Analysis techniques to reduce systematics due to Hadron production

(and other beam related issues)

Michał SZLEPER
Northwestern University

1. How best to use information from the near detector.
   a. Standard approach for an on-axis experiment.
   b. Improved approach and its generalization to off-axis.
2. Prediction of the non-oscillated far detector spectrum.
3. Evaluation of the ν_e component of the beam.

NBI 2002 CERN March 14-18, 2002

Standard approach with near detector I

How to predict accurately the non-oscillated ν_μ spectrum at a far detector?

• Present knowledge - direct predictions from various hadron production models differ by up ro $\sim$ 25%.

• Standard method: predict far detector spectrum based on spectrum measured in a near detector - "double ratio" method:

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

• Nominal Far/Near ratio determined primarily by beamline geometry.

• Non-oscillated far detector spectrum predictible within a few per cent.

Standard approach with near detector II

"Double ratio" method applicable whenever the following is true:

Each neutrino observed in the near detector $\equiv$ expected certain flux of neutrinos in the far detector, with $E_{Far} = E_{Near}$.

i.e., when secondary pion beam sees both detector at the same angle, $\Theta_{Far} = \Theta_{Near}$.

BUT:

- What about a realistic beam treatment (beam with imperfect pion focusing)?

$\Theta_{Far} \neq \Theta_{Near}$

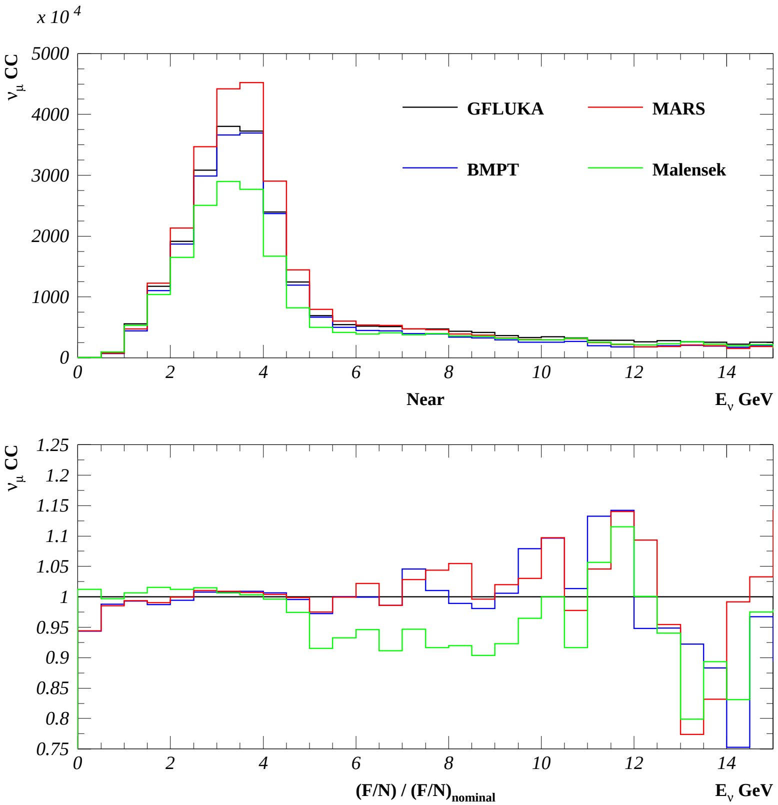
- What about an off-axis experiment?

