Neutrino flux predictions, hadron production and uncertainties at DUNE ND location

based on `DUNE-doc-#19090-v1 and #19168-v1`

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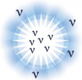


- Neutrinos have non-zero mass (different from the SM) and mixed
- Flavour eigenstate is a coherent superposition of mass eigenstates determined by the PMNS matrix U

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

Here, U is the mixing unitary matrix.

- The probability of a neutrino be detected as ν_β after a time t (or distance, for ultra-relativistic neutrinos ($E \approx p$)):

$$P_{\nu_\alpha\to\nu_\beta} = \left|\,\langle\nu_\beta|\nu_\alpha(t)\rangle\,\right|^2 = \left|\sum_{i=1}^{3}\sum_{j=1}^{3} U^*_{\alpha i}U_{\beta j}\,\langle\nu_j(0)|\nu_i(t)\rangle\right|^2. \tag{2}$$

- The oscillation between two ν's is a good approximation such as in the ν_μ oscillation study at long-baselines in ν beams.

- In these cases, the mixing matrix can be parameterized in terms of the angle θ:

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}. \tag{3}$$

The two-neutrino oscillation probability

$$P_{\nu_\alpha\to\nu_\beta} = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta \mathrm{m}_{\mathrm{ij}}^2 \mathrm{L}}{\mathrm{E}}\right), \tag{4}$$

where L is the distance traveled by the neutrino and E, its energy. The factor "1.27" supposes that E is expressed in GeV, L in km and the squared neutrino mass difference Δm^2 in eV^2/c^4 units.

- L-B ν experiments use a conventional ν beam and a pair of detectors, one close to the neutrino production point (ND) and the other further away (FD). The location of the FD and the beam energy spectrum are chosen to measure the oscillation maxima.

- In the 3-ν oscillation scenario, the PMNS matrix

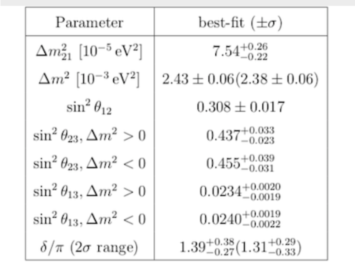
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{5}$$

- There are 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). ν osc. exps can only measure Δm_{ij}^2, not the absolute mass value.

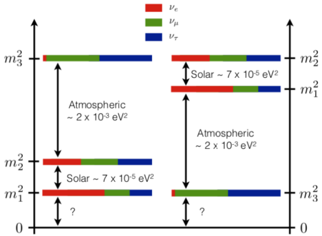
$$\boxed{\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2}:$$

- Normal Hierarchy $(\Delta m^2 > 0)$: $m_1 < m_2 < m_3$,
- Inverse Hierarchy $(\Delta m^2 < 0)$: $m_3 < m_1 < m_2$.

Oscillation parameter status based on the global fit (taken from PDG) and the mass hierarchies :

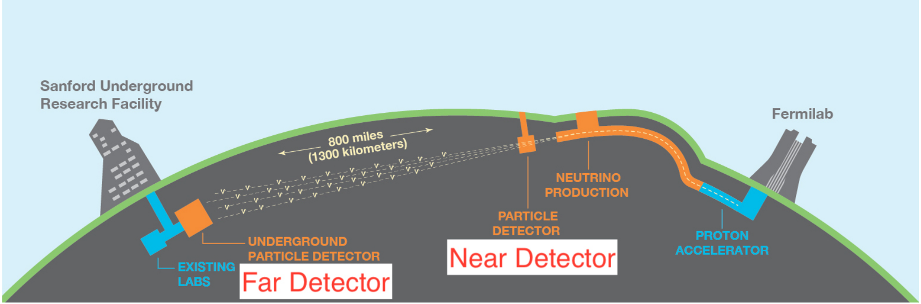


Parameter	best-fit $(\pm\sigma)$
Δm_{21}^2 $[10^{-5}\,\mathrm{eV}^2]$	$7.54^{+0.26}_{-0.22}$
Δm^2 $[10^{-3}\,\mathrm{eV}^2]$	$2.43 \pm 0.06 (2.38 \pm 0.06)$
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}, \Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2\theta_{23}, \Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$
$\sin^2\theta_{13}, \Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$
$\sin^2\theta_{13}, \Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$
δ/π $(2\sigma$ range)	$1.39^{+0.38}_{-0.27} (1.31^{+0.29}_{-0.33})$



