On the Phenomenology of Hidden Valleys with Heavy Flavor

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A preliminary investigation of a large class of Hidden Valley models is presented. These models are more challenging than those considered in [arXiv:0712.2041 [hep-ph]]; although they produce a new light resonance which decays to heavy standard model fermions, they exhibit no light dilepton resonance. A heavy $Z'$ decaying to $\nu$-hadrons, which in turn decay mainly to bottom quarks and tau leptons, is considered; six case studies are investigated, using a new Monte Carlo simulation package. It is found that the one-to-one correspondence of jets and partons is badly broken, and the high-multiplicity heavy-flavor signal probably cannot be isolated by counting jets, with or without heavy-flavor tags. Instead, other measures, such as counting and correlating vertices or displaced tracks, and possibly counting of (non-isolated) muons and use of event-shape variables, should be combined with scalar transverse energy and/or missing transverse energy to reduce backgrounds. Within the resulting sample, searches for the $\nu$-pion mass resonance in both di-jet and single-jet invariant mass can help confirm a signal. The best observable in a perfect calorimeter seems to be single-jet invariant mass for jets of larger radius ($R=0.7$), although this needs further study in a realistic setting. A more detailed signal-to-background study is needed as a next step, but will face the difficulty of estimating the various high-multiplicity backgrounds.

I. INTRODUCTION

The “Hidden Valley” scenario [1], if realized in nature, may result in unusual and little-studied phenomena at the LHC. In this scenario, the standard model is accompanied by a nearly hidden sector containing light particles (a “hidden valley”). These particles cannot currently be abundantly produced, due typically to an energetic barrier or a weak coupling. The increased energy of the LHC may greatly enhance their production. The same barrier can be traversed in the opposite direction to allow some of these particles to decay visibly to standard model particles. A schematic illustration of such models is shown in Fig. 1. Examples of hidden valley models include the original illustrative classes of models given in [1], along with quirk and squirk models [1] [2] [3] [4] and a wide class of “unparticle” models [5] with an added mass gap (e.g. [6]) [7]), whose signals were discussed in detail in [8]. Another related class of examples was studied in [9] [10] [11]. Motivation for such sectors is provided by, among other possibilities, supersymmetry-breaking models, which often introduce one or more hidden gauge groups. While these gauge groups are normally imagined to be unimportant at LHC energies, this reflects a theoretical bias. Such sectors might also be responsible for dark matter, and may have an important role to play in other aspects of particle physics [12], astrophysics and cosmology [13].

The main interest of these models for the LHC era is that their signatures are often distinctive, and can differ from the many supersymmetry, little Higgs, extra-dimensional and technicolor signatures that have been so often discussed. These include high-multiplicity events (generally non-thermal and non-spherical), possibly with large missing energy, and exhibiting large event-to-event fluctuations. New decay modes for Higgs bosons [1] [8] [14], supersymmetric particles [8] [15], and top quarks [8] often arise. Light neutral resonances are common, lighter perhaps than 100 GeV or even 10 GeV.

A common hidden valley signature, but one which I will not address in this paper, is displaced vertices. In certain regions of parameter space, some of the new light particles have long lifetimes, decaying at macroscopic distances. There is no standard model background to compute or estimate. Key issues associated with such signals involve experimental challenges: triggering, detector noise, beam halo, pion collisions with detector material, vertex reconstruction, etc. All of these are detector-specific, and any study of this signature requires a full detector simulation.

However, it may happen that all the new particles decay promptly, or that some decay promptly and all others are stable and invisible. In this case, identifying the resulting high-multiplicity and often low-rate signal, over a large standard model background, becomes a challenge that can be addressed in part through theory and simulation. Below I will consider models of this type.

In some classes of hidden valley models [1] [8], there is a new and frequently-produced particle that often decays to electron and muon pairs. It is then relatively easy to discover the signal, as emphasized in [16]. Simple and rather crude event-shape cuts that remove the largest backgrounds may enhance signal-to-background to the point that, using the excellent low-$p_T$ dilepton mass resolution of the LHC experiments, a resonant peak could be detected.

In this paper, I will consider a much more difficult situation. I will examine a class of hidden valley models with prompt decays and heavy-flavor final states, and with no dilepton resonances. Some of these models also have large missing energy. All have large event-to-event fluctuations in the multiplicity of standard model partons in the final state. The background to such signals is difficult to estimate, because it consists of a cocktail of many different processes, none of which can be calculated beyond leading order in $\alpha_s$, and few of which can be identified and
measured using the data itself. Because of this, it will be a considerable challenge to carry out a concrete signal-to-background study. The goal of this article is to lay the groundwork for such a study, and suggest features of the signal which could be used in any search for a hidden valley of this type.

First I will outline the specific model that is chosen as an exemplar from this class, and will describe the Monte Carlo event generation package used to study it. Then I will describe the case studies, examining the basic phenomenological features of the signal, in Sec. I. After exploring the basic underlying phenomena, I will consider how jets are constructed in the signal. Finding that jets are not fully sufficient for interpreting or isolating the signal, I will consider other non-standard methods for reducing background. Finally, in Sec. III I will examine the question of how to identify the resonance whose observation would confirm the signal, considering both dijet and single jet invariant mass. A summary of results and some additional comments are given in the conclusion; two appendices fill in some details on secondary muons and on jet algorithms.

![FIG. 1: A schematic illustration of models in the hidden-valley scenario. With sufficient energy, available at the LHC but not at LEP, a barrier may be traversed that allows production of new light states in a hidden sector. Dynamics in the hidden sector may produce large numbers of particles. Some of these new particles may decay back to the standard model, often with long lifetimes.]

A. The Models

Several large classes of hidden valley models share the phenomenology of high-multiplicity final states, rich in heavy flavor and possibly missing energy. These include a wide variety of confining hidden sectors whose light stable hadrons are all pseudoscalar and/or scalar mesons with comparable masses; an example was given in [1]. Another class involves weakly-coupled models with multiple electroweak doublet and singlet Higgs bosons which mix together. These models have been discussed widely (see [7] and references therein) but their potential for high-multiplicity heavy-flavor final states was only recently recognized [8, 13, 17]. A third class can include strongly-interacting hidden valleys which couple to the standard model mainly through the Higgs boson; these have not yet been explored fully.

In this paper I will consider the theory in [1], as a very simple example from the first category. This is a hidden valley which closely resembles QCD. To make this study especially straightforward, I have chosen a hidden valley sector ("v-sector") that, like QCD, has an $SU(3)$ gauge group and two light "v-quarks" $U$ and $D$, with masses adjusted so that the light "v-hadron" mass ratios are those of QCD. It is important to emphasize that this model is a stand-in for a much larger class of models. Indeed there is no reason for the physics of a hidden valley to closely resemble QCD, any more than technicolor models should closely resemble QCD. However, for initial studies of v-sector phenomenology, the case of a QCD-like v-sector is simplest to investigate first. This is because the physics is easy to understand, and a Monte Carlo event simulator is easily constructed.

As in [1], where more details are given, I will consider such a v-sector coupled to the standard model through a broken $U(1)$ gauge symmetry, under which both standard model particles and the v-quarks carry a charge. The $Z'$ gauge boson of the $U(1)$ will serve to mediate both production and decay of particles in the v-sector.

![FIG. 2: The spectrum of the v-sector considered in this paper. In analogy to QCD, all v-hadrons rapidly decay down to v-pions and v-nucleons; then the $\pi^0_v$ (and in the B cases, also the $\pi^0_v$ and $\pi^0_v$) decay more slowly to standard model fermion pairs, preferentially to heavy flavor.]

The long-lived v-hadrons of a QCD-like v-sector with two light v-quarks $U$ and $D$ are three light v-pions and a...
heavier v-nucleon doublet, as shown in Fig. 2. All other v-hadrons (such as the v-rho and v-Delta) decay immediately to v-pions and v-nucleons. For simplicity, it is assumed that v-baryon number is conserved, so the v-nucleons are stable and invisible. The three v-pions $\pi_v$, a triplet under v-isospin, consist of a v-flavor off-diagonal pair with quantum numbers of $U \bar{D}$ and $D \bar{U}$, analogous to the $\pi^\pm$ of QCD, and a third, the v-flavor diagonal v-pion with quantum numbers of $U \bar{U} - D \bar{D}$, analogous to the $\pi^0$.

