A triple Z' signal via light Higgs interaction in Z-factories

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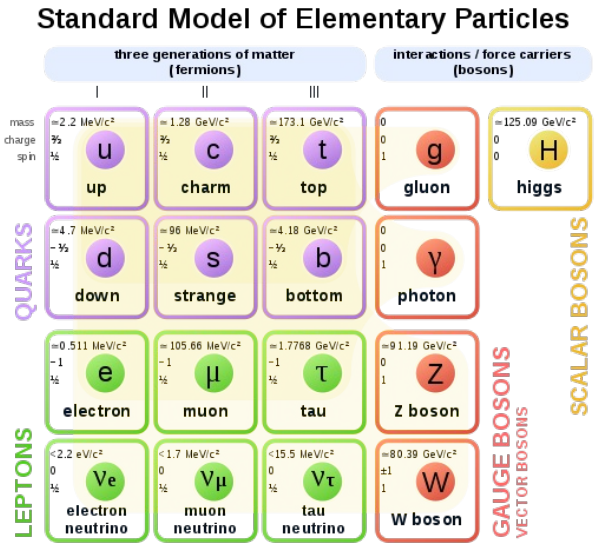
Appearing soon: arXiv: 2410.xxxxx

Outline of the talk

1. Introduction
2. Extra U(1)' and Z' boson
3. Triple Z' signatures
4. Summary

The standard model (SM) of particle physics is successful



The SM is based on gauge symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$

However, there should be beyond the SM (BSM) physics

⇨ Dark matter, neutrino mass etc.

What kind of BSM could be tested in near future?

⇨ New particle(s) from extra U(1)' sector is one candidate

One simple extension of the SM

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

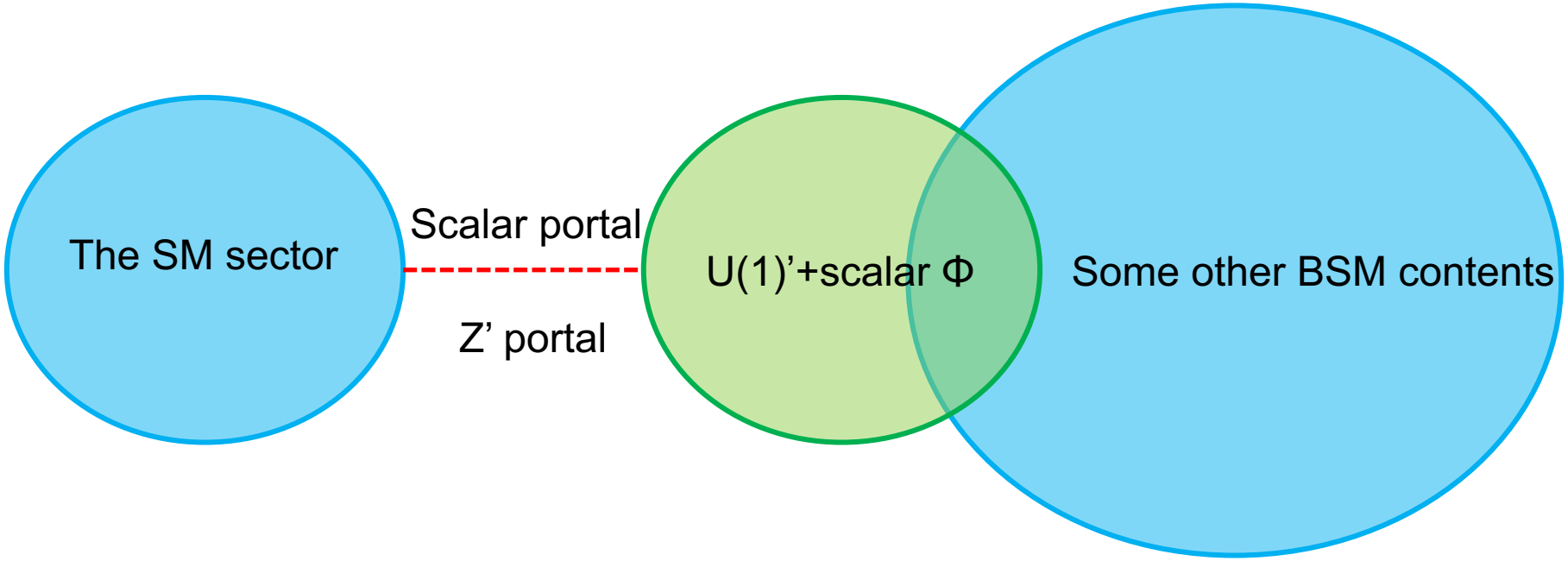
◆The SM is based on gauge symmetry

⇨ **The BSM would be also described by gauge symmetry**

◆It is plausible new physics
providing rich phenomenology, e.g.

