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A Three Higggs Doublet Model with Z3 soft breaking and its probes at future collider experiments

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D. Hernández-Otero, J. Hernández-Sanchez, S. Moretti, and T.S., arXiv:2203.06323

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Extended Higgs sector

- In the SM Higgs sector, there is no principle.
  - How many scalars, what kinds, etc?
  - What's the origin of the EWSB?
  - UV complete picture?
  - …
- For solving problems in the SM such as DM, m_ν, Baryogenesis……, the extended Higgs sector sometimes plays an important role.

The extended Higgs sector can be a key to the BSM physics.

Multi doublet model

- From the phenomenological viewpoint, the SM Higgs sector works very well
  - EW precision test $\rho \simeq 1$ → It's violated in an extended Higgs sector
    e.g. triplet Higgs vev breaks it at the tree level
  - Suppression of dangerous FCNC → Suppression on new flavour mixing

→ Extension in the Higgs sector tends to cause unpreferred situation

- **Multi Higgs doublet models** with **natural flavour conserving**
  - $\rho = 1$ is kept at the tree level
  - FCNC is suppressed by a (discrete) symmetry

Famous 2HDM

A model with two doublet scalars $(\mathbf{1}, \mathbf{2}, \frac{1}{2})$

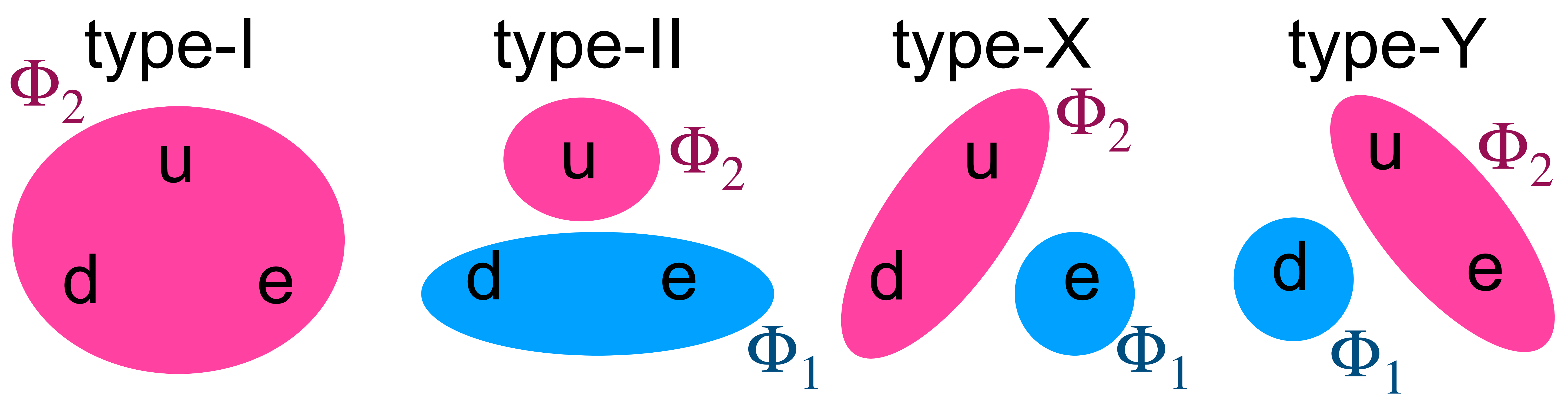
$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ \frac{v_1+\varphi_1^0+i\chi_1^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ \frac{v_2+\varphi_2^0+i\chi_2^0}{\sqrt{2}} \end{pmatrix}$$

- Mass eigen states:
  - Neutral : $\phi_1^0(\simeq h^0), \phi_2^0(H^0), \phi_3^0(A^0)$
  - Charged: $H^\pm$

$$\begin{pmatrix} z^0 \\ \phi_1^0 \\ \phi_2^0 \\ \phi_3^0 \end{pmatrix} = O_H \begin{pmatrix} \varphi_1^0 \\ \varphi_2^0 \\ \chi_1^0 \\ \chi_2^0 \end{pmatrix}$$

$$\begin{pmatrix} w^+ \\ H^+ \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \varphi_1^+ \\ \varphi_2^+ \end{pmatrix}$$

- Mechanism to suppress FCNC
  - Soft broken Z_2 symmetry
  - Alignment: $Y_{f1} \propto Y_{f2}$
  - Decoupling: $m_{H_i} \gg m_h$



V. Barger et al. (1990); Y. Grossman (1994); M. Aoki et al. (2009)

3HDM

One more doublet is added (3 doublets) Φ_1, Φ_2, Φ_3

- Mass eigenstates:
  - 5 Neutral $(h, H_1^0, H_2^0, A_1^0, A_2^0)$ and 2 charged $(H_1^\pm, H_2^\pm)$

new CP sources in the Chaged sector ← $A_{CP}(B \to X_{s+d}\gamma)$, $\Delta A_{CP} = \mathscr{A}^{\pm}_{X_s\gamma} - \mathscr{A}^{0}_{X_s\gamma}$

