Visible Cascade Higgs Decays to Four Photons at Hadron Colliders

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(Received 13 October 2006; published 16 March 2007)

The presence of a new singlet scalar particle a can open up new decay channels for the Higgs boson, through cascades of the form $h \to 2a \to X$, possibly making discovery through standard model channels impossible. If a is CP odd, its decays are particularly sensitive to new physics. Quantum effects from heavy fields can naturally make $h \to 4g$ the dominant decay which is difficult to observe at hadron colliders, and is allowed by CERN LEP for $m_h > 82$ GeV. However, there are usually associated decays, either $h \to 2g2\gamma$ or $h \to 4\gamma$, which are more promising. The decay $h \to 4\gamma$ is a clean channel that can discover both a and h. At the CERN LHC with 300 fb^{-1} of luminosity, a branching ratio of order 10^{-4} is sufficient for discovery for a large range of Higgs boson masses. With total luminosity of ~ 8 fb^{-1}, discovery at the Fermilab Tevatron requires more than 5×10^{-3} in branching ratio.

DOI: 10.1103/PhysRevLett.98.111802 PACS numbers: 12.60.Fr, 13.85.Qk, 14.80.Cp

Introduction.—One of the most important questions in particle physics is the nature of electroweak symmetry breaking. In the standard model (SM), this is achieved through the vacuum expectation value (vev) of the Higgs boson field. The Higgs boson, an excitation about this vev, has well-defined couplings. Current precision electroweak measurements place the best fit value of the Higgs boson mass to be $m_h = 88$ GeV with an upper bound of $m_h < 146$ GeV at 90% CL [1,2]. In contrast, a SM Higgs boson is already excluded by LEP up to 114.4 GeV [3].

The search for the Higgs boson must be considered as the cornerstone of any search for weak-scale physics beyond the SM. Because of the strong predictions of the SM, we have many channels in which to search, for instance $h \to bb$ at LEP, $h \to \tau\tau$, $h \to \gamma\gamma$, and $h \to W^+W^-$ at the LHC. However, in extensions of the SM, it is possible that other decays exist which dramatically suppress the branching ratios to the expected channels. This could open up regions of the Higgs boson mass parameter space which are excluded in the SM, and even make future LHC searches impossible in SM channels.

Explorations of such non-SM decays have motivated additional LEP analyses. In many cases the constraints are comparable to the SM, e.g., invisible or light jet (flavor independent) decays [4,5]. Cascade decays [6] via a new scalar a have been investigated for various decay paths of a. Such cascade decays can occur, for example, in the minimal supersymmetric SM with CP violation [7–9] or an extra singlet [10,11]. The case of four b-jet final states [12,13] is excluded for $m_h < 110$ GeV [14], whereas four tau decays are still allowed [15] and could be observable at the Tevatron [16], while $2j2\tau$ could be visible at the LHC [16]. There can be exotic cascade decays with even more SM final states [17,18].

In this Letter, the discovery prospects of a new Higgs boson cascade decay will be analyzed. The coupling of the Higgs boson to a preserves a Z_2 under which $a \to -a$. The final state of the cascade decay is determined by what a decays are allowed. A natural possibility is a coupling to heavy fermions, which, if colored, allows the dominant decay to gluons, $a \to 2g$. We recently demonstrated, in the context of supersymmetric models, how this scenario can be realized in a natural fashion [17]. Such a decay is only presently excluded by the OPAL decay-independent study [19], which requires $m_h > 82$ GeV, and the OPAL low mass CP odd boson search [20], which places constraints for $m_a \lesssim 12$ GeV when $m_h < 86$ GeV. A dedicated LEP analysis should give stronger constraints, but probably still allows $90 \lesssim m_h \lesssim 100$ GeV [17]. In this note we show that in addition to the gluon decay there is often an associated decay into four photons, which can naturally occur with the right magnitude for discovery.

