Requirements from physics for the FCC-hh detector design

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Abstract

This note addresses the requirements that should satisfy a detector operating in the FCC-hh environment in order to maximise its physics potential. Such a detector will operate in challenging conditions, and will be required to respond optimally in a wide energy range to fulfill a physics programme ranging from the electro-weak scale to the multi-tens of TeV energy frontier. Extreme granularity, excellent energy-momentum resolution beyond the LHC detectors, together will novel algorithms will be needed to achieve optimal object reconstruction and identification.
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The Standard Model (SM) does not provide answers to the existence of dark matter (DM), the non-vanishing neutrino masses and the observed matter/antimatter asymmetry. Moreover, the SM does not provide a dynamical explanation for the electro-weak symmetry breaking (EWSB) and the very large mass difference between the electro-weak (EW) and the Planck scale. Such limitations point to the existence of new states that might extend the SM, but no clear signs have been at found at the LHC so far. This puzzle can be solved in two possible ways: either new states exist but they carry masses well beyond the energy reach of the LHC (but possibly within the reach of a $\sqrt{s} = 100$ TeV collider) or such new states are elusive enough that they escaped detection at the LHC (also within reach of a $\sqrt{s} = 100$ TeV collider given the amount of foreseen data).

The Higgs particle has been discovered at the LHC [1, 2], and only part of its properties, will be measured with high precision at the HL-LHC [3]. The strength of the Higgs self-coupling, if SM-like, is barely accessible at HL-LHC due to a lack of statistics. A $\sqrt{s} = 100$ TeV collider satisfies the needed requirements to measure this coupling to a percent level precision [4–6]. Such a precision could provide valuable insights on the nature of the Higgs potential and on the electro-weak phase transition (EWPT) [7]. In addition, with the abundant samples of Higgs events available at the FCC-hh, rare Higgs decays such as $H \rightarrow \mu^+ \mu^-$ and $H \rightarrow Z \gamma$ will be measurable to the percent level [5], and exclusive decay such as $H \rightarrow \rho \gamma$ and $H \rightarrow Q \gamma$ will potentially give insights to first a second generation Yukawa couplings. It should be noted that new physics can be constrained indirectly by measuring standard model parameters to high accuracy.

A multipurpose detector that collects data within the FCC-hh must therefore operate optimally on three main fronts. Physics at the EW scale, in particular the Higgs, will produce objects in the detector with momenta in the range $p_T = 20 - 100$ GeV. The LHC detectors were built to produce an optimal response in such an energy range. A new regime, at the energy frontier, will be characterised by the energy scale of decay products originating from high mass resonances (potentially as high as $M_X = 50$ TeV). An FCC-hh detector must be therefore capable of reconstructing and identifying leptons, jets, and potentially top, $H$ and $W/Z$ bosons with momenta as large as $p_T = 20$ TeV to provide accurate measurements in a wide energy spectrum. Such a detector must also be able to identify elusive signatures, that might originate from compressed spectra of Beyond Standard Model (BSM) theories [8–10]. Such signatures include soft leptons (with momenta as low as $p_T = 5$ GeV), and more exotic final states originating from the production long-lived particles (neutral or charged), such as disappearing tracks [11, 12] or displaced leptons or jets [13–15]. Since evidence for such signals would unambiguously indicate the presence of new physics, the FCC-hh experimental apparatus must also be designed and optimized to maximize its sensitivity to those elusive signatures.

This note addresses the general specifications that should satisfy a detector operating in the FCC-hh environment in order to maximise the FCC-hh physics potential. The specific choice of detector technologies is not discussed here, and can be found in Refs. [16, 17].