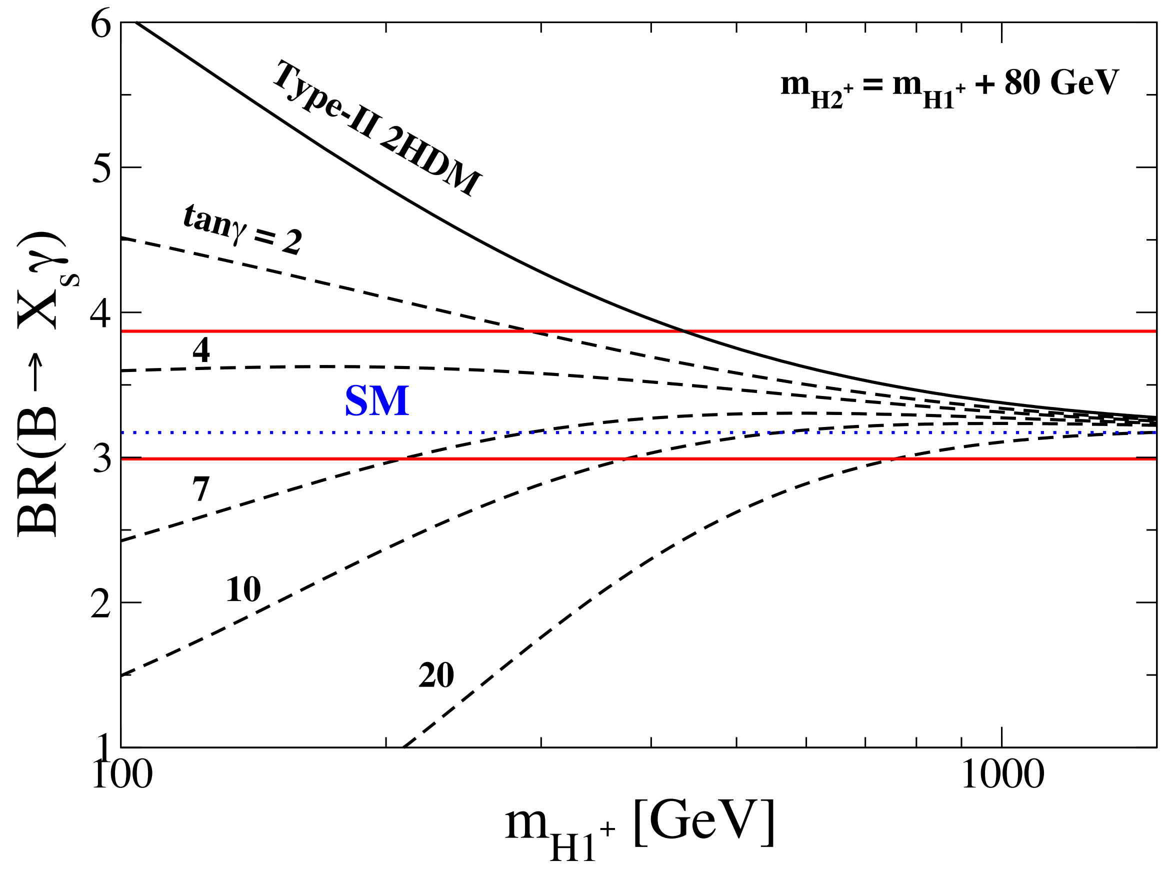
A. Akeroyd, S. Moretti, T.S., and M. Song, PRD(2021)

- Lighter charged Higgs boson is allowed

A. Akeroyd et al. (2018, 2020)

The $\mathrm{B}(B \to X_s\gamma)$ constraint is relaxed

→ $m_{H_i^\pm} \sim 200$GeV is allowed



A. Akeroyd et al. Int. J. Mod. Phys (2017)

Correlation between A_{CP} and EDM

Larger mass difference is, both CP asymmetry and edm become larger

$$\tan\beta = 25\ , \quad \tan\gamma = 1\ , \quad m_{H^\pm} = 170,\ 200\ \text{GeV}$$ in II, Y, Democratic

Untagged asymmetry can be as large as 2~3%

Combined analysis of Akeroyd, Moretti, T.S. and Song Phys.Rev. D(2021)
and Logan, Moretti, Rojas-Ciofalo, and Song JHEP(2021)

Outside of the black ring is allowed by neutron EDM

Flavour structure in 3HDM

Assumption: Each of u, d, e does not couple to more than one doublet

There are five patterns to suppress the FCNC by some symmetry

Φ_1 (and Φ_2 in type-I) might be a DM candidate,

unless the inert doublet(s) mix with active one(s).

