Dark Matter in Two Higgs doublet models with local $U(1)_H$ gauge symmetry

Chaehyun Yu

KOREA INSTITUTE FOR ADVANCED STUDY

Collaboration with P. Ko (KIAS) and Yuji Omura (Nagoya U.)

Based on JHEP 1401, 016; arXiv:1405.2138

17th International Coonference From the Planck Scale to the Electroweak Scale
May 28, 2014, Institut des Cordeliers, Paris, France

Two Higgs doublet model

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

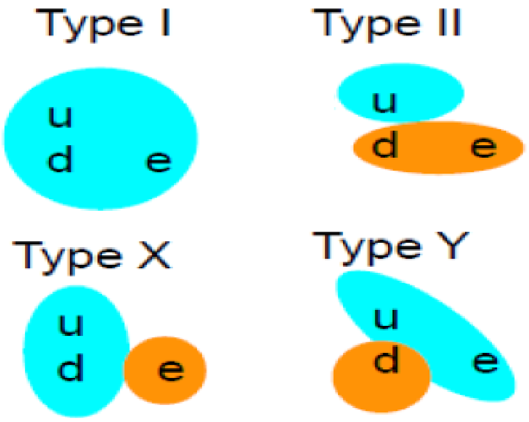
- Two Higgs doublet model could be an effective theory of a high-energy theory.

- 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.) Ma,PRD73;Barbieri,Hall,Rychkov,PRD74
  - baryon asymmetry of the Universe Shu,Zhang,PRL111
  - neutrino mass generation Kanemura,Matsui,Sugiyama,PLB727
  - can resolve experimental anomalies (top A_{FB} at Tevatron, B→D(*)τν at BABAR) Ko,Omura,Yu,EPJC73;JHEP1303

2HDM with Z_2 symmetry (2HDMwZ_2)

- One of the simplest models to extend the SM Higgs sector.
- In general, flavor changing neutral currents (FCNCs) appear.
- A simple way to avoid the FCNC problem is to assign ad hoc Z_2 symmetry.

Type	H_1	H_2	U_R	D_R	E_R	N_R	Q_L, L
I	$+$	$-$	$+$	$+$	$+$	$+$	$+$
II	$+$	$-$	$+$	$-$	$-$	$+$	$+$
X	$+$	$-$	$+$	$+$	$-$	$-$	$+$
Y	$+$	$-$	$+$	$-$	$+$	$-$	$+$



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

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

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 Z_2 symmetry is assumed to be broken softly by a dim-2 operator, $H_1^\dagger H_2$ term.

The softly broken 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?

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.

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

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

U_R	D_R	Q_L	L	E_R	N_R	H_1
u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$

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.

Type-I 2HDM

- Only one Higgs couples with fermions.

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

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

U_R	D_R	Q_R	L	E_R	N_R	H_1	Type
u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$	
0	0	0	0	0	0	0	$h_2 \neq 0$
$1/3$	$1/3$	$1/3$	-1	-1	-1	0	$U(1)_{B-L}$
1	-1	0	0	-1	1	1	$U(1)_R$
$2/3$	$-1/3$	$1/6$	$-1/2$	-1	0	$1/2$	$U(1)_Y$

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

- SM fermions are U(1)$_H$ singlets.
- Z$_H$ is fermiophobic and Higgphilic.

Type-II 2HDM

- H_1 couples to the up-type fermions, while H_2 couples to the down-type fermions.

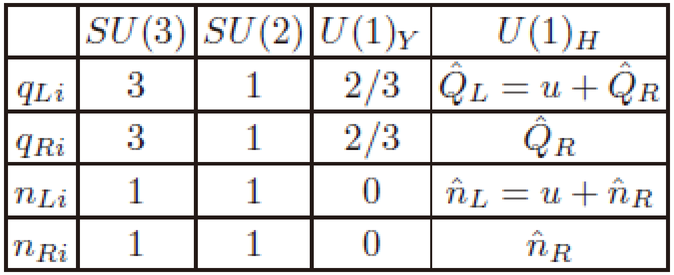
$$V_y = y_{ij}^U \bar{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \bar{Q}_{Li} H_2 D_{Rj} + y_{ij}^E \bar{L}_i H_2 E_{Rj} + y_{ij}^N \bar{L}_i \tilde{H}_1 N_{Rj}$$

U_R	D_R	Q_L	L	E_R	N_R	H_1	H_2
u	0	0	0	0	u	u	0

- Requires extra chiral fermions for cancellation of gauge anomaly.

$U(1)_H^3$

$U(1)_Y U(1)_H^2$



	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$
q_{Li}	3	1	2/3	$\hat{Q}_L = u + \hat{Q}_R$
q_{Ri}	3	1	2/3	$\hat{Q}_R$
n_{Li}	1	1	0	$\hat{n}_L = u + \hat{n}_R$
n_{Ri}	1	1	0	$\hat{n}_R$

+

Two vector-like pairs of $SU(2)_L$

Mixing between new chiral fermions and SM fermions is prohibited by $U(1)_H$ charge assignment.

One of extra fermions could be a candidate for CDM.

