

## Report by ESG Working Group 2b: Project Comparison – Physics Potential

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### Abstract

Future collider facilities are essential to carry out precision measurements in the Higgs sector, perform precision tests of the Standard Model and probe physics beyond it. This document presents a comparative assessment of proposed colliders based on studies in the Physics Briefing Book, focusing on two domains: precision physics – including Higgs physics, electroweak observables, top-quark and flavour physics and strong-interaction studies – and the discovery reach for representative new-physics scenarios. The facilities are evaluated according to their physics potential, energy reach and available centre-of-mass energies. New-physics potential is assessed using benchmark models and a synthesis of direct and indirect sensitivity is made. The methodology and results of the comparisons are summarised.

## 1 Introduction and methodology

Future colliders are essential for deepening our understanding of the full structure of the Standard Model and are critical to exploring what is beyond it. The full exploitation of the HL-LHC is vital: its physics programme will greatly sharpen the precision of a vast domain of observables while continuing to explore the energy frontier through a significant increase in luminosity. The innovative upgrade programmes that will become effective at the end of the decade, complemented by specific further upgrade programmes proposed for flavour and quark–gluon plasma studies, confirm the vivacity of the particle physics community and provide the foundation for any future facility.

This document reviews the criteria used by the Working Group to compare the overall physics potential between proposed projects. It focuses on two areas:

- *Precision physics.* Precise tests of the Standard Model (SM) in Higgs physics, electroweak precision observables (EWPO), top physics, flavour physics and strong interaction (covering precision tests of quantum chromodynamics (QCD), partonic structure and heavy ions).
- *New Physics.* Analysis of the discovery potential in representative, complementary classes of Beyond Standard Model (BSM) models.

This evaluation is based on the studies set out in the Physics Briefing Book [1], where some of the input from various collider projects is interpreted within the framework of the Standard Model Effective Field Theory (SMEFT). The exact parameters and assumptions of the SMEFT results are discussed at length therein (see, for example, appendix A). The input and the associated precision estimates for the various collider projects, which were submitted to the European Strategy update by the project teams, were interpreted and compared by the Physics Preparatory Group and largely left unchanged. This document summarises the input received and the interpretation thereof, as documented in the Physics Briefing Book.

## 2 Precision physics potential

### 2.1 FCC-ee

The FCC-ee operates at multiple centre-of-mass energies: the  $Z$  pole, the  $WW$  threshold, the  $ZH$  Higgs boson threshold and the top-quark pair threshold. This combination and the expected large integrated luminosity yield the best Higgs boson coupling precision when compared to LEP3, LCF-250 and CLIC-380, enabling percent- to subpercent-level determinations of most Higgs boson interactions and providing access to a model-independent extraction of the Higgs boson total width. Its Tera- $Z$  run delivers unrivalled EWPO precision, improving key observables by one to two orders of magnitude compared to present knowledge. The top-quark threshold run provides the most precise top-quark mass determination compared to the other proposed colliders, along with tests of top-gauge and top-Higgs interactions in top-quark-pair production. With these substantial datasets, the Higgs boson self-coupling can be probed via precision single Higgs boson measurements, and the determination of the self-coupling can be improved over that achieved at the HL-LHC.

Flavour physics also benefits from the Tera- $Z$  dataset, which produces large samples of beauty, charm and  $\tau$  leptons, boosted and in a clean environment. Such a dataset would allow measurements to be produced that surpass the reach of the HL-LHC and Belle II across a wide set of rare, CP-violating and lepton-flavour-violating channels. Searches for ultra-rare  $b$ ,  $c$ , and  $\tau$  decays, as well as probes of lepton universality, achieve sensitivities previously associated only with dedicated flavour factories.

In precision QCD, the FCC-ee makes several key measurements. The Tera- $Z$  data sample enables subpercent extractions of the strong coupling,  $\alpha_s$ . The top-quark and  $WW$  runs provide the best measurements of the top-quark and  $W$  boson masses compared to the other proposed colliders. As with other  $e^+e^-$  machines, the FCC-ee has a minimal programme on partonic structure, limited to measurements related to photon structure, fragmentation and hadronisation, and does not contribute to heavy-ion physics.

Also considered here is a descoped scenario of the FCC-ee, which consists of no run at the  $t\bar{t}$  threshold, a reduction in synchrotron radiation power and two instead of four interaction points. The integrated luminosity is reduced by a factor of approximately 0.36 with respect to the baseline FCC-ee scenario and is derived based on the ratio of RF power of 3/5, a factor 1/2 from the number of experiments and a recovery of 20% from optimisation of the machine parameters for two instead of four experiments. More details on the physics projections of this scenario can be found in appendix A.

## 2.2 LEP3

LEP3, operating in the existing LHC tunnel, is conceptually similar to the FCC-ee but at reduced luminosity and, importantly, without a top-quark-threshold run. For Higgs physics, these two points lead to a substantially weaker coupling precision, with no improvement in the determination of the Higgs boson self-coupling beyond that from the HL-LHC. Its EWPO programme benefits from a high-statistics  $Z$ -pole run but at four times less luminosity than the FCC-ee, resulting in a loss in precision for key observables. As LEP3 does not include a top-quark-threshold run, its top-physics sensitivity is limited to what can be inferred from EWPOs. Its flavour programme is also weakened by the reduced luminosity of the  $Z$ -pole run, but provides many results beyond those that can be achieved with the HL-LHC and Belle II. While LEP3 provides reduced but still competitive results relating to the  $W$  boson mass and  $\alpha_s$ , it cannot measure the top-quark mass. In partonic structure, photon structure, fragmentation and hadronisation can be studied with similar systematics to FCC-ee, but with statistics insufficient to match the FCC-ee's precision.

## 2.3 LHeC

The LHeC provides a powerful deep-inelastic scattering (DIS) programme with unprecedented precision in proton and nuclear parton distribution functions (PDFs), generalised parton distributions (GPDs) and related QCD quantities. However, the machine is not a Higgs boson factory and, while it can measure specific channels such as  $HWW$  and  $Hcc$  with good precision, its contribution to a global EFT fit yields sensitivities that are only marginally improved with respect to the HL-LHC baseline. For EWPOs, only a handful of electroweak observables – such as  $\sin^2 \theta_W$  – see modest precision gains. The LHeC lacks any top-quark-threshold capabilities and, although single-top production can be measured, it brings only incremental improvements over HL-LHC precision. Flavour physics does not significantly benefit from the LHeC environment. Where LHeC shines is in its QCD programme. It provides a competitive measurement of  $\alpha_s$  compared to the FCC-ee. For partonic structure, it provides world-leading PDFs and nPDFs and crucial measurements for any future hadron collider, such as the FCC-hh.

## 2.4 LCF-250

At energies of up to 250 GeV, the LCF-250 provides polarised  $e^+e^-$  collisions but operates with a luminosity roughly a factor of three lower than that of the FCC-ee at the  $ZH$  threshold and, importantly, does not include a top-quark-threshold run. As a result, Higgs boson coupling measurements show a noticeable reduction in precision across most channels compared to the full FCC-ee programme. In addition, the LCF-250 does not improve the determination of the Higgs boson self-coupling relative to that from the HL-LHC, as it does not access a second energy point above the Higgs boson threshold nor double Higgs boson production. In EWPOs, LCF-250 is limited by the absence of a high-statistics  $Z$ -pole run, although its ability to have polarised beams partially compensates for the lower luminosity. With approximately 2500 times lower  $Z$ -pole luminosity than the FCC-ee, it cannot match the precision expected from the latter. There is also no top-quark-threshold run, which eliminates the possibility of a precise top-quark-mass determination from threshold scans, and its sensitivity to top-quark operators is worse compared to the full FCC-ee.

In flavour physics, LCF-250's  $Z$  sample is too small to improve on the HL-LHC or Belle II for rare and CP-violating decays, and it cannot approach the broad heavy-flavour programme enabled by the FCC-ee Tera- $Z$  run. It cannot provide precise measurements of  $\alpha_s$  and relies on calculations of this parameter from lattice methods. It does provide a competitive measurement of the  $W$  boson mass. Like all  $e^+e^-$  colliders, it provides a limited programme in partonic structure.

## 2.5 CLIC-380

The first CLIC stage at 380 GeV benefits from higher energy than LCF-250, but still provides lower luminosity (approximately a factor of two below that of the FCC-ee’s  $ZH$  run). Higgs boson coupling precision is therefore weaker than in the FCC-ee and, like LCF-250 and LEP3, CLIC-380 does not improve the determination of the Higgs boson self-coupling relative to that from the HL-LHC, since it does not access a second energy point above the threshold for  $ZH$  production nor double Higgs boson production. In electroweak precision physics, CLIC-380 conducts no  $Z$ -pole programme in its baseline submission [2], eliminating the main handle on high-precision EWPOs. However, it does provide some complementary measurements in this area via diboson and four-fermion processes at high energies. While these give sensitivity to certain EFT operators, the overall precision remains below what the FCC-ee achieves with the Tera- $Z$  dataset. Although not considered here, operations at the  $Z$ -pole are possible [3] and would strengthen its EWPO programme to be similar to that of LCF-250. CLIC-380’s advantage lies in the presence of a top-quark-threshold run, enabling top-quark mass and width measurements at a precision comparable to that of the FCC-ee. The energy reach of the global top-EFT operators approaches that of the FCC-ee.

Flavour physics is not competitive due to the lack of a large  $Z$  sample, bringing no improvements beyond the HL-LHC or Belle II. It also provides no precise measurements of  $\alpha_s$  and relies on calculations of this parameter from lattice methods. For QCD and hadronic final states, CLIC-380 accesses photon structure and hadronisation observables with similar systematics to other  $e^+e^-$  machines, but with a much smaller statistical reach.

## 2.6 Mid-energy linear collider scenarios

Upgraded linear-collider scenarios substantially strengthen the physics case compared to their initial stages. LCF-250+550 reaches energies sufficient for double Higgs boson production, enabling a more precise determination of the Higgs boson self-coupling and yielding comparable precision in single Higgs boson coupling determination compared to the FCC-ee. Precision in electroweak physics improves thanks to high-energy diboson and difermion processes. Top physics benefits from both a small data sample at the top-quark threshold and the 550 GeV centre-of-mass point above the top threshold, yielding improvements relative to LCF-250 alone. CLIC-380+1500, with its higher final energy, also gains Higgs boson self-coupling sensitivity via double Higgs boson production and achieves single Higgs boson coupling precision comparable to the FCC-ee. Operations at the  $Z$ -pole energy would increase its EWPO capabilities, while high-energy measurements provide improved reach in certain EFT directions. The top-physics programme for CLIC-380+1500 is particularly strong: multiple energy points above threshold yield precisions that exceed the FCC-ee on several operator combinations. At even higher energies with LCF-1000 and CLIC-3000, the precision in the Higgs and top-quark sectors improves even further via continued access to multiple Higgs boson production modes and energy-dependent top-quark operators. Flavour physics and measurements of  $\alpha_s$  remain limited by the absence of a large  $Z$  dataset.

## 2.7 FCC-hh

The FCC-hh hadron collider opens up the high-energy regime and provides the best precision in the top-Yukawa coupling and for rare decays such as  $H \rightarrow \mu\mu$  and  $H \rightarrow Z\gamma$ , as well as providing the ultimate precision for the Higgs boson self-coupling, when running directly after either the HL-LHC or the FCC-ee. When running after the FCC-ee, the FCC-hh yields the best overall precision in Higgs and EWPO physics. In top physics and for high-energy reach, it provides unique and complementary information from contributions from four-quark operators and QCD currents compared to high-energy lepton colliders. A hadron machine also benefits from measurements of differential distributions, which are expected to further improve its precision programme, but only a few were included in these comparisons.

