A Higgcision study on the 750GeV Diphoton Resonance and 125GeV Higgs boson with the Higgs-Singlet Mixing

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Collaborators:

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arXiv:1512.07853[hep-ph]

Kavli IPMU, seminar, April 13, 2016

Outlines

- Introduction
- Higgs-Singlet Mixing Framework
- Numerical Results
- Model
- Conclusions

Introduction

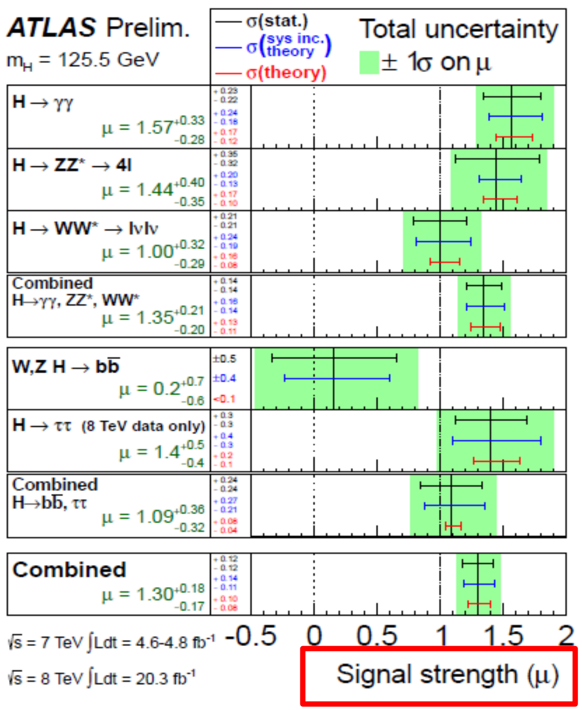
Introduction

- The observed 125GeV Higgs boson, H1, is very SM like at 7-8 TeV LHC run1.

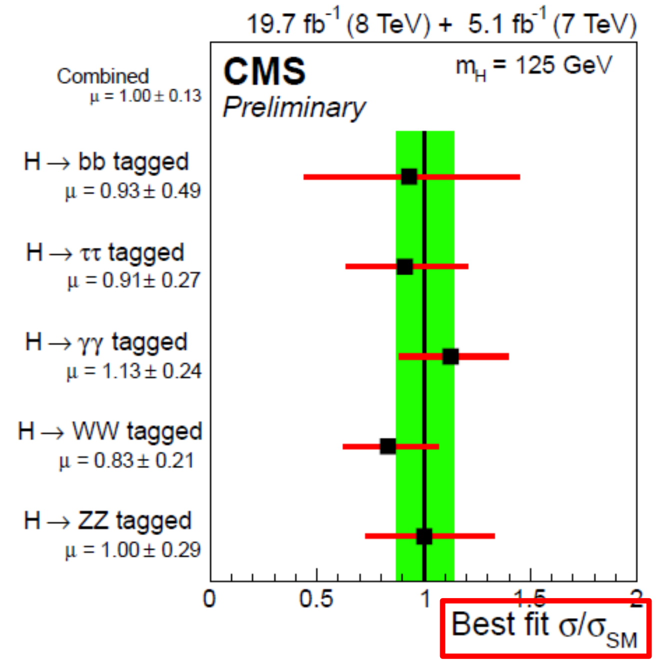
  i). The spin, parity, charge conjugation $J^{PC} = 0^{++}$.

  ii). Its couplings to the SM particles.

ATLAS-CONF-2014-009



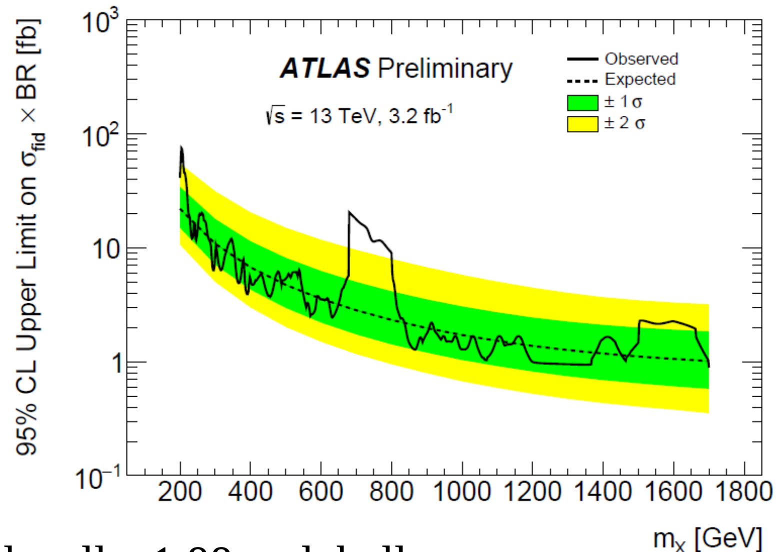
CMS PAS HIG-14-009



Introduction

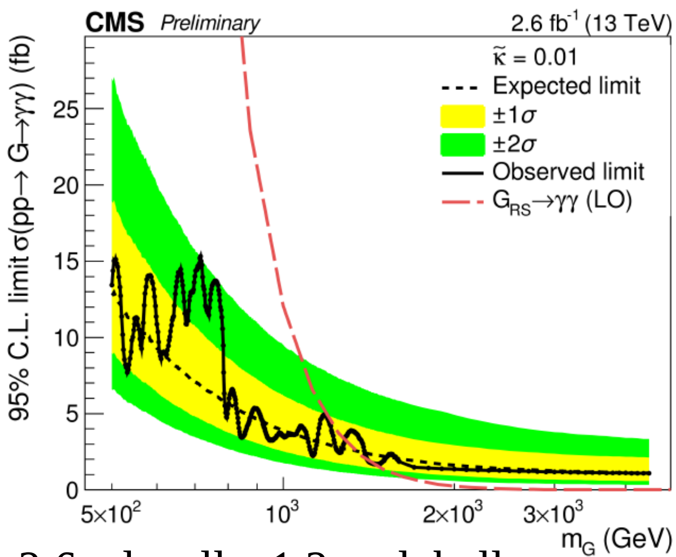
- ATLAS (3.2/fb) and CMS (2.6/fb) at 13TeV, a hint of a new particle at 750 GeV decaying into a photon pair.

ATLAS-CONF-2015-081



3.64σ locally, 1.88σ globally

CMS EXO-15-004-pas



2.6σ locally, 1.2σ globally

ATLAS: $M_{H_2} = 750$ GeV, $\sigma_{\rm fit}(pp \to H_2 \to \gamma\gamma) \approx 10 \pm 3$ fb; (95% CL), $\Gamma_{H_2} \approx 45$ GeV

CMS: $M_{H_2} = 760$ GeV, $\sigma_{\rm fit}(pp \to H_2 \to \gamma\gamma) \approx 9 \pm 7$ fb; (95% CL)

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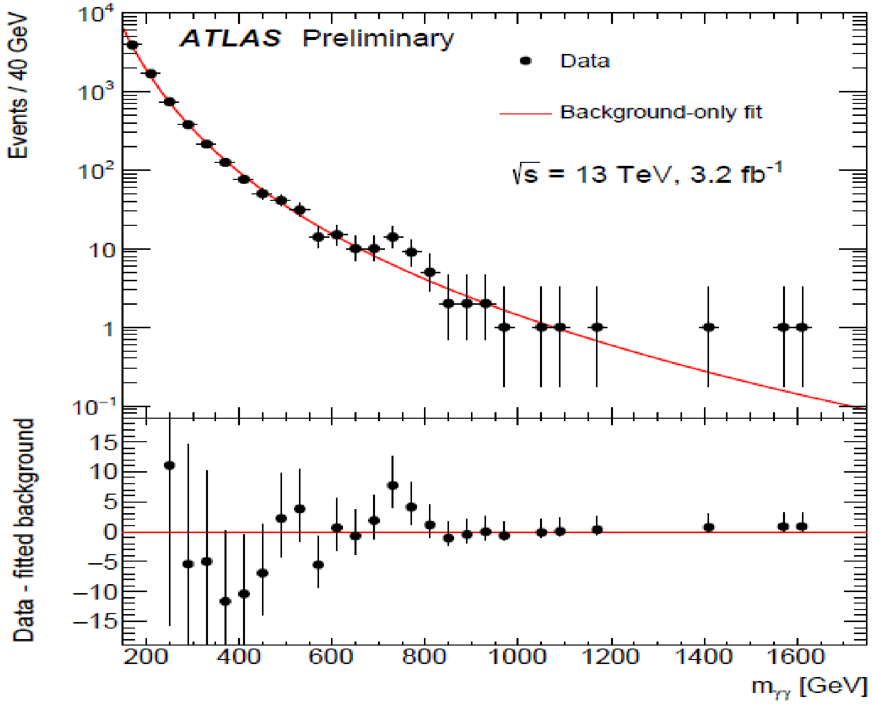

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Introduction

- ATLAS (3.2/fb) and CMS (2.6/fb) at 13TeV, a hint of a new particle at 750 GeV decaying into a photon pair.
- The generic features of interpretation are

(i) Enhance the cross section of pp → H2 → diphoton:

H2 is scalar or pseudo-scalar boson, and add particles enhance $H_2\gamma\gamma$ and H_2gg couplings.

(ii) Broad width of H2:

connection to dark sector and dark matter.

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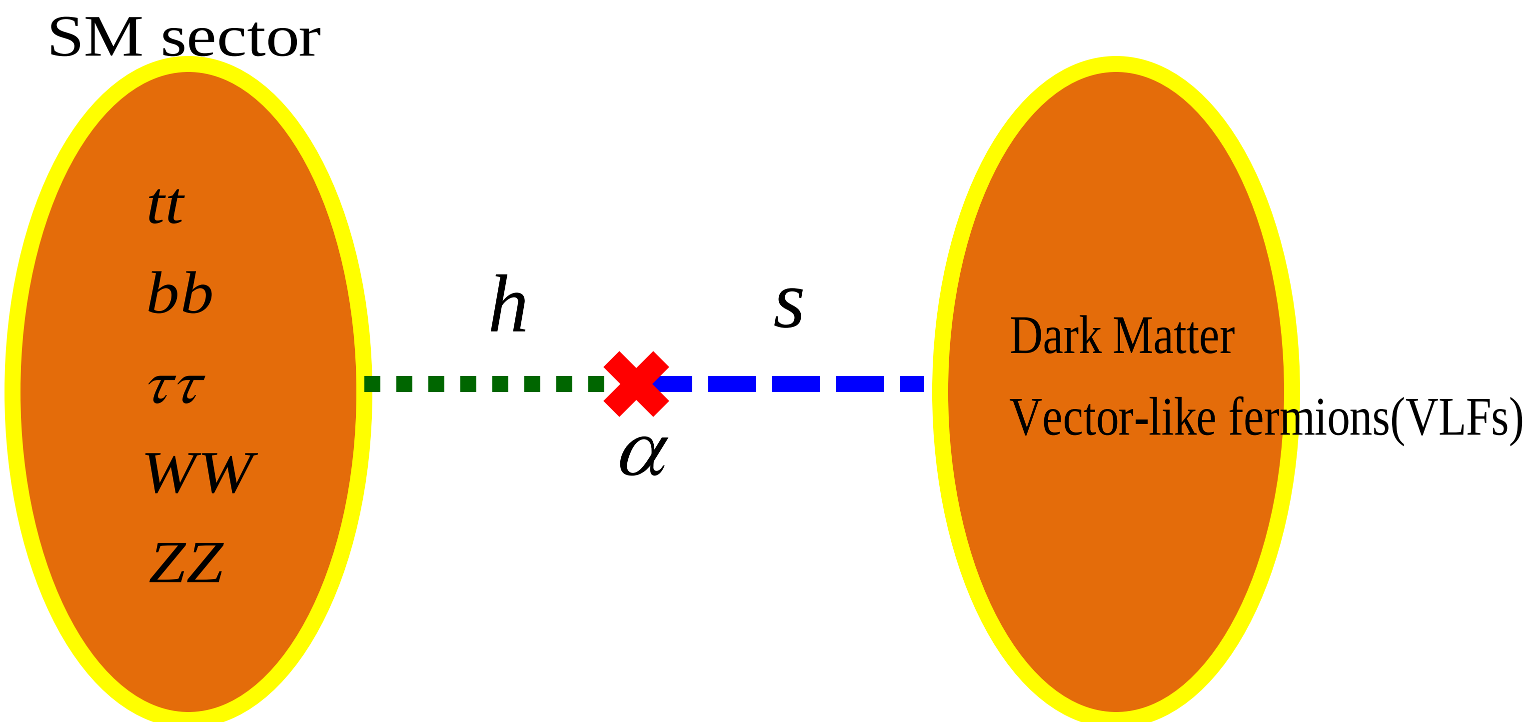
- SU(2) isospin-singlet scalar boson "*s*" at EW scale could mix with SM Higgs boson "*h*".

$$s \text{ couples to} \begin{cases} \text{dark matter} \\ \text{vector-like quarks or leptons} \end{cases}$$



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- Constraint on mixing angle α from the 125GeV Higgs, H1, global fitting.

