Calorimeter frozen shower

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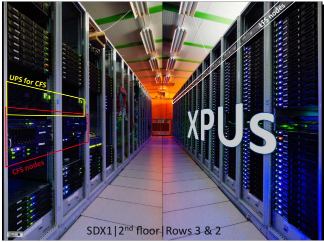
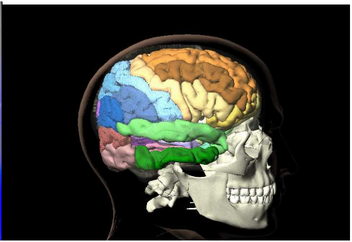
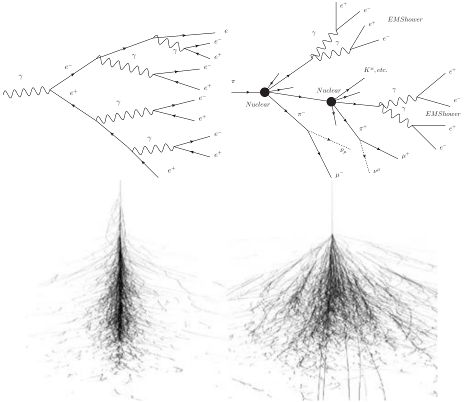
The idea behind frozen showers parameterization

- ATLAS event recording rate is order of several 100 evt/sec, which gives a very large data samples.
- MC samples should be with the same statistics order of billions events. Each requires 6-10 minutes.
- Most of this time is spent into EM-calorimeters (EMB, EMEC, FCAL)
- most important are shower fluctuations for energies $E > E_0$
- large particle multiplicity for energies $E < E_0$
- use full simulation for $E > E_0$. Below this threshold, instead of full simulation of actual low energy particles, use a library of pre-simulated showers.





Showers in the material



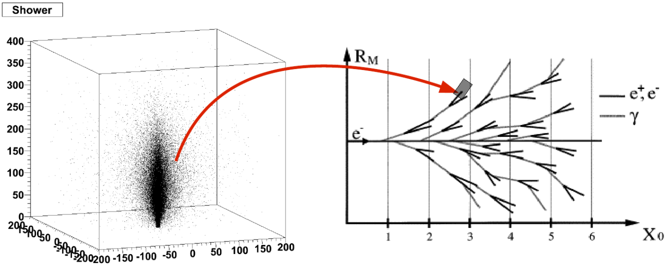
- The shower is a cascade of the secondary particles producing due to the particle interaction with material
- EM shower is much smaller that hadronic and starts early in the calorimeter
- The shape of showers is important for particle identification
- Size of showers also depends on the structure of the calorimeter and energy of particles

Energy measurement and particle ID

- The shape of the showers and energy distribution inside of the shower is important for particle identification
- Particle loose most of they energy in the calorimeter, however mainly in dead material (do not produce any signal response).
- The full energy of the particle can be reconstructed by ratio of the energy which is absorbed in active and dead material.
- The cell – is a smallest structure element of the calorimeter, which can provide a signal response.
- The hit – is a small region of the calorimeter which provides a response from the particle interaction, and normally consist of several cells.
- Calorimeter shower is a collection of hist.

Overview of the Frozen Showers workflow

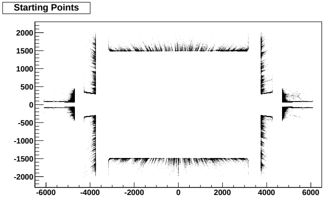
- Low-energy particles are simulated in the EM calorimeters
- All the energy deposition hits made by this particle as a shower are saved
- During the FS simulation the low-energy particle are substituted with pre-generated shower from the library.
- FS in steps:
    - Library creation: need to be performed only ones. Library is created with respect of the shower properties.
    - Fast simulation: Showers from the library is used instead of filly simulated showers



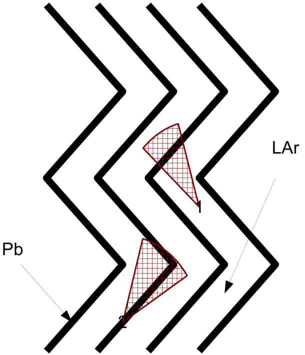
Library creation.

