PROCEEDINGS OF SCIENCE

Neutrinos and Beyond the Standard Model Searches

Michele Lucente[a,b,*]

[a] *Dipartimento di Fisica e Astronomia, Università di Bologna, via Irnerio 46, 40126 Bologna, Italy*

[b] *INFN, Sezione di Bologna, viale Berti Pichat 6/2, 40127, Bologna, Italy*

E-mail: michele.lucente@unibo.it

The massive nature of neutrinos provides a firm evidence for the existence of physics beyond the Standard Model, that in turn can give rise to a rich phenomenology in diverse experimental searches. We review the main features of the tree-level neutrino mass generation mechanisms, and, focusing on the extension of the Standard Model via the addition of Heavy Neutral Leptons, point to the specific phenomenology that is expected for minimal testable frameworks. We discuss the impact of an underlying lepton number symmetry on neutrinoless double beta decay, τ and meson decay and LHC searches.

The 17th International Conference on Heavy Quarks and Leptons (HQL 2025)
15-19 September, 2025
Peking University, Beijing, China

*Speaker

 ISSN 1824-8039 . Published by SISSA Medialab.

1. Introduction

The combined results from neutrino oscillations experiments [1–3] provide a firm evidence that neutrinos are massive and individual lepton flavours are not conserved, thus calling for the existence of new physics beyond the Standard Model (BSM). Remarkably, by interpreting the minimal Standard Model (SM) as an effective field theory (EFT), there exists a single five dimensional operator that, after the electroweak symmetry breaking, generates non-zero neutrino masses and lepton flavour mixing [4]

$$\mathcal{L}_{d=5} = \frac{1}{2}\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{\ell^c_{L\alpha}}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger \ell^\beta_L\right) + h.c.\,, \tag{1}$$

where ℓ_α is the lepton doublet of flavour α, ϕ is the Higgs doublet, $c_{\alpha\beta}$ is a matrix of dimensionless coefficients, and Λ is the new physics energy scale. In turn, the operator in Eq. (1) only admits three tree-level realisations [5, 6], as it can be mediated by heavy neutral leptons (Type-I Seesaw) [7–10], by a scalar triplet (Type-II Seesaw) [11–15] or by a fermion triplet (Type-III Seesaw) [16–23]. In this work we focus on the phenomenology of the first realisation, i.e. SM extended with heavy neutral leptons (HNL), that being gauge singlets can feature a comparatively low new physics scale, possibly accessible in current and future experiments.

2. Small neutrino masses from testable sterile singlets

The Type-I Seesaw represents a minimal and natural extension of the SM field content given that, in the minimal SM, every fermionic field appears in the two states of chirality, left and right, except for neutrinos. The addition of a number n of right-handed neutrino fields N_I allows for the new renormalizable and gauge-invariant terms in the Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\,\overline{N_I}\partial\!\!\!/\, N_I - \left(F_{\alpha I}\,\overline{\ell^\alpha_L}\,\tilde{\phi}\,N_I + \frac{M_{IJ}}{2}\overline{N^c_I}N_J + h.c.\right), \tag{2}$$

where $F_{\alpha I}$ denote the Yukawa couplings, M_{IJ} is a symmetric matrix of Majorana mass terms, and $I = 1, \ldots, n$.

After the electroweak symmetry breaking, a non-zero mass matrix for the light neutrinos is generated, according to

$$m_\nu = -v^2\, F\, M^{-1}\, F^T, \tag{3}$$

where $v \simeq 174$ GeV is the Higgs vev. Laboratory [24] and cosmology [25] constraints impose an upper bound on the value of neutrino masses of 1.1 eV and 0.12 eV, respectively. By employing the EFT approach of Eq. (1), we see that the phenomenological constraints impose the following hierarchy of scales to the model parameters

$$m_\nu^{\alpha\beta} = c_{\alpha\beta}\frac{v}{\Lambda}v \lesssim \text{eV} \ll v. \tag{4}$$

