PIP-II Beamline MC Simulation For Low Energy Neutrinos

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Proton Improvement Plan -II Beamline Monte Carlo Simulation For Low Energy Neutrinos

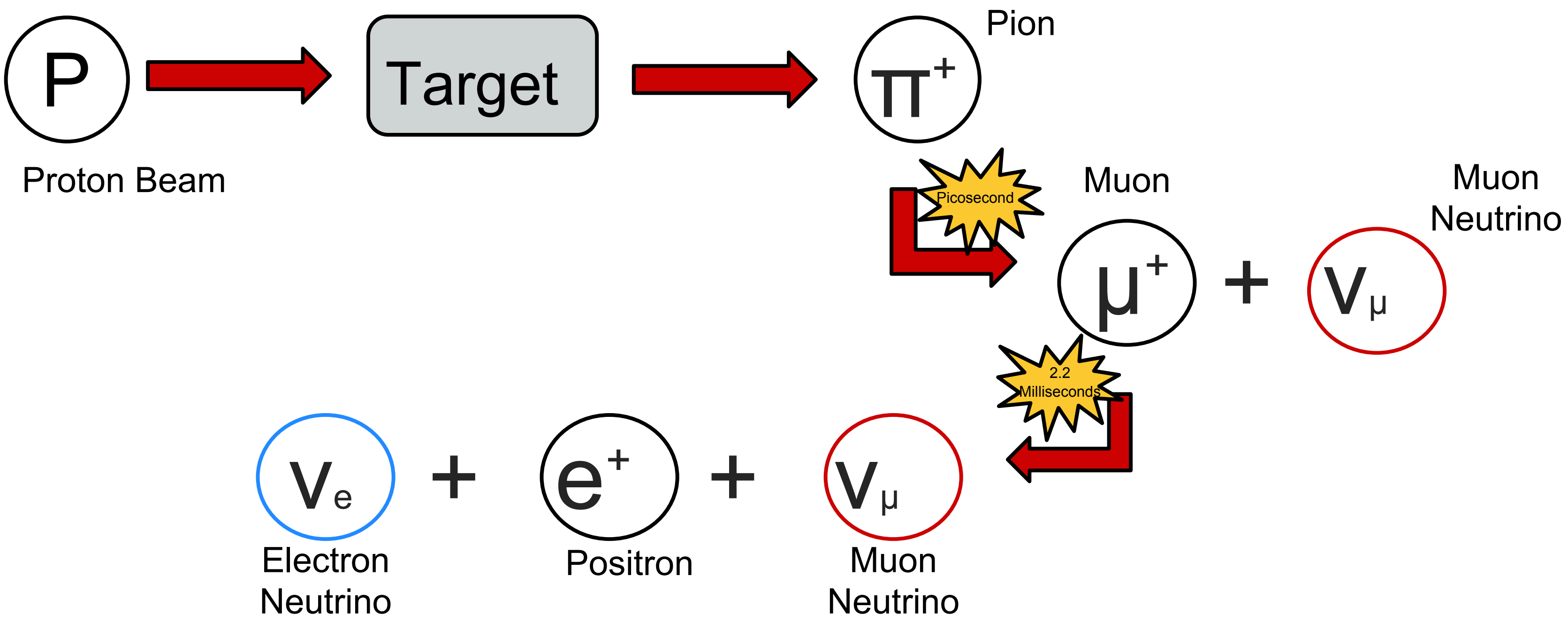
Goal

★ My goal for this project is to simulate several different beamline models in order to help design a new neutrino beam.

Phrases To Know:

- **Neutrinos**: Extremely tiny particles (leptons) that have such a low interaction rate, they practically never collide with anything. 65 billion solar neutrinos pass through every square centimeter on earth each second.
- **Flavors of Neutrinos**: I tested for Electron Neutrinos and Muon Neutrinos. However, there is another type, or flavor, of neutrino called the Tau Neutrino which I did not test for.
- **Anti-Neutrinos**: All particles have an antiparticle. For example, the electron has an antiparticle called a positron. I searched for Electron Anti-Neutrinos and Muon Anti-Neutrinos.

