

cfluxim cosmic ray simulation tool

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Contents

- 1 General information
- 2 Cosmic ray flux – definition
- 3 Simulation design
 - CuboidGenerator
 - TrackAnalyzer.cpp
 - FluxAnalyzer.cpp and quality check
- 4 Example simulation results
- 5 Code description
 - Project class structure
 - Description of selected classes
 - License

General information

About cfluxim

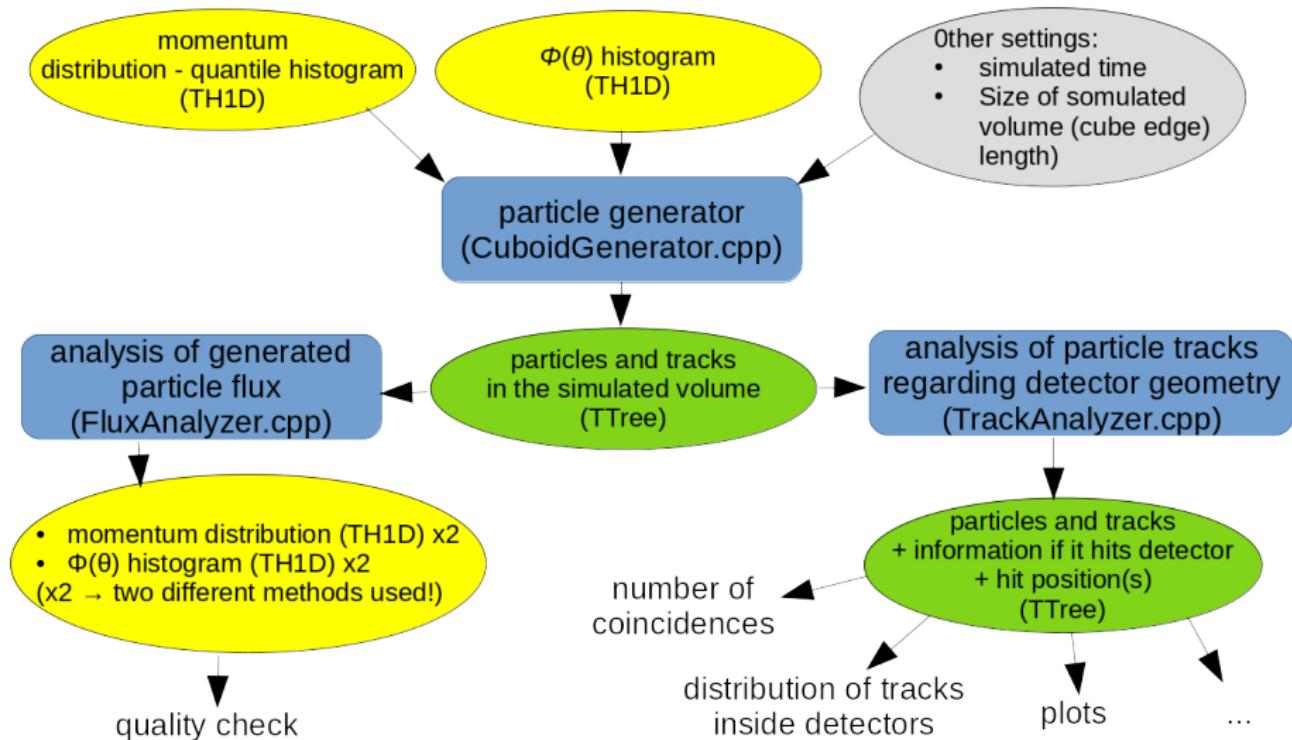
The `cfluxim` project was created to make a simple geometrical simulation of cosmic muons passing through some modules of the MPD detector ([NICA MPD website](#)).

- Cosmic muons are generated inside the given cubic volume.
- $\Phi(\theta)$ and momentum distribution of the simulated flux fits the experimental data with good accuracy.
- For every generated particle, it is checked if it hits the defined detector modules, and the hit position is saved.
- Any energy cutoff can be applied.

General notes

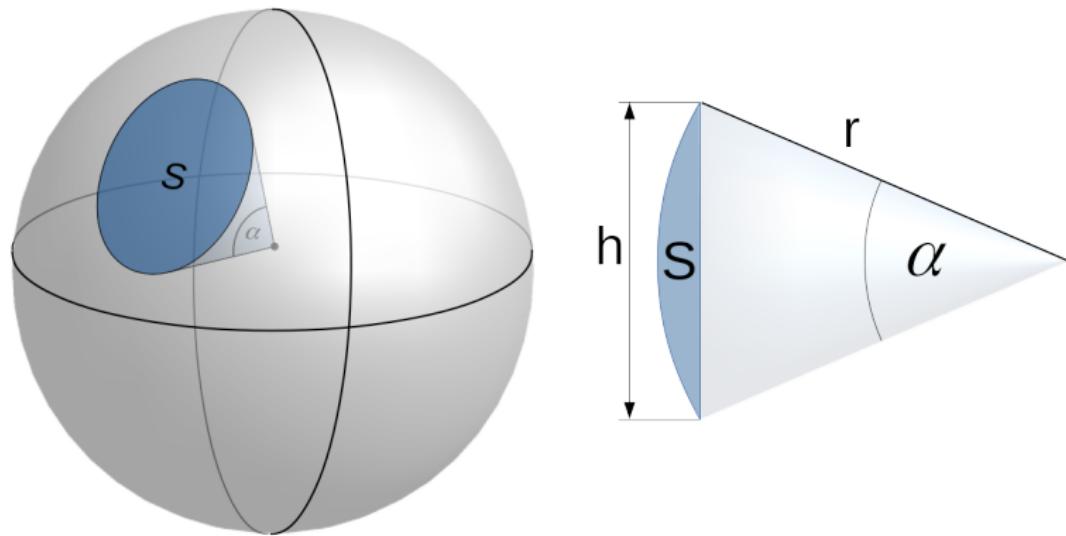
- `cfluxim` uses CERN's ROOT libraries.
- `cfluxim` consists of 3 tools: `CuboidGenerator`, `FluxAnalyzer` and `TrackAnalyzer`.
- Only muons at ground level are implemented, however, implementation of other cosmic ray components is possible.
- `FluxAnalyzer` generates momentum distribution and $\Phi(\theta)$ normalized histogram, so it can be compared with the experimental data as a simple quality check.
- `TrackAnalyzer` does the simple geometrical analysis of the tracks, regarding the defined detector geometry. It does not run the full physical analysis as Geant4 does.
- Generated cosmic muons can be, however, put into the Geant4 simulation.

Project scheme



Basic definitions

Solid angle

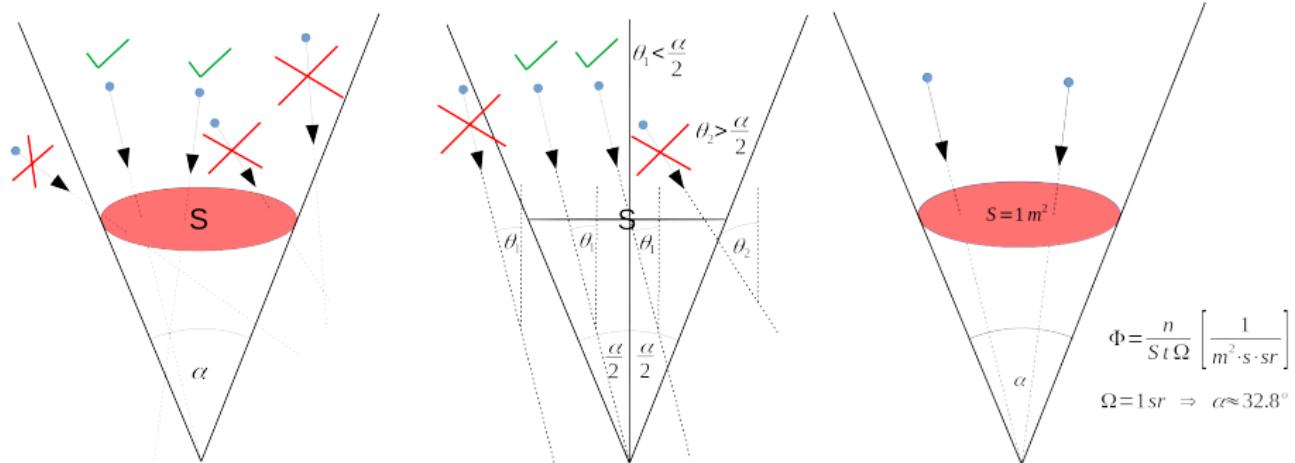


$$\text{area: } S = 2\pi r h = 2\pi r^2(1 - \cos\alpha)$$

$$\text{solid angle: } \Omega = \frac{S}{r^2} = 2\pi(1 - \cos\alpha) \text{ [sr]}$$

