PROCEEDINGS OF SCIENCE

Anomalies in Particle Physics

Andreas Crivellin[a,b,*] **and Bruce Mellado**[c,d]

[a] *Laboratory for Particle Physics, PSI Center for Neutron and Muon Sciences, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland*

[b] *Physik-Institut, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland*

[c] *School of Physics and Institute for Collider Particle Physics, University of the Witwatersrand, Wits, 2050 Johannesburg, South Africa*

[d] *iThemba LABS, National Research Foundation, PO Box 722, Somerset West, 7129 South Africa*

E-mail: andreas.crivellin@psi.ch

We give an updated overview of anomalies, i.e. measured deviations from the Standard Model predictions, in particle physics based on Ref. [1]. They range from the nuclear scale to the electroweak scale to the TeV scale, therefore spanning four orders of magnitude. After discussing the experimental and theoretical status of the anomalies, we summarize possible explanations in terms of new physics. In particular, the indications for new Higgs bosons at the EW scale received additional support recently.

31st International Workshop on Deep Inelastic Scattering (DIS2024)
8–12 April 2024
Grenoble, France

*Speaker

PoS(DIS2024)007

1. Introduction

The Standard Model (SM) of particle physics is the currently accepted mathematical description of the fundamental constituents of matter and their interactions (excluding gravity). With the Higgs discovery at the Large Hadron Collider (LHC) at CERN in 2012 the SM is complete. Furthermore, it has been extensively and successfully tested experimentally [2].

However, it cannot be the ultimate fundamental theory of Nature: In addition to many theoretical arguments for the existence of beyond the SM (BSM) physics, the SM e.g. cannot account for the observations of Dark Matter (DM) nor for the non-vanishing neutrino masses. Unfortunately, no right-handed neutrinos have been observed and Dark Matter direct detection experiments did not see any signal. Furthermore, there are many options for how SM can be extended, spanning a very large mass range (from several keV to the scale of Grand Unification at around 10^{15} GeV), to account for Dark Matter or neutrino masses. Therefore, more experimental information on BSM physics, preferably deviations from the SM predictions (in the best case in the form of new resonances), is imperative to make progress towards a theory superseding the SM.

In fact, an increasing number of hints for new physics (NP), i.e. deviations from the SM predictions called “anomalies”, have been reported [1] which we will review in these proceedings.[1]

2. Anomalies and New Physics

An anomaly is usually defined as a deviation from a rule. In particle physics, this means a discrepancy between the experimental data and the corresponding SM prediction. Here we employ the following criteria for an anomaly:

- A combined global statistical significance of at least 3σ (including the look-elsewhere effect).
- The experimental signature includes more than a single channel (or observable) or is measured by more than one independent experiment.
- The deviation should be explainable by a theoretically robust model without grossly violating constraints from other measurements.

Importantly, if any anomaly in direct or indirect searches were confirmed beyond a reasonable doubt, this would inevitably imply the breakdown of the SM and require its extensions by new particles and new interactions.

For a renormalizable extension of the SM, only scalar bosons (spin 0), fermions (spin 1/2) and vector bosons (spin 1) are possible. In the latter case, a Higgs-like mechanism of spontaneous symmetry-breaking is needed. Here we will focus on the following extensions of the SM:

- Leptoquarks (LQs): Scalar or vector bosons that carry colour and couple quarks directly to leptons [6].
- Di-quarks (DQs): Scalar bosons that are either triplets or sextets of $SU(3)_c$ and couple to a quark and an anti-quark.

[1]Note that due to the latest calculation of the hadronic light-by-light contribution by the BMW collaboration [3], which leads, as well as the CMD III measurement of $e^+e^- \to$hadrons [4], to a SM prediction in agreement with the direct measurement, we do not include $g-2$ of the muon in the list of anomalies anymore. Similarly, due to the latest search for first-generation leptoquarks of CMS [5], we also removed the excesses in non-resonant di-electrons from this list.

- Z' bosons: Neutral heavy vector bosons. They can be singlets under $SU(2)_L$ but also the neutral component of an $SU(2)_L$ multiplet.
- W' bosons: Electrically charged but QCD neutral vector particles.
- Vector-like Quarks (VLQs): Colored fermions with left-handed and right-handed fields heaving the same quantum numbers.
- Vector-like Leptons (VLLs): QCD neutral fermions with left-handed and right-handed fields heaving the same quantum numbers.
- New scalars (S): Color-neutral Higgs bosons
- Heavy gluons (G'): Heavy vector which is electrically neutral but charged under QCD.

