UNIVERSITY OF BERGEN

CONE SIZE DEPENDENCE OF JETS IN HEAVY-ION COLLISIONS

Konrad Tywoniuk

in collaboration with Yacine Mehtar-Tani & Dani Pablos

Extreme Nonequilibrium QCD (online)

5-9 October 2020, International Centre for Theoretical Sciences, Tata Institute for Fundamental Research

OUTLINE

- structure of QCD jets
- matching vacuum and medium evolution equations
- quenching in the improved opacity expansion
- phenomenological application: cone-size dependent jet spectrum

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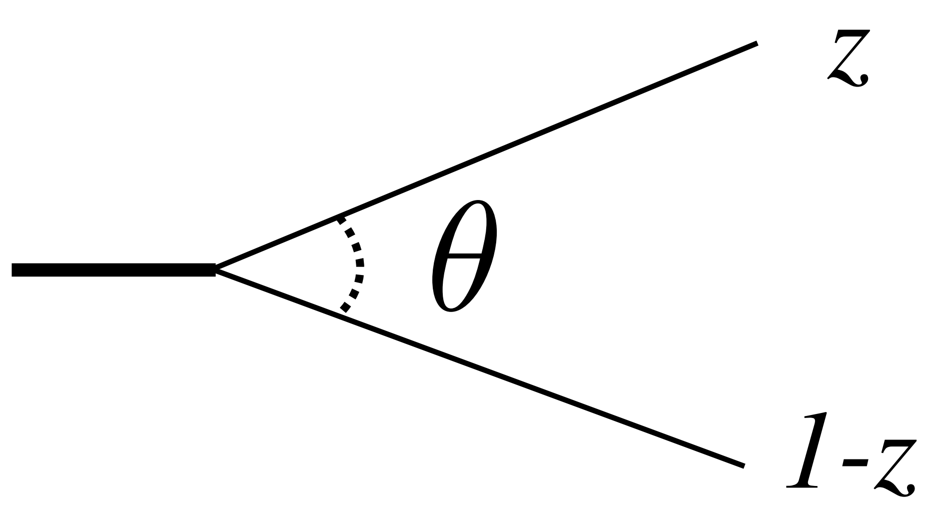
Vacuum splitting

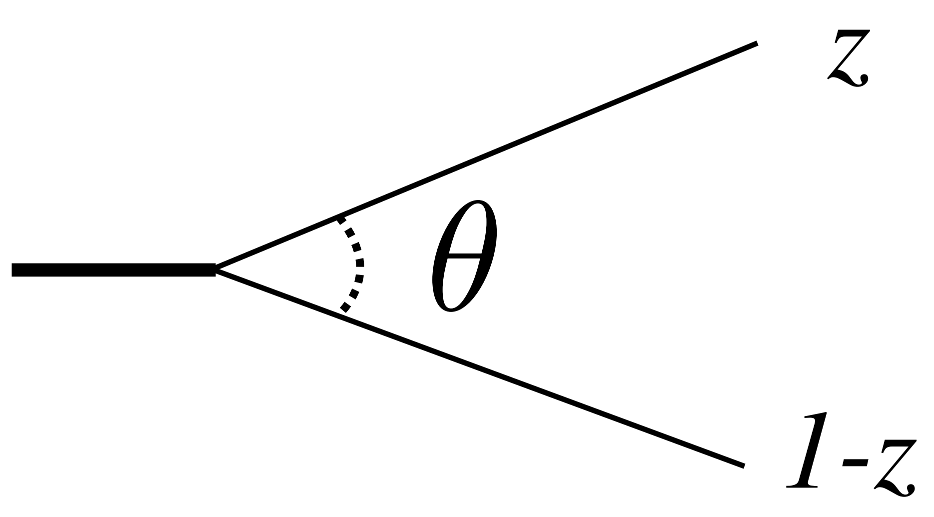


Generic 1→2 (on-shell) splitting in QCD:

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

Diverges for soft & collinear radiation!

VACUUM SPLITTING



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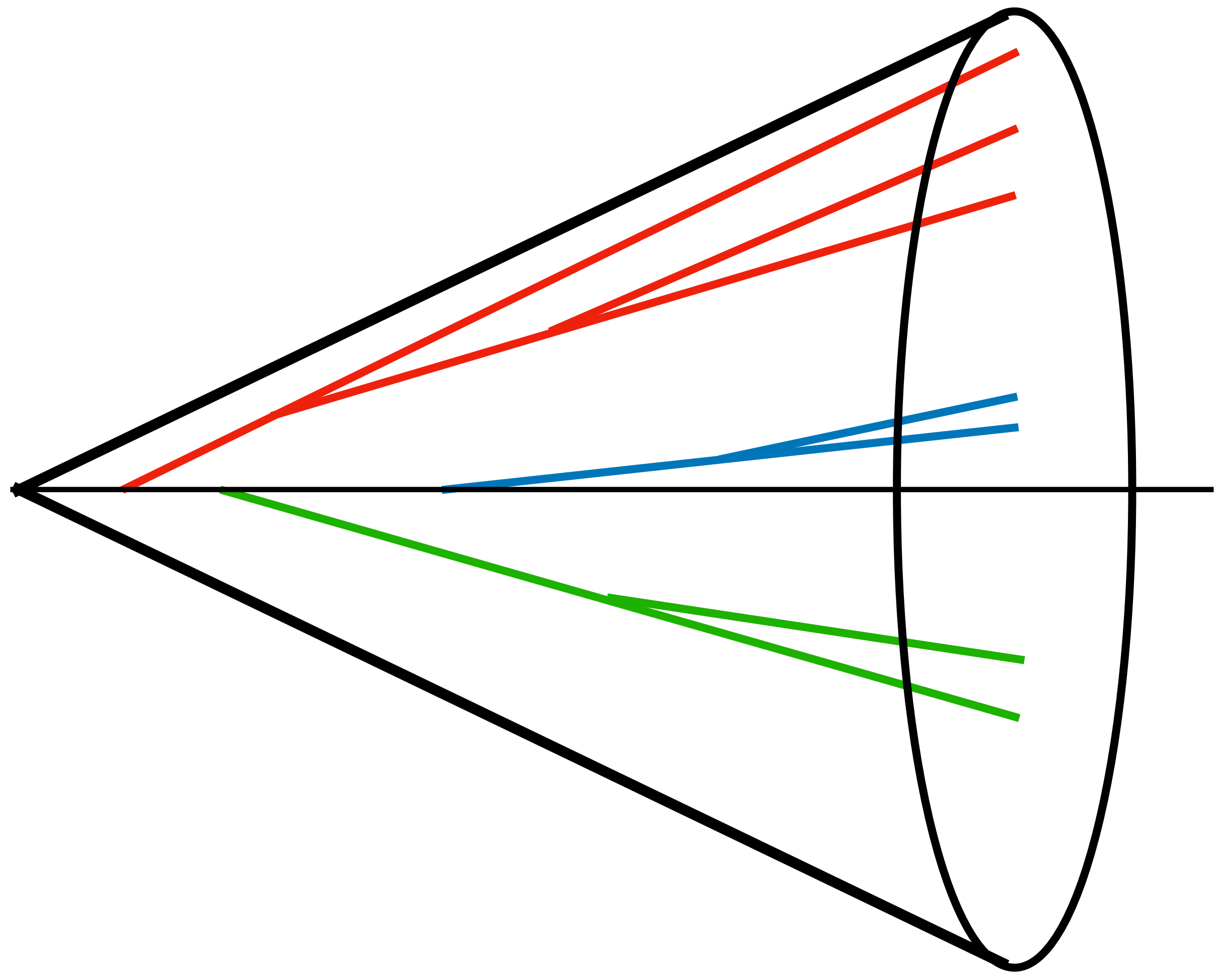
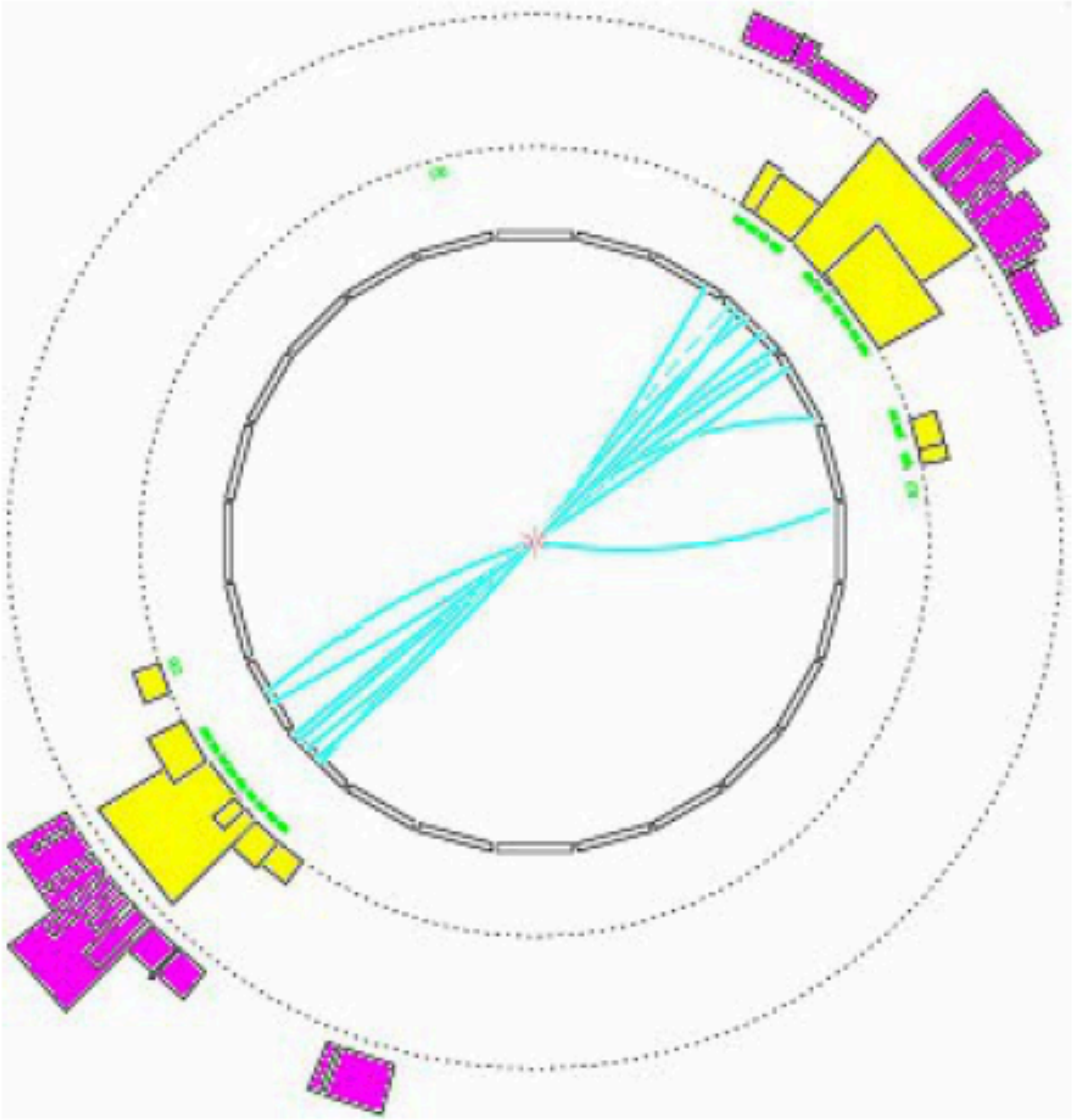


Large phase space for radiation compensates α_s!

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

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

VACUUM SPLITTING



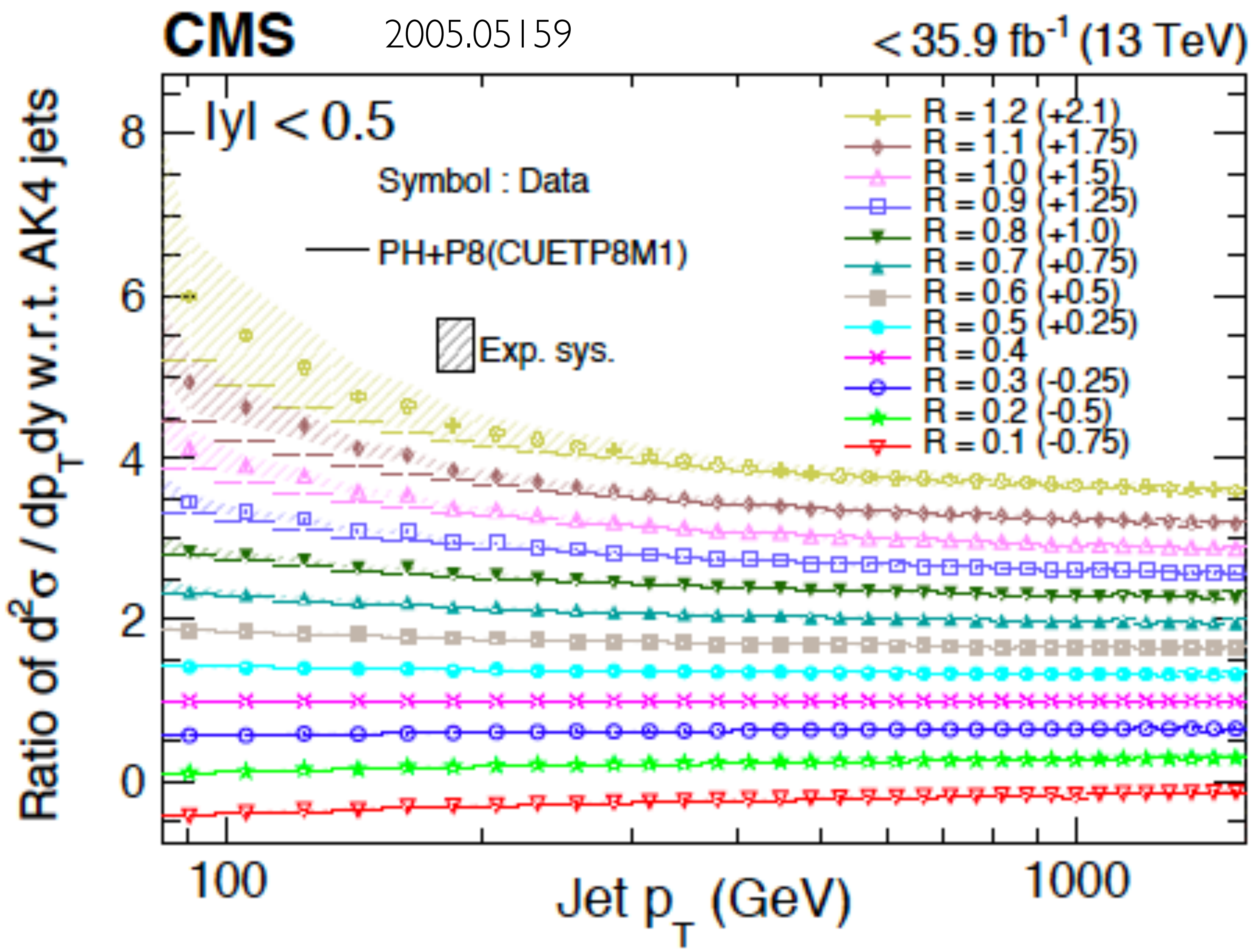
Observed as "jets": collimated sprays of particles/energy.

Sterman, Weinberg (1977)

JET SPECTRUM AT HIGH-p_T

Aversa, Chiappetta, Greco, Guillet NPB1989
de Florian, Vogelsang 0704.1677
Dasgupta, Magnea, Salam 0712.3014

- Jets approximate partons created in hard scatterings
- Result in collimated sprays of particles



Out-of-cone radiation:

$$(\delta p_{\rm T})_q = -C_F \frac{\alpha_s p_T}{\pi} \log \frac{1}{R} \left(2 \log 2 - \frac{3}{8} \right)$$

$$(\delta p_{\rm T})_g = -\frac{\alpha_s p_{\rm T}}{\pi} \log \frac{1}{R} \left[C_A \left(2 \log 2 - \frac{43}{96} \right) + T_{\rm R} n_{\rm f} \frac{7}{48} \right]$$

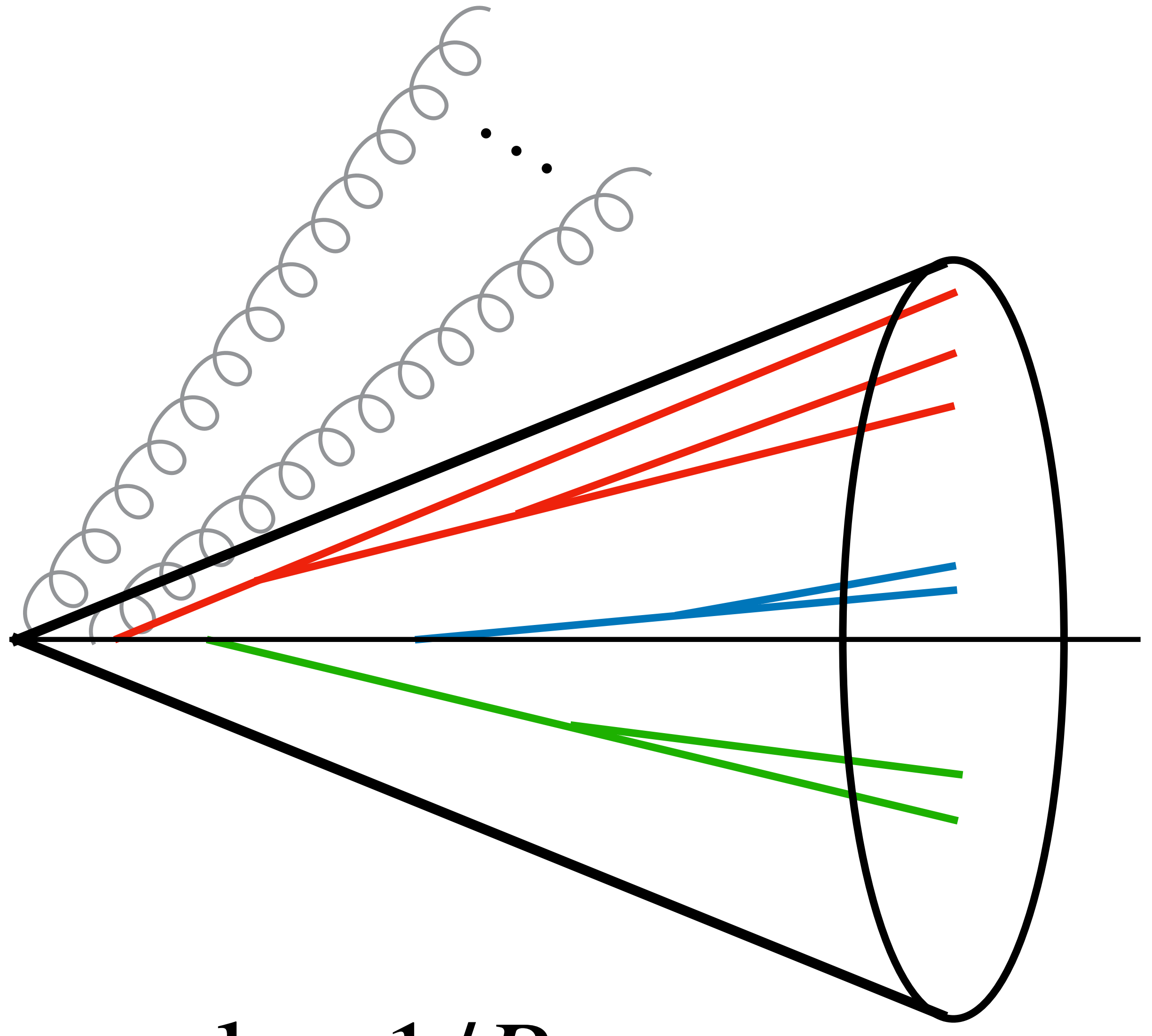
Non-perturbative effects (underlying event): $(\delta p_{\rm T})_{\rm UE} \simeq \frac{1}{2} \Lambda_{\rm UE} R^2$

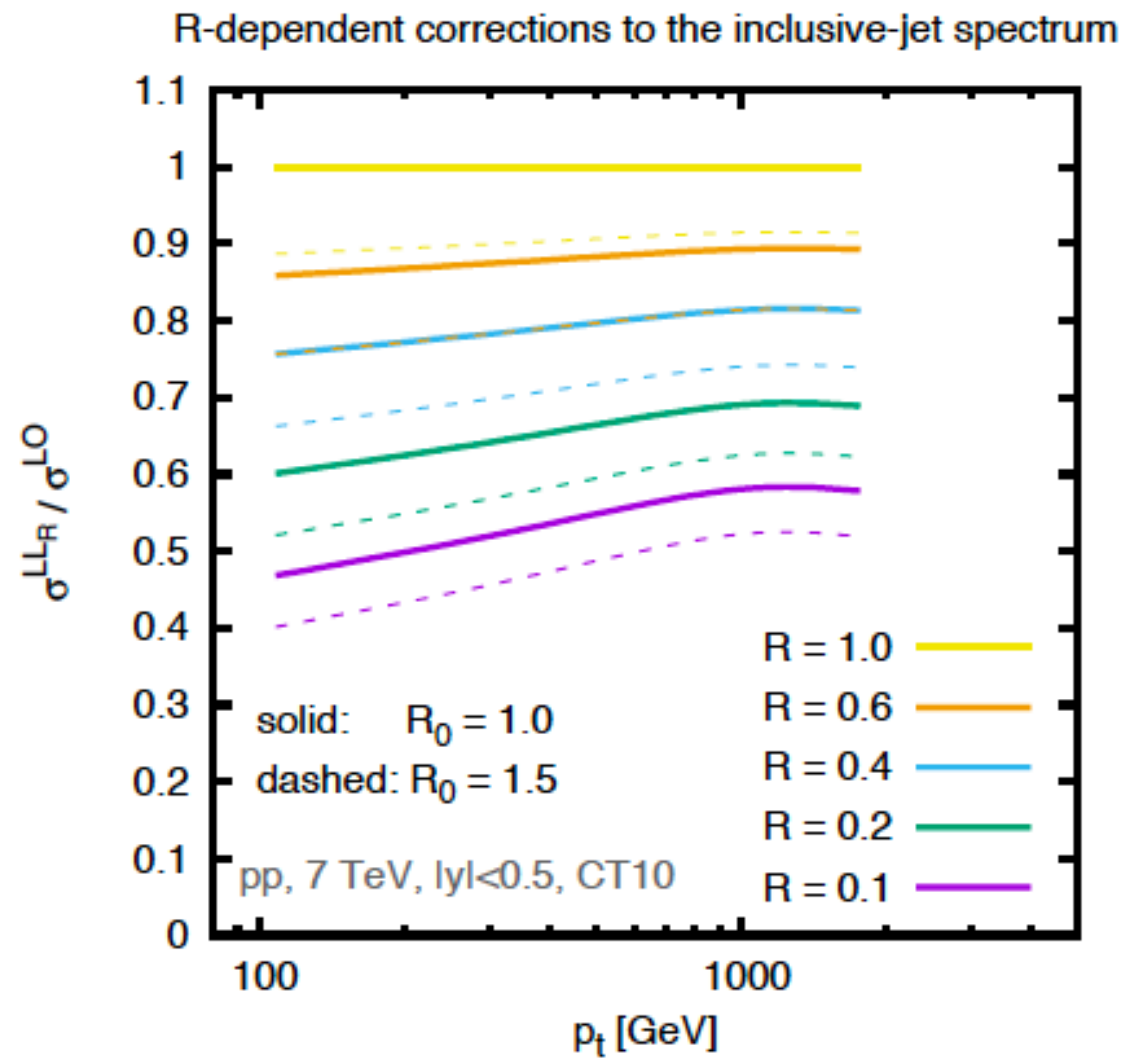
Logarithmic resummation

Konishi, Ukawa, Veneziano Nucl. Phys. B1567 (1979);
Bassetto, Ciafaloni, Marchesini Phys. Rept. 100 (1983);
Dokshitzer, Khoze, Mueller, Troyan "Basics of Perturbative QCD" (1991)

Resummation of leading logarithmic contributions.

