Fostering Swiss collaboration towards a future circular collider via CHEF

Swiss Institute of Particle Physics (CHIPP)

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Abstract

The 2020 European particle physics strategy update concluded that 'an electron-positron Higgs factory is the highest-priority next collider of the particle physics community. In the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. These projects require long-term engagement from the international community to develop options for the detector technology of the collider experiments and their potential to address the important physics questions that remain yet unanswered. Swiss particle physicists have started organising themselves towards participation in these long-term activities around a structure called 'CHEF' (CH Experimental research at the FCC). The term "Experimental" includes detector as well as theoretical research geared towards the realization of such a project. This document aims at collecting the interests of the Swiss community for participating in concrete projects and collaborative activities to establish a strong program of work packages that will help realize the priorities of the particle physics community.

Contents

1 Introduction

The 2020 European particle physics strategy update [CER20] concluded that 'an electron-positron Higgs factory is the highest-priority next collider of the particle physics community. In the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. The 2021 CHIPP Roadmap [CHI] lists as its major findings the strong support for a staged collider approach of FCC-ee followed by FCC-hh, stating "CHIPP recommends the development of a national strategy towards the participation in CERN's program for an FCC, starting with FCC-ee, which encompasses detector development, theoretical research, and data analysis and simulation." CHIPP proposed "CHEF" in 2022, to provide a national (CH) structure for longer-term engagements in experiments (E) and theoretical foundations for the FCC (F). CHEF establishes a platform to take advantage of synergies in detector, theory, and other developments by Swiss institutions and to promote applications in other fields. It serves as a center to enable a coherent strategy for defining the physics goals and deriving instrumentation requirements. It acts as a collaborative link to CERN, ECFA, and efforts in other countries, and as a communication channel to the public.

CHEF activities are a direct continuation of the very successful theoretical and experimental achievements of the Swiss community for the LHC and HL-LHC projects. CHEF will maintain the strong international visibility of Switzerland in innovative detector research, commensurate with the status of Switzerland as a host country. These activities rely on long-term institutional experience and reputation. The Swiss groups have demonstrated the ability to apply innovative concepts to collider experiments, from initial ideas to developing the theoretical and experimental tools, and finally to successfully build, install and commission the systems. Some examples include the silicon and vertexing detectors of ATLAS, CMS, and LHCb, the CMS electromagnetic calorimeter, the ATLAS trigger system, and precise calculations of Higgs processes and theoretical models of quark and lepton flavours. These achievements have placed Switzerland in a leading position, and would not have been possible without strong institutional support over the decades. The experimental, as well as theoretical tools, required to advance science are not available commercially and need to be developed, pushing the boundary of current capabilities. For the FCC detectors, the final design will be chosen based on the technological viability of such developments in order to reach the physics goals. The experience, reputation, and capability of the groups involved in the developments are also crucial. Switzerland is in a prime position to play a leading role by matching the capabilities of its scientists with the needs of the FCC. Past and current collaboration between Swiss institutes towards the LHC and the organization of the Swiss particle physics community in CHIPP has shown that a bottom-up coherent strategy can be achieved in Switzerland. A good balance between topics of common focus (e.g., silicon timing and tracking detectors) and breadth of activities exist. CHEF gives the framework for an organization toward the successful realization of the FCC, with a good balance between topics of common focus (e.g., silicon timing and tracking detectors), as well as activities covering the wide breadth of Swiss interests.

The projects collected in this document provide a concrete foundation for Swiss interests in the FCC that can be organized in CHEF. They are not intended to be direct funding requests, but lay out in a bottom-up approach the interest and plans of the PIs in Switzerland related to FCC detector developments and physics potential. The PIs of these activities have a genuine interest and willingness to pursue the proposed projects. They are based on existing experience and are aligned with topics outlined in the CHIPP roadmap related to detector and theoretical developments.

The timeline of the projects is around the years 2025 to 2028, although the ramping up of activities starting immediately is not excluded.

The FCC planning in brief. The FCC aims at pushing both the energy and intensity frontiers of particle colliders. A series of conceptual design reports[MAB+19, BBB+19, BCGC+19, ZBCG+19] were produced in 2020 in order to provide input to the European Strategy Upgrade. FCC-ee, and electron-positron collider, would be the first part of the FCC project, which is expected to evolve to FCC-hh, a hadron collider, and possibly FCC-eh, a collider of electrons and hadrons. A possible approximate timeline of the project follows (table 1). In preparation for the feasibility study report, a mid-term review is expected to take place in the second half of 2023. The technical, scientific, and financial feasibility studies are due in 2025/2026. The EU strategy update is expected to take place in 2027. The FCC-ee project could be approved by 2028; the tunnel constructed in early 2030s, the machine installed starting 2038 and the first $e^+ - e^-$ collisions could be envisaged from 2045 or soon after. The following table 2 summarises the envisaged runs of the FCC program.

Milestone	When
(LHC upgrade design and development complete)	2022
(LHC upgrade integration and installation)	2022–2027
Mid-term FCC review	second half 2023
FCC Technical, scientific, financial feasibility study	2025/2026
EU strategy update	2027
Potential approval of FCC-ee project	2028
FCC Tunnel construction	> 2030
FCC Machine installation	> 2038
First e^+e^- collisions in FCC-ee	> 2045

Table 1: Rough timeline of the FCC(-ee) project

Machine	Collisions	CME	L (ab^{-1})	N$_{events}$
FCC-ee	$e^+ - e^-$	90 GeV ($Z-$pole)	150	5×10^{12} Z
		160 GeV (WW)	10	5×10^{8} WW
		240 GeV (HZ)	5	5×10^{6} HZ
		365 GeV ($t\bar{t}$)	1.5	5×10^{6} $t\bar{t}$
FCC-hh	$p - p$	100 TeV	30	2×10^{10} H
				3×10^{7} HH
FCC-eh	$e - p$	3.5 TeV		

Table 2: Operating phases of the FCC.

2 Experimental research and development

To benefit from the tremendous number of events, especially at the Z-pole, the systematic uncertainties must be controlled extensively, putting stringent requirements on the FCC-ee detectors. CHEF activities are a direct continuation of the very successful theoretical and detector developments achieved for the LHC and HL-LHC and take the opportunity to maintain the strong international visibility of the Swiss groups (and thus Switzerland) in innovative detector research commensurate with the status of Switzerland as a host country.

Over the last years the focus in Switzerland has been toward pixelated silicon trackers, novel monolithic, fast or diamond sensors, and online data transmission and processing.

2.1 Silicon detector R&D: sensors

FCC-ee detectors must precisely reconstruct the position of the particle interactions (vertices) and measure the trajectories of the outgoing particles (tracks). At the FCC-ee, this is taken care of by two distinct detectors: The innermost vertex detector and the surrounding tracker. Depleted monolithic active pixel sensors (DMAPS) are considered as a potential technology for use in both of these sub-detectors.

2.1.1 DMAPS for FCC-ee vertex detectors

A precise localisation of the vertices and the corresponding impact parameters is crucial e.g for efficient flavour tagging and τ-lepton lifetime measurements. A single-point resolution of $\leq 3\,\mu$m and high hit detection efficiency are needed for the vertex detector sensors to exploit the full potential of the FCC-ee [BBB+19]. At the same time the vertex detector should be as light as possible in order to limit multiple scattering and enable a good momentum resolution of the tracker directly outside the vertex detector. To reach the considered target material budget of $\sim 0.3\%$ per detection layer [BBB+19], the power consumption of the sensors should be below $20\,\mathrm{mW/cm^2}$ so that the vertex detector can be air-cooled [BCR22].