This implies two possibilities to account for the smallness of neutrino masses in this framework: one is that the new physics scale Λ is much larger than the electroweak vev v, $v/\Lambda \ll 1$. Alternatively, an equally viable possibility is that Λ lies around or below the electroweak scale, but the dimensionless coefficients $c_{\alpha\beta}$ are much smaller than unity. The second case can be realised due to an underlying

symmetry, e.g. if the Lagrangian features an approximated lepton number conservation [26–29], by accidental cancellations arising in the matrix equation Eq. (3), or simply by very feeble couplings in the UV complete theory.

The phenomenology of the HNLs is however very different depending on the actual suppression mechanism at play. Considering the full tower of non-renormalizable operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_5}{\Lambda} O^{d=5} + \frac{c_6^i}{\Lambda^2} O_i^{d=6} + \dots \tag{5}$$

we see that, given the five-dimensional operator $O^{d=5}$ is unique and accounts for light neutrino masses and mixings, any new physics effect that can disentangle between the different neutrino mass generation mechanisms is generated by the $d \geq 6$ operators. If the suppression of neutrino masses is only due to a hierarchy of scales or to feeble UV couplings, the same suppression will apply as well to the higher-dimensional operators, $c_6^i/\Lambda^2 \approx (m_\nu/v)^2$, making any new physics effect unobservable. If instead the suppression comes from the dimensionless coefficients, $c_5 \ll 1$, the same suppression does not necessarily apply to the higher-dimensional operators, and a model can give rise to sizeable $d = 6$ observable effects [6]. Notice that in this framework, an important difference arises between accidental cancellations and symmetry motivated scenarios: if the Lagrangian features an approximated symmetry protecting light neutrino masses, the same symmetry will apply at any perturbative order, thus making light neutrino masses stable under radiative corrections, even in the presence of sizeable Yukawa couplings and a low new physics scale. This is not the case if the cancellation is accidental, where higher-order effects can dominate over the tree-level result in Eq. (3), possibly rendering the predicted light neutrino masses incompatible with experimental constraints [30–32].

3. Heavy Neutral Lepton phenomenology

Heavy Neutral Leptons with masses in the MeV to TeV range can be searched for in various ways [33]. Their interactions with the SM particles are governed by the active-sterile mixing matrix $\mathcal{U}$, which in this minimal scenario determines both the production rates and decay widths.

Since we are interested in testable phenomenology, we focus here on symmetry-protected scenarios, considering the special role of lepton number L. It can be demonstrated that, in the SM extended with fermionic gauge singlets, there is an equivalence between L conservation and massless light neutrinos [29]. This implies thus, unless there are accidental cancellations in m_ν, the rate for L violating events is proportional to the small active neutrino masses, and thus suppressed in this minimal framework.

A question arises in this context, on how to preserve L in a theory with Majorana fields, that by definition violate all global symmetries (including L). There are three possibilities: the non-trivial one is to pair two Majorana states N_i and N_j to form a Dirac state (thus having equal masses $M_i = M_j$, maximal mixing and opposite CP phases $\mathcal{U}_{\alpha i} = i\,\mathcal{U}_{\alpha j}$); the more trivial solutions are having a decoupled Majorana state (that thus cannot mediate any L violating process) or having a massless state, for which the Majorana character vanishes. Since neutrino masses are small but finite, L cannot be an exact symmetry of the theory, resulting in the pattern of masses and mixings summarised in Table 1.

	Dirac state	**Decoupled state**	**Massless state**
Exact symmetry	$M_i = M_j$ $\mathcal{U}_{\alpha i} = i\,\mathcal{U}_{\alpha j}$	$\mathcal{U}_{\alpha i} = 0$	$M_i = 0$
Approximate symmetry	$\frac{M_j - M_i}{M_i + M_j} \ll 1$ $\mathcal{U}_{\alpha i} \simeq i\,\mathcal{U}_{\alpha j}$	$\lvert\mathcal{U}_{\alpha i}\rvert \ll \lvert\mathcal{U}_{\alpha, j\neq i}\rvert$	$M_i \ll M_{j\neq i}$

Table 1: Masses and mixings arrangements that preserve L in a theory with Majorana states.

