Discovering Higgs Boson Decays to Lepton Jets at Hadron Colliders

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The Higgs boson may decay predominantly into a hidden sector, producing lepton jets instead of the standard Higgs signatures. We propose a search strategy for such a signal at hadron colliders. A promising channel is the associated production of the Higgs boson with a Z or W. The dominant background is Z or W plus QCD jets. The lepton jets can be discriminated from QCD jets by cutting on the electromagnetic fraction and charge ratio. The former is the fraction of jet energy deposited in the electromagnetic calorimeter and the latter is the ratio of energy carried by charged particles to the electromagnetic energy. We use a Monte Carlo description of detector response to estimate QCD rejection efficiencies of $\mathcal{O}(10^{-3})$ per jet. The expected 5σ (3σ) discovery reach in Higgs boson mass is $\sim$115 GeV (150 GeV) at the Tevatron with 10 fb^{-1} of data and $\sim$110 GeV (130 GeV) at the 7 TeV LHC with 1 fb^{-1}.

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Introduction.—The Higgs boson is currently being searched for at the Tevatron and LHC, and its discovery may well complete the experimental verification of the standard model (SM). Alternatively, the Higgs couplings and branching fractions may differ from the SM predictions. In fact, the Higgs couplings to the light SM fermions are predicted to be very small. The presence of new light particles can thus drastically change the Higgs decay pattern. For this reason, Higgs decays present a promising opportunity for the discovery of new physics. A very generic extension of the SM is the case of extra $U(1)_d$ gauge symmetry. If new states charged under $U(1)_d$ and hypercharge exist at *any* scale, the two symmetries mix at low energy [1]. The presence of extra "hidden" states charged under $U(1)_d$ can also change the Higgs decay properties. For instance, if the hidden photon is light enough, the Higgs boson can decay dominantly into two or more lepton jets plus missing energy [2]. The purpose of this Letter is to propose a concrete search strategy for this Higgs channel at hadron colliders.

A lepton jet (LJ) is a cluster of highly collimated charged particles: electrons, and possibly muons and pions [3,4]. LJs can arise, if there exists a light hidden sector composed of unstable particles with masses in the MeV to GeV range. A well-motivated class of such models contains a massive vector particle (a hidden photon) that has a small kinetic mixing with the SM photon [1]. Because of this mixing, the hidden photon can decay to lighter particles with electric charge. For example, a 100 MeV hidden photon decays exclusively to electrons, whereas a 1 GeV one decays to electrons, muons, and pions. At the Tevatron and LHC, hidden photons and other light hidden particles are produced with large boosts, causing their visible decay products to form jetlike structures. This feature makes LJs similar to ordinary QCD jets and the challenge is to develop experimental techniques that efficiently isolate the new physics signal from the hadronic background.

As of today, Higgs decays to LJs have not been targeted by any experimental analysis, and the efficiency of existing searches for this sort of signal is low. The notable exception is the latest LJ search at D0 [5], which constrains the parameter space of models in Ref. [2]. The D0 search looks for $\Delta R \lesssim 0.2$ clusters, containing an electron or muon of $p_T > 10$ GeV and at least one companion track of $p_T > 4$ GeV. These clusters are required to be isolated in an annulus, $0.2 < \Delta R < 0.4$. LJs, however, can be wider than $\Delta R \simeq 0.2$ and/or can contain a large multiplicity of leptons with $p_T < 10$ GeV. While the D0 search is sensitive to narrow LJs with low multiplicities, it would have missed LJs that are wide or more populated, e.g., in a nonminimal or strongly coupled hidden sector. A Higgs boson decaying to such LJs could have escaped all existing searches even if it is very light, $m_h \simeq 100$ GeV [2].

In this note we concentrate on Higgs production in association with a W or Z and show that the Tevatron or early LHC is sensitive to light Higgs decaying to LJs. Moreover, we demonstrate that despite missing energy in the Higgs decays, it is possible to reconstruct the Higgs boson mass. The proposed search utilizes Higgs-specific kinematic cuts and additional cuts designed to identify LJs with the use of electromagnetic fraction (EMF) and charge ratio (CR). EMF is defined as the ratio of jet energy deposited in the electromagnetic calorimeter (ECAL) to the total jet energy. CR is defined as the ratio of the sum of the charged track p_T in the jet to the transverse energy deposited in the ECAL. We focus on the scenario where the LJs consist of electrons only (this happens when the hidden photon mass is below the $2m_\mu$ threshold). In this case the signal has EMF and CR $\simeq 1$, while QCD jets with EMF near one typically have a CR different from 1. As we show, combining EMF and CR discriminates lepton jets from QCD jets, with a background efficiency on the order of a few $\times 10^{-3}$ per jet.

