JET SUPPRESSION AND ENERGY LOSS

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3) Energy loss

- single-inclusive spectrum
- hadrons (quarks)
- heavy quarks
- jets

JET QUENCHING

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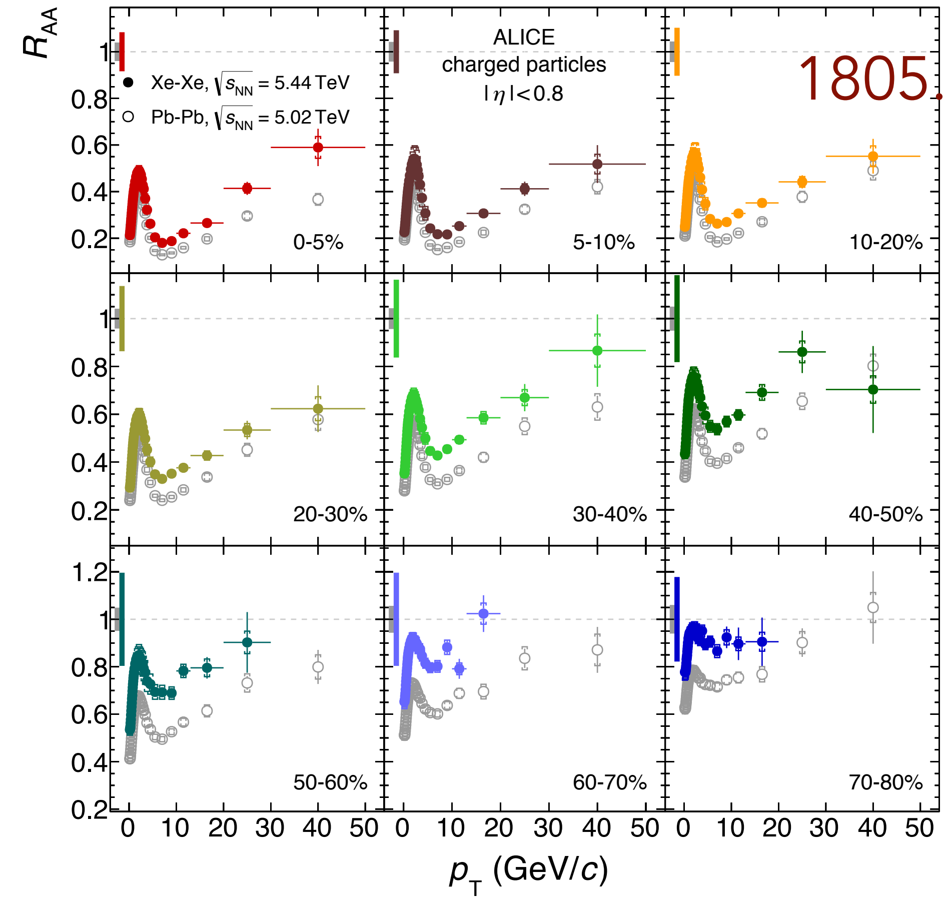

$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y}{\langle T_{AA}\rangle \mathrm{d}\sigma_{pp}/\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y}$$

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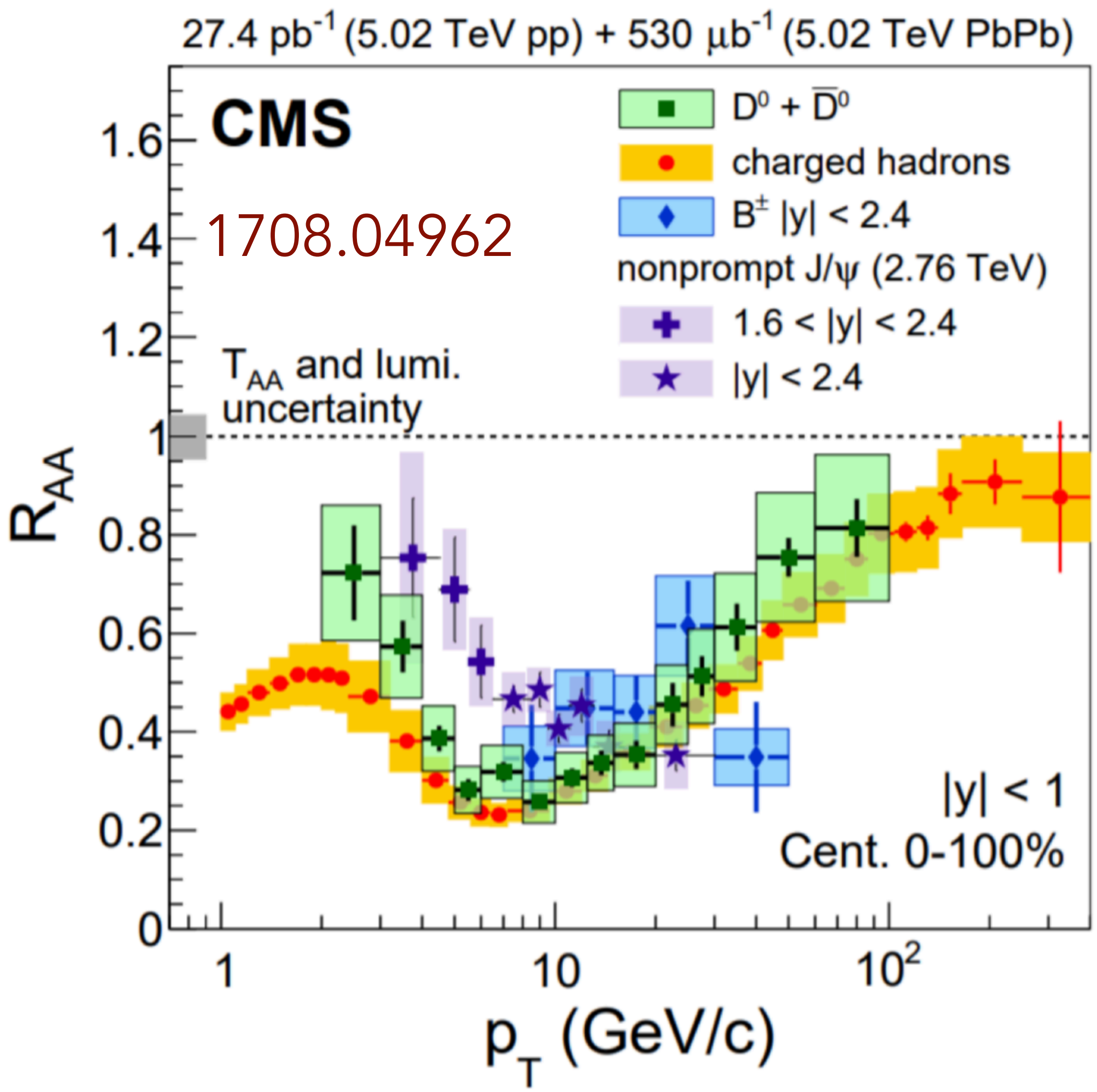
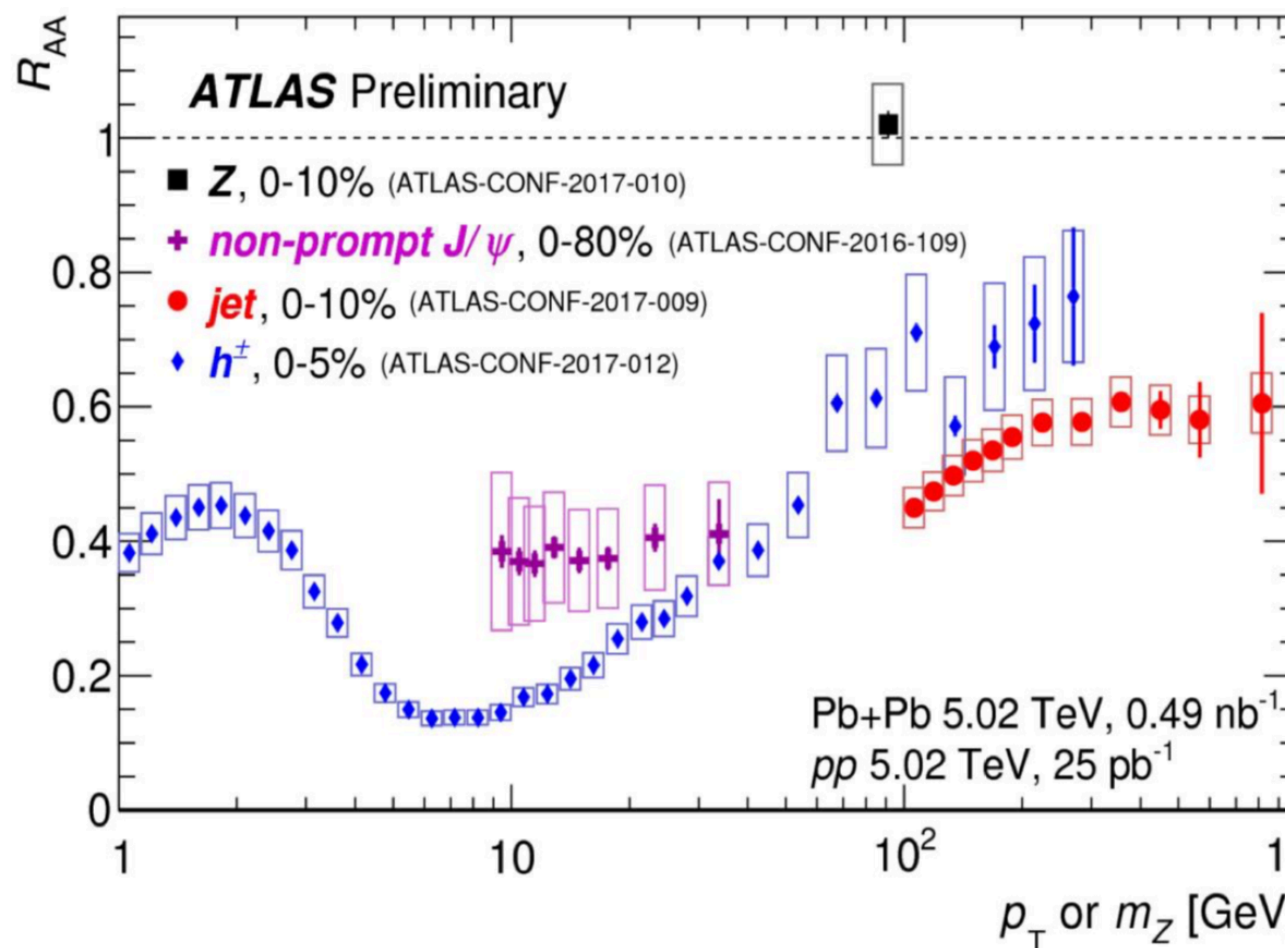


