Quenching effects in the jet spectrum at various cone sizes

Adam Takacs* University of Bergen (Norway)

and others Joao **Barata**, Yacine **Mehtar-Tani**,
Alba **Soto-Ontoso**, Daniel **Pablos**, Konrad **Tywoniuk**

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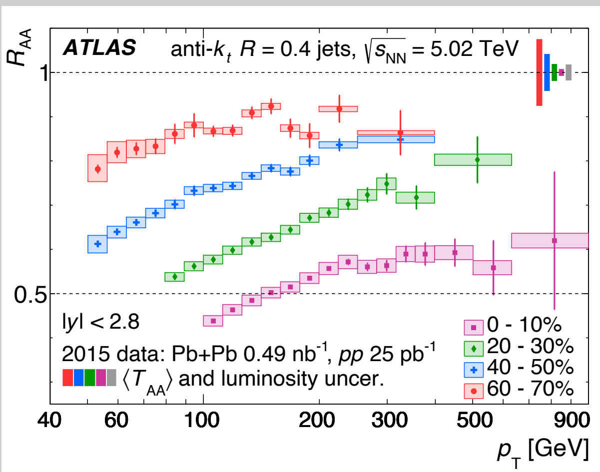
Supported by the Trond Mohn Foundation BFS2018REK01 and
MCnetITN3 H2020 Marie Curie Initial Training Network 722104

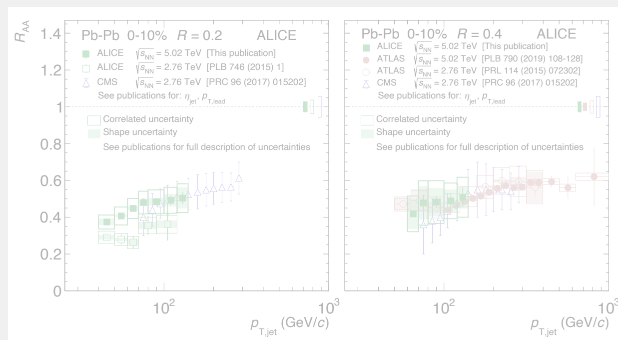
R_{AA} of PbPb @ 5.02 ATeV

ATLAS EXPERIMENT



[Phys. Lett. B 790 (2019) 108]

ALICE



[Phys. Rev. C 101, 034911 (2020)]

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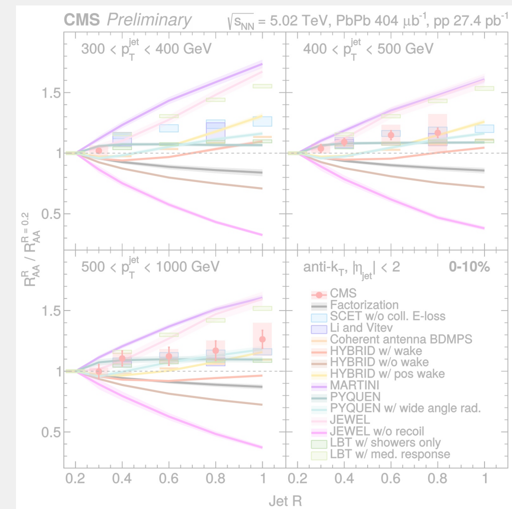
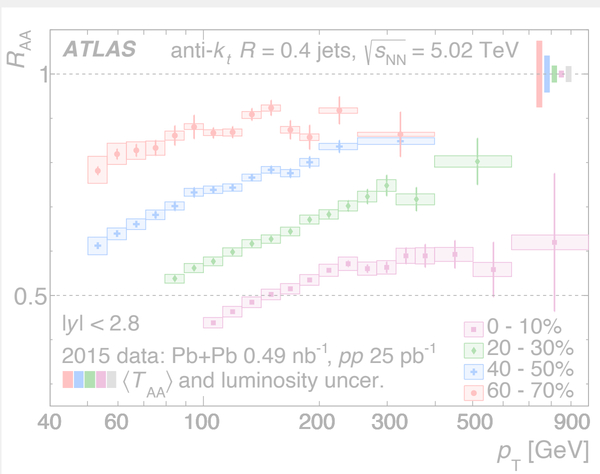


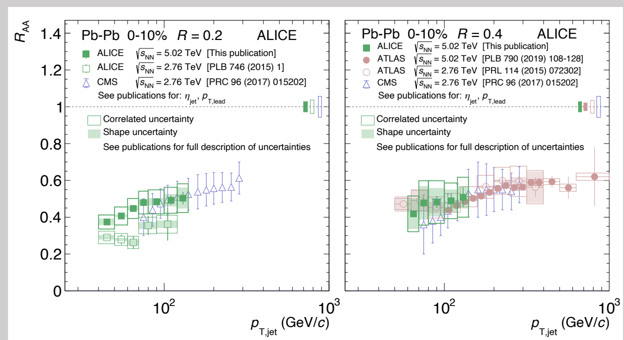
[JHEP 05, 284 (2020)]

Precision! Good idea! Dedication!