DUNE: Long-baseline neutrino oscillation experiment

- DUNE comprises of two neutrino detectors placed in the world's most intense neutrino beam. A baseline of 1300 km
- Near detector @Fermilab to understand the beam
- Far detector @SURF in South Dakota, 1.5 km underground: 4×10 kton (fiducial mass) Liquid Argon TPC's
- Massive liquid argon detectors, and a precision ND
- More than 1000 scientists and engineers from 31 countries

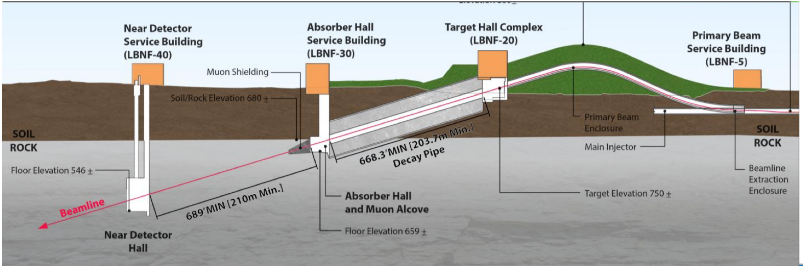


Near Detector

Far Detector

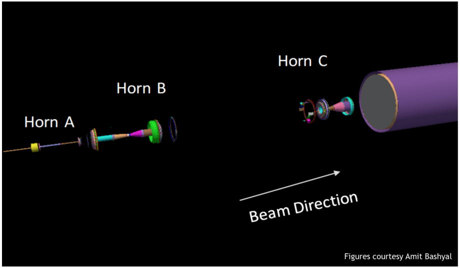
LBNF

- Primary proton beam in 60-120 GeV.
- Initial 1.2 MW beam power, upgradable to 2.4 MW.
- Decay pipe $\approx$ 200 m long, He filled.
- Wide-band beam on-axis with tunable energy spectrum.
- Beamline design:
  Optimized: 3 horn design, 1.5 meters target and 293 kA horn current.



Optimized beamline

- Three horns, different from the NuMI beamline (two horn)
- Primary proton beam that impinges on a 2.2 m long, 16 mm diameter cylindrical graphite target



Figures courtesy Amit Bashyal

- LBNF beamline is written with GEANT4 package (G4LBNF).
- To be able to simulate of particle production, transportation, interactions leading all the way to neutrino event and to understand the flux at near and far detector and their correlations.
- The focusing horns can be operated in forward (FHC) or reverse current (RHC) configurations, creating ν and $\bar{\nu}$ beams, respectively.

Information about the neutrino energy and flux

- The energy and flux of the ν's depend on the decay angle (θ_ν).
- For a two-body decay, the energy of the ν, supposing that ν's are moving in a near forward direction

$$E_\nu \approx \frac{\left(1 - \frac{m_\mu^2}{M^2}\right) E_{\pi(K)}}{1 + \gamma^2 \tan^2 \theta_\nu}. \tag{6}$$

Here, γ is the Lorentz boost factor, $\gamma = \frac{E_{\pi(K)}}{m_{\pi(K)}}$. θ_ν is decay angle between the π's (K's) and produced ν directions.

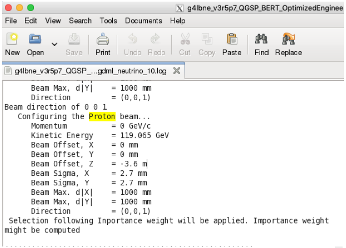
- The flux of the ν observed by the detector at a distance from the target is defined as

$$\Phi_z = \left(\frac{2\gamma}{1 + \gamma^2 \theta_\nu^2}\right)^2 \frac{A}{4\pi z^2}, \tag{7}$$

where A is transverse area of the detector and z distance between decay point and detector locations.

