Review of Accelerator Neutrino Fluxes

Megan Friend

High Energy Accelerator Research Organization (KEK)

Neutrino 2022
Virtual Seoul, South Korea
June 2, 2022

A Personal Message...

A personal message from a flux person to cross section people + everyone else with no near detector:

- You should really really really care about flux errors
- If you do not know the flux, you cannot make a precise cross section measurement
- If you do not know the flux, you cannot make a precise oscillation measurement without a near detector constraint

Even if you do have a near detector, flux errors can (and will) have a significant impact on high-precision measurements now and in the future – you should really care about flux errors too!

Outline

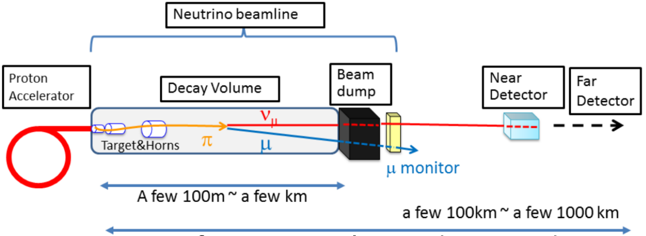
- Overview of conventional accelerator neutrino production
- Predicting and constraining fluxes
- Flux errors (some things to worry about)
  - Hadron production errors
  - Non-hadron production errors

- Request from a friend:

  "A thorough discussion of what is needed to get the most from future measurements is the best – TIA"

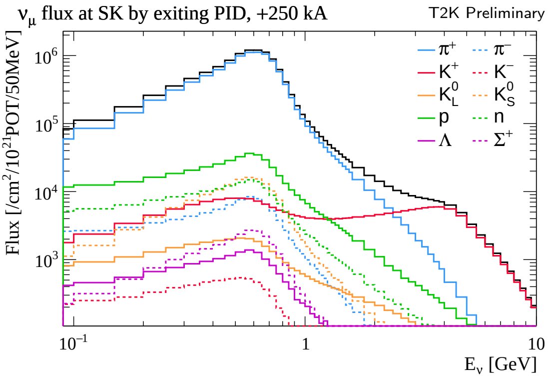
  - Sorry to my friend – I'm not sure I've succeeded at this
  - But, I've tried to give a forward-thinking overview of some issues we will be facing in the next decade or so related to conventional accelerator neutrino beams

Producing A Neutrino Beam



- High energy protons from an accelerator hit a production target and produce hadrons
- Outgoing hadrons are sign selected + focused in electro-magnetic focusing horns
  - Change polarity of horn field to switch between focusing positive or negative hadrons
- Allow hadrons to decay in long decay volume
- Monitor hadrons in hadron monitor at downstream of decay volume, or muons in muon monitor installed in shielding/beam dump
- Stop protons, hadrons, muons, in beam dump or ground, while neutrinos continue on to near and far detectors

Neutrino Parent Particles



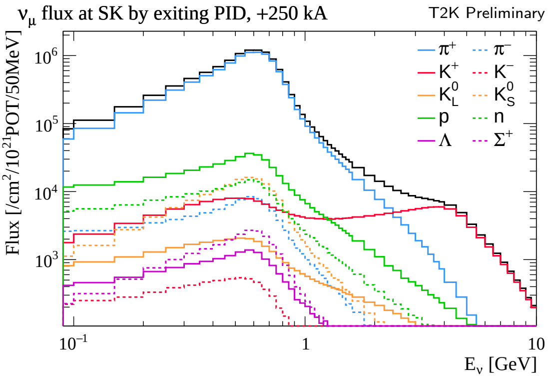
Neutrino parent particles are mostly pions, kaons produced in the target

$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ (BR=99.99%) (right-sign low-E ν_μ's)
$K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ (BR=63.6%) (right-sign high-E ν_μ's)
$\hookrightarrow \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$ (BR=100%) (right-sign ν_e's)

$K_L \rightarrow \pi^\pm + \mu^\mp + \bar{\nu}_\mu(\nu_\mu)$ (BR=27.0%) (right- and wrong-sign ν_μ's)
$K_L \rightarrow \pi^\pm + e^\mp + \bar{\nu}_e(\nu_e)$ (BR=40.6%) (right- and wrong-sign ν_e's)

....

Neutrino Parent Particles



Neutrino parent particles are mostly pions and kaons produced in the target, but can also be from particles produced by secondary interactions of protons and neutrons (+ pions, kaons, ...) in other materials around the beamline

$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ (BR=99.99%) (right-sign low-E ν_μ's)

$K^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ (BR=63.6%) (right-sign high-E ν_μ's)

↳ $\mu^\pm \to e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$ (BR=100%) (right-sign ν_e's)

$K_L \to \pi^\pm + \mu^\mp + \bar{\nu}_\mu(\nu_\mu)$ (BR=27.0%) (right- and wrong-sign ν_μ's)

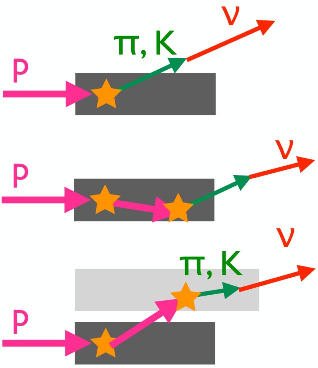
$K_L \to \pi^\pm + e^\mp + \bar{\nu}_e(\nu_e)$ (BR=40.6%) (right- and wrong-sign ν_e's)

....

