Searching for a Hidden Sector Higgs Boson at the LHC

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Introduction

- Generic Motivation for Hidden Sector
  Hidden Sector: Singlets under the SM group $SU(3)_C \times SU(2)_L \times U(1)_Y$
  But may have non-trivial intrinsic gauge structure

  - Practical: GUT theories, SUSY breaking models, String-inspired models,...

  - Philosophical: Nature= Minimal models+ Phantom (Hidden) world?
    $\gg$ Minimal models

  - Experimental constraints?: None

- Can we really SEE the HIDDEN sector ('Hide and Seek'?) at the LHC?

  - Interactions from non-renormalizable terms or loop effects (suppressed):
    low production rate, low signal$\longrightarrow$ In general, **Hard**

- – Two renormalizable interactions (unsuppressed) as 'portals' between the SM and hidden sector:

  1. $U(1)_Y$, $U(1)_{hid}$ with field strengths $B_{\mu\nu}$, $C_{\mu\nu}$
  Kinetic mixing: $\chi B_{\mu\nu}C^{\mu\nu}\rightarrow$ Z' physics (well studied)

  2. The only superrenormalizable term (dim-2) in $\mathcal{L}_{SM}$:
  Higgs mass term $\triangle\mathcal{L} = -\mu^2|\Phi_{SM}|^2$

  $\rightarrow$Higgs field open to renormalizable coupling to hidden sector
  —Our interest: $\eta|\Phi_{SM}|^2|\Phi_H|^2$ (hidden sector Higgs Φ_H,
  $\langle\Phi_H\rangle \neq 0\rightarrow$ mass mixing between Φ_{SM} and Φ_H)

  ———2. applies to more general cases than 1.: hidden sector gauge group can be $U(1)$/non-Abelian groups

Motivation of Our Work:

Important observation: Interesting generic connection between Higgs physics and hidden sector $\Longrightarrow$ mutual enhancement on discovery at the LHC?

Overview of our work

We propose two possible distinct signatures at the LHC:

1. A narrow width trans-TeV Higgs boson

2. Observable $H \to hh$ decay

Are they viable?

1. Simulate the LHC physics
—sufficient signal vs. background for discovery? ✓

2. Satisfy the known constraints from theoretical concern (unitarity, triviality, vacuum stability) and precision EW measurement?✓

Model Review

A $U(1)_{hid}$ gauge symmetry is broken by the vev of Φ_H.Φ_H mixes with Φ_{SM}.

$$\mathcal{L}_{Higgs} = |\mathcal{D}_\mu \Phi_{SM}|^2 + |\mathcal{D}_\mu \Phi_H|^2 + m^2_{\Phi_{SM}}|\Phi_{SM}|^2 + m^2_{\Phi_H}|\Phi_H|^2 - \lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \eta|\Phi_{SM}|^2|\Phi_H|^2 \quad (1)$$

$$\Phi_{SM} = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_{SM} + v + iG^0 \\ G^\pm \end{pmatrix}, \quad \Phi_H = \frac{1}{\sqrt{2}}(\phi_H + \xi + iG') \quad (2)$$

$v(\simeq 246\text{Gev})$ and ξ are vevs. 4 input parameters $\{\lambda, \rho, \eta, \xi\}$

Gauge away Goldstone fields Gs. Rotate from gauge eigenstates ϕ_{SM}, ϕ_H to mass eigenstates h, H

$$\phi_{SM} = \cos\omega h + \sin\omega H \quad (3)$$

$$\phi_H = -\sin\omega h + \cos\omega H \quad (4)$$

the mixing angle ω and the mass eigenvalues are given by

$$\tan\omega = \frac{\eta v \xi}{(-\lambda v^2 + \rho\xi^2) + \sqrt{(\lambda v^2 - \rho\xi^2)^2 + \eta^2 v^2 \xi^2}} \quad (5)$$

$$m^2_{h,H} = (\lambda v^2 + \rho\xi^2) \pm \sqrt{(\lambda v^2 - \rho\xi^2)^2 + \eta^2 v^2 \xi^2}$$

