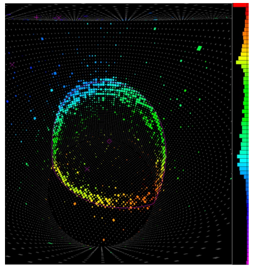
J-PARC neutrino beam performance, monitoring and flux prediction, constrains and uncertainties

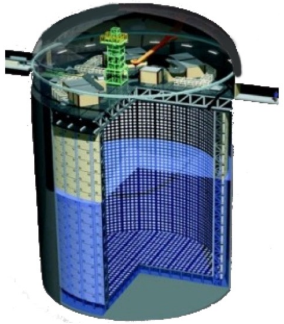
April 16th, 2024

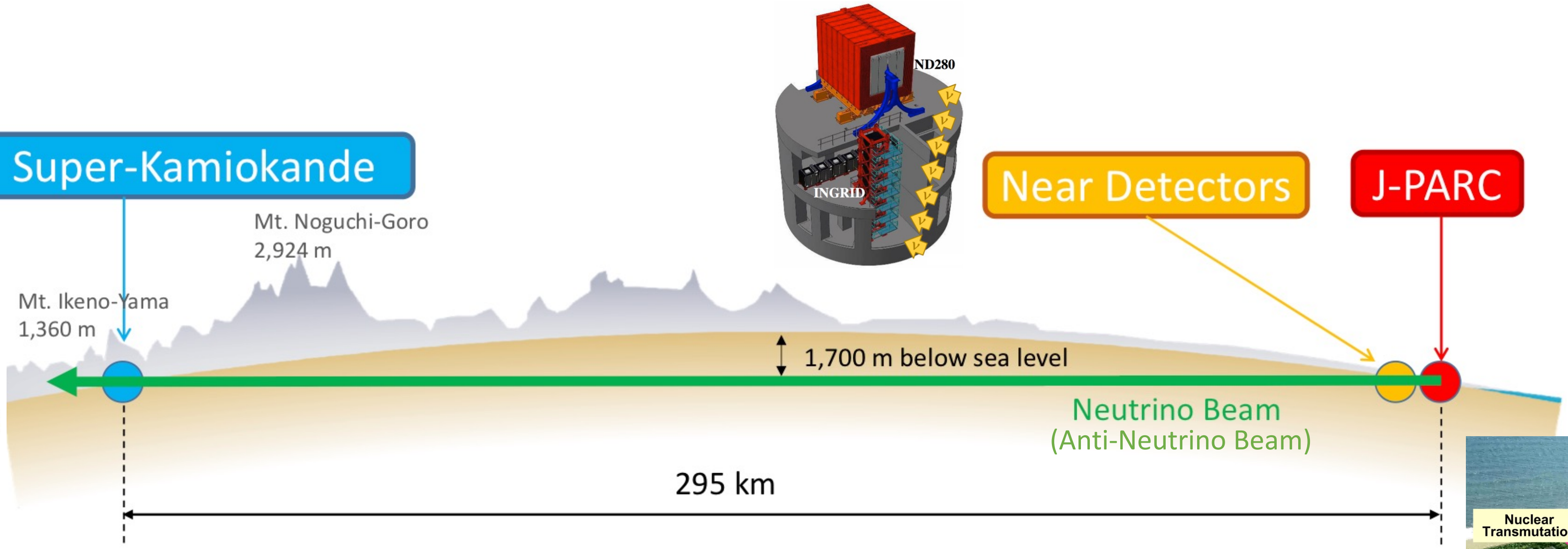
Lucas N Machado, on behalf of the T2K Collaboration

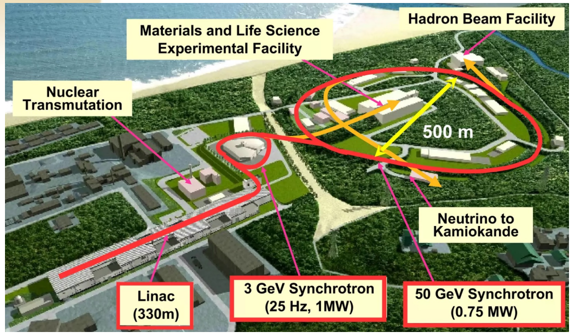
The T2K Experiment

T2K (Tokai-to-Kamioka) is a long baseline neutrino experiment in Japan. A neutrino beam is produced at the accelerator facility at the Japan Proton Accelerator Research Center (J-PARC) and travels from the east to west coasts of Japan to the Super-Kamiokande detector.







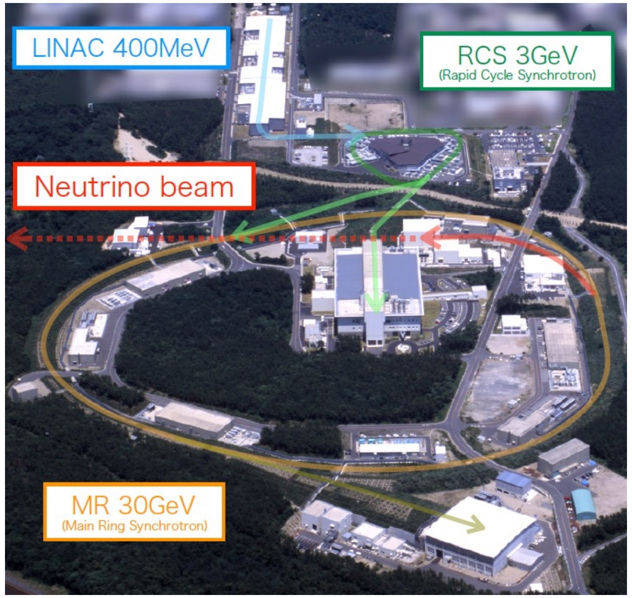


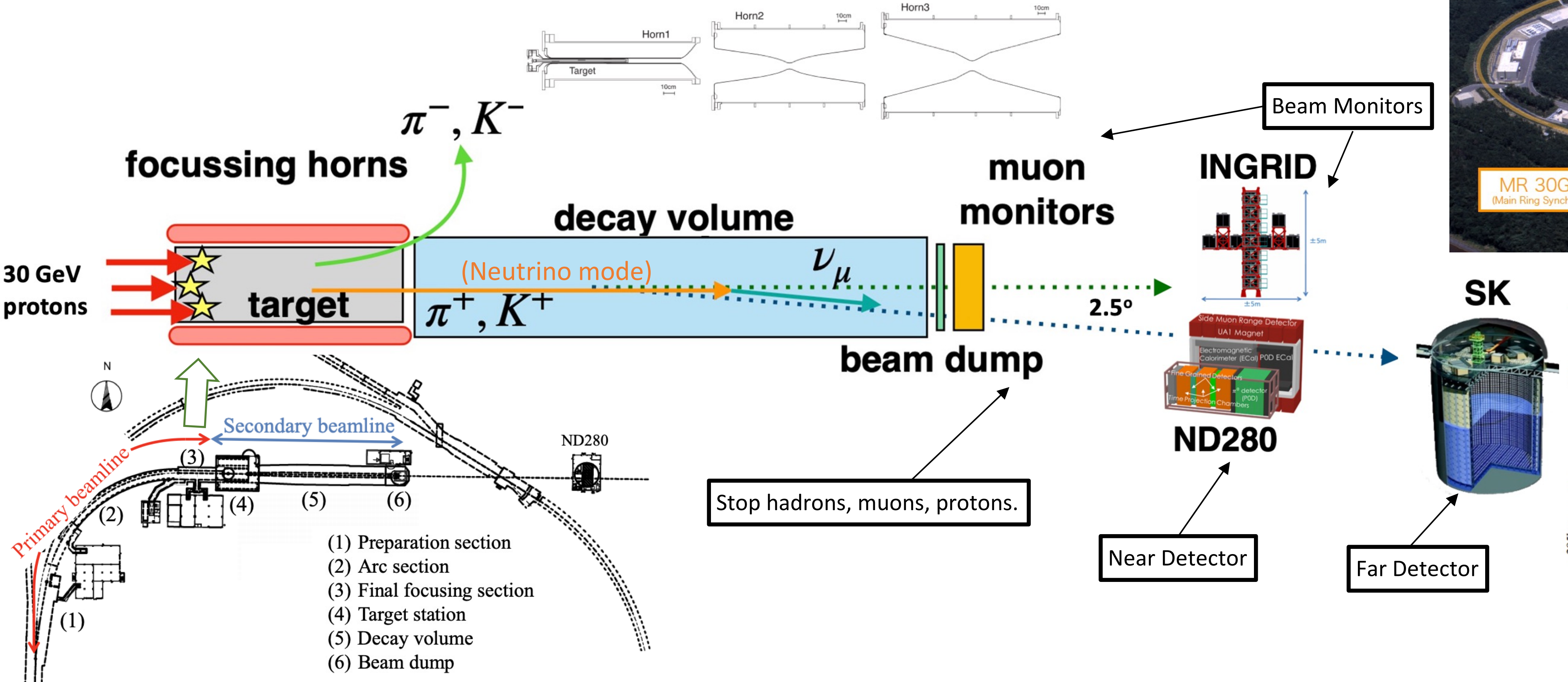
T2K studies the oscillation of neutrinos, observing the disappearance of ν_μ and appearance of ν_e by measuring the beam 280 m after production at the near detector ND280 and further away (295 km) at the far detector Super-Kamiokande.