A point of notation: it is natural to name the v-pions as $(\pi_v^\pm, \pi_v^0)$, in analogy to QCD’s pions $(\pi^\pm, \pi^0)$. This notation was used in [1]. However, the use of the ± superscript proves confusing, because all the v-pions are electrically neutral — after all, they are part of a hidden sector. To avoid any confusion of this type (and at the expense of introducing another), I will call the $U \bar{U} - D \bar{D}$ state $\pi_v^0$, but call the $U \bar{D}$ state $\pi_v^3$, and the conjugate $D \bar{U}$ state $\pi_v^\prime$. In this article, I simply assume that either

$$\pi_v^0$$

or

$$\pi_v^3$$

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If the third component of v-isospin $I_v^3$ is conserved, then the $\pi_v^3$ is stable and invisible, but the breaking of total v-isospin allows the $\pi_v^0$ to decay via a $Z^\prime$ back to standard model particles, as shown in Fig. 3. Helicity suppression assures the spin-zero $\pi_v^0$ decays mainly to heavy fermions (for the same reason that $\pi^+ \rightarrow \mu^+ \nu$ decays dominate over $\pi^+ \rightarrow e^+ \nu$ in QCD); branching fractions are roughly proportional to squares of fermion masses. In the particular model of [1], and for light v-pion masses, the width of the $\pi_v^0$ is

$$\Gamma_{\pi_v^0} \sim 6 \times 10^9 \text{ sec}^{-1} \frac{f_{\pi_v}^2 m_{\pi_v^0}}{(20 \text{ GeV})^3} \left( \frac{10 \text{ TeV}}{m_{Z^\prime}/g'} \right)^4$$

(1)

which has a very strong dependence on model parameters; here $f_{\pi_v}$ is the v-pion decay constant, while $m_{Z^\prime}$ and $g'$ are the $Z^\prime$ mass and coupling.

It is also possible that the third component of v-isospin $I_v^3$ is violated. In this case even the $\pi_v^3$ can decay, with widths that are smaller than that of the $\pi_v^0$ by a factor which is a dimensionless measure of $I_v^3$ breaking. In this article, I simply assume that either (A) $I_v^3$ is conserved (so that the $\pi_v^3$ is stable and invisible) or (B) $I_v^3$ is badly violated (so that the $\pi_v^3$ decays promptly.) The case studies will be divided into “A cases” and “B cases” according to this distinction.

The basic production process for these particles is shown in Fig. 4. It involves $q\bar{q} \rightarrow Z^\prime \rightarrow Q\bar{Q}$, where $Q$ is a v-quark. The v-quarks undergo a parton shower through v-gluon emission, following which they are confined by strong v-interactions into v-hadrons. These v-hadrons decay down to v-nucleons and v-pions, and some of the v-pions may then decay visibly to standard model particles.

In the study below, I will consider a $Z^\prime$ with mass 3.2 TeV. The v-pion masses will range between 50 and 200 GeV. In this case the v-pions decay promptly, and the production cross-section is expected to be of order 10–100 fb in the model of [1], see Fig. 5. In other models the cross-section could be different by a factor of 10 or so, larger or smaller, due for example to different $Z^\prime$ charge assignments, or to a different number of colors in the v-sector.

In summary, the model considered below has gauge group $SU(3) \times SU(2) \times U(1)_A \times U(1)^\prime \times SU(3)_{v}$, with the $U(1)^\prime$ broken at the few TeV scale, the $SU(3)_{v}$ group confining at the few hundred GeV scale, and two light v-flavors of v-quarks $U$ and $D$. Standard model fermions

FIG. 3: The $\pi_v^0$ decays via a $Z^\prime$ to heavy flavor. The $\pi_v^{\pm \prime}$, if unstable, decays through a v-flavor-changing interaction to the same final state.

FIG. 4: A $Z^\prime$ decays to two v-quarks, which emit v-gluons in a v-parton shower. These then are confined into v-pions and v-nucleons. Some of the v-hadrons (shown dotted) are stable and invisible, but others are metastable and decay, mainly to $b\bar{b}$.

FIG. 5: Cross-section for v-particle production via a $Z^\prime$ in the QCD-like model of [1]. The cross-section in other models may easily differ by an order of magnitude; see text.
and v-quarks all carry some charge under the $U(1)'$, allowing the $Z'$ to serve as a communicator between the two sectors.

**B. The Hidden Valley Monte Carlo 0.5**

The event simulator HVMC 0.5, upon which all studies in this paper are based, is described in this section. (A more general Monte Carlo simulator has been developed with S. Mrenna and P. Skands [18], and studies based upon it will be presented elsewhere.) HVMC 0.5 is built on existing tools, which are rather easy to modify for current purposes. In particular, elements of PYTHIA [20] are strung together to simulate a v-sector which is isomorphic to three-color two-flavor QCD, with all masses and other dimensional quantities scaled up, relative to QCD, by a constant factor $R$.

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As noted in Sec. [A], signal cross-sections in the 10–100 fb range are consistent with LEPI and LEPII constraints. The cross-section is easily changed by an additional factor of 10, without altering the observable phenomenology in any other way, by adjusting the $U(1)'$ coupling constant $g'$ (see Fig. [5]). For simplicity, I will study samples of 1000 events, such as might be obtained in a real LHC

A v-sector with three colors, two flavors and confinement scale $\Lambda_3$ has v-pions with mass $m_\pi = m_\pi R$, where $R = \Lambda_3/\Lambda_{QCD}$, and $\Lambda_{QCD}$ is the QCD confinement scale. It also has nucleons with similarly scaled-up masses. The $\eta'$ (the iso-singlet pseudoscalar of 2-flavor QCD) has its mass set to $m_\eta R$. Then, given a mass $M$ for the $Z'$, the simulation of events proceeds as in Fig. [6].

- The process $q\bar{q} \rightarrow Z' \rightarrow Q\bar{Q}$ is simulated, where $q$ and $\bar{q}$ are an ordinary quark and antiquark and $Q$ is a v-quark, using the PYTHIA routine for $q\bar{q} \rightarrow Z' \rightarrow f\bar{f}$.
- The v-parton showering and v-hadronization of the $Q\bar{Q}$ system is simulated. This is done by
  - scaling down the energy of the $Q\bar{Q}$ system from its original energy $E_0$ to the energy $E = E_0/R$;
  - simulating QCD parton showering and hadronization (with the number of light flavors set to 2) of an ordinary quark-antiquark system with center-of-mass energy equal to $E$;
  - the decay of the v-hadrons to standard model partons is simulated using PYTHIA decay routines;
  - the decays, showering and hadronization of the standard model partons and the simulation of the underlying event proceed using the usual PYTHIA routines.

The resulting final states consist of standard model hadrons, photons and leptons, along with stable neutral v-hadrons that escape undetected. All results in this paper are based on analysis of the final state hadrons, photons and leptons without accounting for detector effects, other than geometric acceptance, except where otherwise noted.

For the sake of clarity (though the actual effect on the studies below is small) it should be noted that two-flavor QCD as simulated in this way is not quite a consistent model. The tuning of PYTHIA to match existing data on hadronization, branching fractions, etc., is not correct for a two-flavor model. The iso-singlet would-be Nambu-Goldstone boson $\eta'$ is now affected by the anomaly and takes the place of the $\eta'$. There are small effects on the nucleon mass from the slight differences in the running coupling that are similarly ignored. But these issues are of minor impact on the phenomenology and of minor concern for the current studies. As there is no reason to expect the hidden sector in nature to be of exactly the form considered here, the aim of this paper is not precision but rather phenomenological and experimental guidance, in search of robust analysis strategies.

**II. THE CASE STUDIES**

**A. Preliminaries**

The studies below will all involve decays of a $Z'$ of mass 3.2 TeV to a hidden valley sector. In many models the $Z'$ will already been discovered in its decays to dilepton final states. However, knowledge of its presence and of its mass does not significantly aid in uncovering the hidden valley signal, because of the latter’s complexity. In other models, the branching fraction of the $Z'$ to dileptons will be too small, and the $Z'$ will not yet have been identified when the hidden valley signal is sought. As noted in Sec. [A], signal cross-sections in the 10–100 fb range are consistent with LEPI and LEPII constraints. The cross-section is easily changed by an additional factor of 10, without altering the observable phenomenology in any other way, by adjusting the $U(1)'$ coupling constant $g'$ (see Fig. [5]). For simplicity, I will study samples of 1000 events, such as might be obtained in a real LHC...
FIG. 7: A schematic view of a typical event from case A1. The view is along the beampipe. Charged tracks are shown in the “tracker”, the central disk in the figure. Since there is no magnetic field in this event display, all tracks with $p_T < 3$ GeV have been removed; grey-level corresponds to $p_T$, with hardest tracks shown in black. Neutral hadrons and photons are indicated as outward-pointing lines starting at the outer edge of the tracker, and calorimeter energy in azimuthal angular bins of width $2\pi/60$ are shown as bars at the outer edge of the tracker.

