The 750 GeV diphoton resonance in the light of a 2HDM with $S_3$ flavour symmetry

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Very recently we proposed a predictive 2 Higgs Doublet Model with $S_3$ flavour symmetry that successfully accounts for fermion masses and mixings. In this letter, motivated by the 750 GeV Higgs diphoton resonance recently reported by the ATLAS and CMS collaborations, we modify this model by adding exotic top partners with electric charge $\frac{1}{2}$ and a electrically charged scalar singlet. These exotic top partners decay into a charged scalar singlet and the SM up type quarks, whereas the charged scalar singlet will mainly decay into SM up and down type quarks. This simple modification enables our model to successfully account for the Higgs diphoton excess at 750 GeV provided that the exotic quark masses are in the range $[1, 2]$ TeV, for $O(1)$ exotic quark Yukawa couplings.

Supersymmetric explanations are possible and the excess has been interpreted in the context of the Minimal Supersymmetric Standard Model (MSSM) [33], its R-symmetry violating version [34] and other supersymmetric extensions [35, 36].

Extending the SM gauge symmetry can also explain the excess, as described by [37–48], and models based on strongly coupled theories were considered by [3] [4] [49–56]. An extended broken symmetry with an extra Higgs boson and massive vector bosons can account for the diboson anomaly and the anomalous $t\bar{t}$ forward-backward asymmetry [57].

Models with extra fermions [58], in particular vector-like fermions had been considered before [59–62] and after the announcement [3–5, 10, 63–71], and other works relate the diphoton excess with loop TeV-scale seesaw mechanisms, either at two [44] or three loops [72].

Relating the excess with dark matter has been extensively considered, see [31–33, 37, 38].

There are also sgoldstino [34, 35], radion [37, 38], graviton [39] and exotic heavy axion [49–50, 60], interpretations of the 750 GeV excess.

String-motivated models were considered in [91].

Finally, a rather natural and popular framework to explain the excess is that of 2 Higgs Doublet Models (2HDMs), which have been studied in [63] [94–102] and will also be considered in this letter, where we make a simple modification of an existing 2HDM [103], by adding exotic top quark partners.

The model. We consider the 2HDM that we recently proposed in [103], with the SM gauge symmetry supplemented by the $S_3 \otimes Z_2 \otimes Z'_3 \otimes Z_{14}$ discrete group. The scalar sector has two Higgs doublets (assigned as trivial $S_3$ singlets) plus four SM singlet scalars assigned as one $S_3$ trivial singlet ($\chi$), one $S_3$ non-trivial singlet ($\zeta$) and one $S_3$ doublet ($\xi$). In order to successfully explain the LHC diphoton excess at 750 GeV, we extend the fermion sector of our 2HDM by including four $SU(2)_L$ singlet ex-
otic quark fields with electric charge $\frac{2}{3}$, $T_{1L}, T_{1R}, T_{2L}, T_{2R}$, grouped into two $S_3$ doublets, i.e., $T_L = (T_{1L}, T_{2L}), T_R = (T_{1R}, T_{2R})$. These exotic quark fields are neutral under the $Z_3 \otimes Z_3'$ discrete symmetry but charged under the $Z_{14}$ symmetry as:

$$T_L \rightarrow T_L, \quad T_R \rightarrow e^{\frac{2\pi}{3}}T_R. \quad (1)$$

In addition, the instability of the exotic quarks $T_{1L}, T_{1R}, T_{2L}, T_{2R}$ requires that we extend the scalar sector with a single electrically charged SM scalar singlet $\rho^+$. We assume that $\rho^+$ is a trivial $S_3$ singlet and is neutral under the $Z_3 \otimes Z_3' \otimes Z_{14}$ discrete symmetry. The exotic quarks should then decay into $\rho^+$ and SM up type quarks, through the Yukawa interactions given in Eq. (2), while $\rho^+$ in turn will mainly decay into SM up and down type quarks. The remaining particles have the $S_3 \otimes Z_3 \otimes Z_3'$ charge assignments described in \[103\]. In this model, the $S_3$ symmetry reduces the number of parameters in the Yukawa sector making this 2HDM more predictive, and the remaining symmetries control the allowed Lagrangian terms by distinguishing the fields. For example, the two scalar $SU(2)_L$ doublets have different $Z_3$ charges ($\phi_1$ being neutral). The $Z_3'$ and $Z_{14}$ symmetries shape the hierarchical structure of the fermion mass matrices necessary to get a realistic pattern of fermion masses and mixing. The assignments of the scalar and fermion particles are given in \[103\], giving rise to the following Yukawa terms for the quark and lepton sectors:

$$\mathcal{L}_Y' = e^{(u)}_{33} \bar{q}_{3L} \phi_1 u_{3R} + e^{(u)}_{22} \bar{q}_{2L} \phi_2 u_{3R} \frac{\chi^2}{\Lambda^2} + e^{(u)}_{13} \bar{q}_{1L} \phi_2 u_{3R} \frac{\chi^3}{\Lambda^3} + e^{(d)}_{22} \bar{q}_{2L} \phi_2 d_{3R} \frac{\chi^2}{\Lambda^2} + e^{(d)}_{13} \bar{q}_{1L} \phi_2 d_{3R} \frac{\chi^3}{\Lambda^3} + e^{(d)}_{11} \bar{q}_{1L} \phi_1 d_{3R} \frac{\chi^4}{\Lambda^4} + e^{(d)}_{33} \bar{q}_{3L} \phi_1 d_{3R} \frac{\chi^5}{\Lambda^5} + m_d T_{1L} T_{1R} \rho + m_u T_{1L} T_{1R} \frac{\chi^3}{\Lambda^3} + \text{h.c} \quad (2)$$

As the quark masses are related to the quark mixing parameters, we set the vacuum expectation values (VEVs) of the SM singlet scalars with respect to the Wolfenstein parameter $\lambda = 0.225$ and the new physics scale $\Lambda$:

$$v_\xi \sim v_\zeta \sim v_\chi = \lambda \Lambda. \quad (4)$$

Regarding the Yukawa interactions of $\rho^+$ with quarks and leptons, we only consider operators up to dimension eight and neglect higher dimensional contributions. From the quark Yukawa interactions, it follows that the top partners will decay dominantly into either up or charm quarks and the charged scalar singlet $\rho^+$, whereas the dominant decay mode of $\rho^+$ will be into top and bottom quarks. Let us note that the charged scalar singlet $\rho^+$ cannot decay into charged leptons and right handed neutrinos, since the right handed Majorana neutrinos are much heavier than $\rho^+$, thus not allowing that decay channel. In addition, the charged scalar $\rho^+$ can decay into charged leptons and light active neutrinos but its corresponding decay rate is suppressed by $\lambda^6 \frac{\rho^+}{\Lambda^6}$, as clearly seen from the lepton Yukawa interactions. Consequently, the top partners can be searched at the LHC through their decay channel $T_m \rightarrow \rho^+ u_m \rightarrow t b u_m \rightarrow W b u_m \rightarrow l^3 j E_T$ $(m = 1, 2)$. These top partners are produced in pairs at the LHC via a gluon fusion mechanism, where these exotic quarks are in the triangular loop followed by the propagator of the scalar $\chi$, followed again with a pair of the top partner and its antiparticle (note that the scalar singlet $\chi$ has a renormalizable coupling with these top partners). Thus observing an excess of events with respect to the SM background in the opposite sign dileptons final state can be a signal to confirm this model at the LHC.

From the Yukawa terms given above and considering that the VEV of $\xi$ is aligned as (1,0) in the $S_3$ direction \[103\], we find that the quark, charged lepton and light active neutrino mass matrices are:
where \( v = 246 \text{ GeV} \) and \( a_b \) \((k = 1, 2, 3)\), \( b_1, c_1, g_1, f_1, f_2, e_1, e_2, x_1, y_1, y_2, z_1, z_2 \) and \( \kappa \) are \( \mathcal{O}(1) \) parameters, whereas \( X \) and \( W \) are parameters with dimension \( \sqrt{m} \) where \( m \) has mass dimension. The Cabibbo mixing arises from the down-type quark sector whereas the up-type quark sector contributes to the remaining mixing angles [104]. Furthermore, light active neutrino masses arise via a type I seesaw mechanism with two heavy right-handed Majorana neutrinos \( \nu_1R \) and \( \nu_2R \). We have shown in [103] that the fermion mass textures given above are consistent with the current data on SM fermion masses and mixings.

