

Extra Dimensions and the Universal Suppression of Higgs Boson Observables at High Energy Colliders

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Abstract

Precision electroweak data suggests the existence of a light Standard Model Higgs boson. Its width is very narrow by an accident of the fermion mass hierarchies, and so slight perturbations to the theory induce dramatic changes in the phenomenology of direct Higgs boson production. Several theory ideas motivated by low-scale extra dimensions lead to a universal rate suppression of Higgs boson observables. The Tevatron and LHC will have difficulty accruing compelling evidence for small universal suppression of rate observables, and even more difficulty discerning the underlying cause. A high energy e^+e^- collider would have relatively little trouble.

The narrow Higgs boson

The most effective searches to date for the Higgs boson in the Standard Model (SM) come from $e^+e^- \rightarrow h_{\text{SM}}Z$ experiments at LEP II. They have put a 95% C.L. numerical limit on the Higgs boson mass of $m_{h_{\text{SM}}} > 114.1 \text{ GeV}$ [1]. Meanwhile, precision electroweak analyses based mostly on LEP, SLD and Tevatron data have put indirect limits on the SM Higgs boson mass [2]:

$$\log_{10}(m_{h_{\text{SM}}}/\text{GeV}) = 1.94_{-0.22}^{+0.21}. \quad (1)$$

The 95% C.L. upper bound is 222 GeV [2]. The closer the Higgs boson is to the 114.1 GeV lower bound the better it can account for the precision electroweak data.

If the Higgs boson is less than about $2m_W$ its width is less than 100 MeV. Such a narrow Higgs width is due to the SM accident of all fermions having mass less than 5 GeV except the top quark, which is too heavy for the light Higgs to decay into anyway. The narrowness of the Higgs width makes the Higgs phenomenology highly susceptible to subtle interactions the Higgs might have with other exotic states.

Extra dimensions and the Higgs boson

Large extra dimensions felt by gravity can generate the otherwise unnaturally large hierarchy between the Planck scale and the weak scale [3]. This would effectively preclude the existence of any fundamental scale far above the weak scale. The implications of this idea to the Higgs sector are significant.

For one, supersymmetry might not be needed to solve the quadratic sensitivity problem, since there would be no scales high enough to cause us concern. Superpartners would not be around, and perhaps more important to this discussion, there would be no obvious need for a second Higgs doublet as there is in supersymmetry.

Second, the existence of a large higher-dimensional bulk space can be important in ways that were never relevant in high-scale extra dimensional theories. For example, the mixing of the Higgs boson with graviscalars can radically change Higgs phenomenology [4]. Likewise, the decay of the Higgs boson into bulk states (states that feel the large dimensions with gravity) can change the phenomenology.

Finally, when there is only a few TeV of room to solve all possible problems in particle physics there are sure to be states living just above the weak scale that can mix with the Higgs boson. For example, to solve the proton decay problem may require the introduction of a new protecting gauge symmetry, such as baryon number or lepton number. Although it is not necessary to introduce spontaneous symmetry breaking in the conventional sense for all of these new symmetries, it is likely that at least one SM singlet scalar exists for such purposes which would then mix with the Higgs doublet of the SM and change its phenomenology.

Universal suppression via invisible width

There are many theoretical examples demonstrating the possibility that the Higgs boson can decay into states that are not detectable by our current technology (for review, see e.g., [5]). In the extra dimensional framework there are two interesting and unrelated ideas that could lead to an invisible width of the Higgs boson while not affecting Higgs boson interactions with any other state.

The first idea comes from neutrinos in the bulk [6]. The small neutrino masses that we now believe must exist could be entirely due to Dirac masses that are suppressed by a large volume factor. Since the right-handed neutrino is not charged under any SM gauge symmetry, it is the most likely of all SM fields to join gravity in the bulk. When performing the KK reduction of this state, one finds naturally that the neutrino Dirac mass can be in the sub-eV range from bulk volume suppression.

