2HDM with local $U(1)_H$ gauge symmetry and dark matter

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

Based on JHEP 1401, 016;
arXiv:1405.2138;
work in progress

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Two Higgs doublet model

• an effective theory of high-energy models.

- MSSM, GUT, flavor models, and etc.

• an extension of SM

- extra scalars
- dark matter physics Ma,PRD73;Barbieri,Hall,Rychkov,PRD74
- baryon asymmetry of the Universe Shu,Zhang,PRL111
- neutrino mass generation Kanemura,Matsui,Sugiyama,PLB727
- top A_{FB} at Tevatron and $B \to D^{(*)} \tau \nu$ at BABAR Ko,Omura,Yu,EPJC73;JHEP1303

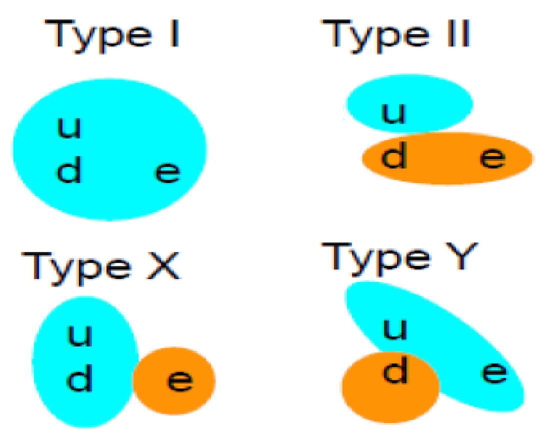
2HDM with Z_2 symmetry (2HDMwZ_2)

- 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.

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

NO FCNC at tree level.

Extensions of 2HDM

- Z_2 symmetry

softly broken Z_2 symmetry

Glashow,Weinberg PRD15

singlet extension

Drozd,Grzadkowski,Gunion,Jiang

S_3 symmetry

kajiyama,Okada,arXiv:1309.6234

U(1) symmetry

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

- vacuum

$$\langle H_1 \rangle = v_1, \langle H_2 \rangle = v_2$$

$$\langle H_1 \rangle = 0, \langle H_2 \rangle = v_2$$

$$\langle H_1 \rangle = v_1 e^{i\xi}, \langle H_2 \rangle = v_2$$

Why softly broken Z_2 sym?

- 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?

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• the origin of the softly breaking term?

$U(1)_H$ extension of Z_2 symmetry could be the origin of the softly breaking terms.

Type-I 2HDM

- Only one Higgs couples with fermions.

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

- 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

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

Type-I 2HDM

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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	$1/2$	$U(1)_Y$

Z_H strongly constrained

Type-I 2HDM

- Only one Higgs couples with fermions.

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

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U_R	D_R	Q_R	L	E_R	N_R	H_1	Type
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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	$1/2$	$U(1)_Y$

- SM fermions are $U(1)_H$ singlets.
- Z_H is fermiophobic and Higgsphilic.

less constrained

Type-I 2HDM

• Only one Higgs couples with fermions.

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

• 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	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$

→ No Dark Matter

• Dark matter could be introduced in Higgs portal or inert type models.

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

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

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.

$U(1)_H^3$

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$
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	$\hat{n}_R$

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

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

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.

Type-II 2HDM

- type-II 2HDM with U(1) inspired by E_6 GUT

$$E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$$

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_b$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
Q^i	3	2	1/6	−1/3	1	−1	−2
U^i_R	3	1	2/3	2/3	−1	1	2
D^i_R	3	1	−1/3	−1/3	−1	−3	−1
L_i	1	2	−1/2	0	1	3	1
E^i_R	1	1	−1	0	−1	1	2
N^i_R	1	1	0	1	−1	5	5
H_1	1	2	1/2	0	2	2	−1
H_2	1	2	1/2	1	−2	2	4

$$Q_\eta = \frac{3}{4}Q_\chi - \frac{5}{4}Q_\psi$$

$$Q_b = \frac{1}{5}(Q_\eta + 2Q_Y)$$

⟹ leptophobic
choose as $U(1)_H$

Extra fermions (required by anomaly-free conditions)

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_b$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
q^i_L	3	1	−1/3	2/3	−2	2	4
q^i_R	3	1	−1/3	−1/3	2	2	−1
l^i_L	1	2	−1/2	0	−2	−2	1
l^i_R	1	2	−1/2	−1	2	−2	−4
n^i_L	1	1	0	−1	4	0	−5

Yukawa interaction for extra fermions

$$V_y^{\rm ex} = y^q_{ij}\Phi\overline{q_L}^i q^j_R + y^l_{ij}\Phi\overline{l_L}^i l^j_R + y^n_{ij}\overline{l_R}^i \widetilde{H}_1 n^j_L + y'^n_{ij}\overline{l^c_L}^i H_2 n^j_L + h.c.$$

Singlet scalar required for $U(1)_H$ breaking and masses for extra fermions

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_b$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
Φ	1	1	0	1	−4	0	5

Mixing of extra neutral fermions

$$\mathcal{L}_\nu = -\frac{1}{2}\left(\overline{\widetilde{\nu}^c_L}\ \overline{\widetilde{\nu}_R}\ \overline{n^c_L}\right)\begin{pmatrix} 0 & m_{\widetilde{e}} & m_M \\ m_{\widetilde{e}} & 0 & m_D \\ m_M & m_D & 0 \end{pmatrix}\begin{pmatrix} \widetilde{\nu}_L \\ \widetilde{\nu}^c_R \\ n_L \end{pmatrix} + h.c.$$

$$= -\frac{1}{2}\left(\overline{N_1}\ \overline{N_2}\ \overline{N_3}\right)\begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}.$$

⟹ The lightest one is CDM.

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.

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

$H_1^\dagger H_2 \Phi$

invariant under $U(1)_H$

no $\lambda 5$ terms!

- neutral Higgs

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

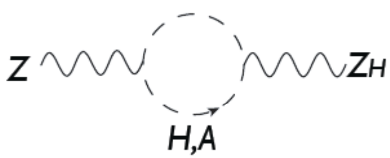
- a pair of charged Higgs + 1 pseudoscalar Higgs + 3 neutral Higgs bosons

Z-Z_H mixing

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

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

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



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

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

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

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

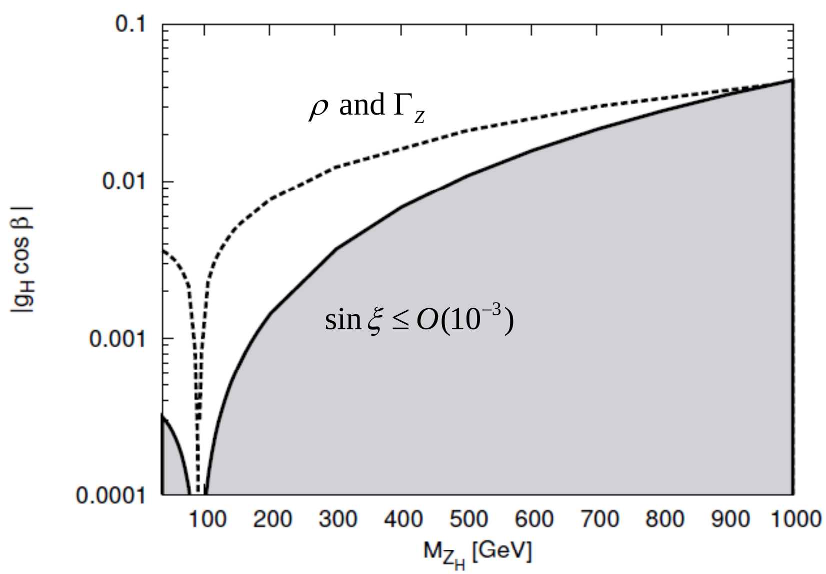
The mixing can appear because of $SU(2)_L \times U(1)_Y$ breaking effects.