The DMAPS detectors for the proposed ALICE ITS3 upgrade [Mus19] have similar performance requirements as the FCC-ee vertex detector. ITS3 foresees DMAPS produced in a modified 65 nm CMOS, TPSCo process [TPS].The usage of 12-inch wafers in this technology would allow us to strive for wafer-scale DMAPS that are thinned to 20-40 μm, and could be bent to form half-barrel layers, minimising material budget. This development is being pursued by a collaboration of ALICE, CERN EP R&D WP 1.2 and other partners.

A collaboration between Universität Zürich and Vrije Universiteit Brussels is investigating the usage of ALICE ITS3-like DMAPS for usage in the FCC-ee in the context of an SNSF project funded through the Weave funding scheme (project number 197195).

List of projects: ALICE ITS3 is as stepping stone for the development of DMAPS and stitching technologies for usage in the FCC-ee vertex detectors. To investigate the usage of chips produced in the 65 nm CMOS TPSCo process for FCC-ee, the following items need to be addressed:

- Characterisation of test chips produced in the 65 nm CMOS TPSCo process in lab and beam tests in terms of single-point resolution and hit efficiency. Comparison of different pixel pitches.
- Sensor TCAD simulations and comparison with characterisation results.
- Optimisation of sensor design to match FCC-ee requirements: minimisation of power consumption and better single-point resolution.
- Design and characterisation of wafer-scale DMAPS for FCC-ee with full digital functionality.
- Development and characterization of an analog frontend (charge amplifier and threshold discriminator) optimized for low power consumption and low noise.
- Development and characterization of a data readout architecture and essential IP blocks (e.g. PLL, serializer, voltage reference).

Interested Swiss institutes: Universität Zürich, ETH Zürich, PSI, Universitat Bern, Université de Genève

Connection to other WPs: The measured performance of these DMAPS chips and their actual material budget can be used as input to flavour-tagging studies (see Sec. 4.1.1). The mechanical design of a vertex detector using wafer-scale DMAPS is investigated in Sec.2.3). Incorporating timing measurements into these designs is considered in Sec. 2.2.1.

2.1.2 DMAPS for extreme radiation environment at FCC-hh

The FCC-hh aims to provide proton-proton collisions at $\sqrt{s} = 100\,\text{TeV}$ with 16 T superconducting magnets. With the expected integrated luminosities of $\sim 20\,\text{ab}^{-1}$ in each of the two foreseen experiments, there will be unprecedented fluences of $\mathcal{O}(10^{18})$ 1 MeV $\text{n}_{\text{eq}}/\text{cm}^2$ (for the innermost silicon layer) and pile-up conditions of about 1000 events per crossing. This represents a major challenge for silicon trackers, and new detectors that are extremely radiation-hard will need to be developed. Several R&Ds efforts focus around the usage of monolithic DMAPS in high radiation environments. For example, the group of the Université de Genève has developed various monolithic chips in 180 nm HV-CMOS technology (ams, TSI) for the ATLAS pixel upgrade at the HL-LHC. Other institutes and collaborations (*e.g.* CERN RD50) are currently investigating different technologies and detector configurations aiming to achieve highly efficient and highly radiation-tolerant devices.

List of projects:

- Characterization of new chip prototypes developed for high-radiation environments.
- Measurements of the chip response in the laboratory (radioactive sources, laser in TCT setup, etc), and in testbeams. Evaluation under different operating conditions (*e.g.* analogue front-end settings, temperature, etc).
- Comparison of performance before and after irradiation of high particle fluences. Annealing studies.

Interested Swiss institutes: Université de Genève

2.2 Silicon detector R&D: timing capability

2.2.1 Timing layer at large radius

Particle identification can greatly improve the reconstruction of heavy flavors, and time-of-flight measurements far away from the production point are an effective tool. A time-of-flight layer at large radius, about 2 m, inside the calorimeter, has been proposed for FCC-ee detectors. Precision timing in such a large system is challenging, and the technologies for signal distribution are being developed as part of the ongoing upgrade of the CMS experiment. Pixel detectors with precise timing are becoming feasible and would provide the added benefit of an additional precise tracking point at high radius. This could also improve momentum resolution and pattern recognition.

Timing resolutions of 50 ps or better are realistic targets, although there is room for improvement. Such resolutions would be sufficient for π/K separation up to momenta of several GeV.

One of the candidate technologies that should be evaluated for this application are hybrid detectors with LGAD sensors. Different approaches are being explored to achieve pixelated LGADs; two of them are AC-LGADs and TI-LGADs. In the TI-LGAD technology, each pixel is implemented by an individual LGAD and the isolation between pixels is obtained by etching trenches in the silicon. Pixel sizes down to 55 μm x 55 μm have been implemented and good timing resolution on the order of 30 ps has been achieved before irradiation [PBB+20, SBB+22]. In the AC-LGAD configuration, the gain layer is not segmented and spreads throughout the entire sensor. The read-out segmentation is obtained at the level of AC-coupled metal pads, which are capacitively coupled to the detector bulk via a dielectric spacer layer deposited between the silicon and the readout. The impact position is reconstructed by exploiting the charge sharing mechanism that occurs in these devices by design. The spatial resolution of an AC-LGAD has been measured to be a factor of 10 lower than the pitch of the readout pads [C+20]. This is very attractive since it allows the design of read-out ASICs with relatively large cell sizes that still attain good position resolution, and achieves good time resolution with reduced power dissipation in comparison to pixels with higher segmentation. A possible alternative path to a Time-of-Flight detector could be based on CMOS pixels where the timing performance is enhanced through a redesign of the collecting electrode and the shaping of the electric field to make the drift path within a pixel cell more uniform. With first prototypes in a 180 nm CMOS process, a time resolution of around 150 ps has been achieved [BBD+22], paving the way for further R&D towards monolithic sensors with good timing capabilities on more advanced CMOS nodes.

In addition to timing sensor R&D, it is important to pursue options for storing and digitizing the timing and position information of the sensors. Some preliminary work by Swiss groups has established potential designs for Time-to-digital converters (TDCs) [SCK+22] achieving timing resolutions of below 30 ps. Synergies with the DMAPS project listed above in Sec. 2.1.1 are evident.

List of projects:

- Develop the requirements in terms of material budget, segmentation, spatial and time resolution for such a layer.
- Evaluate prototype detectors with respect to those requirements and optimize the design for FCC-ee environment.
- Develop ASICs with TDCs, and iteratively move towards smaller technologies (110,65,28 nm).

Interested Swiss institutes: PSI, Universität Zürich, ETH Zürich

2.2.2 Ultra-fast MAPS in SiGe BiCMOS

Monolithic active pixel sensors (MAPS) can be integrated in SiGe BiCMOS to achieve time resolution of 25 ps or better without the need for the avalanche gain mechanism. The Université de Genèvepioneered this technology in 2015 and it is now a world leading institute for timing with MAPS [ea16][ea19][ICD+19][I+22]. This technology is now mature: a first large-area MAPS in 130nm SiGe BiCMOS is being developed for the upgrade of the pre-shower detector of the FASER experiment at the LHC [Boy22].
More recently, the development of a Picosecond Avalanche Detector (PicoAD) at the Université de Genève showed the potential for SiGe BiCMOS MAPS to achieve sub-20ps time resolution, with a three-year goal to prove sub-10ps capability [PMC+22][IZM+22].
Integrating small pixel size and state-of-the-art time resolution in the same device will greatly improve the tracking capability, pile-up suppression, and particle identification in future circular colliders. SiGe BiCMOS MAPS used as a 4D vertex locator would combine with the timing layers at large radius to improve the particle time-of-flight measurement.

