Medium modifications of heavy-flavor jet angularities in heavy-ion collisions

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Outline

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Introduction

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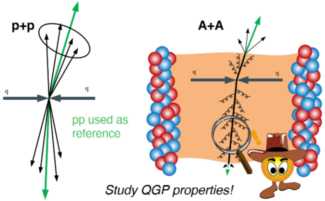
Summary

Hard probes of the QGP

Jet quenching: Jet energy loss and p_T-broadening when a jet propagates in the QGP medium



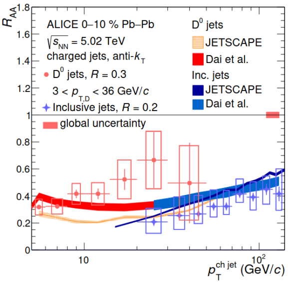
Heavy quarks & heavy-flavor jets

- $m_Q \sim \mathscr{O}(1)$ (GeV/c^2)
- Creation in the early hard scattering process. Calculable in pQCD down to low p_T.
- Dead-cone effect (radiation suppressed at $\theta < m_Q/E$).

Jet transport coefficient: $\hat{q} = \dfrac{\mathrm{d}\langle p_\perp^2\rangle}{\mathrm{d}t}$

- **Energy loss:** $\dfrac{\mathrm{d}E}{\mathrm{d}t}$
- p_T**-broadening:** $\dfrac{\mathrm{d}p_\perp}{\mathrm{d}t}$

$$R_\mathrm{AA}(p_\mathrm{T}) = \frac{1}{\langle N_\mathrm{coll}\rangle}\frac{\mathrm{d}N^2_\mathrm{AA}/\mathrm{d}p_\mathrm{T}\,\mathrm{d}\eta}{\mathrm{d}N^2_\mathrm{pp}/\mathrm{d}p_\mathrm{T}\,\mathrm{d}\eta}$$

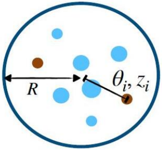


ALICE, arXiv:2409.11939

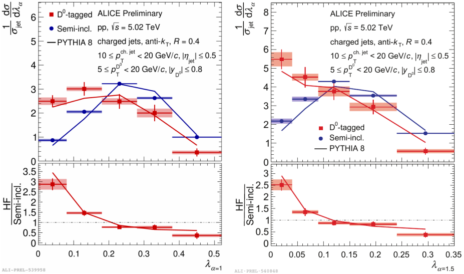
Motivation

Generalized jet angularities:

$$\lambda_\alpha^\kappa = \sum_{i\in \text{jet}} \left(\frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}}\right)^\kappa \left(\frac{\Delta R_{\mathrm{jet},i}}{R}\right)^\alpha \equiv \sum_{i\in \text{jet}} (z_i)^\kappa (\theta_i)^\alpha$$



z_i: Jet p_T fraction carried by constituent i
θ_i: Normalized angular distance of constituent i relative to the jet axis.
$(0 < z_i \leq 1, 0 \leq \theta_i < 1)$



ALICE, PoS HardProbes2023, 140 (2024)

- The smaller angularity of D^0-tagged jets means more concentrated energy distribution around the jet axis;
- The jet angularities allow us to explore the interplay between parton angular redistribution and energy loss during the evolution of heavy-flavor jets in QGP by an adjustment of the two parameters κ and α.