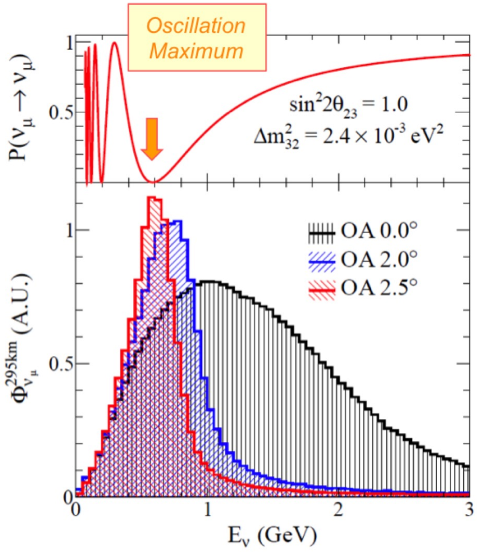
J-PARC Neutrino Beam

Neutrino beam production is done using a 30 GeV proton beam from the J-PARC MR accelerator incident on a carbon target, which produces a secondary hadron beam.

Hadrons are focused by three magnetic horns (sets neutrino/antineutrino mode) and eventually decay into neutrinos in a decay volume (100 m long).

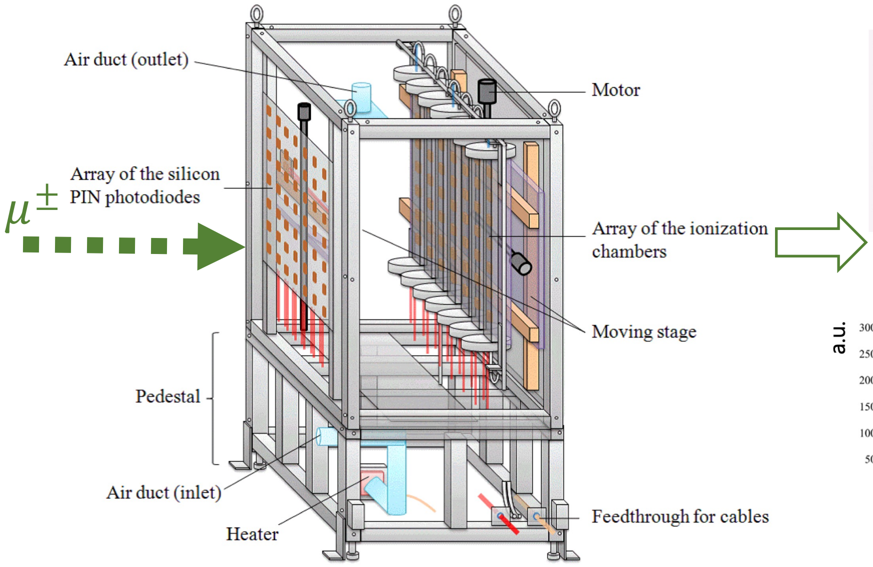


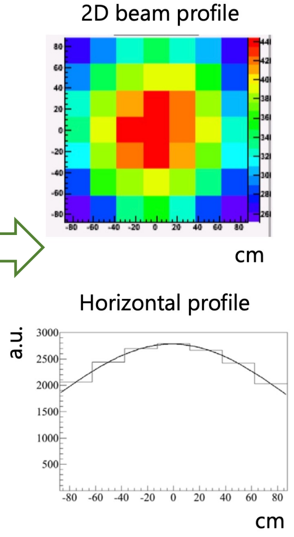




Beamline Monitors

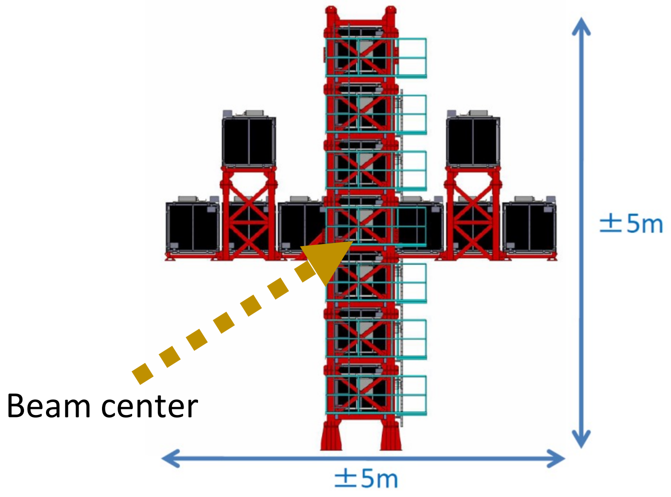
MUMON (Muon Monitor):
- Installed downstream of the beam dump (muon pit)
- Measures intensity and profile of muons.
- Beam direction within 0.3 mrad.