- Stabilizing dark matter and providing DM-SM mediator
- Application to flavor structure (flavor dependent U(1))
- U(1) breaking scalar VEV → Higgs physics
- It would appear from high scale theory (like GUTs, string theory)
- Can be tested if new Z'(scalar) is light (e.g. dark photon(Higgs))

If U(1)' is spontaneously broken introduction of new scalar is natural



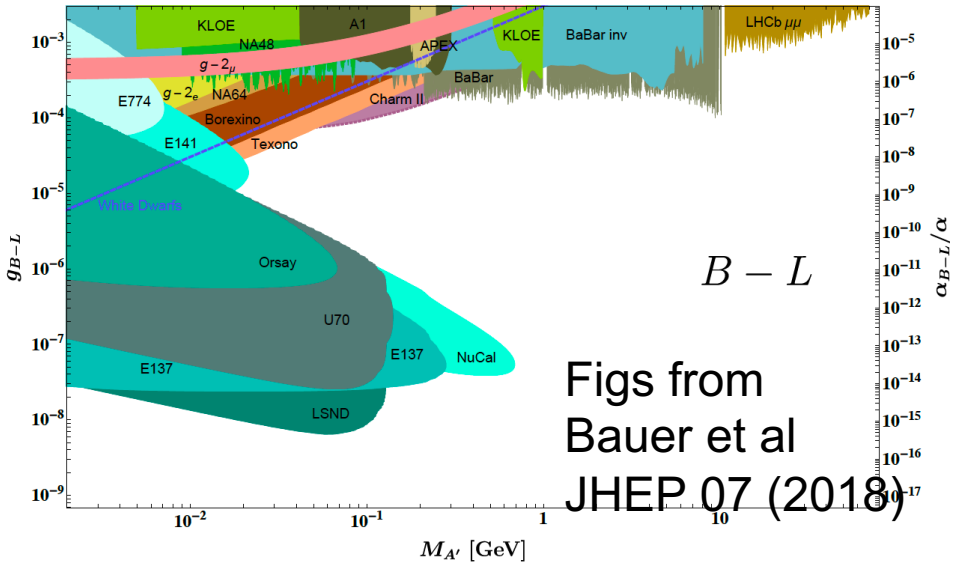
Scalar + Z' portal may connect BSM and the SM

It is more natural to consider scalar and Z' at the same time

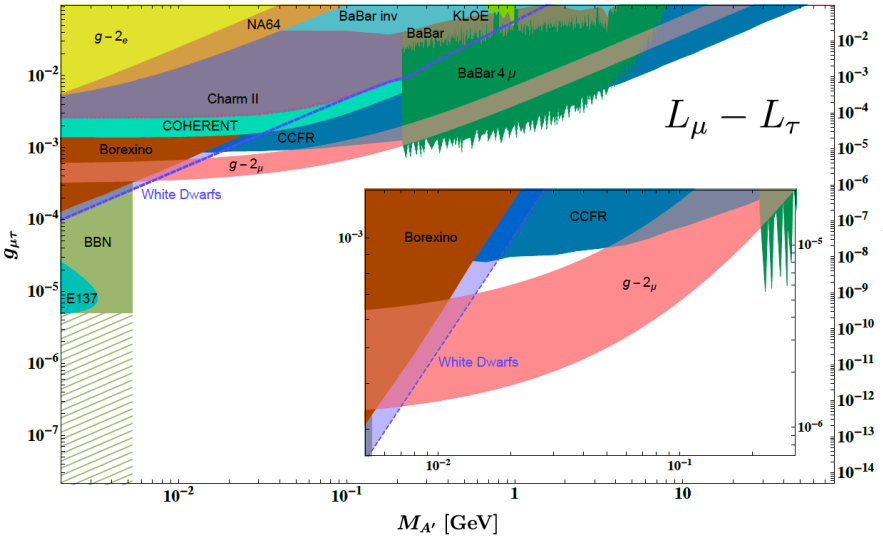
⇩

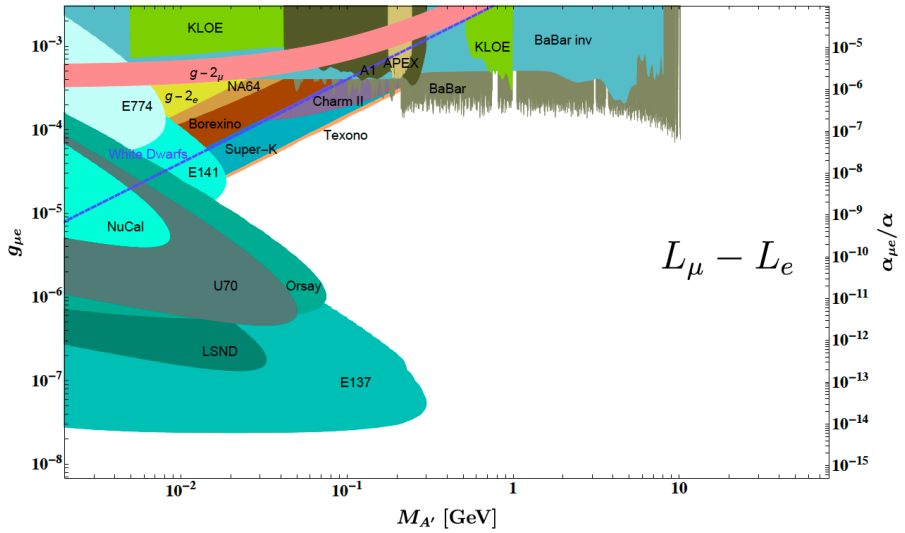
Signatures of spontaneously broken U(1)' gauge symmetry

Many Z‘ boson searches (below electroweak scale)



