Exp-3: Data Analysis

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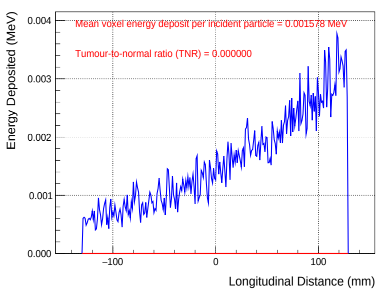
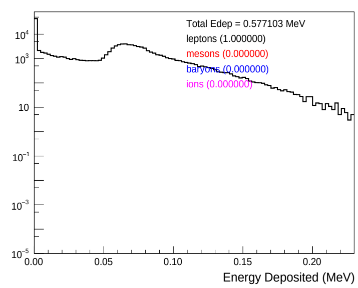
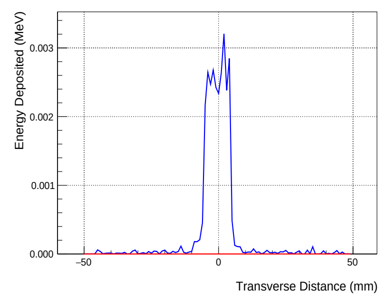
Question 1: **Gamma 1 MeV**



(a) Longitudinal Dose Profile



(b) Dose Profile

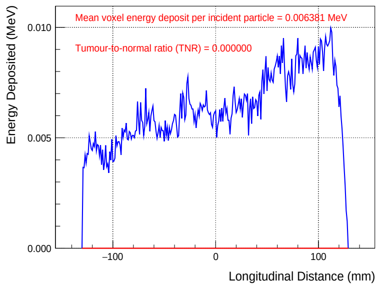


(c) Transverse Dose Profile

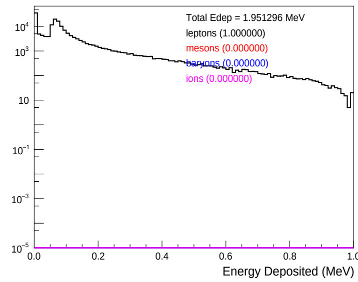
Explanation: Each simulation run outputs 3-plot results: dose profile per particle, longitudinal profile, and transversal profile. Dose profile per particle plot (histogram), represents each beam treatment as a counting event per energy deposition. It also displays total energy deposition and fractional contributions based on each particle type. Longitudinal plot represents a trend of energy per particle depositing as the treatment beam travels alongside parallel to the phantom phantom. Mean voxel just the energy being deposited per longitudinal volume slice. The transverse plot is a representation of the energy being deposited per transversal slice. So that means the beam is perpendicular to the phantom and goes through it. A 1 Mev gamma beam has a total energy deposited of ($E_{dep} = 0.577$ MeV) with about 100 % lepton contribution. This makes since because of scattering and electromagnetic interactions a photon can have with any lepton. For the longitudinal its clear to see as the beam travels parallel through the phantom it deposition decreases indicating a negative slope trend. This is what makes optimal photon beam to use in certain treatment plan because it decreases risk of hitting healthy cells longitudinally. the mean voxel energy was about 0.001578 MeV. For the transverse direction it deposits mostly through the center of the phantom but certain excess electrons deposit very little to the top and bottom of the phantom. You can see the effect of excess electrons by energy fluctuations as you go farther from the center.

Question 2:

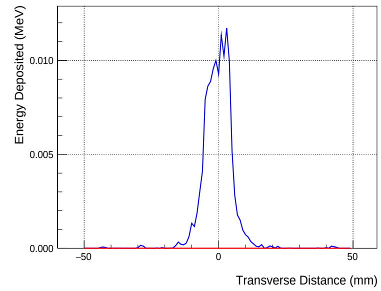
Gamma 5 MeV



(a) Longitudinal Dose Profile

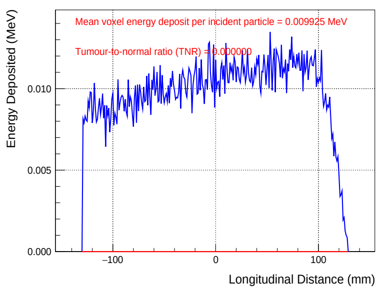


(b) Dose Profile

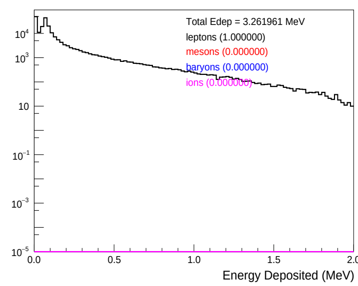


(c) Transverse Dose Profile

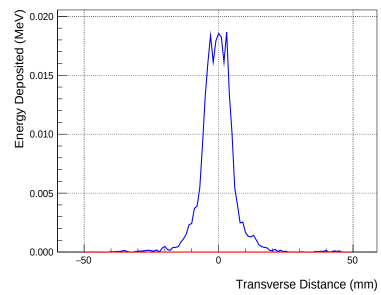
Gamma 10 MeV



(a) Longitudinal Dose Profile

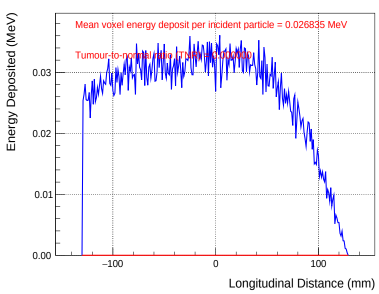


(b) Dose Profile

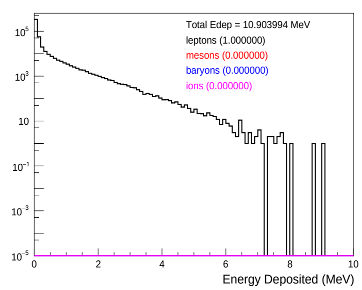


(c) Transverse Dose Profile

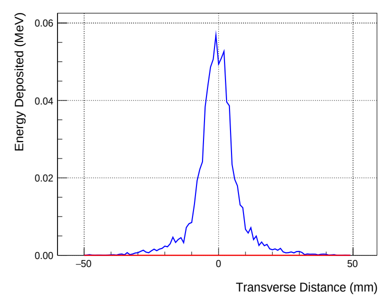
Gamma 50 MeV



(a) Longitudinal Dose Profile



(b) Dose Profile

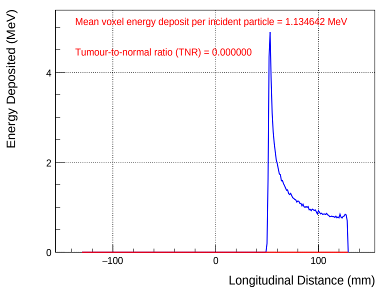


(c) Transverse Dose Profile

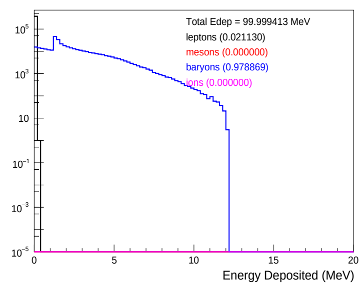
Explanation: For gammas of 10,50, and 100 MeV the first thing that is noticeable is total deposition increase from 1.95, 3.26 and 10.90 MeV. The most important changes arise in the longitudinal plot. Here's what happens, as you increase beam energy of gammas Deposition trend-line increases as the beam travels longitudinally through the phantom and the transversal plot become more broader. This supports the underlying physics that the Bragg peak of higher gammas gradually increase dose while traveling through the phantom. This shows how healthy organs can be hit with radiated beams

Question 3:

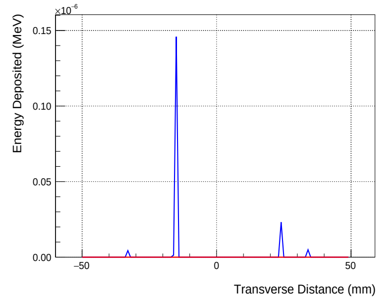
Proton: 100 MeV



(a) Longitudinal Dose Profile

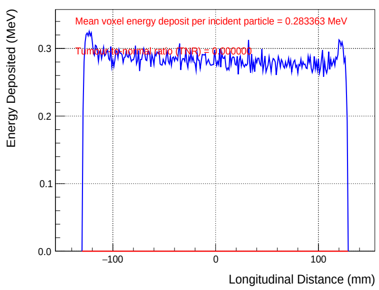


(b) Dose Profile

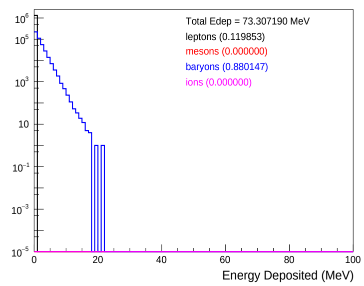


(c) Transverse Dose Profile

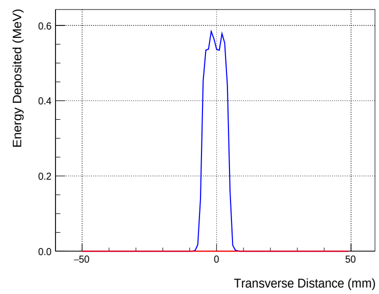
Proton: 500 MeV



(a) Longitudinal Dose Profile

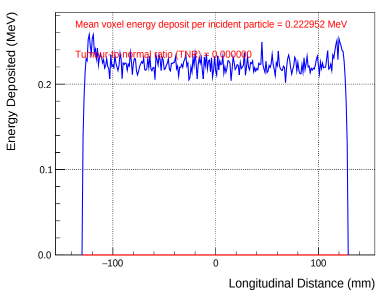


(b) Dose Profile

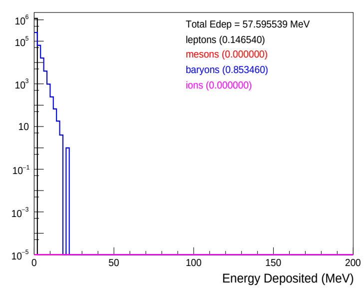


(c) Transverse Dose Profile

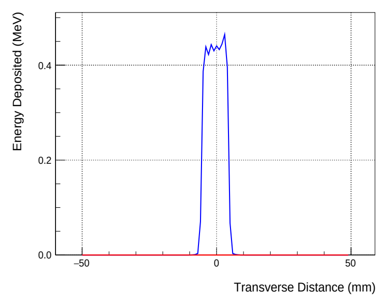
Proton: 1000 MeV



(a) Longitudinal Dose Profile

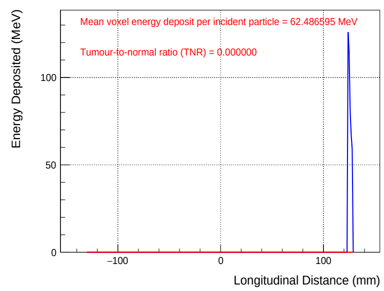


(b) Dose Profile

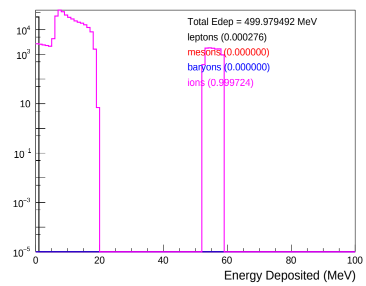


(c) Transverse Dose Profile

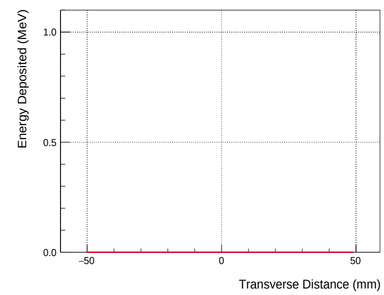
Carbon: 500 MeV



(a) Longitudinal Dose Profile

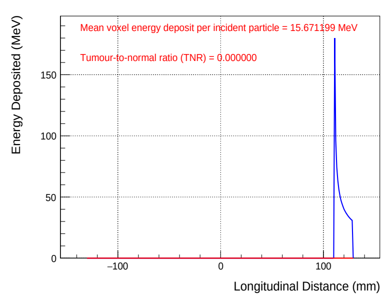


(b) Dose Profile

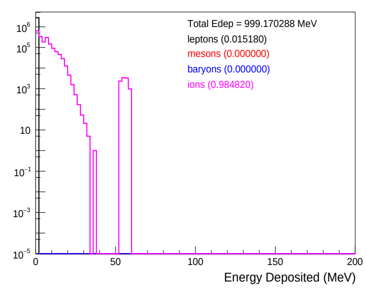


(c) Transverse Dose Profile

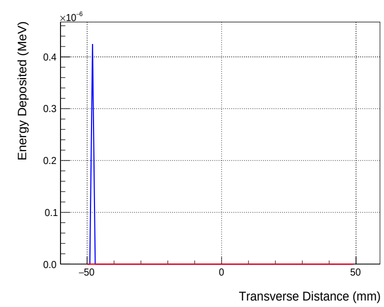
Carbon: 1000 MeV



(a) Longitudinal Dose Profile

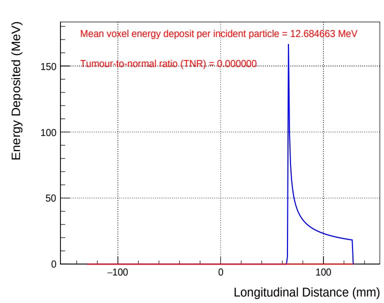


(b) Dose Profile

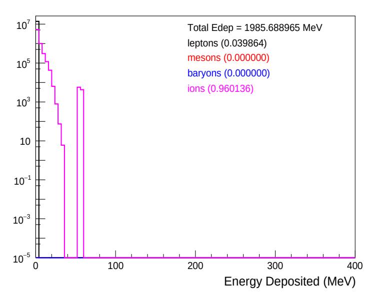


(c) Transverse Dose Profile

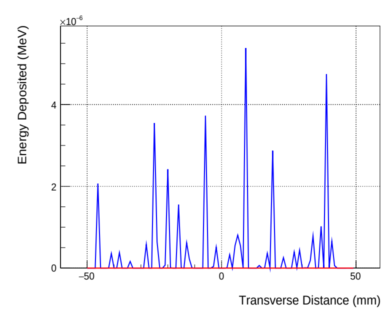
Carbon: 2000 MeV



(a) Longitudinal Dose Profile



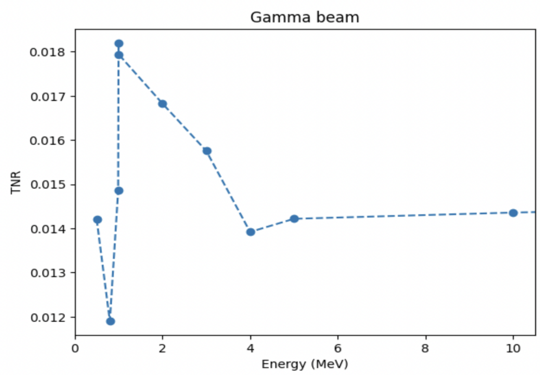
(b) Dose Profile



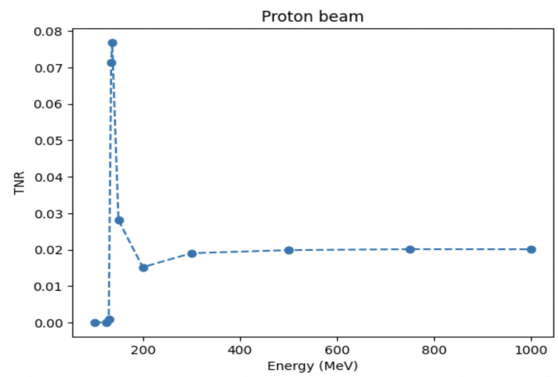
(c) Transverse Dose Profile

Explanation: In this part were using the data/plots of high energy proton and carbon ion beams to understand range of penetration in phantom, nature of energy deposit for hadron beams, length scales of Bragg peaks, and to answer when its possible use these specific beams for cancer treatment. For proton beams at lower MeV (100 MeV) exhibit