Pion Decay and Neutrino Creation

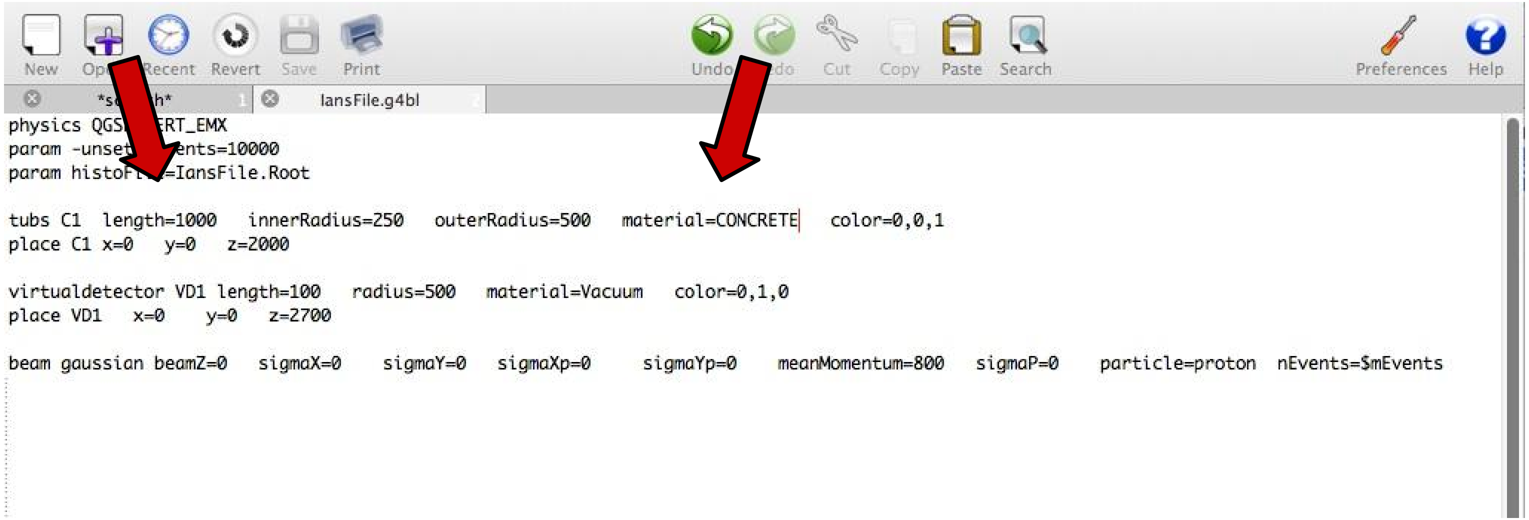


Speed Of The Proton Beam

If the energy of the proton beam is 800 MeV, then the speed of the protons is about 2.034 $x10^5$ km/s. I found this by using an equation for relativistic kinetic energy:

$$E_k = m\gamma c^2 - m_0 c^2 \quad \text{where} \quad \gamma = (\sqrt{(1-(v/c)^2)})^{-1}$$

Writing Simulations

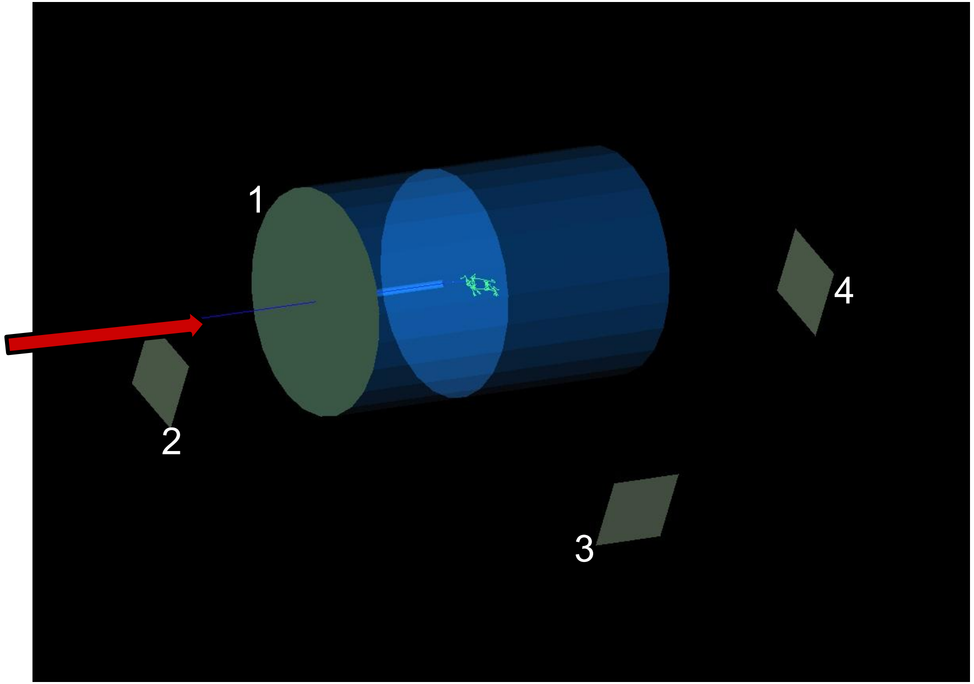


I used Emacs software to write simulations for G4Beamline. This example is instructions for a 1 meter long concrete cylinder and one circular particle detector.

G4Beamline Models and Detectors

This model has 4 detectors, one green circle that measures the initial data and 3 green squares that measure the neutrinos.

