JetMed beyond multiple soft scattering

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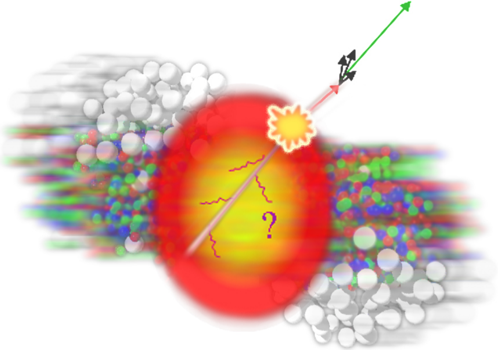
with P. Caucal and G. Soyez (to appear)



Outline

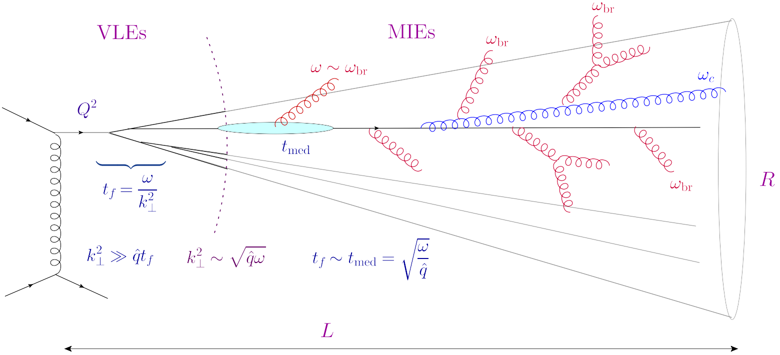
- An evolution of the "Saclay picture" for in-medium jet evolution and the associated Monte-Carlo (JetMed)

  (P. Caucal, E.I., A. Mueller, G. Soyez, PRL 120, 2018)

  (P. Caucal, E.I. and G. Soyez, arXiv:1907.04866, 2005.05852, 2012.01457)

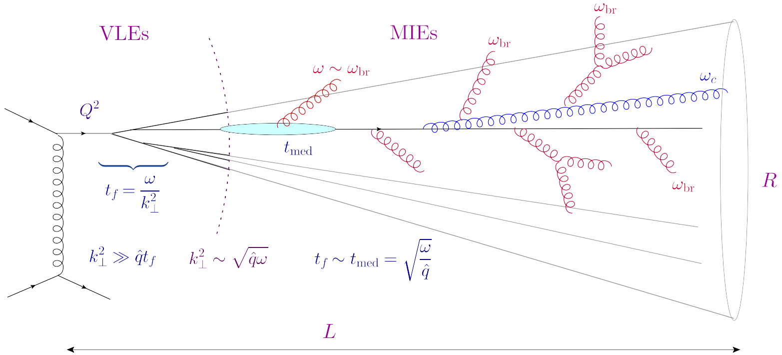
- Brief presentation of JetMed 1
  - physics picture, virtues and limitations
- JetMed 2.0: a major upgrade
  - non-trivial transverse dynamics: D=3+1
  - genuine elastic collisions
  - extension of the BDMPS-Z spectrum towards both lower, and higher, energies (Bethe-Heitler, Gyulassy-Levai-Vitev)
- First applications to phenomenology (R_{AA}, jet substructure)

Parton cascades in a dense QGP



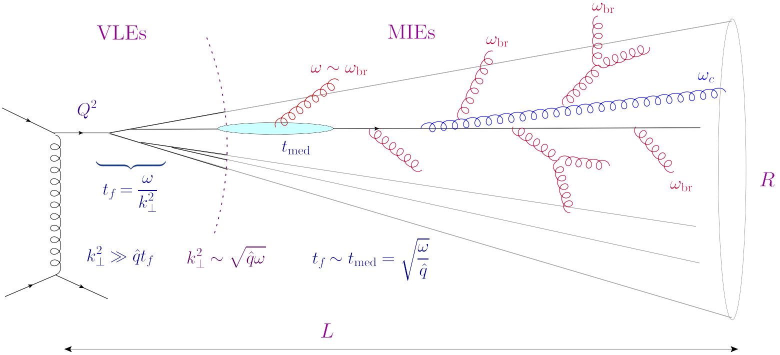
- Hard $2 \rightarrow 2$ scattering $\Longrightarrow$ Virtual parton (Q^2) produced inside the medium
- Parton cascades: Two types of parton branchings ...
  - Vacuum-like emissions (VLEs): driven by the virtuality
  - Medium-induced emissions (MIEs): driven by collisions in the medium
- ... which factorise in time (to logarithmic accuracy in pQCD)

