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Unbiased quantification of jet energy loss

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Bin migration effects hinder a direct connection between the nuclear modification factor R_{AA} and the energy lost by jets. The R_{AA} compares yields of jets in pp and AA collisions that are reconstructed with the same p_T and is thus biased by the steeply falling nature of the jet spectrum. To mitigate these effects, Brewer et al. [1] introduced a novel observable to directly quantify average jet energy loss (Q_{AA}) which is given by the ratio of the transverse momenta that correspond to the same probability quantiles in pp and AA spectra. This work reinforces the claim that Q_{AA} ratio is a reliable proxy for jet energy loss and, by using it, it shows that energy loss decreases with increasing jet radius when QGP response, as implemented in the JEWEL event generator, is accounted for. Further, our results establish that, contrary to recent claims, the difference in R_{AA} between inclusive and boson-jet events is dominated by differences in the spectral shape, leaving the colour charge of the jet initiating parton with a minor role to play. The experimental feasibility of a Q_{AA} measurement is addressed.

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1. Introduction

In heavy-ion (AA) collisions, jets have to plough through the QGP, resulting in them being energetically and structurally modified relative to a well established baseline of pp collisions [2–4]. The aggregate of such modifications is usually referred to as jet quenching [5, 6]. Jet energy loss, in particular, is dominated by wide-angle medium-induced emissions which are radiated outside of the reconstructed jet cone. Furthermore, the jet deposits energy in the medium while travelling through it and part of that energy is reconstructed inside the jet, i.e., medium response. These mechanisms compete for jet radius variation of energy loss [7, 8]. To gain insight into these medium-induced effects, the usual strategy is to compare samples of medium jets produced in heavy-ion collisions with samples of vacuum jets produced in pp collisions. One can then interpret the results at the light of existing jet quenching models and infer the properties of the QGP.

A relevant question then arises: how exactly should one compare samples of vacuum and medium jets? The usual procedure is to choose a window of reconstructed jet p_T and then calculate the value of some observable for jets with a p_T inside such window. This approach to the quantification of jet modifications is, however, problematic. One of the reasons is bin migration - medium jets migrate to lower p_T, i.e. they lose energy, mostly as a consequence of out of cone medium-induced radiation. This implies that we are comparing jets that were initiated by hard partons with different p_T values. This is worsened by the steeply falling nature of the jet p_T spectrum. A prime example illustrating this bias is the R_{AA}, which takes the ratio of pp and AA jet p_T cross sections at the same bin of reconstructed p_T. Hence, it cannot, by definition, accurately quantify jet energy loss. In fact, if we consider two jet spectra with significantly different steepnesses, e.g. inclusive jet samples and boson+jet samples, and impose a fixed energy loss, then the less steeper spectrum will have a R_{AA} closer to 1. This bias can be evaded in boson+jet events, because there we have a proxy for the p_T of the hard parton that originated the jet. This way, one can compare pp and AA jets that started out similarly, i.e. with the same p_T. However, this type of events is still penalized in terms of statistics, so another strategy is needed for inclusive jet samples.

2. The quantile procedure

In [1], a different way to look at the jet p_T spectrum was proposed as an attempt to establish a correspondence between a given p_T in the pp spectrum and another p_T in the AA spectrum. The result of this correspondence is the quantile function $p_T^{q,m}(p_T^v)$, which in this case we write as depending on vacuum jet p_T^v. This function is determined implicitly by an equation which amounts to a search for equal probability quantiles:

$$\int_{p_T^v}^{+\infty} dp_T \frac{d\sigma^v}{dp_T} = \int_{p_T^{q,m}(p_T^v)}^{+\infty} dp_T \frac{d\sigma^m}{dp_T} \tag{1}$$

This is akin to a conservation of number of jets. Such reasoning provides us with a procedure to pick samples of pp and AA jets that, on average, started out similarly, meaning they were produced by hard partons with the same p_T. As is argued in [1], this procedure would be exact if every jet with a given p_T lost the same energy. However, fluctuations arise from both the probabilistic nature of vacuum and medium-induced showers and the existence of QGP background correlated with the jet. Assuming these fluctuations are not disproportionate, in principle, one can correct for bin migration and selection bias by selecting reconstructed p_T windows which are matched via quantile procedure, as was done for m/p_T for dijet events in [1] as a first example. Not only this, but taking the ratio between this pair of corresponding p_T values, the Q_{AA}, one is calculating a proxy for the average relative jet energy loss as a function of vacuum jet p_T:

$$Q_{AA}(p_T^v) = \frac{p_T^{q,m}(p_T^v)}{p_T^v} \sim 1 - \langle \epsilon \rangle (p_T^v) \tag{2}$$

