Beam simulations and target studies for the NOνA experiment using G4NuMI

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Contents

Abstract

This is a technical note about some studies performed with the G4NuMI Monte Carlo simulation. Various study will be presented: a comparison between G4NuMI and Flugg about the number of ν_μ and $\bar{\nu_\mu}$ given by the two software; a study on the variation of the neutrino flux with respect to the position of the far detector; a study on the pion trajectories (eg, how may pions hit a particular region of horn 1 or 2). In the penultimate paragraph there is a study on the target. Various target configurations are taken into account in order to find a better confuguration for the neutrino beam. In the last paragraph a preliminary study is performed with a particular target configuration, the airy target, using the Flugg simulation software.

1 Software framework

The whole software framework used to simulate the beamline is composed by:

G4NuMI * A pure Geant4 based simulation of the beamline.

Dk2Nu The G4NuMI output is converted into Dk2Nu ntuple in order to be read by FluxReader.

FluxReader Is a framework designed to make distributions from Dk2Nu flux files.

In order to get the right number of events is necessary to apply a scale factor to the distributions obtained with FluxReader (we are referring to the version of FluxeReader used in the months of August-September 2014). In fact: (i) the FluxReader output considers neutrino flux over a circle surface of $1m$ radius; (ii) it does not multiply by $10^{-38}cm^2$ for plots with cross section included; (iii) it does not multiply by the number of targets. Since the number of targets is:

$$N_{targets} = T \cdot 10^9 g \cdot N_A / M_{CH_2} \tag{1}$$

where T is the mass of the detector (in kton), N_A is the Avogadro number and M_{CH_2} is the molar mass of CH_2. Putting all the factors together we get the number of events $\tilde{n}$ per proton:

$$\tilde{n} = out \cdot \frac{10^{-38}}{\pi \cdot 100 \cdot N_{POT}} \cdot \frac{T \cdot 10^9 g \cdot N_A}{M_{CH_2}} \tag{2}$$

where T is 0.3 for the ND and 14 for the FD and out is the FluxReader output.

In the following, the number of events will be considerd relative to 6×10^{20} POT. To do that we multiply espression (2) by 1, in the form of $6 \times 10^{20}/6 \times 10^{20}$. We want the number of events for $cm^2 \cdot kton \cdot 6 \times 10^{20} POT$:

$$n_\sigma = out \cdot \frac{10^{-38}}{\pi \cdot 100^2 \cdot N_{POT}} \cdot \frac{\cdot 10^9 g \cdot N_A}{M_{CH_2}} \cdot 6 \times 10^{20} = out \cdot \frac{8.2 \times 10^9}{N_{POT}} \tag{3}$$

For a plot with no cross section included the scale factor is simply:

$$n_{\text{no } \sigma} = out \cdot \frac{1}{\pi \cdot 100^2 \cdot N_{POT}} = out \cdot \frac{3.2 \times 10^{-5}}{N_{POT}} \tag{4}$$

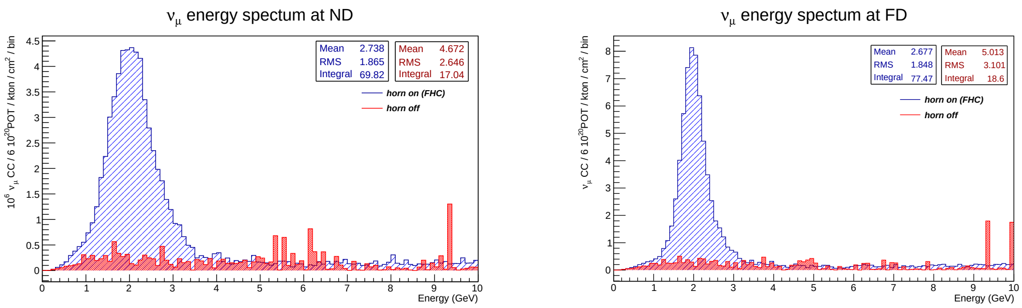
So that, if `histo` is the histogram from the FluxReader output, to get the right number of events we need to scale the histogram in this way:

- cross section: `histo->Scale(8.2e9/N_POT)`
- no cross section: `histo->Scale(3.2e-5/N_POT)`

*Geant4: geant4-09-06-patch-01a; physics list: FTFP_BERT; proto1-numix.

2 Initial spectra

In this section the first plots from the G4NuMI output will be shown. In particular, in Figure 1 we can see the energy distributions for ν_μ both for far (FD) and near detector (ND). The blue histogram is obtained with the standard configuration while the red one is the result obtained switching the horns off, so that the particles are not focused.



(a) *ND* **(b)** *FD*

Figure 1

3 G4NuMI VS Flugg

There are two simulations that are being used in the NOνA experiment, [1]:

G4NuMI A pure Geant4 based simulation of the beamline.

Flugg Uses the same g4numi geometry, but interfaces to fluka for the actual particle physics.

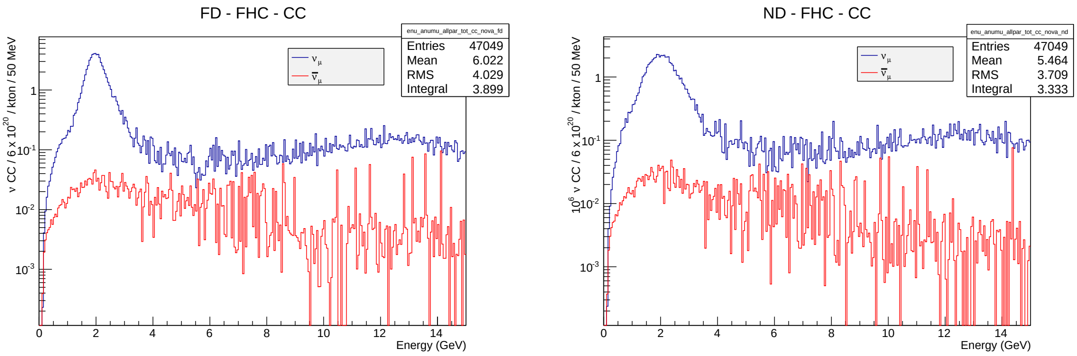
Neutrino spectra calculated with Flugg were provided by R. Schroter [2].

