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A priority based noise tolerant jet framework and algorithm

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Abstract: We introduce a new framework for jet definitions called p-jets that matches the computational speed of the currently used anti-k_T jet algorithm, but avoids combining much of the energy from background pileup events with signal jets. As a first illustration of the p-jet framework, we compare the effectiveness of a p-jet algorithm to the anti-k_T algorithm in reconstructing low energy jets from resonant Z boson production and 50 pileup events.

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Contents

1 Introduction

In the culmination of five decades of experimental searches, the Large Hadron Collider (LHC) at CERN was successful in its runs at 7 TeV and 8 TeV in discovering a Higgs boson [1, 2], the last particle of the standard model, and in making significant improvements to many standard model measurements. In the coming 13 and 14 TeV runs, the LHC will further refine these measurements, and search for evidence of physics beyond the standard model (BSM). Existing limits from searches for BSM particles suggest their production is rare, and if they are found they will likely have one of two detection signatures: either the particles will decay to a small number of well-measured highly energetic objects, or decay to a large number of low energy QCD jets through cascade decays. The signature of low energy (40–60 GeV) jets is a common signal for supersymmetric particles [3] and standard model backgrounds alike. Unfortunately, while highly energetic objects will be well understood, low energy jets will be highly subject to interpretation based on choice of jet algorithm, and on a background that will dominate low energy objects at the LHC.

During the LHC's high energy runs, the number of proton-proton interactions per beam crossing (pileup) will increase from around 20 in the 8 TeV run to 50–140 in the 13 and 14 TeV runs. The large number of simultaneous events will cause significant degradation of both energy resolution and event distinction. For high energy objects the energy contribution from this pileup will be insignificant, but the energy contribution from pileup to low energy objects will be on the order of the energy contribution for the physics processes themselves, resulting in a very low signal to noise ratio. An example of how severe this effect can be is illustrated in Ref. [4]; that study concentrated on the effect of pileup for top quark reconstruction, but the reconstruction of a W boson from dijets is most alarming. With 50 pileup events the reconstructed width of a W approximately doubles, and by 140 pileup events (predicted at the end of a planned luminosity upgrade), the $W \to$ dijet "peak" is nothing more than a falling spectrum. While relatively new to particle physics, this challenge of a large QCD radiation background has long been a limiting factor for jet analyses in heavy-ion collisions. Existing jet algorithms are insufficient to overcome the worst of these backgrounds, hence the need for a qualitatively new framework for jet reconstruction.

In recognition of the coming challenges for jet reconstruction, two paths have been actively pursued. The first is a shift in concentration to the production of high energy jets that would come from the tails of production cross sections. The search for jet substructure [5–7] and boosted jet algorithms [8] show great promise where applicable, but ignore the bulk of the production cross sections, such as the thresholds of all known standard model particles. An alternate series of methods have been proposed to deal with pileup. These range from selective subtraction of energy in the detector to only clustering energy in the tracker (charged tracks) [9–12]. These proposals have some merit in reconstructing large numbers of events, but they share one restriction: they require a statistically large sample for their event-by-event misreconstructions to cancel. This reduces their effectiveness in reconstructing rare events with low energy jets. Most of the BSM processes physicists hope to observe will not have enough events for this cancellation to occur. The result of this is a significant reduction of discovery potential and sensitivity to precision standard model physics.

The difficulties with current jet definitions can be traced to the origin of the concept of jet clustering. Since the observation of jets at PETRA [13], a typical final state with QCD radiation in high energy physics has consisted of a small number of collimated, well isolated groups of hadrons. These groups of hadrons are classified as jets, and various "jet algorithms" were developed to accurately include as much of this energy in a given jet as possible. These jet algorithms have evolved much over the years, but the underlying assumption of isolated jets is still present; the problem is that with 50–140 pileup events this assumption is no longer valid. This paper proposes a new jet framework designed to work in an intrinsically noisy QCD environment. Instead of fully-reconstructed isolated clusters of QCD radiation being the dominant feature of measurements, jets will be small peaks of highly correlated energy sitting on a loosely correlated sea of background noise.

The method of clustering we propose begins with the reminder that, while QCD radiation does tend to peak in particular directions, in hadron colliders it is part of a continuum that connects the beam remnants to energetic regions in the detector. Since detector resolutions and pileup imply we cannot reconstruct all of the QCD radiation spectrum from any given event, we include only a well understood core of the energy that would compose a traditional jet, and compensate for the expected energy outside the small core included. This philosophy embodies itself in the structure of our jet algorithm, the p-jet algorithm; unlike the jet algorithms commonly used in the LHC analyses, known as sequential recombination algorithms, the p-jet algorithm invokes a threshold for inclusion of energy into a cluster that increases as the energy of the jet increases. The ultimate goals of this algorithm are to be unique and stable in the expected high background environment of a 14 TeV LHC, and to maintain accurate reconstruction of states from a low number of events. In section 2 we introduce the p-jet framework, and in section 3 demonstrate a proof of concept with an explicit jet algorithm that can reconstruct resonant Z boson production in a 50 pileup event environment.

