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A framework and goals for FCC-hh physics studies at Snowmass 2021

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Abstract

We summarize the key results obtained by physics studies carried out for the FCC-hh Conceptual Design Report, documenting the existing tools and software framework that were developed. Indications are provided for further work, on physics performance and simulation software development, which could be a target for Snowmass 2021 studies of a pp collider at 100 TeV. The primary goal of this note is to inform about, and document, the existing resources, to encourage coordination and collaboration building on the work already done.

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Contents

1 Introduction

A large body of work has been carried out, over the last several years, to explore the physics potential of a 100 TeV pp collider. Many of these studies appeared as stand-alone papers, mostly of phenomenological nature. Several others have been done directly in the context of the studies for the FCC Conceptual Design Report, released at the end of 2018 [1–4]. For these, dedicated event generation and simulation tools have been developed, providing a more realistic assessment of the physics potential for a few specific observables that, while providing compelling evidence of the exceptional reach of the collider, helped characterizing the key detector requirement, and defining a prototype detector concept. The goal of this note is to summarize the results of this work, collecting the relevant references, and to illustrate and document the existing event-generation and simulation frameworks. We believe that the existing tools can be used as a starting point for further work to be carried out during the Snowmass 2021 studies, avoiding duplication of efforts, and encourage those interested in using and enhancing these tools to join the present development efforts, rather than starting from scratch.

In the first part of this note we review some of the physics studies done using the current simulation of the FCC-hh prototype detector. In the second part we discuss the event generation and simulation frameworks, providing links to the relevant documents, datasets and tutorials. The names of contact people for different topics are provided, in the format firstname.lastname, which can be completed into a e-mail address by adding the @cern.ch domain.

2 The physics studies

The FCC-hh physics studies are documented in the first Volume of the FCC CDR [1] and in an earlier CERN Yellow Report [5–8]. We do not review here all the material, nor the many other studies that appeared as independent papers, most of which are listed in the documents above. We rather focus on the studies singled out for a more thorough detector simulation during the FCC-hh CDR preparation.

2.1 Higgs properties

The precise measurement of Higgs properties is the key guaranteed deliverable of the FCC-hh, and has been the main target of the physics performance assessment[4]. The studies so far, detailed in Ref. [9], focused on the measurement of the Higgs couplings whose precision will be statistics-limited at FCC-ee, or at any other proposed ee collider. This covers the measurement of $\mathrm{H}\to\gamma\gamma$, $\mathrm{H}\to\mu^+\mu^-$, $\mathrm{H}\to\mathrm{Z}\gamma$, $\mathrm{t\bar{t}H}$

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and the ancillary measurement of $\mathrm{H} \to \mathrm{ZZ}^*$, which allows to absolutely normalize all other couplings to the precise BR($\mathrm{H} \to \mathrm{ZZ}^*$) measured at FCC-ee. For all these cases, a precision of 1% or better is obtained for the ratio of couplings relative to g_{HZZ}. The main limitation to the precision, which statistically could well exceed the percent level, is systematics. Luminosity and production modeling systematics can be minimized by considering ratios of branching ratios or production rates (e.g. BR($\mathrm{H} \to \gamma\gamma$)/BR($\mathrm{H} \to \mathrm{ZZ}^*$) or $\sigma(\mathrm{t\bar{t}H})/\sigma(\mathrm{t\bar{t}Z})$). Experimentally, the key systematics are the identification efficiencies for the different final states. The FCC-hh baseline detector, parametrized in DELPHES [10], was assumed for these studies, and experimental systematic uncertainties have been taken of the same order as the projected performance of the ATLAS and CMS Phase-2 upgraded detectors [11]. Selecting Higgs bosons produced at large transverse momentum, $p_{\mathrm{T}}(H)$, allows to minimize the combined statistical+systematic uncertainty by typically choosing $p_{\mathrm{T}}(H)$ in the range $100\,\mathrm{GeV} \lesssim p_{\mathrm{T}}(H) \lesssim 200\,\mathrm{GeV}$, and fixing common $(p_{\mathrm{T}}(H), y^H)$ fiducial regions for all final states. This choice also maximises the robustness of the results with respect to assumptions on the FCC-hh environment (e.g. pile-up mitigation, triggering capabilities). Furthermore, the studies in Ref. [9] demonstrated the sensitivity to invisible Higgs decays at the level of few$\times 10^{-4}$, well below the SM rate of BR($\mathrm{H} \to 4\nu$) $\sim 2 \times 10^{-3}$, and confirmed the suitability of the forward components of the prototype detector to carry out precise vector boson fusion and scattering measurements.

In the case of the Higgs self-coupling, the studies in Ref. [9] using the $\mathrm{b\bar{b}}\gamma\gamma$ channel alone, as reported in Ref. [1], reached a precision in the range of 5-7% , interpreting the measurement of the pp→HH production rate in the context of the SM. A follow-up study [12], combining the sensitivity of $\mathrm{b\bar{b}}\gamma\gamma$, $\mathrm{b\bar{b}}\tau\tau$ and $\mathrm{b\bar{b}b\bar{b}}$ decay modes with a multi-variate analysis of final-state kinematic variables, improved the expected precision, dominated by systematics, to the level of 2.9–5.5%, depending on the systematics assumptions.

