Prospects in BSM physics at FCC

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Abstract

The exceptional opportunities offered by the FCC programme in the search for physics beyond the Standard Model are reviewed. Uniquely to FCC, all frontiers on which the search for new physics must continue are significantly pushed back: Flavour, Intensity, Higgs, Dark, Electroweak and High Energy.

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No Stone Unturned: The FCC Project

The Standard Model (SM) cannot be *the* fundamental theory. This statement follows from evidence and hints for physics beyond the SM (BSM), including compelling astrophysical and cosmological evidence for dark matter, neutrino masses, the baryon asymmetry, the strong-CP problem, the flavour puzzle, and the mysterious origins of the Higgs sector. The variety of possible explanations to these unanswered questions provides little guidance on how to maximise the chances of discovering the more fundamental theory. As a result, the most effective strategy will be to ensure that future generations of particle physicists are equipped with the broadest exploration tools possible, such that they can leave no stone unturned. The contrary; betting on a particular production channel or sector of the SM, risks to leave fundamental physics in the dark.

Six (unranked) key areas for exploration are identified, each playing an indispensable role in particle physics:

- **Intensity Frontier** - The evidence for dark matter reveals the existence of at least one sector very weakly coupled to the SM. Based on experience with the SM it is likely that hidden sectors may contain both stable DM and unstable weakly interacting particles. A future project must be able to probe new hidden sectors with depth and breadth inaccessible to near-term facilities.
- **Flavour Frontier** - Flavour physics comes with a glaring puzzle to be resolved and one of the most powerful means by which to probe the microscopic origins of the SM. A future project must offer significant advances in flavour physics.
- **Higgs Frontier** - The lynchpin of the SM, a future collider must probe the quantum nature of the Higgs boson and its interactions, well beyond the typical scale of SM quantum corrections.
- **Electroweak Frontier** - As a sensitive probe of the common thread linking the quarks, leptons and the Higgs, a significantly deeper exploration of the electroweak sector is required.
- **Dark Frontier** - The SM accounts for less than 20% of all matter in the Universe. A future project must be capable of making progress towards uncovering the nature of the dark matter.
- **Energy Frontier** - There is no alternative to direct exploration of the microscopic world; a lesson well learned at the LHC. A future machine must be capable of directly exploring significantly beyond the scales reached by the HL-LHC and must not be biased towards any particular sector of the SM, colliding a wide variety of initial states to explore with the greatest possible breadth.

In the remaining pages, the unique capacity of the integrated FCC project to make significant advances in all of these areas is detailed. For FCC-ee, most of the results shown here were obtained in the context of the FCC Feasibility Study, and complement what is documented in Volume 1 of the Feasibility Study Report (FSR [1]). For FCC-hh, the extensive study of its BSM reach was carried out towards the Conceptual Design Report. This work is documented in the CDR [2] and, in more detail, in two reports, covering Higgs-specific [3] BSM frameworks and beyond [4]. These early studies remain today a valid reference to assess the power of FCC-hh to cover a broad and diverse landscape of BSM scenarios.[2] We shall make only brief reference to some of these FCC-hh results in the following, addressing the benchmarks proposed by the Preparatory Group, but encourage the readers to further explore the extraordinary discovery potential discussed in those documents.

FCC: Intensity Frontier

The intensity frontier aims to access new physics by increasing the luminosity rather than the energy of colliders. The first stage of the FCC integrated program, FCC-ee, with 6×10^{12} Z bosons, will push that frontier substantially. With a clean environment and large acceptance, FCC-ee would directly access the $\mathcal{O}(1\text{–}100)$ GeV mass range of new, feebly interacting particles.

Hidden sectors typically include a stable particle, fundamental or composite, that could be a DM candidate, and one or more mediator particles coupled to the SM. The spin of the mediator defines the portal: vector (e.g. dark photon), fermion (e.g. sterile neutrino), pseudoscalar (e.g. Axion), or scalar (e.g.

[2] These results were evaluated for $\sqrt{S} = 100$ TeV. For most cases, the extrapolation to the new FCC-hh baseline configuration ($\sqrt{S} = 84$ TeV [5]) is a straight forward rescaling by the beam energy ratio. See [6] for more details.

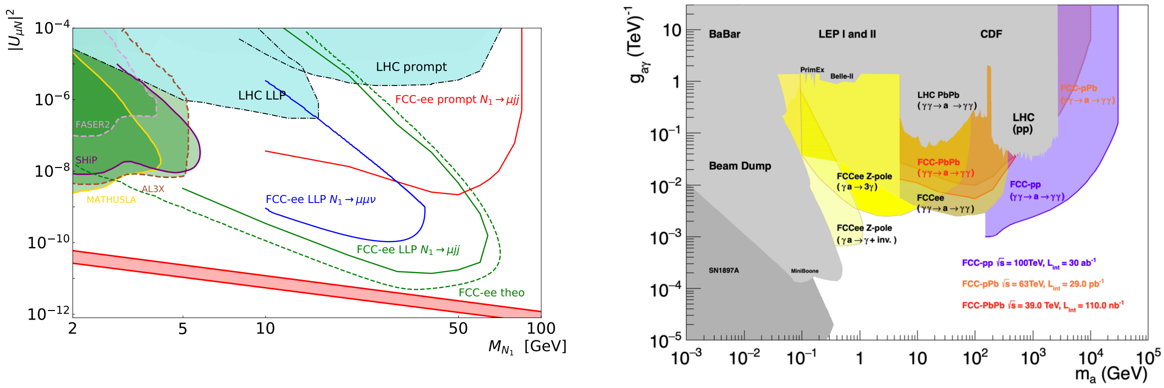

Fig. 1: **Left**: HNL discovery potential in the $m_{N1} - |U_{\mu N}|^2$ plane. The red (green) line represents the prompt (long-lived) HNL decay channel to a muon and two jets. The blue line shows the reach for the dimuon plus a neutrino analysis. The dashed green line indicates where three HNL decay events are observed within the FCC-ee detector. The pink band represents the classic see-saw parameter region. Existing LHC limits are shown in turquoise, and future long-baseline experiment potentials are shown in green. **Right**: Projected sensitivity for ALPs in the photon coupling vs. ALP mass plane from the three following processes at FCC-ee: $e^+e^- \to \gamma a \to 3\gamma$ [20], photon-fusion $\gamma\gamma \to a \to 2\gamma$ [21], and $e^+e^- \to \gamma a \to \gamma + \mathrm{INV}$. Existing limits (in grey) are adapted from Refs. [22, 23]. Also shown are projected exclusion limits at 95% C.L. on the ALP-photon coupling as a function of the ALP mass expected from searches for $\gamma\gamma \to a \to \gamma\gamma$ in pp (violet), pPb (dark pink), and PbPb (orange) collisions at FCC-hh [24].

dark Higgs). At FCC-ee it will be possible to probe each of these portals, providing complementary information to e.g. beam dump experiments.

Benchmark: Heavy Neutral Leptons. Searches for Heavy Neutral Leptons (HNLs) could provide clues not only to the question of neutrino masses, but also to the baryon asymmetry of the universe [7], and even provide a DM candidate [8]. Very low couplings to the existing neutrinos can be exploited in displaced signatures with little to no background [9] complementarily to prompt searches. As shown in the left panel of Fig. 1, searches performed at the Tera-Z run of FCC-ee will cover a wide unconstrained parameter space [10], unreachable by collider options past and present. The FCC-ee discovery potential for HNLs extends down to mixing values of $\mathcal{O}(10^{-11})$ in the mass range of 20 to 80 GeV and to $\mathcal{O}(10^{-9})$ for larger masses [11–19].

Beyond the simplest models that incorporate HNLs, FCC-ee could explore e.g. models with two majorana neutrinos [25] compatible with neutrino oscillations [26]; or the 'Symmetry Protected See-Saw Scenario' [27, 28], that adds two right-chiral neutrinos [29, 30]. The main signature of the latter are lepton flavour violating final states [18, 19]. For HNL masses below 35 GeV, for favourable ratios of the HNL width and of the mass difference between the two pseudo-Dirac states, a striking oscillation signal would allow for the measurement of the mass difference [31]. A large fraction of the parameter space consistent with symmetry-enhanced neutrino mass [32–34] models, would be probed. For masses around 40 GeV, the FCC-ee sensitivity would reach the smallest value of the mixing angle, close to the see-saw limit. The HNL decay branching ratios could be measured with per-cent accuracy [35]; many parameters of the model could be constrained [36, 37]; the leptogenesis hypothesis [35] tested; and underlying flavour and CP symmetries [38] could be probed. The number of HNL events and the measurement of the HNL lifetime can reveal information about the violation of lepton number [10, 14]. Finally, the angular distribution and the energy spectrum of the HNL decay products can provide further information regarding lepton number violation [36].

On the FCC-hh side, recent results [39, 40] indicate that the FCC-hh could potentially discover signs of lepton number violation for HNL masses exceeding the W mass scale down to squared active-sterile mixing angles of nearly $O(10^{-5})$ for HNL mass splittings above about 10 eV.

Benchmark: Axion-like particles. Other feebly-interacting particles within reach at FCC-ee are axion-like particles (ALPs), generically expected in many BSM extensions, most famously in QCD axion models originally introduced to tackle the strong CP problem [41]. At FCC-ee, ALPs will be accessible [22, 42–46] via $e^+e^- \to a\gamma$ [41] and $e^+e^- \xrightarrow{\gamma\gamma} (e^+e^-)a$ [21], with the ALP a decaying as $a \to \gamma\gamma$. Searches at the Tera-Z run of FCC-ee will have sensitivity in the m_a range from 0.1 to 100 GeV, extending current limits by more than two orders of magnitude [20, 47]. A summary is displayed in the right panel of Fig. 1, alongside projections for FCC-hh, discussed later.

