

# Common origin of flavour anomalies and neutrino masses

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# Motivation

## 1. Anomalies in B meson decays:

$$R_D = \frac{\text{Br}(B \rightarrow D\tau\nu)}{\text{Br}(B \rightarrow Dl\nu)}$$

$$R_K = \frac{\text{Br}(B \rightarrow K\mu\mu)}{\text{Br}(B \rightarrow Kee)}$$

$$R_D^{\text{SM}} = 0.300 \pm 0.010$$

$$R_D^{\text{exp}} = 0.388 \pm 0.047$$

$$R_K^{\text{SM}} = 1.0003 \pm 0.0001$$

$$R_K^{\text{LHCb}} = 0.745 \pm_{0.074}^{0.090} \pm 0.036$$

$$R_{D^*}^{\text{SM}} = 0.252 \pm 0.005$$

$$R_{D^*}^{\text{exp}} = 0.321 \pm 0.021$$

[LHCb, Phys. Rev. Lett. 113, 151601 (2014)]  
[BaBar, Phys. Rev. D 88, no. 7, 072012 (2013)]  
[Belle, Phys. Rev. D 92, no. 7, 072014 (2015)]  
[LHCb, Phys. Rev. Lett. 115, no. 11, 111803 (2015)]

$\sim 3.9\sigma$

$\sim 2.6\sigma$

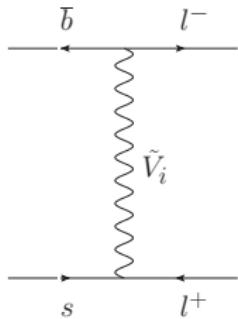
## 2. Unknown origin of neutrino masses

## 3. 750 GeV Diphoton Excess?

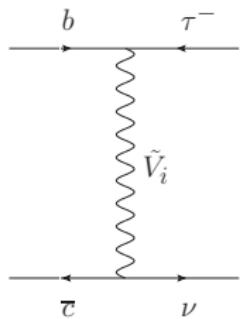
# Leptoquark mediators

**Common solution: Leptoquarks!**

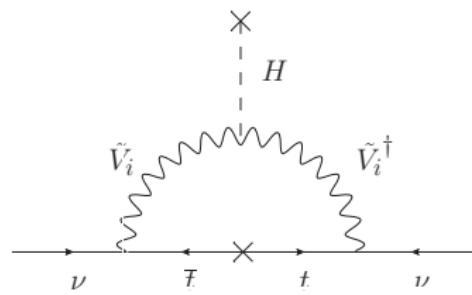
$$R_K : b \rightarrow s l l$$



$$R_D : b \rightarrow c l \nu$$



$$M_\nu :$$



[Freytsis, Ligeti, Ruderman, Phys. Rev. D 92, no. 5 (2015)]

[Fajfer, Kosnik, Phys. Lett. B 755, 270 (2016)]

[Barbieri, Isidori, Pattori, Senia, Eur. Phys. J. C 76 (2016)]

[Calibbi, Crivellin, Ota, Phys. Rev. Lett. 115 (2015)]

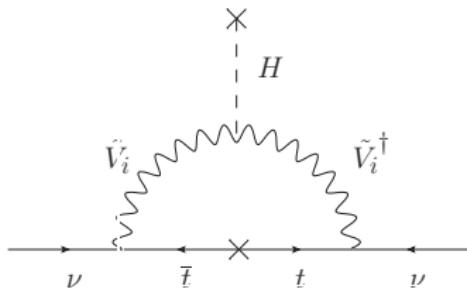
[Hiller, Schmaltz, Phys. Rev. D 90, 054014 (2014)]

[...]

$$\mathcal{L}_{\text{LQ}} = \lambda^L \bar{Q} \gamma^\mu L V_{0,\mu} + \lambda^R \bar{u} \gamma^\mu L V_{1/2,\mu}^\dagger$$

Leptoquark	$V_0$	$V_{1/2}$
$(SU(3), SU(2))$	$(3, 1)$	$(3, 2)$
$Q_{\text{EM}}$	$\frac{2}{3}$	$(\frac{2}{3}, -\frac{1}{3})$
$L$	$-1$	$1$

# Neutrino masses



Leptoquark	$V_0$	$V_{1/2}$
$(SU(3), SU(2))$	$(3, 1)$	$(3, 2)$
$Q_{\text{EM}}$	$\frac{2}{3}$	$(\frac{2}{3}, -\frac{1}{3})$
$L$	$-1$	$1$

$$\mathcal{L}_{\text{LQ}} = \lambda^L \bar{u} \gamma^\mu \nu V_{0,\mu} + \lambda^R \bar{u}^c \gamma^\mu \nu V_{1/2,\mu}^\dagger, \quad V_{\text{LQ}} = h_V H i \tau_2 V_{1/2}^\mu V_{0\mu}^\dagger,$$

