Two Higgs doublet models with a new U(1) gauge symmetry

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Based on arXiv:2512.23450

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1. Introduction

- The SM is based on gauge symmetry

⇒ **BSM sector would contain new/extended gauge symmetry**

Possible and simple remnant of BSM

⇒ An extra U(1) gauge symmetry

This U(1) would be spontaneously broken giving massive Z' boson

- Extra U(1) extension is phenomenologically interesting
  - Stabilizing dark matter and giving portal to SM
  - Extension of Higgs sector for U(1) breaking affects Higgs physics
  - Collider physics; Z' boson and/or new scalar production
  - Etc.

A new U(1) realizes type-I (and other types) 2HDM

Ex) If H_1 is charged under new U(1) while H_2 is not

Also SM fermions are not charged under it

⇨ H_2 only couples with SM fermions

⇨ Type-I 2HDM

Other cases and related phenomenology are also discussed by

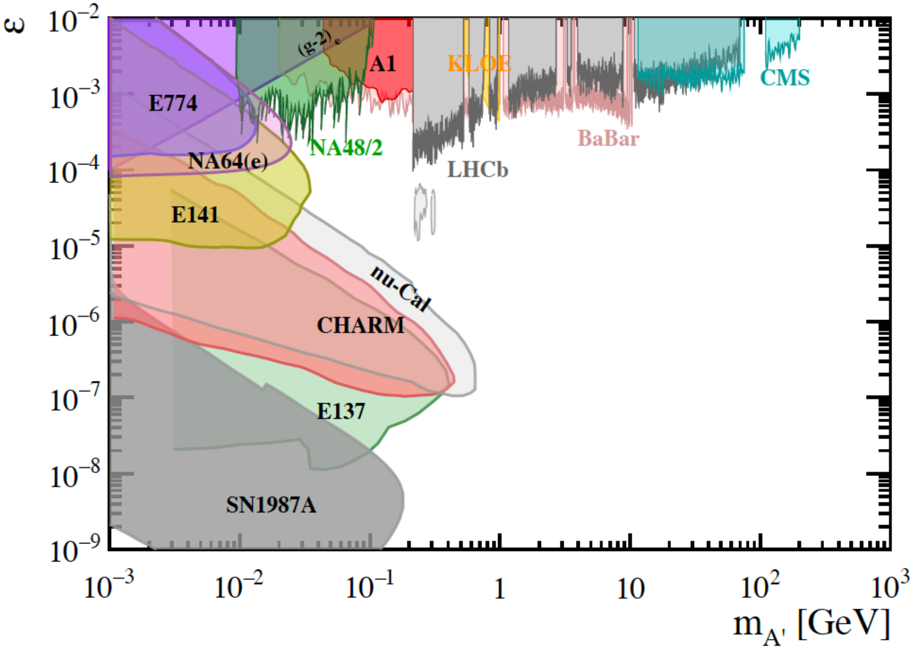
P.Ko, Yuji Omura, Chaehyun Yu, PLB 717 (2012) 202-206 (1204.4588)
P.Ko, Yuji Omura, Chaehyun Yu, JHEP 01 (2014) 016 (1309.7156)
P.Ko, Yuji Omura, Chaehyun Yu, JHEP 11 (2014) 054 (1405.2138)

2HDM + SM singlet scalar with new U(1) is considered
(Z’ can be heavy and easy to avoid experimental constraints)

What if we do not have singlet scalar?

1. Introduction

Constraints regarding Z' boson



Figs from 2005.01515

Dark photon searches

⇩

Coupling is highly restricted for light Z'

More constraints:

- ❖ Constraints from Z-Z' mixing
- ❖ EW precision tests (Z-pole)

Our questions are

- ◆Is minimal 2HDM+U(1) excluded without scalar extension?
- ◆If excluded, which constraint finally excludes it?
- ◆If excluded, what is other way to avoid constraint?

Outline of the talk

1. Introduction
2. Model & Constraints
3. Results
4. Summary

Model structure

	Q_L^i	u_R^i	d_R^i	L_L^i	e_R^i	ν_R^i	$\chi_{L,R}$	Φ_1	Φ_2
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	0	$\frac{1}{2}$	$\frac{1}{2}$
$U(1)_X$	$\frac{1}{3}(x_2 - x_R)$	$\frac{1}{3}(4x_2 - x_R)$	$\frac{1}{3}(-2x_2 - x_R)$	$-x_2 + x_R$	$-2x_2 + x_R$	x_R	x_χ	x_1	x_2

- 2 Higgs doublet model (2HDM) + new U(1) gauge symmetry
  (Flavor independent)
- We consider general anomaly free charge assignment at first
- We add a dark vector-like fermion to change BR of Z'
  (It would be DM candidate)
- This U(1) is spontaneously broken by 2HD VEVs

Lagrangian

$SU(2)_L \times U(1)_Y \times U(1)_X$ sector with kinetic mixing

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} (\tilde{B}_{\mu\nu}, \tilde{X}_{\mu\nu}) \begin{pmatrix} 1 & \sin\epsilon \\ \sin\epsilon & 1 \end{pmatrix} \begin{pmatrix} \tilde{B}^{\mu\nu} \\ \tilde{X}^{\mu\nu} \end{pmatrix}$$

Scalar potential

$$V = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2,$$

Yukawa interactions (Type-I 2HDM)

$$\mathcal{L}_Y = -Y_u \bar{Q}_L \tilde{\Phi}_2 u_R - Y_d \bar{Q}_L \Phi_2 d_R - Y_e \bar{L}_L \Phi_2 e_R - Y_\nu \bar{L}_L \Phi_2 \nu_R + \text{h.c.}$$

Covariant derivative under the gauge symmetry

$$D_\mu \Psi = (\partial_\mu - i g T^a_\Psi W^a_\mu - i g' Y_\Psi B_\mu - i g_X X_\Psi X_\mu) \Psi, \qquad X_\Psi = \tilde{X}_\Psi - Y_\Psi \frac{g'}{g_X} \tan\epsilon$$

Scalar sector

$$V = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2$$

2HDM with new U(1)

⇨ No CP-odd Higgs; it becomes NG boson absorbed by Z'

Scalar bosons: SM-like Higgs h, heavy neutral one H, and charged one $H^\pm$

Physical parameters: $\{m_h,\ m_H,\ m_{H^\pm},\ s_{\beta-\alpha},\ t_\beta,\ v\}$