4. Experimental searches

We review in the following some selected experimental searches for BSM physics connected to neutrinos, highlighting how the implementation of the Type-I Seesaw Lagrangian in Eq. (2) featuring an underlying approximate L symmetry can affect the phenomenology.

Neutrinoless double beta decay The double beta (2β) decay is a process relevant for certain nuclei for which the single beta decay is energetically forbidden. If active neutrinos are massive and of Majorana nature the process can happen without the emission of neutrinos ($0\nu\beta\beta$) [34], resulting in a clear experimental signature with a monochromatic peak at the end of the continuous electron energy $\beta\beta$ distribution [35]. Experimental searches for the $0\nu\beta\beta$ processes are ongoing, using a variety of different isotopies and experimental techniques [36]; this effort can probe not only the nature of the light neutrinos, but also the possible impact of heavier HNL, since the contribution to the amplitude from a Majorana gauge singlet scales as [37–42]

$$\mathcal{A}^{0\nu\beta\beta} \propto \sum_i M_i \mathcal{U}_{ei}^2 \frac{p^2}{p^2 - M_i^2}, \tag{6}$$

with $p^2 \approx -(125\ \text{MeV})^2$ the virtual momentum exchange in the process (dependent on the specific isotope). This contribution can be sizeable, possibly dominating the amplitude even for HNL mixings much smaller than the current bounds. However, notice that the total amplitude results from the coherent sum of the individual states contributions, and in the case of a (pseudo)-Dirac state there is a cancellation between two possibly large individual contributions, cf. the structure of masses and couplings from Table 1. Experimental bounds put constraints on the full mass spectrum and mixings.

Tau and meson decay HNL can mediate L-violating (LNV) decays of pseudo-scalar mesons and the τ lepton [41, 43]. For these processes, the contribution to the decay amplitude is negligible unless the intermediate HNL state can go on-shell, meaning that these experimental searches put constraints on a specific window of mass values, typically between 100 MeV and 10 GeV (the exact range depends on the specific decay channel). It should also be stressed that, in this mass region, HNL can have macroscopic lifetimes, possibly escaping the detector and thus making the LNV decay unobservable, requiring this to be accounted for when converting experimental results in model parameter constraints [41, 43]. Similarly to the $0\nu\beta\beta$ process, the amplitude depends on the combination $M_i \mathcal{U}_{\alpha i} \mathcal{U}_{\beta i}$, and cancellations are expected in case of an underlying L-conserving symmetry. An interesting effect that is expected when multiple intermediate HNL states mediate

the decay is the (constructive or destructive) interference between the amplitudes: depending on the CP-violating phases, this can sizeably modify the rate between L-violating and L-conserving channels [44]. These effects are phenomenologically relevant if the conditions $\Delta M \ll M$ and $\Delta M < \Gamma_N$ are satisfied, where ΔM is the mass splitting among the interfering HNL states and Γ_N is their decay width.