$\Delta L = 2 \Rightarrow \text{Majorana Mass!}$

$$M_{ii'}^\nu = \frac{3}{16\pi^2} \sum_{j=1,2} \sum_{q=u,c,t} m_q B_0(0, m_q^2, m_{V_j}^2) \sin 2\alpha \left[ \lambda_{qi}^R \lambda_{qi'}^L + \lambda_{qi'}^R \lambda_{qi}^L \right]$$

$$B_0(0, m_q^2, m_{V_j}^2) = \frac{m_q^2 \log(m_q^2) - m_{V_j}^2 \log(m_{V_j}^2)}{m_q^2 - m_{V_j}^2}$$

[Aristizabal Sierra, Hirsch, Kovalenko, Phys. Rev. D 77, 055011 (2008)]

# Neutrino masses

Heaviest neutrino mass:

$$m_{2(3)}^\nu \propto m_q \sin 2\alpha \left( \sum_i \lambda_{qi}^L \lambda_{qi}^R \right) \sqrt{\sum_i \left( \lambda_{qi}^L \right)^2 \sum_i \left( \lambda_{qi}^R \right)^2}, \quad \alpha \approx \frac{h_V v_{SM}}{m_{V_{1/2}}^2 - m_{V_0}^2}$$

Options to generate light neutrino masses:

- ① Leptoquarks couple only to light quarks  $\Rightarrow m_q$  small
- ② Tiny leptoquark mixing: Large  $\Delta m_V^2$  or small  $h_V$  coupling
- ③ Suppress leptoquark couplings  $\Rightarrow \lambda_{qi}^{R,L}$  small

Here: Combination of 2 and 3

# Flavour Constraints

## Modeling the leptoquark couplings ( $\epsilon \approx 0.2$ )

- $R_D : \lambda_{b\tau}^L \lambda_{c\nu_\tau}^{L*} - \lambda_{b\mu}^L \lambda_{c\nu_\mu}^{L*} \simeq (0.18 \pm 0.04) \frac{m_{V_0}^2}{\text{TeV}^2} \simeq \epsilon \frac{m_{V_0}^2}{\text{TeV}^2}$

[Freytsis, Ligeti, Ruderman, Phys. Rev. D 92, no. 5, 054018 (2015)]

- $R_K : \lambda_{se}^{L*} \lambda_{be}^L - \lambda_{s\mu}^{L*} \lambda_{b\mu}^L \simeq (1.8 \pm 0.7) \cdot 10^{-3} \frac{m_{V_0}^2}{\text{TeV}^2} \simeq \epsilon^4 \frac{m_{V_0}^2}{\text{TeV}^2}$

[Hiller, Schmaltz, Phys. Rev. D 90, 054014 (2014)]

- Kaon decays:  $|\lambda_{d\mu}^L \lambda_{s\mu}^{L*}| \lesssim \frac{m_{V_0}^2}{(183 \text{ TeV})^2} \simeq \epsilon^7 \frac{m_{V_0}^2}{\text{TeV}^2}$

[Davidson, Bailey, Campbell, Z. Phys. C 61, 613 (1994)]

- $\mu \rightarrow e\gamma : |\lambda_{qe}^L \lambda_{q\mu}^L| \lesssim \frac{m_{V_0}^2}{(34 \text{ TeV})^2} \simeq \epsilon^4 \frac{m_{V_0}^2}{\text{TeV}^2}$

[MEG Collaboration, Phys. Rev. Lett. 110, 201801 (2013)]

⇒ Flavour data requires hierarchical leptoquark patterns with large third and tiny first generation couplings.

$$\lambda^L \simeq \begin{pmatrix} \epsilon^6 & \epsilon^4 & \epsilon^3 \\ \epsilon^4 & \epsilon^3 & \epsilon \\ \epsilon^3 & \epsilon & 1 \end{pmatrix}$$

and  $m_{V_0} \simeq 1 \text{ TeV}$

# Flavour model

- Hierarchical patterns can be modeled well with a Froggatt-Nielsen mechanism
  - ⇒ All fields charged under additional  $U(1)$  symmetry
  - ⇒ Couplings suppressed by flavon insertions
- Other criteria: Realistic fermion masses, CKM mixing,...

