(Fast) Shower Simulation in ATLAS

Wolfgang Ehrenfeld – University of Hamburg/DESY

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Content

- Introduction (LHC and ATLAS)
- Calorimeter Layout and Simulation
- Accelerating Shower Simulation in the Calorimeter
The Large Hadron Collider

- highest energy particle collider ever built
  - pp collisions at $\sqrt{s} = 14$ TeV, $L = 10^{34}$ cm$^{-2}$s$^{-1}$
  - 7 x energy, 100 x luminosity of Tevatron

TeV scale physics can be probed for the first time!
Challenges at the LHC: Event Rates

Running scenarios:
- **start-up**: \( L = 10^{31}-10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
  - No additional minimum bias events
- **low-lumi**: \( L = 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)
  - 3 minimum bias events (~225 particles)
- **high-lumi**: \( L = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
  - 23 minimum bias events (~1725 particles)

Number of events:
- **tt**:
  - \( \sigma \sim 1 \text{ nb} \rightarrow 10 \text{ million events @ 1 fb}^{-1} \)
- **storage rate**:
  - 200 Hz \( \rightarrow 2 \text{ billion events} \)
The ATLAS Detector

- **Calorimetry (|\(\eta|\)<5)**
  - EM: Pb-LAr with Accordion shape
  - HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

- **Muon Spectrometer (|\(\eta|\)<2.7)**
  - air-core toroids with muon chambers

- **Tracking (|\(\eta|\)<2.5, B=2T)**
  - Si pixels and strips
  - Transition Radiation Detector (e/\(\pi\) separation)

Largest collider detector ever built!
Requirements for Detector Simulation

- **Physics**: Excellent description of detector response
  - describe complex geometry of real detector
    - ideal detector
    - misalignment
    - material distortion

- **Timing**: Fast processing
  - the expected rate of physics events is too high to have more MC than data
  - even with the GRID only 20% of the amount of recorded data will be simulated (ATLAS Computing TDR)

- **Usability**: Easy to handle
  - configuration of different geometries
  - changing parameters
  - maintenance

- This talk will concentrate on the second topic!
**Atlas Simulation Chain**

- **Event generator framework interfaces multiple packages**
  - including the Genser distribution provided by LCG-AA

- **Simulation with Geant4**
  - automatic geometry build from GeoModel (~5M volumes)
  - configured using python

- **Digitization**
  - allows inclusion of pile-up events
Simulating the ATLAS detector in Geant4 takes around 10 minutes for an average physics event (not including digitization).

Main time is spend in the calorimeter system.

These numbers are for the QGSP_EMV physics list. The new default list QGSP_BERT will take much longer.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Z -&gt; e+e-</th>
<th>di-jets</th>
<th>SUSY</th>
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<tbody>
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<td>Subsystem</td>
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<td>20,6</td>
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<td>Event</td>
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Improve time consumption of EM shower simulation in order to reduce overall simulation time and increase Monte Carlo data sample.
The ATLAS Calorimeters
The ATLAS Calorimeter

4 calorimeters use Liquid Argon technology:

- Barrel, Endcap, Forward and Hadronic Endcap
- LAr used for radiation hardness and speed

Barrel and Endcap:
Accordian structure for \( \phi \) uniformity
EM Barrel Calorimeter

- Calorimeter consists out of two half barrels
  - services and cables on the outer side

- Liquid Argon chosen for radiation hardness and speed

- Electrodes and absorbers are accordion shaped → ensures azimuthal uniformity (no cracks)
  - absorber is a sandwich of steel and lead
  - 1024 electrodes and absorbers

- Dimensions:
  - $r = 1500 – 1970$ mm
  - $0 < |h| < 0.8$:
    - 1.5 mm lead absorber / 2.1 mm gap
  - $0.8 < |h| < 1.475$:
    - 1.1 mm lead absorber / 2.1 mm gap
EM Barrel Calorimeter

$|\eta| < 1.475$

- Cu/kapton electrode
- Honeycomb spacer
- Stainless-steel-clad Pb absorber plates
EM Barrel Calorimeter: Simulation

- **Geometry:**
  - includes cables and mother boards
  - barrel is filled with Liquid Argon, electrodes and absorbers are positioned into it
  - ignore spacer

- **Material:**
  - take Liquid Argon temperature into account
  - effective material for cables, mother boards and absorber plates (steel, lead, glue)

- **Sagging:**
  - effect of sagging computed with a finite element method
  - maximal amplitude taken from a measurement (1.2 mm)
The calorimeter consists of two endcaps and each endcap of an outer and inner wheel.