- 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

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

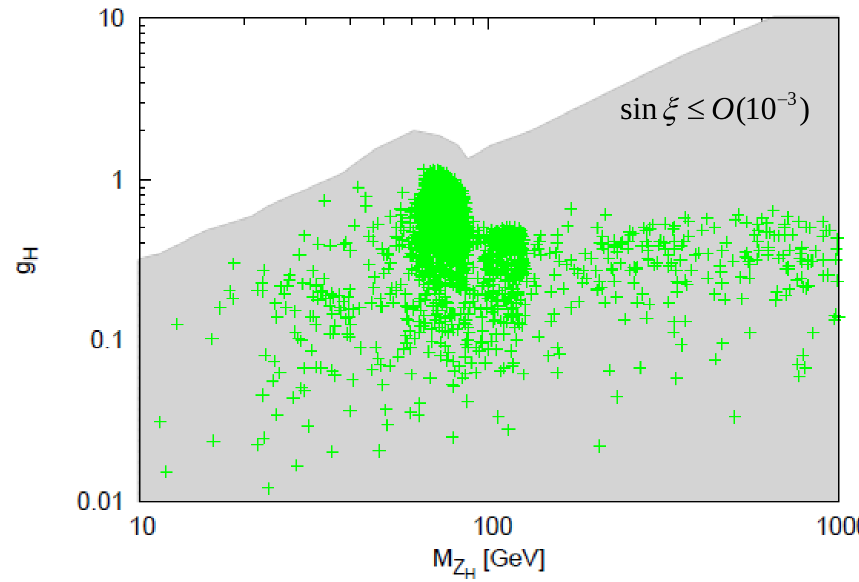
Mass and coupling of Z_H (type-I)

$v_1, v_2 \neq 0$



Tree-level mixing

$v_1 = 0$



loop-level mixing

Includes collider bound, relic density, direct detection and indirect detection

Constraints

- experimental and theoretical constraints

$m_h \sim 126$ GeV

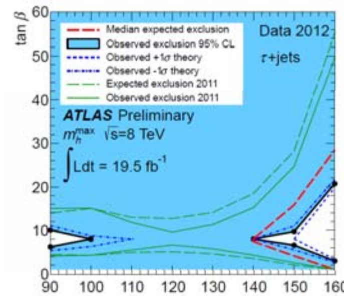
Perturbativity
Unitarity
Vacuum stability

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

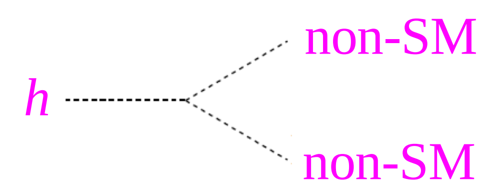
$|m_{H^+} - m_H|$

EWPOs
small mass differences requied

$\sin(\beta - \alpha)$



Invisible Higgs decay

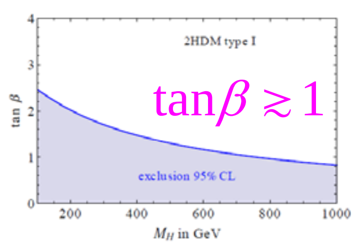


$\tan\beta$

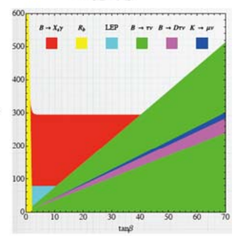
m_{H^+}

Exotic top decay

$b \to s\gamma$



$\tan\beta \gtrsim 1$

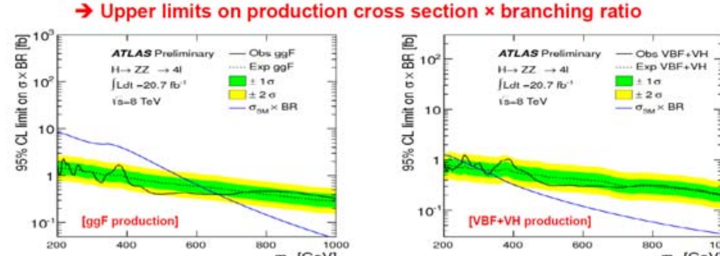


SM-like Higgs

m_H

Heavy Higgs search at LHC

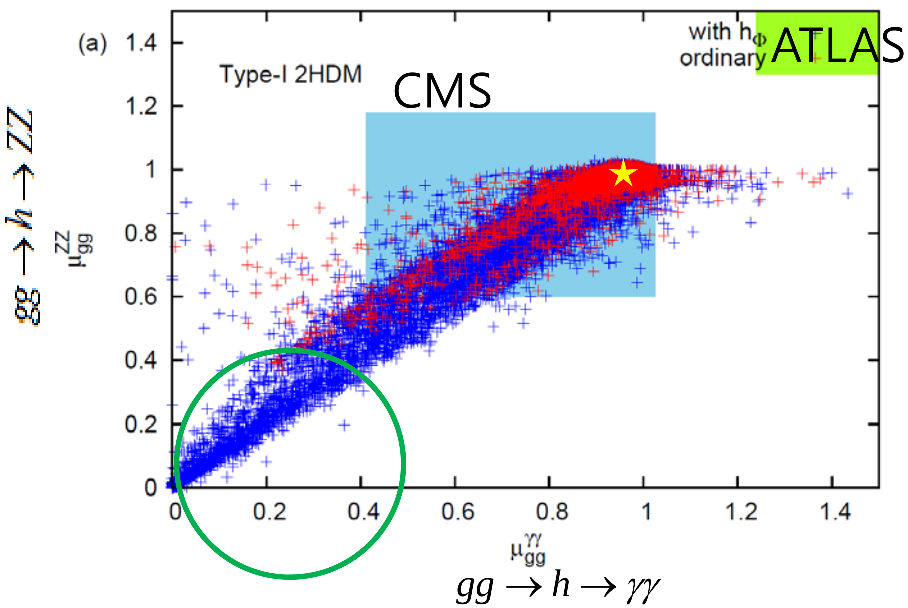
→ Upper limits on production cross section × branching ratio

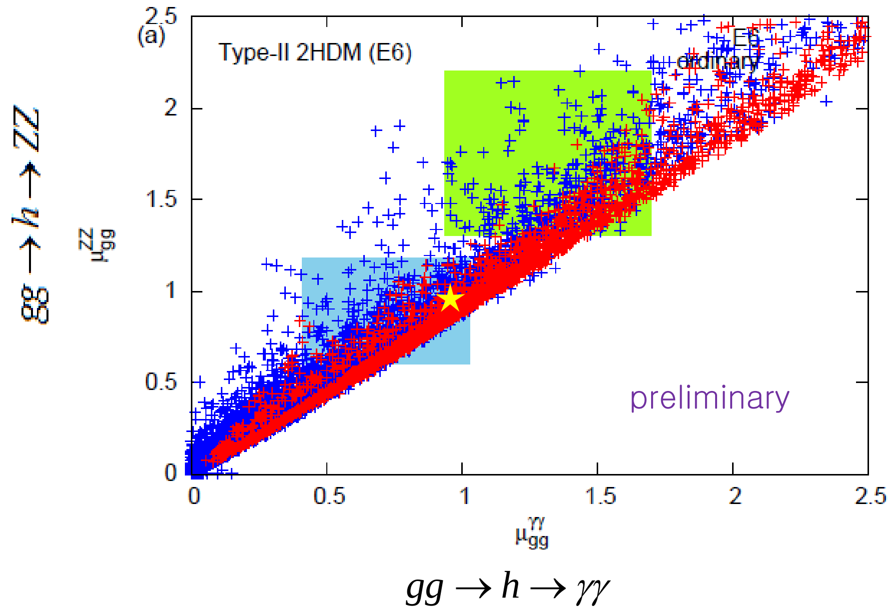


Type-I (with h_Φ) and Type-II (E_6)

