# Monte Carlo Simulations of an electromagnetic sampling calorimeter with semiconductor sensors

**Petru-Mihai Potlog**
Veta Ghenescu, Marian-Traian Ghenescu, Alina-Tania Neagu

ISS INSTITUTE OF SPACE SCIENCE
A subsidiary of INFLPR

LCWS2024 International Workshop on Future Linear Colliders

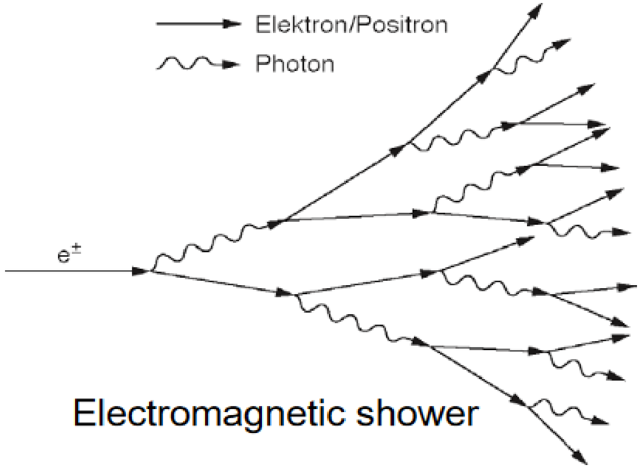
# Monte Carlo Simulations & semiconductor sensors

## goal, method, analysis

- <u>Goal:</u>
  - this contribution focuses on optimizing the electromagnetic calorimeter (such as used in LUXE experiments) foreseen to achieve higher energy resolution, using a Monte Carlo approach.

- <u>Method</u>
  - Geant4-based simulations, study of Si and GaAs sensors response to $e^-$ with energy in the range from 1 to 18 GeV

- <u>Steps:</u>
  - implement of various configurations geometries in Geant4
  - evaluate various physics lists and check their influence
  - collect quantities of interest (eg. hits position, energy deposition)



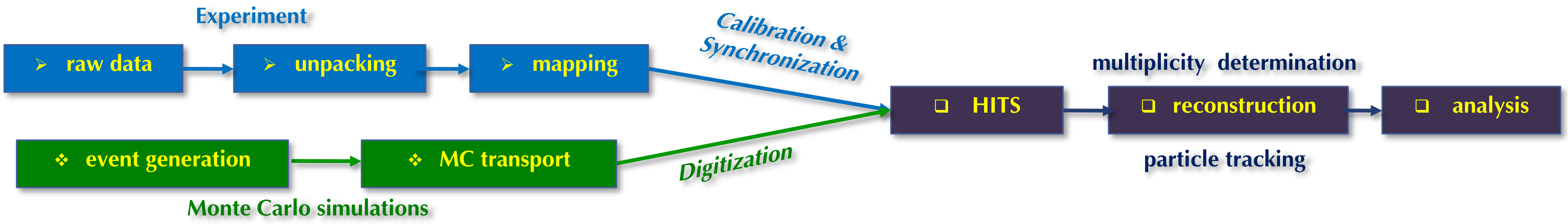
Electromagnetic shower

- <u>Analysis:</u>
  - *Energy response and linearity:* correlate the sensor response to the energy deposition
  - *Longitudinal shower:* energy deposition of electrons as a function of depth in detector
  - *Energy resolution:* the fractions of how much energy is deposited in the absorber and in the detector

**This talk presents the overall simulations.**

# Monte Carlo simulations and data analysis workflow

## FreeCAD, Geant4, Root



- ***2 experimental setups*** generated and exported using simple computer-aided design – **FreeCAD**

  *challenge: export to a format readable by simulation tool*

- ***full response of the sensor*** and the test beam setup with high statistics is simulated with **Geant4.11.06**

  *challenge: choose/construct physics list, write data to file*

- ***data analysis*** of the sensors is performed using **ROOT** framework

  *challenge: extract physical quantities matching foreseen experimental data*

FreeCAD

GEANT4
A SIMULATION TOOLKIT

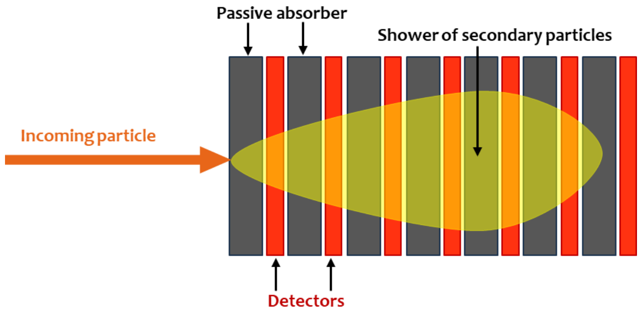
ROOT
Data Analysis Framework

# Monte Carlo Simulations & semiconductor sensors

## Electromagnetic Sampling Calorimeters

### Principles:

- a sampling calorimeter consists of alternating layers of passive absorbers and active detectors.
- typical absorbers are materials with high density, e.g.: Fe, Pb, U

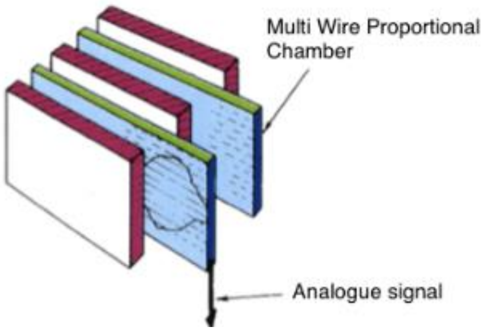


### Advantages:

- can optimally choose the absorber and detector material independently and according to the application.
- by choosing a very dense absorber material the calorimeters can be made very compact.
- the passive absorber material is cheap

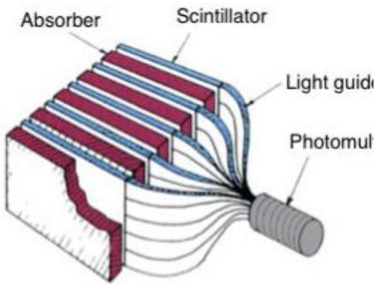
### Possible setups:

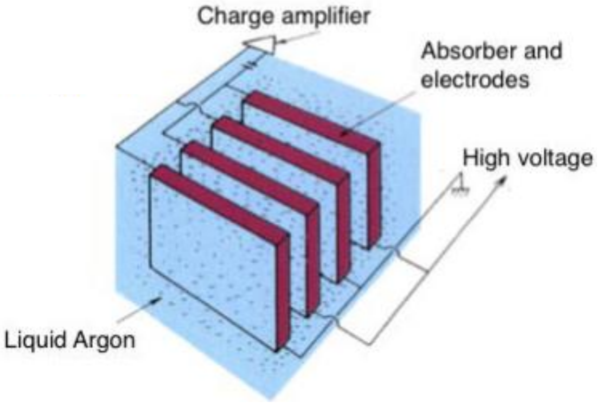
- Plastic scintillators
- Silicon detectors
- Noble liquid ionization chambers
- Gas detectors

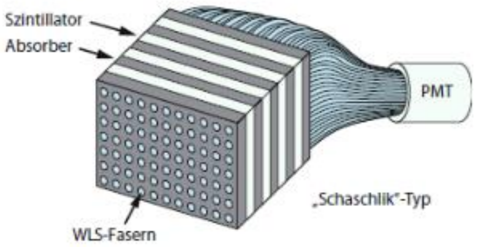


### Disadvantages:

- only part of the particles energy is deposited in the detector layers and measured
- energy resolution is worse than in homogeneous calorimeter (*sampling fluctuations*).







| Experiment | Detector | Detector thickness [mm] | Absorber material | Absorber thickness [mm] | Energy resolution (E in GeV) |
|---|---|---|---|---|---|
| UA1 | Scintillator | 1.5 | Pb | 1.2 | $15\%/\sqrt{E}$ |
| SLD | liquid Ar | 2.75 | Pb | 2.0 | $8\%/\sqrt{E}$ |
| DELPHI | Ar + 20% $CH_4$ | 8 | Pb | 3.2 | $16\%/\sqrt{E}$ |
| ALEPH | Si | 0.2 | W | 7.0 | $25\%/\sqrt{E}$ |
| ATLAS | liquid Ar | | Pb | | $10\%/\sqrt{E} \oplus 0.7\%$* |
| LHCb | Scintillator | | Fe | | $10\%/\sqrt{E} \oplus 1.5\%$* |

