Prospects for physics at FCC-hh

Editors:
M. Mangano [*1], M. Selvaggi [*2], B. Stapf [*2], A. Taliercio [*4], S. Williams [*5]

Contributors:
J. Burridge [*6], J. Cardoso Silva [*7], J. Degens [*8], M. D'Onofrio [*8], J. Eysermans [*9], E. Gallo [*10], E. Lipeles [*11], S. Manzoni [*2], P. Mastrapasqua [*12], E. Mazzeo [*2], J. Nesbitt [*6,13], M. Saito [*14], L. Santos Pereira Trigo [*6,15], R. Sawada [*14], K. Tackmann [*10],

on behalf of the Physics, Experiments and Detectors pillar of the FCC Project

[*1] CERN TH
[*2] CERN EP
[*4] Northwestern University
[*5] University of Cambridge
[*6] University of Manchester
[*7] University of Edinburgh
[*8] University of Liverpool
[*9] MIT
[*10] DESY and University of Hamburg
[*11] University of Pennsylvania
[*12] Université Catholique de Louvain
[*13] University of Glasgow
[*14] Tokyo University
[*15] DESY

Abstract

This submission reviews and updates the extensive work done over the years to explore and quantify the physics potential of FCC-hh, the hadron collider component of the integrated Future Circular Collider facility. The document introduces the context of these studies, as it has developed over the years, and offers an update of key targets of FCC-hh such as the precision Higgs studies and the discovery reach at the highest mass scales. New analyses added or improved with respect to the CDR, are introduced. A general assessment is also given of the impact of the new energy/luminosity baseline for the accelerator, and of alternative configurations, on the physics results.

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CONTEXT AND INTRODUCTION

This document provides a summary of recent developments in the study of the physics potential of FCC-hh [1], the pp collider in the FCC tunnel proposed to follow the completion of FCC-ee operations. Comprehensive studies were performed in the years leading to the FCC CDR, using $\sqrt{s} = 100\,\text{TeV}$ and $\int L = 30\,\text{ab}^{-1}$ as baseline accelerator configuration [2]. These studies, which served as a reference for the 2019 ESPPU assessment, are documented in a Yellow Report [3] (YR) and the CDR itself [2, 4]. A follow-up report [5] describes the conceptual design of an FCC-hh general purpose detector (GPD), used in the CDR projections.

Following the start of the FCC Feasibility Study (FS), the update of FCC-hh physics studies waited for the redefinition of the accelerator layout and for the developments of the high-field magnet programme. The new baseline FCC-hh configuration [6, 7], detailed in the Volume 2 of the FS Report (FSR) [8], foresees the use of 14 T Nb_3Sn dipoles in the 90.7 km FCC tunnel, leading to a centre-of-mass (CM) energy of $\sqrt{s} = 84\,\text{TeV}$ and a luminosity comparable to the CDR design.[1]

The short time since the new accelerator baseline became available did not allow a complete update of all original FCC-hh studies. Efforts were therefore focused on the most representative targets of the physics programme, in particular the precision Higgs measurements. These new results hold for the new reference energy of 84 TeV, but also benefit from improved analysis strategies, as discussed below. For several other results presented in this and in the other FCC PED submissions [9–12] we either recall previous results, or, where possible, we provide well justified extrapolations from 100 TeV.

To highlight the value of the full integrated FCC programme, all FCC-hh projections directly related to the physics benchmarks proposed by the ESPPU preparatory group are presented in the FCC submissions dedicated to the relevant topic (H/EW/top, BSM, QCD, flavour), to facilitate the evaluation of the synergy and complementarity between FCC-ee and FCC-hh. This document includes brief summaries of those results and provides more details and references on the individual analyses.

Several FCC-hh configurations other than the baseline have emerged from discussions in the HEP community ever since the previous ESPPU. On one side, they reflect the desire to anticipate as much as possible the technological readiness and financial affordability of a post-LHC hadron collider, relying on less challenging magnet technologies, even at the expense of a lower CM energy. On the other, progress with high-temperature superconducting (HTS) magnet technology holds the promise to reach energies higher than the baseline, with 120 TeV as the target for 20 T dipoles.

The detailed study of these alternative scenarios did not emerge as a priority from the previous ESPPU, and was not mandated as part of the FS. Work has nevertheless been done both for the assessment of the physics potential and for the technical definition of non-baseline configurations. Some of the results are presented here, for the sake of informing the Strategy discussions. None of this material can be considered as conclusive, nor does it form the basis for any recommendation or alternative scenario endorsed by the FCC project.

HIGGS PHYSICS

That hadron colliders can perform high-precision measurements has been well established by now. Extrapolating precision reach from the LHC to the FCC is not straightforward however: on the one hand, one is tempted to be optimistic, given the huge statistics and the immense measurement potential, and given the long timescale that will allow for further progress in detector technology, analysis strategies and theoretical calculations. On the other hand, facing the challenge of pileup at O(500-1000), or extrapolating the theoretical precision beyond the level of 2-3 loops, can only be done with great caution, since brick walls could be hit any time in the process.

