Search for single hard scattering signatures using substructure observables

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New jet quenching tools workshop, Trento, ECT*
Feb 12, 2024

Work in progress with E. Iancu and G. Soyez.

Outline

- Quenching of high p_t jets: correlation between energy loss and substructure.
  See talk by Guilherme and Leticia this morning.

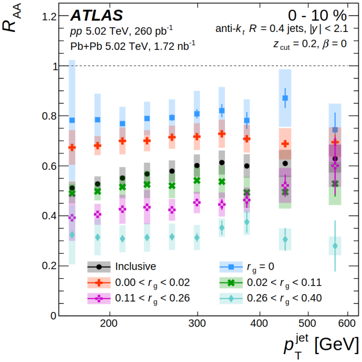
- Brief outline of the JetMed picture.

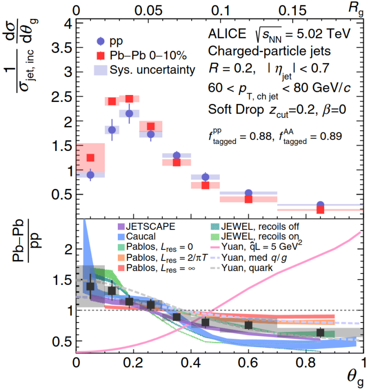
- Implementation of single hard scattering effects.

- Seeing single hard scattering effects in substructure observables?

Correlation between energy loss and jet substructure

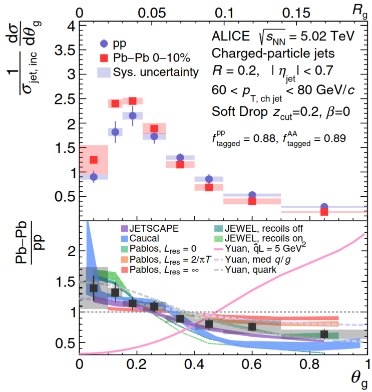
- Jets lose energy in the QGP.
- The energy loss is correlated with jet substructure. ATLAS, 2211.1147, ALICE 2107.12984
- Multiple physical mechanisms lead to this effect.





In-medium vaccum-like emissions and energy loss

- Essential physical mechanism: more VLEs produced inside the medium $\Rightarrow$ more sources for energy loss.
- Shared by many jet quenching models.
- Lead to a "narrowing" effect, seen in substructure observables.



Main question

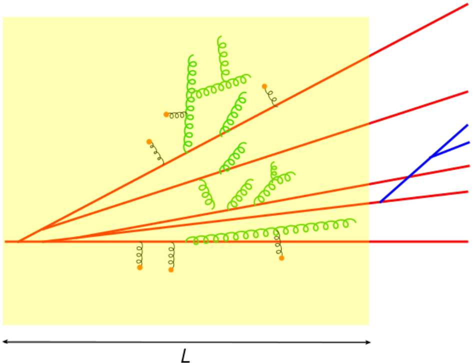
Can we observe effects at large θ due to hard scattering despite the narrowing of substructure observables?

The JetMed picture of jet evolution in a dense medium

- Modification of the phase space for VLEs.
- Factorization in time of the medium-induced emissions.
  (1) one **angular ordered** *vacuum-like shower* inside the medium ,
  (2) *medium-induced emissions* triggered by previous sources,
  (3) finally, a *vacuum-like shower* outside the medium.
- Angular ordering violation due to loss of color coherence.

Caucal, Iancu, Mueller, Soyez, 1801.09703, 1907.04866, 2005.05852, 2012.01457

- In-medium VLEs occur fast $t_f \sim \omega / k_\perp^2$ with $k_\perp$ coming from the hard process.
- MIEs take over when $k_\perp^2 \sim \hat{q} t_f \leftrightarrow k_\perp^2 \sim \sqrt{\hat{q}\omega}$ or $t_f \sim \sqrt{\omega / \hat{q}} \equiv t_{f,\mathrm{med}}$.
- There are also VLEs with $t_f \gg L$ which do not "see" the medium.



