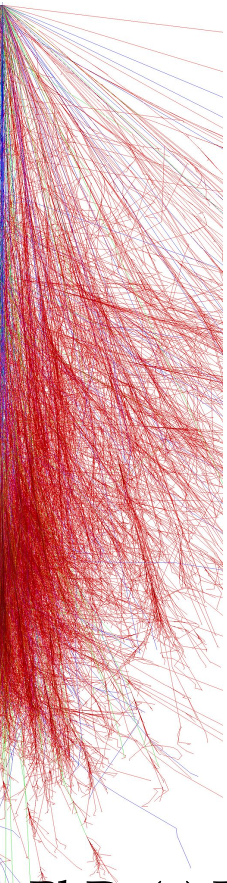

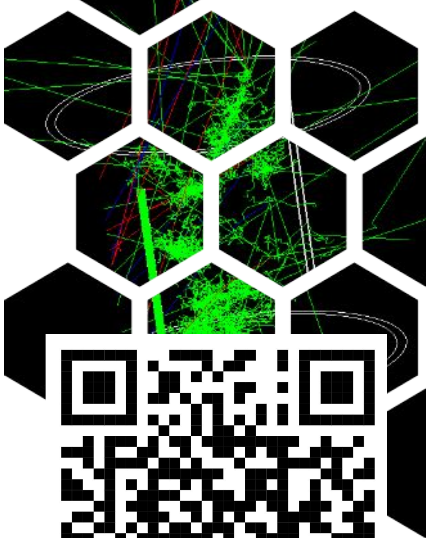

LAGO Workshop

ARTI & Meiga: From Particle Showers to Detector Signals

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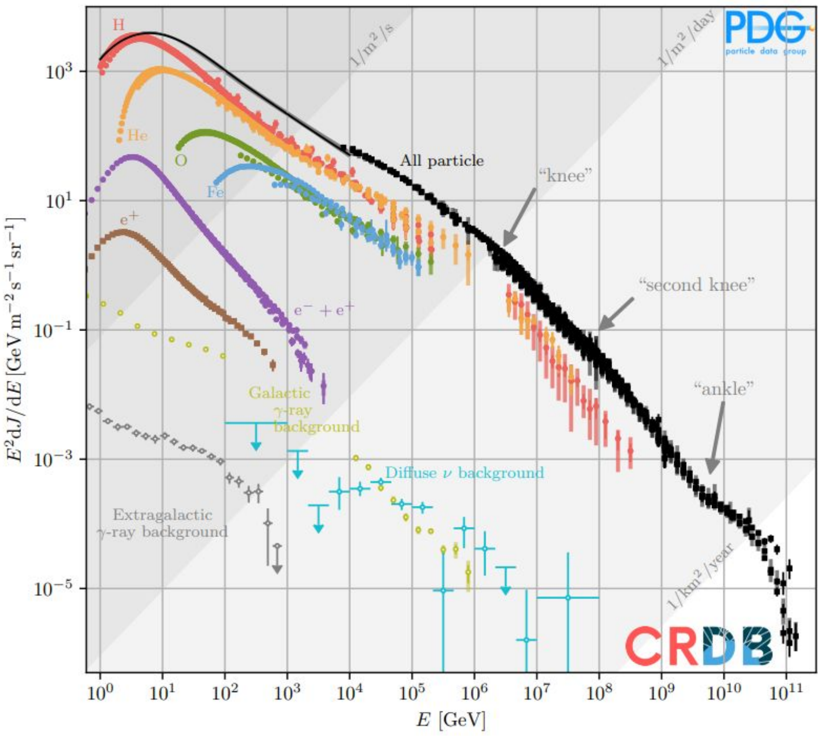
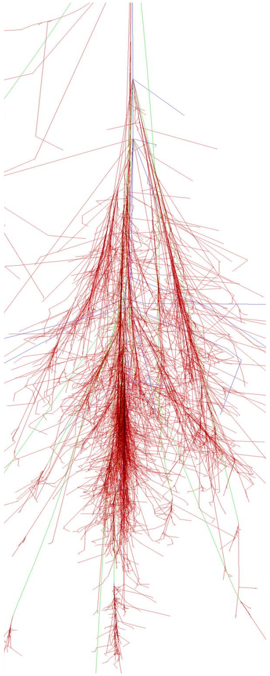
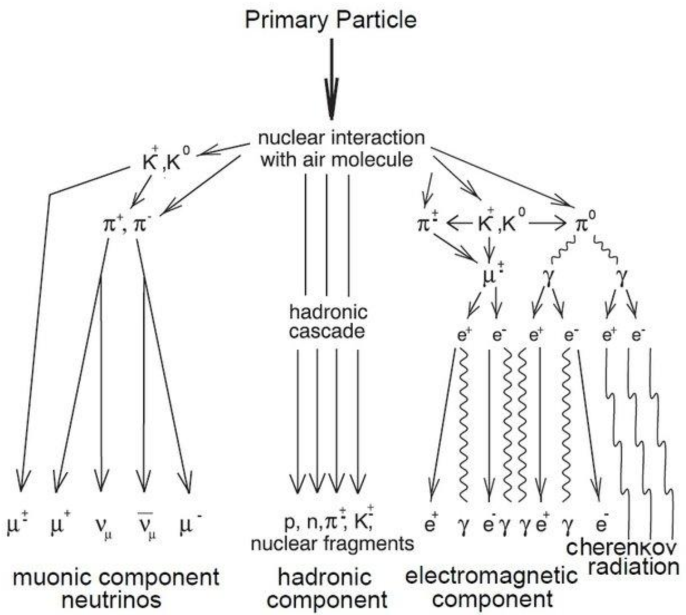
Cosmic rays and EAS

Cosmic-ray primaries are high-energy particles from space. When they hit the atmosphere, they create an **Extensive Air Shower (EAS)** a cascade of secondary particles including photons, electrons, muons, and hadrons.



Spectrum (CRs). [Navas et al.(2024)] PDG





ARTI

ARTI integrates MagnetoCosmics, CORSIKA, and Geant4 to simulate cosmic-ray interactions with the atmosphere. It models site-specific conditions, predicts background and transient signals, and provides ground-level fluxes for applications such as muography.

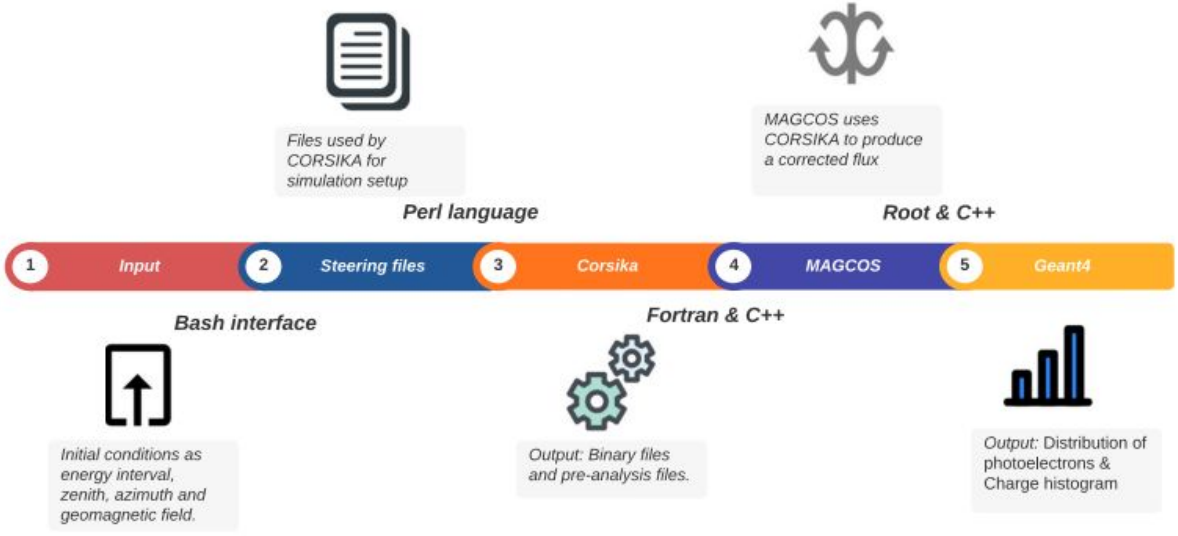


Fig. 2 As the simulation evolves, the different ARTI modules call CORSIKA, MAGCOS, or Geant4 to accurately calculate the signal flux at the detector expected by the integrated cosmic ray flux. The simulation moves forward as a sequence: the results from one steps are used as inputs for the next one

Sarmiento-Cano, C., Suárez-Durán, M., Calderón-Ardila, R. *et al.* The ARTI framework: cosmic rays atmospheric background simulations. *Eur. Phys. J. C* 82, 1019 (2022). https://doi.org/10.1140/epjc/s10052-022-10883-z

Why simulate with ARTI?