2 The p-jet framework and algorithm

In most modern collider experiments, calorimeter towers are clustered into jets using a few sequential recombination algorithms, where objects are combined in order of the smallest measurement of a "distance" metric. The distance metric is measured in the space of pseudorapidity η or rapidity, related to the angle relative to the beam, and the azimuthal angle ϕ. Sequential recombination algorithms are distinguished by their the energy weighting, using some power of the transverse momentum p_T or transverse energy E_T to prioritize which towers are combined first.

The typical distance measure for modern recombination algorithms is

$$d_{ij} = \min(p_{Ti}^{2k}, p_{Tj}^{2k}) \frac{\Delta R_{ij}}{R_{\max}} < p_{Ti}^{2k}\,, \tag{2.1}$$

with

$$\Delta R_{ij} = \sqrt{\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2}\,. \tag{2.2}$$

The power k embodies the choice to prioritize either high or low energetic towers; $k = 1$ clusters low energy objects first (the k_T algorithm [14]), and $k = -1$ clusters high energy objects first (the anti-k_T algorithm [15]). The anti-k_T algorithm has the ability to form nearly conical jets of radius $R_{\max}$, and it is often used to reconstruct non-boosted jets. The choice of $k = 0$ is called the Cambridge-Aachen algorithm, and is frequently used in boosted object algorithms ($p_T >$ 300–500 GeV) and jet substructure studies [5–8]. In this paper we compare to the anti-k_T algorithm for low energy jets, as this is main choice currently in use by the ATLAS and CMS physics groups.

Sequential recombination algorithms operate via the following procedure:

1. Identify all objects to be grouped.
2. Create a list of distances (d_{ij}) between all reconstructed objects i and j.
3. Identify the smallest distance.
4. Combine objects with smallest distance into a cluster.
5. Recalculate all distances between objects, including the cluster as an object.
6. If a $\Delta R_{ij} < R_{\max}$, return to step 3, else clustering is finished.
7. Apply a jet energy correction to the clusters we now call jets.

The anti-k_T version of this algorithm presents a problem for reconstruction in a high pileup environment. The jets it produces are typically cones of radius $R_{\max}$. This allows for simple subtraction of pileup energy based on an estimate of the average noise in the cone's area, but it is highly dependent on a well modeled pileup environment in the region of space around the physical jet.

In any single event the subtraction behaves poorly for light jets, since the pileup noise is a significant fraction of overall anti-k_T jet energy. In addition, the anti-k_T algorithm's "strength" of having well defined jet sizes does not match the physics of the QCD radiation spectrum; the more energetic an anti-k_T jet is, the more likely it is to take up the entire $\pi R_{\max}^2$ phase space due to the inverse energy weighting in d_{ij}. A real high energy jet is boosted such that most of its energy is concentrated in a small cone, while low energy jets have a wide angular distribution of energy — the opposite of the shape of the anti-k_T algorithm.

A new jet algorithm is needed to accurately deal with pileup. This algorithm should satisfy several key features:

1. It should include a significant fraction of the QCD radiation from the hard physics process of interest, while rejecting the bulk of the noise from pileup.
2. It should have a well understood theoretical basis for comparison between experimental objects and theory calculations. This includes retaining both infrared and collinear safety to allow quantities to be theoretically derived.
3. It should be tuned to the shape of the QCD radiation spectrum.
4. It should perform at least as well as anti-k_T in jet reconstructions in low pileup, and outperform in high pileup environments.
5. It needs to work on an event-by-event basis, rather than require statistical cancellations to average out misreconstructions and pileup subtraction.

The p-jet framework we present essentially replaces the distance measure with a new "priority" measure p_{ij}, which can be understood as the percentage of a jet's energy above the threshold of another jet

$$p_{ij} = \max\left(\frac{E_j}{E_i} - T(\Delta R_{ij}), 0\right), \tag{2.3}$$

where $E_i \geq E_j$, and the threshold function $T \in [0, 1]$ specifies the algorithm, and is chosen below. This threshold function sets the "p-jet" algorithm apart from the anti-k_T family, since it no longer guarantees a nearby energy cluster will be absorbed; only objects with energy above the threshold are considered for clustering. This threshold is designed to assure that collinear jets are combined, but non-collinear noise (from low-level radiation and pileup) is ignored. A proper choice of T will also have the strength that it roughly matches the QCD radiation spectrum. The priority function should be proportional to energy so that high energy jets will be narrower than low energy jets, i.e., low energy objects away from the main cluster will be ignored. With the exception of the distance function's replacement with a priority function, the recombination and p-jet frameworks share a similar overall structure and speed.