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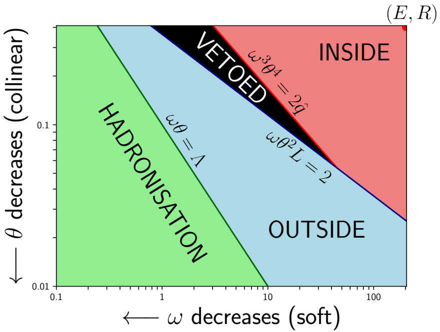

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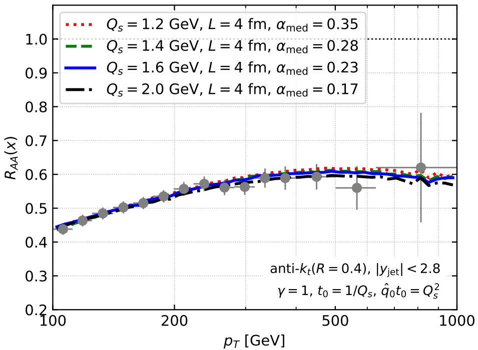
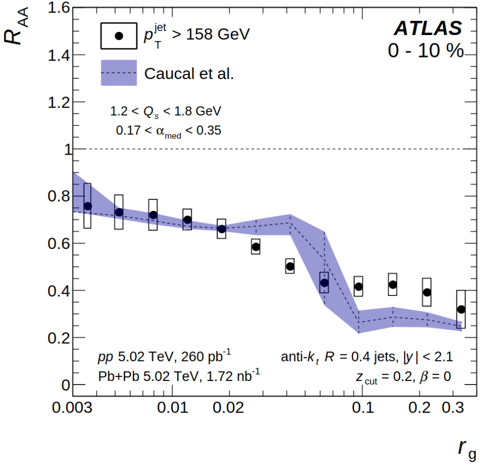
A toy model with many caveats...

- Leading log approximation for VLEs.
- VLEs description valid in the collinear limit, soft wide-angle emissions are not properly included.
- No collision geometry (on going work), but Bjorken longitudinal expansion included in PC, Iancu, Soyez, 2012.01457
- No medium-response.
- No single hard scattering effects... until very recently!
  Implicit in the previous picture: $\lambda_{\mathrm{mfp}} \ll t_f \ll L \Leftrightarrow \omega_{\mathrm{BH}} \ll \omega \ll \omega_c$.

… but qualitatively successfull for phenomenology

Inclusive R_{AA} and R_{AA} correlated with SoftDrop θ_g.





Large θ_g suppression sensitive to the phase space **resolved** by the medium.
Sharp transition will be smoothed by path length fluctuations.

Including single-hard scattering in the picture

- Factorization of medium-induced effects enables us to focus on the second stage of the cascade only.
  - Caveats: factorization in time well justified for BDMPS-Z emissions with $L \gg t_{f,\mathrm{med}} \sim \sqrt{\omega/\hat{q}} \gg t_{f,\mathrm{vac}}$ (by construction), it is less justified when $\omega \gg \omega_c$.
  - We adopt a pragmatic approach : such emissions are rare events so it should be sufficient to control them at $\mathcal{O}(\alpha_s)$ in the parton shower.
- In the following: focus on fragmentation of a high p_t partons via medium-induced emissions and collisions alone (no VLEs)
- VLEs will be included at the end with proper modification of the phase space.

JetMed(v1): no single-hard scattering effects

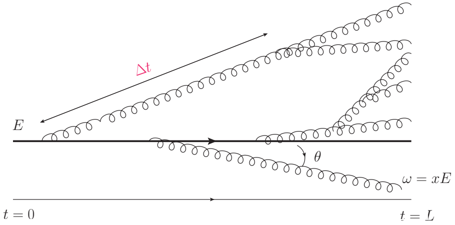
- A MC solution of the **turbulent cascade** equation $(D_g(x,t) = xdN/dx)$

$$\frac{\partial D_g(x,t)}{\partial t} = \bar{\alpha}_s \sqrt{\frac{\hat{q}}{E}} \int_0^1 dz\, \mathcal{K}_{gg}(z) \left[\sqrt{\frac{z}{x}} D_g\left(\frac{x}{z}, t\right) - \frac{z}{\sqrt{x}} D_g\left(x, t\right) \right]$$

