Future Circular Collider
The Integrated Programme (FCC-int)

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Abstract:

The most effective and comprehensive approach to thoroughly explore the open questions in modern particle physics is a staged research programme, integrating in sequence lepton (FCC-ee) and hadron (FCC-hh) collision programmes, to achieve an exhaustive understanding of the Standard Model and of electroweak symmetry breaking, and to maximize the potential for the discovery of phenomena beyond the Standard Model. The project would rely on a shared and cost effective technical and organizational infrastructure, as was the case with LEP followed by LHC. This integrated programme is complementary to other ongoing research activities and leverages cross-disciplinary synergies to expand our understanding of the universe. It cements and enlarges Europe's leadership in particle and high-energy physics for decades to come. This document provides an overview of the physics potential of the integrated FCC programme and outlines its implementation scenario.

The FCC Conceptual Design Report volumes are available for download from 15 January 2019 at
http://fcc-design-report.web.cern.ch

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1 Scientific Context

In ten years of physics at the LHC, the particle physics landscape has greatly evolved. Today, an integrated Future Circular Collider programme consisting of a luminosity-frontier highest-energy lepton collider followed by an energy-frontier hadron collider promises the most far-reaching particle physics programme that foreseeable technology can deliver.

1.1 Introduction

The legacy of the first LHC physics programme phase can be briefly summarised as follows: a) **the discovery of the Higgs boson**, and the **start of a new phase** of detailed studies of its properties, aimed at revealing the deep origin of electroweak (EW) symmetry breaking; b) the indication that **signals of new physics around the TeV** scale are, at best, elusive; and c) the **rapid advance of theoretical calculations**, whose constant progress and reliability inspire confidence in the key role of **ever improving precision measurements**, from the Higgs to the flavour sectors. Last but not least, the **LHC success has been made possible by the extraordinary achievements of the accelerator and of the detectors**, whose performance is exceeding all expectations.

The future circular collider, **FCC, hosted in a 100 km tunnel at CERN, builds on this legacy**, and on the experience of previous circular colliders (LEP, HERA and the Tevatron). The e^+e^- collider (**FCC-ee**) would operate at multiple centre of mass energies $\sqrt{s}$, producing **$5\cdot10^{12}$ Z bosons ($\sqrt{s}$~91 GeV), 10^8 WW pairs ($\sqrt{s}$~160 GeV), over 10^6 Higgses ($\sqrt{s}$~240 GeV), and over 10^6 $t\bar{t}$ pairs ($\sqrt{s}$~340-365 GeV).** The **100 TeV pp collider (FCC-hh)** is designed to collect a total luminosity of **20 ab^{-1}**, corresponding to the production of e.g. **more than 10^{10} Higgs bosons**. The FCC-hh can also be operated with heavy ions (e.g. **PbPb at ($\sqrt{s_{NN}}$~39 TeV**). Optionally, the **FCC-eh**, with 50 TeV proton beams colliding with 60 GeV electrons from an energy-recovery linac, would generate **~2 ab^{-1} of 3.5 TeV ep collisions.**

The integrated FCC programme sets highly ambitious performance goals for its accelerators and experiments. For example, it will:

a) **Uniquely map the properties of the Higgs and EW gauge bosons**, pinning down their interactions with an accuracy order(s) of magnitude better than today, and acquiring sensitivity to, e.g. the processes that, during the **time span from 10^{-12} and 10^{-10} s after the Big Bang**, led to the creation of today's Higgs vacuum field.

b) Improve by close to an order of magnitude the **discovery reach for new particles at the highest masses** and by several orders the **sensitivity to rare or elusive phenomena at low mass**. In particular, the **search for dark matter (DM) at the FCC** could reveal, or conclusively exclude, DM candidates belonging to large classes of models, such as thermal WIMPs (weakly interacting massive particles).

c) **Probe energy scales beyond the direct kinematic reach**, via an extensive campaign of precision measurements sensitive to tiny deviations from the Standard Model (SM) behaviour. The precision will benefit from **event statistics** (for each collider, typically several orders of magnitude larger than anything attainable before the FCC), **improved theoretical calculations**, **synergies within the programme** (e.g. precise strong coupling constant **α_s** and parton distribution functions (PDF) provided to FCC-hh by FCC-ee and FCC-eh, respectively) and suitable **detector performance**.

A more complete overview of the FCC physics potential is presented in Volume 1 of the FCC Conceptual Design Report (CDR), and in the CDR volumes dedicated to the individual colliders. This document highlights some of the most significant findings of those studies that, in addition to setting targets for the FCC achievements, have driven the choice of the collider parameters (energy, luminosity), their operation plans, and contributed to the definition of the critical detector features and parameters.

1.2 Higgs studies

The achievements and prospects of the **LHC Higgs programme** are opening **a new era**, in which the Higgs boson is moving from being the object of a search, to become an exploration tool. The FCC positions itself as the most powerful heir of the future LHC Higgs' legacy. On one hand it will **extend the range of measurable Higgs properties** (e.g. its H→gg, $c\bar{c}$ decays, its total width, and its self-coupling), allowing more incisive and model-independent determinations of its couplings. On the other hand, the **combination of superior precision and energy reach** provides a framework in which **indirect and direct probes of new physics complement each other**, and cooperate to characterise the nature of possible discoveries.

The FCC-ee will measure Higgs production inclusively, from its presence as a recoil to the Z in 10^6 $e^+e^-\rightarrow ZH$ events. This allows the absolute measurement of the Higgs coupling to the Z, which is the starting point for the model-independent determination of its total width, and thus of its other couplings through branching ratio measurements. The **leading Higgs couplings to SM particles** (denoted g_{HXX} for particle X) will be measured by FCC-ee with a **sub-percent precision**, as shown in Table 1. The FCC-ee will also provide a first measurement of the Higgs self-coupling to 34%. As a result of the **model dependence being removed by FCC-ee,** a fully complementary programme will be possible at FCC-hh and FCC-eh, to complete the picture of Higgs boson properties. This will include the **measurement to the percent level of rare Higgs decays such as H→γγ, μμ, Zγ**, the **detection of invisible ones** (H→4ν), the measurement of the **g_{Htt} coupling with percent precision** and the measurement of the **Higgs self-coupling to 5-7%**, as shown for FCC-hh in Table 2.