The introduction of a Z_2-odd singlet scalar into the SM permits the coupling ($v = 250$ GeV)

$$\mathcal{L} \supset \tfrac{c}{2}a^2|H|^2 = \tfrac{c}{4}a^2(v+h)^2. \tag{1}$$

Such a coupling induces a width $h \to 2a$ [6]

$$\Gamma_{h\to 2a} = \frac{c^2v^2}{32\pi m_h}\left(1-4\frac{m_a^2}{m_h^2}\right)^{1/2}. \tag{2}$$

To allow a Higgs boson as light as 82 GeV, present limits on the branching ratio [14] to b's requires $c \gtrsim 0.1$, a rather weak coupling. This also gives a contribution to m_a^2 of $cv^2/2$, but still allows $m_a < m_h/2$, so it is natural for the $h \to 2a$ decays to be kinematically open. We will focus on Higgs boson masses below 160 GeV, as on-shell W^+W^- decays would dominate the decay width.

In addition to $h \to 2a$ dominating, a light Higgs boson requires a Z_2 invariant decay for a, otherwise the Higgs boson decays invisibly. If the Z_2 is CP, a possibility is that the CP odd a mixes with the CP odd A^0, present in a two Higgs boson doublet model. This leads to $a \to 2b$ and $a \to 2\tau$ decays. However, absent mixing with extra scalars, adding new vectorlike fermions allows the only renormalizable coupling to a. Thus, we consider the coupling

$$\mathcal{L} \supset \bar{\psi}(M + i\gamma_5 \lambda a)\psi, \tag{3}$$

where ψ is some new fermion, charged under the SM. Integrating out ψ gives loop induced couplings to gauge bosons that allow a to decay. The decays $a \to 2x$, where $x = g, \gamma$, have width

$$\Gamma_i = \frac{9\lambda^2 b_i^2 \alpha_i^2}{1024\pi^3 M^2} m_a^3 N_D, \tag{4}$$

where N_D is the multiplicity factor in the final state (i.e., 1 for photons and 8 for gluons) and b_i is the contribution of the vectorlike fermion to the beta function for the given gauge group, electromagnetism or color. For, e.g., if ψ is a vectorlike down quark, $b_{SU(3)} = \frac{2}{3}$ and $b_{U(1)_{em}} = \frac{4}{9}$.

If ψ fills out an $SU(5)$ multiplet, for instance a **5**, and both the $h \to 2a$ and $a \to 2x$ decays dominate, we have the branching ratios $B(h \to 4\gamma) \approx 1.4 \times 10^{-5}$, $B(h \to 2g2\gamma) \approx 7.6 \times 10^{-3}$. For a light SM Higgs boson, an important search channel is also a rare decay, $B(h \to 2\gamma) \sim 10^{-3}$ [21]. The background of a 4γ signal is smaller than that for 2γ so it is not unreasonable that branching ratios as small as $10^{-(4-5)}$ might be detectable. A preliminary analysis suggests that the $h \to 2g2\gamma$ decay at this rate is visible at the LHC but not the Tevatron [6]. However, this decay at the LHC might only discover the a boson, due to the difficulty in measuring and finding the soft jets amongst combinatorial background. Another discovery mode for a is production through gluon fusion and subsequent decay into photons, which could be observable at Tevatron/LHC (through an analysis similar to [22,23]). However, the $h \to 4\gamma$ decay is a clean channel that allows discovery of both particles, if the rate is large enough to be detected, since as long [6] as $m_a \gtrsim m_h/40$ the photons are separated enough to be experimentally reconstructed as a four photon event. At the LHC, our analysis suggests that the 10^{-5} branching ratio is almost sufficient. However, it is worth noting that there may be incomplete GUT multiplets that contribute only to the photon decays. A prime example comes from the Higgsinos of supersymmetry. Coupling a to Higgsinos with the same mass and coupling as the **5** increases the branching ratio to 1.3×10^{-4}, which increases if the Higgsinos are lighter or more strongly coupled to a [24].

Another consequence of weak Z_2 violation is the relatively long lifetime of a which could lead to visible displaced vertices. Taking the dominant $2g$ decays as a measure of the decay width, one gets

$$c\tau_a \sim 1\ \mathrm{cm}\left(\frac{30\ \mathrm{GeV}}{m_a}\right)^3 \left(\frac{M}{450\ \mathrm{TeV}}\right)^2 \left(\frac{0.1}{\lambda b_3}\right)^2. \tag{5}$$

Displaced vertices of sufficient length could enhance the Higgs boson discovery prospects at Tevatron and LHC [25]. However, we do not investigate this possibility and assume that a decays promptly.