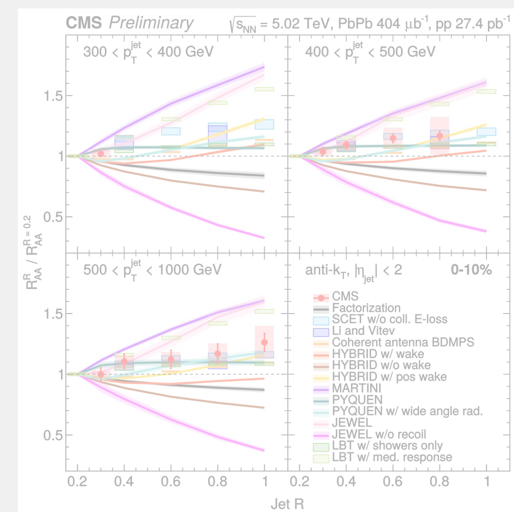
R_{AA} of PbPb @ 5.02 ATeV



[Phys. Lett. B 790 (2019) 108]



[Phys. Rev. C 101, 034911 (2020)]



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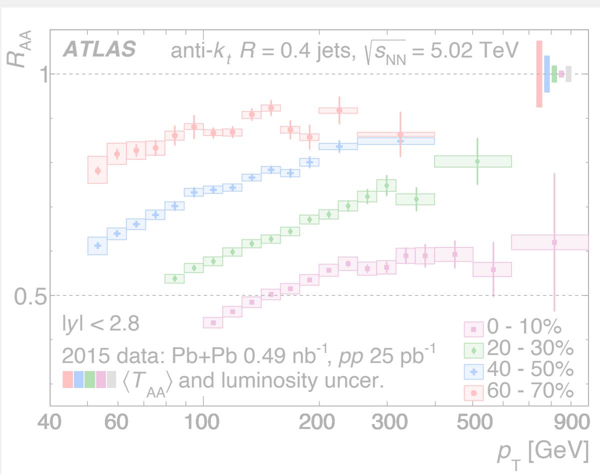

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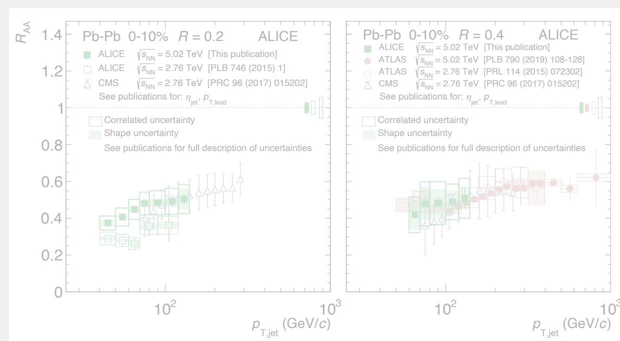
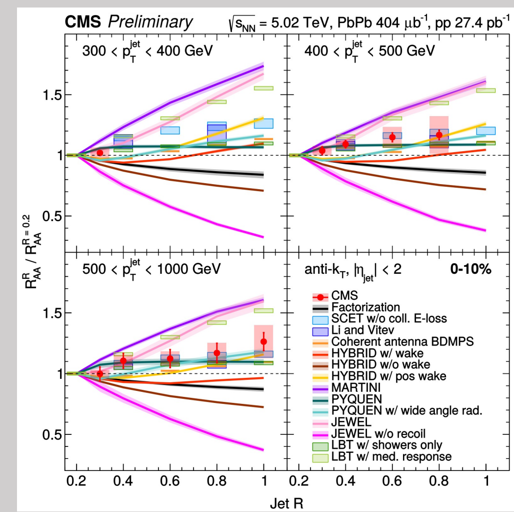


[Phys. Rev. C 101, 034911 (2020)]



[JHEP 05, 284 (2020)]

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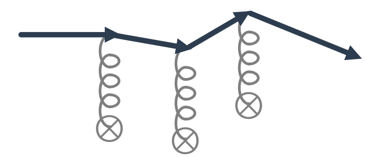
Introduction to the Framework

Jet Quenching - Framework

[Zakharov, BDMPS, GLV, Wiedemann (1996-2000)
Blaizot, Iancu, Salgado, CGC formalism (2012-)]

QCD with medium bkg:

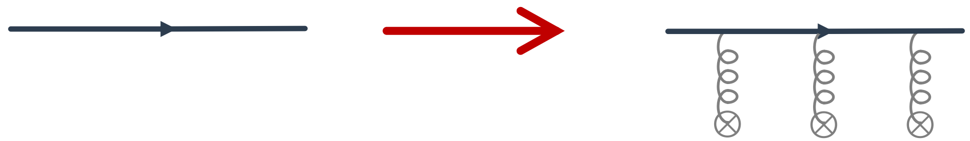
- Colored background $\mathcal{A}_0(t,x)$
- Elastic scatterings
- Multiple scatterings



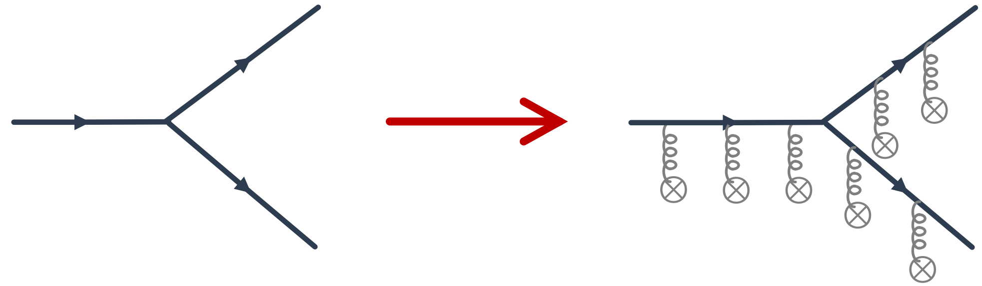
Partial Fourier space $(p^+,\ \boldsymbol{p},\ p^-) \to (p^+,\ \boldsymbol{x},\ t)$

- Effective propagator:

$G_s^c(p^+, \boldsymbol{p}_t, p^-)$ $\qquad$ $G_{s_1 s_2}^{c_1 c_2}(t_f, \boldsymbol{x}_f, t_i, \boldsymbol{x}_i | p^+)$



- Effective vertices:



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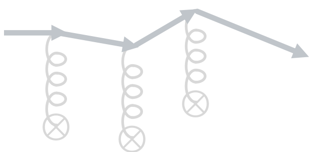


