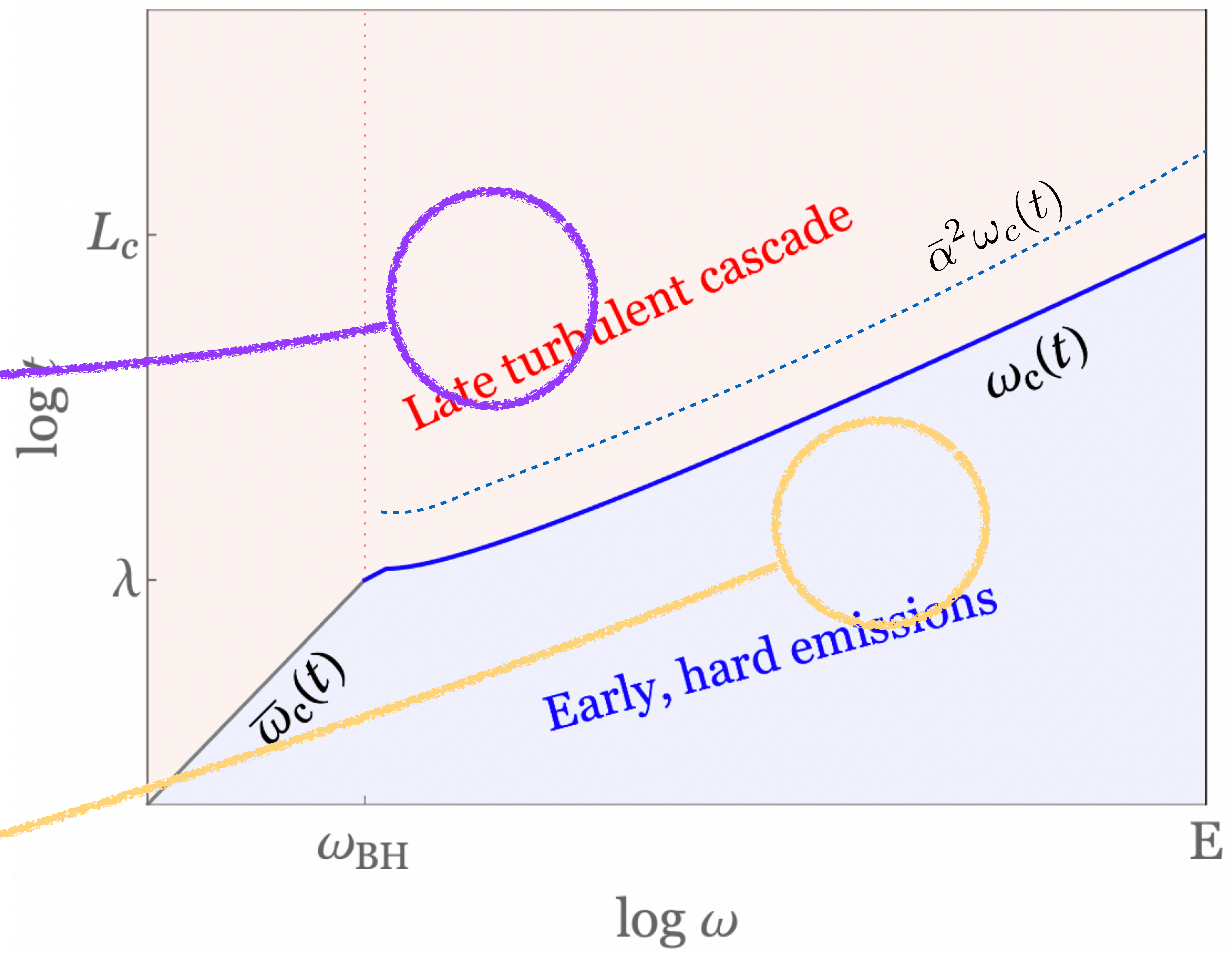
EMERGING SPACETIME PICTURE

Isaksen, Takacs, KT (in preparation)

Schlichting, Soudi 2008.04928

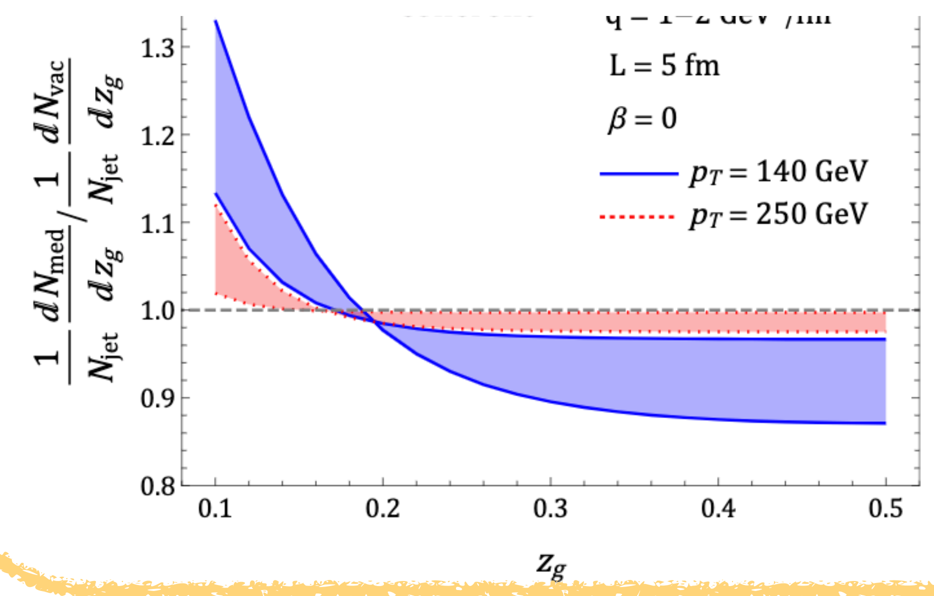


jet energy loss



jet substructure

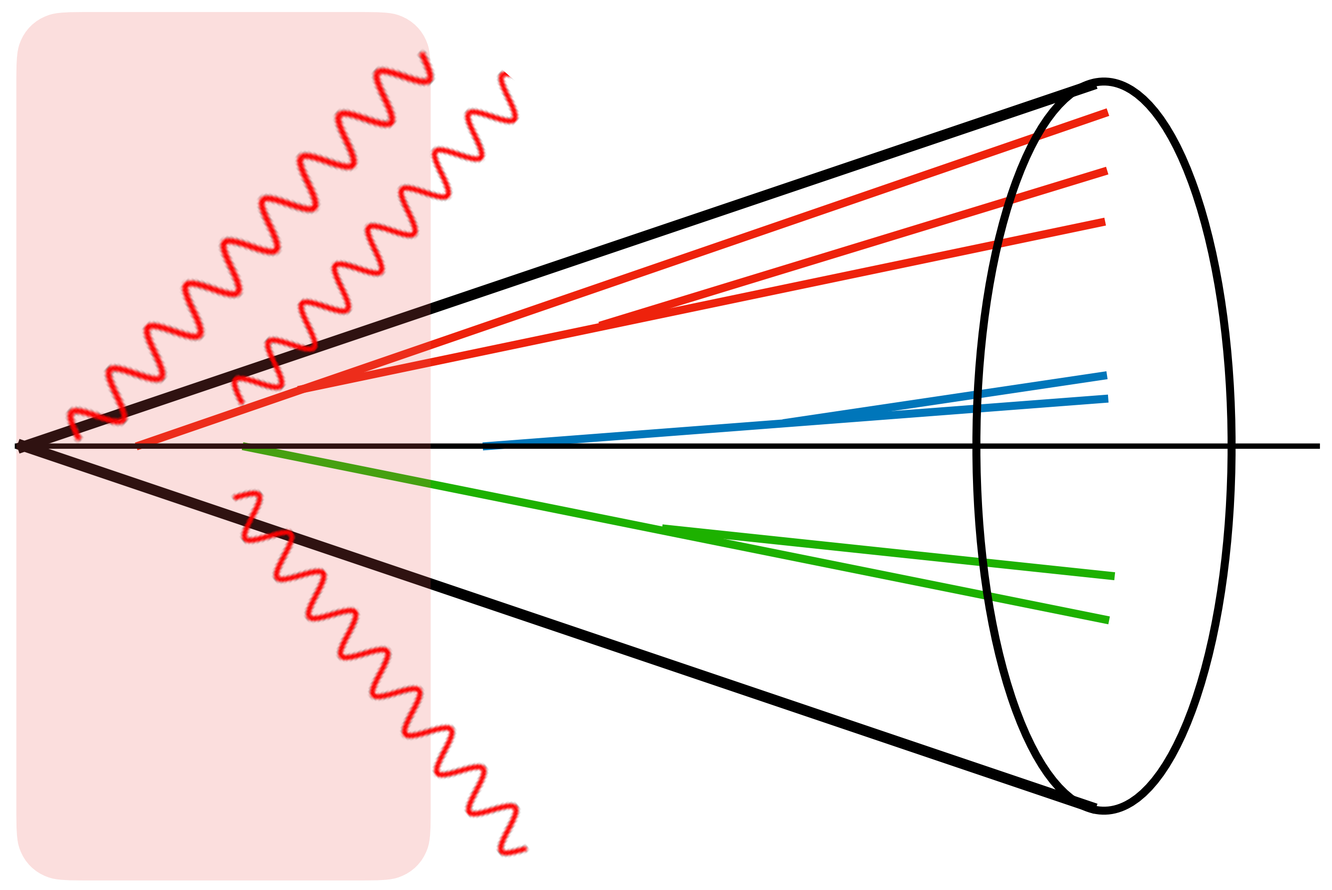
Mehtar-Tani, KT 1610.08930
Caucal, Soto-Ontoso, Takacs 2111.14768



- Effective theory for consistent accounting of fixed-order vs. resummation from emergent scales.
- In progress: need addition ϑ axis to merge with vacuum…

Jet energy loss & modifications

Role of vacum-like and medium-induced emissions



VACUUM RADIATION IN MEDIUM

Vacuum radiation at short timescales was considered first in the context of antenna radiation.

Mehtar-Tani, Salgado, KT PRL (2010), PLB (2012), JHEP (2013); Casalderrey, Iancu JHEP (2011)

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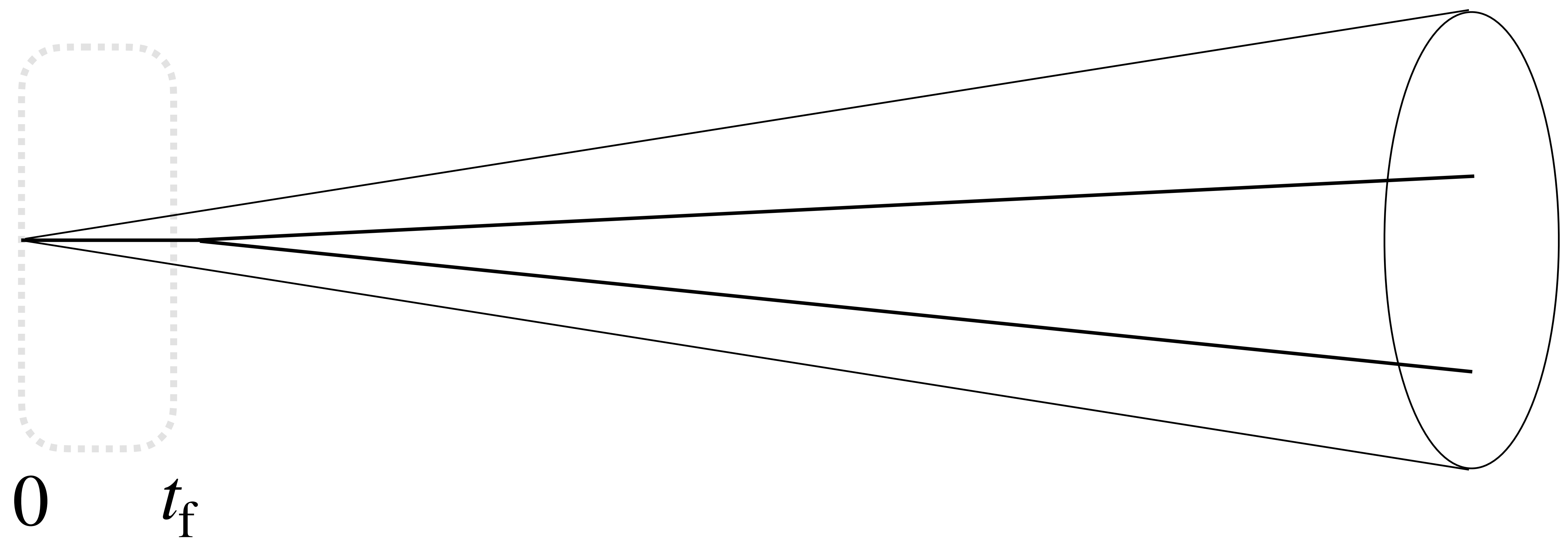
First step: calculation of decoherence and energy loss of an initially color correlated pair

Mehtar-Tani, KT 1706.06047

see also Casalderrey, Mehtar-Tani, Salgado, KT (QM2017)



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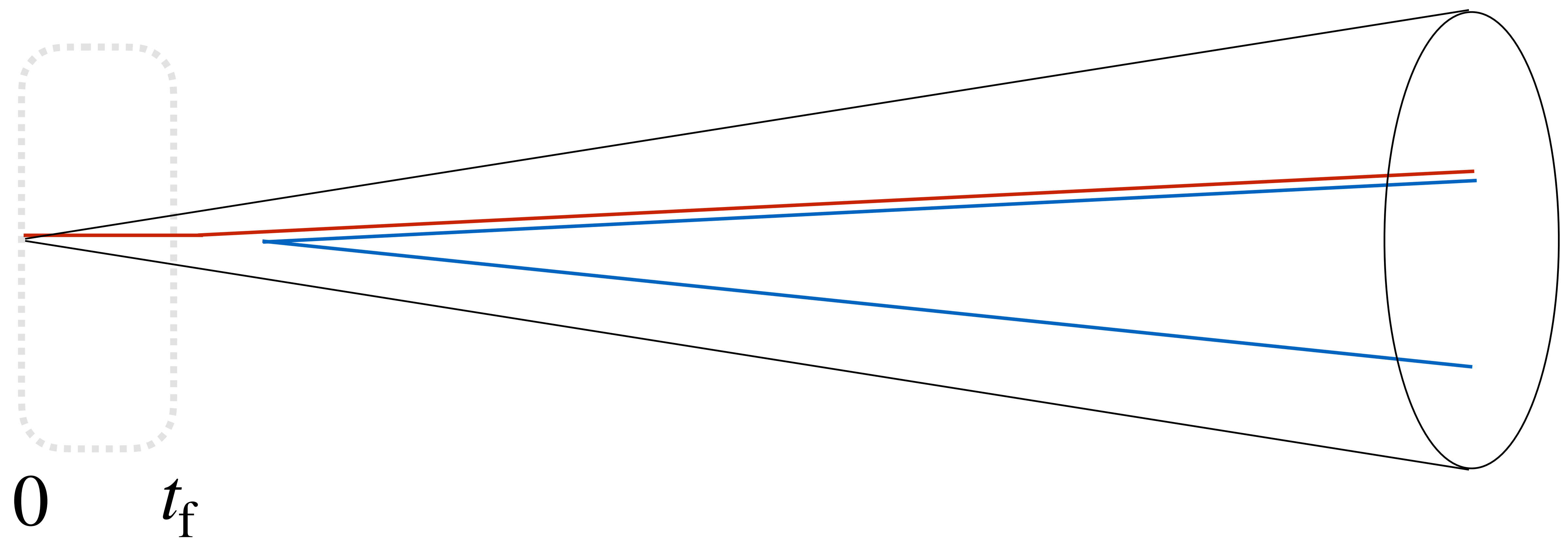
First step: calculation of decoherence and energy loss of an initially color correlated pair

