Multi Lepton-Jets from Quadruple Dark Photon via the Higgs decay at the LHC

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Reference: JHEP04(2025)145, arXiv:2501.17573

Collaborated with Jinmian Li (Sichuan Univerisity)
and Kei Yagyu (Tokyo U. of Science)

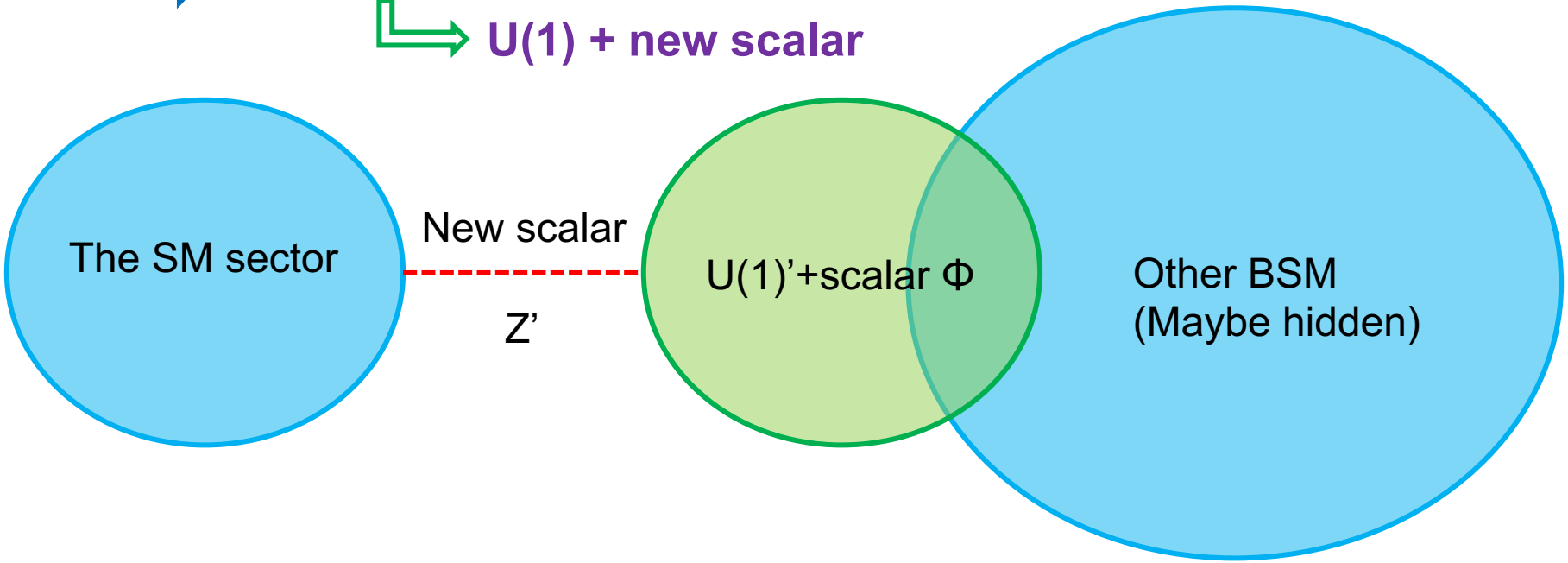
2025-06-10 HPNP2025 @ Osaka University

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'}**

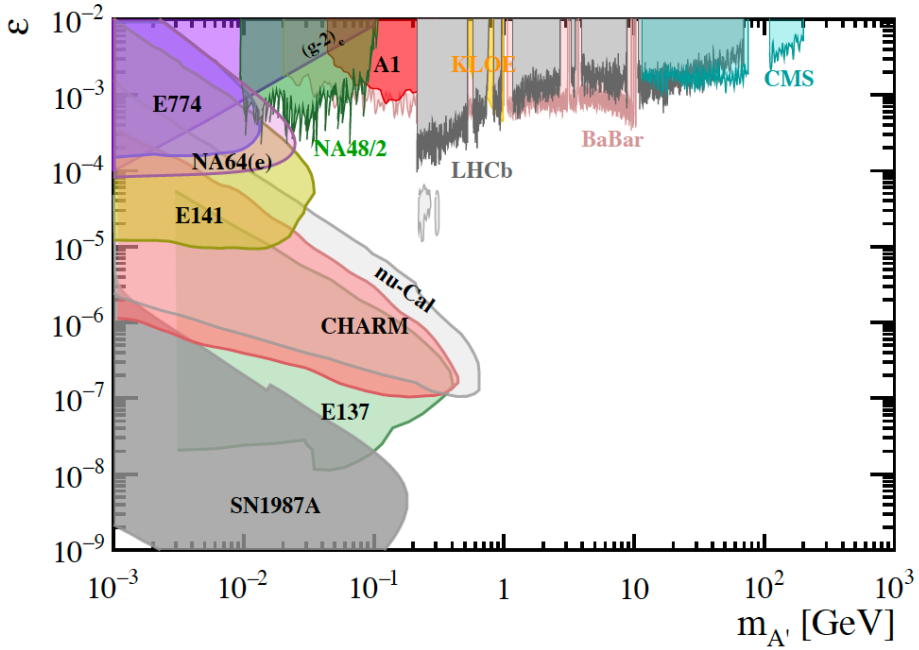
New gauge coupling

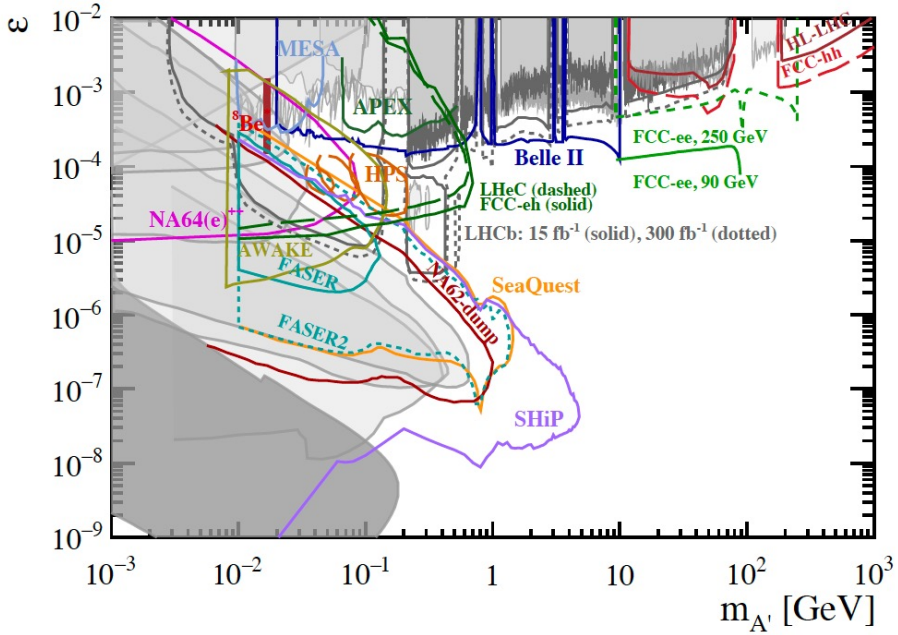
⇩

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

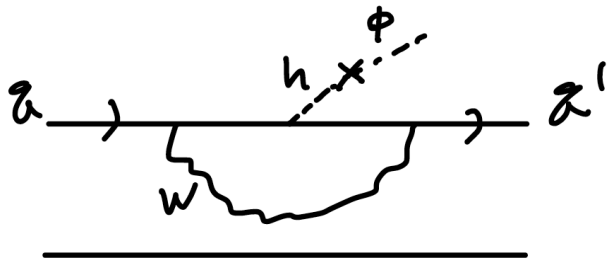
$$-\frac{\sin\epsilon'}{2}B_{\mu\nu}X^{\mu\nu}$$