3. Status and Explanations of the Anomalies

3.1 The 17 MeV Anomaly in excited nuclei decays ($X17$)

The nuclear reaction ^{7}Li(p,e$^+$e$^-$)^{8}Be [7], and similar decays of excited ^{4}He and ^{12}C nuclei [8, 9], show an excess consistent with a new particle with a mass of $\approx$ 17 MeV (6σ) in all decay modes [10]. However, the possibility of an SM effect is still not excluded [11]. From parity consideration (in the case of CP conservation) only the pseudo-scalar option remains valid [12].

3.2 Anomalies in electron neutrino appearance and disappearance (ν_e)

Electron neutrino appearance anomalies are reported by LSND [13] and MiniBooNE [14] ($\approx 4\sigma$). However, a reanalysis of the theoretical uncertainties leads to a smaller tension [15]. A first combined analysis of MiniBooNE and MicroBooNE data [16] within the SM plus a single sterile neutrino finds a preference of 3.4σ [17], and once constraints from MINOS and IceCube are included, the preference for sterile-active neutrino mixing is further diminished [18]. Therefore, more exotic NP options are considered (see Ref. [19] for a review).

Anomalies suggesting the disappearance of electron neutrinos are observed in the Gallium radioactive source experiments GALLEX [20] and SAGE [21] ($\approx 5\sigma$). However, hadronic effects might be underestimated [22]. A straightforward explanation in terms of active-sterile neutrino oscillations is excluded by solar and reactor neutrino experiments [23, 24] such that again more exotic options are considered (see Ref. [22] for a review).

3.3 β-Decay Anomalies (β)

A deficit in first-row CKM unitarity exists and there is a disagreement between the determinations of V_{us} from $K \to \mu\nu$ and $K \to \pi\ell\nu$ decays [25]. Both tensions are slightly below the 3σ level. A sub per mille effect suffices to explain these tensions, e.g. via vector-like quarks (see Ref. [26] for review).

There is also a significant tension ($\approx 4\sigma$) between the neutron lifetime (and thus V_{ud}) determined from beam [27] and bottle experiments [28]. Since in bottle experiments the remaining neutrons are counted, while beam experiments count the decay protons, if the branching ratio of neutrons to final states with protons is not 100%, the lifetime measured in beam experiments would be larger than the real neutron lifetime. Therefore, neutron oscillations into mirror neutrons [29] or neutron decay to light dark matter particles could explain the anomaly while providing a stable proton for fine-tuned mass configurations [30].

PoS(DIS2024)007

3.4 Hadronic meson decays ($M \to mm'$)

SM predictions for $\mathrm{Br}(\bar{B} \to D^{(*)}K)$ and $\mathrm{Br}(\bar{B}_s \to D_s^{(*)}\pi)$ [31] based on QCD factorization [32] deviate from the corresponding measurements [2] by a combined significance of 5.6σ. However, QCD uncertainties might be underestimated [33] and, since it is a tree-level in the SM, a NP explanation such as both W' models [34] and di-quarks are challenged by LHC constraints [35].

The CP asymmetry between $D \to KK$ and $D \to \pi^+\pi^-$ is given by $\Delta A_{CP}^{\mathrm{LHCb}} = (-15.4 \pm 2.9) \times 10^{-4}$ [36]. The corresponding SM prediction, which is notoriously difficult for charm physics, is $|\Delta A_{CP}^{\mathrm{LHCb}}| < 3.6 \times 10^{-4}$ [37]. Furthermore, the CP asymmetry in $D \to K^+K^-$ [38] allows for a test of U-spin symmetry of the SM and shows indications of a violation of it [39]. NP explanations include Z' bosons and di-quarks [40] but are under pressure from LHC searches.

The long-standing $B \to K\pi$ puzzle [41, 42], supported by $B_s \to KK$ measurements [43], shows a significance of around 3σ [44]. Furthermore, there are indications of U-spin violation in polarization observables [45]. While an explanation via Z' bosons or heavy gluons is easier than in the cases discussed above [46], $B_s - \bar{B}_s$ mixing and LHC bounds are non-trivial.

