2HDMs with extended U (1) gauge symmetry at current and future colliders

Xinran Xu (Hong Kong University of Science and Technology)

Published in: JHEP 06 (2026) 169
arXiv: 2512.23450

Collaborated with Yuanchao Lou (Nanjing Normal University)
Takaaki Nomura (Sichuan University)
Kei Yagyu (Tokyo University of Science)

Introduction —— Why a gauged $U(1)_X$ in the 2HDM?

Two-Higgs-Doublet Model

2HDM

- One of the simplest extensions of the SM Higgs sector
- Typically Additional Higgs states: H, A and $H^{\pm}$
- Generic Yukawa structures can lead to tree-level FCNC

Additional $U(1)_X$ Gauge Symmetry

GAUGE EXTENSION

- One of the simplest extensions of the SM gauge sector
- Predicts a new neutral gauge boson Z′
- Z′ mass is commonly generated by an additional singlet VEV

Gauged 2HDM: combining the two extensions

Appropriate $U(1)_X$ charges forbid tree-level Higgs-mediated FCNC.

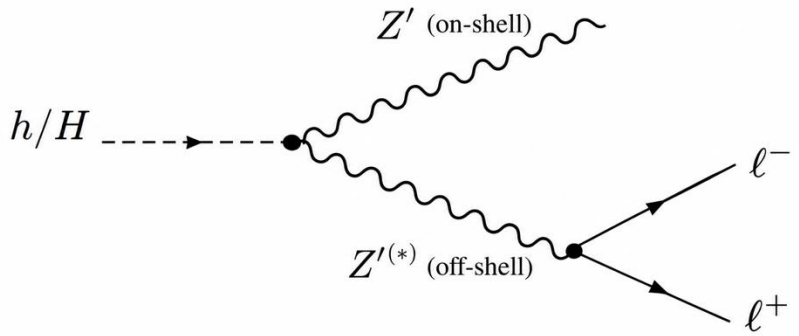
The two doublet VEVs break both electroweak and $U(1)_x$ symmetries—without an extra singlet.

$$SU(2)_L \times U(1)_Y \times U(1)_X \xrightarrow{\langle \Phi_1 \rangle,\, \langle \Phi_2 \rangle} U(1)_{\mathrm{em}}$$

Introduction —— Can this minimal setup survive experimental constraints?

- New Higgs decay channels arise in gauged 2HDMs:

$$h/H \to Z' Z'^{(*)} \to 4\ell.$$



- The minimal model is ruled out by current LHC constraints, particularly those from searches for exotic Higgs decays into four leptons.

- We introduce SM-singlet vector-like fermions (with identical left- and right-handed gauge charges) χ, opening an additional Z′ decay channel: $Z' \to \chi\,\bar{\chi}$ to **suppress the visible four-lepton signal.**

- The surviving parameter space motivates complementary tests at future lepton colliders. At CEPC, precision Higgs measurements and direct Z' searches offer promising probes.

Model and constraints—— Particle content and charge assignments

· 2HDM with a new $U(1)_X$ gauge symmetry, spontaneously broken by VEVs of two Higgs doublets Φ_1 and Φ_2

	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

· In order to satisfy the anomaly cancellation, we introduce three right-handed neutrinos $\nu_R^i (i = 1, \ldots, 3)$.

· SM-singlet vector-like fermions χ are charged under $U(1)_X$ and can serve as dark matter candidates.

· We take $x_1 \neq x_2$ such that the two Higgs doublets have different charges with each other, and thus the FCNCs mediated by Higgs bosons are forbidden.

Model and constraints —— Higgs sector and Yukawa interaction

Higgs Sector:

· The Higgs potential is constrained by $U(1)_X$ charge:

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

· The mixing terms $\Phi_1^\dagger\Phi_2$ and $(\Phi_1^\dagger\Phi_2)^2$ are forbidden.

· After electroweak symmetry breaking, the physical higgs bosons are: h (SM-like)、H、$H^\pm$, and the cp-odd higgs boson A was absorbed by Z'.

Yukawa interactions：

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

- Only Φ_2 couples to SM fermions, realizing a Type-I Yukawa structure.
- This Yukawa structure naturally forbids tree-level Higgs-mediated flavor-changing neutral currents (FCNCs).

Model and constraints —— Gauge-kinetic mixing

· Gauge-kinetic terms: $SU(2)_L \times U(1)_Y \times U(1)_X$ sector with kinetic mixing

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

· Field redefinition: following non unitary transformation:

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

· In the new basis, the covariant derivative is

$$D_\mu \Psi = (\partial_\mu - i g T^a_\Psi W^a_\mu - i g' Y_\Psi B_\mu - i g_X X_\Psi X_\mu)\Psi$$

With the effective charge: $X_\Psi = \tilde{X}_\Psi - Y_\Psi \frac{g'}{g_X} \tan\epsilon$

$U(1)_X$ charge

hypercharge

Model and constraints —— Z-Z′ mixing

· After spontaneous symmetry breaking, the neutral gauge bosons acquire masses through the Higgs kinetic terms:

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

↓

· The neutral gauge boson mass matrix in the (Z, Z′) basis :

$$\mathcal{M}^2_{ZZ'} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{pmatrix}$$

↓

· The off-diagonal element M_{12} induces mixing between the neutral gauge bosons Z and Z′, To eliminate the mass mixing, we impose M_{12} =0

$$M_{12} = -\frac{g g_X}{2c_W} v^2 (c_\beta^2 X_{\Phi_1} + s_\beta^2 X_{\Phi_2}).$$

↓

· This condition establishes a relation between the effective $U(1)_X$ charges of the two Higgs doublets.

$$c_\beta^2 X_{\Phi_1} + s_\beta^2 X_{\Phi_2} = 0 \leftrightarrow \frac{X_{\Phi_1}}{X_{\Phi_2}} = -t_\beta^2.$$