Bragg peaks that rapidly deposit at a certain penetration distance and then deposit rapidly drop. For the 100 Mev plot it can be shown when beam is traveling 100-50 mm distance the deposit rapidly up to 6 Mev then rapidly decreases. This gives important principle for protons at lower Mev they the energy deposition is concentration at a certain depth of a phantom. Even at this energy range the beam is barely crossing through certain surfaces laterally of the phantom. As you go into higher MeV like for 500 and 1000 Mev you see a Bragg peak that has constant deposit at all longitudinal penetration of about 0.2-0.3 MeV per voxel. Even at the transverse direction the beam is very concentrated at the center of the phantom. For protons beams as beam energy increases the FWHM is more broad in terms of desribing the Bragg peak. For carbon ions it exhibit more steep like Bragg peaks as you increase beam energy for example of the data collected from 500-2000 MeV. At 500 MeV the Bragg Peak exhibits more voxel energy deposit compared to the 1000 and 2000 MeV, at around 62.49 MeV. This beam barely penetrates longitudinally. As you increase Carbon beams energy they exhibit Bragg peaks with constant dose deposit for full penetration. For Carbons beams of 500-2000 Mev they have more steep FWHM. This means these beams are good at depositing large amounts of energy abruptly at a specific penetration For treatment plans protons are better and take less beam energy input to get constant dose deposit per whole penetration as in comparison with Carbon ions it takes higher Mev close 5000-7000 Mev. For lower MeV (500-1000 Mev) Carbon ion can have higher deposit if a tumor needs to be hit a specific confined region of penetration.

