

Delphes Parameterisation of the FCC-hh detector

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Abstract

A DELPHES parameterization of the benchmark FCC-hh detector is presented. The tracking performance and the electromagnetic and hadronic calorimeter resolutions have been derived from dedicated simulations of the various sub-detectors. The leptons, photons and heavy flavour identification efficiencies and misidentification probabilities are inspired by the performance of the LHC multipurpose detectors. The FCC-hh DELPHES detector configuration can be used as a baseline parameterization to assess the physics reach of a 80-120 TeV proton proton collider, but should by no means be intended to represent the ultimate performance a detector operating in a future hadron collider experiment. The FCC-hh DELPHES configuration card is available in the official DELPHES release [1].

1 Introduction

Accurate simulation of particle detector responses is essential for the design and interpretation of high-energy physics experiments. While full detector simulations — using tools such as `GEANT4`[2] — provide detailed modeling of particle interactions with matter, they are computationally intensive. DELPHES offers a fast simulation alternative for multipurpose detectors[3], using parameterized detector responses based on resolution functions and efficiencies. The DELPHES simulation includes a track propagation system embedded in a magnetic field, electromagnetic and hadron calorimeters, and a muon identification system. Physics objects that can be used for data analysis are then reconstructed from the simulated detector response. These include tracks and calorimeter deposits and high level objects such as isolated leptons, jets, taus, and missing energy. DELPHES also offers a simplistic particle-flow reconstruction that combines tracks and calorimeter information in an optimal way to form particle candidates. These particle candidates are then used as input for jets clustering as well as the calculation of missing energy and isolation variables. DELPHES also provides heavy flavour tagging parameterizations and jet substructure algorithms. A detailed description of the DELPHES framework can be found in Ref., [3]. An algorithm for reconstructing the track parameters and covariance matrix of charged particles for an arbitrary tracking sub-detector geometries has been recently developed [4]. Additional modules allowing for particle identification using time-of-flight and ionizing energy loss information have been implemented.

The baseline FCC-hh detector is described in Ref. [5]. The FCC-hh DELPHES configurations can be found in the official DELPHES release [1] as well as in the FCC-config software webpage [6]. Several updates and bug fixes are introduced in the latest parametrization for the FCC-hh detector described in this note with respect to a previous version [7] used for the CDR studies. Briefly summarizing, the main updates are:

- A specific parametrization for the momentum resolution of electrons was introduced, which now takes into account the effect of Bremsstrahlung in this case. In consequence, the momentum resolution of electrons is approximately 50% worse than that of charged pions (which was not the case in the previous version).
- The multiple scattering parametrization for muons was adapted to no longer yield a better resolution for pions than for muons in the very central region (around $|\eta| = 0$).
- An issue with the resolution parameterization functions in the forward region that caused undefined values to be obtained was resolved.

2 Tracking

The first step of the simulation implemented by DELPHES is the propagation of long-lived particles within a uniform axial magnetic field with $B_z = 4$ T. The magnetic field is assumed to be localized in the inner tracker volume. In DELPHES only a single cylindrical volume can be defined as the propagation tracking volume. This differs from the actual tracker design [5] of the FCC-hh detector, where a central and forward tracker are defined with different radii and half-lengths. The magnetic field is assumed

to be localized in the inner tracker volume, defined as a cylinder of radius $R_0 = 1.5$ m and a half-length $Z_0 = 5$ m.

