Using GFlash for COMPASS calorimeter simulations

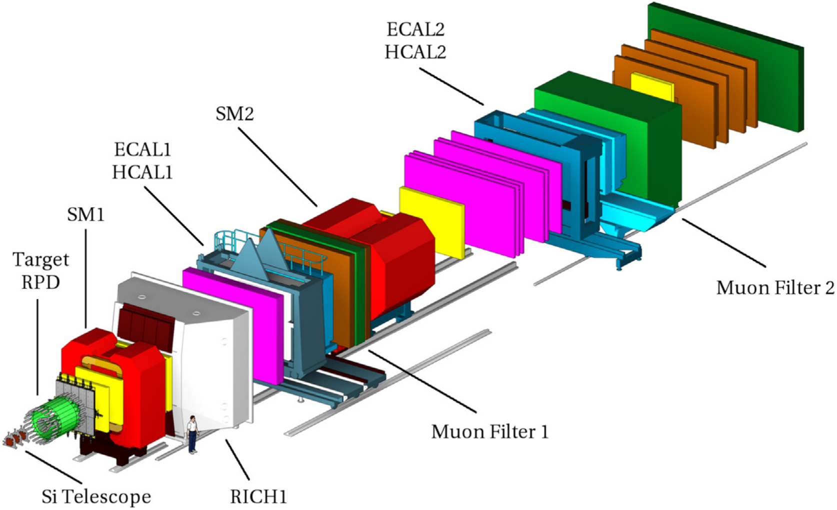
Henri Pekeler and Laney Klipphahn

2nd COMPASS "Analysis Phase" mini-workshop
(COMAP-2023 II)

7th March 2023

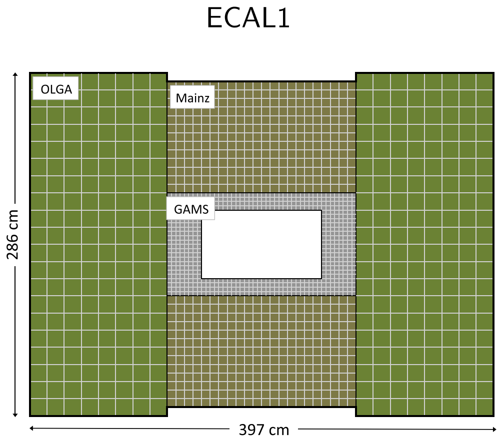
Table of Contents

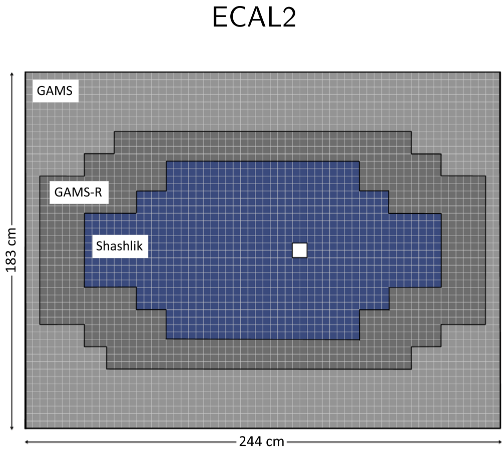
COMPASS Experiment at CERN



[COMPASS, NIM A779, 69-115 (2015)]

Electromagnetic Calorimeters at COMPASS





[COMPASS, NIM A779, 69-115 (2015)]

Calorimeter Modules at COMPASS

General

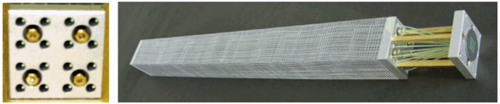
- Homogeneous (lead glass) modules: Mainz, GAMS, GAMS-R and OLGA
  - Single cells composed of just one material
- Inhomogeneous module: Shashlik

Shashlik cells in ECAL2

- Complicated modules built of 154 layers of scintillator / lead slices
- Pierced with WLS Fibers for readout and holding rods for stability
- The Shashlik modules are built to withstand radiation doses up to 20 years of data taking

One Shashlik Cell

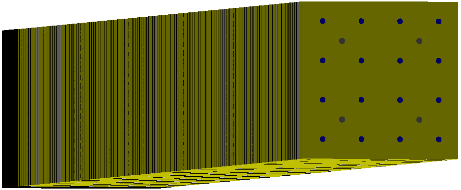
Shashlik module at COMPASS



[COMPASS, NIM A779, 69-115 (2015)]

