Two-Higgs-doublet models with gauged U(1) Higgs symmetry

Yuji Omura (TUM)

with P. Ko, C. Yu (KIAS) (arXiv: 1309.7156)

Introduction

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We can discuss interesting physics

Higgs physics (heavy, pseudoscalar, charged scalars predicted.)

dark matter physics (Inert-Doublet model(IDM))

experimental anomalies (top A_{FB} at Tevatron and $B \to D^{(*)}\tau\nu$ at BaBar)

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- One big issue of this simple extension is flavor physics

  → Higgs symmetry should assigned to distinguish the 2 Higgs doublets

• 2HDM with Gauged U(1) Higgs symmetry

(Ko, YO, Yu)

• spontaneous U(1) symmetry breaking realizes explicitly broken Z_2 symmetry commonly discussed. (Glashow, Weinberg)

• Some GUTs predict 2HDM with U(1) at low energy (ex) E_6 GUT)

• In SUSY, the non-decoupling D-term of $U(1)_H$ shifts the upper bound on Higgs mass.

(Batra,Delgado,Kaplan,Tait;Maloney,Pierce,Wacker;Craig,Katz;Liu,Wang; Athron,King,Miller,Moretti,Nevzorov,etc..)

• There are good dark matter candidates.
(Stability guaranteed by the remnant symmetry of U(1))

My talk

I introduce type-I and type-II 2HDMs with $U(1)_H$, and discuss phenomenology. (Type-II is inspired by E_6 GUT.)

- Setup of 2HDMs with gauged U(1) Higgs symmetry
- Theoretical and Experimental Constraints
- Higgs Physics
- Dark Matter Physics
- Summary

setup of 2HDMs
with gauged U(1) Higgs symmetry

Flavor problem in 2HDM

Simply add one Higgs

$$\overline{Q_L^i}(y^1_{dij}H_1 + y^2_{dij}H_2)D^j_R + \overline{Q_L^i}(y^1_{uij}\widetilde{H_1} + y^2_{uij}\widetilde{H_2})U^j_R$$

$$\xrightarrow{\text{mass matrix}} \quad m_i^d\delta_{ij} = (V_L^{d\dagger} y_d^1 V_R^d)_{ij}\langle H_1\rangle + (V_L^{d\dagger} y_d^2 V_R^d)_{ij}\langle H_2\rangle$$

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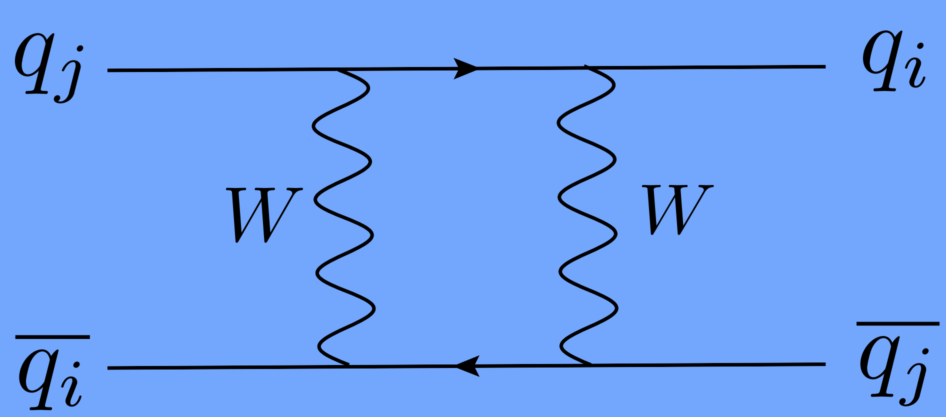
$\xrightarrow{\text{Yukawa coupling}}$ neutral higgs h coupling

$$H_1^0 = h\cos\alpha - H\sin\alpha,\ H_2^0 = h\sin\alpha + H\cos\alpha$$

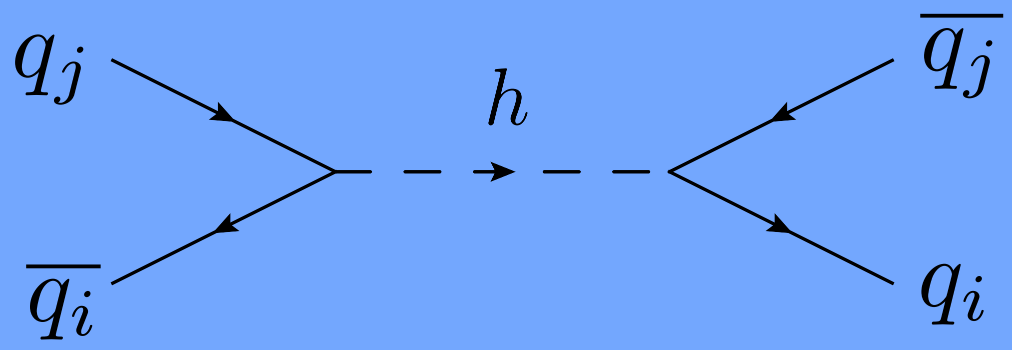
$$\boxed{\{(V_L^{d\dagger} y^1_d V^d_R)_{ij}\underline{\cos\alpha} + (V_L^{d\dagger} y^2_d V^d_R)_{ij}\underline{\sin\alpha}\}} h\overline{\hat{D}^i_L}\hat{D}^j_R$$

generally flavor changing couplings

SM model



with extra Higgs



$$\lambda^u_{ij}\overline{u^i_L}u^j_R h + \lambda^d_{ij}\overline{d^i_L}d^j_R h$$

ex) $K_0 - \overline{K_0}$ mixing

$$10^{-6} \gtrsim |\lambda^d_{12}|^2 \left(\frac{1TeV}{m_h}\right)^2$$

By Blum, Grossman, Nir, Perez

- Higgs symmetry solves the flavor problem

minimal flavor violation

If one sector couples with only one Higgs

Type II : $y^U_{ij}\overline{Q_{Li}}\widetilde{H}_2 U_{Rj} + y^D_{ij}\overline{Q_{Li}}H_1 D_{Rj} + y^E_{ij}\overline{L_i}H_1 E_{Rj} + y^N_{ij}\overline{L_i}\widetilde{H}_2 N_{Rj}.$

diagonal Yukawa of neutral scalars
flavor-changing Yukawa of charged Higgs suppressed by CKM

$\longrightarrow$ *symmetry should be assigned to Higgs and SM fermions*

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→ *symmetry should be assigned to Higgs and SM fermions*

well-known symmetry is Z_2 symmetry (Glashow, Weinberg)

$$Z_2 : (H_1, H_2) \to (+H_1, -H_2) \quad (U_{Rj}, D_{Rj}) \to (-U_{Rj}, D_{Rj})$$

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I consider gauged U(1) symmetry, which may be the origin of the Z2 symmetry

$$U(1)_H : (H_1, H_2, \underbrace{\psi_f}_{\text{SM fermions}}) \to (e^{iq_{H_1}\theta} H_1, e^{iq_{H_2}\theta} H_2, e^{iq_f\theta} \psi_f)$$

(Ko, YO, Yu)

- Scalars in 2HDM

eaten by W, and 1 charged Higgs pair

$$H_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1}{\sqrt{2}} + \frac{1}{\sqrt{2}}(h_1 + i\chi_1) \end{pmatrix}, H_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2}{\sqrt{2}} + \frac{1}{\sqrt{2}}(h_2 + i\chi_2) \end{pmatrix}$$

2 CP-even scalars

eaten by Z, and 1pseudo scalar in Z2 2HDM

8 scalars =2(eaten by W+/-)+1(eaten by Z)+2(CP-even)+1(CP-odd)+1 charged Higgs pair

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U(1)$_H$ extension

$\boxed{\text{both are eaten by Z and U(1)}_H \text{ gauge boson (Z}_H)}$

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but ρ-para. requires very small Z_H mass......

- <u>Scalars in 2HDM</u>

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U(1)H extension

$\boxed{\text{both are eaten by Z and U(1)H gauge boson (ZH)}}$

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but ρ-para. requires very small ZH mass......

Let me introduce a U(1)H-charged SM singlet (Φ)

10 scalars =2(eaten by W+/-)+2(eaten by Z,ZH)+3(CP-even)+1(CP-odd)+1 charged Higgs pair

→ 3 CP-even, 1 (heavy) pseudoscalar, 1 charged Higgs pair, and 1 extra gauge boson (ZH).

- <u>Scalar masses</u>

$$H_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i}{\sqrt{2}} + \frac{1}{\sqrt{2}}(h_i + i\chi_i) \end{pmatrix}, \quad \Phi = \frac{1}{\sqrt{2}}(v_\Phi + h_\Phi + i\chi_\Phi).$$

10 scalars =2(eaten by W+/-)+2(eaten by Z,Z_H)+3(CP-even)+1(CP-odd)+1 charged Higgs pair

3 CP-even Higgs

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

$$m_h^2 + m_H^2 - m_A^2 > 0$$ in 2HDM wo λ_5

no valid in 2HDM with U(1)

- <u>Scalar masses</u>

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$$m_h^2 + m_H^2 - m_A^2 > 0$$ in 2HDM wo λ_5

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1 charged Higgs pair

$$\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} = \begin{pmatrix} \cos\beta \\ \sin\beta \end{pmatrix} G^+ + \begin{pmatrix} -\sin\beta \\ \cos\beta \end{pmatrix} H^+$$

$$m_{H^+}^2 = \frac{\mu\langle\Phi\rangle}{\cos\beta\sin\beta} - \lambda_4\frac{v^2}{2}$$

CP-odd scalars (2 Goldstone bosons+1 pseudoscalar)

$$\left(\langle\Phi\rangle = \frac{v_\Phi}{\sqrt{2}}\right)$$

$$\begin{pmatrix}\chi_\Phi\\ \chi_1\\ \chi_2\end{pmatrix} = \begin{pmatrix}0\\ \cos\beta\\ \sin\beta\end{pmatrix} G_1 + \frac{v_\Phi}{\sqrt{v_\Phi^2 + (v\cos\beta\sin\beta)^2}} \begin{pmatrix}1\\ \frac{v}{v_\Phi}\cos\beta\sin^2\beta\\ -\frac{v}{v_\Phi}\cos^2\beta\sin\beta\end{pmatrix} G_2$$

$$+\frac{v_\Phi}{\sqrt{v_\Phi^2 + (v\cos\beta\sin\beta)^2}} \begin{pmatrix}\frac{v}{v_\Phi}\cos\beta\sin\beta\\ -\sin\beta\\ \cos\beta\end{pmatrix} A$$

pseudoscalar(A) mass

$$m_A^2 = \frac{\mu\langle\Phi\rangle}{\cos\beta\sin\beta}\left(1 + \frac{v^2}{v_\Phi^2}\cos^2\beta\sin^2\beta\right)$$

2 Goldstone bosons (G_1,G_2)

eaten by Z and Z_H

Interesting limits

$v_\Phi \to \infty$: like broken Z_2 symmetric 2HDM

$v_\Phi \to 0$: $m_A \to \infty$. Effectively no-pseudoscalar(A) model

gauge bosons

$$\mathcal{L}_H = \sum_{i=1}^{2} \left| \left(D_\mu^{SM} - i g_H q_{Hi} \hat{Z}_{H\mu} \right) H_i \right|^2 + \left| \left(\partial_\mu - i g_H q_\Phi \hat{Z}_{H\mu} \right) \Phi \right|^2$$

Mass matrix for Z and ZH boson

$$\begin{pmatrix} \hat{M}_Z^2 & \Delta M_{ZZ_H}^2 \\ \Delta M_{ZZ_H}^2 & \hat{M}_{Z_H}^2 \end{pmatrix}$$

$$\hat{M}_Z^2 = \frac{g^2 + g'^2}{4} v^2 = \frac{g_Z^2}{4} v^2, \;\; \hat{M}_{Z_H}^2 = g_H^2 \left\{ \sum_{i=1}^{2} (q_{H_i} v_i)^2 + q_\Phi^2 v_\Phi^2 \right\}$$

$$\Delta M_{ZZ_H}^2 = -\frac{\hat{M}_Z}{v} g_H \sum_{i=1}^{2} q_{H_i} v_i^2$$

Generally Z and ZH mix

ρ-para. strongly constraints the mixing $(\rho_{\rm SM} = 1)$

$$\frac{M_W^2}{M_Z^2 c_W^2} = \rho = 1 + \frac{\Delta M_{ZZ_H}^2}{M_{Z0}^2} \xi + O(\xi^2) \qquad \left(\tan 2\xi = \frac{2\Delta M_{ZZ_H}^2}{\hat{M}_{Z_H}^2 - \hat{M}_Z^2} \right)$$

(We will be back in the next section)

- <u>charge assignments and extra matters for anomaly</u>

<u>Type-I 2HDM</u>

$$y_{ij}^U \overline{Q_{Li}} \widetilde{H_2} U_{Rj} + y_{ij}^D \overline{Q_{Li}} H_2 D_{Rj} + y_{ij}^E \overline{L_i} H_2 E_{Rj} + y_{ij}^N \overline{L_i} \widetilde{H_2} N_{Rj}.$$

H_1 does not couple with SM fermions.

We can discuss the anomaly-free charge assignments without extra fermions.

Type	U_R	D_R	Q_L	L	E_R	N_R	H_2
$U(1)_H$ charge	u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$q_{H_2} = \frac{(u-d)}{2}$
$q_{H_1} \neq 0$	0	0	0	0	0	0	0
$U(1)_{B-L}$	$1/3$	$1/3$	$1/3$	-1	-1	-1	0
$U(1)_R$	1	-1	0	0	-1	1	1
$U(1)_Y$	$2/3$	$-1/3$	$1/6$	$-1/2$	-1	0	$1/2$

Interesting physics is dark matter.

Inert-doublet model (IDM)
(stability of $(H_1)_0$ guaranteed by $U(1)_H$)

mainly I talk about
fermiophobic Z_H

Type-II 2HDM

$$y^U_{ij}\overline{Q_{Li}}\widetilde{H_2}U_{Rj} + y^D_{ij}\overline{Q_{Li}}H_1 D_{Rj} + y^E_{ij}\overline{L_i}H_1 E_{Rj} + y^N_{ij}\overline{L_i}\widetilde{H_2}N_{Rj}.$$

-1 0 0 -1

require extra chiral fermions

type-II 2HDM with U(1) inspired by E6 GUT

(Lodon, Rosner)

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

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
Q^i_L	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

Extra fermions (required by the anomaly-free conditions)

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
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

Mass terms in Type-II 2HDM inspired by E6

Φ for $U(1)_H$ breaking and masses of extra fermions

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

U(1)H×U(1)ψ×U(1)χ symmetric potential

$$y^q_{ij}\Phi\overline{q_L}^i q^j_R + y^l_{ij}\Phi\overline{l_L}^i l^j_R + y^n_{ij}\overline{n_L}^i H_1^T l^j_R + y'^n_{ij}\overline{l_L}^i \widetilde{H}_2 n^{cj}_L + h.c.$$

$\langle\Phi\rangle \neq 0$ induces the masses of the extra

extra neutral particles $l_I^T = (\widetilde{\nu}_I, \widetilde{e}_I)^T \; (I = L, R)$

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

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

lightest one is dark matter.

the remnant symmetry

$U(1)_\psi \to Z_2^\psi$ by Φ, H_i

Comment on SUSY extension

- SUSY version of 2HDM inspired by E6

scalar fermion	$\begin{pmatrix} \sigma_2 H_1^* \\ l_{Li} \end{pmatrix}$	$\begin{pmatrix} \sigma_2 H_2^* \\ l_{Ri} \end{pmatrix}$	$\begin{pmatrix} \Phi^* \\ n_{Li} \end{pmatrix}$

pairs with same quantum number

$\Big\downarrow$ adding extra Higgs doublets and Φ

chiral superfield	$\hat{H}_1^i$	$\hat{H}_2^{i\dagger}$	$\hat{\Phi}^i$

mass terms in non-SUSY

$$y_{ij}^l \Phi \overline{l_L}^i l_R^j + y_{ij}^n \overline{n_L}^i H_1^T l_R^j + y_{ij}'^n \overline{l_L}^i \widetilde{H}_2 n_L^{cj} + h.c.$$

$\Big\downarrow$

superpotential

$$W = c_{ijk} \hat{H}_1^i \hat{H}_2^j \hat{\Phi}^k \xrightarrow{\text{GUT}} \text{all particles come from 27 rep. in E6.}$$

There would be many problems in flavor physics, etc.
I do not consider the constraints from this SUSY embedding.

