Higher order corrections to jet-quenching

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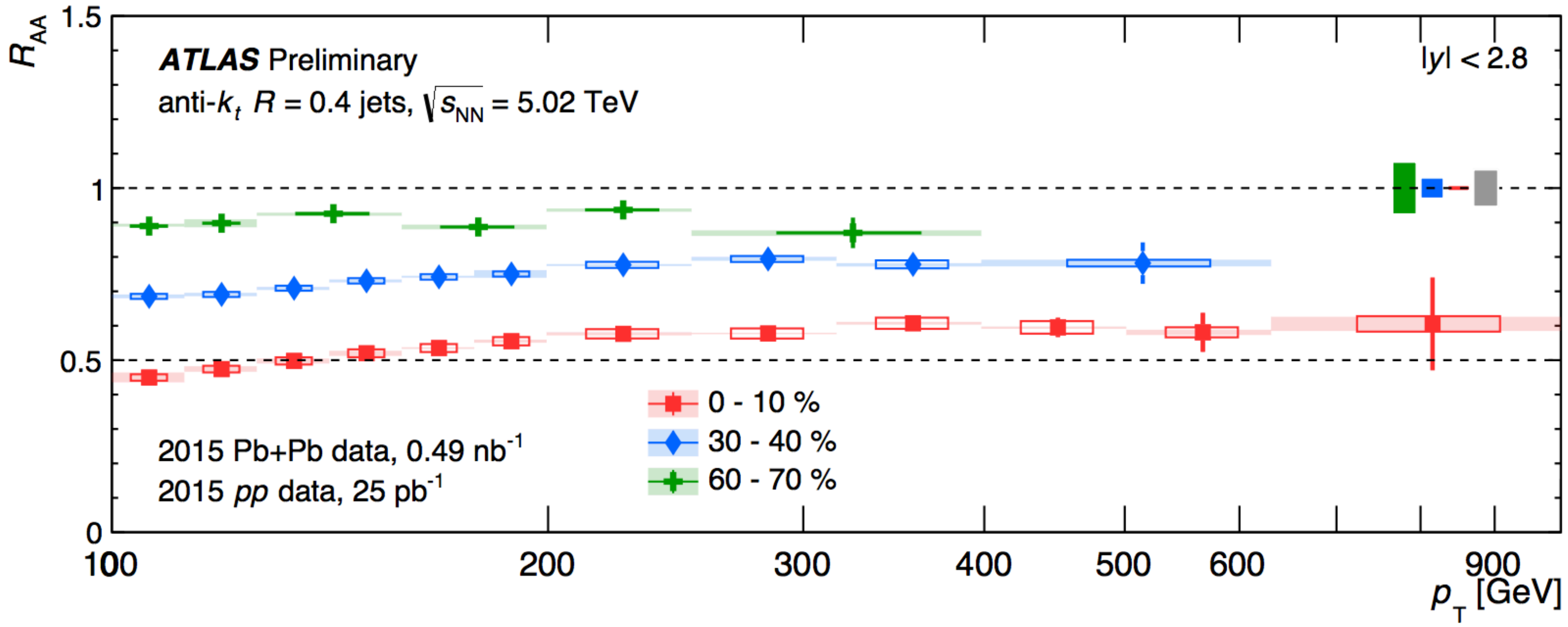
Motivation

- How do jets, as multi-partonic systems, interact with a QCD medium?

- A lot of progress on the computational side. Several Monte Carlo event generators on the market: Hybrid model, JEWEL, LBT, CoLBT, MARTINI, Matter, Q-Pythia, (some already available on JetScape platform)

- Theoretical guidance at high pT? Understanding jet substructure, developing a probabilistic picture (including interferences)

What drives jet suppression



- Strong suppression of jets in PbPb collisions at the LHC (up to 1 TeV) → pertubative expansion breaks down: expect large power corrections at high pT

- **Two competing effects:** (relative) single parton energy loss decreases with pT while parton multiplicity increases

Motivation

- **Amplification of jet quenching** due to increasing multiplicity at high pT qualitatively accounted for in Monte Carlo event generators: JEWEL, MARTINI, Hybrid Model, etc

