New Signals and Challenges for the LHC

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Abstract
Models with hidden sectors, including many non-minimal versions of well-known models, can pose substantial challenges for the LHC experiments. This is illustrated using the hidden valley scenario.

1 Introduction and Motivation

Hundreds of theoretical and experimental studies have been done in preparation for the advent of the Large Hadron Collider (LHC). But these studies are hardly comprehesive; most involve explorations of "minimal" theories, which aim to address a problem in particle physics and contain the minimal structure required for that purpose. For example, most supersymmetric studies are of the Minimal Supersymmetric Standard Model (MSSM). But is the MSSM well-motivated?

On the one hand, supersymmetry (SUSY) is clearly well-motivated. It is our best candidate for solving the hierarchy problem without introducing FCNCs or large corrections to precision electroweak observables. Moreover, it appears naturally in our best current theory of quantum gravity: string theory. On the other hand, *the word "minimal" is not so obviously well-motivated.* Minimalism does not solve any problem in particle physics; it is motivated by aesthetic criteria: elegance, simplicity, etc. One might view such criteria as good motivation if experience suggested that nature always was elegant and simple. But is the Standard Model "minimal"? The muon, the third generation, CP violation and neutral currents have all been viewed, at various times, as unmotivated and unnecessary complications that nature is unlikely to present. Moreover, minimalism is quite difficult to obtain in string theory. Attempts to find the SM within string theory bring along extra gauge factors and matter, some of which are coupled to the SM more strongly than gravitationally.

Why do theorists dislike non-minimal models? A more complicated Lagrangian has more parameters, and therefore fewer precise predictions and more ambiguity about the details of the spectrum, decays, etc., as well as fewer constraints from existing data. But for these features to generate a dislike is a bias — a *cultural* bias, one which nature may not share. The problem is that it is dangerous to disregard non-minimal models: they can have wildly different LHC phenomenology from the corresponding minimal models, and often generate surprising and difficult signatures for the LHC experiments.

1.1 Sensitivity of the Higgs boson

The decay modes of Higgs bosons are easily altered by new interactions. This is especially true of light SM Higgs bosons, or CP-odd Higgs bosons in two-Higgs-doublet models, which are narrow, as they decay through a small coupling (mainly to b quarks.)

As a simple exercise to illustrate the point, let us add one new real scalar S to the SM. Depending on the couplings of S to itself and to the Higgs boson H, one may obtain

- An invisible higgs;
- Two scalars, h decaying to $b\bar{b}$ and H decaying to WW and ZZ;
- Two scalars, h decaying to $\tau^+\tau^-$, and H decaying to hh;
- A Higgs decaying to two long-lived particles, which decay in flight to $b\bar{b}$ or $\tau^+\tau^-$.

Any of these final states poses challenges for reconstruction and experimental analysis at the LHC detectors, and the last even challenges the trigger system.

Some recent investigations of this possibility have focused on the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [1], and have pointed out that the LEP experiments might have missed $h \to aa \to (\tau^+\tau^-)(\tau^+\tau^-)$, where a is a pseudoscalar. Other possible final states include $h \to b\bar{b}b\bar{b}$. These final states would pose a significant challenge for the LHC. In fact, as they pointed out, a search for the a at B factories may be the best approach. Higher multiplicity decays, such as Higgs to 6 or 8 b's or τs, arise in non-minimal SUSY [2] and in wide classes of models within the Hidden Valley Scenario [3–5]. Decays to two new spin-one particles, giving occasional 4-lepton final states, can arise in many models with hidden sectors [3, 6, 7]. Decays to two (or more) long-lived neutral objects, giving 2 or more displaced vertices, arise in Hidden Valleys and other related models [4], and in R-parity Violating SUSY [8].

This diversity of possibilities arises from the ease with which the Higgs can couple to hidden sectors, through a renormalizable coupling $(HH^*)\mathcal{O} \to \langle v\rangle h\mathcal{O}$, where $\mathcal{O}$ is a composite operator built from fields in a new sector.

1.2 Hidden Valleys

But access to hidden sectors, as Zurek and I emphasized [3–6] can occur through many channels. Rare decays of the W and Z, and decays of Z' bosons, new neutrinos, the lightest supersymmetric particle "LSP" (or the lightest Kaluza-Klein particle or T-parity-odd particle [LKP/LTP]), certain KK resonances, black holes, etc., all can serve to open a door to a new sector of particles and forces. These decays (whose branching fractions can sometimes reach 100 %) often exhibit unusual features, such as:

- High multiplicity final states (often mostly jets, sometimes with no leptons or photons; often highly variable in multiplicity; often with unusual clustering; generally non-thermal and often with small cross-sections, unlike black holes)
- Multiple long-lived particles in the final state (with lifetimes often in the psec to μsec range which produce observably-displaced vertices)
- Possible new light neutral particles (with masses essentially unconstrained, as LEP puts very few constraints on electroweak- and color-singlet particles.)