Theoretical and Experimental Constraints

parameters in 2HDM with Z2 (and without λ5)

$$m_h, m_H, m_A, m_{H^+}, \tan\beta, \sin(\beta-\alpha)$$

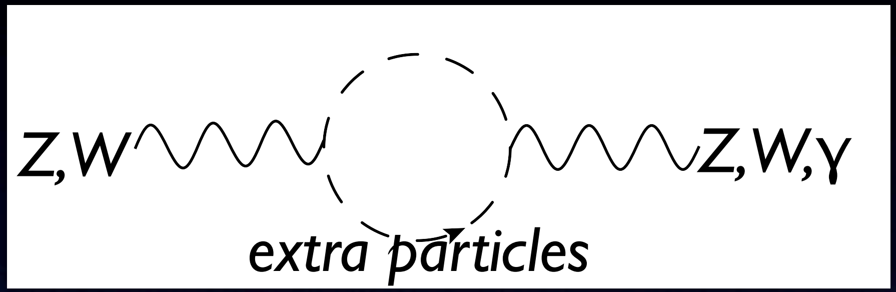
experimental and theoretical constraints

$m_h \sim 126\text{GeV}$

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

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

$\sin(\beta-\alpha)$



EWPOs(S,T,U para.)

small mass differences required

$$\alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$\tan\beta$

m_{H^+}

m_H

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$\sin(\beta-\alpha)$

$\tan\beta$

m_{H+}

m_H

EWPOs(S,T,U para.)

small mass differences required

mass relations

$$m_h^2 + m_H^2 - m_A^2 > 0 \, , m_{H+}^2 - m_A^2 = -\lambda_4 \frac{v^2}{2}$$

perturbativity
vacuum stability
unitarity

Theoretical constraints

(Ko, YO, Yu)

- vacuum stability (to avoid unbounded-from-below)

$$\lambda_1 > 0,\ \lambda_2 > 0,\ \lambda_3 > -\sqrt{\lambda_1\lambda_2},\ \lambda_3 + \lambda_4 > -\sqrt{\lambda_1\lambda_2}$$

$$\lambda_\Phi > 0,\ \lambda_1 > \frac{\widetilde{\lambda_1}^2}{\lambda_\Phi},\ \lambda_2 > \frac{\widetilde{\lambda_2}^2}{\lambda_\Phi},\ \lambda_3 - \frac{\widetilde{\lambda_1}\widetilde{\lambda_2}}{\lambda_\Phi} > -\sqrt{\left(\lambda_1 - \frac{\widetilde{\lambda_1}^2}{\lambda_\Phi}\right)\left(\lambda_2 - \frac{\widetilde{\lambda_2}^2}{\lambda_\Phi}\right)},$$

$$\lambda_3 + \lambda_4 - \frac{\widetilde{\lambda_1}\widetilde{\lambda_2}}{\lambda_\Phi} > -\sqrt{\left(\lambda_1 - \frac{\widetilde{\lambda_1}^2}{\lambda_\Phi}\right)\left(\lambda_2 - \frac{\widetilde{\lambda_2}^2}{\lambda_\Phi}\right)}$$

- unitarity bound

Higgs-Higgs scattering amplitudes give the upper bounds on the quartic couplings.

kanemura, kasai, Y. Okada; Akeroyd, Arhrib, Naimi; Ginzburg, Ivanov

ex) $V_{\rm SM} = \frac{\lambda}{2}|H|^4 \ \rightarrow\ \lambda < 8\pi$ in SM

parameters in 2HDM with Z2 (and without λ5)

$$m_h, m_H, m_A, m_{H^+}, \tan\beta, \sin(\beta-\alpha)$$

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^+}

m_H

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EWPOs(S,T,U para.)

small mass differences required

mass relations

$$m_h^2 + m_H^2 - m_A^2 > 0\ ,\ m_{H+}^2 - m_A^2 = -\lambda_4 \frac{v^2}{2}$$

perturbativity
vacuum stability
unitarity

$\tan\beta$

m_{H+}

exotic top decay
b→sγ, B→τν
lower bound from LEP
$m_{H+} \gtrsim 90\text{GeV}$

m_H

$\tan\beta\ (\text{type}-\text{II})$

$1/\tan\beta\ (\text{type}-\text{I})$

parameters in 2HDM with Z2 (and without λ5)

$$m_h, m_H, m_A, m_{H+}, \tan\beta, \sin(\beta-\alpha)$$

experimental and theoretical constraints

$m_h \sim 126\mathrm{GeV}$

$|m_{H+} - m_A|$

$|m_{H+} - m_H|$

$\sin(\beta-\alpha)$

EWPOs(S,T,U para.)

small mass differences required

mass relations

$$m_h^2 + m_H^2 - m_A^2 > 0 \; , m_{H+}^2 - m_A^2 = -\lambda_4 \frac{v^2}{2}$$

perturbativity
vacuum stability
unitarity

$\tan\beta$

m_{H+}

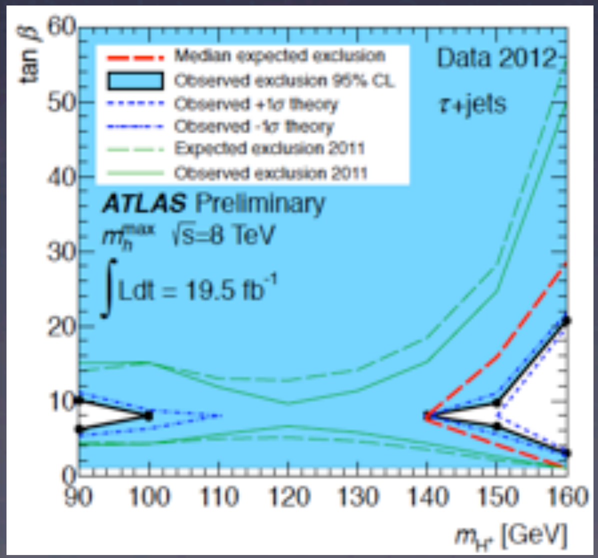
exotic top decay
b→sγ, B→τν
lower bound from LEP
$m_{H+} \gtrsim 90\mathrm{GeV}$

m_H

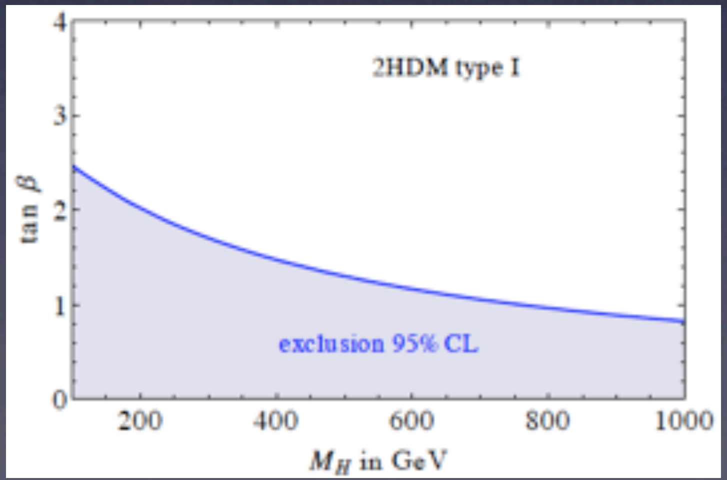
$\tan\beta \; (\mathrm{type-II})$

$1/\tan\beta \; (\mathrm{type-I})$

t->H+b (ATLAS)



b->s γ (Hermann,Misiak,Steinhauser)



type-II

$m_{H+} \gtrsim 360\mathrm{GeV}$

parameters in 2HDM with Z_2 (and without λ_5)

$$m_h, m_H, m_A, m_{H^+}, \tan\beta, \sin(\beta-\alpha)$$

experimental and theoretical constraints

$m_h \sim 126\text{GeV}$

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

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

$\sin(\beta-\alpha)$

EWPOs(S,T,U para.)

small mass differences required

mass relations

$$m_h^2 + m_H^2 - m_A^2 > 0\ ,\ m_{H^+}^2 - m_A^2 = -\lambda_4 \frac{v^2}{2}$$

perturbativity

vacuum stability

unitarity

$\tan\beta$

m_{H^+}

exotic top decay

b→sγ, B→τν

lower bound from LEP

$m_{H^+} \gtrsim 90\text{GeV}$

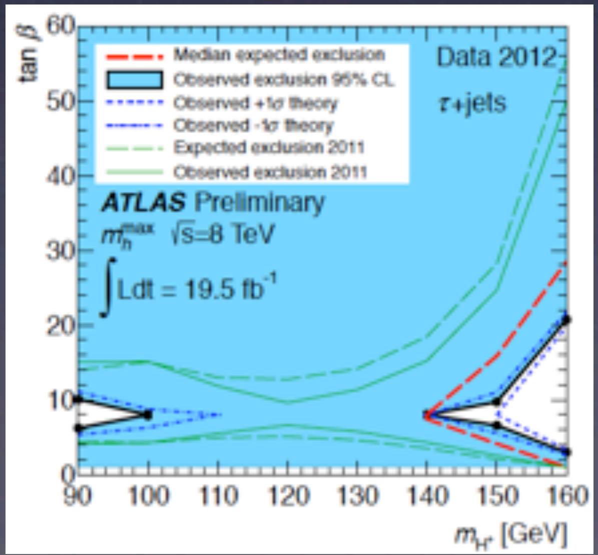
SM-like Higgs will constrain

m_H

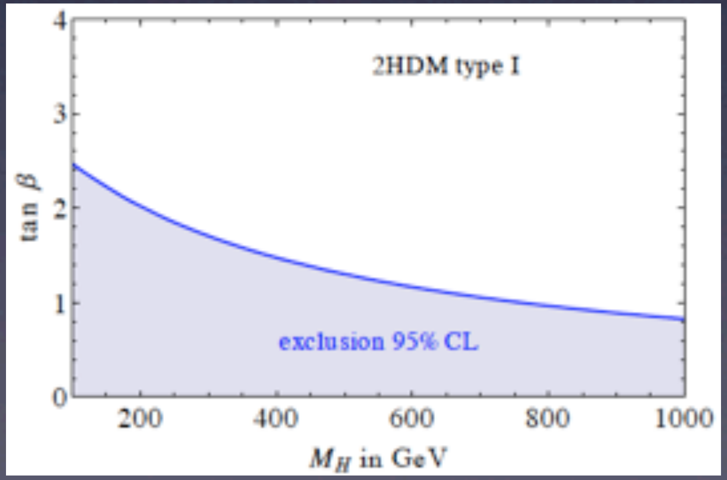
Next section

heavy Higgs search should be included

t->H+b (ATLAS)



b->s γ (Hermann,Misiak,Steinhauser)



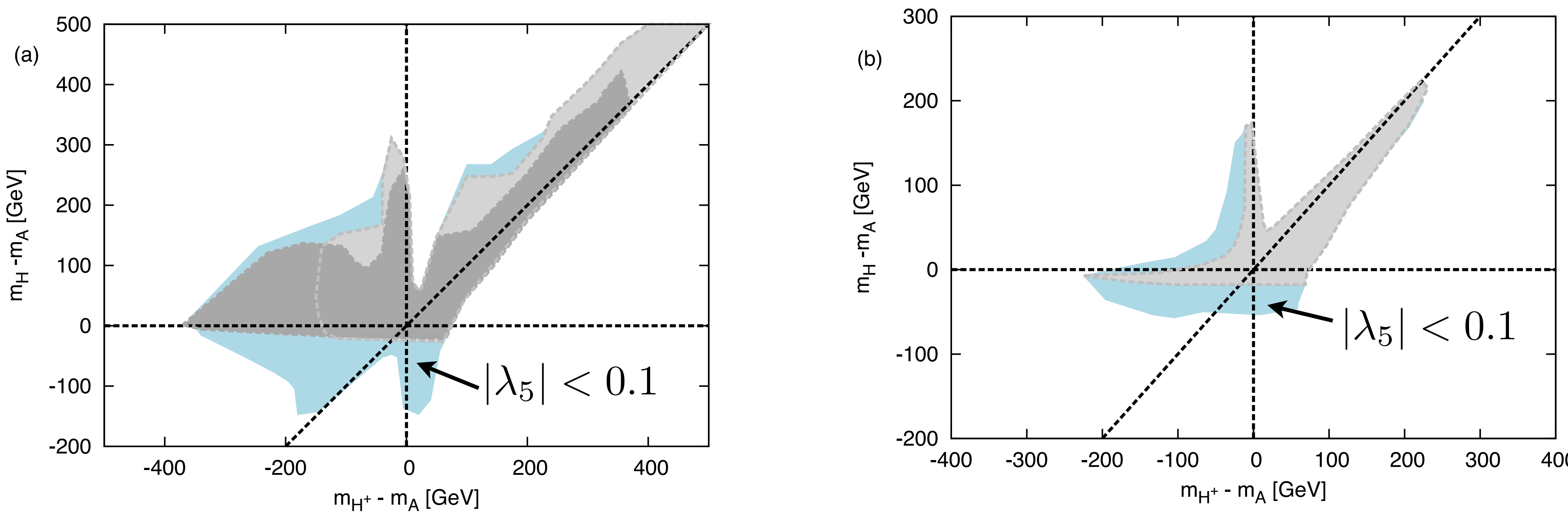
type-II

$m_{H^+} \gtrsim 360\text{GeV}$

allowed region(90CL) in (type-I) 2HDM with Z_2

(Ko, YO, Yu)

$S = 0.03 \pm 0.10,\ T = 0.05 \pm 0.12,\ U = 0.03 \pm 0.10$ (Baak,Kogler)
with $+0.89_{ST}, -0.54_{SU}, -0.83_{TU}$

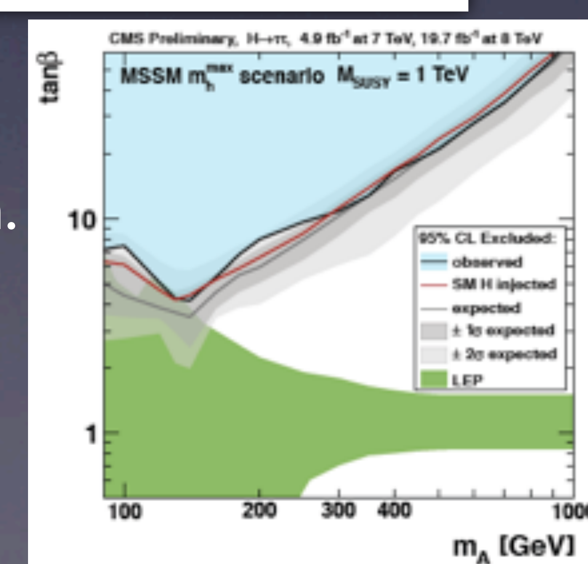


gray: $700\text{GeV} \geq m_A > 300\text{GeV}$
light gray: $300\text{GeV} \geq m_A > 126\text{GeV}$

light gray: $m_A > 700\text{GeV}$

Still large allowed region. (One mass difference can be large.)

