Soft modifications to jet fragmentation in high energy proton–proton collisions

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Abstract

The discovery of collectivity in proton–proton collisions, is one of the most puzzling outcomes from the two first runs at LHC, as it points to the possibility of creation of a Quark–Gluon Plasma, earlier believed to only be created in heavy ion collisions. One key observation from heavy ion collisions is still not observed in proton–proton, namely jet-quenching. In this letter it is shown how a model capable of describing soft collective features of proton–proton collisions, also predicts modifications to jet fragmentation properties. With this starting point, several new observables suited for the present and future hunt for jet quenching in small collision systems are proposed.

Keywords: Quark–Gluon Plasma, QCD, Collectivity, Jet quenching, Hadronisation, Monte Carlo generators

1. Introduction

One of the key open questions from Run 1 and Run 2 at the LHC, has been prompted by the observation of collective features in collisions of protons, namely the observation of a near–side ridge [1], as well as strangeness enhancement with multiplicity [2]. Similar features are, in collisions of heavy nuclei, taken as evidence for the emergence of a Quark–Gluon Plasma (QGP) phase, few fm after the collision.

The theoretical picture of collective effects in heavy ion collisions is vastly different from the picture known from proton–proton (pp). Due to the very different geometry of the two system types, interactions in the final state of the collision become dominant in heavy ion collisions, while nearly absent in pp collisions. The geometry of heavy ion collisions is so different from pp collision that in fact even highly energetic jets suffer an energy loss traversing the medium, known as jet quenching.

The ATLAS experiment has recently shown that the ridge remains in events tagged with a Z-boson [3]. While maybe unsurprising by itself, the implication of this measurement is a solid proof that *some* collective behaviour exists in events where a high $p_\perp$ boson is produced, possibly with an accompanying jet. In this letter this observation is taken as a starting point to investigate how the same dynamics producing the ridge in Z-tagged collisions, may also affect jet fragmentation. To investigate this, the microscopic model for collectivity, based on interacting strings [4, 5, 6] is used. The model has been shown to reproduce the near side ridge in minimum bias pp, and has been implemented in the PYTHIA8 event generator [7], allowing one to study its influence also on events containing a Z and a hard jet.

The non-observation of jet quenching in pp and pPb collisions is, though maybe not surprising due to the vastly different geometry, one of the most puzzling features of small system collectivity. If collectivity in small systems is due to final state interactions, it should be possible to also measure its effect on jets. If, on the other hand, collectivity in small collision systems is *not* due to final state interactions, but mostly due to saturation effects in the initial state – as predicted by Color Glass Condensate calculations [8] – the non-observation of jet quenching will follow by construction. The continued search for jet quenching in small systems is therefore expected to be a highly prioritized venue for the upcoming high luminosity phase of LHC [9].

2. The microscopic model for collectivity

Most general features of pp collisions, such as particle multiplicities and jets, can be described by models based on string fragmentation [10, 11]. The confining colour field between partons, is described as a massless relativistic string. In the original model, such strings have no transverse extension, and hadronize independently. The longitudinal kinematics of the i'th breaking is given by the Lund symmetric fragmentation function:

$$f(z) = Nz^{-1}(1-z)^a \exp\left(\frac{-bm_\perp}{z}\right), \tag{1}$$

where z is the fraction of the *remaining* available momentum taken away by the hadron. N is a normalization constant, and a and b are tunable parameters, relating the fragmentation kinematics to the breakup space-time points of the string, which are located around a hyperbola with a proper time of:

$$\langle\tau^2\rangle = \frac{1+a}{b\kappa^2}, \tag{2}$$

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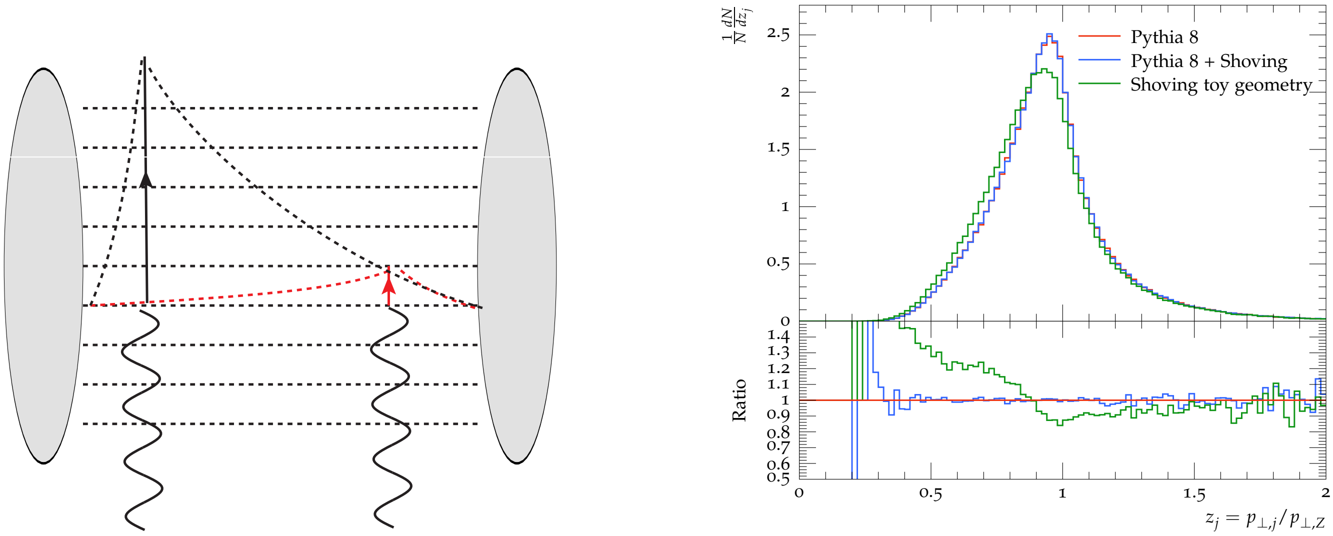

Figure 1: (a) A sketch showing a high multiplicity pp collision in impact parameter space ($\vec{b}$) and rapidity (y), with several MPIs populating the collision with strings. The collision also features a Z boson and a jet. In a normal configuration (black), the hard part of the jet fragments outside the densely populated region. In the used toy geometry (red), the jet is forced to fragment inside the densely populated region. (b) The ratio $z_j = p_{\perp,j}/p_{\perp,z}$ with default Pythia 8 (red), Pythia 8 + shoving with normal event geometry (blue), and the toy event geometry (green).

where $\kappa \sim 1$ GeV/fm is the string tension. The transverse dynamics is determined by the Schwinger result:

$$\frac{d\mathcal{P}}{d^2p_\perp} \propto \kappa \exp\left(\frac{\pi m_\perp^2}{\kappa}\right), \tag{3}$$

where $m_\perp$ is the transverse mass of the *quark* or *diquark* produced in the string breaking[1].

When a $q\bar{q}$ pair moves apart, spanning a string between them, the string length is zero at time $\tau = 0$. To obey causality, also its transverse size must be zero, allowing no interactions between strings for the first short time (< 1 fm/c) after the initial interaction. After this initial transverse expansion, strings may interact with each other, by exerting small transverse shoves on each other. In refs. [4, 5] a model for this interaction was outlined, based on early considerations by Abramowski *et al.* [12]. Assuming that the energy in a string is dominated by a longitudinal colour–electric field, the transverse interaction force per unit string length is for two parallel strings, given by:

$$f(d_\perp) = \frac{g\kappa d_\perp}{\rho^2} \exp\left(-\frac{d_\perp^2}{4\rho^2}\right), \tag{4}$$

where both $d_\perp$ (the transverse separation of the two strings), and ρ (the string transverse width) are time dependent quantities. The parameter g is a free parameter, which should not deviate too far from unity. Equation (2) gives an (average) upper limit for how long time the strings should be allowed to shove each other around, as the strings will eventually hadronize[2]. String hadronization and the shoving model has been implemented in the Pythia 8 event generator, and all predictions in the following are generated using this implementation.

3. Effects on jet hadronization

We consider now a reasonably hard Z-boson, produced back–to–back with a jet. Due to the large $p_\perp$ of the jet, its core will have escaped the transverse region in which shoving takes place well before it is affected. See figure 1 (a, left) in black for a sketch.