$\Theta_{Far} \neq \Theta_{Near}$

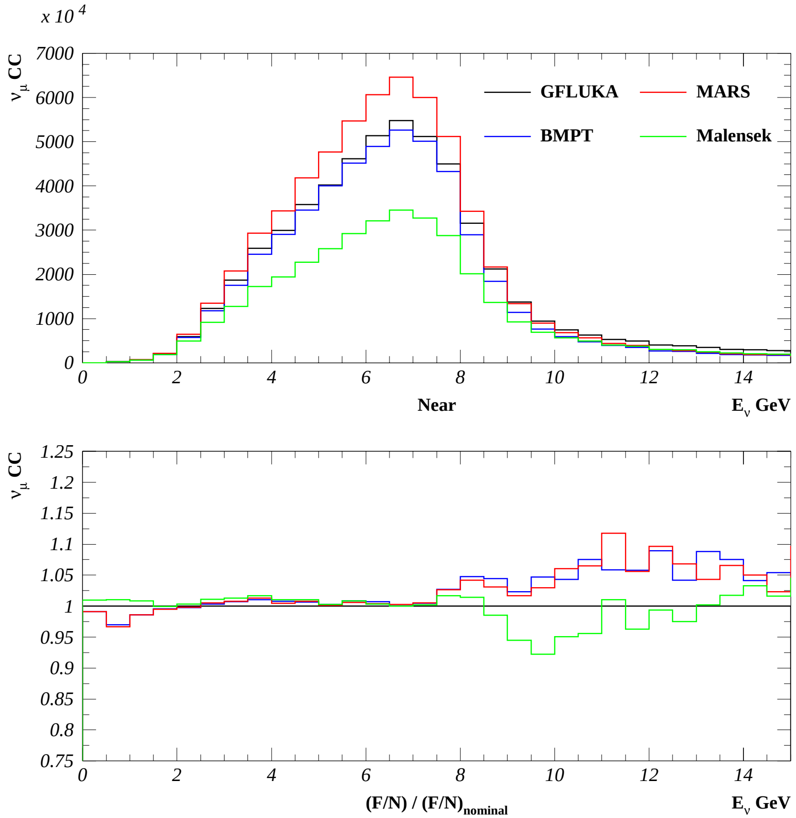
"Double ratio" method breaks down, more general approach required.

Standard approach with near detector III

Low energy beam



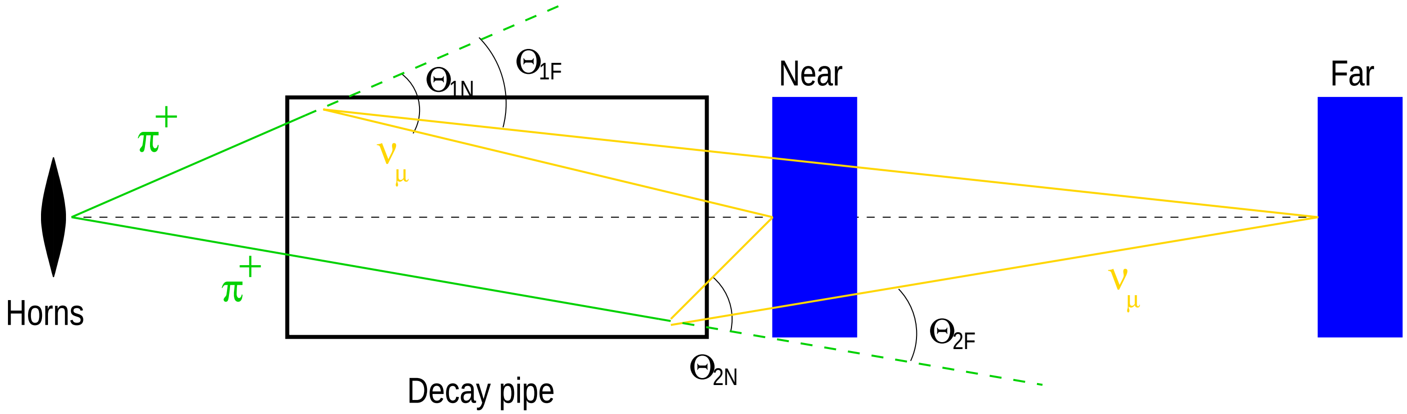
Medium energy beam



Improved approach I

On-axis experiment with imperfect focusing:

• An improved prediction of the far detector spectrum requires exactly the same approach as in off-axis, allowing $E_{Far} \neq E_{Near}$ in the general case.



The difference $\Theta_N - \Theta_F$ increases with z.

Improved approach II

What we want:

Predict far detector spectrum for a realistic beam and an arbitrary location of the detector with accuracy comparable to the on-axis perfect focusing case

• The same parent pion beam implies always a strong correlation between ν spectra in the on-axis near detector and an arbitrary (including off-axis) far detector.

