Multi-Z' signatures from scalar boson decay in spontaneously broken U(1)' models

Presenter

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Introduction/Motivation

One simple extension of the SM

⇨ A model with extra U(1)' gauge symmetry

Ex) $U(1)_{B-L}$　$U(1)_{Li-Lj}$　$U(1)_X$　$U(1)_R$　$U(1)_{Hidden}$　Etc.

Extra U(1)' would come from theory on high scale

⇨ SO(10), E_6 GUTs; String Theories, …

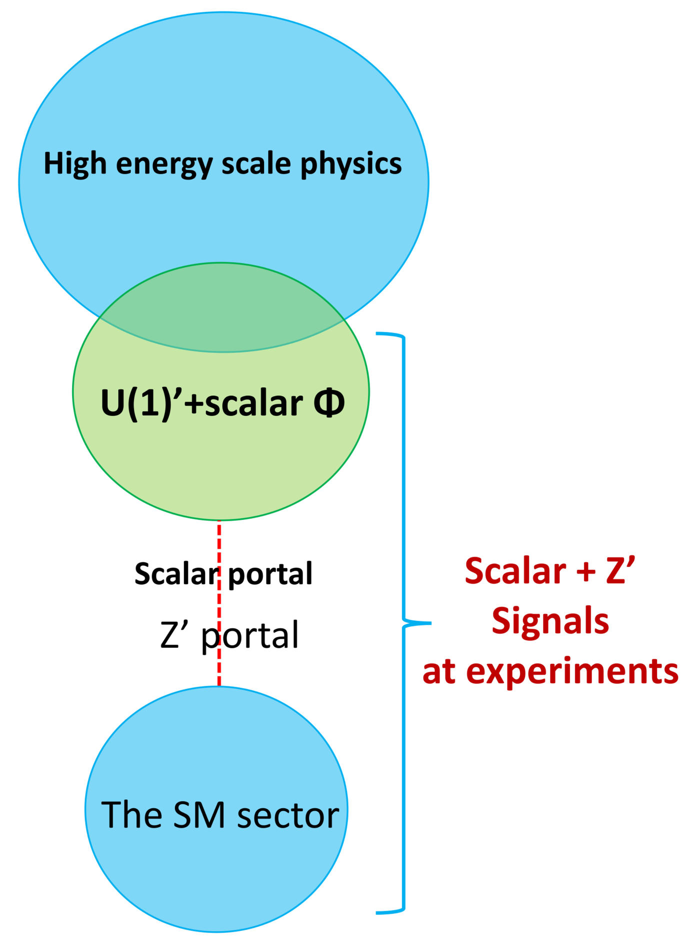
U(1)' ⇨ New neutral gauge boson Z'

Z' boson would be massive

⇨ Spontaneously broken U(1)' is likely

Main idea of the work

In spontaneously broken U(1)' models we should have new scalar field



It is natural to consider scalar and Z' bosons together

What are new signals considering scalar + Z' ?

Multi-Z' boson states

We obtain them from scalar decay

$$h \to Z'Z'$$

$$h \to \phi\phi \to Z'Z'Z'Z'$$

$$\phi \to Z'Z'$$

Signatures of spontaneously broken U(1)'

We consider such signals in three reference mass sets

- Small mass case: $\{m_{Z'}, m_\phi\} = \{0.02, 0.05\}$ GeV
- Middle mass case: $\{m_{Z'}, m_\phi\} = \{20, 50\}$ GeV
- Heavy mass case $\{m_{Z'}, m_\phi\} = \{200, 800\}$ GeV

Models

SM is extended adding a local U(1)' symmetry

Field contents : SM fields + one complex singlet scalar Φ

(U(1)' charge of Φ is fixed to be 1)

	q_L^i	u_R^i	d_R^i	l_L^e	l_L^μ	l_L^τ	e_R	μ_R	τ_R	ν_R^e	ν_R^μ	ν_R^τ
$SU(2)_L$	**2**	**1**	**1**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	0	0	0
$U(1)'$	X_{q_L}	X_{u_R}	X_{d_R}	$X_{l_L^e}$	$X_{l_L^\mu}$	$X_{l_L^\tau}$	X_{e_R}	X_{μ_R}	X_{τ_R}	$X_{\nu_R^e}$	$X_{\nu_R^\mu}$	$X_{\nu_R^\tau}$