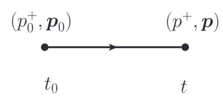
Partial Fourier space (

- Effective pro

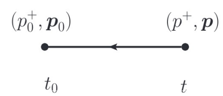
G_S^C

- Effective vert

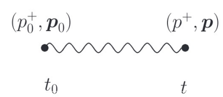
1. **Internal lines:** which correspond to propagators between time t_0 and t read:



$$\frac{i\gamma^-}{4p^+}\,(\boldsymbol{p}|\,\mathcal{G}_{\rm scal}(t,t_0)|\boldsymbol{p}_0)\,(2\pi)\,\delta(p^+-p_0^+) \qquad \text{for quarks} \tag{161}$$

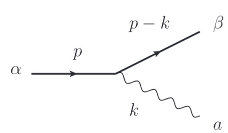


$$\frac{i\gamma^-}{4p^+}\,(\boldsymbol{p}|\,\mathcal{G}^\dagger_{\rm scal}(t,t_0)|\boldsymbol{p}_0)\,(2\pi)\,\delta(p^+-p_0^+) \qquad \text{for anti-quarks} \tag{162}$$

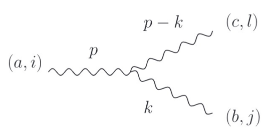


$$\frac{i}{2p^+}\,\delta^{ij}\,(\boldsymbol{p}|\,\mathcal{G}^{\rm adj}_{\rm scal}(t,t_0)|\boldsymbol{p}_0)\,(2\pi)\,\delta(p^+-p_0^+) \qquad \text{for gluons} \tag{163}$$

2. **Vertices:**

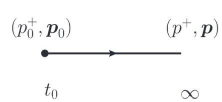


$$\gamma^+\frac{2igt^a}{z\sqrt{1-z}}\left[\left(1-\frac{z}{2}\right)(\boldsymbol{k}-z\boldsymbol{p})^i + i\frac{z}{2}S^3\epsilon^{ij}\,(\boldsymbol{k}-z\boldsymbol{p})^j\right] \tag{164}$$

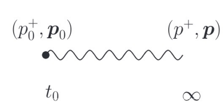


$$-\,2gf_{abc}\left[-\frac{1}{1-z}(\boldsymbol{k}-z\boldsymbol{p})^l\delta^{ij} + (\boldsymbol{k}-z\boldsymbol{p})^i\delta^{jl} - \frac{1}{z}(\boldsymbol{k}-z\boldsymbol{p})^j\delta^{il}\right] \tag{165}$$

3. **Outgoing external lines:**



$$\bar{\xi}(s)\ \mathrm{e}^{i\frac{\boldsymbol{p}^2}{2p^+}t_\infty}\ (\boldsymbol{p}|\,\mathcal{G}_{\rm scal}(\infty,t_0)|\boldsymbol{p}_0) \qquad \text{for quarks} \tag{166}$$

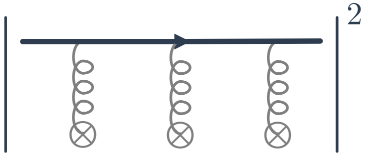


$$\epsilon_\lambda^{*,i}(p)\ \mathrm{e}^{i\frac{\boldsymbol{p}^2}{2p^+}t_\infty}\ (\boldsymbol{p}|\,\mathcal{G}^{\rm adj}_{\rm scal}(\infty,t_0)|\boldsymbol{p}_0) \qquad \text{for gluons} \tag{167}$$

Jet Quenching - Framework

[Zakharov, BDMPS, GLV, Wiedemann (1996-2000)
Blaizot, Iancu, Salgado, CGC formalism (2012-)]

Transverse broadening:



$$\sim \int \mathcal{D}\boldsymbol{r}\,\mathcal{D}\bar{\boldsymbol{r}}\; e^{i\frac{p^+}{2}\int_{t_i}^{t_f} ds\,(\dot{\boldsymbol{r}}^2-\dot{\bar{\boldsymbol{r}}}^2)}\;\underbrace{\frac{1}{d_R}\left\langle \mathrm{Tr}\, e^{-ig\int_{t_i}^{t_f} ds\,[\mathcal{A}_0(\boldsymbol{r})-\mathcal{A}_0^\dagger(\bar{\boldsymbol{r}})]}\right\rangle}_{\approx\, \exp\left[-N_c\int_{t_0}^{t} ds\, n(s)\sigma(\boldsymbol{r}-\bar{\boldsymbol{r}})\right]}$$

Gaussian broadening: $N_c n\sigma(\boldsymbol{r}) \approx \hat{q}\boldsymbol{r}^2/2$

$$\mathcal{P}(\boldsymbol{p},t) = \frac{4\pi}{\hat{q}t}\,e^{-\frac{\boldsymbol{p}^2}{\hat{q}t}} \qquad\qquad \langle \boldsymbol{p}^2\rangle = \hat{q}t$$

Medium induced emission (in addition to vacuum):

$$\sim \frac{dP}{dz\,dk} \sim \frac{\alpha_s}{z^{3/2}} f(\boldsymbol{k})$$

+ color decoherence: $\vartheta_{q\bar{q}} \ll \vartheta_c$

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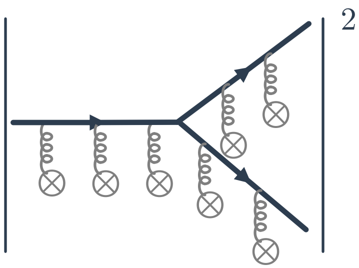

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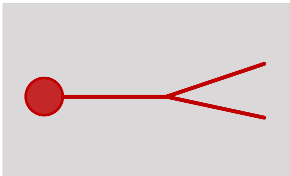