Blaizot, Dominguez, Iancu, Mehtar-Tani, 1311.5823

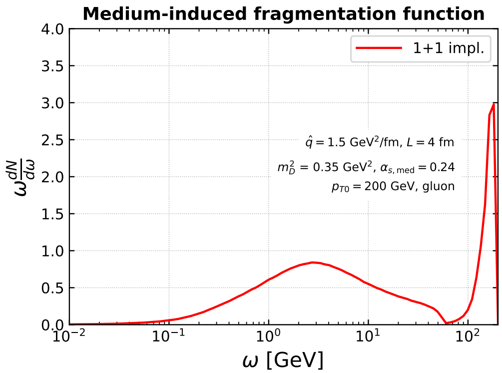
- Accounts for multiple LPM emissions, rate $\propto \bar{\alpha}_s \sqrt{\frac{\hat{q}}{xE}}$
- Angular structure determined afterwards by gaussian broadening between emissions.

$$\mathcal{P}(k_\perp, \Delta t) = \frac{1}{\pi \hat{q} \Delta t} \exp\left(-\frac{k_\perp^2}{\hat{q}\Delta t} \right)$$



Fragmentation via medium-induced emissions

- Count the number of parton with a given energy ω in a cone of angle $R = 0.4$.



- The peak is the remnant of the leading particle.
- In the multiple soft scattering regime, the maximal energy of a medium-induced gluon is $\omega_c \sim \hat{q}L^2/2$.
- Softer gluon are emitted, with typical energy $\omega_{\rm br} = \alpha_s^2\omega_c$, but most of them go outside the jet cone.
- Energy of the second peak $\sim (\hat{q}/(\alpha_s^2 R^4))^{1/3}$.

The cascade equation in 3+1 dimension

- We now want to solve by MC the equation

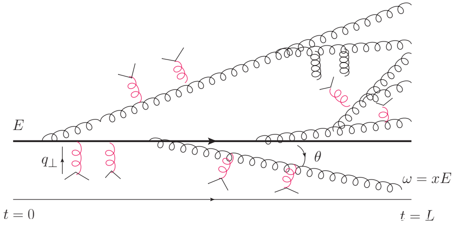
$$\frac{\partial D_g(x,\boldsymbol{k}_\perp,t)}{\partial t} = \bar{\alpha}_s\sqrt{\frac{\hat{q}}{E}}\int_0^1 dz\,\mathcal{K}_{gg}(z)\left[\sqrt{\frac{z}{x}}\frac{1}{z^2}D_g\left(\frac{x}{z},\frac{\boldsymbol{k}_\perp}{z},t\right)-\frac{z}{\sqrt{x}}D_g\left(x,,\boldsymbol{k}_\perp,t\right)\right]+\int_{\boldsymbol{q}_\perp}\mathcal{C}(\boldsymbol{q}_\perp,t)D(x,\boldsymbol{k}_\perp-\boldsymbol{q}_\perp,t)$$

- $\mathcal{C}$ is the HTL collision kernel with $\hat{q}_0 = \alpha_s C_A m_D^2 T$

$$\mathcal{C}(\boldsymbol{q}_\perp,t) = \frac{\hat{q}_0}{\boldsymbol{q}_\perp^2(\boldsymbol{q}_\perp^2+m_D^2)} - \delta(\boldsymbol{q}_\perp)\int d^2\boldsymbol{l}_\perp\frac{\hat{q}_0}{\boldsymbol{l}_\perp^2(\boldsymbol{l}_\perp^2+m_D^2)}$$

Aurenche, Gelis, Zaraket, hep-ph/0204146.

- Angular structure of the cascade is generated dynamically by the collisions.



How to set $\hat{q}$ in the branching rate?