$$m_{Z'} = g_X t_\beta |X_{\Phi_2}| v.$$

Model and constraints —— Two benchmark models

	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

· Hidden $U(1)_H$ model $\quad x_2 = x_R = 0$

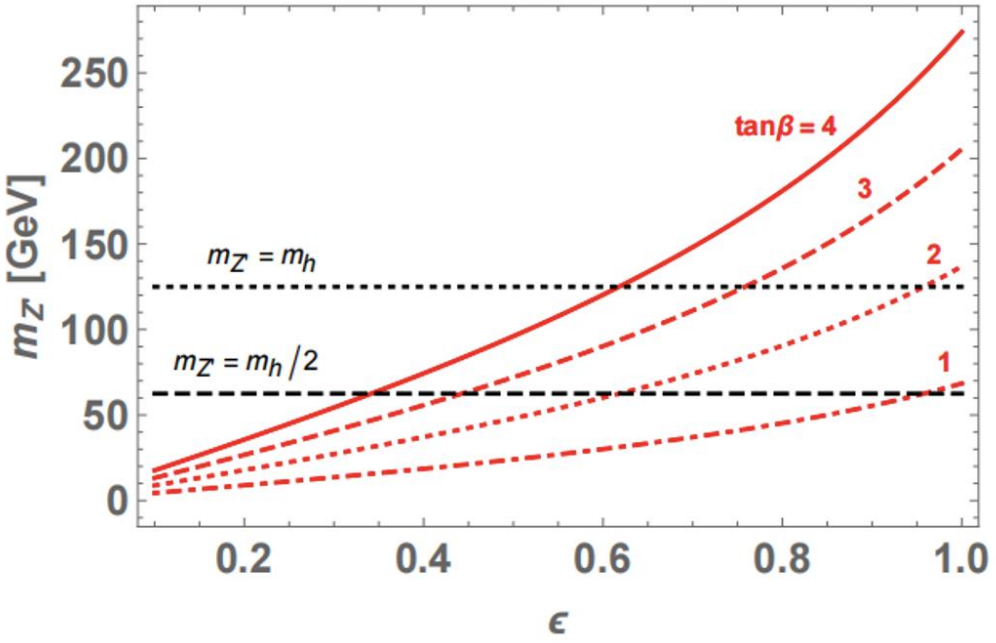
SM fermions are neutral under the $U(1)_X$ symmetry, but interact with Z' through kinetic mixing.

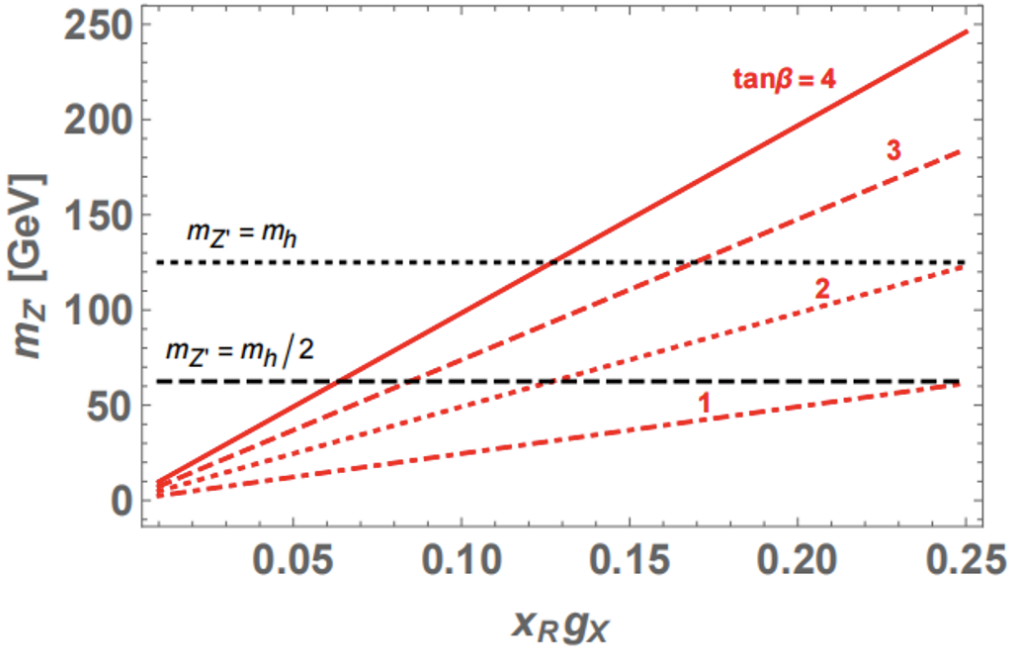
$$t_\epsilon = \frac{2x_1 g_X}{g'(1+t_\beta^2)}, \quad m_{Z'} = \frac{g'}{2} t_\beta t_\epsilon v.$$

· $U(1)_R$ model $\quad x_2 = x_R, \epsilon = 0$

Only right-handed SM fermions carry nonzero $U(1)_X$ charges, allowing direct interactions with Z'.

$$\frac{x_1}{x_R} = -t_\beta^2, \quad m_{Z'} = g_X x_R t_\beta v.$$





Model and constraints —— Relevant interaction under no-mixing condition

· Gauge-gauge-Higgs type interactions:

$$\begin{aligned}\mathcal{L}_{\rm kin} = & \frac{m_Z^2}{v}(s_{\beta-\alpha}h + c_{\beta-\alpha}H)Z_\mu Z^\mu + \frac{2m_W^2}{v}(s_{\beta-\alpha}h + c_{\beta-\alpha}H)W_\mu W^\mu \\ & + \frac{m_{Z'}^2}{v}\left(s_{\beta-\alpha} + c_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right)Z'_\mu Z'^\mu h + \frac{m_{Z'}^2}{v}\left(c_{\beta-\alpha} - s_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right)Z'_\mu Z'^\mu H \\ & + \frac{2m_Z m_{Z'}}{v}(s_{\beta-\alpha}H - c_{\beta-\alpha}h)Z_\mu Z'^\mu \\ & + \frac{2m_W m_{Z'}}{v}H^+ W_\mu^- Z'^\mu + \text{h.c.}\end{aligned}$$

· Z' couplings with a fermion pair

The interaction of Z' with a fermion pair is given by: $\mathcal{L}_{Z'ff} = g_{ffZ'}\overline{f}\gamma^\mu(v_f - a_f\gamma_5)fZ'_\mu$

