A New Two Higgs Doublet Model

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INTRODUCTION : Higgs Overview

- Responsible for breaking of electroweak gauge symmetry
- Gives mass to SM particles
- Mass bound: $m_h > 114.4$ GeV (LEP)
- Dominant decay modes, depending on $m_h$:

\[ H \rightarrow b\bar{b}, \; WW, \; ZZ, \; tt \]

- Experimentally, nothing currently known about Higgs sector
ATLAS TDR for Higgs Search at LHC
Two Higgs Doublet Model

- Both doublets couple to all the fermions $\rightarrow$ serious FCNC problems
- One doublet couples to up-type fermions, the other to down-type fermions (Motivated by SUSY)
- Only one doublet couples to fermions, but both have VEV
- Only one doublet couples to fermions, and only that doublet has VEV, Other doublet is innert. Motivation: Heavy Higgs, Higgs dark matter (Barbieri, Hall, and Rychkov)
Our new Model

• What’s new?
• One doublet gives mass to all SM fermions except neutrinos
• Other doublet gives mass only to neutrinos
• Gives an alternative explanation of small neutrino masses
Model

- Symmetry $SU(3) \times SU(2) \times U(1) \times Z_2$
- Right-handed neutrinos $N_R$ and two Higgs doublets $\chi, \phi$
- SM fermions, $\chi$ even under $Z_2$
- $N_R, \phi$ odd under $Z_2$
- $V_\phi \sim 10^{-2}$ eV, and $V_\chi \sim 250$ GeV $\rightarrow$ large fine tuning $V_\phi/V_\chi \sim 10^{-13}$ similar to $m_h/M_{PL}$ in SM
- Lepton Yukawa interactions:

$$y_l \overline{\psi}_L l_R \chi + y_{\nu_l} \overline{\psi}_L N_R \tilde{\phi} + h.c., \quad \overline{\psi}_L = (\nu_l, \bar{l})_L$$

- $\rightarrow$ Neutrinos get tiny mass from breaking of $Z_2$ symmetry
- Neutrinos are Dirac particles $\rightarrow$ No neutrino-less double beta decay
Model

Higgs Potential:

\[ V = -\mu_1^2 \chi^\dagger \chi - \mu_2^2 \phi^\dagger \phi + \lambda_1 (\chi^\dagger \chi)^2 + \lambda_2 (\phi^\dagger \phi)^2 + \]
\[ + \lambda_3 (\chi^\dagger \chi)(\phi^\dagger \phi) - \lambda_4 |\chi^\dagger \phi|^2 - \frac{1}{2} \lambda_5 \left[ (\chi^\dagger \phi)^2 + (\phi^\dagger \chi)^2 \right] \]

Physical Higgs Particles

- Charged Higgs $H^\pm$
- Neutral pseudoscalar $\rho$
- Two neutral scalars $h, \sigma$
Model

In Unitary Gauge:

\[ \chi = \frac{1}{\sqrt{2}} \left( \sqrt{2} \frac{V}{V} H^+ \right) \]

\[ h_0 + i \frac{V}{V} \rho + V \chi \]

\[ \phi = \frac{1}{\sqrt{2}} \left( -\sqrt{2} \frac{V}{V} H^+ \right) \]

\[ \sigma_0 - i \frac{V}{V} \rho + V \phi \]

\[ V^2 = V_\chi^2 + V_\phi^2 \]
Model

\[ m_H^2 = \frac{1}{2} (\lambda_4 + \lambda_5) V^2, \quad m_\rho^2 = \lambda_5 V^2 \]

\[ m_{h,\sigma}^2 = \left( \lambda_1 V_\chi^2 + \lambda_2 V_\phi^2 \right) \pm \sqrt{\left( \lambda_1 V_\chi^2 - \lambda_2 V_\phi^2 \right)^2 + \left( \lambda_3 - \lambda_4 - \lambda_5 \right) V_\chi^2 V_\phi^2} \]

or, more simply:

\[ m_\sigma^2 = 2 \lambda_2 V_\phi^2 + O(V_\phi^2 / V_\chi^2) \quad \text{Very light scalar} \]

\[ m_h^2 = 2 \lambda_1 V_\chi^2 + O(V_\phi^2 / V_\chi^2) \]
Model

Mass Eigenstates of $h, \sigma$:

$$h_0 = c h + s \sigma, \quad \sigma_0 = -s h + c \sigma$$

where,

$$c = 1 + O(V_\phi^2 / V_\chi^2), \quad s = -\frac{\lambda_3 - \lambda_4 - \lambda_5}{2\lambda_1}(V_\phi / V_\chi) + O(V_\phi^2 / V_\chi^2)$$