Electrodes and absorbers are accordion shaped:
- Absorber is a sandwich of steel and lead
- 768/256 electrodes and absorbers in the outer/inner wheel

Dimensions:
- \( r = 302 - 2034 \) mm
- Thickness: 510 mm
- \( 1.375 < |h| < 2.5: \)
  - 1.7 mm lead absorber / 2.8 - 0.9 mm gap
- \( 2.5 < |h| < 3.2: \)
  - 2.2 mm lead absorber / 3.1 - 1.8 mm gap
The geometry of the endcap accordion is more complex: the height is not constant but a function of the radius.

The geometry in simulation is realized using a G4 custom solid.

Otherwise similar to barrel.
Forward Calorimeters

- Range: $3.1 < |\eta| < 4.9$
- Novel electrode structure: thin annular gaps formed by tubes in an absorber matrix, which are filled with anode rods of slightly smaller radius
- Gap maintained by helically-wound radiation hard plastic fibre
- Three modules: 1 EM, 2 Hadronic

<table>
<thead>
<tr>
<th></th>
<th>Type</th>
<th>Absorber</th>
<th>Gap (μm)</th>
<th>Number of Electrodes</th>
</tr>
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<tbody>
<tr>
<td>FCal1</td>
<td>EM</td>
<td>copper</td>
<td>250</td>
<td>12000</td>
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<tr>
<td>FCal2</td>
<td>HAD</td>
<td>tungsten</td>
<td>375</td>
<td>10000</td>
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<tr>
<td>FCal3</td>
<td>HAD</td>
<td>tungsten</td>
<td>500</td>
<td>8000</td>
</tr>
</tbody>
</table>

Matrix and rods are part of the detector ‘absorber’ and are composed of the same material
Forward Calorimeters

Liquid Argon Gap

Tungsten Rod
Forward Calorimeters: Simulation

- **Geometry:**
  - In the absorber liquid argon filled holes are placed. In these holes the rods are positioned.
  - Ignore spacer
Material Budget

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Fast Shower Simulation in ATLAS
Where to Start?

- ~60% of the simulation time is spent in calorimeters (EM barrel, EM endcap and EM forward)
- **What is the reason?**
  - complex geometry?
  - complex physics?
  - too many particles?!
Accelerating Simulation

Three different approaches:

- **High energy electrons (> ~1 GeV):** fast shower parameterisation
  - Describe longitudinal and transverse shower profile by functions

- **Low energy electrons (< ~1 GeV):** frozen shower library
  - Describe shower by pre-stored hits (frozen shower)

- **Very low energy electrons (< ~10 MeV):** one spot model
  - Substitute very low energy electrons by one energy deposit

**Photons are electrons (pair production)**

These techniques are implemented into the ATLAS Geant4 detector simulation deriving from GFlashShowerModel (Geant4).
Fast Shower Parameterisation Technique

A treatment for showering electrons on a sound mathematical footing is available for electrons:

- Grindhammer, Peters - hep-ex/0001020
- Grindhammer, Rudowicz, Peters - NIMA290:469(1990)

- Describe longitudinal and transverse shower profile by functions

- Estimate parameters from fully simulated showers (Geant4) as a function of a few kinematic quantities
  1. Longitudinal profile ($\Gamma$ function)
  2. Transverse profile (rational function)

- At simulation time substitute an EM shower by random hits sampled from functions for the transfers and longitudinal shower profile at steps of 1/100 $X_0$.

- Approach valid for energies above $\sim$GeV and homogeneous calorimeter
Longitudinal shower profile:

\[ < \frac{1}{E} \frac{dE(t)}{dt} > = \frac{(\beta t)^{\alpha-1} \beta \exp(-\beta t)}{\Gamma(\alpha)} \]

t = longitudinal depth into shower
\[ \alpha = \text{shape parameter} \]
\[ \beta = \text{scaling parameter} \]

Transverse shower profile:

\[ < \frac{1}{E(t)} \frac{dE(t,r)}{dt} > = p \frac{2rR_C^2}{(r^2+R_C^2)^2} + (1-p) \frac{2rR_T^2}{(r^2+R_T^2)^2} \]

\[ R_C(t) = \text{the median of the energy distribution of the core of the shower} \]
\[ R_T(t) = \text{the median of the energy distribution of the tail of the shower} \]
p is a weighting function

\[ p(t) = \frac{E_{\text{core}}(t)}{E_{\text{tail}}(t)} \]
Parameter Extraction: Forward Calo