For this reason, the projections for precision measurements at FCC-hh have focused so far, when possible, on a limited class of observables that, by construction, reduce significantly the impact

[1] The baseline integrated luminosity is kept at $\int L = 20\,\text{ab}^{-1}$ for each of two possible GPDs. As in the CDR, the physics studies assume $30\,\text{ab}^{-1}$, to account for the, possibly partial, statistical combination of the results from the two experiments.

of theoretical and experimental systematic uncertainties.[2] For the study of single-Higgs properties, we considered production ratios among different final states, reconstructed within similar fiducial regions for the parent Higgs. Choosing in particular production in the few 100 GeV p_T region, where the FCC-hh statistics are still large, reduces the backgrounds, the impact of pileup and other uncertainties such as object identification efficiencies. Systematic uncertainties from the theoretical modelling and from the luminosity measurement vanish in these ratios. Absolute determination of Higgs couplings can then be obtained from those ratios by using the FCC-ee absolute measurements (eg of the $H \to 4\ell$ branching ratio, or BR). It was shown in the CDR [4], for example, that this approach leads to sub-% precision in measurements of the Higgs couplings to $\gamma\gamma$, $Z\gamma$ and $\mu\mu$, namely the small couplings which the limited statistics of lepton colliders can determine only at the several per-cent level. The ratio of the $t\bar{t}H$ to the $t\bar{t}Z$ cross sections (with $H,Z \to b\bar{b}$), using the precise FCC-ee measurement of the top EW coupling, can lead to comparable O(%) precision of the top Yukawa coupling [4].

Similar approaches can be used to directly access also some of the couplings that can be measured precisely at FCC-ee. For example, one can use ratios such as WH/WZ with $H(Z) \to \gamma\gamma(ee)$, or VH/VZ with $H/Z \to \tau\tau$ or $b\bar{b}$. Details can be found in Ref. [13], where it was shown that the Higgs coupling to τ, W and b can be measured more precisely than 1% using knowledge of $BR(H \to \gamma\gamma)$. Although only statistical uncertainties were considered, the previous considerations about reduction of the leading experimental systematic uncertainties apply to the study of these ratios, which nevertheless will require further detailed detector simulations.

In this section, we illustrate some recent results, and the improvements recently achieved for several of the earlier projections, adopting new analysis techniques and better estimates of the experimental systematic uncertainties, all corroborated by the progress shown by the LHC experiments. The overall collection of results is included in the Higgs/EW/top submission document [9], to provide the full picture emerging from the integrated FCC-ee+ FCC-hh programme. The studies reported here rely on simulated event samples generated by the MADGRAPH_AMCATNLO [14], POWHEG [15–17] and PYTHIA8 [18] Monte Carlo (MC) programs, and processed through the fast detector simulation package DELPHES [19]. The baseline FCC-hh detector concept [2, 5] was parameterised in DELPHES [20] and the event samples were produced with the KEY4HEP framework [21, 22].

Directly accessing the Higgs self coupling through Higgs pair production is a key goal for FCC-hh, with the CDR noting a target precision on $\delta\kappa_\lambda = 5\%$ through a combination of analysis techniques and decay modes and assuming future progress in signal and background modelling. For this ESPPU, the projections for the precision on the self-coupling achievable in the $bb\gamma\gamma$ and $bb\tau\tau$ decay modes have been updated independently: updated simulation samples are used and state-of-the art analysis techniques (including machine learning) inspired by LHC results are exploited. Additionally, a decay mode not studied for the FCC-hh before, the $bb\ell\ell + E_T^{\text{miss}}$ final state, was explored.

One of the most sensitive channels for Higgs boson pair production is the $bb\gamma\gamma$ channel. On one hand, it suffers from a low branching ratio of only 0.26%. On the other hand, it benefits from high photon resolution and allows for the complete and unambiguous reconstruction of the decay products of both Higgs bosons. Inspired by recent efforts from CMS [23], the updated $bb\gamma\gamma$ analysis [24] employs kinematic selections to identify the Higgs boson candidates, the implementation of multivariate classifiers to enhance the signal-to-background ratio, event categorisation based on the di-b-jet invariant mass, and the extraction of results from a likelihood fit to the di-photon invariant mass distribution. The ultimate goal is to achieve precision at the per-cent level for $\delta\kappa_\lambda$, which would surpass previous projections. A selection of example distributions illustrating the analysis strategy and results of the updated $bb\gamma\gamma$ analysis is shown in Figure 1. Figure 1a shows the Deep Neural Network (DNN) discriminant distribution for signal and background events. Based on this score, events are categorised into medium- and high-purity classes. These classes of events are then further divided into categories

[2] An important exception to this approach is the determination of the Higgs self coupling from the HH production rate. In this case, no analysis to date builds on a "ratio measurement" that could completely eliminate both the luminosity and the theoretical modelling systematic uncertainties. In the following assessment of the HH production measurement, we include a 1% contribution to the systematics due to luminosity but neglect the modelling biases. Obvious cases for future studies include, e.g., the ratio of HH and WW invariant masses in VBF channels.

