NuMI Flux Model Overview
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NuMI Flux model based on GEANT4-based simulation: G4NuMI

- Underlying physics model for HP is FTFP-BERT with v4.9.2.03 for GEANT
- Uses PPFX (from MINERvA, NOvA) to reweight this based on mainly NA49 experimental data
- Thin Target: pC→π/K production in bins of (xF, pT)
• Most of the uncertainties for both are based on:

  • Meson Incident: secondary interactions, basically meson grandparents -> meson parents -> neutrino
  • nucleon-A: primary/secondary but proton/neutron grandparents interact with non-Carbon material and produce mesons decay -> neutrino
  • Uncertainties of $\pi/K$ production from external data on Carbon form subdominant portion of the interaction
• For $\nu_\mu$, split evenly between $\pi$ (low energy) and $K$ (high energy) parents

• For $\nu_e$, split evenly between $K$ and $K_0$ (not as much shape difference. Although more $K_0$ at lower energy)

• Don’t yet have fraction of events from interactions from non-target:
  • But must be significant, since “nucleon-A” uncertainties dominant
Hadron Interaction breakdown

- At off-axis angles, we do see more interactions with non-carbon (Can also include meson secondary interactions)

- Overall data constraint from p+C is expected to be weak.

- NB: within nucleon-A, we try to “extrapolate” NA49 data to non-target material but only within phase space of the experimental dataset

- If it falls outside this range, we rely on FTFP-BERT

- In general, don’t know the exact fraction of events that don’t get a NA49 constraint, but is higher than on-axis experiments
• KL constrained by pC->KX directly: ~18.7%
• KL in MesonInc: ~27.8%
  • KL in MesonInc w/ xF < 0: ~17.4%
• KL in Nucleon-A category: ~53.5%
  • KL extrapolated to NA49: ~7.1%
• KL w/ xF < 0: ~33.95%
• Other KL: ~0.1%

For eg, we looked at \( \kappa_0^\nu \)'s that form \( \nu_e \) and most of the events fall outside the NA49 constraint (~75%)

• Rely entirely on FTFP-BERT here

• ~34% weren’t getting assigned any uncertainties (PPFX bug) — fixed

• Bug affected other hadrons too, basically “nucleon-A” interactions at hadron xF < 0, so general increase in flux uncertainties for \( \nu_e \) and \( \nu_\mu \)
Uncertainties on FTFP-BERT

• PPFX assigns ad-hoc 40% uncertainties on FTFP-BERT motivated by discrepancies seen in other datasets: source unclear (model is a black box)

• For events not constrained by NA49:
  • 7 incident particles (π±, K±, K0, n, p)
  • 7 produced particles (π±, K±, K0, n, p)
  • 4 xF bins (0, 1)
  • 7x7x4 uncorrelated knobs: each 40%

• At negative xF, 40% extra normalization if incident particle was meson (not nucleon - “MesonInc”)

• After bug fixes, essentially:
  • Extended bin ranges from (0, 1) -> (-1, 1) => 7x7x8 uncorrelated knobs: 40%
  • Extended normalization factor to nucleon-A as well (incident nucleons) at negative xF

First principles model of hadronic interactions. Our aim is that the level of agreement between FTFP and existing hadron production datasets is indicative of FTFP’s ability to model interactions for which no data is currently available. Meson and nucleon production measurements exist for pC and, more generally, for pA interactions. That data agrees with the simulation at better than 40% across a broad range of relevant kinematics. We assume that this verifies the FTFP model at the 40% level. In addition, we note that the observed data-simulation discrepancies for production of π±, K±, n and p do not appear to be correlated in any obvious way. Therefore, to handle meson incident interactions we categorize the interactions based on incident particle (π±, K±) and produced particle (π±, K±, n, p). For each combination we break the range 0 < xF < 1 into 4 equally sized bins. In each bin we assign a 40% uncertainty and we treat each bin as being uncorrelated with the others.

Sometimes nucleons interact and produce particles that are outside the kinematic coverage of any dataset. We categorize these interactions in terms of incident particle (n, p) and produced particle (n, p, π±, K±). As for incident mesons, we assume a 40% uncorrelated uncertainty in 4 xF bins, equally spaced in the range 0 < xF < 1. In this category of

Overall Uncertainties

- See significant increase in uncertainties (~17% for $\nu_e$

  - $\nu_\mu$ also at similar level

- However, large $\nu_e$-$\nu_\mu$ correlations moderate this in the fit:

  - They share the same parent (~60%) : $K$

- Correlations in the FTFP-BERT uncertainties for different parents, for eg, $\pi$ and $K_L^0$ are also correlated because presumably : $K_L^0 \rightarrow \nu_e(\bar{\nu}_e) + e^\pm + \pi^\pm$

- Other similar correlations we ended up putting in at negative xF
- Significant flux correlations between $\nu_e$ and $\nu_\mu$
Mike pointed out internal MiniBooNE TN that showed improved NuMI agreement with $\nu_e$ using FLUKA + Geant4 : “FLUGG”

- Previously was using older GEANT3 + some threshold on muon decays

- Seems like :
  - FLUGG was initially used in MicroBooNE as well
  - Switched to dk2nu file format (produced with G4NuMI which uses FTFP-BERT) in order to use PPFX to apply NA49 data constraints
See visible differences between dk2nu (FTFP-BERT) and flugg (FLUKA), especially for $\nu_c$ RHC (run3, part of run1)
Our NuMI $\nu_e$ disagreement is more visible in run3 as well.
Sergey extracted the RHC ratios and applied weights as a function of true energy.