In the type-II (like MSSM), b→sγ and pseudoscalar search strongly constrain.



parameters in 2HDM with U(1)

$$m_h, m_H, m_A, m_{H^+}, \tan\beta, \sin(\beta-\alpha)\quad , \sin(\alpha_1), \sin(\alpha_2), g_H, M_{Z_H}$$

additional parameters contribute to EWPOs, and theoretical constraints

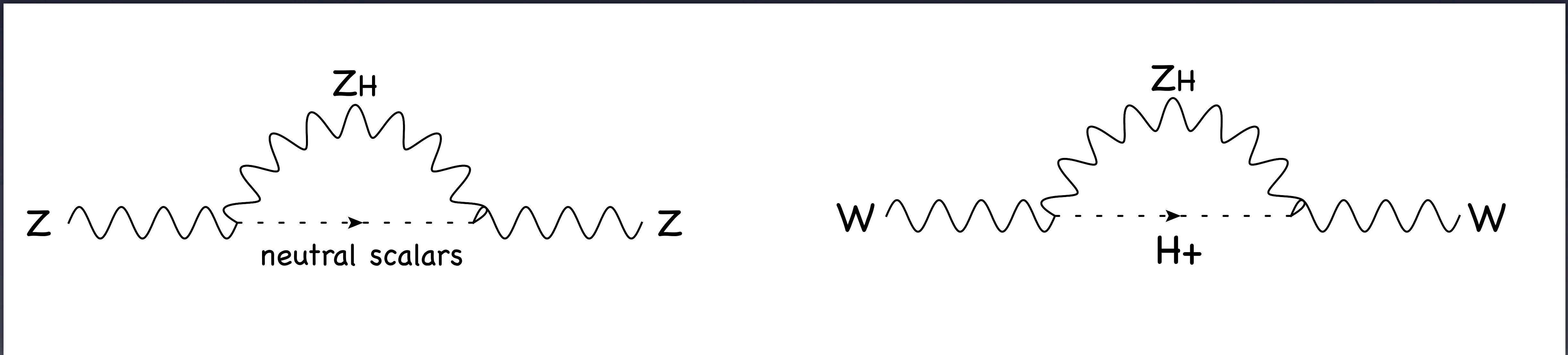
<u>tree-level</u>

$$\frac{M_W^2}{M_Z^2 c_W^2} = \rho = 1 + \boxed{\frac{\Delta M_{ZZ_H}^2}{M_{Z0}^2}\xi + O(\xi^2)} \qquad \left(\tan 2\xi = \frac{2\Delta M_{ZZ_H}^2}{\hat{M}_{Z_H}^2 - \hat{M}_Z^2}\right)$$

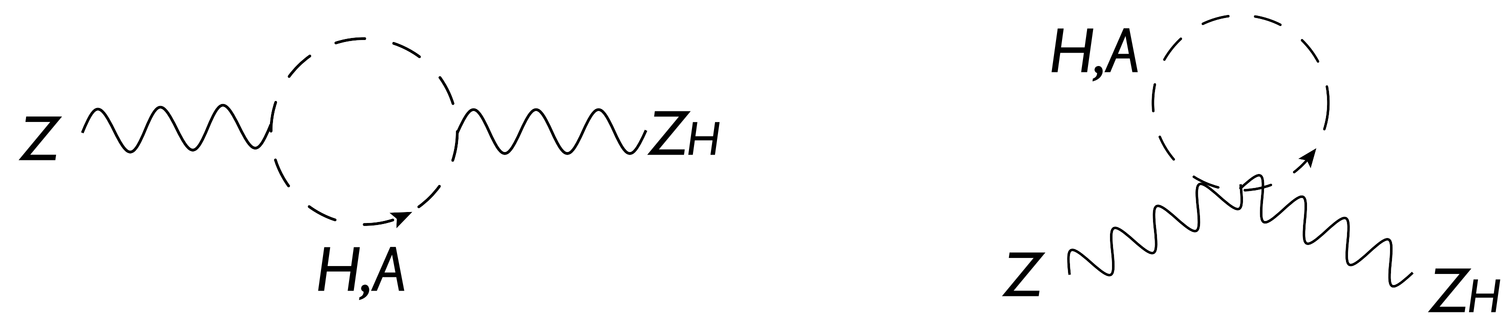
should be small

$$(\rho_{\rm SM} = 1.01051 \pm 0.00011)$$

<u>extra one-level corrections involving ZH</u>



Z-ZH mixing at one-loop level (in the limit, $\cos\beta \to 0$ (IDM limit))



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

$$\langle H_1 \rangle = \frac{v}{\sqrt{2}}\cos\beta$$

H_1 only charged under U(1)H

kinetic mixing U(1)Y×U(1)H (required for renormalization)

$$-\frac{\kappa(\mu)}{2}F_Y^{\mu\nu}F_{H\mu\nu} \to -\frac{\kappa_Z}{2}F_Z^{\mu\nu}F_{H\mu\nu} - \frac{\kappa_\gamma}{2}F_\gamma^{\mu\nu}F_{H\mu\nu}$$

Even if we assume U(1)Y×U(1)H kinetic mixing is negligible at Mw, the mixing appears because of

SU(2)L×U(1)Y breaking effects (mass differences)

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

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

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

degenerate masses make them disappear

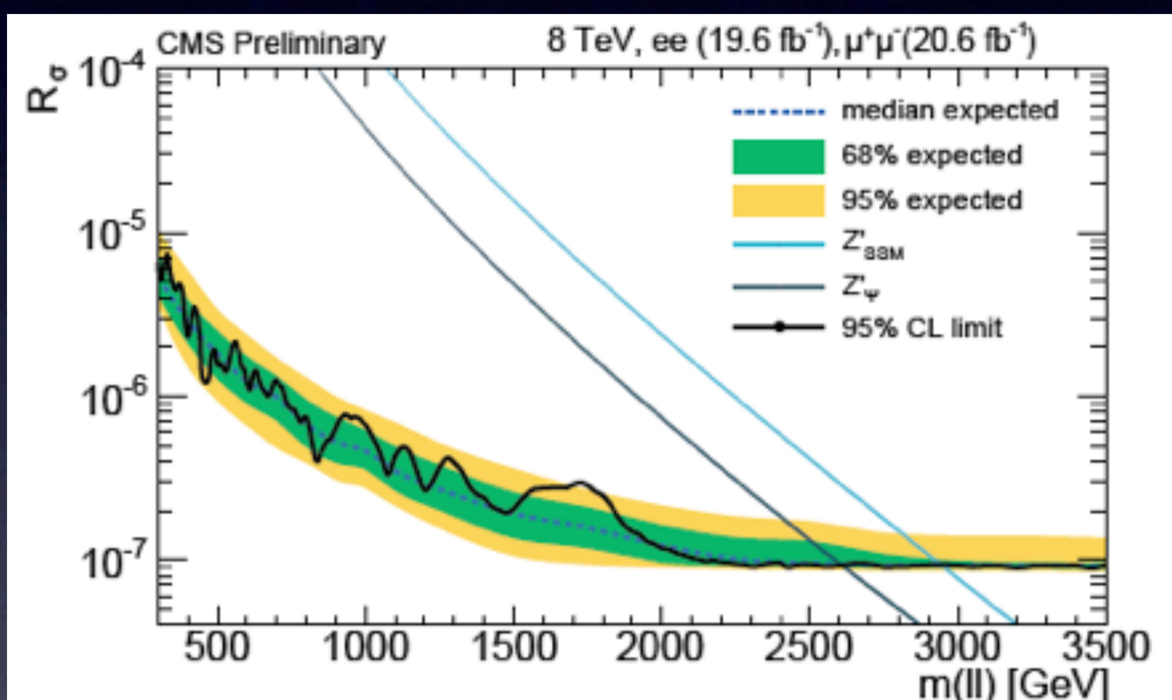
- Z’ search

Collider bound depends on the charge assignment

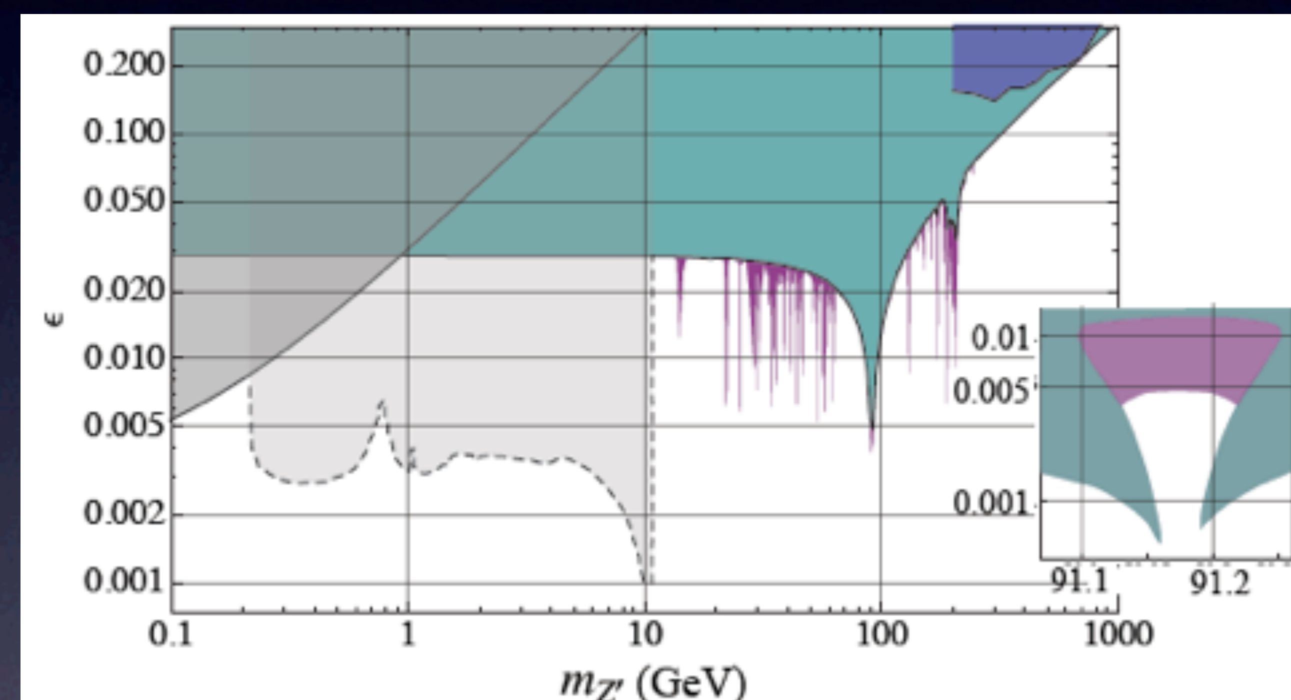
<u>fermiophobic Z_H case (SM fermions not charged)</u>

Through the Z-Z_H mixing, Z_H is produced at the collider

resonance search (CMS,25.2.2013)



Bound on U(1)Y×U(1)’ kinetic mixing (Hook,Izaguirre,Wacker)