The number of events at the near and far detector obtained with G4NuMI are here presented and compared with the Flugg results.

This study was done considering two horn configurations: FHC (forward horn current) and RHC (reversal horn current).

3.1 FHC

The FluxReader software allows to get neutrino spectra at both the detectors. In Figure 2 is possible to see these spectra for ν_μ and $\bar{\nu}_\mu$. The integral of this spectra, i.e. the number of events, is shown in Table 1 (a) and (b) for two different energy regions. There is also the Flugg result and the ratio between the Flugg and the G4NuMI output.



(a) **(b)**

Figure 2

Table 1

(a) *FHC, FD. ratio = Flugg/g4numi for [1,3] GeV.*

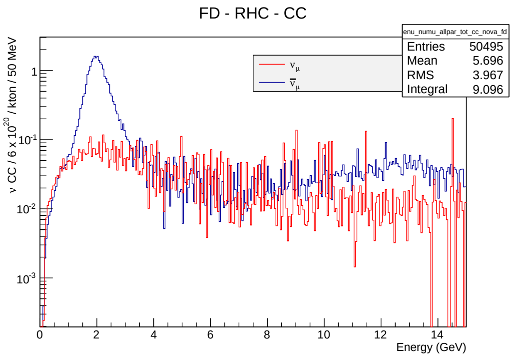
	[1,3] GeV g4numi	[1,120] GeV g4numi	[1,3] GeV Flugg	ratio
ν_μ	63.5	99.4	62.1	97.8%
$\bar{\nu}_\mu$	1.1	5.1	1.0	90.9%
TOT	64.6	104.5	63.1	97.7%
$\bar{\nu}_\mu/\nu_\mu$	1.1%		1.6%	

(b) *FHC, ND. ratio = Flugg/g4numi for [1,3] GeV.* $[\times 10^6]$

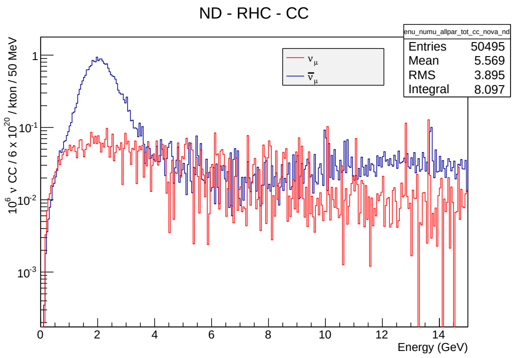
	[1,3] GeV g4numi	[0-120] GeV g4numi	[1,3] GeV Flugg	ratio
ν_μ	53.8	90.1	52.6	97.8%
$\bar{\nu}_\mu$	1.0	4.5	0.9	90.0%
TOT	54.8	94.6	53.5	97.6%
$\bar{\nu}_\mu/\nu_\mu$	1.9%		1.7%	

3.2 RHC

The same study was done by reversing the direction of the current in the horns. In this way we are selecting $\bar{\nu}_\mu$ and the ν_μ are considered as background. The results are shown in Figure 3 (a) and (b) and in Table 8.



(a)



(b)

Figure 3

Table 2

(a) *RHC, FD. ratio = Flugg/g4numi for [1,3] GeV.*

	[1,3] GeV g4numi	[0-120] GeV g4numi	[1,3] GeV Flugg	ratio
ν_μ	2.6	12.1	2.4	92.3%
$\bar{\nu}_\mu$	24.4	35.8	22.5	92.2%
TOT	27.0	47.9	24.9	92.2%
$\nu_\mu/\bar{\nu}_\mu$	10.7%		10%	

(b) *RHC, ND. ratio = Flugg/g4numi for [1,3] GeV.* [$\times 10^6$]

	[1,3] GeV g4numi	[0-120] GeV g4numi	[1,3] GeV Flugg	ratio
ν_μ	2.3	10.6	2.1	91.3%
$\bar{\nu}_\mu$	20.6	32.7	19.1	92.7%
TOT	22.9	43.3	21.2	92.6%
$\nu_\mu/\bar{\nu}_\mu$	11.2%		10%	

4 Variation of neutrino flux with respect to the FD position

The NOνA detectors are placed 14.6*mrad* off-axis with respect to the beam line. The goal of this section is to understand how the neutrino flux varies if the NOνA FD is placed on-axis or off-axis but with an angle different from 14.6*mrad*. 19

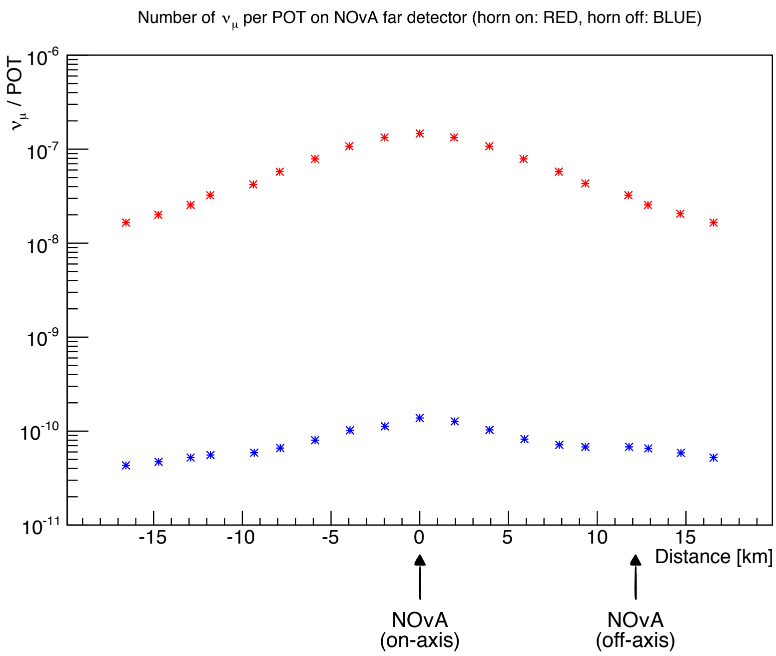


Figure 4: *The distance should be understood as the distance to the beamline. The NOνA FD off-axis position is* $\sim 11km$. *The on-axis position in* $0km$.