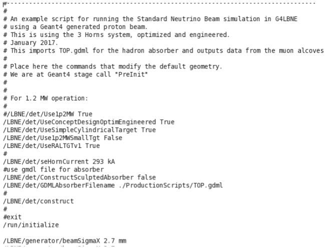
Information for the simulation

- All simulation are based on G4LBNF with 50M protons on target (POT) and ν mode. Macro: OptimizedEngineeredNov2017_gdml
- Hadronic models: FTFP_BERT is for energies > 4 GeV and the Bertini cascade model for energies < 5 GeV. QGSP_BERT is for high energy interactions of hadrons and nuclei and Bertini cascade for primary protons and neutrons with energies $\leq$ 10 GeV.
- G4LBNF version: v3r5p7, GEANT4 version: v4_10_3_p03b
- The neutrino flux is projected towards the center of the detector.
- Neutrino fluxes are calculated at ND: 574 m and FD: 1297 km



```
      Beam Max, d|Y|     = 1000 mm
      Direction          = (0,0,1)
Beam direction of 0 0 1
   Configuring the Proton beam...
      Momentum           = 0 GeV/c
      Kinetic Energy     = 119.065 GeV
      Beam Offset, X     = 0 mm
      Beam Offset, Y     = 0 mm
      Beam Offset, Z     = -3.6 m
      Beam Sigma, X      = 2.7 mm
      Beam Sigma, Y      = 2.7 mm
      Beam Max. d|X|     = 1000 mm
      Beam Max, d|Y|     = 1000 mm
      Direction          = (0,0,1)
 Selection following Inportance weight will be applied. Importance weight
might be computed
```

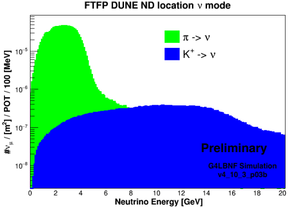
```
<<< Reference Physics List FTFP_BERT is built
```

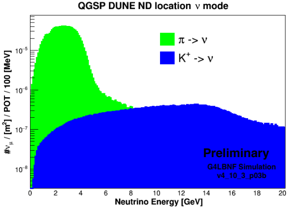


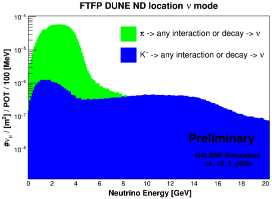
```
#-----------------------------------------------------------------------------
#
# An example script for running the Standard Neutrino Beam simulation in G4LBNE
# using a Geant4 generated proton beam.
# This is using the 3 Horns system, optimized and engineered.
# January 2017.
# This imports TOP.gdml for the hadron absorber and outputs data from the muon alcoves
#
# Place here the commands that modify the default geometry.
# We are at Geant4 stage call "PreInit"
#
#
# For 1.2 MW operation:
#
#/LBNE/det/Use1p2MW True
/LBNE/det/UseConceptDesignOptimEngineered True
/LBNE/det/UseSimpleCylindricalTarget True
/LBNE/det/Use1p2MWSmallTgt False
/LBNE/det/UseRALTGTv1 True
#
/LBNE/det/seHornCurrent 293 kA
#use gmdl file for absorber
/LBNE/det/ConstructSculptedAbsorber false
/LBNE/det/GDMLAbsorberFilename ./ProductionScripts/TOP.gdml
#
/LBNE/det/construct
#
#exit
/run/initialize

/LBNE/generator/beamSigmaX 2.7 mm
```

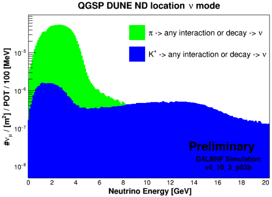
```
<<< Reference Physics List QGSP_BERT is built
```

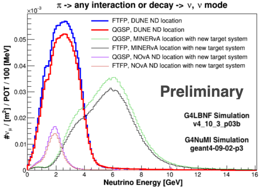
Results of neutrino spectra at near detector locations


