# Estimated Number of Interactions

**Abstract:** The total number of neutrino interactions in the emulsion is estimated using the Monte Carlo with neutrino production estimates.

## Analysis

The Monte Carlo is used for three main functions in this analysis:

1. Generate *v*s in the dump
2. Propagate *v*s to the emulsion target
3. Assign a weight ∝ production kinematics
4. Assign a weight ∝ interaction probability

The separation of production weight and interaction weight is necessary here. It is important to formulate the number of interactions in terms of Monte Carlo variables:

$$N_{\text{int}} = \Phi\sigma N_{\text{nucl}} = \left(\frac{N_v}{pot}\right)(pot)\left(\frac{\sigma^{\text{const}}}{Area}\right)\left(\frac{m_{\text{tgt}}}{m_{\text{nucl}}}\right) f\left\langle \sum EKTt \right\rangle$$

where $\sigma^{\text{const}}$ is the energy-independent part of the neutrino-nucleon cross section, $m_{\text{tgt}}$ is the emulsion target mass (e.g. the *pot*-weighted average), $m_{\text{nucl}}$ the nucleon mass, $E$ neutrino energy, $K$ additional kinematic suppression (CCτ only), $T$ the binary (0 or 1) for $v$ in the target and $t$ the binary for the trigger. The fraction of the neutrino flux in the target area is $f$. Inserting numbers for the constant part yields

$$F_e = \left(5.88\times10^{-4}\right)\left(3.54\times10^{17}\right)\left(\frac{1}{2400\,cm^2}\right)\left(0.505\times10^{-38}\right)\left(\frac{260\,kg}{1.66\times10^{-27}\,kg}\right)$$

This gives 68.7 for electron-neutrino interactions. The value for muon-neutrinos is slightly greater, and the value for tau-neutrino interactions is 10.6. The values for number of neutrinos created per *pot* are from Emily's thesis [1]. See the Appendix for more details.

The part in the summation in the first equation is evaluated as one number for each flavor.

| **Flavor** | $N_v/pot$ | $f\langle\Sigma EKTt\rangle$ | $F_j$ | **Π** |
|---|---|---|---|---|
| *e* | $5.88\times10^{-4}$ | 4.62 | 68.7 | 317 |
| μ(p) | $5.88\times10^{-4}$ | 4.33 | 64.6 | 280 |
| μ(np)* | | | | 179 |
| τ | $9.08\times10^{-5}$ | 2.54 | 10.6 | 30 |

The total number of triggered interactions is estimated to be 806. The total number of interactions ($t$=1) is 863.

To estimate the number of located events we need to multiply by electronic, scan and location efficiencies. The product of live-time, self-veto, stripping and scanning is 0.719±0.058 [2].

The location efficiencies for non-tau and tau events are 0.67 ±0.04 and 0.66±0.04 respectively [3]. The product of these factors is 0.48±0.05 with the systematic uncertainty in efficiency, $\delta\varepsilon = 0.05$.

**Systematics in Neutrino Production**

We need to understand the range of the number of interactions due to uncertainty in neutrino production. Recall that the production of charm in the dump is simulated with the following distribution:

$$\frac{d^2\sigma}{dx\,dp_T} \propto \exp\left(-b\,p_T^2\right)\left(1-x_F\right)^n$$

The parameters $b$ and $n$ are derived from experiment. Only $n$ significantly affects the neutrino momentum. It is estimated to be 7.4±1.4 [1]. Varying $n$ has the effect of changing the $\sum EKTt$ quantity. Using $\sigma_n = 1.4$, events generated with $n = 6.0$ and 8.8 yielded the sum $\sum EKTt$ equal to 6.03 and 3.68. This represents a 31% increase and 20% decrease, respectively.

| ***n*** | $f\langle\Sigma EKTt\rangle[\boldsymbol{e}]$ | $f\langle\Sigma EKTt\rangle[\boldsymbol{\tau}]$ | ratio($e/\tau$) |
|---|---|---|---|
| 6.0 | 6.03 | 3.33 | 1.81 |
| 7.4 | 4.62 | 2.54 | 1.82 |
| 8.8 | 3.68 | 1.95 | 1.88 |

Note that the *ratio* of the energy-dependent factor is almost independent of $n$, the variation may be due to statistics, with a variation of about 3%. This is much less than the variation in the number of interactions.