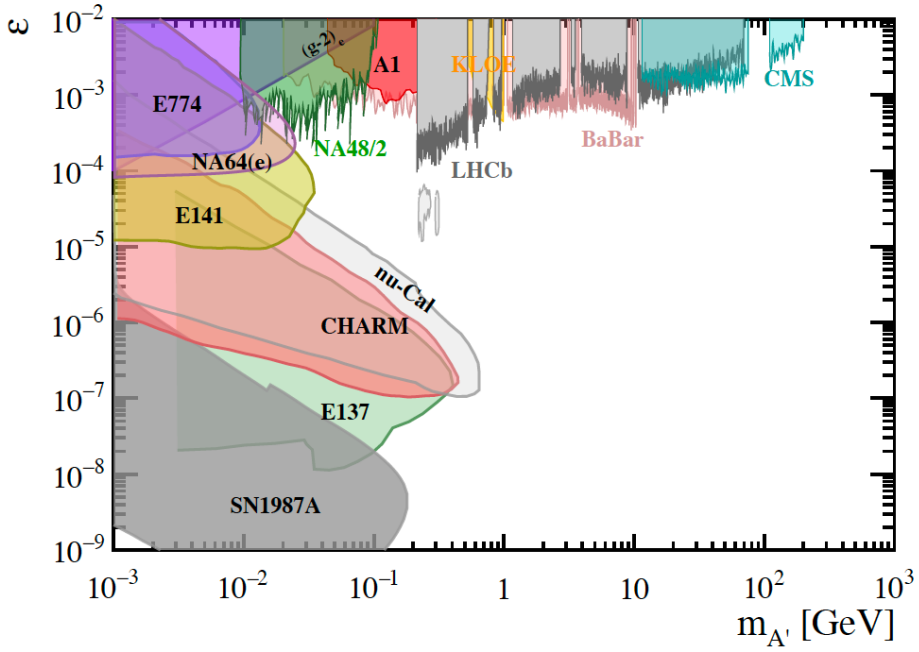
Figs from Bauer et al JHEP 07 (2018)

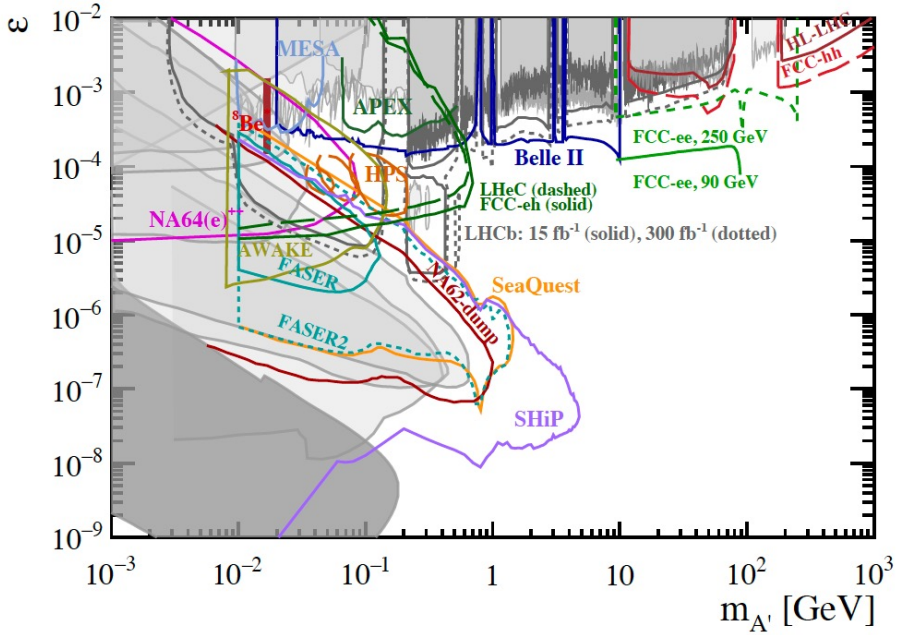




- Beam dump experiments,
- Neutrino scattering,
- Lepton collider experiments,
- Hadron collider experiments,
- Etc.

Dark photon searches are active (below electroweak scale)





