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Echoes of a hidden valley at hadron colliders

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Abstract

We consider examples of "hidden-valley" models, in which a new confining gauge group is added to the standard model. Such models often arise in string constructions, and elsewhere. The resulting (electrically-neutral) bound states can have low masses and long lifetimes, and could be observed at the LHC and Tevatron. Production multiplicities are often large. Final states with heavy flavor are common; lepton pairs, displaced vertices and/or missing energy are possible. Accounting for LEP constraints, we find LHC production cross-sections typically in the 1–100 fb range, though they can be larger. It is possible the Higgs boson could be discovered at the Tevatron through rare decays to the new particles.

As the era of the Large Hadron Collider (LHC) approaches, and the Tevatron accumulates data, it is important to consider well-motivated particle physics models that present novel and challenging experimental signals. There has been much recent work along these lines [1–5].

Here we discuss a class of "hidden-valley" models that has received little study. These are models in which the Standard Model (SM) gauge group $G_{\rm SM}$ is extended by a non-Abelian group G_v. All SM particles are neutral under G_v, but there are new low mass valley particles ("v-particles") charged under G_v and neutral under $G_{\rm SM}$. Higher dimension operators at the TeV scale (induced perhaps by a Z' or a loop of heavy particles carrying both $G_{\rm SM}$ and G_v charges) allow interactions between SM fields and the new light particles in the hidden valley. As a result of the TeV scale suppressed interaction with the standard model particles, the v-particles are rarely produced at LEPI or LEPII, but may be abundantly produced at the LHC, and perhaps even the Tevatron. In a confining hidden-valley model, all v-particles assemble themselves into G_v-neutral "v-hadrons." Some of the v-hadrons can then decay, again via higher dimension operators, to gauge-invariant combinations of SM particles, with observable lifetimes. The diverse masses and lifetimes of the v-hadrons, their multiplicities, and the variety of possible final states make the v-phenomenology complex, and sensitive to underlying parameters, such as v-quark masses.

The hidden-valley scenario is consistent with data and is well motivated; it arises in many top-down models, including string-theory constructions [6]. It appears consistent with most methods for solving the hierarchy problem (supersymmetry, little Higgs models, TeV extra dimensions, Randall–Sundrum scenarios) so the v-phenomenology outlined below may accompany more familiar physics associated with each of these solutions. However, the purpose of this paper is not model-building, but rather to call attention to generic signals which may not yet have been fully explored at the Tevatron or in studies for the LHC.

As there is no clearly "minimal" hidden-valley model, we will present a simple theory exhibiting many phenomena typical of a v-sector, which include the following:

• There are several long-lived v-hadrons, with masses typically of order the v-confinement scale Λ_v. These long-lived v-hadrons may give rise to displaced vertices in the detector when the invisible v-hadron decays to pairs of standard model particles.

• Some v-hadrons may be stable, providing dark matter candidates and missing energy signals, while others decay to neutral combinations of SM particles.

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• Decay lifetimes can vary over many orders of magnitude; v-hadrons may decay promptly, or produce a displaced vertex anywhere in the detector, or typically decay outside the detector.

• Some v-hadrons decay preferentially to heavy flavor, while others decay more democratically to $f\bar{f}$ final states (f any SM fermion) or to $f\bar{f}$ plus another v-hadron; other final states can include two or three gluons, WW or ZZ.

• v-Hadron production multiplicities at the LHC may be large, especially if $\Lambda_v \ll 1$ TeV.

A simple v-model. To the SM, we add a $U(1) \times SU(n_v)$ gauge group, with couplings g' and g_v; we omit the special case $n_v = 2$. The $SU(n_v)$ interaction confines at the scale 1 GeV $< \Lambda_v <$ 1 TeV. The $U(1)$ is broken by a scalar expectation value $\langle\phi\rangle$, giving a Z' of mass $\sim$ 1–6 TeV. We add two v-quark flavors U, $\bar{U}$ and C, $\bar{C}$ in the n_v and $\overline{n_v}$ representation, and three right-handed neutrinos N_i; all become massive by coupling to ϕ. These masses and anomaly cancellation restrict the $U(1)$ charges to those shown in Table 1, with q_+ arbitrary and $q_+ + q_- = -2$. (We omit the special case $q_+ = q_- = -1$.) For definiteness, we take the SM particles (and the N_i) to be charged as under the usual $U(1)_\chi$ subgroup of $SO(10)$ that commutes with G_{SM}; see [7]. We impose a Z_2 symmetry forbidding Dirac neutrino masses, making the N_i stable (and dark matter candidates). Kinetic mixing between $U(1)_\chi$ and hypercharge, via the interaction $\frac{1}{2}kF'_{\mu\nu}F_Y^{\mu\nu}$, cannot be forbidden; we treat k as a free parameter. We may remove k by a field redefinition, at the cost of changing the charges. *In our formulas below, all factors of g' and all $U(1)_\chi$ charges Q_i are defined after removal of k by field redefinition*; the new charges differ from those in Table 1 by $Q_\chi = Q_\chi^0 - (kg_1/g')Y$ and, as expected [8], are no longer quantized. Some other classic $U(1)$ groups, such as B–L, are obtained for special values of k.

