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Experiments at future hadron colliders

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Particle colliders provided many answers about the understanding of the world around us. While current accelerators are running, gathering data, and providing some answers, the next generation of experiments is being designed. This requires many years in order to identify the goals, challenges, work on the technologies that do not yet exist, and ensure that the proposed experiments can extend our knowledge. This paper presents the main challenges for the experiments on the hadron colliders, taking the Future Circular Collider hadron collider (FCC-hh) as an example. A baseline FCC-hh detector was studied in detail, and several key topics have been identified to require much more dedicated studies in order to construct a detector that is able to exploit the physics potential of a next-generation hadron collider.

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1. Future hadron colliders

Different hadron colliders have been studied in recent years. These include a study of the Very Large Hadron Collider (V-LHC) [1], the Super Proton-Proton Collider (SPPC) [?], the High-Energy LHC (HE-LHC) [3], and the Future Circular Collider (FCC-hh) [4]. Hadron collider is a very complex machine, and most of the designs focus in the first order on the accelerator. A study carried out by the FCC-hh community included a design of a baseline experiment, and this will be the focus of this paper. The challenges that it faces are similar to experiments on other future hadron colliders.

2. FCC-hh collider

The future generation of hadron colliders is designed to extend the understanding of the world beyond the capabilities of current accelerators. This could be achieved by going into higher collision energy and higher luminosity. While bringing exciting opportunities to physicists, those accelerator parameters pose challenging conditions for an experiment. In order to understand how to tackle them a detailed study was carried out for the FCC-hh collider [5, 6].

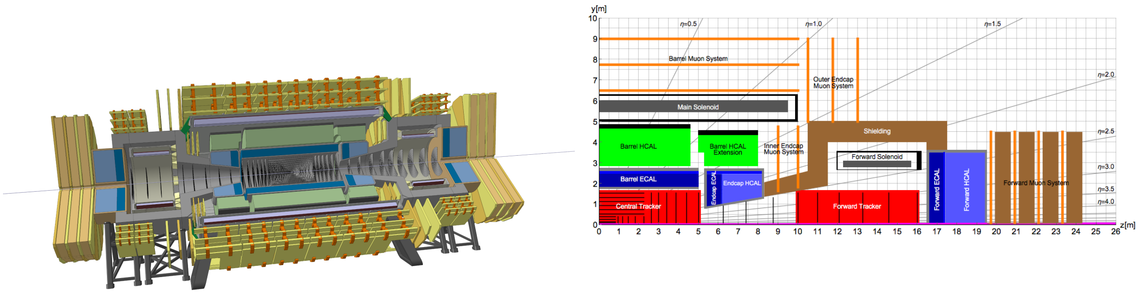
Nominal centre-of-mass collision energy of the FCC-hh is 100 TeV. This increase by a factor of 7, with respect to the 14 TeV at the Large hadron Collider (LHC), brings only moderate increase of the average properties such as the total cross section (increase by 40 %), number of charged tracks per collision (74 %), and average particle momentum (27 %). Particles are, however, produced into a more forward region, detector coverage must increase up to $|\eta| < 6$, with precise momentum and energy measurements possible in the increased region $|\eta| < 4$. Decay products of highly energetic particles created in the collision will be boosted into a similar area of the detector, setting a requirement on high granularity to distinguish those particles.

The biggest challenge for the detectors at the future hadron colliders comes from the increase in the luminosity. The peak luminosity of $30 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ increases by a factor of 30 compared to the LHC and a factor of 6 compared to the High Luminosity LHC (HL-LHC). It means a huge increase in the number of simultaneous collisions, a pile-up, reaching almost 1’000 collisions per bunch crossing, and in the rate of charged tracks, reaching 4’000 GHz. With a ten-fold increase in the integrated luminosity, compared to the HL-LHC, the radiation levels in the detector, especially around the beam-pipe and in the forward region, are unprecedented.

FCC-hh collider is designed to be hosted at CERN, reusing the existing accelerator facility as injectors. Tunnel for the Future Circular Collider is planned to accommodate first an electron-positron collider (FCC-ee), followed by a hadron machine. FCC has four interaction points, able to host two high luminosity experiments, and two additional ones. The focus of the study summarised in the FCC-hh was on the baseline experiment, pointing out the main challenges and vital R&D efforts.

3. Baseline detector design

FCC-hh baseline detector is depicted in Fig. 1. It has a rather typical structure for a collider experiment, with a large coverage leading to the extended instrumentation of the forward region.



(a) **(b)**

Figure 1: FCC-hh baseline detector [4].