3.5 Charged current tauonic B decays ($R(D^{(*)})$)

These charged current transitions have significant branching ratios (up to $O(10^{-2})$). However, the ratios (of branching ratios) $R(D^{(*)}) = \mathrm{Br}(B \to D^{(*)}\tau\nu)/\,\mathrm{Br}(B \to D^{(*)}\ell\nu))$, are measured to be bigger than the SM predictions by approximately 20%, resulting in a $\gtrsim 3\sigma$ significance [47] for NP related to tau leptons.

Because this transition occurs at tree-level in the SM, also a tree-level NP effect is necessary to obtain the needed effect (assuming heavy NP with perturbative couplings). However, also for LQs constraints from $B_s - \bar{B}_s$ mixing, $B \to K^{(*)}\nu\nu$ and LHC searches must be respected. Therefore, for charged Higgses only a small corner of parameter space is left over [48] while the $SU(2)_L$ singlet vector LQ [49] and the singlet-triplet model [50] have somewhat more parameter space left. See Ref. [51] for a review.

3.6 Flavour changing neutral current semi-leptonic B decays ($b \to s\ell^+\ell^-$)

Like all flavour changing neutral current processes, $b \to s\ell^+\ell^-$ transitions are loop suppressed and several observables significantly deviate from the SM predictions. This includes the angular observable P_5' [52] (recently confirmed by CMS [53]), the total branching ratio $\mathrm{Br}(B \to K\mu^+\mu^-)$ [54, 55], $\mathrm{Br}(B_s \to \phi\mu^+\mu^-)$ [56, 57] and also semi-inclusive observables [58]. As a result, global fits find a preference for NP at the 5σ level [59]. The measurements of $R(K^{(*)})$ require dominantly lepton flavour universal NP and $B_s \to \mu^+\mu^-$ constrains axial couplings to leptons, such that an $O(20\%)$ lepton-flavour universal effect (w.r.t. the SM) in C_9 is preferred [60].

This can be achieved by a Z' boson with lepton flavour universal but flavour-violating couplings to bottom and strange quarks [61, 62]. However, due to the bounds from $B_s - \bar{B}_s$ mixing, in combination with LHC and LEP bounds, a full explanation requires some tuning in $B_s - \bar{B}_s$ mixing by a right-handed sb coupling [63] or a cancellation with Higgs boson contributions [64]. Alternatively, τ or charm loops via an off-shell photon penguin [65] can generate C_9^U. The LQs which can give such a tau loop are S_2 LQ [66], the U_1 LQ [67] or the combination of $S_1 + S_3$ [68].

PoS(DIS2024)007

The 2HDM with generic flavour structure [69, 70] and DQ models [71] are also viable options. See Ref. [51] for a review.

3.7 W boson mass (m_W)

The CDF II result [72] for the W mass shows a strong 7σ tension with the SM prediction. However, LHCand LEP results are closer to the SM (1.8σ above the SM) and are thus in tension with the CDF-II value. Therefore, employing a conservative error estimate reduced the combined significance to $3.7\,\sigma$ [77].

The tension in the W mass is most easily explained by a tree-level effect, e.g. an $SU(2)_L$ scalar triplet that acquires a vacuum expectation value or via $Z-Z'$ mixing. However, loop effects of new particles with masses below or at the TeV scale are possible as well (see Ref. [78] for an overview).

3.8 LHC Multi-Lepton Anomalies ($e\mu(+b)$)

The "multi-lepton anomalies", are LHC processes with two or more leptons in the final state (see Ref. [1, 79] for recent reviews), with and without b-jets, where statistically significant disagreements with the SM predictions have been observed. They are most pronounced in the differential lepton distributions of top-quark pair measurements ($> 5\sigma$) [80, 81] such that ATLAS concludes [82]: "No model (SM simulation) can describe all measured distributions within their uncertainties." While missing QCD corrections or toponium might reduce these tensions, also discrepancies in $pp \to WW$ in the opposite sign different flavour lepton mode are observed in the jet-veto category [83, 84] which is expected to be quite insensitive to QCD corrections.

Prime candidates for an explanation are EW scale new Higgses decaying to WW. In particular, in Ref. [85] a UV complete model was proposed which explains the $t\bar{t}$ differential distributions as well as $WW+0j$.

3.9 Higgs-like resonant signals (YY)

There are hints for di-photon resonances at 95 GeV [86–88] and at $\approx$ 152 GeV [89]. The hint at 95 GeV is supported by a ZH signal (with $H \to b\bar{b}$) by LEP [90] as well as the WW channel [83, 84] leading to a combined global significance of 3.4σ [91]. The indications for a new resonance in $\gamma\gamma$ final states at $\approx$152 GeV are most pronounced in associated production channels [92] and WW+missing energy [84]. Combining all channels within a simplified model with $pp \to H \to SS^*$ (with $m_H \approx 270$ GeV and $m_S \approx 152$ GeV), results in a global significance of 3.9σ [93].