If $m_H > 2m_h$, $H \to hh$ (a signal of interest) is allowed kinematically, with partial width

$$\Gamma(H \to hh) = \frac{|\mu|^2}{8\pi m_H}\sqrt{1 - \frac{4m_h^2}{m_H^2}} \tag{6}$$

μ: the coupling in $\triangle\mathcal{L}_{mix} = \mu h^2 H$.

$$\mu = -\frac{\eta}{2}(\xi c_\omega^3 + v s_\omega^3) + (\eta - 3\lambda) v c_\omega^2 s_\omega + (\eta - 3\rho)\xi c_\omega s_\omega^2 \tag{7}$$

Summary of the parameter space

4 input parameters $\{\lambda, \rho, \eta, \xi\}$—— Recall $\xi = \langle \Phi_H \rangle$,

$\mathcal{L}_{Higgs} = |\mathcal{D}_\mu \Phi_{SM}|^2 + |\mathcal{D}_\mu \Phi_H|^2 + m^2_{\Phi_{SM}}|\Phi_{SM}|^2 + m^2_{\Phi_H}|\Phi_H|^2 - \lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \eta|\Phi_{SM}|^2|\Phi_H|^2$

$\Updownarrow$

4 output parameters $\{m_h^2, m_H^2, s_\omega, \mu(\text{or } \Gamma(H \to hh))\}$ (related to observables at the LHC, coordinates of the data points to be analysed)

LHC Studies

- **General Philosophy:**

  Challenge: Mixing⇒Two non-SM Higgs h, H, both with reduced couplings to SM particles ⇒Reduced production cross-section

  Opportunities:
  1. Reduced couplings→Reduced decay rate
  ⇒Narrow-width trans-TeV Higgs H(?)
  (A SM Higgs loses meaning as a particle above $\sim$ 800 GeV)

  2. Two heavily mixed Higgs⇒Significant signal for $H \to hh$(?)
  ⇒Simultaneous discovery of H and h

- **Narrow Trans-TeV Higgs**

  Signal: qqH production followed by $H \to WW \to \ell\nu jj$
  Typical background: $WWjj$, $t\bar{t}jj$

Simulate LHC physics:

Data point C: $\{s_\omega^2 = 0.1, m_h = 120\,\text{GeV}, m_H = 1.1\,\text{TeV}, \Gamma_H = 105\,\text{GeV}\}$

Use MadEvent, with CTEQ6 PDF set to generate both signal and background events$\Longrightarrow$

Fig 1 demonstrates the plausibility of discovering a trans-TeV Higgs at the LHC :

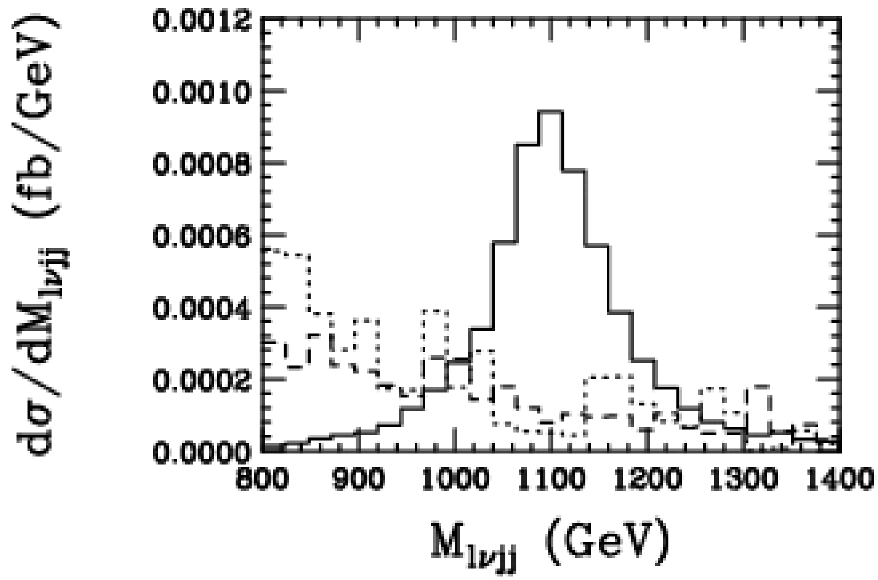


Fig 1: Differential cross-section as a function of the invariant mass of the ℓ, $\not{E}_T$ and two jets reconstructing to the W mass for $H \to WW \to \ell\nu jj$ (solid), $WWjj$ (dashed), and $t\bar{t}jj$ (dotted). (For integrated luminosity=100 fb^{-1}, integral from 1.0 TeV $< M_{l\nu jj} <$ 1.3 TeV$\Rightarrow$12.8 signal events vs 7.7 background events)

