Inert doublet model with local $U(1)$ gauge symmetry

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A Higgs boson discovered

- consistent with the SM Higgs couplings.
- nothing else seen yet at the LHC.
- Multi-Higgs models are still viable possibility, but they might be in

\[ \text{Decoupling limit: } m_H, m_{H'}, m_A \gg v. \]

\[ \text{Alignment (SM-like limit): } g_{hVV} = \sin(\beta - \alpha) \sim 1, \quad g_{HV} = \cos(\beta - \alpha) \sim 0. \]
Two Higgs doublet model

• Many high-energy models predict extra Higgs doublets.
  - SUSY, GUT, flavor symmetric models, etc.

• Two Higgs doublet model could be an effective theory of a high-energy theory.

• Two (or multi) Higgs doublet model itself is interesting.
  - Higgs physics (heavy Higgs, pseudoscalar, charged Higgs physics)
  - **dark matter physics** (one of Higgs scalar or extra fermions could be CDM.)
  - baryon asymmetry of the Universe
  - neutrino mass generation
  - can resolve experimental anomalies (top $A_{FB}$ at Tevatron, $B \rightarrow D(\ast)\tau \nu$ at BABAR)
Inert Doublet Model

• Simple extension of the SM ~ a 2HDM

• Rich phenomenology

• SM-like Higgs boson

• Viable DM candidate

• Thermal evolution of the Universe
Inert Doublet Model (IDMwZ$_2$)

• one of Higgs doublets does not develop VEV and an exact Z$_2$ symmetry is imposed.

• Under the Z$_2$ symmetry, SM particles are even, but the new Higgs doublet is odd.

• DM candidates

\[ H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} H^+ \\ (H) + iA \end{pmatrix}, \quad H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} G^+ \\ (v + h + iG^0) \end{pmatrix} \]

DM candidates \quad SM-like Higgs
Inert Doublet Model (IDMwZ$_2$)

- CP-conserving potential

$$V = \mu_1 (H_1^\dagger H_1) + \mu_2 (H_2^\dagger H_2) - \mu_{12} (H_1^\dagger H_2 + h.c.) + \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2$$

$$+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} \{(H_1^\dagger H_2)^2 + h.c.\}.$$  

- Type-I Yukawa interactions $\sim$ only $H_2$ couples to the SM fermions.

- $h \sim$ SM-like Higgs boson, but acquires additional contribution through charged Higgs loop and hHA couplings.

- $H, A, H^\pm \sim$ do not couples to SM fermions at tree level.
Inert Double Model (IDMwU(1)\(_H\))

- We replace the Z2 symmetry by U(1) gauge symmetry.
- A SM-singlet \(\Phi\) has to be added.
- Without \(\Phi\), \(Z_H\) boson becomes massless.

\[
V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^+ H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^+ H_2) - (m_{12}^2 H_1^+ H_2 + \text{h.c.})
\]
\[
+ \frac{\lambda_3}{2} (H_1^+ H_1)^2 + \frac{\lambda_2}{2} (H_2^+ H_2)^2 + \lambda_3 (H_1^+ H_1)(H_2^+ H_2) + \lambda_4 |H_1^+ H_2|^2
\]
\[
+ \frac{\lambda_5}{2} \{(H_1^+ H_2)^2 + \text{h.c.}\} + m_\phi^2 |\Phi|^2 + \lambda_\phi |\Phi|^4
\]

- \(\Phi\) breaks the U(1)\(_H\) symmetry while \(H_2\) breaks the EW symmetry.
- The remnant symmetry of U(1)\(_H\) is the origin of the exact Z2 symmetry.
Inert Double Model \( (\text{IDMwU}(1)_H) \)

- We replace the \( Z_2 \) symmetry by \( \text{U}(1) \) gauge symmetry.
- A SM-singlet \( \Phi \) has to be added.
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V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \text{h.c.}) \\
+ \frac{\lambda_3}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2 \\
+ \frac{\lambda_5}{2} \{(H_1^\dagger H_2)^2 + \text{h.c.}\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4
\]

- \( \Phi \) breaks the \( \text{U}(1)_H \) symmetry while \( H_2 \) breaks the EW symmetry.
- The remnant symmetry of \( \text{U}(1)_H \) is the origin of the exact \( Z_2 \) symmetry.
**Inert Double Model (IDM\(wU(1)_H\))**