1 General considerations on the acceptance

Proton collisions at $\sqrt{s} = 100$ TeV give access to a wide range of possible kinematics. The comparison of the kinematical coverage in the $(x, M_X)$ plane between $\sqrt{s} = 14$ TeV and $\sqrt{s} = 100$ TeV is shown in Figure 1, where $x$ is the fraction of the proton longitudinal momentum and $M_X$ is the characteristic mass-energy scale of the process under consideration. The large c.o.m. energy allows for the production of resonances with masses up to $M_X = 100$ TeV. Due to the rapid fall-off of the parton distribution functions (PDFs) in the high $x$ region however, the cross-section for producing heavy particles with masses $M_X > 50$ TeV is negligible, even in the case of strongly coupled resonances. Energy momentum conservation requires large $M_X$ resonances to be produced in relatively balanced collision, i.e. mostly at rest. A two body decay for a particle produced at rest results in a 95% probability that both decay products lie in a region of pseudo-rapidity $|\eta| < 2.5$. As a bare minimum, in order to allow for an
1 General considerations on the acceptance

Process occurring at a given characteristic energy scale $Q^2 = M_X$ will be produced on average from collisions that are more asymmetric at $\sqrt{s} = 100$ TeV compared to $\sqrt{s} = 14$ TeV. This effect, clearly visible in Figure 1, is due to the fact that, for a maximally imbalanced collision, the minimum available longitudinal momentum fraction is given by $x_{\text{min}} = M_X^2 s$. A maximally imbalanced collision corresponds to one of the partons entering the collision parton carrying a momentum fraction $x_{\text{max}} = 1$ of the proton momentum. In practice, due to the rapidly falling PDFs at high $x$, one can assume $x_{\text{max}} \approx 0.5$, which gives $x_{\text{min}} \approx \frac{2M_X^2}{s}$ corresponding to a maximal rapidity $y_{\text{max}} = -\ln\left(\frac{2M_X}{\sqrt{s}}\right)$. As a result, at the FCC-hh the decay products of the particles of interest will be produced on average more forward compared to the LHC. For example, at $\sqrt{s} = 14$ TeV, a Higgs boson originating from gluon fusion can be produced up to rapidities $y_{\text{max}} \approx 4$, whereas at $\sqrt{s} = 100$ TeV it can be produced up to $y_{\text{max}} \approx 6$. This effect is illustrated in Figure 2 where the pseudo-rapidity distribution of the most forward lepton in a $H \to ZZ' \to 4\ell$ decay (left) and the most forward jet in vector boson fusion Higgs (right) is shown for two different collision energies.

This aspect of $\sqrt{s} = 100$ TeV collisions sets stringent requirements on the detector acceptance. In particular, in order to maintain high efficiency for reconstructing top, Higgs, W and Z particles, which will constitute a substantial part of the FCC-hh physics programme, the FCC-hh detector must be able to reconstruct decay products up to very large rapidities, $\eta \approx 6$. Since the forward region of the detector...
suffers from the largest levels of radiation and the worse intrinsic achievable detector performance (due to multiple scattering and a higher relative impact of pile-up), such a requirement on the design comes with significant challenges.

Provided that forward detectors can be operated in the extreme environment of the FCC-hh, the missing transverse energy $E_T^{\text{miss}}$ performance can benefit from having a larger geometric acceptance. The probability to reconstruct $E_T^{\text{miss}}$ above some threshold in QCD events (that contain little to no generated invisible energy) is shown in Figure 3 (left) for various assumptions on the detector $\eta$ coverage. The tails in the $E_T^{\text{miss}}$ distribution result from both the intrinsic resolution of the detector active element as well as the lack of hermeticity of the detector. A large acceptance definitely benefits the $E_T^{\text{miss}}$ resolution. A reduction of the $E_T^{\text{miss}}$ tails in QCD or Drell-Yan backgrounds can be highly beneficial to searches involving requiring large $E_T^{\text{miss}}$ in the final states. This is the case for virtually all supersymmetric (SUSY) final states in R-parity conserving scenarios where the $E_T^{\text{miss}}$ is produced by the lightest super-symmetric particle (LSP).