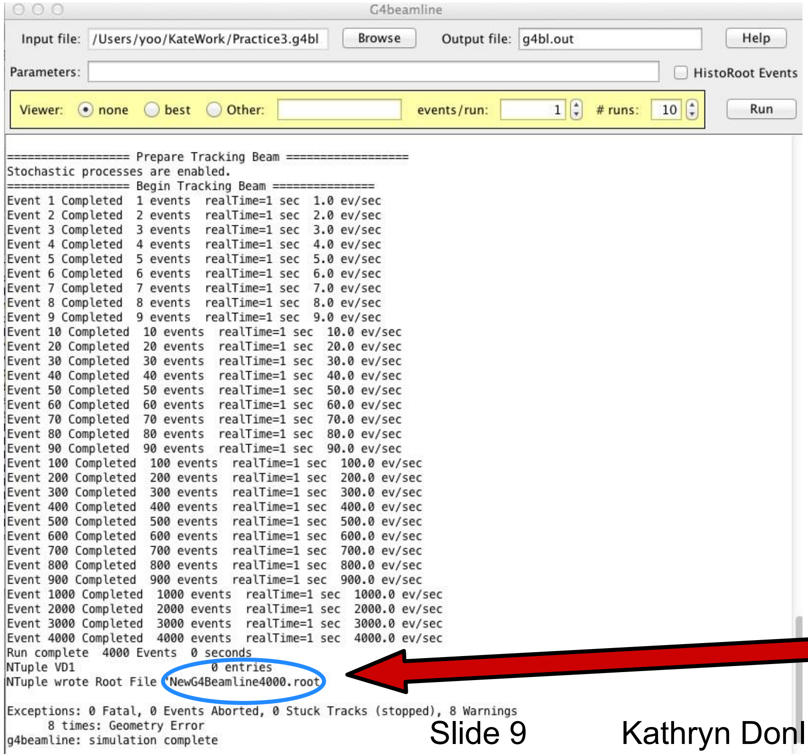
Proton Beam



The squares are all 2mx2m ($4m^2$) and each are 10m away from the collision site.

G4Beamline Data

Once I created the model, I ran the simulation in G4Beamline to collect data.



Then, G4Beamline writes me a ROOT file of the data.

Using ROOT

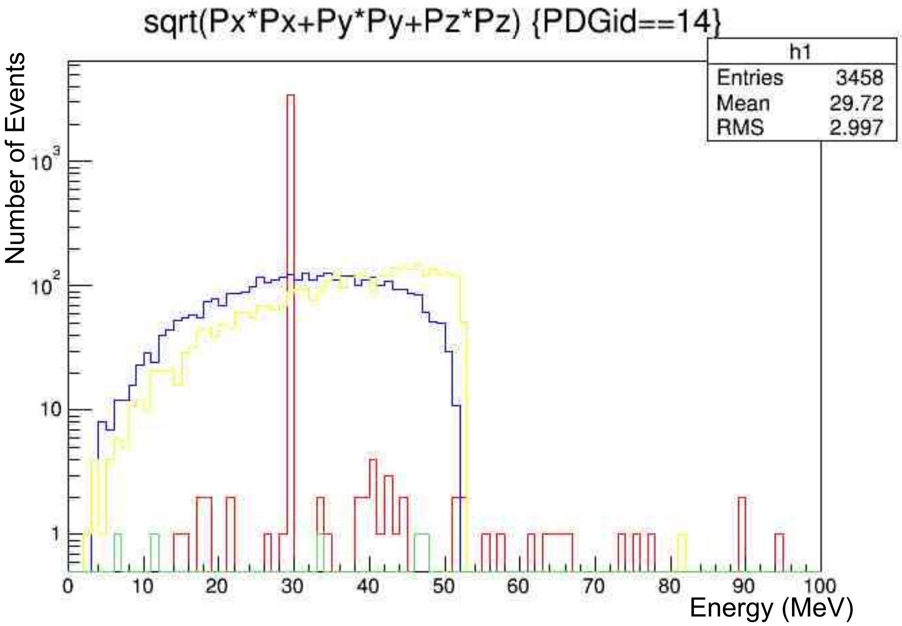
Once G4Beamline has run my simulation and collected data, I put the data into a program called ROOT, which helps me draw histograms. ROOT uses C++ so I had to learn that too.

```
  *******************************************
  *                                         *
  *        W E L C O M E  to  R O O T       *
  *                                         *
  *   Version   5.34/18     14 March 2014   *
  *                                         *
  *  You are welcome to visit our Web site  *
  *          http://root.cern.ch            *
  *                                         *
  *******************************************

ROOT 5.34/18 (v5-34-18@v5-34-18, May 28 2014, 11:18:25 on macosx64)

CINT/ROOT C/C++ Interpreter version 5.18.00, July 2, 2010
Type ? for help. Commands must be C++ statements.
Enclose multiple statements between { }.
root [0] .x Simulation1.C("NewPro10MeV300000.root")
File Name Is: NewPro10MeV300000.root
TDirectoryFile*        VirtualDetector VirtualDetector
 KEY: TNtuple    VD1;1   VirtualDetector/VD1
 KEY: TNtuple    VD2;1   VirtualDetector/VD2
 KEY: TNtuple    VD3;1   VirtualDetector/VD3
Which PDGid Code?
```

Neutrino Energy



Blue: Electron Neutrinos (3,657 Events/4m²)

