Some antineutrino topics

- $\nu \rightarrow \overline{\nu}$ transitions (Details are in `MINOS-doc-1571`.)
  1. Measurement technique
  2. Physics effects
  3. Beam and detector effects
  4. Prospects
- Constraining the ν_e flux from $\overline{\nu}_\mu$ measurements
- Improving the understanding of the ν beam

$\nu \to \overline{\nu}$ measurement technique

Look for a deviation in relative rates of μ^- and μ^+ produced by beam ν_μ and $\overline{\nu}_\mu$ in the far detector (FD) based on the measured rates in the near detector (ND).

In other words, predict the observable number of μ^+ in the FD based on the observed numbers of μ^- in the FD and $\mu^\pm$ in the ND.

What physics effects can change the relative amount of beam ν_μ and $\overline{\nu}_\mu$ as they go from FNAL to Soudan?

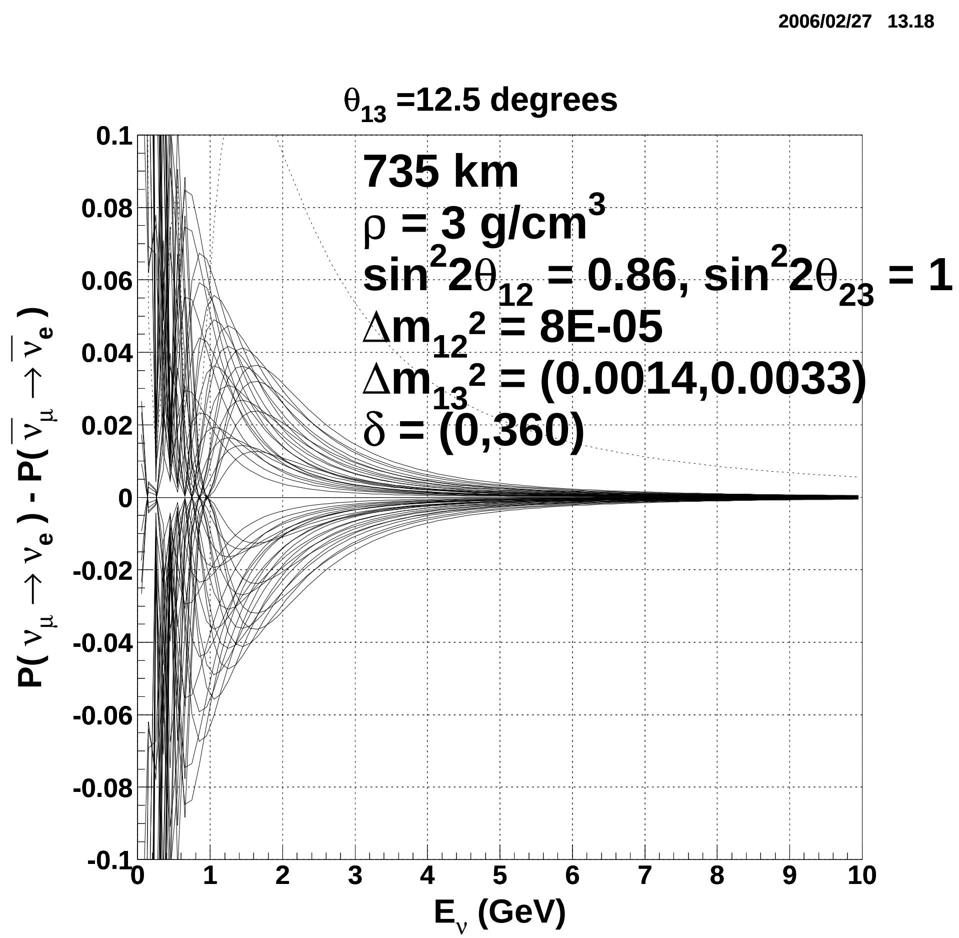
Physics effects and $\nu \rightarrow \overline{\nu}$

1. If ν are Majorana particles, then $P(\nu \rightarrow \overline{\nu}) \propto m_\nu / E_\nu$ ($< 10^{-10}$ for $E_{\nu_\mu} \sim$1GeV)
2. if ν are Dirac & Majorana particles, then $P(\nu \rightarrow \nu_{\rm sterile}) \sim 3 \times 10^{-7} \sin^2(1.27 \Delta m^2 L/E)$
3. CPT implies $P(\nu_\mu \rightarrow \nu_\mu) = P(\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu)$, but CPTV does not necessarily imply $P(\nu_\mu \rightarrow \nu_\mu) \neq P(\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu)$.
4. Matter effects and/or CPV can change the relative ν_μ and $\overline{\nu}_\mu$ fluxes. Limited to a few % at < 2 Gev (see figure)

Refs: Langacker & Wang, PRD**58** 093004; Kostelecky & Mewes, PRD**69** 016005

Allowed range for $P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$ at FD

The difference in the probability of $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations for 735 km baseline and an average density of $3 \mathrm{g/cm}^3$ assuming $\theta_{13} = 12.5^\circ$, $\Delta m^2_{13} = (0.0014, 0.0033)$ eV^2 and $\delta = (0, 360)^\circ$. The various superimposed curves are the result of scanning Δm^2_{13} and the CP-violating parameter δ over the stated ranges.



Technique: Detector and beam effects

Technique: Predict number of observable μ^+ in FD ($\equiv n^+_{\rm FD}$) based on observed number of μ^- in FD ($\equiv n^-_{\rm FD}$) and $\mu^\pm$ in ND ($\equiv n^\pm_{\rm ND}$).

