Neutrino Flux Predictions
Day 2 – Neutrino Flux Simulation

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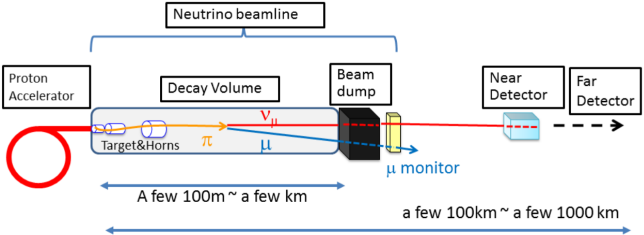
NuSTEC 2024
CERN
June 12, 2024

Outline

- Yesterday :
  - How to make a neutrino beam
  - Accelerators for neutrino beamlines
  - Neutrino beamline components
- Today :
  - Predicting neutrino fluxes
  - Calculating systematic errors on neutrino fluxes

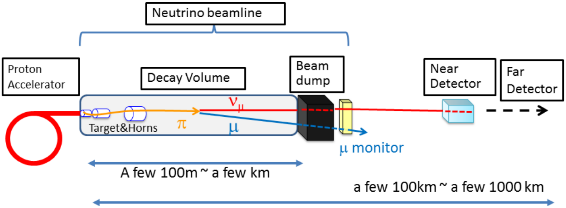
- Often using the J-PARC/T2K neutrino flux as an example
  → Neutrino source for current T2K and future Hyper-K experiments in Japan

Producing A Conventional 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: $\pi^+ \to \mu^+ + \nu_\mu$, ..
- 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

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
  - Hadron production inside the target
  - Hadron production outside of the target
  - Hadron decay/neutrino production in decay volume
  - Position of the neutrino detector (e.g. neutrino beam off-axis angle)

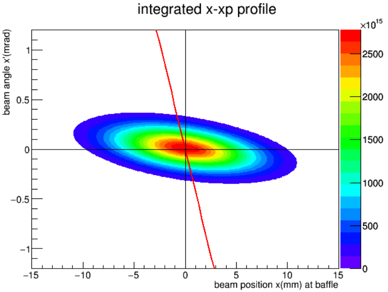
Details of T2K Flux Prediction

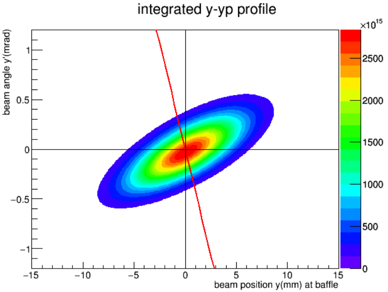
- In the T2K flux simulation, we:
  - Generate a proton beam based on the measured proton beam position, width, emittance at the upstream edge of the baffle
  - Simulate interactions in the baffle and target by Fluka
  - Track particles exiting the target through the horn field and decay volume by Geant3
  - Rates of $\pi^{\pm}$, $K^{\pm}$, p exiting the target's surface are tuned to yields measured by the NA61/SHINE experiment using a weight: $w(p, \theta, z, i) = \frac{\mathrm{d}n^{\mathrm{NA61}}(p,\theta,z,i)}{\mathrm{d}n^{\mathrm{MC}}(p,\theta,z,i)}$
    - High-statistics NA61 data taken on a T2K replica target in 2010 (Eur. Phys. J. C 79 (2019) 100)
  - Interactions outside of the production target are not directly covered by NA61/SHINE data
    - Scale thin target $\pi^{\pm}$, $K^{\pm}$, K^0_s, Λ, p NA61 2009 data (Eur. Phys. J. C 76 (2016) 84) to different center of mass energy and target nuclei
    - Parameterize and cross-check scaling methods with multiplicity data from various older experiments (Eichten et al., Allaby et al., BNL E910)

- Upgrade of simulation Fluka+Geant3 → Geant4 underway now

Proton Beam Measurements at the Baffle

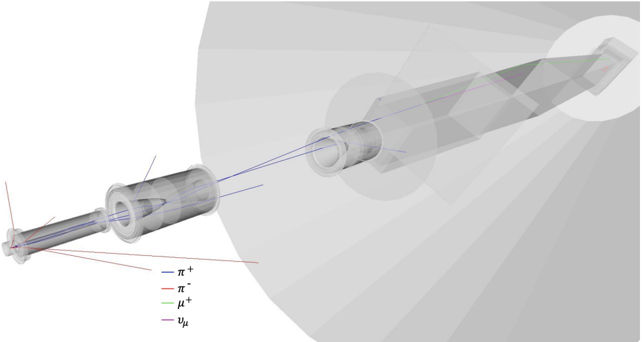
- Continuously measure the proton beam parameters at the baffle and target using proton beam monitoring
- Calculate an average beam profile for each “run period”
    - Measured position, angle, width, emittance, twiss α at the upstream end of the baffle used as inputs for J-PARC flux simulation
- Continuously measure proton beam intensity spill-by-spill using CTs
    - Sum to get total protons on target (POT) for each “run period”
    - Can then also calculate a POT-weighted flux combination of all run periods



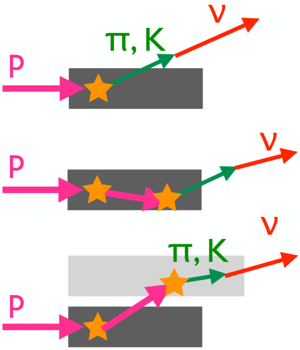


Beamline Geometry

- Implement all beamline components into model geometry
  - Baffle, target, horns, decay volume, beam dump, other material in the secondary beamline
  - Including nominal or measured alignment information for each beamline component
- T2K MC now separates baffle/target (Fluka) and all other secondary beamline components (Geant3), but not for any good reason
  → T2K now preparing combined simulation (Geant4)
  - NUMI already uses Geant4 for full simulation



Interactions Inside and Outside of the Target



- Proton beam can interact a single time in the target

  – Or –
- Multiple times in the target

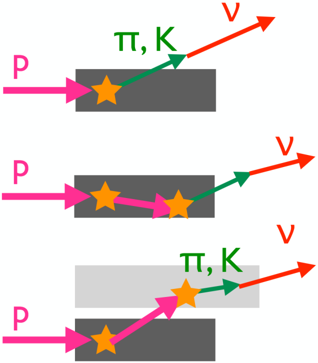
  – Or –
- Outside of the target

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

Interactions Inside and Outside of the Target

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

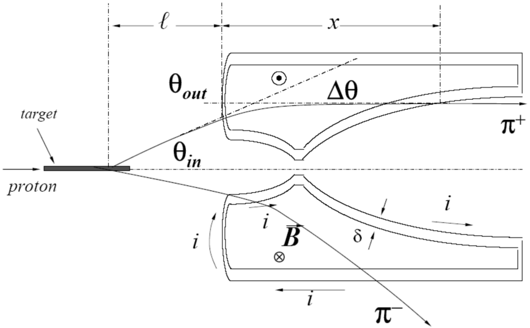
	in-target primary int.	other than the in-target primary int. (out of target int.)
ν_μ	63.2%	36.8% (12.4%)
$\bar{\nu}_\mu$	41.5%	58.5% (45.1%)
ν_e	61.7%	38.3% (12.7%)
$\bar{\nu}_e$	54.0%	46.0% (27.2%)



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

Interactions are complicated, so let me come back to it

Horn Focusing



- Need to know the horn field precisely in order to model it correctly
- Make direct measurements of the horn field before installation using a Hall Probe inserted between the horn outer and inner conductors
- Continuously measure the supplied horn current during beam operation
- Use measured fields scaled to measured horn currents as input into the flux simulation

Secondary Hadron Decay

- Simulate hadron decay in the decay volume
- Branching ratios of hadron decays are very well known

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$ (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)
↳ $\mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e})$ (BR=100%) (right-sign ν_{e}'s)

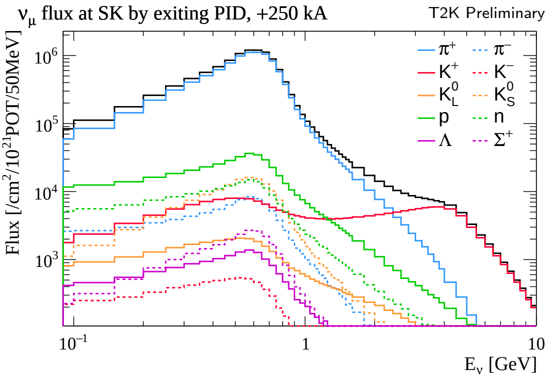
$K_{L}^{0} \rightarrow \pi^{\pm} + \mu^{\mp} + \bar{\nu}_{\mu}(\nu_{\mu})$ (BR=27.0%) (right- and wrong-sign ν_{μ}'s)
$K_{L}^{0} \rightarrow \pi^{\pm} + e^{\mp} + \bar{\nu}_{e}(\nu_{e})$ (BR=40.6%) (right- and wrong-sign ν_{e}'s)
$K_{s}^{0} \rightarrow \pi^{+} + \pi^{-}$ or $\pi^{0} + \pi^{0}$ (BR=99.9%)
....

