# PHYSICS BEYOND THE STANDARD MODEL IN HADRONIC COLLISIONS

Stefan Pokorski

Institute of Theoretical Physics, Faculty of Physics, Uniwersity of Warsaw
Pasteura 5, 02-093 Warszawa, Poland

*(Received June 13, 2016)*

*Dedicated to Andrzej Bialas in honour of his 80th birthday*

The role of hadron colliders in the past discoveries in particle physics and their potential role in the search for physics beyond the Standard Model are briefly reviewed. The emphasis is placed on the production in hadronic collisions of particles that do not interact strongly.

DOI:10.5506/APhysPolB.47.1767

## 1. Introduction

Hadronic collisions played crucial role in the history of particle physics. By the 1960s, experiments at accelerators had revealed scores of hadrons. In 1962, Murray Gell-Mann found a way of gathering them into families. They contained sets of eight and were named by Gell-Mann the Eightfold Way. The SU(3) group which was behind that classification — today we would call it a flavour SU(3) group — inspired Murray Gell-Mann and George Zweig to propose the quark model. With further revolutionary ideas from James Bjorken and Richard Feynman, quark status was painfully "upgraded" from mathematical entities to real particles. That gave birth to the fundamental breakthrough which was the cradle of the SM — the quark–gluon structure of hadrons.

In the sixties, the immense amount of accelerator data made strong interactions the central, if not the leading, area of research in particle physics. Not only the classification of hadrons but also the dynamics of hadron collisions and multiparticle production in such collisions were vigorously investigated by the theorists. Those pre-QCD, often phenomenological, investigations have turned out to have a lasting value, as they form the basis for the effective description of the so-called soft hadron and heavy-ion collisions. Even the Monte Carlo simulation codes, indispensable for the data interpretation nowadays, use the results then obtained. Secondly, several fundamental for particle physics ideas have emerged. It belongs to the meanders of particle physics that those ideas, proposed in the context of strong interactions, have turned out to be more important in some other contexts. Among the most famous examples there certainly is the Brout–Englert–Higgs mechanism. For Robert Brout and Francois Englert, one of the motivations was to interpret the newly discovered $\rho$ resonance as a gauge boson of some gauge symmetry and the question how to introduce its mass in a gauge invariant manner. Peter Higgs was motivated by the Nambu ideas about spontaneous chiral symmetry breaking as the origin of the proton and neutron masses, and proposed his mechanisms to avoid the massless Nambu–Goldstone bosons in the spectrum. The list of spectacular ideas that originated from research on the dynamics of strong interactions is much longer. The S-matrix theory, now reviving as a general tool in quantum field theory complementary to the traditional perturbation theory, the Regge pole theory and its culmination in the form of the Veneziano model as the origin of the string theory ... these are just a few examples.

Strong interactions, investigated so actively and with strong links between theory and experiment, attracted Andrzej Bialas, celebrating his 80$^{\text{th}}$ birthday today and a young theorist at the time, and shaped his research interests for many years to come. Working with his group of students and with his close collaborators, Wiesław Czyż and Kacper Zalewski, he has become one of the most prominent figures in the field of soft hadron and heavy-ion collisions. His impressive research record includes many seminal ideas such as, for instance, using the quark model for soft collisions, understanding the role of particle correlations in the multiparticle production and very important results for heavy-ion collisions.

Most natural use of hadron colliders is for production of strongly interacting particles, either in low momentum transfer (soft) collisions or in, more rare, hard-parton collisions. But it was soon realized that with higher and higher energies and higher and higher luminosities, also weakly interacting particles can be produced via such mechanisms as the Drell–Yann production, vector-boson fusion or effective couplings to gluons generated by the quark loops. Indeed, in the hadronic collisons, there have been discovered the $W$ and $Z$ gauge bosons and, finally, the Higgs boson, beautifully confirming the Standard Model. The proton–(anti)proton accelerators have proved to be of great value as the discovery machines at the energy frontiers. At present, the main goal of particle physics is to discover the physics beyond the Standard Model (SM) and the LHC experiments are in the centre of interest.