Table 1: Precisions determined in the κ framework on the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC. All numbers indicate 68% C.L. sensitivities, except for the last line which gives the 95% C.L. sensitivity on the "exotic" branching fraction, accounting for final states that cannot be tagged as SM decays. The fit to the HL-LHC projections alone (first column) requires assumptions: here, the branching ratios into $c\bar{c}$ and into exotic particles (and those not indicated in the table) are set to their SM values. The FCC-ee accuracies are subdivided in three categories: the first sub-column gives the results of the fit expected with 5 ab^{-1} at 240 GeV, the second sub-column in bold includes the additional 1.5 ab^{-1} at $\sqrt{s}$ =365 GeV, and the last sub-column shows the result of the combined fit with HL-LHC. Similar to the HL-LHC, the fit to the FCC-eh projections alone requires an assumption to be made: here the total width is set to its SM value, but in practice will be taken to be the value measured by the FCC-ee.

Collider	**HL-LHC**	**FCC-ee**			**FCC-eh**
Luminosity (ab^{-1})	3	5 @ 240GeV	+1.5 @ 365GeV	+HL-LHC	2
Years	25	3	**+4**	-	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.3	**0.61**	0.55	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	1.6	**1.01**	0.83	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.4	**0.74**	0.64	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	10.1	**9.0**	3.9	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	4.8	**3.9**	1.1	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	**–**	2.4	1.7
BR_{EXO} (%)	SM (0.0)	<1.2	**<1.0**	<1.0	n.a.

Table 2: Target precision, at FCC-hh, for the parameters relative to the measurement of various Higgs decays, ratios thereof, and of the Higgs self-coupling. Notice that Lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

Observable	**Parameter**	**Precision (stat.)**	**Precision (stat.+syst.+lumi.)**
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(H) \times B(H \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)\, B(H \to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = B(H \to \mu\mu\gamma)/B(H \to \mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}H) \times B(H \to b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

The Higgs couplings to all gauge bosons and to the charged fermions of the second and third generation, except the strange quark, will be known with a precision ranging from few per mil to ~1%. In addition, the prospect of measuring, or at least strongly constraining, the couplings to the three lightest quarks and also to the electron by a special FCC-ee run at $\sqrt{s} = m_{\mathrm{H}}$ is being evaluated. The synergies amongst all components of the FCC Higgs programme are underscored by a global fit of Higgs parameters in the effective field theory (EFT) framework, shown in Fig. 1, and discussed in full detail in Volume 1 of the CDR. Finally, it is worth noting that the tagged H→gg channel at FCC-ee will offer an unprecedented sample of pure high energy gluons.

By way of synergy and complementarity, the integrated FCC programme appears to be the most powerful future facility for a thorough examination of the Higgs boson and EWSB.

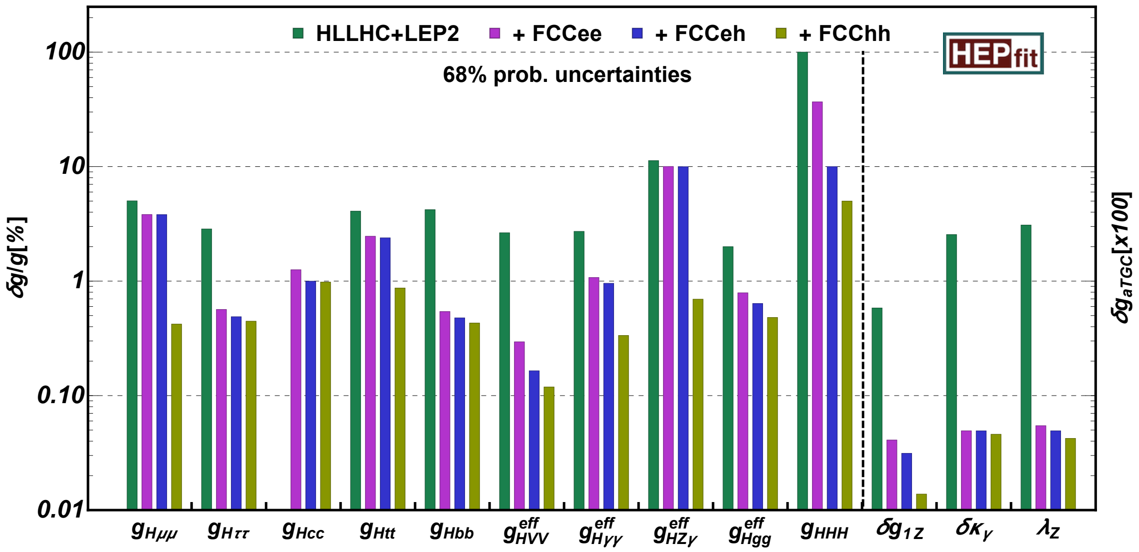

Figure 1: One-σ precision reach at the FCC on the effective single Higgs couplings, Higgs self-coupling, and anomalous triple gauge couplings in the EFT framework. Absolute precision in the EW measurements is assumed. The different bars illustrate the improvements that would be possible by combining each FCC stage with the previous knowledge at that time (precisions at each FCC stage considered individually, reported in Tables 1 and 2 in the κ framework, are quite different).

1.3 Electroweak precision measurements

As proven by the discoveries that led to the consolidation of the SM, EW precision observables (EWPO) can play a key role in establishing the existence of new physics and guiding its theoretical interpretation. We anticipate that this will continue to be the case well after the HL-LHC, and expect the FCC to lead the progress in precision measurements, as improved precision equates to discovery potential.