Based on the above considerations, we require for the FCC-hh detector a pseudo-rapidity coverage up to $|\eta| = 6$. Extensive details on the actual implementation of the detector geometry are discussed in Refs. [16, 17]. More specifically, we require precise calorimetry up to $|\eta| = 6$. Given the intrinsic limitations due to the multiple scattering in the forward region, precise tracking up to $|\eta| = 6$ forward region will be extremely challenging. We therefore require precise tracking up to $|\eta| = 4$ for the FCC-hh detector, as planned for the HL-LHC multipurpose experiments [19, 20], and forward spectrometry up to $|\eta| = 6$.

1.2 Minimum momentum requirements

Higgs and SM related processes are useful benchmarks in order to define minimal detector requirements for reconstructing and identifying low momentum objects. In particular, one of the golden Higgs decay modes is the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel. This decay channel features the presence of a very soft lepton ($p_T \approx 5$ GeV) originating from the off-shell $Z$. Another important physics case for efficiently reconstructing low momentum leptons is electro-weakly produced SUSY. Electro-weakinos in SUSY provide compelling weakly interacting dark matter candidates (WIMPs), the LSP. In the SUSY parameter space LSPs might lie in so-called compressed regions, where the mass difference between the the next-to-LSP (NLSP) and the LSP very small. This class of decay chains typically produce very soft leptons since it involves
the production of highly off-shell $W$ or $Z$ bosons. The probability to reconstruct the softest leptons in $p \rightarrow \chi^\pm \rightarrow \chi^0 \ell^+ \ell^-$ events as a function of the threshold on the $p_T$ of the lepton is given in Figure 3 (right) for three hypothetical compressed SUSY scenario. It appears clearly that in order to maintain the largest possible sensitivity to such signatures the FCC-hh detector will need to be able to reconstruct and unambiguously identify leptons down to momenta of few GeVs.

Electrons and muons are reconstructed as charged particle trajectories in the tracking volume. The identification of the electrons performed via a combination of tracking and electro-magnetic calorimeter (ECAL) based observables. Due to presence of a large magnetic field, electrons can be identified if their momenta is above some threshold $p_T^{\text{min}}$, defined as the momentum required to reach the ECAL. Like-wise, muons can be identified only if they are able reach the muon spectrometers. To be more concrete, we assume a multi-purpose detector setup with a tracking volume and a calorimeter embedded inside a solenoidal magnetic field. Muon chambers are placed after the solenoid, therefore the minimal momentum for reconstructing and identifying muons $p_T^{\text{min}}$ is typically larger than for electrons. As discussed in the next paragraph, a large magnetic field and a large detector volume are desirable in order to obtain a good tracking momentum resolution, which is in tension with the requirement of being able to identify low momentum leptons. Defining the maximum radial distance $R_{\text{max}}$ for the identification detector (ECAL for electrons and first muon station for muons), and using $p_T = 0.3B\rho$, where $B$ is the solenoidal magnetic field strength in $[T]$, $\rho$ is the track curvature in $[m]$ and $R_{\text{max}} = 2\rho$ we can derive $R_{\text{max}}$. We find that in order to reconstruct muons with $p_T^{\text{min}} = 4$ GeV, the first muon station needs to placed at $R_{\text{max}} = 6.5$ m with a detector operating in a field $B = 4$ T. If we consider the energy loss of muons in the calorimeter absorbers the threshold increases by a few GeV to $p_T^{\text{min}} = 6 - 7$ GeV. With a tracking volume defined as a cylinder with $R = 1.5$ m (corresponding approximately to the start of the ECAL), this corresponds to a threshold for being able to identify electrons of $p_T^{\text{min}} = 1$ GeV. It should be noted however that in practice this should be considered as an idealized limit. In current LHC multi-purpose experiments ATLAS and CMS, electrons with $p_T < 3$ GeV can be hardly identified unambiguously due to energy loss, even with a lower lever-arm. We therefore set $p_T^{\text{min}} = 4$ GeV for electrons as a target.

