Geant4 simulations for HMB

PROGRESS, ISSUES & PLANS

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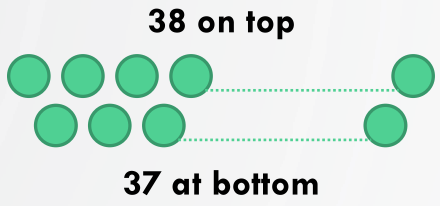
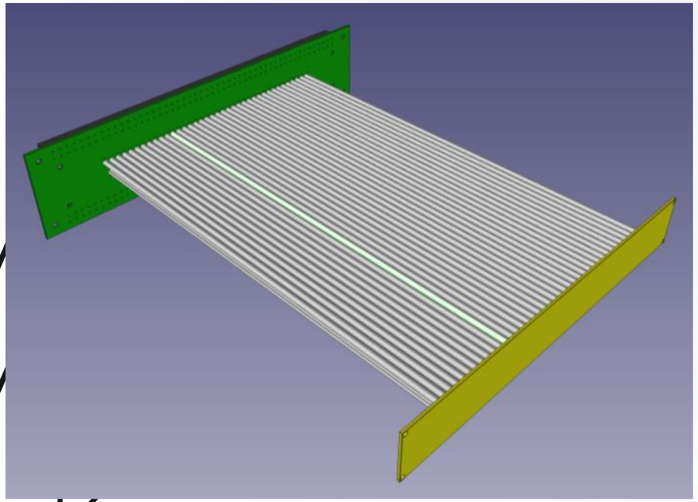
Introduction to GEANT4

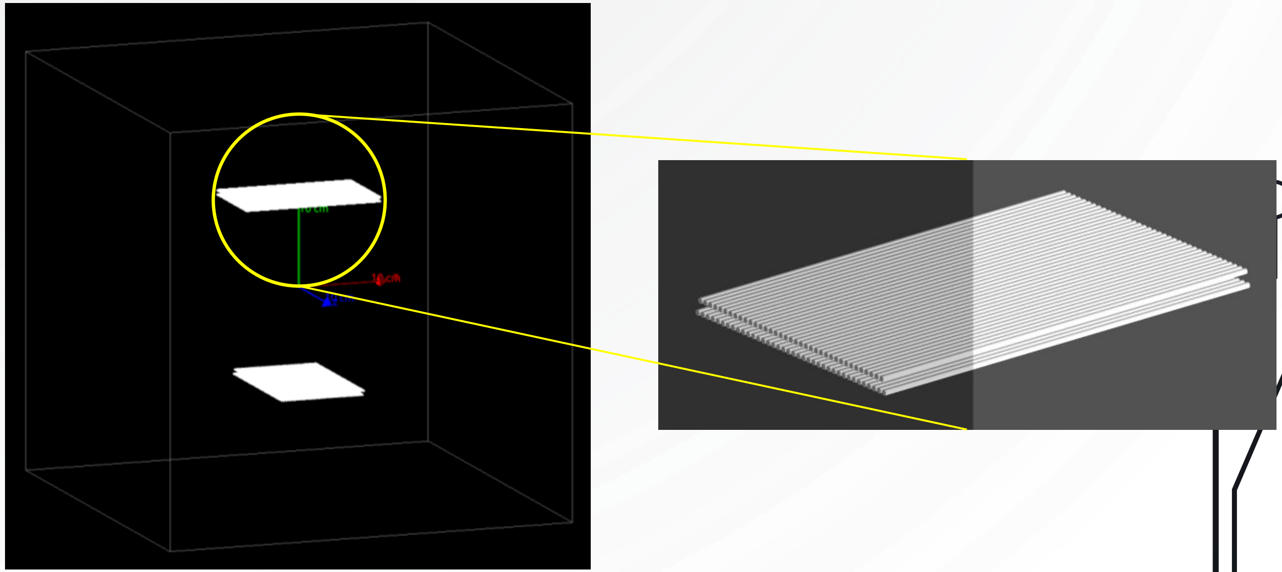
- **GEANT** → **GE**ometry **AN**d **T**racking, a platform (toolkit) for simulation of the passage of particles through matter using Monte Carlo methods.
- Last stable release: ver. 10.6
- Developed in C++ by Geant4 Collaboration
- Documentation: https://geant4.web.cern.ch/support/user_documentation
- Provides a complete range of functionality including tracking, geometry, physics models and hits.
- Extensively used in Particle Phys, Nuclear Phys, Acc. Design, Space Engineering, Optical Phys, & Medical Phys.
- The toolkit can be installed on Windows, Mac OS and various Linux distributions (although, only CentOS 7 is officially supported).

Simple Tracker Geometry

- Started with a simple geometry:
  - 75 silica optical fibres stacked together (38, 37 → double layers)
  - Two double-layered trackers
- Will improve the geometry as we go ahead.
- Looking at DD4hep as well. We'll probably need an xml of the drawing.

