The $\bar{\text{P}}$ANDA TPC software framework
Monte Carlo simulations

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1. Overview of the $\bar{\text{P}}$ANDA experiment

2. The Simulation Framework
   - Particle generation
   - Particle transport
   - ALICE flavor of GEANT3
   - Detector simulation: ”digitization” routine

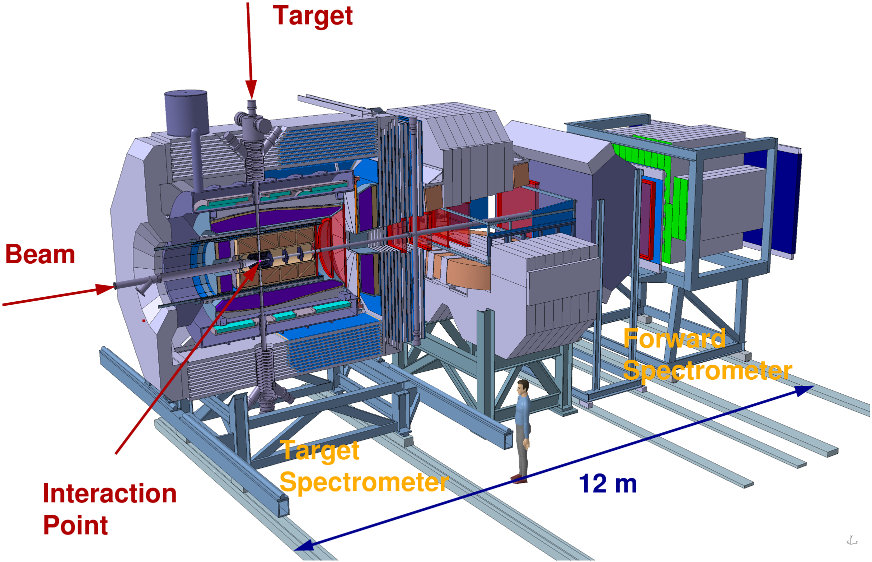
3. Spacecharge simulations

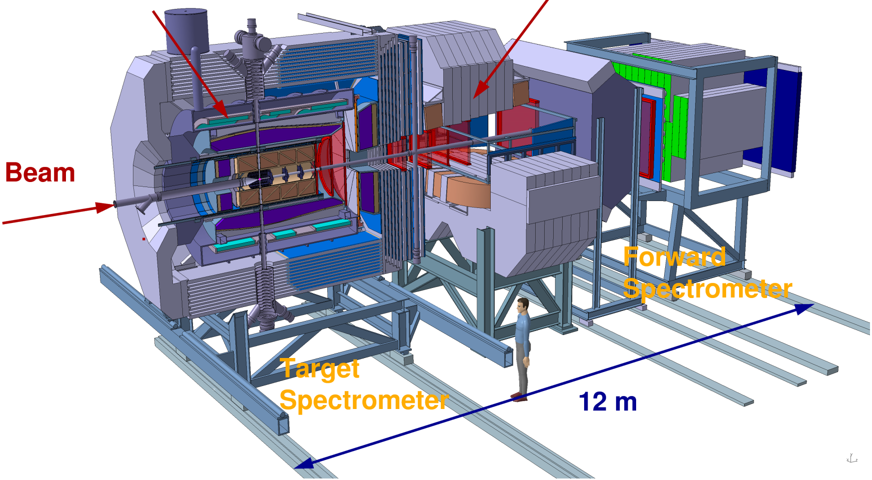
The $\bar{\text{P}}$ANDA Experiment

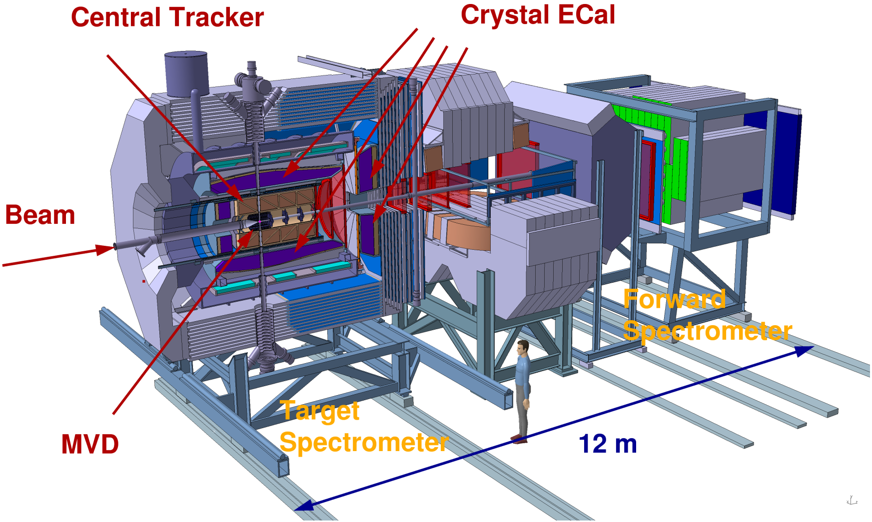
$\bar{\text{P}}$ANDA: Anti**P**roton **An**nihilations at **D**armstadt

- Fixed target experiment
- Location: **F**acility for **A**ntiproton and **I**on **R**esearch (FAIR), GSI
- Antiproton beam (1-15 GeV) from **H**igh **E**nergy **S**torage **R**ing (HESR)
- Design **luminosity**: $2 \cdot 10^{32} (\text{cm}^2\text{s})^{-1}$
- $\bar{p}p$-annihilation rate: $2 \cdot 10^7\,\text{s}^{-1}$

- **Physics program**: Low energy QCD and hadron physics
- Precision measurements


Target
Beam
Interaction Point
Target Spectrometer
Forward Spectrometer
12 m

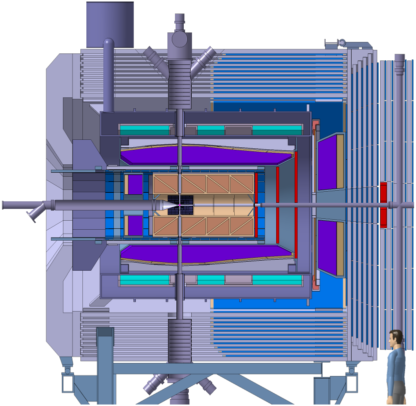

