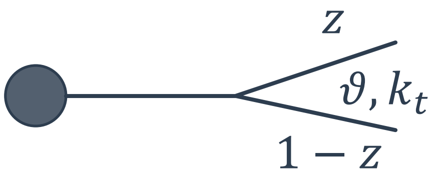
Jets and jet quenching

Probability to emit a gluon:

$$dP(z,k_t) = \frac{\alpha_s}{\pi}\frac{2C_R}{z}\frac{1}{k_t}dzdk_t$$



The probability of radiation $P = \int dP \gg 1$! (from large logarithms of $\frac{p_{T,hard}}{\Lambda_{\text{QCD}}}$)

To resum these emissions: parton showers = jets.

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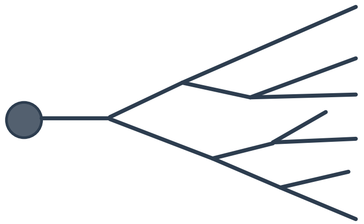

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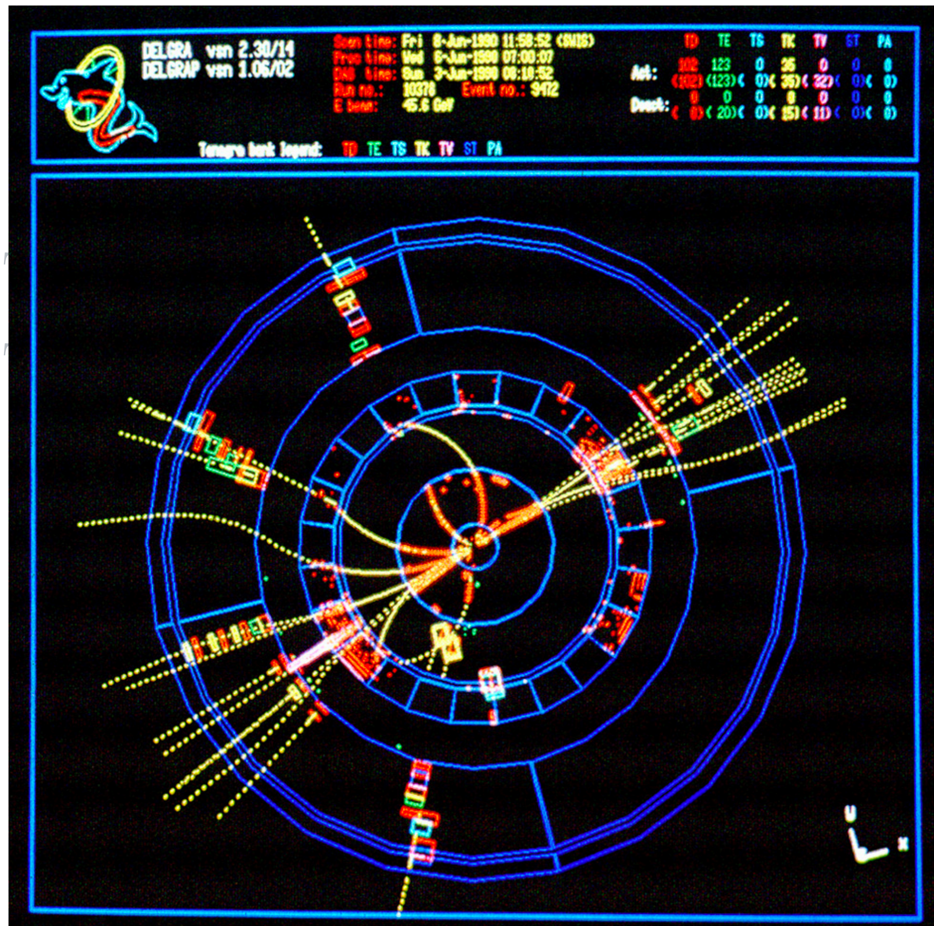

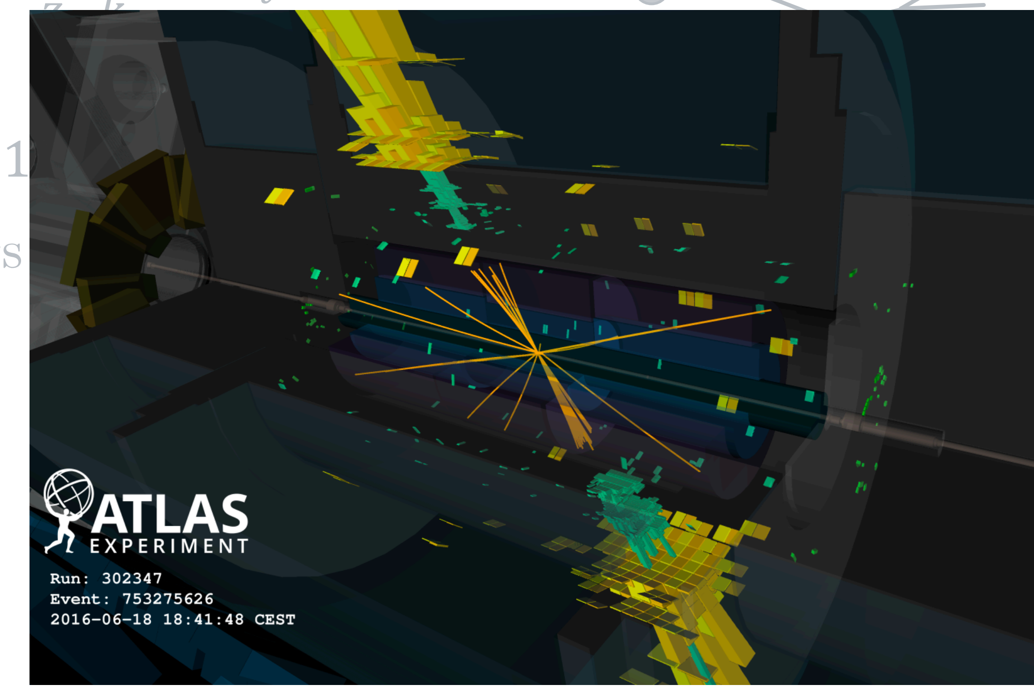

Jets and jet quenching

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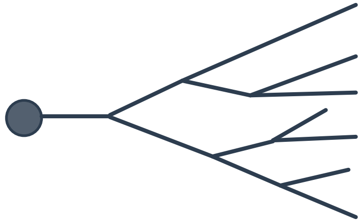

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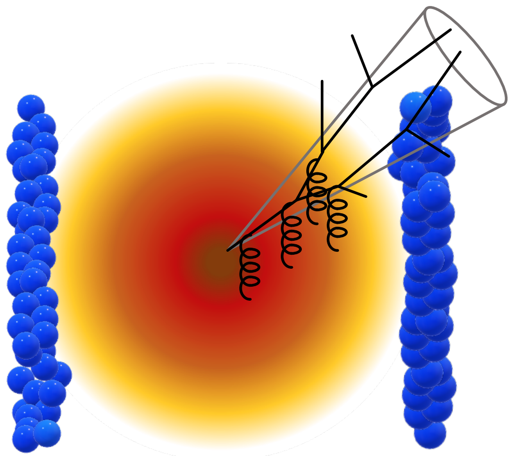
How will jets change in heavy-ion collisions?



Jets and jet quenching

Proba

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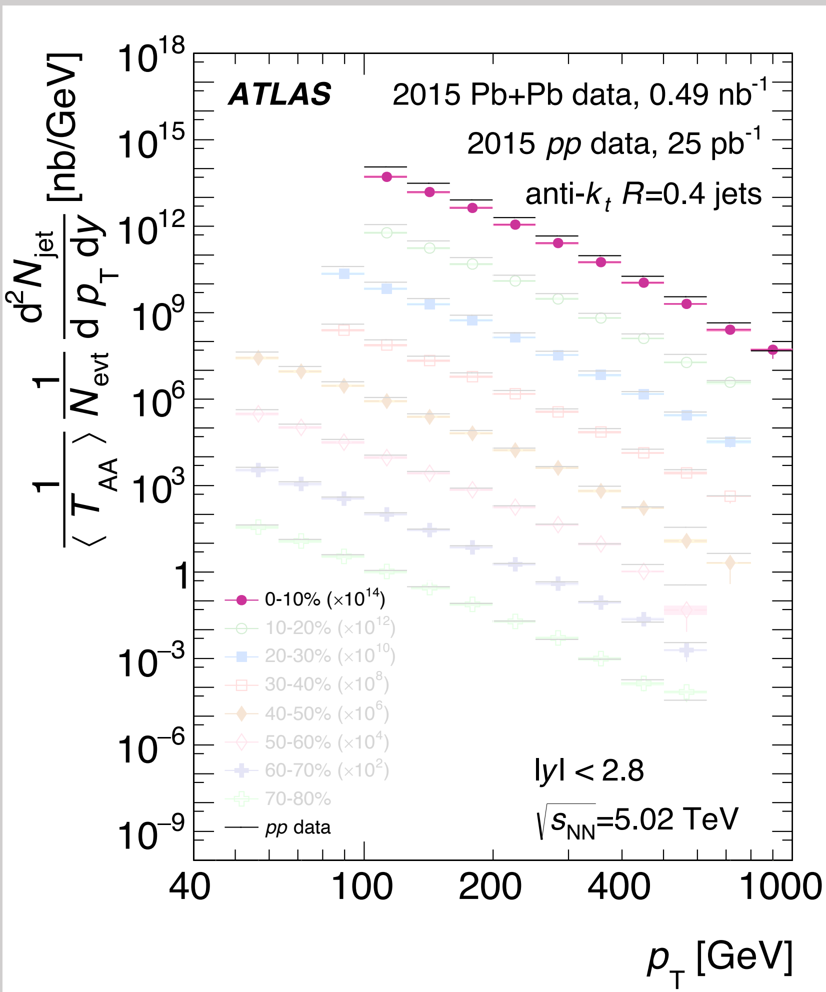
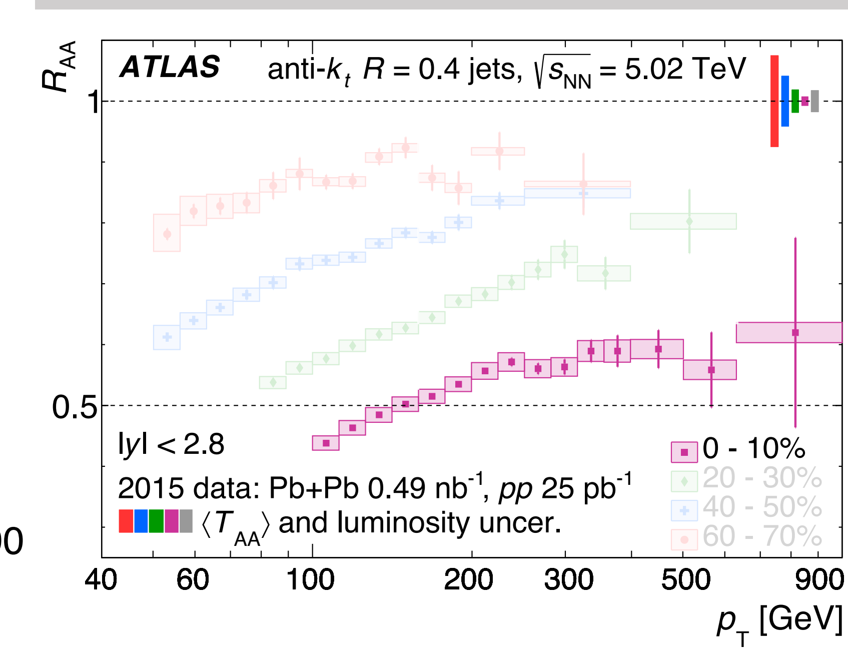
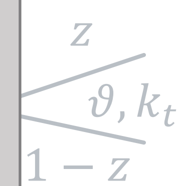
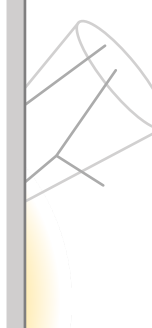