- **Longitudinal shower profile**:  
  - $T = (\alpha - 1)/\beta$ and $\alpha$ are functions of $y=E/E_c$ and $\eta$  
  - $T$ and $\alpha$ are related to moments of the profile

- **Transverse shower profile**:  
  - The core and the trail of the shower are defined in terms of the Molier-Radius $R_m$  
  - The parameters are functions of $y=E/E_c$, $\eta$ and $t$
Performance in Forward Calorimeter

Energy deposition from electrons

- 100 GeV @ \( \eta \) 3.2
- 200 GeV @ \( \eta \) 4.4
- 500 GeV @ \( \eta \) 3.7

Energy resolution

- G4 Simulation
- Resolution Fit
- Parameterization

From fit: \( \frac{\sigma}{E} = 2.7\% \)

Good description of full and fast simulation!
Remarks

- **Parameter extraction complex and time consuming**
  - needs to be redone for every geometry related change
    (G4 version, new geometry, new parameters)

- **Approach valid for high energies**
  - for high energy electrons (1-10 GeV) this approach works quite good
    but this is not the major use case
Frozen Shower Technique

- **In short:**
  At simulation time substitute electron shower below an energy cut-off using pre-stored hits.
  (Similar approach as for minimum bias events or in computer games, where small parts are produced by pre-stored animations.)

- **Idea:**
  - Store only showers for a few discrete Energies and $\eta$ values (bins) in a library
  - Substitute incoming electron below energy cut-off by one shower from the library (get shower from library, interpolate $E$ and $\eta$, transform coordinates)
  - Reuse showers from library many times

- **Design goals:**
  - Significant speed up
  - Good agreement with full simulation
  - Reasonable resource consumption (disk/memory)
Frozen Shower Technique - Details

- **Frozen Shower generation:**
  - Simulate electrons starting from the front of the calorimeter with fixed Energy, \( \eta \), \( \phi \)
  - Store only energy deposits in the sensitive detector (including sampling fluctuations and response)
  - Use local coordinate system (along particle direction) for hit position
  - Compress energy deposits
  - Create library with many showers

- **Simulation time:**
  - If incoming electron is in correct energy range substitute it with a frozen shower
  - Pick shower randomly from adjacent Energy and \( \eta \) bins
  - Interpolate energy and \( \eta \)
  - Transform position of energy deposits into global coordinate system
  - Put energy deposits back into simulation using dedicated sensitive detector
  - For different electrons cycle through the frozen shower library in \( \eta \) and \( E \) bins
Reduction of Frozen Shower Size

**Clustering:**
- Find a pair of energy deposits with the smallest spatial separation $R$
  - If $R < R_{\text{min}}$, 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 $x_i - x_{\text{ave}}$, $y_i - y_{\text{ave}}$ for the remaining deposits such that the second momentum of the original shower is preserved

Use $R_{\text{min}} = 5$ mm and $f = 95\%$. 
Reduction of Frozen Shower Size
Reduction of Frozen Shower Size - Zoom
Optimization of Frozen Shower Library

- **Energy binning:**
  - 10, 20, 50, 100, 200, 500, 1000 MeV
  - smooth distribution of deposited energy over all bins

- **η binning:**
  - Accordion structure is non-pointing
  - effective sampling fraction varies with η
  - compensation by change of absorber depth
    - Barrel: η=0.8
    - Endcap: η=2.5
  - compensation by HV (Endcap)
Optimization of Frozen Shower Library

- The $\eta$ binning is not working or needed for the forward calorimeter
  - the geometry is not $\eta$ dependent
  - except for the geometrical effect (quite small for $3.1 < |\eta| < 4.9$

- The distance between shower and liquid argon gap is more important
  - exchange $\eta$ binning for a distance binning (two bins: inside and outside of gap)
  - this new development is still preliminary and not included into the plots

