Hadron Production Uncertainties at NuMI

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1. Extrapolation Near $\rightarrow$ Far at NuMI.
   a. On-axis experiment with on-axis near detector (MINOS).
   b. Off-axis experiment with on-axis near detector.
2. Systematic uncertainties in the ν_μ spectrum prediction.
3. Evaluation of the ν_e component of the beam.

NuFact02 London July 1-6, 2002

Extrapolation Near $\rightarrow$ Far at NuMI

• Standard, approximative method for an on-axis experiment: predict far detector spectrum based on spectrum measured in a near detector - "Far/Near ratio":

$$\frac{dN_{Far}}{dE} = \left[\frac{\frac{dN_{Far}}{dE}}{\frac{dN_{Near}}{dE}} \right]_{nominal} \times \frac{dN_{Near}}{dE}$$

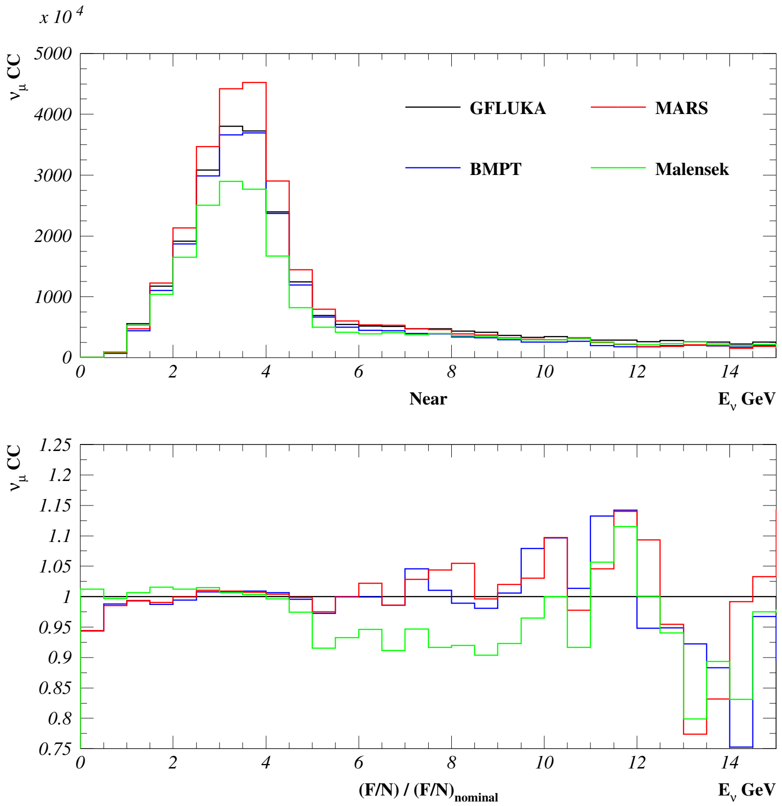
• Nominal Far/Near ratio is determined primarily by beamline geometry and calculable from simulations once the latter is known.

• Most physics and beamline related uncertainties will cancel in the "double ratio" **(Far/Near)**$_{actual}$**/(Far/Near)**$_{nominal}$.

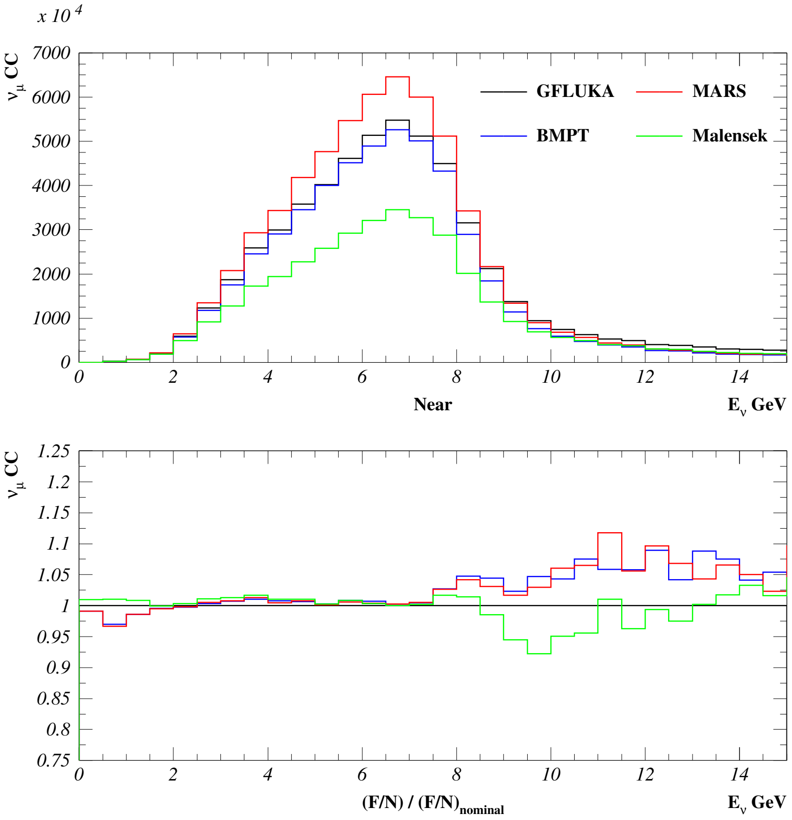
• Non-oscillated far detector spectrum is predictible typically within a few per cent after a near site spectrum is measured.