[Phys. Lett. B 790 (2019) 108]

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







Quenching effects in the cumulative jet spectrum

Adam Takacs* University of Bergen (Norway)

Konrad Tywoniuk University of Bergen (Norway)

*adam.takacs@uib.no

Introduction: What is the jet R_{AA}?

- Definition:

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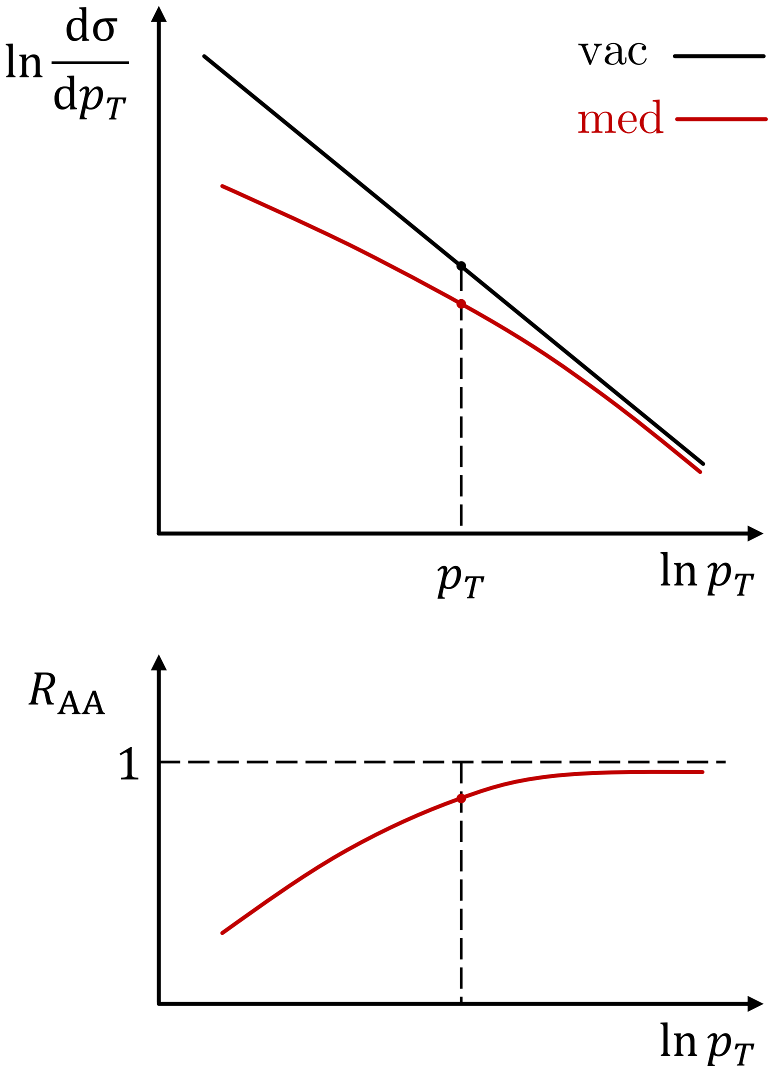
- R_{AA}: Compares jets in vacuum to jets in medium at the **same** p_T.
- Jet with p_T in medium loose energy and ends up with p_T - ε.
- Complication 1:
  R_{AA} doesn't compare the "same" jets!
- The spectrum is steeply falling $n \gg 1$.

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

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



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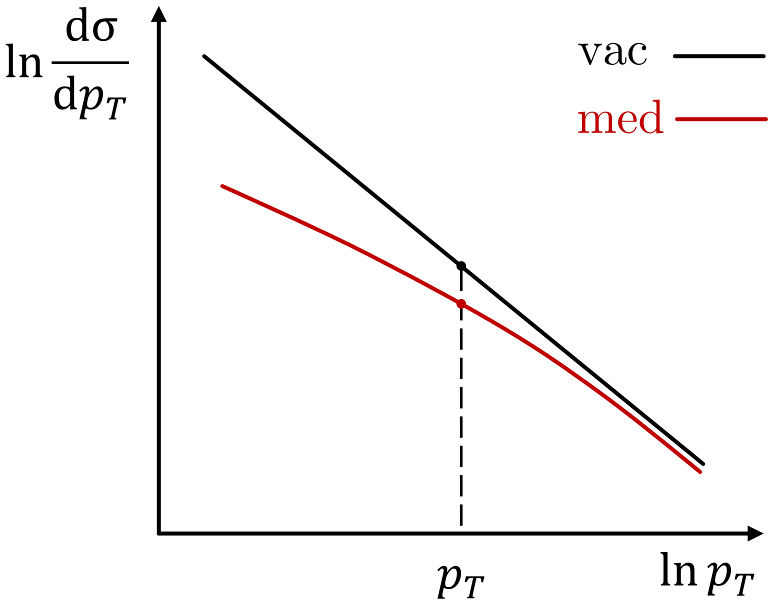

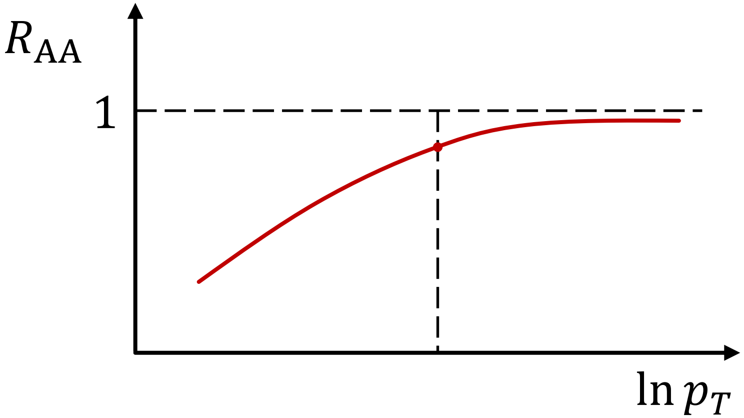

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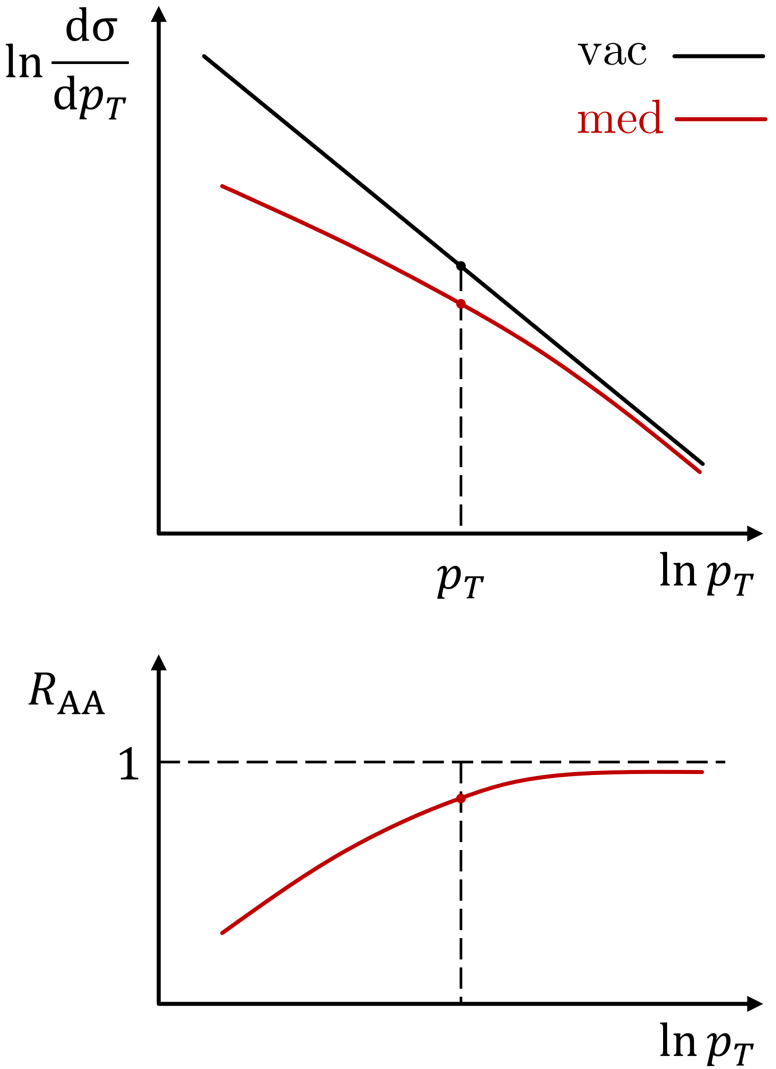