Mehtar-Tani, KT 1706.06047

see also Casalderrey, Mehtar-Tani, Salgado, KT (QM2017)



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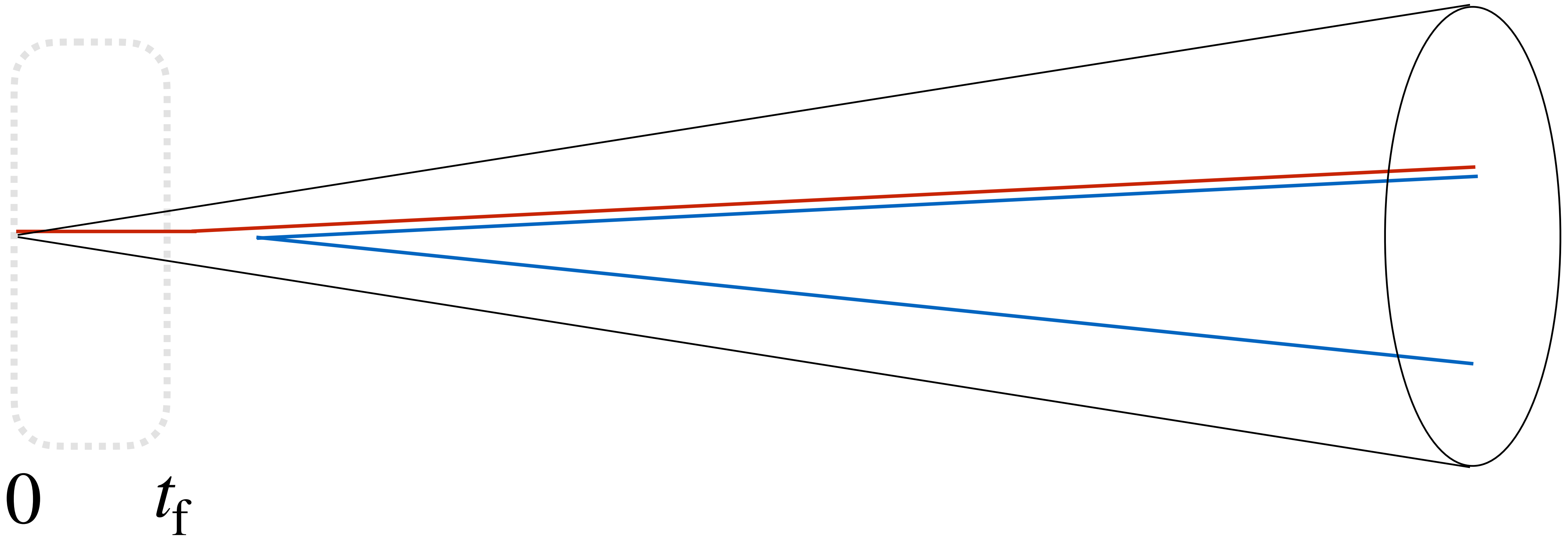

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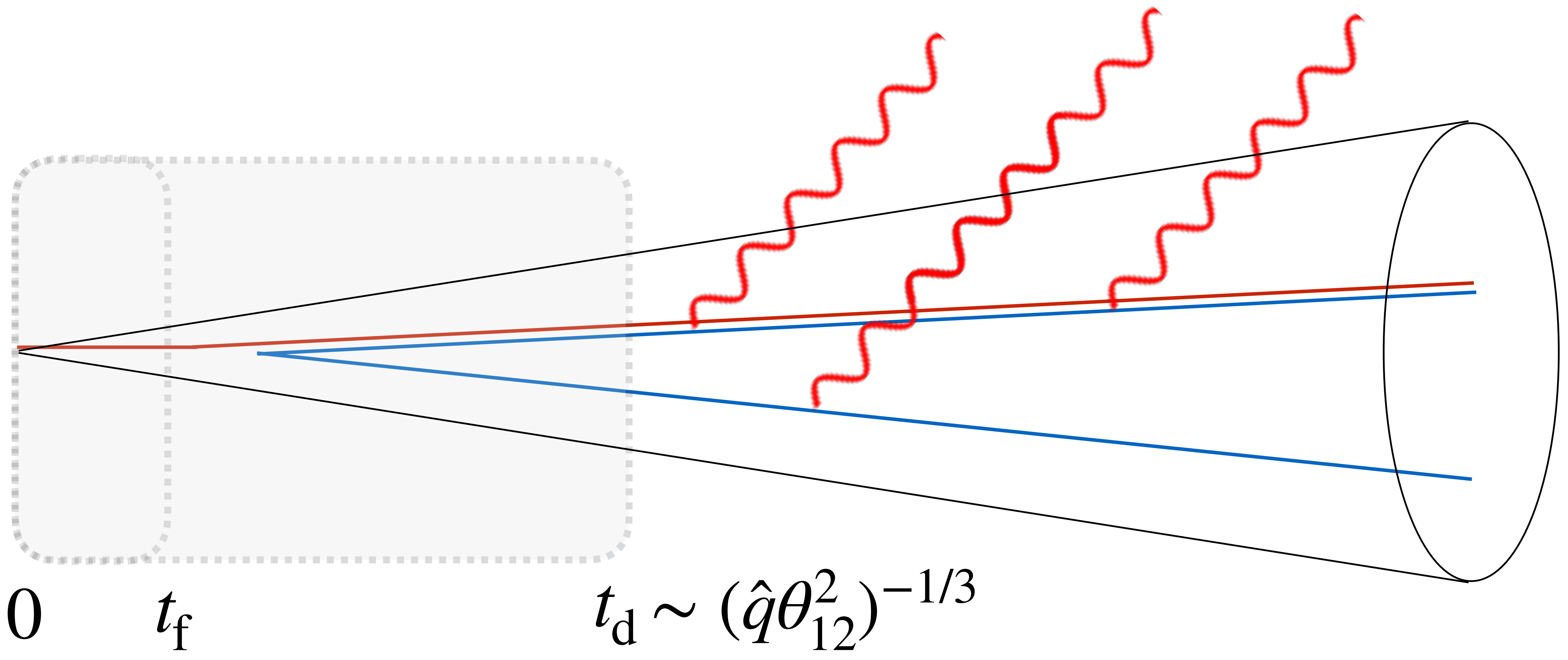

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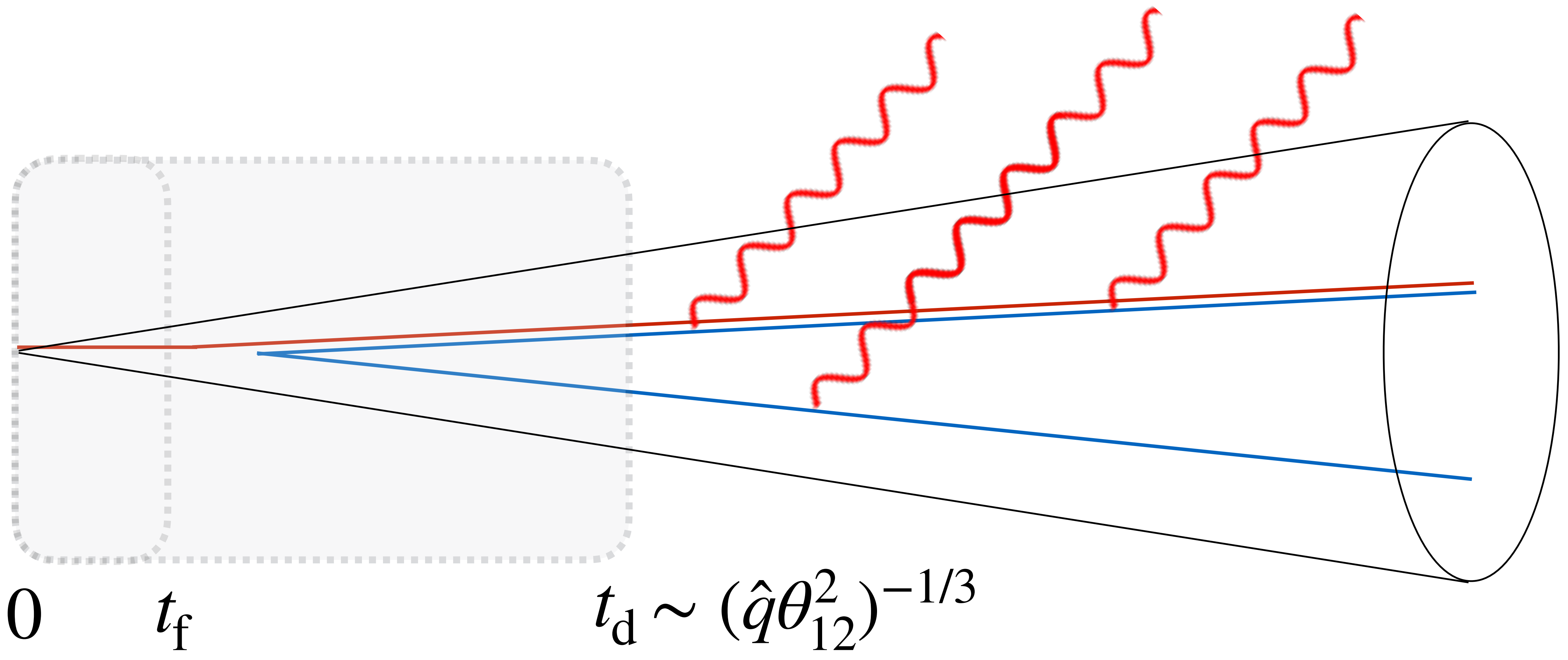


