DELPHES, a framework for fast simulation of a general purpose LHC detector

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Abstract

Knowing whether theoretical predictions are visible and measurable in a high energy experiment is always delicate, due to the complexity of the related detectors, data acquisition chain and software. We introduce here a new framework, DELPHES, for fast simulation of a general purpose experiment. The simulation includes a tracking system, embedded into a magnetic field, calorimetry and a muon system, and possible very forward detectors arranged along the beamline. The framework is interfaced to standard file formats (e.g. Les Houches Event File) and outputs observable analysis data objects, like missing transverse energy and collections of electrons or jets. The simulation of detector response takes into account the detector resolution, and usual reconstruction algorithms for complex objects, like FASTJET. A simplified preselection can also be applied on processed data for trigger emulation. Detection of very forward scattered particles relies on the transport in beamlines with the HECTOR software. Finally, the FROG 2D/3D event display is used for visualisation of the collision final states. An overview of DELPHES is given as well as a few use-cases for illustration.

Keywords: DELPHES, fast simulation, LHC, smearing, trigger, FASTJET, HECTOR, FROG

1 Introduction

Experiments at high energy colliders are very complex systems, in several ways. First, in terms of the various detector subsystems, including tracking, central calorimetry, forward calorimetry, and muon chambers. These detectors differ with their principles, technologies, geometries and sensitivities. Then, due to the requirement of a highly effective online selection (i.e. a *trigger*), subdivided into several levels for an optimal reduction factor, but based only on partially processed data. Finally, in terms of the experiment software, with different data formats (like *raw* or *reconstructed* data), many reconstruction algorithms and particle identification schemes.

This complexity is handled by large collaborations of thousands of people, which restrict the

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availability of the data, software and documentation to their members. Real data analyses require a full detector simulation, including the various detector inefficiencies, the dead material, the imperfections and the geometrical details. Moreover, detector calibration and alignment are crucial. Such simulation is very complicated, technical and slow. On the other hand, phenomenological studies, looking for the observability of given signals, may require only fast but realistic estimates of the observables.

A new framework, called DELPHES [**?**], is introduced here, for the fast simulation of a general purpose collider experiment. Using the framework, observables can be estimated for specific signal and background channels, as well as their production and measurement rates, under a set of assumptions. Starting from the output of event generators, the simulation of the detector response takes into account the subdetector resolutions, by smearing the kinematical properties of the visible final particles. Tracks of charged particles and calorimetric towers (or *calotowers* are then created.

DELPHES includes the most crucial experimental features, like (1) the geometry of both central or forward detectors; (2) lepton isolation; (3) reconstruction of photons, leptons, jets, b-jets, τ-jets and missing transverse energy; (4) trigger emulation and (5) an event display (Fig. **??**).

Although this kind of approach yields much realistic results than a simple "parton-level" analysis, a fast simulation comes with some limitations. Detector geometry is idealised, being uniform, symmetric around the beam axis, and having no cracks nor dead material. Secondary interactions, multiple scatterings, photon conversion and bremsstrahlung are also neglected.

Three formats of input files can currently be used as input in DELPHES[1]. In order to process events from many different generators, the standard Monte Carlo event structure STDHEP can be used as an input. Besides, DELPHES can also provide detector response for events read in "Les Houches Event Format" (LHEF) and ROOT files obtained using the **h2root** utility from the ROOT framework [**?**].

The output of DELPHES contains a copy of the generator level data (GEN tree), the analysis data objects after reconstruction (Analysis tree), and possibly the results of the trigger emulation (Trigger tree). The program is driven by input cards. The detector card (`data/DataCardDet.dat`) allows a large spectrum of running conditions by modifying basic detector parameters, including calorimeter and tracking coverage and resolution, thresholds or jet algorithm parameters. The trigger card (`data/trigger.dat`) lists the user algorithms for the simplified online preselection.

2 Detector simulation

The overall layout of the general purpose detector simulated by DELPHES is shown in Fig. 2. A central tracking system (TRACKER) is surrounded by an electromagnetic and a hadron calorimeters (ECAL and HCAL, resp.). Two forward calorimeters (FCAL) ensure a larger geometric coverage for the measurement of the missing transverse energy. Finally, a muon system (MUON) encloses the central detector volume The fast simulation of the detector response takes into account geometrical acceptance of sub-detectors and their finite resolution, as defined in the smearing data card[2]. If no such file is provided, predifined values are used. The coverage of the various subsystems used in the default configuration are summarised in table 1.

[1] `[code]` See the `HEPEVTConverter`, `LHEFConverter` and `STDHEPConverter` classes.

[2] `[code]` See the `RESOLution` class.

Table 1: Default extension in pseudorapidity η of the different subdetectors. The corresponding parameter name, in the smearing card, is given.

TRACKER	`CEN_max_tracker`	$0.0 \leq \|\eta\| \leq 2.5$
ECAL, HCAL	`CEN_max_calo_cen`	$0.0 \leq \|\eta\| \leq 3.0$
FCAL	`CEN_max_calo_fwd`	$3.0 \leq \|\eta\| \leq 5.0$
MUON	`CEN_max_mu`	$0.0 \leq \|\eta\| \leq 2.4$

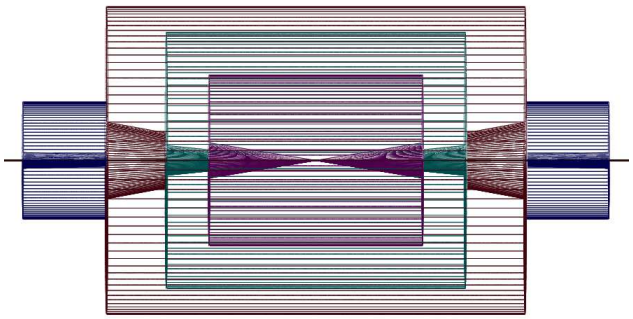

Figure 2: Profile of layout of the generic detector geometry assumed in DELPHES. The innermost layer, close to the interaction point, is a central tracking system (pink). It is surrounded by a central calorimeter volume (green) with both electromagnetic and hadronic sections. The outer layer of the central system (red) consist of a muon system. In addition, two end-cap calorimeters (blue) extend the pseudorapidity coverage of the central detector. The detector parameters are defined in the user-configuration card. The extension of the various subdetectors, as defined in Tab. 1, are clearly visible. The detector is assumed to be strictly symmetric around the beam axis (black line). Additional forward detectors are not depicted.