Figure 3: Left: Probability of reconstructing $E_T^{\text{miss}}$ greater than $E_T^{\text{miss}}(\text{min})$ in di-jet QCD events for various assumptions on the detector acceptance. Right: Probability of reconstructing the softest lepton in electroweakino production for different scenarios of compressed super-symmetric spectra.
2 Energy-momentum resolution

The scope of the FCC-hh is to carry an extensive programme of Standard Model and Higgs measurements and to explore the energy frontier by directly probing the production of multi-TeV resonances. Therefore the decay products of the particles of interest have to be detected and measured as precisely as possible in a wide range of energies.

The energy resolution in calorimeters as function of the incoming particle energy $E$ is given by:

$$\frac{\sigma_E}{E} = \frac{A}{E} \oplus \frac{B}{\sqrt{E}} \oplus C\%,$$

where $A$ is noise the term, $B$ is the stochastic term and $C$ is the constant term. The relative resolution is a decreasing function of the energy. At high energy, the resolution asymptotically tends to $C$, which is ultimately determined by inhomogeneities in the detector and eventual energy leakages due to partial shower containment.

The tracking gives access to the momentum of charged particles by measuring the curvature $\rho$ (or the "sagitta" $s$) of the trajectory. The relative uncertainty on the momentum resolution is given by:

$$\frac{\sigma_p}{p} = a \oplus b \cdot p,$$

where $a$ is the constant term determined by the amount of material responsible for multiple scattering in the tracking volume. In contrast to the energy measurement in calorimeters, the momentum resolution increases linearly with the incoming particle momentum, in the high energy limit. The constant $b$ is proportional to $\sigma_x/BL^2$, where $\sigma_x$ is the single point resolution of the tracking elements, $B$ is the field strength and $L$ is the tracker radius. The measurements provided by the tracking system and the calorimeters are therefore complementary, for particles like charged hadrons or electrons that deposit in both sub-detectors.

2.1 The low energy limit

2.1.1 Tracking

It is crucial to design a detector that maximises the achievable precision in measurements of rare Higgs decay modes such as $H \rightarrow Z\gamma$ or $H \rightarrow \mu^+\mu^-$ since such measurements will still be statistically dominated at the end of HL-LHC. The expected precision in these modes relies on the reconstruction of a narrow mass peak over a large background continuum. In order to achieve the best possible precision excellent electron and muon momentum resolution is needed. For charged particles in the low momentum regime ($p_T < 100$ GeV) maximizing the performance requires minimizing the impact of multiple-scattering. This can be achieving both by minimizing the total material budget in tracker and the beam-pipe as well by adopting a so-called tilted module geometry. For the FCC-hh detector we require a track momentum resolution $\sigma_p/p \approx 0.5\%$ in the multiple scattering limit at $\eta \approx 0$, which corresponds roughly to $0.2X_0$ radiation length of material for the entire tracking volume. In Figure 4 (left) we show the impact of the muon momentum resolution on the $H \rightarrow \mu^+\mu^-$ invariant mass peak obtained with the CMS-Phase II tracker [21] and the FCC-hh tracker prototype. The tracking requirements are summarized in Table 1. We note that the muon spectrometers have a negligible impact on the muon momentum resolution in the low momentum regime, and the resolution is driven almost entirely by the tracking system.

