FUTURE
CIRCULAR
COLLIDER

Mid-Term Review Report

PED Deliverables

C. Grojean, P. Janot and M. Mangano (Editors)

Abstract

Extract from Ref. [1]: Consolidation of the physics case and detector concepts for both colliders. In the area of physics, experiments, and detectors, covered by the Physics, Experiments and Detectors work package, activities will continue on consolidating the physics case for the integrated FCC programme and the corresponding requirements on theoretical calculations and Monte Carlo generators. The FCC-hh detector concepts will be revisited in light of the evolution of the physics landscape and the experience gained with the High-Luminosity LHC detector upgrades, whilst for FCC-ee several detector concepts are being considered and benchmarked to meet the requirements of ultra-precise Higgs boson and electroweak measurements. The cost drivers for construction and operation will be evaluated and requirements on accelerator performance, technical infrastructure, integration and civil engineering will be formulated. Detector design and R&D will proceed in collaboration with the R&D for future detectors initiative at CERN, and with the activities that will emerge from the Detector Roadmap being developed under the auspices of ECFA.

1 Physics case

Documentation of the specificity and complementarity of the FCC-ee and FCC-hh physics cases, in particular for the Standard Model Higgs boson characterisation.

Editors: M. McCullough (chair), F. Simon, A. Blondel + main editors

The update of the physics case for FCC is a core deliverable for the mid-term report. This will document completed end-to-end FCC-ee studies (from theory to detector response simulation), and a roadmap to further work left for the final report. Topics covered include:

- The characterization of the Higgs boson, which goes hand-in-hand with the exploration of the electroweak sector. We shall present the standalone potential of FCC-ee, through its role as a Higgs factory and as a uniquely powerful EW facility based on its Tera-Z, WW and top-threshold runs.
- The specificity of FCC-ee [2, 3] (and of its combination with FCC-hh) for Higgs characterization, regarding physics performance and carbon footprint per physics outcome [4]. Comparison with other Higgs factories. In particular, explain design choice favouring transverse over longitudinal beam polarization.
- A clear articulation of the discovery landscape at FCC-ee, covering the exploration of dark portals, the neutrino sectors, exotic long-lived states and more.
- The significant advancement of our understanding of the Standard Model at FCC-ee, from precision Quantum Chromodynamics to a new frontier of flavour physics, specifically cataloguing sensitivities for bottom quark and tau lepton physics.

In addition, complementarities on these physics fronts with the longer-term next steps will be presented, covering

- The role of FCC-hh in extending FCC-ee's precision characterization of the Higgs boson to rare decays, to the study of its self-coupling and to probing its inner structure and EW interactions at scales above the TeV.
- The potential of FCC-hh to pinpoint the microscopic origin of potential SM deviations observed at FCC-ee.
- The FCC-hh role in the search for and study of dark sectors and dark matter particles
- The precision and discovery reach of FCC-hh in comparison with other high-energy lepton machines

2 Theoretical calculations

Strategic plan for improved calculations needed to reduce theoretical uncertainties towards matching the FCC-ee expected statistical precision on the most important measurements.

Editors: A. Freitas (chair), J. Gluza, G. Isidori, S. Jadach, P. Monni, A. Blondel + main editors

FCC-ee: The full exploitation of the significantly increased experimental precision in Z-pole observables, W boson and top quark masses, b and τ decays, and a broad array of Higgs observables, necessitates SM predictions accurate at a level commensurate with this precision (most notably: inclusive and exclusive processes, matching with MC generators). This perfect matching in precision may already lead to discoveries (anomalies). In addition detailed precision analysis of BSM effects within concrete models and effective theories will open widely new options on the way to discoveries.

On top of that, FCC-hh will have unique capabilities for testing SM phenomena at ultra-high energies, in particular the mechanism of electroweak symmetry breaking, and broad coverage for direct particle discovery. Theory calculations are needed for the evaluation of (often large) backgrounds, expected signal rate, and optimization of experimental search strategies.

2.1 List of relevant observables

- For FCC-ee: Z-pole (LEP electroweak pseudo-observables), WW threshold and continuum, Higgs production and decays, top-antitop, Bhaba and $\gamma\gamma$ for luminosity measurements, b and τ decays (mainly leptonic and semileptonic modes, with focus on precise-SM tests, such as lepton universality, CKM unitarity, etc...)
- For FCC-ee: jet processes to understand q/g jets, non-perturbative corrections, heavy-quarks fragmentation. Important for Higgs, WW, top measurements (jet tagging, kinematic distributions, signal and background theoretical control)
- For FCC-hh: Identify similar list of important SM measurements.
- Proposed format of deliverable: Tables of (pseudo-)observables, with estimate of experimental (statistical) target precision for each entry; accompanying text with brief explanations for theory inputs that are needed for the "measurement" of these quantities. [3-5 pages]
- A special attention will also be paid on identifying (and calculating with high precision) high-p_T observables to be accessed at HL-LHC for a later combination with pole measurements at FCC-ee in a global fit analysis.