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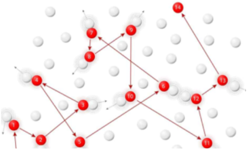
SHELL Model: **S**imulating **H**eavy quarks **E**nergy **L**oss with **L**angevin equations

The motion of heavy quarks in hot dense medium can be regarded as Brownian motion and described by modified Langevin equations:

Brownian motion



$$\vec{x}(t+\Delta t) = \vec{x}(t) + \frac{\vec{p}(t)}{E}\Delta t \tag{1}$$

$$\vec{p}(t+\Delta t) = \vec{p}(t) - \eta_D \vec{p}(t)\Delta t + \vec{\xi}(t)\Delta t - \vec{p}_g \tag{2}$$

G. D. Moore and D. Teaney PRC 71, 064904 (2005); S. Cao, G. Y. Qin and S. A. Bass PRC 88, 044907 (2013)

where $\vec{\xi}(t)$ satisfies $\langle \xi^i(t)\xi^j(t')\rangle = \kappa\delta^{ij}\delta(t-t')$, η_D is the drag coefficient, $\kappa = 2\eta_D ET = 2T^2/D_s$, $2\pi TD_s = 4.0$ is extracted by a χ^2 fitting to the D meson R_{AA} data measured by CMS and ALICE.

The collisional energy loss of light quarks and gluons are calculated under the Hard Thermal Loop (HTL) approximation:

$$\frac{\mathrm{d}E^{\mathrm{coll}}}{\mathrm{d}t} = \frac{\alpha_s C_s \mu_D^2}{2}\ln\frac{\sqrt{ET}}{\mu_D} \tag{3}$$

PRD 83, 065012 (2011); PLB 726, 251 (2013)

SHELL Model: Radiative energy loss mechanisms

Higher-Twist Approach:

The medium-induced gluon radiation of partons (heavy quarks, light quarks and gluons) are sampled based on the higher-twist spectra:

$$\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}k_\perp^2\,\mathrm{d}t} = \frac{2\alpha_s C_s P(x)\hat{q}}{\pi k_\perp^4}\sin^2\left(\frac{t-t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2+x^2M^2}\right)^4 \tag{4}$$

X. f. Guo and X. N. Wang, PRL 85, 3591-3594 (2000); B. W. Zhang, E. Wang and X. N. Wang, PRL 93, 072301 (2004); A. Majumder, PRD 85, 014023 (2012)

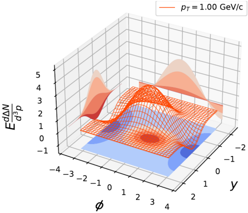
- x: energy fraction of the radiated gluon
- $k_\perp$: transverse momentum of the radiated gluon
- $P(x)$: splitting function in vacuum
- $\tau_f = 2Ex(1-x)/(k_\perp^2 + x^2M^2)$: gluon formation time
- $\hat{q} \propto q_0(T/T_0)^3$, $q_0 = 1.2$ GeV^2/fm (EPJC 79, 518 (2019))

SHELL Model: Medium response (Hybrid Model)

In order to conserve the momentum and energy lost by the jet, we follow the approach of implementing the medium response effect in the Hybrid Model:

$$E\frac{d\Delta N}{d^3p} = \frac{1}{32\pi}\frac{m_T}{T^5}\cosh(y-y_j)\exp\left[-\frac{m_T}{T}\cosh(y-y_j)\right] \times \left\{p_T \Delta P_T \cos(\phi-\phi_j) + \frac{1}{3}m_T \Delta M_T \cosh(y-y_j)\right\} \quad (5)$$

J. Casalderrey-Solana et al., JHEP 03, 135 (2017)



The emitted thermal particles:

- m_T: transverse mass
- p_T: transverse momentum
- y: rapidity
- ϕ: azimuthal angle

Collisional scattering process:

- ΔP_T: the transverse momentum transferred from the jet to the medium
- ΔE: the energy transferred from the jet to the medium
- $\Delta M_T = \Delta E / y_j$

pp baseline: POWHEG+PYTHIA8

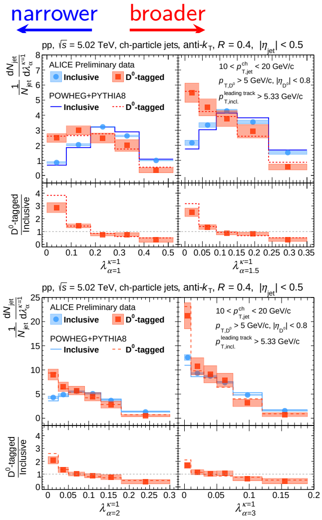
- NLO partonic QCD dijet process: POWHEG (The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method.)
- PDF: CT18NLO
- Tune: Pythia8 Monash 2013