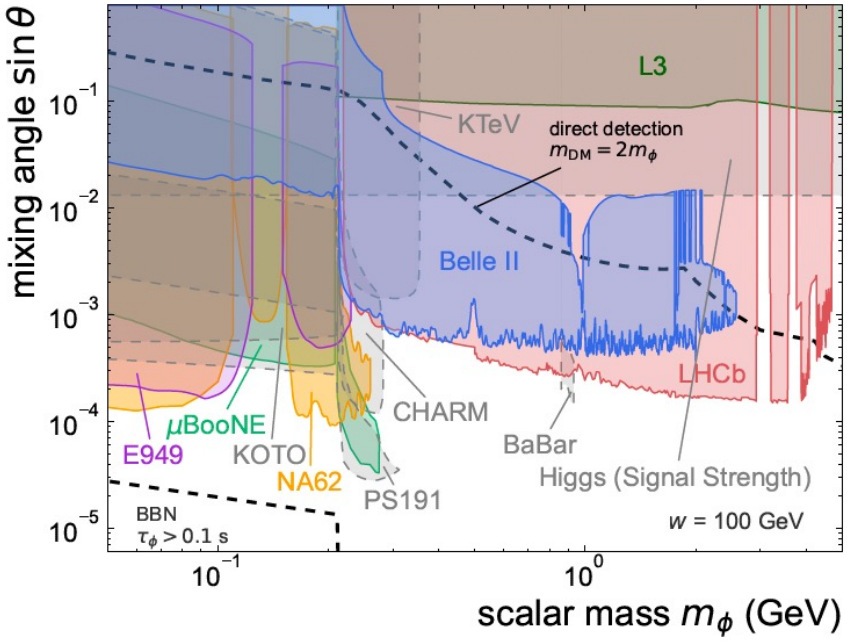
Figs from 2005.01515

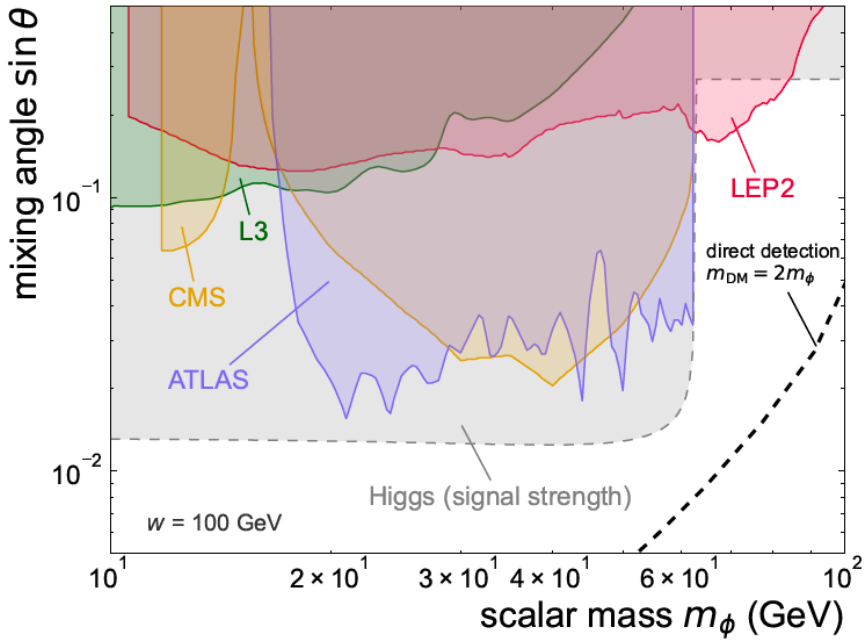
- ✓ Kinetic mixing parameter can be tested
- ✓ Many constrains and future prospects

$$-\frac{\sin\epsilon'}{2}B_{\mu\nu}X^{\mu\nu}$$

$$\mathcal{L}_{A'f\bar{f}} \simeq e\epsilon Q_f \bar{f}\gamma^\mu f A'_\mu$$

Light scalar is also searched for





Figs from 2305.16169

Constraint on scalar mixing (new scalar and SM Higgs)

In particular, meson decays constrain the mixing strongly ($m_{scalar} < 5$ GeV)

New signal would appear considering both scalar and Z'

We discuss new Z boson decay chain

⇨ $Z \to Z'\phi \to Z'Z'Z'$ **Providing triple Z'**

It is a good target at Z-factories (e+e- collision with $\sqrt{s} \simeq m_Z$)

⇨ Can be realized at CEPC, FCC-ee, etc.

In Z-factories we expect O(10^{12}) Z boson production (Tera-Z)

⇨ High sensitivity to Z boson decay

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We consider simple setting

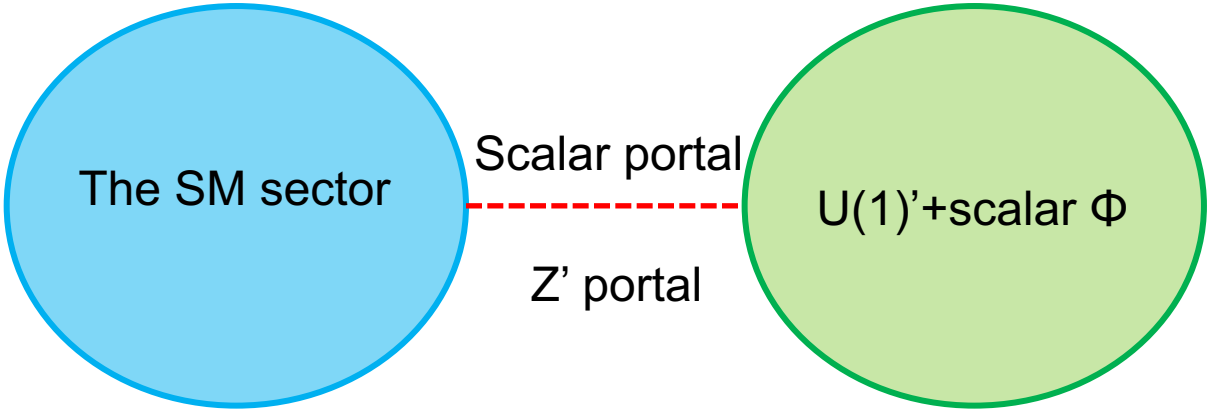
New U(1)' gauge symmetry

+

SM singlet scalar Φ with non-zero U(1)' charge

The scalar field develops a vacuum expectation value (VEV) to break U(1)'

It is **the simplest** field contents for spontaneously broken local U(1)' scenario



For SM + extra $U(1)_X$ gauge symmetry

U(1) Gauge sector

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sin\epsilon'}{2}B_{\mu\nu}X^{\mu\nu}$$

