Fast Parameterisation of Electromagnetic Showers in the ATLAS LAr Calorimeter:

Optimisation of the Frozen Shower Libraries

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1 Introduction

1.1 ATLAS - an Introduction

The Large Hadron Collider (LHC) is currently approaching completion at CERN, Geneva Switzerland. The accelerator is designed to collide protons with centre-of-mass energies of up to 14 TeV. This high energy together with the LHC's enormous luminosity will be exploited to answer some of the most fundamental questions of particle physics and check long-anticipated extensions of the Standard Model of particle physics. The First collisions are scheduled for mid 2008.
In order to study the collisions, four experiments are currently under construction: ATLAS, CMS, ALICE and LHCb. ATLAS and CMS are designed as general purpose detectors, while ALICE and LHCb are experiments dedicated to heavy ion physics and b-physics respectively [1].
ATLAS ("A Toridial LHC-ApparatuS") is located about 100 m underground and has a length of about 40 m and a diameter of 22 m. The detector, shown in fig 1.1, includes [2]:

- An inner detector composed of a semi-conductor pixel and strip detectors for accurate measurements of the charge particle trajectories and a straw-tube detector giving many hits per track and independent electron identification using transition rate. A thin superconducting solenoid coil provides a 2 T magnetic field for the inner detector.

- A calorimeter with a inner cylinder using lead LAr technology followed at large radius values by an iron-scintillator tile calorimeter providing good jet energy resolution and complete coverage for measuring the missing transverse energy.

- A high precision stand-alone muon spectrometer surrounding the calorimeter and a superconducting air-core torroidal magnet system which provides the magnetic field.

1.2 ATLAS LAr Calorimeter

The ATLAS electromagnetic calorimeter (fig 1.2) is a lead-liquid argon sampling calorimeter with accordion shaped absorbers and electrodes [3]. Liquid argon technology has been chosen because of its intrinsic linear behaviour as function of the deposited energy, stability of the response and radiation tolerance. The electromagnetic calorimeter is divided into a barrel part (EMB) covering

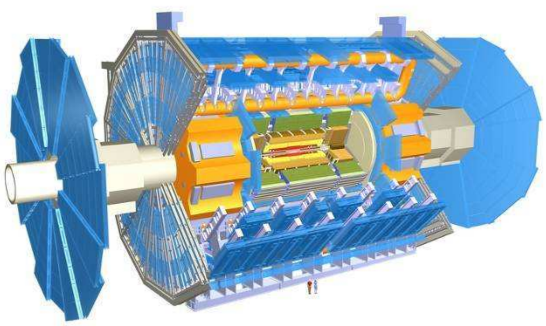


Figure 1.1: *A virtual reality image of ATLAS detector.*

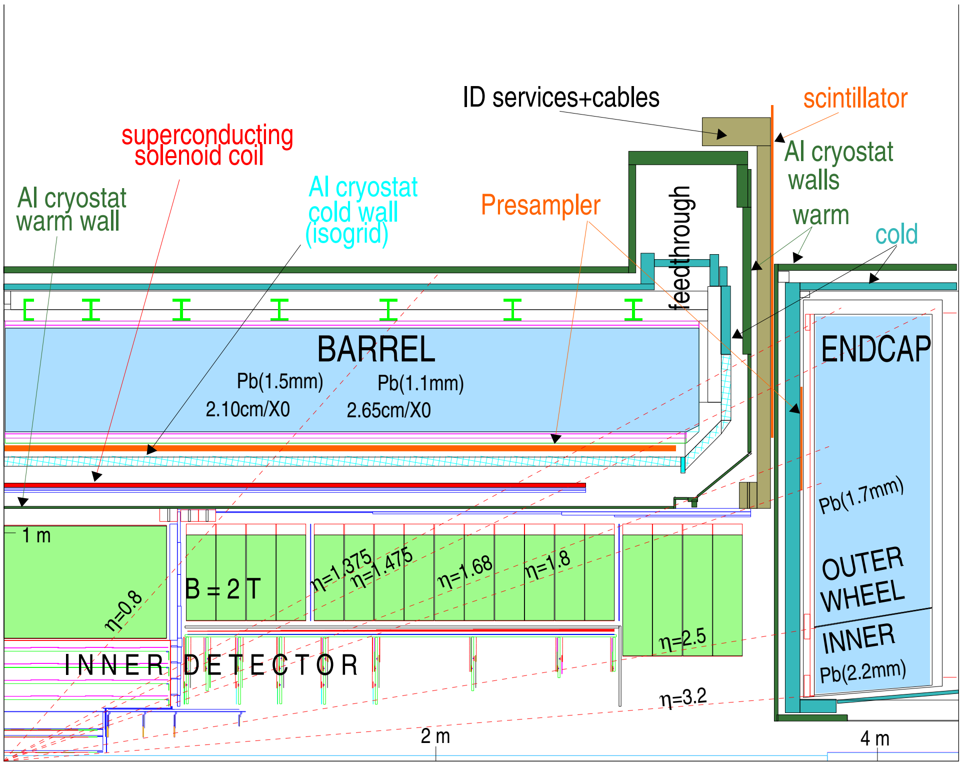


Figure 1.2: *A longitudinal view of a quadrant of the EM calorimeter.*

approximately $|\eta| < 1.5$ and two end-caps (EMEC) covering $1.4 < \eta < 3.2$[1]. The calorimeter has a cylindrical symmetry with a longitudinal segmentation along the radius of the cylinder and transverse segmentation along the pseudorapidity η.
In order to perform angular measurements and discriminate particles, the calorimeter has a fine-grained position-sensitive structure. This is realized by segmenting the first longitudinal sampling into narrow cells of size $\Delta\eta \times \Delta\phi \sim 0.003 \times 0.1$ in the barrel and $\Delta\eta \times \Delta\phi \sim 0.003 \div 0.006 \times 0.1$ in the end-cap.

[1] In the following, the beam direction defines the z axis and the xy plane is transverse to the beam direction. The azimuthal angle ϕ is measured around the beam axis and the polar angle θ is the angle from the beam axis; the pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$

2 Fast simulation

2.1 Parameterization of the electromagnetic shower in the ATLAS calorimeter

The ATLAS detector simulation is based on GEANT4 [4]. GEANT4 simulates detector effects on physics events using a detailed microscopic description of the interactions between particles and matter. It is very accurate but the computing time needed for such kind of simulations at LHC energies can easily become prohibitive. For physics analysis a large number of simulated events may have to be produced and a full simulation approach is not viable.
In particular the simulation of electromagnetic showers in calorimeters is expected to account for a considerable amount of the total simulation time. Using parameterizations of electromagnetic showers can speed up the simulations considerably, and tuned parameterisation allow to maintain the precision of the full simulation.
Currently two fast parameterisations are used in ATLAS LAr calorimeter. The first uses probability density functions to describe the shower at high energy. The second is called "Frozen Shower" (*FS*) and uses shower templates to describe showers below 1 GeV. Furthermore, at very low energy (below 10 MeV) a "*Killing*" process is used to speed up the simulation depositing all the energy of the particle in a single spot.