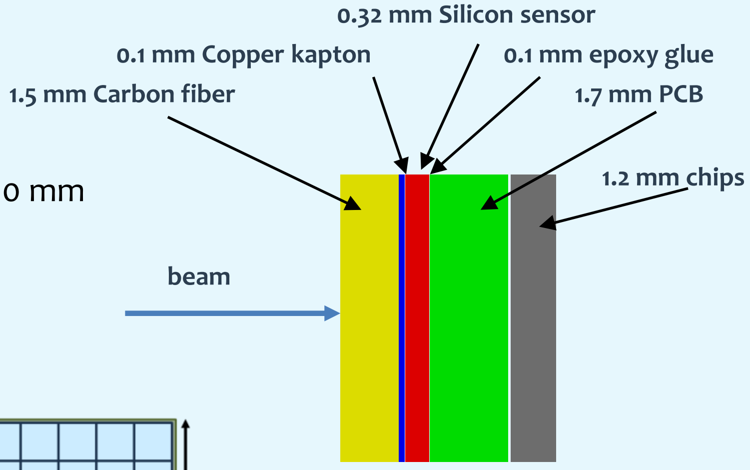
* Design values

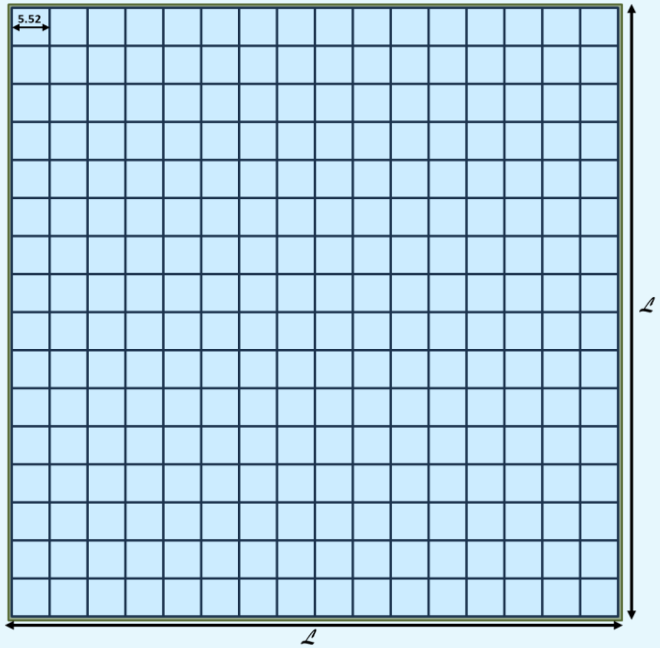
# Configurations design

## Semiconductor sensors

### ▪ Si sensor

- **Squared shape:**
- **X * Y dimension:** 90 mm * 90 mm
- **Separated** in 256 pads
- **Thickness**: 320 μm

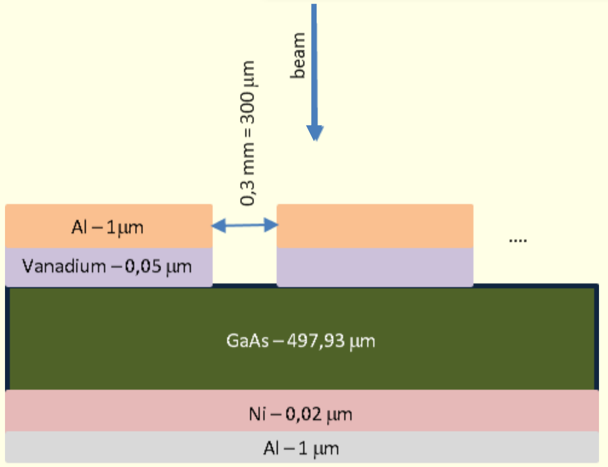


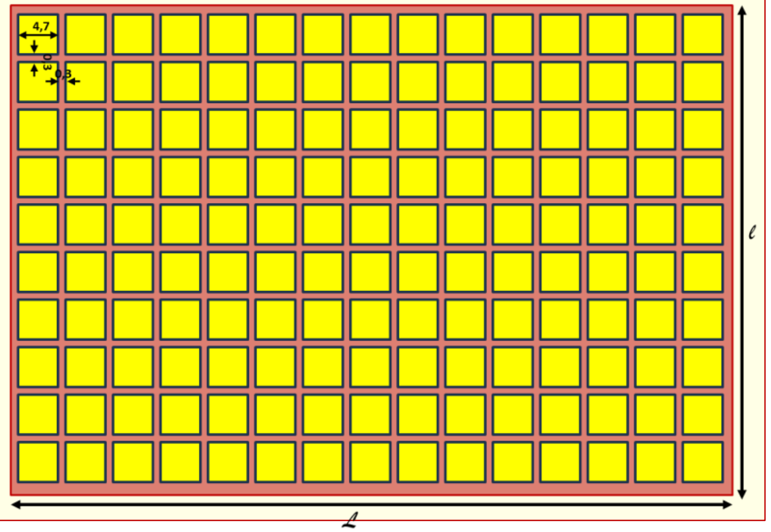


| Property | Si | GaAs |
|---|---|---|
| Bandgap at 300 K (eV) | 1.12 | 1.43 |
| Relative Dielectric Constant | 11.8 | 12.8 |
| Saturated Drift Velocity (cm/s) | 1 x $10^7$ | 2 x $10^7$ |
| Thermal Conductivity (W/cm -℃) | 1.5 | 0.5 |
| Maximum Operating Temperature (K) | 300 | 460 |
| Melting temperature (°C) | 1415 | 1238 |
| Electron mobility at 300 (cm²/Vs) | 1400 | 8500 |
| Breakdown Electric Field (V/cm) | 3 x $10^5$ | 4 x $10^5$ |

### ▪ GaAs sensor

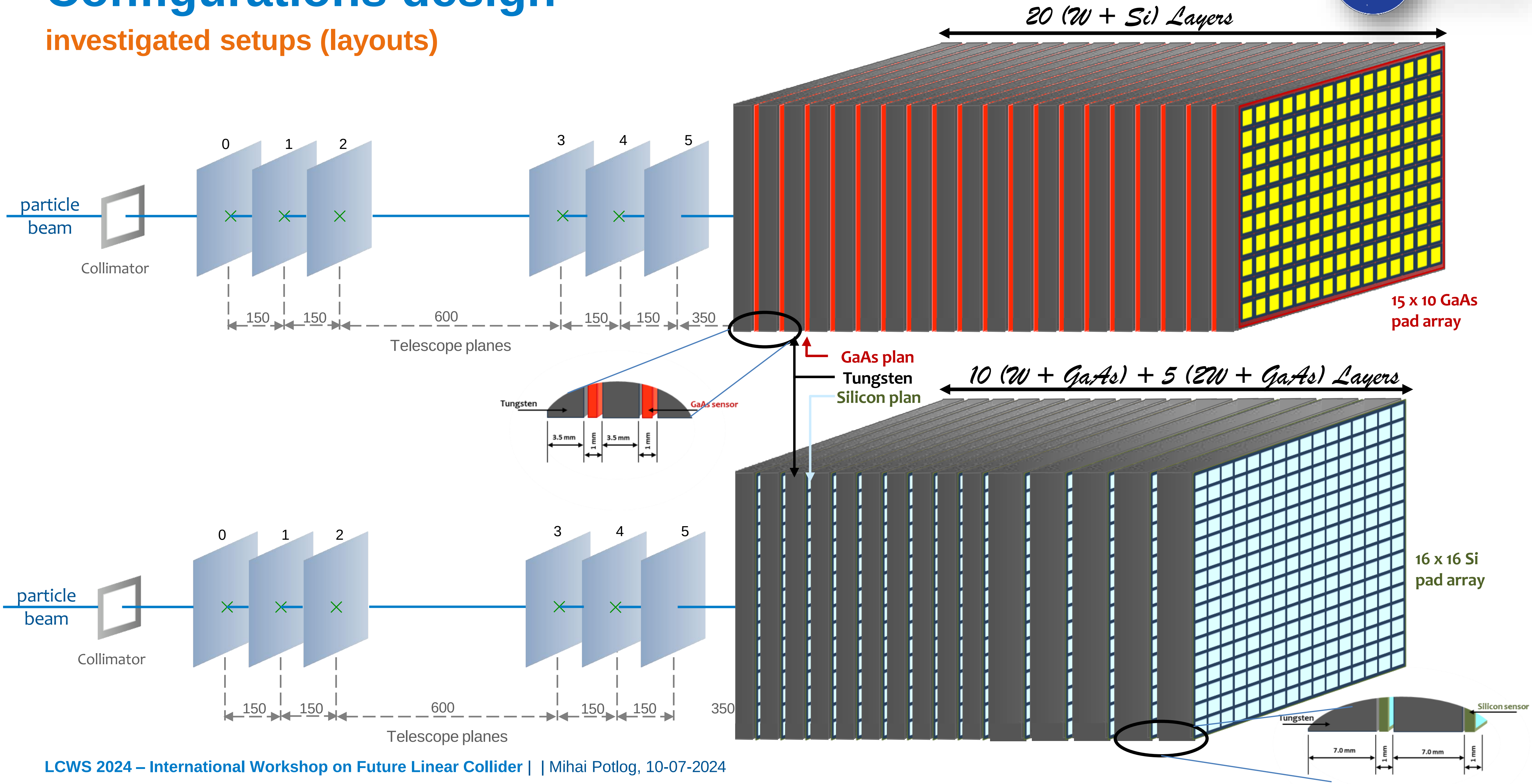
- **Rectangular shape**
- **X dimension:** 𝓛 = 4,7mm*15 (pad) + 0,3mm*14(gap) = = 74,7 mm
- **Y dimension:** ℓ = 4,7mm*10(pad) + 0,3mm*9(gap) = = 49,7 mm
- **Thickness:** 500 μm





# Configurations design

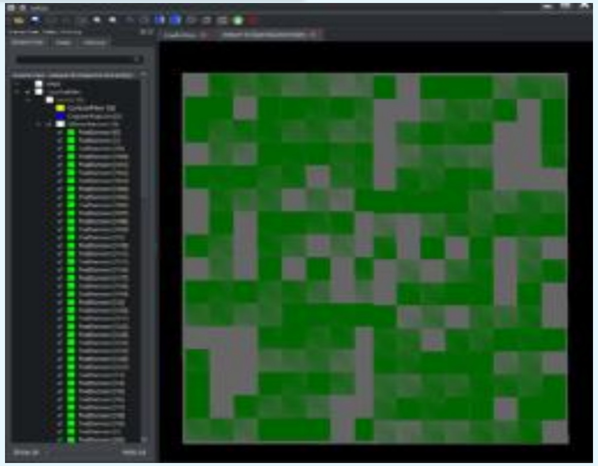
## investigated setups (layouts)