FIG. 8: As in Fig. 7, a schematic view of a typical event from case B1.

Note the obvious progressions in the table. Comparing A1, A2 and A3, one sees the decrease in the multiplicity of v-pions; the same trend appears in B1, B2 and B3. Meanwhile the B cases, with a decaying $\pi^0_v$, have roughly triple the number of visibly decaying pions, much higher visible energy, and much less $E_T$, compared to the A cases for the same v-pion mass. For illustration, event displays of one event each from cases A1, B1 and A3 are given in Figs. 7–9. However the reader should bear in mind that event-to-event fluctuations in appearance are much

$$\hat{H}_T \equiv \sum_{towers} |\vec{p}_T| \Theta(|\vec{p}_T| - 5 \text{ GeV}) \Theta(\eta - 3) ;$$

$$\hat{E}_T \equiv \left| \sum_{towers} \vec{p}_T \right| .$$

The calorimeter towers combine the 3-momenta of the various hadrons, electrons, photons and muons in $0.1 \times 0.1$ bins in pseudorapidity $\eta$ and azimuthal angle $\phi$. For $H_T$ I include only towers with $p_T > 5$ GeV and $|\eta| < 3$, as indicated by the $\Theta$ functions, to reduce significantly the impact of the underlying event. (However, for a fully realistic study, an $H_T$ variable built from the reconstructed jets might be much more robust; in these models, a variable $H_T^{(jet)}$, defined as the scalar summed $p_T$ of all jets with $p_T > 25$ GeV and $|\eta| < 3$, takes values about 10 percent larger than $H_T$ defined above.) Meanwhile $M_4$, the invariant mass of the four highest-$p_T$ central jets, is built from jets defined using the midpoint cone algorithm of cone radius 0.4; see Sec. II D and Appendix B below.

The quantities $\hat{H}_T$ and $\hat{E}_T$ are computed here using scalar and vectorial sums of the $p_T$ of all calorimeter towers,

$$\hat{H}_T \equiv \sum_{towers} |\vec{p}_T| \Theta(|\vec{p}_T| - 5 \text{ GeV}) \Theta(\eta - 3) ;$$

$$\hat{E}_T \equiv \left| \sum_{towers} \vec{p}_T \right| .$$

The case studies are distinguished by the masses of the v-pions and by whether the $\pi^0_v$ are stable or decay promptly. In Table I the cases are listed. In addition to the masses and decay settings, the table shows the average multiplicity of visibly-decaying v-pions and some kinematic information: the transverse calorimeter energy $\hat{H}_T$, the invariant mass $M_4$ of the four highest-$p_T$ jets, and the average missing transverse momentum ($\hat{E}_T$, or $E_T$). The quantities $\hat{H}_T$ and $\hat{E}_T$ are computed here using scalar and vectorial sums of the $p_T$ of all calorimeter towers,

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TABLE I: The case studies, showing the stability of the $\pi^0_v$, the mass of the v-pion, the ratio $R = \Lambda_v/\Lambda_{QCD}$, the average number of visible v-pion decays, and the average $\hat{H}_T$, $M_4$, and $\hat{E}_T$.

| Case | $\pi^0_v$ stable? | $m_{\pi^0_v}$ (GeV) | $R$ | $\# \pi^0_v$ decays | $\hat{H}_T$ (GeV) | $M_4$ (GeV) | $\hat{E}_T$ (GeV) |
|------|------------------|----------------|-----|------------------|----------------|-------------|-----------------|
| A1   | Yes              | 50             | 4.0 | 667              | 590            | 318         | \              |
| A2   | Yes              | 120            | 2.4 | 765              | 667            | 400         | \              |
| A3   | Yes              | 200            | 1.5 | 886              | 770            | 459         | \              |
| B1   | No               | 50             | 10.3| 1650             | 1427           | 214         | \              |
| B2   | No               | 120            | 6.1 | 1835             | 1562           | 182         | \              |
| B3   | No               | 200            | 3.9 | 2248             | 1810           | 145         | \              |

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FIG. 9: As in Fig. 7, a schematic view of a typical event from case A3.

FIG. 10: The distribution of missing transverse momentum (MET) versus $H_T$ in TeV. These quantities are defined in Eqs. (2)-(3).

larger here than in most standard model backgrounds or traditional new signals such as gluino production.

Figure 10 shows $H_T$ versus $E_T$ for the various cases. The difference between the A cases, where roughly $2/3$ of the v-pions are stable and escape undetected, and the B cases, where the v-pions all decay promptly and most of the debris from the $Z'$ is observed, is obvious. Occasional v-baryons (stable and invisible in all present case studies) can provide some $E_T$ even in the B cases. There is additional and sometimes substantial $E_T$ from secondary neutrinos produced in semileptonic decays of $b$ and $c$ quarks and especially in $\tau$ decays.

Already from these plots, one sees clearly that the A cases will have much larger standard model backgrounds than the B cases. The B cases are more similar to those studied in [16], though with a higher invariant mass, lower rate, and no dilepton resonance. I will show in Sec. II D that they have many reconstructed hard jets. Backgrounds are high-multiplicity QCD events with many $b$ quarks, including $t\bar{b}$, $b\bar{b}bjj$, $ttt$, $t\bar{t}Z$, etc. These signals tend to be in the few pb range or less, and will be greatly reduced by an $H_T$ cut at, say, 800 GeV. The A cases, by contrast, despite their large $E_T$, are often in the same overall kinematic regime as relatively low-energy standard model processes with a few jets and $E_T$. These much larger backgrounds include $W$ or $Z$ plus jets (especially heavy flavor), $t\bar{t}$ plus jets, $t\bar{t}W$ or $t\bar{t}Z$, $t\bar{b}$, etc. Cuts on $H_T$ and $E_T$ that have high efficiency for the signal will still leave considerable amounts of background behind.

In contrast to standard model backgrounds, triggering should not be a problem for either the A or B cases. Most of the events in this signal will pass the various jet(s) or jet(s)-plus-$E_T$ triggers, with the latter being most efficient for the A cases. Even in the A cases, due to secondary muons, many events will also pass dimuon and muon-plus-$E_T$ triggers; see Appendix A. The trigger will mainly remove unspectacular, low-visible-energy events, which are rare in the B cases and consist of a large minority in the A cases. But the events that fail these triggers are precisely those which would be especially difficult to distinguish from standard model background off-line. Conversely, the events which are most distinctive — with multiple acoplanar high-$p_T$ jets and possibly large $E_T$ — will be among those which will pass the trigger. For this reason, the effect of the trigger is likely to be relatively minor, compared to the other issues addressed below.

B. The v-pions

In these case studies, the $Z'$ decay produces a substantial number of v-pions, organized into two rather fat v-jets. All of these v-pions decay visibly in the B cases, while about a third are visible in the A cases. (Actually the fraction is a bit larger in these QCD-like models, due to v-isospin violation that, as in QCD, biases the decay of the $\eta_v$ toward $\pi_v^0$s.) The number of visible v-pions is
FIG. 11: For the case studies, with 1000 events, the distribution of the number of visibly-decaying \( \pi \) v-pions, each decaying to two standard model particles.

shown in Fig. 11. Since the only difference between case B1 and case A1 is the stability of the \( \pi^{\land \lor} \), the distribution of visible v-pions in case B1 equals the distribution of all v-pions, visible and invisible, in case A1. The same applies for B2 and A2, and for B3 and A3.

In Fig. 12 are shown the \( p_T \) distributions of the v-pions; notice few have \( p_T < 50 \) GeV, and most are relativistic. Fig. 13 shows the \( p_T \) distribution of the highest-\( p_T \) visibly decaying v-pion, which is almost always relativistic, often with a boost factor above 3. This is relevant because the majority of events have a highly-boosted v-pion whose decay products are separated in \( \eta \) and \( \phi \) by \( \Delta R < 0.5 \); here \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \) as usual. We will see in Sec. III D and Sec. III E that the decay products of high-\( p_T \) v-pions often are merged into single jets.

As an aside, let us note that the multiplicity distribution and \( p_T \) distribution of the v-pions, and the distribution of final-state quark and lepton flavors, is quite different from a thermal distribution, as one would (at least naively) expect in a black hole decay [21, 22], another potential source of high-multiplicity events. Also the events are not in general spherical (see Figs. 7–9) in contrast to expectations for black holes. (See however Sec. IV D of [8].)