2.2 Frozen Shower

The *FS* parameterisation is based on the idea of using subshower templates according to the kind of the beginning particle, its energy and its direction. These templates are stored in libraries which contain a thousand subshowers for each energy bin and η bin. There are ten energy bins[1], from 1 MeV to 1 GeV, and twenty-five η bins, from the barrel η values to the first FCAL module values[2].
Originally the Frozen Shower parameterisation was designed to use only one library containing subshowers generated by electrons. Currently also a library containing subshowers generated by photons is being studied to improve the accuracy of the shower description and the computing time.
The *FS* parameterisation starts when an electron (or a photon if the photons library is used) is produced with an energy below 1 GeV. At this time a *FS* template is used to describe the shower development until all the energy is deposited. The thousand templates for each η and energy bin are used one after the other when similar particles are produced.

2.3 Frozen Shower analysis

The first part of this work consisted in testing the full simulation and the Frozen Shower approach with different particles in various conditions for EMB and EMEC.
The shower shapes and the energy distributions in the different samplings are studied for many particles with different η and initial energy values. This analysis led to the identification of some problematic plots in which *FS* shows some deviation from the full simulation. These observations are collected in the appendix A.2. However, most plots show a good agreement between *FS* and full simulated data and a remarkable improvement in computing time using *FS*. For instance, the plots in fig 2.1 show the distributions of the total deposited energy and the computing time for e^-,π^+, π^0 and μ^-. For these plots a thousand events were generated for each particle through the use of the full and

[1]The default energy bins in *FS* libs are 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000 MeV

[2]The default η bins in *FS* libs are: 0.1, 0.3, 0.5, 0.81, 0.83, 1.1, 1.3 in the barrel; 1.62, 1.78, 1.82, 1.98, 2.02, 2.08, 2.12, 2.28, 2.32, 2.4, 2.6, 2.78, 2.82, 3.15 in the EMEC and 3.2, 3.7, 4.2, 4.7 in the FCAL1

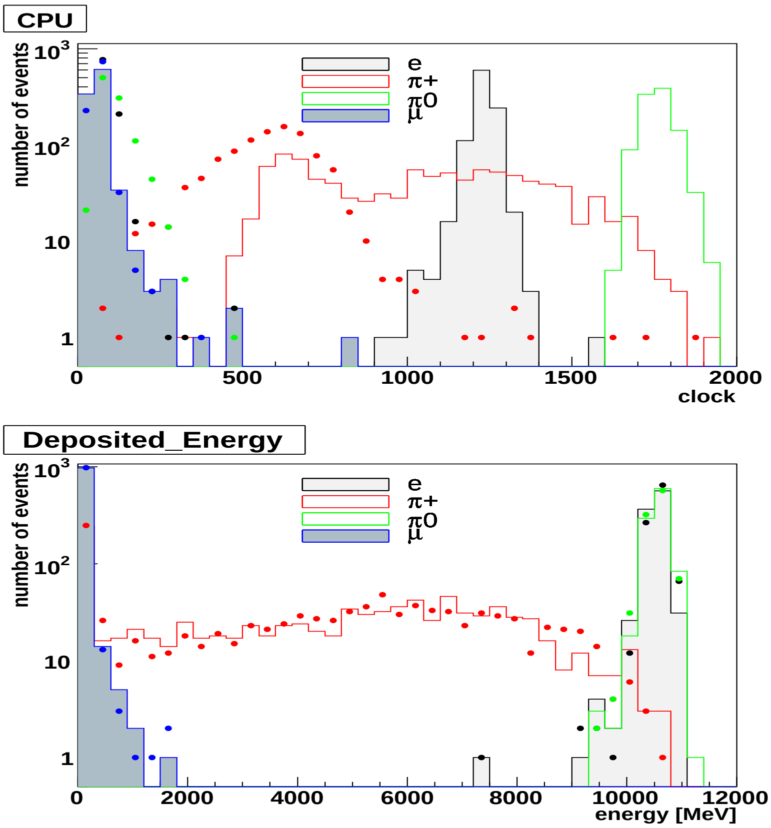


Figure 2.1: *Cpu clocks and deposited energy distributions for full simulation and FS. All the particles were generated with initial energy of* 64 *GeV and for* $\eta = 0.25$*. The full simulation data are plotted using histograms, the FS data using dots.*

the Frozen Shower simulation. The "Deposited_energy" plot confirms the expected behaviors: muons interact weakly with the calorimeter, π^+ have a broad profile and electrons with π^0 have the same distributions, as π^0 is expected to decay shortly in two photons.

Subsequently the differences between the different Frozen Shower simulations are analysed: events simulated with the electron libraries (*FS1*) and with both electrons and phothons libraries (*FS3*) are compared. The most important quantities in this study are the energy distribution and the average time to elaborate an event. In order to check the shower profile two further quantities are used: $\Delta\phi$ and $\Delta\eta$. These variables are defined as:

$$\Delta\phi = R_{xy}\frac{\sum_i E_i(\phi_i - \phi_0)}{E_{tot}} \qquad\qquad \Delta\eta = R_{xy}\frac{\sum_i E_i(\eta_i - \eta_0)}{E_{tot}}$$

where ϕ_0 and η_0 are ϕ and η of the initial particle and the sum is above all the hits produced in the calorimeter. In the LAr calorimeter R_{xy} is approximately 1.5 m.
The distrubutions of these quantities for electron at high (64 GeV) and low energy (5 GeV) are shown respectively in fig 2.2 and in fig 2.3. In these plots the *FS1* and *FS3* performances are compared with the full simulation, with and without *killing* procces. The purpose of this analysis was to analyse the level of agreement between full simulation and the different fast simulations, taking into account the computing time. The following table sums up the average value of time, deposited energy and number of hits per event:

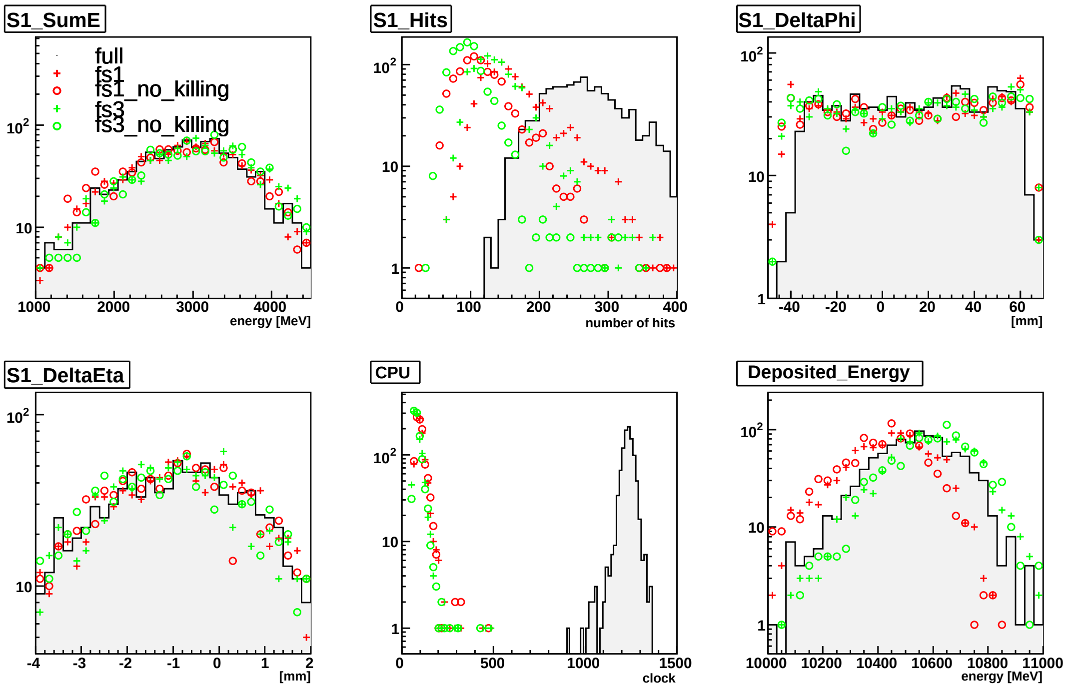


Figure 2.2: *Simulations of electrons with initial energy of* 64 *GeV for* $\eta = 0.25$ *for GEANT4 and FS, with and without killing.*