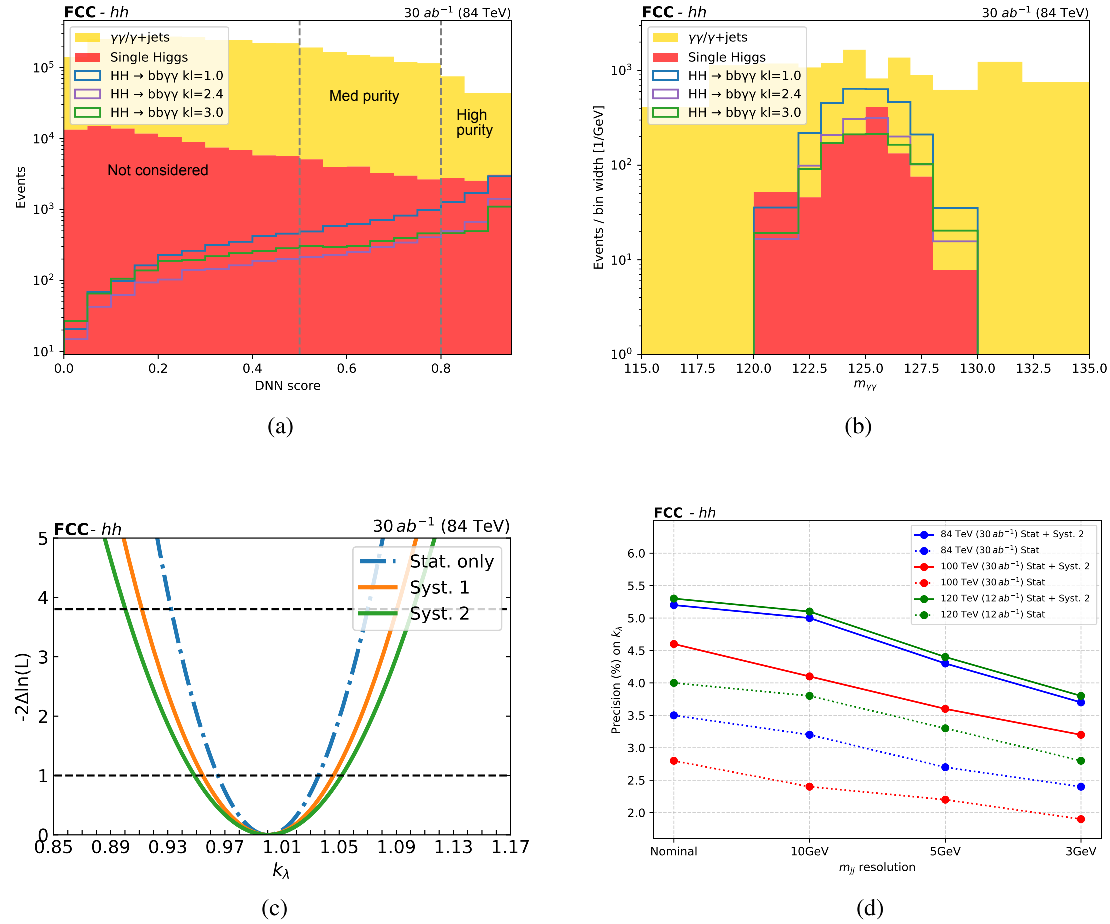


Fig. 1: Examples of distributions and results of the updated bb$\gamma\gamma$ Higgs self-coupling analysis [24]: (a) Distribution of the Deep Neural Network (DNN) score for signal and background events, indicating the categorisation into medium and high purity analysis regions (b) Distributions of the invariant mass of the di-photon system in the high purity category, and (c) likelihood scans for κ_λ for different systematic scenarios, (d) κ_λ precision as a function of center-of-mass energy and di-jet mass resolution.

based on the value of $m_{\rm bb}$. Figure 1b shows the distribution of the invariant mass of the di-photon system in the high purity region, $m_{\gamma\gamma}$, which displays a resonant peak from the signal processes, and a large non-resonant background. The final result is then extracted from a profile likelihood fit on the $m_{\gamma\gamma}$ distributions. Figure 1c shows the negative log-likelihood (NLL) as function of κ_λ at 84 TeV, employing a realistic detector scenario along with two different systematic assumptions: 1% uncertainties for photon efficiency, b-tagging efficiency, luminosity and signal cross section (labelled Syst. 1), and 2% uncertainties for photon efficiency, b-tagging efficiency, luminosity (labelled Syst. 2). The expected statistical uncertainty on κ_λ is 3.5%. With systematic assumptions Syst. 1(2), the expected precision is 4.6% (5.2%). The expected precisions obtained for different center-of-mass energies are reported later in Tab. 3 in the section on non-baseline collider scenarios and in Figure 1d. Figure 1d also illustrates how the expected precision on κ_λ varies as a function of center-of-mass energy and the di-b-jet mass resolution. Improving the di-b-jet mass resolution through detector design and advanced analysis techniques, such as a ML-based mass regression, could dramatically improve the precision of the self-coupling at the FCC-hh.

For the bb$\tau\tau$ channel the updated feasibility studies considered both the fully hadronic and the lepton-hadron decay modes of the taus, leveraging advanced Graph Neural Network (GNN) techniques for event classification [25]. This technique significantly improves the signal-to-background discrimination. At 84 TeV, preliminary results yield a significance around 30 for the fully hadronic channel alone assuming a 2% uncertainty on the $\mathrm{t\bar{t}}$ background. This promises to further improve the self-coupling precision to around 3% or below when combining the result with the $\mathrm{bb}\gamma\gamma$ analysis.

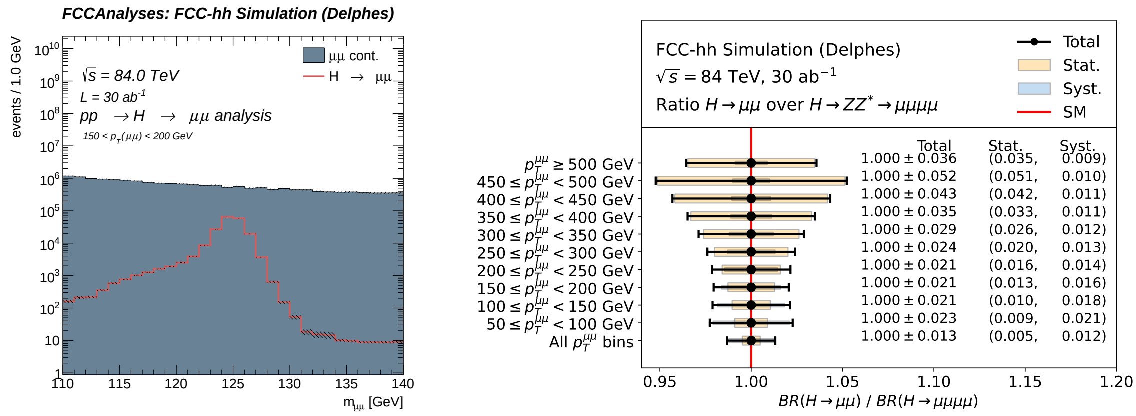
With the results presented in Ref. [26], a new analysis of the fully leptonic decay mode of the taus in the bb$\tau\tau$ channel, as well as of the bbWW and bbZZ channels, was added to the set of Higgs self-coupling measurement projections for FCC-hh. This $\mathrm{bb}\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ analysis poses a more challenging measurement than the previously discussed channels, with low branching ratios, overwhelmingly large backgrounds such as top-quark pair production and a direct dependence on complex reconstructed quantities such as the missing transverse energy, and therefore on the reconstruction performance. In consequence, the precision achieved on the Higgs self-coupling modifier κ_λ is not competitive, reaching only between 20% to 35% in the CDR baseline scenario of operating at 100 TeV, but this channel would merit further study as a direct probe to derive benchmarks for the reconstruction of missing transverse energy in the face of the high levels of pile-up at FCC-hh.