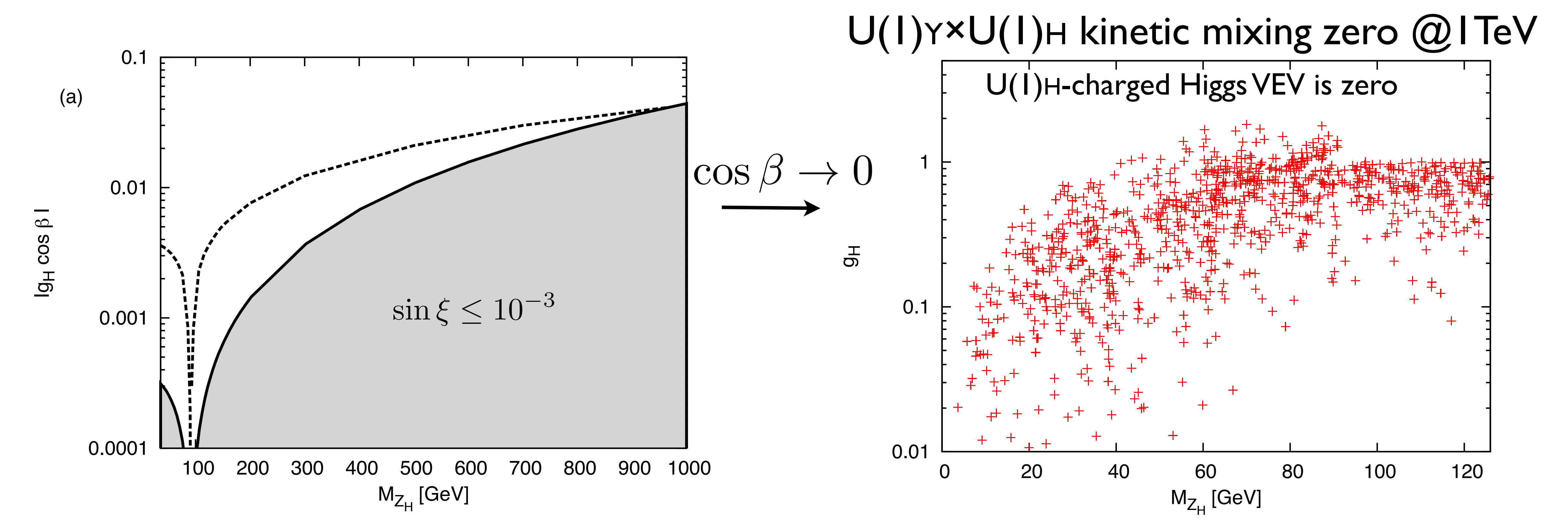


<u>bound on Z-Z_H mixing</u>

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

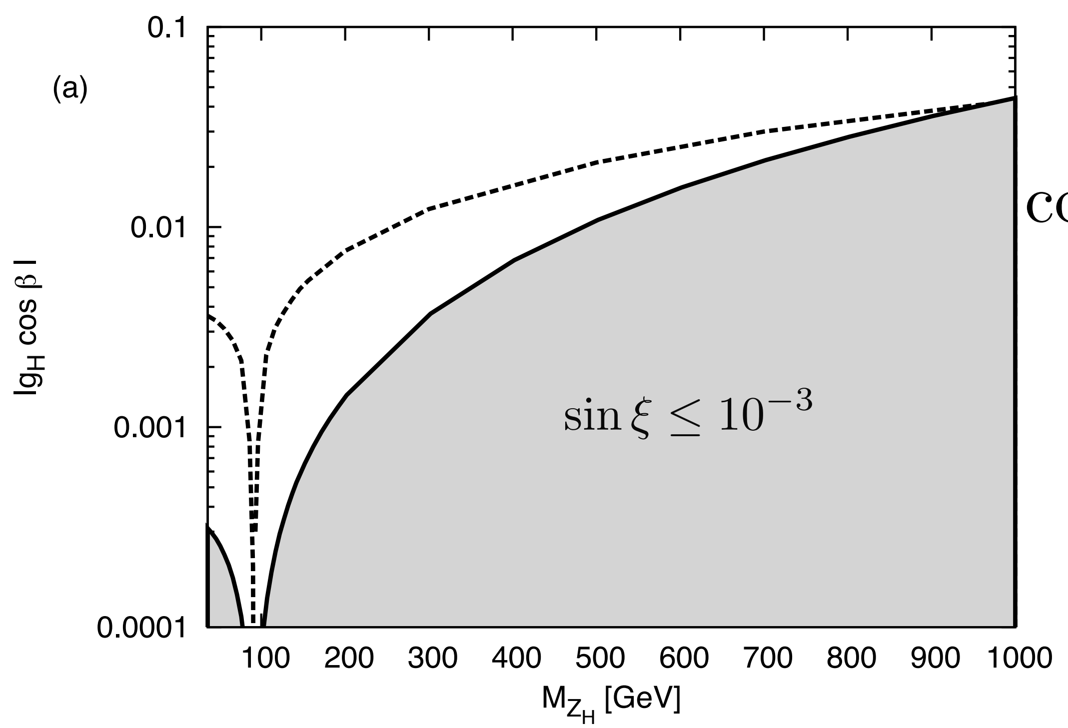
Constraints on g_H and M_{Z_H}

fermiophobic Z_H



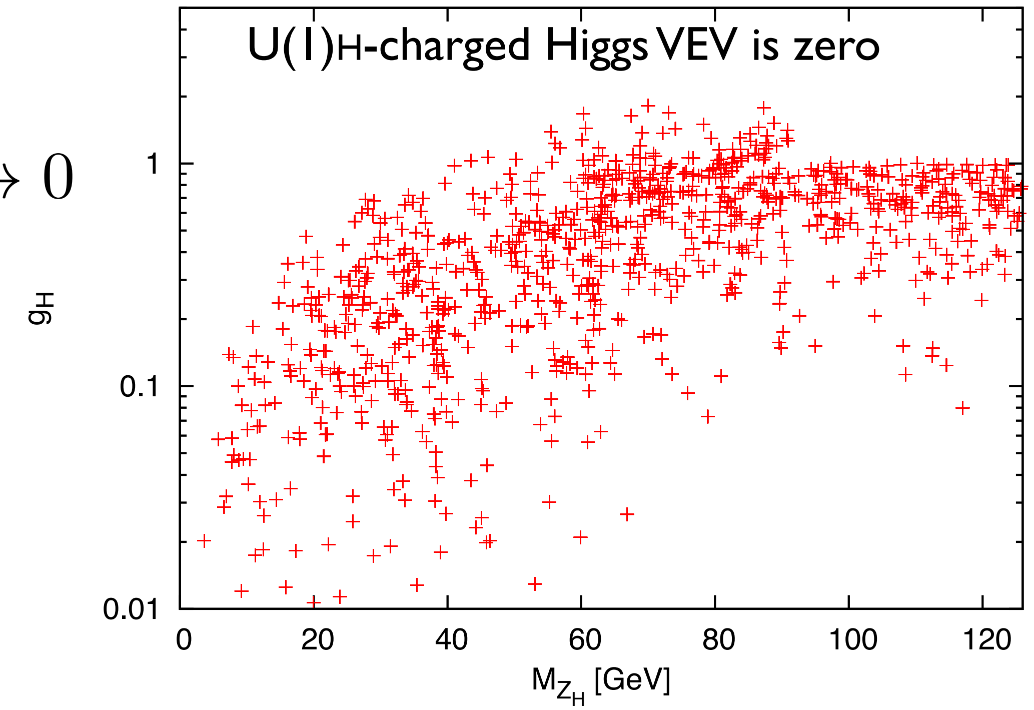
Constraints on g_H and M_{Z_H}

fermiophobic Z_H



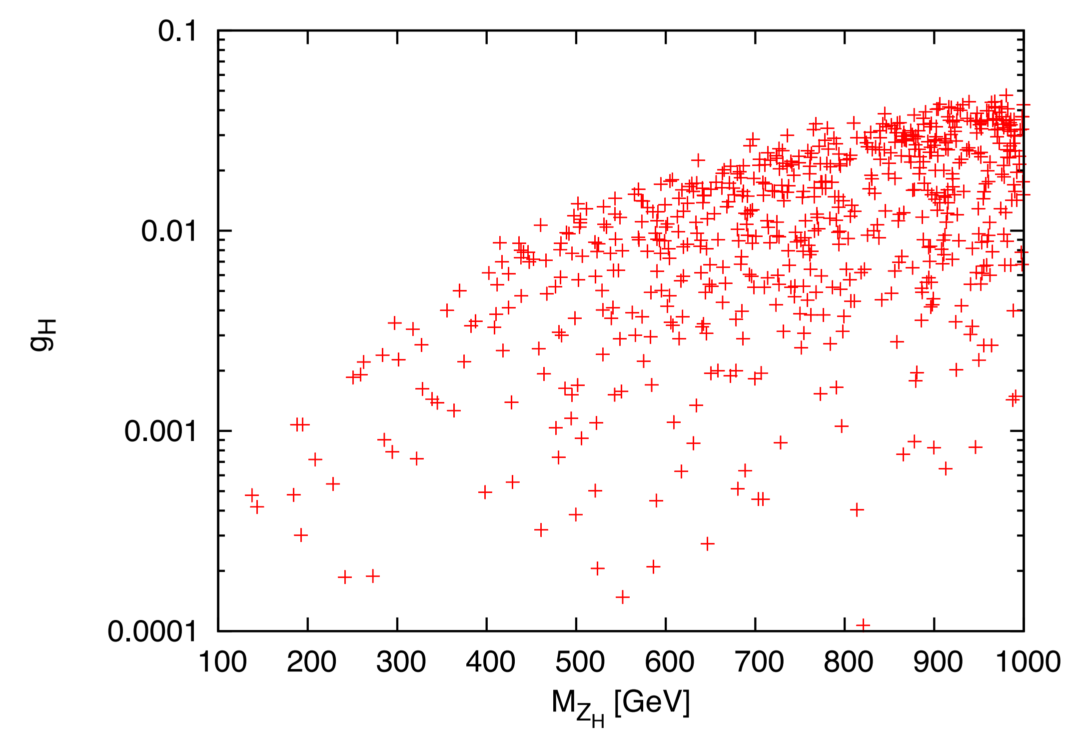
$\cos\beta \to 0$

U(1)$_Y$×U(1)$_H$ kinetic mixing zero @1TeV



E6 Z_H

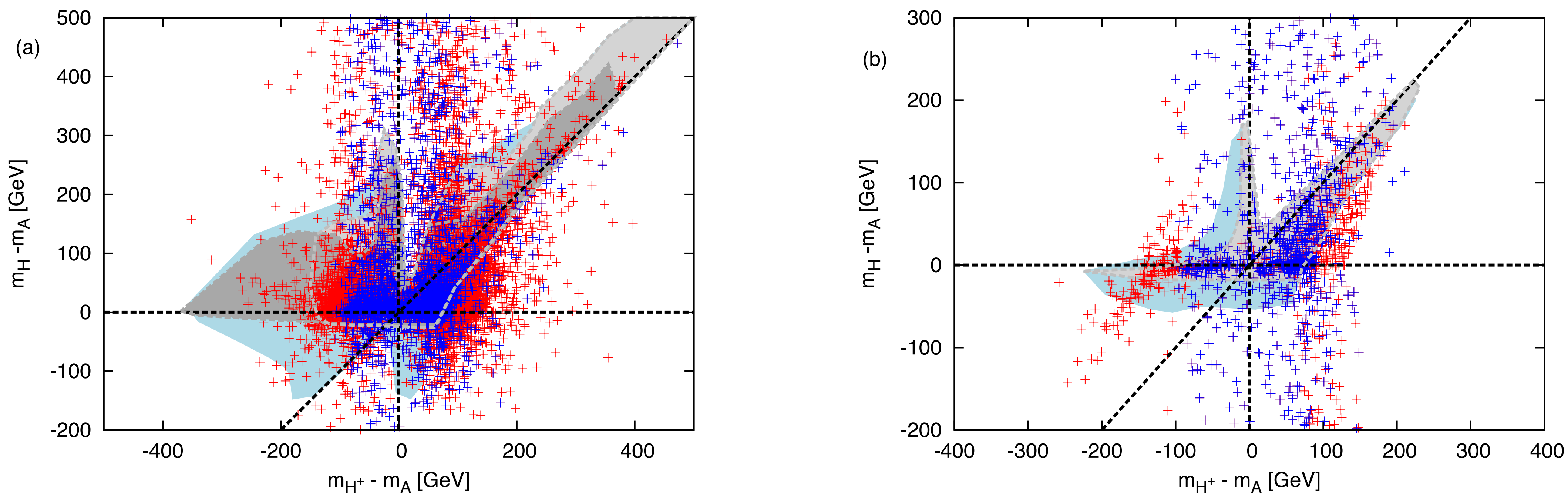
ρ-para. strongly constrain.→ small g_H required.



allowed region in (type-I) 2HDM with U(1)H

(Ko, YO, Yu)

CP-even scalar mixing relaxes the bound on the mass differences.



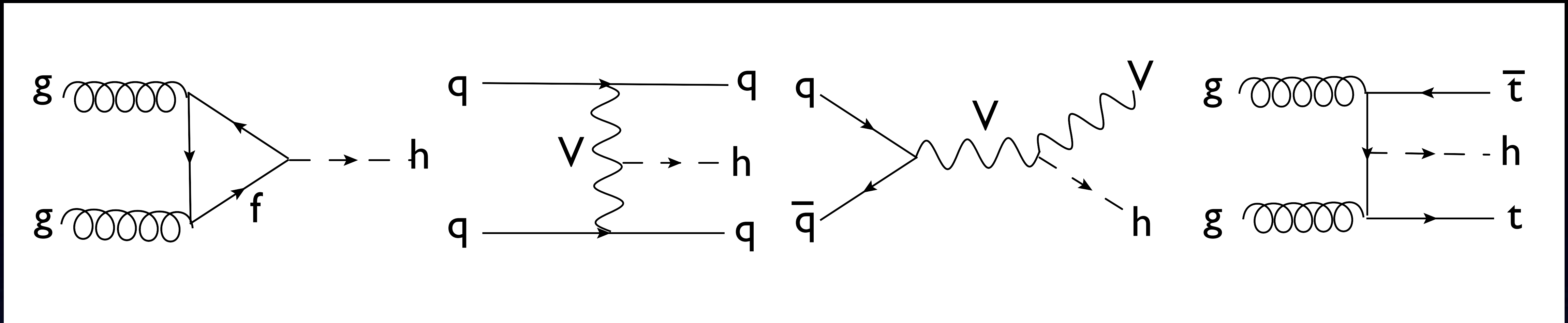
$" + " - |\lambda_{hf\bar{f}}| = |\sin(\beta - \alpha)\cos\alpha_1| > 0.9$ SM-like

In the type-II (inspired by E6), we have extra corrections from the extra fermion loops

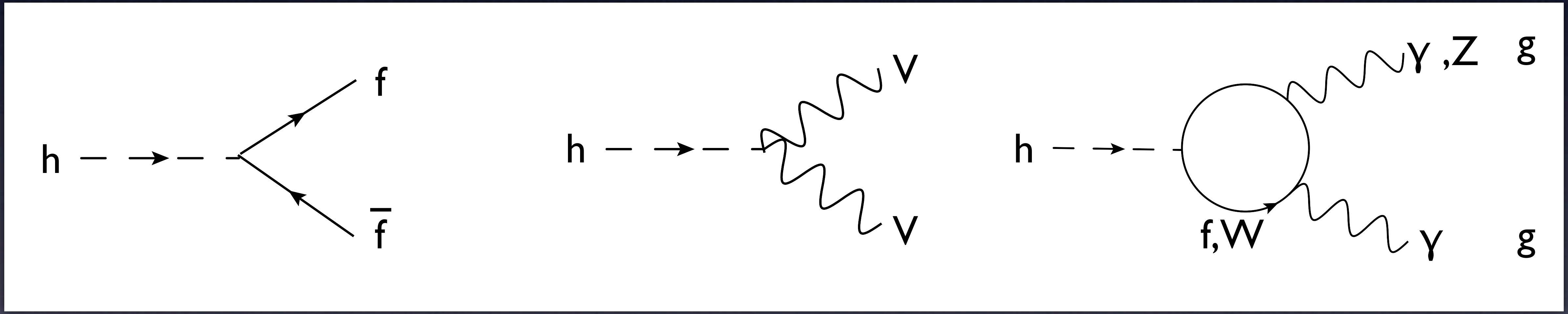
Higgs Physics

Higgs search

Higgs Production



Higgs Decay



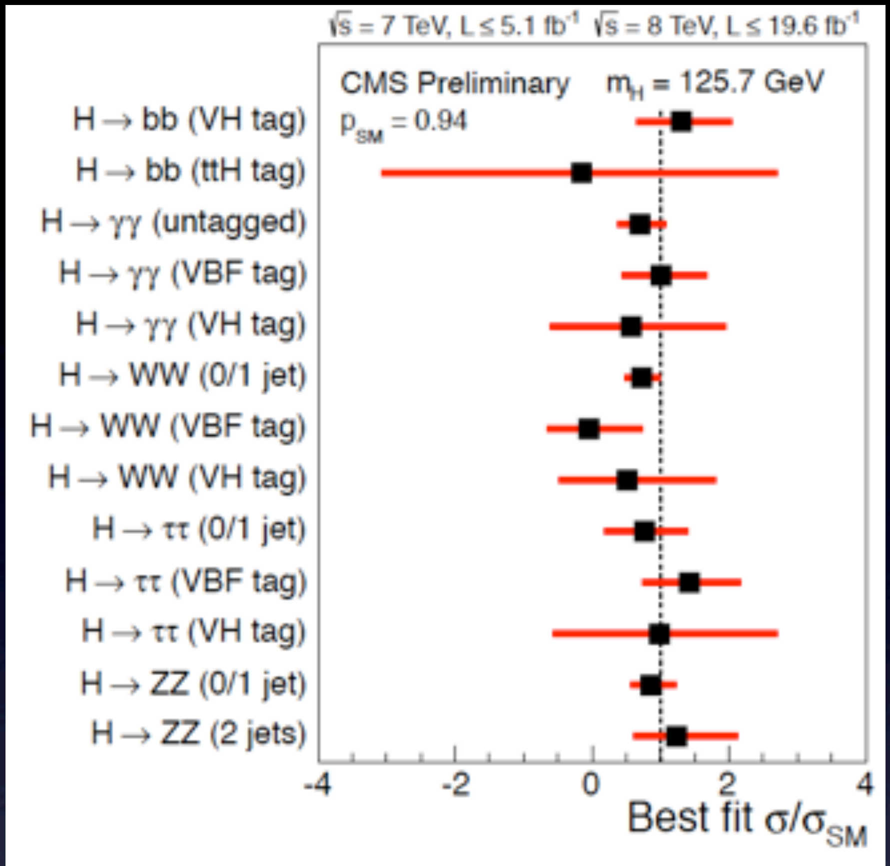
Signal Strength

$$\mu_j^i = \frac{\sigma(pp \to h)^j_{\mathrm{2HDM}} \mathrm{Br}(h \to i)_{\mathrm{2HDM}}}{\sigma(pp \to h)^j_{\mathrm{SM}} \mathrm{Br}(h \to i)_{\mathrm{SM}}}$$

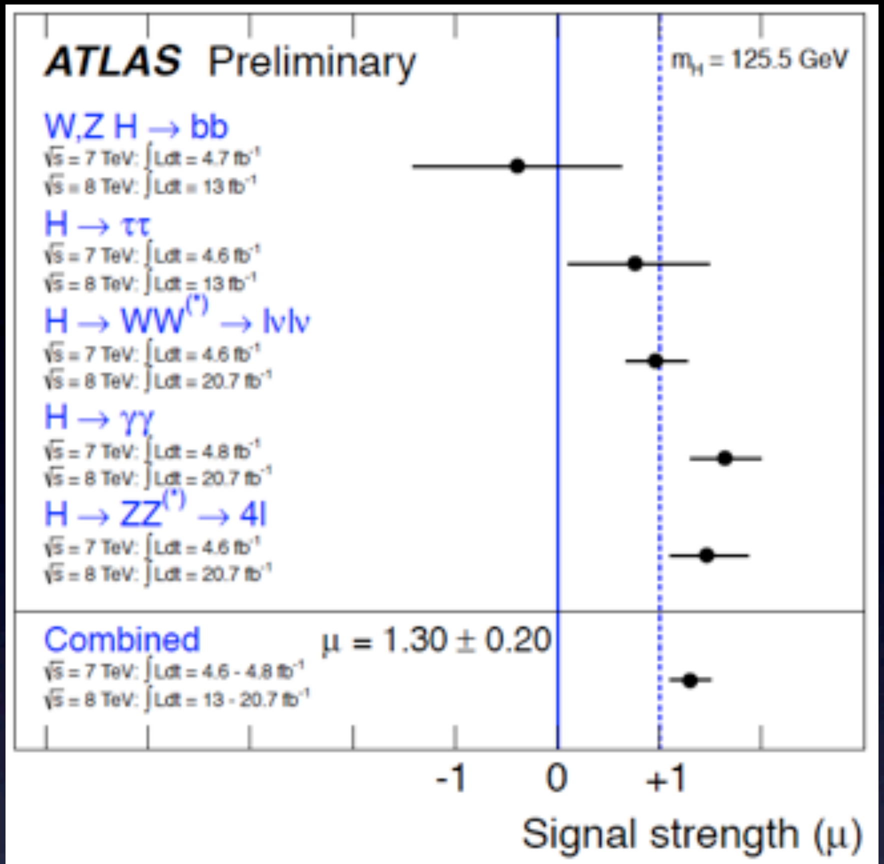
j : Higgs production

i : Higgs production

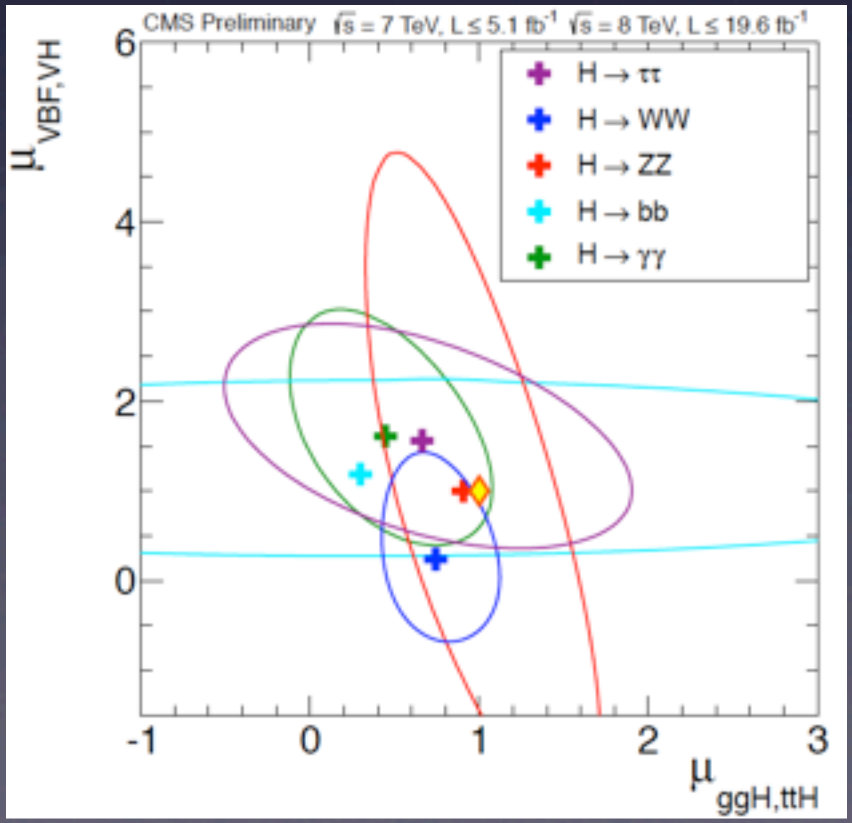
LHC results



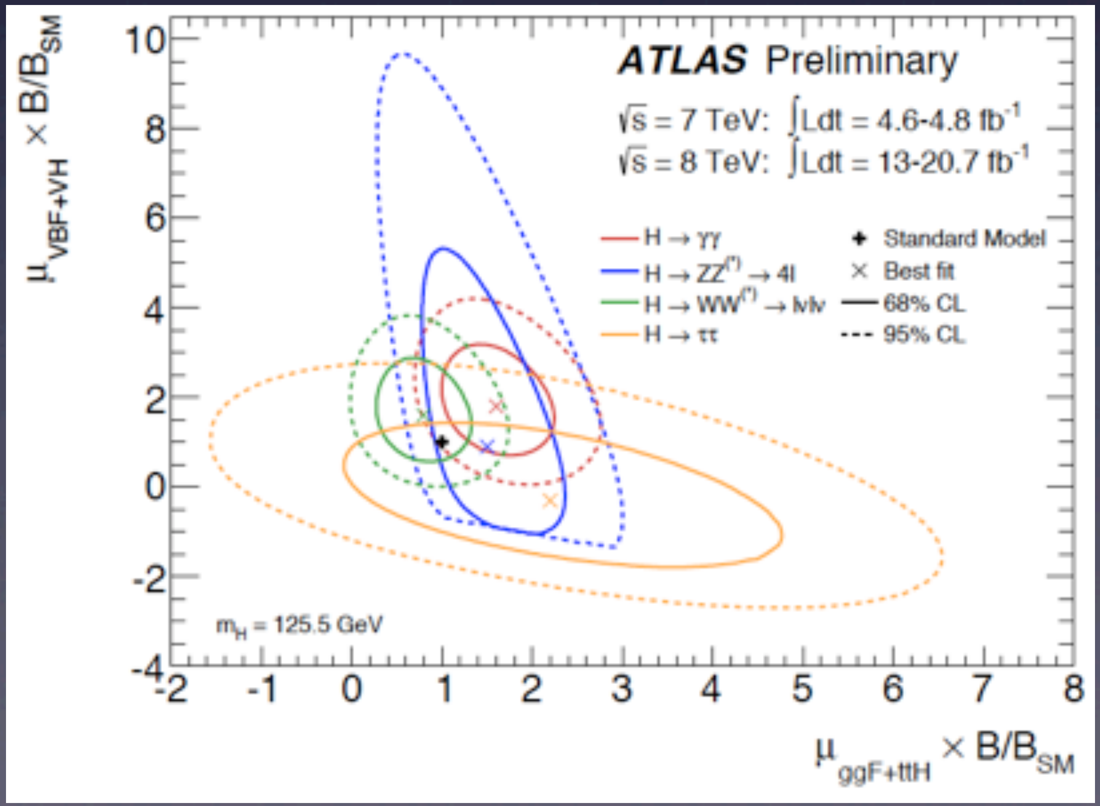
$\sqrt{s}$ = 7 TeV, L ≤ 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L ≤ 19.6 fb^{-1}
CMS Preliminary
m_H = 125.7 GeV
p_{SM} = 0.94
H → bb (VH tag)
H → bb (ttH tag)
H → γγ (untagged)
H → γγ (VBF tag)
H → γγ (VH tag)
H → WW (0/1 jet)
H → WW (VBF tag)
H → WW (VH tag)
H → ττ (0/1 jet)
H → ττ (VBF tag)
H → ττ (VH tag)
H → ZZ (0/1 jet)
H → ZZ (2 jets)
-4 -2 0 2 4
Best fit σ/σ_{SM}