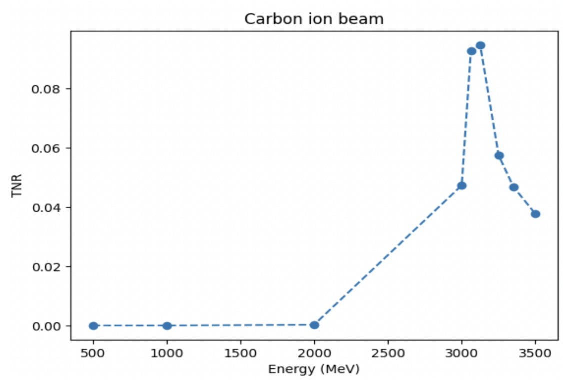
Question 4: The tumor was switched on by editing the line in the macros/DetectorSetup.mac by changing the spherical tumor volume to 1. Afterwards the objective is to find the energy that would maximize the TNR ratio. This was done by observing the variation in the TNR value for different energies and doing a binary search to obtain the maximized value. Below shown is the analysis plot conducted to obtain the maximized TNR ratio for gamma, protons and carbon ions. **Question 5:** It can be observed that the



(a) Gamma beam



(b) Proton beam



(c) Carbon ion beam

Table 1: Maximized TNR values for respective energies

Beam	**Energy (MeV)**	**TNR value**	**Error in TNR**
Gamma beam	0.999	0.018197	0.0033
Proton beam	137	0.076894	0.0488
Carbon ion beam	3125	0.094831	0.0019

energy of leptons, baryons, mesons and ions have increased when there's hadronic interactions. This increase of composition of the particles is due to the strong force that governs hadronic interactions which results in the creation of new particles. It can be observed that after the Hadronic interactions the energy

Table 2: Proton beams: 130 (MeV)

Particles	**Energy deposit per particle (MeV): Before**	**Energy deposit per particle (MeV)**
Leptons	0.031	0.032
Mesons	0.000	0.000
Baryons	0.969	0.958
ions	0.000	0.097
Total energy deposited	129.9946	125.6270

Table 3: Proton beams: 300 (MeV)

Particles	**Energy deposit per particle (MeV): Before**	**Energy deposit per particle (MeV)**
Leptons	0.0962	0.0838
Mesons	0.000	0.0000
Baryons	0.904	0.8959
ions	0.000	0.0204
Total energy deposited	101.3952	115.3085

