Medium Modifications to Jet Angularities

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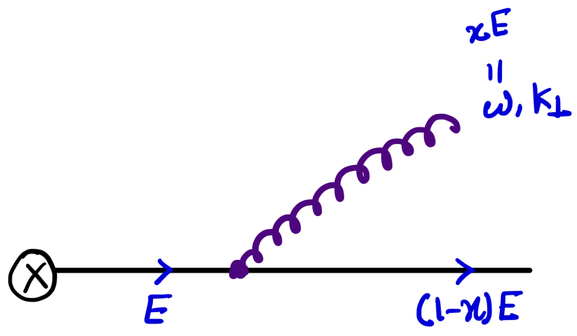
Based on : **arXiv:2305.10237**

Jets in vacuum vs matter

Vacuum

- For an energetic parton produced at the hard interaction, the bremsstrahlung spectrum is

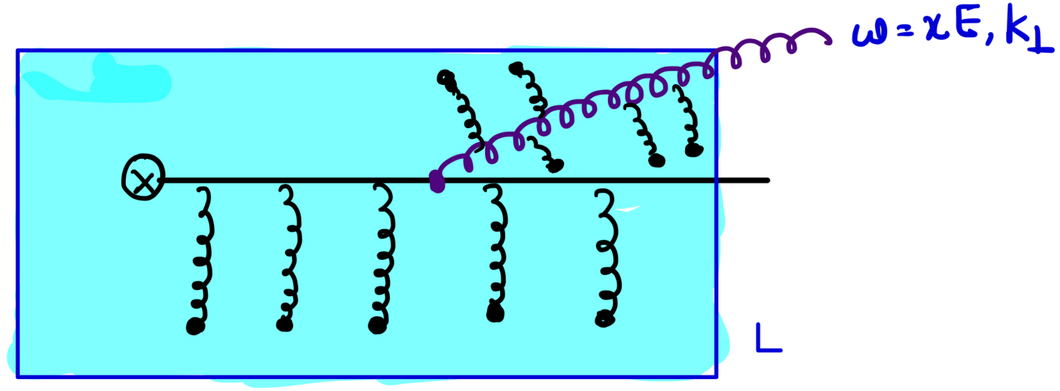


$$dI^{\rm vac} = \frac{\alpha_s(\mu)\, C_F}{\pi} P(\omega)\, d\omega \frac{d\theta}{\theta}$$

$$\approx_{\omega \ll 1} \frac{\alpha_s(\mu)\, C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta}{\theta}$$

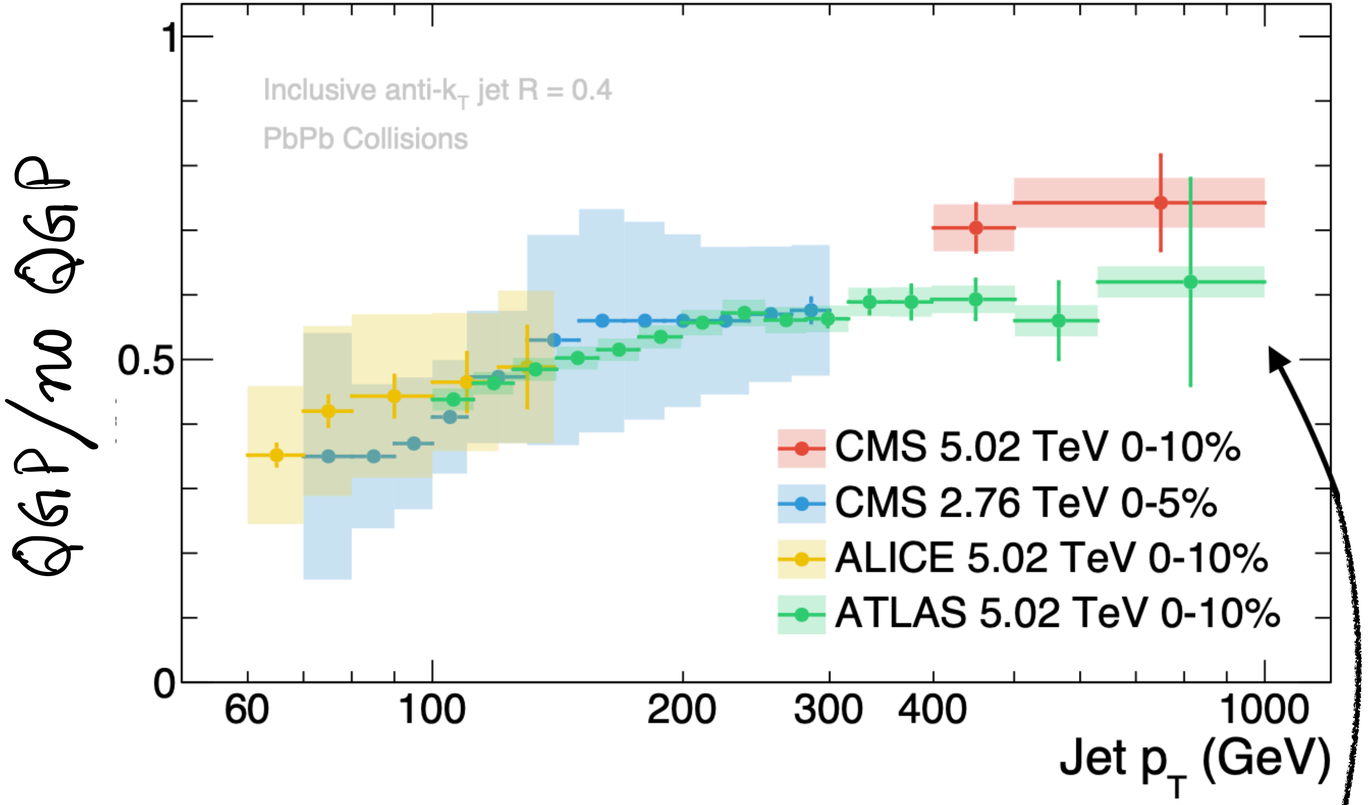
Medium

- Assuming the medium is a homogenous brick of length L



- Jet spectrum modified due to multiple soft interactions with the medium constituents.