The p-jet framework mirrors a recombination algorithm procedurally:

1. Identify all objects to be grouped.
2. Create priority lists p_{ij} of all objects i on all objects j.

3. Identify the largest priority (closest to 1).
4. Combine objects with largest priority into a cluster a.
5. Recalculate all *changed* priorities, (p_{ia}, p_{ai}), where the cluster is treated as a new object.
6. If a non-zero priority exists, return to step 3. If all priorities are 0, proceed.
7. Apply a jet energy correction to final clusters we call jets.

The above framework can be used to build an explicit jet algorithm with a suitable choice of threshold function T. The difference between this framework and the sequential recombination algorithms is the priority function, whose difference from an arbitrary distance measure is its distance-dependent energy-based threshold for inclusion. As an explicit example we choose a threshold function which is designed to approximate the dominant QCD dipole radiation spectrum as closely as possible,

$$T(\Delta R_{ij}) = 2\sin\left(4\pi\frac{\Delta R_{ij}}{R_{\max}}\right). \tag{2.4}$$

Matching the exact QCD spectrum is not absolutely necessary, but an approximation is desirable as it enhances the ratio of signal to noise without losing too much of the original signal. The general guidelines for any threshold function are as follows: The threshold must be 0 at the origin and be monotonically increasing or flat. The k_T algorithm can be thought of as a limiting case of the p-jet family, where we set the threshold function to be $T(\Delta R_{ij}) = \Theta(\Delta R_{ij} - R_{\max})$, i.e., set the threshold to 0 within the radius of $R_{\max}$.

Pileup will have an approximately isotropic distribution due to its source (low energy proton-proton scatterings). The loosely correlated assortment of pileup in any given crossing can be subtracted from anti-k_T jets using a local area-based subtraction. This is typically calculated in anti-k_T algorithms by introducing "ghost" particles across the detector with 0 energy and keeping track of which jet the ghost is clustered into. The area encapsulated by the ghosts can be then used to estimate how much energy to subtract from the anti-k_T jets. For a large number of events this *average* subtraction will be correct. For a small number of events, such as those in a discovery search, this average subtraction method will reduce the jet energy resolution and lead to a broadening of any potential mass peak.

Formally, any nontrivial p-jet threshold function produces a zero-area jet, because the pairwise addition of energies above the thresholds combines isolated points with zero area support. This implies an area-based subtraction of pileup for p-jets is unnecessary. Finite detector resolutions, found for example in physical calorimeter towers, reintroduce small effective areas to the objects that are summed. Hence, some area subtraction could be introduced, but we find it is generally not helpful. Because significantly less pileup is included into the jets by construction, there is no need for a large statistical average to cancel out background fluctuations. This leads to smaller jet energy corrections, faster reconstructions, and better mass resolution in high pileup p-jet analyses than in corresponding anti-k_T analyses.

3 Benchmark Z boson reconstruction

We benchmark the p-jet framework, and the threshold function given by eq. 2.4, by simulating reconstruction of resonant production of Z bosons decaying to dijets, and comparing to anti-k_T jets. Although the purpose of p-jets is to perform well in a high pileup environment, we consider reconstruction with a moderate 50 minimum-bias events on top of the dijet signal, as this is closer to the current environment at the LHC. The simulation uses MadEvent 4 [16] to produce $Z \to q\bar{q}$, and PYTHIA 6 [17] for showering, hadronization, and minimum-bias event generation. In order to compare similar size jets, all reconstructions use $R_{\max} = 0.5$.

We use tracking information to distinguish vertices resulting from the Z decay from the pileup events.[1] To simulate the tracking information available in a detector, the stable charged particles from PYTHIA are identified with their original vertex. These tracked particles are then clustered normally, and the resultant jets are then associated with their dominant vertices. Although each jet will contain particles from several vertices, only a subset of those vertices are likely candidates. We considered two metrics to categorize the jets: the number of charged particles inside the jet, or the energy from charged particles inside the jet. Since particles from pileup are not coming from hard interactions, and tend to be lower in energy and widely distributed, we choose to assign jets to the vertex that contributed the most charged energy to a given jet. More energetic and tightly clustered groups of particles are likely coming from the hard interaction, so they will add a significant amount of energy to only a few jets. This means that an energy-weighted charged track count is better able to distinguish between jets from the hard interaction and the minimum bias interactions, regardless of the actual number of charged particles produced.