These hints for resonances point towards the extension of the Higgs boson sector of the SM because only scalars can decay to photons. For the 95 GeV excess, at least an $SU(2)_L$ doublet [94], triplet [95] or a more complex scalar sector is needed [96]. The 152 GeV excess can be accounted for by adding a doublet [97] or a triplet [98]. In both cases, a significance at or above 4σ is obtained. Furthermore, the model of Ref. [85] provides a combined explanation of the 95 GeV and 152 GeV excesses and the multi-lepton anomalies.

3.10 (di-)di-jet resonances ($jj(-jj)$)

ATLAS [99] observed a weaker-than-expected limit in resonant di-jet searches slightly below 1 TeV and CMS [100] found hints for the (non-resonant) pair production of di-jet resonances with a

PoS(DIS2024)007

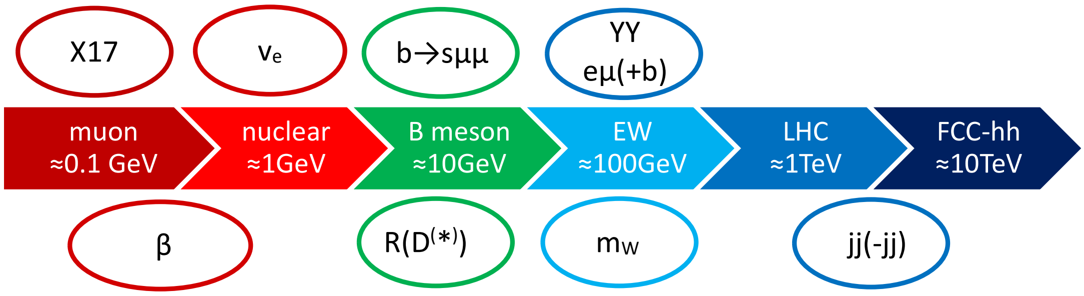

Figure 1: Overview of the anomalies ordered by increasing energy.

mass of ≈ 950 GeV with a local (global) significance of 3.6σ (2.5σ). Furthermore, considering the process $pp \to Y^{(*)} \to XX \to (jj)(jj)$ Ref. [101] finds a global 3.2σ significance at $m_Y \approx 3.6$ TeV. ATLAS finds a di-di-jet excesses [102] at ≈ 3.3 TeV with a di-jet mass of 850 GeV which could be compatible with the CMS one once the quite poor jet energy resolution is taken into account. As explanations, two options come to mind [101]: two scalar DQ or new massive gluons seem to be the most plausible candidates.

4. Comparison, conclusions and outlook

The anomalies observed in particle physics are summarized in Fig. 1, together with their corresponding energy scale, showing that they range over at least five orders of magnitude. While one cannot expect that all anomalies will be confirmed, it is also statistically unlikely that all will disappear. Many extensions for explaining the anomalies point towards new Higgs-like scalars. In particular, the agreement between the mass of the scalar suggested by the multi-lepton anomalies and the $\gamma\gamma$ excesses around 152 GeV is striking. LQ are also interesting candidates and allow for a combined and correlated explanation of $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$ via the tau-loop.

Acknowledgements

A.C. thanks the organizers of DIS 2024, especially Ingo Schienbein, for the excellent organisation of this great conference. The work of A.C. is supported by a professorship grant from the Swiss National Science Foundation (No. PP00P2_211002). B.M. wants to thank the Department of Science and Innovation and the National Research Foundation for various forms of support.

References

[1] A. Crivellin and B. Mellado, Nature Rev. Phys. **6** (2024) no.5, 294-309 [arXiv:2309.03870 [hep-ph]].

[2] R. L. Workman *et al.* [Particle Data Group], PTEP **2022** (2022), 083C01

[3] A. Boccaletti, S. Borsanyi, M. Davier, Z. Fodor, F. Frech, A. Gerardin, D. Giusti, A. Y. Kotov, L. Lellouch and T. Lippert, *et al.* [arXiv:2407.10913 [hep-lat]].

[4] F. V. Ignatov *et al.* [CMD-3], Phys. Rev. Lett. **132** (2024) no.23, 231903 [arXiv:2309.12910 [hep-ex]].

