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

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Reference: PRD 111 (2025) 095012, arXiv:2412.06302

Collaborated with Kei Yagyu (Tokyo U. of Science)

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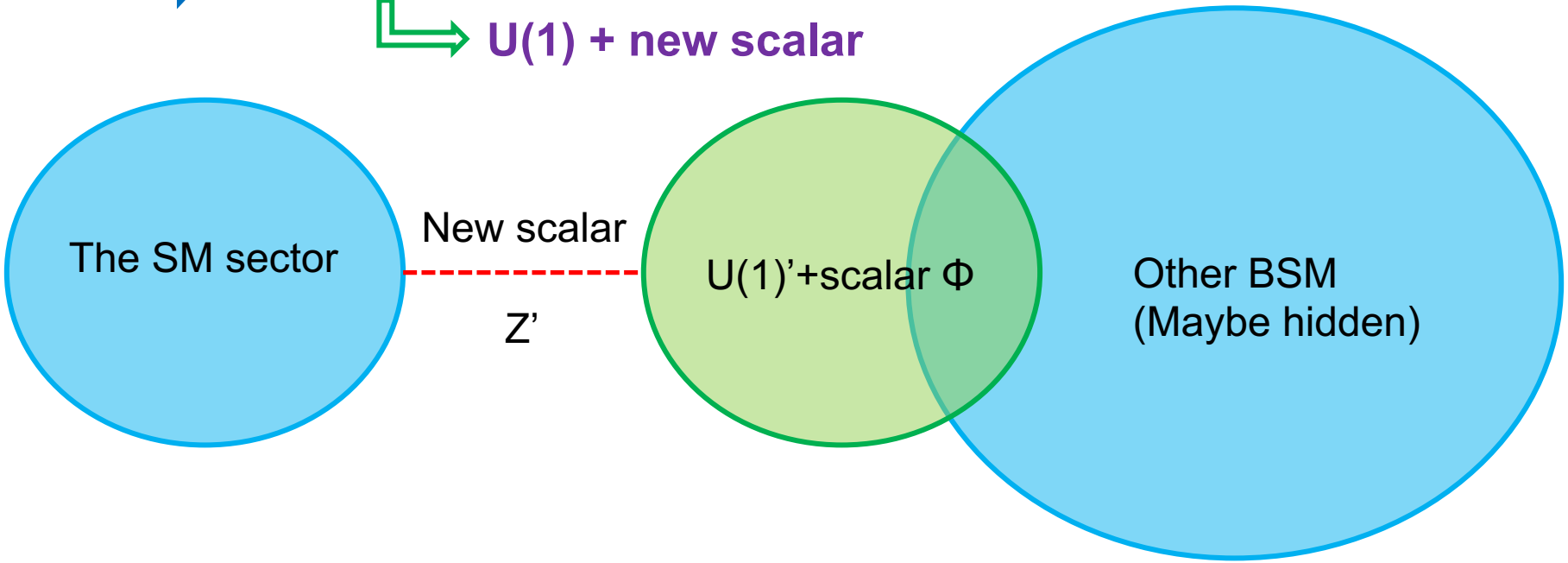
Introduction

Beyond the SM sector would contain a new U(1) gauge symmetry

Plausibly this U(1) is spontaneously broken

U(1) + new scalar



New scalar + Z' boson as relics of BSM

Typically in a similar mass scale

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

Signatures of spontaneously broken U(1)' gauge symmetry

New particles : gauge boson Z'(A') and scalar boson Φ

Z' interact with SM particle via kinetic mixing : $-\frac{\sin\epsilon'}{2}B_{\mu\nu}X^{\mu\nu}$

⇨ **Dark photon interaction** $\mathcal{L}_{A'f\bar{f}} \simeq e\epsilon Q_f \bar{f}\gamma^\mu f A'_\mu \qquad \epsilon \equiv \cos\theta_W \tan\epsilon'$

New scalar mixes with the SM Higgs $\begin{pmatrix} h \\ \phi \end{pmatrix} = O_{\text{even}}^T \begin{pmatrix} \tilde{h} \\ \tilde{\phi} \end{pmatrix} \qquad O_{\text{even}} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$

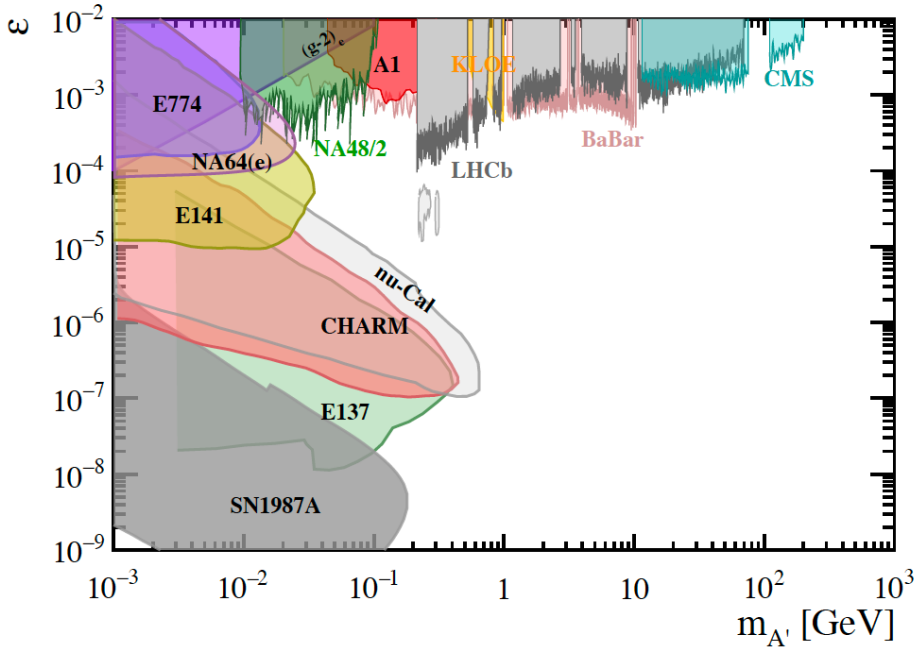
New parameters **{$m_{Z'}$, m_ϕ, sinα, g_X, ε'}**