Let $N^\nu_{\rm F,N} \equiv$ true number of ν_μ interactions in FD,ND (similarly for $\overline{\nu}_\mu$), then

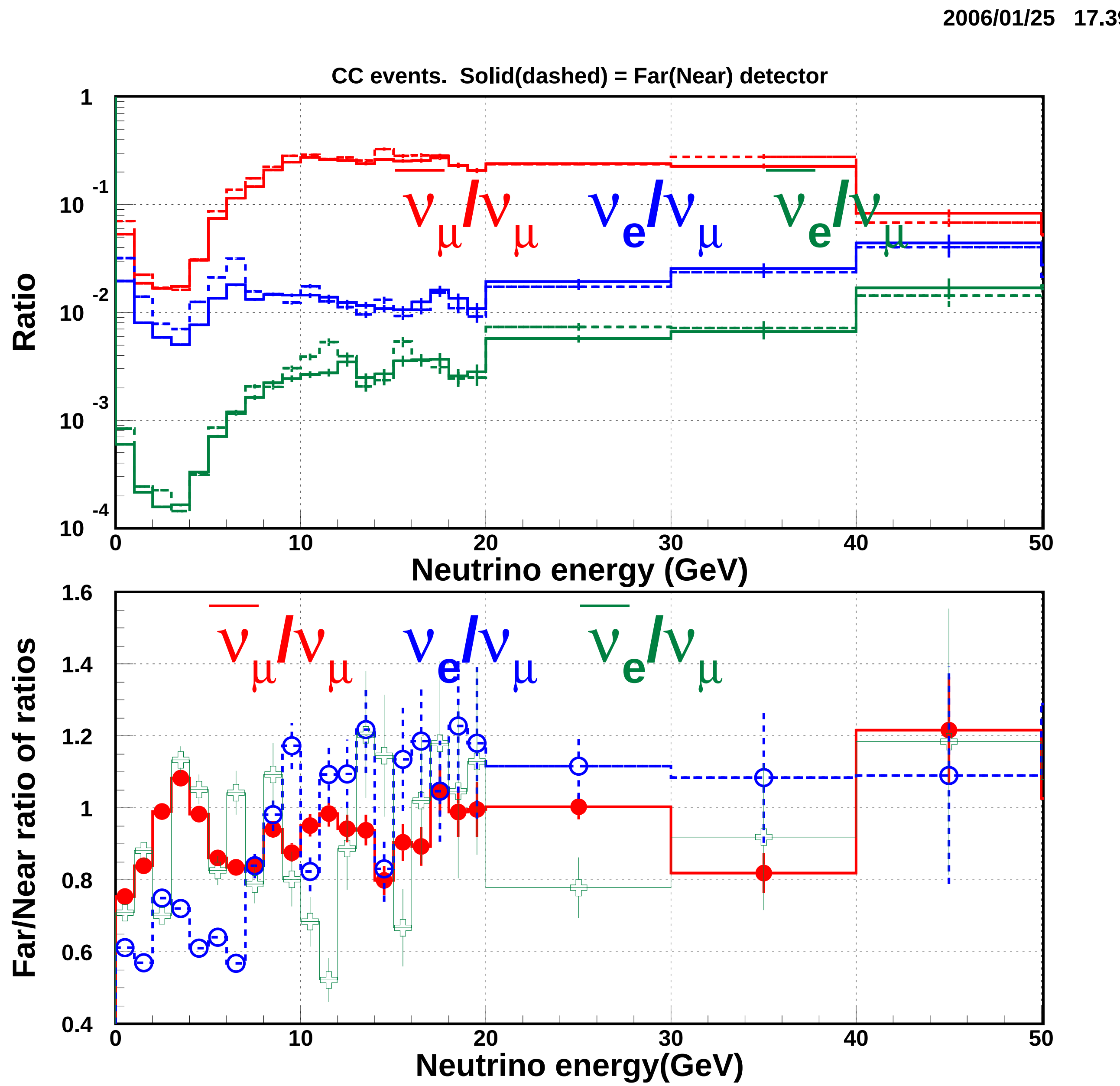
$$N^\nu_{\rm N} = (n^-_{\rm N} - b^-_{\rm N})p^-_{\rm N}/\epsilon^-_{\rm N} \quad \text{where}$$

- $b^-_{\rm N} \equiv$ the expected number of observed background μ^- at the ND,
- $p^-_{\rm N} \equiv$ the purity of μ^- selection at the ND, the purity is the fraction of correctly tagged ν_μ , and
- $\epsilon^-_{\rm N} \equiv$ the efficiency of μ^- selection at the ND.

Technique: Detector and beam effects (cont.)

Also assume that the relative rates of ν_μ and $\overline{\nu}_\mu$ at the two detectors can be written as $N^{\bar{\nu}}_{\mathrm{F}}/N^{\nu}_{\mathrm{F}} = K \times N^{\bar{\nu}}_{\mathrm{N}}/N^{\nu}_{\mathrm{N}}$ where K is a correction factor within $\sim$10% of unity.

Figure: Ratios wrt ν_μ flux and FD/ND ratio of ratios with GNUMI V15



Technique: Detector and beam effects (cont.)