different positions were taken into account moving the FD on a line that connects the current FD position to the on-axis position. In this section we are only reffering about the flux, so that in the following plots will be shown the number of neutrinos that reach the FD surface per proton.

This study was done with FHC but also without current in the horns (WHC), i.e. without focusing the particles. This because we want to see how the spread of the distribution of the neutrino flux as a function of the distance varies if are focusing or not the secondaries produced in the target.

FluxReader enables to get the neutrino flux at various position of the FD. In fact is possible to add other *fake* detectors and to get distributions relative to them. To do so we just need to specify the new detector characteristics in the file `Detectors.h`.

The results are shown in Figure 4. A logaritmic scale was used in order to show the FHC (red) and the WHC (blue) contributions.

The difference between the value at the on-axis position and the off-axis (i.e. between the red peak and the red lower point) is 1.1×10^{-7} for FHC and 8.0×10^{-11} for WHC (tha same for the blue points).

In Figure 5 is shown the number of ν_μ for WHC divided by that for FHC. It is possile to see that as we move from the on-axis position to the off-axis the ratio

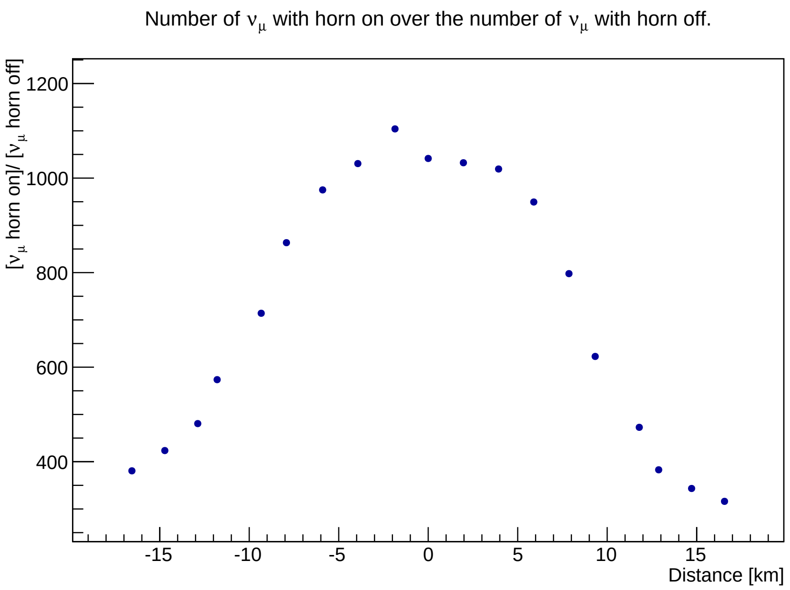
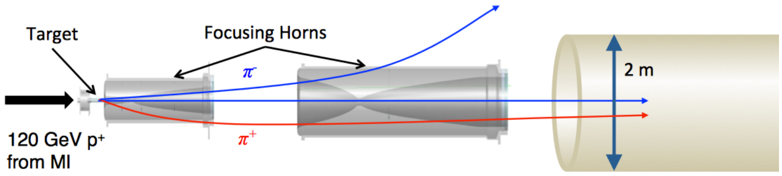


Figure 5: *In this plot is shown the ratio between the blue and the red values in Figure 4.*

increases. This is due to the fact that in the WHC case the distrubution given in Figure 4 is wider than the FHC case.

5 Study on pion trajectories

The beam line for the NOνA experiment is shown here:



There are two horns that produce magnetic fields that focus secondaries. This section is focused on the study of pions trajectories.

The results shown in this section come from a G4NuMI simulation with 10000POT. To reconstruct the trajectory of each pion generated by Geant4, some lines of code were added in the class `NumiSteppingAction`. This class is called by the Geant4 after every step of the simulation; in this way is possible to keep track of each step of a particle: pions in our case.

The total number of pions generated in the simulation is: 20749.

In table 3 is possible to see the number of pions that hit a particular region of horn 1 and 2. Four angular regions, α, β, γ and δ, were defined as shown in Figure 6.

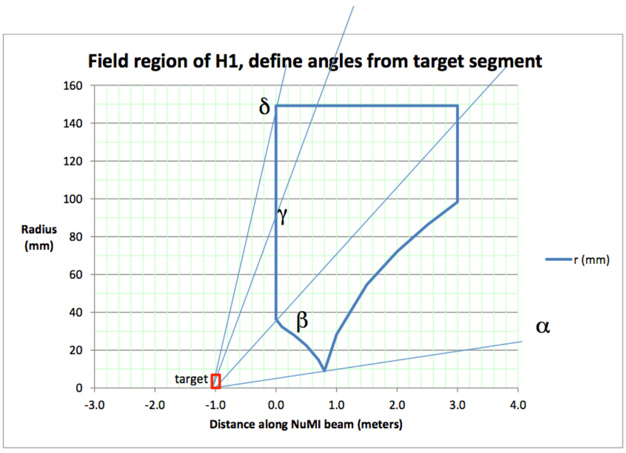


Figure 6: *Schematic rapresentation of a horn.*

The ratios in the tables are calculated dividing the numer of π^+ hitting that particular region of the horn by the total number of pions hitting the whole horn.