Dani Pablos' talk on Thursday

Milhano, Zapp EPJC 76 (2016) 288
Casalderrey et al. JHEP 1703 (2017) 135

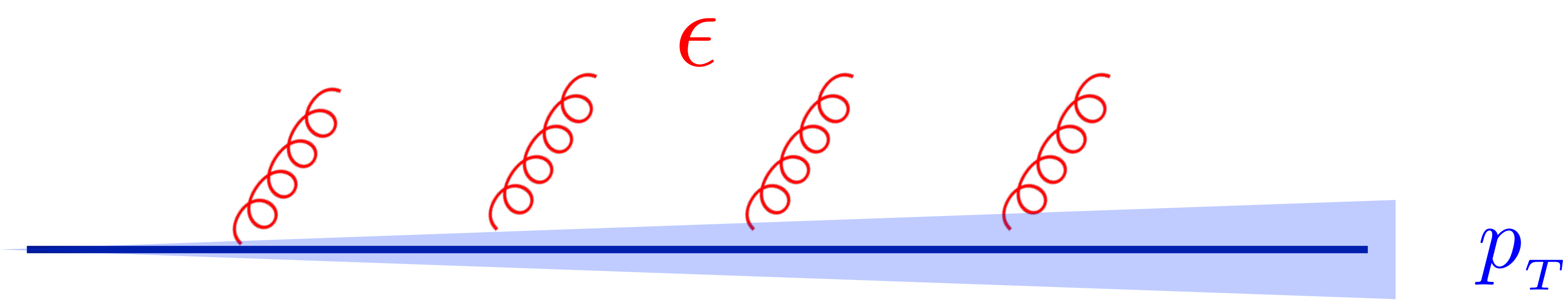
- **This talk**: analyze the structure of higher order corrections (including interferences effects) to the inclusive jet spectrum → provide MC prescription

Work in collaboration with Konrad Tywoniuk

arXiv: 17017.07361 (PRD), arXiv:17017.06047 (NPA)

Single parton energy loss

- Standard analytic approaches to energy loss: medium-induced radiative energy loss of a single quark or gluon



- Jet spectrum: convolution of pp jet spectrum with energy loss probability distribution

$$\frac{\mathrm{d}\sigma(p_T)}{\mathrm{d}^2 p_T \mathrm{d}y} = \int_0^\infty \mathrm{d}\epsilon\, \mathcal{P}(\epsilon)\, \frac{\mathrm{d}\sigma^{\mathrm{vac}}(p_T + \epsilon)}{\mathrm{d}^2 p_T \mathrm{d}y}$$

Single parton energy loss

- Due to the steep initial spectrum, energy loss biased towards small values (< mean energy loss)

$$\epsilon \sim \frac{p_T}{n} \ll \bar{\epsilon} \sim \bar{\alpha}\hat{q}L^2$$

Baier, Dokshitzer, Mueller, Schiff, JHEP (2001)

- large n approximation (not necessary): $\frac{\mathrm{d}\sigma(p_T+\epsilon)}{\mathrm{d}^2 p_T} \sim \frac{1}{(p_T+\epsilon)^n} = \frac{\mathrm{e}^{-\frac{n\epsilon}{p_T}}}{p_T^n}(1+\mathcal{O}(n\epsilon^2/p_T^2))$

$$R_{\mathrm{AA}} \simeq Q(p_T) \equiv \int \mathrm{d}\epsilon\, \mathcal{P}(\epsilon)\, \mathrm{e}^{-\frac{n\epsilon}{p_T}}$$