• Different angle implies different neutrino energy:

$$E_\nu = \frac{0.43\ E_\pi}{1+\gamma^2\theta^2} \quad \rightarrow \quad E_{Far} \neq E_{Near}.$$

• 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 III

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.

• For a point-like pion source, 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 IV

- Far spectrum prediction in finite energy bins:

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

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

M - Near-to-far correlation matrix, in general non-diagonal.

Toy example with 2 energy bins

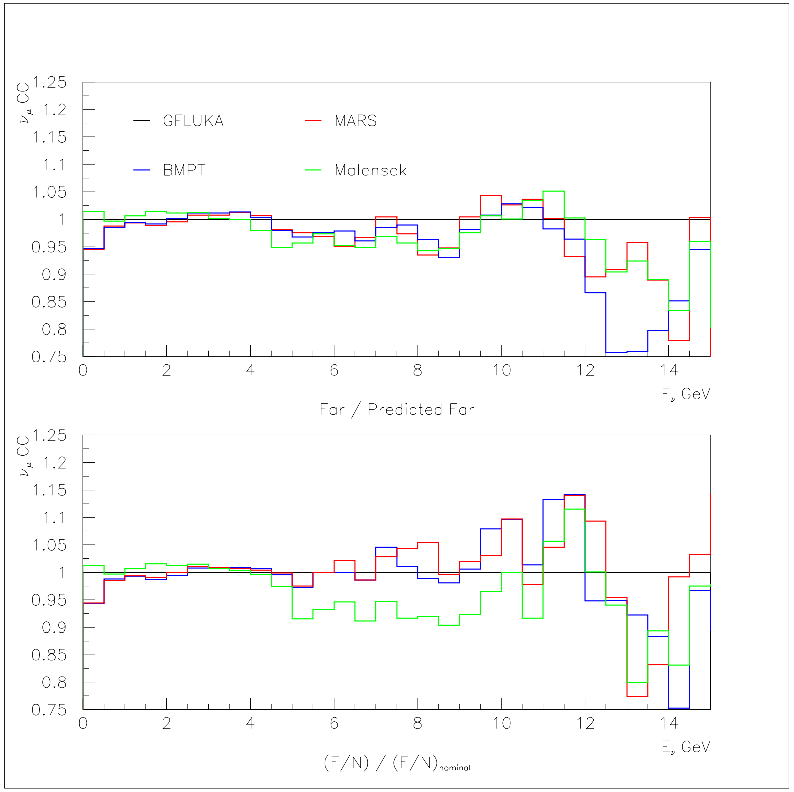
$$\left(N_1^{Far}, N_2^{Far}\right) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} N_1^{Near} \\ N_2^{Near} \end{bmatrix} \quad (1)$$

- On-axis, perfect focusing: $M_{12}, M_{21} = 0$.
- Realistic on-axis: $M_{21} > 0$.
- Off-axis: $M_{12} >> 0, M_{21}, M_{22} \approx 0$.