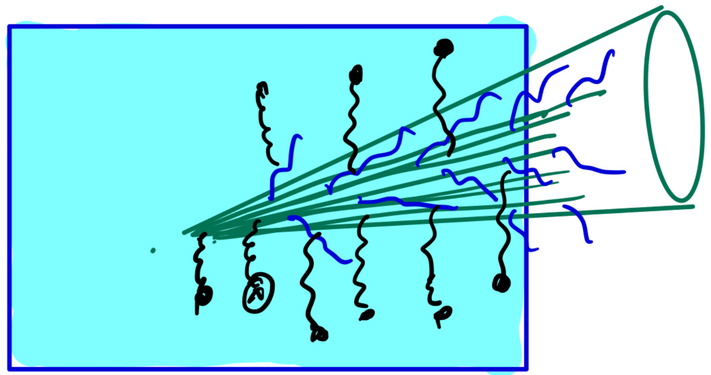
Jet suppression



Nuclear modification factor

$$\frac{\sigma \text{ with QGP (PbPb)}}{\sigma \text{ no QGP (pp)}} \sim 0.6 - 0.7$$

at 1TeV



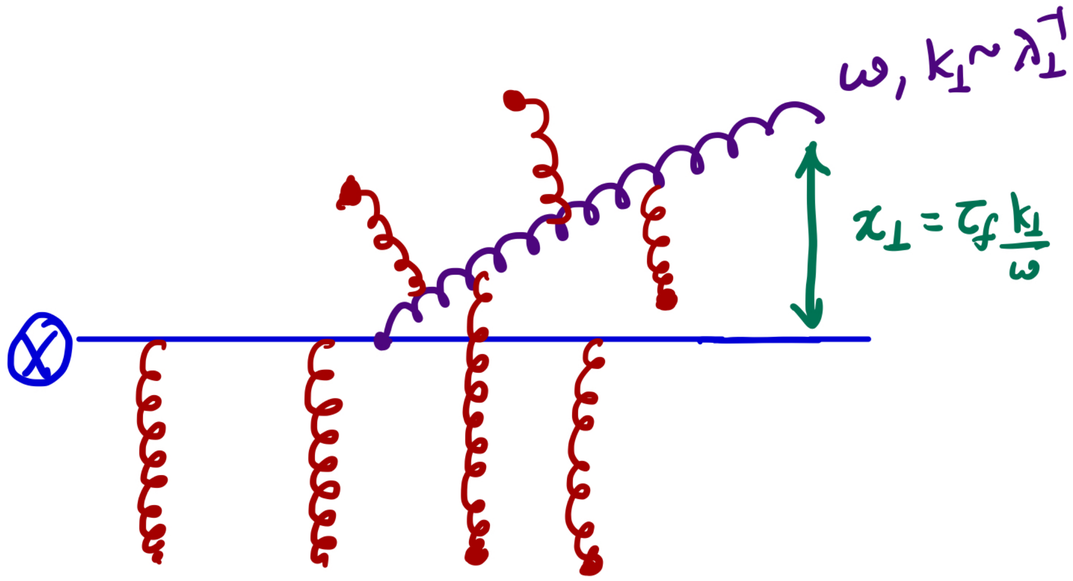
Jet production is suppressed

"Jets quench"

Understanding Jet propagation in matter

- The most important scale to characterize the radiation process is the *formation time* τ_f

$$\tau_f \frac{k_\perp}{\omega} \simeq \frac{1}{k_\perp} \implies \tau_f \simeq \frac{\omega}{k_\perp^2} \simeq \frac{1}{\omega\,\theta_f^2}$$

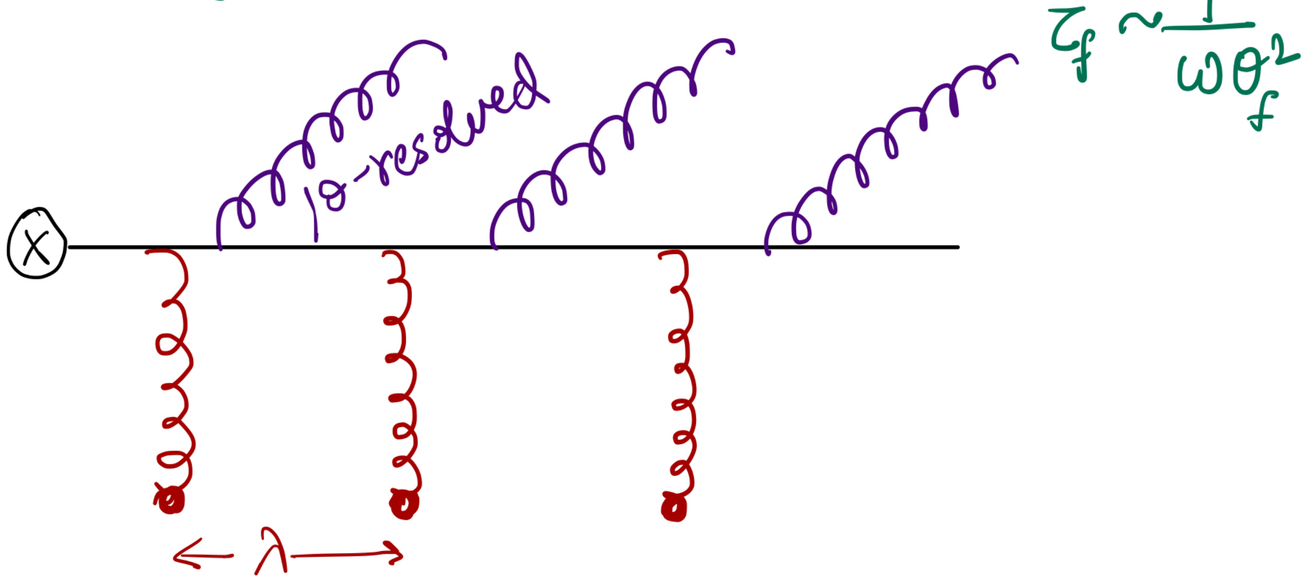


- Physically, τ_f defines the resolution scale of the medium. If $\tau_f = 0$, the medium has an infinite resolution while for $\tau_f \simeq O(\infty)$ the medium is completely opaque.

- θ_f sets a minimum angular scale $\implies$ unlike vacuum, no collinear singularity in the medium

Understanding Jet propagation in matter

- For the gluon to be formed inside the medium, we require $\tau_f \leq L$
- For the high energy parton traversing the medium, we may further associate a mean free path λ
- $\tau_{\mathbf{f}} \lesssim \lambda$ (small formation time)



