Can we estimate the ν_e flux with the measured μ^+ rate?

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Abstract

Milind suggested that measurement of the $\overline{\nu}_\mu$ flux via reconstructed μ^+ in CC interactions could be used to estimate the ν_e flux if $\mu^+ \rightarrow e^+\overline{\nu}_\mu\nu_e$ is a significant fraction of $\overline{\nu}_\mu$ production. Based on studies with GNUMI and GMINOS, this suggestion is not totally crazy if the shape of the $\overline{\nu}_\mu$ spectrum from non-muon decays can be reliably estimated from MC. Horn-off data will be useful in confirming the shape prediction.

1 Disclaimer

This note follows the development of this study in chronological order.

2 Initial study and results

If $\mu^+ \rightarrow e^+\overline{\nu}_\mu\nu_e$ is a substantial contribution to the $\overline{\nu}_\mu$ flux, then measurement of μ^+ in the near detector could give us a handle on the ν_e flux. Figures 1 and 2 show that the only contribution from muon decays occurs at less than 10 GeV and attains $\sim 15\%$ of the total ν_μ flux based on GNUMI R15. For antineutrino energies less than 20 GeV, the $\overline{\nu}_\mu$ flux is dominated by $\overline{\nu}_\mu$ from π^- decays. If the $\overline{\nu}_\mu$ from pions in the 10-20 GeV range can be used to estimate the pion-produced $\overline{\nu}_\mu$ spectrum at < 10 GeV, then the method might work. The extrapolation to the < 10 GeV range would require some input from simulation. Based on Jeff Hartnell's studies [1], it looks possible.

For completeness, I show the composition of the $\overline{\nu}_\mu$, ν_e and $\overline{\nu}_e$ fluxes in Figures 3, 4, 5, and 6. In Figure 7, the expected $\overline{\nu}_\mu$ and ν_e energy spectra extrapolated to the center of the front of the near detector are compared. Note the difference of $\sim 17\%$ in the relative $\overline{\nu}_\mu$ and ν_e fluxes that strike the near detector.

3 Overview of proposed technique

Here is a brief outline of the proposed technique, originally shown in a presentation [3] for ν_e working group:

1. Measure ND μ^+ rate as a function of E_ν after fiducial and quality cuts
2. Subtract ν_μ and NC backgrounds
3. Use measured $\overline{\nu}_\mu$ event rate for $E_\nu > E_{\text{cut}}$ to normalized MC spectrum
4. Subtract normalized spectrum from measured spectrum: The excess is $\overline{\nu}_\mu$ from $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$
5. Deconvolve ν_e spectrum from measured $\overline{\nu}_\mu(\mu^+)$ spectrum
6. Extrapolate from ND to FD

I use the following fiducial and quality cuts
(based on NCAnalysisCuts and Jeff Hartnell's Oxford Jan2006 talk [1]):

- $z_{\text{vtx}} = (1, 5)$ meters, vertex radius within 1 m of ν beam axis,
- $|U_{\text{vtx}} - V_{\text{vtx}}| < 6$ planes,
- fit.pass == 1,
- Prob(χ^2,ndf) > 0.1,
- $|\sigma(q/p)/(q/p)| < 0.3$,
- $q/p > 0$

Jeff also recommends a cut at > 0.4 on David Petyt's PID that I have not yet implemented. From Jeff's slides, I estimate that the PID cut is $\sim 80\%$ efficient for for low energy $\overline{\nu}_\mu$.

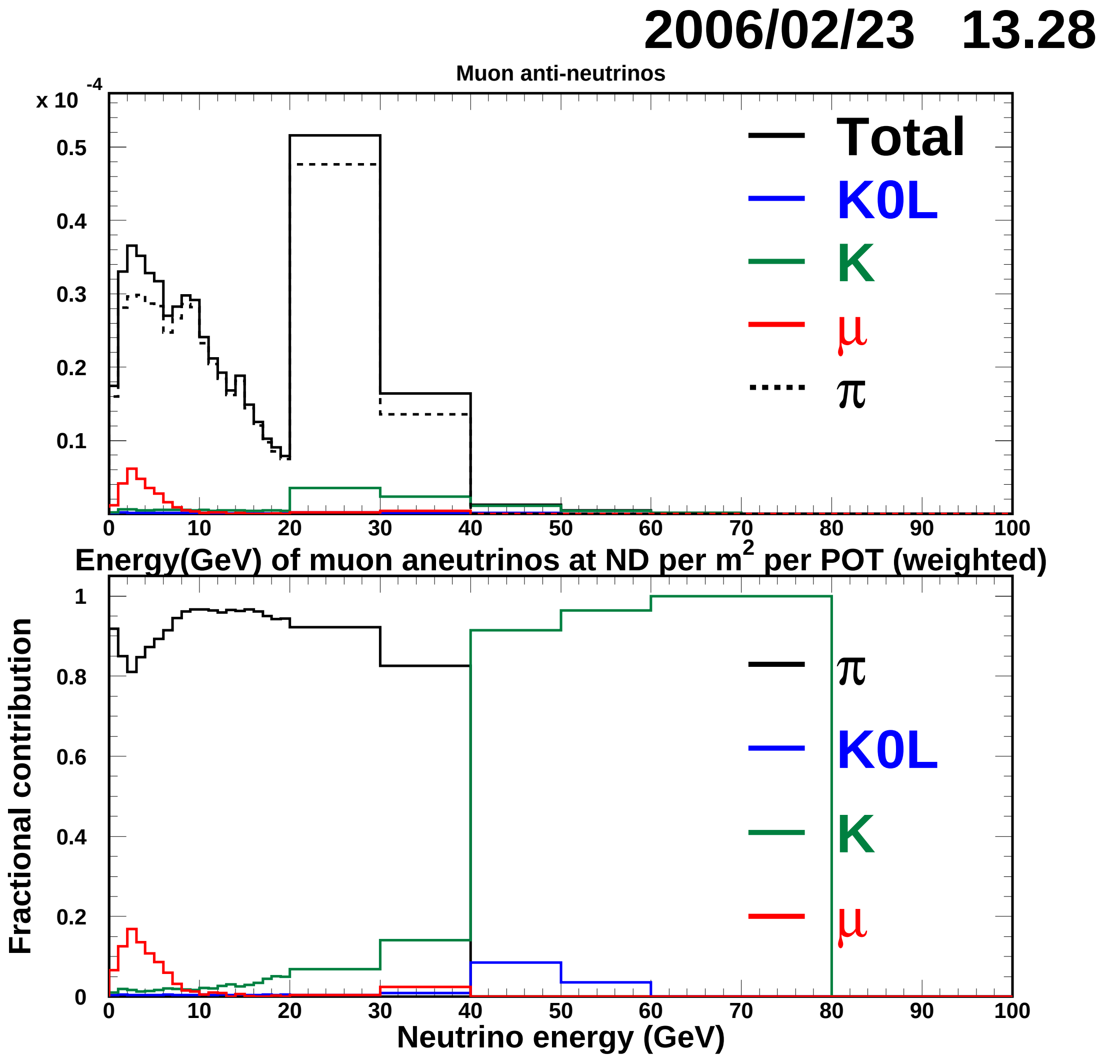

Figure 1: Upper: The total flux (solid black line) as a function of energy of $\overline{\nu}_{\mu}$ at the near detector. The contribution from pion, K0L, kaon and muon decays is indicated by the black dashed, dark blue, green and red lines, respectively. Lower: The fractional contribution to the neutrino flux as a function of energy from pions (black), K0L (dark blue), kaons (green) and muons (red). See Ref. [2].