- No closed analytic solution for secondary cosmic ray flux
- Energy and angular distributions are complex and site–dependent
- Atmosphere and geomagnetic field strongly affect the flux
- Simulations allow testing scenarios not accessible to experiments (rare events, extreme conditions)
- Simulations allow us to test models and compare with data
- ARTI provides a unified framework to do all this

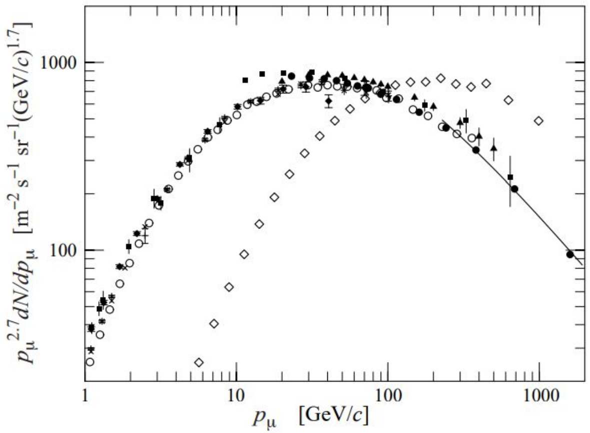


Figure 30.6: Spectrum of muons at $\theta = 0°$ (♦ [67], ■ [71], ▼ [72], ▲ [73], ×, + [69], ○ [62], and ● [70] and $\theta = 75°$ ◊ [74]). The line plots the result from Eq. (30.4) for vertical showers.

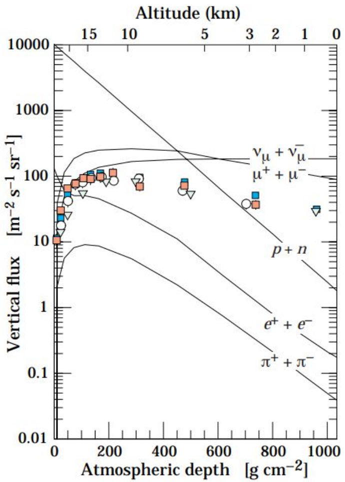
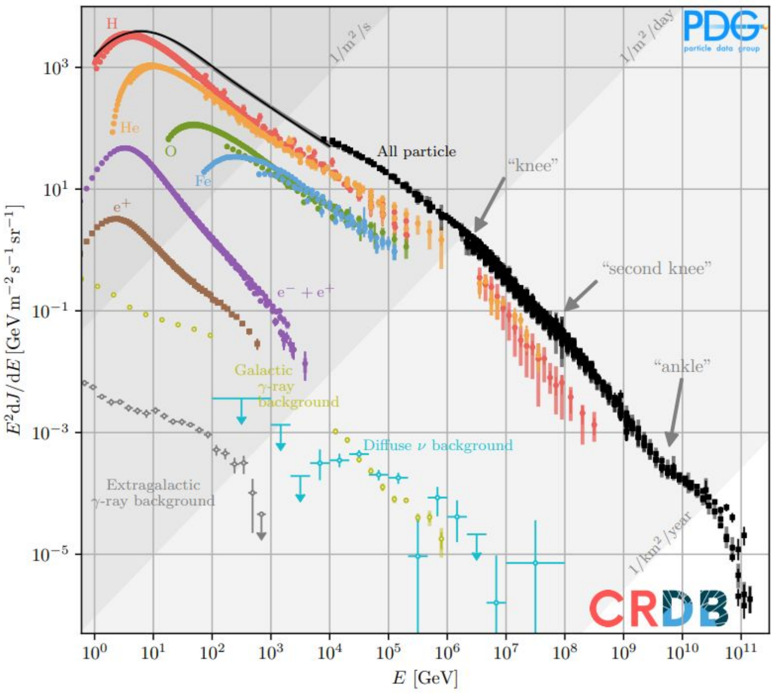


Figure 30.5: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq. (30.2). The experimental points show measurements of negative muons with $E_\mu > 1$ GeV [57–62].

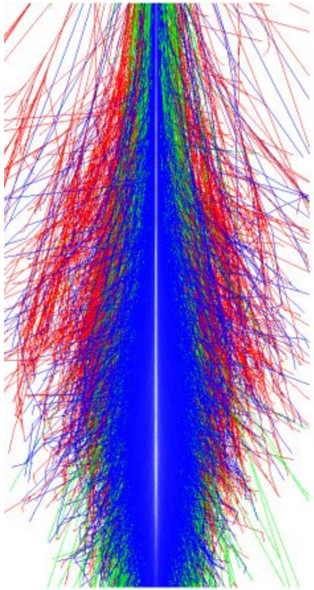
Integrate the flux

We model the primary cosmic ray flux as an isotropic flow reaching Earth's atmosphere at 112 km. ARTI integrates this flux from protons to iron, considering energy ranges, spectral indices, site altitude, and atmospheric models. The framework automatically sets up simulations in CORSIKA, grouping primaries and managing distributed computing resources

$$\Phi(E_p, Z, A, \Omega) = j_0(Z, A)\left(\frac{E_p}{E_0}\right)^{\alpha(E_p, Z, A)}$$



Spectrum (CRs). [Navas et al.(2024)] PDG

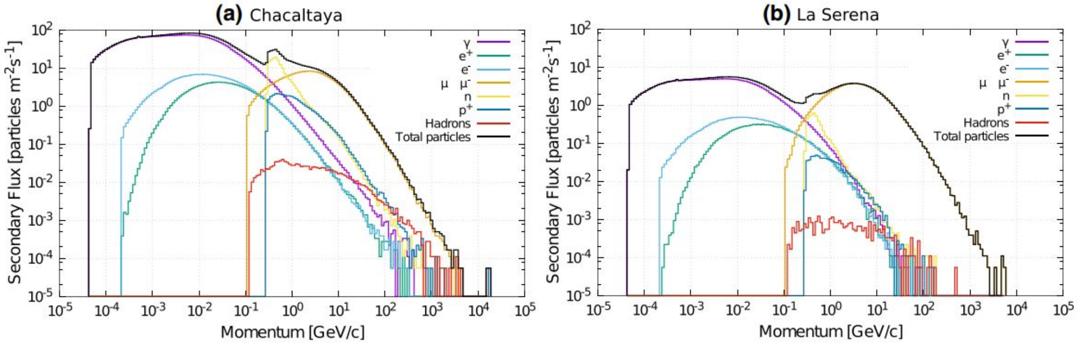


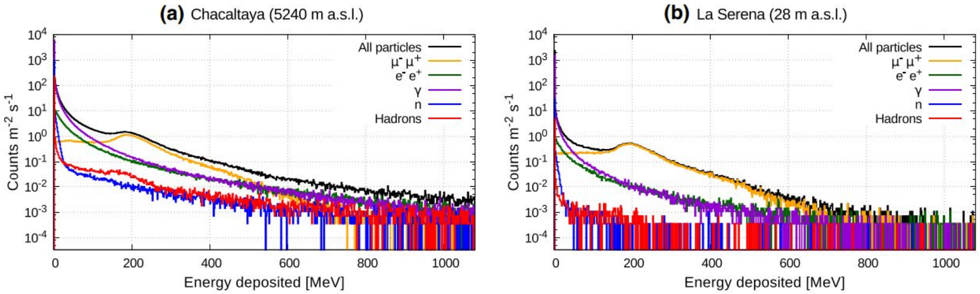
Secondary flux

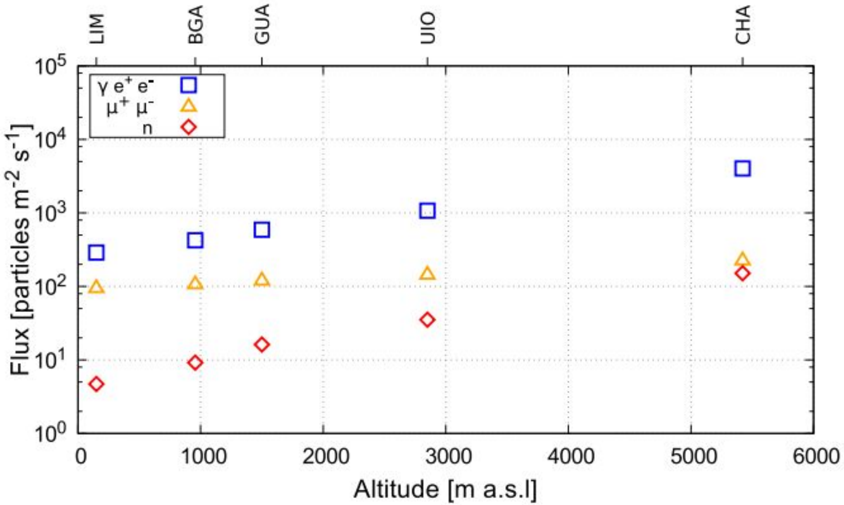
The flux of secondary particles depends on the observation altitude, the local geomagnetic field, and the atmospheric profile.