LHC searches In proton collisions, HNL can be produced through a variety of mechanisms, including Drell-Yan, gluon fusion, and electroweak vector boson fusion [45, 46]. L violating processed can manifest with clean experimental signatures, e.g. two same-sign leptons (any flavour combination of e and μ) and at least one jet [47]. For sufficiently large mixings, the HNL decays are prompt and can be probed through multi-lepton signatures. Searches for these processes have been performed by both CMS [48, 49] and ATLAS [50, 51]. A further interesting probe is the vector boson fusion channel mediated by HNL [52, 53] which, being a t-channel process, is less sensitive to the mass of the intermediate state and can probe larger HNL masses [54, 55]. For smaller mixings, HNLs can be long-lived on detector scales, giving rise to displaced vertices. Such signatures are searched for HNL produced in the decay of both $W-Z$ bosons [56, 57] and B mesons [58]. Recently, a search for long-lived HNL with lepton flavour conserving or violating decays and coupling scenarios involving the three lepton generations has been performed [59]. It must be stressed that, whenever multiple HNL featuring an approximate L-symmetry can contribute in mediating a L-violating decay, the cancellation among the individual L-violating contributions relies on the coherence of the quantum state, which can be lost if the HNLs undergo many oscillations before their decay [60–62]. Analysis performed in the framework of realistic, symmetry-motivated Type-I Seesaw models demonstrated that L-violation is expected to be the rule for displaced vertex signatures or at fixed target experiments, while the rate of L-violating processes is generally suppressed for HNL masses above the electroweak scale [62].

5. Conclusions

HNLs provide a minimal and well-motivated extension of the SM capable of accounting for neutrino masses and lepton flavour mixing. They give rise to a rich phenomenology, with signatures that can directly probe the new physics realisation for HNL masses up to the TeV energy scale. Examples of relevant phenomenological searches include $0\nu\beta\beta$ decay, the τ and meson decay and searches at LHC experiments. While studying the testability of a model, it is important to consider that the HNL couplings to the SM states are generally suppressed as $O(m_\nu/M_{\rm HNL})$ (and thus unobservable), unless symmetry-motivated scenarios are considered. These scenarios imply specific relations between masses and mixings, that generally result in a suppression of the L-violating processes, although the exact quantitative determinations depend on the experimental setup.

Other than accounting for massive neutrinos, testable HNLs can simultaneously provide a mechanism for the origin of matter in the Universe [63], as well as explain the dark matter nature [64–67], thus providing a common framework to address the main open BSM questions.

Acknowledgments

ML is funded by the European Union under the Horizon Europe's Marie Sklodowska-Curie project 101068791 — NuBridge.

References

[1] F. Capozzi, W. Giarè, E. Lisi, A. Marrone, A. Melchiorri and A. Palazzo, Phys. Rev. D **111** (2025) no.9, 093006 doi:10.1103/PhysRevD.111.093006 [arXiv:2503.07752 [hep-ph]].

[2] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. P. Pinheiro and T. Schwetz, JHEP **12** (2024), 216 doi:10.1007/JHEP12(2024)216 [arXiv:2410.05380 [hep-ph]].

[3] P. F. de Salas, D. V. Forero, S. Gariazzo, P. Martínez-Miravé, O. Mena, C. A. Ternes, M. Tórtola and J. W. F. Valle, JHEP **02** (2021), 071 doi:10.1007/JHEP02(2021)071 [arXiv:2006.11237 [hep-ph]].

[4] S. Weinberg, Phys. Rev. Lett. **43** (1979), 1566-1570 doi:10.1103/PhysRevLett.43.1566

[5] E. Ma, Phys. Rev. Lett. **81** (1998), 1171-1174 doi:10.1103/PhysRevLett.81.1171 [arXiv:hep-ph/9805219 [hep-ph]].

[6] A. Abada, C. Biggio, F. Bonnet, M. B. Gavela and T. Hambye, JHEP **12** (2007), 061 doi:10.1088/1126-6708/2007/12/061 [arXiv:0707.4058 [hep-ph]].

[7] P. Minkowski, Phys. Lett. B **67** (1977), 421-428 doi:10.1016/0370-2693(77)90435-X

[8] M. Gell-Mann, P. Ramond and R. Slansky, Conf. Proc. C **790927** (1979), 315-321 [arXiv:1306.4669 [hep-th]].

[9] T. Yanagida, Conf. Proc. C **7902131** (1979), 95-99 KEK-79-18-95.