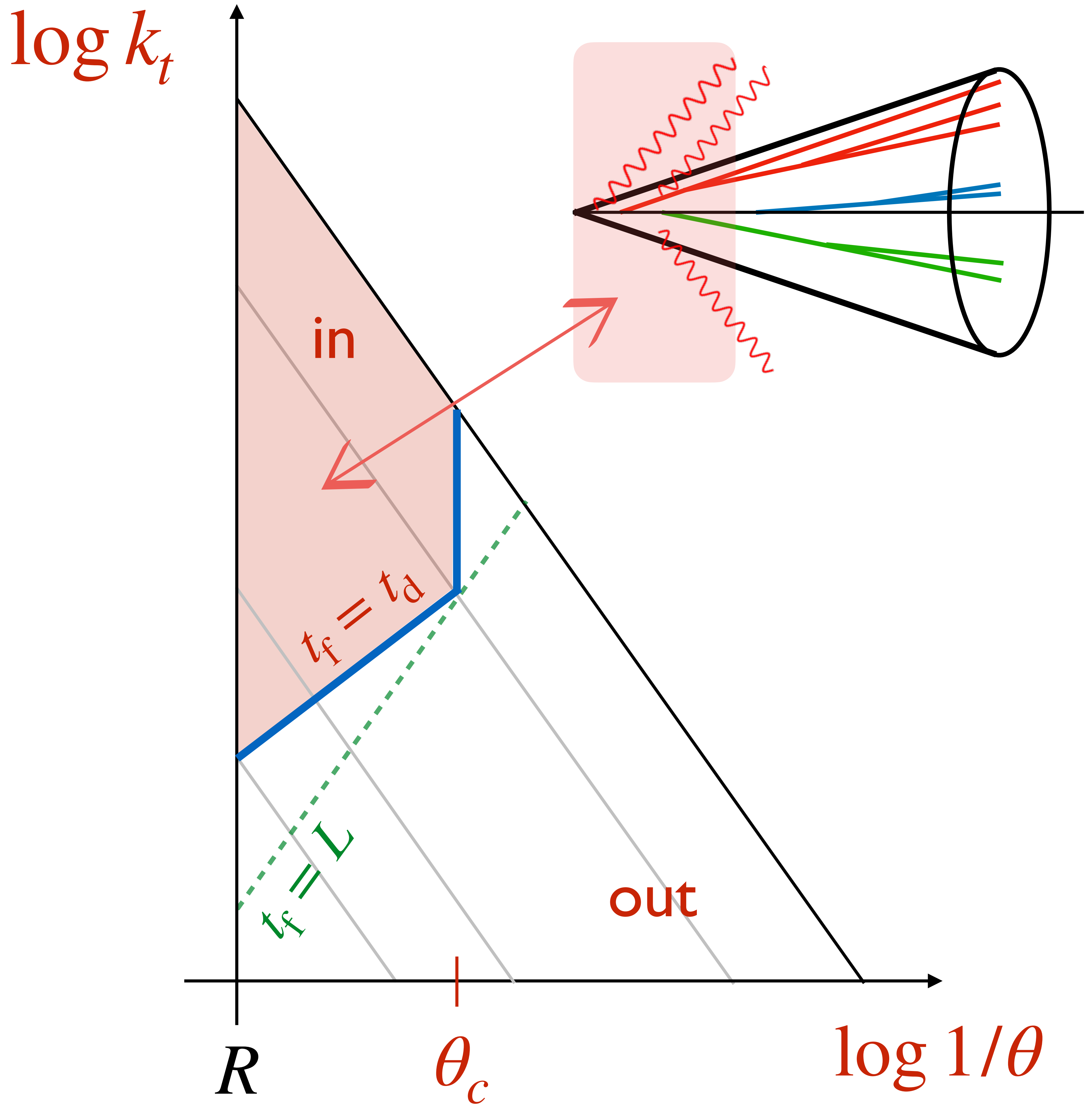
$$t_{\rm d} \sim L$$

$$\Downarrow$$

$$\theta_c \sim \sqrt{\frac{1}{\hat{q} L^3}}$$

Phase space analysis

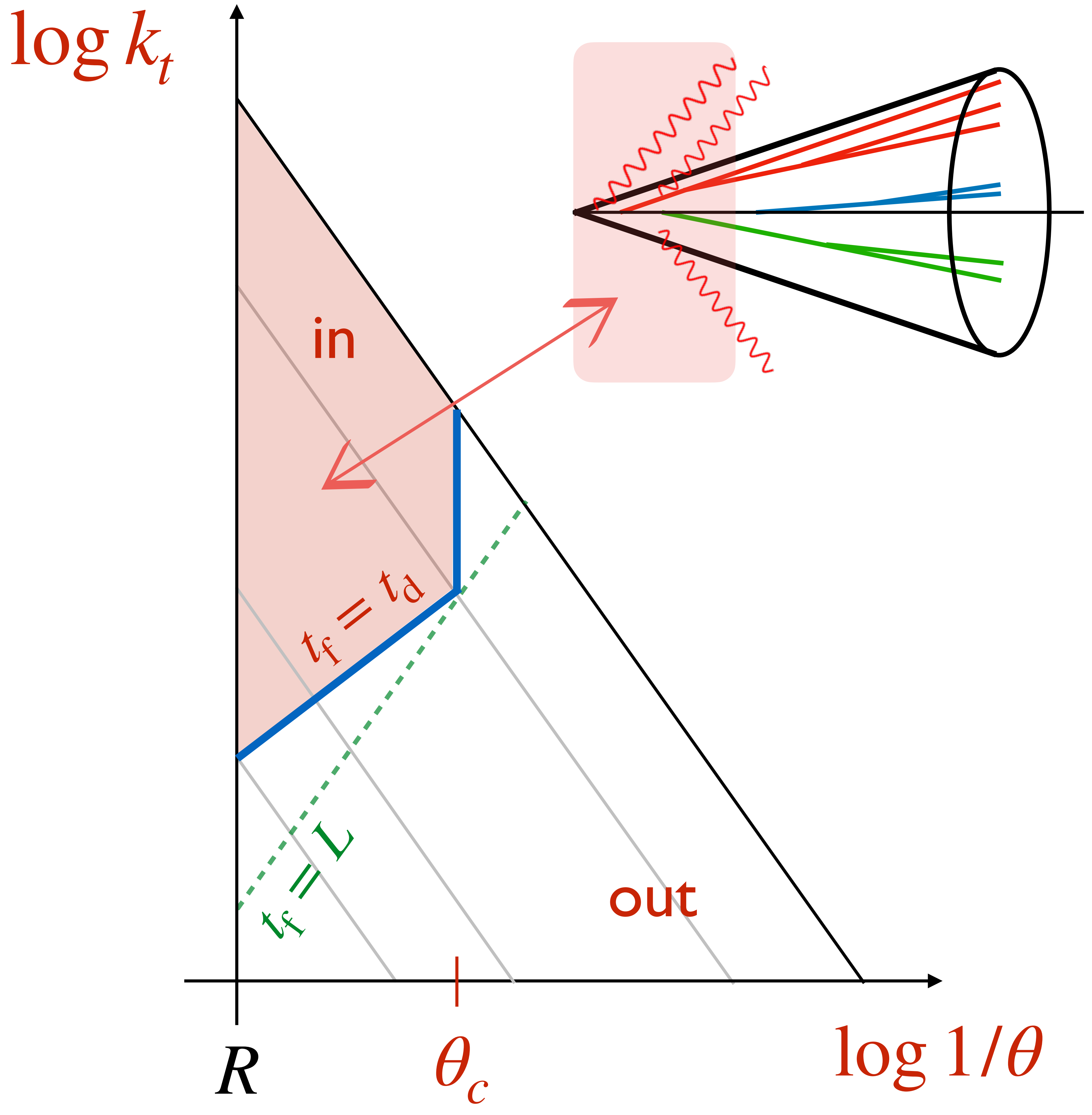
Y. Mehtar-Tani, KT 1706.06047, 1707.07361



Vacuum emissions w/ $k_t^2 > \sqrt{\hat{q}\omega}$ and $\theta > \theta_c$ are emitted inside plasma and resolved by the medium. So far, calculations have been done only in the soft limit and strong ordering (DLA).

PHASE SPACE ANALYSIS

Y. Mehtar-Tani, KT 1706.06047, 1707.07361



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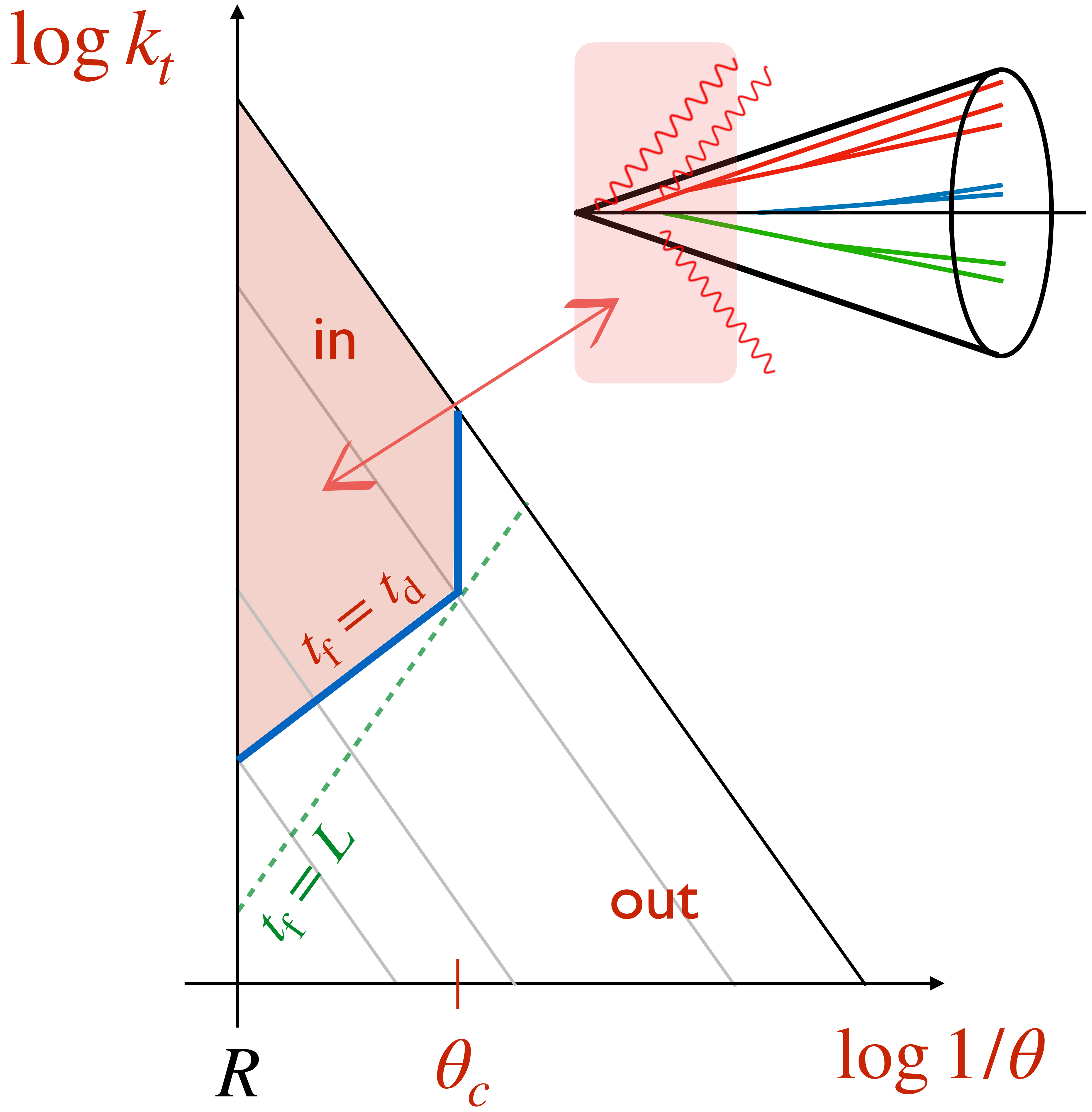
How many modes are emitted inside?

$$(\mathrm{PS})_{\mathrm{in}} \approx 2\frac{\alpha_s C_R}{\pi} \log\frac{R}{\theta_c}\left(\log\frac{p_T}{\omega_c} + \frac{2}{3}\log\frac{R}{\theta_c}\right)$$

Potentially large and needs to be resummed.

PHASE SPACE ANALYSIS

Y. Mehtar-Tani, KT 1706.06047, 1707.07361



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Potentially large and needs to be resummed.

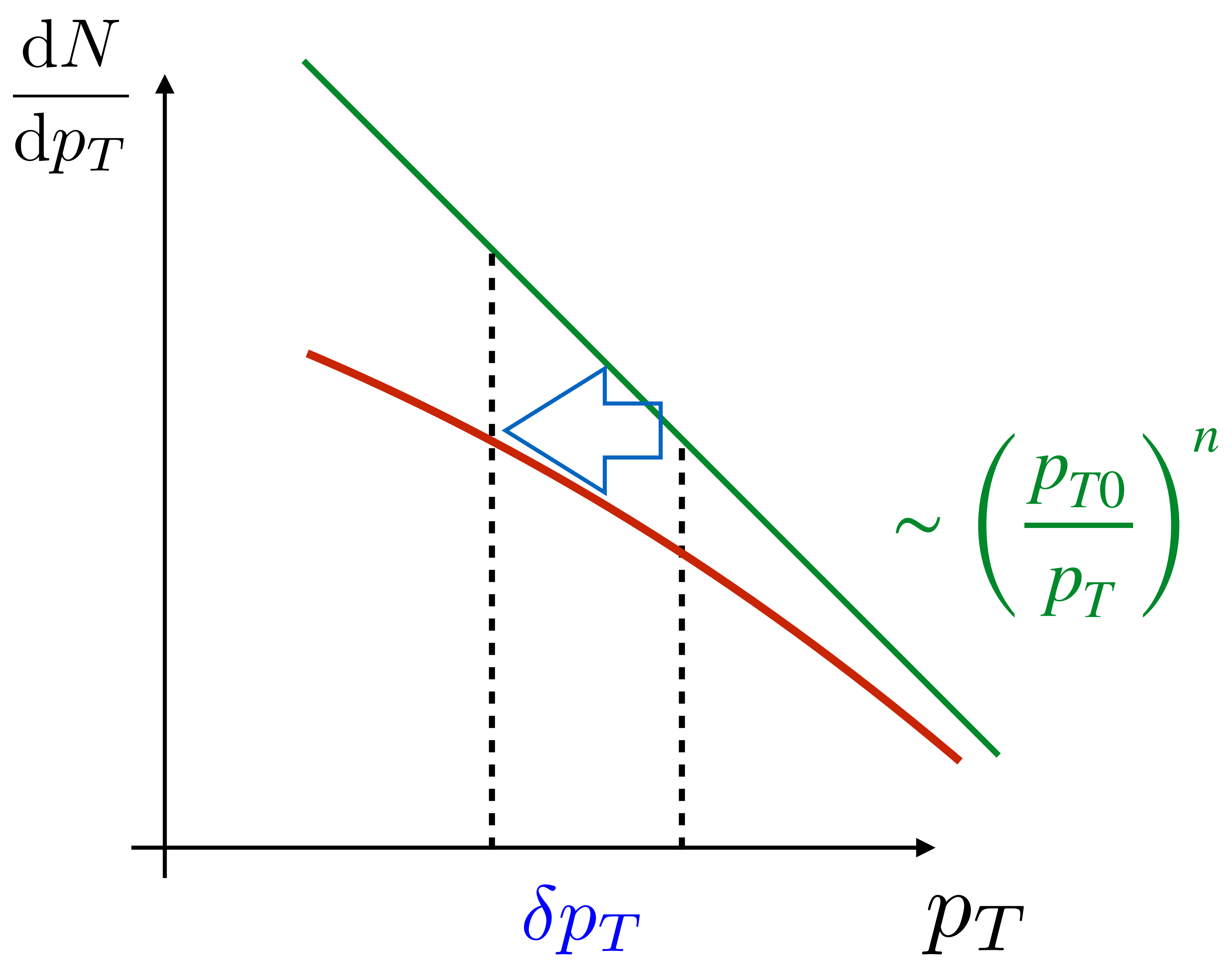
Interpretation: vacuum-like emissions created on short distances inside the medium act as sources of medium-induced radiation & cascade.

Monte Carlo implementations: Caucal, Iancu, Mueller, Soyez 1801.09703
Takacs, Pablos, KT (in preparation)

QUENCHING HARD PARTONIC SPECTRUM

Baier, Dokshitzer, Mueller, Schiff (2001)
Salgado, Wiedemann (2003)

$$\mathcal{P}(\epsilon) = \mathrm{e}^{-\int \mathrm{d}\omega \, \frac{\mathrm{d}I}{\mathrm{d}\omega}} \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int \mathrm{d}\omega_i \, \frac{\mathrm{d}I}{\mathrm{d}\omega_i} \right] \delta(\epsilon - \sum_{i=1}^{n} \omega_i)$$



Quenching factor

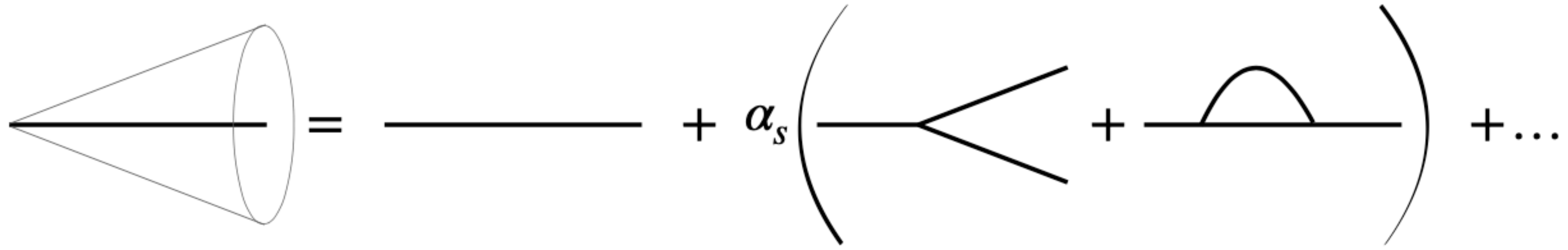
$$\frac{\mathrm{d}\sigma_{\mathrm{med}}}{\mathrm{d}p_T} = \int_0^\infty \mathrm{d}\epsilon \, \mathcal{P}(\epsilon) \, \frac{\mathrm{d}\sigma_{\mathrm{vac}}}{\mathrm{d}p'_T}\bigg|_{p'_T = p_T + \epsilon}$$

$$\approx \frac{\mathrm{d}\sigma_{\mathrm{vac}}}{\mathrm{d}p_T} \underbrace{\int_0^\infty \mathrm{d}\epsilon \, \mathcal{P}(\epsilon) \mathrm{e}^{-\epsilon \frac{n}{p_T}}}_{Q(p_T)}$$

- applies for small energy losses & steeply falling spectra
- probability distribution $\mathscr{P}(\epsilon)$ resums contribution from multiple emissions

Diagrammatic approach

Mehtar-Tani, KT 1707.07361
Mehtar-Tani, KT (in preparation)

