Possible excess of multi-lepton signal from dark Higgs

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Summary

We consider the possible excess in $m_{\mu\mu} = 2.41$GeV with dark photon dark Higgs scenario with two dark sector. If this simple scenario can be tested in the future collider associated with ZH production in Higgs factory. By event reconstruction, we can identify the specific signals.

Multi muon excess

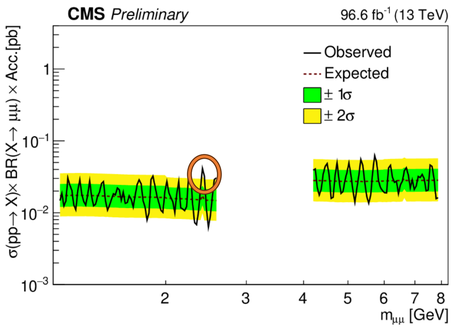
Recently…Dimuon excess in CMS (CMS-PAS-EXO-21-005)

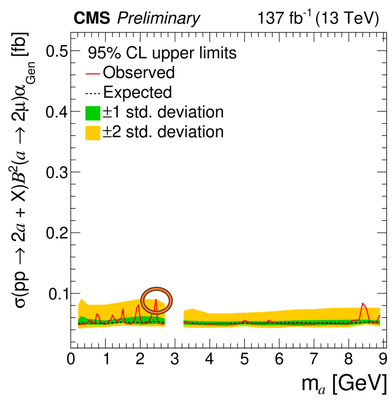
$m_{\mu\mu} \simeq 2.41$GeV , Local significance 3.24σ (Moriond 2023)

$\sigma(pp \to X)BR(X \to \mu\mu) \times Acc \simeq 3 \times 10^{-2}$ [pb]

Four muon excess $\sim 2\sigma$ (Moriond 2024)

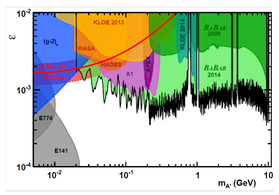
$\sigma(pp \to X)BR(X \to \mu\mu) \times Acc \simeq 0.1$ [pb]





Dark photon from Higgs ?

Naive account from Higgs ?
$h(125) \to \gamma\gamma' \cdots \epsilon^2$ suppression
$h(125) \to \gamma'\gamma' \cdots \epsilon^4$ suppression
From BaBar $\epsilon < 10^{-3}$ too small ? ? ?



BaBar constraint (Phys.Rev.Lett.113(2014)20.201801, arxiv:1406.2980)

Photon vs Dark photon…photon massless ↔ dark photon can be massive

Suppose that Dark photon mass is from dark Higgs.
→dark Higgs can decay into dark photon at tree level: $h \to \gamma'\gamma' \cdots$ no ϵ suppression
Suppressed by dark Higgs Higgs mixing $\sin\theta$

However,
If $m_{\gamma'} \ll m_h$, dark photon can be identified with dark Higgs NG boson longitudinal mode(equivalence theorem)
→no suppression from ϵ nor $\sin\theta$

Setting

Contents… SM + dark photon $U(1)_D$ + singlet scalar S +Dark sector2

$L \supset L_{kin} + L_{scalar}$

$$L_{kin} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{4}V_{D\mu\nu}V_D^{\mu\nu} - \frac{\epsilon_1}{2}B_{\mu\nu}V^{\mu\nu} - \frac{\epsilon_2}{2}V_{D\mu\nu}V^{\mu\nu}$$

$$L_{scalar} = \left|D_\mu H\right|^2 + \left|D_\mu S\right|^2 - V(H,S)$$

$$V(H,S) = \frac{\mu_H^2}{2}H^2 + \frac{\mu_S^2}{2}S^2 + \frac{\lambda}{4}H^4 + \frac{\lambda'}{4}S^4 + \frac{\kappa}{4}H^2S^2$$