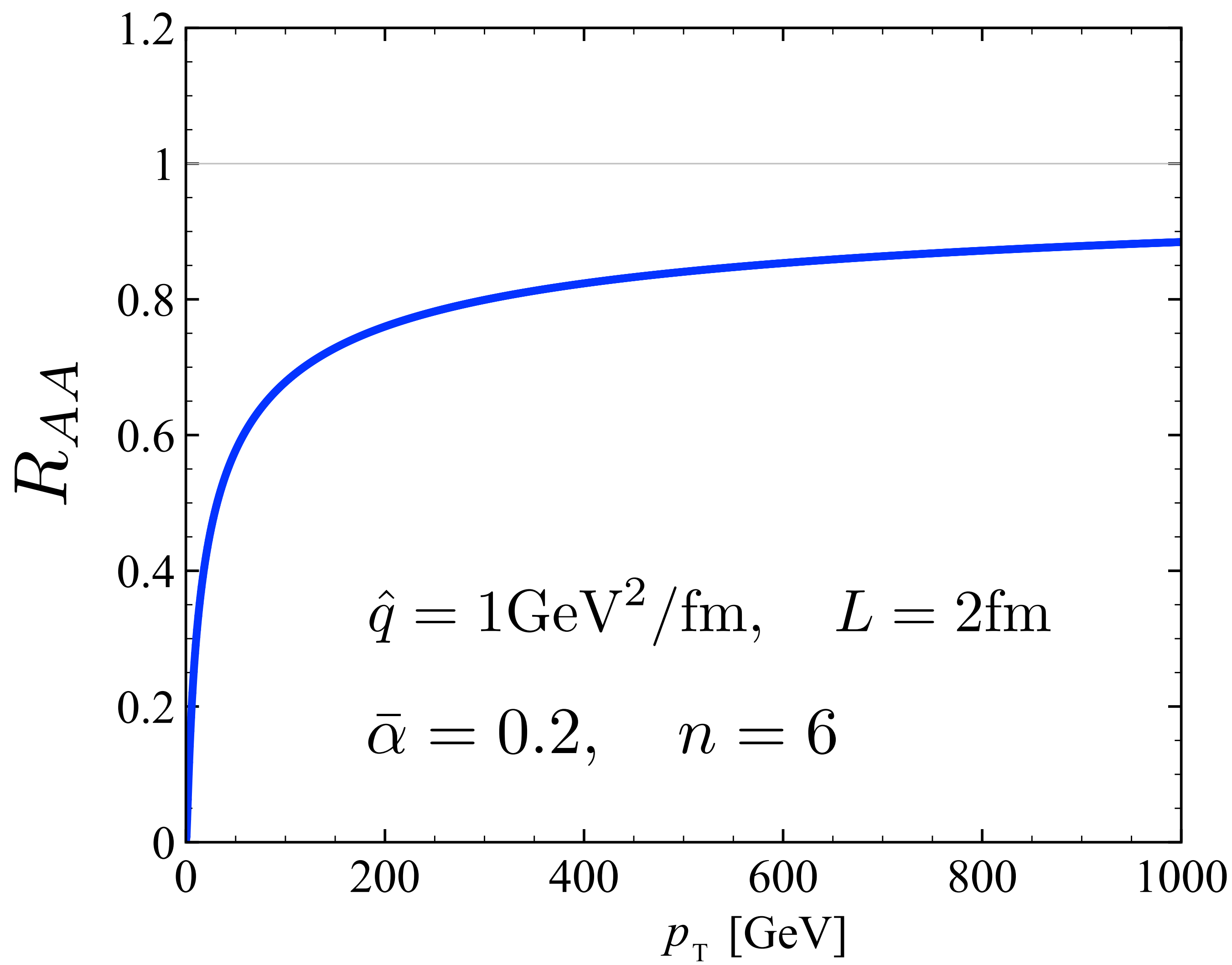
- In this limit multiple gluon radiation/scattering cannot be neglected (in contrast with single hard gluon radiation approx. HT, GLV, SCETg)

Jeon, Moore (2003) , Blaizot, Dominguez, Iancu, MT (2013)

Single parton energy loss