As a result, different sites will exhibit distinct background secondary spectra.

Therefore, the background flux of secondary particles is site-dependent and must be evaluated for each location individually.



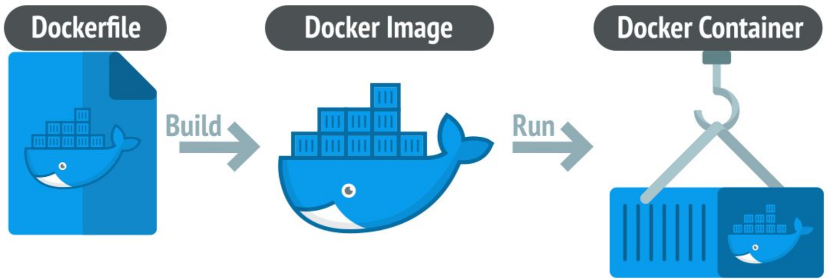




What is Docker?

- Runs software in a **container**
- A container is like a **small box** with all it needs
- Works the same on any computer
- Makes any program **portable and easy to share**

Docker allows ARTI to run the same everywhere, from laptops to clusters, without installing dependencies.



[Docker](#) [Docker Hub](#)

Create & Run Containers

- docker pull <image> — Download image from Docker Hub
- docker run -it --name <container> <image> — Run interactively
- docker run -dit --name <container> <image> — Run in detached mode

▶ Manage Containers

- docker ps — List running containers
- docker ps -a — List all containers
- docker start <id|name> — Start container
- docker stop <id|name> — Stop container
- docker restart <id|name> — Restart container
- docker rm <id|name> — Remove container
- docker container prune — Remove stopped containers

Interact with Containers

- docker exec -it <id|name> bash — Open Bash shell
- docker exec -it <id|name> <cmd> — Run command inside
- docker attach <id|name> — Attach to container

Copy Files

- docker cp file.txt <id|name>:/path — Host → Container
- docker cp <id|name>:/path/file.txt . — Container → Host

Images

- docker images — List local images
- docker rmi <id|name> — Remove image
- docker image prune — Remove unused images

Hands-on activity

To view the commands in plain text, check the `.txt` files in the repository

https://gitmilab.redclara.net/martinezr/lago_workshop_arti_meiga.git

```
## 1. Enable systemd in WSL2
sudo nano /etc/wsl.conf
#write
[boot]
systemd=true

# In PowerShell:
wsl --shutdown

## 2. Install dependencies and add official Docker repository
sudo apt-get update
sudo apt-get install -y ca-certificates curl gnupg
sudo install -m 0755 -d /etc/apt/keyrings

# Download and install Docker GPG key
curl -fsSL https://download.docker.com/linux/$(.
/etc/os-release; echo "$ID")/gpg \
  | sudo gpg --dearmor -o /etc/apt/keyrings/docker.gpg

# Set permissions for the GPG key
sudo chmod a+r /etc/apt/keyrings/docker.gpg

# Add Docker repository to sources list
echo "deb [arch=$(dpkg --print-architecture) \
signed-by=/etc/apt/keyrings/docker.gpg] \
https://download.docker.com/linux/$(. /etc/os-release; echo
"$ID") \
$(. /etc/os-release; echo "$VERSION_CODENAME") stable" \
  | sudo tee /etc/apt/sources.list.d/docker.list > /dev/null
```

```
## 3. Install Docker Engine and plugins
sudo apt-get update
sudo apt-get install -y docker-ce
docker-ce-cli containerd.io \
  docker-buildx-plugin
docker-compose-plugin

## 4. Post-installation steps OPTIONAL
# Add current user to the docker group
sudo usermod -aG docker $USER
# Apply the group change without
rebooting
newgrp docker
# Enable and start Docker service
sudo systemctl enable --now docker

## 5. Test Docker installation
docker --version
docker run hello-world
```

```
## 6. Pull ARTI

docker pull rmartinezmaple/arti_lidera:latest

## 5. run and mount it in a local folder

docker run -it --name arti_name_of_container -v
/local/path:/workspace --entrypoint bash
rmartinezmaple/arti_lidera:latest

# By example.

docker run -it --name arti_dev -v
/home/rafael/proyectos:/workspace --entrypoint
bash rmartinezmaple/arti_lidera:latest

## 7. go to /opt/arti/sim

./rain.pl -r ../../corsika/run/ -v 78010 -h QGSIII
-f fluka -s bga -m 1E5 -p 1 -q 0

## 8. go to /opt/corsika/run/nameoffoldermono and
run the bin analysis
```

arti/

- **analysis/** – analysis scripts
- **docs/** – documentation
- **eas/** – air-shower simulations
- **sims/** →
  - Main executables: **do_sims**, **rain.pl**

corsika/ – CORSIKA source code and resources

- Configuration files, licenses, and documentation
- Physics modules: **epos/**, **herwig/**, **pythia/**, **nexus/**, **urqmd/**
- Source code (**src/**), libraries (**lib/**)
- **run/** – scripts and executables to run simulations

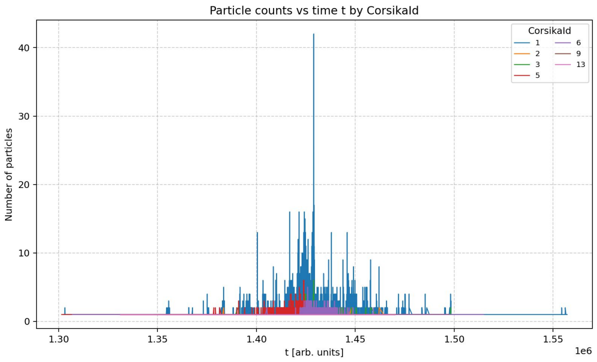
fluka/ – FLUKA code and data

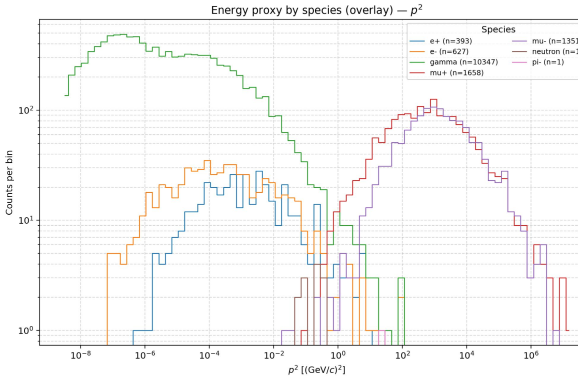
- Input files (`*.inp`), binaries, licenses, and manual
- Libraries and tools (**flutil/**, **gcrtools/**)
- Data and physics models (`*.grid`, `*.bin`, `*.dat`)

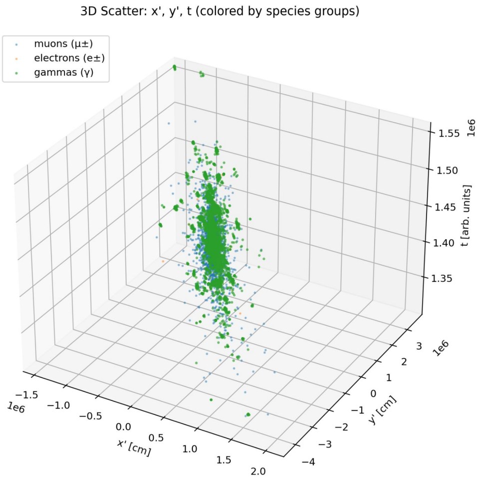
```
for i in DAT??????.bz2; do j=$(echo $i | sed -e 's/.bz2//'); u=$(echo $j | sed -e 's/DAT//'); bzip2 -d
-k $i; echo $j | ../../../arti/analysis/lagocrkread | ../../../arti/analysis/analysis -p -v $u; rm $j;
done
```