Far/Near ratio in an on-axis experiment

Low energy beam



Medium energy beam



Far/Near ratio in an on-axis experiment II

• Hadron production uncertainties: ~25% discrepancies between models in the absolute predictions. Far/Near ratio stable to ~2% in the energy region of good pion focusing and ~10% outside.

Why does the "Far/Near ratio" work?

Each neutrino observed in the near detector ≡ expected certain flux of neutrinos in the far detector, with $E_{Far} = E_{Near}$. Strictly speaking, only true when every decaying pion/kaon sees both detectors at the same angle, $\Theta_{Far} = \Theta_{Near}$. Hence:

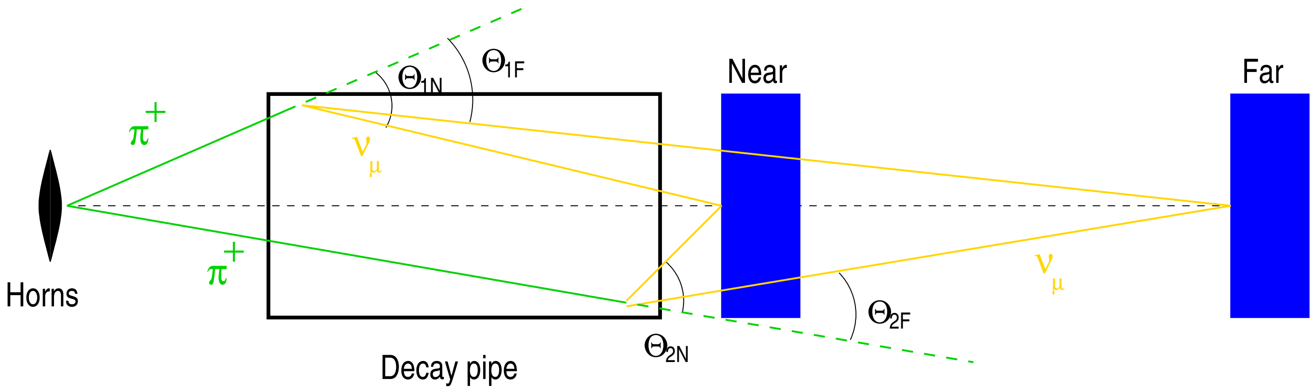
• True with two well aligned detectors and a pencil-like, perfectly focused beam.

• Not strictly true for an imperfectly focused beam (for a badly focused pion/kaon $\Theta_{Far} \neq \Theta_{Near}$).

• Breaks down in an off-axis experiment, unless a dedicated off-axis near detector is used. A more general approach is required.

Improved approach

When $\Theta_N \neq \Theta_F$:



• The same parent pion beam strongly correlates the Near and Far spectra, but $E_{Far} \neq E_{Near}$.

• Each neutrino observed in the near detector $\equiv$ expected certain flux of neutrinos in the far detector, with $P(E_{Far}, E_{Near}) \neq \delta(E_{Near})$:

$$\frac{dN_{Far}}{dE_{Far}} = \int P(E_{Far}, E_{Near}) \frac{dN_{Near}}{dE_{Near}} dE_{Near}.$$

• $P(E_{Far}, E_{Near})$ determined primarily by beamline geometry (and location of the far detector).

Improved approach II

How to get $P(E_{Far}, E_{Near})$

• Every decaying pion is assigned to weights: $w_{Near/Far} = w_{Near/Far}(E_\pi, \Theta_\pi, z, r)$, defined as the fraction of all decays with a neutrino ending up in the near/far detector.

• Neutrino energies $E_{Near/Far}$ are unambiguously given by E_π, Θ_π, z, r, assuming point-like detectors (good approximation for NuMI).

• For a given pion decay, every neutrino with E_{Near} implies w_{Far}/w_{Near} neutrinos with E_{Far}.

• For a non-trivial, known, pion decay distribution $\Phi_\pi(E_\pi, \Theta_\pi, z, r)$:

$$P(E_{Far}, E_{Near}) = \frac{\int\int\int\int \ \Phi_\pi \ w_{Far} \ dE_\pi \ d\Theta_\pi \ dz \ dr}{\int\int\int\int \ \Phi_\pi \ w_{Near} \ dE_\pi \ d\Theta_\pi \ dz \ dr}$$

with integration over all phase space yielding E_{Near} and E_{Far} in the numerator, and E_{Near} in the denominator.