2T Solenoid Magnet
2T Dipole Magnet
Beam
Forward Spectrometer
Target Spectrometer
12 m


Central Tracker
Crystal ECal
Beam
MVD
Target
Spectrometer
Forward
Spectrometer
12 m

- One option for the $\bar{\text{P}}$ANDA central tracker is a continuously running **T**ime **P**rojection **C**hamber (TPC) with GEM amplification
- Main device for momentum reconstruction

Central Tracker requirements

- Full solid angle coverage
- Secondary vertex resolution $\sigma_{r,\phi} = 150\mu\text{m}$, $\sigma_z = 1\text{mm}$
- Momentum resolution σ_p/p of $\mathcal{O}(1\%)$
- Particle Identification
- "Lightweight", $X/X_0 \approx 1\%$ $\longrightarrow$ 20 000 crystal ECAL



Simulation Framework

Particle Generation

C++ framework based on the CERN **ROOT** framework

Particle Generation:

- Several options for particle generation, including a background generator for $\bar{p}p$ reactions (**D**ual **P**arton **M**odel (DPM) generator)

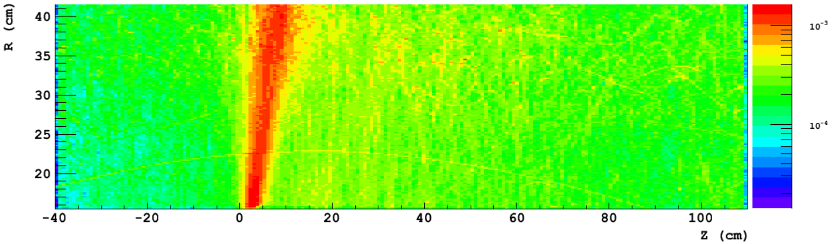


Figure: Energy deposited in the TPC chamber by 10000 background events created by the DPM generator integrated over chamber azimuth, arb. units.