The broad set of EWPO's accessible to FCC-ee, thanks to immense statistics at the various beam energies and to the exquisite centre-of-mass energy calibration, will give it access to various possible sources and manifestations of new physics. Direct effects could occur because of the existence of a new interaction such as a Z' or W', which could mix or interfere with the known ones; from the mixing of light neutrinos with their heavier right-handed counterparts, which would effectively reduce their coupling to the W and Z in a flavour dependent way. New weakly coupled particles can affect the W, Z or photon propagators via loops, producing flavour independent corrections to the relation between the Z mass and the W mass or the relation between the Z mass and the effective weak mixing angle; or the loop corrections can occur as vertex corrections, leading to flavour dependent effects as is the case in the SM for e.g. the $\mathrm{Z} \to \mathrm{b}\bar{\mathrm{b}}$ couplings. The measurements above the $\mathrm{t}\bar{\mathrm{t}}$ production threshold, directly involving the top quark, as well as precision measurements of production and decays of 10^{11} τ's and 2×10^{12} b's, will further enrich this programme. Table 3 shows a summary of the target precision for EWPO's at FCC-ee.

The FCC-hh achieves indirect sensitivity to new physics by exploiting its large energy, benefiting, from the ability to achieve precision of a previously unexpected level in pp collisions, as proven by the LHC. EW observables, such as high-mass lepton or gauge-boson pairs, have a reach in the multi-TeV mass range, as shown in Fig. 2. Their measurement can expose deviations that, in spite of the lesser precision w.r.t. FCC-ee, match its sensitivity reach at high mass. For example, the new physics scale Λ, defined by the dim-6 operator $\widehat{W} = 1/\Lambda^2\left(D_\rho W^a_{\mu\nu}\right)^2$, will be constrained by the measurement of high-mass $\ell\nu$ pairs to $\Lambda > 80$ TeV. High-energy scattering of gauge bosons, furthermore, is a complementary probe of EW interactions at short distances. The FCC-eh, with precision and energy in between FCC-ee and FCC-hh, integrates their potential well. For example, its ability to separate individual light quark flavours in the proton gives it the best sensitivity to their EW couplings. Furthermore, its high energy and clean environment enable precision measurements of the weak coupling evolution at very large Q^2. More details can be found in Volume 1 of the FCC Conceptual Design Report ("Physics Opportunities").

Table 3: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precision. The systematic uncertainties are present estimates and might improve with further examination. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in some specific new physics models.

Observable	**present value ± error**	**FCC-ee stat.**	**FCC-ee syst.**	**Comment and dominant exp. error**
m_Z (keV)	91186700±2200	5	100	Z line shape scan; beam energy calibration
Γ_Z (keV)	2495200±2300	8	100	Z line shape scan; beam energy calibration
R_l^Z (×10³)	20767±25	0.06	0.2-1.0	ratio hadrons / leptons, lepton acceptance
α_s (m_Z) (×10⁴)	1196±30	0.1	0.4-1.6	from R_l^Z above
R_b (×10⁶)	216290±660	0.3	<60	ratio $b\bar{b}$/hadrons, stat. extrapol. from SLD
σ_{had}^0 (×10³) (nb) N_ν (×10³)	41541±37 2991±7	0.1 0.005	4 1	peak hadronic cross section, luminosity meas. Z peak cross sections, luminosity measurement
$\sin^2\theta_W^{\mathrm{eff}}$ (×10⁶)	231480±160	3	2-5	from $A_{FB}^{\mu\mu}$ at Z peak, beam energy calibration
$1/\alpha_{\mathrm{QED}}(m_Z)$ (×10³)	128952±14	4	Small	from $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ (×10⁴)	992±16	0.02	1-3	b-quark asymmetry at Z pole, from jet charge
$A_{FB}^{\mathrm{pol},\tau}$ (×10⁴)	1498±49	0.15	<2	τ polarisation, charge asymmetry, τ decay physics
m_W (MeV)	80350±15	0.6	0.3	WW threshold scan; beam energy calibration
Γ_W (MeV)	2085±42	1.5	0.3	WW threshold scan; beam energy calibration
α_s (m_W) (×10⁴)	1170±420	3	Small	from R_l^W
N_ν(×10³)	2920±50	0.8	Small	ratio invisible to leptonic in radiative Z returns
m_{top} (MeV)	172740±500	20	Small	$t\bar{t}$ threshold scan; QCD errors dominate
Γ_{top} (MeV)	1410±190	40	Small	$t\bar{t}$ threshold scan; QCD errors dominate
$\lambda_{\mathrm{top}}/\lambda_{\mathrm{top}}^{\mathrm{SM}}$	1.2±0.3	0.08	Small	$t\bar{t}$ threshold scan; QCD errors dominate
ttZ couplings	±30%	0.5 – 1.5%	Small	from $E_{CM} = 365$ GeV run

The FCC EW measurements are a crucial element of, and a perfect complement to, the FCC Higgs physics programme.

1.4 The EW phase transition

Explaining the origin of the cosmic matter-antimatter asymmetry is a challenge at the forefront of particle physics. One of the most compelling explanations connects this asymmetry to the generation of elementary particle masses through electroweak symmetry-breaking (EWSB). This scenario relies on two ingredients: a sufficiently violent transition to the broken-symmetry phase, and the existence of adequate sources of CP-violation. As it turns out, these conditions are not satisfied in the SM, but they can be met in a variety of beyond the Standard Model BSM scenarios. CP violation relevant to the matter-antimatter asymmetry can arise from new interactions over a broad range of mass scales, possibly well above 100 TeV. Exhaustively testing these scenarios may, therefore, go beyond the scope of the FCC. On the other hand, for the phase transition to be sufficiently strong, there must be new particles with masses typically below one TeV, whose interactions with the Higgs boson modify the Higgs potential energy in the early universe. Should they exist, these particles and interactions would manifest themselves at FCC, creating a key scientific opportunity and priority for the FCC, as shown by various studies completed to date.