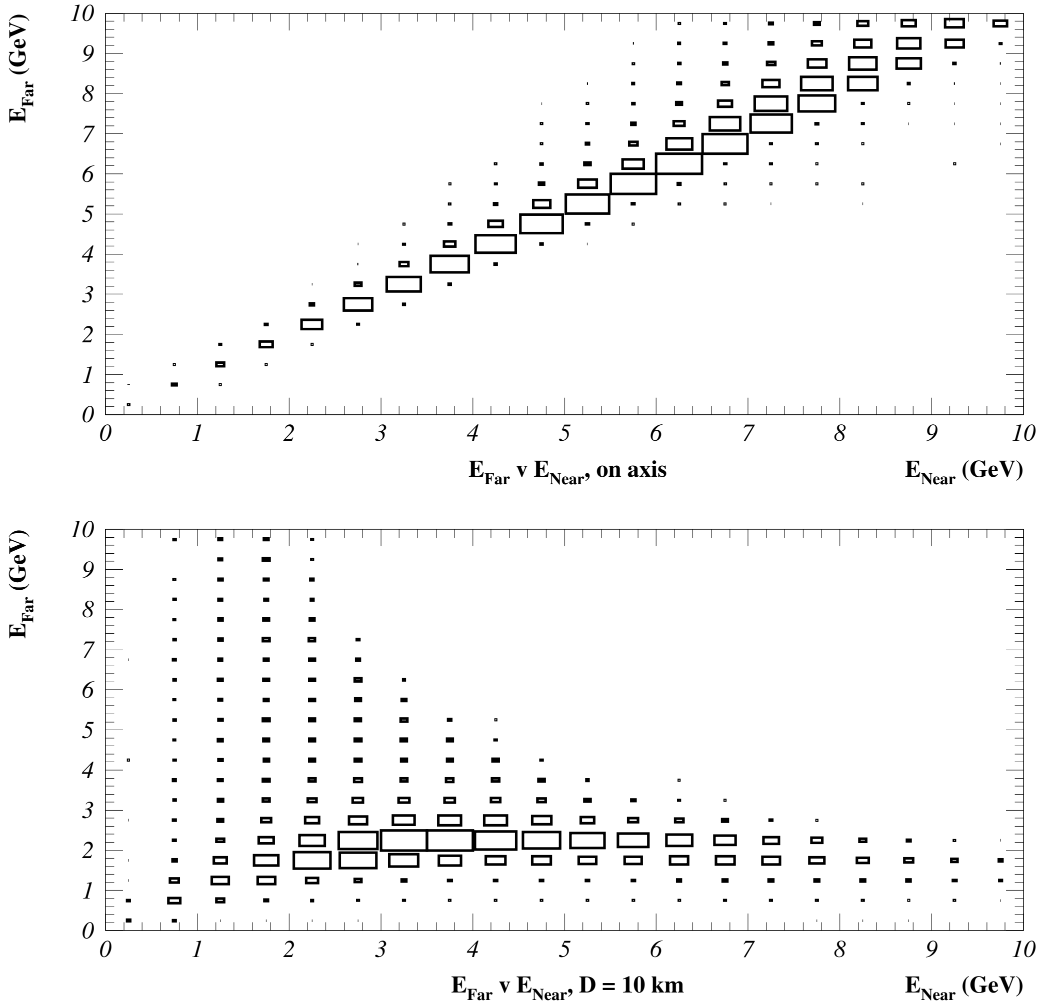
Improved approach III

- Far spectrum prediction in finite energy bins:

$P(E_{Far}, E_{Near}) \rightarrow M(N_{bins} \times N_{bins})$.

$$\vec{N}_{Far} = M \cdot \vec{N}_{Near}$$

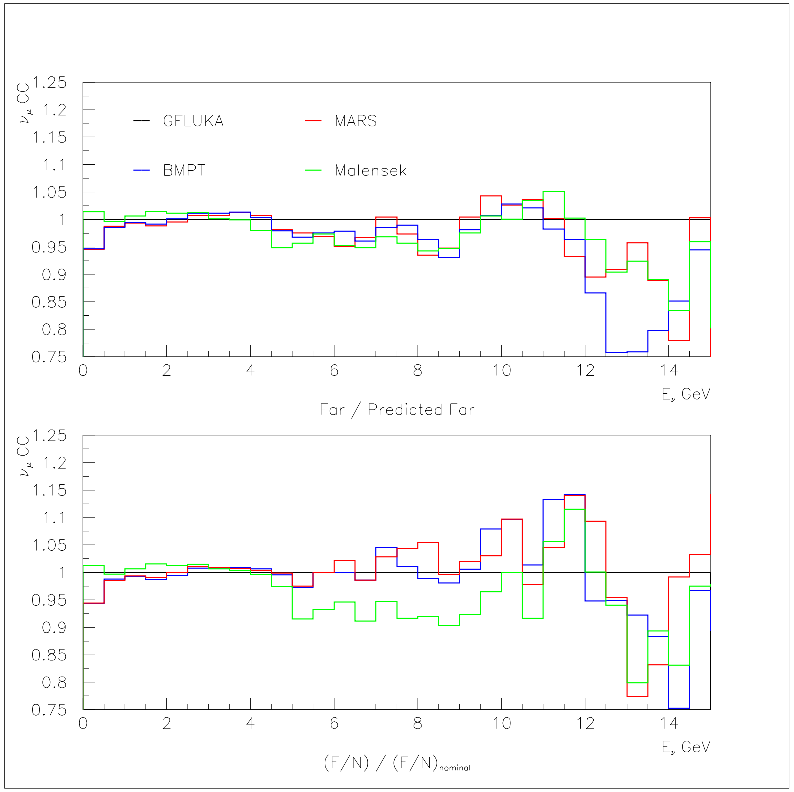
M - Near-to-far correlation matrix, constructed from correlated (E_{Near}, E_{Far}) pairs; in general non-diagonal.