Constraints

- experimental and theoretical constraints

$m_h \sim 126\ \mathrm{GeV}$

$|m_{H^+} - m_A|$

$|m_{H^+} - m_H|$

$\sin(\beta - \alpha)$

$\tan\beta$

m_{H^+}

SM-like Higgs

m_H

Perturbativity

Unitarity

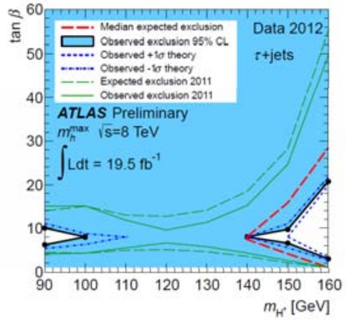
Vacuum stability

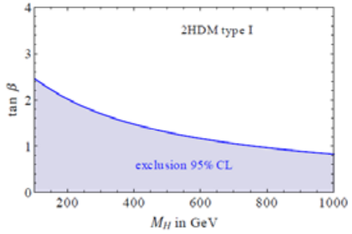
EWPOs

small mass differences requied

Exotic top decay

$b \rightarrow s\gamma$

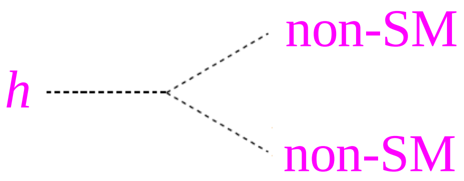




$\tan\beta \gtrsim 1$

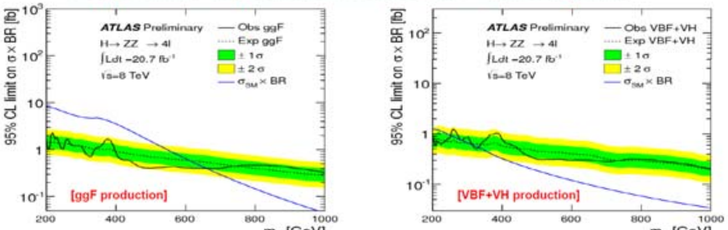
Hermann,Misiak,Steinhauser, JHEP1211 (2012) 036

Invisible Higgs decay



Heavy Higgs search at LHC

➔ Upper limits on production cross section × branching ratio

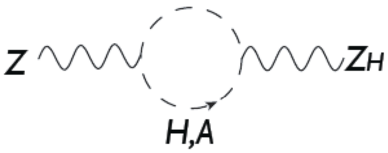


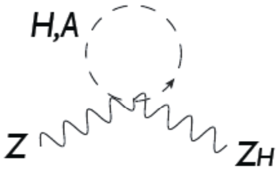
Z-Z_H mixing

- tree-level mixing ($v_i \neq 0$)

$$\Delta M^2_{ZZ_H} = -\frac{\hat{M}_Z}{v} g_H \sum_{i=1}^{2} \boxed{q_{H_i} v_i^2}. \qquad \tan 2\xi = \frac{2\Delta M^2_{ZZ_H}}{\hat{M}^2_{Z_H} - \hat{M}^2_Z}.$$

- loop-level mixing ($v_1=0$, $v_2 \neq 0$)





$$\kappa_Z = \frac{q_H g_H e c_W}{16\pi^2 s_W} \left\{ \frac{1}{3} \ln\left(\frac{m_A^2}{m_{H+}^2} \right) - \frac{1}{6} \frac{m_A^2 - m_H^2}{m_A^2} \right\},$$

$$\kappa_\gamma = \frac{q_H g_H e}{16\pi^2} \left\{ \frac{1}{3} \ln\left(\frac{m_A^2}{m_{H+}^2} \right) - \frac{1}{6} \frac{m_A^2 - m_H^2}{m_A^2} \right\},$$

$$\Delta M^2_{Z_H Z} = -\frac{q_H g_H e}{32\pi^2 s_W c_W} (m_A^2 - m_H^2).$$

$$-\frac{\kappa_Z}{2} F_Z^{\mu\nu} F_{H\mu\nu} - \frac{\kappa_\gamma}{2} F_\gamma^{\mu\nu} F_{H\mu\nu} + \Delta M^2_{Z_H Z} \hat{Z}^\mu \hat{Z}_{H\mu}$$

The mixing can appear because of $SU(2)_L \times U(1)_Y$ breaking effects.

- collider bound depends on the $U(1)_H$ charge assignment.

- In the fermiophobic Z_H case, the Z_H boson can be produced through the Z-Z_H mixing and the bound for the mixing angle is

$$\sin\xi \lesssim O(10^{-2}) \sim O(10^{-3})$$

Inert Doublet Model (IDMwZ$_2$)

- a 2HDM ~ one of the simplest extension

- One of Higgs doublets does not develop VEV and exact Z$_2$ symmetry is imposed.

- The new Higgs doublet does not participate in the EW symmetry breaking.

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

- Viable DM candidate

$$H_1 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\boxed{H} + i\boxed{A}) \end{pmatrix}, \quad H_2 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \boxed{h} + iG^0) \end{pmatrix}$$

DM candidates

SM-like Higgs

Inert Doublet Model (IDMwZ$_2$)

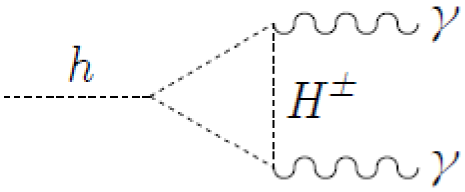
- CP-conserving potential

forbidden by the Z$_2$ symmetry

$$V = \mu_1 (H_1^\dagger H_1) + \mu_2 (H_2^\dagger H_2) \cancel{- \mu_{12} (H_1^\dagger H_2 + \mathrm{h.c.})} + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2$$
$$+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) \; + \lambda_4 | H_1^\dagger H_2 |^2 \; + \frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + h.c.\}.$$

- Type-I Yukawa interactions ~ only H$_2$ couples to the SM fermions.

- The h decay to two photons receives additional contribution through charged Higgs loop.



- H,A,H$^\pm$ ~ do not couple to SM fermions at tree level.

Inert Double Model (IDMwU(1)$_H$)

- We replace the Z_2 symmetry by U(1) gauge symmetry.
- A SM-singlet Φ has to be added.
- Without Φ, Z_H boson becomes massless.

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

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

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

- Φ 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 Z_2 symmetry.

Inert Double Model (IDMwU(1)$_H$)

- We replace the Z_2 symmetry by U(1) gauge symmetry.
- A SM-singlet Φ has to be added.
- Without Φ, Z_H boson becomes massless.

forbidden
by the Z_2 symmetry

$$\begin{aligned}V=&(m_1^2+\tilde{\lambda}_1|\Phi|^2)(H_1^\dagger H_1)+(m_2^2+\tilde{\lambda}_2|\Phi|^2)(H_2^\dagger H_2)\cancel{-(m_{12}^2H_1^\dagger H_2+\mathrm{h.c.})}\\&+\frac{\lambda_1}{2}(H_1^\dagger H_1)^2+\frac{\lambda_2}{2}(H_2^\dagger H_2)^2+\lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2)+\lambda_4|H_1^\dagger H_2|^2\\&\cancel{+\frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2+h.c.\}}+m_\Phi^2|\Phi|^2+\lambda_\Phi|\Phi|^4\end{aligned}$$

forbidden by the U(1)$_H$ symmetry ($q_{H_2}=0, q_{H_1}\neq 0$)

- Φ 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 Z_2 symmetry.