Field	$\overline{Q}_1$	$\overline{Q}_2$	$\overline{Q}_3$	$d$	$s$	$b$	$u$	$c$	$t$
$Q(U(1)_{\text{FN}})$	3	2	0	4	3	3	5	2	0

Field	$L_1$	$L_2$	$L_3$	$V_0$	$H$
$Q(U(1)_{\text{FN}})$	$q_\tau + 3$	$q_\tau + 1$	$q_\tau$	$-q_\tau$	0
Field	$e$	$\mu$	$\tau$	$V_{1/2}^\dagger$	$\eta$
$Q(U(1)_{\text{FN}})$	$q_\tau - 6$	$q_\tau - 4$	$q_\tau - 3$	$q_\tau$	-1

$$\begin{aligned} \mathcal{L}_{\text{LQ}} &= \lambda^L \overline{Q} \gamma^\mu L V_{0,\mu} + \lambda^R \overline{u} \gamma^\mu L V_{1/2,\mu}^\dagger, & V_{\text{LQ}} &= h_V H i \tau_2 V_{1/2}^\mu V_{0\mu}^\dagger \\ &\rightarrow \lambda^L \overline{Q} \gamma^\mu L V_{0,\mu} \underbrace{\left(\frac{\langle \eta \rangle}{\Lambda}\right)^{|-q_Q+q_L+q_V|}}_{\epsilon} & & + \lambda^R \overline{u} \gamma^\mu L V_{1/2,\mu}^\dagger \underbrace{\left(\frac{\langle \eta \rangle}{\Lambda}\right)^{|q_u+q_L-q_V|}}_{\epsilon} \end{aligned}$$

# Flavour model

Resulting leptoquark patterns:

$$\lambda_{V_{1/2}}^R \simeq \begin{pmatrix} \epsilon^{|8+2q_\tau|} & \epsilon^{|6+2q_\tau|} & \epsilon^{|5+2q_\tau|} \\ \epsilon^{|5+2q_\tau|} & \epsilon^{|3+2q_\tau|} & \epsilon^{|2+2q_\tau|} \\ \epsilon^{|3+2q_\tau|} & \epsilon^{|1+2q_\tau|} & \epsilon^{|2q_\tau|} \end{pmatrix},$$

e.g., for  $q_\tau = 5$ :

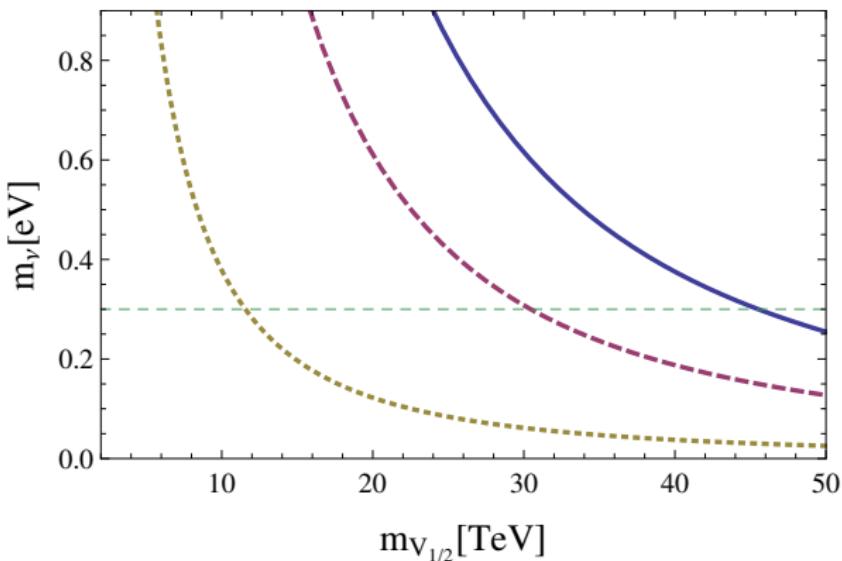
$$\underbrace{\lambda_{V_0}^L \simeq \begin{pmatrix} \epsilon^6 & \epsilon^4 & \epsilon^3 \\ \epsilon^5 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon & 1 \end{pmatrix}}_{\text{Explains } R_D \text{ and } R_K \text{ (with } m_{V_0} \sim 1 \text{ TeV)}} \quad , \quad \underbrace{\lambda_{V_{1/2}}^R \simeq \begin{pmatrix} \epsilon^{18} & \epsilon^{16} & \epsilon^{15} \\ \epsilon^{15} & \epsilon^{13} & \epsilon^{12} \\ \epsilon^{13} & \epsilon^{11} & \epsilon^{10} \end{pmatrix}}_{\text{irrelevant for B decays}}$$

$\Rightarrow$  Neutrino masses  $m^\nu \sim \lambda_{qi}^L \lambda_{qi}^R$  suppressed by small  $\lambda^R$  couplings.