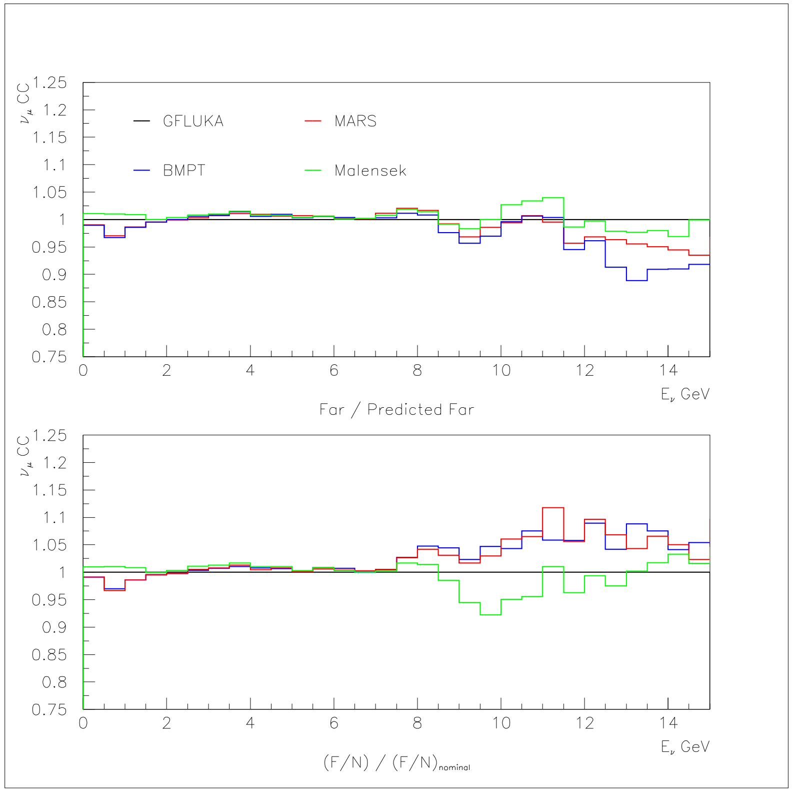
On-axis experiment - hadron production

Correlation matrix vs Far/Near ratio

Low energy beam



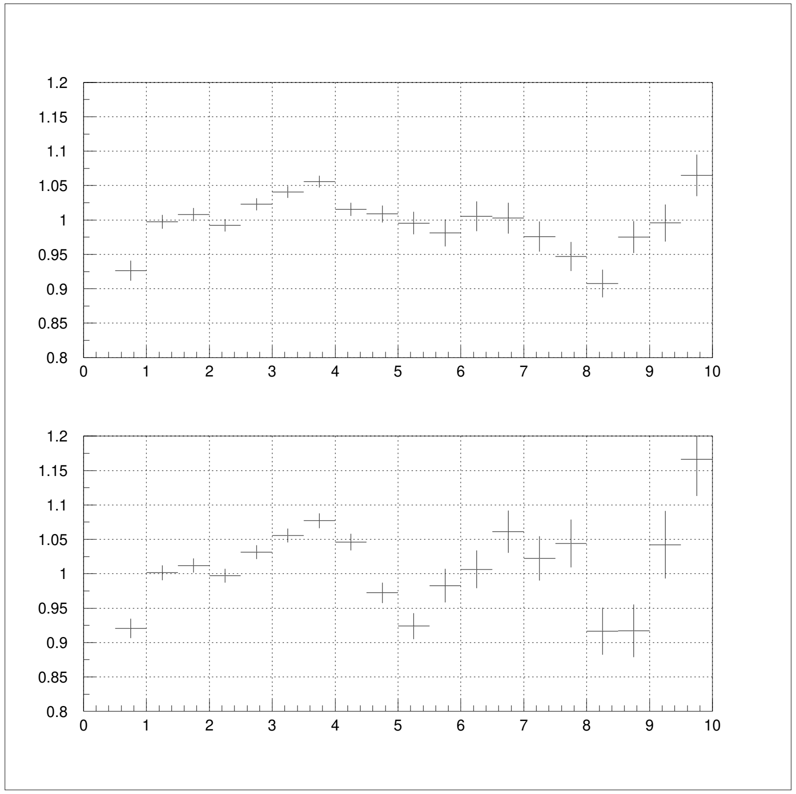
Medium energy beam



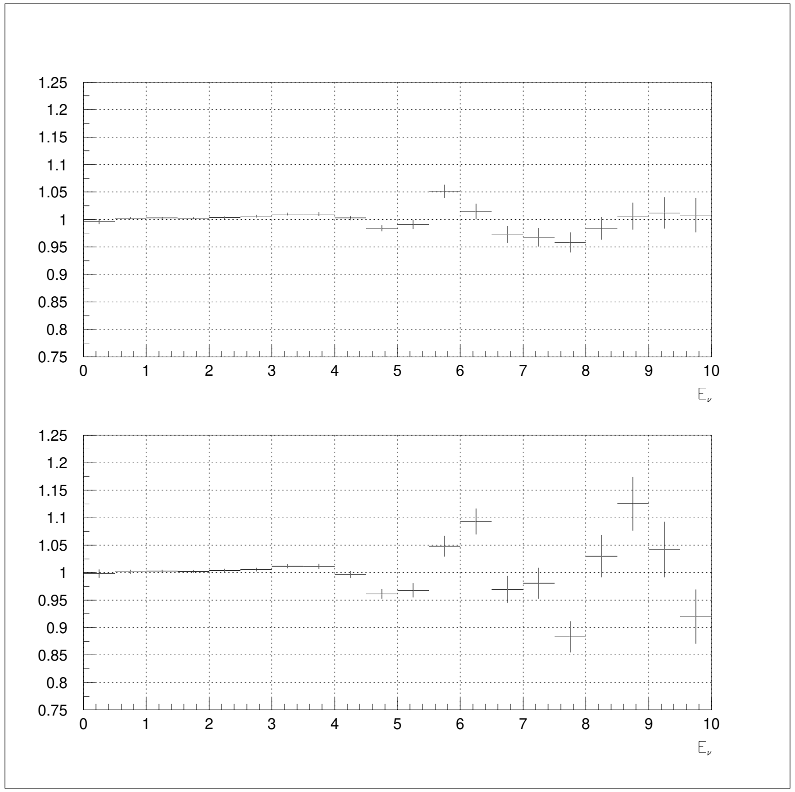
On-axis experiment - other beam related issues

Correlation matrix (upper plots) vs Far/Near ratio (lower plots)

Beam simulation (PBEAM spectrum)