2.1.2 Calorimetry

The precise measurement of the Higgs self-coupling in the $HH \rightarrow b\bar{b}\gamma\gamma$ decay mode relies on excellent energy photon resolution in the $E = 50 - 100$ GeV energy range. A di-photon invariant mass resolution $\Delta m_{\gamma\gamma} \approx 1\%$ for photons from $H \rightarrow \gamma\gamma$ decays can be achieved only if the stochastic term $B$ defined in
Equation 1 is a the level $\sigma_E/E \sim 10\%/\sqrt{E}$ and the noise term is kept under control. Pile-up will lead to additional noise in the calorimeter. The effect of the noise term of pile-up on the photon energy resolution has been studied extensively in full simulation and is discussed in Ref. [17]. The expected pile-up of $\langle \mu \rangle = 200$ and $\langle \mu \rangle = 1000$ for the FCC-hh baseline and ultimate scenario, respectively, will lead to energy deposits from pile-up collisions on top of the hard scatter of interest. The induced degradation has been parameterised directly on the di-photon invariant mass and its impact on the expected precision of the Higgs self-coupling has been studied and summarised in Ref. [5]. The result of this study, shown in Figure 4 (right), shows that the presence $\langle \mu \rangle = 200$ pile-up interactions can lead to an absolute degradation of $\approx 1\%$ (or 20% relative) on the self-coupling precision. It should be noted that this study does not include the effect of pile-up on the photon isolation and it assumes a standalone calorimeter reconstruction. A combined reconstruction using tracking, calorimetry and timing information will be needed to reduce the impact of pile-up and achieve the target photon energy resolution.

### 2.2 The high energy limit

With the exception of muons and neutrinos, all particles originating from the collision end their journey in the calorimeters. Therefore, the energy resolution of electrons, photons and jets at high energy will be determined entirely by the calorimeter performance. In contrast, high energy muons traverse calorimeters and their momentum is determined via a combination of tracking, calorimeter and muon chambers measurements. Multi-TeV resonances constitute useful processes for determining detector performance goals in the high energy regime. A summary of the physics reach of the FCC-hh for heavy resonances searches can be found in Refs. [22, 23].

#### 2.2.1 Electrons, photons and hadrons

As discussed previously, the energy resolution at high energy is determined by the constant term defined in Equation 1. The value of the constant term is different for electro-magnetic (ECAL) and hadronic (HCAL) calorimeters. It is ultimately determined by the choice of the calorimeter technology and the design. Large constant term typically originate from inhomogeneities among different detector elements
and energy leakages due to sub-optimal shower containment. The calorimeters of the FCC-hh detector must therefore be capable of containing EM and hadronic showers in the multi-TeV regime in order to achieve small constant terms. Compatibly with the LHC experiments, we require a performance of $\sigma_E/E \approx 0.3\%$ and $\sigma_E/E \approx 3\%$ for the ECAL and HCAL respectively. As shown in Figure 5 (left), the effect induced by the magnitude of the hadronic calorimeter constant term on the expected discovery reach for heavy $Z'$ resonances decaying hadronically is sizable. We note that, despite the fraction of electromagnetic energy from $\pi^0$'s large in jets, the sensitivity is entirely driven by the hadronic calorimeter resolution given its worse intrinsic resolution. The shower maximum in the longitudinal direction grows logarithmically with the energy. Naive scaling leads therefore to an increase respectively of $1X_0$ and $1\lambda_I$ compared to the calorimeters of the LHC experiments. More detailed studies, summarised in Ref. [17, 24], show that an average 95% containment of $E = 20$ TeV particles showers can be achieved with $\approx 30X_0$ radiation lengths for EM particles and a total thickness of $\approx 11\lambda_I$ for hadrons allowing to match respectively the required criteria for the electro-magnetic and hadronic calorimeters constant terms.

### 2.2.2 Muons

Muons can hardly be fully reconstructed with calorimetric methods. Since the muon momentum is obtained through a fit of the trajectory that uses as input a combination of track and muon spectrometer hits, the muon momentum resolution resolution degrades with increasing momentum, as shown already in Equation 2. As with jets, electrons and photons, a good muon momentum resolution at multi-TeV energy is crucial for maintaining a high sensitivity in searches for heavy new states that might decay to muons. The reach for a $Z' \rightarrow \mu\mu$ resonance obtained with various assumptions on the muon resolution is illustrated in Figure 5. The best sensitivity is achieved with an assumed $\sigma_p/p \approx 5\%$ at $p_T = 20$ TeV corresponding to our target for the FCC-hh detector, as opposed to the projected CMS resolution of $\sigma_p/p \approx 40\%$. In order to reconstruct and measure accurately the momentum of $p_T = 20$ TeV a large lever arm is needed and excellent spatial resolution and precise alignment of the tracking plus muon systems is needed. The specifics of design that allows to reach such required performance is discussed extensively in Ref. [25].