Benchmark: Dark photons. Dark photons can be searched for in $e^+e^- \to A'\gamma$ production, where the dark photon A' decays to $\mu^+\mu^-$. Small coupling values, around $\sim 2 \times 10^{-4}$ for $m_{A'}$ ranging from 10 to 80 GeV [48], can be reached at FCC-ee. Alternatively, dark photons or dark Z' bosons can be investigated via $e^+e^- \to A'H$ or $Z'H$ production at the WW threshold or above [49]. Recent sensitivity estimates can be found in Ref. [50]. The associated production of a neutrino and a dark sector fermion can also be searched for at FCC-ee in mono-photon signatures [51], with sensitivity up to mass values in excess of 1 TeV. Other searches, such as Z boson decays to an invisible dark photon [52] can also be exploited. Searches for dark photons in FCC-hh are documented in [53].

Benchmark: Exotic Higgs and Z decays. The large Higgs boson event sample and clean environment at FCC-ee will provide opportunities for direct searches for exotic decays of the Higgs boson. Exotic decays are predicted by a variety of BSM theories [54–57], including extended scalar sectors, SUSY, and dark sector models with Higgs or vector portals. Higgs branching ratios up to four orders of magnitude lower than the expected HL-LHC reach can be probed at FCC-ee, giving access to entirely new channels [58].

Searches for exotic Z decays can also be carried out at FCC-ee during the Z pole run. In models of R-parity-violating supersymmetry [59], the FCC-ee sensitivity to long-lived light neutralinos in Z decays exceeds that of hadron colliders and of future dedicated experiments by three orders of magnitude. Comparable gains in sensitivity can be obtained e.g. in searches of Z decays into hidden mesons [60].

The available parameter space for new SM-neutral vector bosons (Z') that couple exclusively to leptons could be significantly extended, offering the best performance of all future collider projects in the kinematically allowed mass range (from 5 to 360 GeV) [61].

In summary, taking full advantage of the large Higgs and Tera-Z event samples, the programme at FCC-ee extends intensity-frontier discovery potential significantly. It provides access to very-weakly-interacting dark-sectors with couplings so small that they are usually considered typical of beam-dump experiments, but in a mass range complementary to other intensity-frontier experiments. Given that there is no preferred mass range for such states, this mass-range extension by more than two orders of magnitude provides unique scientific opportunities in particle physics unavailable elsewhere.

FCC: Flavour Frontier

Two key aspects of flavour are important for BSM searches at FCC-ee:

1) Flavour programme at Tera-Z. The FCC-ee flavour programme stands to cover significantly greater BSM territory than currently approved flavour physics experiments, both at HL-LHC and at lower-energy e^+e^- colliders (in particular Belle II at Super KEKB). The key features of the flavour physics programme during the Z-pole run at FCC-ee can be summarised as follows.

– *Clean environment* (as in B-factories), with exceptional momentum and tagging efficiency of the pair-produced b's, c's, and τ's from Z decays, and with ~ 10 times more $b\bar{b}$ and $c\bar{c}$, and ~ 5 times more $\tau^+\tau^-$ pairs, than the total collected by Belle II (as shown in Table 6 of Ref. [1]).
– *Boosted b's and τ's*, leading to a significant efficiency for modes with missing energy (especially multiple-ν modes) and inclusive modes, as well as smaller uncertainties in lepton ID efficiencies.

Consequently, FCC-ee opens up new frontiers for precision flavour tests of BSM. For example:

(i) new physics in $\mathrm{b} \to \mathrm{s}\tau\tau$ transitions, which is not directly accessible with current experiments unless enhanced over the SM by orders of magnitude, can be discovered at FCC-ee by measuring e.g. $\mathcal{B}(\mathrm{B} \to \mathrm{K}^*\tau^+\tau^-)$ at close to the SM rate [62]; or (ii) similarly, $\mathrm{B_c} \to \tau\nu$ decays can be observed only at FCC-ee, thanks to the clean environment and running above the B_c threshold; a few per-cent precision has been demonstrated [63, 64]. Both these offer unprecedented opportunities to test third-generation-philic BSM models, such as leptoquarks capable of explaining current tensions in $R_{\mathrm{D}^{(*)}}$ [65–67]. In addition to establishing these new frontiers, FCC-ee can make great strides in processes for which current experiments are specialised. For example, new physics in $\mathrm{b} \to \mathrm{s}\nu\bar{\nu}$ [68] could be probed to per-cent precision [69] via measuring e.g. $\mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^{0*}\nu\bar{\nu})$, an order-of-magnitude improvement on what is possible at Belle II (similarly for measurements of LFUV and exotic τ decays [70, 71]). The clean environment plus high statistics provides excellent prospects to increase precision in $\mathrm{b} \to \mathrm{s}\ell\ell$ ($\ell \in \{e, \mu\}$) processes such as $\mathrm{B} \to \mathrm{K}^*\ell^+\ell^-$, currently best measured at the LHC (see Fig. 2 of [72]). These processes, being rare in the SM, are sensitive to new physics weakly coupled to muons and third generation quarks. Finally, prospects for probing rare flavour-violating Z decays are discussed in [73].

2) Flavour-Precision Electroweak Interplay. It is well known that any new physics at nearby energy scales must have a flavour structure. Compatibility with both flavour and LHC data hints at new physics coupled universally to the light families, while it may have a larger coupling to the third generation, a scenario described by $\mathrm{U}(2)^n$ flavour symmetries. This configuration naturally results in a strong synergy between the flavour and precision EW programmes, as third-generation new physics typically leads to $3 \to 2, 1$ flavour-changing processes as well as large running effects in precision observables.

In Ref. [74], it was reported that new physics with an approximate $\mathrm{U}(2)^5$ flavour symmetry could exist at the TeV scale whilst remaining consistent with all constraints, if dominantly coupled to the third family. The high energy states in such a scenario necessarily give rise to modifications of the SM, captured by families of dimension-6 SMEFT operators. Their coefficients are shown in Fig. 16 of Ref. [1], alongside present-day constraints from flavour, precision EW, and high-energy collider probes, as well as future projections for a Tera-Z programme at FCC-ee. Not only is the sensitivity of operators that enter the Z pole at tree level enhanced to the ten TeV scale, but many more third generation operators are strongly constrained at loop level via RG evolution. The synergy with flavour-changing $3 \to 2, 1$ processes at Tera-Z is illustrated in Fig. 9 of Ref. [67], showing complementary sensitivity and probing the flavour alignment. Similar conclusions hold about the sensitivity of Tera-Z to all BSM mediators coupling linearly to the SM [75–77], making FCC-ee an almost inescapable probe of heavy new physics at the TeV scale and beyond.

In this contribution, only a summary of BSM implications is presented, with a particular focus on those scenarios which are called for in the context of the ESPPU BSM benchmarks.

Benchmark: Scalar and vector leptoquarks with third generation specificities. In Refs. [64, 67], the FCC-ee flavour prospects for a scalar (S_1) and a vector (U_1) leptoquark scenario were studied. Both leave their imprint in $\mathrm{B_q} \to \tau\nu$ transitions. Figs. 12 and 13 of Ref. [64] present current and future indirect reach on these models from $\mathrm{B}(\mathrm{B_c^+} \to \tau^+\nu)$ decays. In these figures, the C parameters are the Wilson coefficients, with normalisation provided in Ref. [64], and β_R is a relative phase between a vector and scalar Wilson coefficient. Future FCC-ee reach is impressive, being barely visible in both plots. This work has recently been extended and updated in Ref. [67].

Leptoquarks also contribute to $\mathrm{e^+e^-} \to \mathrm{f\bar{f}}$ processes above the Z pole, as well as inducing sizable one-loop corrections to Z-pole observables and τ decays [78, 79]. Via these effects combined with improvements in flavour tagging, FCC-ee can probe the entire parameter space favoured by the B-meson anomalies in scalar (S_3) and vector (U_1) leptoquark models [80].

Benchmark: Compositeness (indirectly from EFT fits). Composite Higgs models are a class of scenarios in which the Higgs boson is a composite bound state of a new strongly-coupled dynamics at the TeV scale. The magnitude of the top quark Yukawa coupling naturally points toward a scenario where the left and/or right-handed top quarks are also partially composite. This observation brings flavour considerations to the fore when attempting to understand the origins of the Higgs sector.

Via an EFT analysis, Ref. [81] considers the role that an FCC-ee precision EW programme would play in probing the possibility of Higgs/top quark compositeness. Strong dynamics respecting custodial symmetry is typically assumed of such models to evade current electroweak precision bounds from the T parameter. However, RG effects lead to SM-induced custodial violations, including a two-loop double-log contribution of four-top operators to the T parameter. These effects render swathes of parameter space accessible to FCC-ee, as shown in Fig. 17 of Ref. [1], where FCC-ee projections are compared to nearer-term HL-LHC and flavour projections. A significant increase in projected reach is observed, testing Higgs/top compositeness to scales of 25 TeV.

Benchmark: New gauge forces. Flavour deconstruction at FCC-ee. To give an example of concrete scenarios explored through a combination of the unprecedented precision on Z-pole and WW-threshold observables with excellent capabilities as a flavour factory, a special class of theories based on 'flavour deconstruction' [82] is considered, whereby part of the EW gauge symmetry is extended into three generation-specific copies G_i (with the Higgs coupled to G_3). This symmetry, which arises, e.g. from gauge-flavour unification [83] or from extra-dimensions [84], is broken to the SM in two steps that generate hierarchical fermion masses and mixings, resulting in new TeV-mass gauge bosons coupling mostly to the third generation.

These electroweakly-charged and flavour non-universal gauge bosons give rise to a rich phenomenology across flavour, electroweak, and LHC measurements, as quantified by considering deconstructed hypercharge [85] and deconstructed $SU(2)_L$ [86, 87]. As shown in Table 5 of Ref. [1], FCC-ee is an optimal machine for probing theories of flavour deconstruction because it achieves comparable sensitivity across diverse measurements traditionally separated into 'electroweak' and 'flavour' categories.