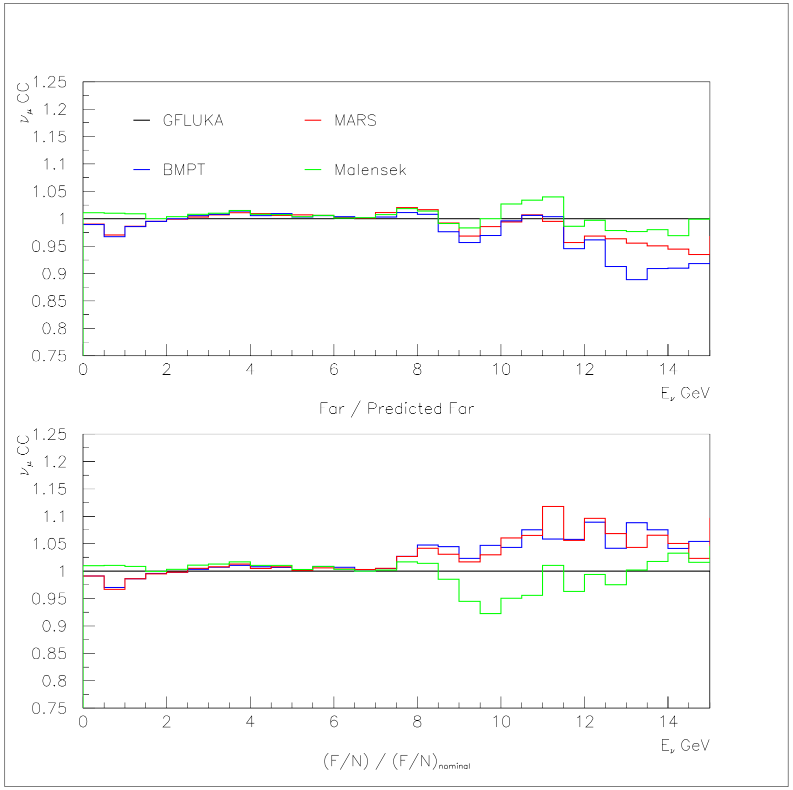
On-axis experiment - hadron production

Realistic on-axis experiment

Low energy beam



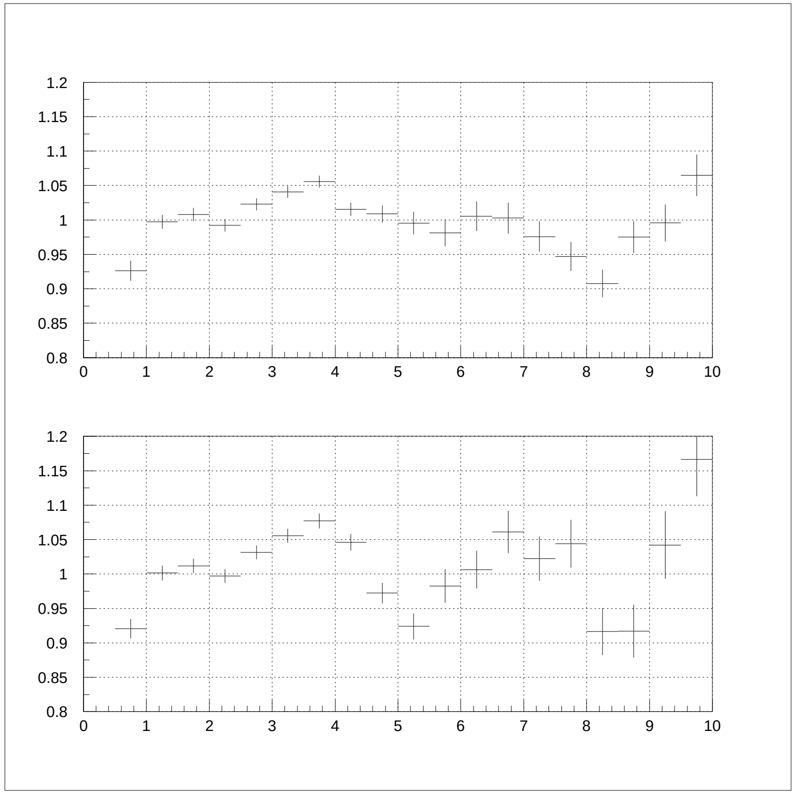
Medium energy beam



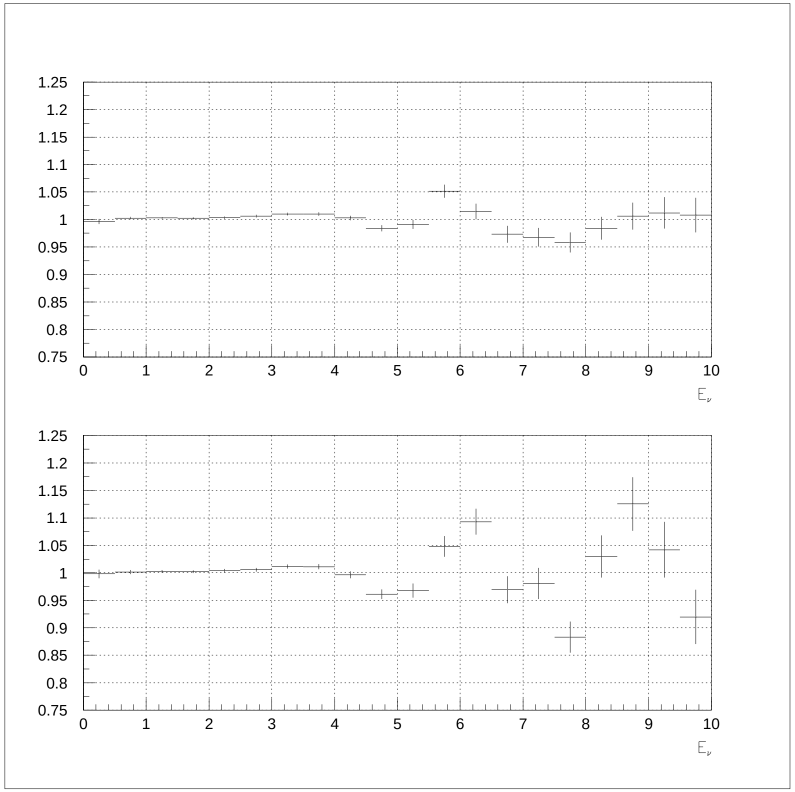
On-axis experiment - other beam related issues

Upper plots: *M* matrix, lower plots: double ratio

Beam simulation (PBEAM spectrum)



