Delphes 3: Latest Developments

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Abstract. Latest developments in Delphes 3, such as the implementation of photons conversions into electron positron pairs, as well as a renovated energy-flow algorithm, which has been specifically designed to reconstruct complex boosted objects using all the available detector information, are described in this note.

1. Introduction
Delphes is a C++ framework [1, 2, 3], performing a fast multipurpose detector response simulation. The simulation includes a tracking system, embedded into a magnetic field, calorimeters and a muon system. The framework is interfaced to standard file formats [4, 5, 6] and outputs observables such as isolated leptons, missing transverse energy and collection of jets which can be used for dedicated analyses. The simulation of the detector response takes into account the effect of magnetic field, the granularity of the calorimeters and sub-detector resolutions.

Latest developments have to scope of extending the reach of Delphes. Complex event reconstruction algorithms are needed in the context of novel detector configurations, such as prototypes for future colliders experiments. Such detectors will operate at extreme conditions, and will be required to precisely reconstruct particle of large momenta in an environment of higher average occupancy compared to present detectors. An improved version of the energy-flow algorithm has been developed to be able to cope with such conditions and will be presented in section 2. Another recent development deals with the reconstruction of photons which has been made more realistic by including the simulation of photon conversions. Such improvement will be presented in section 3.

2. Energy-flow algorithm
Future detector environments will feature large instantaneous luminosities which typically result in high particle occupancy in the detector. Specific reconstruction algorithms [7] are needed to be able to reject particle originating from secondary scattering (pile-up interactions). In addition, largely “boosted” jets typically display the presence of high momentum hadrons and photons separated by small angles. Given that such boosted objects might indicate the presence of new physics at high scales, specific procedures to reconstruct them accurately are needed.

The detector model in Delphes is simple: charged and neutral particles originating from the interaction point propagate within a cylindrical volume embedded in a magnetic field until they reach the calorimeters. Calorimeters are described by a two-dimensional surface in the $(\eta, \phi)$...
Figure 1. (Left) Delphes event display, showing the inner tracking volume surrounded by the calorimeter. The segmentation in \((\eta, \phi)\) is taken as \((0.1 \times 0.1)\), and matches the typical angular resolution from the hadronic calorimeters of the ATLAS and CMS experiments. (Right) Distribution of conversion vertices obtained with the material density map of the CMS tracker.

plane surrounding the propagation volume (see figure 1, left). This surface is subdivided in elementary cells that are called towers.

The main goal of the energy-flow algorithm in Delphes is to make use of all the available energy deposit information to optimally reconstruct objects such as tracks and tower deposits. These objects are later processed to form high-resolution complex objects such as jets, missing energy, or well identified particles. More specifically one wants to be able to exploit the difference in the performance provided in various energy-momentum range by the two main subdetectors: the tracker and the calorimeters. It is well known that tracking algorithms take advantage of the curvature of charged particles to be able to reconstruct their momenta. Therefore the momentum resolution of tracks is optimal for low transverse momenta, e.g. \(p_T \leq 20\) GeV for the ATLAS [8] or CMS [9] detectors. Conversely, large energy deposits are well reconstructed by calorimeters.

We will now describe in detail the algorithm. Each calorimeter tower is characterised by its edges, which delimit its size (and control the angular resolution of the calorimeter) and by its total energy deposit, \(E^{cal}\). For each tower, we count the number of tracks \(N\) that propagate into it, and separate them into two distinct categories:

- \(N_{\text{good}}\) tracks, such that \(\sigma_{\text{trk}} < \sigma_{\text{cal}}\), depositing total charged energy \(E^{\text{trk}}_{\text{good}}\),
- \(N_{\text{bad}}\) tracks, such that \(\sigma_{\text{trk}} > \sigma_{\text{cal}}\), depositing total charged energy \(E^{\text{trk}}_{\text{bad}}\),

where \(\sigma_{\text{trk}}\) and \(\sigma_{\text{cal}}\) are respectively the momentum resolution obtained with the tracking and the energy resolution obtained with the calorimeter. Good tracks have typically low transverse momentum, since they are reconstructed with high precision by the tracking system, whereas bad tracks have high momenta and are better reconstructed by calorimeters.

We define the excess neutral energy as:

\[
\Delta E \equiv \max(E^{cal} - E^{trk}_{\text{good}}, 0).
\]  
(1)
According to the number $N_{\text{bad}}$ of bad tracks that are found within a given tower, the algorithm proceeds in the following way:

(i) if no bad tracks are found, $N_{\text{bad}} = 0$:

If the excess energy $\Delta E$ is significant, that is, if:

\[
\begin{align*}
\Delta E &> E_{\text{min}}, \\
\frac{\Delta E}{\sigma_{\text{cal}}(\Delta E)} &> S_{\text{min}},
\end{align*}
\]

(2)

where $E_{\text{min}}$ and $S_{\text{min}}$ are two configurable parameters, that respectively represent the minimal energy and the minimum significance for a deposit to be retained. If the above conditions are satisfied, a single neutral energy-flow tower object is produced, with energy $E = E_{\text{cal}} - E_{\text{trk}}^{\text{good}}$. The original (good) tracks are kept unchanged, and are simply re-labeled as energy-flow tracks.