## 2. Why beyond the SM?

The SM is in perfect shape. The measured Higgs boson couplings to fermions and gauge bosons are, within the experimental errors of (10–20)%, in agreement with the predictions of the SM with one elementary Higgs doublet. Its potential

$$V = m_H^2 |H|^2 + \frac{\lambda}{2}|H|^4 \tag{1}$$

links the Higgs boson mass to the coupling $\lambda$,

$$m_h^2 = -2m_H^2 = 2\lambda v^2 \,, \tag{2}$$

where $v = 246$ GeV is the electroweak vacuum expectation value. The mass of 125 GeV gives $\lambda = 0.12$ and this value is well within perturbative regime. Thus, a particle that looks very much like the elementary Higgs boson of the SM has been discovered. The simplest dynamical sector (considered by many as a toy model) — a selfinteracting scalar field — is now promoted to a real thing (Guido Altarelli, Warsaw 2014). At least at the electroweak scale, the SM is the correct effective theory of elementary interactions. But, even more surprisingly, the SM seems to be a mathematically consistent theory up to the Planck scale. This conclusion relies strongly on the measured values of the top-quark and the Higgs boson masses. The electroweak vacuum is (meta)stable up to the Planck scale (with its lifetime much longer than the age of the universe) [1, 2] and the coupling $\lambda$ remains small when evolved with the renormalization group equation (no Landau pole below the Planck scale). And the SM is a renormalizable theory.

So, the SM looks mathematically consistent up to the Planck scale but is it also physically valid up to that scale? Is it not indeed just an effective theory, an approximation to a deeper one (similarly to QED, mathematically consistent up to the Planck scale but only a low-energy approximation to the SM, describing electromagnetic interactions below the electroweak scale)? Although consistent up to the Planck scale, the SM needs, for sure, some extension, at least to account for the empirical facts that remain unexplained, such as the neutrino masses, the presence of dark matter in the universe, and matter–antimatter asymmetry. We are far from full satisfaction on the theoretical side as well. The dynamical origin of the Fermi constant (that is of the electroweak vacuum) and the hierarchy of the fermion masses are not addressed by the SM. But even if we accept them as "unexplainable" parameters of the theory, the SM suffers from a serious conceptual problem known as the naturalness problem.

In short, the naturalness problem of the SM lies in potentially large radiative corrections $\delta m_H^2$ to the Higgs field mass parameters in Eq. (1) because of their quadratic sensitivity to new mass scales. Including them into Eq. (2), it is clear that the larger the quantum corrections the larger must be the cancellation between the tree-level parameter and the quantum corrections to obtain the physical Higgs mass. An exact degree of acceptable cancellations is, to a large extent, a matter of taste but qualitatively the problem is clear. It can be illustrated with a well-known example. If the SM is valid up to a certain physical cut-off scale $\Lambda$ (let it be $M_{\mathrm{PL}}$; we exclude here the possibility that the SM is the Theory of Everything, with no other mass scales at all in the quantum physics), then the 1-loop corrections to $m_H^2$ from the exchange of the gauge bosons, top quark and the Higgs itself, cut-off at the scale $\Lambda$, give

$$\delta m_H^2 = \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right) \frac{3\Lambda^2}{32\pi^2 v^2}\,. \tag{3}$$

It is evident that a high degree of fine tuning between the physical scale $\Lambda$ and the tree-level parameters of the SM is necessary to get the Higgs mass parameter much smaller than $\Lambda$. A natural expectation then is that the SM is embedded into a deeper theory with new degrees of freedom at a scale $M$, not much above the electroweak scale, which would also contribute to quantum corrections to the Higgs mass, so that the quadratic sensitivity to the large scale $\Lambda$ is replaced by quadratic sensitivity to $M$ and at most a logarithmic one to $\Lambda$. Theories of physics beyond the Standard Model that address the hierarchy problem generally involve top partners, new particles that ensure that mechanism to work at least for the terms associated with the large Yukawa coupling of the Higgs boson to the top quark. An attractive dynamical solution is to propose a new symmetry which protects the Higgs mass against large radiative corrections in the way described above. Two general directions have been proposed, supersymmetry and composite Higgs models where the Higgs doublet is a pseudo-Goldstone boson of a new global symmetry in a new strongly interacting sector. In supersymmetric models, those partners of the top quark are scalars and in composite Higgs models, there are new fermions playing that role.

Another aspect of the naturalness problem is that new degrees of freedom with large masses, $\tilde{M} \gg M$, also potentially present in the extended theory, should not bring it back. A new degree of freedom with mass $\tilde{M}$, widely separated from the weak scale, that couples to the Higgs boson has to be included in the quantum correction to $\delta m_H^2$. For instance, for a scalar $S$ coupled to the Higgs boson, via the so-called Higgs portal, by the term $\lambda_{HS}|H|^2|S|^2$ added to the potential (1), the 1-loop diagram gives the correction

$$\delta m_H^2 \approx \frac{\lambda_{HS}}{16\pi^2}\tilde{M}^2 \ln\frac{\tilde{M}^2}{\Lambda^2}\,, \tag{4}$$

where $\Lambda$ is a cut-off to the extended theory. Clearly, new degrees of freedom would violate the naturalness principle, to the degree depending on the product of their mass and the coupling to the Higgs boson, and also logarithmically on the value of the cut-off $\Lambda$. Supersymmetry is the unique solution to that problem as well, even with $\Lambda$ as high as the Planck scale.