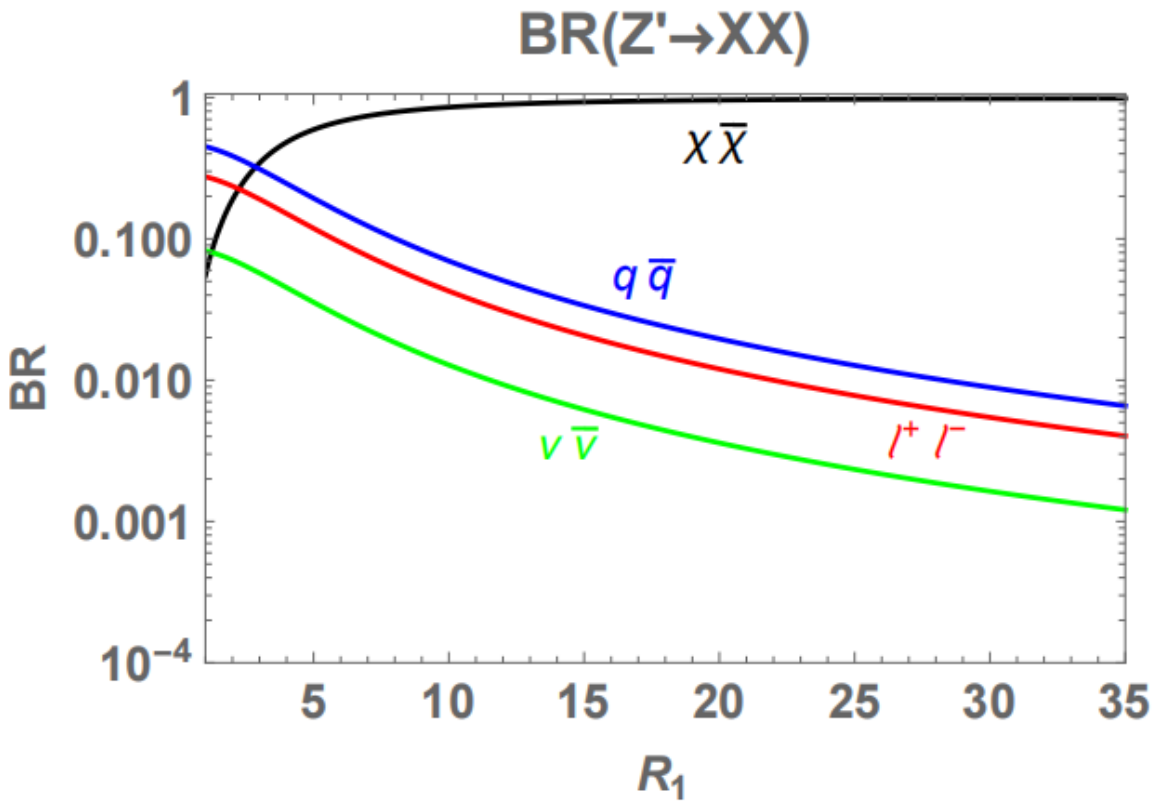
The Z' couplings to fermions differ between the two benchmark models, leading to different decay branching ratios.

	$g_{ffZ'}$	v_e	v_{ν_L}	v_d	v_u	v_{ν_R}	v_χ	a_e	a_{ν_L}	a_d	a_u	a_{ν_R}	a_χ
$U(1)_H$	$\frac{1}{2}g'\tan\epsilon$	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{6}$	$-\frac{5}{6}$	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

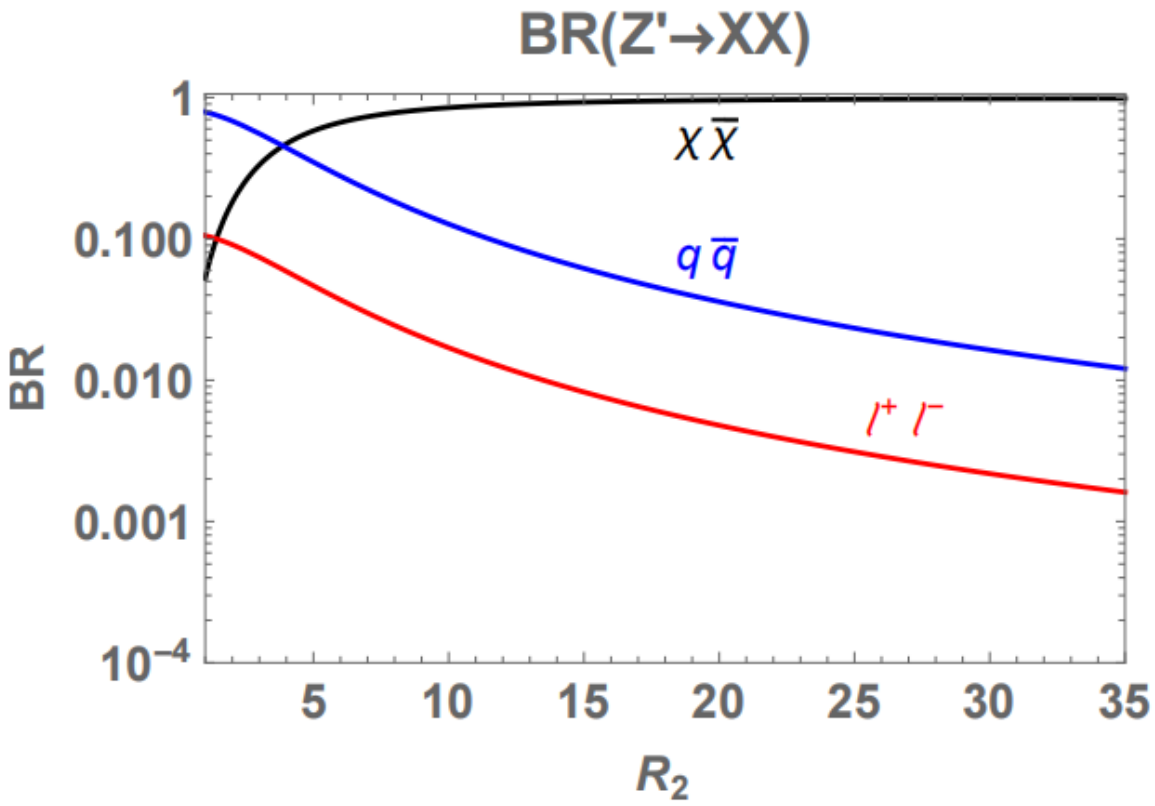
$R_1 \equiv (1+\tan^2\beta)x_\chi/(x_1\cos\epsilon)$ and $R_2 \equiv 2x_\chi/x_R$.

Model and constraints —— Decay of Z′

Hidden $U(1)_H$ model



$U(1)_R$ model



· For $m_f \ll m_z$,the partial decay width is approximately given by

$$\Gamma_{Z' \to f\bar{f}} \simeq g_{ffZ'}^2 \frac{v_f^2 + a_f^2}{12\pi} m_{Z'}$$

· The decay $Z' \to \bar{\chi}\chi$dominates for sufficiently large R_1 orR_2 . This suppresses the visible Z' decay channels and weakens the constraints from Higgs decays into four leptons.

Model and constraints —— Higgs decay

$$\mathcal{L}_{\rm kin} = \frac{m_Z^2}{v}(s_{\beta-\alpha}h + c_{\beta-\alpha}H)Z_\mu Z^\mu + \frac{2m_W^2}{v}(s_{\beta-\alpha}h + c_{\beta-\alpha}H)W_\mu W^\mu$$
$$+ \frac{m_{Z'}^2}{v}\left(s_{\beta-\alpha} + c_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right)Z'_\mu Z'^\mu h + \frac{m_{Z'}^2}{v}\left(c_{\beta-\alpha} - s_{\beta-\alpha}\frac{1-t_\beta^2}{t_\beta}\right)Z'_\mu Z'^\mu H$$
$$+ \frac{2m_Z m_{Z'}}{v}(s_{\beta-\alpha}H - c_{\beta-\alpha}h)Z_\mu Z'^\mu$$
$$+ \frac{2m_W m_{Z'}}{v}H^+ W_\mu^- Z'^\mu + \text{h.c.}$$