Jets-inside-jets: microjet spectrum.





Example: small-R resummation in $t = \log 1/R$:

$$\frac{\partial}{\partial t} f_{\mathrm{jet}/i}(z,t) = \int_0^1 \frac{\mathrm{d}z'}{z'}\,\frac{\alpha_s}{\pi} P_{ji}(z) f_{jet/j}\left(\frac{z}{z'},t\right)$$

Evolution from hard scale to jet scale via DGLAP.

Dasgupta, Dreyer, Salam, Soyez 1411.5182, 1602.01110
Kang, Ringer, Vitev 1606.06732
Dai, Kim, Leibovitch 1606.07411

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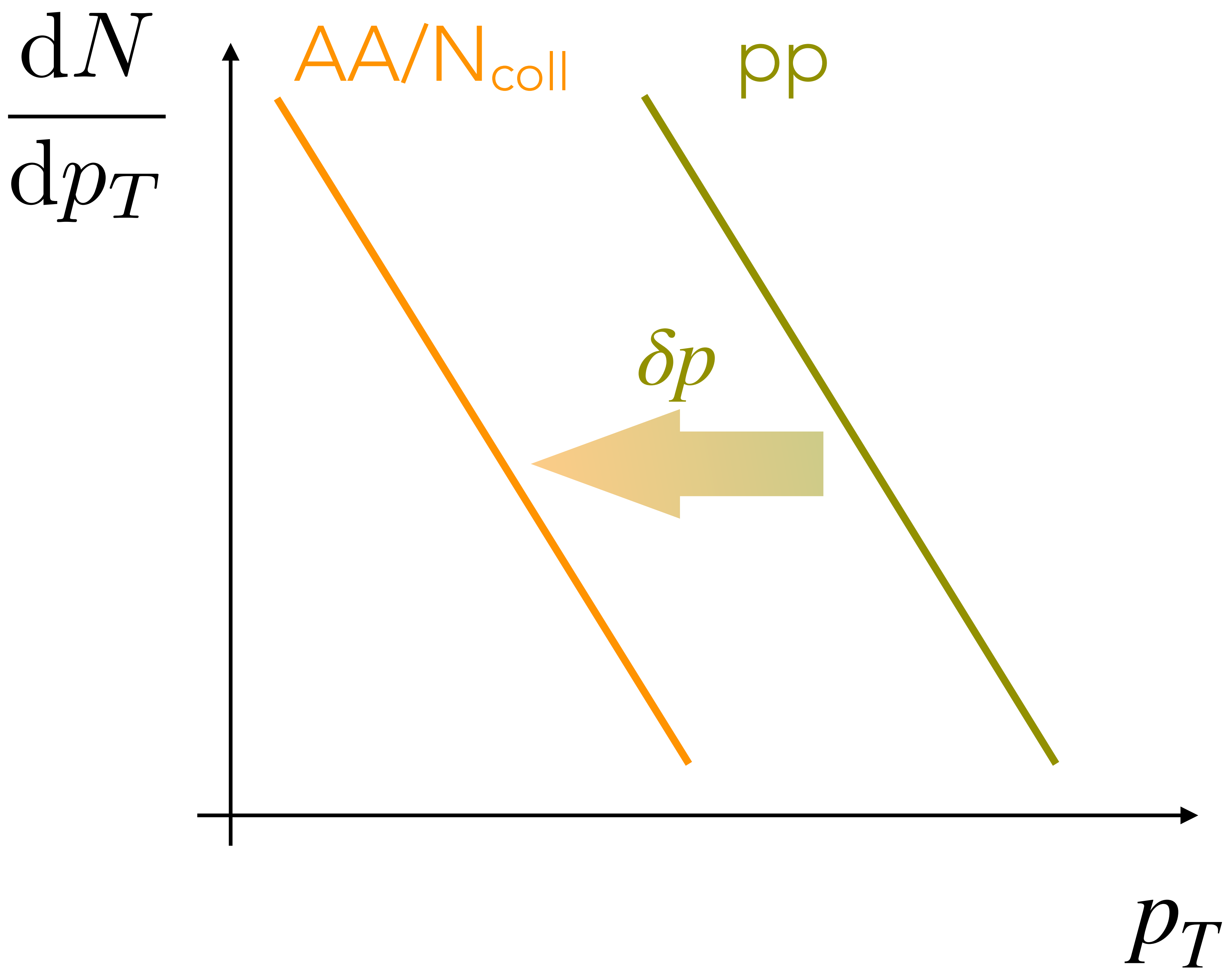
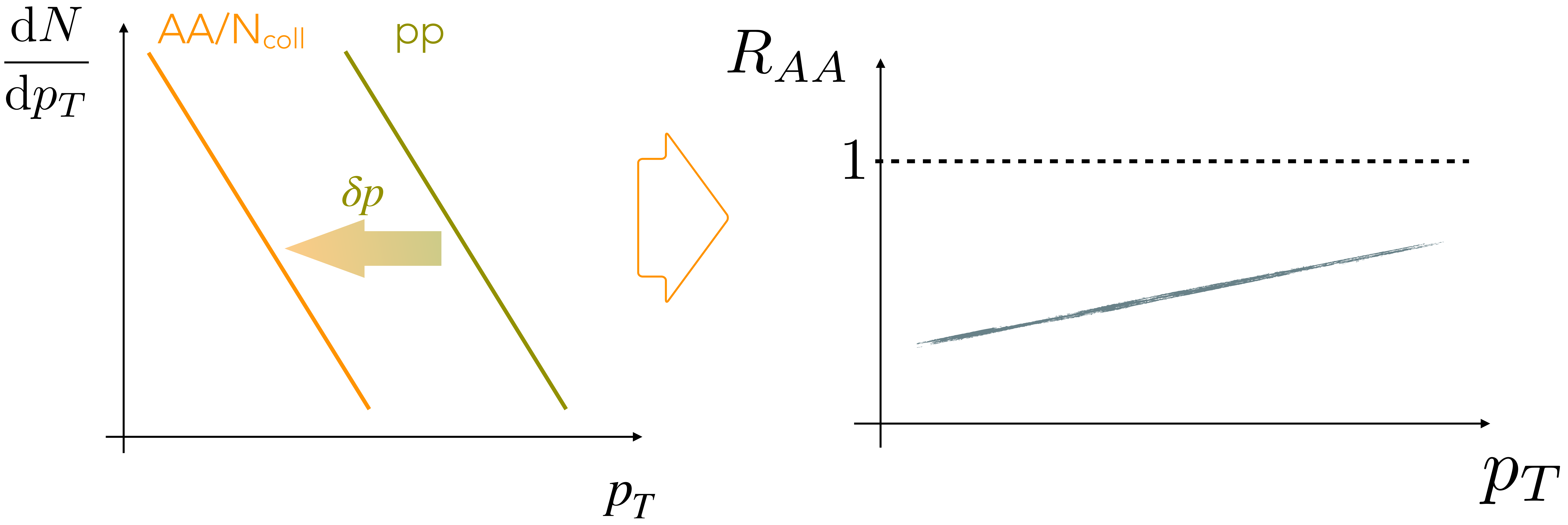
Nuclear modification factor



Workhorse of the field: measuring & parameterizing the shift of spectrum to access information about medium interactions.

Nuclear modification factor



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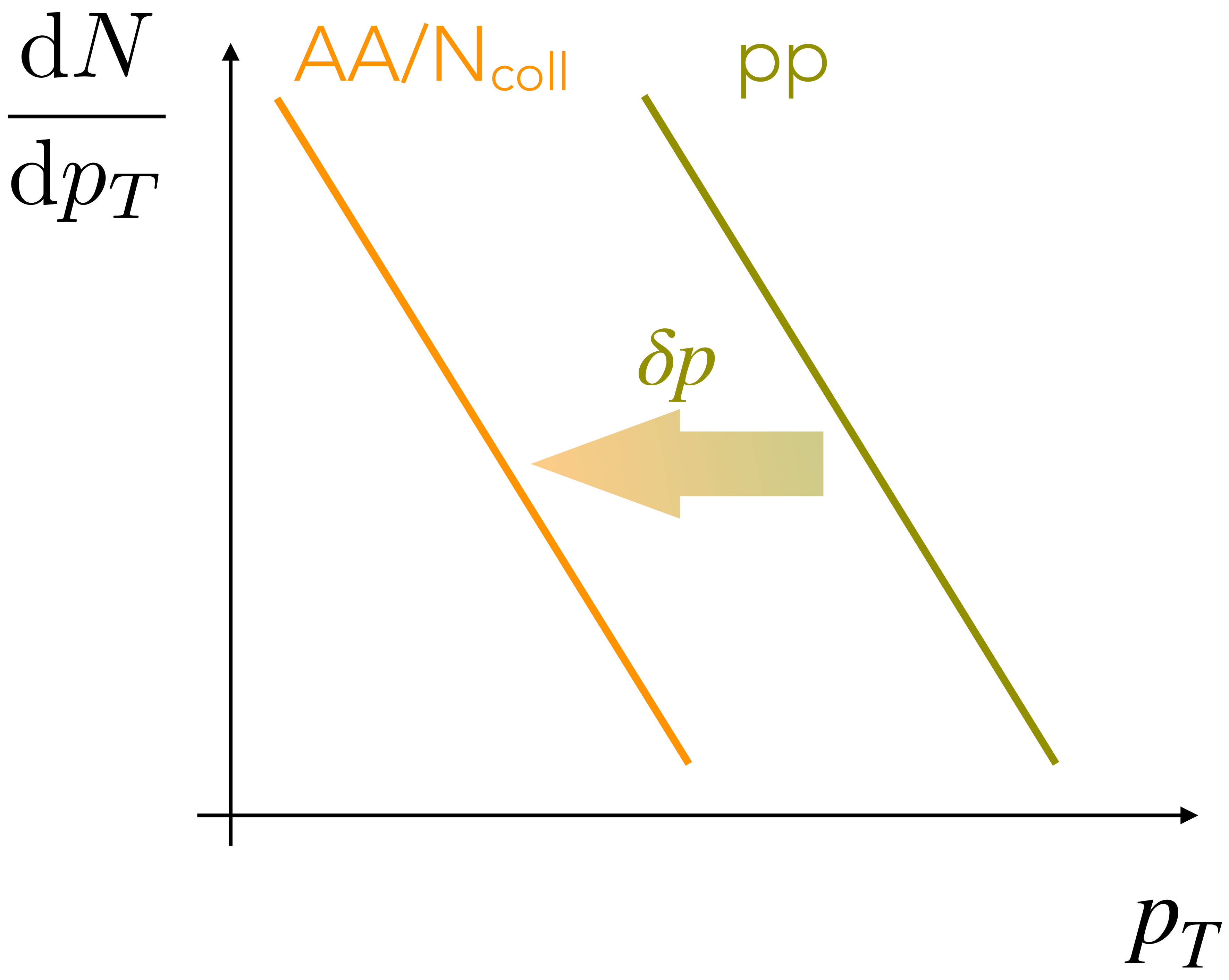

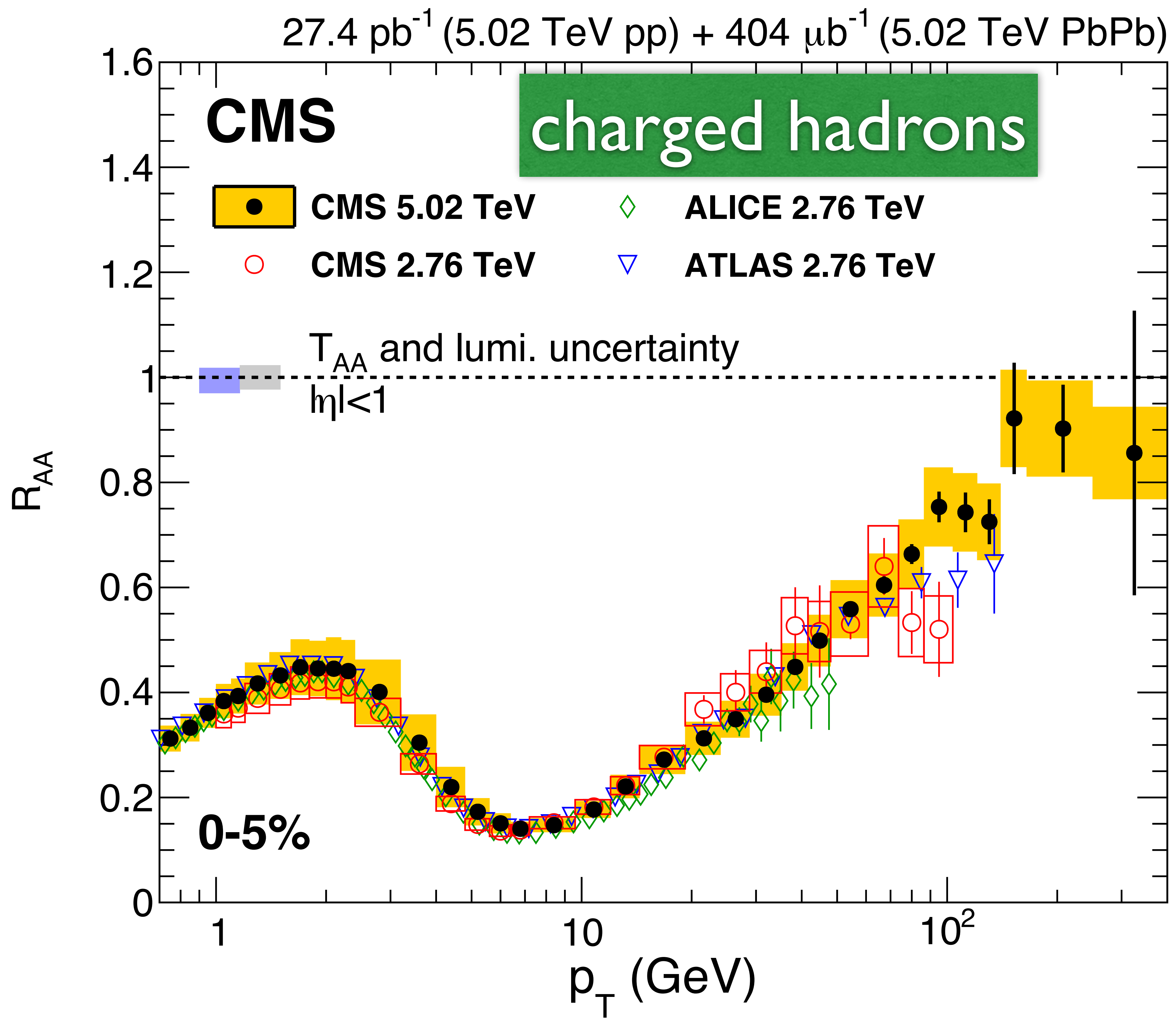

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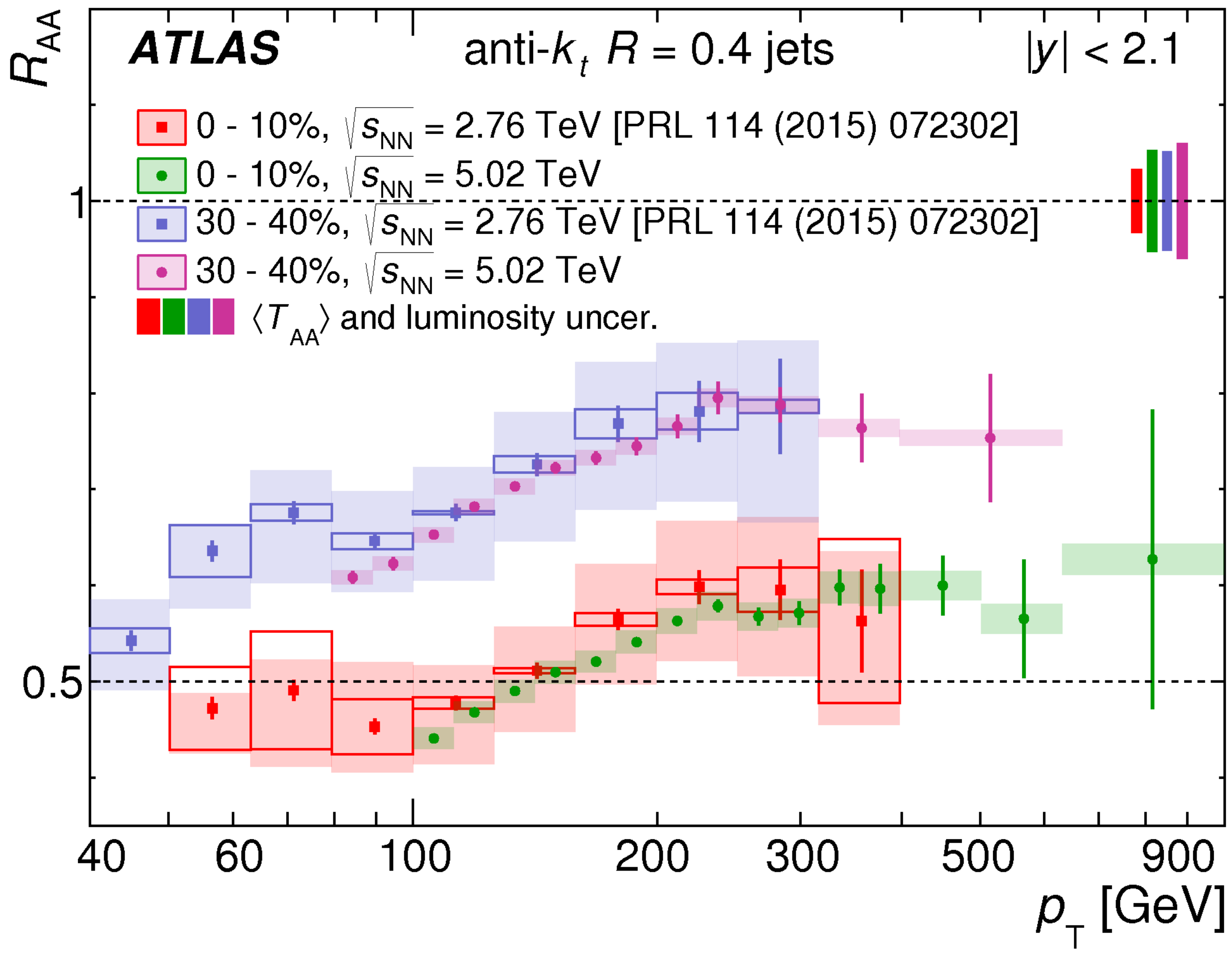
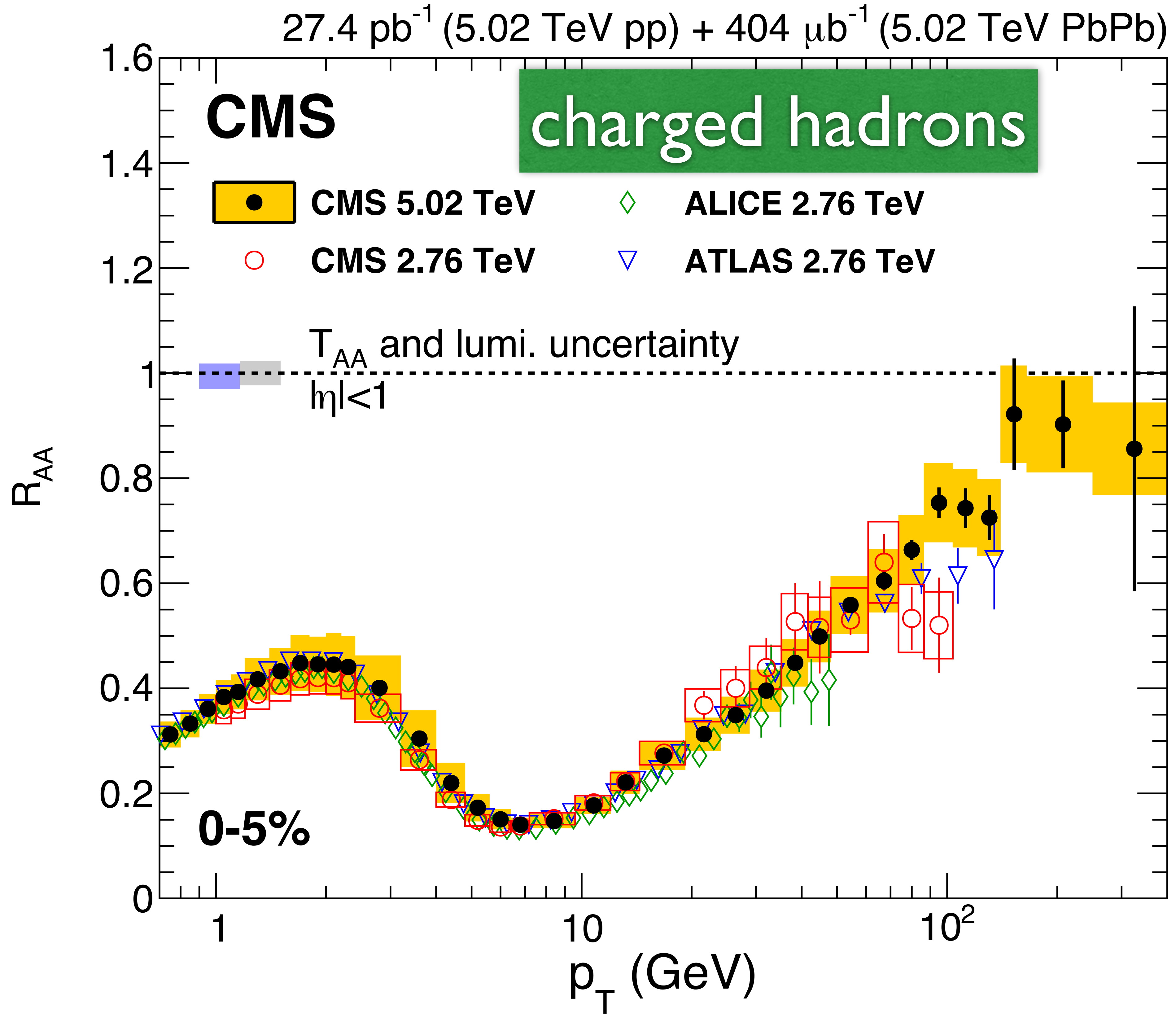
NUCLEAR MODIFICATION FACTOR





Workhorse of the field: measuring & parameterizing the shift of spectrum to access information about medium interactions.