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

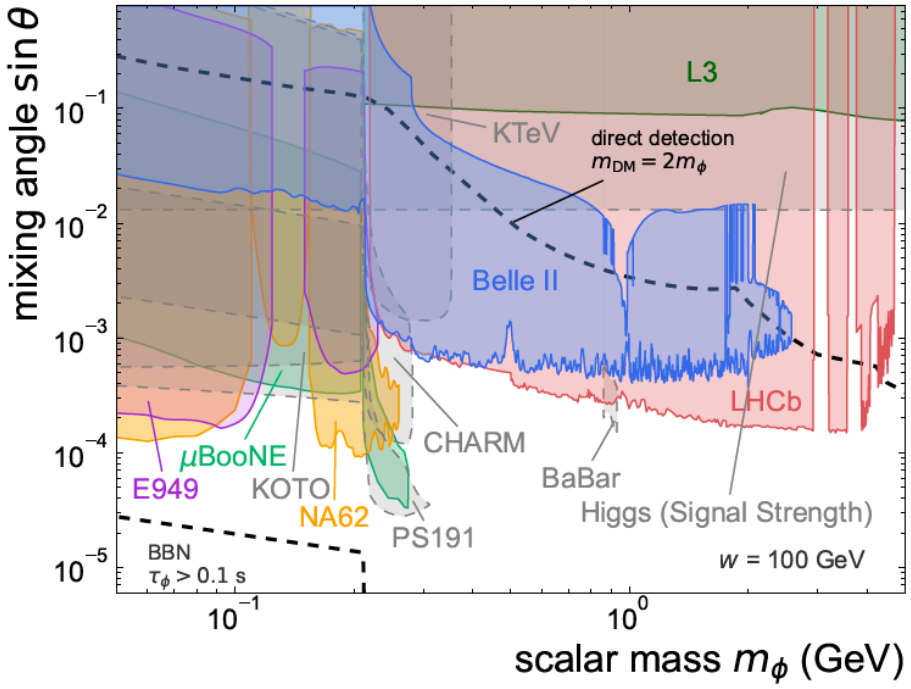
$$\epsilon \equiv \cos\theta_W \tan\epsilon'$$

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

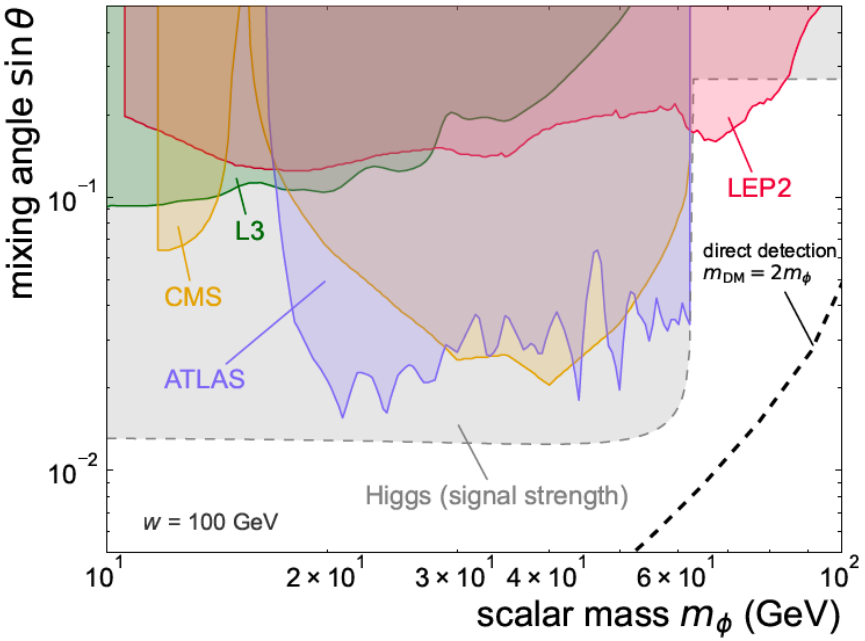
BaBar: $B \rightarrow X_S \phi(\rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-)$
Phys. Rev.Lett. 114 (17) (2015) 171801, Phys. Rev. D 99 (1) (2019) 015018

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

Relatively heavier scalar is also searched for



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

LEP2: $e^+e^- \to Z^*\phi$
Phys.Lett.B565:61-75,2003

CMS: $pp \to h \to \phi\phi$
Phys. Lett. B 785 (2018) 462

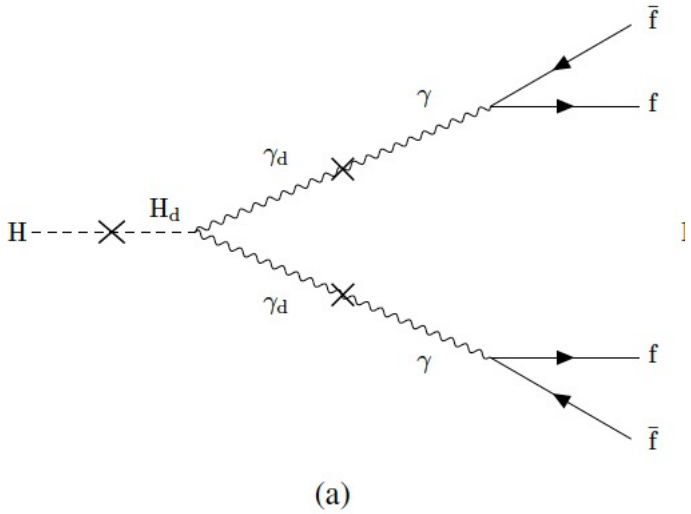
ATLAS: $pp \to h \to \phi\phi$
Phys. Rev. D 105 (2022) 012006

Figs from 2305.16169

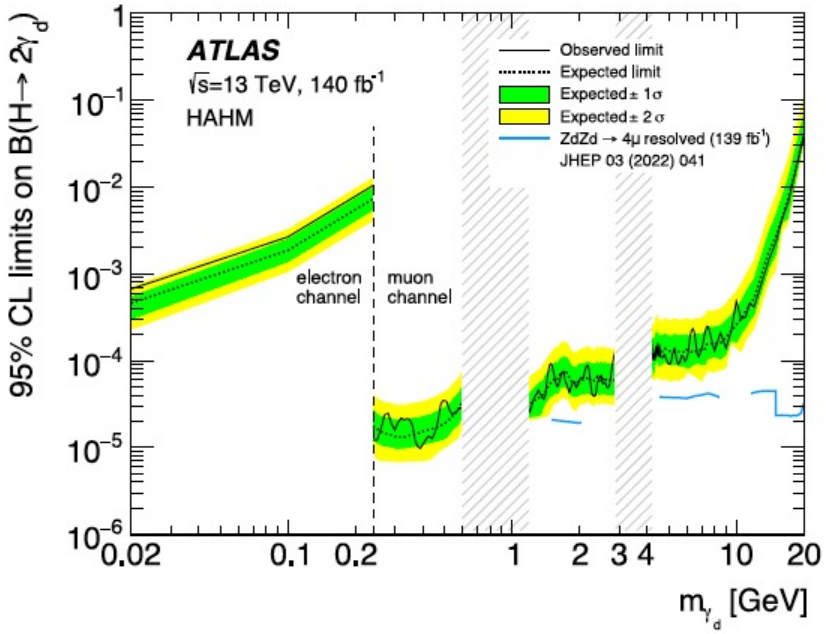
Constraint on scalar mixing (new scalar and SM Higgs)

Constraint is weaker compared to light mass region

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



(a)



(a)

EPJC 85 (2025) 3, 335, arXiv:2407.09168 (ATLAS)