In order to understand better the pion trajectories, some distributions regarding the position were the pions are born and were they decay are illustrated in the following.

Table 3: *Number of π^+ that hit a particular region of horn 1 and 2.*
The number of pions hitting horn 2 divided by the number of those hitting horn 1 is: $2321/5107 = 45.4\%$

	Horn 1	ratio H1	Horn 2	ratio H2
$< \alpha$	137	2.7%	145	6.2%
$\alpha - \beta$	2261	44.2%	1814	78.2%
$\beta - \gamma$	1957	38.3%	225	9.7%
$\gamma - \delta$	752	14.7%	137	5.9%
sub TOT	5107		2321	
$> \delta$	1503		694	
TOT	6610		3015	

Table 4: *π^+ disappearance before horn 1 and between horn 1 and horn 2.*
Threshold means that the pion disappeared due to an energy cut of 0.5 GeV by default in the simulation.

	TOT	Reason	# of π^+
Before horn 1	1927	Decay	75
		Threshold	0
		Other	1852
Between h1 and h2	8392	Decay	528
		Threshold	0
		Other	7864

Table 5: *π^+ disappearance along the all beamline.*

	# of π^+ missing
Decay	1696
Threshold	2
Other	19051
TOT	20749

To retrive the position of the π^+ generated in the simulation that decay to generate the neutrino flux the ancestor list in the G4NuMI output has been used. In particular, the following n-tuples were used:

- `startz`: it stores the z position were the particle is created;
- `pdg`: it stores the pdg code of the secondaries.

Table 6: π^+ *disappearance along the all beamline.*
The number of pions that are born and disappeared between horn 1 and horn 2 is: 4480.

	Before H1	Between H1 and H2	After H2	TOT
Born	8519	4798	7432	20749
Dead	1927	8392	10430	20749

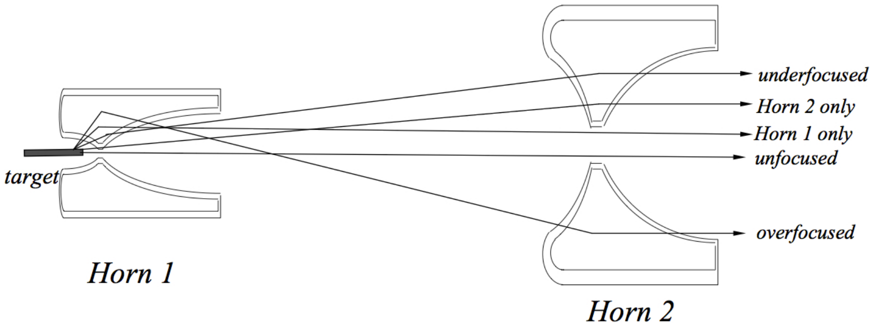
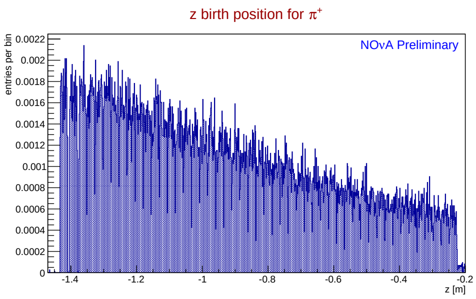
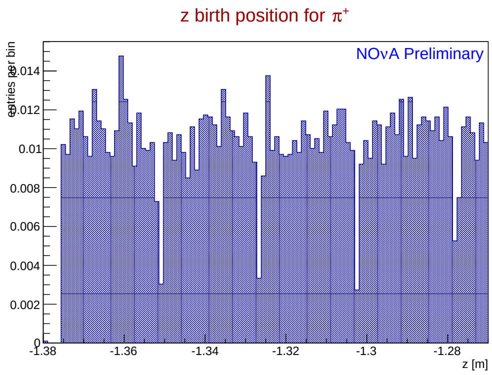


Figure 7: *Horns.*

In Figure 8 is shown the distribution of the positions along the beam line were the π^+ are produced.



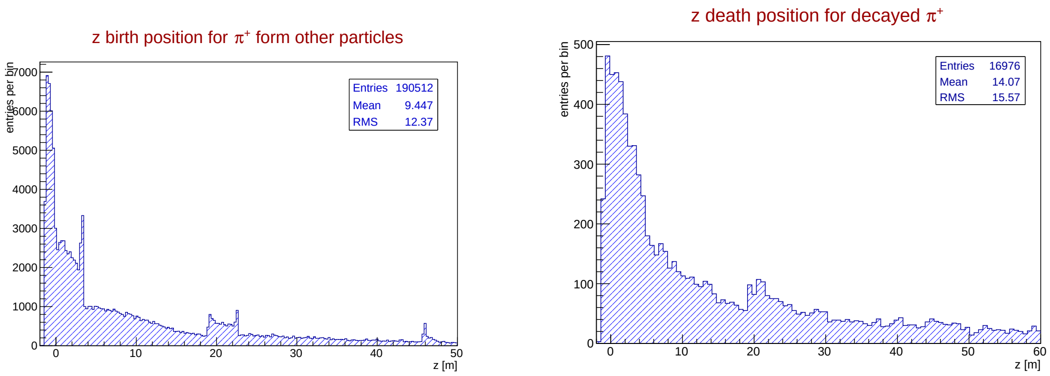
(a)



(b)

Figure 8: *Distributions of the starting point along the beam line were the* π^+ *are produced. Plot (b) is just an enlargement of plot (a) where is possible to see the target structure, made of small fins.*

In Figure 9(a) is shown the distribution of the points along the beam line were the π^+ are born from other interactions (i.e. not from a primary proton). Instead in Figure 9(b) is shown the distribution of the positions were the π^+ decay.