Significant difference of hadron and jet suppression at high-p_T!

QUENCHING OF PARTONIC HARD SPECTRUM

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

Probability of radiating energy ϵ away from parton (1 gluon emission)

$$\mathcal{P}(\epsilon) \simeq \delta(\epsilon)\left[1 - \int_0^\infty \mathrm{d}\omega \, \frac{\mathrm{d}I_>}{\mathrm{d}\omega}\right] + \frac{\mathrm{d}I_>}{\mathrm{d}\epsilon}$$

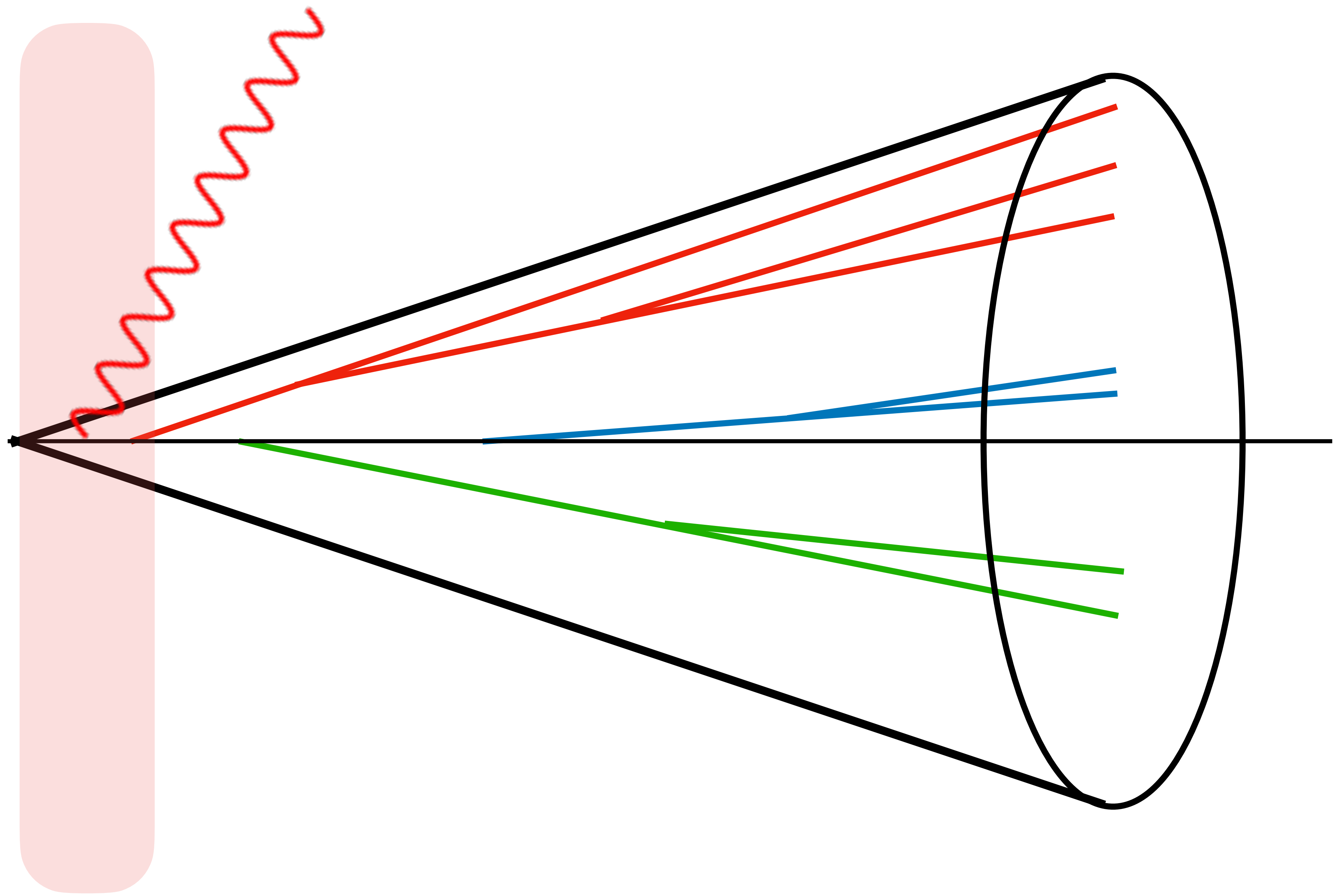
Quenching factor

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

- Poissonian process
- applies for small energy losses & steeply falling spectra
  - good approximation at RHIC/LHC
- energy loss distribution $P(\epsilon)$ includes fluctuations

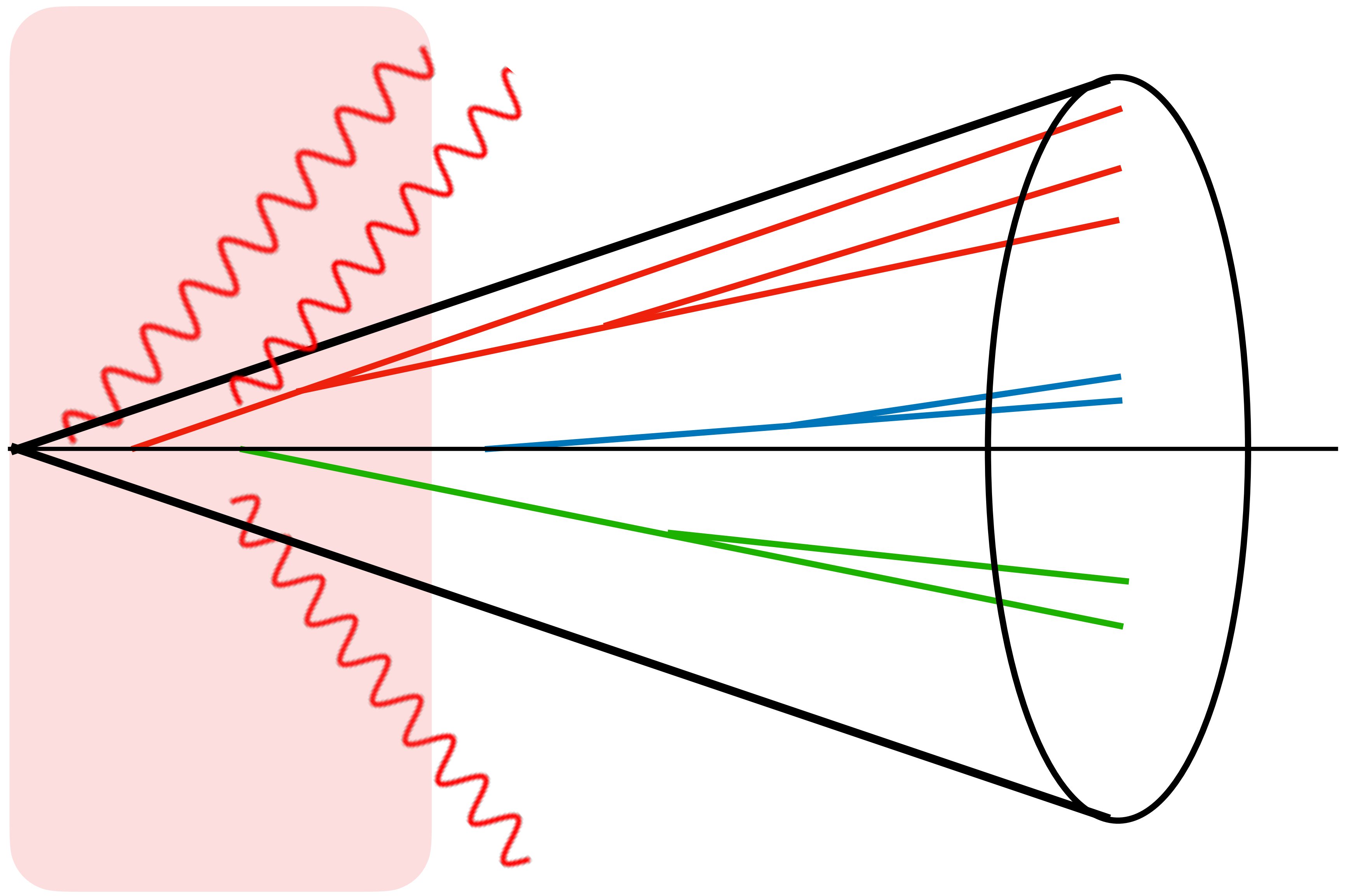
JET QUENCHING

- enhancement of energy loss out of the cone due to elastic and radiative processes
  - previously: quenching of hadron spectra - new tools are needed!
  - pheno: how much & how does energy flow out of the cone?
- jets are multi-parton objects with spacetime structure
  - how many partons are contributing to energy loss?
  - important to gain understanding from analytical approaches
- distribution of subjets within a jet
  - what is the distribution of fragments inside the cone?



1 emitter (coherent)

factorisation



n emitters (partially incoherent)

factorisation breaking

new element: importance of jet substructure fluctuations!

also seen in MC studies: Milhano, Zapp 1512.08107; Casalderrey-Solana, Milhano, Pablos, Rajagopal 1808.07386

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 (20132; Casalderrey, Iancu JHEP (2011)

Dominguez, Milhano, Salgado, KT, Vila 1907.03653

VACUUM RADIATION IN MEDIUM

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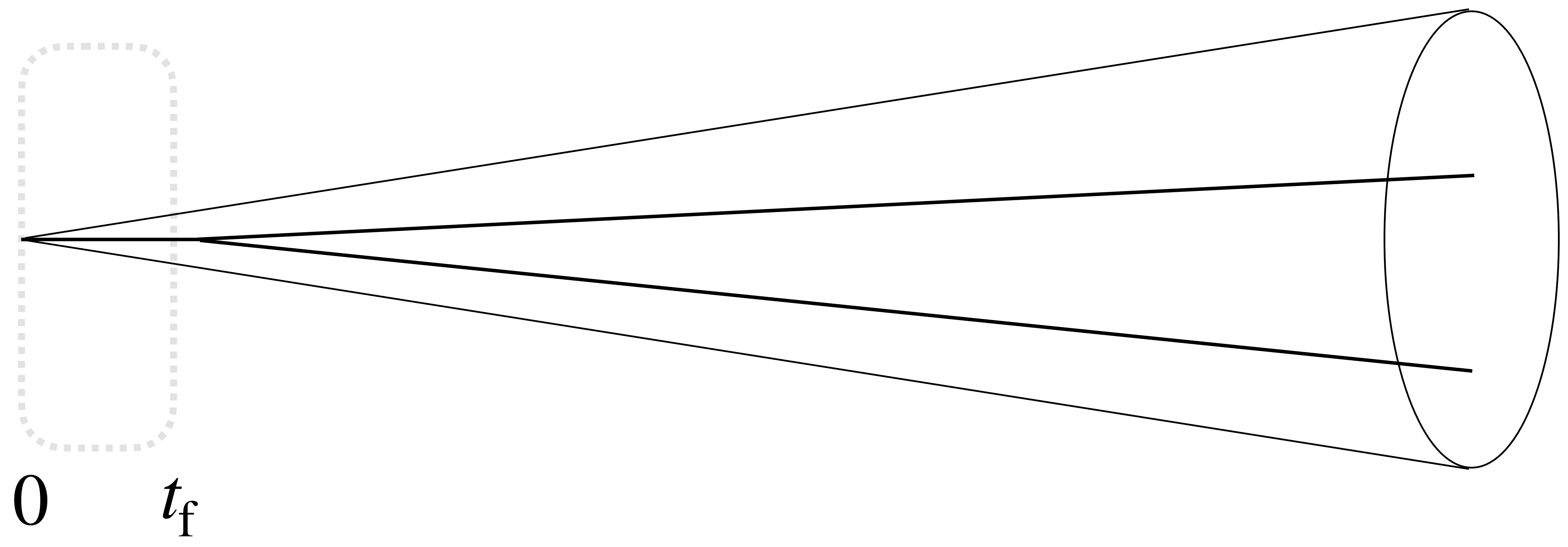
First step: calculation of decoherence and energy loss of an initially color correlated pair

Mehtar-Tani, KT 1706.06047



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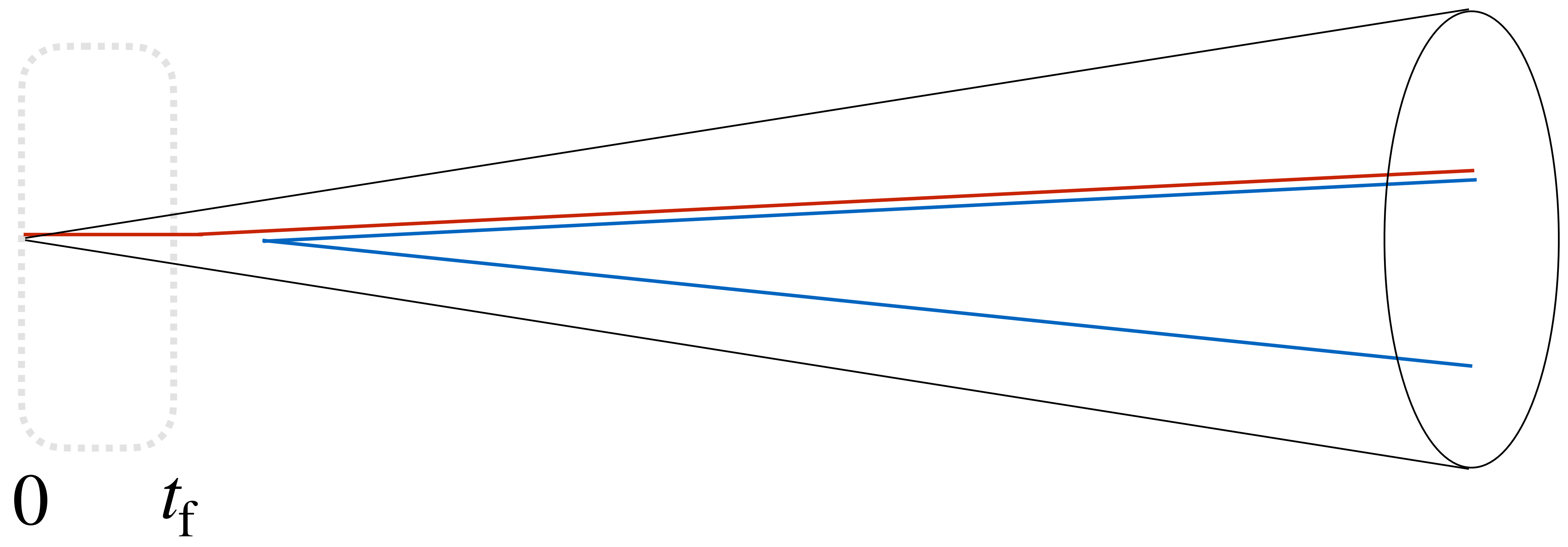

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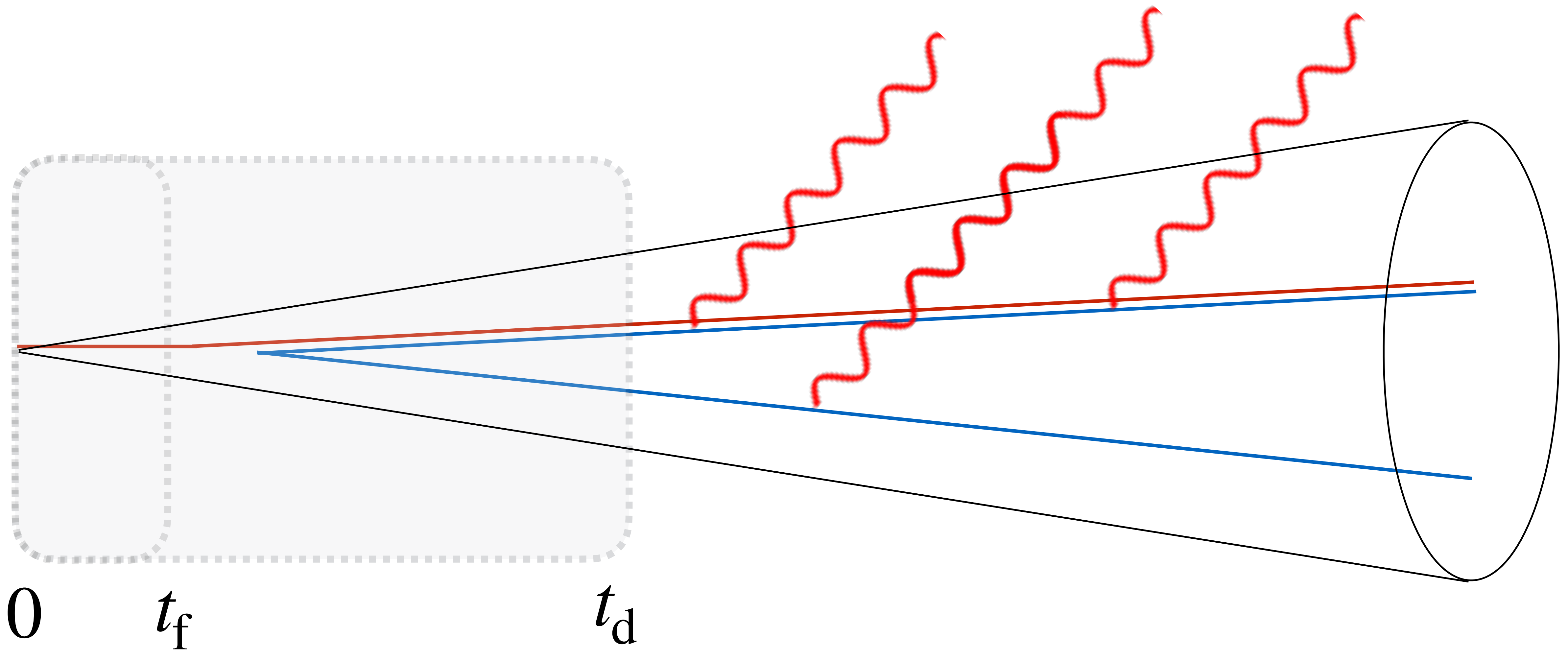


$$t_\mathrm{d} \sim (\hat{q}\theta_{12}^2)^{-1/3}$$

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

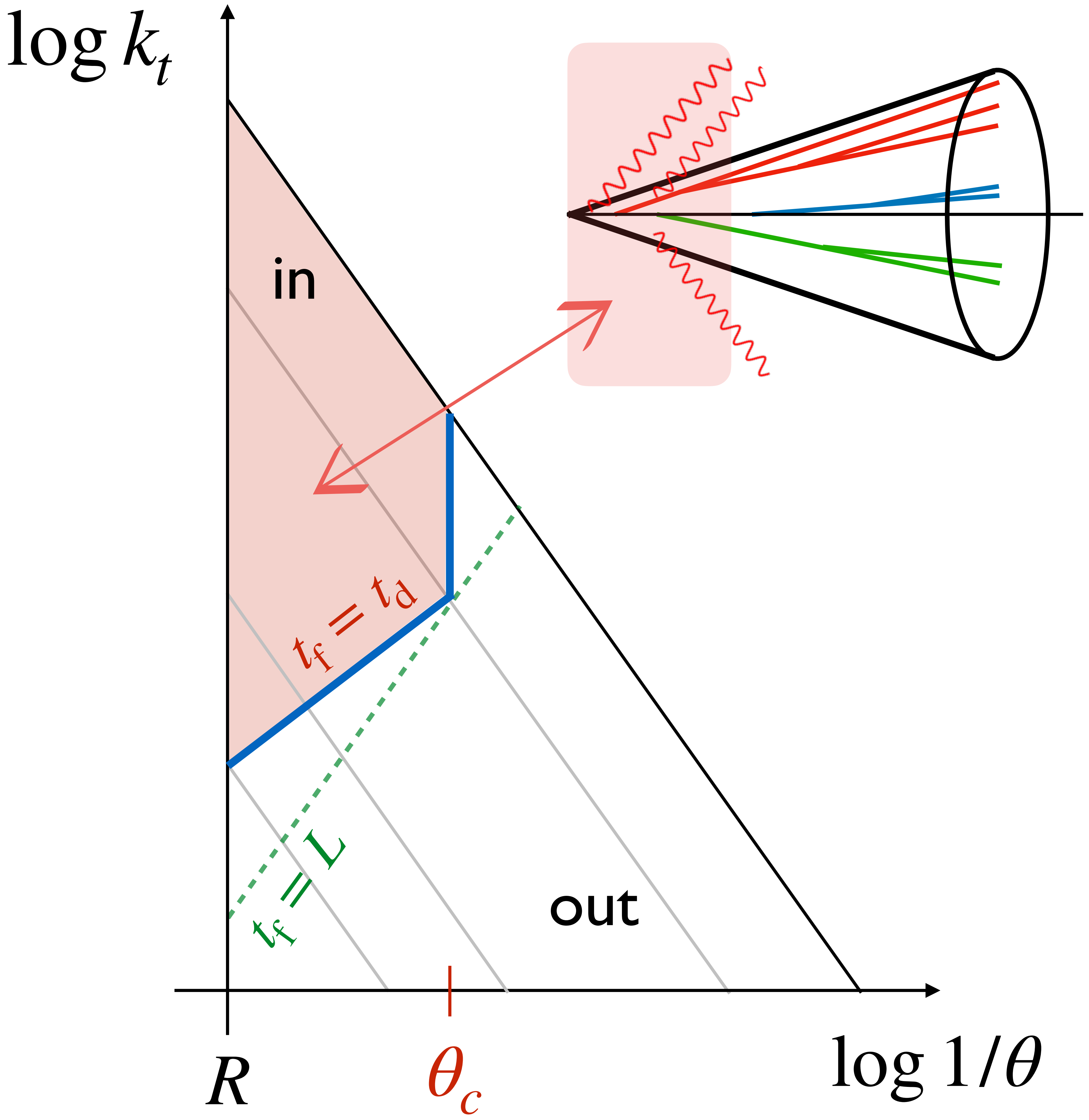
$$Q_2(p_T) = Q(p_T) \times Q_{\mathrm{sing}}(p_T)$$

energy loss of total color charge

delayed energy loss from resolved partons

Phase space analysis

Y. Mehtar-Tani, KT 1706.06047, 1707.07361
Caucal, Iancu, Mueller, Soyez 1801.09703



Vacuum emissions w/ $k_t^2 > \sqrt{\hat{q}\omega}$ and $\theta > \theta_c$ are emitted inside plasma and will eventually be resolved by the medium (red area).