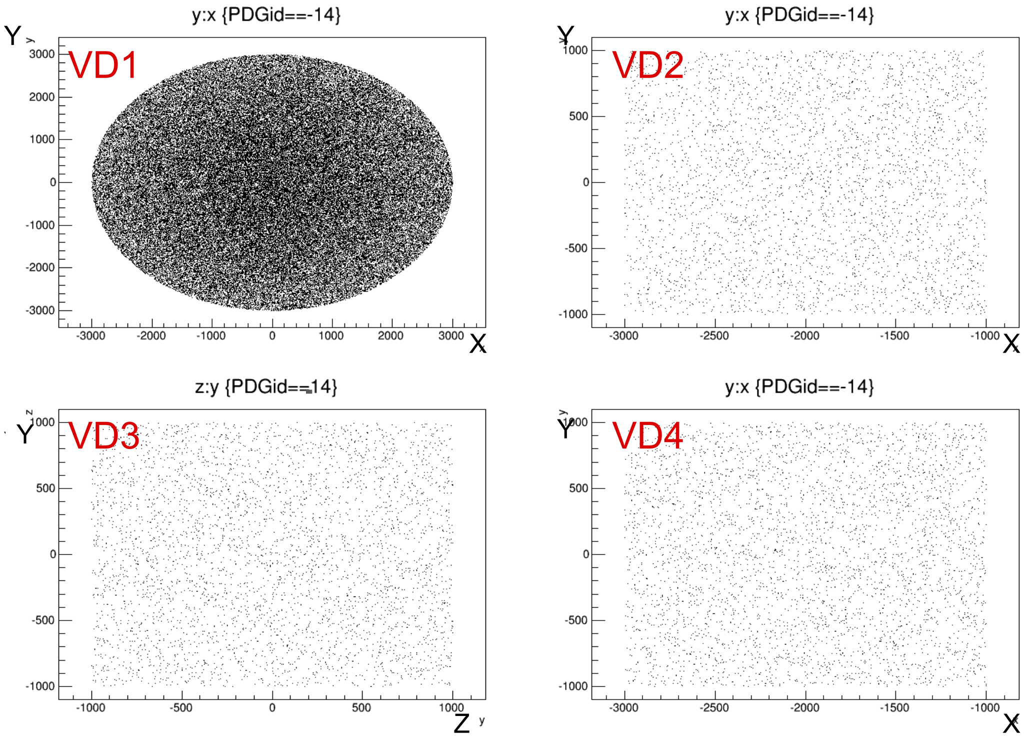
Green: Electron Anti-Neutrinos (5 Events/4m²)

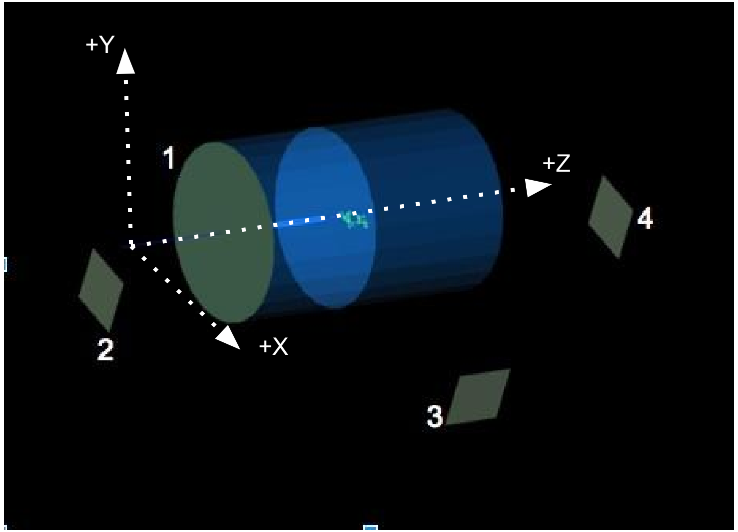
Red: Muon Neutrinos (3,458 Events/4m²)

Yellow: Muon Anti-Neutrinos (3,567 Events/4m²)

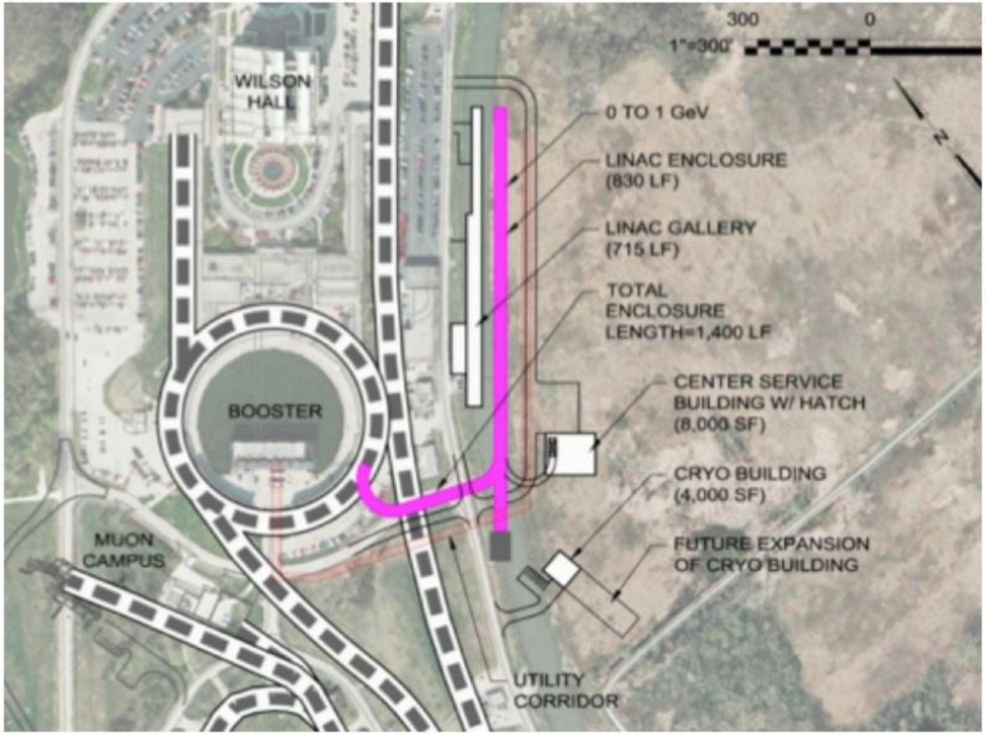
(This data is from detector 4)