While some of these phenomena have appeared before in the literature, typically in corners of parameter space of minimal or nearly-minimal models, very few have they been studied by the experimental groups. And in models with hidden sectors, they are commonplace!

In the Hidden Valley (HV) scenario [3], a hidden sector interacts with the SM at the TeV scale, as illustrated in Fig. 1. The scenario covers a very wide variety of models. A typical model has a valley-sector, or "v-sector", containing a new gauge group and matter; this is represented by the "valley" on the right, with the standard model sector on the left. One or more particles serves to connect the two sectors, and is represented by the mountain between the two valleys.

HV models often produce high-multiplicity events because of the effects shown in the figure: first, v-particles are produced; then valley dynamics, which might include v-cascade decays, v-parton showers, v-hadronization, etc., can increase the number of v-particles; and finally, if the v-sector dynamics prevents some v-particles from decaying within the v-sector, these v-particles may decay to the SM sector. Each step increases the number of particles.

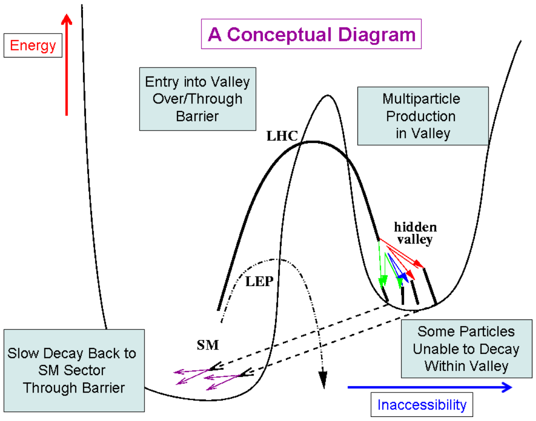

Fig. 1: Conceptual diagram of a Hidden Valley.

High multiplicity events may confuse standard reconstruction algorithms, defy typical search strategies, etc. Backgrounds to such events are hard to calculate or measure. In events with many quarks, jets from jet algorithms will not match to short-distance quarks. Highly-boosted v-particles, which are common, can have daughters that merge into a single jet, or which violate standard isolation criteria for taus, leptons and photons. Soft quarks are also common, and these, rather than producing jets, may be confused with an active underlying event or with effects of pileup.

Meanwhile, v-particle decays to the SM are often slow because they are mediated by a product of a standard model operator times a v-sector operator: $\mathcal{O}_{SM} \times \mathcal{O}_v$. If the total dimension of the product > 4, decay rates are suppressed. For example, a v-particle of mass m with a decay through a dimension 7 operator has a decay width proportional to $(m/\mathrm{TeV})^6$.

Long-lived particles can pose substantial challenges for detectors. Though they have no SM background, they typically have detector backgrounds arising from "secondary" interactions: collisions of high-momentum hadrons with detector material. Moreover, no trigger pathway is aimed at such particles, and existing triggers can have poor efficiency, especially for low-energy displaced jets. Also, reconstruction software can be confused by the unusual tracking environment. CDF and D0 analyses searching for Higgs decays to two long-lived particles have taken 2 years. In fact, as we pointed out, LHCb, designed to find B mesons, could actually beat ATLAS and CMS to a discovery of new long-lived particles [4, 8].

Example: A Higgsed Hidden Valley: As illustration, consider a theory with v-gauge group G, broken completely so that the v-gauge bosons Y get mass $g\langle X\rangle$, where X is a v-Higgs boson of mass m_X. Through loop effects, the Y bosons can mix with the standard model Z, typically with a tiny mixing angle. Just as in the SM, $X \to YY$ is allowed if $m_X > 2m_Y$. The presence of an X^2H^2 term allows mixing of X and H and a coupling $H \to XX$. Putting these together, a number of processes, if kinematically allowed, are predicted, including

- $H \to X^* \to YY \to Z^*Z^* \to$ 2 pairs of SM fermions
- $H \to XX \to YYYY \to Z^*Z^*Z^*Z^* \to$ 4 pairs of SM fermions

(where Z^* is an off-shell Z). One can uncover this hidden sector through Higgs boson decays, with the light neutral Y resonance(s) appearing first in dilepton pairs, then the X and H resonances in Y resonance pairs. If the Y is long-lived, it might first be discovered through its decay by a displaced vertex.

Example: A Confining Hidden Valley: Here is another example. A heavy resonance, such as a Z' or heavy Higgs, can decay into a hidden valley. In Fig. 2 is shown a process in which a quark-antiquark pair make a Z' boson, which then decays to v-quarks which are charged under the v-group G. In a QCD-like v-sector, the v-quarks undergo a v-parton shower and form v-jets of v-hadrons. Some of these v-hadrons can decay back to standard model particles, making a complex, high-multiplicity final state. Depending on parameters, the decays of the v-hadrons may be prompt or displaced. The resulting final states can look like Fig. 3.