Horn 1 shifted by 2 mm



Off-axis experiment - hadron production

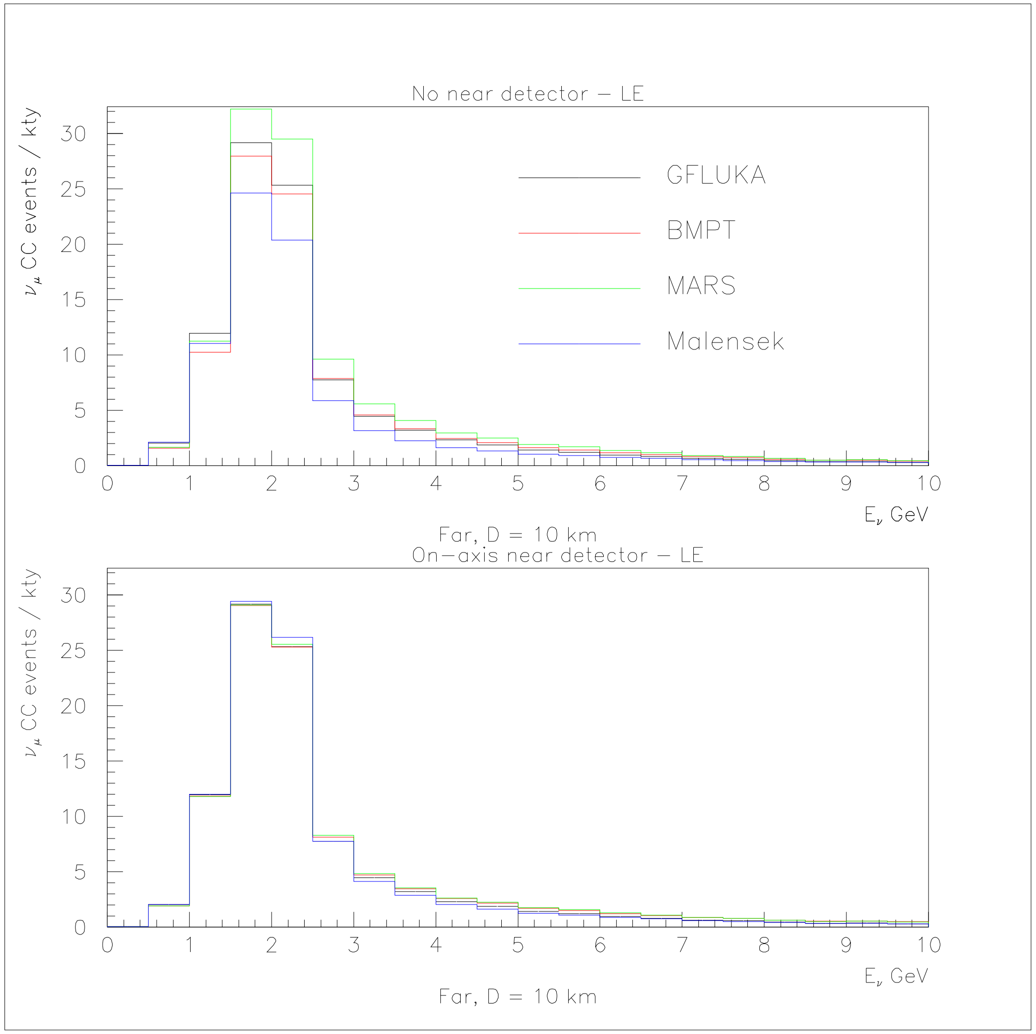
Low energy option

Predictions for far detector spectra (NuMI beamline, LE, L = 735 km), D = 10 km off axis.

• On absence of any near detector: ∼25% uncertainty.

• With an on-axis near detector (M matrix derived from each model):