3. Results

The vacuum and medium event samples analyzed in this work were generated using the `JEWEL 2.3` [9] event generator including medium response and with the event-wise subtraction described in [10] performed prior to jet reconstruction. The implementation is based on the code available on `JEWEL`'s website[1]. This takes into account the energy deposited by the jets on the medium that is reconstructed as part of the jet.

Both p+p collisions and Pb+Pb ([0-10]% centrality) collisions are generated at $\sqrt{s} = 5.02$ TeV, using the CT14NLO PDFs [11] and the EPPS16NLO nuclear PDFs [12], respectively. Importantly, in this phenomenological study, collisions in vaccum are generated with nuclear PDFs EPPS16NLO, which are isospin averaged, as initial conditions. Hence, vacuum samples are actually nucleon-nucleon collisions with no QGP. This is an attempt at isolating the role of quenching effects in the differences between vacuum and medium samples by minimizing the role of nuclear effects, which is significant for γ+jet events [13]. These samples consist of 10^6 dijet events and 10^6 γ+jet events. The particles produced in the hard scattering have a minimum transverse momentum of 20 GeV and the medium is generated with `JEWEL`'s default parameters. Initial state radiation is included.

With regards to kinematic cuts:

- jets: $p_T^{jet} \geq 50$ GeV and $|y^{jet}| \leq 2.8$
- photons: $p_T^{\gamma} \geq 50$ GeV and $|y^{\gamma}| \leq 2.37$
- jets required to be azimuthally separated by $\Delta\phi^{\gamma,jet} \geq 7\pi/8$ from the photon

One should first validate if in fact the Q_{AA} is a good proxy for average relative energy loss if we deviate from the idealized scenario we alluded to, where every jet with a given p_T loses the same energy. We can do this by checking if the Q_{AA} gives us the same information that the p_T of the photon does in γ+jet events. In Fig. 1, one compares, for each bin of photon p_T, the ratio between the mean reconstructed p_T of AA jets ($\langle p_T^m \rangle$) and the mean reconstructed p_T of pp jets ($\langle p_T^v \rangle$) with the ratio of the mean value of $p_T^{q,m}$ and $\langle p_T^v \rangle$. These quantities are calculated according to:

$$\langle p_T^{v/m} \rangle = \int dp_T \frac{dN^{v/m}}{dp_T}[p_T^{\gamma}] \cdot p_T \qquad \langle p_T^{q,m} \rangle = \int dp_T \frac{dN^{v}}{dp_T}[p_T^{\gamma}] \cdot p_T^{q,m}(p_T) \tag{3}$$

where $\frac{dN^X}{dp_T}[p_T^{\gamma}]$ is the normalized transverse momentum distribution of jets for a given bin of photon transverse momentum p_T^{γ}. The agreement is reasonable considering the presence of various sources of fluctuations.

[1] `https://jewel.hepforge.org/`

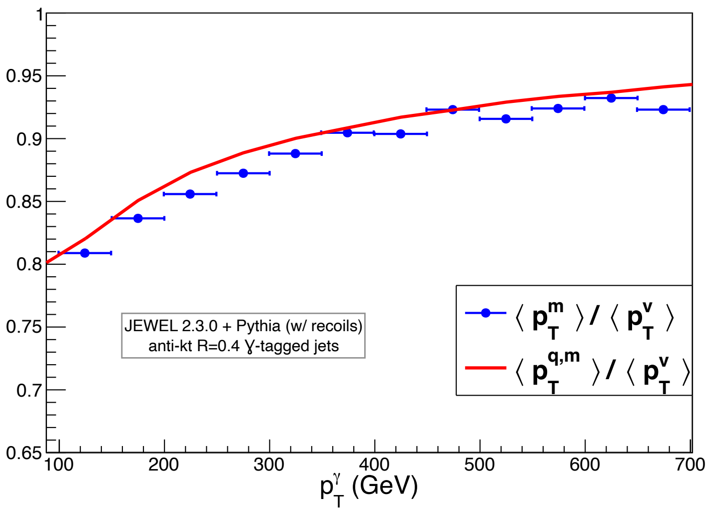

Figure 1: Validation of the quantile procedure by comparing it with the information obtained by using the photon's p_T as a reference.

