PROCEEDINGS OF SCIENCE

Status of Detector Requirements for FCC-ee

Marina Cobal[a,*]

[a] *University of Udine INFN Gruppo Collegato di Udine,*
Via delle Scienze 206, Udine, Italy

E-mail: `marina.cobal@cern.ch`

For the future lepton collider FCC-ee, different detector designs are studied and optimized. They must first achieve the required performances for heavy-flavour tagging, particle identification, tracking and particle-flow reconstruction, as well as lepton, jet, missing energy and angular resolutions, needed to successfully develop the very broad FCC-ee physics program, and exploit the extremely high statistical precision offered by this future collider. On top of that, they must all satisfy the constraints imposed by the challenging interaction region layout. FCC feasibility studies are being now carried out, using benchmark physics processes to determine, via appropriate simulations, the requirements on the detector performance which can guarantee that the systematic uncertainties of the measurements will be lowered as far as possible with the tiny statistical uncertainties as the target. Additionally, the potential for discovering very weakly coupled new particles, in decays of Z or Higgs bosons, motivates dedicated detector designs that would increase the efficiency for reconstructing the unusual signatures of such processes. These studies are crucial input to the further optimization of the two concepts described in the FCC-ee Conceptual Design Report, CLD and IDEA, and to the development of new concepts which might prove to be even better suited for the FCC-ee physics program.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

---

[*] Speaker

https://pos.sissa.it/

PoS(ICHEP2022)353

1. Experimental challenges at the FCC-ee Collider

In order to extend the research currently being conducted at the LHC, once the High-Luminosity phase will reach its conclusion around 2040, a Future Circular Collider (FCC) is proposed, a new research infrastructure to push the energy and intensity frontiers of particle physics, with the aim of ultimately reaching collision energies of 100 TeV. The FCC will work in three different scenarios: electron–positron collisions (FCC-ee), proton–proton and heavy ion collisions (FCC-hh). Other options include proton–electron, heavy ion collisions. The first FCC-ee stage (described in detail in [1] and [2]) is a high-luminosity, high-precision e^+e^- circular collider. Two separate e^+ and e^- storage rings with very strong focusing, fed by a full size continuous injector, will provide collision luminosities ranging from (per interaction point) 230×10^{34} cm^{-2}s^{-1} at the Z-pole, 28 (8.5) $\times 10^{34}$ cm^{-2}s^{-1} at the W^+W^+ (ZH) production maximum (160 (240) GeV)) and 1.7×10^{34} cm^{-2}s^{-1} at the $t\bar{t}$ threshold and up to 365 GeV. Two to four interaction points are considered. The run plan of 15-20 years yields 5×10^{12} Z-bosons, 10^8 W pairs, 1.3×10^6 Higgs bosons and 10^6 top quark pairs. Given the availability of transverse polarization, the energy calibration at 100 keV precision offers unprecedented precision for measurements of Z and W properties. The possibility of s-channel Higgs production at $\sqrt{s}$=125 GeV, giving an unique access to the electron Yukawa coupling, is under study [3].

2. Detector Concepts

In [1], two initial detector concepts can be found: CLD [5], based on the detector concept developed for the CLIC collider, and IDEA [6], a new detector design with a new approach and new technology choices. CLD has a full silicon vertex detector and tracker, a CALICE-like calorimeter, a large coil and a muon system. IDEA has a silicon vertex detector, an ultra light drift chamber, ideal for particle identification, a compact and light coil, monolithic, parallel fibre dual readout calorimeter and a muon system. Its performance could be improved by adopting a crystal electromagnetic calorimeter. In addition, a third detector concept has been recently proposed, composed by a drift chamber (or silicon) tracker, a noble Liquid based, high granularity electromagnetic calorimeter, a CALICE-like hadron calorimeter and a muon system. Here, the coil would be in the same cryostat as the noble liquid.