- the gg fusion

★ =SM



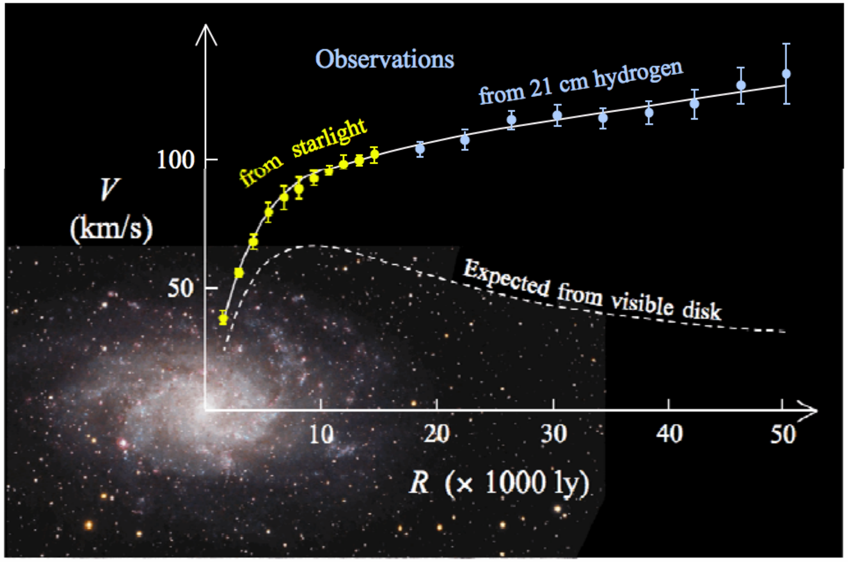


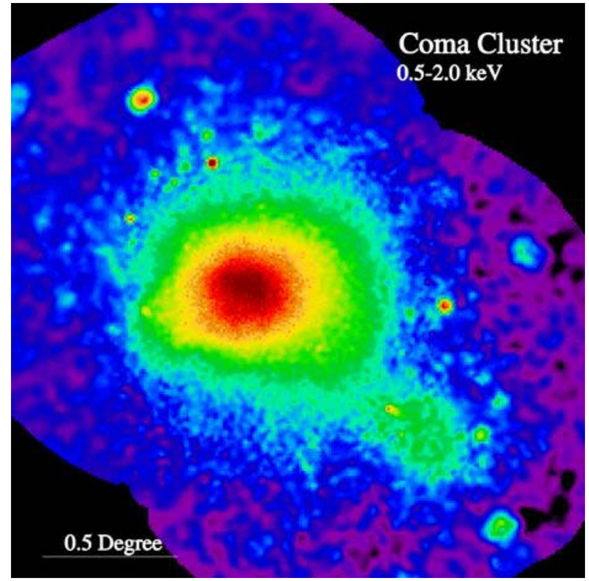
Ko,Omura,Yu, JHEP1401 (2014) 016

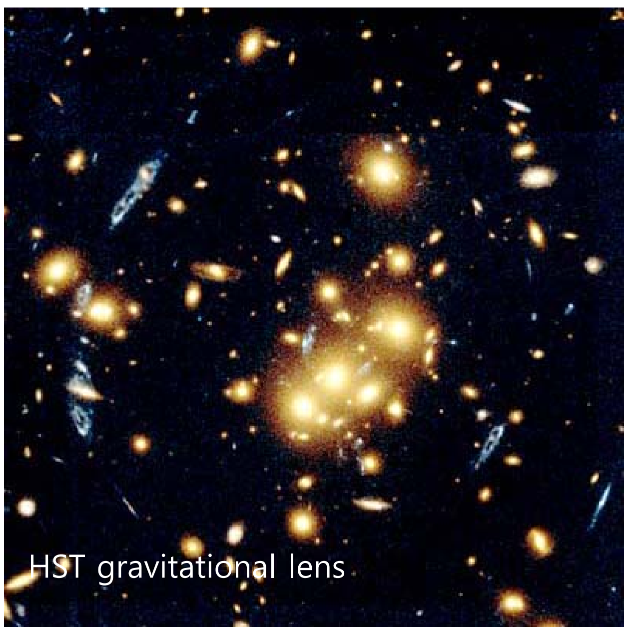
- Data are consistent with the SM prediction.

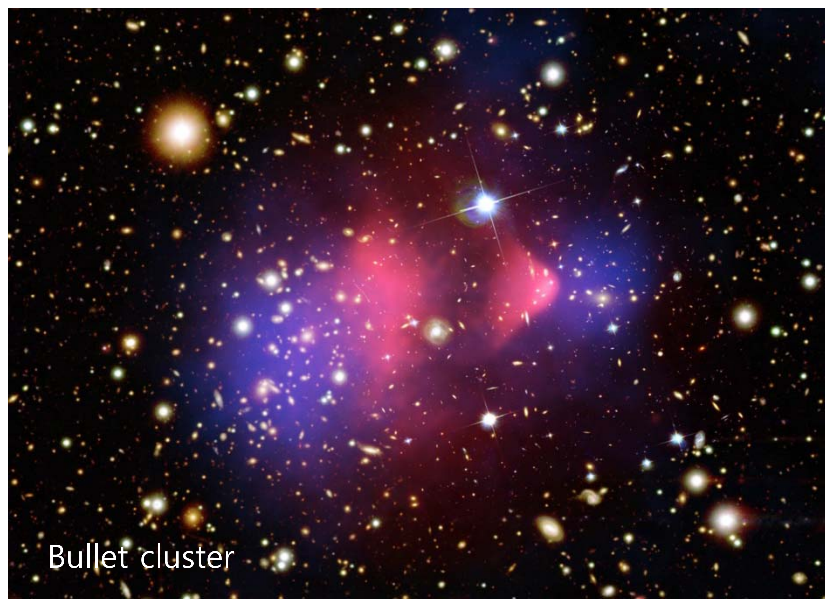
- To distinguish models, it is necessary to discover other scalar and Z_H bosons.

Dark Matter


Observations
from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)


Coma Cluster
0.5-2.0 keV
0.5 Degree


HST gravitational lens


Bullet cluster

Inert Doublet Model (IDMwZ_2)

- One of Higgs doublets does not develop VEV and exact Z_2 symmetry is imposed.

- Under the Z_2 symmetry, SM particles are even, but the new Higgs doublet is odd.

forbidden by the Z_2 symmetry

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

- Viable DM candidate

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

DM candidates (H, A) SM-like Higgs (h)

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

choose negative λ_5.

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

- We extend the Z_2 symmetry to U(1) gauge symmetry.
- A SM-singlet Φ has to be added.
- Without Φ, Z_H boson becomes massless and U(1) does not break.

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

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

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

- 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 extend the Z_2 symmetry to 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

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

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

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

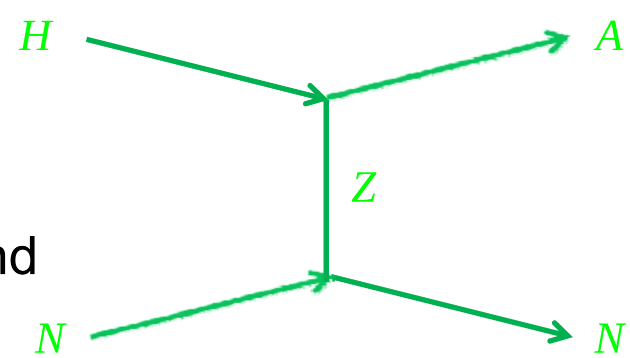
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$

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

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.

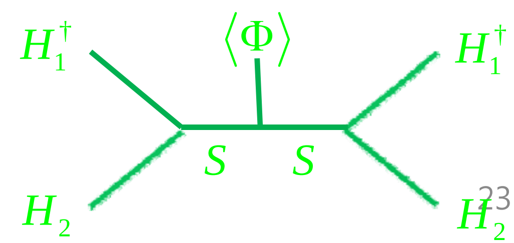
forbidden
by the Z_2 symmetry

$$V=(m_1^2+\tilde{\lambda}_1|\Phi|^2)(H_1^\dagger H_1)+(m_2^2+\tilde{\lambda}_2|\Phi|^2)(H_2^\dagger H_2)-(m_{12}^2 H_1^\dagger H_2+\mathrm{h.c.})$$
$$+\frac{\lambda_1}{2}(H_1^\dagger H_1)^2+\frac{\lambda_2}{2}(H_2^\dagger H_2)^2+\lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2)+\lambda_4|H_1^\dagger H_2|^2$$
$$+\{c_l\left(\frac{\Phi}{\Lambda}\right)^l(H_1^\dagger H_2)^2+h.c.\}+m_\Phi^2|\Phi|^2+\lambda_\Phi|\Phi|^4$$

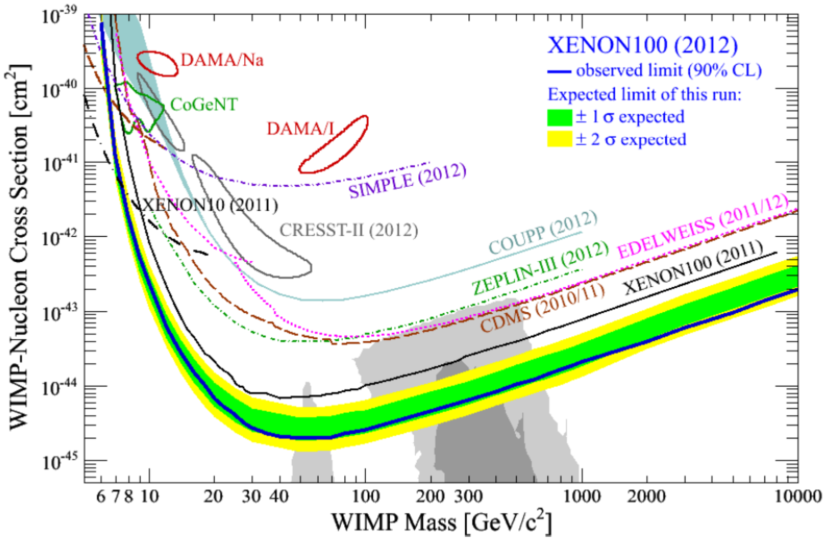
- The λ_5 term can effectively be generated by a higher-dimensional operator.
- It could be realized by introducing a singlet S charged under U(1)$_H$ with $q_S=q_{H_1}$.