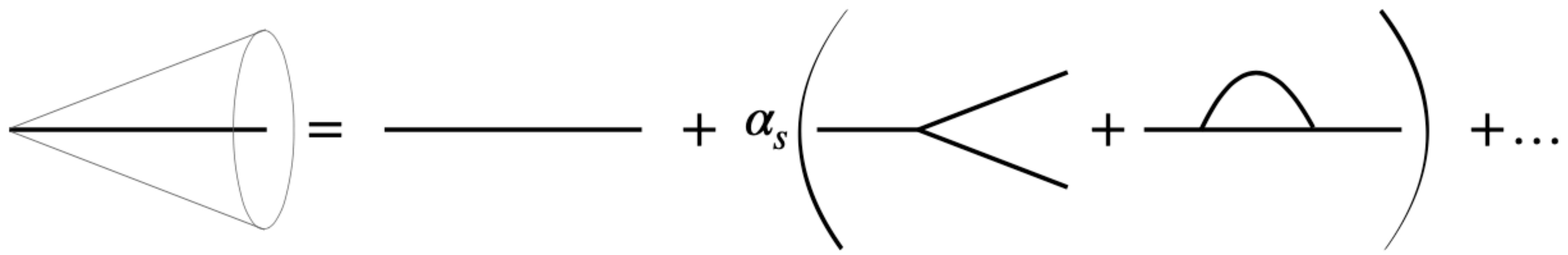


Expanding the jet spectrum:

$$\frac{\mathrm{d}\sigma_i^{\mathrm{jet}}}{\mathrm{d}p_T} = \frac{\mathrm{d}\sigma_i^{(0)}}{\mathrm{d}p_T} + \alpha_s \frac{\mathrm{d}\sigma_i^{(1)}}{\mathrm{d}p_T} + \dots$$

DIAGRAMMATIC APPROACH

Mehtar-Tani, KT 1707.07361
Mehtar-Tani, KT (in preparation)



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Full splitting function in the presence of energy loss (jet calculus):

$$P_i^{\rm med}(z,\theta,p_T) = \Theta_{\rm in} \int_0^\infty d\epsilon_1 \int_0^\infty d\epsilon_2\, \mathcal{P}_i(\epsilon_1)\mathcal{P}_g(\epsilon_2) P_{gi}(\tilde{z},\theta)\, \frac{d\sigma_0}{dp'_T}\bigg|_{p'_T=p_T+\epsilon_1+\epsilon_2} + (1-\Theta_{\rm in}) P_{gi}(z,\theta) \int_0^\infty d\epsilon\, \mathcal{P}_i(\epsilon)\, \frac{d\sigma_0}{dp'_T}\bigg|_{p'_T=p_T+\epsilon}$$

DIAGRAMMATIC APPROACH

Mehtar-Tani, KT 1707.07361
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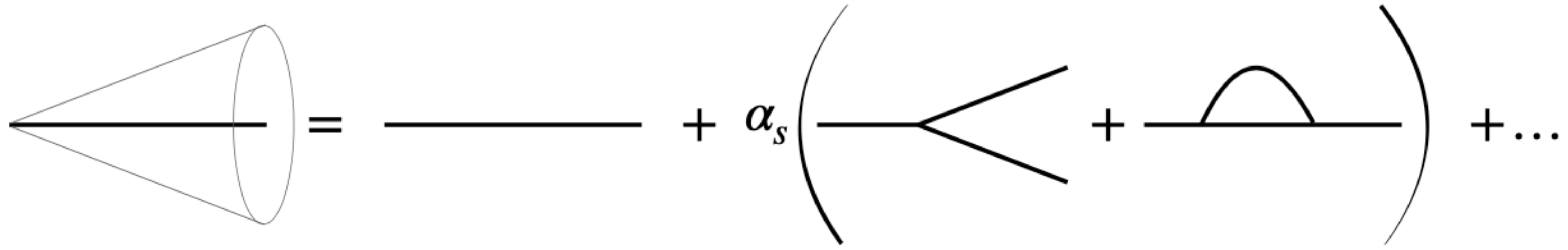

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→ emission inside the medium

→ emission outside of the medium

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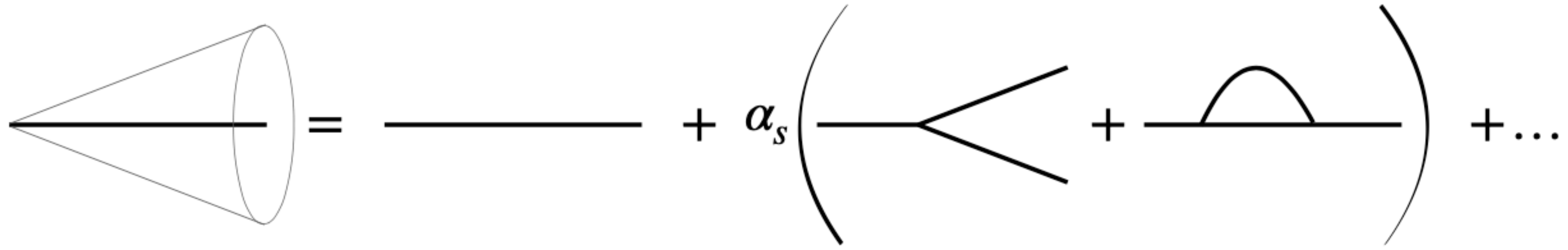

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$$\alpha_s \frac{d\sigma_i^{(1)}}{dp_T} = \int_0^R d\theta \int_0^1 dz\, \left[P_i^{\rm med}(z,\theta) - \mathcal{Q}_i P_i^{\rm vac}(z,\theta)\right] \hat{\sigma}_i$$

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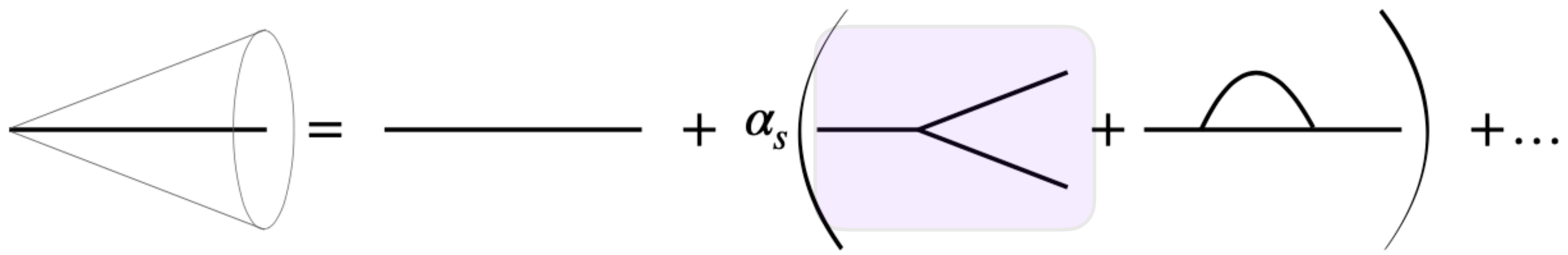
Mehtar-Tani, KT (in preparation)



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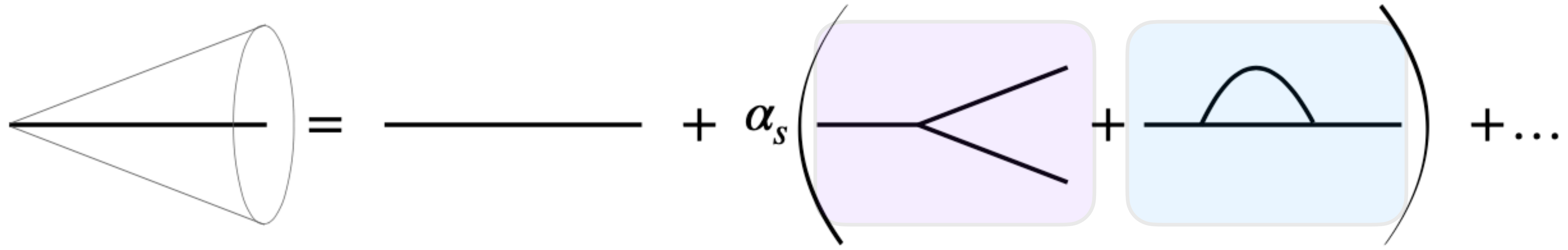
real emission (quenching x2)

DIAGRAMMATIC APPROACH

Mehtar-Tani, KT 1707.07361
Mehtar-Tani, KT (in preparation)



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real emission (quenching x2)

virtual correction (quenching x1)

Resummed quenching factor

Mehtar-Tani, KT 1707.07361
Mehtar-Tani, Pablos, KT 2101.01742

Non-linear evolution of jet quenching

$$\frac{d\sigma_i^{\text{jet}}}{dp_T} = Q_i(p_T, R)\hat{\sigma}_i$$

Normalization of the GF ($Z = 1$). Initial condition at $R = 0$ is the "bare" $Q_i^{(0)}$.

RESUMMED QUENCHING FACTOR

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Mehtar-Tani, Pablos, KT 2101.01742

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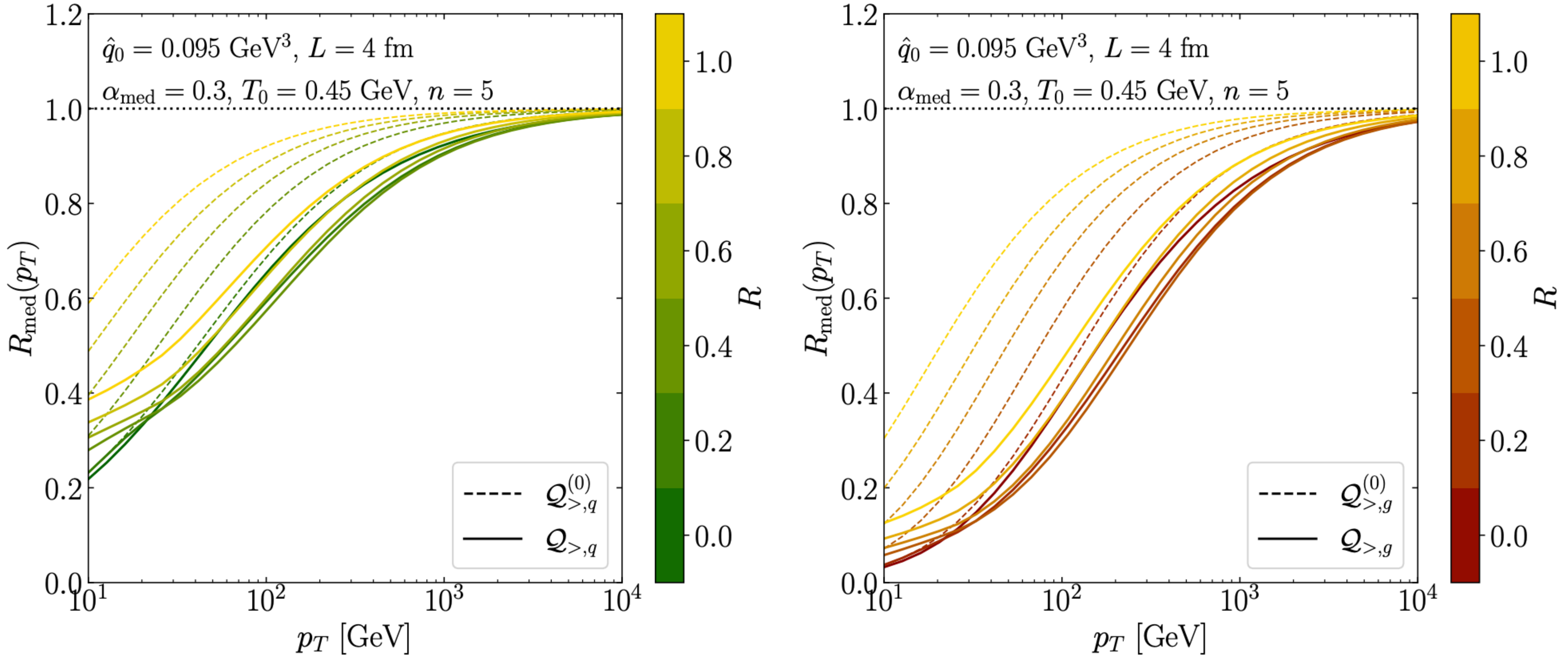
$$\frac{\partial Q_i(p,\theta)}{\partial \ln \theta} = \int_0^1 {\rm d}z \, \frac{\alpha_s(k_\perp)}{2\pi} p_{ji}^{(k)}(z)\Theta_{\rm in}(z,\theta)[Q_j(zp,\theta)Q_k((1-z)p,\theta) - Q_i(p,\theta)]$$

Takacs, KT 2103.14676



Milder R-dependence than for single-parton quenching.