C. v-Pion Decay Products

As noted in Sec. I A, the decay rates of the \( \pi^0_v \) (and the \( \pi^{\land \lor}_v \) if unstable) to quarks and leptons are roughly proportional to the square of the final-state fermion masses. The fermion mass used should be evaluated at the v-pion mass scale. For simplicity the relative branching ratios to quarks and leptons are taken to be those of a Higgs boson of the same mass as the \( \pi_v \). Since the \( \pi_v \) does not decay (at tree level) to \( WW \) and \( ZZ \), these decay channels are first removed before the branching fractions are computed. In the mass ranges considered here, the unstable v-pions decay mainly to \( b \bar{b} \) pairs with a large branching fraction (\( \sim 90\% \) for the lighter v-pions), with the remainder going mainly to \( \tau^+ \tau^- \), \( c \bar{c} \) and gluon pairs. The number of final-state (short-distance) standard model particles is simply double the number of visibly-decaying v-pions. Note from Table II that the average multiplicity of final-state partons ranges from 3 in case A3 to 20 in case B1. Also, note in Fig. 11 the wide fluctuations and the long tail, which reaches 42 in case B1 and even in case A3 extends to 12. (However, a fraction of these partons have low transverse momentum, as will be seen below.) The event-to-event fluctuations in the multiplicity of final-state partons are exceptionally high compared to most new-physics signals. This is part of what makes...
FIG. 13: As in the previous figure, the $p_T$ distribution of the hardest (i.e., highest-$p_T$) visibly decaying v-pion.

this signal challenging.

1. Bottom Quarks and Taus

Most of the final state partons, especially for lighter v-pions where decays to gluons are suppressed, are $b$ quarks and antiquarks. The $p_T$ spectrum of the central ($|\eta| < 2$) $b$ quarks is shown in Fig. 14. For lighter v-pions, the higher multiplicity of $b$ quarks is somewhat compensated by their lower $p_T$, which makes them less likely to produce jets above kinematic cuts and to decay with detectable vertices. The fraction of bottom quarks that are central ($|\eta| < 2$) and hard ($p_T > 50$ GeV) varies from about 55% for cases A1 and B1 to nearly 85% for cases A3 and B3.

Taus are produced in roughly ten percent of the v-pion decays, and are common in these events. One could imagine that central hadronic taus could be useful in identifying this signal. However, in the present studies, few events have more than two tau leptons, which is not enough to be unusual (given $t\bar{t}$ rates). In addition, one or both tau's will sometimes fail isolation requirements, either because they are too close together (as we will see below) or because of the high multiplicity environment in which they are produced. For this reason, the number of taus identified is likely to be too small for it to play a role in extracting the signal. But it should be noted that in other hidden valley models, where the $\tau$–to–$b$ ratio might be enhanced, the role of taus in signal identification might be more important.

2. Secondary Muons and Electrons

In these models, unlike those of [16], electrons and muons do not provide a direct handle for discovering the v-hadrons directly. The branching fraction of the v-pion to muons is tiny (unless the v-pion is lighter than $2m_b$, in which case it will be very long lived). However, because these events have high multiplicity, and because the v-pions decay mainly to $b$, $c$ and $\tau$, which in turn can produce light leptons (generally non-isolated), it is very

![Graphs showing transverse momentum distribution](image)

**TABLE II:** Fraction of events with multiple muons. All cases studies have 1000 events.
common for one or more electron or muon to be produced as a secondary. The presence of these light leptons could assist with reducing backgrounds.

Since the leptons in question are not typically isolated, I focus on muons, which are easier to identify. The numbers of events with three or more muons that have $p_T > 3$ GeV and $|\eta| < 2.5$, with no isolation requirement, are shown in Table II. Note the large number in the B cases. This implies that requiring multiple muons may serve as one of several useful criteria for selecting events for analysis. Unfortunately the number of muons is too small to be of much use in the A cases.

Additional plots related to lepton distributions appear in Appendix A.

FIG. 15: For the case studies, with 1000 events, the number of jets (formed using the midpoint cone algorithm with cone-size $\Delta R = 0.4$; see text for more details) with $p_T > 50$ GeV and $|\eta| < 3$. The number of jets is considerably smaller than twice the number of visibly-decaying $\nu$-pions, Fig. [I].

FIG. 16: For the A cases, with 1000 events, the number of partons versus the number of hadronic jets (left plot) and the number of partonic jets versus the number of hadronic jets (right plot). Jets are formed using the midpoint cone algorithm with cone-size $\Delta R = 0.4$; see text for more details. Cuts of $p_T > 50$ GeV and $|\eta| < 3$ are imposed on both partons and jets. One sees that that partonic and hadronic jets are in correspondence, but partons do not correspond as well to jets.

D. Jets

Typically one characterizes events on the basis of “objects”, where the objects include electrons, muons, photons, hadronic taus, and jets, which may be tagged or untagged. Since the majority of the many jets in the signal are from $b$'s, one might expect about half of them on average to be tagged, with a few events containing an exceptional number of tags. One might expect these events to be the ones that stand out above standard model background.

This expectation is not entirely wrong, but it is also too naive. In particular, the standard jet-parton correspondence does not work in this signal. As we will see, the number of well-reconstructed and taggable jets is typically considerably smaller than the number of $b$ quarks. Many jets contain two or more $b$ quarks. While the tagging efficiency may be somewhat higher in such jets, that the number of tagged jets obviously cannot be exceptional if the number of jets itself is not exceptional.

Instead, here and in Sec. IIE I will argue that treating jets as objects, characterized as either “tagged” or “untagged”, would throw away crucial information needed to separate this signal from background. A substantial fraction of the jets in this signal are not standard jets, and it appears that this fact may be critical in suppressing backgrounds.
the reason for this. Let us first quantify the degree to which the jets do not correspond well to the partons in the event. (In this section, “partons” refers to v-pion daughters, which appear at short distance; it does not refer to partons emerging through subsequent showering.) That there is a mismatch is hardly surprising, given the cluttered nature of these high-multiplicity events. In the left-hand plots of Figs. [16] and [17] are shown the number of partons versus the number of jets; here $p_T > 50$ GeV and $|\eta| < 3$ for both partons and jets. Notice these often differ by as much as a factor of 1.5 to 2. This breakdown of the jet-parton correspondence is natural and indeed has been seen before; it will certainly can occur in $t\bar{t}t\bar{t}$ events, and in events with highly boosted massive particles, such as $W$’s, $Z$’s, $h$’s and $t$’s. In this signal, however, it can become extreme.

Fortunately, there remains a close connection between the clustering of hadrons and the clustering of partons. This is partly due to the fact that the final-state quarks are all produced in the decays of the color-singlet v-pions, which limits the radiation of gluons at large angles. In the right-hand plots of Figs. [16] and [17] is shown the relation between jets of hadrons and jets of partons. Here, the hadrons are clustered according to an algorithm, the partons (i.e., the short-distance v-pion daughters) are clustered according to the same algorithm, and the results are compared. Clearly the correspondence of hadronic jets and partonic jets is much closer than that of hadronic jets and partons themselves. In other words, even in this signal, a fixed algorithm applied at the hadron level gives jets that do correspond well to the jets obtained by applying the algorithm at the parton level. It is shown in Appendix B that this result is robust for both cone and $k_T$ algorithms; compare the figures above with Figs. [36] and [37]. In particular, although cone and $k_T$ algorithms will find different jets in general, both algorithms find the same jets in short-distance partons as they do in hadrons.

Since the partonic jets are a good surrogate for the hadronic jets, one can take a short-cut to learn about the failure of the jet-parton correspondence. To determine precisely the number of $b$ quarks in each jet, one should examine the $B$ mesons within the hadronic jets, but this is technically tedious and has subtleties. Instead, one can examine the number of partons collected within partonic jets in various $p_T$ ranges, as shown in Fig. [18]. This provides sufficient information to illustrate the key phenomenological points.

Several effects tend to cause multiple partons to be combined into a single jet. First, a high-$p_T$ jet is likely to be a single boosted v-hadron, and so contains two partons. This effect becomes substantial for boost factors above about 3 or 4. This is visible in the right-hand plots of Fig. [18] where it can be seen that jets with $p_T > 200$ GeV have a substantial probability to contain two partons, ranging from 1/3 for the higher-mass v-pions of cases A3 and B3 to 3/4 for the lower-mass v-pions of cases A1 and B1.

In the plots shown in the main part of this article, the midpoint-cone jet algorithm is used, with cone size 0.4; more details on the parameters chosen are given in the appendix. Changing parameters, or choosing other algorithms, will change the details, but as argued in Appendix B, will not change the main conclusions of this section. The same may not be said for finding the v-pion resonance, however; see Sec. III.