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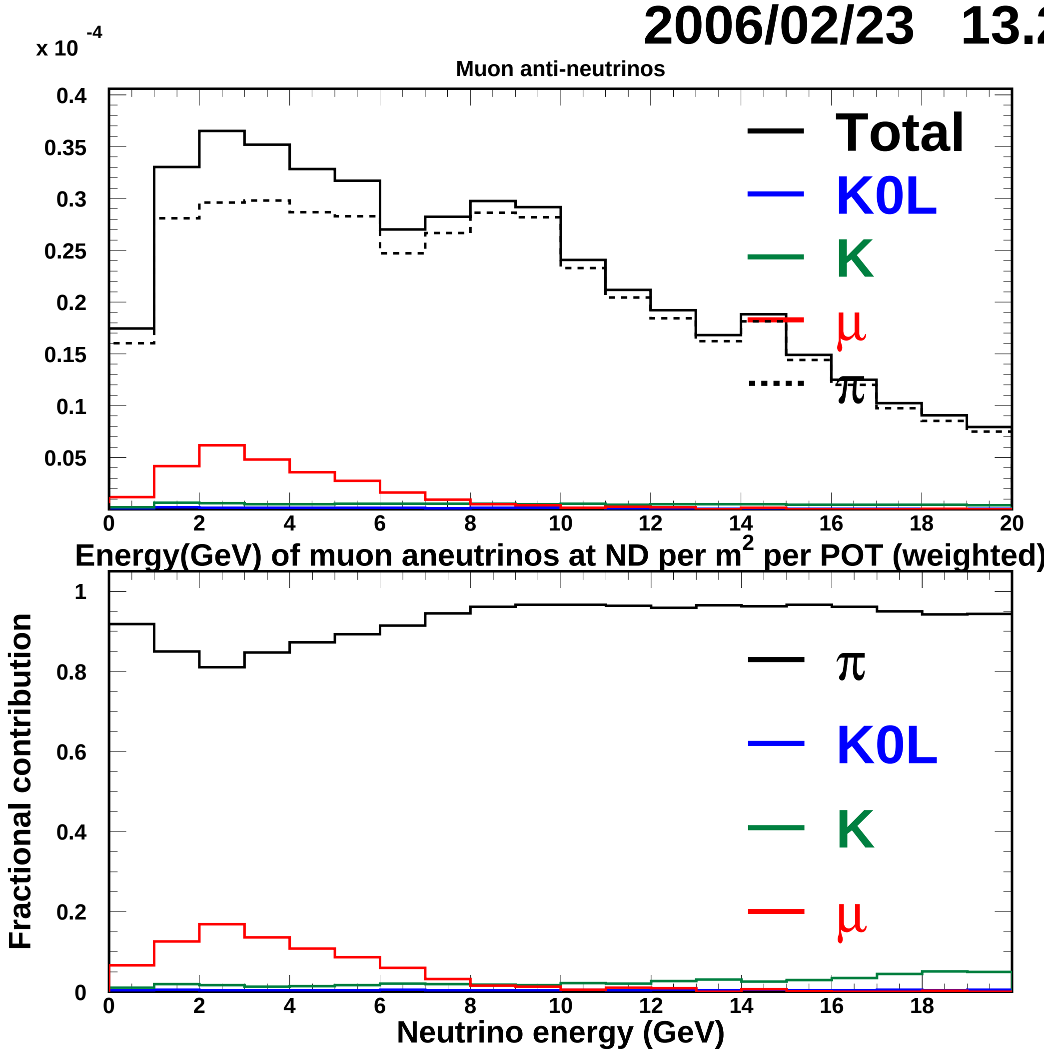


Figure 2: Same as Figure 1 but with linear ordinate and restricted to $E_\nu < 20$ GeV. See Ref. [2].