Neutrino Parent Interactions

Percentage of neutrino-mode T2K far detector flux from in-target or out-of-target interactions :

	in-target primary int.	other than the in-target primary int. (out of target int.)
ν_μ	63.2%	36.8% (12.4%)
$\bar{\nu}_\mu$	41.5%	58.5% (45.1%)
ν_e	61.7%	38.3% (12.7%)
$\bar{\nu}_e$	54.0%	46.0% (27.2%)



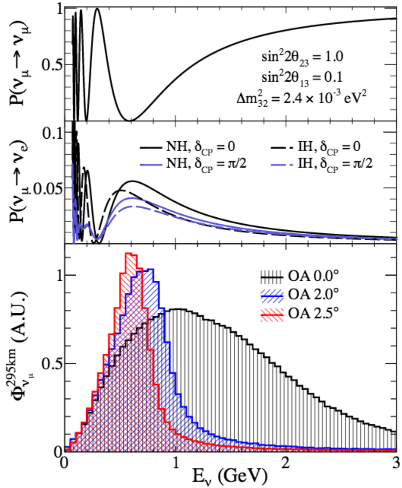
- In-target primary interactions are the main contribution
- However, there is a significant contribution from secondary+tertiary and/or out of target interactions, especially for the wrong sign flux

Controlling the Flux – Off-Axis Beam

- "Off-axis" beam concept :
  - Due to pion decay kinematics, the neutrino energy depends on the outgoing neutrino angle:

    $E_\nu = \frac{(1-(m_\mu/m_\pi)^2)E_\pi}{1+\gamma^2\theta^2}$
  - So, an "off-axis" beam gives a smaller range of neutrino energies
- Many experiments use an off-axis beam to select a neutrino flux with a peak energy near the oscillation maximum

Flux + Osc. Prob. at T2K



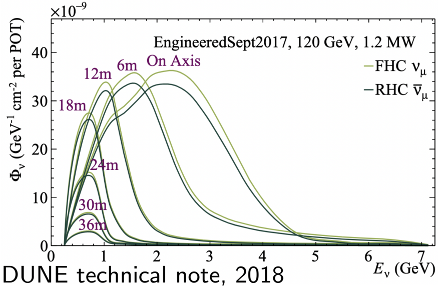
- Install detectors off-axis from the center of the neutrino beam to select the energy
- Precise understanding of the neutrino beam direction essential

Controlling the Flux – Off-Axis Beam

- "Off-axis" beam concept :
  - Due to pion decay kinematics, the neutrino energy depends on the outgoing neutrino angle:

    $E_\nu = \frac{(1-(m_\mu/m_\pi)^2)E_\pi}{1+\gamma^2\theta^2}$
  - So, an "off-axis" beam gives a smaller range of neutrino energies

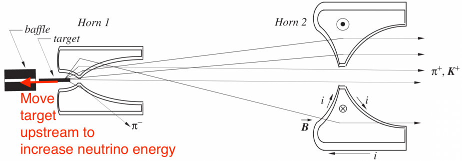
Flux at DUNE PRSIM



DUNE technical note, 2018

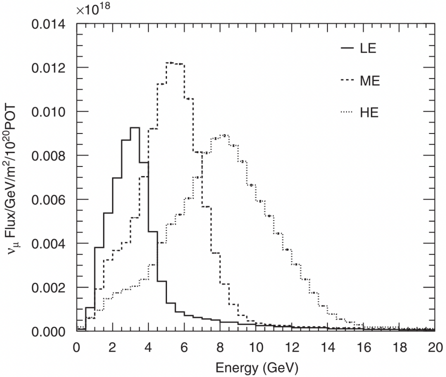
- Movable detectors can also be used to select a desired energy spectrum
- Again, precise understanding of the neutrino beam direction and detector positions essential

Controlling the Flux – Adjusting the Beamline Configuration



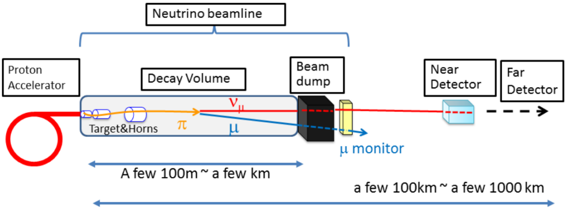
- A movable target in the NUMI beamline allows for control of the neutrino flux distribution
- Moving the target upstream directs smaller-angle, higher-momentum particles into the horn field, resulting in a higher energy neutrino beam

Flux at NuMI Near Detector



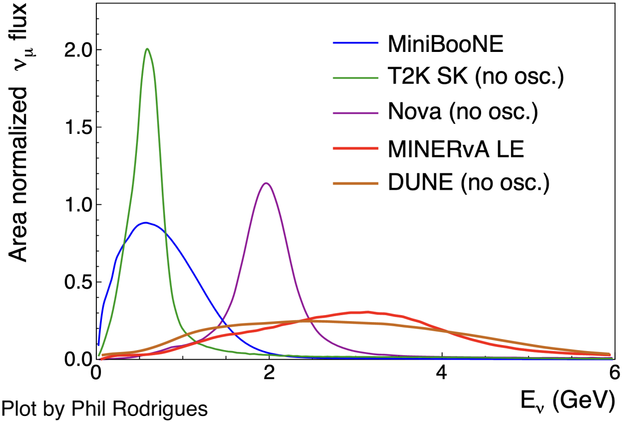
Nucl. Instrum. Meth. A 568 (2006)

Predicting the Neutrino Flux



- Directly measuring the flux is difficult/impossible – must simulate it
- Simulate the neutrino flux taking into account each component:
    - Proton beam incident on the target
        - Proton beam position, width, angle, intensity (number of protons)
    - Taking into account all components in the beamline, for example:
        - Baffle (ie upstream of target), target, horns, decay volume, beam dump, other material in the secondary beamline
        - Alignment of all components
        - Horn field, Earth field in decay volume
    - Neutrino beam off-axis angle
    - Hadron production inside the target
    - Hadron production outside of the target
    - Hadron decay/neutrino production in decay volume