The SM Higgs decay into $Z'Z'$ $\quad 2m_{Z'} < m_h$

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

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

For $m_{Z'}/m_h \ll 1$, alignment limit

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

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

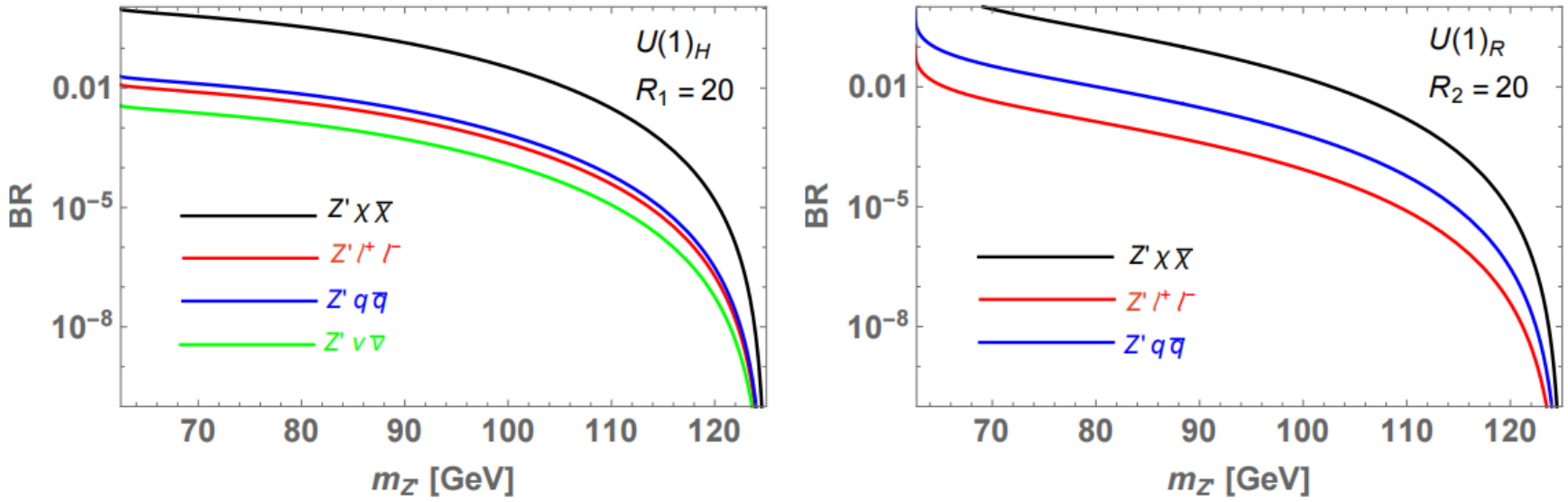
$\Gamma_h^{SM} = 4.1MeV$

Model and constraints —— Higgs decay

$2m_{Z'} > m_h$

$h \to Z'Z'$ is not kinematically allowed, but $h \to Z'Z'^* \to Z'f\bar{f}$ is possible with f being a SM fermion if $m_{Z'} < m_h$

$$\Gamma(h \to Z' f \bar{f}) = \frac{m_{Z'}^4 g_{ffZ'}^2 (v_f^2 + a_f^2)}{32\pi^3 m_h v^2} N_f^c \left(s_{\beta-\alpha} + c_{\beta-\alpha} \frac{1 - t_\beta^2}{t_\beta} \right)^2 H(x_{Z'}, x_{Z'})$$



LHC data (ATLAS) constrains $\sigma_{4\ell} \lesssim 0.1$ fb $\Rightarrow$ $\sigma(gg \to h) BR(h \to Z'\ell^+\ell^-) BR(Z' \to \ell^+\ell^-) \lesssim 0.1$ fb

(ATLAS, PLB 824, 136832, 2022)

We also consider Higgs invisible decay constraint

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

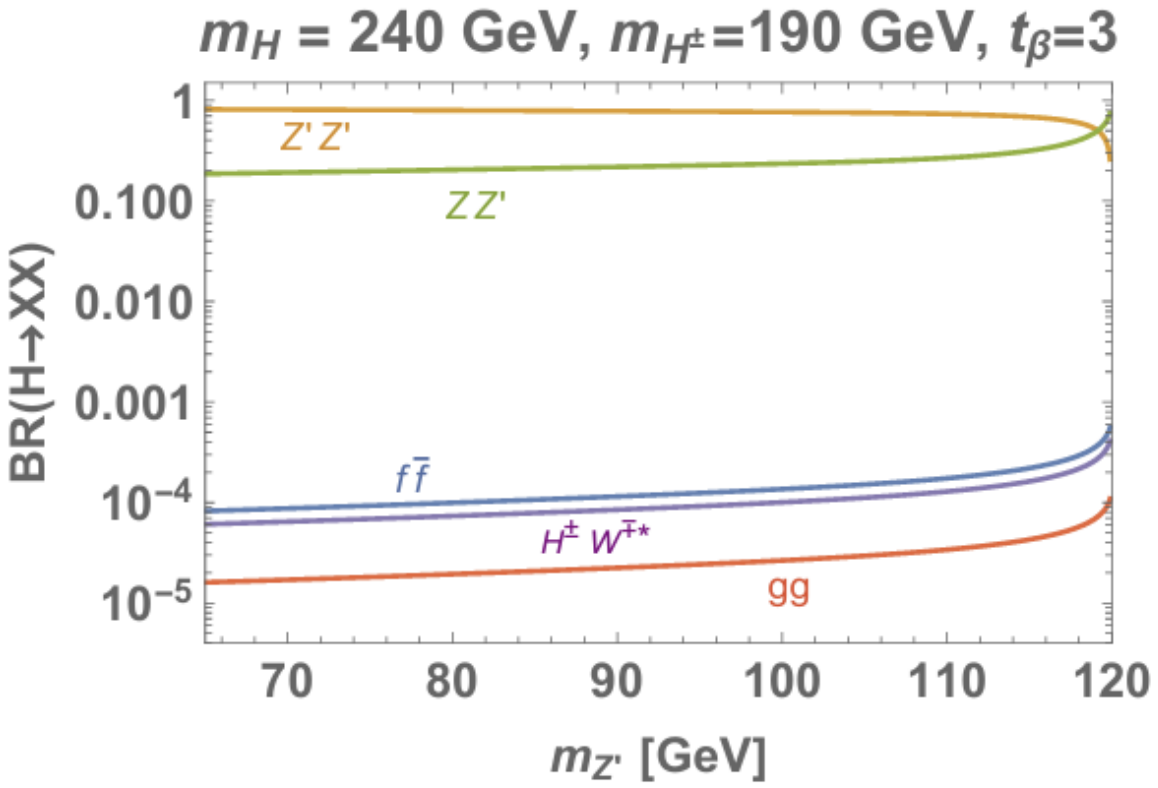
(ATLAS, PLB 842, 137963, 2023)