- Upstream aluminium plate where holding rods are fixed to
- Rods and fibers indicated in the left picture
- Yellow nut is much bigger than holding rod

Monte Carlo implementation



- Upstream, black: The aluminium plate where holding rods are fixed to
- Black: lead layers
- Yellow: scintillator layers
- Blue circles: fibers
- Gray circles: holding rods

Monte Carlo Simulations at COMPASS

Simulations with TGEANT

- Based on GEANT4
- Implementation of detectors
- Tracking of particles through the geometry
- Save detector hits, to be reconstructed

CORAL as reconstruction program

- Reconstruct events simulated with TGEANT
- Reconstruct events taken with the COMPASS spectrometer

PHAST as analysis program

- Analysis on event-by-event basis
- Event selection, efficiency studies and more

Detector Design with GEANT4 at COMPASS

Construct geometry

- Build any 3D object with GEANT4 solids
- Construct logical volumes of these solids, specifying a material and more
- Place logical volume inside some other volume

Design philosophy

- Start with large (world) volume that holds all of COMPASS
- Place smaller volumes that can hold detectors in the world volume
- Repeat until all detectors are included

Benefit: Each (sub)detector can be developed independently and relative to its mother

- Daughter volume always supersedes mother volume

Readout of detectors

- A logical volume can be marked as sensitive detector
- Energy deposited in these volumes are stored within TGEANT and saved
- Energy deposited in non-sensitive volumes is lost
- One sensitive detector usually mirrors one readout plane of a COMPASS detector

Layout of one calorimeter module

- Each module is build of multiple cells
- Cells are grouped in squares to simplify description
- These groups are read in by TGEANT

Implementation of one calorimeter module in TGEANT

- All groups are combined to one calorimeter module region (used by GFlash later)
- For each group, cells are built and placed in the modules volume
- Only scintillator volume is marked as sensitive

Tracking with GEANT4

Layout

- Each particle is tracked one step at a time through the logical volumes
- At each step, registered physics processes are checked
  - Transportation, decay, user processes such as event generators, ...
- They are invoked, when the trigger condition for the process is met
  - Certain distance in target for event generator
  - Lifetime hits 0 for deacys ...
- If triggered, the particle is changed within the process
- Processes can stop / destroy / change kinematics of particles

Note!

- Every particle type has its own physics processes associated
- Apart from this, neutral and charged particles are not treated differently

Physics processes in electromagnetic calorimeters

- Electrons and positrons will create photons via bremsstrahlung
- Photons will create electrons and positrons via pair production
- Leads to creation of many particles ⇒ electromagnetic shower

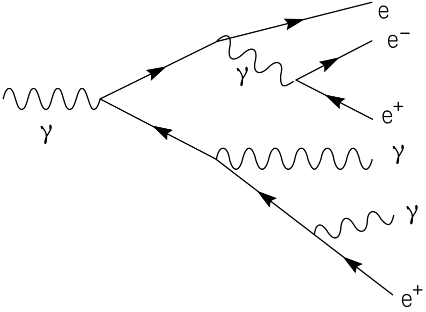


Figure: Schematic view of the start of an electromagnetic shower

Tracking through a Calorimeter Module

Tracking electrons, positrons and photons the accurate way

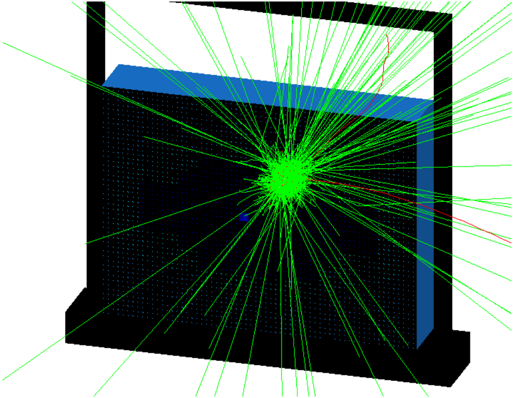
- Tracking of every particle in the shower
- Especially time expensive in Shashlik cells (10 - 200 s) per initial particle