P. Nason et al., JHEP 11, 040 (2004)

S. Frixione et al., JHEP 11, 070 (2007)

S. Alioli et al., JHEP 06, 043 (2010)

S. Alioli et al., JHEP 04, 081 (2011)



[ALICE Data: PoS HardProbes2023, 140 (2024)]

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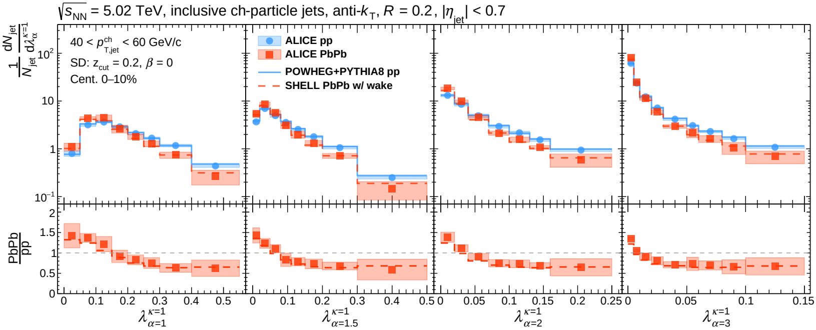
Medium modifications of λ_α^κ of inclusive jets

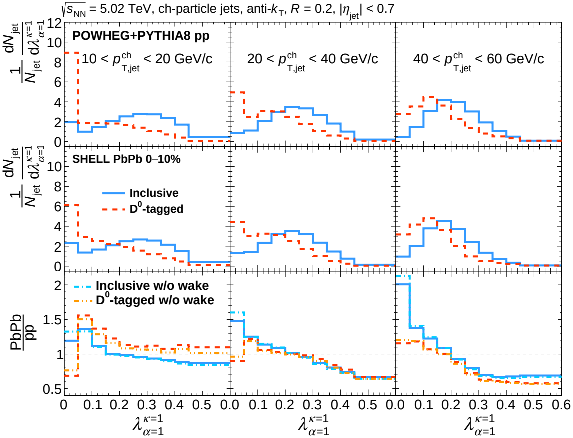
narrower ← → broader



[ALICE Data: 2405.16955; 2411.03106]

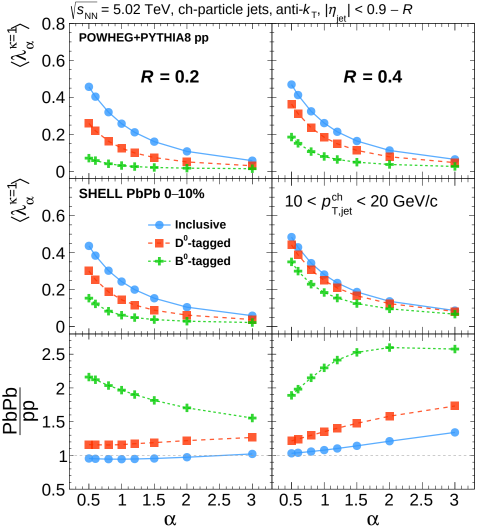
- The "selection bias" effect plays a role;
- The increased fraction of survived narrower jets lead to an enhancement at small $\lambda_\alpha^{\kappa=1}$ and a suppression at large $\lambda_\alpha^{\kappa=1}$.