Inert Double Model (IDMwU(1)$_H$)

- IDM + SM-singlet Φ.

forbidden
by the Z_2 symmetry

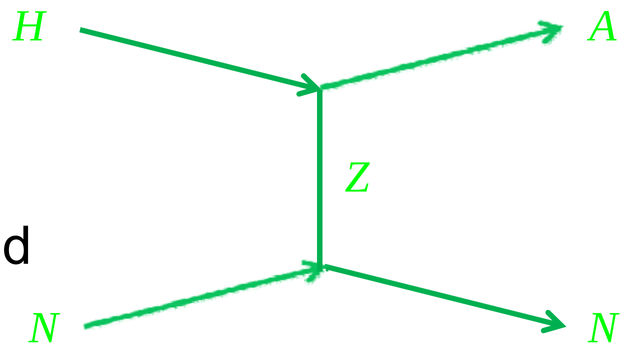
$$
\begin{aligned}
V = {} & (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - \cancel{(m_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.})} \\
& + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2 \\
& + \cancel{\frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + h.c.\}} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4
\end{aligned}
$$

forbidden by the U(1)$_H$ symmetry ($q_{H_2}=0, q_{H_1} \neq 0$)

- Without λ_5, H and A are degenerate.

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

- Direct searches for DM at XENON100 and LUX exclude this degenerate case.



Inert Double Model (IDMwU(1)$_H$)

- IDM + SM-singlet Φ.

forbidden
by the Z_2 symmetry

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

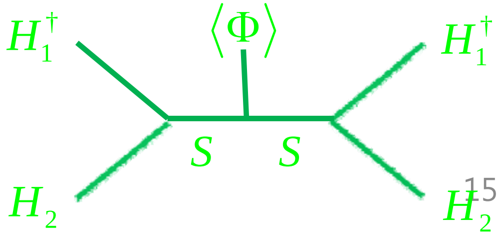
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$

$$+\left\{c_l \left(\frac{\Phi}{\Lambda}\right)^l (H_1^\dagger H_2)^2 + h.c.\right\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

- The λ_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 $q_S = q_{H_1}$.

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

$$\lambda_H = \lambda_H^0 S \qquad \lambda_5 \sim \frac{(\lambda_H^0)^2}{2} \frac{\Delta m^2}{m_{Re(S)}^2 m_{Im(S)}^2},$$

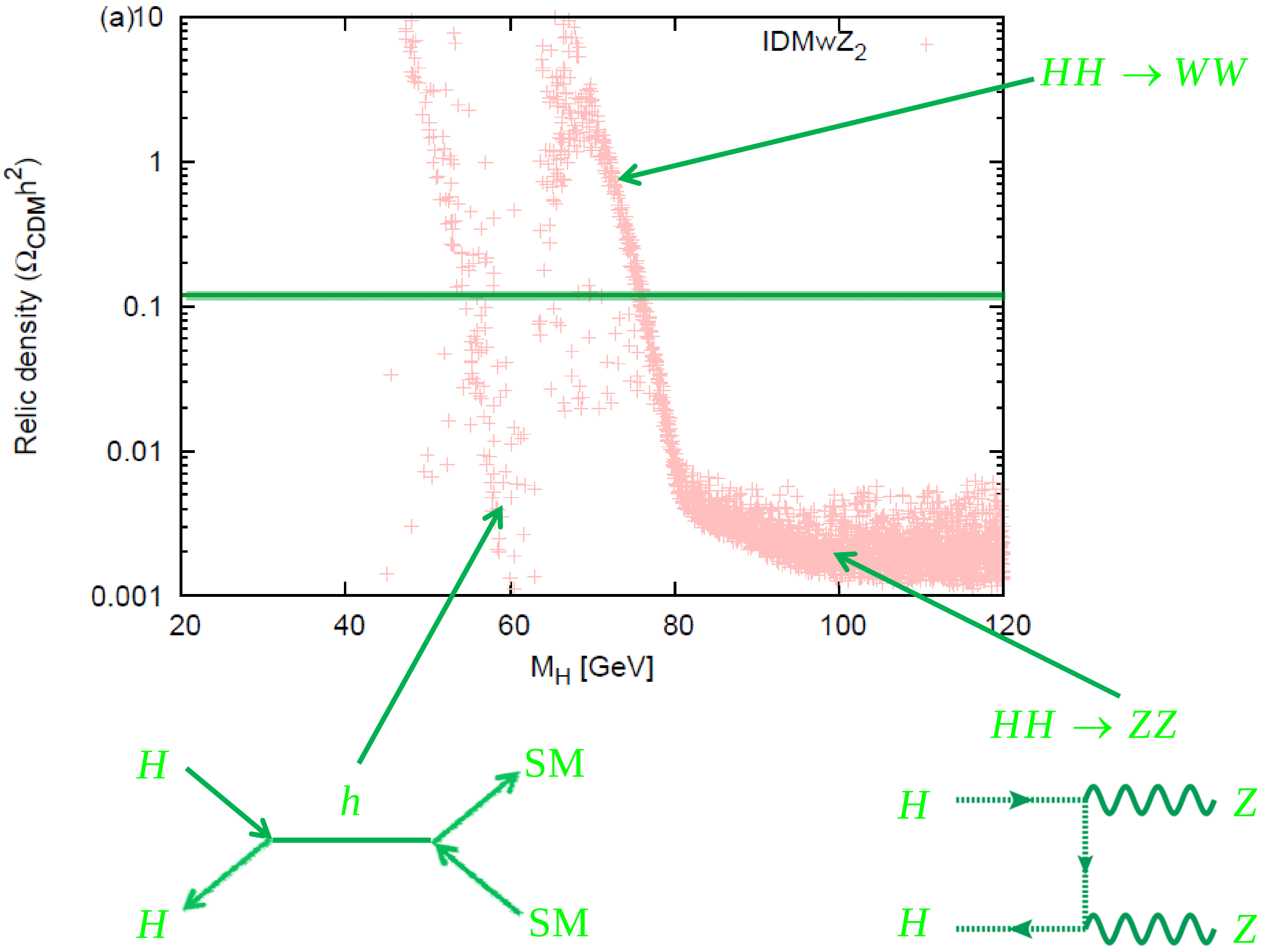


Relic density (low mass)

