Extra Higgs Singlet and Electroweak Precision Observables

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Outline

Motivation of an Extra Higgs Singlet

- Resonance detected on July 4th, 2012
  $\Rightarrow$ SM Higgs?
- Extended Higgs sector possible!
  $\Rightarrow$ Modified couplings?
  $\Rightarrow$ Light weakly coupled states?
  $\Rightarrow$ Heavy states?
- Possible dark matter candidate?
- Electroweak vacuum stability could be assured!
  (O.Lebedev, arXiv:hep-ph/1203.0156)

Extended Lagrangian (1)

- Lagrangian of the extended Higgs sector:

$$\mathcal{L}_{\Phi_s,\Phi_h} = (D_\mu\Phi_s)^\dagger (D^\mu\Phi_s) + (\partial_\mu\Phi_h)^\dagger (\partial^\mu\Phi_h) - V(\Phi_s,\Phi_h)$$

- Standard Higgs doublet Φ_s and hidden Higgs singlet Φ_h
- Φ_h is a singlet under $SU(3)\times SU(2)\times U(1)$
- Modified Higgs potential:

$$V(\Phi_s,\Phi_h) = -\mu_s^2\Phi_s^\dagger\Phi_s + \frac{\lambda_s}{4}(\Phi_s^\dagger\Phi_s)^2 - \mu_h^2\Phi_h^\dagger\Phi_h + \frac{\lambda_h}{4}(\Phi_h^\dagger\Phi_h)^2 + \eta\Phi_s^\dagger\Phi_s\Phi_h^\dagger\Phi_h$$

- $\eta \neq 0 \Rightarrow$ Interaction between the standard and the hidden sector
- Both Φ_s and Φ_h aquires a vev:

$$\Phi_s(x) = \begin{pmatrix} \phi^+(x) \\ \frac{1}{\sqrt{2}}\left[v_s + H(x) + i\varphi_s(x)\right] \end{pmatrix},$$

$$\Phi_h(x) = \frac{1}{\sqrt{2}}\left[v_h + \chi(x) + i\varphi_h(x)\right]$$

Extended Lagrangian (2)

- Resulting mixing matrix:

$$\mathcal{M}^2 := \begin{pmatrix} \frac{1}{2}\lambda_s v_s^2 & \eta v_s v_h \\ \eta v_s v_h & \frac{1}{2}\lambda_h v_h^2 \end{pmatrix}$$

- Diagonalization of $\mathcal{M}^2 \Rightarrow$ Physical Higgs fields:

$$H_1 = c_\alpha H + s_\alpha \chi,$$
$$H_2 = -s_\alpha H + c_\alpha \chi$$

- Corresponding masses:

$$M_{H_{1/2}}^2 = \frac{1}{4}\left(\lambda_s v_s^2 + \lambda_h v_h^2\right) \pm \frac{1}{4}\left(\lambda_s v_s^2 - \lambda_h v_h^2\right)\sqrt{1+\tan^2 2\alpha}$$

- Mixing angle α defined by:

$$\tan 2\alpha = \frac{4\eta v_s v_h}{\lambda_s v_s^2 - \lambda_h v_h^2}$$

- Mixing between H and χ:
  $\Rightarrow$ Tree-level couplings of $H_{1/2}$ to gauge fields and massive fermions
- Quantization similar compared with SM

Renormalization of Higgs Sector Parameters

- Introduce counterterms before diagonalization to physical fields
  $\Rightarrow$ Introduce counterterm mass-matrix $\delta\mathcal{M}^2_{phys}$:

$$\mathcal{L}_0 = -\frac{1}{2}\left(H_0, \chi_0\right)\mathcal{M}^2\begin{pmatrix}H_0\\ \chi_0\end{pmatrix} - \frac{1}{2}\left(H, \chi\right)\delta\mathcal{M}^2\begin{pmatrix}H\\ \chi\end{pmatrix} + \dots$$
$$= -\frac{1}{2}\left(H_{1,0}, H_{2,0}\right)\mathcal{M}^2_{diag}\begin{pmatrix}H_{1,0}\\ H_{2,0}\end{pmatrix} - \frac{1}{2}\left(H_1, H_2\right)\delta\mathcal{M}^2_{phys}\begin{pmatrix}H_1\\ H_2\end{pmatrix} + \dots$$