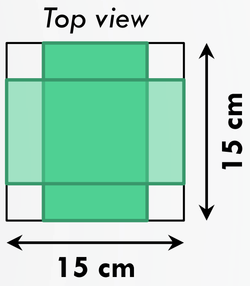


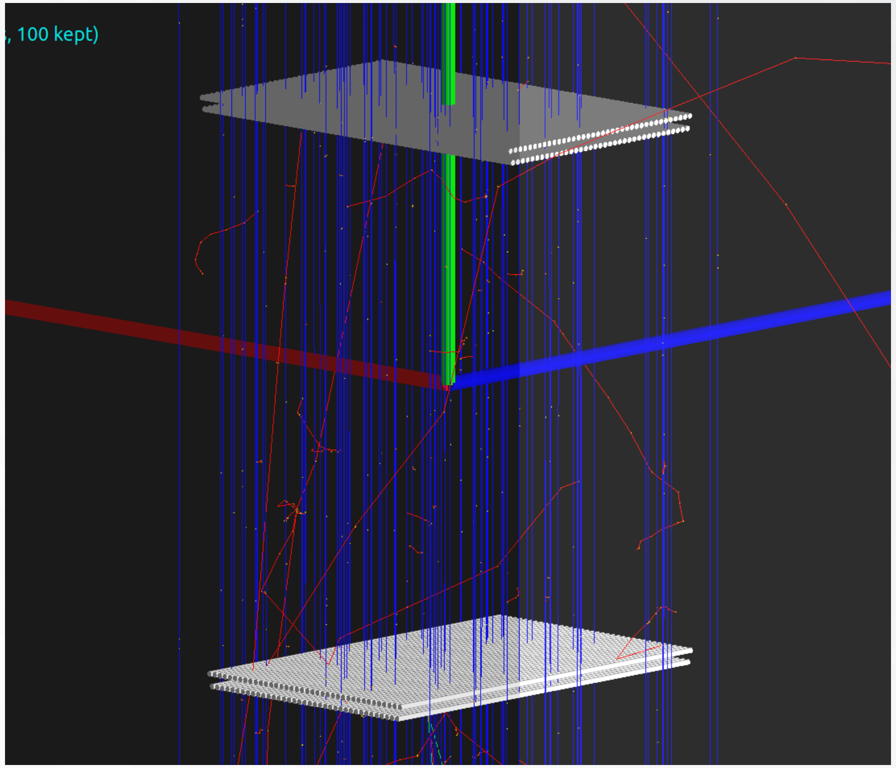


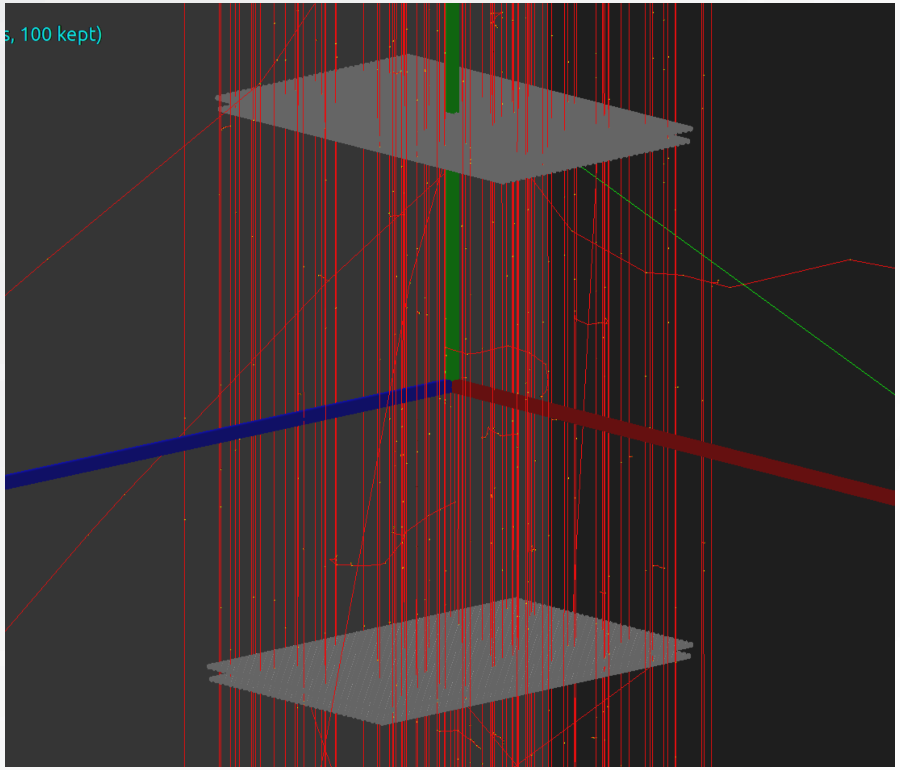


4 GeV muons (μ^+, μ^-)

Incident with a moving particle gun







https://github.com/HawaiianMuonBeamline/dd4hep_geant4_root

Geant4, DD4hep, & root installation instructions are on git. Assumes installation on clean Ubuntu 20.04.

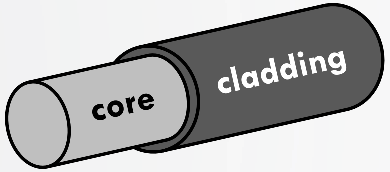
CRY (Cosmic-ray Shower Library)

- Installed it on my virtual machine running Ubuntu 20.04.
- Tested out some included examples, installation seems to be fine.
- Looking into more details.

Importing CAD geometry in DD4hep

- Documentation says it is possible with the assimp package (available on git). Supports import from ~**53 filetypes**.
- I haven't tried this yet. What filetypes can the geometry be exported in with Solid Edge or SOLIDWORKS? Is XML supported?
- Do we want to import everything in black box for Geant4 simulations?

Scintillating Fiber Geometry & Material
(Single-clad fibers - confirmed)



Core

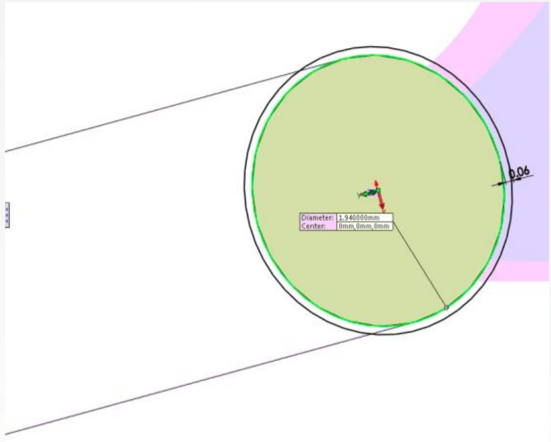
- Material: Polystyrene
- Refractive index: 1.60
- Density: 1.05 g/cc

- Diameter: 1.94 mm

Cladding

- Material: Acrylic (PMMA)
- Refractive index: 1.49
- Density: 1.2 g/cc

- Thickness: 60 μm



Importing CAD files in DD4hep

- Start from a very simple CAD file, maybe collada export (.dae) – similar to xml
- Looking into assimp package examples
- *Would like to try out a few different filetypes:*

  STL, **STEP → DAE**, **3DXML**, **IFC**, **XAML**

Sample Collada (.dae) export


```xml
<COLLADA xmlns="http://www.collada.org/2005/11/COLLADASchema" version="1.4.1">
  <asset>
    <contributor />
    <created>2020-10-03T20:13:56.930669</created>
    <modified>2020-10-03T20:13:56.930669</modified>
    <unit meter="1.0" name="meter" />
    <up_axis>Z_UP</up_axis>
  </asset>
  <library_effects>
    <effect id="effect_Sphere" name="effect_Sphere">
      <profile_COMMON>
        <technique sid="common">
          <phong>
            <emission>
              <color>0.0 0.0 0.0 1.0</color>
            </emission>
            <ambient>
              <color>0.0 0.0 0.0 1.0</color>
            </ambient>
            <diffuse>
              <color>0.800000011920929 0.800000011920929 0.800000011920929 1.0</color>
            </diffuse>
            <specular>
              <color>1 1 1 1.0</color>
            </specular>
            <shininess>
              <float>0.0</float>
            </shininess>
            <reflective>
              <color>0.0 0.0 0.0 1.0</color>
            </reflective>
            <reflectivity>
              <float>0.0</float>
            </reflectivity>
            <transparent>
              <color>0.0 0.0 0.0 1.0</color>
            </transparent>
            <transparency>
              <float>1.0</float>
            </transparency>
          </phong>
        </technique>
        <extra>
          <technique profile="GOOGLEEARTH">
            <double_sided>0</double_sided>
          </technique>
        </extra>
      </profile_COMMON>
    </effect>
    <effect id="effect_Box" name="effect_Box">
      <profile_COMMON>
        <technique sid="common">
          <phong>
            <emission>
```