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

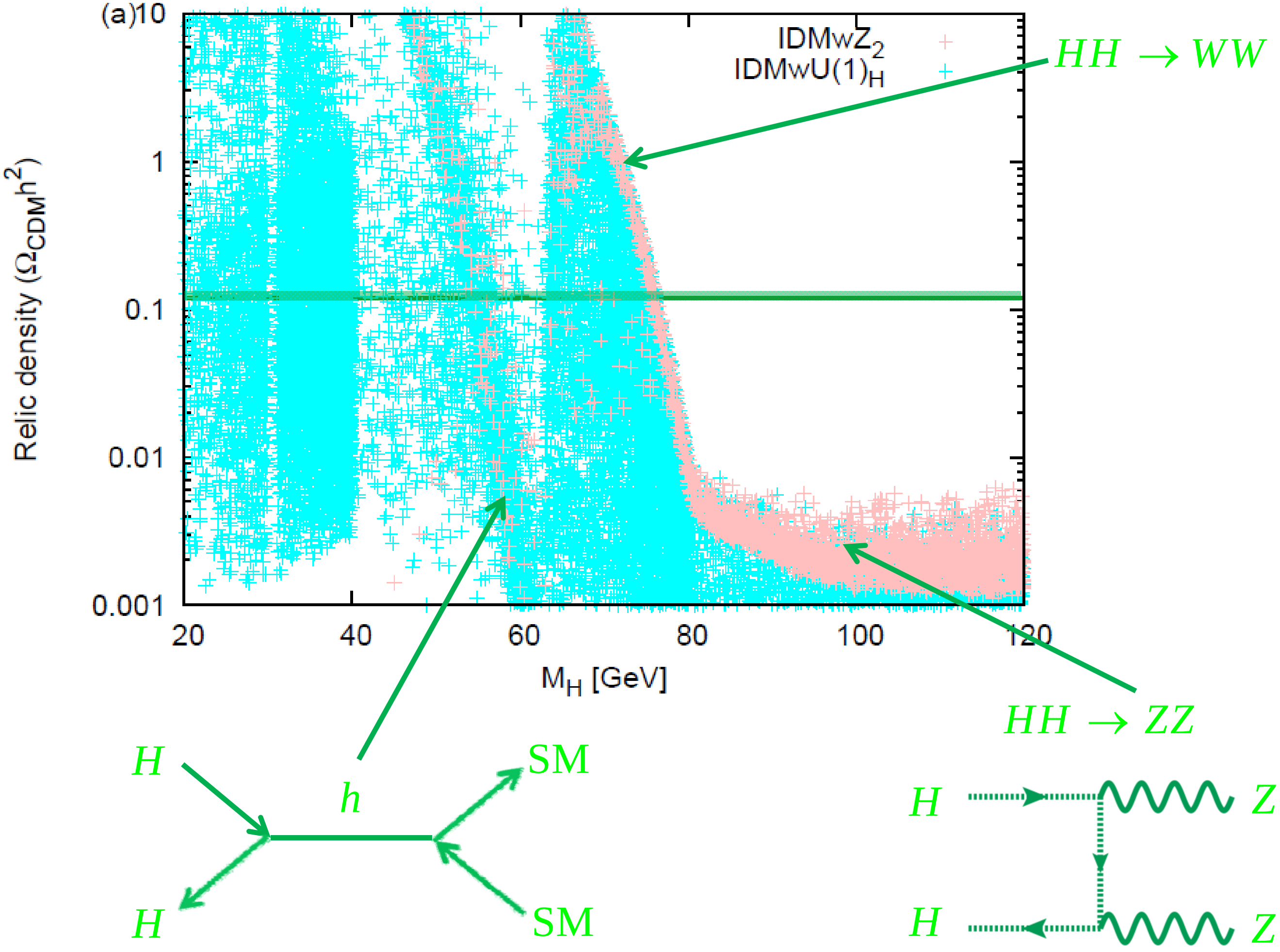
+ IDMwZ_2

LUX bound is satisfied.



Relic density (low mass)

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



+ IDMwZ$_2$
+ IDMwU(1)$_H$

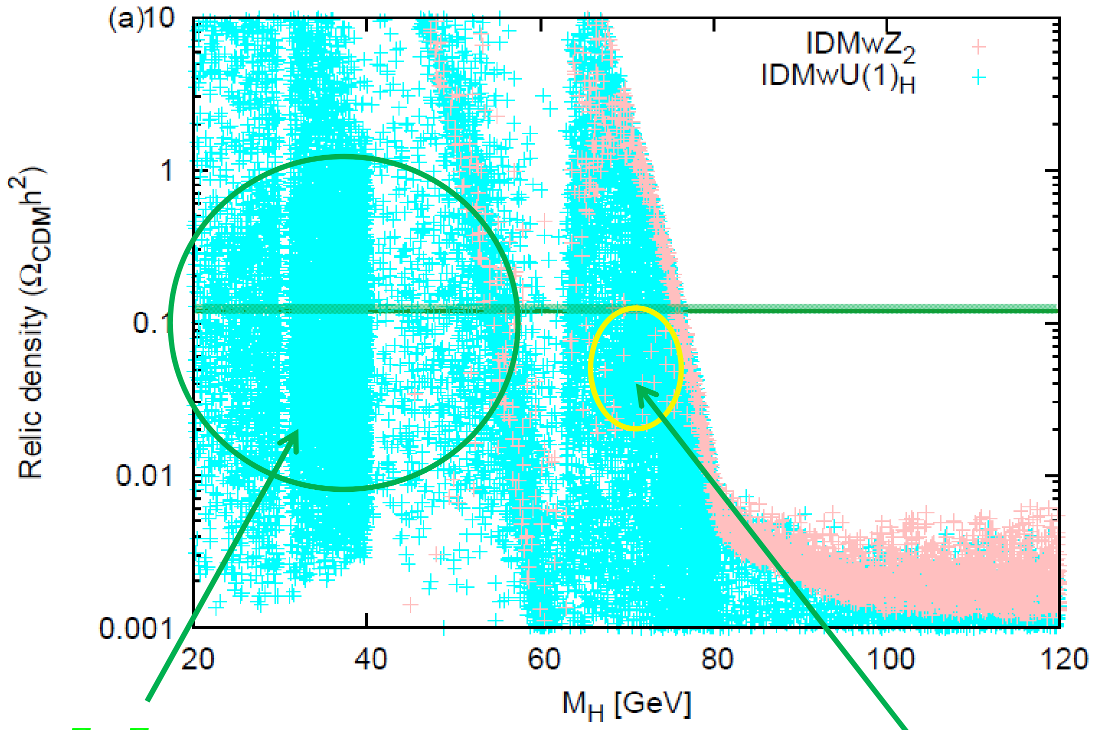
LUX bound is satisfied.