Horn 1 shifted by 2 mm



Off-axis experiment - hadron production

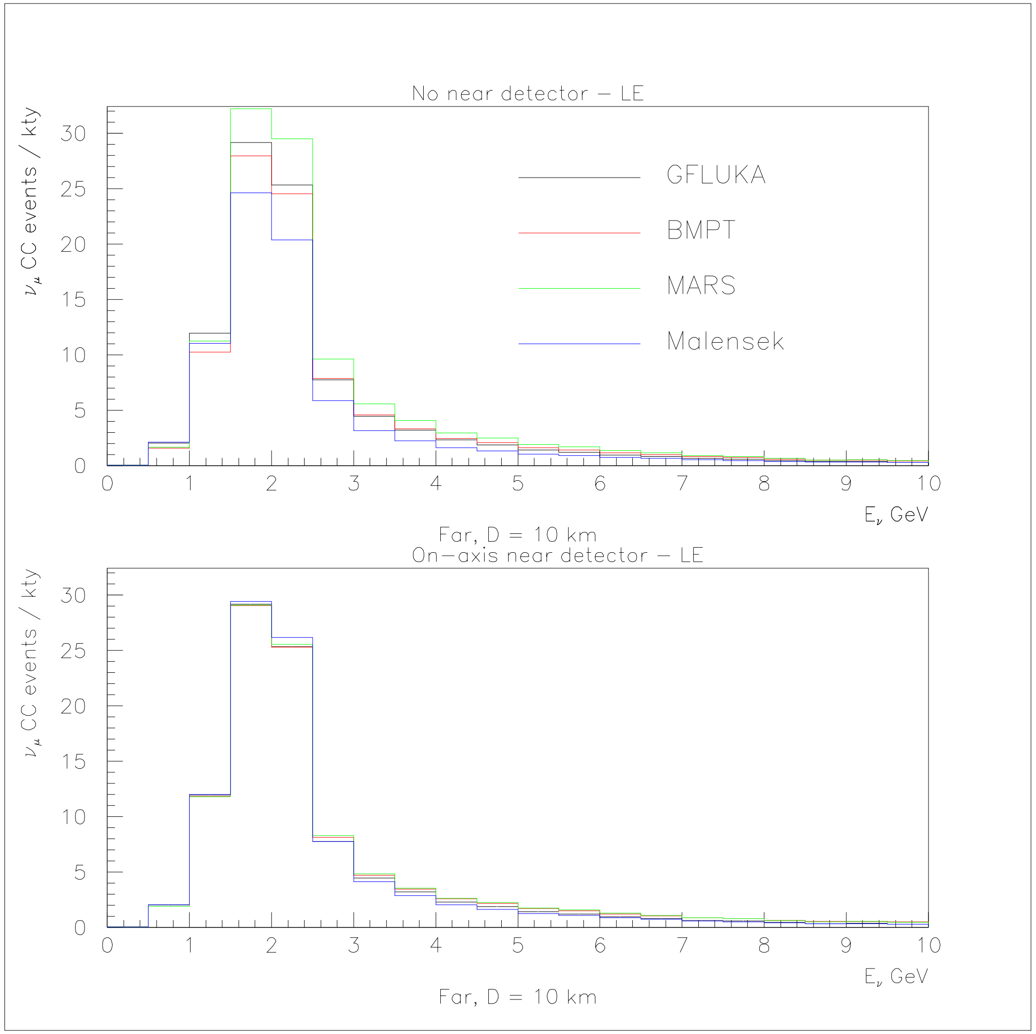
Low energy option

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