Competition of two effects:

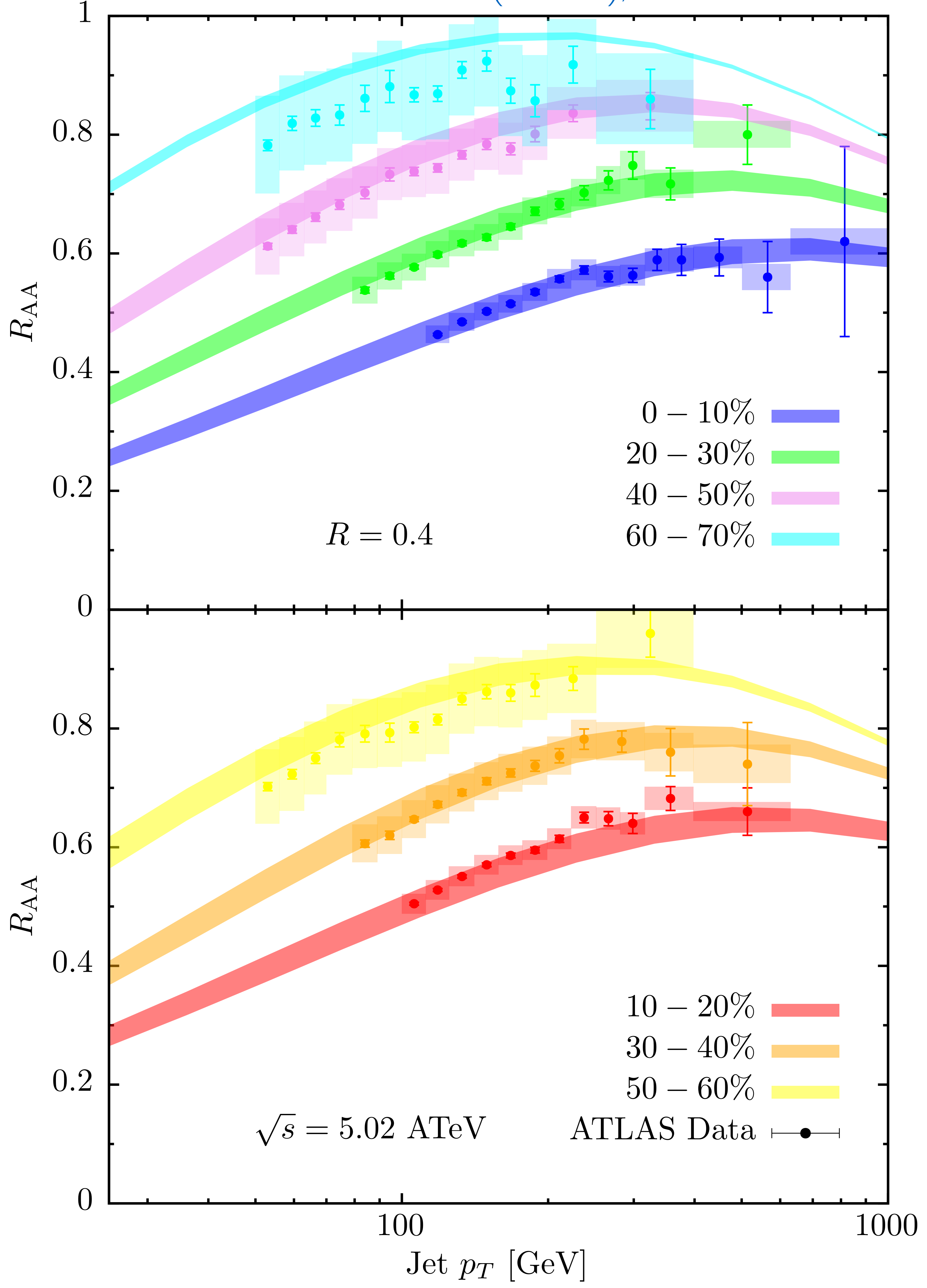
- recovery of radiated energy at large R
- more color sources from vacuum-like emissions at large R

[see also Blok, KT 1901.07864 for heavy quark jets]

NUMERICAL RESULTS

Mehtar-Tani, Pablos, KT 2101.01742 (accepted in PRL)
Takacs, KT 2103.14676

M. Aaboud et al. (ATLAS), 1805.05635



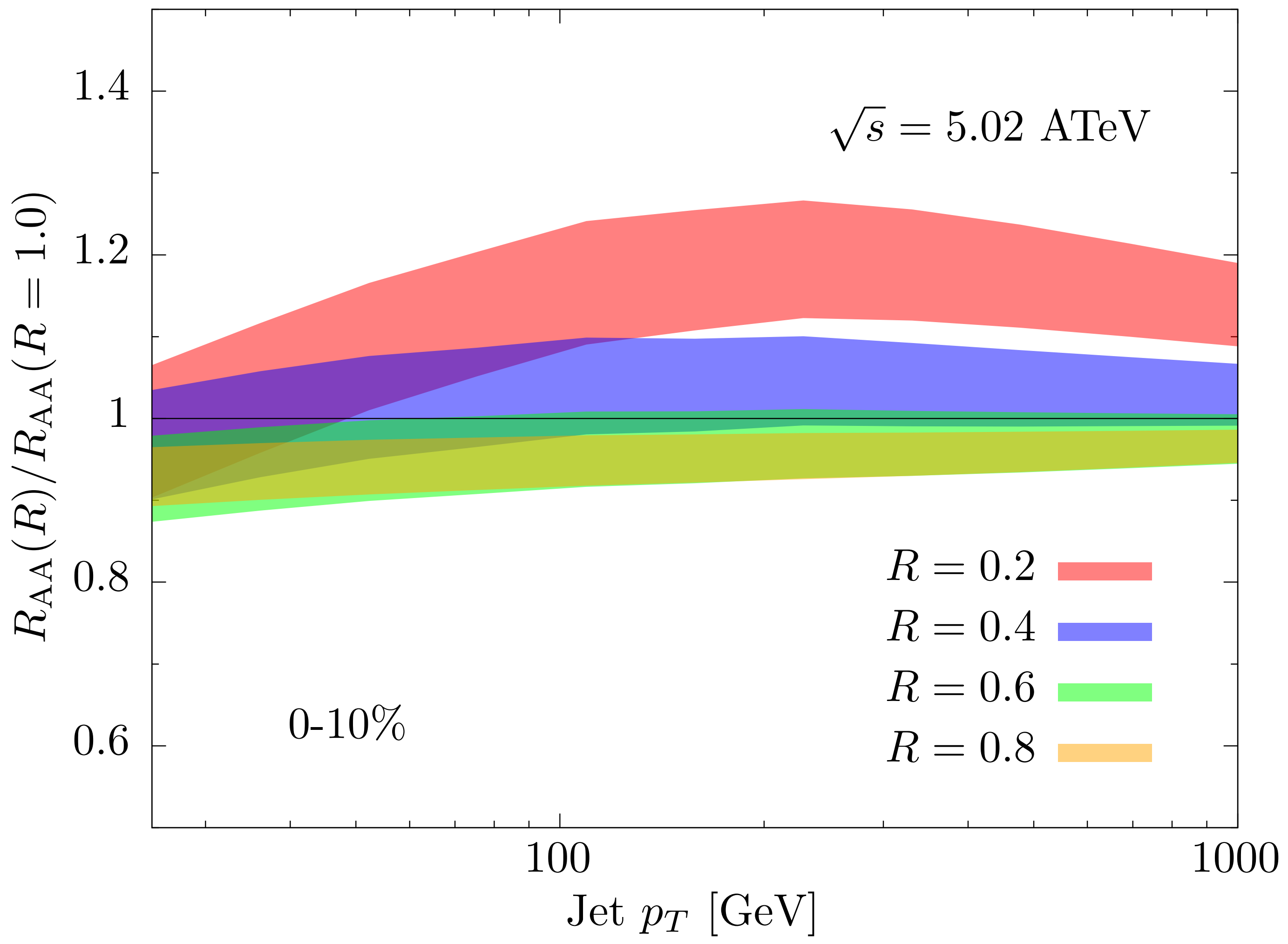
- collinear factorization w/nPDF (EPS09)
- DGLAP evolution to $R = 0.4$
- full resummation of radiative and elastic processes in the medium
- sampling of geometry and medium evolution (VISHNU) Shen, Qiu, Song, Bernhard, Bass, Heinz 1409.8164
- only two free parameters:

$g_{\rm med}$ medium coupling

$R_{\rm rec}$ non-pert recovery angle

CONE-SIZE DEPENDENCE

Mehtar-Tani, Pablos, KT 2101.01742
M. Aaboud et al. (ATLAS) 1805.05635
S. Acharya et al. (ALICE) 1909.09718
CMS-PAS-HIN-18-014



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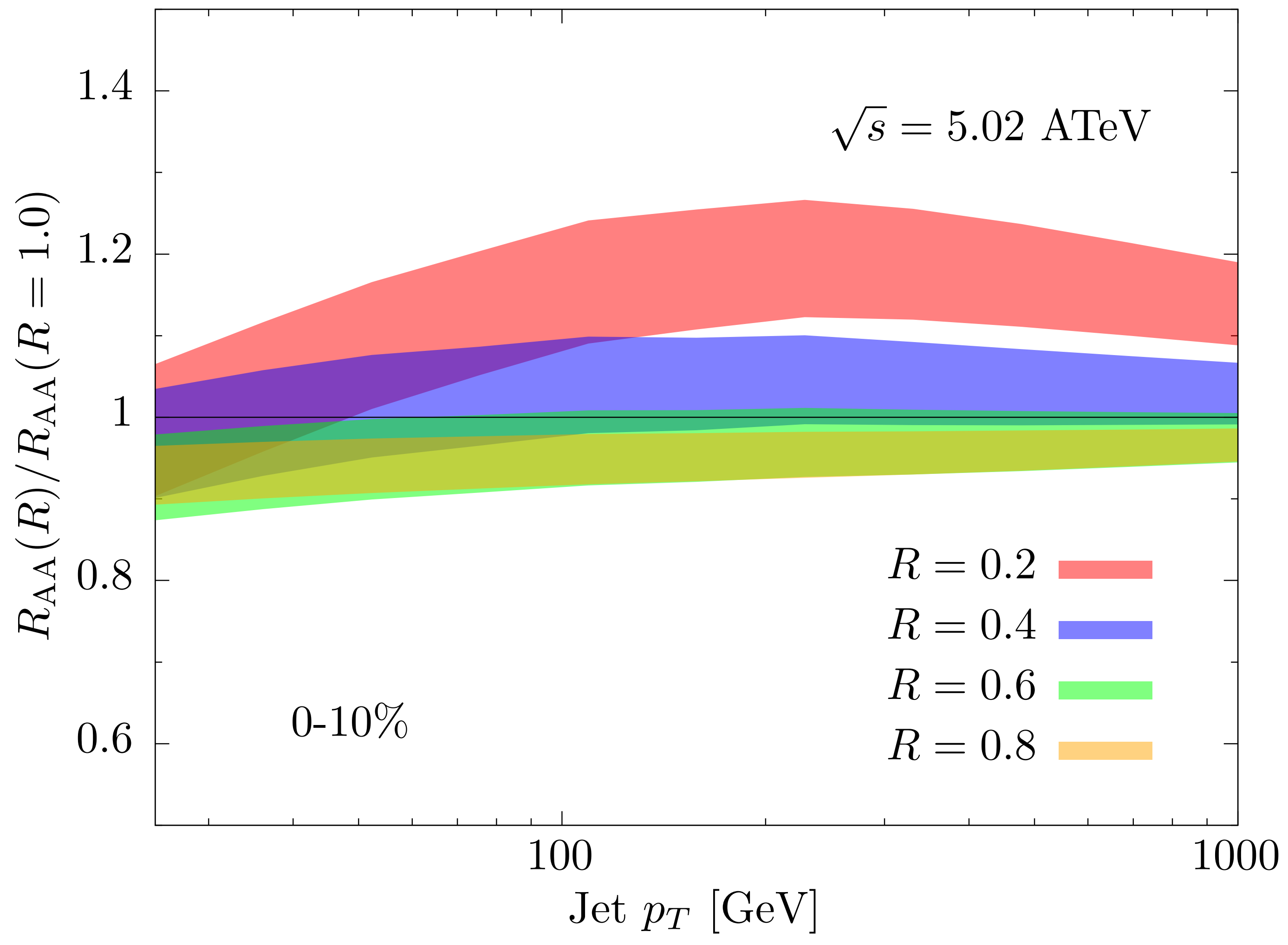

- excellent agreement with ATLAS and ALICE data at $R = 0.4$

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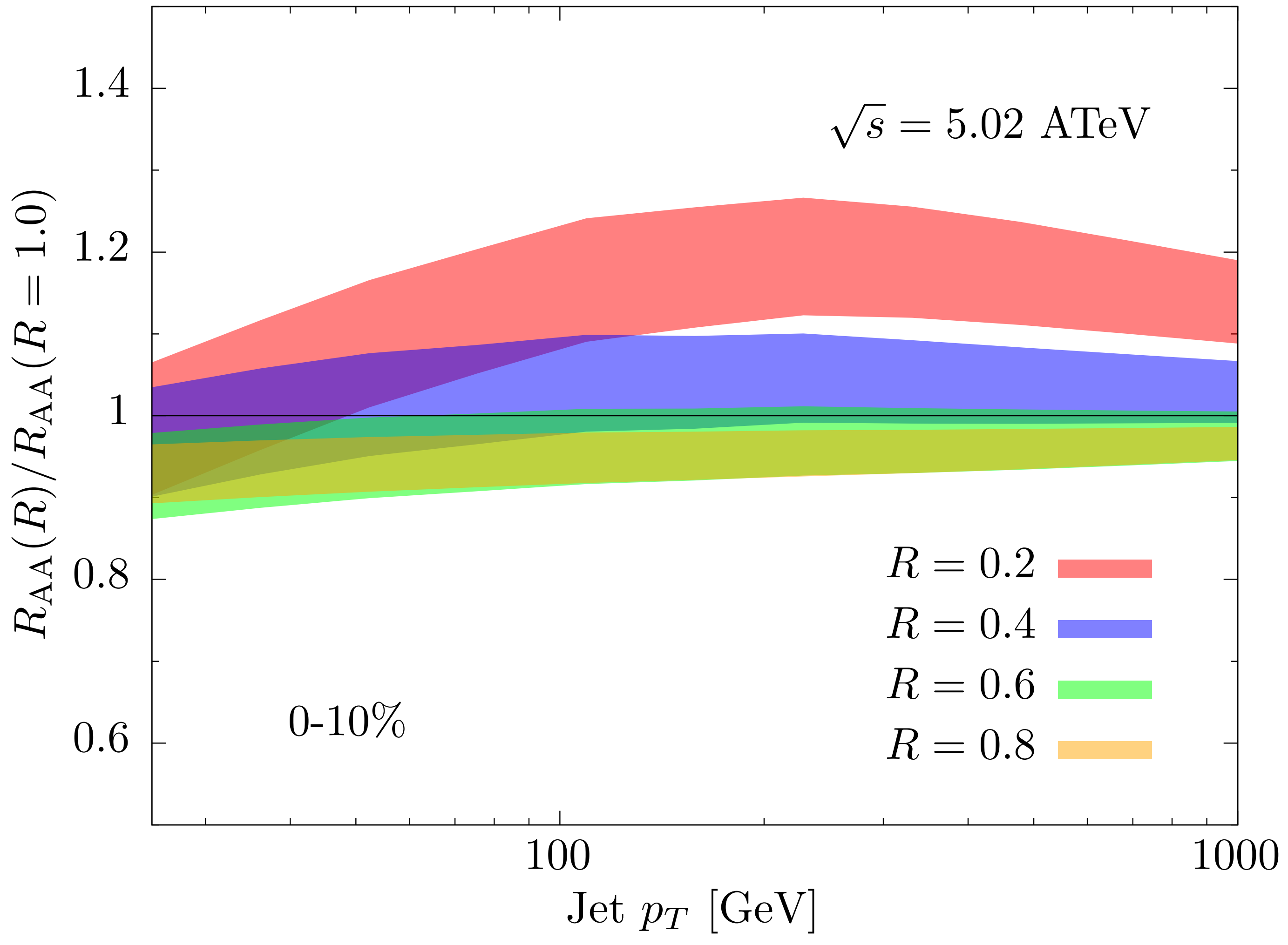