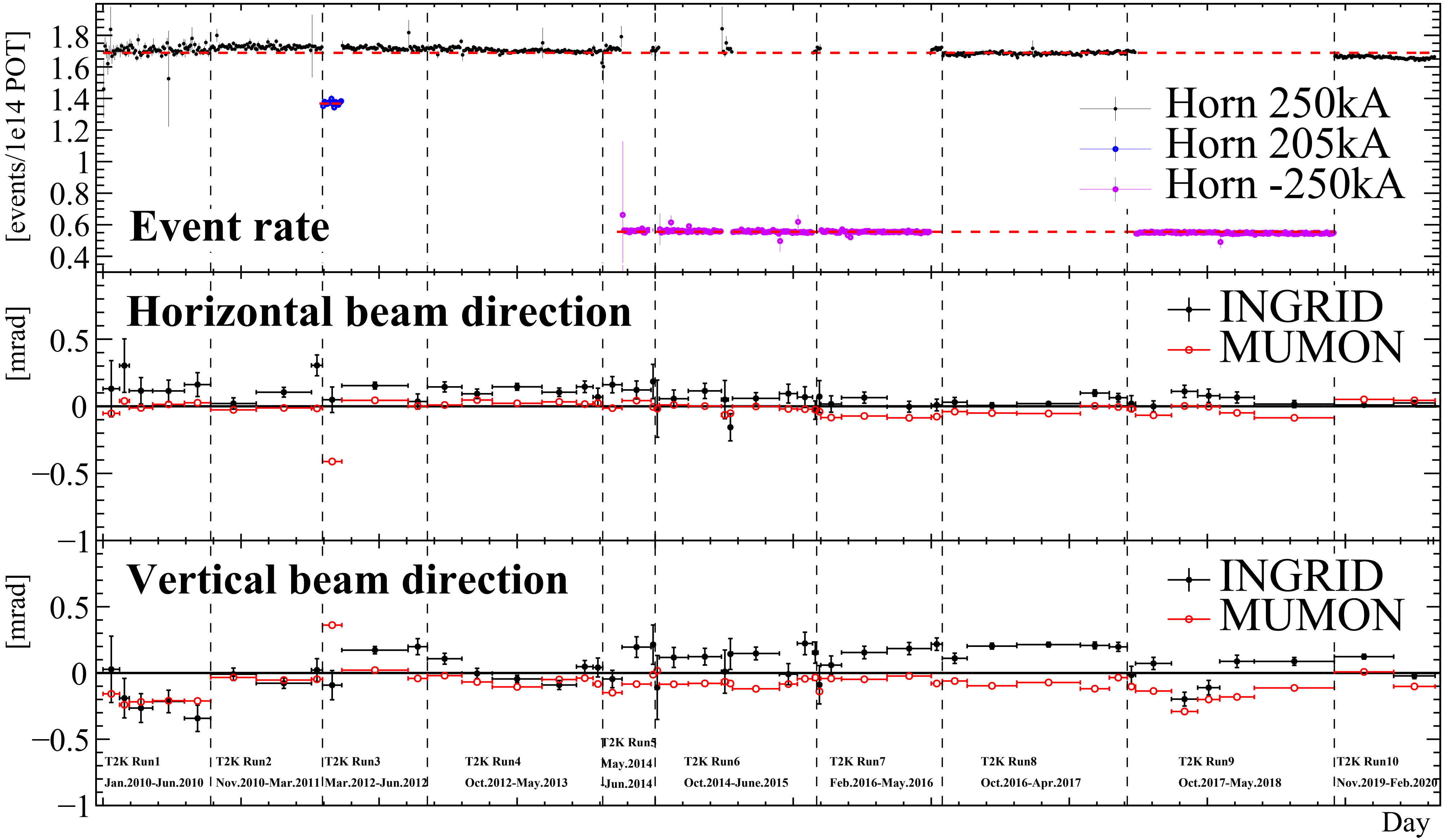
Ionization chambers and silicon sensors. Si sensors require frequent replacement. R&D underway for improved sensors.

On-axis near detector **INGRID** (Interactive Neutrino GRID) :
- Profiling detector.
- Monitors beam stability, intensity and direction.
- Interactions with iron and scintillators.



INGRID consists of 16 modules arranged in vertical and horizontal arrays and placed near the beam center.

Beamline Monitors



Beam direction within << 1mrad.

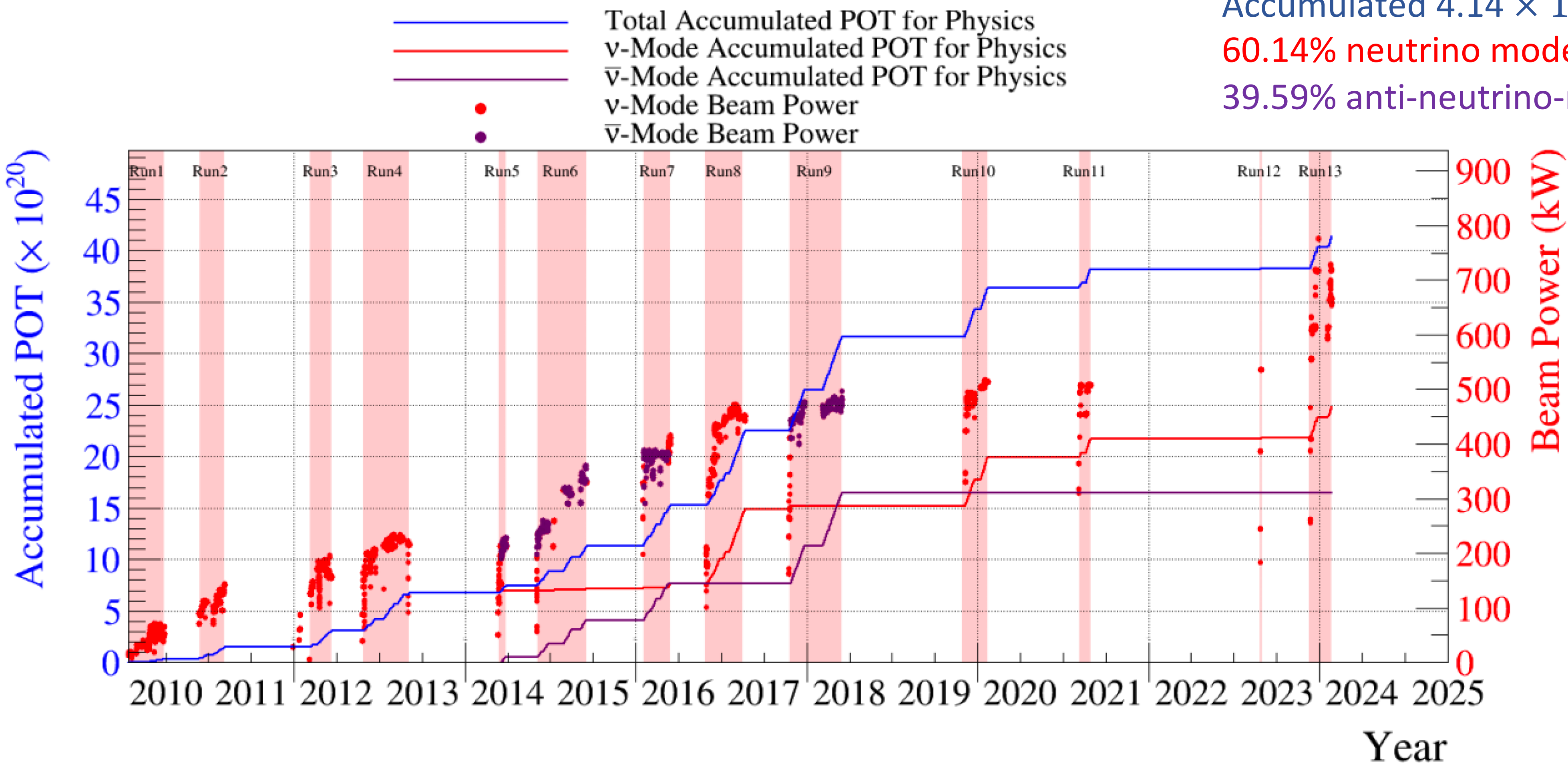
J-PARC Neutrino Beam History

From January 2010 to February 2024:

Accumulated 4.14×10^{21} protons on target (POT).

60.14% neutrino mode.

39.59% anti-neutrino-mode.