ATLAS Preliminary
m_H = 125.5 GeV
W,Z H → bb
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 fb^{-1}
H → ττ
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 fb^{-1}
H → WW$^{(*)}$ → lνlν
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 20.7 fb^{-1}
H → γγ
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 20.7 fb^{-1}
H → ZZ$^{(*)}$ → 4l
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 20.7 fb^{-1}
Combined
μ = 1.30 ± 0.20
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 - 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 - 20.7 fb^{-1}
-1 0 +1
Signal strength (μ)



CMS Preliminary $\sqrt{s}$ = 7 TeV, L ≤ 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L ≤ 19.6 fb^{-1}
$\mu_{VBF,VH}$
H → ττ
H → WW
H → ZZ
H → bb
H → γγ
$\mu_{ggH,ttH}$



ATLAS Preliminary
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13-20.7 fb^{-1}
H → γγ
H → ZZ$^{(*)}$ → 4l
H → WW$^{(*)}$ → lνlν
H → ττ
Standard Model
Best fit
68% CL
95% CL
m_H = 125.5 GeV
$\mu_{VBF+VH} \times B/B_{SM}$
$\mu_{ggF+ttH} \times B/B_{SM}$

factors from 2HDM

<u>h-V-V coupling</u>

$$\lambda_V = \sin(\beta - \alpha)$$

<u>h-f-f coupling</u>

top: $\lambda_t = \lambda_b = \lambda_V + \dfrac{\cos(\beta-\alpha)}{\tan\beta}$

type-I

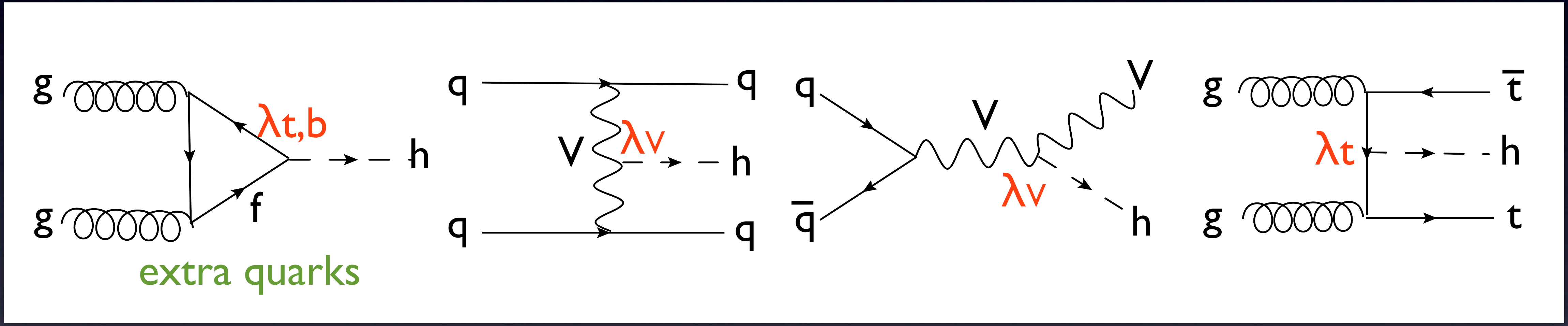
top: $\lambda_t = \lambda_V + \dfrac{\cos(\beta-\alpha)}{\tan\beta}$

bottom: $\lambda_b = \lambda_V - \cos(\beta-\alpha)\tan\beta$

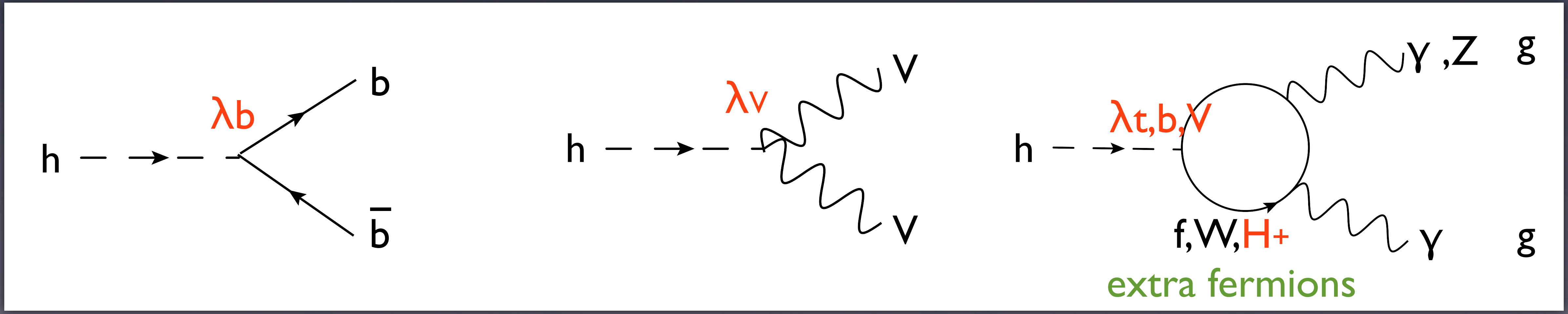
type-II

2HDM with U(1)H: $\lambda_{t,b,V} \to \lambda_{t,b,V}\cos\alpha_1$

Higgs Production



Higgs Decay

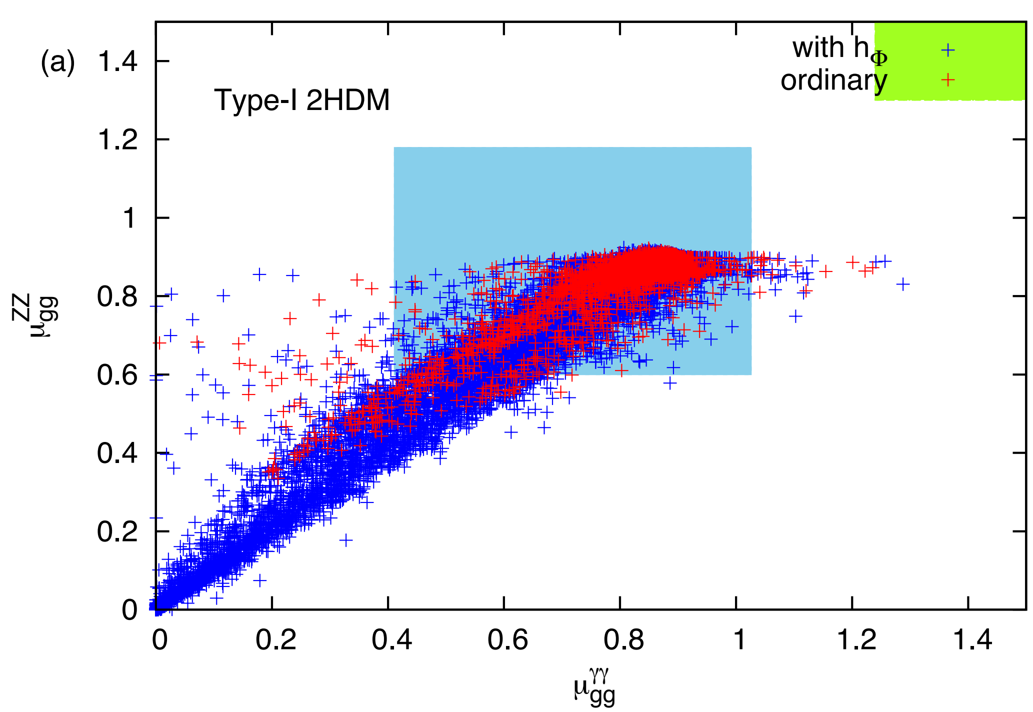


signal strength in 2HDMs (Ko, YO, Yu)

type-I

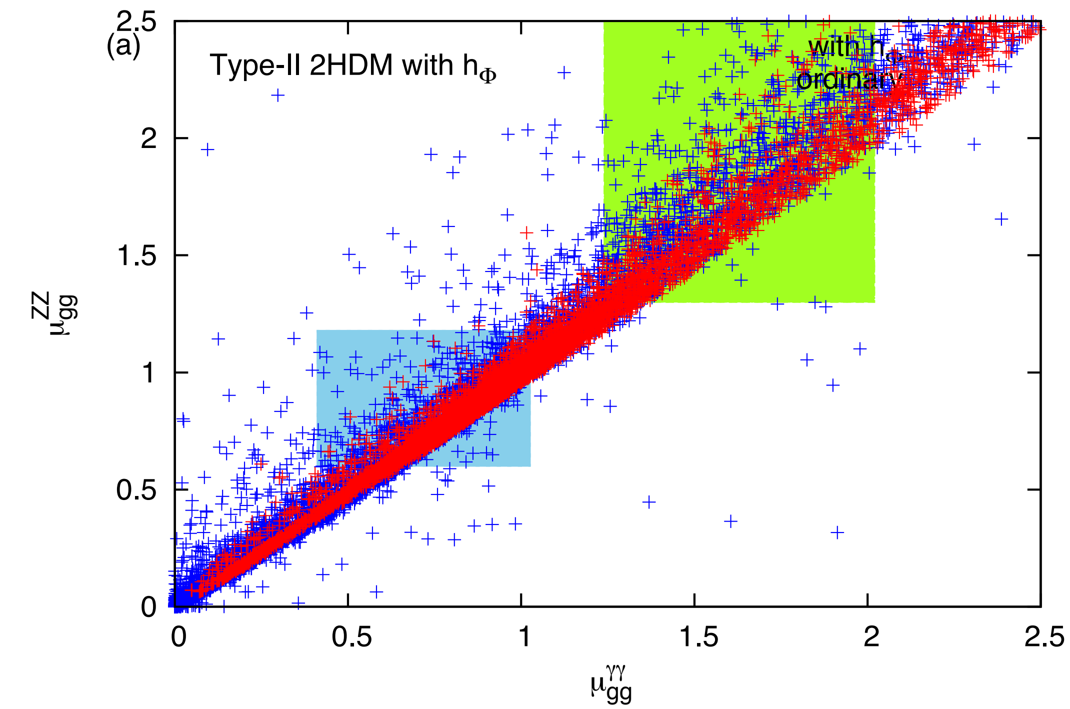
type-II

gg fusion



charged Higgs loop enhance $h \to \gamma\gamma$

ATLAS cannot be achieved

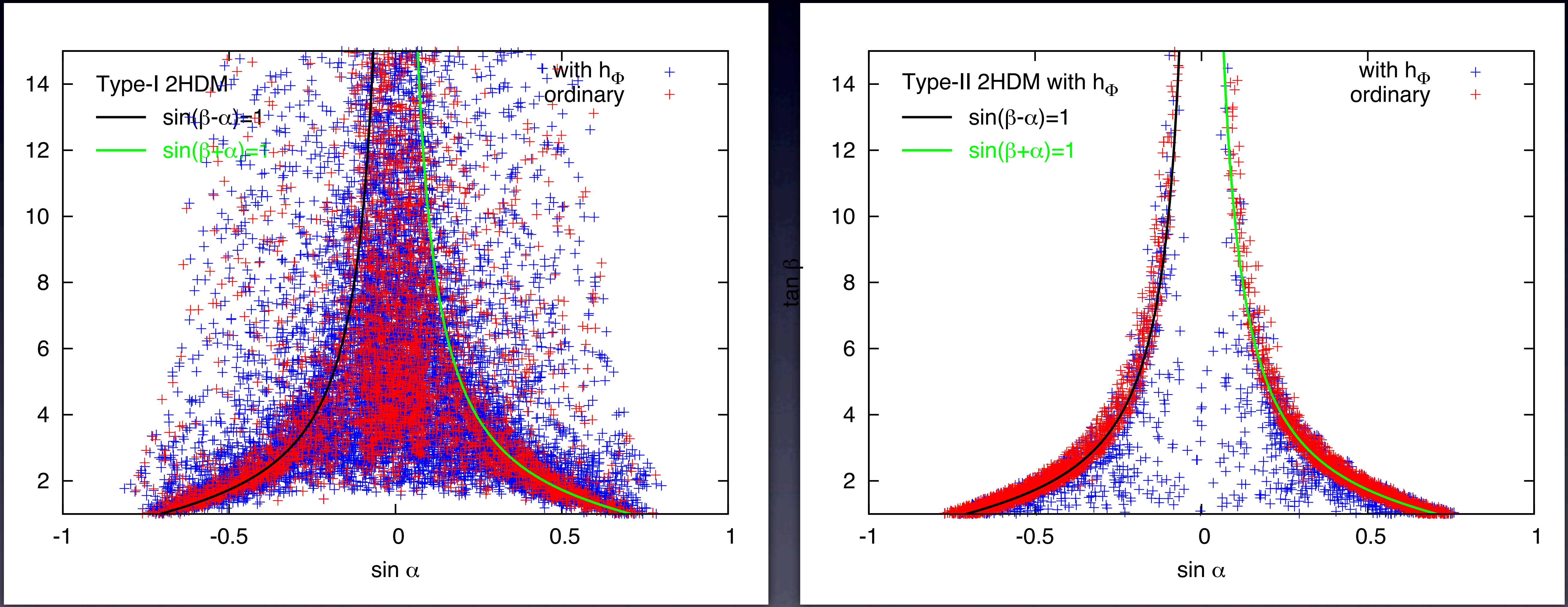


$h \to bb, \tau\tau$ easily enhanced (reduced)

Under constraints from gg→h→γγ,ZZ@CMS (Ko,YO,Yu)

$(\mu^{\gamma\gamma}_{gg,\mathrm{CMS}} = 0.70^{+0.33}_{-0.29}, \mu^{ZZ}_{gg,\mathrm{CMS}} = 0.86^{+0.32}_{-0.26})$

type-I　　　　type-II



Type-II will be constrained strongly

If large signal strength is favored, type-I may be excluded.