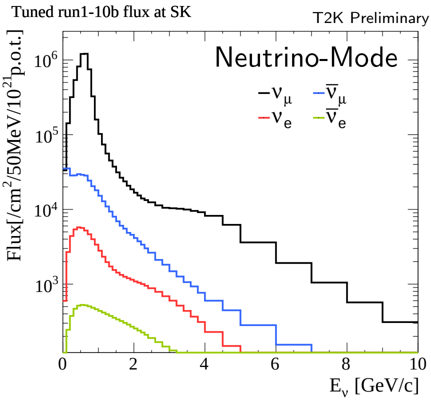
Example Accelerator Neutrino Fluxes

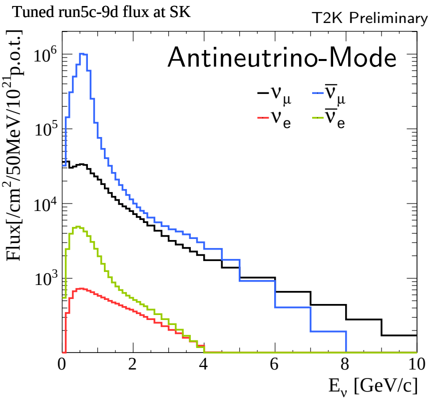


Plot by Phil Rodrigues

- Various accelerator neutrino fluxes used for various experiments
- Fluxes tend to peak around 0.5$\sim$a few GeV
- Can tune the width of the energy spectrum based on the off-axis angle and target/horn configuration

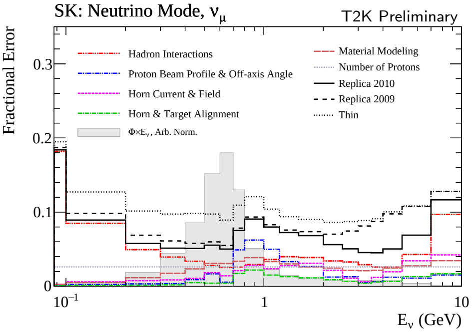
Example Accelerator Neutrino Fluxes

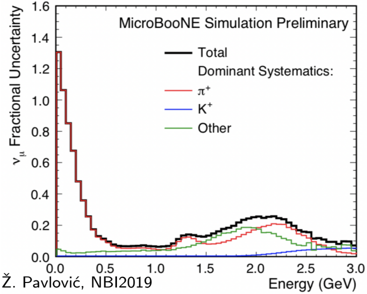




- Accelerators can produce a relatively pure beam of right-sign muon neutrinos (ie ν_μ's in neutrino-mode and $\bar{\nu}_\mu$'s in antineutrino-mode)
- At J-PARC:
  - $\sim$3% contamination of beam wrong-sign ν_μ at flux peak
  - $<$1% contamination of beam ν_e at flux peak

Example Flux Errors – Where We Are Now

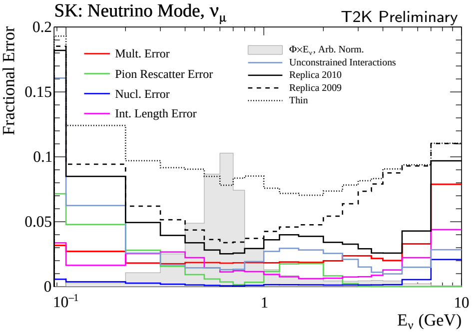


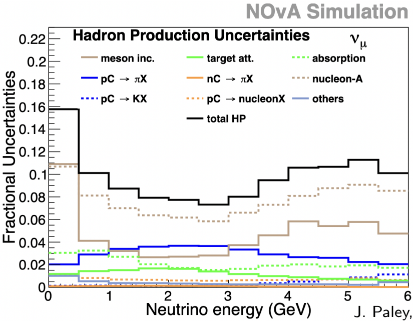


Ž. Pavlović, NBI2019

- Total current flux errors are around ∼5∼10% near the flux peak for various experiments
  - Can be (significantly) higher at low and high energies
- Significant contribution from hadron production uncertainties
  - For more details: great overview by M. Pavin at Neutrino2020
- As hadron production errors are reduced by external measurements, errors related to beamline hardware are becoming important

Example Hadron Production Flux Errors – Where We Are Now

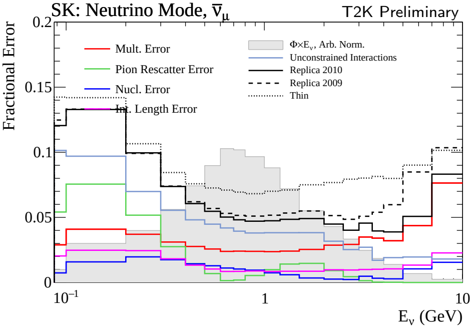


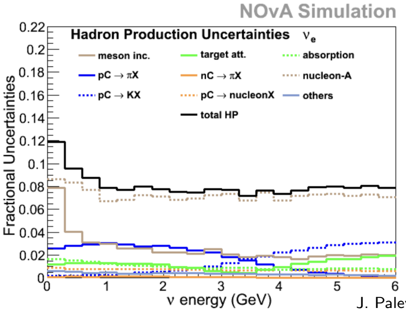


J. Paley, NBI2019

- Hadron production errors are coming from numerous relatively small sources – non-trivial to reduce (although we're working on it!)
- Especially, interactions not constrained by external measurements ("Unconstrained interactions") are becoming important
  - Interaction of low-momentum particles on materials in the beamline other than the target ("nucleon-A")