Stationary point $\begin{pmatrix} v^2 \\ w^2 \end{pmatrix} \equiv \begin{pmatrix} \langle H\rangle^2 \\ \langle S\rangle^2 \end{pmatrix} = \frac{1}{4\lambda\lambda' - \kappa^2}\begin{pmatrix} 2\kappa\mu_S^2 - 4\lambda'\mu_H^2 \\ 2\kappa\mu_H^2 - 4\lambda\mu_S^2 \end{pmatrix}$

Expand around the VEV, $H = v + h$ and $S = w + h'$
mass matrix for h and h': $V(h,h') \supset \frac{1}{2}(h,h')M^2\begin{pmatrix} h \\ h' \end{pmatrix}$ with $\mathrm{M}^2 = \begin{pmatrix} 2\lambda v^2 & \kappa vw \\ \kappa vw & 2\lambda' w^2 \end{pmatrix}$

⇨ Higgs mass eigenstate: $\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} h \\ h' \end{pmatrix}$

with $\tan 2\theta = \frac{\kappa vw}{-\lambda v^2 + \lambda' w^2}$, $m_{H_{1,2}}^2 = \lambda v^2 + \lambda' w^2 \mp \frac{-\lambda v^2 + \lambda' w^2}{\cos 2\theta}$

5 parameters to characterize Higgs: $(\lambda, \lambda', \kappa, v, w) \leftrightarrow (m_{H_1}^2, m_{H_2}^2, \sin\theta, v, \kappa)$

$\lambda = \frac{m_{H_1}^2}{2v^2} + \sin^2\theta\frac{m_{H_2}^2 - m_{H_1}^2}{2v^2}$, $\lambda' = \frac{2\kappa^2}{\sin^2 2\theta}\frac{v^2}{m_{H_2}^2 - m_{H_1}^2}\left(\frac{m_{H_2}^2}{m_{H_2}^2 - m_{H_1}^2} - \sin^2\theta\right)$

Mass matrix for Vector bosons

$$\frac{1}{2}\left(V_\mu\ B_\mu\ W_\mu\right)\begin{pmatrix} \frac{2e_D^2w^2}{1+\epsilon^2} + \frac{e^2v^2}{2c_W^2}\frac{\epsilon^2}{1+\epsilon^2} & -\frac{e^2v^2}{2c_W^2}\frac{\epsilon}{\sqrt{1+\epsilon^2}} & \frac{e^2v^2}{2c_Ws_W}\frac{\epsilon}{\sqrt{1+\epsilon^2}} \\ -\frac{e^2v^2}{2c_W^2}\frac{\epsilon}{\sqrt{1+\epsilon^2}} & \frac{e^2v^2}{2c_W^2} & -\frac{e^2v^2}{2c_Ws_W} \\ \frac{e^2v^2}{2c_Ws_W}\frac{\epsilon}{\sqrt{1+\epsilon^2}} & -\frac{e^2v^2}{2c_Ws_W} & \frac{e^2v^2}{2s_W^2} \end{pmatrix}\begin{pmatrix} V^\mu \\ B^\mu \\ W^\mu \end{pmatrix}$$

Diagonalize mass matrix at leading order $\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} c_W & s_W \\ -s_W & c_W \end{pmatrix}\begin{pmatrix} B_\mu \\ W_\mu \end{pmatrix}$ and $m_Z^2 = \frac{2e^2v^2}{c_W^2s_W^2}$, $m_{\gamma'}^2 = 2e_D^2w^2$

3 parameters to characterize Dark photon: $(\alpha_D, \epsilon_1, \epsilon_2) \leftrightarrow (m_{\gamma'}, \epsilon_1, \epsilon_2)$

Account for excess… Dark Photon+Dark sector

To see dimuon $h \to \chi\chi(\gamma'\gamma') \to \mu\mu(+\mu\mu)$

For longitudinal dark photon $\Gamma_{h\to\gamma'\gamma'} = \frac{\kappa^2v^2}{16\pi m_h}\sqrt{1 - \frac{4m_{\gamma'}^2}{m_h^2}}$