with

$$\delta\mathcal{M}^2_{\text{phys}} = \begin{pmatrix}\delta M^2_{H_1} & \delta M^2_{H_1 H_2}\\ \delta M^2_{H_1 H_2} & \delta M^2_{H_2}\end{pmatrix} := \begin{pmatrix}c_\alpha & s_\alpha\\ -s_\alpha & c_\alpha\end{pmatrix}\delta\mathcal{M}^2\begin{pmatrix}c_\alpha & -s_\alpha\\ s_\alpha & c_\alpha\end{pmatrix}$$

- Tadpole counterterms:

$$\delta t_{H_1} = c_\alpha \delta t_H + s_\alpha \delta t_\chi,$$
$$\delta t_{H_2} = -s_\alpha \delta t_H + c_\alpha \delta t_\chi$$

- Replace counterterms of the original parameters:
  $\delta\lambda_s,\ \delta\lambda_h,\ \delta\mu_s^2,\ \delta\mu_h^2,\ \delta\eta \Rightarrow \delta M^2_{H_1},\ \delta M^2_{H_1 H_2},\ \delta M^2_{H_2},\ \delta t_{H_1},\ \delta t_{H_2}$

Renormalization of Higgs Sector Fields

- Introduction of field counterterms before diagonalization of $\mathcal{M}^2$:

$$H_0 = \left(1 + \frac{1}{2}\delta Z_H\right) H, \qquad \chi_0 = \left(1 + \frac{1}{2}\delta Z_\chi\right) \chi \quad \Rightarrow \quad H_{1,0} = c_\alpha H_0 + s_\alpha \chi_0, \qquad H_{2,0} = -s_\alpha H_0 + c_\alpha \chi_0$$

- Introduction of field counterterms after diagonalization of $\mathcal{M}^2$:

$$\begin{pmatrix} H_{1,0} \\ H_{2,0} \end{pmatrix} = \begin{pmatrix} 1 + \frac{1}{2}\delta Z_{H_1 H_1} & \frac{1}{2}\delta Z_{H_1 H_2} \\ \frac{1}{2}\delta Z_{H_2 H_1} & 1 + \frac{1}{2}\delta Z_{H_2 H_2} \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

- Relation between field counterterms of both approaches:

$$\delta Z_{H_1 H_1} = c_\alpha^2 \delta Z_H + s_\alpha^2 \delta Z_\chi,$$
$$\delta Z_{H_2 H_2} = c_\alpha^2 \delta Z_\chi + s_\alpha^2 \delta Z_H,$$
$$\delta Z_{H_1 H_2} = \delta Z_{H_2 H_1} = -s_\alpha c_\alpha \delta Z_H + s_\alpha c_\alpha \delta Z_\chi$$

On-shell Renormalization Conditions

- Masses of physical fields equal to real parts of propagator poles:

$$\delta M^2_{H_i} = Re\Sigma_{H_i H_i}\left(M^2_{H_i}\right)$$

- Real parts of residues of renormalized propagators equal to one:

$$\delta Z_{H_i H_i} = -Re\frac{\partial\Sigma_{H_i H_i}\left(k^2\right)}{\partial k^2}\bigg|_{k^2=M^2_{H_i}},$$

$$\delta Z_{H_1 H_2} = \frac{s_\alpha c_\alpha}{c^2_\alpha - s^2_\alpha}\left(\delta Z_{H_2 H_2} - \delta Z_{H_1 H_1}\right)$$

- δt_{H_1} and δt_{H_2} fixed by setting renormalized Higgs field one-point amputated Green's functions of H_1 and H_2 equal to zero
- $\delta M^2_{H_1 H_2}$ fixed by requiring $\hat{\Gamma}^{H_1 H_2}\left(M_{H_1}\right) \stackrel{!}{=} 0$:

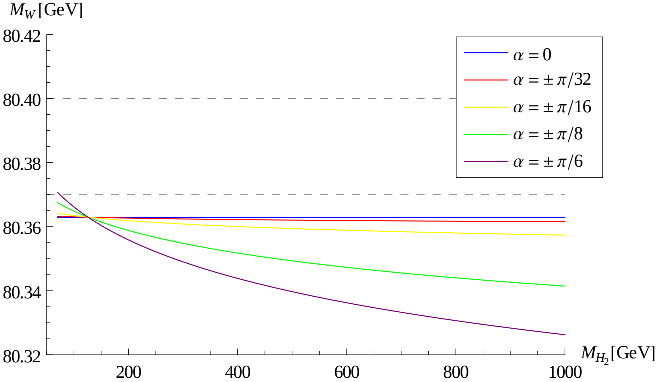
$$\delta M^2_{H_1 H_2} = \Sigma_{H_1 H_2}\left(M^2_{H_1}\right) + \frac{M^2_{H_1} - M^2_{H_2}}{2}\delta Z_{H_1 H_2}$$

Mass of the W-boson

- Muon decay at one-loop level:

$$M_W^2 = M_Z^2 \left(\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\alpha_{em}\pi}{\sqrt{2} G_\mu M_Z^2} \left(1 + \Delta r(M_{H_1}, M_{H_2}, \alpha; M_W, \ldots)\right)} \right)$$

- Δr summarizes corresponding radiative NLO corrections
- $M_{H_1} = 126\mathrm{GeV} \Rightarrow$ Two free parameters left: α and M_{H_2}



Z Pole Observables (1)

- Process: $e^+e^- \to f\bar{f}, \quad f \neq e$
- Z-exchange amplitude:

$$A_Z = \frac{J_\mu^{(e)} \otimes J^{(f)\mu}}{s - M_Z^2 + is\frac{\Gamma_Z}{M_Z}}$$

- Fermionic neutral current vertices:

$$J_\mu^{(f)} = \left(\sqrt{2}G_\mu M_Z^2\right)^{1/2} \left[g_V^f \gamma_\mu - g_A^f \gamma_\mu \gamma_5\right]$$

- Non-standard NLO contributions included in effective vector and axial vector couplings:

$$g_V^f = \left[v_f + F_V^{Zf}\right](1 - \Delta r)^{1/2},$$
$$g_A^f = \left[a_f + F_A^{Zf}\right](1 - \Delta r)^{1/2}$$

Z Pole Observables (2)

- Effective leptonic mixing angle:

$$\sin^2 \theta_{eff}^{lep} := \frac{1}{4}\left(1 - \frac{g_V^e}{g_A^e}\right)$$

- Forward-backward pole asymmetries:

$$A_{FB}^{0,f} = \frac{3}{4} A_e A_f, \qquad A_f = \frac{2 g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}$$

- Partial width ratios:

$$R_b = \frac{\Gamma_b}{\Gamma_h}, \qquad R_l = \frac{\Gamma_h}{\Gamma_e}$$

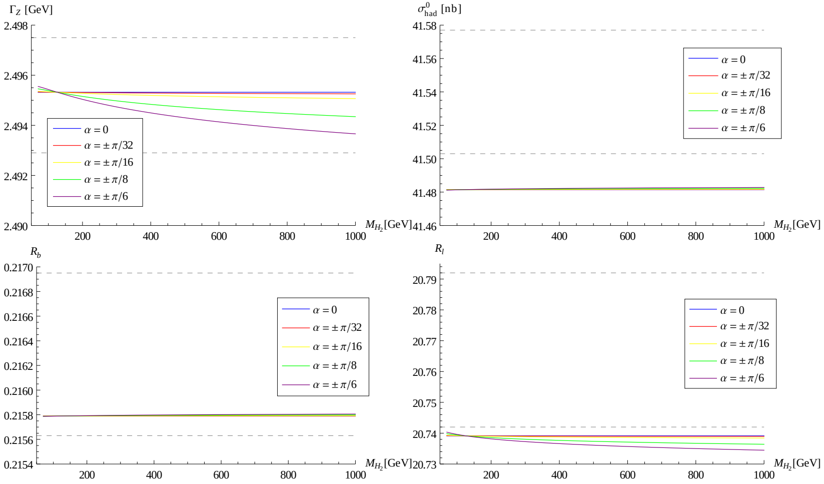
- Hadronic peak cross-section:

$$\sigma_{had}^0 = 12\pi \frac{\Gamma_e \Gamma_h}{M_Z^2 \Gamma_Z^2}$$

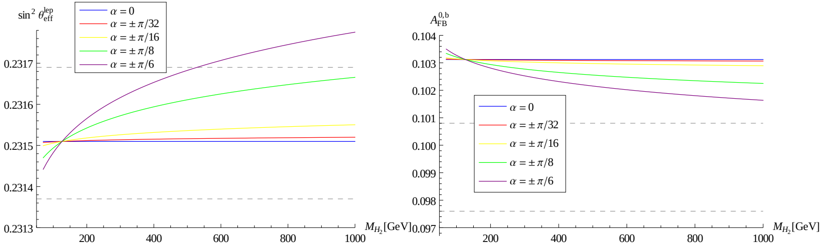
- $Z \to f\bar{f}$ partial widths given by:

$$\Gamma_f = 4 N_c^f \Gamma_0 \left[(g_V^f)^2 R_V^f + (g_A^f)^2 R_A^f \right]$$

Z Pole Observables: Numerical Results (1)



Z Pole Observables: Numerical Results (2)



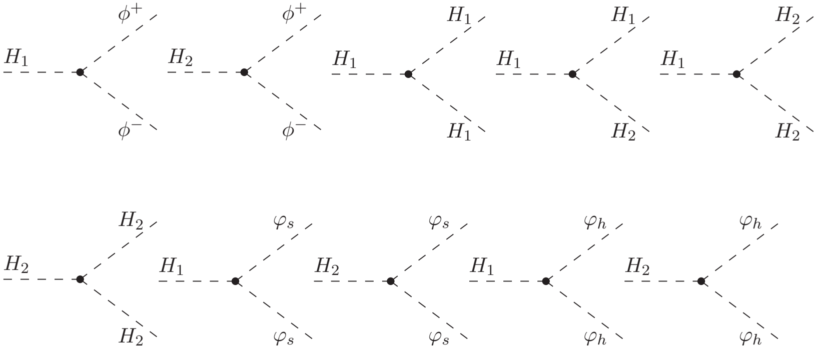
- Prediction of Γ_Z, R_b, R_l, σ^0_{had}:
  $\Rightarrow$ No significant deviations from associated SM predictions
- Prediction of $\sin^2\theta^{lep}_{eff}$:
  $\Rightarrow$ More than 1σ deviation of experimental central value possible!
- Prediction of $A^{0,b}_{FB}$:
  $\Rightarrow$ More compatible with experiment for large α and large M_{H_2}!

Future Prospects

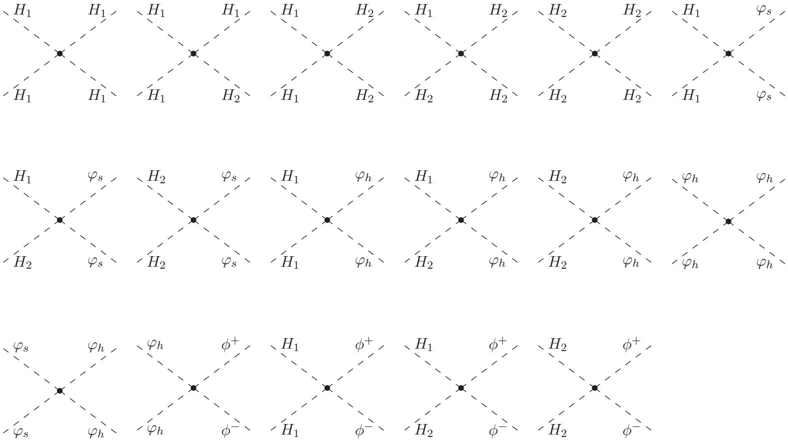
- Non-standard NLO contributions to Higgs decays
- Dark matter properties of H_2
- Phenomenological impact of a hidden $U(1)$
- Higher order (NNLO) non-standard effects

Thank you for the attention!