$\otimes$ SD fit $\rightarrow$ Singlet DM models :

$$\underline{|\sin\alpha| \leq 0.51,} \quad \Delta\Gamma_{\text{tot}} \leq 1.24 \text{ MeV.}$$

$\otimes$ SQ fit $\rightarrow$ Singlet plus a vector-like quark :

$$\underline{|\sin\alpha| \leq 0.71,} \quad \Delta\Gamma_{\text{tot}} \leq 4.7 \text{ MeV.}$$

K. Chung, P. Ko, J.S. Lee, P.Y. Tseng, JHEP10 (2015) 057.

Introduction

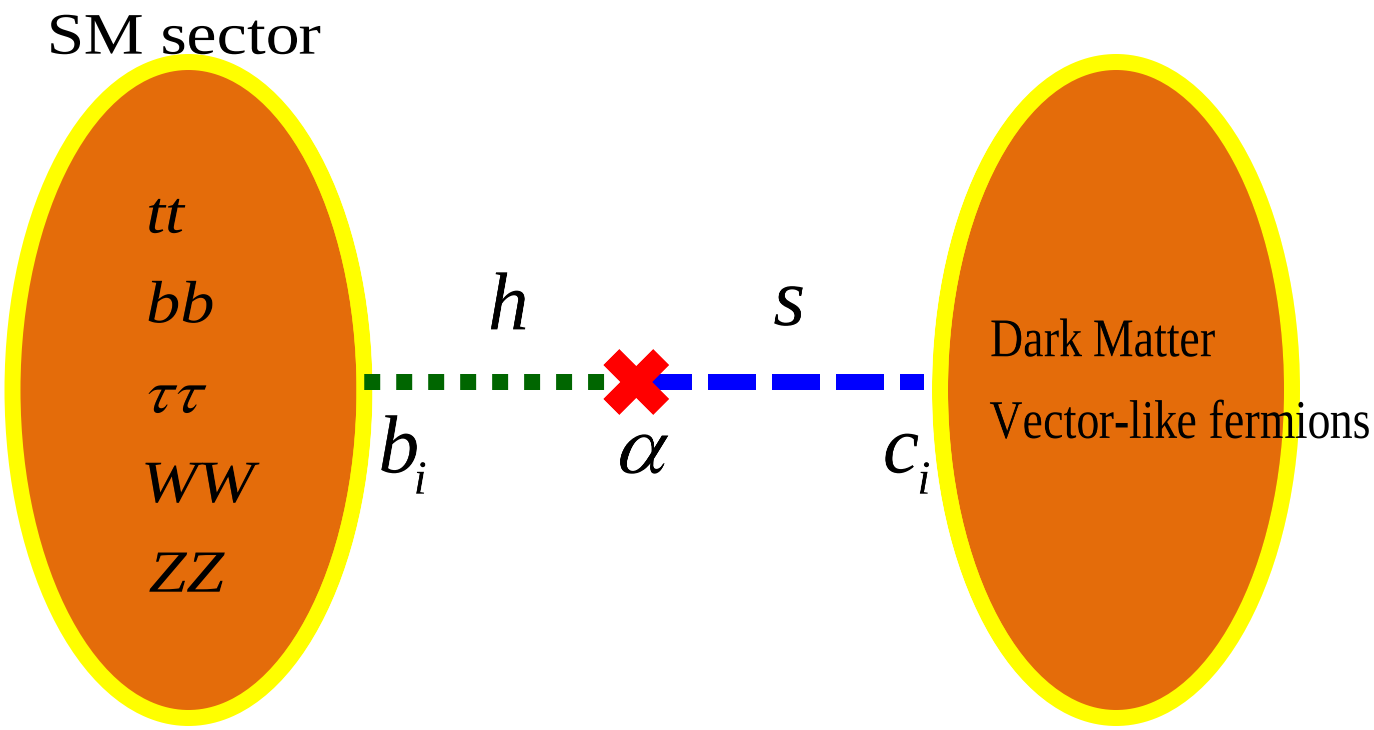
- Adding Vector-like quarks (VLQ) is crucial to enhance the gg fusion production cross section and diphoton rate for H2.

- Without VLQ, gg fusion production rate suppress by $\sin^2\alpha$, and $Br\left(H_2 \to \gamma\gamma\right) \approx 10^{-6}$.

$$
\begin{aligned}
&\sigma\left(pp \to H_2\right) \times \mathrm{Br}\left(H_2 \to \gamma\gamma\right) \\
&= \sin^2\alpha \times \sigma_{\mathrm{SM}}\left(pp \to H_2\right) \times \mathrm{Br}\left(H_2 \to \gamma\gamma\right) \\
&\approx \sin^2\alpha \times 800\ \mathrm{fb} \times 10^{-6} \ll 10\ \mathrm{fb}
\end{aligned}
$$

Higgs-Singlet Mixing framework

- Higgs-singlet mixing:



At tree-level: $b_{t,b,\tau,W,Z} \simeq 1$ and $c_{t,b,\tau,W,Z} \simeq 0,$

$b_{g,\gamma} \simeq c_{g,\gamma}$

Higgs-Singlet mixing framework

- SM Higgs doublet "*h*" and singlet scalar "*s*" mix to two mass eigenstate H1, H2; H1 is the observed 125 GeV Higgs boson; H2 is 750 GeV.

$$H_1 = h\cos\alpha - s\sin\alpha \;;\quad H_2 = h\sin\alpha + s\cos\alpha$$

- Yukawa interactions:

$$-L_Y = h\sum_{f=t,b,\tau}\frac{m_f}{v}\bar{f}f + s\sum_{F=Q,L} g^S_{s\bar{F}F}\bar{F}F$$

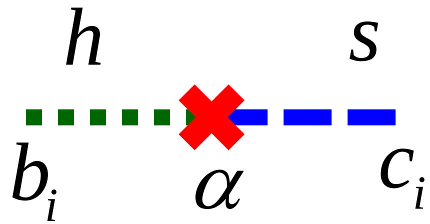
f is the 3rd generation fermions, F is the VLQ or VLL.

- Only "*s*" couples to VLFs, but **not** to SM fermions, W, Z.

Higgs-Singlet mixing framework

$$H_1 = h\cos\alpha - s\sin\alpha \; ; \quad H_2 = h\sin\alpha + s\cos\alpha$$

- H1, H2 couples to **SM particles**



$$H_1 : \; b_i\cos\alpha - c_i\sin\alpha$$
$$H_2 : \; b_i\sin\alpha + c_i\cos\alpha \qquad (i = f, W, Z, \gamma, g)$$

→

$$-L_Y = H_1\left[\cos\alpha \sum_{f=t,b,\tau} \frac{m_f}{v}\bar{f}f - \sin\alpha \sum_{F=Q,L} g^S_{s\bar{F}F}\bar{F}F\right]$$
$$H_2\left[\sin\alpha \sum_{f=t,b,\tau} \frac{m_f}{v}\bar{f}f + \cos\alpha \sum_{F=Q,L} g^S_{s\bar{F}F}\bar{F}F\right]$$

- H2 couples to SM fermions, W, Z be suppress by $\sin^2\alpha$. Evade constraints from WW, ZZ, dijet observations.

Higgs-Singlet mixing framework

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- H1, H2 couples to **gg**

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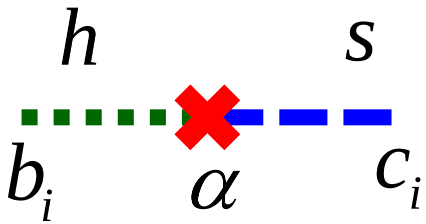

→

$$S^g_{H_1} = \cos\alpha S^{g(SM)}_{H_1} - \sin\alpha S^{g(Q)}_{H_1}$$
$$= \cos\alpha \sum_{f=t,b} F_{sf}(\tau_{1f}) - \sin\alpha \sum_Q g^S_{s\bar{Q}Q} \frac{v}{m_Q} F_{sf}(\tau_{1Q})$$
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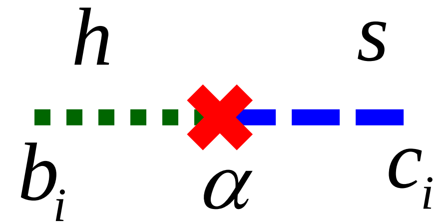

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SM particles contributions

Higgs-Singlet mixing framework

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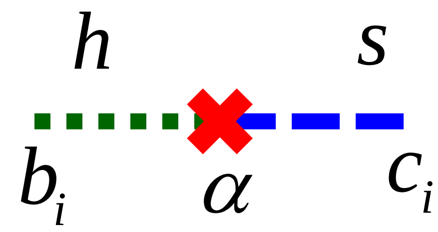

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VLQs contributions

$$\equiv S^{g(Q)}_{H_1}, \ S^{g(Q)}_{H_2}$$

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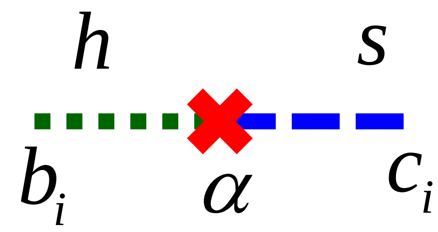
- H1, H2 couples to **gg**



$$H_1 : \quad b_i\cos\alpha - c_i\sin\alpha$$
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→ VLQ enhance the H2gg coupling more significantly than H1gg.

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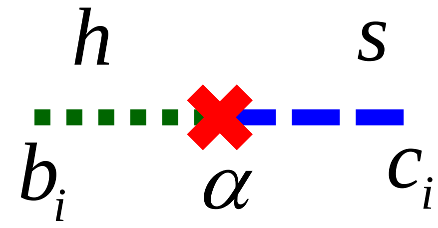

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$\tau_{1,2Q} \equiv M^2_{H_{1,2}} / 4m_Q^2$.