- Illustration: neglecting finite size effects and medium geometry

$$R_{AA} \simeq \exp\left(-\bar{\alpha}\, L \sqrt{\frac{\pi \hat{q}\, n}{p_T}}\right)$$



Strong quenching

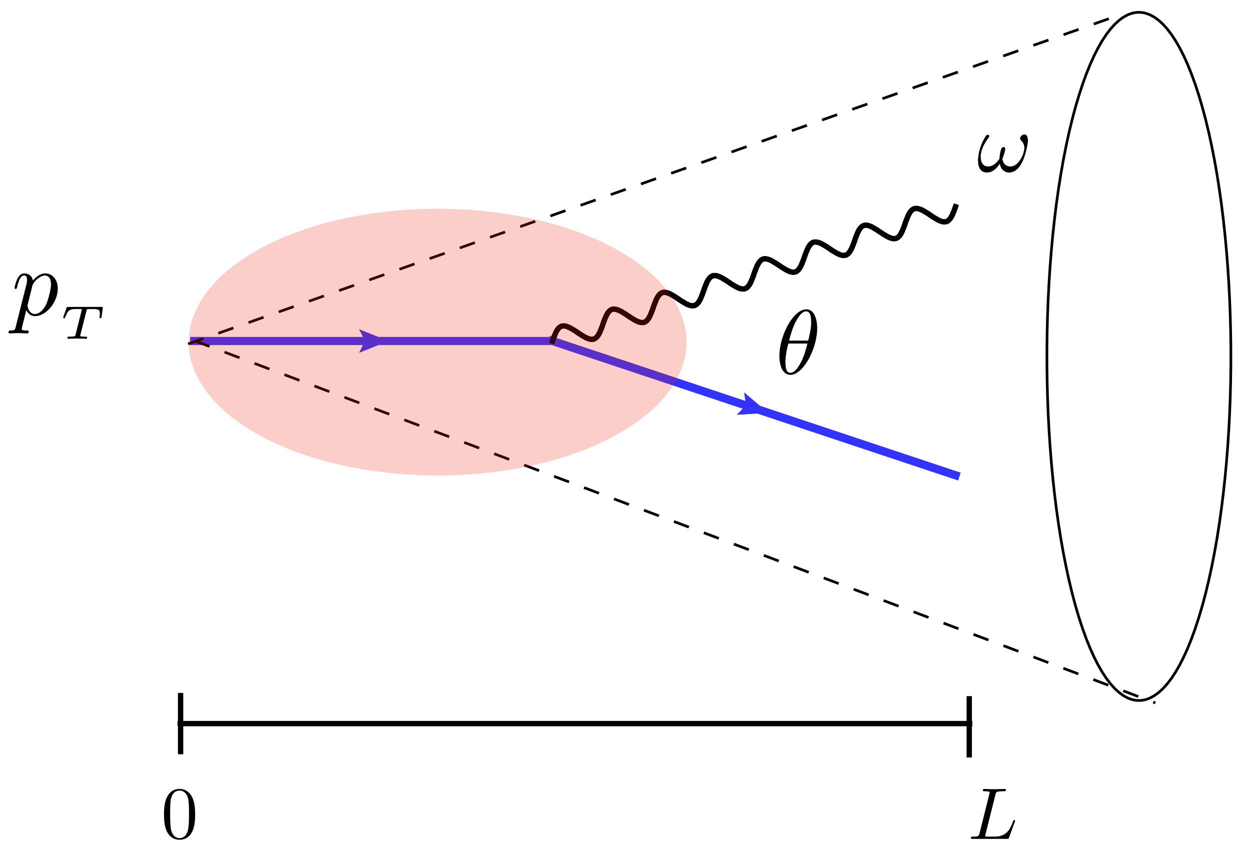
$$p_T \ll \pi\, n\, \bar{\alpha}^2 \hat{q} L^2$$