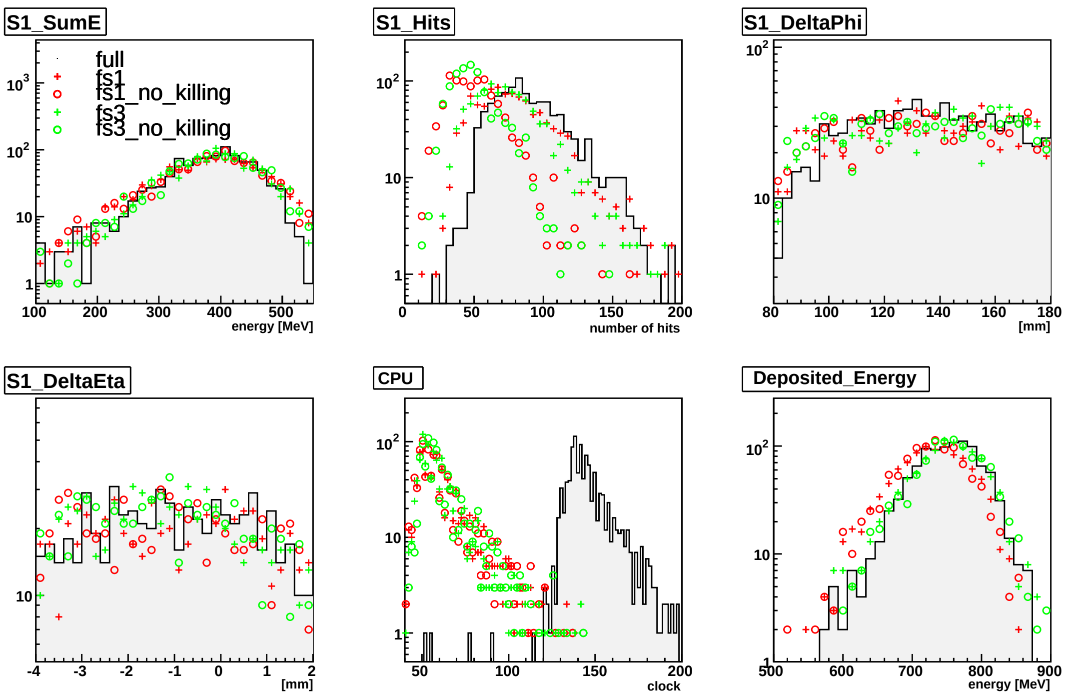


Figure 2.3: *Simulations of electrons with initial energy of* 5 *GeV for* $\eta = 0.25$ *for GEANT4 and FS, with and without killing.*

64 Gev	*time*	*Deposited Energy*	*number oh hits*
full	12.023 +- 0.012	10524.7	583
FS1	0.674 +- 0.009	10422.1	327
FS1, kill(false)	0.692 +- 0.009	10396.3	267
FS3	0.507 +- 0.009	10575.2	270
FS3, kill(false)	0.503 +- 0.008	10585.8	222

5 Gev	*time*	*Deposited Energy*	*number of hits*
full	1.180 +- 0.005	749.6	158
FS1	0.302 +- 0.005	726.7	120
FS1, kill(false)	0.307 +- 0.006	724.3	88
FS3	0.266 +- 0.004	748.0	115
FS3, kill(false)	0.270 +- 0.004	752.1	91

These data show that all the simulations have relatively similar energy, $\Delta\eta$ and $\Delta\phi$ distributions. In general the use of the photon library improves the computing time by roughly 25% for high energy electrons and by 12% for low energy electrons. It also influences the mean value of the deposited energy. With *killing* the average time is generally improved by few percents. It is also interesting to observe the approximately linear relationship between time and the number of hits.

3 Optimisation of the Frozen Shower Libraries

3.1 Libraries Features

The Frozen Shower libraries are characterised by the kind of the initial particle, its energy and its direction. In a library a thousand templates are stored for each energy bin and η bin. A template is a collection of hits generated by the interaction between particles and liquid argon. Every hit is defined as a three dimensional point with a peculiar energy value.
A template is created from the hits distribution of a full simulated event. In the full simulated event all hits with a spatial separation smaller than a defined distance, called *max radius*, are merged and replaced by a new point at the center of energy. This process is repeated until the smallest distance exceeds *max radius*. In addition, only the hits with the highest energy values are kept to create a template. For this purpose, the hits are sorted in energy and only those are saved which have combined energy exceeding 95% of the initial shower energy. The different steps are shown in fig 3.1.

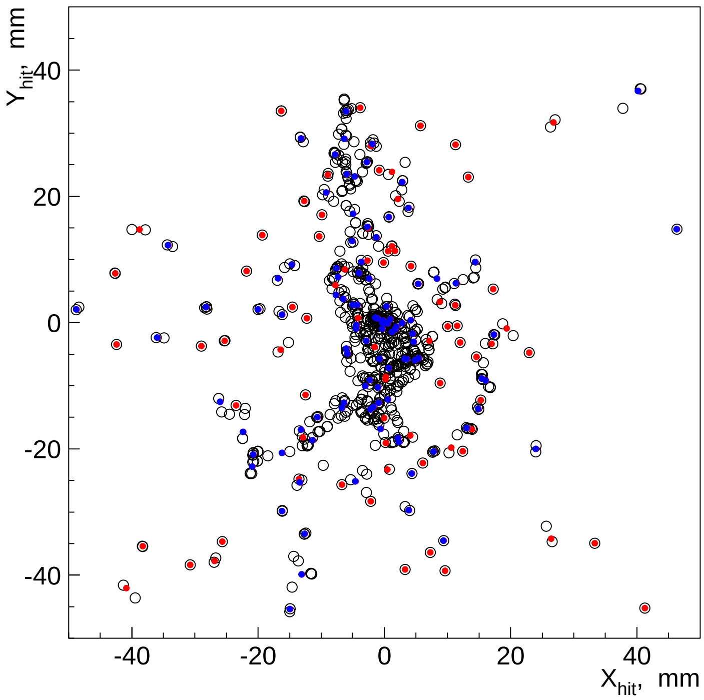


Figure 3.1: *An example of hits merged to create a template. The original hits are black, the merged hits are red and the merged and stored hits are blue.*

Decreasing the number of hits can speed up the simulations considerably, without sacrificing the energy distibution precision. Currently the default value of *max radius* is 5 mm[1], and the typical library size is ∽ 50 MB.