Relic density (low mass)

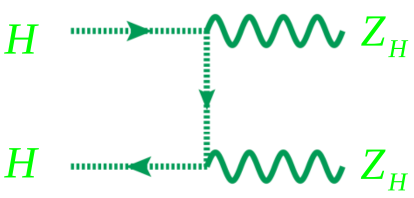
$$\Omega_{\mathrm{CDM}} h^2 = 0.1199 \pm 0.0027$$

+ IDMwZ_2
+ $\mathrm{IDMwU(1)}_H$

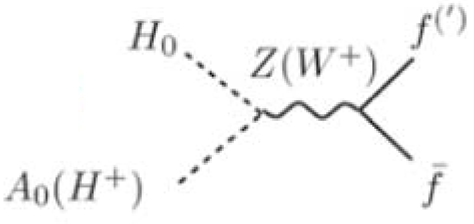
LUX bound is satisfied.



$HH \to Z_H Z_H, ZZ_H$



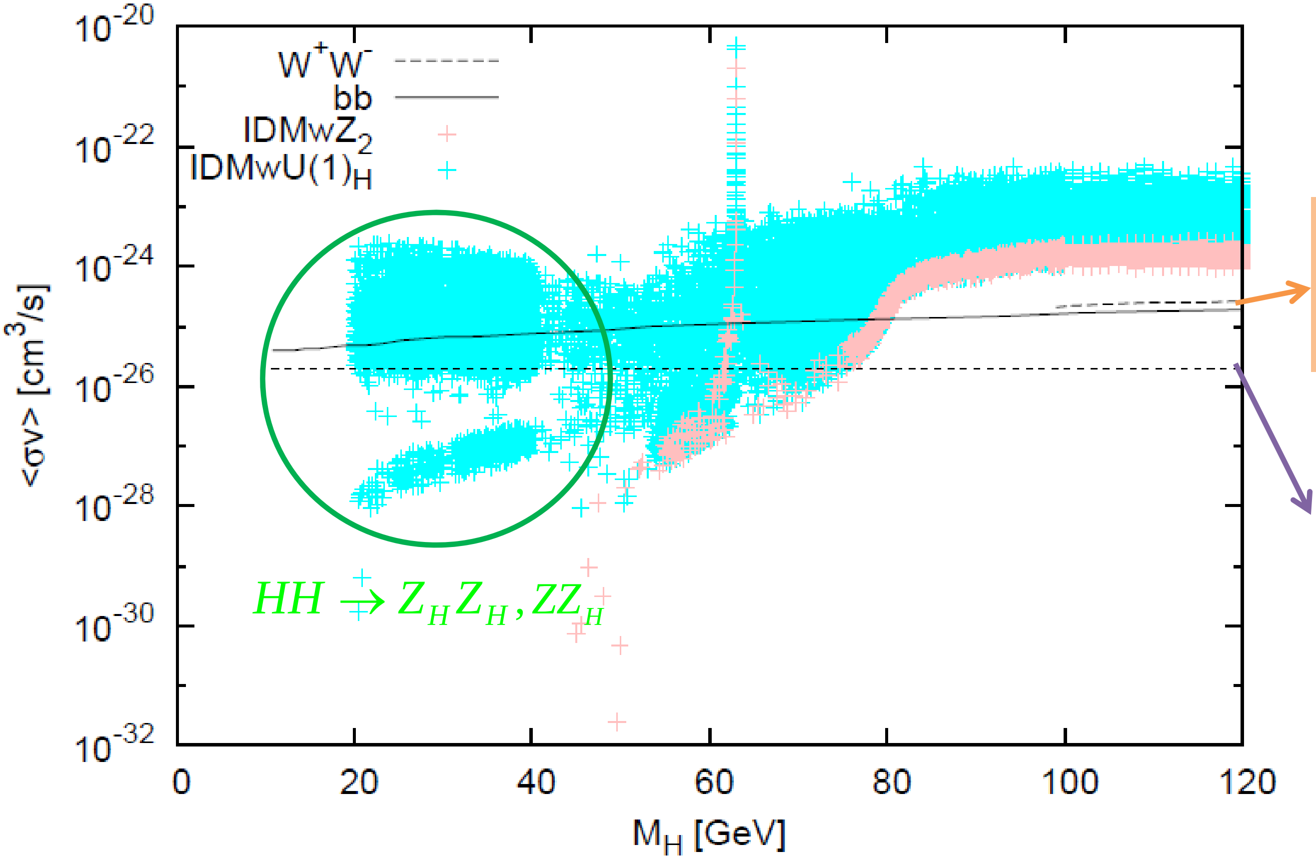
Co-annihilation



$HA, HH^{\pm} \to \mathrm{SM} + \mathrm{SM}^{(\prime)}$

$H^+H^- \to A + Z_H, Z + Z_H, \ldots$

Indirect searches (low mass)