# Back to neutrino masses

$$m^\nu \sim a \cdot \epsilon^{10}, \quad \text{with} \quad a \approx \frac{3}{16\pi^2} m_t \frac{h_V v_{\text{SM}}}{\Delta m_V^2} \log \left[ \frac{m_{V_{1/2}}^2}{m_{V_0}^2} \right]$$

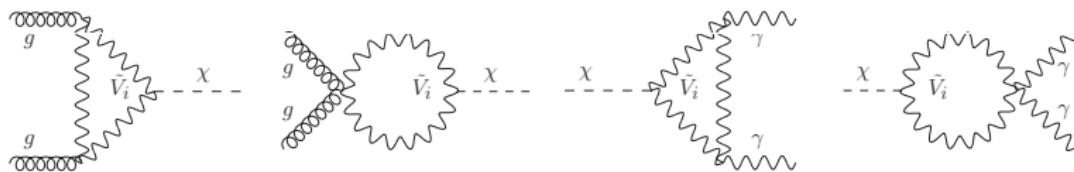
$m^\nu$  for  $m_{V_0} = 1 \text{ TeV}$  and  $h_V = 1, 0.5, 0.2 \text{ TeV}$ :



# Diphoton Excess

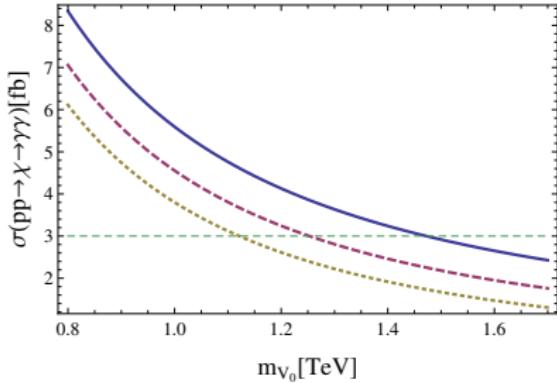
Vector leptoquarks can also explain the diphoton excess!

$$\mathcal{L}_{V\chi} = \kappa v_i \chi V_{\mu,i}^\dagger V_i^\mu + \text{h.c.},$$

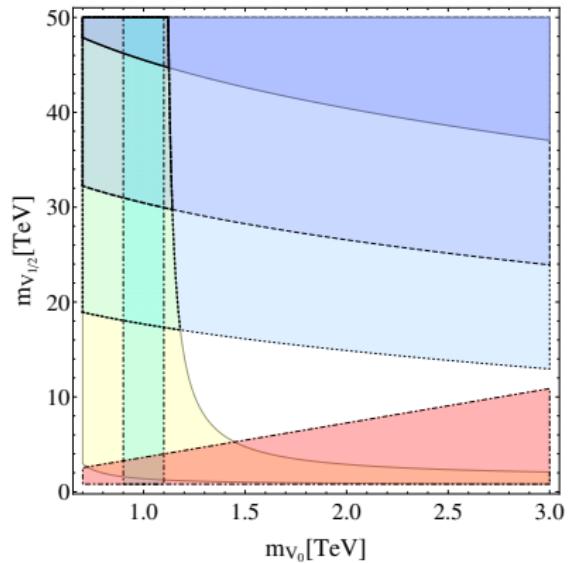


- Vector loop function  $|A_1| \gg |A_{1/2}| \gg |A_0|$  can nicely explain large diphoton cross section without many additional particles...
- ... however only narrow width.
- Gluon fusion dominant because of small  $\lambda_{qI}$  couplings

# Diphoton Excess



Observation: Data best explained by  $m_{V_0} \approx 1$  TeV and  $m_{V_{1/2}} \gtrsim 5$  TeV if  $\kappa_{V_i} \approx m_{V_i}$



Model:

$$\sigma_{\gamma\gamma} \propto |4\kappa_{V_0}/m_{V_0}^2 + 5\kappa_{V_{1/2}}/m_{V_{1/2}}^2|^2$$

Signal region:

$$\sigma_{\text{ATLAS}} = (10 \pm 3) \text{ fb}$$

$$\sigma_{\text{CMS}} = (6 \pm 3) \text{ fb}$$

# Summary

- Two leptoquarks with a  $\Delta L = 2$  leptoquark-Higgs coupling generate neutrino masses on one-loop level
- One of these leptoquarks can also explain deviations in B meson flavour data if  $M_V \sim 1 \text{ TeV}$
- Suitable coupling matrices can be modeled with a Froggatt-Nielsen symmetry
- Vector leptoquarks could additionally explain the 750 GeV diphoton excess
- All constraints combined point to a combination of one light ( $\sim 1 \text{ TeV}$ ) and one heavy leptoquark ( $\sim 30 \text{ TeV}$ )

Thank you!