The FCC should conclusively probe new states required by a strong 1st order EW phase transition.

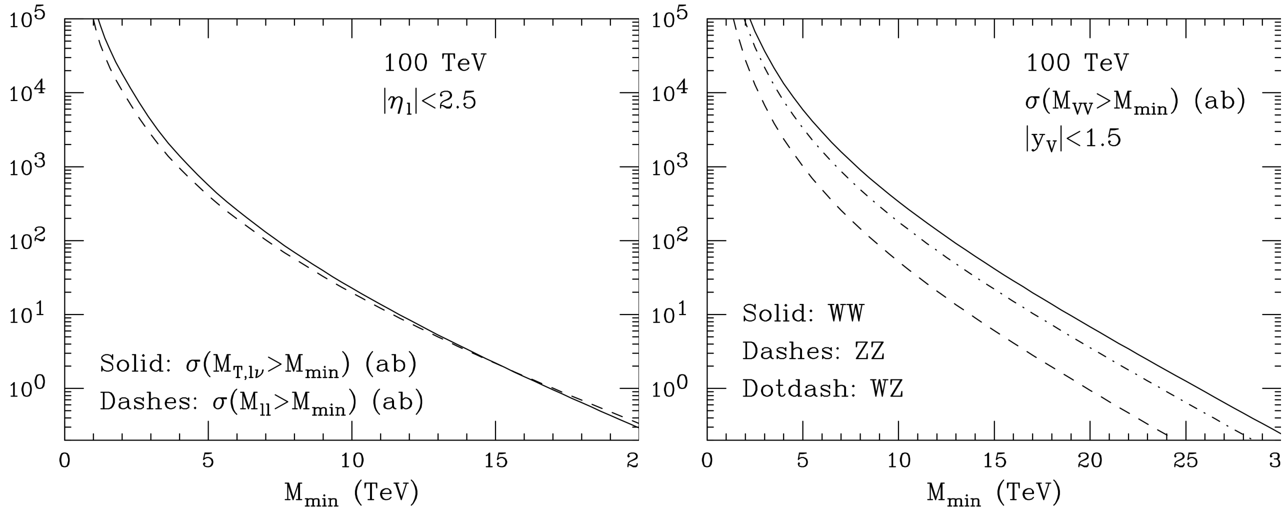

Figure 2: Left: integrated lepton transverse (dilepton) mass distribution in pp→ $W^*\to\ell\nu$ (pp→ $Z^*/\gamma^*\to\ell^+\ell^-$). One lepton family is included, with $|\eta_l|<2.5$. Right: integrated invariant mass spectrum for the production of gauge boson pairs in the central kinematic range $|y|<1.5$. No branching ratios included.

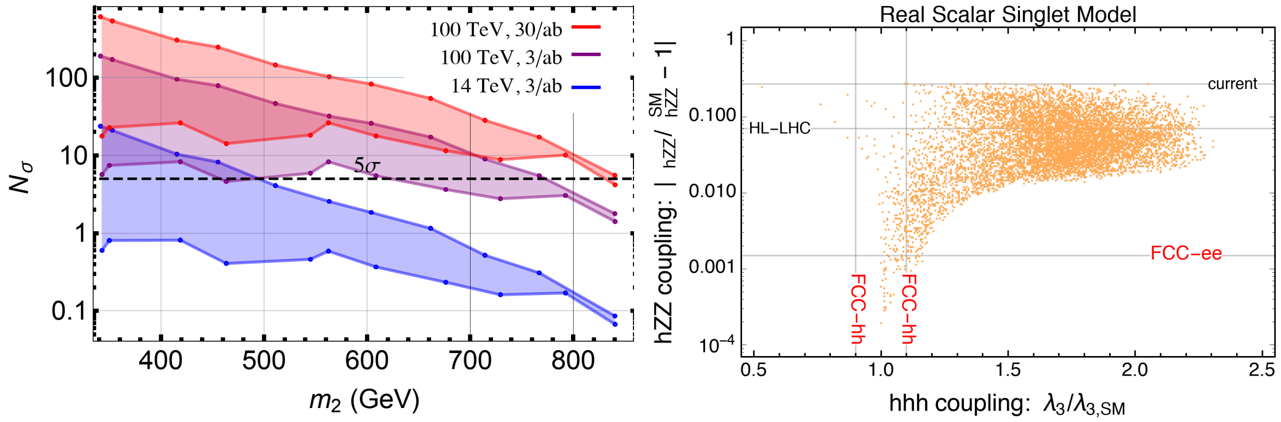

Figure 3: Manifestations of models with a singlet-induced strong first order EWPT. Left: discovery potential at HL-LHC and FCC-hh, for the resonant di-Higgs production, as a function of the singlet-like scalar mass m_2, 4τ, and $b\bar{b}\gamma\gamma$ final states are combined. Right: correlation between changes in the HZZ coupling (vertical axis) and the HHH coupling scaled to its SM value (horizontal axis), in a scan of the models' parameter space. All points give rise to a first order phase transition.

As an example, we show the results of the study of the extension of the SM scalar sector with a single real singlet scalar. The set of model parameters leading to a strongly first order phase transition is analysed from the perspective of a direct search, via the decays of the new singlet scalar to a pair of Higgs bosons, and of precision measurements of Higgs properties. The results of the former case are shown in the left plot of Fig. 3: FCC-hh with 30 ab^{-1} has sensitivity greater than 5 standard deviations to all relevant model parameters. For these models, the deviations in the Higgs self-coupling and in the Higgs coupling to the Z boson are then shown in the scatter plot on the right of Fig. 3. With the exception of a small parameter range, most of these models lead to deviations within the sensitivity reach of FCC, allowing the cross-correlation of the direct discovery via di-Higgs decays with the Higgs property measurements. This will help the interpretation of a possible discovery, and assess its relevance for the nature of the EW phase transition.