A further possible improvement in the precision measurement of the Higgs self-coupling from HH events may come from the study of kinematic differences between triangle and box contributions in the gluon-gluon fusion production, as shown in Ref. [27].

Accessing rare Higgs decays using the large statistics at FCC-hh will provide results complementary to those at FCC-ee. Taking $\mathrm{H} \to \mu\mu$ as a case-study and relying on the high statistics at high p_{T}(H) where experimental uncertainties are smaller, a previous study from the CDR has been updated to use a more sensitive analysis [28]: while the previous results were obtained from a simple counting experiment, the new strategy exploits the different shapes of the $m_{\mu\mu}$ invariant mass and $p_{T,\mu\mu}$ distributions between signal and background in a 2D template fit. Moreover the estimation of the experimental systematic uncertainties was further refined, using p_T-dependent scale factors capturing the reconstruction efficiency uncertainties of each muon, and measuring the non-resonant background in a data-driven way from the large statistics in the sidebands. By considering the ratio of the $\mathrm{H} \to \mu\mu$ results over those obtained by a comparable analysis of the $\mathrm{H} \to 4\mu$ final state, the common theoretical and experimental uncertainties cancel (at least partially), allowing to achieve an overall precision on the ratio of signal strengths (and therefore branching ratios) of 1.3%, in the 84 TeV baseline scenario. As the branching ratio of $\mathrm{H} \to 4\mu$ decays will be measured very precisely at FCC-ee, this result (naively) translates to a precision on the Higgs to muon coupling of $\delta g_{\mathrm{H}\mu\mu}/g_{\mathrm{H}\mu\mu}$ = 0.66% . Since the analysis is dominated by systematic uncertainties, the achievable precision including systematics for the other operating scenarios is comparable. The $m_{\mu\mu}$ distribution for signal and background for large $p_{T,\mu\mu}$ is shown in Figure 2(a). The differential sensitivity on the ratio $\mathcal{B}(\mathrm{H} \to \mu\mu)/\mathcal{B}(\mathrm{H} \to \mu\mu\mu\mu)$ as a function of $p_{T,\mu\mu}$ is shown in Figure 2(b). Clearly the differential binning in $p_{T,\mu\mu}$ can be further optimized. Work on this aspect will be performed in the coming months, and the new analysis strategy will be applied also to other rare Higgs decay modes.

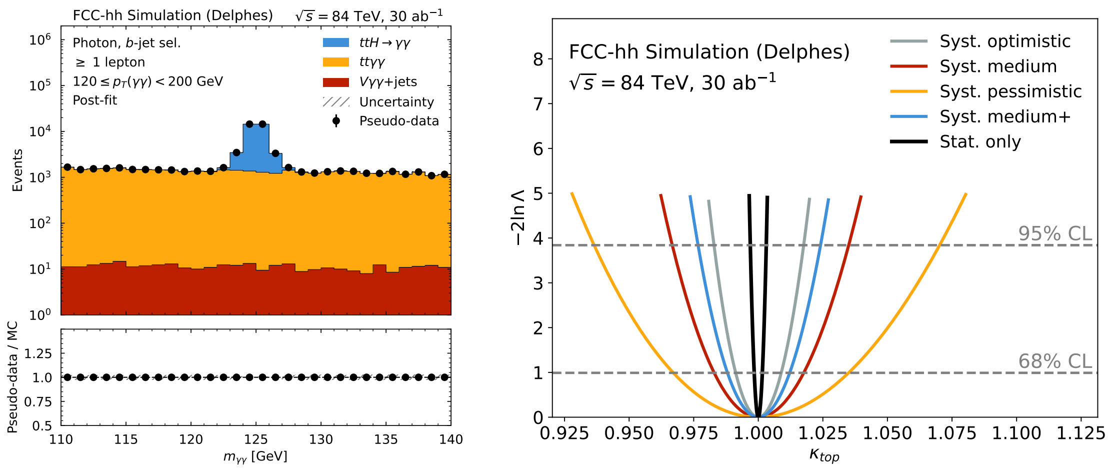
Another FCC-hh benchmark measurement that can be probed only with limited precision at FCC-ee, is that of the top Yukawa coupling. A new study of the ttH($\gamma\gamma$) channel [29], previously unexplored at FCC-hh, strengthens the CDR results. Although rare, due to the small H$\to\gamma\gamma$ branching ratio, this channel boasts a clean experimental signature with excellent mass reconstruction of the Higgs decay and high signal-to-background ratio, allowing for a precision measurement of the top Yukawa coupling. This makes the ttH($\gamma\gamma$) measurement competitive with the previously studied more abundant ttH(bb) channel: in the stand-alone ttH($\gamma\gamma$) analysis presented in Ref. [29], a precision of 0.9%-1.2% on the top Yukawa coupling modifier κ_{t} is achieved depending on the systematic uncertainties considered (0.2% stat only). Extending the study to consider the ratio with the ttZ process (i.e. with ttZ(ee) in this case), as previously done, will improve the precision and the robustness of the result as common modeling and experimental uncertainties cancel. This extension is planned as an update to be completed by the June Open Symposium.