At FCC-hh energies, the proton’s partonic structure is mapped with unprecedented kinematic reach, accessing Bjorken- $x$  values down to  $10^{-7}$  and multi-TeV momentum transfers. This dramatically improves PDF uncertainties, enabling precision measurements and enhancing the sensitivity to new heavy states across all channels. In heavy-ion mode, the FCC-hh probes QCD matter at temperatures and densities far beyond those achieved at the HL-LHC, giving access to the early time dynamics of the quark–gluon plasma. This extends the study of collectivity, jet quenching and nuclear PDFs into an unexplored regime, providing a unique window on strongly coupled QCD.

## 2.8 Muon Collider

The muon collider (muC) offers an alternative to the high-energy regime. In the Higgs sector, it achieves similar sensitivity to single-Higgs boson couplings (apart from rare decays) and Higgs boson self-coupling as the FCC-hh. With forward muon tagging, it can determine the absolute Higgs boson width and the absolute coupling normalisation. In electroweak physics, the absence of  $Z$ -pole running removes the main handle on LEP-style precision measurements. However, the muon collider instead gains sensitivity from high-energy diboson and fermion-pair processes, which provides excellent reach in certain EFT operator directions but cannot match the global precision achievable at the FCC-ee. For top physics, the lack of a top-quark-threshold scan precludes a threshold-based top-mass determination; nevertheless, the very high energies of a muon collider give strong leverage on energy-dependent top operators, yielding competitive or superior reach in specific EFT combinations compared to  $e^+e^-$  options.

The flavour physics programme based on low-energy observables (i.e.  $b$ ,  $c$ , and  $\tau$  decays) is limited by the absence of a large  $Z$  dataset; however, a significant fraction of flavour-violating contact interactions – particularly those involving muons or electroweak gauge bosons – can be probed with high precision via high-energy measurements (such as  $\mu^+\mu^- \rightarrow b\bar{s}$ ). In the strong interaction area, the muon collider accesses multi-TeV jet and photon-initiated final states with systematic uncertainties similar to other lepton colliders, so it can lead to new tests of QCD at very high energies. The SM observables at the  $Z$  peak, including  $\alpha_s$ , as well as  $W$  and top masses, can be measured with a precision similar to that obtained at the FCC-ee, provided that a comparable luminosity can be achieved in the relevant energy domains.

## 2.9 Overall project rankings in precision physics

The rankings in precision are in the categories of Higgs Physics, EWPOs, top-quark physics, flavour physics, precision QCD and QCD partonic structure and heavy ions. They are defined here and summarised in table 1.

The Higgs physics ranking evaluates two key components: Higgs boson couplings and the Higgs boson self-coupling. For Higgs boson couplings, a score of five corresponds to the best statistical precision across all couplings, including rare decays, the top-quark Yukawa coupling and the best attainable self-coupling precision. A score of four reflects the best statistical precision in a single coupling or enhanced coverage of multiple production modes thanks to high-energy operations and access to double-Higgs boson production. A score of three indicates improved precision across many couplings relative to a collider running at only a single energy for Higgs boson production, while a score of two represents the overall precision achievable from a collider running at only a single energy for Higgs boson production. A score of one applies when only a small number of couplings show improvements with respect to the HL-LHC.

The EWPO ranking is driven by the availability of large  $Z$  and  $W$  datasets and the presence of a top-quark-threshold run. A score of five corresponds to the highest statistics in  $Z$  and  $W$  production, combined with a precision top-quark-threshold programme for the determination of the top-quark mass. A score of four is assigned either to colliders with very large  $Z$  and  $W$  datasets but without access to the top-quark mass, or to those with modest statistics supplemented by high-energy running. A score of

**Table 1:** Indicative relative reach (1–5) of future collider projects in precision physics, from yellow (weakest) to green (best). For CLIC, operations at the  $Z$ -pole are possible but not considered in the Briefing Book studies; such operations would strengthen its EWPO programme, as noted by the “\*” in the table, bringing its rank to the same level as the LCF project.

| Project                     | Higgs                                                | EWPO           | Top | Flavour | QCD<br>(precision) | QCD<br>(PDF + HIs) |
|-----------------------------|------------------------------------------------------|----------------|-----|---------|--------------------|--------------------|
| HL-LHC                      | State-of-the-art starting point at the end of HL-LHC |                |     |         |                    |                    |
| Lepton and $ep$ Colliders   |                                                      |                |     |         |                    |                    |
| FCC-ee                      | 4                                                    | 5              | 3   | 5       | 5                  | 1                  |
| FCC-ee no-top               | 2                                                    | 4              | 2   | 5       | 4                  | 1                  |
| FCC-ee descoped             | 2                                                    | 4              | 2   | 4       | 3                  | 1                  |
| LEP3                        | 2                                                    | 4              | 2   | 4       | 3                  | 1                  |
| LCF-250                     | 2                                                    | 3              | 2   | 1       | 2                  | 1                  |
| CLIC-380                    | 2                                                    | 2*             | 3   | 1       | 2                  | 1                  |
| LHeC                        | 1                                                    | 2              | 1   | 1       | 3                  | 5                  |
| Mid-Energy Lepton Colliders |                                                      |                |     |         |                    |                    |
| LCF-550                     | 4                                                    | 4              | 4   | 1       | 2                  | 1                  |
| LCF-1000                    | 4                                                    | 4              | 4   | 1       | 2                  | 1                  |
| CLIC-1500                   | 4                                                    | 3*             | 4   | 1       | 2                  | 1                  |
| CLIC-3000                   | 4                                                    | 3*             | 4   | 1       | 2                  | 1                  |
| Energy frontier             |                                                      |                |     |         |                    |                    |
| FCC-hh                      | 3                                                    | No information |     | 3       | 2                  | 5                  |
| muC                         | 4                                                    | 3              | 5   | 3       | 1                  | 2                  |
| Precision w/ energy         |                                                      |                |     |         |                    |                    |
| LHeC + FCC-hh               | 3                                                    | 2              | 2   | 3       | 4                  | 5                  |
| LEP3 + FCC-hh               | 4                                                    | 4              | 3   | 4       | 3                  | 5                  |
| LEP3 + muC                  | 4                                                    | 5              | 5   | 4       | 3                  | 2                  |
| LCF-1000 + muC              | 4                                                    | 5              | 5   | 3       | 3                  | 2                  |
| FCC-ee descoped + FCC-hh    | 4                                                    | 4              | 3   | 4       | 4                  | 5                  |
| <b>FCC-ee + FCC-hh</b>      | 5                                                    | 5              | 5   | 5       | 5                  | 5                  |

three applies when  $Z$  and  $W$  statistics are more limited (with or without capacity to run at the top-quark threshold), or when there are no  $Z$ - or  $W$ -pole runs but substantial high-energy coverage. A score of two describes facilities without  $Z$  or  $W$  runs but with a dedicated top-quark-threshold scan. The same score is also assigned to the LHeC, where incremental improvements in a small subset of observables would be possible. For CLIC, operations at the  $Z$ -pole are possible but were not considered as part of the baseline programme for the Physics Briefing Book. Such a run would strengthen its EWPO programme to be similar to that of the LCF; this is indicated in the ranking table with an “\*”. There is insufficient input to evaluate the performance of the FCC-hh running directly after the HL-LHC in this category. It is therefore not ranked in the table and is given a conservative rank of one in the plots.

For top-quark physics, the highest score is reserved for programmes combining a top-quark-threshold scan with the highest-energy measurements. A score of four corresponds to a top-quark-threshold run together with several high-energy operating points. A score of three is assigned when the collider has access to the top-quark threshold or to top-quark measurements from a hadron machine. A score of two applies when sensitivity comes primarily through EWPOs, and a score of one indicates improvements in only a limited set of top-quark couplings. For the FCC-hh running directly after the HL-LHC, there is insufficient input to evaluate its performance in this category. It is therefore not ranked in the table and is given a conservative rank of one in the plot.

The flavour physics ranking reflects both the statistical power and the breadth of accessible chan-

nels. A score of five corresponds to the best possible performance in beauty, charm and  $\tau$  physics, including at least an order-of-magnitude improvement over the HL-LHC and Belle II sensitivity for all missing-energy channels, together with competitive CKM constraints from  $W$  decays. A score of four indicates roughly a factor of four reduction in statistics relative to a score of five. A score of three characterises programmes that achieve an order-of-magnitude gain in fully visible  $b$  and  $c$  decays – such as  $B_s \rightarrow \mu\mu$  – but no improvement in channels with two or more neutrinos, nor in  $\tau$  decays compared to Belle II. A score of one applies when no improvements in  $b$ ,  $c$  or  $\tau$  physics are expected, leaving only the CKM programme derived from  $W$  production.

The precision-QCD ranking, focused on benchmarks such as  $\alpha_s$ ,  $m_{\text{top}}$ , and  $m_W$ , assigns a score of five to the configurations achieving the best possible precision. A score of four corresponds to a reduced precision relative to this, or to best precision in some benchmarks but the lack of a  $m_{\text{top}}$  measurement. A score of three indicates results that are roughly a factor of two worse compared to a score of five. A score of two refers to a moderate precision improvement versus the HL-LHC achieved for one of the benchmarked observables and a score of one applies when only small improvements beyond the HL-LHC are attainable.

For partonic structure and heavy-ion physics, machines are ranked according to their suitability for deep-inelastic scattering and access to the relevant kinematic regimes and observables. A score of five is assigned to hadron and  $ep$  machines: LHeC offers substantial coverage of partonic structure kinematics and an extensive programme of precise proton-structure investigations, through transverse-momentum-dependent PDFs (TMDs), GPDs and small- $x$  dynamics, while hadron machines, such as the FCC-hh, greatly extend the parton kinematics domain and offer unique heavy-ion physics opportunities. A score of two is assigned to the muon collider due to the opportunity to measure the nucleon PDFs through DIS of an intense neutrino beam issued from the in-flight decays of the circulating muons. A score of one corresponds to  $e^+e^-$  machines, which allow only limited studies of partonic structure, with access to some observables, such as TMDs, GPDs and small- $x$  dynamics, but with significantly reduced reach compared to DIS or hadron facilities.

As explained above, in several categories the FCC-hh running directly after the HL-LHC has no entry in the table due to a lack of input available for comparison. Extensive studies are still needed to produce a full, quantitative physics case across Higgs physics, precision electroweak measurements, top physics and flavour observables in order to assess the potential of this option.

### 3 New Physics

#### 3.1 Methodology

The comparative assessment of the discovery and exclusion potential for representative new physics scenarios has been carried out in two complementary steps, combining the simplest possible quantitative metrics with a more global qualitative synthesis.

It should be stressed that, at each step, a certain level of discretion is applied. However, since the choices have been made independently of specific collider projects and encompass different types of new physics, the results are less dependent on particular details. Summarised below are the main points of the approach, starting from the Physics Briefing Book assumptions:

- A limited set of questions on fundamental interactions, which seek an answer in BSM theories and can be addressed through collider experiments, are selected.
- For each question, among a very large set of new physics models providing possible answers or solutions, one or two specific implementations are chosen. The primary criterion at this stage is the simplicity of the models. These “benchmark models” were defined and communicated at the beginning of the Strategy update process, in order to maximise the availability and comparability of existing studies.