At border: all inside emissions get quenched

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.

Obs: phase space wo/coherence effects $t_f < L$ is larger $\propto \log^2 p_T$

SUPPRESSION OF EXCLUSIVE SPECTRUM

Simplified example: consider a $1 \to N$ process followed by energy loss.

$$\frac{\mathrm{d}\sigma_{\mathrm{excl}}}{\mathrm{d}k_1\ldots\mathrm{d}k_N} = \int \mathrm{d}p \left\{ \prod_i \int \mathrm{d}\epsilon_i \, \mathscr{P}(\epsilon_i) \right\} f_{1\to N}\left(k_1+\epsilon_1, \ldots, k_N+\epsilon_N \,|\, p\right) \delta\left(p - \sum_i k_i - \sum_i \epsilon_i\right) \frac{\mathrm{d}\sigma_0}{\mathrm{d}p}$$

At leading order:

$$\frac{\mathrm{d}\sigma_{\mathrm{excl}}}{\mathrm{d}k_1\ldots\mathrm{d}k_N} \simeq \left(\int \mathrm{d}\epsilon \mathscr{P}(\epsilon) \mathrm{e}^{-n\epsilon/p} \right)^N \frac{\mathrm{d}\sigma_{0,\mathrm{excl}}}{\mathrm{d}k_1\ldots\mathrm{d}k_N} + \ldots$$

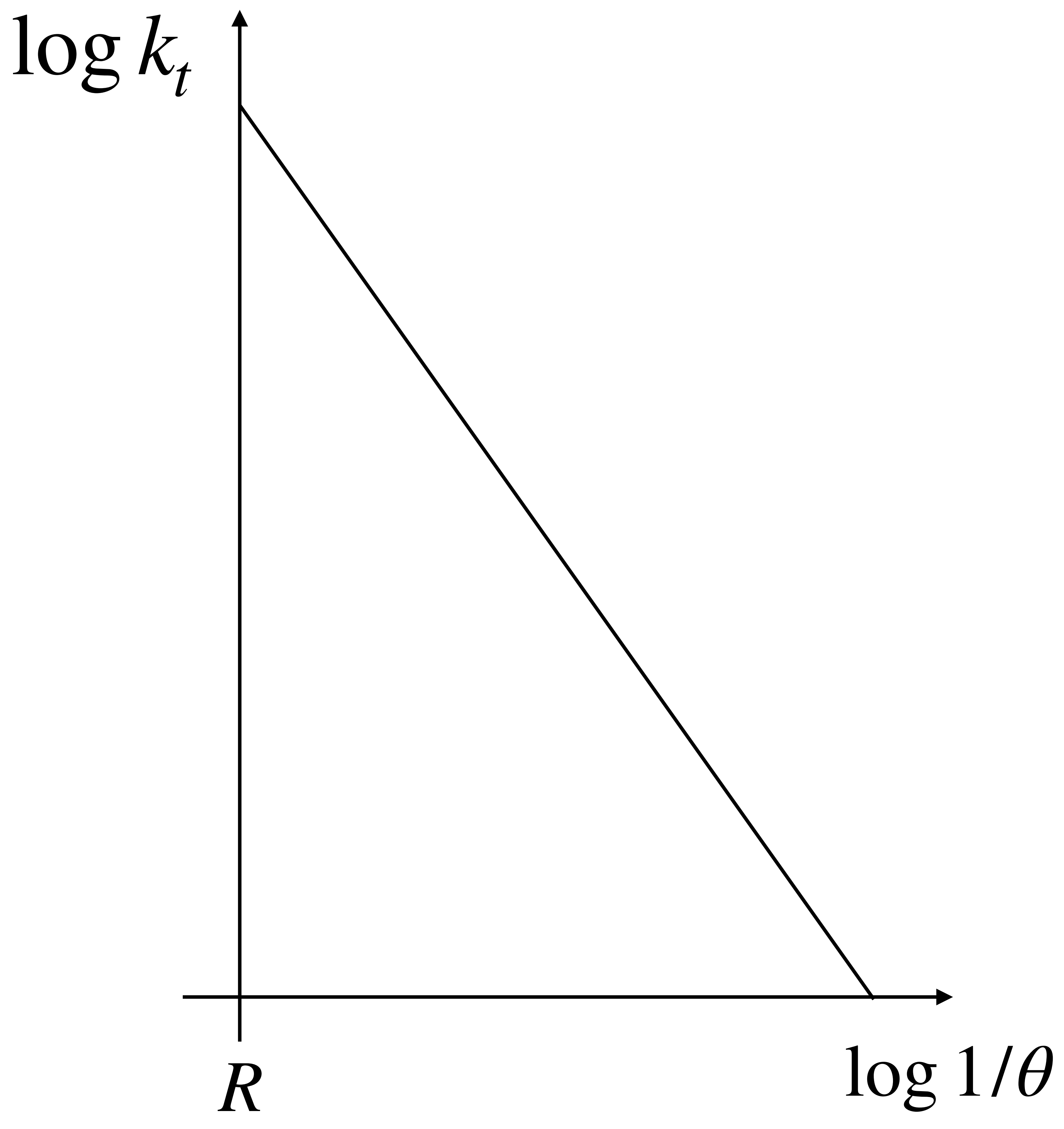
systematically improvable…

Provides a framework for studying multi-parton energy-loss effects for inclusive observables !

Effective theory of jet quenching

Mehtar-Tani, KT in preparation

A probabilistic picture can be established due to the separation of jet and medium scales.



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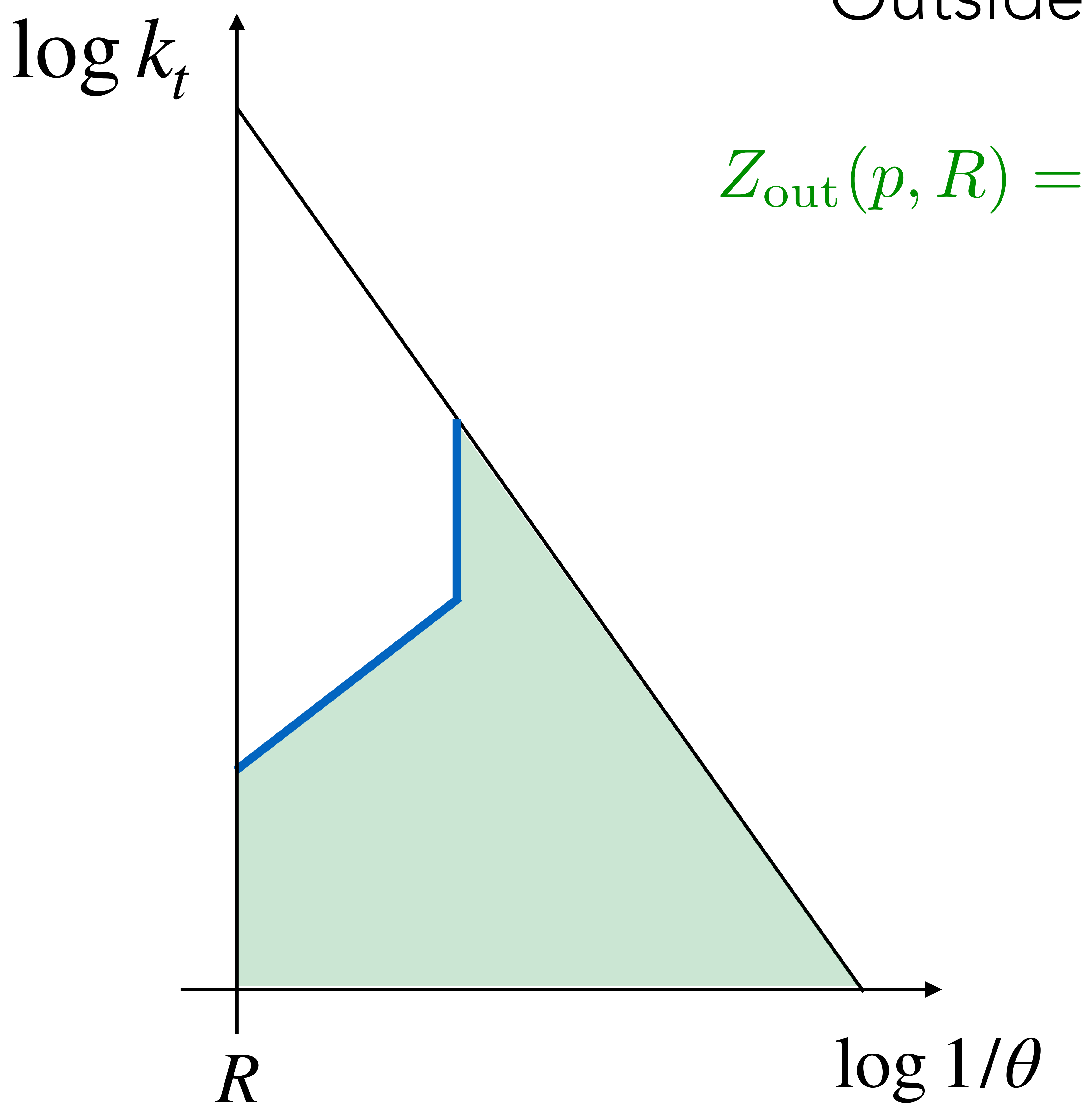

Outside of the medium, we have AO vacuum (vetoed shower):

$$Z_{\rm out}(p,R) = u(p) + \int^{R} {\rm d}\Pi \,(1-\Theta_{\rm in})\left[Z_{\rm out}(zp,\theta)Z_{\rm out}((1-z)p,\theta) - Z_{\rm out}(p,\theta)\right]$$

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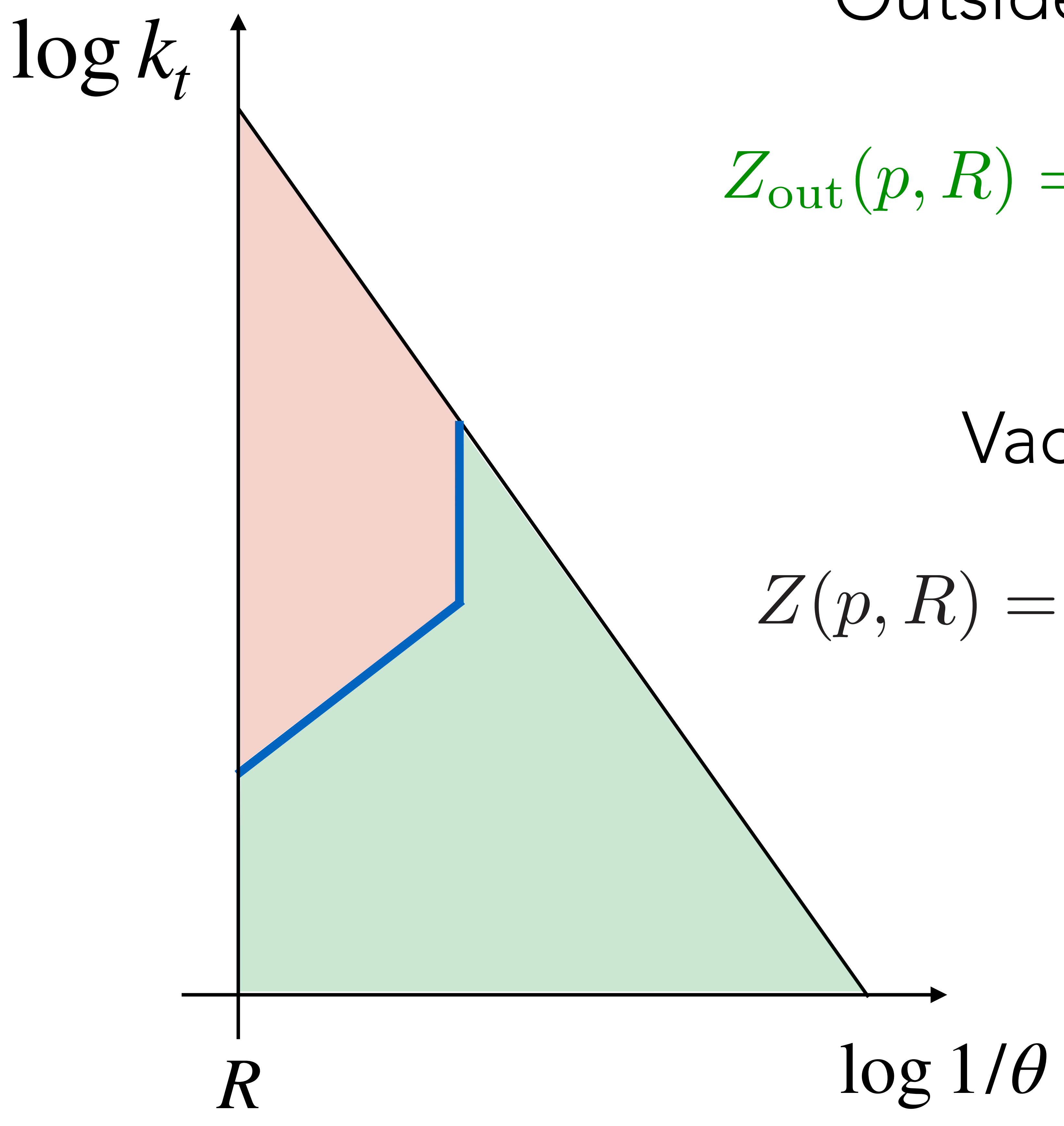

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Vacuum-like (vetoed) AO shower inside the medium

$$Z(p,R) = Q(p_{\rm T})Z_{\rm out}(p,1) + \int^R \mathrm{d}\Pi\,\Theta_{\rm in}\left[Z(zp,\theta)Z((1-z)p,\theta) - Z(p,\theta)\right]$$

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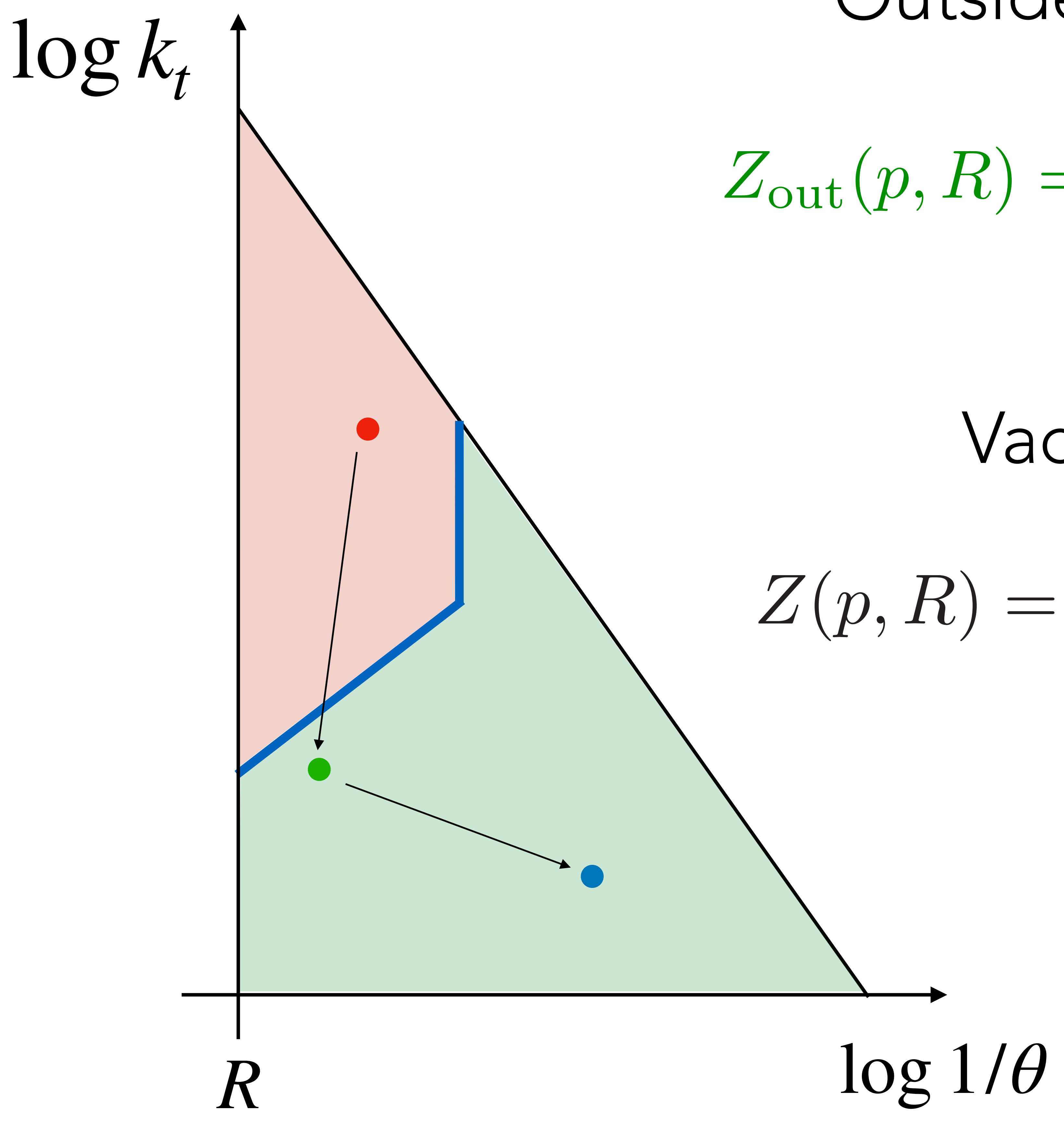

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out-shower restarted from max angle (AAO)

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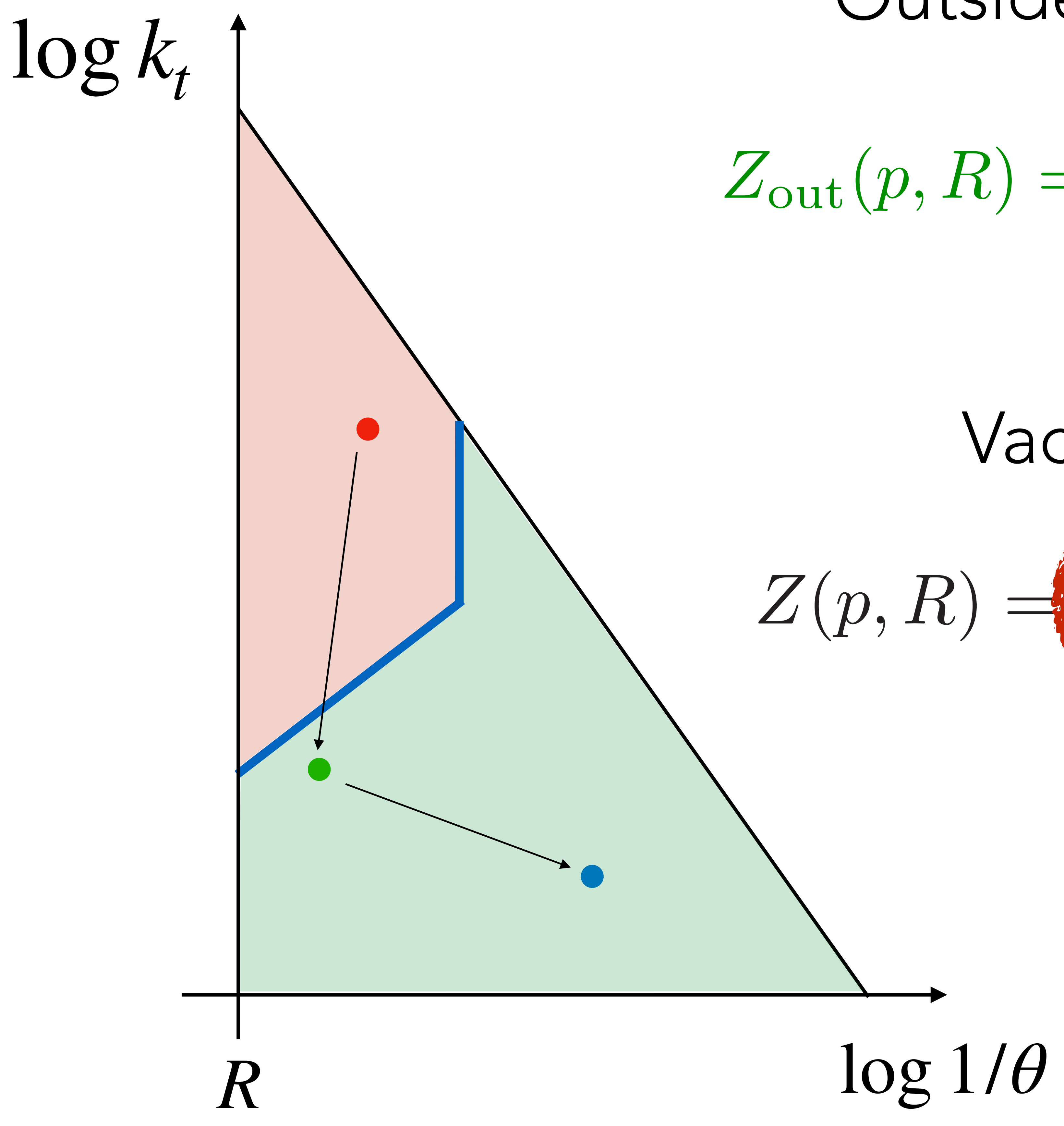