Models.—The LJ structure is very sensitive to the details of the hidden sector. To be able to explore a wide range of LJ collider signatures we use an N-step cascade effective model. The hidden sector includes the hidden photon γ_d mixing with the SM photon, a stable scalar n mimicking the lightest hidden fermion described above, and a set of $N - 1$ hidden scalars $h_{d,i}$, that populate the cascade in the hidden sector. The Higgs boson first decays to a pair of hidden scalars $h_{d,1}$, which then decay to another pair of scalars $h_{d,2}$, and so forth, cf. Fig. 1. Finally, $h_{d,N-1}$ decays to either a pair of γ_d or n and subsequently, the hidden photons decay to pairs of electrons, while n counts as missing energy.

The tunable parameters of the effective model include the number of cascade steps (controlling the electron multiplicity and p_T), the hidden particle masses (controlling the number and width of LJs), and the branching fraction of $h_{d,N-1}$ into n (controlling the amount of missing energy). The effective model has sufficient flexibility to simulate the multitude of LJ signatures available in the parameter space of Ref. [2] and in more general hidden sectors.

In this Letter, we present results assuming a 3-step benchmark model. The masses of the two unstable scalars, h_{d_1}, h_{d_2}, are chosen to be 10 and 4 GeV, while the hidden photon, γ_d, and stable scalar, n, have masses of 100 and 90 MeV, respectively. The branching fraction of $h_{d,2}$ to n is 20%. This benchmark typically produces wide LJs with $\Delta R \sim 0.3$–0.4. Because of this feature, our benchmark is not excluded by the D0 LJ search of Ref. [5] (which requires no activity in the annulus 0.2–0.4 around the lepton jet) even for the Higgs mass as low as $\sim$100 GeV. The D0 search has an even lower efficiency for models with longer cascades (more steps), such that the leptons are softer than the search's p_T requirement of 10 GeV.

Electron jets vs QCD jets.—To discover Higgs decays to LJs we need to tell LJs apart from ordinary QCD jets

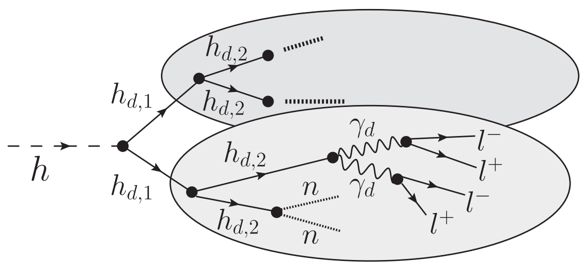

FIG. 1. Cascade higgs decay forming two lepton jets.

initiated by quarks and gluons. This is not completely straightforward as closely spaced leptons do not satisfy the usual isolation criteria and will not be reconstructed as leptons by the experiments. A number of LJ properties may distinguish them from average QCD jets, e.g., EMF, jet shapes, and the pair invariant masses of nearby tracks [2]. As we show below, the combination of EMF and CR is a particularly powerful discriminating tool that may open the way to a Higgs discovery. This approach is orthogonal to the one taken in Ref [5] and captures a different part of the LJ parameter space.

For the signal jets, the electrons typically leave all of their energy in the ECAL, so that EMF $\simeq 1$. This gets corrected by occasional leakage of electromagnetic showers into the hadronic calorimeter (HCAL), HCAL noise, or lepton jets overlapping with ordinary jets. Nonetheless, most of the signal has EMF > 0.95 (see Fig. 2).

For the background, the picture is more complicated. By the time a QCD jet reaches the detector, it mainly consists of charged pions and photons from π^0 decay. Most $\pi^\pm$ deposit a sizable fraction of their energy in the HCAL, while photons deposit almost all their energy in the ECAL. The precise jet composition, and consequently EMF, fluctuates highly event-by-event. The distribution is further broadened by fluctuations of the electromagnetic and hadronic cascades, and by energy smearing in the detector (the latter also leads to a fraction of jets having EMF > 1). The end result is that the EMF distribution of QCD jets peaks around 0.5–0.8, depending on the detector. A few percent of jets have EMF $\simeq 1$. Thus the EMF alone provides only limited discriminatory power.