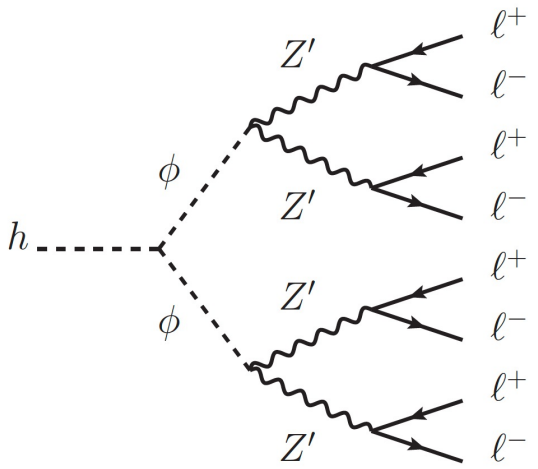
Collimated leptons from dark photon in Higgs decay

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

New signals appear considering both dark photon and Higgs

Good target at LHC and future collider experiments

In this talk we consider following process



At LHC

Lepton jets from dark photon at LHC

Signatures of spontaneously broken U(1)' at LHC

⇨ Decay of scalar bosons into Z'Z' mode

It is induced by interactions after spontaneous symmetry breaking

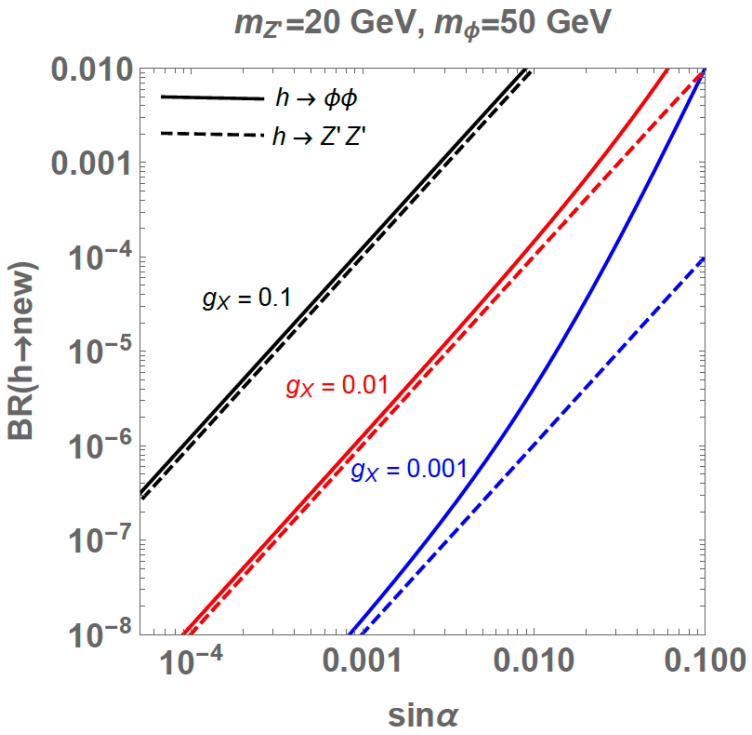
$$\frac{m_{Z'}^2}{v_\Phi} Z'_\mu Z'^\mu (\phi \cos\alpha + h \sin\alpha)$$

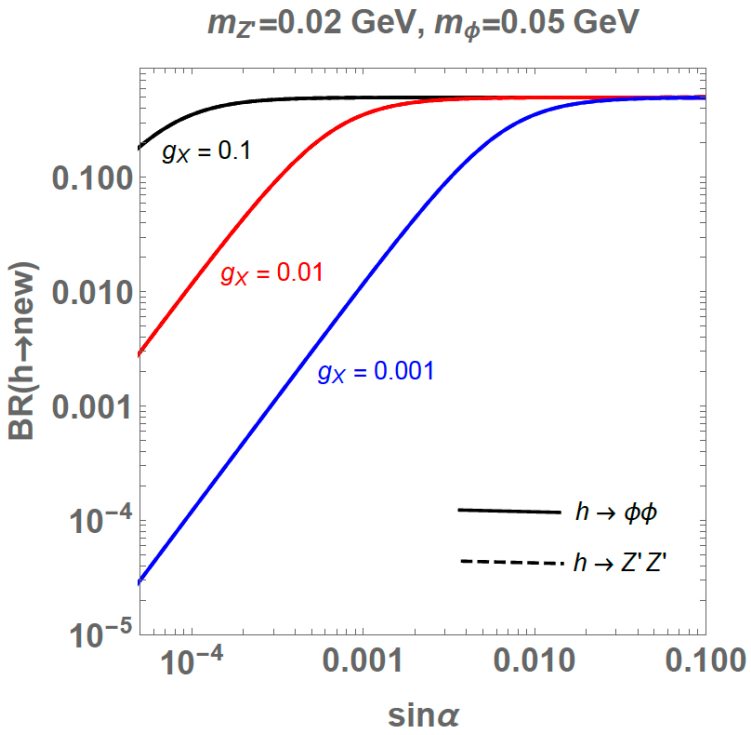
SM Higgs can also decay into two new scalar bosons via

$$\mathcal{L} \supset \lambda_{\phi\phi h} h\phi\phi \qquad \lambda_{\phi\phi h} = -\frac{\sin 2\alpha (m_h^2 + 2m_\phi^2)(v\cos\alpha + v_\Phi \sin\alpha)}{4 v v_\Phi}$$

✓ A new scalar Φ dominantly decays into Z'Z' ($m_\Phi > 2m_{Z'}$, small mixing)

Behavior of BRs of h decays for new modes





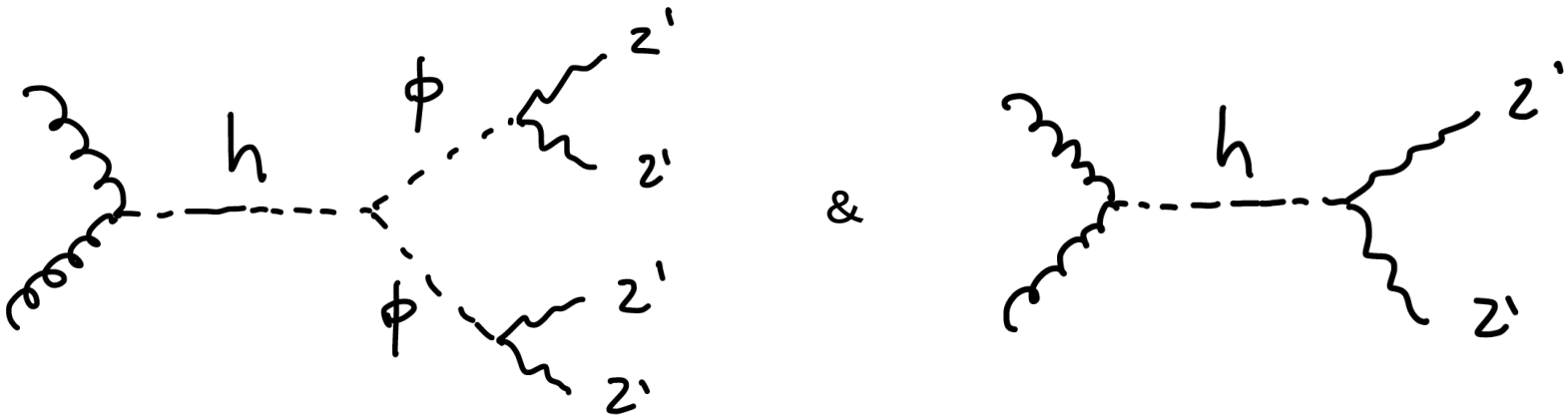
T.N., K. Yagyu, *PRD* 111 (2025) 1, 015034

✓ For light Z' and scalar, BRs for Z'Z' and ΦΦ modes are almost the same

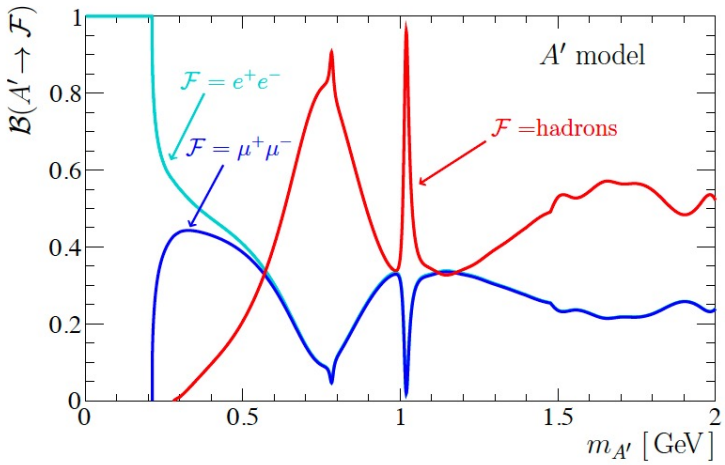
⇒ Equivalence between longitudinal mode of Z' and NG boson