- IDM + SM-singlet \(\Phi\).

\[
V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \text{h.c.})
\]

\[
+ \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2
\]

\[
+ \frac{\lambda_5}{2} \{(H_1^\dagger H_2)^2 + \text{h.c.}\} + m_\Phi |\Phi|^2 + \lambda_\Phi |\Phi|^4
\]

- Without \(\lambda_5\), A and H are degenerate.

\[
m_A = \sqrt{m_H^2 - \lambda_5 v^2}
\]

- Direct searches for the DM at XENON100 and LUX exclude this degenerate case.
Inert Double Model (IDMwU(1)_{H})

- IDM + SM-singlet $\Phi$.

$V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + h.c.)$

$+ \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$

$+ \left\{ c_l \left( \frac{\Phi}{\Lambda} \right) \right\} (H_1^\dagger H_2)^2 + h.c.$

$+ m_\phi^2 |\Phi|^2 + \lambda_\phi |\Phi|^4$

- The $\lambda_5$ term can effectively be generated by a higher-dimensional operator.
- It could be realized by introducing a singlet $S$ charged under $U(1)_H$ with $q_S = q_{H_1}$.

$V_\Phi(|\Phi|^2, |S|^2) + V_H(H_i, H_i^\dagger) + \lambda_S(\Phi)S^2 + \lambda_H(S)H_1^\dagger H_2 + h.c.$

$\lambda_H = \lambda_H^0 S$

$\lambda_5 \sim \frac{(\lambda_H^0)^2 \Lambda m^2}{2 m_{Re(S)}^2 m_{Im(S)}^2}$.
Type-I 2HDM

- Only one Higgs couples with fermions.

\[ V_y = y_{ij}^U \bar{Q}_{Li} H_1 U_{Rj} + y_{ij}^D \bar{Q}_{Li} H_1 D_{Rj} + y_{ij}^E \bar{L}_i H_1 E_{Rj} + y_{ij}^N \bar{L}_i \tilde{H}_1 N_{Rj} \]

- anomaly free U(1)_H without no extra fermions except RH neutrinos.

<table>
<thead>
<tr>
<th>( U_R )</th>
<th>( D_R )</th>
<th>( Q_R )</th>
<th>( L )</th>
<th>( E_R )</th>
<th>( N_R )</th>
<th>( H_1 )</th>
<th>Type</th>
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</thead>
<tbody>
<tr>
<td>( u )</td>
<td>( d )</td>
<td>( \frac{u+d}{2} )</td>
<td>( -3(u+d)/2 )</td>
<td>( -(2u+d) )</td>
<td>( -(u+2d) )</td>
<td>( \frac{u-d}{2} )</td>
<td>( h_2 \neq 0 )</td>
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<td>-1</td>
<td>0</td>
<td>1/2</td>
<td>U(1)_{Y}</td>
</tr>
</tbody>
</table>

- SM fermions are U(1)_H singlets.
- \( Z_H \) is fermiophobic and Higgphilic.

Ko, Omura, Yu, PLB717, 202(2013)
Constraints

- experimental and theoretical constraints

\[ m_h \sim 126 \text{ GeV} \]

\[ |m_{H^+} - m_A| \]

\[ |m_{H^+} - m_H| \]

\[ \sin(\beta - \alpha) \]

\[ \tan \beta \]

\[ m_{H^+} \]

SM-like Higgs

\[ m_H \]

Heavy Higgs search at LHC

Perturbativity

Unitarity

Vacuum stability

EWPOs

small mass differences required

Invisible Higgs decay

\[ b \rightarrow s\gamma \]

Exotic top decay

\[ \tan \beta \gtrsim 1 \]

Exotic top decay

non-SM

Hermann, Misiak, Steinhauser, JHEP1211 (2012) 036

Higgs non-SM
Z-Z\textsubscript{H} mixing

- tree-level mixing (v\textsubscript{i} ≠ 0)

\[ \Delta M_{ZZ_H}^2 = -\frac{\hat{M}_Z}{y} g_H \sum_{i=1}^{2} q_{H_i} v_{i}^2 \]

\[ \tan 2\xi = \frac{2\Delta M_{ZZ_H}^2}{M_{Z_H}^2 - M_Z^2} \]

- loop-level mixing (v\textsubscript{1} = 0, v\textsubscript{2} ≠ 0)

The mixing can appear because of SU(2)\textsubscript{L}×U(1)\textsubscript{Y} breaking effects.