(a) **(b)**

Figure 9: *In plot (a) is shown the distribution of the points along the beam line were the π^+ are born from other kind of interactions (i.e. not from a primary proton). Instead in plot (b) is shown the distribution of the points were the π^+ are decayed..*

The actual target is made of 48 fins plus two budal monitors for the beam alignement. The target, with its dimensions, is shown in Figure 10.

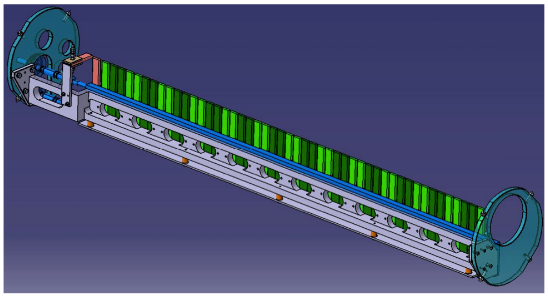


Figure 10: *The NOνA medium energy target. It is composed of 48 graphite fins (green) plus two budal monitors (orange) for alignement. Each fin is end rounded and its dimensions are* $24mm \times 7.4mm \times 63mm$*. There is a gap of* $0.5mm$ *between each fin.*

6 Target studies

It is necessary to optimize the geometry of the target in order to get as many neutrinos as possible. Neutrinos are produced by the decays of the secondaries resulting from protons interactions in the target.

To change the target in the G4NuMI simulation, the two classes `NumiDataInput` and `NumiNOvATarget` need to be modified. For example, in the `NumiDataInput.cc` file, the lines of code that have been modified are:

```
// =================================================
// Nova Medium Energy Target
// =================================================

//  48 Target segments
// + 1 Budal VFHS (Vertical Fin for Horizontal Scan)
// + 1 Budal HFVS (Horizontal Fin for Vertical Scan)

pSurfChk = true;
TargetSegLength       = 24.0*mm;
TargetSegWidth        = 7.4*mm;
TargetSegHeight       = 63.0*mm;
TargetSegPitch        = 0.5*mm;
TargetGraphiteHeight  = 150.0*mm;
TargetEndRounded      = true;
TargetSegmentNo       = 48;
BudalVFHSLength       = TargetSegLength;
BudalVFHSWidth        = TargetSegWidth;
BudalVFHSHeight       = TargetSegHeight;
BudalVFHSPitch        = 4.5*mm;
BudalVFHSEndRounded   = TargetEndRounded;
BudalHFVSLength       = TargetSegLength;
BudalHFVSWidth        = TargetSegWidth;
BudalHFVSHeight       = TargetSegHeight;
BudalHFVSPitch        = 5.0*mm;
BudalHFVSEndRounded   = TargetEndRounded;
```

Listing 1: *From `NumiDataInput.cc`*

6.1 The *airy* target

A preliminary study showed that a lot of pions, once created, interact immediatly in the target. In this way they do not have time to decay. To let them escape, the 48 fins were divided adding more space between them: with a gap of 4 mm between each fin (instead of 0.5mm of the current target).

The neutrino spectra for both the near and the far detectors are shown in Figure 12. The integra value in the plot gives the number of events (due to CC and NC interactions) for $(kton \cdot cm^2 \cdot 6 \times 10^{20} POT)$. In this case we get 4.1% of more flux for the ND and 6.3% for the FD.

In Figure 13 is possible to see the starting point along the beam line were the π^+ are produced for the case in which the airy target is used.

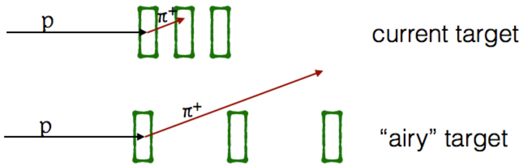
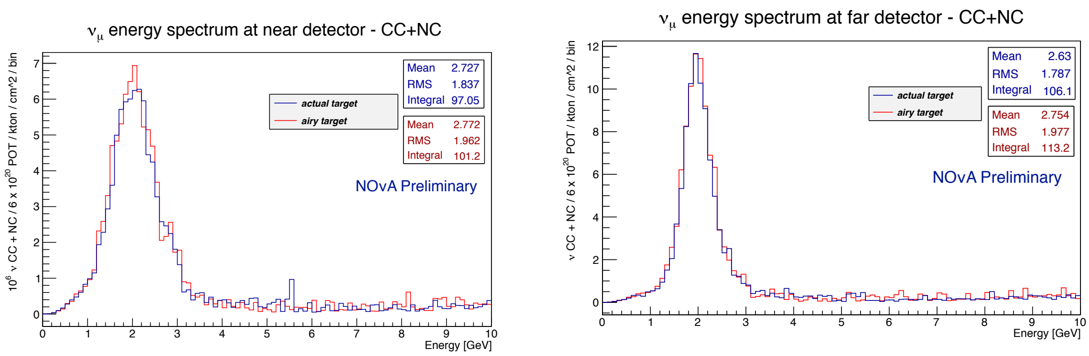


Figure 11: *In this picture the fins are schematized in green. The idea is that with the* airy *target the pions have more space to excape once created.*

So there is the possibility to increase the neutrino flux, but to have a quantitative idea more studies are required.