Other parameters are written by

$$v^2\lambda_1 = (m_h^2 + m_H^2 t_\beta^2)s_{\beta-\alpha}^2 + (m_h^2 t_\beta^2 + m_H^2)c_{\beta-\alpha}^2 - (m_h^2 - m_H^2)s_{2(\beta-\alpha)}t_\beta,$$

$$v^2\lambda_2 = (m_h^2 + m_H^2/t_\beta^2)s_{\beta-\alpha}^2 + (m_h^2/t_\beta^2 + m_H^2)c_{\beta-\alpha}^2 + (m_h^2 - m_H^2)s_{2(\beta-\alpha)}/t_\beta,$$

$$v^2\lambda_3 = 2m_{H^\pm}^2 + (m_H^2 - m_h^2)(s_{\beta-\alpha} + c_{\beta-\alpha}/t_\beta)(s_{\beta-\alpha} - c_{\beta-\alpha}t_\beta),$$

$$v^2\lambda_4 = -2m_{H^\pm}^2.$$

Neutral gauge boson masses

$$\mathcal{L}_{\rm kin} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2$$

$$\Rightarrow \quad \mathcal{L}_{\rm mass} = \frac{v^2}{8}(W_3^\mu, B_\mu, X_\mu) \begin{pmatrix} g^2 & -gg' & -2gg_X(c_\beta^2 X_{\Phi_1} + s_\beta^2 X_{\Phi_2}) \\ & g'^2 & 2g'g_X(c_\beta^2 X_{\Phi_1} + s_\beta^2 X_{\Phi_2}) \\ & & 4g_X^2(c_\beta^2 X_{\Phi_1}^2 + s_\beta^2 X_{\Phi_2}^2) \end{pmatrix} \begin{pmatrix} W_3^\mu \\ B_\mu \\ X_\mu \end{pmatrix}$$

$$= \frac{v^2}{8}(A^\mu, Z_\mu, Z'_\mu) \begin{pmatrix} 0 & 0 & 0 \\ 0 & m_Z^2 & 0 \\ 0 & 0 & m_{Z'}^2 \end{pmatrix} \begin{pmatrix} A^\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix},$$

$$\begin{pmatrix} \tilde{B}_\mu \\ \tilde{X}_\mu \end{pmatrix} = \begin{pmatrix} 1 & -\tan\epsilon \\ 0 & \sec\epsilon \end{pmatrix} \begin{pmatrix} B_\mu \\ X_\mu \end{pmatrix}$$

$$\begin{pmatrix} W_3^\mu \\ B_\mu \\ X_\mu \end{pmatrix} = \begin{pmatrix} s_W & c_W & 0 \\ c_W & -s_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\zeta & -s_\zeta \\ 0 & s_\zeta & c_\zeta \end{pmatrix} \begin{pmatrix} A^\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

Mass eigenstates

Z-Z' mixing is not very suppressed unless g_X << 1 or some cancellation effect

⇨ We consider no Z-Z' mixing condition

2. Model & Constraints

No (Z-Z') mixing condition

	Q_L^i	u_R^i	d_R^i	L_L^i	e_R^i	ν_R^i	$\chi_{L,R}$	Φ_1	Φ_2
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**2**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	0	$\frac{1}{2}$	$\frac{1}{2}$
$U(1)_X$	$\frac{1}{3}(x_2 - x_R)$	$\frac{1}{3}(4x_2 - x_R)$	$\frac{1}{3}(-2x_2 - x_R)$	$-x_2 + x_R$	$-2x_2 + x_R$	x_R	x_χ	x_1	x_2

From the mass matrix for Z-Z'

$$m^2_{Z,Z'} = M_{11}c^2_\zeta + M_{22}s^2_\zeta \pm M_{12}s_{2\zeta}$$

$$t_{2\zeta} = \frac{2M_{12}}{M_{11} - M_{22}},$$

$$\left\{\begin{aligned} M_{11} &= \frac{g^2}{4c^2_W}v^2, \\ M_{22} &= g^2_X v^2 (c^2_\beta X^2_{\Phi_1} + s^2_\beta X^2_{\Phi_2}), \\ M_{12} &= -\frac{g g_X}{2c_W} v^2 (c^2_\beta X_{\Phi_1} + s^2_\beta X_{\Phi_2}) \end{aligned}\right.$$

Mixing vanishes if $M_{12} = 0$

$$\Rightarrow \quad c^2_\beta X_{\Phi_1} + s^2_\beta X_{\Phi_2} = 0 \leftrightarrow \frac{X_{\Phi_1}}{X_{\Phi_2}} = -t^2_\beta$$

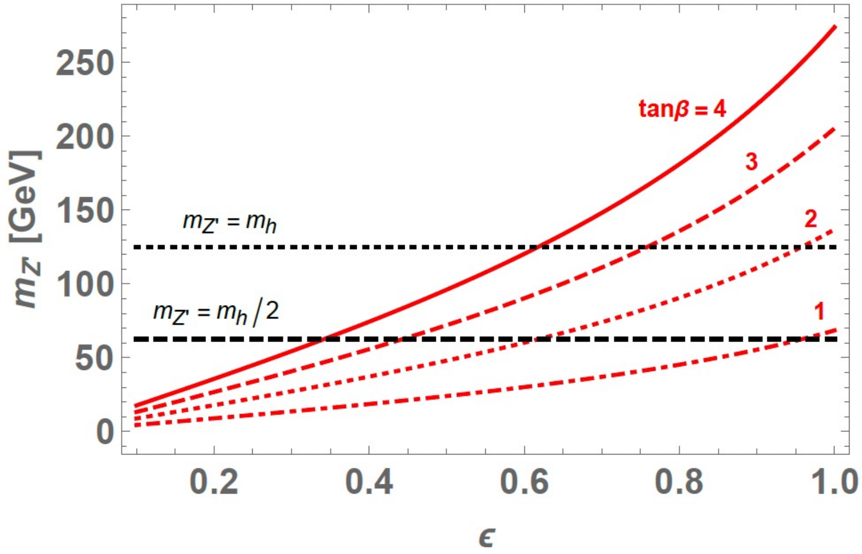
$$\left(\begin{aligned} X_\Psi &= \tilde{X}_\Psi - Y_\Psi \frac{g'}{g_X} \tan\epsilon \\ \tilde{X}_{\Phi 1(2)} &= x_{1(2)} \end{aligned} \right)$$

For benchmark models, we adopt

- Hidden $U(1)_H$ model $\quad x_2 = x_R = 0 \quad \Rightarrow \quad t_\epsilon = \dfrac{2x_1 g_X}{g'(1+t^2_\beta)}, \quad m_{Z'} = \dfrac{t_\beta}{1+t^2_\beta} x_1 g_X v$
- $U(1)_R$ model $\quad x_2 = x_R, \epsilon = 0 \quad \Rightarrow \quad \dfrac{x_1}{x_2} = -t^2_\beta, \quad m_{Z'} = g_X x_2 t_\beta v$

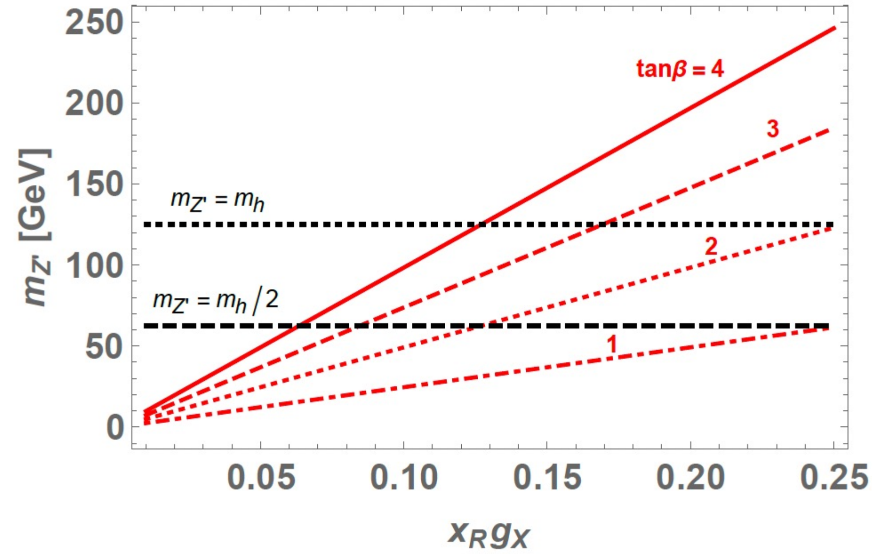
  (Only right-handed fermions are charged)