Dark Matter Physics

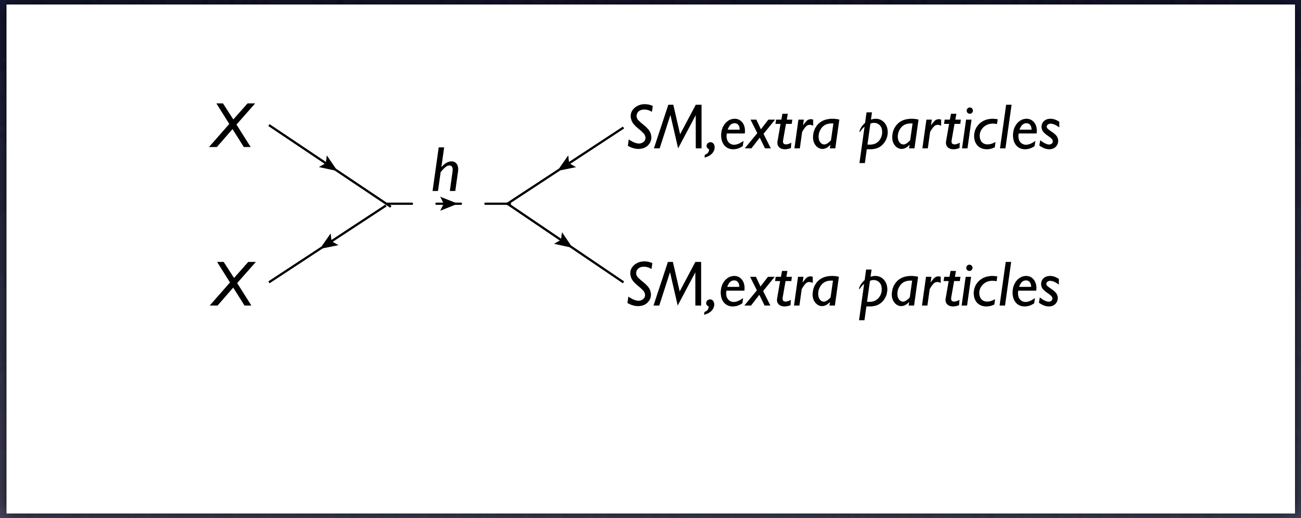
U(1)H extension realizes stable neutral particle

dark matter candidates

scalar component in type-I

extra neutral fermion for anomaly-free conditions in type-II

relevant interaction and constraints



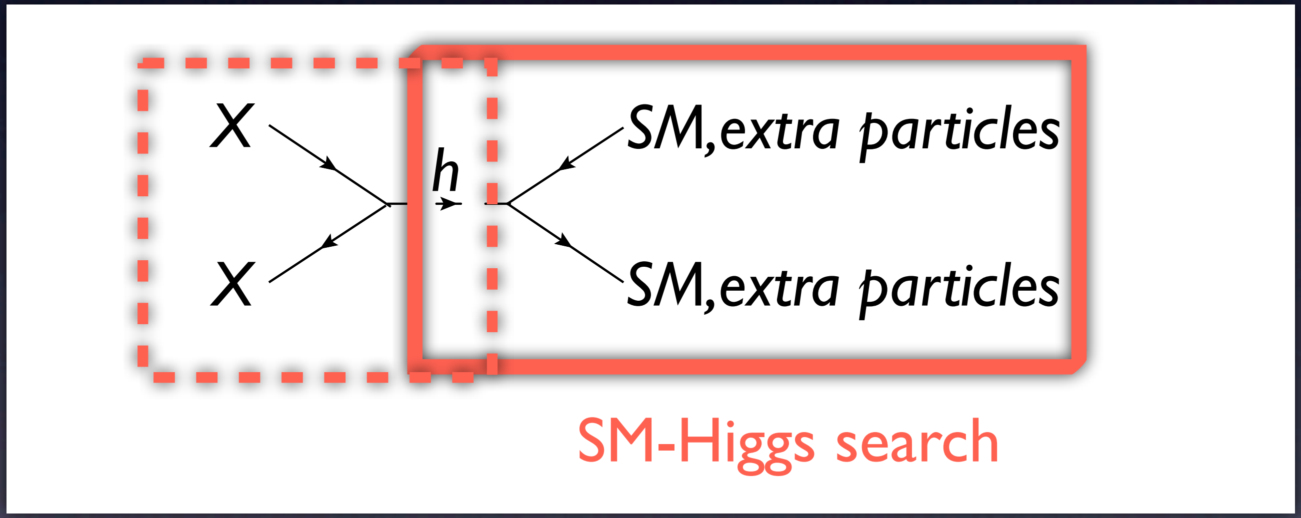
U(1)H extension realizes stable neutral particle

dark matter candidates

scalar component in type-I

extra neutral fermion for anomaly-free conditions in type-II

relevant interaction and constraints



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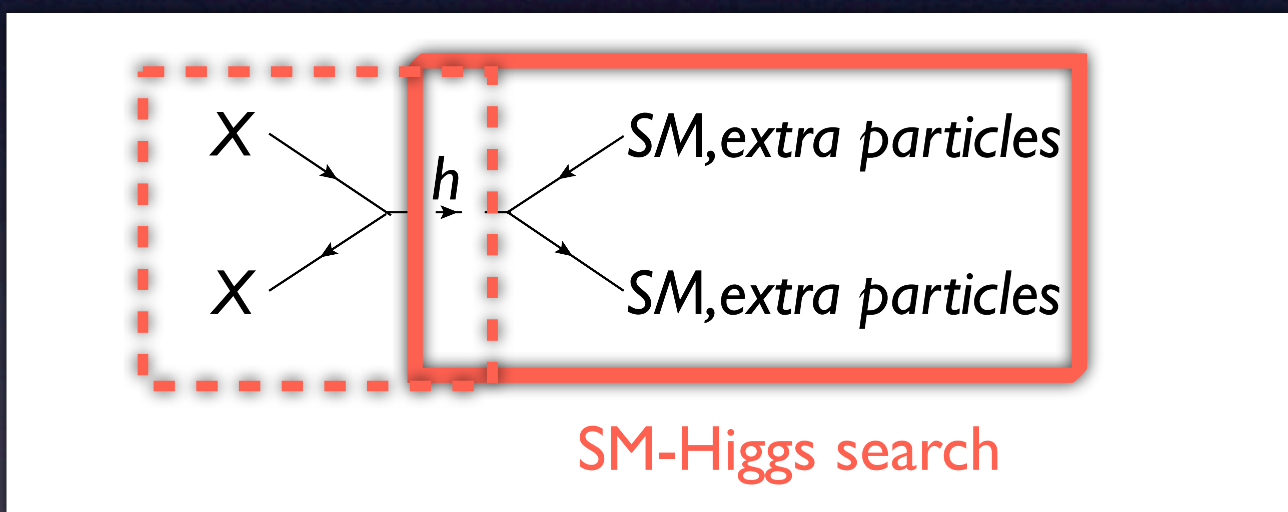
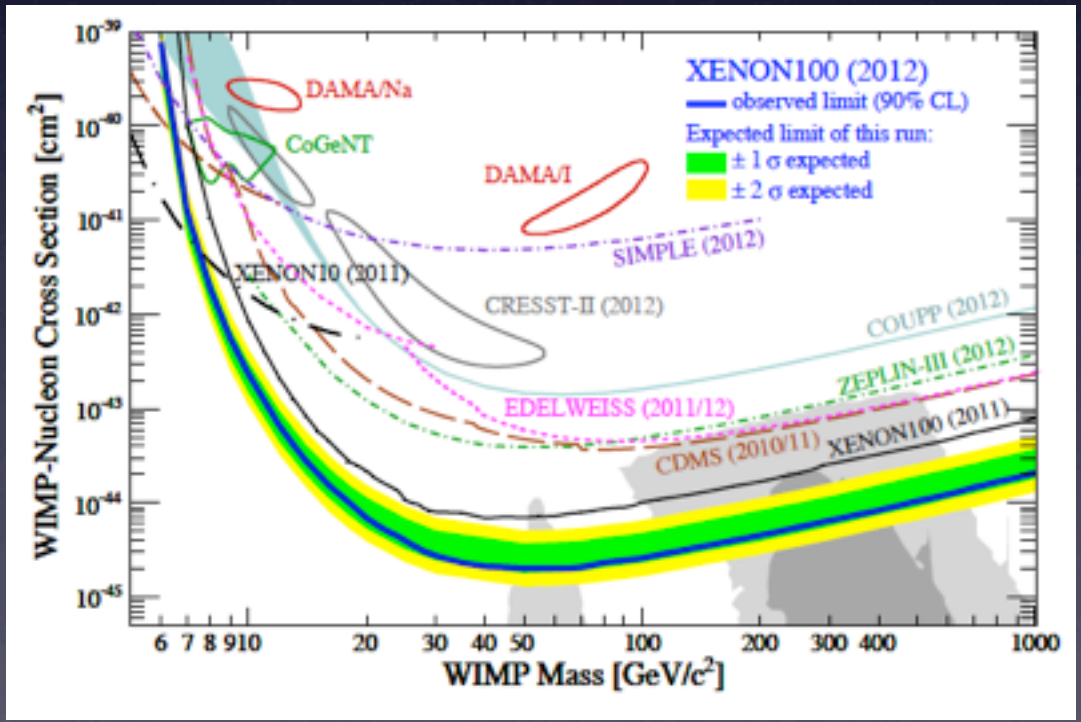


direct detection (XENON100,LUX,etc.)



indirect search
(Fermi-LAT,etc)

relic density

$\Omega h^2 = 0.1109 \pm 0.017(3\sigma)$ (WMAP)

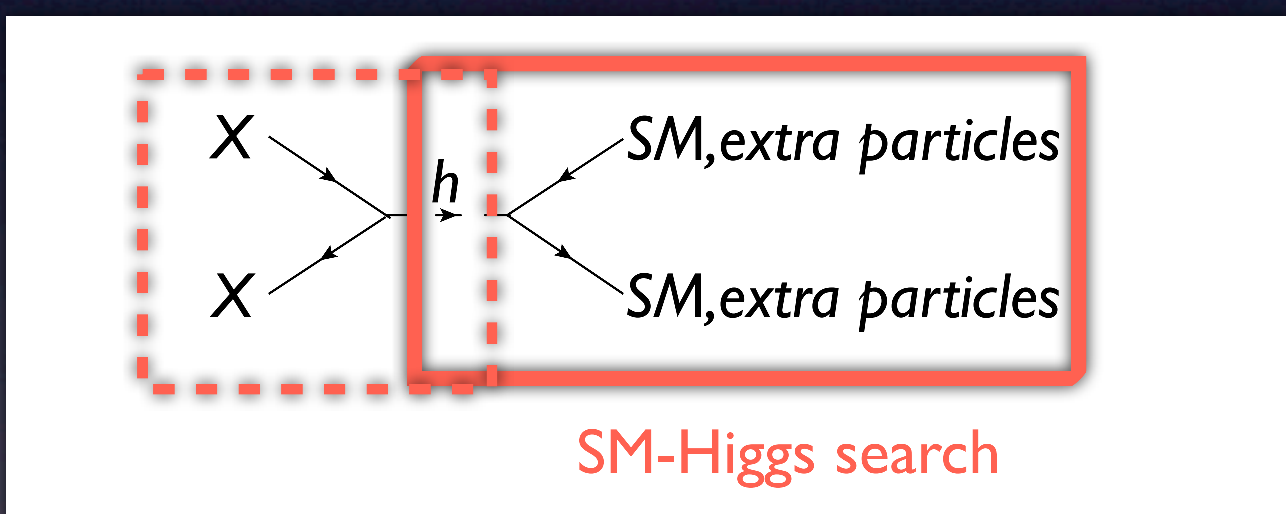
U(1)H extension realizes stable neutral particle

dark matter candidates

scalar component in type-I

extra neutral fermion for anomaly-free conditions in type-II

relevant interaction and constraints

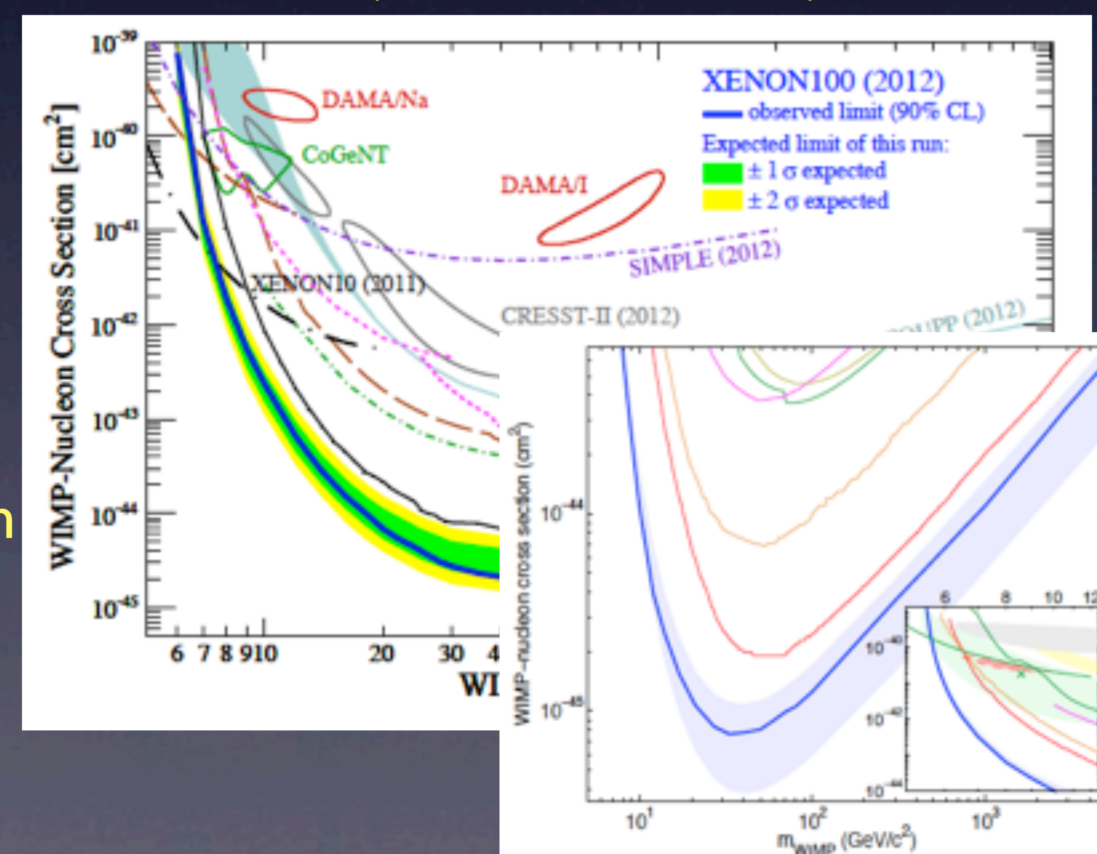


direct detection (XENON100,LUX,etc.)

indirect search (Fermi-LAT,etc)

relic density

$\Omega h^2 = 0.1109 \pm 0.017(3\sigma)$ (WMAP)



(LUX)

Dark Matter Candidates in type-I

- In type-I 2HDM, well-known dark-matter model is Inert-doublet model (IDM)

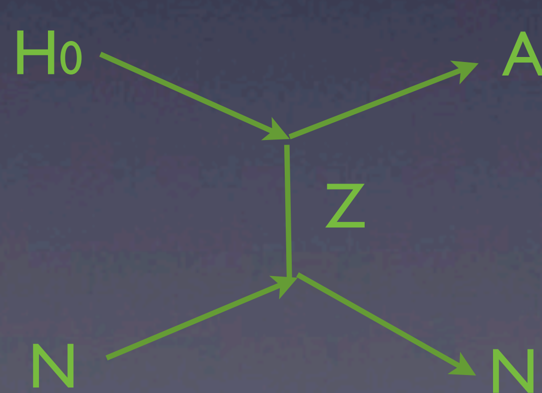
If H_1, which does not couple with SM fermions, does not get VEV, scalar component is a good dark matter candidate

$$H_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(H_0 + iA) \end{pmatrix}$$

Zn-odd CDM candidate

$\langle \Phi \rangle \neq 0$ only breaks $U(1)_H$: $U(1)_H \rightarrow Z_n$ (n = Φ charge)

The mass difference between H0 and A is required by XENON100, etc.