	X_{q_L}	X_{u_R}	X_{d_R}	$X_{l_L^e}$	$X_{l_L^\mu}$	$X_{l_L^\tau}$	X_{e_R}	X_{μ_R}	X_{τ_R}	$X_{\nu_R^e}$	$X_{\nu_R^\mu}$	$X_{\nu_R^\tau}$
$U(1)_{B-L}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-1	-1	-1	-1	-1	-1	-1	-1	-1
$U(1)_{L_e-L_\mu}$	0	0	0	1	-1	0	1	-1	0	1	-1	0
$U(1)_{L_e-L_\tau}$	0	0	0	1	0	-1	1	0	-1	1	0	-1
$U(1)_{L_\mu-L_\tau}$	0	0	0	0	1	-1	0	1	-1	0	1	-1
$U(1)_D$	0	0	0	0	0	0	0	0	0	0	0	0

5-models distinguished by the choice of U(1)'

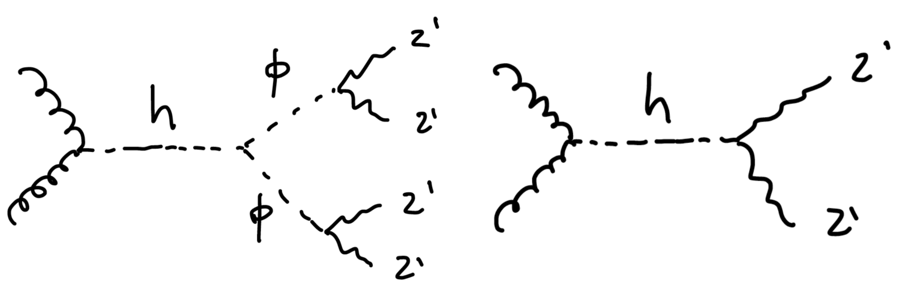
Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu} + g_X X_\mu J_X^\mu + |D_\mu\Phi|^2 - V(H,\Phi) + \mathcal{L}_{\nu_R}$$

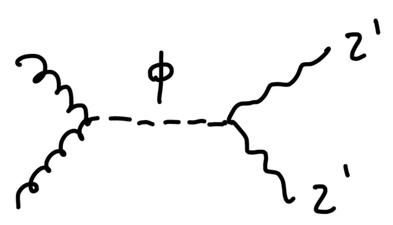
$$V(H,\Phi) = -\mu_H^2 H^\dagger H - \mu_\Phi^2 \Phi^*\Phi + \frac{\lambda_H}{2}(H^\dagger H)^2 + \frac{\lambda_\Phi}{2}(\Phi^*\Phi)^2 + \lambda_{H\Phi}(H^\dagger H)(\Phi^*\Phi)$$

Signal processes/BRs

❖ Higgs boson production/decay



❖ New scalar boson production/decay



Via scalar mixing

Z' boson decays into the SM particles

	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	$\nu\bar\nu$	jj	$b\bar b$
$U(1)_D$	0.15	0.15	0.15	0	0.50	0.049
$U(1)_{B-L}$	0.16	0.16	0.16	0.24	0.22	0.054
$U(1)_{L_e-L_\mu}$	0.33	0.33	0	0.33	0	0
$U(1)_{L_e-L_\tau}$	0.33	0	0.33	0.33	0	0
$U(1)_{L_\mu-L_\tau}$	0	0.33	0.33	0.33	0	0

BRs of Z' for $m_{Z'}$ = 20 GeV

Decay widths

❖ Main Decay widths of new scalar boson

$$\Gamma(\phi \to Z'Z') = \frac{m_{Z'}^4 \cos^2\alpha}{8\pi v_\Phi^2 m_\phi}\beta(x_{Z'})\left[2 + \frac{1}{4x_{Z'}^2}(1-2x_{Z'})^2\right]$$

$$\Gamma(\phi \to hh) = \frac{\lambda_{\phi hh}^2}{8\pi m_\phi}\beta(x_h),$$

$$x_i = m_i^2/m_\phi^2 \text{ and } \beta(x) = \sqrt{1-4x}$$

Free parameters $\{m_{Z'}, m_\phi, \sin\alpha, g_X, (\epsilon)\}$

❖ New decay modes of Higgs boson

$$\Gamma(h \to Z'Z') = \frac{m_{Z'}^4 \sin^2\alpha}{8\pi v_\Phi^2 m_h}\beta(z_{Z'})\left[2 + \frac{1}{4z_{Z'}^2}(1-2z_{Z'})^2\right]$$

$$\Gamma(h \to \phi\phi) = \frac{\lambda_{\phi\phi h}^2}{8\pi m_h}\beta(z_\phi),$$