In Fig. [15] is shown the number distribution of jets per event with $|\eta| < 3$ and $p_T > 50$ GeV. The average number of jets is rather large but not spectacular in the B cases, and not very large in the A cases, which do not even have a substantial tail on the high side. This means one cannot find this signal by simply demanding large numbers of hard jets; in the A cases, a requirement of more than six jets removes most of the signal, and preserves only half of the signal in the B cases. Recall that these signals are in the 10–100 fb range, whereas multi-$b$ backgrounds with 8 or more jets, from $t\bar{b}b$, $t\bar{t}Z$, etc., are in the 1–10 pb range. A hard cut on the number of jets cannot be afforded.

Note also that in all cases the average number of jets is significantly lower than twice the average number of visibly decaying v-pions, shown in Fig. [11]. The typical v-pion is not producing two jets. It is important to identify the reason for this.
FIG. 18: For the case studies, with 1000 events, the number of partons inside of partonic jets (which correspond well to hadronic jets) for jets with $|\eta| < 3$ and $p_T$ in three ranges: $50 < p_T < 100$ GeV (left plots), $100 < p_T < 200$ GeV (middle plots) and $p_T > 200$ GeV (right plots).

Also, the fat v-hadronic jets from the $Z'$ decay tend to throw multiple v-hadrons into the same region of $\eta$ and $\phi$, so the probability that partons from different v-pions are nearby in $\eta$ and $\phi$ is non-negligible. Furthermore, the presence of soft partons from the softer v-pions tends to increase the probability that harder partons will be merged by a jet algorithm. These combined effects can be seen in Fig. 18 which shows that a significant number of jets contain 3 or more partons, even as many as 6 or so, for the cases with lower v-pion mass and consequent higher-multiplicity. Of course the effect is more dramatic for the B cases.

Table III provides some information about $b$ quarks with $p_T$ less than 30 GeV, which often cannot generate a clean jet and are rarely taggable. Recall that the multiplicity distributions in these signals have long tails, so the average number is less than half the maximum. This completely different effect also tends to reduce the number of jets relative to the number of v-pion daughters. Particularly in the case of lighter v-pions, these low-$p_T$ $b$ quarks contribute additional sources of confusion for jet reconstruction, as well as adding tracks and neutrals in the few GeV range but without providing a detectable vertex.

Altogether, this means that the number of jets is significantly less than the number of partons. This is a bit disappointing, as the high multiplicity of partons is a unique and striking feature of the signal. The mere counting of jets, even with heavy-flavor tags, is unlikely to be enough to separate signal from background, especially in the A cases.

E. Beyond Jets: Vertexing and Tracking

To identify this signal, it seems likely that tagging of individual jets is not enough. By definition, the number of heavy-flavor-tagged jets cannot be larger than the number of jets. But the number of $B$ mesons can greatly exceed the number of tagged jets, as suggested in Figs. 16 and 17. In other words, although these events do not have an exceptional number of taggable jets, often four or less in the A cases, they do have an unusual number of $B$ mesons. Thus to distinguish the signal from background, it is essential to detect as many vertices from the $B$ mesons as possible.

More precisely, a remarkable feature of this signal is the number of vertices and the distinctive correlations be-

| Fraction of $b$ quarks with $p_T < 30$ GeV | A1 | A2 | A3 | B1 | B2 | B3 |
|-------------------------------------------|----|----|----|----|----|----|
| # $b$ quarks per event with $p_T < 30$ GeV | 1.86 | 0.44 | 0.12 | 4.49 | 1.02 | 0.28 |

TABLE III: Average distributions over 1000 events of soft $b$ quarks.
tween vertices and hadronic jets. Most of the high-$p_T$ jets contain more than one $B$-meson vertex. This can occur in some standard model backgrounds (through boosted $h$ decays, boosted $Z$ decays, and most commonly through $g \rightarrow b \bar{b}$ splitting) but the probability of having two or more jets with multiple $B$ mesons is low, and the probability of having additional $B$ mesons in the event is also low. (Of course, even a single $B$ may produce a second vertex when its daughter $D$ meson decays, but the kinematic correlations between the parent and daughter vertex are distinctive and different from those of the two $B$ mesons from a $\pi_v$ decay.) It thus appears that moving beyond “tagged jets” and “untagged jets” as the basic objects of analysis is important for separating signal and background.

![FIG. 19: For the case studies, over 1000 events, the number of displaced tracks versus the total number of tracks. In this plot all tracks have $|\eta| < 2$, $p_T > 2$ GeV, and displacement in three dimensions must exceed 300 microns.](image)

FIG. 19: For the case studies, over 1000 events, the number of displaced tracks versus the total number of tracks. In this plot all tracks have $|\eta| < 2$, $p_T > 2$ GeV, and displacement in three dimensions must exceed 300 microns.

Meanwhile, vertex/jet correlations are not the only non-object-based measure that can be useful. Consider Fig. [19](image) in which distributions of the number of tracks with $|\eta| < 2$, $p_T > 2$ GeV, versus the number of such tracks with three-dimensional impact parameter $> 300 \mu m$, are shown. This is a measure of both the number of $B$ mesons produced and the fraction of tracks that were produced in a $B$ meson decay. In particular, notice that the slope (the fraction of tracks that are displaced) is somewhat larger than in the right-hand plot of Fig. [20](image) which shows $t\bar{t}$ produced at $\sqrt{s} \geq 1$ TeV. Thus high-multiplicity heavy-flavor events will have many tracks of which an unusually large fraction will be displaced.

The clustering of the displaced tracks may also be a useful variable, which I have not yet considered. It would be interesting to explore a clustering observable acting upon them.

Presumably, the techniques discussed here would be useful for many other possible new signals. The need to move beyond “tagged” or “untagged” jets is far more general than this particular class of models. It should apply in any signal in which a $b\bar{b}$ pair is produced by a boosted particle, such as a $Z$ or $h$. (For recent relevant work, see [23].) Obviously the number of tracks and the fraction of tracks displaced are blunt instruments, sensitive to any process with long-lived particles, whether $b$’s or something exotic and new. The clustering of tracks and vertices, however, will be variable from signal to signal. For instance, although in the present signal the number of vertices is larger than the number of jets, this inequality need not hold. In signals with novel heavier long-lived particles, which may decay to multiple jets at a displaced point inside the beampipe, a number of jets may share the same vertex, and then the number of vertices per jet may be smaller than one. For example, were case B3 altered so that the lifetime of the $\pi_v^{\Lambda V}$ were a few picoseconds, and were the dominant decay $\pi_v^{\Lambda V} \rightarrow gg$, then a single decaying $\pi_v^{\Lambda V}$ would make two jets, with many displaced tracks, emerging from a single vertex. At the other extreme, there are models in which a large number of light long-lived states are produced, and these can have many vertices. Examples would include cases A1 and B1 with the $v$-pion mass reduced to 30 GeV and its lifetime extended to a few picoseconds. Then the number of vertices could be very large due to a large $v$-pion multiplicity, one vertex per $v$-pion at the point of its decay, and one vertex for each of the daughter $B$ mesons from the $v$-pion decay. This complex of vertexing issues deserves a thorough exploration by the $b$-tagging community at the LHC detectors, including LHCb.
cylindrical detector along the plane perpendicular to the transverse thrust axis into two hemicylinders, and computing the invariant mass of all activity within the hemicylinder. To reduce the impact of the underlying event and of initial state radiation, only calorimeter cells satisfying certain $p_T$ and $|\eta|$ cuts were used.

In [10], the presence of a dilepton resonance makes even a low signal-to-background ratio acceptable. Here, the signal is smaller, and a much better signal-to-background ratio is needed for the signal to be confirmed (through the methods of the Sec. [11]). This requires that all cuts have high efficiency for the signal. There are important multi-jet backgrounds (with and without $E_T$ for the A and B cases respectively) that can be disregarded in the case study of [10], but cannot be ignored here.

A proper background study needs to account for many background processes. Below we consider only two, for illustration. These are the $\sim 10$ fb $Z_{b\bar{b}}b\bar{b}$ process and the $\sim 2$ pb $Z_{b\bar{j}j}$ process (where $j$ is any non-$b$ quark or gluon, at least two jets have $p_T > 200$ GeV, and the $Z$ decays to neutrinos.) [30] The numbers of events shown in the plots are 4200 for $Z_{b\bar{b}}b\bar{b}$ and 10000 for $Z_{b\bar{j}j}$.