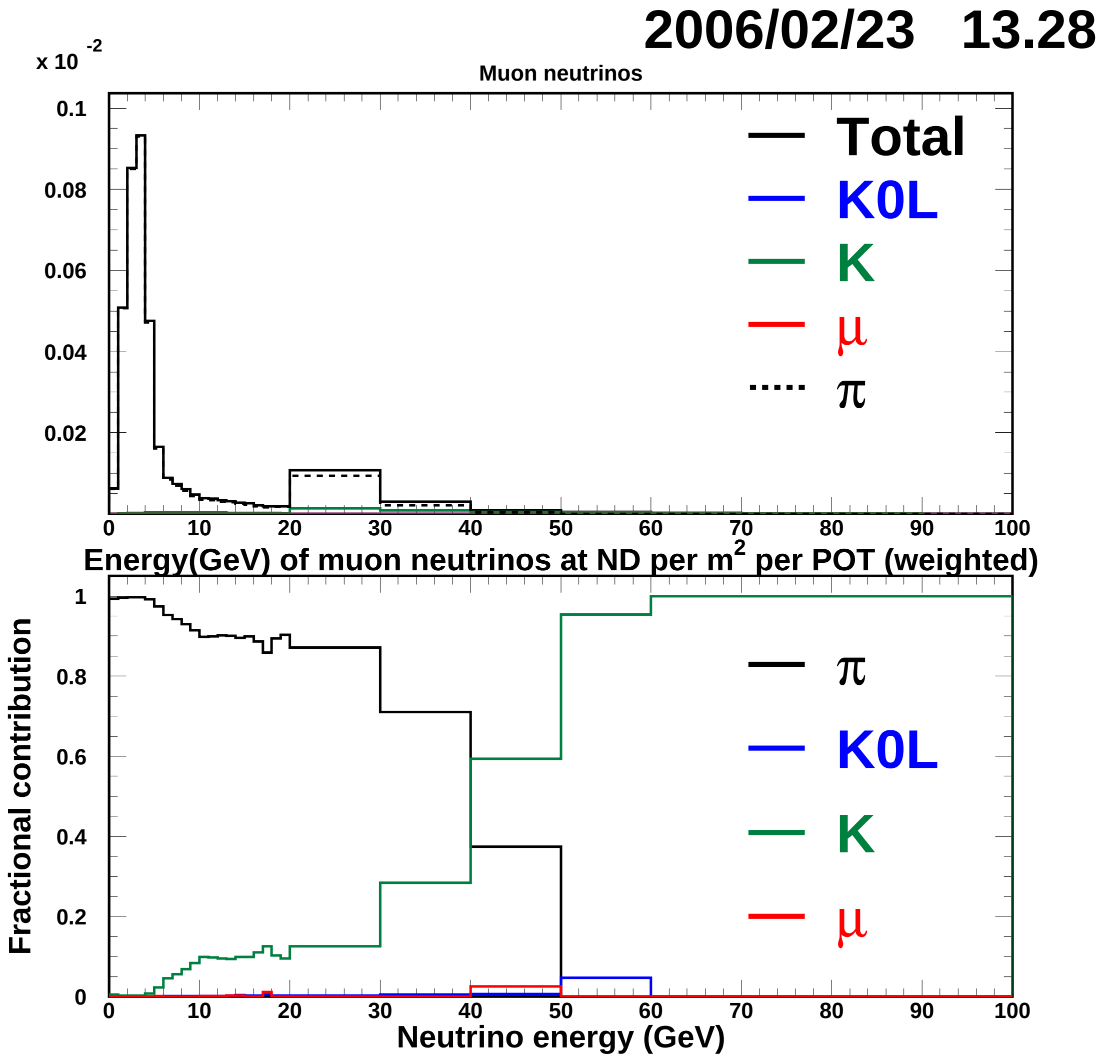


Figure 3: Upper: The total flux (solid black line) as a function of energy of ν_μ at the near detector. The contribution from pion, K0L, kaon and muon decays is indicated by the black dashed, dark blue, green and red lines, respectively. Lower: The fractional contribution to the neutrino flux as a function of energy from pions (black), K0L (dark blue), kaons (green) and muons (red). See Ref. [2].

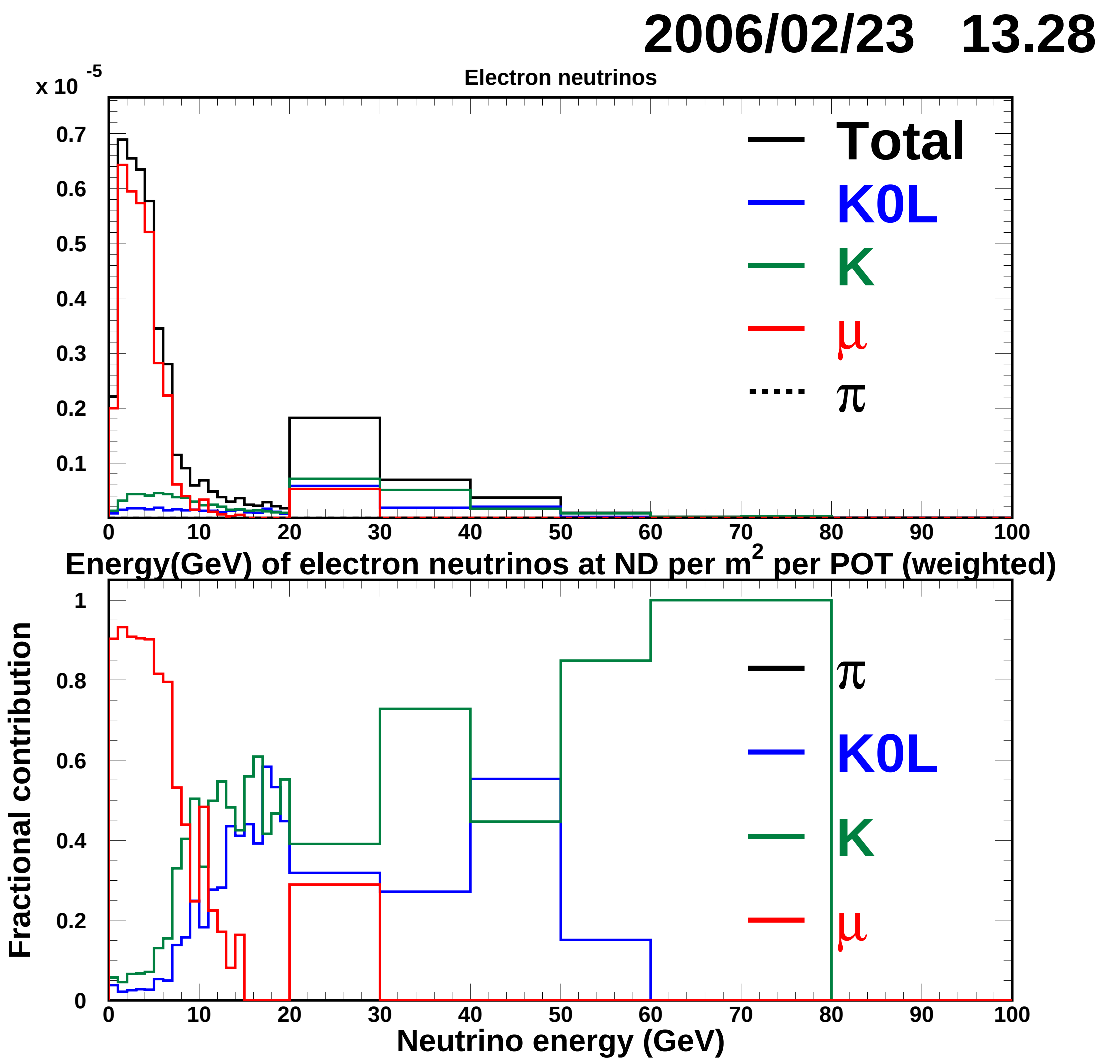


Figure 4: Upper: The total flux (solid black line) as a function of energy of ν_e at the near detector. The contribution from pion, K0L, kaon and muon decays is indicated by the black dashed, dark blue, green and red lines, respectively. Lower: The fractional contribution to the neutrino flux as a function of energy from pions (black), K0L (dark blue), kaons (green) and muons (red). See Ref. [2].