Pion vs Muon Decay

- ν_e component of the beam is mostly from μ's from π decay
- Since every π produces a μ which will eventually decay, would have equal number of ν_μ and ν_e for an infinitely long decay tunnel
- With a decay tunnel of length L longer than the π lifetime $\gamma_\pi c\tau_\pi$ but shorter than the muon lifetime $\gamma_\mu c\tau_\mu$, all pions would decay while most muons are decelerated at the end of the decay tunnel
  → Strongly defocused low-energy ν_e component
- ν_e contamination can be estimated as:
  $\frac{\Phi(\nu_e)}{\Phi(\nu_\mu)} = 1 - \exp(-\frac{L}{\gamma_\mu c\tau_\mu}) \simeq \frac{L}{\gamma_\mu c\tau_\mu}$
- For T2K, $\gamma_\mu \simeq 20$, $L \simeq 100$m
  $\tau_\mu = 2.2\mu$s
  $\Phi(\nu_e)/\Phi(\nu_\mu) \simeq 1\%$

  → Need much longer decay volume before you start worrying about significant contamination from ν_μ decays

Neutrino Parent Particles



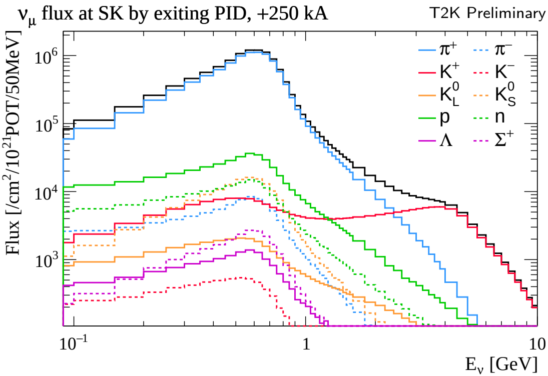
Neutrino parent particles are mostly pions, kaons produced in the target

$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ (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

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$ (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)

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

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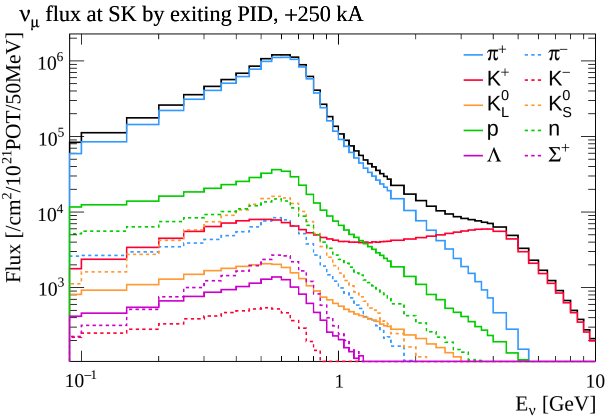
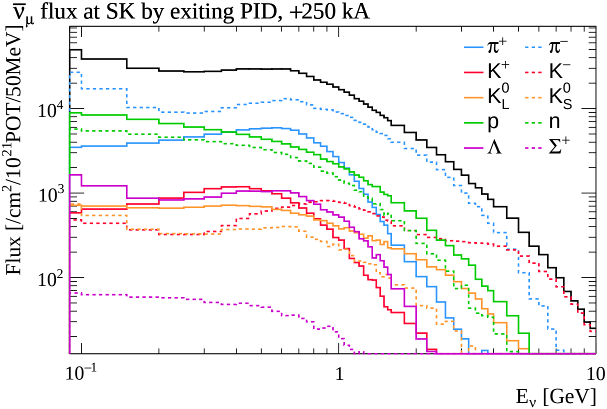
....

Neutrino Parent Particles



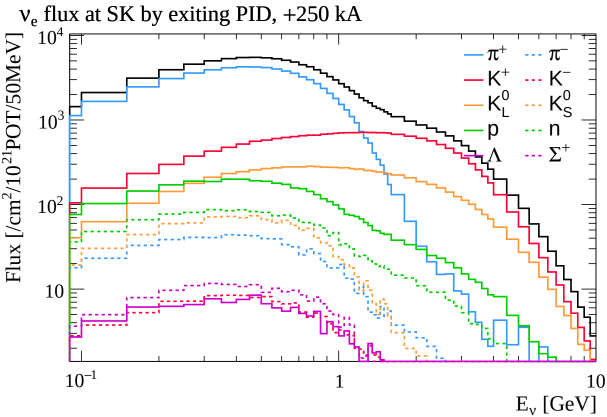
- Main contribution of right-sign flux from right-sign pions near flux peak, right-sign kaons at higher energies
- Then hadrons produced by proton interactions with materials outside of the target, then others..

Neutrino Parent Particles



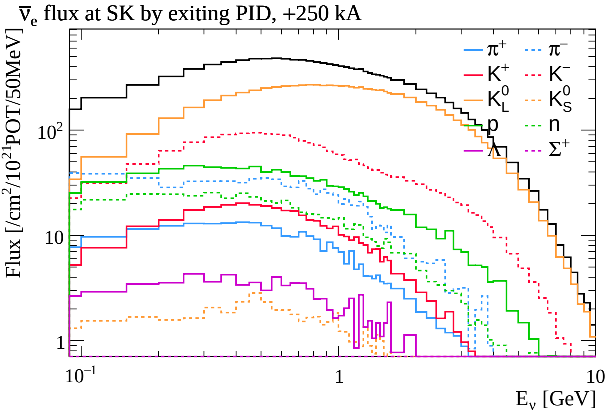
- Main contribution of wrong-sign flux from wrong-sign pions, muons from right-sign pion decay
- Then hadrons produced by proton/neutron interactions with materials outside of the target

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

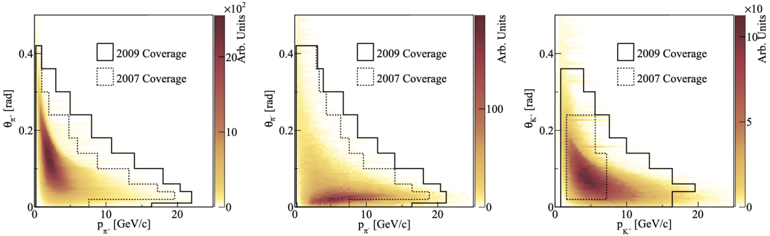


- Main contribution of $\bar{\nu}_e$ flux from K_L^0, then muon decay from wrong-sign kaons
- Then hadrons produced by proton/neutron interactions with materials outside of the target, muon decay from wrong-sign pions, ...

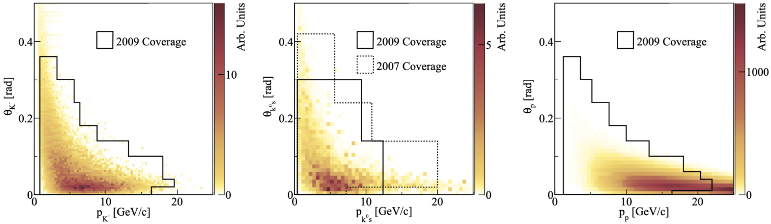
Phase Space Contributing to the Flux

- Outgoing (p, θ) phase space of particles contributing to the flux

Neutrino mode



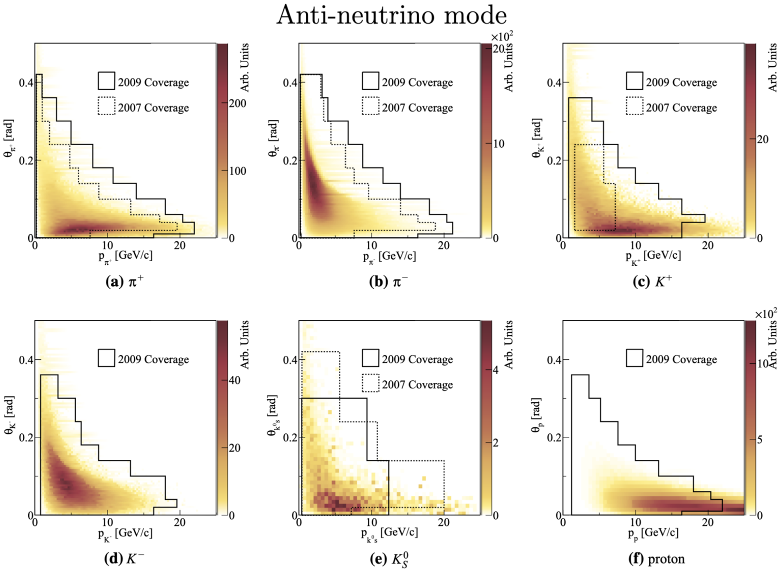
(a) π^+ (b) π^- (c) K^+



(d) K^- (e) K^0_S (f) proton

Phase Space Contributing to the Flux

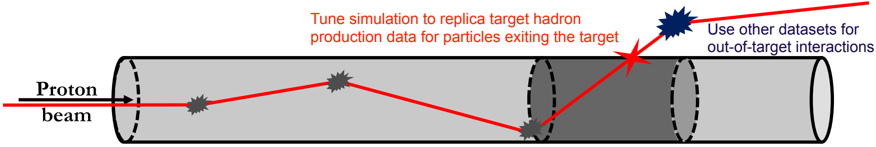
- Outgoing (p, θ) phase space of particles contributing to the flux



(a) π^+ (b) π^- (c) K^+

(d) K^- (e) K^0_S (f) proton

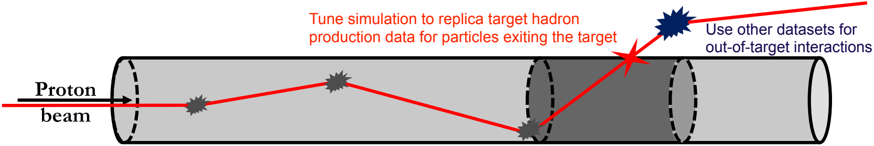
Tuning to Hadron Production Data



- Decay branching ratios of outgoing particles very well known
- But, we don't precisely know the probability of proton interacting
- And, we don't know the probability of producing each parent particle
  → Make dedicated hadron production measurements!