3.2 The Merging Algorithm

The computing time needed to generate a library with the default algorithm grows at a rate corresponding to the cube of the number of the merged hits. The number of merged hits is proportional to the energy of the initial particle and of the *max radius* value. Therefore generating libraries with a high

[1] The defualt $R_{max} = 5$ mm is equals to the size of the strips in the first sampling expressed in η units

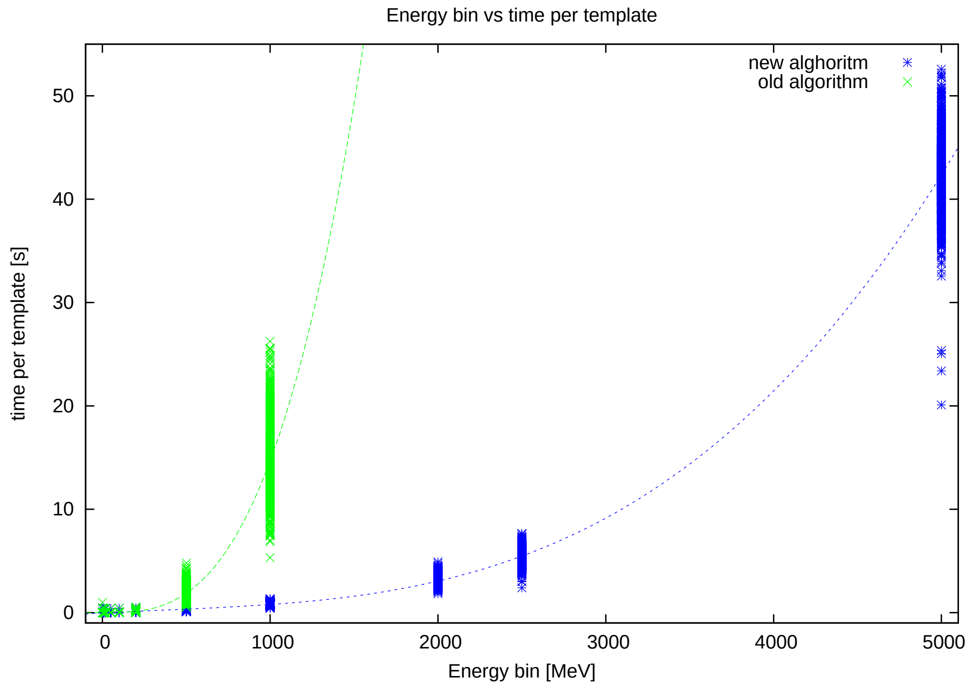


Figure 3.2: *Time needed to generate and to record a template vs the energy bins. To generate a 1 GeV energy template with new algorithm is factor* $\backsim 20$ *faster.*

max radius or with a initial particle energy greater than 1 GeV using the default algorithm can easily become prohibitive. An important result achieved in this work is the improvement of the algorithm and the study of the new library generated by it. The new algorithm performances are shown in fig 3.2. In this plot the old and the new algorithm time per template are compared for different energy bins. The average time taken to generate a 1 GeV template by using the old algorithm is equals to that taken to generate a 4 GeV template by using the new algorithm. The improvement is achieved using sorted lists to identify the closest pair of hits. When two hits are merged and a new hit is created, the next closest pair of hits is calulated approximately in a linear computing time compared with the number of the hits. Only in the worst case the time to find the smallest distance is quadratic.

3.3 *Max radius* analysis

Several libraries were generated to study the relationship between libraries features and the *max radius* value. The purpose was to optimize the merging distance as well as to reduce the libraries size and to speed up computing time by decreasing the total number of the hits without sacrificing the accuracy of the shower description. To achieve this the size versus the *max radius* was first studied. The result is shown in fig 3.3 in which both EMB and EMEC data are reported. Observing this plot, as far as the library size is concerned, increasing the *max radius* above 20 mm appears useless.

On the other hand with the increasing of the *max radius* value the spatial resolution becomes worse. To investigate this, events generated with different *max radius* libraries are matched to analize the differences. The plots in fig 3.4 show the distributions of energy, $\Delta\eta$ and $\Delta\phi$ for samples generated with libraries from 1 mm to 44.7 mm. In these plots all the series below 28.3 mm appear to be very similar. According to these results a reasonable value for *max radius* could be 24.5 mm. For this particular value also a photon library was generated, in order to compare the *FS3* simulation between the default *max radius*=5 mm and the new value 24.5 mm (plots showed in fig 3.5). The *FS3* distributions appears to be very close; moreover, there is a small improvement in computing time. The size of the new library corresponds to 20% of the old one.

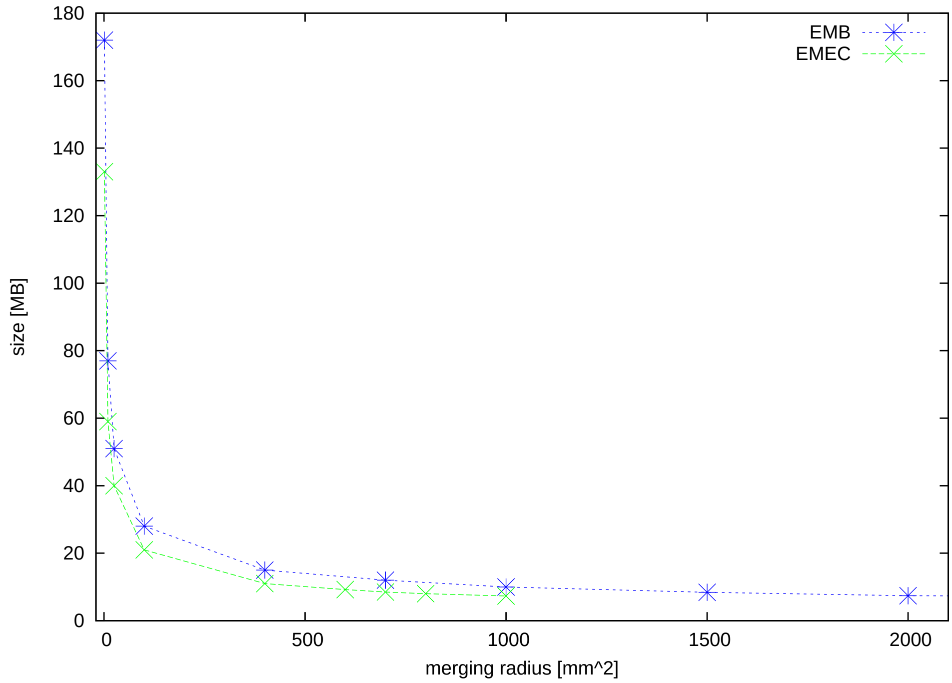


Figure 3.3: *Size of the FS electron libraries versus clustering merging radius square for EMB and EMEC. Currently the default electron libraries (5 mm) has a size of approximately 50 MB.*

