Neutrino Flux Analysis and Monitoring for Power Improvements in NuMI

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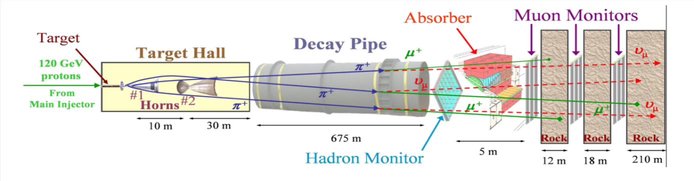
prepared for the New Perspectives 2020

July-21/2020

Outline

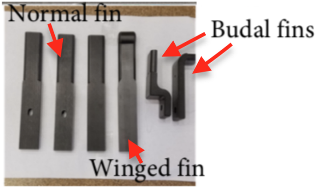
1. Overview
2. NuMI neutrino flux production simulation with new target
   - New 1-MW capable target studied for different physics model
   - PPFX package applies external data to flux generation
3. Focusing components for NuMI beamline
   - Studying the effect of the focusing on different components of the beam flux
4. Muon Monitor studies
   - NuMI beamline has 3 muon monitors for additional flux information

NuMI beamline and experiments



- 120 GeV protons hit the target and π^+ produced
- Magnetic horns to focus π^+
- π^+ decay to $\mu^+\nu$ in long low-density He-filled pipe
- ν beam travels through earth to experiment
- MINERνA (Main Injector Experiment for ν - A)
  $\rightarrow$ On-axis experiment located at Fermilab
  $\rightarrow$ It completed physics run in 2019
- NOνA (NuMI Off-axis ν_e Appearance)
  $\rightarrow$ Off-axis angle 14.6 mrad
  $\rightarrow$ Near Detector at Fermilab and Far Detector at Ash River

New target (for 1-MW beam operation)



The new graphite target consists of 2 Budal fins, 4 winged fins, and 44 normal fins

The total target length is 1.2 m

It is capable of operating with a 1-MW beam

Bigger fin cross-section to mitigate thermal shock

Budal fin: Charge read-out (Budal) target position monitoring fins added upstream of the target

Winged fin: Protect downstream beam element

Fin dimension	Width (mm)	Height (mm)	Length (mm)
New target (MET-05)	9.0	155.3	24.0
Old target (MET-03)	7.4	143.0	24.0

Bigger RMS beam spot size for wider temperature distribution

In our simulation, we use 1.5 mm RMS spot size

Beam power (kW)	RMS beam size (mm)
900	1.5
700	1.3

Simulation tools

- Flux simulation with GEANT4 (version 09-02-p3) based code (G4NuMI)
- G4NuMI uses FTFP_BERT and QGSP_BERT as physics list *(A. Dotti et al. 2011)*

  $\rightarrow$ For neutrino beam studies

- PPFX (**P**ackage to **P**redict the **F**lux)

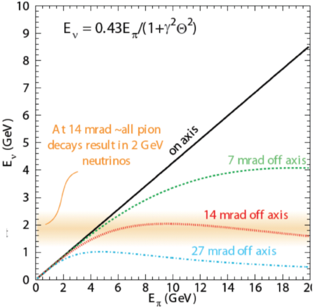
  $\rightarrow$ PPFX corrects the hadron production model using external data and propagates the uncertainties *(Phys. Rev. D 94, 092005 (2016))*

  $\rightarrow$ We use external thin target data (NA49) for the correction of the hadron production

Neutrino spectrum at on- and off-axis detectors

For a two-body decay, the energy of the neutrino:

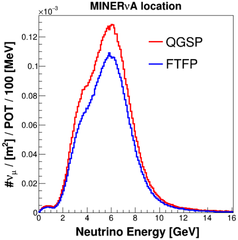
$$E_\nu \approx \frac{\left(1 - \frac{m_\mu^2}{m_{\pi(K)}^2}\right) E_{\pi(K)}}{1 + \gamma^2 \tan^2 \theta_\nu}.$$

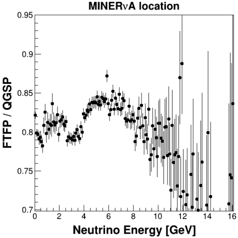


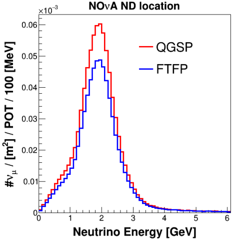
→ For MINERνA (on-axis), $\theta_\nu = 0$ and then $E_\nu \approx 0.43 E_\pi$, linear relation.

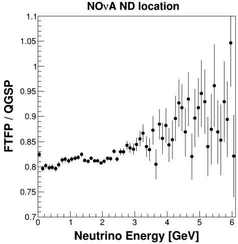
→ For NOνA (off-axis), $\theta_\nu \approx 14$ mrad. The relation becomes non-linear.