**Backup**

$R_K$

HQEFT:  $\mathcal{H}_{\text{eff}} = -4 \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i \mathcal{O}_i$

Operators:  $\mathcal{O}_9^I = [\bar{s}\gamma^\mu P_L b] [I\gamma_\mu I], \quad \mathcal{O}_{10}^I = [\bar{s}\gamma^\mu P_L b] [I\gamma_\mu\gamma_5 I]$

Wilson-Coefficients:  $C_9^I = -C_{10}^I = \frac{\pi}{\alpha_e} \frac{\lambda_{se}^{L*} \lambda_{be}^L}{V_{tb} V_{ts}^*} \frac{\sqrt{2}}{2m_{V_0}^2 G_F}$

$R_K$  data implies  $0.7 \lesssim \text{Re}[X^e - X^\mu] \lesssim 1.5$  with  $X^I = 2C_9^I$

$$X^e - X^\mu = \frac{\pi}{\sqrt{2}\alpha_e G_F V_{tb} V_{ts}^* m_{V_0}^2} (\lambda_{se}^{L*} \lambda_{be}^L - \lambda_{s\mu}^{L*} \lambda_{b\mu}^L)$$

$$\Rightarrow \lambda_{se}^{L*} \lambda_{be}^L - \lambda_{s\mu}^{L*} \lambda_{b\mu}^L \simeq (1.8 \pm 0.7) \cdot 10^{-3} \frac{m_{V_0}^2}{\text{TeV}^2}$$

**tu**

$R_D$

Operator:  $\mathcal{O}_V = [\bar{c}\gamma^\mu P_L b] [l\gamma_\mu \nu_l]$

Wilson-Coefficient:  $C_{L,l\nu}^{cb} = \frac{1}{2\sqrt{2}G_F V_{cb} m_{V_0}^2} \lambda_{bI}^L \lambda_{c\nu}^{L*}$

⇒ Explaining  $R_D$  requires large leptoquark couplings to third generation fermions:

$$\lambda_{b\tau}^L \lambda_{c\nu_\tau}^{L*} - \lambda_{b\mu}^L \lambda_{c\nu_\mu}^{L*} \simeq (0.18 \pm 0.04) \frac{m_{V_0}^2}{\text{TeV}^2}$$

# Flavour model masses and mixings

The mass matrices have a hierarchical structure, therefore, also the corresponding mixing is hierarchical:

$$\begin{aligned} M_u &\simeq \begin{pmatrix} \epsilon^8 & \epsilon^5 & \epsilon^3 \\ \epsilon^7 & \epsilon^4 & \epsilon^2 \\ \epsilon^5 & \epsilon^2 & 1 \end{pmatrix}, & M_d &\simeq \begin{pmatrix} \epsilon^7 & \epsilon^6 & \epsilon^6 \\ \epsilon^6 & \epsilon^5 & \epsilon^5 \\ \epsilon^4 & \epsilon^3 & \epsilon^3 \end{pmatrix}, \\ M_I &\simeq \begin{pmatrix} \epsilon^9 & \epsilon^7 & \epsilon^6 \\ \epsilon^7 & \epsilon^5 & \epsilon^4 \\ \epsilon^6 & \epsilon^4 & \epsilon^3 \end{pmatrix}. & & \\ V_{u,d}^L &\simeq \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}, & V_I^{L,R} &\simeq \begin{pmatrix} 1 & \epsilon^2 & \epsilon^3 \\ \epsilon^2 & 1 & \epsilon \\ \epsilon^3 & \epsilon & 1 \end{pmatrix}, \\ V_u^R &\simeq \begin{pmatrix} 1 & \epsilon^3 & \epsilon^5 \\ \epsilon^3 & 1 & \epsilon^2 \\ \epsilon^5 & \epsilon^2 & 1 \end{pmatrix}, & V_d^R &\simeq \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}. \end{aligned}$$

Because of the hierarchical mixing, the leptoquark patterns involving down-type quarks and charged leptons do not change under transformation into mass bases.