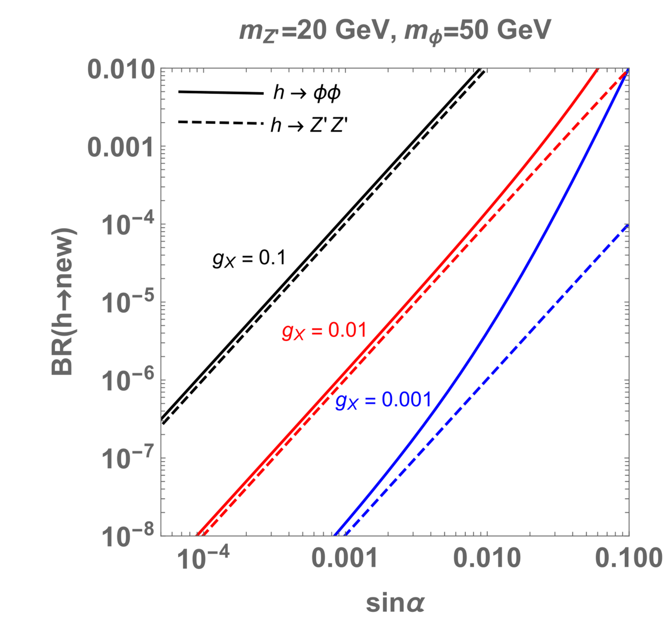
$$\lambda_{\phi hh} = \frac{\sin 2\alpha(2m_h^2 + m_\phi^2)(v_\Phi\cos\alpha - v\sin\alpha)}{4vv_\Phi}$$

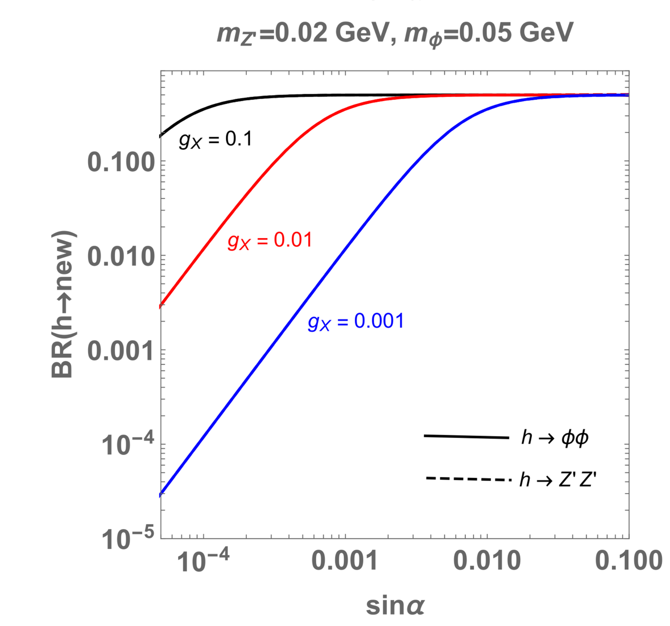
✓ Behavior for α→0 limit

$$\Gamma(h \to Z'Z') = \frac{m_h^3\alpha^2}{32\pi v_\Phi^2} + \mathcal{O}(\alpha^4),$$

$$\Gamma(h \to \phi\phi) = \frac{m_h^3\alpha^2}{32\pi v_\Phi^2}\left(1 + \frac{2m_\phi^2}{m_h^2}\right)^2\left(1 + 2\alpha\frac{v_\Phi}{v}\right) + \mathcal{O}(\alpha^4).$$

BRs of new Higgs decay modes





Scalar sector

Scalar Fields: SM Higgs + complex singlet

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \tilde h + iG) \end{pmatrix}, \quad \Phi = \frac{1}{\sqrt{2}}(v_\Phi + \tilde\phi + iG_\Phi)$$