D^0-tagged vs. inclusive jet angularities in Pb+Pb collisions



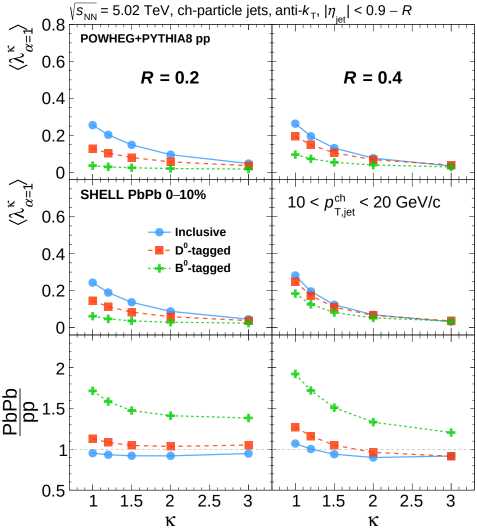
- At $10 < p_{\mathrm{T,jet}} < 20$ GeV/c, a slightly broader angularity of D^0-tagged jets observed in Pb+Pb compared to p+p;
- At $p_{\mathrm{T,jet}} > 20$ GeV/c, the angularity distributions of inclusive and D^0-tagged jets both get narrower in Pb+Pb compared to p+p due to the strong influence of the selection bias.

Average value of jet angularities as function of α



- $\langle\lambda_\alpha^{\kappa=1}\rangle_{\text{incl.}} > \langle\lambda_\alpha^{\kappa=1}\rangle_{\text{D-jet}} > \langle\lambda_\alpha^{\kappa=1}\rangle_{\text{B-jet}}$ for each α;
- The heavy-flavor jets, especially the B^0-tagged one, suffer more distinct modifications of $\langle\lambda_\alpha^{\kappa=1}\rangle$ in Pb+Pb compared to p+p due to a more narrower initial angularity;
- At $R = 0.4$, we observe a broader angularity for both inclusive and heavy-flavor jets. As alpha increases, the ratios also show an increasing trend. Since α controls the weight of the opening angle, higher α value will enhance the contribution of wide-angle particles in jets.

Average value of jet angularities as function of κ



- Since κ controls the weight of particle momentum fraction, higher κ value will suppress the contribution of soft particles in jets. As κ increases, the ratios show an decreasing trend for all types of jets.

Outline

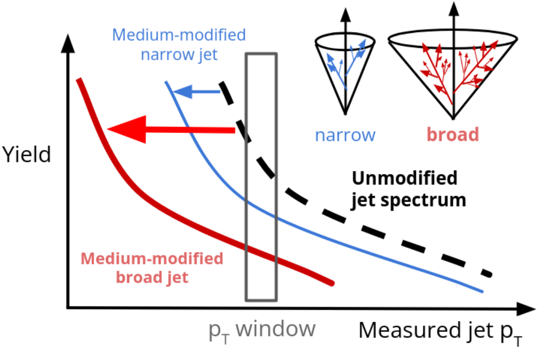
Summary

We present the first theoretical study of heavy-flavor jet angularities in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV:

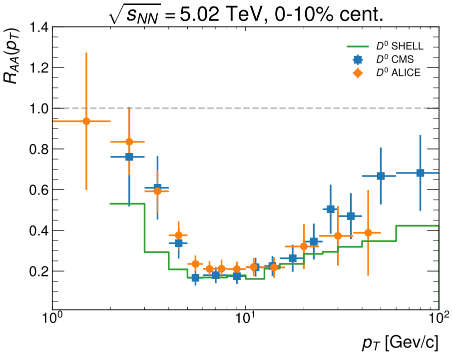
1. At $10 < p_{\mathrm{T,jet}} < 20$ GeV/c, a slightly broader angularity of D^0-tagged jets observed in Pb+Pb compared to p+p;
2. At $10 < p_{\mathrm{T,jet}} < 20$ GeV/c, the heavy-flavor jets, especially the B^0-tagged one, suffer more distinct modifications of $\langle \lambda_{\alpha}^{\kappa=1} \rangle$ in Pb+Pb compared to p+p due to a more narrower initial angularity;
3. At $10 < p_{\mathrm{T,jet}} < 20$ GeV/c, we observe a broader angularity for both inclusive and heavy-flavor jets at $R = 0.4$. As alpha increases, the ratios also show an increasing trend.

