Study of open heavy flavors and heavy jets in a transport approach

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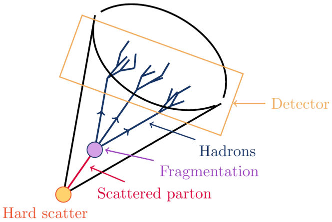
Heavy flavor and jet production

Heavy flavors:

- Flavor tagged hard probes interacting with the quark-gluon plasma.
- Probes single particle evolution. Mass hierarchy of medium modifications.

Jets:

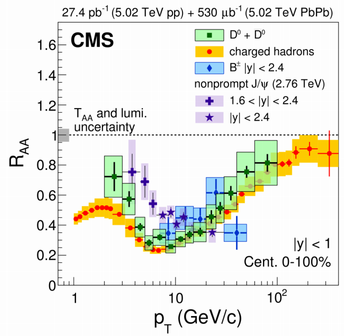
- Initial hard scatterings at large momentum scale $Q \sim p_T$. (perturbative, few-body).
- Parton radiation evolves down to scale $Q \gtrsim \Lambda \to$ hadronization + decay.



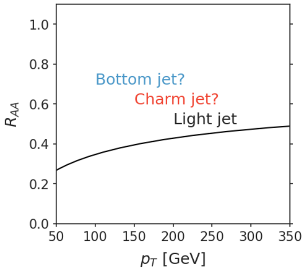
- Experimentally: operational definition by clustering "nearby" particles with distances $d_{ij} = \min(k_{T,i}^{2p}, k_{T,j}^{2p})\sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}/R$
- Theoretically: analog of parton produced in hard collisions.
- In a medium: interactions between both hard and soft ($\gtrsim 3T$) partons and the medium.

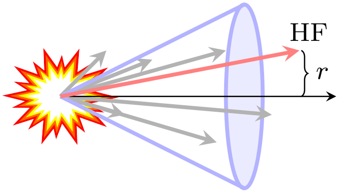
Reasons to look at heavy-flavor jets

Flavor dependence of single particle R_{AA} Credits to CMS, NPA 982, 647-650



- Heavy flavor jet suppression: mass effect in medium modifications, heavy trigger effect.
- More differential information helps to constrain model. The correlation between medium modified heavy flavor and jet.





1 Introduction

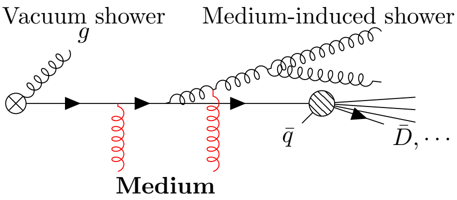
2 Transport of hard parton and soft energy-momentum in the LIDO model

3 Applications to open-heavy flavors and jet observables

4 Summary

Elastic collisions of hard partons

Elastic collisions in a thermal medium



Equilibrium distribution $f(p) \sim e^{-p\cdot u/T}$, T, u from hydrodynamic simulation.

- A diffusion equation for small-q interactions

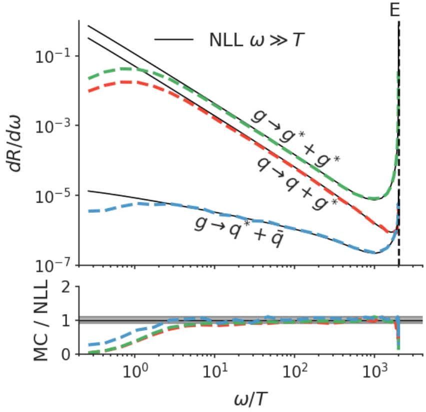
$$\frac{dp}{dt} = -\eta_D p + \xi, \quad \langle \xi_i \xi_j \rangle = \frac{\delta_{ij}}{2}\hat{q}_s$$
$$\hat{q}_s = \alpha_s C_R m_D^2 T \ln({Q_{\mathrm{cut}}}^2/m_D^2)$$

- Large-q collision rate,

$$R = \int dk^3 f(k) v_{rel} \int_{q^2 > Q_{\mathrm{cut}}^2} dq^2 \frac{d\sigma}{dq^2}$$

Coulomb like cross-section $d\sigma/dq^2 \propto 1/q^4$ for processes with $q^2 \gg m_D^2$.