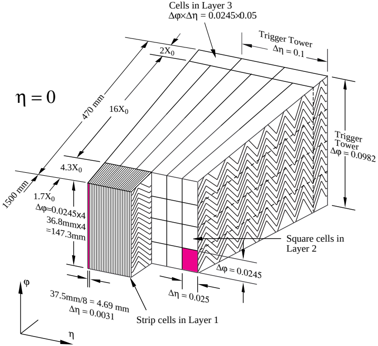
A sample of different high energy particles ($t\bar{t}$, W, Z) is used as a source for library creation

- Generation of showers starting points in the calorimeter
  - The fair (GEANT4) simulation of these particles gives the realistic distribution of the showers' starting points both in energy and geometry
- Generation of showers
  - particles start at the interaction point, propagate to the calorimeter using GEANT4.
  - Generation-time containment check
  - Post processing
- Saving library
- Validation and tunning



Active and passive showers



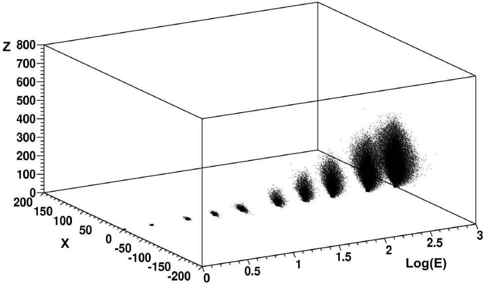


- Showers with origin in LAr (active material) are called “Active”
- Showers with origin in Pb (dead material) are called “Passive”
- Active showers supposed to deposit more energy especially for low energies

- Active and passive showers can be separated

Generation-time containment check

- The library bins, which are situated on the borders of the calorimeter regions have lots of showers, which deposit substantial part of their energy outside of the region
- The amount of energy deposited by the shower outside of the region is calculated
- Only the showers with most of it's energy deposited inside the region (about 98%) are saved in the library
- For FCAL, about 70% of the showers satisfy this condition



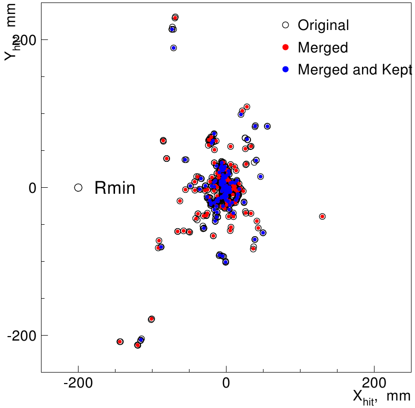
Reduction of shower size

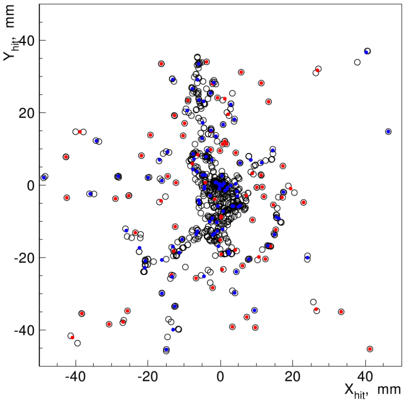
- Clustering:
  - Find a pair of energy deposits with the smallest spacial separation R
  - If $R < R_{min}$, replace the pair by one deposit at the center of energy
  - Repeat first step
- Truncation:
  - Sort deposits following the energy
  - Calculated running sum
  - Keep deposits corresponding to fraction f of the total energy
- Rescaling:
  - Rescale $x_i - x_{ave}$, $y_i - y_{ave}$ for the remaining deposits such that the second momentum of the original shower is preserved
- Use $R_{min} = 5$ mm and $f = 95\%$

Clustering and truncation of the showers make library more robust, removing extreme fluctuations