- Applied to all runs (including FHC)
- Seems like it agrees much better
Sergey extracted the RHC ratios and applied weights as a function of true energy.

- Applied to Run3 only (RHC)
- Seems like it agrees much better
• PPFX requires `dk2nu` file format generated only with FTFP-BERT

• `dk2nu` stores interaction cascade upto neutrino from proton beam across beamline geometry (carbon, non-C etc)

• PPFX reweights this based on different criteria:
  • Within NA49 phase space, applies constraint from external measurement
  • Outside, uses FTFP-BERT prediction for CV (Uncertainty treatment is a bit complicated)
Reweighting to FLUKA

• One approach (Option 1):
  • Reweight CV outside NA49 phase space to FTFP-BERT prediction and carry over current uncertainties
  • Requirements: Need $\frac{FLUKA_{i,j,k}}{FTFP\_BERT_{i,j,k}}$
    • $i$: incident hadron species
    • $j$: produced hadron species
    • $k$: ($x_F$, $p_T$) bin index
  • If we have these ratios, should be relatively easy to incorporate into PPFX

• Another approach (Option 2):
  • Apply ratio between FLUKA and FTFP_BERT predicted flux as an additional uncertainty on top of existing (probably correlated + uncorrelated)
  • Similar to “reweighting uncertainties” considered in WC cross-section analyses
  • Can consider different ratios in different regions of phase space (split by hadron parent, $x_F$ etc)

• Can also consider Option 1 + Option 2: Option 3
Reweighting to FLUKA

• Pros:
  • Maybe don’t need to convert FLUKA to dk2nu file format: not sure if possible/feasible anyway?
    • Can use existing flux files, reweighting to FLUKA handled by PPFX (+ adding extra uncertainty knobs)
    • Just need ratio numbers: Do we have the ability to obtain this?
    • Technically seems easiest (atleast on the PPFX side)
    • Reprocessing is straightforward, no need to re-run reco
  • Cons:
    • Depend on FTFP_BERT prediction for interaction cascade, don’t know if there’s key differences here between the two models
To keep FTFP-BERT

• We need to:

  • Verify if current uncertainties cover FLUGG prediction and if not, add new uncertainties
  • Have to check with $\nu_e-\nu_\mu$ correlations as well
  • CV could stay the same as before, potentially have to add new knobs to PPFX to cover remaining differences
Switching to FLUGG

• To switch to FLUGG entirely (Option 4):
  • Get full information but probably have to overhaul our current simulation?
  • Or maybe produce dk2nu with FLUKA which PPFX can then read
    • Probably need to modify some weights inside PPFX as well to incorporate new physics model
  • What about uncertainties?
    • Have to develop new ones or keep FTFP-BERT?
    • Rely on PPFX for NA49 constraints?
  • Reprocessing?
Backup
\( \nu_e - \nu_\mu \) Correlations

The diagram illustrates correlations between \( \nu_e \) and \( \nu_\mu \) for different energy ranges and bin indices. The color gradient represents the correlation strength, with darker shades indicating stronger correlations.

- \( \nu_e \) from \( K_L^0 \) Parents only
- \( \nu_e \) from \( K_L^0 \) Parents only
- All \( \nu_\mu \)

The axes represent the bin index along the x-axis and the true neutrino energy along the y-axis, with the energy range indicated as \((0, 5)\) GeV.
\( \nu_e - \nu_\mu \) Correlations

![Correlations Plot]

- \( \nu_e \) from \( K \) Parents only
- \( \nu_\mu \) from \( K \) Parents only

True Neutrino Energy

(0, 5) GeV

Bin Index

\( \nu_e \) from \( K \) Parents only

\( \nu_\mu \) from \( K \) Parents only

\( \nu_e \) from \( K \) Parents only

\( \nu_\mu \) from \( K \) Parents only
$\nu_e - \nu_\mu$ Correlations

True Neutrino Energy

(0, 5) GeV (0, 5) GeV

$\nu_e$ from $K_L^0$ Parents only

$\nu_\mu$ from $\pi$ Parents only

$\nu_\mu$ from $\pi$ Parents only $\nu_e$ from $K_L^0$ Parents only
$\nu_e - \nu_\mu$ Correlations

![Graph showing correlations between $\nu_e$ and $\nu_\mu$](image-url)