- collider bound depends on the U(1)\textsubscript{H} charge assignment.

- In the fermiophobic Z\textsubscript{H} case, the Z\textsubscript{H} boson can be produced through the Z-Z\textsubscript{H} mixing and the bound for the mixing angle is

\[ \sin \xi \lesssim O(10^{-2}) \sim O(10^{-3}) \]
Relic density (low mass)

$$\Omega_{\text{CDM}} h^2 = 0.1199 \pm 0.0027$$

LUX bound is satisfied.
Relic density (low mass)

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LUX bound is satisfied.
Relic density (low mass)

$$\Omega_{CDM} h^2 = 0.1199 \pm 0.0027$$

Co-annihilation

$$HH \rightarrow Z_H Z_H, ZZ_H$$

$$H, H^\pm \rightarrow SM + SM^{(*)}$$

$$H^+ H^- \rightarrow A + Z_H, Z + Z_H, ...$$
Indirect Detection: constraints

\( b{\gamma} \) from DM annihilations in Sagittarius Dwarf

\[ W^-, Z, b, \tau^-, t, h \ldots \rightarrow e^\pm, p, D \ldots \text{ and } \gamma \]

\[ W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightarrow e^\pm, p, D \ldots \text{ and } \gamma \]
Indirect searches (low mass)

- All points satisfy constraints from the relic density observation and LUX experiments.

Constraints on the DM annihilation cross section from Fermi-LAT’s analysis of 15 dwarf spheroidal galaxies.

Fermi-LAT, arXiv:1310.0828

Constraint on the S-wave DM annihilation from the relic density observation
Indirect searches (low mass)

Indirect DM signals depend on the decay patterns of produced particles from annihilation or decay of DMs.
Gamma ray flux from DM annihilation

- Dwarf spheroidal galaxies are excellent targets to search for annihilating DM signatures because of DM-dominant nature without astrophysical backgrounds like hot gas.

\[
\phi_s(\Delta \Omega) = \frac{1}{4\pi} \langle \sigma v \rangle \frac{1}{m_{DM}^2} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma \cdot \int_{\Delta \Omega} \rho^2(r) d\Omega.
\]

The final $\gamma$-ray spectrum.

A 95% upper bound is $\Phi_{PP} = 5.0^{+4.3}_{-4.5} \times 10^{-30} \text{ cm}^3 \text{s}^{-1} \text{GeV}^{-2}$

Geringer-Sameth, Koushiappas, PRL107
Indirect searches (low mass)

Constraints on the DM annihilation cross section from Fermi-LAT’s analysis of 15 dwarf spheroidal galaxies.

Constraint on the S-wave DM annihilation from the relic density observation

\[ m_H \approx m_{Z_H} \]

\[ 10^{-20} \]

\[ 10^{-22} \]

\[ 10^{-24} \]

\[ 10^{-26} \]

\[ 10^{-28} \]

\[ 10^{-30} \]

\[ 10^{-32} \]

\[ 10^{-34} \]

\[ 0 \]

\[ 20 \]

\[ 40 \]

\[ 60 \]

\[ 80 \]

\[ 100 \]

\[ 120 \]

\[ M_H \text{ [GeV]} \]

\[ <\sigma v> \text{ [cm}^3\text{s}^{-1}] \]
Relic density (high mass)

$\Omega_{\text{CDM}} h^2 = 0.1199 \pm 0.0027$
Indirect searches (high mass)

Constraints on the DM annihilation cross section from Fermi-LAT’s analysis of 15 dwarf spheroidal galaxies.

Constraint on the S-wave DM annihilation from the relic density observation.

Fermi-LAT, arXiv:1310.0828
Conclusions

• 2HDM may be an effective theory of a high-energy theory and useful to test the underlying theory.

• The U(1) extension could introduce dark matter candidates whose stability are guaranteed by the remnant symmetry of U(1)\textsubscript{H}.

• In type-I, a light CDM scenario is possible in the IDMwU(1)\textsubscript{H}.