- Library size is 100 MB for all three calorimeters
Simulation Strategy

Barrel/Endcap

- Full Simulation (Geant 4)
- Frozen Showers
- Killing

Forward

- Parameterisation
- Full Simulation (Geant 4)
- Killing

Energy Profile in Barrel

1 GeV
0.5 GeV
10 MeV
∞
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 Events

### Single electrons/positrons

<table>
<thead>
<tr>
<th></th>
<th>full [s]</th>
<th>fast [s]</th>
<th>improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>2,3</td>
<td>0,7</td>
<td>3,3</td>
</tr>
<tr>
<td>Endcap</td>
<td>4,4</td>
<td>0,9</td>
<td>4,9</td>
</tr>
<tr>
<td>Forward</td>
<td>1,1</td>
<td>0,4</td>
<td>2,8</td>
</tr>
</tbody>
</table>

### Physics events

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Z -&gt; e+e-</th>
<th>di-jets</th>
<th>SUSY</th>
<th>Time/Event [%]</th>
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<tr>
<td></td>
<td>full</td>
<td>fast</td>
<td>full</td>
<td>fast</td>
</tr>
<tr>
<td>Tracker</td>
<td>3,7</td>
<td>7,8</td>
<td>3,8</td>
<td>7,2</td>
</tr>
<tr>
<td>Calo - barrel</td>
<td>5,9</td>
<td>6,0</td>
<td>7,3</td>
<td>5,8</td>
</tr>
<tr>
<td>Calo - endcap</td>
<td>32,0</td>
<td>24,0</td>
<td>46,1</td>
<td>27,1</td>
</tr>
<tr>
<td>Calo - forward</td>
<td>33,4</td>
<td>19,0</td>
<td>14,5</td>
<td>10,9</td>
</tr>
<tr>
<td>Calo - hadronic</td>
<td>3,0</td>
<td>5,7</td>
<td>6,6</td>
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<tr>
<td>Muon</td>
<td>5,7</td>
<td>13,0</td>
<td>6,4</td>
<td>12,5</td>
</tr>
<tr>
<td>Other</td>
<td>9,8</td>
<td>11,7</td>
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<tr>
<td>Dead</td>
<td>6,5</td>
<td>12,7</td>
<td>6,3</td>
<td>11,1</td>
</tr>
<tr>
<td><strong>Event</strong></td>
<td>7,7 min</td>
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<td>6,5 min</td>
</tr>
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*acceleration factor: ~2*
50 GeV Electrons/Positrons from IP, flat distribution in $\phi$:

- Overall agreement is good
- Small, constant offset in barrel
- Some discrepancy around edges in endcap
The $\phi$ Modulation

- $\phi$ modulation has a strong effect on low energy showers
- generating the libraries at a fixed $\phi$ is not optimal
- averaging over full $2\pi$ helps
Other Quantities at Generated Level

Overall agreement is good
Small shift in deposited energy
$\phi$ resolution in 2nd sampling needs better modeling

50 GeV $e^+/e^-$ from IP, flat $\phi$, $\eta=0.25$

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Fast Shower Simulation in ATLAS
50 GeV $e^+/e^-$ from IP, flat $\phi$, $\eta=0.25$

$\langle E \rangle = 51.4$ GeV
$\sigma = 0.91$ GeV

$\langle E \rangle \rightarrow -0.9\%$
$\sigma \rightarrow -8.6\%$

- full sim
- fast sim
w/o $\phi$ correction

same effect as at generator level
is constant over energy
also seen by validation team
problem understood
Reconstructed Shower Shapes

Checks on reconstructed electrons: quantities for e/\gamma ID

- **Shower width in 3 strips:**
  width in \(\eta\) calculated from three strips in 1\textsuperscript{st} sampling

- **Lateral shower shape \(R_{\eta(37)}\):**
  ratio of energy reconstructed in 2\textsuperscript{nd} sampling in a 3x7 and 7x7 cluster (\(\eta\times\phi\))

Agreement already quiet good.

Need study if e/\gamma ID is effected!
Summary

- In order to produce a sufficiently large Monte Carlo dataset the Atlas detector simulation needs to be accelerated.
- The calorimeters are the main time consumers.
- Different acceleration techniques are possible:
  - Fast shower parameterisation
  - Frozen Shower library
  - One spot model
- All three methods have been implemented and tested within the ATLAS detector simulation:
  - Factor 10 time gain for electrons and photons
  - Factor 2-3 time gain for average physics event
  - Main time gain comes from Frozen Showers
  - Fast shower parameterisation only good for high energy electrons
  - Good description of quantities at simulation and reconstruction level