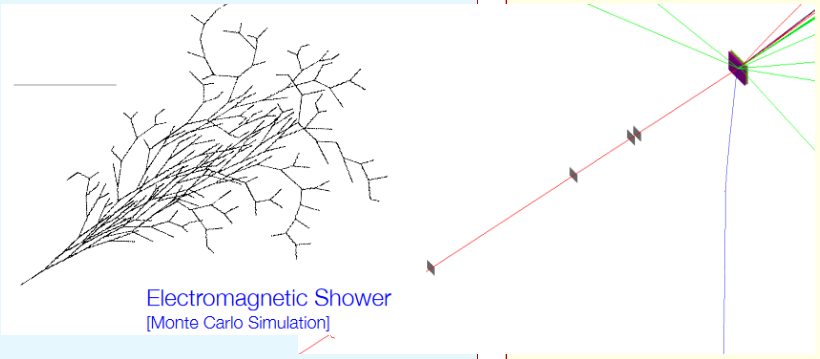


# Geant4 geometry implementation

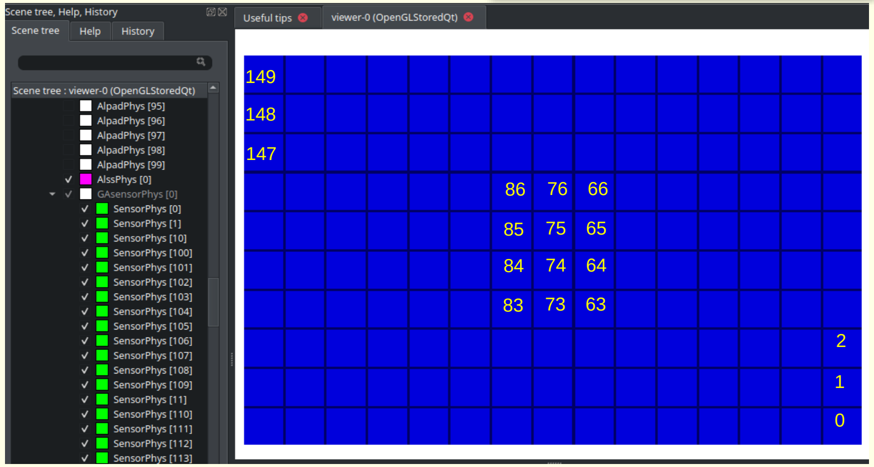
## sensors, setups, visualization

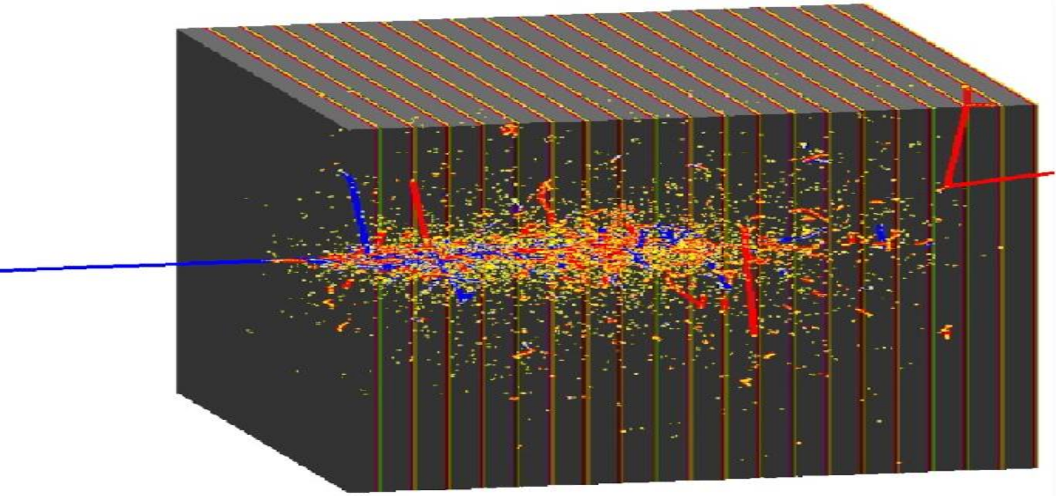
- **Si sensor**





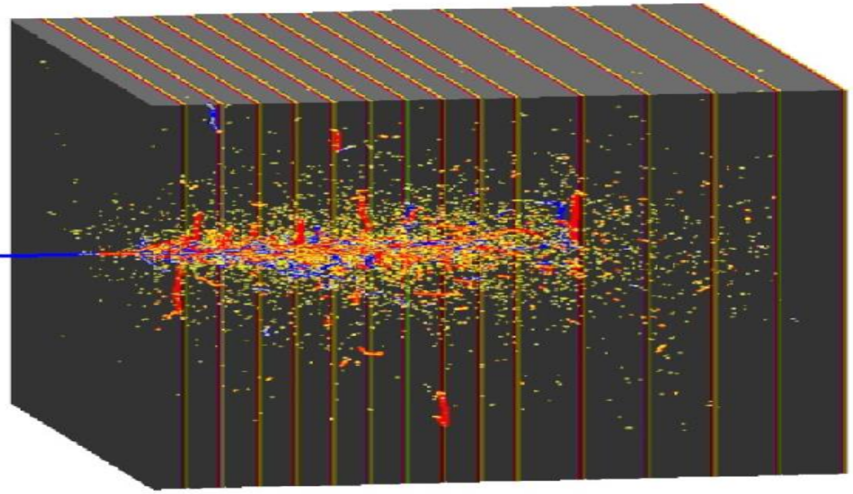
- **GaAs sensor**





### Geant4 visualization

- **1$^{st}$ configuration (left)** consist of **20 layers** of alternating **3.5 mm (1X$_0$) tungsten** absorbers and **Si/GaAs sensors.**
- **2$^{nd}$ configuration (right)** use the first **10 layers** of **3.5 mm (1X$_0$) tungsten** plates and the following **5 layers** of **7.0 mm (2X$_0$) tungsten** plates interleaved with **Si/GaAs sensors.**

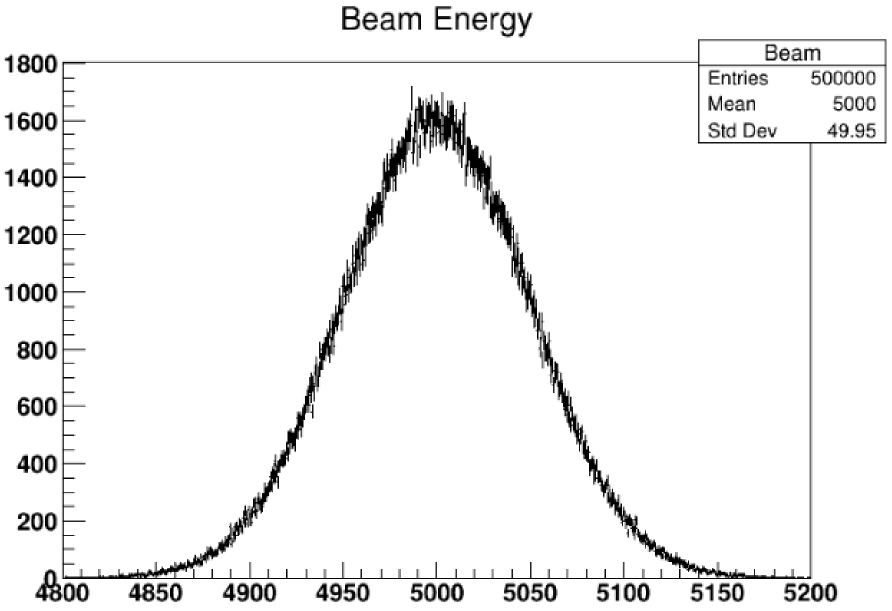


# Primary particle generation & Physics list

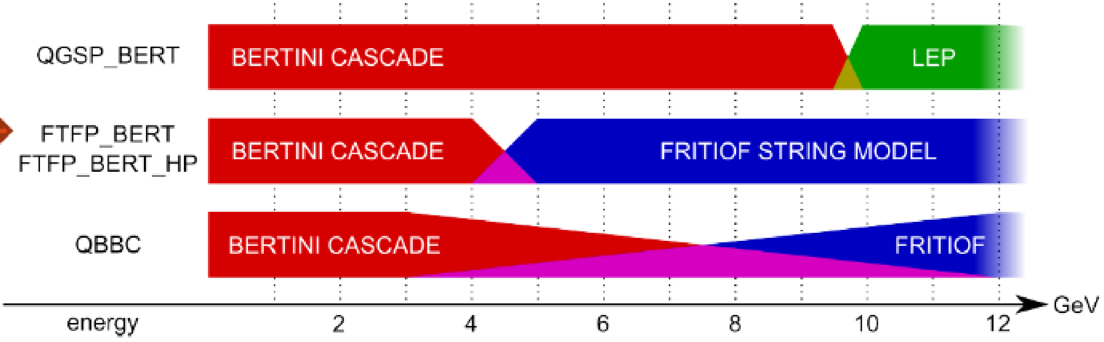
## GPS source, G4VUserPhysicsListPhysics, G4VModularPhysicsList