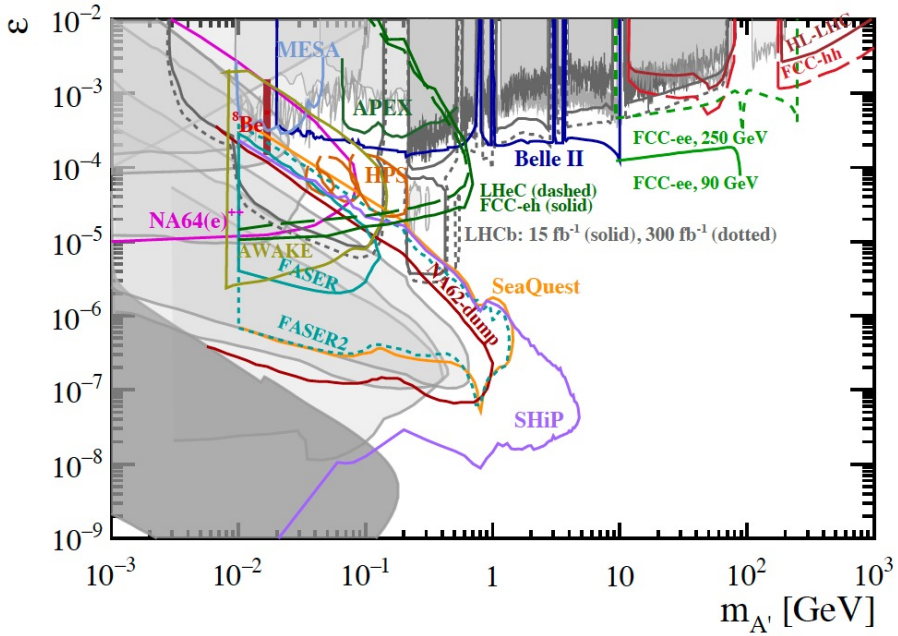
⇩ New gauge coupling

They are constrained by various experiments

- ✓ Searches for dark photon interactions
- ✓ New scalar boson search
- ✓ Etc.

Dark photon searches are active





Figs from 2005.01515

- ✓ Kinetic mixing parameter can be tested
- ✓ Many constrains and future prospects
  - Bremsstrahlung of DP
  - DP from meson decay
  - DP in s-channel
  - etc

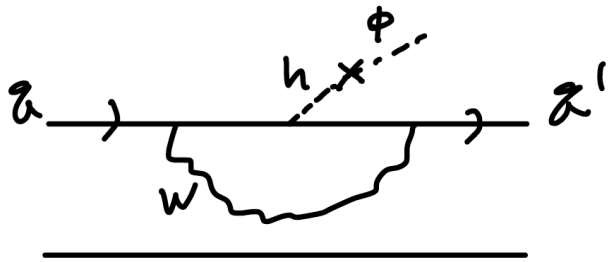
$$-\frac{\sin\epsilon'}{2}B_{\mu\nu}X^{\mu\nu}$$

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

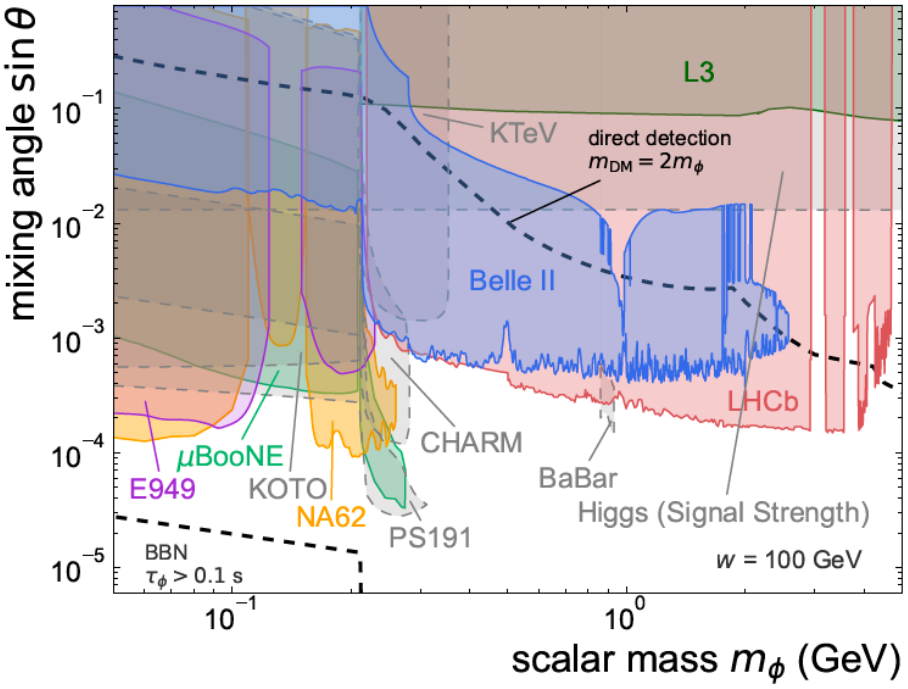
$$\epsilon \equiv \cos\theta_W \tan\epsilon'$$