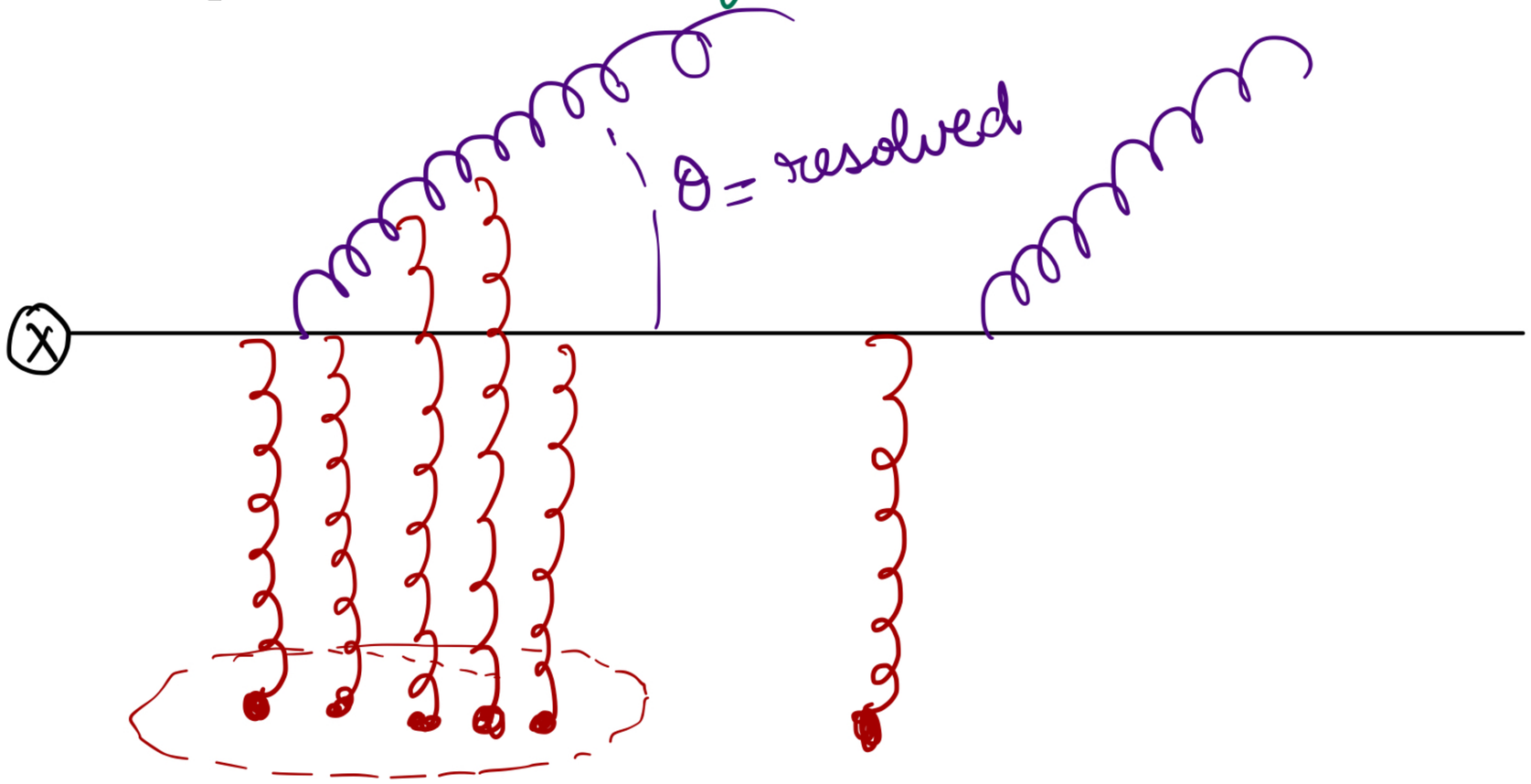
$$dI^{\text{incoh}} = \frac{\alpha_s(\mu)\, C_F}{\pi} \frac{d\omega}{\omega} \frac{d\tau_f}{\tau_f}$$

$$\approx \frac{\alpha_s(\mu)\, C_F}{\pi} \frac{d\omega}{\omega} \frac{L}{\lambda}$$

multiple “incoherent emissions” with the medium

Understanding Jet propagation in matter

- $\lambda < \tau_f < L$ (relatively large formation time)



multiple scattering centres act coherently until the radiation is resolved by the medium

The Landau-Pomeranchuk Migdal effect (LPM)

- During the formation time, multiple scattering centres act coherently. This yields a medium-induced spectrum of the radiation.

- The radiation formation time, together with the transverse momentum broadening defines the LPM time scale

$$\tau_f \sim \omega / k_\perp^2$$

$$k_\perp^2 \sim \hat{q}\, \tau_f$$

$$\Longrightarrow \qquad \tau_f = \sqrt{\frac{\omega}{\hat{q}}}$$

and the radiation spectrum can be written as

$$dI^{\text{coh}} = \frac{\alpha_s(\mu)\, C_F}{\pi} \frac{d\omega}{\omega} \frac{d\tau_f}{\tau_f}$$

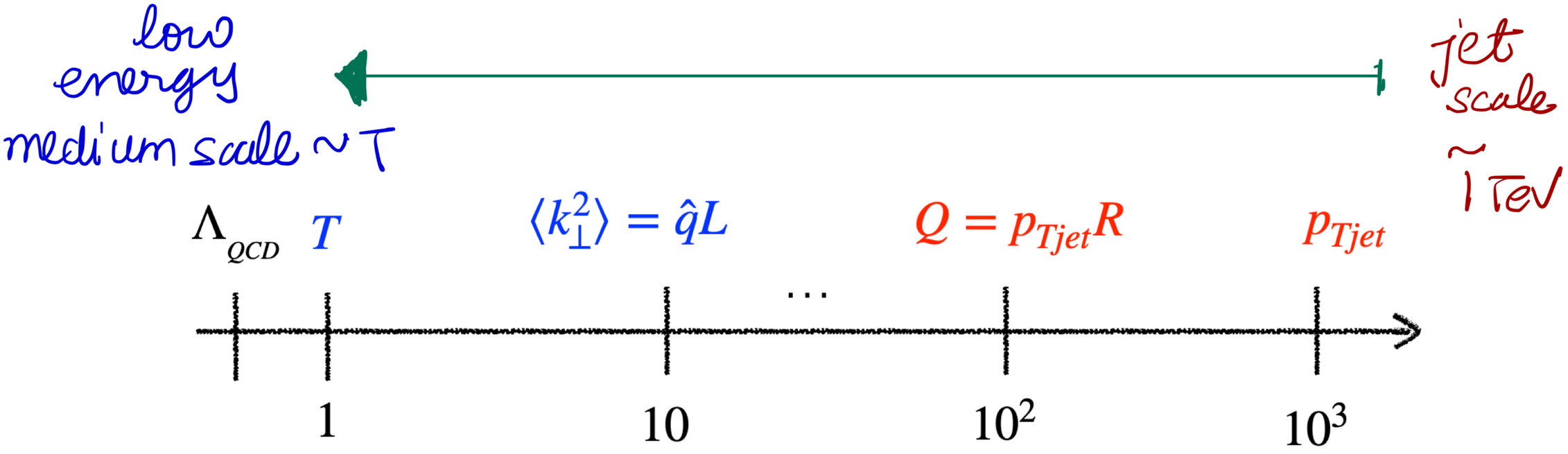
$$\approx \frac{\alpha_s(\mu)\, C_F}{\pi} \frac{d\omega}{\omega} \sqrt{\frac{\hat{q}}{\omega}} L$$

medium-induced spectrum is enhanced for soft radiations

Probing the QGP by looking inside jets

- Jets are multi-scale objects.

  How is energy transported from energetic parton to low momenta and dissipated in the QGP ?



- Study the substructure of a jet by looking at observables designed to probe separately the various regimes.