### Create 'diverging' beam

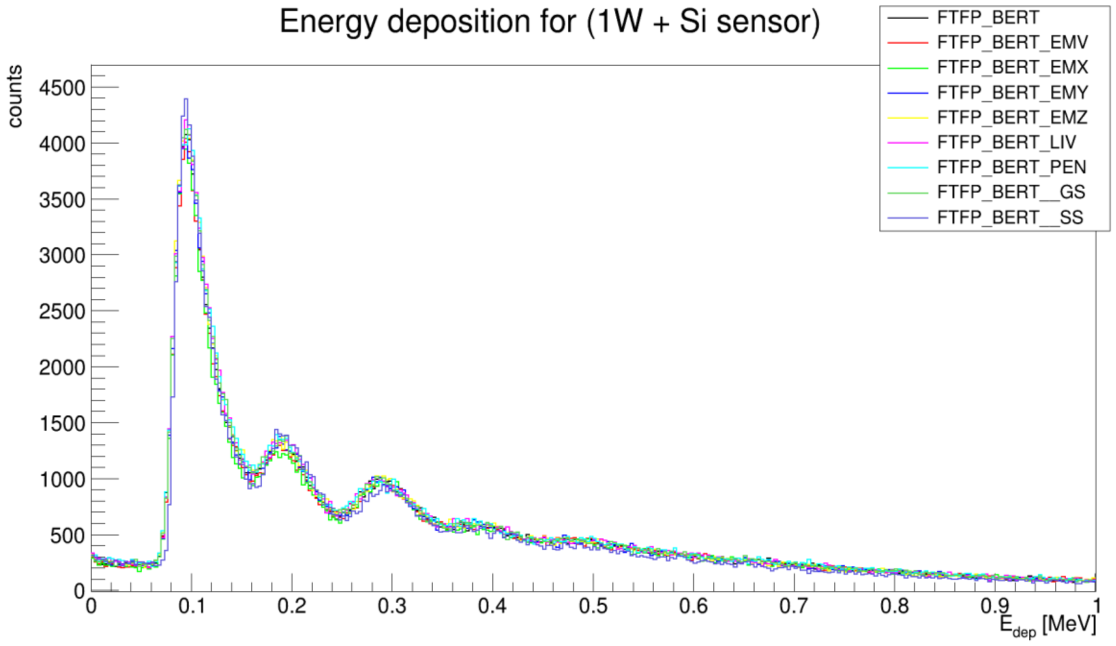
- when firing an accelerator based beam, the beam will have some divergence and shape
- 12 x 12 mm$^2$ collimator -> square source
- **gaussian energy distribution** with 0.1% spread
- 0.752 mrad **divergence**



- FTF_BIC
- FTFP_BERT
- FTFP_BERT_HP
- FTFP_BERT_TRV
- FTFP_BERT_ATL
- FTFP_INCLXX
- FTFP_INCLXX_HP
- FTFP_QGSP_BERT
- LBE
- NuBeam
- QGSP_BERT
- QGSP_BERT_HP
- QGSP_BIC
- QGSP_BIC_HP
- QGSP_BIC_AllHP
- QGSP_FTFP_BERT
- QGSP_INCLXX
- QGSP_INCLXX_HP
- QGS_BIC
- Shielding
- ShieldingLEND



**Name of most physics list follows name of physics constructor for hadronic inelastic, optionally followed by EM option**

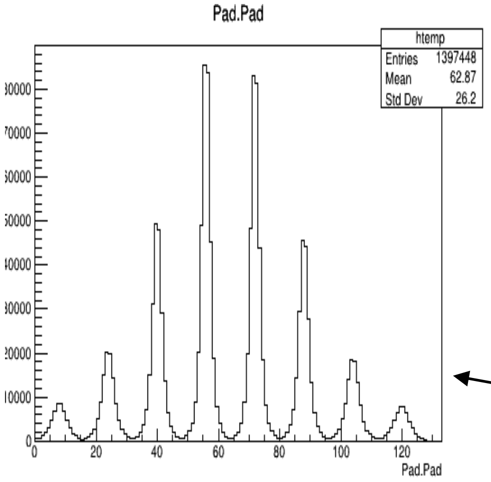


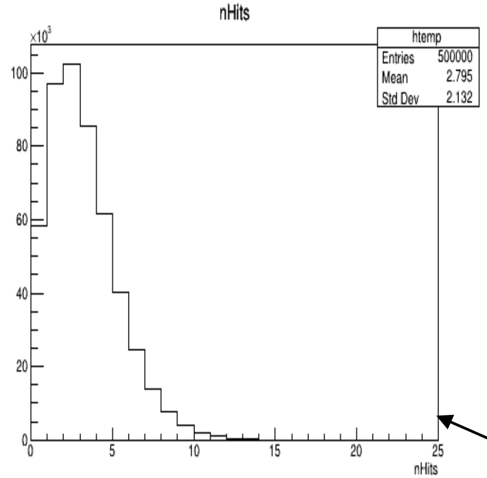
# Hits collection

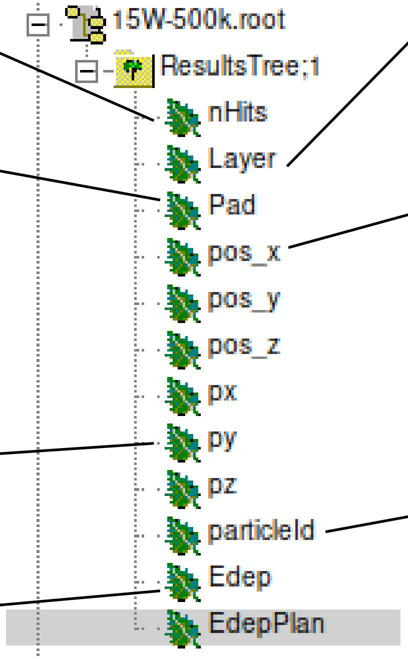
## sensitive detector

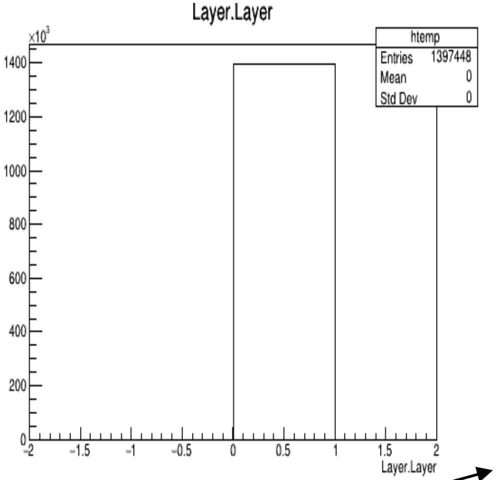
### 7 observables

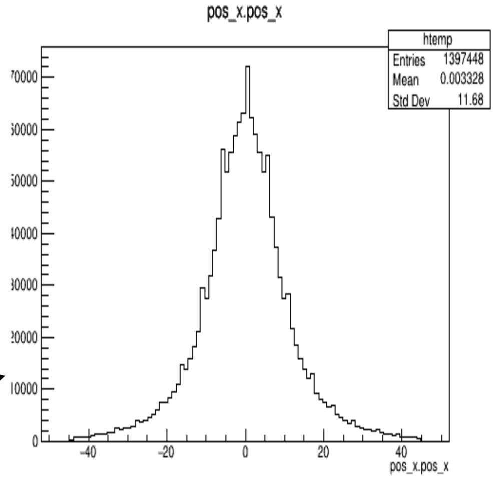
- Number of hits
- Pads hits
- Position of hits (x, y, z)
- Hits momentum (px, py, pz
- Particle identification
- Total energy per event
- Total energy of hits