Mass matrix for physical components

$$M_{\rm even}^2 = \begin{pmatrix} \lambda_H v^2 & \lambda_{H\Phi}vv_\Phi \\ \lambda_{H\Phi}vv_\Phi & \lambda_\Phi v_\Phi^2 \end{pmatrix}$$

Mass eigenvalues and eigenstates

$$\begin{pmatrix} h \\ \phi \end{pmatrix} = O_{\rm even}^T \begin{pmatrix} \tilde h \\ \tilde\phi \end{pmatrix} \qquad O_{\rm even} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$\tan 2\alpha = \frac{2\lambda_{H\Phi}vv_\Phi}{\lambda_H v^2 - \lambda_\Phi v_\Phi^2}$$

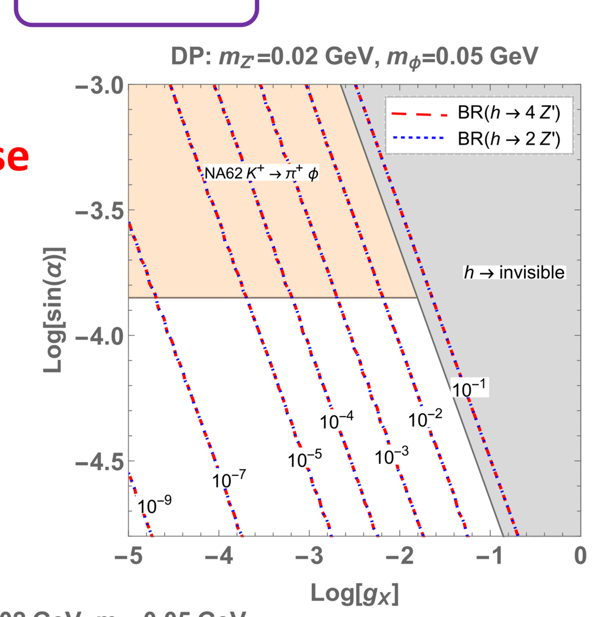
$$m_h^2 = \lambda_H v^2\cos^2\alpha + \lambda_\Phi v_\Phi^2\sin^2\alpha + 2\lambda_{H\Phi}vv_\Phi\sin\alpha\cos\alpha,$$

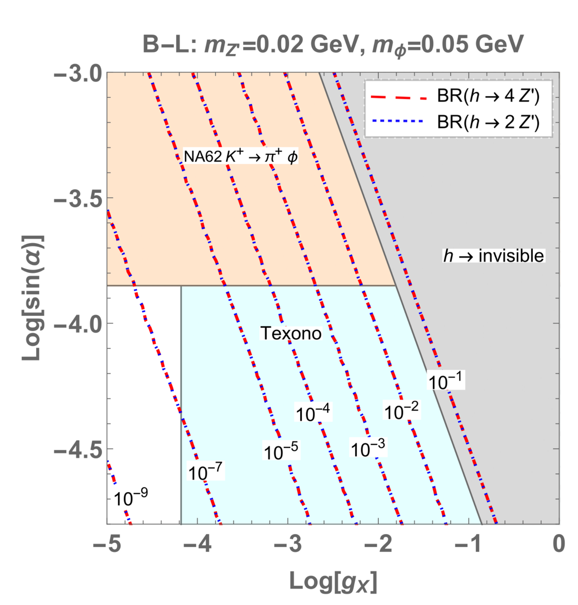
$$m_\phi^2 = \lambda_\Phi v_\Phi^2\cos^2\alpha + \lambda_H v^2\sin^2\alpha - 2\lambda_{H\Phi}vv_\Phi\sin\alpha\cos\alpha.$$