In the following simulations, this semi-realistic geometry is created by picking transverse coordinates for each MPI according to the convolution of the two proton mass distributions, which are assumed to be 2D Gaussians. In a heavy ion collision, the jet must still traverse through a densely populated region, due to the much larger geometry. In central Pb–Pb collisions, the observed effect by CMS [13], is that the z_j distribution moves to the left. To investigate whether shoving can give a qualitatively similar signature, a set–up similar to that of the experiment, just for pp collisions at $\sqrt{s} = 7$ TeV, is studied in the following. A Z-boson reconstructed from leptons with 80 GeV< M_Z < 100 GeV, $p_\perp$ > 40 GeV is required, and the leptons are required each to have $p_\perp$ > 10 GeV. The leading anti-$k_\perp$ [14] jet (using FastJet [15] in Rivet [16]) is required to have $p_\perp$ > 80 GeV and $\Delta\phi_{zj} > 3\pi/4$. We study three different situations, with the result given in figure 1 (b).

In red default Pythia 8 is shown, in blue Pythia 8 + shoving, with an event geometry as indicated above with the jet escaping, and in green Pythia 8 + shoving with a toy geometry. In the toy geometry, the jet is placed in origo, and strings are allowed to shove each other already from the initial interaction, thus

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[1] The formalism does dictate whether to use current or constituent quark masses. In Pythia the supression factors s/u and diquark/quark are therefore determined from data, with resulting quark masses providing a consistency check.

[2] Eq. (2) is written up with a string in vacuum in mind. It might be possible that the string life time is modified in the dense environment of a heavy ion collision.

violating causality. This has the effect that the strings of the underlying event are allowed to shove even the hardest fragment of the jet. The toy model is clearly not a realistic picture of a pp interaction, but is implemented in order to give an effect similar to what one would expect from a heavy ion collision, where the event geometry allows strings from other nucleon–nucleon sub–collisions, to interact also with the hardest jet fragment. The toy model is sketched in figure 1 (a, right) in red, compared to the normal, more realistic setup in black. In the normal setup, the strings are allowed to propagate for a finite time, indicating the time it takes for the strings to grow from infinitesimal transverse size, to their equilibrium size.

While shoving in a toy geometry produces an effect qualitatively similar to what one would expect from jet quenching, the effect in a realistic geometry is far too suppressed (comparing blue to red in figure 1 (b)). Several suggestions exist for overcoming this geometric suppression, prominently using jet substructure observables [17], or *e.g.* using a delayed signal from top decays [18] (in AA collisions). In the remaining paper another approach will be described. Instead of looking for deviations in the spectrum of a narrow jet compared to a "vacuum" expectation, we start from the wide-R ($R^2 = \Delta\eta^2 + \Delta\phi^2$) part where collectivity in the form of a ridge is known to exists even in pp collisions. The same observable is then calculated as function of R, all the way to the core, where the soft modification is expected to vanish.

4. Near side ridge in Z-tagged events

The ridge, as recently measured by ATLAS in events with a Z boson present [3], provides an opportunity. The requirement of a Z boson makes the events in question very similar to the events studied above. The Z does not influence the effect of the shoving model, and in figure 2 we show high multiplicity events with and without shoving, with the appearance of a ridge in the latter – in accordance with the experimental results[3].

It is instructive to discuss the result of figure 2 with the sketch in figure 1 (a) in mind. Since the ridge analysis requires a $|\Delta\eta|$ gap of 2.5, the jet region is, by construction, cut away. (Keeping in mind that in this case there is no required jet trigger.) The underlying event does, however, continue through the central rapidity range, and even "under" the jet, a ridge should be visible, if only one could perform a true separation of jet particles from underlying event particles in an experiment. If that is not possible, it is reasonable to naively ask if the presence of a ridge in the underlying event will by itself give rise to a shift in z_j. The result in figure 1 (b) (blue line) suggests that it does not.

5. Influence on jet observables

As the ATLAS measurement has established, there is indeed collectivity present in (high multiplicity) events with a Z present. In the previous section it was shown that the measured signature can be adequately described by the shoving model. Now the situation will be extended to include also a high-$p_\perp$ jet trigger in the same way as in section 3, and the effect of the collective behaviour on the jet will be discussed.