$$Q(p_T) \ll 1$$

Jet energy loss

Jet energy loss: phase-space analysis

- How important are jet substructure fluctuations?



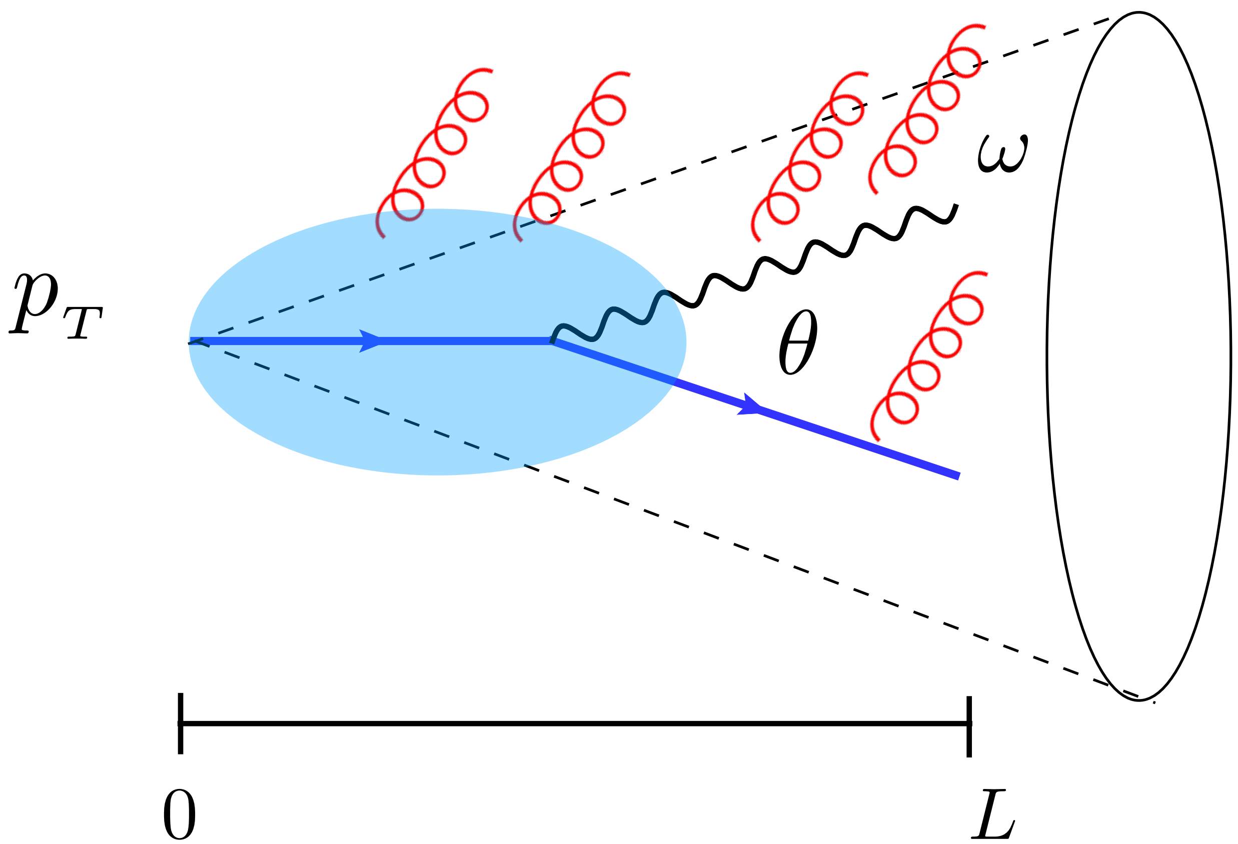
formation time

$$t_\mathrm{f} \sim \frac{1}{\omega\theta^2}$$

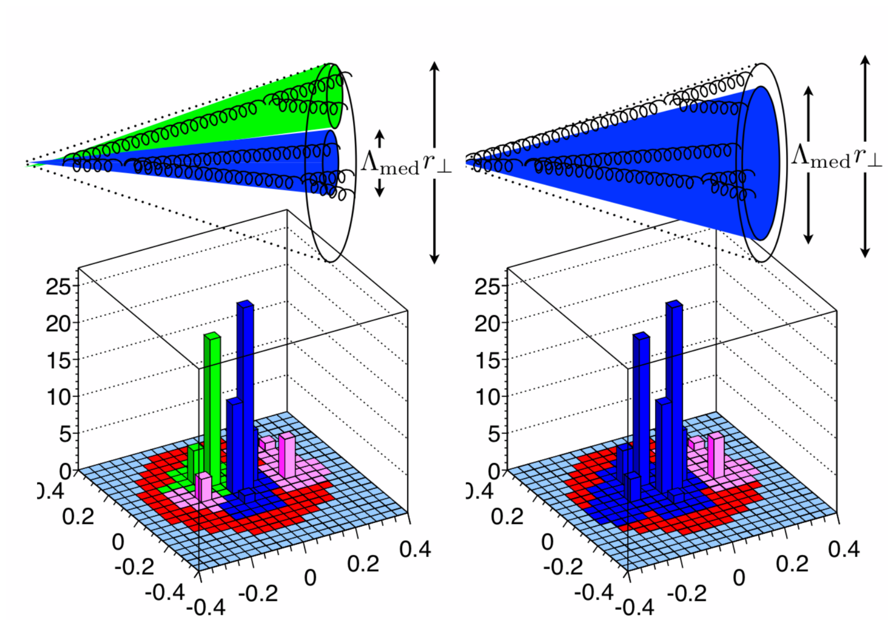
$$\mathrm{PS} = \bar{\alpha} \int_0^{p_T} \frac{\mathrm{d}\omega}{\omega} \int_0^{R} \frac{\mathrm{d}\theta}{\theta}\, \Theta(t_\mathrm{f} > L) = \frac{\bar{\alpha}}{4} \ln^2 \left(p_T R^2 L\right) \gtrsim 1$$

Jet energy loss: phase-space analysis

- Double logarithmic phase-space (from first principles):



MT, Salgado, Tywoniuk (2010-11)
Iancu, Casalderrey-Solana (2011)