Particle Transport

Particle Transport:

- Transport through the chamber respecting magnetic field, material, interactions
- At certain points in space energy loss is stored ("Monte Carlo (MC) Points")
- Particle transport is done by GEANT3 in ALICE mode

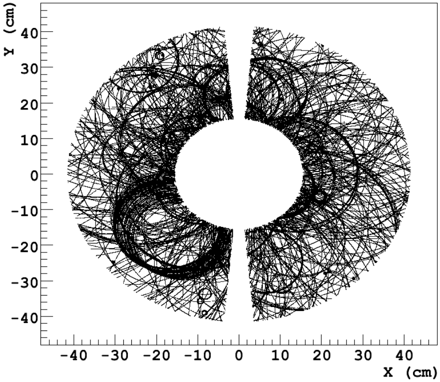


Figure: GEANT MC points of 200 background events from DPM in the TPC

Why ALICE MC ?

GEANT3 standard:

- Create MC hits only when crossing boundaries between different media or when reaching a certain energy loss threshold
- Soft energy loss from tables + Landau-Vavilov straggling

Problems

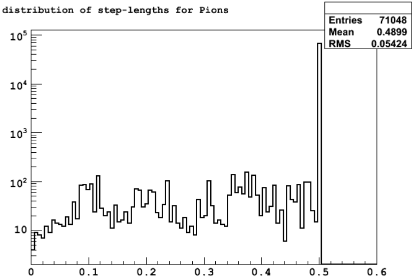
- MC hits have nothing to do with the real physical hits
- Unsatisfactory cluster distribution method for a TPC
- This method also may produce unphysical depletion / accumulation of clusters around the MC hits
- GEANT3 standard produces some features that are not understood, e.g. dE/dx distribution

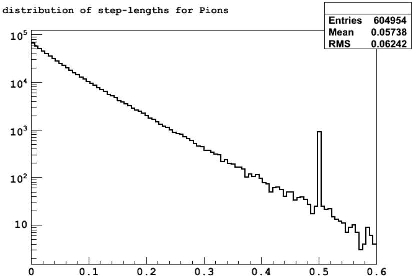
How does ALICE MC work?

GEANT3 ALICE:

- Sample next step-length $\mathcal{L}$ from from pdf $\mathrm{f}(x) = \frac{1}{\lambda}\exp^{(-\frac{x}{\lambda})}$

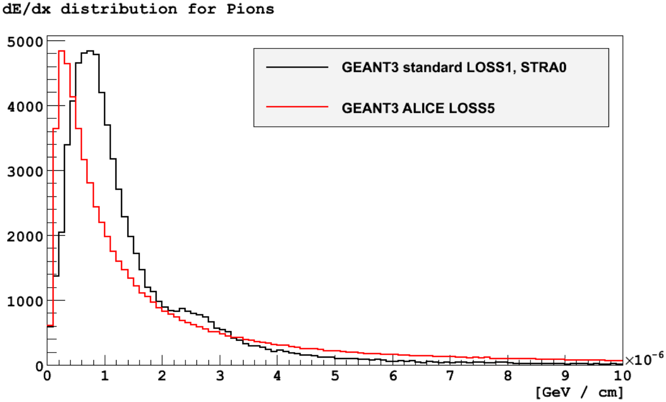
  $\mathcal{L} = -\lambda \ln(r)$ (λ: mean free path, r: random number $\in$ [0,1])
- Force GEANT to make a step there
- $\lambda(p) \propto (\frac{dE}{dx})^{-1}$ from normalized Bethe-Bloch parametrization
- Energy loss straggling directly obtained from a tuned Rutherford cross section





Energy loss in G3 and G3 ALICE

- One example of problems with GEANT in its standard settings: GEANT3 standard shows a strange second bump in the energy loss distribution:



- Even bigger problems with energy loss using GEANT4

GEANT3 ALICE: Conclusion

- GEANT3 in standard configuration not optimal for a gas detector
  - MC point creation unphysical
  - Energy loss distribution unclear
- ALICE configuration much more transparent:
  - Physical cluster distribution, no clustering ”by hand”
  - Simple and transparent energy loss model (LOSS=5, see gfluct.F in the GEANT package)
- **Crosscheck** performed with HEED showed good agreement with our simulations
- Performance: Slower, but acceptable

Detector Response: Digitization

Detector Response: Digitization I

Simulation of detector response ("digitization") happens in several steps:

1. Clusterization
   - Conversion of energy loss at each MC point into number of created electrons ("primary cluster")
   - No cluster distribution "by hand" needed in ALICE mode

   ⟶ primary electrons

2. Drifting
   - Drift each primary electron through the chamber to the readout
   - Depending on starting coordinates, apply
     - ⋆ Attachment
     - ⋆ Diffusion (property of the drift-gas)
     - ⋆ Drift distortions (Space-charge!)