1.5 Dark matter

No experiment, at colliders or otherwise, can probe the full range of dark matter (DM) masses allowed by astrophysical observations. However, there is a very broad class of models for which theory motivates the GeV – 10's of TeV mass scale, and which therefore could be in the range of the FCC. These are the models of weakly interacting massive particles (WIMPs), present during the early universe in thermal equilibrium with the SM particles. These conditions, broadly satisfied by many models of new physics, establish a correlation between the WIMP masses and the strength of their interactions, resulting in mass upper limits. While the absolute upper limit imposed by unitarity is around 110 TeV, most well motivated models of WIMP DM do not saturate this bound, but rather have upper limits on the DM mass in the TeV range. As an example, DM WIMP candidates transforming as a doublet or triplet under the SU(2) group of weak interactions, like the higgsinos and winos of supersymmetric theories, have masses constrained below ~1 and ~3 TeV, respectively. The full energy and statistics of FCC-hh are necessary to access these large masses. With these masses, neutral and charged components of the multiplets are almost degenerate due to SU(2) symmetry, with calculable mass splittings induced by electromagnetic effects, in the range of few hundred MeV. The peculiar signatures of these states are disappearing tracks, left by the decay of the charged partner to the DM candidate and a soft, unmeasured charged pion. Dedicated analysis, including detailed modelling of various tracker configurations and realistic pile-up scenarios, are documented in Volume 3 of the FCC Conceptual Design Report. The results are shown in Fig. 4.

The FCC covers the full mass range for the discovery of these WIMP Dark Matter candidates.

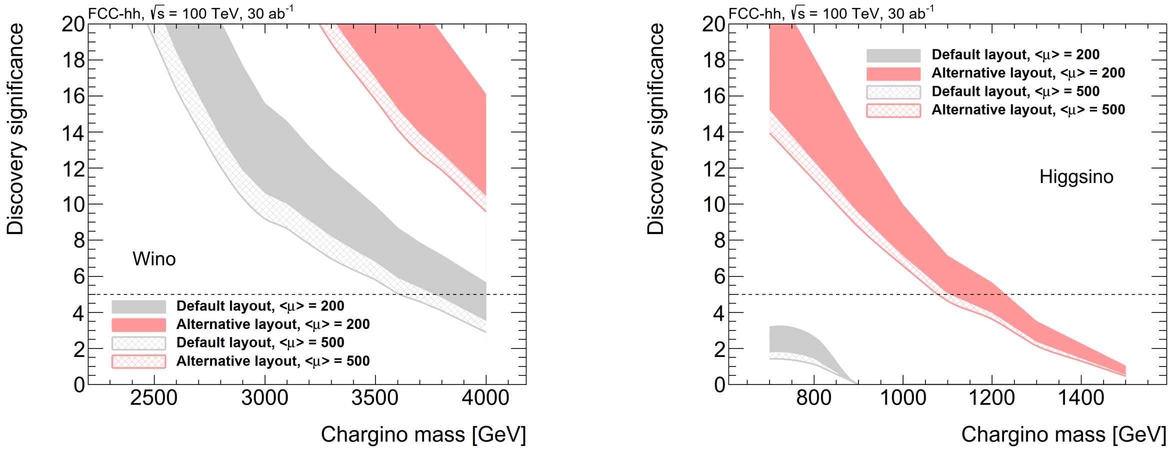

Figure 4: Expected discovery significance for higgsino and wino DM candidates at FCC-hh, with 500 pile-up collisions. The black and red bands show the significance using different layouts for the pixel tracker, as discussed in the FCC-hh CDR. The bands' width represents the difference between two models for the soft QCD processes.

1.6 Direct searches for new physics

At the upper end of the mass range, the reach for the direct observation of new particles will be driven by the FCC-hh. The extension with respect to the LHC will scale like the energy increase, namely by a factor of 5 to 7, depending on the process. The CDR detector parameters have been selected to guarantee the necessary performance up to the highest particle momenta and jet energies required by discovery of new particles with masses up to several tens of TeV. Examples of discovery reach for the production of several types of new particles, as obtained in dedicated detector simulation studies, are shown in Fig. 5. They include Z' gauge bosons carrying new weak forces and decaying to various SM particles, excited quarks Q^*, and massive gravitons G_{RS} present in theories with extra dimensions. Other standard scenarios for new physics, such as supersymmetry or composite Higgs models, will likewise see the high-mass discovery reach greatly increased. The top scalar partners will be discovered up to masses of close to 10 TeV, gluinos up to 20 TeV, and vector resonances in composite Higgs models up to masses close to 40 TeV. The direct discovery potential of FCC is not confined to the highest masses. In addition to the dark matter examples given before, Volume 1 documents the extraordinary sensitivity to less-than-weakly coupled particles, ranging from heavy sterile neutrinos (see Fig. 5, right) down to the see-saw limit in a part of parameter space favourable for generating the baryon asymmetry of the Universe, to axions and dark photons.

The FCC has a broad, and in most cases unique, reach for less-than-weakly coupled particles. The Z running of FCC-ee is particularly fertile for such discoveries.