The fast way

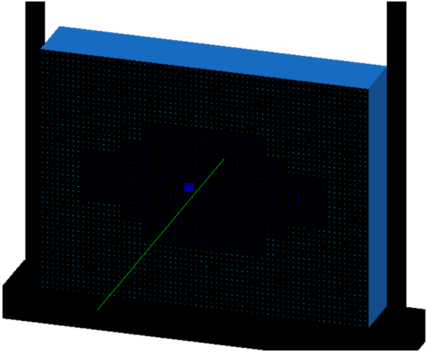
- Using GFlash as fast shower simulation algorithm
- Originally developed for CMS
- Tuned for TGEANT, so that the energy yield of GFlash showers matches the energy yield of showers without GFlash
- Simulation of the shower in effective material, No secondary particles
- Time per initial particle reduced to (1 - 5 s)

Visual of an Electromagnetic Shower

Without GFlash



With GFlash



GFlash

General

- Works as any other physics process
- Trigger condition is checked during stepping
- Shower is simulated and energy deposit is fed back to detector geometry

Trigger condition

- Containment of 90% of the shower in the module region
- Radial containment estimated via Molière Radius
- Longitudinal containment estimated via radiation length and particle energy
- Calorimeter modules are large enough in longitudinal direction to always contain the electromagnetic shower

GFlash

Input to GFlash

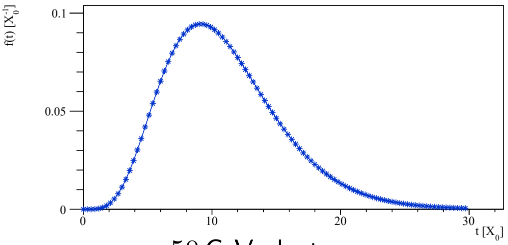
- Materials and their weights ⇒ Compute effective material
  - Radiation length, Molière Radius, critical energy ...

Workflow of GFlash

- Compute longitudinal profile for one shower
- Simulate shower in steps of this profile
  - Look at the energy deposit in one longitudinal interval
  - Smear energy with sampling resolution
  - With this energy, determine the number of spots with equal energy in one interval
  - For each spot the radius and angle are determined according to the respective profiles
- Feed spots to calorimeter geometry
- Only energy in sensitive detectors is stored within TGEANT

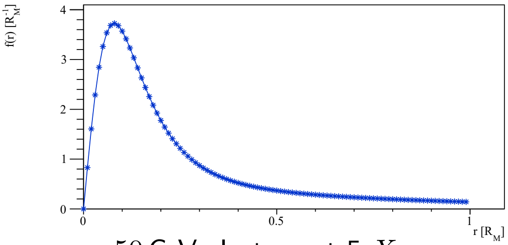
$$\mathrm{d}E(\vec{r}) = Ef(t)\mathrm{d}t f(r)\mathrm{d}r f(\phi)\mathrm{d}\phi$$