Cosmic ray flux

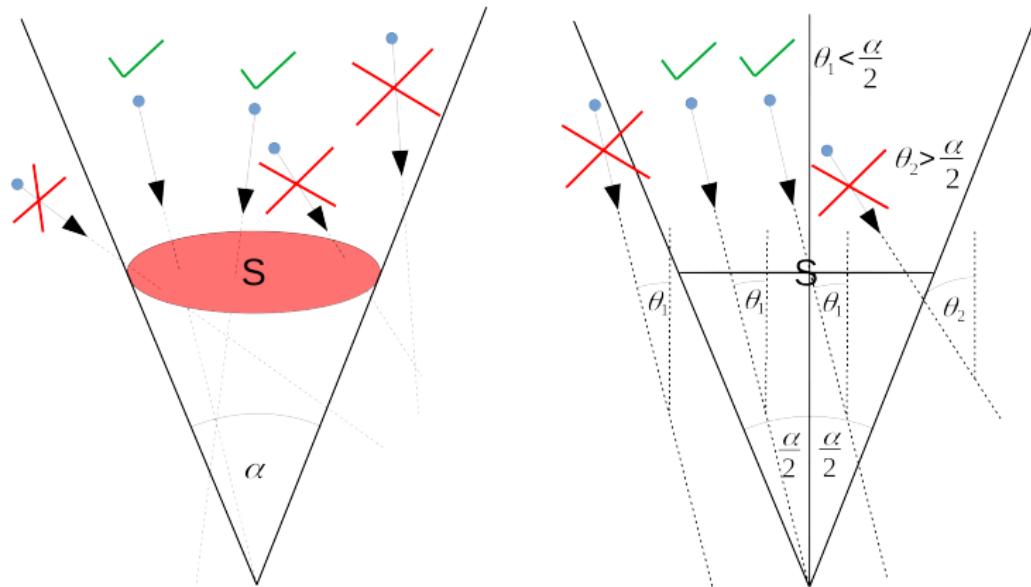
Cosmic ray flux = number of particles that come from unit solid angle, passing through unit area, per unit of time



particles coming from a given solid angle
passing through area S

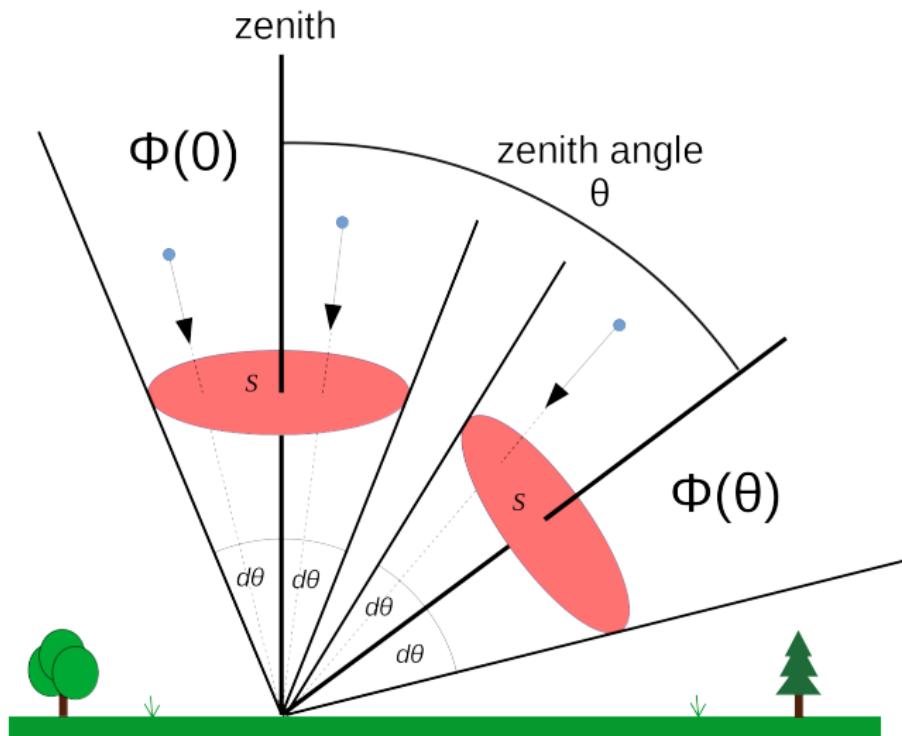
standard normalization

Cosmic ray flux

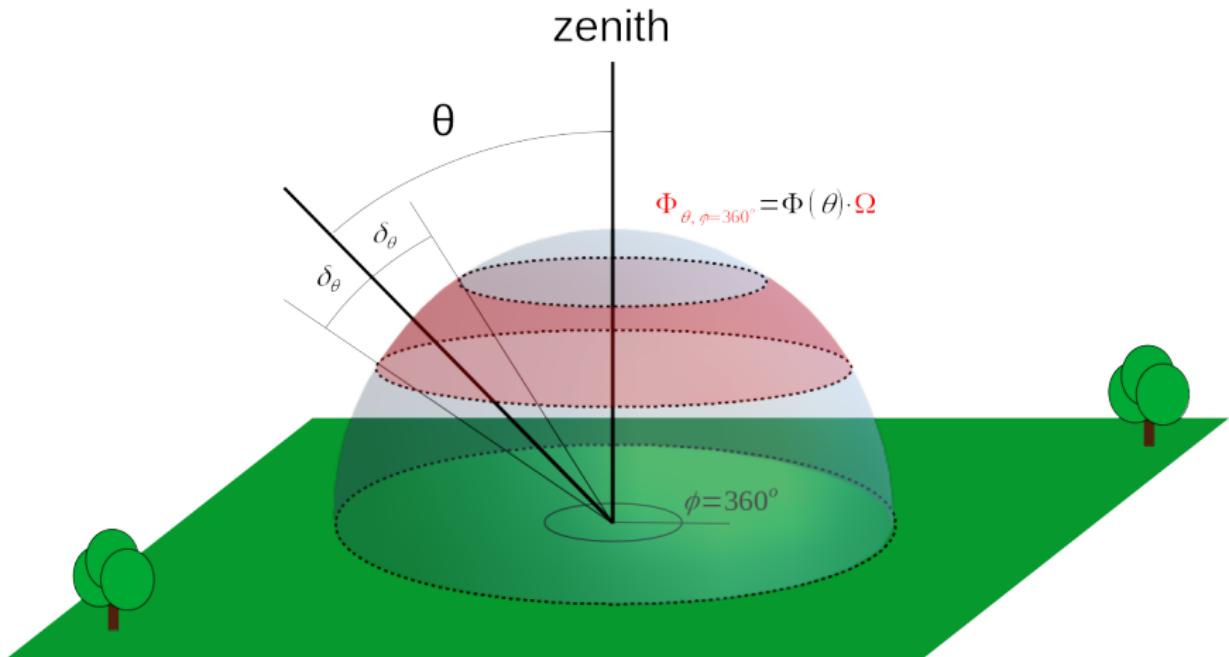


Solid angle limits the *direction* of incoming particle momentum, but not the position on the ‘probing area’ S . To count a particle as coming from the given solid angle, momentum angular limitations must be fulfilled and the particle must hit the probing area.

Cosmic ray flux dependant on zenith angle



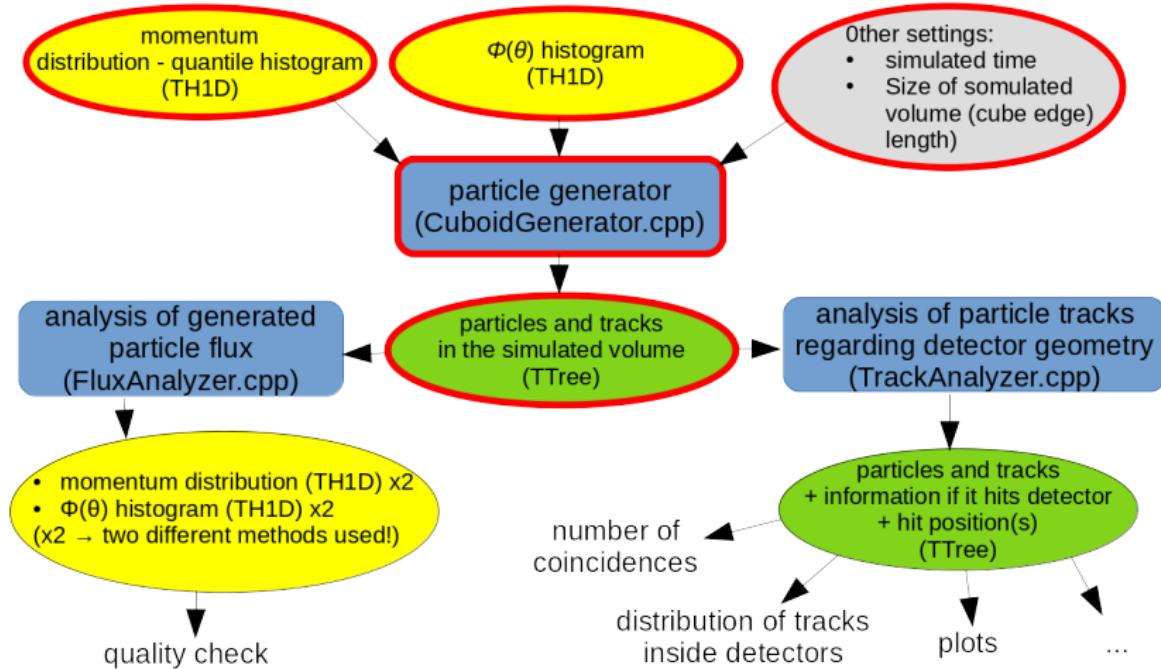
Cosmic ray flux dependant on zenith angle – full azimuth angle case



$$\Omega = 2\pi(\cos(\theta - \delta_\theta) - \cos(\theta + \delta_\theta))$$

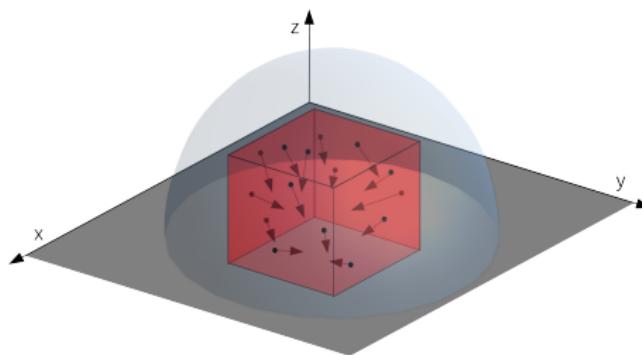
Simulation design

CuboidGenerator



CuboidGenerator – the idea

The idea: generation of particles and its momenta, coming from half-sphere ($\Omega = 2\pi$), that would pass through a cubic volume.