Supported filetypes with ASSIMP package

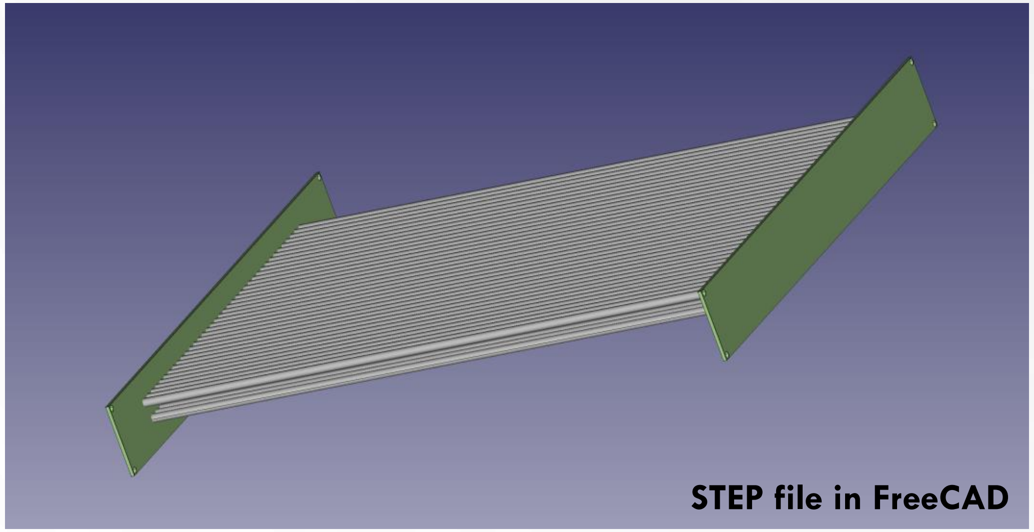
Collada (*.dae;*.xml)
Blender (*.blend) 3
Biovision BVH (*.bvh)
3D Studio Max 3DS (*.3ds)
3D Studio Max ASE (*.ase)
Wavefront Object (*.obj)
Stanford Polygon Library (*.ply)
AutoCAD DXF (*.dxf)
IFC-STEP, Industry Foundation Classes (*.ifc)
Neutral File Format (*.nff)
Sense8 WorldToolkit (*.nff)
Valve Model (*.smd,*.vta) 3
Quake I (*.mdl)
Quake II (*.md2)
Quake III (*.md3)
Quake 3 BSP (*.pk3) 1
RtCW (*.mdc)
Doom 3 (*.md5mesh;*.md5anim;*.md5camera)
DirectX X (*.x).
Quick3D (*.q3o;q3s)

Raw Triangles (.raw)
AC3D (*.ac)
Stereolithography (*.stl)
Autodesk DXF (*.dxf)
Irrlicht Mesh (*.irrmesh;*.xml)
Irrlicht Scene (*.irr;*.xml).
Object File Format (*.off).
Terragen Terrain (*.ter)
3D GameStudio Model (*.mdl)
3D GameStudio Terrain (*.hmp)
Ogre (*.mesh.xml, *.skeleton.xml, *.material)3
Milkshape 3D (*.ms3d)
LightWave Model (*.lwo)
LightWave Scene (*.lws)
Modo Model (*.lxo)
CharacterStudio Motion (*.csm)
Stanford Ply (*.ply)
TrueSpace (*.cob, *.scn)
XGL (*.xgl, *.zgl)

Importing CAD geometry in DD4hep

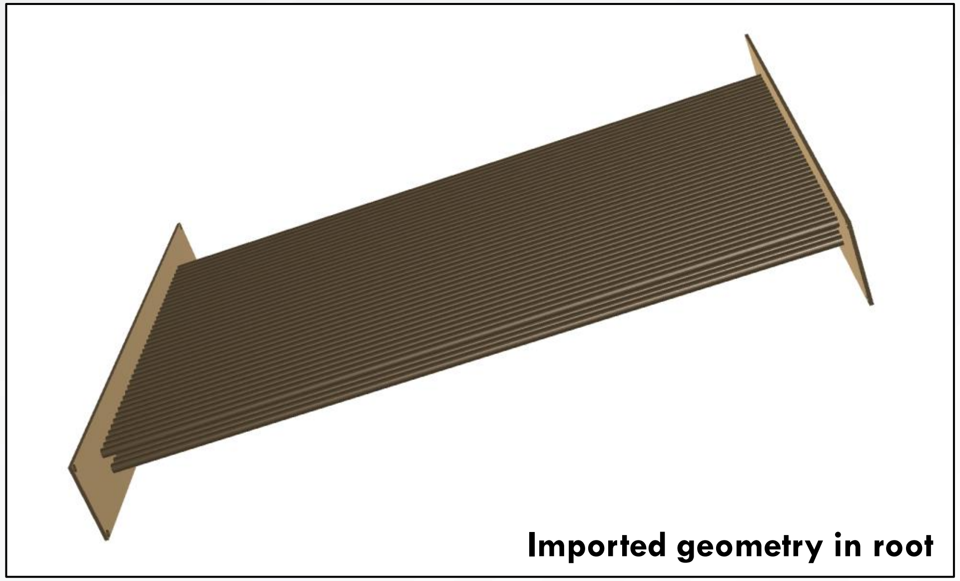
- Open .STEP file in FreeCAD software and export selected parts to a Collada .dae file.
- Import this .dae file (detector assembly) in DD4hep with DDCAD and then, ***root*** may be used for visualization.

In FreeCAD (STEP file) → Collada (.dae)



STEP file in FreeCAD

Imported in DD4hep → Visualize with ***root***



Imported geometry in root

Import & Display CAD Geometry in DD4hep/DDCAD

test.xml (simple layout):

```
<lccdd>
  <includes>
    <gdmlFile
ref="../../ClientTests/compact/CheckShape.xml"/>
  </includes>
  <detectors>
    <detector id="1" name="HMB_STL"
type="DD4hep_TestShape_Creator">
      <check vis="T1_Fiber">
        <shape type="CAD_Assembly"
ref="/mnt/hgfs/VMShared/HMB/allGeo.stl"/>
      </check>
    </detector>
  </detectors>
</lccdd>
```

<lccdd>

<info> ... </info> Auxiliary detector model information

<includes> ... </includes> Section defining GDML files to be included

<define> ... </define> Dictionary of constant expressions and variables

<materials> ... </materials> Additional material definitions

<display> ... </display> Definition of visualization attributes

<detectors> ... </detectors> Section with sub-detector definitions

<readouts> ... </readouts> Section with readout structure definitions

<limits> ... </limits> Definition of limit sets for Geant4

<fields> ... </fields> Field definitions

</lccdd>

```
geoDisplay –compact test.xml
```

CAD drawings from STL → GDML

geoConverter -compact2gdml -input test.xml -output test.gdml

- GDML: XML like syntax, compatible with Geant4
- This can be used in an independent Geant4 simulation (independent of DD4hep)
- Material info in CAD files, perhaps lost in translation! Does STL have material info?
- The resulting GDML file might not be efficiently processed with Geant4 though, especially for complex detector geometries.

```
  <position name="Shape_0inworld_volumepos" x="0" y="0"
</define>
<materials>
  <material name="dummy" Z="0">
    <D unit="g/cm3" value="0"/>
    <atom unit="g/mole" value="0"/>
  </material>
  <element name="N_elm" formula="N" Z="7">
    <atom unit="g/mole" value="14.0068"/>
  </element>
  <element name="O_elm" formula="O" Z="8">
    <atom unit="g/mole" value="15.9994"/>
  </element>
  <element name="Ar_elm" formula="Ar" Z="18">
    <atom unit="g/mole" value="39.947699999999998"/>
  </element>
  <material name="Air">
    <D unit="g/cm3" value="0.0011999999999999999"/>
    <fraction n="0.012000000104308128" ref="Ar_elm"/>
    <fraction n="0.75400000810623169" ref="N_elm"/>
    <fraction n="0.23399999737739563" ref="O_elm"/>
  </material>
</materials>
<solids>
  <box name="world_volume_shape_0x55e9c5d3b220" x="600"
  <tessellated name="vol_0_shape_0x55e9c63a2d10">
```