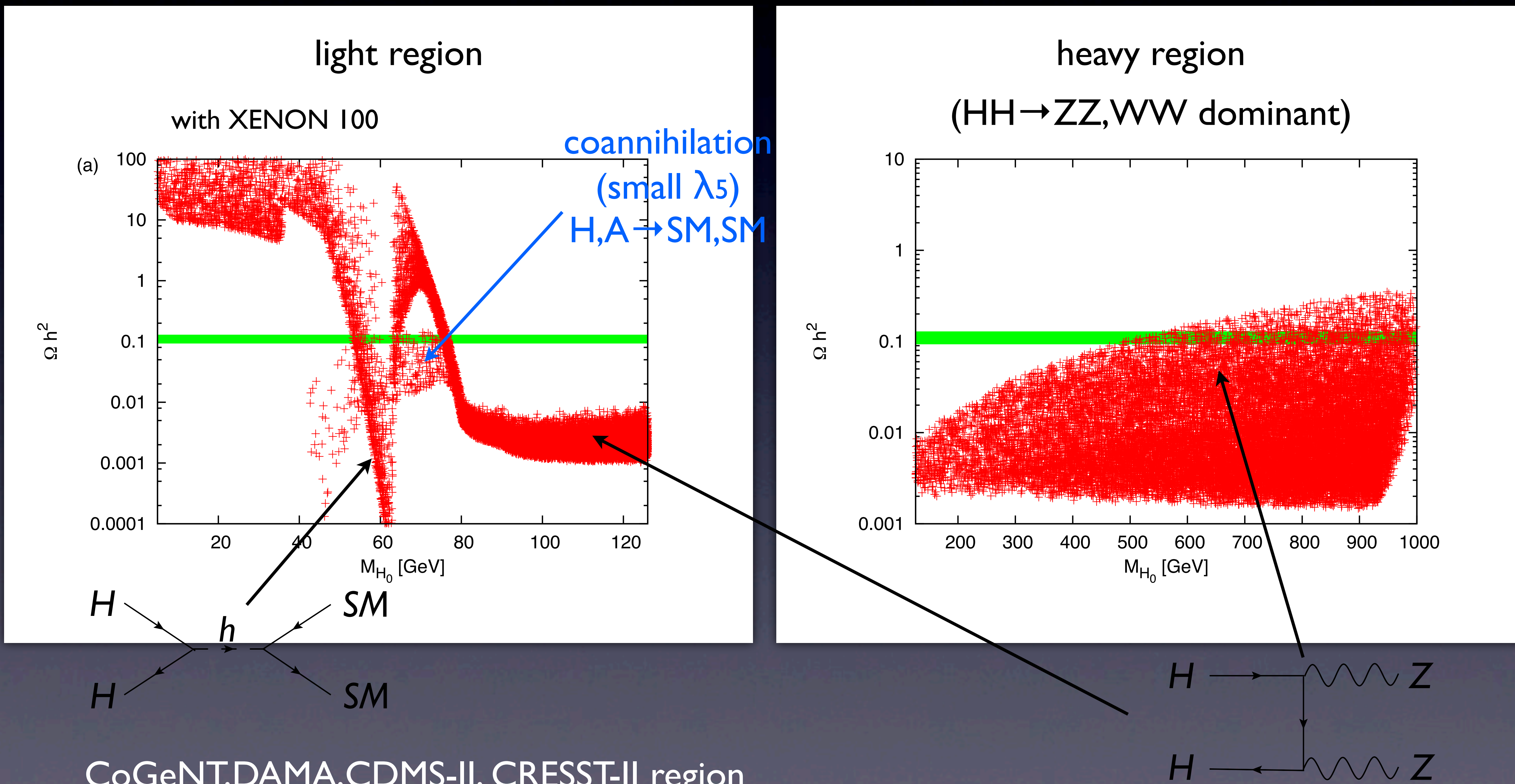


small $\lambda 5$ is given by higher-dim. ope.

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

Relic Density vs. Dark Matter in IDM(type-I)

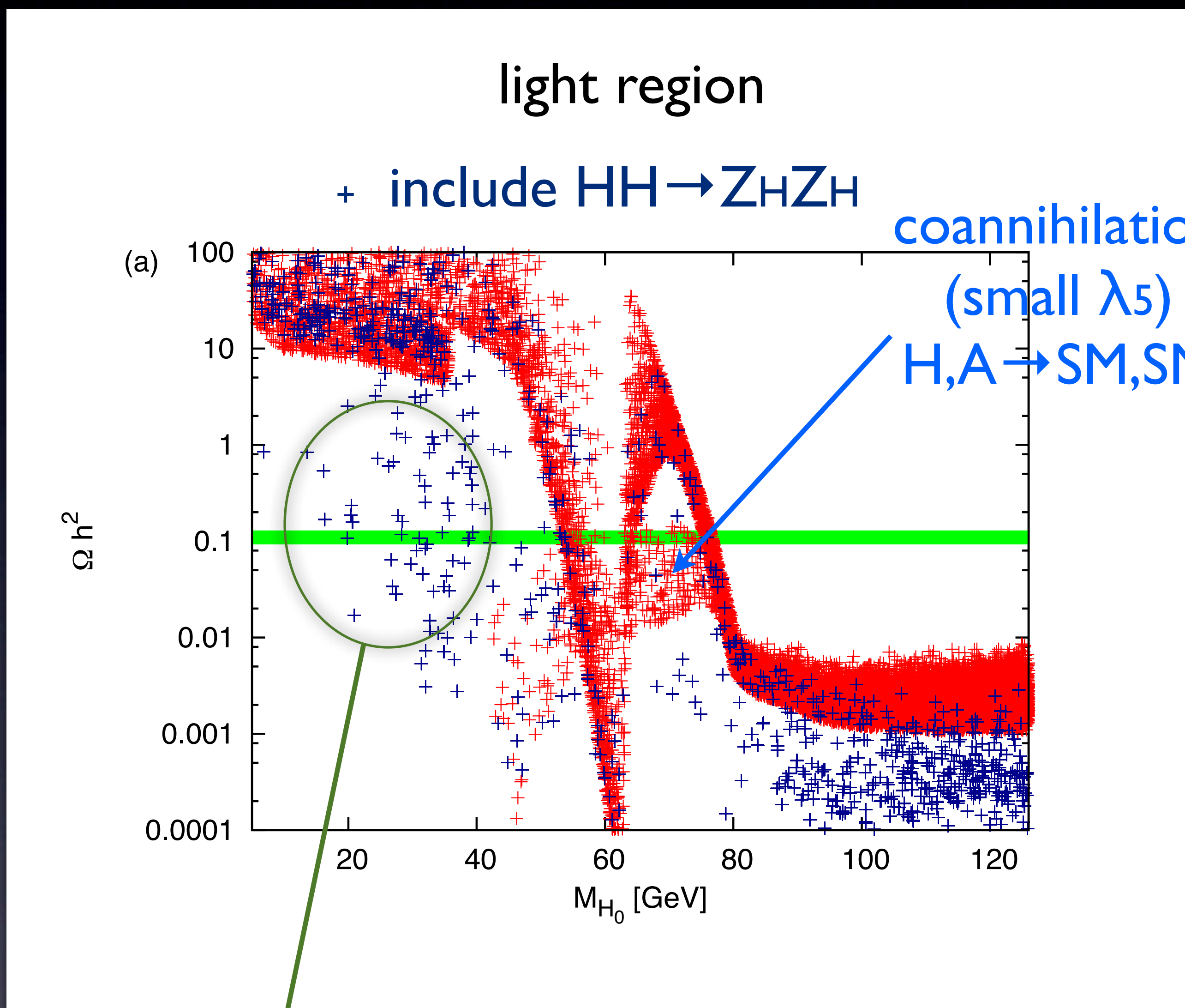
There are two interesting regions: M_{H_0}<126GeV, M_{H_0}>500GeV.



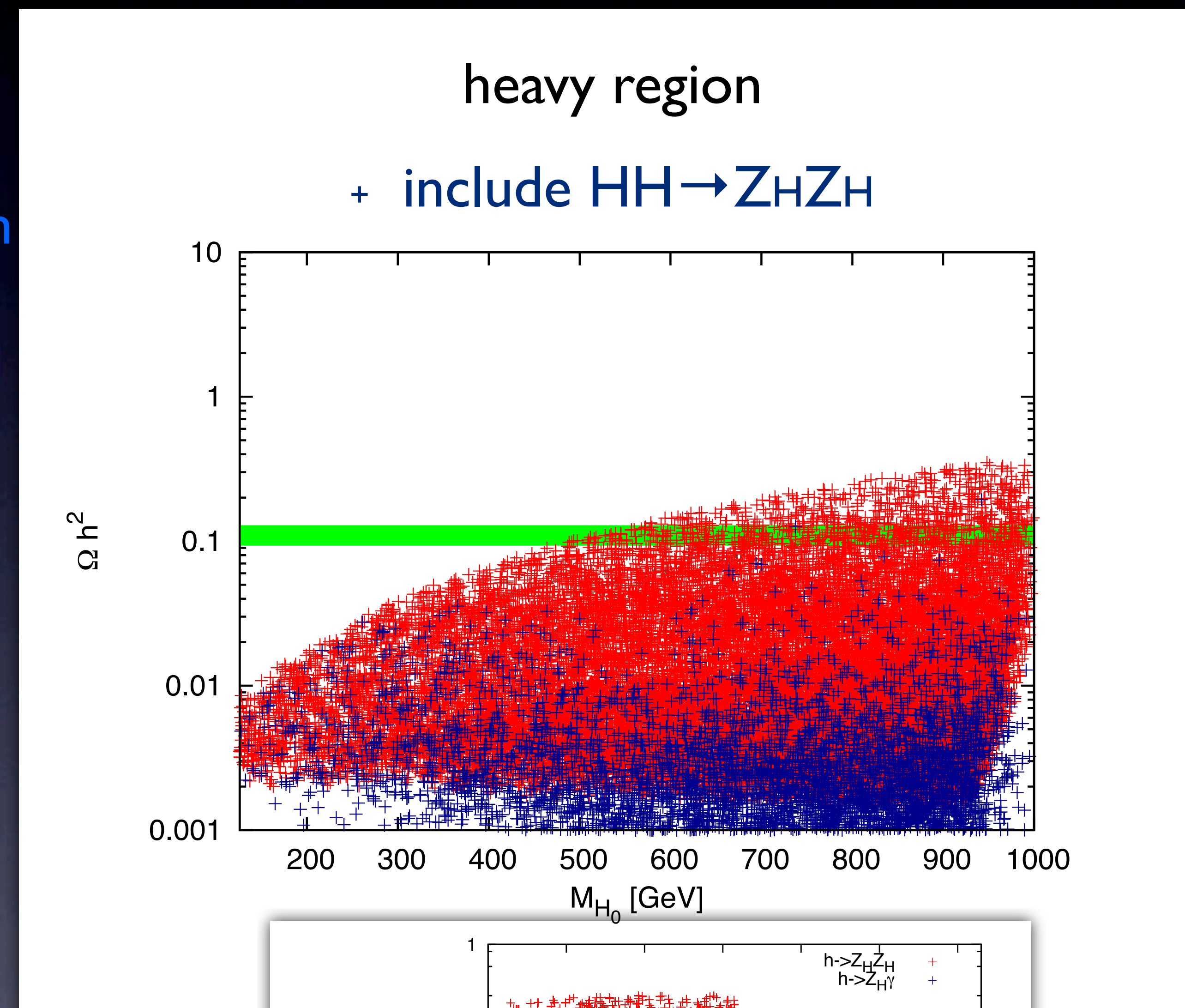
CoGeNT,DAMA,CDMS-II, CRESST-II region
are excluded by the invisible decay

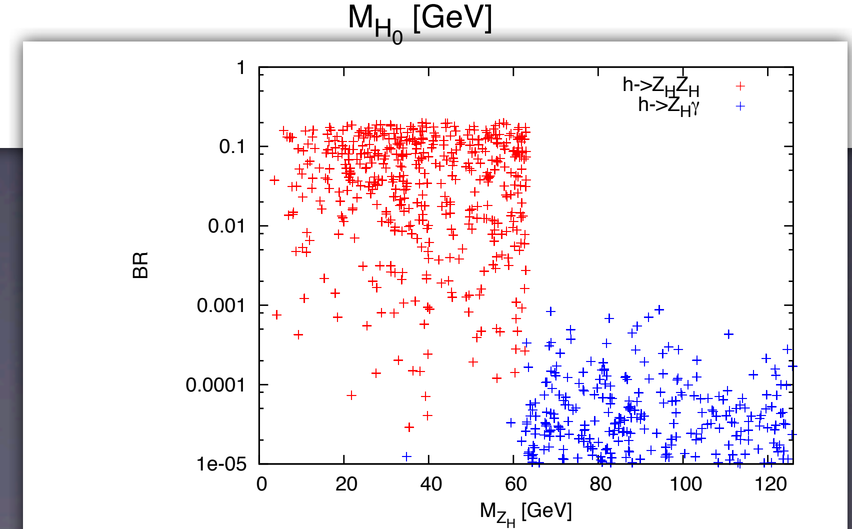
Relic Density vs. Dark Matter in IDM with U(1)

$HH \to Z_H Z_H$ reduce the relic density



coannihilation
(small λ_5)
$H,A \to SM,SM$





$BR(h \to HH) + BR(h \to Z_H Z_H) + BR(h \to Z_H \gamma)$ less than 0.2

Bound from global fitting

$B_{\rm inv} \lesssim 0.2$

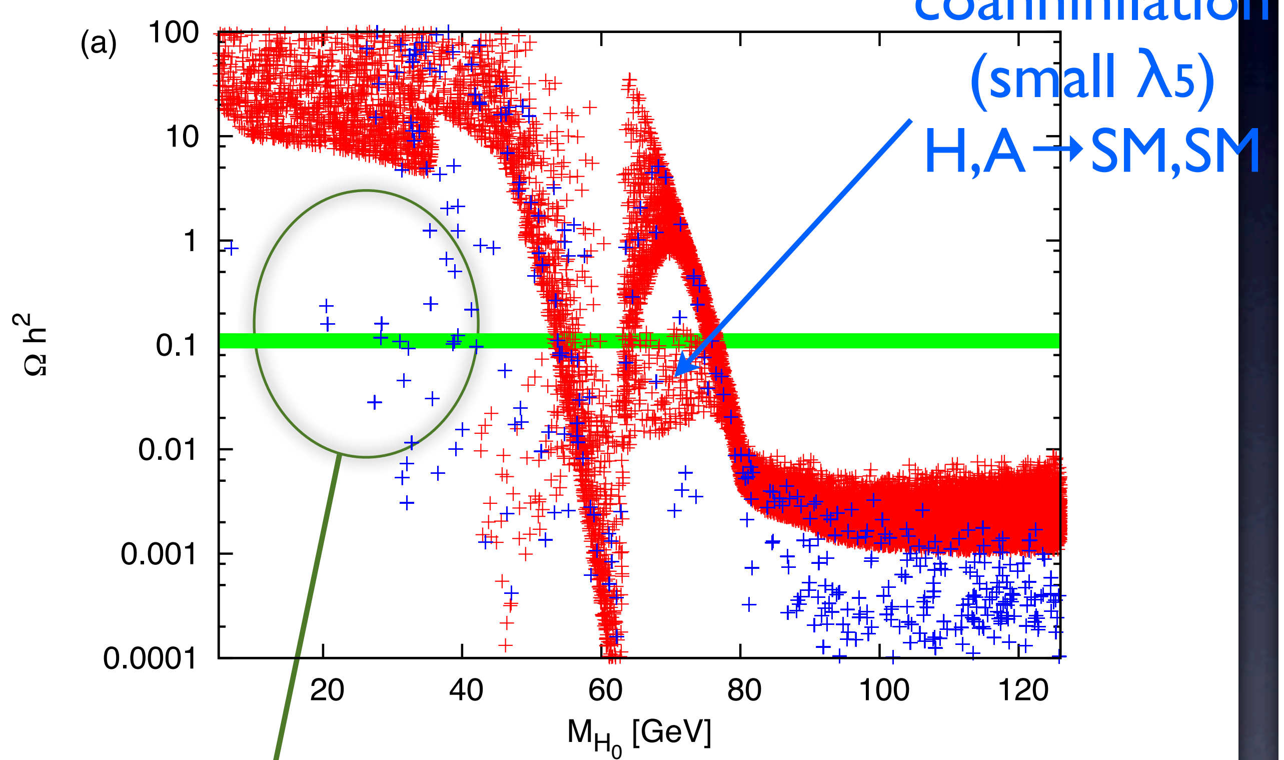
(Belanger,Dumont,Ellwanger,Gunion,Kraml
;Espinosa,Grojean,Mühlleitner,Trott)

Relic Density vs. Dark Matter in IDM with U(1)