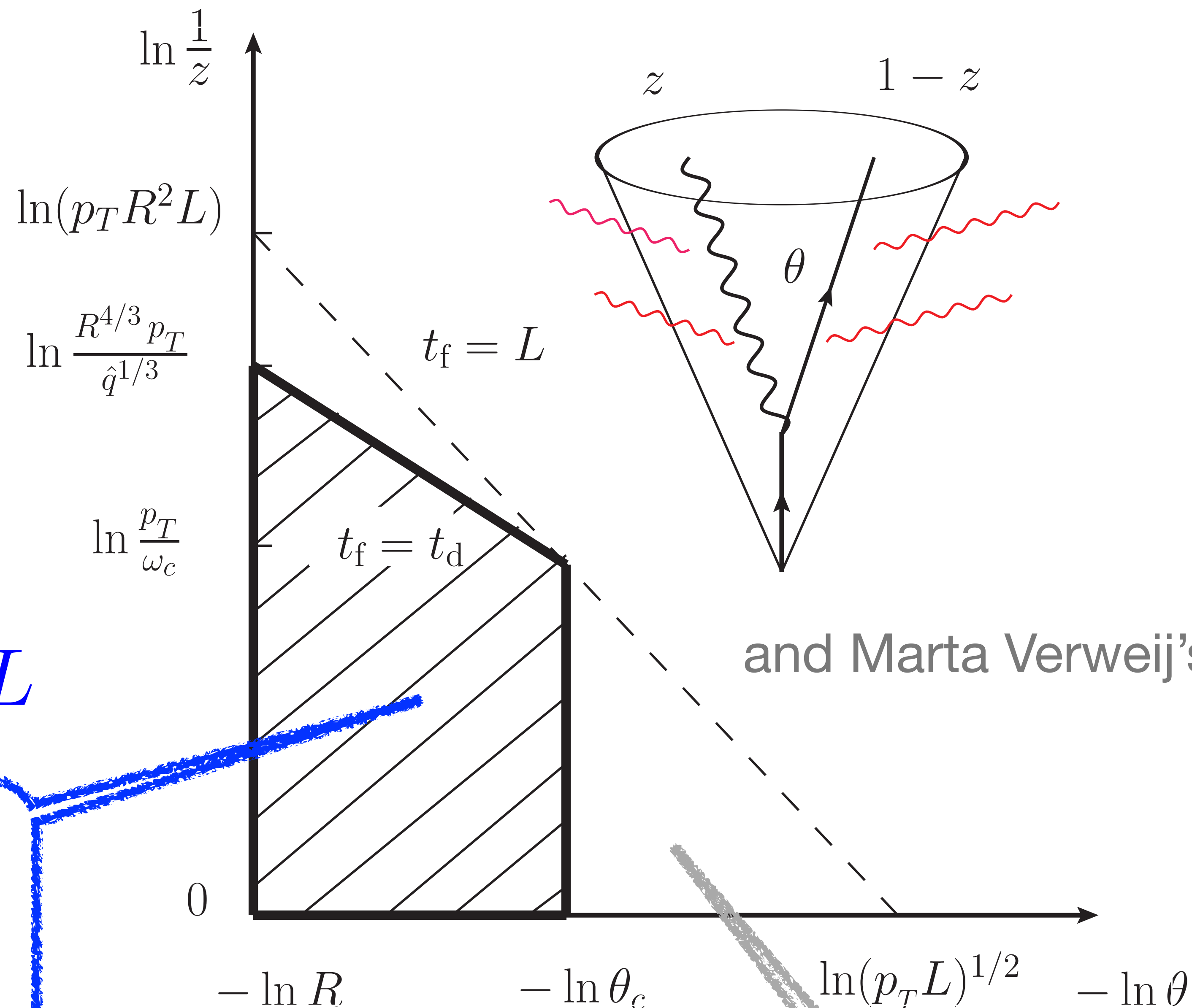
Casalderrey-Solana, MT, Salgado, Tywoniuk (2012)
Apolinario et al (2014) MT, Tywoniuk (2017)

- Additional time scale: the **color decoherence** time associated with the resolution of subjects by the medium

$$t_{\rm d} \sim (\hat{q}\,\theta^2)^{-1/3} < L$$

Jet energy loss: phase-space analysis

See Paul Caucal's talk on Thursday
[Caucal et al 2018]



$\theta_c \equiv 1/\sqrt{\hat{q}L^3}$

$\omega_c \equiv \hat{q}L^2$

and Marta Verweij's talk on Wednesday

$t_{\rm f} \ll t_{\rm d} \ll L$

decoherent In-medium vacuum shower

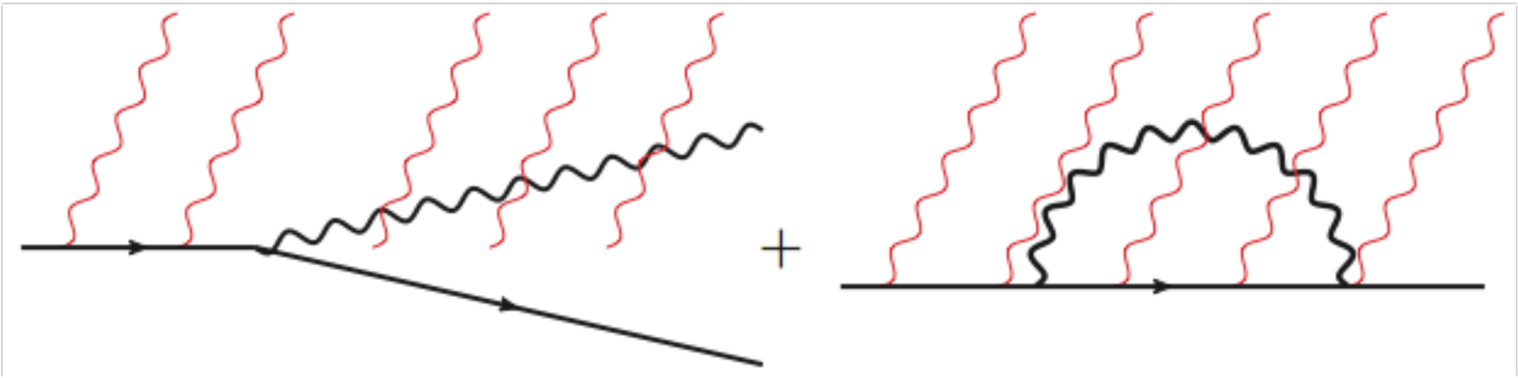
coherent in-medium vacuum shower

NLO corrections to the jet spectrum

$$R_{\mathrm{AA}} = Q^{(0)} + \bar{\alpha}\, Q^{(1)} + \mathcal{O}(\bar{\alpha}^2)$$