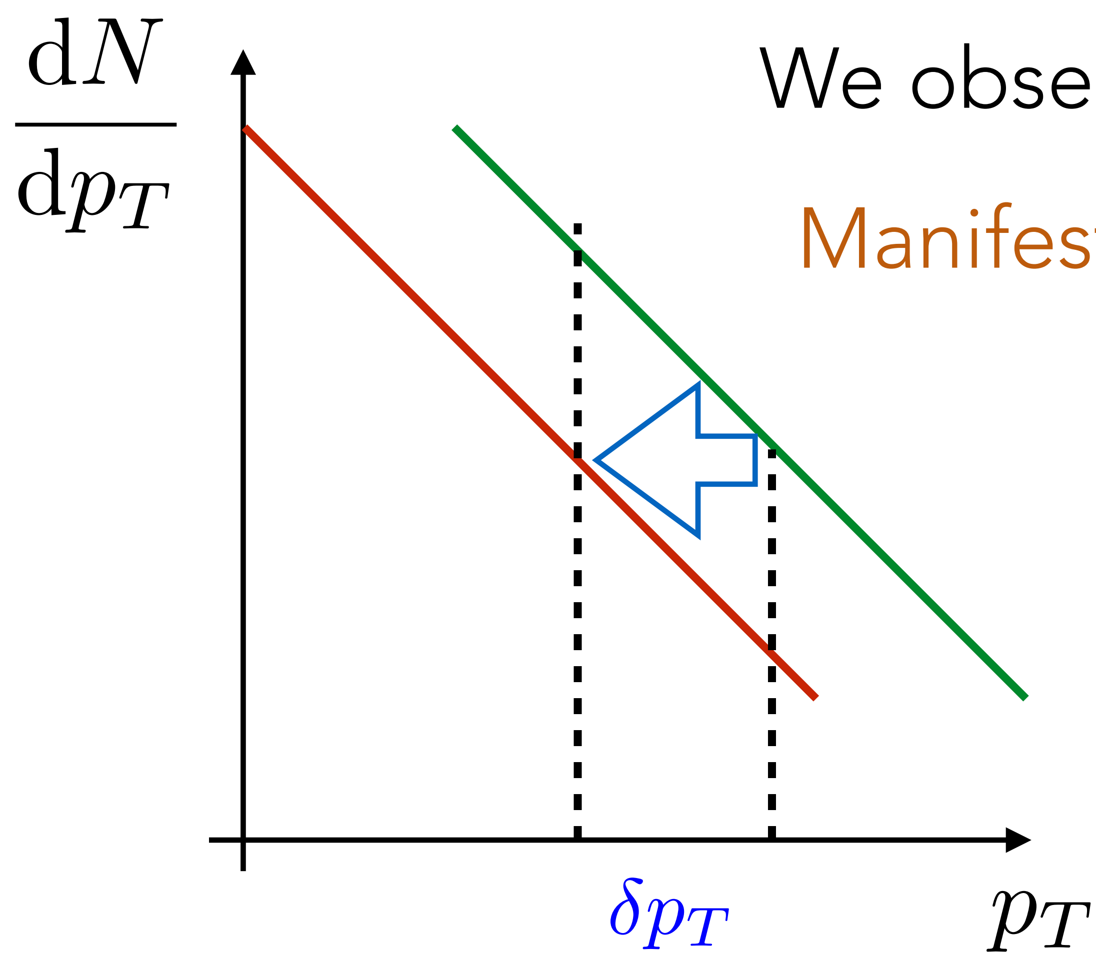


JET QUENCHING

- strong suppression of wide range of probes of large range in p_T
- sensitive to color charge
- interesting centrality dependence
- common features/unified description?
  - charged hadrons (light quarks/gluons)
  - heavy mesons (heavy quarks/gluons
  - jets

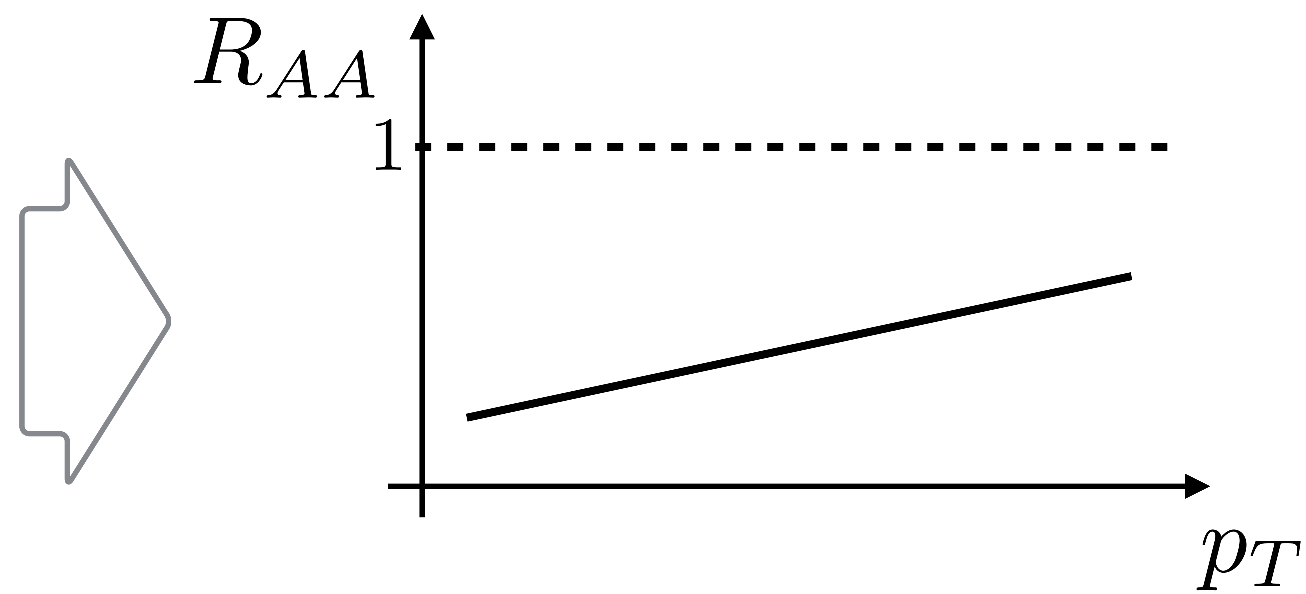
The goal of studying jets it to extract information about the properties of the medium; independent and complementary probes!