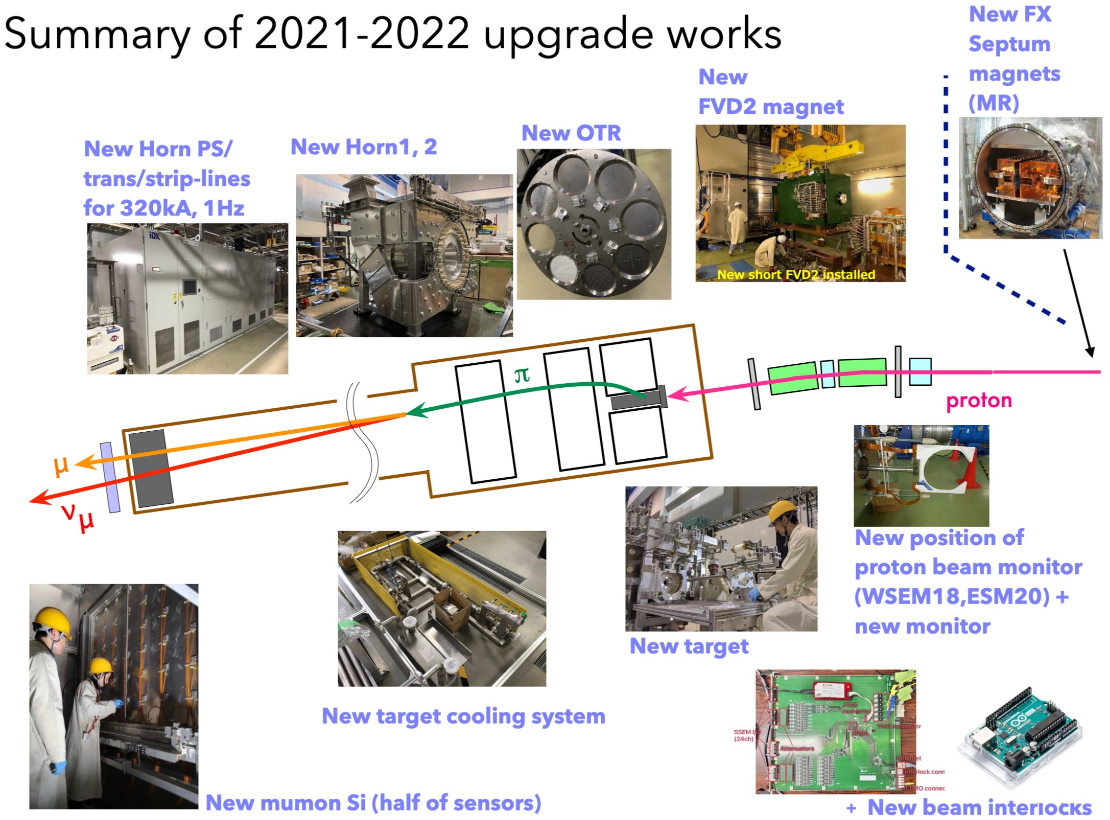


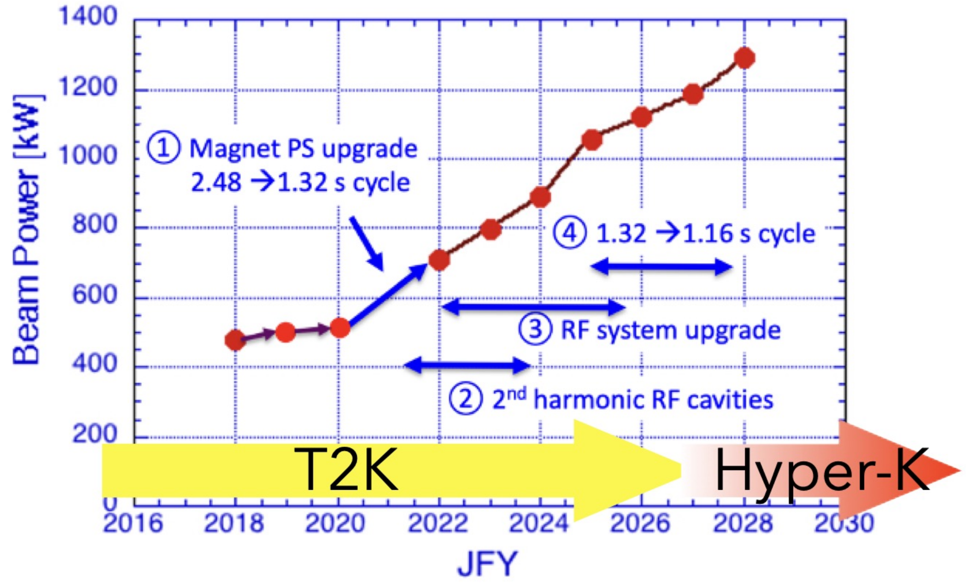
Maximum Power:
780.63 kW

J-PARC Beam Performance

Hyper-Kamiokande is currently under construction and will start data taking in 2027 -> upgraded neutrino beam.
Goal: 1.3 MW Beam Operation.

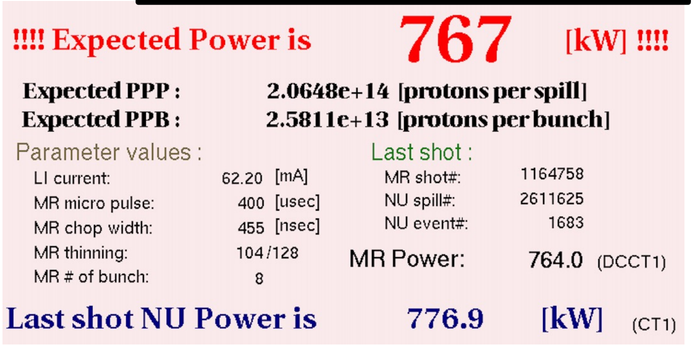
Summary of 2021-2022 upgrade works





arXiv:1908.05141

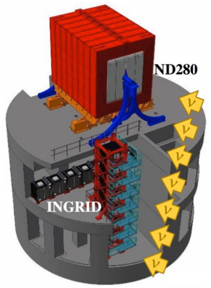
Beam at designed operation power in December 2023.



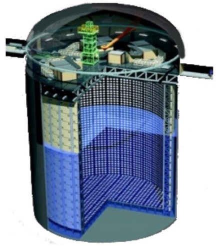
Each horn operates with a separate power supply and with increased current (250 -> 320 kA)
Faster cycling with increased power (500 kW, 2.48 s -> 750 kW, 1.32 s), delivering more protons per second.

T2K Flux Predictions (1)

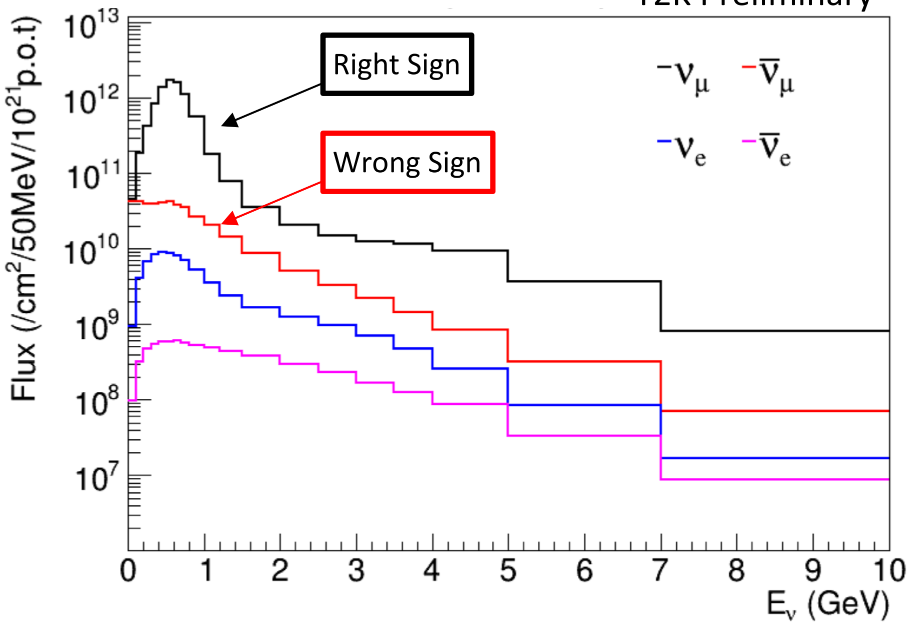
T2K needs to efficiently predict the neutrino fluxes at near and far detectors to measure various neutrino oscillation parameters such as mixing angles, mass differences and the CP-violating phase.



$$N_{\nu_e}^{SK} = P_{\nu_\mu \to \nu_e} \times \boldsymbol{\Phi_{\nu_\mu}^{SK}} \times \sigma_{\nu_e}^{SK}$$



$$N_{\nu_e}^{ND280} = \boldsymbol{\Phi_{\nu_\mu}^{ND280}} \times \sigma_{\nu_e}^{ND280}$$



Fluxes at the Near Detector (neutrino mode, 320 kA)

Need to produce and keep track of interactions producing neutrinos.