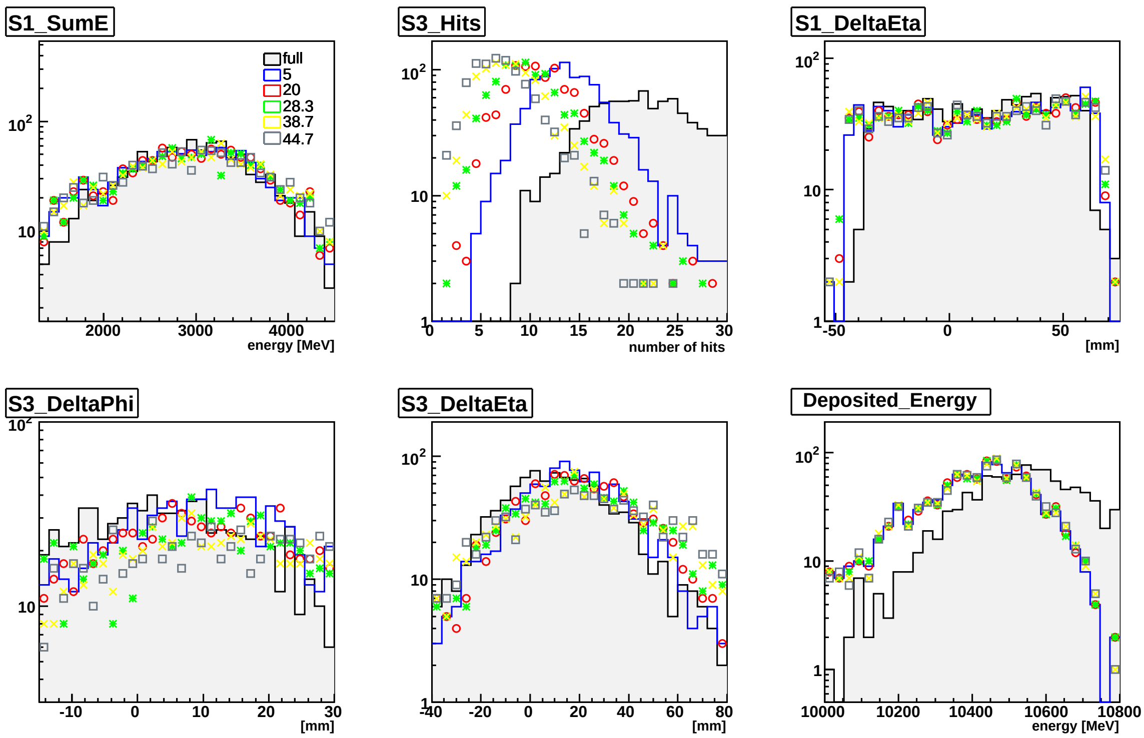


Figure 3.4: *Electrons simulated with initial energy of* 64 *GeV for* $\eta = 0.25$ *using libraries with* max radius *values from* 1 *mm to* 44.7 *mm*

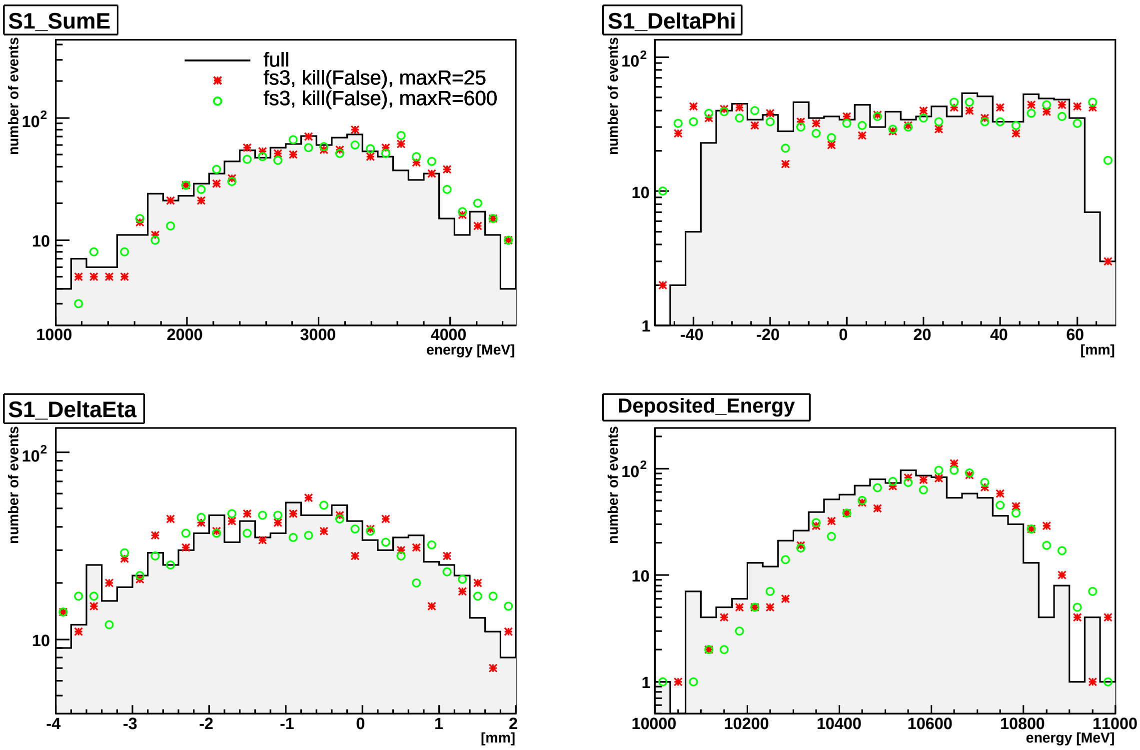


Figure 3.5: *Electrons simulated with initial energy of* 64 *GeV for* $\eta = 0.25$ *using electron and photon libraries with the defualt* max radius *value and with the new optimised value (*max radius*=24.5).*

3.4 *FS* libraries extended to higher energies

An other important analysis viable with the new alghoritm studies the extention to higher energies of the Frozen Shower libraries (recall that with default algorithm this FS library creation time exceeds a week, see fig 3.2). A new electron library with an additional energy bin at 2000 MeV was created and used to generate high energy events. Including this new energy bin in the library caused an increase of library size by a factor $\backsim 2$. This library was created with the default *max radius*. With a large *max radius* the libraries size becomes less important. In fig 3.6 the new library is matched with the default one.

The distributions appear to be very similar but using the new library the average computing time shift from 0.692 ± 0.009 to 0.614 ± 0.009. The improvement in time is approximately 12%, therefore studing higher energies libraries could be an important further possibility to speed up the simultion.