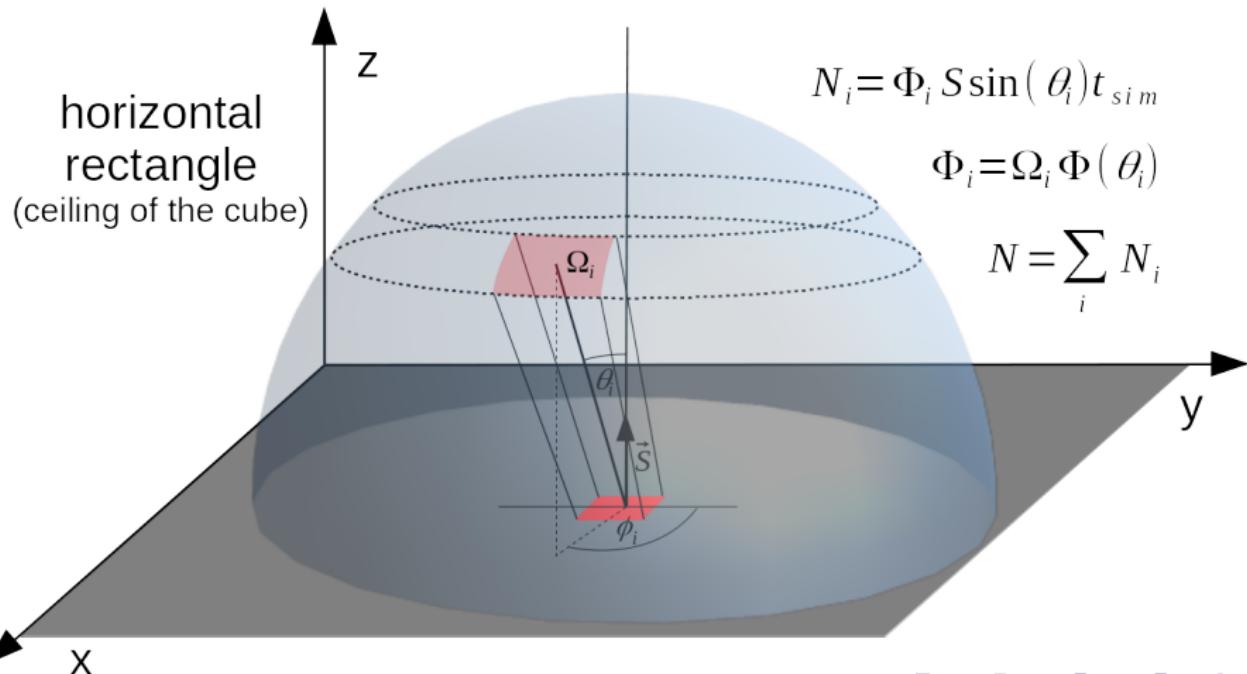
Particle's 'initial' position on the cube wall and its momentum vector define the track inside the cube!

Key problems:

- $\Phi(\theta)$ of generated particles must reproduce the experimental data with sufficient accuracy.
- Same for momentum distribution.

Horizontal area problem

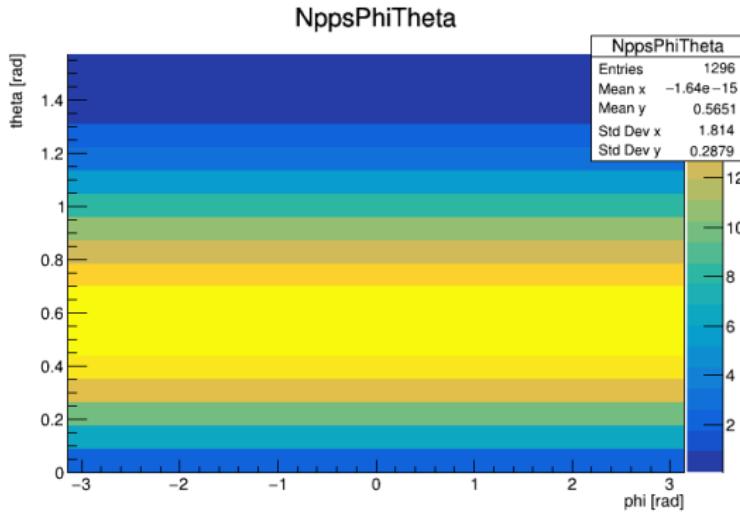
- ① 2π solid angle is divided into small Ω_i ; solid angles
 - ② for each Ω_i : the number of incoming particles from this Ω_i in simulated time t_{sim} is calculated – N_i



Horizontal area problem

Number of incoming particles from Ω_i per second can be mapped, regarding θ_i and ϕ_i :

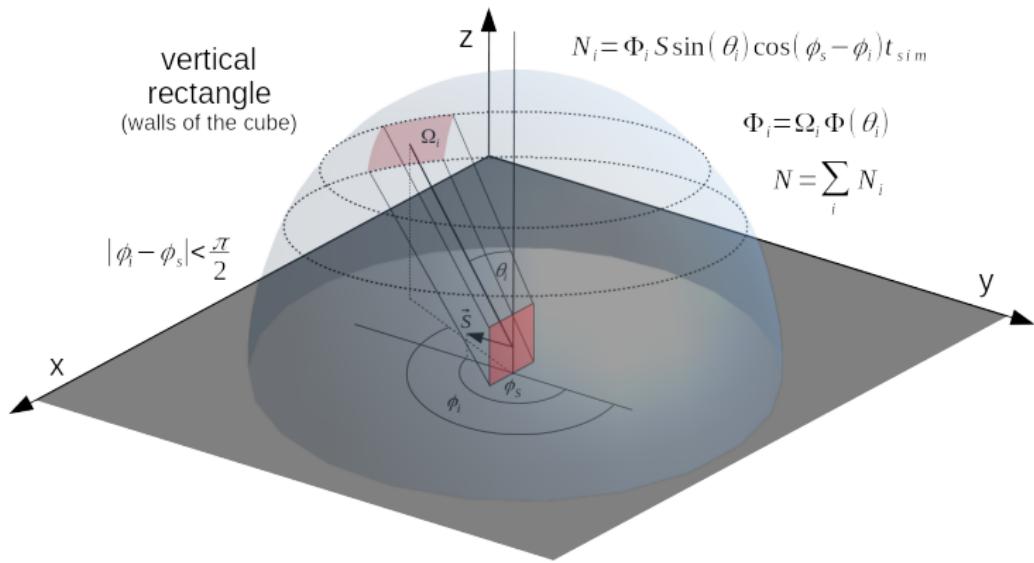
$$N_{pps} = \Omega_i \Phi(\theta_i) S \sin(\theta_i)$$



The cube ceiling is horizontal \Rightarrow flux depends only on θ

Vertical area problem

- ① Ω_i and N_i – same as for horizontal area
- ② Only particles that come from one side of the wall are generated $\Rightarrow \phi_i$ range is limited!
- ③ N_i depends on both θ_i and ϕ_i



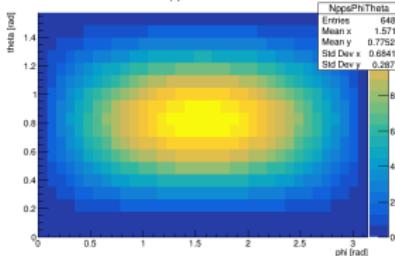
Vertical area peoblem

N_{pps_i} formula for vertical walls of the cube:

$$N_{pps_i} = \Omega_i \Phi(\theta_i) S \sin(\theta_i) \cos(\phi_s - \phi_i)$$

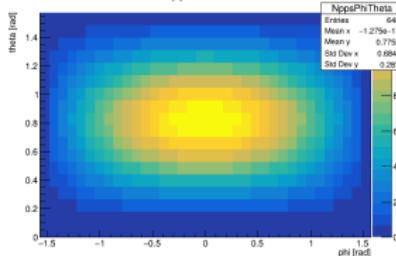
wall 1

$N_{ppsPhiTheta}$



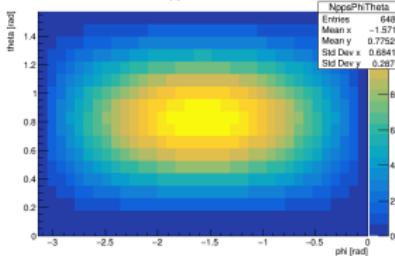
wall 2

$N_{ppsPhiTheta}$



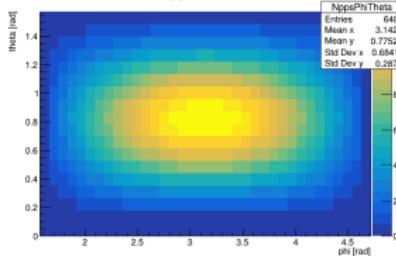
wall 3

$N_{ppsPhiTheta}$



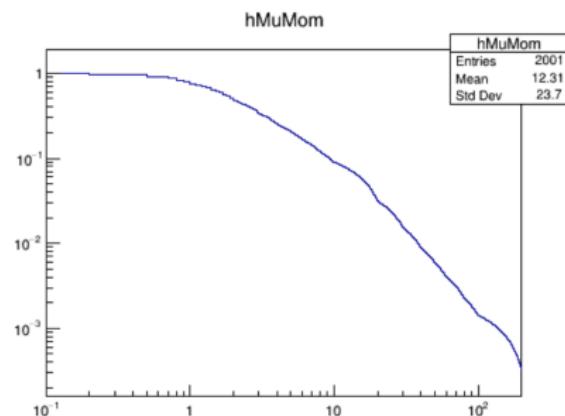
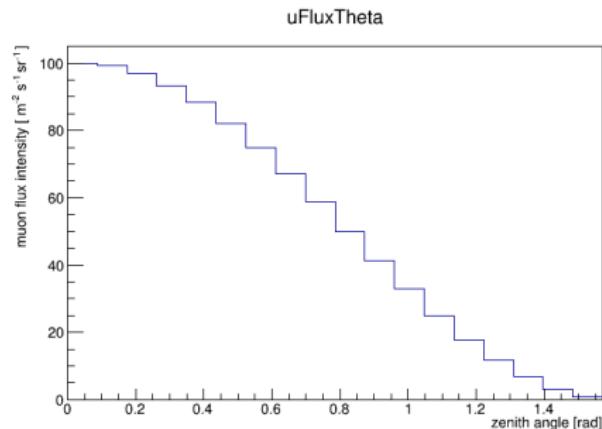
wall 4