Uncertainties in hadronic production models

⇩

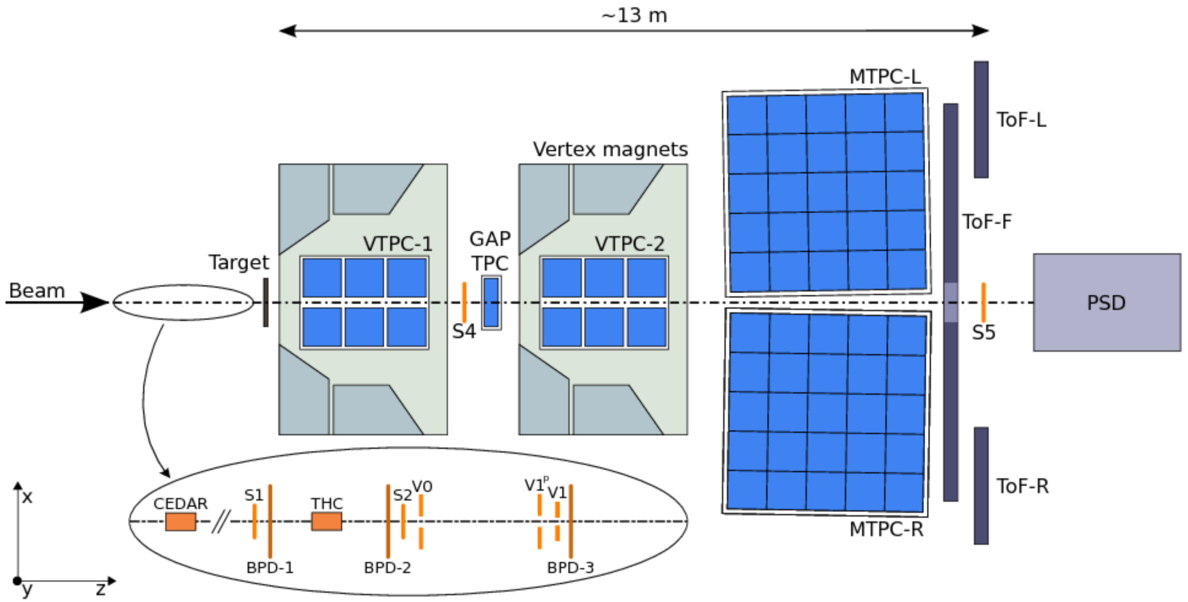
External data to constrain predictions

Flux percentage of each (all) flavor(s)

Parent	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0(55.6)%	41.8(2.5)%	31.9(0.4)%	2.8(0.0)%
$K^\pm$	4.0(3.7)%	4.3(0.3)%	26.9(0.3)%	11.3(0.0)%
K_L^0	0.1(0.1)%	0.9(0.1)%	7.6(0.1)%	49.0(0.1)%
Tertiary				
$\pi^\pm$	34.4(31.9)%	50.0(3.0)%	20.4(0.2)%	6.6(0.0)%
$K^\pm$	1.4(1.3)%	2.6(0.2)%	10.0(0.1)%	8.8(0.0)%
K_L^0	0.0(0.0)%	0.4(0.1)%	3.2(0.0)%	21.3(0.0)%

T2K Flux Predictions (2)

External data for neutrino flux constrains: hadron production experiment NA61/SHINE.

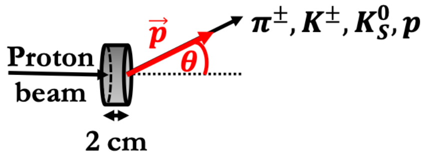


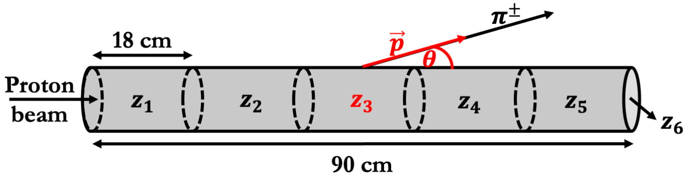
Schematic view of the NA61/SHINE experiment [3]

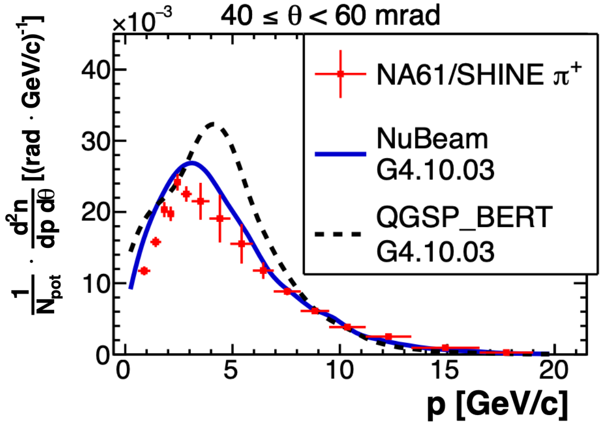
See Andrew's talk.

NA61/SHINE Measurements for T2K

Year	Target	Statistics	Outgoing PID	Reference
2007	Thin	0.7×10^6	$\pi^\pm, K^\pm, K_S^0, \Lambda$	[1]
2009	Thin	5.4×10^6	$\pi^\pm, K^\pm, K_S^0, \Lambda$	[2]
2007	Replica	0.2×10^6	$\pi^\pm$	[3]
2009	Replica	2.8×10^6	$\pi^\pm$	[4]
2010	**Replica**	$\mathbf{10 \times 10^6}$	$\boldsymbol{\pi^\pm, K^\pm, p}$	**[5]**







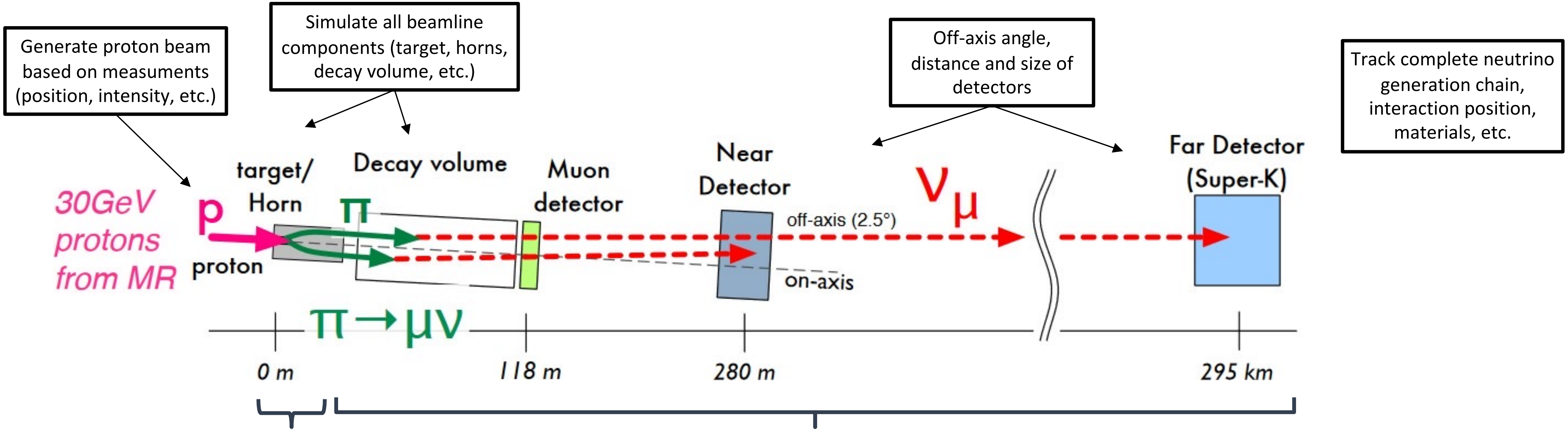
Double differential π^+ yields for upstream longitudinal bin of T2K replica target [5].