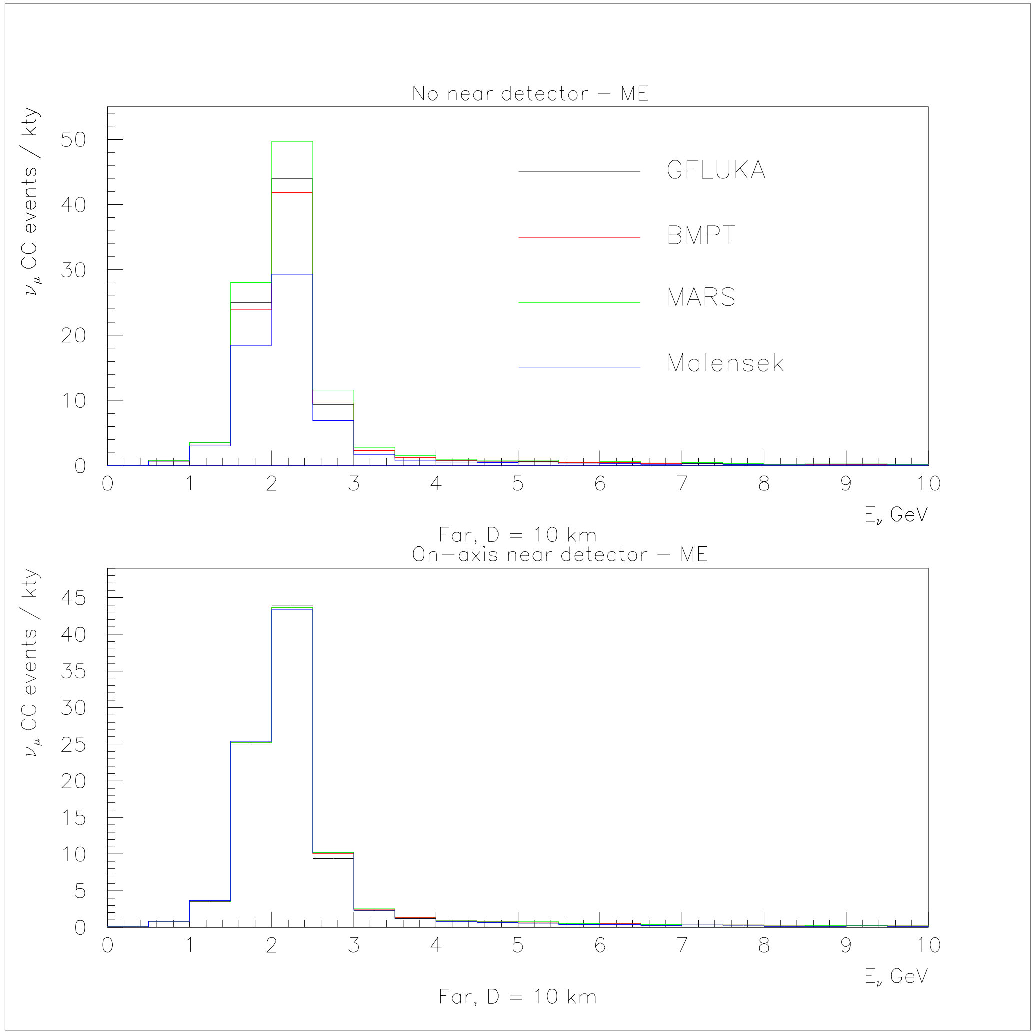
Medium energy option

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

- On absence of any near detector: ~40% 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.