For these two backgrounds, and presumably other multi-jet processes that are the dominant backgrounds remaining after simple cuts, it appears the transverse thrust variable is not helpful. Neither signal nor backgrounds resemble back-to-back di-jets, while neither is spherical, so no cut removes a large fraction of the background without removing most of the signal. But the situation with the cluster mass variable is more promising, as shown in Fig. 21 for signal and in Fig. 22 for the two backgrounds. The cluster masses are here constructed from jets, with $p_T > 25$ GeV and $|\eta| < 2$ to reduce sensitivity to the underlying event and initial state radiation. (This is in contrast to [10], which computed this quantity at parton-level; because of jet merging in the present signal, such an approach would not be reliable here.) The backgrounds (for which jet-parton correspondence is more likely to hold) are shown at parton-level; although this reduces the cluster mass in some events, the effect appears small enough to not affect the general conclusions below.

The larger $Z_{b\bar{j}j}$ background is clearly the more serious problem. It can be reduced if three $b$ tags are required of the events, but at a cost of considerable signal in the A cases. The cluster mass distribution of the signal for the A cases lies underneath the background, and appears not to be useful. By contrast, the B cases (which, as in [10], have few invisible final-state particles) are much more forgiving, as they are for many variables; the cluster invariant mass moves the signal far from the backgrounds shown. A loose cut on this variable, combined with other selection criteria (such as at least three $b$-tagged jets) should help this signal to stand out.

As an aside, note that the $v$-pion mass appears visibly in the cluster mass distribution. There is a small but non-negligible probability that a one or both hemicylinders contains only a single $v$-pion, so that the cluster mass

**F. A Comment on Event-Shape Variables**

Here I will briefly explore an event-shape variable for the signals and for two backgrounds. In [16] it was suggested that transverse thrust (defined in the two dimensional plane transverse to the beamline) is a useful variable for separating signal and background. Another variable used was “cluster mass”, obtained by dividing the

![FIG. 21: For the case studies, over 1000 events, the (jet-level) cluster mass in the two hemi-cylinders divided along the transverse thrust axis. Cuts of $p_T > 25$ GeV and $|\eta| < 2$ are imposed on the jets. See cautionary remarks in the text.](image)

![FIG. 22: The (parton-level) cluster mass distribution for the $Z_{b\bar{b}}b\bar{b}$ background ($\sigma \sim 10$ fb, 4200 events shown) and $Z_{b\bar{j}j}$ background ($\sigma \sim 2$ pb, 10000 events shown). See text for more details and cautionary remarks.](image)
is just the v-pion mass. However the region in which this is easiest to see lies underneath the background. It seems unlikely that this fact can assist with identifying the signal.

As noted in [10], the cluster mass variable is not sufficiently robust for use in a realistic analysis. Studies for the present paper have shown marked dependence, at the level of 20 percent or more, on the treatment of the underlying event and initial state radiation. The plots above should therefore be treated with caution. They are useful for characterizing differences between signal and background, but a more stable version of this variable should be used in any experimental analysis.

The conclusions in this section are thus preliminary. More robust event-shape variables should be studied, but the cluster mass appears to reduce background in the B cases. However, the B cases are already distinctive in other ways. This variable may be most useful in case B3, where the number of jets is not so extreme as in case B1, but the total invariant mass of the jets in each hemisphere is still very large. On the other hand, this particular variable may not be so useful in the A cases, so a different event-shape variable must be sought.

III. CLINCHING THE CASE: DETECTING THE V-PION RESONANCE

I have discussed a number of features of the signal which make its phenomenology atypical. Despite the unusual features of the signal outlined above, they are not obviously sufficient to allow for easy separation of signal from background, if the signal cross-section is indeed 10-100 fb. The standard model backgrounds are large and variegated, consisting of tails of distributions from a number of different processes. A complete and convincing study will be difficult with present tools. In any case, it seems unlikely that the backgrounds can be understood well enough from data to allow a counting experiment, especially in the A cases, where the number of jets, tracks, vertices, etc. is not so large.

Instead, it seems likely that a different strategy is needed. Given the unusual features of the signal discussed above, one might apply loose cuts on these features that have high efficiency for the signal. (For instance, one could require substantial $E_T$ and/or $H_T$, several jets with at least three tagged, indications of many displaced tracks and vertices, etc.) The standard model background surviving the cuts would not be calculable or easily measured, so the signal-to-background ratio would not be well-known. But within this enriched sample, one could then search for the key kinematic feature of the signal – the v-pion resonance – which if observed would confirm that new physics is present.

Simply plotting dijet invariant masses, where the jets are selected at random, cannot reveal the v-pion resonance. The huge combinatoric background, the fact that many jets contain multiple $b$-quarks, and relatively poor resolution for jet momentum and energy would eliminate any signal.

Since many v-pions are boosted, they often form a single jet, or dissociate into two nearby jets. I will use these facts below in studying both dijet invariant mass $m_{jj}$ and single-jet invariant mass $m_j$ below. Clearly both might be used; there is no sharp dividing line between them in any case, since any jet algorithm separates the two in an arbitrary way. (Approaches that avoid this division are under study [25].) It appears that it is important to choose one’s jets carefully.

A proper study of these variables would account for the finite resolution in jet energy, momentum and mass. There are many issues here, some beyond the scope of a theoretical investigation. In this study I will include decays, showering and hadronization but will work only with a perfect calorimeter – perfect except for its granularity of $0.1 \times 0.1$ in $\eta$ and $\phi$ and its limited pseudorapidity coverage — and will show that substantial challenges arise even before realistic detector issues are accounted for.
FIG. 24: As in the previous figure, except that the jets have $p_T > 100$ GeV and pairs are within $\Delta R = 0.9$ of one another.

A. Dijet masses

Let us begin with dijet invariant mass. A plot of the invariant masses of all pairs of jets above a certain $p_T$ cut would suffer from an overwhelming combinatoric background, because of the high jet multiplicity. Instead, it is best to use the fact that high-energy $Z'$ decays provide a substantial boost to many of the v-hadrons, as we saw in Sec. II. Most high-$p_T$ jets are either single v-hadrons, whose decay products have merged, or they represent a single quark produced by the decay of a v-hadron whose other decay product will lie close by in $\Delta R$. The difference between these two cases is (on average) that the former class of jets will have a single-jet invariant mass $m_j$ larger than the latter class. In particular, we will distinguish between “thin” and “thick” jets, thin jets being those with $m_j < 0.15p_T$, and thick jets being those with $m_j > 0.15p_T$. (This terminology has been introduced in [25].) By selecting thin jets with high $p_T$, and plotting the dijet invariant mass of pairs of such jets with $\Delta R$ not large, one might hope to significantly reduce the combinatoric background. (This same method works for finding $W$ bosons in high-energy $t\bar{t}$ events.)

In Fig. 23 is shown a plot of dijet masses for cone jets (defined as described in Sec. II D and in Appendix B.) I demand that both jets are thin and have $p_T > 25$ GeV and $|\eta| < 3$, and require that the two jets have $\Delta R < 1.2$. In Fig. 24 is shown a similar plot with lower statistics but lower background, using $p_T > 100$ GeV and $\Delta R < 0.9$. Either approach is a challenge for cases A1 and B1, which is not surprising, since reconstruction of a 50 GeV resonance using jets is no easy task. As can be seen from the plots, the number of v-pions reconstructed is disappointingly low; recall there are thousands in the data (see Table I.) Smearing and mismeasurements, not included here, will only make matters worse. It would appear that dijet invariant mass is not a particularly good variable for reconstructing the v-pion resonance.

B. Single jet masses

Now let us turn to single jet invariant mass $m_j$. In Fig. 25 $m_j$ versus $p_T$ is shown for all jets in these events with $|\eta| < 3$. The same is shown in Fig. 26 for the highest-$p_T$ jet in each event. In both classes of plots, a band of jets with invariant mass near to the v-pion mass is clearly seen. However, this information is not entirely observable. High $p_T$ QCD jets will often develop an invariant mass of order 15 percent of their $p_T$, just from the emission of a moderate-$k_T$ gluon that lies out-
FIG. 26: For the highest-\(p_T\) jet in each event, the distribution of \(m_j\) versus \(p_T\), in TeV.

side the parton-shower approximation used in PYTHIA’s simulation of jets. Also, jets which are too narrow will not have a well-measured invariant mass, for various detector-related reasons. One might therefore wisely exclude from analysis any jet whose mass is less than, say, 15 or 20 percent of its \(p_T\), thus excluding the hardest jets. Refinements of this measurement deserve more attention than can be given here. However, some preliminary indications are presented in Fig. 27 where the single jet invariant mass of all jets with \(p_T > 100\) GeV is shown on the left, and the same with the additional condition that the jet be “thick”, \(m_j > 0.15 p_T\), is shown in the second-to-left column. Clearly the additional condition has the advantage of removing many ordinary isolated jets, reducing the QCD continuum that peaks at low mass, and allowing the signal to stand out more clearly. This more refined measure of invariant mass is shown again in the right-hand plots of Fig. 27 for the highest-\(p_T\) and second-highest-\(p_T\) jet in each event. Interestingly, in case B1 — the case with highest multiplicity, where the highest-\(p_T\) jet often is a merging of more than two partons (Fig. 18) — the second-highest-\(p_T\) jet shows the \(\nu\)-pion mass more clearly. The correlation between the masses of the two highest jets can also be a useful variable; a scatter plot of the masses of the two highest-\(p_T\) jets (if both are central and thick) is shown in Fig. 28. Note that in case B1 the high multiplicity tends to spread out the peak, whereas in case A3 the peak is almost invisible due to low statistics, but for the other cases this plot can help reveal the resonance.