Higgs production cross section 56.9[pb](by PDG)
Probability from dark photon into dimuon 3/8

$$56.9[pb] \times \frac{3}{8} \times \frac{h \to \gamma'\gamma'_{\Gamma_h}}{\Gamma_h}\frac{1}{(1+x)^2}\left(\frac{3}{8} + \frac{2x}{4}\right) = 4 \times 10^{-2}[pb]$$

Probability from dark photon into four muon 1/16

$$56.9[pb] \times \frac{1}{16} \times \frac{h \to \gamma'\gamma'_{\Gamma_h}}{\Gamma_h}\frac{1}{(1+x)^2} = 0.1\ [fb]$$

$\kappa \simeq 4.8 \times 10^{-3}$ and $x \simeq 33$ for usual case

$\kappa \simeq 8.7 \times 10^{-3}$ and $x \simeq 1.5 \times 10^2$ for lighter DH case ($5 \leq m_{H_1} \leq 62.5$GeV)

Tested by HL-LHC missing signal

Constraint・Future prospect

・Signal strength $\mu = \cos^2\theta\frac{\Gamma_h^{SM}\cos^2\theta}{\Gamma_h^{SM}\cos^2\theta + \Gamma_{h\to dark}}$

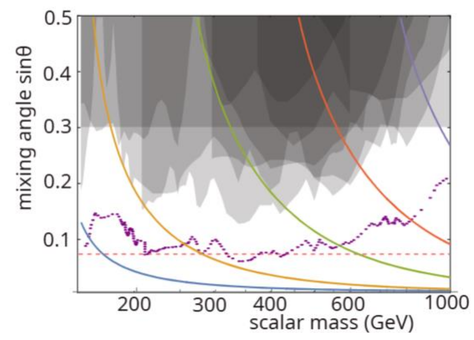
- 1.05 ± 0.06 (ATLAS) Nature 607 (7917) (2022) 52-59 arxiv: 2207.00092
- 1.00 ± 0.06 (CMS) Nature 607 (7917) (2022) 60-68 arxiv: 2207.00043

⟶ $\sin\theta < 0.3$

・Heavy region ($m_{H_1} < m_{H_2}$)

・Collider search
Heavy particle(W,Z,H) pair production
LHC experiment(ATLAS, CMS)

Current Luminosity 300fb⁻¹improve for HL-LHC 3ab⁻¹

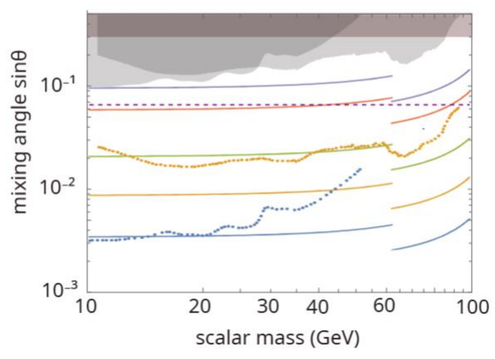


・Middle region($2m_{\gamma'} < m_{H_2} < m_{H_1}$)

・Collider search

For $m_{H_1} > 2m_{H_2}$, SM-like Higgs can decay into another (ATLAS,CMS)

e^+e^- to ZH' LEP(L3,LEP2)



・multi-muons ($m_h > 2m_{h'}$)

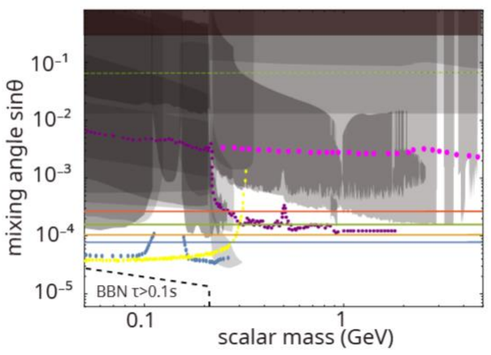
By $h' \to 2\gamma', h \to 2h' \to 4\gamma' \to 4\mu$ (mainly decay into dark sector: missing signal)

・Light region ($m_{H_2} < 2m_{\gamma'}$)