Example Hadron Production Flux Errors – Where We Are Now

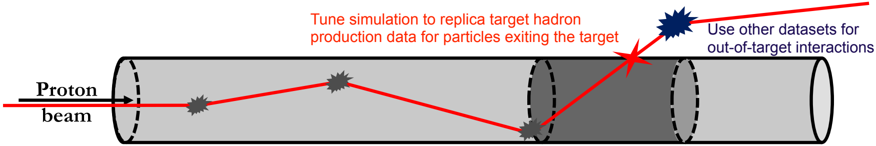




J. Paley, NBI2019

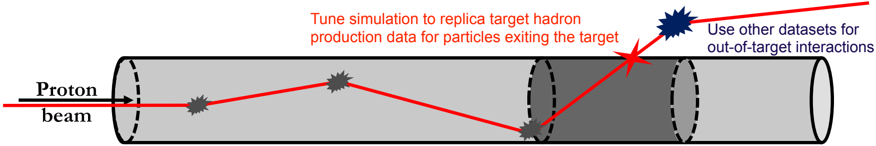
- These unconstrained and out-of-target secondary interactions are even more of an issue for the wrong-sign neutrino flux and beam intrinsic electron neutrino flux

Tuning to Hadron Production Data



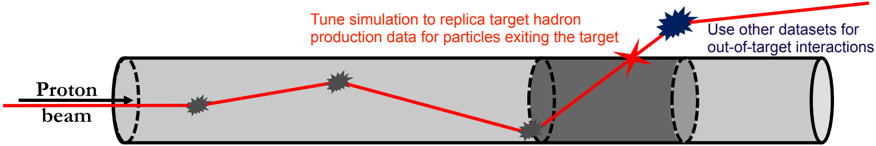
- Decay branching ratios of outgoing particles very well known, but we don't precisely know the probability of producing each particle $\rightarrow$ Make dedicated hadron production measurements!
- Can then directly tune the Monte Carlo prediction to measurements

Tuning to Hadron Production Data



- With high-precision data on a replica of the actual target at the actual proton beam energy, can do a relatively simple tuning of the MC for particles exiting the target surface
  - Don't need to worry about secondary interactions inside the target
- On the other hand, lower momentum particles exiting the target can re-interact on materials around the beamline
  - Need either lots and lots of datasets on many different materials with many different energy beams of different parent particles (better)
  - Or, need to scale existing datasets to the correct phase space, particle type, etc using various techniques (often need to apply large errors, some interactions remain unconstrained, etc)

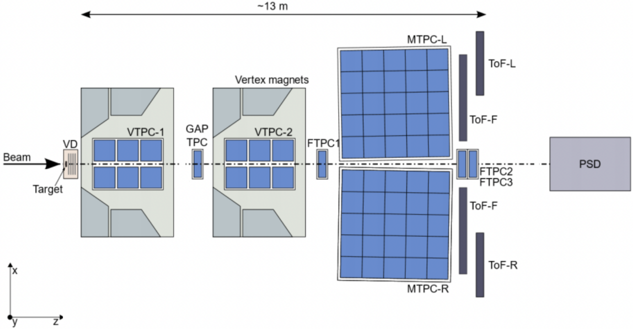
Tuning to Hadron Production Data



- Current status:
  - High-precision dedicated hadron production measurements for various experiments on replica targets recently/currently underway
    - Need higher statistics measurements are requirements get stricter for future precision neutrino oscillation experiments
    - Need additional high-precision replica target datasets as target designs for future facilities are fixed
  - Starting to get more serious about measurements for lower momentum particles exiting the target which can re-interact on materials around the beamline
    - Many of these are currently unconstrained by external datasets
    - Plans to make many dedicated measurements of these soon

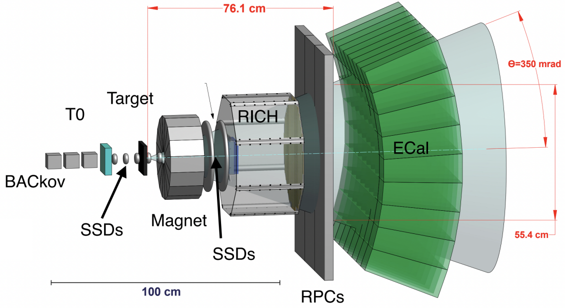
Current/Future Hadron Production Measurements: NA61/SHINE

- NA61/SHINE at CERN SPS



- Receives secondary hadron beams between 13 GeV/c and 350 GeV/c
- Large acceptance for charged particles with good momentum and particle identification resolution
- Thin and replica target data
- Future upgrades to allow for $<$13 GeV/c proposed

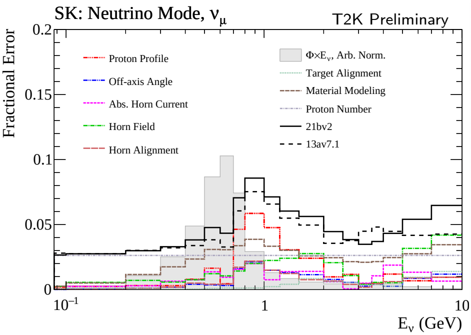
Current/Future Hadron Production Measurements: EMPHATIC

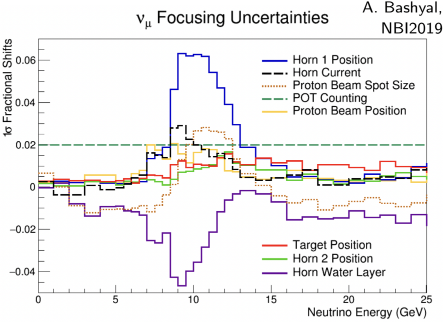


- EMPHATIC at Fermilab Test Beam Facility
- Collaboration dedicated to collecting data for neutrino fluxes