3HDM with 2 inert doublets

We focus on a 3HDM with symmetry under Z_3 transformation

$$\Phi_1 \to \omega\Phi_1 \qquad \Phi_2 \to \omega^2\Phi_2 \qquad \Phi_3 \to \Phi_3 \qquad \omega = e^{i2\pi/3}$$

SM fermions are singlet under the Z_3

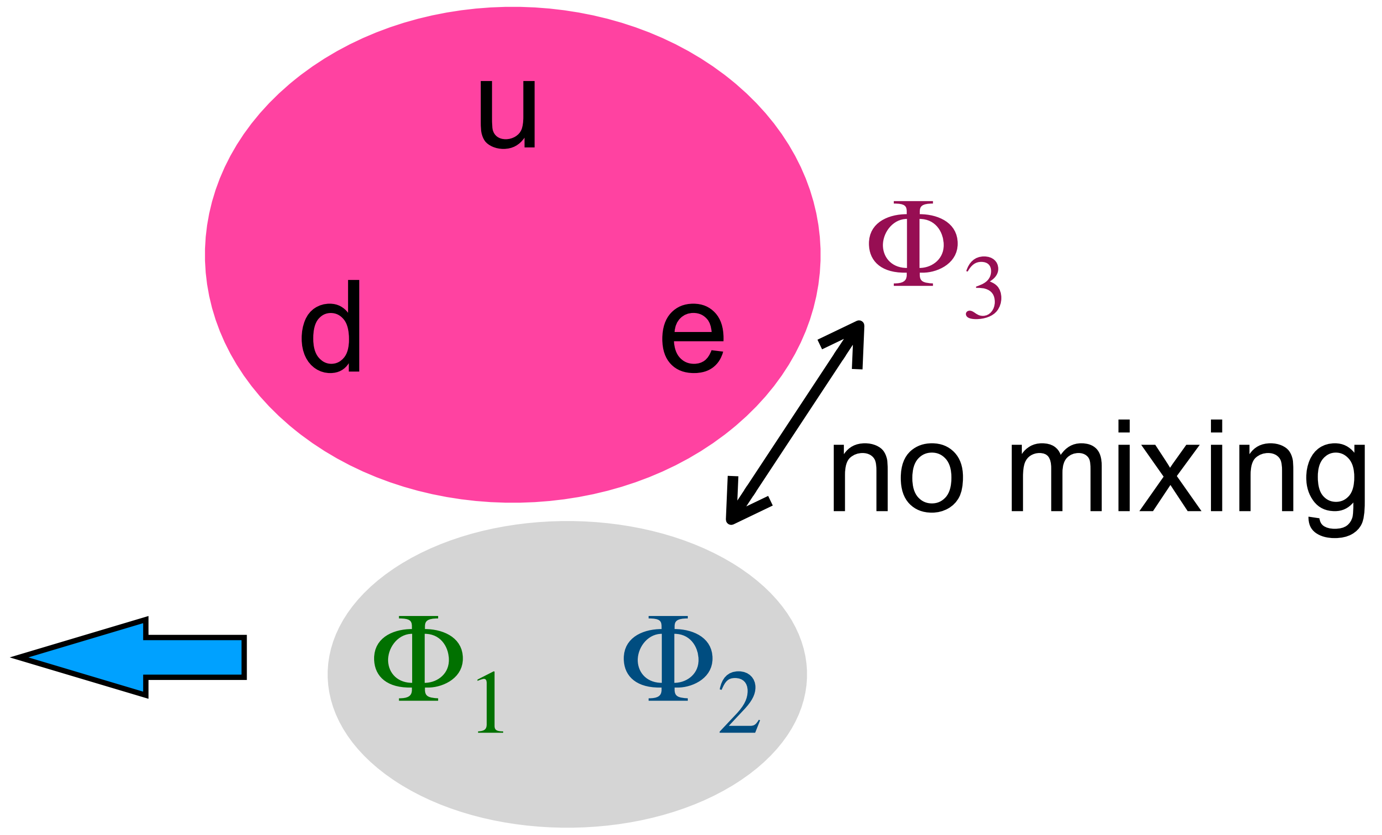
And we consider the case that only Φ_3 has a vev

↑

SM-like, h

Yukawa structure is type-I

DM candidate(s)



Z_3 symmetric potential

$$V = V_0 + V_{Z_3}$$

$$\begin{aligned}V_0 = {} & \mu_1^2(\Phi_1^\dagger\Phi_1) + \mu_2^2(\Phi_2^\dagger\Phi_2) + \mu_3^2(\Phi_3^\dagger\Phi_3) \\ & +\lambda_{11}(\Phi_1^\dagger\Phi_1)^2 + \lambda_{22}(\Phi_2^\dagger\Phi_2)^2 + \lambda_{33}(\Phi_3^\dagger\Phi_3)^2 \\ & +\lambda_{12}(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_{23}(\Phi_2^\dagger\Phi_2)(\Phi_3^\dagger\Phi_3) + \lambda_{31}(\Phi_3^\dagger\Phi_3)(\Phi_1^\dagger\Phi_1) \\ & +\lambda'_{12}(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \lambda'_{23}(\Phi_2^\dagger\Phi_3)(\Phi_3^\dagger\Phi_2) + \lambda'_{31}(\Phi_3^\dagger\Phi_1)(\Phi_1^\dagger\Phi_3)\end{aligned}$$

$$V_{Z_3} = \lambda_1(\Phi_2^\dagger\Phi_1)(\Phi_3^\dagger\Phi_1) + \lambda_2(\Phi_1^\dagger\Phi_2)(\Phi_3^\dagger\Phi_2) + \lambda_3(\Phi_1^\dagger\Phi_3)(\Phi_2^\dagger\Phi_3) + \text{h.c.}$$