Output

```
# # # sec
# # This is the Secondaries file - ARTI     v1r9
# # 12 column format is:
# # CorsikaId px py pz x' y' t shower_id prm_id prm_energy prm_theta prm_phi
0001 -1.33713E-03 +1.46172E-03 +2.98208E-03 -7.76381E+03 -1.39895E+04 +5.30158E+05 00000001 0001 +1.00000E+05 +41.978 +124.105
0001 +3.32742E-05 +3.85560E-05 +1.06865E-04 +7.38943E+04 +5.89166E+04 +5.30866E+05 00000001 0001 +1.00000E+05 +41.978 +124.105
0001 -7.76306E-03 +1.51338E-02 +1.65510E-02 +6.14893E+04 +6.71568E+04 +5.31030E+05 00000001 0001 +1.00000E+05 +41.978 +124.105
0001 -3.28871E-04 +3.78274E-05 +7.49673E-04 +2.31580E+04 -1.11807E+05 +5.28303E+05 00000001 0001 +1.00000E+05 +41.978 +124.105
0001 -6.30307E-03 +8.50501E-03 +1.17131E-02 -9.25848E+03 -9.97871E+03 +5.30212E+05 00000001 0001 +1.00000E+05 +41.978 +124.105
0001 -6.06957E-04 +1.82243E-03 +2.93813E-03 +1.91960E+04 -3.13733E+03 +5.30077E+05 00000001 0001 +1.00000E+05 +41.978 +124.105
```





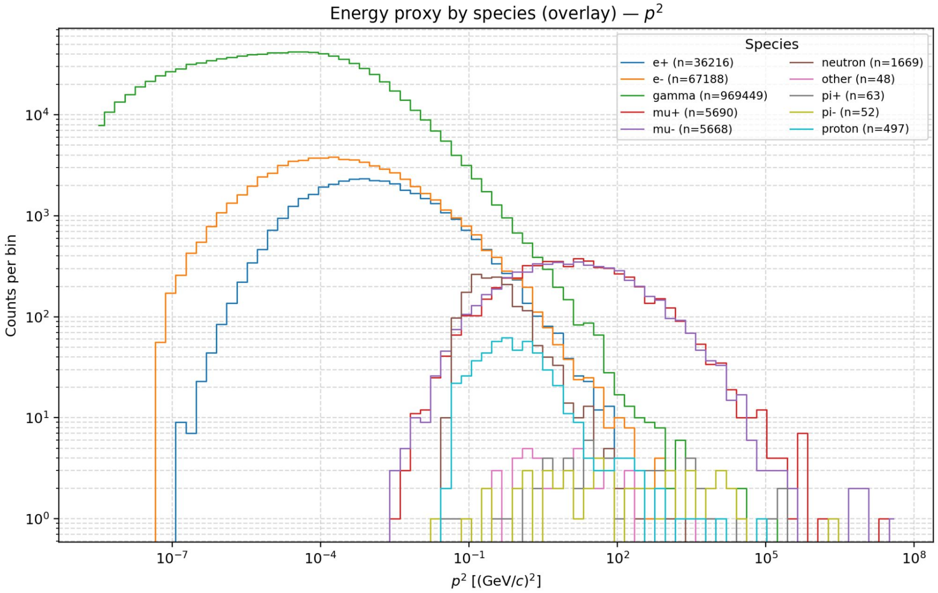


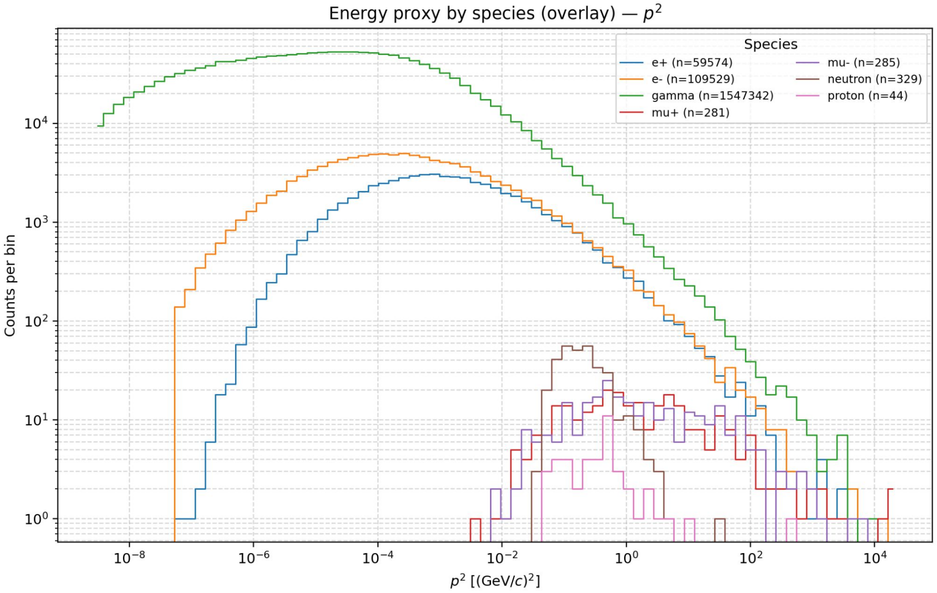
Models of analysis: https://github.com/rmartinezra/LAGOworkshopARTI_MEIGA.git

Choose another particle, inject it, and repeat the analysis. Save the plots in the mounted folder, or share the data file to work locally.

Particle identifications			
Identification	Particle	Identification	Particle
1	γ	50	ω
2	e^+	51	ρ°
3	e^-	52	ρ^+
		53	ρ^-
5	μ^+	54	Δ^{++}
6	μ^-	55	Δ^+
7	π°	56	Δ°
8	π^+	57	Δ^-
9	π^-	58	$\overline{\Delta}^{--}$
10	K_L°	59	$\overline{\Delta}^-$
11	K^+	60	$\overline{\Delta}^\circ$
12	K^-	61	$\overline{\Delta}^+$
13	n	62	$K^{*\circ}$
14	p	63	K^{*+}
15	$\overline{p}$	64	$\overline{K^*}^-$
A × 100 + Z	nucleus of Z protons and A − Z neutrons ($2 \leq A \leq 56$)		

proton 1E6 GeV vs gamma 1E6 GeV





do_sims.sh

```
./do_sims.sh version v1r9

USAGE ./do_sims.sh:

Simulation parameters
  -w <working dir>                   : Working directory, where bin (run) files are located
  -p <project name>                  : Project name (suggested format: NAMEXX)
  -v <CORSIKA version>               : CORSIKA version
  -h <HE Int Model (EPOS|QGSII)>     : Define the high energy interaction model to be used. Default: QGSJET-II-04
  -f <LE Int Model (gheisha|fluka)>  : Define the lown energy interaction model to be used. Default: gheisha
  -u <user name>                     : User Name.
  -j <procs>                         : Number of processors to use

Physical parameters
  -t <flux time>                     : Flux time (in seconds) for simulations
  -m <Low edge zenith angle>         : Low edge of zenith angle.
  -n <High edge zenith angle>        : High edge of zenith angle.
  -r <Low primary particle energy>   : Lower limit of the primary particle energy.
  -i <Upper primary particle energy> : Upper limit of the primary particle energy.
  -a <high energy ecuts>             : High energy cuts for ECUTS; (if set value in GV = enabled).
  -y                                 : Select volumetric detector mode (default=flat array)

Site parameters
  -s <site>                          : Location (several options)
  -k <altitude, in cm>               : Fix altitude, even for predefined sites
  -c <atm_model>                     : Fix Atmospheric Model even for predefined sites.
  -o <BX>                            : Horizontal comp. of the Earth's mag. field.
  -q <BZ>                            : Vertical comp. of the Earth's mag. field.
  -b <rigidity cutoff>               : Rigidity cutoff; (if set value in GV = enabled, <0 = disable).
  -g <Lat, Lon> *dev                 : Obtain the current values of BX and BZ for a site located at (Lat,Lon,Alt),
en (Lat,Lon,Alt) will be taken from the standard characterization of the site.
```