Signatures of spontaneously broken U(1)' at the LHC

- Higgs boson decay into light dark scalar/photon



Z' decays into SM fermions via kinetic mixing effect

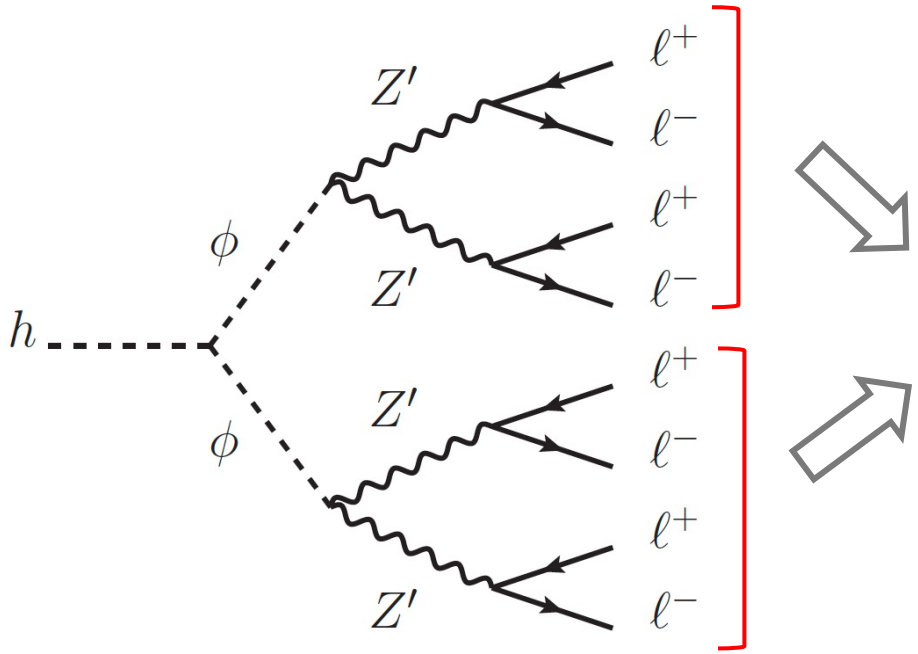


P. Ilten, Y. Soreq, M. Williams, and W. Xue,
JHEP 06, 004

Leptonic modes are the clearest signal

We consider kinetic mixing parameter as
- ✓ Sufficiently small to avoid constraints
- ✓ Larger than long-lived Z' region

Our target process for light dark scalar/photon case



Collimated leptons

↳ **Lepton jets (LJs)**

Lepton jets from the decay chain of the SM Higgs boson

Simulating lepton jets at LHC

We generate events for the process

$$pp \to h \to \phi\phi \to Z'Z'Z'Z' \to (\ell^+\ell^-) \times 4$$

Event generation : MadGraph5

Initial/final state radiation + hadronization : Pythia8

Detector level simulation : Delphes

Applying basic kinematical cuts

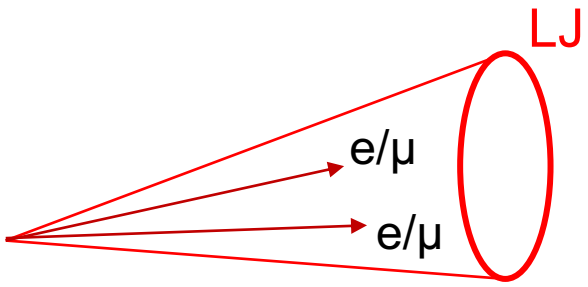
$$p_T^e \geq 4.5 \text{ GeV}, \quad |\eta^e| \leq 2.47,$$

$$p_T^\mu \geq 3 \text{ GeV}, \quad |\eta^\mu| \leq 2.5,$$

Identifying LJs

We adopt following basic conditions to identify LJs

- ✓ Leptons are within ΔR < 0.4
- ✓ LJs contain at least two charged lepton constituents



ΔR = 0.4

$$\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

: measure of LJ cone size

$\Delta\phi$: difference of azimuthal angle

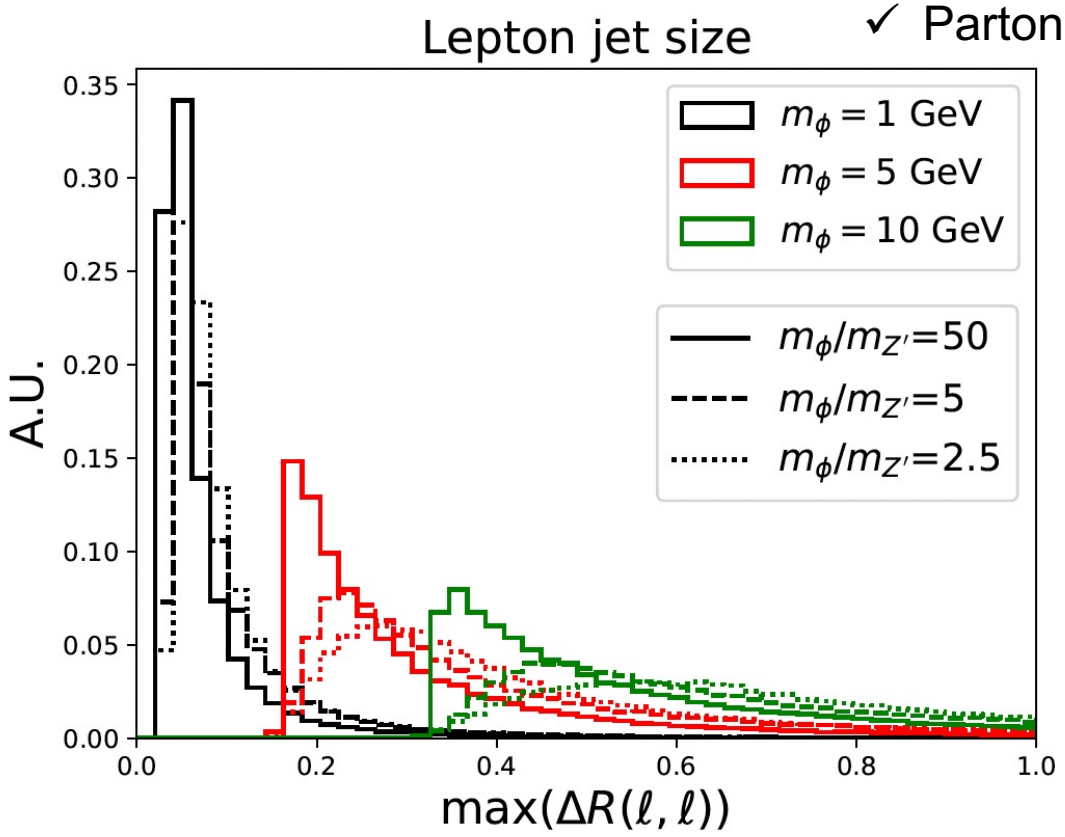
$\Delta\eta$: difference of pseudo rapidity

Some detailed conditions are added, e.g. to avoid double counting of leptons (details are omitted here)

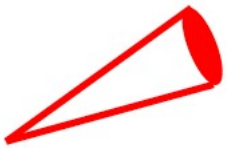
2. Lepton jets from dark photon at LHC

How much are leptons collimated?