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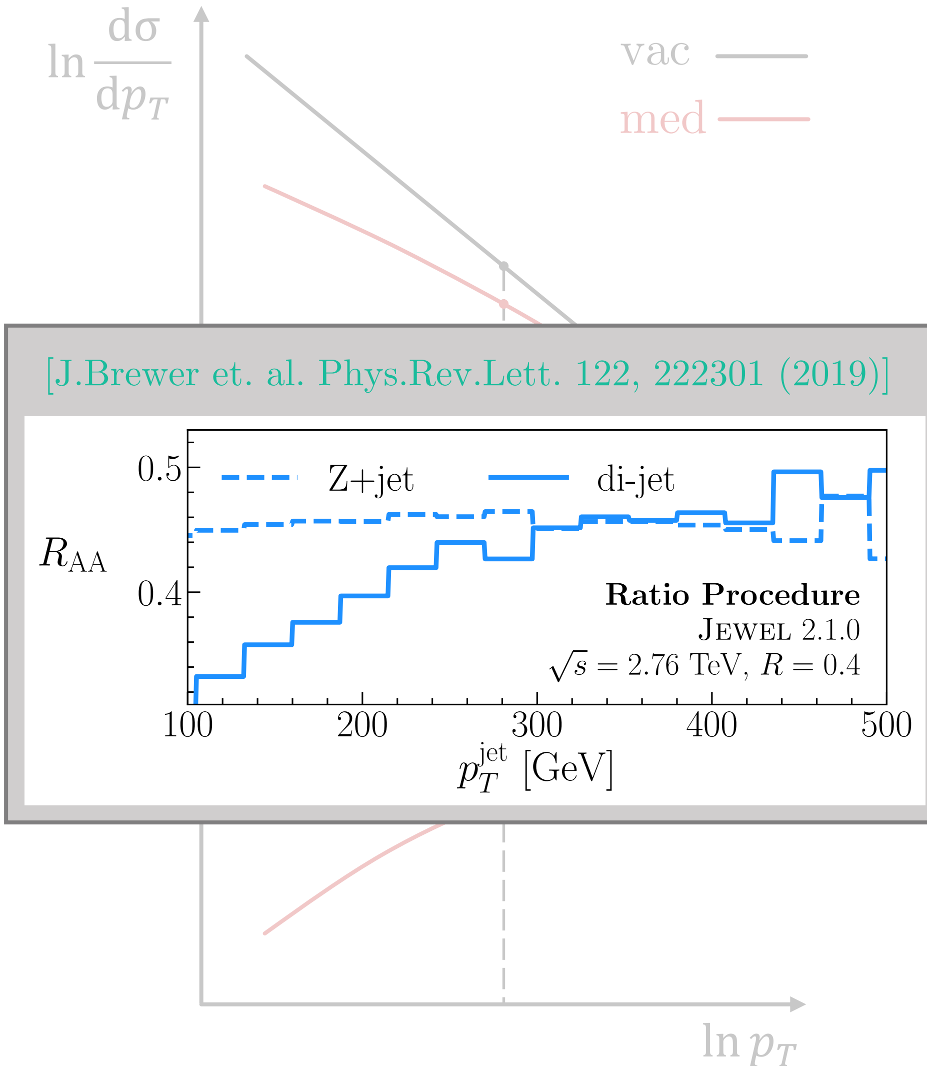

Other possibilities

- To decrease the bias:
  Use the cumulative distribution instead.

- What is the "original" p_T?
  Instead of the spectrum, use the probability (cumulative).
- Quantile procedure

  [J.Brewer et. al. Phys.Rev.Lett. 122, 222301 (2019)]

$$\int_{p_T^{q,m}}^{\infty} dp_T \frac{d\sigma^{med}}{dp_T} = \int_{p_T^{q,v}}^{\infty} dp_T \frac{d\sigma^{vac}}{dp_T}$$

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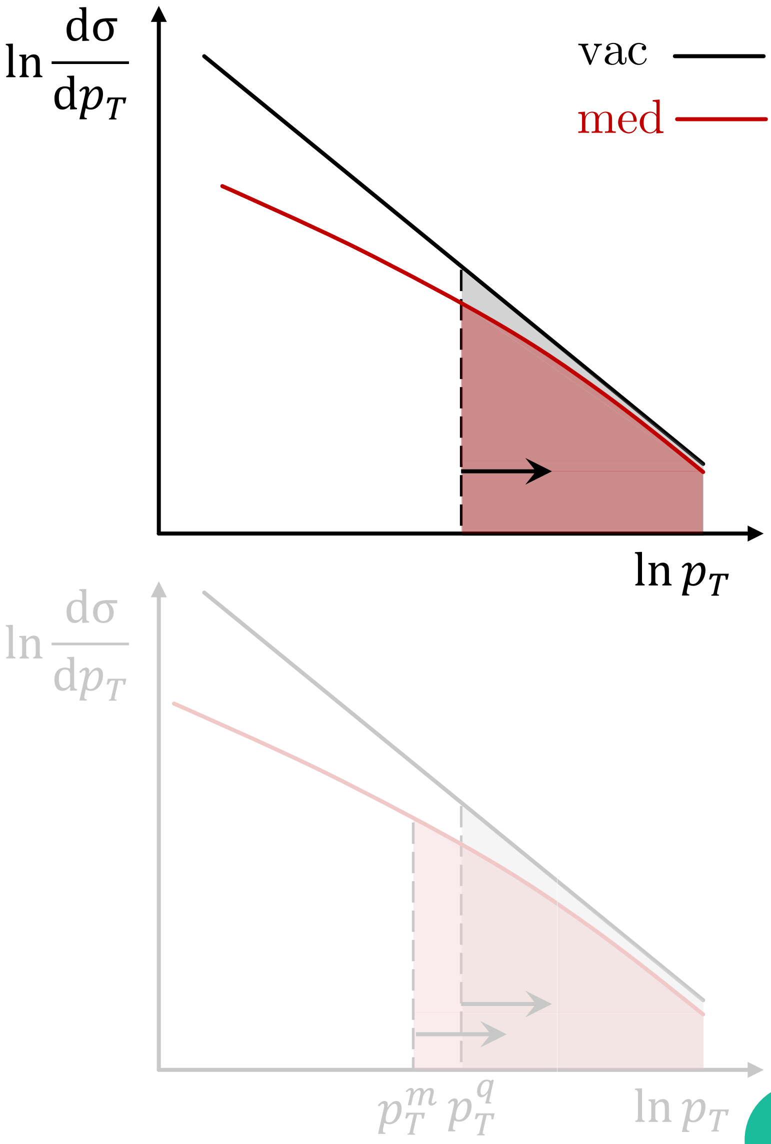

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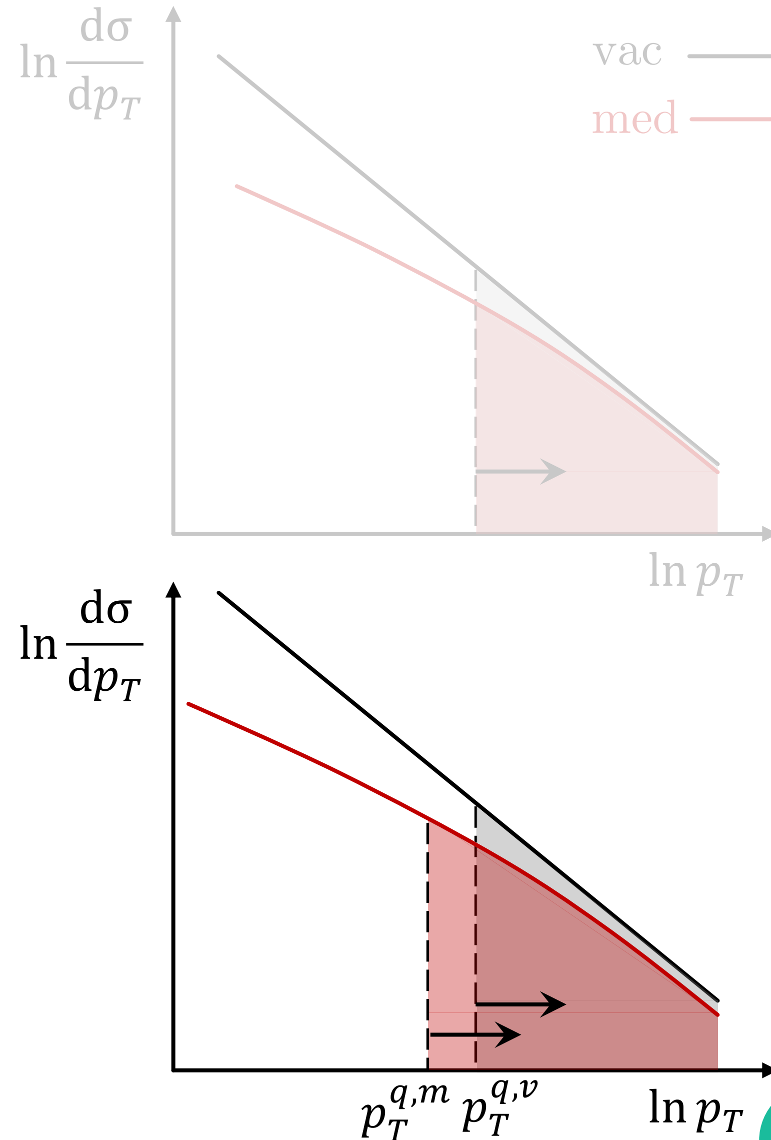