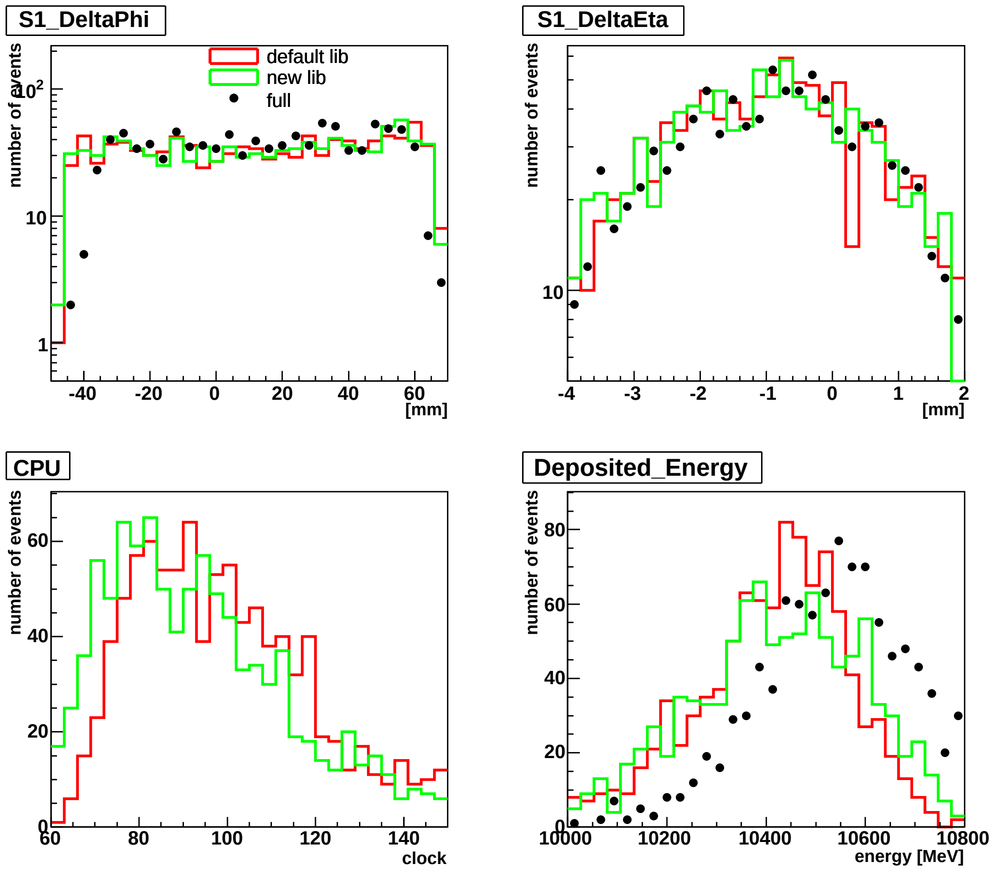


Figure 3.6: *Electrons simulated with initial energy of* 64 *GeV for* $\eta = 0.25$ *using the default electrons library and the new library with the* 2000 *MeV energy bin*

4 Summary

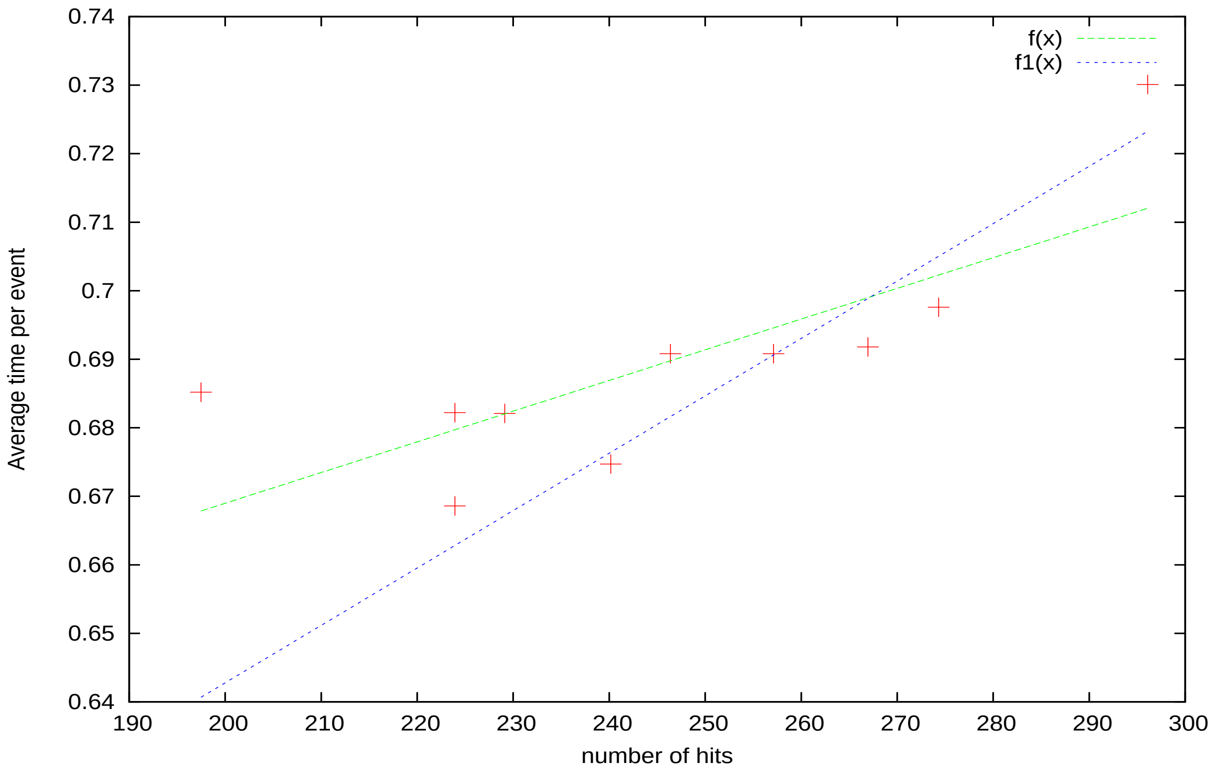
- The *FS* approach was tested for the most common particles with different initial conditions (energy, η, EMB and EMEC...).
- The improvement of the clustering algorithm speeds up the the FS libraries generation so new kind of studies are now viable.
- The cluster distance analysis confirmed the possibility to increase the *max radius* in order to optimize the merging radius (EMB and EMEC); other studies are necessary to define the best value.
- For the first time higher energy libraries were studied! Investigate higher energy libraries could be an important possibility to speed up further the simulation.

Further studies may include combinations of high energy bin and high merging radius values such that simulation time becomes reduced and size is not increased.

A Appendix

A.1 Number of hits vs time

merging radius	number of hits	average time	library size
1	296.094	0.7301	172
10	274.324	0.6976	77
25	266.946	0.6918	51
100	257.118	0.6908	28
400	246.374	0.6908	15
700	240.161	0.6747	12
1000	223.93	0.6686	10
1500	229.109	0.6821	8.4
2000	223.930	0.6822	7.4
10000	197.483	0.6852	4.2



Fit parameters:

- all the points ($f(x) = a + bx$):
  $a = 0.58 \pm 0.03$
  $b = 0.0004 \pm 0.0001$

- only the points with $number\_of\_hits > 240$ ($f_1(x) = a_1 + b_1 x$):
  $a_1 = 0.47 \pm 0.04$
  $b_1 = 0.0008 \pm 0.0002$

A.2 Plots

Figure A.1: e^{-}, $E = 64$ GeV, $\eta = 0.25$, *full, fs1, fs1 no killing, fs3, fs3 no killing.*