If $g^S_{s\bar{Q}Q} > 0$ for all Q's

$$\Rightarrow \frac{2}{3} S^{g(Q)}_{H_2} < S^{g(Q)}_{H_1} < S^{g(Q)}_{H_2}.$$

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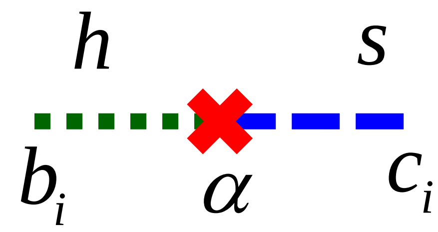

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$$S_{H_1}^{g(Q)} = \eta^{g(Q)} \times S_{H_2}^{g(Q)}$$

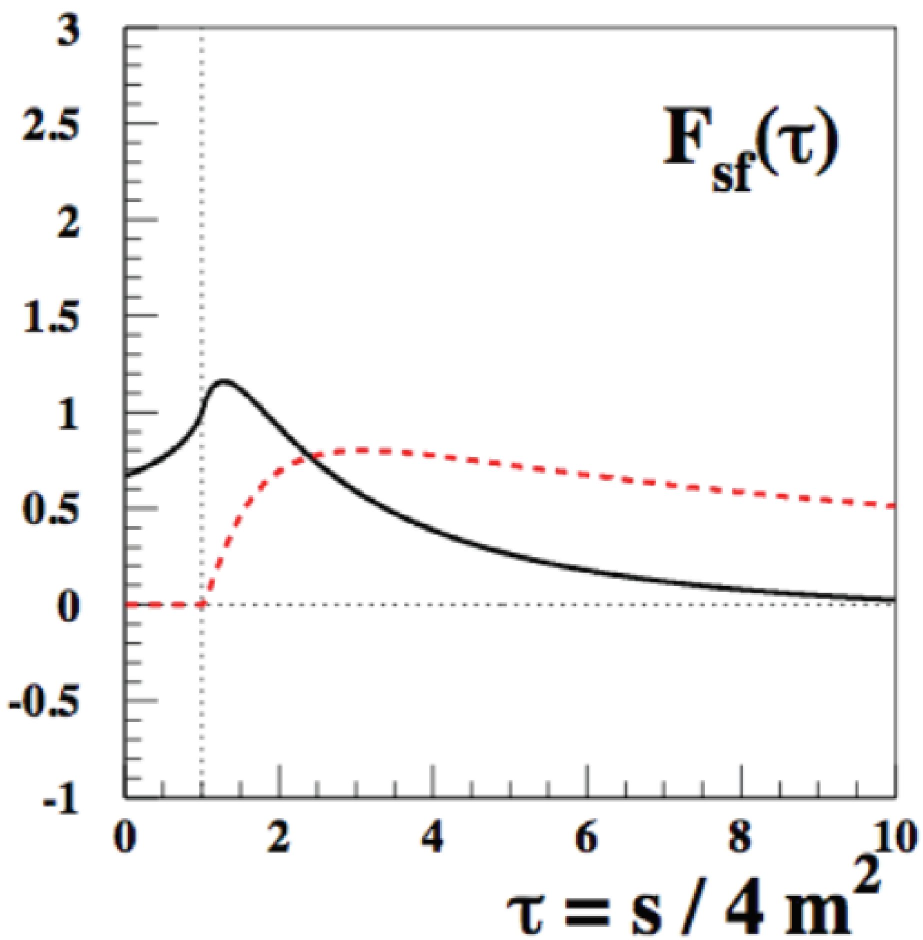
$\eta^{g(Q)} = 0:$ VLQs not contribute to $H_1 gg$ coupling.

$\eta^{g(Q)} = 2/3:$ $M_Q = M_{H_2}/2.$

$\eta^{g(Q)} = 1:$ $M_Q \gg M_{H_2}.$

Higgs-Singlet mixing framework

- The loop function:



$$F_{sf}(0) = \frac{2}{3}$$

$$F_{sf}(1) = 1$$

$$\tau_{1,2Q} \equiv M^2_{H_{1,2}} / 4m_Q^2.$$

If $m_Q = 500$ GeV

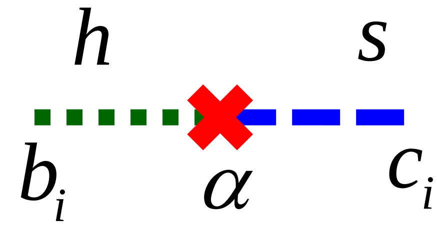
$$\Rightarrow \tau_{1Q} \approx 0, \quad \tau_{2Q} = 0.56 < 1$$

$$\Rightarrow \frac{2}{3} F_{sf}(\tau_{2Q}) < F_{sf}(\tau_{1Q}) < F_{sf}(\tau_{2Q}).$$

Higgs-Singlet mixing framework

$$H_1 = h\cos\alpha - s\sin\alpha\ ; \quad H_2 = h\sin\alpha + s\cos\alpha$$

- H1, H2 couples to **diphoton**



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$$S^{\gamma}_{H_1} = \cos\alpha S^{\gamma(SM)}_{H_1} - \sin\alpha S^{\gamma(F)}_{H_1}$$
$$= \cos\alpha\left[2\sum_{f=t,b,\tau} N_C Q_f^2 F_{sf}(\tau_{1f}) - F_1(\tau_{1W})\right] - \sin\alpha\left[2\sum_F N_C Q_F^2 g^S_{s\bar{F}F}\frac{v}{m_F}F_{sf}(\tau_{1F})\right]$$
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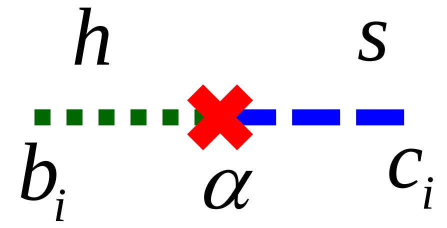

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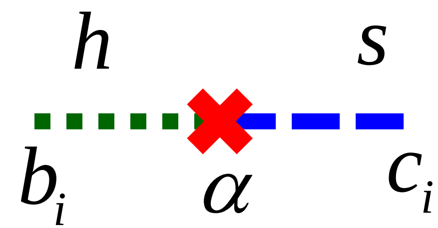

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$$\text{VLFs,} \equiv S^{\gamma(F)}_{H_1},\; S^{\gamma(F)}_{H_2}$$

$$= \sin\alpha\left[2\sum_{f=t,b,\tau} N_C Q_f^2 F_{sf}(\tau_{2f}) - F_1(\tau_{2W})\right] + \cos\alpha\left[2\sum_F N_C Q_F^2 g^S_{s\bar{F}F}\frac{v}{m_F}F_{sf}(\tau_{2F})\right]$$

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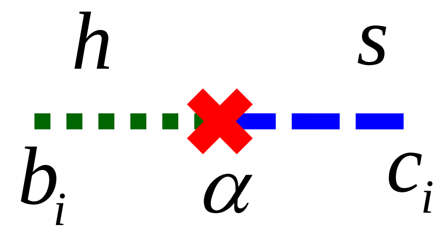

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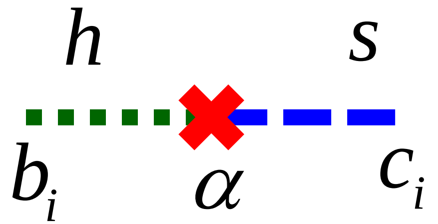
- H1, H2 couples to **diphoton**



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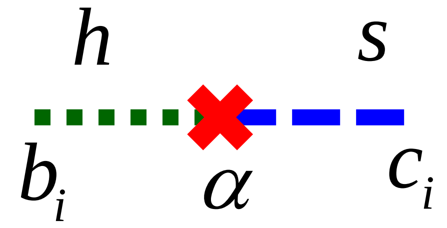


$$H_1: \quad b_i\cos\alpha - c_i\sin\alpha$$

$$H_2: \quad b_i\sin\alpha + c_i\cos\alpha \qquad (i = f, W, Z, \gamma, g)$$

→

$$S_{H_1}^{\gamma(F)} = \eta^{\gamma(F)} \times S_{H_2}^{\gamma(F)}$$

$\eta^{\gamma(F)} = 0$: VLFs not contribute to $H_1\gamma\gamma$ coupling.

$\eta^{\gamma(F)} = 2/3$: $M_F = M_{H_2}/2$.

$\eta^{\gamma(F)} = 1$: $M_F \gg M_{H_2}$.

Higgs-Singlet mixing framework

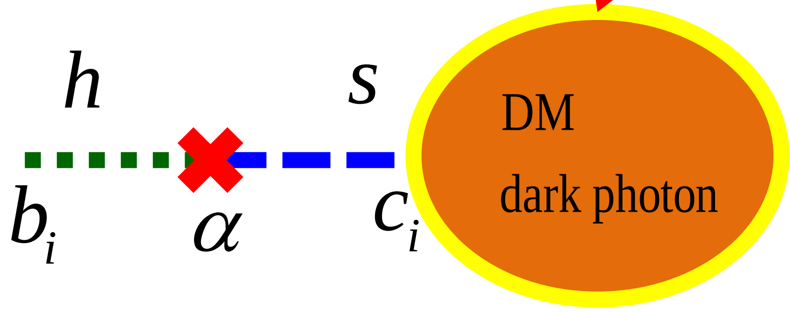
- **Total decay width of H2:**

$$\Gamma_{H_2} = \sin^2\alpha\,\Gamma_{SM}\left(H_2 \to WW, ZZ, t\bar{t}, b\bar{b}, \tau\tau\right) + \Gamma\left(H_2 \to gg, \gamma\gamma\right) + \Gamma\left(H_2 \to H_1 H_1\right) + \Gamma_{inv}^{H_2}$$

where $\Gamma_{SM}\left(H_2\right) \simeq 250$ GeV

and,

$$\Gamma_{H_2}^{\text{non-SM}} \equiv \Gamma\left(H_2 \to H_1 H_1\right) + \Delta\Gamma_{inv}^{H_2}$$



- Γ_{H_2} **needs to satisfy the 45 GeV width from ATLAS.**

Higgs-Singlet mixing framework

- The varying parameters are:

$$\alpha,\ S^{g(Q)}_{H_2},\ S^{\gamma(F)}_{H_2},\ \Gamma^{\text{non-SM}}_{H_2},\ \eta^{g(Q)},\ \eta^{\gamma(F)}$$

where non-SM decay channels:

$$\Gamma^{\text{non-SM}}_{H_2} \equiv \Gamma\left(H_2 \to H_1 H_1\right) + \Delta\Gamma^{H_2}_{inv},$$

$\eta^{g(Q)},\ \eta^{\gamma(F)} \subset \left[\frac{2}{3},\ 1\right]$ dictate the ratio $S^{g(Q)}_{H_1}, S^{\gamma(F)}_{H_1}$ and $S^{g(Q)}_{H_2}, S^{\gamma(F)}_{H_2}$

$$S^{g(Q)}_{H_1} \equiv \eta^{g(Q)} \times S^{g(Q)}_{H_2}, \quad S^{\gamma(F)}_{H_1} \equiv \eta^{\gamma(F)} \times S^{\gamma(F)}_{H_2}$$

$$\frac{2}{3} S^{g(Q)}_{H_2} < S^{g(Q)}_{H_1} < S^{g(Q)}_{H_2}, \qquad \frac{2}{3} S^{\gamma(F)}_{H_2} < S^{\gamma(F)}_{H_1} < S^{\gamma(F)}_{H_2}$$

Numerical results

Numerical results

- The diphoton excess at 750 GeV:

ATLAS: $M_{H_2} = 750\ \text{GeV},\ \ \sigma_{\text{fit}}(pp \to H_2 \to \gamma\gamma) \approx 10 \pm 3\ \text{fb; (95\% CL)},\ \Gamma_{H_2} \approx 45\ \text{GeV}$

CMS: $M_{H_2} = 760\ \text{GeV},\ \ \sigma_{\text{fit}}(pp \to H_2 \to \gamma\gamma) \approx 9 \pm 7\ \text{fb; (95\% CL)}$