Even with Z_3 breaking V_{soft}, no mixing between $\Phi_{1,2}$ and Φ_3 is induced

$$V_{\text{soft}} = -\mu_{12}^2(\Phi_1^\dagger\Phi_2) + \text{h.c.}$$

Z_3 breaking only in the inert sector

Mass eigenstates

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ \frac{\varphi_1^0 + i\chi_1^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ \frac{\varphi_2^0 + i\chi_2^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_3 = \begin{pmatrix} w^+ \\ \frac{v + h + iz^0}{\sqrt{2}} \end{pmatrix}$$

NG boson (w^+, z^0)

Neutral

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} c_h & s_h \\ -s_h & c_h \end{pmatrix} \begin{pmatrix} \varphi_1^0 \\ \varphi_2^0 \end{pmatrix} \qquad \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \begin{pmatrix} c_a & s_a \\ -s_a & c_a \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}$$

Charged

$$\begin{pmatrix} H_1^+ \\ H_2^+ \end{pmatrix} = \begin{pmatrix} c_c & s_c \\ -s_c & c_c \end{pmatrix} \begin{pmatrix} \varphi_1^+ \\ \varphi_2^+ \end{pmatrix}$$

$$\tan 2\theta_h = \frac{-\lambda_3 v^2 + 2\mu_{12}^2}{\mu_1^2 - \Lambda_1 - \mu_2^2 + \Lambda_2} \qquad \tan 2\theta_a = \frac{\lambda_3 v^2 + 2\mu_{12}^2}{\mu_1^2 - \Lambda_1 - \mu_2^2 + \Lambda_2}$$

$$\tan 2\theta_c = \frac{4\mu_{12}^2}{2\mu_1^2 - \lambda_{31} v^2 - 2\mu_2^2 + \lambda_{23} v^2}$$

$$\Lambda_1 = (\lambda_{31} + \lambda_{31}')v^2/2$$

$$\Lambda_2 = (\lambda_{23} + \lambda_{32}')v^2/2$$

Dark democracy limit

It is interesting to consider a special case: $\mu_1^2 = \mu_2^2\,, \quad \lambda_{31} = \lambda'_{31}\,, \quad \lambda_{23} = \lambda'_{23}$

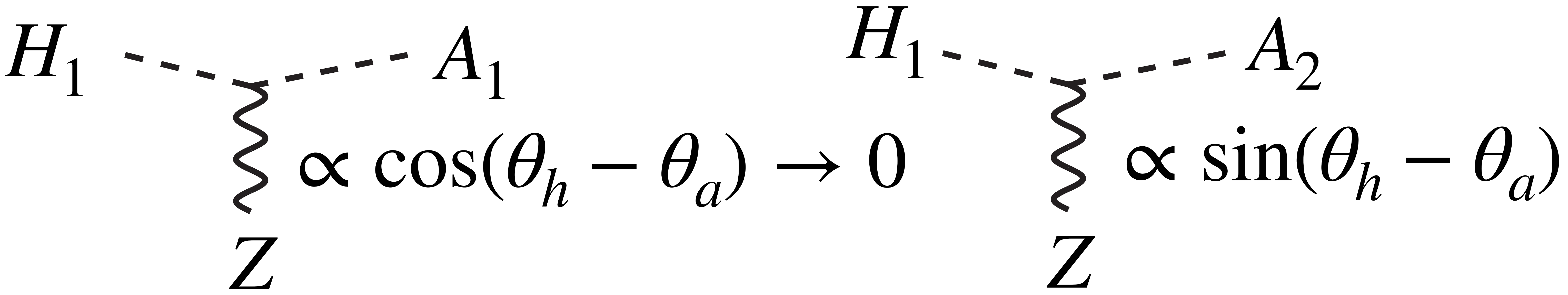
V. Keus, S. F. King, S. Moretti and D. Sokolowska, JHEP(2014) …

$$\theta_a = -\,\theta_h = \frac{\pi}{4}$$ (We also assume $\mu_{12}^2 < \lambda_3 v^2$)