In most of the proposed concrete theories based on those ideas, the new symmetry that is protecting the Higgs mass commutes with the SM gauge symmetries, and so the top partners have identical quantum numbers to those of the top quark. In particular, they are charged under the SM colour group. Thus, given the expectation that these particles masses are close to the electroweak scale, they should be produced at the LHC with high rates. They can be pair produced in the quark and gluon collisions and then would decay into SM particles and some other particles of the extended theory. A generic signature is a jet plus missing transverse energy since among the final products of the chain decays of the top partners we expect to have an invisible particle (like *e.g.* neutralino in supersymmetry).

Searches for coloured top partners, both scalar and fermionic, have so far given null results. Broadly speaking, their masses are constrained to lie above around 700–800 GeV. This means roughly 1:100 cancellations in the Higgs potential and puts such solutions to the naturalness problem under certain pressure.

## 3. Uncoloured way beyond the SM

After the negative Run 1 LHC results, if we follow the naturalness paradigm, several options can be considered. Here, we list several of them.

1. The simplest possibility is that a radiative correction $\delta m_H^2$ which is $\mathcal{O}(100)$ times larger than the physical Higgs boson mass is, for some unknown reason, still "natural" and a coloured partner of the top quark with mass around 1 TeV will be found in the next LHC run. After all, this is still very little as compared to the fine-tuning $m_h^2/M_{\rm PL}^2 \approx 10^{-34}$.

2. It is also conceivable that a light coloured particle has so far escaped detection because of some pecularities in the spectrum. For instance, supersymmetric spectrum may be compressed [3] and the missing energy too small to be detected.

3. A more radical possibility is that the coloured particles are heavier but the naturalness of the Higgs potential is saved because the Higgs mass has "double protection". Here, it might be instructive to have again a look at the theories that address the naturalness issue. They require top partners to stabilize the weak scale beyond $\mathcal{O}(1\ \text{TeV})$. Those can be scalars, like in the MSSM, or fermions — as in the Little Higgs theories [4] and in composite Higgs models [5]. In those non-supersymmetric models, the Higgs boson is a pseudo-Goldstone boson of some spontaneously broken global symmetry.

The global symmetry is also broken explicitly (softly) but the quadratically divergent top 1-loop contribution to the Higgs boson mass is cancelled by the fermionic top partner contribution. Since the cancellation occurs only at 1-loop level, the models require a low cut-off, $\mathcal{O}(10\ \mathrm{TeV})$, with some unspecified dynamics above that scale. It is then an interesting possibility that their UV completions are in supersymmetry, ensuring all order cancellation of the quadratic divergences and providing a "double protection" of the Higgs potential, by a spontaneoulsy broken global symmetry and by supersymmetry [6–10].

At the same time, viewed as non-minimal extensions of the MSSM, with a global symmetry imposed on it, such models ameliorate the fine-tuning problem of the MSSM since the Higgs boson is a pseudo-Goldstone boson of the spontaneously broken global symmetry and it is naturally light. The spectrum contains stops and coloured vector-like fermions, both can easily be in a few TeV range, beyond the reach of the LHC. The electroweak sector would then be the main "low energy" signature of such models. Weakly interacting BSM particles can be pair produced at the LHC in the Drell–Yan processes and in the vector-boson fusion and they can give a number of different signatures.

The last point is nicely illustrated by supersymmetric models $R$-parity conservation. The Lightest Supersymmetric Particle (LSP) has to be neutral and its thermal relic abundance must satisfy the experimental bound $\Omega h^2 \leq 0.12$ (in general, the LSP can be only a (small) fraction of a multi-component dark matter). Systematic studies of the MSSM-like electroweak sector with the above constraint show that it is often characterized by very small mass splittings between the LSP and the next to the lightest particle (chargino or neutralino), see *e.g.* [11], so that the latter would be long-lived. A long-lived chargino, with very soft decay products, would manifest itself as a disappearing track in the detector. Another way to search for produced in pairs electroweakinos with small mass difference, so that the decay products of the NLSP are soft and the transverse missing momentum is cancelled among the two produced states, is to look for the events in which these particles are produced associated with hard initial state radiation. These events are sensitive to the monojet search which requires large missing energy recoiling against one or two energetic jets.