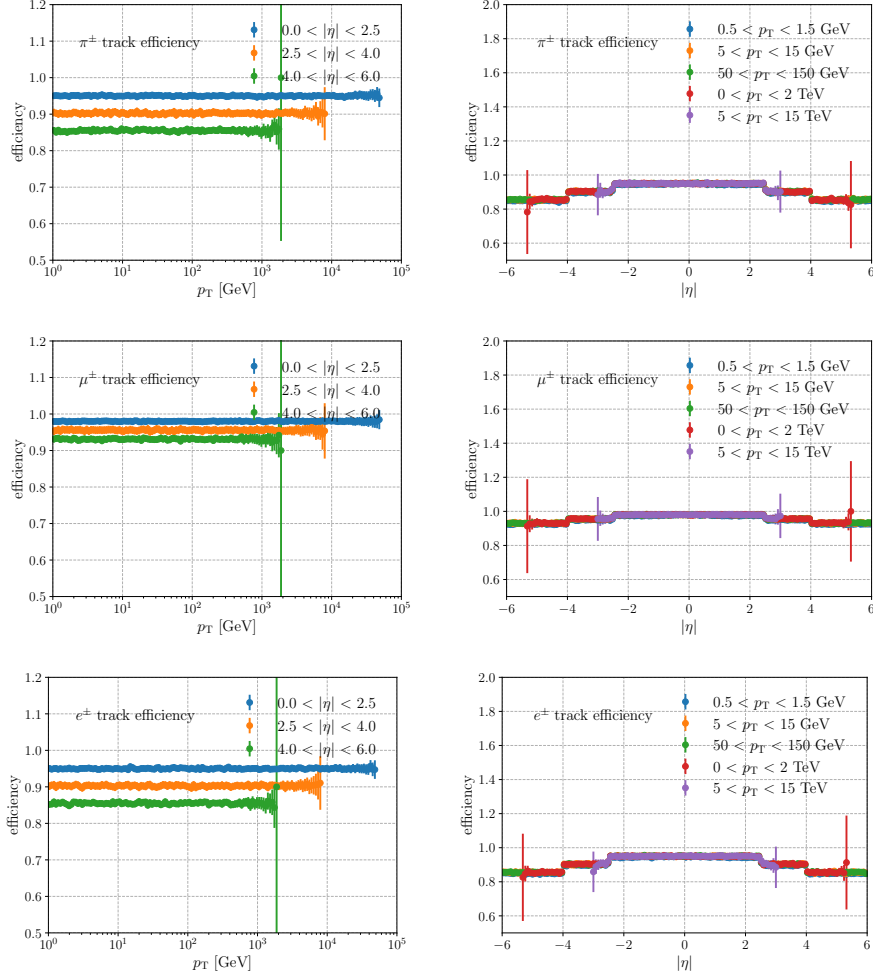


Fig. 1 Top: Charged hadron tracking efficiency as a function of p_T (left) and η (right). Middle: Muon tracking p_T efficiency as a function of p_T (left) and η (right). Bottom: Electron tracking p_T efficiency as a function of p_T (left) and η (right).

Charged particles have a user-defined probability of being reconstructed as tracks in the central tracking volume, which can be defined individually for different types of physics objects. In the parametrization of the FCC-hh benchmark detector, different tracking efficiency modules are defined for charged hadrons, electrons and muons. The different efficiency functions as a function of the generated particle transverse momentum, p_T , as well as pseudorapidity, η , are shown in Figure 1. It should be noted that since the reconstruction efficiencies are defined as a function of pseudo-rapidity,

the (forward) tracker acceptance is equal to that of the full tracker, despite its shorter length.