- $H \to hh$ **Signal**

Data point 1: $\{s_\omega = 0.5, m_h = 115\,\text{GeV}, m_H = 300\,\text{GeV}, BR(H \to hh) = 1/3\}$

Signal: ggH production followed by $H \to hh \to \gamma\gamma b\bar{b}$ decays

Simulate LHC physics→Fig 2. demonstrates the opportunity to discover both H and h through $H \to hh$ decay

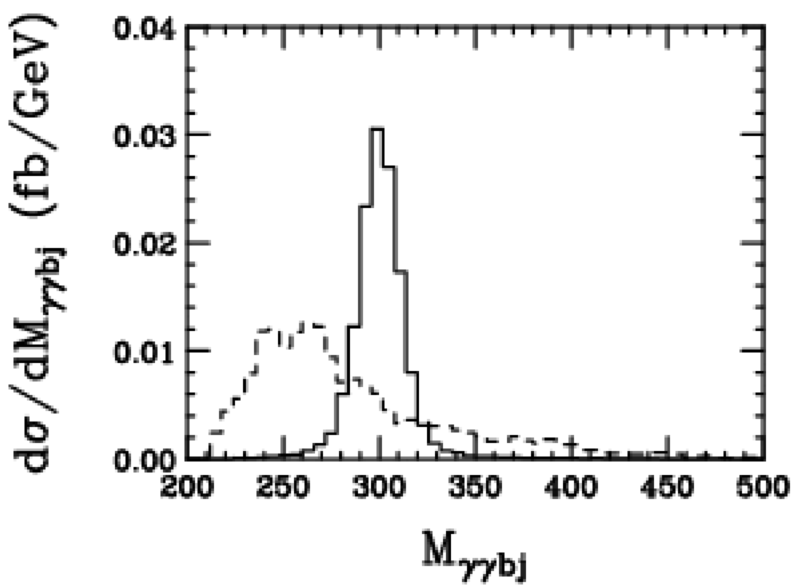


Fig 2: Differential cross-section as a function of invariant mass of $\gamma\gamma b\bar{b}$ for $H \to hh \to \gamma\gamma \bar{b}b$ (solid) and the sum of the backgrounds (dashed) requiring one b-tag.

Theoretical Bounds on Higgs Masses

- Defend the validity of perturbative description of EW theory up to high scale?⇒Perturbative unitarity constraint

  Partial-wave unitarity condition on tree-level amplitudes of scatterings involving W_L, Z_L, H⇒Upper bound on Higgs mass

  1. SM Higgs: $m^2_{\phi_{SM}} \leq \frac{4\pi\sqrt{2}}{3G_F} \simeq (700\ \text{GeV})^2$

  2. Our model: A trans-TeV Higgs allowed because of mixing?

TEST:

1. Derive the unitarity constraints for our model (15 inequalities)
2. Monte Carlo method: generate 10^7 points in the perturbative region of input parameter space $\lambda \subset [0, 4\pi], \rho \subset [0, 4\pi], \eta \subset [-4\pi, 4\pi], \xi \subset [0, 5\ \text{TeV}]$

Pick out the points that satisfy all the inequalities and make $m_H - m_h$ plots for certain narrow ranges of s_ω^2 (Fig 3)

$\Rightarrow$ Trans-TeV H allowed for small/medium mixing ($s_\omega^2 \lesssim 0.4$) ✓