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out-shower restarted from max angle (AAO)

accounts for quenching through iterative use of GF

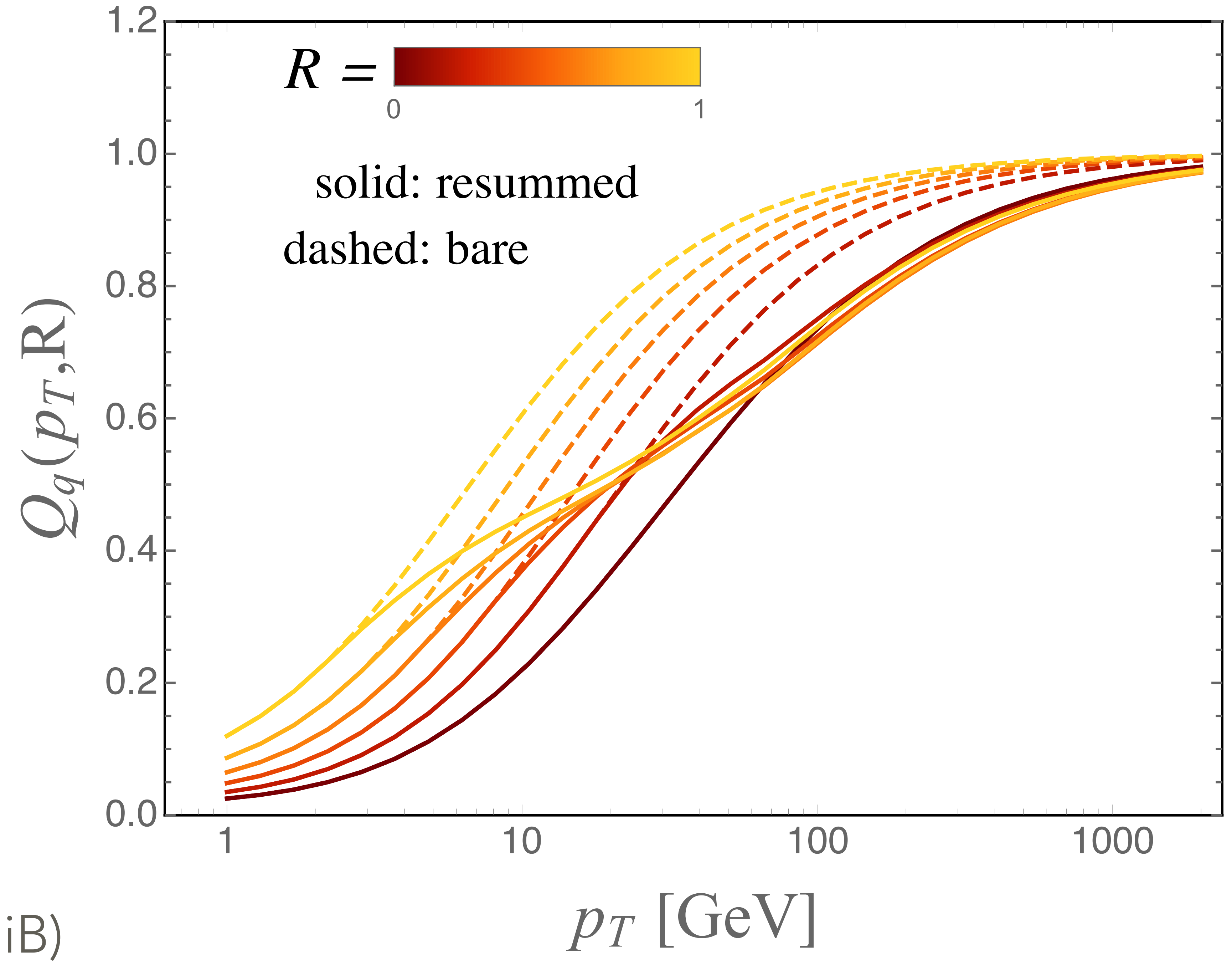
RESUMMED QUENCHING FACTOR

Mehtar-Tani, KT 1707.07361
Mehtar-Tani, Pablos, KT in preparation

Non-trivial normalization of the GF: $Z(p,R;\{u=1\}) = Q(p,R)$!

$$Q(p,R) = Q(p_\mathrm{T}) + \int^R \mathrm{d}\Pi\,\Theta_\mathrm{in}\left[Q(zp,\theta)Q((1-z)p,\theta) - Q(p,\theta)\right]$$

coupled eqs for non-linear evolution of quenching

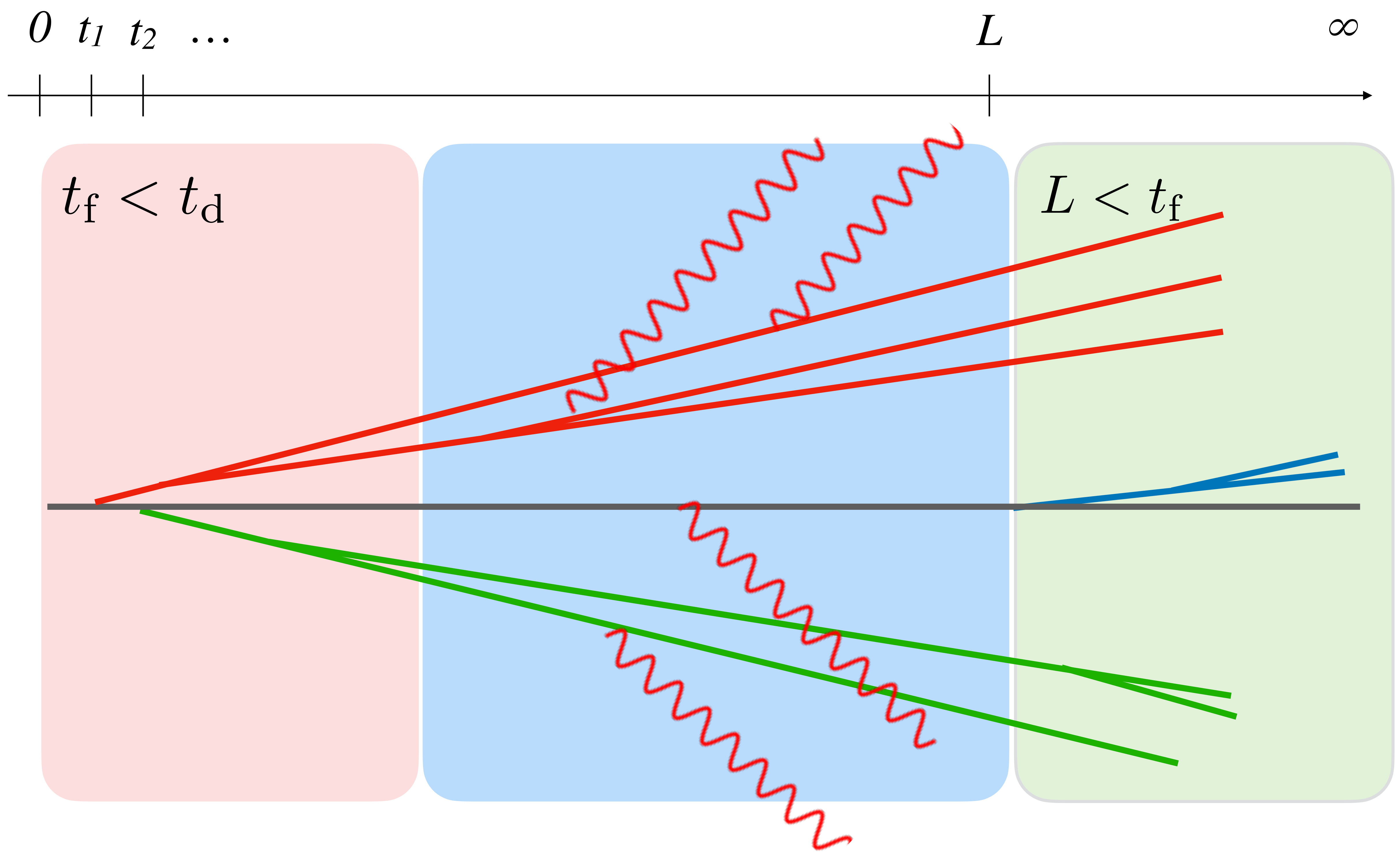


Approximately:

$$Q_i(p_T,R) = Q_i(p_T)\exp\left[\int^R \mathrm{d}\Pi\,\Theta_\mathrm{in}\left(Q_g(p_T)-1\right)\right]$$

The R-dependence is much milder than for bare quenching!

Emerging probabilistic picture



hard, in-medium vacuum-like radiation

energy loss, broadening, wake

"out" radiation, hadronization

[See also Caucal, Iancu, Soyez, Mueller 1801.09703]

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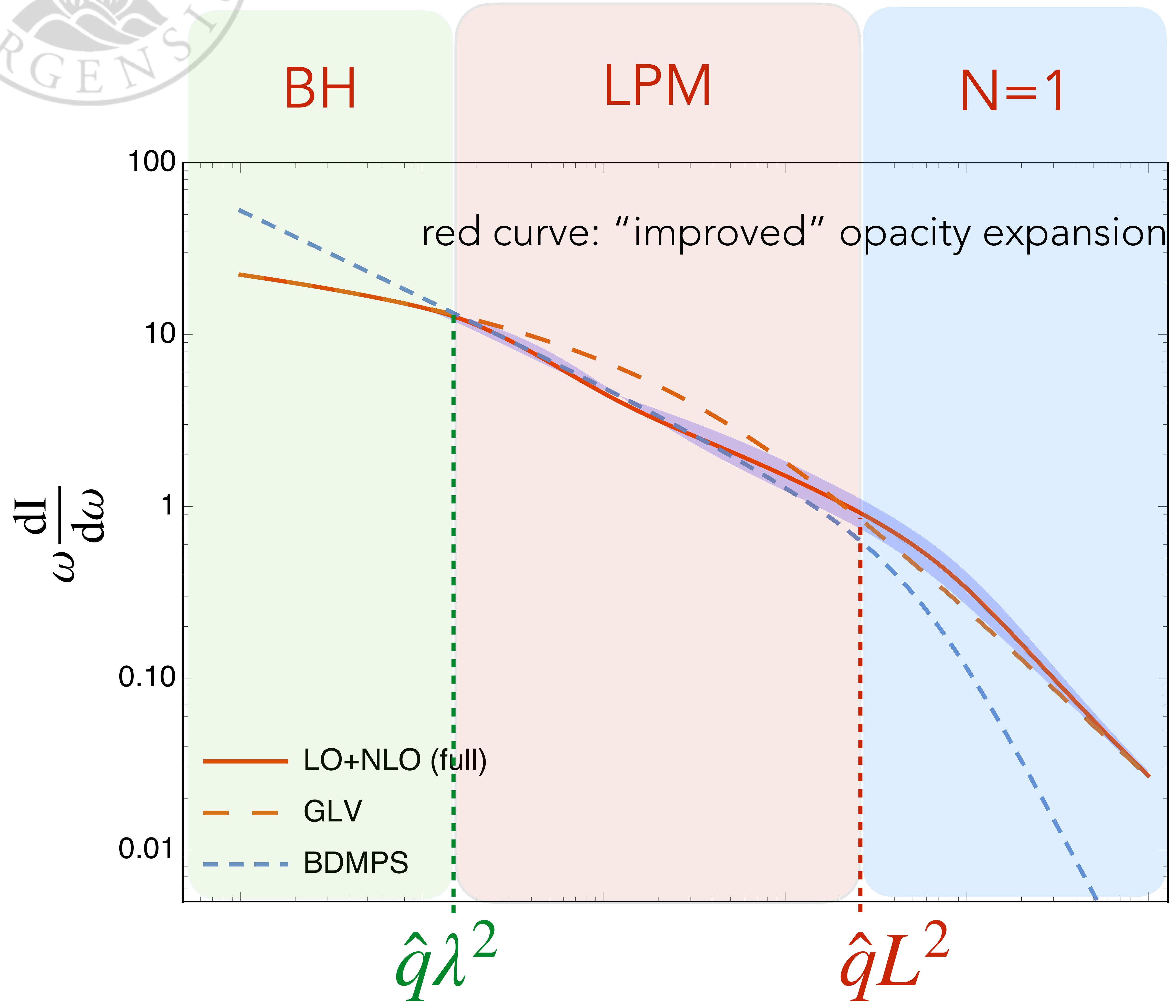
RADIATIVE ENERGY LOSS

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



Momentum broadening $\langle \boldsymbol{k}^2 \rangle \sim \hat{q}t$ leads to modified bremsstrahlung spectrum → no collinear divergence!

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \frac{\alpha_s C_R}{\pi} \frac{L}{t_\mathrm{f}} = \frac{\alpha_s C_R}{\pi} \sqrt{\frac{\hat{q}L^2}{\omega}}$$

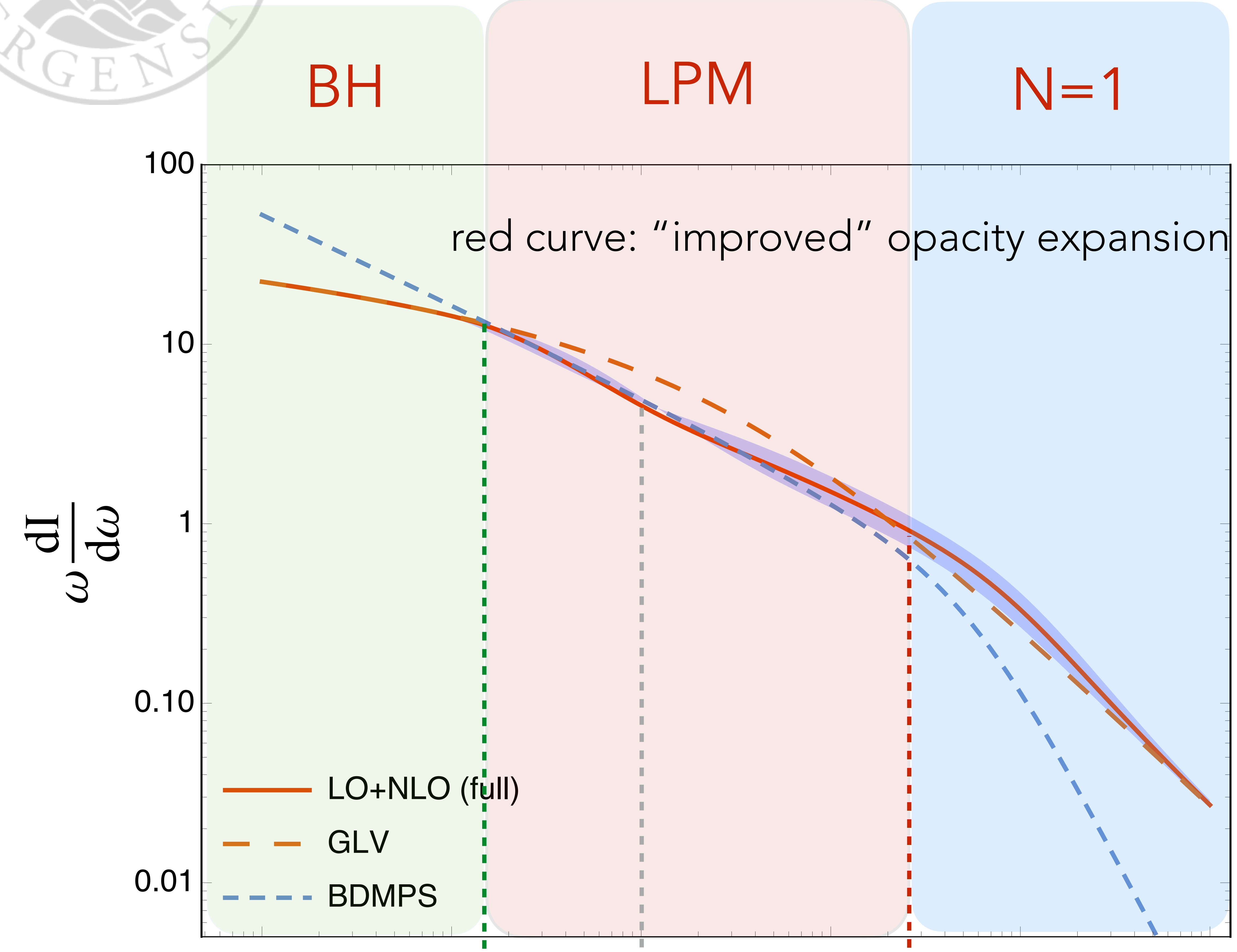
Bethe-Heitler regime ($t_\mathrm{f} \lesssim \lambda$)

LPM regime ($\lambda < t_\mathrm{f} < L$)

N=1 regime ($L < t_\mathrm{f} \sim E/\mu^2$)

Radiative energy loss

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



$$\hat{q}\lambda^2 \ll \alpha_s^2 \hat{q} L^2 \ll \hat{q} L^2$$

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Bethe-Heitler regime ($t_\mathrm{f} \lesssim \lambda$)

LPM regime ($\lambda < t_\mathrm{f} < L$)

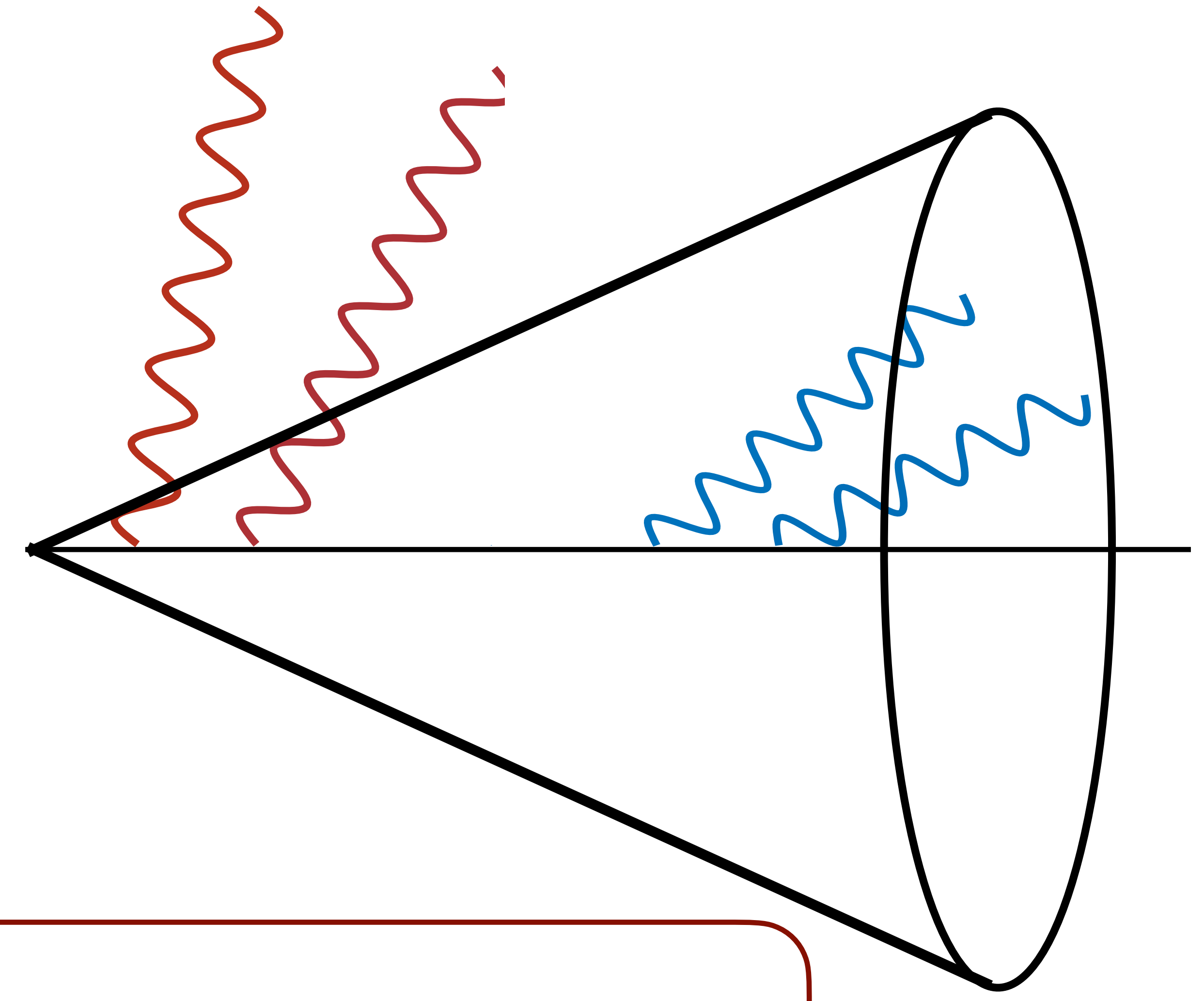
N=1 regime ($L < t_\mathrm{f} \sim E/\mu^2$)

Soft scale: copious, large angle gluons leading to energy loss & thermalization.