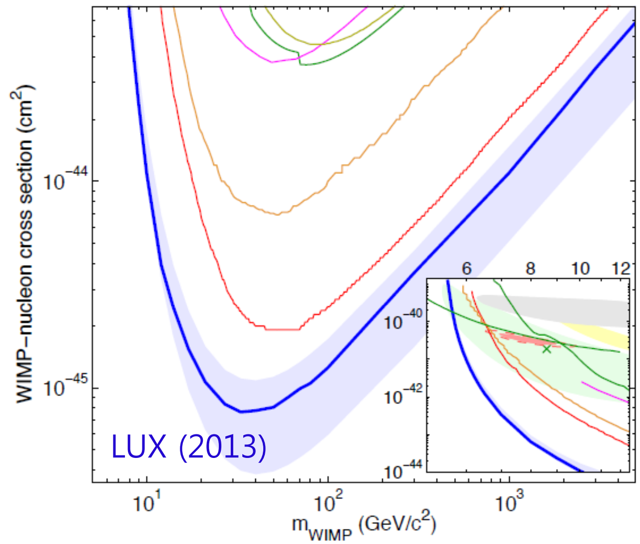
$$V_\Phi(|\Phi|^2,|S|^2)+V_H(H_i,H_i^\dagger)+\lambda_S(\Phi)S^2+\lambda_H(S)H_1^\dagger H_2+h.c..$$

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

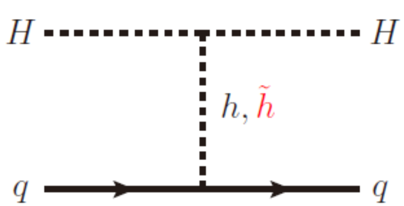


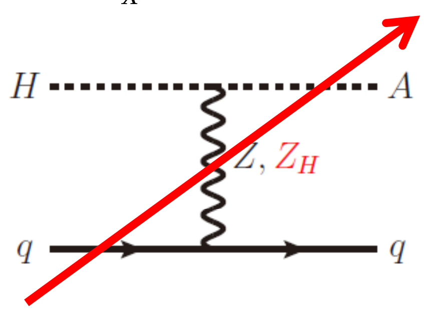
Direct detection





$$\sigma_{SI} \leq 10^{-45}\,\mathrm{cm}^2 \text{ at } M_X \sim 33 \text{ GeV}$$



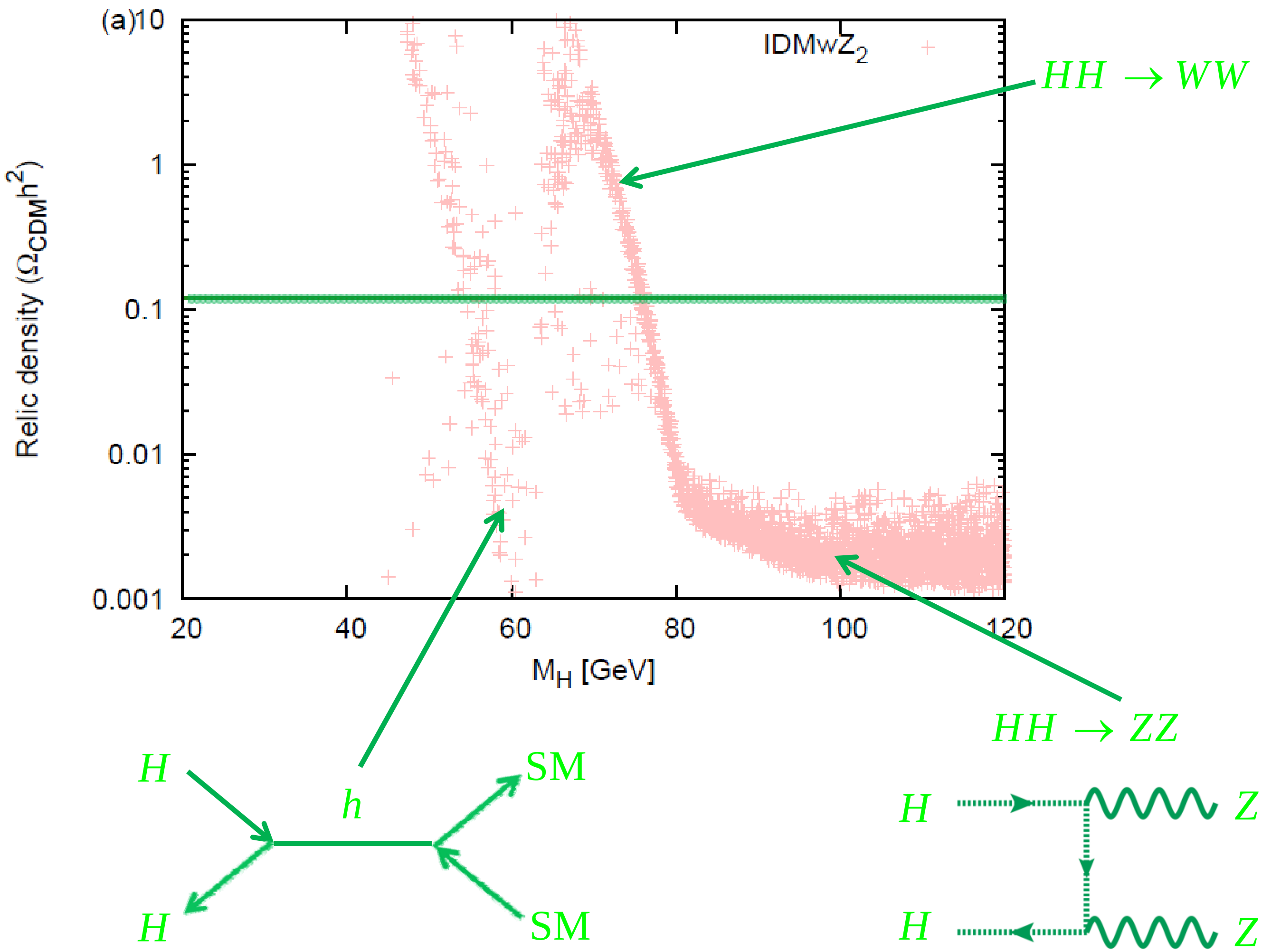


$$m_A = \sqrt{m_H^2 - \lambda_5 v^2}$$

$$\sigma_{SI} = \frac{\mu^2 f^2 m_N^2}{4\pi m_H^2}\left\{\left(\frac{\cos^2\alpha}{m_h^2} + \frac{\sin^2\alpha}{m_{\tilde{h}}^2}\right)(\lambda_3+\lambda_4+\lambda_5) + \left(\frac{1}{m_h^2} - \frac{1}{m_{\tilde{h}}^2}\right)\frac{v_\Phi \widetilde{\lambda}_1 \cos\alpha\sin\alpha}{v}\right\}^2$$

Relic density (low mass)

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



+ $IDMwZ_2$

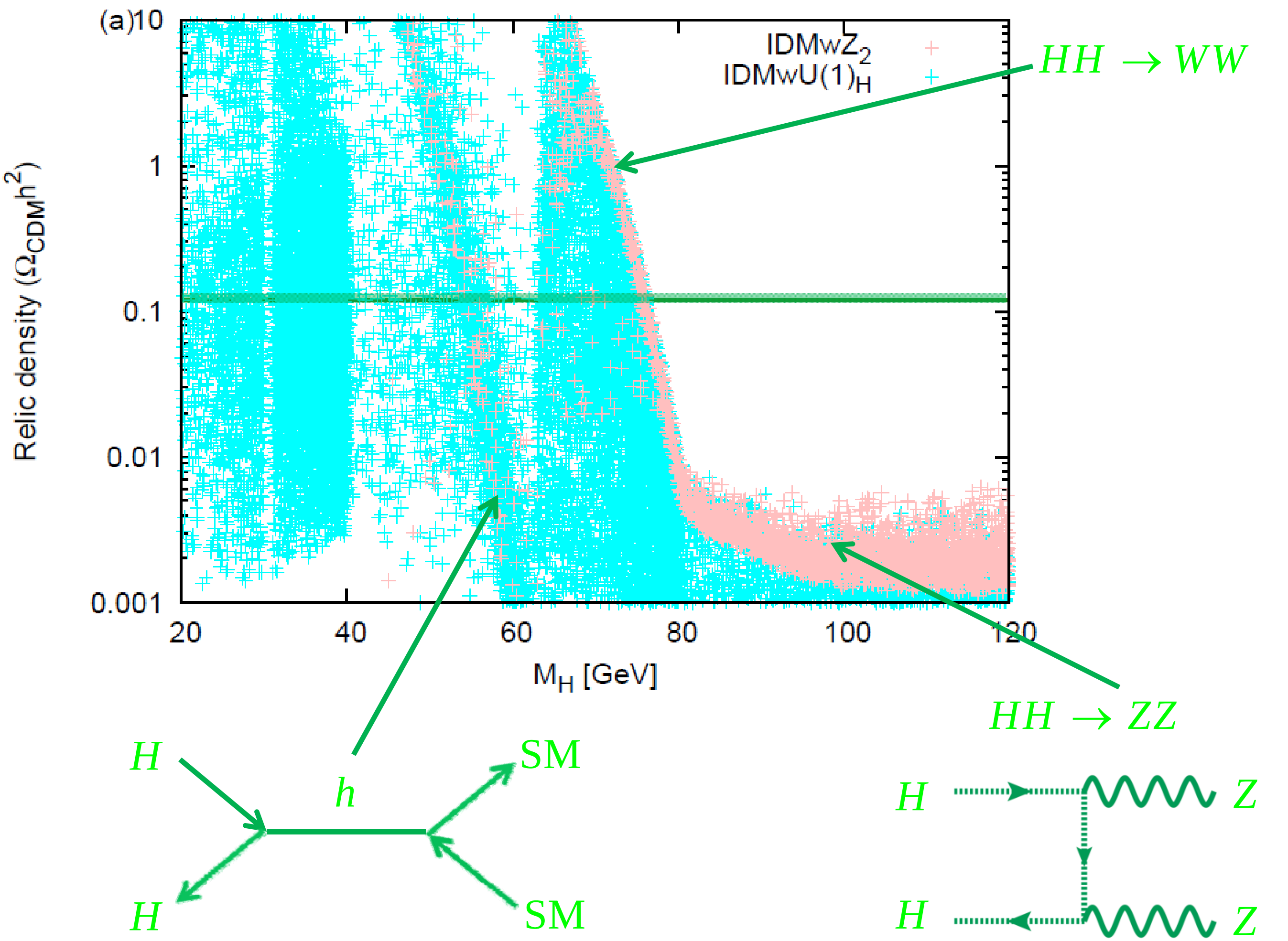
LUX bound is satisfied.