In the 4-dimensional picture, the sum over the enormous number of KK states accessible in $h \rightarrow \nu_L \bar{\nu}_R^{(i)}$ decays contributes substantially to the Higgs width:

$$\Gamma_{\text{inv}}(h \rightarrow \nu_L \bar{\nu}_R^{(i)}) \simeq (1 \text{ MeV}) 20^{6-\delta} \left(\frac{m_h}{150 \text{ GeV}} \right)^{1+\delta} \left(\frac{m_\nu^2}{10^{-3} \text{ eV}^2} \right) \left(\frac{3 \text{ TeV}}{M_D} \right)^{2+\delta}, \quad (2)$$

where δ is the number of extra dimensions and M_D is the fundamental scale of gravity. Each KK state is long-lived, so the above expression leads to a potentially significant invisible width of the Higgs boson [6].

There is another source of invisible width coming from kinetic mixing of the Higgs boson with graviscalars in the low scale gravity action [4, 7],

$$S = -\xi \int d^4x \sqrt{-g_{\text{ind}}} R(g_{\text{ind}}) H^\dagger H. \quad (3)$$

Expanding this action out in terms of the physical graviton and graviscalar fields, substituting $H = e^{i\eta}(v+h)/\sqrt{2}$, and utilizing the equations of motion, we find a mixing term between the Higgs and graviscalar fields $\varphi_G^{(\vec{n})}$ induced in the Lagrangian [4],

$$\mathcal{L}_{\text{mix}} = -\frac{2\xi v m_h^2}{M_P} \sqrt{\frac{3(\delta-1)}{\delta+2}} h \sum_{\vec{n}} \varphi_G^{(\vec{n})}. \quad (4)$$

The mass gap spacing is sufficiently small between the KK excitations of the graviscalars that we can talk meaningfully about oscillations of the Higgs field into graviscalars. This oscillation is equivalent to giving the Higgs an invisible width,

$$\Gamma_{\text{inv}}(h \rightarrow \varphi_G^{(\vec{n})}) \simeq (8 \text{ MeV}) 20^{2-\delta} \xi^2 S_{\delta-1} \frac{3(\delta-1)}{\delta+2} \left(\frac{m_h}{150 \text{ GeV}}\right)^{1+\delta} \left(\frac{3 \text{ TeV}}{M_D}\right)^{2+\delta}, \quad (5)$$

where $S_{\delta-1}$ is the surface area of a δ -dimensional unit radius sphere.

Having established that extra dimensional theories have several ways in which they could produce an invisible decay width to the Higgs boson, we now analyze the effect it has on Higgs boson observables at high energy colliders.

Each rate observable is a multiplication of a particular Higgs boson production cross-section $\sigma_i(h)$ (i labels the other final state particles in the process) times the relevant branching fraction $B_j(h)$ of the final state of the Higgs we are interested in. Ignoring the complications of experimental efficiencies and background reduction techniques, what will be measured is the total rate of a particular signal,

$$R_{ij}(h) = \sigma_i(h) B_j(h). \quad (6)$$

Since the width of the light Higgs boson is smaller than the experimental resolution, the only observables possible at the Tevatron and LHC are these rate observables $R_{ij}(h)$ and simple mass reconstruction of the Higgs boson.

An invisible width will not change the production cross section of the Higgs. However, the branching ratios into observable SM states do change:

$$B_i = \frac{\Gamma_i}{\Gamma_{\text{tot}} + \Gamma_{\text{inv}}} = B_i^{\text{SM}}(1 - B_{\text{inv}}). \quad (7)$$

It is important to emphasize that the reduction in all SM branching fractions is independent of the final state, and is given by the universal value $1 - B_{\text{inv}}$.