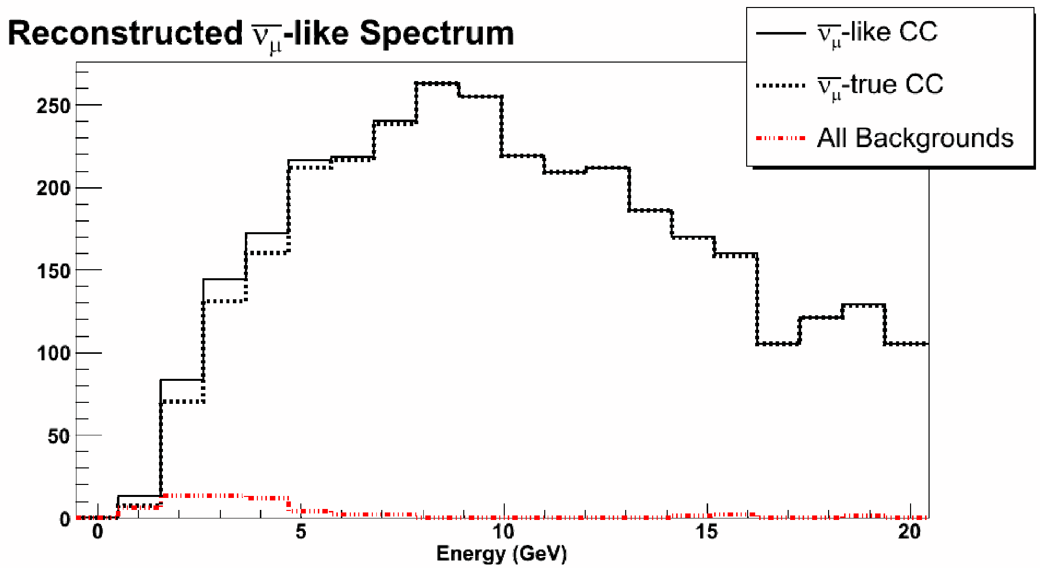
- Purity p of $\mu^{\pm}$ selection differs at FD,ND. A MC-based correction must be applied. See `MINOS-doc-1571` for a proposal to use stopped μ decays to check the MC estimate.

- $\mu^{\pm}$ selection efficiency ϵ differs at FD,ND. This must also be corrected using MC. Can the correction be checked with a cosmic data/MC comparison?

- By definition, background is a reconstructed μ candidate that is not produced by a beam ν_{μ} or $\overline{\nu}_{\mu}$. μ candidates from ν_e, ν_{τ}, $\overline{\nu}_e$ or $\overline{\nu}_{\tau}$ interactions and cosmic $\mu^{\pm}$ are possible backgrounds.

Jeff Hartnell showed that high purity ($p^{+}_{\mathrm{N}} > 95\%$) and low background ($< 1\%$ relative) could be achieved in ND MC (next slide).

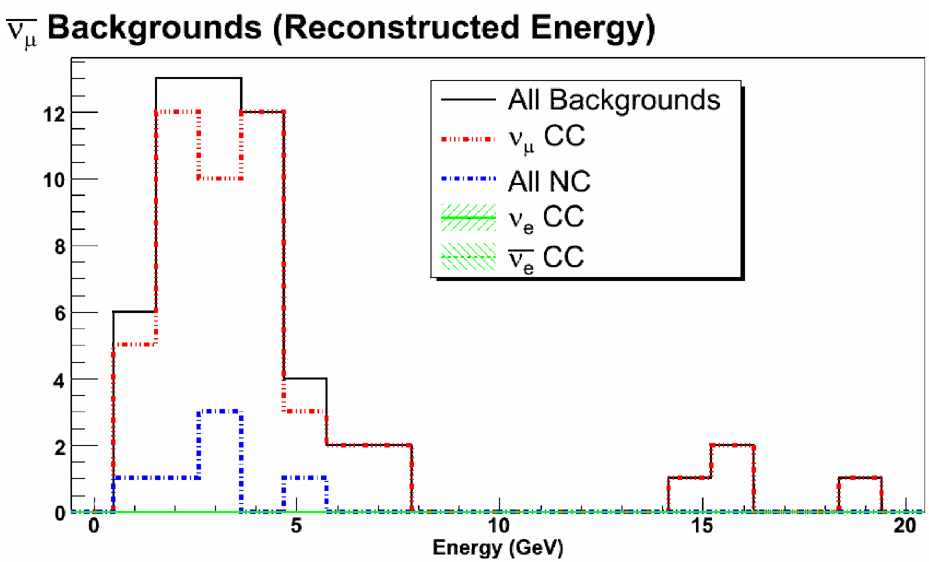
After tighter DP ID and Fit Probability cuts



Significantly reduced background with two new cuts
- NC are almost completely removed by tight DP ID cut.
- Only a few NuMu-CC remaining.

Cuts are yet to be optimised fully...

MC



taken from MINOS-doc-1409-v1, Jeff Hartnell, Oxford Jan 2006

Technique: Some other effects and comments

Other effects:

- Charm production and subsequent semileptonic can produce wrong sign muons. This must be taken into account in the MC-estimated purity.
- Different energy scales at ND and FD complicate the use of the ND ratio to produce the FD ratio.

Comments:

- All beam energies, not just LE-10, should be used for this measurement.
- Rock muons should probably be used mainly because they can increase the FD sample by $\sim$70% (Ref:M.L.Marshak, MINOS-doc-1379-v1)

Prospects for a $\nu_\mu \longrightarrow \overline{\nu}_\mu$ measurement

The deviation Δ in the expected μ^+ rate at the FD is

$$\Delta \equiv n^+_{\rm F} - \left\{ K \times E \times P \times (n^-_{\rm F} - b^-_{\rm F}) \frac{n^+_{\rm N} - b^+_{\rm N}}{n^-_{\rm N} - b^-_{\rm N}} + b^+_{\rm F} \right\}$$

where

- $E \equiv \frac{\epsilon^+_{\rm F}}{\epsilon^-_{\rm F}} \times \frac{\epsilon^-_{\rm N}}{\epsilon^+_{\rm N}}$ is the efficiency double ratio, and
- $P \equiv \frac{p^-_{\rm F}}{p^+_{\rm F}} \times \frac{p^+_{\rm N}}{p^-_{\rm N}}$ is the purity double ratio.