## 3 Object reconstruction and identification performance

As a general rule, object identification requires the use of the combined information of several sub-detector systems and relies on complex algorithms that require a detailed knowledge of the detector and

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4 Calorimetric information can however help for muon identification, especially at high energies. For example a 20 TeV muon deposits through radiative energy loss on average $\Delta E = 200$ GeV in 3 meters of iron, corresponding to 1% of the initial muon energy.
a mature simulation framework, none of which is available at this stage. However simple heuristics from first principles can help in defining the criteria for optimal performance object reconstruction and identification. High performance in object identification is equivalent to high identification efficiency for a low false positive rate (or fake-rate).

### 3.1 Electrons

Electron identification requires the use of the tracker, ECAL and HCAL information. More specifically, an electron object is a track that matches an ECAL deposit, with the requirement of a small HCAL energy deposit. To ensure a small HCAL deposit for electrons in a wide range of energies, one must design an ECAL with a large enough number of \( X_0 \), which is already ensured by the requirement of a small constant term in the energy resolution. The 3D shape of the EM shower in the calorimeter is distorted by the presence of brehmsstrahlung photons in the \( \phi \) direction, which can help in discriminating against photons that accidentally match the extrapolation of a charged hadron trajectory (in jets for instances), or directly against charged hadrons that happen to have small HCAL deposits. A precise reconstruction of the full shower shape is therefore of vital importance in order to achieve a low electron fake-rate from charge hadrons, and can be achieved with a high granularity calorimeter that gives access to an "image" of the shower.

### 3.2 Photons

Photon identification requires the presence of an ECAL deposit, and the absence of a track with compatible momentum pointing to it, and a negligible HCAL deposit. The probability of reconstructing "fake" photons from mis-reconstructed neutral hadrons can be kept small with a thick ECAL detector. However, the largest contribution of fake photons typically originates from \( \pi^0 \rightarrow \gamma\gamma \) decays, that are produced copiously at hadron colliders. To be more specific, a \( \pi^0 \) with \( p_T = 20 \text{ GeV} \) will decay into two photons separated by an average angular distance \( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 10 \text{ mrad} \). A large prompt photon identification efficiency and low mis-identification probability can be obtained with a highly segmented calorimeter, both in the transverse and in the longitudinal direction. An ECAL with transverse granular-
3 Object reconstruction and identification performance

$$\lambda/\text{obs}\lambda = \lambda_k^{0.8 \ldots 1.2}$$

![FCC-hh Simulation (Delphes)](image)

Figure 6: Left: Expected precision on the Higgs self-coupling modifier $\kappa_\lambda$ obtained for three scenarios of nominal degraded ($\times5$) and improved ($\times0.2$) photon mistag rate. Right: Discovery potential for a $Z'$ decaying to a $t\bar{t}$ pair for various scenarios of b-tagging efficiencies at very large $p_T$. The nominal efficiency is given in Ref.[26], and scenarios 1, 2, and 3 correspond to reduction of the slope in Table 7 respectively by a factor 25%, 33% and 50%.

... 1 cm$^2$ (placed at > 1 m from the IP) can achieve the required separation capability. In addition, the probability to resolve two photons from a $\pi^0$ decay can be increased by exploiting the full 3D shower information, thus improving the $\pi^0$ background rejection efficiency. The transverse and longitudinal calorimeter requirements a summarized in Table 1.