Data From Different Planes





Fermilab Linear Accelerator → Proton Improvement Plan (Future)



LINAC beam energy: **800 MeV**

LINAC beam power capability: **200kW**

Number of protons per pulse: **1×10^{14} protons/pulse**

Repetition rate: **15 Hz (=1.6×10^{15} protons/s)**

Results

My proton beam has 10 million protons. This is how many neutrinos were detected:

Electron Neutrinos: **3,657** Events / $4m^2$

Electron Anti-Neutrinos: **5** Events / $4m^2$

Muon Neutrinos: **3,458** Events / $4m^2$

Muon Anti-Neutrinos: **3,567** Events / $4m^2$

The LINAC at Fermilab releases **$1x10^{14}$** protons per pulse instead of the **$1x10^{7}$** I simulated.

3,657 neutrinos / $4m^2$ = 914.25 neutrinos / m^2

However, I can use the ratio of:
914.25 electron neutrinos / $1x10^{7}$ protons
in order to estimate the number of neutrinos I would create per square meter for **$1x10^{14}$** protons in the actual beam.

$9.1425x10^{2}$ / 10^{7} = $9.1425x10^{9}$ / 10^{14}

So I could expect to create about **9.14 billion** electron neutrinos per square meter of detector.

Total Neutrino Statistics

Predicted number of created neutrinos per $1x10^{14}$ protons

Electron Neutrinos: $9.1425x10^{9}$ or 9.1425 billion neutrinos / square meter

Electron Anti-Neutrinos: $1.25x10^{7}$ or 12.5 million / square meter

Muon Neutrinos: $8.645x10^{9}$ or 8.645 billion / square meter

Muon Anti-Neutrinos: $8.9175x10^{9}$ or 8.9175 billion / square meter

Summary

★ I created neutrinos beam simulations using a variety of software

★ I collected and analyzed the data from the simulations

★ I theorized what the data would be like in a real life experiment with different variables

Special Thanks To:

- ★ Jong-Hee Yoo
- ★ Chris Stoughton
- ★ George Dzuricsko
- ★ Ian McNair
- ★ Andrew Olivier

- ★ **FermiLab**
- ★ **QuarkNet**

- ★ Emacs
- ★ G4Beamline
- ★ ROOT

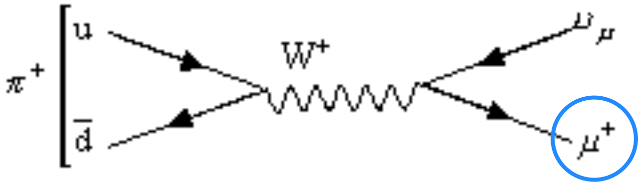
The End!

Thanks for listening!

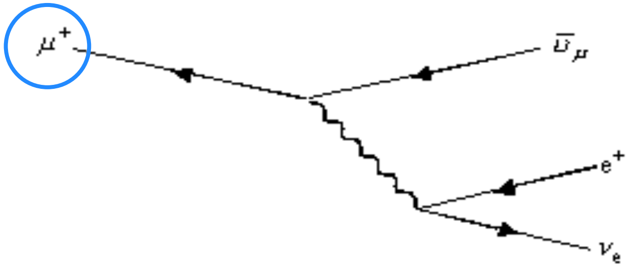
Backup Slides

How Are the Neutrinos Created?

When the proton beam hits the target, pions are created.

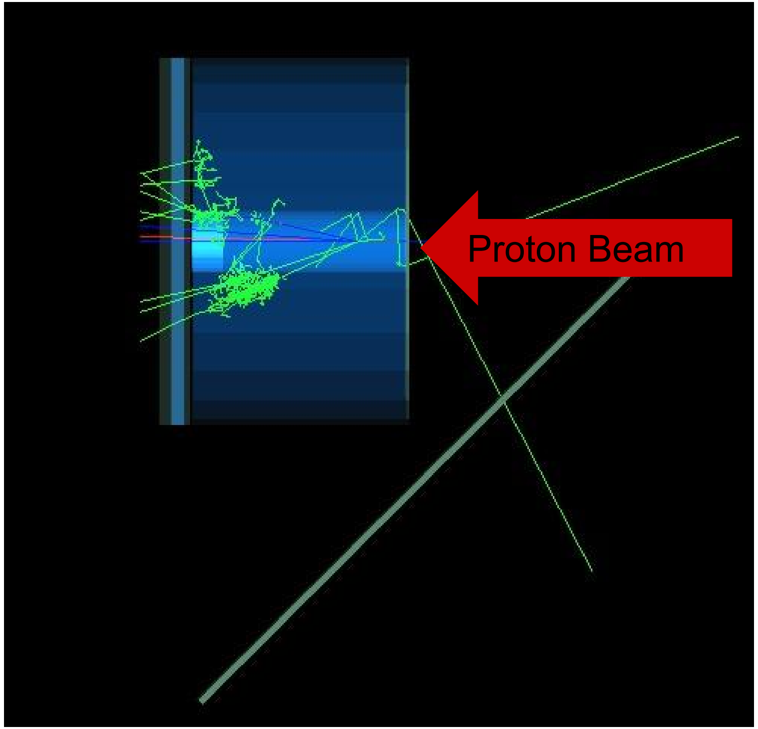


The pions decay into muons and muon neutrinos.