Prospects for a $\nu_\mu \rightarrow \overline{\nu}_\mu$ measurement (cont.)

Approximate uncertainty in Δ:

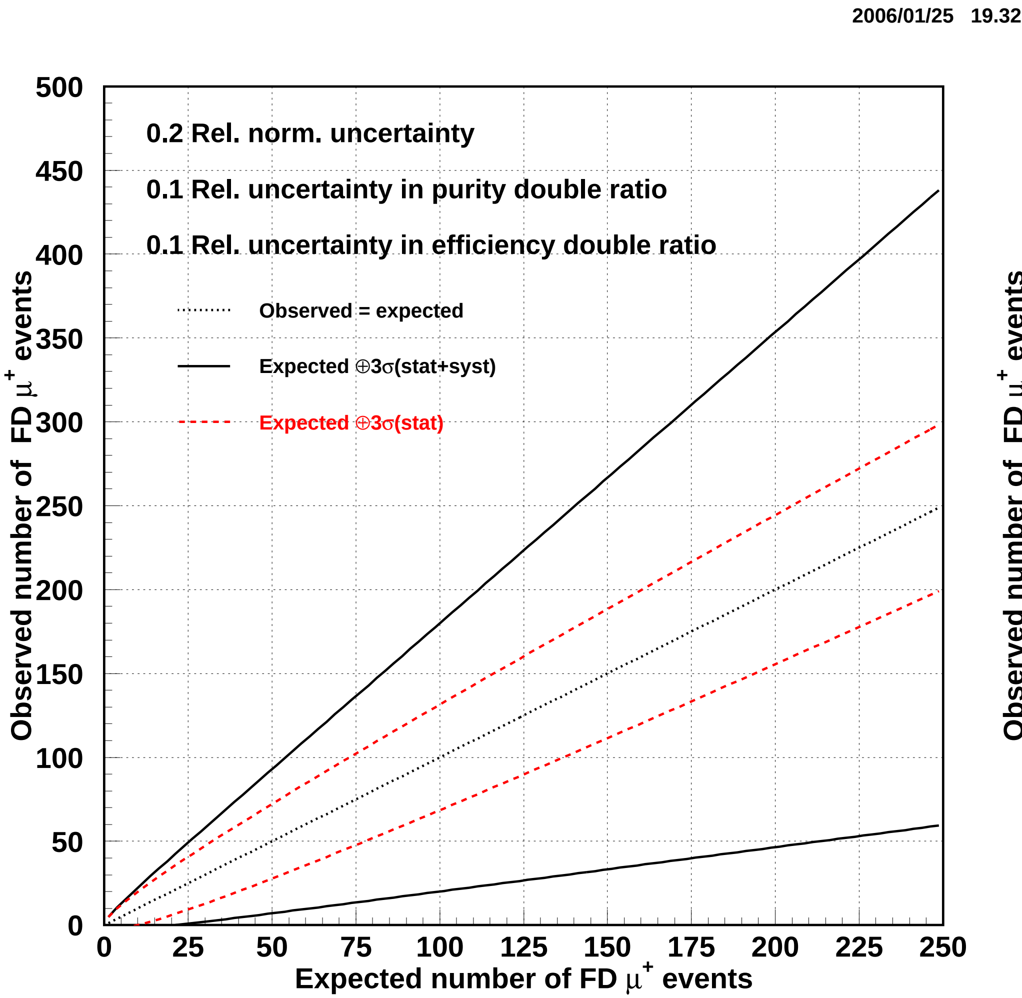
$$\delta\Delta \approx \sqrt{n_{\rm F}^{+} + R^2 n_{\rm F}^{-} + (R n_{\rm F}^{-})^2 \times (\delta K^2 + \delta P^2 + \delta E^2)}$$