What is going on?



Imagine we shoot a well-controlled flux of particles into the plasma.
We observe suppression because of pT shift.

Manifestation of a energy loss mechanism!



$$\frac{\mathrm{d}N_{AA}(p_T)}{\mathrm{d}p_T} = \frac{\mathrm{d}N_{pp}(p'_T = p_T + \delta p_T)}{\mathrm{d}p'_T} \times \left| \frac{\mathrm{d}p'_T}{\mathrm{d}p_T} \right|$$

Generalities

Our best candidate:
radiative energy loss!

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

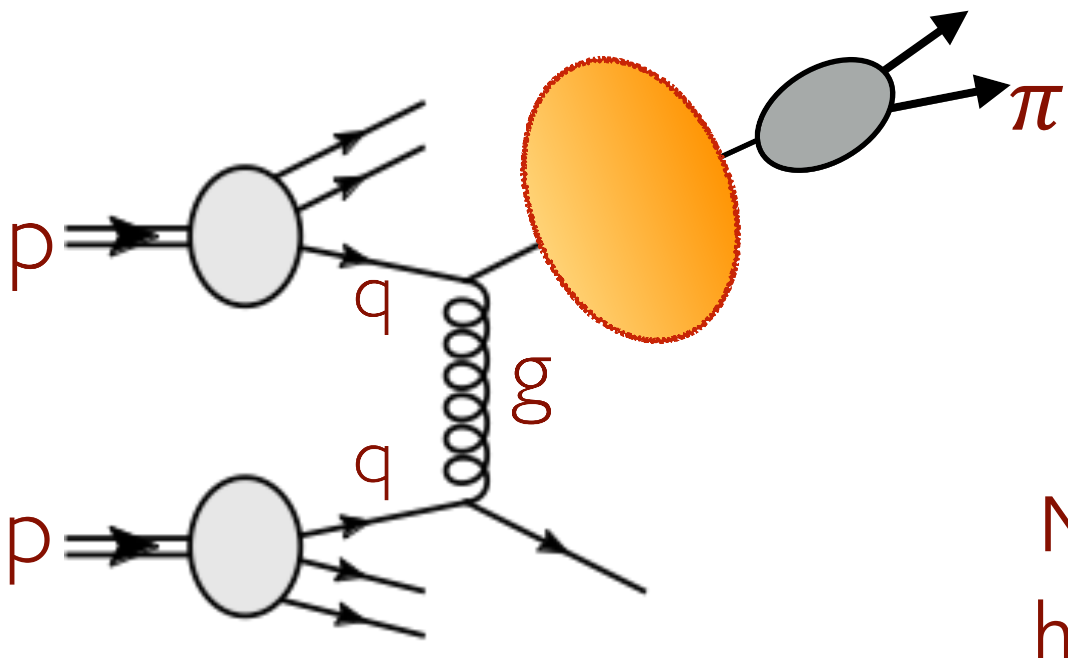
- any color object propagating through the medium sources radiation, leads to energy loss
- but, in principle, other processes can also contribute [elastic energy loss, broadening & absorption]

Probability for losing energy from one emission

$$\mathcal{P}(\epsilon) = \delta(\epsilon) \left(1 - \int \mathrm{d}\omega \, \frac{\mathrm{d}I}{\mathrm{d}\omega} \right) + \frac{\mathrm{d}I}{\mathrm{d}\epsilon}$$

Problem gets more complicated if we consider more sources of radiation (vacuum radiation) and multi-gluon medium-induced radiation!

QUENCHING OF HADRONS I



Assume single quark/gluon propagates through the medium and fragments outside!

Not a bad approximation since high-p_T hadrons come from hard fragmentation (hadrons ~ narrow jets).

$$\frac{d\sigma^h_{\rm med}}{dp_{\rm T}^2 dy} = \int dq_{\rm T}^2 dz \, \frac{d\sigma^k_{\rm vac}}{dq_{\rm T}^2 dy} D^{k\to h}(z,\mu_F^2)\, \mathcal{P}_k(\epsilon)\delta(p_{\rm T} - z(q_{\rm T}-\epsilon))$$

$q_{\rm T} = p_{\rm T}/z + \epsilon$ steeply falling spectrum… hence z~1

Refinement: can also replace $\langle z \rangle$ in the delta function, and integrate out z.

QUENCHING OF HADRONS II

quenching weight: probability distribution of losing energy

$$\frac{d\sigma_{\rm med}}{dp_T^2 dy} = \int_0^\infty d\epsilon\, \mathcal{P}(\epsilon) \frac{d\sigma_{\rm vac}(p_T+\epsilon)}{dp_T^2 dy}$$

quenching factor = nuclear modification factor

$$R_{\rm jet} = \left(\frac{d\sigma_{\rm med}}{dp_T^2 dy}\right) \Big/ \left(\frac{d\sigma_{\rm vac}}{dp_T^2 dy}\right)$$

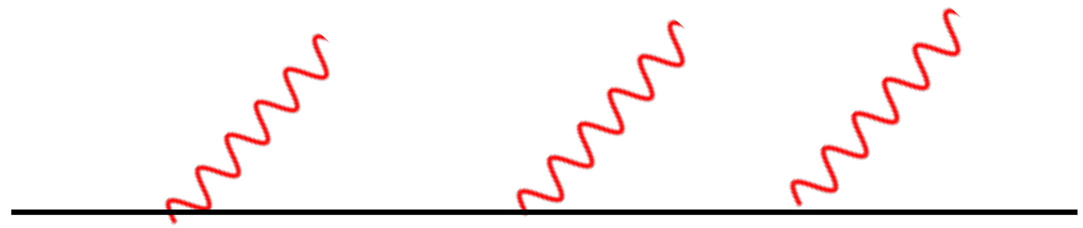
For $\epsilon/p_T \ll 1$ and large n: $\frac{1}{(p_T+\epsilon)^n} \approx \frac{1}{p_T^n} e^{-\epsilon n/p_T}$

$$R_{\rm jet} \sim \tilde{\mathcal{P}}(n/p_T) \equiv \mathcal{Q}(p_T)$$

quenching factor is Laplace transform of energy loss probability

[For now, n=const, but this can be improved and finite-n corrections can be implemented.]