List of projects

- Define architecture for a large-area prototype SiGe BiCMOS MAPS with picosecond time resolution.
- Further develop PicoAD technology to achieve sub-10ps time resolution.
- Define strategy to time-synchronize a vertex detector with picosecond time-stamping capability.
- Qualify SiGe BiCMOS technology for radiation hardness in FCC-ee and FCC-hh environment.
- Prototype SiGe BiCMOS MAPS with more advanced lithography nodes.

Interested Swiss institutes : Université de Genève

2.3 Silicon detector R&D: mechanics and other construction aspects

2.3.1 Construction of a gas cooled DMAPS vertex detector demonstrator

In order to achieve the required material budget below $\frac{x}{X_0} = 0.3\,\%$, the FCCee vertex detector needs to be constructed with a minimal "module" concept and nearly no mechanical support and cooling structures. The most minimal module concept based on bent wafers is described and investigated in Sec. 2.1.1. Possible alternatives should be studied, such as sensors connected to ultra-lightweight services based on aluminum flex technologies. The envisaged cooling system relies on a constant flow of cold gas through the vertex detector volume. For efficient cooling, a significant gas flow and careful selection of the gas is needed, because the gain in material budget can be significant for different gas types. For example the radiation length of Helium is 94.3 g/cm^2 [Tsa74], compared to a radiation length of only 37.9 g/cm^2 for nitrogen [Tsa74].

Recently, the $\mu 3e$-collaboration has successfully constructed and commissioned a detector cooling system based on Helium gas. A similar cooling system should be developed for evaluation of the sensor prototypes and module concepts in a realistic operation environment. The mechanical and electrical support of a "mini vertex detector" should be developed and integrated with the modules developed in Sec. 2.1.1.

List of projects:

- Study "bent wafer" layer concepts as well as layer concepts using aluminum flexes and minimal mechanical support structures. Compare the performance in terms of material budget and thermal resistivity to the cooling gas.
- Evaluate and identify viable cooling gases and the trade-off of their cooling performance verses radiation length.
- Develop a conceptual design of the cooling system and optimize the parameters using thermal simulations.
- Construct a cooling plant and a vertex detector volume. Equip the volume with electrical and mechanical support to test different DMAPS prototypes cooled with gas.
- Construct a "mini vertex" detector and operate it in the gas-cooled volume.

Interested Swiss institutes: ETH Zürich, Universitat Bern

Connection to other WPs: The cooling system serves as realistic test bench for sensor developments in Sec. 2.1.1. With a viable sensor prototype and module concept, a realistic section of vertex detector can be constructed together with the layout optimizations performed in Sec. 2.3. This allows for an realistic estimation of the material budget and performance of an FCCee vertex detector system that is based on a demonstrated system and can provide input for Sec. 3.

2.4 Diamond detector R&D

A high displacement-energy threshold and high electron and hole mobility make diamond an attractive candidate for particle detection in high radiation environments, such as those anticipated in the inner layers of the vertex detectors of FCC-hh. In addition, the low dielectric constant, high heat conductivity, and the large band gap allow diamond detectors to have low noise and low leakage currents while operating without the need for cooling, thus reducing the amount of inactive material and infrastructure costs. Polycrystalline (pCVD) diamond sesnors can now be produced in large sizes with sufficiently high and reproducible quality (charge collection distance >250 µm) that are adequate for large-scale applications.

2.4.1 Radiation hard 3D diamond detectors for FCC-hh

The use of 3D device architecture in diamond (originally proposed for silicon sensors [PKS97]) will make diamond sensors significantly more radiation hard. In the 3D architecture the charge collection electrodes are constructed inside the sensor bulk, therefore the distance between them is not limited by the sensor thickness, but can be determined by the projected mean free path (m.f.p.) in diamond for the anticipated maximum fluence at an FCC-hh detector. Another advantage of 3D sensors in diamond, in comparison to similar sensors in silicon, is an availability of a unique technique that allows for the creation of extremely thin electrodes. The technique utilizes a femtosecond laser that locally converts diamond to a conductive mixture of various carbon phases with a high proportion of graphite among them [SSB14]. The diameter of the electrodes in the current prototypes created with this technique is 2.6 µm. Such thin electrodes allow for a significant shrinking of the 3D cell, which, in addition to strengthening the radiation hardness of the sensor, also improves its resolution, an important parameter for vertex detectors.

The study of 3D diamond detectors is performed by several groups within the RD42 collaboration at CERN (the ETH Zürich IPA group among them). The collaboration has recently published the updated coefficients of the radiation hardness of diamonds for a large range of fluences and particle species. Using those coefficients one can estimate, for example, that for a fluence of $3\times10^{16}\,\mathrm{cm}^{-2}$ of 800 MeV protons, the charge carriers in diamond will have a mean free path on the order of 35 µm [BAA+19]. This distance is roughly equal to the distance between the electrodes in one of the 3D diamond sensor prototypes, a pixelated 3D sensor with a 50 µm×50 µm square cell. This device was recently tested by the ETH Zürich IPA group and has demonstrated >99% hit detection efficiency, while the 2D detector on the same diamond operating at the same bias voltage and pulse detection threshold had a hit detection efficiency of <50%.

List of projects:

- Study of the radiation hardness of 3D diamond sensors.
- Development of pixel detector with a 3D diamond sensor.

Interested Swiss institutes: ETH Zürich

2.5 Fast data processing (online and offline)

2.5.1 Real time event selection

The most challenging of the FCC-ee phases in terms of data acquisition requirements is the Z-pole run, which will collect 3×10^{12} events with an instantaneous luminosity of 2×10^{36} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The crossing rate will be 50 MHz. It is expected that the Z production will occur at 100 kHz rate. About 100 kHz more will correspond to other processes ($\gamma\gamma \to$ hadrons and Bhabha) as well as beam backgrounds. A total of $2 - 4 \times 10^9$ channels is expected to be read out by the detectors. The experiments will be working in the "big-data " regime. It will be essential that advanced data-acquisition and computing solutions are developed; the HL-LHC developments will constitute an important predecessor to what will be required for FCC-ee. These constitute (a) the use of heterogeneous computing combining CPUs with GPUs or/and FPGAs and (b) the development of advanced algorithms that involved machine learning, especially those in heterogeneous computing architectures. The relevant technologies are rapidly evolving in a market driven by industry.

List of projects:

- Develop heterogeneous computing demonstrators as predecessors to FCC-ee computing.
- Develop tools that make possible the use of state-of-the-art advanced algorithms including ML to GPUs and FPGAs.

Interested Swiss institutes: Université de Genève, Universität Zürich

2.5.2 Development of photonic integrated circuits for vertex detector control and data aggregation and transmission

In current high-energy physics experiments, optical links are widely used to transport control signals and data between on- and off-detector electronic devices. Such links are composed of custom-developed optical transceivers for the front-end and commercial off-the-shelf components for the off-detector end of the link. The front-end transceivers are separate components from the readout ASICs and increase the material and power budgets of the detector, which is detrimental for a light-weight detector design.

Photonic Integrated Circuits (PICs) provide a platform where all the components required for the establishment of an optical link are highly integrated. Compatibility of silicon PICs with the CMOS fabrication technology allows for co-integration of the photonics with electronics. Such opto-electonic technology could potentially be employed to develop low-material and low-power frontend readout for future experiments at FCC-ee. Moreover, the possibly of wavelength-division multiplexing in PICs allows for a high throughput bi-directional link over a single optical fiber for multiple detector modules. Silicon PICs have been shown to have a high radiation tolerance, hence the development of such technology for the FCC-ee would pave the way for the development of radiation-hard integrated circuits to be used at the FCC-hh.