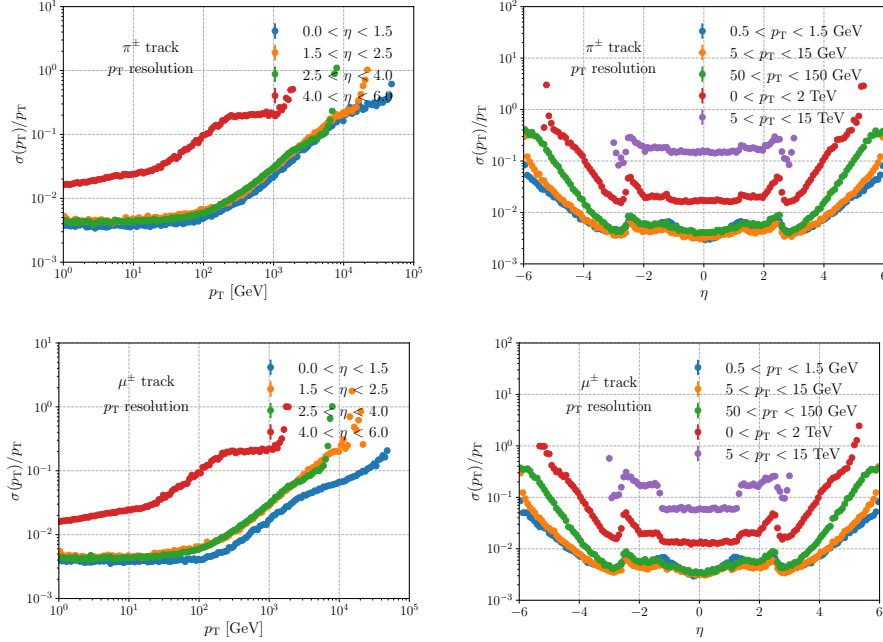


Fig. 2 Top: Charged hadron tracking p_T resolution as a function of p_T and η . Bottom: Muon combined p_T resolution as a function of p_T and η .

A smearing on the norm and the direction of the charged particle momentum vector is applied at the stage of particle propagation. To account for bremsstrahlung, the electron tracking resolution is 50% worse compared to charged hadrons. As discussed in Section 4, the final electron objects are reconstructed by accounting for the calorimeter measurement, which provides a better performance at high energies. The muon resolution, on the other hand, is parameterized separately and accounts for the combined measurement of the tracker and muon chambers. The p_T resolution of charged hadrons (and electrons) tracks and muons as a function of p_T and η is shown in Figure 2. For example, the FCC-hh detector design allows respectively for $\sigma(p_T)/p_T \approx 20\%$ at $p_T = 10$ TeV for central tracks as well as $\sigma(p_T)/p_T \approx 10\%$ for $p_T = 20$ TeV muons.

3 Calorimetry

After their propagation in the magnetic field, long-lived particles reach the calorimeters. The electromagnetic calorimeter, ECAL, is responsible for measuring the energy of electrons and photons, while the hadron calorimeter, HCAL, measures the energy of charged and neutral hadrons. In DELPHES, the calorimeters have a finite lateral

segmentation in pseudo-rapidity and azimuthal angle (η, ϕ) and no longitudinal segmentation. The assumed (η, ϕ) transverse segmentation of the FCC-hh calorimeters is assumed to be of order 0.02 rad. The coordinate of the resulting calorimeter energy deposit, the tower, is randomly smeared across the cell.

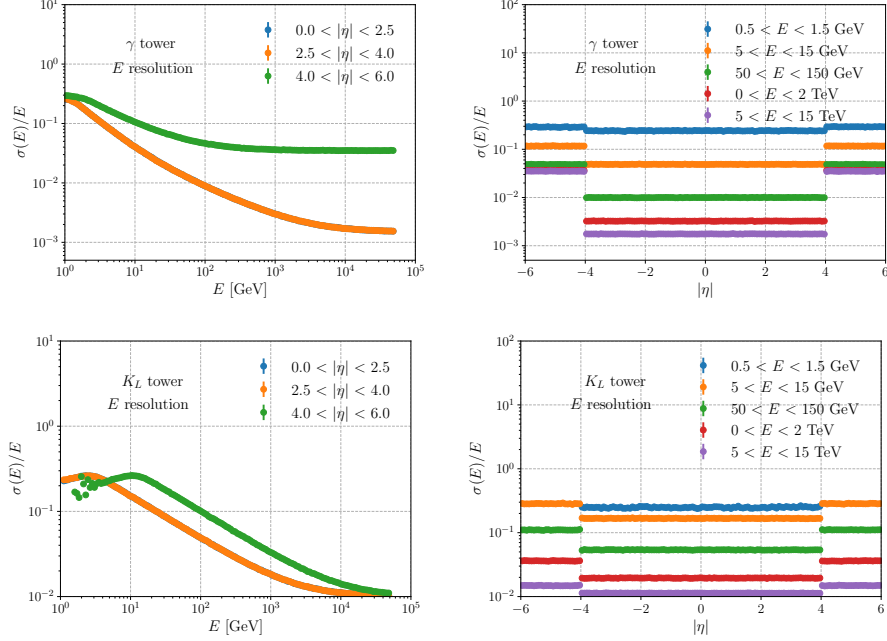


Fig. 3 Top: Photon energy resolution as a function of energy and η . Bottom: Hadron energy resolution as a function of p_T and η . FIXME KL PLOT, and overlaying colors barrel endcaps