The large statistics at FCC-hh will also extend constraints on BSM effects in Higgs couplings. For example, Ref. [30] has studied interference effects in CP-odd observables to constrain anomalous CPV-violating HVV interactions induced by dimension-six effective field theory (EFT) operators. For FCC-hh the study was performed at $\sqrt{s}$ = 100 TeV and considered ZH production (with $H \to$bb), $H \to 4\ell$ production and VBF H$\to \tau\tau$ production, and concludes that FCC-hh can provide order



(a) (b)

Fig. 2: (a) Invariant mass spectrum of the Higgs di-muon candidate for signal and background at large Higgs p_T in the $H \to \mu\mu$ analysis [28]. (b) Differential measurement of the ratio $\mathcal{B}(H \to \mu\mu)/\mathcal{B}(H \to \mu\mu\mu\mu)$ for different values of $p_T(H)$.



(a) (b)

Fig. 3: (a) Invariant mass spectrum of the Higgs di-photon candidate for signal and background at large Higgs p_T in the $ttH(\gamma\gamma)$ analysis [29]. (b) Negative log-likelihood scan over the top Yukawa coupling modifier κ_t.

of magnitude improvements relative to the constraints obtained at the HL-LHC and FCC-ee and that further improvements can arise through the use of ML techniques.

Finally, inspired by LHC results, a new study has been performed considering fitting the ratio of VBF H→WW to VBS WW production rates [31]. Being proportional to κ_W^4/Γ_H, this ratio promises a large sensitivity to the HWW coupling. The expected precision in the VBF-to-VBS ratio is found to be 2% for the FCC-hh baseline scenario at 84 TeV.

HIGH-Q^2 EFT PROBES

The extended kinematic range accessible to FCC-hh for production of SM final states X at very large momentum transfer Q (e.g. at large p_T(X) or M(X)), provides unique indirect probes of high-dimension EFT operators, inducing possible corrections of $\mathcal{O}(Q^2/\Lambda^2)$ to the SM expectations. This sensitivity to BSM effects is complementary to what can be achieved via the precision measurements in the Higgs and EW sectors accessible at FCC-ee. Several examples have been worked out in the literature, both in the EW sector (see e.g. [32]) and in the top sector (see e.g. [33]). As input to the work of the ESPPU Preparatory Group, a compilation of data for production at high-Q^2 of $t\bar{t}$, W^+W^- and four-top final states is provided in Ref. [34]. This gives estimates of signal and background rates, as well as preliminary estimates of the relevant experimental systematic uncertainties. The key conclusions of this study indicate that an overall uncertainty below 10% can be achieved for the measurement of the $t\bar{t}$ invariant mass up to 30 TeV, of the eμ invariant mass from WW decays up to 8.5 TeV, and an overall uncertainty of 4% in the production of four-top final states, with the prospect for a further reduction to the per-cent level from a more refined analysis.

BSM SEARCHES

Following the operations of FCC-ee, with its potential to expose deviations from the SM via precision measurements, the FCC-hh brings to the integrated FCC programme its far-reaching prospects for the direct discovery of new particles, with a reach in the several tens of TeV mass range. The exploration of the broad BSM potential of FCC-hh has been extensively studied in the years leading to the CDR, as documented in Refs. [4,35,36], and as discussed during the previous ESPPU.[3] The BSM scenarios discussed in those works span a broad range, making it impossible to even summarise in a meaningful way all discovery limits, so we just briefly list here the main ones, referring to [4,35,36] for the details: (i) supersymmetry, with studies of the reach for squarks, gluinos, stops, electroweakinos, long-lived charged particles, as well as analyses of post-discovery opportunities for the measurement of the model parameters [37]; (ii) dark matter, in a variety of different dark-sector models and signatures [38], proving in particular the conclusive discovery or exclusion of thermal DM WIMP candidates [39]; (iii) new bosonic and fermionic resonances, weakly or strongly coupled, appearing in new gauge interactions, in models for neutrino masses, composite Higgs, flavour or low-scale gravity [40]; (iv) BSM aspects of Higgs physics, ranging from resonance searches in extended Higgs sectors [41] to the quest for signatures of models with strong first order EW phase transition [42]. Some explicit examples of reach for resonances are shown in a section below, to illustrate the variation of the discovery potential across different accelerator energy-luminosity configurations.

The FCC-hh BSM results, including recent developments that directly address the list of benchmarks requested by the Preparatory Group, are listed in the dedicated FCC BSM submission [11], together with the discovery potential of FCC-ee.

OTHER PHYSICS OPPORTUNITIES

As proven by the LHC, a hadron collider facility offers multiple opportunities to broaden the physics programme well beyond the flagship energy-frontier topics for which the designs of the accelerator and two general-purpose detectors are optimised. Since its beginning, the LHC incorporated in its programme a dedicated experiment to exploit the huge production of bottom hadrons, as well as the accelerator infrastructure to enable a dedicated experiment to explore the physics of heavy-ion collisions. Further experiments were added subsequently to extend the sensitivity to physics in the forward region and searches for exotica, such as magnetic monopoles and long-lived particles. FCC-hh offers similar opportunities, which must be incorporated in the design of the facility (accelerator and infrastructure) from the beginning to maximise their physics potential. This is true not just of the collider, but also of the injector complex. An early assessment of possible physics opportunities with FCC-hh injectors is contained in Ref. [43].