# Matrices in mass bases

$$\begin{aligned}\tilde{\lambda}_{dl}^L &= V_d^L \lambda_{V_0}^L V_I^{L\dagger}, & \tilde{\lambda}_{u\nu}^L &= V_u^L \lambda_{V_0}^L V_\nu^{L\dagger}, \\ \tilde{\lambda}_{ul}^R &= V_u^R \lambda_{V_{1/2}}^R V_I^{L\dagger}, & \tilde{\lambda}_{u\nu}^R &= V_u^R \lambda_{V_{1/2}}^R V_\nu^{L\dagger}.\end{aligned}$$

Since charged lepton mixing is small, neutrino mixing has to be large to account for the large PMNS mixing angles:

$$V_\nu^{L\dagger} \sim \begin{pmatrix} 1 & 1 & \epsilon \\ 1 & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \quad \text{The rotation by } V_\nu \text{ affects the leptoquark pattern } \lambda_{u\nu}, \text{ increasing the first generation couplings.}$$

$$\tilde{\lambda}_{u\nu}^L \simeq \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon & 1 & 1 \end{pmatrix}, \quad \tilde{\lambda}_{dl}^L \simeq \begin{pmatrix} \epsilon^6 & \epsilon^4 & \epsilon^3 \\ \epsilon^5 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon & 1 \end{pmatrix}$$

$\Rightarrow$

# Leptoquark mixing

Leptoquark potential and mass matrices:

$$V(V_i, H) = h_V H i \tau_2 V_{1/2}^\mu V_{0\mu}^\dagger - (m_{V_i}^2 - g_{V_i} H^\dagger H) V_{i,\mu}^\dagger V_i^\mu.$$

$$M_{2/3}^2 = \begin{pmatrix} m_{V_0}^2 - g_{V_0} v_{\text{SM}}^2 & h_V v_{\text{SM}} \\ h_V v_{\text{SM}} & m_{V_{1/2}}^2 - g_{V_{1/2}} v_{\text{SM}}^2 \end{pmatrix},$$

$$M_{-1/3}^2 = m_{V_{1/2}}^2 - g_{V_{1/2}} v_{\text{SM}}^2.$$

Mixing depends on  $h_V$  and leptoquark masses

$$\begin{pmatrix} \tilde{V}_0 \\ \tilde{V}_{1/2} \end{pmatrix} = R \begin{pmatrix} V_0 \\ V_{1/2} \end{pmatrix}, \quad R = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix}$$

$$\text{with } \tan 2\alpha = \frac{2h_V v_{\text{SM}}}{m_{V_{1/2}}^2 - m_{V_0}^2} = \frac{2h_V v_{\text{SM}}}{\Delta m_V^2},$$

Coupling  $h_V$  is bounded from above by perturbativity of the theory

$$h_V \leq m'_{V_0} m'_{V_{1/2}} / v_{\text{SM}} \quad \text{with} \quad m'_{V_i} \equiv \sqrt{m_{V_i}^2 - g_{V_i} v_{\text{SM}}^2}.$$

# Diphoton excess

Total cross section:

$$\sigma(pp \rightarrow \chi \rightarrow \gamma\gamma) = \frac{\pi^2}{8s} \frac{\Gamma(\chi \rightarrow \gamma\gamma)}{\Gamma_{\text{tot}}} \frac{\Gamma(\chi \rightarrow gg)}{m_\chi} f_{gg}(m_\chi^2/s)$$
$$\Gamma_{gg} = \frac{\alpha_s^2 m_\chi^3 K^{gg}}{128\pi^3} \left| \sum_i \frac{\kappa_{V_i} A_1(\tau_{V_i})}{m_{V_i}^2} \right|^2, \quad \Gamma_{\gamma\gamma} = \frac{\alpha_e^2 m_\chi^3}{256\pi^3} \left| \sum_i \frac{\kappa_{V_i} N_c Q_{V_i}^2 A_1(\tau_{V_i})}{m_{V_i}^2} \right|^2.$$

Loop functions for Spin 0, 1/2 and 1:

$$A_1(\tau) = \frac{1}{\tau^2} [2\tau^2 + 3\tau + 3(2\tau - 1) \arcsin^2 \sqrt{\tau}] , \quad \tau_{V_i} = m_\chi^2 / (4m_{V_i}^2) < 1$$

$$A_0(\tau) = -\frac{1}{\tau^2} [\tau - \arcsin^2 \sqrt{\tau}] , \quad A_{1/2}(\tau) = \frac{2}{\tau^2} [\tau + (\tau - 1) \arcsin^2 \sqrt{\tau}] ,$$

Assuming  $m_{V_i}$  ranging from  $\sim 0.8$  TeV to 50 TeV:

$$\frac{|A_1(\tau)|}{|A_0(\tau)|} \approx 20 , \quad \frac{|A_1(\tau)|}{|A_{1/2}(\tau)|} \approx 5$$