The resolutions of ECAL and HCAL are parameterized as a function of the particle energy and the pseudo-rapidity:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S(\eta)}{\sqrt{E}}\right)^2 + C(\eta)^2, \quad (1)$$

where S and C are respectively the *stochastic* and *constant* terms. The electromagnetic and hadronic energy deposits are independently smeared by a log-normal distribution. For simplicity, it is assumed that electromagnetic particles such as electrons, photons and neutral pions (if undecayed by the Monte Carlo event generator) exclusively deposit their energy in the ECAL. Likewise, long-lived hadrons (such as charged pions, kaons, protons etc..) only deposit energy in the HCAL and muons do not leave any energy deposit in the calorimeters at all. The values of S and C adopted for the FCC-hh calorimeters are summarized in Table 1. A complete description of the calorimetry requirements of the FCC-hh can be found in Refs. [8, 9]. The corresponding single particle resolutions as a function of energy and pseudo-rapidity are shown

in Figure 3. We point out here that the fine lateral segmentation and the small constant terms (Table 1) are key to the efficient reconstruction of jets with a transverse boost as high as 20 TeV.

	$ \eta < 4.0$	$4.0 < \eta < 6.0$
S_{ECAL}	8.2%	48%
C_{ECAL}	0.15%	1%
S_{HCAL}	48%	100%
C_{HCAL}	1%	1%

Table 1 Resolution parameters of the electromagnetic and hadronic calorimeters as a function of $|\eta|$. S and C are respectively the *stochastic* and *constant* terms. The assumed functional form for the energy resolution is given in Equation 1.

4 Particle-flow

The philosophy of the particle-flow approach is to use a maximum amount of information provided by the various sub-detectors for reconstructing the event. This modus operandi has been adopted by some experimental collaborations (see for example [10]) and depends on the specificity of the experimental device. In DELPHES the particle-flow event reconstruction is based on a simplified approach that uses as input the tracks and the calorimeters towers.

If the momentum resolution of the tracking system is better than the energy resolution of calorimeters (typically for momenta below some threshold), it is convenient to measure the charged particles momenta using the tracking information. Vice-versa at high energy, calorimeters provide a better momentum measurement. The particle-flow algorithm exploits this complementarity to provide the best possible single charged particle measurement — the *particle-flow tracks*. These contain electron, muons and charged hadrons. The comparison of a pure tracking (calorimetric) measurement and the output particle-flow algorithm for charged hadrons and electrons is shown in Figure 4 (left and center). Thanks to the excellent tracking resolution assumed for the FCC-hh detector, the particle-flow electron (charged hadron) resolution is dominated up to $E = 500$ GeV ($E = 2$ TeV) by the tracker. At higher energies the measurement is mainly driven by calorimeters.

If a significant neutral energy deposit that exceeds the charged deposited energy is detected in a given calorimeter tower, *particle-flow photons* or *particle-flow neutral hadrons* are formed. Together with the *particle-flow tracks*, they form the (generically labelled) *particle-flow candidates* collection and are used as an input for electrons, muons and photons identification and isolation, as well as jets and missing transverse energy. The performance of jets using particle-flow input as opposed to calorimeter towers is shown in Figure 4(right). Again, a substantial improvement of the whole energy range can be observed by using particle-flow reconstruction. We note that this expected improvement obtained with the particle-flow is a DELPHES prediction.

Studies performed with full-simulation are discussed in Ref. [8] and are found to be in good agreement with the pure calorimetric jet response. We stress however that only a full fledged particle-flow algorithm based on full-simulation will predict the ultimate jet performance under the FCC-hh conditions.

