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Physics requirements for the FCC-hh calorimeter system

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Physics requirements for the FCC-hh calorimeter system

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Abstract. The future proton-proton collider (FCC-hh) will deliver collisions at a center of mass energies up to $\sqrt{s}$ = 100 TeV at an unprecedented instantaneous luminosity of $\mathcal{L} = 3\ 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, resulting in extremely challenging radiation conditions up to a maximum of 5 $10^{18}\mathrm{cm}^2$ MeV neutron equivalent fluence and dose up to 5 GGy in the forward calorimeters (up to $|\eta|$ =6) and up to 1000 simultaneous proton-proton interactions per bunch-crossing. By delivering an integrated luminosity of few tens of ab^{-1}, the FCC-hh will provide an unrivalled discovery potential for new physics. Requiring high sensitivity for resonant searches at masses up to tens of TeV imposes strong constraints on the design of the calorimeters. Resonant searches in final states containing jets, taus and electrons require both excellent energy resolution at multi-TeV energies as well as outstanding ability to resolve highly collimated decay products resulting from extreme boosts. In addition, the FCC-hh provides the unique opportunity to precisely measure the Higgs self-coupling in the di-photon and b-jets channel. Excellent photon and jet energy resolution at low energies as well as excellent angular resolution for pion background rejection are required in this challenging environment.

1. Introduction

The Future Circular Collider (FCC) is the ambitious project of an accelerator complex in the CERN area for the after LHC era. An electron-positron collider (FCC-ee) is considered as a possible first step to measure precisely the Higgs properties. The main drive on the complex tunnel and infrastructure is set by a 100 TeV hadron circular collider (FCC-hh). Such center of mass energy can be achieved by means of a 100 km tunnel and 16 T bending dipole magnets. The FCC-hh will deliver a peak luminosity of $\mathcal{L} = 3\ 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ in its ultimate phase. This will result in O(20) ab^{-1} of integrated luminosity per experiment. Such high luminosity defines stringent requirements on the radiation hardness of the detector, in particular in the forward region at small angular distances from the beampipe.

The FCC-hh machine allows for a direct exploration of massive particles up to 40 TeV [4], improving by approximately one order of magnitude the LHC sensitivity for discovering heavy resonant states. In addition, during its lifetime the FCC-hh is expected to produce trillions of top quarks and tens of billions of Higgs bosons allowing for a rich standard model precision program [3]. Most importantly, a 100 TeV machine will be the only machine allowing for a percent level measurement of the Higgs self-coupling [3]. It is therefore essential to design detectors that provide excellent energy resolution in a wide range of energy.

In this note we will describe the requirements that are imposed upon the calorimeter design by the accelerator environment such as the pile-up and by a set of benchmark physics channels.

2. Calorimeter requirements and performance

The full description of the present implementation of the FCC-hh calorimeters and detector is given in [8]. Rather than discussing the FCC-hh calorimeter prototype in detail, we discuss here the physics arguments that constrain the detector design and in turn the impact that such design has on specific object and physics performance.

2.1. Requirements at low energy

The FCC-hh will feature an extensive standard model precision program. In particular, the large statistics driven by the increase in the production cross-sections of interesting physics processes and the ≈ 6 times higher luminosity compared to the high-luminosity LHC (HL-LHC) will allow for percent level precision in the Higgs coupling measurements [3]. Final states produced at a given chacteristic energy scale Q, will be produced on average at higher rapidities at $\sqrt{s} = 100$ TeV compared to $\sqrt{s} = 14$ TeV. As an illustration of such an effect, in Figure 1 we show respectively the pseudo-rapidity of most forward jet (lepton) in vector boson fusion (gluon fusion H, H $\rightarrow 4\ell$) events at the FCC-hh and the LHC. In order to maintain the acceptance for such events, it is crucial to design calorimeters that extend to up to $|\eta| = 6$ for the FCC-hh as opposed to $|\eta| = 5$ for the LHC. Needless to say, in the calorimeter endcaps the radiation levels will be extremely high, e.g. the 1 MeV neutron equivalent fluence will be $\approx 2\ 10^{16}\text{cm}^{-2}$ implying that radiation hardness will be a key requirement for such sub-detectors.