- Constraints:

i) LHC 125 GeV Higgs boson observable

ii) Upper limits from

$$\sigma(pp \to H_2 \to VV) < 150 - 200\ \text{fb at 13 TeV}$$

$$\sigma(pp \to H_2 \to t\bar{t}) < 0.5 - 1\ \text{pb at 8 TeV}$$

$$\sigma(pp \to H_2 \to \text{dijet}) < 1 - 2\ \text{pb at 8 TeV}$$

Numerical results

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CMS: $M_{H_2} = 760\text{ GeV},\ \sigma_{\text{fit}}(pp \to H_2 \to \gamma\gamma) \approx 9 \pm 7\text{ fb; (95\% CL)}$

- Constraints:

$$S_{H_1}^{g(\text{SM})} = 0.651 + 0.050i,\quad S_{H_1}^{\gamma(\text{SM})} = -6.55 + 0.039i$$
$$S_{H_2}^{g(\text{SM})} = 0.291 + 0.744i,\quad S_{H_2}^{\gamma(\text{SM})} = -0.94 - 0.043i$$

i) LHC 125 GeV Higgs boson observable

$C_{H_1}^{g,\gamma} = \left|S_{H_1}^{g,\gamma}\right| / \left|S_{H_1}^{g,\gamma(SM)}\right|$ within 10% deviation from SM value

$$\Rightarrow \quad \left|S_{H_2}^{g(Q)}\right| \le \frac{0.1}{|\sin\alpha|},\quad \left|S_{H_2}^{\gamma(F)}\right| \le \frac{1}{|\sin\alpha|},\ \text{for } \eta^{g(Q)} = \eta^{\gamma(F)} = 2/3.$$

Therefore we resticted $|\sin\alpha| < 0.1$,

in order to have $\left|S_{H_2}^{g(Q)}\right| = O(1)$ and $\left|S_{H_2}^{\gamma(F)}\right| = O(10)$.

Numerical results

- The diphoton excess at 750 GeV:

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$$\text{CMS: } M_{H_2} = 760\ \text{GeV},\ \ \sigma_{\text{fit}}(pp \to H_2 \to \gamma\gamma) \approx 9 \pm 7\ \text{fb; (95\% CL)}$$

$$S_{H_1}^{g(\text{SM})} = 0.651 + 0.050i, \quad S_{H_1}^{\gamma(\text{SM})} = -6.55 + 0.039i$$

$$S_{H_2}^{g(\text{SM})} = 0.291 + 0.744i, \quad S_{H_2}^{\gamma(\text{SM})} = -0.94 - 0.043i$$

- Recall:

H1, H2 couples to **diphoton**

$$S_{H_1}^{\gamma} = \cos\alpha S_{H_1}^{\gamma(SM)} - \sin\alpha S_{H_1}^{\gamma(F)}$$

$$S_{H_2}^{\gamma} = \sin\alpha S_{H_2}^{\gamma(SM)} + \cos\alpha S_{H_2}^{\gamma(F)}$$

$$S_{H_1}^{g(Q)} \equiv \eta^{g(Q)} \times S_{H_2}^{g(Q)}, \quad S_{H_1}^{\gamma(F)} \equiv \eta^{\gamma(F)} \times S_{H_2}^{\gamma(F)}$$

Numerical results

- The production cross section of H2 by gluon-fusion:

$$\sigma(gg \to H_2) = \frac{\left|S_{H_2}^{g}\right|^2}{\left|S_{H_2}^{g(SM)}\right|^2} \sigma_{SM}(gg \to H_2),$$

with $\sigma_{SM}(gg \to H_2) \approx 800$ fb is the SM cross section for $M_{H_2} = 750$ GeV at $\sqrt{s} = 13$ TeV.

- When $\sin\alpha \sim 0,$ numerically we have:

$$\sigma(gg \to H_2) = 1250 \left|S_{H_2}^{g(Q)}\right|^2 \text{ fb},$$

$$\Gamma(H_2 \to \gamma\gamma) = 4.67 \times 10^{-5} \left|S_{H_2}^{\gamma(F)}\right|^2 \text{ GeV},$$

$$\Gamma(H_2 \to gg) = 8.88 \times 10^{-2} \left|S_{H_2}^{g(Q)}\right|^2 \text{ GeV},$$

$$\sigma(gg \to H_2) \times B(H_2 \to \gamma\gamma) = 11.8 \frac{\left(\left|S_{H_2}^{g(Q)} S_{H_2}^{\gamma(F)}\right| / 90\right)^2}{\left(\Gamma_{H_2} / 40 \text{ GeV}\right)} \text{ fb},$$

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$$\sigma(gg \to H_2) \times B(H_2 \to \gamma\gamma) = 11.8\frac{\left(\left|S^{g(Q)}_{H_2}S^{\gamma(F)}_{H_2}\right|/90\right)^2}{\left(\Gamma_{H_2}/40\ \text{GeV}\right)} \text{fb},$$

Numerical results

- We need $S_{H_2}^{g(Q)} \times S_{H_2}^{\gamma(F)} \approx 90$ and we know $S_{H_2}^{\gamma(F)} \approx 10 \times S_{H_2}^{g(Q)}$ because

$$S_{H_2}^{\gamma(F)} = 2\sum_F N_C Q_F^2 g_{s\bar{F}F}^S \frac{v}{m_F} F_{sf}(\tau_{2F}) \quad \text{and} \quad S_{H_2}^{g(Q)} = \sum_F g_{s\bar{F}F}^S \frac{v}{m_F} F_{sf}(\tau_{2F})$$

- We can chose $S_{H_2}^{g(Q)} = 3,\ S_{H_2}^{\gamma(F)} = 30,\ \Gamma_{H_2}^{\text{non-SM}} = 40\ \text{GeV}$. That requires 6VLQ with mass about 500 GeV and coupling of order 1.

$$\Gamma(H_2 \to \gamma\gamma) = 4.67 \times 10^{-5} \left|S_{H_2}^{\gamma(F)}\right|^2 = 0.04\ \text{GeV},$$

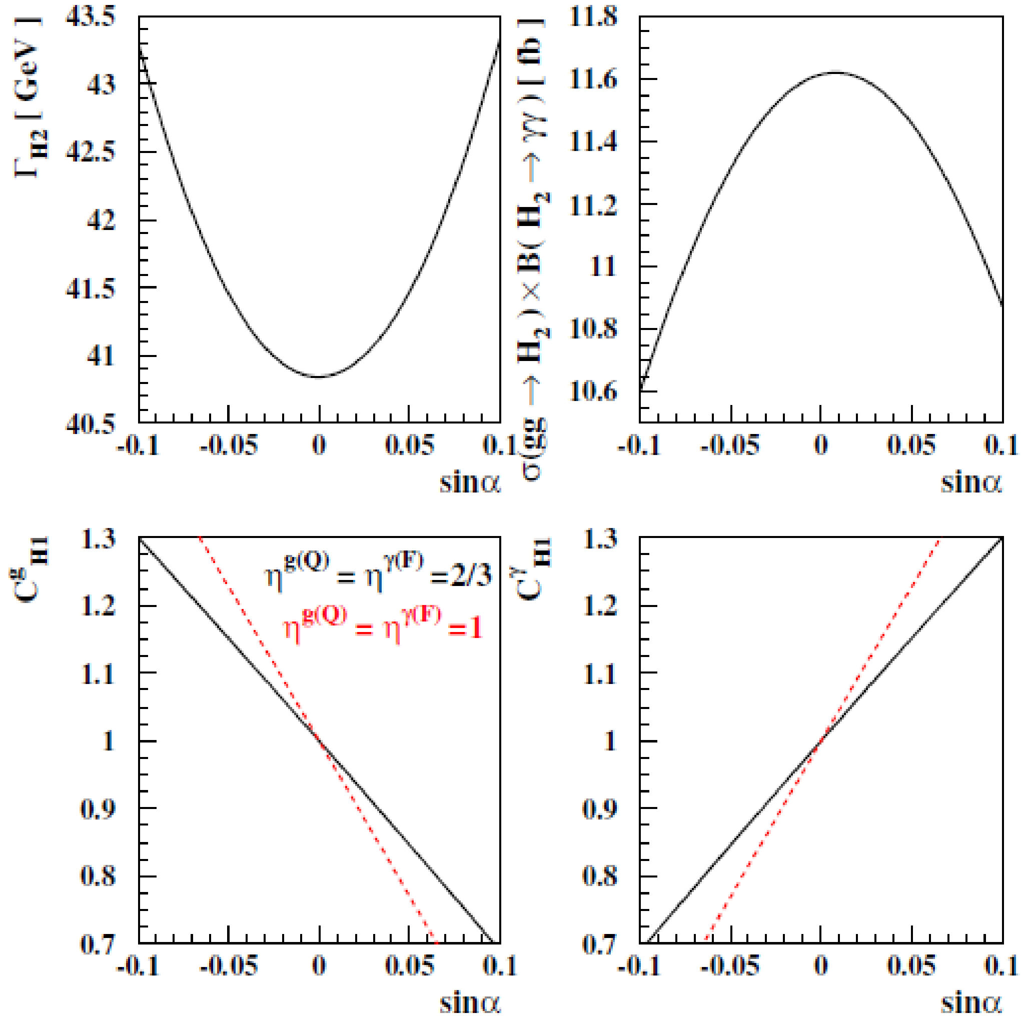
$$\Gamma(H_2 \to gg) = 8.88 \times 10^{-2} \left|S_{H_2}^{g(Q)}\right|^2 = 0.8\ \text{GeV}.$$

$$\text{Total decay width: } \Gamma_{H_2} = \Gamma(H_2 \to \gamma\gamma) + \Gamma(H_2 \to gg) + \Gamma_{H_2}^{\text{non-SM}}$$

Numerical results

- One benchmark point under $\eta^{g(Q)} = \eta^{\gamma(F)} = 2/3$ scenario.

$\Gamma^{\text{non-SM}} = 40$ GeV , $S^{g(Q)}_{H2} = 3$, $S^{\gamma(F)}_{H2} = 30$



$$C^{g,\gamma}_{H_1} \equiv \frac{\left|S^{g,\gamma}_{H_1}\right|}{\left|S^{g,\gamma(\text{SM})}_{H_1}\right|}$$

$$S^{g(Q)}_{H_1} = \eta^{g(Q)} S^{g(Q)}_{H_2}$$

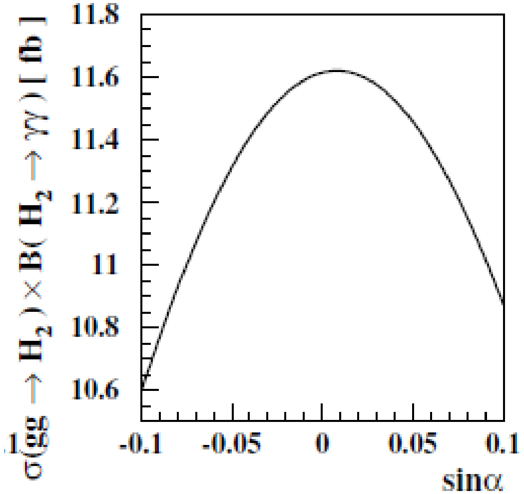
$$S^{\gamma(F)}_{H_1} = \eta^{\gamma(F)} S^{\gamma(F)}_{H_2}$$

Numerical results

- One benchmark point under $\eta^{g(Q)} = \eta^{\gamma(F)} = 2/3$ scenario.