FCC: Higgs Frontier

Benchmark: Single Higgs Couplings. At FCC-ee, a sub-percent precision on single Higgs couplings can be achieved with the runs at 240 and 365 GeV in less than ten years [88]. Contrary to the precision on the Higgs couplings reachable at the HL-LHC, where the impact of the current knowledge of EPWO from LEP and SLC is not significant, in the case of the achievable precision at FCC-ee, the current (experimental and theoretical) precision on electroweak quantities would become a limitation without the Z-pole run of FCC-ee, which is instrumental in avoiding contamination from electroweak coupling uncertainties in the Higgs boson characterisation. Improved precision in the Electroweak sector allows dependencies between the Electroweak and Higgs couplings to be removed in the case of an interpretation via SMEFT (Figs. 4 and 6 of Ref. [1]).

Origins of the Higgs Sector. Determining the origins of the Higgs sector and EW scale is of upmost importance in high energy physics, suggestive of new physics close to the EW scale. The precision previously outlined is necessary to provide sensitivity to several concrete BSM models which could explain these origins, including Supersymmetry and Composite Higgs scenarios. Sec. 9 of [2] and included references discuss FCC prospects in detail (see also Tab. 5 of Ref. [89] and associated references).

Benchmark: Higgs self-coupling from single-Higgs measurements via SMEFT fit In e^+e^- collisions there is sensitivity to the Higgs self-coupling, κ_λ, via 1-loop radiative corrections to single-Higgs production cross sections [90]. These corrections depend on the centre-of-mass energy, making measurements at 240 and 365 GeV sufficient to disentangle the effect of new physics in the HZZ coupling and κ_λ, allowing for a determination of κ_λ with a precision of 27%, as shown in Fig. 13 (left) of Ref. [1]. Moreover, a recent study has shown that under reasonable assumptions, FCC-ee can complement HL-LHC sensitivity even when taking into account all possible new physics contributions at the 1-loop level in a global SMEFT analysis [91]. The fully marginalised FCC-ee sensitivity is shown in Fig. 1 of Ref. [91], under the assumption of several well-motivated flavour symmetries. If new physics is dominantly coupled to the Higgs and 3rd-generation fermions, as is the case for many well-motivated models addressing the flavour and/or EW hierarchy problems, the expected global sensitivity is estimated there to be $\delta\kappa_\lambda \lesssim 33\%$.

Benchmark: Higgs Portal. The clean environment of FCC-ee and its potential precise measurement of the total Higgs cross section and width in a model-independent fashion through the so-called recoil-mass method, allows a greater sensitivity to possible decays of the Higgs boson to invisible non-SM particles, such as dark matter candidates or additional scalars [58]. A preliminary study shows that when accounting for the possibility of exotic decays, branching fractions lower than 0.07% can be excluded at the 95% CL or a 5σ observation can be obtained if greater than 0.18% [92,93]. The study of jet+missing E_T at FCC-hh provides sensitivity to BR(H→invisible) at the level of few $\times 10^{-4}$ [94].

In addition, direct searches for long-lived particles (LLPs) arising from Higgs decays provide another avenue for Higgs portal sensitivity. If the Higgs couples to a light scalar that decays with a displaced vertex, the clean environment of FCC-ee, combined with its high-granularity detectors, allows for efficient detection of such signatures. Sensitivity to long-lived scalars with decay lengths of order 1 mm to 10 m, is achieved, with the peak sensitivity for decay lengths around 0.3 m, as shown in Fig. 31 of Ref. [1]. This search channel is relevant in scenarios where the new scalar is weakly coupled, leading to macroscopic lifetimes [95]. Additional scalars can also be searched for directly at FCC-ee, as in Ref. [96]. If vacuum metastability is related to a solution to the hierarchy problem [97, 98], natural regions of parameter space with a light ALP in the $\mathcal{O}(10)$ GeV range can be discovered or excluded at FCC-ee [99].

Benchmark: Minimal real scalar sector giving first order EW phase transition. The SM extended by a real singlet scalar ϕ with a Z_2 symmetry is the minimal scenario to realise a first-order EW phase transition [100, 101]. The only interaction with the SM is the Higgs portal $\kappa\phi^2|H|^2$, allowing for the so-called 'loryon' scenario wherein ϕ can get most of its mass from the Higgs [102]. The leading phenomenology consists of one-loop modifications of the Higgs kinetic term [103] and self-coupling, making the model notoriously difficult to probe. However these effects may be tested at FCC-ee, where they modify the ZH cross section and Z-pole observables as shown in the right panel of Fig. 25 in Ref. [1]. In particular, FCC-ee will be able to probe all of the viable parameter space for a first-order EW phase transition [104].

FCC: Electroweak Frontier

EFT interpretation of EWK precision measurements. An impressive number of electroweak precision observables (EWPOs) will be measured by FCC-ee, with accuracies ranging from a factor 50 (e.g. for the W mass) to a factor 1000 (e.g. for R_b) better than today [1]. Interpreting SMEFT as a low-energy effective realisation (EFT) of a higher scale UV complete theory, the FCC-ee EWPO precision allows sensitivity to Wilson coefficients to be improved by one to several order(s) of magnitude. The current status of the global SMEFT fit is shown in Fig. 3 of Ref. [1]. In this figure, the results of the fit for the different dimension-six operators affecting electroweak processes at tree-level (including anomalous triple gauge couplings aTGCs, and boson-fermion couplings) or Higgs processes, or both simultaneously, are projected onto a physically meaningful set of effective couplings capturing the effects of new physics.

Precision Top properties measurements (Mass and Couplings). Proposed solutions to important open questions motivate couplings of BSM physics to the third generation, which also happens to be among the least constrained sectors of the SM. Therefore, the precise measurements of the top quark mass and other top quark characteristics such as its electroweak couplings [105] are crucial for BSM precision exploration. An improvement by more than an order of magnitude in the top mass measurement can be achieved at FCC-ee [106], especially given the improvement in the determination of the strong coupling constant [107] which represents one of the relevant parametric uncertainties in the top mass measurement. For studies of top properties of relevance to BSM scenarios (rare and forbidden decays, anomalous couplings), see [108] and Section 6 of the CDR [2].

Benchmark: BSM Sensitivity in EW Couplings The complementarity between the Tera-Z and the higher-energy runs is illustrated in Fig. 1 of Ref. [109], which shows the sensitivity (in terms of the effective new physics scale Λ) to dimension-6 SMEFT operators entering directly in four-fermion, gauge, and Higgs observables in the higher-energy (denoted 'above-pole') runs compared to indirect loop con-

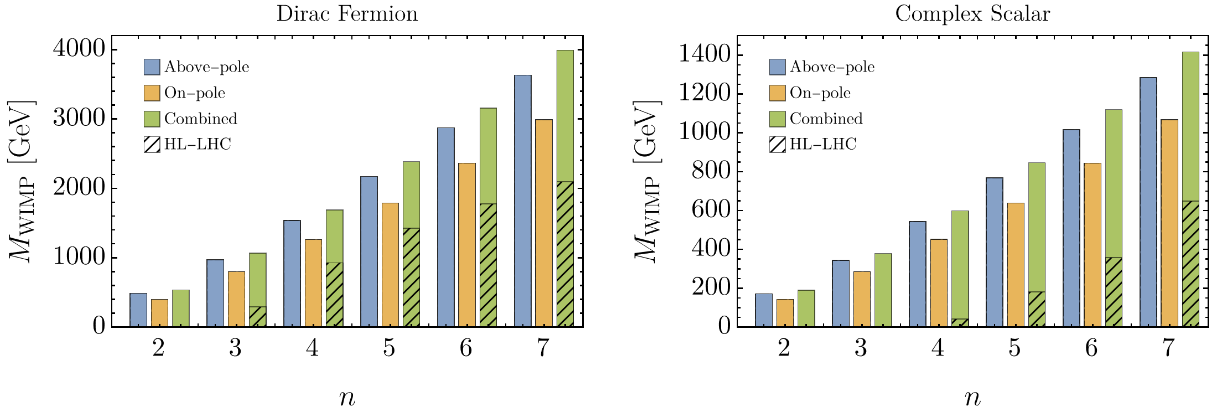

Fig. 2: Projected 95% CL sensitivities at FCC-ee to electroweak n-plet Dirac fermion and complex scalar WIMPs with zero hypercharge [109], compared to expected sensitivity at HL-LHC (hatched) [113].

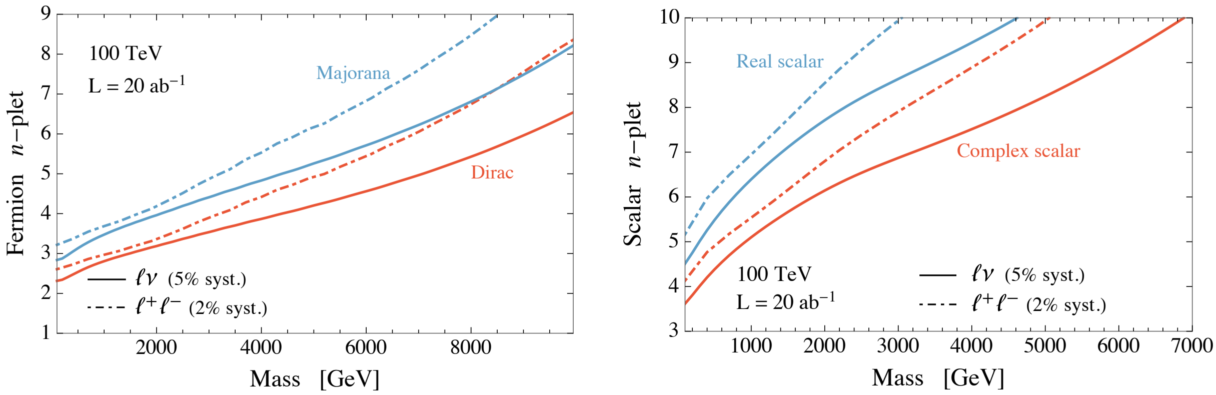

Fig. 3: Projected 95% CL sensitivities at FCC-hh to electroweak n-plet WIMPs in neutral- and charged-current Drell-Yan processes. Taken from Ref. [113].

tributions to Z-pole observables [75–77]. Besides often being stronger, the on-pole bounds also constrain different directions in the SMEFT parameter space. This remark illustrates the importance of combining results from the Tera-Z programme with those of the higher-energy runs in order to lift flat directions and maximise the new physics reach of FCC-ee. This complementarity is illustrated by the W and Y oblique parameters, as shown in [80]. The running of the EW coupling up to the multi-TeV scale at FCC-hh is a further indirect probe of BSM weakly-coupled particles, as discussed in [110, 111].