[10] R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44** (1980), 912 doi:10.1103/PhysRevLett.44.912

[11] M. Magg and C. Wetterich, Phys. Lett. B **94** (1980), 61-64 doi:10.1016/0370-2693(80)90825-4

[12] J. Schechter and J. W. F. Valle, Phys. Rev. D **22** (1980), 2227 doi:10.1103/PhysRevD.22.2227

[13] C. Wetterich, Nucl. Phys. B **187** (1981), 343-375 doi:10.1016/0550-3213(81)90279-0

[14] G. Lazarides, Q. Shafi and C. Wetterich, Nucl. Phys. B **181** (1981), 287-300 doi:10.1016/0550-3213(81)90354-0

[15] R. N. Mohapatra and G. Senjanovic, Phys. Rev. D **23** (1981), 165 doi:10.1103/PhysRevD.23.165

[16] R. Foot, H. Lew, X. G. He and G. C. Joshi, Z. Phys. C **44** (1989), 441 doi:10.1007/BF01415558

[17] E. Ma and D. P. Roy, Nucl. Phys. B **644** (2002), 290-302 doi:10.1016/S0550-3213(02)00815-5 [arXiv:hep-ph/0206150 [hep-ph]].

[18] T. Hambye, Y. Lin, A. Notari, M. Papucci and A. Strumia, Nucl. Phys. B **695** (2004), 169-191 doi:10.1016/j.nuclphysb.2004.06.027 [arXiv:hep-ph/0312203 [hep-ph]].

[19] B. Bajc and G. Senjanovic, JHEP **08** (2007), 014 doi:10.1088/1126-6708/2007/08/014 [arXiv:hep-ph/0612029 [hep-ph]].

[20] B. Bajc, M. Nemevsek and G. Senjanovic, Phys. Rev. D **76** (2007), 055011 doi:10.1103/PhysRevD.76.055011 [arXiv:hep-ph/0703080 [hep-ph]].

[21] I. Dorsner and P. Fileviez Perez, JHEP **06** (2007), 029 doi:10.1088/1126-6708/2007/06/029 [arXiv:hep-ph/0612216 [hep-ph]].

[22] P. Fileviez Perez, Phys. Lett. B **654** (2007), 189-193 doi:10.1016/j.physletb.2007.07.075 [arXiv:hep-ph/0702287 [hep-ph]].

[23] P. Fileviez Perez, Phys. Rev. D **76** (2007), 071701 doi:10.1103/PhysRevD.76.071701 [arXiv:0705.3589 [hep-ph]].

[24] M. Aker *et al.* [KATRIN], Phys. Rev. Lett. **123** (2019) no.22, 221802 doi:10.1103/PhysRevLett.123.221802 [arXiv:1909.06048 [hep-ex]].

[25] N. Aghanim *et al.* [Planck], Astron. Astrophys. **641** (2020), A6 [erratum: Astron. Astrophys. **652** (2021), C4] doi:10.1051/0004-6361/201833910 [arXiv:1807.06209 [astro-ph.CO]].

[26] G. Ingelman and J. Rathsman, Z. Phys. C **60** (1993), 243-254 doi:10.1007/BF01474620

[27] J. Gluza, Acta Phys. Polon. B **33** (2002), 1735-1746 [arXiv:hep-ph/0201002 [hep-ph]].

[28] J. Kersten and A. Y. Smirnov, Phys. Rev. D **76** (2007), 073005 doi:10.1103/PhysRevD.76.073005 [arXiv:0705.3221 [hep-ph]].

[29] K. Moffat, S. Pascoli and C. Weiland, [arXiv:1712.07611 [hep-ph]].

[30] J. Lopez-Pavon, S. Pascoli and C. f. Wong, Phys. Rev. D **87** (2013) no.9, 093007 doi:10.1103/PhysRevD.87.093007 [arXiv:1209.5342 [hep-ph]].

