Funded by
the European Union

Grant Agreement No: 101094300

MuCoL

A Design Study for a Muon Collider complex at 10 TeV centre of mass

Horizon Europe Framework Programme

MILESTONE REPORT

RELEASE OF SIMPLIFIED DETECTOR PERFORMANCE MODEL (DELPHES CARD OR/AND SIMILAR FORMAT)

MILESTONE NO 11

Document identifier:	MuCol_Mil_11_WP2_v1-0.pdf
DOI:	10.5281/zenodo.14001529
Due date of milestone:	31/10/2024 (End of Month 20)
Justification for delay	New due date approved by EU Officer
Work package:	WP2: Physics and Detector Requirements
Lead beneficiary:	UNIPD
Report release date:	30/10/2024
Document version:	1.0
Document status:	Final

Abstract:

This report describes the structure of the DELPHES card of the MUSIC detector concept, which has been designed to enable physics measurements for 10 TeV centre-of-mass energy muon collisions. The validation of the card is also presented.

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Delivery Slip

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Executive summary

This report describes the implementation of the MUSIC DELPHES card, a tool for fast simulation of the detector concept designed to collect data at 10 TeV centre-of-mass energy in muon collisions. The validation of the card is also presented.

1. Introduction

A DELPHES card [1-3] is a tool developed for the fast simulation of collider experiments. The geometry of the MUSIC detector concept [4] along with performance parameters extracted from simulation studies is implemented in DELPHES parameter card. The MUSIC detector represents an experiment designed for data collection in muon collisions at $\sqrt{s} = 10\,TeV$. The detector configuration is presented in Section 2.1 with a dedicated discussion on the tracking and calorimeter systems in Sections 2.1.1 and 2.1.2, respectively.

The MUSIC DELPHES card can be found in the official Muon Collider Software repository: https://github.com/MuonColliderSoft/Delphes/tree/main.

To properly use the DELPHES card, this procedure can be followed:

1. clone the repository
   `git clone git@github.com:MuonColliderSoft/Delphes.git Delphes`
2. compile the required libraries
   `source /cvmfs/sft.cern.ch/lcg/views/LCG_105/x86_64-el9-gcc12-opt/setup.sh`
3. compile your DELPHES project
   `make`

The repository also allows the MUSIC DELPHES card to be used with the compilation of Pythia8 libraries. In this repository, it is possible to:

- perform a dedicated DELPHES reconstruction using the MUSIC detector configuration, starting from some generated physics events;
- perform a validation of the MUSIC DELPHES card, with the usage of particle guns.

To launch a dedicated DELPHES reconstruction using the MUSIC detector configuration starting from generated physics events (in .hepmc format), the following command can be used:

```
./DelphesHepMC2 cards/delphes_card_MUSICDet_target.tcl delphes_output.root input.hepmc
```

The validation of the MUSIC DELPHES card is obtained following the instructions in the `validation` folder.

2. DELPHES CARD DESCRIPTION

2.1. DETECTOR DESCRIPTION

The MUSIC detector concept consists of a tracking system, an electromagnetic (ECAL), a hadronic calorimeter (HCAL), and a muon sub-detector. The tracking devices and ECAL are located inside a superconducting solenoid with a 2-metre inner radius that generates a 5-Tesla magnetic field. The hadronic calorimeter is immediately outside the magnet followed by a muon detector. The detector design must account for unique background conditions associated with muon collisions. Two primary processes are considered significant contributors to the detector background. First, muon decay products interacting with machine components and with the nozzles (detector shielding structures) generate high fluxes of low-momentum particles, many of which are out of time, that reach the detector [5]. Second, at $\sqrt{s} = 10\, TeV$ electron-positron pairs are incoherently [6] produced at the bunch crossings and enter the detector at the interaction point simultaneously with primary particles. The effects of these background particles on physics objects reconstruction have been extensively validated for a 3 TeV centre-of-mass energy [7]. This study suggests that the performance of physics objects reconstruction can be evaluated without background sources and then corrected for their effect. The jet reconstruction and identification algorithms need further optimization, as explained in Section 2.1.2.