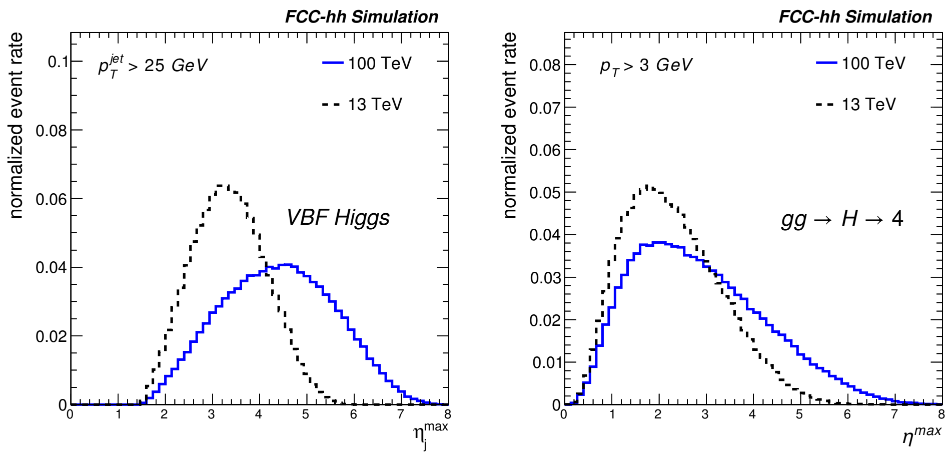

Figure 1. Maximum jet pseudo-rapidity for vector-boson fusion Higgs (left) and maximum lepton pseudo-rapidity for gluon-gluon fusion Higgs decaying to 4 leptons (right).

2.1.1. Pile-up jet identification Pile-up interactions can affect the global event reconstruction in many ways. In extreme pile-up regimes (PU$>$ 200), random associations of low energy showers can fake prompt jets, especially in the forward region of the detector where large amounts of energy are deposited. This can have large effects on measurements of processes that feature the presence of forward jets such as vector boson fusion Higgs production. Pile-up jets can be disentangled from prompt jets by exploiting the difference in the longitudinal and transverse energy profile. In Figure 2 (left) the energy of the jet per layer normalized to the total jet energy is shown as a function of the layer number. It can be seen clearly that a large fraction of the energy is deposited in the first layers for pile-up jets. The explanation is that pile-up jets feature a uniform soft energy distribution among its consituents that penetrate few layers of the calorimeter, as opposed to a prompt QCD jet that is typically made up of fewer and harder long lived hadrons. Similarly the transverse energy profile, integrated over all layers of the ECAL and HCAL subdetectors can be seen respectively in Figures 2 (center and right). Prompt jets concentrate their deposited energy on a well-defined center whereas pile-up jets feature a uniform diffuse transverse energy profile. Having at disposal such handles, provided by a high longitudinal and tranverse segmentation will clearly improve the identification of pile-up jets. Finally we note that an optimal pile-up rejection can be performed with the so-called particle flow approach [5] that aims at combining optimally calorimetric and tracking information into single particle candidates. Since particle-flow does rely on extrapolating and matching reconstructed tracks to calorimeter deposits, it is clear that in order to achieve an optimal performance with such an approach the highest possible transverse and longitudinal granularity should be aimed for.