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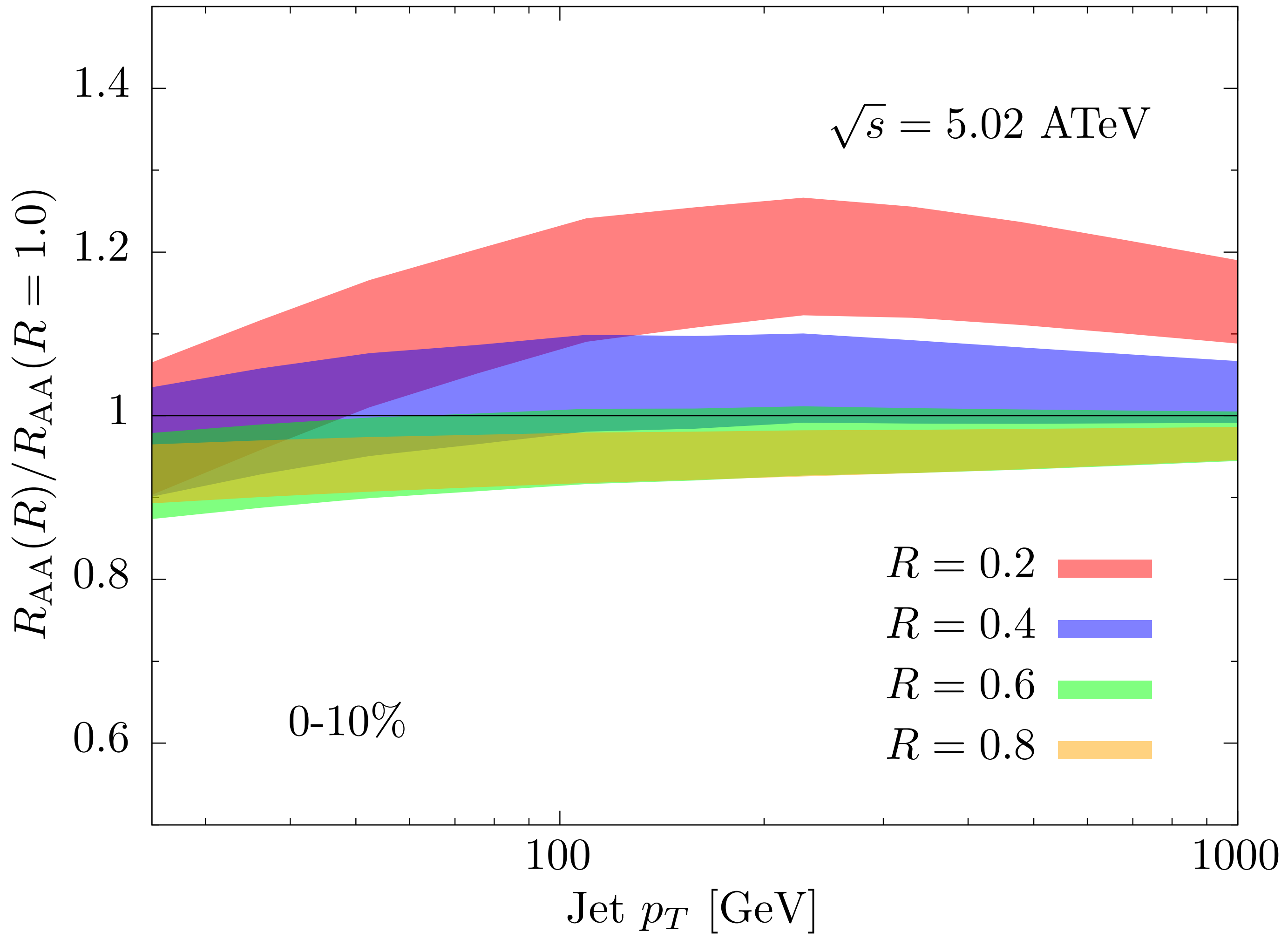


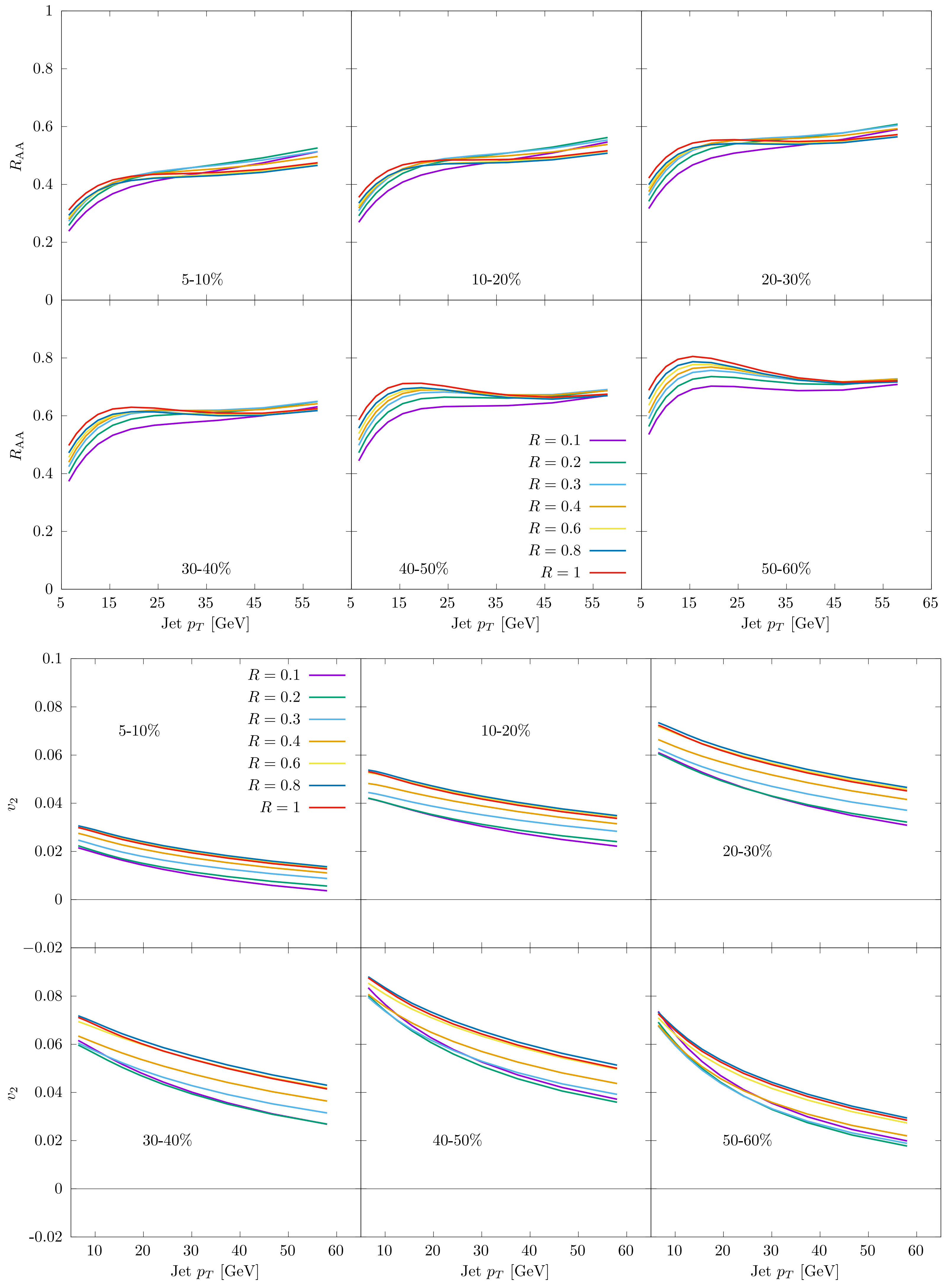
Parameter	Variation	Effect
θ_c	$[\theta_c/2,\ 2\theta_c]$	$\lesssim 20\%$
IOE	LO/NLO	$\sim 2\%$
n	± 1	$\sim 10\%$
R_{rec}	$[1,\ \infty]$	$\lesssim 10\%$
ω_s	$[\omega_s/2,\ 2\omega_s]$	$\lesssim 8\%$

- excellent agreement with ATLAS and ALICE data at $R = 0.4$
- cone-size dependence follows trend seen by CMS
- main uncertainties for $R \leq 0.6$:
  - perturbative sector (vacuum-like emissions + medium-induced $\omega > \omega_s$) dominates!
  - higher-twist contributions at IOE-NLO are negligible
  - details of thermalization/recovery (R_{rec}) important at $R \gtrsim 0.6$

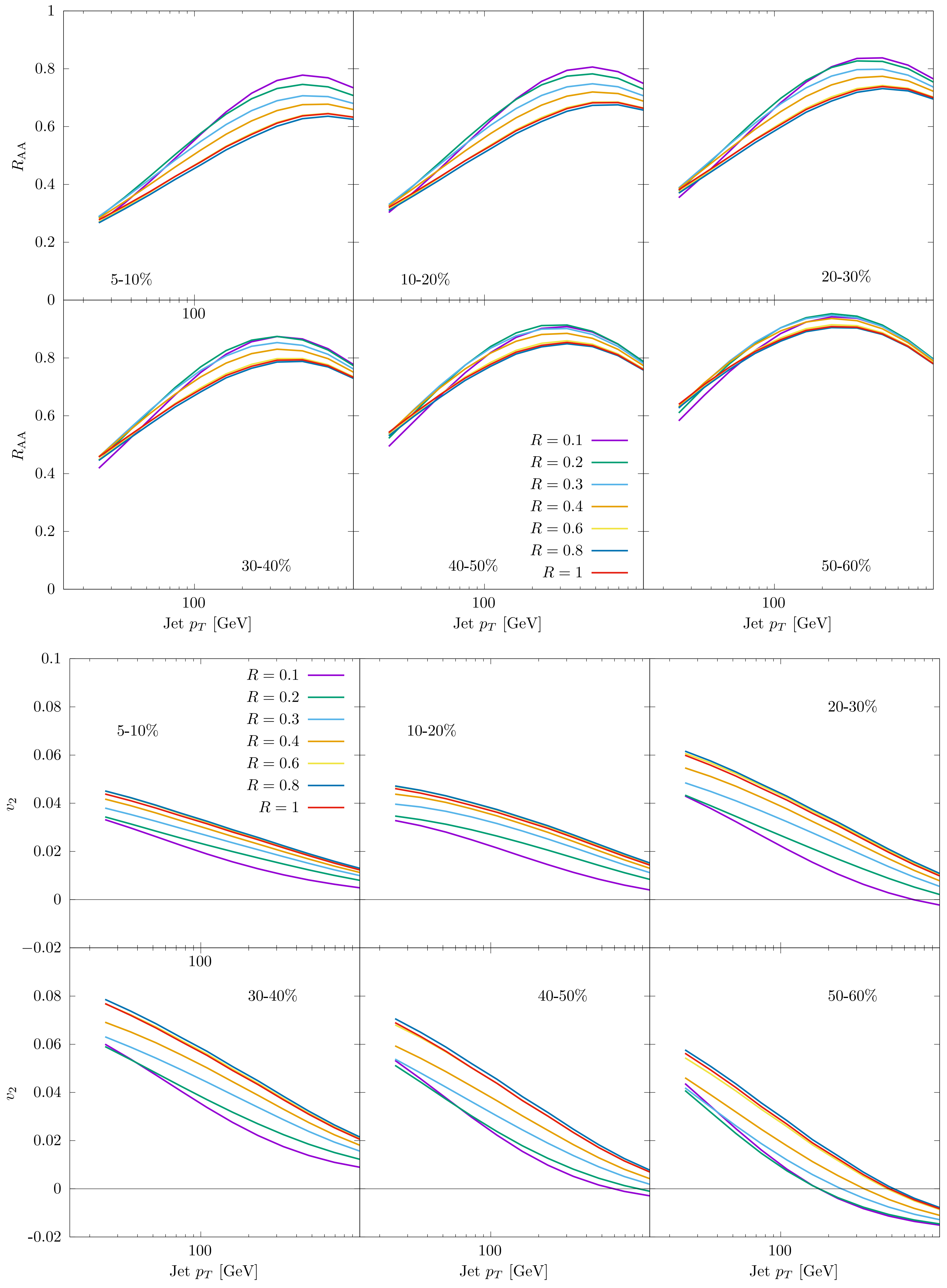
PREDICTIONS FOR RHIC & LHC

Mehtar-Tani, Pablos, KT (in preparation)