2.1.1. TRACKING SYSTEM AND TRACK RECONSTRUCTION DESCRIPTION

The tracking system is composed of a vertex detector (VXD), an inner tracker (IT), and an outer tracker (OT). The VXD is a $25 \times 25\ \mu m^2$ silicon pixel detector with hit spatial and time resolutions of 5 μm × 5 μm and 30 ps, respectively. The inner and outer trackers feature 50 μm × 1 mm macropixels with 7 μm × 90 μm hit spatial resolution and 60 ps hit time resolution. Track reconstruction is based on the ACTS package [8], but in this card, the tracking performance is evaluated by using the `TrackCovariance` software tool, recently added to the DELPHES package. This tool allows a parametric reconstruction of tracks, following a specific design of the tracking system. In the context of the MUSIC DELPHES card, the exact implementation of the tracking system (number of layers, dimensions, and placement) as used in the full simulation software is used. Track momenta are smeared according to the design of the tracking system, while tracking reconstruction efficiencies are based on the case without beam-induced background, since it has been demonstrated that its effect is almost negligible.

2.1.2. CALORIMETER SYSTEM AND PHYSICS OBJECTS RECONSTRUCTION

The ECAL is a semi-homogeneous electromagnetic crystal calorimeter with longitudinal segmentation (CRILIN) [9]. It consists of $10 \times 10 \times 45\text{-}mm^3$ lead-fluorite crystals arranged in six layers for a total of 26.5 radiation lengths. It is located inside the solenoid to guarantee high energy resolution for the electromagnetic objects. The HCAL is inherited from the CLIC detector concept [10]. It is an iron-scintillator sampling calorimeter comprising 70 layers of 20-mm iron absorber and $30 \times 30\ mm^2$ scintillator pads, for a total of approximately 7 nuclear interaction lengths. The magnetic field flux is closed using the HCAL iron absorber. The MUSIC DELPHES card takes into account the granularity of the calorimeter in terms of pseudorapidity and azimuthal angle, based on the geometry implemented in the full simulation framework. Electrons/positrons and photons are reconstructed by assuming an ECAL energy resolution of $10\%/\sqrt{E\,[GeV]}$, with reconstruction efficiencies extracted from a scenario without beam-induced background contribution and then corrected for its contribution. A similar procedure is used for HCAL, hadrons are reconstructed assuming an HCAL energy resolution of $30\%/\sqrt{E\,[GeV]}$ that includes background effects. Jets are reconstructed using the k_T clustering algorithm with radius R=0.4, taking in input all tracks and calorimeter clusters with the proper resolutions and efficiencies applied. To further take into account beam-induced background effects, a smearing factor is applied to jet momentum. A b-jet tagging algorithm is applied to all reconstructed jets, using a working point of 75%, with relatively low mistag efficiencies for c- and light-quark jets.

3. DELPHES CARD VALIDATION

The current version of the DELPHES package includes a validation tool, allowing users to generate a set of plots for the particles and quantities defined in the card. In this section, only plots of quantities for which a detailed study has been performed at 3 TeV centre-of mass energy, and for which a validation at $\sqrt{s} = 10\,TeV$ is in progress, are presented.

Track reconstruction: Track reconstruction performance is evaluated for different kinds of particles. Since the reconstruction does not yet distinguish between different particles, the results are very