$N_{ppsPhiTheta}$



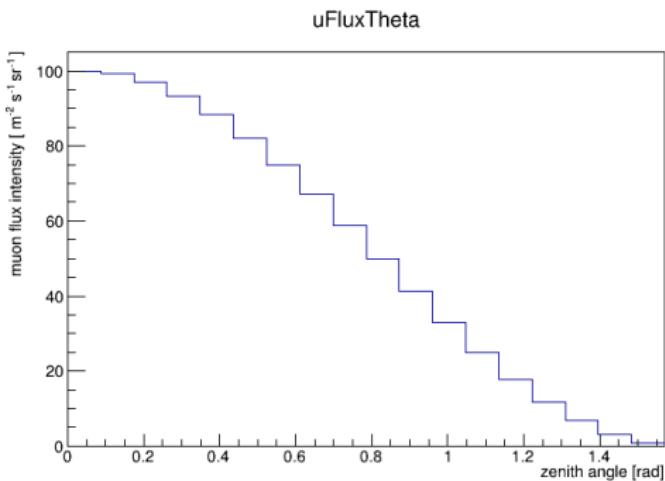
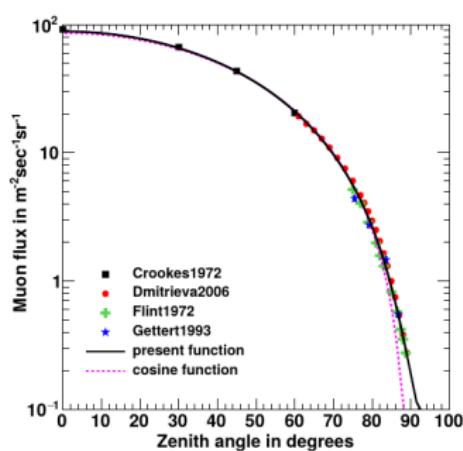
How momentum is generated

These two histograms made from experimental data are necessary for momentum generation



$\Phi(\theta)$ – input histogram

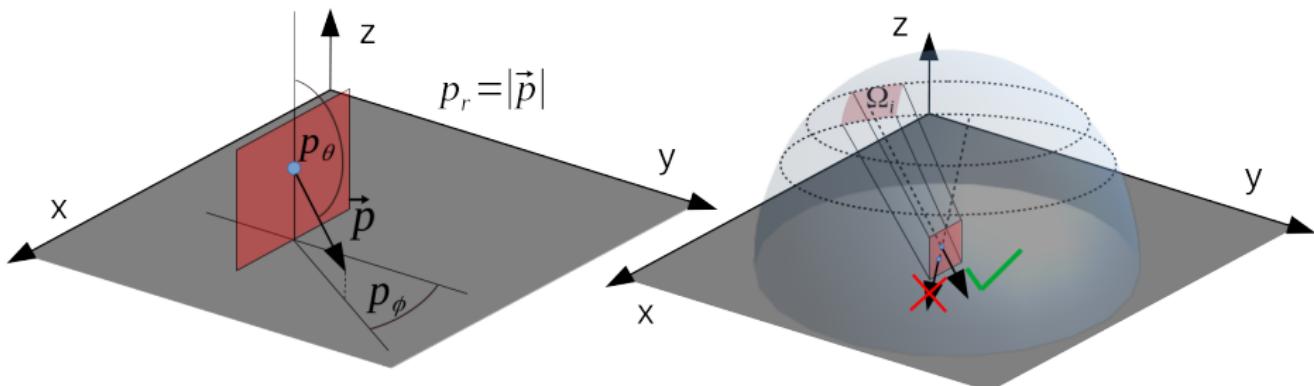
On the left: measured vertical muon flux at the sea level (log scale), fitted with ‘cosine function’: $\Phi(\theta) = \cos^2(\theta)$. Data source:
<https://arxiv.org/pdf/1606.06907.pdf>



On the right: the input histogram of $\Phi(\theta)$ (linear scale). Since $\cos^2(\theta)$ fits the data precisely enough, the histogram is just filled with $\cos^2(\theta)$ distribution.

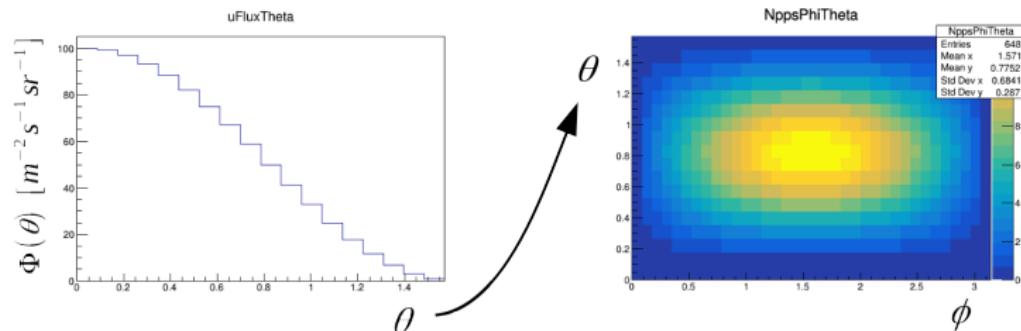
$\Phi(\theta)$ and flux mapping $\rightarrow p_\theta$ and p_ϕ

1. Momentum coordinates p_θ and p_ϕ are limited by the solid angle Ω_i :



$\Phi(\theta)$ and flux mapping $\rightarrow p_\theta$ and p_ϕ

2. Flux is mapped into $\theta-\phi$ space regarding $\Phi(\theta)$ histogram:



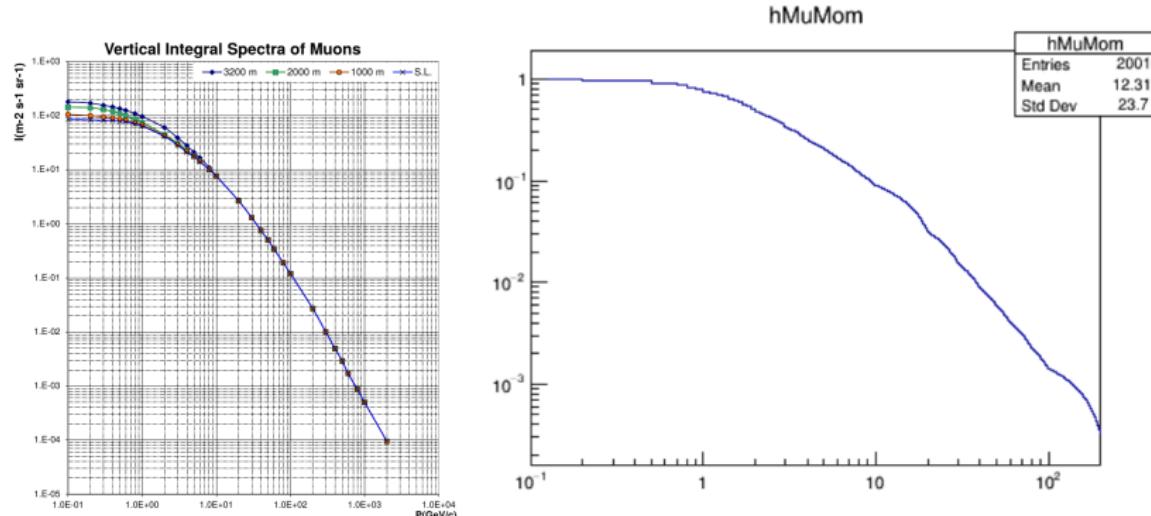
$$N_{pps_i} \propto \Phi(\theta_i)$$

3. Ω_i corresponds with the intervals: $[\theta_i, \Delta_\theta)$ and $[\phi_i, \Delta_\phi)$. Within the intervals, p_θ and p_ϕ is drawn from uniform distribution.