- After the submission of the input, the availability of information in the context of the analysed projects was verified and complemented with any missing information whenever possible.
- The reaches were then compared, and the results compiled in the Physics Briefing Book, which contains a detailed analysis of each benchmark.
- To represent the results in a concise form for evaluation by the ESG, they are summarised in table 2, which provides a grading from one (worst) to five (best). A two-step procedure was used to arrive at these indicators:
  1. **Analytic and quantitative evaluation.** For each specific model discussed in the Physics Briefing Book [1], the results in terms of the scale and the coupling strength of the model in question was analysed. When possible, the reach of a given facility in terms of the underlying new-physics scale at fixed coupling was characterised. This scale is extracted from dedicated sensitivity studies and global fits presented in the individual subsections of the Physics Briefing Book. When this is not representative (e.g. in the case of portal models), step 2 was followed and a dedicated procedure, whose rationale is detailed on a case-by-case basis, was used.
  2. **Synthesis into discrete performance levels.** In the second step, the continuous estimates are mapped onto five discrete scores (5–1) that summarise, in a concise form, the overall reach of each project relative to the others. The highest score (5) corresponds to the facility providing the best reach or sensitivity among the considered options, while the lowest (1) denotes only marginal improvements over the capabilities of the HL-LHC. Intermediate values (2–4) reflect progressively weaker or more limited coverage in mass scale, coupling strength or coverage of the parameter space. When assigning the discrete scores, additional qualitative considerations, such as the actual differences in reach and complementarity between direct and indirect probes, are taken into account.

### 3.2 Compositeness

For composite Higgs-boson models, the limits are driven from the SMEFT global fits, including renormalisation group effects and cover an area on the plane  $(m_*, g_*)$ . The various colliders are ordered based on the reach at the reference value of  $g_* \simeq 4$ . For composite vectors (spin-1  $\rho$ -like), the limits are both direct and indirect and cover an area on the plane  $(m_*, g_*)$ . For indirect limits, the same rationale as above is used. The limits are similar to those obtained for the Strongly-Interacting-Light-Higgs (SILH) model. Direct limits are provided only for three high-energy colliders and their relevance is addressed in the final evaluation.

The best score is assigned to the FCC-hh (also because of the direct reach) and the muon colliders (for the outstanding indirect reach). A score of four is assigned to the FCC-ee for the indirect reach through EWPO and to the CLIC-3000 (indirect also through  $VV$  production). A score of three is assigned to the next-highest-energy lepton colliders. All other  $e^+e^-$  facilities are assigned a score of two.

### 3.3 SUSY QCD and EW

The analysis presented in the Physics Briefing Book focuses on simplified supersymmetric benchmarks representative of both coloured and electroweak states. The comparison includes direct production of coloured sparticles, such as gluinos and squarks, as well as electroweakinos (charginos and neutralinos). In this case, the plots are directly expressed as reach in masses and further reductions/simplifications are not needed. The results are translated into the scale, with energy frontier projects obtaining the highest ratings.

**Table 2:** Indicative relative reach (1–5) of future collider projects for each of the specific models considered in the Physics Briefing Book. A score of five corresponds to the best reach in terms of mass or interaction scale probed for fixed benchmark couplings. Indicative relative reach (1–5) ranges from yellow (weakest) to green.

| Project                     | Comp.<br>H & V                                       | SUSY<br>(QCD) | SUSY<br>(EW) | DM | Scalar<br>Singlet | New forces | Portals |
|-----------------------------|------------------------------------------------------|---------------|--------------|----|-------------------|------------|---------|
| HL-LHC                      | State-of-the-art starting point at the end of HL-LHC |               |              |    |                   |            |         |
| Lepton and $ep$ Colliders   |                                                      |               |              |    |                   |            |         |
| FCC-ee                      | 4                                                    | 3             | 2            | 2  | 4                 | 4          | 4       |
| FCC-ee no-top               | 3                                                    | 3             | 2            | 2  | 3                 | 4          | 4       |
| FCC-ee descoped             | 2                                                    | 2             | 2            | 2  | 3                 | 3          | 3       |
| LEP3                        | 2                                                    | 2             | 2            | 2  | 3                 | 3          | 3       |
| LCF-250                     | 2                                                    | 2             | 2            | 2  | 2                 | 3          | 3       |
| CLIC-380                    | 2                                                    | 2             | 2            | 2  | 2                 | 3          | 3       |
| LHeC                        | 1                                                    | 1             | 1            | 1  | 1                 | 1          | 1       |
| Mid-Energy Lepton colliders |                                                      |               |              |    |                   |            |         |
| LCF-550                     | 2                                                    | 2             | 2            | 2  | 3                 | 3          | 3       |
| CLIC-1500                   | 3                                                    | 2             | 2            | 2  | 3                 | 3          | 3       |
| LCF-1000                    | 3                                                    | 2             | 2            | 2  | 3                 | 4          | 3       |
| CLIC-3000                   | 4                                                    | 3             | 3            | 3  | 4                 | 4          | 3       |
| Energy frontier             |                                                      |               |              |    |                   |            |         |
| FCC-hh                      | 5                                                    | 5             | 5            | 5  | 4                 | 5          | 4       |
| muC                         | 5                                                    | 4             | 5            | 5  | 5                 | 5          | 4       |
| Precision w/ energy         |                                                      |               |              |    |                   |            |         |
| LHeC+ FCC-hh                | 5                                                    | 5             | 5            | 5  | 4                 | 5          | 4       |
| LEP3 + FCC-hh               | 5                                                    | 5             | 5            | 5  | 4                 | 5          | 4       |
| LEP3 + muC                  | 5                                                    | 4             | 5            | 5  | 5                 | 5          | 4       |
| LCF + muC                   | 5                                                    | 4             | 5            | 5  | 5                 | 5          | 4       |
| FCC-ee descoped + FCC-hh    | 5                                                    | 5             | 5            | 5  | 4                 | 5          | 4       |
| FCC-ee + FCC-hh             | 5                                                    | 5             | 5            | 5  | 5                 | 5          | 5       |

For squarks and gluinos, a three is assigned to the Tera- $Z$ -pole run of the FCC-ee, as this is the only precision run that significantly improves on the HL-LHC limits and provides information in the simplified scenario explored here (see e.g. fig. 8.1, sec. 8.2 of the Physics Briefing Book [1]). A two is assigned to all other linear lepton colliders, except for CLIC-3000, as they provide complementary information but do not significantly improve the limits. A three is assigned to CLIC-3000, as it provides significant improvement with respect to the lower-energy linear colliders. The muon collider is given a four, as it improves on CLIC-3000 but its reach remains significantly short of that of an FCC-hh and only covers cases such as compressed spectra. The FCC-hh is given the highest score.

For electroweakinos, a two is assigned to all low-energy lepton colliders. A three is given to CLIC-3000, which is the first collider in the energy ranking that provides a significant improvement with respect to the HL-LHC. The muon collider and the FCC-hh are assigned a five, as they have comparable and complementary reaches.

### 3.4 Simplified models for DM

Section 9.4.3 of the Physics Briefing Book reviews collider searches for weakly interacting massive particles (WIMPs) within the broader heavy dark-matter programme. It highlights the complementarity between collider, direct and indirect detection experiments, with colliders probing, *inter alia*, scenarios inaccessible to underground searches. Current and future facilities – such as the LHC, the HL-LHC, the FCC-ee, the FCC-hh and high-energy lepton colliders – explore simplified and UV-motivated models, including Higgs-, vector- and two SUSY-inspired mediators. Signatures involve missing-transverse-

energy final states with jets, photons or electroweak bosons, and searches for long-lived particles. Next-generation colliders are expected to extend coverage of the thermal-relic parameter space, probing weak-scale couplings up to the TeV range and complementing direct and indirect detection efforts.

Even though the features of specific models are different, overall, the situation closely mirrors the reach for electroweakinos. The muon collider results are not available for the scalar and axial vector. However, it is obvious from the energy scaling that the scalar will do best. For the axial vector, a muon collider is expected to provide better limits than the FCC-hh.

### 3.5 Scalar singlet

The focus is on the simplest benchmark of a real singlet scalar coupled to the Higgs boson through the portal interaction. Such states can mix with the Higgs boson, modifying its couplings and leading to new resonant signatures. The score (based on fig. 8.7 sec. 8.2 of the Physics Briefing Book) summarises the combined direct and indirect collider sensitivities in the plane of the singlet mass  $m_S$  versus the squared mixing angle  $\sin^2 \theta$ , under the custodial limit  $\text{BR}(S \rightarrow ZZ) = \text{BR}(S \rightarrow hh) = \text{BR}(S \rightarrow WW)/2$ . Direct searches at hadron and muon colliders, in particular through  $S \rightarrow ZZ$  and  $S \rightarrow hh$  decays, cover the largest masses and smallest mixing angles, while precision measurements at Higgs boson factories (FCC-ee, LCF-250, CLIC-1500) constrain the same parameter space via deviations in universal Higgs boson couplings and electroweak precision observables. The figure highlights the strong complementarity between the precision and energy frontiers.

In this case, there is not a unique way of scoring the various projects. However, it is clear from the exclusion curves drawn in the plane  $(M, \sin^2 \theta)$  that the best direct sensitivity comes from a muon collider at 10 TeV, followed by the combination of precision and energy given by FCC-ee+FCC-hh, thanks to the high precision from both the Z-pole and Higgs boson couplings.

### 3.6 New forces

Several models predicting new gauge interactions that give rise to heavy spin-1 resonances, such as  $Z'$  or  $W'$  bosons, are considered, as they appear in extended gauge frameworks, including grand-unified and flavour models. Collider sensitivities in the coupling-mass plane: lepton colliders (FCC-ee, CLIC, muon colliders) set strong indirect bounds via four-fermion operators, whereas the FCC-hh dominates in direct searches. A 10 TeV muon collider could test  $Z'$  masses up to  $\mathcal{O}(100)$  TeV. FCC-ee Tera-Z precision data probe most of the viable parameter space, with the FCC-hh extending the reach to tens of TeV.

Ranking projects based on these scenarios is a very difficult endeavour, as they feature direct and indirect constraints. As a result, each scenario is evaluated in turn, considering direct and indirect constraints equally, independently of the fact that indirect results typically set stronger constraints on the scale.

For a universal  $Z'$ , the ordering of the indirect reach is (from best to worst): muC-10TeV, CLIC-3 TeV, LCF-1000, CLIC-1500, FCC-hh, LCF-550, FCC-ee, CLIC-380, LEP3, LCF-250. The best direct reach is by far that of the FCC-hh. For this reason, the FCC-hh and the muon collider are scored as the best.

For a  $L_\mu - L_e$   $Z'$  an absolute ranking is very challenging. However, in general, lepton colliders have a significantly better reach than hadron colliders, working at the same parton-parton energy. A muon collider has the strongest indirect reach, followed by precision lower-energy lepton colliders. The FCC-hh is assigned a score of two. In this case, the high energy of the FCC-hh gives the best direct reach, which, in the case of the triplet, is actually competitive with the coverage given by the Tera-Z run. The energy frontier colliders are therefore given a score of five.

The cases of flavoured vector bosons, either  $U(1)$  or  $SU(2)$  triplet, are similar. In this case, the lowest-energy lepton colliders, with the exception of the FCC-ee, do far worse than their higher-energy counterparts. The grading is continuous up to the FCC-hh and the muon collider, which have a very

strong indirect reach.

Finally, the vector leptoquarks coupling predominantly to quarks in the third generation can be strongly constrained directly at the FCC-hh. Then, depending on whether they couple to second- or third-generation leptons, different handles can be used. In this case, the plots do not provide information on the intermediate-energy linear lepton colliders.