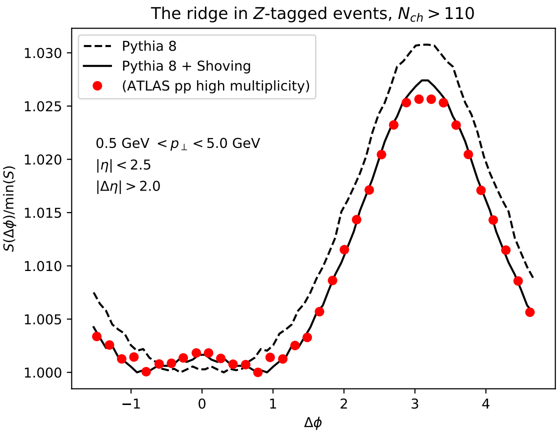

Figure 2: The ridge in Z-tagged, high multiplicity pp collisions at 8 TeV, with default Pythia 8 (dashed line, no ridge), and Pythia 8 + shoving (full line, ridge). Simulation is compared to preliminary ATLAS data [3].

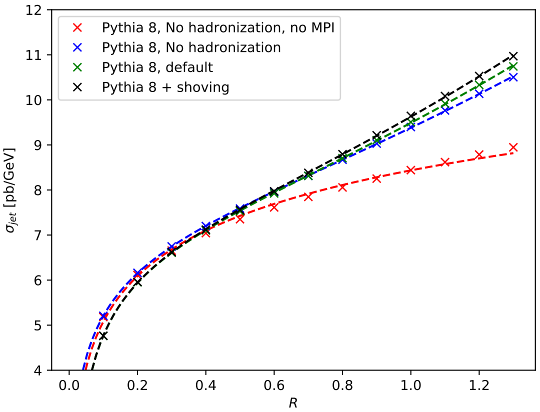

Figure 3: The R dependence of σ_j for four configurations of the leading jet in Z+jet in pp collisions at 7 TeV. Special attention is given to the difference between Pythia default and Pythia + shoving in the large-R limit.

From equations (1) and (3) we see that two physical quantities are present in the hadronization model and its modification, namely the hadron $p_\perp$ and the mass[4]. These quantities need to be cast into observables that provide information about the full jet. This will be done in the following, and the effect of the shoving model examined.

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[3] The simulation is compared to preliminary ATLAS data, with the caveat that the analysis procedure is very simplistic compared to the experimental one. Instead of mixing signal events with a background sample, distributions are instead divided each with their minimum to obtain comparable scales.

[4] In eq. (3) the relevant mass is the quark mass, but once the quark content of a hadron is decided, also the hadron mass is determined.

[pb/GeV]	No MPI, no had.	No had.	Default	Shoving
A	1.46 ± 0.03	1.31 ± 0.01	1.28 ± 0.04	1.29 ± 0.05
B	8.44 ± 0.03	8.22 ± 0.01	8.18 ± 0.02	8.19 ± 0.03
C	-	1.16 ± 0.01	1.35 ± 0.03	1.49 ± 0.03
D	-	-	0.05 ± 0.01	0.05 ± 0.01

Table 1: Parameters obtained by fitting equation (6) to Pythia 8. Errors are fit errors (1σ), fits shown in figure 3.

5.1. *Effect on jet-$p_\perp$: The jet cross section*

As there is little effect on the raw jet-$p_\perp$ spectra, the jet cross section is introduced:

$$\sigma_j = \int_{p_{\perp,0}}^{\infty} dp_{\perp,j} \frac{d\sigma}{dp_{\perp,j}}, \tag{5}$$

where $p_{\perp,j}$ is the $p_\perp$ of the leading jet in the event, and $p_{\perp,0}$ is the imposed phase space cut–off. It was pointed out by Ellis *et al.* [19], that the R-dependence of σ_j under the influence of MPIs in a pp collision, can be parametrized as $A + B\log(R) + CR^2$. Later Dasgupta *et al.* [20] noted that hadronization effects contributes like $-1/R$. This gives a total parametrization:

$$\sigma_j(R) = A + B\log(R) + CR^2 - DR^{-1}. \tag{6}$$

By construction, the ridge effect from the previous chapter is far away from the jet in η, and therefore also in R. Any contribution from shoving can be reasonably expected to be most pronounced for large R. Equation (4) gives a contribution of $\langle dp_\perp/d\eta\rangle \propto f(\langle d_\perp\rangle)$, where $\langle d_\perp\rangle$ is density dependent. In the previously introduced semi-realistic geometry, we would therefore expect a contribution to σ_j, which is $\propto R^2$, *i.e.* a correction to the parameter C in equation (6).