List of projects:

- Development and characterization of optical part in PICs.
- Integration of the front-end readout electronics into PICs.

Interested Swiss institutes: PSI

3 Physics reach

The FCC-ee project will provide electron-positron collisions at previously unprecedented energies and with luminosities that are many times larger than at previous e^+e^- colliders. It will enable a broad physics program [A^+19] of precision studies and of searches for ultra-rare processes.

Besides its flagship objective of precision studies of the of the Higgs boson, it will enable to probe the dynamics of the electroweak and the strong (QCD) interactions at an unprecedented level of accuracy, and allow for precision studies and new physics searches in quark and lepton flavour physics.

The ambitious physics program of the FCC-ee relies crucially on a close interplay of theory and experiment, which is required to design and perform the precision measurements, which are then confronted with equally precise theory predictions to challenge the Standard Model and to uncover potential new physics effects. In the following, we discuss several of the key areas of the FCC-ee physics program and identify important preparatory works required to enable them.

3.1 Precision studies of the Higgs boson

The FCC-ee will be a Higgs factory, producing a large number of Higgs bosons (around 10^6, [A^+19]) in a very clean experimental environment, thereby allowing for precision studies of the Higgs boson in multiple decay modes. Owing to the fully reconstructed final state, non-standard and invisible Higgs boson decays will also become accessible.

Higgs bosons at FCC-ee are always produced in association with a Z boson (Higgsstrahlung process), such that the final states contain the decay products of both the Higgs and Z bosons. Leptonic Z boson decays offer the cleanest final state signatures, which are however at the expense of low branching ratios, compared to hadronic and invisible Z decays. Likewise, the dominant Higgs boson decay modes are all-hadronic, while the original LHC Higgs discovery modes to two photons or to four leptons actually correspond to relatively rare decays. To fully exploit the Higgs boson yield at FCC-ee, it will become crucial to assess the maximum of combinations of Z and Higgs boson decay modes.

3.1.1 Hadronic event shapes in Higgs production

Higgs bosons decay predominantly to pairs of b quarks, and also have substantial branching fractions to c quarks and to gluons. These all-hadronic decay modes are very difficult to assess at the LHC, and yield only coarse measurements. The FCC-ee is ideally suited to probe these Higgs boson decay modes, which will for example provide precision measurements of the Higgs boson Yukawa coupling structure to b and c quarks, thereby elucidating the flavour structure of the Higgs sector.

The Higgs boson decay into a pair of gluons offers the novel situation of a purely gluonic final states, with perfectly defined gluon jets composing a color singlet of exactly the mass of the Higgs boson. Given the high efficiency of b and c jet tagging, and the low branching ratio of the Higgs into light quarks, this offers an unprecedented laboratory for the study of gluon hadronization.

Hadronic event shapes have been used extensively at previous e^+e^- colliders to study strong interaction dynamics, especially in Z-boson decays at LEP. They could become important tools to disentangle different all-hadronic Higgs boson decay modes [CGDRP22], or may be further extended to study Higgs boson decays to vector boson pairs yielding all-hadronic or semi-leptonic Higgs boson final states.

To unleash the full physics potential of Higgs boson production at the FCC-ee, events with hadronic decays of the associated Z boson must also be included in Higgs precision studies. For these, progress on precision calculations for fully exclusive final states will need to combine with the development of new strategies for the experimental final-state classification and object identification.

List of projects:

- Precision calculations of hadronic event shapes in Higgs boson decays from ZH tagged events.
- Experimental feasibility studies of precision measurements of Higgs boson properties in semi-hadronic, all-hadronic, and two-gluon final states.

Interested Swiss institutes: ETH Zürich, Universität Zürich, PSI, Université de Genève

3.1.2 Higgs boson decays

SM Higgs bosons dominantly decay into bottom quarks, $H \to b\bar{b}$, and to a lesser extent to $\tau^+\tau^-$ and $c\bar{c}$ pairs. These decay modes are known with sub-percent precision from the theoretical side. However, the rare and loop-induced decay modes into gluon and photon pairs as well as the decay mode $H \to Z\gamma$ play a crucial role due to potential contributions of BSM particles to the decay widths at leading order. While the theoretical calculations for the gluonic and photonic decay widths are known at higher orders with residual uncertainties at the 1–3% level, the situation is different for the decay mode $H \to Z\gamma$ that reaches a branching ratio of a bit less than 2×10^{-3}. For this, the NLO electroweak corrections are unknown, while the full NLO QCD corrections are known to be small [SDZ92, BDDF+15, GGK15]. This is reflected by the estimate of the related theoretical uncertainty of about 5% for the inclusive observable [dF+16], i.e. of the expected size of the electroweak corrections. This decay mode, however, is not observable as such, since the Z boson will decay into fermion-antifermion pairs so that the decay mode $H \to Z\gamma$ is part of the full spectrum of Higgs Dalitz decays $H \to f\bar{f}\gamma$ [ABCDR97, AR06, AR05, DR13, CQZ13, Pas13, SCG13, KNN20, KNN22, VOTNP22] that contain significant contributions beyond the resonant Z-boson part. The Dalitz decays span the full range of photon-conversion decays $H \to \gamma^*\gamma \to f\bar{f}\gamma$ for small invariant $f\bar{f}$ masses, $H \to Z\gamma \to f\bar{f}\gamma$ for invariant $f\bar{f}$ masses around the Z-boson mass, and radiative fermionic Higgs decays $H \to f\bar{f}\gamma$ that are part of the electroweak corrections to $H \to f\bar{f}$. The Dalitz decays are only known at LO as well, while electroweak corrections to the relevant distributions are expected to be larger than 5% in general.

The rare SM Higgs boson decay mode $H \to Z\gamma$ has not yet been observed at the LHC. Its observation is expected in the future runs of the LHC as part of the Higgs Dalitz decays $H \to f\bar{f}\gamma$ [ABCDR97, AR06, AR05, DR13, CQZ13, Pas13, SCG13, KNN20, KNN22, VOTNP22]. Next to the direct Yukawa coupling the Dalitz decay mode is mediated by triangle and box W- and t/b-loops. It plays a crucial role in global analyses of the SM Higgs boson couplings, since it is sensitive to different combinations of potential anomalous couplings than the other observed decay and production modes of the Higgs boson, see e.g. Ref. [EMEMP13]. The analysis of novel Higgs boson couplings, however, requires an accurate knowledge of the SM prediction for the partial decay width, because the associated uncertainties limit the sensitivity to anomalous effects. The dominant uncertainties originate from unknown electroweak corrections and are estimated at the level of $5-10\%$. To reduce this uncertainty below the percent level, the determination of the full electroweak NLO corrections to the Higgs Dalitz decay $H \to f\bar{f}\gamma$, and thus to the resonant rare decay mode $H \to Z\gamma$, is mandatory. The accuracy will be crucial at future e^+e^- colliders. This requires the computation of two-loop, three- and four-point functions involving several mass scales. Since there is no systematic method to calculate them analytically with the present state of the art, it is necessary to perform a purely numerical integration of the related two-loop diagrams with a successful method that has already been applied to other processes such as $gg \to HH$ [BCG+19, BCG+20, BCG+21] and MSSM Higgs-boson production $gg \to A$ [BFL+22].