$\Gamma^{\text{non-SM}} = 40$ GeV, $S^{g(Q)}_{H2} = 3$, $S^{\gamma(F)}_{H2} = 30$

$$\sigma(pp \to H_2 \to \gamma\gamma) \propto \cos^4\alpha$$



$$C^{g,\gamma}_{H_1} \equiv \frac{\left|S^{g,\gamma}_{H_1}\right|}{\left|S^{g,\gamma(\mathrm{SM})}_{H_1}\right|}$$

$$S^{g}_{H_2} = \sin\alpha S^{g(SM)}_{H_2} + \cos\alpha S^{g(Q)}_{H_2}$$

$$S^{\gamma}_{H_2} = \sin\alpha S^{\gamma(SM)}_{H_2} + \cos\alpha S^{\gamma(F)}_{H_2}$$

$$S^{g(Q)}_{H_1} = \eta^{g(Q)} S^{g(Q)}_{H_2}$$

$$S^{\gamma(F)}_{H_1} = \eta^{\gamma(F)} S^{\gamma(F)}_{H_2}$$

1

Numerical results

- One benchmark point under $\eta^{g(Q)} = \eta^{\gamma(F)} = 2/3$ scenario.

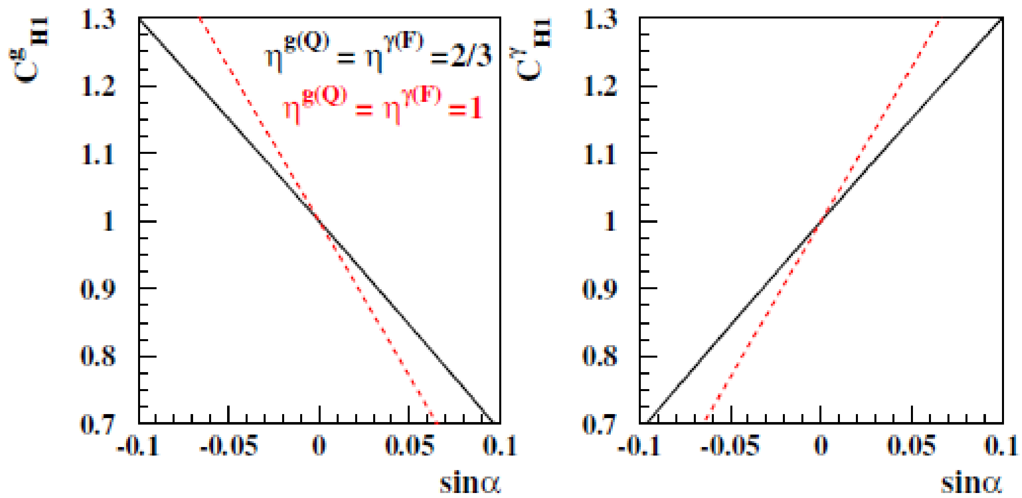
$\Gamma^{\text{non-SM}} = 40$ GeV , $S^{g(Q)}_{H2} = 3$, $S^{\gamma(F)}_{H2} = 30$

$$C^{g,\gamma}_{H_1} \propto 1 + \sin\alpha$$

$$S^{g}_{H_1} = \cos\alpha S^{g(SM)}_{H_1} - \sin\alpha S^{g(Q)}_{H_1}$$

$$S^{\gamma}_{H_1} = \cos\alpha S^{\gamma(SM)}_{H_1} - \sin\alpha S^{\gamma(F)}_{H_1}$$

$$C^{g,\gamma}_{H_1} \equiv \frac{\left|S^{g,\gamma}_{H_1}\right|}{\left|S^{g,\gamma(\text{SM})}_{H_1}\right|}$$



$$S^{g(Q)}_{H_1} = \eta^{g(Q)} S^{g(Q)}_{H_2}$$

$$S^{\gamma(F)}_{H_1} = \eta^{\gamma(F)} S^{\gamma(F)}_{H_2}$$

Numerical results

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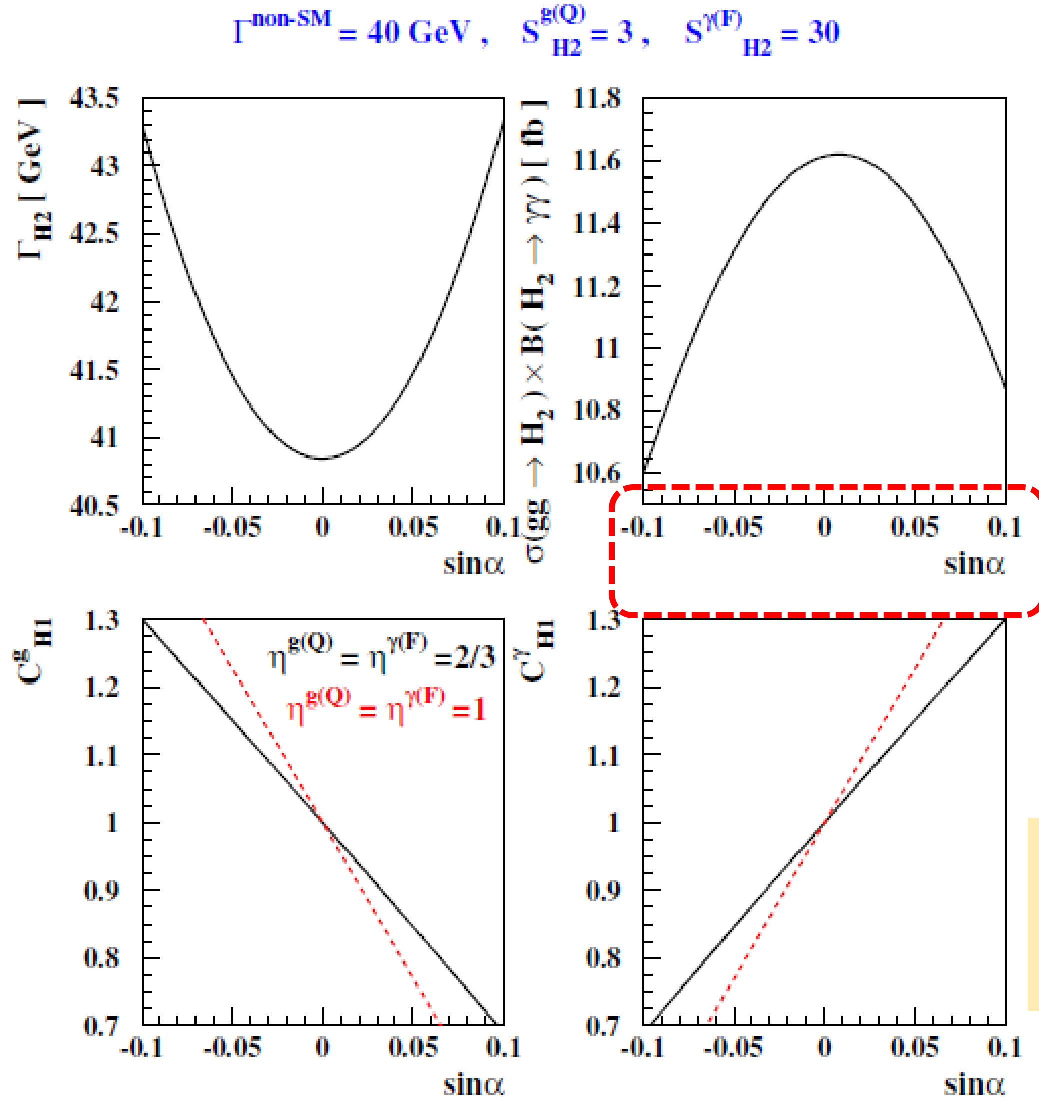

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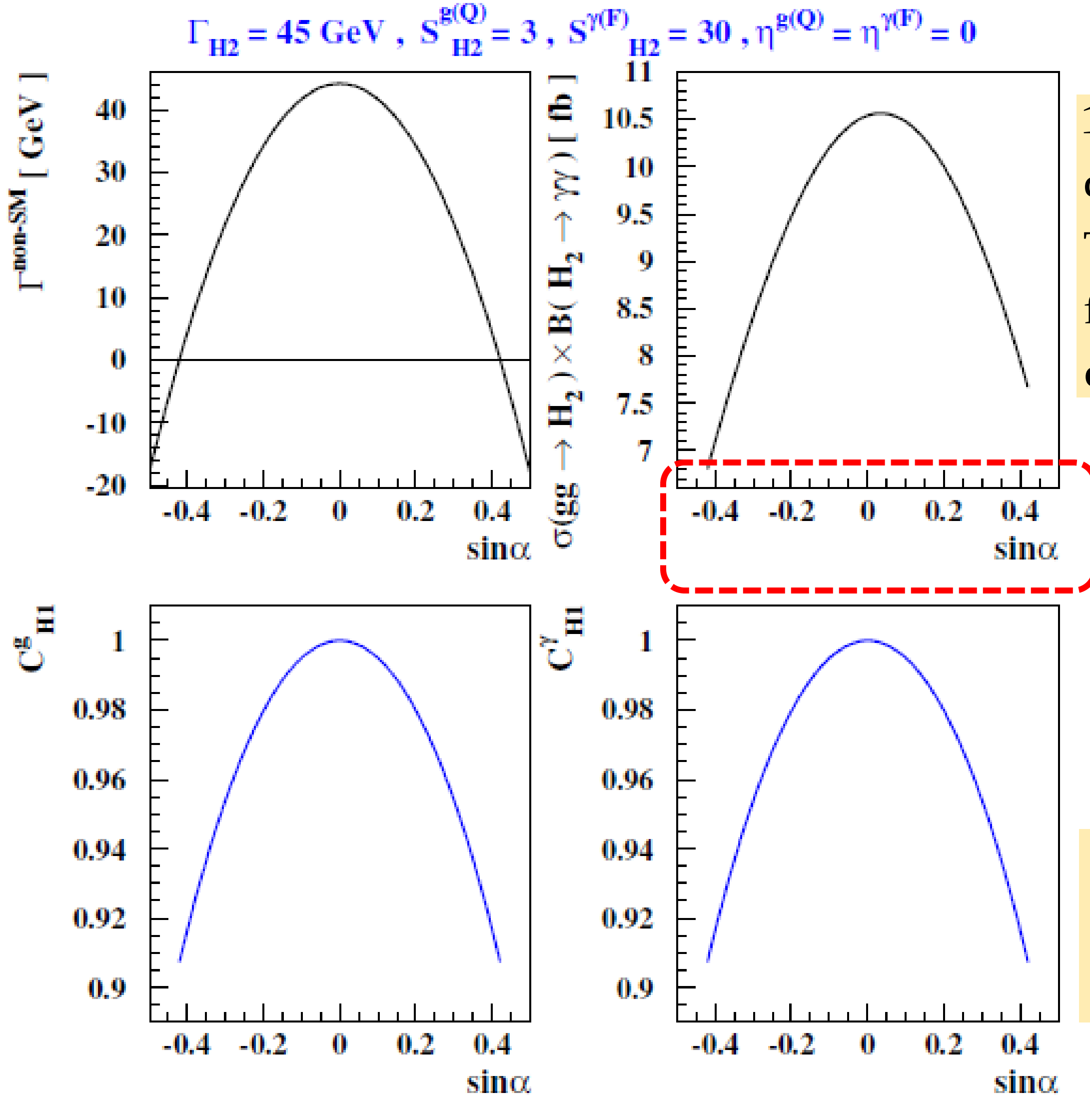
$$S^{\gamma(F)}_{H_1} = \eta^{\gamma(F)} S^{\gamma(F)}_{H_2}$$

Numerical results

- One benchmark point under $\eta^{g(Q)} = \eta^{\gamma(F)} = 0$ scenario.