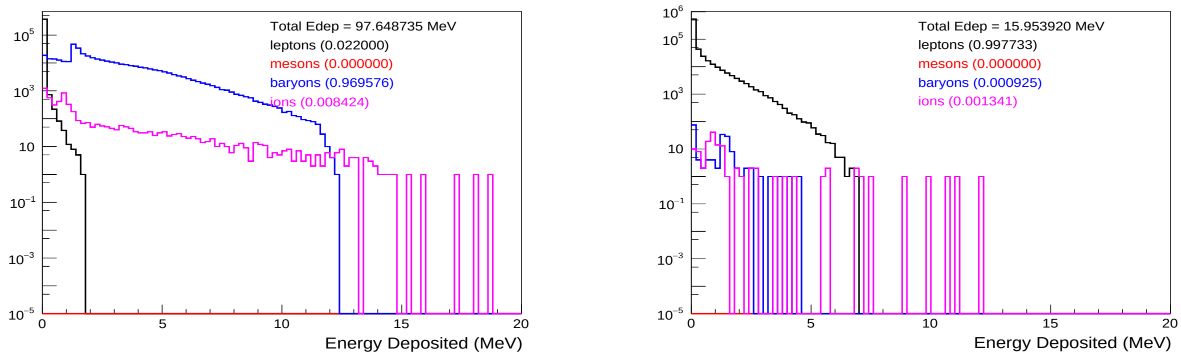
Table 4: Gamma beams: 50 (MeV)

Particles	**Energy deposit per particle (MeV): Before**	**Energy deposit per particle (MeV)**
Leptons	0.9961	0.9961
Mesons	0.000	0.000
Baryons	0.0016	0.0016
ions	0.0022	0.0022
Total energy deposited	10.4693	10.4693

Table 5: Carbon ion beams: 3000 (MeV)

Particles	**Energy deposit per particle (MeV): Before**	**Energy deposit per particle (MeV)**
Leptons	0.0587	0.05880
Mesons	0.0000	0.0000
Baryons	0.0000	0.0515
ions	0.9413	0.8897
Total energy deposited	2953.5344	2686.2268

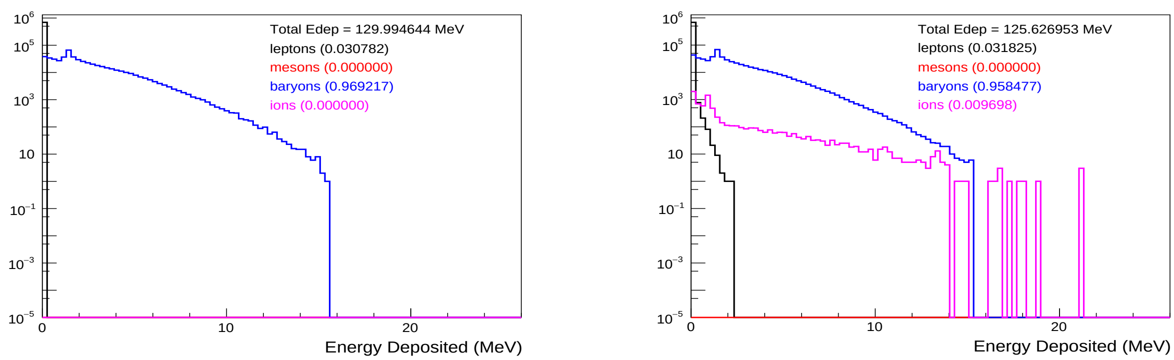
deposited per particle has increased. Ions, mesons, Baryons and leptons are byproducts of the Hadronic interactions. These secondary particles are produced due to nuclear fragmentation, strong force interactions and through the decay of secondary particles. We could also observe a increase in the total energy deposited. This might be due to the fact that the energy is distributed among the secondary particles. Carbon ion beams produce more secondary particles in comparison. This is due to the fact that carbon beams are more heavier and possess a higher charge and are most likely to undergo nuclear fragmentation. Protons have a much smaller mass and therefore has less probability of nuclear fragmentation in comparison to carbon ions. The secondary particles created contains less energy. Finally photon beams have lowest impact when considering the creation of secondary particles as the primary mode of particle production is through Compton scattering and photoelectric absorption and they do not produce secondary particles as heavy ions do. It can be seen in Table 4 that the energy distribution is extremely similar and is not as significant as heavy ions. The secondary particles deposits energy out of the primary beam path mainly around the Bragg peak resulting in an increase in the dose in those regions. This might lead to unintended dose distributions around healthy tissues as well.