All these studies allowed to define the detector performance targets in areas ranging from rapidity coverage, to b-tagging efficiency and EM energy resolution, as discussed in greater detail in Refs. [13, 14].

A lot of work remains to be done and could be useful material for the Snowmass 2021 studies. For example: studying the precision reach for Higgs couplings expected to be well measured in ee, like $\mathrm{H} \to \tau\tau$, $\mathrm{H} \to \mathrm{WW}^*$, $\mathrm{H} \to \mathrm{b\bar{b}}$ or $\mathrm{H} \to \mathrm{c\bar{c}}$. While the precision of these BR measurements at FCC-hh is highly unlikely to exceed that achievable at FCC-ee, the observables at FCC-hh could provide additional and complementary information, should FCC-ee detect deviations from the SM. For example, probing the HWW coupling at high Q^2 in pp→HW at large mass or in vector-boson fusion (VBF) is complementary to measuring BR($\mathrm{H} \to \mathrm{WW}^*$). For these, the use of Higgs bosons produced at large p_T, as done in the study or the rarer decays, could help reducing the measurement systematics. In parallel, one could revisit the rare decays by removing the high-p_T constraints, increasing the statistics and trying to address the systematics limitations by other means (for example, the uncertainty on the ratio BR($\mathrm{H} \to \gamma\gamma$)/BR($\mathrm{H} \to 4\ell$) could statistically drop well below 10^{-3}).

A remarkable observation from the early studies of Ref. [7] indicated that the hierarchy between the various Higgs production mechanisms evolves significantly at large $p_{\mathrm{T}}(H)$. This could open new opportunities for measurements of Higgs couplings at large Q^2, with an impact on the extraction of EFT constraints, via correlations among different processes and kinematical regimes.

Last but not least, useful work can be done by exploring new opportunities to reduce the systematics by data-driven techniques. For example, the precision of ratios of Higgs BRs can be improved by increasing the correlation between the identification efficiencies of different objects (e, μ, γ, ...). For example, correlations between the efficiencies of e and μ (and possibly also γ and τ) can be obtained by comparing $\mathrm{Z} \to \ell^+\ell^-$ and $\mathrm{Z} \to \ell^+\ell^-\gamma$ decays for different leptons, benefiting also from the huge rates available even at large p_{T} (Z). On the simulation side, a more rigorous handling of the pile-up environment, beyond the current parameterization in terms of detection (in)efficiencies, would be highly desirable.

2.2 BSM studies

In addition to the Higgs studies, a handful of representative BSM topics have been selected to test the detector concepts and refine the design and performance targets. These studies represent only a tiny fraction of all work done independently to explore BSM processes at 100 TeV, as documented e.g. in Refs. [5, 8], but help validating the performance assumptions used by the more phenomenological analyses.

The reach for high-mass resonances produced in the s-channel, by naive extrapolation from the LHC results at 13 TeV, would extend to several tens of TeV. To fulfill the naive energy-scaling sets however challenging demands on energy and momentum resolution for jets and leptons in this multi-TeV region. The studies[5] in Ref. [15, 16] helped define the depth, granularity and resolution of the hadronic calorimeter[6], and the muon momentum resolution. In turn, these set the transverse radius of the prototype FCC-hh detector, and showed that the desired performance can be obtained with an overall size comparable with that of the ATLAS detector [13, 14].

The search for multi-TeV stop squarks, decaying to a top quark and an invisible neutralino[7], challenges the detector ability to reconstruct the internal substructure of multi-TeV hadronic jets, providing further requirements on the calorimeter granularity. The mass reach for stops undergoing these decays reaches 10 TeV [18], again compatible with a naive energy scaling from the LHC.

Weakly interacting massive particles (WIMP) in the TeV mass region are DM candidates at the upper limit of the mass domain allowed by primordial thermal production. The typical close mass degeneracy between charged and neutral states leads to disappearing track signatures. The signals are short tracks of the charged SU(2) partner of the DM candidate, traversing the tracker for few cm, and then decaying to the stable neutral DM particle plus a soft, typically non-reconstructed, track (lepton or pion). The study in Refs. [19, 20][8] analyzed these final states with several pixel tracker layouts, including a simulation of up to 500 pile-up events. A tracker configuration compatible with the prototype detector was found, allowing to extend the mass reach beyond the upper limit imposed by the DM constraints on these WIMP candidates.

Flavour-changing neutral couplings of the top quark have been studied in single-top t-channel production processes such as qg→tg (q=u,c) [21][9]. The projected constraints, obtained from the simulation of signal and backgrounds using the prototype FCC-hh detector, can be expressed in terms of branching ratios for the decays t→qg, resulting in limits of order 10^{-9}.