Thank you for your attention!

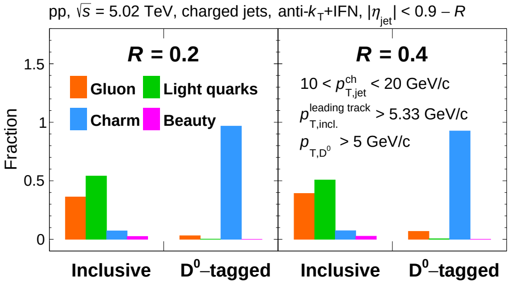
Selection bias effect



Nuclear modification factor R_{AA} of D^0 meson



The fraction of jet flavor



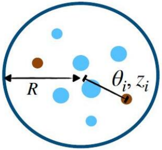
Generalized jet angularities

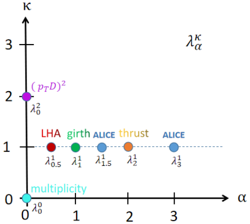
Define:

$$\lambda_{\alpha}^{\kappa} = \sum_{i \in \mathrm{jet}} \left(\frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \right)^{\kappa} \left(\frac{\Delta R_{\mathrm{jet},i}}{R} \right)^{\alpha} \equiv \sum_{i \in \mathrm{jet}} (z_i)^{\kappa} (\theta_i)^{\alpha}$$

z_i: Jet p_{T} fraction carried by constituent i
θ_i: Normalized angular distance of constituent i relative to the jet axis.

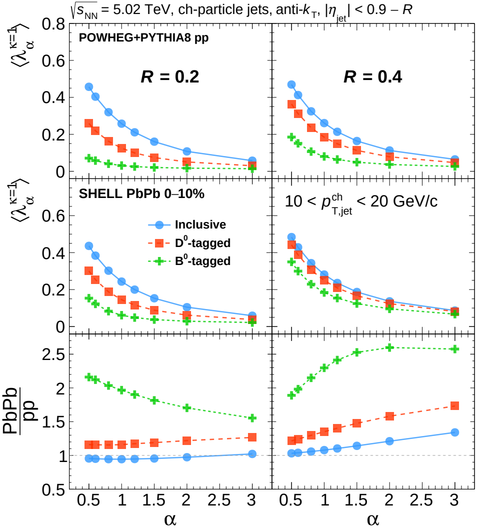
- Infra-Red and Collinear (IRC) safe observable for $\kappa = 1, \alpha > 0 \rightarrow$ calculable from pQCD.





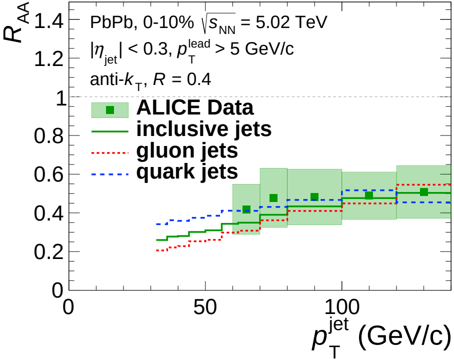
$(\kappa,\ \alpha)$	(1, 1)	$\Rightarrow$	girth
	(2, 0)	$\Rightarrow$	$(p_{\mathrm{T}} D)^2$
	(0, 0)	$\Rightarrow$	hadron multiplicity
	(1, 2)	$\Rightarrow$	thrust
	(1, 0.5)	$\Rightarrow$	Les Houche Angularity(LHA)

Average value of jet angularities as function of α



- The ratio of PbPb/pp for B^0-tagged jets exhibits an inverted trend between $R = 0.2$ and $R = 0.4$ (Single B^0 jets: pp ~ 74%, PbPb ~ 39% $(R = 0.2)$; pp ~ 34%, PbPb ~ 5.8% $(R = 0.4)$).