### 3.7 Portals

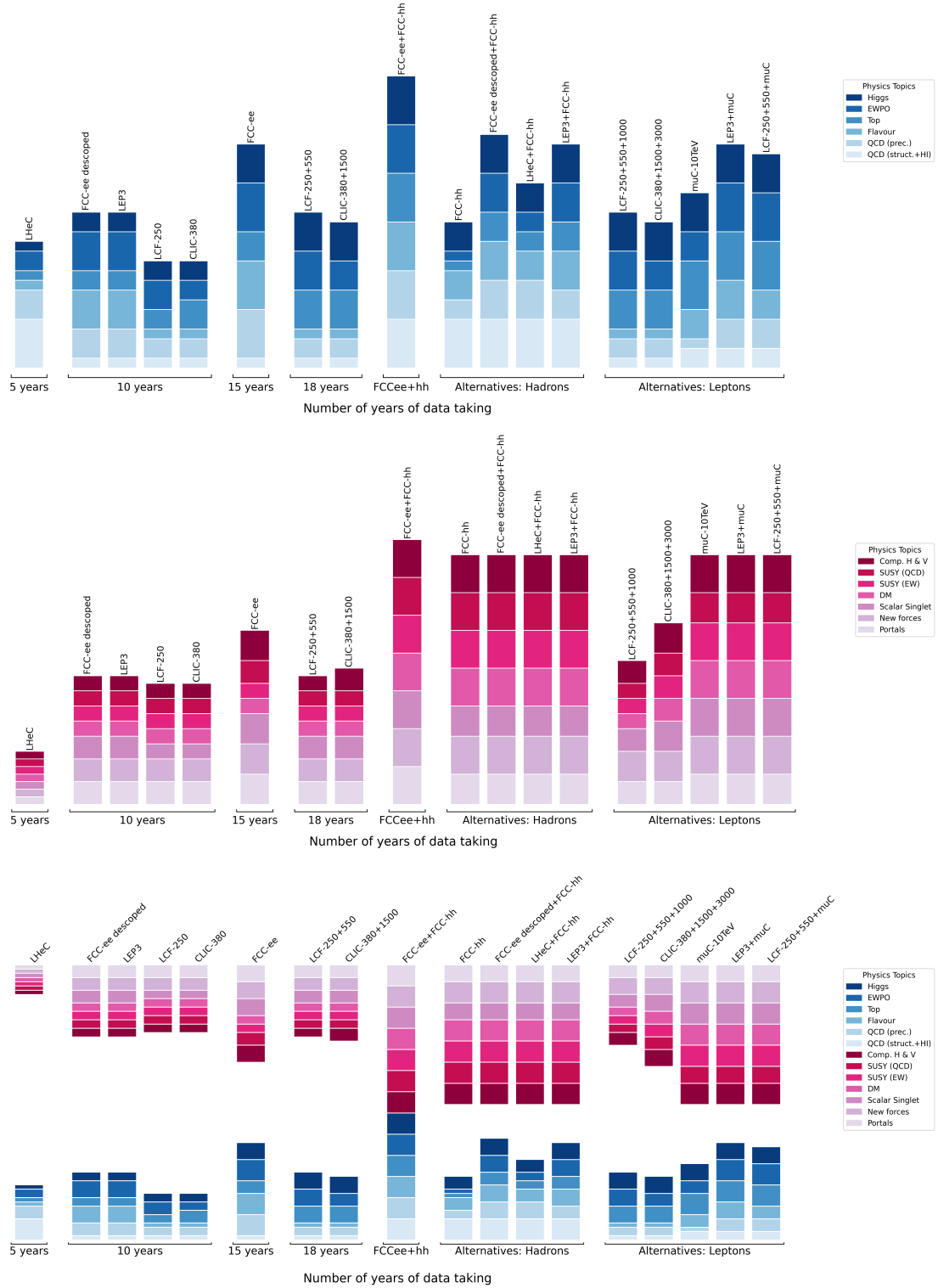
Portal scenarios have been examined where new neutral sectors interact with the Standard Model through a limited set of renormalisable or higher-dimensional operators. Such interactions can provide access to hidden sectors potentially linked to dark matter, neutrino masses or other cosmological phenomena. The analysis considers four representative cases: *dark photons*, *axion-like particles* (ALPs), *dark scalars*, and *heavy neutral leptons* (HNLs). Each offers a minimal, signature-driven framework illustrating how new states may appear indirectly, through deviations in precision observables, or directly, via missing-energy or long-lived-particle signatures. Collider and non-collider searches are highly complementary: precision measurements at lepton colliders constrain effective couplings, while hadron colliders and beam-dump experiments extend sensitivity to higher masses and smaller mixings, respectively. Together these studies highlight the broad discovery potential of future collider programmes for exploring hidden sectors connected to fundamental open questions in particle physics and cosmology.

It should be emphasised, however, that, in the case of portal scenarios, it is particularly difficult to define a unique and quantitative metric for comparing projects. The sensitivity of different experiments spans a two-dimensional parameter space, coupling versus mass, with widely varying coverage and detection strategies. As a result, the corresponding reaches cannot be easily projected onto a single scale or ranked consistently across facilities without losing essential physical information.

In short, no comparison plot is included for the scalar portal, as information is available only for the FCC-ee. LEP3 information is obtained by simply assuming a corresponding rescaling of the luminosity.

## 4 Summary Plots

The rankings from table 1 and table 2 are summarised in plot form in figure 1. These plots show the stacked ranking in each physics area or BSM model as a function of the estimated total amount of time from the start of the data taking. Also shown are combinations of the lower-energy projects with a high-energy option. In the top and middle plots of figure 1, the stacking starts at the bottom axis. For the bottom plot, which shows both together, the precision stacking starts on the bottom axis, while the BSM stacking starts at the top axis and stacks downwards.



**Figure 1:** Stacked ranking for each physics area or BSM model as a function of the estimated total amount of time from the start of the project's data taking. Precision rankings (top), BSM rankings (middle) and precision and BSM rankings (bottom).

## Appendix

### A Electroweak physics potential for a descoped FCC-ee

In this appendix, the results presented in chapter 3 of the Physics Briefing Book [1] are extended, including comparisons of the electroweak, Higgs and top physics potential of a descoped version of the FCC-ee project. This descoped scenario consists of:

- Removing the top-quark runs around the  $t\bar{t}$  threshold and at 365 GeV.
- Decreasing the synchrotron radiation (SR) power from 50 MW per beam to 30 MW.
- Constructing only two interaction points (IPs), instead of four.

Assuming the same operation time as in the original project, i.e. nine years without the top-quark run, the overall impact on the total amount of data collected by the descoped version is a reduction factor of 0.36. This is derived based on the ratio of RF power of 3/5, a factor 1/2 from the number of experiments and a recovery of 20% from optimisation of the machine parameters for two instead of four experiments.

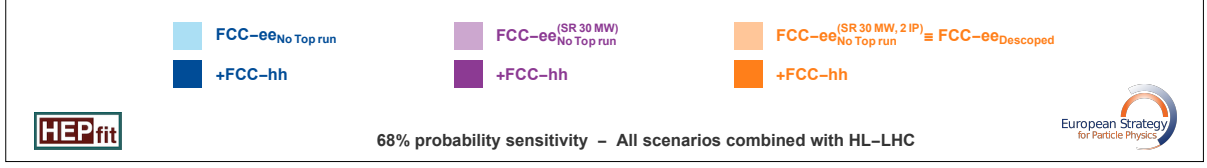
To illustrate the impact of each of the descopings items, the results for the FCC baseline project in ref. [1] are compared with those obtained by removing only the top run, then also decreasing the SR power to 30 MW and, finally, for the fully descoped scenario, also removing two IPs. Note that the physics potential of the fully descoped scenario (reduced SR power, two IPs, no top-quark run) running for 15 years is similar to the scenario of no top-quark run and reduced SR power, but with four IPs, running for nine years. Similarly, the fully descoped scenario running for 21 years is similar to that of the baseline FCC-ee scenario without the top-quark run (running for nine years). The impact on the whole integrated FCC programme, i.e. after running the FCC-hh, is also shown. No descopings is assumed for the FCC-hh, which remains as in the original proposal for the FCC project [4].

#### A.1 Comparisons with respect to the baseline FCC-ee project

Figures A.1-A.5 compare the physics reach of each of the items described above for the descoped FCC-ee with respect to the full FCC-ee programme. For the Kappa and EFT comparisons discussed in ref. [1], the figures show the ratio of the sensitivity obtained in the descoped scenario and that of the baseline FCC-ee programme.

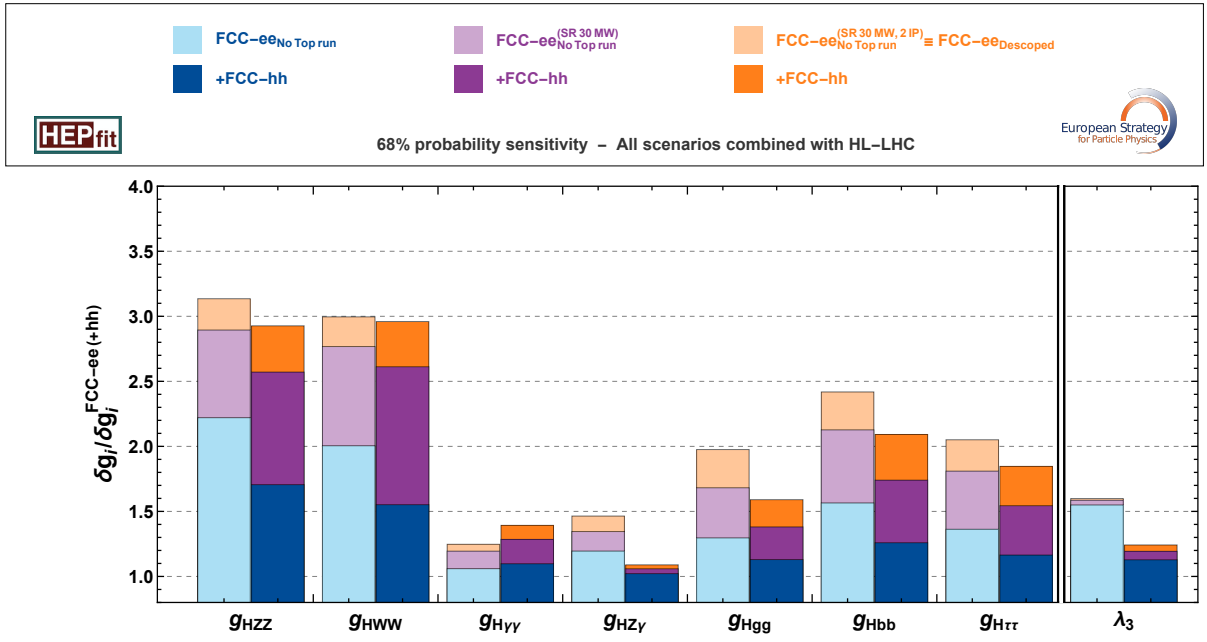
The comparison in figure A.1 illustrates the substantial impact of the removal of the top run on the Higgs physics programme, with no access to the vector boson fusion production channel, which offers complementary information on the Higgstrahlung process accessible at 240 GeV. This is most notably reflected in  $\kappa_W$ , but also translates into a 50% decrease in precision on the Higgs width. The impact of the reduction of the SR power and of having only two IPs follows the expected decrease in statistical precision due to having approximately three times less data, which could be compensated with a longer run time. Running at only 240 GeV also has implications in the determination of the Higgs self-coupling  $\lambda_3$  (see fig. A.2). The absence of Higgs data at a second energy point would preclude the FCC-ee from obtaining information about this coupling from its loop effects in single Higgs measurements. In this situation, the FCC-ee would not be able to improve the precision of  $\lambda_3$  with respect to the HL-LHC result of 27%.