The fact that the single-jet invariant mass is a good observable in all 6 cases is a simple consequence of the fact that relatively light particles are being produced with a large boost, through the decay of a heavy \(Z'\). (Clearly the same strategy will not work for \(\nu\)-pions produced in decays of lighter particles, such as Higgs bosons [1] [14] or supersymmetric particles [15].) There are important and little-studied backgrounds from all-hadronic decays.
of boosted W’s, Z’s, and t’s, which are produced with an enormous rate. These will swamp any new resonance unless events are first selected with the unusual features of this signal. Should the v-pion mass lie close to 80-90 GeV or to 170 GeV, the difficulties will be very much greater. We must hope nature does not choose this scenario, or at least provides a large cross-section in return.

C. Some Improvement Using Fatter Jets

We have seen that single jet invariant mass reconstructs more v-pions than does dijet invariant mass. By widening the jet cone, one might hope to reconstruct even more. Here I will explore increasing the cone radius from 0.4 to 0.7, and will show some increase in efficiency.

Comparing Fig. 29 to Fig. 25, we see that a larger fraction of the jets of radius 0.7 are single v-pions, compared to those of radius 0.4. This is very clear in the left-hand plots of Fig. 30, whereas the thickness criterion (the cut in $m_j/p_T$) is essential to remove random jets in the signal in Fig. 27, it is less essential, but still effective, with the larger cone size. Comparison of Fig. 30 with Fig. 27 and of Fig. 31 with Fig. 28 shows that the larger cone size generally allows a marked improvement in both efficiency and resolution, for both the hardest and second-hardest jet in the event.

The one interesting exception, among the case studies, is case B1. Here the number of partons in the final state is so large that confusion background dominates. Most high-$p_T$ jets contain multiple $b$ quarks, and the hardest jets tend to contain more than 2, a tendency already visible in Fig. 18. With a cone size of 0.4, rather few of the high-$p_T$ jets are single v-pions, and a larger cone-size makes this problem worse. It appears it is best in this case to work with the jets of radius 0.7 that do not have the highest $p_T$, and even then the background from random jets in the signal is rather large (see Fig. 30, fourth line, second plot from left). Background from standard model processes would be very problematic except for the fact that case B1 is also the easiest case to separate from the standard model using other methods. This case has the highest multiplicity of jets ($\sim 7$) and vertices ($\sim 20$), the highest multiplicity of secondary muons ($\sim 3$), the most tracks ($\sim 100$) and displaced tracks ($\sim 50$), very high $\hat{H}_T$ ($\sim 1.6$ TeV), and a striking event shape (sum of the two cluster masses $\sim 1.2$ TeV). Perhaps this signal can even be identified in a counting experiment, where the standard model backgrounds can be estimated from the data by looking at event samples that share some but not all of these striking features. It is conceivable that
FIG. 30: As in Fig. 27, but with cone size 0.7 instead of 0.4; from left to right, (a) the mass $m_j$ of jets with $p_T > 100$ GeV and $|\eta| < 3$; (b) the same but with $m_j/p_T > 0.15$; (c) $m_j$ for the highest-$p_T$ jet with jets with $p_T > 100$ GeV, $|\eta| < 3$ and $m_j/p_T > 0.15$; and (d), the same but for the second-highest-$p_T$ jet.

the v-pion resonance can be better identified with a more sophisticated variable than single jet mass, looking more carefully at the substructure of the jets. (It is even possible that, with so many v-pions per event, and with a bit more statistics than available here, the v-pion can be discovered through its rare tree-level decay to muon pairs or its loop-induced decay to photon pairs.) More generally, it is important to study further how best to look for resonances in very-high-multiplicity signals, such as case B1.

I have given evidence that single jet mass, using a larger cone size than typically used for jets at the LHC, is the variable to use in searching for the v-pion resonance. Why are the fatter jets a better choice? If a single boosted v-pion has a boost factor greater than 6, it will typically form a single thin jet. Thus, thick jets arise from v-pions with a boost below 6, whose daughters typically have an opening angle of order 0.3 or larger. This is why, if a thickness criterion is applied, jets of radius 0.7 have a much higher efficiency for containing a single v-pion than jets of radius 0.4.

These conclusions are somewhat suspect, and the plots above unrealistic, because no energy smearing or magnetic field were included in the simulation of the calorimeter. A more serious study is needed, using a more complete detector simulation. Several remarks are in order.

It will be of considerable interest to learn the jet-mass resolution of the LHC detectors. This information should be available in the early data from studies of $W$ bosons and $t$ quarks in boosted $t\bar{t}$ events. It will also be interesting to see plots of the QCD continuum background to

FIG. 31: As in Fig. 28, but with cone size 0.7 instead of 0.4; jet-invariant mass (in GeV) for the highest and second-highest $p_T$ jets in each event, where jets are required to have $p_T > 100$ GeV, $m_j > 0.15p_T$, and $|\eta| < 3$.

D. Comments

- FIG. 31: As in Fig. 28, but with cone size 0.7 instead of 0.4; jet-invariant mass (in GeV) for the highest and second-highest $p_T$ jets in each event, where jets are required to have $p_T > 100$ GeV, $m_j > 0.15p_T$, and $|\eta| < 3$.
jet-mass measurements.

Since angular resolution is essential for jet mass measurements, the curvature of tracks due to the magnetic field should be removed. Clearly the use of something like “particle flow” — combining angular information from the tracker as well as the electromagnetic and hadronic calorimeters — should significantly aid in improving the resolution on jet mass.

An additional handle for reducing backgrounds to boosted v-pions may lie in detecting the substructure within the jet, such as recently considered in [23]. This is easiest to do with clustering algorithms such as the \( k_T \) algorithm, and using tracking as well as calorimetry. In fact, for the most energetic v-pions, whose daughters have the lowest angular separation, the granularity of the calorimeter, especially its hadronic component, will badly degrade jet-mass resolution. In this case tracking is crucial (see for example [26]). By studying the locations of the highest-\( p_T \) tracks, one may be able to significantly improve angular resolution on the substructure of the jet, and improve the invariant mass measurement. These issues deserve much more attention and will be explored elsewhere [25].

**IV. CONCLUSION**

In this paper I have investigated the phenomenology of a large class of hidden valley models, illustrated by six case studies within a particular model, but intended to apply in a much broader context. The models present a single new narrow resonance (more precisely, in the particular case studied, a triplet of nearly degenerate resonances \( \pi^0_v, \pi^\pm_v, \pi^\nu_v \)) that decays promptly, and predominantly to heavy flavor. Importantly, there is no measurable rate for decay to \( \mu^+\mu^- \) or \( e^+e^- \). In this sense this class is largely orthogonal to the large class studied in [10]. In production mechanisms (\( Z' \) decay) that lead to high-multiplicity heavy-flavor final states, the phenomenology is very different from that of most supersymmetry, technicolor, Randall-Sundrum, or little Higgs models that have so often been studied.