4. It is also possible that the symmetries that protect the naturalness of the weak scale do not commute with the SM gauge groups or, at least, with QCD. Here, an example is the Twin Higgs model [12, 13] and its supersymmetric version [14], where the fermionic top partner furnished by double protection is neutral under the SM gauge groups but charged under "hidden" $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$. Another benchmark model is Folded Supersymmetry [15]. Its spectrum consists of the SM fermions and F-sfermions, with the

electroweak charges but not the QCD charges. Instead, they are charged under a mirror (hidden) QCD. Thus, supersymmetry does not commute with QCD and this can be achieved by certain theoretical constructions. In such models, with new particles hidden to the SM interactions or at least to QCD, the Higgs portal plays a crucial role. The lightest states of the hidden QCD can be hidden glueballs which couple to the SM Higgs sector with some effective couplings (*e.g.* in Folded Supersymmetry via the loop of the scalar top partner carrying the electroweak charges, or in Twin SUSY via the SM Higgs mixing with the "hidden" Higgs). The Higgs bosons can decay to these long-lived glueballs and the experimental signature would be displaced decays at colliders. If the top partners carry the electroweak charges, they can also be produced in Drell–Yan processes, then they could annihilate into hidden glueballs. Some glueballs will decay visibly in detector giving emerging jets in the final state. These are just some examples of new experimental signatures that may be characteristic of the underlying, but more hidden than initially expected, solution to the naturalness problem.

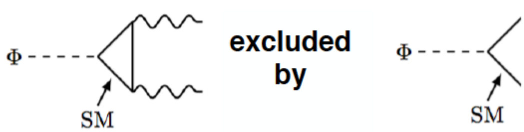
The ideas discussed in item 3 and 4 are not new but they have recently received a lot of attention.

So far, we have discussed the scenarios where physics beyond the SM plays some role in stabilizing the electroweak scale, in one way or another. But it may be that its role is different, for instance to ensure the unification of elementary forces, like in supersymmetric models or to explain the origin of dark matter. Coloured particles may be heavy (like in the Split Supersymmetry models) or absent. Weakly interacting or "hidden" sectors communicating with the SM particles via the Higgs portal or via the gauge boson kinetic mixing may be the only manifestation of the BSM physics in hadronic colliders.

## 4. Who ordered that?

So far, no new particle motivated by the naturalness issue or as the dark matter candidate has been discovered. Instead, there are some hints for beyond the SM (BSM) physics which can remind us the famous Isaac Rabi question after the discovery of the muon: Who ordered that? Recently, the ATLAS and CMS collaborations have observed an excess of events in the diphoton final state at 13 TeV collision energy at a diphoton invariant mass of 750 GeV. Although not fully significant statistically (at the level of about $3.5\sigma$), it has attracted a lot of theorists attention [16–76]. The most natural interpretation of the excess would be as prodution of a new spin 0 or spin 2 resonance (spin 1 cannot decay into two photons). The data are consistent with a very narrow but also a quite broad resonance, with the width of about 45 GeV, and the $\sigma \times \mathrm{BR}_{2\gamma}$ of about few femtobarns. There have also been found some hint of a similar effect in the 8 TeV data, although there is some tension between the expected on the basis of the rescaled 8 TeV data signal at 13 TeV and the actual measurement at 13 TeV. The experimental situation is far from being clear and the signal, even if real, can be consistent with a large range of production cross section, two-photon branching ratio and the resonance width. Many plausible interpretations have been proposed but none of the "ready" BSM models can explain it. Although, in principle, they contain "sufficient ingredients", some degree of theoretical tuning is usually present. There have been discussed perturbative and non-perturbative scenarios, purely effective models and also attempts to incorporate the effect into the existing frameworks like supersymmetric or extra-dimensional models.

To get a flavour of the scenarios that could explain the diphoton excess, let us assume its origin is a two-photon decay of a directly produced spin zero particle (CP even, for definitness), in a perturbative framework. It can be produced in $pp$ collisions and decay into two photons due to its effective couplings to the SM quarks, gluons and vector bosons. Suppose, moreover, that the scalar $\Phi$ is the only new degree of freedom beyond the SM. Then, the effective couplings to gluons and photons can originate only from the quark and lepton loops, that is from the couplings of $\Phi$ to the SM fermions. For gauge invariance, $\Phi$ has to be then a SU(2) doublet, its main production channel would be gluon–gluon fusion and, moreover, it would decay dominantly to the SM fermions and gluons, resulting in a very strong suppression of the two-photon rate (see Fig. 1).




$$\frac{\mathrm{BR}(\Phi \to \mathrm{SM\ SM})}{\mathrm{BR}(\Phi \to \gamma\gamma)} \approx \left(\frac{4\pi}{\alpha}\right)^2 \sim 0.2 \times 10^5$$

Fig. 1.