We therefore conclude that all SM rate observables involving the Higgs boson will be reduced by the same universal constant

$$R_{ij}(h) = R_{ij}^{\text{SM}}(h)(1 - B_{\text{inv}}). \quad (8)$$

Using only pure rate observables, it is therefore impossible to determine whether the cross-section or branching fraction (or both) is the cause of the reduction in rate.

Universal suppression via singlet mixing

Suppose the low-energy effective theory contains another real singlet field S , which does not couple to any SM state, but mixes with the real SM Higgs field according to the Lagrangian,

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h_{\text{SM}})^2 - \frac{1}{2}m_{h_{\text{SM}}}^2 h_{\text{SM}}^2 + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \mu^2 h_{\text{SM}} S + \mathcal{L}_I^{\text{SM}}(h_{\text{SM}}) + \dots \quad (9)$$

where $\mathcal{L}_I^{\text{SM}}(h_{\text{SM}})$ contains the well-known interactions between the SM Higgs and other SM particles.

One possible origin of the field S could be from symmetry breaking of a TeV scale $U(1)$ gauge symmetry. Extra $U(1)$'s are ubiquitous at the string scale in string model building and discrete remnants are very useful in protecting symmetries to all orders such as may be required to solve the proton decay issue in low-scale extra dimensional theories. Although all or some of the $U(1)$ symmetries might possibly be broken by other means, condensing scalar fields obviously remain a viable and attractive means to accomplish symmetry breaking.

The coupling of a charged, complex singlet field $\Phi_S = S + iA_S$ to the SM states would be

$$\mathcal{L}(\Phi_S) = \sum \frac{|\Phi_S|^2}{\Lambda^2} \mathcal{O}_i^{\text{SM}} + m_\Phi^2 |\Phi_S|^2 - \lambda_1 |\Phi_S|^4 - \lambda_2 |\Phi_S|^2 |H_{\text{SM}}|^2 + \dots \quad (10)$$

where $\mathcal{O}_i^{\text{SM}}$ are all the marginal operators of the SM. After spontaneous symmetry breaking the A_S field is eaten by the extra gauge symmetry and the S is left over to mix with the remaining real degree of freedom h_{SM} from the SM Higgs doublet H_{SM} . In the limit $\Lambda \rightarrow$ large the coupling to SM fermions and gauge fields goes to zero, recovering the limit of no interactions of S with SM fields except through its mixing with the SM Higgs.

The mass eigenstates σ and h are obtained by replacing S and h_{SM} with

$$\begin{aligned} S &\rightarrow \cos \omega \sigma - \sin \omega h \\ h_{\text{SM}} &\rightarrow \sin \omega \sigma + \cos \omega h \end{aligned}$$

where

$$\begin{aligned} \tan 2\omega &= \frac{2\mu^2}{m_S^2 - m_{h_{\text{SM}}}^2}, \quad \text{and} \\ m_{\sigma,h}^2 &= \frac{1}{2} \left[m_S^2 + m_{h_{\text{SM}}}^2 \pm \sqrt{(m_S^2 - m_{h_{\text{SM}}}^2)^2 + 4\mu^4} \right]. \end{aligned}$$

After diagonalizing the Lagrangian the new Higgs boson h couples like the SM Higgs boson except its couplings to SM fields are reduced by a factor of $\cos \omega$. Since S by construction has zero or, more realistically, negligible interactions with the SM states, the component of the mass eigenstate h that overlaps with S does not contribute to h