By construction we miss some of the hadrons which originate with the hard process. To correct for the missing energy (or remove residual pileup energy) we apply a jet energy correction (JEC). We characterize the JEC for p-jets (and anti-k_T, for comparison purposes) on a jet-by-jet basis using Z+jet balancing. The JEC for any algorithm can always be fit to a known resonant state, but we are interested in the relative performance under the supposition that we may not know what new state we are looking for. To calculate the JEC we simulate $pp \to Zj$ in MadEvent, hadronize in PYTHIA, and then cluster. The energy of the partons (from MadEvent) and the corresponding jets (from the clustered algorithm) are compared, and a correction curve is calculated to adjust the energy of the jets back to that of the original parton.

One subtlety of the JEC is that it must be calculated for each pileup environment. We compare the performance of the algorithms below by considering the energy contribution from pileup to the predominately "real" jets in three forms: Subtract the typical energy from pileup from each cell in the detector before clustering, subtract the pileup energy from each clustered jet based on its size, or allow the energy-based JEC to do all energy adjustment. If the JEC is left to account for pileup by itself, the correction approaches -40% for anti-k_T, and the p-jet correction is slightly less. If a per-cell subtraction is done before clustering,

[1] In this version of the algorithm we make no use of tracking information to improve jet energy resolution or scale. This is clearly an area for improvement in future implementations.

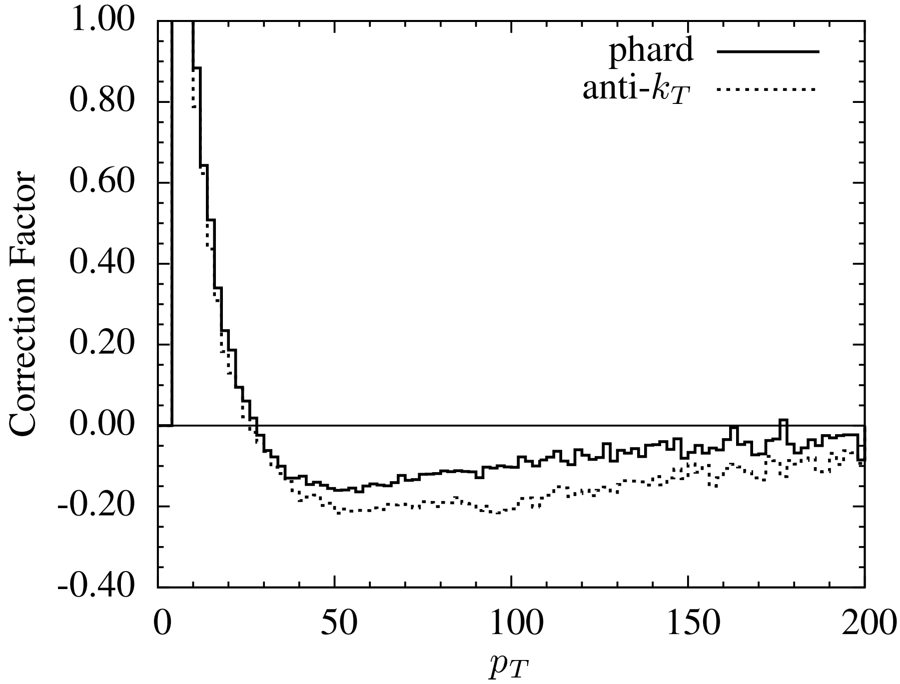

Figure 1. The fractional jet energy correction for p-jets and anti-k_T jets (using an area-based subtraction scheme) from $Z + j$ balancing with 50 events of pileup.

the JEC shrinks significantly. With an area-based subtraction after clustering, the JEC shrinks to a minimum for the options considered, but still remains negative for most jets.

The jet energy correction required for p-jets is positive and greater than for anti-k_T jets before pileup is added. This is due to stricter requirements for energy inclusion in p-jets (proximity *and* energy rather than just proximity) than in anti-k_T jets. The JEC calculated in the presence of pileup is generally negative — very energetic jets cluster more energy from pileup than is lost by the truncated size of the jet. Due to its stricter requirements for clustering, the p-jet correction is less severe (shown in figure 1), in this case being much closer to 0, than the correction for anti-k_T jets, which is strongly negative, even after an area based subtraction is implemented. The relatively small JEC is a sign that the p-jet framework is successful in its goals to attenuate the effects of pileup, while retaining the primary jets.

When we apply a jet energy correction, but do not do any per cell energy subtraction, the p-jet algorithm performs significantly better than anti-k_T in reconstructing the position of the $Z \to$ dijet invariant mass peak, and in energy resolution. As we see in figure 2, the 102 GeV reconstructed mass from p-jets is slightly higher than the Z boson mass of 91 GeV, but slight shifts are expected when using single-jet calibration to model dijet samples. The jet energy resolution leads to a reconstructed width of 53 GeV. The anti-k_T algorithm, by contrast reconstructs a central value of 188 GeV with a width of 82 GeV. Current analyses typically perform additional corrections to improve anti-k_T jets, but the p-jet algorithm is already performant.