Thank you for your attention.
Back up
Evidences for Dark Matter
Constraints on DM

Direct searches

Indirect searches

CMB

Allowed
Higgs Potential

- in the ordinary 2HDM with $Z_2$ symmetry

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \frac{1}{2} \lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2} \lambda_2 (H_2^\dagger H_2)^2 + \frac{1}{2} \lambda_3 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{1}{2} \lambda_5 (H_1^\dagger H_2)^2 + h.c.$$  

not invariant under $U(1)_H$

- in the 2HDM with $U(1)_H$, we include an extra singlet scalar $\Phi$, which makes $Z_H$ heavy.

$$V = \hat{m}_1^2 (|\Phi|^2) H_1^\dagger H_1 + \hat{m}_2^2 (|\Phi|^2) H_2^\dagger H_2 - \left( m_3^2 (\Phi) H_1^\dagger H_2 + h.c. \right)$$

$$+ \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$

$$+ m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4.$$  

no $\lambda_5$ terms!

- neutral Higgs

$$\begin{pmatrix} h_\Phi \\ h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha - \sin \alpha & 0 \\ 0 & \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \cos \alpha_1 & 0 & -\sin \alpha_1 \\ 0 & 1 & 0 \\ \sin \alpha_1 & 0 & \cos \alpha_1 \end{pmatrix} \begin{pmatrix} \cos \alpha_2 & -\sin \alpha_2 & 0 \\ \sin \alpha_2 & \cos \alpha_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{h} \\ H \\ h \end{pmatrix}$$

- a pair of charged Higgs + 1 pseudoscalar Higgs + 3 neutral Higgs bosons
$\langle \sigma v \rangle \uparrow$

abundance $\Downarrow$

$\langle \sigma v \rangle \sim 10^{-26} \text{ cm}^3\text{s}^{-1}$
2HDM with $Z_2$ symmetry (2HDMwZ$_2$)

- One of the simplest models to extend the SM Higgs sector.
- In general, flavor changing processes appear.
- Strong constraints on the Flavor changing neutral current (FCNC).
- A simple way to avoid the FCNC problem is to assign ad hoc $Z_2$ symmetry.

<table>
<thead>
<tr>
<th>Type</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>$U_R$</th>
<th>$D_R$</th>
<th>$E_R$</th>
<th>$N_R$</th>
<th>$Q_L,L$</th>
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<td>−</td>
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<td>+</td>
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<td>+</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>+</td>
</tr>
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</table>

Fermions of same electric charges get their masses from one Higgs VEV.

$$\mathcal{L} = \bar{L}_i (y^E_{1ij} H_1 + \cancel{y^E_{2ij} H_2}) E_{Rj} + \text{H.c.}$$

or vice versa

NO FCNC at tree level.
Generic problems of 2HDM

• It is well known that discrete symmetry could generate a domain wall problem when it is spontaneously broken.

• Usually the $\mathbb{Z}_2$ symmetry is assumed to be broken softly by a dim-2 operator, $H_1^\dagger H_2$ term.

The softly broken $\mathbb{Z}_2$ symmetric 2HDM potential

\[
V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - (m_{12}^2 H_1^\dagger H_2 + h.c.) + \frac{1}{2} \lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2} \lambda_2 (H_2^\dagger H_2)^2 \\
+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{1}{2} \lambda_5 [(H_1^\dagger H_2)^2 + h.c.]
\]

• the origin of the softly breaking term?

$\mathbb{Z}_2$ symmetry in 2HDM can be replaced by new $U(1)_H$ symmetry associated with Higgs flavors.
Type-I 2HDM

• Only one Higgs couples with fermions.

\[ V_y = y_{ij}^U \bar{Q}_{Li} \hat{H}_1 U_{Rj} + y_{ij}^D \bar{Q}_{Li} H_1 D_{Rj} + y_{ij}^E \bar{L}_i H_1 E_{Rj} + y_{ij}^N \bar{L}_i \hat{H}_1 N_{Rj} \]

• anomaly free U(1)_H without extra fermions except RH neutrinos.

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<td>( \frac{(u - d)}{2} )</td>
</tr>
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2 parameters

• In general, extra fermions are required in order to cancel gauge anomaly.

→ one of extra fermions can be a candidate for the cold dark matter.