FCC: Dark Frontier

Uncovering the unknown nature of dark matter, whose candidates span a tremendously wide range of BSM models of varying masses and couplings, requires an open-ended exploration of dark sectors across a variety of dedicated and general-purpose experiments. In this major scientific endeavour, FCC has a unique role to play in covering regions of dark matter parameter space inaccessible by other means. The search for DM at FCC-hh is amply documented, covering multiple scenarios and signatures, in [112].

Benchmark: Minimal DM. The minimal dark matter paradigm consists of new electroweakly charged states of all viable representations, assumed to interact only via gauge interactions [114]. While the larger representations are typically very heavy and cannot be directly produced at colliders, the leading indirect probe comes from 1-loop, energy-enhanced corrections to EW gauge boson propagators, the so-called W, Y parameters [115]. FCC-ee is sensitive to W, Y at the 10^{-5} level in both precision EW measurements at the Z pole as well as in higher energy $e^+e^- \to f\bar{f}$ processes [80, 109], with a combined sensitivity to WIMPs with mass in the TeV range as shown in Fig. 2. Ultimately, FCC-hh sensitivity to W, Y in high-energy Drell-Yan tails is better, probing the thermal relic mass for some EW representations [113, 116] (Fig. 3). FCC-hh has direct search capabilities for a variety of minimal DM scenarios [117], covering in particular the entire mass range for Higgsino and Wino thermal relics (see [118] and the updates for alternative energy scenarios in Fig. 43 of [1] and in Table 4 of [6]).

Benchmark: Heavy DM. Leptophilic WIMP dark matter in the $\mathcal{O}(10-100)$ GeV range is an ideal target for FCC-ee, for example in mono-photon or missing energy plus dilepton channels, that can probe further beyond the parameter space excluded by HL-LHC for thermal relic dark matter and its associated mediator [119, 120]. Asymmetric DM is one motivated model in this mass range where the FCC-ee sensitivity to its leptophilic couplings can be an order of magnitude greater than at the LHC [121]. Annihilating TeV-scale WIMPs could also lead to indirect detection at gamma ray telescopes and scattering at direct detection experiments. The experimental exploration of TeV-scale WIMPs at colliders complements and is synergistic to these indirect observational searches for their astrophysical and cosmological signatures. Further details on DM searches at FCC, including for simplified models, are available in the FCC CDR [2] and in [112], with extensive references to recent FCC-ee work contained in the FCC FSR [1].

Benchmark: Light DM. Simple models of light dark matter with spin 0, 1/2, or 1, that evade all current direct detection, indirect detection and collider bounds, can be probed at FCC-ee, potentially with the possibility of disentangling their spin [122].

Dark matter may also be naturally light if realised as a pseudo-Nambu-Goldstone boson (pNGB) of some global symmetry, e.g. in composite Higgs models. Depending on the stability of the dark matter, it may be searched for at FCC-hh via the derivative Higgs portal [123], or in some constructions via direct production of extra states to which it couples [124].

Benchmark: Dark Showers. Hidden Valley [125, 126] and dark sector models of dark matter from a strongly coupled confining sector can lead to novel phenomenological signatures of dark showers [127, 128]. These have been extensively studied at the LHC but the low energy scales in the $\mathcal{O}(1-100)$ GeV range of the hidden sector and dark matter candidates in these scenarios make them ideal candidates to target at flavour factories and lepton colliders [129] such as FCC-ee.

FCC: Energy Frontier

The FCC-hh would expand the energy horizon significantly beyond any other proposed future collider. Fig. 39 of Ref. [1], and its discussion there, demonstrates that for a wide variety of initial states numerous new resonance production events could be observed at a CM energy significantly above 10 TeV. Alternative proposed high-energy colliders can only access such energy scales indirectly, masking the identity of associated phenomena. This expectation is confirmed in the context of specific models, such as those detailed in Table 9 of Ref. [1]. In general, the FCC-hh discovery reach at high mass covers areas going well beyond the themes proposed in the ESPPU benchmarks, such as for example the exploration of BSM Higgs sectors (e.g. 2HDM) for scalar states with masses up to and above 10 TeV [130]. We focus here on just some examples relevant to the benchmarks, and recommend the consultation of [3, 4] for a broader perspective on BSM physics at FCC-hh.

Benchmark: New Gauge Forces and Compositeness. Just as the electroweak interactions emerge above the weak scale from an extended gauge sector, so too may there be an extended gauge sector at energies above the weak scale. To unambiguously discover such interactions requires directly viewing such resonances. Reference [131] recently performed a comprehensive study of such a possibility.[3] Fig. 4, taken from Ref. [131], shows the FCC-hh reach for right-handed new gauge forces for the case of a $\mathrm{U}(1)_{B-L}$ force and two more examples described in Ref. [131]. For a sequential $\mathrm{U}(1)_Y$ and an $\mathrm{SU}(2)_L$ HVT force, we refer to the previous European Strategy Briefing Book [132]. Fig. 5 shows the reach for a right-handed HVT and for the kind expected to arise in composite Higgs scenarios. There is also a significant interplay between flavour and compositeness which cannot be overlooked, for which FCC-

[3] Reference [2] gives a compilation of previous studies.

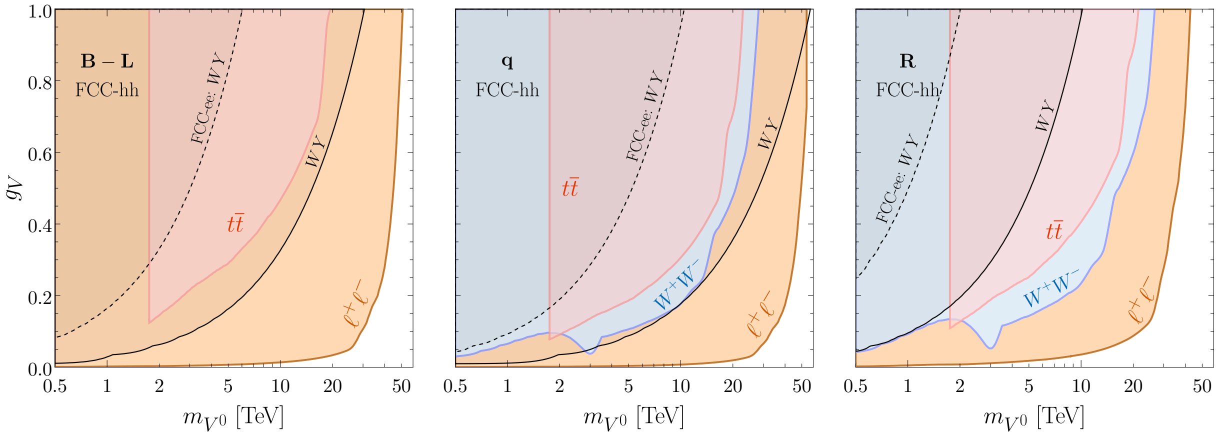

Fig. 4: FCC-hh reach for selected benchmark models $U(1)_{\mathrm{B-L}}$ (left), $U(1)_{\mathrm{q}}$ (centre) and $U(1)_{\mathrm{R}}$ (right). Further details can be found in Ref. [131].

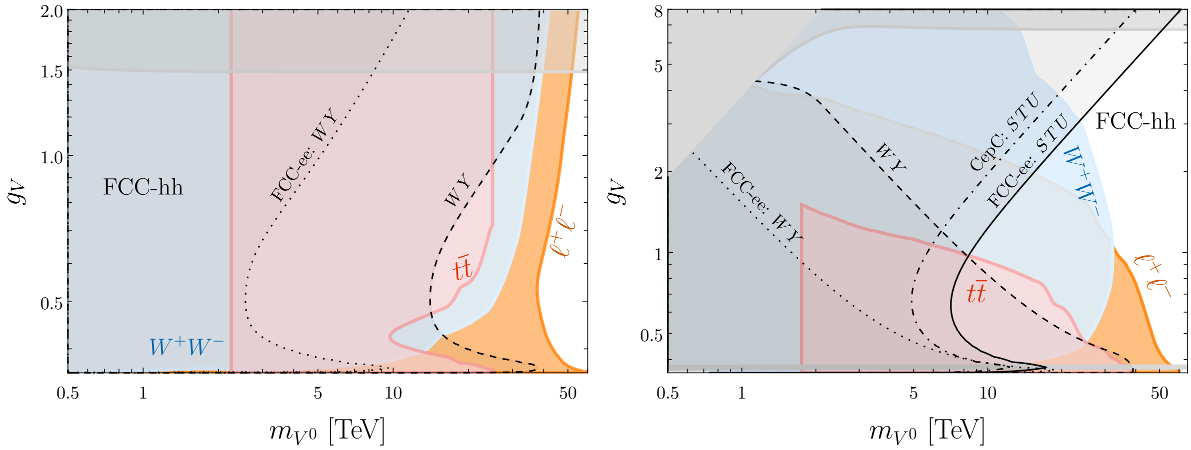

Fig. 5: Reach projections for a right-handed HVT (left, 'Model D') and a HVT expected to arise in composite Higgs models (right, 'Model E'). For all details, the reader is referred to Ref. [131].

hh would play an integral role [133]. Further studies of high-mass resonance searches, motivated by a broad variety of BSM models, were presented in [134]. The discovery reach for a selection of s-channel resonances in FCC-hh is presented in [135] and the general impact of non-baseline energy/luminosity scenarios for high-mass searches is discussed in [6]. In summary, the general *direct* reach of FCC-hh for new gauge forces and vector resonances extends considerably beyond the 10 TeV scale.