The physics potential and accelerator options of the heavy ion FCC facility were studied in the context of the CDR [2, 4], and presented in detail in Ref. [44]. The increase in energy from LHC to FCC, with the increase in the QGP temperature and the more extended kinematical reach, opens new regimes not accessible at the LHC (e.g. a thermalised charm) and allows for qualitatively new probes of the underlying dynamics (see e.g. [45]). A brief summary of these findings is included in the FCC QCD submission [10], to highlight the full breadth of the integrated FCC programme towards deepening our quantitative understanding of strong interactions in the various regimes created by e^+e^-, pp, pA and AA collisions.

The LHC experiments are playing today a crucial role in the study of the internal proton struc-

[3] We note that all those results were obtained at 100 TeV. For the class of scenarios and observables considered, the projections for 84 TeV are well-approximated by just rescaling the 100 TeV results by the energy ratio.

ture, with measurements that significantly improve the knowledge of the proton PDFs. Although no specific study has been done as yet (except for the measurements of a possible FCC-eh collider [4,46]), it is clear that improving on PDFs will be a key outcome of the FCC-hh experiments, whose full potential will also heavily rely on the theoretical progress. In addition to this, building on the recent success of the FASER [47] and SND@LHC [48] experiments, new opportunities are being proposed for proton structure studies, using e.g. high-energy neutrinos from the pp collisions [49]. A brief summary is given in the FCC QCD contribution [10]. Note that such a forward-physics facility would also offer a probe of BSM long-lived particles, complementary to the sensitivity of the GPDs. Finally, some considerations on the physics potential of FCC-hh for the study of flavour are contained in the FCC Flavour submission [12]. Looking back at the evolution of the LHC experimental programme, at how its diversity has grown hand in hand with the experience of both accelerator and experiments, driving creativity and unexpected progress, there is no doubt that FCC-hh will offer an equally multifaceted facility capable of stimulating a multitude of scientific interests complementary and ancillary to the main integrated FCC targets.

NON-BASELINE COLLIDER SCENARIOS

Various operational and luminosity scenarios for different options of Nb_3Sn and HTS dipole technologies are documented in Ref. [7]. A summary of the parameters relevant for the physics studies is given in Table 1. We note the significant reduction in beam current at the highest energy, needed to contain within the cryogenic power budget the increase of synchrotron radiation (SR) [7]. As a result, we highlight the important drop in affordable luminosity at $\sqrt{s} = 120$ TeV.[4] On the contrary, at 72 TeV one could afford doubling the 84 TeV baseline luminosity, if the corresponding higher pileup (2800 vs 600) can be tolerated by the detectors. Note that the original goal of 100 TeV can be now attained if 17 T HTS dipoles were available. Operating at higher temperature, the reduction in overall cryogenic power might alleviate the cost of additional SR with respect to 84 TeV at the same luminosity, as assumed in the Table. The goal of collisions at 100 TeV, or above, remains therefore desirable.

Table 1: Key parameters of possible FCC-hh running scenarios with Nb_3Sn (F12* and F14) and HTS dipoles (F17 and F20). The integrated luminosity figures assume 75% beam availability during 160 days of physics running, and 5 h turn around time. These values are conservative with respect to the actual LHC performance.

Scenario	F12LL	F12HL	F12PU	F14	F17	F20
$\sqrt{s}$ (TeV)	72	72	72	84	102	120
Peak arc dipole field (T)	12	12	12	14	17	20
Beam current (A)	0.5	1.12	1.12	0.5	0.5	0.2
SR power (2 beams, MW)	1.3	2.9	1.9	2.4	5.3	4.0
Pileup	580	2820	955	590	732	141
Luminosity / yr (fb^{-1})	850	2000	1300	940	920	370

In 2019, another option was considered in response to requests from the Strategy Group: a 37.5 TeV collider based on 6 T NbTi dipoles [50], providing an integrated luminosity of $\sim$10 ab^{-1} per GPD over 20 years. With the current accelerator layout, this magnet option would give $\sqrt{s} = 36$ TeV. The physics assessment of this option is documented in Ref. [51], where various key benchmark processes were compared against the 100 TeV baseline and against the HE-LHC projections (documented in the 2018 Workshop on "Physics at HL-LHC and HE-LHC" [52,53], and in the HE-LHC CDR [54], to which we refer for further details on this additional non-FCC post-LHC pp collider option). The bottom line of these comparisons was a loss in precision for Higgs couplings by factors of 2-3, a loss by a factor of 3 in high-mass reach, and by a factor of 2 in the search for Higgsino-like DM candidates, down to 650 GeV and well below the theoretical upper limit of $\sim$ 1 TeV. We refer to Ref. [51] for the

[4] To first approximation, at a given beam energy the SR power grows linearly with the luminosity.

Table 2: Variation of the projected precision for Higgs couplings (inferred from the ratios of BRs with respect to four-lepton final states), comparing the old (100 TeV) and the new (84 TeV) project baselines (30 ab^{-1}), with 72 and 120 TeV scenarios (with integrated luminosities scaled with respect to 30 ab^{-1} by the relative yearly integrated luminosities shown in Table 1). The identity between F12LL and F20 results is a numerical coincidence, due to the compensation between cross sections and integrated luminosities.