Flux simulations for two hadronic models with new target



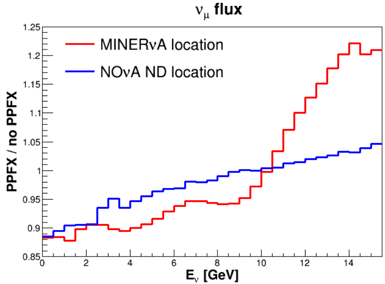






→ Energy peak is around 6 GeV for MINERνA, and 2 GeV for NOνA ND locations which agrees with the equation on slide 6.
→ QGSP predicts higher ν_μ flux than FTFP by $\sim 15\%$.

Neutrino flux simulation with and without PPFX correction with new target

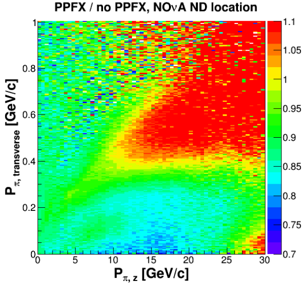


PPFX reweights are specifically made by FTFP_BERT model

In the plots, no PPFX: nominal value for FTFP_BERT,
PPFX: central value (PPFX correction)

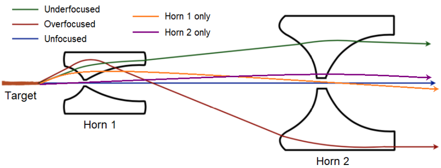
PPFX reduces neutrino flux which is lower energy than 10 GeV

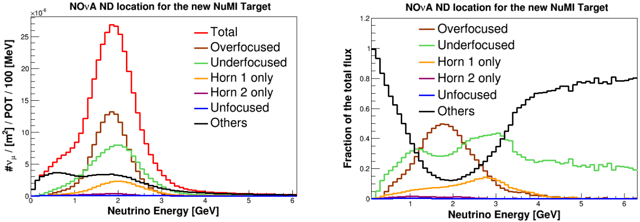
PPFX increases neutrino flux which is higher energy than 10 GeV



P_z (longitudinal momenta) vs. P_T (transverse momenta) of secondary pions at NOνA ND location plot shows the ratio of PPFX to no PPFX is $\leq$ 1 for the range $P_T \lesssim 0.4$ GeV/c.

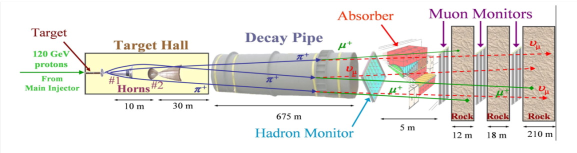
Simulate neutrino spectra with various focusing conditions

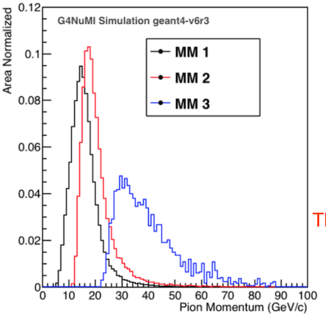




→ 74 % neutrinos at the NOνA ND are from pions that are focused by one or two horns while 26 % neutrinos are from pions that completely miss horns.
→ Simulation predicts that ν_μ flux for new target is $\sim 3\%$ lower than the old target at the NOνA FD.

Muon monitors and their momentum cut





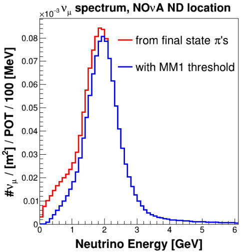
Three Muon Monitors (MM, 2×2 m^2) are downstream of the hadron absorber

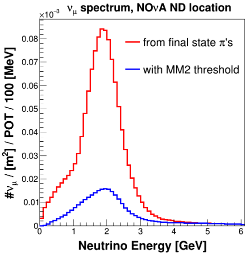
Each monitor has a different momentum cut of pions: 5, 12 and 22 GeV/c

The plot shows the pion momentum threshold for MM1, MM2 and MM3

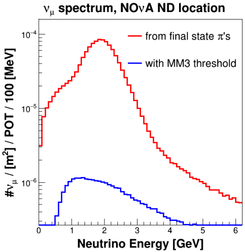
The plot is made by Amit Bashyal

ν_μ spectrum with muon monitor momentum cuts





The threshold shifts to higher energies when we go from MM1 to MM3 because we have a substantial amount (12 and 18 m) of rock between MMs.



$\rightarrow$ MM3 has lower energy peak than other monitors even though the momentum cut is the highest.

Conclusions

- I presented the status of my flux studies of 1-MW capable (new) target at the NuMI detectors using simulation.
- The simulation ν_μ flux for the new target is $\sim 3\%$ lower than that for the old target per PoT. However, a significant increase of PoT is expected with in the upcoming 1-MW era.
- I checked the focusing process and the hadron production impact on the neutrino flux using the new target. They look consistent with the old target with small differences. These differences are under study now.
- Each muon monitor sees a different part of neutrino flux. Especially, MM3 has the lowest neutrino energy peak even though it has the highest momentum cut. Further study is in progress.