It is easy to check that $\sigma \times \mathrm{BR}_{2\gamma}$ is orders of magnitude below the experimental signal. Those arguments hold as well for more complete models like the 2HDM and the MSSM.

Thus, $\Phi$ has to be a SU(2) singlet, with no renormalizable couplings to the SM fermions and with small mixing with the Higgs boson after the electroweak symmetry breaking, to strongly suppress its decays into the SM particles. Its effective couplings to the gauge bosons read

$$\mathcal{L} = \frac{\Phi}{\Lambda}\left(g_{GG}G^2 + g_{WW}W^2 + g_{BB}B^2 + \ldots\right) , \tag{5}$$

where the dots include the couplings to the SM fermions. The effective couplings must be obtained from loops of new, vector-like fermions carrying some of the SM quantum numbers (at least the colour and electric charges) and coupled as

$$\mathcal{L} = c_F \Phi \bar{F} F + \ldots \tag{6}$$

The resonance $\Phi$ would be still produced dominantly by gluon fusion and, for $m_F > 750$ GeV/2 (the experimental limits on strongly interacting new fermions are around 700 GeV), its unavoidable decays would be into gluon jets and photons. Depending on the other SM quantum numbers of the vector-like fermions, the resonance could also decay into pairs of the other gauge bosons. Clearly, the smaller the two-photon decay rate the larger has to be the production cross section controlled mainly by the coupling $g_{GG}$, the vector-like quark masses and their number. It turns out that, to account for the experimental signal, the generic predictions of such a scenario is that several pairs of vector-like fermions have to be added and/or the couplings $c_F$ have to be large, $\mathcal{O}(1)$. Moreover, the signal should also be observed at least in the invariant mass of the gluon jets but, more generically, also in other two electroweak gauge boson decay channels. If confirmed, the diphoton excess would mean an indirect discovery of several new particles. The described here "uneasiness" in a quantitative explanation of the observed diphoton excess (and in reconciling the 8 TeV and 13 TeV data) is typical for most of the scenarios considered so far. The forthcoming LHC data will certainly shed more light on the significance of the signal and its details.

Speaking about the role of the LHC in the search for BSM physics, one should also remember about the LHCb. In fact, there are, as well, breaking news if confirmed, namely some hints for lepton flavour universality violation in $B$ meson semileptonic decays. To put it in the right perspective, let us remember that, in a certain sense, flavour is a beyond the SM concept! There are three families of quarks and leptons with identical quantum numbers, and, in consequence, identical gauge interactions. The fermion families differ only by their interactions with the Higgs field. A very important conclusion follows: in the approximation of massless neutrinos, the charged lepton flavour is conserved and their gauge interactions are universal. Thus, universality violation and lepton flavour non-conservation in the SM are predicted to be extremely tiny. Such processes are, therefore, expected to be very sensitive to the BSM physics. Recently, there have been observed at the level of 3–4$\sigma$ deviations from the SM predictions in several processes. One is the ratio

$$R(K) = \frac{B \to K\mu\mu}{B \to Kee} \tag{7}$$

which is predicted to be $1.003 \pm 0.0001$ and the measurement gives $0.745 \pm$

$0.09 \pm 0.036$. Similarly, some deviations from the SM predictions are present in the $B$ decays into $D$ and $D^*$ mesons

$$R\left(D^{(*)}\right) \equiv \frac{\mathrm{Br}\left(B \to D^{(*)}\tau\nu\right)}{\mathrm{Br}\left(B \to D^{(*)}l\nu\right)}\,. \tag{8}$$

Also, certain angular distributions in the decay $B \to K^*\mu\mu$ do not agree with the SM predictions. Although far from being fully convincing, those results have attracted a lot of theoretical speculations. No plausible explanation of all those effects simultaneously have been found but several options are opened for explaining some of them. This is illustrated in Fig. 2.