GENERATION OF PARTICLES WITH CRY LIBRARY

CRY: Cosmic-ray Shower Library (v1.7)

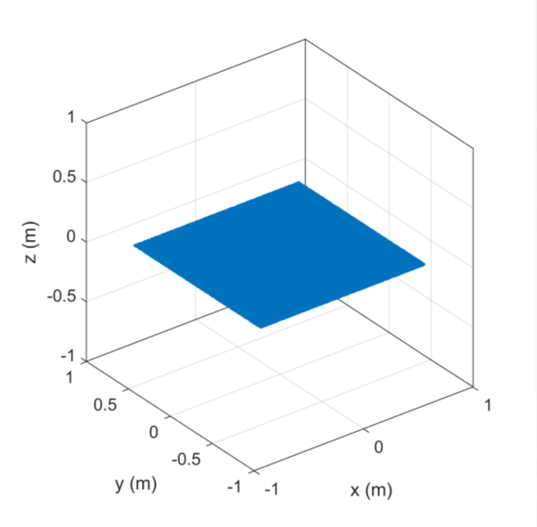
`~/cry/test/testOut.cc setup.file 100000`

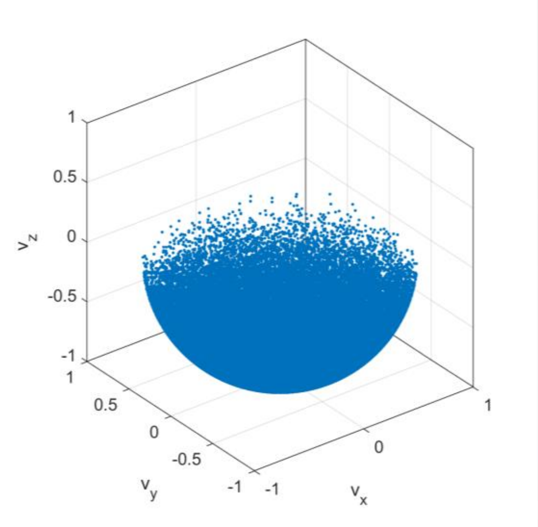
Output file → `shower.out`:

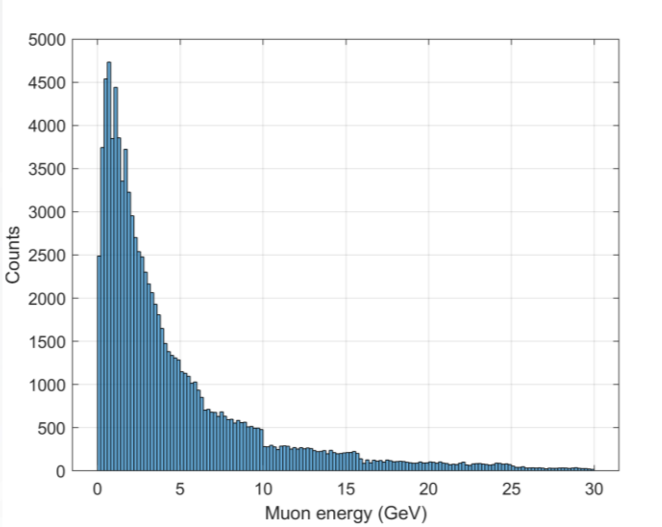
#	nEvent	nSecondary	KE	x	y	z	u	v	w
0	0	4	1183	-0.35553	-0.17427	0	0.21387	0.5026	-0.83764
1	0	4	6618	-0.74499	-0.38886	0	-0.3633	0.047603	-0.93046
2	0	4	6580.5	0.68209	-0.18992	0	-0.27037	-0.38348	-0.88309
3	0	4	4150.8	-0.19935	-0.59347	0	0.22575	-0.32956	-0.91675

```
returnNeutrons 0
returnProtons 0
returnGammas 0
returnElectrons 0
returnMuons 1
returnPions 0
returnKaons 0
date 1-12-2021
latitude 21.3
altitude 0
subboxLength 1.5
```