List of projects: The organization into individual projects can be organized as:

- NLO electroweak corrections to the Higgs-boson decay $H \to Z\gamma$.

- NLO electroweak corrections to the full Dalitz decays $H \to f\bar{f}\gamma$ with a proper matching to and merging with $H \to f\bar{f}, Z\gamma, \gamma\gamma$.

- Experimental feasibility study of the measurement of $H \to Z\gamma$.

Interested Swiss institutes: PSI

3.2 Quark flavour physics

The outstanding open question of particle physics is the flavor puzzle. Why are there three generations of matter? What is the organizing principle behind the Yukawa interactions, which introduce most of the free parameters in the Standard Model? What is the origin of hierarchies in the charged fermion masses, which spans over six orders of magnitude? Why is the quark mixing matrix aligned with the unit matrix and has hierarchical off-diagonal elements?

The peculiar observed values of the quark masses and mixings give rise to the approximate quark flavor symmetries in the Standard Model. Testing these symmetries is a powerful strategy to discover the physics beyond the Standard Model. Even minor symmetry violations give unique and clean experimental signatures. Furthermore, finding new physics in the flavor sector will provide a new clue toward addressing the aforementioned flavor puzzle.

Based on a very few preliminary studies reported in Ref. [A+19], the FCC-ee seems to be a promising future project for the continuation of the flavour physics program after the end of the LHCb Upgrade and the Belle II experiments. To firmly establish this claim, a through feasibility study needs to be performed.

3.2.1 Bottom and charm physics

FCC-ee operation at the Z pole would be an excellent factory of heavy quark flavors. The projected statistics on $b\bar{b}$ and $c\bar{c}$ is about one order of magnitude more than the projected final Belle II statistics [A+19]. Unlike Belle II, which operates at $\Upsilon(4S)$, at FCC-ee, there is access to a broad spectrum of hadrons, including B_s and Λ_b. Similar to LHCb, hadrons are produced at more significant boosts, which allows for better reconstruction. Unlike LHCb, the environment is cleaner, and the backgrounds are lower. Furthermore, initial energy constraints and negligible trigger losses with full detector coverage provide support for the flavor physics program. Finally, excellent PID, vertexing/tagging, and energy/momentum resolution are expected in the FCC-ee detector designs.

Flavor changing $b \to q\ell^+\ell^-$ transitions where $q = d, s$ and $\ell = e, \mu, \tau$ are mediated in the Standard Model by the electroweak penguin loops and are further suppressed by small CKM elements. They are, therefore, extremely rare processes sensitive to new physics effects. Recent LHCb measurements (mainly in the muonic channel with large statistics) show deviations from the Standard Model prediction, which can be interpreted as new physics. While the results are not yet conclusive, the effect could be due to a new particle with mass $\mathcal{O}(10\,\text{TeV})$, which is beyond the reach of direct production. This example shows the potential of rare B decays to (indirectly) discover heavy new physics inaccessible in direct searches.

However, the physics program of $b \to q\ell^+\ell^-$ decays is challenging both experimentally and theoretically. Much work is needed on both frontiers to obtain the most from the data. On the theoretical side, the challenge is evaluating local and non-local hadronic matrix elements, incorporating QED corrections, the definition of SM-clean and BSM-sensitive observables, global EFT interpretation, etc. On the experimental side, measurements with electrons are challenging in a busy environment such as the LHCb, while tau leptons are not so feasible. The FCC-ee can make tremendous progress in this field. For example, the best present limit on the branching ratio of $B^0 \to K^*\tau^+\tau^-$ is four orders of magnitude above the Standard Model prediction. At the same time, the FCC-ee can observe $\mathcal{O}(1000)$ events in the Standard Model [KMSS17], so that we will go from complete ignorance to a precise study of this crucial process. In many motivated scenarios beyond the SM, the effects in the third generation are expected to be enhanced, motivating further the $\tau^+\tau^-$ channel.

Other interesting rare decays include $b \to q\nu\bar{\nu}$ as well as charm FCNC decays which have not yet been discussed in the context of FCC-ee.

List of projects:

- Improving the Standard Model predictions of $b \to q\ell^+\ell^-$ transitions where $q = d, s$ and $\ell = e, \mu, \tau$, matching the statistical precision achievable at FCC-ee.
- Quantifying the impact of QED corrections for the lepton flavour universality ratios in $b \to s\ell^+\ell^-$ and $b \to c(u)\ell\bar{\nu}$ decays.
- New physics potential of $b \to q\ell^+\ell^-$ transitions where $q = d, s$ and $\ell = e, \mu, \tau$. Effective field theory interpretation.
- New physics potential and experimental feasibility study of $b \to q\nu\bar{\nu}$ transitions where $q = d, s$.
- New physics potential and experimental feasibility study of $c \to u\ell^+\ell^-$ transitions where $\ell = e, \mu$.

Interested Swiss institutes: Universität Basel, Universität Zürich

3.2.2 Quark FCNC in processes with Z bosons, Higgs bosons, or top quarks

The universality of gauge interactions predicts the absence of tree-level flavor-changing neutral currents in the Standard Model. This can be tested experimentally in Z boson decays to $q_i\bar{q}_j$ where the Standard Model rates are extremely suppressed for $i \neq j$. An interesting example would be to compare the FCC-ee direct reach on the $Z \to b\bar{s}$ coupling with the indirect bound from $B_s \to \mu\mu$ decay. Similar studies should be performed in the Higgs sector since the absence of flavor-changing Higgs boson decays is an essential test of the Standard Model Higgs mechanism. The Standard Model prediction can easily be modified with new physics, for example, by the presence of an extra Higgs boson doublet. Finally, transitions of the top quark to charm or up quarks can be investigated at the FCC-ee, either from top quark decays or from $e^+e^- \to tj$ production. None of these studies have been performed so far for the FCC-ee.

List of projects:

- New physics potential and experimental feasibility study of FCNC decays of the Z and Higgs bosons to quarks. Effective field theory interpretation and study of correlations with flavor-changing observables in quark and lepton decays.
- New physics potential and experimental feasibility study for FCNC top quark couplings arising in $e^+e^- \to tj$ production and top quark decays.

Interested Swiss institutes: Universität Basel, Universität Zürich

3.3 Lepton flavour physics

Individual lepton flavor is an exact, accidental symmetry of the Standard Model at the perturbative level. Despite extensive searches, no flavor violation has so far been detected in the charged lepton sector. On the other hand, neutrino oscillations are empirical evidence for lepton flavor violation. The feedback of the (minimal) neutrino sector into the charged lepton flavor violation (cLFV) is strongly GIM-suppressed and much below any projected experimental sensitivity, making cLFV effectively null tests of the Standard Model. Several motivated new physics scenarios predict cLFV at the detectable level. Lepton flavor universality (LFU) is an approximate accidental symmetry of the Standard Model broken explicitly by the difference in the small lepton Yukawa interactions.

Searching for cLFV and LFU violation is an excellent consistency test of the SM and a motivated strategy to discover new physics. The FCC-ee has the potential to improve on both aspects significantly.

List of projects:

- **Tau lepton studies:** Solidifying the Standard Model theory predictions for LFU tests in τ lepton decays to match the precision of the FCC-ee.
- **Tau lepton studies:** New physics potential and experimental feasibility study of LFU and cLFV in τ lepton decays.
- **Leptonic FCNC in Z, Higgs and Top:** New physics potential and experimental feasibility study of FCNC decays of the Z and Higgs boson, and top quark decays to leptons.