The high EMF tail of QCD is due to jets with a high photon content. These jets leave few tracks and are

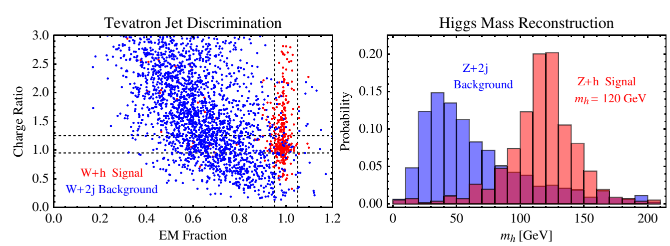

FIG. 2 (color online). Left: Scatter in electromagnetic fraction (EMF) and charge ratio (CR) for lepton jets (red) and background QCD jets (blue) in the $W + h$ channel at the Tevatron ($m_h = 120$ GeV). These events have passed the kinematic cuts of Eqs. (1) and (2) and the jets have at least 4 tracks. EMF is the fraction of jet energy deposited in the ECAL and CR is the ratio of the sum of track p_T to the transverse energy deposited in the ECAL. The signal is clustered at EMF, CR $\simeq 1$, while these variables are anticorrelated for the QCD background. The cuts used in the analysis are denoted by dashed lines. Right: Reconstruction of Higgs mass in the $h + Z$ channel at the Tevatron for $m_h = 120$ GeV, obtained using the approximation that the MET is collinear with the observed lepton jets. The signal (red) is clearly separated from the $Z +$ jets background (blue).

therefore expected to have small CR. In contrast, LJs composed of electrons have CR $\simeq 1$. The QCD jets and the electron jets are thus well separated in the EMF-CR plane, as shown in Fig. 2.

*Analysis and results.—*The dominant Higgs production mechanism via gluon fusion has overwhelming dijet background. Instead, we turn to Higgs production in association with electroweak gauge bosons. We search for a leptonically decaying W or Z accompanied by 2 LJs. The main background is W/Z + jets that mimic LJs.

We generated event samples for the D0 detector at the Tevatron and the ATLAS detector at the LHC with 7 TeV center-of-mass energy. Signal and background are generated at the parton level using MADGRAPHV4 [6] and BRIDGE [7], and then showered and hadronized in PYTHIA 6.4.21 [8], including multiple interactions and pileup. The cross sections are normalized to next-to-leading order using MCFM [9]. For detector simulation we use PGS4 and a private code (see below). We first employ kinematic cuts that target the $Z/W + h$ signal. For the search in the $Z + h$ channel we require two opposite sign same flavor isolated leptons ($l = e, \mu$) and exactly 2 jets satisfying:

$$p_T(j) > 15 \text{ GeV}, \qquad \Delta R_{j_1,j_2} > 0.7, \tag{1}$$

$$p_T(l) > 10 \text{ GeV}, \qquad |m(l^+l^-) - m_Z| < 10 \text{ GeV}. \tag{2}$$

The rapidity cuts are $|\eta| < 2.5$ for D0 (removing the $1.1 < |\eta| < 1.5$ region with worse ECAL coverage) and $|\eta| < 2$ for ATLAS for all jets and leptons. For the $W + h$ channel we use the same cuts on jets, but require one lepton and missing p_T satisfying,

$$p_T(l) > 20 \text{ GeV}, \qquad p_{T,\text{miss}} > 20 \text{ GeV}, \tag{3}$$

and veto on additional isolated leptons harder than 10 GeV. The above cuts have efficiency of $\mathcal{O}(10 - 20\%)$ for the signal, see Table I.

The kinematic cuts are insufficient to overcome the background. We therefore also employ EMF and CR cuts that are targeted at LJs. We stress that these cuts are not directly related to LJs arising from Higgs decays and would be suitable in any LJ search at hadron colliders.

The PGS4 implementation of calorimeter depositions is too simplistic for our purpose as it does not take into account realistic electromagnetic (EM) and hadronic cascades which are essential for EMF predictions. We therefore implement a fast calorimeter simulation for both D0 and ATLAS using a parametrization of EM showers in sampling calorimeters [10] and the Bock parametrization of hadronic cascades tuned to D0 [11] and ATLAS [12]. We allow fluctuations of all parameters and take into account detection efficiency of hadronic and EM energy (the noncompensation parameter h/e). Moreover, we simulate EM energy loss of heavy particles using the Landau-Vavilov distribution and detector smearing effects tuned to the detectors. For further details and references, see Ref. [13]. Finally we tune our simulation, in particular h/e, to D0 and ATLAS EMF data in dijets, obtaining accurate fits.

In order to ensure that our results are not significantly modified by photon conversions in the tracker, which we do not simulate, we require at least 4 tracks per jet. Next we use the code, described above, to estimate the EMF of the signal and background jets that pass the track cut and the kinematic cuts (1)–(3). We estimate the CR of the jets using track p_T from PGS4 divided by jet ECAL deposits obtained from our code. Sample results for $W + h$ at the Tevatron are plotted in Fig. 2. The electron jets are concentrated near EMF, CR $\simeq 1$, while the QCD jets display clear anticorrelation of the two variables: most of the QCD jets with EMF of order unity have a CR different from 1. Because of the difference in detector performances, we tune the EMF cut differently for D0 and ATLAS. In particular, we find that a tighter EMF cut is required for ATLAS; for D0 we take $0.95 < \text{EMF} < 1.05$, while for ATLAS, $0.99 < \text{EMF} < 1$. The CR cut is kept the same for both detectors, but different for the $W + h$ and $Z + h$ channels. The latter has a smaller cross section and requires looser cuts to retain enough statistics. We take $0.9 < \text{CR} < 1.9$ for $Z + h$ and $0.95 < \text{CR} < 1.25$ for $W + h$.