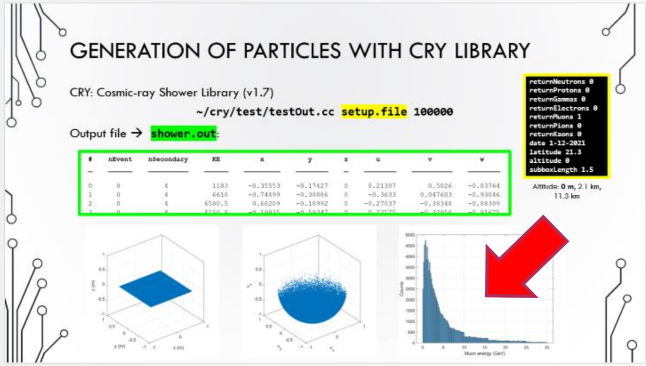
Altitude: **0 m**, 2.1 km, 11.3 km

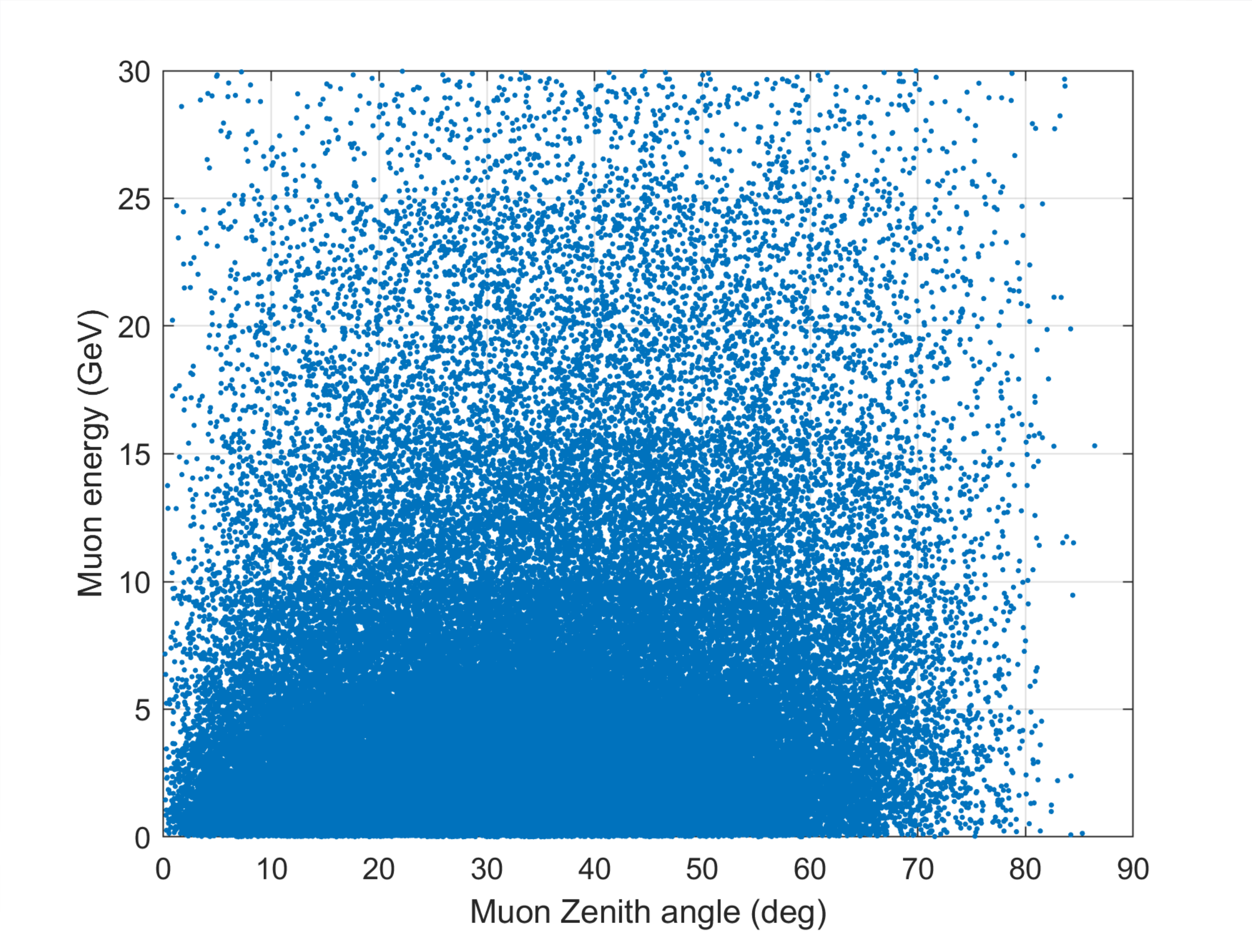






Incident Muon's Zenith Angle vs KE





Zenith angle: $\cos^{-1}(-w)$

w is the z-component of the particle velocity.

CRY Library Data File

```
%%%%%%%%%%% Primary binning %%%%%%%%%%
% bin boundaries for Energy (MeV) of primary cosmic ray proton
% 34 bins
binning primaryBins = {
    1000 2000 3000 4000 5000 6000
    7000 8000 9000 10000 11000 12000
    13000 14000 15000 25118.9 39810.7 63095.7
    100000 158489 251189 398107 630957 1000000
    1.58489e+06 2.51189e+06 3.98107e+06 6.30957e+06 10000000 1.58489e+07
    2.51189e+07 3.98107e+07 6.30957e+07 100000000
};


%%%%%%%%%%% Secondary binning %%%%%%%%%%
% bin boundaries for Energy (MeV) of secondary particles produced in the shower
% 86 bins
binning secondaryBins = {
  1e-09 1.58489319246111e-09 2.51188643150958e-09 3.98107170553497e-09 6.30957344480193e-09
  1e-08 1.58489319246111e-08 2.51188643150958e-08 3.98107170553497e-08 6.30957344480194e-08
  1e-07 1.58489319246111e-07 2.51188643150958e-07 3.98107170553498e-07 6.30957344480194e-07
  1e-06 1.58489319246112e-06 2.51188643150958e-06 3.98107170553498e-06 6.30957344480194e-06
  1e-05 1.58489319246112e-05 2.51188643150958e-05 3.98107170553498e-05 6.30957344480194e-05
  0.0001 0.000158489319246112 0.000251188643150959 0.000398107170553498 0.000630957344480195
  0.001 0.00158489319246112 0.00251188643150959 0.00398107170553498 0.00630957344480195
  0.01 0.0158489319246112 0.0251188643150959 0.0398107170553498 0.0630957344480195
  0.1 0.158489319246112 0.251188643150959 0.398107170553499 0.630957344480195
  1 1.58489319246112 2.51188643150959 3.98107170553499 6.30957344480196
  10 15.8489319246112 25.1188643150959 39.8107170553499 63.0957344480196
  100 158.489319246112 251.188643150959 398.107170553499 630.957344480196
  1000 1584.89319246112 2511.88643150959 3981.07170553499 6309.57344480196
  10000.0000000001 15848.9319246112 25118.8643150959 39810.7170553499 63095.7344480197
  100000.000000001 158489.319246112 251188.643150959 398107.1705535 630957.344480197
  1000000.00000001 1584893.19246112 2511886.4315096 3981071.705535 6309573.44480197
  10000000.0000001 15848931.9246112 25118864.315096 39810717.05535 63095734.4480197
  100000000.000001
};
```

33 primary bins

85 secondary bins

```
%%%%%%%%%%% Muon KE distribution %%%%%%%%%%
pdf muonKEDist::primaryBins[1.0e-9,1.0e8,log] = {
 { 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 1.9608E-02 1.9608E-02 5.8824E-02 3.9216E-02 1.9608E-01
   3.3333E-01 1.5686E-01 9.8039E-02 7.8431E-02 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 }
 { 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   1.4903E-03 2.9806E-03 7.4516E-03 1.7884E-02 3.7258E-02 9.3890E-02
   1.9374E-01 2.1311E-01 2.3845E-01 1.1624E-01 6.4083E-02 1.1923E-02
   1.4903E-03 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 }
 { 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   2.3889E-04 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 4.7778E-04
   9.5557E-04 2.8667E-03 7.8834E-03 1.4095E-02 3.1056E-02 6.8084E-02
   1.1228E-01 1.7296E-01 2.2862E-01 2.0401E-01 1.2183E-01 3.2967E-02
   1.6722E-03 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
   0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
```

85x33 values

CRY DATA FILE: ORGANIZATION OF PARTICLE PDFs

E_p (MeV)
1500
2500
:
5.14×10^7
8.15×10^7

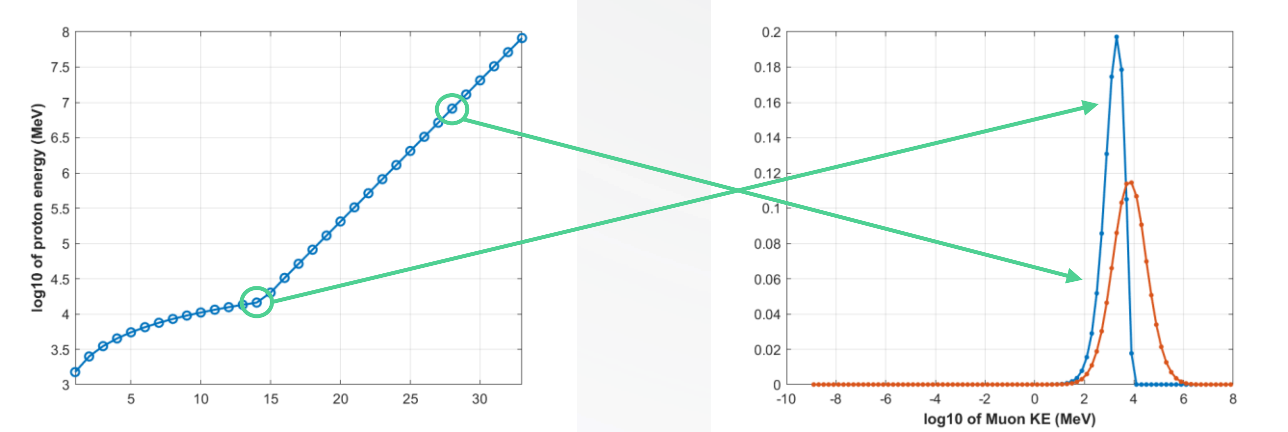
Primary cosmic ray proton energies (33 primary bins)