   ⟶ drifted electrons

Detector Response: Digitization II

3. GEM response
   - Create avalanches respecting
     - ⋆ Gain
     - ⋆ Gain stability
     - ⋆ Spread

   ⟶ avalanche

4. Pad Response
   - Depending on avalanche position and ”size”
     - ⋆ Decide which pads have been hit
     - ⋆ Evaluate amplitude from avalanche size, gain
     - ⋆ Add noise
     - ⋆ Cut on amplitude and create

   ⟶ signal

Detector Response: Digitization III

5. Electronics
   - From map of hit pads for each event, simulate
     - ⋆ Simulation of CRRC shaper (shaping time: 58 ns)
     - ⋆ Digitize data with given sampling rate and ADC resolution
     - ⋆ Pulse shape analysis (PSA)
       ⟶ amplitude, time of found pulses

   ⟶ "digi"

6. Create clusters of digis
   - Group digis belonging together

   ⟶ cluster

Space-charge Simulations

Space-charge Simulations I

The space-charge simulations are an external package creating input files for digitization and reconstruction

- $\bar{\text{P}}$ANDA requires ungated, continuous operation of the TPC at high rates
- Starting point: Large number of background events from the DPM generator

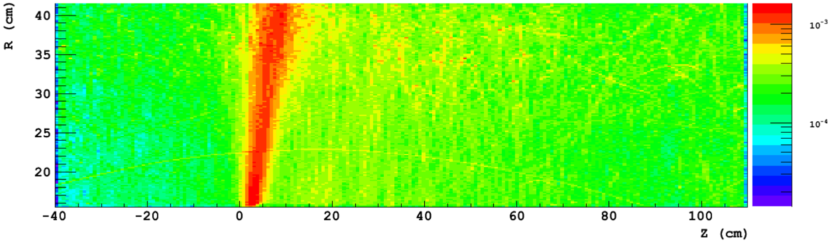


Figure: Energy deposited in the TPC chamber by 10000 background events created by the DPM generator integrated over full chamber azimuth, arb. units.

Space-charge Simulations II

- Convert energy deposit into ion charge and store into a binned map
- For each primary ion create ϵ back-flow ions above the GEMs, assuming instantaneous electron drift

$$t^{el}_{drift} \sim 50\,\mu s \qquad\qquad t^{ion}_{drift} / t^{el}_{drift} \sim 1000$$

- Here: $\epsilon = 4$: realistic value, based on measurements with a test chamber
- Result: Prototype space-charge map

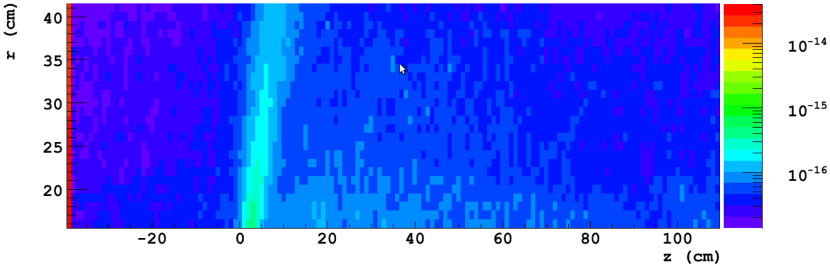


Figure: Ion space-charge (C cm^{-3})of 10 000 events in the TPC chamber, integrated over chamber azimuth

Space-charge Simulations III

Simulate ion drift:

- Multiply space-charge map prototype so that the # events corresponds to the time needed for an ion to drift through one bin-width in Z
- This is the final prototype
  - Shift the complete map by one bin in ion drift direction
  - Superimpose again with the prototype map
  - Repeat until equilibrium is reached
- Result: Final space-charge map

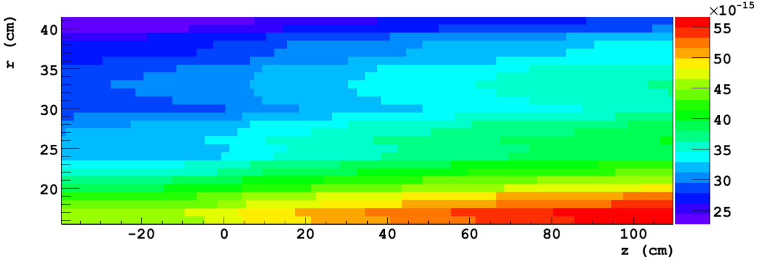


Figure: Final ion space-charge ($C\,cm^{-3}$), integrated over chamber azimuth

Space-charge Simulations IV

Calculate resulting electrical field:

- Use finite element software with proper boundary conditions (DOLFIN)
- Obtain electrical distortion field

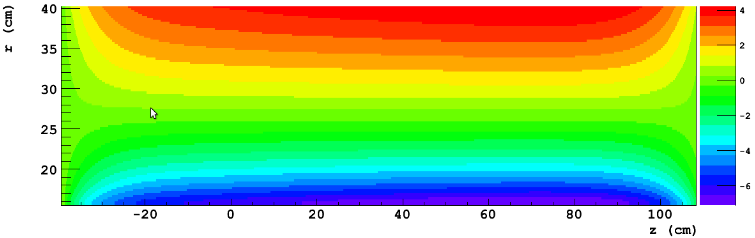


Figure: Radial component of electrical field generated by space-charge (V/cm)

Space-charge Simulations V

- Superimpose distortion field with homogeneous drift field
- Integrate the equation of motion of the electrons for a grid of points in the TPC volume
- Method: 5^{th} order adaptive step-size Runge Kutta algorithm
- Obtain final quantity:

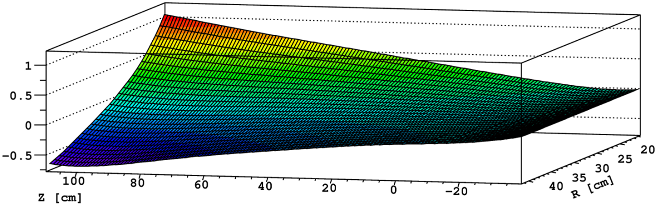


Figure: Final drift distortions (in ϕ) as function of the volume coordinates (cm)

- This serves as an input file for our digitization (Drifter!)
- Throughout this procedure azimuthal symmetry is assumed!

Backup Slides

Backup slide: TPC geometry

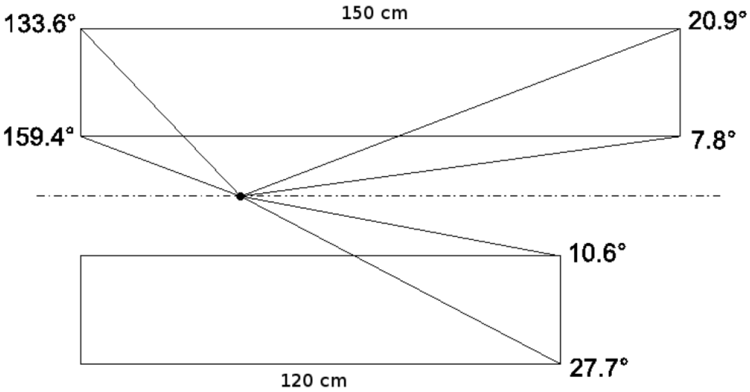
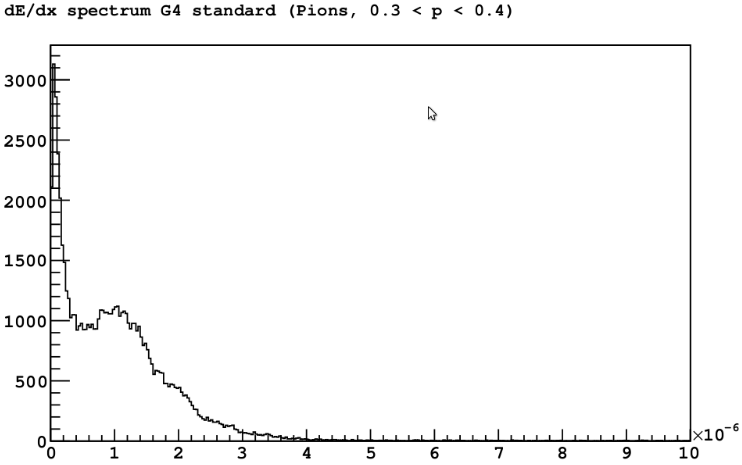
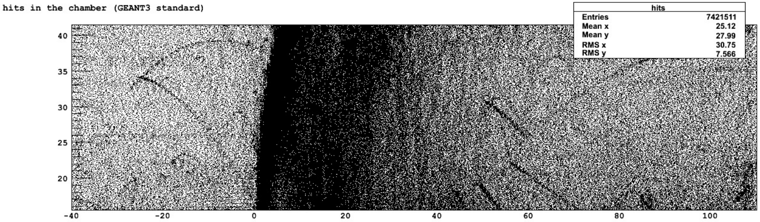