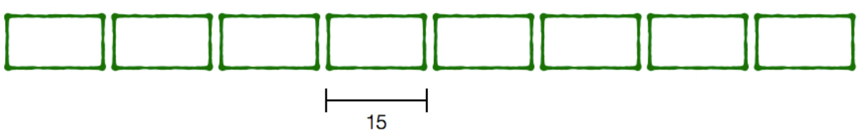


(a) (b)

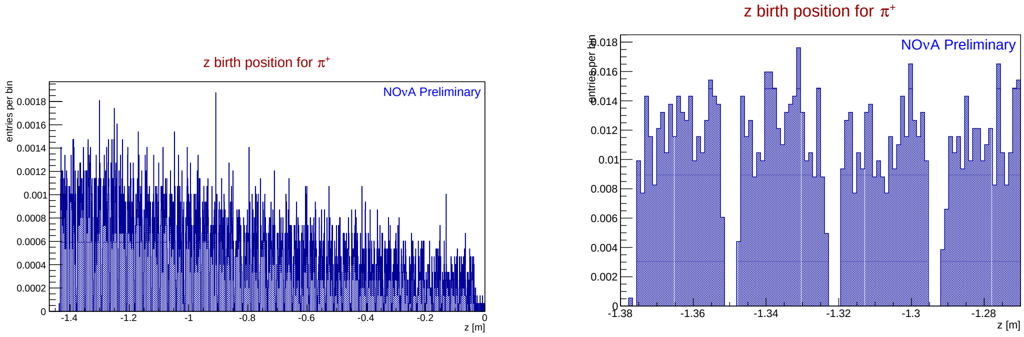
Figure 12: *Comparison between the neutrino spectra with the actual and the* airy *target.*

6.2 Variation of neutrino flux with respect to the number of fins

In this section the variation of neutrino energy spectrum with respect to the number of fins will be study. In this section we will consider fins of 15cm length. To start, we can emulate the current target placing 8 15cm fins together:



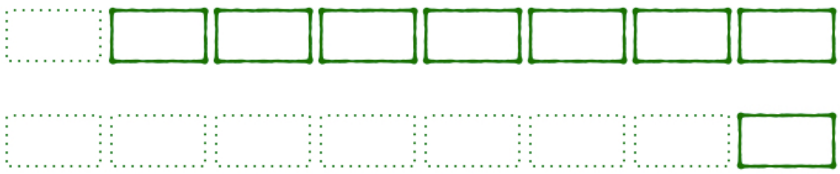
the energy spectrum relative to this configuration is shown in Figure 14(a). To understand how the flux varies with the number of the fins, the 15cm fins were



(a) **(b)**

Figure 13: *Distributions of the starting point along the beam line were the* π^+ *are produced. Plot (b) is just an enlargement of plot (a).*

removed gradually as in the following pictures:



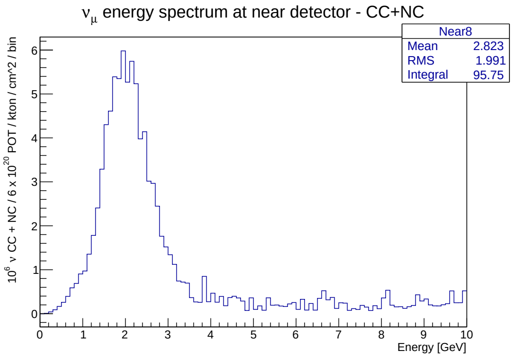
The spctra for these other configurations are shown in Figure 14(b)-(c).

Finally, in Figure 14(e) is possible to see the integral of the previous spectra, i.e. the number of events at the near detector as a function of the number of fins.

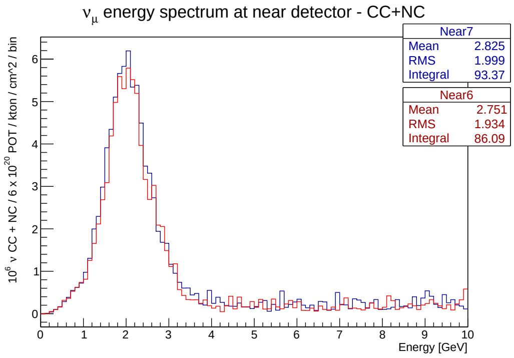
Another study that has been performed is to see how the number of events at the detectors varies removing only the even fins,

ore removing only the second one:

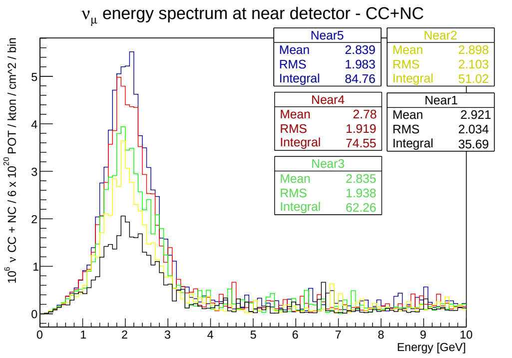
The spectra for these two configurations is shown in Figures 15 and 16.



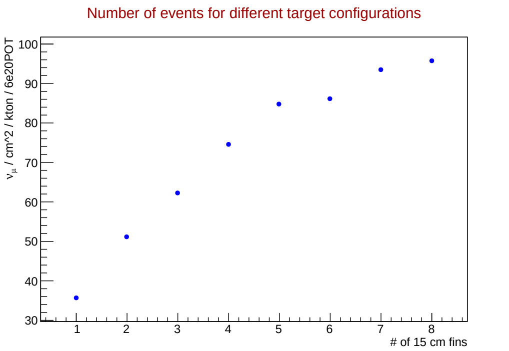
(a) *Target made of 8 15cm fins.*



(b) *Target made of 7 and 6 15cm fins.*

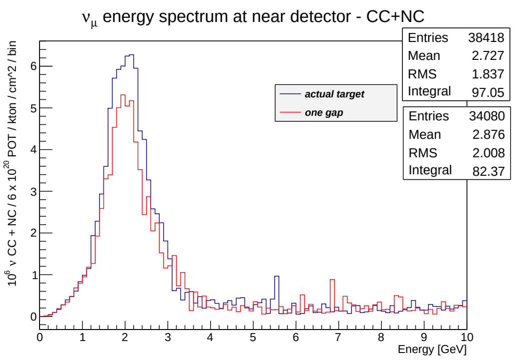


(c) *Target made of 5, 4, 3, 2 and 1 15cm fins.*

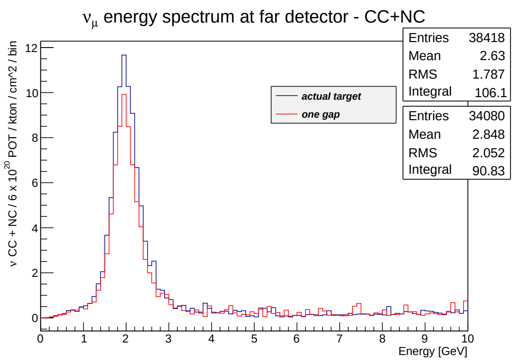


(d) *Integral of previous spectra VS number of 15cm fins.*

Figure 14: *Neutrino spectra at near detector for different target configurations.*