$$m_{H_2}^2 = m_{H_1}^2 + (\lambda_3 v^2 - 2\mu_{12}^2)$$

$$m_{A_1}^2 = m_{H_1}^2 - 2\mu_{12}^2$$

$$m_{A_2}^2 = m_{H_2}^2 + 2\mu_{12}^2$$



DD constraint can be satisfied even for $m_{H_1} \sim m_{A_1}$

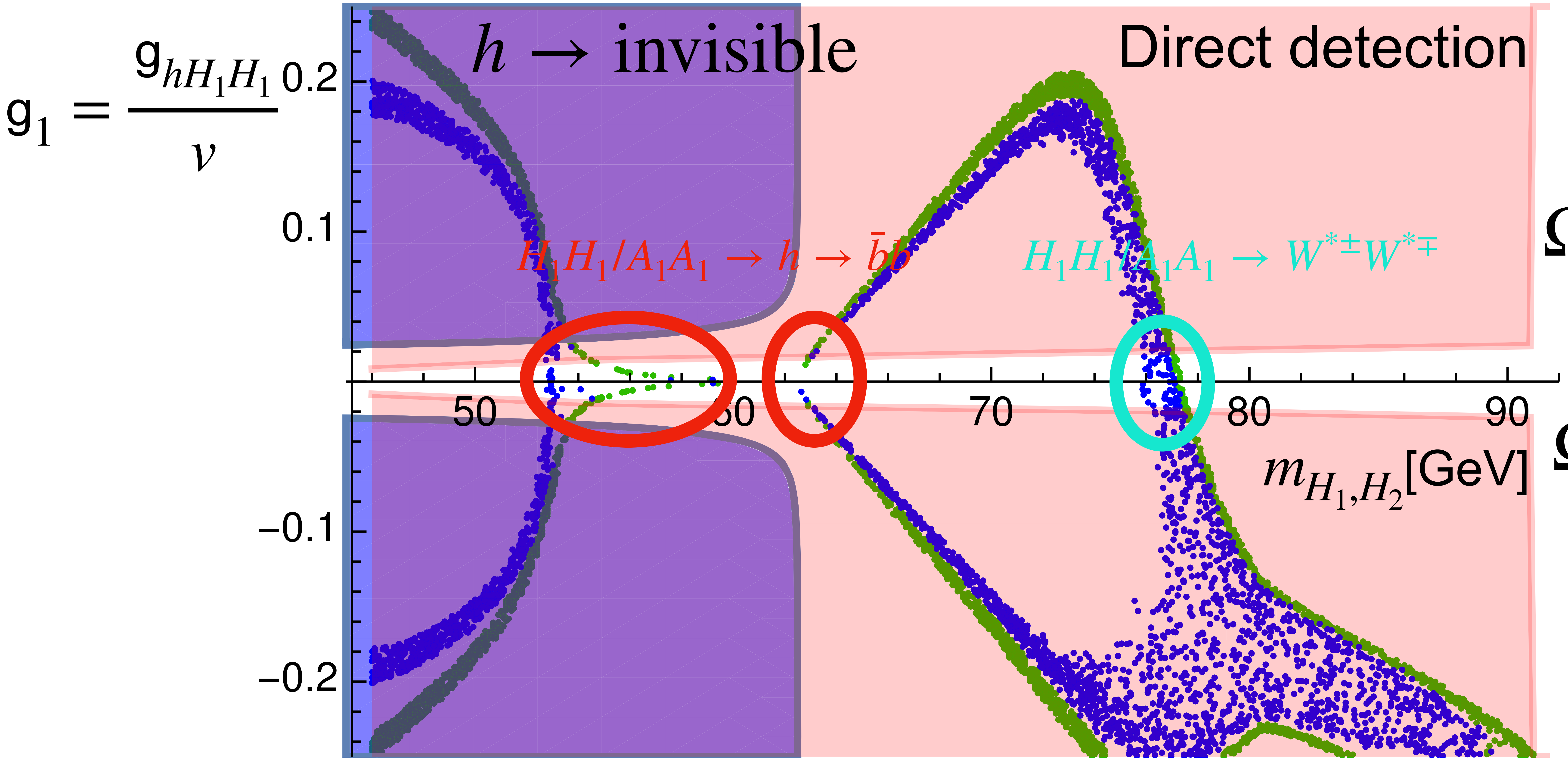
$$m_{H_1}^2 \le m_{A_1}^2 < m_{H_2}^2 \le m_{A_2}^2$$ H_1 can be DM

In the Z_3 symmetric case, $m_{H_1} = m_{A_1} < m_{H_2} = m_{A_2}$ Two components DM!