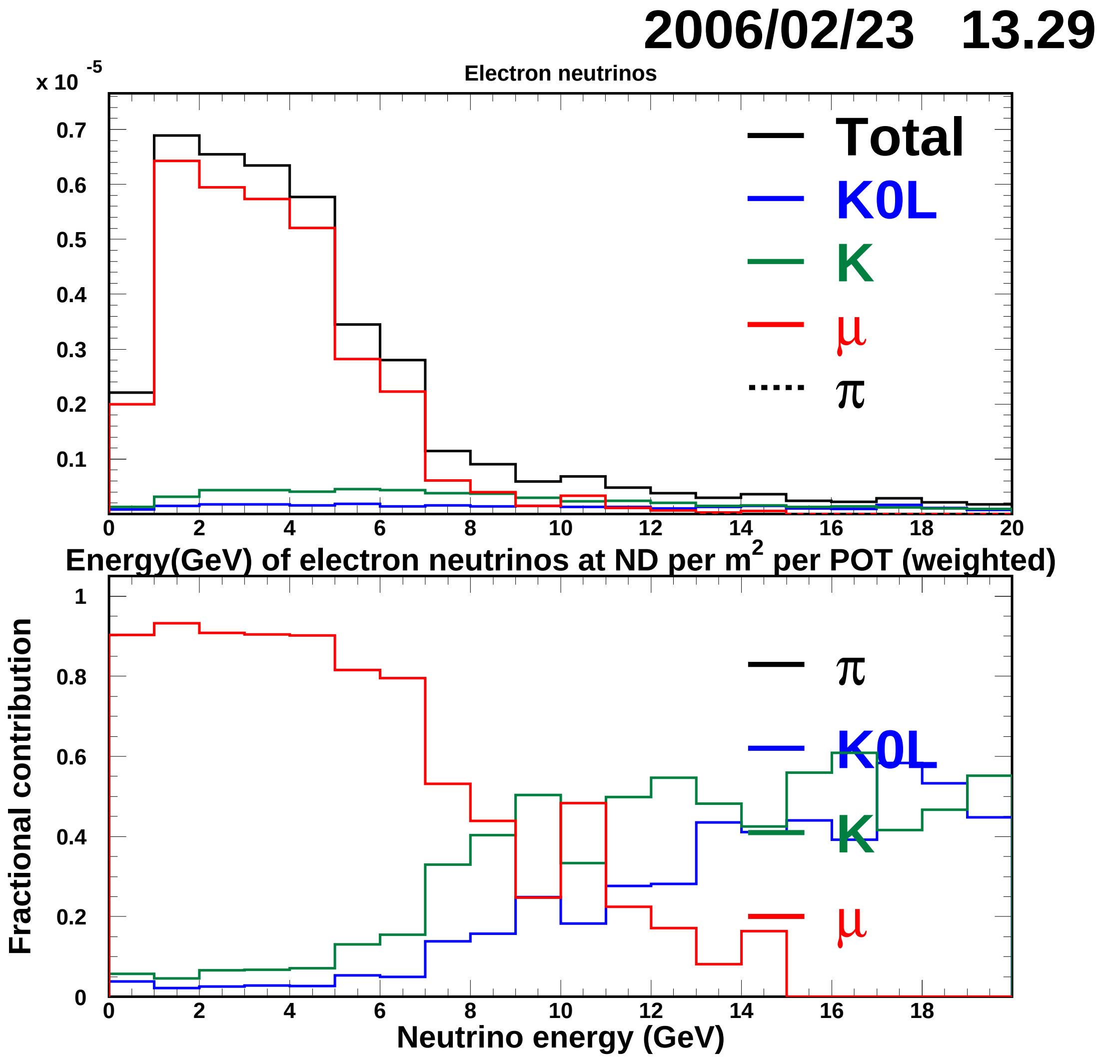


Figure 5: Same as Figure 4 but with linear ordinate and restricted to $E_\nu < 20$ GeV. See Ref. [2].

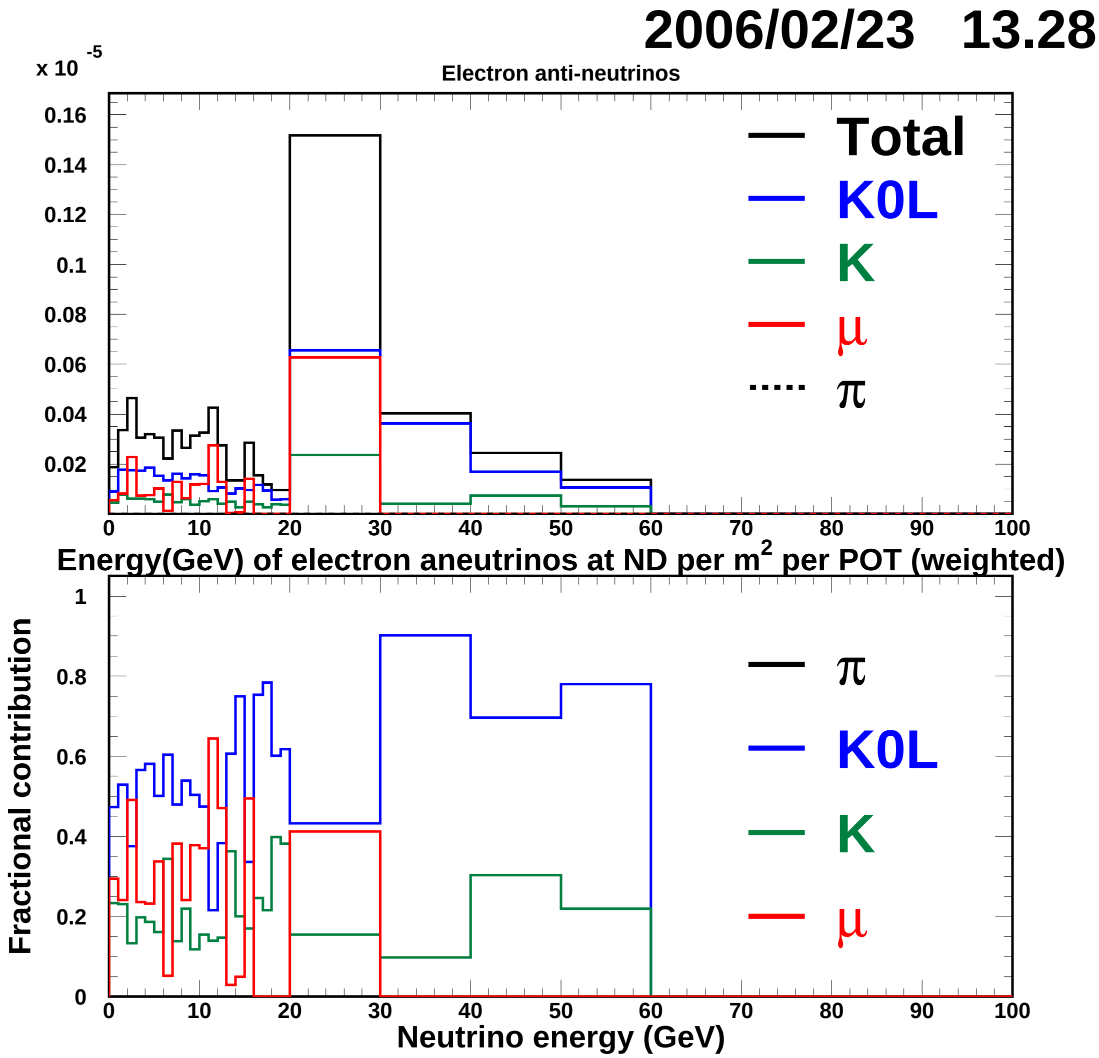


Figure 6: Upper: The total flux (solid black line) as a function of energy of $\overline{\nu}_e$ at the near detector. The contribution from pion, K0L, kaon and muon decays is indicated by the black dashed, dark blue, green and red lines, respectively. Lower: The fractional contribution to the neutrino flux as a function of energy from pions (black), K0L (dark blue), kaons (green) and muons (red). See Ref. [2].