Then the muons decay into electrons, electron neutrinos, and more muon neutrinos.

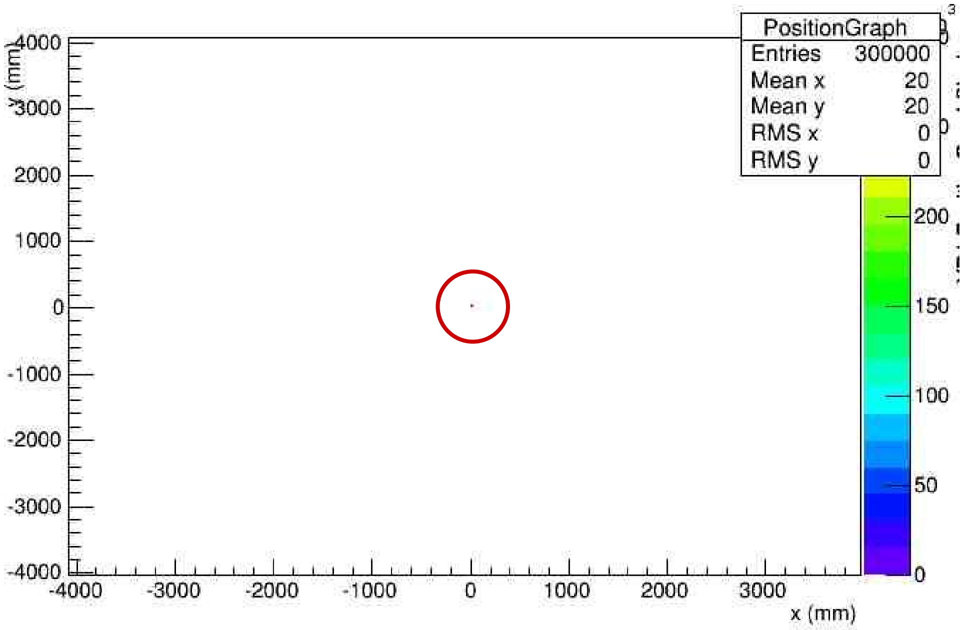
G4Beamline Models



This is a G4Beamline preview of a simulation. I used this to check that I had the model exactly the way I wanted it before I collected data.

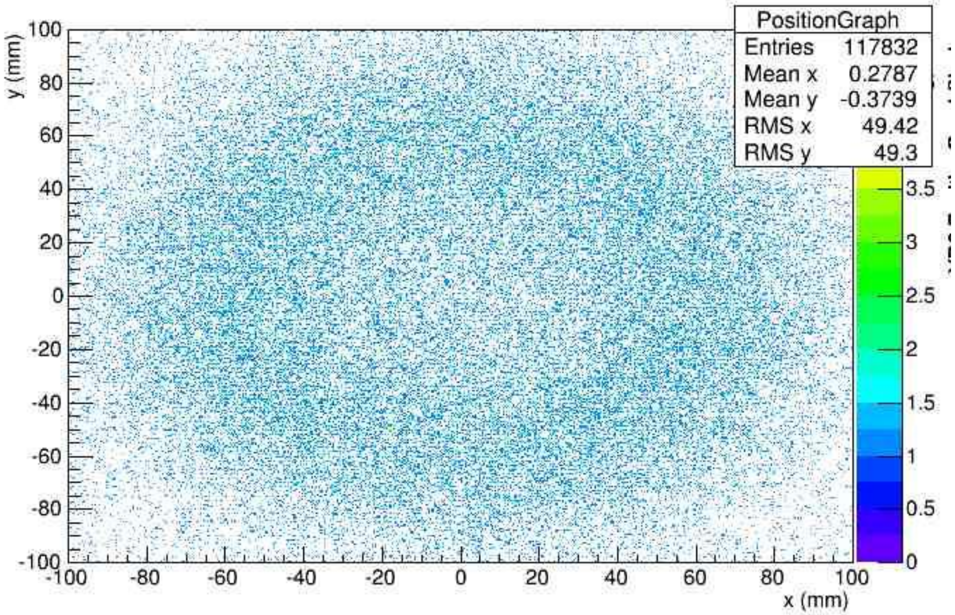
The neon jets are paths that some of the particles took when I ran the simulation.