4. **Generation of $N_i \propto N_{pps_i}$ particles from each Ω_i solid angle guarantees that the given $\Phi(\theta)$ is reconstructed by the generated particles.** The accuracy of this reconstruction is sufficient if $\Delta\theta$ is small enough.

p_r distribution

On the left: measured vertical integral spectra of muons. Data source:
<http://crd.yerphi.am/Muons>

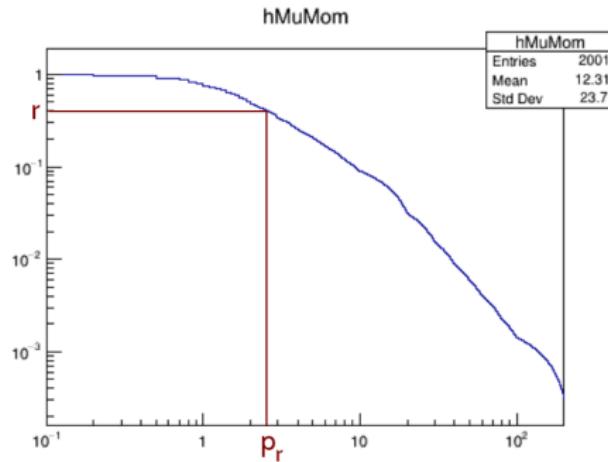


On the right: historgam made from measured integral momentum spectra od muons. Linear interpolation between data points was applied. It is scaled, so the maximum equals 1.

p_r generation

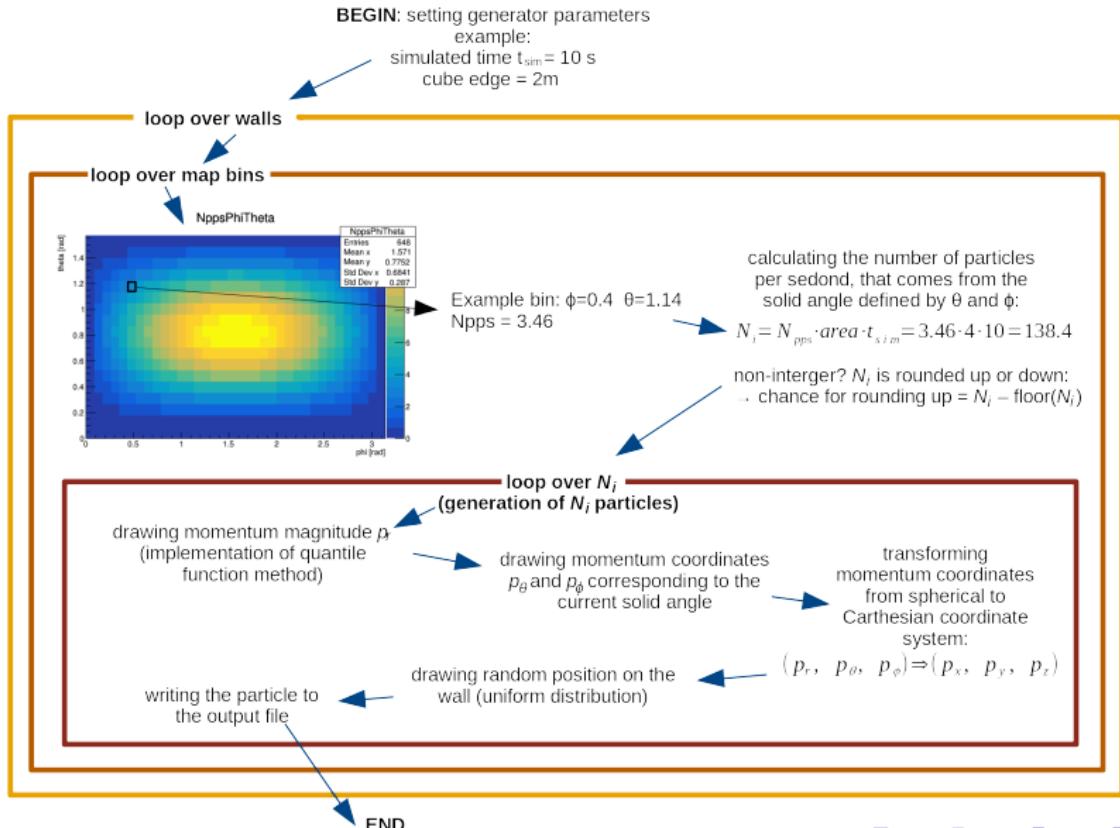
The algorithm:

- ① a random number $r \in [0, 1)$ is generated (uniform distribution),
- ② hMuMom: finding last bin which value is greater than r ,
- ③ bin center of the bin ('x value') is the drawn p_r [GeV].

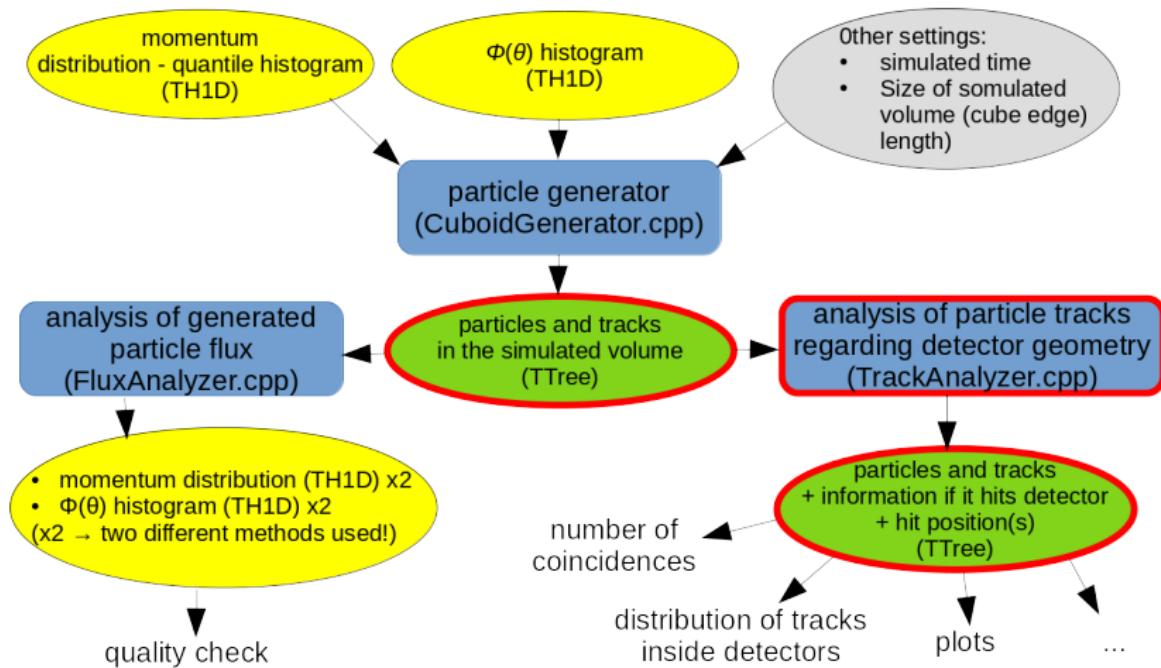


This procedure is very similar to drawing random number using quantile function.

Generation of particles step by step



TrackAnalyzer.cpp



TrackAnalyzer.cpp

Detector elements are defined in the source code (no input config file) – so far it is good enough for my needs.

Implemented shapes (C++ classes):

- Rectangle
- Disk
- Cylinder

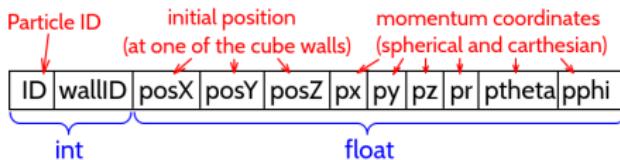
Every shape has a methods that detects if the particle hits the detector module (shape instance) and calculates hit position(s).

More detailed description of the classes is presented in the section Technical details and class description.

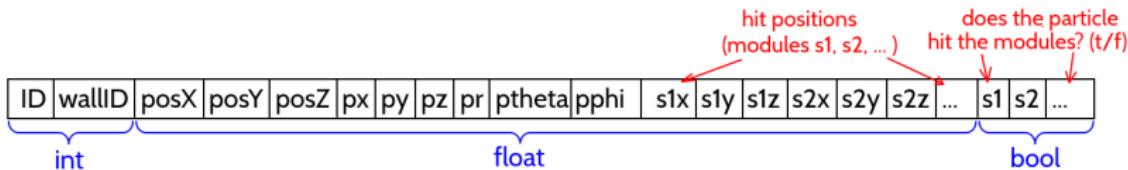
TrackAnalyzer.cpp – input and output tree

Input tree from CuboidGenerator – every entry represents one particle.

Variables are stored in different branches:



Output tree = inout tree + information if the particle hits each module and hit positions:



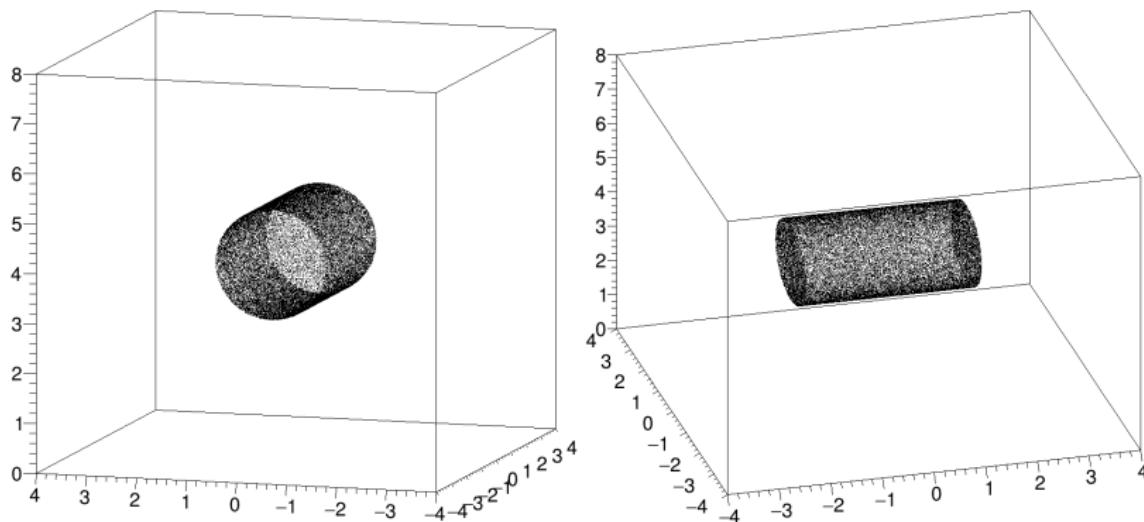
This output tree pattern works fine for simple detector lauoyt, but is not optimal regarding the output file size. For more complicated detector geometries (hundreds of elements), a different way of creating output tree may be needed.