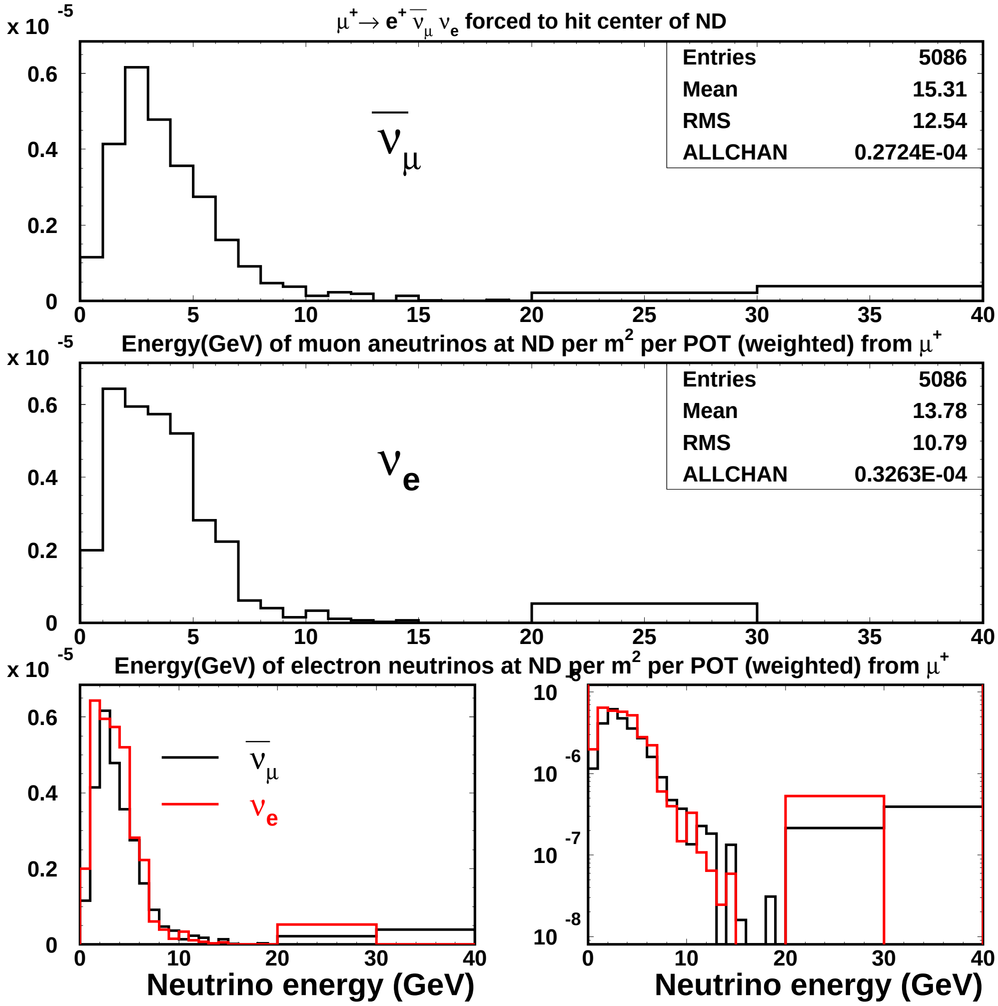


Figure 7: Upper: $\overline{\nu}_\mu$ flux as a function of energy at the near detector. Middle: ν_e flux as a function of energy at the near detector. Bottom: The two distributions are overlaid on linear (left) and logarithmic (right) scales. See Ref. [2].

Figure 8 shows the components of the $\overline{\nu}_\mu$ spectrum as a function of the reconstructed neutrino energy for μ^+ events after the fiducial and quality cuts listed above. The PID cut has not been applied. Note that I have used MC truth information to select only μ^+ from $\overline{\nu}_\mu$ to make this Figure. Carrot MC LE-10 185A processed with R1.18.2 was used to make this Figure.

The total number of reconstructed $\overline{\nu}_\mu$ events for 10^{20} POT is estimated to be $\sim 86 \times 10^3$ after the PID cut. The events are roughly equally distributed above and below 10 GeV in reconstructed neutrino energy. The estimated number of $\overline{\nu}_\mu$ from μ^+ decays is approximately 1/12 the number of events below 10 GeV or roughly 3600.

From Jeff's slides, there are 46 ν_μ CC and 6 NC events compared to the yield of 1294 candidates from $\overline{\nu}_\mu$ below 8.5 GeV $\sim 1/25$ of the $\overline{\nu}_\mu$ yield below 10 GeV and is dominated by ν_μ CC.

The measured number of $\overline{\nu}_\mu$ from μ^+ decay can be written as

$$f_{\mu\to\overline{\nu}}(E) = f_{\overline{\nu}}(E) - \left(\int_{E_{\rm cut}}^{\infty} dE f_{\overline{\nu}}(E) / \int_{E_{\rm cut}}^{\infty} dE f_{\overline{\nu}}^{\rm MC}(E)\right) f_{\overline{\nu}}^{\rm MC}(E)$$

where the term in parentheses is the correction factor for MC and

$$\begin{aligned} f_{\overline{\nu}}(E) &\equiv f_{\mu^+}(E) - f_{\rm NC}^{\rm MC}(E) - f_{\nu}^{\rm MC}(E) \\ &= \text{number of } \overline{\nu}_\mu \text{ candidates after NC}, \overline{\nu} \text{ subtraction.} \end{aligned}$$

$f_{\mu^+}(E)$ = number of μ^+ candidates after cuts as function of E,
$f_{\overline{\nu}}^{\rm MC}(E)$ = number of $\overline{\nu}_\mu$ events in MC
$E_{\rm cut}$ = 'cut-off' energy, above which there is no contribution to the $\overline{\nu}_\mu$ spectrum from μ^+ decays ($\sim$10 GeV)

In Figure 9, I show the estimated fractional uncertainty on $f_{\mu\to\overline{\nu}}(E)$ assuming that

- the correction factor $C \equiv \left(\int_{E_{\rm cut}}^{\infty} dE f_{\overline{\nu}}(E) / \int_{E_{\rm cut}}^{\infty} dE f_{\overline{\nu}}^{\rm MC}(E)\right)$ is approximately unity,
- that the fraction of $\overline{\nu}_\mu$ from μ^+ decays is $\int_0^{E_{\rm cut}} dE f_{\mu\to\overline{\nu}}(E) \approx (\int_0^{E_{\rm cut}} dE f_{\overline{\nu}}(E))/12$,
- that the ν_μ and NC background is $\sim 1/25$ of the $\overline{\nu}_\mu$ yield.