[31] J. Lopez-Pavon, E. Molinaro and S. T. Petcov, JHEP **11** (2015), 030 doi:10.1007/JHEP11(2015)030 [arXiv:1506.05296 [hep-ph]].

[32] E. Fernandez-Martinez, J. Hernandez-Garcia, J. Lopez-Pavon and M. Lucente, JHEP **10** (2015), 130 doi:10.1007/JHEP10(2015)130 [arXiv:1508.03051 [hep-ph]].

[33] A. M. Abdullahi, P. B. Alzas, B. Batell, J. Beacham, A. Boyarsky, S. Carbajal, A. Chatterjee, J. I. Crespo-Anadon, F. F. Deppisch and A. De Roeck, *et al.* J. Phys. G **50** (2023) no.2, 020501 doi:10.1088/1361-6471/ac98f9 [arXiv:2203.08039 [hep-ph]].

[34] W. H. Furry, Phys. Rev. **56** (1939), 1184-1193 doi:10.1103/PhysRev.56.1184

[35] F. T. Avignone, III, S. R. Elliott and J. Engel, Rev. Mod. Phys. **80** (2008), 481-516 doi:10.1103/RevModPhys.80.481 [arXiv:0708.1033 [nucl-ex]].

[36] J. J. Gómez-Cadenas, J. Martín-Albo, J. Menéndez, M. Mezzetto, F. Monrabal and M. Sorel, Riv. Nuovo Cim. **46** (2023) no.10, 619-692 doi:10.1007/s40766-023-00049-2

[37] F. L. Bezrukov, Phys. Rev. D **72** (2005), 071303 doi:10.1103/PhysRevD.72.071303 [arXiv:hep-ph/0505247 [hep-ph]].

[38] M. Blennow, E. Fernandez-Martinez, J. Lopez-Pavon and J. Menendez, JHEP **07** (2010), 096 doi:10.1007/JHEP07(2010)096 [arXiv:1005.3240 [hep-ph]].

[39] A. Abada and M. Lucente, Nucl. Phys. B **885** (2014), 651-678 doi:10.1016/j.nuclphysb.2014.06.003 [arXiv:1401.1507 [hep-ph]].

[40] A. Faessler, M. González, S. Kovalenko and F. Šimkovic, Phys. Rev. D **90** (2014) no.9, 096010 doi:10.1103/PhysRevD.90.096010 [arXiv:1408.6077 [hep-ph]].

[41] A. Abada, V. De Romeri, M. Lucente, A. M. Teixeira and T. Toma, JHEP **02** (2018), 169 doi:10.1007/JHEP02(2018)169 [arXiv:1712.03984 [hep-ph]].

[42] A. Babič, S. Kovalenko, M. I. Krivoruchenko and F. Šimkovic, Phys. Rev. D **98** (2018) no.1, 015003 doi:10.1103/PhysRevD.98.015003 [arXiv:1804.04218 [hep-ph]].

[43] A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP **05** (2009), 030 doi:10.1088/1126-6708/2009/05/030 [arXiv:0901.3589 [hep-ph]].

[44] A. Abada, C. Hati, X. Marcano and A. M. Teixeira, JHEP **09** (2019), 017 doi:10.1007/JHEP09(2019)017 [arXiv:1904.05367 [hep-ph]].

[45] Y. Cai, T. Han, T. Li and R. Ruiz, Front. in Phys. **6** (2018), 40 doi:10.3389/fphy.2018.00040 [arXiv:1711.02180 [hep-ph]].

[46] C. Degrande, O. Mattelaer, R. Ruiz and J. Turner, Phys. Rev. D **94** (2016) no.5, 053002 doi:10.1103/PhysRevD.94.053002 [arXiv:1602.06957 [hep-ph]].

[47] A. M. Sirunyan *et al.* [CMS], JHEP **01** (2019), 122 doi:10.1007/JHEP01(2019)122 [arXiv:1806.10905 [hep-ex]].