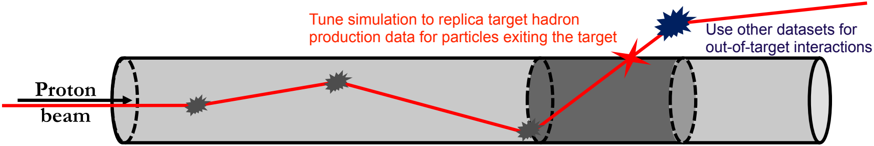
- Can then directly tune the Monte Carlo prediction to measurements

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

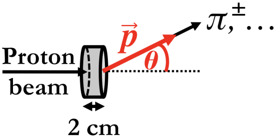


- Current status:
  - High-precision dedicated hadron production measurements for various experiments on replica targets recently/currently underway
    - Need higher statistics measurements as requirements get stricter for future precision neutrino experiments
    - Need additional high-precision replica 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

Method for Tuning to Hadron Production Data

- Total probability of hadron interactions and outgoing hadron multiplicities are tuned to match hadron production measurements
  - As a function of:
    - Incoming proton momentum
    - Outgoing hadron momentum and angle or Feynman variables (x_F, p_T)
- Necessary external data for precise flux tuning:
  - Total cross section
    - Used to constrain interaction probabilities of hadrons
  - Differential production multiplicity
    - Used to constrain hadron production multiplicities
  - Generally provided by each experiment in bins of hadron (p, θ) or (x_F, p_T) $(x_F = 2p_L^{CoM}/\sqrt{s})$

Thin Target Data



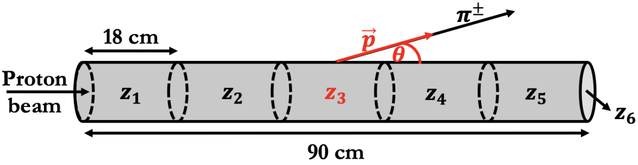
- Thin target beam data
  - Study single interactions
  - A few % radiation length target, typically 2cm thick
  - Various material types
  - Various incident particles ($p,\ \pi,\ K$)
- From thin targets, can measure:
  - Total cross sections:

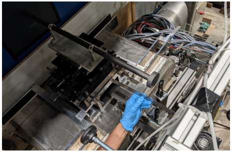
$$\sigma_{inel} = \sigma_{total} - \sigma_{el}$$
$$\sigma_{prod} = \sigma_{inel} - \sigma_{qe}$$

  - Differential hadron yields (differential cross section)

$$\frac{d^2 n}{dp d\theta} = \frac{1}{\sigma_{prod}} \frac{d^2\sigma}{dp d\theta}$$

Replica Target Data





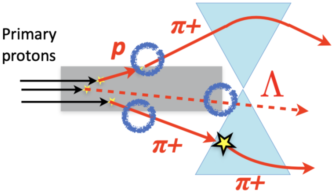
- Replica target beam data
  - Geometry and material identical to associated neutrino production target
  - Incident proton beam of relevant energy
- From replica targets, can measure:
  - Beam attenuation (production cross section)

    $P_{survival} = e^{-Ln\sigma_{prod}}$
  - Differential hadron yields

    $\frac{d^3n}{dpd\theta dz}$

Replica Tuning to Data

- Two corrections to constrain model ambiguity
  - Interaction length: tune production cross-section to external measurement
  - Multiplicity: tune differential hadron multiplicity to external measurement
- For replica target data, tune all interactions in the target to measurements from the target surface
  - Don't need to worry about what's happening inside of the target
- Out-of-target interactions still need to be tuned to thin target data



	Interaction length	**Multiplicity**
(replica target data) At exiting point 	N/A	"replica" weight $\left(\frac{d^3n}{dp\,d\theta\,dz}\right)_{\mathrm{Data}} \Big/ \left(\frac{d^3n}{dp\,d\theta\,dz}\right)_{\mathrm{MC}}$
(thin target data) At interaction 	"vertex" weight $\sigma_{\mathrm{Data}} / \sigma_{\mathrm{MC}}$	"thin" weight $\left(\frac{d^2n}{dp\,d\theta}\right)_{\mathrm{Data}} \Big/ \left(\frac{d^2n}{dp\,d\theta}\right)_{\mathrm{MC}}$
For distance L traversed 	"attenuation" weight $e^{-(\sigma_{\mathrm{Data}}-\sigma_{\mathrm{MC}})\rho L}$	N/A

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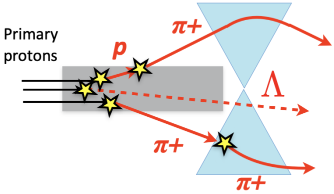
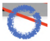
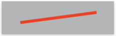
Thin Tuning to Data

- If replica target weights are not available, need to rely on tuning to thin weights, including for re-interactions in the target
- Thin target tuning is a bottom-up approach where every single interaction and propagation is reweighted to match experimental results
  - Need to record the interaction chain of every particle eventually decaying into a neutrino



	Interaction length	Multiplicity
(replica target data) At exiting point 	N/A	"replica" weight $\left(\frac{d^3n}{dp\,d\theta\,dz}\right)_{\mathrm{Data}} \Big/ \left(\frac{d^3n}{dp\,d\theta\,dz}\right)_{\mathrm{MC}}$
(thin target data) At interaction 	"vertex" weight $\sigma_{\mathrm{Data}}/\sigma_{\mathrm{MC}}$	"thin" weight $\left(\frac{d^2n}{dp\,d\theta}\right)_{\mathrm{Data}} \Big/ \left(\frac{d^2n}{dp\,d\theta}\right)_{\mathrm{MC}}$
For distance L traversed 	"attenuation" weight $e^{-(\sigma_{\mathrm{Data}}-\sigma_{\mathrm{MC}})\rho L}$	N/A

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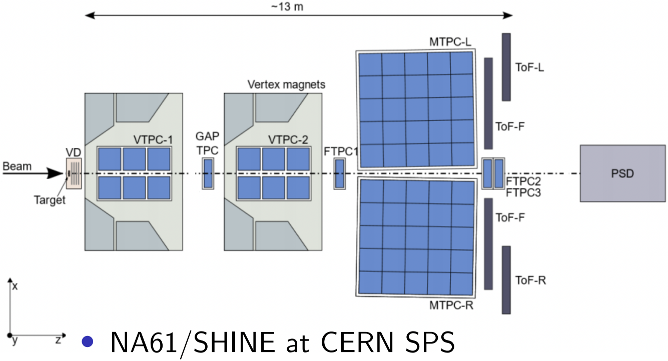
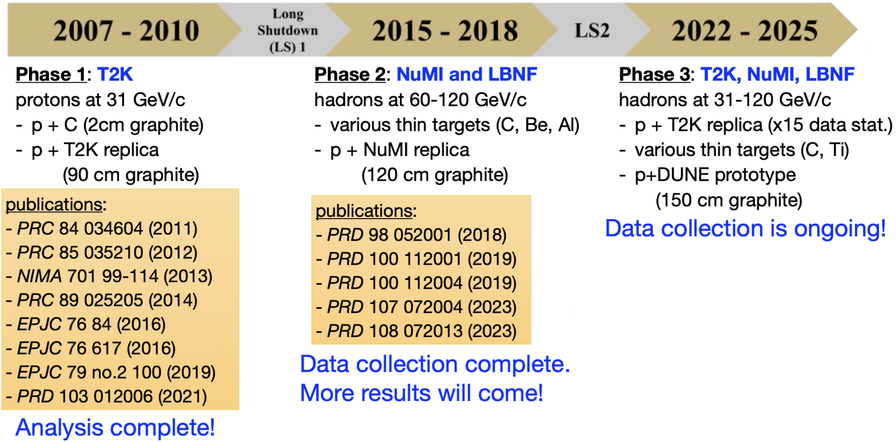
Current/Future Hadron Production Measurements: NA61/SHINE



- NA61/SHINE at CERN SPS
- 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

NA61/SHINE Data So Far



2007 - 2010 | **Long Shutdown (LS) 1** | **2015 - 2018** | **LS2** | **2022 - 2025**

Phase 1: **T2K**
protons at 31 GeV/c
- p + C (2cm graphite)
- p + T2K replica
  (90 cm graphite)

publications:
- *PRC* 84 034604 (2011)
- *PRC* 85 035210 (2012)
- *NIMA* 701 99-114 (2013)
- *PRC* 89 025205 (2014)
- *EPJC* 76 84 (2016)
- *EPJC* 76 617 (2016)
- *EPJC* 79 no.2 100 (2019)
- *PRD* 103 012006 (2021)

Analysis complete!

Phase 2: **NuMI and LBNF**
hadrons at 60-120 GeV/c
- various thin targets (C, Be, Al)
- p + NuMI replica
  (120 cm graphite)

publications:
- *PRD* 98 052001 (2018)
- *PRD* 100 112001 (2019)
- *PRD* 100 112004 (2019)
- *PRD* 107 072004 (2023)
- *PRD* 108 072013 (2023)

Data collection complete.
More results will come!