Reduction of shower size

Transverse view of the shower at different steps of the post-precessing





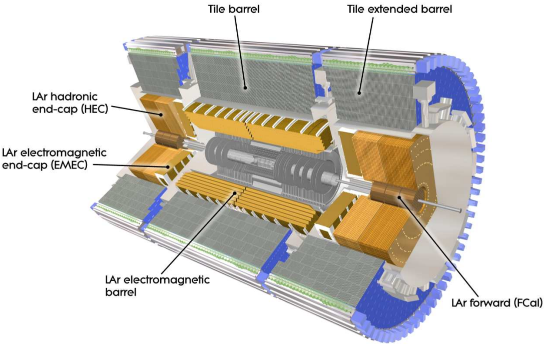
Energy limitation

- Size of the showers and number of hist depends on the energy
- library post-processing, especially clustering requires a lot of CPU time for large showers ($\sim n^3$ or $\sim n^2 \ln n$)
- Using of large showers is also complicated
- Only the showers, which are initiated by electrons with $E < 1$ GeV and photons with $E < 10$ MeV are considered
  - Photons with higher energy rapidly convent to e^+e^- pairs.

Frozen-shower library

- The purpose of the library is to store the shower and the condition, with which this shower was generated
- When asked, the library should return the shower with the generation conditions as close to the required, as possible
- The most challenging part in library design is to distinguish the most important factors, and to make an adequate binning, describing these factors

Calorimeter system

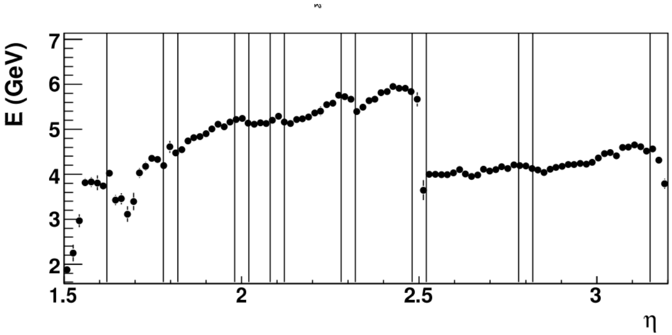


LAr EM calorimeter:

- EMB $|\eta| < 1.47$
- EMEC
  - EMEC-OW $1.37 < |\eta| < 2.5$
  - EMEC-IW $2.5 < |\eta| < 3.2$
- FCAL $3.1 < |\eta| < 4.9$

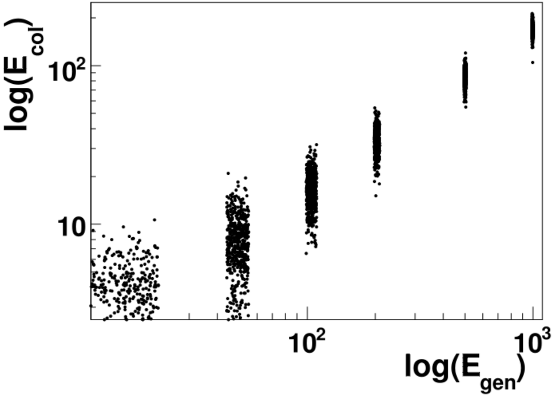
- EM and Hadronic part
- Energy measurement and particle identification (ID)

η binning in central calorimeter



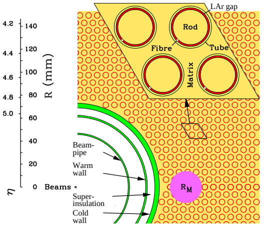
- Energy response depends on η for the central calorimeter.
- Position of bins is introduced to describe this energy response

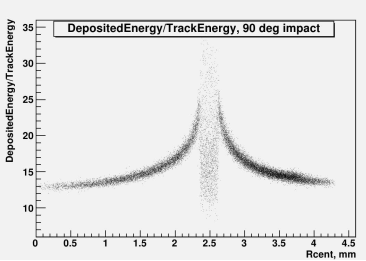
Energy binning in central calorimeter

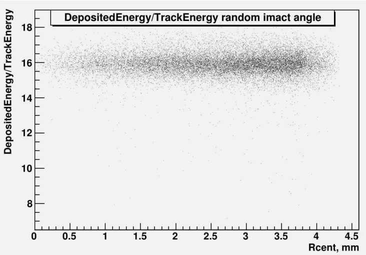


- Energy response depends on energy of the particle
- Early FS:
  - several energy bins with logarithmically growing positions
  - smooth distribution of deposited energy over all bins
- Current FS:
  - Continuous energy binning

Energy response in FCal







- Energy response depends on the distance from the center of rods in the FCal.