Medium-induced radiation of hard partons



- Diffusion-induced radiation ($1 \to 2$) and large-q inelastic collisions ($2 \to 3$).
- The radiation rate is suppressed by $\frac{\lambda}{\tau_f(t)}$ to account for the LPM effect in dense medium + qualitative path-length dependence.
- Dead-cone approximation for gluon radiation from heavy quarks,

$$R_{Qg}^{Q} = R_{qg}^{q}\left(1+\theta_D^2/\theta^2\right)^{-2},$$
$$\theta^2 = \frac{k_\perp^2(t=t_0+\tau_f)}{k^2}, \theta_D^2 = \frac{M^2}{E^2}.$$

A simple ansatz for energy-momentum transported by soft partons

- To impose energy-momentum conservation & behavior of medium excitation[1].
- For energy-momentum deposits to medium $(x_{\perp,0}, \eta_{s,0})$, use linearized hydrodynamic equation for $\delta e, \delta g$ (neglect viscosity, radial flow. Constant c_s, $\eta_s \approx \eta_{s,0}$.)

$$\partial_t e + \vec{k} \cdot \vec{g} = \delta p^0, \quad \partial_t \vec{g} + c_s^2 \vec{k} \vec{e} = \delta \vec{p}$$

- For jet, we only interested in the angular distribution of energy-momentum,

$$(\Delta e, \Delta g)_{k'} = (1, 3c_s \hat{k}) \frac{\delta p^0 + \hat{k} \cdot \delta \vec{p}/c_s}{4\pi} \Delta\Omega_k, \quad x_\perp \gg x_{\perp,0}$$

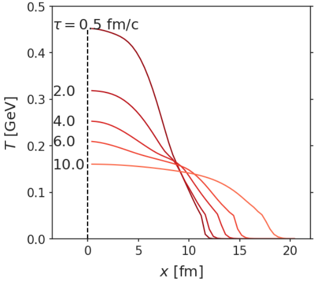
- Convert $\Delta e, \Delta g$ into variation of the (massless) distribution function with an average radial velocity $v \approx 0.6\hat{k}$ for 0-10% Pb+Pb collisions.

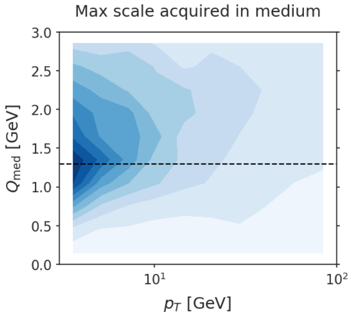
$$\frac{d\Delta p_T}{d\phi d\eta} = \int \Delta f(p) p_T^2 dp_T$$

[1] In principle, this requires a coupled evolution of both hard partons and medium. For example, the CoLBT model developed at CCNU, Chen et al, PLB 777 86-90

Simulation framework

- Medium[2]: 0-10% averaged initial condition + free-stream + (2+1)D viscous hydro.
- A Pythia8 final-state shower down to Q_0 initializes the transport equation. Q_0 around the scale partons acquired from in-medium broadening & induced radiation.
- In-medium transport evolution ceases at $T = 160$ MeV.
- Use Pythia for radiation outside the medium and hadronization (fragmentation only).





[2] Modified from `hic-eventgen`, Bernhard arXiv:1804.06469

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2. Transport of hard parton and soft energy-momentum in the LIDO model
3. **Applications to open-heavy flavors and jet observables**
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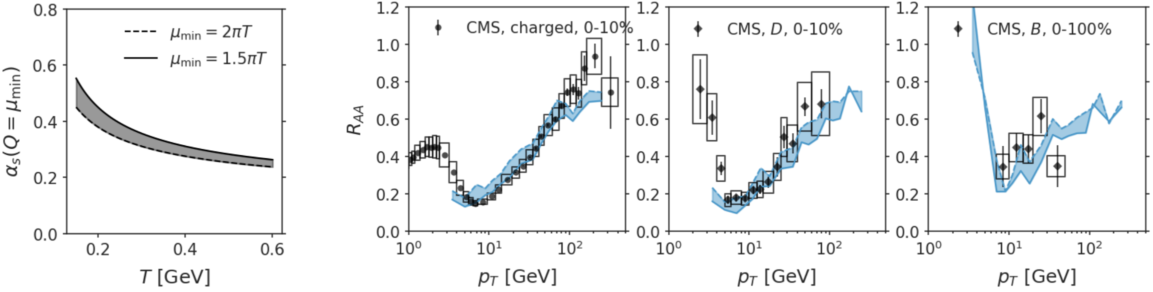
The flavor dependence of inclusive particle R_{AA}