This leads to very small mixing

Note: $h$ behaves essentially like the SM Higgs in interactions with fermions and gauge bosons
Phenomenological Implications

Light Scalar $\sigma$:
Possible decay modes:

$$\sigma \rightarrow \bar{\nu}\nu, \quad if \quad m_\sigma > 2m_\nu$$

$$\sigma \rightarrow \gamma\gamma \quad (one \ loop)$$

$$\Gamma \sim \frac{e^8}{4} \frac{m_\sigma^5}{m_q^4} \Rightarrow \tau \sim 10^{20} \text{ yrs}$$

$\rightarrow \sigma$ only observable at colliders as missing energy

Couplings of $\sigma$ to quarks and charged leptons are highly suppressed
Phenomenological Implications

$ZZ\sigma$ coupling is proportional to $V_\Phi$, so

$$e^+e^- \rightarrow Z^* \rightarrow Z\sigma, \text{ and } Z \rightarrow Z^*\sigma \rightarrow f\bar{f}\sigma$$

are suppressed by a factor of $(V_\Phi/m_Z)^2$

However, $ZZ\sigma\sigma$ coupling is unsuppressed:

$$Z \rightarrow Z^*\sigma\sigma \rightarrow f\bar{f}\sigma\sigma$$

$$\sum_f \Gamma(Z \rightarrow f\bar{f}\sigma\sigma) = 2.5 \times 10^{-7} \text{ GeV}$$

Total $Z$ width $= 2.4952 \pm 0.0023$ GeV (PDG)

At LEP1, $\approx 1.7 \times 10^7$ $Z$’s $\rightarrow \approx 2$ such events
Phenomenological Implications

Coupling of \( \sigma \) to neutrinos is relatively large, so

\[
Z \rightarrow \nu \bar{\nu} \sigma
\]

can be significant

\[
\Gamma(Z \rightarrow \nu \bar{\nu} \sigma) \simeq (0.64 \text{ MeV}) \left( \sum y_{\nu}^2 \right)
\]

For \( \sum y_{\nu}^2 \sim 1 \), this is \(<1.5 \text{ MeV}\)

Invisible Z width = \( 499 \pm 1.5 \text{ MeV} \) (PDG)
Phenomenological Implications

Pseudoscalar $\rho$:
Assume $\rho$ has no strong coupling, so
\[
\frac{\lambda_5^2}{4\pi} \leq 1 \quad \Rightarrow \quad m_\rho \leq 470 \text{ GeV}
\]

$Z \rightarrow \rho \sigma, \quad Z \rightarrow \rho^* \sigma \rightarrow \nu\bar{\nu}\sigma$

Note: Couplings of $\rho$ to quarks and charged leptons are VEV suppressed

If $m_\rho < m_Z$, then $\rho \rightarrow \nu\nu$ will be the dominant decay mode, and $Z \rightarrow \rho \sigma$ will be invisible

Invisible Z width = 499 ± 1.5 MeV (PDG)
Further Implications

\[ \Gamma(Z \rightarrow \rho \sigma) = \frac{G_F m_Z}{24\sqrt{2}\pi} \left(1 - \frac{m^2}{m_Z^2}\right)^3 < 1.5 \text{ MeV} \Rightarrow m_\rho > 78 \text{ GeV} \]

For \( m_\rho > m_Z \), we have

\[ e^+ e^- \rightarrow Z^* \rightarrow \rho \sigma \]

\[ \sigma = \frac{G_F m_Z^4 (g_V^2 + g_A^2) s}{24\pi} \left(\frac{1}{s-m_Z^2}\right)^2 \left(1-\frac{m_\rho^2}{s}\right)^3 \]

At LEP2, with \( \sqrt{s} \sim 200 \text{ GeV} \) and \( \sim 3000 \text{ pb}^{-1} \) of data, < 1 event is expected for \( m_\rho > 95 \text{ GeV} \)
Heavy Scalar $h$

Essentially SM Higgs

Invisible decay mode $h \rightarrow \sigma \sigma$:

$$\Gamma(h \rightarrow \sigma \sigma) = \frac{\left(\lambda_3 + \lambda_4 + \lambda_5\right)^2 V^2}{32 \pi m_h}$$

$$m_h^2 = 2 \lambda_1 V^2 + O\left(V^2_{\phi} / V^2_{\chi}\right)$$

$$\Gamma(h \rightarrow \sigma \sigma) = \frac{\left(\lambda_3 + \lambda_4 + \lambda_5\right)^2 m_h}{64 \pi \lambda_1} \equiv \frac{\lambda^* m_h}{64 \pi}$$
Invisible Higgs Decay

\[ \lambda^* = 0.1 \]
For a wide range of $\lambda^*$, the invisible mode is dominant for $m_h < 160$ GeV

