Discussion on Diphoton and Flavor

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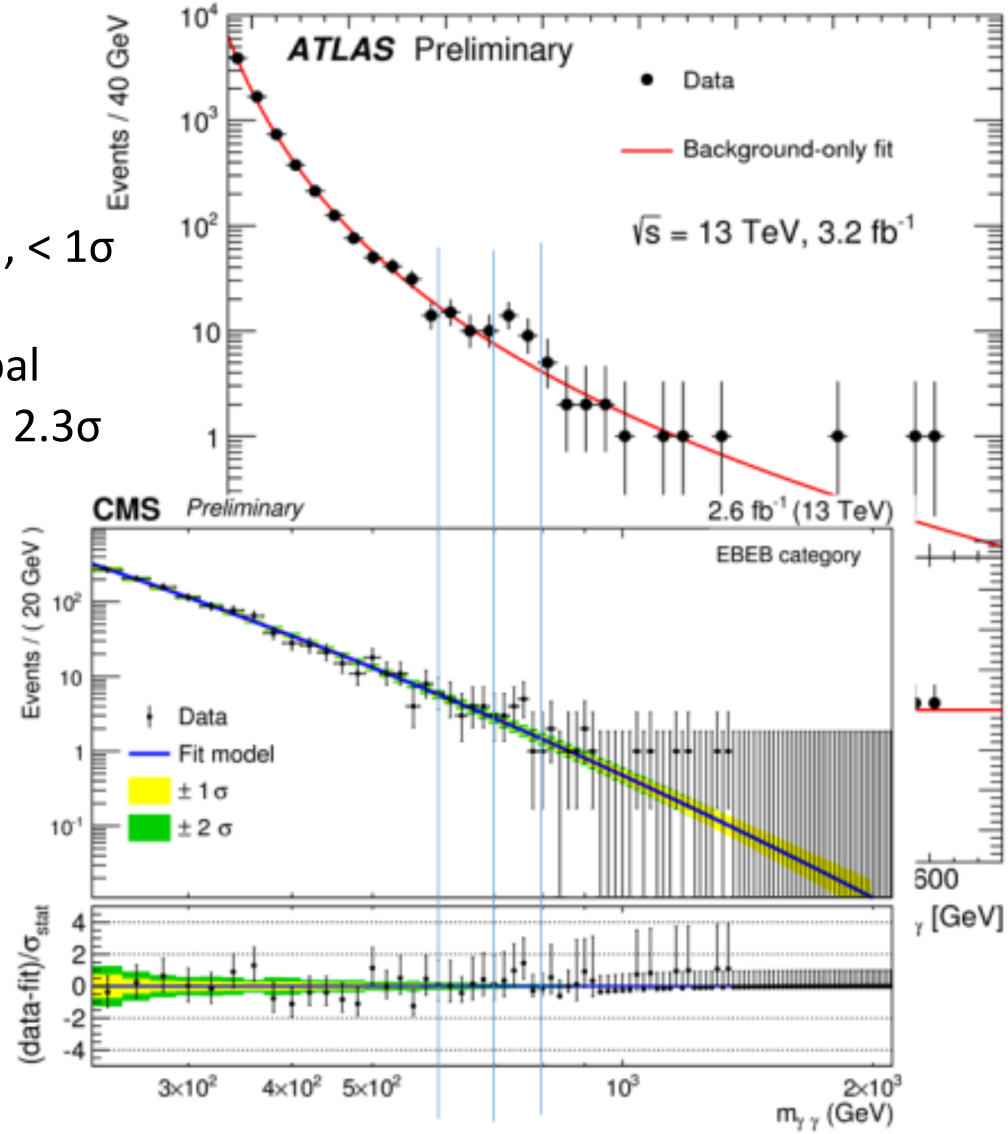
Higgs Tasting Workshop, Benasque
In collaboration with Jager, Kats,Perez and Stamou
(arxiv:1512.05332)

Diphoton excess

CMS 2015 data (improved, Mar.) 2.9σ local, < 1σ global
CMS 2015+2012 data: 3.4σ local, 1.6σ global
ATLAS 2015 Data (Dec and Mar) 3.9σ local, 2.3σ global

ATLAS Preferred width:45 GeV

Cross-Section: 6.9 fb



Questions

- Resonance or not ?
- Produced by quarks or gluons ?
- Spin 0 or Spin 2 ?
- Singlet or Doublet?
- Scalar or/and Pseudoscalar?