With the FCC-ee energy reach reduced below the  $t\bar{t}$  threshold, a direct measurement of the top mass and determinations of the top interactions from top-pair production would not be possible. The former implies that there would be no improvement in the  $m_t$  precision beyond the result of 200 MeV expected from the HL-LHC. Thus, although a descoped FCC-ee scenario would still bring a huge improvement in the measurements of EWPOs, the interpretation of these observables would be hindered by a large  $m_t$  parametric uncertainty, which, in several cases, would be significantly above the expected experimental precision. Aside from the removal of the top run, the lower luminosity would also affect

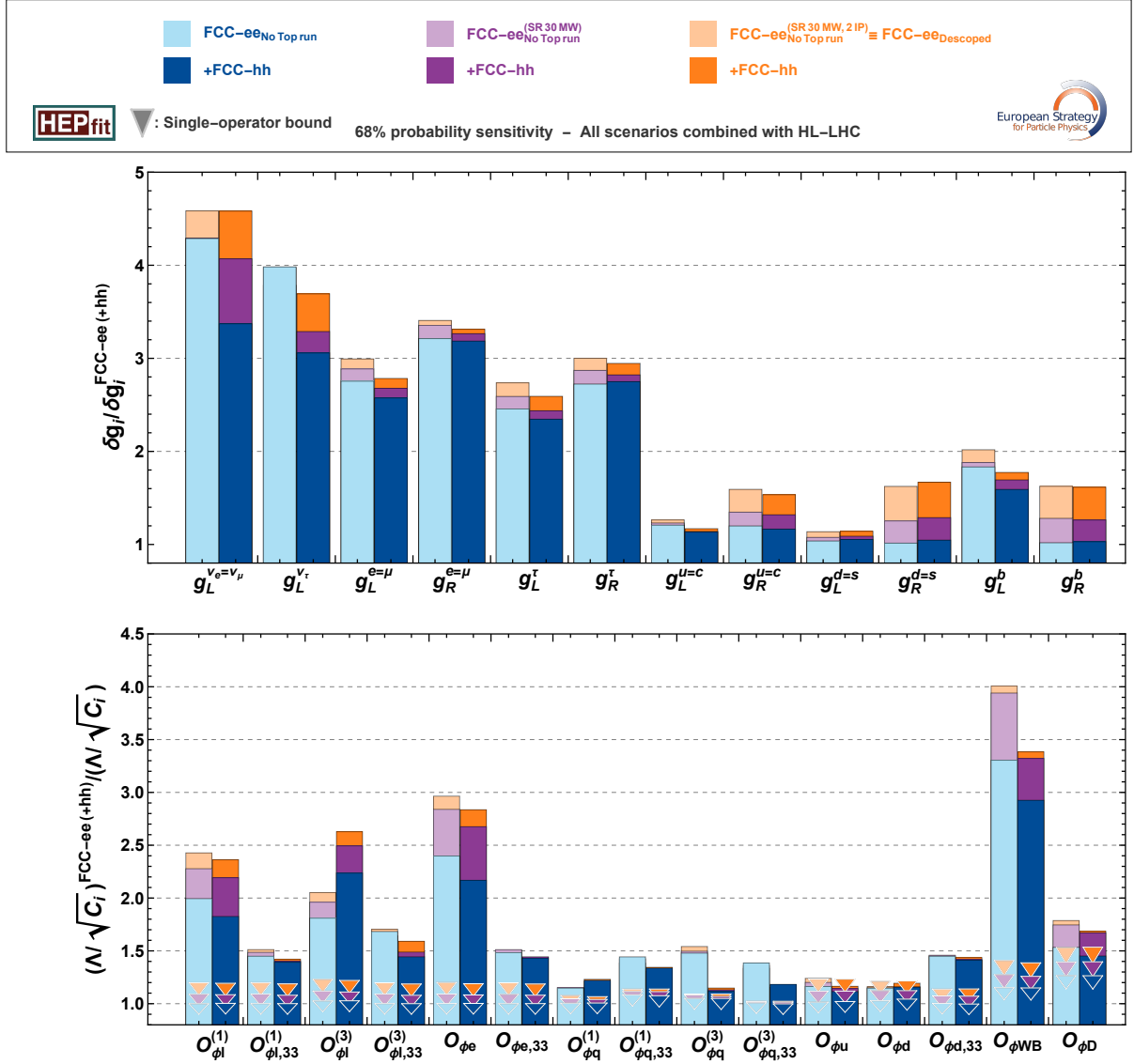


**Figure A.1:** Decrease in sensitivity for the different  $\kappa$  parameters with respect to the FCC-ee baseline project (light shade columns) and the combination with the FCC-hh (dark shade columns). From a fit of the Kappa-framework to Higgs measurements, as described in section 3.1.5 in ref. [1].

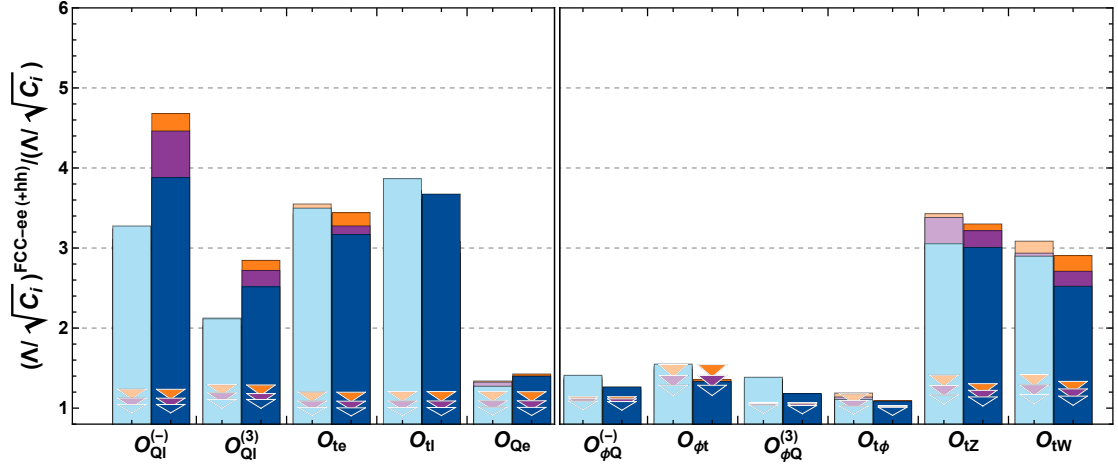
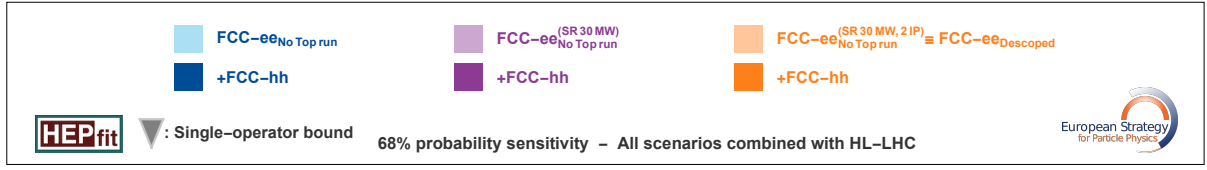
the EWPO programme. In this regard, however, some observables are still limited by either systematics or other parametric uncertainties, and the impact on the EFT interpretation of these measurements turns out to be less than the expected statistical decrease in precision (see figure A.3). Figure A.4, on the other hand, illustrates how running up to only 240 GeV would affect the knowledge of top interactions, with a reach that would be worse by a factor of up to 3–4 in terms of the new physics interaction scale associated with the different dimension-six operators modifying the top properties. Finally, figure A.5 shows the impact on interactions inducing  $E^2$ -enhanced effects in diboson and difermion processes. In this case, the FCC-ee baseline results benefit from 365 GeV data but, as shown in figure 3.9 in ref. [1], given the much larger amount of data at 240 GeV (plus the fact that the operators in that figure also contribute to other EWPOs), the removal of the top run has only a minor effect on the results for the descoped scenario; this effect is comparable to that associated with the reduction in the luminosity of the project due to the lower SR power and having only half the number of interaction points.



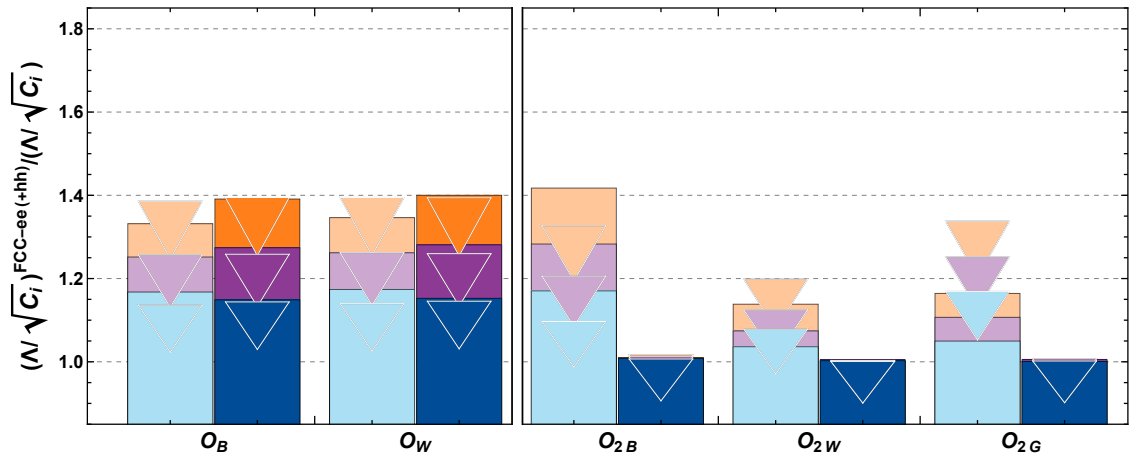
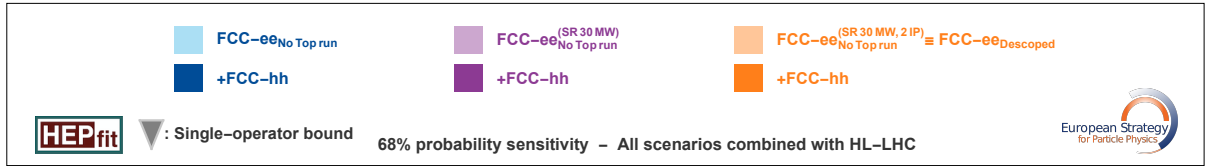
**Figure A.2:** Decrease in sensitivity for the different effective Higgs coupling parameters with respect to the FCC-ee baseline project (light shade columns) and the combination with the FCC-hh (dark shade columns), from the same type of SMEFT fit described in section 3.5 of ref. [1]. In the case of the Higgs self-coupling, shown in the last two columns, with the removal of the top-quark run the descoped FCC-ee would not improve on the HL-LHC result (see figure A.8).



**Figure A.3:** Top: Decrease in sensitivity for the different effective electroweak coupling parameters with respect to the FCC-ee baseline project (light shade columns) and the combination with the FCC-hh (dark shade columns). Bottom: The same for the scale associated with the operators entering in the EWPOs at leading order. From the same type of SMEFT fit described in [1].



