# Separating quark and gluon jet distributions in heavy-ion collisions

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## Problem

A crucial aspect of probing the underlying interactions of the quark–gluon plasma is quantifying how the modification of a jet depends on its QCD color charge. Although quark- and gluon-initiated (henceforth, quark and gluon) jets cannot be defined unambiguously at the hadron level, at the parton level they carry different net color that changes their structure. From an experimental point of view, it remains almost entirely unknown how these differences impact the modification of jets in the quark–gluon plasma. The challenge of accessing independent information about quark and gluon jets experimentally arises dominantly from the fact that all jet measurements are an unknown mixture of contributions from both types of jets. In this work we provide a data-driven procedure to extract jet observable distributions separately for quark and gluon jets and illustrate how to use this information to measure their separate energy loss.

## "Demixing" mixture distributions

Given two probability density functions (PDFs) $p_1(x), p_2(x)$, define

$$\kappa_{ij} = \inf_x \frac{p_i(x)}{p_j(x)}. \tag{1}$$

Two PDFs are *mutually irreducible* if $\kappa_{12} = \kappa_{21} = 0$. Given PDFs $p_1(x), p_2(x)$ that are not necessarily mutually irreducible, we define the *topics* to be [1]

$$b_1(x) = \frac{p_1(x) - \kappa_{12} p_2(x)}{1 - \kappa_{12}}, \quad b_2(x) = \frac{p_2(x) - \kappa_{12} p_2(x)}{1 - \kappa_{21}}.$$

These are the unique mutually irreducible PDFs from which $p_1(x), p_2(x)$ can be built as convex combinations. Specifically,

$$p_j(x) = f_j b_1(x) + (1 - f_j) b_2(x)$$

with

$$f_1 = \frac{\kappa_{12} - 1}{\kappa_{12}\kappa_{21} - 1}, \quad f_2 = \frac{\kappa_{21}(\kappa_{12} - 1)}{\kappa_{12}\kappa_{21} - 1}.$$

When using normalized histograms instead of continuous PDFs, the infimum in Eq. (1) is replaced with a minimum over bins.

## Topics

Under relatively minimal assumptions about the properties of quark and gluon jets, it is possible to use the Demix method to use two jet samples to extract topics that are in good agreement with the parton-level definition of quark and gluon jets. This method has also been applied to jets in proton-proton collisions [2]. Those assumptions are *sample independence* and *mutual irreducibility*:

1. ***Sample independence***: The two jet samples different only by having different fractions of quark and gluon jets, but the features of quark and gluon jets in both samples are the same.
2. ***Mutual Irreducibility***: $\kappa_{12} = \kappa_{21} = 0$. Conceptually this choice is necessary to resolve the ambiguity of decomposing distributions into mixture distributions. It has been shown in [3] that counting observables, including various constituent multiplicities and Soft Drop multiplicity, are Poissonian in the high energy limit. Poissonians with different means are mutually irreducible, so quark and gluon jets are mutually irreducible in these observables in the high energy limit.

Using the Demix approach, we can extract the topics from input distributions of the constituent multiplicity of soft-dropped jets ($\beta = 1.5$ and $z_{\text{cut}} = 0.5$) for dijet and photon+jet samples in proton–proton and heavy-ion collisions, see Fig. 1.

