

Delphes Parameterisation of the FCC-hh detector

Michele Selvaggi^{1*} and Birgit Stapf^{1*}

¹CERN, Geneva, Switzerland.

*Corresponding author(s). E-mail(s): michele.selvaggi@cern.ch;
birgit.stapf@cern.ch;

Abstract

A DELPHES parameterisation 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 from the performance of the LHC multipurpose detectors. The FCC-hh DELPHES detector configuration can be used as a baseline parameterisation 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 future hadron collider experiment. The FCC-hh DELPHES configuration card is available in the official DELPHES release [1] and in the FCC software webpage [2].

1 Introduction

DELPHES is a framework for multipurpose detector fast-simulation [3]. Instead of simulating the time-consuming interactions of stable particles with matter (as done in [4] for example), DELPHES makes use of a parameterised detector response in the form of 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 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 includes a simplistic particle-flow reconstruction that combines optimally tracks and calorimeter information to form particle candidates. Such particles are then used as input for jets clustering, missing energy, and isolation variables. DELPHES also provides heavy flavour tagging and jet substructure algorithms. A detailed description of the DELPHES framework can be found in here [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 [3]. Additional modules allowing for particle identification using time-of-flight and ionizing energy loss information have been implemented.

The FCC-ee DELPHES configurations can be found in the official DELPHES release [1] as well as in the FCC-config software webpage [2].

2 Tracking

The first step carried 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 cylinder of radius $R_0 = 1.5$ m and an half-length $Z_0 = 5$ m.

Charged particles have a user-defined probability to be reconstructed as tracks in the central tracking volume. The charged hadron tracking efficiencies for the FCC-hh detector are given in Table 3. 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.

A smearing on the norm and the direction of the charged particle momentum vector is applied at the stage of particle propagation. An momentum independent angular resolution of $\sigma_\theta = 10^{-3}$ rad on tracks is assumed. This scale is compatible with the tracking angular resolution found in more detailed tracking studies. In addition, whenever two or more tracks fall within an angular separation σ_θ , only the highest momentum track is reconstructed. This effect can result in an additional inefficiency to that shown in Table 3, and affects tracks in the core of highly boosted jets, as shown in Figure 3 (left).

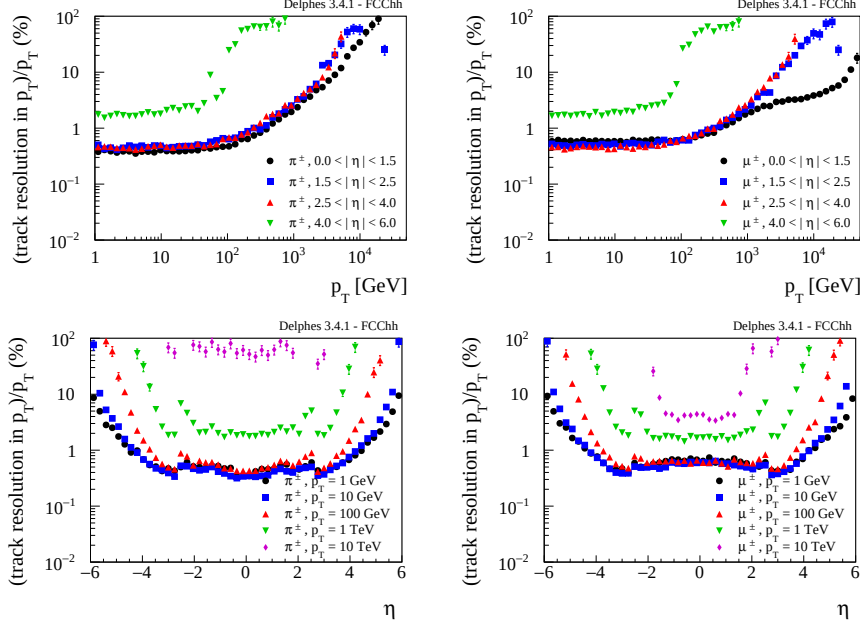


Fig. 1 Left: Charged hadron tracking p_T resolution as a function of p_T (top) and η (bottom). Right: Muon combined p_T resolution as a function of p_T (top) and η (bottom).

As an approximation, electrons and charged hadrons tracks are assumed to have an equal tracking performance. As discussed in Section 4, the final electron objects are reconstructed by accounting for the calorimeter measurement, that provides a better performance at high energies. The muon resolution is on the other hand parameterised separately, and accounts altogether 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 1. For example, the FCC-hh detector design allows respectively for $\sigma(p_T)/p_T \approx 20\%$ at $p_T = 20$ TeV for central tracks as well as $\sigma(p_T)/p_T \approx 5\%$ for $p_T = 20$ TeV.