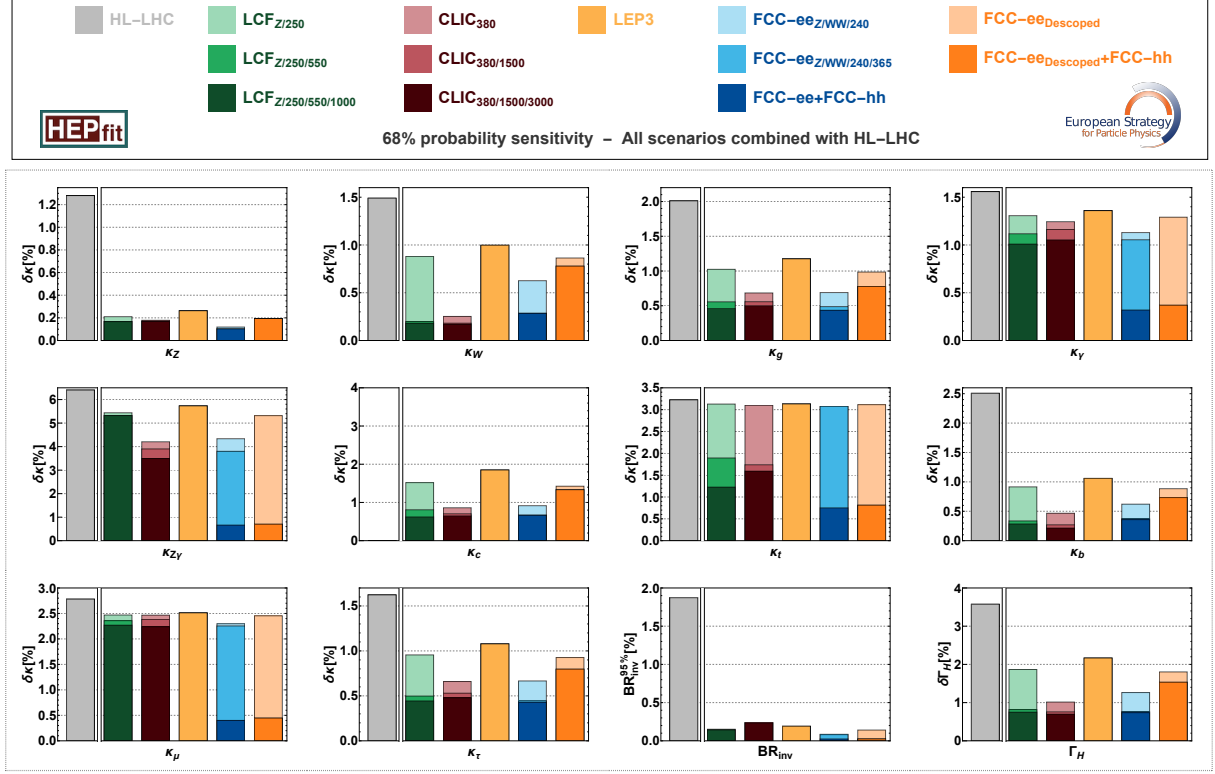
**Figure A.4:** Decrease in sensitivity to the scale associated with the different top-quark operators (four-fermion and two-fermion interactions) discussed in figure 3.8 in ref. [1]. As in previous figures, the columns with light shades denote the results compared to the FCC-ee baseline project, and those with dark shades the results when combined with the FCC-hh.



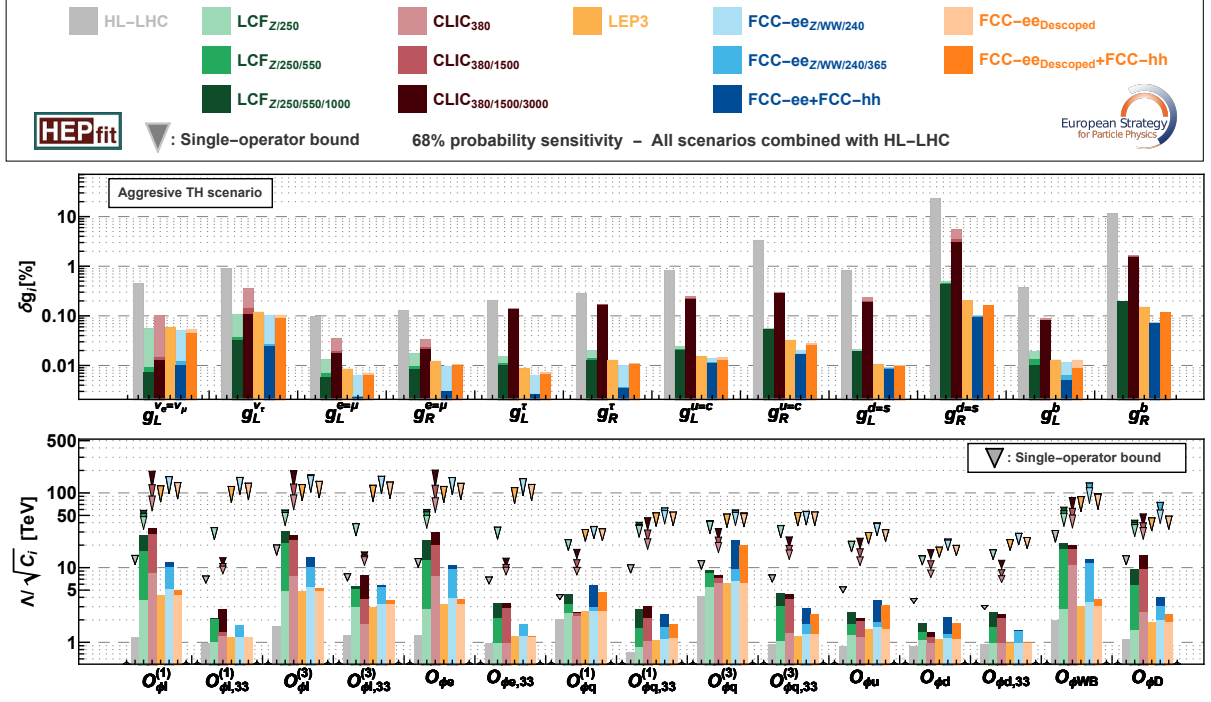
**Figure A.5:** Decrease in sensitivity to the scale associated with the different universal two-fermion/two-boson and four-fermion interactions discussed in figure 3.9 in ref. [1]. As in previous figures, the columns with light shades denote the results compared to the FCC-ee baseline project, and those with dark shades the results when combined with the FCC-hh.

## A.2 Comparisons with other $e^+e^-$ projects

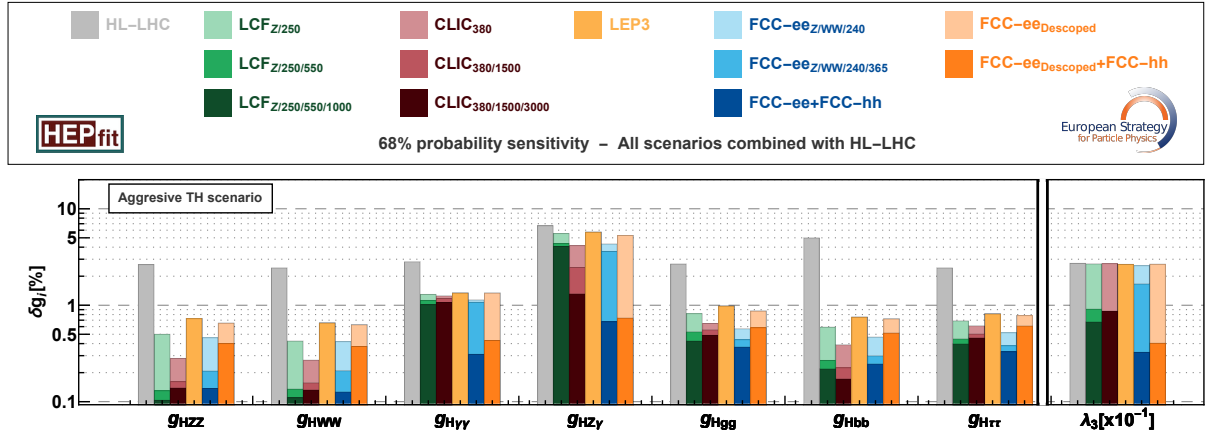
While the previous subsection focused on the comparison of the descoped FCC-ee scenario with respect to the baseline, here, in figures A.6-A.10, the results are compared with other  $e^+e^-$  colliders, using the same format presented in chapter 3 of ref. [1]. (The HL-LHC results are still shown for reference.) In all figures, the descoped FCC-ee scenario is shown in the last column, in orange, and also in combination with the FCC-hh.



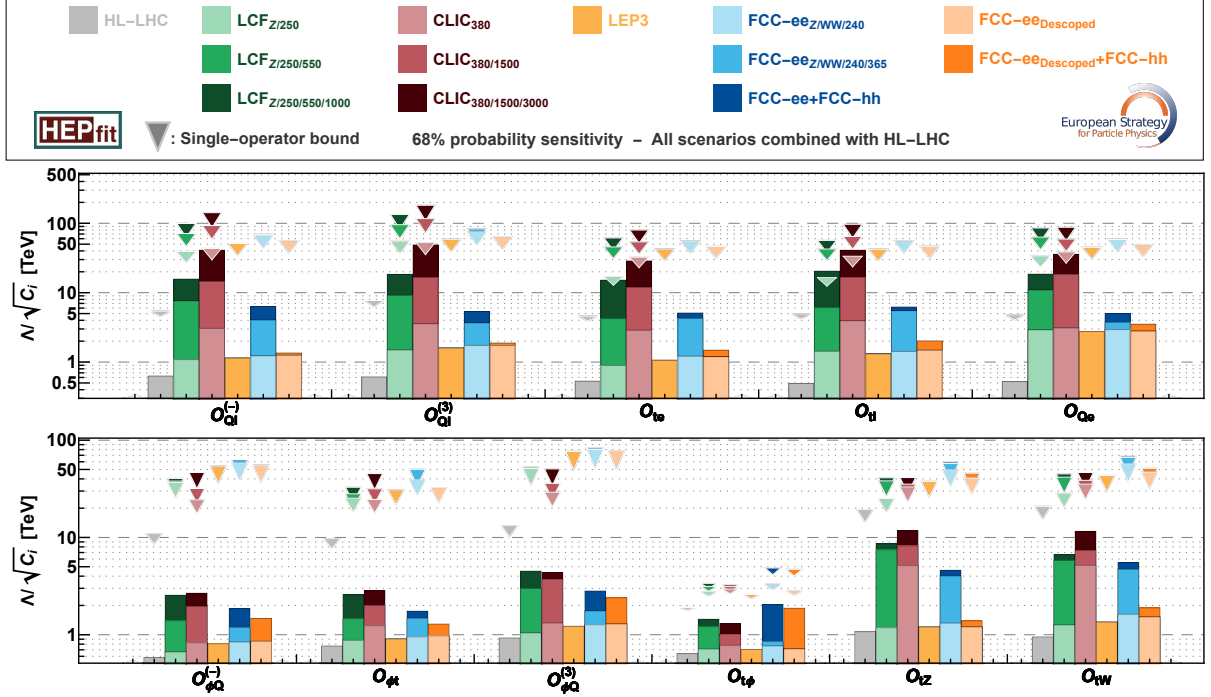
**Figure A.6:** Comparison of the sensitivity to deviations from the SM in the different  $\kappa$  parameters, as in figure 3.1 of [1], but focused on the different  $e^+e^-$  projects and adding the descoped FCC-ee case (last columns, in orange).



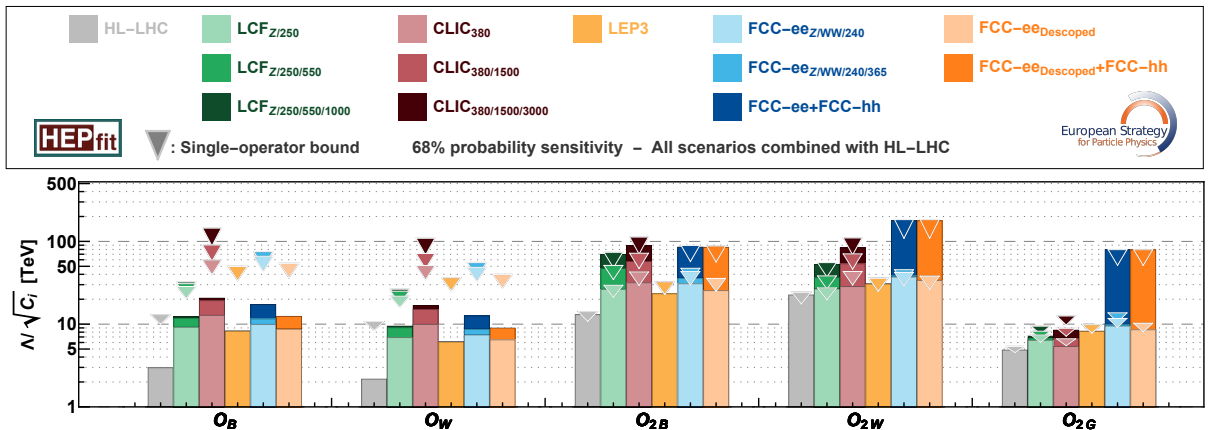
**Figure A.7:** Comparison of the sensitivity to deviations from the SM in the different effective electroweak couplings and EFT operators, as in figure 3.5 of ref. [1], but focused on the different  $e^+e^-$  projects and adding the descoped FCC-ee case (last columns, in orange).