RESUMMATION OF MULTIPLE GLUONS



Soft gluons: copious, large angle, short formation time

no interferences!

$$\mathcal{P}(\epsilon) = \delta(\epsilon)\left(1 - \int \mathrm{d}\omega \, \frac{\mathrm{d}I}{\mathrm{d}\omega}\right) + \frac{\mathrm{d}I}{\mathrm{d}\epsilon}$$

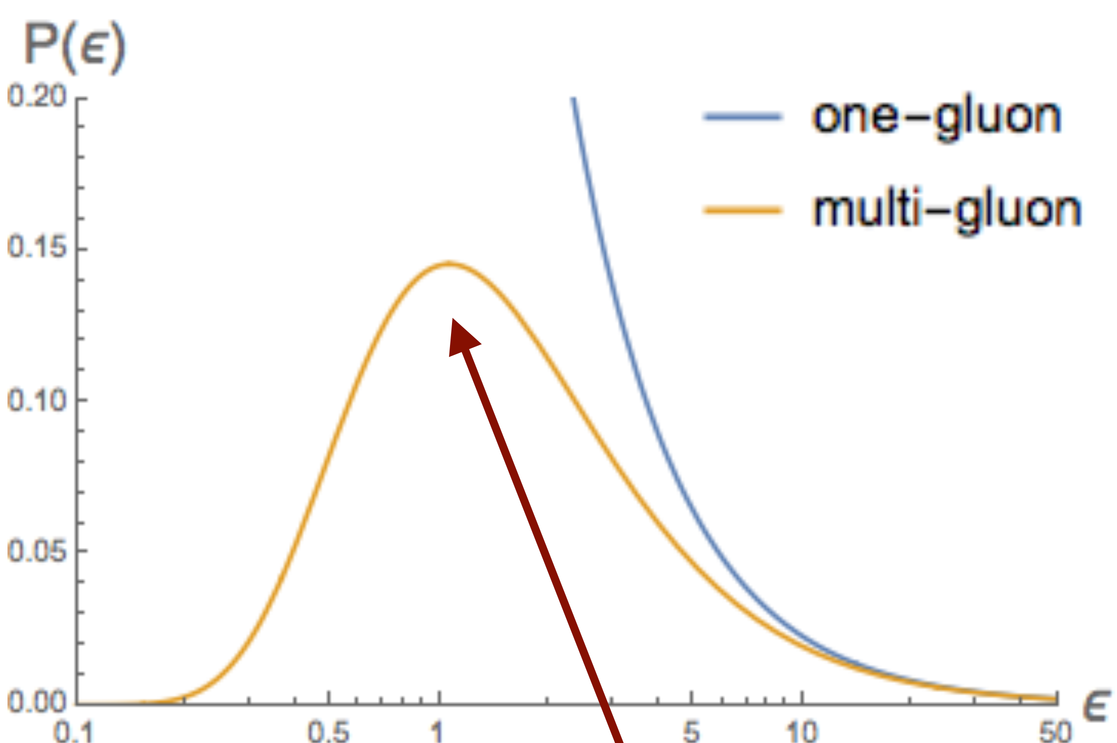
$$\mathcal{P}(\epsilon, L) = \delta(\epsilon) + \int_0^L \mathrm{d}t \int \mathrm{d}\omega \left[\frac{\mathrm{d}I}{\mathrm{d}\omega \mathrm{d}t} - \delta(\omega) \int \mathrm{d}\omega' \, \frac{\mathrm{d}I}{\mathrm{d}\omega' \mathrm{d}t}\right] \mathcal{P}(\epsilon - \omega, t)$$

$$\frac{\mathrm{d}I}{\mathrm{d}\omega \, \mathrm{d}t} \simeq \frac{\bar{\alpha}}{\omega t_{\mathrm{br}}(\omega)}$$

Constant rate for infinite medium; time-dependent rate in general

Rate equation

$$\frac{\partial}{\partial t}\mathcal{P}(\epsilon,t) = \int \mathrm{d}\omega \left[\frac{\mathrm{d}I}{\mathrm{d}\omega \mathrm{d}t} - \delta(\omega)\int \mathrm{d}\omega' \frac{\mathrm{d}I}{\mathrm{d}\omega' \mathrm{d}t}\right]\mathcal{P}(\epsilon-\omega,t)$$



E-loss dominated by max of distribution!

$$\tilde{f}(\nu) = \int_0^\infty \mathrm{d}\omega\, \mathrm{e}^{-\nu\omega} f(\omega)$$

$$\frac{\partial}{\partial t}\tilde{\mathcal{P}}(\nu,t) = \gamma(\nu,t)\tilde{\mathcal{P}}(\nu,t)$$

$$\gamma(\nu,t) = \int_0^\infty \mathrm{d}\omega\,\left(\mathrm{e}^{-\nu\omega}-1\right)\frac{\mathrm{d}I}{\mathrm{d}\omega \mathrm{d}t}$$

$$= -2\sqrt{\pi\nu\,\bar{\alpha}^2\hat{q}}$$

$$\mathcal{P}(\epsilon) = \sqrt{\frac{\omega_s}{\epsilon^3}}\mathrm{e}^{-\frac{\pi\omega_s}{\epsilon}}$$

QUARK QUENCHING FACTOR

$$\mathcal{Q}(p_\mathrm{T}) = \mathrm{e}^{-2\bar\alpha L\sqrt{n\pi\hat q/p_\mathrm{T}}} \qquad \bar\alpha = \frac{\alpha_s C_R}{\pi}$$

$$\mathcal{Q}_g(p_\mathrm{T}) = \left(\mathcal{Q}_q(p_\mathrm{T})\right)^{N_c/C_F}$$

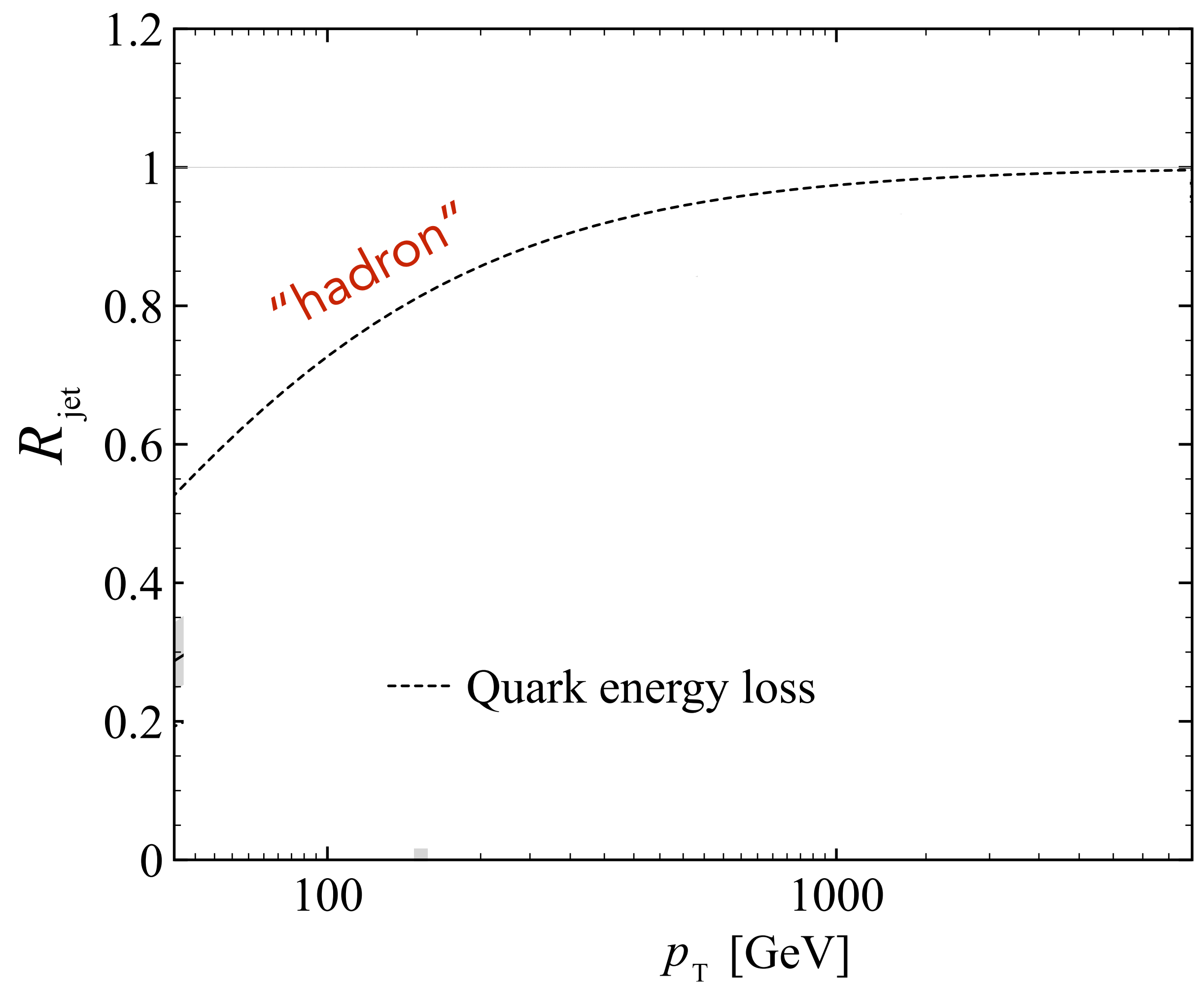
- form factor suppression related to multiplicity of virtual gluons