$\sqrt{s}$ scenario int. lumi ab^{-1}	100 TeV CDR baseline 30	84 TeV FSR baseline 30	72 TeV F12LL 27	72 TeV F12HL 64	120 TeV F20 12
$\delta g_{\mathrm{H}\gamma\gamma}/g_{\mathrm{H}\gamma\gamma}$ [%]	0.40	0.42	0.45	0.39	0.45
$\delta g_{\mathrm{H}\mu\mu}/g_{\mathrm{H}\mu\mu}$ [%]	0.64	0.68	0.75	0.62	0.75
$\delta g_{\mathrm{HZ}\gamma}/g_{\mathrm{HZ}\gamma}$ [%]	0.88	0.96	1.08	0.84	1.08

details, and do not further discuss these lower-energy options here. In this section, we present some examples of the impact of non-baseline scenarios on the physics potential of the FCC-hh.

Precision Higgs measurements We show in Table 2 the change in the projected precision for the Higgs couplings to γγ, μμ and Zγ. We assume here that the systematic uncertainties are independent of the beam energy and luminosity (which is not a trivial assumption in the case of F12HL, given the immense pileup), and the changes are therefore entirely driven by the different statistics for the different scenarios. In the case of μμ, we note that this naive scaling leads to an almost identical result of the direct analysis shown in Fig. 2, hence validating the procedure also for the γγ and Zγ couplings. In particular, it is clear that the 120 TeV scenario, F20, is penalised with respect to the baseline by the reduced luminosity. The new 84 TeV baseline shows only a minor loss of precision compared to the previous CDR results, well within the range of the uncertainty on the detector performance assumptions that drive the systematic uncertainties.

Additionally, Table 3 reports the achievable precision on the self-coupling from the HH $\rightarrow \mathrm{bb}\gamma\gamma$ channel alone for the FSR and CDR baselines and the F20 scenarios. The FSR and CDR baselines can achieve $\sim 3\%$ statistical precision, while the F20, being penalized due to its reduced luminosity, can reach only 4%. The results of this study were shown in Fig. 1, and are documented in more detail in Ref. [24].

Table 3: Projected precision on the Higgs self-coupling the various scenarios shown in Table 1. The projections only exploit the HH $\rightarrow \mathrm{bb}\gamma\gamma$ channel [24] and are expected to improve substantially with the combination of additional channels.

$\sqrt{S}$ scenario int. lumi ab^{-1}	84 TeV FSR baseline 30	100 TeV CDR baseline 30	120 TeV F20 12
$\delta\kappa_\lambda$ (stat.) [%]	3.5	2.8	4.0
$\delta\kappa_\lambda$ (syst. 1) [%]	4.6	4.0	4.6
$\delta\kappa_\lambda$ (syst. 2) [%]	5.2	4.6	5.3

High-mass reach The part of the physics programme that is most directly affected by the choice of beam energy is the search for new phenomena at high-Q^2, whether by direct production of new particles or through deviations in the tails of some distribution. Many examples of such searches are documented in the YR and in the CDR and, for the specific benchmarks required by the Physics Preparatory Group, are discussed above and in the FCC PED BSM submission. We show here how to extrapolate the reach projections performed in the YR and CDR to different CM energies, with applications to the new scenarios discussed.

The production rates for both signals and backgrounds of new phenomena are proportional to the partonic luminosity calculated at the relevant mass scale M (e.g. $M = m$ for for an s-channel resonance of mass m, $M = 2m$ for pair production, $M \sim p_{\mathrm{T}}$ for production at high p_{T}, etc.). With due exceptions, not relevant for the cases discussed here, signal and backgrounds are driven by the same initial partonic luminosity, and therefore it is a good approximation to extrapolate the reach by comparing the relative partonic luminosities at different energies. A useful interactive tool, *Collider Reach* [55], facilitates this task, and was used for the results presented in Table 4. The Table shows, for the various collider scenarios, the extrapolation from the results obtained in the past with fast detector simulations [19] at 100 TeV. The $\tilde{\mathrm{W}}^0$ and $\tilde{\mathrm{h}}^0$ objects are the *wino* and *higgsino* WIMP DM candidates and the corresponding search exploiting a disappearing track signature was presented in Ref. [39].[5] Should they exist and provide the observed DM abundance, their masses would be constrained by cosmological considerations to lie below ~3.5 and 1 TeV, respectively. These upper limits are saturated by the searches at FCC-hh for all scenarios discussed here, although barely so at the lowest energy and at lower 120 TeV luminosities.

The variation of the mass discovery reach, relative to what is achievable in the baseline scenario, is shown in Fig. 4. This highlights the important interplay of energy and luminosity, whereby a high-luminosity scenario for 72 TeV has a wider discovery reach, for masses up to 10 TeV, than even the 120 TeV option. For reference, we also show the curves for a 50% higher luminosity target at 120 TeV. Overall, these results underscore that the sustainability of the power demand from cryogenics is a critical challenge for the full exploitation of the highest energies possibly allowed by the future progress with high-field magnets. Fig. 4b shows the dependence on the collider scenario of the production rates for final states at a given CM energy M (for the gg and $\mathrm{q\bar{q}}$ channels). The curves provide the relative statistics to be delivered by a given collider, with respect to F14, for statistically equivalent observations at a given mass scale M.

Table 4: Evolution across different FCC-hh scenarios of the 5σ discovery reach for various BSM candidates. Entries represent mass values in TeV. The definitions of the various BSM models, as well as the description of the reference 100 TeV analyses, are given in Refs. [39, 56].