Constraints on new scalar

Light scalar boson can be induced from meson decay via Higgs mixing



$M \rightarrow M'\varphi$ (via Higgs mixing)



E949: $K^+ \rightarrow \pi^+ \phi(\rightarrow \text{inv.})$
Phys. Rev. D 79 (2009) 092004

KOTO: $K_L^0 \rightarrow \pi^0 \phi(\rightarrow \text{inv.})$
Phys. Rev. Lett. 126 (12) (2021) 121801

μBooNE: $K^+ \rightarrow \pi^+ \phi(\rightarrow e^+e^-, \mu^+\mu^-)$
Phys. Rev. Lett. 127 (15) (2021) 151803, Phys. Rev. D 106, 092006 (2022)

NA62: $K^+ \rightarrow \pi^+ \phi(\rightarrow \text{inv.})$
JHEP 02 (2021) 201, JHEP 06 (2021) 093

PS191: $K^\pm \rightarrow \pi^\pm \phi(\rightarrow e^+e^-, \mu^+\mu^-)$
Phys. Lett. B 203(1988) 332–334, Phys. Lett. B 820 (2021) 136524

CHARM: $K^\pm \rightarrow \pi^\pm \phi(\rightarrow e^+e^-, \mu^+\mu^-)$
Phys. Lett. B 203(1988) 332–334, Phys. Lett. B 820 (2021) 136524

Belle II: $B \rightarrow K^{(*)} \phi(\rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-)$
arXiv:2306.02830 [hep-ex] 2023

KTeV: $K_L^0 \rightarrow \pi^0 \phi(\rightarrow \mu^+\mu^-)$
Phys. Rev. Lett. 84(2000) 5279–5282, Phys. Rev. D 99 (1) (2019) 015018

BaBar: $B \rightarrow X_S \phi(\rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-)$
Phys. Rev.Lett. 114 (17) (2015) 171801, Phys. Rev. D 99 (1) (2019) 015018

L3: $e^+e^- \rightarrow Z^* \phi$
Phys. Lett. B 385 (1996) 454–470

LHCb: $B \rightarrow K^{(*)} \phi(\rightarrow \mu^+\mu^-)$
Phys. Rev.Lett. 115 (16) (2015) 161802, Phys. Rev. D 95 (7) (2017) 071101, Phys. Rev. D 99 (1) (2019) 015018

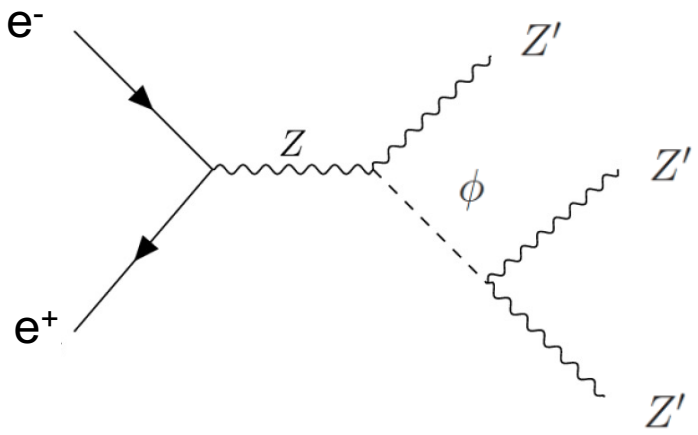
From arXiv: 2305.16169

Interesting signals considering both dark photon and Higgs

⇩

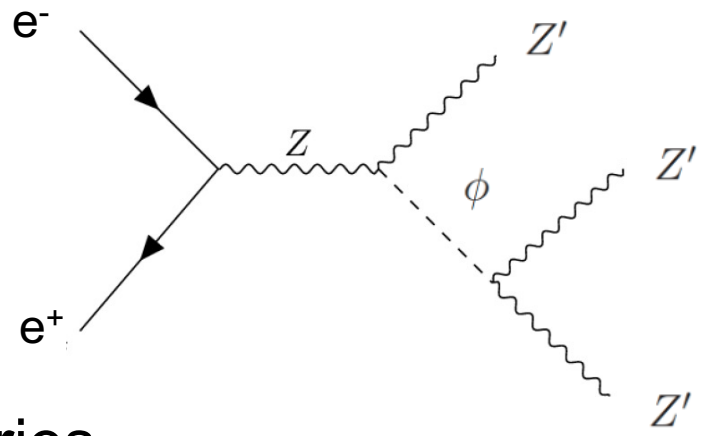
Good target at LHC and future collider experiments

In this talk we consider following processes



At Z-factories

1. Introduction



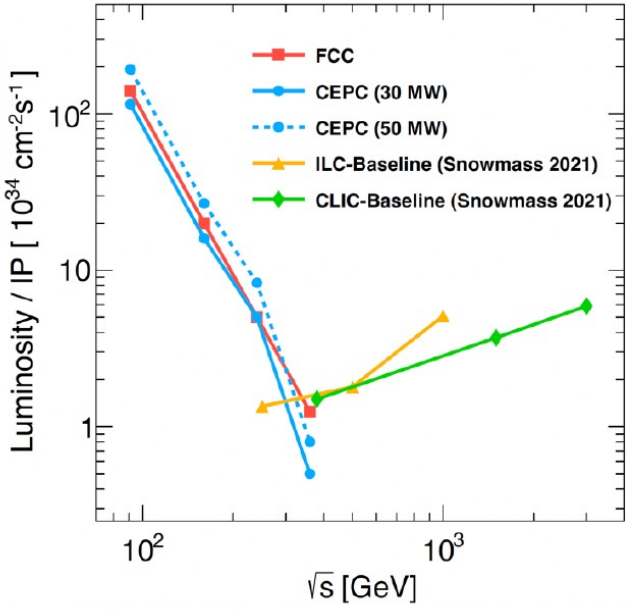
At Z-factories

❖ Future Z-factories

It can be realized by CEPC and FCC-ee

Ex) CEPC (from CEPC review, 2412.19743)

Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, per IP)	191.7	26.7	8.3	0.83
Integrated luminosity (ab^{-1}, 2 IPs)	100	6.9	21.6	1
Event yields	4.1×10^{12}	2.1×10^{8}	4.3×10^{6}	0.6×10^{6}



10^{12} Z boson! (Tera-Z) ➢ $O(10^5)$ larger than LEP statistics

Very rare decay process could be tested

2. Extra U(1) and Z' boson

We consider simple setting

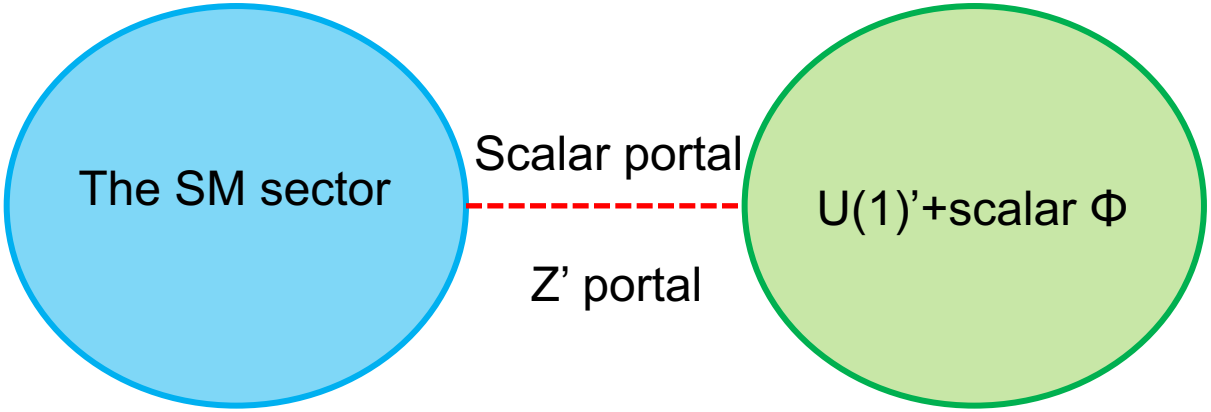
New U(1)' gauge symmetry

+

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)' 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

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

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

$\tilde{X}_\psi$: U(1)' charge of ψ

Z-Z' mass matrix

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

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

$$\delta \equiv g_X X_H$$

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 ($\zeta \ll 1$)

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

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

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

⇨ ZZ'Φ interaction

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

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

3. Triple dark photon at Z-factory

New signal considering both scalar and Z'

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

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

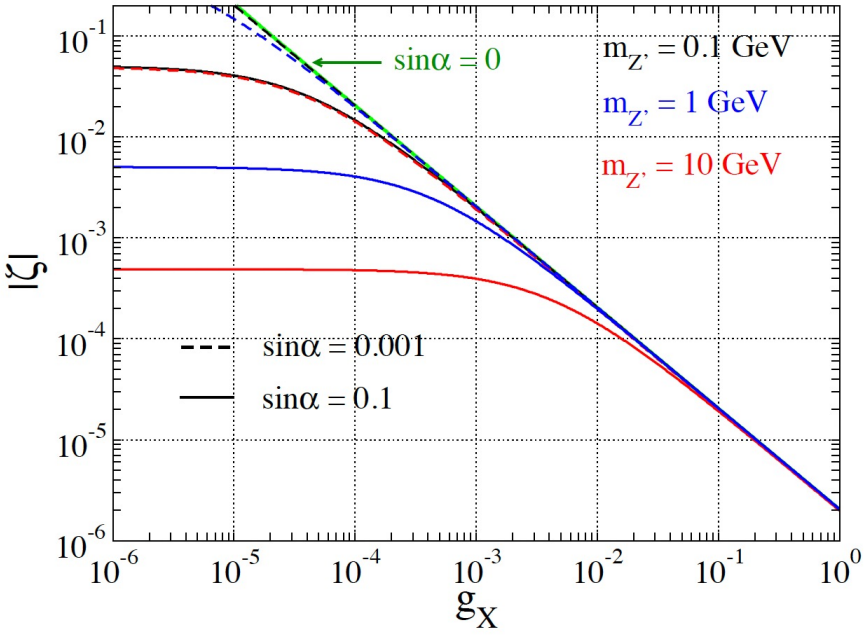
Decay BR

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

$$\delta = g_X X_H = -\frac{1}{2}e\frac{\cos\theta_W \tan\epsilon'}{\varepsilon}$$

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

Decay BRs of Z → Z'Φ process



$$\sin 2\zeta = \frac{g_Z v^2 \delta}{m_{Z'}^2 - m_Z^2}$$

$$\delta = g_X X_H = -\frac{1}{2} e \frac{\cos\theta_W \tan\epsilon'}{\varepsilon}$$

$$m_\phi = 2.5\, m_{Z'}$$

Parameters on each curve give $BR(Z \to Z'\phi) = 10^{-12}$

(larger BR above curves)

- ✓ We have sensitivity even for small ζ if g_X is sizable
- ✓ Contribution from scalar mixing for tiny g_X but not very large
  - ❖ We consider α → 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