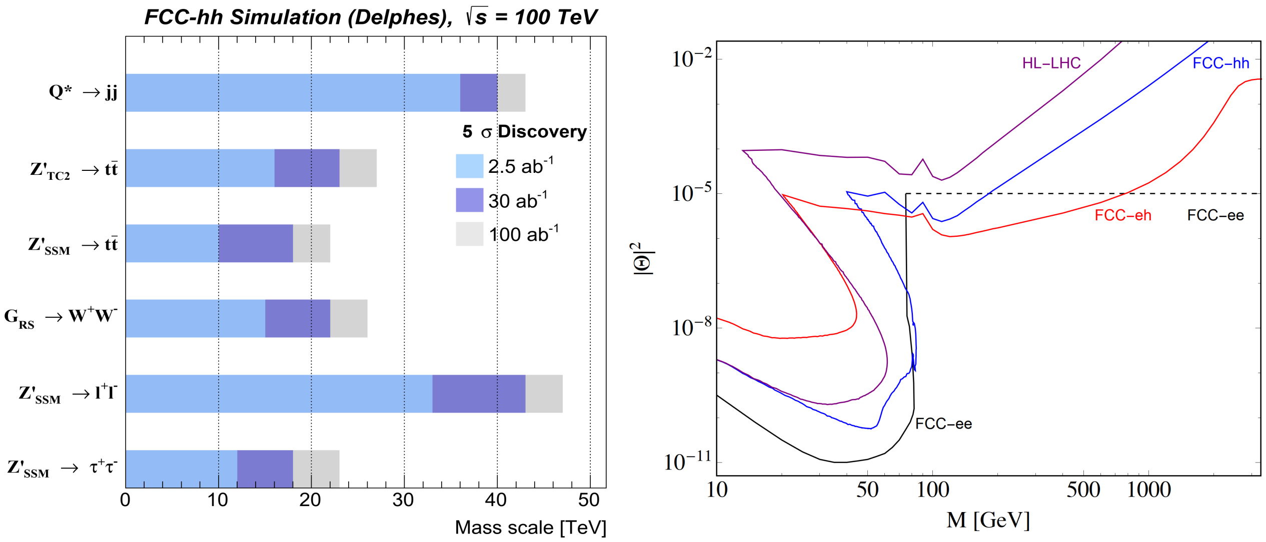

Figure 5: Left: FCC-hh mass reach for different s-channel resonances. Right: Summary of heavy sterile neutrino discovery prospects at all FCC facilities. Solid lines show direct searches at FCC-ee (black, in Z decays), FCC-hh (blue in W decays) and FCC-eh (in production from the incoming electron). The dashed line denotes the impact on precision measurements at the FCC-ee, it extends up to more than 60 TeV.

1.7 QCD matter at high density and temperature with heavy-ion beams

Collisions of heavy ions at the energies and luminosities allowed by the FCC-hh will open new avenues in the study of collective properties of quarks and gluons.

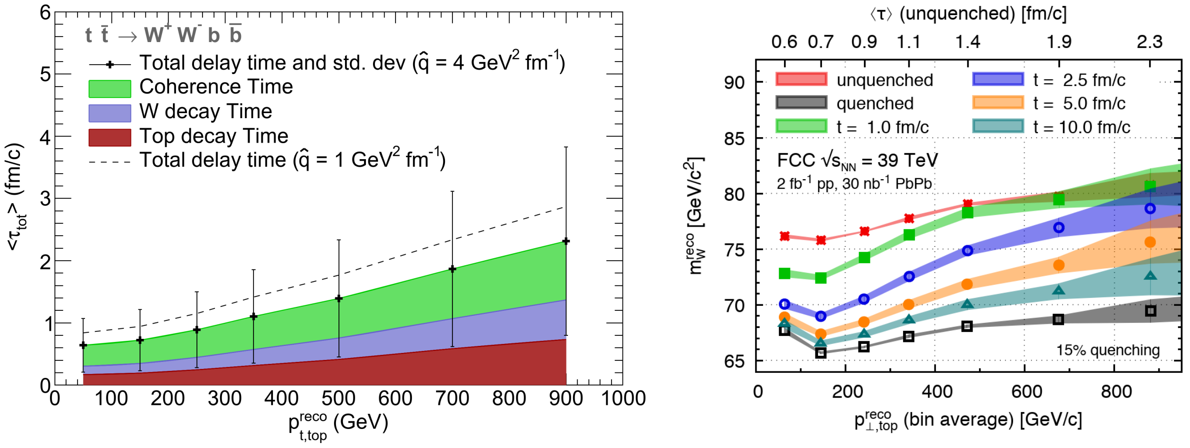

Figure 6: Left: Total delay time for the QGP energy-loss parameter $\hat{q}=4$ GeV^2/fm as a function of the top transverse momentum (black dots) and its standard deviation (error bars). The average contribution of each component is shown as a coloured stack band. The dashed line corresponds to a $\hat{q}=1$ GeV^2/fm. Right: Reconstructed W boson mass, as a function of the top p_T. The upper axis refers to the average total time delay of the corresponding top p_T bin.

The thermodynamic behaviour of Quantum Chromodynamics (QCD) presents features that are unique amongst all other interactions. Pertinent physics opportunities at FCC are extensively discussed in the CDR Volume 1. Heavy ions accelerated to FCC energies give access to an uncharted parton kinematic region at x down to 10^{-6}, which can be explored also exploiting the complementarity of proton-nucleus and electron-nucleus collisions at the FCC-hh/eh. The quark gluon plasma (QGP) could reach a temperature as high as 1 GeV, at which charm quarks start to contribute as active thermal degrees of freedom in the equation of state of the QGP. In the studies of the QGP with hard probes the FCC has a unique edge, thanks to cross section increases with respect to LHC by factors ranging from ~20 for Z+ jet production, to ~80 for top production. We present here just one example: FCC will provide large rates of highly-boosted top quarks and the $q\bar{q}$ jets from t→ W→ $q\bar{q}$ are exposed to energy loss in the QGP with a time delay (see Fig. 6-left), providing access to time-dependent density measurements for the first time. The effect of this time-delayed quenching can be measured using the reduction of the reconstructed

W mass, as shown in Fig. 6-right, where the modifications under different energy loss scenarios are considered as examples.