The 750 GeV scalar resonance. The recently reported excess in the diphoton final state can be attributed to the \( Z_{14} \) breaking scalar \( \chi \), which, taking into account the heavy exotic fermions, is predominantly produced via gluon fusion through the triangular loop diagrams with \( T_1 \) and \( T_2 \). The corresponding total cross section \( \sigma \) is a function of the gluon production rate \( \Gamma(gg \rightarrow \chi) \) and the consequent decay rate into photons \( \Gamma(\gamma \gamma \rightarrow \chi) \)

\[
\Gamma(gg \rightarrow \chi) = K^{gg} \frac{\alpha^2 m_S^3}{32 \pi^2 v^2} F(x_T)^2, \quad (7)
\]

\[
\Gamma(\gamma \gamma \rightarrow \chi) = \frac{\alpha^2 m_S^3}{64 \pi^2 v^2} N_c Q^2_F F(x_T)^2, \quad (8)
\]

where \( m_S \approx 750 \text{ GeV} \) denotes the resonance mass, \( x_T = 4m_T^2/m_S^2 \), \( m_T = y_T v_S \), and \( K^{gg} \sim 1.5 \) accounts for higher order QCD corrections. \( F(x) \) is a loop function given by

\[
F(x) = 2x (1 + (1 - x) f(x)), \quad f(x) = \left( \arcsin \sqrt{1/x} \right)^2
\]

with \( x_T > 1 \Leftrightarrow 4m_T^2 > m_S \). Finally, we obtain

\[
\sigma = \frac{\pi^2}{8} \Gamma(\gamma \gamma \rightarrow \chi) \frac{1}{2} \int_0^1 \frac{ds}{s} f_g(s) f_g \left( \frac{m_S^2}{s} \right) \Gamma(gg \rightarrow \chi)
\]

with \( \sqrt{s} = 13 \text{ TeV} \) being the LHC center of mass energy, \( \Gamma_S \) the total decay width of \( \chi \) and \( f_g(s) \) the gluon distribution function. To obtain a rough estimate of \( \sigma \) we assume for simplicity unified and natural Yukawa couplings of the exotic quarks \( y_T \sim 1 \), which with \( v_S \approx 1.2 \text{ TeV} \) amounts to \( \sigma \sim 8 \text{ fb} \). This is well within the limits given by the ATLAS and CMS experiments [1]

\[
\sigma_{\text{ATLAS}} = 10 \pm 3 \text{ fb}, \quad \sigma_{\text{CMS}} = 6 \pm 3 \text{ fb}.
\]

The total cross section was computed using the MSTW2008 next-to-leading-order gluon distribution functions [105] as a function of \( v_S \) for different values of the exotic quark Yukawa couplings. As shown in Fig. [1] the cross section depends crucially on the VEV \( v_S \) as well as on the Yukawa couplings, which if sizable can also enhance \( \sigma \) significantly in particular for lower \( v_S \) values.

If we further require that \( \sigma \) be within the experimental limits given by ATLAS and CMS, we predict \( v_S \) to be smaller than 2 TeV, which on the one hand sets the \( Z_{14} \) breaking scale and on the other hand fixes the expected particle masses of \( \chi \) and the exotic quarks \( T_i \) to be in the same region.

Conclusion. The same flavon that is responsible for the shaping of the fermion mass and mixing matrices can explain the recently reported 750 GeV excess in the diphoton channel. This is shown using a predictive flavor model based on the \( S_3 \otimes Z_3 \otimes Z_3' \otimes Z_{14} \) symmetry with the addition of heavy exotic fermions with electric charge \( \frac{3}{2} \) and an electrically charged scalar singlet. These heavy exotic quarks decay into a charged scalar singlet and the SM up type quarks, whereas the charged scalar singlet will mainly decay into SM up and down type quarks. Attributing the \( Z_{14} \) breaking scalar to the resonance allows one to fix the energy of the breaking scale and, hence, enables immediate testing of the model at the current LHC run.