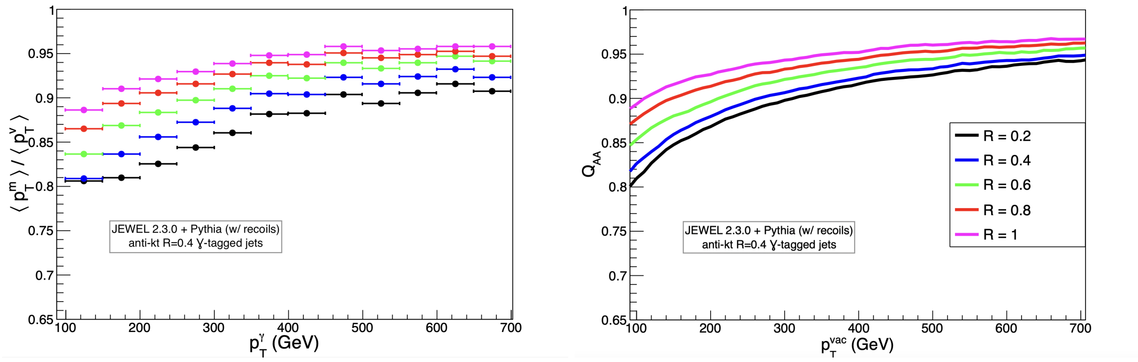

Figure 2: Evolution of average jet energy loss proxies (ratio of mean values of reconstructed p_T (left) and Q_{AA} (right)) with jet radius.

One can try to check if this agreement is maintained as one varies the jet radius. By using information from the photon's p_T, we could already see (left plot in Fig. 2) that the ratio between average AA jet p_T and average pp jet p_T increases as one increases the jet radius. This translates to larger jets losing less energy. This means that medium response compensates for the fact that increasing the jet radius increases the number of jet components that can lose energy. The evolution of the Q_{AA} with jet radius (right plot in Fig. 2) has the exact same scaling, so increasing the jet radius does not spoil its validity.

We also considered the dependence of jet energy loss on color charge, that is whether the jet is initiated by a quark or a gluon. Analysis of this kind usually rely on the R_{AA} to conclude that the color charge of the initial hard parton greatly influences the jet's energy loss [13]. A strong argument in favour of this claim is that the strength of medium-induced radiation is proportional to

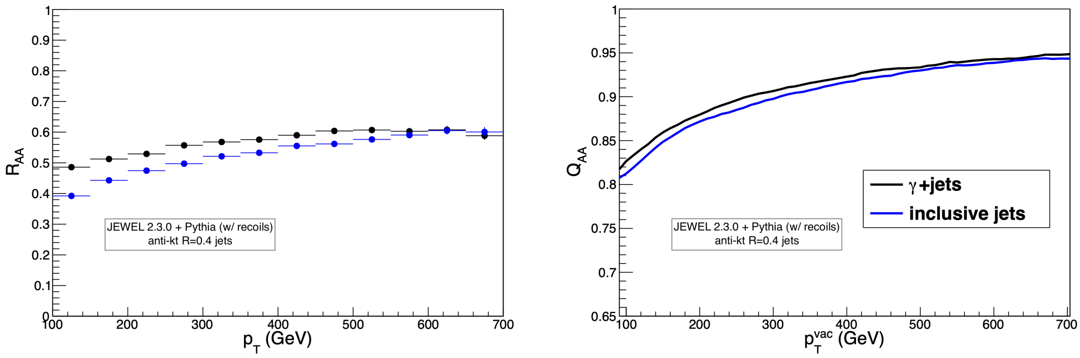

Figure 3: Comparison of γ+jet and inclusive jet R_{AA} (left) and Q_{AA} (right).