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This talk.

Lagrangian

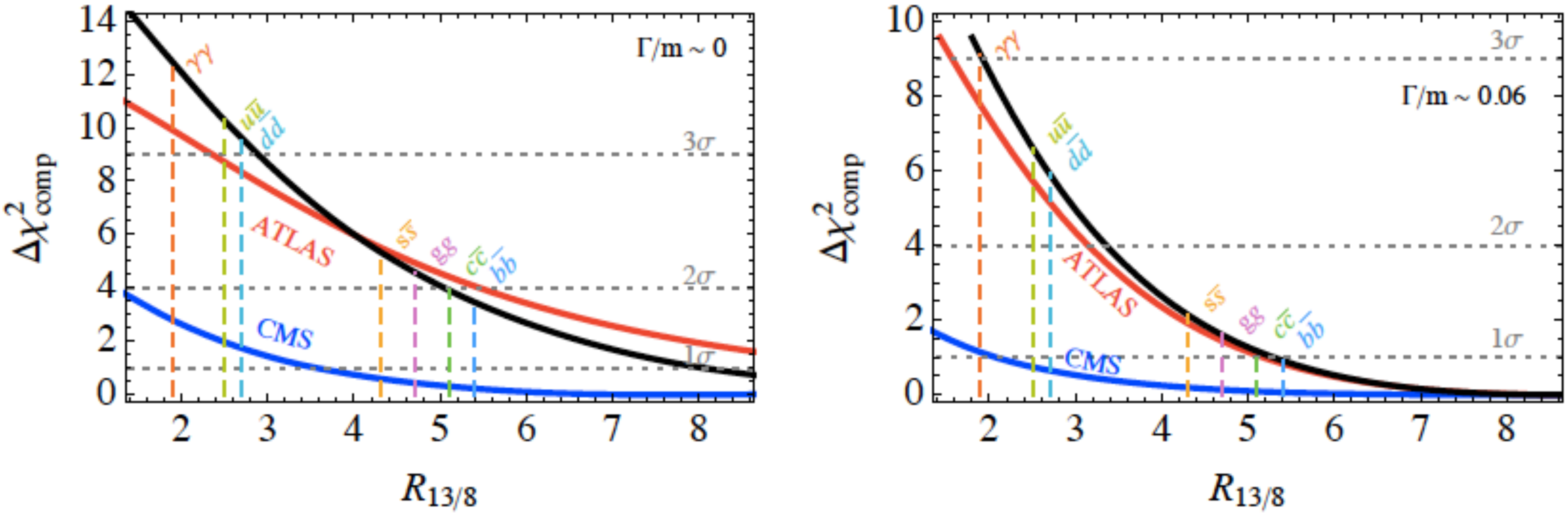
$$\mathcal{L} = -\frac{1}{16\pi^2}\frac{1}{4}\frac{c_\gamma}{M}\mathcal{S}F^{\mu\nu}F_{\mu\nu} - \frac{1}{16\pi^2}\frac{1}{4}\frac{c_g}{M}\mathcal{S}G^{\mu\nu,a}G^a_{\mu\nu}$$
$$- c_W m_W \mathcal{S}W^{+\mu}W^-_\mu - \frac{1}{2}c_Z m_Z \mathcal{S}Z^\mu Z_\mu - \sum_f c_f \mathcal{S}\bar{f}f$$

Singlet: $\frac{\mathcal{S}}{\Lambda}(\Phi_{SM}q)Yu^c + h.c.$ non-renormalizable

Doublet: $(\Phi_b q)Yu^c + h.c.$ renormalizable

(For pseudoscalars: $F^{\mu\nu}F_{\mu\nu} \to F^{\mu\nu}\tilde{F}_{\mu\nu}$, $G^{\mu\nu,a}G^a_{\mu\nu} \to G^{\mu\nu,a}\tilde{G}^a_{\mu\nu}$ $\mathcal{S}\bar{f}f \to i\mathcal{S}\bar{f}\gamma^5 f$
$c_W = c_Z = 0$)

Compatibility of 8 and 13 TeV by production mechanism.



Production by light quarks not compatible at <2 σ level.
Gluon or heavy quark production favoured.