Phase 3: **T2K, NuMI, LBNF**
hadrons at 31-120 GeV/c
- p + T2K replica (x15 data stat.)
- various thin targets (C, Ti)
- p+DUNE prototype
  (150 cm graphite)

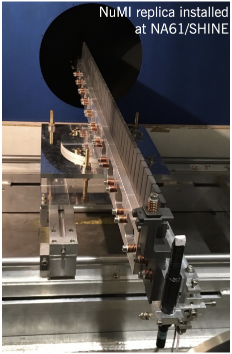
Data collection is ongoing!

Including T2K
replica target
$\pi^{\pm}$, $K^{\pm}$, p data

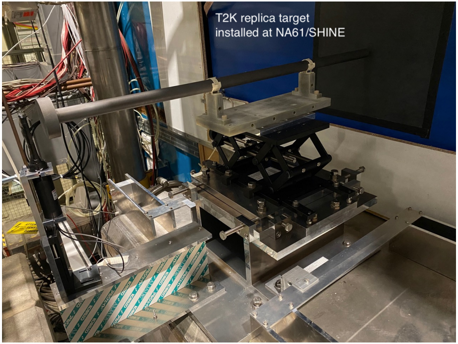
Including T2K
replica target
high momentum
kaon data

NA61/SHINE Recent Status

- Various recent hadron production measurements for neutrino flux constraints:
  - Thin target data for FNAL in 2016∼2017
  - Replica target data for NUMI in 2018
  - Replica target data for T2K in 2022
    - Almost 20× higher statistics than 2010 T2K replica target run
    - Mainly for measurement of high momentum kaon production



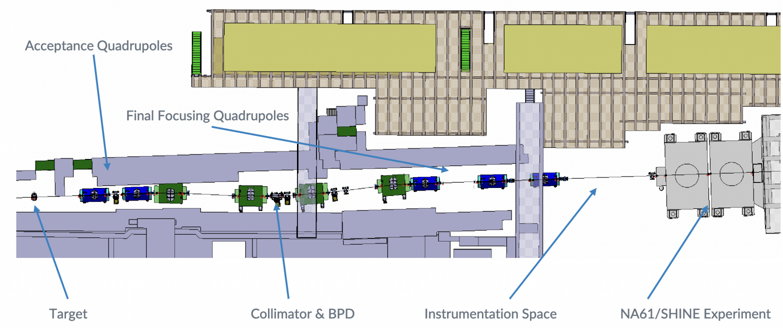
NuMI replica installed at NA61/SHINE



T2K replica target installed at NA61/SHINE

- High statistics dataset in 2022 possible due to major upgrades in 2019∼2022:
  - Upgraded TPC electronics
  - Upgraded trigger/DAQ → ∼100 Hz → ∼1 kHz
  - + Other detector upgrades

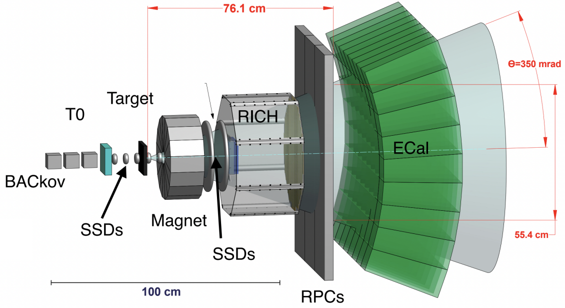
NA61/SHINE Low Energy Beamline Upgrade Plan



C. Mussolini, NBI2022

- Now designing low energy (1∼13 GeV) beamline for NA61/SHINE
  - Constrain secondary interactions outside of neutrino production target
  - + Atmospheric neutrino flux, spallation sources, ...
- Under development by CERN beam group in collaboration with NA61/SHINE collaboration
- Aim to have low energy beam available from 2025∼

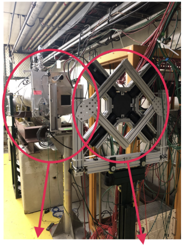
Current/Future Hadron Production Measurements: EMPHATIC



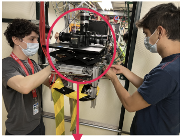
- EMPHATIC at Fermilab Test Beam Facility
- Collaboration dedicated to collecting data for neutrino fluxes

- 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

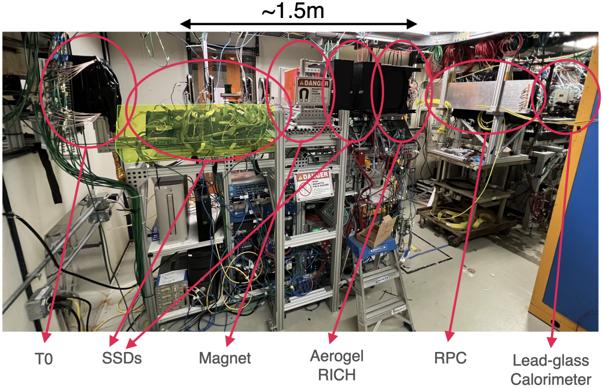
EMPHATIC Recent Status



Gas Ckov + Trigger



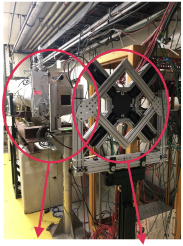
Beam aerogel Ckov

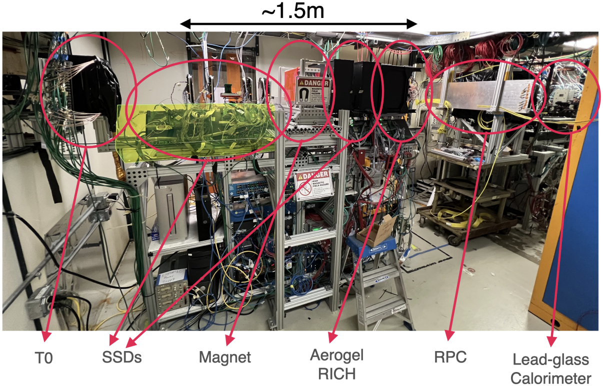


J. Paley, NuFACT2022

- Took Phase 1 data in several periods during 2022∼2023:
  - Low and high momentum hadron production data (with 100 mrad acceptance) + elastic/quasi-elastic scattering data
  - 2, 4, 8, 12, 20, 31, 60, 120 GeV/c proton, pion, kaon beams
  - On C, CH_2, Al, Fe, Be, Ti, Ca, H_20 targets

EMPHATIC Future Plan





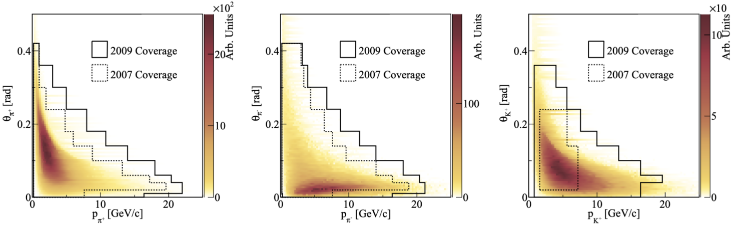
J. Paley, NuFACT2022

- Phase 2 planned
  - Higher acceptance spectrometer
  - Dedicated beamline for EMPHATIC spectrometer – plenty of beamtime to take many high-statistics measurements on many materials

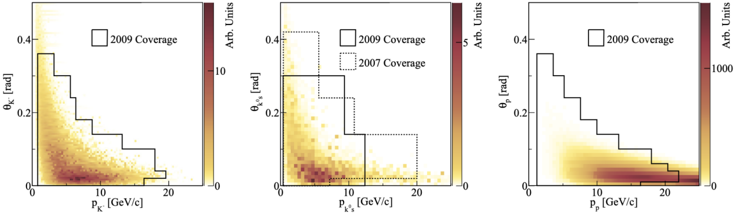
Phase Space Contributing to the Flux

- Most of the T2K phase space is covered by 2009/2010 NA61/SHINE replica target data, but some part is not covered
  - Additional data taken in 2022 + planned in future

Neutrino mode



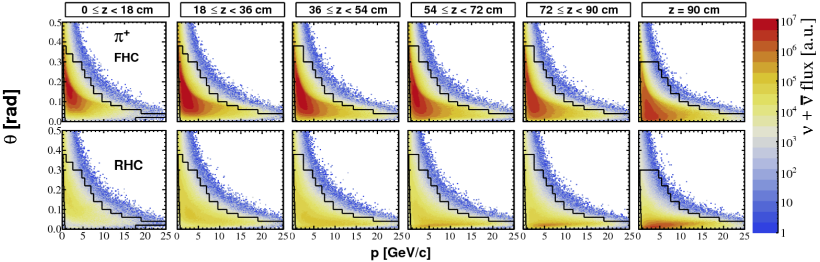
(a) π^+ **(b)** π^- **(c)** K^+

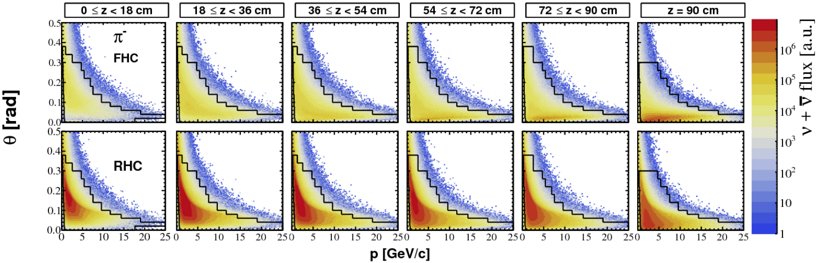


(d) K^- **(e)** K^0_S **(f)** proton

Phase Space Contributing to the Flux

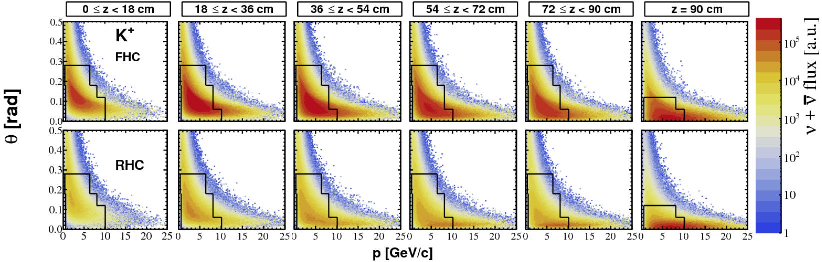
- 2010 NA61/SHINE replica target pion data coverage