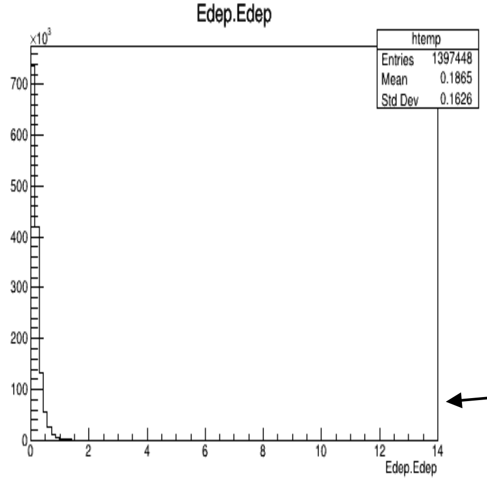


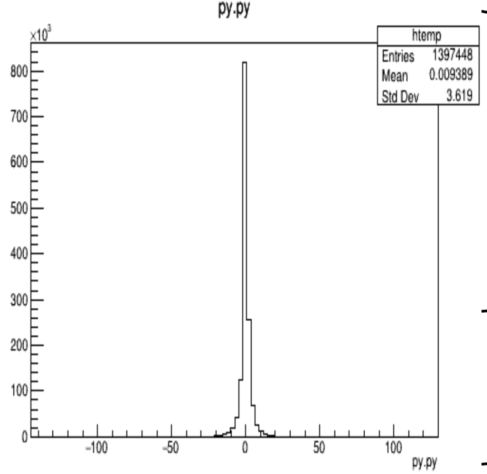


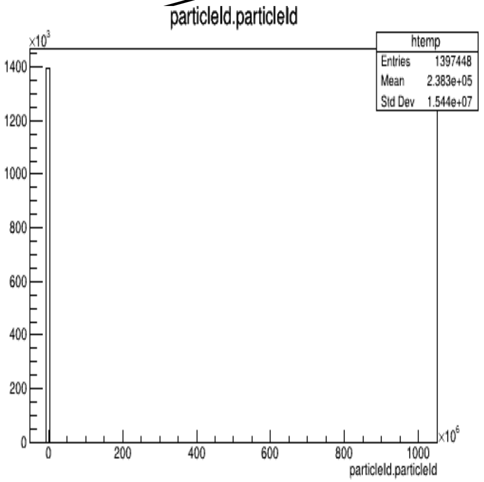


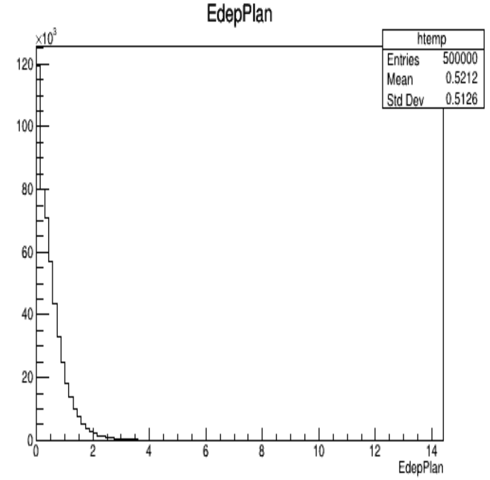












# Hits versus digits

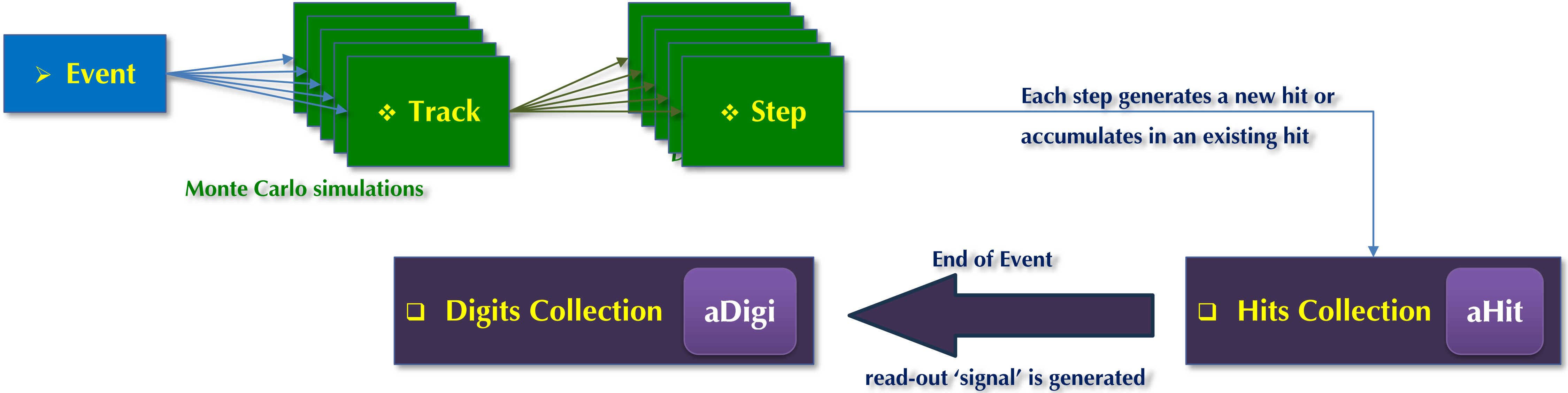
## sensitiveDetector, DigitizerModule

### G4VHit

- **Hits** are a "snapshot" of the physical interaction of a track (step) or an accumulation of interactions of tracks in the sensitive region of the detector, thus hits represent the "true" energy deposited in the detector

### G4VDigitizerModule

- **Digits** are instead intended to be used to simulate the process of reading-out of the signal: for example "true" energy is transformed into collected charge, electronic noise can be applied together with all instrumental effects

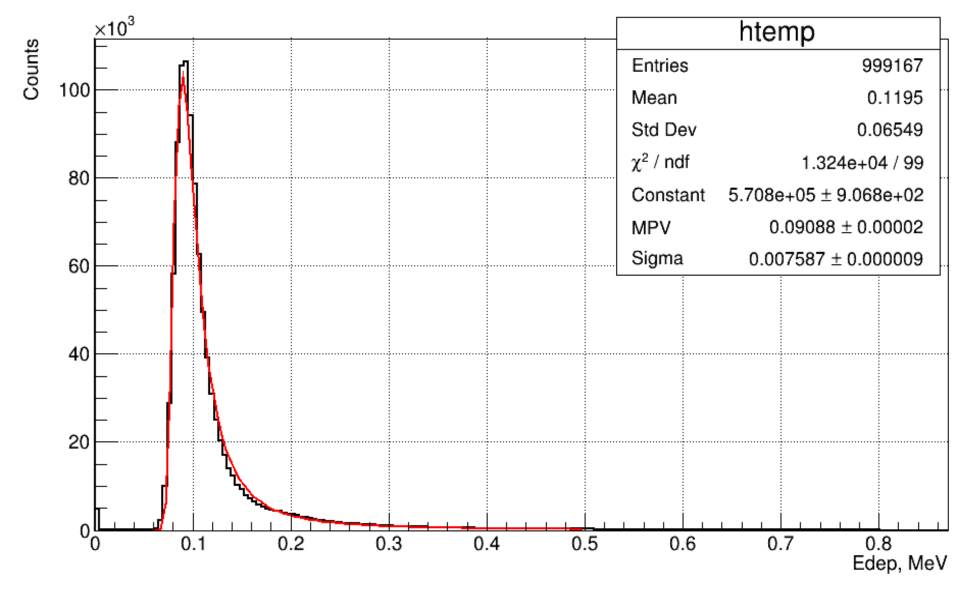


**No digitization has been applied to simulations performed for this task**

# Number of e-h pairs created

## sensor materials

### ▪ Si sensor

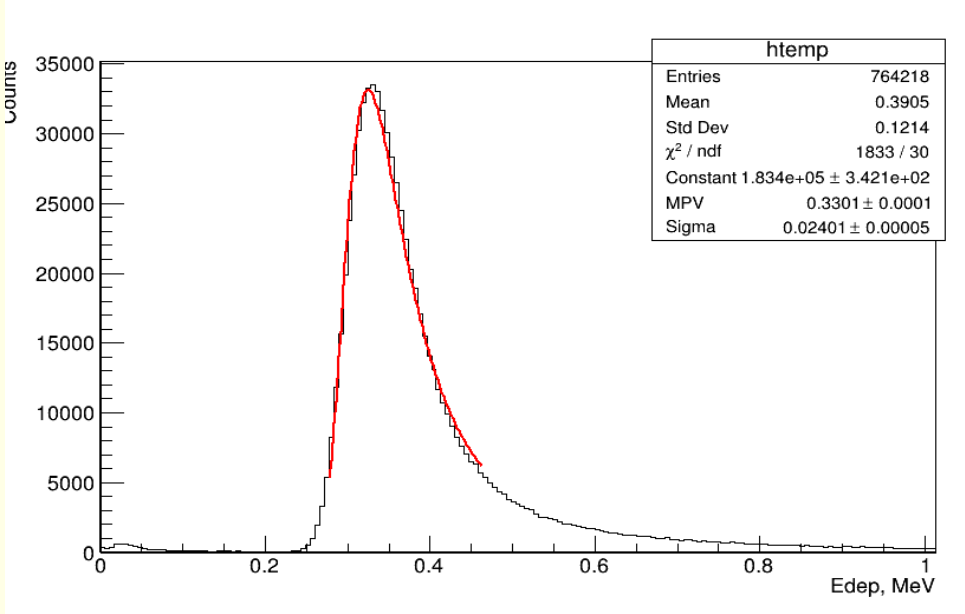


**Energy deposition:**

- **320 µm** thickness
- **5 GeV** mono-energetic e-
- **3.62 eV** ionization energy

| | |
|---|---|
| **Dep. en. (MeV)** | **0.1195** |
| **e-hole pairs / µm** | **78.45** |

### ▪ GaAs sensor



| | |
|---|---|
| **Dep. en. (MeV)** | **0.3905** |
| **e-h pairs / µm** | **165.12** |

**Energy deposition:**

- **550 µm** thickness
- **5 GeV** mono-energetic e-
- **4.3 eV** ionization energy

**Physics list used: FTFP_BERT_EMZ**

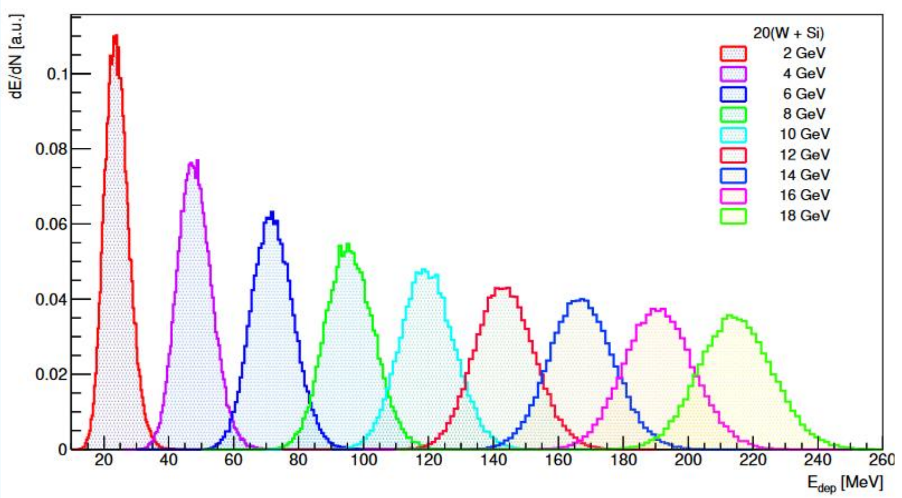
# Energy response

## sensors, configurations, energy deposition

**▪ Si sensor**

**Physics list used: FTFP_BERT_EMZ**

**▪ GaAs sensor**



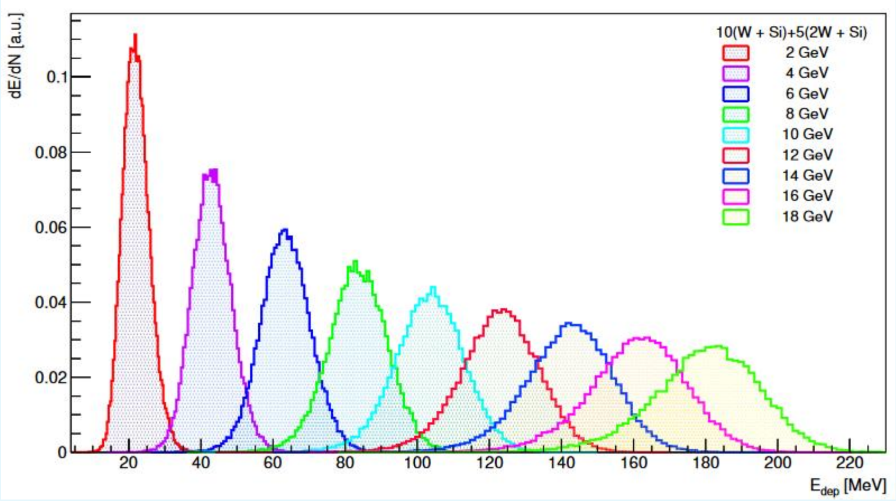
- **$1^{st}$ configuration (up): 20 (W +Si) layers**