Parton cascades in a dense QGP (2)

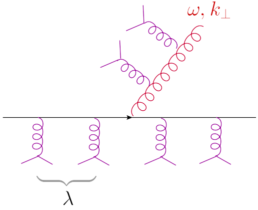


- VLEs occur faster: large $k_\perp^2 \sim Q^2$, short formation times $t_f \simeq \frac{\omega}{k_\perp^2}$
- Angular ordering $\Longrightarrow$ transverse momenta are rapidly decreasing
- Collisions take over and trigger radiation when $k_\perp^2 \sim \hat{q} t_f$

$$k_\perp^2 \sim \hat{q}\,\frac{\omega}{k_\perp^2} \quad \Longrightarrow \quad k_\perp^2 \sim \sqrt{\hat{q}\omega} \quad \& \quad t_f \sim \sqrt{\frac{\omega}{\hat{q}}} \equiv t_{med}$$



- Implicit in this picture: multiple soft scattering and independent MIEs

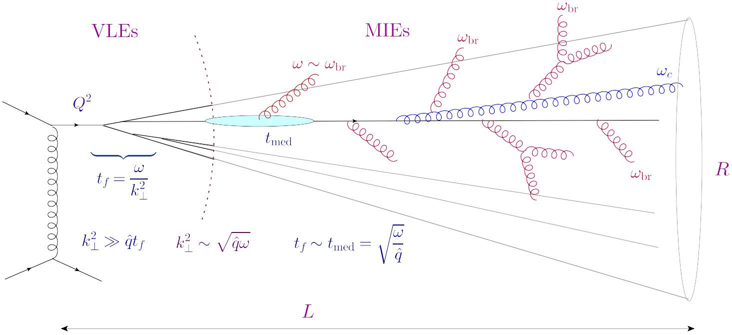


$$\lambda \ll t_{\rm med} = \sqrt{\frac{\omega}{\hat{q}}} \ll L$$

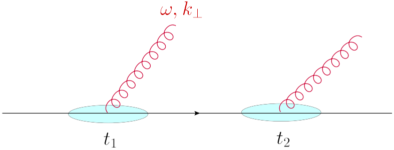
$$\omega_{\rm BH} \equiv \hat{q}\lambda^2 \ll \omega \ll \omega_c \equiv \hat{q}L^2$$

$$1\,{\rm GeV} \ll \omega \ll 50\,{\rm GeV}$$

Parton cascades in a dense QGP (4)



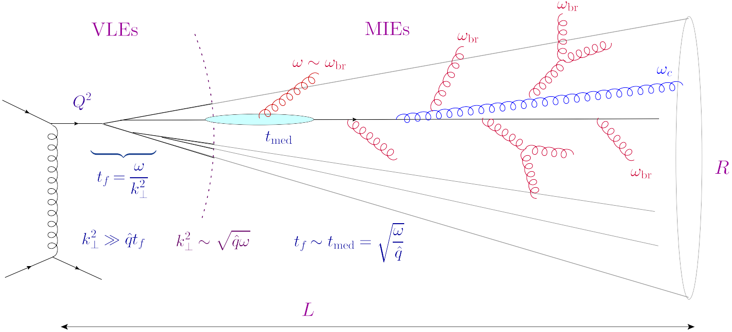
- Branching rate for MIEs (BDMPS-Z spectrum): wave turbulence