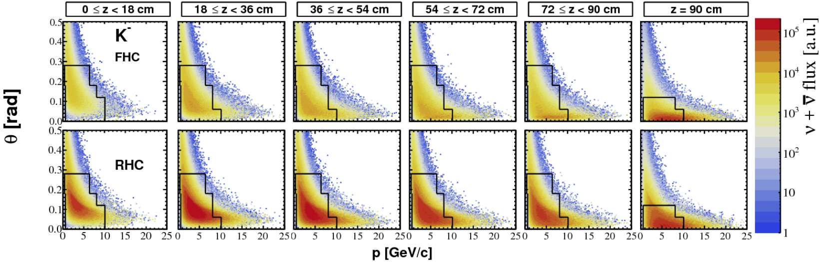




Phase Space Contributing to the Flux

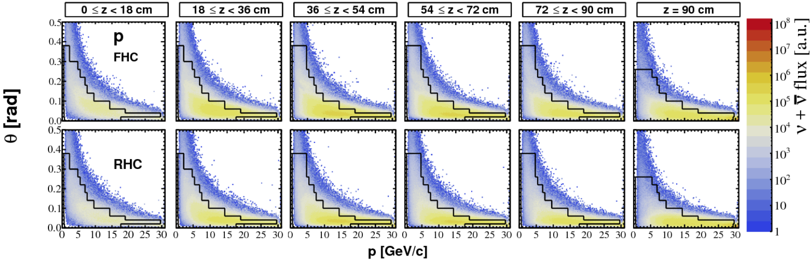
- 2010 NA61/SHINE replica target kaon data coverage





Phase Space Contributing to the Flux

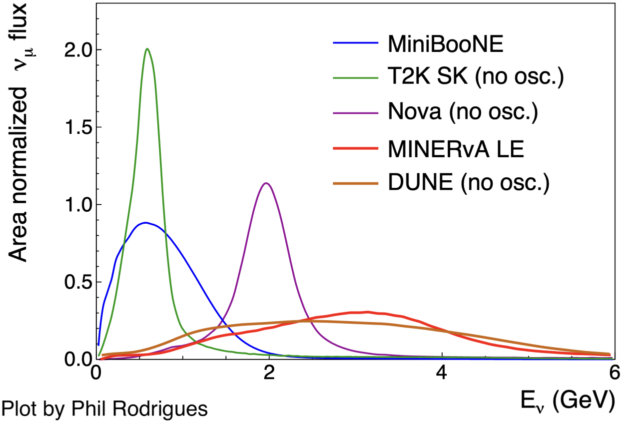
- 2010 NA61/SHINE replica target proton data coverage



Predicted Neutrino Fluxes

- So, putting all of these parts together, can predict the expected neutrino flux..

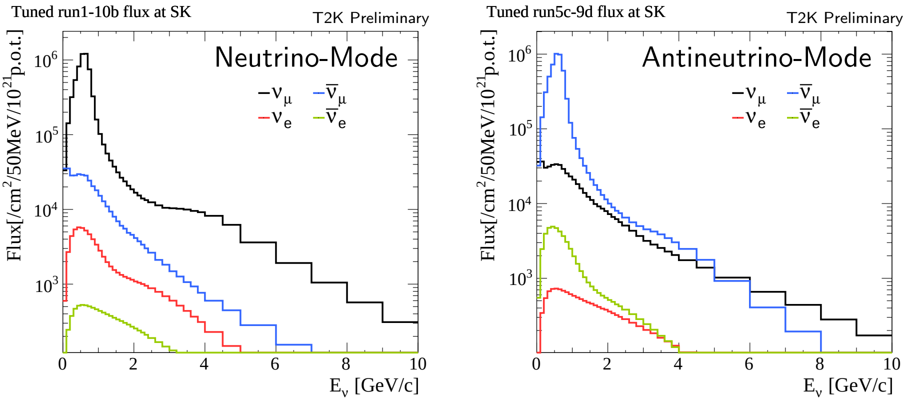
Example Accelerator Neutrino Fluxes



Plot by Phil Rodrigues

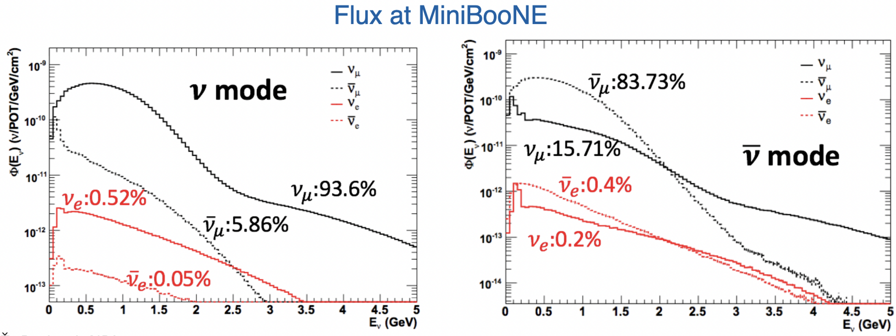
- Various accelerator neutrino fluxes used for various experiments
- Fluxes tend to peak around 0.5∼a few GeV
- Can tune the width of the energy spectrum based on the off-axis angle and target/horn configuration

Neutrino Flux at T2K



- 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

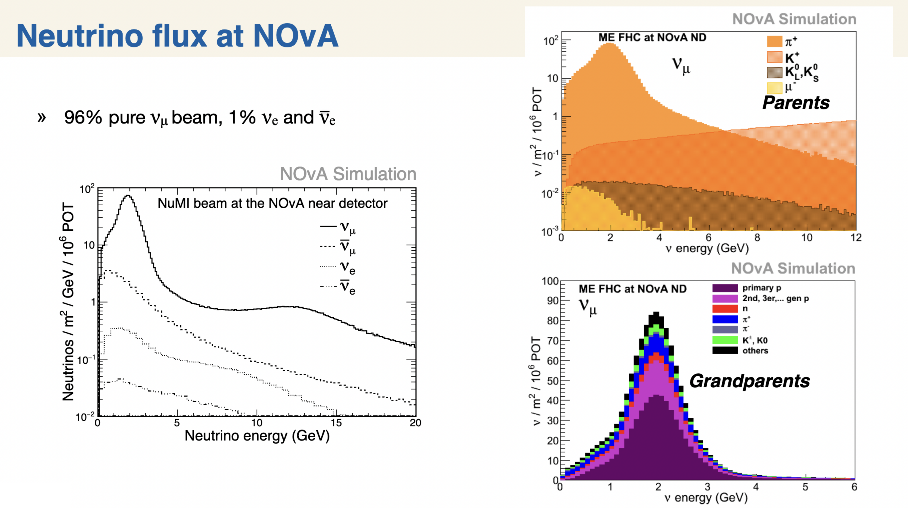
Neutrino Flux at MiniBooNE



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

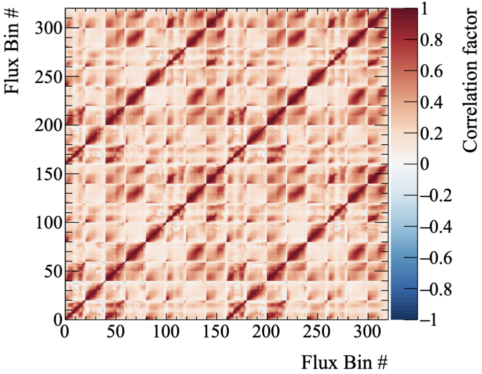
- 96% pure ν_μ beam, 1% ν_e and $\bar{\nu}_e$

L. Aliaga, NA61/SHINE LowE Workshop 2020

Calculating Flux Errors

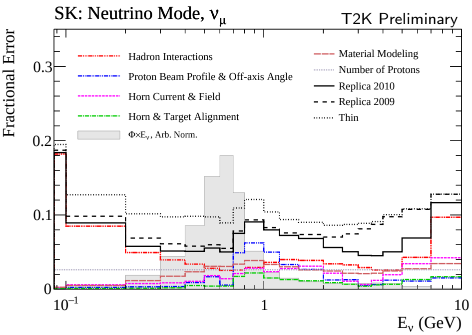
- Flux errors are calculated by re-running or weighting simulation results based on the assigned systematic error on each parameter
    - For T2K in-target hadron production errors, systematic error matrix is provided by NA61
        - Propagate uncertainties to the flux prediction by generating (100) throws from this matrix and tuning the flux using modified NA61/MC weights
    - For T2K out-of-target hadron production errors, systematic errors assigned from fits to various external datasets
        - Often large errors
    - For hardware errors, need to re-run the simulation while varying each systematic within the assigned error