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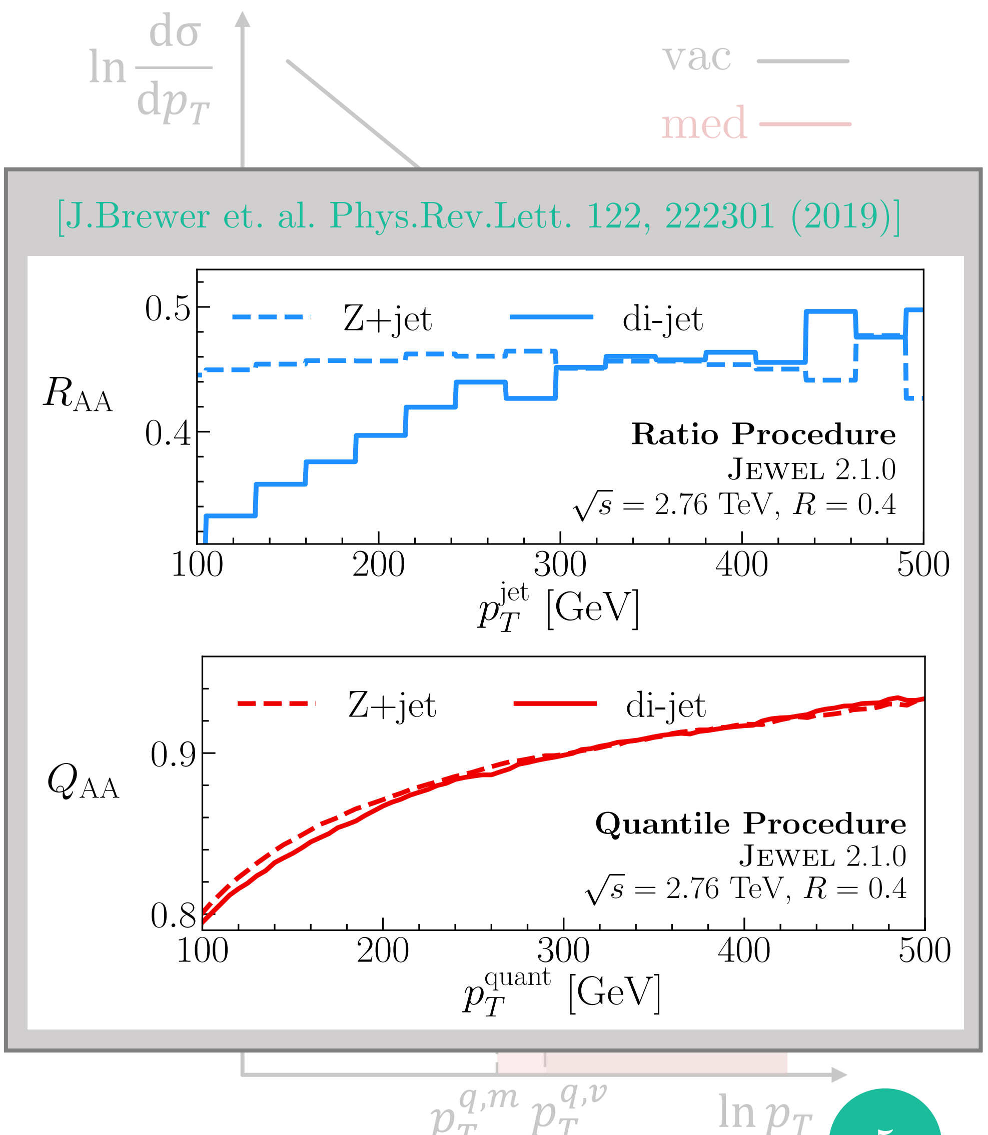

Building up the quenched jet spectrum

1. The quenching weight

The quenched spectrum: the quenching weight

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

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

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

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

The R_{AA} is the quenching weight

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

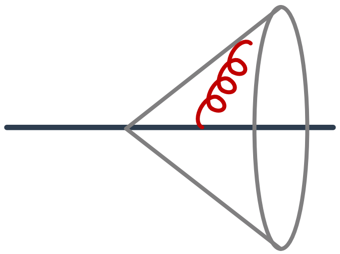
Building up the quenched jet spectrum

1. Medium Induced Emissions

From single parton to jets

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]

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

From single parton to jets

Single parton, single medium induced emission

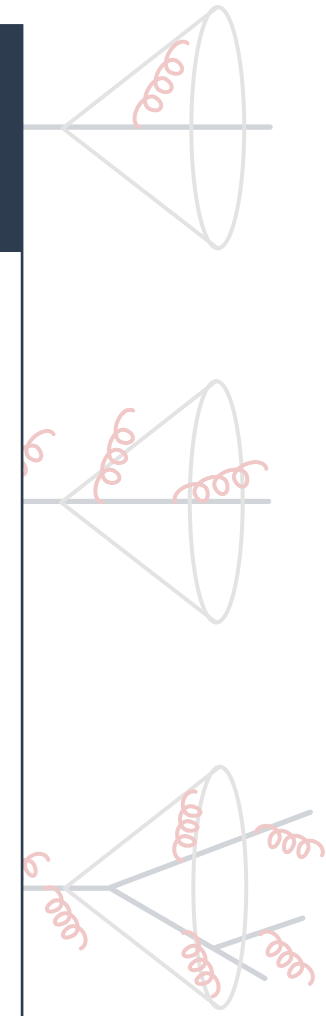
Single parto

Multi parto

Medium Induced Parton Showers

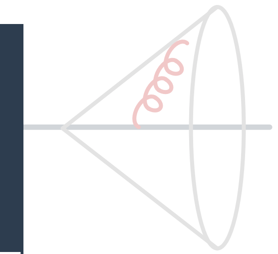
Adam Takacs* University of Bergen (Norway)

*adam.takacs@uib.no

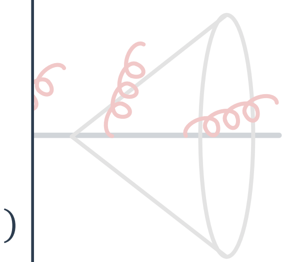


From single parton to jets

Single parton - single medium-induced emission



Single parto



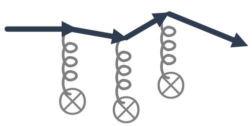
Multi parto

Modern Jet Quenching - Medium Induced Emission

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

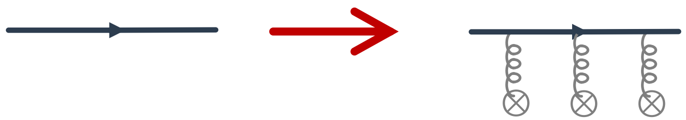
QCD with medium bkg:

- Colored background $\mathcal{A}_0(t, x)$
- Energy is conserved (p^+), transverse kick ($\boldsymbol{p}$)
- Multiple scatterings

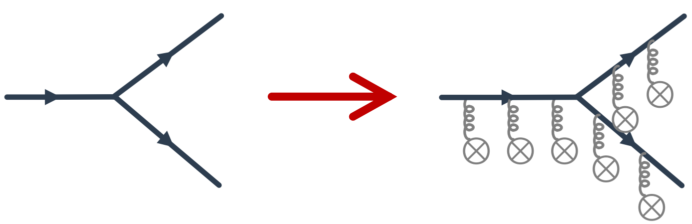


Keeping space-time: partial Fourier space (p^+, $\boldsymbol{p}$, p^-) → (p^+, $\boldsymbol{x}$, t)

- Effective propagator: $G_s^c(p^+, \boldsymbol{p}_t, p^-)$ $G^{c_1 c_2}_{s_1 s_2}(t_f, \boldsymbol{x}_f, t_i, \boldsymbol{x}_i | p^+)$



- Effective vertices:



A1

Adam Takacs Presentception seminar 2021

From single parton to jets

Single parton, single medium induced emission

Single parto

Multi parto

Modern Jet Quenching - Medium Induced Emission

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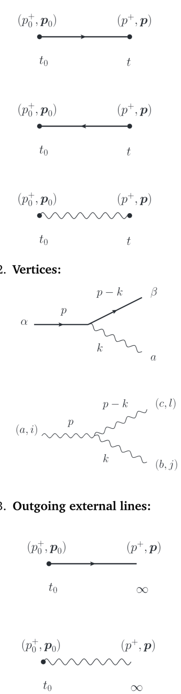
QCD with medium bkg:

- Colored ba
- Energy is c
- Multiple sc

Keeping space-time: partial

- Effective p
- Effective v

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



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

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

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

2. **Vertices:**

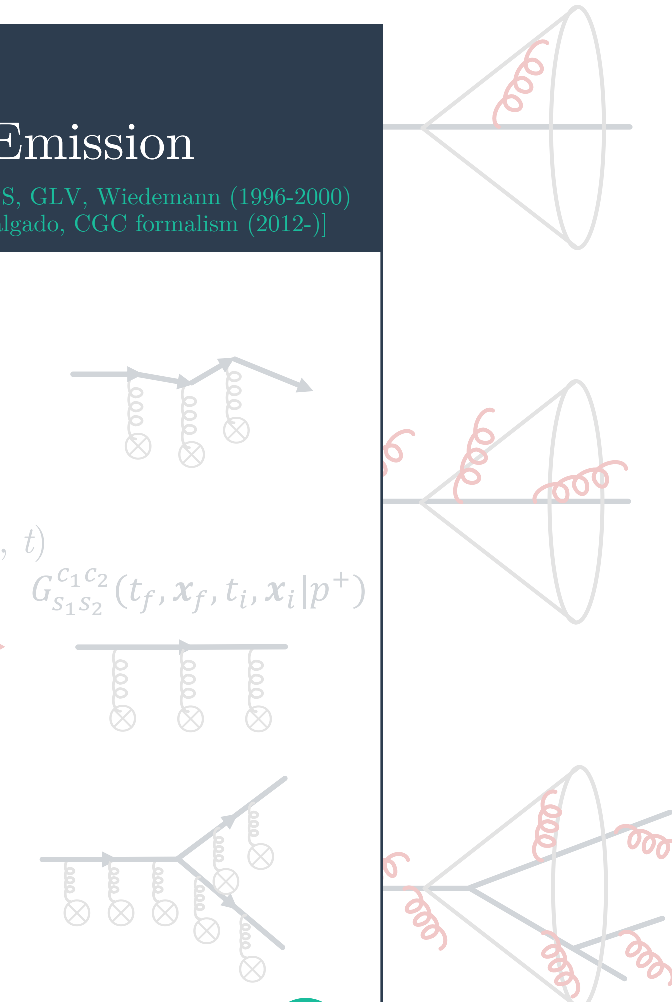
$$\gamma^+\frac{2igt^a}{z\sqrt{1-z}}\left[\left(1-\frac{z}{2}\right)(\boldsymbol{k}-z\boldsymbol{p})^i + i\frac{z}{2}S^3\epsilon^{ij}\,(\boldsymbol{k}-z\boldsymbol{p})^j\right] \tag{164}$$