Results

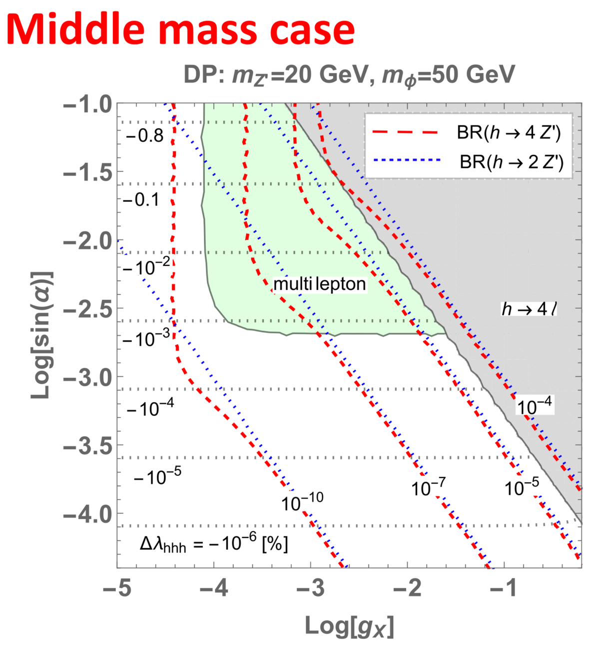
Small mass case

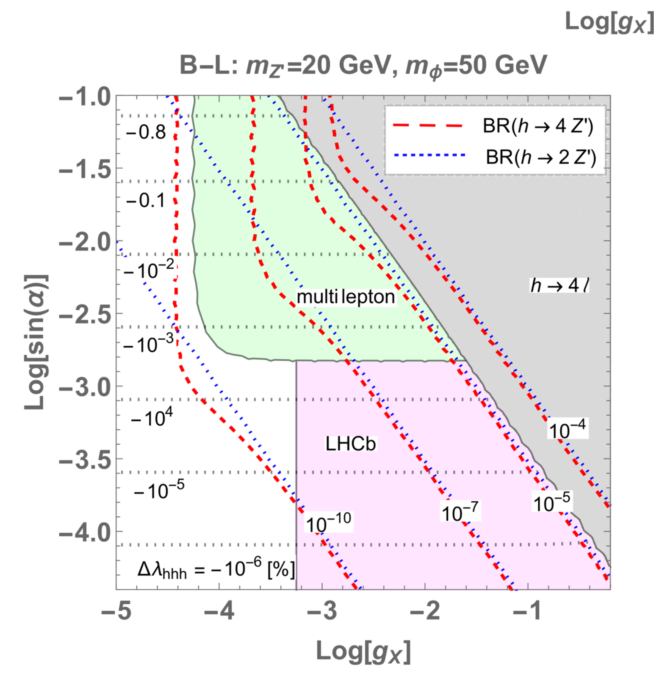
Dark photon & Z' from B – L (as representative)





Middle mass case



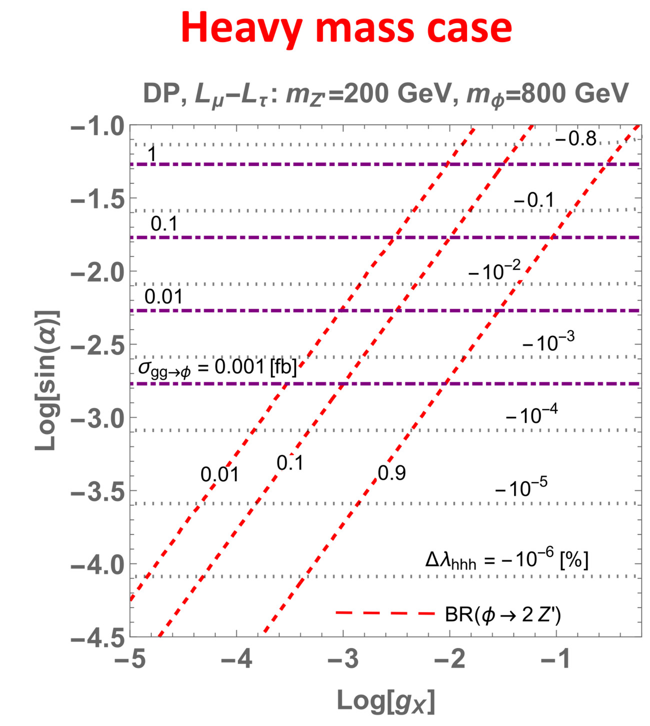


Multi-lepton

gg → ϕ → Z'Z'

(Z' → l⁺ l⁻)