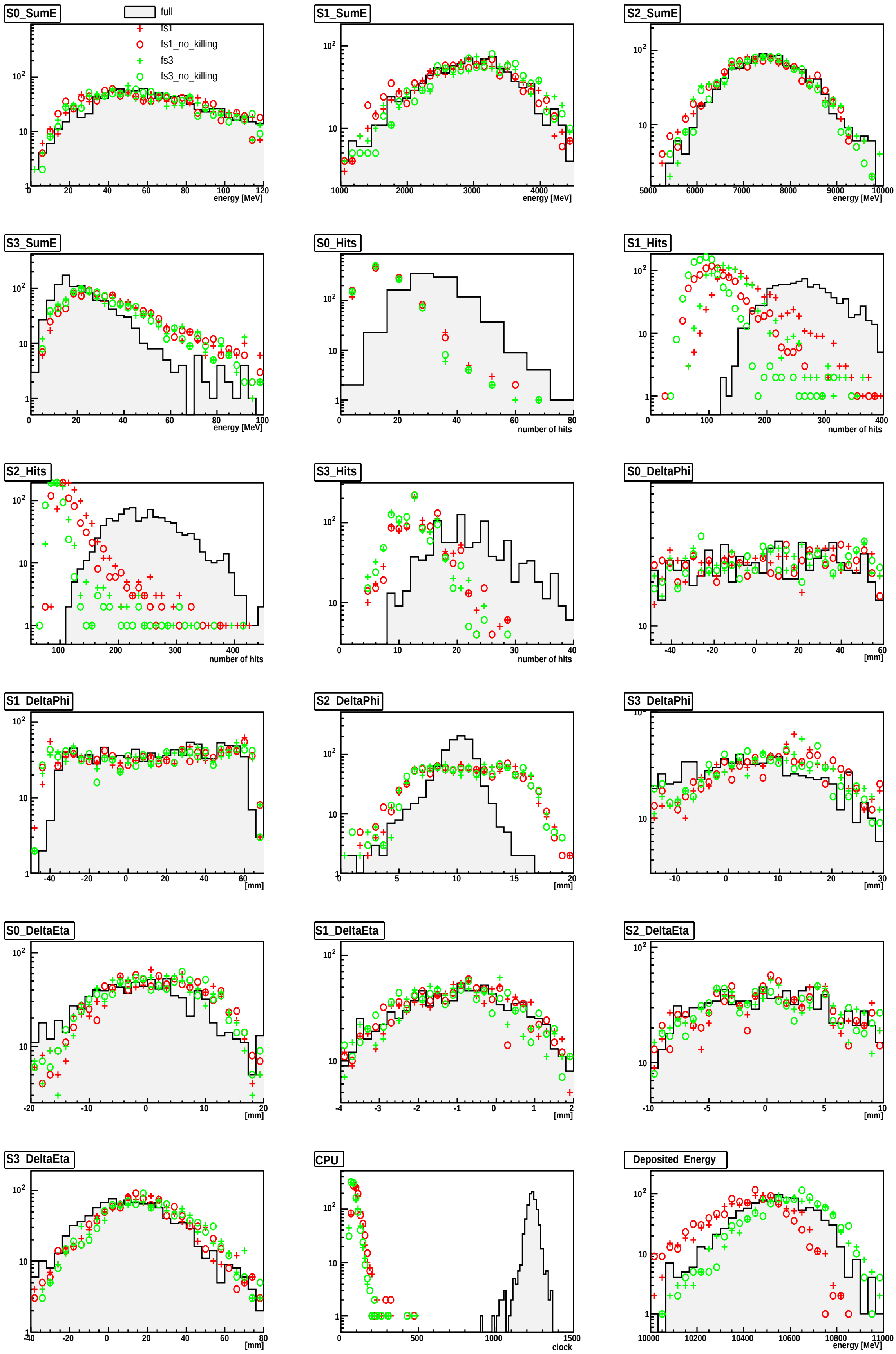


Figure A.2: *Blue:* μ^-, $E = 64$ GeV, $\eta = 0.25$, *full, fs1, fs3. Black:* μ^-, $E = 64$ GeV, $\eta = 2$, *full, fs1, fs3*

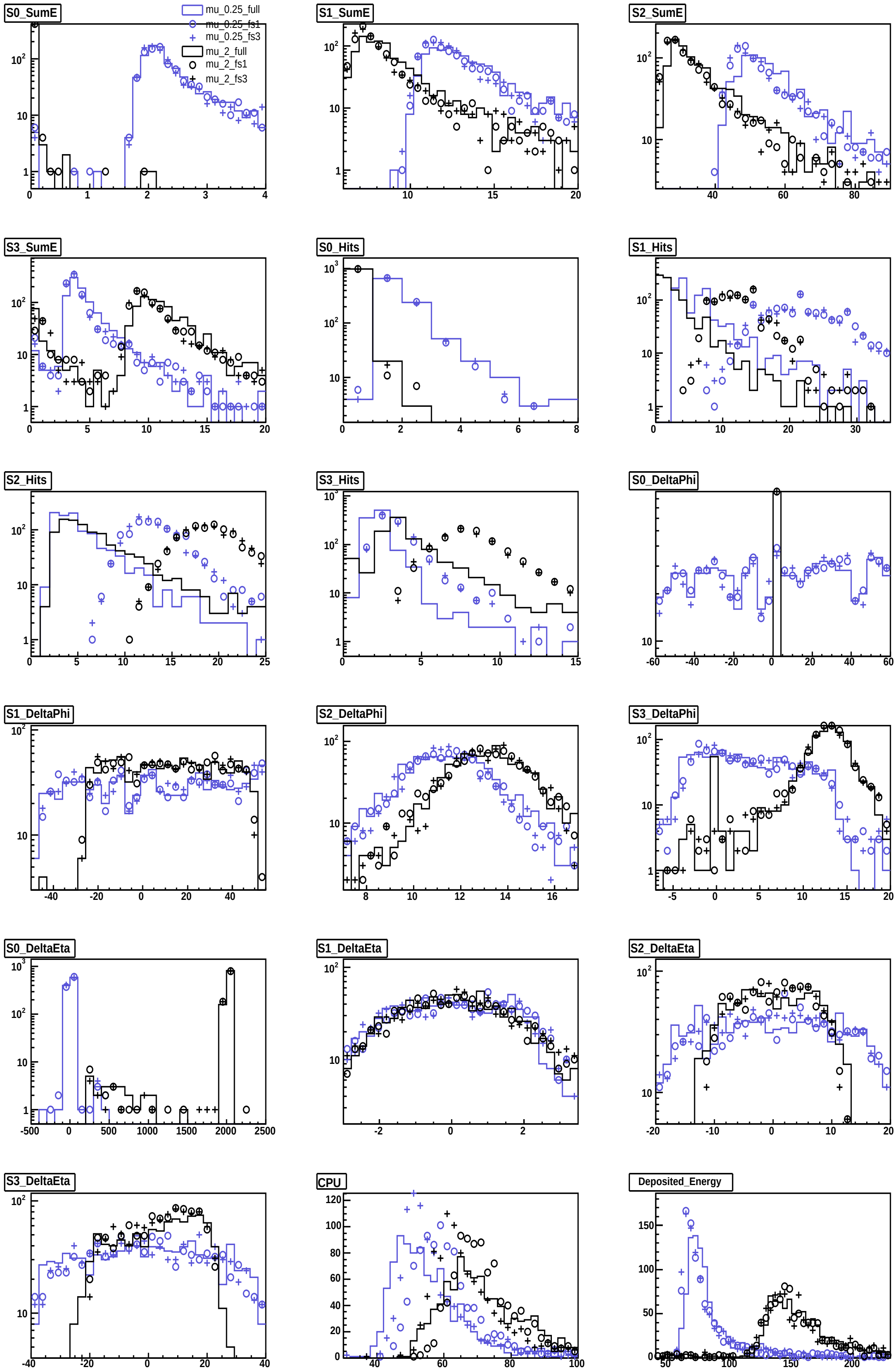


Figure A.3: *Blue:* π^+*,* $E = 64$ *GeV,* $\eta = 0.25$*, full, fs1, fs3. Black:* π^+*,* $E = 64$ *GeV,* $\eta = 2$*, full, fs1, fs3*