[48] A. Hayrapetyan *et al.* [CMS], JHEP **06** (2024), 123 doi:10.1007/JHEP06(2024)123 [arXiv:2403.00100 [hep-ex]].

[49] A. Hayrapetyan *et al.* [CMS], Phys. Rept. **1115** (2025), 570-677 doi:10.1016/j.physrep.2024.09.012 [arXiv:2405.17605 [hep-ex]].

[50] [ATLAS], ATL-PHYS-PUB-2025-008.

[51] G. Aad *et al.* [ATLAS], [arXiv:2508.20929 [hep-ex]].

[52] B. Fuks, J. Neundorf, K. Peters, R. Ruiz and M. Saimpert, Phys. Rev. D **103** (2021) no.11, 115014 doi:10.1103/PhysRevD.103.115014 [arXiv:2012.09882 [hep-ph]].

[53] B. Fuks, J. Neundorf, K. Peters, R. Ruiz and M. Saimpert, Phys. Rev. D **103** (2021) no.5, 055005 doi:10.1103/PhysRevD.103.055005 [arXiv:2011.02547 [hep-ph]].

[54] A. Tumasyan *et al.* [CMS], Phys. Rev. Lett. **131** (2023) no.1, 011803 doi:10.1103/PhysRevLett.131.011803 [arXiv:2206.08956 [hep-ex]].

[55] G. Bird [ATLAS], PoS **LHCP2024** (2025), 032 doi:10.22323/1.478.0032

[56] A. Tumasyan *et al.* [CMS], JHEP **07** (2022), 081 doi:10.1007/JHEP07(2022)081 [arXiv:2201.05578 [hep-ex]].

[57] G. Aad *et al.* [ATLAS], JHEP **07** (2025), 196 doi:10.1007/JHEP07(2025)196 [arXiv:2503.16213 [hep-ex]].

[58] A. Hayrapetyan *et al.* [CMS], JHEP **06** (2024), 183 doi:10.1007/JHEP06(2024)183 [arXiv:2403.04584 [hep-ex]].

[59] A. Hayrapetyan *et al.* [CMS], JHEP **03** (2024), 105 doi:10.1007/JHEP03(2024)105 [arXiv:2312.07484 [hep-ex]].

[60] Y. Nir, Conf. Proc. C **9207131** (1992), 81-136 SLAC-PUB-5874.

[61] G. Anamiati, M. Hirsch and E. Nardi, JHEP **10** (2016), 010 doi:10.1007/JHEP10(2016)010 [arXiv:1607.05641 [hep-ph]].

[62] M. Drewes, J. Klarić and P. Klose, JHEP **11** (2019), 032 doi:10.1007/JHEP11(2019)032 [arXiv:1907.13034 [hep-ph]].

[63] M. Drewes, Y. Georis and J. Klarić, Phys. Rev. Lett. **128** (2022) no.5, 051801 doi:10.1103/PhysRevLett.128.051801 [arXiv:2106.16226 [hep-ph]].

[64] A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens and O. Ruchayskiy, Prog. Part. Nucl. Phys. **104** (2019), 1-45 doi:10.1016/j.ppnp.2018.07.004 [arXiv:1807.07938 [hep-ph]].

[65] M. Lucente, Phys. Lett. B **846** (2023), 138206 doi:10.1016/j.physletb.2023.138206 [arXiv:2103.03253 [hep-ph]].

[66] A. Abada, G. Arcadi, M. Lucente, G. Piazza and S. Rosauro-Alcaraz, JHEP **11** (2023), 180 doi:10.1007/JHEP11(2023)180 [arXiv:2308.01341 [hep-ph]].

[67] A. Abada, G. Arcadi, M. Lucente and S. Rosauro-Alcaraz, JHEP **09** (2025), 145 doi:10.1007/JHEP09(2025)145 [arXiv:2503.20017 [hep-ph]].