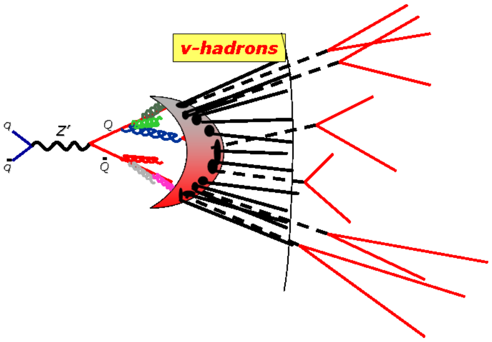

Fig. 2: Decay of a Z' into v-quarks Q, leading to v-jets of v-hadrons, some of which decay to SM particles.

So far I have assumed QCD-like confinement here. But nonperturbative phenomena in other theories are very different from QCD. For example, v-jets may be very different from QCD jets. In these cases, the resulting signatures cannot be reliably predicted. (There is one exception: a v-sector with a large 't Hooft coupling and an AdS/CFT dual description is known to have no jets at all, and to produce spherical events with many soft particles [6, 9].) At the LHC, a model of a phenomenon is often needed in order to find it; otherwise, it is hard to determine backgrounds, trigger efficiencies, and so forth. Thus the unknown dynamics of a hidden valley could obscure it at the LHC if we are not sufficiently thoughtful in advance. What range of analysis methods should be used to look for hidden valleys? At the moment there is no satisfactory answer, and more study is clearly needed.

Models with quirks: The coupling of the SM to a v-sector can come through a loop effect. Consider a confining hidden valley with v-group G, no light v-quarks, and a confinement scale Λ. In addition the model has massive particles ($m \gg 100$ GeV) charged under both the SM and the v-group. These particles are sometimes called "quirks" [10]. Flux tubes in the group G are stable, so quirks are eternally bound. Quirks are created in pairs in an excited state; they oscillate, gradually decay to their ground state, and finally annihilate to v-gluons or to SM gauge bosons. In the former case, the v-gluons form v-glueballs, which in turn decay slowly to SM gauge bosons through interactions induced by quirk loops. Remarkable unstudied phenomena can result, depending on the scale Λ.

- Two heavy charged/colored objects bound together by a macroscopically long, microscopically thick string;
- A mesoscopic dipole state;
- Relaxation to the ground state via emission of many soft pions or photons.

I'd like to say a couple of words about the last case [11]. Colored quirks with mass of 1 TeV will typically be produced ~ 300 GeV above threshold. Annihilation may sometimes occur only after relaxation to the ground state; if so, where does the 300 GeV of kinetic energy go? Kang and Luty showed that for a wide range of Λ, the answer is: "soft pions". While many of the resulting 100–200 soft charged pions do not reach the calorimeter, their tracks from the primary vertex are notable. In events where the quirk annihilation products are visible (for example, if the quirks annihilate to two TeV-scale jets, leptons or photons) a large number of tracks from the primary vertex should also appear, distributed in a spherical or oblong shape in the quirk rest frame, rather than cylindrically distributed in the lab frame, as for a typical underlying event.

The v-gluons to which quirks sometimes annihilate may give a strong HV signature. Since there are no light v-quarks, the v-gluons form v-glueballs. From lattice simulations we know there are many stable v-glueballs: 0^{++}, 0^{-+}, 2^{++}, 2^{-+}, 1^{+-}, etc. Via loops of quirks, the v-glueballs will decay to two SM gauge bosons (gluons, Ws, Zs, photons) or to a photon/Z plus another v-glueball [12]. The resulting final states have mostly jets, with occasional photons. One may trigger on and select events with 1 or more hard photon, and then detect the resonances from v-glueball decays to photon pairs, and/or the displaced jet-pairs from any long-lived v-glueballs.

In summary, non-minimal models are motivated by string theory and disfavored only by aesthetic criteria. They can drastically alter the phenomenology of common models, such as the SM itself, SUSY, Extra Dimensions, etc. In the Hidden Valley scenario and beyond, little-studied high-multiplicity final states, with new light and often long-lived neutral particles, can result. High-multiplicity challenges jet reconstruction and event interpretation; long lifetimes can be problematic for experimental analysis, reconstruction, and even the trigger. Quirks often arise in Hidden Valley models. In addition to the typical HV signatures (resonant v-glueball decays, possibly displaced), they can give a novel signature that hides in the underlying event.

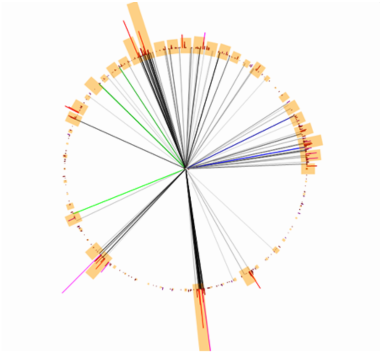

Fig. 3: Event display of a high-multiplicity state arising from the process in Fig. 2, in a model where the v-hadrons decay mainly to $b\bar{b}$ pairs.

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