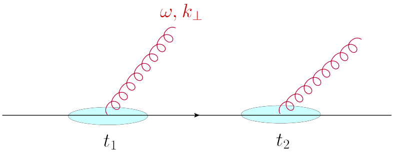
$$\omega \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\omega \mathrm{d}t} \simeq \frac{\alpha_s}{t_{\rm med}} = \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$$

$$\Delta t = t_2 - t_1 \simeq \frac{1}{\alpha_s} t_{\rm med}$$

- Multiple emissions when $\Delta t \lesssim L \implies \omega \lesssim \omega_{\rm br} \equiv \alpha_s^2 \hat{q} L^2$



- Transverse momentum broadening in the diffusion approximation



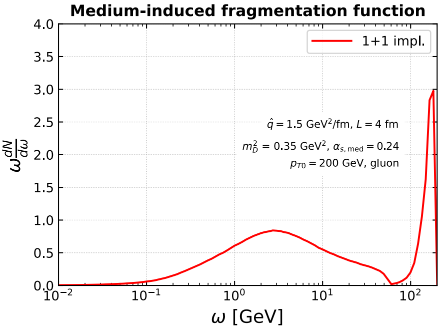
$$\frac{\mathrm{d}N}{\mathrm{d}^2\boldsymbol{k}_\perp} = \frac{1}{\pi\hat{q}\Delta t}\exp\left\{-\frac{k_\perp^2}{\hat{q}\Delta t}\right\}$$

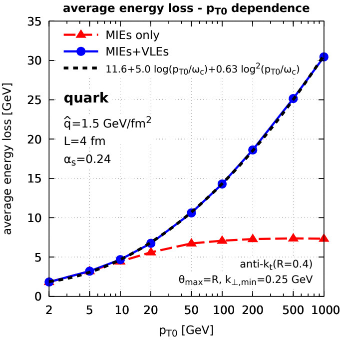
$$\langle k_\perp^2 \rangle = \hat{q}\Delta t$$

- Soft gluons $\Rightarrow$ large angles $\theta \sim k_\perp/\omega > R \Rightarrow$ energy loss by the jet

Monte Carlo results: Energy loss & Jet R_{AA}

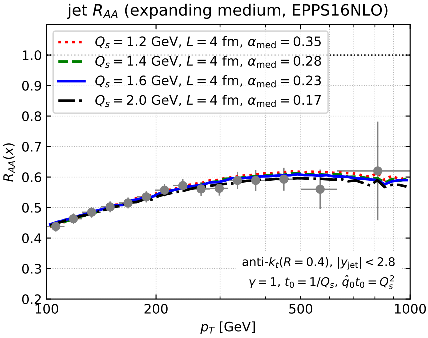
- JetMed 1 : VLEs $(\omega, \theta) \otimes$ MIEs (ω, t)
- Left: Spectrum of MIEs as produced by a single parton:
  - leading parton peak, BDMPS-Z spectrum, energy loss (low ω)

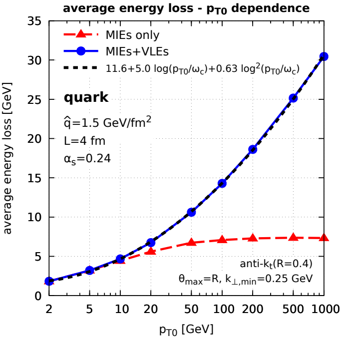




- Right: MIEs only: the energy loss by the jet saturates: $\Delta E_{\rm jet} \sim \omega_{\rm br} \sim 5$ GeV
- Blue: adding VLEs: the energy loss increases with p_{T0}

- JetMed 1 : VLEs $(\omega,\,\theta) \otimes$ MIEs $(\omega,\,t)$
- R_{AA} suppression persists at high p_T because energy loss increases with p_T





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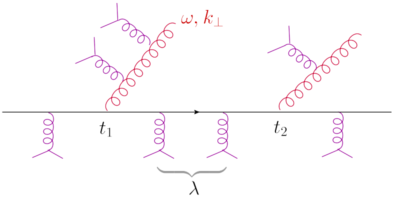
- Blue: adding VLEs: the energy loss increases with p_{T0}

Adding real scatterings & transverse dimensions

- Our original MC for MIEs: branchings process in D=1+1 (time and energy)