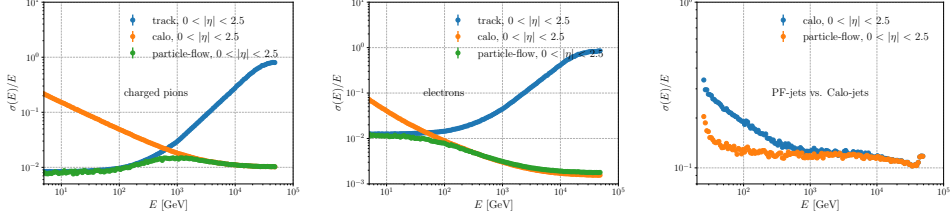


Fig. 4 Particle-flow performance as a function of energy compared to standalone tracking and calorimeter reconstruction for charged hadrons (left), electrons (center) and jets (right).

5 Object identification

5.1 Leptons and photons

In DELPHES, a lepton (electron or muon) from the *particle-flow tracks* collection, or a photon from the *particle-flow photon* collection, has a probability of being identified. For charged particles, the identification efficiency is applied on top of the tracking efficiency discussed in the previous section. The total identification efficiencies for the FCC-hh detector are summarised in Figures 5. The isolation variable for leptons and photons is computed by DELPHES as:

$$I = \frac{\sum_{i \neq p}^{\Delta R < R, p_T(i) > p_T^{min}} p_T(i)}{p_T(P)}, \quad (2)$$

where the sum runs over the full list of *particle-flow candidates* within a cone R , excluding the particle under consideration. Both isolated and non-isolated collections are stored in the output file, allowing custom isolation criteria to be applied at the analysis level.

5.2 Jets and Missing energy

The missing transverse energy p_T^{miss} is computed as the magnitude of the total transverse momentum carried by the full list of reconstructed particle-flow candidates. The DELPHES framework integrates the FastJet package [11], allowing for jet reconstruction with the most popular jet clustering algorithms. In the FCC-hh detector configuration jet collections using the anti- k_T algorithm [12] are provided with several jet clustering R parameters ($R = 0.2, 0.4, 0.8, 1.5$). As mentioned earlier, several jet collections are