Kamenik, Safdi, Soreq and Zupan (arxiv: 1603.06566)

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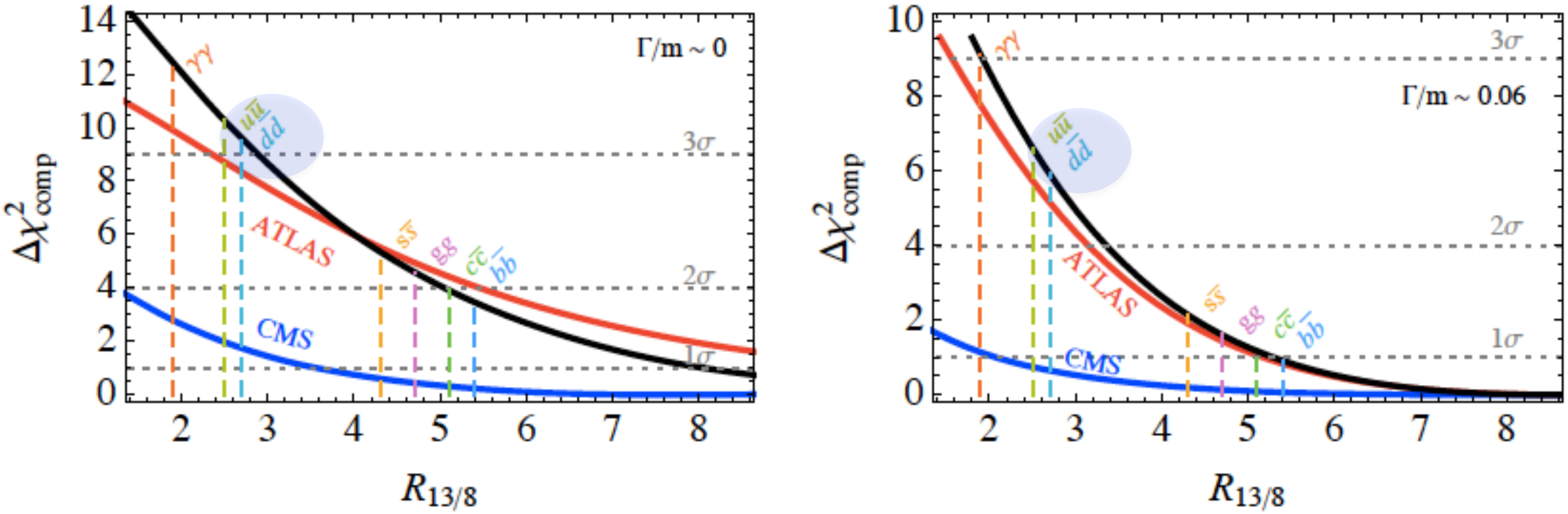

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Production by quarks

- To explain signal and large width preferred by ATLAS we need:

$$|c_\gamma c_p| = \{530,\ 2.9,\ 3.7,\ 12,\ 15,\ 22\} \times \sqrt{\left(\frac{N}{20}\right)\left(\frac{\Gamma}{45\ \text{GeV}}\right)\left(\frac{5.8\ \text{fb}^{-1}}{\mathcal{L}_{13}}\right)}$$

$$p = gg,\ u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b}$$

- 8 TeV dijet constraints: $|c_p| < \{97,\ 0.31,\ 0.35,\ 0.70,\ 0.79,\ 0.99\} \times \left(\frac{\Gamma}{45\,\text{GeV}}\right)^{1/4}$
- Width < 45 GeV implies: c_f <0.7
- This implies:

$$|c_\gamma| > \{5.5,\ 9.4,\ 11,\ 17,\ 19,\ 22\} \times \sqrt{\left(\frac{N}{20}\right)\left(\frac{5.8\ \text{fb}^{-1}}{\mathcal{L}_{13}}\right)}\left(\frac{\Gamma}{45\,\text{GeV}}\right)^{1/4}$$

Narrow width case

- For $\Gamma_{pp} \gg \Gamma_{\gamma\gamma}$ dependence of number of events on c_f:

$$N_{events} = \frac{\sigma_p^0 \Gamma_{\gamma\gamma}}{\Gamma_{pp} + \Gamma_{\gamma\gamma}} \approx \frac{\sigma_p^0 \Gamma_{\gamma\gamma}}{\Gamma_{pp}} \sim F(p)\frac{c_p^2 c_\gamma^2}{c_p^2} \sim F(p) c_\gamma^2.$$

$$c_\gamma = \{2.7,\ 4.1,\ 5.2,\ 17.0,\ 20.5,\ 30.5\}$$
$$p = gg,\ u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b}$$

- So we can satisfy dijet bound and in the case of doublets FCNC bound (to be discussed later) by making c_f small enough and still explain the observed no of events.
- But can c_f be arbitrarily small?