GFLUKA: 74.2 events 1-3 GeV,
BMPT: 74.3 events,
MARS: 74.7 events,
Malensek: 75.4 events.



Off-axis experiment - hadron production

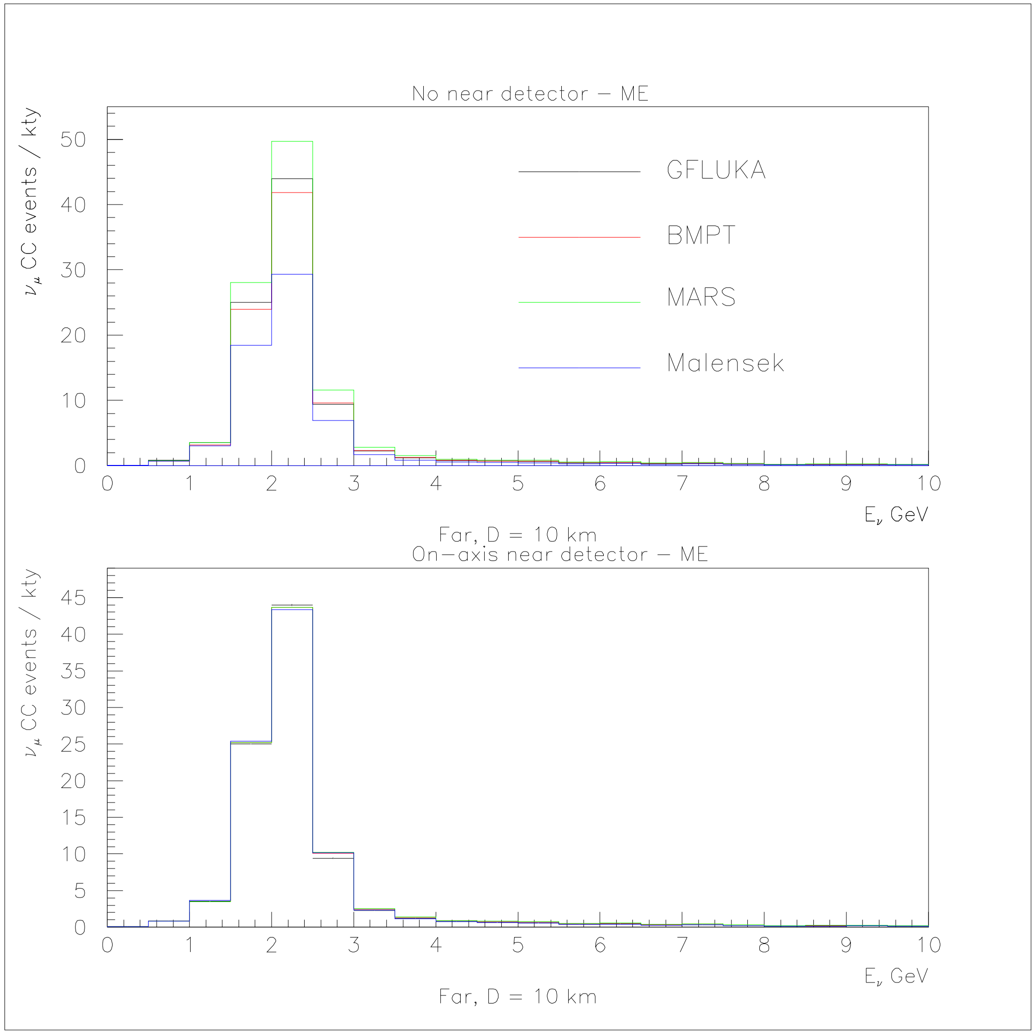
Medium energy option

Predictions for far detector spectra (NuMI beamline, ME, L = 735 km), D = 10 km off axis.