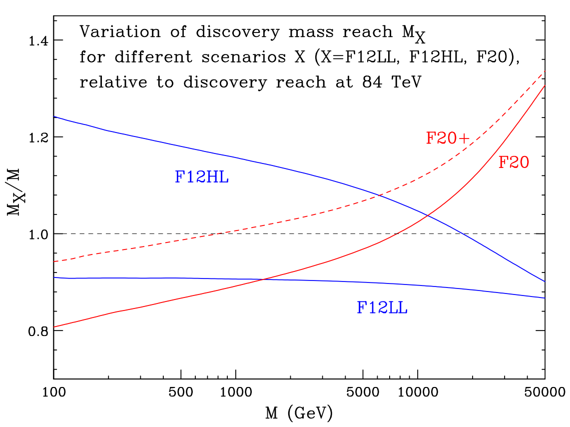
BSM object (%)	100 TeV CDR baseline	84 TeV FSR baseline	72 TeV F12LL	72 TeV F12HL	120 TeV F20
$\mathrm{Z'}_{SSM} \to \ell\ell$	43	37	32	34	46
$\mathrm{Z'}_{SSM} \to \tau\tau$, tt	18	16	14	16	17
$\mathrm{Z'}_{TC} \to$ tt	23	20	18	20	23
$\mathrm{G}_{RS} \to$ WW	22	19	17	19	22
$\mathrm{Q}^* \to$jj	40	35	30	32	43
$\tilde{\mathrm{W}}^0$	4.4	4.0	3.6	4.3	3.9
$\tilde{\mathrm{h}}^0$	1.2	1.1	1.0	1.3	1.0

FURTHER ONGOING STUDIES

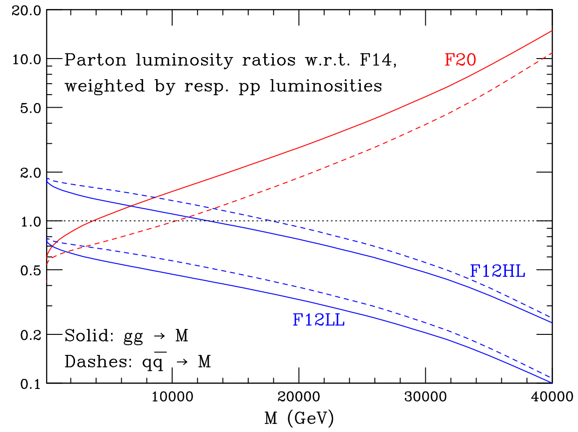
The new results on the FCC-hh physics reach presented here and in the other FCC PED submissions arose from work done in the context of the FCC-hh physics working group, established after the release of the new FCC-hh accelerator baseline, and in preparation for the ESPPU. The activities of this WG are documented in the Indico category of its meetings [57]. We highlight in this section some further results that, with different degrees of readiness to date, are emerging from the WG. The WG is committed to continue its activity beyond the March 31 submission deadline, in particular in preparation for the June ESPPU Open Symposium.

Concerning Higgs physics, several extensions are anticipated to the studies already performed. As described above, the ttH($\to\gamma\gamma$) analysis aims to exploit the ratio with ttZ($\to$ee), in order limit the impact of systematic uncertainties due to the cancellation and to make the study more robust by removing the dependence on certain assumptions for e.g the uncertainty on the luminosity measurement

[5] To corroborate the Collider Reach extrapolation of the $\tilde{\mathrm{W}}^0$ and $\tilde{\mathrm{h}}^0$ reach, this was validated against the re-evaluation at 80 TeV of the complex analysis introduced in Ref. [39].



(a)



(b)

Fig. 4: (a) Variation of the discovery/exclusion reach for alternative scenarios with the respect to the baseline FCC-hh 84 TeV configuration. The curves, derived from Collider Reach [55], average over three possible initial-state compositions (gg, $q\overline{q}$ and qg), whose predictions vary from each other by only few percent. The scenario F20+ corresponds to F20, with a 50% increase in luminosity ($550\,\mathrm{fb}^{-1}$/yr). (b) Ratios of the partonic gg, $q\overline{q}$ luminosities, as a function of partonic CM energy M, among the various energy-luminosity scenarios. The ratios are weighted also by the relative pp luminosities.

or the signal production cross-section by the time of the FCC-hh. The updated Higgs couplings study for the Hμμ channel aims to expand to the other previously considered rare decay modes, Hγγ and Zγ. For di-Higgs production, the completion of the $\mathrm{bb}\tau\tau$ and combination with the $\mathrm{bb}\gamma\gamma$ channel are foreseen as updates. We also plan to extend these HH studies to the case of resonant production of Higgs pairs, in particular in the context of models with a strong first order phase transition.

The FCC-hh physics working group has also discussed studies performed prior to the updated baseline on the physics potential of FCC-hh. Longitudinal vector boson scattering provides an important probe of electroweak symmetry breaking and same-sign WW production provides an important benchmark in pp collisions due its small backgrounds. Studies in Ref. [58] reported an expected precision in the cross section for purely longitudinal scattering of around 15% at 100 TeV based on an analysis strategy exploiting boosted decision trees (BDTs) to separate signal and background and distinguish possible polarisation states. This is more conservative than the CDR projections for this process of 3% for $30\,\mathrm{ab}^{-1}$ at 100 TeV [2]. Further studies of this important process, particularly in view of the progress done by the LHC experiments in preparing for its study with HL-LHC, are clearly necessary.

Additional studies, presented during the working group meetings, are briefly documented in the FCC BSM submission [11]: the search for heavy neutral leptons [59], the search for ALPs in γγ collisions [60], the search for heavy vector SU(2) singlets [61]. Others are in progress or in an early stage: searches for ttHZ final states [62], DM searches in mono-X and VBF production [63], resonant di-Boson searches ($\mathrm{X} \to \mathrm{hh}, \mathrm{ZZ}$), and $\tau\tau$ production via non-resonant t-channel LQ exchange. Overall it is clear that only a fraction of the full measurement and discovery potential of FCC-hh has been explored. We trust that the discussions at the forthcoming ESPPU will stimulate further progress.

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