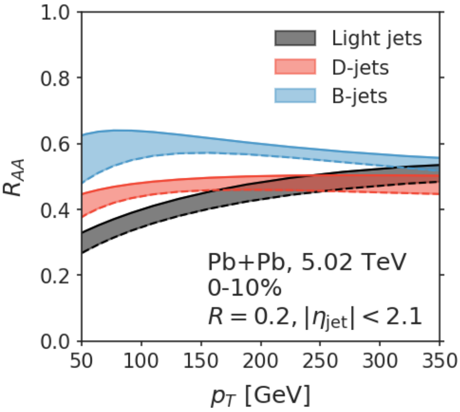


- An leading order running coupling constant with $N_f = 3$, $\alpha_s = \frac{2\pi}{9\ln(\max\{Q,\mu_{\min}\}/\Lambda)}$
- Restrict to vary only one parameter $\mu_{\min}$: controls maximum in-medium coupling.
- Reasonable agreement with charged particle[3], heavy flavor (D, B) R_{AA} with CMS data[4] at 5.02 TeV using $\mu_{\min} \in [1.5\pi T, 2\pi T]$

[3] The calculation is for π only

[4] Charged R_{AA} JHEP 04 (2017) 039; D-meson PLB 782 (2018) 474; B-meson PRL 119, 152301 (2017)

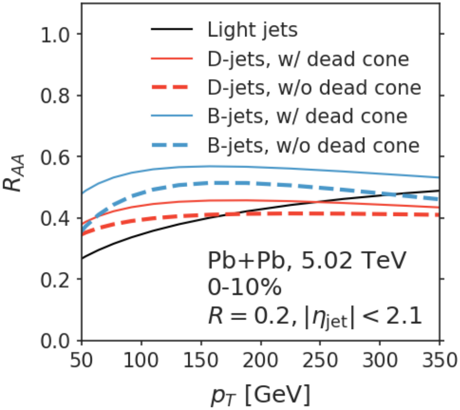
The flavor dependence of jet R_{AA}



Prediction for light-jet, and heavy-jet R_{AA} using the same parameter range $\mu_{\rm min} \in [1.5\pi T, 2\pi T]$. To be compared to ATLAS measurement.

- Jet distance parameter $R = 0.2$.
- B-jet: B meson $dR < 0.3$, $p_T > 5$ GeV.
- D-jet: D meson $dR < 0.3$, $p_T > 5$ GeV.
- Light-jet: no B or D within $dR < 0.3$.

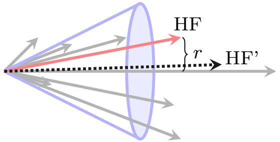
The flavor dependence of jet R_{AA}

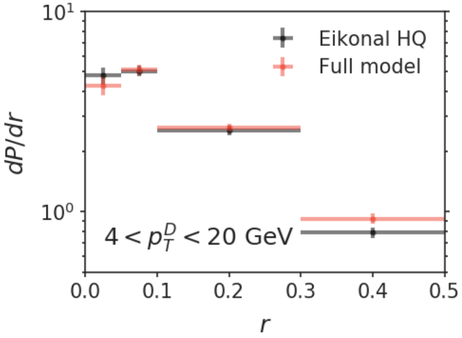


The simulation shows a flavor dependence:

- Dashed lines: without dead-cone factor for the medium induced radiation.
- The flavor dependence is only partly due to the dead-cone effect.
- Heavy trigger also selects different jet samples via its production mechanism $\rightarrow$ details to be quantified in future work.

Heavy-flavor in jets: radial profile relative to jet



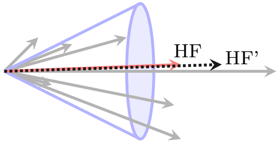


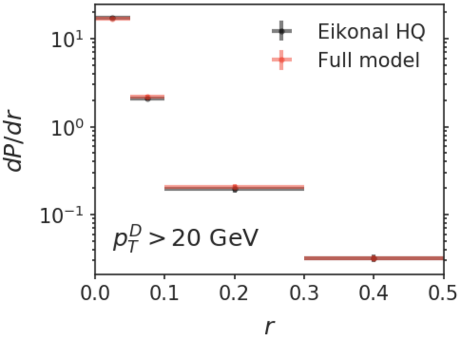
- Radial profile of D meson ($4 < p_T < 20$ GeV) relaive to jet ($p_T^{\mathrm{jet}} > 60$ GeV) axis.

$$\frac{dP}{dr} = \frac{1}{N_{J,D}} \frac{\Delta N_{J,D}}{\Delta r}$$

- Black: heavy quark move on Eikonal trajectory (losing energy w/o changing direction). An idealized baseline.
- Red: w/ transverse recoil of heavy quark.
- Low-p_T heavy quark has a wider radial profile due to its broadened momentum.