G4Beamline Scatter Plots



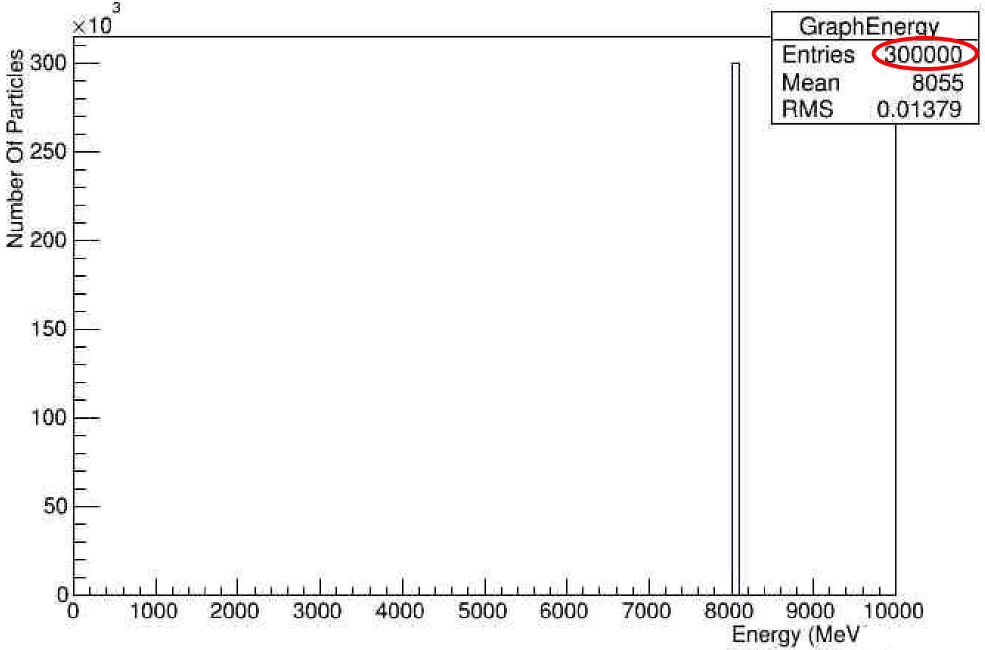
This is a scatter plot of 300,000 protons before hitting a target. They are tightly compacted into a beam, which is why all 300,000 points look like one tiny point.

G4Beamline Scatter Plots Cont.



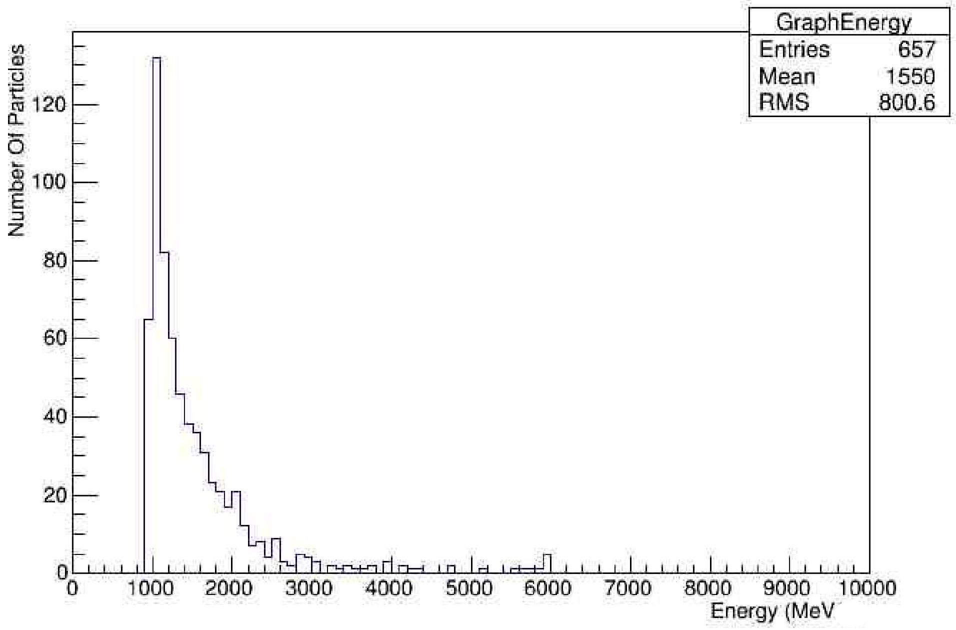
This plot represents the positions of a group of protons that dispersed after hitting a target.

Histograms



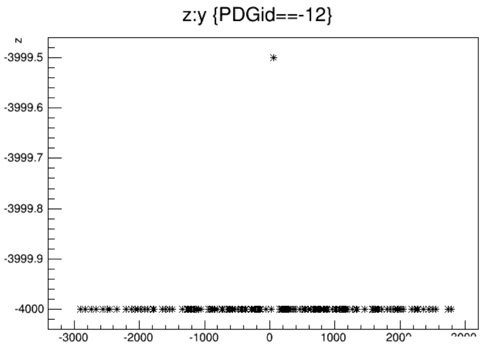
This graph represents the energy of 300,000 protons before they make contact with a target.

Histograms Cont.

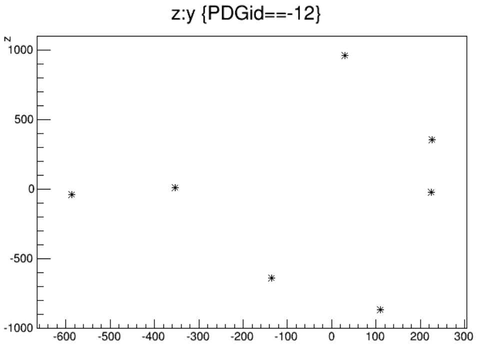


This graph represents the energy of a group of protons after making contact with a target.