Benchmark: Leptoquarks. In Ref. [136], leptoquark models were considered for various future colliders in the context of the B-physics anomalies. As depicted in Fig. 6, FCC-hh has considerable direct reach, through a combination of pair production and t-channel single lepto-quark contributions to $\mu\mu$ final states. It is important to note that, as emphasised in Ref. [136], FCC-hh offers to directly discover the leptoquarks, as opposed to indirectly constrain them.

Benchmark: EW Phase Transition. Probing BSM modifications of the nature of the EW phase transition, through measurements of the Higgs self-coupling, is an important component of an energy frontier programme. Fig. 15 of Ref. [1], adapted from Ref. [137], shows the reach for a real singlet scalar model (without a Z_2-symmetry), wherein all orange points have a first-order phase transition (FOPT), the vast majority of which are within the reach of FCC through the fractional change in the Higgs coupling to a pair of Z bosons relative to its SM value ('hZZ coupling') vs. the triple-Higgs coupling normalised to its SM value ('hhh coupling'). The region outside the two FCC-hh lines and above the FCC-ee line can be

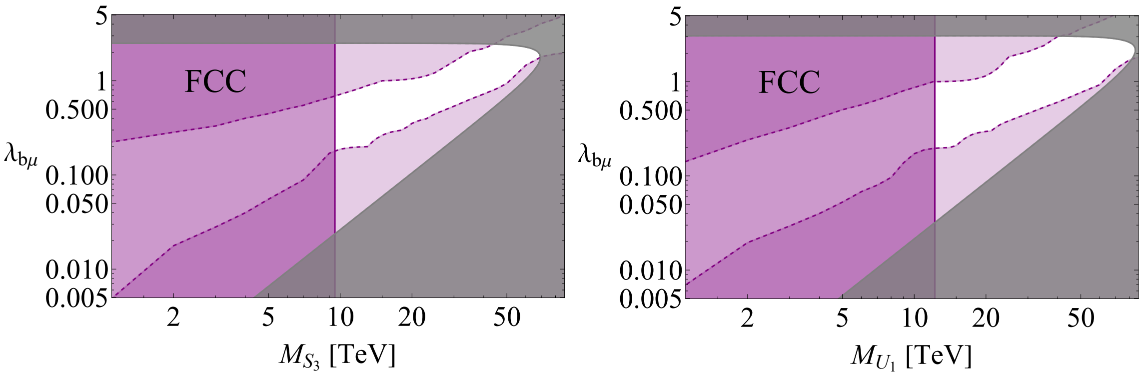

Fig. 6: The 5σ discovery prospects for the S_3 and U_1 leptoquark models. The perturbative limit $\Gamma_{S_3}/M_{S_3} < 0.25$ is violated in the grey region. The discoverable region is on the side of the line where the corresponding label is. Further details may be found in Ref. [136].

covered at those facilities. For the prospects of direct discovery of new particles predicted in models of FOPT, see [138].

Benchmark: Supersymmetry. Supersymmetry remains a key benchmark when considering the reach of a future high energy facility to explore wide-ranging phenomena coupled to EW and QCD gauge forces. Fig. 41 of Ref. [1] demonstrates the capacity for FCC-hh to probe EW-charged states up to 5 TeV and QCD charged states up to mass scales as high as 20 TeV, well beyond the 5 TeV reach limit for pair-production of sparticles at any collider limited to 10 TeV CM energy. An extensive discussion of FCC-hh discovery reach and post-discovery measurements, for several Supersymmetry models including and beyond the minimal one, is contained in [139].

Benchmark: ALPs. The exclusive photon-fusion production of 'photophilic' ALPs decaying into a pair of photons, $\gamma\gamma \to a \to \gamma\gamma$, studied for FCC-ee (Fig. 1, right), has been considered also for 'ultraperipheral' pp, pPb and PbPb collisions at the FCC-hh [24]. Parametrized FCC-hh detector simulations based on a dual readout electromagnetic calorimeter [140] are used to evaluate the impact of the γ acceptance and reconstruction efficiencies. Event selection criteria are applied to identify a resonant diphoton excess on top of the light-by-light $\gamma\gamma \to \gamma\gamma$, continuum background [141]. Upper limits at 95% confidence level (CL) on the ALP-photon coupling $g_{a\gamma}$, are obtained as a function of ALP mass (Fig. 1). The results indicate that pp collisions at the FCC-hh (violet area) will be able to search for ALPs with couplings as low as $g_{a\gamma} \approx 10^{-3}$–$10^{-1}$ TeV^{-1} over $m_a \approx 0.2$–30 TeV, improving the current LHC limits (up to $m_a \approx 2.5$ TeV) by more than one order-of-magnitude, and probing the very heavy ALPs region for the first time. For lighter masses ($m_a \lesssim 0.2$ TeV), the large pileup will likely preclude any observation in pp collisions, and the limits from FCC-ee and FCC-hh PbPb collisions will be the most competitive.

FCC: Further Reading

This concludes this 10-page submission. In addition to the material contained here, the FCC FSR [1] and CDR [2], including their extensive references, contain a great deal of important additional information and benchmark analyses.

References

[1] M. Benedikt, et al., Future Circular Collider Feasibility Study Report Volume 1: Physics, Experiments, Detectors. Tech. rep., CERN, Geneva (2025). https://doi.org/10.17181/CERN.9DKX.TDH9. URL https://cds.cern.ch/record/2928193

[2] A. Abada, et al., FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1. Eur. Phys. J. C **79**, 474 (2019). https://doi.org/10.1140/epjc/s10052-019-6904-3

[3] R. Contino, et al., Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies (2016). https://doi.org/10.23731/CYRM-2017-003.255. arXiv:1606.09408 [hep-ph]

[4] T. Golling, et al., Physics at a 100 TeV pp collider: beyond the Standard Model phenomena (2016). https://doi.org/10.23731/CYRM-2017-003.441. arXiv:1606.00947 [hep-ph]

[5] M. Benedikt, et al., Future Circular Collider Feasibility Study Report Volume 2: Accelerators, technical infrastructure and safety. Tech. rep., CERN, Geneva (2025). https://doi.org/10.17181/CERN.EBAY.7W4X. URL https://cds.cern.ch/record/2928793

[6] M. Mangano, M. Selvaggi, B.S. Stapf, A. Taliercio, S.L. Williams, Prospects for physics at FCC-hh (2025). https://doi.org/10.17181/bzhc2-mem17. Submitted to the 2025 Update of the European Strategy for Particle Physics

[7] S. Davidson, E. Nardi, Y. Nir, Leptogenesis. Phys. Rept. **466**, 105–177 (2008). https://doi.org/10.1016/j.physrep.2008.06.002. arXiv:0802.2962 [hep-ph]

[8] S. Dodelson, L.M. Widrow, Sterile-neutrinos as dark matter. Phys. Rev. Lett. **72**, 17–20 (1994). https://doi.org/10.1103/PhysRevLett.72.17. arXiv:hep-ph/9303287

[9] A. Blondel, E. Graverini, N. Serra, M. Shaposhnikov, Search for Heavy Right Handed Neutrinos at the FCC-ee. Nucl. Part. Phys. Proc. **273**, 1883 (2016). https://doi.org/10.1016/j.nuclphysbps.2015.09.304. arXiv:1411.5230 [hep-ex]

[10] M. Drewes, Distinguishing Dirac and Majorana Heavy Neutrinos at Lepton Colliders. PoS **ICHEP2022**, 608 (2022). https://doi.org/10.22323/1.414.0608. arXiv:2210.17110 [hep-ph]

[11] D. Moulin, Probing heavy neutral leptons in the ejj channel et the FCC-ee: kinematic signatures and discovery potential. Master's thesis, Université de Genève (2023)

[12] T.M. Critchley, The hunt for heavy neutrinos: Machine learning techniques to probe heavy neutral leptons in the $e\nu jj$ final state at the e^+e^- future circular collider. Master's thesis, Université de Genève (2024)

[13] L. Bellagamba, G. Polesello, N. Valle. Searches for heavy neutral leptons at fcc-ee in final states including a muon (2025). URL https://arxiv.org/abs/2503.19464

[14] A. Blondel, et al., Searches for long-lived particles at the future FCC-ee. Front. in Phys. **10**, 967881 (2022). https://doi.org/10.3389/fphy.2022.967881. arXiv:2203.05502 [hep-ex]

[15] S. Ajmal, P. Azzi, S. Giappichini, M. Klute, O. Panella, M. Presilla, X. Zuo. Searching for type i seesaw mechanism in a two heavy neutral leptons scenario at fcc-ee (2024). URL https://arxiv.org/abs/2410.03615

[16] S. Williams. Updated studies on the sensitivity of fcc-ee to heavy neutral leptons coupling to electrons at the z-pole run (2025). https://doi.org/10.17181/akxye-jqz25. URL https://doi.org/10.17181/akxye-jqz25

[17] G. Sadowski, J. Andrea, Z. ElBitar, A. Besson, M. Meena. Search for hnl at fccee, and comparisons between fast and full simulation (2025). https://doi.org/10.17181/k3faq-d1f12. URL https://doi.org/10.17181/k3faq-d1f12

[18] S. Antusch, J. Hajer, B.M.S. Oliveira, Heavy neutrino-antineutrino oscillations at the FCC-ee. JHEP **10**, 129 (2023). https://doi.org/10.1007/JHEP10(2023)129. arXiv:2308.07297