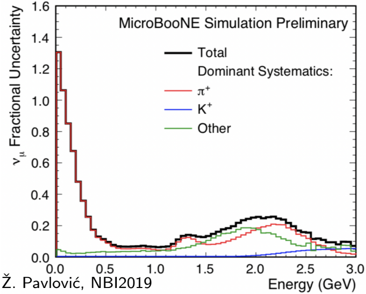
Example Flux Error Systematic Error Covariance Matrix



- T2K flux error covariance matrix with binning:
  - Each flux component has 20 bins in the order ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$,
  - For ND280 ν-mode (0–79), $\bar{\nu}$-mode (80–159)
  - Super-K ν-mode (160–239), and $\bar{\nu}$-mode (240–319)

Example Flux Errors – Where We Are Now

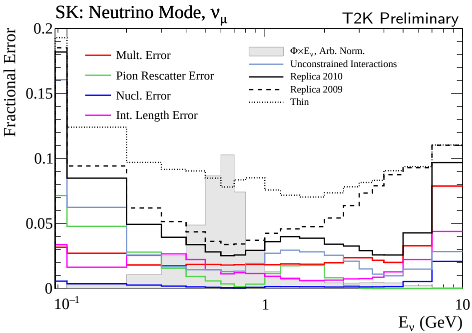


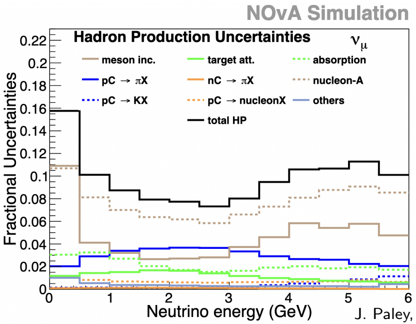


Ž. Pavlović, NBI2019

- 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
- 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

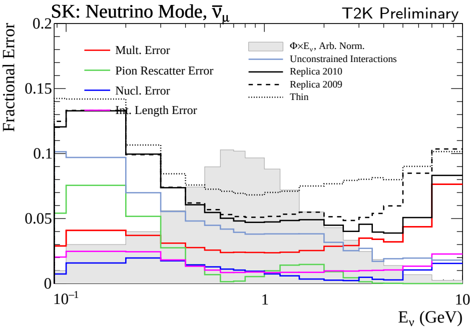


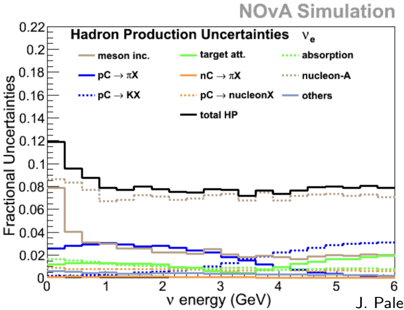


J. Paley,
NBI2019

- 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

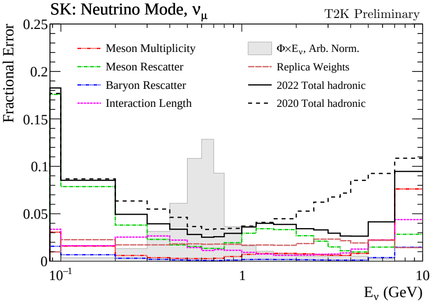




J. Paley, NBI2019

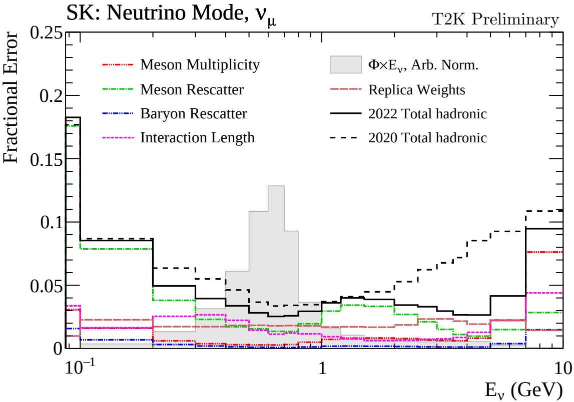
- These unconstrained and out-of-target secondary interactions are even more of an issue for the wrong-sign neutrino flux and beam intrinsic electron neutrino flux

T2K Hadron Production Flux Errors



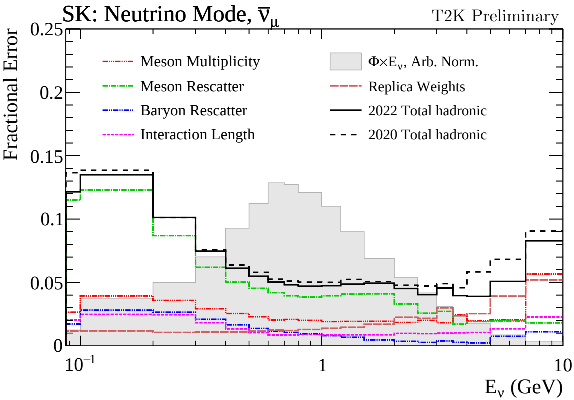
- Meson Multiplicity: propagated from NA61 thin-target based tuning
- Meson Rescatter: all rescattering processes that produce pions – predominantly $\pi^+ \to \pi^+$ on water, other non-negligible contribution from $\pi^- \to \pi^+$ and $p \to \pi^+$ (for right sign, RHC)
- Baryon Rescatter: all rescattering processes that produce baryons, primarily protons
- Interaction Length: predominantly proton production cross-section
- Replica Weights: multiplicity uncertainty for hadrons tuned by NA61 replica data

T2K Hadron Production Flux Errors



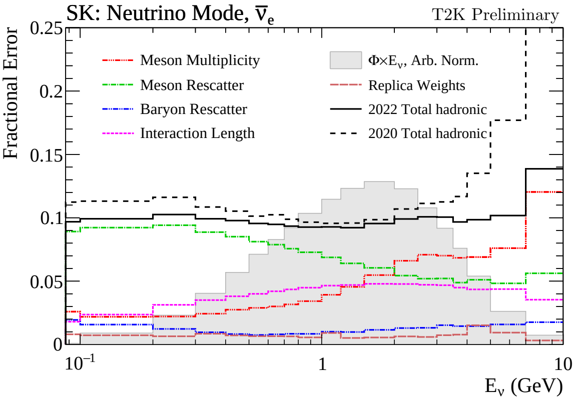
- Errors at high energy significantly reduced 2020 → 2022 due to inclusion of new high-statistics NA61 2010 kaon dataset
- Hadron production errors at the flux peak are coming from numerous relatively small sources – non-trivial to reduce
- Interactions not constrained by external measurements – Rescatter errors – are largest

T2K Hadron Production Flux Errors



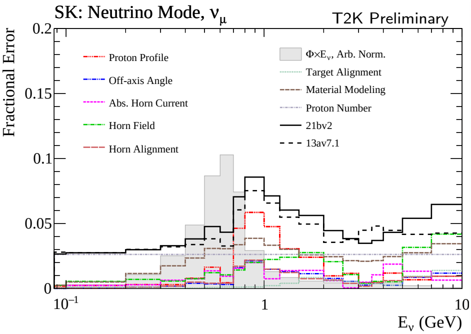
- Unconstrained and out-of-target secondary interactions are even more of an issue for the wrong-sign neutrino flux and beam intrinsic electron neutrino flux