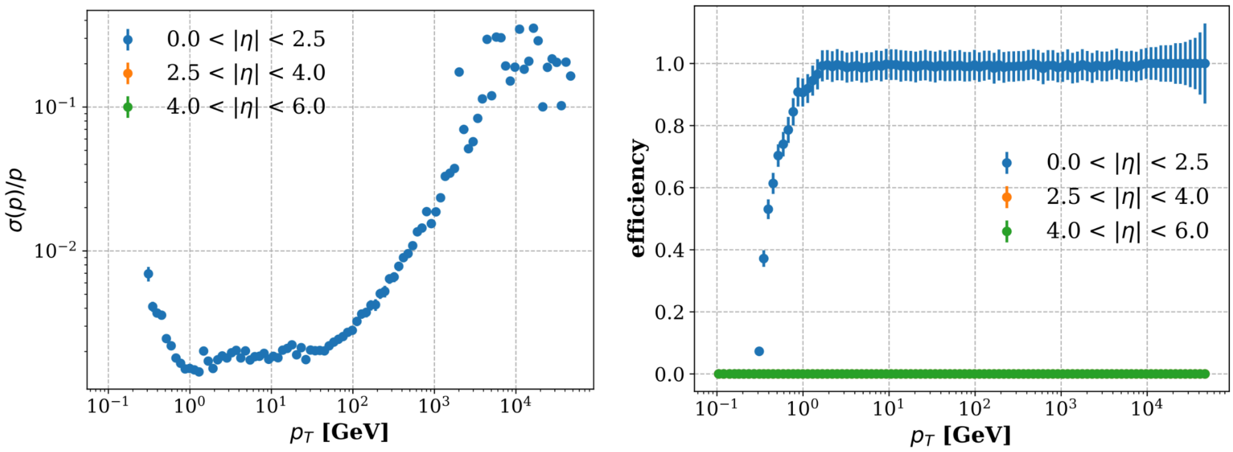

Fig. 1 Track momentum resolution (left) and track reconstruction efficiency (right) as a function of the particle transverse momentum.

similar. Figure 1 shows, on the left, the momentum resolution as a function of the transverse momentum of a particle. On the right side, the reconstruction efficiency as a function of the particle transverse momentum is displayed. Due to the presence of the nozzles inside the detector along the beamline, only particles with $|\eta| < 2.5$ are considered. The results are in agreement with the expected performance.

Calorimeter performance: The calorimeter energy resolution as a function of the particle energy is shown in Figure 2 for electrons/positrons (left) and photons (right). The behaviour corresponds to the expected one for the CRILIN calorimeter. Figure 3 contains the reconstruction efficiency as a function of the energy still for electrons/positrons (left) and photons (right). Plots showing resolution and efficiency as a function of other variables are produced by the software but not included here. Also in this case, results are limited to $|\eta| < 2.5$ due to the presence of the nozzle.

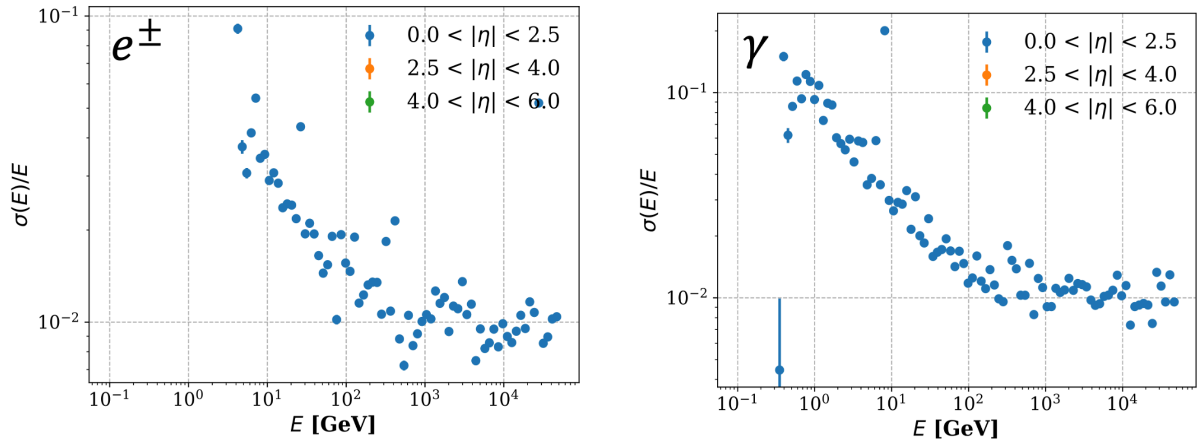

Fig. 2 Electrons/positrons (left) and photons (right) energy resolution as a function of the particle energy.