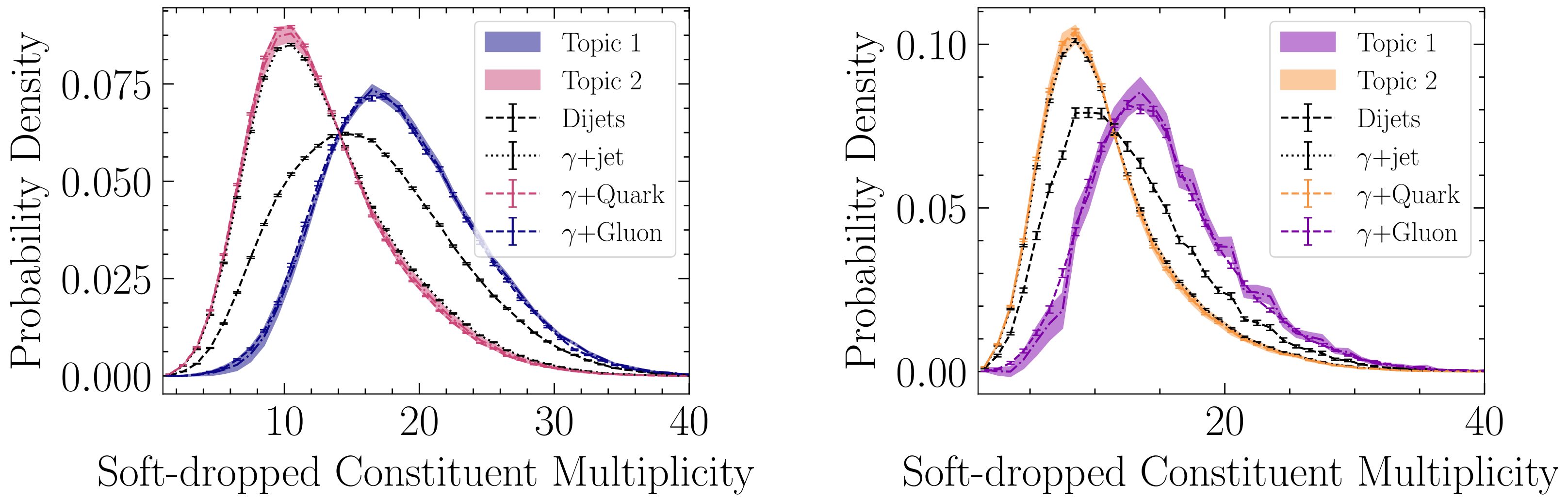

Fig. 1: Constituent multiplicity for soft-dropped dijet and photon+jet samples in proton–proton (left) and heavy-ion (right) collisions, along with underlying topics. All data were generated using Jewel 2.1.0 at 5.02 TeV with $R = 0.4$. We consider the two leading jets in dijet events and the single leading jet in photon+jet events. The distributions shown are for jet $p_T \in (100, 110)$GeV. As shown, the data-driven extraction of the topics (colored bands) is in excellent agreement with the parton-level definition of quark and gluon jets (colored lines).

## Quark and gluon jet energy loss

One application of this procedure is to enable measurements of the separate energy loss of quark and gluon jets. The topic fractions $f_1, f_2$ can be extracted as a function of $p_T$ by performing the procedure shown in Fig. 1 over multiple bins in $p_T$. These fractions of quarks and gluons in the sample as a function of $p_T$, along with the total spectrum, immediately yield the separate quark and gluon spectra. We interpolate these spectra using the functional form $p_T^{a+b\log(p_T)}$ and use a Markov Chain Monte Carlo to estimate the uncertainties in this interpolation. In Fig. 2, we show the jet suppression as a function of $p_T$ ($R_{AA}$) and the average fractional leftward shift of the $p_T$ spectrum as a function of $p_T$ ($Q_{AA}$) introduced in [4].