Cuts.—To analyze the detection reach at the LHC, we implement a parton-level analysis of the signal and background, leaving a more realistic simulation to future work. We apply the following cuts on our analysis: transverse momentum ($p_T > 20$ GeV for all photons), isolation ($\Delta R > 0.4$ between all photons), rapidity acceptance ($|\eta| < 2.5$), and consistent pairing (a photon pairing such that $|m_{\mathrm{pair1}} - m_{\mathrm{pair2}}| < 5$ GeV). The p_T cut satisfies the triggering requirement and also helps to reduce the background. The rapidity cut focuses the analysis in the detector region capable of precision EM measurements. The consistent pairing is an attempt to veto on background events that are inconsistent with a cascade decay. For the signal we used CTEQ5L, the default in PYTHIA, for the parton distribution functions whereas for the background we used CTEQ6L1 which maximizes rates (and thus makes our analysis more conservative). We use a photon reconstruction efficiency of 80% per photon [21], detector simulations would be required to determine if this is realistic; even in the worst case, we do not expect this to be smaller than 60%. The only other detector effects we take into account are Gaussian smearing of the photon energies and angles with numbers given by ATLAS [21]. We do not do so for the background, although we expect that with our relatively weak cuts that the numbers will not be largely affected and should be within our background uncertainty.

Signal.—To determine the signal acceptance for our cuts we implemented the $h \to 2a$ and $a \to 2\gamma$ decays in PYTHIA [26]. For fixed m_h, the acceptance is much larger when m_a is almost $m_h/2$ (due to the p_T cut) and decreases quickly when m_a is below about 10 GeV (due to the isolation cut), this behavior is reflected in the shape of Fig. 2. Away from these two extremes, the acceptance is subpercent until $m_h \sim 100$ GeV, it is about 5% at 130 GeV, and above 10% at 160 GeV.

Within our simulation, we evaluated the expected mass resolutions. We found that $\Delta m_{h(a)} \sim 0.1\sqrt{m_{h(a)}/\mathrm{GeV}}$, $\mathcal{O}(1\ \mathrm{GeV})$, $\mathcal{O}(0.5\ \mathrm{GeV})$ respectively, in the region of interest. Given the weak consistent pairing requirement, sometimes there are incorrect photon pairings within the signal which give fake m_a solutions. To distinguish the correct pairing from the incorrect it is usually sufficient to look for the most consistent value of m_a.

Finally, to take into account higher order corrections to the production cross section, we use a mass independent K factor of 2, which is characteristic of next to next to leading order (NNLO) calculations in our mass range [27,28]. In doing so, we assume that the acceptances and mass resolutions would not change much under the NNLO calculation.

Background.—For the LHC, we used ALPGEN [29] to estimate the background both from prompt photon production as well as jets faking photons. To take into account the jet fake rate, we fit the numbers in the ATLAS TDR [21] to a piecewise linear function of p_T so that 1 in $\min(3067, -1333 + 110 p_T/\mathrm{GeV})$ jets fakes a photon. We nominally use a factorization scale of $\mu_{p_T} = \sqrt{\sum_{i=1}^{n} p_T^2/n}$ although we also calculate the cross sections for $\mu_F = \mu_{p_T}/2$ and $2\mu_{p_T}$, and take the largest result. In this way, we are being pessimistic on the higher order corrections to the background. Using ALPGEN, we computed the background of $i\gamma + (4-i)\gamma_j$ (for $i = 0-4$), where γ_j is a jet faking a photon. Despite the larger cross section for jet production the fake rate is small enough that the dominant prompt background is 4 photon production. ALPGEN computes only at tree level so processes such as $gg \to 4\gamma$ are missed. However, for the background of $h \to 2\gamma$ the gluon fusion contribution is about 33% of the tree level processes [30], which for our purposes is small enough to be neglected.