[hep-ph]
[19] S. Antusch, J. Hajer, B.M.S. Oliveira, Discovering heavy neutrino-antineutrino oscillations at the Z-pole. JHEP **11**, 102 (2024). https://doi.org/10.1007/JHEP11(2024)102. arXiv:2408.01389 [hep-ph]
[20] G. Polesello. Sensitivity of the fcc-ee to decay of an axion-like particle into two photons (2025). URL https://arxiv.org/abs/2502.08411
[21] P. Rebello Teles, D. d'Enterria, V.P. Gonçalves, D.E. Martins, Searches for axionlike particles via $\gamma\gamma$ fusion at future e^+e^- colliders. Phys. Rev. D **109**, 055003 (2024). https://doi.org/10.1103/PhysRevD.109.055003. arXiv:2310.17270 [hep-ex]
[22] P. Agrawal, et al., Feebly-interacting particles: FIPs 2020 workshop report. Eur. Phys. J. C **81**, 1015 (2021). https://doi.org/10.1140/epjc/s10052-021-09703-7. arXiv:2102.12143 [hep-ph]
[23] C. Antel, et al., Feebly Interacting Particles: FIPs 2022 workshop report (2023). arXiv:2305.01715 [hep-ph]
[24] P. Rebello-Teles, D. d'Enterria, Searches for axion- and graviton-like particles via $\gamma\gamma$ fusion at the FCC-hh (2025). In preparation
[25] J.L. Tastet, O. Ruchayskiy, I. Timiryasov, Reinterpreting the ATLAS bounds on heavy neutral leptons in a realistic neutrino oscillation model. JHEP **12**, 182 (2021). https://doi.org/10.1007/JHEP12(2021)182. arXiv:2107.12980 [hep-ph]
[26] A.M. Abdullahi, et al., The present and future status of heavy neutral leptons. J. Phys. G **50**, 020501 (2023). https://doi.org/10.1088/1361-6471/ac98f9. arXiv:2203.08039 [hep-ph]
[27] M. Shaposhnikov, A Possible symmetry of the nuMSM. Nucl. Phys. B **763**, 49–59 (2007). https://doi.org/10.1016/j.nuclphysb.2006.11.003. arXiv:hep-ph/0605047
[28] J. Kersten, A.Y. Smirnov, Right-Handed Neutrinos at CERN LHC and the Mechanism of Neutrino Mass Generation. Phys. Rev. D **76**, 073005 (2007). https://doi.org/10.1103/PhysRevD.76.073005. arXiv:0705.3221 [hep-ph]
[29] S. Antusch, E. Cazzato, O. Fischer, Sterile neutrino searches at future e^-e^+, pp, and e^-p colliders. Int. J. Mod. Phys. A **32**, 1750078 (2017). https://doi.org/10.1142/S0217751X17500786. arXiv:1612.02728 [hep-ph]
[30] S. Antusch, J. Hajer, J. Rosskopp, Simulating lepton number violation induced by heavy neutrino-antineutrino oscillations at colliders. JHEP **03**, 110 (2023). https://doi.org/10.1007/JHEP03(2023)110. arXiv:2210.10738 [hep-ph]
[31] G. Polesello, N. Valle. FCC note: Measuring the HNL model parameters at FCC-ee (2025). https://doi.org/10.17181/xee7v-h4y88
[32] R.N. Mohapatra, J.W.F. Valle, Neutrino Mass and Baryon Number Nonconservation in Superstring Models. Phys. Rev. D **34**, 1642 (1986). https://doi.org/10.1103/PhysRevD.34.1642
[33] E.K. Akhmedov, M. Lindner, E. Schnapka, J.W.F. Valle, Left-right symmetry breaking in NJL approach. Phys. Lett. B **368**, 270 (1996). https://doi.org/10.1016/0370-2693(95)01504-3. arXiv:hep-ph/9507275
[34] E.K. Akhmedov, M. Lindner, E. Schnapka, J.W.F. Valle, Dynamical left-right symmetry breaking. Phys. Rev. D **53**, 2752 (1996). https://doi.org/10.1103/PhysRevD.53.2752. arXiv:hep-ph/9509255
[35] S. Antusch, E. Cazzato, M. Drewes, O. Fischer, B. Garbrecht, D. Gueter, J. Klaric, Probing Leptogenesis at Future Colliders. JHEP **09**, 124 (2018). https://doi.org/10.1007/JHEP09(2018)124. arXiv:1710.03744 [hep-ph]
[36] A. Blondel, A. de Gouvêa, B. Kayser, Z-boson decays into Majorana or Dirac heavy neutrinos. Phys. Rev. D **104**(5), 055027 (2021). https://doi.org/10.1103/PhysRevD.104.055027.

arXiv:2105.06576 [hep-ph]
[37] M. Drewes, Y. Georis, J. Klarić, A. Wendels, On the collider-testability of the type-I seesaw model with 3 right-handed neutrinos (2024). arXiv:2407.13620 [hep-ph]
[38] M. Drewes, Y. Georis, C. Hagedorn, J. Klaric, Low-scale seesaw with flavour and CP symmetries – from colliders to leptogenesis (2024). arXiv:2412.10254 [hep-ph]
[39] S. Antusch. Talk the FCC-hh WG meeeting, Sept 3, 2024. URL https://indico.cern.ch/event/1439072/contributions/6107072
[40] S. Antusch, J. Hajer, B. Oliveira. In preparation
[41] M. Bauer, M. Heiles, M. Neubert, A. Thamm, Axion-Like Particles at Future Colliders. Eur. Phys. J. C **79**, 74 (2019). https://doi.org/10.1140/epjc/s10052-019-6587-9. arXiv:1808.10323 [hep-ph]
[42] D. d'Enterria, Collider constraints on axion-like particles (2021). arXiv:2102.08971 [hep-ex]
[43] K. Cheung, C.J. Ouseph, Axionlike particle search at Higgs factories. Phys. Rev. D **108**, 035003 (2023). https://doi.org/10.1103/PhysRevD.108.035003. arXiv:2303.16514 [hep-ph]
[44] L. Calibbi, Z. Huang, S. Qin, Y. Yang, X. Yin, Testing axion couplings to leptons in Z decays at future $\mathrm{e}^+\mathrm{e}^-$ colliders. Phys. Rev. D **108**, 015002 (2023). https://doi.org/10.1103/PhysRevD.108.015002. arXiv:2212.02818 [hep-ph]
[45] J. Liu, X. Ma, L.T. Wang, X.P. Wang, ALP explanation to the muon (g-2) and its test at future Tera-Z and Higgs factories. Phys. Rev. D **107**, 095016 (2023). https://doi.org/10.1103/PhysRevD.107.095016. arXiv:2210.09335 [hep-ph]
[46] H.Y. Zhang, C.X. Yue, Y.C. Guo, S. Yang, Searching for axionlike particles at future electron-positron colliders. Phys. Rev. D **104**, 096008 (2021). https://doi.org/10.1103/PhysRevD.104.096008. arXiv:2103.05218 [hep-ph]
[47] M. Meena, J. Andrea, A. Besson, G. Sadowski, Z. El Bitar. FCC note: Search for Axion-Like Particles decaying into a pair of gluons at FCC-ee (2025). https://doi.org/10.17181/2zh7p-v9a72
[48] M. Karliner, M. Low, J.L. Rosner, L.T. Wang, Radiative return capabilities of a high-energy, high-luminosity e^+e^- collider. Phys. Rev. D **92**, 035010 (2015). https://doi.org/10.1103/PhysRevD.92.035010. arXiv:1503.07209 [hep-ph]
[49] P. Giffin, I.M. Lewis, Y.J. Zheng, Higgs production in association with a dark-Z at future electron positron colliders. J. Phys. G **49**, 015003 (2022). https://doi.org/10.1088/1361-6471/ac38c1. arXiv:2012.13404 [hep-ph]
[50] S. Airen, E. Broadberry, G. Marques-Tavares, L. Ricci, Vector Portals at Future Lepton Colliders (2024). arXiv:2412.09681 [hep-ph]
[51] S.F. Ge, K. Ma, X.D. Ma, J. Sheng, Associated production of neutrino and dark fermion at future lepton colliders. JHEP **11**, 190 (2023). https://doi.org/10.1007/JHEP11(2023)190. arXiv:2306.00657 [hep-ph]
[52] M. Cobal, C. De Dominicis, M. Fabbrichesi, E. Gabrielli, J. Magro, B. Mele, G. Panizzo, Z-boson decays into an invisible dark photon at the LHC, HL-LHC and future lepton colliders. Phys. Rev. D **102**, 035027 (2020). https://doi.org/10.1103/PhysRevD.102.035027. arXiv:2006.15945 [hep-ph]
[53] *Light Mediators: Dark Photons*, Section 4.4.4 of [4]
[54] D. Curtin, et al., Exotic decays of the 125 GeV Higgs boson. Phys. Rev. D **90**, 075004 (2014). https://doi.org/10.1103/PhysRevD.90.075004. arXiv:1312.4992 [hep-ph]
[55] M. Cepeda, S. Gori, V.M. Outschoorn, J. Shelton, Exotic Higgs Decays p. 119 (2021). https://doi.org/10.1146/annurev-nucl-102319-024147. arXiv:2111.12751 [hep-ph]
[56] S. Ma, K. Wang, J. Zhu, Higgs decay to light (pseudo)scalars in the semi-constrained

NMSSM. Chin. Phys. C **45**, 023113 (2021). https://doi.org/10.1088/1674-1137/abce4f. arXiv:2006.03527 [hep-ph]

[57] S. Alipour-Fard, N. Craig, M. Jiang, S. Koren, Long Live the Higgs Factory: Higgs Decays to Long-Lived Particles at Future Lepton Colliders. Chin. Phys. C **43**, 053101 (2019). https://doi.org/10.1088/1674-1137/43/5/053101. arXiv:1812.05588 [hep-ph]

[58] Z. Liu, L.T. Wang, H. Zhang, Exotic decays of the 125 GeV Higgs boson at future e^+e^- lepton colliders. Chin. Phys. C **41**(6), 063102 (2017). https://doi.org/10.1088/1674-1137/41/6/063102. arXiv:1612.09284 [hep-ph]

[59] Z.S. Wang, K. Wang, Long-lived light neutralinos at future $Z-$factories. Phys. Rev. D **101**, 115018 (2020). https://doi.org/10.1103/PhysRevD.101.115018. arXiv:1904.10661 [hep-ph]