Z' mass and model parameters under no-mixing condition



U(1)$_H$ model

$$m_{Z'} = \frac{t_\beta}{1+t_\beta^2} x_1 g_X v$$



U(1)$_R$ model

$$m_{Z'} = g_X x_2 t_\beta v$$

$(x_2 = x_R, \epsilon = 0)$

Interactions under no-mixing condition

$$\mathcal{L}_{\rm kin} = \frac{m_Z^2}{v}(s_{\beta-\alpha}h + c_{\beta-\alpha}H)Z_\mu Z^\mu + \frac{2m_W^2}{v}(s_{\beta-\alpha}h + c_{\beta-\alpha}H)W_\mu W^\mu$$
$$+ \frac{m_{Z'}^2}{v}\left(s_{\beta-\alpha} + c_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right)Z'_\mu Z'^\mu h + \frac{m_{Z'}^2}{v}\left(c_{\beta-\alpha} - s_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right)Z'_\mu Z'^\mu H$$
$$+ \frac{2m_Z m_{Z'}}{v}(s_{\beta-\alpha}H - c_{\beta-\alpha}h)Z_\mu Z'^\mu$$
$$+ \frac{2m_W m_{Z'}}{v}H^\pm W_\mu^\mp Z'^\mu$$
$$\equiv \sum_{\phi=\{h,H,H^\pm\}} \sum_{V,V'=\{W^\pm,Z,Z'\}} g_{\phi VV'}\phi V_\mu V'^\mu.$$

Gauge-Higgs interactions

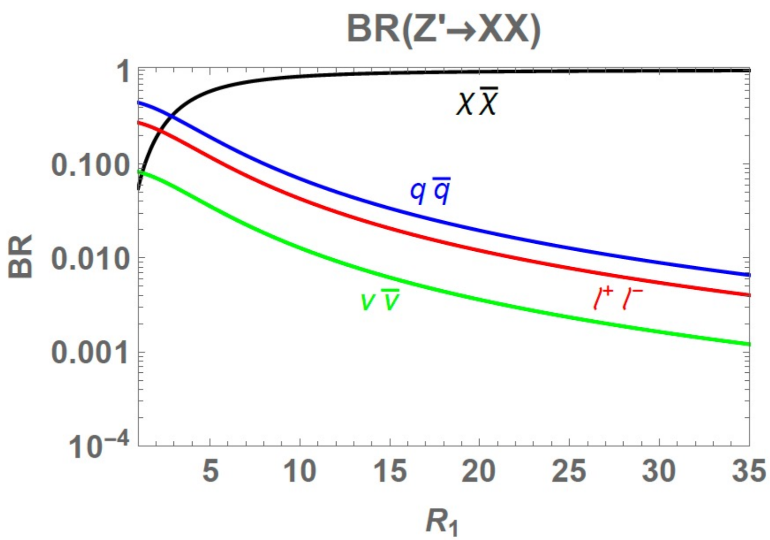
$$\mathcal{L}_{Z'ff} = g_{ffZ'}\overline{f}\gamma^\mu(v_{Z'f} - a_{Z'f}\gamma_5)fZ'_\mu$$

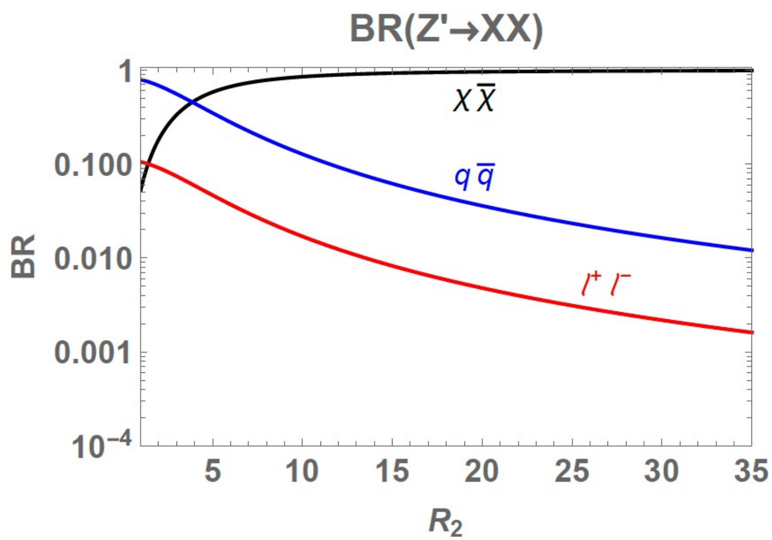
Z'-fermion interactions

	$g_{ffZ'}$	$v_{Z'e}$	$v_{Z'\nu_L}$	$v_{Z'd}$	$v_{Z'u}$	$v_{Z'\nu_R}$	$v_{Z'\chi}$	$a_{Z'e}$	$a_{Z'\nu_L}$	$a_{Z'd}$	$a_{Z'u}$	$a_{Z'\nu_R}$	$a_{Z'\chi}$
$U(1)_H$	$\frac{1}{2}g'\tan\epsilon$	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{6}$	$-\frac{5}{6}$	0	R_1	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	0	0
$U(1)_R$	$\frac{1}{2}g_X x_R$	-1	0	-1	1	1	R_2	1	0	1	-1	-1	0

$$R_1 \equiv (1+\tan^2\beta)x_\chi/(x_1\cos\epsilon) \text{ and } R_2 \equiv 2x_\chi/x_R$$

Z’ decay





$$\Gamma_{Z'\to f\bar{f}} \simeq (g_{ffZ'})^2 \frac{(v_{Z'f})^2 + (a_{Z'f})^2}{12\pi} m_{Z'}$$

We can modify BR by charge of dark particle

	$g_{ffZ'}$	$v_{Z'e}$	$v_{Z'\nu_L}$	$v_{Z'd}$	$v_{Z'u}$	$v_{Z'\nu_R}$	$v_{Z'\chi}$	$a_{Z'e}$	$a_{Z'\nu_L}$	$a_{Z'd}$	$a_{Z'u}$	$a_{Z'\nu_R}$	$a_{Z'\chi}$
$U(1)_H$	$\frac{1}{2}g'\tan\epsilon$	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{6}$	$-\frac{5}{6}$	0	R_1	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	0	0
$U(1)_R$	$\frac{1}{2}g_X x_R$	-1	0	-1	1	1	R_2	1	0	1	-1	-1	0

$$R_1 \equiv (1+\tan^2\beta)x_\chi/(x_1\cos\epsilon) \text{ and } R_2 \equiv 2x_\chi/x_R$$

Phenomenological constraints

Higgs sector

Constraints regarding Higgs potential and Yukawa interactions are similar to type-I 2HDM

Differences are:
- ✓ We don't have CP-Odd scalar; it becomes NG boson absorbed by Z'
- ✓ Some terms in potential are forbidden by U(1) gauge symmetry