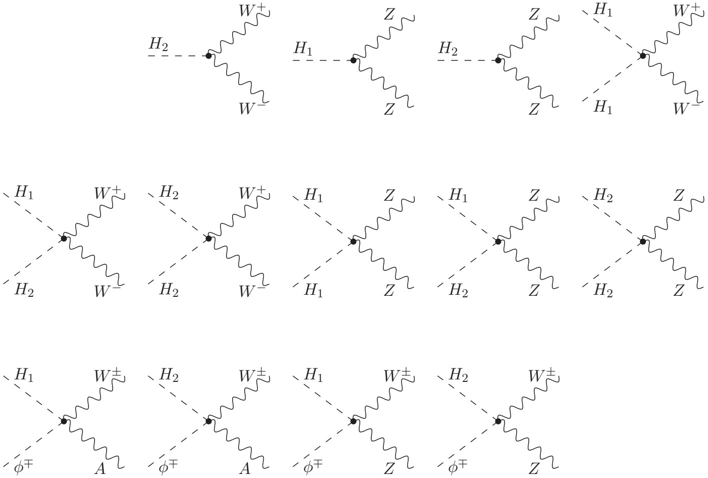
Backup: Non-standard Triple Scalar Self-couplings



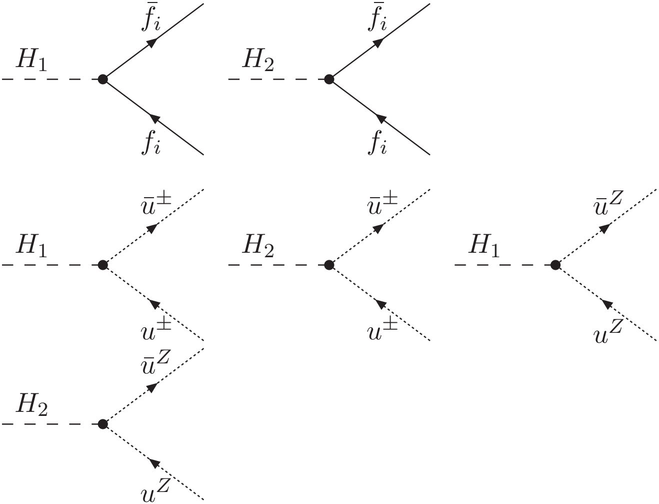
Backup: Non-standard Quartic Scalar Self-couplings



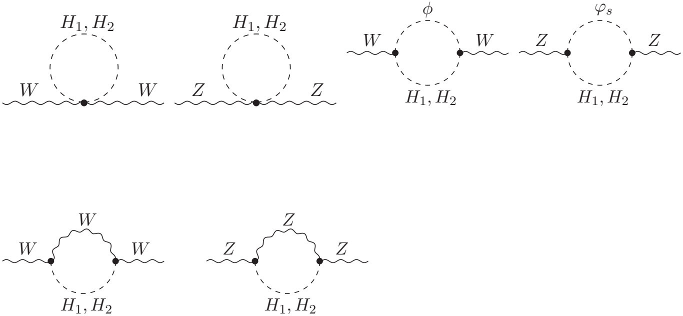
Backup: Non-standard Couplings to Gauge Bosons



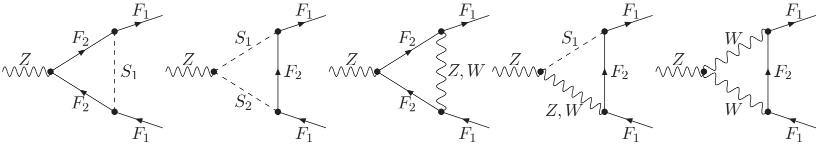
Backup: Non-standard Couplings to Massive Fermion and Ghost Fields



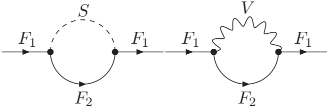
Backup: Non-standard Contributions to the Gauge Boson Self-energies



Backup: Non-standard Contributions to Effective Couplings



Scalar fields: $S_1, S_2 = H_1, H_2, \varphi_s, \phi$
Fermion fields: $F_1, F_2 = l_i, \nu_i, u_j, d_k$



Scalar fields: $S = H_1, H_2, \varphi_s, \phi$
Fermion fields: $F_1, F_2 = l_i, \nu_i, u_j, d_k$.
Gauge fields: $V = Z, W$