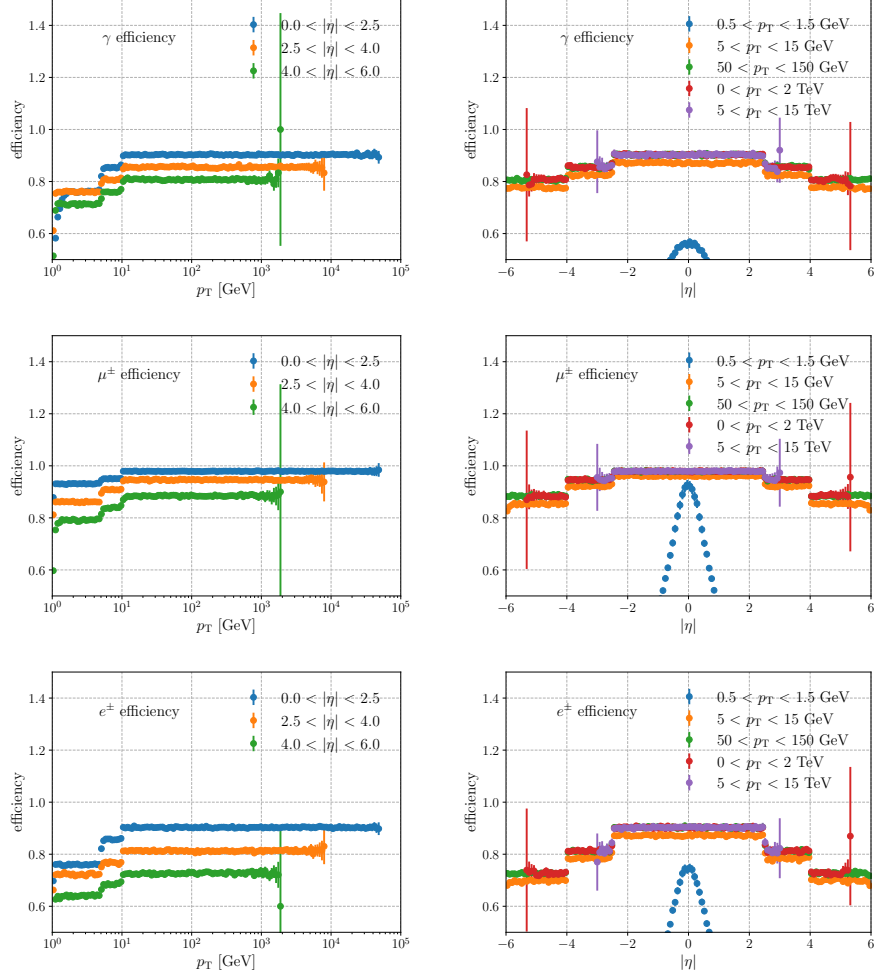


Fig. 5 Top: Photon reconstruction efficiency as a function of p_T (left) and η (right). Middle: Muon reconstruction efficiency as a function of p_T (left) and η (right). Bottom: Electron reconstruction efficiency as a function of p_T (left) and η (right).

formed using several different input objects such as tracks (*Track-jets*), calorimeter (*Calo-jets*) and particle-flow candidates (*PF-jets*).

5.3 Heavy-flavour tagging

The identification of jets that result from τ decays or the hadronization of heavy flavour quarks — typically b or c quarks — typically involves the input from tracking information, such as vertex displacement or low level detector input such as hit multiplicity [13]. Such information is not available by default in Delphes. Instead, a purely parametric approach based on Monte-Carlo generator information is used.

The probability to be identified as b or τ depends on user-defined parameterizations of the b and τ tagging efficiency. The user can also specify a mis-tagging efficiency parameterization, that is, the probability that a particle other than b or τ be wrongly identified as a b or a τ . The parameterisations of the b , and τ tagging efficiencies for the Medium Working point in the FCC-hh detector and their respective misidentification rates from QCD jets are given in Figures 6 and 7. These parameterizations follow state-of-the-art LHC Run III tagging performances [14, 15].