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 transverse segmentation of the FCC-hh calorimeters is given in Table 1. The coordinate of the resulting calorimeter energy deposit, the tower, is randomly smeared across the cell.

	$ \eta < 2.5$	$2.5 < \eta < 6.0$
ECAL	0.01	0.025
HCAL	0.025	0.05

Table 1 Lateral segmentation in (η, ϕ) (rad) of the electromagnetic and hadronic calorimeter.

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 in HCAL and muons do not leave any energy deposit in the calorimeters. The values of S and C adopted for the FCC-hh calorimeters are summarized in Table 2. A complete description of the calorimetry requirements of the FCC-hh can be found in Refs. [6, 7]. We simply point out here the fine lateral segmentation (in Table 1) and the small constant terms (Table 2) is key for an efficient reconstruction of jets with a transverse boost as high as 20 TeV.

	$ \eta < 1.7$	$1.7 < \eta < 4.0$	$4.0 < \eta < 6.0$
S_{ECAL}	10%	10%	30%
C_{ECAL}	0.7%	0.7%	3.5%
S_{HCAL}	50%	60%	100%
C_{HCAL}	3%	3%	10%

Table 2 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 [8]) 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 2 (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 2(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. [6] 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.

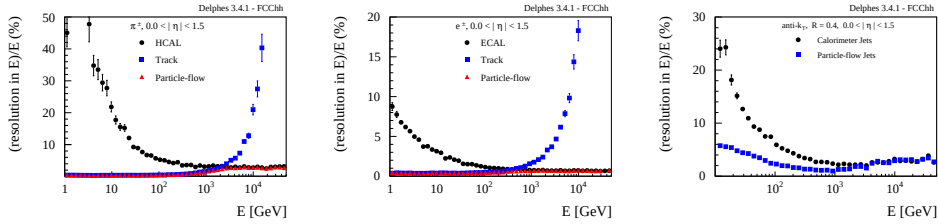


Fig. 2 Particle-flow performance as a function of energy compared to standalone tracking and calorimeter reconstruction for charged hadrons (left), electrons (center) and jets (right).

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 assumed identification efficiencies for

the FCC-hh detector are summarised in Tables 4, 5 and 6. 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.

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 [9], 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 [10] are provided with several jet clustering R parameters ($R = 0.2, 0.4, 0.8, 1.5$). As mentioned earlier, several jet collections are formed using several different input objects such as tracks (*Track-jets*), calorimeter (*Calo-jets*) and particle-flow candidates (*PF-jets*).

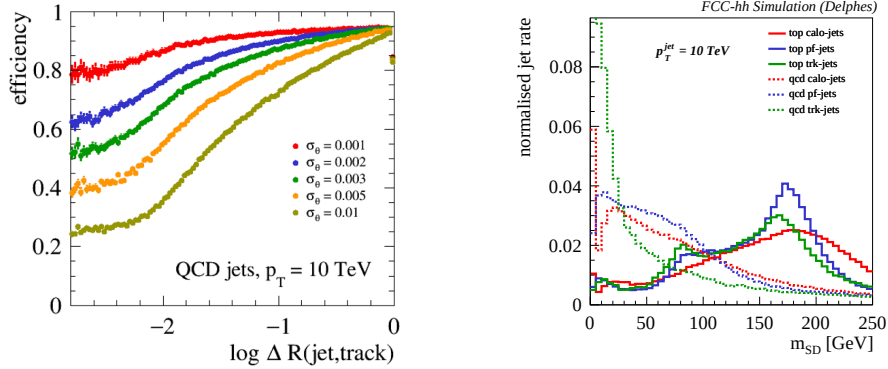


Fig. 3 Left: Track reconstruction efficiency inside highly QCD boosted jets as function of the angular distance between the track and the center of the jet. Right: Reconstructed jet mass of highly boosted top and QCD jets using respectively as input to the jet clustering algorithm tracks, calorimeters towers or particle-flow candidates.

Common jet shape observables used for jet substructure analysis such as N-subjettiness [11] and the soft-dropped mass [12] are computed on-the-fly and stored in the output jet collections. This large number of jet collections (with varying R -parameter and input collections) is needed for physics analyses that feature highly boosted hadronic jets in the final states, spanning over more than one order of magnitude in energy range (e.g $Z' \rightarrow t\bar{t}$ searches). As an illustration, the reconstructed soft-dropped mass for top and QCD jets with $p_T = 10$ TeV and $R = 0.2$ in

Figure 3(right). Thanks to the superior tracker segmentation, we find *Track-jets* to perform better in terms of QCD background rejection despite the slightly worse jet mass resolution.

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 as a 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 in the FCC-hh detector and their respective misidentification rates from QCD jets are given in Tables 7 and 8.