Due to the absence of a pointing track that can be associated to the hard interaction vertex, background photons from $\pi^0$ decays become more severe in the presence of pile-up. The reduction of such background will therefore necessarily require high resolution timing detectors that allow by triangulation to link neutral energy deposit to given interaction vertices. A large photon fake-rate can have a negative impact on flagship measurements at the FCC-hh, as shown for example in the case of the Higgs self-coupling in the $HH \rightarrow b\bar{b}\gamma\gamma$ channel in Figure 6 (left).

3.3 Muons

The mis-identification of muons results from in-flight charged pion decays or punch-throughs, i.e. hadron shower that are not fully contained in the HCAL and leak into the muon system. Again, such phenomenon can be contained by requiring a deep HCAL sub-detector, which is again automatically ensured by requiring high energy resolution for hadrons in the multi-TeV regime.

3.4 Boosted topologies

In addition to the more standard leptons, photons, jets and missing energy final states, new physics will be searched for in final states that include the presence of boosted objects topologies, i.e. boosted particles decaying hadronically and forming collimated jets. Such hadronic jets, as opposed to simple QCD jets, display an internal sub-structure, featuring 2 or more prongs. Moreover, the invariant mass of the jet $m_J \approx m_B$, of order the mass scale of the parent particle $B$, where $B = \tau, W, Z, H, t$. The reconstruction of boosted topologies is highly complex and will necessarily rely on the combined measurement of

5 To further complicate things, $\tau$ leptons are also long-lived, as discussed in Section 3.5. As a result, a significant fraction of multi-TeV $\tau$ will produce highly displaced ($\gamma \tau > 5$ cm) vertices.
several subdetectors. To be able to resolve the jet substructure, in addition to good energy resolution, an excellent angular resolution is necessary. For instance, in a $W$-jet with $p_T = 10$ TeV, the two hard prongs will be separated on average by angular distance $\Delta R = 0.02$, which is the typical transverse size of an ECAL crystal in the CMS detector. Reference [27] investigated the impact of different calorimeter granularities on the identification capability of highly boosted $Z'$ decaying to tops and $W$ bosons. While at moderate boost ($p_T < 10$ TeV) a better granularity improves the identification efficiency, at large momenta ($p_T > 10$ TeV) the efficiency saturates. Indeed extreme granularity at the calorimeter level will be anyway limited by the transverse size of the showers in the absorber, and only an optimized particle-flow approach, that fully exploits tracking and calorimeter information can extract the maximum information from highly boosted topologies. From these preliminary studies, it is however clear that high transverse (and possibly longitudinal) granularity is therefore required for optimal boosted topologies identification performance, both in the tracking and the calorimeter systems. While further studies in full-simulation are needed to address this point we set targets for the lateral and longitudinal segmentation of the FCC-hh calorimeters to fulfill the parameters given in Table 1.

3.5 Heavy flavour

New heavy states could decay to multi-TeV $c$ and $b$-quarks. FCC-hh detectors must therefore be capable of efficiently identifying multi-TeV long-lived hadrons. A $p_T = 5$ TeV $b$-hadron is qualitatively very different from $p_T = 100$ GeV $b$-hadron. The latter decays on average within the vertex detector acceptance and can be identified by means of displaced vertex reconstruction. Conversely, the former decays on average at a distance $\gamma c\tau = 50$ cm, well outside the pixel detector volume. Reconstructing such highly displaced b-jets will require a paradigm shift in heavy flavour reconstruction. Algorithms exploring large hit multiplicity discontinuities among subsequent tracking layers [28] are required. The success of such algorithms heavily relies on excellent granularity of the tracking system, in both longitudinal and transverse directions. High efficiencies ($\varepsilon_b > 60\%$) for corresponding low mis-identification probability ($\varepsilon_u,d,s < 1\%$) from light jets have to be achieved up to $p_T = 5$ TeV. For example, searches for heavy resonances decaying to hadronic $t\bar{t}$ pairs heavily rely on efficient $b$-tagging performance at such energies. The discovery reach for a specific $Z'$ model assuming several scenarios for $b$-jet identification at high energies is shown in Figure 6.
References