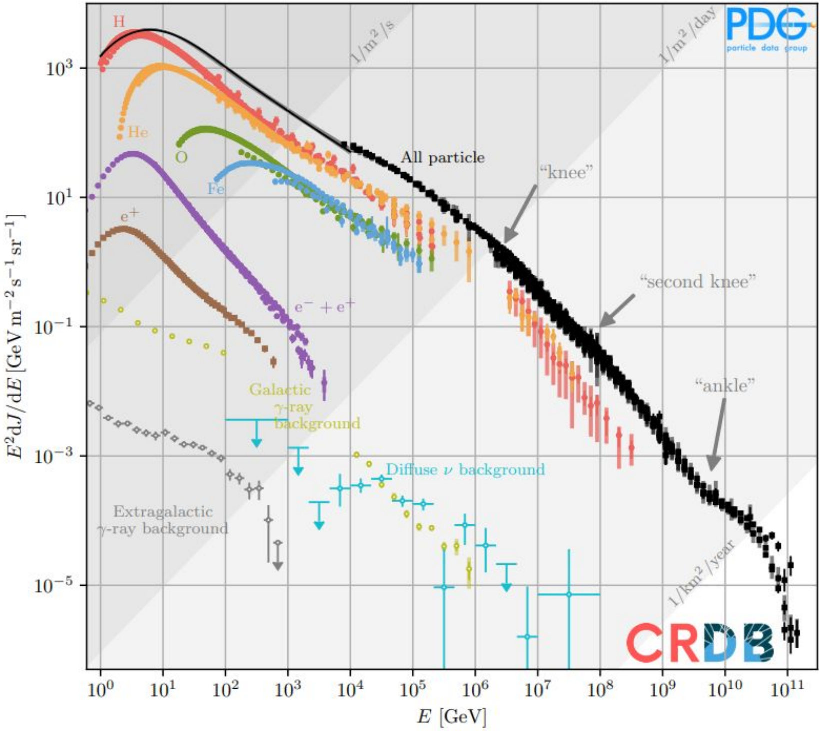
Example for 15 s in Bucaramanga

```
./do_sims.sh -w ../../corsika/run/ -p pruebacampinas -v 78010 -h QGSIII -f fluka -u username -t 15 -s bga
```

```
INFO: bga parameters were obtained from the LAGO DMP

Flux time: 15 s (39132 showers, 5<E<1000000, 0<q<90 at site bga (h=950, atm=E1)
igidity cutoff.

A Z X N_prim E_min
----------------------------
0 1 H 35145 5.08727376361682
4 2 He 3537 10.6741812099781
12 6 C 91 32.0150800892802
16 8 O 88 42.684424943156
7 3 Li 35 16.3616427647163
11 5 B 24 27.0210369889867
28 14 Si 21 74.6918968673335
24 12 Mg 20 64.0227258144722
14 7 N 18 37.3520267580472
56 26 Fe 17 140.047185693648
20 10 Ne 16 53.3535942296987
55 25 Mn 15 135.064155532052
52 24 Cr 14 129.381128178879
51 23 V 13 124.4008543988
48 22 Ti 12 118.715949234128
45 21 Sc 11 113.036737093726
9 4 Be 10 21.6901846959085
40 20 Ca 9 106.700044763755
39 19 K 8 101.693104050173
40 18 Ar 7 97.3891143907054
35 17 Cl 6 91.024243496356
32 16 S 5 85.3611547579485
31 15 P 4 80.3556598219191
27 13 Al 3 69.6873929930859
23 11 Na 2 59.0195164152307
19 9 F 1 48.3521776179461
```



Spectrum (CRs). [Navas et al.(2024)] PDG

9. Go to /opt/corsika/run/ where the corsica bins are located and you will see

```
root@0c7dfaf47689:/opt/corsika/run# ls
EGSDAT6_.05        all-inputs-cerenkov  atmprof5.dat                      dpmjpar.dat                        go-pruebacampinas_000015-pr-6.sh
EGSDAT6_.15        all-inputs-epos      atmprof6.dat                      glaubint.glb                       go-pruebacampinas_000015-pr-7.sh
EGSDAT6_.25        all-inputs-inclined  atmprof9.dat                      glaubtar.glb                       go-pruebacampinas_000015-pr-8.sh
EGSDAT6_.4         all-inputs-mthin     atmprof99.dat                     go-pruebacampinas_000015-all-01.sh gr3.txt
EGSDAT6_1.         all-inputs-nexus     conex-3D-inputs                   go-pruebacampinas_000015-all-02.sh mirreff.dat
EGSDAT6_3.         all-inputs-st        conex-epos-inputs                 go-pruebacampinas_000015-all-03.sh monobga
Makefile           all-inputs-stackin   corsika78010Linux_DPMJET_urqmd    go-pruebacampinas_000015-all-04.sh parallel-inputs
Makefile.am        all-inputs-thin      corsika78010Linux_EPOS_fluka      go-pruebacampinas_000015-all-05.sh pruebacampinas_000015
Makefile.in        atmabs.dat           corsika78010Linux_EPOS_fluka_thin go-pruebacampinas_000015-all-06.sh qgsdat-II-04.bz2
NUCNUCCS           atmo.c               corsika78010Linux_QGSIII_fluka    go-pruebacampinas_000015-he.sh     qgsdat-III
QGSDAT01           atmo.h               corsika78010Linux_QGSIII_fluka_thin go-pruebacampinas_000015-pr-1.sh quanteff.dat
SECTNU             atmprof1.dat         corsika78010Linux_SIBYLL_fluka    go-pruebacampinas_000015-pr-2.sh   rain.pl
UrQMD-1.3.1-xs.dat atmprof2.dat         corsika78010Linux_SIBYLL_fluka_thin go-pruebacampinas_000015-pr-3.sh runner.sh
VENUSDAT           atmprof3.dat         dataCardPrueba                    go-pruebacampinas_000015-pr-4.sh   sectnu-II-04
all-inputs         atmprof4.dat         dpmCT14LL.pds                     go-pruebacampinas_000015-pr-5.sh   sectnu-III
```

10. You have to execute all the .sh files, you can do it manually or use [runner.sh]

./runner.sh &> Cache &

runner.sh must be tuned to your PC cores. On clusters, use more aggressive settings. It runs files in groups and waits for them to finish.

NOW...

Wait…

Just wait until the simulation finishes. You can check progress using `htop` or `top`.

Script: Loop over all compressed .lst files, print filename and last line of each (quick check of simulation results)

```bash
#!/bin/bash

for file in DAT*.lst.bz2; do
  echo -n "$file: "
  bzcat "$file" | tail -n 1
done
~
```

Command: Decompress secondary particle files and analyze them with "showers" tool

```bash
bzcat *sec.bz2 | ../../../arti/analysis/showers -a 10 -d 10 -c 956. -n 1 1 -v salida
```

`salida_apx.dst` → Lateral distribution of secondaries at ground level

`salida_apx.hst` → Energy distribution of secondaries

`salida_apx.dse` → Energy distribution of secondaries as a function of distance

Simulating any site

I need the altitude, atmospheric model, and components of your magnetic field.

```
./do_sims.sh -w ../../corsika/run/ -p pruebacampinas -v 78010 -h QGSIII -f fluka
-u username -t 15 -k altitud_cm -c Atm_Model -o B_hor -q B_ver
```

https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm

Magnetic Field X

Model Used:	IGRF2025
Latitude:	22° 49' 27" S
Longitude:	47° 4' 0" W
Elevation:	680.0 km Mean Sea Level

Date	Declination (+ E | - W)	Inclination (+ D | - U)	Horizontal Intensity	North Comp (+ N | - S)	East Comp (+ E | - W)	Vertical Comp (+ D | - U)	Total Field
2025-08-18	-18° 5' 19"	-36° 44' 2"	13,966.5 nT	13,276.2 nT	-4,336.4 nT	-10,423.1 nT	17,427.1 nT
Change/year	-0° 2' 25"/yr	-0° 17' 23"/yr	[illegible]3.1 nT/[illegible]	-63.0 nT/yr	10.3 nT/yr	[illegible]62.9 nT/yr	-13.0 nT/yr

Choose another location in Brazil and repeat the analysis. If you want, you can save the data here to share it with the group and make comparisons

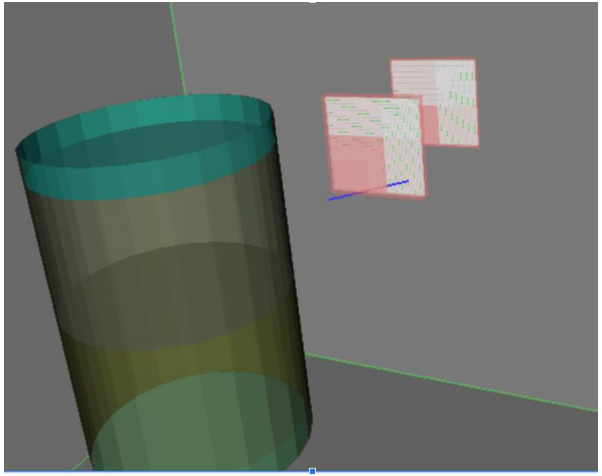
What is MEIGA

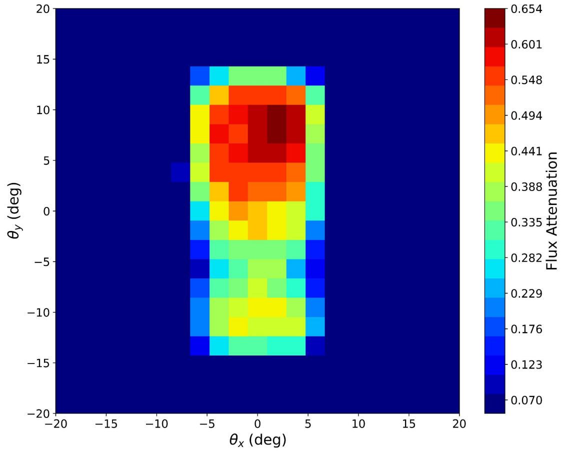
What is it?
MEIGA is a framework based on C++ classes. It combines three elements:

- Cosmic-ray flux calculation
- Particle propagation
- Detector response simulation

How does it work?