✓ Parton level simulation



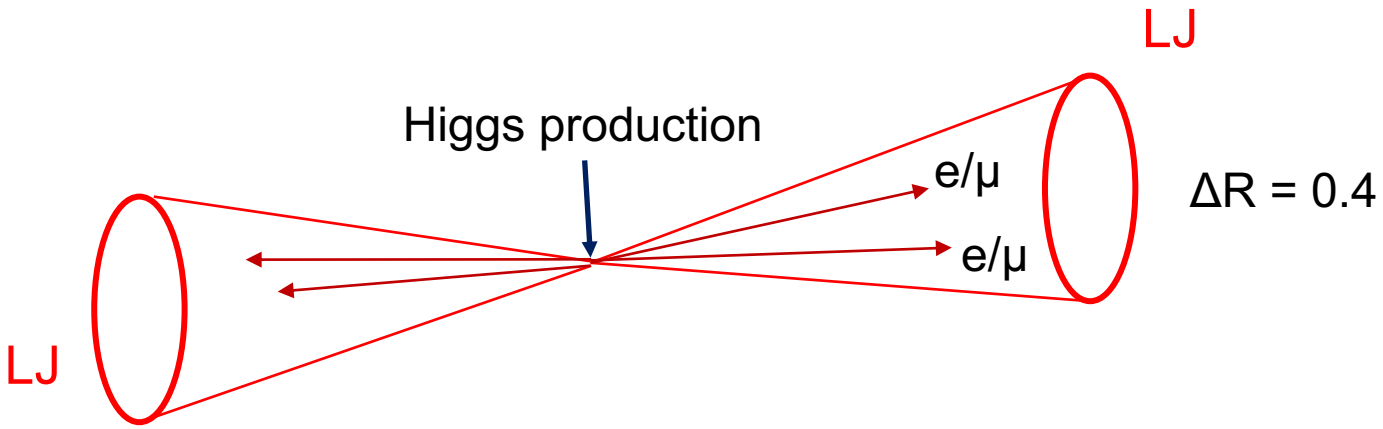
$\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$: measure of LJ cone size



$\Delta\eta$: difference of pseudo rapidity

$\Delta\phi$: difference of azimuthal angle

Total signal event



At least two LJs for signal event

- Leading LJ : it has the largest transverse momentum p_T
- Second LJ : it has the largest azimuthal angle separation from the leading jet (when there are more than two LJs)

Background simulation

❖ Main BG for electronic (e) LJs

⇨ Random overlap of electrons from Z boson decay
with inner-detector (ID) track (corresponding to charged hadron)

❖ Main BG for muonic (μ) LJs

⇨ Overlap of muon from Z decay and that from hadron decay

⇩

We simulate BG processes

$$Z_\ell + \text{jets}, \quad Z_\ell Z_\ell$$

(Z_l : Z boson decaying into leptons)

Three signal regions (SRs)

SR1: Both selected LJs must contain at least three charged leptons

$$\Rightarrow \; n_\ell^{(LJ_1)} \geqslant 3, \quad n_\ell^{(LJ_{2,3\ldots})} \geqslant 3$$

SR2: One selected LJ must contain at least three charged leptons, while the other must contain at least two charged leptons

$$\Rightarrow \; n_\ell^{(LJ_1)} \geqslant 3, \quad n_\ell^{(LJ_{2,3\ldots})} \geqslant 2$$

SR3: Only basic LJ requirements;
two LJs must contain at least two charged leptons

$$\Rightarrow \; n_\ell^{(LJ_1)} \geqslant 2, \quad n_\ell^{(LJ_{2,3\ldots})} \geqslant 2$$

These are adopted to reduce BG events

2. Lepton jets from dark photon at LHC

Efficiencies for different SRs in reducing BGs

	$Z_\ell Z_\ell$	Z_ℓ + jets
SR1-e	6.8×10^{-6} (1.2×10^{-6}) $[\lesssim 4 \times 10^{-7}]$	2.31×10^{-6} (5.53×10^{-7}) $[5.03 \times 10^{-8}]$
SR2-e	1.44×10^{-5} (2.4×10^{-6}) $[4 \times 10^{-7}]$	6.39×10^{-6} (2.26×10^{-6}) $[1.51 \times 10^{-7}]$
SR3-e	2.88×10^{-5} (6.4×10^{-6}) $[8 \times 10^{-7}]$	9.91×10^{-6} (4.93×10^{-6}) $[1.11 \times 10^{-6}]$
SR1-μ	$\lesssim 4 \times 10^{-7}$	$\lesssim 5.03 \times 10^{-8}$
SR2-μ	$\lesssim 4 \times 10^{-7}$	1.01×10^{-7}
SR3-μ	2.28×10^{-5}	4.52×10^{-7}

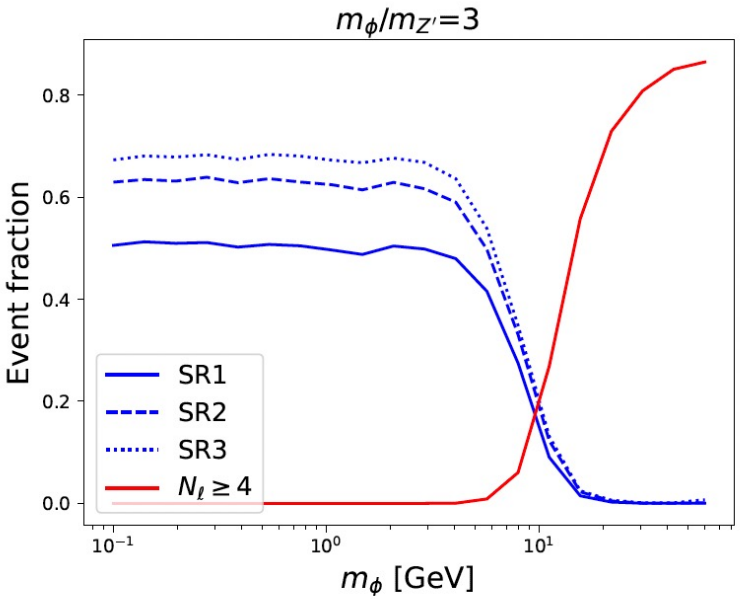
Value in (): with additional cut $m_{Lj} <$ 2 GeV

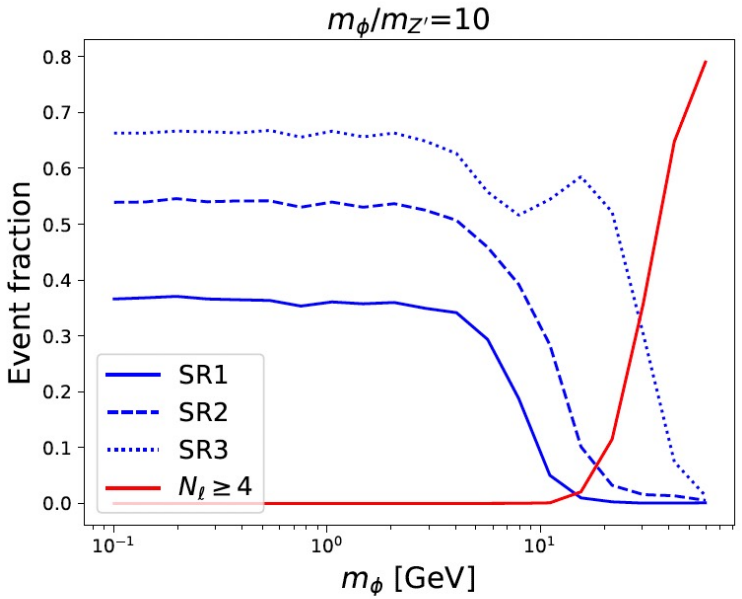
Value in []: with additional cut $m_{Lj} <$ 1 GeV

The BGs are highly reduced by the SRs

Results

Efficiencies of three SRs for signal (blue curves)





Red curve: requirement having at least 4 charged leptons (no LJs)