  $$\mathcal{Q}(p_\mathrm{T}) \sim \mathrm{e}^{-N(\omega > p_\mathrm{T}/n)}$$

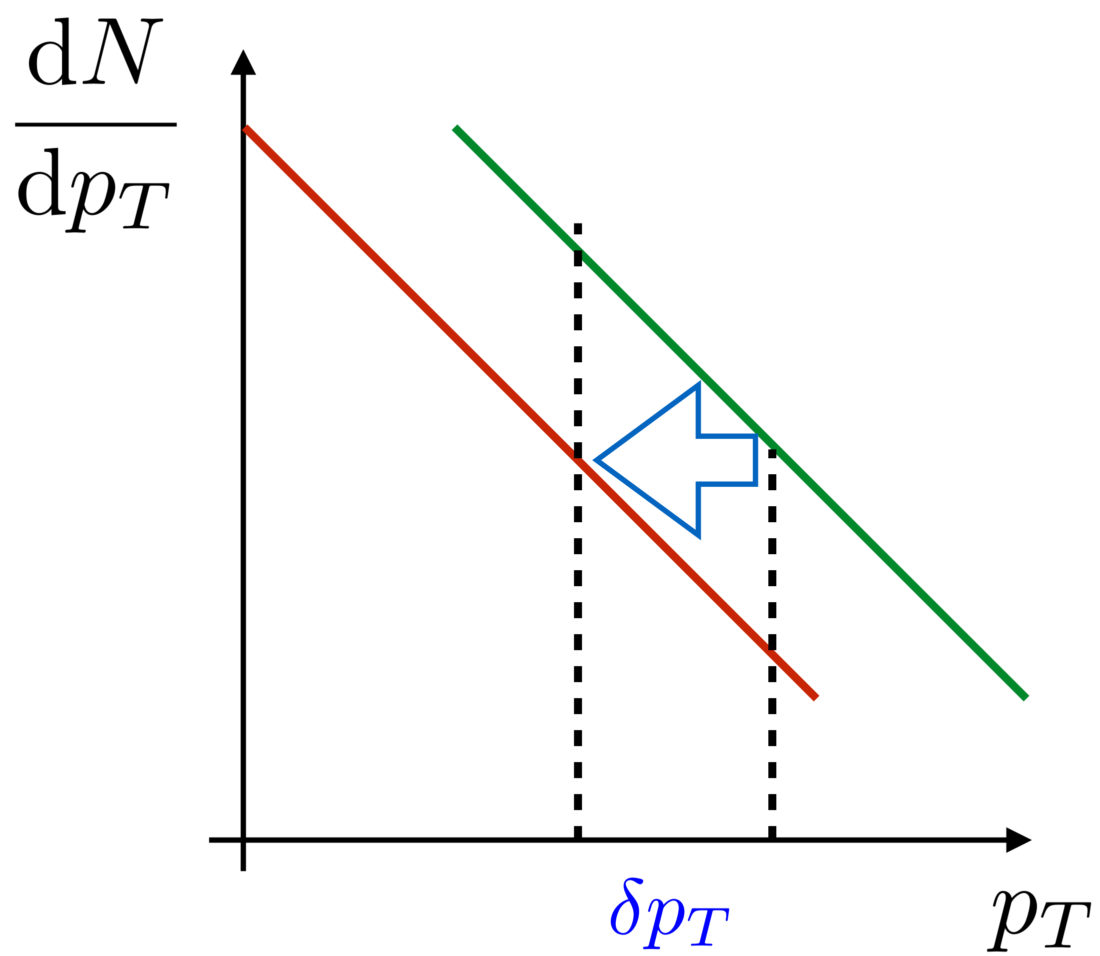
- strong quenching for

  $$p_\mathrm{T} \ll n\bar\alpha^2\hat q L^2$$

- scale related to multiplicity of emitted gluons (not energy)



SHIFTING THE SPECTRUM



Our analysis have resulted in a "model" w/

$$\delta p_T = \sqrt{\frac{8\pi\bar{\alpha}^2\hat{q}L^2\, p_T}{n}}$$

- for a static medium,….

Recall, that naïve expectation

$$\delta p_{\mathrm{T}} = \bar{\alpha}\hat{q}L^2$$

This only holds in the high-pT limit!