1.8 Parton Structure

The FCC-eh resolves the parton structure of the proton in an unprecedented range of x and Q^2 to very high accuracy, providing a per mille accurate measurement of the strong coupling constant.

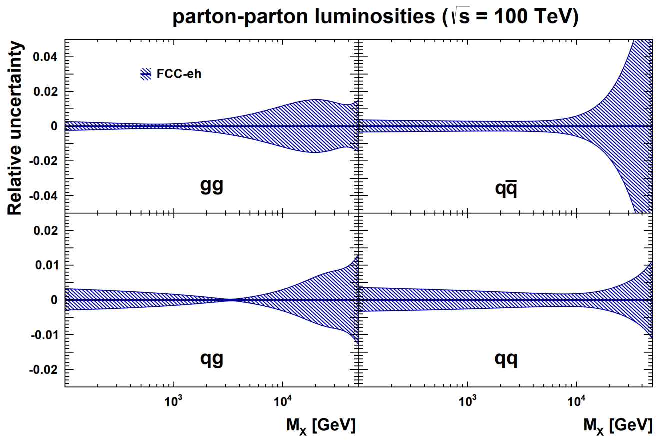

Figure 7: Relative PDF uncertainties on parton-parton luminosities, resulting from the FCC-eh PDF set, as a function of the mass of the heavy object produced, M_X, at $\sqrt{s}$ = 100 TeV. Shown are the gluon-gluon (top left), quark-antiquark (top right), quark-gluon (bottom left) and quark-quark (bottom right) luminosities.

Deep inelastic scattering measurements at FCC-eh will allow the determination of the PDF luminosities with the precision shown in Fig. 7. These results provide an essential input for the FCC-hh programme of precision measurements and improve the sensitivity of the search for new phenomena, particularly at high mass. The FCC-eh measurements will extend the exploration of parton dynamics into previously unexplored domains: the access to very low Bjorken-x is expected to expose the long-predicted BFKL dynamic behaviour and the gluon saturation phenomena required to unitarise the high-energy cross sections. The determination of the gluon luminosity at very small x will also link directly to ultra-high energy (UHE) neutrino astroparticle physics, enabling more reliable estimates of the relevant background rates.

1.9 Flavour physics

The FCC flavour programme receives important contributions from all 3 machines, FCC-ee, hh, eh.

The Z run of the FCC-ee will fully record, with no trigger, 10^{12} Z→ $\bar{b}b$ and Z→ $\bar{c}c$ events. This will give high statistics of all b- and c-flavoured hadrons, making FCC-ee the natural continuation of B-factories, Table 4.

Table 4: Expected production yields for b-flavoured particles at FCC-ee at the Z run, and at BELLE II (50 ab^{-1}).

Particle production (10^9)	$B^0/\bar{B}^0$	B^+/B^-	$B^0_s/\bar{B}^0_s$	$\Lambda_b/\bar{\Lambda}_b$	$c/\bar{c}$	τ^+/τ^-
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	1000	1000	250	250	550	170

Of topical interest will be the study of possible lepton flavour and lepton number violation. FCC-ee, with detection efficiencies internally mapped with extreme precision, will offer 200,000 $B^0 \rightarrow K^*(892)\, e^+e^-$, 1,000 $K^*(892)\, \tau^+\tau^-$ and 1,000(100) B_s (resp B^0)$\rightarrow\mu\mu$ events, one order of magnitude more than the LHCb upgrade. The determination of the CKM parameters will be correspondingly improved. First observation of CP violation in B mixing will be within reach; a global analysis of BSM contributions in box mixing processes, assuming Minimal Flavour Violation, will provide another, independent, test of BSM physics up to an energy scale of 20 TeV.

Tau physics in Z decays has shown to be extremely precise already from LEP; 1.7 10^{11} $\bar{\tau}\tau$ pairs, FCC-ee will achieve precision of 10^{-5} or better for the leptonic branching ratios and the charged lepton-to-neutrino weak couplings – this allowing a measurement of G_F and tests of charged-weak-current universality at the 10^{-5} precision level. Finally, lepton number violating processes, such as $Z \rightarrow \tau\ \mu/e$, $\tau \rightarrow 3\mu$, $e\gamma$ or $\mu\gamma$, can be detected at the 10^{-9}-10^{-10} level, offering sensitivity to several types of neutrino-mass generation models.

2 Strategic Objectives

The ESPP 2013 stated "*To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update*". The **FCC study has implemented the ESPP recommendation** by **developing a long-term vision for an *"accelerator project in a global context"*.** It consists of a high-intensity lepton collider as a first phase and an energy-frontier hadron collider as a second phase that re-uses the entire infrastructure of the first phase. This approach leverages in an optimum fashion the existing assets that all nations contributing to CERN's research programme have contributed over the last sixty years and makes the best use of a new infrastructure. This programme ***"in collaboration with national institutes, laboratories and universities worldwide"***, and enhanced by a **strong participation of industrial partners,** starts with the next ESPP recommendation in 2020 to serve a worldwide science community until the end of the 21st century. The **coordinated effort** will build upon a solid foundation of more than 130 collaborating institutes worldwide.

Europe needs to strengthen and extend its global leadership in fundamental research to **bind the brightest minds and financial support** of nations worldwide in order **to achieve, what cannot be achieved alone**: the continued deep exploration of the microcosm to reach an understanding of what the universe is made of at its very core. This programme creates the necessary **long-term cohesion among the European partners** through a **consensus-based common long-term vision** for an attractive, extensible and future-proof research infrastructure.