Blaizot, Dominguez, Iancu, Mehtar-Tani 1301.6102

TWO SEPARATED REGIMES

see also Kurkela, Wiedemann 1407.0293



Energy loss for jets is driven by out-of-cone emissions.

$$\omega \sim \omega_c = \hat{q}L^2$$
$$N \sim \mathcal{O}(\alpha_s)$$
$$\theta_{\rm br} \sim \theta_c = (\hat{q}L^3)^{-1/2}$$

perturbative: rare, small-angle radiation

intra-jet structure modifications

$$\omega \sim \omega_s = \alpha_s^2 \hat{q}L^2$$
$$N \sim 1$$
$$\theta_{\rm br} \sim \frac{1}{\alpha_s^2}\theta_c$$

non-perturbative: copious, large-angle emissions

out-of-cone energy-loss, thermalization

Two separated regimes

see also Kurkela, Wiedemann 1407.0293

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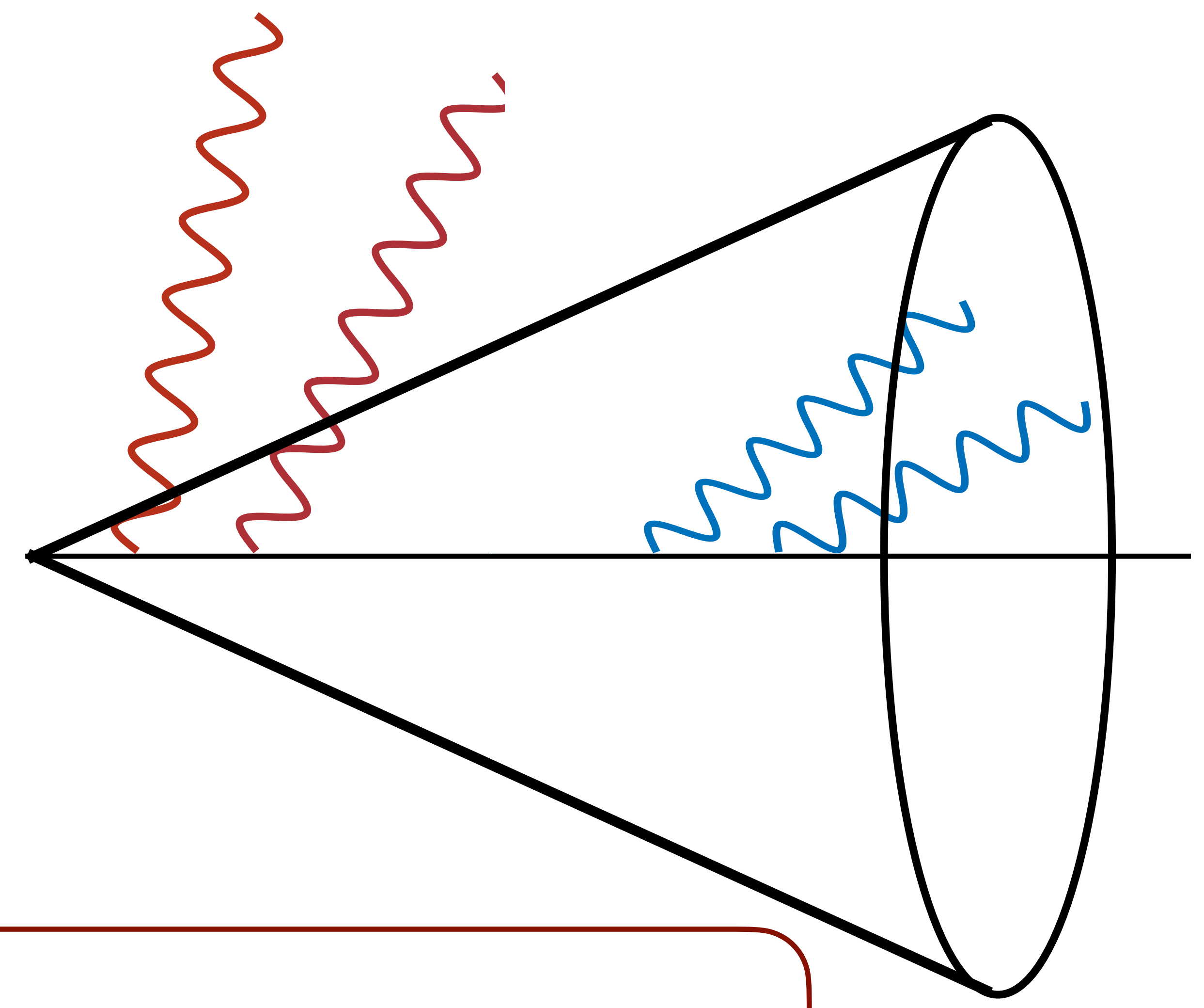

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non-perturbative: copious, large-angle emissions

out-of-cone energy-loss, thermalization

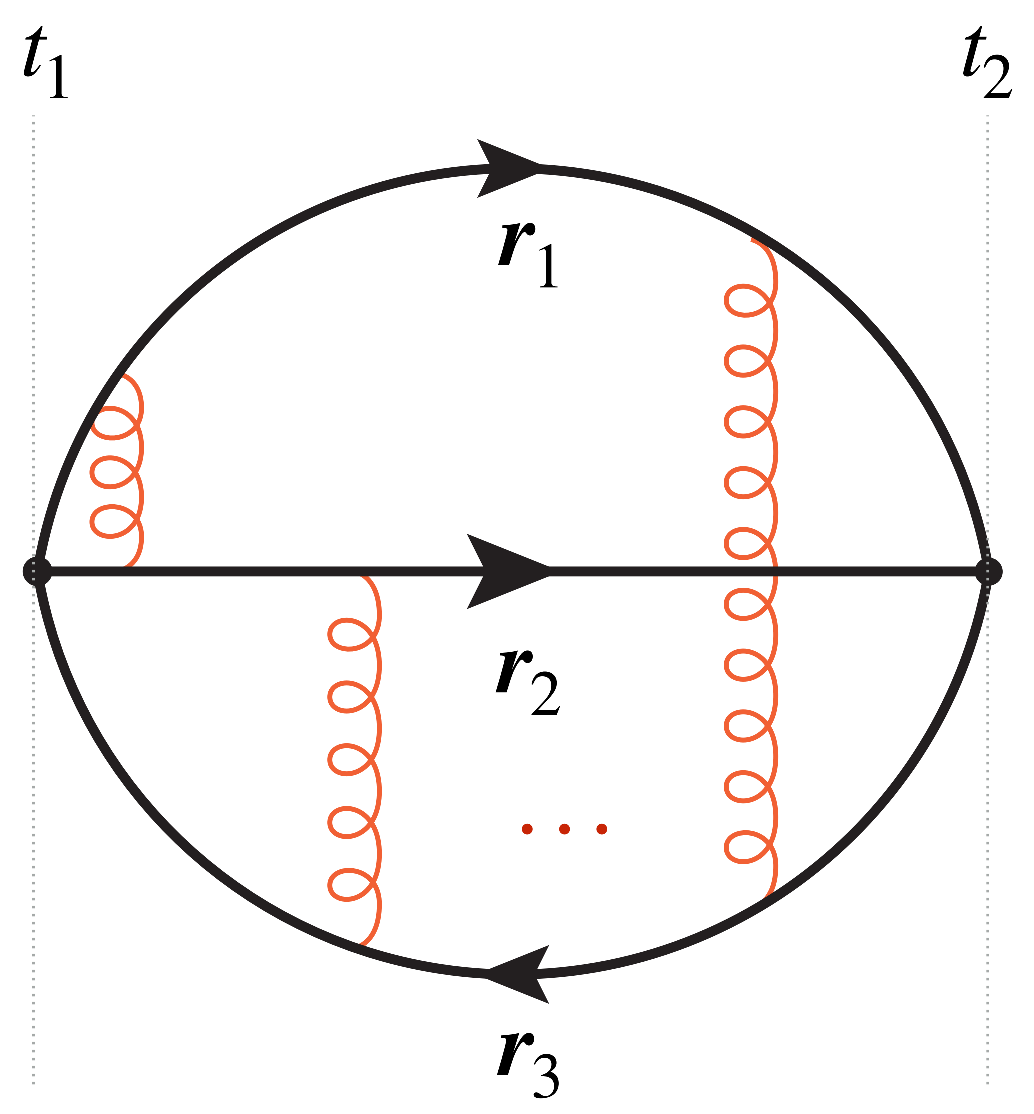
Gluons with $\omega_s \sim 5\,\mathrm{GeV}$ melt into the plasma!

Blaizot, Dominguez, Iancu, Mehtar-Tani 1301.6102

MEDIUM-INDUCED RADIATION

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); …

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



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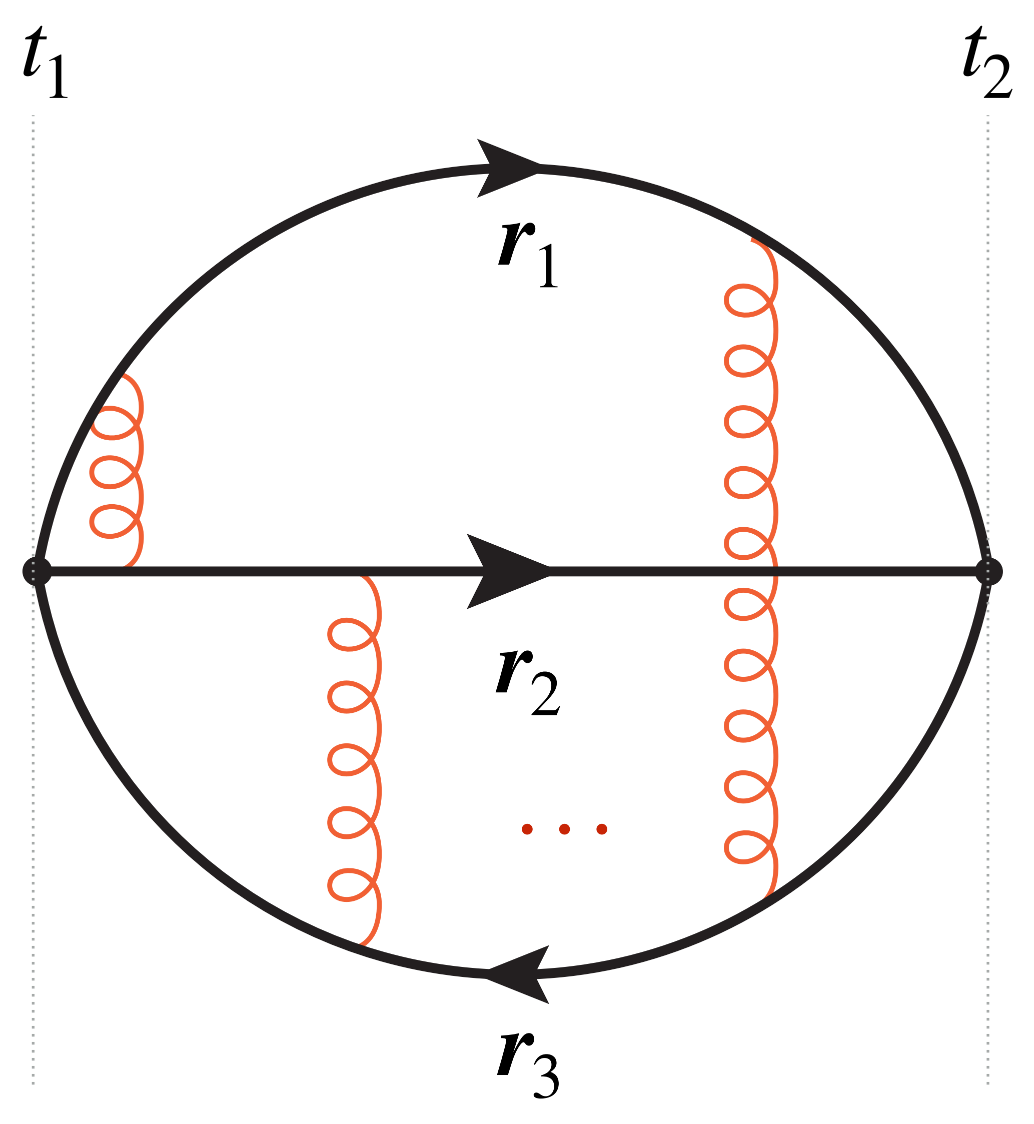


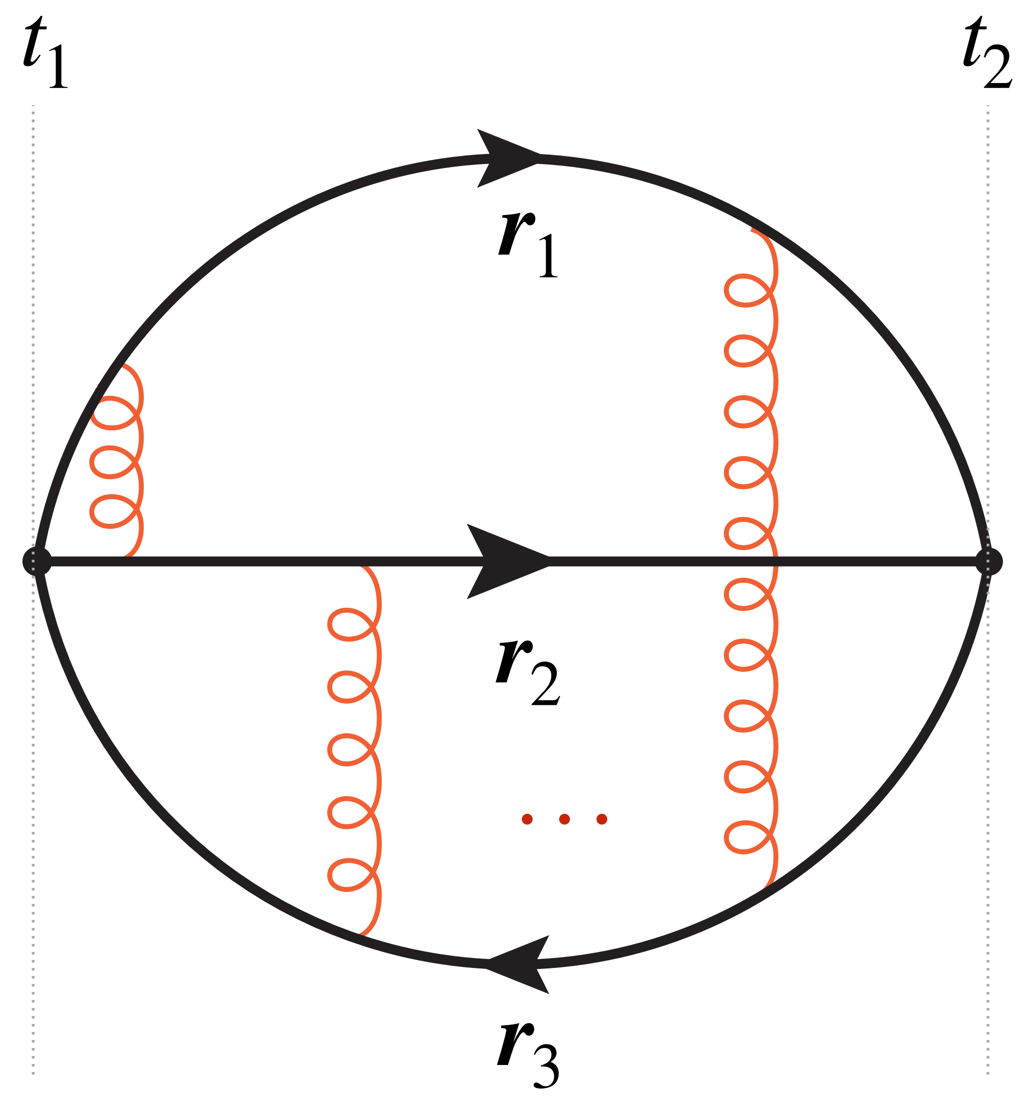
3-body interactions of the medium via Schrödinger equation with potential:

Solved numerically in Caron-Huot, Gale 1006.2379, Feal, Vazquez 1811.01591

$$v(\boldsymbol{x}, t) = \int_{\boldsymbol{q}} \frac{\mathrm{d}\sigma_{\rm el}}{\mathrm{d}^2\boldsymbol{q}}\left(1 - \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right) \approx \underbrace{\frac{1}{4}\hat{q}\boldsymbol{x}^2}_{\text{HO}} \log\frac{4}{\mu^2\boldsymbol{x}^2}$$

Medium-induced radiation

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); …



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

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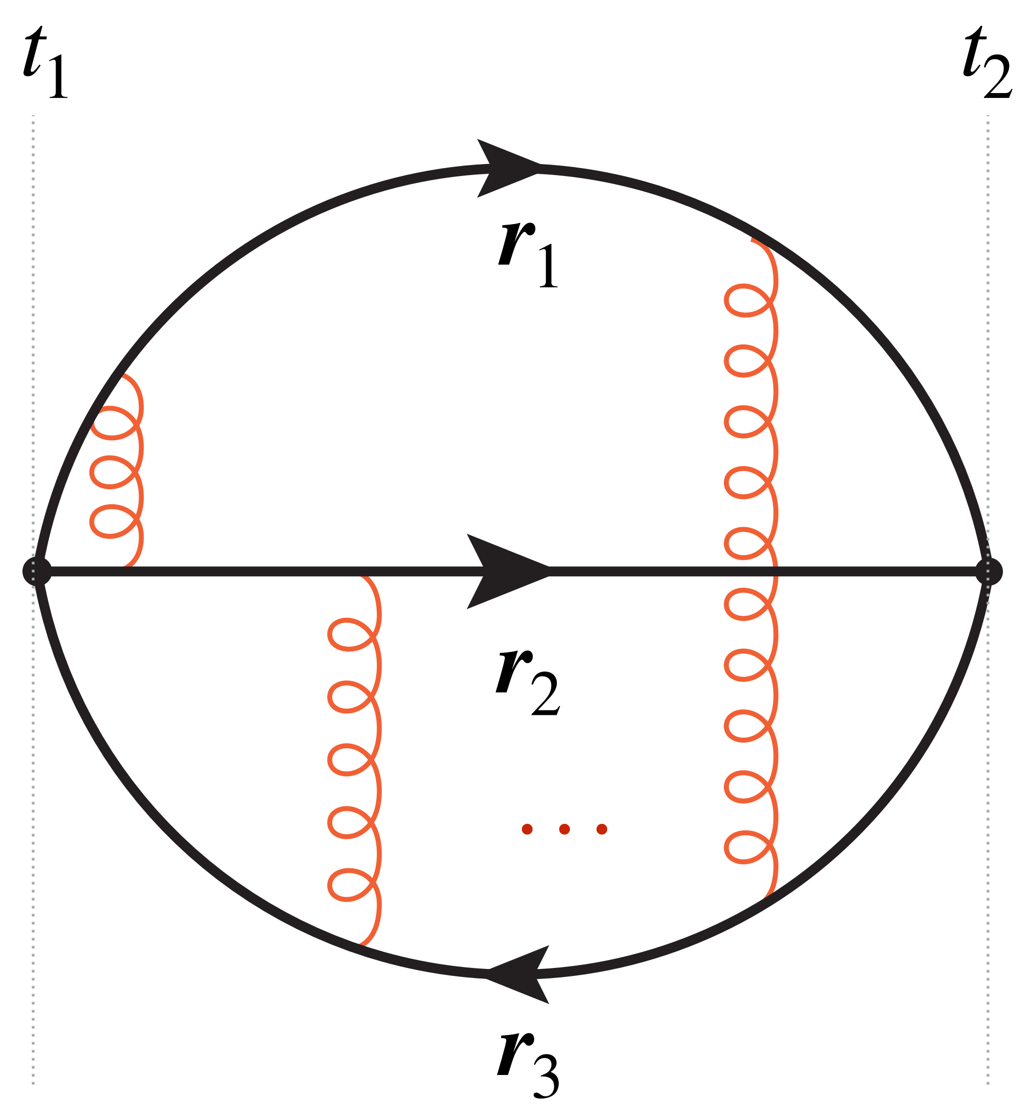
$$\mathcal{K}(t_2,t_1) = \mathcal{K}_0(t_2-t_1) + \int \mathrm{d}t\, \mathcal{K}_0(t_2-t)\, v(t)\, \mathcal{K}(t,t_1)$$

opacity expansion

Wiedemann (2000); Gyulassy, Levai, Vitev (2001); Sievert, Vitev, Yoon 1903.06170

MEDIUM-INDUCED RADIATION

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); …



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opacity expansion

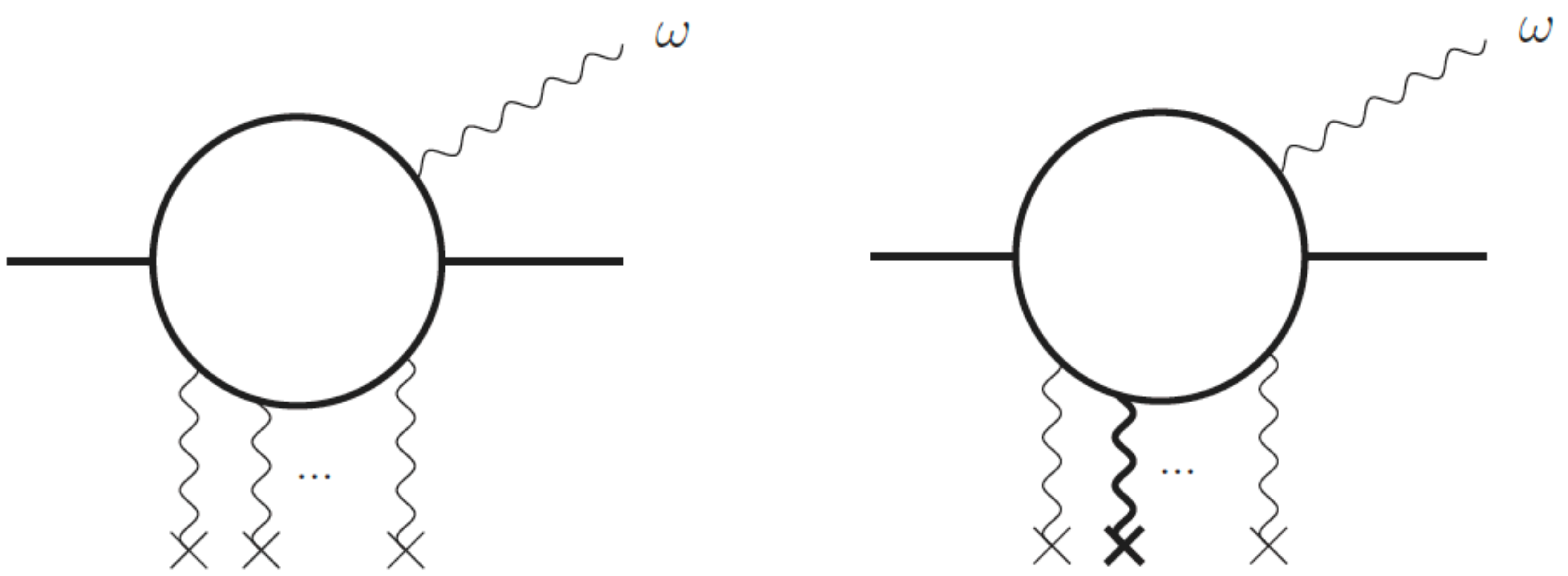
Wiedemann (2000); Gyulassy, Levai, Vitev (2001); Sievert, Vitev, Yoon 1903.06170

$$\mathcal{K}(t_2,t_1) = \mathcal{K}_{\mathrm{HO}}(t_2,t_1) + \int \mathrm{d}t\, \mathcal{K}_{\mathrm{HO}}(t_2,t)\delta v_{\mathrm{hard}}(t)\mathcal{K}(t,t_1)$$