$HH \rightarrow Z_H Z_H$ reduce the relic density

light region

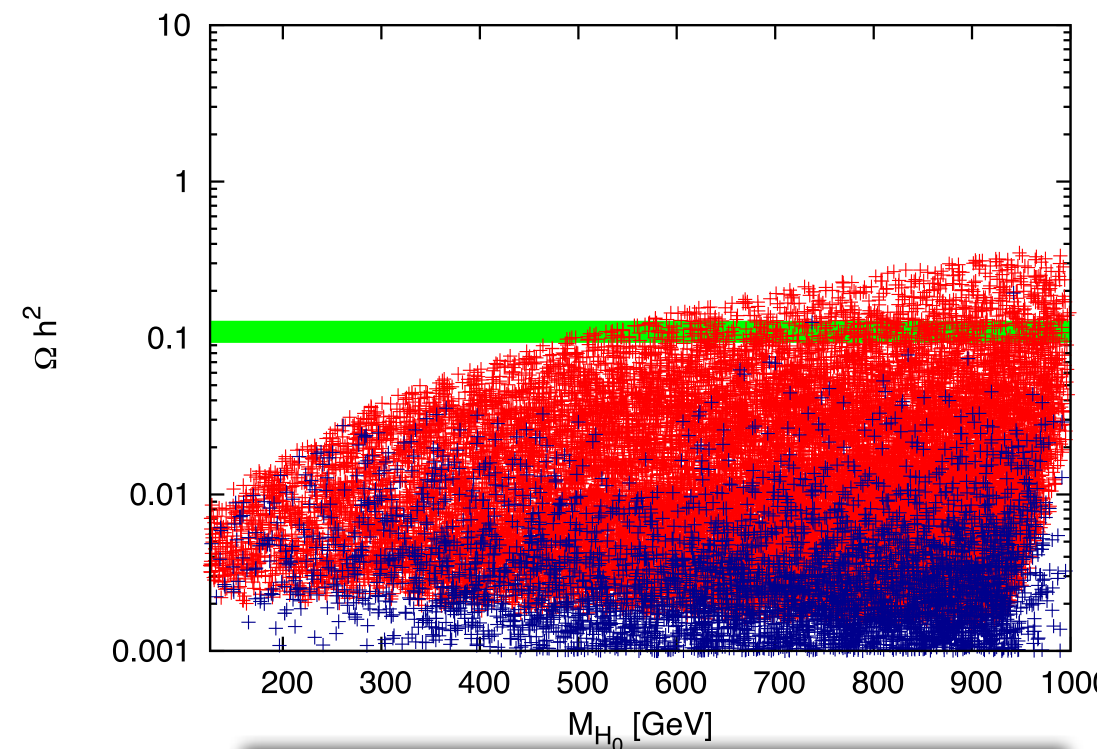
+ include $HH \rightarrow Z_H Z_H$

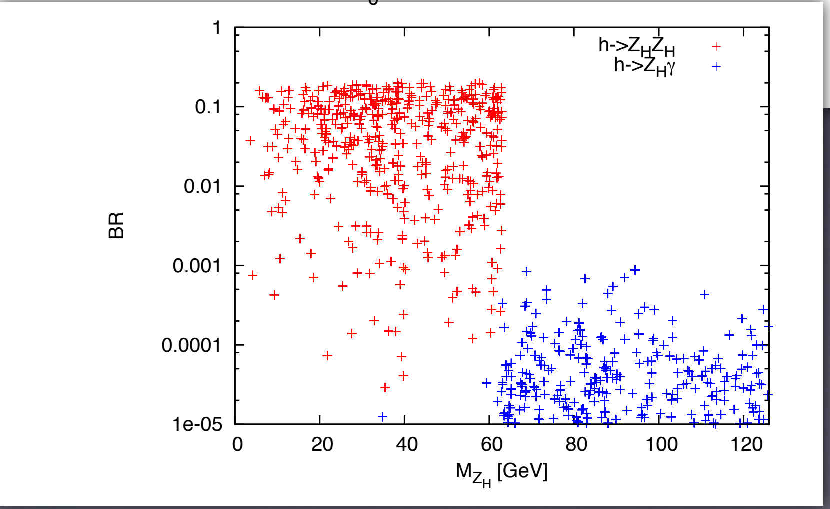


" + " — $\sigma_{\rm SI} < 7.6 \times 10^{-46} \rm cm^2$ (from LUX)

heavy region

+ include $HH \rightarrow Z_H Z_H$





$\mathrm{BR}(h \rightarrow HH) + \mathrm{BR}(h \rightarrow Z_H Z_H) + \mathrm{BR}(h \rightarrow Z_H \gamma)$ less than 0.2

Bound from global fitting

$B_{\rm inv} \lesssim 0.2$

(Belanger,Dumont,Ellwanger,Gunion,Kraml
;Espinosa,Grojean,Mühlleitner,Trott)

Dark Matter Candidates in type-II

- In type-II 2HDM inspired by E6 GUT

neutral particles from the extra leptons

$$l_I^T = (\widetilde{\nu}_I, \widetilde{e}_I)^T \ (I = L, R), \ n_L$$

$$\longrightarrow \quad \begin{pmatrix} \widetilde{\nu}_L \\ \widetilde{\nu}_R^c \\ n_L \end{pmatrix} = (U_{ab}) \begin{pmatrix} N_{L1} \\ N_{L2} \\ N_{L3} \end{pmatrix}$$

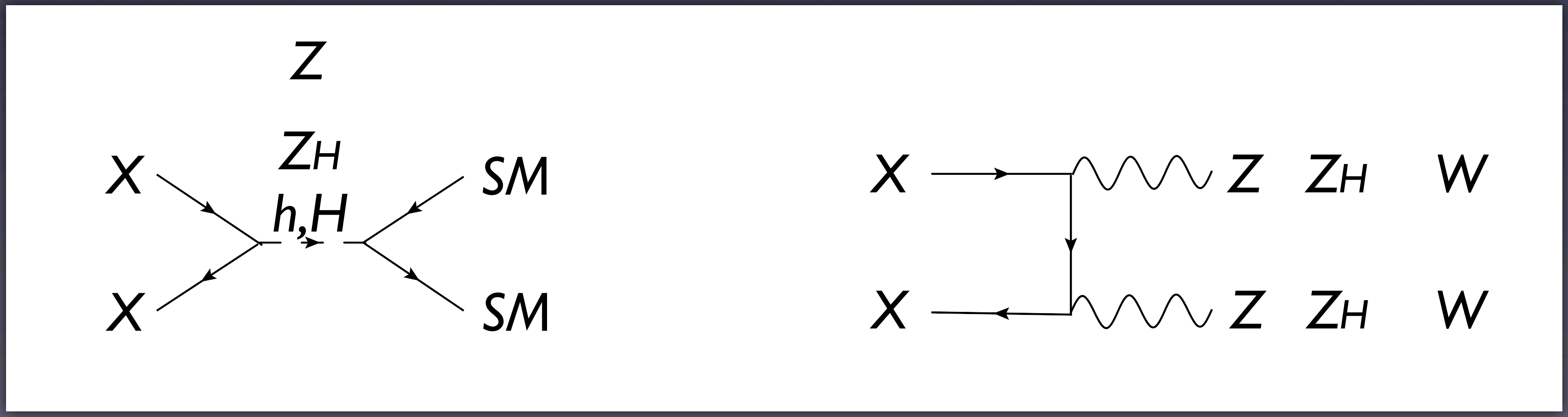
lightest N_{Li} is dark matter candidates

stability is guaranteed by (remnant) Z_2 symmetry for the extra particles

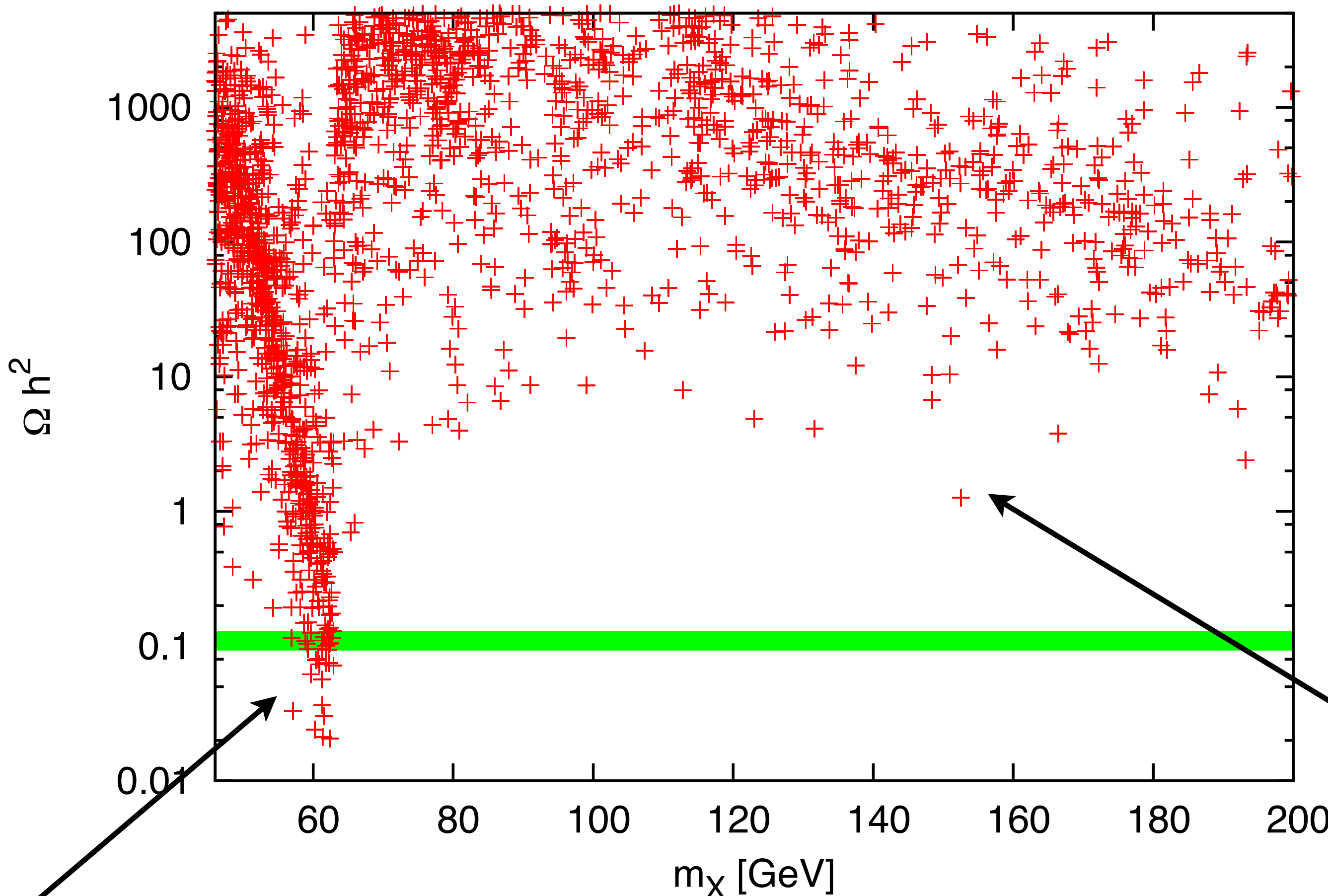
$$q_I, l_I, n_L \to -q_I, -l_I, -n_L \qquad (Z_2^\psi \times (-1)^{2s})$$

$$(U(1)_\psi \to Z_2^\psi)$$

annihilation



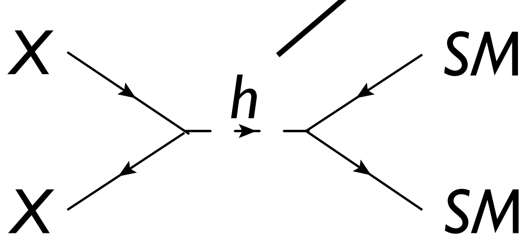
Relic Density vs. Dark Matter in type-II



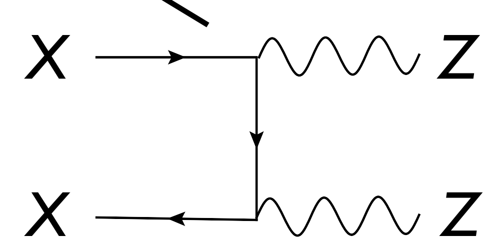
with the bounds on
EWPOs
$b \to s\gamma$
$B \to \tau\nu$
extra scalar search
extra fermion search

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

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



very large Yukawa couplings required



mono-jet bound constraints
(CMS,2013.3)
pp→j,DM,DM

Summary

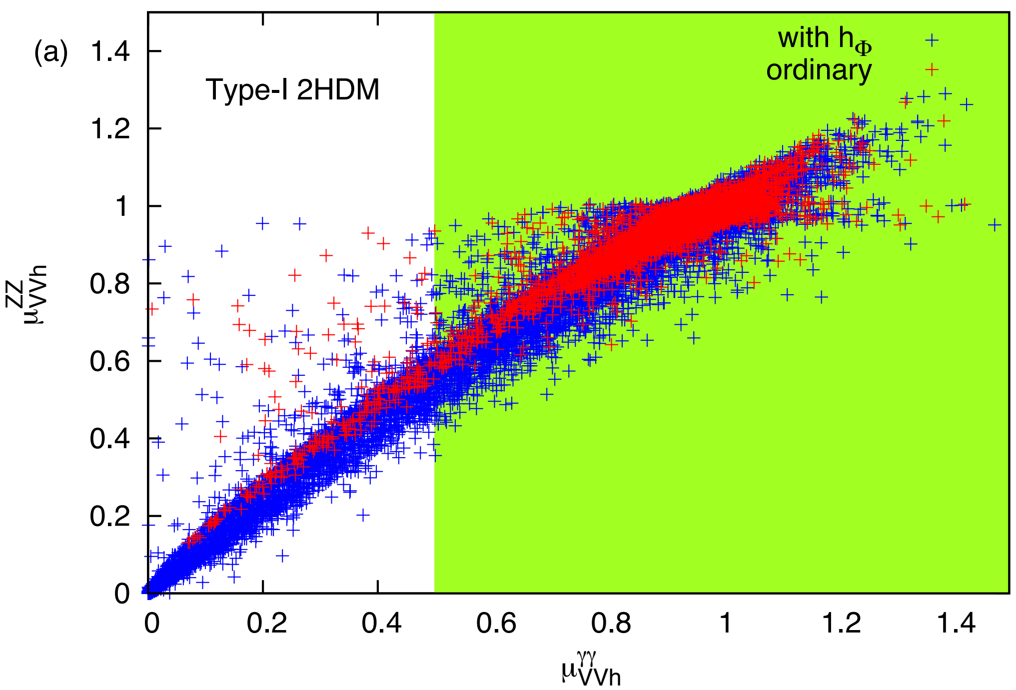
- 2HDM may be a effective model of High-energy theory, and useful to test the underlying theories.
- I consider 2HDM with $U(1)_H$ Higgs symmetry, which might be one of the effective models.
- The U(1) extension solves the flavor problem, and could introduce dark matter candidates. Stability of CDMs guaranteed by the remnant symmetry of $U(1)_H$.
- EWPOs and flavor physics are stringent constraints in 2HDMs with $U(1)_H$. The mixing among the scalars relaxes the bound on the mass differences.
- SM-Higgs search will constrain 2HDMs strongly. Especially, the allowed region for type-II is smaller because of $h \to bb, \tau\tau$ $\tan\beta$ dependence.
- If large signal strength of $gg \to h \to \gamma\gamma, ZZ$ is favored, type-I could be excluded.
- In type-I, light CDM (<40GeV) scenario is possible in IDM. $h \to Z_H Z_H$ is predicted. Indirect detection of CDM may be interesting.
- The type-II may be embed in E6 GUT. The extra fermions for anomaly-free are CDMs. (In the SUSY, the CDM candidate is super-partner of Higgs and Φ.) Dark matter mass should be around mh/2~63GeV. O(1) Yukawa is required.

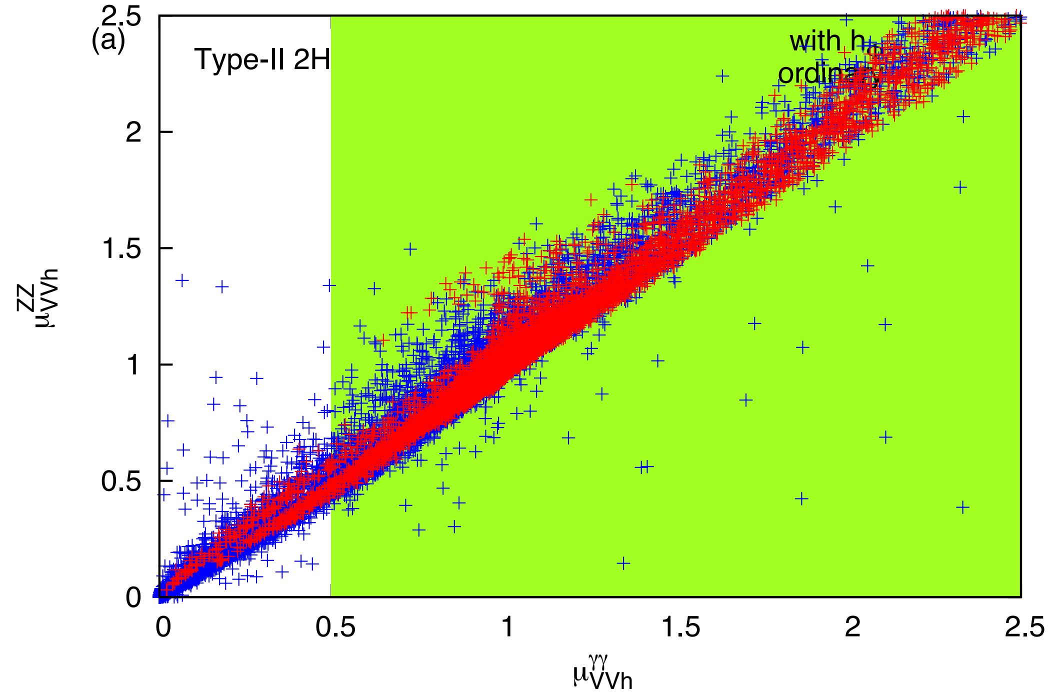
signal strength in 2HDMs (Ko, YO, Yu)

type-I

type-II

VV fusion





h→bb,ττ easily enhanced (reduced)