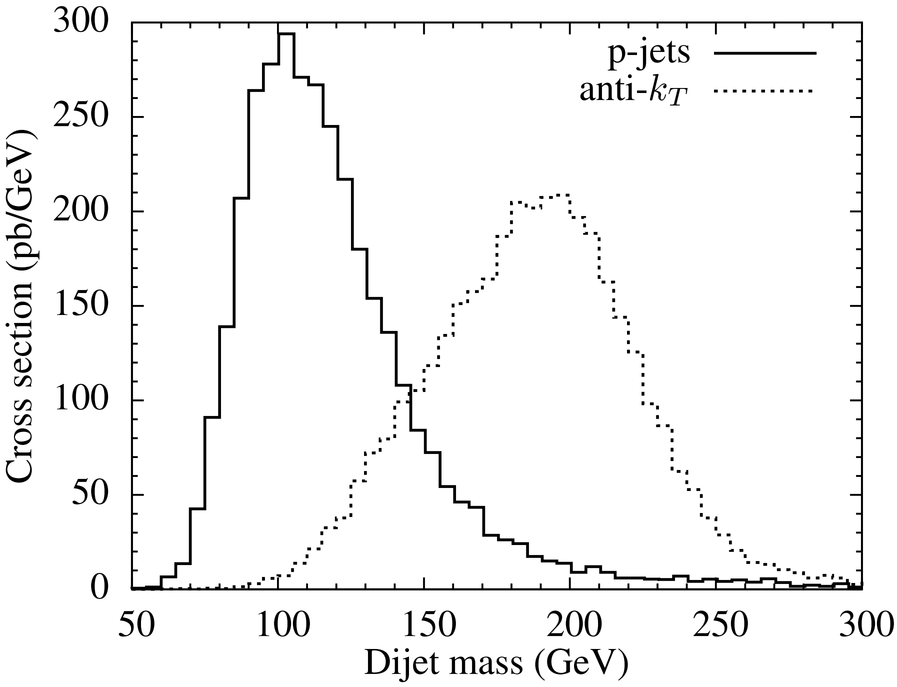

Figure 2. The reconstructed dijet mass peak from Z boson decay in 50 events of pileup using p-jets and anti-k_T jets after the jet energy correction.

A fairer comparison to anti-k_T involves additional subtractions from the anti-k_T jets tuned to the local jet environment [9–12]. If a per-cell energy subtraction is performed before clustering, the resultant anti-k_T mass peak is reduced to 147 GeV with a width of 73 GeV, but has a long tail to higher energies. P-jets perform slightly worse with subtractions (105 GeV with a 60 GeV width), as is expected since p-jets are formally zero-area jets — there is no energy×area to subtract, so we are merely adding noise. The best Z boson reconstruction for anti-k_T jets is obtained by performing an area-based subtraction after reconstruction. In figure 3 we see the best reconstruction of both algorithms, where anti-k_T reconstructed jets with area subtraction lead to a mass measurement of 122 GeV and a width of 68 GeV. This compares to the simple JEC p-jet of 102 GeV and width of 53 GeV above.

While anti-k_T jets can be further improved, our analysis illustrates that without additional reclustering techniques, such as pruning, p-jets outperforms anti-k_T in the presence of pileup. It is tempting to think these techniques will produce jets equivalent to p-jets given that, like p-jets, they remove soft energy from the jet. However, recalling eq. 2.4, the p-jet threshold function we choose removes that energy predominantly from the tails of the dipole radiation spectrum with only the softest radiation removed near the core of the jet. This represents the philosophy behind the p-jet definition — we cannot tell the difference between small fluctuations and low-energy pileup, but those fluctuations are expected by the real radiation spectrum. Hence, we do not want to artificially remove them as would be done by equivalently uniformly raising the reconstruction energy threshold.