Lower bound on c_f

Must at least be large enough to give the minimal production cross section 6.9 fb:

$$|c_u| \gtrsim 0.005$$

$$|c_d| \gtrsim 0.007$$

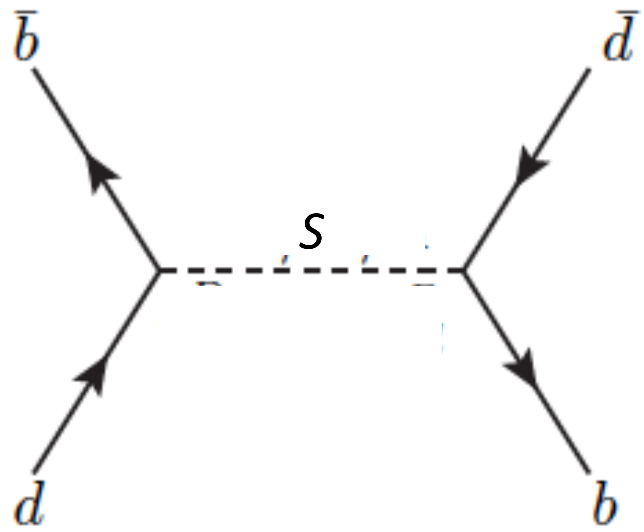
$$|c_s| \gtrsim 0.022$$

$$|c_c| \gtrsim 0.026$$

$$|c_b| \gtrsim 0.040$$

Flavor Bounds on off-diagonal couplings

- The off-diagonal couplings of *S* lead to tree level FCNC:



- These are strongly constrained by meson mixing.

Bounds on *cf*

Diagonal Couplings

$$0.31 > |c_u| \gtrsim 0.005$$
$$0.35 > |c_d| \gtrsim 0.007$$
$$0.7 > |c_s| \gtrsim 0.022$$
$$0.7 > |c_c| \gtrsim 0.026$$
$$0.7 > |c_b| \gtrsim 0.040$$

Width or dijet (upper bounds)

To obtain 6.9 fb production cross-section (lower bounds)

Off-diagonal Couplings

Δm_K	$\sqrt{\mathrm{Re}\, c_{sd} c^*_{ds}} < 10^{-4}$
ϵ_K	$\sqrt{\mathrm{Im}\, c_{sd} c^*_{ds}} < 10^{-6}$
Δm_D	$\sqrt{\mathrm{Re}\, c_{cu} c^*_{uc}} < 10^{-4}$
$\lvert q/p\rvert, \phi_D$	$\sqrt{\mathrm{Im}\, c_{cu} c^*_{uc}} < 10^{-4}$
Δm_{B_d}	$\sqrt{\mathrm{Re}\, c_{bd} c^*_{db}} < 10^{-3}$
$S_{\psi K_s}$	$\sqrt{\mathrm{Im}\, c_{bd} c^*_{db}} < 10^{-4}$
Δm_{B_s}	$\sqrt{\mathrm{Re}\, c_{bs} c^*_{sb}} < 10^{-3}$

Must find an alignment mechanism to suppress off-diagonal couplings !

Franchescini et al (1604.06446)
Goertz, Kamenik, Katz & Nardacchia (1512.08500)

S from a doublet

- *H,A* can give rise to diphoton resonance

$$\begin{aligned}\mathcal{L} &= (\Phi_b q) Y u^c + h.c. \\ &= H^+ d V^T Y u^c - \frac{H_0 + i A_0}{\sqrt{2}} u Y u^c + \text{h.c.},\end{aligned}$$

- Irreducible Flavor constraint: Cannot make couplings of all scalar components flavor diagonal simultaneously !