Structure of the library

- Number of discrete parameters: η, R_{rod}
- Number of bins for a given parameter
- Number of showers for a given bin
- Shower parameters for a given shower:
  - energy
  - size
  - starting point
  - direction
  - size of hits
- hits:
  - position
  - energy
  - time

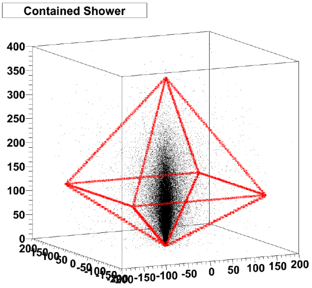
Library is created in bins of η for the central calorimeter and in bins of η and R_{rod} (distance from the center of rod) for FCal.

FS simulation

- Full simulation of the electrons or photons showers is performing until the energy reach threshold.
- If incoming particle is in correct energy range, we stop full simulation (FastSimModel) and substitute it with a frozen shower
- Pick shower randomly from adjacent Energy and η
- Some production checks
- Modification of the shower
- Put energy deposits back into simulation using dedicated sensitive detector

Production-time checks

- Applicable checks: Do not take for parameterization the particle, for which library is not available.
- Containment check: Do not parameterize the particle, if the corresponding shower will propagate outside the calorimeter region
  - Each library stores the average sizes of the showers for each bin. If the containment conditions are met, we can be sure that most of the energy will be deposited inside the calorimeter region

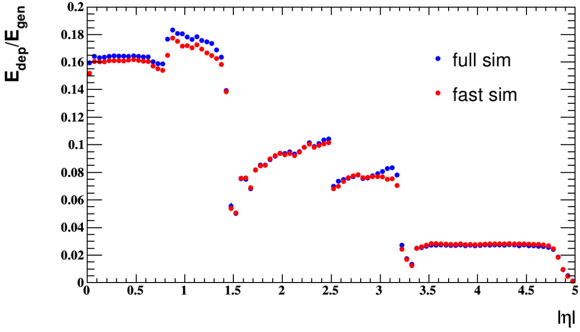


Searching and modification of the shower

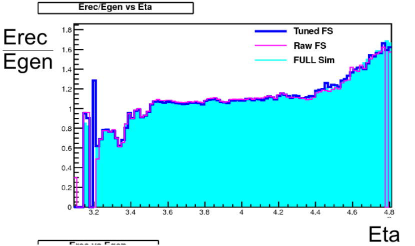
- The η bin is chosen randomly from the two adjacent η bins in the library, where the probability $p(\eta)$ to choose bin η_l is given by $p(\eta) = \frac{\eta - \eta_l}{\eta_r - \eta_l}$.
- Find shower with proper energy and position
- Transform position of energy deposits into global coordinate system.

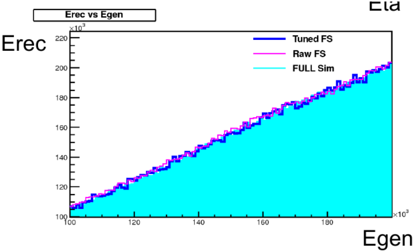
Single particles validation

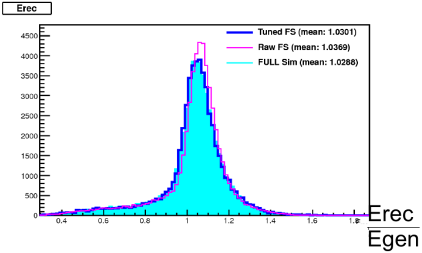
- First validation of the FS simulation is performed using single-particle events: propagation of one specific particle through detector.
- Validation is performed at simulated level.
- Energy response as a function of η in different samplings of the calorimeter is important distribution for the validation.