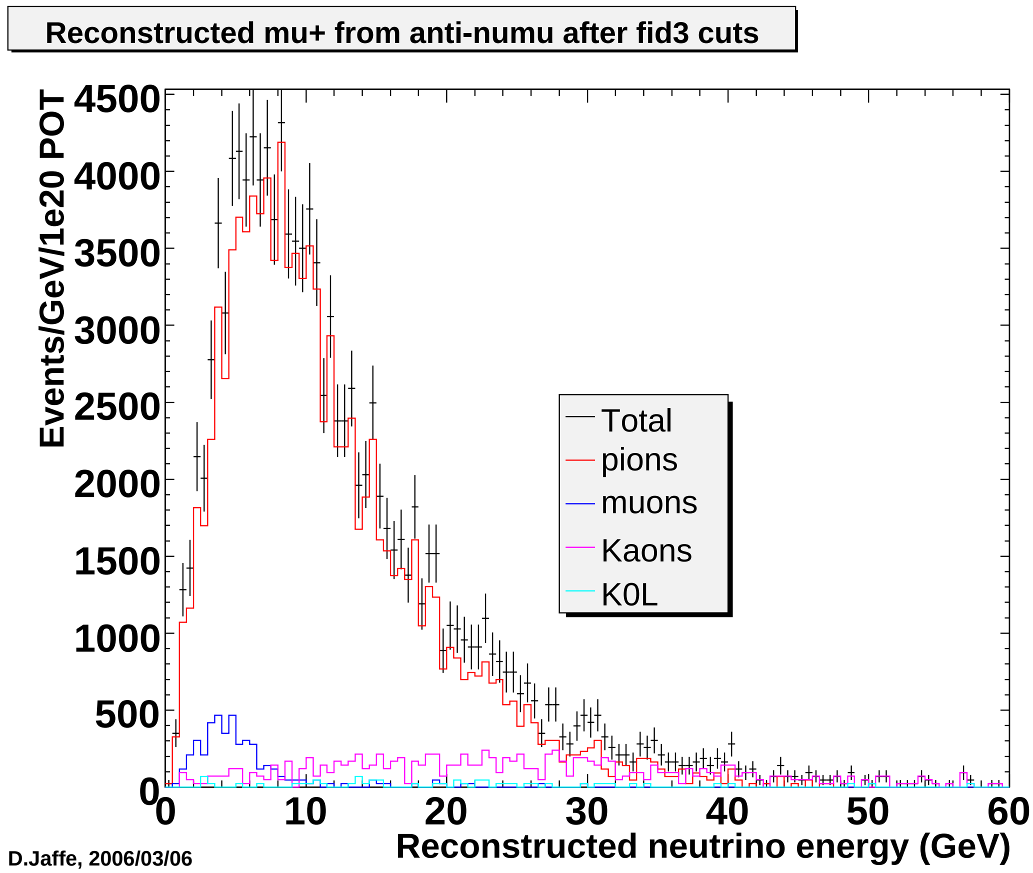
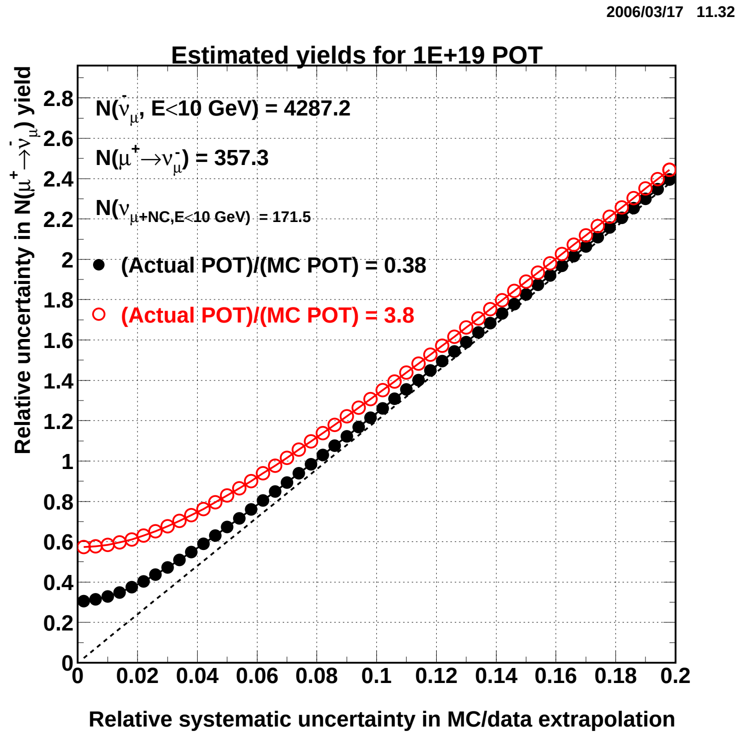


Figure 8: Components of the $\overline{\nu}_\mu$ spectrum as a function of reconstructed neutrino energy. The PID cut has not been applied. MC truth information has been used to select only those μ^+ candidates that originate from $\overline{\nu}_\mu$ CC interactions. The error bars reflect the MC statistics and not the expected statistical uncertainty in the $\overline{\nu}_\mu$ yield. They are shown to indicate the precision of the estimated spectral shapes.



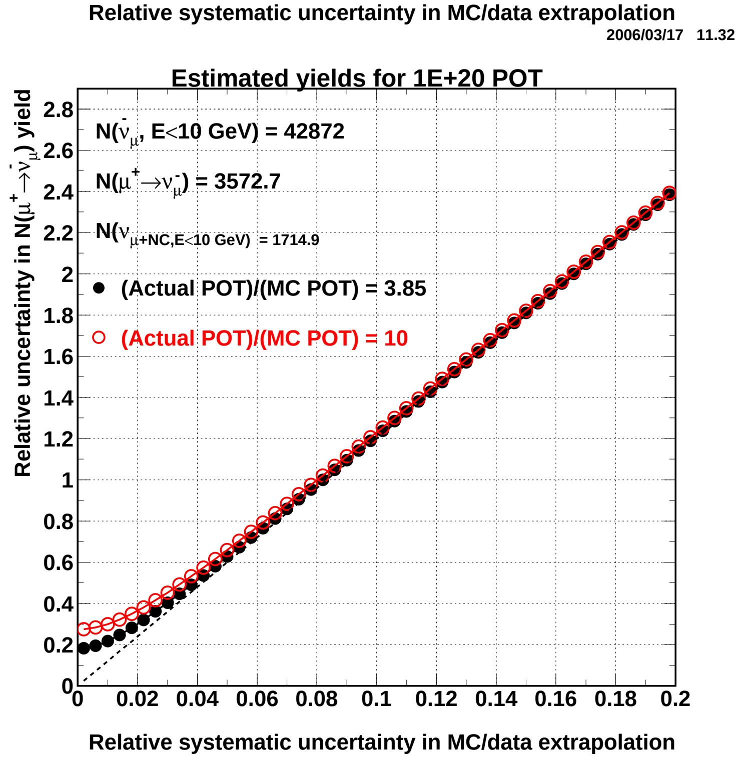


Figure 9: Estimated uncertainty in reconstructed $\overline{\nu}_\mu$ flux from μ^+ decays for 10^{19}(top) and 10^{20}(bottom) POT. The black points show the estimated uncertainty for the currently generated sample of carrot L010185 MC (as of 16 Mar 2006). The dashed line shows the result for infinite statistcs (data and MC).

