Realistic calorimeter hit digitisation in the `ILDCaloDigi` processor

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Abstract

Description of quasi-realistic calorimeter hit digitisation in ILD, as implemented in the `ILDCaloDigi` processor in the `MarlinReco` package.

1 Introduction

Possibilities for more realistic treatment of calorimeter hits from silicon– and scintillator–based calorimeters have been implemented in the `ILDCaloDigi` processor within `MarlinReco`. The aim of these is to allow the study of the effects of various detector "defects" such as mis-calibrations, limited dynamic ranges, and signal fluctuations, and also to allow more robust comparisons between technologies under more realistic conditions. This notes discusses the implementation as defined by rev.4744 of the `MarlinReco` package, available at `https://svnsrv.desy.de/viewvc/marlinreco/MarlinReco/`.

The energy of `SimCalorimeterHits` produced by the `Mokka` simulation is the energy deposited in the detection element (silicon or scintillator) as calculated by `GEANT4`. They therefore take account of Landau fluctuations in the energy deposits. The role of the digitisation is to simulate the behaviour of the process which converts this energy deposit into the reconstructed energy of hits used in detector reconstruction: this includes effects due to the detection medium (e.g. creation of electron-hole pairs in silicon), the read-out system (e.g. pixelated photo-detectors (PPD - SiPM/MPPC)) used to readout scintillation light, and the electronics which treat these signals (e.g. limited dynamic range).

This note describes a parameterised model which to model such effects. The parameters to be used should be decided by the detector groups, by comparing to data collected during test beam campaigns.

`ILDCaloDigi` also applies a threshold on the energy of hits, as well as possibilities for requirements on the timing of energy deposits. These are not described in this note, since they were not developed by the author.

2 General

The various effects implemented for realistic digitisation are controlled by parameters of the `ILDCaloDigi` processor which can be set at run time via the `Marlin` steering file (i.e. without recompiling). Which type of digitisation to apply to ECAL hits is controlled by the `ECAL_apply_realistic_digi` parameter: a value of 0 (the default) turns off the realistic effects described in this note, and a value of 1 (2) applies the silicon– (scintillator–) specific effects. In the case of the scintillator HCAL, the parameter `HCAL_apply_realistic_digi` plays a similar role, with a value of 0 (1) turning off (on) the simulation of realistic digitisation effects.

Several digitisation parameters are specified in terms of MIP units, so the `ILDCaloDigi` processor requires factors with which to convert the deposited energy (in GeV) to MIP units: these are passed by the `CalibECALMIP` and `CalibHCALMIP` parameters for the ECAL and HCAL, respectively.

Various detector parameters are taken from the `gear` file, in particular the layer layout and number of virtual cells per scintillator strip. If these are not available in the `gear` file, they can be specified via the parameters `ECAL_default_layerConfig` and `StripEcal_default_nVirtualCells` (if values are found in the `gear` file, they take precedence over the value of these parameters).

3 Technology-blind effects

3.1 Mis-calibrations

The effect of imperfect energy calibrations can be simulated by the use of the parameters `ECAL_miscalibration_uncorrel` and `ECAL_miscalibration_correl`, which causes hit energies to be smeared as

$$\begin{aligned} E' =& E \times \\ & \texttt{RandGauss}(1, \texttt{ECAL\_miscalibration\_uncorrel}) \times \\ & \texttt{RandGauss}(1, \texttt{ECAL\_miscalibration\_correl}), \end{aligned}$$

where $\texttt{RandGauss}(\mu, \sigma)$ represents a random number taken from a Gaussian distribution of mean μ and standard deviation σ. In the case of `ECAL_miscalibration_uncorrel`, a new random number is taken for each calorimeter hit (simulating completely uncorrelated mis-calibrations), while in the case of `ECAL_miscalibration_correl`, a single random number is used for all ECAL hits in a given event (simulating completely correlated mis-calibrations).

The uncorrelated miscalibrations induced by `ECAL_miscalibration_uncorrel` of each detector cell can be chosen to be either the same from event to event, or newly chosen for each event. This is controlled by setting the parameter `ECAL_miscalibration_uncorrel_memorise = true` or `false` respectively. The first approach is closer to reality, however in the case of a calorimeter with many cells, can lead to large memory consumption; in the case of typical physics events randomly spread across the whole ILD detector, the second, more memory-efficient, approach is almost certainly sufficient. The first approach is probably only necessary in the case of repeated injection into the same detector region, as occurs, for example, in test beams.

3.2 Dead detector cells

The effect of dead detector cells can be simulated by use of the parameter `ECAL_deadCellRate`, which causes the energy of hits to be set to zero if a random number taken from a uniform distribution in the range [0, 1] is smaller than the value of the `ECAL_deadCellRate` parameter.

3.3 Dynamic range of readout electronics

The saturation of the readout electronics can be simulated by setting the parameter `ECAL_maxDynamicRange_MIP`, in which case the energy of the hit is limited to this value of this parameter (specified in MIP units):

$$E'_{MIP} = min(\texttt{ECAL\_maxDynamicRange\_MIP}, E_{MIP}).$$

3.4 Noise

Uncorrelated, random noise can be simulated by the parameter `ECAL_elec_noise_mips`, which alters the hit energy by

$$E'_{MIP} = E_{MIP} + \texttt{RandGaus}(0, \texttt{ECAL\_elec\_noise\_mips}).$$

4 Silicon ECAL hits

A rather simple approach is followed in the case of silicon readout: the energy deposit in the silicon is converted into a number of electron-hole (e-h) pairs, using the parameter `energyPerEHpair` which gives the energy required to create an e-h pair (in eV). This number of e-h pairs is then used to define the mean of a Poisson distribution, from which a random number is taken to get a statistically smeared number of e-h pairs. This approach is an over-simplification: it ignores, for example, the Fano effect which reduces the fluctuation of e-h pairs with respect to this simple Poisson approximation. Since these fluctuations are anyway much smaller than the Landau fluctuations in energy deposit, they have an almost negligible effect.