Model and constraints —— Higgs decay

Heavy neutral Higgs decays ($H \to VV, V = Z, Z'$)

$2m_{Z'} < m_{\mathrm{H}}$

ZZ mode is the same as 2HDM



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

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

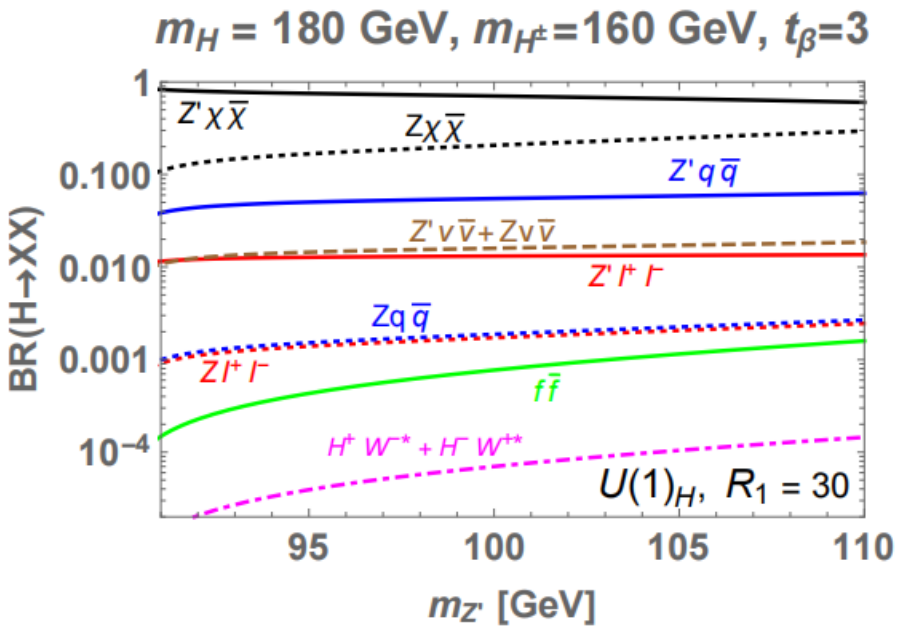
Model and constraints —— Higgs decay

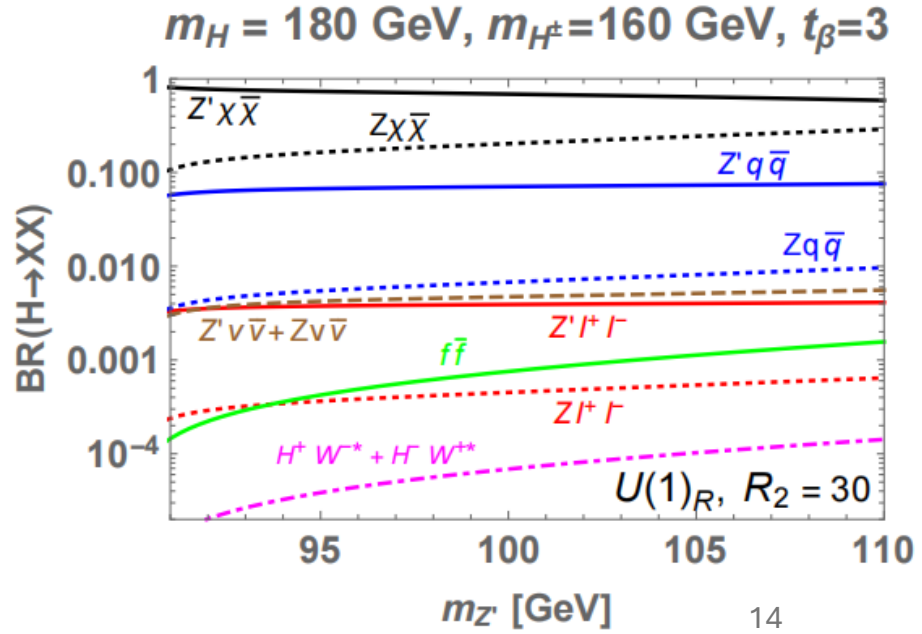
$$2m_{Z'} > m_{\mathrm{H}} > m_{Z'}$$

$$\Gamma(H \to Z'Z'^* \to Z'f\bar{f}) = \frac{m_{Z'}^4 g_{ffZ'}^2 (v_f^2 + a_f^2)}{32\pi^3 m_H v^2} N_f^c \left(c_{\beta-\alpha} - s_{\beta-\alpha} \frac{1 - t_\beta^2}{t_\beta} \right)^2 H(y_{Z'}, y_{Z'}),$$

$$\Gamma(H \to ZZ'^* \to Zf\bar{f}) = \frac{m_Z^2 m_{Z'}^2 g_{ffZ'}^2 (v_f^2 + a_f^2)}{32\pi^3 m_H v^2} N_f^c s_{\beta-\alpha}^2 H(y_Z, y_{Z'}),$$

$$\Gamma(H \to Z'Z^* \to Z'f\bar{f}) = \frac{m_Z^2 m_{Z'}^2 g_Z^2 [(v_f^{\mathrm{SM}})^2 + (a_f^{\mathrm{SM}})^2]}{32\pi^3 m_H v^2} N_f^c s_{\beta-\alpha}^2 H(y_{Z'}, y_Z),$$