Tuning





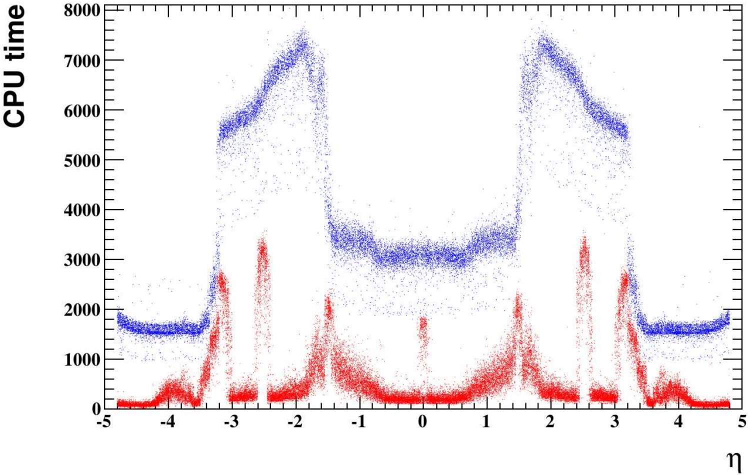


- The generated libraries requires small tuning (app. 1-2%) in energy response and resolution
- Energy scaling was performed in each bin in the library

Results - Timing

Single electrons/positrons with E=50 GeV from IP:

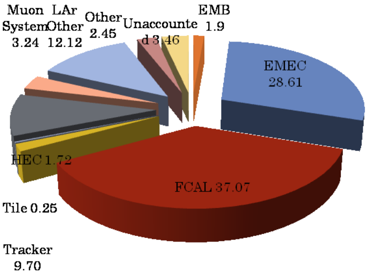
- average time gain of 10
- Cracks and intersections clearly visible

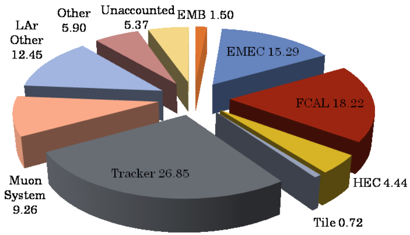


Results - Timing of physics event

- Single electrons (in seconds):
  - Barrel: 2.3/0.7 = 3.3
  - EndCap: 4.4/0.9 = 4.9
  - FCal: 1.1/0.4 = 2.8
- $Z \to e^+e^-$: 7.7/3.3(min) = 2.3
- di-Jet: 13.6/6.5(min) = 2.1
- SUSY: 12.8/6.3(min) = 2.0

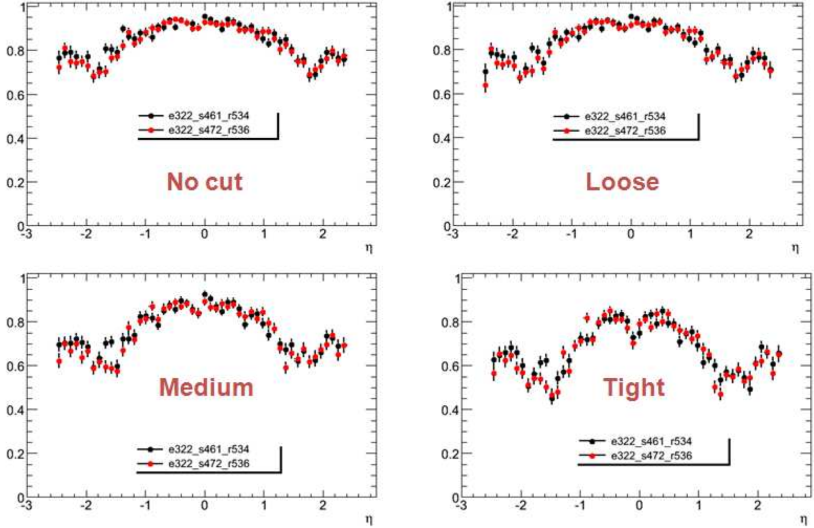
Calo active volumes no longer dominate the simulation.





Comparison with full simulation. $Z \to ee$ analysis.