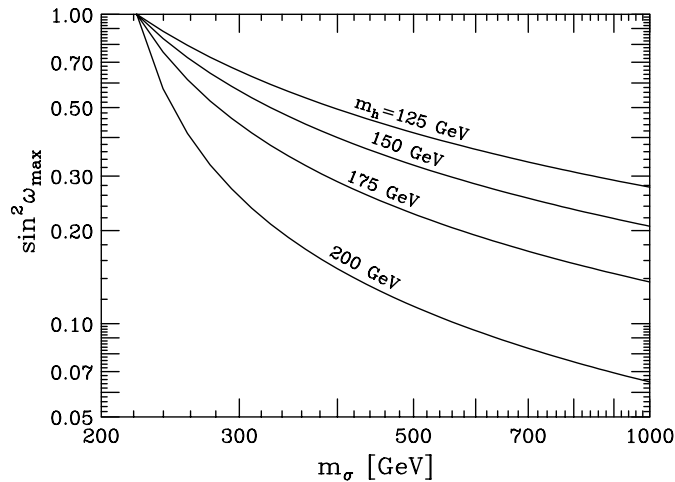


Figure 1: 95% C.L. limits on heavier singlet state and its mixing with the Higgs boson from precision electroweak data fits. For example, if the Higgs boson is found at 175 GeV, the value of $\sin^2 \omega$ must be less than about 0.14 for $m_\sigma \simeq 1$ TeV.

phenomenology. The field σ picks up interactions by virtue of its overlap with h_{SM} of strength $\sin \omega$. Therefore, σ also has an effect on the precision electroweak analysis.

We can quickly see the interesting effects of a heavy σ by the following rough analysis. If there is non-zero $\sin^2 \omega$, the mixed singlet will also contribute at one-loop to the electroweak precision observables. The $\log m_{h_{\text{SM}}}$ in Eq. 1 now becomes

$$\log(m_{h_{\text{SM}}}/\text{GeV}) \longrightarrow \log(m_h/\text{GeV}) + \sin^2 \omega \log m_\sigma/m_h. \quad (11)$$

For $m_\sigma > m_h$ the upper limit on the Higgs mass is never greater than what it is in the SM. If the singlet mass is too high, the total χ^2 fit would be unacceptably high. In Fig. 1 I estimate the 95% C.L. limit of the maximum value of $\sin^2 \omega$ allowed as a function of σ mass for various Higgs masses. This plot gives a sense of how large the mixing is allowed to be for very heavy singlets inaccessible to high energy collider production. In that case only the lighter h field will be accessible at the colliders, and all information must come from its study.

The h field will decay with exactly the same branching fractions as the SM Higgs, however its production cross section will be suppressed by a factor of $\cos^2 \omega$. For rate observables this translates into a suppression compared to the expected SM rates,

$$R_{ij}(h) = R_{ij}^{\text{SM}}(h)(1 - \sin^2 \omega). \quad (12)$$

Notice that again the suppression factor is a universal, process independent suppression factor. By measuring any number of SM rate observables it is impossible to distinguish B_{inv} from $\sin^2 \omega$ (cf. eq. 8 with eq. 12).

Challenges for present and future colliders

The power of experiment derives from its ability to collect otherwise inaccessible experience about nature, thus enabling us to refine our theories of natural law. An important measure of progress is the continuing ability to eliminate competing ideas.

In the above paragraphs I have outlined several generic ways in which a light Higgs boson can have the same signal rates as the SM Higgs except with a universal rescaling factor. That discussion highlights three main challenges that all present and future colliders should seriously consider:

- To what sensitivity can experiment measure deviations of the $R_{ij}(h)$ rate observables compared to the SM expectation?
- How much evidence can one accrue that all $R_{ij}(h)$ rate observables are rescaled by a universal suppression factor?
- Is it possible to distinguish a universal suppression factor in the branching fraction from a universal suppression factor in the production cross-section?

At the Tevatron, obtaining a 3σ evidence for a SM Higgs boson with mass up to 180 GeV will require summing over all possible rate observables in 30 fb^{-1} per experiment of integrated luminosity [8]. Significance of discovery and sensitivity to deviations in any one channel will be a significant challenge. One could attempt to measure a non-SM rate observable associated with the invisible decay of the Higgs boson, say, in $p\bar{p} \rightarrow Zh \rightarrow l^+l^- + \cancel{E}_T$. However, even if the invisible branching ratio were 100% it is unlikely that Tevatron would find a significant signal for this very challenging rate observable [5]. It only gets worse when the branching fraction decreases.