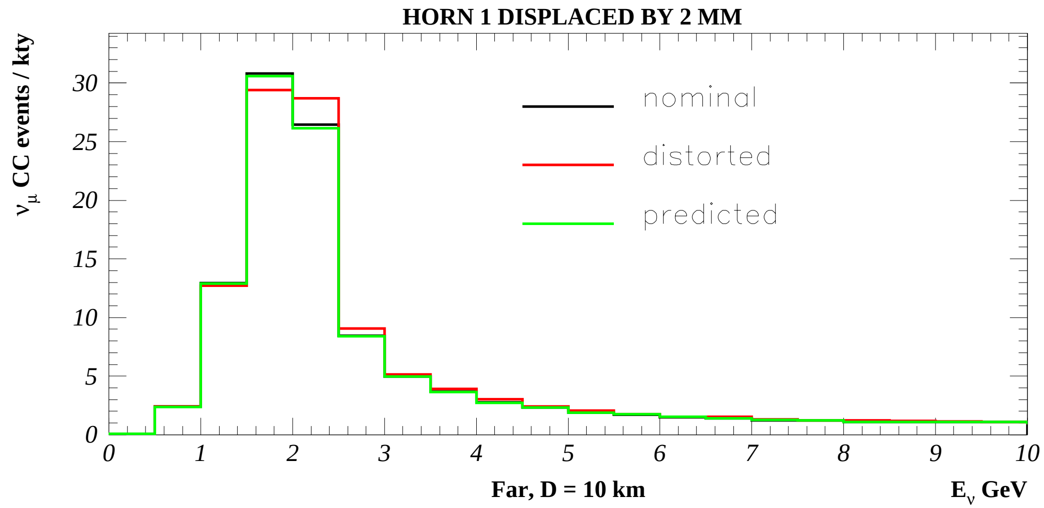


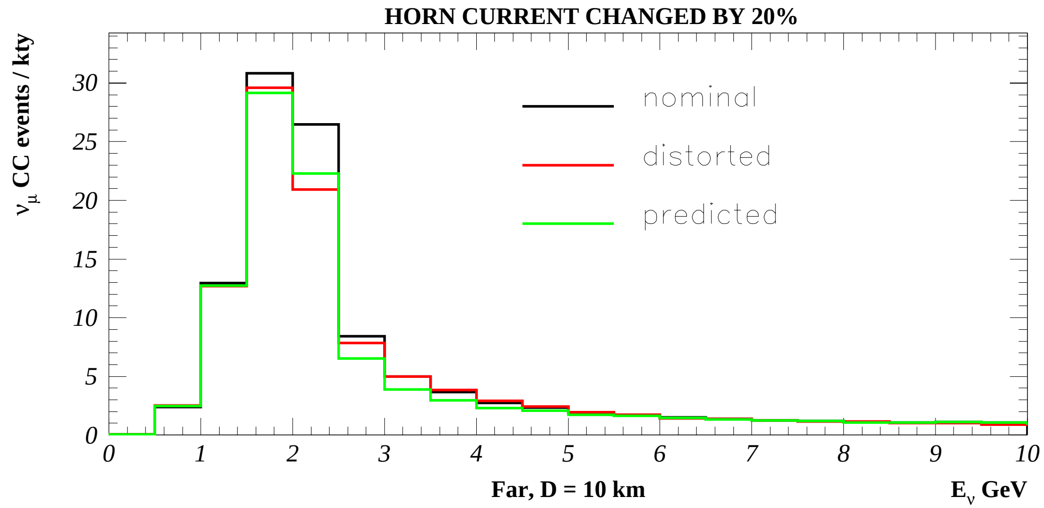
Off-axis experiment - focusing system

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 $\sim$5%.





Off-axis experiment - ν_e background

Hadron production related uncertainties are minimized by using ν_μ information from the on-axis near detector.

E.g., for $1 < E_\nu < 2.5$ GeV, the total rate is predictible to $\sim$6%.

Here, a Near-ν_μ-to-far-ν_e correlation matrix *M'* can be evaluated $\longrightarrow$ possibly a still more accurate prediction.