3. Detector Requirements

The FCC-ee Machine Detector Interface [1] imposes tight constraints: the last focusing quadrupole will be two meters from the interaction point; the experiment magnetic field is presently constrained to 2 T for the run at the Z-pole; the angular coverage of the detector cannot extend below 100 mrad from the beam axis. The experimental environment (high physics event rates, small bunch spacing) also sets important constraints. The detector requirements imposed by the physics program [2, 7], at a centre-of-mass energy $\sqrt{s}$ of 240 GeV and above, have already been studied extensively for the linear colliders, but have to be revisited in the context of the FCC-ee environment. In addition, the specific discovery potential for very weakly coupled particles, offered by the huge FCC-ee statistics, should be kept in mind too when designing the detectors. One of the

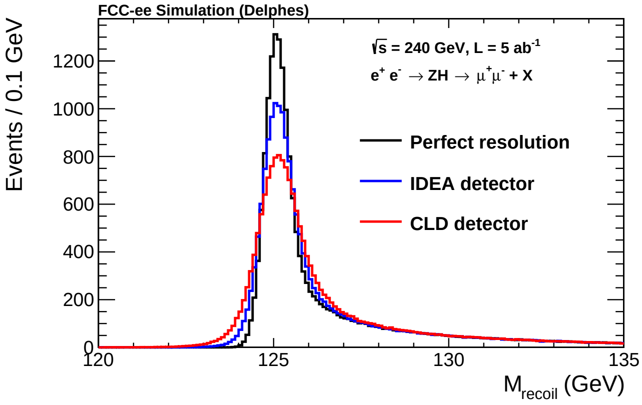

Figure 1: Distribution of the Higgs recoil mass in ZH events, with Z→ $\mu^+\mu^-$, with: an ideal momentum resolution (black line); the IDEA detector momentum resolution (blue); the CLD detector momentum resolution (red).

strongest requirements imposed by the physics program at the Z-pole is related to the acceptances, which, generally, have to be known with a relative accuracy in the range from a few 10^{-6} to 10^{-4}. For example, for the luminosity measurement [8], the goal is to reach an absolute precision of 10^{-4} from low-angle Bhabha events, which would match the present theoretical precision on the Bhabha cross section. With the luminosity monitor at 1 m only from the interaction point, and the measurement starting at an angle of 65 mrad, the monitor inner radius must be known to within 1.6 μm only [1].

3.1 Momentum measurements

The beam energy spread (BES), which amounts to 0.13% (0.16%) of its energy at $\sqrt{s}$ = 91.2 GeV (240 GeV), sets a target for the track momentum resolution. Fig. 1 [9] shows the Higgs recoil mass in ZH events with Z $\longrightarrow \mu^+\mu^-$. The reconstruction of the recoil mass should be limited by the BES and not by the detector resolution. The very light tracker of IDEA, with a resolution of $\mathcal{O}(0.15\%)$ for central, 50 GeV muons, is close to this goal, while the heavier full silicon tracker of CLD is a bit worse because, in the momentum range of interest, the resolution is dominated by multiple scattering. The determination of the Higgs mass (for which a precision of a few MeV would be needed in view of a possible run at the Higgs resonance [10]) will clearly benefit from the better momentum resolution offered by a light, gaseous tracker.

A momentum resolution comparable to the BES for beam-energy muons is also important for Z physics (i.e., for the search or Lepton Flavour Violating Z $\longrightarrow \tau\mu$ where one needs a clear tau decay in one hemisphere, and a beam-energy muon in the other, in order to suppress the Z $\longrightarrow \tau^+\tau^-$ background: the sensitivity improves linearly with the momentum resolution of the muon [11]). Requirements are also expected from flavour physics, where a good mass resolution is required to suppress backgrounds and separate peaks (e.g.: $B_s \longrightarrow D_s K$ [10]).

3.2 Vertex Detector Performance

High requirements on the resolution of the track impact parameter will have to be reached. In addition to the measurement of the Higgs couplings to pairs of b/c-quarks and gluons, which requires a high-performance flavour tagging, other requirements on the vertex detector will come from the measurement of heavy-quark electroweak observables and the heavy-quark forward-backward asymmetries for which a huge improvement is expected compared to LEP, both thanks to the large luminosity increase, and also from exceptional improvements in detector technology, which, currently, leads to b-tagging efficiencies that are three times larger than those achieved at LEP for the same mis-tag efficiency. On top of that, the rich flavour physics program at the Z-pole, complementing and surpassing in many cases the physics reach of the LHCb and B-factories experiments [12], is expected to provide demanding goals on the resolutions with which vertices are reconstructed. For example, an excellent vertexing is fundamental to extract a signal of $\mathrm{B} \rightarrow \mathrm{K}^{*}\tau\tau$ with both τ's decaying into three charged pions, allowing this decay to be fully reconstructed, and will be crucial also for the sensitivity to new long-lived particles signatures and reduction of Standard Model backgrounds. The current requirements on impact parameter resolution come from Linear Collider Higgs studies and need to be revisited for FCC, in view of the Z and WW runs.