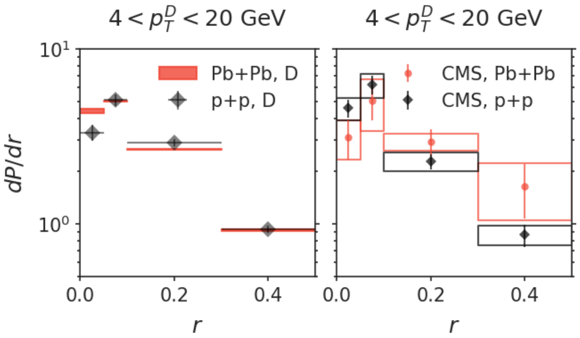
Heavy-flavor in jets: radial profile relative to jet





- Radial profile of D meson ($p_T > 20$ GeV) relaive to jet ($p_T^{\rm jet} > 60$ GeV) axis.
- Black: heavy quark move on Eikonal trajectory.
- Red: w/ transverse recoil of heavy quark.
- Negligible change to radial profile from heavy flavor broadening. Modification to the high-p_T D^0 profile will reflect the "diffusion" of other stuff in the jet.

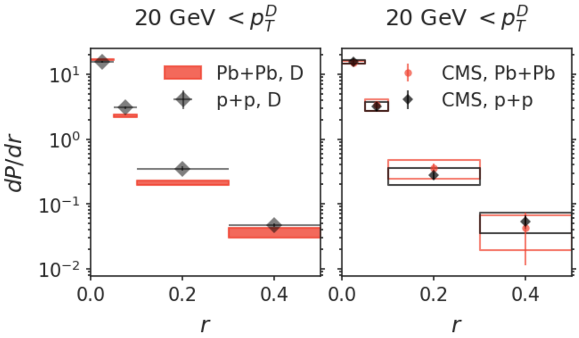
Heavy-flavor radial profile in jet compared to data



Left: calculation with μ_{min} variation
Right: CMS measurement CMS-PAS-HIN-18-007

- CMS measurement: Jet $R = 0.3$, $p_T^{\text{jet}} > 60$ GeV, $|\eta| < 1.6$. Lower p_T bin for D^0, $4 < p_T < 20$ GeV.
- Note the "baseline" is measured in p+p w/o heavy flavor quenching or medium broadening. But still useful as a reference point.
- Compared to the "reference", the current calculation results in a too collimated profile in Pb+Pb.
- Not enough HQ diffusion? Not enough jet axis drifting?

Heavy-flavor radial profile relative to jets: comparison to data



Left: calculation with μ_{min} variation

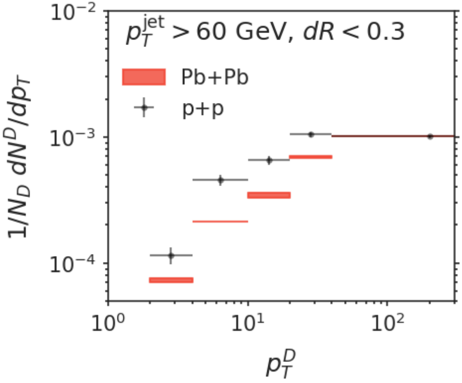
Right: CMS measurement CMS-PAS-HIN-18-007

- CMS measurement:
  Jet $R = 0.3$, $p_T^{\text{jet}} > 60$ GeV, $\eta| < 1.6$.
  Lower p_T bin for D^0, $p_T > 20$ GeV.
- High p_T D meson profile is also too collimated in Pb+Pb calculation $\rightarrow$ the model underestimate the decorrelation due to drifting of jet direction.

Summary

- A transport model approach to the hard probes in QGP medium:
  - Hard partons: elastic collisions + medium induced radiations.
  - Soft partons: hydrodynamic-like medium excitations.
- We studied open-heavy-flavor and heavy-jet suppression.
  - Parameter was chosen to fit open heavy flavor and light particle R_{AA}.
  - A prediction of flavor dependent jet R_{AA}, partly due to dead-cone effect.
- Radial profile of D in jet measures the angular decorrelation of D, jet evolution.
- Current calculations yield in too collimated D profile might suggest insufficient jet axis drifting in the model.