Other external datasets are used: Eichten et al. [6], Allaby et al. [7], BNL E910 [8].

NA61/SHINE took new replica target data in Summer 2022 (including K_S^0).

T2K Flux Predictions (3)

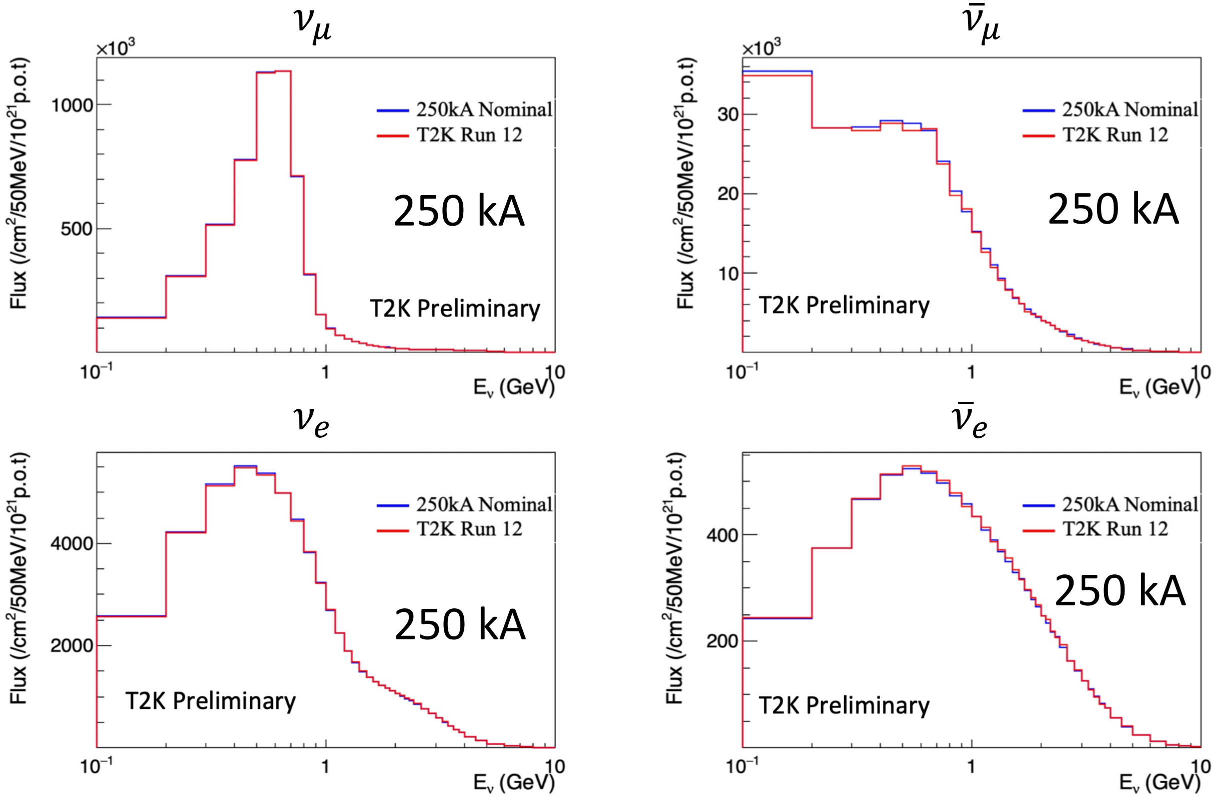
The Monte Carlo simulation, JNUBEAM, describing the physical processes producing neutrinos, is based on the simulation software GEANT3, and relies also on FLUKA for the description of hadronic interactions that are fed to GEANT3.



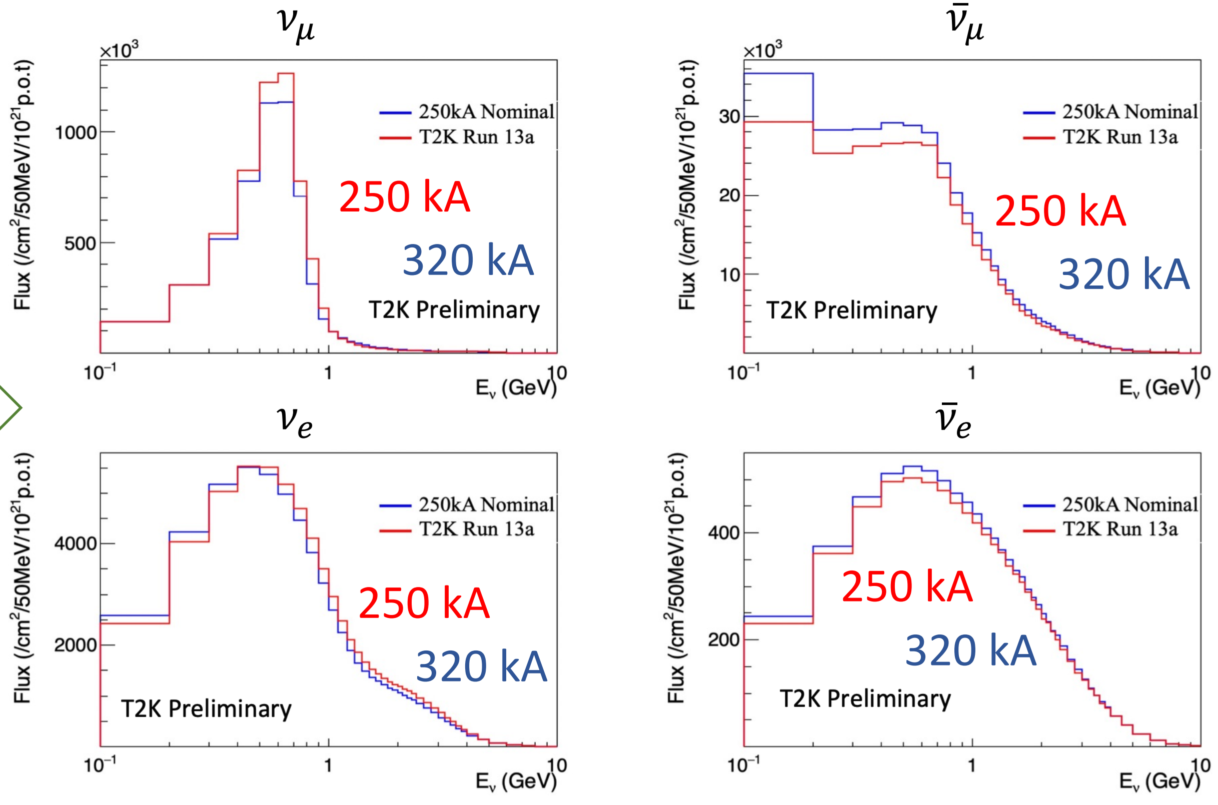
FLUKA: Hadronic interactions in the baffle/target → JNUBEAM: Tracking of particles exiting the target; neutrino production → Re-weighting using external data → **<u>Neutrino fluxes</u>**

T2K Flux Predictions (4)

Input parameters need to be carefully measured. Differences in flux with increase in the horn current:



Comparisons between nominal 250 kA with T2K Run 12 (~ 250 kA) with measured parameters.