FTFP DUNE ND location ν mode


QGSP DUNE ND location ν mode

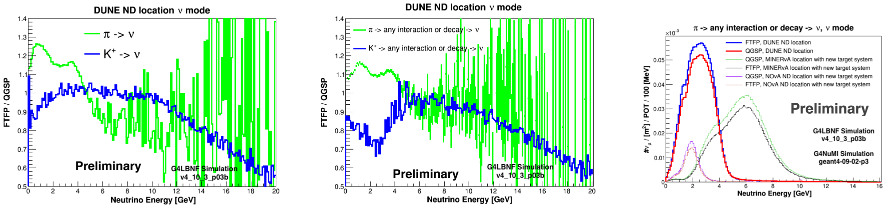

FTFP DUNE ND location ν mode


QGSP DUNE ND location ν mode

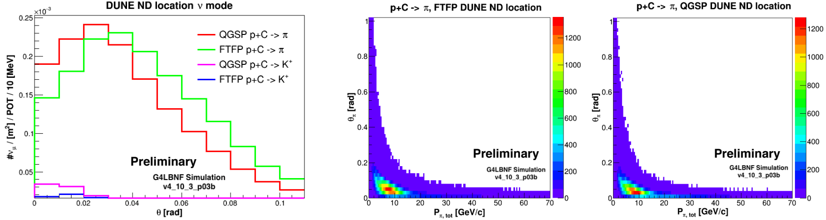

π -> any interaction or decay -> ν, ν mode

- For ν_μ flux coming from π's, focusing peak is $\approx$ 3 GeV for both hadronic models.
- For ν_μ flux coming from K^+'s in the top figs., focusing peak is $\approx$ 14 GeV for both FTFP & QGSP.
- Due to the two decay modes of kaons, two different peak can be seen in the bottom first and second figures for both hadronic models. One is $\approx$ 2 GeV and the second one is $\approx$ 14 GeV.
- Neutrinos in the "focusing peak" from mesons that were redirected by the horns. Very high energy mesons that are produced at very low p_T are not focused.
- The flux in the high energy predominantly comes from K^+'s and its peak value is uncorrelated with coming from π decay.
- Contrary to ν_μ fluxes coming from π's for MINERvA and NOvA ND loc., FTFP predicts higher ν_μ flux than QGSP at DUNE ND. (last fig.).

Results of neutrino spectra at near detector locations



- Around focusing peak for two interaction chain, for ν_μ flux, the ratio of FTFP and QGSP is $\approx$ 1.1 for π's.
- Around focusing peak for two interaction chain, for ν_μ flux, the ratio of FTFP and QGSP is $\approx$ 0.9 for K^+'s.
- For π's interactions, FTFP predicts higher ν_μ flux than QGSP around focusing peak. For K^+'s, QGSP predicts > FTFP .

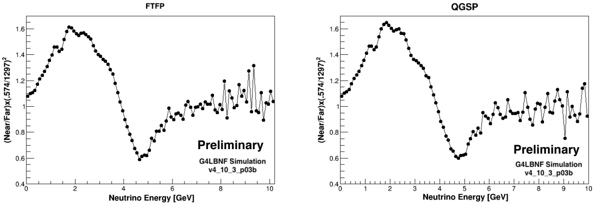


- QGSP generates more neutrino events than FTFP. FTFP generates pions which have wider angular spread than QGSP.
- ⋆ As a result, LBNF 3-horn system collects more π, which has a wide angular distribution in a low energy region. ⋆

Results of spectra ratio of near detector to far detector locations

⋆ The unoscillated flux at the ND & FD are similar but not identical and neutrino spectra is highly correlated between them. ⋆ ND detects more ν flux than FD because of the distance between ND and FD locations.

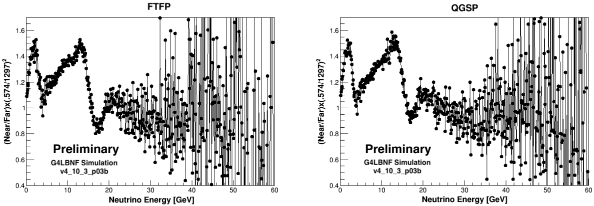
Secondary Pions to final state neutrinos $p + C \rightarrow \pi^+ \rightarrow$ any interaction or decay $\rightarrow \nu_\mu$:



→ Between 2-5 GeV, parent neutrinos (π's and K's that decay to give ν's) are well focused. Above 6 GeV, most of the parent ν's are forward.