Taking into account these differences, we consider

- ❖ Stability and perturbative unitarity
- ❖ Oblique parameter constraints (STU)
- ❖ Constraints from meson decays

(We adopt *SuperIso code*)
https://superiso.in2p3.fr/

$$B_s \to X_s \gamma, \quad B \to \tau\nu, \quad B_s \to \mu^+\mu^-, \quad B_d \to \mu^+\mu^-, \quad D_s \to \mu\nu, \quad D_s \to \tau\nu, \quad \frac{K \to \mu\nu}{\pi \to \mu\nu}$$

- ❖ Diphoton decay of the SM Higgs (charged Higgs contribution)

$$\Gamma_{h\to\gamma\gamma} \simeq \frac{\sqrt{2} G_F \alpha_{\rm em}^2 m_h^3}{16\pi^3} \left| (t, W)_{\rm SM} - \frac{1}{12} - \frac{19}{360} \frac{m_h^2}{m_{H^\pm}^2} \right|^2 \qquad \mu_{\gamma\gamma} = 1.04^{+0.10}_{-0.09}$$

ATLAS, JHEP 08 (2022) 088

Higgs decays

$$\begin{aligned}\mathcal{L}_{\rm kin} &= \frac{m_Z^2}{v}(s_{\beta-\alpha}h + c_{\beta-\alpha}H)Z_\mu Z^\mu + \frac{2m_W^2}{v}(s_{\beta-\alpha}h + c_{\beta-\alpha}H)W_\mu W^\mu \\ &+ \frac{m_{Z'}^2}{v}\left(s_{\beta-\alpha} + c_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right) Z'_\mu Z'^\mu h + \frac{m_{Z'}^2}{v}\left(c_{\beta-\alpha} - s_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right) Z'_\mu Z'^\mu H \\ &+ \frac{2m_Z m_{Z'}}{v}(s_{\beta-\alpha}H - c_{\beta-\alpha}h)Z_\mu Z'^\mu \\ &+ \frac{2m_W m_{Z'}}{v}H^\pm W_\mu^\mp Z'^\mu \\ &\equiv \sum_{\phi=\{h,H,H^\pm\}} \sum_{V,V'=\{W^\pm,Z,Z'\}} g_{\phi VV'}\phi V_\mu V'^\mu .\end{aligned}$$

hZ'Z' and HZ'Z' couplings
are not suppressed in alignment limit
($c_{\beta-\alpha}=0$)

h → Z'Z'
H → Z'Z'
can be dominant

The SM Higgs decay into Z'Z' ($2m_{Z'} < m_h$)

$$\Gamma(h\to Z'Z') = \frac{m_h^3}{32\pi v^2}\left(s_{\beta-\alpha} + c_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right)^2 \left[12x_{Z'}^2 + \lambda(x_{Z'},x_{Z'})\right]\lambda^{1/2}(x_{Z'},x_{Z'})$$

$$\Gamma(h\to ZZ') = \frac{m_h^3}{16\pi v^2}c_{\beta-\alpha}^2\left[12x_Z x_{Z'} + \lambda(x_Z,x_{Z'})\right]\lambda^{1/2}(x_{Z'},x_Z),$$

$$\lambda(x,y) \equiv (1-x-y)^2 - 4xy$$

$$x_V \equiv m_V^2/m_h^2.$$

Z'Z' mode (alignment limit)

$$\Rightarrow \Gamma(h\to Z'Z') = \frac{m_h^3}{32\pi v^2}[1-6x_{Z'} + \mathcal{O}(x_{Z'}^2)] \simeq 0.3\left[1-0.04\left(\frac{m_{Z'}}{10\ \mathrm{GeV}}\right)^2\right]\ \mathrm{GeV}$$

We find BR(h→Z'Z') becomes dominant ⇒ We should require ($2m_{Z'} > m_h$)

Higgs decays $(2m_{Z'} > m_h)$

$$\Gamma(h \to Z' f\bar{f}) = \frac{g_{hZ'Z'}^2 g_{ffZ'}^2 (v_{Z'f}^2 + a_{Z'f}^2)}{128\pi m_h} H(x_{Z'}^h, x_{Z'}^h),$$

$$H(x, y^*) = \frac{\arctan\left(\frac{1 - x - y^*}{\sqrt{-\lambda(x, y^*)}}\right) + \arctan\left(\frac{1 - x + y^*}{\sqrt{-\lambda(x, y^*)}}\right)}{2x\sqrt{-\lambda(x, y^*)}}$$

$$\times \left[(1 - y^*)^3 - 3x^3 + (9y^* + 7)x^2 - 5(1 - y^*)^2 x\right]$$

$$+ \frac{1}{12xy^*}\Big\{(x - 1)\left[6y^{*2} + y^*(39x - 9) + 2(1 - x)^2\right]$$

$$- 3y^*\left[y^{*2} + 2y^*(3x - 1) - x(3x + 4) + 1\right]\ln x\Big\}$$

We need to take into account constraints from four lepton final states

⇨ LHC data (ATLAS) constrains $\sigma_{4\ell} \lesssim 0.1\ \mathrm{fb}$ (ATLAS, PLB 824, 136832, 2022)

⇩

$$\sigma(gg \to h) BR(h \to Z'\ell^+\ell^-) BR(Z' \to \ell^+\ell^-) \lesssim 0.1\ \mathrm{fb}$$

We also consider Higgs invisible decay constraint

$$BR(h \to invisible) = BR(h \to Z'\chi\bar{\chi}) BR(Z' \to \chi\bar{\chi}) < 0.107$$

(ATLAS, PLB 842, 137963, 2023)

Higgs decays

Heavy neutral Higgs decays (H→VV, V=Z,Z')

- ❑ $2m_{Z'} < m_H$ (ZZ mode is the same as 2HDM)

$$\begin{cases} \Gamma(H \to Z'Z') = \frac{m_H^3}{32\pi v^2}\left(c_{\beta-\alpha} - s_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right)^2 \left[12y_{Z'}^2 + \lambda(y_{Z'}, y_{Z'})\right] \lambda^{1/2}(y_{Z'}, y_{Z'}), \\ \Gamma(H \to ZZ') = \frac{m_H^3}{16\pi v^2} s_{\beta-\alpha}^2 \left[12 y_Z y_{Z'} + \lambda(y_Z, y_{Z'})\right] \lambda^{1/2}(y_Z, y_{Z'}), \end{cases}$$