- Table-top size experiment
- Focused on hadron production measurements <15 GeV/c, but also make measurements with 20-120 GeV/c
- Thin target data on various materials
- Future upgrades planned:
  - Higher acceptance
  - Measure hadron flux downstream of a target and focusing horn with spectrometer on a motion table

Example Non-Hadron Production Errors – Where We Are Now



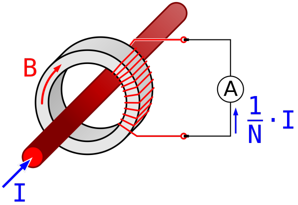


Medium Energy neutrino flux at MINERvA/on-axis detector

- Non-hadron production errors (beamline hardware related errors) can also have ∼5% energy-dependent contribution
- Becoming more important as hadron production errors are reduced
- These errors are related to beamline hardware, so can be time-dependent – need to worry about correlations between different run periods, etc

Proton Beam Intensity

- Uncertainties on the proton beam position, width, angle give rise to energy-dependent errors on the neutrino flux



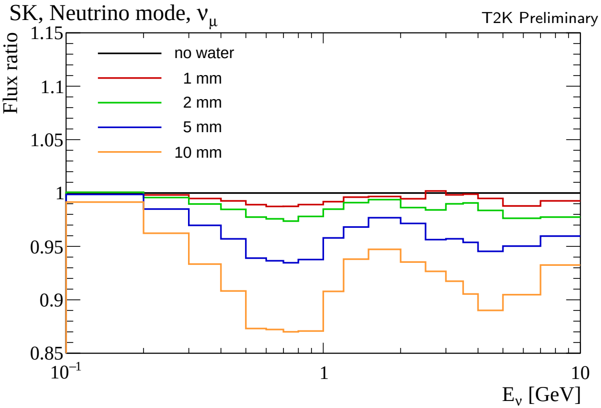
- Uncertainty on the proton beam intensity yields flat uncertainty on the neutrino rate
- Proton beam intensity is measured by Current Transformer (CT) mounted on the beam pipe
  - Beam intensity is proportional to current in wire wound around CT core
- Currently assign 2∼3% error on beam intensity
- But:
  - Non-trivial to calibrate
    - Frequency dependence
    - "Test" coils unreliable
    - Need to worry about electronics calibration
    - ...
  - Calibration can gradually drift over time
- Is your CT calibration correct today?!?

Horn Cooling Water

- Focusing horns are cooled by water sprayed between inner and outer conductors

- Difficult to precisely measure thickness of water layer pooled at horn inner conductor (3 mm $\pm$ 2 mm assigned at J-PARC now)
- Significant impact on flux due to pion absorption/scattering
- Precise dedicated measurements needed (underway at J-PARC)

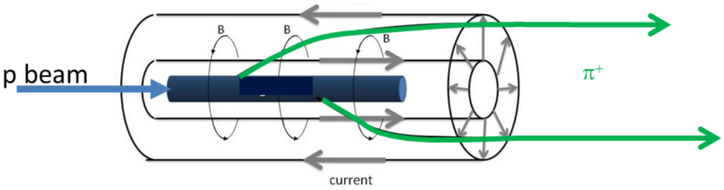
Horn Cooling Water



- Focusing horns are cooled by water sprayed between inner and outer conductors

- Difficult to precisely measure thickness of water layer pooled at horn inner conductor (3 mm $\pm$ 2 mm assigned at J-PARC now)
- Significant impact on flux due to pion absorption/scattering
- Precise dedicated measurements needed (underway at J-PARC)

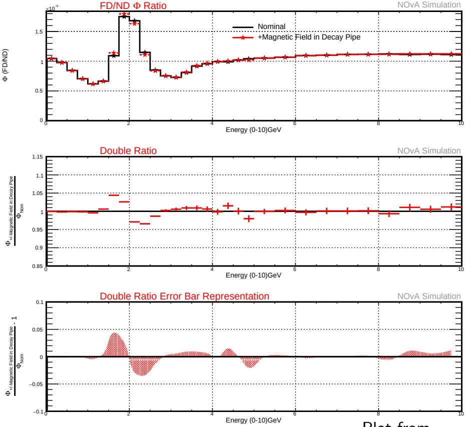
Horn Field Corrections



- Something people are starting to worry about (should be worrying about?): are additional corrections needed to simple hall probe measurements of the horn field?
- We know proton-beam-induced space-charge effects cause a field near the proton beam
  - Do we have to worry about similar effects in the horns from protons or ions produced in the target?
- How about the horn cooling water? Do we need to consider corrections to the horn field from that?

Earth Field Impact

Antineutrino-mode

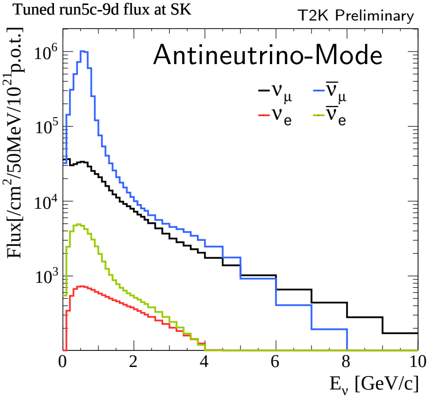


Plot from
Linda Cremonesi

- Impact of Earth's magnetic field on particles in the decay volume can be non-negligible
- Effect from simulation is up to 5% on the NOvA near/far double ratio in focusing peak
  - Based on magnetic field measurements taken when the decay pipe was built (before it was filled with helium)

- NOvA is currently trying to estimate the effect of the Earth's magnetic field using measurements from downstream muon monitors