Comparisons between nominal 250 kA with T2K Run 13a (320 kA) parameters.

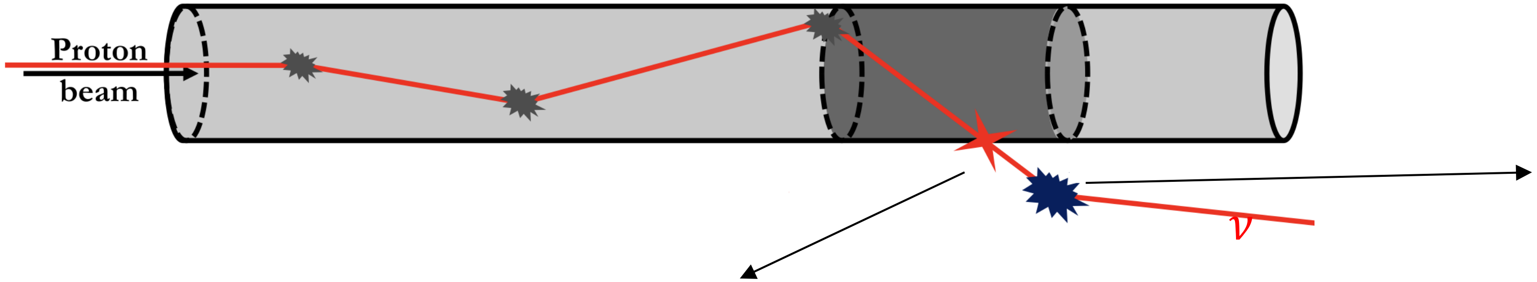
Nominal: standard beam profile (gaussian), horn current 250 kA.

T2K Run 12: April 2023, measured beam profile, horn current ~250 kA.

T2K Run 13a: November/December 2023, measured beam profile, horn current ~320 kA.

T2K Flux Predictions: Flux Tuning

One of the main systematic uncertainty sources of the neutrino flux predictions comes from the hadrons produced from the interactions of the proton beam with the target and re-interactions outside of the target in other beamline components.



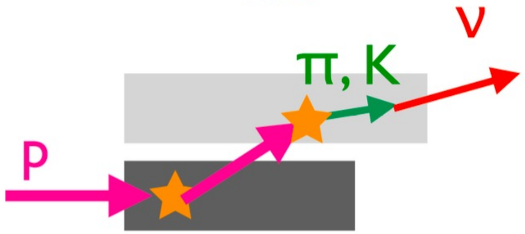
Out-of-target interactions:

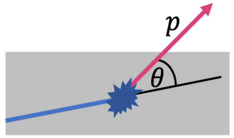
- Use other external datasets (material, particle, energy);
- Apply data/MC weight **scaling thin target measurements** (NA61/SHINE 2009).
- Attenuation weights (cross section) to account distance travelled through materials before interaction.

→ large uncertainties, unconstrained interactions.

In-target interactions:

Apply weight on exiting target particles based NA61/SHINE 2010 measurements from **replica target**.





$$weight(p,\theta) = \frac{\left[\frac{d^2n(p,\theta)}{dpd\theta}\right]_{data}}{\left[\frac{d^2n(p,\theta)}{dpd\theta}\right]_{MC}}$$

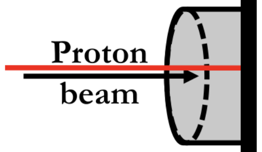
Re-interaction of low-momenta particles (e.g., horn cooling water) have large uncertainties in the wrong-sign neutrino flux.

Future measurements: NA61 low energy programme / EMPHATIC (talks later in this session)

NuInt 2018 – The T2K Flux Prediction (T. Vladisavljevic) (more detail)

T2K Flux Predictions: Flux Tuning

One of the main … uced from the
interactions of th … mponents.



In…
Apply weight …
NA61/SHINE 2010 …

…ets (material,

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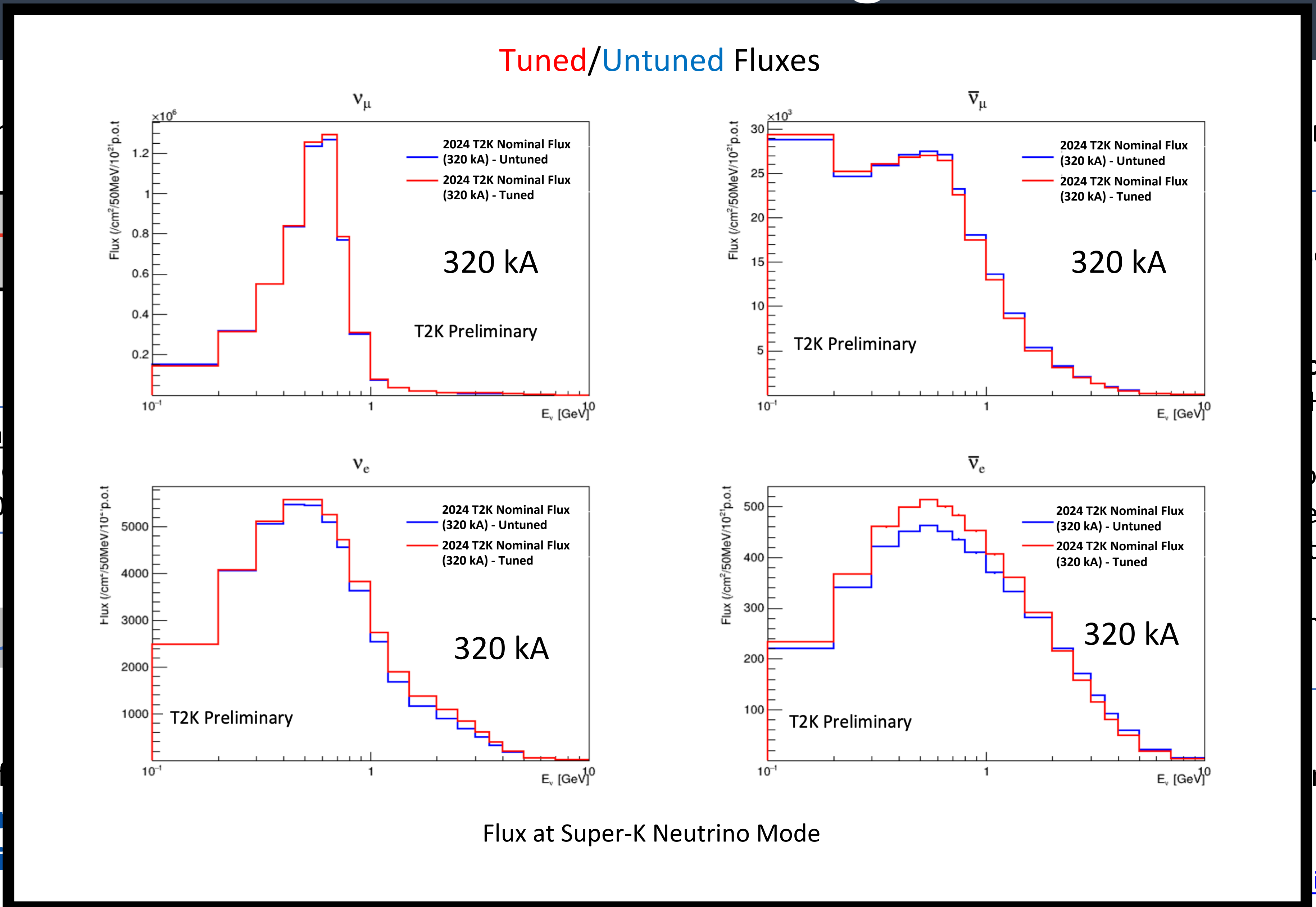


Re-interaction of … neutrino flux.