5 Scintillator hits

In the case of the scintillator ECAL, several effects are included: non-uniformity of response along the strip length, and the finite number of photo-electrons and PPD pixels. These processes typically have much larger effects than in the case of silicon-based readout. For the scintillator-based HCAL, the same effects, except the strip non-uniformity, are included. The names of the relevant parameters for the HCAL have "`ECAL_`" replaced by "`HCAL_`".

Non-uniformity along strip length

In Mokka simulation, scintillator strips can be split along their length into virtual cells, in each of which a `SimCalorimeterHit` can be produced. ILD-CaloDigi identifies all virtual-cell hits coming from the same strip, and combines them into a single `CalorimeterHit`. Different weights can be given to the energies of different virtual cells within a strip, to simulate non-uniformity along the strip length. A simple exponential dependence has been implemented, controlled by the parameter `ECAL_strip_absorbtionLength`. The energy of the final `CalorimeterHit` is then given by

$$E'_{MIP} = \sum_i E_i \times exp(\delta x_i / \texttt{ECAL\_strip\_absorbtionLength})$$

where the index i runs over the virtual cells of a strip, and δx_i is the distance between the centres of the virtual cell and the strip. This energy is then treated in the following steps:

Conversion of energy to MIP equivalents

The deposited energy in the scintillator is converted to MIP units using the parameter `CalibECALMIP`

$$E_{MIP} = \texttt{CalibECALMIP} \times E_{GeV}.$$

Finite number of photo-electrons

A finite number of photo-electrons (p.e.) are produced in the PPD by energy deposited in the scintillator. The energy deposited in the scintillator is converted to an average number of photo-electrons in the PPD:

$$n_{pe}^{ave} = E_{MIP} \times \texttt{ECAL\_PPD\_PE\_per\_MIP},$$

and the actual number of p.e. n_{pe} is then randomly taken from a Poisson distribution with mean n_{pe}^{ave}.

Finite number of PPD pixels

The finite number of PPD pixels introduces both a saturation effect on the average response and additional signal fluctuations relevant mostly at high signal levels. A simple model of PPD response has been implemented, which ignores cross-talk between pixels, after pulses, and similar effects. The average number of fired PPD pixels n_{pix}^{ave} for a given number of input p.e. n_{pe} is modeled as

$$n_{pix}^{ave} = \texttt{ECAL\_PPD\_N\_Pixels} \times (1 - exp(-n_{pe}/\texttt{ECAL\_PPD\_N\_Pixels})),$$

and fluctuations in the number of fired PPD pixels due to the limited number of pixels are modeled as [?]:

$$\begin{aligned} n_{pix} =& n_{pix}^{ave} + \delta n, \text{ where} \\ \delta n =& \texttt{RandGauss}(0, w) \\ w =& \sqrt{\texttt{ECAL\_PPD\_N\_Pixels} \times exp(-\alpha) \times (1 - (1 + \alpha) \times \exp(-\alpha))} \\ \alpha =& n_{pix}^{ave}/\texttt{ECAL\_PPD\_N\_Pixels} \end{aligned}$$

Variations in pixel response

Variations in individual pixel signals (due to e.g. variations in capacitance) can be simulated by using the parameter `ECAL_pixel_spread`, which introduces extra variations in the PPD signal n_{pe}^{sig}

$$n_{pix}^{sig} = n_{pix} \times \texttt{RandGauss}(1, \texttt{ECAL\_pixel\_spread}/\sqrt{(}n_{pix})).$$

Electronics noise

Electronics noise is then added to n_{pix}^{sig}, as described in section **??**.

Mis-calibration of total pixel number, unfolding of average PPD response

A mis-calibration in this number of total PPD pixels can be introduced by the parameter `ECAL_PPD_N_Pixels_uncertainty`, in which case the assumed number of PPD pixels is defined to be:

$$N_{pix} = \texttt{ECAL\_PPD\_N\_Pixels} \times \texttt{RandGauss}(1, \texttt{ECAL\_PPD\_N\_Pixels\_uncertainty}).$$

This mis-calibrated number of total pixels is then used to unfold the PPD response by using the inverse of the saturation curve:

$$n_{pe}^{\text{unfold}} = -N_{pix} \times log(1 - min(n_{pix}^{sig}, N_{pix} - \epsilon)/N_{pix})),$$

where $\epsilon = 1$ is a small number which ensures that the logarithm is well behaved.

Conversion back to energy

The unfolded number of p.e. is then converted back into a scintillator energy deposit using the parameters `ECAL_PPD_PE_per_MIP` and `CalibECALMIP`.

6 Conclusion

Possibilities for realistic modeling of silicon– and scintillator–based calorimeter energy readout have been implemented in `ILDCaloDigi`. The modeling is rather simple, but should be adequate to allow a comparably realistic simulation of the different technologies. Tuning of the processor parameters should be performed by comparisons with data collected by detector prototypes in test beams.

References

[1] A.Stoykov et al., “On the limited amplitude resolution of multipixel Geiger-mode APDs”, arXiv:0706.0746.