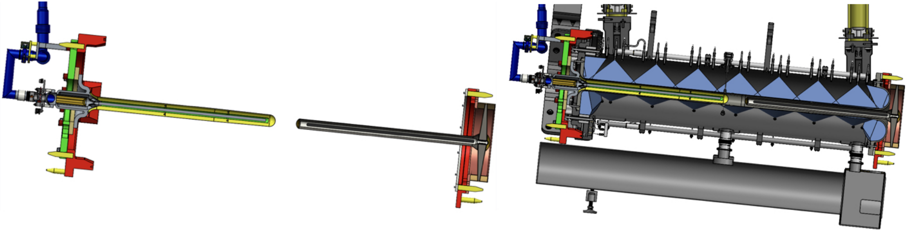
Minimizing the Wrong-Sign Component



- For future accelerator neutrino beams – is it possible to further reduce the wrong-sign component by adjusting the target design?
- Simply using a **longer target** could help by absorbing forward going (non-horn-focused) hadrons, but:
  - Technically (mechanically) difficult
  - Don't want to absorb too many right-sign hadrons
- Installing a second target (or "beam plug") at the downstream end of the first horn
  - Mechanically simpler than a single long target
- Different materials could help to optimize the effect

Minimizing the Wrong-Sign Component

DUNE target concept:



C. Densham, NuFACT2019

- Installing a second target (or “beam plug”) at the downstream end of the first horn
    - Mechanically simpler than a single long target
- Different materials could help to optimize the effect
    - Can tune/optimize material of downstream target
    - “Hybrid” target with higher density core, lower density sheath could be anther option (also maybe mechanically difficult?)

Conclusion

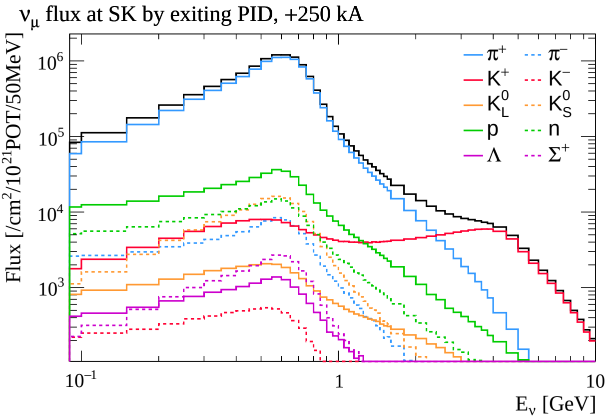
- Yes, even YOU should care about accelerator neutrino fluxes and their errors
- Hadron production errors are the dominant uncertainty now
  - Need to be constrained by dedicated hadron production measurements
- Beamline hardware errors also have a significant (time-dependent) impact

- Now soliciting interesting/novel ways to constrain, or, even better, control conventional accelerator neutrino beam fluxes
  - Neutrino factory?
  - Instrumented decay volume?

    $\rightarrow$ These are great, but require lots of R&D + new facilities
  - Please think about interesting new ideas to improve fluxes at current conventional beamlines!

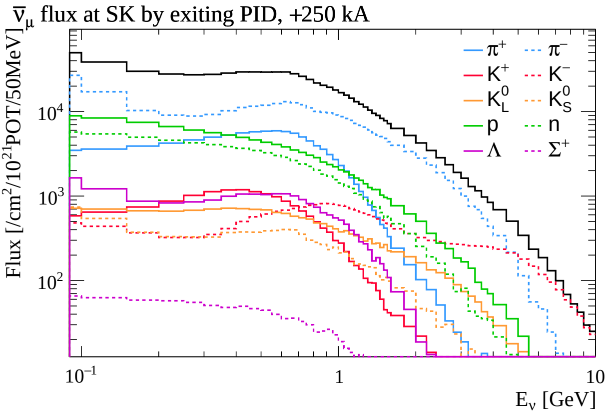
Backup Slides

Neutrino Parent Particles



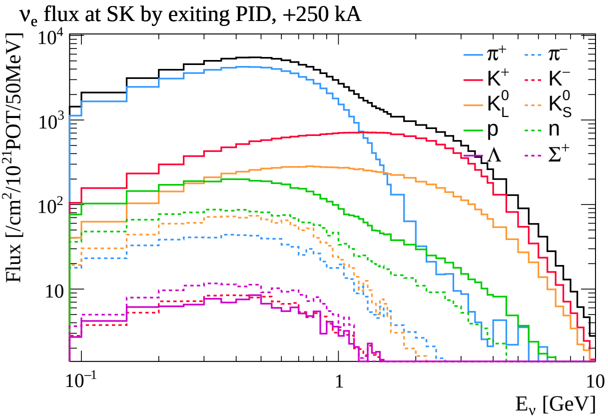
- Main contribution of right-sign flux from right-sign pions near flux peak, right-sign kaons at higher energies
- Then hadrons produced by proton interactions with materials outside of the target, then others..