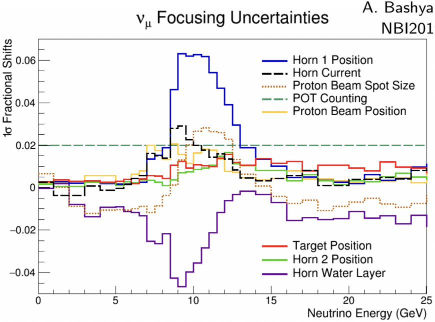
T2K Hadron Production Flux Errors



- 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

Example Non-Hadron Production Errors – Where We Are Now



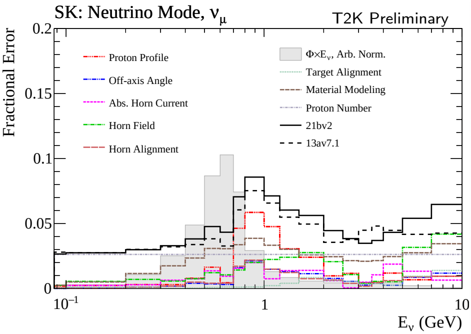


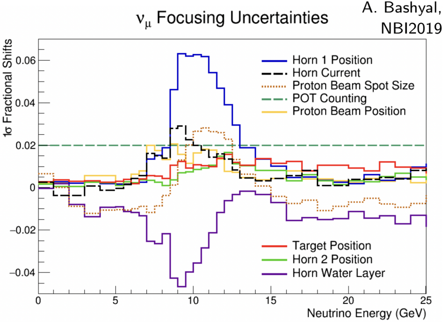
A. Bashyal, NBI2019

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

Example Non-Hadron Production Errors – Where We Are Now

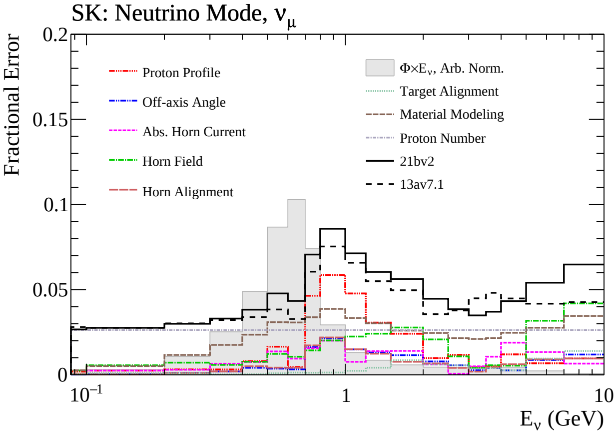




Medium Energy neutrino flux at MINERvA/on-axis detector

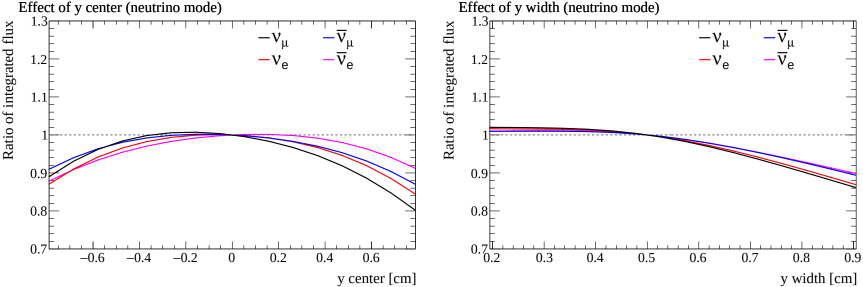
- At T2K, largest contribution is from proton beam profile and then material modeling (horn cooling water layer)
- At MINERvA, largest contributions are from Horn 1 position and horn water layer

Proton Profile Uncertainty



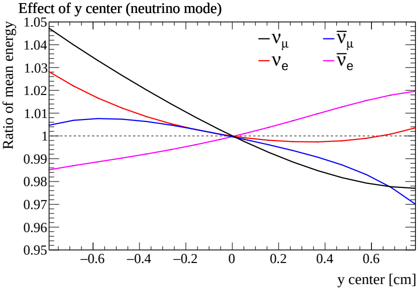
- For T2K, main non-hadronic flux error is coming from proton beam profile uncertainties
  - Uncertainty on the beam position at the target leads to an uncertainty on the beam off-axis angle
  - Directly shifts the shape of the flux peak

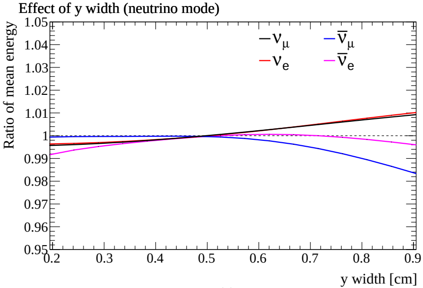
Effect of Shifting the Proton Beam



- Shifting the proton beam center has the largest effect on the flux
  - Other parameters not shown (θ, ϵ, Twiss α) have very small impact
- Proton beam is Gaussian
  - Number of protons hitting the target is reduced when beam moves away from target center $\rightarrow$ flux decreases
- Weak correlation between particle exiting position and exiting azimuthal angle
  - Because re-interaction probability changes with amount of matter traversed
- Exiting azimuthal angle has strong influence on neutrino energy
  - Because horn focusing is not perfect

Effect of Shifting the Proton Beam





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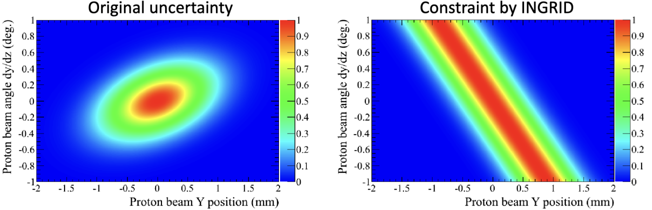
Off-Axis Angle Uncertainty

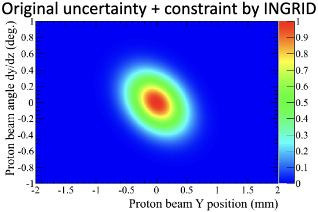


Original uncertainty

Constraint by INGRID

Proton beam measurement and INGRID neutrino beam measurement are correlated

Can use INGRID constraint to reduce uncertainties on proton beam profile

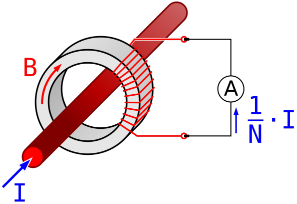


Original uncertainty + constraint by INGRID

- At T2K, we also measure the off-axis angle using the on-axis INGRID neutrino detector
- That data is correlated with proton beam position data, so should be able to constrain the "proton profile" errors with neutrino data
- Working now to update/improve this at T2K

Proton Beam Intensity Uncertainty

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



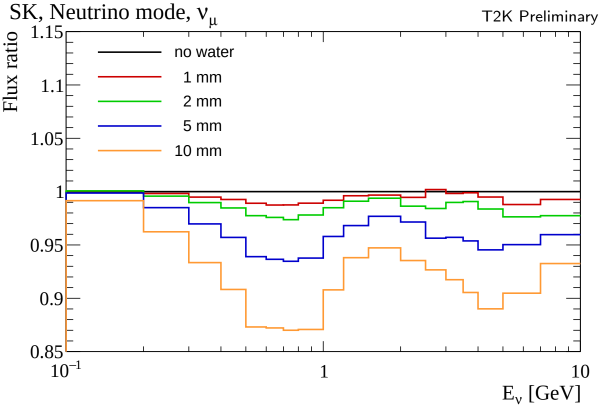
- Uncertainty on the proton beam intensity yields flat uncertainty on the neutrino rate
- Proton beam intensity is measured by Current Transformer (CT) mounted on the beam pipe
  - Beam intensity is proportional to current in wire wound around CT core
- Currently assign 2∼3% error on beam intensity
-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

Material Modeling Uncertainty – Horn Cooling Water

- Focusing horns are cooled by water sprayed between inner and outer conductors
- Main contribution to material modeling error at J-PARC

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

Material Modeling Uncertainty – Horn Cooling Water



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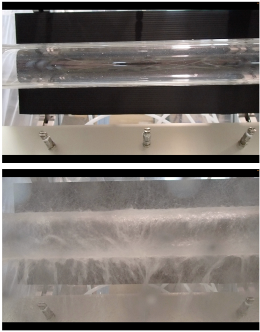
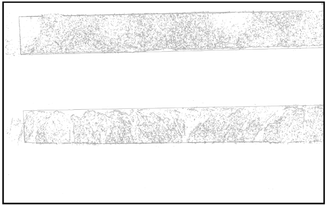
Horn Water Measurement at J-PARC





Overlay

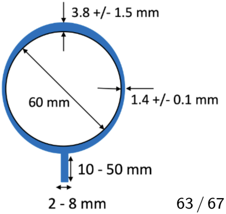
Made mockup of actual horn inner conductor

Analyze photos of mockup horn w/ and w/out water, determine water thickness using Canny method

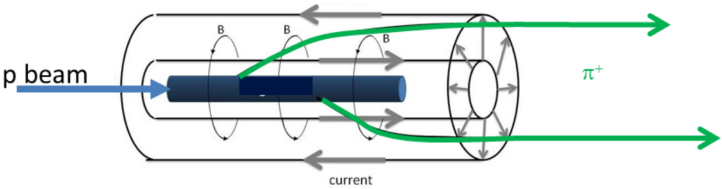
S. Nishimori @NBI2022

- Improved measurement of the horn cooling water layer completed – to be implemented the next version of the T2K flux analysis
  - Significantly reduce errors:

Energy range	Symmetry	New distribution
0 – 2 GeV	+2.4 % / -2.5 %	**+1.5 % / -1.5 %**
0.4 – 0.8 GeV	+2.8 % / -2.8 %	**+1.5 % / -1.6 %**



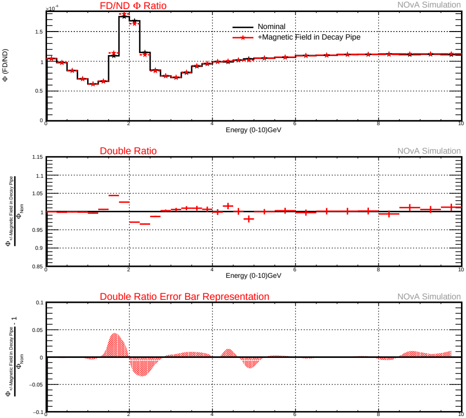
Horn Field Corrections



- 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



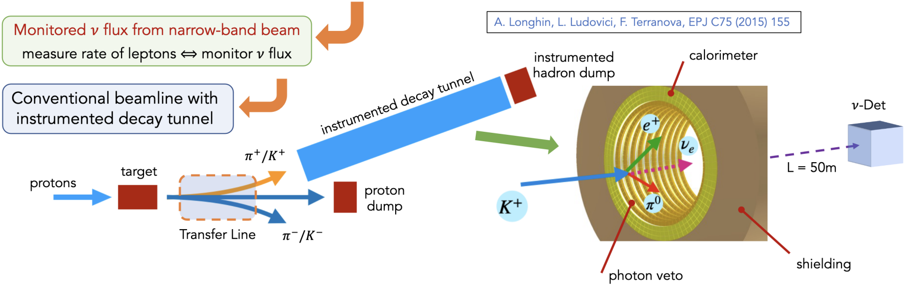
Plot from
Linda Cremonesi

- 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

Instrumented Decay Volume – ENUBET

How do we achieve such a precision on the neutrino cross-section, flavor composition and energy?