- LJ analysis is efficient for scalar mass less than around 10 GeV

3. Results

Estimating the constraint on Higgs BR

The limit is calculated by signal to BG ratio (assuming systematic uncertainty 5 %)

$$\frac{\sigma_S \epsilon_S \times \sqrt{\mathcal{L}}}{\sqrt{\sigma_{Z_\ell Z_\ell} \epsilon_{Z_\ell Z_\ell} + \sigma_{Z_\ell+\text{jets}} \epsilon_{Z_\ell+\text{jets}} + [0.05 \times (\sigma_{Z_\ell Z_\ell} \epsilon_{Z_\ell Z_\ell} + \sigma_{Z_\ell+\text{jets}} \epsilon_{Z_\ell+\text{jets}})]^2 \mathcal{L}}} = 2$$

σ_i : production cross section, ε_i : efficiency for each event, L : luminosity

Signal cross section: $\sigma_S = \sigma_h \times \mathrm{BR}(h \to 4Z') \times [\mathrm{BR}(Z' \to \ell^+\ell^-)]^4$

Higgs production cross section

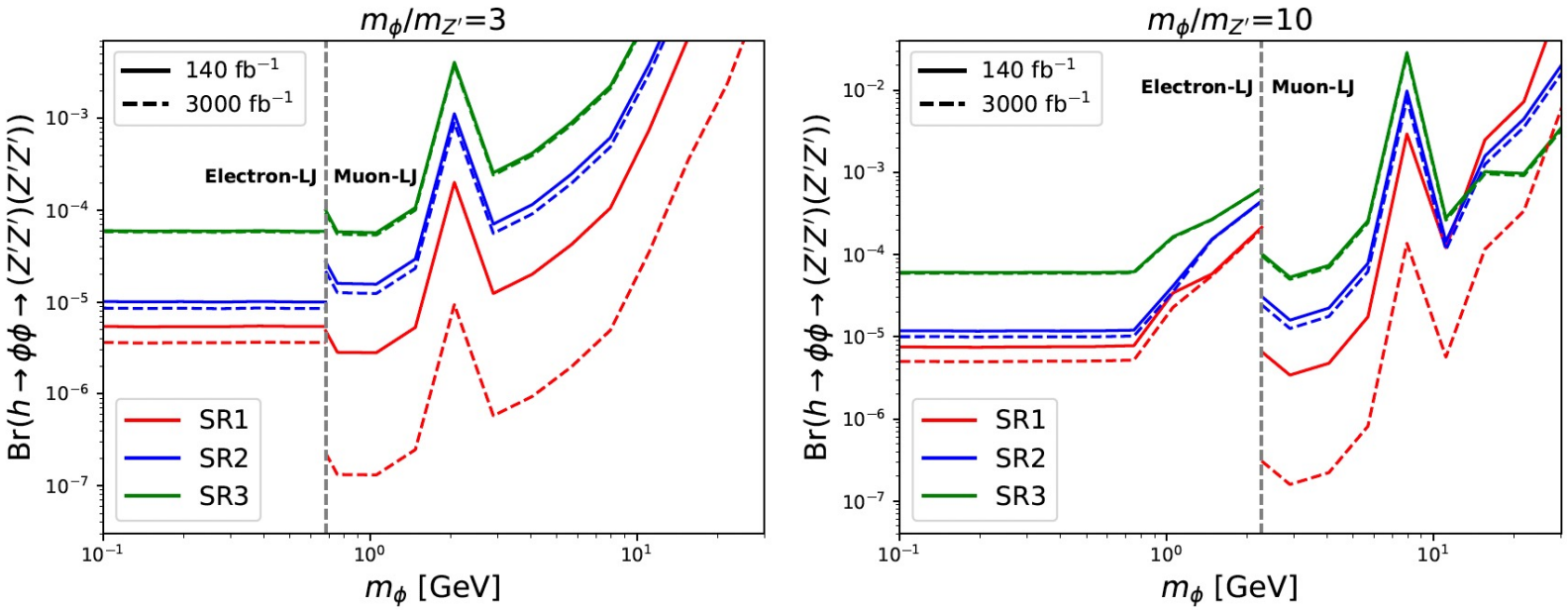
$$[\mathrm{BR}(Z' \to \ell^+\ell^-)]^4$$

$$= \begin{cases} \left[\mathrm{BR}(Z' \to \mu\mu) + \mathrm{BR}(Z' \to ee)\right]^4\Big|_{n_\mu \geq 2} & \text{for } \; m_{Z'} \geq 2m_\mu \\ [\mathrm{BR}(Z' \to ee)]^4 \;\; \text{for } \; m_{Z'} < 2m_\mu, \end{cases}$$

We apply BRs of Z' in dark photon case

3. Results

Constraints on the Higgs decay branching ratio



✓ The bump around $m_{Z'}$ ~ 1 GeV due to hadronic resonances

SR1 provides the strongest limit on the BR

Extract limit on the model parameters

$$\Gamma(h \to \phi\phi) = \frac{m_h^3 \sin^2\alpha}{32\pi v_\Phi^2} \cos^2\alpha (1+2x_\phi) \left(\cos\alpha + \sin\alpha \frac{v_\Phi}{v}\right)^2 \beta(x_\phi),$$

$$\Gamma(\phi \to Z'Z') = \frac{m_\phi^3 \cos^2\alpha}{32\pi v_\Phi^2}(1 - 4y_{Z'} + 12y_{Z'}^2)\beta(y_{Z'}), \qquad (v_\Phi = m_{Z'}/(X_\Phi g_X))$$

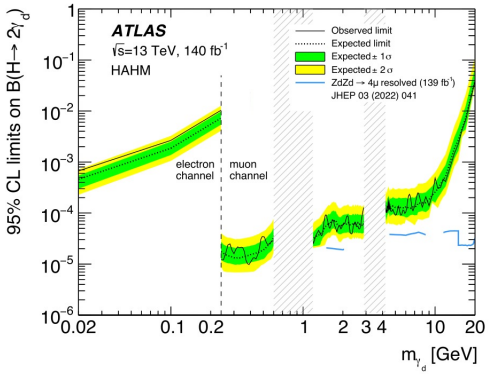
BRs depend on model parameters **$\{m_{Z'}, m_\Phi, \sin\alpha, g_X\}$**

(insensitive to gauge kinetic mixing parameter)

⇨ The limit on BR is converted to that of parameters

We also compare the limit on BR(h→Z'Z') applying data in arXiv: 2407.09168 (ATLAS)