Longitudinal profile



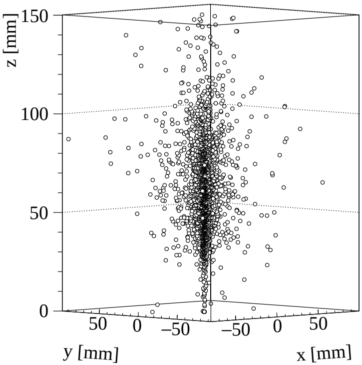
50 GeV electron

Radial profile



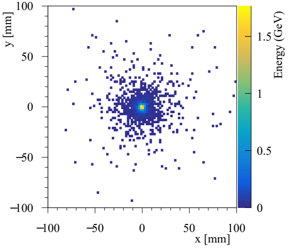
50 GeV electron at 5 X_0

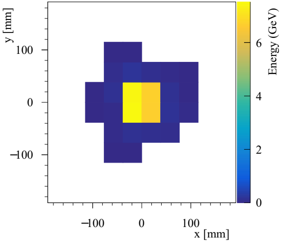
Full GFlash Shower



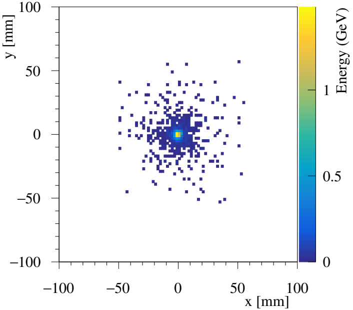
$N_{\text{spot}} = 2349$

Electron at 30 GeV

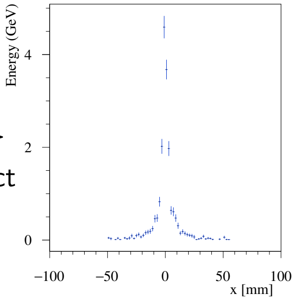




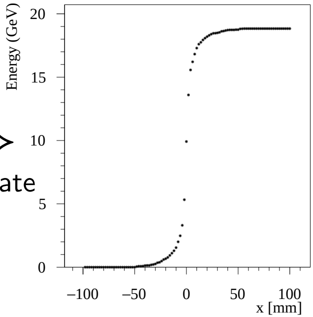
One dimensional shown for simplicity. In CORAL we reconstruct in two dimensions



$\Rightarrow$ project



$\Rightarrow$ integrate



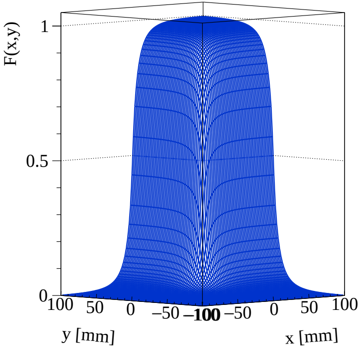
One dimensional Lednev function: $F(x) = \frac{1}{\pi}\sum_{i=1}^{3} a_i \arctan x/b_i + \frac{1}{2}$

Two dimensionsional Lednev function:

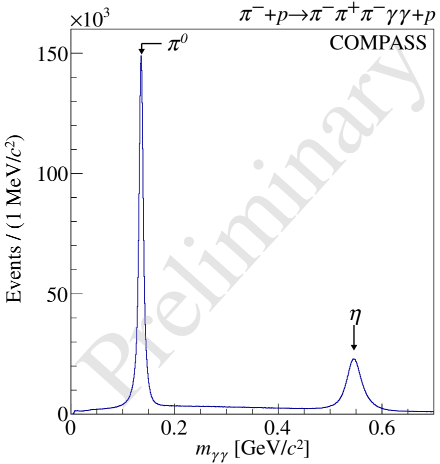
$$F(x,y) = \frac{1}{2\pi}\sum_{i=1}^{3} a_i\left(\arctan\left(\frac{x}{b_i}\right) + \arctan\left(\frac{y}{b_i}\right) + \arctan\left(\frac{x\cdot y}{b_i\sqrt{b_i^2+x^2+y^2}}\right)\right) + \frac{1}{4}$$

For real data showers
in Shashlik modules:

$$a_1 = 0.885$$
$$a_2 = -0.14$$
$$b_1 = 8.104$$
$$b_2 = 55.86$$
$$b_3 = 1.52$$

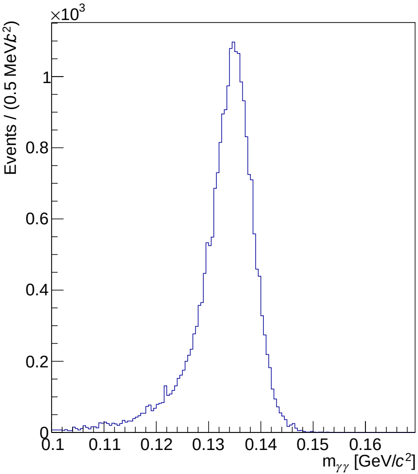


Diffractive 2008 / 2009 COMPASS data



[wwwcompass.cern.ch/compass/results/2022/february_evtsel_3Pi2G/Event_Selection_3Pi2G_06_04.pdf]

Monte Carlo data



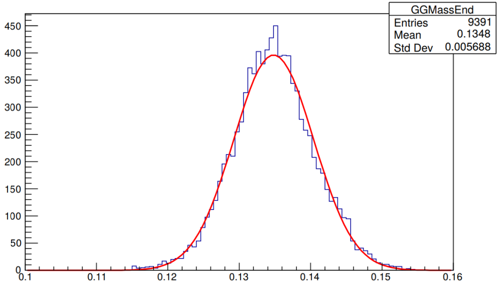
How to fix the Asymmetry

a) Change reconstruction

\+ Done already by Waldemar Renz

[wwwcompass.cern.ch/compass/notes/2019-1/2019-1.pdf]