- On absence of any near detector: ~35% uncertainty.

- With an on-axis near detector (M matrix derived from each model):

GFLUKA: 81.9 events 1-3 GeV,
BMPT: 82.4 events,
MARS: 82.6 events,
Malensek: 82.6 events.

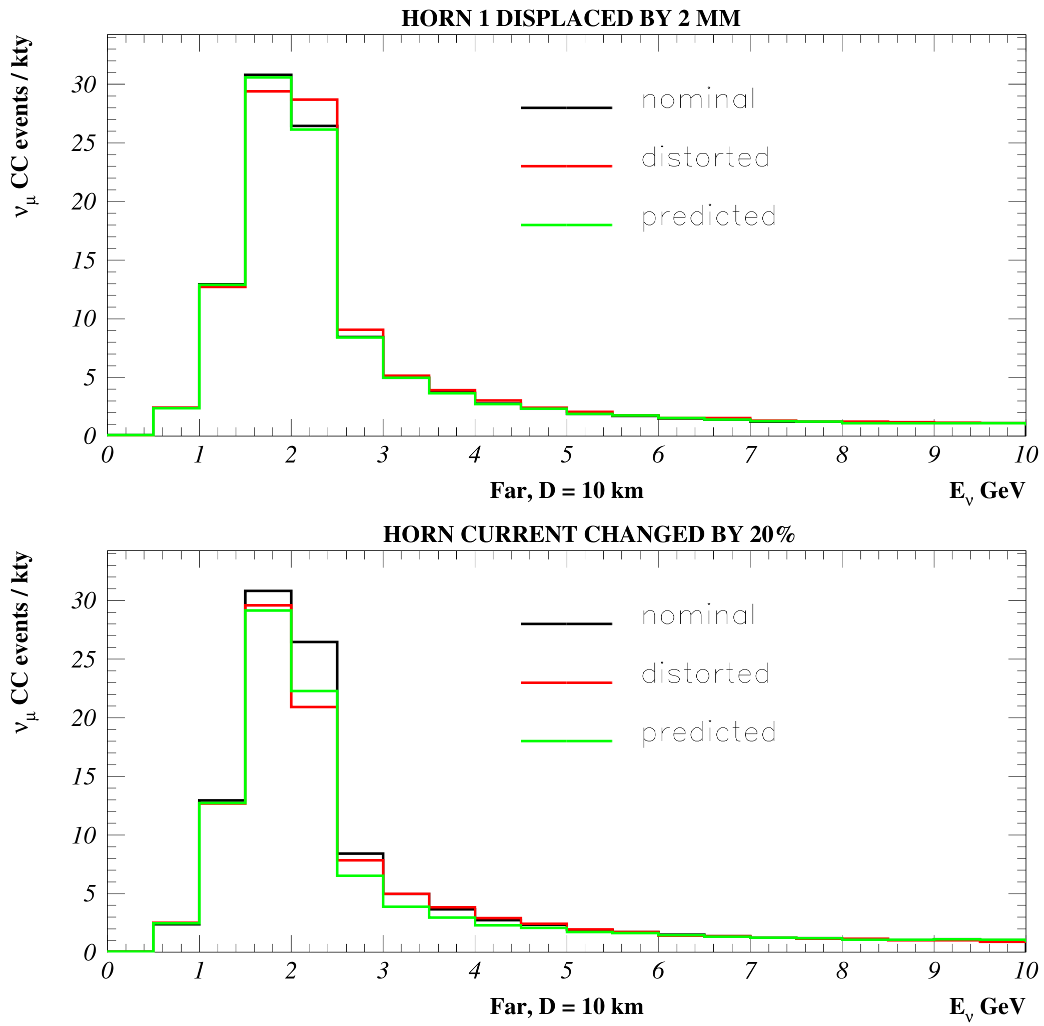


Off-axis experiment - focusing system

Presence of an on-axis near detector assumed.

Prediction: Undistorted M matrix applied to the distorted near detector spectrum.