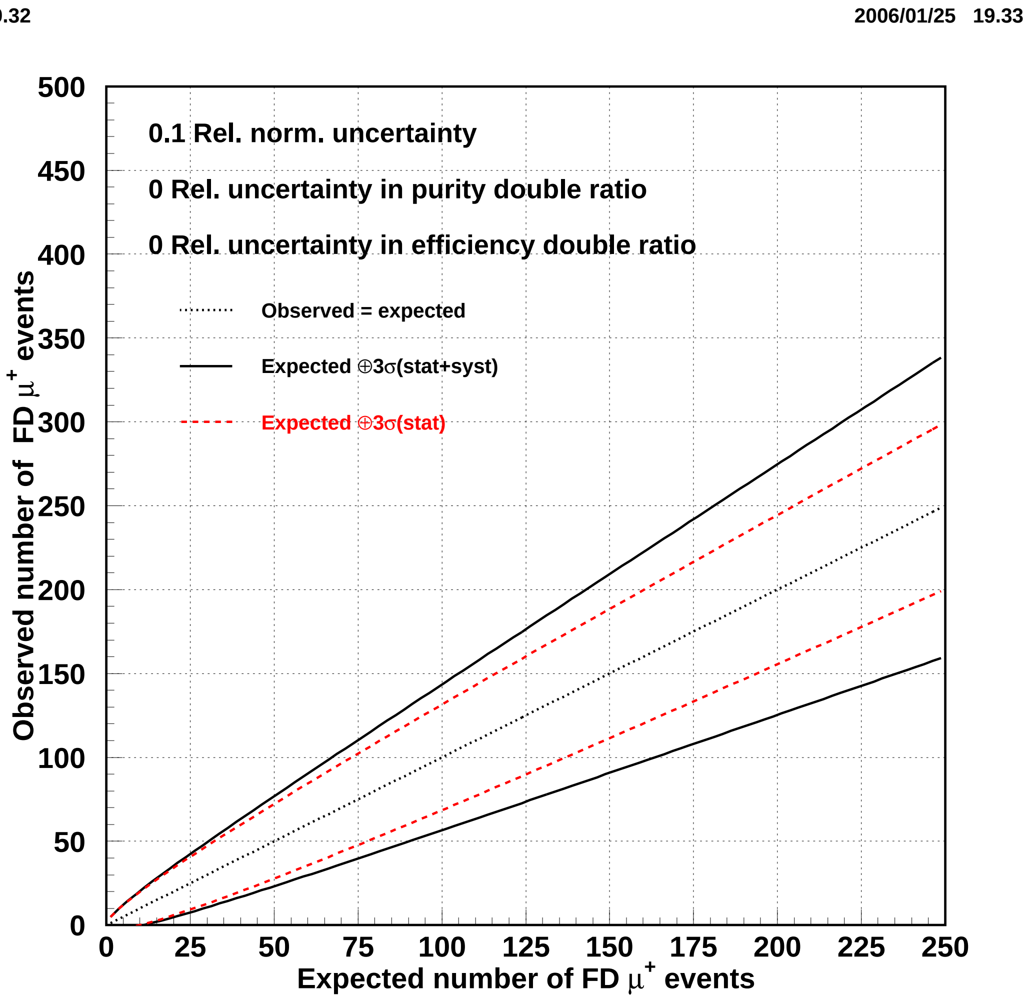
Under these assumptions:

- No correlations between the terms in Δ,
- $K \approx P \approx E \approx 1$,
- Background is negligible, and
- drop all terms multiplied by the far-to-near ratio, $(n_{\rm F}^{-} - b_{\rm F}^{-})/(n_{\rm N}^{-} - b_{\rm N}^{-})$.

I also assume that $R \equiv (n_{\rm N}^{+} - b_{\rm N}^{+})/(n_{\rm N}^{-} - b_{\rm N}^{-}) \approx 1/10$ and $n_{\rm F}^{-}/R \approx n_{\rm F}^{+}$ to produce following figure:

Three standard dev. limits in observed $n_{\mathbf{F}}^{+}$ *vs* expected $n_{\mathbf{F}}^{+}$ (red is stat. only)





Pessimistic:

$$\delta K/K = 0.2,\ \delta P/P = \delta E/E = 0.1$$

Optimistic:

$$\delta K/K = 0.1,\ \delta P/P = \delta E/E = 0$$

Measuring $\nu_\mu \to \overline{\nu}_\mu$: Some conclusions

$$\delta\Delta \approx \sqrt{n_{\mathrm{F}}^{+} + R^2 n_{\mathrm{F}}^{-} + (R n_{\mathrm{F}}^{-})^2 \times (\delta K^2 + \delta P^2 + \delta E^2)}$$

- Statistical uncertainty in the number of observable μ^+ in FD dominates the ability to limit $\nu_\mu \to \overline{\nu}_\mu$ transitions.

- Systematic uncertainty associated with the ND/FD extrapolation (K) needs to be kept at the $\leq 10\%$ level. It may be worthwhile to consider an analysis that ignores the ND and uses MC to predict $\overline{\nu}_\mu/\nu_\mu$ at the FD (idea from P.Ochoa).

- Measurement of purity (p), efficiency (ϵ) and background (b) from data is desired, but may not be essential. (Since p, ϵ appear as double ratios and b is probably negligible)

- Ultimately must develop methods to use $\nu_\mu \to \overline{\nu}_\mu$ results to limit (or measure!) parameters of models that predict $\nu_\mu \to \overline{\nu}_\mu$ transitions.

Constraining the ν_e flux from $\overline{\nu}_\mu$ measurements

Motivation: Beam ν_e are an irreducible and especially pernicious background in the $\nu_\mu \rightarrow \nu_e$ appearance analysis.