The LHC may be able to measure SM rate observables in many different channels. The approachable channels depend on the mass of the Higgs boson. For $m_h = 130 \text{ GeV}$ it may be possible to measure the rate observables in $gg \rightarrow h \rightarrow \gamma\gamma$, $gg \rightarrow h \rightarrow WW \rightarrow l^+l^- + \cancel{E}_T$, $q\bar{q} \rightarrow Wh \rightarrow l\bar{b} + \cancel{E}_T$, $VV \rightarrow h \rightarrow WW^*$ and $q\bar{q} \rightarrow Wh \rightarrow WWW \rightarrow 3l + \cancel{E}_T$. The measurement of all rate observables at the LHC will never yield a result with better than 10% uncertainty with the possible exception of $VV \rightarrow h \rightarrow WW^*$ with 200 fb^{-1} of data [9]. Furthermore, the QCD uncertainties suggest significant challenges in the theoretical prediction of rates at hadron colliders [10].

It has been shown [11] that if one makes several assumptions about how the Higgs boson interacts with SM particles and makes the assumption that there is very little interaction with anything else (not satisfied in large invisible width case), one might be able to infer the total width of the SM Higgs to within 10-20% for $120 \text{ GeV} < m_h < 250 \text{ GeV}$ with 100 fb^{-1} of data. As the production rate goes down, indicating a larger invisible width or more mixing with a singlet, the statistical and systematic errors in inferring the Higgs width will increase.

Even in the ideal case that a large deviation is found for each rate observable, and the evidence points to a universal suppression, it still looks difficult to distinguish between the radically different prospects of a Higgs with an invisible decay rate and a Higgs

that merely mixes with a weakly coupled singlet. Finding evidence for a non-SM rate observable using the invisible decay rate of the Higgs would be beneficial. However, in many cases just trying to see evidence for an invisibly decaying Higgs boson with 100% branching ratio is challenging enough [12] without contemplating measuring a rate observable associated with a smaller invisible branching ratio with sufficient precision to confirm $R_{ij}(h) = R_{ij}^{\text{SM}}(h)(1 - B_{\text{inv}})$.

The other way to distinguish between ideas at a hadron collider is to find the heavier Higgs state. The SM Higgs rate observables for this state would be the same as the SM Higgs boson of the same mass except rescaled by a factor $\sin^2 \omega$. Precisely measuring this rescaling factor for the heavier Higgs boson and adding it to the rescaling factor in eq. 12 would sum to 1. The heavier Higgs state would almost assuredly not be accessible at the Tevatron. If it is accessible at the LHC, and depending on its mass, one might be able to make these measurements with sufficient precision to test the weak singlet mixing hypothesis.

At an e^+e^- linear collider, there exist straightforward observables to distinguish $\sin^2 \omega$ from B_{inv} in the rate observables of eqs. 8 and 12. A most effective one is the measurement of the total cross-section for $e^+e^- \rightarrow hZ$. One identifies the Z from reconstructing its mass in $Z \rightarrow f\bar{f}$ decays, and measures the recoil spectrum from the beam constraint [13]. Everything from the h decays, whether visible or invisible, will show up as a peak at $m_{\text{recoil}}^2 = m_h^2$. This is not a $\sigma_i(h) \cdot B_j(h)$ rate observable, but rather a pure cross-section observable which would be unaffected by invisible decays of the Higgs but would be suppressed by singlet mixing.

The percent-level measurements of this cross-section and the myriad of other Higgs boson observables would easily confirm universal suppression to a compelling level and also distinguish between the possible reasons behind it. Furthermore, once the Higgs mass and $\sin^2 \omega$ were known to high precision, one could conceivably combine it with the precision electroweak data to do an analysis similar to what was done to produce Fig. 1 and identify a new mass scale at higher energies for future colliders.

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