# Diphoton excess

Gluon luminosity function

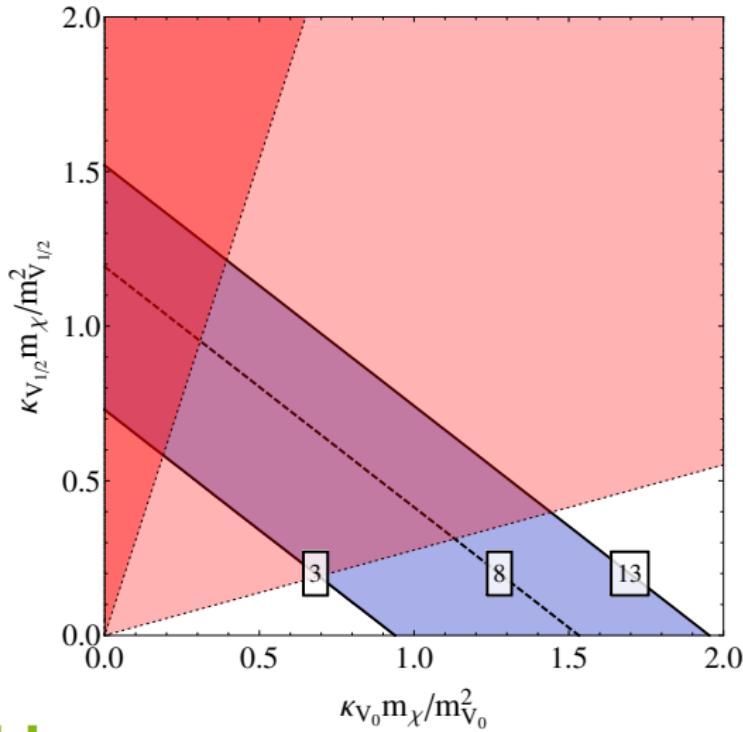
$$f_{gg} = \int_{m_\chi^2/s}^1 f_g(x) f_g(m_\chi^2/(xs)) \frac{dx}{x} = 2141.7,$$

At  $\kappa v_i = \frac{4}{3} m_{V_i}$ ,  $m_{V_0} = 1 \text{ TeV}$  and  $m_{V_{1/2}} = 20 \text{ TeV}$  we have

$$\frac{\Gamma_{gg}}{m_\chi} \simeq 2 \cdot 10^{-4}, \quad \frac{\Gamma_{\gamma\gamma}}{m_\chi} \simeq 8 \cdot 10^{-7}, \quad \sigma_{\gamma\gamma} \simeq 4 \text{ fb}.$$

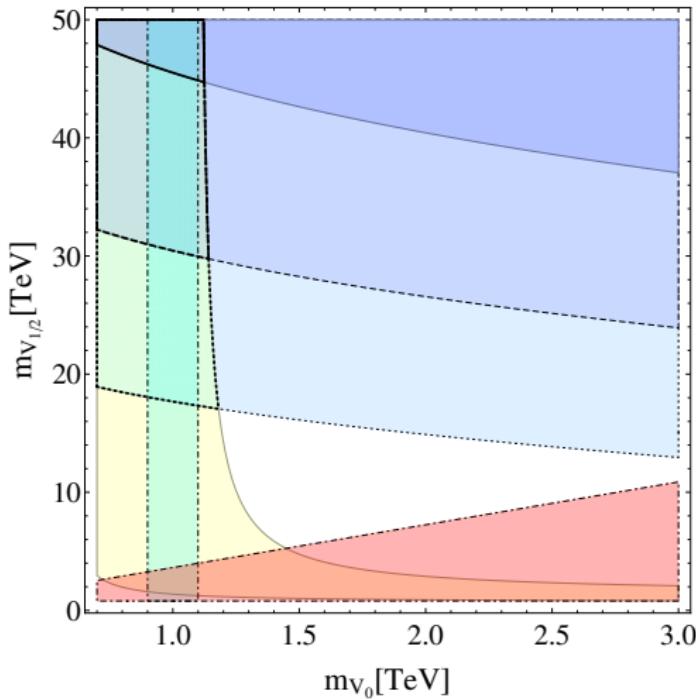
⇒ Cannot explain wide width observed by ATLAS

# Diphoton excess



- Red area excluded by diboson searches
- Blue area corresponds to  $\sigma_{\gamma\gamma} \in (3, 13) \text{ fb}$
- $\kappa_{V_i} \propto m_{V_i}$  explains data well