(ii) if at least one bad track is found, $N_{\text{bad}} > 0$:

In this case there is no way to assert whether the excess $\Delta E$ is really originating from a neutral particle hitting the calorimeter, or if it is simply the result of poor tracking resolution producing an over-smeared track. We then use the superior calorimeter resolution to assess to momenta of bad tracks. The momenta of bad tracks are rescaled by a factor:

\[
r = \frac{E_{\text{cal}} - E_{\text{trk}}^{\text{good}}}{E_{\text{trk}}^{\text{bad}}}.\]

(3)

In this case no energy-flow tower are created, good tracks are kept unchanged and re-labeled as energy-flow tracks as in the previous case, and bad tracks have their momenta rescaled by $r$. This approach ensures total energy conservation, since by construction we now have, after rescaling:

\[
\sum E_{\text{trk}}^{\text{bad}} = E_{\text{cal}} - E_{\text{trk}}^{\text{good}}.\]

(4)
Case (i) is easily obtained in high-pile-up scenarios where a significant number of low momentum tracks randomly populate the detector. Case (ii) is instead very frequent when reconstructing highly energetic jets.

To resume, in both cases, for each calorimeter elementary cell, the energy-flow algorithm produces a set of objects called respectively energy-flow towers and energy-flow tracks. These energy-flow objects can be used as input to jet clustering algorithms, or to compute isolation variables or missing energy. The algorithm described in this note has been included starting from Delphes version 3.3.0.

The performance of the energy-flow procedure is shown in figure 2. In older Delphes versions, the simplistic assumption was made that $\sigma_{trk} < \sigma_{cal}$ regardless of the charged particle momentum, which resulted in poor jet resolution performance at high momenta, i.e. $p_T > 1$ TeV. Instead, the algorithm presented above dynamically accounts for the the two different momentum regimes, and gives the most precise measurement in all the considered energy range. Both versions of the energy-flow jets are compared to the calorimeter jets (i.e. reconstructed with pure calorimeter information). At low energies, the energy-flow jets outperforms calorimeter jets thanks to the superior tracking resolution, whereas at high energies both give comparable performance as expected.

3. Photon conversions

About 50% of the total number of long-lived particles produced in a collider experiment are photons originating from $\pi^0$ decays. Accurately reconstructing photons is therefore crucial. For incoming photon energies $E_\gamma \geq 1$ MeV, the presence of material in detectors is responsible for photon conversions into electron positron pairs. The pair of resulting charged particles can be reconstructed as tracks. This phenomenon can be used to measure photons more precisely, especially at moderate energies where the tracking provides excellent angular and momentum resolutions.

The number of photons “surviving” after travelling a distance $\Delta x$ in a given material is:

$$N_\gamma(x) = N_0 e^{-\frac{\Delta x}{\lambda}},$$

(5)

where $\lambda$ is the mean free path and $N_0$ is the number of photons present in the incident beam. Hence, the probability for a photon of converting after travelling a distance $x$ is given by:

$$P(x) = 1 - e^{-\frac{\Delta x}{\lambda}}.$$  

(6)

A basic algorithm can therefore be built upon two simple external inputs:

- the step length, $\Delta x$, which controls the accuracy of the photon conversion simulation,
- the material budget map, $\lambda^{-1}(r, z, \phi)$, the average conversion rate per unit length.  

Also, we consider only a regime such that $E_\gamma \gg m_e$, we can therefore assume that the two resulting particles are emitted collinear to the photon. Within such massless approximation, one can simply generate the energy fraction $x_F$ that gets attributed to each electron, according to the following formula [10]:

$$\frac{d\sigma}{dx_F} = 1 - \frac{4}{3} x_F (1 - x_F).$$

(7)

The conversion algorithm proceeds as follows:

1 In terms of well known quantities, $\lambda^{-1} = \frac{\tau}{\rho X_0}$, where $\rho$ is the material density and $X_0$ is the radiation length of the material.
Figure 3. Distribution of the mass difference $M_{\mu^+\mu^-\gamma} - M_{\mu^+\mu^-\gamma}$ for $\chi_{c1}$ and $\chi_{c2}$ using calorimeter photons (left) and converted photons (right).

(i) the initial photon at $x_0$ is propagated for a distance $\Delta x$ into position $x_1$,
(ii) the values $\lambda^{-1}(x_1)$ and $P(x_1)$ are computed,
(iii) a random number $p$ between 0 and 1 is thrown,
(iv) if $p > P(x_1)$, keep propagating the photons from step (i). Otherwise the photon is converted according to formula 7 and the resulting $e^+$ and $e^-$ are propagated from until they reach the calorimeters.

For sake of illustration, we show in figure 1 (right) a longitudinal projection of the distribution of conversion vertices obtained after specifying the material density map of the CMS tracker. The material distribution can be exactly reconstructed.

A possible application of photons conversions is the reconstruction of narrow resonances decaying into low energy photons [11]. For instance, $\chi_{c1}$ and $\chi_{c2}$ charmonia states decay to $J/\psi\gamma$ and have almost identical masses. Relying simply on calorimeter photons to reconstruct such resonances can result in not being able to distinguish the two distinct states figure 3 (left). Using converted photons instead, thanks the superior angular and momentum resolution of the tracking system at low energies, can help in resolving the two distinct states.

4. Conclusion
Recent developments such as an extension of the energy flow algorithm and the implementation of photon conversions in Delphes have been presented. Further developments on the energy flow algorithm include the possibility of parameterising efficiency loss as a function of high local particle occupancy. In order to account for the difficulty to reconstruct tracks originating from very displaced vertices, a parameterisation of the track reconstruction efficiency as a function of the transverse impact parameter might be beneficial as a possible extension of the photon conversion algorithm.

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