TrackAnalyzer.cpp – plot of example output

An example cylinder was defined:

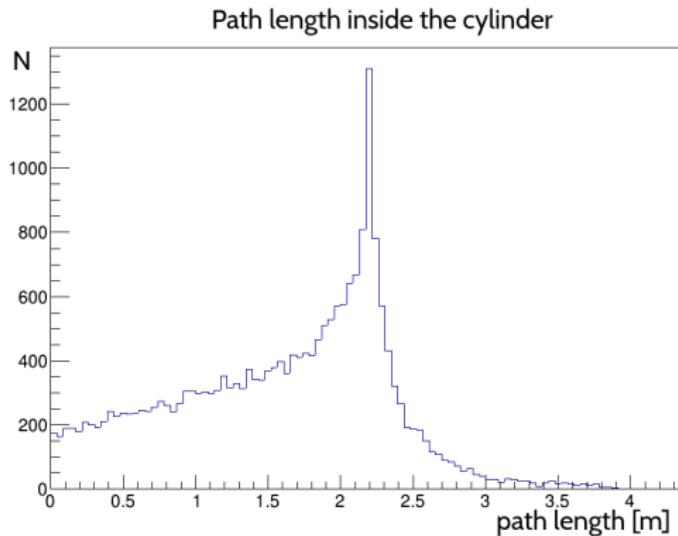
- radius: $r = 1.1 \text{ m}$
- length $L = 3.4 \text{ m}$

One can print the points, where the particle track intersects the cylinder surface. Cylinder shape reveals \Rightarrow geometry implementation works correctly



TrackAnalyzer.cpp – plot of example output

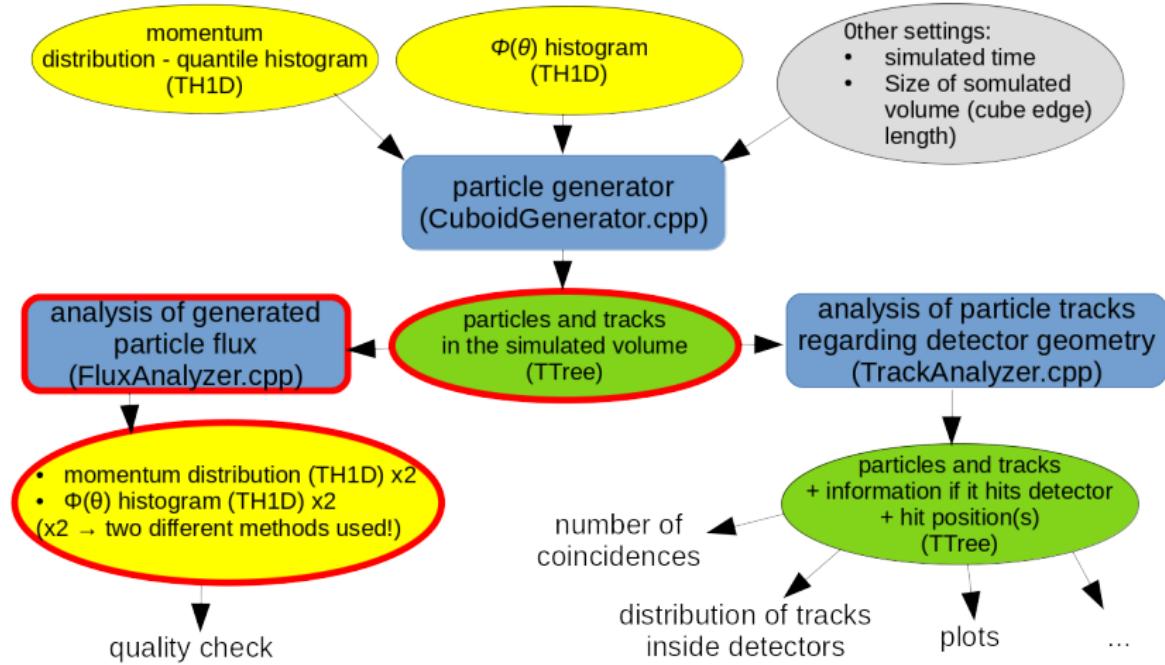
One can also plot a distribution of the path length inside the cylinder:



The distribution is correct:

- The longest possible path length is $s_{max} = \sqrt{(4r^2 + L^2)} \approx 4.1$ [m]
- Regarding most particles come from the 'ceiling', the most common track length should be approximately equal to $2r = 2.2$ [m]

FluxAnalyzer.cpp and quality check



FluxAnalyzer.cpp and quality check

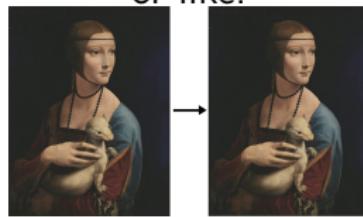
Quality check of generated particles:

- Are the initial positions ok?
- How well $\Phi(\theta)$ and momentum distribution resembles the given experimental data?

Is it like:



or like:



?

FluxAnalyzer.cpp – two methods of investigating $\Phi(\theta)$

① floor method:

- ① Filling θ distribution histogram with particles that hits the cube floor (bin width: $\Delta\theta$).
- ② Normalizing the distribution to obtain $\Phi(\theta)$. Normalization function:

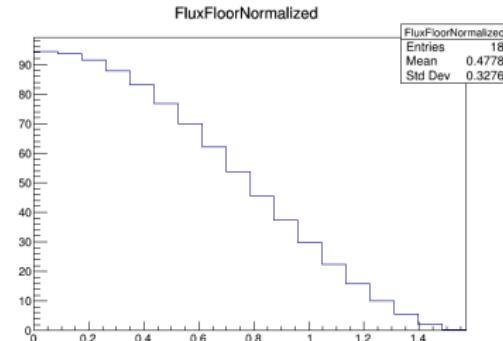
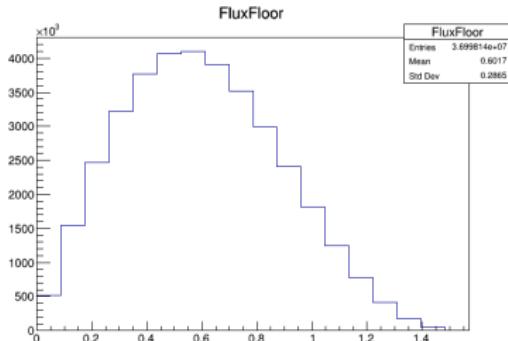
$$f_n(\theta) = \frac{1}{S \times t_{sim} \times \cos(\theta) \times \Omega(\theta)}$$

② rotating rectangle method:

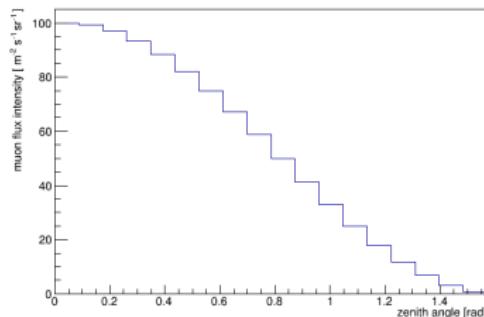
- ① Initializing a horizontal rectangle inside the cube the cube. The center of the cube is also the center of this rectangle.
- ② Rotating it through angle $\Delta\theta$. Rotation axis: contains the center of the cube, parallel to the x axis.
- ③ filling θ distribution histogram with particles that hit the rectangle and come from the limited solid angle $\Omega(\theta)$ in front of the rectangle.
- ④ Normalizing the distribution to obtain $\Phi(\theta)$. Normalizaing function:

$$f_n(\theta) = \frac{1}{S \times t_{sim} \times \Omega'(\theta)}$$

Quality check: θ distribution – floor method

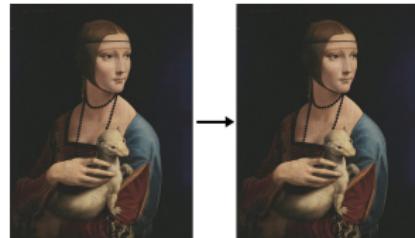


Before normalization



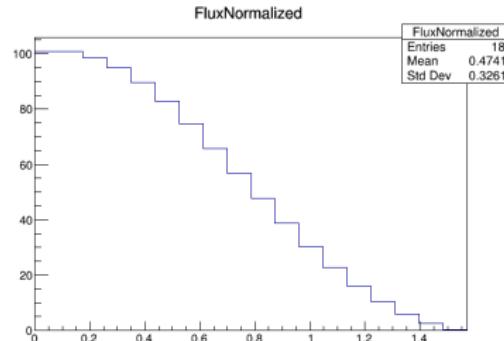
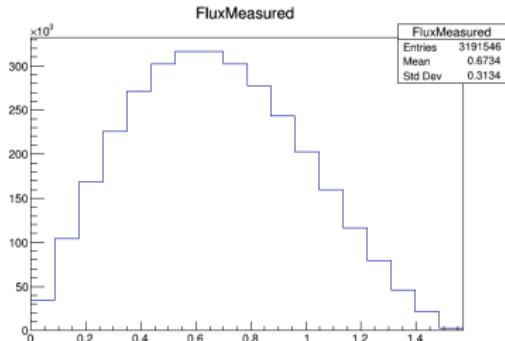
Input $\Phi(\theta)$

Normalized

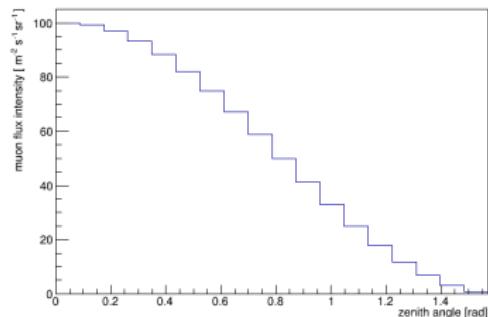


Very well!