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

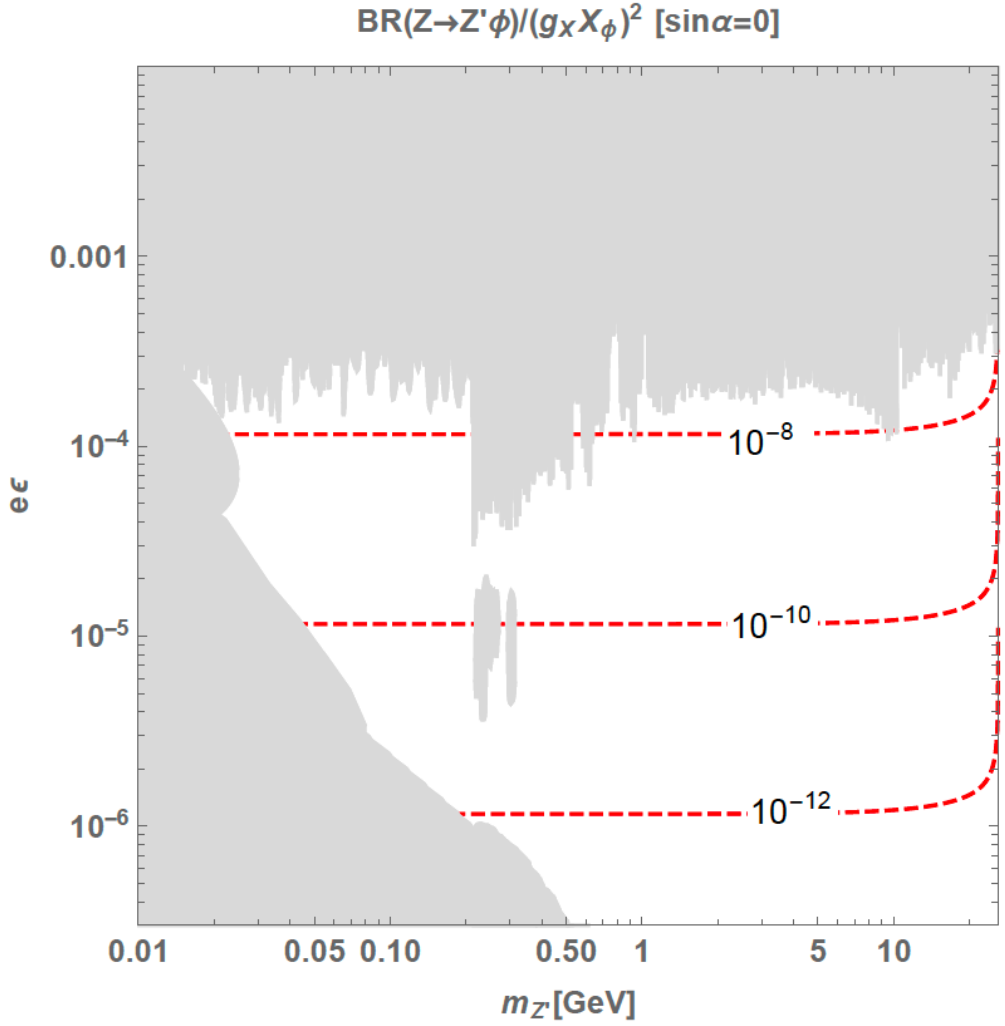
$$\Gamma(h \to \phi\phi) = \frac{\lambda_{\phi\phi h}^2}{8\pi m_h}\beta(z_\phi),$$

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

✓ New Higgs decay modes also vanish in the limit

3. Triple dark photon at Z-factory

The branching ratio (dark photon case)



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

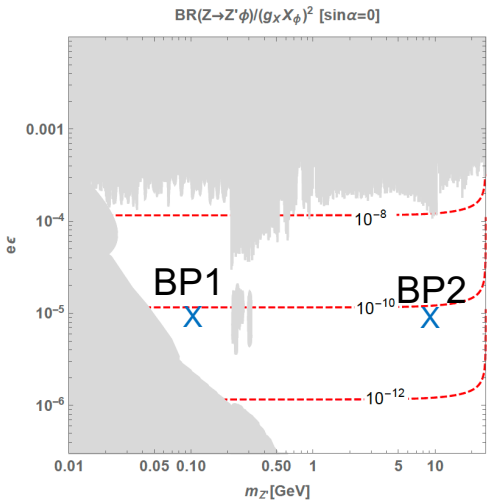
✓ Gray region is excluded by dark photon searches

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

3. Triple dark photon at Z-factory

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 also roughly estimate BG

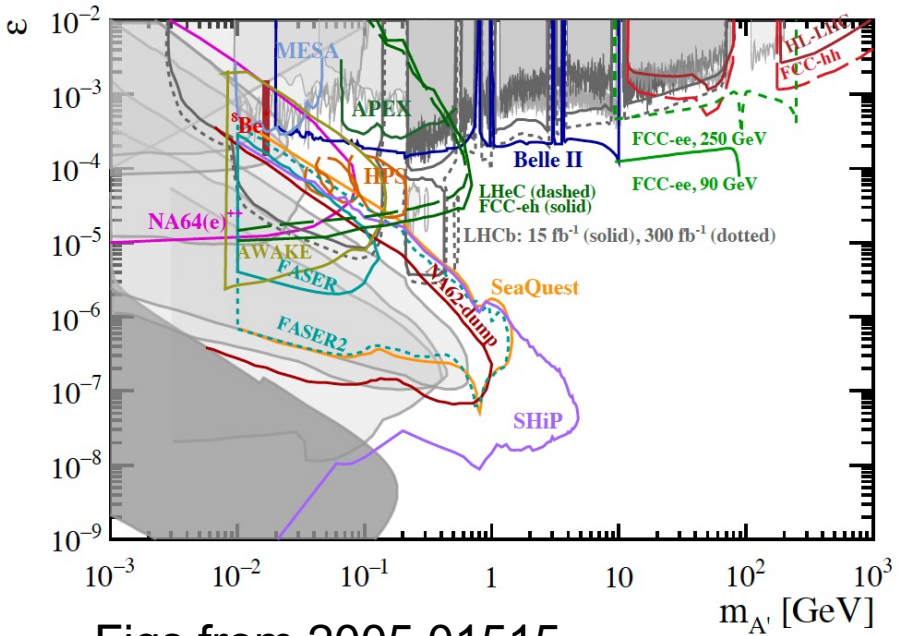
$$\sigma(e^+e^- \to 3 \times (\ell^+\ell^-)) \simeq 2.3 \times 10^{-1} \text{ fb},$$
$$\sigma(e^+e^- \to 2 \times (\ell^+\ell^-) + 2 \text{ jets}) \simeq 3.1 \text{ fb}.$$