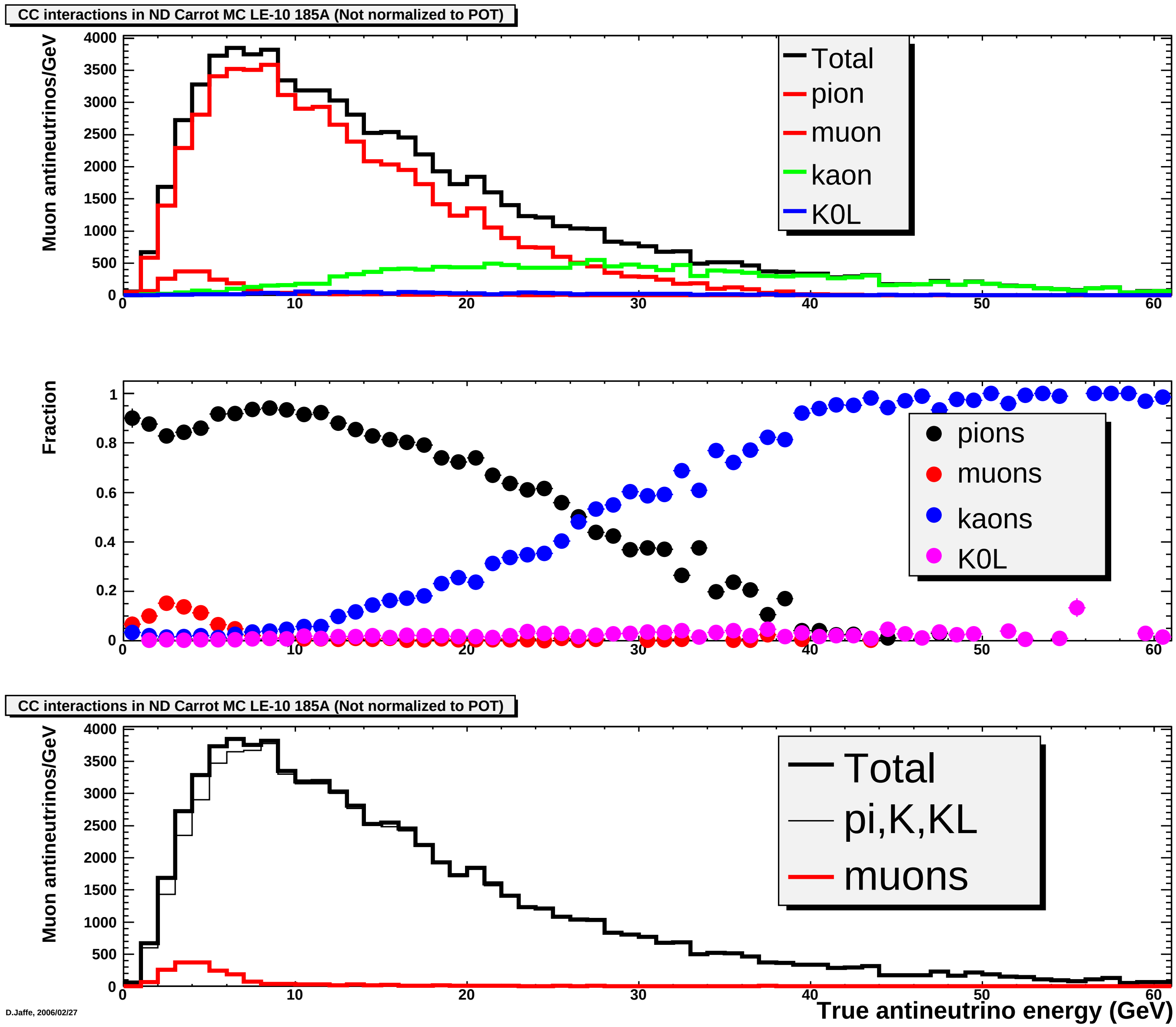
NC	CC	ν_τ	Beam ν_e	ν_e	From p.15 of MINOS-doc-1143
20.4	4.7	1.7	4.7	6.2	by Mayly Sanchez

Milind Diwan suggested that a measurement of the $\overline{\nu}_\mu$ flux could be used to constrain the ν_e flux because ν_e production is dominated by $\mu^+ \rightarrow e^+ \overline{\nu}_\mu \nu_e$ at low energy.

To this end, the relative fluxes at the center of the ND were studied with GNUMI V15 as well as the number of CC interactions in Carrot ND MC processed with R1.18.2. Reconstruction effects not yet investigated.

The tentative conclusion is that an $\mathcal{O}(100\%)$ constraint on the ν_e flux at the ND should be possible, see figure on following page (and at end of presentation).

$\overline{\nu}_\mu$ CC interactions at ND, carrot MC, R1.18.2, not norm'ed to POT



Method: Estimate $\overline{\nu}_\mu$ from π, K for $10 < E_\nu < 20$ GeV and extrapolate to $< 10 GeV$ using MC.