3.3 Particle ID

Excellent lepton and photon identification capabilities are essential for many analyses. In particular, a good separation e/γ, γ/π^{0}, e/π, and an excellent separation of photons from neutral hadrons, are key ingredients for an effective particle-flow reconstruction working also in collimated topologies, as required by a precise measurement of the τ polarisation for example. Moreover, charged particle identification will be mandatory to the flavour physics program. A separation of pions from kaons, in a momentum range that extends up to at least 10 GeV, will be crucial for time-dependent CP violation measurements. Separation at higher momentum will be extremely useful too; for example, the spectrum of the kaon in the $\mathrm{B_s} \rightarrow \mathrm{D_s K}$ decay, a process that suffers from an order-of-magnitude larger background from $\mathrm{B_s} \rightarrow \mathrm{D_s}\pi$, extends up to $\sim$ 30 GeV. The precise determination of the branching ratios of the τ, and of the τ polarisation, will also benefit from a separation of pions from kaons up to $\sim$ 45.6 GeV to suppress background contamination in many flavour physics analyses. Beyond an excellent performance of b- and c-quark tagging, the ability to discriminate jets from strange quark hadronisation is also required, opening the way to improve the sensitivity of the Higgs to strange quark coupling. In addition, an improved light-quark vs. gluon separation is also fundamental to extract the electron Yukawa coupling in the run at the Higgs pole [3]. Candidate technologies are being reviewed. With the IDEA drift chamber, the “cluster counting" method looks promising and may cover the whole momentum range of interest. For a detector with a full silicon tracker, no ideal solution exists yet, as it is not easy to cover the whole momentum range considering the addition of TOF or RICH [4] detectors and, at the same time, comply with the space and hermeticity constraints of the experiment.

3.4 Calorimetry performance

A good jet energy resolution is mainly relevant for those events where the kinematic constraints are not enough to provide jet energies reconstruction which relies on their angles (i.e.: multi-jet events with missing energy) or when there is a need for a strong background rejection in the early stage of an analysis. The jet energy resolution is affected both by the algorithm choice and by the stochastic nature of the fragmentation process, which cannot be fully disentangled. It might turn better then, to rather exploit the resolution of a color singlet object such as a W, Z, or Higgs boson, and use the particle mass to assess the detector performance. In the case of a lepton collider, this variable could also be not a specific particle but the visible mass of the event or the missing mass. As an example, a CLIC study [13], which will have to be repeated for the FCC-ee case, found that Z and W in their hadronic decays can be separated with a resolution of $\sigma(E_{\mathrm{jet}})/E_{\mathrm{jet}} \simeq 30\%/\sqrt{E_{\mathrm{jet}}}$, whatever can be the overall event environment. A benchmark where the hadronic resolution on the missing mass is crucial to distinguish between similar processes is the separation of $\mathrm{e^+e^-} \to \mathrm{H}\nu\nu$ (via WW fusion) from $\mathrm{e^+e^-} \to \mathrm{ZH}$ with $\mathrm{Z} \to \nu\bar{\nu}$, instrumental for the determination of the Higgs width. For the Higgs to $\gamma\gamma$ coupling measurement, being very statistically limited at FCC-ee even with an excellent stochastic term and a constant term well below 1%, it will be difficult to achieve a precision significantly better than that of the HL-LHC measurement. On the other hand, requirements of a resolution much better than $15\%/\sqrt{E}$, in particular at rather low energies, are expected from flavour physics, since many important measurements of CP violation rely on the reconstruction of decays with several π^0's in the final state, as in $B^0 \to \pi^+\pi^-\pi^0\pi^0$. The extraction of a $B_s \to D_s K$ signal in modes with neutral pions, which would considerably increase the statistics collected in modes with charged tracks only (since the branching fraction for the decay $D_s^\pm \to \Phi\rho^\pm$ is twice larger than the one for $D_s^\pm \to \Phi\pi^\pm$), is likely to require a resolution of $3\%/\sqrt{E}$ or better, which can be achieved with state-of-the-art crystal calorimetry [14]. Moreover, the electromagnetic resolution is a key for pushing the sensitivity to rare or forbidden processes, like the $\tau \to \mu\gamma$ or $\mathrm{Z} \to \tau e$ decays [11], and its role in searches for long-lived resonances (e.g. dark photons) decaying into electrons should be studied too, as electron tracks resulting from such decays will be badly measured if they are very short. In addition to what has been said, a high granularity (< 1 cm) plays indeed a crucial role in the identification of individual photons in jets, of close-by photons coming for example from the decay of π^0's from τ's and H, or low mass axions or axion-like particles (ALPs), and, more generally, is a key for an optimal particle-flow reconstruction. Requirements on the granularity will be studied using as benchmarks the measurement of the tau polarisation, and the sensitivity on low mass ALPs, that could be copiously produced in Z decays [15, 16].