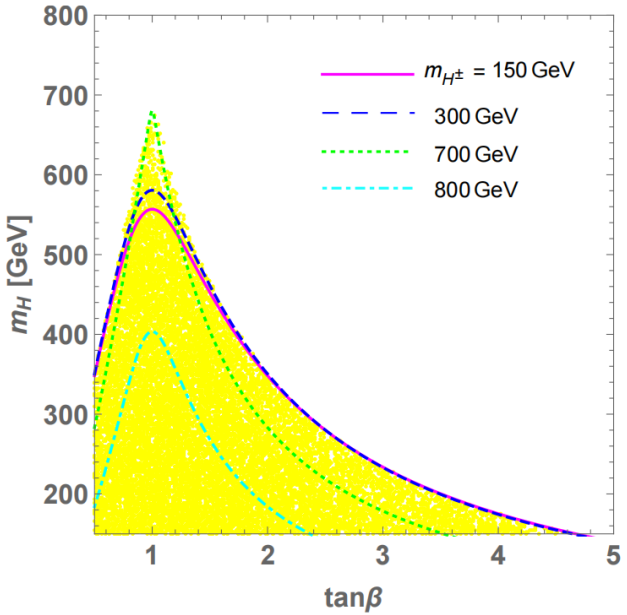


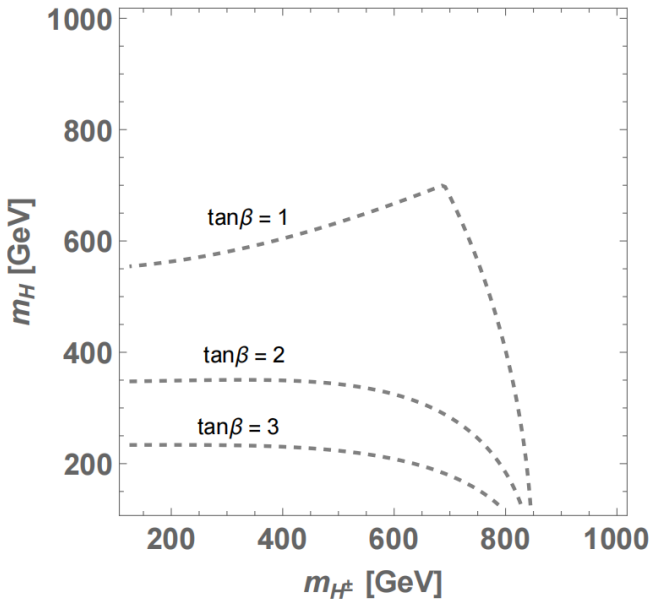
Consider the four leptons constraint

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

Results —— Constraints from Higgs related phenomena

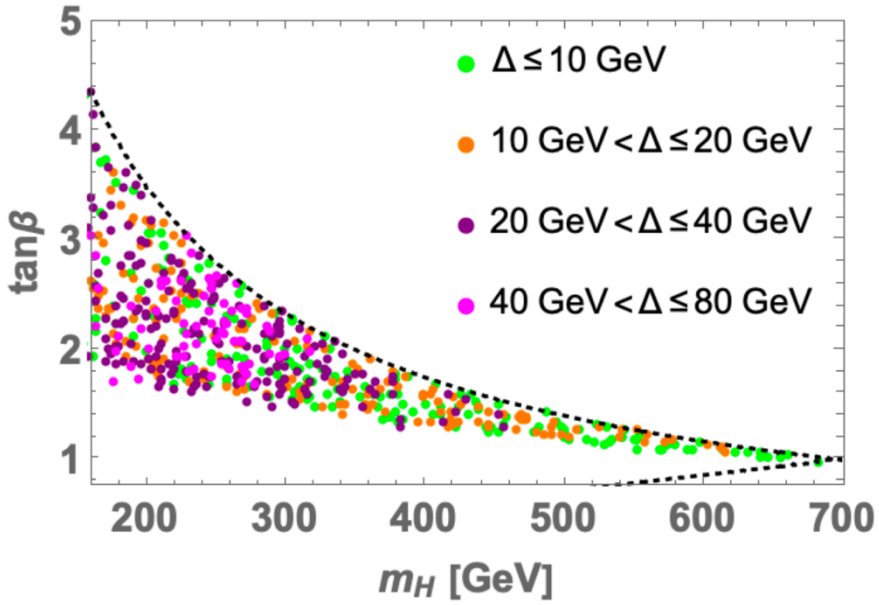
Allowed region by unitarity





Unitarity+STU+flavor constraints

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



- **Vacuum stability and perturbative unitarity**
  Require a bounded scalar potential and perturbative scalar scattering amplitudes.

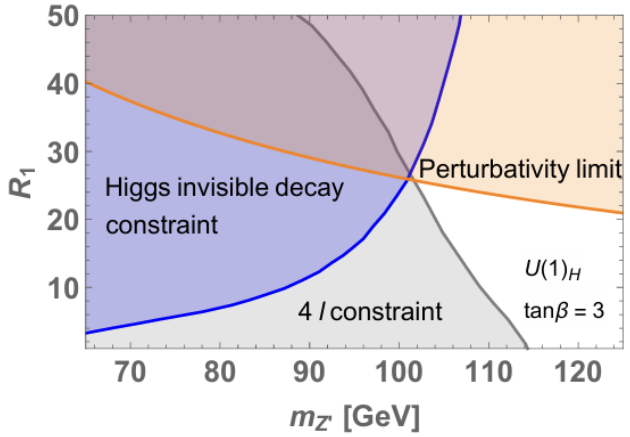
- **Electroweak precision constraints (S, T, U)**
  Restrict the additional Higgs spectrum and mass splittings.

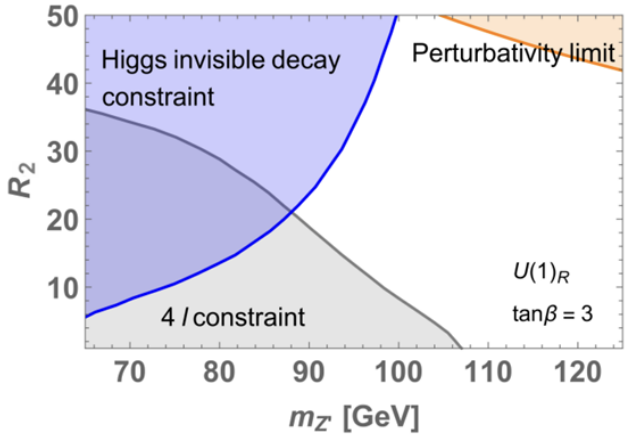
- **Flavor constraints**
  Meson decay observables constrain the charged-Higgs sector. Evaluated using **SuperIso**.

  https://superiso.in2p3.fr/

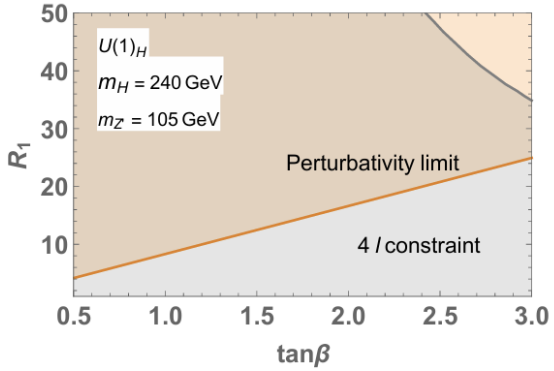
Results —— Constraints from Higgs decay

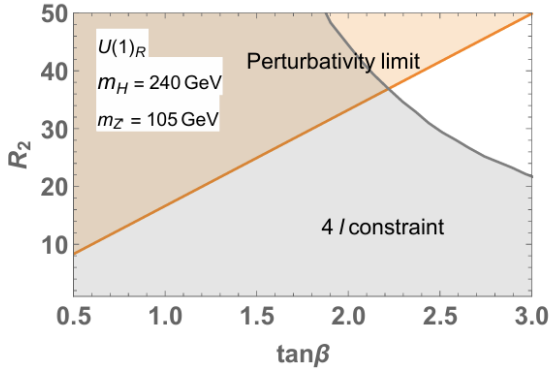
SM Higgs:

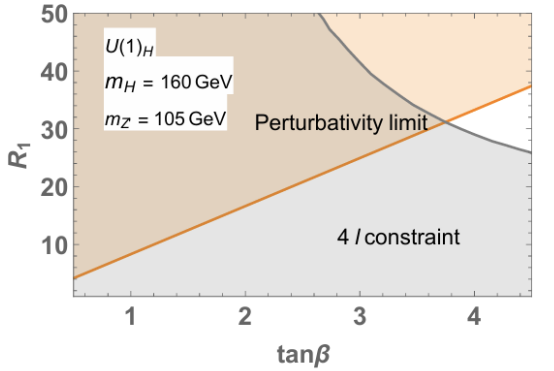


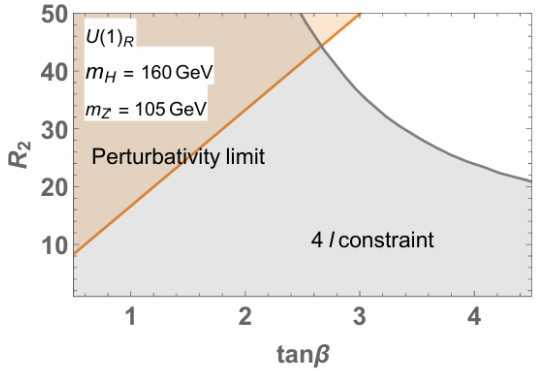


Heavy Higgs:









Perturbative limit:

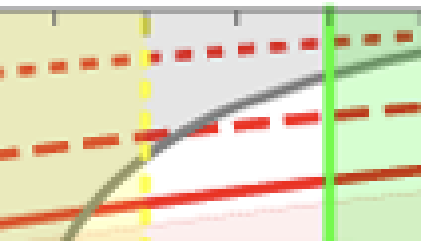
$$R_{1,2} g_{\chi\chi Z'} < \sqrt{4\pi}$$

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

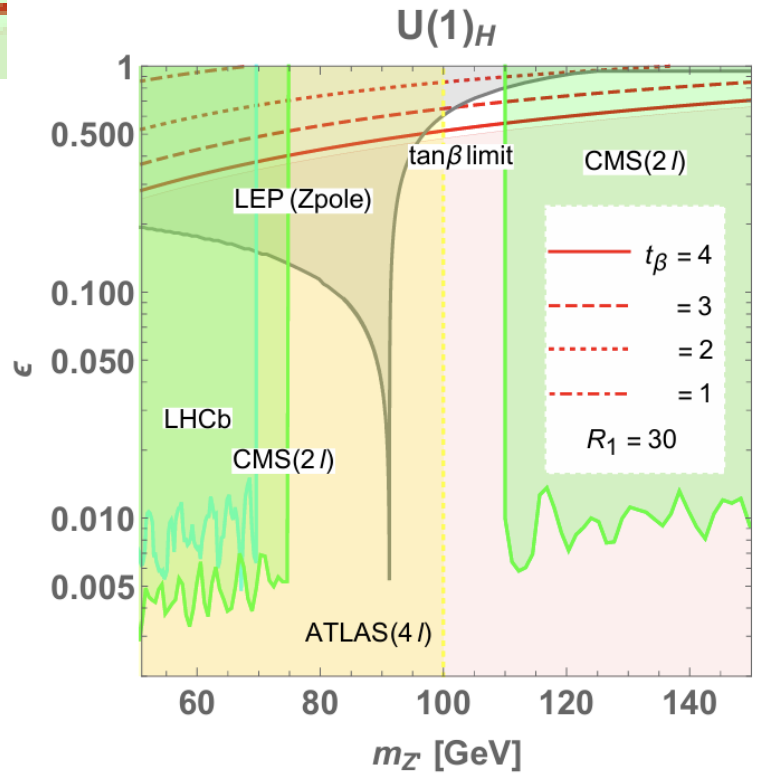
No dark particle case is excluded by H decay

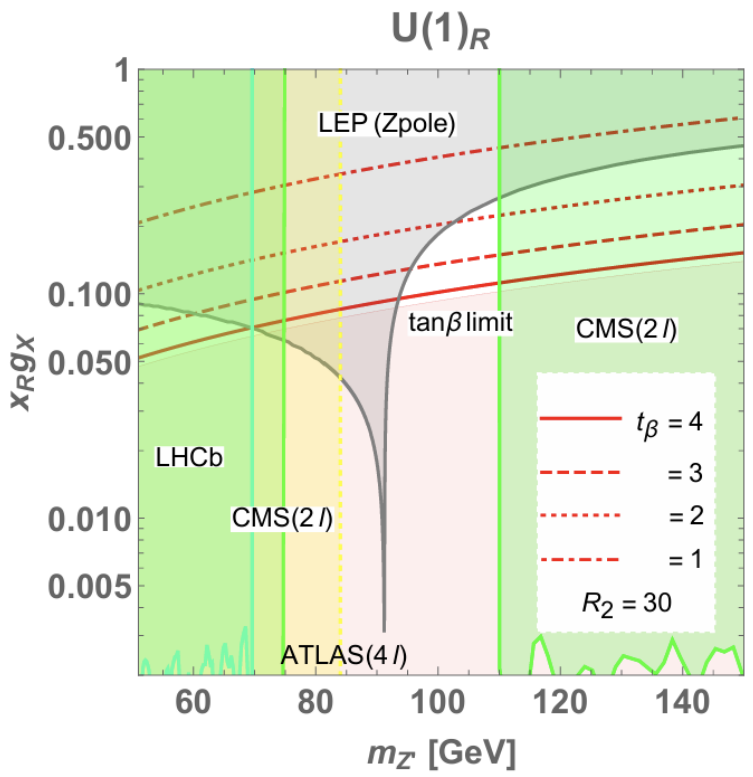
$R_{1,2} = 0$ is not allowed

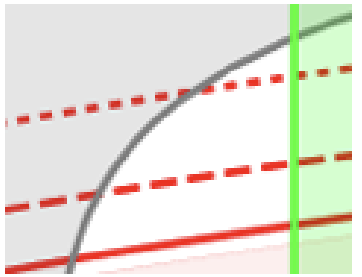
Results —— Allowed regions (Z' mass and interaction)