# Numerical example



$$m_{V_0} = 1 \text{ TeV}$$

$$m_{V_{1/2}} = 30 \text{ TeV}$$

$$h_V = 0.2 \text{ TeV}$$

$$\kappa_{V_i} = \frac{4}{3} m_{V_i}$$

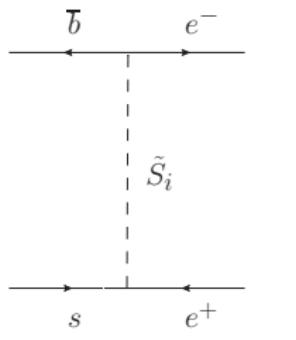
$$m_3^\nu \approx 0.06 \text{ eV}$$

$$\sigma_{\gamma\gamma} \approx 4.0 \text{ fb}$$

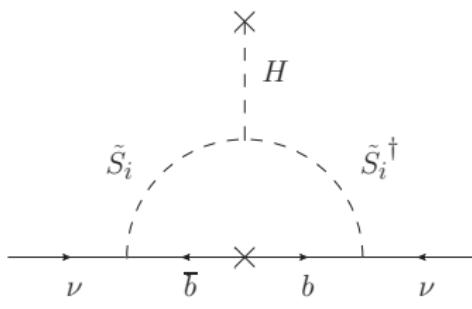
# Scalar leptoquarks

Different leptoquarks, same principle:

Leptoquark	$(SU(3), SU(2))_{U(1)_Y}$	$Q_{EM}$	$B$	$L$
$S_{1/2}$	$(3, 2)_{1/6}$	$(-1/3, 2/3)$	$1/3$	-1
$S_1$	$(3, 3)_{-1/3}$	$(2/3, -1/3, -4/3)$	$1/3$	1



(a)



(b)

$$\begin{aligned} \mathcal{L}_{LQ} = & \lambda_{S_{1/2}}^R \bar{d} P_L L S_{1/2} \\ & + \lambda_{S_1}^L \overline{Q^c} P_L i \tau_2 S_1^\dagger L \end{aligned}$$

$$V_{LQ} \supset h_S H i \tau_2 S_1 S_{1/2}^\dagger$$

# Scalar leptoquarks

Inverse hierarchical couplings:

Field	$\bar{Q}_1$	$\bar{Q}_2$	$\bar{Q}_3$	$d$	$s$	$b$	$u$	$c$	$t$
$Q(U(1)_{\text{FN}})$	-2	-1	0	9	6	3	10	5	0

Field	$\bar{L}_1$	$\bar{L}_2$	$\bar{L}_3$	$S_1$
$Q(U(1)_{\text{FN}})$	$-q_\tau - 1$	$-q_\tau$	$-q_\tau$	$q_\tau - 1$
Field	$e$	$\mu$	$\tau$	$S_{1/2}$
$Q(U(1)_{\text{FN}})$	$q_\tau + 10$	$q_\tau + 5$	$q_\tau + 3$	$11 - q_\tau$

For  $q_\tau = 6$ :

$$\lambda_{S_1}^L \simeq \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon^2 & \epsilon & \epsilon \end{pmatrix}, \quad \lambda_{S_{1/2}}^R \simeq \begin{pmatrix} \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon^6 & \epsilon^5 & \epsilon^5 \\ \epsilon^9 & \epsilon^8 & \epsilon^8 \end{pmatrix},$$

⇒ Light and heavy down-type quarks contribute equally to neutrino masses since  $m_q \lambda_{qi}^R \lambda_{qi'}^L \approx m_b \epsilon^9$ ,  $m_s \approx m_b \epsilon^2$  and  $m_d \approx m_b \epsilon^4$ .

# Scalar leptoquarks

Notes:

- Since  $S_1$  couples also to down-type quarks and neutrinos,  $R_D$  cannot be explained without exceeding limits of  $B \rightarrow K\nu\nu$  ( $R_D$  requires large  $\lambda_{b\tau}\lambda_{c\nu} \approx \epsilon$ , which implies also  $\lambda_{b\nu}\lambda_{s\nu} \approx \epsilon$ )
- The inverse hierarchical patterns can induce notable effects in  $0\nu\beta\beta$  decay if simultaneously the leptoquark mixing is large  
[Hirsch, Klapdor-Kleingrothaus, Kovalenko, Phys. Lett. B 378, (1996)]

$$C [\bar{\nu} P_R e^c] [\bar{u} P_R d] , \quad \text{with} \quad C = \lambda_{S_1}^L \lambda_{S_{1/2}}^R \left( \frac{R_{11} R_{12}}{M_{S_1}^2} + \frac{R_{21} R_{22}}{M_{S_{1/2}}^2} \right)$$
$$T_{1/2}^{0\nu\beta\beta}({}^{76}\text{Ge}) > 2.1 \times 10^{25} \text{ yr}, \quad T_{1/2}^{0\nu\beta\beta}({}^{76}\text{Ge}) \approx \frac{2.5 \times 10^{21} \text{ yr}}{(\cos \alpha \sin \alpha)^2} \frac{M_{S_{1/2}}^4 M_{S_1}^4}{\Delta M_S^4 (\text{TeV})^4}$$

[GERDA, Phys. Rev.Lett. 111, no. 12, 122503 (2013)]