Interested Swiss institutes: Universität Basel, Universität Zürich

3.4 Standard model precision physics

Operating at different centre-of-mass energies (Z mass, and WW, ZZ, ZH, and $t\bar{t}$ production thresholds), the FCC-ee offers access to a multitude of precision measurements of QCD and electroweak observables. Compared to LEP, FCC-ee will produce an event yield [A+19] that is larger by a factor of 10^6 for on-shell Z boson production and by a factor 10^5 for WW and ZZ production. The resulting increase in statistical accuracy requires an understanding of experimental systematic uncertainties at a comparable level and calls for substantial improvements to theory calculations. It is only through the combination of increased statistics, improved experimental systematic uncertainties, and advances in theory that the full potential of Standard Model precision physics at the FCC-ee will be attained, thereby enabling highly precise determinations of its parameters and searches for tiny deviations signaling new physics effects.

3.4.1 Precision Monte Carlo calculations

Electroweak precision physics at LEP was based on the determination of so-called pseudo-observables, which are idealized quantities that are extracted from the experimental measurements. Pseudo-observables are, for example, total cross sections or inclusive cross-section asymmetries, which are obtained by extrapolating measured cross sections or asymmetries from their fiducial measurement regions to the full acceptance. These measurements are then compared to theoretical predictions for the pseudo-observables, obtained as precision predictions in the Standard Model through higher-order perturbative corrections. Likewise, the impact of new physics effects could also be quantified through predictions for these pseudo-observables, which thus provided an elegant interface between experimental results and theoretical predictions.

With experimental samples of 2.5 10^{12} Z decays for each of 2 to 4 experiments, of which 7.5 10^{11} decays into each of $ee, \mu\mu, \tau\tau$ pairs, the FCC-ee will provide an improvement by a factor of 500 over LEP statistics, and with much improved detectors. Precision experimental studies of the initial and final state photon radiation, and their interference will be possible with a unprecedented level of precision, thus offering a detailed and precise test of the theoretical developments.

The two-lepton final state offers in addition many experimental outputs, with discovery-level physics observables, in particular

- the forward-backward asymmetry for lepton pairs around the Z pole provides, from the energy dependence, a *direct* determination of the QED coupling constant $\alpha_{QED}(m_Z)$ with a precision of 3×10^{-5}
- and from the value at the Z pole, a determination of the electroweak mixing angle $\sin^2 \vartheta^{\rm eff}_{\rm lept}$, with a precision of 2×10^{-6}.

The same events provide measurements of great interest as accelerator diagnostics and detector performance benchmarks

- from the lepton pairs, one can extract the beam energy spread from the di-lepton acolinearity, while testing initial state radiation for large acollinearity events.
- The same events provide a determination of the average event boost, providing a test of the beam energy losses with a precision of a few keV for every day of data taking.

- These events also allow a determination of the beam sizes at the interaction points, in the three coordinates x,z and t; in case of monochromatization, they provide a direct measurement of the reduction of the energy spread.

- These events also provide a direct measurement of momentum reconstruction, time resolution, angular resolution, and impact parameter resolution, as well as many constraints on detector alignment.

With increasing statistical precision, the extrapolation from measured fiducial cross sections to idealized pseudo-observables starts to become a limiting factor in terms of systematic uncertainty, which is moreover very difficult to quantify. Already for a few years, the LHC experiments compare their precision measurments with precision theory at the level of fiducial cross sections.

Their computation in perturbation theory is however considerably more challenging than for pseudo-observables (which correspond to much more simplified kinematical situations). Precision calculations of fiducial cross sections are typically performed using parton-level Monte Carlo event generators [GGDRG+17, GKW18], which incorporate all processes that contribute to a desired perturbative order, and subject them to the same event reconstruction and selection criteria as used in the experimental measurements. A very successful example are vector boson pair production processes at the LHC, where corrections up to next-to-next-to-leading order (NNLO) in QCD in parton-level event generator form [GKW18, GKL+20] are required to meet the precision of the measured fiducial cross sections. Standard Model precision physics at FCC-ee will require the development of particle-level event generators including higher-order QED effects, especially related to initial-state radiation [BCF+22], QCD at NNLO and beyond, as well as mixed QCD-electroweak and NNLO electroweak corrections. All these directions will require novel conceptual advances in terms of calculational techniques for multi-loop matrix elements and their efficient numerical implementation.

List of projects:

- Calculation of multi-loop amplitudes with QED, QCD, and electroweak corrections and combinations thereof.

- Direct test of QED and the Standard Model using lepton-pair final states.

- Development of a parton-level Monte Carlo event generator for FCC-ee physics at different energies.

- Experimental feasibility studies of precision measurements at the Z pole, in vector-boson pair production, and in top-quark pair production.

Interested Swiss institutes: ETH Zürich, Universität Zürich

3.4.2 QCD precision measurements using jets and jet substructure

Since the LEP era, huge progress has been made in the understanding of jet substructure [N+22]. However, the various parton shower simulation programs such as PYTHIA, HERWIG, and SHERPA still differ significantly in their predictions for jets and typical jet substructure variables such as energy correlation functions [LST13]. Precision calculations, including higher order contributions and resummation of large logarithmic terms, are often not available to sufficient accuracy.

At the FCC-ee, effects that are notoriously difficult to simulate, such as the underlying event and pileup, and that spoil predictions for hadron colliders will be significantly reduced. This creates an opportunity to investigate several poorly understood QCD processes in detail to then be able to perform more precise measurements of other quantities such as the top quark mass. An example of a QCD measurement would be the color flow between high-energy particles. The color flow affects the structure of the emitted radiation and therefore also the structure of the resulting jets [B+83, A+18, BCLM20]. By performing measurements in multi-jet final states and Lorentz-boosted boson decays, these color reconnection effects can be measured to high precision. Similarly, modern jet substructure techniques [N+22] can be combined with machine learning approaches to discriminate between quark- and gluon-initated jets, thereby allowing a probe of their fragmentation and hadronization dynamics.

List of projects:

- Measurement of color flow in top quark-antiquark events.
- Investigation of jet substructure variables for use in parton shower tuning.
- Precision calculations for jet substructure observables.
- Measurements of hadronic showers in the clean FCC-ee environment for improving simulations, preparing for FCC-hh.

Interested Swiss institutes: PSI, Université de Genève, Universität Zürich

3.5 Searches for new phenomena

3.5.1 Heavy neutral leptons and the origin of neutrino masses

Heavy neutral leptons appear in extensions of the Standard Model (SM) by singlet fermions (also called sterile or right-handed neutrinos), often with the aim of generating the masses of the light neutrinos observed in neutrino flavour oscillations. Such singlet fermions can have Majorana mass terms as well as Yukawa couplings to the lepton and Higgs doublets. After electroweak symmetry breaking, the latter yield mixing terms in the neutral lepton mass matrix. The eigenvalues are the light neutrinos (mainly consisting of the SM neutrinos) and the heavy neutrinos (mainly consisting of the singlet fermions). However due to the mixing, also the heavy neutral leptons (HNLs) participate in the weak interactions, enabling their production and decay at colliders. Depending on the heavy neutral lepton masses and couplings, they can be LLPs or decay rather promptly.

Heavy neutral lepton masses of around the electroweak scale can appear when an approximate lepton-number-like symmetry makes the light neutrinos light. In such theory models, the HNLs typically come in so-called "pseudo-Dirac pairs" of two states with almost degenerate masses and coupling strengths such that lepton number is almost conserved. The existing but suppressed lepton number violation (LNV) is on the one hand responsible for the lightness of the light neutrinos, but on the other hand makes observing LNV processes at colliders challenging. Nevertheless, probing lepton number violation is essential for testing whether the HNLs are indeed involved in the generation of the light neutrino masses.