Quality check: θ distribution – rotating rectangle method

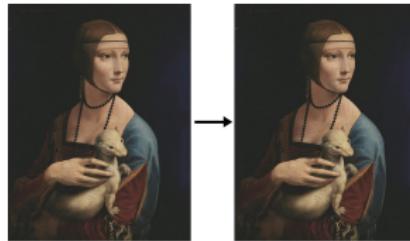


Before normalization



Input $\Phi(\theta)$

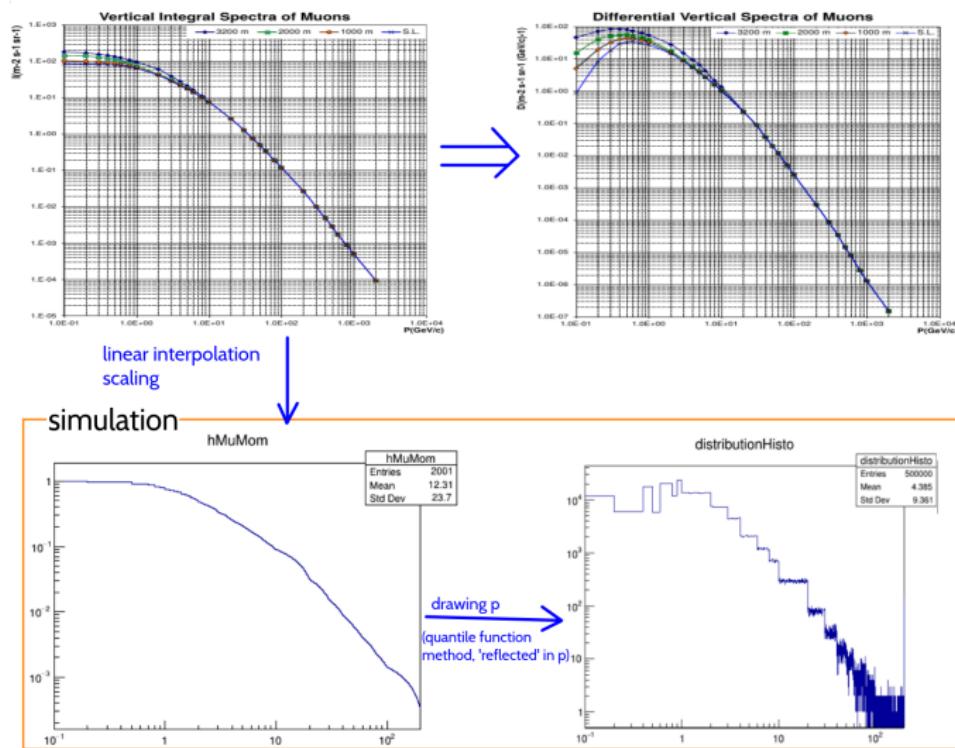
Normalized



Even better!

Quality check: p_r

experimental data



Quality check: p_r evaluation

Key notes:

- No normalization implemented for reconstructed $p_r \Rightarrow$ measured and reconstructed p_r cannot be directly compared.
- The shape of reconstructed p_r seems to be correct, but the reason for size of steps will be investigated.

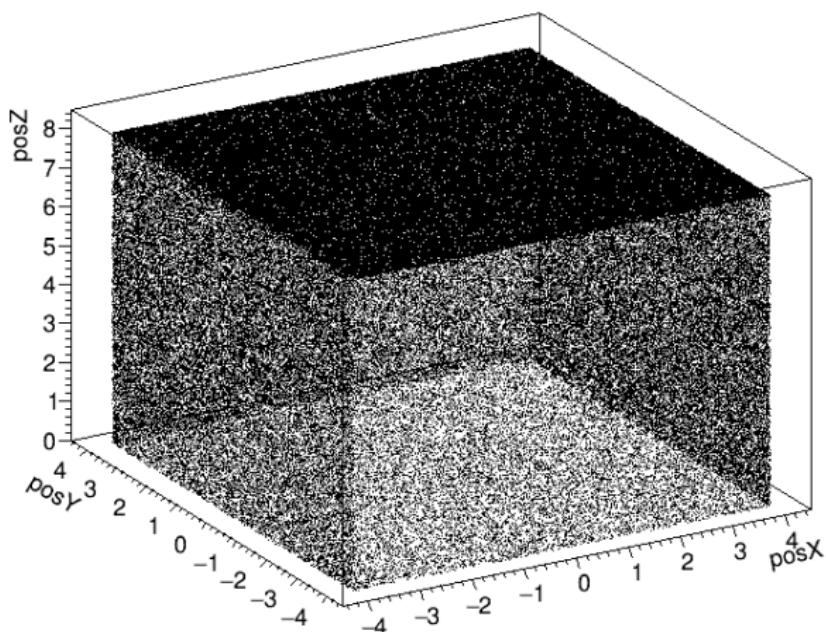
It is yet not obvious whether the p_r reconstruction is as bad as:



and it was good enough to produce some preliminary results, however, the quantile function implementation is planned for improvements.

Quality check: initial positions

Initial positions are uniformly distributed on each wall of the cube. Also, the highest particle 'surface density' of particles is observed on the cube ceiling.



Initial positions are correctly generated!

Example simulation

Example simulation - general parameters

General parameters (CuboidGenerator.cpp):

- cube edge: 8 [m]
- central point: $x=0, y=0, z=4$
- simulated time: 1 [h]
- simulated $p_{min} = 0.1$ [GeV/c]

For detection, $p_{min} = 1.6$ [GeV/c] was assumed. Tracks with lower momenta are ignored (TrackAnalyzer.cpp)

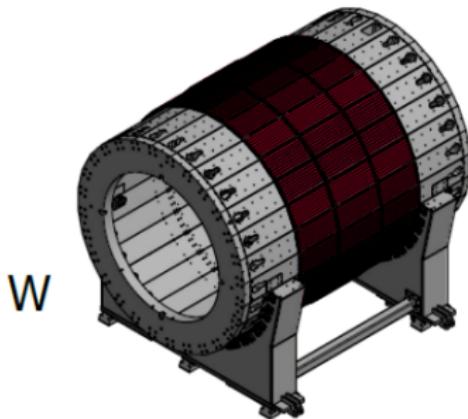
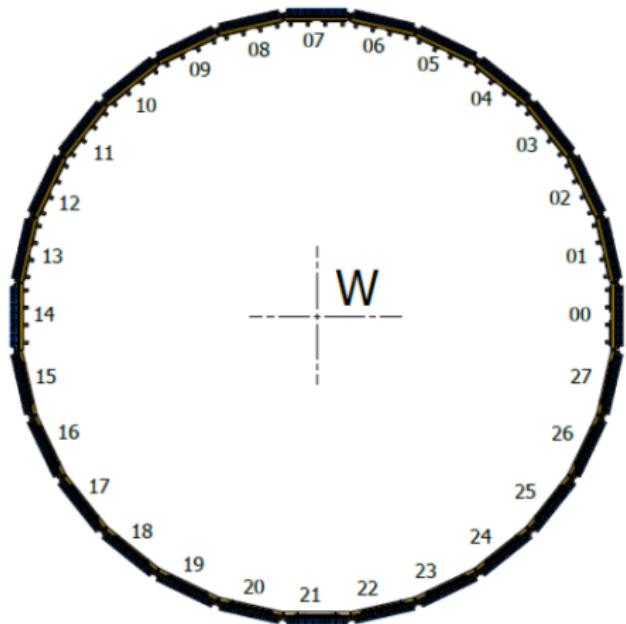
TPC parameters

- a single cylinder – length = 3.4 [m]; radius = 1.1 [m]
- axis of symmetry: parallel to the X axis, in the center of the cube ($y=0, x=4$)
- efficiency $\eta = 1$

Simulated detector geometry

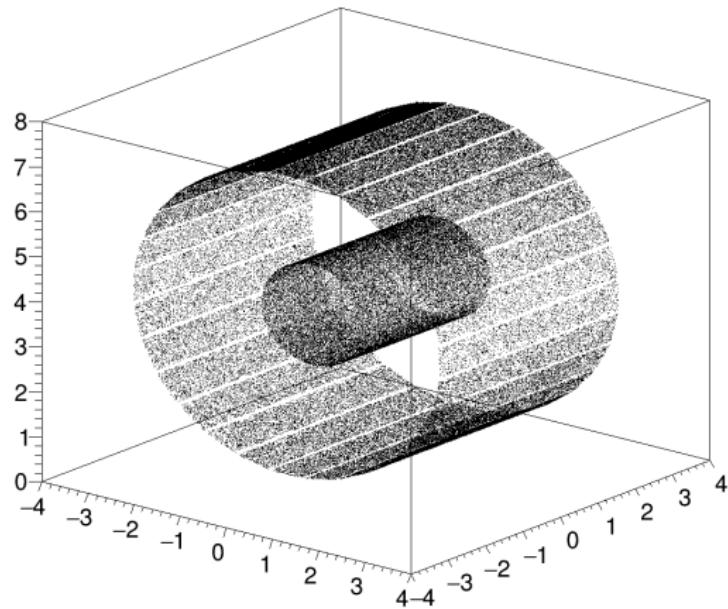
Scintillating modules

- rectangular modules – length = 4.784 [m]; width = 0.675 [m]
- efficiency $\eta = 0.9$
- placed around TPC axis