In addition, there is a comparable background from multiple interactions within a bunch crossing, primarily from two fake photon production occurring twice in the crossing. Pointing information for the photons could be a discriminant, since there could be distinguishable interaction vertices, but we do not attempt to determine its effectiveness. We simulated this pileup background for the dominant process of $2\gamma_j \oplus 2\gamma_j$. Pileup involving $\gamma + \gamma_j$ or 2γ is small enough in comparison to be ignored.

We plot, in Fig. 1, the differential cross section $d^2\sigma/dm_h dm_a$ for the sum of both the single and multiple interaction backgrounds, as binned in 5 GeV windows for both m_h and m_a. From the simulated mass resolutions of the signal, these mass windows are generously large, but essentially all signal events would be accepted and the background estimate should be robust to the ignored detector effects. To summarize, the background estimates should be accurate up to order one factors, which is sufficient, given the size of the background.

Detection prospects.—We can now determine what branching ratios are required for discovery given 300 fb^{-1} at the LHC. Since the number of background events in a bin (B) is particularly low (with $B \lesssim 0.03$), 5σ Poisson statistics would usually require only a couple of events, but to be conservative, we require at least 5 signal events for discovery. The branching ratios required for this appear in Fig. 2. There appears to be a reasonably large region of parameter space where a branching ratio under 10^{-4} is capable of detecting both the Higgs boson and *a* scalar.

In comparison, the Tevatron is sensitive to a smaller region of parameter space. The background remains small enough to only require 5 signal events to claim discovery. However, Tevatron's reach is weakened by a smaller integrated luminosity (up to about 8 fb^{-1} expected at the end of run II) and by its lower Higgs boson production cross section. However, since the jet fake rate at the Tevatron has been measured down to 10 GeV [31], we can lower the overall p_T cut to this, which gives more reasonable acceptances (around 10%–50%). Ultimately, the Tevatron requires branching ratios larger than about 5×10^{-3} to discover the Higgs boson in this mode. Since we expect LEP to have strong constraints on such Higgs boson decays, this suggests that the only range where the Tevatron can certainly probe such a Higgs boson is above about 120 GeV, where LEP limits would not apply. If the actual LEP constraint is weaker then our expected 10^{-3} constraint, Tevatron could still probe below the LEP2 kinematic limit.

To increase signal rates, one either has to increase the acceptance or the integrated luminosity. We find that the acceptance improves by a factor of 4–10, if the overall p_T cut is lowered to 15 GeV; there still need to be $2p_T \geq 20$ GeV photons to trigger on. Unfortunately, then our background estimation is much less certain. ATLAS simulations of jet fake rate go down to 20 GeV. Extrapolations to 15 GeV (where 1 in 300 jets fake a photon), suggest our background rates remain under control with $B \lesssim 0.4$. Nonetheless, a measurement of the low E_T jet fake rate is necessary to determine what would constitute discovery in this case.

For the case of $m_a < 10$ GeV, acceptance would improve by replacing our isolation cut with an isolation condition that allows closer photons, this would also increase the background rate. More drastically, acceptance gains occur by changing the search, by looking instead for excesses in inclusive searches for 3 or more photons but,

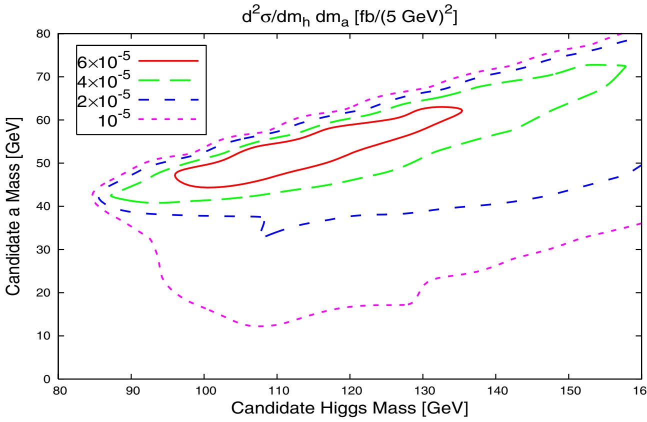

FIG. 1 (color online). LHC background under the cuts given in the text, in femtobarns. There is no point with value above 10^{-4}.