The choice of technologies for the sub-detectors of the FCC-hh experiment must account for the radiation studies performed for this baseline detector, especially for the forward calorimetry. The most challenging region is probably around the beampipe, covering the first few layers of the tracking detector. The 1 MeV neutron equivalent fluence is 30 times higher than for the HL-LHC at the distance of $r = 2.5\,\mathrm{cm}$ from the beampipe (at $z = 0$). The radiation tolerance limit decreases with radius r and at $r = 27\,\mathrm{cm}$ it meets the HL-LHC radiation tolerance limit ($\approx 10^{16}\,\mathrm{cm}^{-2}$). Hence, the sensors for the first few layers of the tracker need yet to be developed, more radiation hard than the existing ones.

3.1 Magnets

There are two designs considered for the experiment's magnet system. A reference one contains three solenoids: one central, and two in the forward regions. An alternative one replaces forward solenoids with dipoles. The choice of the magnet system has a direct effect on the track momentum resolution. In the forward region, the dipole magnetic field offers a better track momentum resolution than the forward solenoid.

An important aspect of the magnet system design is the lack of shielding. Stray field was studied, both on a surface, and in the service cavern, and is far below the safe threshold of 5 mT.

3.2 Tracking system

Different layouts of the tracker system were studied, and two optimised trackers are presented: with flat sensors and inclined with respect to the detector planes. The inclination of sensors allows minimising the effect of multiple scattering, reducing the material budget. The optimisation took into account the pattern recognition algorithms and vertexing.

An important task of the tracking system would be pile-up mitigation. With 1'000 simultaneous collisions per bunch crossing, the average distance between the vertices (taking into account the spread of beam spot) is $\approx 120\,\mu\mathrm{m}$ and 0.4 s. With the same estimation for the HL-LHC, the average distance is $\approx 1\,\mathrm{mm}$ and 3 ps. Therefore tracker, with its pointing and timing capabilities, can reduce the pile-up to the so-called effective pile-up, defined as a number of vertices that fall within the window of the reconstructed vertex. The better the pointing and time resolution of the tracker, the smaller the effective pile-up. For 1 GeV/c particles at $|\eta| = 4$ it is estimated to the effective pile-up of 20 if a tracker is unable to perform a time measurement. The introduction of time measurement with 25 ps resolution leads to a reduction of the effective pile-up to 8, and with 5 ps it could be even reduced to the effective pile-up of 2.

3.3 Calorimetry

Calorimetry designed for the baseline detector is inspired by ATLAS calorimetry. An alternative for the central electromagnetic system has been also included, based on silicon sensors. It is however unsuitable for the endcap and forward regions due to the radiation levels. The baseline design for the central electromagnetic calorimeter, as well as for the combined calorimetry in the endcaps and forward regions is based on liquid argon. The hadronic calorimeter in the central region uses scintillator tiles. Much higher granularity is considered with respect to the ATLAS detector. In the central electromagnetic calorimeter it is possible thanks to straight multilayer electrodes and for the hadronic calorimeter thanks to the silicon photo multipliers. Performance measurements demonstrate that target resolution is met for single pions and for e/gamma even in the presence of a pile-up of 1000. JThe jet energy resolution was studied without the magnetic field or pile-up as those studies require combined performance measurements with the tracker system.

3.4 Muon system

Combined measurements with the tracking system are vital also for muons, allowing good momentum resolution measurements. Standalone measurements are sufficient for triggering or muon identification, however, in the forward region, those would be possible only if combined with the dipole forward magnet. Triggering on muons does require combined information with calorimetry, to filter muons coming from abundant b and c decays.

3.5 Software and computing

An important aspect of the studies carried out for the FCC-hh detector is taking into account software as a vital part of the instrumentation. Computing is a challenge for the HL-LHC experiments and could limit the physics potential of the experiments due to insufficient resources. Therefore, efforts are taken to ensure a proper design, reuse of validated solutions, and work on the common software that may serve more than one experiment. Initial work that was done for the FCC colliders, serving multiple experiments on FCC-ee, and FCC-hh. It is now the base of the Key4hep [7].

4. Summary

A feasibility study of the general purpose detector for a 100 TeV hadron collider was concluded. Conceptual Design Report describes in detail the achieved results and conclusions, with the main challenges and design choices being presented here. Key R&D items have been identified, including ultra-radiation hard silicon sensors, timing detectors, low power radiation hard optical links, granular calorimeters, and efficient software. Carrying out research in those areas is vital for the construction of the detector that may fully exploit the potential of a 100 TeV hadron collider.

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