[5] [CMS], CMS-PAS-EXO-22-013.

[6] W. Buchmuller, R. Ruckl and D. Wyler, Phys. Lett. B **191** (1987), 442-448 [erratum: Phys. Lett. B **448** (1999), 320-320]

[7] A. J. Krasznahorkay, M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, T. J. Ketel, A. Krasznahorkay, I. Kuti and B. M. Nyakó, *et al.* Phys. Rev. Lett. **116** (2016) no.4, 042501 [arXiv:1504.01527 [nucl-ex]].

[8] A. J. Krasznahorkay, M. Csatlós, L. Csige, J. Gulyás, A. Krasznahorkay, B. M. Nyakó, I. Rajta, J. Timár, I. Vajda and N. J. Sas, Phys. Rev. C **104** (2021) no.4, 044003 [arXiv:2104.10075 [nucl-ex]].

[9] A. J. Krasznahorkay, A. Krasznahorkay, M. Begala, M. Csatlós, L. Csige, J. Gulyás, A. Krakó, J. Timár, I. Rajta and I. Vajda, *et al.* Phys. Rev. C **106** (2022) no.6, L061601 [arXiv:2209.10795 [nucl-ex]].

[10] D. S. M. Alves, D. Barducci, G. Cavoto, L. Darmé, L. Delle Rose, L. Doria, J. L. Feng, A. Frankenthal, A. Gasparian and E. Goudzovski, *et al.* Eur. Phys. J. C **83** (2023) no.3, 230

[11] A. Aleksejevs, S. Barkanova, Y. G. Kolomensky and B. Sheff, [arXiv:2102.01127 [hep-ph]].

[12] C. J. G. Mommers and M. Vanderhaeghen, [arXiv:2406.08143 [hep-ph]].

[13] A. Aguilar *et al.* [LSND], beam," Phys. Rev. D **64** (2001), 112007 [arXiv:hep-ex/0104049 [hep-ex]].

[14] A. A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **121** (2018) no.22, 221801 [arXiv:1805.12028 [hep-ex]].

[15] V. Brdar and J. Kopp, Phys. Rev. D **105** (2022) no.11, 115024 [arXiv:2109.08157 [hep-ph]].

[16] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) no.24, 241801 [arXiv:2110.14054 [hep-ex]].

[17] A. A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **129** (2022) no.20, 201801 [arXiv:2201.01724 [hep-ex]].

[18] M. Dentler, Á. Hernández-Cabezudo, J. Kopp, P. A. N. Machado, M. Maltoni, I. Martinez-Soler and T. Schwetz, JHEP **08** (2018), 010 [arXiv:1803.10661 [hep-ph]].

[19] M. A. Acero, C. A. Argüelles, M. Hostert, D. Kalra, G. Karagiorgi, K. J. Kelly, B. Littlejohn, P. Machado, W. Pettus and M. Toups, *et al.* [arXiv:2203.07323 [hep-ex]].

[20] F. Kaether, W. Hampel, G. Heusser, J. Kiko and T. Kirsten, Phys. Lett. B **685** (2010), 47-54 [arXiv:1001.2731 [hep-ex]].

PoS(DIS2024)007

[21] J. N. Abdurashitov *et al.* [SAGE], Phys. Rev. C **80** (2009), 015807 [arXiv:0901.2200 [nucl-ex]].

[22] V. Brdar, J. Gehrlein and J. Kopp, JHEP **05** (2023), 143 [arXiv:2303.05528 [hep-ph]].

[23] C. Giunti, Y. F. Li, C. A. Ternes and Z. Xin, Phys. Lett. B **829** (2022), 137054 [arXiv:2110.06820 [hep-ph]].

[24] J. M. Berryman, P. Coloma, P. Huber, T. Schwetz and A. Zhou, JHEP **02** (2022), 055 [arXiv:2111.12530 [hep-ph]].

[25] V. Cirigliano, A. Crivellin, M. Hoferichter and M. Moulson, Phys. Lett. B **838** (2023), 137748 [arXiv:2208.11707 [hep-ph]].

[26] A. Crivellin, [arXiv:2207.02507 [hep-ph]].

[27] A. T. Yue, M. S. Dewey, D. M. Gilliam, G. L. Greene, A. B. Laptev, J. S. Nico, W. M. Snow and F. E. Wietfeldt, Phys. Rev. Lett. **111** (2013) no.22, 222501 [arXiv:1309.2623 [nucl-ex]].

