Simulation of particle physics processes using Geant4 toolkit

Bachelor thesis

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April 6, 2018

Geant4

- Toolkit for simulation of passage of particles through matter.
- Used in high-energy, nuclear and accelerator physics.
- Provides tools for all aspects of simulation: geometry, tracking, detector response, visualization and more.

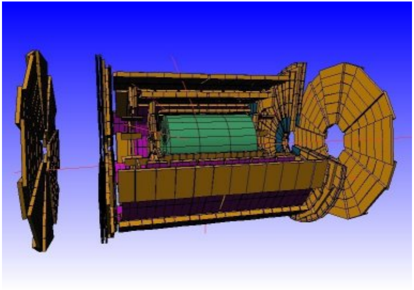


Figure: ATLAS detector.

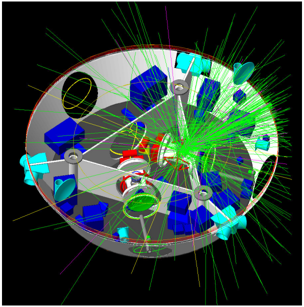


Figure: Nuclear reaction in LISA Pathfinder sensor.

Range of alpha particles in air - Phenomenology

- Kinetic energy T of an alpha particle after traversing air of thickness x is given by an empirical formula

$$T(x) = \left(T_0^a - \frac{x}{\xi} \right)^{\frac{1}{a}},$$

where $a = 1{,}5\ \mathrm{mm}$ and $\xi = 3{,}1\ \mathrm{mm} \cdot \mathrm{MeV}^{-3/2}$ (experimentally established).

- **Goal:** Simulate the passage of alpha particles through air and establish values of a and ξ.

Range of alpha particles in air - Simulation

- Alpha particle source (8 MeV) placed inside an air block, particle emission along the block axis.
- Moving the particle source inside the air block → changing the effective air thickness.
- Tracking of each particle – information about energy and distance travelled in air obtained.

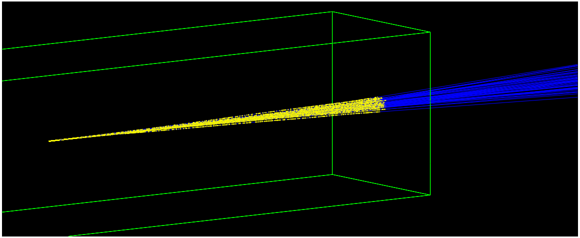
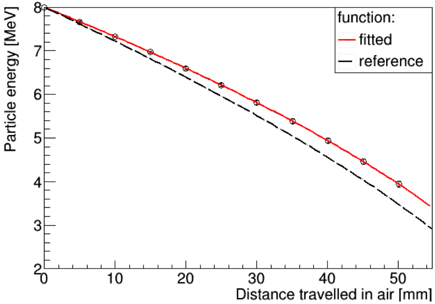


Figure: Alpha particles passing through the air block (green). Visible interaction points (yellow) and particle trajectories (blue).

Range of alpha particles in air - Data analysis

- Analysis using ROOT.
- Particle energy as a function of distance travelled in air plotted. These data points were fitted with a function:

$$f(x) = \left(A^B - \frac{x}{C}\right)^{\frac{1}{B}}.$$



Range of alpha particles in air - Results

- Values of a and ξ obtained from the fitted function's parameters.

	reference	obtained	difference
a [mm]	1,5	$1{,}7 \pm 0{,}1$	$2\sigma_a$
ξ [mm·MeV$^{-3/2}$]	3,1	$2{,}1 \pm 0{,}6$	$1{,}67\sigma_\xi$

- Obtained and reference values of the parameters in reasonable agreement.

Energy loss in silicon - Intro

- Particle camera MX-10 previously used for detection of μ and π from testbeams at CERN (AFP ToF detector).
  - Timepix sensor chip – 256×256 pixels, 2 cm^2 active area.
- **Goal:** Simulate the passage of μ and π through a model of the sensor chip. Establish energy loss rates of these particles from experiment and simulation data.

Figure: MX-10 Particle Camera

Energy loss in silicon - Experiment

- Passage of 120 GeV μ and π recorded using MX-10 particle camera.
- Information about deposited energy in every pixel obtained.
- Output text files processed using ROOT.

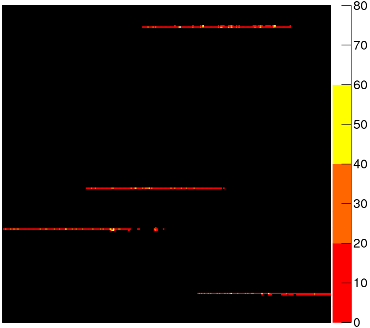


Figure: Testbeam μ passing through the sensor chip. Deposited energy in keV.