- Uses **JSON configuration files** (input/output paths, detector setup, physics lists, verbosity).
- Runs **Geant4 simulations**, injecting particles at ground level.
- Tracks particles inside the detector geometry defined by XML files.
- Collects detector response (energy deposits, SiPM signals, time traces).



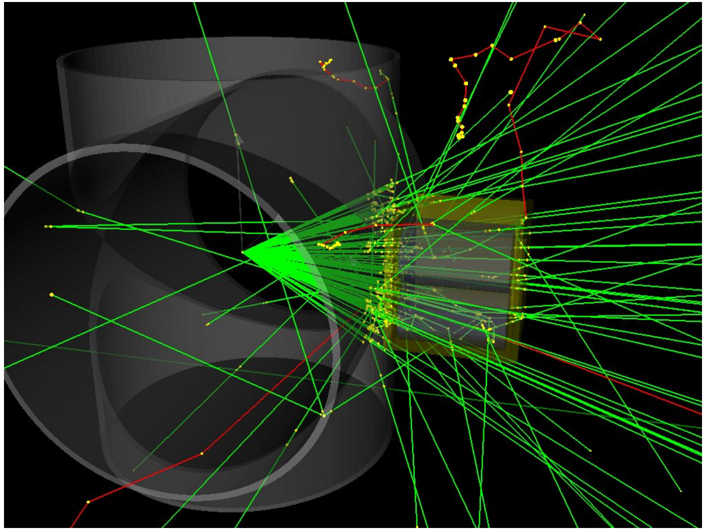


The core of MEIGA is GEANT4

- Toolkit to simulate **particle interactions with matter**.
- Uses databases, cross-sections, and physics models.
- Widely used in **HEP, medical physics, and space science**.

Key Features

- **Physics List**
  - Define particles
  - Define processes
- **Detector Construction**
  - Define materials
  - Build geometry
  - Set sensitive regions
- **User Action Classes**
  - Generate primary particles
  - Extract data (energy, tracks, steps)



Hands-on activity

```
## 1. Pull MEIGA

docker pull rmartinezmaple/meiga_lidera:1.0

## 2. run and mount it in a local folder

docker run -it --name meiga_name_of_container -v /local/path:/workspace --entrypoint bash rmartinezmaple/meiga_lidera:1.0

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docker run -it --name meiga_name_of_container -v /local/path:/workspace --entrypoint bash rmartinezmaple/meiga_lidera:1.0

## 3. go to /opt/meiga/build/Applications/G4WCDsimulator

./G4WCDSimulator -c G4WCDSimulator.json

## 4. decompress de output with gunzip

gunzip output.json.gz

## scrips of analysis /opt/meiga/src/Analysis
```

Directory Structure

GEANT4

`src and build`

ROOT

`src and build`

MEIGA

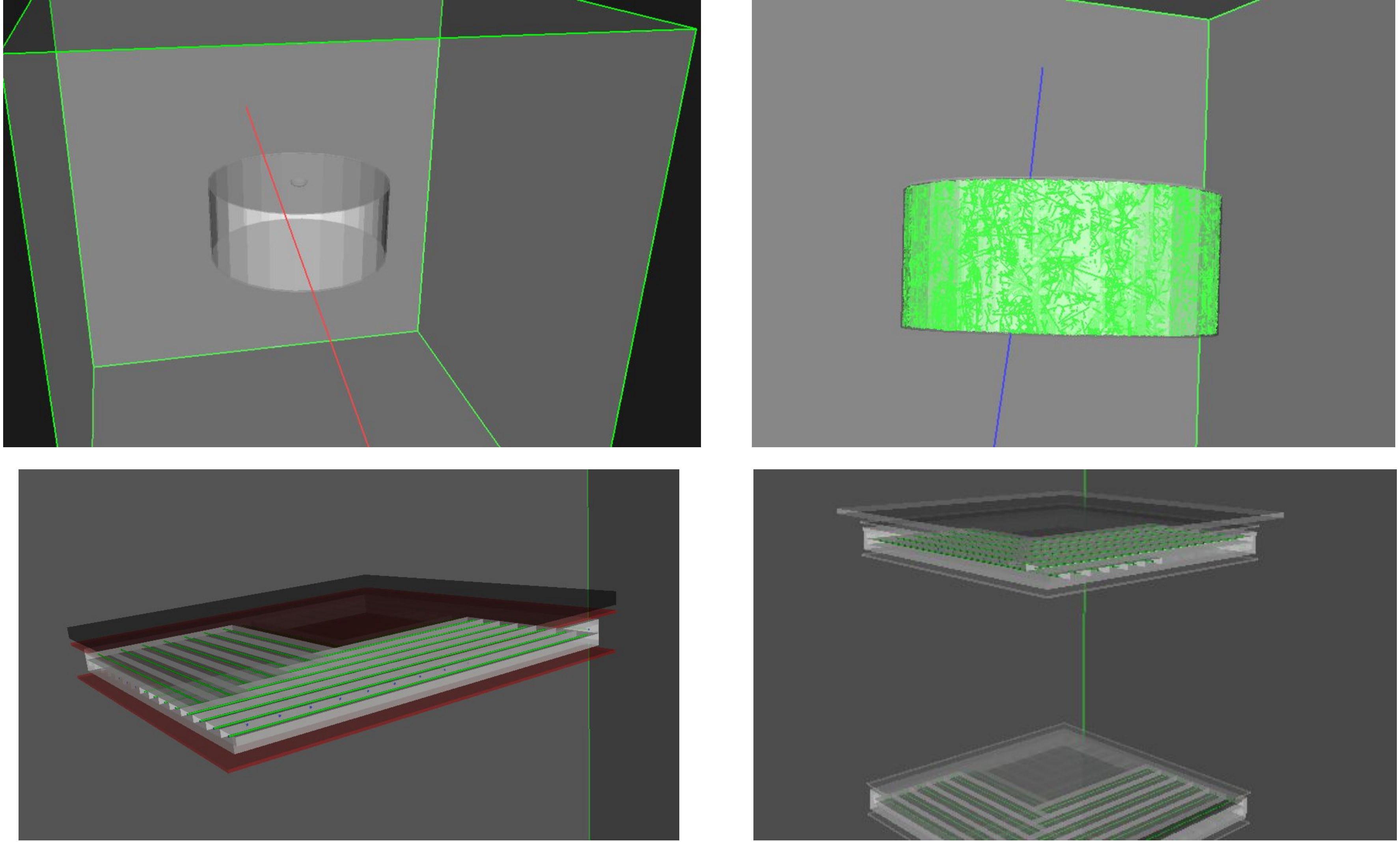
`build/` → compiled modules (Applications, Framework, IO, Utilities, G4Models)
`install/` → final bin, include, lib
`src/` → main source code:

- Applications (simulations)
- Framework (base classes)
- G4Models (Geant4 links)
- Analysis (data routines)
- IO, Utilities, Documentation

Before the analysis, let see the simulation

```
{
        "Input" :
        {
                "Mode" : "UseEcoMug",
                "InputFileName" : "../../../src/Documentation/SampleFlux/salida_bga_30.shw",
                "InputNParticles" : 1
        },
        {
                "SimulationMode" : "eFast",
                "GeoVisOn" : true,
                "TrajVisOn" : true,
                "CheckOverlaps" : false,
                "Verbosity" : 1,
                "RenderFile" : "VRML2FILE",
                "PhysicsName" : "QGSP_BERT_HP"
        }
}
```

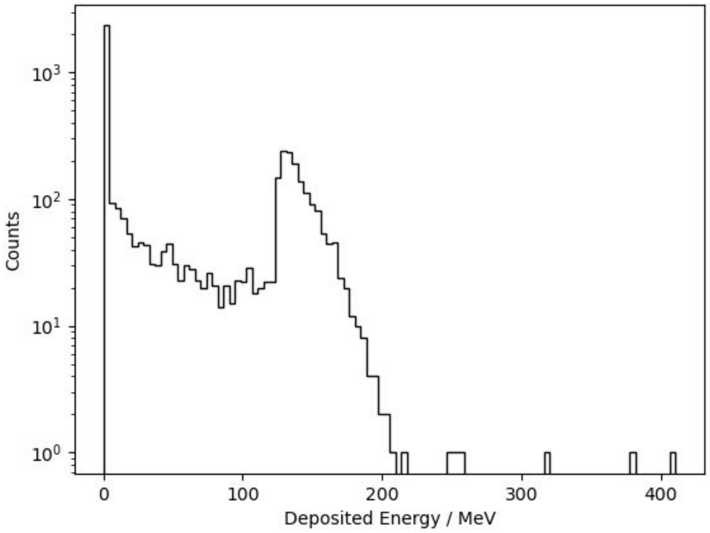
sudo apt install view3dscene # Program for see the g4_##.wrl file with de 3d file