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

3. **Outgoing external lines:**

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

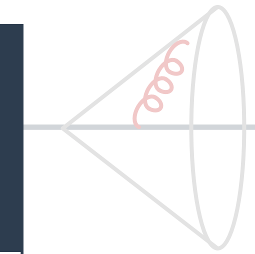
$$\epsilon^{*,i}_\lambda(p)\ \mathrm{e}^{i\frac{\boldsymbol{p}^2}{2p^+}t_\infty}\ (\boldsymbol{p}|\,\mathcal{G}^{\text{adj}}_{\text{scal}}(\infty,t_0)|\boldsymbol{p}_0) \quad \text{for gluons} \tag{167}$$



A2

From single parton to jets

Single parton, single medium induced emission

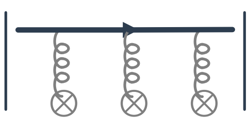


Modern Jet Quenching - Medium Induced Emission

[Blaizot, Iancu, Mehtar-Tani,, Salgado, Tywoniuk, ...]

Single parto

Transverse broadening:



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

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

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

Medium induced emission (in addition to vacuum):

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

Multi parto

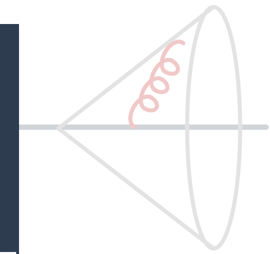
A3

From single parton to jets

Single parton, single medium induced emission

Single parto

Multi parto



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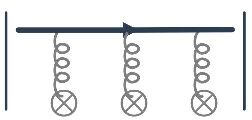

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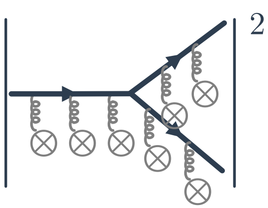
$$\mathcal{P}(\boldsymbol{p},t) = \frac{4\pi}{\hat{q}t}\, e^{-\frac{\boldsymbol{p}^2}{\hat{q}t}} \qquad \langle \boldsymbol{p}^2\rangle = \hat{q}t$$

Medium induced emission (in addition to vacuum):



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

Decoherence: $\vartheta_{q\bar{q}} \ll \vartheta_c$

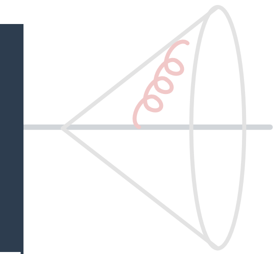
A3

From single parton to jets

Single parton, single medium induced emission

Single parto

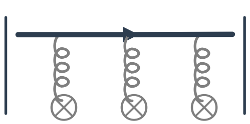
Multi parto



Modern Jet Quenching - Medium Induced Emission

[Blaizot, Iancu, Mehtar-Tani,, Salgado, Tywoniuk, ...]

Transverse broadening:



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

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

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

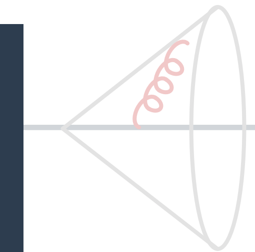
Medium induced emission (in addition to vacuum):

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

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

From single parton to jets

Single parton, single medium induced emission



Single parto

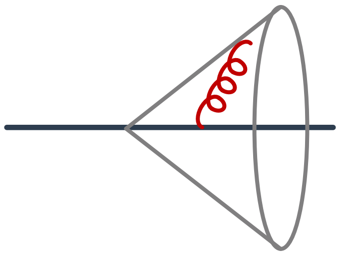
Multi parto

Thank you for your attention!

From single parton to jets

Single parton, single medium induced emission

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



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

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

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

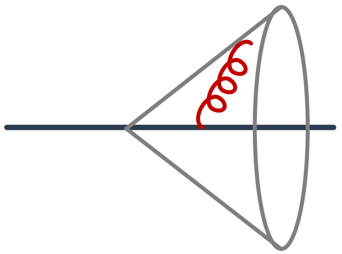
Multi parton (jet), multiple induced emission [Phys.Rev.D98 (2018) 051501]

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

From single parton to jets

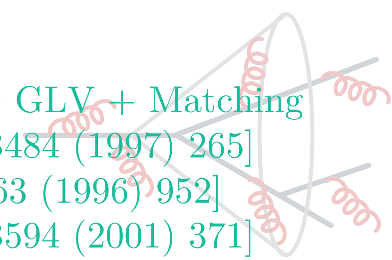
Single parton, single medium induced emission

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

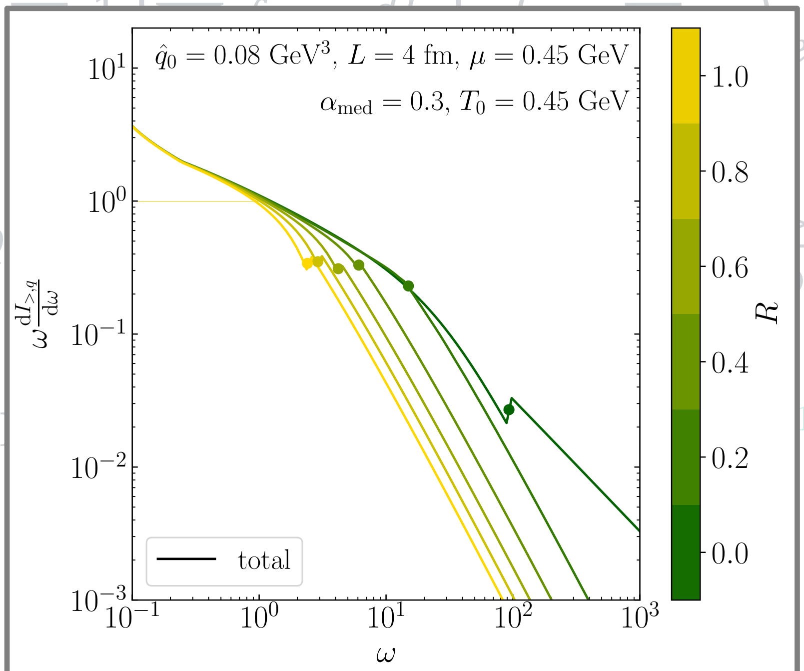


Single parton, multiple induced emission [JHEP09 (2001) 033]

Multi parton (jet), multi… …18) 051501]



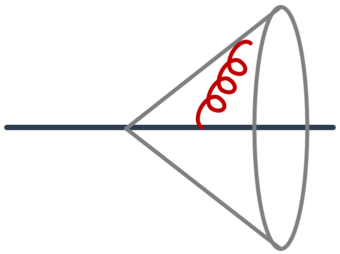
Medium induced emission spectrum



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

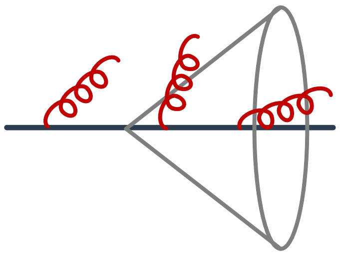
From single parton to jets

Single parton, single medium induced emission



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

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



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

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

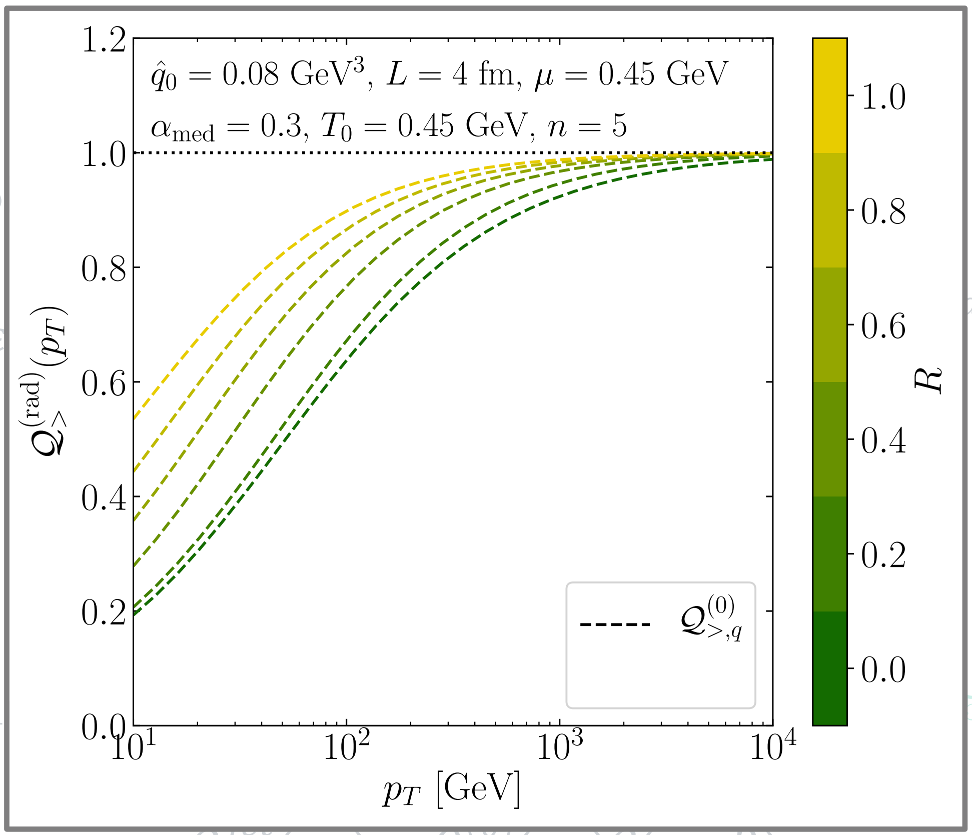
Multi parton (jet), multiple induced emission [Phys.Rev.D98 (2018) 051501]