- In the previous equation, there are two $\hat{q}$: one in the collision rate, another in the branching rate.
- $\hat{q}_0 = \alpha_s C_A m_D^2 T$ reflects the microscopic properties of the QGP, while $\hat{q}$ is an effective parameter which comes out from the HO approximation:

$$\hat{q}(Q) = \int^{Q} d^2\boldsymbol{q}_\perp \boldsymbol{q}_\perp^2 \mathcal{C}(\boldsymbol{q}_\perp, t) \sim \hat{q}_0 \ln\left(\frac{Q^2}{m_D^2}\right)$$

- at LO and to leading logarithmic accuracy, $Q^2 \sim \sqrt{\hat{q}\omega}$ in the emission rate

$$\hat{q}(\omega) = \hat{q}_0 \ln\left(\sqrt{\hat{q}\omega}/m_D^2\right)$$

See Liou, Mueller, Wu, 1304.7677, Blaizot, Mehtar-Tani, 1403.2323, Iancu 1403.1996, PC, Mehtar-Tani 2109.12041, Ghiglieri, Weitz 2207.08842 beyond LO See also talk by Jacopo on Wednesday

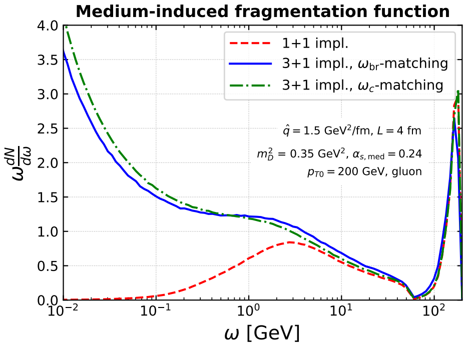
- $\hat{q}$ depends logarithmically on the energy in the branching rate.
- To compare 1+1 vs 3+1 implementation of the cascade, we use a matching at $\omega_{\rm br}$

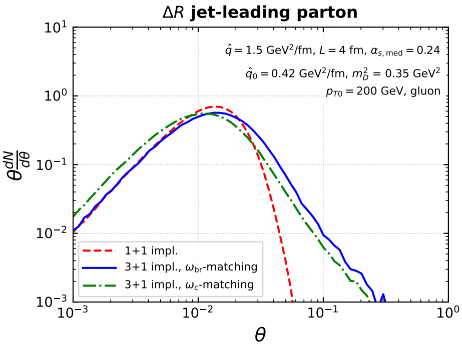
$$\hat{q}_{1+1} = \hat{q}(\omega_{\rm br})$$

A mathematical issue

- The equation in 3+1D is pathological in the infrared.
- When $\Delta t \leq m_D^2/\hat{q} \sim \lambda_{\rm mfp}$, no momentum transfer via collisions $\Rightarrow$ gluons remain collinear to the emitter and stay inside the jet.
- In the LPM regime, the time between two branchings is $\Delta t \sim 1/\alpha_s\sqrt{\omega/\hat{q}}$.
  $\Rightarrow$ gluons with $\omega \leq \alpha_s^2 m_D^4/\hat{q}$ artificially remain in the jet.

Fragmentation function from "naive" implementation





Compare red and the two other curves

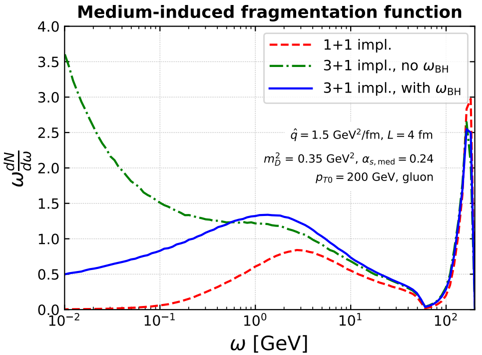
- Artificial divergence of the fragmentation function in the infra-red.
- These gluons should go out of the jet and eventually thermalize. See e.g. Schlichting, Soudi 2008.04928
- Broadening distribution displays the $1/k_\perp^4$ tail at large $k_\perp$ as expected.