$$\left(y_X \equiv m_X^2/m_H^2 \right)$$

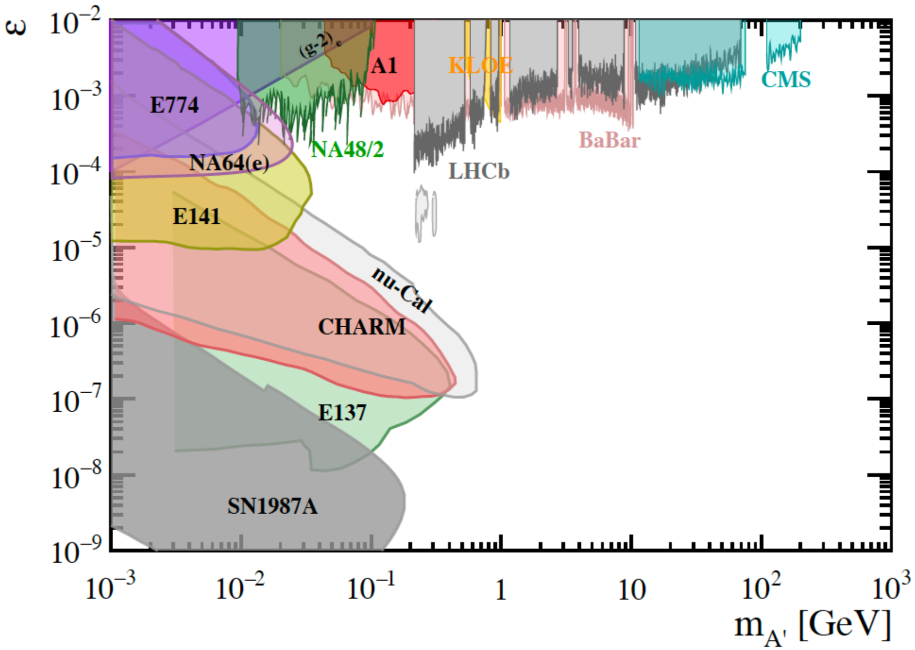
- ❑ $2m_{Z'} > m_H > m_{Z'}$

$$\begin{cases} \Gamma(H \to Z'Z'^* \to Z'f\bar{f}) = \frac{m_{Z'}^4 g_{ffZ'}^2 (v_f^2 + a_f^2)}{32\pi^3 m_H v^2} N_f^c \left(c_{\beta-\alpha} - s_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right)^2 H(y_{Z'}, y_{Z'}), \\ \Gamma(H \to ZZ'^* \to Zf\bar{f}) = \frac{m_Z^2 m_{Z'}^2 g_{ffZ'}^2 (v_f^2 + a_f^2)}{32\pi^3 m_H v^2} N_f^c s_{\beta-\alpha}^2 H(y_Z, y_{Z'}), \\ \Gamma(H \to Z'Z^* \to Z'f\bar{f}) = \frac{m_Z^2 m_{Z'}^2 g_Z^2 [(v_f^{\rm SM})^2 + (a_f^{\rm SM})^2]}{32\pi^3 m_H v^2} N_f^c s_{\beta-\alpha}^2 H(y_{Z'}, y_Z), \end{cases}$$

We also consider the four leptons constraint

$$\sigma(gg \to H) BR(H \to 4l) \leq 0.1 \text{fb}$$

Z' searches



For $m_{Z'} > m_h/2$, we consider

- CMS constraints

  (CMS, 2019)

- LHCb constraints

  (LHCb, 2020, PRL 124)

$$pp \to Z' \to \mu^+\mu^-$$

We also consider LEP constraint from Z-pole cross section

$$e^+e^- \to Z'/Z \to l^+l^- \qquad \sigma^{\text{exp}}_{\mu^+\mu^-} = 2.0018 \pm 0.0060 \text{ nb with } \sqrt{s} = 91.23 \text{ GeV}$$

consistent with the SM

Existence of Z' modify the cross section

(ALEPH PLB 399, 392, 1997)

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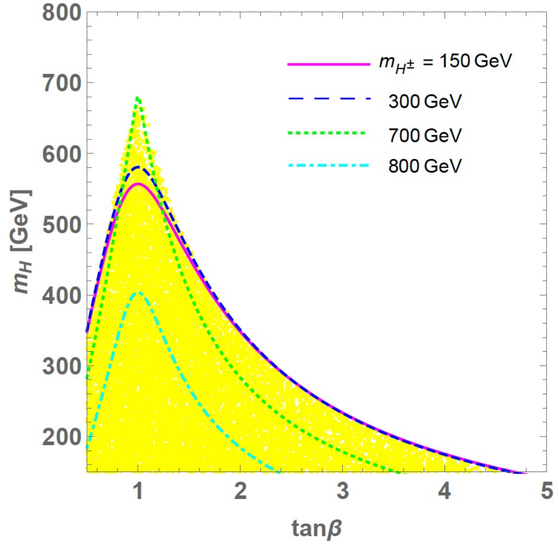
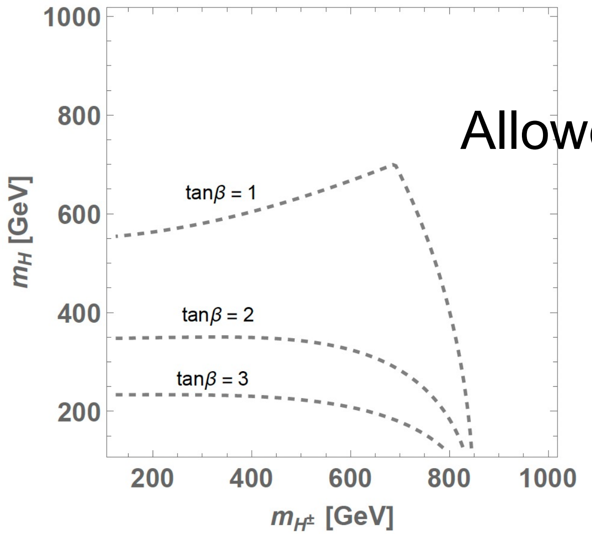
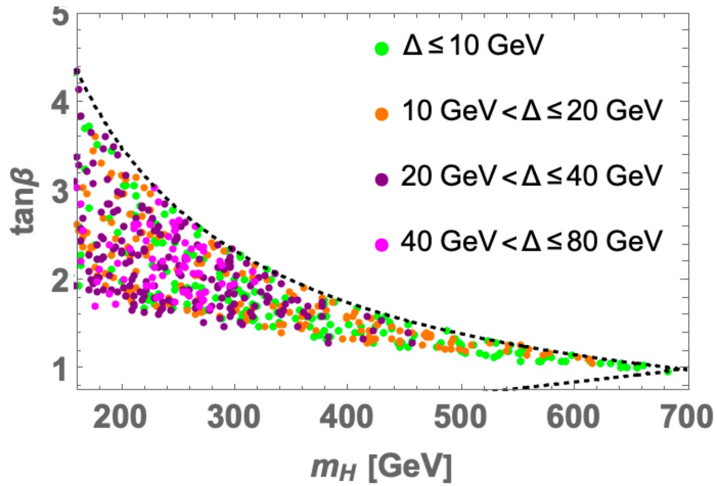
Constraints from Higgs related phenomena