Jet Angularities

- Angularities are a class of jet substructure observables that characterize the angular and momentum distribution of partons inside a jet through a continuous free parameter a

- In pp collisions, the jet angularity is defined as

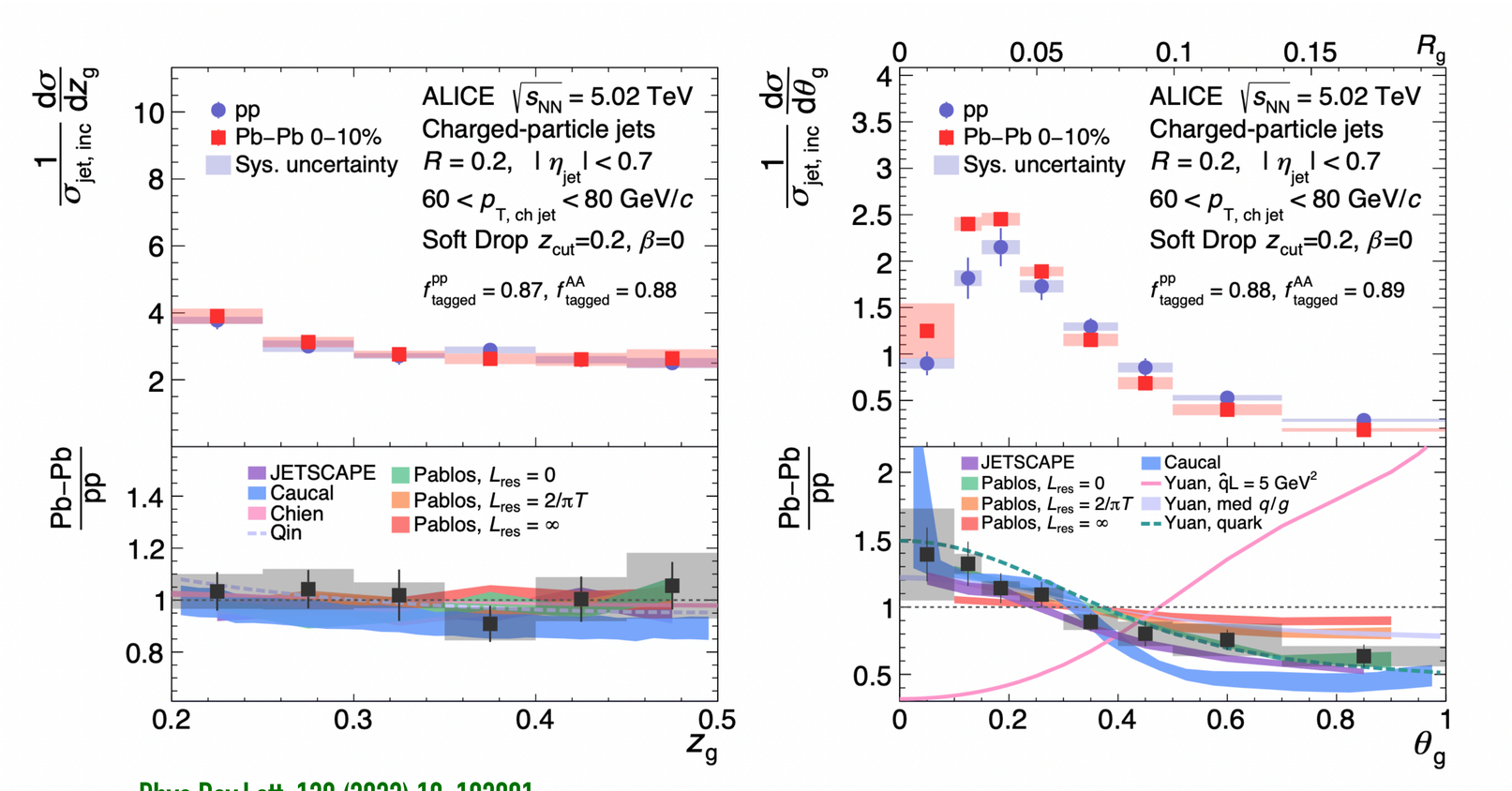
$$\tau_a = \frac{1}{p_T} \sum_{i \epsilon \text{jet}} \vec{p}_T^{\,i} \left(\frac{\Delta R_{iJ}}{R} \right)^{2-a} \qquad \text{where} \qquad \Delta R_{iJ} = \sqrt{(\Delta\eta_{iJ})^2 + (\Delta\phi_{iJ})^2},$$

- Varying the exponent 'a' changes the sensitivity of the observable to collinear and soft radiation in the jet.

- For $a < 1$, the observable weighs collinear radiation more strongly while for a close to 1, the effect of soft radiation to the measured value of the observable cannot be ignored.

- We focus on ungroomed jet angularities with a sufficiently away from 1 in this talk.

What have we learned so far ?



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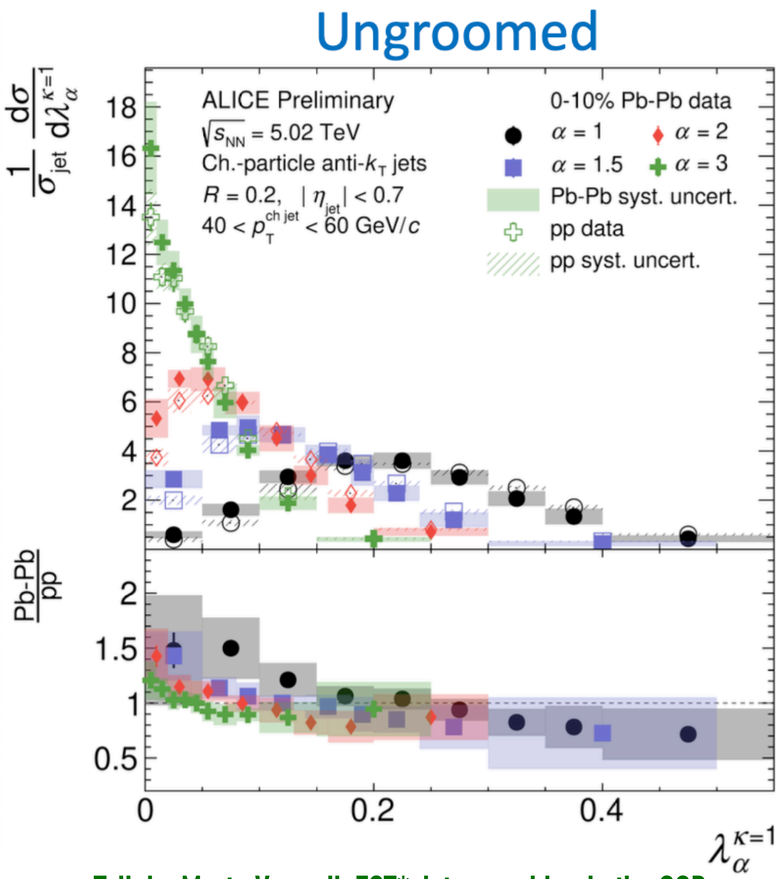


Talk by Marta Verweij, ECT* Jet quenching in the QGP

- Splitting fraction with larger z_{cut} is not modified much.
- Observables sensitive to angular distributions show a narrowing of the jet core in the medium.