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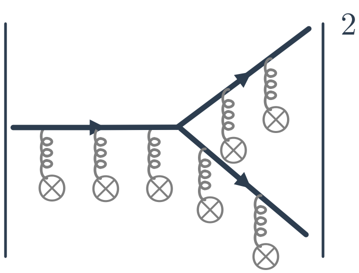

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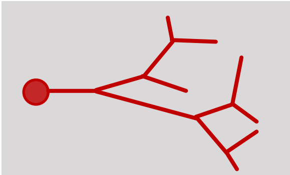
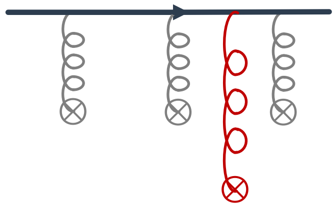


Introduction to jet quenching - Framework

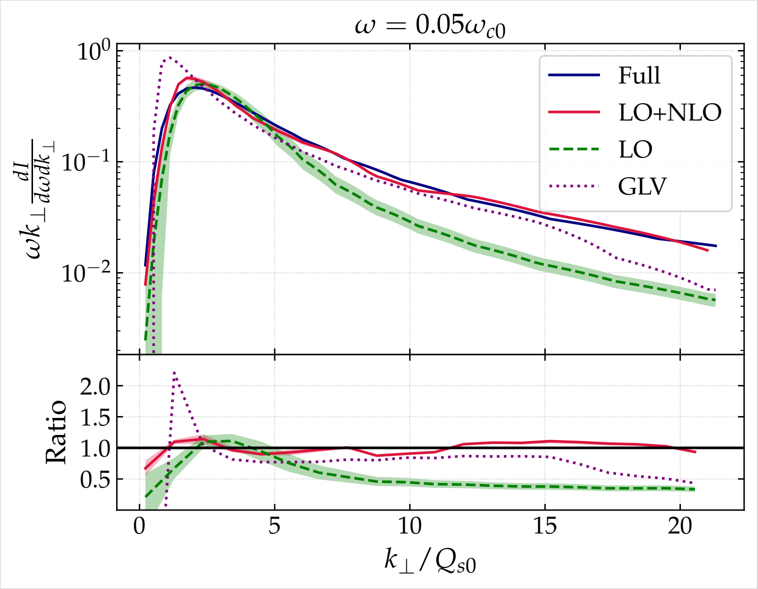
[Barata, Mehtar-Tani, Soto-Ontoso, Tywoniuk]

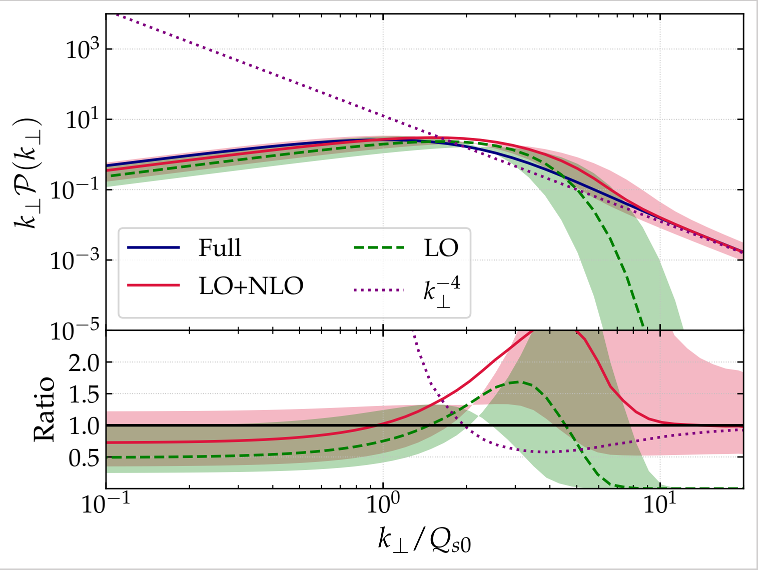
Improved opacity expansion:



$$\sigma(\boldsymbol{r}) = \sigma_{HO} + \delta\sigma$$

hard scattering





[arXiv:2106.07402 , Full: JHEP07114 (2020)]

Application: Quenched jet spectrum

[arXiv:2101.01742, 2103.14676]

The quenched spectrum: the quenching weight

[Baier, Dokshitzer, Mueller, Schiff (1998), Salgado, Wiedemann (2001)]

The quenched spectrum (probability $\mathcal{P}$ of loosing ε energy)

$$\frac{d\sigma^{med}}{dp_T}(p_T) \equiv \int_0^\infty d\varepsilon\, \mathcal{P}(\varepsilon) \frac{d\sigma^{vac}}{dp_T}(p_T+\varepsilon) \approx \frac{d\sigma^{vac}}{dp_T}(p_T) \int_0^\infty d\varepsilon\, \mathcal{P}(\varepsilon) e^{-\frac{n\varepsilon}{p_T}}$$

$\frac{d\sigma^{vac}}{dp_T}(p_T) \sim p_T^{-n}$ [Dasgupta, Dreyer, Salam, Soyez]

The $R_{\rm AA}$ is the quenching weight

$$R_{\rm med}(p_T) \equiv \frac{\mathrm{d}\sigma^{\rm med}}{\mathrm{d}p_T}(p_T) \Big/ \frac{\mathrm{d}\sigma^{\rm vac}}{\mathrm{d}p_T}(p_T) \approx \int_0^\infty d\varepsilon\, \mathcal{P}(\varepsilon) e^{-\frac{n\varepsilon}{p_T}} \equiv \mathcal{Q}_{med}(p_T)$$

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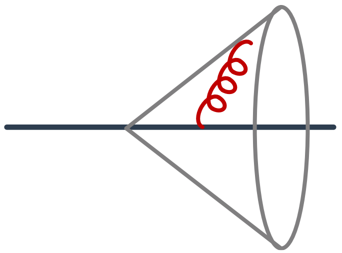
What is $\mathcal{P}(\varepsilon)$?