RHIC

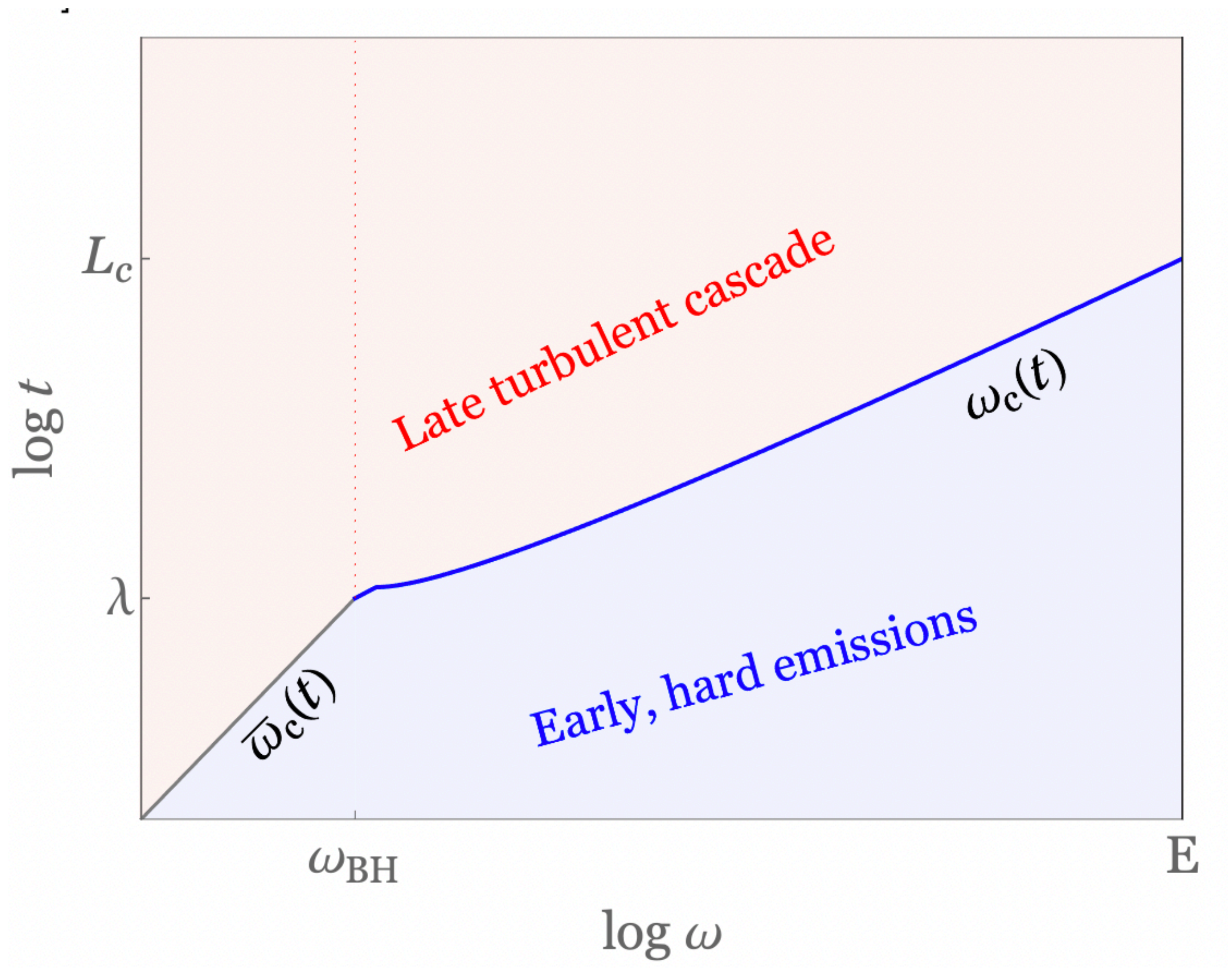


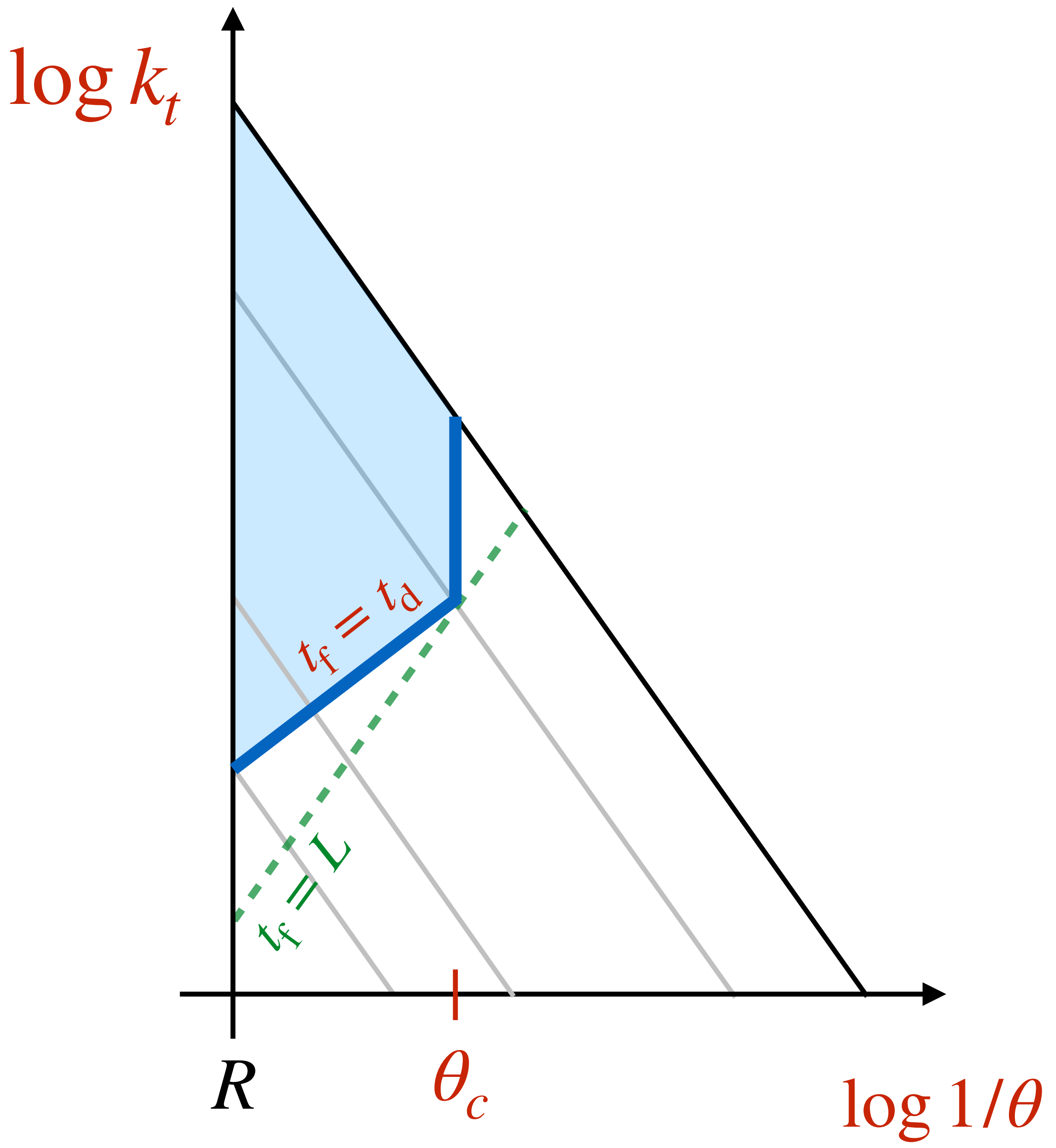
LHC



Prominent role of θ_c: grouping in R-dependence!

SUMMARY & OUTLOOK



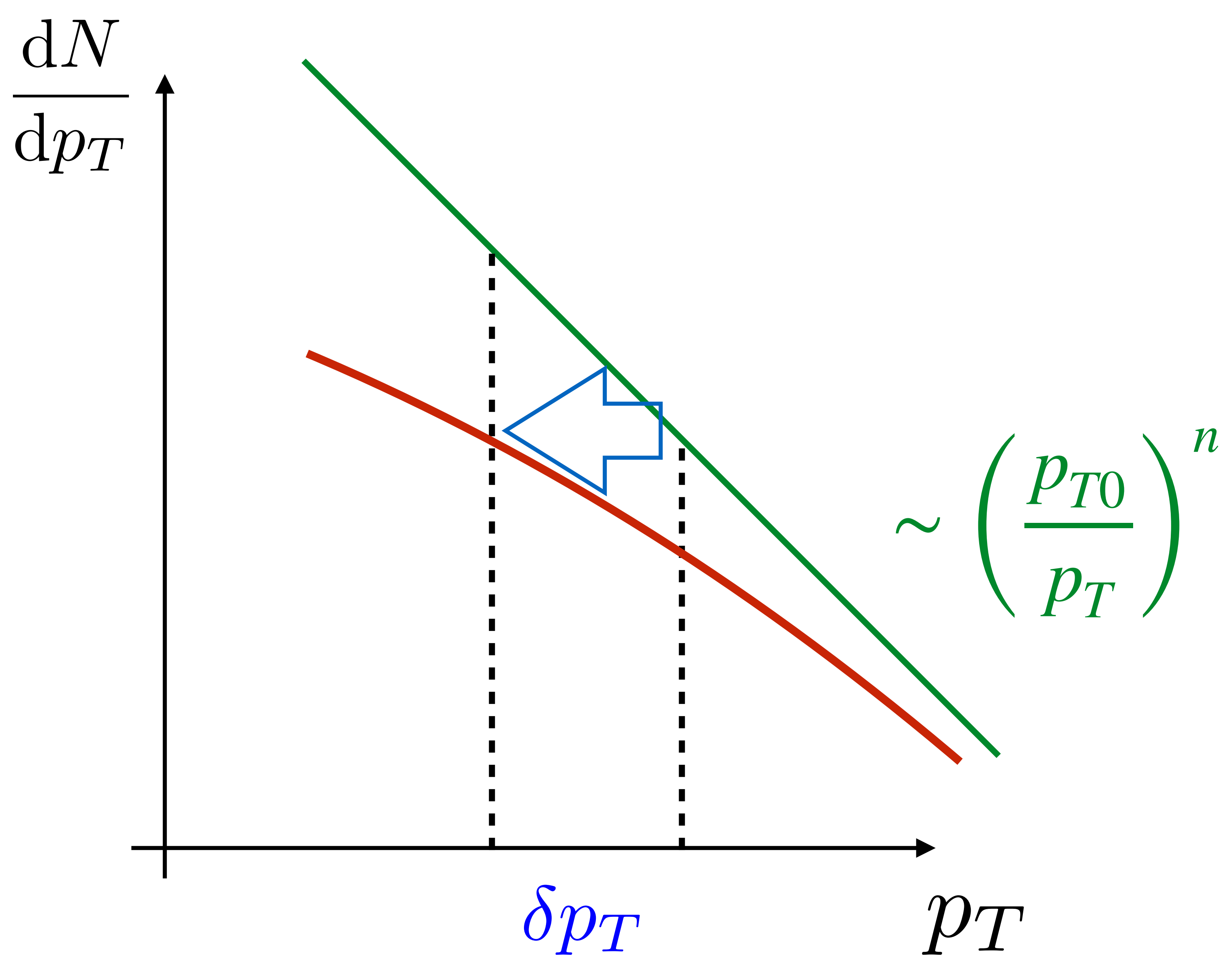


- Theory improvements provide a solid basis for higher-order precision calculations of hard probes - central to achieve predictive power!
  - analytical control of full medium-induced phase space!
- First steps to merge emergent spacetime picture of vacuum and medium processes.
- Many further avenues to explore (jet substructure, low-p_T, small systems,…)
  - $\hat{q}$ is a measure of both the amount of energy lost & the resolution properties of the medium (color coherence)

Backup

FURTHER IMPLICATIONS OF QUENCHING

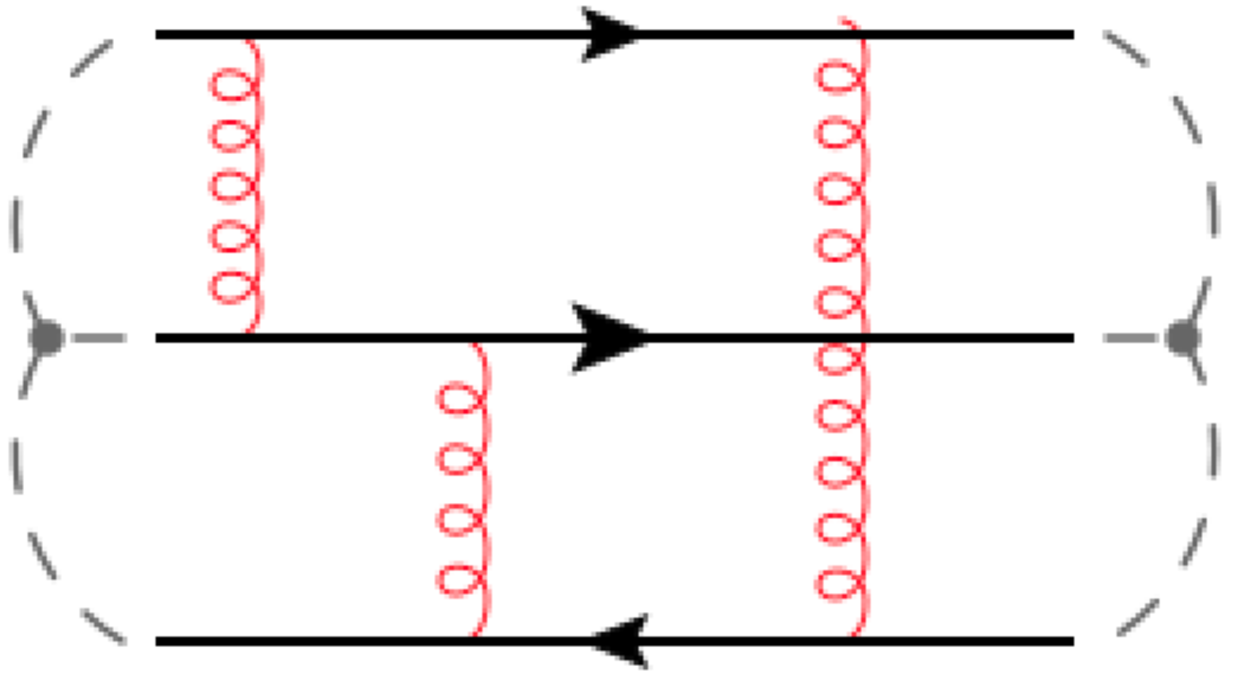
- **Bias effect:** shift of spectrum affects many observables that are computed at a given final/measured
  - in heavy-ion we compare jets from a higher bin that have migrated down with jets in pp at that bin.
  - jets at high- have different characteristics due to DGLAP evolution!
  - depends on $n(p_T)$
- **Color charge effect:** quark jets (i.e. jets originating from quarks) are less quenched than gluon jets.
  - observables in heavy-ions will have a different quark/gluon mix than in pp!



Medium-induced radiation

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996) (Arnold, Moore, Yaffe (2003))

$$z\frac{\mathrm{d}I_{ba}}{\mathrm{d}z} = \frac{\alpha_s\, zP_{ba}(z)}{(z(1-z)E)^2}\, 2\mathrm{Re}\int_0^\infty \mathrm{d}t_2 \int_0^{t_2} \mathrm{d}t_1$$
$$\boldsymbol{\partial}_{\boldsymbol{x}} \cdot \boldsymbol{\partial}_{\boldsymbol{y}} \Big[\mathcal{K}_{ba}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) - \mathcal{K}_0(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1)\Big]_{\boldsymbol{x}=\boldsymbol{y}=0}$$



- integrated over $\boldsymbol{k}$, divergences regulated by vacuum subtraction

$$\left[i\frac{\partial}{\partial t} + \frac{\boldsymbol{\partial}^2}{2z(1-z)E} + i v_{\boldsymbol{ba}}(\boldsymbol{x}, t)\right] \mathcal{K}_{\boldsymbol{ba}}(\boldsymbol{x}, t; \boldsymbol{y}, t_0) = i\delta(t - t_0)\delta(\boldsymbol{x} - \boldsymbol{y})$$

3-body potential:

$$v^c_{\boldsymbol{ba}}(\boldsymbol{x}, t) = \frac{C_b + C_c - C_a}{2}\tilde{v}(\boldsymbol{x}, t) + \frac{C_c + C_a - C_b}{2}\tilde{v}(z\boldsymbol{x}, t) + \frac{C_a + C_b - C_c}{2}\tilde{v}\big((1-z)\boldsymbol{x}, t\big)$$

OPACITY EXPANSION

Wiedemann (2000); Gyulassy, Levai, Vitev (2001)