The uncertainty in total charm cross sections is also significant. Taking values from [1], the relative error weighted by cross section value from the three processes giving $D^0$, $D^\pm$, and $\Lambda$ is 13%, assumed symmetric. The uncertainty in the $A$ dependence, assumed to be $A^\alpha$, is given by the uncertainty in $\alpha$=0.987±0.023 which gives (with $A$=181) a relative error in the charm (and tau) production of 12%. Combining in quadrature gives 18% for charm. The uncertainties for tau-neutrino production are 28% and 12% ($A$ dep.) giving a total error of 30%.

The range of the number of triggered interactions is given in the following table.

| **Method** | **Low** | **Mean** | **High** |
|---|---|---|---|
| $\delta n \oplus \delta\sigma \oplus \delta\varepsilon$ | 629 | 806 | 1091 |
| $\delta n + \delta\sigma + \delta\varepsilon$ | 516 | 806 | 1225 |

The estimated number of located events is thus 0.48×806 = 371 with a low range (quadrature, linear) of [302, 248] and high range of [524, 588].

This may indicate that charm production from hadrons is best modeled by smaller $n$ (~6).

The systematic uncertainty in the number of $\nu_e$ or $\nu_\mu$ interactions, using geometric addition is +36% and -22%.

**References**

[1] Emily's Thesis

[2] B. Lundberg presentation on *Efficiencies* 10 Dec 2005

[3] T. Furukawa analysis meeting presentations

## Appendix A

### Computing the Number of Interactions

Start with the definition of cross section for neutrino-nucleon interactions:

$$N_{\rm int} = \Phi \sigma N_{\rm nucl} \qquad (1)$$

The flux, Φ, is the number of neutrinos created at the dump into the area (cm$^{-2}$) which contains the number of nucleons, $N_{\rm nucl}$. In DONuT this area is "shadow" of the emulsion targets illuminated by a point source at the dump. Note that because the modules are distributed over 1m along the beam at a distance of 36 m, the flux is not quite the same at each one. This is a 2% correction for the most upstream and downstream parts of the target assembly relative to the center, but we will ignore this for now.

We now expand Eq. (1) into components that are calculated by the Monte Carlo and collect the constants.

$$N_{\rm int} = \frac{\sigma^{\rm const}}{Area} \cdot \frac{M_{\rm tgt}}{m_{\rm nucl}} \sum E\,K\,T\,t \,\frac{N_\nu^{\rm exp}}{N_\nu^{\rm MC}} \qquad (2)$$

Here, $E$ is the neutrino energy, $K$ is a kinematic factor due to lepton mass effects (CC only), $T$ is a binary [ 1 = IN target ; 0 otherwise ], $t$ is the trigger binary [1 = triggered ], and $N_{\rm exp}/N_{\rm MC}$ corrects for the number of generated neutrinos in the MC to the number generated in the experiment. We can rewrite this as

$$N_{\rm int} = \frac{N_\nu^{\rm exp}}{\rm pot} \cdot {\rm pot} \cdot \frac{\sigma^{\rm const}}{Area} \cdot \frac{M_{\rm tgt}}{m_{\rm nucl}} \cdot \frac{f}{N_\nu^{\rm MC}} \sum EKTt = C_\ell \left\langle \sum EKTt \right\rangle \qquad (3)$$