$U(1)_Y$ U(1)' U(1) kinetic mixing

Scalar potential

$$V = -\mu_H^2|H|^2 - \mu_\Phi^2|\Phi|^2 + \frac{\lambda_H}{2}|H|^4 + \frac{\lambda_\Phi}{2}|\Phi|^4 + \lambda_{H\Phi}|H|^2|\Phi|^2.$$

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

Scalar develops VEVs: $\langle H(\Phi)\rangle = v(v_\Phi)/\sqrt{2}$ ⇨ Electroweak and U(1)' break

Scalar mass and mixing

$$\begin{pmatrix} \tilde{h} \\ \tilde{\phi} \end{pmatrix} = R(\alpha)\begin{pmatrix} h \\ \phi \end{pmatrix}, \quad R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

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

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

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

2. Extra U(1) and Z' boson

Kinetic term of U(1) gauge fields can be diagonalized by

$$\begin{pmatrix} X_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} \mathrm{cosec}\,\epsilon' & 0 \\ -\tan\epsilon' & 1 \end{pmatrix} \begin{pmatrix} \tilde{Z}'_\mu \\ \tilde{B}_\mu \end{pmatrix}$$

General kinetic term after the transformation

$$D_\mu \Psi = \left[\partial_\mu - ig(T^+ W_\mu^+ + \text{c.c.}) - ieQ_\Psi A_\mu \right.$$
$$\left. -ig_Z(T^3_\Psi - s^2_W Q_\Psi)\tilde{Z}_\mu - ig_X X_\Psi \tilde{Z}'_\mu \right] \Psi$$

$$X_\Psi = \tilde{X}_\Psi - Y_\Psi \frac{g'}{g_X}\tan\epsilon'$$

$\tilde{X}_\psi$: U(1)' charge

Z-Z' mass term

$$M_{ZZ'} = \begin{pmatrix} m_Z^2 - \delta_Z^2 & -m_Z v\delta \\ -m_Z v\delta & m_{Z'}^2 - \delta_{Z'}^2 + v^2\delta^2 \end{pmatrix} + \mathcal{O}(\delta^3)$$

$$\delta_Z^2 = \frac{g_Z^2 v^4}{g_Z^2 v^2 - 4g_X^2 X_\Phi^2 v_\Phi^2}\delta^2,$$
$$\delta_{Z'}^2 = -\frac{4g_X^2 X_\Phi^2 v^2 v_\Phi^2}{g_Z^2 v^2 - 4g_X^2 X_\Phi^2 v_\Phi^2}\delta^2.$$

$$\delta \equiv g_X X_H$$

Mass eigenstates

$$\begin{pmatrix} \tilde{Z}_\mu \\ \tilde{Z}'_\mu \end{pmatrix} = R(\zeta)\begin{pmatrix} Z_\mu \\ Z'_\mu \end{pmatrix}, \quad \sin 2\zeta = \frac{g_Z v^2 \delta}{m_{Z'}^2 - m_Z^2}$$

(δ << 1 to suppress Z-Z' mixing)

Gauge-Gauge-Scalar interaction

$$\mathcal{L}_{\rm int} = (Z_\mu, Z'_\mu) R^T(\zeta) M_{\rm int} R(\zeta) \begin{pmatrix} Z^\mu \\ Z'^\mu \end{pmatrix} + \mathcal{O}(\delta^3),$$

$$M_{\rm int} = \begin{pmatrix} (m_Z^2 - \delta_Z^2)\frac{\tilde{h}}{v} & -m_Z v\delta\frac{\tilde{h}}{v} \\ -m_Z v\delta\frac{\tilde{h}}{v} & (m_{Z'}^2 - \delta_{Z'}^2)\frac{\tilde{\phi}}{v_\Phi} + v\delta^2\tilde{h} \end{pmatrix},$$

⇩ For tiny Z-Z' mixing (ζ << 1)

$$\mathcal{L}_{\rm int} = (Z_\mu, Z'_\mu) \begin{pmatrix} \Lambda_{11} & \Lambda_{12} \\ \Lambda_{12} & \Lambda_{22} \end{pmatrix} \begin{pmatrix} Z^\mu \\ Z'^\mu \end{pmatrix}$$

$$\Lambda_{11} = \frac{m_Z^2}{v}\tilde{h} + \frac{m_Z^2 m_{Z'}^2 v^2}{(m_Z^2 - m_{Z'}^2)^2}\left(\frac{\tilde{\phi}}{v_\Phi} - \frac{\tilde{h}}{v}\right)\delta^2 + \mathcal{O}(\delta^4),$$

$$\Lambda_{22} = \frac{m_{Z'}^2}{v_\Phi}\tilde{\phi} - \frac{m_{Z'}^4 v^2}{(m_Z^2 - m_{Z'}^2)^2}\left(\frac{\tilde{\phi}}{v_\Phi} - \frac{\tilde{h}}{v}\right)\delta^2 + \mathcal{O}(\delta^4),$$

$$\Lambda_{12} = \frac{m_Z m_{Z'}^2 v}{m_{Z'}^2 - m_Z^2}\left(\frac{\tilde{\phi}}{v_\Phi} - \frac{\tilde{h}}{v}\right)\delta + \mathcal{O}(\delta^3).$$