R_{AA} of gluon and quark jet



Wake particles spectrum (medium response)

The spectrum of hadrons from the boosted, heated up, wake in the fluid can be expressed as

$$\begin{aligned} E\frac{d\Delta N}{d^3p} = \frac{1}{32\pi}\,\frac{m_T}{T^5}\cosh(y-y_j)\exp\left[-\frac{m_T}{T}\cosh(y-y_j)\right] \\ \times\left\{p_T\Delta P_T\cos(\phi-\phi_j)+\frac{1}{3}m_T\,\Delta M_T\cosh(y-y_j)\right\}. \end{aligned} \tag{6}$$

We assume a proton to pion ratio of 0.05, neglect hadrons other than protons and pions, and use the following momentum-dependent “temperatures”:

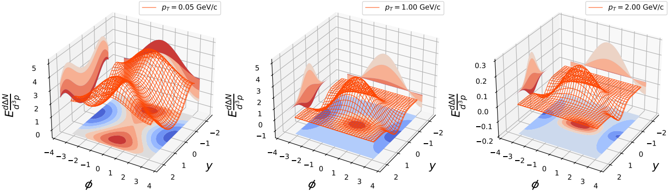
$$T_\pi(p_T)=\begin{cases} 0.19\ \text{GeV} & \text{if}\quad p_T<0.7\ \text{GeV} \\ 0.21\left(\frac{p_T}{\text{GeV}}\right)^{0.28}\ \text{GeV} & \text{if}\quad p_T>0.7\ \text{GeV} \end{cases} \tag{7}$$

$$T_p(p_T)=\begin{cases} 0.15\ \text{GeV} & \text{if}\quad p_T<0.07\ \text{GeV} \\ 0.33\left(\frac{p_T}{\text{GeV}}\right)^{0.3}\ \text{GeV} & \text{if}\quad 0.07\ \text{GeV}<p_T<1.9\ \text{GeV} \\ 0.4\ \text{GeV} & \text{if}\quad p_T>1.9\ \text{GeV} \end{cases} \tag{8}$$

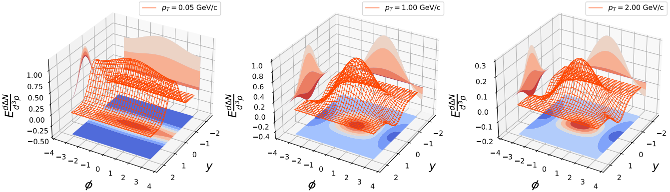
J. Casalderrey-Solana et al, JHEP **03** (2017), 135

Wake particles spectrum (medium response)

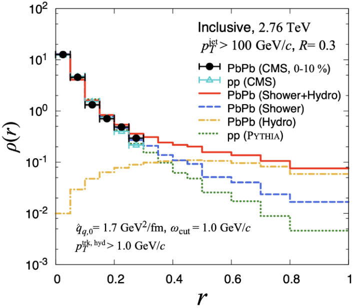
Pion Number Density Distribution
$y_j = 0, \phi_j = 0, \Delta p_T = 10$ GeV/c, $\Delta E = 12$ GeV

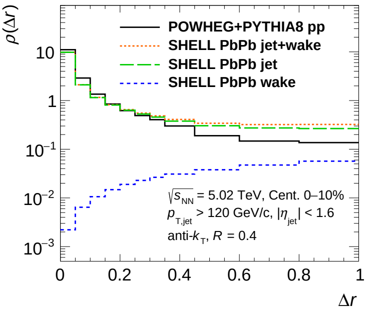


Proton Number Density Distribution
$y_j = 0, \phi_j = 0, \Delta p_T = 10$ GeV/c, $\Delta E = 12$ GeV



Wake particles spectrum





S. Cao and G. Y. Qin, Ann. Rev. Nucl. Part. Sci. **73** (2023), 205-229 [arXiv:2211.16821 [nucl-th]]