p_T cut

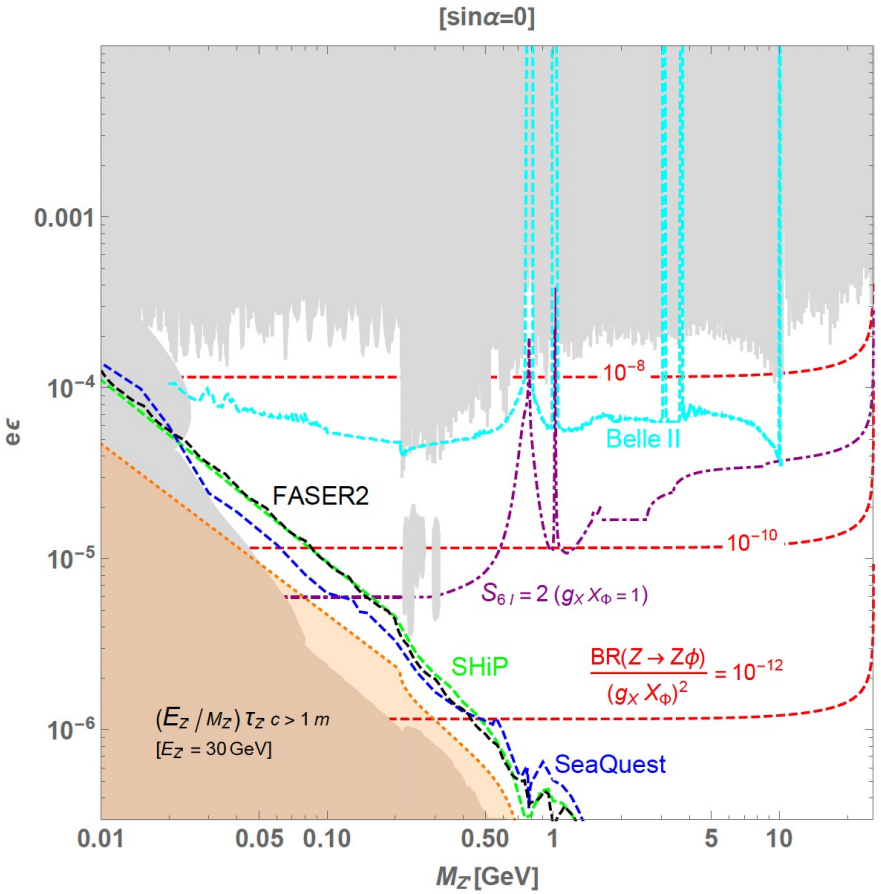
$$\sigma(e^+e^- \to 3 \times (\ell^+\ell^-)) \simeq 3.7 \times 10^{-4} \text{ fb} \; (p_T > 5 \text{ GeV}),$$
$$\sigma(e^+e^- \to 2 \times (\ell^+\ell^-) + 2 \text{ jets}) \simeq 1.4 \times 10^{-3} \text{ fb} \; (p_T > 5 \text{ GeV}).$$

Signal efficiency under p_T cut ~ 0.14

Comparing with other future prospects (L=10^5 fb^{-1})



Figs from 2005.01515



We can explore extra parameter region around GeV ~ several 10 GeV dark photon

(If $m_Z > m_{Z'} + m_\Phi$)

$$S_{6\ell} = \frac{N^S_{6\ell}}{\sqrt{N^S_{6\ell} + N^{\rm BG}_{6\ell} + \epsilon^2_{\rm mis} N^{\rm BG}_{4\ell 2j}}},$$