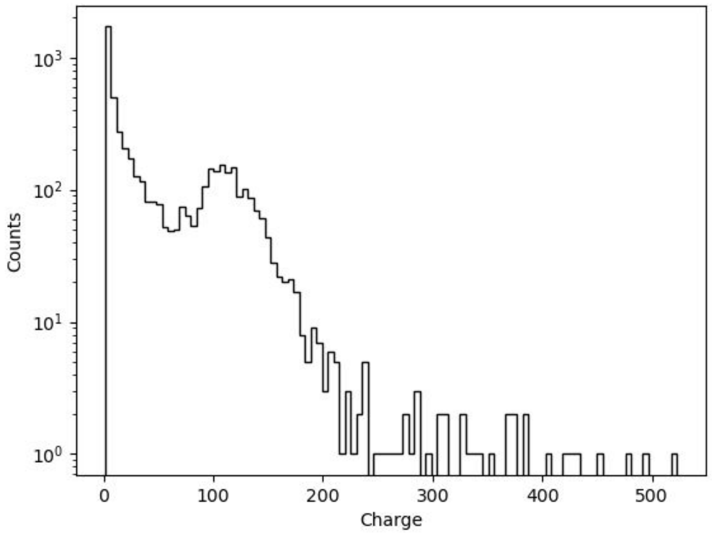


The analysis files are in: /opt/meiga/src/Analysis

Copy <u>G4WCDSimulator_Analysis.py</u> <u>SimDataReader.py</u> <u>output.json</u> in your local system a run the analysis with:

```
python3 G4WCDSimulator_Analysis.py -f output.json
```





Change the detector properties

Open DetectorList.xml

```xml
<detector id="0" type="eWCD">
        <x unit="cm"> 0.0 </x>
        <y unit="cm"> 0.0 </y>
        <z unit="cm"> 0.0 </z>
        <tankRadius unit="cm"> 40 </tankRadius>
        <tankHeight unit="cm"> 250 </tankHeight>
        <tankThickness unit="mm"> 15 </tankThickness>
        <impuritiesFraction> 0.0 </impuritiesFraction>
 </detector>
```

Run again and look the .wrl file

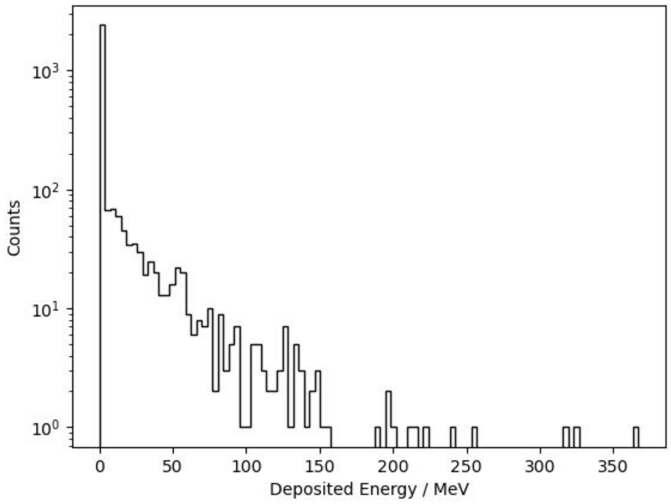
Change the injection mode to ARTI and run the simulation and do the analysis. **"DON'T FORGET TO TURN OFF THE VISUALIZATION"**

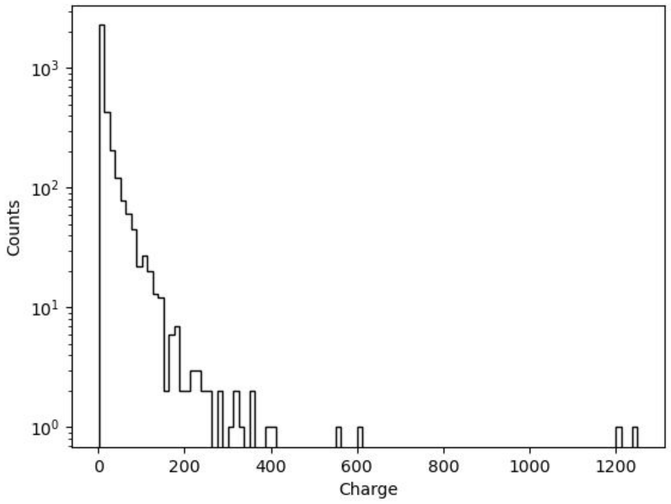
Change the detector properties

Now, copy and paste in your container the file [mufilter.sh]() in the repository

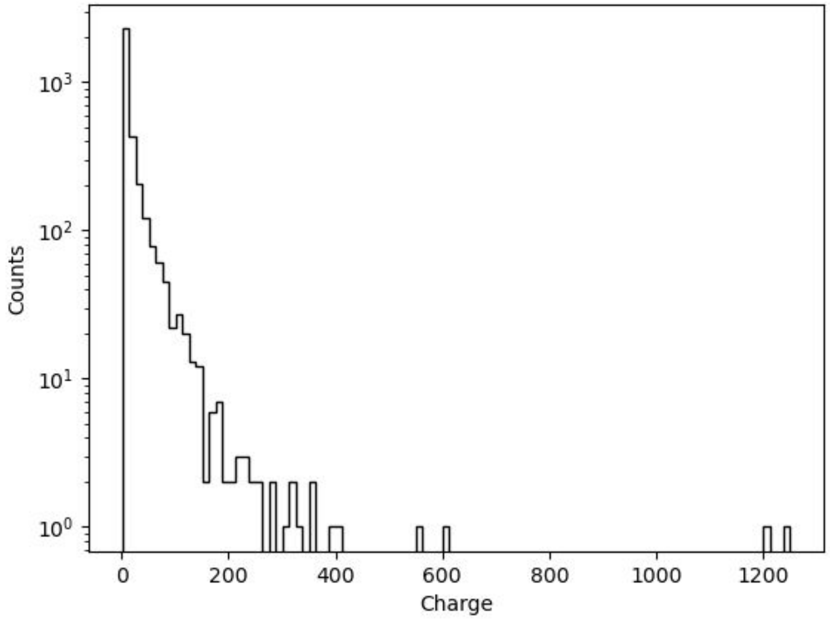
```
./filter_ids.sh salida_bga_30.shw filtered.shw
```

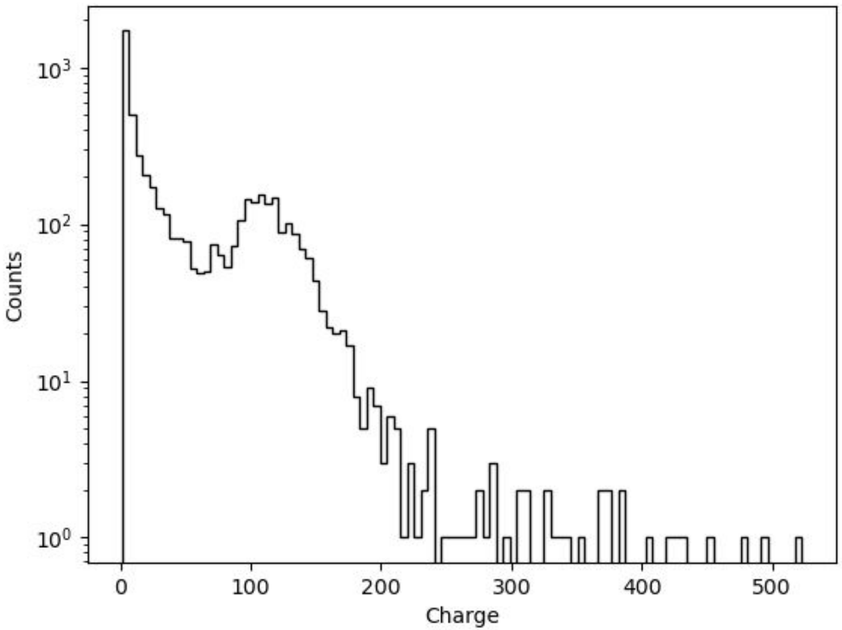
Change path the file of injection in the .json and run the simulation and do the analysis.