→ Either most of the decays occur in the most downstream region of the decay pipe or they are absorbed in the absorber.

Secondary Kaons to final state neutrinos $p + C \rightarrow K^+ \rightarrow$ any interaction or decay $\rightarrow \nu_\mu$:

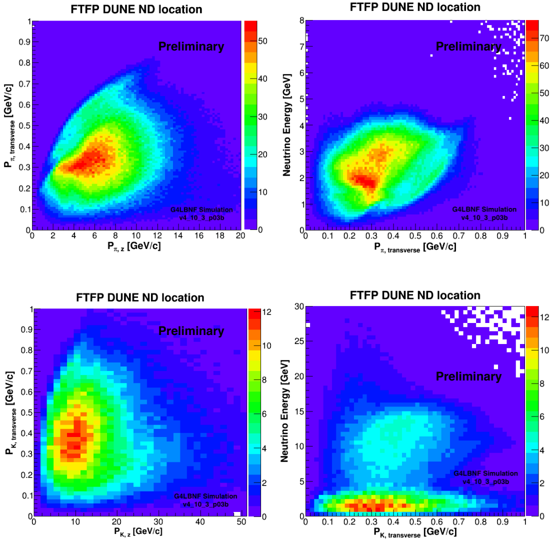


→ Parent neutrinos are well focused between 2-5 GeV and 5-15 GeV due to the two decay modes of kaons.

→ Above 20 GeV, most of the parent neutrinos are forward.

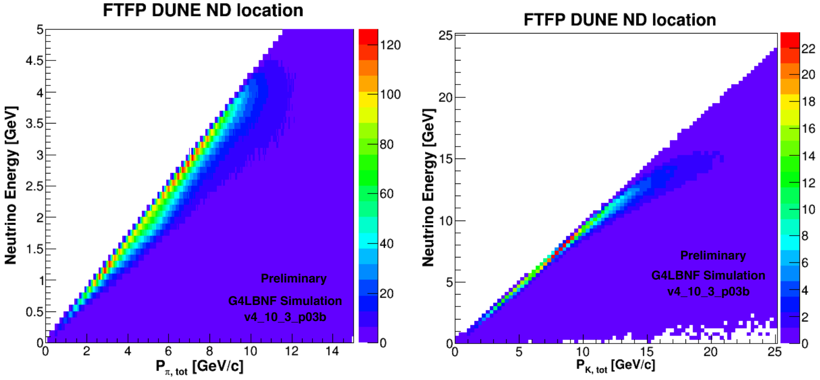
Results of distribution of P_z vs P_T & P_T vs E_ν

$p + C \rightarrow \pi^+ \rightarrow$ any interaction or decay $\rightarrow \nu_\mu$ and $p + C \rightarrow K^+ \rightarrow$ any interaction or decay $\rightarrow \nu_\mu$:



Most of the π's are focused in the region between 2-15 GeV/c long. mom and transv. mom. < 700 MeV/c. The biggest contribution comes from $p_z = 7$ GeV/c. For K's are focused: between 2-30 GeV/c long. mom. (more extensive area acc. to the pions) and trans. mom. < 850 MeV/c. The biggest contribution comes from $p_z = 10$ GeV/c. Around focusing peak, $p_T \approx$ 300 MeV/c.

$p + C \rightarrow \pi^+ \rightarrow \nu_\mu$ and $p + C \rightarrow K^+ \rightarrow \nu_\mu$:



These plots show the correlation between neutrino energy to the hadron momentum that explains the kinematical relationship of the pion and kaon decay to the neutrinos

The distribution is wider in the < 20 GeV region for π^+'s & K^+'s decay to ν's.