Hermaphrodite DM scenario

A. Aranda, D. Hernández-Otero, J. Hernández-Sanchez, V. Keus, S. Moretti, D. Rojas-Ciofalo, and T.S., PRD(2021)

Z_3 symmetric case: Both H_1 and A_1 are DM (Two component DM)



$$\Omega_{H_1}h^2 \simeq \Omega_{A_1}h^2 \simeq \frac{1}{2}\Omega_{DM}h^2$$

$$\Omega_{DM}h^2 = 0.1198 \pm 0.0027$$

- $m_{H_1,A_1} \ll m_{H_2,A_2} \ll m_{H^\pm_{1,2}}$
- $m_{H_1,A_1} \lesssim m_{H_2,A_2} \ll m_{H^\pm_{1,2}}$

Phenomenology in soft breaking Z_3 case

- The hermaphrodite scenario is attractive, but it will be difficult to separate two DM components by collider experiment

- We here consider the case with $V_{\rm soft}$ to introduce mass difference between H_1 and A_1

  - Even with $V_{\rm soft}$, $\theta_a = -\theta_h = \frac{\pi}{4}$ can be realised ⇒ $H_1 A_1 Z$ is highly suppressed
    no $A_1 \to H_1 Z^*$

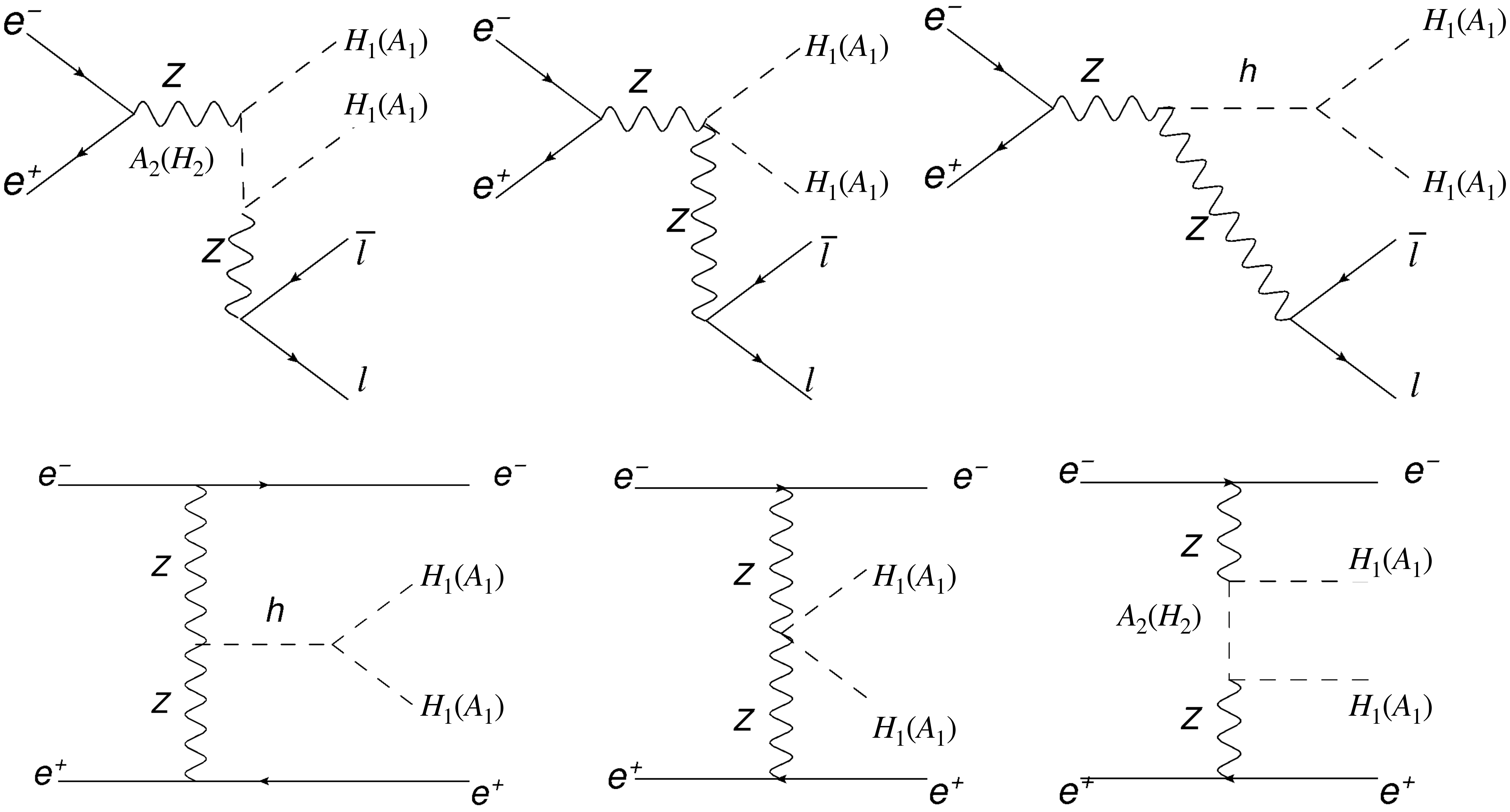
  - A_1 decays: $A_1 \to (A_2^*)h \to (Z^* H_1)(\bar{b}b) \to \nu\bar{\nu}\bar{b}bH_1$