Truth reconstruction probabilities



Support of the FS

- FS simulation is sensitive to the detector geometry and reconstruction algorithm.
- New version of ATHENA requires new FS libraries and new tunning.
- Present version of the FS is much stable, compare to version used for mc11 production.
- Library creation and tuning is almost automatized with scripts. Additional programming is not required.

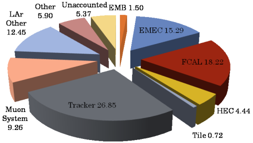
Summary

- A frozen shower technique has been developed for the ATLAS calorimeters and works now across all of the electromagnetic calorimetry. The development was guided by a goal of not sacrificing physics for speed; careful attention was given to shower shapes and calorimeter response.
- Chief result is that the procedure accelerates the simulation by about a factor of 10 in stiff electrons (64 GeV), and by about a factor of 2-3 for physics events.
- Simulation of EM processes in calorimeters are no longer dominant in the simulation;
- FS simulation is used for MC12 production in FCal region (which requires most CPU time and less precision) and speedup simulation to about 25%
- Differences between FS and full simulation is much smaller than between data and MC

Backup

Other approaches for improvement

- Keep working on the calorimeters: frozen hadron showers will ultimately reduce the remaining CPU time in active calo pieces to near zero.
- New algorithms for FS simulation: Using graphics cards to rotate the showers.
- Dead materials need attention: Showering of the particle in the Cryostat.
- Optimize the tracker: about 80% of CPU time is spend in the inner detector.



ATLAS MC production

- Generation and digitization are normally fast and order of few seconds.
- Simulation of the particle propagation requires most of the CPU time
- The reconstruction procedure is applied for both data and MC and therefore it is dangerous to change this procedure for MC.
- The "Frozen shower" (FS) technique is applied to speedup the simulation step.
- Base idea: change the detector simulation such, that reconstruction procedure, which runs on the fast and full simulated samples, will provide the same result.
- Finally, fast simulation should not bring additional systematic uncertainty for analysis.

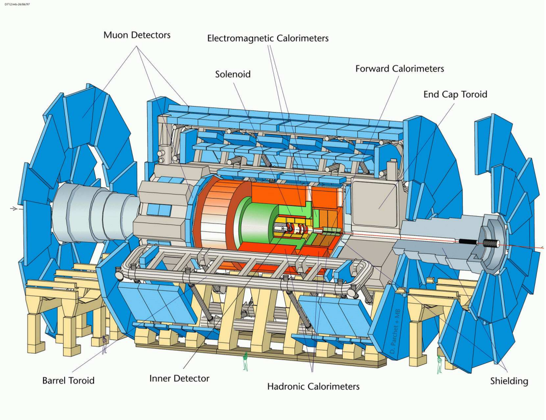
Theoretical background of the FS

- Simulation is a complicated procedure: ATLAS detector is a 7000 tons of the dense material, which absorbs few (or few tens) TeV for each event
- The knowledge of the detector structure and propagation of the high energy particles through detector material is necessary to understand the FS technique.

Particle propagation

- Most of the particles, which are under investigation in ATLAS (W, Z, t, H) are decay in the beam-pipe and only products of their decays propagate to the detector
- Inner detector is a most transparent part of the detector. Bremsstrahlung of the light charges particles is dominated. Short lived particles decay and produce secondary vertices.
- Calorimeter is constructed to absorb most of the particle energy. Light charged particles and photons quickly lose their energy in the EM calorimeter by producing EM shower. Hadronic particles loose their energy with Hadroniq shower, which is much large than EM.
- Other particle (neutral leptons, possible tail of the hadron showers) can propagate in the muon system or even outside the detector.
- Simulation of the calorimeter requites most of the CPU time.

The ATLAS detector



- Nominally forward-backward symmetric
- Each sub-detector is divided into barrel and end-cap regions
- Designed to cover the full physics potential of the LHC

Main components:

- Inner detector
- Calorimetric system
- Muon spectrometer

Kinematics:

- z-axis: beam-direction
- ϕ and p_T are defined in x- and y-plane
- $\eta = -\log(\tan(\frac{\theta}{2}))$