Aloni, Blum, Efrati, Drery and Nir (arxiv: 1512.05778)

S from a doublet

- Box diagrams can mediate:

$K^0 - \bar{K}^0$ mixing : $\frac{1}{32\pi^2}\left((V^\dagger Y Y^\dagger V)_{12}\right)^2 < 2\times 10^{-5}$

$D^0 - \bar{D}^0$ mixing : $\frac{1}{32\pi^2}\left((Y Y^\dagger)_{12}\right)^2 < 10^{-5}$

H⁺ *loop*

H loop

2 special cases

Couplings *H* : $Y = \mathrm{diag}(y,0,0)$ $Y_{ij} = y V_{i1}\delta_{j1}$

H⁺: $(V^\dagger Y)_{ij} = y V^*_{1j}\delta_{i1}$ $V^\dagger Y = \mathrm{diag}(y,0,0)$

$y < 0.5$

$c_f \lesssim 0.3$

- Problematic for large width case (constraint comparable to dijet constraint). Not an issue if resonance is actually narrow.

Aloni, Blum, Efrati, Drery and Nir (arxiv: 1512.05778)

Way out ?

- With the choice,

$$Y = \mathrm{diag}(y, y, 0) \text{ or } V^\dagger Y = \mathrm{diag}(y, y, 0)$$

however,

$$\left((YY^\dagger)_{12}\right)^2 \quad \text{and} \quad \left((V^\dagger YY^\dagger V)_{12}\right)^2$$

become diagonal and these bounds can be avoided.

- But in this case dijet bounds more stringent

Aloni, Blum, Efrati, Drery and Nir (arxiv: 1512.05778)

Doublet harder than singlet Example:

- With a single 700 GeV color triplet charge 5/3 vector-like fermion we can explain the excess and theory valid up to Planck scale.

- To explain the excess 6 flavours of color triplet fermions in Altmannsohfer et al.
- Large number of flavors can contribute heavily in RG and lead to low cut-off.

Altmannsohfer, Galloway, Gori, Martin and Zupan (arxiv: 1512.07616)
Bertuzzo et al,(1601. 07508)

Doublet harder than singlet Example:

- With a single 700 GeV color triplet charge 5/3 vector-like ... the excess and theory ...

$$
\begin{aligned}
\beta_{g'} &= \beta_{g'}^{2HDM} + \frac{4N_f}{3}\frac{g'^3}{16\pi^2}(9Q^2+6Q+3/2),\\
\beta_{g} &= \beta_{g}^{2HDM} + 2N_f\frac{g^3}{16\pi^2},\\
\beta_{g_3} &= \beta_{g_3}^{2HDM} + 2N_f\frac{g_3^3}{16\pi^2},\\
\beta_{y_t} &= \beta_{y_t}^{2HDM},\\
\beta_{\lambda_1} &= \beta_{\lambda_1}^{2HDM} - 3N_f\frac{|y_1^Q|^4+|y_1^D|^4}{4\pi^2},\\
\beta_{\lambda_2} &= \beta_{\lambda_1}^{2HDM} - 3N_f\frac{|y_2^Q|^4+|y_2^D|^4}{4\pi^2},\\
\beta_{\lambda_3} &= \beta_{\lambda_3}^{2HDM} - 3N_f\frac{|y_1^Q|^2|y_2^Q|^2+|y_1^D|^2|y_2^D|^2}{4\pi^2},\\
\beta_{\lambda_4} &= \beta_{\lambda_4}^{2HDM} - 3N_f\frac{|y_1^Q|^2|y_2^Q|^2+|y_1^D|^2|y_2^D|^2}{4\pi^2},\\
\beta_{\lambda_5} &= \beta_{\lambda_5}^{2HDM} - 3N_f\frac{(y_1^{Q*}y_2^Q)^2+(y_1^D y_2^{D*})^2}{4\pi^2},\\
\beta_{\lambda_6} &= \beta_{\lambda_6}^{2HDM} - 3N_f\frac{y_1^{Q*}y_2^Q|y_1^Q|^2+y_1^D y_2^{D*}|y_1^D|^2}{4\pi^2},\\
\beta_{\lambda_7} &= \beta_{\lambda_7}^{2HDM} - 3N_f\frac{y_1^{Q*}y_2^Q|y_2^Q|^2+y_1^D y_2^{D*}|y_2^D|^2}{4\pi^2}.
\end{aligned}
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- To explain ... olor triplet fermions i...
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\beta_{\lambda_2} &= \beta_{\lambda_1}^{2HDM} - 3N_f\frac{|y_2^Q|^4+|y_2^D|^4}{4\pi^2},\\
\beta_{\lambda_3} &= \beta_{\lambda_3}^{2HDM} - 3N_f\frac{|y_1^Q|^2|y_2^Q|^2+|y_1^D|^2|y_2^D|^2}{4\pi^2},\\
\beta_{\lambda_4} &= \beta_{\lambda_4}^{2HDM} - 3N_f\frac{|y_1^Q|^2|y_2^Q|^2+|y_1^D|^2|y_2^D|^2}{4\pi^2},\\
\beta_{\lambda_5} &= \beta_{\lambda_5}^{2HDM} - 3N_f\frac{(y_1^{Q*}y_2^Q)^2+(y_1^D y_2^{D*})^2}{4\pi^2},\\
\beta_{\lambda_6} &= \beta_{\lambda_6}^{2HDM} - 3N_f\frac{y_1^{Q*}y_2^Q|y_1^Q|^2+y_1^D y_2^{D*}|y_1^D|^2}{4\pi^2},\\
\beta_{\lambda_7} &= \beta_{\lambda_7}^{2HDM} - 3N_f\frac{y_1^{Q*}y_2^Q|y_2^Q|^2+y_1^D y_2^{D*}|y_2^D|^2}{4\pi^2}.
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Singlet: production by quarks