125 GeV Higgs decouples from VLQs. Then less constraints from 125 GeV Higgs observables.

$$C_{H_1}^{g,\gamma} \equiv \frac{\left|S_{H_1}^{g,\gamma}\right|}{\left|S_{H_1}^{g,\gamma(\mathrm{SM})}\right|}$$

$$S_{H_1}^{g(Q)} = \eta^{g(Q)} S_{H_2}^{g(Q)}$$

$$S_{H_1}^{\gamma(F)} = \eta^{\gamma(F)} S_{H_2}^{\gamma(F)}$$

Numerical results

- One benchmark point under $\eta^{g(Q)} = \eta^{\gamma(F)} = 0$ scenario.

$\Gamma_{H2} = 45$ GeV , $S^{g(Q)}_{H2} = 3$, $S^{\gamma(F)}_{H2} = 30$, $\eta^{g(Q)} = \eta^{\gamma(F)} = 0$

$$C^{g,\gamma}_{H_1} \propto \cos\alpha$$

$$S^{g}_{H_1} = \cos\alpha S^{g(SM)}_{H_1} - \sin\alpha S^{g(Q)}_{H_1}$$

$$S^{\gamma}_{H_1} = \cos\alpha S^{\gamma(SM)}_{H_1} - \sin\alpha S^{\gamma(F)}_{H_1}$$

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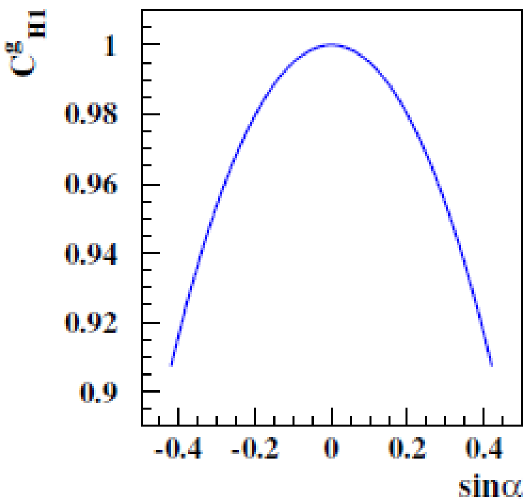

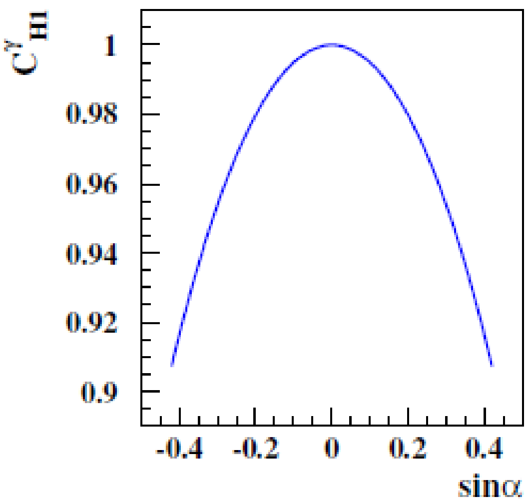

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Numerical results

- H2 decay into WW, ZZ, tt, gg, and experimental upper limits:

$$\sigma(gg\to H_2)\times B(H_2\to WW)\simeq 400\text{fb}\left(\frac{S_{H_2}^{g(Q)}}{3}\right)^2\left(\frac{\sin\alpha}{0.1}\right)^2\left(\frac{40\text{GeV}}{\Gamma_{H_2}}\right)^2\left(\frac{\sigma_{\rm SM}(gg\to H_2)}{800\text{fb}}\right)$$

$$\sigma(gg\to H_2)\times B(H_2\to ZZ)\simeq 200\text{fb}\left(\frac{S_{H_2}^{g(Q)}}{3}\right)^2\left(\frac{\sin\alpha}{0.1}\right)^2\left(\frac{40\text{GeV}}{\Gamma_{H_2}}\right)^2\left(\frac{\sigma_{\rm SM}(gg\to H_2)}{800\text{fb}}\right)$$

$$\sigma(gg\to H_2)\times B(H_2\to t\bar{t})\simeq 90\text{fb}\left(\frac{S_{H_2}^{g(Q)}}{3}\right)^2\left(\frac{\sin\alpha}{0.1}\right)^2\left(\frac{40\text{GeV}}{\Gamma_{H_2}}\right)^2\left(\frac{\sigma_{\rm SM}(gg\to H_2)}{800\text{fb}}\right)$$

$$\sigma(gg\to H_2)\times B(H_2\to gg)\simeq 200\text{fb}\left(\frac{S_{H_2}^{g(Q)}}{3}\right)^4\left(\frac{40\text{GeV}}{\Gamma_{H_2}}\right)^2\left(\frac{\sigma_{\rm SM}(gg\to H_2)}{800\text{fb}}\right)$$

Upper limits:

$$\sigma(pp\to H_2\to VV)<150-200\text{ fb at 13 TeV}$$

$$\sigma(pp\to H_2\to t\bar{t})<0.5-1\text{ pb at 8 TeV}$$

$$\sigma(pp\to H_2\to \text{dijet})<1-2\text{ pb at 8 TeV}$$

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- The parameter region with $|\sin\alpha|\leq 0.1$ are safe from those upper limits.

Model

SQ fit: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$

- There are dark Higgs Φ and scalar DM X_I in the $U(1)_X$ gauged dark sector.

S. Baek, P. Ko, W.-Il Park, PLB747 (2015) 255-259
P. Ko, and T. Nomura, arXiv:1601.02490 [hep-ph]

	Fermions								Scalar	
	E_L	E_R	N_L	N_R	U_L	U_R	D_L	D_R	Φ	X
SU(3)	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$
SU(2)	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U}(1)_Y$	-1	-1	0	0	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{-1}{3}$	$\frac{-1}{3}$	0	0
$\mathrm{U}(1)_X$	a	$-b$	$-a$	b	$-a$	b	a	$-b$	$a+b$	a

- After symmetry breaking by dark Higgs and SM Higgs, dark Higgs s can mix with SM Higgs h .
- Dark fermions are vector-like under SM symmetry, carry SM quantum numbers, and they will couple to photon and gluon.

SQ fit: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$

- There are dark Higgs Φ and scalar DM X_I in the $U(1)_X$ gauged dark sector.

S. Baek, P. Ko, W.-Il Park, PLB747 (2015) 255-259
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	Fermions								Scalar	
	E_L	E_R	N_L	N_R	U_L	U_R	D_L	D_R	Φ	X
SU(3)	**1**	**1**	**1**	**1**	**3**	**3**	**3**	**3**	**1**	**1**
SU(2)	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	-1	-1	0	0	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{-1}{3}$	$\frac{-1}{3}$	0	0
$U(1)_X$	a	$-b$	$-a$	b	$-a$	b	a	$-b$	$a+b$	a

- Local gauge $U(1)_X$ is broken by dark Higgs Φ , then the remaining global symmetry Z_2 stabilized the DM X_I .
- S can decay into pair of dark photon Z', and realize $\Gamma_{H_2} \approx 40\ \text{GeV}$.

Conclusions

Conclusions

- We consider the SM Higgs boson and singlet scalar mixing.
- We use the heavier H2, 750 GeV, to explain the recent 750 GeV diphoton excess with the help of VLQ.
- The lighter H1, 125 GeV still satisfies the Higgs data.
- Benchmark values:

$$|\sin\alpha| < 0.1$$

$$\Gamma_{H_2} \approx \Gamma(H_2 \to H_1 H_1) + \Delta\Gamma_{\rm inv}^{H_2} \approx 40\ \mathrm{GeV}$$

$$\left|S_{H_2}^{g(Q)} \times S_{H_2}^{\gamma(F)}\right| \approx 90$$

Conclusions

- Vector-Boson Fusion production channel at 750 GeV is almost background free.

$$\sigma^{\mathrm{VBF}}\left(pp \to H_2 jj \to \gamma\gamma\, jj\right)$$

- ATLAS and CMS are looking into the $H_2 \to Z\gamma$ at 750 GeV.

Thank you !

Back up

Introduction

- The observed 125GeV Higgs boson at LHC very SM like.

i). The spin, parity, charge conjugation $J^{PC} = 0^{++}$.

ii). Its couplings to the SM particles.

- The 125 GeV Higgs couplings to SM particles are often parameterized in terms of the

$$\kappa_i^2 = \frac{\Gamma(H \to ii)}{\Gamma(H \to ii)_{\rm SM}}, \qquad \kappa_H^2 = \frac{\Gamma_{\rm tot}(H) + \Delta\Gamma_{\rm tot}}{\Gamma_{\rm SM}}$$

$i = W, Z, f, g, \gamma$

$\Gamma_{\rm SM}$: SM total decay width

$\Gamma_{\rm tot}(H)$: total decay width to SM particles

$\Delta\Gamma_{\rm tot}$: non-SM decay width

Introduction

- New physics BSM will modify $\kappa_i \neq 1$.
- New physics decoupled from SM sector→ nonrenormalizable higher dimensional operators.
- Isospin-singlet scalar boson "*s*" at EW scale could mix with SM Higgs boson "*h*".

$$s \text{ couples to} \begin{cases} \text{dark matter} \\ \text{vector-like quarks or leptons} \\ \text{new charged or neutral vector bosons} \end{cases}$$

Introduction

- Singlet mix SM Higgs includes many BSM.

  i). Higgs-portal DM model.

  ii). DM models with local dark gauge symmetries.

  iii). Non-SUSY $U(1)_{B-L}$ model.

  iv). Vector-like fermions affect $h \to gg, \gamma\gamma$.

- Merits of singlet scalar:

  i). stabilized Higgs potential.

  ii). No strong constraint from rho parameter and EWPT.

  iii). Baryongenesis, 1^{st} order phase transition, CPV source.

  iv). DM candidate.

Formalism: SM Higgs

- SM Higgs h couplings to fermions:

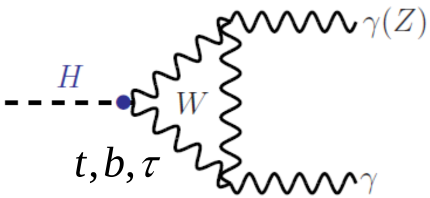
$$\mathcal{L}_{h\bar{f}f} = -\sum_{f=u,d,l} \frac{g m_f}{2 M_W} b_f \, h \, \bar{f} \, f$$

- SM Higgs h couplings to massive vector boson:

$$\mathcal{L}_{hVV} = g \, M_W \left(b_W W_\mu^+ W^{-\mu} + b_Z \frac{1}{2 \cos^2 \theta_W} Z_\mu Z^\mu \right) h$$

Formalism: SM Higgs

- SM Higgs h couplings to di-photon:



A Djouadi, Phys.Rept.457 (2008)1-216

$$\mathcal{M}_{\gamma\gamma h} = -\frac{\alpha M_H^2}{4\pi\, v}\, S_h^\gamma\, (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*)$$

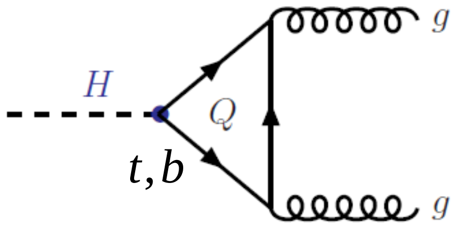
- The scalar form factor is:

$$S_h^\gamma = 2 \sum_{f=b,t,\tau} N_C\, Q_f^2\, b_f\, F_{sf}(\tau_f) - b_W\, F_1(\tau_W) + \Delta S_h^\gamma \equiv b_\gamma\, S_{\rm SM}^\gamma$$

Formalism: SM Higgs

- SM Higgs h couplings to gluon:

$$\mathcal{M}_{ggh} = -\frac{\alpha_s\, M_H^2\, \delta^{ab}}{4\pi\, v}\, S_h^g\, (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*)$$