3 The software infrastructure

From the very beginning, the FCC software (FCCSW) has been designed to support all types of colliders, and as of today the core components of FCCSW have not changed [10]. They have even been upgraded as main components of the KEY4HEP[11] effort [22–24] namely the Event Data Model (EDM) and the underlying framework engine K4FWCORE based on GAUDI [25]. For the physics studies summarized in the previous sections, dedicated common modules were used and are described below. Given the limited time to deliver the CDR, the physics results were obtained mostly with a DELPHES [10] parameterised detector simulation, but dedicated detector studies have been carried out by means of GEANT4 [26] full simulation to help inform the parameterisation. For example, the FCC-hh calorimeter system has been extensively studied in full simulation and documented in Ref. [14]. In this context it was possible to

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[6] For independent, thorough studies of hadron-calorimeter design optimization at 100 TeV, see Ref. [17]

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[11] KEY4HEP aims at providing turn-key software solutions for high energy physics experiments, such as underlying processing framework, reconstruction algorithm, etc.

study in full simulation the effect of pileup on photon reconstruction and thus on the Higgs boson mass resolution. While simple techniques were used to mitigate the 1000 pileup events, it was found that the mass degradation was compatible with the requirements and thus it does not significantly impact the Higgs self-coupling determination in the $b\bar{b}\gamma\gamma$ channel.

In terms of resources, the public instance of EOS at CERN is used as a storage element together with the HTCONDOR CERN batch system. Finally, a detailed documentation of FCCSW can be obtained from the main web-page [27].

3.1 Event generation chain

Monte Carlo (MC) event samples for signals and backgrounds have been used to simulate the hard scattering, parton shower, hadronization and detector response [12]. Hard scattering events were produced either in the form of Les Houches Events (LHE) (via POWHEG [28–30] or MADGRAPH5_aMC@NLO [31]) or directly with PYTHIA8 [32]. Shower evolution and hadronization were performed with PYTHIA8. The FCC-hh detector response was simulated with DELPHES [10]. In the latest stages of the MC generation, PYTHIA8 [32] and DELPHES have been interfaced directly to the FCCSW, allowing to produce final stage events in the FCC EDM format. All the generated signal and background events can be found in a database, which represents a total of 3.3 billions events in the LHE format [33] and 2.1 billions events in the FCC EDM format [34, 35]. The infrastructure that allows to produce LHE (either directly or from gridpacks) and reconstructed events in the FCC-EDM format is called EVENTPRODUCER and be obtained via Ref. [36].

3.2 Simulation of the detector response

The detector response has been simulated via the DELPHES software package [10], with the configuration card for the FCC-hh baseline detector available at Ref. [37] [13]. A description of the FCC-hh detector can be found in Refs. [3, 14, 38]. A detailed description of the FCC-hh detector parametrization in DELPHES is available in Ref. [39]. We stress that the overall contribution of pile-up has been neglected in the parametrised simulation. Although DELPHES allows for such possibility, including pile-up interactions would have resulted in an overly conservative object reconstruction performance since the current DELPHES FCC-hh setup does not possess well-calibrated pile-up rejection tools that allow to recover the nominal detector performance. Moreover for high-mass resonance searches, pile-up is expected to have a negligible relative impact on multi-TeV objects.

3.3 Analysis framework

The analysis framework used is based on HEPPY [40], developed in the context of CMS, but adapted to the FCC workflow [14]. HEPPY processes FCC-EDM events to produce custom analysis-dependent flat ROOT n-tuples. A full list of FCC-hh HEPPY physics analysis can be found in Ref. [41]. A lightweight python code called FLATTREEANALYZER [42] is then used to produce ROOT histograms and plots, that could then be used for final user specific analysis (limit setting, ...).

3.4 How to get started

Interested users [15] can get started simply cloning the relevant GITHUB repositories [36, 40–42]. Developers are requested to fork the repository, then proceed with developments and submit pull requests.

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In order to use the resources at CERN for computing and accessing the data on EOS, interested users are also requested to register to the following e-groups:

- **fcc-eos-read-hh-sm21**: allows to access physics events (controls read access to eos for FCC-hh)
- **fcc-eos-write-hh-sm21**: allows to access physics events, and to produce new events (controls read and write access to eos for FCC-hh)
- **fcc-experiments-comp-sm21**: allows to produce new events at CERN (controls the access to computing resources, including HTCONDOR)

3.5 Ongoing work

All the existing FCC-hh physics analyses can be easily reproduced and the existing infrastructure described above can be used to perform new analyses [16]. Recently, however, the HEPPY + FLATTREEANALYZER steps have been replaced by a more efficient custom RDATAFRAME-based framework. This transition was motivated by the need to significantly increase the processing speed [43]. It is foreseeable that the future physics analyses will be developed within this new approach, and we welcome future developments in this direction [17].

We also mention ongoing work towards the development of an FCC-hh DELPHES configuration card that includes pile-up simulation, together with time-of-flight propagation, 4-dimensional vertexing, and dE/dx simulation. These developments will allow for a more realistic simulation of the FCC-hh environment and open up the possibility of studying more exotic signatures (e.g. long-lived particles) at the FCC-hh as well as in other detector setups [18].

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