An EFT for the medium (SCET with Glaubers)

- SCET has no quenching effects so we need extra degrees of freedom to allow for jet-medium interactions; Achieved via off-shell modes thought to be generated from color gauge fields in the medium

- Consider the medium sources as static which scale as $\sim (1,1,1)$. Soft scatterings of the jet parton with medium constituents $\Rightarrow$ t-channel dominance; Glaubers

- Treat Glaubers as background fields generated from colour charges in the QGP $p_G \sim Q(\tilde{\lambda}^2, \tilde{\lambda}^2, \tilde{\lambda})\,;\, \tilde{\lambda} \sim \dfrac{T}{Q}$

- Glauber gluons interact with both collinear $p_C \sim Q(\lambda^2,1,\lambda)$ and soft $p_S \sim Q(\lambda^{2-a}, \lambda^{2-a}, \lambda^{2-a})$ modes of the theory ; $\lambda \sim \tau^{\frac{1}{2-a}}$

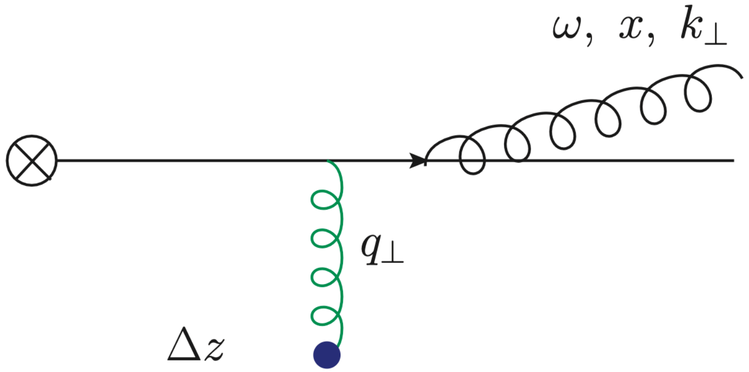
- The Lagrangian in terms of collinear and Glauber field is

[Ovanesyan and Vitev]

$$\mathscr{L}_G(\xi_n, A_n, A_G) = g \sum_{p,p'} e^{-i(\vec{p}-\vec{p}')\cdot\vec{x}} \left(\bar{\xi}_{n,p'} t^a \frac{\gamma\cdot\bar{n}}{2} \xi_{n,p} - i f^{abc} A^{\lambda,c}_{n,p'} A^{\nu,b}_{n,p} g^{\perp}_{\nu\lambda} \bar{n}\cdot p \right) n\cdot A^a_G$$

Medium modified Splittings via SCETG

- The interaction between jet and medium is approximated by a screened potential



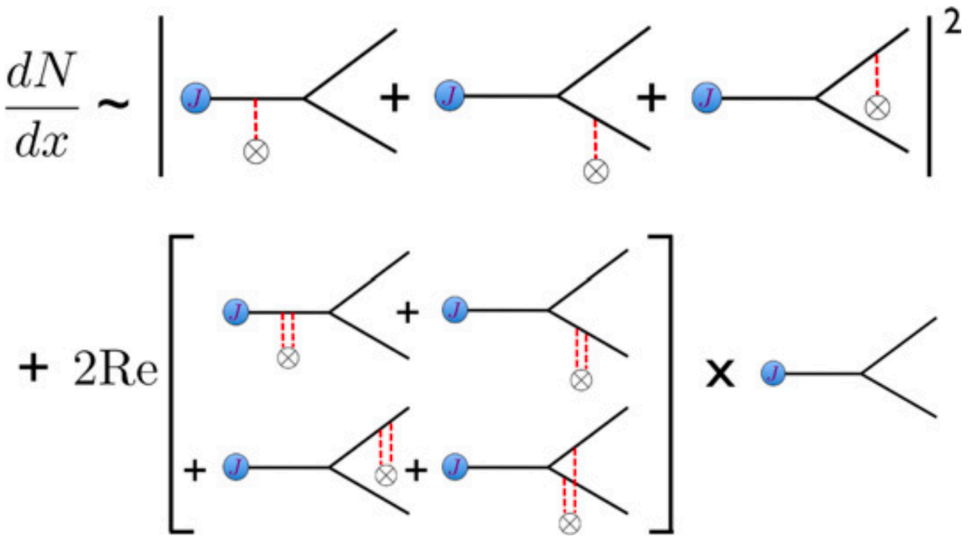
$$\frac{1}{\sigma}\frac{d\sigma}{d^2q_\perp} = \frac{m_D^2}{\pi(q_\perp^2 + m_D^2)^2}$$

- To see the LPM effect, we require minimum two scattering sources. To leading order, in the small x-limit

$$x\frac{dN_{q\to q\,g}}{dx d^2k_\perp} = \tilde{\alpha}\int_0^{\bar{L}} \frac{d\Delta z}{\lambda} d^2q_\perp \frac{1}{\sigma}\frac{d\sigma}{d^2q_\perp}\frac{2k_\perp\cdot q_\perp}{k_\perp^2(q_\perp - k_\perp)^2}\left[1 - \cos\left(\frac{(q_\perp - k_\perp)^2\Delta z}{x\,\omega}\right)\right]$$

with

$$\tau_f = \frac{x\,\omega}{(q_\perp - k_\perp)^2}$$



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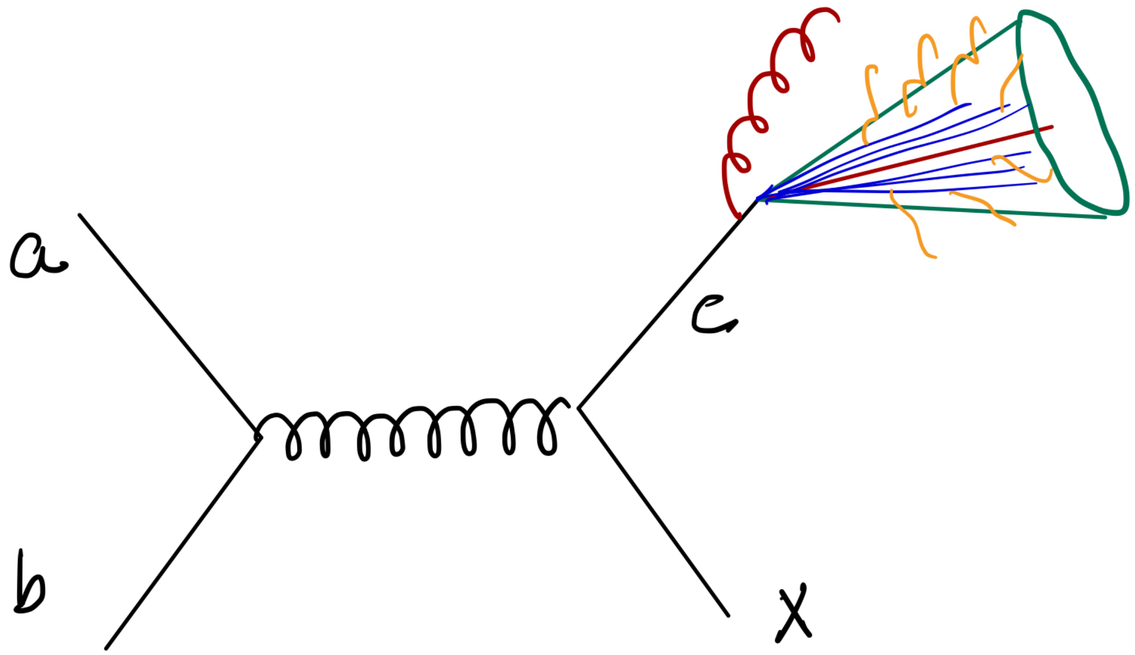
Computation Tool (Factorization)