+ IDMwZ_2
+ IDMwU(1)$_H$

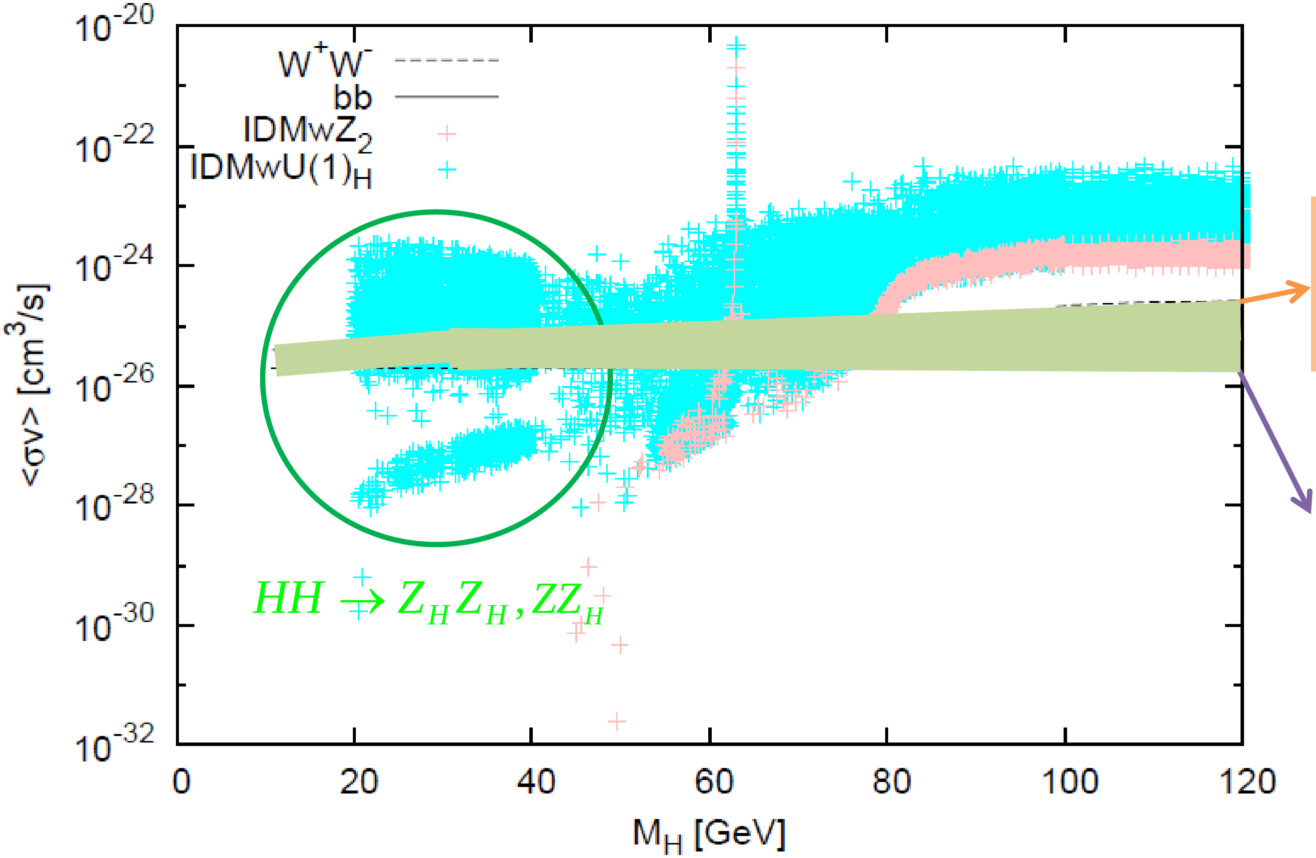
Constraints on the DM annihilation cross section from Fermi-LAT's analysis of 15 dwarf spheroidal galaxies.

Fermi-LAT, arXiv:1310.0828

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

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

Indirect searches (low mass)



+ $\mathrm{IDMwZ_2}$
+ $\mathrm{IDMwU(1)_H}$

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

- But, 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.

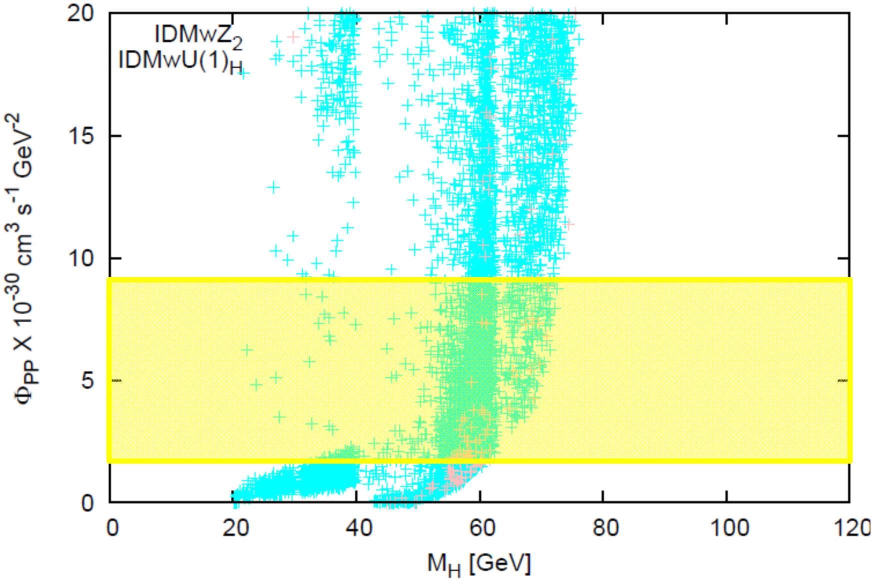
$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\Phi_{\rm PP}} \cdot \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(r){\rm d}l\right\}{\rm d}\Omega'}_{\text{J-factor}} .$$

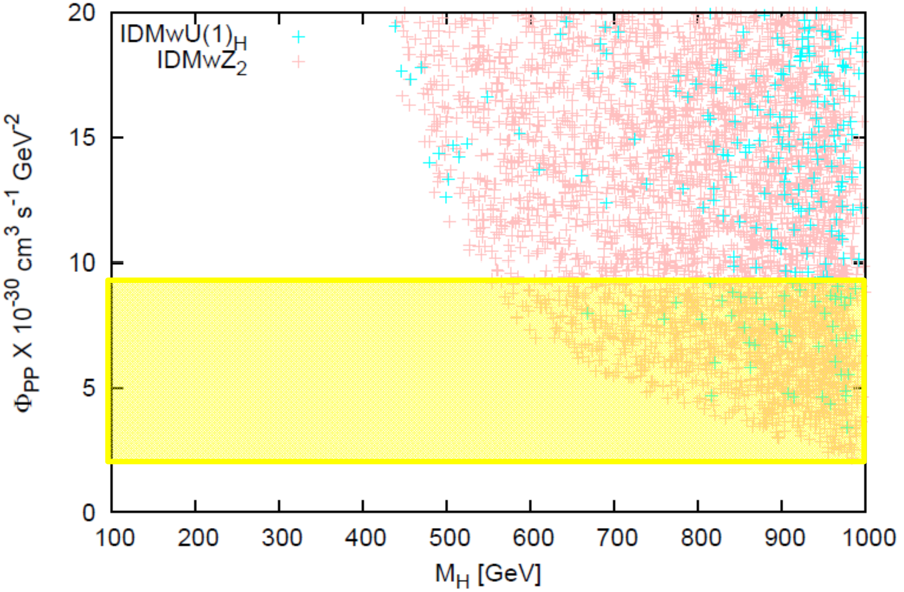
The final γ-ray spectrum.

contains information about the distribution of DM.