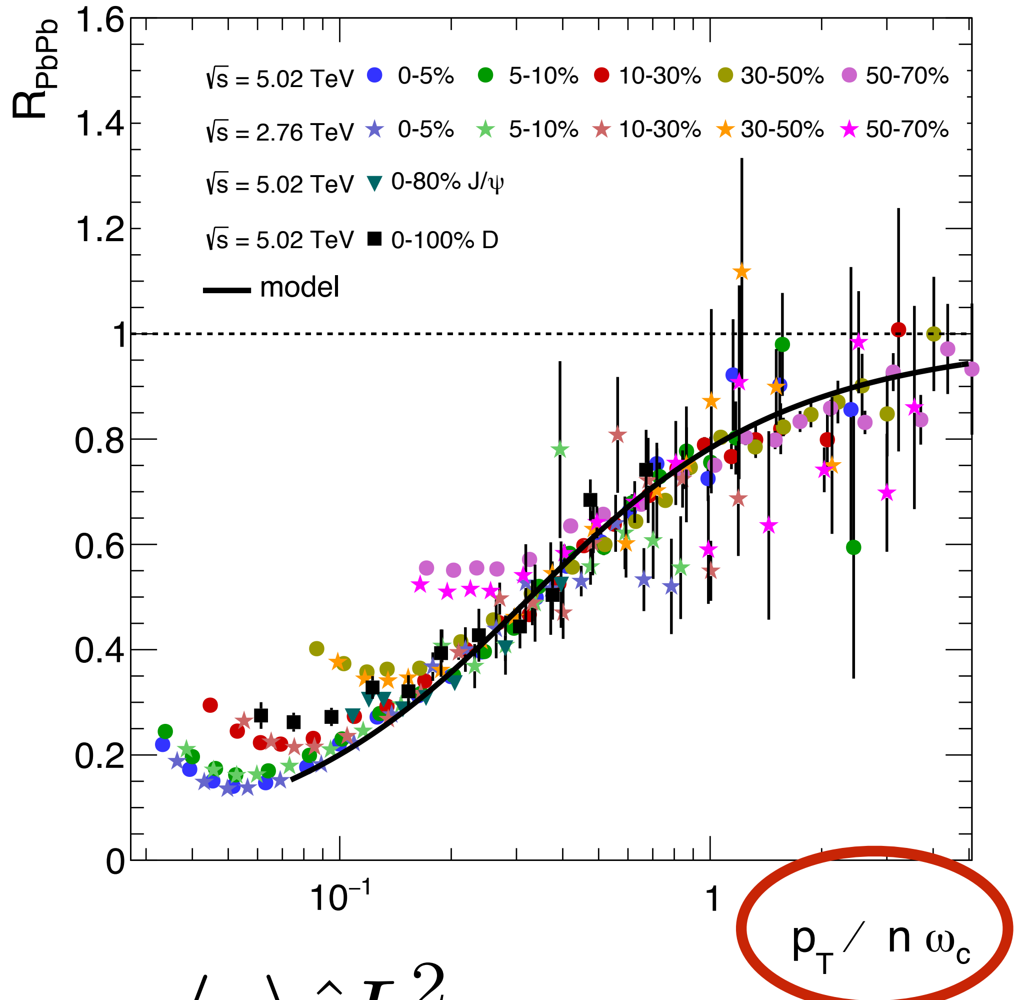
$$p_{\mathrm{T}} > n\hat{q}L^2$$

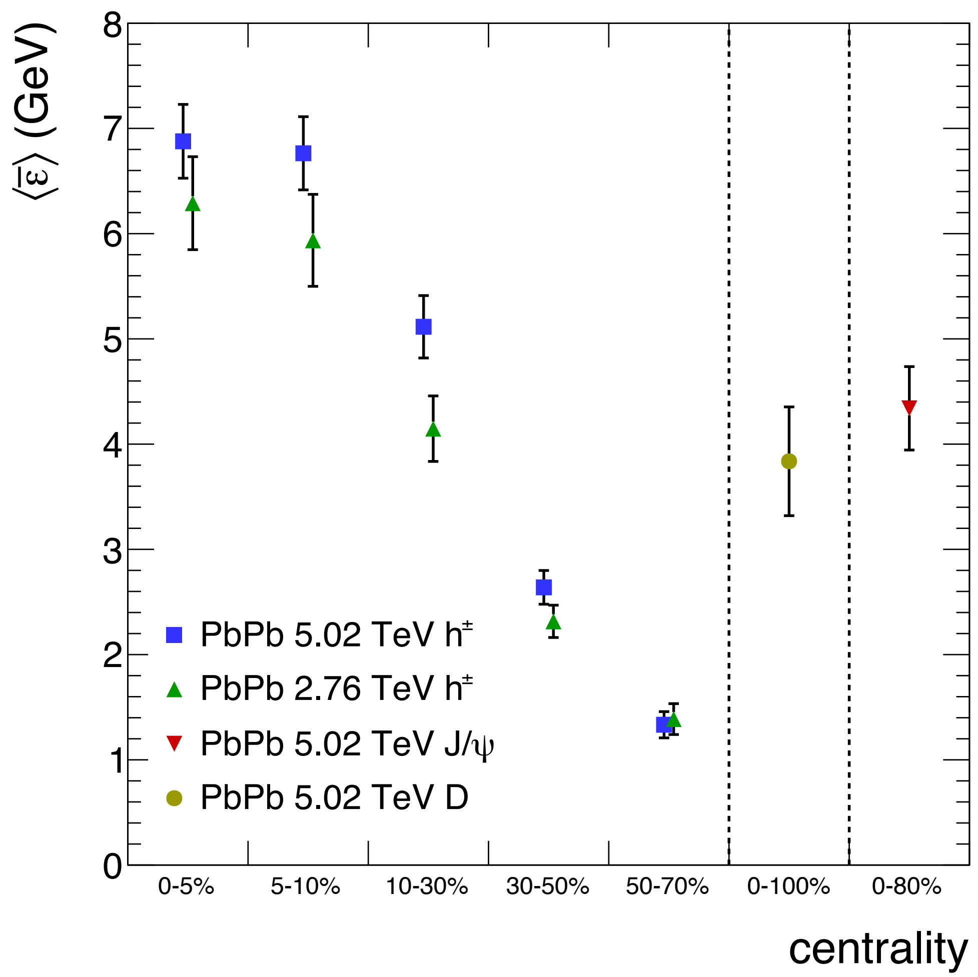
But in that limit, quenching is weak because the multiplicity is small!

$$\mathcal{Q}(p_{\mathrm{T}} > n\hat{q}L^2) \sim \exp[-N(\omega > \omega_c)] \sim \mathrm{e}^{-\bar{\alpha}} \sim 1 - \bar{\alpha}$$

SCALING FEATURE

Arleo (2017)



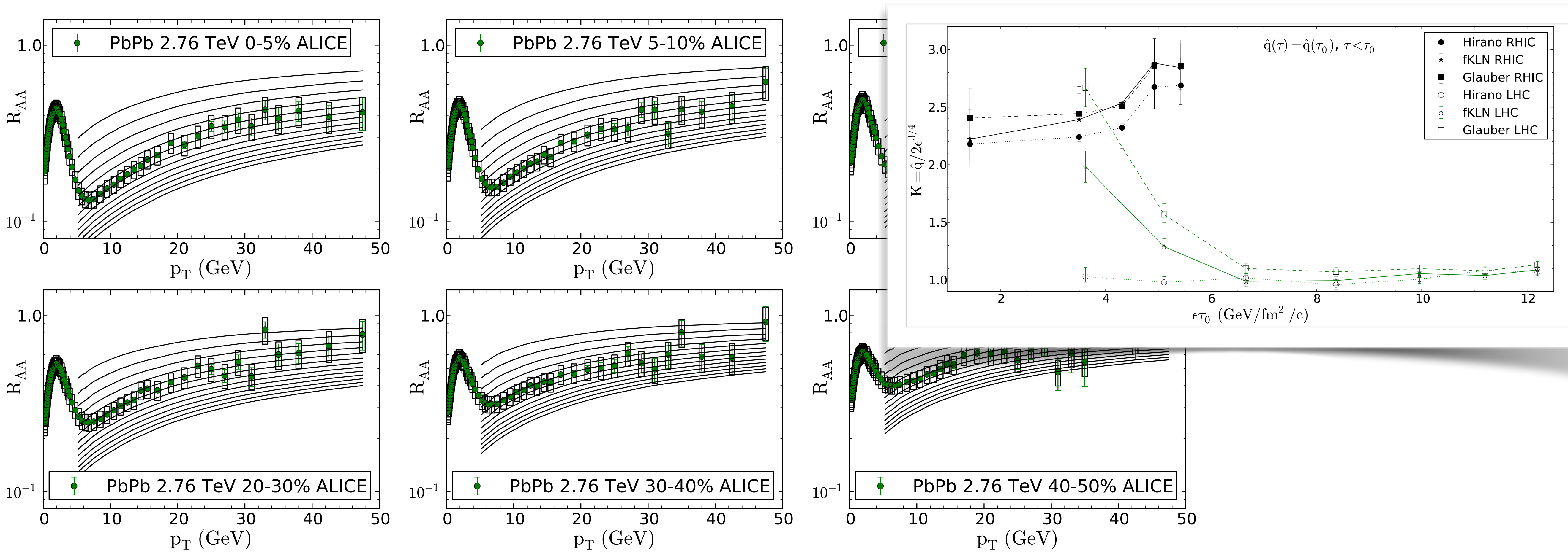


$$\bar{\omega}_c = \langle z \rangle \hat{q} L^2$$

Due to the convolution with a steeply falling spectrum, we are only sensitive to the combination - valid even for heavy particles! Breaks down at low p_T (small n)…

PHENOMENOLOGICAL ANALYSIS

Andres, Armesto, Luzum, Salgado, Zurita (2016)



Extracting $\hat{q}$ from data (w/ realistic hydro, FF, NLO etc..) $\hat{q}(\xi) = K \cdot 2\epsilon^{3/4}(\xi)$

State of the art calculations allow to extract medium properties, check for consistency…

HEAVY-QUARK QUENCHING

$$\mathrm{d}N^{\mathrm{vac}} = \bar{\alpha}\frac{\mathrm{d}z}{z}\frac{k_\perp^2\,\mathrm{d}k_\perp^2}{[k_\perp^2+(zm)^2]^2} = \bar{\alpha}\frac{\mathrm{d}\omega}{\omega}\frac{\mathrm{d}\theta^2}{\theta^2}\left(1+\frac{\theta_0^2}{\theta^2}\right)^{-2}$$

"dead cone" effect
$\theta_0 = m/p_{\mathrm{T}}$

$$\mathrm{d}N^{\mathrm{med}} = \bar{\alpha}\frac{\mathrm{d}\omega}{\omega}\sqrt{\frac{\hat{q}L^2}{\omega}}\left(1+\frac{\theta_0^2}{\theta_{\mathrm{br}}^2(\omega)}\right)^{-2}$$