Neutrino Parent Particles



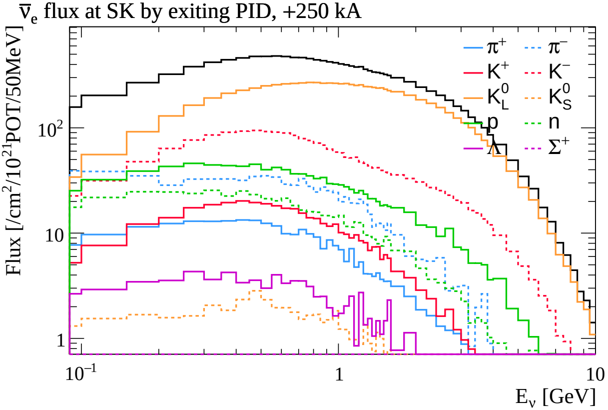
- Main contribution of wrong-sign flux from wrong-sign pions, muons from right-sign pion decay
- Then hadrons produced by proton/neutron interactions with materials outside of the target

Neutrino Parent Particles



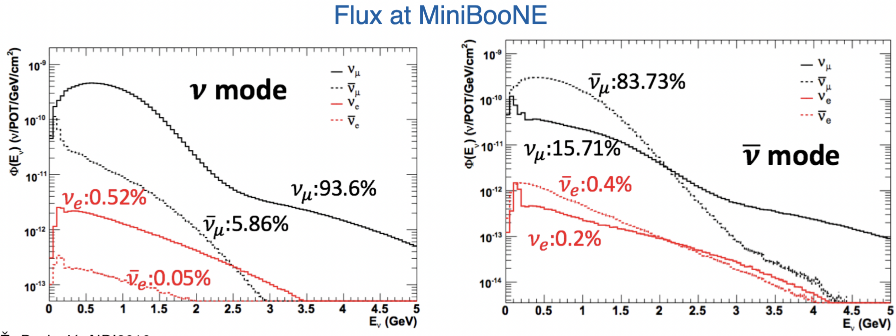
- Main contribution of ν_e flux from muon decay from right-sign pions and kaons
- Then K^0, hadrons produced by proton/neutron interactions with materials outside of the target, ...

Neutrino Parent Particles



- Main contribution of $\bar{\nu}_e$ flux from K_L^0, then muon decay from wrong-sign kaons
- Then hadrons produced by proton/neutron interactions with materials outside of the target, muon decay from wrong-sign pions, ...

Neutrino Flux at MiniBooNE



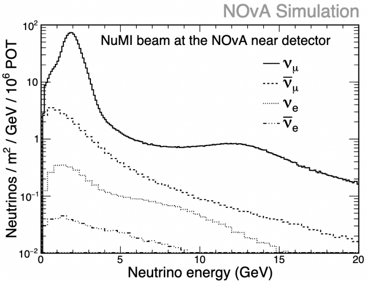
Ž. Pavlović, NBI2019

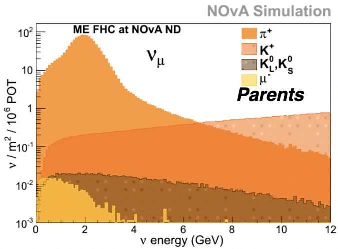
- Predominantly $\nu_\mu + \bar{\nu}_\mu$ flux (>99%)
- Small ~0.5% intrinsic electron neutrino component
- Larger wrong sing component in anti-neutrino mode, amplified by higher neutrino cross-sections

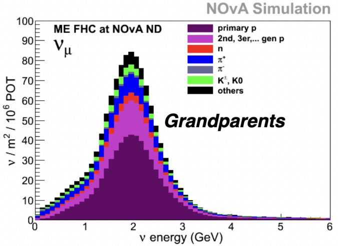
Neutrino Flux at NOvA

Neutrino flux at NOvA

» 96% pure ν_μ beam, 1% ν_e and $\bar{\nu}_e$

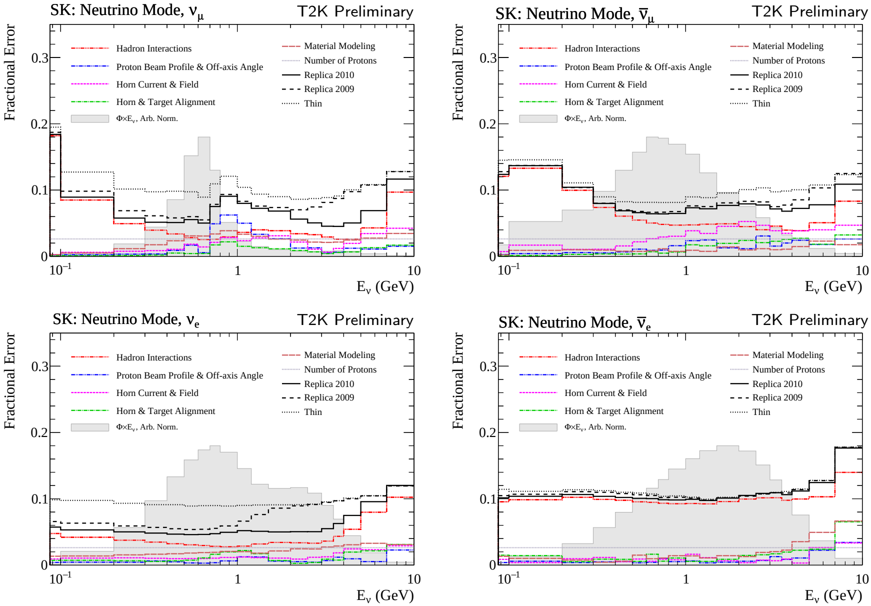




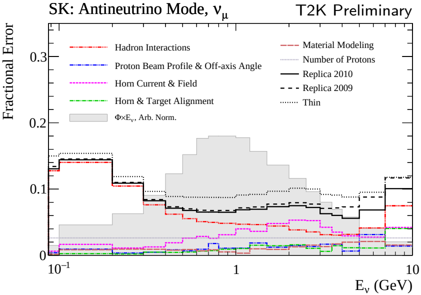


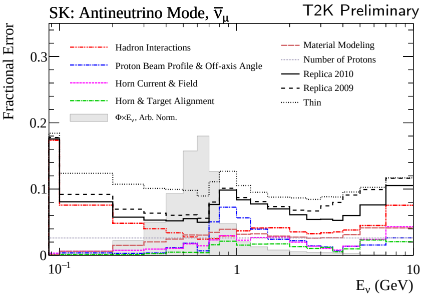
L. Aliaga, NA61/SHINE LowE Workshop 2020