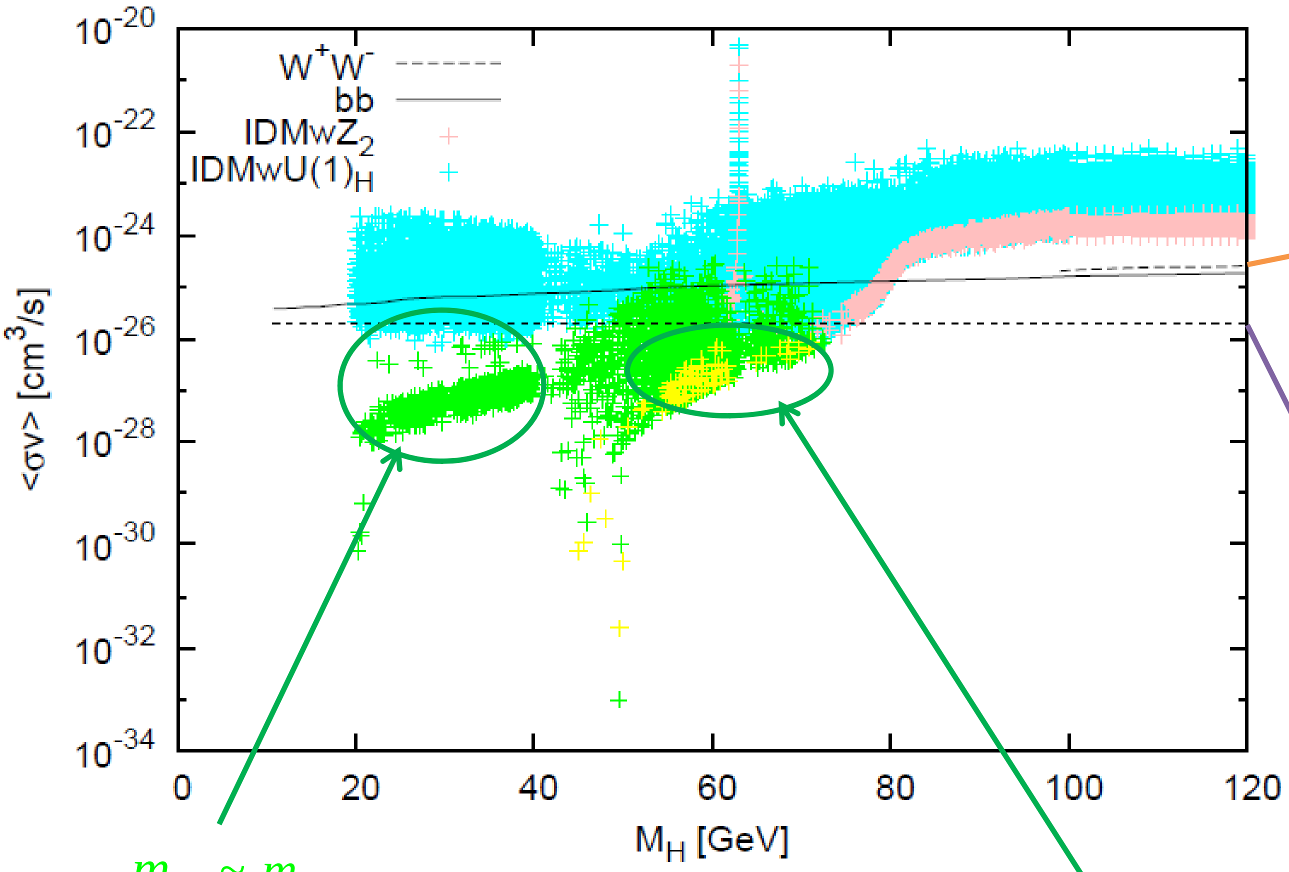
A 95% upper bound is $\Phi_{PP} = 5.0^{+4.3}_{-4.5} \times 10^{-30}\,\mathrm{cm}^3\mathrm{s}^{-1}\mathrm{GeV}^{-2}$

Geringer-Sameth,Koushiappas, PRL107





Indirect searches (low mass)