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

From single parton to jets

Single parton, single medium induced emission

Single parton, multip



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

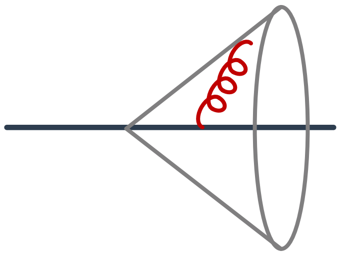
Multi parton (jet), m … 51501]

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

From single parton to jets

Single parton, single medium induced emission

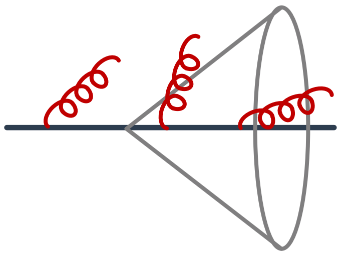
$$\mathcal{P}_{>}^{(0)}(\varepsilon) \approx \frac{dI_{>}}{d\varepsilon}$$



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

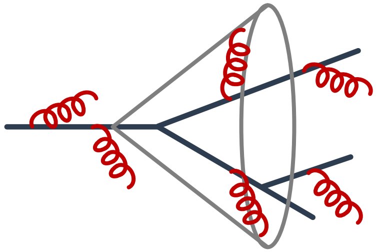
$$\mathcal{P}_{>}^{(0)}(\varepsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{j}^{n} \int d\omega_j \frac{dI_{>}}{d\omega_j} \right] \delta\left(\varepsilon - \sum_{j=1}^{n} \omega_j \right) e^{-\int d\omega_j \frac{dI_{>}}{d\omega_j}}$$

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



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

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

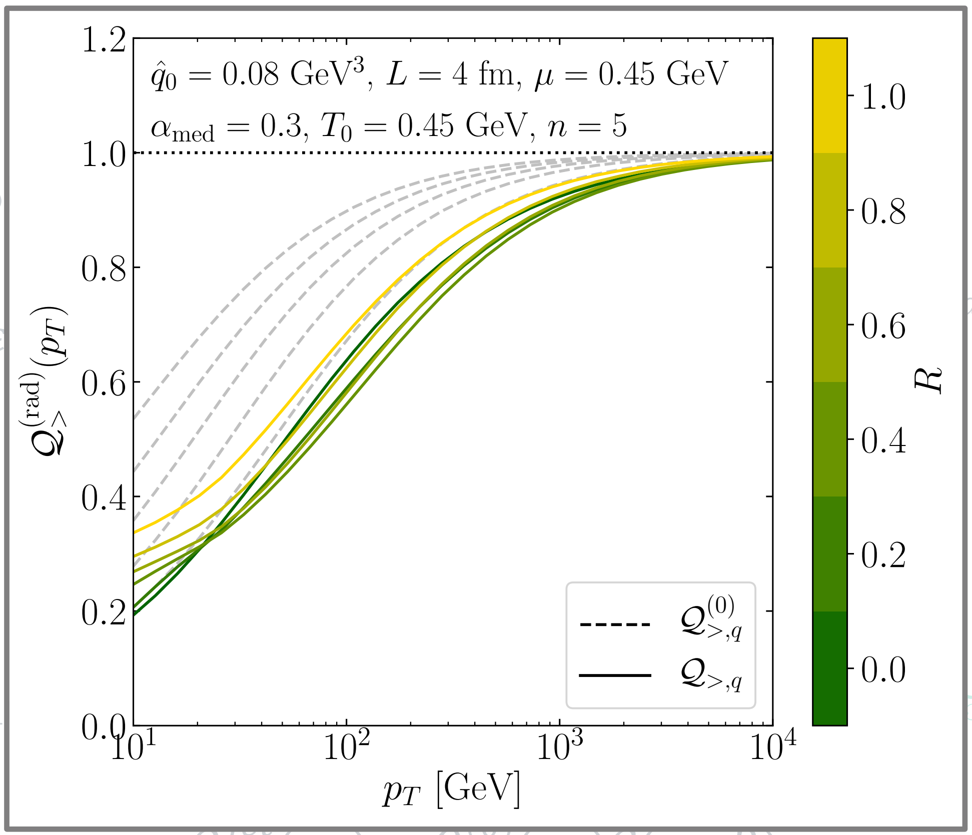


From single parton to jets

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]

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

Comparison to data

To include more effects:

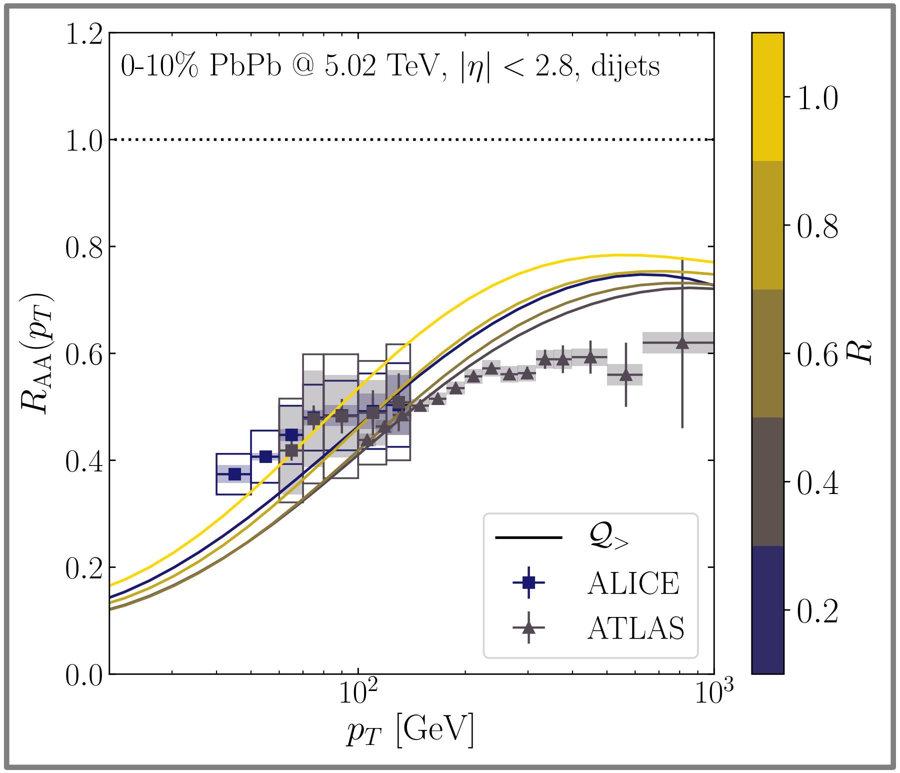
- Assuming factorization: PDF and nPDF effects, quark/gluon ratio
- Medium resolution and color coherence effects
- Broadening of the induced gluons in/out of the cone
- Thermalizing soft gluons
- Energy loss from elastic scattering

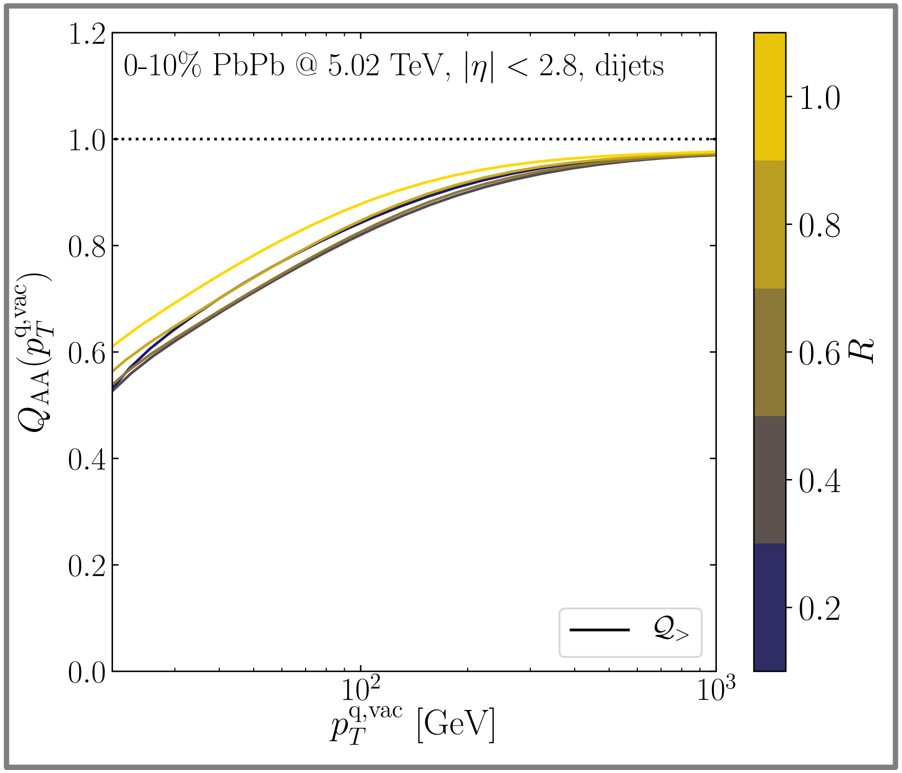
Missing:

- Geometry and time dependence
- Fluctuations

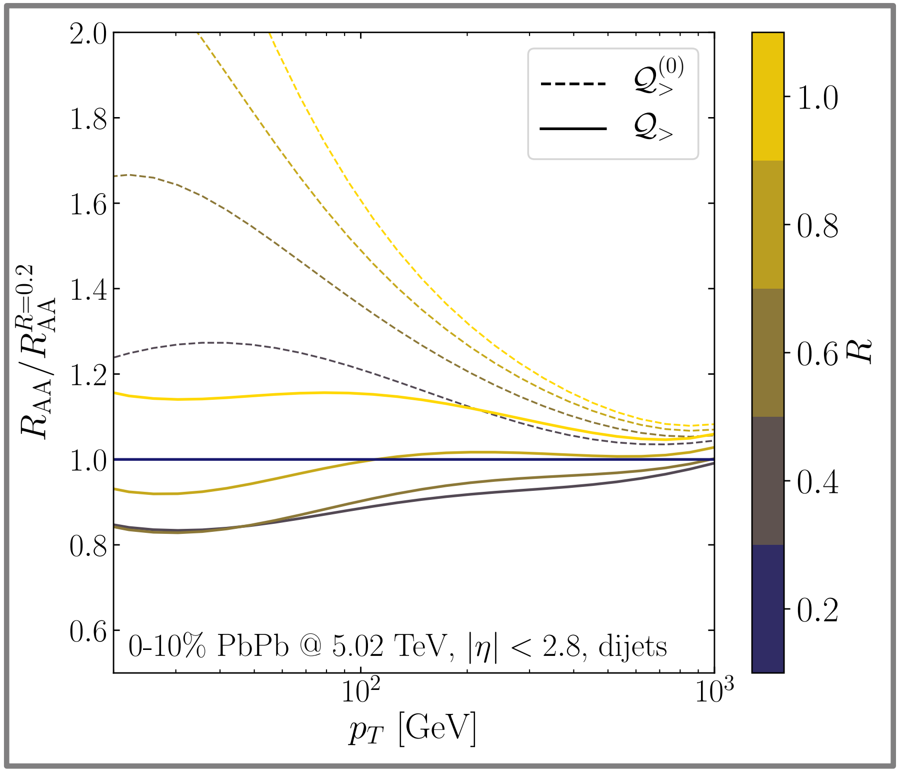
0-10% PbPb @ 5.02TeV, $|\eta| < 2.8$

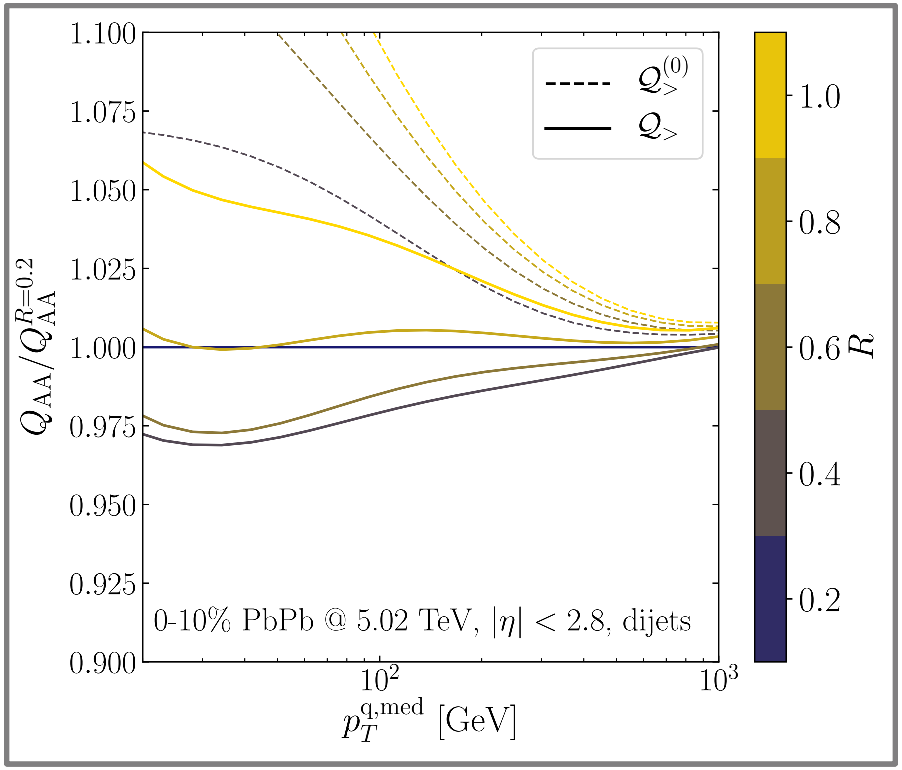
[see RAA also in arXiv:2101.01742]



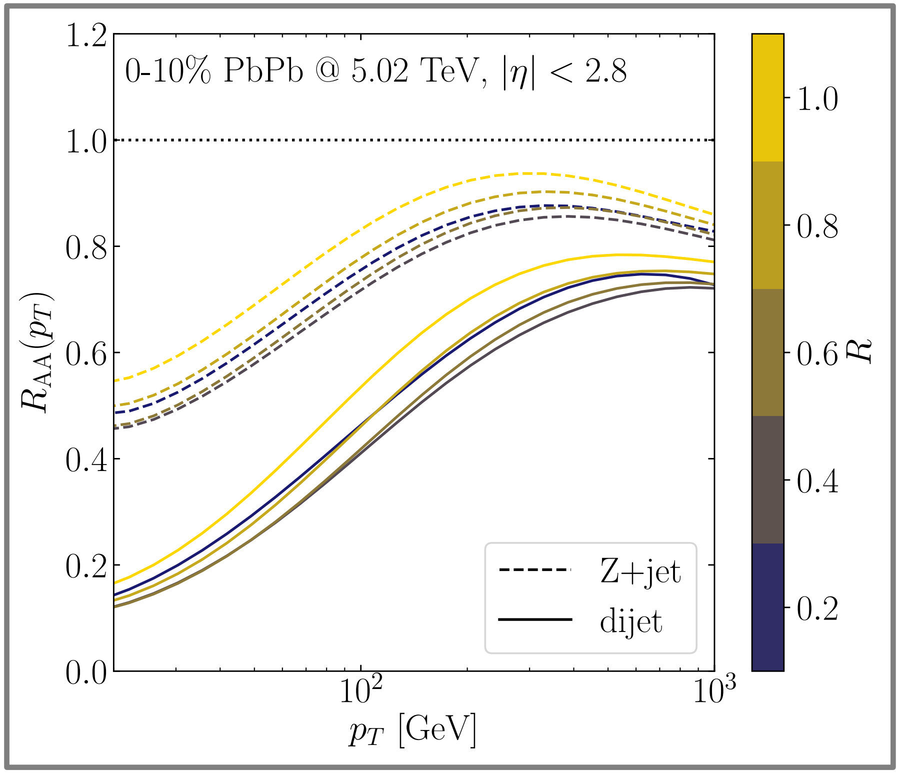


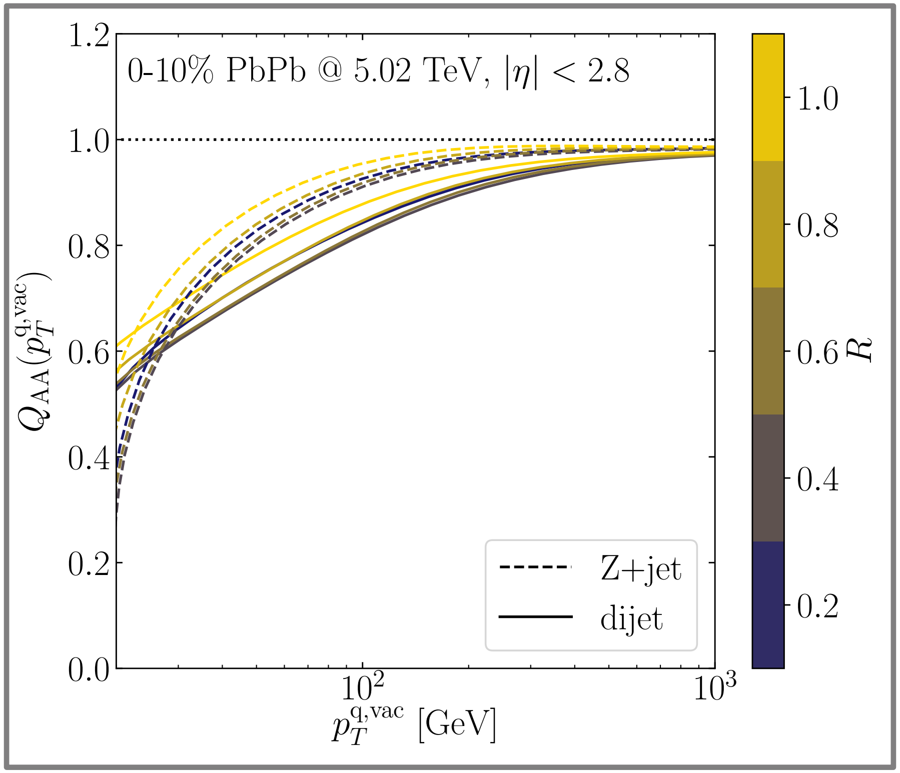
0-10% PbPb @ 5.02TeV, $|\eta| < 2.8$



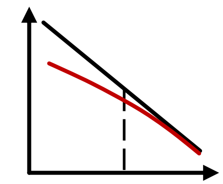
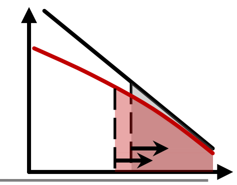
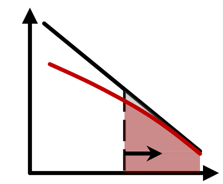
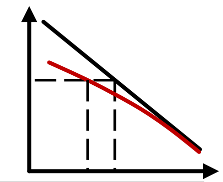
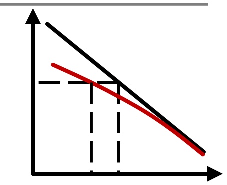