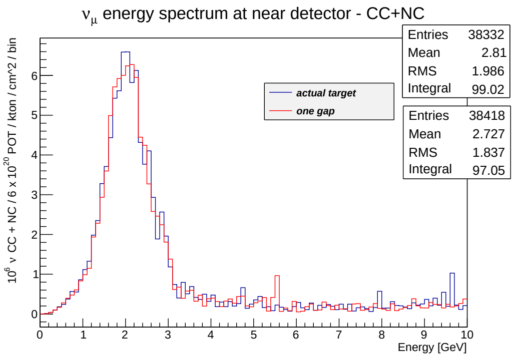


(a) *ND*

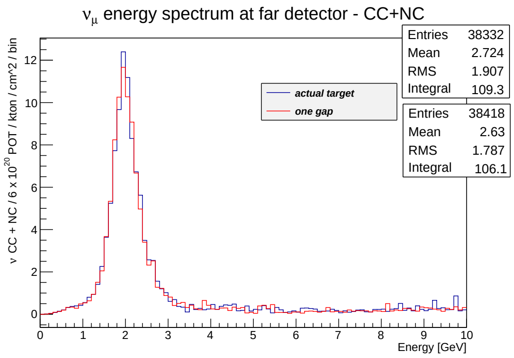


(b) *FD*

Figure 15: *Target with only odd fins (4 fins in total).*



(a) *ND*



(b) *FD*

Figure 16: *Target with the second fin missing (7 fins in total).*

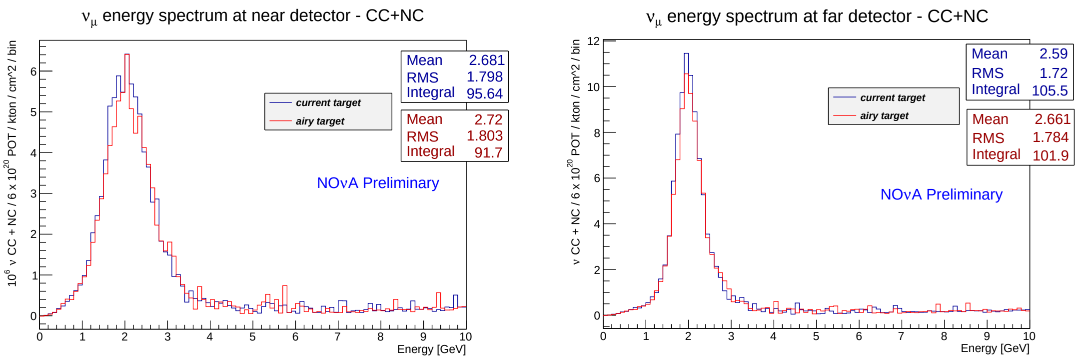
7 Flugg results with the *airy* target

In this section the *airy target* is studied using Fluka instead of G4NuMI. The Flugg package has been installed using the instruction given in the wiki: `https://cdcvs.fnal.gov/redmine/projects/numi-beam-sim/wiki/How_to_build_the_FLUGG_code`. FluxReader was used to analyze the Flugg output as well as for G4NuMI. It should be noted that FluxReader has been update since its first use with G4NuMI.

Flugg uses Fluka for the physics, but Geant4 for the geometry of the experiment. So the way to change the target, in order to have the *airy* one, is the same as G4NuMI. In particular, the following file was modified (if `myVersionBase_mn` is the directory where Flugg is installed):
`myVersionBase_mn/g4numi/src/NumiDataInput.cc`.

This file contains the same informations as in Listing 1. The variable to modify is `TargetSegPitch`.

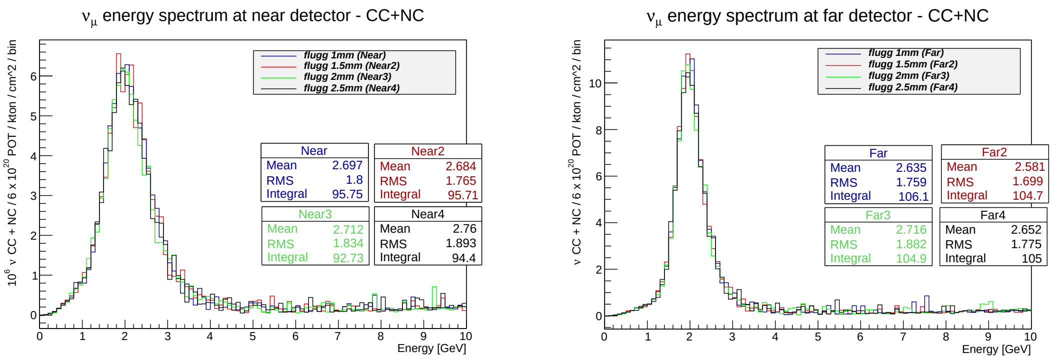
A comparison between the current target and the *airy* target obtained with Flugg is shown in Figure 17.