Solution: regulate the LPM behaviour

- Very soft gluons are copiously emitted by the turbulent cascade.
- Need to introduce the BH regime to cut the LPM tail for $\omega \leq \omega_{\rm BH} = \hat{q}_0 \lambda_{\rm mfp}^2$.
- Parametrically, the emission rate becomes

$$\omega \frac{d\mathcal{P}_{\rm br}}{d\omega dt} = \bar{\alpha}_s \sqrt{\frac{\hat{q}(\omega)}{\omega + \omega_{\rm BH}}} \to \frac{\bar{\alpha}_s}{\lambda_{\rm mfp}} \quad \text{for } \omega \ll \omega_{\rm BH}$$

Fragmentation function with new 3+1D implementation

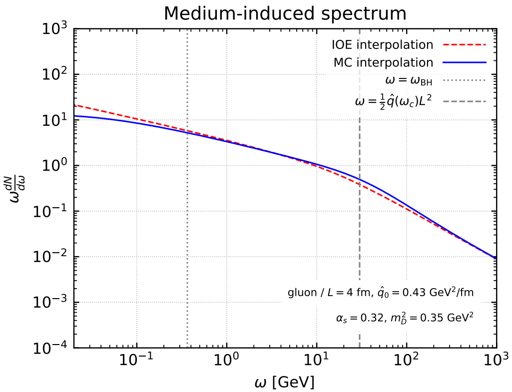


Compare green and blue curves

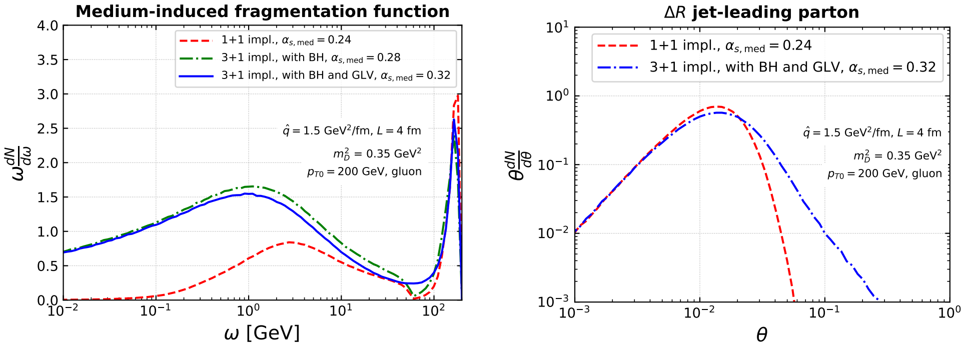
- The infrared divergence is now cured.
- Turbulent spectrum disturbed by the BH regulator.

Adding GLV emissions

- Single hard scattering also affects the radiative part of the cascade.
  Gyulassy, Levai, Vitev, Nucl.Phys.B594
- Trigger emissions with energy larger than ω_c
- We use an interpolating formula which captures the $\omega \gg \omega_c$ limit.
  See also Mehtar-Tani 1903.00506 and Barata, Mehtar-Tani 2004.02323
- Systematically improvable using recent techniques to evaluate the single-gluon emission spectrum.
  Andres, Apolinario, Dominguez, 2002.01517, Andres, Dominguez, Gonzalez Martinez, 2011.06522, Isaksen, Tywoniuk, 2303.12119



Fragmentation function with GLV emissions



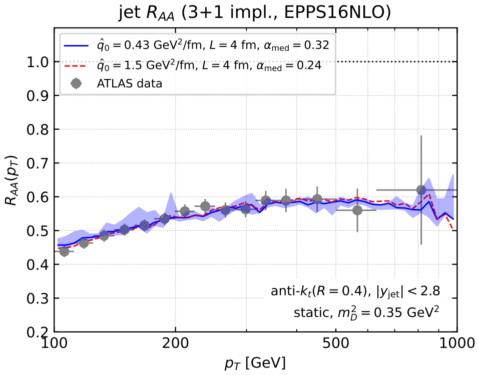
Compare green and blue curves

- Smooth behaviour of the fragmentation function via MIEs around ω_c.
- We have now both fragmentation and broadening under control with single-hard scattering effects.