Information about PPFX

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

  Wiki Page is: https://cdcvs.fnal.gov/redmine/projects/ppfx/wiki/PPFX

  PPFX is developed by Leo Aliaga for the MINERvA and it is currently used by NOvA and DUNE as well

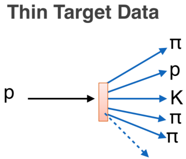
- Correction for hadron production uncertainties using existing thin target data sets

- PPFX provides Hadron Production correction based on external data

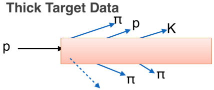
- PPFX provides a central value correction and a vector of weights to calculate the Hadron Production uncertainty with "multi-universe" technique to propagate uncertainties event by event.

- PPFX study: predict the systematic uncertainties in neutrino flux

Which data is available to correct our hadronic interaction in the beamline simulation?



- Hadron production: NA49 pion, kaon, proton and neutron production @ 158 GeV (x_F and p_T dependence). NA61 pion and Kaon production @ 31 GeV. MIPP $/K$ from $p - C$ @ 120 GeV for $p_z > 20$GeV.
- Inelastic/absoption cross section: Belletinni, Denisov, etc. cross sections of $p - C$, $\pi - C$, $\pi - Al$ etc. at different energies and NA61 and NA49 p-C at 31 and 158 GeV.

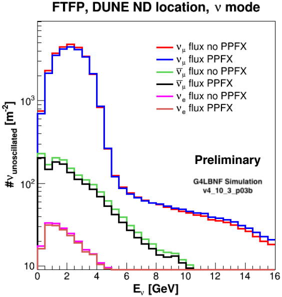


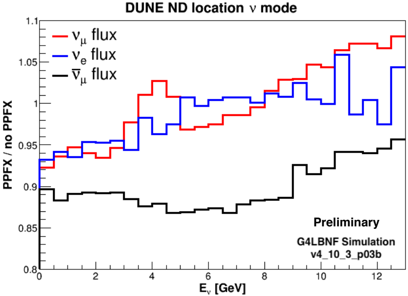
- MIPP: proton on a LE NuMI spare target @ 120 GeV. Pion production up to 80 GeV/c and K/π for $p_z > 20$ GeV/c.

⋆ We will use thin target data to correct our hadronic interaction model in the beamline simulation ⋆

PPFX reweights are specifically made by FTFP_BERT model.

In the plots, no PPFX: nominal value for FTFP_BERT, PPFX: central value (PPFX correction, average flux, not nominal) and MIPP (thick target) is off.





Around focusing peak, the ratio of PPFX and no PPFX is ≈ 0.95 for ν_μ and ν_e fluxes. For $\bar{\nu}_\mu$ flux, the ratio is ≈ 0.9.

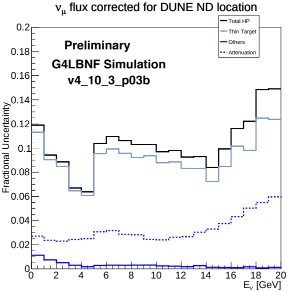
Frac. Unc. shows how we can estimate the neutrino flux properly. For number of universe: 100 and hadronic model: FTFP

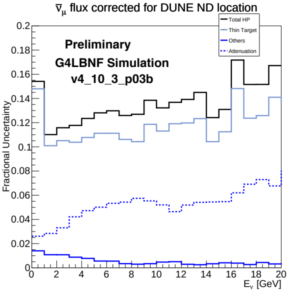
Total HP: Total Hadron Production Interactions

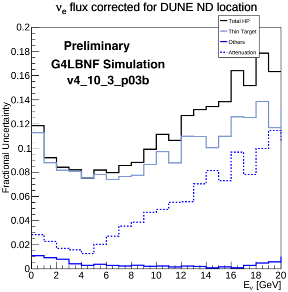
Thin Target: Based on pC Thin Target Data $(pC \rightarrow \pi X, pC \rightarrow KX, nC \rightarrow \pi X, pC \rightarrow nucleonX)$