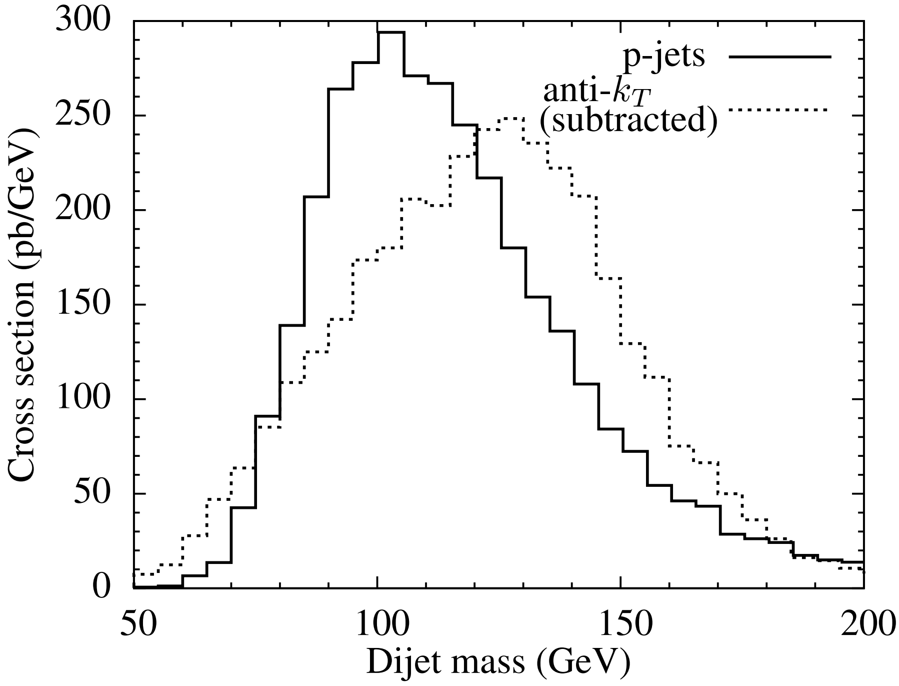

Figure 3. The best reconstructed dijet mass peak from Z boson decay in 50 events of pileup. The p-jet reconstruction includes a JEC. The anti-k_T jets include both a JEC and a jet-area based energy subtraction.

For a simple channel, such as $Z \to$ dijets, both p-jets and well-calibrated anti-k_T can reconstruct to similar results. The algorithms, however, do lead to differences in detail at the level of a single event. We conclude this section by examining in figure 4 a single Z decay with a hard initial state radiation before and after pileup are included. Before pileup we see that p-jets and anti-k_T jets reconstruct similar clusters, but anti-k_T swaps the order of the leading and second jet (when compared to the "truth" level). After pileup is added, both algorithms find jets with the same relative energy ordering, but clearly the p-jets are physically smaller. As expected, anti-k_T jets form compact cones of uniform size, regardless of the the distribution of the energy in the event. This is a reminder that p-jets are much more like those that would be found by a k_T algorithm.

The effectiveness of our choice of charged-particle energy vertex association also appears in the pileup graphs of figure 4. E.g., the large tower at $\eta = -3$ is not associated with our signal. Other large energy towers are due to the random overlap from multiple vertices, and are ignored by our clustering technique. Our the p-jet procedure is found to give a robust and unique reconstruction, even in high density environments.

4 Conclusions

We present a new priority-based framework, called "p-jets," for the reconstruction of jets in high luminosity environments. Within the p-jet framework, we examine one possible algorithm defined by its threshold function T designed to capture the dominant QCD dipole