One effect that may allow the discovery of LNV at the FCC is "heavy neutrino-antineutrino oscillations": When a HNL is produced together with an anti-lepton, we call it a heavy neutrino, if produced with a lepton, we call it a heavy antineutrino. These interaction states are superpositions of the (almost degenerate) HNL mass eigenstates. When the mass eigenstates interfere during their propagation, an oscillation between the heavy neutrino and antineutrino states occurs, depending on the lifetime of the HNL before it decays. The oscillation time depends on the mass splitting between the (almost degenerate) mass eigenstates.

If the HNL is long-lived, there is a potential chance to resolve the heavy neutrino-antineutrino oscillations at colliders [ACF19]. But even when not resolvable, the oscillations can induce LNV and might be measurable via a non-trivial total ratio between LNV and lepton number conserving (LNC) events [AHN16]. Only recently, the formulae for heavy neutrino-antineutrino oscillations have been derived in [AR21] within QFT with external wave packets, which allows the proper inclusion of decoherence and localisation effects. Further investigations are required in order to clarify the prospects of resolving heavy neutrino-antineutrino oscillations at the FCC and of testing LNV and the origin of neutrino masses in general.

List of projects:

- Experimental feasibility studies of HNL discovery in all channels (fully leptonic, semileptonic, fully hadronic), and as a function of parameter space.
- Probe LNV and heavy neutrino-antineutrino oscillations at the FCC-ee (theory and experimental feasibility study).
- Link the experimental aspects to detector design: calorimetry and tracking / vertexing for energy and spatial resolution, and timing requirements for PID.

Interested Swiss institutes: Universität Basel, Université de Genève, EPFL

4 Physics tools

4.1 Reconstruction and performance

4.1.1 Flavour tagging

Jet-flavour identification algorithms are of paramount importance to maximise the physics potential of the FCC. Out of the extensive FCC-ee physics program, flavour tagging is crucial for the Higgs physics program, given the dominance of the hadronic decays of the Higgs boson. Highly efficient discrimination of b-, c-, s-, and gluon-jets allows access to novel decay modes that cannot be identified at the LHC, adding quantitatively new dimensions to the Higgs physics programme.

Transformers are a class of Neural Networks that make use of a self-attention mechanism to exploit particle-level information that can identify the flavour of jets. In the context of the FCC feasibility study, transformers have a significant advantage compared to other machine-learning techniques thanks to their rapid training time. This allows for efficient and fast evaluation of the flavour tagging performance of various detector designs, which is crucial for the optimisation of the FCC-ee detectors.

A collaboration between Universität Zürich and Vrije Universiteit Brussels is developing a transformer-based, jet-flavour tagger specifically for FCC-ee in the context of an SNSF project funded through the Weave funding scheme (project number 197195).

Interested institutes: Universität Zürich

Connection to other WPs: This topic is closely related to development of new jet reconstruction techniques (Sec. 4.1.3), all physics-reach studies using jet flavour (Sec. 3), and depends heavily on the performance of the vertex detector (Sec. 2.1.1 and 2.3), and on particle identification techniques (Sec. 2.2).

4.1.2 Application of Machine Learning Methods to the reconstruction and simulation of FCC-ee events

Usage of multivariate methods, such as neural networks, has been very common in particle physics for many years, even decades, already. While in the early days such methods have mainly been applied in data analysis, in order to boost the performance of selection and classification tasks, since several years machine learning algorithms have seen an impressive rise in almost all aspects of modern particle physics. Besides the aforementioned applications in high-level data analyses, such tools are used for particular reconstruction and identification tasks (e.g. b-tagging), and for anomaly detection. Recently, applications at the hardware low-latency trigger level are being investigated, and efforts exist towards establishing very fast simulation tools.

In view of the recent and anticipated further enormous advances in the field of artificial intelligence, combined with ever more powerful computing facilities, it is very natural to assume that such methods will be at the very heart of most, if not all, software and computing applications relevant for the design, preparation and running of FCC-ee experiments. Therefore, concerted efforts should be started now towards setting up the relevant frameworks, first pilot projects, and proofs of principle. In particular, an attempt should be made to attack the ultimate challenge of using Machine Learning for the

- complete reconstruction of a collision event; that is, obtain an estimate of the original particles created in the event from the direct input of signals in the various sub-detectors.
- Similarly, significant advances are needed towards fast simulation tools based on machine learning. The proposed project aims at taking the necessary steps in these directions.

Interested institutes: ETH Zürich, Université de Genève

Connection to other WPs: Obviously, close interaction is needed with other work packages related to detector design.

4.1.3 Jet reconstruction / pflow

In order to fully benefit from the FCC-ee, the large hadronic branching fractions of the different target processes must be successfully used and integrated in the full physics programme. Moreover, there is the real potential to have excellent results in semi-leptonic or even fully hadronic final states, due to the collision environment involving much less ambient hadronic activity.

In order to attain such objectives, it is important to revisit jet reconstruction strategies, including the input objects to jet reconstruction (particle flow objects) and the jet algorithms. Both of these aspects have improved dramatically since LEP, and the approaches used at the LHC are not necessarily optimal in the FCC-ee environment. The very different background in e+e- collisions compared to hadronic collisions, as well as changes to detector technologies, necessitate different particle flow algorithms and subsequent optimisations. At a higher level, the jet algorithms should be revisited, both to compare inclusive vs exclusive jet finding in key physics cases, as well as to study variations on recombination schemes and other associated algorithmic strategies. Standard anti-kT algorithm may not be optimal, as studied in Ref. [BFG+18].

List of projects:

- Revisit particle flow algorithms, combining knowledge gained at the LHC with projections for the different FCC-ee conditions and detector hardware.
- Study different jet algorithms and variations thereof for optimal performance at the FCC-ee.
- Investigate the portability of different LHC techniques to the FCC-ee environment, including constituent-level modifiers, grooming algorithms, and similar modern jet reconstruction developments.

Interested institutes: Université de Genève

Connection to other WPs: This topic is at the interface of several others, particularly between detector/trigger developments and physics potential. It furthermore has strong links to other transversal topics (machine learning, flavour tagging, etc).

5 Outlook

Switzerland has historical and leading participation in high energy collider experiments, both in detector construction and exploitation of the acquired data in terms of physics results. The future of high energy physics lies on ambitious projects that are currently under evaluation, such as the Future Circular Collider (FCC).

The international FCC community has grown significantly since the kick-off in 2014. A total of five FCC Physics Weeks and eight general FCC weeks have been held since then. Many of the national particle physics communities have as well organised meetings dedicated to the FCC. Both the UK and Italian particle physics communities have recently organised their first workshops, while France has already organised a total of three FCC workshops. Italy and France have furthermore organised their first joint France-Italy FCC workshop in 2022 [fccb].

In Switzerland, two workshops were organised in 2021 and 2022 to foster the Swiss collaboration towards the Future Circular Collider and to spearhead the collaboration among Swiss institutions. This series of workshops was a kick-off for the Swiss activities on experimental and theoretical developments for the FCC project and has created much interest in the community, with more than forty in-person, and many more remote participants to both workshop. Particle physicists from all Swiss institutes participated and both workshops also attracted many young scientists who were engaged in the discussions.

In terms of funding, significant investments have already gone into the FCC project. The FCC feasibility study running from 2021 to the end of 2025 comprises a total of 100 MCHF. This is mainly used to investigate the financial feasibility, the technical and administrative feasibility of the tunnel, and to develop accelerator and experimental technologies such as magnets, also with a goal of minimising the environmental impact.