Summary and Discussions

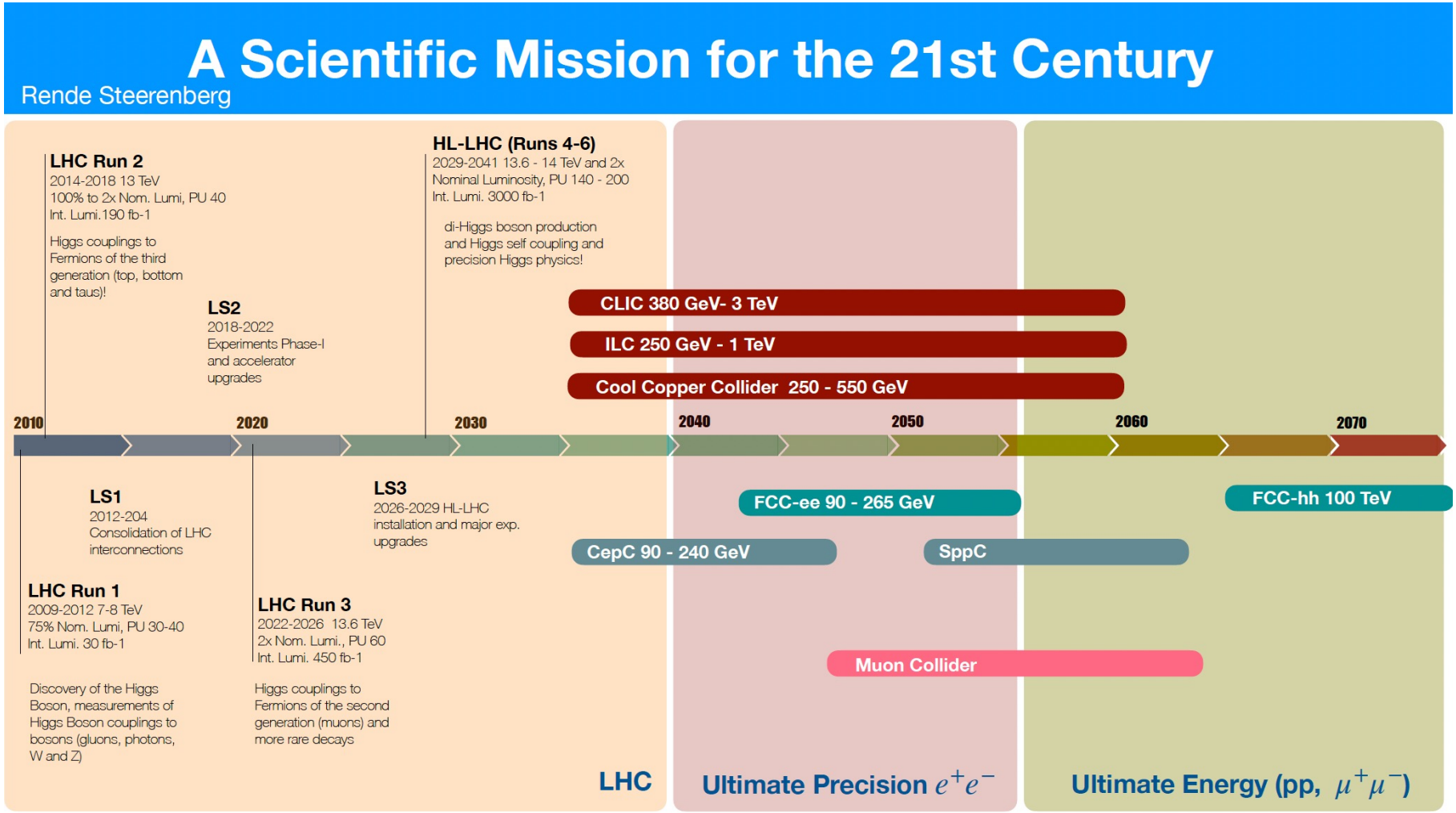
Extension of the SM with extra U(1)' gauge symmetry

- ✓ 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

- ✓ $Z \rightarrow Z'\Phi \rightarrow Z'Z'Z'$ decay chain
- ✓ Sensitivity to kinetic mixing > 10^{-5} at Tera Z-factories
- ✓ Clear signals are expected in dark photon case
- ✓ Potential of direct BSM discovery at Tera Z-factories

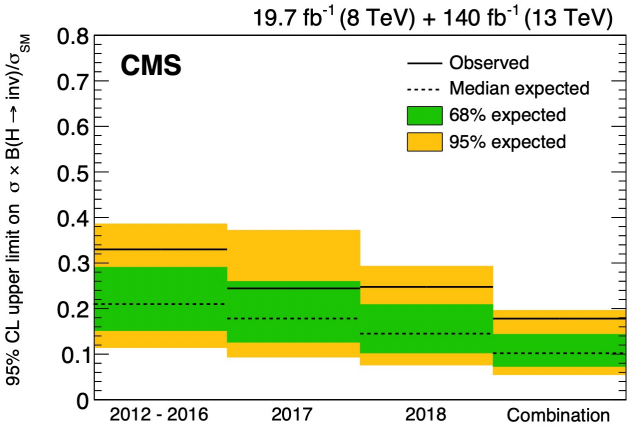
Future experiments



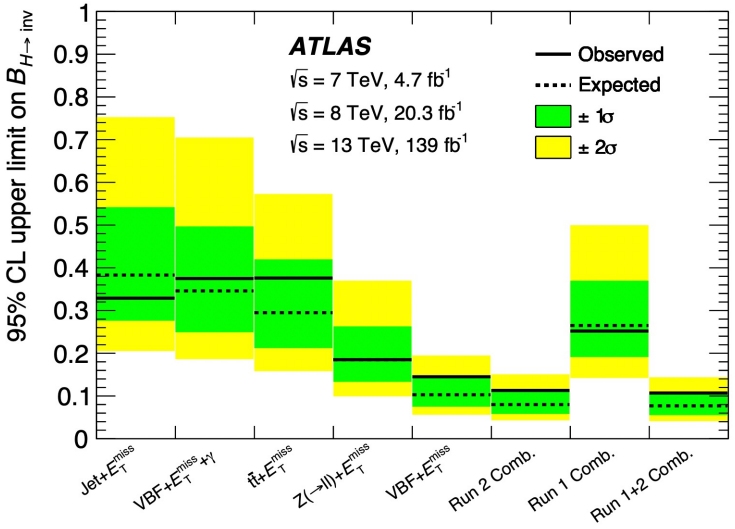
(From slides of talk by Marumi Kado at ICHEP 2024)

Constraints from exotic Higgs decay

❖ Higgs invisible decay



CMS(2022)



ATLAS(2023)