Others: Interactions not covered by any of the previous categories

Attenuation: Absorption inside and outside the target





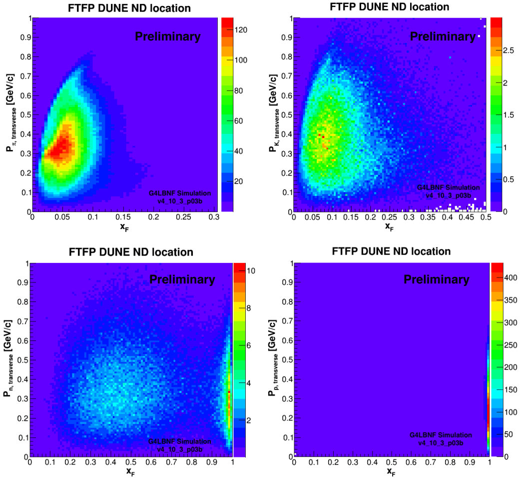


$\rightarrow$ ν_μ flux has a peak value between 6-8 GeV and a dip value region is at between 4-6 GeV.

$\rightarrow$ Around focusing peak, hadronic uncertainties are roughly 8% for ν_μ flux, 10% for $\bar{\nu}_\mu$ and 8% for ν_e flux and the uncertainties for attenuation increase in the high energy region because of the high energy kaons. Others decreases in the high energy region for ν_μ, $\bar{\nu}_\mu$ and ν_e flux.

Hadron production in the target

Hadron production from the primary beam interacting in the target for ν_μ flux passing through DUNE ND location. $x_F \approx p_z/p_0$.



→ For pions, focusing peak region: $x_F < 0.15$ and $0.05 < p_T < 0.8$. This region contributes to the focusing peak. K^+ production has an extensive area, the region of interest is $x_F > 0.18$ where they become dominant in the neutrino spectrum.
→ Neutrons make a very small contribution to the flux. The regions can be divided in two regions: $x_F < 0.95$ where has the peak value is around 0.45 and $x_F > 0.95$.
→Protons have a wider x_F range than the others, x_F region can be divided in two regions as well: $x_F < 0.98$ and $x_F > 0.98$. $x_F \approx 1$ region corresponds to protons likely to be quasi-elastics.

Conclusions

- Focusing peak for ν energy at the DUNE ND $\approx$ 3 GeV for π's and FTFP generates more ν events than QGSP and FTFP model has a wider angular distribution at LE than QGSP.
- We mentioned the LBNF horn system collects more pions, which has a wide angular distribution in a low energy region, with three horns.
- For K's interaction, due to the two body decay modes of kaons, we observed two peak: one is $\approx$ 2 GeV and the second one is $\approx$ 14 GeV. For K's interaction, QGSP predicts higher ν_μ flux than FTFP.
- We showed the hadronic uncertainties are $\approx 8\%$ for ν_μ flux, 10% for $\bar{\nu}_\mu$ and 8% for ν_e flux around focusing peak.
- We showed that neutrons make a very small contribution to the flux and $x_F \approx 1$ region corresponds to protons likely to be quasi-elastics.

THANK YOU

Hadron Production corrections

- Hadron Production (HP): The Cascade leading to neutrino such as interaction kinematics and material traversed, is categorized at generation and stored in the dk2nu files.

- For thin target data (NA49, ..):

$$correction(x_F, p_T, E) = \frac{f_{Data}(x_F, p_T, E = 158GeV) \times scale(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)}, \quad (8)$$

$f = E\frac{d^3\sigma}{dp^3}$, x_F is a Feynman-x scaling and $x_F = \frac{2p_L^{CM}}{\sqrt{s}}$.

- The scale allows us to use NA49 for proton on carbon in 12-120 GeV.

Attenuation corrections

From Leo's thesis:

FIG. 4.1: Particle beam traversing a volume. Left side: particle leaving the volume without interacting. Right side: particle interacting in the volume.

- When a particle traverses through the volume (without interacting), attenuation correction is:

$$correction(r) = e^{-r\frac{N_A\rho(\sigma_{Data}-\sigma_{MC})}{A}}. \tag{9}$$

- When an interaction happens inside a volume:

$$correction(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-r\frac{N_A\rho(\sigma_{Data}-\sigma_{MC})}{A}}. \tag{10}$$

In the eq.s, N_A is the Avogadro number. ρ is the nuclei volume density and σ is the absorption cross-section per nucleus. $rN_A\rho$ is the material traversed that is independent of the specific material and it can be expressed as mol/cm^2.