Switzerland plays a key role in the FCC accelerator development thanks to the CHART (Swiss Accelerator Research and Technology) program (https://chart.ch). R&D for theoretical and experimental work towards the FCC, however, is far less covered. In Italy, for example, a dedicated FCC R%D program was launched recently with six work packages ranging from physics, software, and accelerators, to dedicated research on detector technologies. In 2021, a total of 17.45 FTE were working on FCC for example [fccc, fcca].

There is a strong bottom-up push for the FCC both in the international and the Swiss particle physics community. In Switzerland, all major institutions have shown interest in working towards the FCC. If Switzerland is to ensure its leading role in particle physics research, then having the Future Circular Collider at CERN is essential. To enable the successful completion of the FCC feasibility study, the effort in experimental and theoretical research for the FCC needs to start now. This document collects concrete projects that the Swiss particle physics community is eager to realise, and which greatly support the experimental and theoretical feasibility of the FCC project. The community is open to evaluate new technologies, for example in the direction of advanced electronics and computing (e.g. quantum computing).

Outreach to the public, to highlight the amazing potential of the FCC program is also vital for demonstrating that such a project will inspire the public imagination.

To ensure the successful completion of the FCC feasibility study, more effort is needed. This CHEF document will serve as a starting point, in order to communicate Swiss interest in the FCC project, and to help steer the organizational structure of CHEF over the next few years. The next steps are to reach out to Swiss institutions and funding agencies, and formalize a plan for how CHEF research projects can be realized. A timely implementation of CHEF has the potential to greatly impact the success of the FCC project.

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A CHEF (Swiss Experimental Research for the FCC) : CHIPP Plan for Promoting FCC detector research and development

Prepared by CHIPP Executive board, July 14, 2022.

The 2020 European Strategy for particle physics update document puts forth a vision of an electron-positron collider operating as a Higgs boson factory, followed by a future hadron collider operating at a center-of-mass energy 10 times higher than the LHC.
"An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."

This staged proposal of FCC-ee (Future Circular Collider colliding electrons and positrons) and FCC-hh (colliding hadrons) sequentially occupying the same tunnel at CERN has been gaining traction in the community. The European Committee for Future Accelerators (EFCA) Detector R&D Roadmap Process Group has published the 2021 Detector Research and Development Roadmap to outline the high priority detector research necessary in order to realize such future particle physics experiments. This includes technology developments necessary for detectors at e+e- Higgs-EW-Top factories, as well as long-term R&D for detectors at future 100 TeV hadron colliders integrating luminosities up to 30 ab-1. In December 2021 the CERN council was presented a Roadmap, after endorsement by Plenary ECFA https://cds.cern.ch/record/2784893 (incl. a short Synopsis Document)]. The CERN Council has then mandated ECFA to work out an implementation plan in close collaboration with the funding agencies and the relevant research organisations, encouraging international funding agencies to provide long-term funding support to enable detector technologies for the FCC.

In Switzerland, the 2021 CHIPP roadmap lists as its major findings the strong support for a staged collider approach of FCC-ee followed by FCC-hh, stating "CHIPP recommends the development of a national strategy towards the participation in CERN's program for an FCC, starting with FCC-ee, which encompasses detector development, theoretical research, and data analysis and simulation." The two major technological areas needed for this future physics program are accelerator development and detector development. Switzerland has already in place since 2016 the CHART (Swiss Accelerator Research and Technology) organization, which has a mission to support accelerator development geared toward the FCC.

Here, we provide a concept for a development similar to CHART, geared towards supporting the detector development necessary for experiments part of FCC-ee and FCC-hh. The organization is to be called CHEF (Swiss Experimental research for FCC). This organization will provide oversight and a structure for contributing to long-term detector R&D. The creation of CHEF is timely now with CERN and ECFA defining the implementation of the strategy for particle physics adopted by the CERN council.

CHEF will provide a national (CH) structure for longer-term engagements in detector instrumentation work. CHEF establishes a platform to take advantage of synergies in detector developments between Swiss institutions and to promote applications in other fields. It serves as a center to enable a coherent strategy for defining the physics goals and deriving instrumentation requirements. It acts as a collaborative link to CERN, ECFA, and efforts in other countries, and as a communication channel to the public.

CHEF activities are a direct continuation of the very successful of the theoretical and detector developments achieved for the LHC and HL-LHC and take the opportunity to maintain the strong international visibility of the Swiss groups (and thus Switzerland) in innovative detector research commensurate with the status of Switzerland as a host country.

The organizational structure of CHEF is as follows. A management board will establish working groups that will permit Swiss groups to contribute to FCC experimental developments. The management board will evaluate proposals from groups and allocate resources to specific projects. An independent advisory board will oversee the distribution of resources, and will be reported to regularly by the management board. CHEF will invite participation from Swiss cantonal and federal Universities.

A possible sketch for the organization of CHEF is shown in Fig. 1.

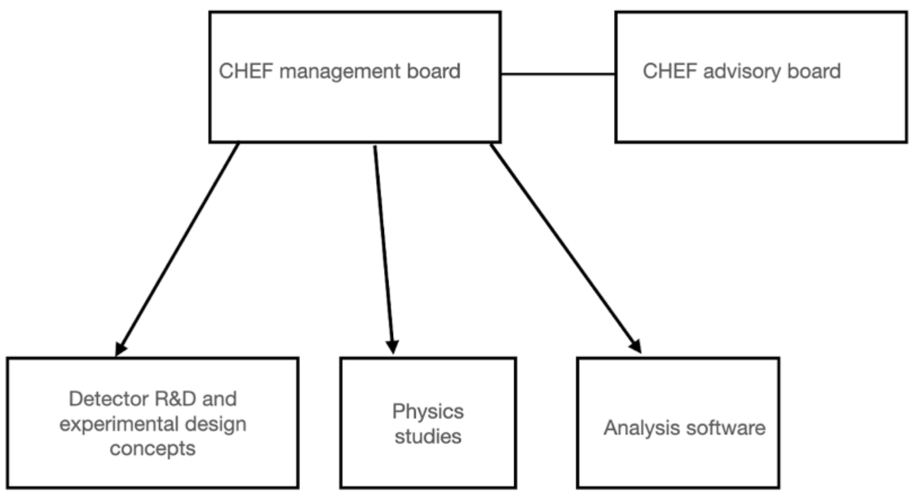

Figure 1: Sketch of the structure of CHEF

The "detector R&D and experimental design concepts" group will focus on following up the strengths of developing detector R&D towards FCC experiments. A second work package will be established to channel physics studies. These are required to guide the detector R&D and define the overall FCC scope and goals. Analysis software and tools is a further fundamental tool for particle physics research to cope with the information density and quantity from the experiments.

CHIPP and its institutions will develop the CHEF structure with its partner institutions and boards as the financing and participation is secured. We envisage a combination of federal funds from SERI with a matching scheme similar to CHART, in which Swiss institutions and CERN will contribute with either funds or in-kind contributions in addition to providing the facilities.

The expected overall funding level for the period 2025-2028 is of the order of 6 MCHF. This would provide personnel and research funds for Swiss institutions to contribute to the working groups above.

Timeline :

- 2023: Develop CHEF structure, develop contacts with Swiss institutions.
- 2024: Finalize agreements between SERI, Swiss institutions, and CHEF.
- 2024: Establish CHEF management board and advisory board.
- 2025-2028: Funding for CHEF from SERI and other Swiss institutions.