4 Using horn-off data

Stan pointed out that horn-off data could be useful in determining the component of $\overline{\nu}_\mu$ from μ^+ decays. Simulation (Figure 10) shows that turning off the horn removes nearly all of the $\overline{\nu}_\mu$ from μ^+ decays as expected due to the non-focussing of positive pions. Simulation also shows that the overall $\overline{\nu}_\mu$ flux increases with the horn off.

References

[1] Jeff Hartnell, "A preliminary look at Anti-neutrinos in the Near detector", MINOS-doc-1409-v1, Presentation at January 2006 MINOS collaboration meeting.

[2] All plots were made with GNUMI R15 for the LE beam so they don't have the latest and greatest information about the beams. The gross features probably don't change much.

[3] D. E. Jaffe, "Constraining the ν_e flux from $\overline{\nu}_\mu$ measurements", MINOS-doc-1605, 7 March 2006.

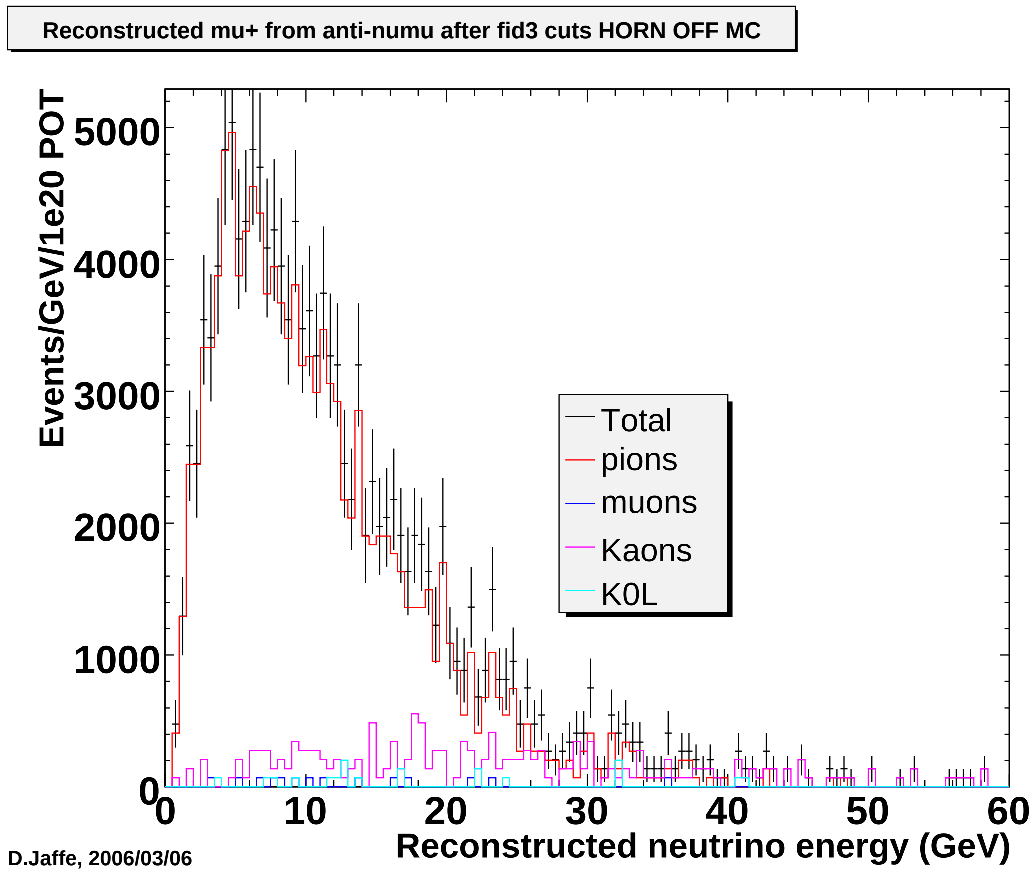


Figure 10: Components of the $\overline{\nu}_\mu$ spectrum as a function of reconstructed neutrino energy for horn-off MC. The PID cut has not been applied. MC truth information has been used to select only those μ^+ candidates that originate from $\overline{\nu}_\mu$ CC interactions. The error bars reflect the MC statistics and not the expected statistical uncertainty in the $\overline{\nu}_\mu$ yield. They are shown to indicate the precision of the estimated spectral shapes.