[60] H.C. Cheng, L. Li, E. Salvioni, C.B. Verhaaren, Light Hidden Mesons through the Z Portal. JHEP **11**, 031 (2019). https://doi.org/10.1007/JHEP11(2019)031. arXiv:1906.02198 [hep-ph]

[61] R. Gonzalez Suarez, B. Pattnaik, J. Zurita, Leptophilic Z' bosons at the FCC-ee: discovery opportunities (2024). arXiv:2410.12903 [hep-ph]

[62] T. Miralles, Study of hadronic B meson decays with the LHCb spectrometer (at LHC) and an investigation of detector requirements for the Future Circular Collider (FCC-ee). Theses, Université Clermont Auvergne (2024). URL https://theses.hal.science/tel-04959240

[63] Y. Amhis, M. Hartmann, C. Helsens, D. Hill, O. Sumensari, Prospects for $B_c^+ \to \tau^+\nu_t$ at FCC-ee. JHEP **12**, 133 (2021). https://doi.org/10.1007/JHEP12(2021)133. arXiv:2105.13330 [hep-ex]

[64] X. Zuo, M. Fedele, C. Helsens, D. Hill, S. Iguro, M. Klute, Prospects for B_c^+ and $B^+ \to \tau^+\nu_\tau$ at FCC-ee. Eur. Phys. J. C **84**(1), 87 (2024). https://doi.org/10.1140/epjc/s10052-024-12418-0. arXiv:2305.02998 [hep-ex]

[65] A. Angelescu, D. Bečirević, D.A. Faroughy, F. Jaffredo, O. Sumensari, Single leptoquark solutions to the B-physics anomalies. Phys. Rev. D **104**(5), 055017 (2021). https://doi.org/10.1103/PhysRevD.104.055017. arXiv:2103.12504 [hep-ph]

[66] J. Aebischer, G. Isidori, M. Pesut, B.A. Stefanek, F. Wilsch, Confronting the vector leptoquark hypothesis with new low- and high-energy data. Eur. Phys. J. C **83**, 153 (2023). https://doi.org/10.1140/epjc/s10052-023-11304-5. arXiv:2210.13422 [hep-ph]

[67] L. Allwicher, G. Isidori, M. Pesut, Flavored Circular Collider: cornering New Physics at FCC-ee via flavor-changing processes (2025). arXiv:2503.17019 [hep-ph]

[68] L. Allwicher, M. Bordone, G. Isidori, G. Piazza, A. Stanzione, Probing third-generation New Physics with K$\to\pi\nu\nu^-$ and B$\to$K($*$)$\nu\nu^-$. Phys. Lett. B **861**, 139295 (2025). https://doi.org/10.1016/j.physletb.2025.139295. arXiv:2410.21444 [hep-ph]

[69] Y. Amhis, M. Kenzie, M. Reboud, A.R. Wiederhold, Prospects for searches of $b \to s\nu\overline{\nu}$ decays at FCC-ee. JHEP **01**, 144 (2024). https://doi.org/10.1007/JHEP01(2024)144. arXiv:2309.11353 [hep-ex]

[70] A. Lusiani, *Tau Physics Prospects at FCC-ee* (2025). https://doi.org/10.17181/9bkm6-h8906. URL https://doi.org/10.17181/9bkm6-h8906

[71] M. Dam, Tau-lepton Physics at the FCC-ee circular e$^+$e$^-$ Collider. SciPost Phys. Proc. p. 041 (2019). https://doi.org/10.21468/SciPostPhysProc.1.041. URL https://scipost.org/10.21468/SciPostPhysProc.1.041

[72] M. Bordone, C. Cornella, J. Davighi, Precision Tests in $b \to s\ell^+\ell^-$ ($\ell = e, \mu$) at FCC-ee (2025). arXiv:2503.22635 [hep-ph]

[73] J.F. Kamenik, A. Korajac, M. Szewc, M. Tammaro, J. Zupan, Flavor-violating Higgs and Z boson decays at a future circular lepton collider. Phys. Rev. D **109**, L011301 (2024). https://doi.

org/10.1103/PhysRevD.109.L011301. arXiv:2306.17520 [hep-ph]

[74] L. Allwicher, C. Cornella, G. Isidori, B.A. Stefanek, New physics in the third generation. A comprehensive SMEFT analysis and future prospects. JHEP **03**, 049 (2024). https://doi.org/10.1007/JHEP03(2024)049. arXiv:2311.00020 [hep-ph]

[75] L. Allwicher, M. McCullough, S. Renner, New Physics at Tera-Z: Precision Renormalised (2024). arXiv:2408.03992 [hep-ph]

[76] J. Gargalionis, J. Quevillon, P.N.H. Vuong, T. You, Linear Standard Model extensions in the SMEFT at one loop and Tera-Z (2024). arXiv:2412.01759 [hep-ph]

[77] J. ter Hoeve, L. Mantani, A.N. Rossia, J. Rojo, E. Vryonidou, Connecting Scales: RGE Effects in the SMEFT at the LHC and Future Colliders (2025). arXiv:2502.20453 [hep-ph]

[78] F. Feruglio, P. Paradisi, A. Pattori, On the Importance of Electroweak Corrections for B Anomalies. JHEP **09**, 061 (2017). https://doi.org/10.1007/JHEP09(2017)061. arXiv:1705.00929 [hep-ph]

[79] L. Allwicher, G. Isidori, J.M. Lizana, N. Selimovic, B.A. Stefanek, Third-family quark-lepton Unification and electroweak precision tests. JHEP **05**, 179 (2023). https://doi.org/10.1007/JHEP05(2023)179. arXiv:2302.11584 [hep-ph]

[80] A. Greljo, H. Tiblom, A. Valenti, New Physics Through Flavor Tagging at FCC-ee (2024). arXiv:2411.02485 [hep-ph]

[81] B.A. Stefanek, Non-universal probes of composite Higgs models: New bounds and prospects for FCC-ee (2024). arXiv:2407.09593 [hep-ph]

[82] J. Davighi, G. Isidori, Non-universal gauge interactions addressing the inescapable link between Higgs and flavour. JHEP **07**, 147 (2023). https://doi.org/10.1007/JHEP07(2023)147. arXiv:2303.01520 [hep-ph]

[83] J. Davighi, J. Tooby-Smith, Electroweak flavour unification. JHEP **09**, 193 (2022). https://doi.org/10.1007/JHEP09(2022)193. arXiv:2201.07245 [hep-ph]

[84] J. Fuentes-Martin, G. Isidori, J.M. Lizana, N. Selimovic, B.A. Stefanek, Flavor hierarchies, flavor anomalies, and Higgs mass from a warped extra dimension. Phys. Lett. B **834**, 137382 (2022). https://doi.org/10.1016/j.physletb.2022.137382. arXiv:2203.01952 [hep-ph]

[85] J. Davighi, B.A. Stefanek, Deconstructed hypercharge: a natural model of flavour. JHEP **11**, 100 (2023). https://doi.org/10.1007/JHEP11(2023)100. arXiv:2305.16280 [hep-ph]

[86] J. Davighi, A. Gosnay, D.J. Miller, S. Renner, Phenomenology of a Deconstructed Electroweak Force. JHEP **05**, 085 (2024). https://doi.org/10.1007/JHEP05(2024)085. arXiv:2312.13346 [hep-ph]

[87] B. Capdevila, A. Crivellin, J.M. Lizana, S. Pokorski, SU(2)$_L$ deconstruction and flavour (non)-universality. JHEP **08**, 031 (2024). https://doi.org/10.1007/JHEP08(2024)031. arXiv:2401.00848 [hep-ph]

[88] A. Blondel, C. Grojean, P. Janot, G. Wilkinson, Higgs factory options for CERN: A comparative study (2024). arXiv:2412.13130 [hep-ph]

[89] T. Barklow, K. Fujii, S. Jung, R. Karl, J. List, T. Ogawa, M.E. Peskin, J. Tian, Improved Formalism for Precision Higgs Coupling Fits. Phys. Rev. D **97**, 053003 (2018). https://doi.org/10.1103/PhysRevD.97.053003. arXiv:1708.08912 [hep-ph]

[90] M. McCullough, An Indirect Model-Dependent Probe of the Higgs Self-Coupling. Phys. Rev. D **90**, 015001 (2014). https://doi.org/10.1103/PhysRevD.90.015001. [Erratum: Phys.Rev.D 92, 039903 (2015)]. arXiv:1312.3322 [hep-ph]

[91] V. Maura, B.A. Stefanek, T. You, The Higgs Self-Coupling at FCC-ee (2025). arXiv:2503.13719 [hep-ph]

[92] A. Mehta, N. Rompotis, S. Randles. Higgs to invisible at the fcc-ee (2025). https://doi.org/