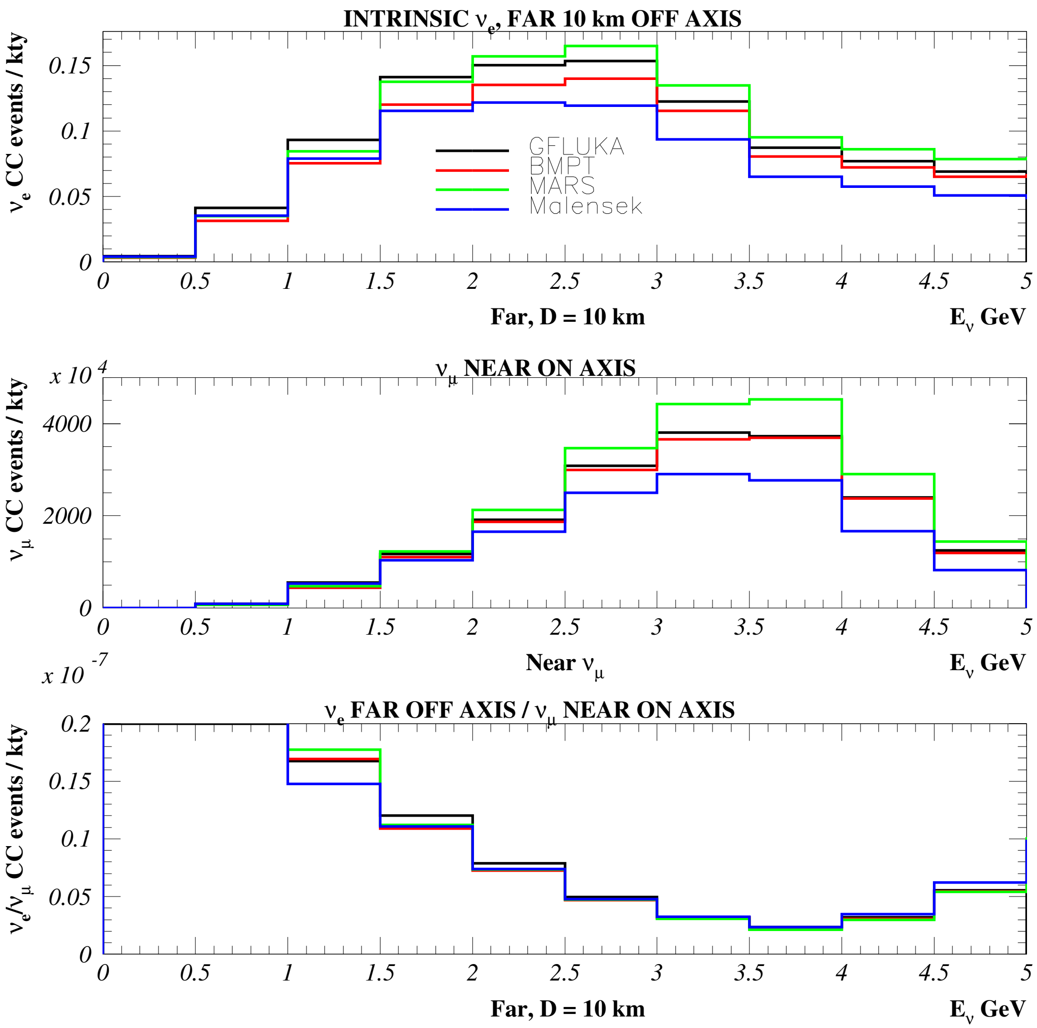
Total expected ν_μ CC rate for $1 < E_\nu < 2.5$ GeV can be predicted within ~5%.



Off-axis experiment - ν_e background

- Hadron production related uncertainties in evaluating the intrinsic ν_e component of the beam are minimized by using ν_μ information from the on-axis near detector.

- In the same pion beam, the number of intrinsic ν_e is strongly correlated to the number of ν_μ measured in the near detector.



Off-axis experiment - ν_e background II

- Optimization of the prediction is done by appropriately choosing the energy range of ν_μ, such that they come from as much as possible from the same pions as the ν_e in the signal region.

- A simple ratio (ν_e Far Off-axis)/(ν_μ Near On-axis) integrated over $1 < E_\nu < 3$ GeV is predictible to ~6% (for LE and pion decays only).

- For the ME option, a similar result is obtained by correlating (ν_e Far Off-axis 1-3 GeV) with (ν_μ Near On-axis 3-8 GeV).

- Kaon decays contribute less than 10% in the near detector in this energy region.

- Possible improvements:

  1. a Near-ν_μ-to-far-ν_e correlation matrix can be evaluated $\rightarrow$ possibly a more accurate prediction,
  2. correlate ν_e to $\bar{\nu_\mu}$ in the near detector $\rightarrow$ the same muon decays lead to an even stronger correlation.

Summary

1. The spectrum at a far (including off-axis) site can be accurately predicted from a near on-axis site, using a Near-to-Far correlation matrix.

2. Uncertainties due to hadron production in a NuMI Off-axis experiment are of 1-2% for both the LE and ME options. This is enough in a ν_e appearance experiment. The ultimate systematic errors are likely to come from other sources (e.g., knowledge of cross sections).

3. By measuring ν_μ at the near site, one can estimate of the ν_e component of the beam at a far off-axis site within $\sim$6%. A more detailed near-to-far correlation analysis should decrease this uncertainty even further.