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[1] ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2015-081.
[2] CMS Collaboration [CMS Collaboration], collisions at 13TeV, CMS-PAS-EXO-15-004.
[3] D. Buttazzo, A. Greljo and D. Marzocca, arXiv:1512.04929 [hep-ph].
[4] R. Franceschini et al., arXiv:1512.04933 [hep-ph].
[5] J. Ellis, S. A. R. Ellis, J. Quevillon, V. Sanz and T. You, arXiv:1512.05327 [hep-ph].
[6] R. S. Gupta, S. Jäger, Y. Kats, G. Perez and E. Stamou, arXiv:1512.05332 [hep-ph].
[7] J. Chakrabortty, A. Choudhury, P. Ghosh, S. Mondal and T. Srivastava, arXiv:1512.05767 [hep-ph].
[8] P. Agrawal, B. Heidenreich, M. Reece and J. Chakrabortty, arXiv:1512.06083 [hep-ph].
[9] S. Matsuzaki and K. Yamawaki, arXiv:1512.05564 [hep-ph].
[10] A. Falkowski, O. Slone and T. Volansky, arXiv:1512.05777 [hep-ph].
[11] D. Aloni, K. Blum, A. Dery, A. Efrati and Y. Nir, arXiv:1512.05778 [hep-ph].
[12] F. P. Huang, C. S. Li, Z. L. Liu and Y. Wang, arXiv:1512.06732 [hep-ph].
[13] W. S. Cho, D. Kim, K. Kong, S. H. Lim, K. T. Matchev, J. C. Park and M. Park, arXiv:1512.06824 [hep-ph].
[14] S. Kanemura, N. Machida, S. Odori and T. Shindou, arXiv:1512.09053 [hep-ph].
[15] A. Salvio and A. Mazumdar, arXiv:1512.08184 [hep-ph].
[16] L. Marzola, A. Racioppi, M. Raidal, F. R. Urban and H. Vermeie, arXiv:1512.09136 [hep-ph].
[17] J. Jaeckel, M. Jankowiak and M. Spannowsky, Phys. Dark Univ. 2, 111 (2013) doi:10.1016/j.dark.2013.06.001 [arXiv:1212.3620 [hep-ph]].
[18] J. de Blas, M. Chala, M. Perez-Victoria and J. Santiago, JHEP 1504, 078 (2015) doi:10.1007/JHEP04(2015)078 [arXiv:1412.8480 [hep-ph]].
[19] S. Fichet, G. von Gersdorff and C. Royon, arXiv:1512.05751 [hep-ph].
[20] Q. H. Cao, Y. Liu, K. P. Xie, B. Yan and D. M. Zhang, arXiv:1512.05542 [hep-ph].
[21] B. Dutta, Y. Gao, T. Ghosh, I. Gogoladze and T. Li, arXiv:1512.05439 [hep-ph].
[22] A. Alves, A. G. Dias and K. Sinha, arXiv:1512.06091 [hep-ph].
[23] H. Han, S. Wang and S. Zheng, arXiv:1512.06562 [hep-ph].
[24] J. Chang, K. Cheung and C. T. Lu, arXiv:1512.06671 [hep-ph].
[25] O. Antipin, M. Mojaza and F. Sannino, arXiv:1512.06708 [hep-ph].
[26] J. Zhang and S. Zhou, arXiv:1512.07889 [hep-ph].
[27] K. Cheung, P. Ko, J. S. Lee, J. Park and P. Y. Tseng, arXiv:1512.07853 [hep-ph].
[28] A. E. C. Hernández, arXiv:1512.09092 [hep-ph].
[29] W. Altmannshofer, J. Galloway, S. Gori, A. L. Kagan, A. Martin and J. Zupan, arXiv:1512.07616 [hep-ph].
[30] C. Cai, Z. H. Yu and H. H. Zhang, arXiv:1512.08440 [hep-ph].
[31] M. Bauer and M. Neubert, arXiv:1512.08628 [hep-ph].
[32] C. W. Murphy, arXiv:1512.06976 [hep-ph].
[33] S. Chakraborty, A. Chakraborty and S. Raychaudhuri, arXiv:1512.07527 [hep-ph].
[34] B. C. Allanach, P. S. B. Dev, S. A. Renner and K. Saturai, arXiv:1512.07645 [hep-ph].
[35] F. Wang, L. Wu, J. M. Yang and M. Zhang, arXiv:1512.06715 [hep-ph].
[36] F. Wang, W. Wang, L. Wu, J. M. Yang and M. Zhang, arXiv:1512.08434 [hep-ph].
[37] Q. H. Cao, Y. Liu, K. P. Xie, B. Yan and D. M. Zhang, arXiv:1512.08441 [hep-ph].
[38] S. M. Boucenna, S. Morisi and A. Vicente, arXiv:1512.06878 [hep-ph].
[39] A. E. C. Hernández and I. Nisandzic, arXiv:1512.07165 [hep-ph].
[40] K. M. Patel and P. Sharma, arXiv:1512.07468 [hep-ph].
[41] Q. H. Cao, S. L. Chen and P. H. Gu, arXiv:1512.07541 [hep-ph].
[42] J. Cao, F. Wang and Y. Zhang, arXiv:1512.08392 [hep-ph].
[43] G. M. Pelaggi, A. Strumia and E. Vigiani, arXiv:1512.07225 [hep-ph].
[44] W. Chao, arXiv:1512.08484 [hep-ph].
[45] W. Chao, arXiv:1512.06297 [hep-ph].
[46] Y. Jiang, Y. Y. Li and T. Liu, arXiv:1512.09127 [hep-ph].
[47] P. V. Dong and N. T. K. Ngan, arXiv:1512.09073 [hep-ph].
[48] A. Dasgupta, M. Mitra and D. Borah, arXiv:1512.09202 [hep-ph].
[49] K. Hariyaga and Y. Nomura, arXiv:1512.04850 [hep-ph].
[50] E. Molinaro, F. Sannino and N. Vignaroli, arXiv:1512.05334 [hep-ph].
[51] L. Bian, N. Chen, D. Liu and J. Shu, arXiv:1512.05759 [hep-ph].
[52] D. Curtin and C. B. Verhaaren, arXiv:1512.05753 [hep-ph].
[53] J. M. No, V. Sanz and J. Setford, arXiv:1512.05700 [hep-ph].
[54] S. Matsuzaki and K. Yamawaki, arXiv:1512.05564 [hep-ph].
[55] J. S. Kim, J. Reuter, K. Rolbiecki and R. D. de Austri, arXiv:1512.06083 [hep-ph].
[56] M. Son and A. Urbano, arXiv:1512.08307 [hep-ph].
[57] J. de Blas, J. Santiago and R. Vega-Morales, arXiv:1512.07229 [hep-ph].
[58] L. Basso, O. Fischer and J. J. van der Bij, Europ. Phys. Lett. 101, 51004 (2013) doi:10.1209/0295-5075/101/51004 [arXiv:1212.5560 [hep-ph]].
[59] N. Bonne and G. Moreau, Phys. Lett. B 717, 409 (2012) doi:10.1016/j.physletb.2012.09.063 [arXiv:1206.3360 [hep-ph]].
[60] G. Moreau, Phys. Rev. D 87, no. 1, 015027 (2013) doi:10.1103/PhysRevD.87.015027 [arXiv:1210.3977 [hep-ph]].
[hep-ph].