10.17181/9b128-qqc43. URL https://doi.org/10.17181/9b128-qqc43
[93] G. Haghighat, M. Mohammadi Najafabadi, K. Sakurai, W. Yin, Probing a light dark sector at future lepton colliders via invisible decays of the SM-like and dark Higgs bosons. Phys. Rev. D **107**, 035033 (2023). https://doi.org/10.1103/PhysRevD.107.035033. arXiv:2209.07565 [hep-ph]
[94] L. Borgonovi, et al., Higgs and Electro-weak symmetry breaking at the FCC-hh (2019)
[95] G. Ripellino, M.V. Voorde, A. Gallen, R. Gonzalez Suarez, Searching for long-lived dark scalars at the FCC-ee (2024). arXiv:2412.10141 [hep-ex]
[96] E. Curtis, A.M. Magnan, T. Robens, A. Bal, B. Maier, N. Wardle, *Search for additional scalar bosons within the Inert Doublet Model in a final state with two leptons at the FCC-ee* (2025). https://doi.org/10.17181/rtrkc-n8804. URL https://doi.org/10.17181/rtrkc-n8804
[97] G.F. Giudice, M. McCullough, T. You, Self-organised localisation. JHEP **10**, 093 (2021). https://doi.org/10.1007/JHEP10(2021)093. arXiv:2105.08617 [hep-ph]
[98] J. Khoury, T. Steingasser, Gauge hierarchy from electroweak vacuum metastability. Phys. Rev. D **105**(5), 055031 (2022). https://doi.org/10.1103/PhysRevD.105.055031. arXiv:2108.09315 [hep-ph]
[99] M. Detering, T. You, Vacuum Metastability from Axion-Higgs Criticality (2024). arXiv:2412.03542 [hep-ph]
[100] C. Grojean, G. Servant, J.D. Wells, First-order electroweak phase transition in the standard model with a low cutoff. Phys. Rev. D **71**, 036001 (2005). https://doi.org/10.1103/PhysRevD.71.036001. arXiv:hep-ph/0407019
[101] I. Banta, A strongly first-order electroweak phase transition from Loryons. JHEP **06**, 099 (2022). https://doi.org/10.1007/JHEP06(2022)099. arXiv:2202.04608 [hep-ph]
[102] I. Banta, T. Cohen, N. Craig, X. Lu, D. Sutherland, Non-decoupling new particles. JHEP **02**, 029 (2022). https://doi.org/10.1007/JHEP02(2022)029. arXiv:2110.02967 [hep-ph]
[103] N. Craig, C. Englert, M. McCullough, New Probe of Naturalness. Phys. Rev. Lett. **111**(12), 121803 (2013). https://doi.org/10.1103/PhysRevLett.111.121803. arXiv:1305.5251 [hep-ph]
[104] G. Crawford, D. Sutherland, Non-decoupling scalars at future colliders (2024). arXiv:2409.18177 [hep-ph]
[105] P. Janot, Top-quark electroweak couplings at the FCC-ee. JHEP **04**, 182 (2015). https://doi.org/10.1007/JHEP04(2015)182. arXiv:1503.01325 [hep-ph]
[106] M.M. Defranchis, J. de Blas, A. Mehta, M. Selvaggi, M. Vos, A detailed study on the prospects for a $\mathrm{t\bar{t}}$ threshold scan in $\mathrm{e^+e^-}$ collisions (2025). arXiv:2503.18713 [hep-ph]
[107] D. d'Enterria, et al., The strong coupling constant: state of the art and the decade ahead. J. Phys. G **51**, 090501 (2024). https://doi.org/10.1088/1361-6471/ad1a78. arXiv:2203.08271 [hep-ph]
[108] M.L. Mangano, et al., Physics at a 100 TeV pp Collider: Standard Model Processes (2016). https://doi.org/10.23731/CYRM-2017-003.1. arXiv:1607.01831 [hep-ph]
[109] V. Maura, B.A. Stefanek, T. You, Accuracy complements energy: electroweak precision tests at Tera-Z (2024). arXiv:2412.14241 [hep-ph]
[110] D.S.M. Alves, J. Galloway, J.T. Ruderman, J.R. Walsh, Running Electroweak Couplings as a Probe of New Physics. JHEP **02**, 007 (2015). https://doi.org/10.1007/JHEP02(2015)007. arXiv:1410.6810 [hep-ph]
[111] See Section 5.3.2 of [4]
[112] See section 4 of [4]

[113] L. Di Luzio, R. Gröber, G. Panico, Probing new electroweak states via precision measurements at the LHC and future colliders. JHEP **01**, 011 (2019). https://doi.org/10.1007/JHEP01(2019)011. arXiv:1810.10993 [hep-ph]

[114] M. Cirelli, N. Fornengo, A. Strumia, Minimal dark matter. Nucl. Phys. B **753**, 178–194 (2006). https://doi.org/10.1016/j.nuclphysb.2006.07.012. arXiv:hep-ph/0512090

[115] R. Barbieri, A. Pomarol, R. Rattazzi, A. Strumia, Electroweak symmetry breaking after LEP-1 and LEP-2. Nucl. Phys. B **703**, 127–146 (2004). https://doi.org/10.1016/j.nuclphysb.2004.10.014. arXiv:hep-ph/0405040

[116] S. Matsumoto, S. Shirai, M. Takeuchi, Indirect Probe of Electroweak-Interacting Particles with Mono-Lepton Signatures at Hadron Colliders. JHEP **03**, 076 (2019). https://doi.org/10.1007/JHEP03(2019)076. arXiv:1810.12234 [hep-ph]

[117] *WIMP Dark Matter: Standard Model Mediators*, Section 4.3 of [4]

[118] M. Saito, R. Sawada, K. Terashi, S. Asai, Discovery reach for wino and higgsino dark matter with a disappearing track signature at a 100 TeV pp collider. Eur. Phys. J. C **79**, 469 (2019). https://doi.org/10.1140/epjc/s10052-019-6974-2. arXiv:1901.02987 [hep-ph]

[119] S.I. Horigome, T. Katayose, S. Matsumoto, I. Saha, Leptophilic fermion WIMP: Role of future lepton colliders. Phys. Rev. D **104**, 055001 (2021). https://doi.org/10.1103/PhysRevD.104.055001. arXiv:2102.08645 [hep-ph]

[120] C. Cesarotti, G. Krnjaic, Hitting the Thermal Target for Leptophilic Dark Matter (2024). arXiv:2404.02906 [hep-ph]

[121] A. Roy, B. Dasgupta, M. Guchait, Constraining Asymmetric Dark Matter using colliders and direct detection. JHEP **08**, 095 (2024). https://doi.org/10.1007/JHEP08(2024)095. arXiv:2402.17265 [hep-ph]

[122] B. Grzadkowski, M. Iglicki, K. Mekala, A.F. Zarnecki, Dark-matter-spin effects at future e^+e^- colliders. JHEP **08**, 052 (2020). https://doi.org/10.1007/JHEP08(2020)052. arXiv:2003.06719 [hep-ph]

[123] M. Ruhdorfer, E. Salvioni, A. Weiler, A Global View of the Off-Shell Higgs Portal. SciPost Phys. **8**, 027 (2020). https://doi.org/10.21468/SciPostPhys.8.2.027. arXiv:1910.04170 [hep-ph]

[124] M. Ramos, Composite dark matter phenomenology in the presence of lighter degrees of freedom. JHEP **07**, 128 (2020). https://doi.org/10.1007/JHEP07(2020)128. arXiv:1912.11061 [hep-ph]

[125] M.J. Strassler, K.M. Zurek, Echoes of a hidden valley at hadron colliders. Phys. Lett. B **651**, 374–379 (2007). https://doi.org/10.1016/j.physletb.2007.06.055. arXiv:hep-ph/0604261

[126] T. Han, Z. Si, K.M. Zurek, M.J. Strassler, Phenomenology of hidden valleys at hadron colliders. JHEP **07**, 008 (2008). https://doi.org/10.1088/1126-6708/2008/07/008. arXiv:0712.2041 [hep-ph]

[127] T. Cohen, M. Lisanti, H.K. Lou, S. Mishra-Sharma, LHC Searches for Dark Sector Showers. JHEP **11**, 196 (2017). https://doi.org/10.1007/JHEP11(2017)196. arXiv:1707.05326 [hep-ph]

[128] A. Carmona, F. Elahi, C. Scherb, P. Schwaller, Dark showers from sneaky dark matter (2024). arXiv:2411.15073 [hep-ph]

[129] R. Essig, P. Schuster, N. Toro, Probing Dark Forces and Light Hidden Sectors at Low-Energy e+e- Colliders. Phys. Rev. D **80**, 015003 (2009). https://doi.org/10.1103/PhysRevD.80.015003. arXiv:0903.3941 [hep-ph]

[130] See Section 6.7 of [3]

[131] M.J. Baker, T. Martonhelyi, A. Thamm, R. Torre, A Simplified Model of Heavy Vector Singlets for the LHC and Future Colliders (2024). arXiv:2407.11117 [hep-ph]

[132] R.K. Ellis, et al., Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020 (2019). arXiv:1910.11775 [hep-ex]

[133] A. Glioti, R. Rattazzi, L. Ricci, L. Vecchi, Exploring the Flavor Symmetry Landscape (2024). arXiv:2402.09503 [hep-ph]

[134] See Sections 5.1 and 5.2 of [4]

[135] C. Helsens, D. Jamin, M.L. Mangano, T.G. Rizzo, M. Selvaggi, Heavy resonances at energy-frontier hadron colliders. Eur. Phys. J. C **79**, 569 (2019). https://doi.org/10.1140/epjc/s10052-019-7062-3. arXiv:1902.11217 [hep-ph]

[136] A. Azatov, F. Garosi, A. Greljo, D. Marzocca, J. Salko, S. Trifinopoulos, New physics in $b \to s\mu\mu$: FCC-hh or a muon collider? JHEP **10**, 149 (2022). https://doi.org/10.1007/JHEP10(2022)149. arXiv:2205.13552 [hep-ph]

[137] P. Huang, A.J. Long, L.T. Wang, Probing the Electroweak Phase Transition with Higgs Factories and Gravitational Waves. Phys. Rev. D **94**(7), 075008 (2016). https://doi.org/10.1103/PhysRevD.94.075008. arXiv:1608.06619 [hep-ph]

[138] See Section 11 of [2] and Section 6.3 of [3]

[139] See section 3 of [4]

[140] M.T. Lucchini, W. Chung, S.C. Eno, Y. Lai, L. Lucchini, M.T. Nguyen, C.G. Tully, New perspectives on segmented crystal calorimeters for future colliders. JINST **15**(11), P11005 (2020). https://doi.org/10.1088/1748-0221/15/11/P11005. arXiv:2008.00338 [physics.ins-det]

[141] D. d'Enterria, G.G. da Silveira, Observing light-by-light scattering at the Large Hadron Collider. Phys. Rev. Lett. **111**, 080405 (2013). https://doi.org/10.1103/PhysRevLett.111.080405. [Erratum: Phys.Rev.Lett. 116, 129901 (2016)]. arXiv:1305.7142 [hep-ph]