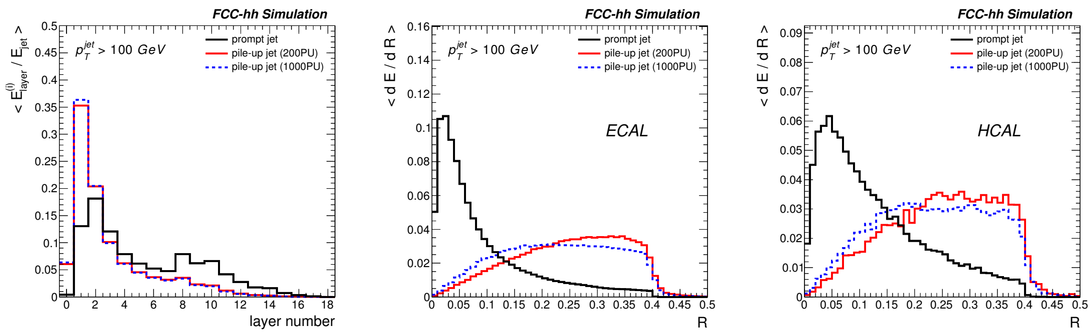

Figure 2. Left: Energy of the jet per layer normalized to the total jet energy is shown as a function of the layer number. Center and Right: Transverse energy profile, integrated over all layers of the ECAL (center) and HCAL (right) subdetectors.

2.1.2. Photon resolution and identification The precise assessment of the Higgs self-coupling λ is a key measurement at the FCC-hh. The golden channel for measuring this SM parameter is the HH $\rightarrow$ bb$\gamma\gamma$ channel. A resolution of 1.5 GeV on the di-photon mass is mandatory in order to measure λ with a 5% precision with $\mathcal{L} = 30$ ab^{-1} [3]. To ensure such precision a small stochastic term for the calorimetric response, at the level of $10\%/\sqrt{E}$ is required.

This channel is swamped by a large QCD background, where jets, and in particular neutral pions in jets can mimic prompt photons. For instance, a π^0 with $p_T = 50$ GeV will decay into two photons separated by an average angular distance ΔR = 2 mrad. A high 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. By exploiting the full 3D shower information, it is expected that the two photons from a π^0 decay could be resolved, at least partially, hence considerably improving the background rejection effciency. Further studies with full simulation are needed in order to assess the minimum transverse granularity.

The high-luminosity phase of the FCC-hh, with 1000 simultaneous interactions per bunch crossing will pose a significant challenge for photon reconstruction. Figure 3 (left) shows the effect of pile-up on the di-photon mass spectrum. On the right we show the effect of a degradation of the invariant mass resolution on the expected precision on the Higgs trilinear coupling determination. A sizeable 1.5% deterioration on the measurement can be observed with the presence of high pile-up, highlighting the importance of efficient pile-up rejection. Charged particle-flow candidates originating from pile-up vertices can be rejected. It is clear however that additionnal handles to reject pile-up will be necessary in such an evironment, such as timing information to reject neutral energy deposits that are not compatible with the hard scattering vertex. In addition, in order to obtain the best possible mass resolution, the energy momentum vectors of the photons will have to be matched to (and corrected for) the position of the primary vertex. For this purpose, designing an electromagnetic calorimeter with an excellent pointing capability is crucial. Such a feature can be achieved with sufficiently fine longitudinal segmentation. Nevertheless, the additional use of the photon time of flight will be vital in order to improve the photon vertex compatibility. Again, accurate full simulation studies are needed in this area, but based on preliminary results from HL-LHC [2] it is foreseen that timing capabilities below 10 ps will be needed.

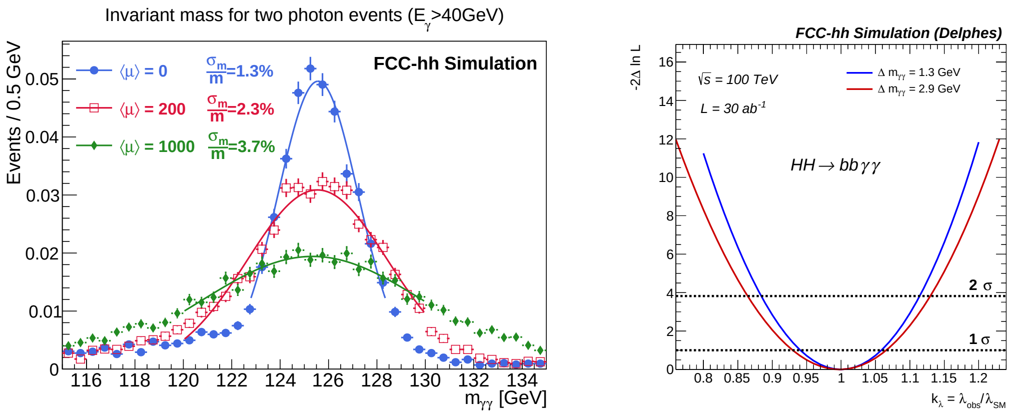

Figure 3. Left: Di-photon invariant mass spectrum in the presence of 0, 200 and 1000 pile-up interactions. Right: Sensitivity of the precision on the Higgs self-coupling in the HH $\rightarrow$ bb$\gamma\gamma$ final state obtained with two different assumptions on the di-photon mass resolution.