85 secondary bins (sBins)

Increasing sBins require interpolation of:

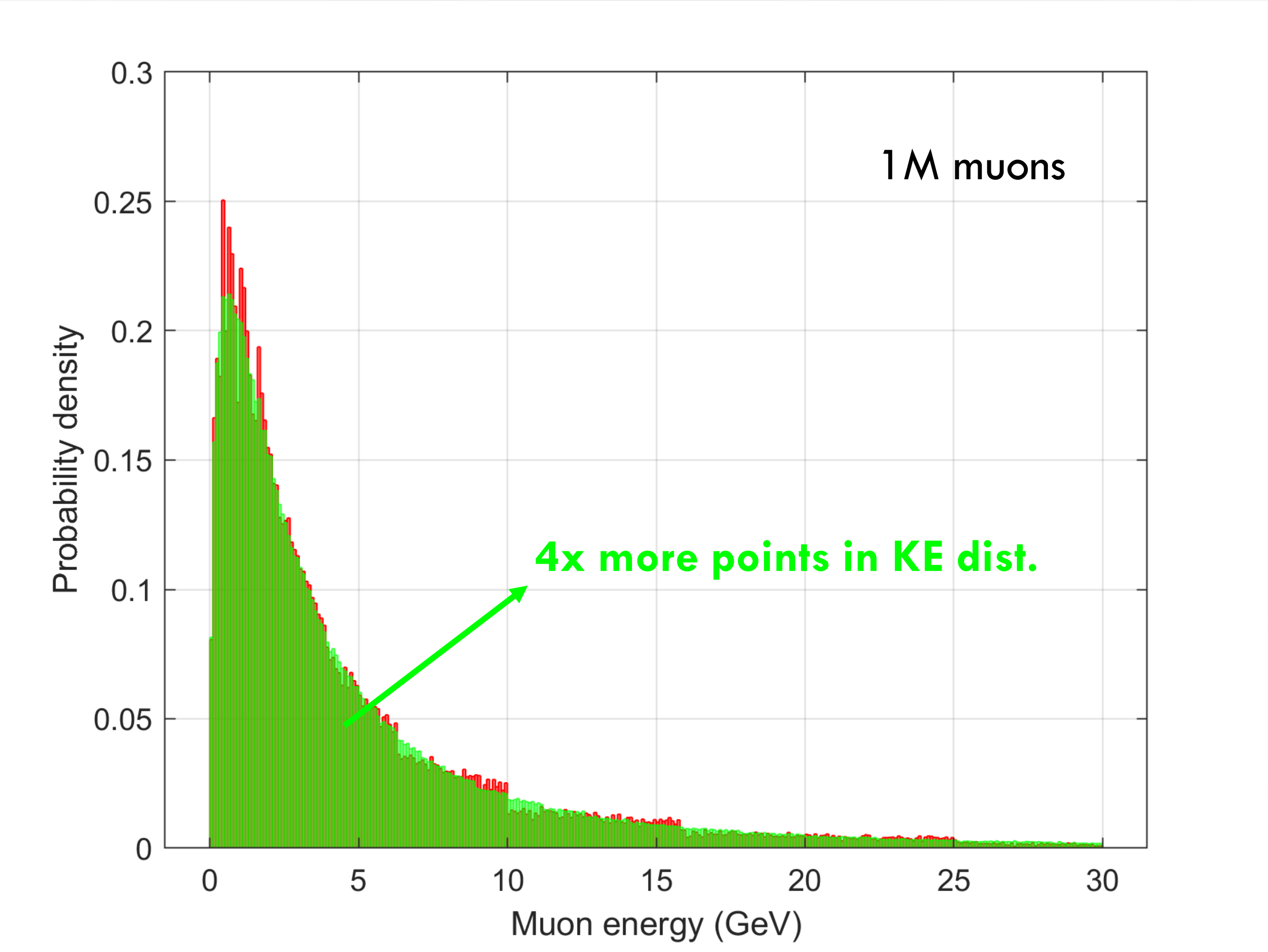
- **Energy** distribution
- **Time** distribution
- **$\cos\theta$** distribution
- **Charge** distribution

For all secondary particles



Muon Energy Distribution

(After interpolation of almost all distributions in CRY data files)



More details on NaI Calorimeter

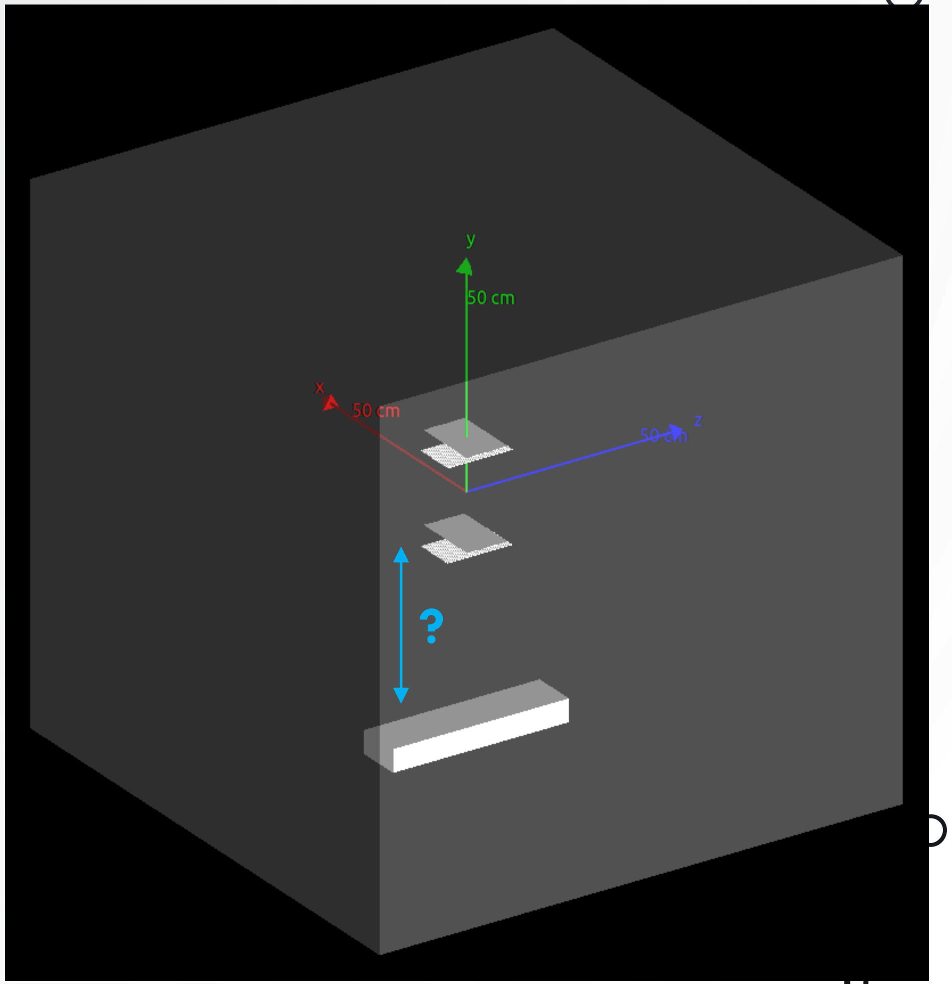
Good references:

- *General Info:* https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/square-or-rectangular-detector.pdf
- *Product list:* https://www.crystals.saint-gobain.com/products/radiation-detection-products/standard-scintillation-product-list
- *Material reference:* https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/sodium-iodide-material-data-sheet_0.pdf
- *Similar product drawings:*
    - https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/s600-8532.pdf
    - https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/s600-8565.pdf
    - https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/s600-8391.pdf

NaI Scintillator Slab (Calorimeter)

<u>Missing details:</u>

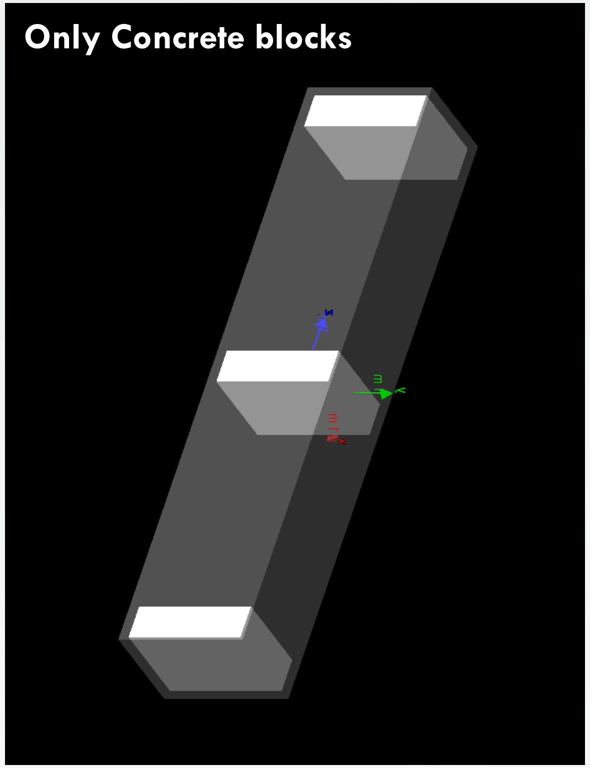
- Spacing between various elements
- Placement/Alignment of NaI Slab inside the HMB Box

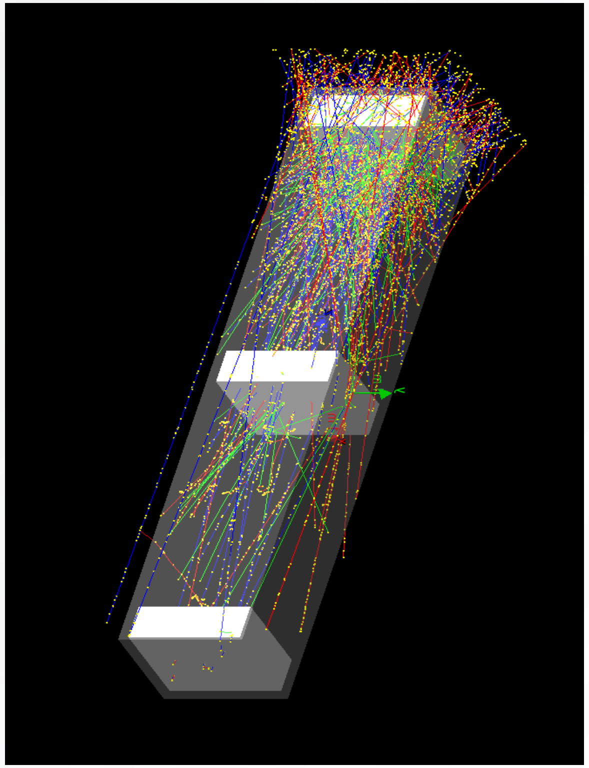


Change in Muon KE due to Concrete & Rebars

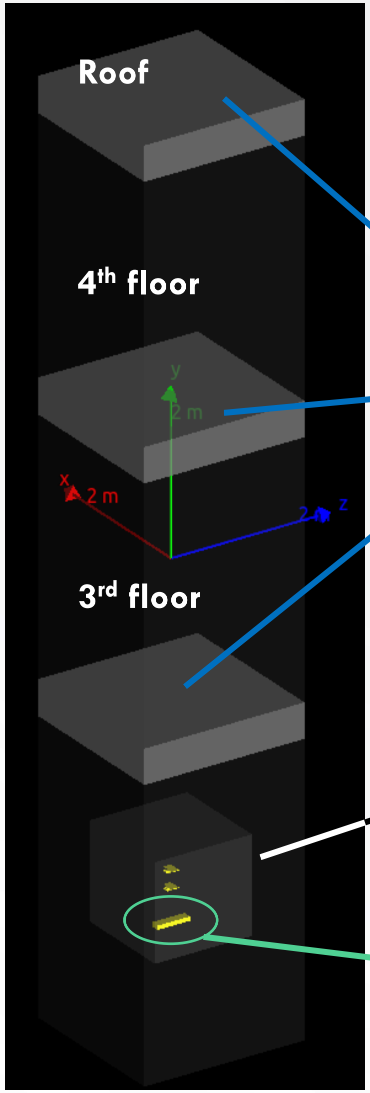
- Concrete thickness: 8.25 in
- Material: G4_CONCRETE

- Estimated thickness of rebars: 1 in.
- Material: G4_Fe





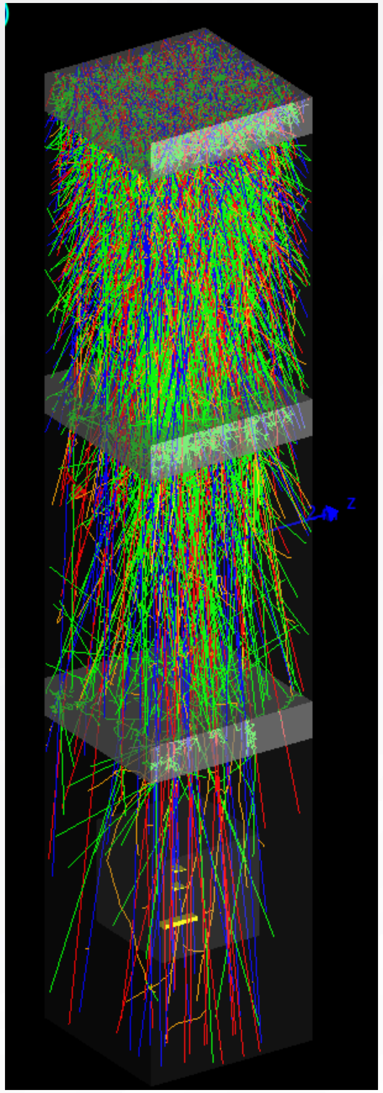
Including building structures in simulation



Concrete slabs (no rebars yet)