(a) *ND* **(b)** *FD*

Figure 17: *Comparison between the current target and the* airy *target with Flugg.*

As a further study, the simulation was made spacing the fins with different gaps: 1, 1.5, 2, 2.5 mm. The result is shown in Figure 18.



(a) *ND* **(b)** *FD*

Figure 18: *Flugg output considering different gaps between the fins: 1, 1.5, 2, 2.5 mm.*

8 Conclusions

The NOvA experiment official flux simulation was done by using Flugg, this is one of the first study and comparison with G4NuMI. It should be noted that this is a preliminary study and provide the basis for a future and more-in-depth study. There is the possibility to increase the neutrino flux, but to have a quantitative idea more studies are required.

At the moment it is not correct to make a direct comparison between G4NuMI and Flugg due to differences in the physics lists and the geometry description in the two codes.

In the following tables is presented a summary of the results obtained with the normal and the *airy* target using both G4NuMI and Flugg.

In Figure 19(b) is possible to see the flux variation as a function of the gap width for Flugg. The flux variation is compatible with the general flux fluctuation so it is not possible to draw conclusions.

Table 7: *Number of ν_μ events for $(cm^2 \cdot kton \cdot 6 \times 10^{20} POT)$ for the normal and the airy target with 4mm gaps in the 0-10 GeV and 1-3 GeV energy regions. There are also the results obtained with the Minos detector with G4NuMI and Flugg.*

(a) *1-10 GeV energy region.*

G4NuMI - 4mm - ν_μ	NOνA ND	NOνA FD	MINOS ND	MINOS FD
Normal Target	97.05	106.1	1280	1406
Airy Target	101.2	113.2	1310	1460
	4.28%	6.69%	2.34%	3.84%

(b) *1-10 GeV energy region.*

Flugg - 4mm - ν_μ	NOνA ND	NOνA FD	MINOS ND	MINOS FD
Normal Target	95.64	105.5	1388	1520
Airy Target	91.7	101.9	1519	1646
	-4.12%	-3.41%	9.44%	8.29%

(c) *1-3 GeV energy region.*

G4NuMI - NOνA - 4mm - ν_μ	ND	FD
Normal Target	76.42	88.28
Airy Target	80.04	93.09
	4.74%	5.45%

(d) *1-3 GeV energy region.*

Flugg - NOνA - 4mm - ν_μ	ND	FD
Normal Target	76.04	88.81
Airy Target	71.52	84.51
	-5.94%	-4.84%

Table 8: *Number of ν_e events for $(cm^2 \cdot kton \cdot 6 \times 10^{20} POT)$ for the normal and the airy target with 4mm and 1mm gaps in the 0-10 GeV energy regions. Both for G4NuMI and Flugg.*

(a)

G4NuMI - NOνA - 4mm - ν_e	ND	FD
Normal Target	1.874	2.318
Airy Target	1.683	1.912
	-8.88%	-17.52%

(b)

Flugg - NOνA - 4mm - ν_e	ND	FD
Normal Target	1.662	2.016
Airy Target	1.797	2.075
	8.12%	2.93%

(c)

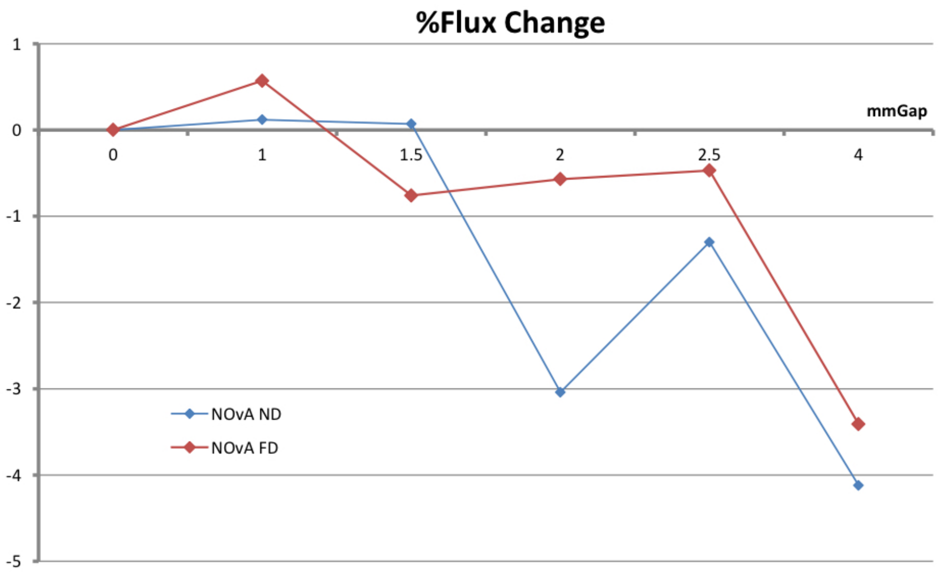
G4NuMI - NOνA - 1mm - ν_e	ND	FD
Normal Target	1.874	2.318
Airy Target	1.712	2.262
	-8.64%	-2.42%

(d)

Flugg - NOνA - 1mm - ν_e	ND	FD
Normal Target	1.662	2.016
Airy Target	1.573	1.660
	-5.35%	-1.77%

NOVA			
ND	%	FD	%
95.64	0	105.5	0
95.75	0.12	106.1	0.57
95.71	0.07	104.7	-0.76
92.73	-3.04	104.9	-0.57
94.4	-1.3	105	-0.47
91.7	-4.12	101.9	-3.41

(a) *Number of* ν_μ *events for* $(cm^2 \cdot kton \cdot 6 \times 10^{20} POT)$ *for the normal and the airy target in the 0-10 GeV obtained with Flugg for different values of the gaps (from top to bottom): 0, 1, 1.5, 2, 2.5, 4 mm.*



(b) *In this plots are reported the results obtained in Figure 19(a) (Flugg).*

Figure 19

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