6 Conclusion and discussion

The FCC-hh baseline detector has been parameterised in DELPHES. This detector configuration has been used to study a list of benchmark physics analyses described in the CDR Volumes 1 [14] and 3 [5] and in further documented in Refs. [15–20]. 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.

References

- [1] Delphes releases. <https://github.com/delphes/delphes/releases>
- [2] FCC-hh detector DELPHES card. <https://github.com/delphes/delphes/blob/master/cards/FCC/scenarios/FCChh.II.tcl>
- [3] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, M. Selvaggi, DELPHES 3, A modular framework for fast simulation of a generic collider experiment. *JHEP* **02**, 057 (2014). [https://doi.org/10.1007/JHEP02\(2014\)057](https://doi.org/10.1007/JHEP02(2014)057). [arXiv:1307.6346](https://arxiv.org/abs/1307.6346) [hep-ex]
- [4] S. Agostinelli, et al., GEANT4: A simulation toolkit. *Nucl. Instrum. Meth. A* **506**, 250 (2003). [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
- [5] M. Benedikt, et al., FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2. *Eur. Phys. J. ST* **228**(2), 261–623 (2019). <https://doi.org/10.1140/epjst/e2019-900045-4>
- [6] M. Aleksa, et al., Calorimeters for the FCC-hh (2019). [arXiv:1912.09962](https://arxiv.org/abs/1912.09962) [physics.ins-det]
- [7] M. Selvaggi, Physics requirements for the FCC-hh calorimeter system. *J. Phys. Conf. Ser.* **1162**(1), 012010 (2019). <https://doi.org/10.1088/1742-6596/1162/1/012010>
- [8] A.M. Sirunyan, et al., Particle-flow reconstruction and global event description with the CMS detector. *JINST* **12**(10), P10003 (2017). <https://doi.org/10.1088/1748-0221/12/10/P10003>. [arXiv:1706.04965](https://arxiv.org/abs/1706.04965) [physics.ins-det]
- [9] M. Cacciari, G.P. Salam, G. Soyez, FastJet User Manual. *Eur. Phys. J.* **C72**, 1896 (2012). <https://doi.org/10.1140/epjc/s10052-012-1896-2>. [arXiv:1111.6097](https://arxiv.org/abs/1111.6097) [hep-ph]
- [10] M. Cacciari, G.P. Salam, G. Soyez, The anti- k_t jet clustering algorithm. *JHEP* **04**, 063 (2008). <https://doi.org/10.1088/1126-6708/2008/04/063>. [arXiv:0802.1189](https://arxiv.org/abs/0802.1189) [hep-ex]
- [11] J. Thaler, K. Van Tilburg, Identifying Boosted Objects with N-subjettiness. *JHEP* **03**, 015 (2011). [https://doi.org/10.1007/JHEP03\(2011\)015](https://doi.org/10.1007/JHEP03(2011)015). [arXiv:1011.2268](https://arxiv.org/abs/1011.2268) [hep-ph]
- [12] A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft Drop. *JHEP* **05**, 146 (2014). [https://doi.org/10.1007/JHEP05\(2014\)146](https://doi.org/10.1007/JHEP05(2014)146). [arXiv:1402.2657](https://arxiv.org/abs/1402.2657) [hep-ph]
- [13] E. Perez Codina, P.G. Roloff, Hit multiplicity approach to b-tagging in FCC-hh. Tech. Rep. CERN-ACC-2018-0023, CERN, Geneva (2018). URL <https://cds.cern.ch/record/2631478>

- [14] A. Abada, et al., FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1. *Eur. Phys. J. C* **79**(6), 474 (2019). <https://doi.org/10.1140/epjc/s10052-019-6904-3>
- [15] L. Borghoni, S. Braibant, B. Di Micco, E. Fontanesi, P. Harris, C. Helsens, D. Jamin, M. Mangano, G. Ortona, M. Selvaggi, A. Sznajder, M. Testa, M. Verducci, Higgs measurements at FCC-hh. Tech. Rep. CERN-ACC-2018-0045, CERN, Geneva (2018). URL <https://cds.cern.ch/record/2642471>
- [16] M.L. Mangano, G. Ortona, M. Selvaggi, Measuring the Higgs self-coupling via Higgs-pair production at a 100 TeV p-p collider. *Eur. Phys. J. C* **80**(11), 1030 (2020). <https://doi.org/10.1140/epjc/s10052-020-08595-3>. [arXiv:2004.03505](https://arxiv.org/abs/2004.03505) [hep-ph]
- [17] L. Gouskos, A. Sung, J. Incandela, Search for stop scalar quarks at FCC-hh. Tech. Rep. CERN-ACC-2019-0036, CERN, Geneva (2018). URL <https://cds.cern.ch/record/2642475>
- [18] C. Helsens, M. Selvaggi, Search for high-mass resonances at FCC-hh. Tech. Rep. CERN-ACC-2019-0028, CERN, Geneva (2018). URL <https://cds.cern.ch/record/2642473>
- [19] C. Helsens, D. Jamin, M.L. Mangano, T.G. Rizzo, M. Selvaggi, Heavy resonances at energy-frontier hadron colliders. *Eur. Phys. J. C* **79**(2), 569 (2019). <https://doi.org/10.1140/epjc/s10052-019-7062-3>. [arXiv:1902.11217](https://arxiv.org/abs/1902.11217) [hep-ph]
- [20] L. Dudko, E. Boos, A. Chernoded, M. Perfilov, G. Vorotnikov, P. Volkov, Prospects for the Search of gluon mediated flavour changing neutral currents at FCC. Tech. Rep. CERN-ACC-2018-0043, CERN, Geneva (2018). URL <https://cds.cern.ch/record/2643278>. Note to support FCNC section of the FCC CDR