Allowed region by unitarity



Unitarity + STU + flavor constraints

$$\Delta \equiv |m_{H^\pm} - m_H|$$

❖ Higgs diphoton decay constrain charged Higgs mass: $m_{H\pm}$>160 GeV

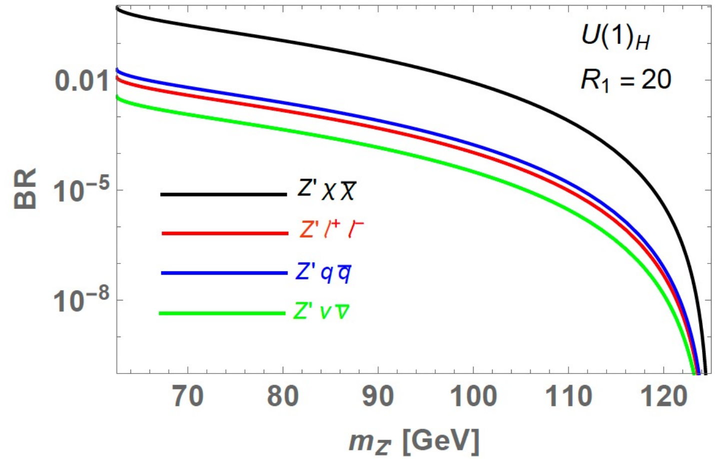
3. Results

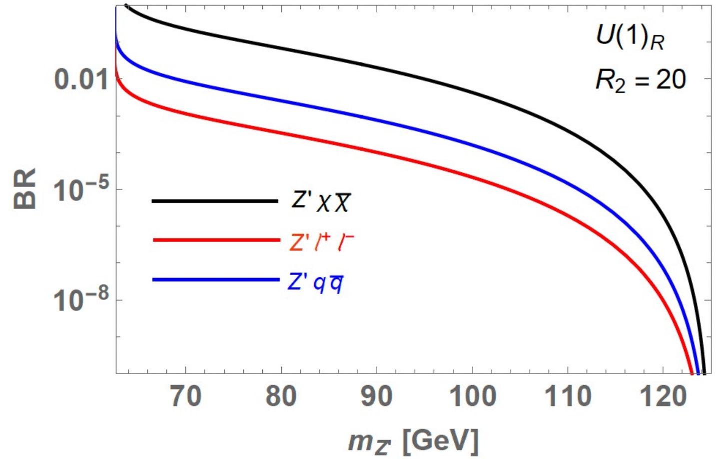
BRs of Higgs decays

$$\mathcal{L}_{Z'ff} = g_{ffZ'}\overline{f}\gamma^{\mu}(v_{Z'f} - a_{Z'f}\gamma_5)fZ'_{\mu}$$

	$g_{ffZ'}$	$v_{Z'e}$	$v_{Z'\nu_L}$	$v_{Z'd}$	$v_{Z'u}$	$v_{Z'\nu_R}$	$v_{Z'\chi}$	$a_{Z'e}$	$a_{Z'\nu_L}$	$a_{Z'd}$	$a_{Z'u}$	$a_{Z'\nu_R}$	$a_{Z'\chi}$
$U(1)_H$	$\frac{1}{2}g'\tan\epsilon$	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{6}$	$-\frac{5}{6}$	0	R_1	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	0	0
$U(1)_R$	$\frac{1}{2}g_X x_R$	-1	0	-1	1	1	R_2	1	0	1	-1	-1	0

SM Higgs decay (new modes)

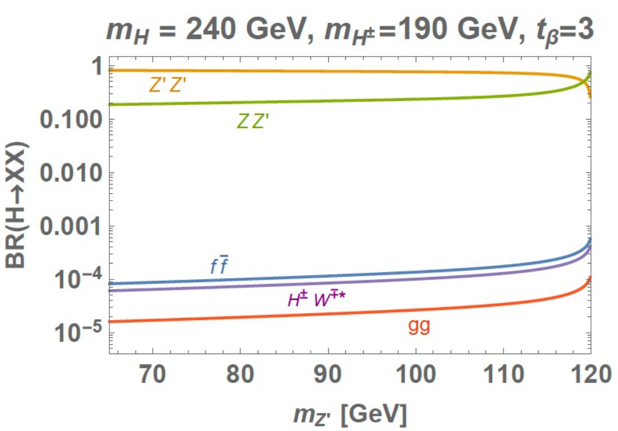


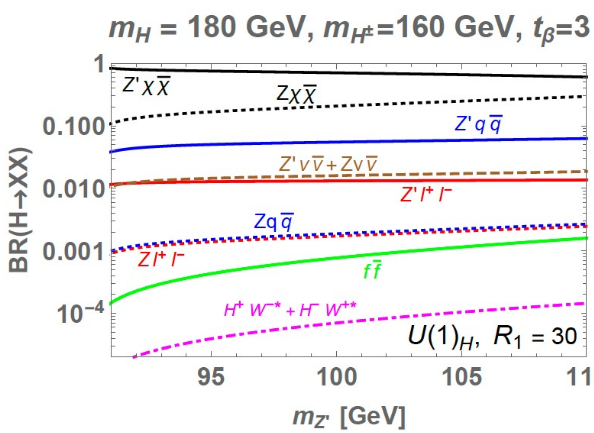


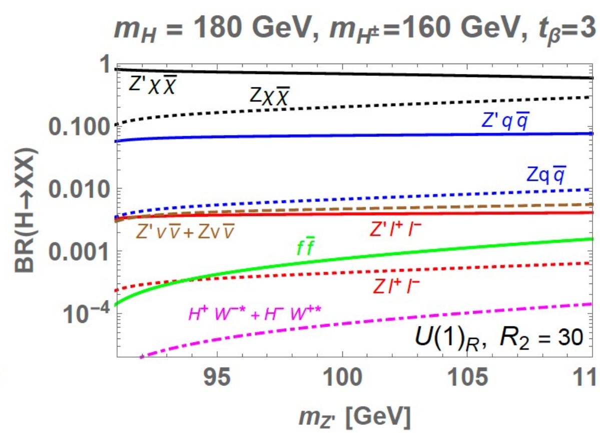
Heavy Higgs decay

On-shell Z'

One off-shell Z'