[Bayesian: Phys. Rev. Lett. 122 (2019)
ML: JHEP 2021, 206 (2021)]

The quenched spectrum: energy loss probability

Single parton, single medium induced emission

$$\mathcal{P}_{>}^{(0)}(\varepsilon) \approx \frac{dI_>}{d\varepsilon}$$



Single parton, multiple induced emission [JHEP09 (2001) 033]

$$\mathcal{P}_{>}^{(0)}(\varepsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{j}^{n} \int d\omega_j \frac{dI_>}{d\omega_j} \right] \delta\left(\varepsilon - \sum_{j=1}^{n} \omega_j \right) e^{-\int d\omega_j \frac{dI_>}{d\omega_j}}$$

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

Multi parton (jet), multiple induced emission [Phys.Rev.D98 (2018) 051501]

$$\mathcal{Q}_{>}^{jet}(p_T) \approx \mathcal{Q}_{>}^{(0)}(p_T) \mathcal{C}(p_T, R)$$

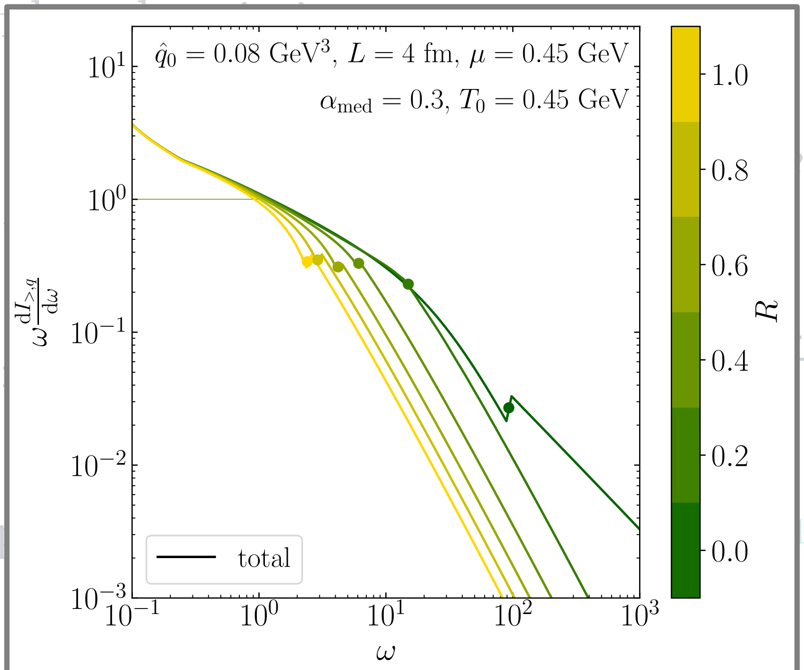
The quenched spectrum: energy loss probability

Single parton, single medium induced emission

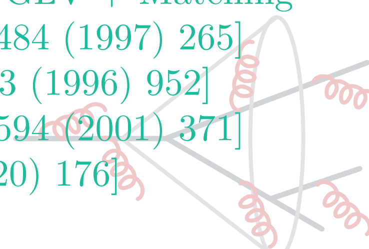
$$\mathcal{P}^{(0)}_{>}(\varepsilon) \approx \frac{dI_{>}}{d\varepsilon}$$

Single parton, multiple in…

$$\mathcal{P}^{(0)}_{>}(\varepsilon) = \ldots - \int d\omega_j \frac{dI_{>}}{d\omega_j}$$



Multi parton (jet), multi…



BDMPS-Z + GLV + Matching
[Nucl.Phys.B484 (1997) 265]
[JETP Lett.63 (1996) 952]
[Nucl.Phys.B594 (2001) 371]
[JHEP10 (2020) 176]

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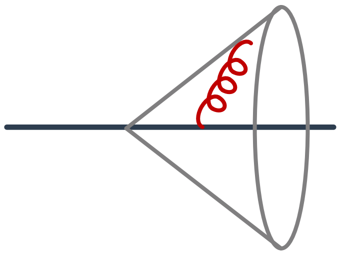

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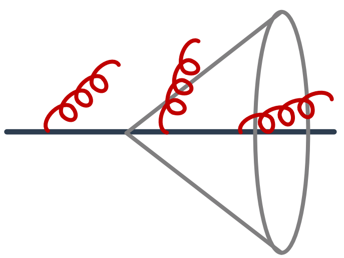


Multi parton (jet), multiple induced emission [Phys.Rev.D98 (2018) 051501]