Relic density (low mass)

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

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

LUX bound is satisfied.

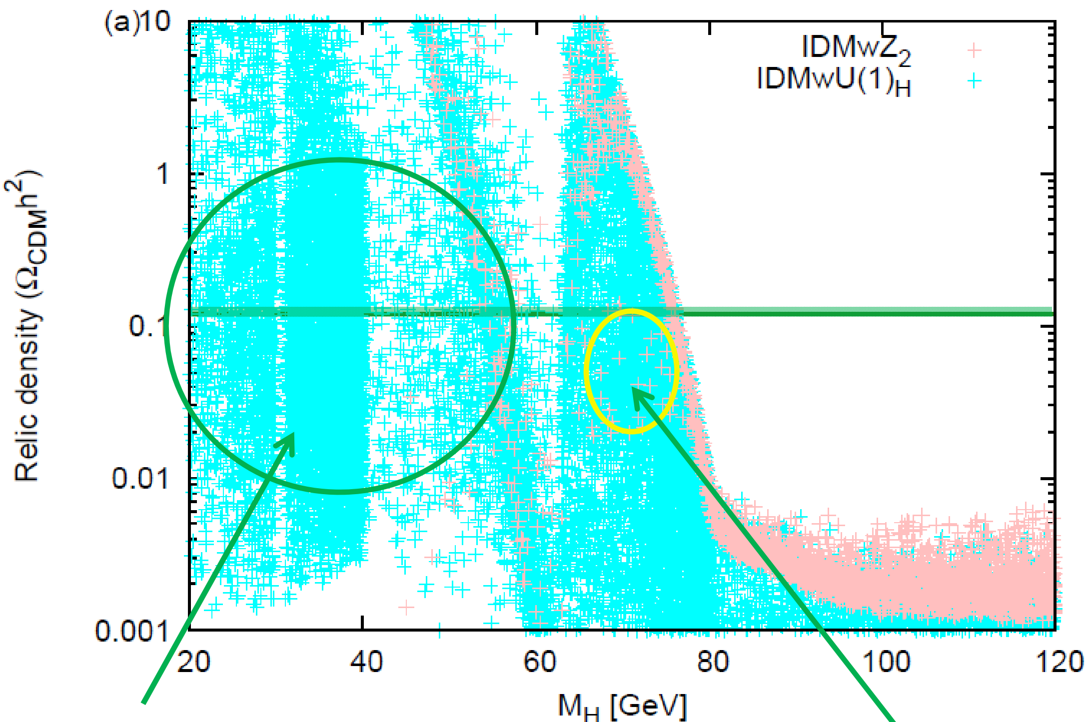


Relic density (low mass)

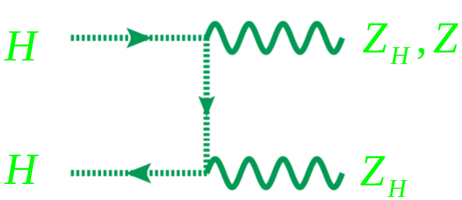
$$\Omega_{\text{CDM}} h^2 = 0.1199 \pm 0.0027$$

+ IDMwZ_2
+ IDMwU(1)_H

LUX bound is satisfied.



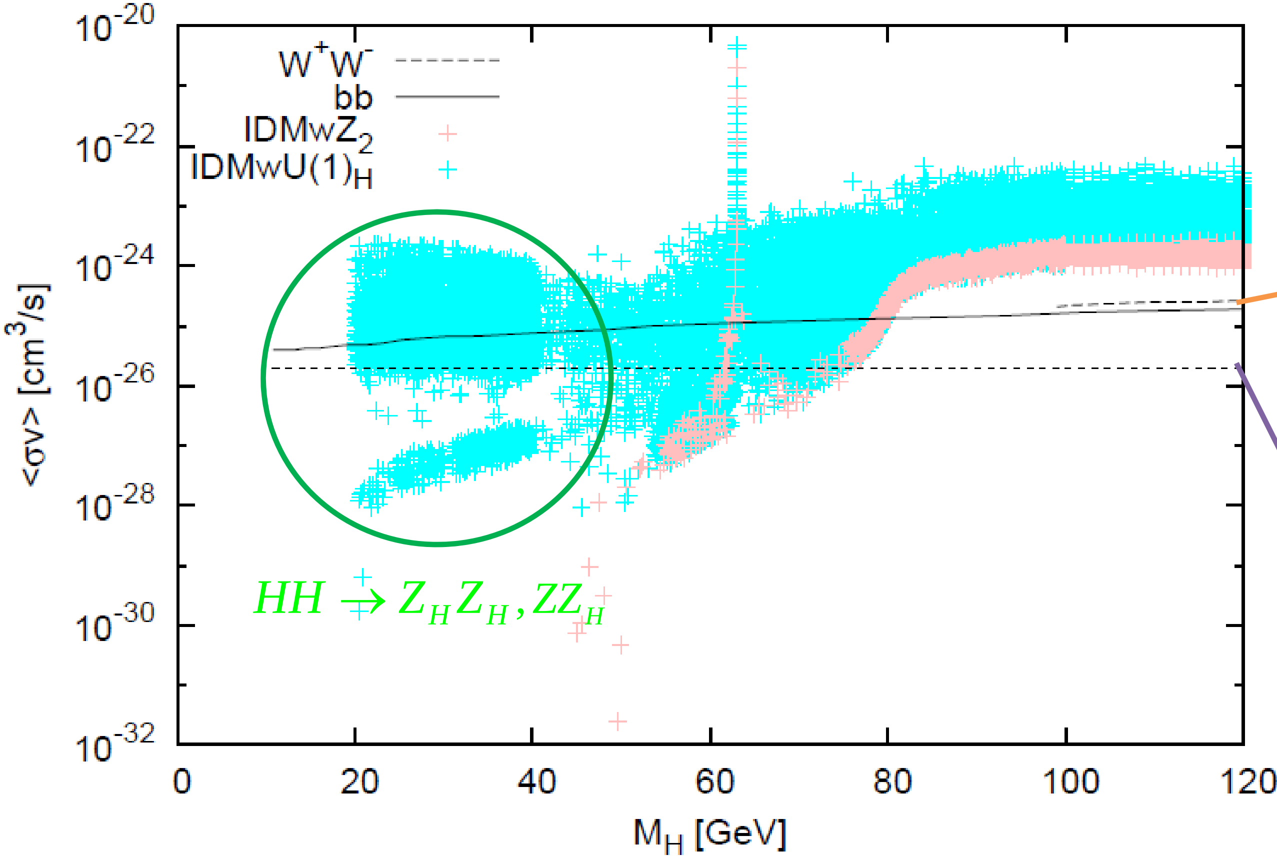
$$HH \to Z_H Z_H, ZZ_H$$



Co-annihilation $HA, HH^{\pm} \to \text{SM}+\text{SM}^{(\prime)}$

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

Indirect searches (low mass)