+ IDMwZ$_2$

+ IDMwU(1)$_H$

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

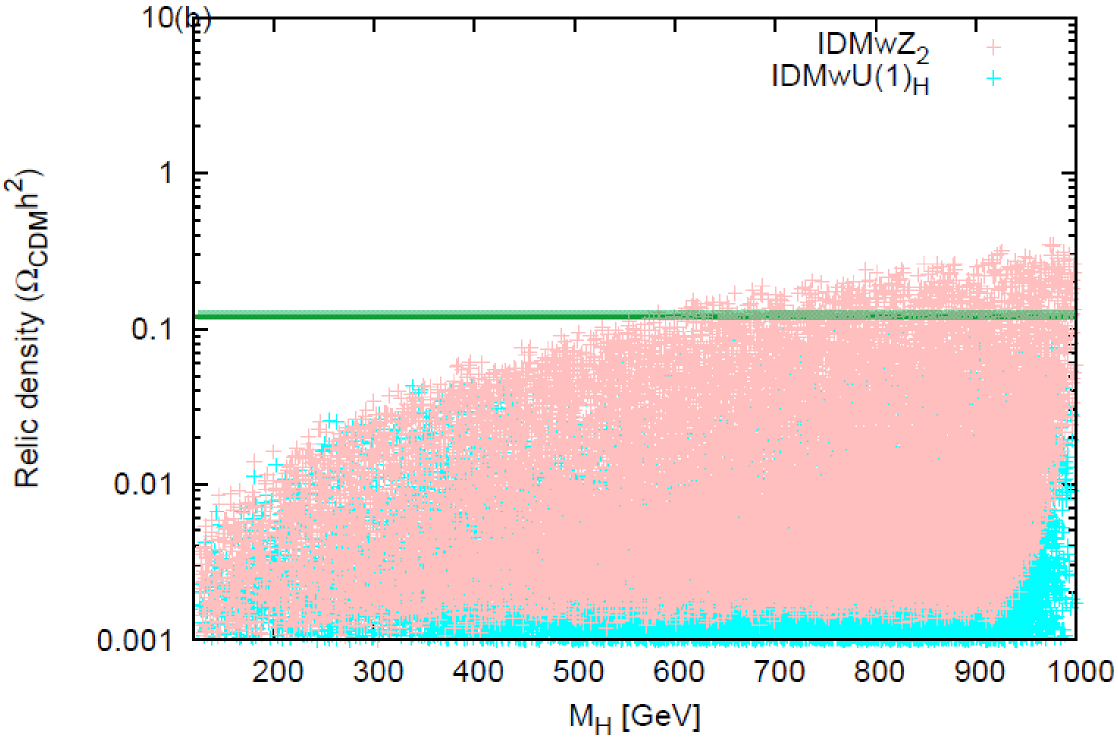
$m_H \sim m_{Z_H}$

Co-annihilation

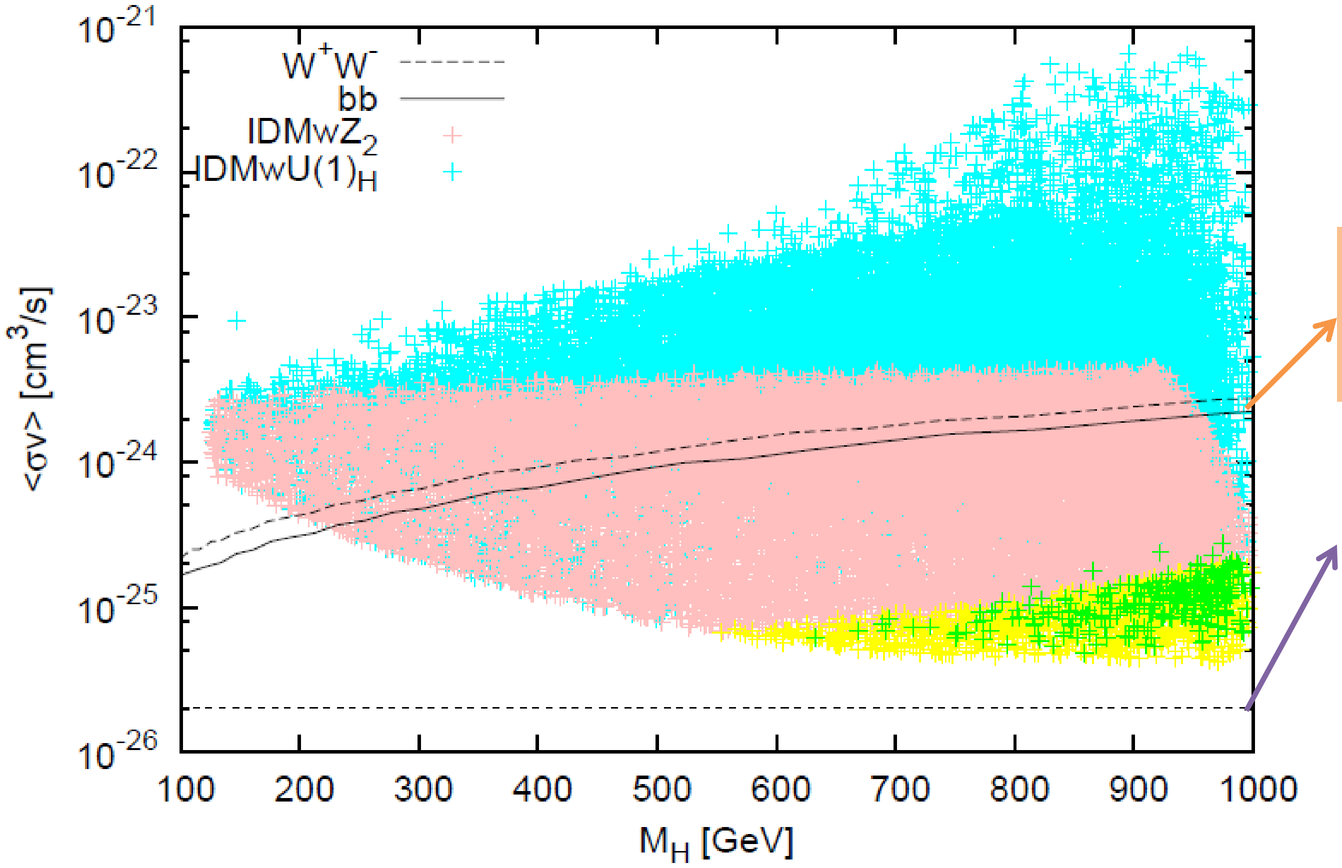
Relic density (high mass)

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

+ IDMwZ_2
+ IDMwU(1)_H



Indirect searches (high mass)



+ IDMwZ_2
+ IDMwU$(1)_H$

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

Conclusions

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

- 2HDM can easily be extended to a gauged model and the U(1) gauge symmetry could be the origin of Z_2 symmetry.

- The U(1) extension to inert doublet model could introduce dark matter candidates whose stability are guaranteed by the remnant symmetry of $U(1)_H$.

- In type-I, a light CDM scenario is possible in the $IDMwU(1)_H$.

Back up

Higgs Potential

- in the ordinary 2HDM with Z_2 symmetry

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

not invariant under $U(1)_H$

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

$$V = \hat{m}_1^2(|\Phi|^2) H_1^\dagger H_1 + \hat{m}_2^2(|\Phi|^2) H_2^\dagger H_2 - \left(m_3^2(\Phi) H_1^\dagger H_2 + h.c.\right)$$
$$+\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$
$$+m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4.$$

$\boxed{H_1^\dagger H_2 \Phi}$

invariant under $U(1)_H$

no λ5 terms!

- neutral Higgs

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

- a pair of charged Higgs + 1 pseudoscalar Higgs + 3 neutral Higgs bosons