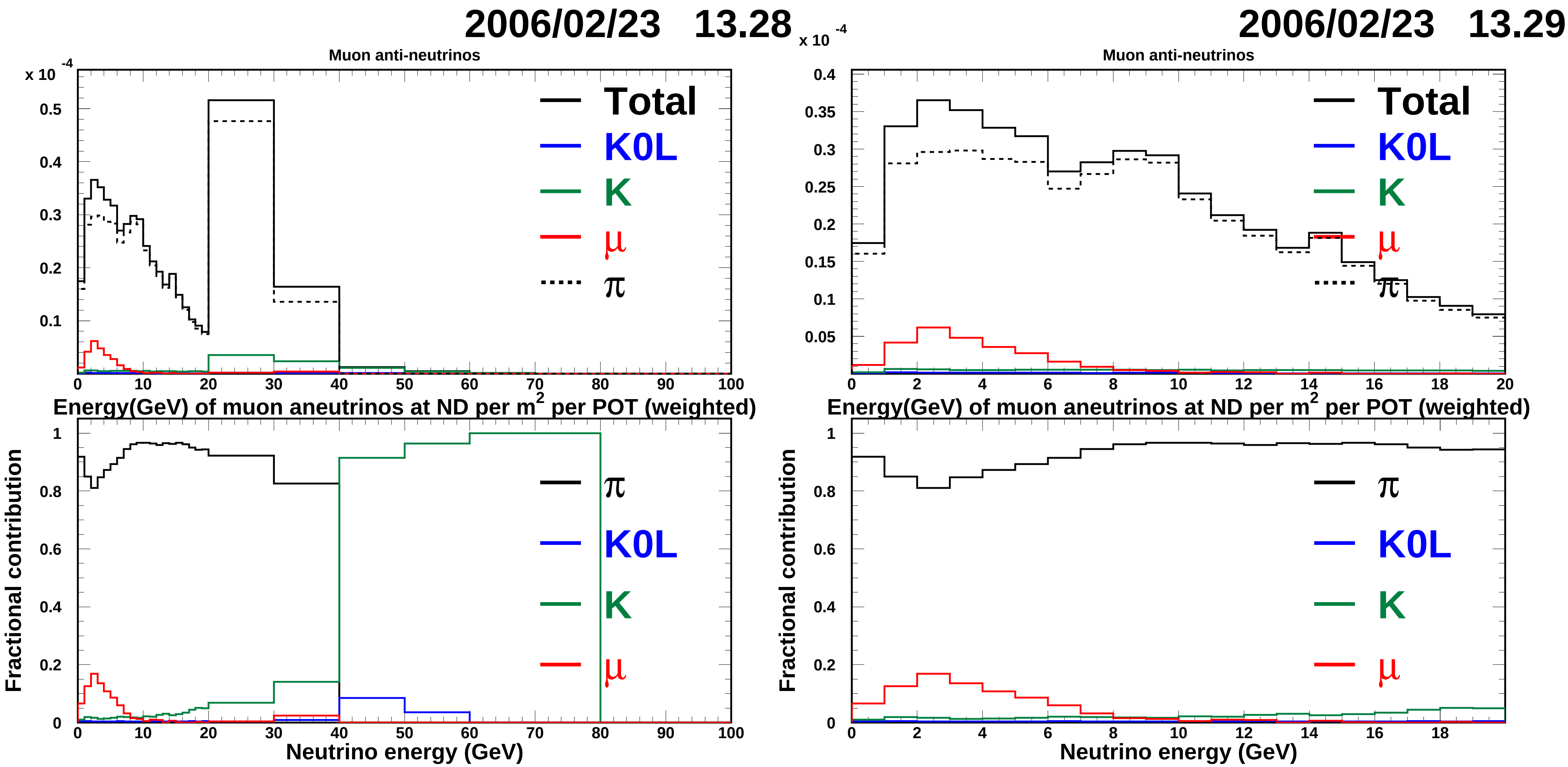
Summary

- An analysis method to search for $\nu_\mu \rightarrow \overline{\nu}_\mu$ was presented. The primary uncertainty is due to the statistics of the number of observable FD μ^+. The main systematic uncertainty is due to knowledge of the beam $\overline{\nu}_\mu$ to ν_μ ratio. Details in `MINOS-doc-1571`.
- Approximately 15% of the low energy $\overline{\nu}_\mu$ CC rate at the ND is due to $\overline{\nu}_\mu$ from μ^+ decay. It should be possible to estimate this contribution to the $\overline{\nu}_\mu$ CC rate using higher energy data and MC and thus constrain low energy, beam ν_e flux.
- Measurement of the $\overline{\nu}$ flux should improve the knowledge of the ν flux (statement of the obvious?)

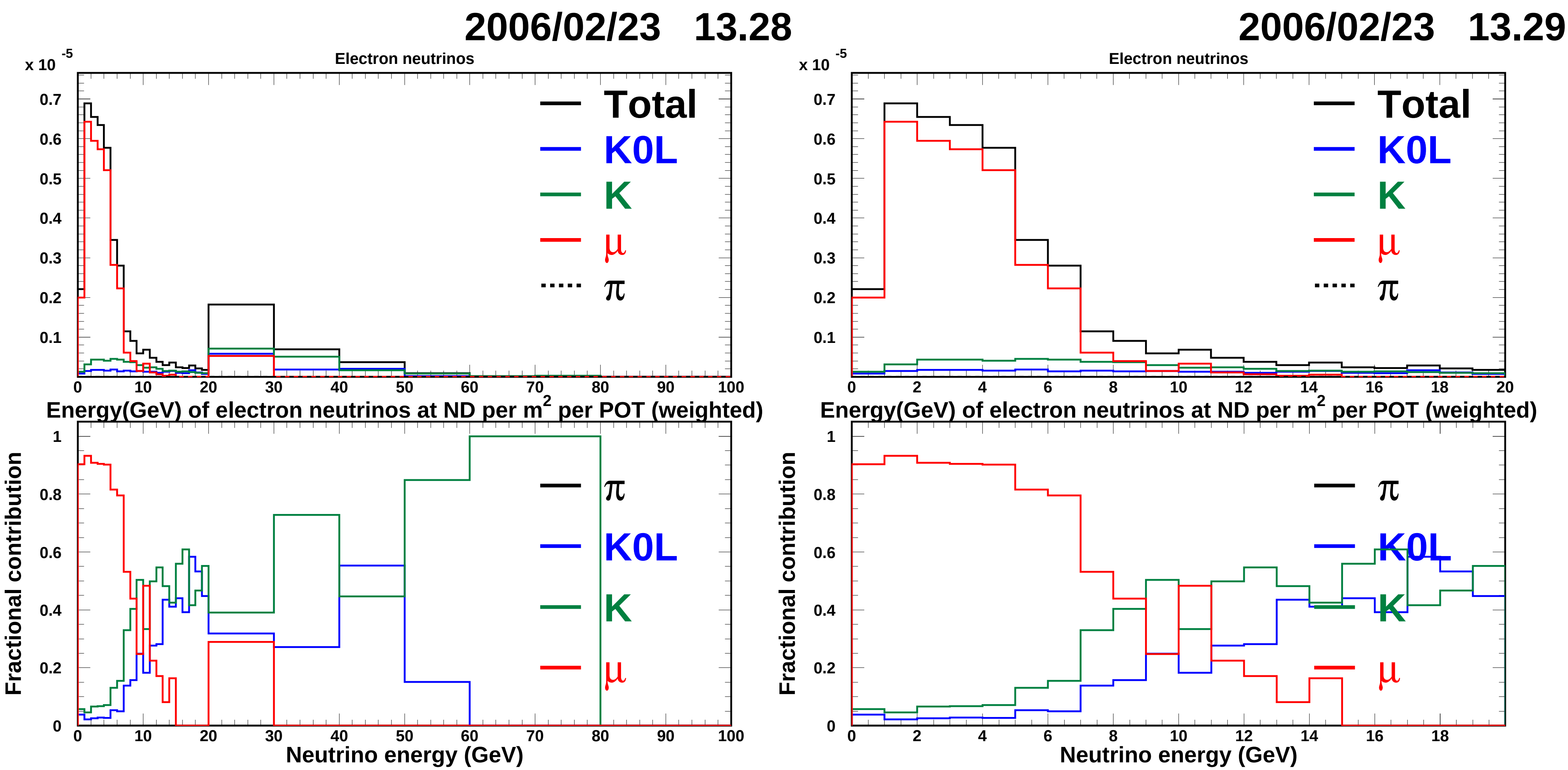
Thanks to M.Bishai, M.Dierckxsens, M.Diwan, J.Hartnell, A.Marino, P.Ochoa, B.Viren.