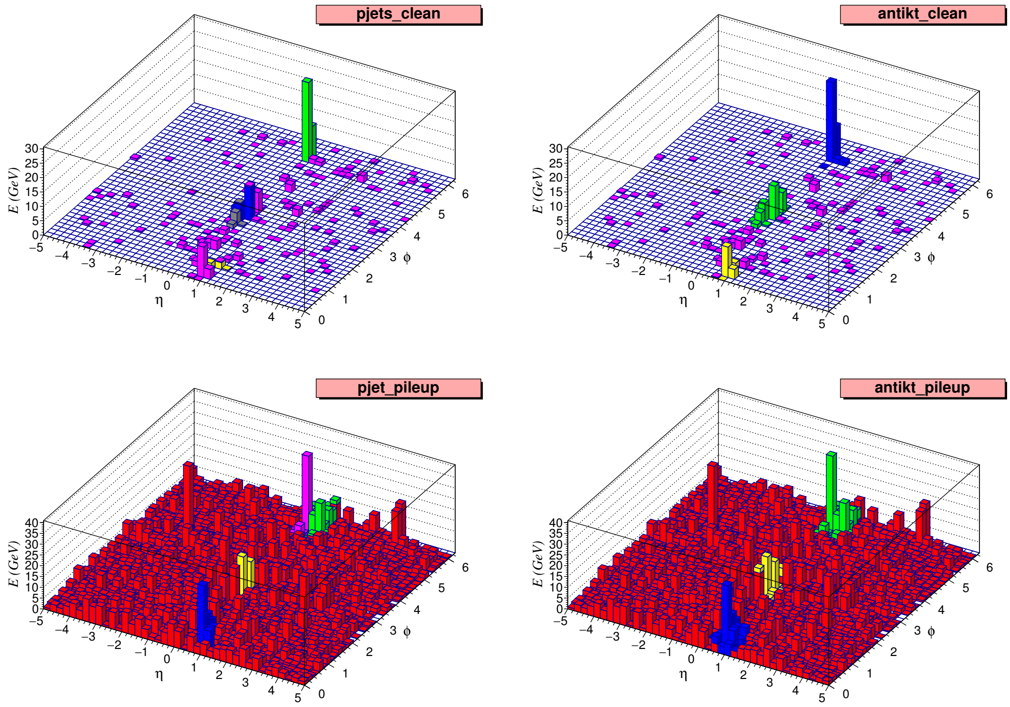

Figure 4. A resonant Z boson decay to dijets with initial state radiation reconstructed with (left) p-jets and (right) anti-k_T jets with (top) no pileup or (bottom) 50 pileup events.

shower. As a proof of principle, we show that resonant Z boson production into dijets in high pileup is better reconstructed by p-jets, than by the commonly used anti-k_T algorithm unless significant additional corrections are applied to anti-k_T to subtract noise absorbed within the jet cone. Other than a jet energy correction, which is applied to any jet, p-jets reach their potential without additional subtractions as they are formally zero-area jets, and avoid most pileup by construction.

The algorithm presented here is a starting point for p-jets. Similar quality of fit can be obtained for the modest luminosity examined here using jet pruning and trimming techniques that recluster jets, rather than avoiding noise absorption in the initial clustering. P-jets should be examined under a broad range of pileup scenarios, and for a variety of jet threshold functions. Ideally the choice of threshold function would be optimized to improve signal extraction from physics backgrounds. For example, light quark or gluon-initiated jets tend to have wider showers than heavy-quark initiated jets. A threshold function designed to reflect this could be used to improve b or c tagging.

The p-jet framework offers a new robust method for clustering QCD radiation that is highly tolerant to noisy conditions, such as from pileup in high luminosity colliders. With a speed comparable to existing algorithms, it should allow the capture of additional structure on and event-by-event basis — precisely what is needed for rare BSM searches.

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A Small angle limit and infrared safety

In QCD a jet algorithm removes singularities in a cross section (σ) calculation that arise in the perturbative calculation of higher order radiation. A simple example of this problem can be seen in the three to two jet ratio arising in the process $e^+e^- \to \gamma \to q\bar{q}(+g)$.

$$\frac{\sigma_{q\bar{q}g}}{\sigma_{q\bar{q}}} = \int \frac{X_1^2 + X_2^2}{(1-X_1)(1-X_2)}, \tag{A.1}$$

where $X_i = 2E_i/\sqrt{s}$, and $\sqrt{s}$ is the center of momentum energy of the process. The $\frac{1}{1-X}$ terms produce collinear singularities, since there is a direct relation between $1-X$ and the angle θ_{jk} between two particles

$$(1 - X_i) = X_j X_k (1 - \cos(\theta_{jk})) \simeq \theta_{jk}^2. \tag{A.2}$$

An infrared singularity arises if the energy of the emitted gluon approaches 0; e.g., if $X_3 \to 0$ (the gluon energy approaches 0), $X_1, X_2 \to 1$, which again causes the integral to be singular.

Both the infrared and collinear singularities are only an issue near $X \to 1$. The cross-section ratio can be made finite by multiplying by a jet algorithm kernel that appropriately weights the integral near $X = 1$. We choose to implement a weighting term of the form θ^n (which translates to $(1-X)^n$)

$$\int \frac{(X_1^2 + X_2^2)\theta_{23}^{n\geq 0}}{1-X} = \int \frac{(X_1^2 + X_2^2)}{(1-X_1)^{n<1}} = \text{finite}. \tag{A.3}$$

For any $n > 0$, the integral becomes finite as $X \to 1$ (which is equivalent to $\theta \to 0$). This weighting term is the heart of the p-jet framework, as we have chosen to require only the minimally sufficient condition to renormalize the singularities. By only specifying the endpoint limit, the p-jet framework provides significant freedom in the choice of threshold function. When combined with the clustering procedure to produce a unique reconstruction this freedom can be used to optimize the signal to background ratio in noisy environments.

In order for a jet algorithm to be well defined, it must satisfy both collinear and infrared safety. We have illustrated how p-jets satisfies this requirement from theory, but it must hold true for an experiment as well. Collinear safety arises as a stability issue when the angle between two particles approaches zero, while infrared safety refers to when the energy of the final state particles approaches zero. In practice, either of these singularities could cause uniqueness issues from small fluctuations in jet energies resulting in changes in the number of energetic reconstructed jets, which should be constant despite small energy fluctuations.