Benchmarking the new code with inclusive R_{AA}

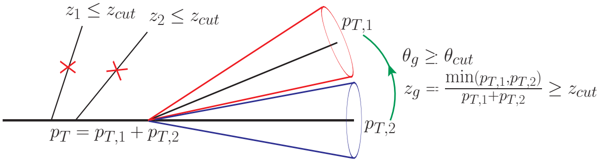
- We now include the vacuum-like cascade.
- In-medium phase space modified to include the Coulomb log in $\hat{q}$: $\hat{q}_0 \to \hat{q}(\omega)$.
- Still provide a decent description of the data.

for the same number of free parameters $(\hat{q}_0, L, \alpha_{s,\mathrm{med}}) \to (m_D^2, L, \alpha_{s,\mathrm{med}})$



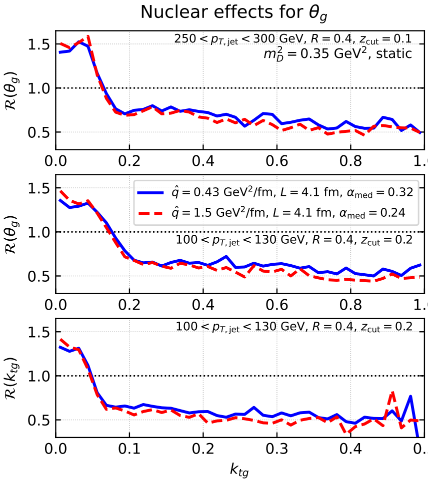
SoftDrop observables: dominance of energy loss physics

- Grooming angle and k_t after Soft Drop.
  Larkoski, Marzani, Soyez, Thaler, 2014



- Large θ_g / k_{tg} jets are more suppressed due to bias effect.

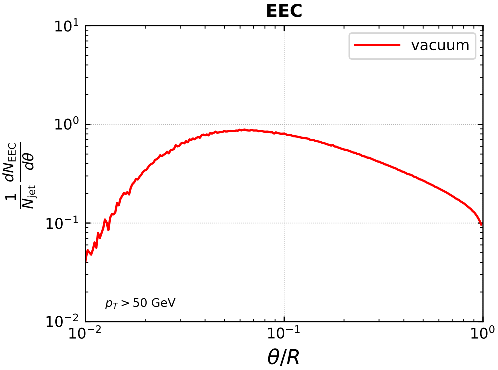
- Almost no effect of single hard scattering!
  $\Rightarrow$ Energy loss dominated observables.



Energy-energy correlator within jets

- For each pair (i, j) of particles in a jet, add the angle $\theta_{ij} = \sqrt{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}$ of the pair to the histogram with weight $p_{t,i} p_{t,j} / p_{t,\mathrm{jet}}^2$.
- Large θ slope $1/\theta^{1-\bar{\alpha}_s\gamma(3)}$ controlled by pQCD.
  Basham, Brown, Ellis, Love, 1978-1979
- Small-θ region sensitive to NP hadronization physics.
  Measured in *pp* collisions, see ALICE and CMS talks at QM2023
- Recently revived in various colliding system due to their sensitive to emergent angular scales.
  Andres, Dominguez, Kunnawalkam Elayavalli, Holguin, Marquet, Moult, 2209.11236,
  Liu, Liu, Pan, Yuan, Zhu, 2301.01788
  Yang, He, Moult, Wang, 2310.01500

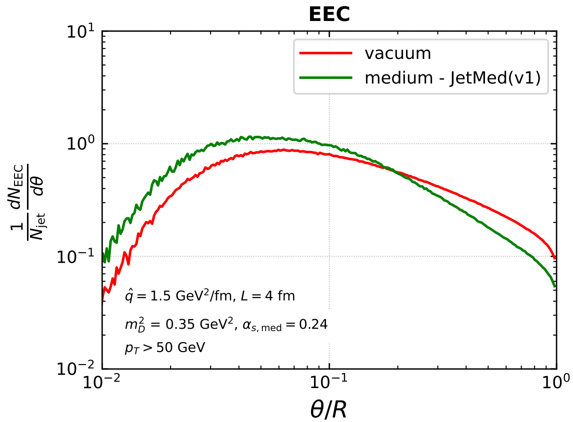
  Many talks on EEC tomorrow!