the color (Casimir) factor of the parton. Hence, gluon initiated jets would, in principle, lose more energy than quark initiated jets. It is often claimed that this effect is strong enough to produce the large observed difference between the γ+jet R_{AA}, where quark jets are predominant, and inclusive jet R_{AA} [13]. The problem with this conclusion is that it ignores the existence of p_T bin migration exacerbated by the steeply falling nature of the jet p_T spectrum. So, in principle, the γ+jet and inclusive R_{AA} could be different simply because their jet spectra have different steepness values. Furthermore, as was argued in [8], the color factor dependence can be diluted as the jet cascade develops, breaking Casimir scaling. In order to deconvolute bin migration and spectrum shape influence from the actual jet energy loss we can try to calculate the Q_{AA} for γ+jets and dijets and get a less biased estimate. By looking at Fig. 3, we conclude that the relative difference between the two Q_{AA} curves is much smaller than what is observed for R_{AA}. This makes it clear that the difference in spectrum steepness does play a significant role in R_{AA} comparisons.

Finally, one can ask whether measuring the Q_{AA} experimentally is feasible. A possible obstacle to this is that the calculation of the quantile function requires one to integrate the jet p_T spectrum up to infinity. Evidently, one does not have jets being produced with arbitrarily large p_T in nature and the jet spectrum is steeply falling, implying increasingly small sample sizes for larger p_T jets. We can, nevertheless, study the impact of imposing a cutoff on the spectrum. For this, it is useful to cast Eq. (1) in a form particularly useful for spectra with a cutoff:

$$\int_{p_T^v}^{p_T^c} dp_T \frac{d\sigma^v}{dp_T} = \int_{p_T^{q,m}(p_T^v)}^{p_T^{q,m}(p_T^c)} dp_T \frac{d\sigma^m}{dp_T} \tag{4}$$

If the pp spectrum has a cutoff at a value p_T^c then the upper integration limit of the medium spectrum should be $p_T^{q,m}(p_T^c)$ (a lower cutoff than in vacuum), which is not known. Nevertheless, by looking at Fig. 4, where the same cutoff is applied to both spectra, we see that for values of p_T^v sufficiently smaller than p_T^c, the sensitivity to the medium spectrum's upper integration limit is nonexistent. For values comparable to p_T^c, however, the value of this limit becomes relevant and the Q_{AA} loses accuracy. Hence, as long as the range of jet p_T used in an analysis is sufficiently lower than the experimental cutoff, integrating the spectrum only up to a finite value is acceptable.

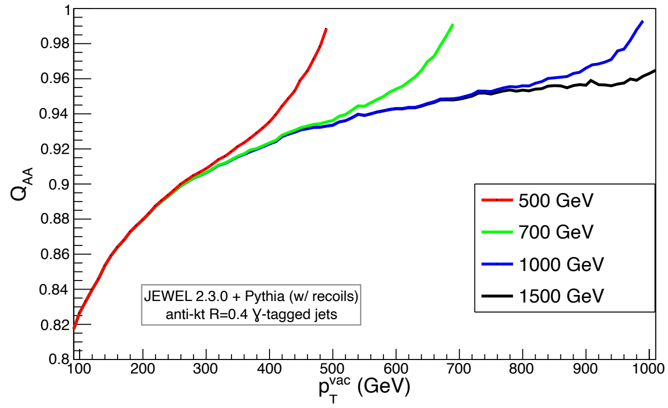

Figure 4: Sensitivity of Q_{AA} to the cutoff of the jet p_T spectrum. Each curve comes from calculating Q_{AA} in Eq. (4) with both upper integration limits equal to a given p_T^c.

Another possible workaround for this obstacle is to use a variant of the Q_{AA}, the pseudo-quantile $\tilde{Q}_{AA}$ [1], to get a better estimate of the quantile value at the cutoff $p_T^{q,m}(p_T^c)$ and thus apply Eq. (4) with approximately matched upper limits. The success of this workaround follows from $\tilde{Q}_{AA}$ and Q_{AA} being in good agreement at large enough p_T.

4. Summary

We present a proxy for selecting samples of vacuum and medium jets that started out with similar p_T without the need for a reference p_T that is only available for boson+jet events. We evaluated the color charge dependence using the Q_{AA} and our first results show it is not as significant as R_{AA} based comparisons suggest. We addressed the experimental feasibility of a Q_{AA} measurement, focusing particularly on the obstacle posed by the spectrum cutoff. The conclusion is that this obstacle is easily circunvented, possibly by using the pseudo-quantile $\tilde{Q}_{AA}$ solely for estimating the quantile that matches the cutoff p_T.

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