"improved"
unifying HO & N=1

Mehtar-Tani, Tywoniuk 1910.02032

Deeper understanding of the scales



$$\hat{q}_0 = \begin{cases} 4\pi\alpha_s^2 C_R n & \text{for GW} \\ \alpha_s C_R m_D^2 T & \text{for HTL} \end{cases}$$

Möller expansion (Mehtar-Tani 1903.00506)

Expanding: $\tilde{v}(\boldsymbol{x}, t) = \frac{1}{4N_c}\hat{q}_0\, \boldsymbol{x}^2 \ln \frac{1}{\mu^2 \boldsymbol{x}^2} = \frac{1}{4N_c}\hat{q}_0\, \boldsymbol{x}^2 \ln \frac{Q^2}{\mu^2} + \frac{1}{4N_c}\hat{q}_0\, \boldsymbol{x}^2 \ln \frac{1}{Q^2 \boldsymbol{x}^2}$

Improved opacity expansion (Mehtar-Tani, Tywoniuk 1910.02032)

$$\mathcal{K}(\boldsymbol{x}, t_1; \boldsymbol{y}, t_0) = \mathcal{K}_{\rm HO}(\boldsymbol{x}, t_1; \boldsymbol{y}, t_0) - \int \mathrm{d}^2\boldsymbol{u} \int_{t_0}^{t_1} \mathrm{d}t\, \mathcal{K}_{\rm HO}(\boldsymbol{x}, t_1; \boldsymbol{u}, t)\delta v(\boldsymbol{u}, t)\mathcal{K}(\boldsymbol{u}, t; \boldsymbol{y}, t_0)$$

IMPROVED OE: NLO CORRECTION

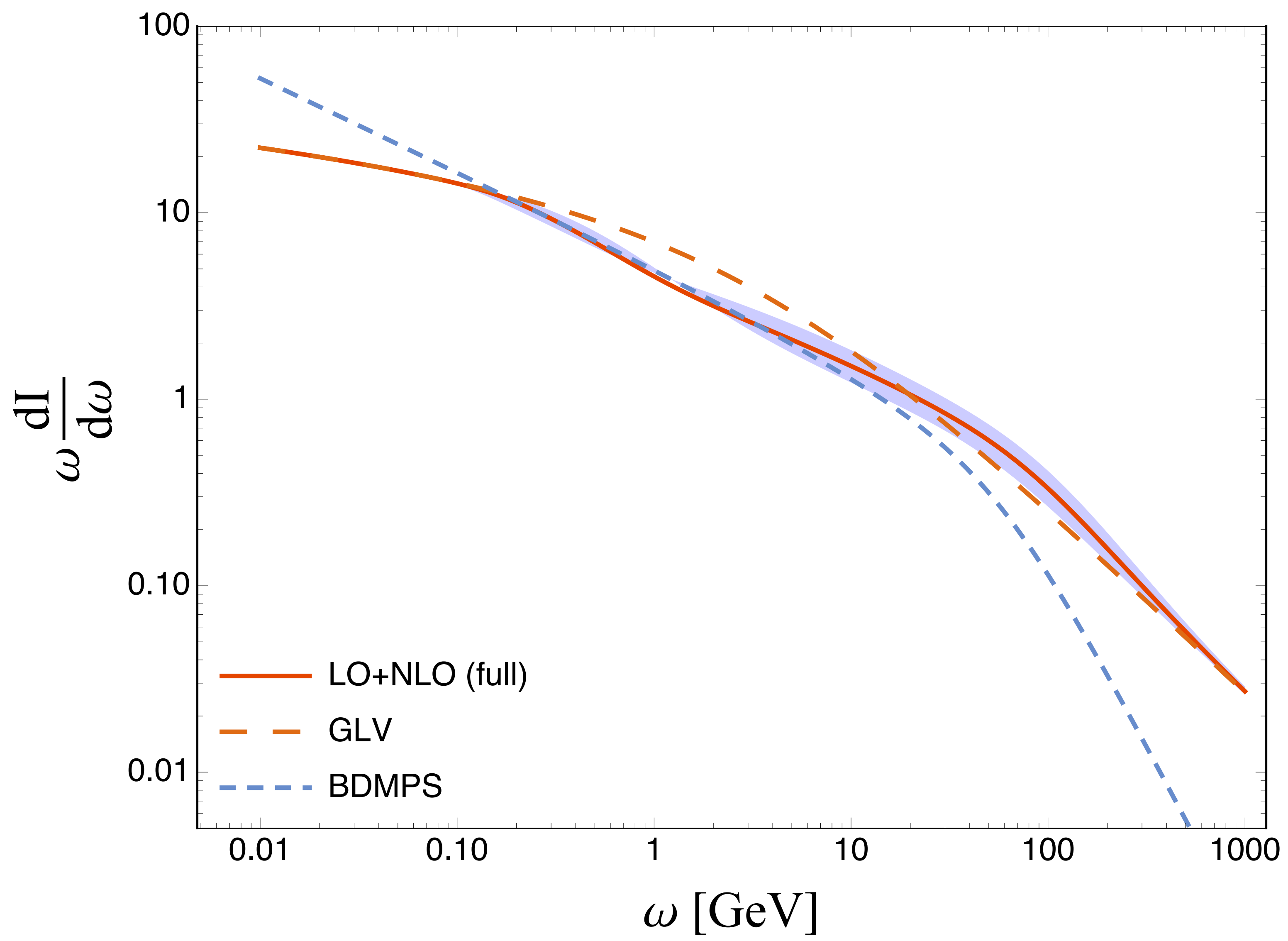
Mehtar-Tani, Tywoniuk 1910.02032
Barata, Mehtar-Tani 2004.02323

$$\frac{\mathrm{d}I^{(0)}}{\mathrm{d}\omega} = \frac{2\alpha_s C_R}{\pi\omega} \ln|\cos\Omega L| \;,$$

$$\frac{\mathrm{d}I^{(1)}}{\mathrm{d}\omega} = \frac{\alpha_s C_R \hat{q}_0}{2\pi} \mathrm{Re} \int_0^L \mathrm{d}s \, \frac{-1}{k^2(s)} \left[\ln \frac{-k^2(s)}{Q^2} + \gamma_E \right]$$

$$k^2(s) = i\frac{\omega\Omega}{2}\left[\cot\Omega s - \tan\Omega(L-s)\right]$$

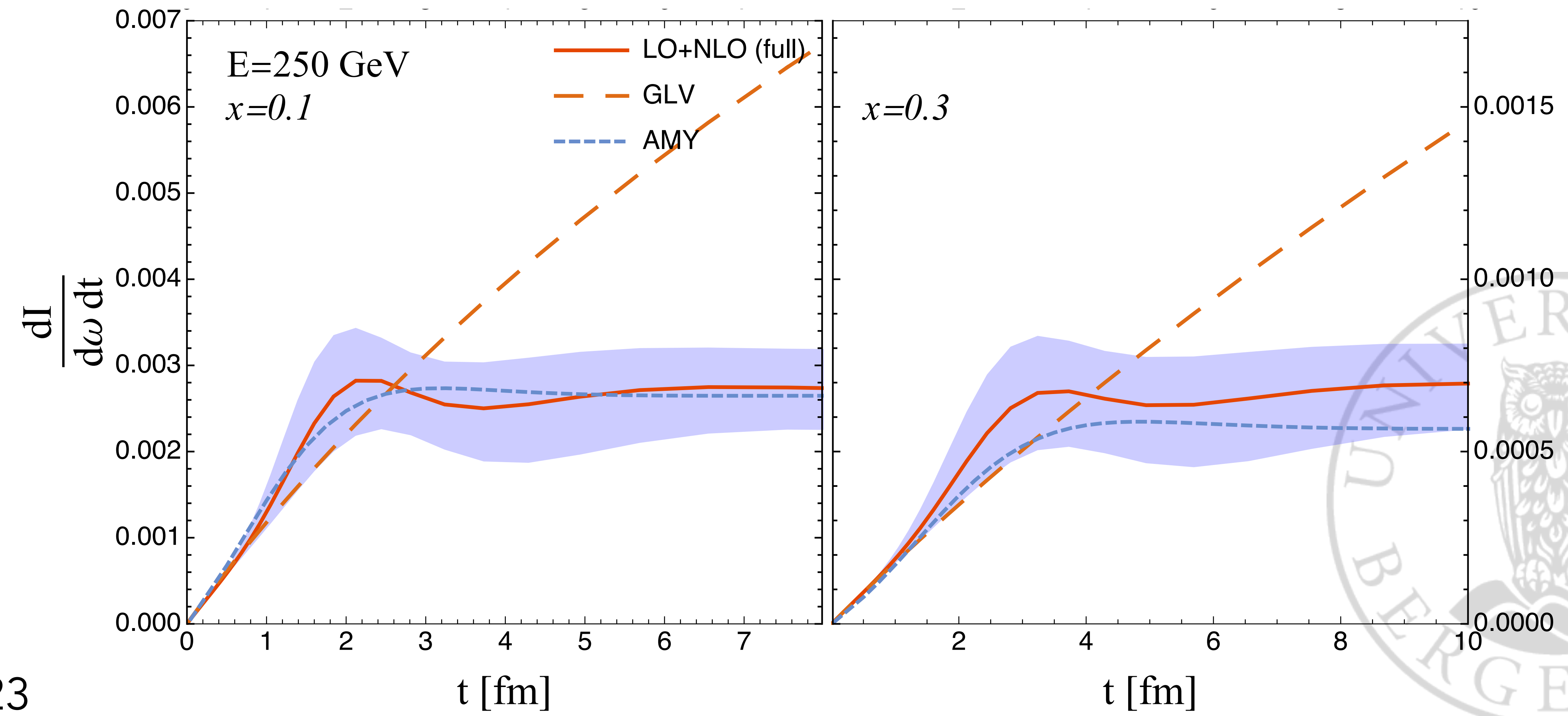
$$Q^2 = \sqrt{\hat{q}_0 \omega \ln \frac{Q^2}{\mu^2}}$$ matching scale



Interpolates well between the three regimes.

Compact, analytic formula.

Rate (*dI/dωdt*) agrees well with full numerical solution.



CONTRIBUTIONS TO $\hat{q}$

Barata, Mehtar-Tani 2004.02323

In the LPM regime ($\omega < \omega_c$), contributions up to NNLO$_{\text{IOE}}$ can be absorbed as:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega \mathrm{d}L} = \bar{\alpha} \sqrt{\frac{\hat{q}_{\text{eff}}(Q_c)}{\omega}}$$

$$\hat{q}_{\text{eff}}(Q_c) = \hat{q}_0 \log\left(\frac{Q_c^2}{\mu^{\star 2}}\right)\left[1 + \frac{1.016}{\log\left(\frac{Q_c^2}{\mu^{\star 2}}\right)} + \frac{0.316}{\log^2\left(\frac{Q_c^2}{\mu^{\star 2}}\right)} + \mathcal{O}\left(\log^{-3}\left(\frac{Q_c^2}{\mu^{\star 2}}\right)\right)\right]$$

- evaluated at the scale: $Q_c^2 = \sqrt{\hat{q}_0\, \omega \log\left(\frac{Q_c^2}{\mu^{\star 2}}\right)}$

- significant (logarithmic) contributions from hard scattering to the "bare" $\hat{q}_0$
- accommodates straightforward comparison between different medium models through μ_*^2

Broadening factor at NLO

Barata, Mehtar-Tani, Soto-Ontoso, KT 2009.13667

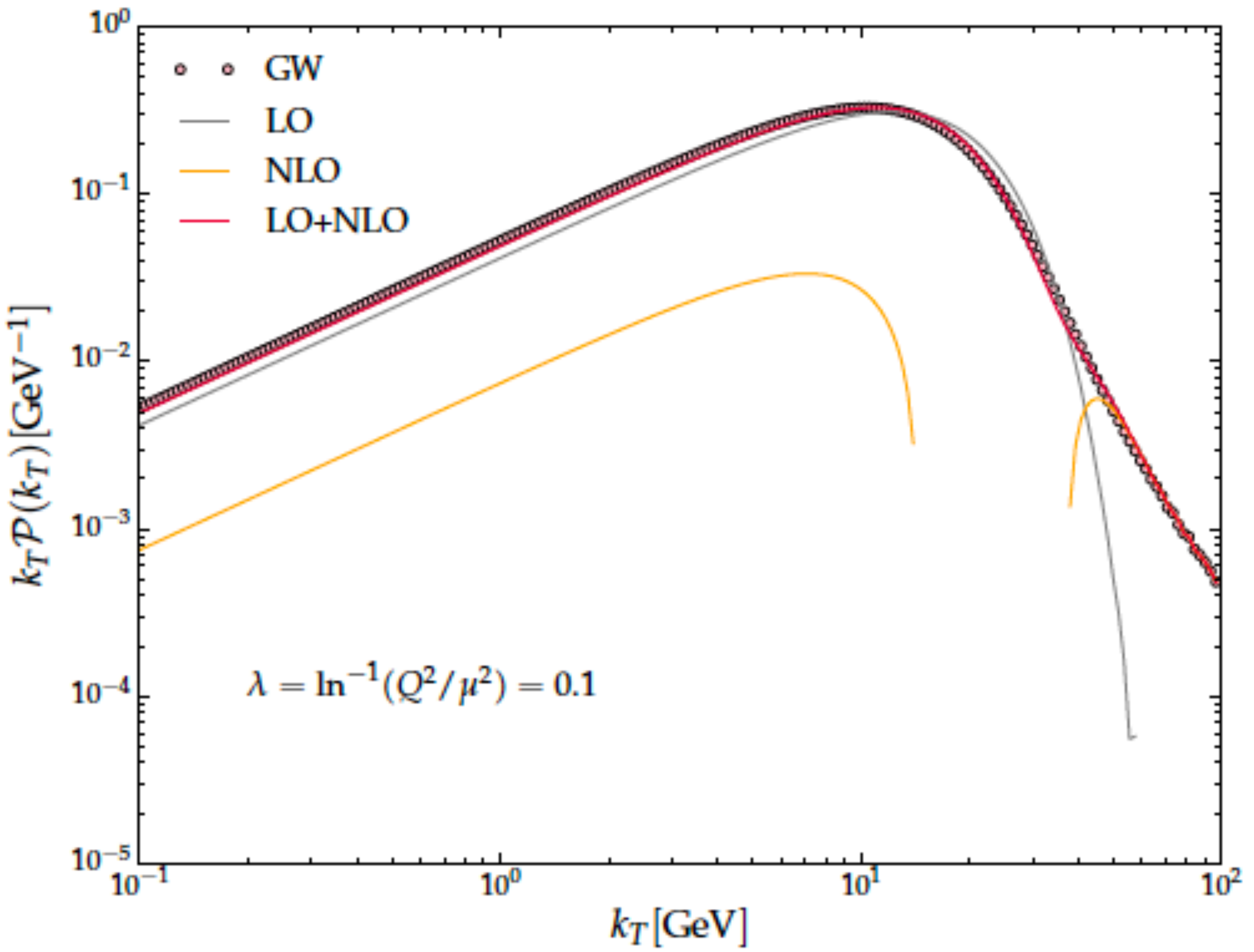
Parametric estimates:

$$\mathcal{P}(\boldsymbol{k}) \simeq \begin{cases} \frac{4\pi}{Q_s^2}\mathrm{e}^{-\boldsymbol{k}^2/Q_s^2} & k_\perp^2 \ll Q_s^2 \\ \frac{4\pi\,\hat{q}_0 L}{\boldsymbol{k}^4} & k_\perp^2 \gg Q_s^2 \end{cases} .$$

Calculation within IOE gives ($x = \boldsymbol{k}/Q_s^2$):

$$\mathcal{P}^{\mathrm{LO+NLO}}(\boldsymbol{k},L) = \frac{4\pi}{Q_s^2}\mathrm{e}^{-x}\Big\{1-\lambda\left(\mathrm{e}^{x}-2+(1-x)\,\left(\mathrm{Ei}\,(x)-\log(4x\,a)\right)\right)\Big\}$$

(already found by Moliére in 1948!)

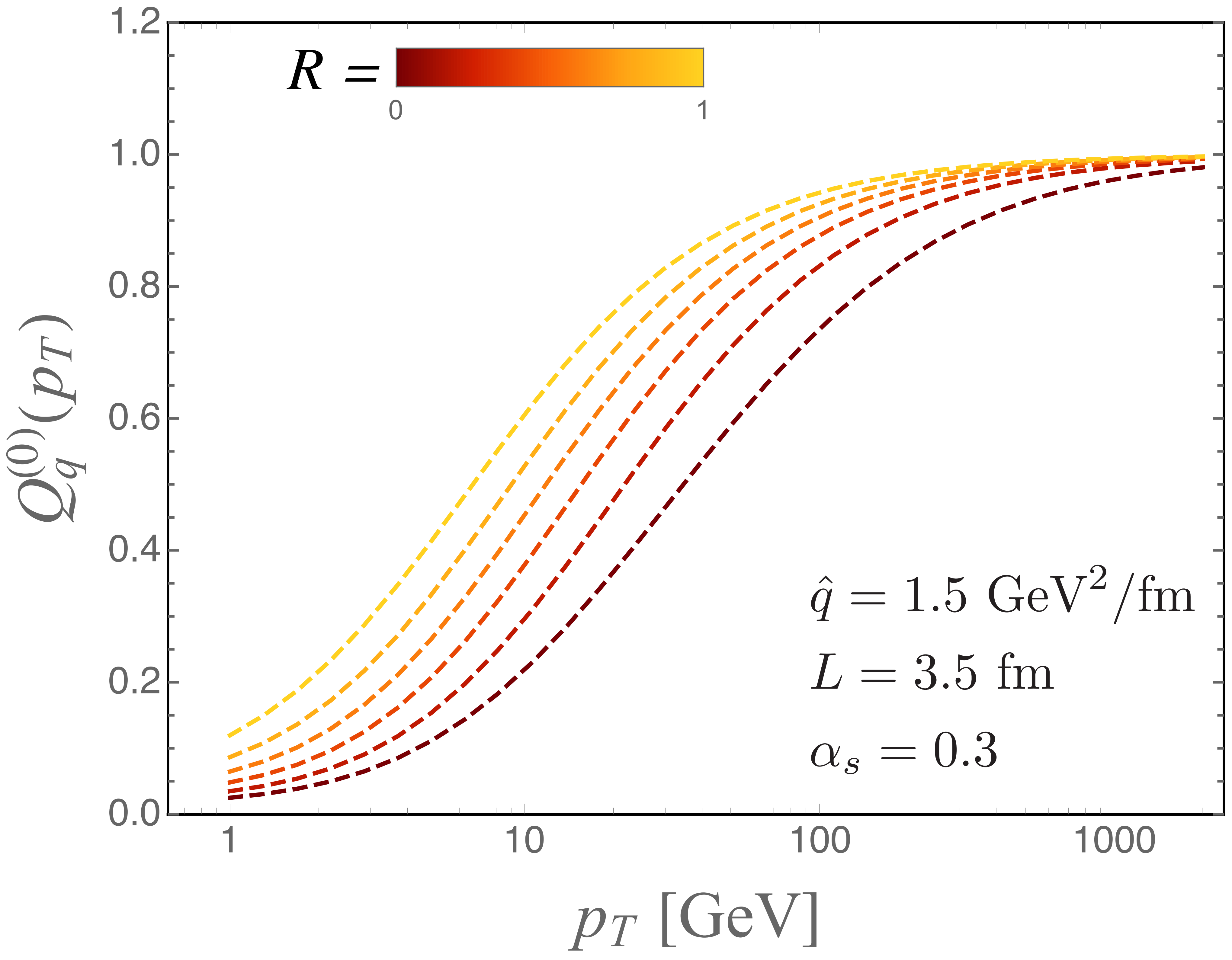


For the time being, we assume for out-of-cone emissions:

$$\frac{\mathrm{d}I_>}{\mathrm{d}\omega} = \frac{\mathrm{d}I}{\mathrm{d}\omega} \times \int_{\omega^2 R^2}^{\infty} \frac{\mathrm{d}\boldsymbol{k}^2}{4\pi}\mathcal{P}(\boldsymbol{k})$$

BARE QUENCHING FACTOR

$$Q^{(0)}(p_T) = \exp\left[-\int_0^\infty \mathrm{d}\omega \, \frac{\mathrm{d}I_>}{\mathrm{d}\omega}\left(1-\mathrm{e}^{-\omega\frac{n}{p_T}}\right)\right]$$



radiative & elastic energy loss out of the jet cone

recovery of energy at large angles:

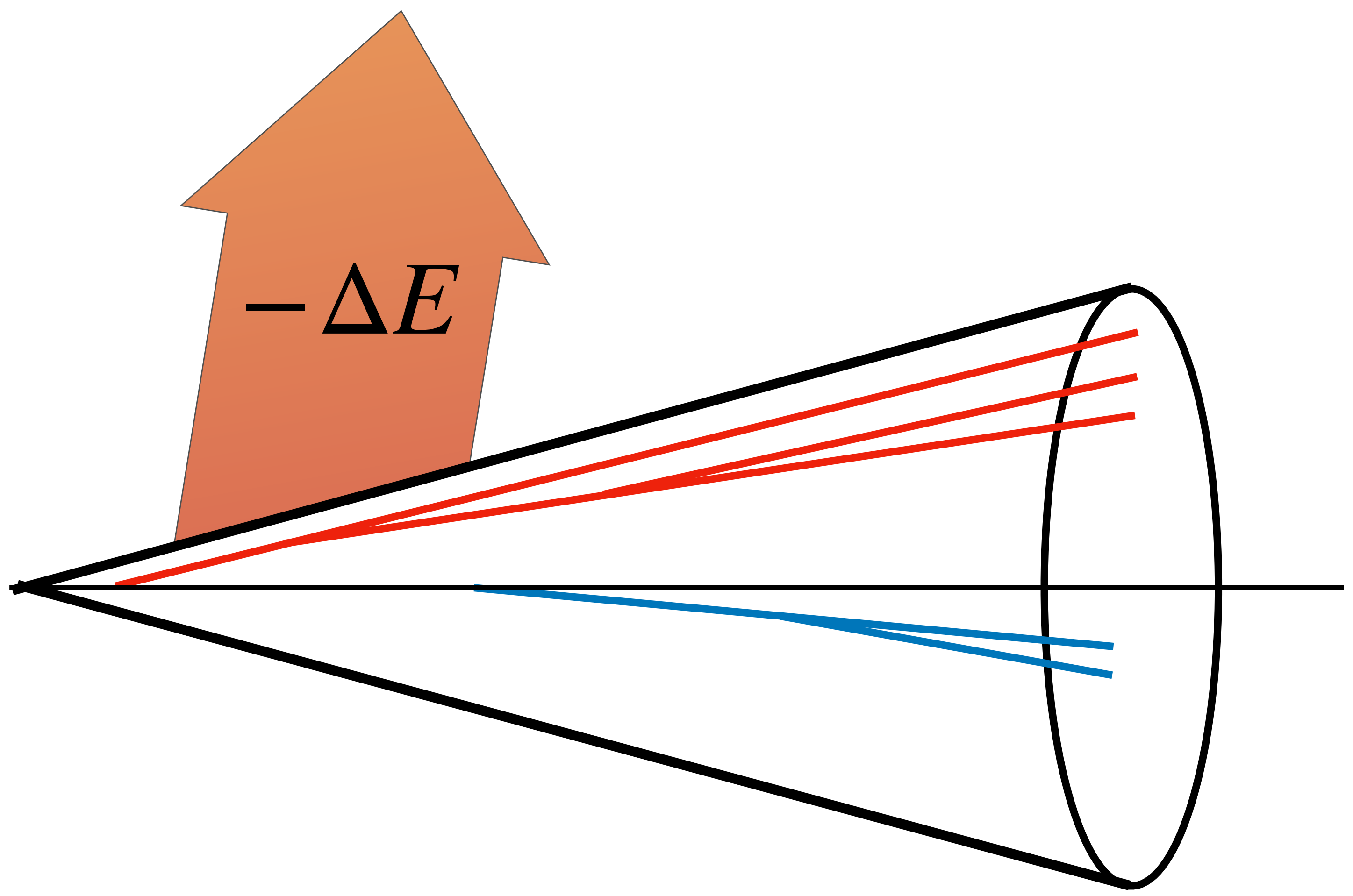
- hard gluons stay within cone
- soft gluons thermalize and drift back into the cone

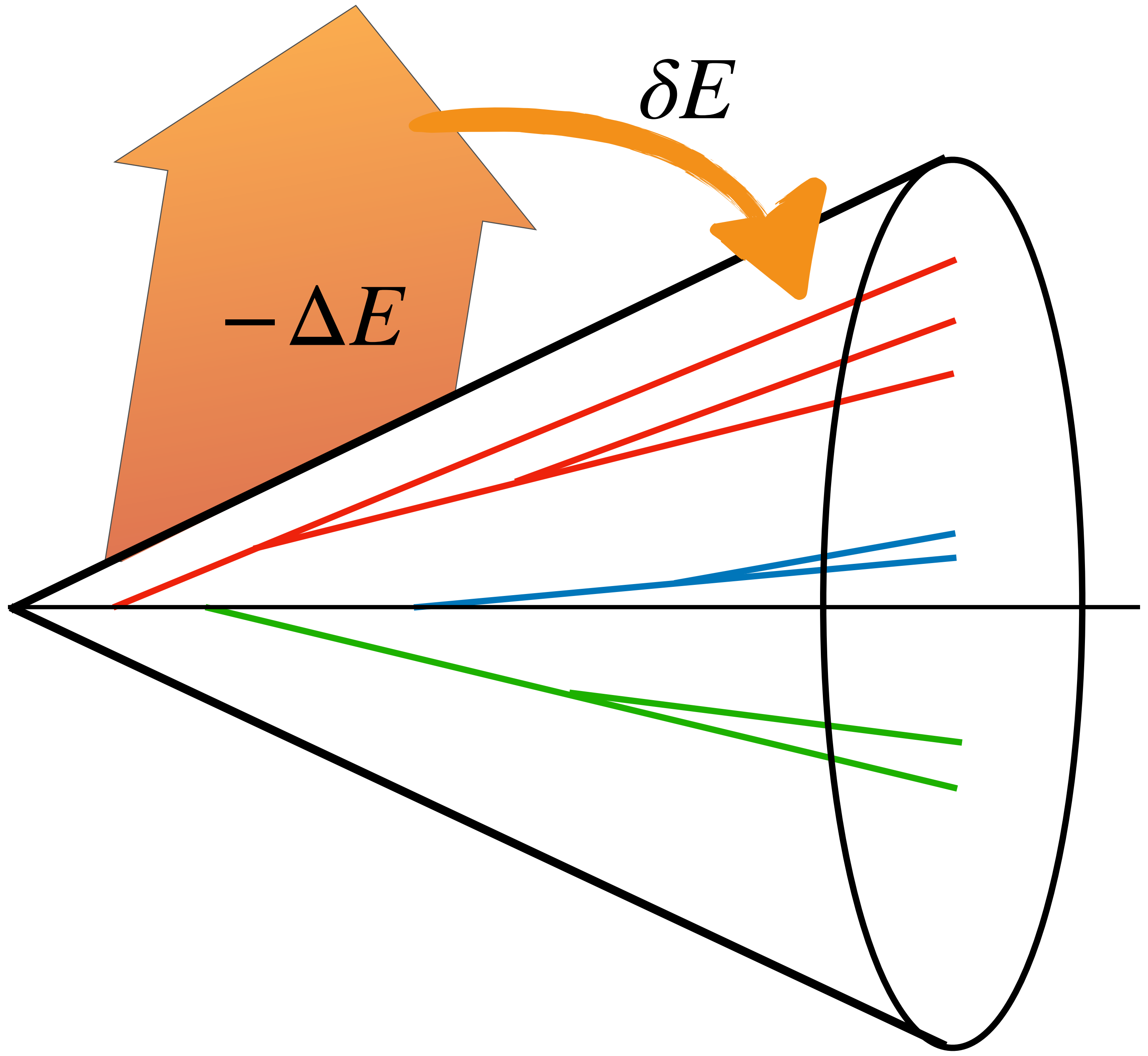
Casimir scaling: $$Q_q(p_T) \approx \left(Q_g(p_T)\right)^{C_F/C_A}$$

Outline

- structure of QCD jets
- matching vacuum and medium evolution equations
- quenching in the improved opacity expansion
- phenomenological application: cone-size dependent jet spectrum

GENERAL PICTURE





fewer color sources - less energy lost
easier for energy to flow out-of-cone

more color sources - more energy lost
recovery of lost energy

beware of biases: jet population is different!

JET SPECTRUM IN HEAVY-ION COLLISIONS

$$\sigma_{AA}(p_T, R) = f^{(n-1)}_{\text{jet}/k}(R|p_T, R_0)\,\hat{\sigma}_k(p_T, R_0)$$

$$f^{(n-1)}_{\text{jet}/k} = \sum_{i=q,g} Q_i(p_T, R) f^{(n-1)}_{i/k}$$

- hard spectrum at LO contains nPDFs (EPS09)
- $\log 1/R$ resummation using moments of microjet fragmentation functions
- quenching factors evaluated including event-by-event fluctuations through hydrodynamic background

$$f^{(n)}_{\text{jet}/k}(R|p_\mathrm{T}, R_0) = \int_0^1 \mathrm{d}x\, x^n f_{\text{jet}/k}(x, R_0)$$

$$\frac{\mathrm{d}}{\mathrm{d}t} f^{(n)}_i(t) = \gamma_{ij}(t) f^{(n)}_j(t)$$

ENERGY-LOSS

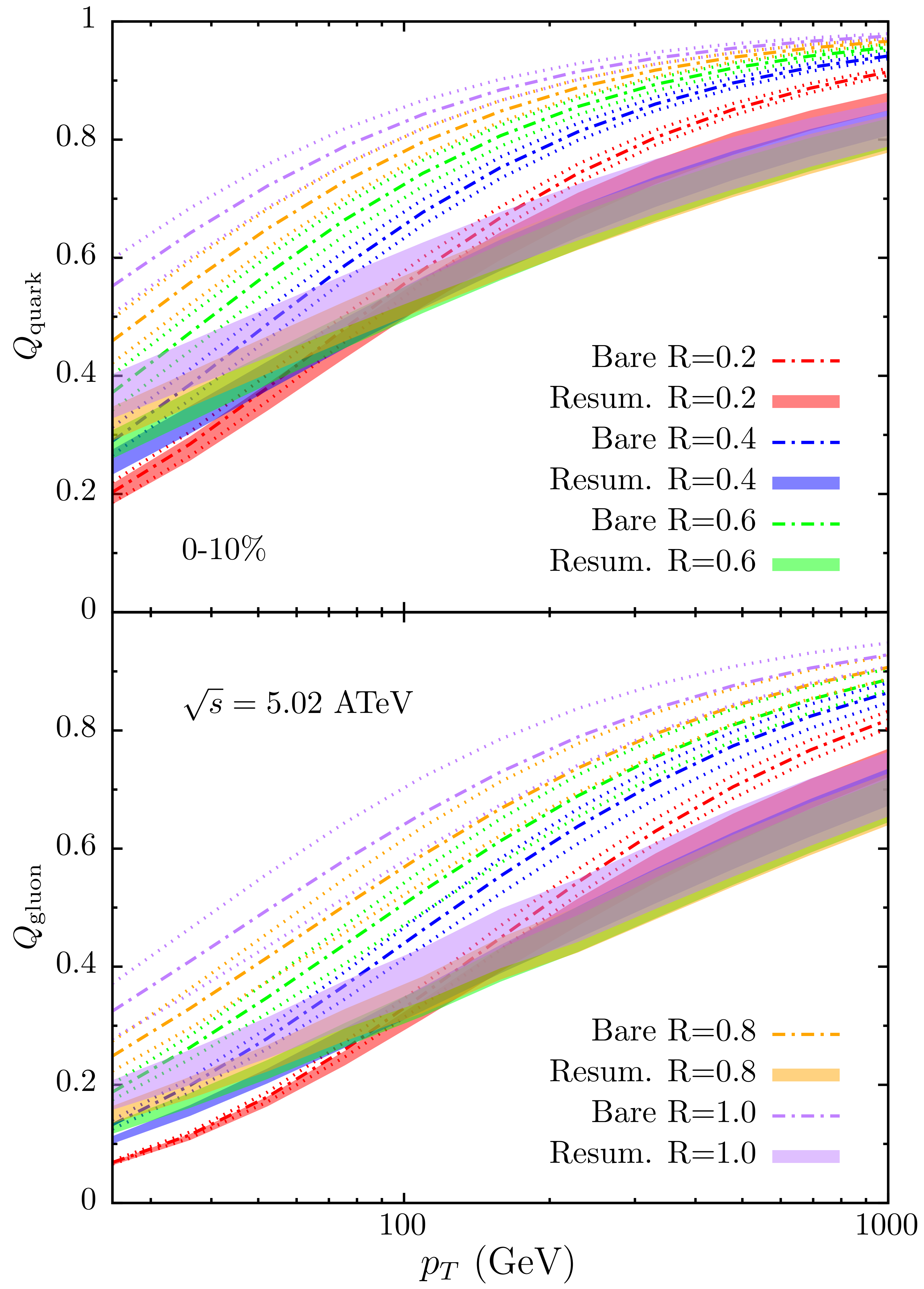
$$Q_i(p,0) = Q^{(0)}_{\mathrm{rad},i}(\nu) Q^{(0)}_{\mathrm{el},i}(\nu)$$

$$-\ln Q^{(0)}_{\mathrm{rad}}(\nu) = \int_{\omega_s}^{\infty} \mathrm{d}\omega \, \frac{\mathrm{d}I_>}{\mathrm{d}\omega} \left(1 - \mathrm{e}^{-\nu\omega}\right) + \int_T^{\omega_s} \mathrm{d}\omega \, \frac{\mathrm{d}I}{\mathrm{d}\omega} \left(1 - \mathrm{e}^{-\nu\omega(1-(R/R_{\mathrm{rec}})^2)}\right)$$

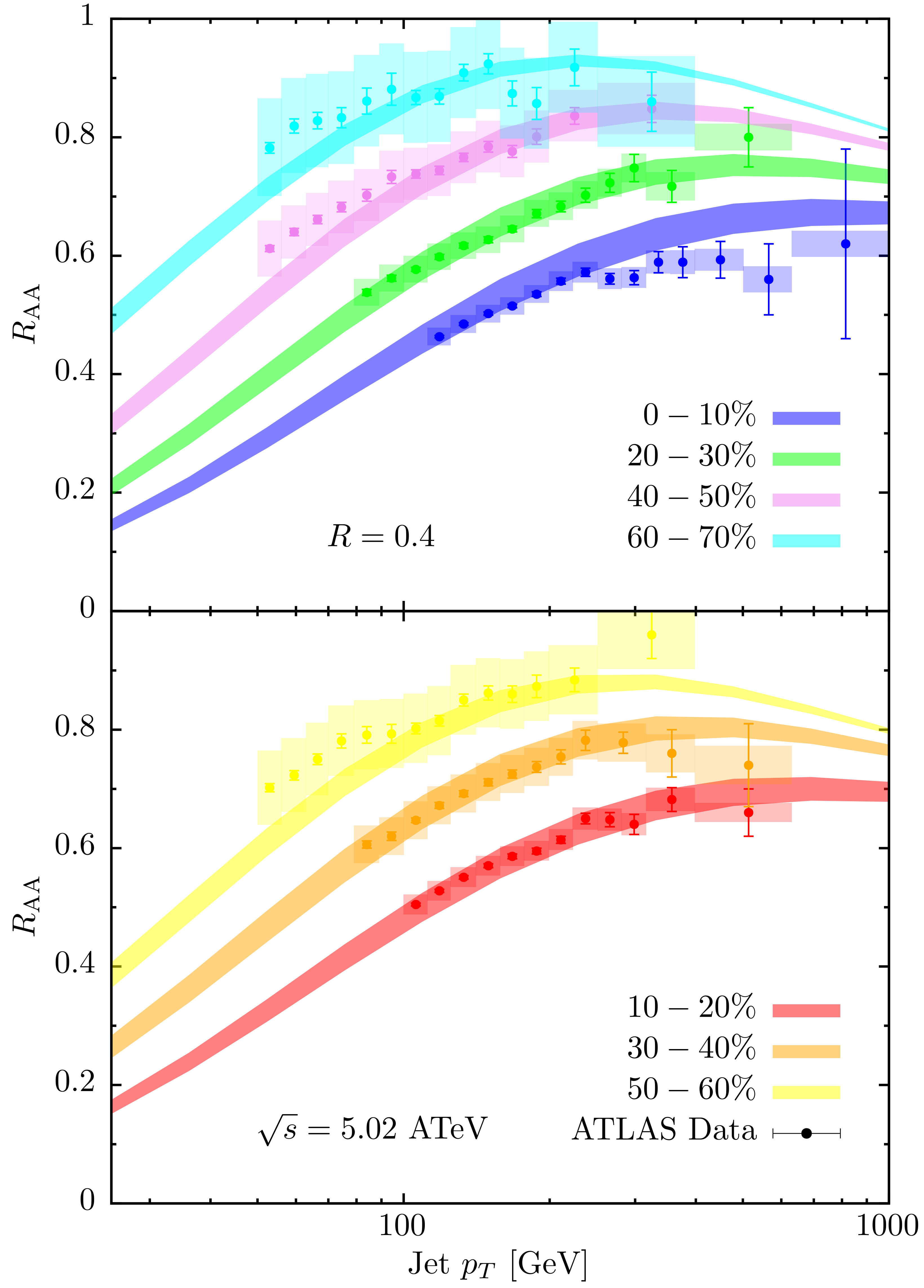
$$-\ln Q^{(0)}_{\mathrm{el}}(\nu) = \hat{e} L \nu (1 - (R/R_{\mathrm{rec}})^2)$$

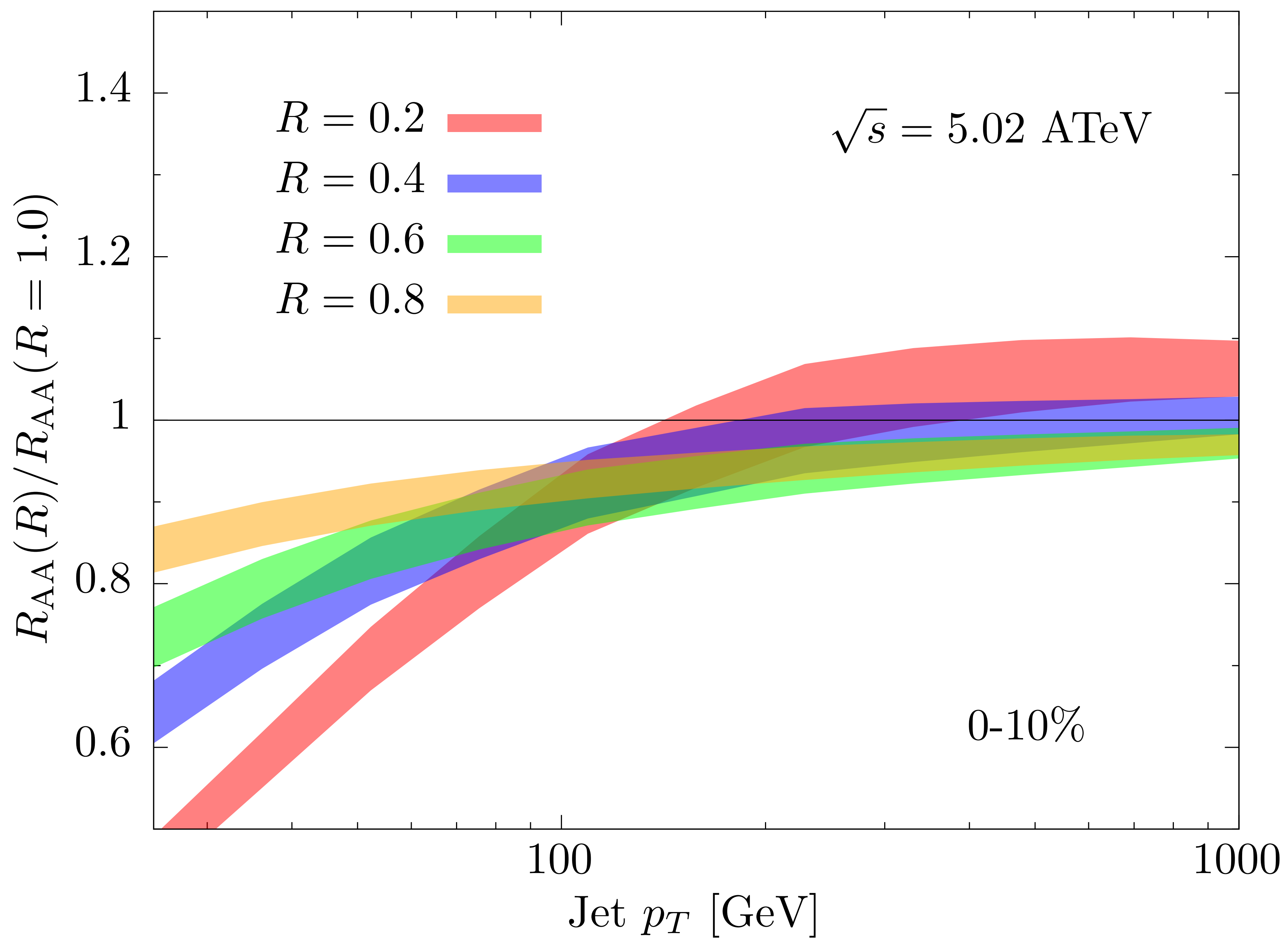
- both radiative and elastic energy loss implemented
- perturbative sector strongly constrained (only one parameter g_{med})
- non-perturbative sector: two modeling parameters ω_s and R_{rec}
  - numerically confirmed modest dependence on these parameters

QUARK AND GLUON QUENCHING FACTORS



Centrality and R-dependence





Good agreement with experimental data!

Still prelim results, stay tuned for final parameters and interpretation!

OUTLOOK

- advances in theory of jet quenching allows for precision era in jet quenching physics
- perturbative merging of vacuum+in-medium evolution
  - modeling of ultra-soft sector via phenomenological parameters
  - connection to thermalization to be further explored
- $\hat{q}$ is a measure of both the amount of energy lost & the resolution properties of the medium (color coherence)
  - R_{AA} vs. R a rich observable to probe regimes

THANK YOU!