[61] J. A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer and M. Pérez-Victoria, Phys. Rev. D 88, no. 9, 094010 (2013) doi:10.1103/PhysRevD.88.094010 [arXiv:1306.0572 [hep-ph]].

[62] A. Angelescu, A. Djouadi and G. Moreau, arXiv:1510.07527 [hep-ph].

[63] A. Angelescu, A. Djouadi and G. Moreau, arXiv:1512.04921 [hep-ph].

[64] A. Kobakhidze, F. Wang, L. Wu, J. M. Yang and M. Zhang, arXiv:1512.05585 [hep-ph].

[65] R. Benbrik, C. H. Chen and T. Nomura, arXiv:1512.06028 [hep-ph].

[66] M. Dhuria and G. Goswami, arXiv:1512.06782 [hep-ph].

[67] K. Das and S. K. Rai, arXiv:1512.07789 [hep-ph].

[68] J. Liu, X. P. Wang and W. Xue, arXiv:1512.07885 [hep-ph].

[69] Y. L. Tang and S. h. Zhu, arXiv:1512.08323 [hep-ph].

[70] G. Li, Y. n. Mao, Y. L. Tang, C. Zhang, Y. Zhou and S. h. Zhu, arXiv:1512.08255 [hep-ph].

[71] P. S. B. Dev, R. N. Mohapatra and Y. Zhang, arXiv:1512.06782 [hep-ph].

[72] S. Kanemura, K. Nishiwaki, H. Okada, Y. Orikasa, S. C. Park and R. Watanabe, arXiv:1512.09048 [hep-ph].

[73] Y. Nakai, R. Sato and K. Tobioka, arXiv:1512.04924 [hep-ph].

[74] S. Knappen, T. Molia, M. Papucci and K. Zurek, arXiv:1512.04928 [hep-ph].

[75] R. Martinez, F. Ochoa and C. F. Sierra, arXiv:1512.05617 [hep-ph].