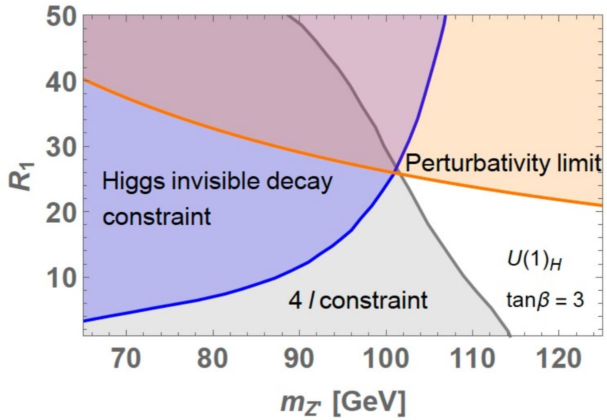


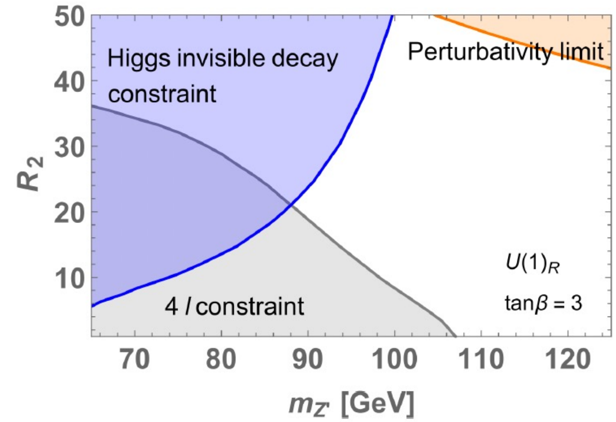


3. Results

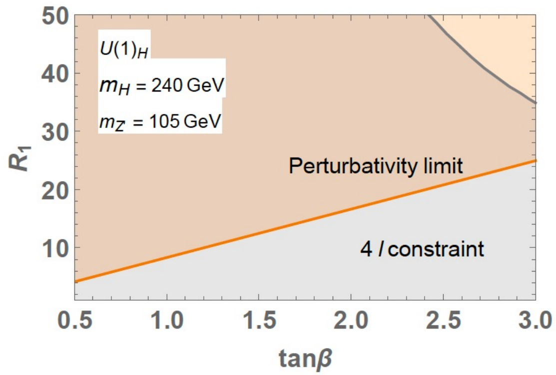
Constraints from Higgs decays

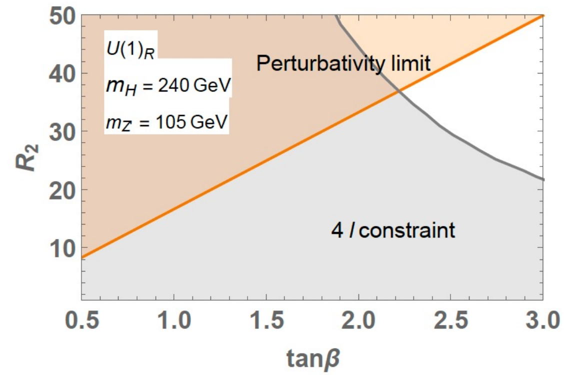
SM Higgs

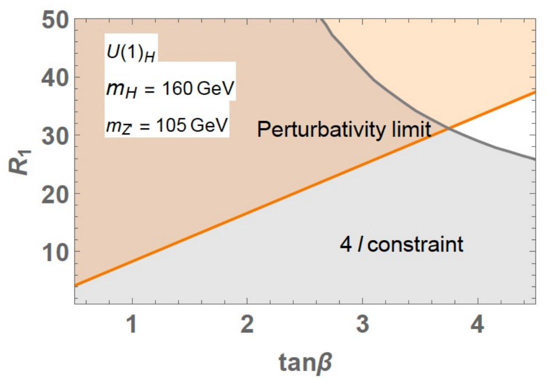


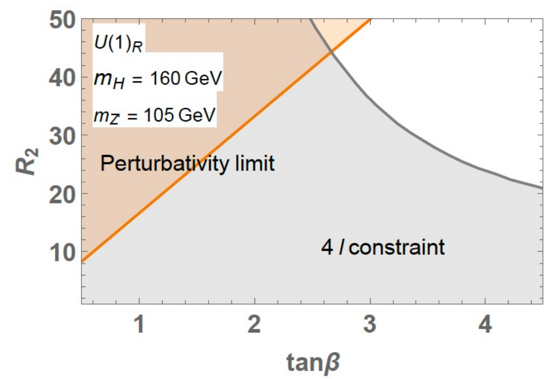


Heavy Higgs









Perturbative limit:

$$R_{1,2}\, g_{\chi\chi Z'} < \sqrt{4\pi}$$

We need large $R_{1,2}$ to avoid 4l constraint

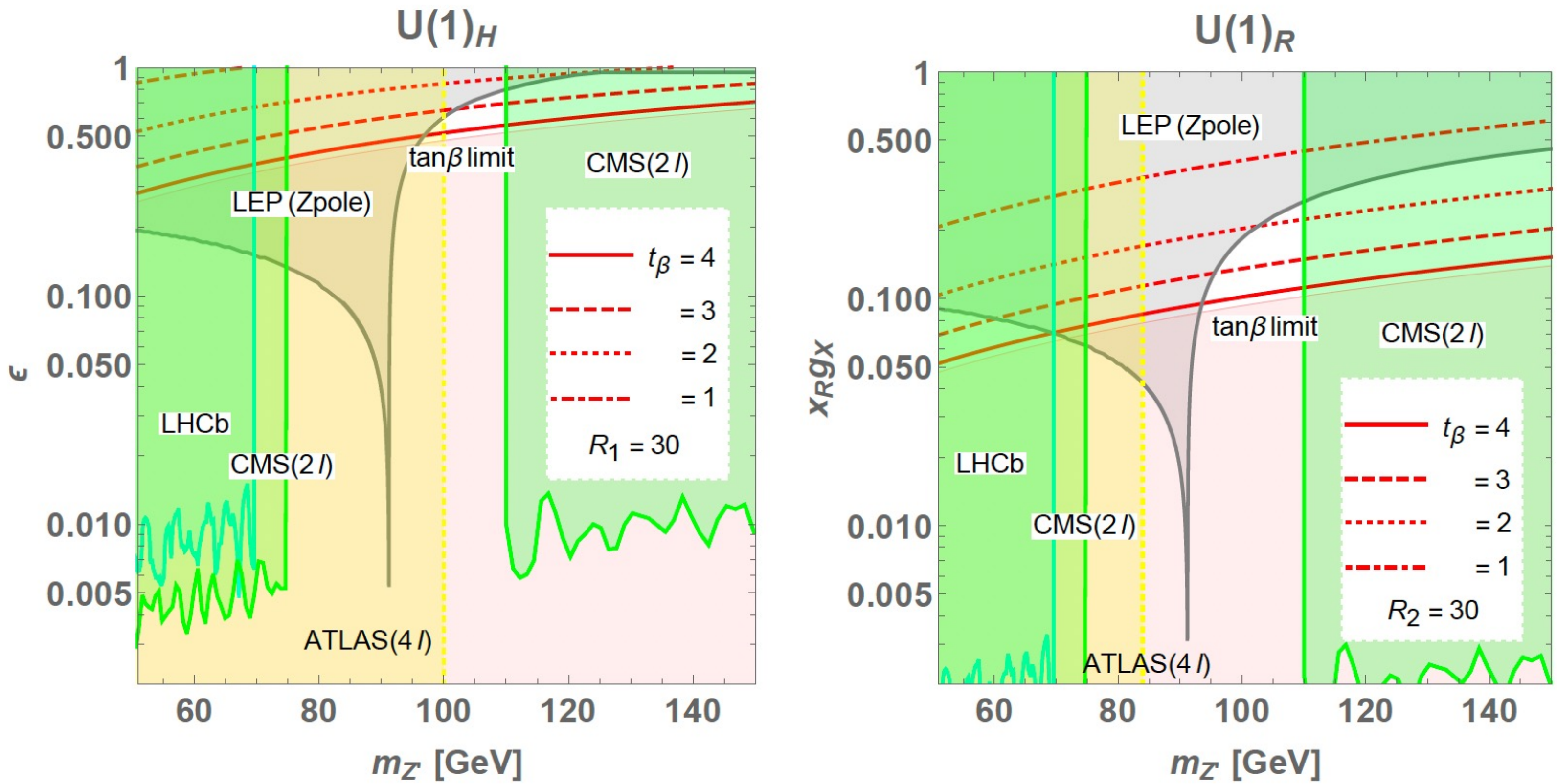
No dark particle case is excluded by H decay

($R_{1,2}$ = 0 is not allowed)

3. Results

Allowed regions (Z' mass and interaction)

Regarding Z' mass and coupling (taking into account Higgs constraints)