Backup

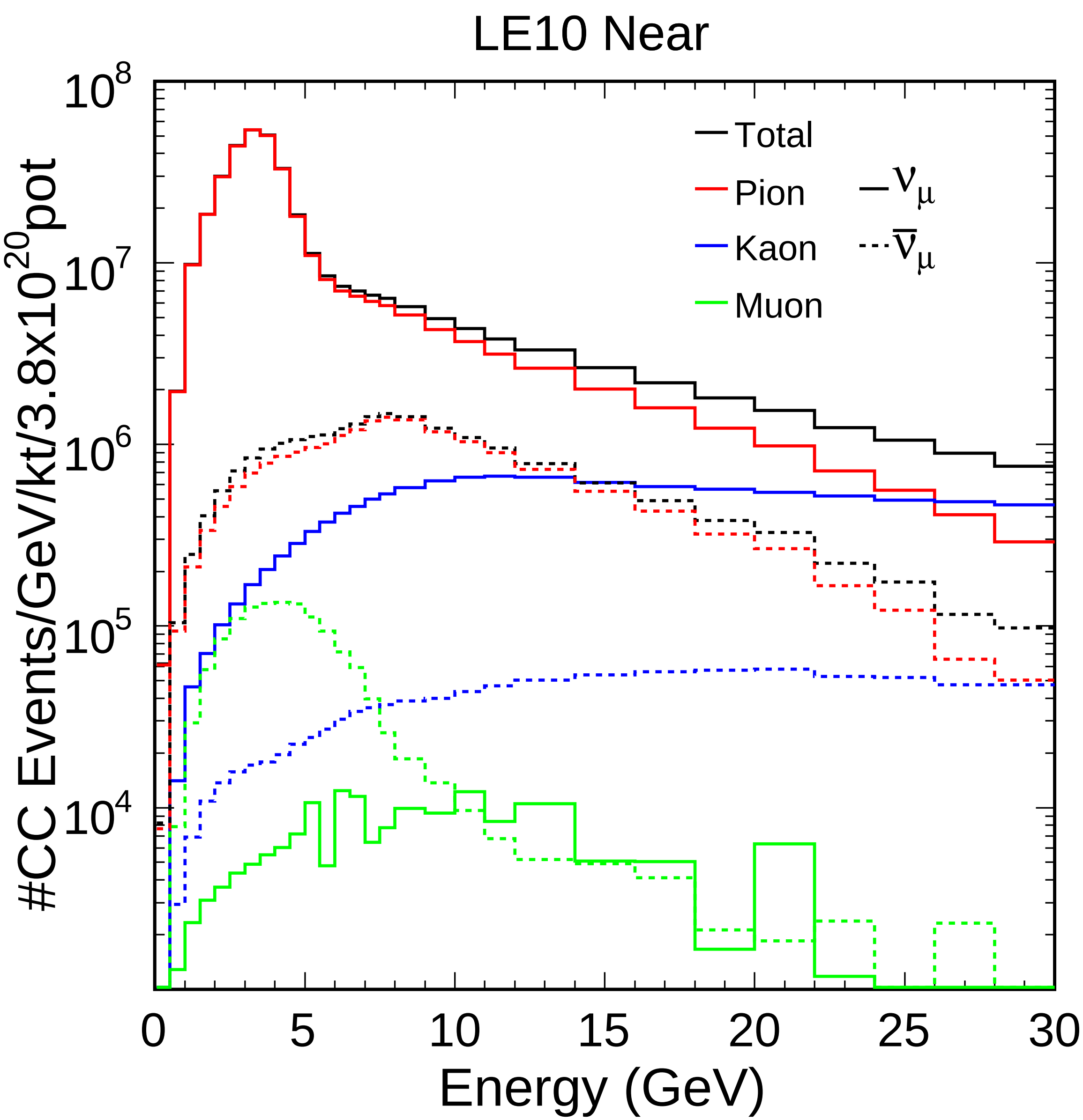
$\overline{\nu}_\mu$ flux at ND from GNUMI V15



ν_e flux at ND from GNUMI V15



ND CC rates from "Official Beam Plots"



www.hep.utexas.edu/numi/beamMC/blessed-plots/basic-fluxes/LE10_CCNear_log.eps