- For $a < 1$ angularities and $\tau_a^{\frac{1}{2-a}} \ll R$, the factorized differential distribution is



Step 1: Factorize jet pro-
-duction

$$\bar{f}_a \otimes \bar{f}_b \otimes H^c_{ab} \otimes G_c(z, \tau_a)$$

Step 2: $\tau_a^{\frac{1}{2-a}} \ll R$

$$G_c(z, \tau_a) = \mathcal{H}_{c\to i}(z) \times J(\tau_a^c) \otimes S(\tau_a^s)$$

$$\frac{d\sigma^{AA\to(jet\,\tau_a)X}}{d\tau_a\, dp_T\, d\eta} = \sum_{abc}\sum_i \tilde{f}_a(x_a,\mu) \otimes \tilde{f}_b(x_b,\mu) \otimes H^c_{ab}(x_a, x_b, \eta, p_T/z, \mu) \otimes \mathscr{H}_{c\to i}(z, p_T R, \mu) \times J(\tau_a^c, p_T, R, \mu) \otimes S(\tau_a^s, p_T, R, \mu)$$

Medium Modified Jet function

- Medium modified splitting functions give jet function

$$J_i^{\text{med}}(\tau_a, p_T, R, \mu) = \frac{\alpha_s(\mu)}{2\pi^2} \frac{e^{\epsilon\gamma_E}\mu^{2\epsilon}}{\Gamma(1-\epsilon)} \int_0^{2\pi} d\phi \sum_j \int dx \frac{dk_\perp}{k_\perp^{2\epsilon-1}} P_{ij}(x, k_\perp)\delta(\tau_a - \hat{\tau}_a)$$

[Ritzmann and Waalewijn]

$$J_i^{\text{med}}(\tau_a, p_T, R, \mu)_{i^* \to j,k} = \frac{1}{2-a} \frac{\alpha_s}{\pi} \frac{e^{\epsilon\gamma_E}\mu^{2\epsilon}}{\Gamma(1-\epsilon)} \frac{p_T^{2-2\epsilon}}{\tau_a^{\frac{2\epsilon-a}{2-a}}} \sum_j \int_0^1 dx \left(x^{\frac{1-a}{2-a}}\right)^{2-2\epsilon} P_{ij}\left(x, (p_T^{2-a}\tau_a x^{1-a})^{\frac{1}{2-a}}\right)$$

- No extra divergences induced by the medium. Soft IR divergence of the integral regulated by the LPM effect.

- Total jet function in AA collision $J_i^{\text{tot}}(\ldots) = J_i^{\text{vac}}(\ldots) + J_i^{\text{med}}(\ldots)$

- RGE for J^{tot} remains the same as vacuum

Energy loss in the medium

- Medium modified splittings also modify the energy lost by a jet parton outside the jet cone.

- A jet measured in a given p_T range can now have contributions from various higher p_T initiated jets that have lost a sufficient amount of energy.

- Estimate the energy loss by computing the average fraction of energy lost out of the jet cone

$$\epsilon_q = \left[\int_0^{1/2} dx\, x + \int_{1/2}^{1} dx\, (1-x) \right] \int_{x(1-x)\omega\, tan\frac{R}{2}}^{x(1-x)\omega\, tan\frac{R_0}{2}} dk_\perp \left[P^{\text{med}}_{q\to qg}(x, k_\perp) + P^{\text{med}}_{q\to gq}(x, k_\perp) \right]$$

- Average p_T of the jet parton

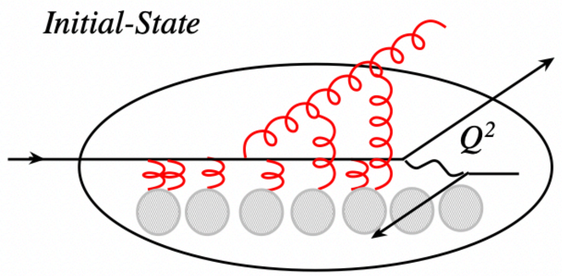
$$p^{\text{med}}_{T,q} = p^{\text{vac}}_{T,q} * (1 - \epsilon_q) \approx p^{\text{vac}}_{T,q} \exp(-\epsilon_q)$$

Initial state energy loss

- For AA collisions, we use the CTEQ nuclear PDFs for the initial state.

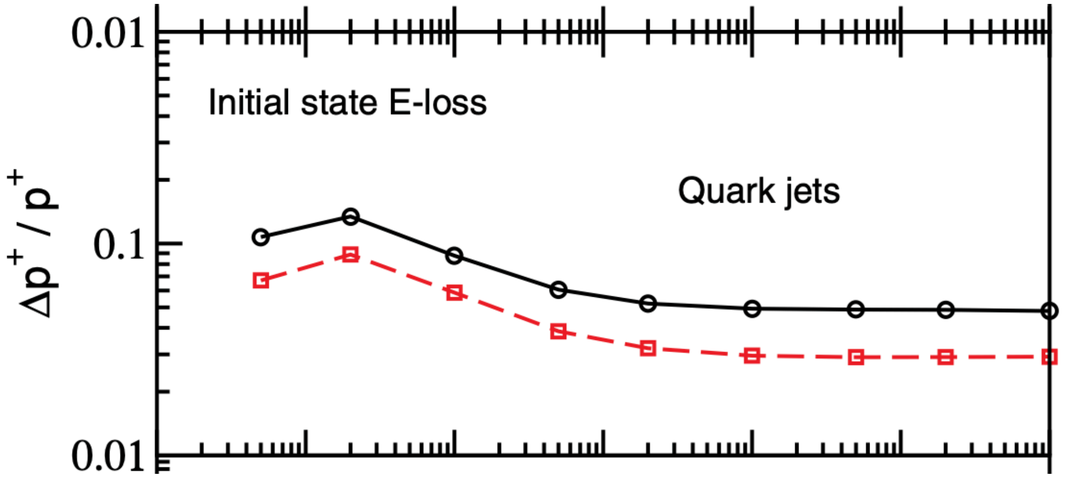
- This only incorporates the intrinsic modifications of the parton distribution functions.

- The jet parton, may however, undergo an additional energy loss due to the complex nuclear state even before the hard collision.



- We incorporate this effect in a rather simple fashion

$$f^A(x,\mu) \to f^A\left(\frac{x}{1-\epsilon_{in}},\mu\right) \approx f^A\left(x(1+\epsilon_{in}),\mu\right)$$



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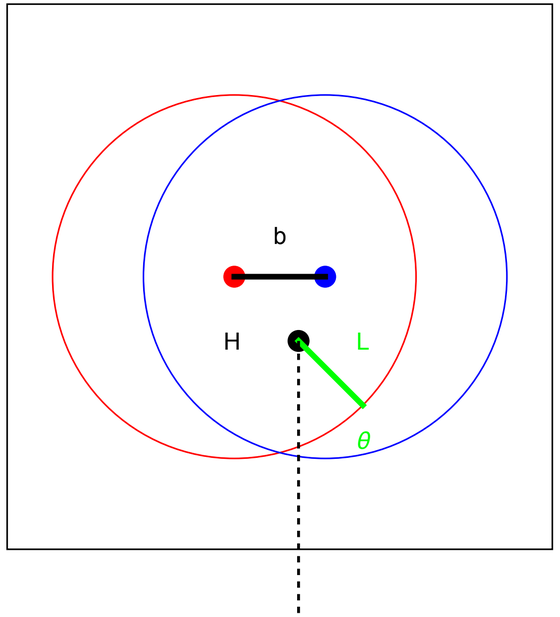
Computing medium parameters

- So far, we considered the medium to be a homogenous brick of a fixed length.