- Include genuine collisions with the plasma constituents: D=3+1



$$\frac{\mathrm{d}\Gamma}{\mathrm{d}^2\boldsymbol{k}\mathrm{d}t} = \frac{\hat{q}_0}{(\boldsymbol{k}^2 + m_D^2)^2}$$

$$\hat{q}_0 \equiv \alpha_s^2 C_R n\,, \;\; n : \text{density}$$

$$\lambda = \frac{m_D^2}{\hat{q}_0} \;:\; \text{mean free path}$$

- Diffusion recovered when $\Delta t \gg \lambda$ ... but with a Coulomb logarithm

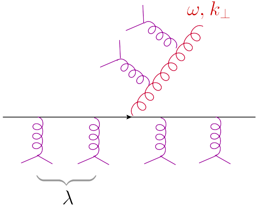
$$\hat{q}(\Delta t) = \int \mathrm{d}^2\boldsymbol{k}\, k_\perp^2 \frac{\mathrm{d}\Gamma}{\mathrm{d}^2\boldsymbol{k}\mathrm{d}t} \sim \hat{q}_0 \ln\frac{\hat{q}\Delta t}{m_D^2} \;: \;\; \text{non-local in time}$$

- $1/k_\perp^4$ tail at large $k_\perp$ due to single hard scattering

$$\frac{\mathrm{d}N}{\mathrm{d}^2\boldsymbol{k}_\perp} = \Delta t\, \frac{\mathrm{d}\Gamma}{\mathrm{d}^2\boldsymbol{k}\mathrm{d}t} \simeq \frac{\hat{q}_0 \Delta t}{k_\perp^4} \quad \text{for} \quad k_\perp^2 \gg \hat{q}(\Delta t)\Delta t$$

Changing the branching rate: the Coulomb log

- $\hat{q}$ also enters the BDMPS-Z rate for MIEs: what is the corresponding scale ?



$$\omega \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\omega \mathrm{d}t} \simeq \frac{\alpha_s}{t_{\rm med}} = \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$$: which $\hat{q}$?

- Natural scale: $k_\perp$–broadening during formation: $k_\perp^2 = \hat{q} t_f = \sqrt{\hat{q}\omega}$

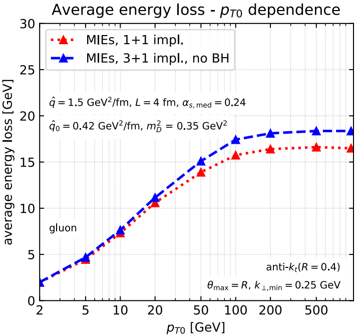
$$\hat{q}(\omega) = \hat{q}_0 \ln \frac{\sqrt{\hat{q}(\omega)\omega}}{m_D^2}$$: energy dependent

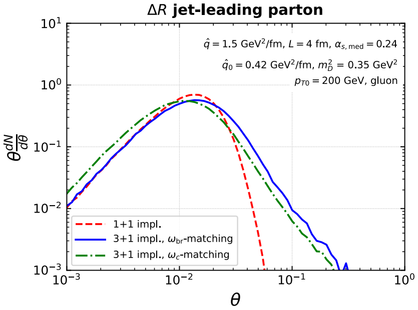
- How to choose $\hat{q}_0$? Matching to the original $\hat{q}$ in D=1+1 at $\omega = \omega_{\rm br}$

$$\hat{q} = \hat{q}_0 \ln \frac{\sqrt{\hat{q}\omega_{\rm br}}}{m_D^2} = \hat{q}_0 \ln \frac{\alpha_s \hat{q} L}{m_D^2}$$: solve for $\hat{q}_0$

Monte Carlo (MIEs only): 1+1 vs. 3+1

- Energy loss: 1+1 (red) vs. 3+1 with $\omega_{\rm br}$-matching (blue)
  - energy losses are comparable (slightly larger for the 3+1 case)





- $k_\perp$ broadening for the leading parton (θ–distribution of the LP peak)
  - more broadening: wider distribution, $1/k_\perp^4$ tail