– Different Lednev parameters for simulated data compared to COMPASS data



b) Improve on GFlash tuning

\+ Nothing changes in reconstruction

\+ Simulation is closer to reality

– Many parameters to tune

How to tune GFlash

Change parametrisation

- Radial profile parameters
- Longitudinal profile parameters (less impact)

Reconstruction

- Keep Lednev parameters as for COMPASS data
- Reconstruct large enough sample of π^0 data to see impact
- Iterative procedure

Current status

- Study ongoing, no final parameters yet

Summary and Outlook

Summary

- Good understanding of Monte Carlo workflow at COMPASS
- ECAL2 Shashlik modules are built to highest precision in TGEANT
- Tracking of every shower particle takes much time
- GFlash shortens the process a lot while simulating the shower to a high accuracy
  - Shashlik material is taken into account while depositing energy
  - Good understanding of GFlash workflow within TGEANT

Outlook

- Tune GFlash to remove asymmetry without new lednev parameters (ongoing)

Additional material

GFlash trigger condition

GFlash is triggered when the 90% of the shower is contained in the given region, e.g. Shashlik of ECAL2

- 90% longitudinal is estimated via the incoming energy, and the radiation length
- The Shashlik modules are large enough, so that this always happens
- 90% radial is estimated via $1.5 \cdot R_M$
- Molière Radius; $R_M = \frac{E_s}{E_c} \cdot X_0$
- $E_s = m_e c \sqrt{4\pi/\alpha} = 21.2$ MeV and α being the fine structure constant
- X_0 is the radiation length, i.e. the distance after which an electron has only $1/e$ of its original energy left
- E_c is the critical energy, i.e. the energy where energy loss due to ionization and radiation is equal

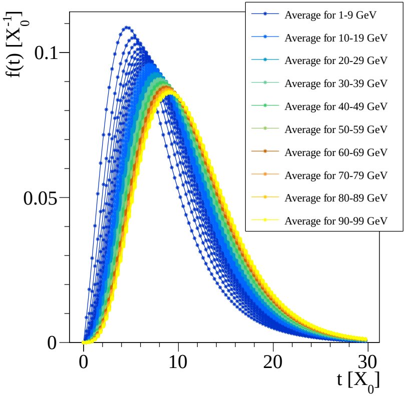
Effective material properties formulas

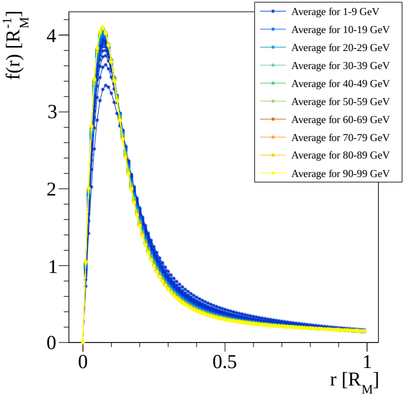
$$X_{0,\mathrm{eff}} = \frac{1}{\sum_{\mathrm{i=1}}^{\mathrm{i=k}} w_\mathrm{i}/X_{0,\mathrm{i}}}, \quad R_{\mathrm{M,eff}} = \frac{E_S}{\sum_{\mathrm{i=1}}^{\mathrm{i=k}} w_\mathrm{i} \cdot E_{\mathrm{c,i}}/X_{0,i}}, \quad E_{\mathrm{c,eff}} = X_{0,\mathrm{eff}} \cdot \sum_{\mathrm{i=1}}^{\mathrm{i=n}} \frac{w_\mathrm{i} \cdot E_{\mathrm{c,i}}}{X_{0,\mathrm{i}}}$$

With the weight w_k of each material given as

$$w_\mathrm{k} = \frac{d_\mathrm{k} \cdot \rho_\mathrm{k}}{\sum_{\mathrm{i=1}}^{\mathrm{i=k}} d_\mathrm{i} \cdot \rho_\mathrm{i}}$$

Where d_k corresponds to the respective thickness, material k takes up in one layer, ρ_k corresponding to the density of material k and $E_s = 21\,\mathrm{MeV}$
Effective properties: $X_0 = 6.45\,\mathrm{mm}$, $E_{\mathrm{c,eff}} = 7.26\,\mathrm{MeV}$ and $R_{\mathrm{M,eff}} = 18.66\,\mathrm{mm}$





Average of 10^5 profiles