This work is supported by DOE Grant No. DE-SC0010113

THANK YOU

- Neutrinos have non-zero mass (different from the SM) and mixed
- Flavor eigenstate is a coherent superposition of mass eigenstates determined by the PMNS matrix U

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}\, |\nu_i\rangle \,. \qquad (1)$$

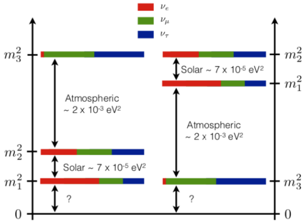
Here, $\alpha = e, \mu, \tau$. U is the mixing unitary matrix.

- The mixing matrix parameterized as follows

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \mathcal{P}. \qquad (2)$$

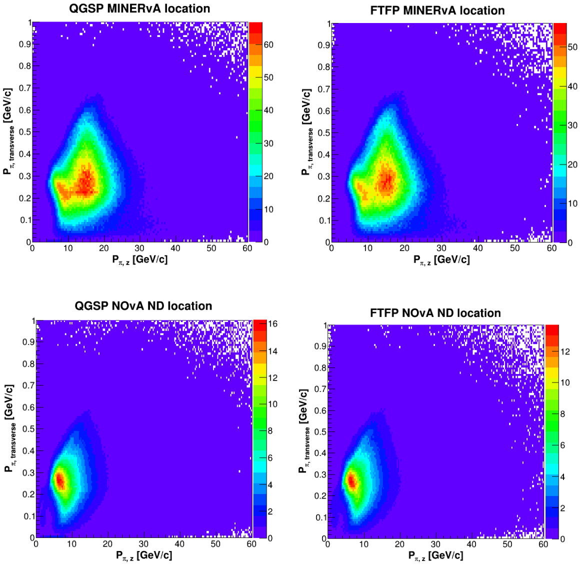
If neutrinos are Dirac fermions, $\mathcal{P}$ is a diagonal and identity ($\mathcal{P} = \mathbb{1}$) but if they are Majorana fermions, $\mathcal{P}$ includes two additional phases, $\mathcal{P} = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$. However, the Majorana phases α_1 and α_2 do not contribute to the neutrino oscillations. The angles θ_{ij} can be taken to lie in the first quadrant, $\theta_{ij}\ \epsilon[0, \pi/2]$, and the phase $\delta_{CP}\ \epsilon[0, 2\pi]$.

- The PMNS matrix has 7 independent parameters: 3 masses (m_1, m_2, m_3), 3 mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and 1 CP-violation phase (δ_{CP}).
- ν osc. exps can only measure Δm^2_{ij}, not the absolute mass value. The data present a hierarchy between the mass splittings: $\Delta m^2_{21} \ll \left|\Delta m^2_{31}\right| \simeq \left|\Delta m^2_{32}\right|$ with $\Delta m^2_{ij} \equiv m^2_i - m^2_j$ (arXiv:1708.01186).
- Normal Ordering (NO) $(\Delta m^2_{31} > 0) \rightarrow \; m_1 < m_2 < m_3$,
- Inverted Ordering (IO) $(\Delta m^2_{32} < 0) \rightarrow \; m_3 < m_1 < m_2$.



- Some unknowns, such as the octant of θ_{23}, the type of the neutrino mass ordering, and the status of the complex phase δ_{CP}, can be understood via short- and long-baseline different neutrino oscillation experiments.

Kinematical distributions

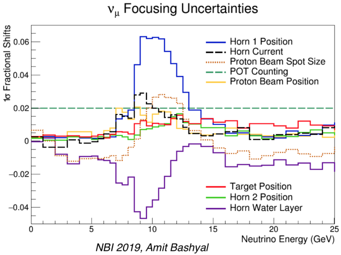


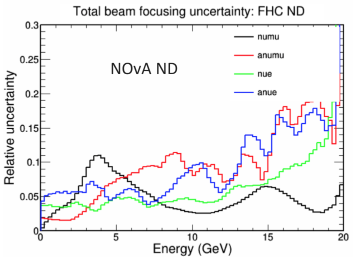
The categories of focusing components

- Unfocused: Mesons pass through the necks of both horns. They have high momentum (> 15 GeV/c) and very small p_T (< 0.1 GeV/c).
- Horn 2 only: Mesons pass through the neck of first horn and cross the Horn 2. Their momentum between $9 - 15$ GeV/c and p_T creates a small deviation from the beamline.
- Underfocused: Mesons pass through both horn receiving a correction in Horn 1 and complemented by Horn 2. Their momentum between $7 - 15$ GeV/c and $p_T > 0.2$ GeV/c.
- Horn 1 only: Mesons affected just by the Horn 1 and not by the Horn 2. $p_T > 0.2$ GeV/c (same as the underfocused) but less momentum. Mesons decay into neutrinos early.
- Overfocused: Mesons with low momentum (< 5 GeV/c) that are overcorrected by the Horn 1 and that are also corrected by the Horn 2.

Beam focusing uncertainties

→ These are calculated directly from the G4NuMI ntuples shifting components by their expected uncertainties and looking at the effect on the flux respect to neutrino energy.





- Left plot is for MINERνA ME and the right one is for NOνA ND.
- Shifting components by their expected uncertainties and looking at the effect on the flux respect to neutrino energy.
- Assuming that each systematics are independent each other and only calculate $+1\ \sigma$ shift.