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





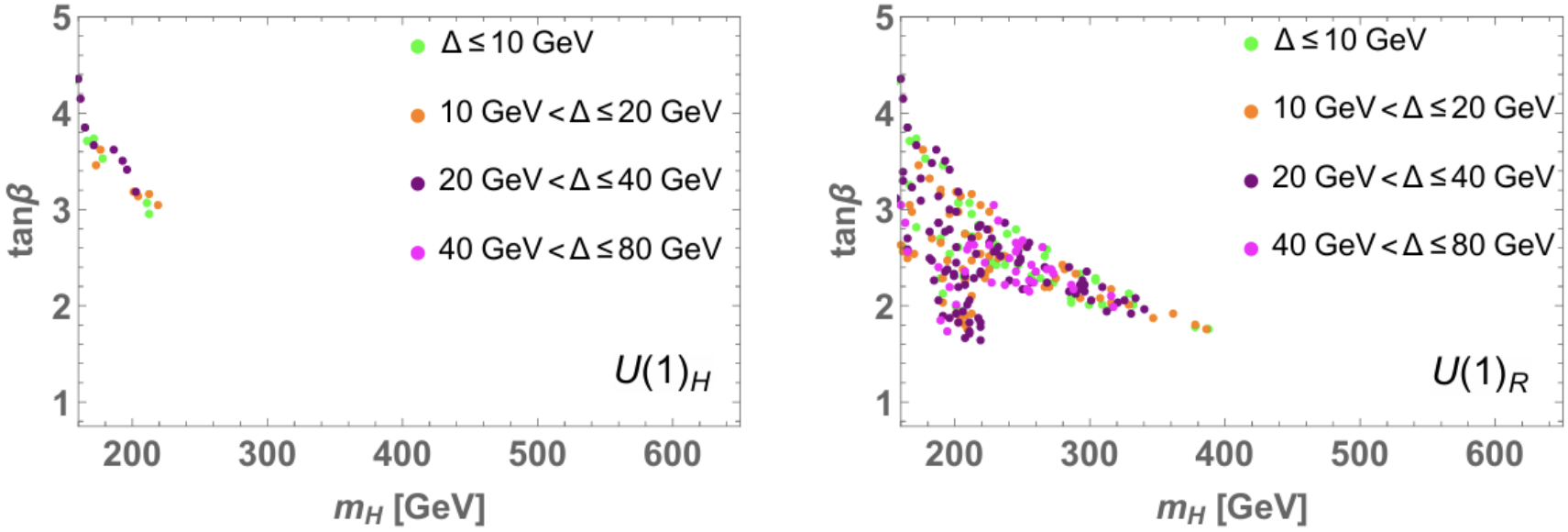


Red curves satisfy: $m_{Z'} = \frac{t_\beta}{1+t_\beta^2} x_1 g_X v$ (U(1)H) $m_{Z'} = g_X x_2 t_\beta v$ (U(1)R)

A narrow region near the Z pole survives, motivating precision tests at future lepton colliders.

Results —— Allowed regions (m_H and $\tan\beta$)

constraints from vacuum stability, perturbative unitarity, oblique parameters, flavor data,and $h/H \to 4l$ in the $U(1)_H(U(1)_R)$ case



✓ Scalar decay constraints excludes small tanβ region

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

Summary

- Two Higgs doublets break both electroweak and $U(1)_X$ symmetries, and gauge symmetry forbids tree-level FCNCs.
- The $hZ'Z'$ coupling survives in the Higgs alignment and zero Z– Z'mixing limits.
- Taking $2m_{Z'} > m_h$ closes $h \to Z'Z'$, but off-shell Higgs decays and additional-Higgs decays still yield strong four-lepton constraints.
- Introducing a dark matter candidate χ allows $Z' \to \chi\bar{\chi}$, suppressing leptonic branching fractions and reopening viable parameter space.
- Combined constraints leave restricted regions in the $U(1)_H$and $U(1)_R$benchmarks, motivating further collider studies.

Prospects at CEPC and future colliders

Precision Higgs measurements	Invisible / exotic Higgs decays in Zh production Charged-Higgs loop effects in $h \to \gamma\gamma$	$e^+e^- \to Zh$ $h \to Z'Z'^* \to$ invisible / exotic
Z' searches and precision tests	Visible and invisible Z′ production with a photon Fermion-pair production via Z′ exchange	$e^+e^- \to \gamma Z'$
Additional Higgs searches at higher energies	Charged-Higgs pair production above threshold Searches for $H^\pm \to W^\pm Z'^{(*)}$	$e^+e^- \to H^+H^-$ $H^\pm \to W^\pm Z'^{(*)}$

Precision Higgs measurements and direct Z′ searches provide complementary tests.

Dedicated sensitivity studies are needed to quantify coverage of the surviving parameter space.

Thanks for listening!

Back up

Perturbative unitarity: We require $|\mathrm{Re}\, a_i| \leq 1/2$ for all eigenvalues of the scalar s-wave scattering matrix.

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

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

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

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

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

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

Back up

STU parameters in our models

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

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

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

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

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

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

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

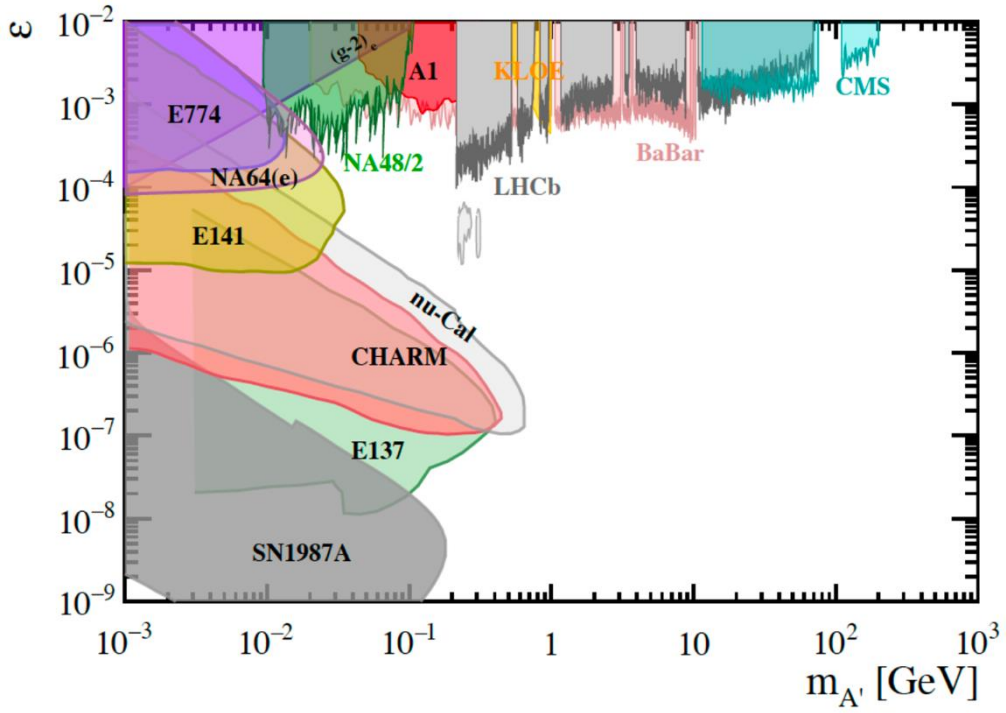
$$x_5 = 2\int_0^1 [x\,m_A^2 + (1-x)m_{H^\pm}^2]\ln[x\,m_A^2 + (1-x)m_{H^\pm}^2]dx$$

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

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

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

Back up 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)