[28] F. M. Gonzalez *et al.* [UCNτ], Phys. Rev. Lett. **127** (2021) no.16, 162501 [arXiv:2106.10375 [nucl-ex]].

[29] Z. Berezhiani, Eur. Phys. J. C **79** (2019) no.6, 484 [arXiv:1807.07906 [hep-ph]].

[30] B. Fornal and B. Grinstein, Phys. Rev. Lett. **120** (2018) no.19, 191801 [erratum: Phys. Rev. Lett. **124** (2020) no.21, 219901] [arXiv:1801.01124 [hep-ph]].

[31] M. Bordone, N. Gubernari, T. Huber, M. Jung and D. van Dyk, Eur. Phys. J. C **80** (2020) no.10, 951 [arXiv:2007.10338 [hep-ph]].

[32] M. Beneke, G. Buchalla, M. Neubert and C. T. Sachrajda, Nucl. Phys. B **606** (2001), 245-321 [arXiv:hep-ph/0104110 [hep-ph]].

[33] M. L. Piscopo and A. V. Rusov, JHEP **10** (2023), 180 [arXiv:2307.07594 [hep-ph]].

[34] S. Iguro and T. Kitahara, Phys. Rev. D **102** (2020) no.7, 071701 [arXiv:2008.01086 [hep-ph]].

[35] M. Bordone, A. Greljo and D. Marzocca, JHEP **08** (2021), 036 [arXiv:2103.10332 [hep-ph]].

[36] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **122** (2019) no.21, 211803 [arXiv:1903.08726 [hep-ex]].

[37] M. Chala, A. Lenz, A. V. Rusov and J. Scholtz, JHEP **07** (2019), 161 [arXiv:1903.10490 [hep-ph]].

[38] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **131** (2023) no.9, 091802 [arXiv:2209.03179 [hep-ex]].

[39] R. Bause, H. Gisbert, G. Hiller, T. Höhne, D. F. Litim and T. Steudtner, Phys. Rev. D **108** (2023) no.3, 035005 [arXiv:2210.16330 [hep-ph]].

[40] W. Altmannshofer, R. Primulando, C. T. Yu and F. Yu, JHEP **04** (2012), 049 [arXiv:1202.2866 [hep-ph]].

PoS(DIS2024)007

[41] A. J. Buras, R. Fleischer, S. Recksiegel and F. Schwab, Phys. Rev. Lett. **92** (2004), 101804 [arXiv:hep-ph/0312259 [hep-ph]].

[42] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **126** (2021) no.9, 091802 [arXiv:2012.12789 [hep-ex]].

[43] R. Aaij *et al.* [LHCb], Phys. Rev. D **98** (2018) no.3, 032004 [arXiv:1805.06759 [hep-ex]].

[44] R. Fleischer, R. Jaarsma and K. K. Vos, Phys. Lett. B **785** (2018), 525-529 [arXiv:1712.02323 [hep-ph]].

[45] M. Algueró, A. Crivellin, S. Descotes-Genon, J. Matias and M. Novoa-Brunet, JHEP **04** (2021), 066 [arXiv:2011.07867 [hep-ph]].

[46] L. Calibbi, A. Crivellin, F. Kirk, C. A. Manzari and L. Vernazza, Phys. Rev. D **101** (2020) no.9, 095003 [arXiv:1910.00014 [hep-ph]].

[47] Y. S. Amhis *et al.* [HFLAV], Phys. Rev. D **107** (2023) no.5, 052008 [arXiv:2206.07501 [hep-ex]].

[48] A. Crivellin and S. Iguro, Phys. Rev. D **110** (2024) no.1, 015014 [arXiv:2311.03430 [hep-ph]].

[49] L. Calibbi, A. Crivellin and T. Ota, Phys. Rev. Lett. **115** (2015), 181801 [arXiv:1506.02661 [hep-ph]].

[50] A. Crivellin, D. Müller and T. Ota, JHEP **09** (2017), 040 [arXiv:1703.09226 [hep-ph]].

[51] B. Capdevila, A. Crivellin and J. Matias, Eur. Phys. J. ST **1** (2023), 20 [arXiv:2309.01311 [hep-ph]].

[52] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **125** (2020) no.1, 011802 [arXiv:2003.04831 [hep-ex]].

[53] [CMS], CMS-PAS-BPH-21-002.

[54] R. Aaij *et al.* [LHCb], JHEP **06** (2014), 133 [arXiv:1403.8044 [hep-ex]].