Current limit for invisible Higgs: $m_h > 112.3$ GeV (L3)
Invisible Higgs Signal at LHC

At LHC, invisibly decaying Higgs is observable through WBF:

\[ qq \rightarrow qqWW \rightarrow qqh, \quad qq \rightarrow qqZZ \rightarrow qqh \]

Signal: Two q’s with high $p_T$ + invisible

This signal can be observed at 95% C.L. with $>10 \text{ fb}^{-1}$ of data if $B(h \rightarrow \text{invisible}) > 30\%$ and $m_h < 400$ GeV (Eboli and Zeppenfeld)

Difficult to identify invisible particle as Higgs
Implications for Charged Higgs

\[
\chi = \frac{1}{\sqrt{2}} \left( \sqrt{2} \frac{V_{\phi}}{V} H^+ \right), \quad \phi = \frac{1}{\sqrt{2}} \left( -\sqrt{2} \frac{V_{\chi}}{V} H^+ \right)
\]

\[
V^2 = V_{\chi}^2 + V_{\phi}^2, \quad V_{\chi} \sim V, \quad V_{\phi} \sim 10^{-2} \text{ eV}
\]

Charged Higgs essentially resides in $\varphi$

Its coupling with quarks is highly suppressed
(Chromophobic charged Higgs)

Coupling with neutrinos and charged leptons \textit{not} suppressed
Implications for Charged Higgs

\[ L_Y = -\sqrt{2} \left( \frac{m_\nu}{V_\chi} \right) r_\chi \left[ \overline{\ell}_L \nu_R H^- + \overline{\nu}_L \ell_R H^+ + h.c. \right] \]

\[ + \sqrt{2} r_\phi \left[ \left( \frac{m_d}{V_\chi} \right) \overline{u}_L d_R H^+ - \left( \frac{m_u}{V_\chi} \right) \overline{d}_L u_R H^- + h.c. \right] \]

where, \( r_\chi = V_\chi / V \), and \( r_\phi = V_\phi / V \)

\( \Rightarrow \) coupling with neutrinos \( \propto \) neutrino masses

\( HW\sigma, HW\rho : \) usual gauge interaction
Main Decay Modes of $H^\pm$

$H^\pm \rightarrow \sigma W^\pm$

$H^\pm \rightarrow \rho W^\pm$

$H^\pm \rightarrow \ell \nu_\ell$, ($\ell = e, \mu, \tau$)

leptonic coupling $\propto \frac{m_{\nu_\ell}}{V_\phi}$

Thus the leptonic decay mode will be determined by the neutrino mass hierarchy
Neutrino Mass Hierarchy

\[ \nu_\tau \quad \nu_\mu \quad \nu_e \]

Normal Hierarchy

\[ H^\pm \rightarrow \nu_\tau \tau \]

Inverted Hierarchy

\[ H^\pm \rightarrow \ell \nu_\ell, \quad (\ell = e, \mu) \]
Collider Signals of $H^\pm$

- Usual production of charged Higgs via:

  $$bg \rightarrow tH^-, \text{ or } \bar{b}g \rightarrow \bar{t}H^+$$

  is not available

- In our model via Drell-Yan:

  $$pp \text{ (or } p\bar{p} \text{)} \gamma,Z \rightarrow H^+H^-$$
Branching Ratios of $H^\pm$ (inverted hierarchy)

Parameters: $\lambda_1 = 0.12, \lambda_2 = 1.0, \lambda_3 = 2.0$, 

$$\lambda_5 = \frac{m^2_\rho}{V^2}, \quad \lambda_4 = \frac{2m^2_{H^\pm}}{V^2} - \lambda_5$$

6/19/2008

S.Nandi, talk at Fermilab
Model

Higgs Potential:

\[ V = -\mu_1^2 \chi^\dagger \chi - \mu_2^2 \phi^\dagger \phi + \lambda_1 (\chi^\dagger \chi)^2 + \lambda_2 (\phi^\dagger \phi)^2 + \lambda_3 (\chi^\dagger \chi)(\phi^\dagger \phi) - \lambda_4 |\chi^\dagger \phi|^2 - \frac{1}{2} \lambda_5 \left[ (\chi^\dagger \phi)^2 + (\phi^\dagger \chi)^2 \right] \]

Physical Higgs Particles:

Charged Higgs \( H^\pm \)
Neutral pseudoscalar \( \rho \)
Two neutral scalars \( h, \sigma \)
Collider Signals of $H^\pm$

- **Signal:**
  \[ pp \rightarrow H^+H^- \rightarrow \ell^+\ell^- + \text{missing } E_T \]

- **Background:**
  \[ pp \rightarrow W^+W^- \rightarrow \ell^+\ell^- + \text{missing } E_T \]
  \[ pp \rightarrow Z^0Z^0 \rightarrow \ell^+\ell^- + \text{missing } E_T \]
  \[ \ell = e, \mu \]

- $H^\pm$ has a large BR to $e$ or $\mu$ compared to $W^\pm$

- Missing $E_T$ reduces the background since $m_{H^\pm} > m_W$

LHC: $\sqrt{s} = 14$ TeV

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at LHC with $L = 30 \, fb^{-1}$, with cuts:

\[ p_T^\ell > 25 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad \Delta R_{\ell\ell} \geq 0.4 \]

\[ M_{\ell\ell}^{\text{inv}} > 100 \text{ GeV}, \text{ missing } E_T > 100 \text{ GeV} \]
at LHC with $L = 30 \, fb^{-1}$, with cuts:

\begin{align*}
    p_T^\ell &> 25 \, GeV, \quad |\eta_\ell| < 2.5, \quad \Delta R_{\ell \ell} \geq 0.4 \\
    M_{\ell \ell}^{inv} &> 100 \, GeV, \quad \text{missing } E_T > 100 \, GeV
\end{align*}

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Reach for $H^\pm$ at LHC

- For $5\sigma$ significance:

- With $L=10 \text{ fb}^{-1}$ we can discover $H^\pm$ with a mass up to 200 GeV

- With $L=100 \text{ fb}^{-1}$ we can discover $H^\pm$ with a mass up to 250 GeV
Case for Normal Hierarchy

\[ pp \rightarrow H^+H^- \rightarrow \tau^+\tau^- + \text{missing } E_T \]

- Signal is same as e,\( \mu \) case
- Background is reduced by factor of 4
- However, tau’s must decay which reduces the effective signal
Cosmological Implications

• **Neutrino star formation**
  The interaction of the almost massless scalar, sigma, with the neutrinos are strong
  → neutrino star formation

• **Effect on supernova explosion**
  Strong interaction with sigma will affect the neutrino emission during supernova explosion
  → will affect SN explosion dynamics

• **Effect on big bang nucleosynthesis**
Big Bang Nucleosynthesis

- Predicted light element abundances depend on the number $g^*$ of light spin degrees of freedom in thermal equilibrium at $T \sim 1$ MeV

$$g^* = g_b + \frac{7}{8} g_f$$

- In the standard scenario (SBBN), this includes $\gamma$, $e^\pm$, $\nu$'s:

$$\left(g^*_S\right)_{SBBN} = 2 + \frac{7}{8} (4) + \frac{7}{8} (6) = 10.75$$

- In our model, relatively strong interactions between left- and right-handed neutrinos and the light scalar $\sigma$ will keep them in thermal equilibrium

$$g^* = \left(g^*_S\right)_{SBBN} + 1 + \frac{7}{8} (6) = 17$$
Big Bang Nucleosynthesis

• Reactions that interconvert protons and neutrons:

\[ n \leftrightarrow p + e^- + \bar{\nu}, \quad \nu + n \leftrightarrow p + e^- , \quad e^+ + n \leftrightarrow p + \bar{\nu} \]

• For \( T \gg \Delta m = m_n - m_p = 1.293 \text{ MeV}, \) \( \Gamma_{p \leftrightarrow n} \gg H, \) and these reactions are in thermal equilibrium

\[ \Rightarrow \frac{n}{p} = e^{-\frac{\Delta m}{T}} \frac{\mu_e - \mu_{\nu}}{T} \]

• We know \( \mu_e/T \sim 10^{-10} \). Assume also that \( \mu_{\nu}/T \approx 0 \)

\[ \Rightarrow \frac{n}{p} = e^{-\frac{\Delta m}{T}} \]
Big Bang Nucleosynthesis

• The reactions that interconvert protons and neutrons freeze out when $\Gamma_{p\leftrightarrow n} \sim H$.

$$H = 1.66 \sqrt{g_*} \frac{T^2}{M_{PL}}$$

$$\Gamma_{p\rightarrow n} = \frac{1}{1.636 \tau_n} \int_{\Delta m/m_e}^{\infty} d\varepsilon \frac{\varepsilon(\varepsilon - \Delta m/m_e)^2 \sqrt{\varepsilon^2 - 1}}{[1 + \exp(\varepsilon \Delta m/T)][1 + \exp((\Delta m - \varepsilon m_e)/T)]}$$