The efficiencies of our kinematic and LJ cuts are summarized in Table I for a Higgs boson, of a mass of 120 GeV, decaying into LJs modeled by the 3-step cascade described above. A 5σ discovery is possible in $W + h$ signal for Higgs masses up to ~145 GeV by combining CDF and D0 with 10 fb^{-1} each, and up to Higgs masses ~125 GeV at early LHC by combining ATLAS and CMS with 1 fb^{-1} each. In Fig. 3 we also show the 95% C.L. exclusion reach

TABLE I. The number of signal and background events for the $W + h$ and $Z + h$ channels, with $m_h = 120$ GeV, at the Tevatron and LHC. Event counts are shown after the cuts of Eqs. (1)–(3) and requiring at least 4 tracks per jet (Kinematic), and also after including the cuts on electromagnetic fraction and charge ratio (EMF + CR).

$m_h = 120$ GeV		$W + h$			$Z + h$		
		Signal (Eff.)	Bckg.	S/B	Signal (Eff.)	Bckg.	S/B
Tevatron	Kinematic	87 (18%)	4.4×10^5	2×10^{-4}	10.6 (18%)	2.8×10^4	4×10^{-4}
(10 fb^{-1})	EMF + CR	14.4 (3%)	5.9	2.4	3.5 (6%)	1.4	2.5
LHC	Kinematic	35 (17%)	4.9×10^5	7×10^{-5}	5.2 (25%)	3.6×10^4	10^{-4}
(1 fb^{-1})	EMF + CR	4.9 (2%)	0.7	7	1.5 (7%)	0.7	2.1

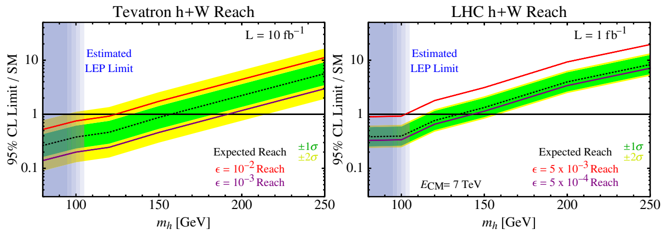

FIG. 3 (color online). Higgs mass exclusion reach at the Tevatron (left) and the early LHC (right) with luminosities of 10 and 1 fb^{-1}, respectively. The limits are for the $h + W$ channel and are normalized to the SM Higgs production cross section, assuming a 100% branching ratio into lepton jets. The expected 95% C.L. exclusion limit (black, dashed) assumes the EMF and CR rejection efficiencies, per QCD jet, extracted from our simulation and shown in Table I: $\epsilon = 3.7 \times 10^{-3}$ at the Tevatron and $\epsilon = 1.2 \times 10^{-3}$ at the LHC. The green and yellow bands show the 1σ and 2σ deviations due to statistical fluctuations of the background. For comparison, the limits derived from more optimistic (lower) and more pessimistic (higher) values of ϵ are shown in purple and red, respectively. Although this signal has not been searched for at LEP, we estimated that the limit is $m_h \simeq 100$ GeV in Ref. [2], and this regime is shaded blue.

of individual experiments. A $\sim$155 GeV (and perhaps as high as 190 GeV) Higgs is accessible at the Tevatron, and $\sim$135 GeV Higgs can be probed at the early LHC. The exclusion reach is much smaller in the $Z + h$ channel due to the smaller cross section: $\sim$110 GeV ($\sim$ 80 GeV) at the Tevatron (early LHC). With more LHC data, the reach will improve significantly for both channels.

Higgs mass.—Finally, we comment that the Higgs mass can be reconstructed from the LJs in the $Z + h$ channel. Although there is missing energy in the final state carried by the n's, we can assume that it is collinear with the two LJs (much like the $h \to \tau\tau$ channel in the SM [14]). This gives 2 unknowns (the magnitudes of the two missing 4-vectors which are taken to be massless), that are fixed by transverse momentum conservation. The result of applying this procedure is shown in Fig. 2 for our benchmark model, and the Higgs mass peak is clearly visible. The limiting factor is the small cross section in the leptonic $Z + h$ channel, which may render the mass reconstruction feasible only for light Higgs mass ($\lesssim$ 120 GeV) or with more data.

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