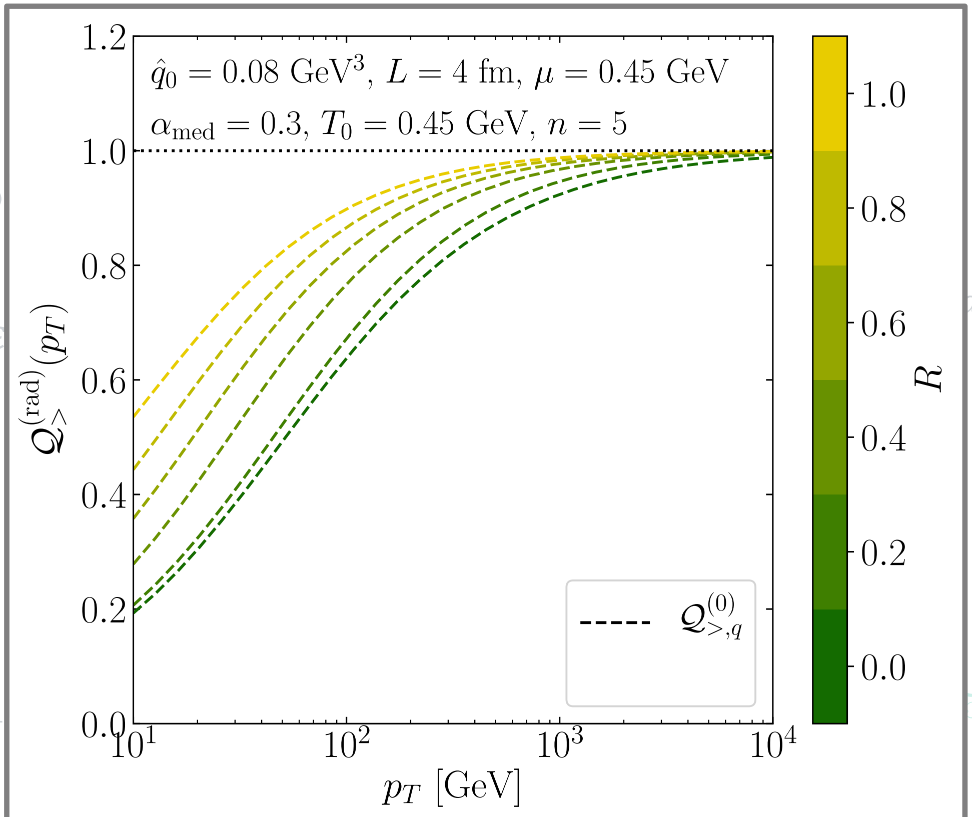
$$\mathcal{Q}_{>}^{jet}(p_T) \approx \mathcal{Q}_{>}^{(0)}(p_T)\,\mathcal{C}(p_T, R)$$

The quenched spectrum: energy loss probability

Single parton, single medium induced emission

Single parton, multip

$\mathcal{P}^{(0)}_{>}(\varepsilon$ ... $d\omega_j \frac{dI_>}{d\omega_j}$



Multi parton (jet), m ... 51501]

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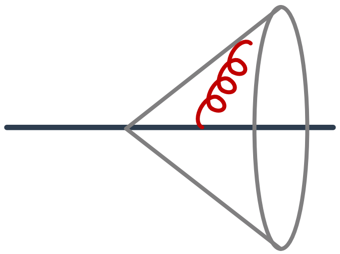
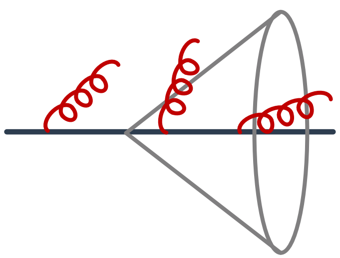
The quenched spectrum: energy loss probability

Single parton, single medium induced emission



$$\mathcal{P}_{>}^{(0)}(\varepsilon) \approx \frac{dI_{>}}{d\varepsilon}$$

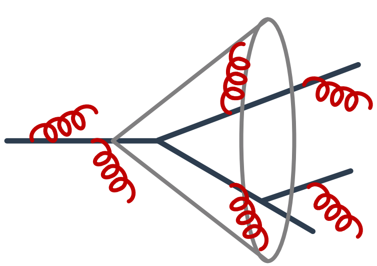
Single parton, multiple induced emission [JHEP09 (2001) 033]



$$\mathcal{P}_{>}^{(0)}(\varepsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{j}^{n} \int d\omega_j \frac{dI_{>}}{d\omega_j} \right] \delta\left(\varepsilon - \sum_{j=1}^{n} \omega_j \right) e^{-\int d\omega_j \frac{dI_{>}}{d\omega_j}}$$

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

Multi parton (jet), multiple induced emission [Phys.Rev.D98 (2018) 051501]



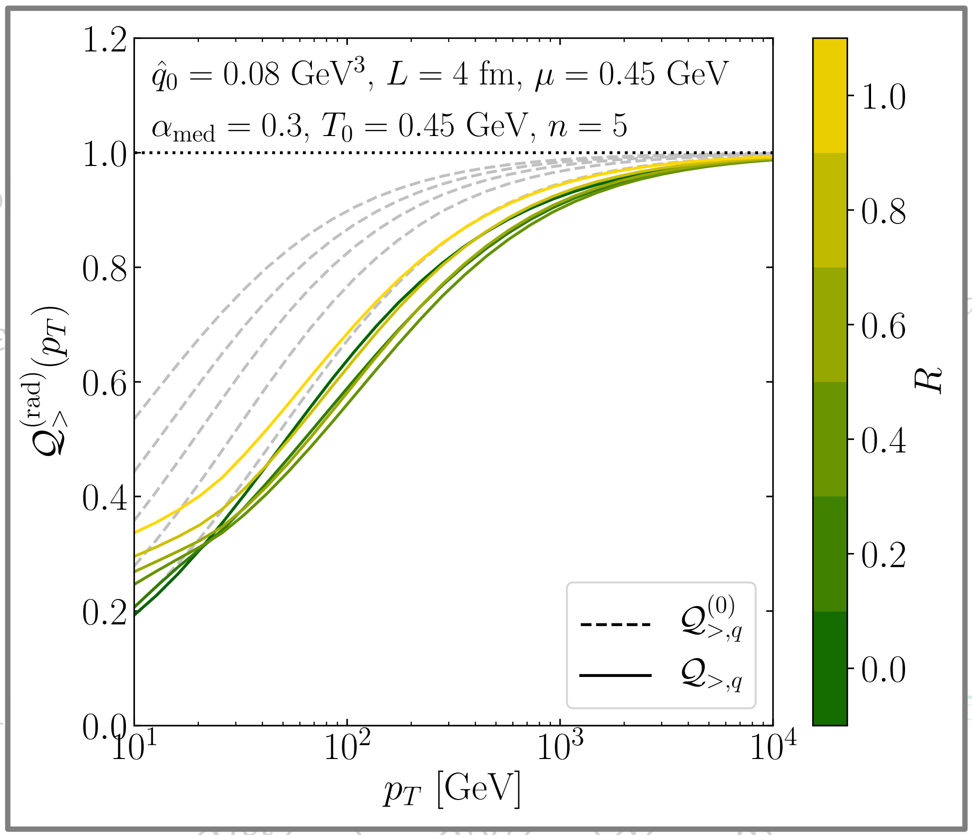
$$\mathcal{Q}_{>}^{jet}(p_T) \approx \mathcal{Q}_{>}^{(0)}(p_T)\mathcal{C}(p_T, R)$$