• In SBBN (with $g_* \approx 10.75$), this gives $T_F \approx 0.8$ MeV

$$\Rightarrow \frac{n}{p} = e^{-\frac{\Delta m}{T_F}} \approx \frac{1}{6}$$
Big Bang Nucleosynthesis

• By the time nucleosynthesis begins at $T \approx 0.3$ MeV, neutron decays have reduced $n/p$ to $\approx 1/7$.
• $\rightarrow$ To a good approximation, all neutrons end up in He-4.
The mass fraction of He-4 is

$$Y_P = \frac{4n_{He}}{n_N} \approx \frac{4(n_n/2)}{n_p + n_n} = \frac{2(n/p)}{1 + (n/p)} = 0.25$$

• Observed value: $Y_P = 0.249 \pm 0.009$ (PDG)
Big Bang Nucleosynthesis

• Larger $g_*$ implies larger $T_F$

• For low temperature, $\Gamma_{p\leftrightarrow n} \sim T^5$

\[
\Rightarrow \frac{\Gamma_{p\leftrightarrow n}}{H} \sim \frac{T^3}{\sqrt{g_*}} \Rightarrow T_F \sim g_*^{1/6}
\]

• For $g_* = 17$, $T_F \approx 0.86 \text{ MeV}$

\[
\Rightarrow \frac{n}{p} = e^{\Delta m \left(\frac{1}{0.8 \text{ MeV}} - \frac{1}{0.86 \text{ MeV}}\right)} \left(\frac{n}{p}\right)_{SBBN} \approx 1.2 \left(\frac{n}{p}\right)_{SBBN}
\]

\[
\Rightarrow Y_p \approx 0.30
\]
Possible Solution: Large Neutrino Density

• Since relic neutrinos haven’t been detected, $\mu_\nu$ is unknown

$$\frac{n}{p} = e^{-\frac{\mu_\nu}{T}} \left( \frac{n}{p} \right)_{\mu_\nu = 0}$$

$\mu_\nu \approx 0.15 \text{ MeV} \implies e^{\frac{\mu_\nu}{T}} \approx \frac{1}{1.2}$

• $g_*$ is consistent with BBN for $\mu_\nu \approx 0.15 \text{ MeV}$
Another Possible Solution: Late Decaying Particles

• The energetic decay products of a massive particle ($m > \text{a few GeV}$) that decays during or after nucleosynthesis can cause nuclear reactions among background nuclei, altering light element abundances

• Non-BBN Bounds on Number of Neutrinos:

  • WMAP: $0.8 < N_\nu < 7.6$ (Ichikawa, Kawasaki, Takahashi, Nov. 2006)
  • Seljak, Sloshar, McDonald (WMAP + several other astrophysical data sources) claim that more than 3 neutrinos is required (Sep. 2006)
Conclusions

• Proposed new two Higgs doublet model based on $\text{SM} \times Z_2$

• $Z_2$ broken at $\sim 10^{-2} \text{ eV}$

• Gives new mechanism for tiny neutrino mass

• Neutrinos are Dirac particles, → no neutrinoless double beta decay

• Higgs: $H^\pm$, $h$, $\rho$ → mass at EW scale, $\sigma$ → extremely light

• $h$ like SM, but possibly dominant invisible decay mode $h \rightarrow \sigma \sigma$

• Alters Higgs signals at LHC, but observable through WBF

• Unusual signal for $H^\pm$: $e$ and $\mu$ in the final state at the LHC.

• Cosmological implications: neutrino star, supernova and BBN
$\text{Branching Ratio}$

$\sigma \ W^+$

$\rho \ W^+$

$V_\phi = 1 \text{ eV}$

$m_{\nu_{\tau}} = 0.01 \text{ eV}$

$M_{H^+} \ (\text{GeV})$

$\text{Branching Ratio}$

$V_\phi = 0.01 \text{ eV}$

$m_{\nu_{\tau}} = 0.01 \text{ eV}$

$M_{H^+} \ (\text{GeV})$
$\tau^+ + \tau^-$

$M = 100$ GeV

$M = 200$ GeV

$M = 300$ GeV

$H^+$

Number of events/bin

$\Delta R_{\tau^+ \tau^-}$

$M_{H^+} = 100$ GeV

$M_{H^+} = 200$ GeV

$M_{H^+} = 300$ GeV

SM

Number of events/bin

$M_{\tau^+ \tau^-}$(GeV)