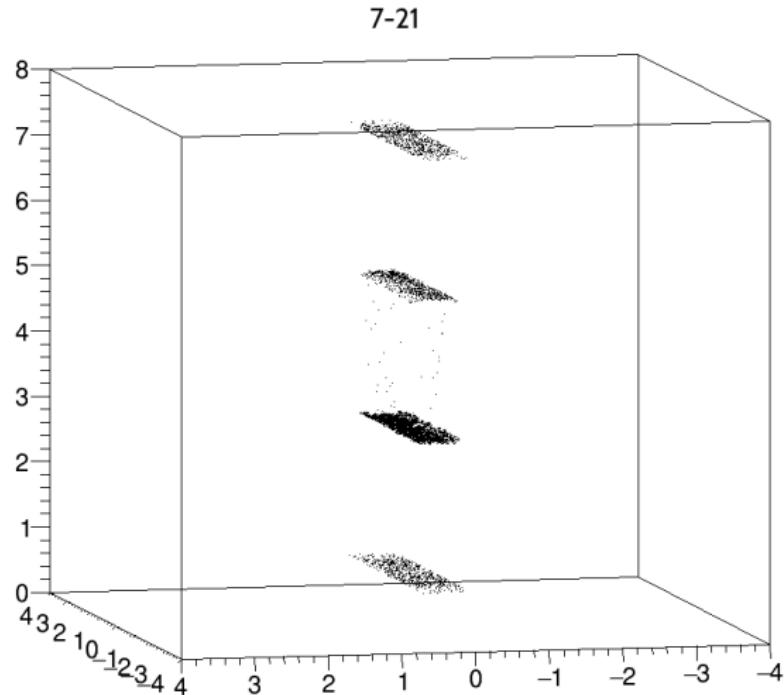


Obtained detector geometry visualisation

Drawing positions where tracks hits the detectors reveals geometry of the detectors

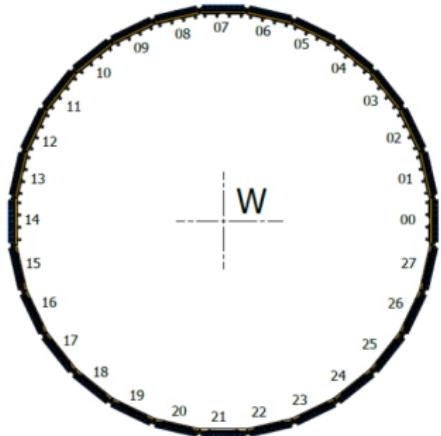
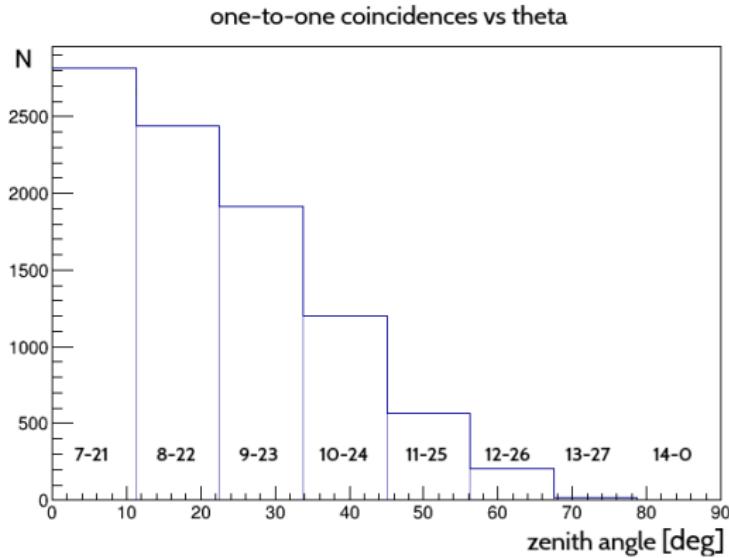


One-to-one coincidences

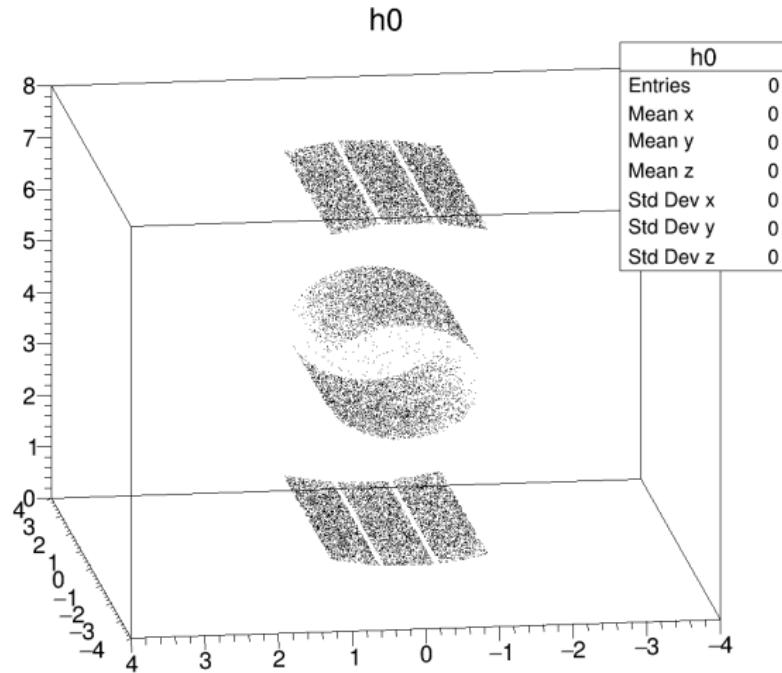


One-to-one coincidences (with TPC)

Similar to $\cos^2(\theta)$ function – correct!

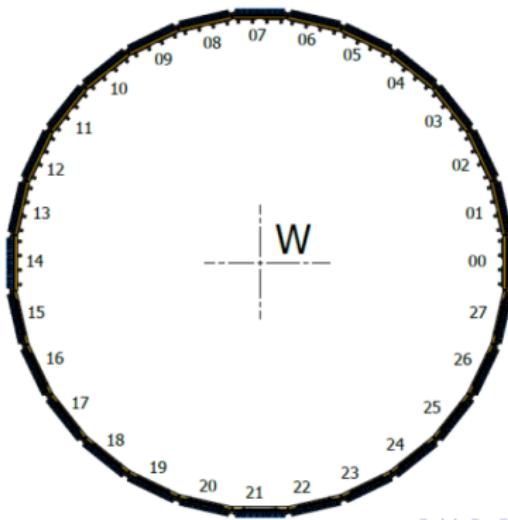


Layout 1: modules close to each other

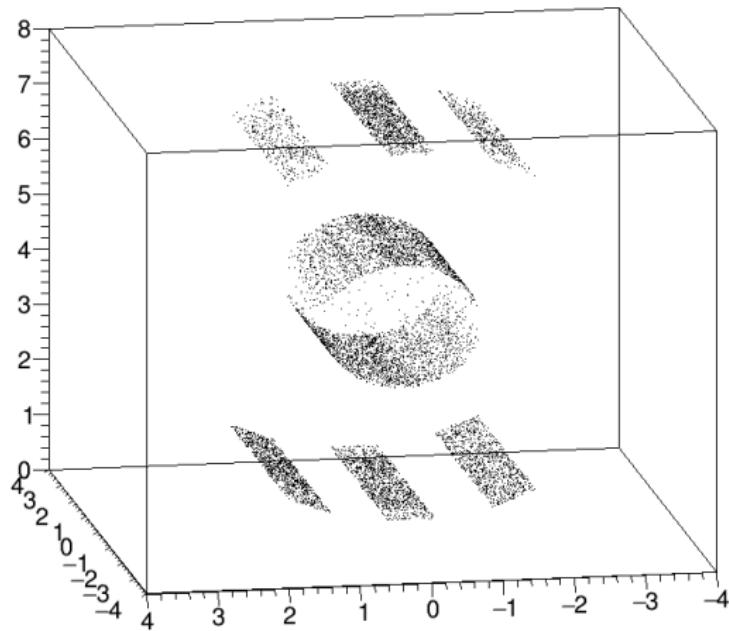


Layout 1: modules close to each other

- (6 or 7 or 8) and (20 or 21 or 22) and TPC – 23341 coincidences per hour
- (9 or 10 or 11) and (23 or 24 or 25) and TPC – 15415 coincidences per hour
- (12 or 13 or 14) and (26 or 27 or 0) and TPC – 1956 coincidences per hour

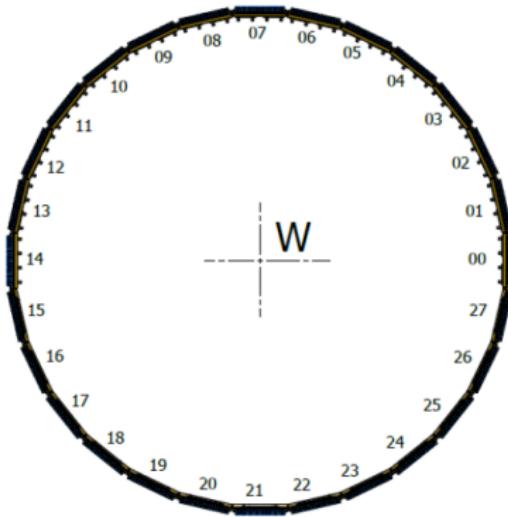


Layout 2: space between modules



Layout 2: space between modules

- (5 or 7 or 9) and (19 or 21 or 23) and TPC – 31402 coincidences per hour
- (10 or 12 or 14) and (24 or 26 or 0) and TPC – 4892 coincidences per hour



Code description

Thank you for your attention!