- The scalar form factor is:

$$S_h^g = \sum_{f=b,t} b_f\, F_{sf}(\tau_f) + \Delta S_h^g \;\equiv\; b_g\, S_{\rm SM}^g$$

Formalism: Singlet scalar couplings and mixing

- Singlet scalar "*s*" couples to SM particle:

$$\mathcal{L}_{s\bar{f}f} = -\sum_{f=u,d,l} \frac{g m_f}{2M_W} c_f\, s\, \bar{f} f\,, \tag{2.10}$$

$$\mathcal{L}_{sVV} = g\, M_W \left(c_W W^+_\mu W^{-\mu} + c_Z \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu \right) s\,,$$

$$S^\gamma_s = 2 \sum_{f=b,t,\tau} N_C\, Q_f^2\, c_f\, F_{sf}(\tau_f) - c_W\, F_1(\tau_W) + \Delta S^\gamma_s \;\equiv\; c_\gamma\, S^\gamma_{\rm SM}\,,$$

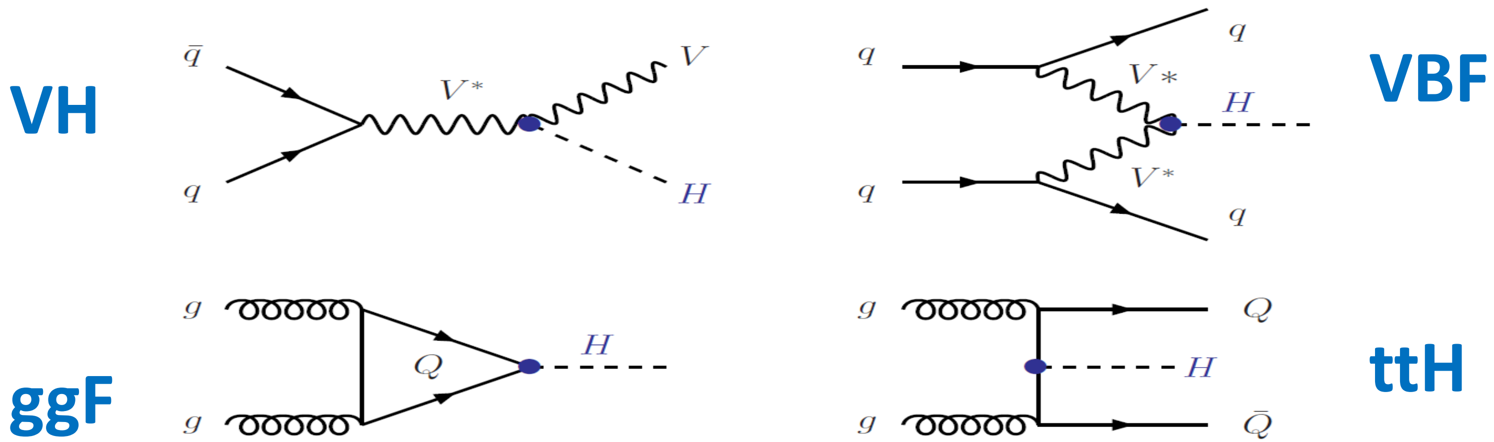
$$S^g_s = \sum_{f=b,t} c_f\, F_{sf}(\tau_f) + \Delta S^g_s \;\equiv\; c_g\, S^g_{\rm SM}\,,$$

$$S^{Z\gamma}_s = 2 \sum_{f=t,b,\tau} Q_f N_C^f m_f^2 \frac{I_3^f - 2\sin^2\theta_W Q_f^2}{\sin\theta_W \cos\theta_W} c_f\, F_f^{(0)} + M_Z^2 \cot\theta_W\, c_W\, F_W + \Delta S^{Z\gamma}_s \equiv c_{Z\gamma}\, S^{Z\gamma}_{\rm SM}.$$

Formalism: Signal strength

- Higgs production modes: gluon fusion (**ggF**), vector-boson fusion (**VBF**), associated production (**VH**) and (**ttH**).

A Djouadi, Phys.Rept.457 (2008)1-216



- Theoretical signal strength:

$$\widehat{\mu}(\mathcal{P},\mathcal{D}) \simeq \widehat{\mu}(\mathcal{P})\ \widehat{\mu}(\mathcal{D})$$

P: production channels, D: decay channels.

Formalism: Signal strength

- More explicitly, production:

$$\widehat{\mu}(\mathrm{ggF}) = (b_g c_\alpha - c_g s_\alpha)^2, \quad \widehat{\mu}(\mathrm{VBF}) = \widehat{\mu}(VH) = (b_V c_\alpha - c_V s_\alpha)^2,$$

$$\widehat{\mu}(\mathrm{VBF}) = \widehat{\mu}(VH) = (b_V c_\alpha - c_V s_\alpha)^2, \quad \widehat{\mu}(ttH) = (b_t c_\alpha - c_t s_\alpha)^2$$

decay: $$\widehat{\mu}(\mathcal{D}) = \frac{B(H \to \mathcal{D})}{B(H_{\mathrm{SM}} \to \mathcal{D})}$$

$$B(H \to \mathcal{D}) = \frac{\Gamma(H \to \mathcal{D})}{\Gamma_{\mathrm{tot}}(H) + \Delta\Gamma_{\mathrm{tot}}} = \frac{(b_i c_\alpha - c_i s_\alpha)^2 B(H_{\mathrm{SM}} \to \mathcal{D})}{\Gamma_{\mathrm{tot}}(H)/\Gamma_{\mathrm{SM}} + \Delta\Gamma_{\mathrm{tot}}/\Gamma_{\mathrm{SM}}}$$

$\Gamma_{\mathrm{tot}}(H_1)$: total decay width to SM particles

$\Delta\Gamma_{\mathrm{tot}}$: non-SM decay width

Formalism: Singlet scalar couplings and mixing

- Singlet "*s*" couplings from nonrenormalizable interactions. They are suppressed by heavy mass scale or loop factor.

$$c_i \sim \text{“0”} + \frac{g^2 m^2}{(4\pi)^2 M^2}\,, \quad \text{or} \quad \text{“0”} + \frac{g^2 m^2}{M^2}$$

- For SM Higgs "*h*", deviations from higher dim operators or new particles running in the loop:

$$b_i \sim \text{“1”} + \frac{g^2 m^2}{(4\pi)^2 M^2}\,, \quad \text{or} \quad \text{“1”} + \frac{g^2 m^2}{M^2}$$

Models: Dark matter model/Higgs portals

- We consider DM models where DM is stabilized by spontaneously broken local dark gauge symmetries.
- The dark Higgs Φ will mix with SM Higgs via the Higgs-portal interaction:

$$\lambda_{H\Phi}\left(H^\dagger H - \frac{v^2}{2}\right)\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)$$

- Non-standard Higgs decays into a pair of

1. dark Higgs bosons
2. dark gauge bosons
3. dark matter

parameterized by $\Delta\Gamma_{\text{tot}}$.

Models: Non-SUSY $U(1)_{B-L}$ extensions of the SM

- This model extent SM with 3RH neutrinos, which is anomaly free, no new colored or EW charged fermions.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - V(H,\Phi) - \left(\frac{1}{2}\lambda_{N,i}\Phi\bar{N}_i^c N_i + Y_{N,ij}\bar{\ell}H^{\dagger}N + \text{h.c.}\right)$$

$$V(H,\Phi) = -\mu_H^2 H^{\dagger}H - \mu_{\phi}^2\Phi^{\dagger}\Phi + \frac{\lambda_h}{2}|H|^4 - \lambda_{h\phi}|H|^2|\Phi|^2 + \frac{\lambda_{\phi}}{2}|\Phi|^4$$

- The Φ , B-L charge 2, breaks B-L symmetry, and resulting singlet scalar ϕ mix with SM Higgs.
- If the B-L gauge boson Z' is light enough, 125 GeV Higgs can decay into pair of Z'.
- Higgs phenomenology is analogy to the previous one.

Models: Vector-like fermions

- If the vector-like leptons are colorless $SU(2)_L$ singlets S_L^-, S_R^- with $Q_e = -1 = Y$, it CANNOT directly couple to SM Higgs doublet. Therefore one need a singlet scalar field S:

$$\mathcal{L} = \overline{S_L^-} i \not{D} S_L^- + \overline{S_R^-} i \not{D} S_R^- - \left\{ \overline{S_L^-} (m_S + \lambda S) S_R^- + y_{Si} \overline{l_{Li}} H S_R^- + H.c. \right\}$$

S. Choi, S. Jung and P. Ko, JHEP 10 (2013) 225.

- Vector-like charged scalar $S^{\pm}$ will generator $s \to \gamma\gamma$ and $s \to Z\gamma$ at one loop level.
- $H \to \gamma\gamma$ and $H \to Z\gamma$ be modified via the mixing of S^- and e_{Rj} after EWSB.

Models: Vector-like fermions

- If the vector-like leptons doublet

S. Choi, S. Jung and P. Ko, JHEP 10 (2013) 225.

Models: Vector-like fermions

- In these types of vector-like fermions models, the 125 GeV Higgs boson couplings are:

- Assuming $b_f = b_V = 1$ and $c_f = c_V = 0$

$\otimes$ $g^S_{H\bar{f}f} = (b_f \cos\alpha - c_f \sin\alpha) = \cos\alpha;$

$\otimes$ $g^S_{HVV} = (b_V \cos\alpha - c_V \sin\alpha) = \cos\alpha;$

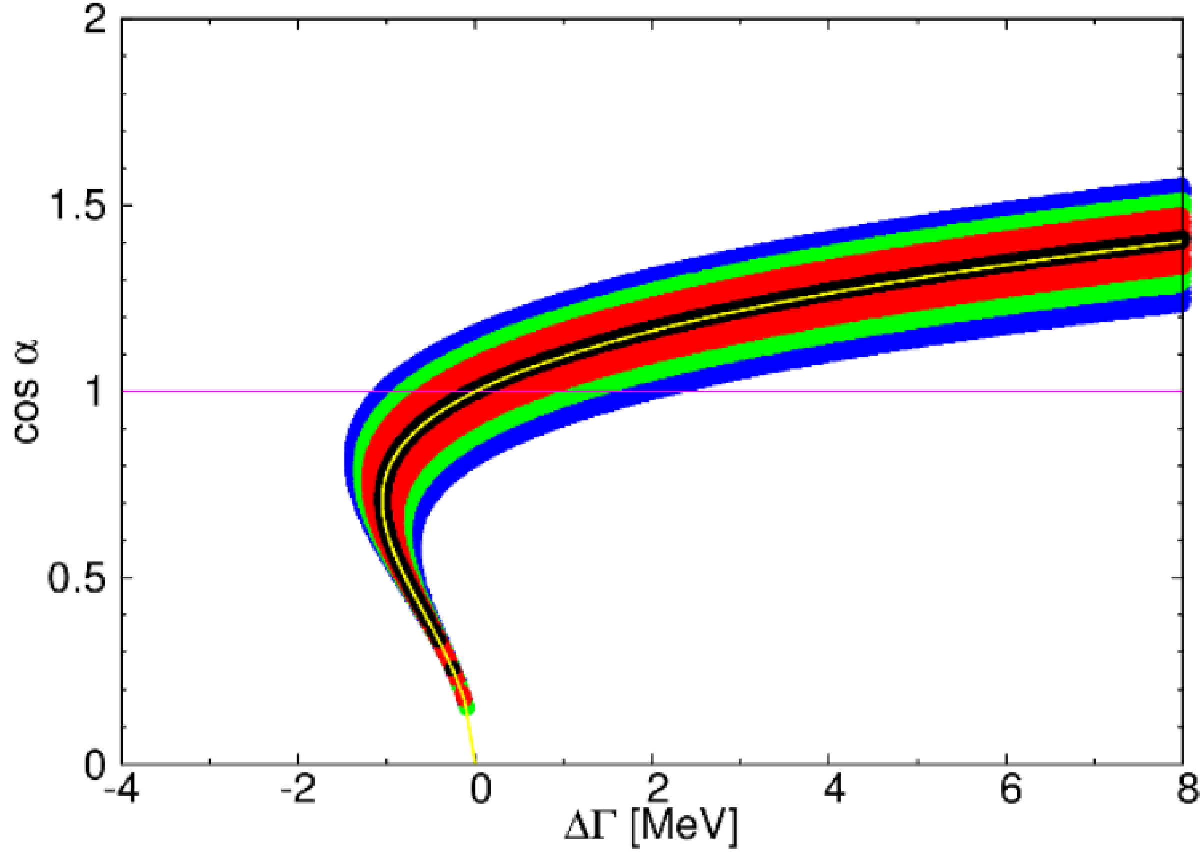
$\otimes$
$$\begin{aligned} g_H^{\gamma,g,Z\gamma} &= (S_h^{\gamma,g,Z\gamma} \cos\alpha - S_s^{\gamma,g,Z\gamma} \sin\alpha) \\ &= \cos\alpha S_{\rm SM}^{\gamma,g,Z\gamma} + (\Delta S_h^{\gamma,g,Z\gamma} \cos\alpha - \Delta S_s^{\gamma,g,Z\gamma} \sin\alpha) \\ &\equiv \cos\alpha S_{\rm SM}^{\gamma,g,Z\gamma} + \Delta S_H^{\gamma,g,Z\gamma}. \end{aligned}$$