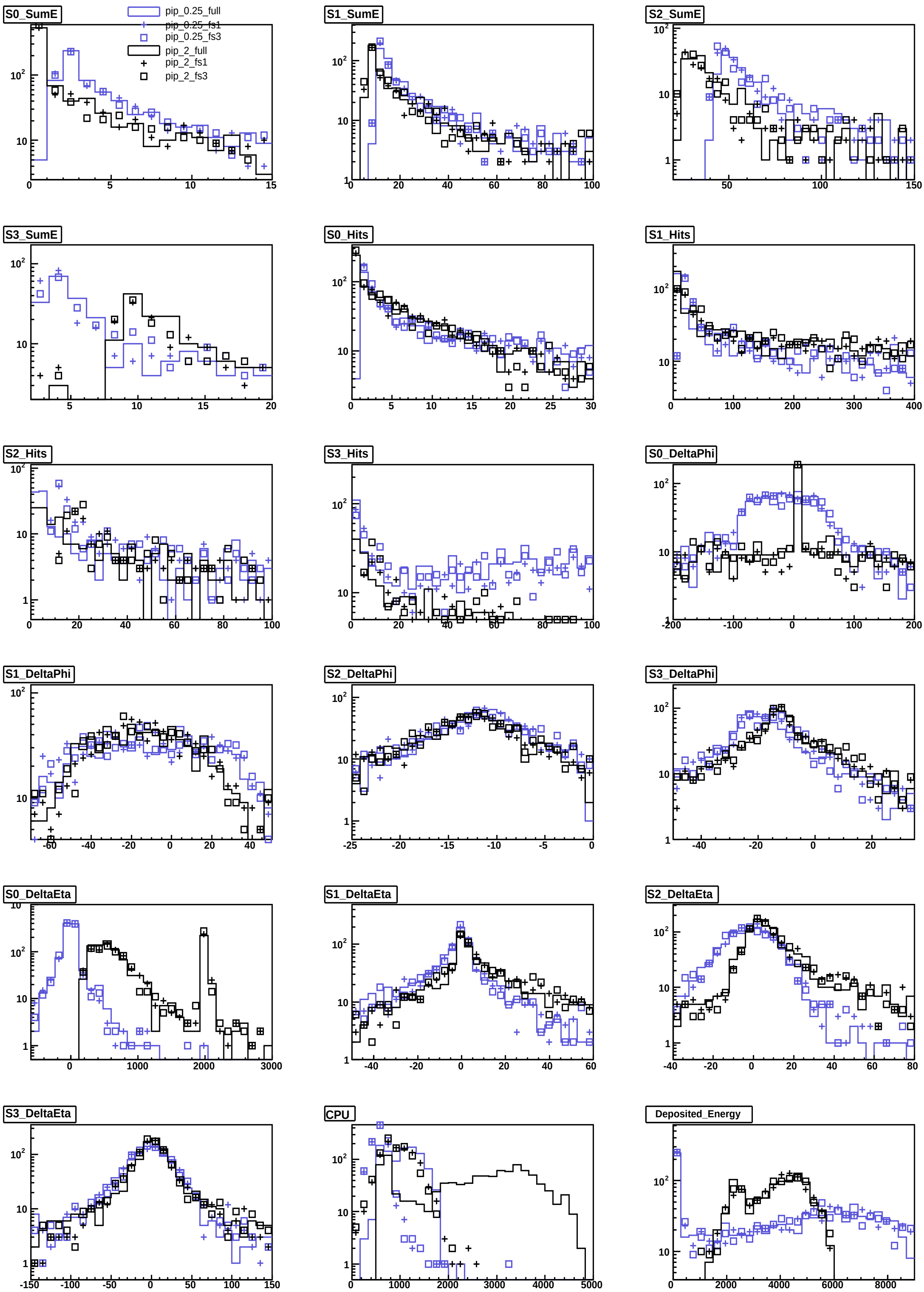
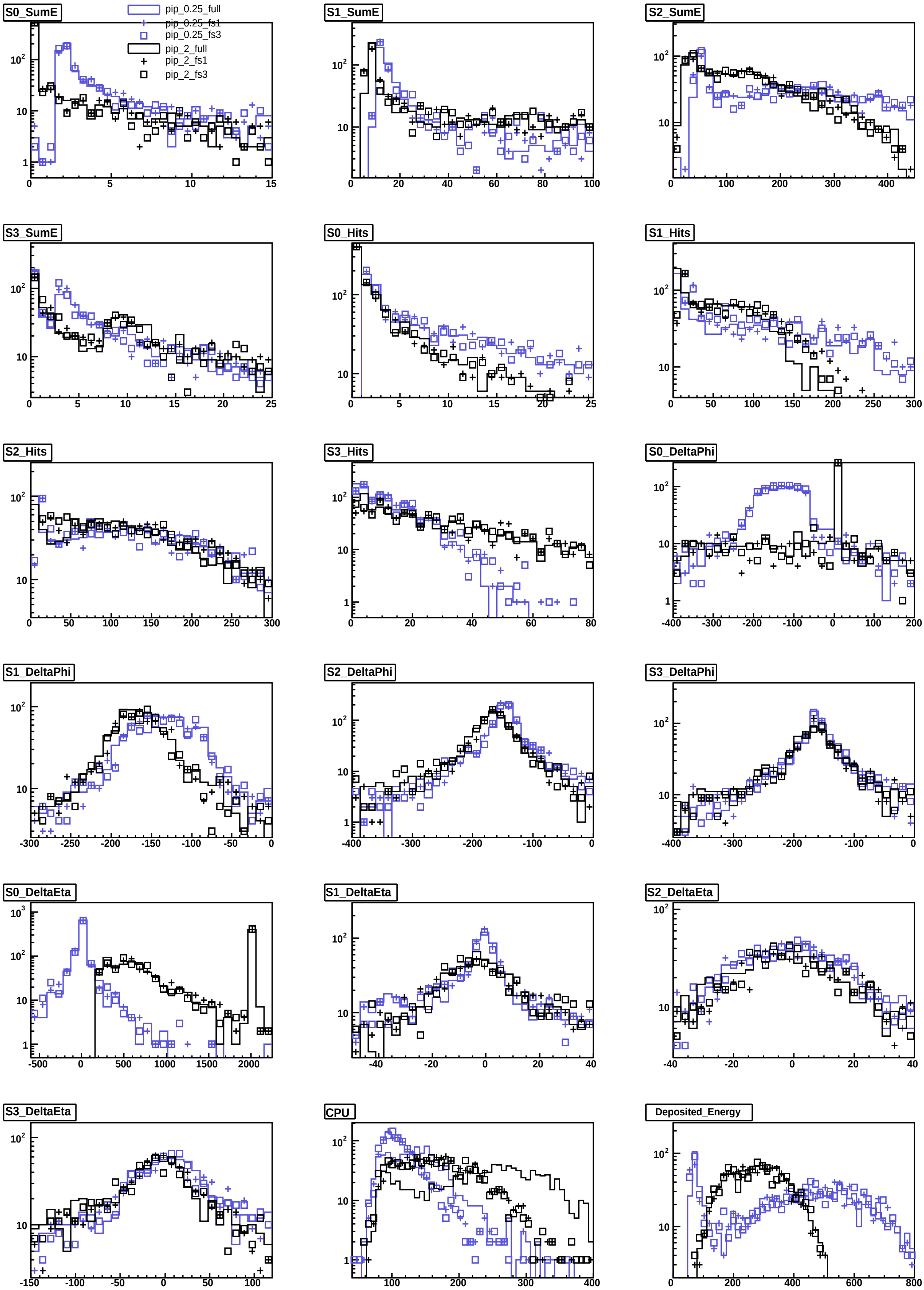


Figure A.4: *Blue:* π^+, $E = 5$ *GeV*, $\eta = 0.25$, *full, fs1, fs3. Black:* π^+, $E = 5$ *GeV*, $\eta = 2$, *full, fs1, fs3*



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