The six case studies were divided into the A cases (where the \( \pi^\nu_v \) are invisible and stable) and the B cases (where all three types of \( \pi_v \) decay promptly). The main results were the following:

- Missing energy and total transverse energy are useful global variables.
  - In the A cases, \( E_T \) and \( H_T \) are of the same order, many hundreds of GeV for 50 GeV v-pions and closer to a TeV for 200 GeV v-pions.
  - In the B cases, the \( E_T \) is much smaller and the \( H_T \) is in the 1.5–2.5 TeV range.
- Multiplicities of v-hadrons, and their daughter standard model partons (mostly bottom quarks), are very large.
  - In the A cases, the number of v-hadron daughters ranges from an average of 3 with a tail to 12 (for heavy v-pions) to an average of 8 with a tail to 24 (for lighter v-pions).
  - In the B cases, the number of v-hadron daughters ranges from an average of 8 with a tail to 20 (for heavy v-pions) to an average of 20 with a tail to 42 (for lighter v-pions).
- However the multiplicity of jets is somewhat smaller, because jets often contain multiple v-hadron daughters; this is due to the high boost and high concentration of the v-pions.
  - In the A cases, this effect is especially important, because by reducing the number of hard jets it leaves the signal with larger standard model backgrounds.
  - In the B cases, the effect is more pronounced, but the resulting multiplicity of jets is still large compared to most standard model processes.
- In the A cases, counting of heavy-flavor-tagged jets appears insufficient for separating signal from background, because the multiplicity of jets is too low. The situation in the B cases is somewhat more promising.
- The signal is particularly unusual in the numbers of vertices, of tracks, and of displaced tracks, and the clustering of and correlations among jets, tracks and vertices. These features may be useful in separating signal from background.
- Other observables, including event-shape variables (particularly one similar to the \( M_{\text{cluster}} \) variable of [10]) and numbers of secondary muons, might serve as additional tools for event selection, though their utility needs more study. They may not be helpful in the A cases, and they may not be needed in the B cases.
- If the unusual features of the signal can be used to obtain a sample with a reasonable signal-to-background ratio, an attempt can be made to find the v-pion resonance.
  - Because of combinatorics, a naive approach to dijet masses cannot work.
  - Since many v-pions are boosted, it is better to consider dijet masses of jets which are close in \( \eta \) and \( \phi \), or single-jet masses of individual jets which are “thick” (have a large mass-to-\( p_T \) ratio.)
  - Single-jet mass for a relatively fat jet definition seems to be an observable with a high efficiency for the signal. Here \( R = 0.7 \) cone-jets were shown to be better than those with
Correlations between the single-jet mass of the highest- and second-highest-$p_T$ jets may be useful in reducing background.

With extreme multiplicity, as in case B1, jet mass for high-$p_T$ jets is less useful, because too many of these jets contain more than a single $v$-pion. An alternative observable is not yet known, but also such signals are particularly spectacular, with low standard model backgrounds, and a discovery claim might not require reconstruction of the resonance.

It is possible but rather unlikely that multiplicities and event rates will be high enough to allow reconstruction of the $\pi_v$ resonance through the rare decays $\pi_v \rightarrow \mu^+ \mu^-$ or $\pi_v \rightarrow \gamma \gamma$.

In all cases, the phenomenological issues that arise are somewhat unusual, and need to be explored further in more fully realistic studies. Generating relevant and realistic background samples for these unusual signals represents a substantial challenge.

I should again emphasize that the issues and observables discussed in this paper are not limited to these specific models, but will apply more broadly. In a number of classes of hidden valley models, new resonances that decay to heavy flavor are produced in high-multiplicity environments, sometimes with a substantial boost. This can also happen in models beyond the hidden valley scenario.

Conversely, it is important to stress that this particular class of models is special, and relatively easy, in that there is only one $v$-hadron resonance to be found. In many other models, there will be multiple $v$-hadrons of different masses, and so the resonance signal just described will be spread out among several resonances, making it harder to extract. One may still hope, however, for an enhancement in jet and dijet masses that will be inconsistent with Standard Model background. And some models are even easier to find, as in the example [1] studied phenomenologically in [16], because of the presence of electron-pair and muon-pair resonances. These may easily be seen above background even with a rather impure sample of hidden valley events.

Several other classes of hidden valley models with distinct phenomenology from those studied here and in [16] remain to be investigated. To examine these in detail requires a significant extension of the current Monte Carlo simulation package. An initial extension is now complete [18]. Preliminary results on some models, with their own unusual signals, will be presented soon [27].

I thank G. Ciapetti, A. De Roeck, C. Dionisi, S.D. Ellis, S. Giagu, T. Han, J.W. Huston, P. Loch, H.J. Luhbatti, G.P. Salam, Z. Si, C.K. Vermillion, J.R. Walsh and K.M. Zurek for useful discussions. I am especially indebted to S. Mrenna and P.Z. Skands for advice and assistance in the writing of the HVMC 0.5 Monte Carlo package. This work was supported in part by Department of Energy grant DE-FG02-96ER40956.

\[ R = 0.4, \text{ but a thorough study of the best jet radius was not carried out, nor were other algorithms carefully considered. More work remains to optimize this measurement [25].} \]

\[ \text{Correlations between the single-jet mass of the highest- and second-highest-$p_T$ jets may be useful in reducing background.} \]

\[ \text{With extreme multiplicity, as in case B1, jet mass for high-$p_T$ jets is less useful, because too many of these jets contain more than a single $v$-pion. An alternative observable is not yet known, but also such signals are particularly spectacular, with low standard model backgrounds, and a discovery claim might not require reconstruction of the resonance.} \]

\[ \text{It is possible but rather unlikely that multiplicities and event rates will be high enough to allow reconstruction of the $\pi_v$ resonance through the rare decays $\pi_v \rightarrow \mu^+ \mu^-$ or $\pi_v \rightarrow \gamma \gamma$.} \]

\[ \text{In all cases, the phenomenological issues that arise are somewhat unusual, and need to be explored further in more fully realistic studies. Generating relevant and realistic background samples for these unusual signals represents a substantial challenge.} \]

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\[ \text{FIG. 32: The distribution of the number of secondary muons.} \]

\[ \text{APPENDIX A: OBSERVATIONS CONCERNING LEPTONS} \]

\[ \text{Plots of the number of central prompt or semi-prompt (appearing within the beampipe) muons, with $p_T > 3$ GeV and $|\eta| < 2$, are shown in Fig. 32 and their $p_T$ distributions are shown in Fig. 33. No isolation criteria are imposed.} \]

\[ \text{APPENDIX B: CHECKING THE CORRESPONDENCE OF HADRONIC JETS AND PARTONIC JETS} \]

\[ \text{Here I will show more carefully that the partonic and hadronic jets, constructed with a reasonable algorithm, do correspond, as claimed in the main text.} \]

\[ \text{The jet algorithms used in this study are shown in Table IV. All studies use the multi-algorithm software Spar-} \]

\[ \text{tyJet of [28], which includes the FastJet $k_T$ algorithm [29]. In the plots within the main text, the midpoint merging version of the cone algorithm was used, with} \]

\[ \text{FIG. 32: The distribution of the number of secondary muons.} \]
cone size $R = 0.4$. In this appendix, a cone of $R = 0.7$ is also used, along with the $k_T$ algorithm with the $R$ parameter set to give $k_T$ jets of radius approximately 0.4 and 0.7.

First, let us check the correspondence between hadronic jets and parton jets. One may confirm that the $p_T$ of the highest-$p_T$ partonic jet matches with the $p_T$ of the highest-$p_T$ hadronic jet; this is shown in Fig. 34. The pseudorapidities match as well. Nor is this an accident limited to the highest-$p_T$ jet; the same figure for the second-highest $p_T$ jet shows that the strong correlation between the hadronic and partonic jets persists.

Now I turn to the $k_T$ algorithm. As with the cone algorithm we see, in Figs. 36 and 37 a failure of the correspondence of partons to hadronic jets, and better agreement between partonic jets and hadronic jets. Figures 38 and 39 further confirm the quantitative correspondence of the partonic and hadronic jets. Thus the cone and $k_T$ algorithms both allow reconstruction of the partonic jets using hadronic jets.

| Midpoint Cone Algorithm | cone radius | seed threshold | search cone area fraction | merge fraction |
|-------------------------|-------------|----------------|--------------------------|---------------|
| 0.4                     | 1 GeV       | 0.25           | 0.75                     |               |
| 0.7                     | 1 GeV       | 0.25           | 0.75                     |               |

| FastJet $k_T$ Algorithm | $R$ parameter | minimum cell $p_T$ | $d_{out}$ |
|-------------------------|---------------|--------------------|----------|
| 0.52                    | 5 GeV         | $(5 \text{ GeV})^2$|          |
| 0.91                    | 5 GeV         | $(5 \text{ GeV})^2$|          |

TABLE IV: The parameters used in the cone and $k_T$ algorithms used in this study.
These studies have been repeated for jets with larger settings of the cone size or $R$ parameter (0.7 and 1.0 for cone jets). The correspondence of partonic and hadronic jets continues to hold firm.

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FIG. 38: As in Fig. 34, for the $k_T$ algorithm with $R$ parameter 0.52 (see Table IV).

FIG. 39: As in Fig. 35, for the $k_T$ algorithm with $R$ parameter 0.52 (see Table IV).

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