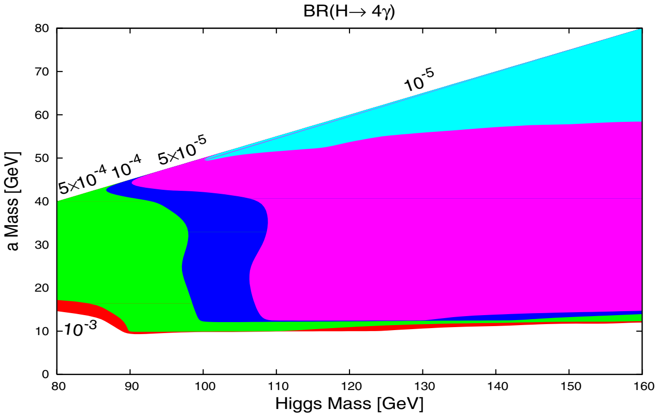

FIG. 2 (color online). Branching ratios sufficient for discovery (≥ 5 signal events), given 300 fb^{-1} of integrated luminosity at LHC.

there would be no direct way to measure the Higgs boson mass. These acceptances are very sensitive to the photon triggers. The signal would be destroyed if the triggers were pushed much higher than 20 GeV. If this is required to meet the trigger rate budget, a multiple photon trigger of 15–20 GeV would still efficiently trigger on this decay.

In terms of luminosity, LHC or Tevatron experiments could combine their results, giving an additional factor of 2 in the expected number of events. Looking further ahead, the signal could also benefit from an order of magnitude increase in luminosity, as in an SLHC upgrade [32]; here the background is less under control, as the multiple interaction background would naively increase by a factor of 100 and thus we would need many more than 5 events, requiring stronger background rejection.

There are many ways to lower the background rate, which could be important since our attempts at boosting the signal tend to make the background nonnegligible. Bins for m_h and m_a could be chosen to be as low as 4 and 2.5 GeV, respectively (for $\pm 2\sigma$ windows). Also, the consistent pairing criterion is far too weak, as the signal usually has a mass difference of less than 1 GeV. At higher luminosity the main issue is multiple interactions, it may be possible to reject these based on discernible multiple interaction vertices.

Conclusion.—Because of its small width to SM states the Higgs boson decays may be altered by physics beyond the SM. We focused here on the case $h \to 2a$ where the new scalar, a, decayed to gauge bosons, $a \to 2g$ and $a \to 2\gamma$, with widths proportional to α_s^2 and $\alpha_{\rm EM}^2$, respectively. We concentrated on searching for the Higgs *and* the light scalar through the rare decay $h \to 2a \to 4\gamma$, which may be the only way of discovering this type of Higgs.

We have found that standard cuts render this search essentially background free. Under the requirement of 5 signal events for discovery, LHC has a wide reach for branching ratios of order 10^{-4} and Tevatron has a reach for the bosons heavier than 120 GeV for branching ratios greater than 5×10^{-3}, this lower bound is sensitive to the details of the LEP constraints on $h \to 4\gamma$ and may be weaker if the constraints are weaker than we expect. With some improvements in acceptance or luminosity, the LHC could potentially probe the expected minimal branching ratio 10^{-5} for this Higgs boson decay. In general, reasonable signal acceptance remains an issue, which motivates a multiple photon trigger.

We thank M. Boonekamp, B. McElrath, M. Oreglia, M. Papucci, M. Perelstein, A. Sopczak, J. Thaler, J. Wacker, and S. Willenbrock for useful conversations, and R. Enberg for assistance with PYTHIA. We especially thank K. Matchev and T. Plehn for carefully reading the manuscript. The work of S. Chang and N. Weiner was supported by NSF CAREER Grant No. PHY-0449818 and by the DOE OJI program under Grant No. DE-FG02-06ER41417. P. J. Fox was supported in part by the Director, Office of Science, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the US Department of Energy under contract No. DE-AC02-05CH11231.

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