Quenching weight





Different observable possibilities

Name	def.	n sensit.	statistics	cartoon
• Nuclear modification:	$R_{\mathrm{AA}} = \left.\frac{\sigma_{AA}}{\sigma_{pp}}\right\vert_{p_T}$	ok	ok	
• Quantile ratio:	$Q_{AA} = \left.\frac{p_T^{AA}}{p_T^{pp}}\right\vert_{\Sigma^{eff}}$	smaller	better	
• Cumulative-R_{AA}: Behaves as $\sim Q_{AA}^{n-1}$	$\tilde{R}_{\mathrm{AA}} = \left.\frac{\Sigma_{AA}}{\Sigma_{pp}}\right\vert_{p_T}$	ok	better	
• Pseudo-Quantile: Behaves as $\sim R_{AA}^{-1/n}$	$\tilde{Q}_{AA} = \left.\frac{p_T^{AA}}{p_T^{pp}}\right\vert_{\sigma^{eff}}$	smaller	ok	
• Spectrum shift: Equivalent to $\tilde{Q}_{AA}$	$\sigma^{AA}(p_T) = \sigma^{pp}(p_T + S)$	smaller	ok	

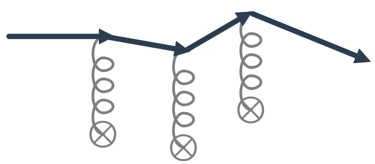
Thank you for your attention!

Modern Jet Quenching - Medium Induced Emission

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

Scattering on the medium (of an energetic parton):

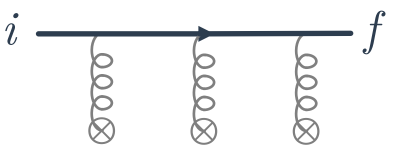
- Colored background $\mathcal{A}_0(t, x)$
- Energy is conserved (p^+), transverse kick $(\boldsymbol{p})$
- Multiple scatterings



Keeping space-time: partial Fourier space $(p^+,\, \boldsymbol{p},\, p^-) \to (p^+,\, \boldsymbol{x},\, t)$

$G_s^c(p^+, \boldsymbol{p}_t, p^-)$

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



2-d Schrodinger equation with imaginary potential

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

$$G(t, \boldsymbol{x}, t_0, \boldsymbol{x}_0 | p^+) = \int_{\boldsymbol{x}_i}^{\boldsymbol{x}_f} \mathcal{D}\boldsymbol{r}\; e^{i\frac{p^+}{2}\int_{t_i}^{t_f} ds\, \dot{\boldsymbol{r}}^2(s)}\; \mathcal{T} e^{-ig\int_{t_i}^{t_f} ds\, \mathcal{A}_0(\boldsymbol{r}(s))}$$

Modern Jet Quenching - Medium Induced Emissions

Medium induced emission:

$$\omega \frac{dI}{d\omega d^2\boldsymbol{k}} = \frac{2\alpha_s C_R}{(2\pi)^2\omega^2} \mathrm{Re} \int_0^L dt \int_t^L d\bar{t} \int d^2\boldsymbol{x}\, e^{-\int ds\, v(\boldsymbol{x})} \partial_{\boldsymbol{x}}\partial_{\boldsymbol{y}}\, G(\bar{t}, \boldsymbol{x}, t, \boldsymbol{y} \to 0\, |\omega)$$

$$G(t, \boldsymbol{x}, t_0, \boldsymbol{x}_0 | p^+) = \int_{\boldsymbol{x}_i}^{\boldsymbol{x}_f} \mathcal{D}\boldsymbol{r}\; e^{\int_{t_i}^{t_f} ds \left[i \frac{p^+}{2} \dot{\boldsymbol{r}}^2 - v(\boldsymbol{r}, s) \right]}$$

Elastic scattering potential:

$$v(\boldsymbol{x}) = N_c \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} \frac{d^2\sigma_{el}}{d^2\boldsymbol{q}} (1 - e^{i\boldsymbol{x}\boldsymbol{q}})$$

$$v(\boldsymbol{x}) = \frac{\hat{q}_0(t)}{4} \boldsymbol{x}^2 \qquad \frac{d^2\sigma_{el}^{G-W}}{d^2\boldsymbol{q}} = \frac{4\pi}{N_c} \frac{\hat{q}_0(t)}{(\boldsymbol{q}^2 + \mu^2)^2}$$

Medium resolution:

Modern Jet Quenching - Medium Induced Emissions

[Blaizot, Iancu, Mehtar-Tani (2014)]

Medium induced parton shower

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

$$t_*^{-1} = \bar{\alpha}\sqrt{\frac{\hat{q}}{E}} \qquad \mathcal{K}(z) = \frac{[1-z+z^2]^{5/2}}{[z(1-z)]^{3/2}}$$

With transverse broadening $D(x,\boldsymbol{k},t) = (2\pi)^2 x\,\frac{dN}{dx\,d^2\boldsymbol{k}}$

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

Comparison to data

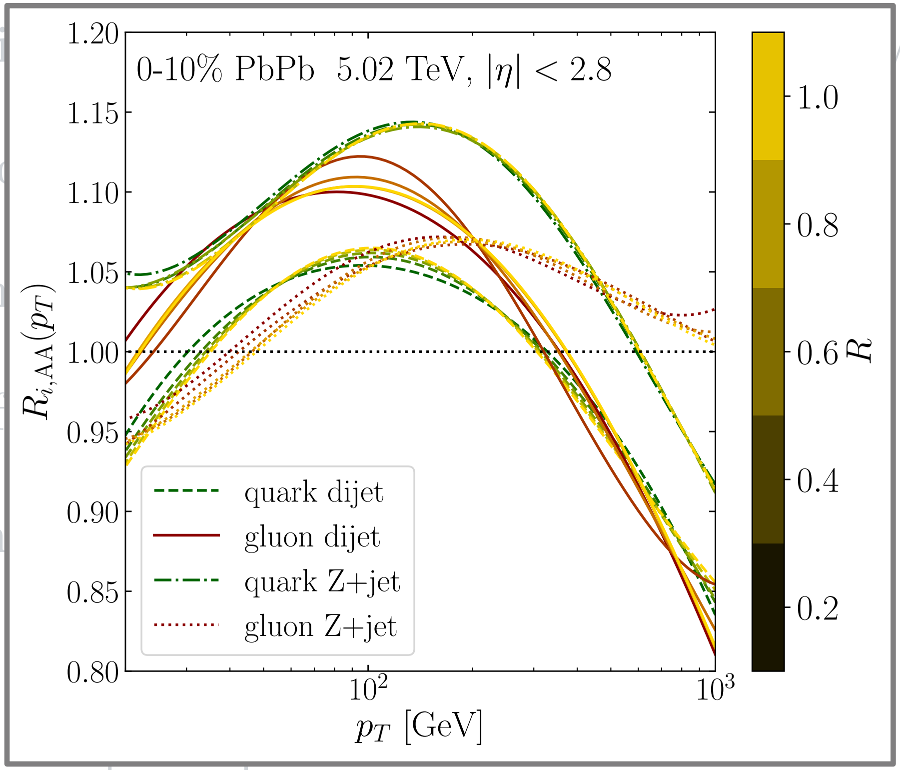
To include more effects:

- Assuming factori[...] /gluon ratio
- Medium resoluti[...]
- Broadening of th[...]
- Thermalizing sof[...]
- Energy loss from[...]

Missing:

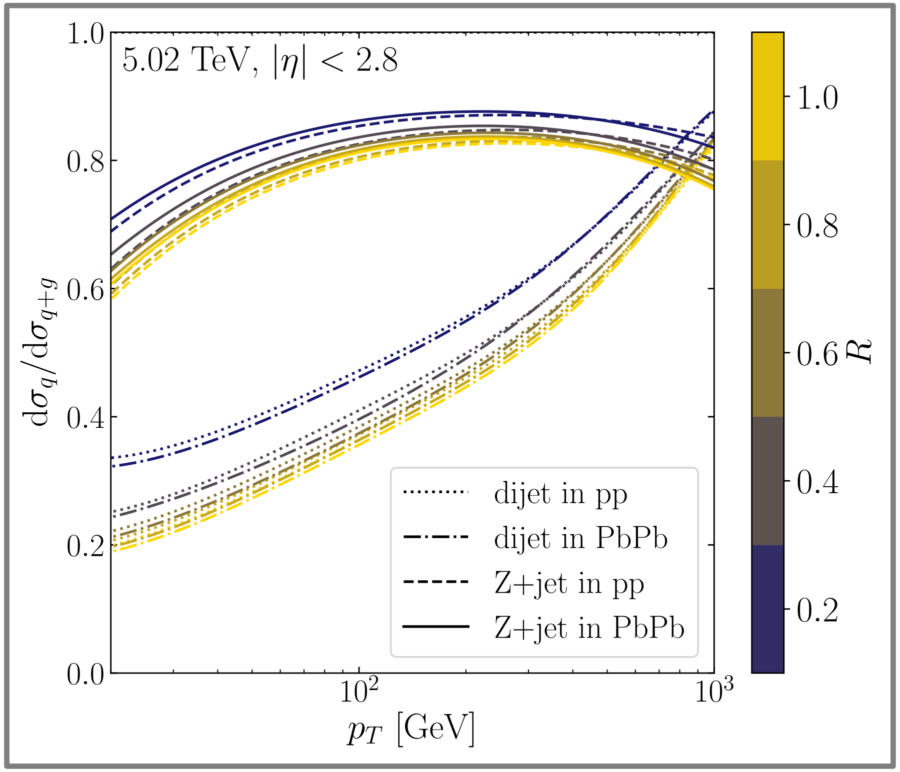
- Geometry and time dependence
- Fluctuations

nPDF effects



Quenching weight

Before quenching



After quenching