[55] W. G. Parrott *et al.* [HPQCD], Phys. Rev. D **107** (2023) no.1, 014511 [erratum: Phys. Rev. D **107** (2023) no.11, 119903] [arXiv:2207.13371 [hep-ph]].

[56] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **127** (2021) no.15, 151801 [arXiv:2105.14007 [hep-ex]].

[57] N. Gubernari, M. Reboud, D. van Dyk and J. Virto, JHEP **09** (2022), 133 [arXiv:2206.03797 [hep-ph]].

[58] G. Isidori, Z. Polonsky and A. Tinari, Phys. Rev. D **108** (2023) no.9, 093008 [arXiv:2305.03076 [hep-ph]].

[59] M. Algueró, A. Biswas, B. Capdevila, S. Descotes-Genon, J. Matias and M. Novoa-Brunet, Eur. Phys. J. C **83** (2023) no.7, 648 [arXiv:2304.07330 [hep-ph]].

[60] M. Algueró, J. Matias, B. Capdevila and A. Crivellin, Phys. Rev. D **105** (2022) no.11, 113007 [arXiv:2205.15212 [hep-ph]].

PoS(DIS2024)007

[61] A. J. Buras and J. Girrbach, JHEP **12** (2013), 009 [arXiv:1309.2466 [hep-ph]].

[62] R. Gauld, F. Goertz and U. Haisch, Phys. Rev. D **89** (2014), 015005 [arXiv:1308.1959 [hep-ph]].

[63] A. Crivellin, L. Hofer, J. Matias, U. Nierste, S. Pokorski and J. Rosiek, Phys. Rev. D **92** (2015) no.5, 054013 [arXiv:1504.07928 [hep-ph]].

[64] A. Crivellin, G. D'Ambrosio and J. Heeck, Phys. Rev. D **91** (2015) no.7, 075006 [arXiv:1503.03477 [hep-ph]].

[65] C. Bobeth, U. Haisch, A. Lenz, B. Pecjak and G. Tetlalmatzi-Xolocotzi, JHEP **06** (2014), 040 [arXiv:1404.2531 [hep-ph]].

[66] A. Crivellin, B. Fuks and L. Schnell, JHEP **06** (2022), 169 [arXiv:2203.10111 [hep-ph]].

[67] A. Crivellin, C. Greub, D. Müller and F. Saturnino, Phys. Rev. Lett. **122** (2019) no.1, 011805 [arXiv:1807.02068 [hep-ph]].

[68] A. Crivellin, D. Müller and F. Saturnino, JHEP **06** (2020), 020 [arXiv:1912.04224 [hep-ph]].

[69] A. Crivellin, D. Müller and C. Wiegand, JHEP **06** (2019), 119 [arXiv:1903.10440 [hep-ph]].

[70] S. Iguro, Phys. Rev. D **107** (2023) no.9, 095004 [arXiv:2302.08935 [hep-ph]].

[71] A. Crivellin and M. Kirk, Phys. Rev. D **108** (2023) no.11, 11 [arXiv:2309.07205 [hep-ph]].

[72] T. Aaltonen *et al.* [CDF], Science **376** (2022) no.6589, 170-176

[73] M. Aaboud *et al.* [ATLAS], Eur. Phys. J. C **78** (2018) no.2, 110 [erratum: Eur. Phys. J. C **78** (2018) no.11, 898] [arXiv:1701.07240 [hep-ex]].

[74] S. Chatrchyan *et al.* [CMS], Phys. Rev. D **84** (2011), 112002 [arXiv:1110.2682 [hep-ex]].

[75] R. Aaij *et al.* [LHCb], JHEP **11** (2015), 190 [arXiv:1509.07645 [hep-ex]].

[76] R. Aaij *et al.* [LHCb], JHEP **01** (2022), 036 [arXiv:2109.01113 [hep-ex]].

[77] J. de Blas, M. Pierini, L. Reina and L. Silvestrini, Phys. Rev. Lett. **129** (2022) no.27, 271801 [arXiv:2204.04204 [hep-ph]].

[78] A. Strumia, JHEP **08** (2022), 248 [arXiv:2204.04191 [hep-ph]].

[79] O. Fischer, B. Mellado, S. Antusch, E. Bagnaschi, S. Banerjee, G. Beck, B. Belfatto, M. Bellis, Z. Berezhiani and M. Blanke, *et al.* Eur. Phys. J. C **82** (2022) no.8, 665 [arXiv:2109.06065 [hep-ph]].