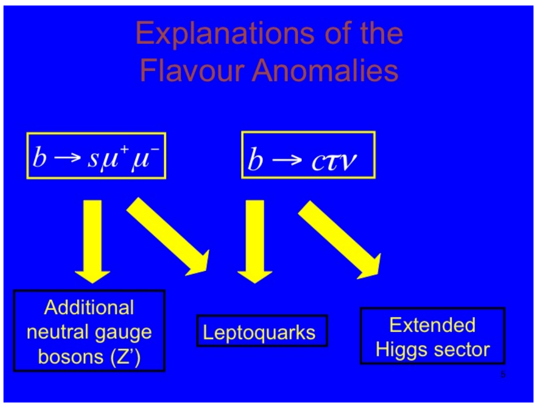



Fig. 2.

## 5. Summary

The results of the LHC experiments will shape particle physics for the next decades. Motivated by the issue of naturalness, searches for new particles have been mostly focused on new light coloured particles and the missing transverse energy signature (MET). However, such particles may be more hidden than suggested by the simplest models. It is conceivable that the particle spectrum in the extension of the SM is such that the MET is too small to be seen, or that the solution to the naturalness problem does not require new coloured degrees of freedom as light as widely expected (*e.g.* because the Higgs mass is further protected or it is protected by colourless degrees of freedom) or our present view on the naturalness issue is misleading. Then, the electroweak sector may play the leading role in discovering the BSM physics. Further progress in experimental techniques for discovering long-lived particles such as anomalous ionization energy loss, disappearing tracks or displaced vertices might be very helpful, and an exciting possibility is that something that has not been ordered is confirmed. It will be then a challenge to incorporate it into a more complete theoretical framework.

This work is supported by the National Science Centre, Poland, under research grants DEC-2014/15/B/ST2/02157, DEC-2012/04/A/ST2/00099 and DEC-2015/18/M/ST2/00054.

## REFERENCES

[1] G. Degrassi *et al.*, *J. High Energy Phys.* **1208**, 098 (2012) [arXiv:1205.6497 [hep-ph]].
[2] D. Buttazzo *et al.*, *J. High Energy Phys.* **1312**, 089 (2013) [arXiv:1307.3536 [hep-ph]].
[3] N.F. Martin *et al.*, *Mon. Not. R. Astron. Soc.* **380**, 281 (2007) [arXiv:0705.4622 [astro-ph]].
[4] N. Arkani-Hamed, A.G. Cohen, H. Georgi, *Phys. Lett. B* **513**, 232 (2001) [arXiv:hep-ph/0105239].
[5] K. Agashe, R. Contino, A. Pomarol, *Nucl. Phys. B* **719**, 165 (2005) [arXiv:hep-ph/0412089].
[6] A. Birkedal, Z. Chacko, M.K. Gaillard, *J. High Energy Phys.* **0410**, 036 (2004) [arXiv:hep-ph/0404197].
[7] P.H. Chankowski, A. Falkowski, S. Pokorski, J. Wagner, *Phys. Lett. B* **598**, 252 (2004) [arXiv:hep-ph/0407242].
[8] Z. Berezhiani, P.H. Chankowski, A. Falkowski, S. Pokorski, *Phys. Rev. Lett.* **96**, 031801 (2006) [arXiv:hep-ph/0509311].
[9] A. Falkowski, S. Pokorski, M. Schmaltz, *Phys. Rev. D* **74**, 035003 (2006) [arXiv:hep-ph/0604066].
[10] S. Chang, L.J. Hall, N. Weiner, *Phys. Rev. D* **75**, 035009 (2007) [arXiv:hep-ph/0604076].
[11] M. Badziak *et al.*, *J. High Energy Phys.* **1511**, 053 (2015) [arXiv:1506.07177 [hep-ph]].
[12] Z. Chacko, H.S. Goh, R. Harnik, *Phys. Rev. Lett.* **96**, 231802 (2006) [arXiv:hep-ph/0506256].
[13] N. Craig, A. Katz, M. Strassler, R. Sundrum, *J. High Energy Phys.* **1507**, 105 (2015) [arXiv:1501.05310 [hep-ph]].
[14] N. Craig, K. Howe, *J. High Energy Phys.* **1403**, 140 (2014) [arXiv:1312.1341 [hep-ph]].
[15] G. Burdman, Z. Chacko, H.S. Goh, R. Harnik, *J. High Energy Phys.* **0702**, 009 (2007) [arXiv:hep-ph/0609152].