Heavy mass case



Summary of BRs and signatures

(i) Small mass case	$U(1)_D$	$U(1)_{B-L}$	$U(1)_{L_e-L_\mu}$	$U(1)_{L_e-L_\tau}$	$U(1)_{L_\mu-L_\tau}$
$\text{BR}(h \to Z'Z'/\phi\phi)$	$\lesssim 0.05$	$\lesssim 10^{-6}$	$\lesssim 10^{-6}$	$\lesssim 10^{-6}$	$\lesssim 10^{-4}$
Signal of Multi-Z'	e-jets	e-jets $(+\not{E}_T)$	e-jets $(+\not{E}_T)$	e-jets $(+\not{E}_T)$	$\not{E}_T$ [+e-jets]

(ii) Middle mass case	$U(1)_D$	$U(1)_{B-L}$	$U(1)_{L_e-L_\mu}$	$U(1)_{L_e-L_\tau}$	$U(1)_{L_\mu-L_\tau}$
$\text{BR}(h \to Z'Z'/\phi\phi)$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-7}$
Signal of Multi-Z'	multi-j/ℓ	multi-j/ℓ $(+\not{E}_T)$	multi-ℓ $(+\not{E}_T)$	multi-ℓ $(+\not{E}_T)$	multi-ℓ $(+\not{E}_T)$

(iii) Large mass case					
Signal of Multi-Z'	multi-j/ℓ	multi-j/ℓ $(+\not{E}_T)$	multi-ℓ $(+\not{E}_T)$	multi-ℓ $(+\not{E}_T)$	multi-ℓ $(+\not{E}_T)$

✓ σ(gg→h) ~ 50 pb (=50000 fb) at the LHC 13/14 TeV (L = 3000 fb^{-1} @ HL-LHC)

Z' boson

Diagonalizing kinetic term :

$$\begin{pmatrix} X_\mu^3 \\ B_\mu \end{pmatrix} = \begin{pmatrix} r & 0 \\ -\epsilon r & 1 \end{pmatrix}\begin{pmatrix} \tilde Z'_\mu \\ \tilde B_\mu \end{pmatrix}$$

$$\mathcal{L}_M = \frac{1}{2}(\tilde Z_\mu, \tilde Z'_\mu)\begin{pmatrix} m_{Z_{\rm SM}}^2 & \epsilon r\sin\theta_W m_{Z_{\rm SM}}^2 \\ \epsilon r\sin\theta_W m_{Z_{\rm SM}}^2 & r^2\left(g_X^2 v_\Phi^2 + \epsilon^2 m_{Z_{\rm SM}}^2\sin^2\theta_W\right)\end{pmatrix}\begin{pmatrix} \tilde Z^\mu \\ \tilde Z'^\mu \end{pmatrix}$$

$$\left[\ \tilde Z_\mu = \cos\theta_W W_\mu^3 - \sin\theta_W \tilde B_\mu \text{ and } m_{Z_{\rm SM}}^2 = v^2 g^2/(4\cos^2\theta_W)\ \right]$$

Mass eigenstates :

$$\begin{pmatrix} \tilde Z_\mu \\ \tilde Z'_\mu \end{pmatrix} = \begin{pmatrix} \cos\chi & \sin\chi \\ -\sin\chi & \cos\chi \end{pmatrix}\begin{pmatrix} Z_\mu \\ Z'_\mu \end{pmatrix} \qquad \sin 2\chi = -\frac{2\epsilon r\sin\theta_W m_{Z_{\rm SM}}^2}{m_Z^2 - m_{Z'}^2}$$

$$m_{Z'} = g_X v_\Phi[1 + \mathcal{O}(\epsilon^2)]$$

Relevant interactions

$$\mathcal{L}_{Z'f\bar f} = g_X \bar f\gamma^\mu(v'_f - a'_f\gamma_5)fZ'_\mu$$

$$v'_f = X_f r\cos\chi + \frac{e}{g_X}Q_f\epsilon r\cos\theta_W\cos\chi - \frac{g}{g_X\cos\theta_W}\left(\frac{T_{3f}}{2} - Q_f\sin^2\theta_W\right)(\sin\chi + \epsilon r\sin\theta_W\cos\chi),$$

$$a'_f = -\frac{g}{g_X\cos\theta_W}\frac{T_{3f}}{2}(\sin\chi + \epsilon r\sin\theta_W\cos\chi),$$