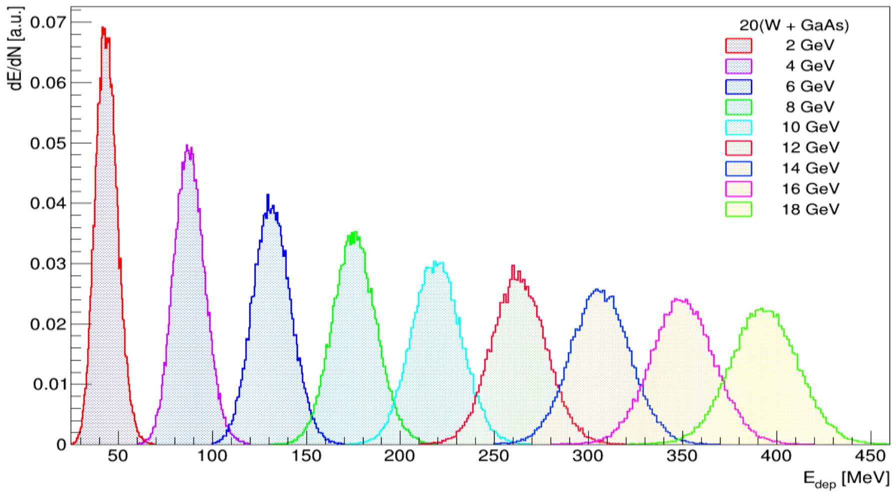
### Energy deposition

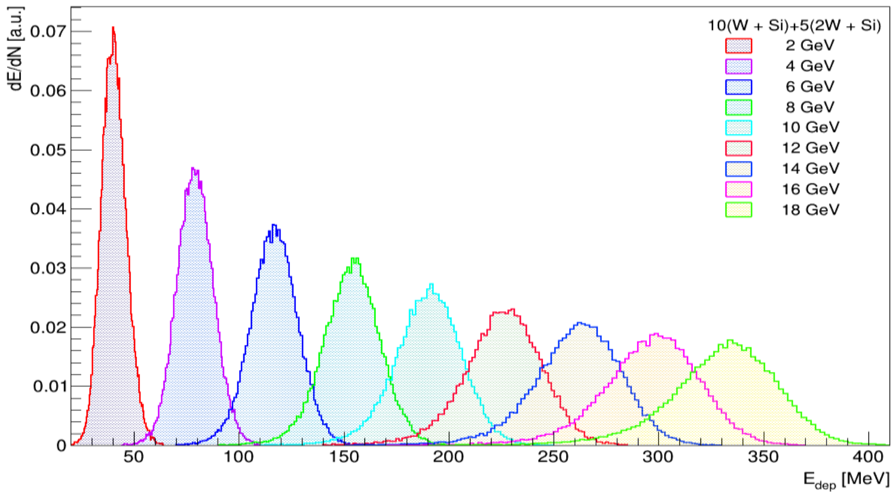
- The spatial extension of a shower depends on the material.
- **Radiation length ($X_0$)** is the distance in which the projectile looses 1/e (≈63.2%) of its energy due to radiation
- Approximation:

$$X_0 = \frac{716.4\ A}{Z(Z+1)\ln(287/\sqrt{Z})}\, gcm^{-2}$$

- **$2^{nd}$ configuration (down): 10 (W+Si) + 5 (2W+Si) layers.**







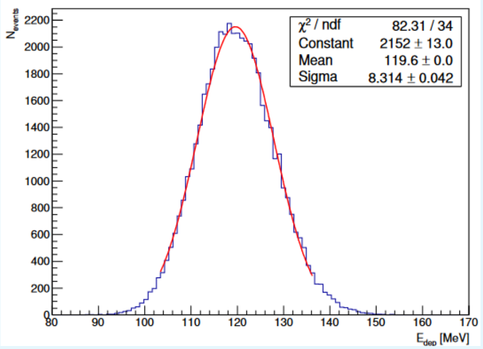
# Liniarity

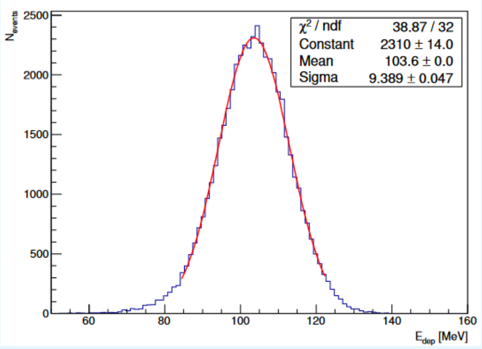
## sensors, configurations, energy deposition

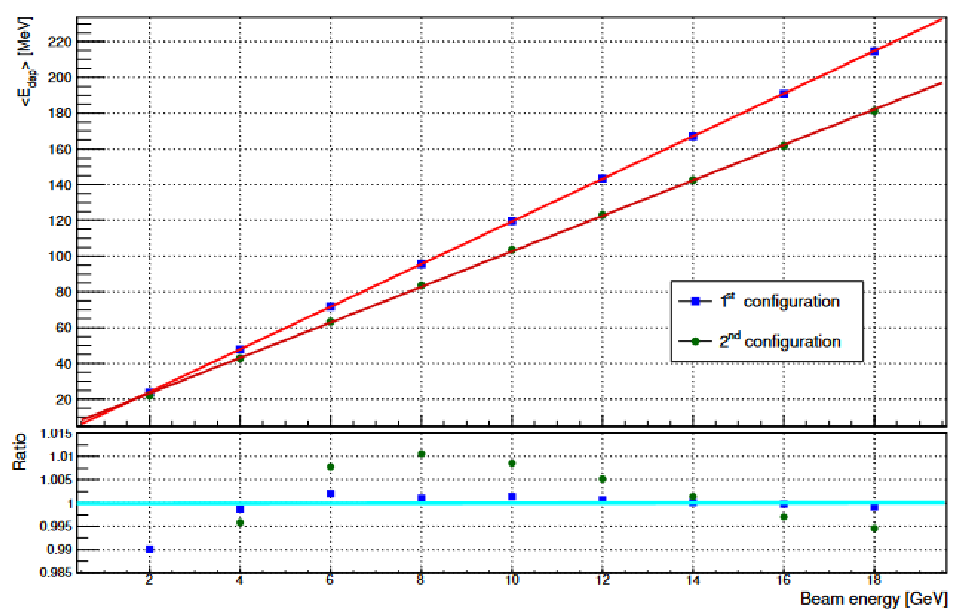
**▪ Si sensor**

**Physics list used: FTFP_BERT_EMZ**

**▪ GaAs sensor**



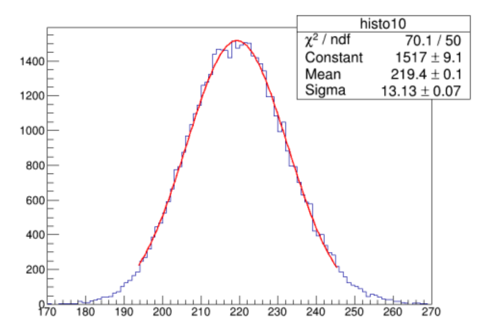


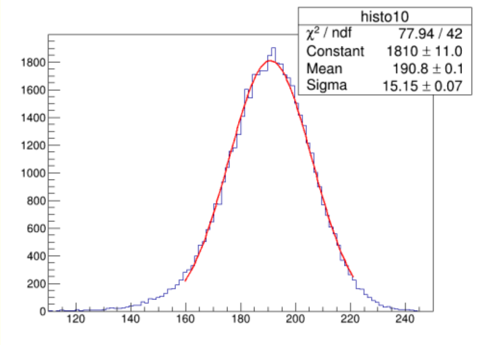


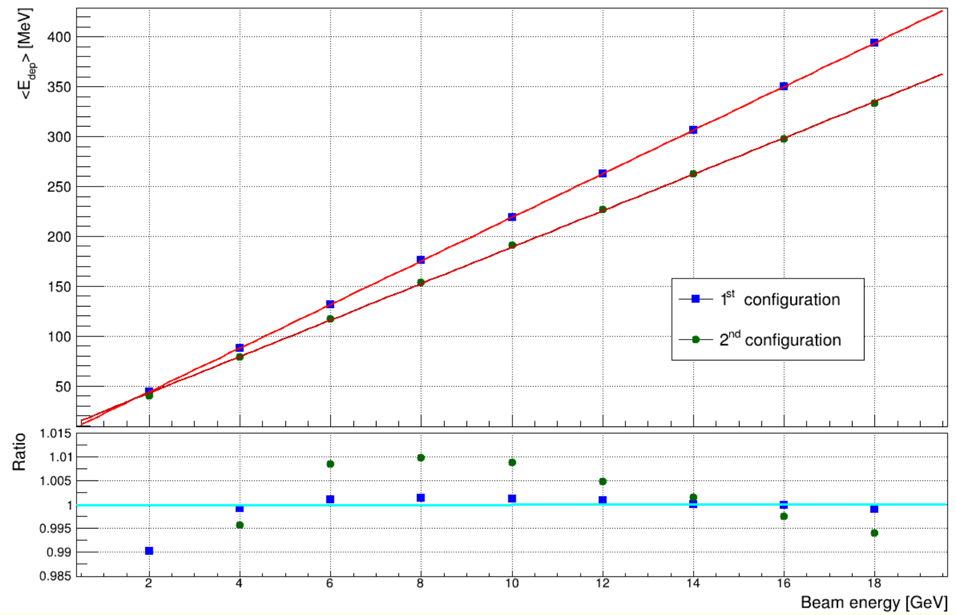
### Detector response -> Linearity

- The average calorimeter signal vs. the energy of the particle
- Electromagnetic calorimeters are linear
- All energy deposited through ionization/ excitation of absorber

| | 1st configuration | | 2nd configuration | |
|---|---|---|---|---|
| | Si | GaAs | Si | GaAs |
| E [GeV] | μ[MeV] | | | |
| 4 | 47.82 | 87.90 | 42.93 | 79.19 |
| 6 | 71.87 | 131.82 | 63.46 | 117.06 |
| 8 | 95.67 | 175.64 | 83.70 | 154.13 |
| 10 | 119.58 | 219.35 | 103.57 | 190.82 |
| 12 | 143.37 | 263.05 | 123.18 | 226.78 |
| 14 | 167.13 | 306.51 | 142.61 | 262.64 |
| 16 | 190.92 | 350.17 | 161.78 | 298.04 |
| 18 | 214.61 | 393.51 | 181.13 | 333.33 |