$$\mathcal{L} \supset -\frac{16\pi^2 \mathcal{S}}{\sqrt{N_c}\Lambda}\left(Y^d_{ij} H \overline{Q_i} d_j + Y^u_{ij} \tilde{H} \overline{Q_i} u_j + h.c.\right)$$

- As the doublet case also has a small cut-off generically, having non-renormalizable couplings not so bad.

Singlet: production by quarks

- Cut off required ?

For large width case we might want to saturate the dijet bound, i.e.,

$$c_f \sim 0.7 \Rightarrow \Lambda \sim 23\text{TeV}$$

For narrow width case we only require that be large enough to give at least 5.9 fb production cross-section:

$$|c_u| \gtrsim 0.005 \;\; \Rightarrow \;\; \Lambda \lesssim 3200 \text{ TeV}$$
$$|c_d| \gtrsim 0.007 \;\; \Rightarrow \;\; \Lambda \lesssim 2300 \text{ TeV}$$
$$|c_s| \gtrsim 0.022 \;\; \Rightarrow \;\; \Lambda \lesssim 720 \text{ TeV},$$
$$|c_c| \gtrsim 0.026 \;\; \Rightarrow \;\; \Lambda \lesssim 610 \text{ TeV},$$
$$|c_b| \gtrsim 0.040 \;\; \Rightarrow \;\; \Lambda \lesssim 400 \text{ TeV}$$

Flavor in singlet case

- Tree level FCNC bound as mentioned before, requires we find a mechanism for alignment,
- Irreducible flavour bound as in doublet case ? Same spurions still exist. $\left((YY^\dagger)_{12}\right)^2$ $\left((V^\dagger YY^\dagger V)_{12}\right)^2$
- But these contributions arise at 3-loop order as each H^+ line is now replaced by a S and G^+ line.

Conclusions

* Diagonal couplings of *S* to fermions:

(1) Upper bound from dijet constraints and requirement of width.

(2) Lower bound from requiring cross-section is at least 6.9 fb.

(3) Upper bound from irreducible Flavour constraint. More stringent for doublet case.

* Off-diagonal couplings: Strongly constrained by Meson mixing

* Singlet case requires dimension-5 operator but cut-off low in doublet case also.

S from a doublet

- Higgs basis:

$$\Phi_a = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + \varphi_a^0 + iG^0\right) \end{pmatrix}, \qquad \Phi_b = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(\varphi_b^0 + iA\right) \end{pmatrix}$$

$$H = \varphi_a^0 \cos(\beta - \alpha) - \varphi_b^0 \sin(\beta - \alpha)$$

$$h = \varphi_a^0 \sin(\beta - \alpha) + \varphi_b^0 \cos(\beta - \alpha)$$

- Why alpha-be
- EWPT require
- Must suppress H->WW/ZZ decays.

- In the limit we have the SM doublet and an inert Higgs doublet.