**Figure A.8:** Comparison of the sensitivity to deviations from the SM in the different effective Higgs couplings, as in figure 3.6 of ref. [1], but focused on the different  $e^+e^-$  projects and adding the descoped FCC-ee case (last columns, in orange). The precision on the determination of the Higgs self-coupling is shown separately, in the  $\lambda_3$  panel.



**Figure A.9:** Comparison of the sensitivity to the scale associated with the different top-quark EFT operators, as in figure 3.8 of ref. [1], but focused on the different  $e^+e^-$  projects and adding the descoped FCC-ee case (last columns, in orange).



**Figure A.10:** Comparison of the sensitivity to the scale associated with the different universal EFT operators presented in figure 3.9 of ref. [1], but focused on the different  $e^+e^-$  projects and adding the descoped FCC-ee case (last columns, in orange).

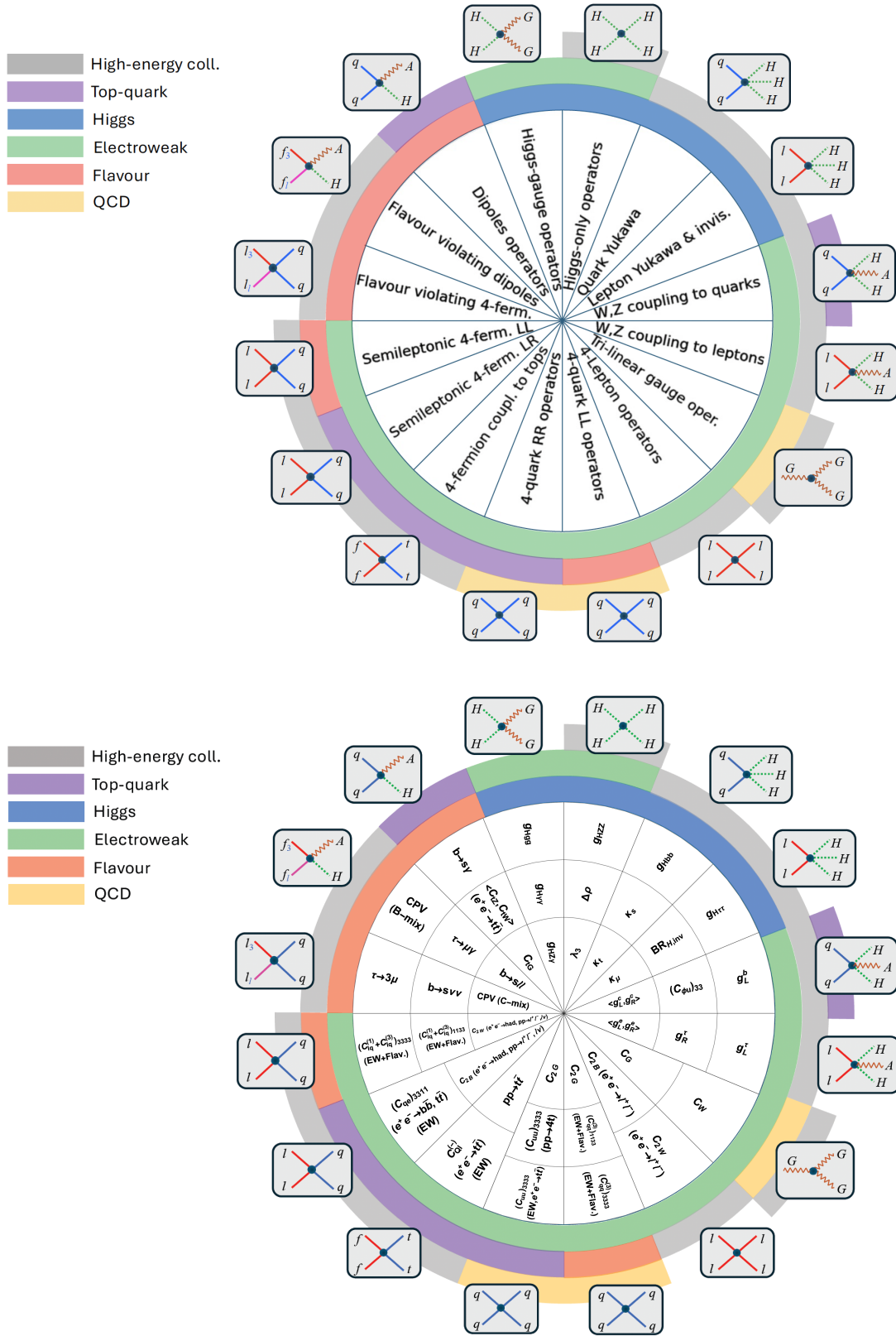
## B Additional ranking of the projects

Based on the results presented in the Physics Briefing Book [1], and for the descoped FCC-ee option in the above appendix, an alternative and more granular assessment of the physics potential of the different future colliders in probing physics beyond the SM is presented here. This assessment is based on the capabilities of the various colliders to probe, through specific measurements, different sectors of the dimension-six operators in the SMEFT. As discussed in Ref. [1], these operators describe, in general terms, new effective contact interactions that could arise in the presence of heavy new physics. Note that this ranking provides an alternative to that presented in Section 2.9. The two ranking approaches lead to the same overall conclusions, although some individual criteria differ.

An important element of this quantitative and more granular assessment is the selection of the effective operators (or, equivalently, the set of measurements) to be considered. At dimension-six, the SMEFT contains a large number of operators; the goal is therefore to identify a set that is both sufficiently general and manageable, while avoiding redundancies. To this end, the SMEFT is divided into 16 sectors, reflecting the different field content and electroweak structure of the operators. Within each sector, two or three key observables (or subsets of operators) are identified, in order to provide a more detailed characterization of the sector (e.g., the involvement of light or heavy quarks). To ensure an effective graphical representation, each sector is depicted as an equally sized slice, as shown in Figure B.1 (top). Within each slice, the two or three key observables define different areas (subsectors), see Figure B.1 (bottom). Observables and operators that are more difficult to access at low-energy  $e^+e^-$  colliders are placed in the innermost subsectors.

In more detail, the 16 different sectors of effective interactions and the specific observables considered in this comparison, are illustrated in Figure B.1. In clockwise order, these include:

- **Higgs-only operators:** These are bosonic operators involving only the Higgs doublet and its covariant derivatives. These modify the SM couplings of the Higgs to  $Z$  and  $W$  bosons, including also custodial breaking contributions (also testable in EW physics), as well as modifications of the Higgs-boson self-coupling (the latter effect is located in the innermost subsector).
- **Quark Yukawa:** Operators modifying the quark-Higgs interactions are collected in this sector. These can be tested either in Higgs-boson decays or, for the top quark, via  $ttH$  production at lepton and hadron colliders.
- **Lepton Yukawa & invisibles:** This sector includes operators modifying the leptonic-Higgs interactions. A possible (non-standard) invisible Higgs-boson decay width is also included even if, strictly speaking, this is an effect that is not described within the SMEFT.
- **$W, Z$  coupling to quarks (leptons):** These two categories include operators with Higgs and fermion fields that modify the neutral- and charged-current fermion couplings to the EW gauge bosons. With the exception of those involving the top quark (which is present in the slice dedicated to quarks), these are typically best tested via EWPO.
- **Pure gauge operators:** This category includes dimension-six bosonic operators involving only gauge field-strengths. They modify, e.g., the triple-gauge couplings for EW gauge bosons and gluons. Here the granular distinction is only in two sub-categories: gluons vs. EW gauge bosons.
- **4-lepton operators:** This category characterises the capabilities to test growing-with-energy effects in two-to-two lepton processes (exclusively). Operators describing new physics exchanges between singlet and triplet fermionic  $SU(2)$  currents, via the  $O_{2B}$  and  $O_{2W}$  universal operators, respectively are considered.
- **4-quark operators ( $LL$  and  $RR$ ):** These two categories include four-quark interactions involving totally or partially the third-family, which could be tested via radiative corrections in electroweak,



**Figure B.1:** (Top): A drawing of the different sectors used for the ranking as detailed in the text. (Bottom): The same sectors but now showing the EFT interactions or observables used to determine the ranking, using the notation as defined in the Physics Briefing Book [1]. The diagrams on the outer circle provide a qualitative indications of the type of contact interactions involved in each sector, while the different colours highlight the type of measurements involved.

flavour (LL only) and top observables at  $e^+e^-$  colliders, or in  $t\bar{t}$  and four-top production at FCC-hh; as well as operators involving only light quarks, tested best at  $pp \rightarrow jj$  at high energies, and illustrated here via the universal operator  $\mathcal{O}_{2G}$ .

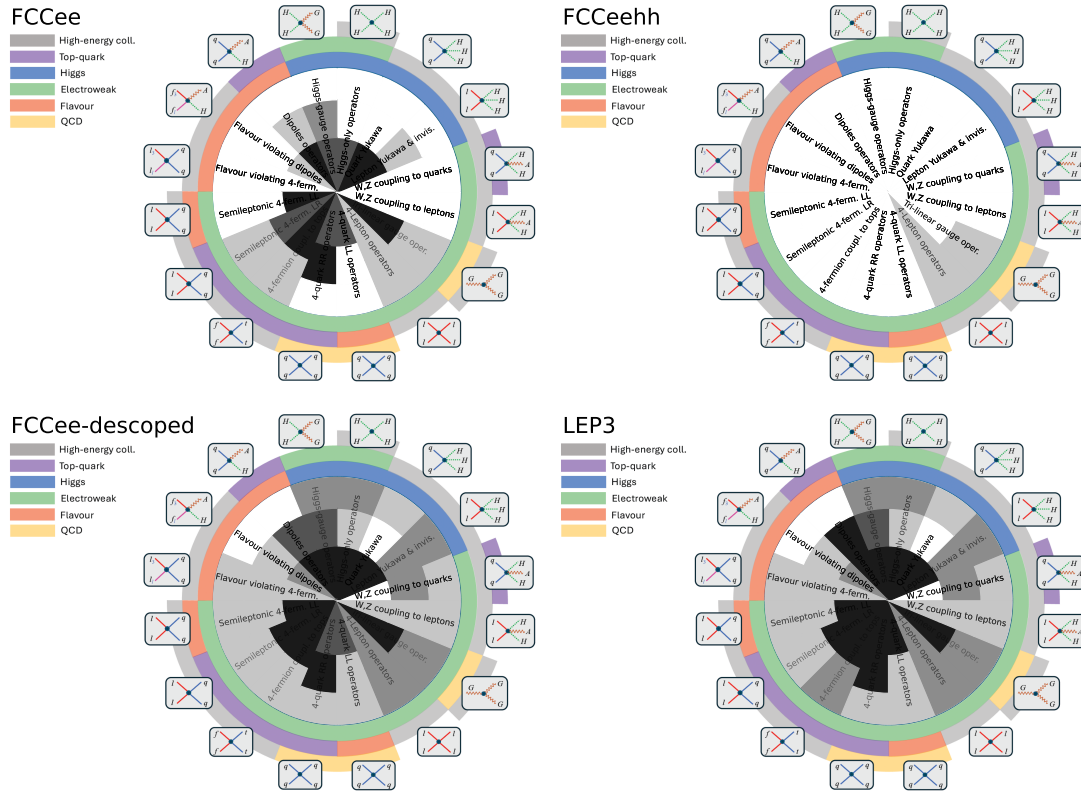
- **4-fermion couplings to tops:** This category includes additional four-fermion operators involving top quarks, coupled to light quark or lepton currents, which are better tested at high energies. We consider a representative contribution to  $e^+e^- \rightarrow t\bar{t}$  and another one for  $pp \rightarrow t\bar{t}$ .
- **Semileptonic 4-fermions (LL and LR):** These include operators with two leptons and two quark fields. When the left-handed bottom-quark is involved, these receive strong constraints from flavour physics, but can also be constrained with EW measurements and via their contributions to  $e^+e^- \rightarrow b\bar{b}$ . For interactions involving light quarks, the  $\mathcal{O}_{2B}$  and  $\mathcal{O}_{2W}$  universal operators are again considered, ranking in this case the constraints coming exclusively from  $e^+e^- \rightarrow q\bar{q}$  or  $pp \rightarrow \ell^+\ell^-, \ell\nu$  processes.
- **Flavour violating 4-fermions:** This category includes representative effects of flavour-violating four-fermion contact interactions in leptonic observables ( $\tau \rightarrow 3\mu$ ), hadronic ones ( $D$ -meson mixing), and semileptonic ones ( $b \rightarrow s\nu\bar{\nu}$ ).
- **Flavour violating dipoles:** This category includes representative effects of flavour-violating dipole interactions in leptonic ( $\tau \rightarrow \mu\gamma$ ) and hadronic observables (via  $b \rightarrow s\ell^+\ell^-$ ), as well as their possible impact in time-dependent CP-violating observables.
- **Dipole operators:** Here flavour-conserving quark-dipole operators are collected (the projects under consideration do not allow to derive competitive constraints on flavour-conserving lepton dipole interactions). EW dipole operators involving the bottom and the top quarks, as well as the chromomagnetic operator involving the top quark, are considered.
- **Higgs-gauge operators:** This category includes bosonic interactions of the form  $\phi^\dagger\phi V_{\mu\nu}V^{\mu\nu}$ . They are constrained by the Higgs decays into gauge bosons, which are loop-induced in the SM, namely  $H \rightarrow gg, \gamma\gamma, Z\gamma$ .