Here, $C_{e,\mu} = 68.7 \times f$ and $C_\tau = 10.6 \times f$, $f$ is the fraction of the neutrino flux from the dump (or fraction of the number of neutrinos) intercepted by the emulsion and mean of sum is the quantity computed by Monte Carlo. It is important to understand that:

- $f$ is the ratio of the number of neutrinos (not interacted flux) in the target to the total number created

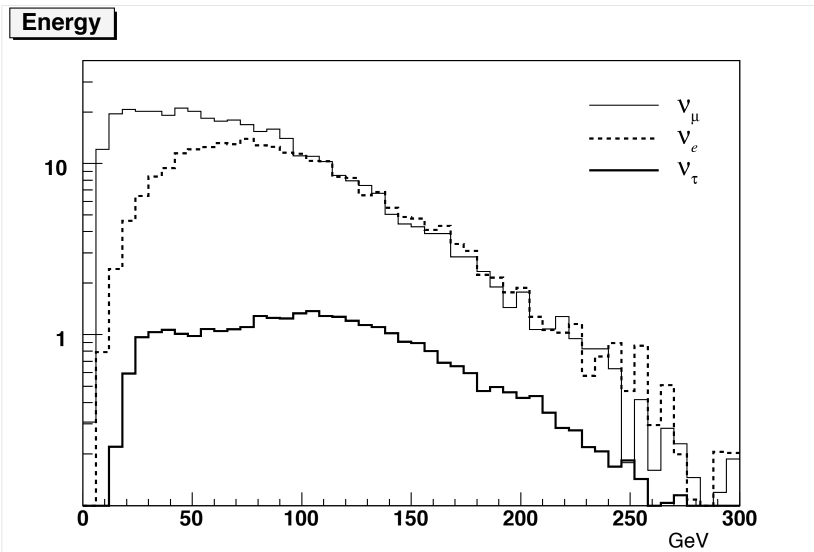
- $\left\langle \sum EKTt \right\rangle$ is only accumulated for neutrinos passing through the target area

- the sum automatically takes into account any correlations between energy, radial distance and target boundaries

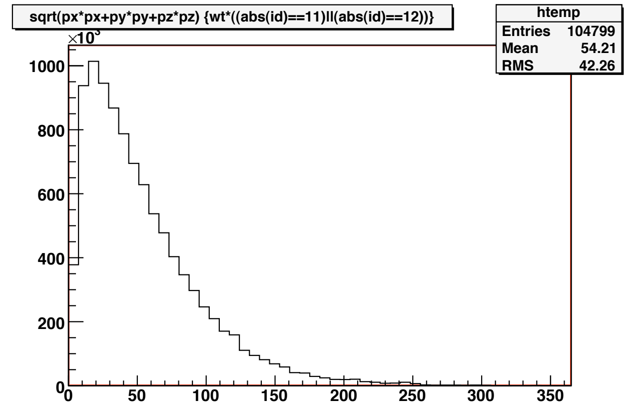
- $f$ is computed for each neutrino type

One could also subdivide the target into $n$ smaller areas and accumulate $n$ sums and fractions, $f$. This would be useful for understanding how triggered interactions are distributed in the targets, but is not needed to compute the total numbers.

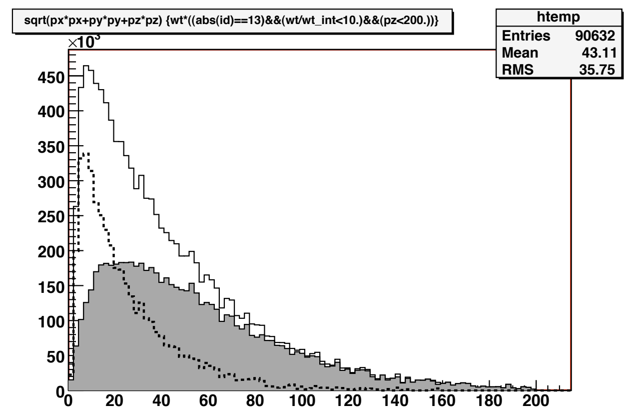
In Emily's thesis [1], the value of $f$ (taken to be 0.064) multiplies the mean value of $E \times K$ for the unrestricted spectrum of the neutrino flux. This is incorrect, since $f$ is taken to be valid at a specific area, and hence the mean value of $EK$ must be computed at this location. This is clear if one takes the same fractional acceptance ($f$) and moves the targets 10 m off-axis. The number of interactions must be greatly reduced, but this is not predicted in [1].