[16] R. Franceschini *et al.*, *J. High Energy Phys.* **1603**, 144 (2016) [arXiv:1512.04933 [hep-ph]].
[17] S.D. McDermott, P. Meade, H. Ramani, *Phys. Lett. B* **755**, 353 (2016) [arXiv:1512.05326 [hep-ph]].
[18] J. Ellis *et al.*, *J. High Energy Phys.* **1603**, 176 (2016) [arXiv:1512.05327 [hep-ph]].
[19] R.S. Gupta *et al.*, arXiv:1512.05332 [hep-ph].
[20] R. Martinez, F. Ochoa, C.F. Sierra, arXiv:1512.05617 [hep-ph].
[21] S. Fichet, G. von Gersdorff, C. Royon, *Phys. Rev. D* **93**, 075031 (2016) [arXiv:1512.05751 [hep-ph]].
[22] L. Bian, N. Chen, D. Liu, J. Shu, *Phys. Rev. D* **93**, 095011 (2016) [arXiv:1512.05759 [hep-ph]].
[23] A. Falkowski, O. Slone, T. Volansky, *J. High Energy Phys.* **1602**, 152 (2016) [arXiv:1512.05777 [hep-ph]].
[24] Y. Bai, J. Berger, R. Lu, *Phys. Rev. D* **93**, 076009 (2016) [arXiv:1512.05779 [hep-ph]].
[25] M. Dhuria, G. Goswami, arXiv:1512.06782 [hep-ph].
[26] I. Chakraborty, A. Kundu, *Phys. Rev. D* **93**, 055003 (2016) [arXiv:1512.06508 [hep-ph]].
[27] F. Wang, L. Wu, J. M. Yang, M. Zhang, *Phys. Lett. B* **759**, 191 (2016) [arXiv:1512.06715 [hep-ph]].
[28] A.E. Cárcamo Hernández, I. Nisandzic, arXiv:1512.07165 [hep-ph].
[29] W.-C. Huang, Y.-L. Sming Tsai, T.-C. Yuan, *Nucl. Phys. B* **909**, 122 (2016) [arXiv:1512.07268 [hep-ph]].
[30] M. Badziak, *Phys. Lett. B* **759**, 464 (2016) [arXiv:1512.07497 [hep-ph]].
[31] M. Cvetič, J. Halverson, P. Langacker, arXiv:1512.07622 [hep-ph].
[32] B.C. Allanach, P.S.B. Dev, S.A. Renner, K. Sakurai, *Phys. Rev. D* **93**, 115022 (2016) [arXiv:1512.07645 [hep-ph]].
[33] K. Cheung *et al.*, arXiv:1512.07853 [hep-ph].
[34] J. Zhang, S. Zhou, *Chin. Phys. C* **40**, 081001 (2016) [arXiv:1512.07889 [hep-ph]].
[35] L.J. Hall, K. Harigaya, Y. Nomura, *J. High Energy Phys.* **1603**, 017 (2016) [arXiv:1512.07904 [hep-ph]] .
[36] F. Wang *et al.*, arXiv:1512.08434 [hep-ph].
[37] A. Salvio, A. Mazumdar, *Phys. Lett. B* **755**, 469 (2016) [arXiv:1512.08184 [hep-ph]].
[38] M. Son, A. Urbano, *J. High Energy Phys.* **1605**, 181 (2016) [arXiv:1512.08307 [hep-ph]].
[39] C. Cai, Z.-H. Yu, H.-H. Zhang, *Phys. Rev. D* **93**, 075033 (2016) [arXiv:1512.08440 [hep-ph]].

[40] N. Bizot, S. Davidson, M. Frigerio, J.L. Kneur, *J. High Energy Phys.* **1603**, 073 (2016) [arXiv:1512.08508 [hep-ph]].

[41] Y. Hamada, T. Noumi, S. Sun, G. Shiu, *Phys. Rev. D* **93**, 123514 (2016) [arXiv:1512.08984 [hep-ph]].

[42] S.K. Kang, J. Song, *Phys. Rev. D* **93**, 115012 (2016) [arXiv:1512.08963 [hep-ph]].

[43] Y. Jiang, Y.-Y. Li, T. Liu, *Phys. Lett. B* **759**, 345 (2016) [arXiv:1512.09127 [hep-ph]].

[44] S. Jung, J. Song, Y.W. Yoon, *J. High Energy Phys.* **1605**, 009 (2016) [arXiv:1601.00006 [hep-ph]].

[45] J. Gu, Z. Liu, *Phys. Rev. D* **93**, 075006 (2016) [arXiv:1512.07624 [hep-ph]].

[46] F. Goertz, J.F. Kamenik, A. Katz, M. Nardecchia, *J. High Energy Phys.* **1605**, 187 (2016) [arXiv:1512.08500 [hep-ph]].