・Meson rare decay

B→K(∗)Φ or K→πΦ associated with light scalar

・Unitarily bound $\alpha_D < 4\pi$

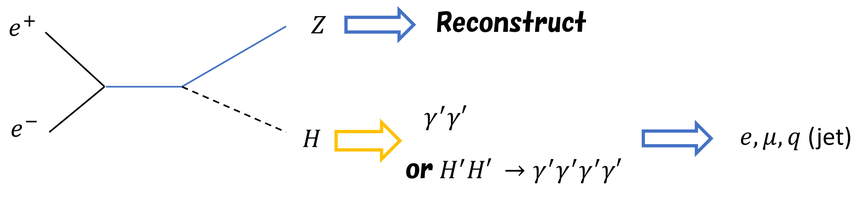


・BBN

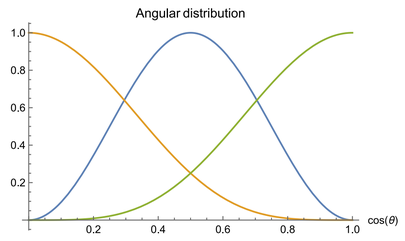
Long lived particle can break BBN

Higgs factory

10^6 Higgs production is expected



Longitudinal… Angular distribution property
→ can reconstruct in future Higgs factory



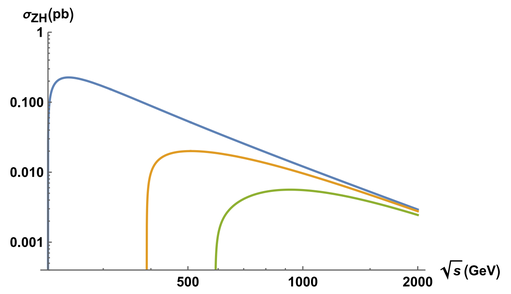
Usual case

$2e+$ missing	4.4×10^2
$2\mu+$ missing	4.4×10^2
$2q+$ missing	8.8×10^2
$2e + 2\mu$	3.4
$2e + 2q$	6.7
$2\mu + 2q$	6.7
$4e$	1.7
4μ	1.7
$4q$	6.7

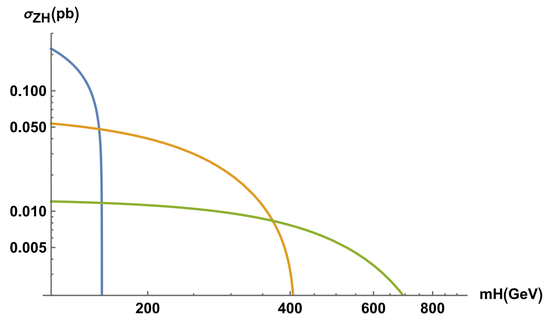
Light case

$2e+$ missing	3.5×10^2
$2\mu+$ missing	3.5×10^2
$2q+$ missing	7.0×10^2
$2e + 2\mu+$ missing	3.5
$2e + 2q+$ missing	7.1
$2\mu + 2q+$ missing	7.1
$4e+$ missing	1.8
$4\mu+$ missing	1.8
$4q+$ missing	7.1

ZH production cross section

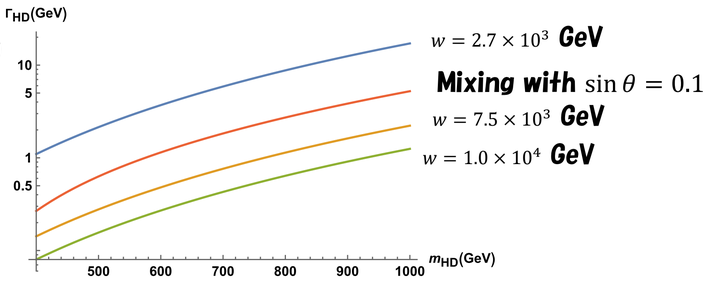


(with fixed $m_H = 125, 300, 500$GeV)



(with fixed $\sqrt{s} = 250, 500, 1000$GeV)

Dark photon vs SM Higgs mixing



It will be possible to directly access the dark Higgs scenario in the future Higgs factory!