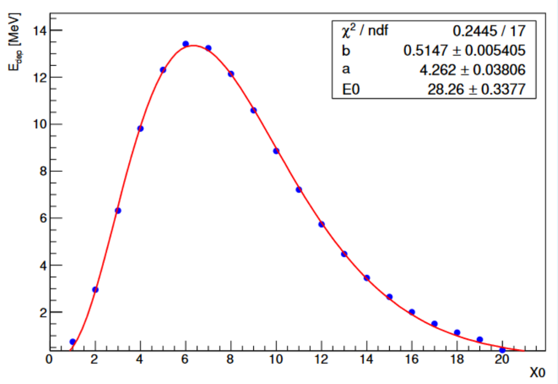


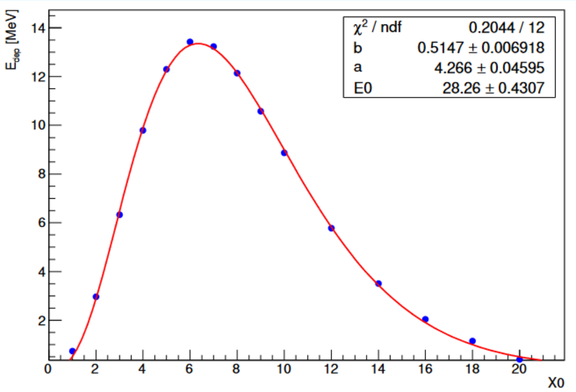
# Longitudinal shower

## 10 GeV incident e-, 2 configurations

**Physics list used: FTFP_BERT_EMZ**

- **Si sensor**





| | 1st configuration | 2nd configuration |
|---|---|---|
| E [GeV] | $t_{max}[X_0]$ | |
| 2 | 4.602 | 4.599 |
| 4 | 5.350 | 5.357 |
| 6 | 5.788 | 5.788 |
| 8 | 6.095 | 6.106 |
| 10 | 6.338 | 6.346 |
| 12 | 6.532 | 6.541 |
| 14 | 6.700 | 6.705 |
| 16 | 6.844 | 6.854 |
| 18 | 6.969 | 6.966 |

**Parametrization**

*[Longo 1975]*

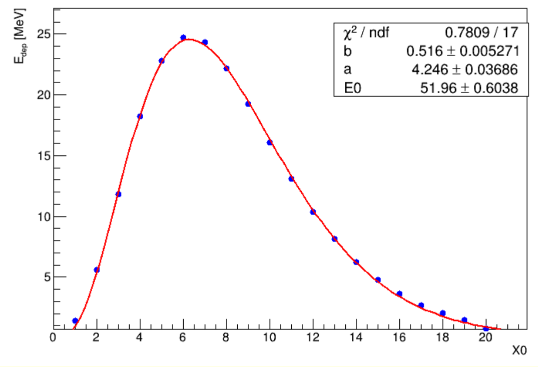
$$F(E,t) = E_0 b \frac{(bt)^{a-1}\exp(-bt)}{\Gamma(a)}$$

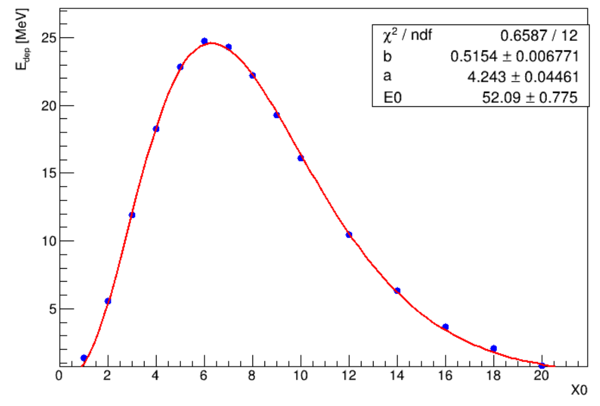
- ***t …*** shower depth in units of Xo
- ***$E_0$*** … energy of incident particle
- ***Γ*** … Euler's Gamma function:
- ***a, b*** … fit parameters (in first approximation ***$b \sim 0.5$, $a = bt_{peak}$***)

**Position of the shower maximum** in units of $X_0$:

$$t_{max} = \frac{a-1}{b}$$

- **GaAs sensor**





| | 1st configuration | 2nd configuration |
|---|---|---|
| E [GeV] | $t_{max}[X_0]$ | |
| 2 | 4.563 | 4.547 |
| 4 | 5.303 | 5.308 |
| 6 | 5.735 | 5.738 |
| 8 | 6.049 | 6.051 |
| 10 | 6.291 | 6.293 |
| 12 | 6.487 | 6.497 |
| 14 | 6.654 | 6.656 |
| 16 | 6.790 | 6.806 |
| 18 | 6.915 | 6.929 |