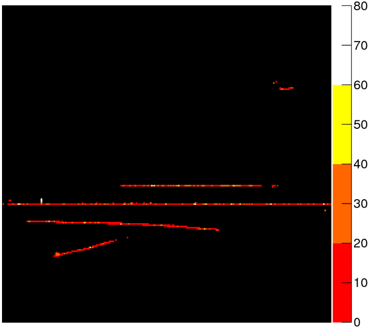


Figure: Testbeam π passing through the sensor chip. Deposited energy in keV.

Energy loss in silicon - Simulation

- A simple model of the silicon sensor chip created.
- Particles emitted from a surface source to ensure parallel trajectories.
- 100 simulation runs, 15 particles emitted in each run – 1500 trajectories.

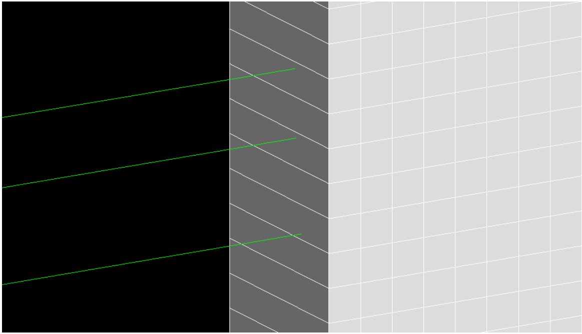


Figure: A model of the sensor chip. Green lines represent particle trajectories.

- Structure of output files identical to camera's output – processing with one program.

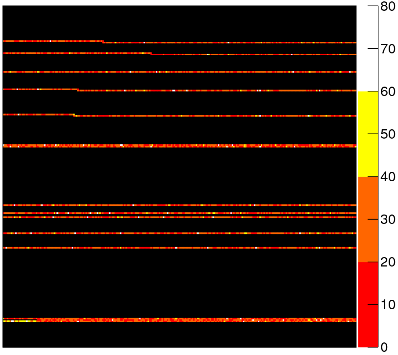


Figure: Simulated passage of μ through the model of the sensor chip.

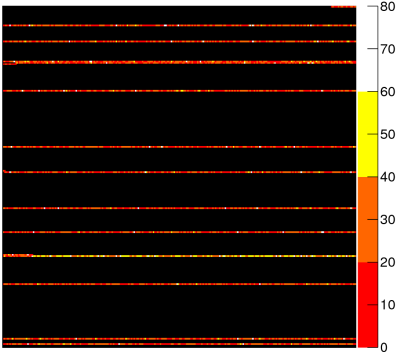


Figure: Simulated passage of π through the model of the sensor chip.

Energy loss in silicon - Data analysis

- Experimental ($\sim$ 300 values) and simulation ($\sim$ 1500 values) data sets analysed using the same program.
- Energy loss rate of every analysed trajectory calculated $\Rightarrow$ Energy loss rate distributions obtained.

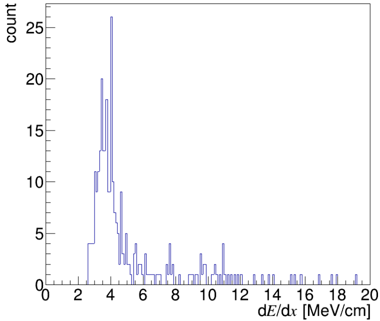


Figure: Energy loss rate distribution of testbeam μ.

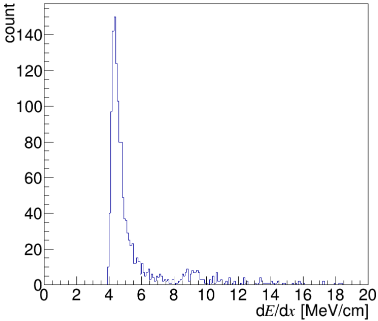


Figure: Energy loss rate distribution of simulated μ.

Energy loss in silicon - Data analysis

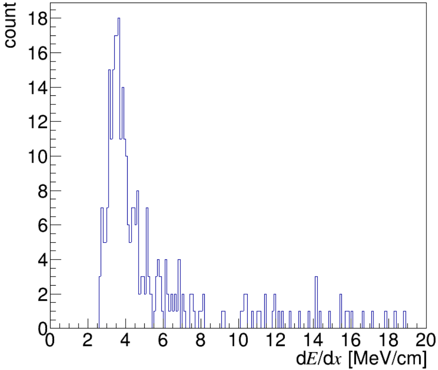


Figure: Energy loss rate distribution of testbeam π.