In Figure B.1, the outer coloured rings indicate qualitatively the different category of the measurements (indicated via the legend) that provide the leading constraints on the corresponding sector. The gray ring ("high-energy colliders") indicates observables that benefit from cross-section measurements at high energies, either at hadronic or at leptonic colliders. As can be seen, each sector is sensitive to two or more categories of measurements.

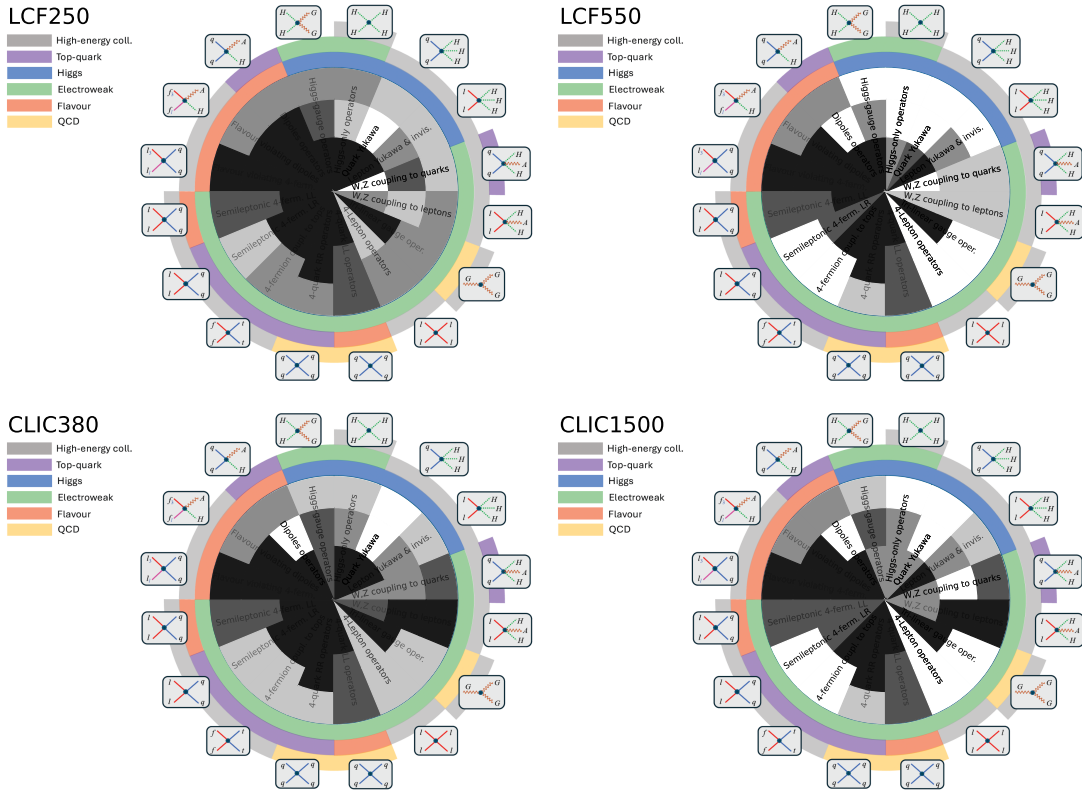
For each of the 44 independent subsectors the factor of improvement with respect to the HL-LHC of the corresponding measurement (or set of measurements) is evaluated. This is mapped using a log scale into a discrete range of five values from 0 to 4, where 4 is the maximal possible improvement. The latter is defined by the best precision achievable, on the relevant set of measurements, with any of the proposed future projects included in the comparison. The logarithmic scale implies a power law of the potential improvements of the type  $p^n$ , where  $p^0 = 1$  corresponds to no improvement with respect to HL-LHC, and  $p^4$  to the best possible improvement. Note that the scale factor  $p$  is different for each subsector.

Using this discrete mapping, the physics reach of each project is illustrated using a five-level gray scale, from black, associated to 0 (i.e. no relevant improvement with respect to HL-LHC) to white, associated to 4 (i.e. the best precision). For this comparison, only the following collider options are considered: FCC-ee, FCC-ee followed by an FCC-hh, the descoped FCC-ee, LEP3, LCF-250, LCF-550, CLIC-380 and CLIC-1500.

Figure B.2 shows the results for the circular collider options of the FCC-ee and the FCC-ee followed by an FCC-hh, the descoped FCC-ee and LEP3. Figure B.3 shows the results for the linear collider options of LCF-250, LCF-550, CLIC-380 and CLIC-1500.



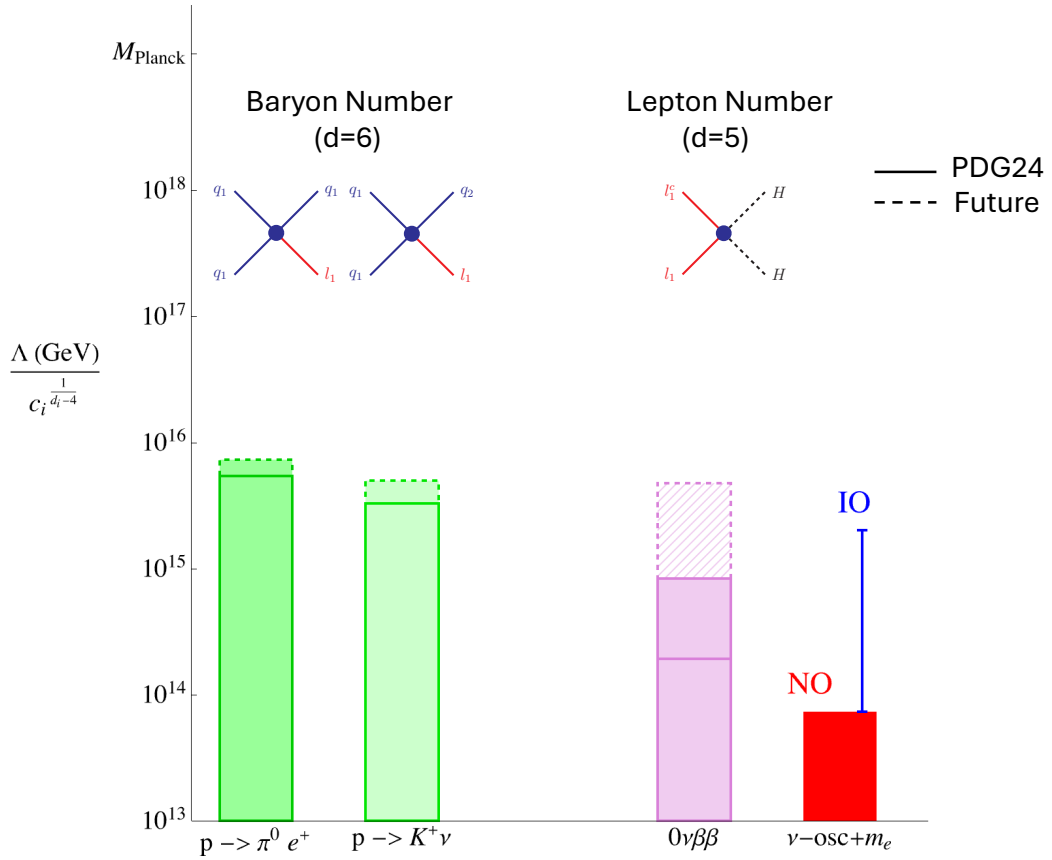
**Figure B.2:** A five-level, gray-scale visualization of the ranking, where the highest rank is shown in white and the lowest rank is shown in black. The outer coloured rings indicate the different physics sectors that provide constraints on the corresponding operators. (Top-left): the results for the FCC-ee. (Top-right): the results for the FCC-ee plus FCC-hh. (Bottom-left): the results for the FCC-ee descoped scenario. (Bottom-right): the results for LEP3.



**Figure B.3:** A five-level, gray-scale visualization of the ranking, where the highest rank is shown in white and the lowest rank is shown in black. The outer coloured rings indicate the different physics sectors that provide constraints on the corresponding operators. (Top-left): the results for the LCF-250. (Top-right): the results for the LCF-550. (Bottom-left): the results for CLIC-380. (Bottom-right): the results for CLIC-1500.

## C Summary plots for neutrino experiments

Figure C.1 shows a summary plot prepared for neutrino experiments, which highlights the present and future limits from neutrino and proton-decay experiments on some of the dimension-six baryon number violating operators (BNV) and the dimension-five lepton number violating operator (LNV) in the SMEFT. The limits on BNV operators are shown for the two most sensitive searches of proton decay:  $p \rightarrow \pi_0 e^+$  and  $p \rightarrow K^+ \nu$ . The limits on the LNV operator are shown for the searches of neutrinoless double-beta decay. The present best limit corresponds to that in the PDG24 for the Xe isotope. The range indicates the uncertainty in the nuclear matrix elements. The future limit assumes the target lifetime limit of  $10^{28}y$ , while the range indicates the present spread of nuclear matrix elements of Xe, Ge and Mo. The measurements of neutrino oscillations and the laboratory limits on the neutrino mass provide a limit in the case of normal neutrino ordering (NO), and a range for the inverted ordering (IO).



**Figure C.1:** Present and future limits from neutrino and proton-decay experiments on some of the dimension-six baryon number violating operators (BNV) and the dimension-five lepton number (LNV) violating operator in the SMEFT. The limits on BNV operators are shown for the two most sensitive searches of proton decay:  $p \rightarrow \pi_0 e^+$  and  $p \rightarrow K^+ \nu$ . The limits on the LNV operator are shown for the searches of neutrinoless double-beta decay. The present range, marked by the two solid lines, corresponds to the best PDG24 limit for Xe, assuming the largest (upper solid line) and lowest (lower solid line) estimates of the Xe matrix element. The future one corresponds to a target limit on the lifetime of  $10^{28}y$ , considering the maximum nuclear matrix element estimates among the Xe, Ge and Mo isotopes (upper boundary of hashed region) or the minimum (lower boundary of hashed region). Limits from neutrino oscillations and neutrino mass measurements are also shown for the normal neutrino ordering (NO) and the inverted ordering (IO).

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