The quenched spectrum: energy loss probability

Single parton, single medium induced emission

Single parton, multip

$\mathcal{P}_>^{(0)}(\varepsilon$ ... $d\omega_j \frac{dI_>}{d\omega_j}$



Multi parton (jet), m ... 51501]

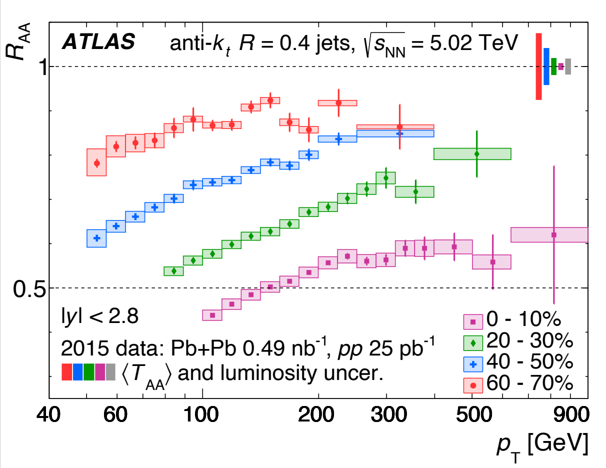
$\mathcal{Q}_>^{jet}(p_T) \approx \mathcal{Q}_>^{(0)}(p_T)\mathcal{C}(p_T,R)$

Comparison to data

To include more effects:

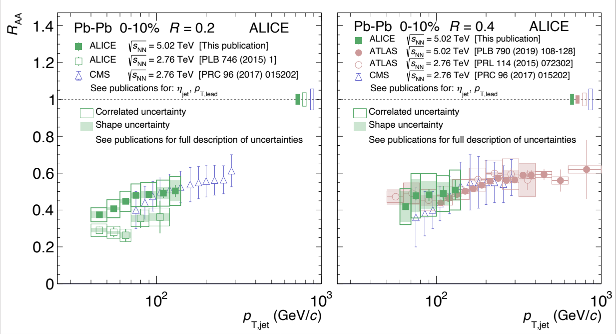
- PDF and nPDF effects, quark/gluon ratio
- Medium resolution and color coherence effects
- Broadening of the induced gluons in/out of the cone
- Thermalizing soft gluons
- Energy loss from elastic scattering
- Geometry and time dependence
- Fluctuations

Experimental Success: R_{AA} of PbPb @ 5.02 ATeV



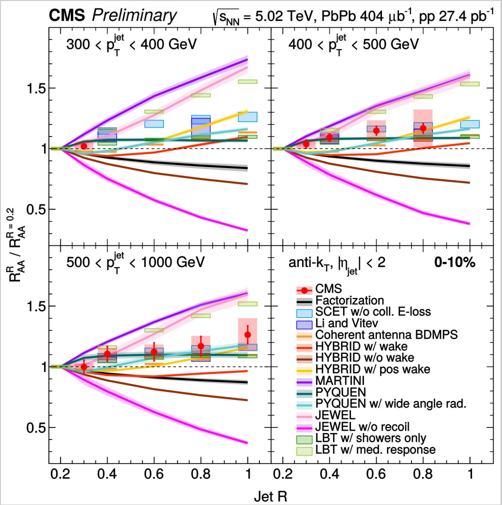
[Phys. Lett. B 790 (2019) 108]

Precision!



[Phys. Rev. C 101, 034911 (2020)]

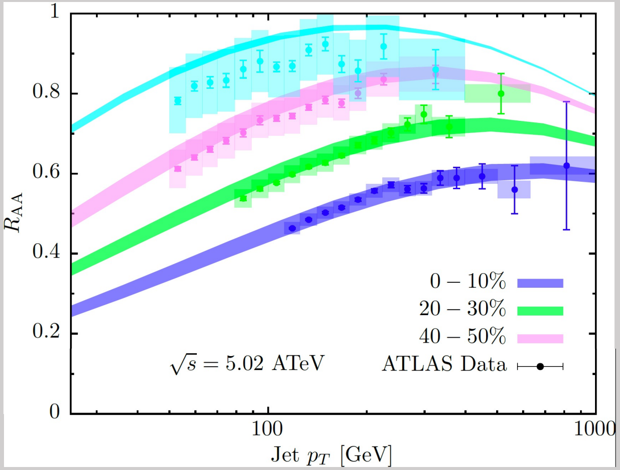
Good idea!



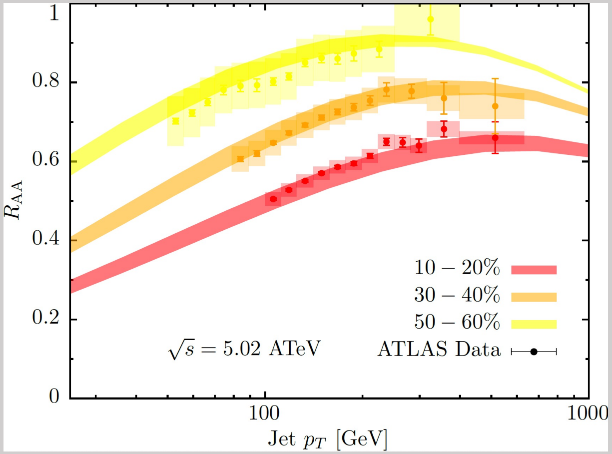
[JHEP 05, 284 (2020)]

Dedication!