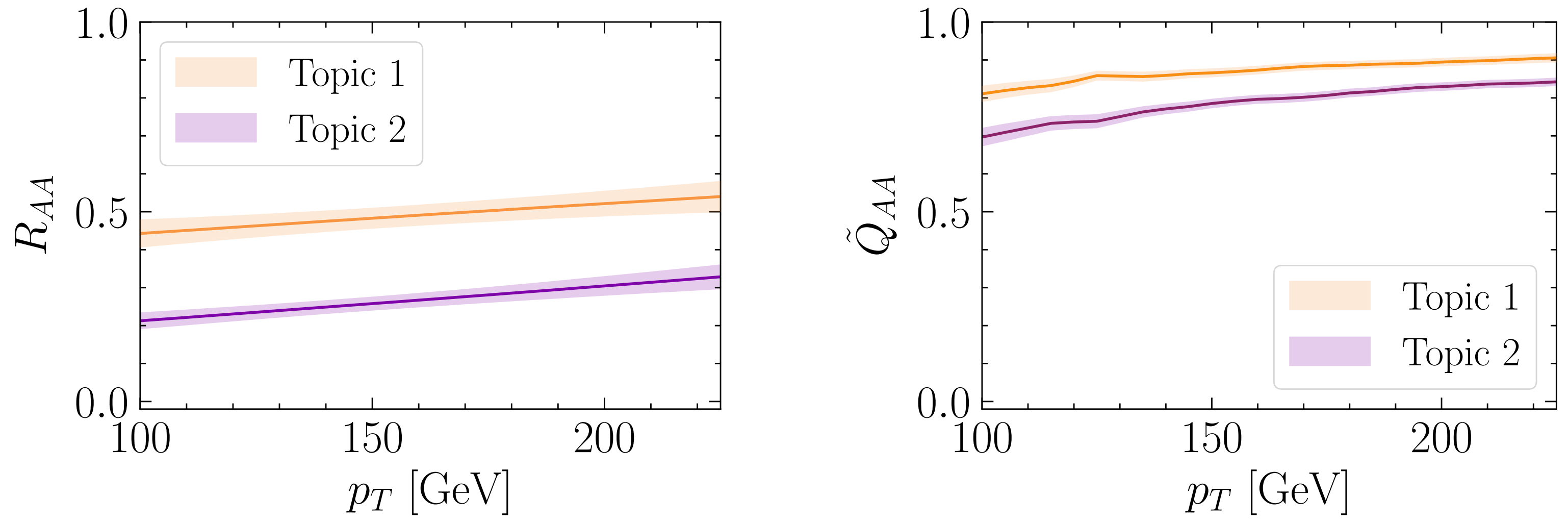

Fig. 2: $R_{AA}$ (left) and $Q_{AA}$ (right) for quark-like (orange) and gluon-like (purple) topics.

As expected, both the $R_{AA}$ and $Q_{AA}$ indicate more substantial energy loss for gluon jets. However, it is interesting to note that although the difference in $R_{AA}$ between quark and gluon jets is substantial, their average fractional energy loss in Jewel only differs by 5–10%. This arises from the fact that quark and gluon jet spectra are substantially different and highlights the clearer interpretation of $Q_{AA}$ as compared to $R_{AA}$. We finally emphasize that the goal of this work is not to provide predictions for quark and gluon energy loss based on Jewel, but to illustrate a method toward measuring separate quark and gluon jet energy loss in experimental data.

## Fraction versus quark/gluon modification

We emphasize that once the topic fractions are known (for example through having been extracted from constituent multiplicity as in Fig. 1), those fractions can be used to extract the quark and gluon distributions of any jet observable, regardless of quark and gluon mutual irreducibility. This opens to the door to measurements of the modification of any observable for quark and gluon jets. In addition, typical jet modification observables in heavy-ion collisions confound both the modification of the quark/gluon fractions between proton–proton and heavy-ion collisions and of the underlying quark and gluon distributions $b_1, b_2$. The topic fractions are substantially different in proton–proton and heavy-ion collisions for jets of the same $p_T$. As a result, even in the absence of any genuine modification of jets by the plasma, there is still an apparent modification of jet distributions arising from the difference in production properties of quark and gluon jets. The Demix approach can distinguish these effects, which highlights the substantial importance of this method for interpreting jet modification observables in heavy-ion collisions.

## Conclusions

We have demonstrated a fully data-driven method to separate the contribution to any jet observable coming from two jet topics that are excellent proxies for quark and gluon jets. We showed how this method can be used to disentangle the quark/gluon fraction modification from the distribution-level modification of quark and gluon jets in heavy-ion collisions. This is critical to quantitative interpretations of any jet modification observables, particularly in dijet events where the quark/gluon fraction is substantially different in proton–proton and heavy-ion samples. We showed how the modification of the quark/gluon fraction as a function of $p_T$ can be used to compute a proxy for the spectra of quark and gluon jets. This enables us to calculate the nuclear modification factor $R_{AA}$ and the average energy loss $Q_{AA}$ separately for quarks and gluons in a fully data-driven way. If measured experimentally, this would provide the first direct measurement of differences in the energy loss of quark and gluon jets in the quark–gluon plasma, which is a critical unsolved problem in understanding how the quark–gluon plasma resolves the color structure of jets.

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