[80] S. Buddenbrock, A. S. Cornell, Y. Fang, A. Fadol Mohammed, M. Kumar, B. Mellado and K. G. Tomiwa, JHEP **10** (2019), 157 [arXiv:1901.05300 [hep-ph]].

[81] S. Banik, G. Coloretti, A. Crivellin and B. Mellado, [arXiv:2308.07953 [hep-ph]].

[82] G. Aad *et al.* [ATLAS], JHEP **07** (2023), 141 [arXiv:2303.15340 [hep-ex]].

[83] S. von Buddenbrock, A. S. Cornell, A. Fadol, M. Kumar, B. Mellado and X. Ruan, J. Phys. G **45** (2018) no.11, 115003 [arXiv:1711.07874 [hep-ph]].

[84] G. Coloretti, A. Crivellin, S. Bhattacharya and B. Mellado, Phys. Rev. D **108** (2023) no.3, 035026 [arXiv:2302.07276 [hep-ph]].

[85] G. Coloretti, A. Crivellin and B. Mellado, [arXiv:2312.17314 [hep-ph]].

[86] [CMS], CMS-PAS-HIG-20-002.

[87] [ATLAS], ATLAS-CONF-2023-035.

[88] G. Aad *et al.* [ATLAS], JHEP **08** (2024), 164 [arXiv:2405.20040 [hep-ex]].

[89] G. Aad *et al.* [ATLAS], JHEP **10** (2021), 013 [arXiv:2104.13240 [hep-ex]].

[90] R. Barate *et al.* [LEP Working Group for Higgs boson searches, ALEPH, DELPHI, L3 and OPAL], Phys. Lett. B **565** (2003), 61-75 [arXiv:hep-ex/0306033 [hep-ex]].

[91] S. Bhattacharya, G. Coloretti, A. Crivellin, S. E. Dahbi, Y. Fang, M. Kumar and B. Mellado, [arXiv:2306.17209 [hep-ph]].

[92] G. Aad *et al.* [ATLAS], JHEP **07** (2023), 176 [arXiv:2301.10486 [hep-ex]].

[93] A. Crivellin, Y. Fang, O. Fischer, S. Bhattacharya, M. Kumar, E. Malwa, B. Mellado, N. Rapheeha, X. Ruan and Q. Sha, Phys. Rev. D **108** (2023) no.11, 115031 [arXiv:2109.02650 [hep-ph]].

[94] U. Haisch and A. Malinauskas, JHEP **03** (2018), 135 [arXiv:1712.06599 [hep-ph]].

[95] S. Ashanujjaman, S. Banik, G. Coloretti, A. Crivellin, B. Mellado and A. T. Mulaudzi, Phys. Rev. D **108** (2023) no.9, L091704 [arXiv:2306.15722 [hep-ph]].

[96] T. Biekötter, S. Heinemeyer and G. Weiglein, Eur. Phys. J. C **83** (2023) no.5, 450 [arXiv:2204.05975 [hep-ph]].

[97] S. Banik and A. Crivellin, [arXiv:2407.06267 [hep-ph]].

[98] A. Crivellin, S. Ashanujjaman, S. Banik, G. Coloretti, S. P. Maharathy and B. Mellado, [arXiv:2404.14492 [hep-ph]].

[99] M. Aaboud *et al.* [ATLAS], Phys. Rev. Lett. **121** (2018) no.8, 081801 [arXiv:1804.03496 [hep-ex]].

[100] A. Tumasyan *et al.* [CMS], JHEP **07** (2023), 161 [arXiv:2206.09997 [hep-ex]].

[101] A. Crivellin, C. A. Manzari, B. Mellado and S. E. Dahbi, Phys. Rev. D **107** (2023) no.5, 054045 [arXiv:2208.12254 [hep-ph]].

PoS(DIS2024)007

[102] G. Aad *et al.* [ATLAS], Phys. Rev. D **108** (2023) no.11, 112005 [arXiv:2307.14944 [hep-ex]].

[103] M. Fernández Navarro and S. F. King, JHEP **02** (2023), 188 [arXiv:2209.00276 [hep-ph]].

[104] J. Aebischer, G. Isidori, M. Pesut, B. A. Stefanek and F. Wilsch, Eur. Phys. J. C **83** (2023) no.2, 153 [arXiv:2210.13422 [hep-ph]].