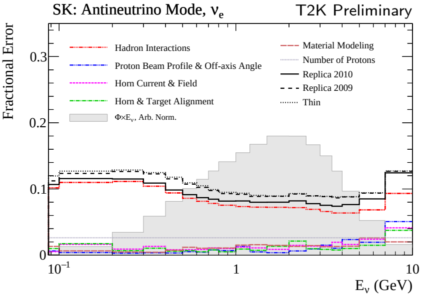
T2K Neutrino-Mode Flux Errors

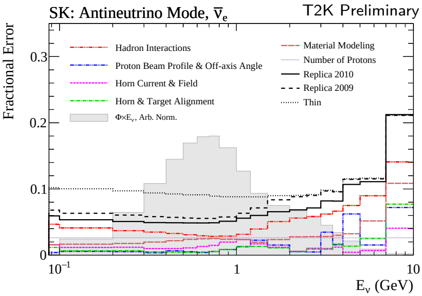


T2K Antineutrino-Mode Flux Errors



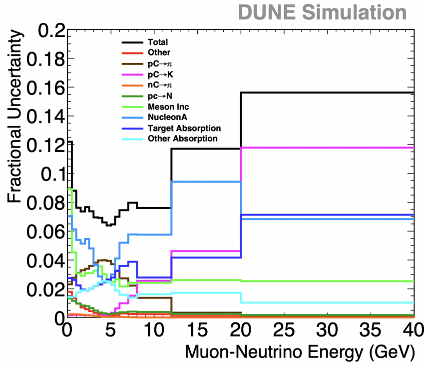


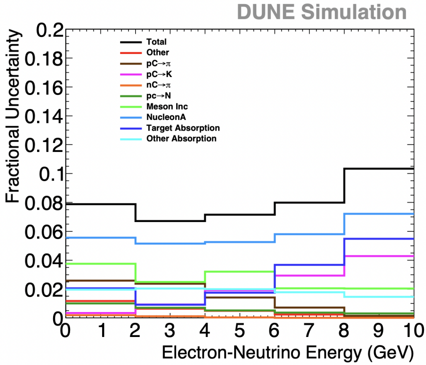




DUNE Flux Uncertainties from Hadron Production

J. Paley, NBI2019

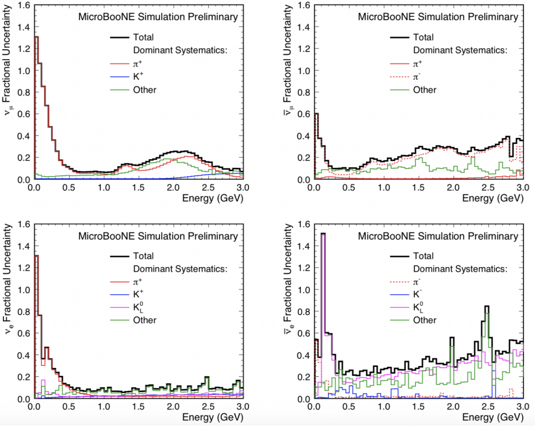




- Dominant flux uncertainties come from 40% xsec uncertainties on interactions in the target and horns that have never been measured (or have large uncertainties/spread)
- Lack of proton and pion scattering data at lower beam energies

Neutrino Flux Uncertainties at MicroBooNE

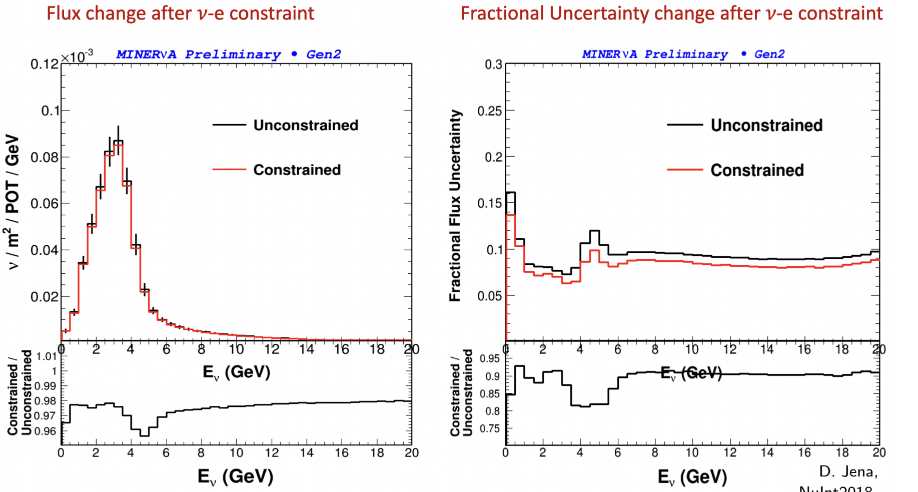
- Integrated over whole energy range uncertainties at ~10% level



Systematic	$\nu_\mu/\%$	$\bar{\nu}_\mu/\%$	$\nu_e/\%$	$\bar{\nu}_e/\%$
Proton delivery	2.0	2.0	2.0	2.0
π^+	11.7	1.0	10.7	0.03
π^-	0.0	11.6	0.0	3.0
K^+	0.2	0.1	2.0	0.1
K^-	0.0	0.4	0.0	3.0
K_L^0	0.0	0.3	2.3	21.4
Other	3.9	6.6	3.2	5.3
Total	12.5	13.5	11.7	22.6

Ž. Pavlović, NBI2019

Constraining the Flux by Neutrino-Electron Scattering



D. Jena, NuInt2018

- Precisely known neutrino scattering on electrons as standard candle for flux estimation