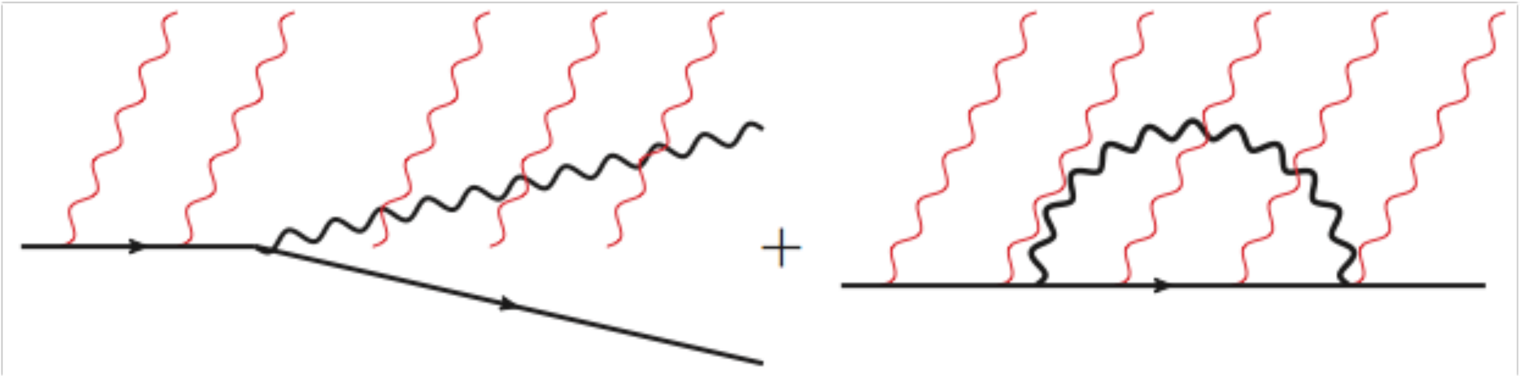
- To leading-log (LL) accuracy: cancellation between real and virtual contributions (KLN theorem) except in the region

$$t_{\mathrm{f}} \ll t_{\mathrm{d}} \ll L$$



NLO correction to the jet spectrum

Mismatch between real and virtual



gluon + quark energy loss $\gg$ quark energy loss

$$Q^{(1)}(p_T) = \bar{\alpha} \int_{\theta_c}^{R} \frac{\mathrm{d}\theta}{\theta} \int_{(\hat{q}/\theta^4)^{1/3}}^{p_T} \frac{\mathrm{d}\omega}{\omega} \left[Q_q^2(p_T) - 1 \right] \; Q_{\mathrm{tot}}(p_T)$$

NLO correction to the jet spectrum

- LL contributions exponentiate in the **strong quenching limit**: only the leading particle survives albeit suppressed by a **Sudakov form factor** in addition to its total charge energy loss

$$C(p_T) = \exp\left[-2\bar{\alpha}\ln\frac{R}{\theta_c}\left(\ln\frac{p_T}{\omega_c} + \frac{2}{3}\ln\frac{R}{\theta_c}\right)\right]$$

- Now we have:

$$R_{\rm AA} \sim Q(p_T) = Q_{\rm tot}(p_T) \times C(p_T)$$

- Increasing suppression with R (at large R energy must be recovered, not included here). Effect observed on groomed jets with JEWEL [Andrews et al (2018)]