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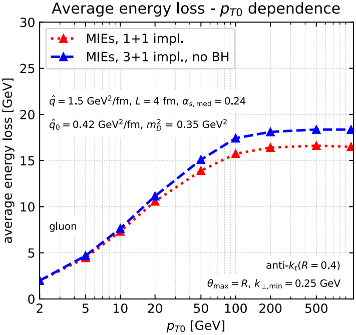
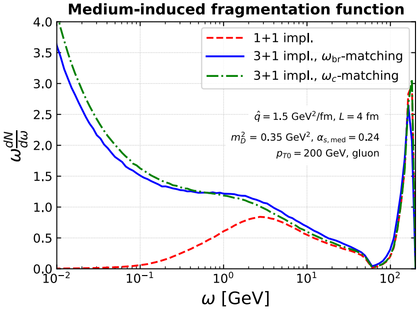
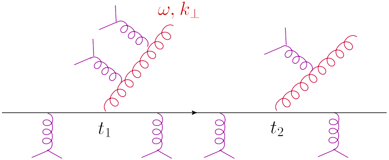




- Fragmentation function (spectrum): 1+1 (red) vs. 3+1 (blue)
  - 3+1: accumulation of gluons at low energies (unphysical) ☹

Bethe-Heitler regime: single soft scattering

- Soft gluons should be deviated by collisions at large angles $\theta \simeq k_\perp/\omega > R$
- Broadening mostly occurs between the branchings: $\Delta t \sim t_{\rm med}/\alpha_s \gg t_{\rm med}$



$$\Delta t = t_2 - t_1 \simeq \frac{1}{\alpha_s}\sqrt{\frac{\omega}{\hat{q}(\omega)}}$$

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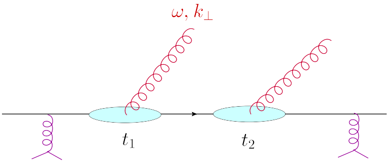

$$\Delta t = t_2 - t_1 \simeq \frac{1}{\alpha_s}\sqrt{\frac{\omega}{\hat{q}(\omega)}}$$

- For sufficiently small ω, $\Delta t < \lambda \implies$ gluons don't undergo collisions !
  - unphysical: there are no MIEs in the absence of collisions

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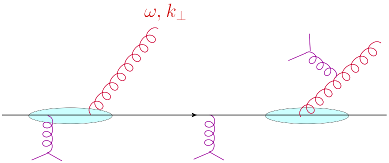


$$t_{\rm med} = \sqrt{\frac{\omega}{\hat{q}(\omega)}} \lesssim \lambda$$

$$\omega \lesssim \omega_{\rm BH} \equiv \hat{q}_0 \lambda^2$$

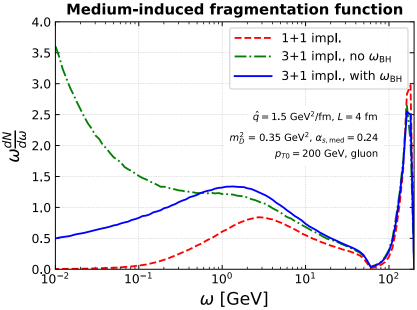
- For sufficiently small ω, $\Delta t < \lambda \implies$ gluons don't undergo collisions !
  - unphysical: there are no MIEs in the absence of collisions
- BDMPSZ breaks down already when $t_{\rm med} \sim \lambda$, i.e. when $\omega \sim \omega_{\rm BH}$

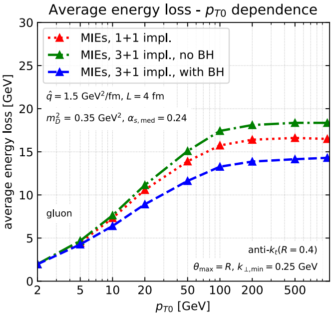
$$\omega \frac{{\rm d}\mathcal{P}}{{\rm d}\omega {\rm d}t} \simeq \alpha_s \sqrt{\frac{\hat{q}(\omega)}{\omega + \omega_{\rm BH}}} \longrightarrow \frac{\alpha_s}{\lambda} \quad \text{when } \omega \ll \omega_{\rm BH}$$