EM signal vs muons signal





Backup

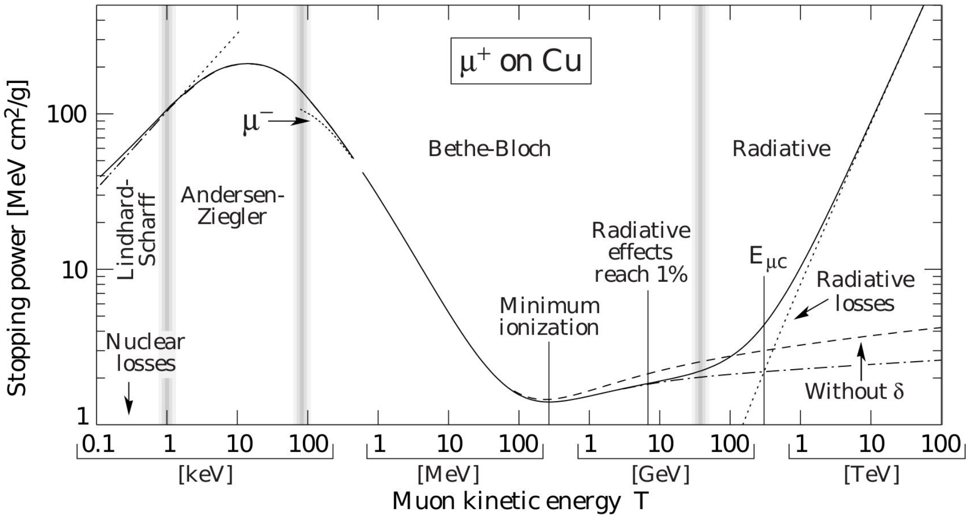
Stopping power

Mechanisms:

- Pair production
- Bremsstrahlung radiation
- Inelastic collisions with nuclei
- Ionization

The energy loss depends on:

- Muon kinetic energy
- Material density



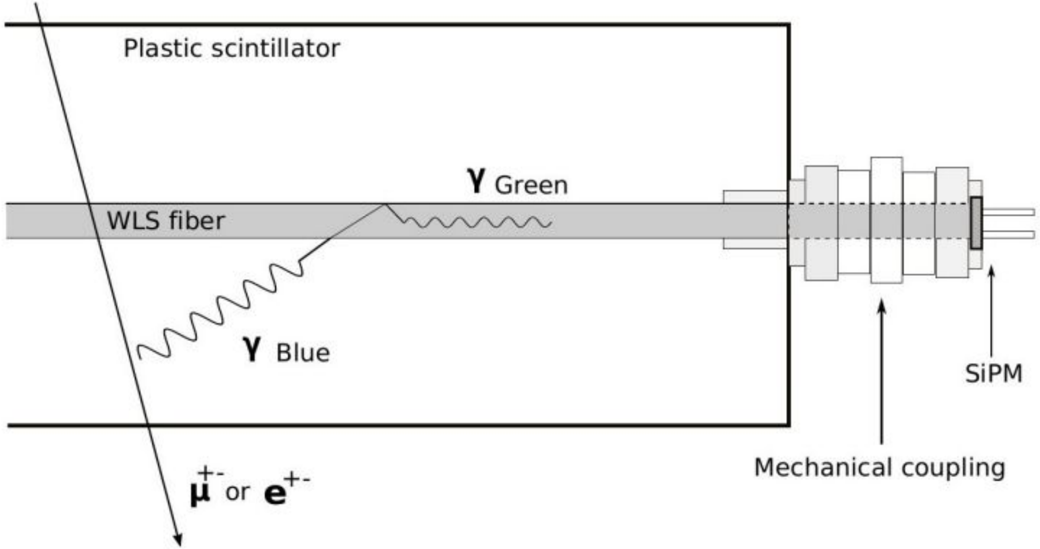
$$\frac{-dE}{d\varrho} = a(E) + b(E)E$$

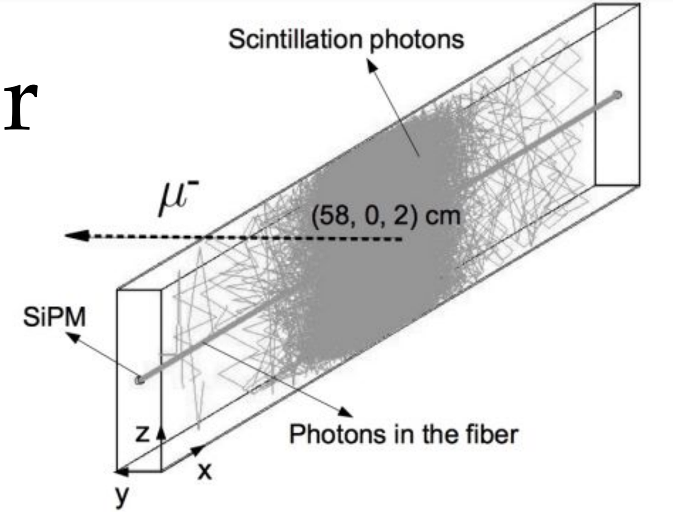
$$P(E_\mu, v)_{br}dv = \alpha\frac{N_A}{A}Z^2r_e^2\left(\frac{m_e}{m_\mu}\right)^2\frac{16}{3}\left(\frac{3v}{4} + \frac{(1-v)}{v}\right)dv\cdot$$
$$\left[\ln\left(\frac{12}{5}\frac{(1-v)}{v}\frac{E_\mu}{m_\mu Z^{1/3}}\right) - \frac{1}{2}\right],$$

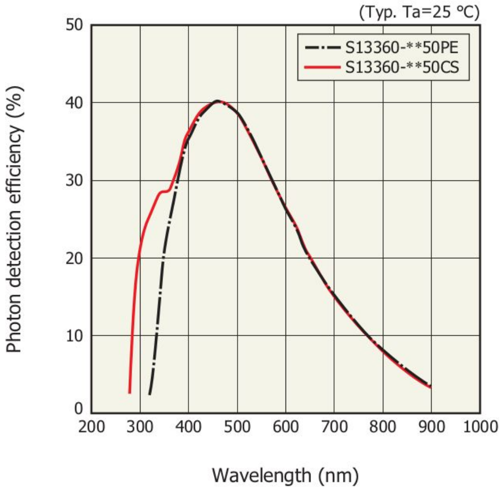
$$b(E)E < 10^{-2}a(E) \longrightarrow \quad E < \ 100GeV$$

$$\frac{d\sigma}{dvd\rho} = 2\frac{(Z\alpha r_e)^2}{3\pi}\left(\frac{1-v}{v}\right)\left[\Phi_e(E_\mu,\rho,v) + \left(\frac{m_e}{m_\mu}\right)^2\Phi_\mu(E_\mu,\rho,v)\right]$$

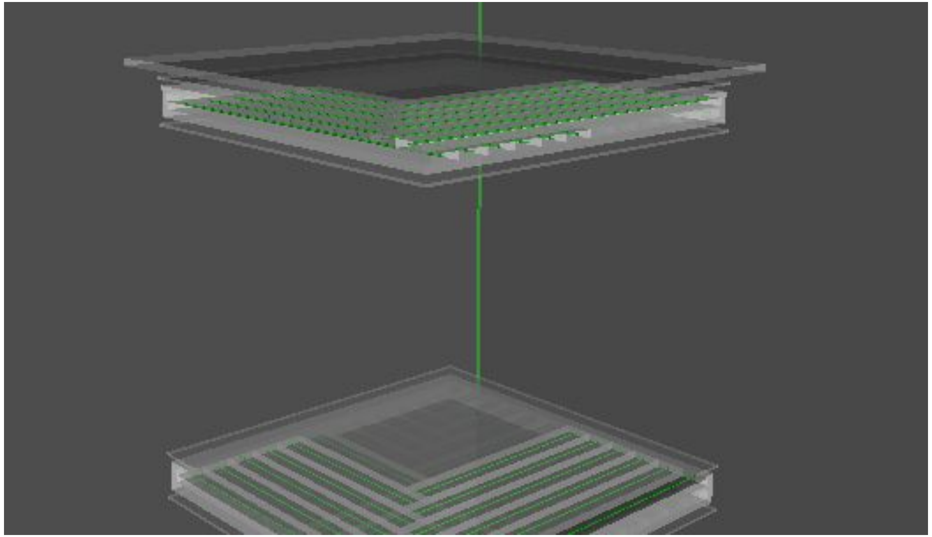
Detection in a scintillator







Detector Modeling



- Scintillator bars in an **N×N array**, arranged in two perpendicular panels.
- **Bar dimensions**: width, length, and thickness adjusted to the simulation.
- **External case**: protects and changes the optical behavior of emitted light.

Optical Properties of the Scintillator

- **Photon energy**: from 2.00 eV to 4.20 eV.
- **Refraction index**: constant, 1.5.
- **Absorption length**: from 4 cm to 24 cm, depending on the energy.
- **Fast and slow components**: simulation of time response.

Optical Fibers and Detection

- **Photon transport**: PMMA optical fibers with refraction index 1.60.
- **Optical detection**: photomultipliers with quantum efficiency modeled.

Reflection and Dispersion

- **Surface roughness**: controls photon dispersion.
- **Specular reflection**: 20% of light reflected in a lobe, not exact specular reflection.

Cherenkov Tank