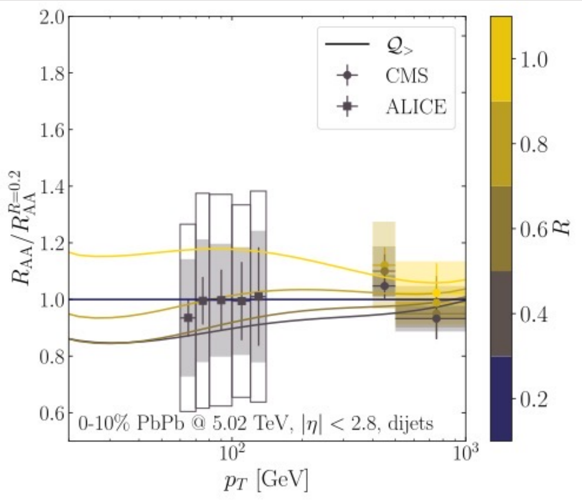
Experimental Success: R_{AA} of PbPb @ 5.02 ATeV



[arXiv:2101.01742]



[arXiv:2101.01742]



[arXiv:2103.14676]

Summary:

- Medium = color background, multiple elastic scatterings
- Effective Feynman rules, soft scatterings
- Hard scattering corrections
- Theory applied to observables

Outlook:

- Substructure observables
- Improved medium-cascade

Thank you for your attention!

Introduction: What is the jet R_{AA}?

- Definition:

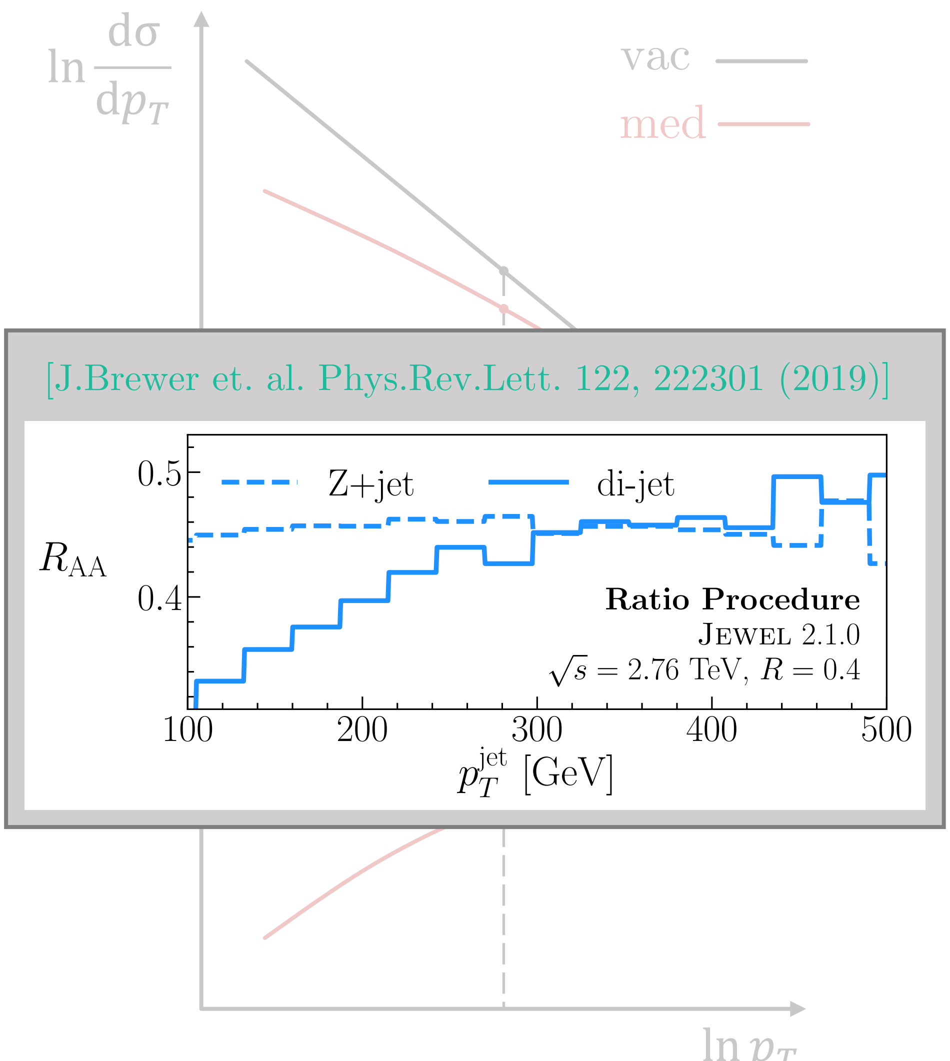
$$R_{\mathrm{AA}}(p_T) = \frac{d\sigma^{\mathrm{med}}}{dp_T}(p_T) \Bigg/ \frac{d\sigma^{\mathrm{vac}}}{dp_T}(p_T)$$

- R_{AA}: Compares jets in vacuum to jets in medium at the **same** p_T.
- Jet with p_T in medium loose energy and ends up with p_T - ε.
- Complication 1:
  R_{AA} doesn't compare the "same" jets!

- The spectrum is steeply falling $n \gg 1$.

$$\frac{d\sigma}{dp_T} \sim p_T^{-n}$$

- Complication 2:
  R_{AA} is sensitive to n (bias on energy loss)!



Quenching weight