⇨ ZZ'Φ interaction

$$\begin{pmatrix} \tilde{h} \\ \tilde{\phi} \end{pmatrix} = R(\alpha)\begin{pmatrix} h \\ \phi \end{pmatrix}, \quad R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

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New signal of spontaneously broken U(1)' at Z factories

⇨ Decay of Z boson into Z'Φ mode

It is induced by interactions after spontaneous symmetry breaking

$$\mathcal{L}_{ZZ'\phi} \simeq \frac{m_Z m_{Z'}^2 v}{m_{Z'}^2 - m_Z^2} \frac{\cos\alpha}{v_\Phi} \delta\, Z_\mu Z'^\mu \phi$$

We consider the BR of the process in focusing on dark photon case

$$X_H = -\frac{1}{2}\frac{g'}{g_X}\tan\epsilon' \quad (\tilde{X}_H = 0) \Rightarrow \delta = g_X X_H = -\frac{1}{2} e \frac{\cos\theta_W \tan\epsilon'}{\varepsilon}$$

$$\mathcal{L}_{Z' f\bar{f}} \simeq e\epsilon Q_f \bar{f}\gamma^\mu f Z'_\mu$$ Dark photon interaction with SM fermions

⇨ Explore sensitivity to kinetic mixing ε (and new gauge coupling g_X)

Decay BRs of $Z \to Z'\Phi$ process

Decay width

$$\Gamma(Z \to Z'\phi) = \frac{m_Z}{48\pi}\left(s_\alpha + \frac{v}{v_\Phi}c_\alpha\right)^2 \frac{x_{Z'}\delta^2}{(1-x_{Z'})^2} \times \left[(1+x_{Z'}-x_\phi)^2 + 8x_{Z'}\right]\lambda^{1/2}(x_{Z'}, x_\phi)$$

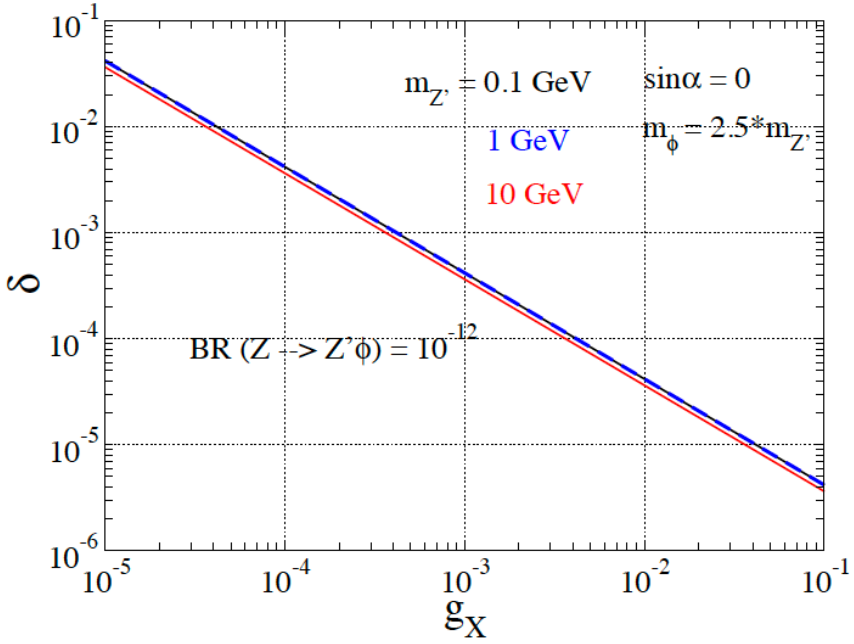
$x_{Z'} = m_{Z'}^2/m_Z^2$ and $x_\phi = m_\phi^2/m_Z^2$ $\qquad$ $\lambda(x,y) = 1 + x^2 + y^2 - 2x - 2y - 2xy$

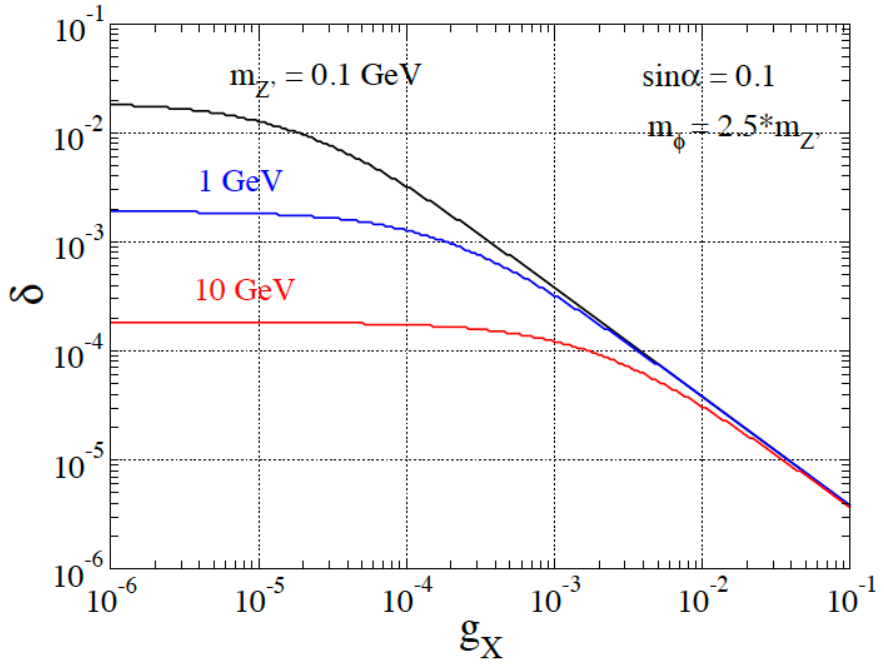
Decay BR

$$\mathrm{BR}(Z \to Z'\phi) \sim \frac{m_Z}{48\pi}\left(s_\alpha + \frac{v}{v_\Phi}c_\alpha\right)^2 \frac{x_{Z'}\delta^2}{\Gamma_Z^{\mathrm{obs}}} \sim 0.24 \times \left(s_\alpha + \frac{v}{v_\Phi}c_\alpha\right)^2 x_{Z'}\delta^2$$