- The probability distribution of the nuclear matter within the overlap region can be estimated by the well known initial state models.

- Additionally, the medium formed expands and eventually cools down. To incorporate this expansion, we consider a longitudinal Bjroken expansion of the form

$$T(t) = T(t_0)\left(\frac{t_0}{t}\right)^{1/3}$$

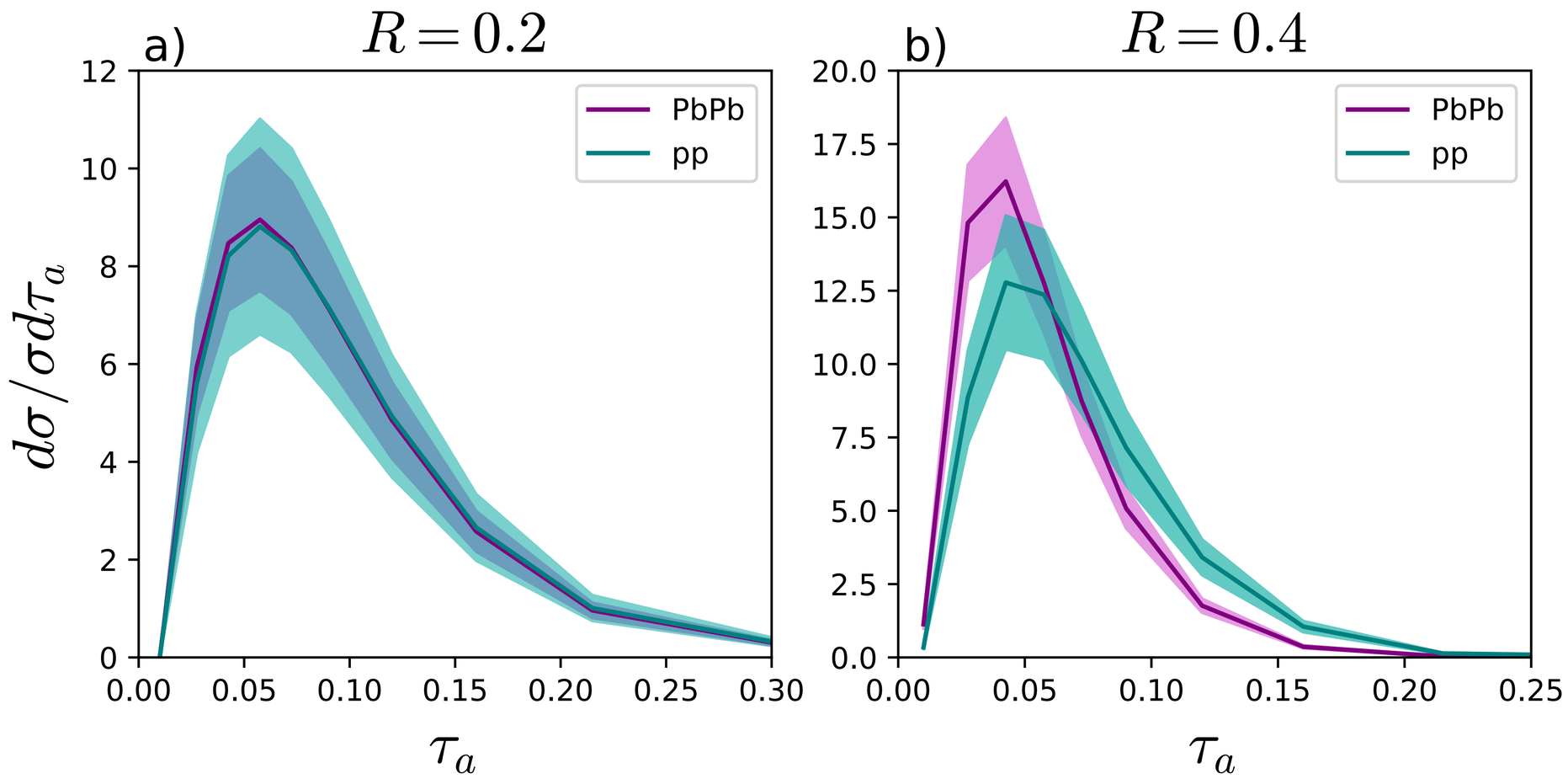
- Furthermore, the extent of the medium that the jet traverses fluctuates on a jet-by-jet basis depending on the location of hard scattering within the overlap region.

- We compute an average path length for a jet in a given centrality class by averaging over all locations and angles.