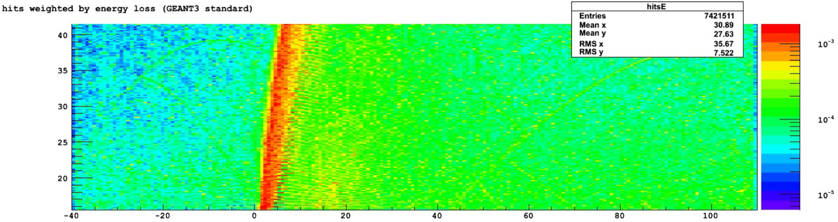
Figure: The two length options and resulting key angles

Backup slide: GEANT4 energy loss

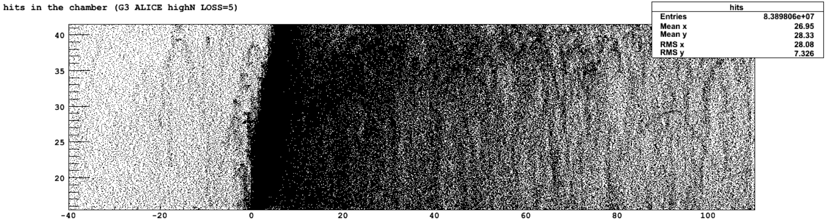


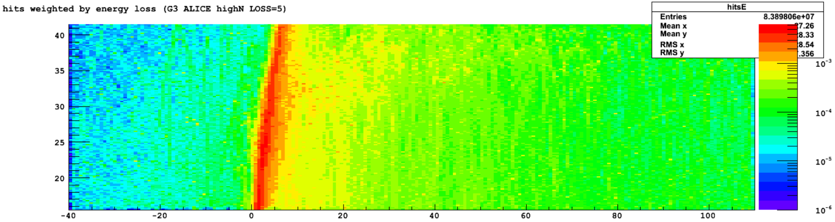
Backup slide: GEANT3 standard TPC hits



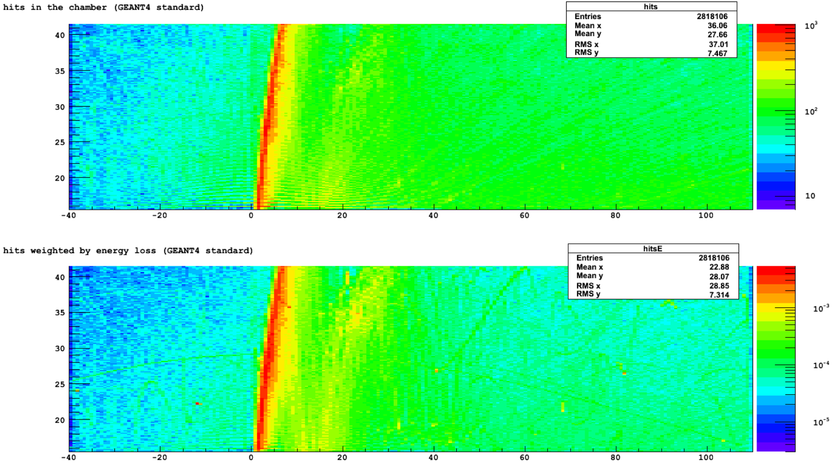


Backup slide: GEANT3 ALICE TPC hits





Backup slide: GEANT4 standard TPC hits



Backup slide: G3 ALICE configuration

- Set max. number of G3 steps to very high value:
  `GEANT3->SetMaxNStep(1000000);`
- Set energy LOSS energy model to ”unofficial” value 5 (see gfluct.F):
  `gMC->SetProcess("LOSS",5);`
- Calculate step-lengths etc. in the FairDetector class
- Adapt clusterization

- Delta electrons: Just as you like, set
  - DCUTE
  - DCUTM
  - CUTELE