4. Conclusions

FCC-ee has an enormous physics potential, not only being a high energy e+e- collider, but also an intensity frontier factory. The expertise on how to build detectors for high energy e+e- collisions exists already, but FCC-ee poses additional challenges: the instrumentation needed to fully exploit the physics potential is challenging and exciting. A list of benchmark processes, that allow requirements to be quantified and defined, is now identified, and these processes are and will be studied carefully in order to complete the “wish-list" of detector requirements. To provide a coherent guidance, a Detector Concepts working group has been formed early this year: a forum where progress, ideas, and results from individual R&D efforts and test-beam activities are presented, discussed and reviewed, acting also as a link between the Physics, the Machine Detector Interface and the Accelerator groups.

References

[1] FCC Collaboration, *FCC-ee: The Lepton Collider*, The European Physical Journal Special Topics, vol. 228, nr. 2, pag. 261–623 (2019), doi: 10.1140/epjst/e2019-900045-4.

[2] A. Blondel, P. Janot, *FCC-ee overview: new opportunities create new challenges* in *A future Higgs and Electroweak factory (FCC): Challenges towards discovery*, EPJ+ special issue, Focus on FCC-ee, arXive: 2106.13885 (2021).

[3] D. D' Enterria, A. Poldaru, G. Wojcik, *Measuring the electron Yukawa coupling via resonant s-channel Higgs production at FCC-ee*, EPJ+ 137 (2022) 2, 201 (2022).

[4] https://indico.desy.de/event/33640/contributions/128392/attachments/77681/100501/ARC_Presentation_ECFA_Workshop_DESY_6th_October_2022.pdf

[5] N. Bacchetta et al., *CLD – A Detector Concept for the FCC-ee*, arXiv:1911.12230 (2019).

[6] G. F. Tasselli, *A proposal of a drift chamber for the IDEA experiment for a future e+e- collider*, PoS(ICHEP2020)877 (2021).

[7] FCC Collaboration, *FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1* , vol. 79, nr. 6, pag. 474 (2019).

[8] M. Dam, *Luminosity measurement at FCC-ee* in *A future Higgs and Electroweak factory (FCC): Challenges towards discovery*, EPJ+ special issue, Focus on FCC-ee, arXiv: 2106.13885 (2021).

[9] P. Azzi and E. Perez, *Exploring requirements and detector solutions for FCC-ee*, EPJ+ special issue, Focus on FCC-ee, arXiv:2107.04509 (2021).

[10] P. Azzurri et al., *A special Higgs challenge: Measuring the mass and production cross section with ultimate precision at FCC-ee* in *A future Higgs and Electroweak factory (FCC): Challenges towards discovery*, EPJ+ special issue, Focus on FCC-ee, arXiv: 2106.15438 (2021).

[11] M. Dam, *Tau-lepton Physics at the FCC-ee circular e^+e^- Collider*, SciPost Phys. Proc., vol. 1, pag. 041 (2019).

[12] S. Monteil and G. Wilkinson, *Heavy-quark opportunities and challenges at FCC-ee*, EPJ+, vol. 136, nr. 837 (2021).

[13] *Physics and Detectors at CLIC*, CLIC Conceptual Design Report, CERN-2012-003.

[14] R. Aleksan, L. Oliver, E. Perez, *CP violation and determination of the bs "flat" unitarity triangle at FCC-ee*, Phys. Rev. D 105, 053008, (2022).

[15] M. Bauer at al., *Axion-Like Particles at Future Colliders*, EPJC, vol. 79, nr. 74 (2019).

[16] N. Steinberg and J.D. Wells, *Axion-Like Particles at the ILC Giga-Z*, JHEP, nr. 120, (2021).