2.2 Current theoretical uncertainties

- Discussion of methods for assessing theory uncertainties (include also discussion about bayesian approaches).
- Theory work needed for extraction of relevant quantities from real data (background predictions, suitable expansions, QED/QCD effects, Monte-Carlo simulations, ...) [5, 6]:

  Summary of available calculations and tools and evaluation of numerical uncertainties for relevant observables (fairly comprehensive list for FCC-ee, few preliminary examples for FCC-hh).
- For FCC-ee: Theoretical calculations needed for SM parameter extraction, e.g. W mass from WW threshold, α_s from Z BRs, $\Delta\alpha$ from $A_{FB}^{\mu\mu}$, ... [7].
- For FCC-ee: SM predictions for Z/W/Higgs precision pseudo-observables (to search for possible evidence of BSM physics by comparing experimental results to these predictions):

  Summary of available calculations and evaluation of uncertainties; identification of most important improvements [7].
- For FCC-ee: SM predictions for the key observables in b and τ decays, status of MC tools relevant to these measurmenents (focus on QED corrections); expected improvement form running/planned experiments (LHC & Belle-II) and potential role of FCC-ee.
- For FCC-ee: Theoretical QCD calculations, see also [8] and the material of FCC-ee CERN workshop for reference:
  - Higher order calculations: fixed order and resummed perturbation theory for multi-jet final states and heavy quark production, resonance EFT effects. Non-perturbative corrections: prospects for current techniques and bottlenecks for the future
  - Monte Carlo generators: NNLL parton showers and interleaved QCD/QED evolution, subleading colour corrections; consistent inclusion of higher order corrections to hard scattering; prospects for reduction of non-perturbative (tuning) uncertainties with more accurate MCs
  - Jet physics: study or performance of jet algorithms ($S/\sqrt{B}$ vs. "calculability"); jet flavour definition for FCC-ee (Higgs, top); calculation and extraction of fragmentation functions
- TBD (1): Brief discussion of needed calculations for BSM effects (for limit setting or discovery), e.g. using effective operators (?)
- TBD (2): Brief illustration of the discovery power of selected observables (especially via combinations, e.g. EW & flavor) using concrete benchmark models.
- Proposed format: 5-10 pages text, tables with list of relevant quantities and uncertainty estimates + projections, several pages of references]

2.3 Plans to improve: Computations needed, Techniques improvements, Manpower over the next 20 years.

- Summary of theory work that will definitely be needed for different categories of observables at FCC-ee and FCC-hh (fixed-order loop calculations, resummation of soft and threshold effects, improved Monte-Carlo generators, integrated EW/QED/QCD parton showers and parton distribution functions, theoretical tools for W/Z/Higgs/top jets, ...).
- Discussion of promising technical improvements: New ideas for more efficient numerical and semi-numerical methods are already being developed and will be very useful for the FCC-ee (and partially also FCC-hh) theory program (numerical amplitude construction and reduction, Quasi-Monte-Carlo integration, series solutions of differential equations, analytic techniques with new special functions).
- Implementation plan: Series of focused workshops (similar to LHC Les Houches workshops); establish wishlists and advertise broadly at other meetings; seek commitment from funding agencies to support FCC theory calculations; call for N (tbd) dedicated positions funded by CERN (only a fraction of the estimated global effort, but will serve as a catalyst for the latter).
- Proposed format: few pages text, additional entries in tables mentioned in Section 2.2, references

3 FCC-ee Detector requirements

First documentation of the main detector requirements to fully exploit the FCC-ee physics opportunities, in particular to reduce experimental uncertainties towards matching the expected statistical precision on the most important measurements.

Editors: P. Azzi (chair), M. Dam, E. Perez, F. Simon + main editors

- Evaluate the requirements for FCC-ee experiments using key physics processes that drive the physics case as benchmarks. A complete analysis of specific processes chosen for their impact on detector requirements (case studies) will be performed on the course of the feasibility study, using fast or fully simulated data, to extract the needed performances that satisfy the ultimate desired uncertainty on the measurement.
- Particular emphasis on the identification of the main systematic uncertainties, and on strategies to reduce systematic uncertainties to meet the expected statistical precision.
- Development and evaluation of experiment concepts, with both general-purpose concepts and concepts primarily targeting specific physics cases, such as flavour.

References

[1] *Main deliverables and timeline of the FCC feasibility study. Video-meeting: Restricted and Open Council - Two-Hundred-and-Third Session*,. http://cds.cern.ch/record/2774007.

[2] C. Grojean, *FCC-ee: physics motivations*, *Eur. Phys. J. Plus* **137** no. 1, (2022) 116.

[3] A. Blondel and P. Janot, *Circular and Linear* e^+e^- *Colliders: Another Story of Complementarity*, `arXiv:1912.11871 [hep-ex]`.

[4] P. Janot and A. Blondel, *The carbon footprint of proposed* e^+e^- *Higgs factories*, in *2022 Snowmass Summer Study*. 8, 2022. `arXiv:2208.10466 [hep-ph]`.

[5] S. Jadach, W. Płaczek, M. Skrzypek, B. F. L. Ward, and S. A. Yost, *The path to 0.01% theoretical luminosity precision for the FCC-ee*, *Phys. Lett. B* **790** (2019) 314–321, `arXiv:1812.01004 [hep-ph]`.

[6] S. Jadach and M. Skrzypek, *QED challenges at FCC-ee precision measurements*, *Eur. Phys. J. C* **79** no. 9, (2019) 756, `arXiv:1903.09895 [hep-ph]`.

[7] A. Freitas *et al.*, *Theoretical uncertainties for electroweak and Higgs-boson precision measurements at FCC-ee*, `arXiv:1906.05379 [hep-ph]`.

[8] P. F. Monni and G. Zanderighi, *QCD at the FCC-ee*, *Eur. Phys. J. Plus* **136** no. 11, (2021) 1162.