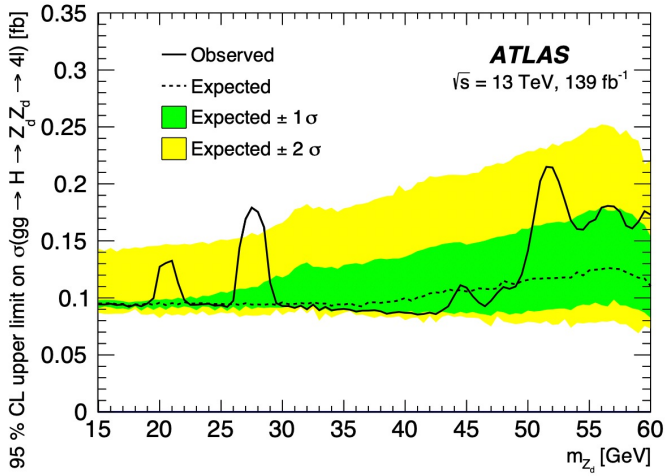
$$\mathrm{BR}(h \to \text{invisible}) < 0.107$$

❖ Higgs decay into 4 lepton

It appears from $h \to Z'Z' \to l^+l^-l^+l^-$

ATLAS: JHEP 03, 041 (2022)

CMS: EPJC 82, 290 (2022)



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

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

Φ : SM singlet scalar field

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

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

New particles : neutral gauge boson Z' & scalar boson Φ

Diagonalizing U(1) gauge sector

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

General kinetic term after the transformation

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

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

$\tilde{X}_\psi$: 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)

For light Z': $\mathcal{L}_{A' f\bar{f}} \simeq e\epsilon Q_f \bar{f}\gamma^\mu f A'_\mu \quad \epsilon \equiv \cos\theta_W \tan\epsilon'$ (A'=Z') Dark photon interaction

Scalar bosons after symmetry breaking

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

Mass matrix for physical scalars : $M^2_{\text{even}} = \begin{pmatrix} \lambda_H v^2 & \lambda_{H\Phi} v v_\Phi \\ \lambda_{H\Phi} v v_\Phi & \lambda_\Phi v_\Phi^2 \end{pmatrix}$

Mass eigenvalues and eigenstates:

$$\begin{pmatrix} h \\ \phi \end{pmatrix} = O^T_{\text{even}} \begin{pmatrix} \tilde{h} \\ \tilde{\phi} \end{pmatrix} \qquad O_{\text{even}} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \qquad \tan 2\alpha = \frac{2\lambda_{H\Phi} v v_\Phi}{\lambda_H v^2 - \lambda_\Phi v_\Phi^2}$$

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

h : SM-like Higgs boson, Φ : new scalar boson

Decay BRs of scalar bosons

Decay widths of new scalar boson

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

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

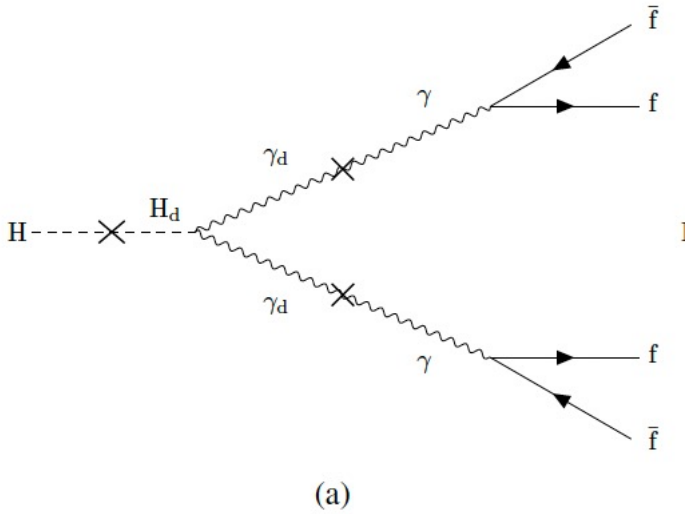
✓ Decay widths for the SM particles modes can be obtained via H-Φ mixing

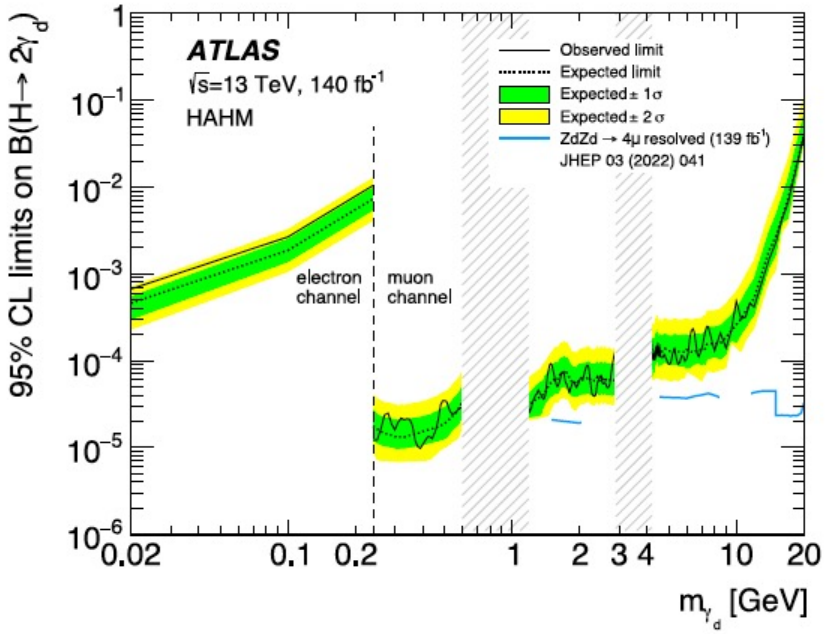
Decay widths of SM Higgs boson for new modes

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

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

❖ Search for h → Z'Z' (light dark photon case)





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Collimated leptons from dark photon in Higgs decay

This kind of process appears considering both Z' and dark Higgs