$$\mathcal{L} \supset \left(\frac{m_Z^2}{v}Z_\mu Z^\mu + \frac{2m_W^2}{v}W_\mu^+W^{-\mu} - \sum_{f_{\rm SM}}\frac{m_{f_{\rm SM}}}{v}\overline{f_{\rm SM}}f_{\rm SM}\right)(h\cos\alpha - \phi\sin\alpha) + \frac{m_{Z'}^2}{v_\Phi}Z'_\mu Z'^\mu(\phi\cos\alpha + h\sin\alpha) + \sum_{\rm scalars}\lambda_{\varphi_i\varphi_j\varphi_k}\varphi_i\varphi_j\varphi_k,$$

Appendix A : list of constraints

The major constraints on { g_X, sinα } for each mass case

❖ Small mass case: $\{m_{Z'}, m_\phi\} = \{0.02, 0.05\}$ GeV

- $K^+ \to \pi^+\phi$ search at NA64, NA64, JHEP06 (2021)
- h→invisible tests at the LHC ATLAS,PLB842 (2023)
  - ✓ e^+e^- from Z' is collimated and difficult to detect
- Neutrino scattering: Texono (B-L, L_e-L_τ, L_e-L_μ) Texono, PRD81, (2010)
- Borexino (L_μ-L_τ) Borexino, PRL107, (2011)

❖ Middle mass case: $\{m_{Z'}, m_\phi\} = \{20, 50\}$ GeV

- Multi-lepton searches at the LHC, ATLAS,PLB824 (2022)
- h→4 lepton searches at the LHC ATLAS,JHEP03 (2022), CMS, EPJC82 (2022)
- LHCb (B-L), PRL124 (2020)
- pp → μ+μ- μ+μ- (L_e-L_μ, L_μ-L_τ) CMS(2018), ATLAS(2023)
- Texono (L_e-L_τ)

❖ Heavy mass case $\{m_{Z'}, m_\phi\} = \{200, 800\}$ GeV

- LEP bound on Z' interactions

Appendix B : hhh coupling

❖ hhh vertex at 1-loop level

$$\hat\Gamma_{hhh} = \Gamma_{hhh}^{\rm tree} + \Gamma_{hhh}^{\rm 1PI} + \delta\Gamma_{hhh}$$

Tree level: $\Gamma_{hhh}^{\rm tree} = 3!\lambda_{hhh}$

$$\lambda_{hhh} = -\frac{m_h^2(v_\Phi\cos^3\alpha + v\sin^3\alpha)}{2vv_\Phi}$$

Counterterm contribution :

$$\delta\Gamma_{hhh} = 3!\left(\delta\lambda_{hhh} + \frac{3}{2}\lambda_{hhh}\delta Z_h + \lambda_{\phi hh}\delta Z_{\phi h}\right)$$

$$\delta\lambda_{hhh} = \frac{m_h^2\cos^3\alpha}{2v}\frac{\delta v}{v} + \frac{m_h^2\sin^3\alpha}{2v_\Phi}\frac{\delta v_\Phi}{v_\Phi} - \frac{1}{2vv_\Phi}(v\sin^3\alpha + v_\Phi\cos^3\alpha)\delta m_h^2 + \frac{3m_h^2}{4vv_\Phi}\sin 2\alpha(v_\Phi\cos\alpha - v\sin\alpha)(\delta\alpha + \delta\alpha_{\rm PT}).$$

Counterterms are obtained by calculating 1PI diagrams

Summary & Discussions

Extension of the SM with U(1)' gauge symmetry

- ✓ Z' boson from extra U(1)'
- ✓ Possibility of models with anomaly cancellation condition
- ✓ Z' and scalar boson can be heavy or light
- ✓ Experimental constraints are considered

❖ Multi-Z' signatures of U(1)'models

- ✓ Electron-jets signals for light Z' and scalar
- ✓ Dark photon case is less constrained
- ✓ Multi-leptons/jets signals for heavier bosons
- ✓ Sizable number of events is possible

Electron-jets signals are interesting possibility

$$h \to Z'Z' \to (e^+e^-)(e^+e^-)$$

$$h \to \phi\phi \to (Z'Z')(Z'Z') \to (e^+e^-e^+e^-)(e^+e^-e^+e^-)$$

Challenging to analyze ⇨ The work in progress!