A poorly designed jet algorithm would not immediately combine these adjacent pairs, and possibly split what should be a single jet combined into a single jet. An example of where this type of failure can occur is in a simple algorithm that absorbs all energy within the $R_{\rm cone}$ radius of the most energetic tower. If the energy in the detector is instead split between two cells, the formerly second most energetic single tower can become the most energetic and seed the new jet causing a finite shift in the jet position. Despite preferential clustering around the highest energy objects, anti-k_T avoids splitting problems because the ΔR_{ij} term in the distance measure will approach 0 for nearly collinear jets faster than the inverse energy weighting for any finite energy object. In p-jets, $\Delta R_{ij} \to 0$ as well because the $T(\Delta R_{ij})$ will be 0 for collinear clusters and p_{ij} will therefore be 1, which is the maximum priority.

In experiment, infrared safety is an issue when it can cause jets to merge or not due to small fluctuations in nearby energy. Anti-k_T jets avoid this issue by combining all minimal energy objects into the highest energy cluster within range. This causes the highest energy jets to carve out a circular region in η–ϕ space from nearby overlapping lower-energy jets. The priority threshold function $T(\Delta R_{ij})$ ensures a unique combination of objects as the minimum value of all threshold functions evaluated at a point in η–ϕ space identifies which cluster will be chosen to combine with the object.

References

[1] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [arXiv:1207.7214 [hep-ex]].

[2] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [arXiv:1207.7235 [hep-ex]].

[3] ATLAS Collaboration, *Search for massive supersymmetric particles decaying to many jets using the ATLAS detector in pp collisions at* $\sqrt{s} = 8$ *TeV*, *Phys. Rev. D* **91** (2015) 112016 [*Erratum ibid* **93** (2016) 039901] [arXiv:1502.05686 [hep-ex]].

[4] R. Calkins, S. Chekanov, J. Conway, J. Dolen, R. Erbacher, J. Pilot, R. Poschl, S. Rappoccio, Z. Sullivan and B. Tweedie, *Reconstructing top quarks at the upgraded LHC and at future accelerators*, arXiv:1307.6908 [hep-ph].

[5] J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, *Jet substructure as a new Higgs search channel at the LHC*, *Phys. Rev. Lett.* **100** (2008) 242001 [arXiv:0802.2470 [hep-ph]].

[6] S. D. Ellis, C. K. Vermilion and J. R. Walsh, *Techniques for improved heavy particle searches with jet substructure*, *Phys. Rev. D* **80** (2009) 051501 [arXiv:0903.5081 [hep-ph]].

[7] D. Krohn, J. Thaler and L. T. Wang, *Jet Trimming*, *JHEP* **1002** (2010) 084 [arXiv:0912.1342 [hep-ph]].

[8] A. Abdesselam et al., *Boosted objects: A probe of beyond the Standard Model physics*, *Eur. Phys. J. C* **71** (2011) 1661 [arXiv:1012.5412 [hep-ph]].

[9] M. Cacciari, G. P. Salam and G. Soyez, *SoftKiller, a particle-level pileup removal method*, *Eur. Phys. J. C* **75** (2015) 59 [arXiv:1407.0408 [hep-ph]].

[10] D. Krohn, M. D. Schwartz, M. Low and L. T. Wang, *Jet cleansing: Pileup removal at high luminosity*, *Phys. Rev. D* **90** (2014) 065020 [arXiv:1309.4777 [hep-ph]].

[11] A. Perloff, *Pileup measurement and mitigation techniques in CMS*, *Journal of Physics: Conference Series* **404** (2012) no. 1, 012045.

[12] ATLAS Collaboration, *Tagging and suppression of pileup jets*, ATLAS-CONF-2014-018, ATLAS-COM-CONF-2014-025.

[13] TASSO Collaboration, *Evidence for planar events in* e^+e^- *annihilation at high-energies*, *Phys. Lett. B* **86** (1979) 243.

[14] S. D. Ellis and D. E. Soper, *Successive combination jet algorithm for hadron collisions*, *Phys. Rev. D* **48** (1993) 3160 [arXiv:hep-ph/9305266].

[15] M. Cacciari, G. P. Salam and G. Soyez, *The Anti-k(t) jet clustering algorithm*, *JHEP* **0804** (2008) 063 [arXiv:0802.1189 [hep-ph]].

[16] J. Alwall *et al.*, *MadGraph/MadEvent v4: The new web generation*, *JHEP* **0709** (2007) 028 [arXiv:0706.2334 [hep-ph]].

[17] T. Sjostrand, S. Mrenna and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **0605** (2006) 026 [hep-ph/0603175].

[18] D. P. Barber, et al., *Discovery of three jet events and a test of quantum chromodynamics at PETRA energies*, *Phys. Rev. Lett.* **43** (1979) 830.