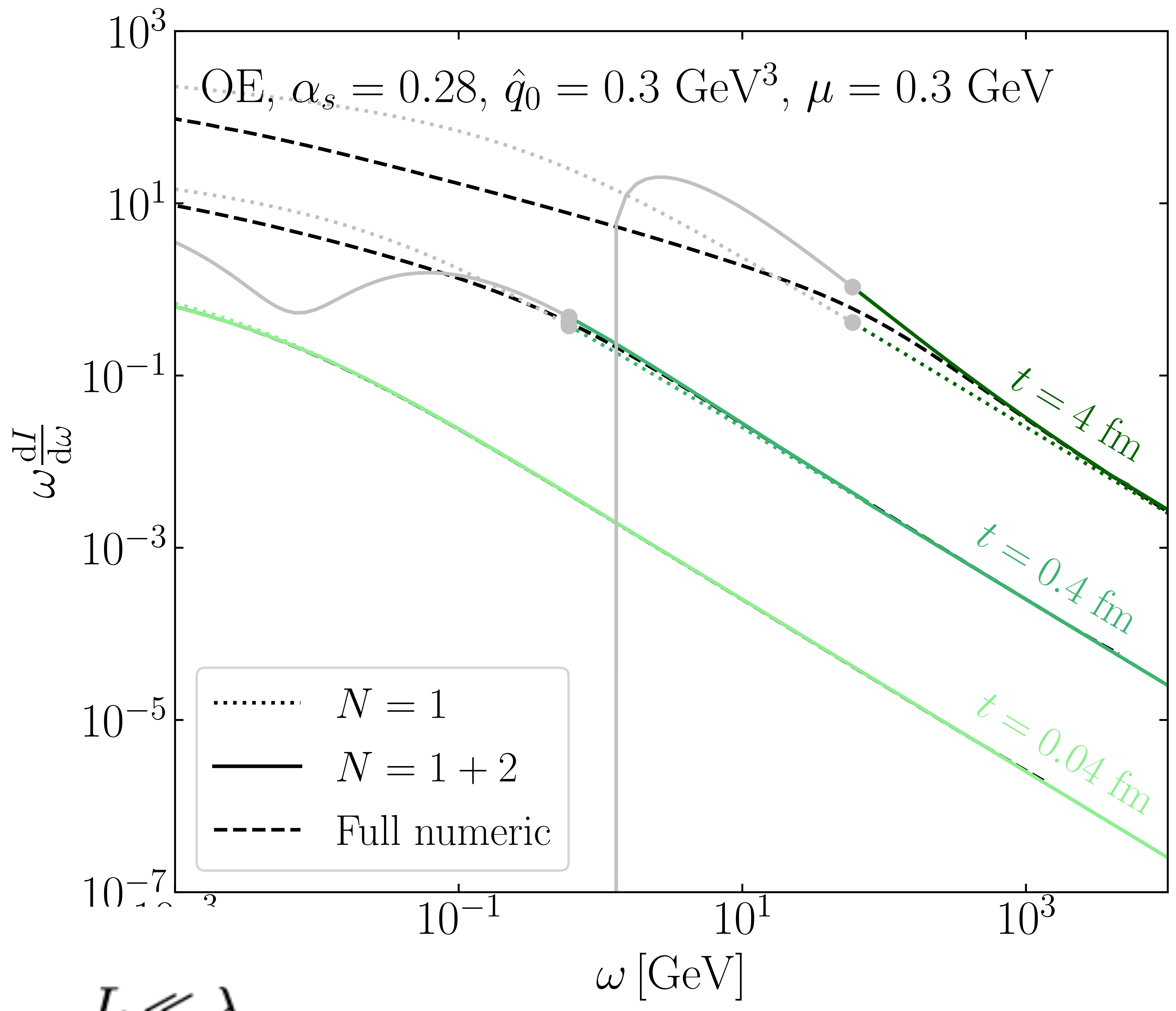
Spectrum reads:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \frac{4\alpha_s C_R}{\omega} \mathrm{Re}\, i \int_0^L \mathrm{d}t_2 \int_0^{t_2} \mathrm{d}t_1 \int_{\boldsymbol{p},\boldsymbol{p}_0} \Sigma(\boldsymbol{p}^2, t_2) \frac{\boldsymbol{p}\cdot\boldsymbol{p}_0}{\boldsymbol{p}^2} \mathcal{K}(\boldsymbol{p}, t_2; \boldsymbol{p}_0, t_1)$$

$$\Sigma(\boldsymbol{k}^2, s) = \int_{\boldsymbol{q}} \sigma(\boldsymbol{q}, s) \Theta(\boldsymbol{q}^2 - \boldsymbol{k}^2)$$

Expansion in medium scatterings:

$$\mathcal{K}(\boldsymbol{p}, t_2; \boldsymbol{p}_0, t_1) = (2\pi)^2 \delta(\boldsymbol{p} - \boldsymbol{p}_0) \mathcal{K}_0(\boldsymbol{p}; t_2 - t_1) - \int_{t_1}^{t_2} \mathrm{d}s \int_{\boldsymbol{q}} \mathcal{K}_0(\boldsymbol{p}; t_2 - s) v(\boldsymbol{q}, s) \mathcal{K}(\boldsymbol{p} - \boldsymbol{q}, s; \boldsymbol{p}_0, t_1)$$



All-order structure:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \begin{cases} \bar{\alpha} \sum_{n=1}^{\infty} \left(\frac{L}{\lambda}\right)^n h_n\left(\frac{\omega}{\bar{\omega}_c}\right), & L \ll \lambda, \\ \bar{\alpha} \sum_{n=1}^{\infty} \left(\frac{L}{\lambda}\frac{\bar{\omega}_c}{\omega}\right)^n \tilde{h}_n\left(\frac{\bar{\omega}_c}{\omega}\right), & \omega \gg \frac{L}{\lambda}\bar{\omega}_c \end{cases}$$

RESUMMED OPACITY EXPANSION

Wiedeman (2000)
Andres, Dominguez, Gonzalez Martinez 2011.06522
Isaksen, Takacs, KT (in preparation)

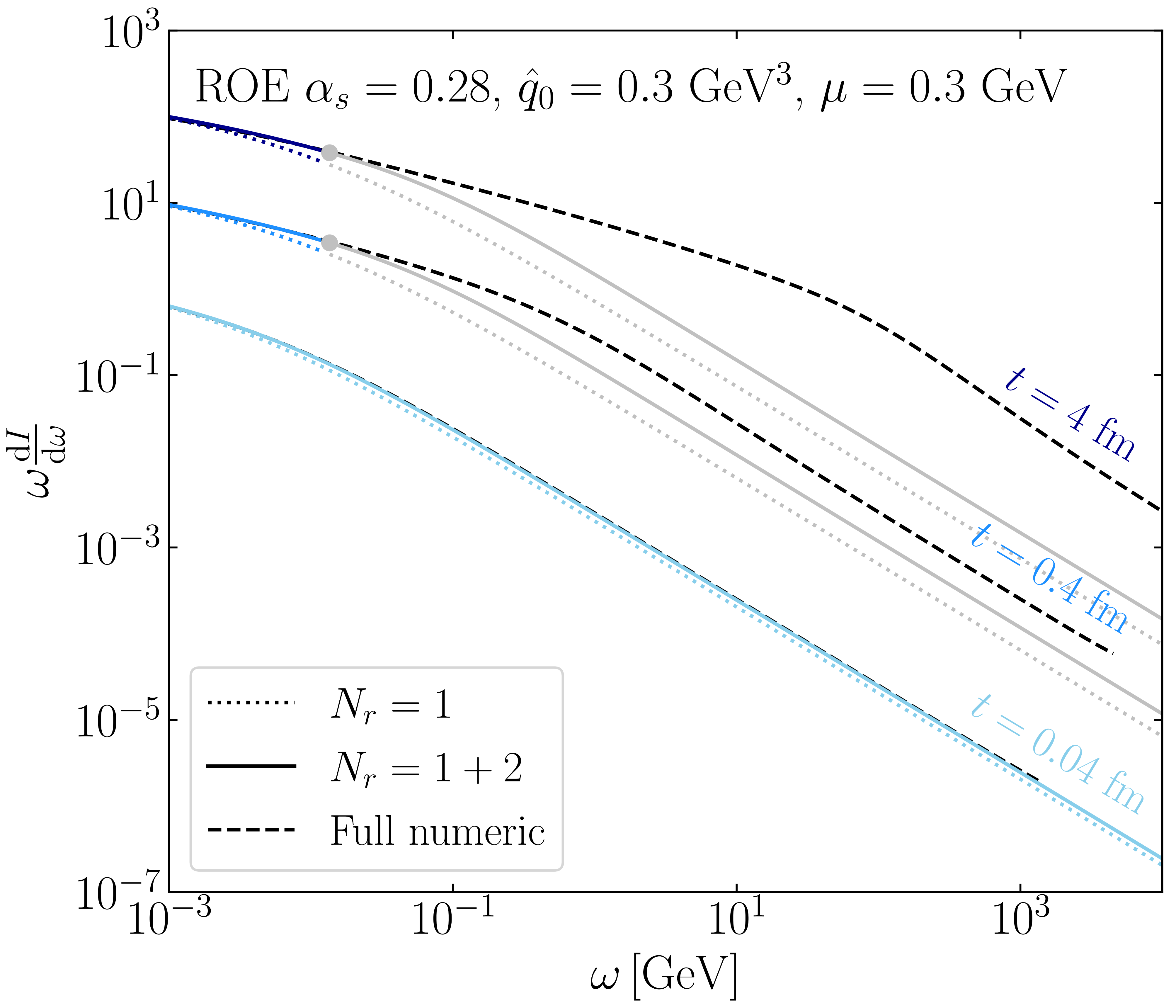
Expansion in "real" scatterings (virtual resummed):

$$\mathcal{K}(\boldsymbol{p},t;\boldsymbol{p}_0,t_0) = (2\pi)^2\delta(\boldsymbol{p}-\boldsymbol{p}_0)\Delta(t,t_0)\mathcal{K}_0(\boldsymbol{p};t-t_0) + \int_{t_0}^{t} \mathrm{d}s \frac{\Delta(t,t_0)}{\Delta(s,t_0)} \int_{\boldsymbol{q}} \mathcal{K}_0(\boldsymbol{p};t_2-s)\sigma(\boldsymbol{q},s)\mathcal{K}(\boldsymbol{p}-\boldsymbol{q},s;\boldsymbol{p}_0,t_0)$$

$$\Delta(t,t_0) \equiv \mathrm{e}^{-\int_{t_0}^{t}\mathrm{d}s\,\Sigma(s)} = \mathrm{e}^{-\Sigma(t-t_0)}$$

probability of no elastic scattering

$$\Sigma(t) = \int_{\boldsymbol{q}} \sigma(\boldsymbol{q},t)$$



Equivalent to OE at $L \ll \lambda$ and formally breaking down at ω_{BH}.

Improved opacity expansion

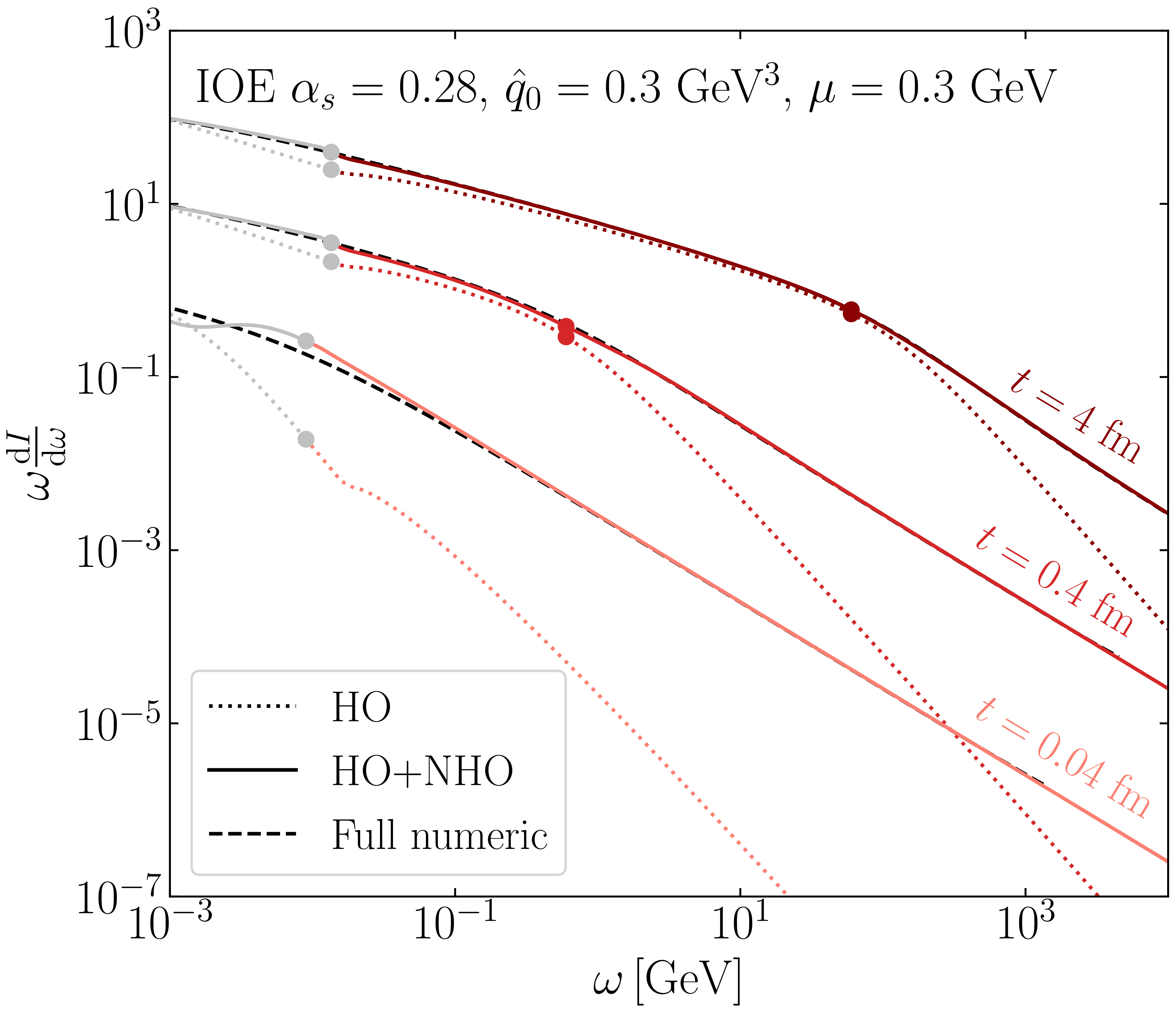
Mehtar-Tani 1903.00506
Mehtar-Tani, Tywoniuk 1910.02032
Mehtar-Tani, Barata 2004.02323

Leading-log potential split into HO and remainder:

$$v^{\rm LT}(\boldsymbol{x}) \equiv v^{\rm HO}(\boldsymbol{x}) + \delta v(\boldsymbol{x}) = \frac{1}{4}\hat{q}_0 \boldsymbol{x}^2 \log \frac{Q^2}{\mu_\star^2} + \frac{1}{4}\hat{q}_0 \boldsymbol{x}^2 \log \frac{1}{Q^2 \boldsymbol{x}^2}$$

Expanding around the harmonic oscillator

$$\mathcal{K}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) = \mathcal{K}_{\rm HO}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) - \int_{\boldsymbol{z}} \int_{t_1}^{t_2} ds\, \mathcal{K}_{\rm HO}(\boldsymbol{x}, t_2; \boldsymbol{z}, s)\delta v(\boldsymbol{z}, s)\mathcal{K}(\boldsymbol{z}, s; \boldsymbol{y}, t_1)$$



Separation scale implicitly solved:

$$Q^2(\omega) = \sqrt{\hat{q}_0\, \omega \log \frac{Q^2}{\mu_\star^2}}$$

Redefinition: "dressed" transport coefficient:

$$\hat{q} = \frac{\langle k_\perp^2 \rangle_{\rm typ}}{L} = \hat{q}_0 \log \frac{Q_s^2}{\mu_*^2}$$