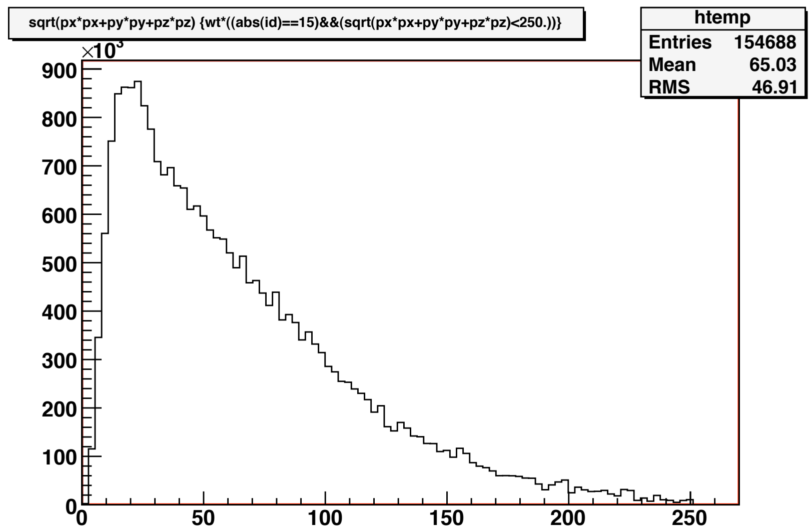

Neutrino energy spectra weighted for interactions in the emulsion.



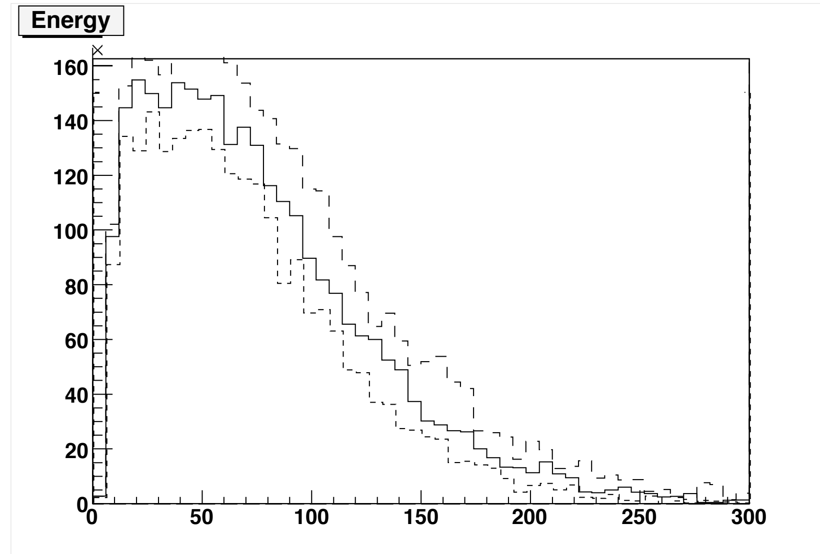

Electron spectra from CC$e$ interactions




Muon spectra from CC$\mu$ interactions. Shown are the sum and prompt (*shaded*) and non-prompt components.




Tau lepton spectrum from CCτ interactions.




Muon spectra (within mu-ID system) for *n*=6.0 (*top*), *n*=7.4 (*middle*), *n*=8.8 (*bottom*). The shapes are too similar to distinguish. All are CCμ interactions.