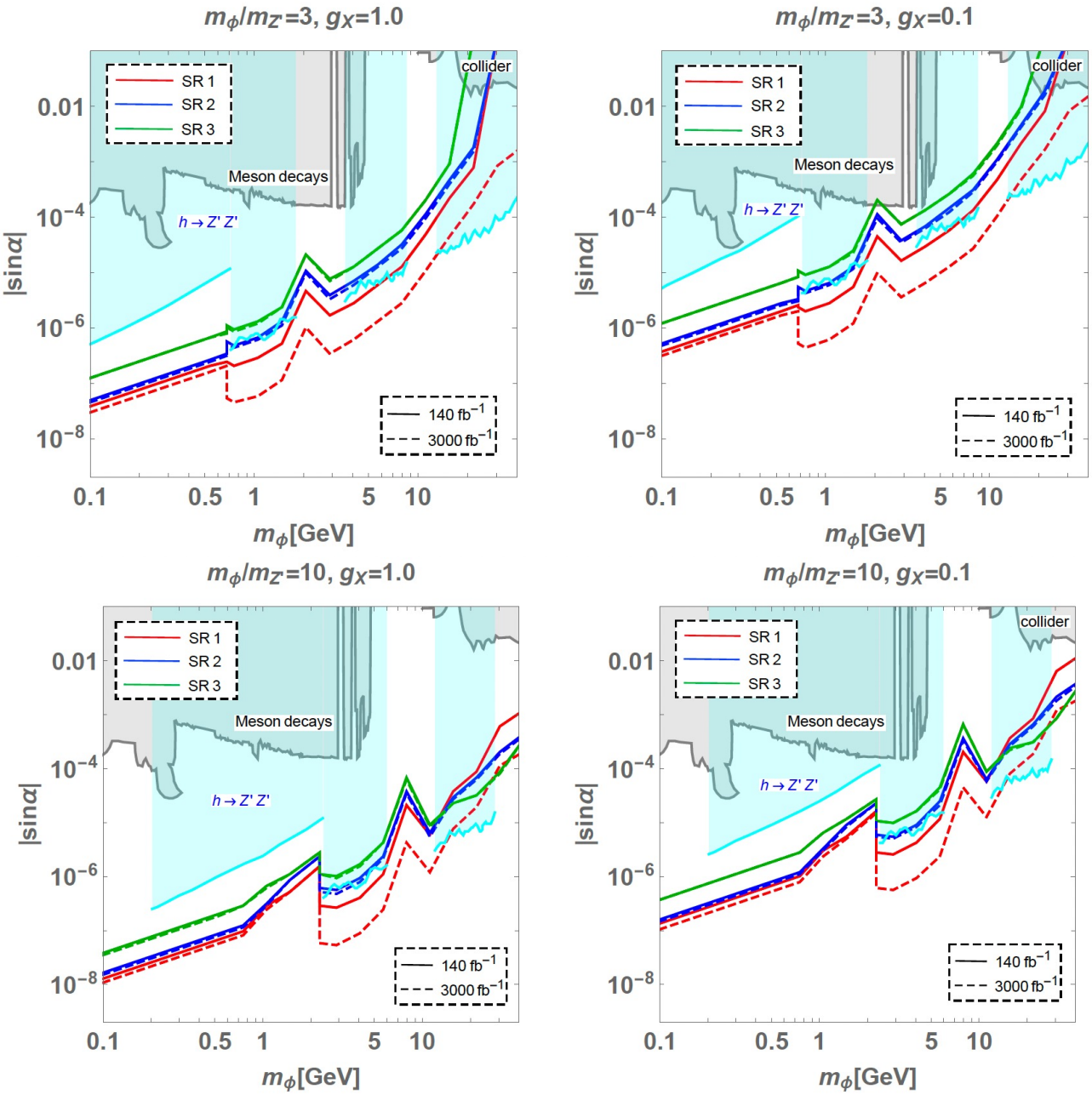
with $\Gamma(h \to Z'Z') = \frac{m_h^3 \sin^2\alpha}{32\pi v_\Phi^2}(1 - 4x_{Z'} + 12x_{Z'}^2)\beta(x_{Z'}),$



(a)

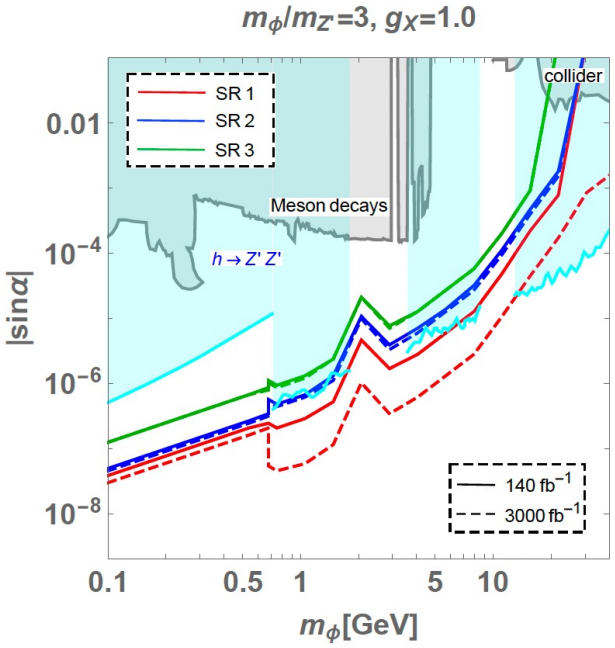
3. Results

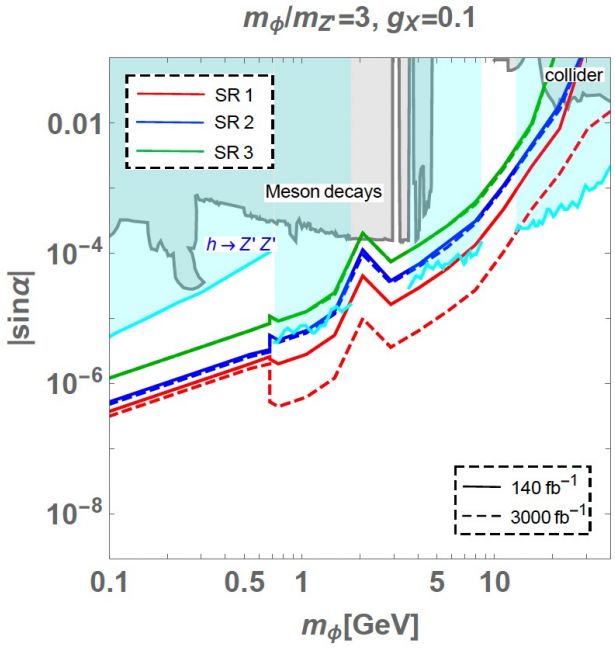
Results:

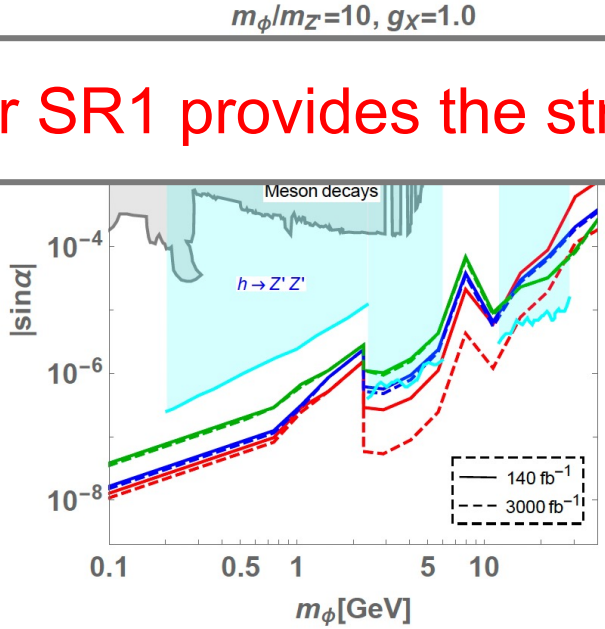


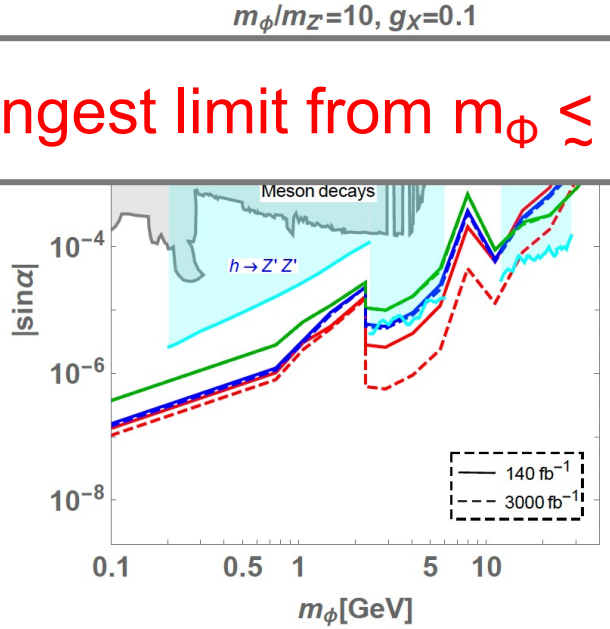
3. Results

Results:









Our SR1 provides the strongest limit from $m_\Phi \lesssim 10$ GeV

Summary

Dark photon from extra U(1)' gauge symmetry

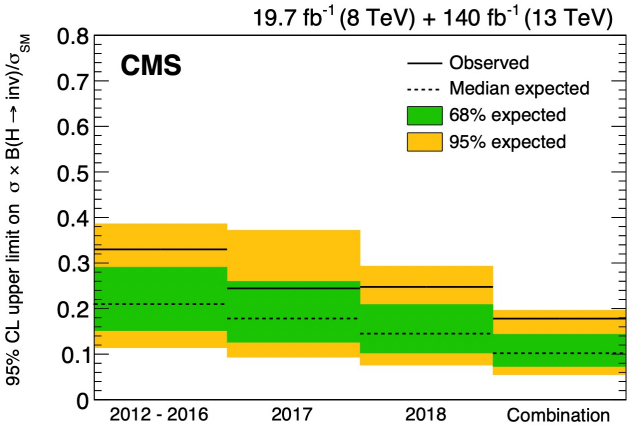
- ✓ Z' boson from extra U(1)'
- ✓ Hidden U(1) + kinetic mixing = dark photon
- ✓ Z' and scalar boson typically appear together via SSB
- ✓ Many experimental constraints are considered

☐ Signatures of multi dark photon

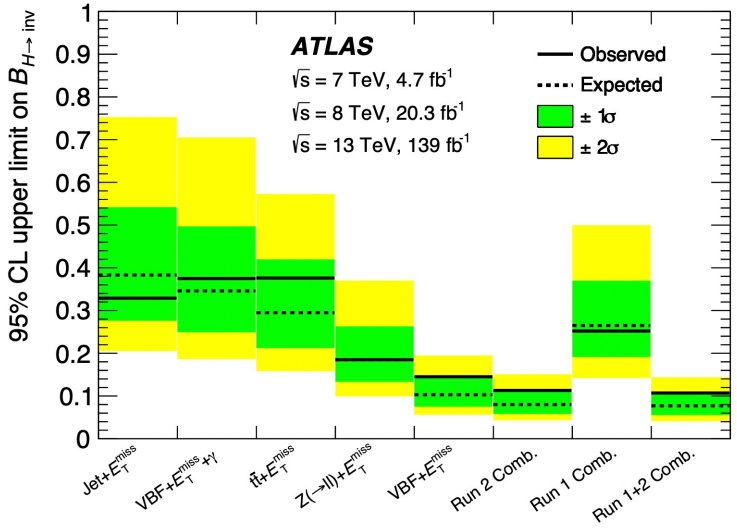
- ✓ Analysis of lepton jets at LHC can constrain scalar mixing
- ✓ Dark photon + scalar is good target at future collider experiments

Constraints from exotic Higgs decay

❖ Higgs invisible decay



CMS(2022)



ATLAS(2023)

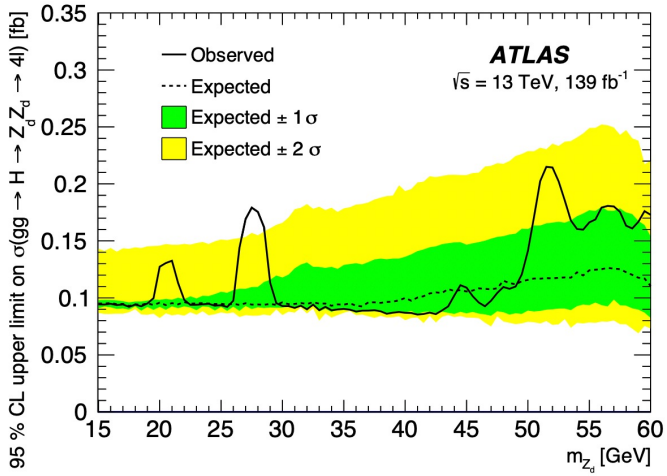
$$\mathrm{BR}(h \rightarrow \text{invisible}) < 0.107$$

❖ Higgs decay into 4 lepton

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

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

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

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

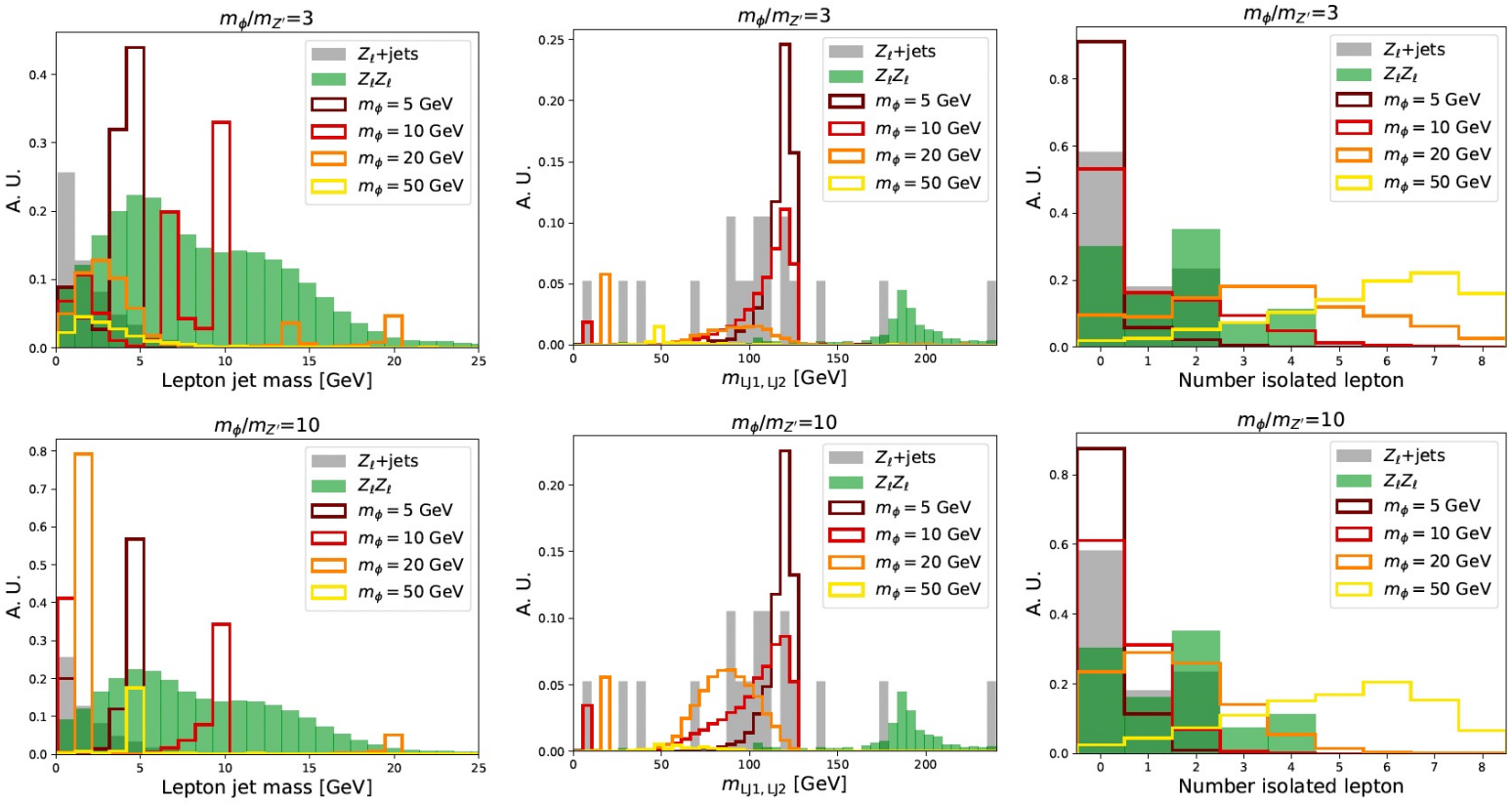
✓ Decay widths for the SM particles modes can be obtained via H-Φ mixing

Decay widths of SM Higgs boson for new modes

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

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

Distributions of some representative quantities



✓ Invariant mass of two LJs around Higgs mass