- Simple interpolation: precise form below $\omega_{\rm BH}$ is not essential

Monte Carlo (MIEs only): 3+1 with BH

- Left: Fragmentation function: focus on the blue curve
  - soft gluons efficiently removed from the spectrum ☺





- Right: Energy loss: adding BH significantly reduces the energy loss ☹
  - less singular spectrum at low energies disturbs the turbulent cascade

$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega} \propto \frac{1}{\sqrt{\omega}} \longrightarrow \omega \frac{\mathrm{d}N}{\mathrm{d}\omega} \sim const.$$

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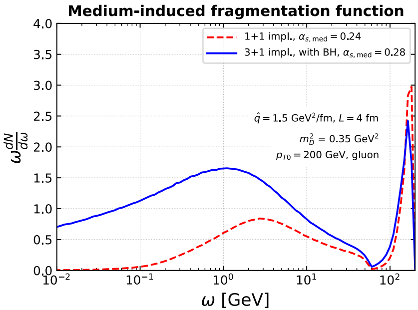
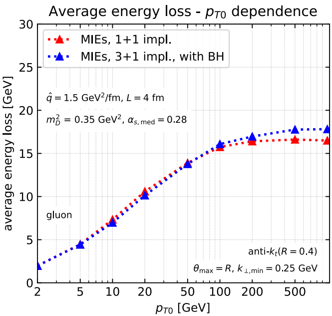


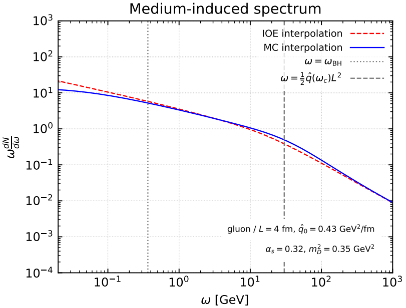


- Right: Energy loss: adding BH significantly reduces the energy loss ☹
- Easy to remedy: use a (slightly) larger coupling: $\alpha_s = 0.24 \rightarrow 0.28$ ☺

More energetic emissions: adding GLV

- So far: elastic collisions, Coulomb log, Bethe-Heitler + BDMPS-Z
- MI spectrum also changes for larger energies: $\omega \gtrsim \omega_c = \hat{q}L^2$ $(t_{\rm med} \gtrsim L)$

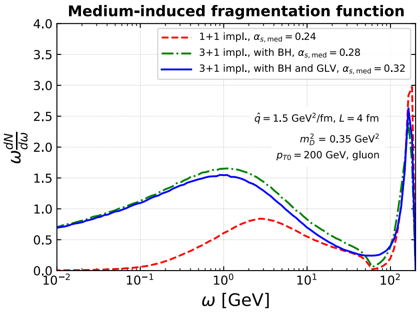
$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega} \simeq \alpha_s \begin{cases} \frac{L}{\lambda} & \omega \lesssim \omega_{\rm BH} \\ \sqrt{\frac{\hat{q}(\omega)L^2}{\omega}} & \omega_{\rm BH} \ll \omega \ll \omega_c \\ \left[\frac{\hat{q}(\omega_c)L^2}{\omega}\right]^2 & \omega \gtrsim \omega_c \\ \frac{\hat{q}_0 L^2}{\omega} & \omega \gg \omega_c \end{cases}$$

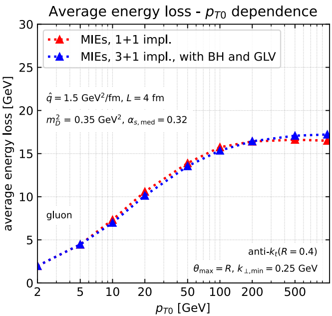


- The full spectrum has been computed numerically
  Caron-Huot and Gale, 2010; Feal, Vazquez, 2018; Andres et al, 2020-21 ...
- Analytic interpolations (Improved Opacity Expansion)
  Mehtar-Tani and Tywoniuk, 2019; Barata et al, 2022; Isaksen et al, 2022 ...