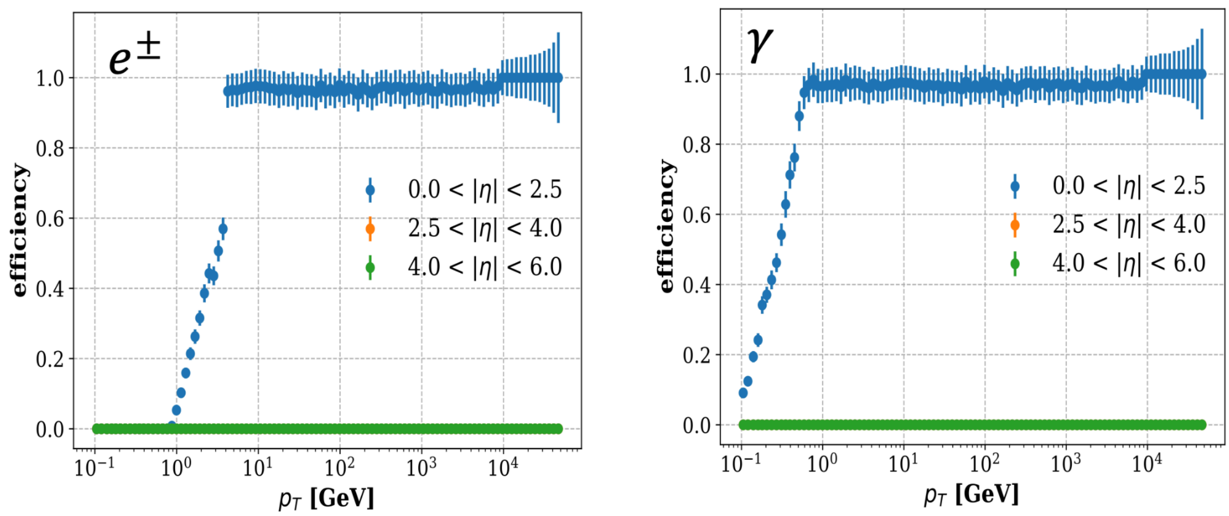

Fig. 3 Electrons/positrons (left) photons (right) efficiency as a function of the particle energy.

Particle-flow reconstruction: The performance achievable with particle-flow is available for any particle considered in the reconstruction software. For example, Figure 4 shows the results for electron and jet reconstruction. The particle-flow algorithm utilises the best available information to reconstruct electrons: tracking at low momenta and calorimeter at high ones. On the left of Figure 4, this behaviour is evident for the energy resolution. Jet reconstruction is obtained only with particle-flow algorithms. On the right of Figure 4, the jet energy resolution as a function of the energy is shown.