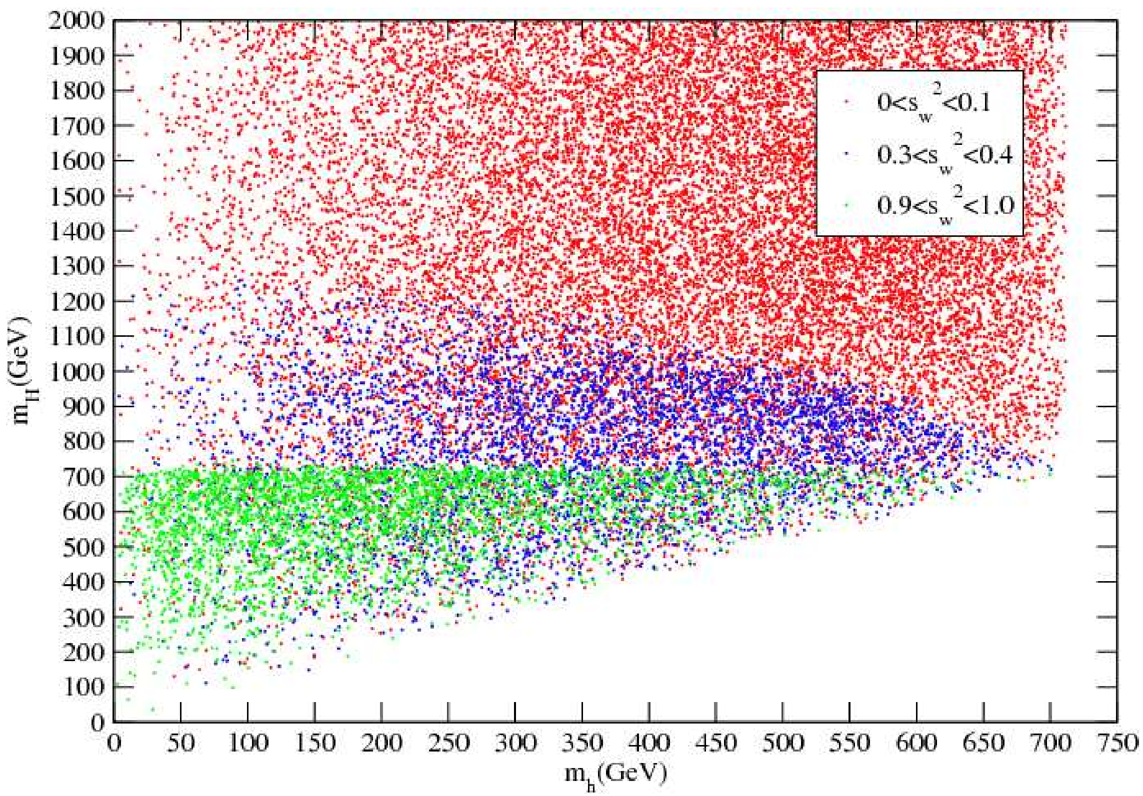


Fig 3: Red: $0 < s_\omega^2 < 0.1$, Blue: $0.3 < s_\omega^2 < 0.4$, Green: $0.9 < s_\omega^2 < 1.0$

- Triviality Bounds and Vacuum Stability Bounds

1. In SM: both are relevant to the RGE running of λ

Triviality bound: Landau pole of λ is above the new physics scale Λ_*
Vacuum Stability Bound: λ remains > 0 until $\Lambda_* (\sim 1\,\text{TeV?})$

In the SM, simple relation $m_h^2 = 2\lambda v^2 \Rightarrow 160\,\text{GeV} < m_h < 750\,\text{GeV}$

2. In our model: $m_{h,H}^2 = (\lambda v^2 + \rho\xi^2) \pm \sqrt{(\lambda v^2 - \rho\xi^2)^2 + \eta^2 v^2 \xi^2}$
$\Rightarrow$Four determinants. RGEs for λ, ρ, η are needed:

$$\frac{d}{dt}\lambda = \frac{1}{16\pi^2}\left\{\frac{1}{2}\eta^2 + 12\lambda^2 + 6\lambda y_t^2 - 3y_t^4 - \frac{3}{2}\lambda(3g^2 + g_1^2) + \frac{3}{16}[2g^4 + (g^2 + g_1^2)^2]\right\} \quad (8)$$

$$\frac{d}{dt}\rho = \frac{1}{16\pi^2}(\eta^2 + 10\rho^2 + E) \quad (9)$$

$$\frac{d}{dt}\eta = \frac{1}{16\pi^2}\eta\left[6\lambda + 4\rho + 2\eta + 3y_t^2 - \frac{3}{4}(3g^2 + g_1^2) + E'\right] \quad (10)$$