HMB black box

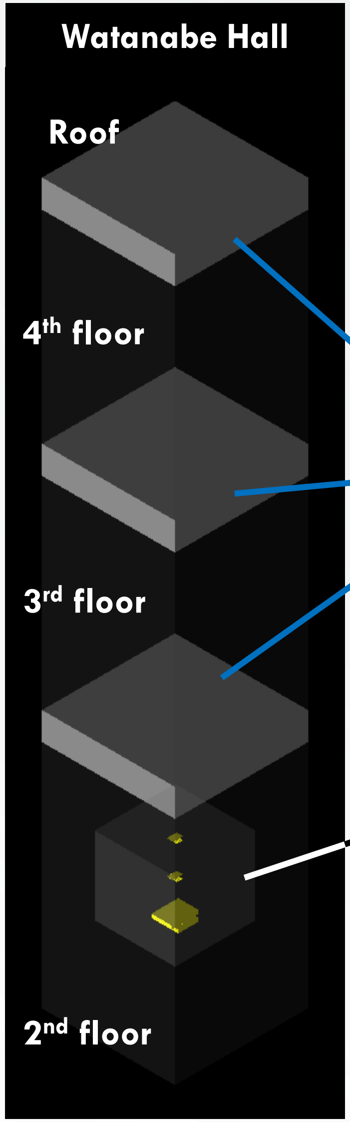
Single NaI slab



Color codes:

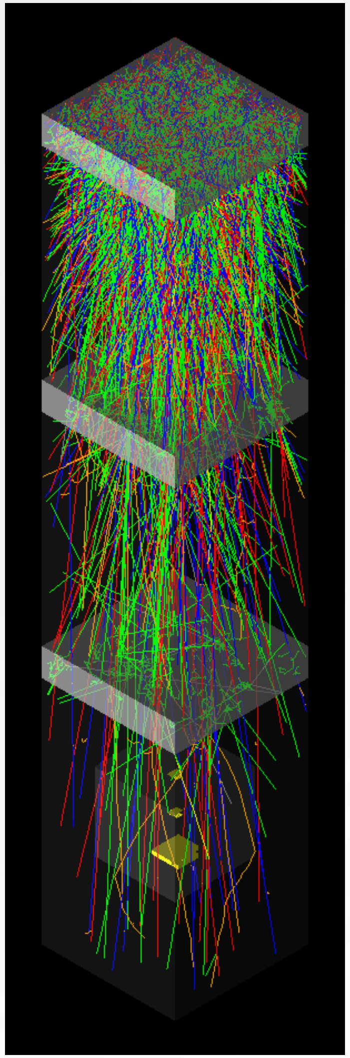
Default color: grey
μ+ : blue
μ- : red
gamma : green
e+ : yellow
e- : orange
neutron : grey
pi+ : grey
pi- : grey
proton : grey

Improved Geometry, Physics & output to Root



Concrete slabs (no rebars yet)

HMB black box

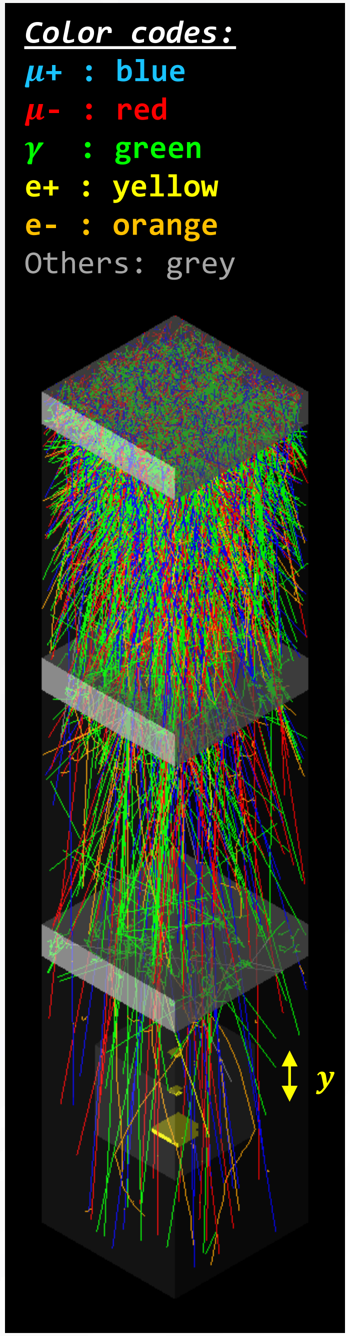


Color codes:
μ+ : blue
μ- : red
γ : green
e+ : yellow
e- : orange
Others: grey

Using FTFP_BERT Reference Physics List

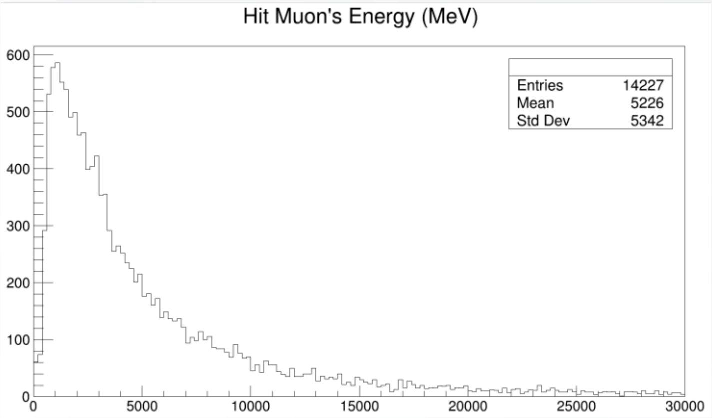
Recommended for Cosmic ray HEP, HEP tracking, HEP calorimetry simulations

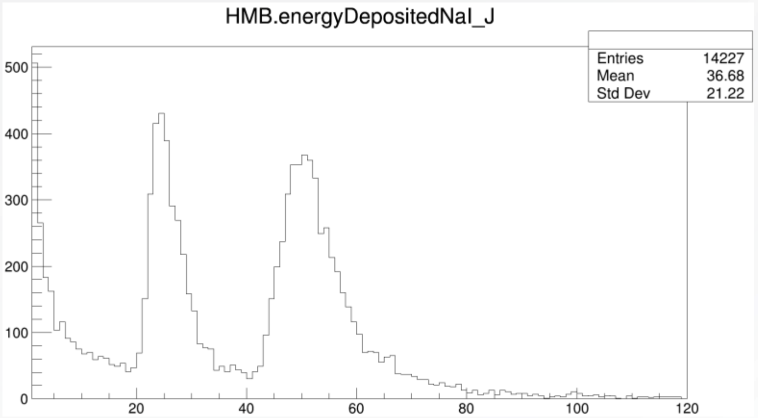
No treatment of optical photons



10M particle simulation ($y = 50$ cm):

- Out of 10M incident Muons, 14249 Muons hit NaI slabs – 0.14%
- Avg. Muon incident rate: 2175 hits per hour (~36 hits/min on NaI slab)
- Total energy deposited: 413.38 ± 5.00 kJ in ~6.5 hours assuming above hit rate (~17.66 J/s or ~1.0 kJ/min)





FTFP_BERT: Fritiof parton model (FTF), Bertini and Precompound models.