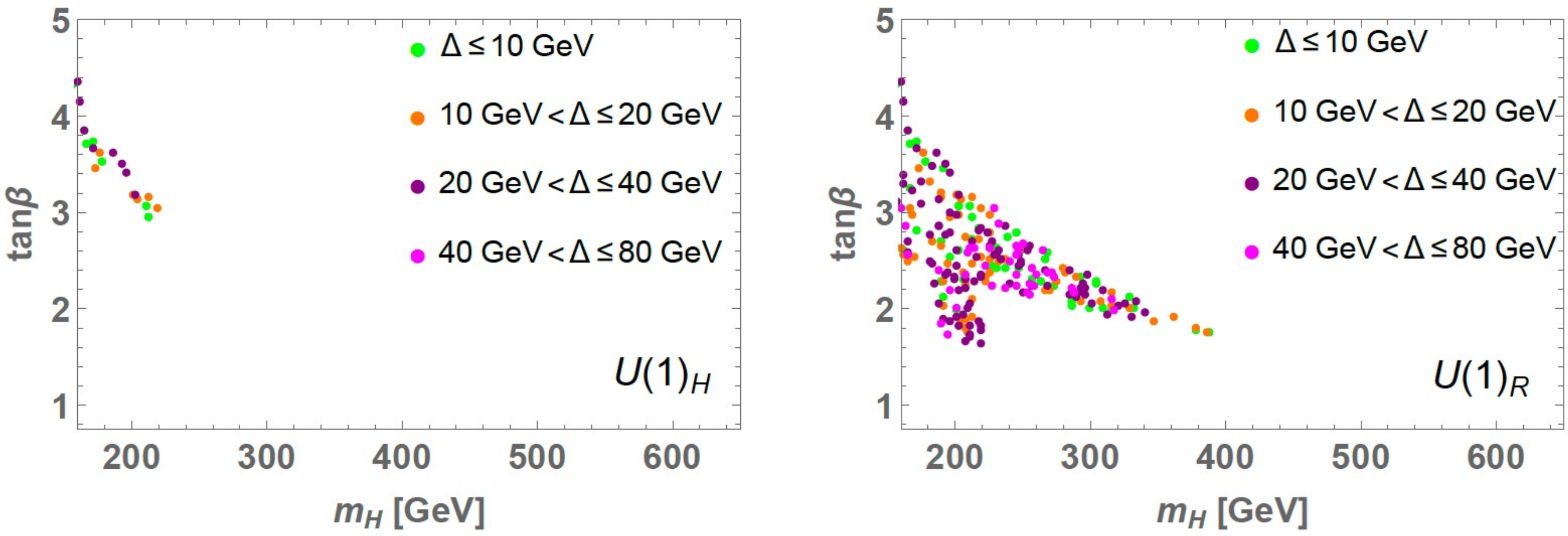


Red curves satisfy: $m_{Z'} = \frac{t_\beta}{1+t_\beta^2} x_1 g_X v$ ($U(1)_H$) $m_{Z'} = g_X x_2 t_\beta v$ ($U(1)_R$)

3. Results

Allowed regions (m_H and tanβ)

Combining, stability, unitary, flavor, STU parameter, Higgs diphoton decay and Higgs decay constraints



✓ Scalar decay constraints excludes small tanβ region

✓ Constraint is stronger in $U(1)_H$ case due to larger $BR(Z' \to l^+ l^-)$

Summary and discussion

2HDM with extra U(1) gauge symmetry is investigated

Answers to our questions

- ◆Is minimal 2HDM+U(1) excluded without scalar extension?

  Yes, minimal model is excluded

- ◆If excluded, which constraint finally excludes it?

  Neutral Higgs decay excludes the minimal model

- ◆If excluded, what is other way to avoid constraint?

  If we introduce a dark particle we can avoid constraints

The allowed region is still quite limited

It can be tested in future experiments

Thanks for listening!

Appendix

Eigenvalues of s-wave amplitude matrix for 2-2 scattering

$$a_1^{\pm} = \frac{1}{32\pi}\left[3(\lambda_1+\lambda_2) \pm \sqrt{9(\lambda_1-\lambda_2)^2 + 4(2\lambda_3+\lambda_4)^2}\right],$$

$$a_2^{\pm} = \frac{1}{32\pi}\left[\lambda_1+\lambda_2 \pm \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2}\right],$$

$$a_3^{\pm} = \frac{1}{32\pi}\left[\lambda_1+\lambda_2 \pm \sqrt{(\lambda_1-\lambda_2)^2}\right],$$

$$a_4 = \frac{1}{16\pi}(\lambda_3+2\lambda_4),$$

$$a_5 = \frac{1}{16\pi}\lambda_3,$$

$$a_6 = \frac{1}{16\pi}(\lambda_3+\lambda_4).$$

STU parameters in our models

$$S = \frac{(1-2\sin^2\theta_W)^2 x_3 + x_4 + x_7 - x_8 - 4m_{H\pm}^2(1-2\sin^2\theta_W + 2\sin^4\theta_W)\log[m_{H\pm}^2]}{4m_Z^2\pi}$$

$$T = \frac{-x_1 + x_3 - 4\sin^2\theta_W x_3 + 4\sin^4\theta_W x_3 - x_5 + x_7 - 8m_{H\pm}^2\sin^2\theta_W(-1+\sin^2\theta_W)\log[m_{H\pm}^2]}{16m_Z^2\pi\sin^2\theta_W(-1+\sin^2\theta_W)}$$

$$U = \frac{1}{4m_Z^2\pi(-1+\sin^2\theta_W)}\big(-x_1 + x_2 + x_3 - 5\sin^2\theta_W x_3 + 8\sin^4\theta_W x_3 - 4\sin^6\theta_W x_3 - x_4 + \sin^2\theta_W x_4$$
$$-x_5 + x_6 + x_7 - \sin^2\theta_W x_7 - x_8 + \sin^2\theta_W x_8 + 8m_{H\pm}^2\sin^2\theta_W(-1+\sin^2\theta_W)^2\log[m_{H\pm}^2]\big)$$

$$x_1 = 2\int_0^1 [x\,m_H^2 + (1-x)m_{H\pm}^2]\ln[x\,m_H^2 + (1-x)m_{H\pm}^2]dx$$

$$x_2 = 2\int_0^1 [-x(1-x)m_W^2 + x\,m_H^2 + (1-x)m_{H\pm}^2]\ln[-x(1-x)m_W^2 + x\,m_H^2 + (1-x)m_{H\pm}^2]dx$$

$$x_3 = 2\int_0^1 m_{H\pm}^2\ln(m_{H\pm}^2)dx$$

$$x_4 = 2\int_0^1 [-x(1-x)m_Z^2 + (1-x)m_{H\pm}^2]\ln[-x(1-x)m_Z^2 + (1-x)m_{H\pm}^2]dx$$

$$x_5 = 2\int_0^1 [x\,m_A^2 + (1-x)m_{H\pm}^2]\ln[x\,m_A^2 + (1-x)m_{H\pm}^2]dx$$

$$x_6 = 2\int_0^1 [-x(1-x)m_W^2 + x\,m_A^2 + (1-x)m_{H\pm}^2]\ln[-x(1-x)m_W^2 + x\,m_A^2 + (1-x)m_{H\pm}^2]dx$$

$$x_7 = 2\int_0^1 [x\,m_H^2 + (1-x)mA^2\ln[x\,m_H^2 + (1-x)m_A^2]dx$$

$$x_8 = 2\int_0^1 [-x(1-x)m_Z^2 + x\,m_H^2 + (1-x)m_A^2]\ln[-x(1-x)m_Z^2 + x\,m_H^2 + (1-x)m_A^2]dx$$