7 Efficiency tables

	$ \eta < 2.5$	$2.5 < \eta < 4.0$	$4.0 < \eta < 6.0$	$ \eta > 6.0$
$p_T < 0.5$ GeV	0%	0%	0%	0%
$0.5 < p_T < 1.0$ GeV	90%	85%	80%	0%
$p_T > 1.0$ GeV	95%	90%	85%	0%

Table 3 Tracking efficiency as a function of p_T and $|\eta|$ for charged hadrons.

	$ \eta < 2.5$	$2.5 < \eta < 4.0$	$4.0 < \eta < 6.0$	$ \eta > 6.0$
$p_T < 4$ GeV	0%	0%	0%	0%
$p_T > 4$ GeV	95%	90%	85%	0%

Table 4 Identification efficiency for electrons as a function of p_T and $|\eta|$.

	$ \eta < 2.5$	$2.5 < \eta < 4.0$	$4.0 < \eta < 6.0$	$ \eta > 6.0$
$p_T < 4$ GeV	0%	0%	0%	0%
$p_T > 4$ GeV	99%	99%	99%	0%

Table 5 Identification efficiency for muons as a function of p_T and $|\eta|$.

	$ \eta < 2.5$	$2.5 < \eta < 4.0$	$4.0 < \eta < 6.0$	$ \eta > 6.0$
$1 < p_T < 5$ GeV	70%	60%	50%	50%
$5 < p_T < 10$ GeV	85%	80%	70%	70%
$p_T > 10$ GeV	95%	90%	80%	80%

Table 6 Identification efficiency for photons as a function of p_T and $|\eta|$.

	$ \eta < 2.5$	$2.5 < \eta < 4.0$	$4.0 < \eta < 6.0$
b-tagging efficiency			
$30 < p_T < 15000$ GeV	$(1 - p_T [\text{TeV}]/15) \cdot 85\%$	$(1 - p_T [\text{TeV}]/15) \cdot 64\%$	0%
$p_T > 15000$ GeV	0%	0%	0%
c-mistag efficiency			
$30 < p_T < 15000$ GeV	$(1 - p_T [\text{TeV}]/15) \cdot 5\%$	$(1 - p_T [\text{TeV}]/15) \cdot 3\%$	0%
$p_T > 15000$ GeV	0%	0%	0%
light mistag efficiency			
$30 < p_T < 15000$ GeV	$(1 - p_T [\text{TeV}]/15) \cdot 1\%$	$(1 - p_T [\text{TeV}]/15) \cdot 0.75\%$	0%
$p_T > 15000$ GeV	0%	0%	0%

Table 7 B-tagging efficiencies and light mistag rates as a function of p_T and $|\eta|$.

	$ \eta < 2.5$	$2.5 < \eta < 4.0$	$4.0 < \eta < 6.0$
τ -tagging efficiency			
$30 < p_T < 15000 \text{ GeV}$	$(1 - p_T [\text{TeV}]/30) \cdot 60\%$	$(1 - p_T [\text{TeV}]/30) \cdot 40\%$	0%
$p_T > 15000 \text{ GeV}$	0%	0%	0%
QCD mistag efficiency			
$30 < p_T < 15000 \text{ GeV}$	$(1 - p_T [\text{TeV}]/30) \cdot 1\%$	$(1 - p_T [\text{TeV}]/30) \cdot 0.75\%$	0%
$p_T > 15000 \text{ GeV}$	0%	0%	0%
electron mistag efficiency			
$30 < p_T < 15000 \text{ GeV}$	$(1 - p_T [\text{TeV}]/30) \cdot 0.5\%$	$(1 - p_T [\text{TeV}]/30) \cdot 0.3\%$	0%
$p_T > 15000 \text{ GeV}$	0%	0%	0%

Table 8 τ -tagging efficiencies and light mistag rates as a function of p_T and $|\eta|$.