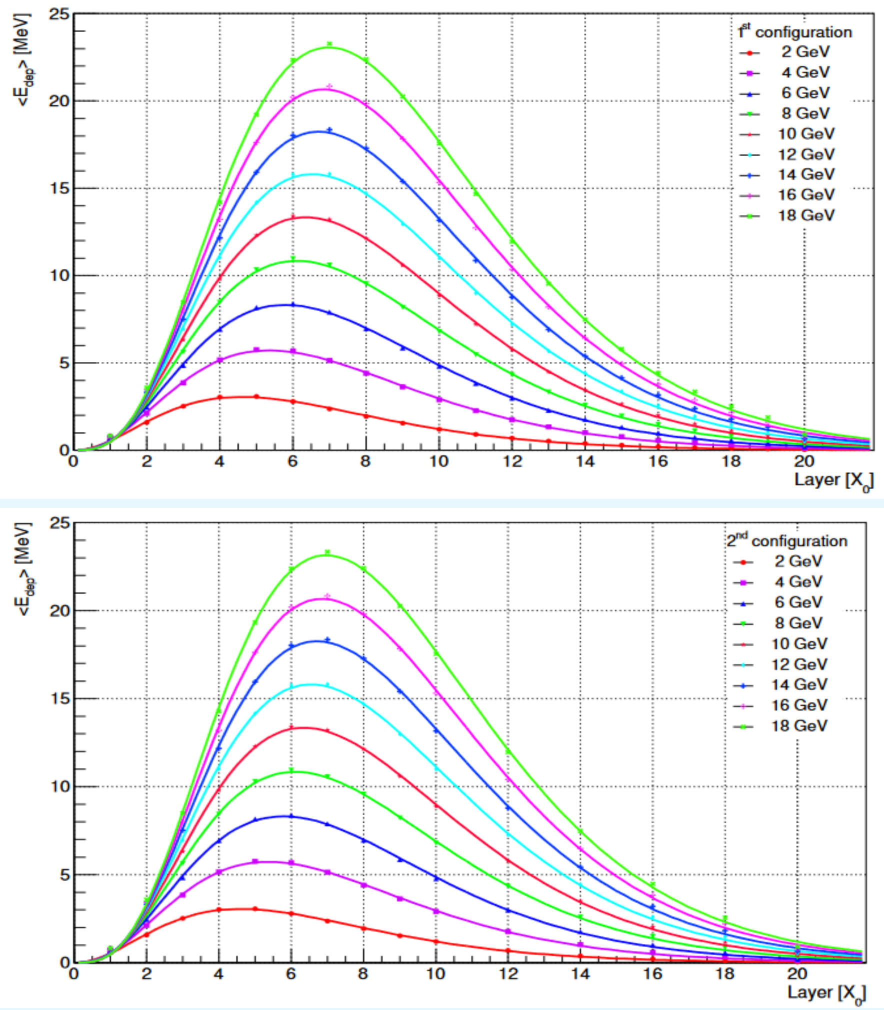
# Longitudinal shower

## all incident energies, 2 configurations

- **Si sensor**

**Physics list used: FTFP_BERT_EMZ**

- **GaAs sensor**

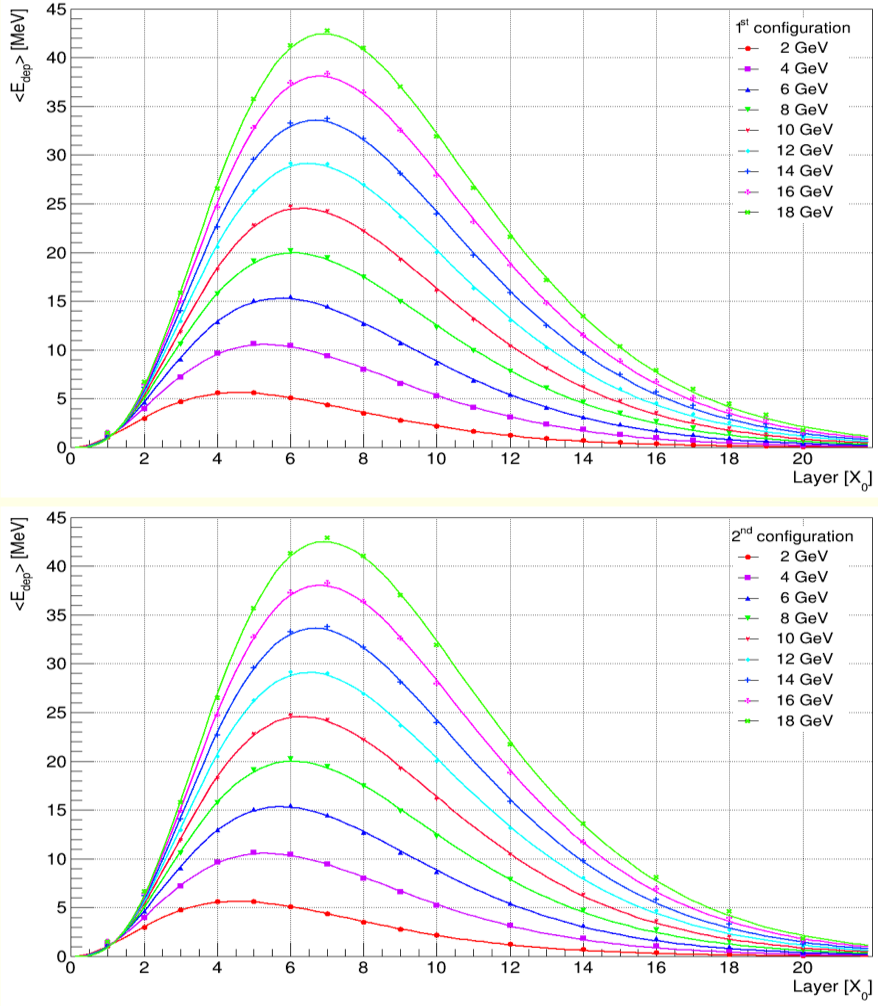


- **1st configuration (up):**
  **20 (W +Si) layers**

- Important for the design of calorimeter is, first of all, the longitudinal dimension of the shower.
- About 95% of the energy of the incident particle is contained within the depth T (*semi empirical formula*)

$$T(95\%) = t_{max} + 0.08Z + 9.6\ [X_0]$$

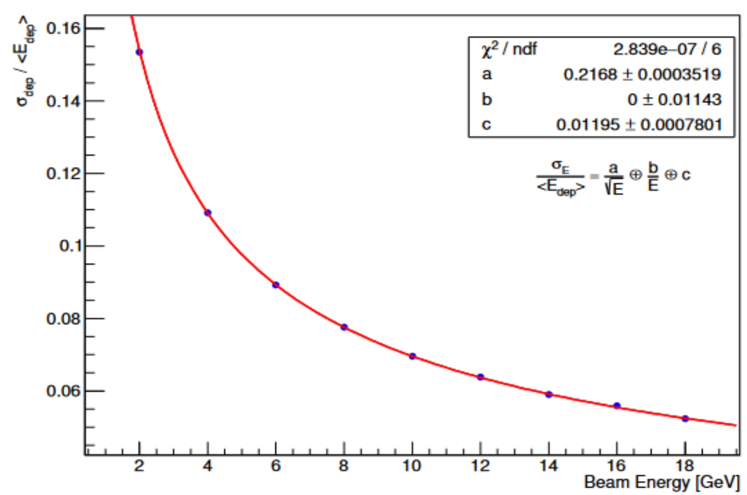
- **2nd configuration (down):**
  **10 (W+Si) + 5 (2W+Si) layers.**

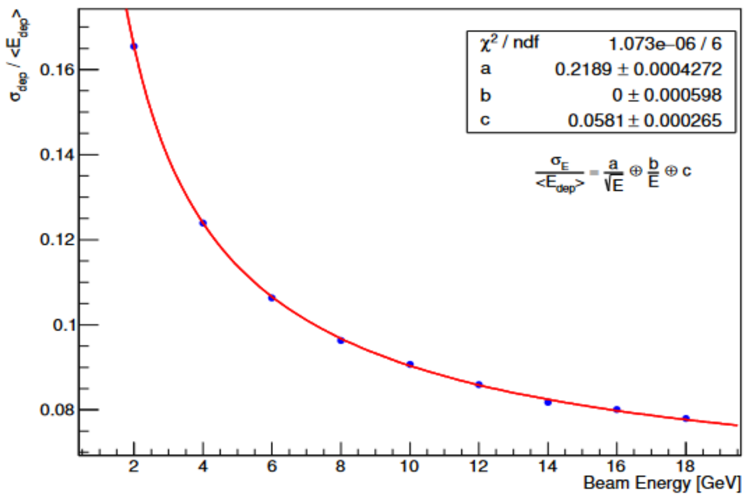


# Energy resolution

## Energy deposition per plane

### Si sensor

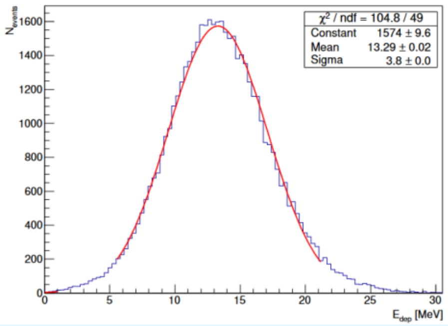




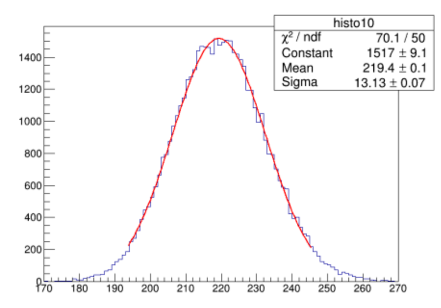
## Relative energy resolution

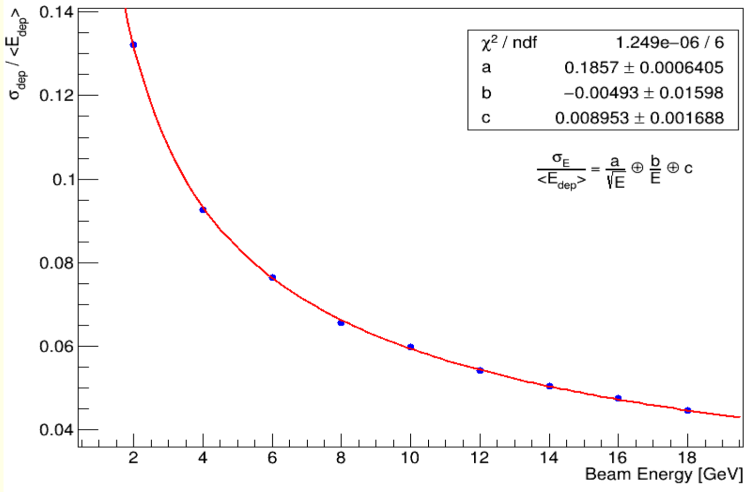
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

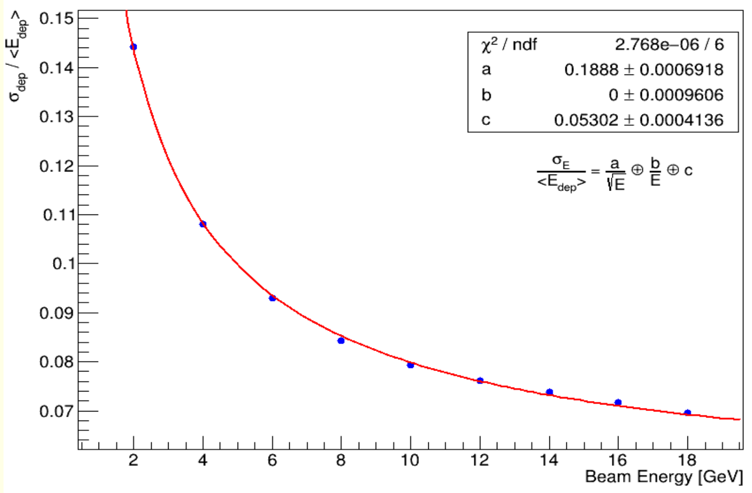
- ***a: stochastic term***
  - intrinsic statistical shower fluctuations
  - sampling fluctuations
  - signal quantum fluctuations (e.g. photo-electron statistics)
- ***b: noise term***
  - readout electronic noise
  - Radio-activity, pile-up fluctuations
- ***c: constant term***
  - inhomogeneities (hardware or calibration)
  - imperfections in calorimeter construction (dimensional variations, etc.)
  - non-linearity of readout electronics
  - fluctuations in longitudinal energy containment (leakage can also be ~ $E^{-1/4}$)
  - fluctuations in energy lost in dead material before or within the calorimeter



### GaAs sensor







# Conclusions

## simulations, analysis

### Simulations

- define electromagnetic calorimeter configurations to be used
- construct geometries in FreeCad and import in Geant4
- define source and control via GPS commands
- define sensitive detector and construct hits collection to gather information
- collect relevant data in a Root format

### Analysis

- calculate e-hole pairs for different material of sensors
- test various physics lists and their influence
- evaluate each pad energy deposition
- fit the energy deposition histograms to get the MPV
- evaluate MPV for different setup configurations
- find the longitudinal shower distribution for different configurations
- evaluate resolution of the configurations investigated

**Acknowledgements**

- this research was supported by the Romanian Ministry of Research, Innovation and Digitalization through Programme 5.9/Subprogramme 5.9.2 / Module FAIR-RO, coordinated by Institute of Atomic Physics – contract NeuSMaL – 2024;
- this research was supported by the Romanian Ministry of Research, Innovation and Digitalization under the Romanian National Core Program LAPLAS VII – contract no. 30N/2023.

# Thank you!