$$\Rightarrow \begin{cases} \mathrm{BR}(Z \to Z'\phi) \sim 1.76 \times g_X^2 X_\Phi^2 \delta^2 & \text{for} \quad s_\alpha \to 0 \\ \mathrm{BR}(Z \to Z'\phi) \sim 0.24 \times s_\alpha^2 x_{Z'}\delta^2 & \text{for} \quad |s_\alpha| \gg v/v_\Phi \end{cases}$$

Decay BRs of $Z \rightarrow Z'\Phi$ process





- ✓ We have sensitivity for small δ if g_X is sizable
- ✓ Contribution from scalar mixing for tiny g_X but not very large
  - ❖ We consider $\alpha \rightarrow 0$ limit for simplicity

Dark photon case is promising since we can have g_X = O(1)-O(0.1)

Note: $m_\Phi \geq m_{Z'}$ and g_X = O(1)-O(0.1) is plausible case (SM: $m_h \geq m_Z$, $0.1 < g,g' < 1$)

Decay BRs of scalar bosons

Decay widths of new scalar boson

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

$$\Gamma(\phi \to hh) = \frac{\lambda_{\phi hh}^2}{8\pi m_\phi}\beta(x_h), \qquad x_i = m_i^2/m_\phi^2 \text{ and } \beta(x) = \sqrt{1-4x}$$

✓ Decay widths for the SM particles modes also exist via H-Φ mixing

Decay widths of SM Higgs boson for new modes

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

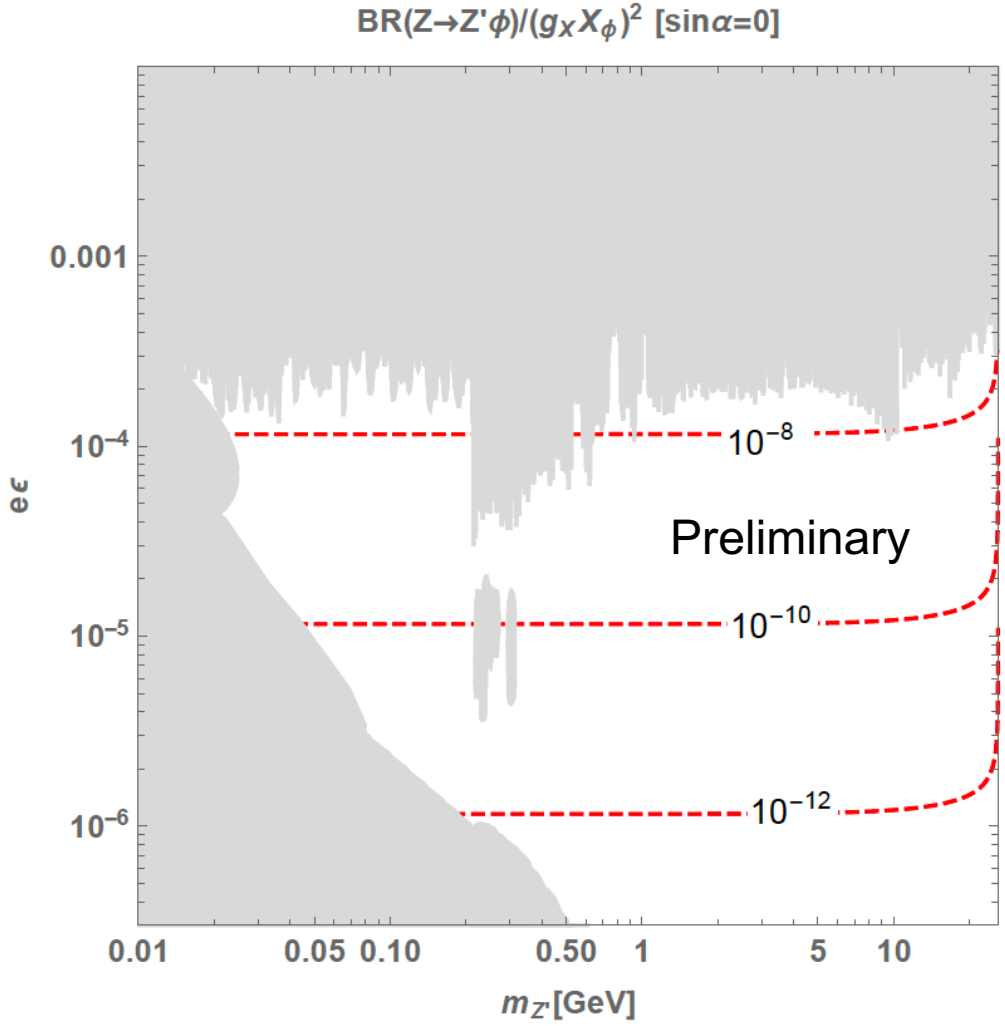
$$\Gamma(h \to \phi\phi) = \frac{\lambda_{\phi\phi h}^2}{8\pi m_h}\beta(z_\phi),$$