2.2. Requirements in the boosted regime

The main purpose of the FCC-hh will be to explore the energy frontier. The detector will need to be capable of measuring decaying objects with transverse momenta as high as 20 TeV. For such purpose, the hadronic and electromagnetic calorimeters need to ensure sufficient shower containment, high uniformity and hence a small constant term in the energy resolution. Figure 4 (left) shows that 11λ_I nuclear interaction lengths are needed to contain 98% of the shower energy for jets with $p_T = 20$ TeV. The impact of the hadronic calorimeter constant term can be readily seen by studying the sensitivity for discovering high mass narrow resonances for a given integrated luminosity. In Figure 4 (right), taken from [7], we show the expected significance as a function of the resonance mass for various di-jet mass resolution assumptions. The horizontal dashed line represents the 5-σ threshold needed for discovery. As expected, large gains are observed by assuming the highest possible di-jet mass resolution $\Delta = 1\%$, i.e the smallest calorimeter constant term. It should be noted that a compromise between full containment and detector size should be achieved: the external radius of the hadronic calorimeter defines the radius of the solenoid, which ultimately drives the cost of the detector.

High mass resonances can decay not only to QCD jets, but also to boosted W, Z bosons, top quark and Higgses, that can in turn decay hadronically. Such hadronic jets, as opposed to simple QCD jets, are characterised by an internal substructure, featuring 2 or more prongs and a jet mass of order the mass scale of the boosted object. To be able to resolve the jet substructure, in addition to good energy resolution, an excellent angular resolution is necessary. For instance,

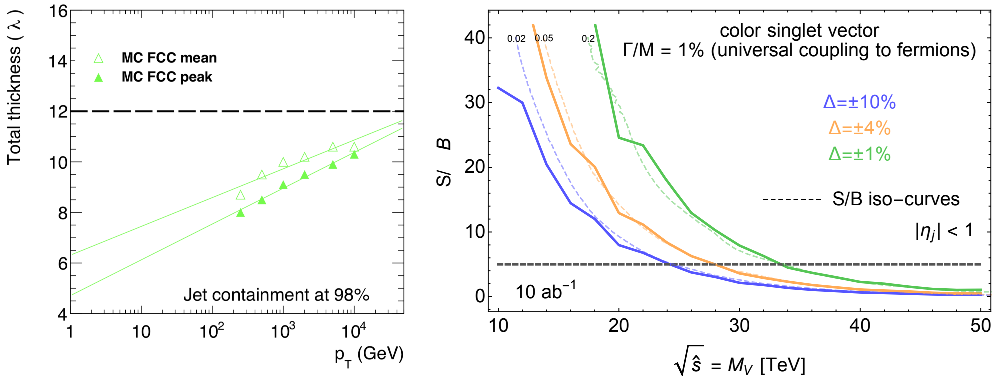

Figure 4. Left: Total depth in units opf interaction length needed to contain 98% of the shower energy as a function of the jet p_T. Right: Expected significance for observing heavy narrow mass states as a function of the resonance mass for various di-jet mass resolution assumptions.

in a W jet with $p_T = 10$ TeV, the two prongs will be separated on average by $\Delta\mathrm{R} = 0.02$, the typical transverse size of an ECAL crystal in the CMS detector. A similar conclusion as for the π^0 decay case applies here: a high transverse (and possibly longitudinal) granularity is required. An open question, to be answered in further studies is whether the calorimeter segmentation translates in actual separation power. Indeed at some small lateral size, possibly smaller than the transverse shower size, the improvement is expected to reach a plateau. We discussed in the previous section several additional reasons (π^0 rejection, particle-flow reconstruction, pile-up jet identification) for aiming at maximum detector granularity, a compromise should however be reached between performance versus cost and data rate, since high granularity implies a large number of channel, and large amounts of data to be read out.