+ IDMwZ_2
+ IDMwU$(1)_H$

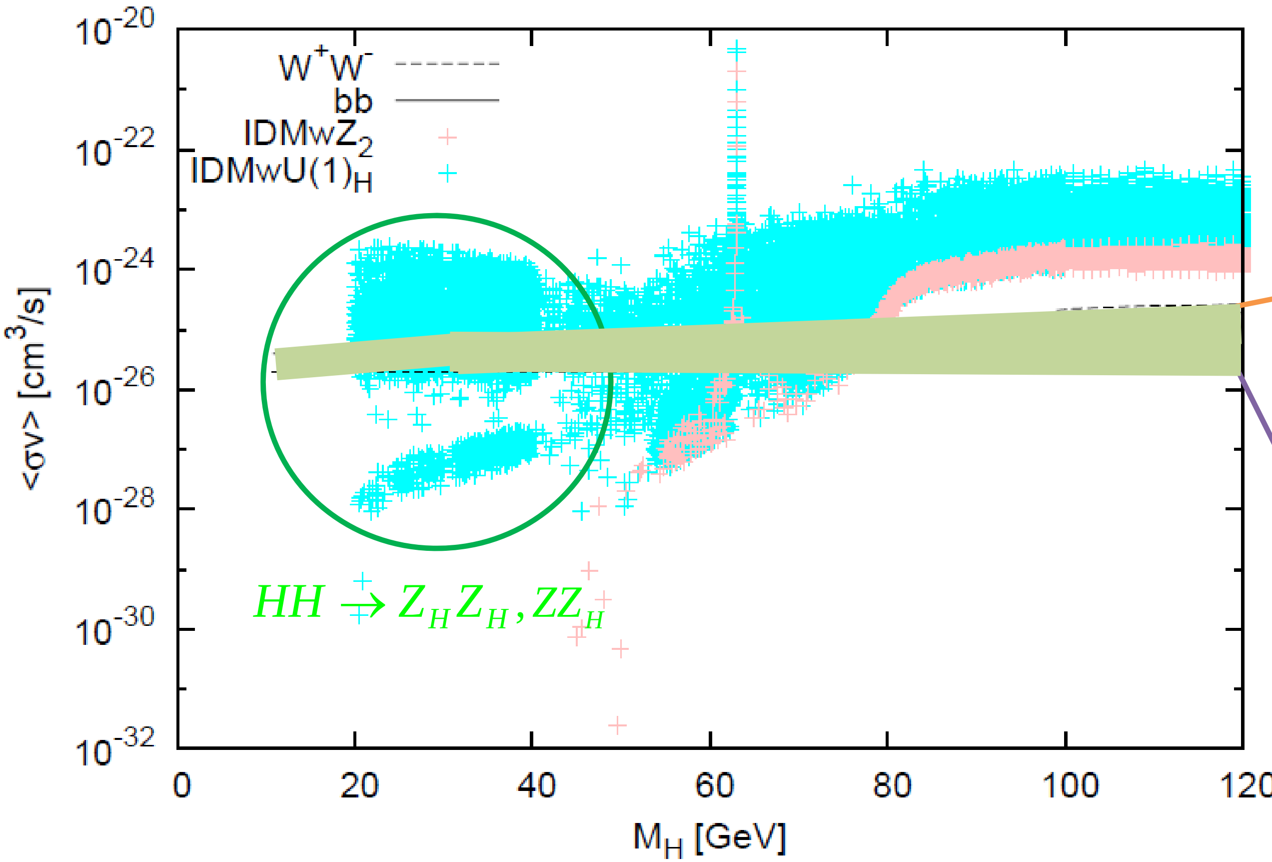
Constraints on the DM annihilation cross section from Fermi-LAT's analysis of 15 dwarf spheroidal galaxies.

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)



+ 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

- 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.

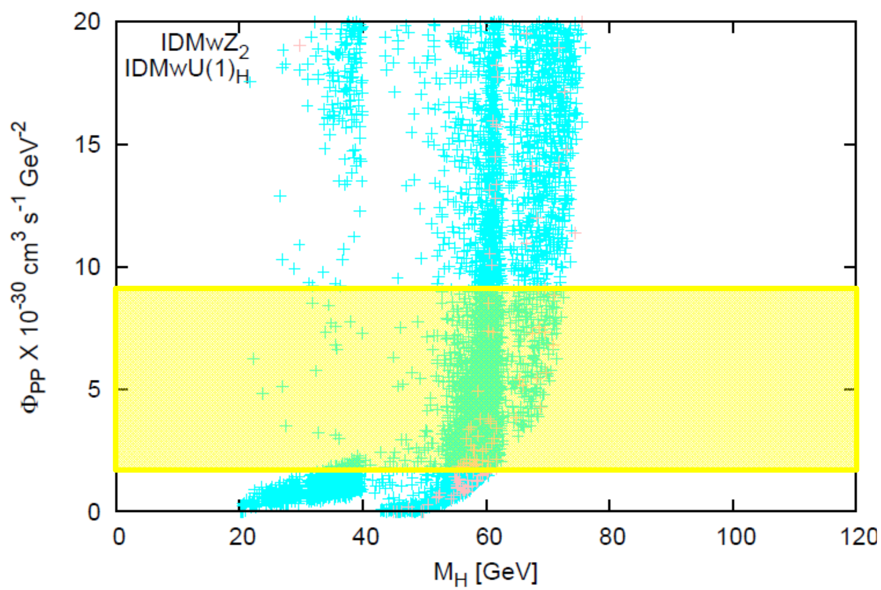
$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma}_{\Phi_{\rm PP}} \cdot \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(r)dl\right\}d\Omega'}_{\text{J-factor}} .$$

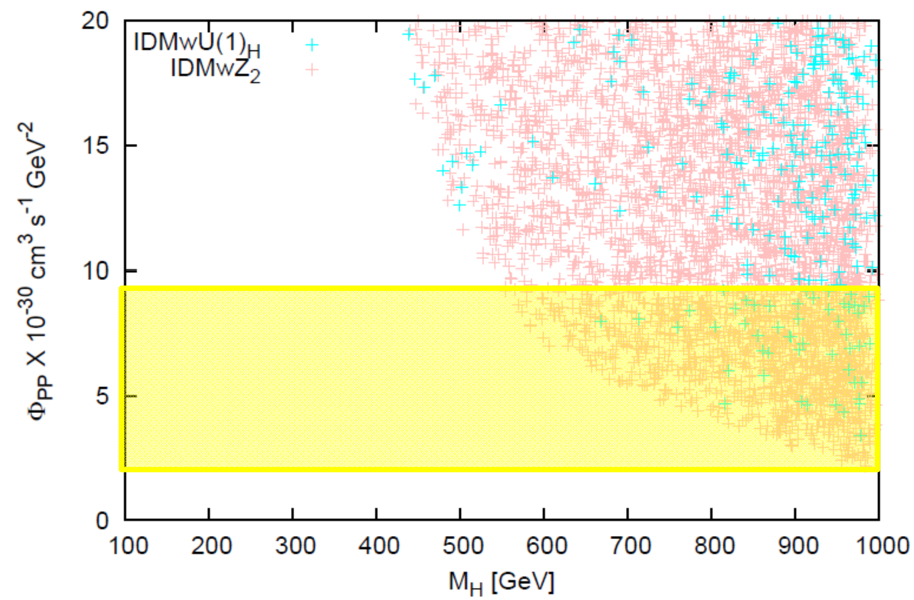
The final γ-ray spectrum.

contains information about the distribution of DM.