[47] P. Ko, Y. Omura, C. Yu, *J. High Energy Phys.* **1604**, 098 (2016) [arXiv:1601.00586 [hep-ph]].

[48] E. Palti, *Nucl. Phys. B* **907**, 597 (2016) [arXiv:1601.00285 [hep-ph]].

[49] A. Karozas, S.F. King, G.K. Leontaris, A.K. Meadowcroft, *Phys. Lett. B* **757**, 73 (2016) [arXiv:1601.00640 [hep-ph]].

[50] S. Bhattacharya, S. Patra, N. Sahoo, N. Sahu, *J. Cosmol. Astropart. Phys.* **1606**, 010 (2016) [arXiv:1601.01569 [hep-ph]] .

[51] J. Cao *et al.*, *Eur. Phys. J. C* **76**, 239 (2016) [arXiv:1601.02570 [hep-ph]].

[52] A.E. Faraggi, J. Rizos, *Eur. Phys. J. C* **76**, 170 (2016) [arXiv:1601.03604 [hep-ph]].

[53] X.-F. Han, L. Wang, J. M. Yang, *Phys. Lett. B* **757**, 537 (2016) [arXiv:1601.04954 [hep-ph]].

[54] J. Kawamura, Y. Omura, *Phys. Rev. D* **93**, 115011 (2016) [arXiv:1601.07396 [hep-ph]].

[55] S.F. King, R. Nevzorov, *J. High Energy Phys.* **1603**, 139 (2016) [arXiv:1601.07242 [hep-ph]].

[56] T. Nomura, H. Okada, *Phys. Lett. B* **756**, 295 (2016) [arXiv:1601.07339 [hep-ph]].

[57] K. Harigaya, Y. Nomura, *J. High Energy Phys.* **1603**, 091 (2016) [arXiv:1602.01092 [hep-ph]] .

[58] C. Han, T.T. Yanagida, N. Yokozaki, *Phys. Rev. D* **93**, 055025 (2016) [arXiv:1602.04204 [hep-ph]].

[59] Y. Hamada, H. Kawai, K. Kawana, K. Tsumura, arXiv:1602.04170 [hep-ph].

[60] K.J. Bae, M. Endo, K. Hamaguchi, T. Moroi, *Phys. Lett. B* **757**, 493 (2016) [arXiv:1602.03653 [hep-ph]].

[61] A. Salvio, F. Staub, A. Strumia, A. Urbano, *J. High Energy Phys.* **1603**, 214 (2016) [arXiv:1602.01460 [hep-ph]].

[62] R. Barbieri, D. Buttazzo, L.J. Hall, D. Marzocca, arXiv:1603.00718 [hep-ph].

[63] M. Badziak, M. Olechowski, S. Pokorski, K. Sakurai, arXiv:1603.02203 [hep-ph].

[64] A. Pilaftsis, *Phys. Rev. D* **93**, 015017 (2016) [arXiv:1512.04931 [hep-ph]].

[65] P.S. Buhpal Dev, D. Teresi, arXiv:1512.07243 [hep-ph].

[66] P.S. Bhupal Dev, R.N. Mohapatra, Y. Zhang, *J. High Energy Phys.* **1602**, 186 (2016) [arXiv:1512.08507 [hep-ph]].

[67] C. Arbeláez, A. E. Cárcamo Hernández, S. Kovalenko, I. Schmidt, arXiv:1602.03607 [hep-ph].

[68] A.E. Cárcamo Hernández, I. de Medeiros Varzielas, E. Schumacher, arXiv:1601.00661 [hep-ph].

[69] A.E. Cárcamo Hernández, arXiv:1512.09092 [hep-ph].

[70] S.-F. Ge, H.-J. He, J. Ren, Z.-Z. Xianyu, *Phys. Lett. B* **757**, 480 (2016) [arXiv:1602.01801 [hep-ph]].

[71] W. Chao, arXiv:1601.04678 [hep-ph].

[72] W. Chao, arXiv:1601.00633 [hep-ph].

[73] X.-F. Han, L. Wang, *Phys. Rev. D* **93**, 055027 (2016) [arXiv:1512.06587 [hep-ph]].

[74] X.-F. Han *et al.*, *Phys. Lett. B* **756**, 309 (2016) [arXiv:1601.00534 [hep-ph]].

[75] L.A. Anchordoqui *et al.*, *Phys. Lett. B* **755**, 312 (2016) [arXiv:1512.08502 [hep-ph]].

[76] K. Harigaya, Y. Nomura, *Phys. Lett. B* **754**, 151 (2016) [arXiv:1512.04850 [hep-ph]].