  - It would be a single-component DM

Phenomenology at e+e- collider

We focus on $e^+e^- \to \ell^+\ell^- + 2\phi^0 \quad (\phi^0 = H_1, A_1)$

D. Hernández-Otero, J. Hernández-Sanchez, S. Moretti, and T.S., arXiv:2203.06323



For $\sqrt{s} = 250$GeV

	cross section
H_1^0	0.586pb
A_1^0	0.027pb

$m_{H_1} = 53$GeV

$m_{A_1} = 103$GeV

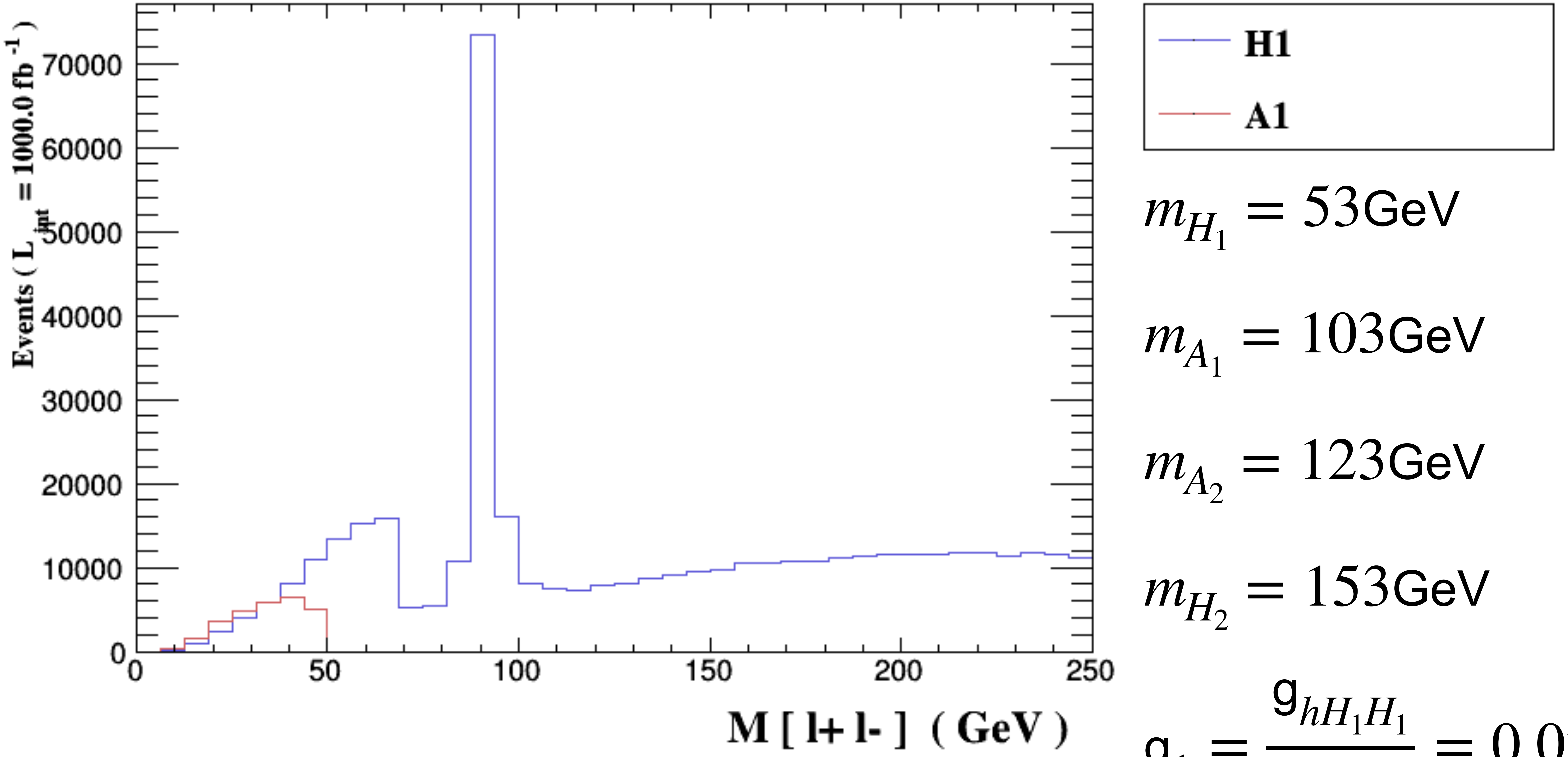
$m_{A_2} = 123$GeV

$m_{H_2} = 153$GeV

$A_1 \to (A_2^*)h \to (Z^*H_1)(\bar{b}b) \to \nu\bar{\nu}\bar{b}bH_1$ is not considered in the analysis