Table 1
Charge assignments for the model before removal of kinetic mixing; $q_+ + q_- = -2$

	q_i	$\bar{u}_i$	$\bar{d}_i$	ℓ_i	e_i^+	N_i	U	$\bar{U}$	C	$\bar{C}$	H	ϕ
$SU(3)$	**3**	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)$	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	0	0	0	0	$\frac{1}{2}$	0
$U(1)_\chi$	$-\frac{1}{5}$	$-\frac{1}{5}$	$\frac{3}{5}$	$\frac{3}{5}$	$-\frac{1}{5}$	-1	q_+	q_-	$-q_+$	$-q_-$	$\frac{2}{5}$	2
$SU(n_v)$	**1**	**1**	**1**	**1**	**1**	**1**	$\mathbf{n_v}$	$\overline{\mathbf{n_v}}$	$\mathbf{n_v}$	$\overline{\mathbf{n_v}}$	**1**	**1**

Two Light Flavors (2LF). We first consider the regime $m_U \sim m_C \ll \Lambda_v$, where the physics resembles that of QCD (Fig. 1). An approximate v-isospin between U and C quarks controls the spectrum; by analogy we call the (neutral!) v-pions $\pi_v^\pm, \pi_v^0$. All v-hadrons decay rapidly to v-pions and v-nucleons, of which all are stable and invisible except the π_v^0. The π_v^0 is unique: with v-quark wave function $U\bar{U} - C\bar{C}$, it can decay via $Q\bar{Q} \to Z' \to f\bar{f}$, where $Q = U, C$ and f is any SM fermion. Using $Q_f + Q_{\bar{f}} = \pm Q_H$ for all f, and $q_+ + q_- = -Q_\phi$, we find (except near $m_{\pi_v} \sim m_Z$, where Γ_Z must be included)

$$\Gamma_{\pi_v^0} = \frac{1}{8\pi} \frac{g'^4}{m_Z'^4} \frac{Q_\phi^2 Q_H^2 f_{\pi_v}^2 m_{\pi_v}^5}{(m_{\pi_v}^2 - m_Z^2)^2} \sum_f N_c^f m_f^2 v_f. \tag{1}$$

Here m_f, v_f are the mass and velocity of f; $N_c^f = 3$ for quarks (1 for leptons). (For very small m_{π_v} or Q_H, a loop effect may be dominant.) The extra factor of $(m_{\pi_v}/m_Z)^4$ at low m_{π_v} arises because the axial currents for Q and f decouple at low momentum. Heavy flavor is favored, due to the same helicity-flip that enhances $\mu^+\nu$ in usual π^+ decay. If $2m_b < m_{\pi_v} < 2m_t$, the dominant decay is $\pi_v \to b\bar{b}$. For $m_{\pi_v} \gg m_Z$,

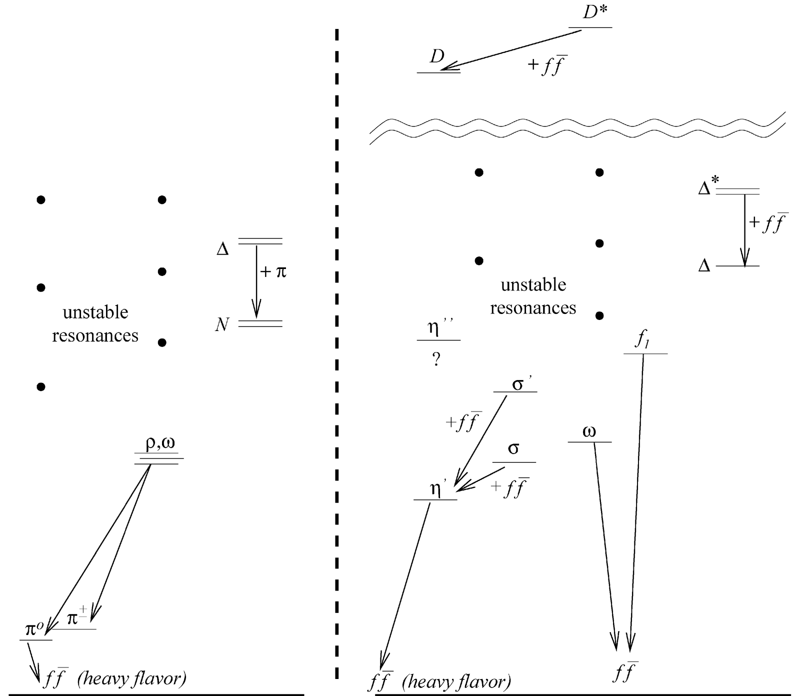

Fig. 1. Partial spectrum and decay modes in the two-light-flavor regime (left) and one-light-flavor regime (right); the latter is partly guesswork.