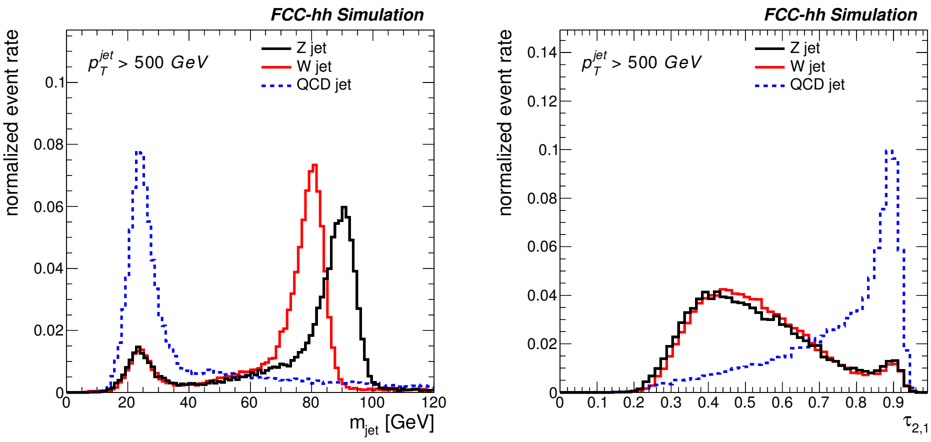

Figure 5. Jet substructure observables for boosted QCD, W and Z jets with $p_T = 500\mathrm{GeV}$. Left: Jet mass. Right: N-subjettiness ratio $\tau_{2,1}$.

The impact of a high lateral segmentation can be seen on observables that are sensitive to the angular separation in jets. The mass of a highly boosted jet depends both on the energy and the angular separation of hadrons and can be used for such an investigation. Another useful variable is the N-subjettiness ratio $\tau_{2,1}$. A detailed description of this complex observable can be found here [6]. We simply point out that this variable is also built from the energy-momentum vector of the jets constituents. It is expected to peak at values close to 0 if the jet features a 2-prong structure (such as W, Z of Higgs jets) and close to 1 if the jet substructure is one prong-like. Jets are reconstructed with anti-kT algorithm [1] with R=0.2 directly from calorimeter hits. No magnetic field was applied in the simulation implying that charged and neutral hadrons are treated equally and no pile-up was assumed. In Figure 5 (left) we show the reconstructed jet mass for W, Z and QCD with $p_T = 500$ GeV. A good separation between QCD and V=W,Z jets can be observed, as well as decent discrimination between W and Z bosons. In Figure 5 (right) we show the $\tau_{2,1}$ variable. Although W and Z jets can hardly be discriminated with $\tau_{2,1}$ (both feature a two-prong structure), it is clear that this observable provides a handle versus background QCD jets. It should be noted that this preliminary study does not make use of tracking, that is expected to provide additional angular separation power for jets, especially in combination with calorimetric information using the so-called particle-flow approach. In such paradigm, high (transverse) granularity is indeed crucial in order to uniquely assign tracks to calorimeter deposits.

3. Conclusion

The FCC-hh 100 TeV pp collider will present a unique opportunity for measuring key standard model parameters such as the Higgs self-coupling and Higgs rare decay branching ratios. This machine will also allow for unprecendeted high mass reach, with possible direct discovery of yet unknown states in the multi tens of TeV regime. Designing a detector that can maximize the potential for both discovery and precision, while being capable of withstanding an extremely challenging environment in terms of radiation and data rates as well as complying with cost constraints is a complex task. In this note we have restricted the discussion the calorimeter design, by focussing on the basic specifications that such a sub-detector necessarily needs to possess: high radiation tolerance, high resolution in low and high energy regimes, high longitudinal and transverse granularity and robustness against pile-up. Following these guidelines, a prototype calorimeter system with such specifications has been designed [8] and further detailed studies are ongoing.

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