Neutrino Positions

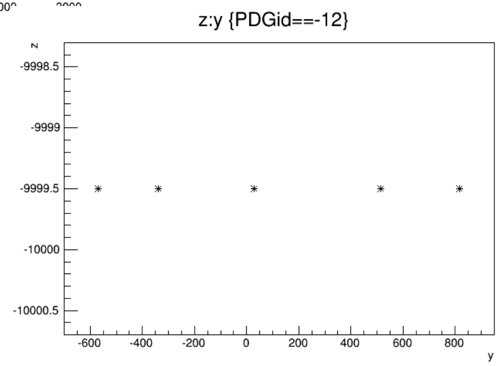


Virtual Detector 2

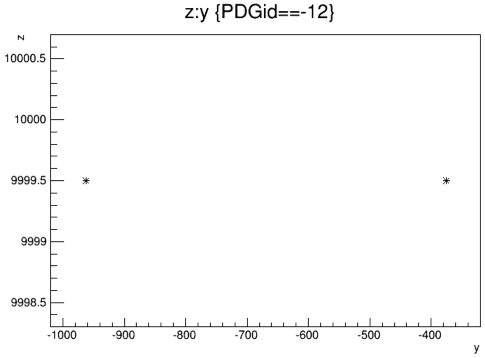


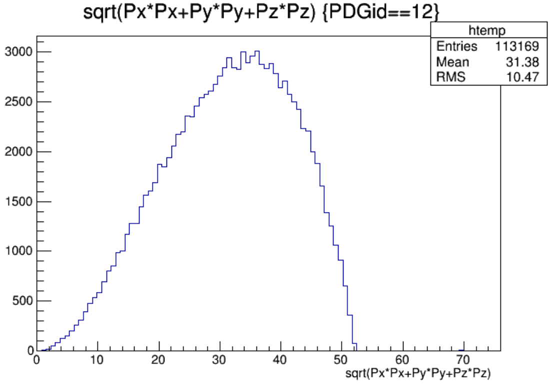
Virtual Detector 4

Virtual Detector 1



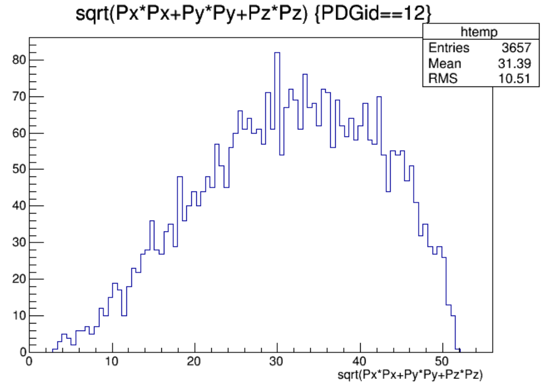
Virtual Detector 3

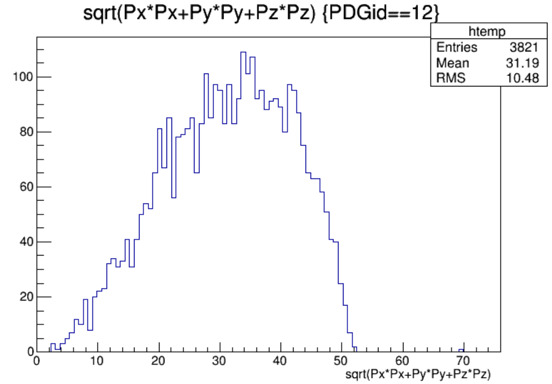




Virtual Detector 1

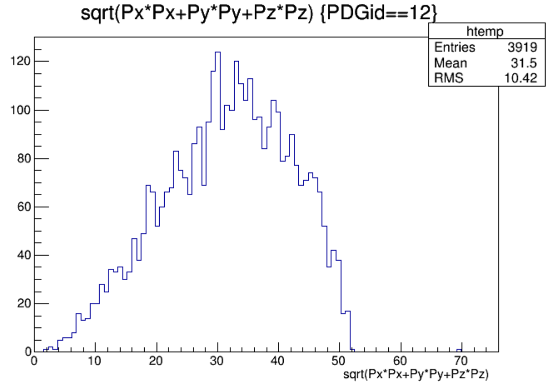
Virtual Detector 2





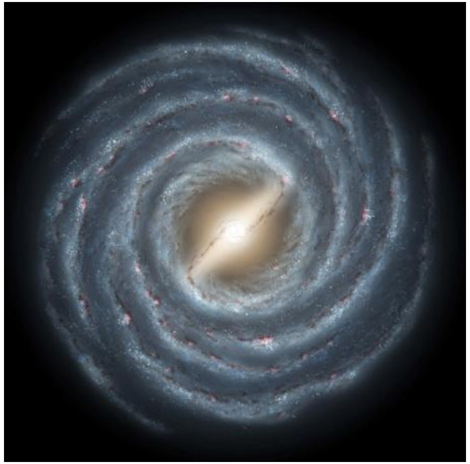
Virtual Detector 3

Virtual Detector 4



Fun Fact!

Did you know more neutrinos would fit in the Sears tower than Sears towers would fit in the Milky Way Galaxy?



Yes, I actually did the math.