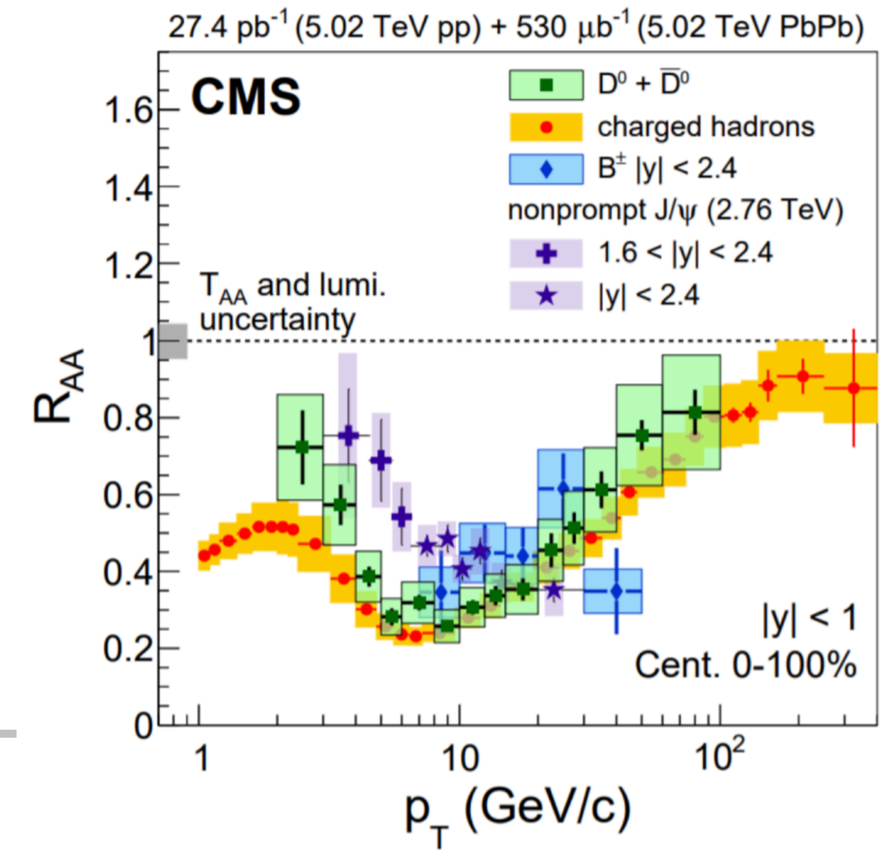
Dokshitzer, Kharzeev (2001); Armesto, Salgado Wiedeman (2003)

0th order expectation:

$$\frac{\mathcal{Q}(p_{\mathrm{T}},m)}{\mathcal{Q}(p_{\mathrm{T}},0)} \simeq \exp\left[2\bar{\alpha}L\sqrt{\pi}\left(\frac{\hat{q}}{\theta_0^2}\right)^{1/3}\right]$$

Heavy-quarks should be less quenched than light!

Data: realistic spectrum, effect of elastic e-loss



WHAT ABOUT JETS?

time-scale

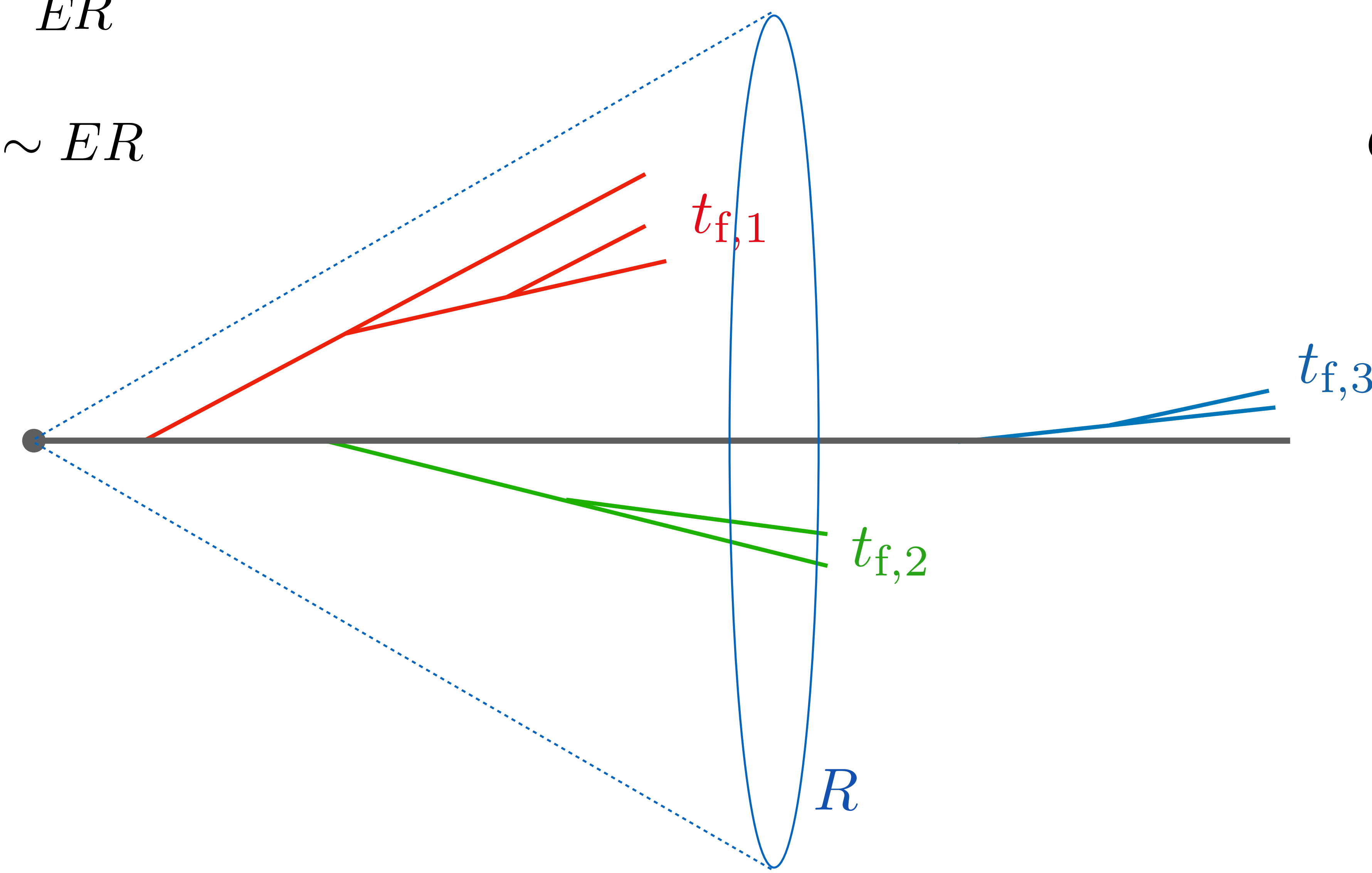
transverse scale

$$t_{\mathrm{f}} \sim \frac{1}{ER}$$

$$Q \sim ER$$

$$t_{\mathrm{f}} \sim \frac{E}{\Lambda_{\mathrm{QCD}}^{2}}$$

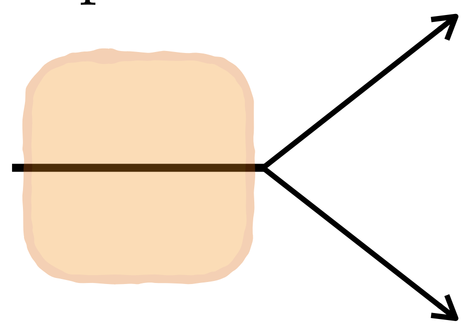
$$Q \sim \Lambda_{\mathrm{QCD}}$$

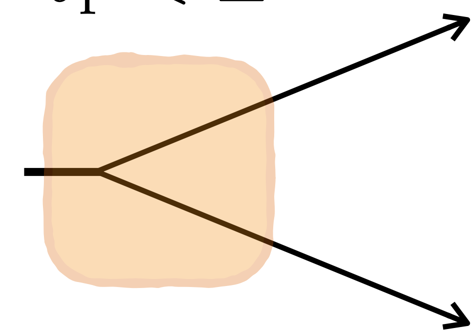


Generally have to deal with multi-gluon emissions!