Monte Carlo (MIEs only): 3+1 with BH & GLV

- Fragmentation function: significant change only at $\omega \gtrsim \omega_c$
  - turbulent cascade frustrated (again) by the change in the spectrum

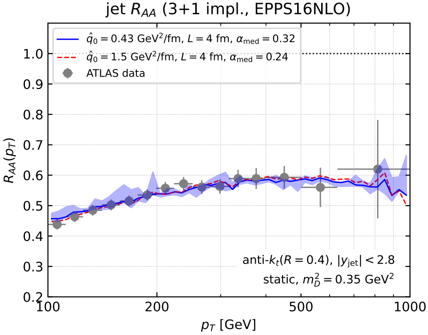


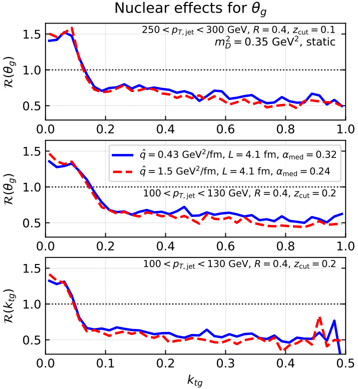


- Same energy loss at the expense of slightly increasing α_s (from 0.28 to 0.32)
  - $k_\perp^2 \simeq \sqrt{\hat{q}(\omega)\omega} = 2 \div 6$ GeV^2 $\Longrightarrow$ $\alpha_s = 0.30 \div 0.35$
- Pronounced differences in the fragmentation function (compare blue vs. red)

Phenomenology & Conclusions

- JetMed 2.0: state-of-the-art pQCD for parton cascades in a dense QGP





- First phenomenology tests (R_{AA}, $\mathcal{R}(\theta_g)$ for SoftDrop) consistent with 1+1
  - controlled by energy loss and vacuum-like emissions
- Other observables (fragmentation, jet shape ...): to be worked out

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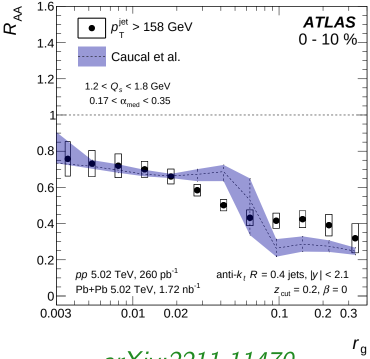
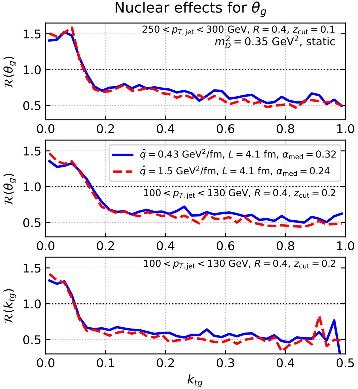


arXiv:2211.11470



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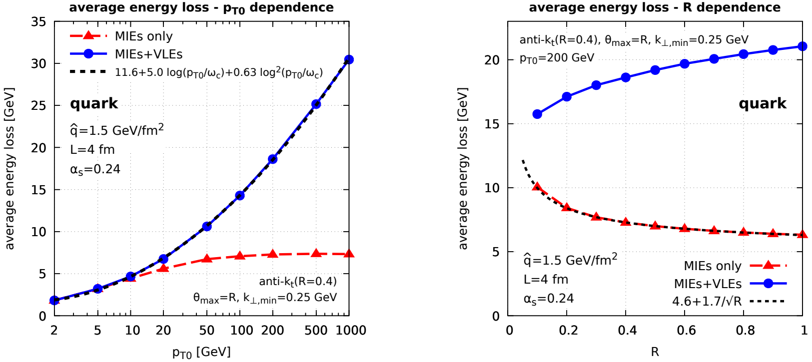
R–dependence of R_{AA} within JetMed

- Energy loss in JetMed:
  - MIEs only: $\Delta E_{\rm jet}$ saturates as a function of p_T and decreases wit R
  - Adding VLEs: $\Delta E_{\rm jet}$ increases with both p_T and R
- Increase in the phase-space for VLEs: additional sources for energy loss



- R_{AA} slowly decreases with R (medium response not included)