In figure 3, $\sigma_j(R)$ is shown without MPIs and hadronization (red), with MPI, no hadronization (blue), Pythia 8 default (green) and Pythia 8 + shoving (black). The analysis setup is the same as in section 3. Results from the Monte Carlo is shown as crosses, and the resulting fits as dashed lines, with parameters given in table 1.

From the fits it is visible that shoving contributes to the R^2 dependence as expected. Directly from figure 3 it is visible that shoving contributes to the jet cross section at a level comparable to hadronization effects.

In order to use this procedure to set limits on jet quenching in small systems, comparison must be made to predictions. In figure 3 only LO predictions are given, but while NLO corrections are sizeable enough that figure 3 cannot be taken as a numerically accurate prediction, such corrections will not affect the relative change in σ_j with and without shoving, and will not affect the result. More crucial is the effect of parton density uncertainties, which may affect σ_j up to 10% for this process [21]. This points to the necessity of more precise determinations of PDFs, if microscopic non-perturbative effects on hard probes in pp collisions are to be fully understood.

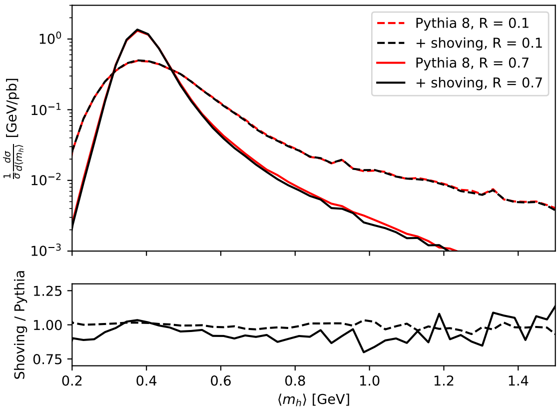

Figure 4: The average hadron mass in the leading anti-$k_\perp$ jet with $R = 0.1$ (dashed) and $R = 0.7$ (full) in Z+jet, using default Pythia (red) and Pythia + shoving (black). The deviation imposed by shoving grows larger with increasing R.

5.2. *Soft measures: Average hadron mass and charge*

The hadrochemistry of the jet is here quantified in a quite inclusive manner by the average hadron mass:

$$\langle m_h\rangle = \frac{1}{N_p}\sum_i^{N_p} m_{h,i}, \tag{7}$$

where N_p is the number of hadrons in the jet, and m_h are the individual hadron masses. Furthermore the total jet charge is studied:

$$Q_j = \frac{1}{N_p}\sum_i^{N_p} q_{h,i}, \tag{8}$$

where q_i are the individual hadron electric charges. As shoving only affects these quantities indirectly, the predicted effect is not as straight forward as was the case for jet cross section, but requires a full simulation to provide predictions. In figure 4 the average hadron mass in the leading jet (still in Z+jet collisions as above) is shown for two exemplary values of R. For small R, $\langle m_h\rangle$ is unchanged, but as R grows, a significant change, on the order of 10% is visible.

The Q_j distribution for $R = 0.3$ jets is shown in figure 5. It is seen directly, that for this particular value of R, shoving widens the distribution, and also the mean is further shifted in the positive direction. The R-dependency of this behaviour is shown in figure 6. Here both the mean and the width of the jet distribution at different values of R is shown (note the different scales on the axes). It is seen that this observables shows deviations up to 40% in the large-R limit. Jet identification techniques to reveal whether the seed parton is a gluon or a quark [22] might be able to increase the discriminatory power even further.

It should be noted that the jet charge has been a challenge for fragmentation models since the days of e^+e^- collisions at LEP [23]. The renewed interest in fragmentation properties from the observation of collectivity in small systems provides a good opportunity to also go back and revisit older observations.