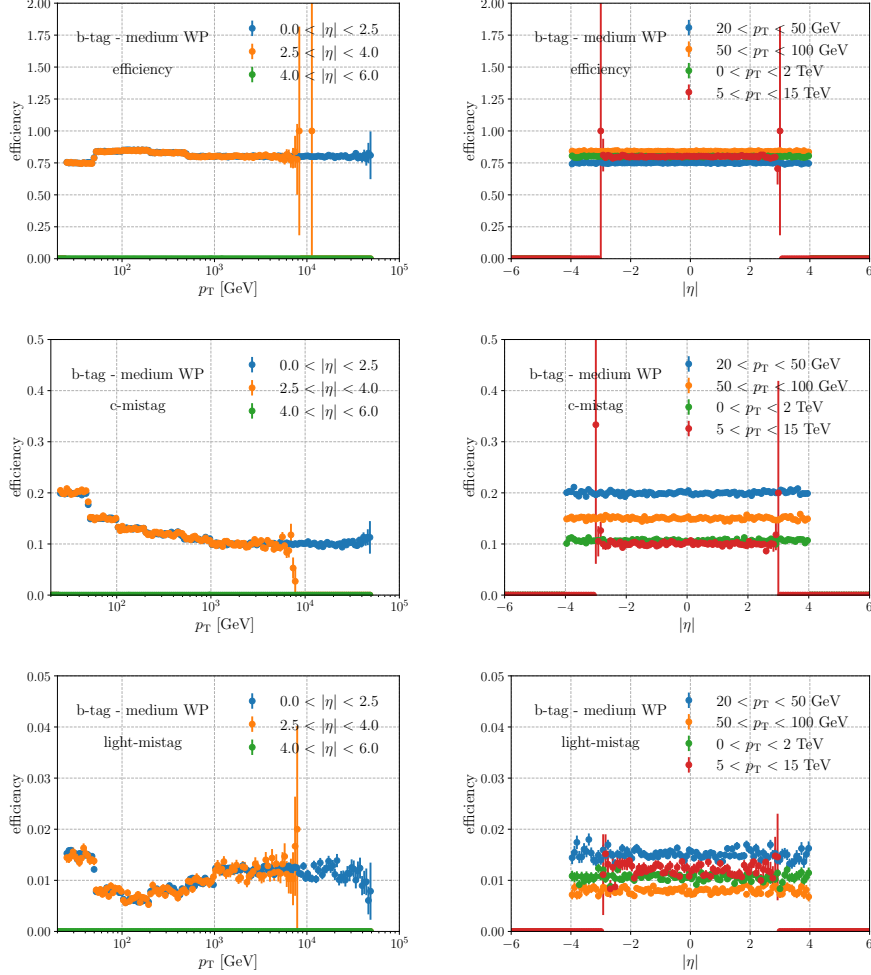


Fig. 6 Medium Working Point B-tagging efficiency and mistag rates as a function of p_T and η . Top: B-tagging efficiency. Middle: Charm mis-tag rate. Bottom: Light quark and gluon jet mistag rate.

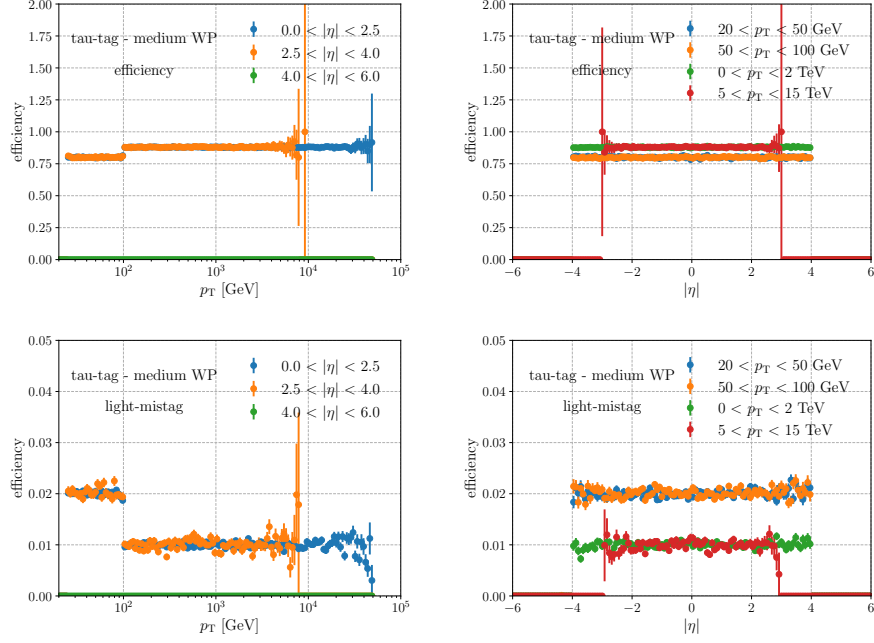


Fig. 7 Medium Working Point τ -tagging efficiency and mistag rates as a function of p_T and η . Top: τ -tagging efficiency. Bottom: Light quark and gluon jet mistag rate.

6 Conclusion and discussion

The FCC-hh baseline detector [5] has been parameterised in DELPHES. This detector configuration has been used to study a list of benchmark physics analyses described in the ESPPU 2025 submission [16]. We stress that pile-up simulation was not included in this FCC-hh detector description for the reason that an accurate description of pile-up effects on reconstructed quantities requires thorough studies that are on-going. However, we note that only the nominal detector assumption has been presented here. In many analyses that are discussed in the Physics Chapter, deviations from the baseline detector assumptions have been tested in order to explore the impact on the sensitivity of the various measurements, including possible indirect effects of the pile-up on specific observables.

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