The most promising approach to achieve this goal is **first to dedicate** the available **resources to a technology-ready machine** that leads to a physics-programme optimised design of a subsequent energy-frontier collider. The approach **creates a new window in time** in which to develop the advanced technologies needed to build a long-term cost- and energy-efficient highest energy hadron collider. This integrated project leverages best **CERN's existing machine complex**, notably the HL-LHC, its **infrastructures** and pre-accelerators. They can **serve as injectors for both FCC-ee and FCC-hh**. The combination of available infrastructure, organisational and administrative services suitable for large-scale technology research projects **is the key to the successful implementation of a large-scale project**. As is best practice, the international **collaborations carry out the experimental research programme** based on detector and accelerator R&D collaborations, theoretical physics initiatives and data analysis initiatives worldwide.

A research infrastructure with a long-term strategic programme serving a worldwide community, tightly involving industrial partners and providing training at all education levels over multiple decades will deliver the highest socio-economic impacts. The yearly social discount rate gradually reduces the benefits generated by short-term investments, but also rapidly leads to an amortisation of the initial tunnel and surface site civil engineering expenses. The combined LEP/LHC/HL-LHC cost-benefit-analysis revealed that a long-term programme consisting of a technology-ready lepton collider (FCC-ee), followed by a highest energy hadron collider (FCC-hh) is most likely to generate the highest possible socio-economic impact. It is therefore **from a socio-economic point of view an unbeatable scenario.**

3 Methodology

The **most efficient method for the thorough exploration of the open questions in modern physics is a staged, integrated research programme**, consisting of a high-intensity lepton collider to achieve an exhaustive understanding of the Standard Model to an extent that guides the optimised design of a cost-effective and sustainable energy-frontier collider that re-uses the entire existing technical and organisational infrastructures. As was the case with LEP followed by LHC, **this approach permits the control of technical and financial risks** without self-imposed constraints. It **cements and enlarges Europe's leadership** in particle and high-energy physics **for decades to come**.

The experimental research will be **based on international collaborations** with long-term **open access** to detector data and on a **community-based scientific analysis** supported by a worldwide data processing infrastructure, as is best practice in high-energy physics. This **program is complementary to other ongoing research activities** (e.g. long-baseline neutrino experiments in the US and Japan) and leverages cross-disciplinary synergies to expand our understanding of the universe (e.g. DM searches complementing astroparticle physics research projects).

3.1 Technical Feasibility and Long-term Sustainability

The technologies to create a new underground infrastructure and a highest-luminosity circular lepton collider **exist today**. Strategic R&D over the coming years will concentrate on minimising construction costs and energy consumption, whilst maximising the socio-economic impact with a focus on benefits for industry and training.

A well-defined physics programme for FCC-ee with a committed user community permits swift progress to the design of detectors for which the lepton collider can then be further optimised. The operation of such a machine is highly energy-efficient and can, together with an optimised maintenance and repair concept, remain within the envelope of the HL-LHC operation budget. The **physics outcome** (in any unit of performance from integrated luminosity to the number of produced Higgs particles) **per cost of construction and operation** of this programme **is far above any other technically feasible particle collider proposal under discussion at present**.

The **additional time window** until about 2055 created by a lepton-collider research programme will be **used to develop alternative technologies for the hadron collider**, e.g. magnets based on high temperature superconductors, with, potentially important impact on the collider parameters (e.g. increase of beam energy), relaxation of infrastructure requirements (cryogenics system) and increased energy efficiency (temperature of magnets and beam screen). In addition, the hadron collider **can be optimised for specific physics research goals** based on findings from the lepton collider operation. This is also **relevant for the development of detectors and data processing infrastructures** which will need to cope with unprecedented data rates and volumes.

3.2 Implementation Model

Given that an eight-year period is necessary for project preparation and administrative processes with the host states, the construction of a new infrastructure can start in 2028. The investments in a new, large-scale underground and surface site infrastructure are best justified with a long-term exploitation plan. This is also in the interest of the host states. Common work has therefore already begun to develop a feasible schedule. Activities will now aim at **achieving a consensus in the community to support the project and the commitment of nations** to contribute. The project scenario needs to be validated and a legal framework needs to be agreed by the host states. Various stakeholders must be engaged in the design phase, for the assessment of environmental and socio-urbanistic impacts.

The first step of the implementation model is to establish governing and management structures for a lean and effective organisation, which is needed to advance at a good pace. The design period includes a detailed cost analysis and the development of a sustainable funding strategy. It will establish the necessary legal framework to manage the commitment of contributions from member and non-member states and to create a suitable procurement and in-kind supply framework based on competitive performance of suppliers leading to control of the overall total-cost-of-ownership. It will create the framework to employ human resources under conditions corresponding to the needs of the sustainable preparation and construction of the project. This phase concludes with the set-up of an appropriate auditing scheme, ensuring transparency to all stakeholders.

The construction of a new tunnel with about twelve surface sites is the first, and administratively most challenging, part, due to the rapid urban evolution in the “Grand Genève” region, on both the Swiss and French sides. Therefore, **a swift start of the detailed design** of the **infrastructure is of utmost importance for the reservation of the locations, negotiating the land-plot and underground-volume rights-of-way,** and **reducing cost-uncertainties for the tendering procedures**. This activity comprises geological investigations, environmental impact screenings, geological surveys, work with authorities and representatives of the public to optimise the placement to minimise necessary compensation measures, and the development of concrete synergies.

4 Challenges

This integrated FCC programme is characterised by the **smallest set of uncertainties** that could potentially adversely impact its implementation. The timely implementation of the intensity-frontier lepton collider can be ensured **with an early start of the project preparatory phase**. Residual technical challenges for the subsequent energy-frontier hadron collider **can be addressed through a well-focused R&D** programme.

The commitment of the host states is a pre-requisite for preparing the project. An eight-year preparatory phase is necessary and adequate to carry out the permission-related administrative processes and to develop funding and in-kind plans for the first phase, focusing on new infrastructure and a high intensity lepton collider. An immediate challenge is the creation of a worldwide consortium of scientific contributors who reliably commit resources for the development and preparation of the scientific part of the project from 2020 onwards.