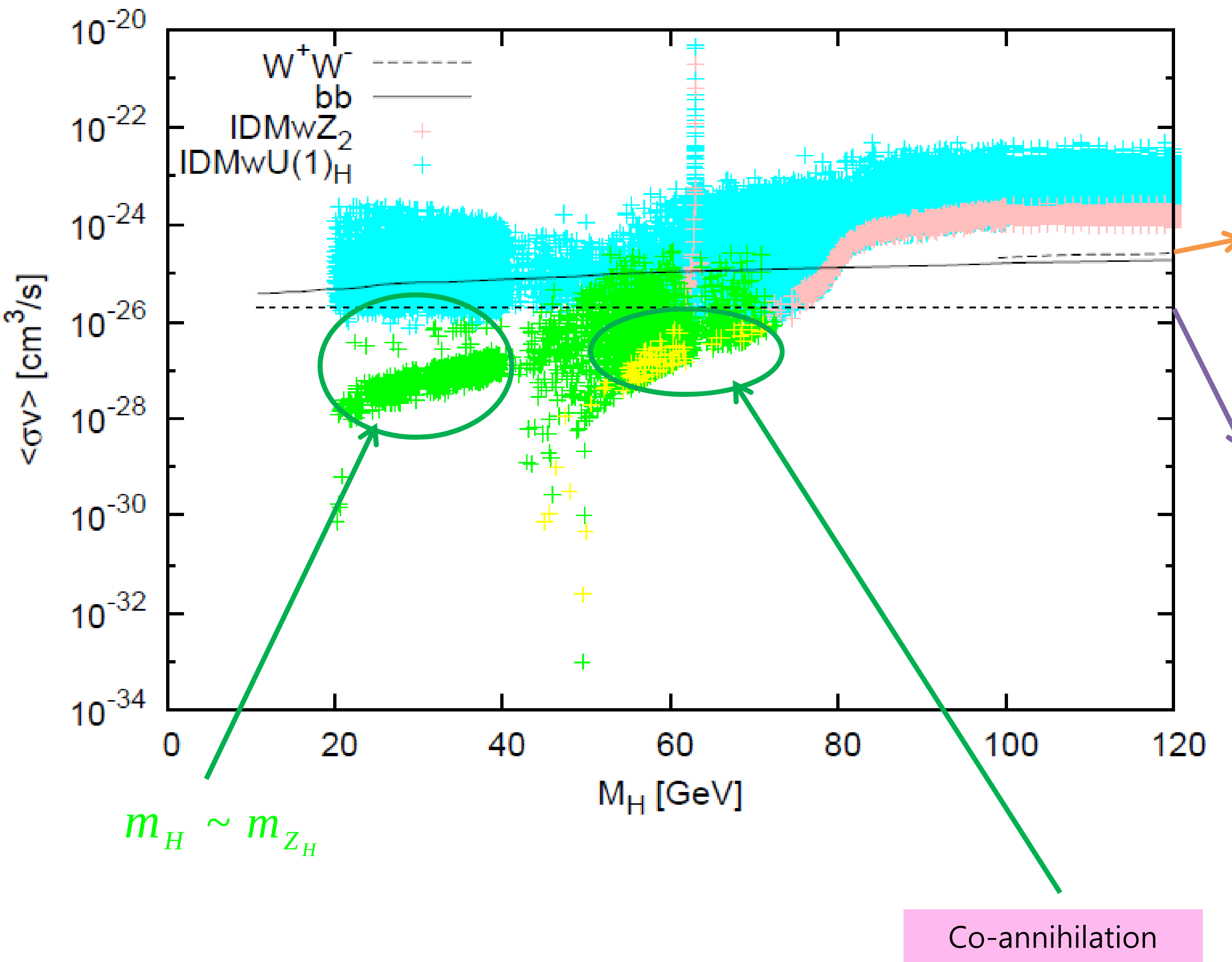
A 95% upper bound is $\Phi_{PP} = 5.0^{+4.3}_{-4.5}\times 10^{-30}\,\mathrm{cm^3 s^{-1} GeV^{-2}}$

Geringer-Sameth, Koushiappas, PRL107





Indirect searches (low mass)



+ $IDMwZ_2$
+ $IDMwU(1)_H$

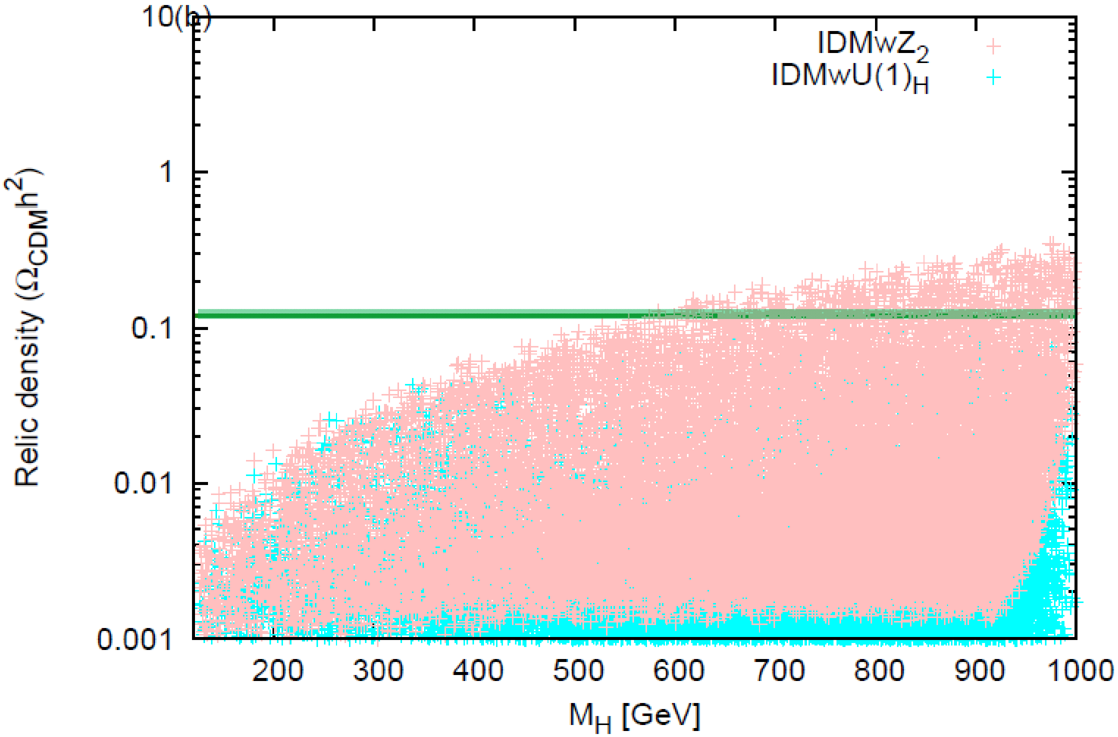
Constraints on the DM annihilation cross section from Fermi-LAT's analysis of 15 dwarf spheroidal galaxies.

Fermi-LAT,arXiv:1310.0828

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

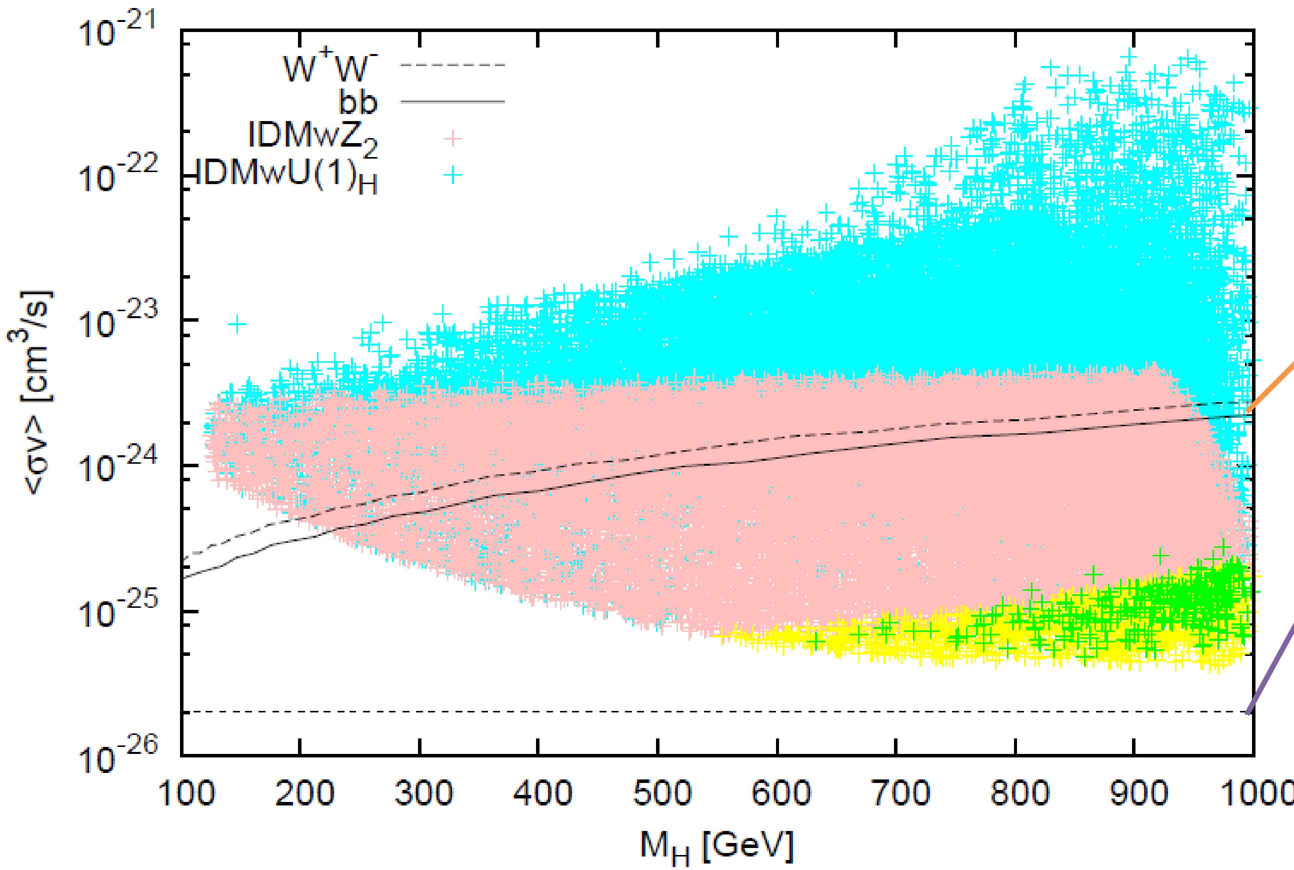
Relic density (high mass)