Monitored ν flux from narrow-band beam

measure rate of leptons ⇔ monitor ν flux

Conventional beamline with instrumented decay tunnel

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

A. Branca, TAUP 2023

- Instrumented decay volume for precise measurement of decay products – tagged neutrino beam
- Challenging due to extremely messy environment in decay volume, weakly interacting neutrino
- ENUBET prototype beam test completed (!)

Conclusion

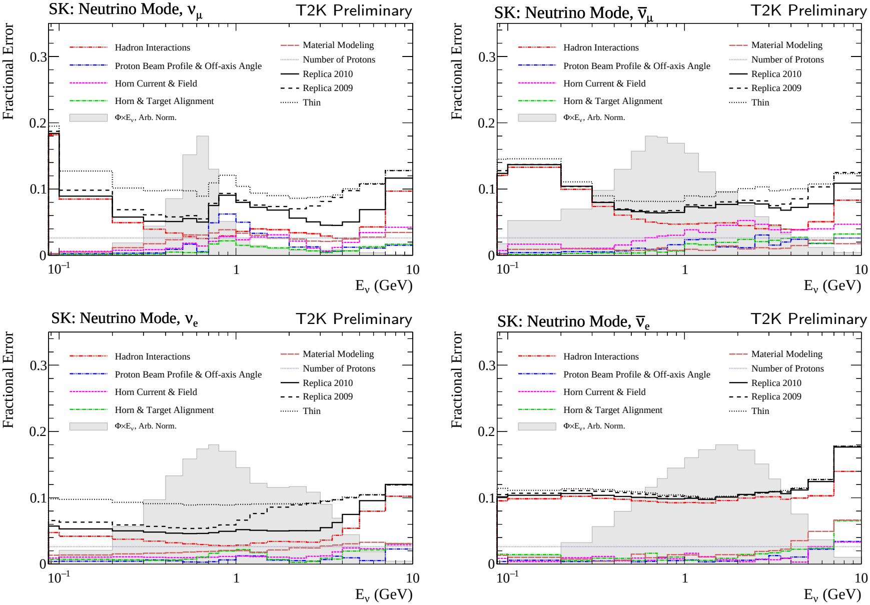
- Conventional neutrino beam flux simulation:
  - Based on measurements of actual beamline equipment
  - Hadron production is tuned to data from dedicated external experiments

- Systematic errors on the flux:
  - Energy dependent, 5$\sim$10%

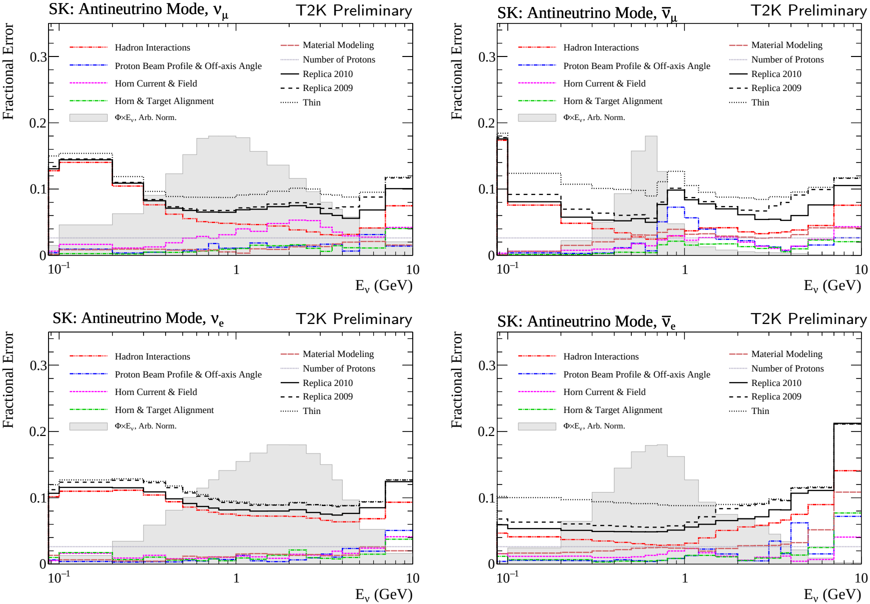
- Expect further future improvements on the flux errors:
  - Reduction of beamline hardware errors from improved understanding of beamline components
  - Additional hadron production measurements, with higher statistics
    - Especially, lower momenta pion and kaon measurements on different materials, to constrain out-of-target interactions

Backup Slides

T2K Neutrino-Mode Flux Errors



T2K Antineutrino-Mode Flux Errors



SK: Antineutrino Mode, ν_μ

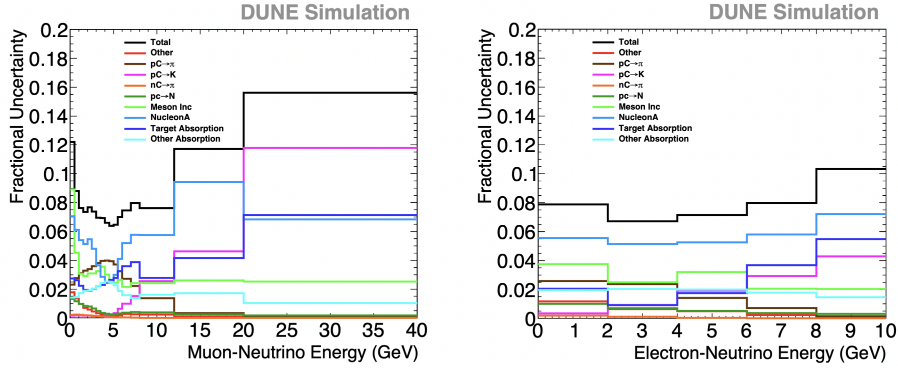
SK: Antineutrino Mode, $\bar{\nu}_\mu$

SK: Antineutrino Mode, ν_e

SK: Antineutrino Mode, $\bar{\nu}_e$

DUNE Flux Uncertainties from Hadron Production

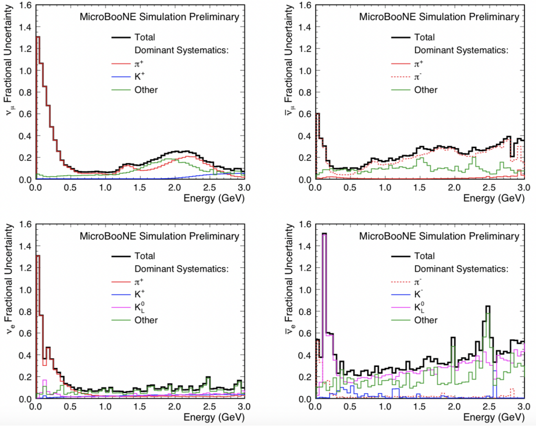
J. Paley, NBI2019

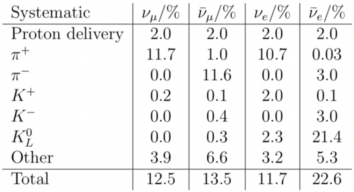


- Dominant flux uncertainties come from 40% xsec uncertainties on interactions in the target and horns that have never been measured (or have large uncertainties/spread)
- Lack of proton and pion scattering data at lower beam energies

Neutrino Flux Uncertainties at MicroBooNE

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



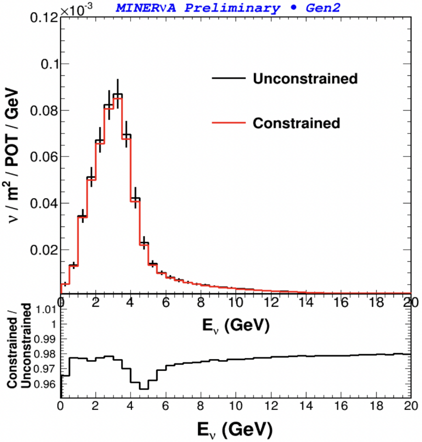


Systematic	$\nu_\mu/\%$	$\bar{\nu}_\mu/\%$	$\nu_e/\%$	$\bar{\nu}_e/\%$
Proton delivery	2.0	2.0	2.0	2.0
π^+	11.7	1.0	10.7	0.03
π^-	0.0	11.6	0.0	3.0
K^+	0.2	0.1	2.0	0.1
K^-	0.0	0.4	0.0	3.0
K^0_L	0.0	0.3	2.3	21.4
Other	3.9	6.6	3.2	5.3
Total	12.5	13.5	11.7	22.6

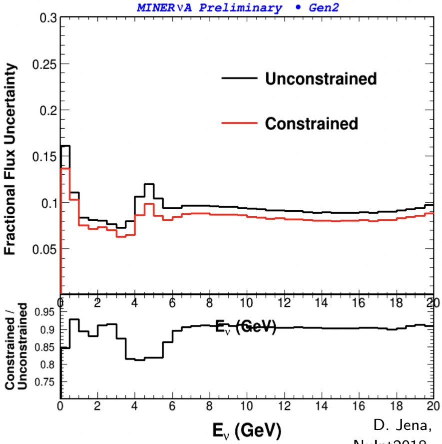
Ž. Pavlović, NBI2019

Constraining the Flux by Neutrino-Electron Scattering

Flux change after ν-e constraint



Fractional Uncertainty change after ν-e constraint



D. Jena,
NuInt2018

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