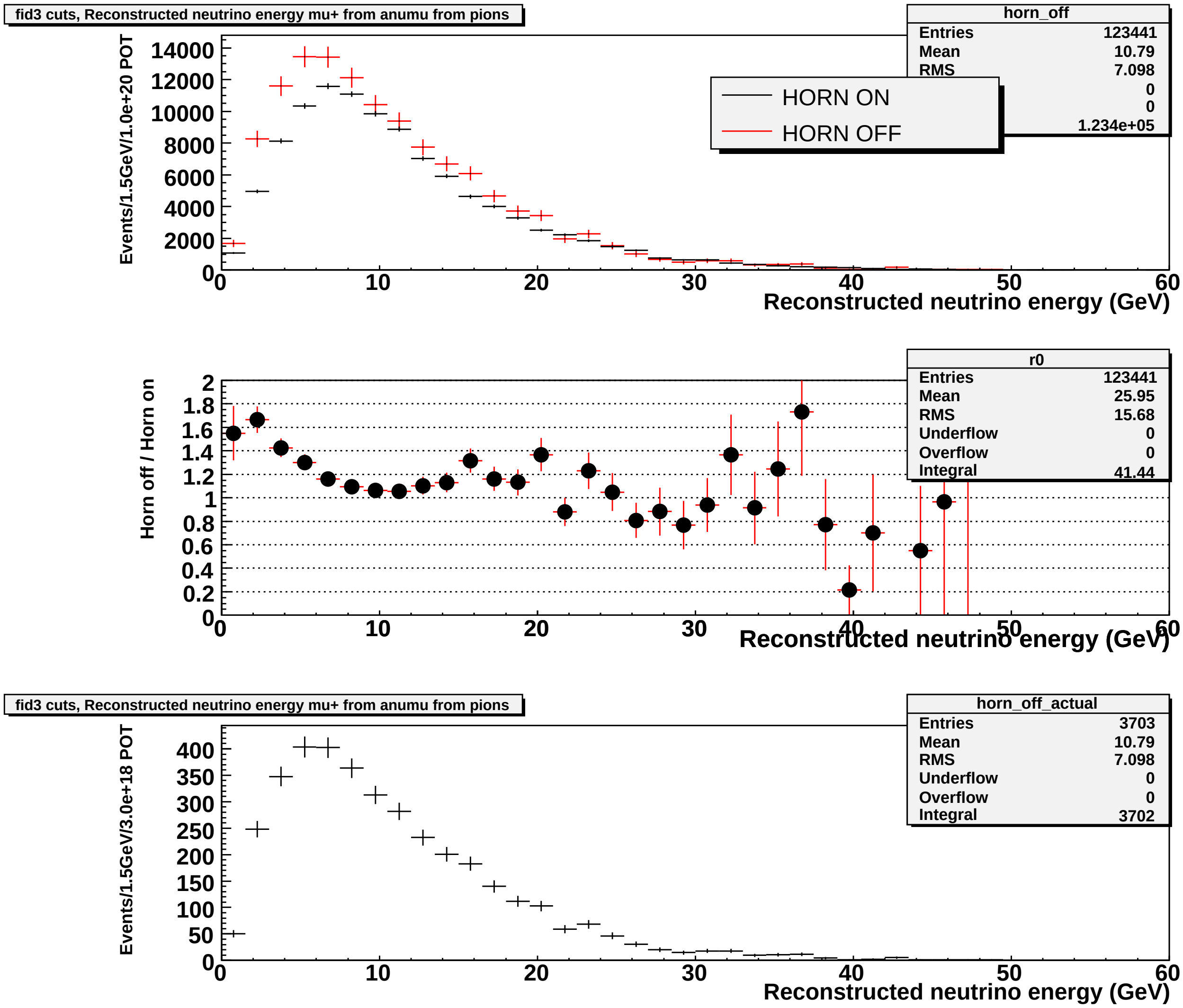


Figure 11: Top: Comparison of estimated reconstructed $\overline{\nu}_\mu$ fluxfor 10^{20} POT. Middle: Ratio of horn-off to horn-on. MC statistics only. Bottom: Expected yield of $\overline{\nu}_\mu$ for horn-off exposure of 3×10^{18} POT

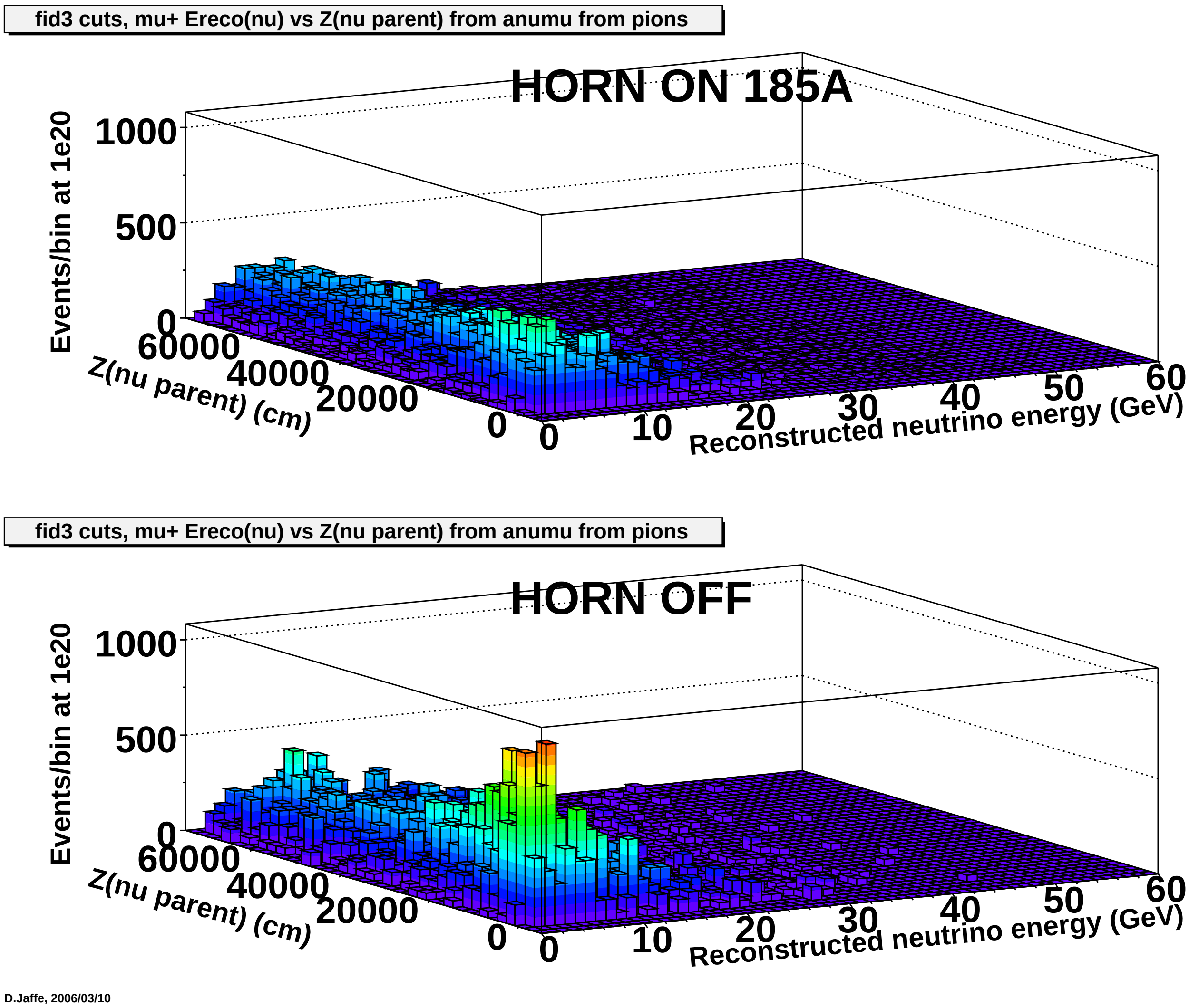


Figure 12: The true neutrino energy *vs* the z of the $\overline{\nu}$ decay point for horn-on(top) and horn-off(bottom) MC normalized to 10^{20} POT. The decrease in $\overline{\nu}_{\mu}$ flux due to the defocussing of negative pions by the horn is clear.