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



+ 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

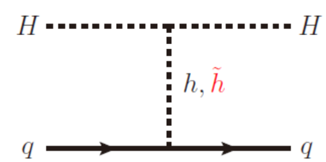
Constraint on the S-wave DM annihilation from the relic density observation

Benchmark points

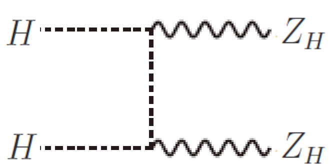
❑ L1

- dark matter mass $m_H = 38.6$ GeV
- Z_H mass $M_{Z_H} = 39.2$ GeV
- direct detection $\lambda_5 = -0.174$ $m_A = 110$ GeV

  $\sigma_{\rm SI} = 2.3 \times 10^{-46}$ cm^2

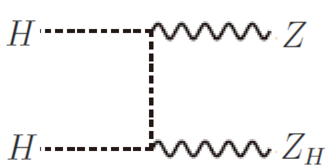


- relic density $\Omega h^2 = 0.113$

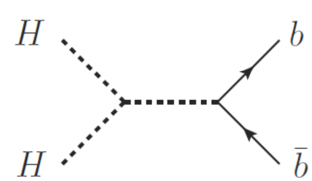


~ 100%

- annihilation cross section $\langle \sigma v \rangle_0 = 8.6 \times 10^{-28}$ cm^3/s



~ 98%



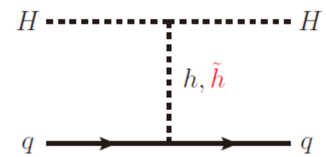
~ 2%

Benchmark points

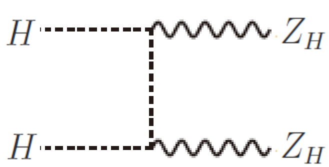
❑ L2

- dark matter mass $m_H = 53.8$ GeV
- Z_H mass $M_{Z_H} = 29.6$ GeV
- direct detection $\lambda_5 = -0.144$ $m_A = 108$ GeV

  $\sigma_{\rm SI} = 2.9 \times 10^{-46}$ cm^2



- relic density $\Omega h^2 = 0.117$



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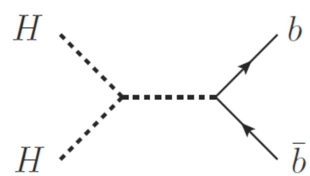
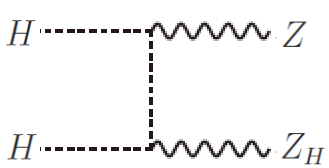
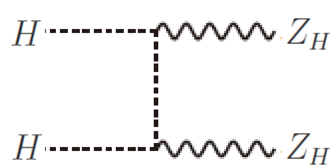


~ 34%

- annihilation cross section $\langle \sigma v \rangle_0 = 2.20 \times 10^{-26}$ cm^3/s



~ 52%



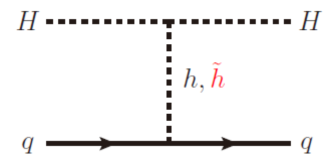
~ 45%

Benchmark points

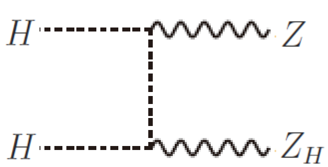
H1

- dark matter mass $m_H = 821$ GeV
- Z_H mass $M_{Z_H} = 985$ GeV
- direct detection $\lambda_5 = -0.164$ $m_A = 827$ GeV

  $\sigma_{\rm SI} = 6.1 \times 10^{-46}$ cm^2



- relic density $\Omega h^2 = 0.119$



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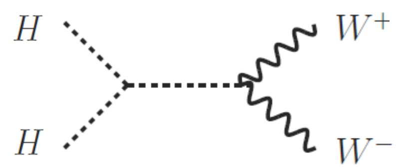
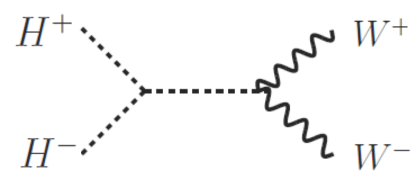
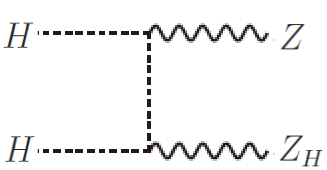


~ 10%



~ 9%

- annihilation cross section $\langle \sigma v \rangle_0 = 5.89 \times 10^{-26}$ cm^3/s



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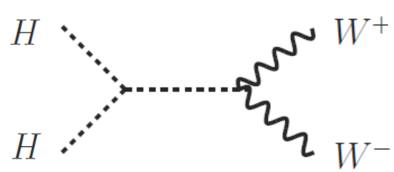

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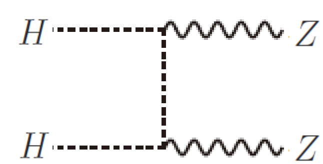
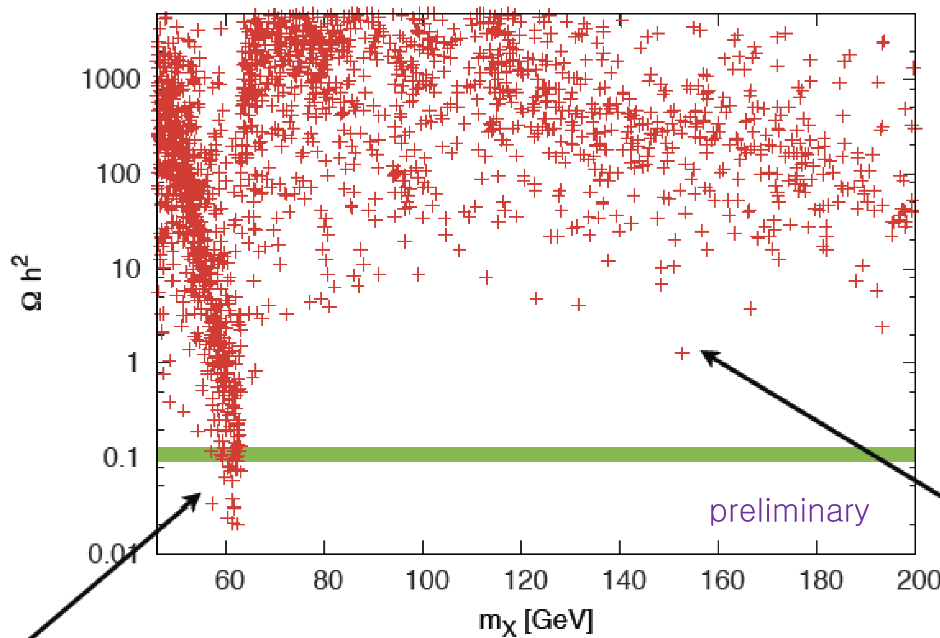


~ 23%

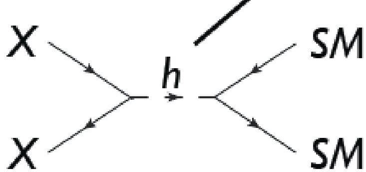
Relic density in Type-II



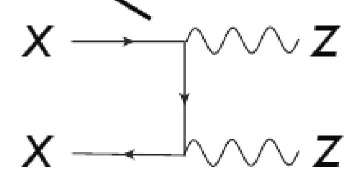
with the bounds on
EWPOs
$b \to s\gamma$
$B \to \tau\nu$
extra scalar search
extra fermion search

$pp \to l_{ex} l_{ex} \to ll + \text{missing}$

$m_{l_{ex}}, m_{q_{ex}} \gtrsim 1\text{TeV}$



very large Yukawa couplings required



work in progress

Conclusions

- 2HDM may be an effective theory of high-energy models 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 $U(1)_H$.

- A light CDM scenario can be possible in the Type-I IDMw$U(1)_H$.

- Type-II 2HDM with local U(1) symmetry is under study.

Mass and coupling of Z_H (type-II)

$v_1, v_2 \neq 0$