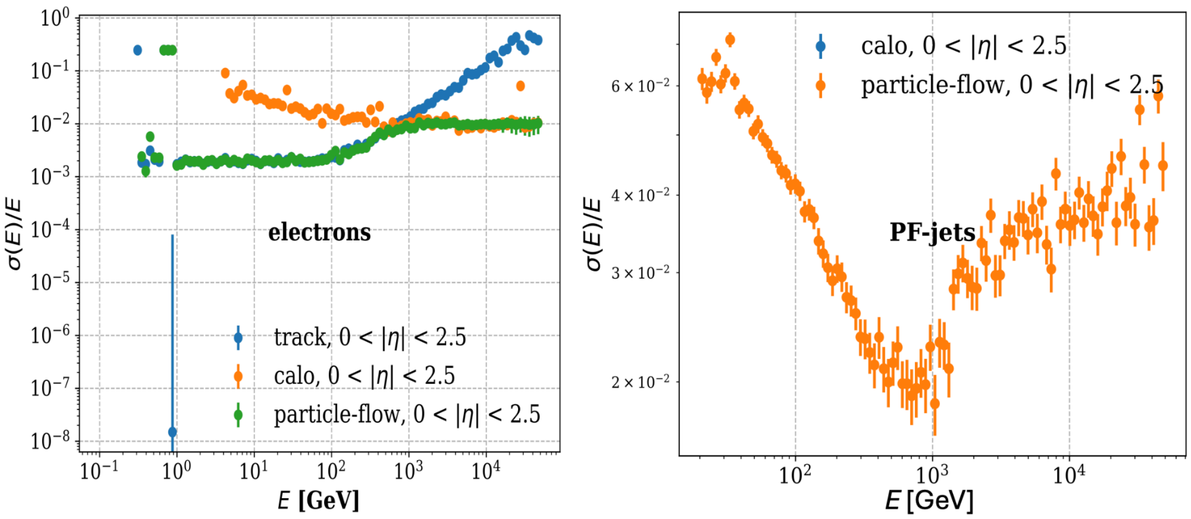

Fig. 4 Left: Particle-flow reconstruction of electrons. Right: jet energy resolution as a function of energy.

<u>Jet-flavor tagging:</u> Jets originated by *b*- or *c*-quarks are identified by using a very simple algorithm at the moment, based on the search for vertices displaced with respect to the primary interaction. Requirements on the reconstructed decay length, the invariant mass associated with the secondary vertex, and good quality of the vertex itself are applied to distinguish *b*- from *c*- and light-jets. The performance of the current algorithm is reported in Figure 5. The *b*-tag efficiency as a function of the jet momentum is around 75%, as shown on the left of Figure 5, while the mistag due to *c*- and light-quark jets is around 5% and 1%, respectively (see center and right of Figure 5). A *b*- and *c*-jet tagging algorithm based on advanced machine learning software is currently under development and the MUSIC Delphes card will be updated when ready.

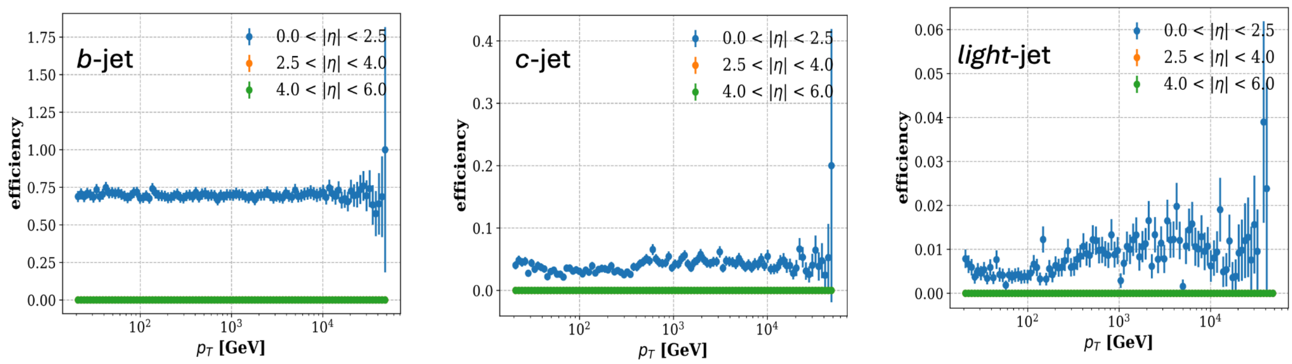

Fig. 5 b-jet tagging efficiency (left) with c-jet mistag (center) and light-jet mistag (right) as a function of jet transverse momentum.

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Annex: Glossary

Acronym	Definition
MUSIC	MUon System for Interesting Collision
ACTS	A Common Tracking Software
CRILIN	CRystal calorImeter with Longitudinal InformatioN
CLIC	Compact LInear Collider