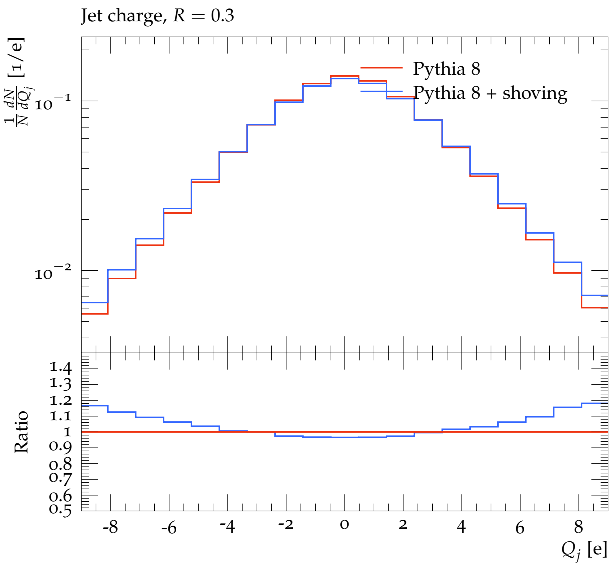

Figure 5: An example of a jet charge distribution for the leading anti-$k_\perp$ jet in Z+jet with $R = 0.3$. Shoving has the effect of making the distribution wider.

The jet hadrochemistry can be studied in a more exclusive manner, by means of particle identification, similar to what is done in nuclear collisions. Such observables will also be largely affected by formation of colour multiplets, increasing the string tension [24, 6]. Some studies of this effect in jets in pp collisions have been performed [25], but could require further attention to the important space–time structure, as described in section 3. Such detailed studies will be deferred to a future publication.

6. Conclusions

The non-observation of jet quenching in small systems is one of the key open questions to understand collective behaviour, similar to those in heavy ion collisions, in collisions of protons. For the coming high luminosity era at LHC, the search for new observables to either observe jet quenching, or provide quantitative exclusion limits is necessary. In this letter we have shown that the microscopic model for collectivity implemented in Pythia 8, can reproduce one observed collective feature already observed in pp collisions with a hard probe, namely the ridge in Z tagged events, as observed by ATLAS. Basic features like z_j are, however, unaffected, but highly sensitive to the collision geometry. In this letter it was shown that, for a toy event geometry, the model produces features similar to those observed in Pb–Pb collisions by CMS. The toy geometry study highlights the need for a better motivated theoretical description of the space–time structure of the initial state. The realization that the complicated interplay between fragmentation time and spatial structure is significant for precision predictions, dates back to the 1980's for collisions of nuclei [26]. With the discovery of small system collectivity, several approaches have been developed also for pp collisions (*e.g.* [27, 28, 29]), most (but not all) aiming for a description of flow effects. It is crucial for the future efforts that such space–time models attempt at describing both soft and hard observables at once, in order to avoid "overtuning" of sensitive parameters. In this letter it was done by first describing the ridge in Z-tagged events, and then proceed to investigate jet observables with the same parameters.

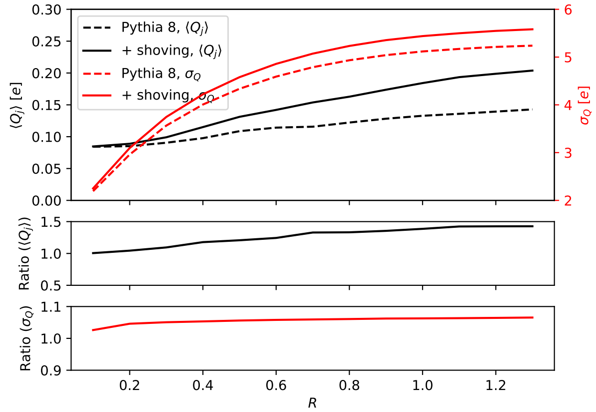

Figure 6: R-dependency of the average jet charge and the distribution (see fig. 5) width with and without shoving. Note the different scales for the two quantities.

The major contribution of this letter is the proposal of several new observables to understand the effects on jet fragmentation from the shoving model in Z+jet events. The main idea behind these observables is to go from the wide-R region (wide jets), where collective effects, in form of the ridge, is already observed, to the very core of the jet, where only little effect is expected. The jet-$p_\perp$ is only affected little, and the observed 5% effect on the integrated quantity σ_j, will be difficult to observe when also taking into account uncertainties from PDFs an NLO corrections, but nevertheless provides a crucial challenge for the upcoming high luminosity experiments at LHC, where larger statistics can help constraining the theoretical uncertainties better. More promising are the effects observed on hadron properties inside the jet, where the average hadron mass shows a 10% deviation and jet charge even larger. Even if an effect this large is not observed in experiment, its non-observation will aide the understanding of soft collective effects better, as the shoving model predicting the effect, adequately describes the ridge in Z-tagged collisions.

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