Jet suppression: numerics

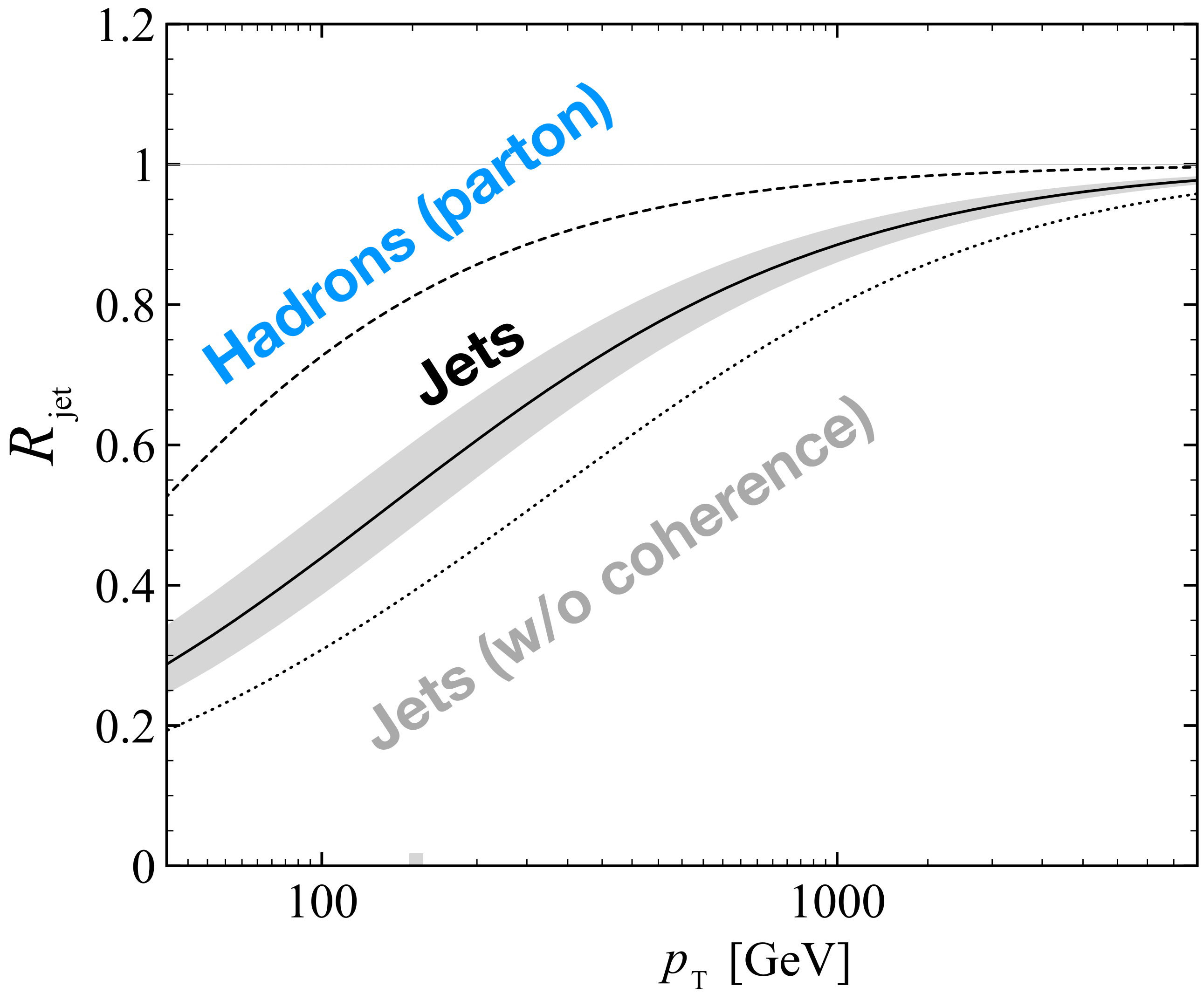
- Including running coupling, full LO splitting function and finite quenching, we obtain a non-linear evolution equation:

$$C_q(p_T, R) = 1 + \int_0^1 \mathrm{d}z \int_0^R \frac{\mathrm{d}\theta}{\theta} \frac{\alpha_s(k_\perp)}{\pi} P_{qg}(z)\ \Theta(t_\mathrm{f} < t_\mathrm{d} < L)$$
$$\times \left[\ C_q(zp_T, \theta)\ C_g(zp_T, \theta)\ \mathcal{Q}_q^2(p_T) - \ C_q(zp_T, \theta)\ \right]$$

- Caveats: pT-broadening, mini-jet absorption, in-cone medium-induced radiation, medium back-reaction neglected

Jet suppression: numerics

$$R_{\rm jet} = Q_{\rm tot}(p_T) \times C(p_T)$$



$R = 0.4$

$\hat{q} = 1\mathrm{GeV}^2/\mathrm{fm}$

$L = 3\mathrm{fm}$

Summary

- Important high order corrections to jet quenching: sensitivity of the inclusive jet spectrum to fluctuations of jet substructure (encoded qualitatively in MC's not in analytic approaches)

- To leading log accuracy in the strong quenching limit we obtain a **Sudakov suppression factor**

- **Probabilistic picture to LL accuracy:** (i) early in-medium vacuum shower generated by medium-modified Sudakov. (ii) Unresolved vacuum shower for $\theta < \theta_c$. (iii) Resolved partons for $\theta > \theta_c$ undergo medium-induced cascade over a distance of order the medium length. (iv) Final stage: fragmentation in vacuum with modified angular ordering

- **Outlook:** Investigate jet substructure observables, combine analytic and MC studies, …