$M(\ell^+\ell^-)$ distribution for $e^+e^- \to \ell^+\ell^- + 2\phi^0$

D. Hernández-Otero, J. Hernández-Sanchez, S. Moretti, and T.S., arXiv:2203.06323



$m_{H_1} = 53\text{GeV}$

$m_{A_1} = 103\text{GeV}$

$m_{A_2} = 123\text{GeV}$

$m_{H_2} = 153\text{GeV}$

$$g_1 = \frac{g_{hH_1H_1}}{v} = 0.029$$

$M(\ell^+\ell^-)$ distribution for $e^+e^- \to \ell^+\ell^- + 2\phi^0$

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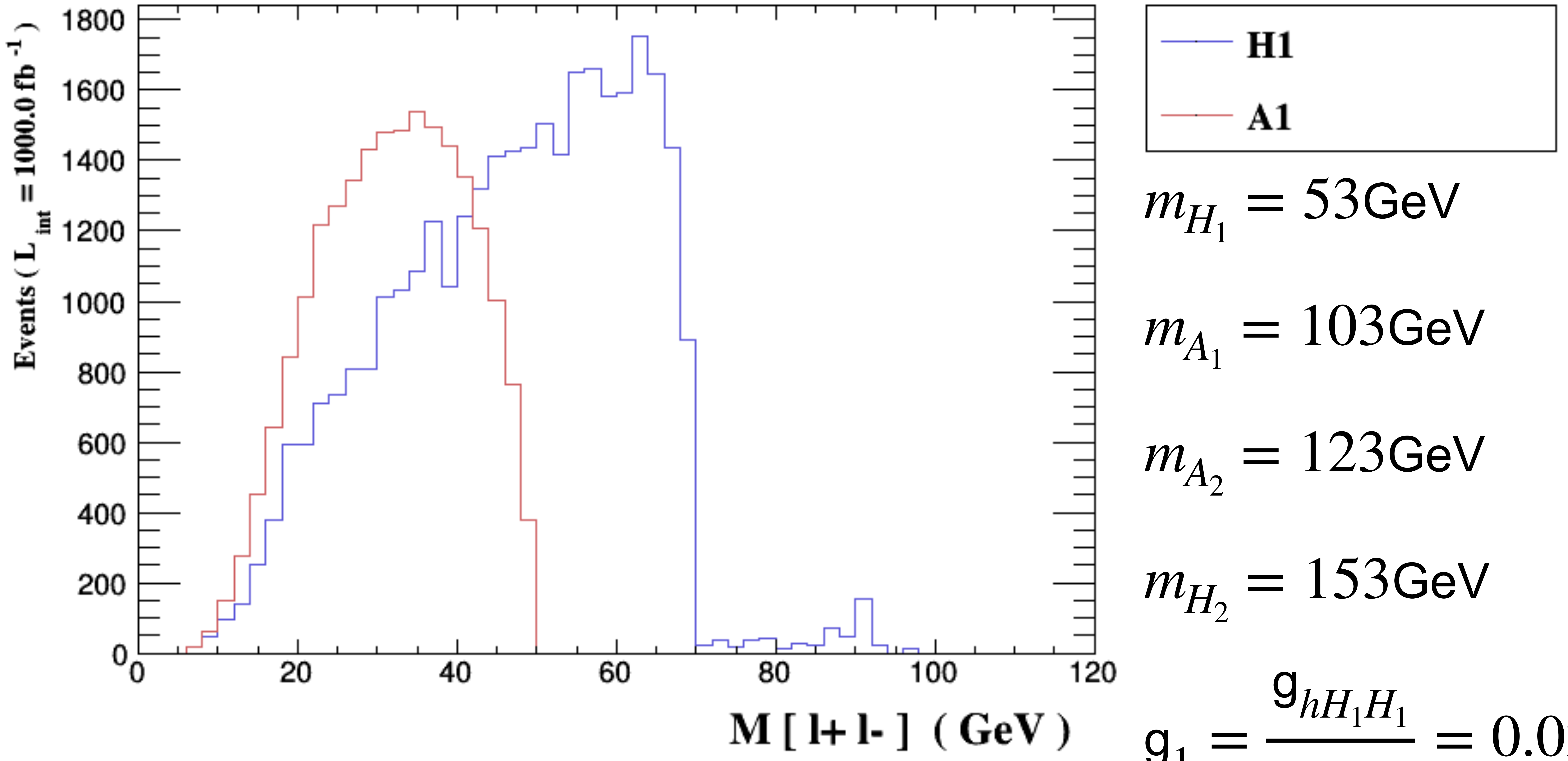

$m_{H_1} = 53\text{GeV}$

$m_{A_1} = 103\text{GeV}$

$m_{A_2} = 123\text{GeV}$

$m_{H_2} = 153\text{GeV}$

$g_1 = \frac{g_{hH_1H_1}}{v} = 0.029$

With cuts, $\not{E}_T < 120\text{GeV}$ and $\Delta R(\ell^+\ell^-) < 1.4$

Summary

- There are several problems, such as neutrino mass, DM,… in the SM
- Many new physics models are proposed, and many of them include extended Higgs sector
- EW precision test and flavour experiments might suggest a multi-doublet structure with natural flavour conserving
- We consider 3HDM as an attractive example
  - In an inert model, we have DM candidates
  - Future e^+e^- collider may be possible to probe the scenario