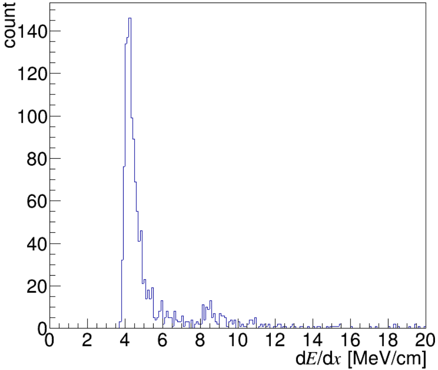


Figure: Energy loss rate distribution of simulated π.

Energy loss in silicon - Results

- Mean energy loss rates obtained from the experiment and from the simulation are in agreement.

$-\left\langle \frac{dE}{dx} \right\rangle$	reference	experiment	simulation
μ	5,59	$5{,}2 \pm 0{,}2$	$5{,}49 \pm 0{,}06$
π	5,58	$5{,}3 \pm 0{,}2$	$5{,}38 \pm 0{,}07$

Table: Mean energy loss rates in MeV/cm. Reference values calculated using Bethe-Bloch equation.

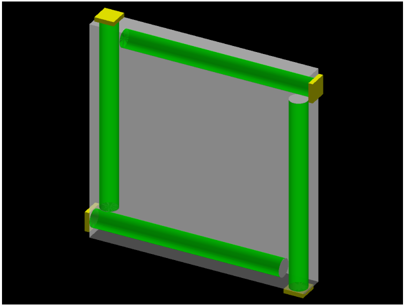
- Most probable energy loss rates from the experiment and from the simulation differ significantly.

$-\left(\frac{dE}{dx}\right)_{\mathrm{prob}}$	experiment	simulation
μ	$3{,}67 \pm 0{,}05$	$4{,}51 \pm 0{,}02$
π	$3{,}66 \pm 0{,}06$	$4{,}33 \pm 0{,}02$

Table: Most probable energy loss rates in MeV/cm.

Geometry optimization

- Work in progress.
- 4 wave-length shifting (WLS) fibres placed inside a scintillator block. Every fibre has a respective detector.
- **Goal:** Find the optimal geometry parameters (block thickness and fibre diameter) to get the best time resolution.



Geometry optimization - Simulation

- Simulation of particle passage through the scintillator for 14 fibre diameters and 10 block thicknesses ⇒ 140 geometry configurations.
- 5000 particles emitted for each geometry configuration.
- Detectors tracked time of arrival of scintillation photons.

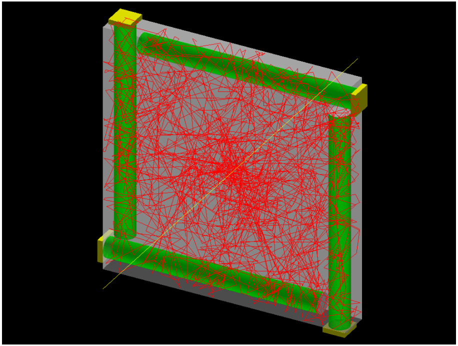


Figure: Scintillation photons (red) emitted as a result of a passing particle (yellow trajectory).

Geometry optimization - Data analysis

- Hits from 4 detectors and combined into a „pulse“ for every geometry configuration.
- Analysis of the pulse (FWHM) $\Rightarrow$ information about time resolution.

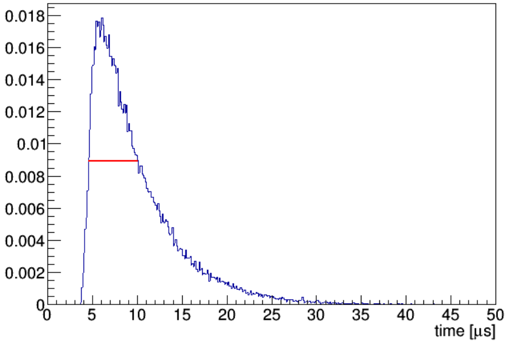


Figure: Detector response pulse. Red line signifies FWHM of the pulse.

Geometry optimization - Data analysis

- Pulse FWHM for every geometry configuration plotted as a 2D graph.

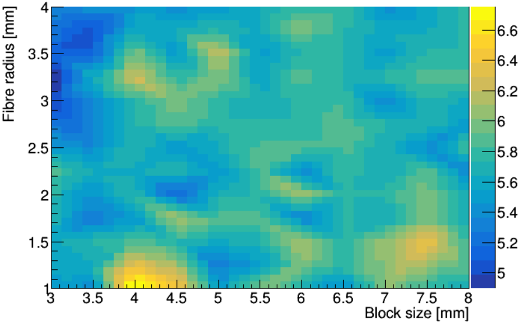


Figure: A graph of FWHMs (in μs) for every geometry configuration.

- Geometry configuration doesn't seem to significantly influence time resolution.