[76] X. J. Bi, Q. F. Xiang, P. F. Yin and Z. H. Yu, arXiv:1512.06787 [hep-ph].

[77] D. Barducci, A. Goudelis, S. Kulkarni and D. Sengupta, arXiv:1512.06842 [hep-ph].

[78] U. K. Dey, S. Mohanty and G. Tomar, arXiv:1512.07212 [hep-ph].

[79] P. S. B. Dev and D. Teresi, arXiv:1512.07243 [hep-ph].

[80] H. Han, S. Wang and S. Zheng, arXiv:1512.07992 [hep-ph].

[81] J. C. Park and S. C. Park, arXiv:1512.08117 [hep-ph].

[82] B. Bellazzini, R. Franceschini, F. Sala and J. Serra, arXiv:1512.05330 [hep-ph].

[83] C. Petersson and R. Torre, arXiv:1512.05333 [hep-ph].

[84] S. V. Demidov and D. S. Gorbunov, arXiv:1512.05723 [hep-ph].

[85] A. Ahmed, B. M. Dillon, B. Grzadkowski, J. F. Gunion and Y. Jiang, arXiv:1512.05771 [hep-ph].

[86] D. Bardhan, D. Bhatia, A. Chakraborty, U. Maitra, S. Raychaudhuri and T. Samui, arXiv:1512.06674 [hep-ph].

[87] M. T. Arun and P. Saha, arXiv:1512.06335 [hep-ph].

[88] A. Pilaftsis, arXiv:1512.04931 [hep-ph].

[89] J. J. Heckman, arXiv:1512.06773 [hep-ph].

[90] M. Cvetić, J. Halverson and P. Langacker, arXiv:1512.07622 [hep-ph].

[91] L. A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lust and T. R. Taylor, arXiv:1512.08502 [hep-ph].

[92] S. Di Chiara, L. Marzola and M. Raidal, arXiv:1512.04939 [hep-ph].

[93] D. Becirevic, E. Bertuzzo, O. Sumensari and R. Z. Funchal, arXiv:1512.05623 [hep-ph].

[94] X. F. Han and L. Wang, arXiv:1512.06587 [hep-ph].

[95] M. Badziak, arXiv:1512.07462 [hep-ph].

[96] S. V. Demidov and D. S. Gorbunov, arXiv:1512.05723 [hep-ph].

[97] A. Ahmed, B. M. Dillon, B. Grzadkowski, J. F. Gunion and Y. Jiang, arXiv:1512.05771 [hep-ph].

[98] D. Bardhan, D. Bhatia, A. Chakraborty, U. Maitra, S. Raychaudhuri and T. Samui, arXiv:1512.06674 [hep-ph].

[99] M. Cvetić, J. Halverson and P. Langacker, arXiv:1512.07622 [hep-ph].

[100] L. A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lust and T. R. Taylor, arXiv:1512.08502 [hep-ph].

[101] S. Di Chiara, L. Marzola and M. Raidal, arXiv:1512.04939 [hep-ph].

[102] D. Becirevic, E. Bertuzzo, O. Sumensari and R. Z. Funchal, arXiv:1512.05623 [hep-ph].

[103] X. F. Han and L. Wang, arXiv:1512.05657 [hep-ph].

[104] M. Badziak, arXiv:1512.07497 [hep-ph].

[105] S. Moretti and K. Yagyu, arXiv:1512.07462 [hep-ph].

[106] X. J. Bi et al., arXiv:1512.08497 [hep-ph].

[107] N. Bizot, S. Davidson, M. Frigerio and J.-L. Kneur, arXiv:1512.08508 [hep-ph].

[108] S. K. Kang and J. Song, arXiv:1512.08636 [hep-ph].

[109] W. C. Huang, Y. L. S. Tsai and T. C. Yuan, arXiv:1512.07268 [hep-ph].

[110] A. E. C. Hernández, I. d. M. Varzielas and E. Schumacher, arXiv:1509.02083 [hep-ph].

[111] A. E. C. Hernández and I. d. M. Varzielas, J. Phys. G 42, no. 6, 065002 (2015) doi:10.1088/0954-3899/42/6/065002 [arXiv:1410.2481 [hep-ph]].

[112] A. D. Martin, W. J. Stirling, R. S. Thorne and G. Watt, Eur. Phys. J. C 63, 189 (2009) doi:10.1140/epjc/s10052-009-1072-5 [arXiv:0901.0002 [hep-ph]].