- Varying parameters: $\cos\alpha$, $\Delta S^{\gamma}_{h,s}$, and/or $\Delta S^{g}_{h,s}$, and possibly $\Delta\Gamma_{\rm tot}$.

Results

Results: SD

- Plot of non-standard decay width vs mixing angle



red: 68% CL

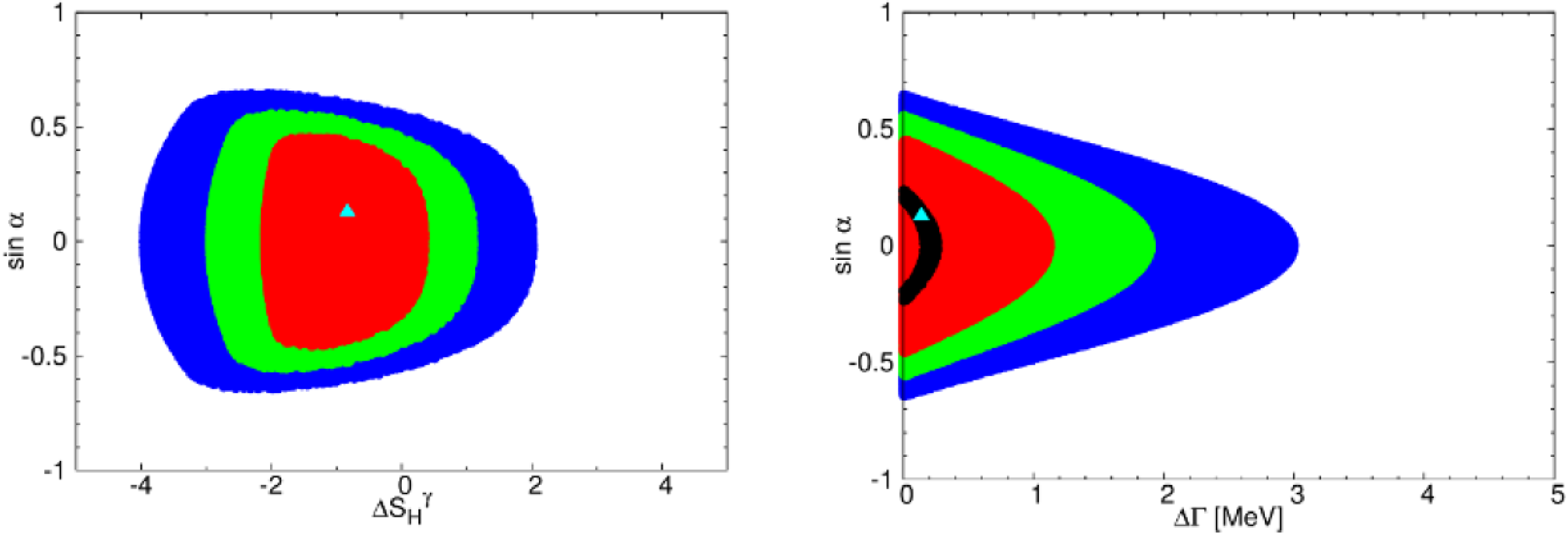
green: 95% CL

blue: 99.7% CL

yellow line: SM signal strength $\Rightarrow \mu(P,D) = \dfrac{\cos^4\alpha}{\cos^2\alpha + \Delta\Gamma_{tot}/\Gamma_{SM}} = 1$

Results: SL case

- SL case: varying parameters: s_α, $\Delta\Gamma_{\text{tot}}$, ΔS_h^γ, and ΔS_s^γ.
- Allowed region:



recall: $\Delta S_{H_1}^\gamma = \Delta S_h^\gamma \cos\alpha - \Delta S_s^\gamma \sin\alpha$

red: 68% CL

green: 95% CL

blue: 99.7% CL

Results: SL

- SL case: varying parameters: s_α, $\Delta\Gamma_{\text{tot}}$, ΔS_h^γ, and ΔS_s^γ.
- Allowed region:

$$\cos\alpha \gtrsim 0.83\,(0.76) \text{ at } 95\%\,(99.7\%) \text{ CL};$$

$$|\sin\alpha| \lesssim 0.56\,(0.65) \text{ at } 95\%\,(99.7\%) \text{ CL};$$

$$\Delta\Gamma_{\text{tot}} \lesssim 1.90\,(3.00)\,\text{MeV at } 95\%\,(99.7\%) \text{ CL};$$

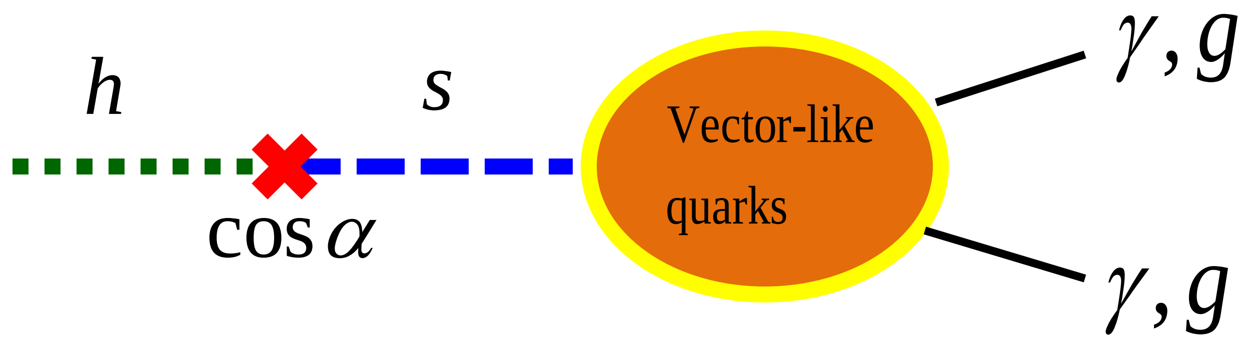
$$-2.95\,(-3.96) \lesssim \Delta S_H^\gamma \lesssim 1.10\,(2.02) \text{ at } 95\%\,(99.7\%) \text{ CL}.$$

recall: $\Delta S_{H_1}^\gamma = \Delta S_h^\gamma \cos\alpha - \Delta S_s^\gamma \sin\alpha$

Diphoton at 750 GeV

Diphoton at 750 GeV: SQ fit (VLQ)

- In these types of vector-like fermions (VLF) models, the 750 GeV Higgs boson, H2, couplings are:



$$H_1 = h\cos\alpha - s\sin\alpha \; ; \quad H_2 = h\sin\alpha + s\cos\alpha$$

$$\begin{aligned} H_1 &: \; b_i\cos\alpha - c_i\sin\alpha \\ H_2 &: \; b_i\sin\alpha + c_i\cos\alpha \qquad (i = f, W, Z, \gamma, g) \end{aligned}$$

- For H2, couplings to f,W,Z be suppress by $\sin\alpha$, but $c_{\gamma,g}$ can be enhanced by VLQ.

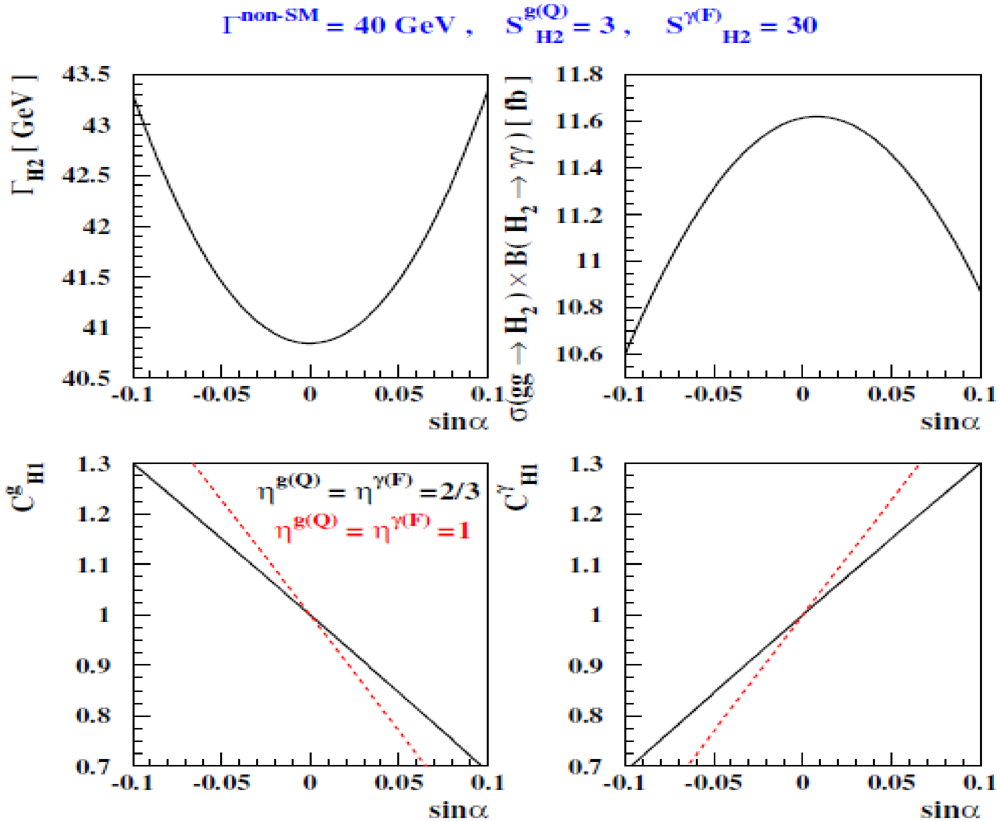
Diphoton at 750 GeV: SQ fit (VLQ)

- We find a benchmark point for

i). Production cross section of 750GeV diphoton ~ 10 fb.

ii). Width 45GeV for the resonance.

iii). Not significantly modify H1 couplings.



$S^{g(Q)}_{H_2} = 3, \quad S^{\gamma(F)}_{H_2} = 2N_C Q_F^2 \, S^{g(Q)}_{H_2}$

can be realized:

6 VLQ with $m_Q = 400$ GeV

and $g^S_{sQQ} = 1$.

K.Cheung, P. Ko, J.S. Lee, J. Park, PY Tseng, arXiv:1512.07853