Q: did the gluons form inside or outside of the medium?

A SIMPLE MODEL





Quenching effect very different in the two situations…
(quenching of two vs. quenching of one)

Let's assume that the medium quenches completely all emissions inside the medium!

$$N(t_\mathrm{f} < L) = \bar{2}\alpha \int_{(\omega\theta^2)^{-1}<L} \frac{\mathrm{d}\omega}{\omega}\frac{\mathrm{d}\theta}{\theta} = \frac{\bar{\alpha}}{2}\ln^2 p_\mathrm{T} R L$$

could affect many splittings!

Radiative corrections

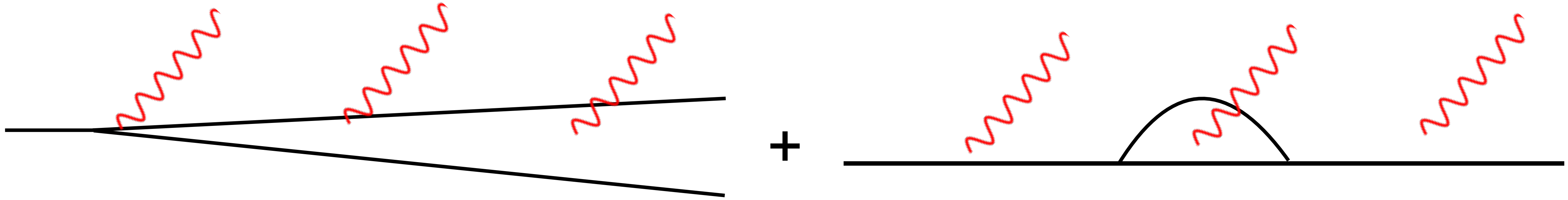
$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^2} = \frac{\mathrm{d}\sigma_{\mathrm{Born}}}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^2}\left[1 + \alpha_s \left(\int \mathrm{d}\Pi_{\mathrm{real}} - \int \mathrm{d}\Pi_{\mathrm{virt}}\right) + \mathcal{O}(\alpha_s^2)\right]$$

- higher-order corrections not enhanced by phase space when balance between real & virtual emissions for sufficiently inclusive observables
- does this hold in the medium (final-state interactions)?

$$R_{\mathrm{jet}} = \mathcal{Q}^{(0)}(p_{\mathrm{T}}) + \mathcal{Q}^{(1)}(p_{\mathrm{T}}) + \mathcal{O}(\alpha_s^2)$$

- expanding quenching factor corresponds to accounting for the quenching of higher-order vacuum emissions (substructure fluctuations)

Higher-order correction to quenching



sensitive to quark+gluon quenching

sensitive to quark quenching

$$\mathcal{Q}^{(1)}(p_{\rm T}) = \int_0^1 {\rm d}z\, P_{gq}(z) \int_0^R \frac{{\rm d}\theta}{\theta}\, \frac{\alpha_s(k_\perp)}{\pi} \left[\mathcal{Q}_{gq}(p_{\rm T}) - \mathcal{Q}_q(p_{\rm T})\right]$$

$$\simeq -\mathcal{Q}_q(p_{\rm T}) N(t_{\rm f} < L)$$

- real & virtual are differently affected by energy loss effects!
- the mismatch is largest at short formation times

Our model simply kills all real emissions!

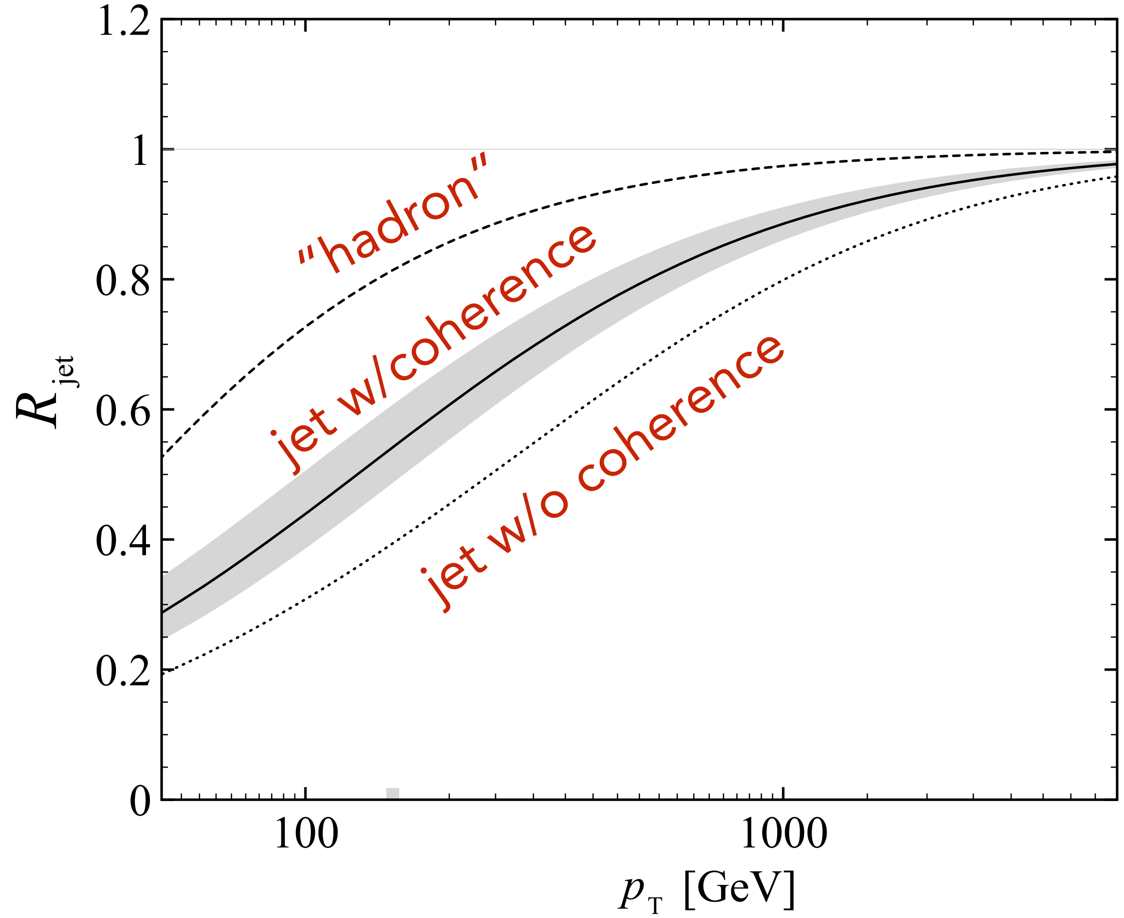
SUDAKOV SUPPRESSION OF JETS

$$R_{\rm jet} = \mathcal{Q}_q(p_{\rm T}) \times \mathcal{C}(p_{\rm T}, R)$$

jet loses energy via total charge & resolved substructure fluctuations

Strong quenching:
Sudakov form factor, depends explicitly on jet scales

$$\mathcal{C}(p_{\rm T}, R) \simeq {\rm e}^{-N(t_{\rm f}<L)}$$



- finite quenching: non-linear evolution equation for $\mathcal{C}(p_{\rm T}, L)$
- minimal resolution angle ~θ_c of the medium (coherence)
- hierarch sensitive to jet scales

SUMMARY

- the spectra of particles (light, heavy) and jets are suppressed due to interactions with the medium
  - can be experimentally accessed as a δp_T shift
- radiative energy loss (sensitive to mass)
- jets are multi-gluon objects: additional quenching
- 0th order expectation is a hierarchy

$$R_{\mathrm{Q}} > R_{\mathrm{q}} > R_{\mathrm{jet}}$$

OUTLOOK

- jets are interesting physical objects at colliders
  - calibrated: theoretical tools & MC
- radiative processes in the medium leads to energy loss
- different phenomenological implications for single-inclusive spectra for hadrons & jets
- also, di-jet/boson-jet great for pinning down short- and long-distance pieces
- promising new observables: jet substructure