Medium parameters

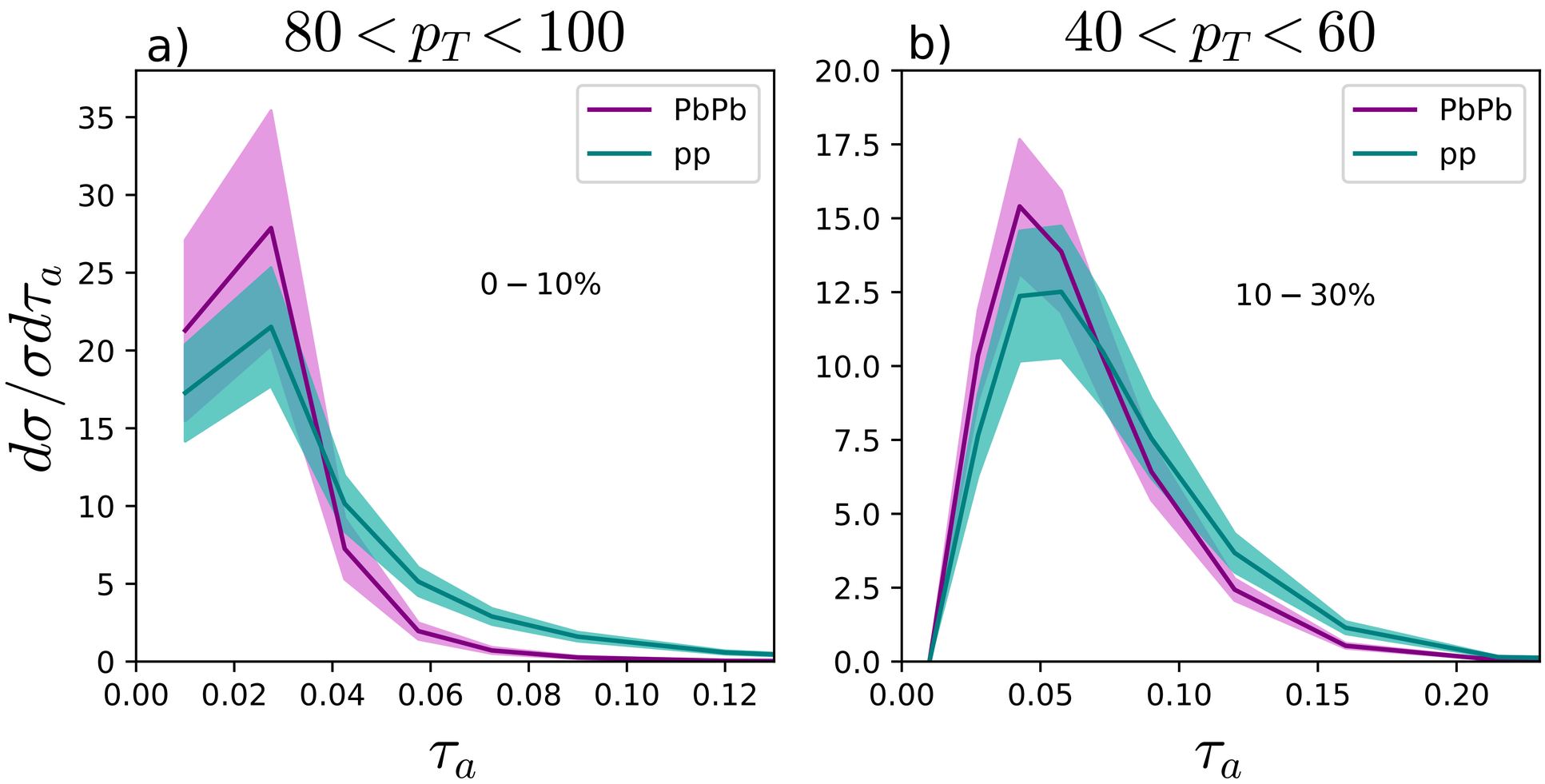
Parameter	$0-10\,\%$	$10-30\,\%$
$b\ (fm)$	3.34	7.01
$L\ (fm)$	4.96 ± 1.22	3.56 ± 0.99
$T_0\ (MeV)$	456	437
$T\ (MeV)$	248 ± 128	308 ± 84

Angularity distributions in medium for different cone size



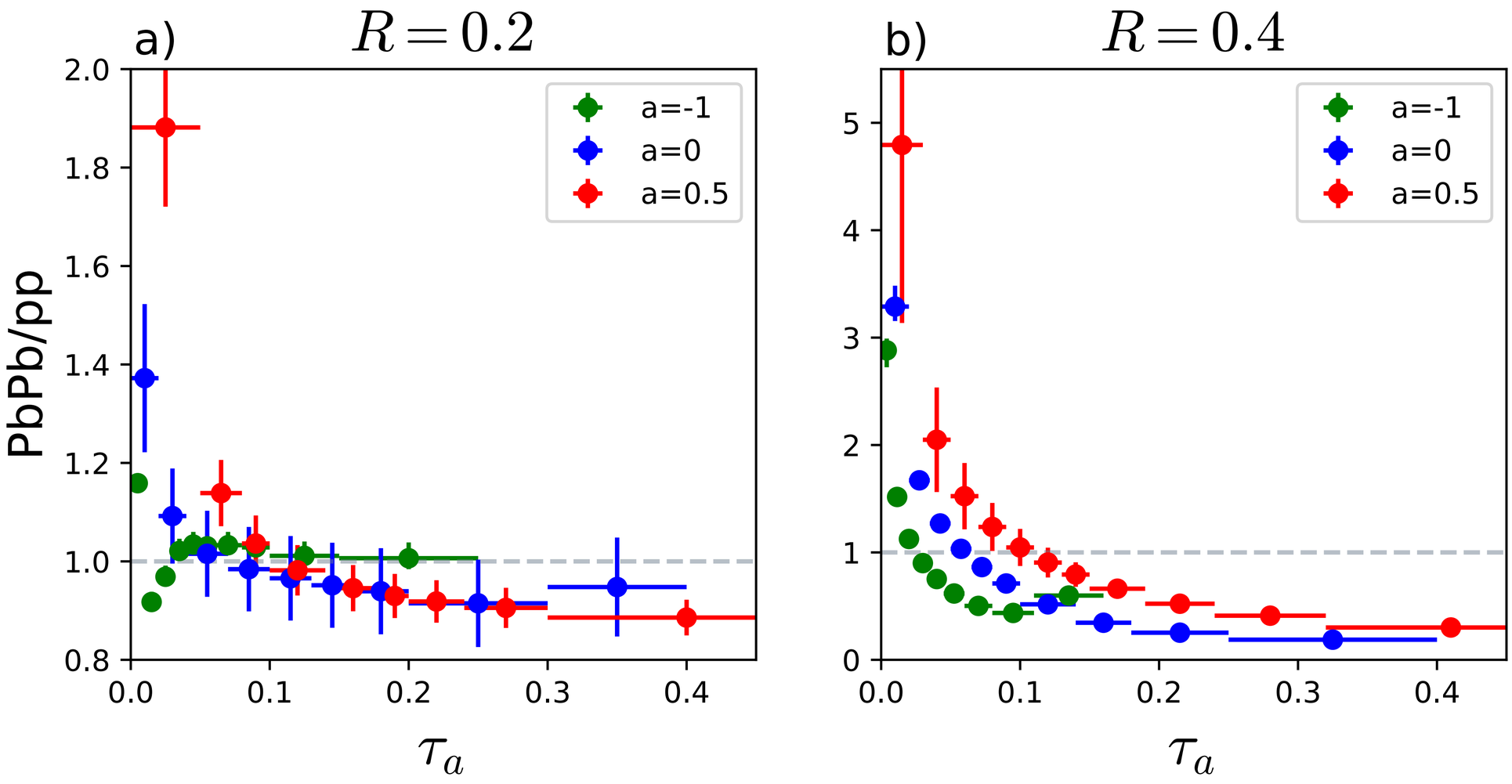
Normalised differential distributions in PbPb (central) and pp for $a = 0$, jet parameters $40 < p_T < 60$ and (a) $R = 0.2$, (b) $R = 0.4$. The theoretical error bands correspond to variation in μ from p_T to $2p_T$.

Medium sensitivity to jet p_T and less central collision



Normalised angularity distributions for $a = 0$ with (a) $80 < p_T < 100$, $0 - 10\,\%$ centrality and (b) $40 < p_T < 60$, $10 - 30\,\%$ centrality, for a jet with $R = 0.4$

Ratio of angularity distributions in PbPb vs pp



Summary and Outlook

- Jet angularities allow to study a class of substructure observables with sensitivity to collinear emissions controlled by a continuous parameter, a.

- Jet-medium interactions modelled through off-shell Glauber gluons generated by color gauge fields of the medium.

- For $a < 1$, all medium modifications consistently incorporated in the medium modified jet function through the medium splittings.

- Narrowing of the jet distributions in the medium is observed as a cumulative effect of energy loss and medium modified splittings.

- For a cleaner understanding of medium effects on the jet core, one needs to look at groomed angularities $\rightarrow$ less sensitive to hadronization and jet selection effects