$\Rightarrow$Triviality and vacuum stability bounds on $m_{h,H}$ are quite model-dependent $(\lambda, \rho, \eta, ...)$
$\Rightarrow$The points allowed by unitarity are also allowed by these two bounds in a large region of full parameter space✓

Constraints from Precision EW Measurements

Philosophy: Virtual excitations of Higgs boson can contribute to physical observables (loop corrections) (e.g. m_W)

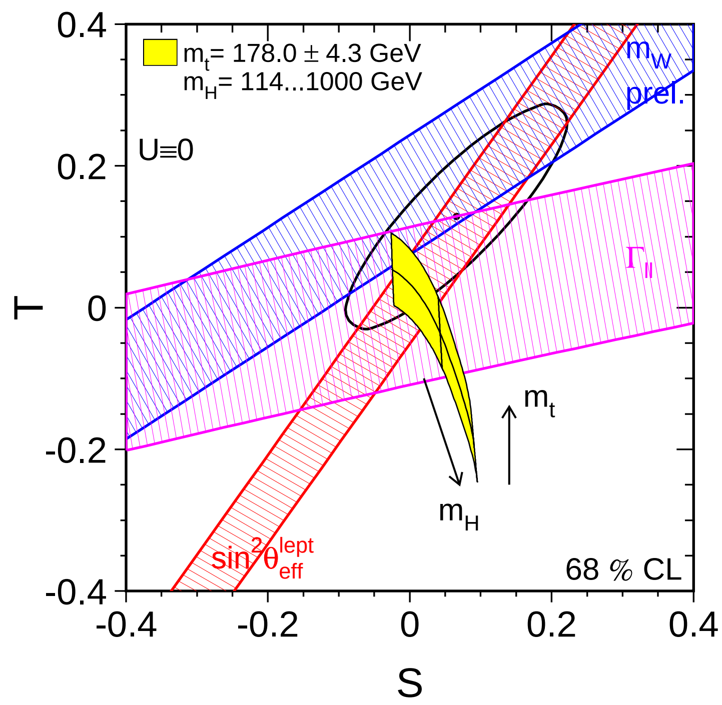
1. SM Higgs: $\lesssim$ 200 GeV at 95% C.L from precision EW analysis

2. Our model: $S - T$ analysis for the points of interest

Point C (trans-TeV): ($s_\omega^2 = 0.1$, $m_h = 120$ GeV, $m_H = 1.1$ TeV), $(S, T) = (-0.01, -0.01)$✓

Point 1 ($H \to hh$): ($s_\omega^2 = 0.5$, $m_h = 115$ GeV, $m_H = 300$ GeV)$(S, T) = (0.01, -0.03)$

—mildly out of 68% C.L allowed region (LEP result), Z' contribution ($U(1)_{hid}$) can pull (S, T) back towards the center⇒✓



Conclusions (1st of 2 pages)

- Reemphasis on the Motivation of Hidden Sector

  LHC: Looking for new particles and interactions beyond the SM

  – States charged under the SM group $SU(3)_C \times SU(2)_L \times U(1)_Y$–direct participants in EW physics (ubiquitous in SUSY, technicolor, extra dimensions...)

  – States as singlets under the SM group–Hidden sector (E.g. S in NMSSM for generating μ term, exotic gauge structure in string-inspired models)⇒May connect to EW physics in an indirect but significant way

- Summary of Our Work
  - Consider a $U(1)_{hid}$ sector which is connected to Higgs physics through a renormalizable mixing term $\eta|\Phi_{SM}|^2|\Phi_H|^2(\langle\Phi_H\rangle \neq 0)$
  - Propose two possible distinct signatures for discovery at the LHC:
    * A narrow width trans-TeV Higgs
    * Observable $H \to hh$ decay
  - Study the viability of the proposed signatures
    * LHC physics simulation ✓
    * Theoretical bounds from unitarity, triviality, vacuum stability; Constraints from precision EW measurements ✓