Magnetic field

In addition to the subdetectors, the effects of a dipolar magnetic field is simulated for the charged particles[3]. This simply modifies the corresponding particle direction before it enters the calorimeters.

2.1 Tracks reconstruction

Every stable charged particle with a transverse momentum above some threshold and lying inside the fiducial volume of the tracker provides a track. By default, a track is assumed to be reconstructed with 90% probability[4] if its transverse momentum p_T is higher than 0.9 GeV and if its pseudorapidity $|\eta| \leq 2.5$.

2.2 Simulation of calorimeters

The energy of each particle considered as stable in the generator particle list is smeared, with a Gaussian distribution depending on the calorimeter resolution. This resolution varies with the subcalorimeter (ECAL, HCAL, FCAL) measuring the particle. The response of each sub-calorimeter is parametrised as a function of the energy:

$$\frac{\sigma}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C, \qquad (1)$$

where S, N and C are the *stochastic*, *noise* and *constant* terms, respectively.

The particle four-momentum p^μ are smeared with a parametrisation directly derived from

[3] `[code]` See the `TrackPropagation` class.

[4] `[code]` The reconstruction efficiency is defined in the smearing datacard by the `TRACKING_EFF` term.

the detector techinal designs[5]. In the default parametrisation, the calorimeter is assumed to cover the pseudorapidity range $|\eta| < 3$ and consists in an electromagnetic and an hadronic part. Coverage between pseudorapidities of 3.0 and 5.0 is provided by forward calorimeters, with different response to electromagnetic objects ($e^{\pm}, \gamma$) or hadrons. Muons and neutrinos are assumed no to interact with the calorimeters[6]. The default values of the stochastic, noisy and constant terms are given in Table **??**.

The energy of electrons and photons found in the particle list are smeared using the ECAL resolution terms. Charged and neutral final state hadrons interact with the ECAL, HCAL and FCAL. Some long-living particles, such as the K_s^0, possessing lifetime $c\tau$ smaller than 10 mm are considered as stable particles although they decay before the calorimeters. The energy smearing of such particles is performed using the expected fraction of the energy, determined according to their decay products, that would be deposited into the ECAL (E_{ECAL}) and into the HCAL (E_{HCAL}). Defining F as the fraction of the energy leading to a HCAL deposit, the two energy values are given by

$$\begin{cases} E_{\text{HCAL}} = E \times F \\ E_{\text{ECAL}} = E \times (1 - F) \end{cases} \quad (2)$$

where $0 \leq F \leq 1$. The electromagnetic part is handled as the electrons. The resulting final energy given after the application of the smearing is then $E = E_{\text{HCAL}} + E_{\text{ECAL}}$. For K_S^0 and Λ hadrons, the energy fraction is F is assumed to be worth 0.7.

[5] `[code]` The response of the detector is applied to the electromagnetic and the hadronic particles through the `SmearElectron` and `SmearHadron` functions.

[6] In the current DELPHES version, particles other than electrons ($e^{\pm}$), photons (γ), muons ($\mu^{\pm}$) and neutrinos (ν_e, ν_μ and ν_τ) are simulated as hadrons for their interactions with the calorimeters. The simulation of stable particles beyond the Standard Model should subsequently be handled with care.

Table 2: Default values for the resolution of the central and forward calorimeters. Resolution is parametrised by the *stochastic* (S), *noise* (N) and *constant* (C) terms (Eq. 1). The corresponding parameter name, in the smearing card, is given.

Resolution Term	Card flag	Value
ECAL		
S	`ELG_Scen`	0.05
N	`ELG_Ncen`	0.25
C	`ELG_Ccen`	0.0055
FCAL, electromagnetic part		
S	`ELG_Sfwd`	2.084
N	`ELG_Nfwd`	0
C	`ELG_Cfwd`	0.107
HCAL		
S	`HAD_Shcal`	1.5
N	`HAD_Nhcal`	0
C	`HAD_Chcal`	0.05
FCAL, hadronic part		
S	`HAD_Shf`	2.7
N	`HAD_Nhf`	0.
C	`HAD_Chf`	0.13

2.3 Calorimetric towers

The smallest unit for geometrical sampling of the calorimeters is a *tower*; it segments the (η, ϕ) plane for the energy measurement. All undecayed particles, except muons and neutrinos produce a calorimetric tower, either in ECAL, in HCAL or FCAL. As the detector is assumed to be symmetric in ϕ and with respect to the $\eta = 0$ plane, the smearing card stores the number of calorimetric towers with $\phi = 0$ and $\eta > 0$ (default: 40 towers). For a given η, the size of the ϕ segmentation is also specified. Fig. **??** illustrates the default segmentation of the (η, ϕ) plane.

The calorimetric towers directly enter in the calculation of the missing transverse energy, and as input for the jet reconstruction algorithms. No longitudinal segmentation is available in the sim-