✓ For α→0, new scalar decays into Z'Z' with 100% BR

✓ New Higgs decay modes also vanish in the limit

3. Triple Z' signatures

The branching ratio (dark photon case)

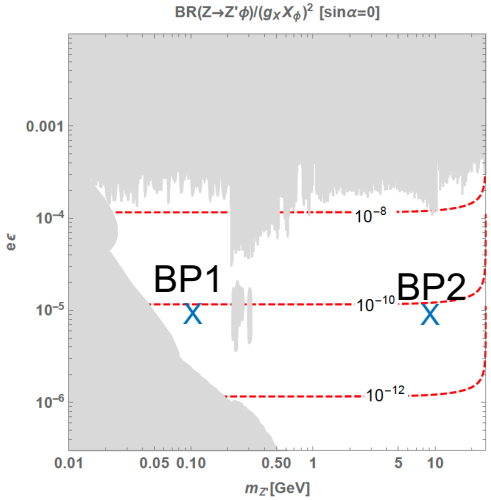


($m_\Phi = 2.5 m_{Z'}$)

✓ Gray region is excluded by dark photon searches

We expect sizable number of event at Z-factories: a few × 10^{12} Z boson

3. Triple Z' signatures



Benchmark points

$$\text{BP1}: \; m_{Z'} = 0.1 \text{ GeV}, \; e\epsilon = 10^{-5}, \; g_X = 0.5,$$
$$\text{BP2}: \; m_{Z'} = 10 \text{ GeV}, \; e\epsilon = 10^{-5}, \; g_X = 0.5,$$

Z' (dark photon) decaying into SM fermions and BRs are

$$BR(Z' \to e^+e^-) \simeq 1.0 \qquad \textbf{BP1}$$

$$BR(Z' \to e^+e^-/\mu^+\mu^-/\tau^+\tau^-) \simeq 0.15, \quad BR(Z' \to \text{hadron}) \simeq 0.55 \qquad \textbf{BP2}$$

Expected number of events for BPs with 10^{12} Z

	6ℓ	4ℓ+had.	2ℓ+had.	had.
BP1	46.	0	0	0
BP2	1.1	6.1	11.	6.6

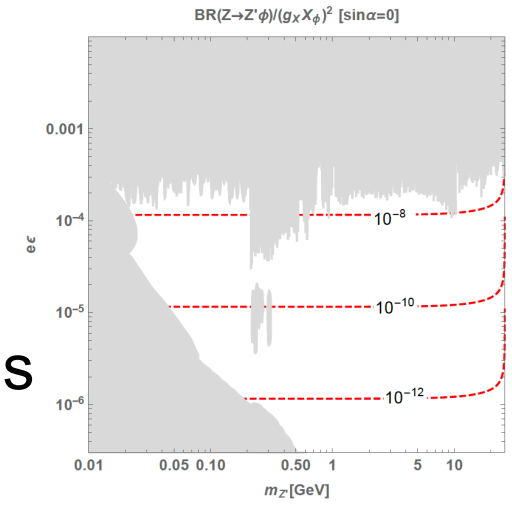
had. = hadrons
ℓ = e, μ

We expect clear signal at Z-factories

Summary and Discussions

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

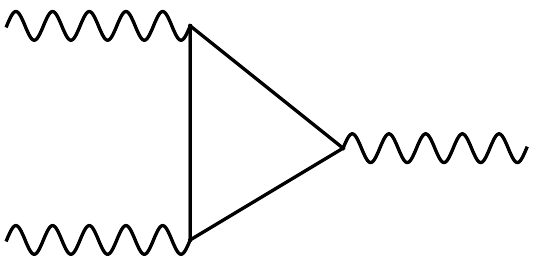
- ✓ Z' boson from extra U(1)'
- ✓ We also would have new scalar boson via SSB
- ✓ Z' and scalar boson would be similar mass scale
- ✓ Z decay into scalar + Z' can happen



- ☐ Triple Z' (dark photon) signal at Z-factories
  - ✓ Z→Z'Φ→Z'Z'Z' decay chain
  - ✓ Sensitivity to kinetic mixing > 10^{-6} at Tera Z-factories
  - ✓ Clear signals are expected in dark photon case
  - ✓ Potential of direct BSM discovery at Tera Z-factories

Gauge anomaly free conditions

In constructing an extra U(1)' gauge symmetric model
charge assignment of fermion contents should be anomaly free



$$\sum_f \left(Tr[T_i T_j T_k]_R - Tr[T_i T_j T_k]_L \right) = 0$$

T_i : generator of gauge group

$[SU(3)_c]^2\, U(1)_X$ $\quad$ $[SU(2)_L]^2\, U(1)_X$

$[U(1)_Y]^2\, U(1)_X$ $\quad$ $[U(1)_X]^2\, U(1)_Y$

$[U(1)_X]^3$ $\quad$ $[\text{gravity}]^2\, U(1)_X$

Conditions in addition to the SM gauge anomaly free conditions