Sensitivity to energy loss

- Suppression at large angles due to energy loss.
- Qualitatively similar to the narrowing observed for θ_g or k_{tg}.

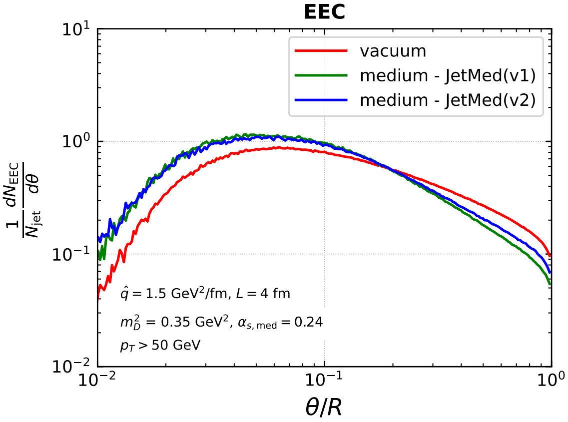
See talk by Alba on Tuesday



$\Rightarrow$ now initial hard scattering spectrum included.

Effect of single-hard scatterings

- Compare now green and blue curves.
- Blue curve includes $1/k_\perp^4$ tail in the broadening of the partons inside the medium.
- More significant enhancement seen at large angles.
- This is because the bias effect is less pronounced for EEC due to the energy weighting.
- Need complementary semi-analytical studies to confirm this picture.



Concluding remarks

- A new version of JetMed including single-hard scattering effect.
- Substructure observables like θ_g after SoftDrop or Dynamical grooming mostly probe the narrowing of jets in heavy-ion collisions.
- In the JetMed picture, narrow jets lose less energy because they contain less sources for energy loss (or because they are quark jets).
- Acplanarity is historically standard candle to look for single-hard scattering. see recent ALICE 2308.16131
  Observable difficult to compute in our approach (*pp* baseline not yet under control).
- Preliminary study suggests that EEC may be sensitive to Molière scattering.
  Simulations and global fits with realistic event generators are needed to confirm this picture.

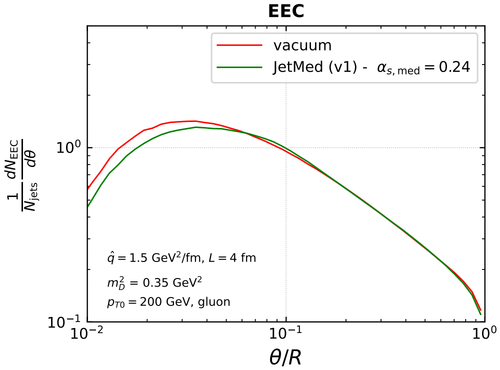
Future plans

- Improve the vacuum parton shower to control large-angle soft emissions.
- Allows us to study the acoplanarity, for instance in γ-jet events.
- Include running coupling effect in the medium-induced cascade. $\Rightarrow$ less free parameters in the model.
- Include a more realistic description of the geometry of the collision.
- It will help us to better constrain the remaining physical parameters by looking at R_{AA} in several centrality classes.

BACK-UP SLIDES

Sensitivity to BDMPS-Z emissions

- Soft BDMPS-Z emissions at large angles are soft $\omega \sim \omega_{br}$ and do not count to the EEC due to energy weighting.
- Only rare relatively hard MIEs with $\omega \lesssim \omega_c$ contribute.
- They are typically emitted around the θ_c angle.



$\Rightarrow$ we shoot a high p_t gluon in the medium (no hard scattering spectrum)

Other effects at large angles in the EEC

- Medium-response has a strong effect at large θ. Yang, He, Moult, Wang, 2310.01500
- Background contamination as well.
- Idea: mesure EEC on primary subjets with a $k_{t,\mathrm{cut}}$. Decluster the jet following the hard branch using C/A and include θ_{ij} between the two subjets at each step, with weight $p_{t,i}p_{t,j}/p^2_{t,\mathrm{jet}}$ in the histogram, provided $k_t = \min(p_{t,i}, p_{t,j})\theta_{ij} \geq k_{t,cut}$.