(a) Before Hadron Interactions

(b) After Hadron interactions

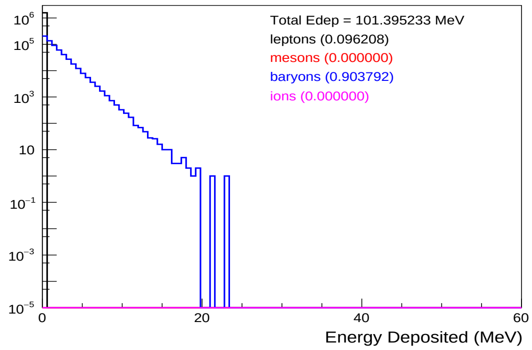
Figure 12: Proton beam: 100 MeV



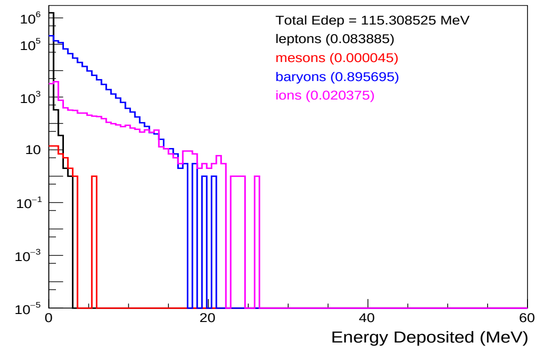
(a) Before Hadron Interactions

(b) After Hadron interactions

Figure 13: Proton beam: 130 MeV

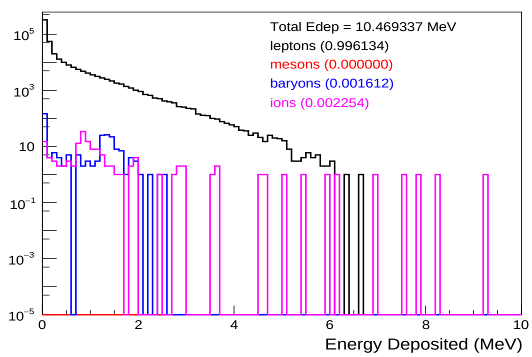


(a) Before Hadron Interactions

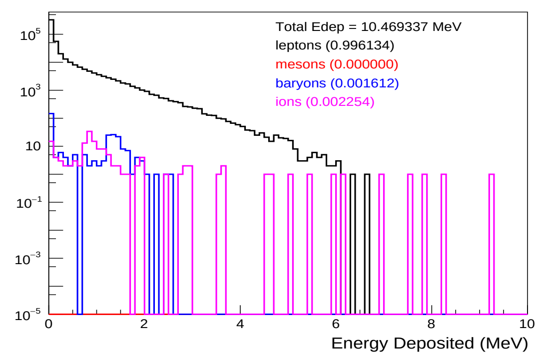


(b) After Hadron interactions

Figure 14: Proton beam: 300 MeV

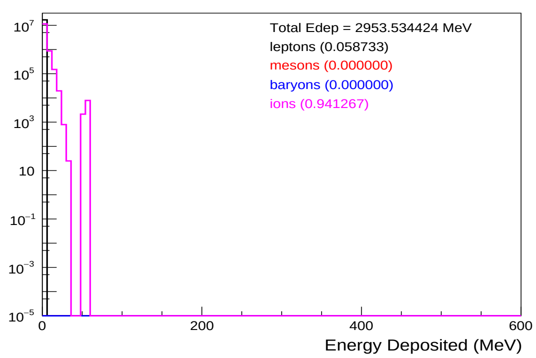


(a) Before Hadron Interactions

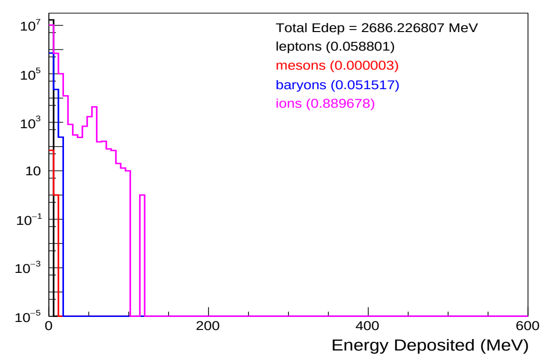


(b) After Hadron interactions

Figure 15: Gamma beam: 50 MeV



(a) Before Hadron Interactions



(b) After Hadron interactions

Figure 16: Carbon ion beam: 3000 MeV