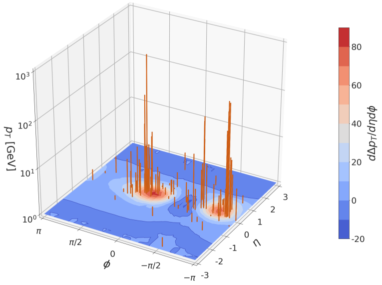
Back up: heavy-flavor in jets, transverse momentum spectrum



- D meson in jets with $p_T^{\rm jet} > 60$ GeV, $dR_{D,J} < 0.3$.
- Black: p+p, Red: Pb+Pb, $1.5\pi T < \mu_{\rm min} < 2\pi T$.
- The sample of D-mesons in jets focus on large p_T. Radiative process dominated and fragmentation hadronization dominated region.

Back-up: Jet finding with both hard and soft momentum transport

p_T on η, ϕ grid



- The grid P_{ij}^μ is used to do jet finding. Anti-k_T algorithm as implemented in `FastJet`[1]
- The background is implicitly treated as the "unperturbed" medium.

$$P_{ij}^\mu = \sum_{\Delta y \Delta \phi} p_{\rm hard}^\mu + \frac{d\Delta p^\mu}{d\phi dy} \Delta y \Delta \phi + (\text{background}).$$

[1] Cacciari and Salam, PLB 641 (2006) 57.

Back-up: assumptions for the hydro-like response

Assumptions:

- The frequency / wave-number of the perturbations are much larger than those of the background variation: $[\partial_\tau, \partial_\perp, \partial_\eta/\tau](e, U^\mu) \ll [\partial_\tau, \partial_\perp, \partial_\eta/\tau](\delta e, \delta u^\mu)$.
- Speed-of-sound $c_s \approx$ constant.
- Propagation in the η_s is small: $\Delta\eta_s \sim \frac{\Delta z}{\tau} \sim \frac{c_s \Delta\tau}{\tau} \sim c_s$.
- Neglect radial flow when computing the angular distribution the energy-momentum density.

Then, in the co-moving frame of $u^\mu = (\cosh(\eta_s), 0, 0, \sinh(\eta_s))$, we still have,

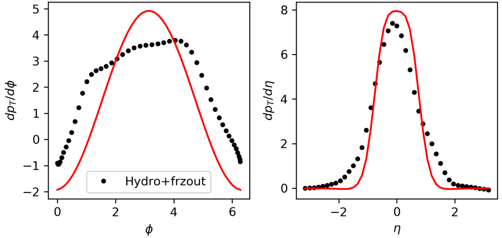
$$\frac{de}{d\Omega_{k'}} \sim \frac{\delta p^0 + \hat{k}' \cdot \delta\vec{p}/c_s}{4\pi}, \quad \frac{d\vec{p}}{d\Omega_{k'}} \sim \frac{3(c_s\delta p^0 + \hat{k}' \cdot \delta\vec{p})\hat{k}'}{4\pi}$$

Back-up: freeze out effect

- Convert the change in energy-momentum density into change in distribution function (massless particle).
- Use a naïve freeze surface proportional to the velocity profile $\Delta\Sigma \sim \Delta V u^\mu$ with $v_{\hat{k}} = v_r \hat{k}$.

$$\frac{d\Delta p_T}{d\phi d\eta} = \int \Delta f(p) p_T^2 dp_T = \sum_i \int \frac{3}{4\pi} \frac{\frac{4}{3}\sigma u_\mu - \hat{p}_\mu}{\sigma^4} \Delta G_i^\mu(\hat{k}) \frac{d\Omega_{\hat{k}}}{4\pi}$$

$$\sigma = \gamma_\perp \left[\cosh(\eta - \eta_s - \eta_{\hat{k}}) - v_\perp \cos(\phi - \phi_{\hat{k}})\right]$$

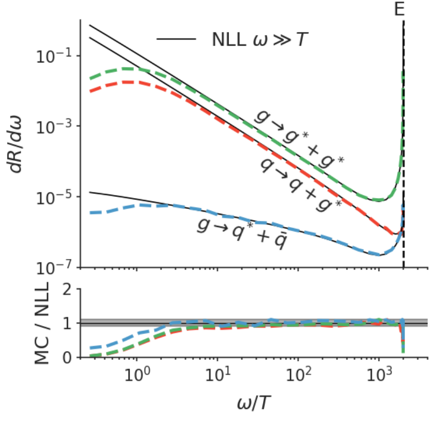


Comparison of a specific scenario with hydrodynamic simulations provided by CCNU,

- A source depositing $dE/dt = dp_x/dt = 1$ GeV/fm, moving from origin to $x = 4$ fm.
- Need more extensive tests + event averaging.

Medium-induced radiation of hard partons

Infinite static medium:
simulation from transport equation compared to next-to-leading-log solution of the rate in infinite limit.



Finite size effect:
path-length dependence of the radiation rate, simulation compared to numerical solution of the rate in finite medium