Future measure…
(talks later in thi…

…isavljevic) (more detail)

T2K Flux Predictions: Flux Errors

Total current flux errors are around ~5% near the flux peak (using NA61/SHINE 2010 replica target data).

- Previous: ~10% with NA61/SHINE 2009 replica target data.
- Also reduced at high energies (using NA61/SHINE 2010 replica target **kaon** data).

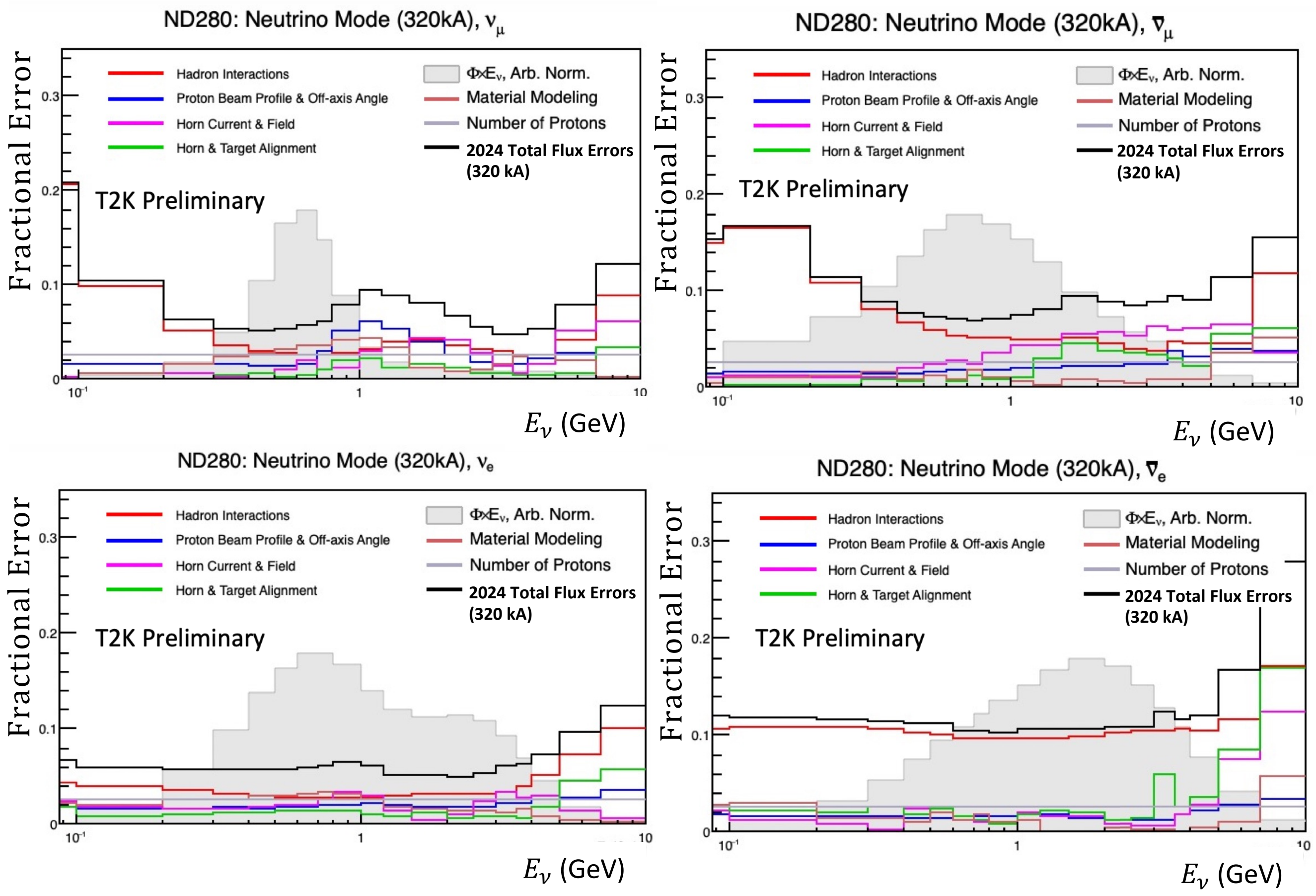
At higher and low energies:
significant contribution from hadron interaction uncertainties (π and K re-scattering)

Material modelling: now includes water distribution (significant impact on flux due to pion absorption/scattering)

Proton beam can be further constrained using INGRID measurements.

Horn/Target Alignment: beam optics improvements.

Total Errors



Flux prediction uncertainties vs neutrino energy in the neutrino mode for T2K, at the far detector.

T2K Flux Predictions: Flux Errors

Total current flux errors are around ∼5% near the flux peak (using NA61/SHINE 2010 replica target data).

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significant contribution from hadron interaction uncertainties (π and K re-scattering)

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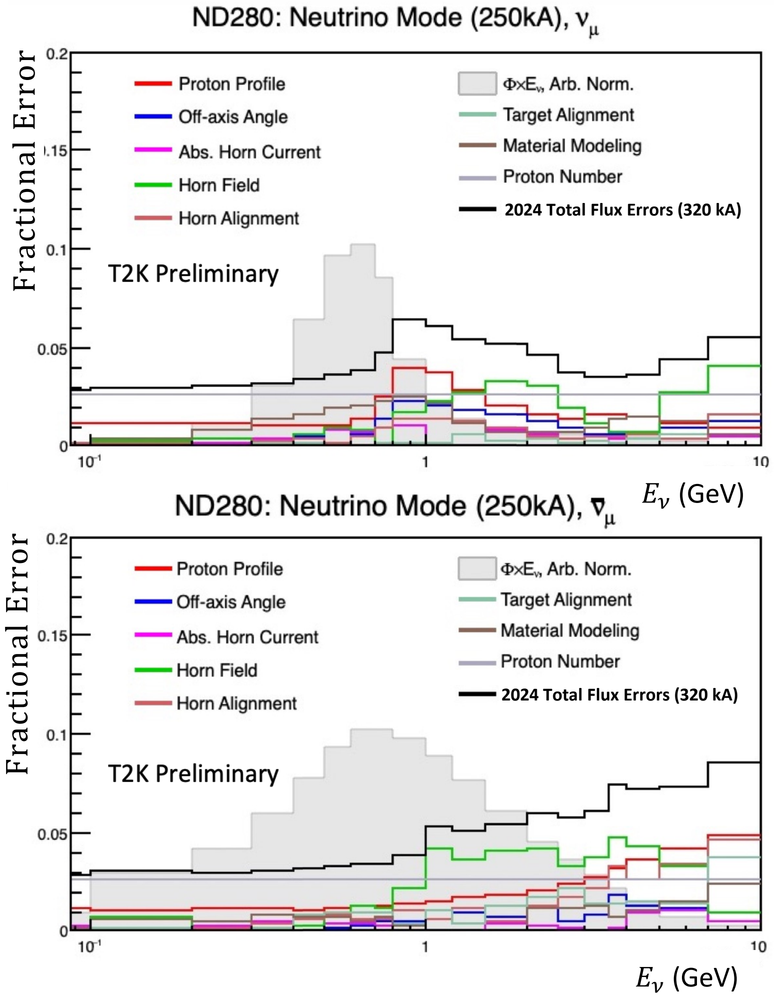
Proton beam can be further constrained using INGRID measurements.

Horn/Target Alignment: beam optics improvements.

Non-hadronic Errors

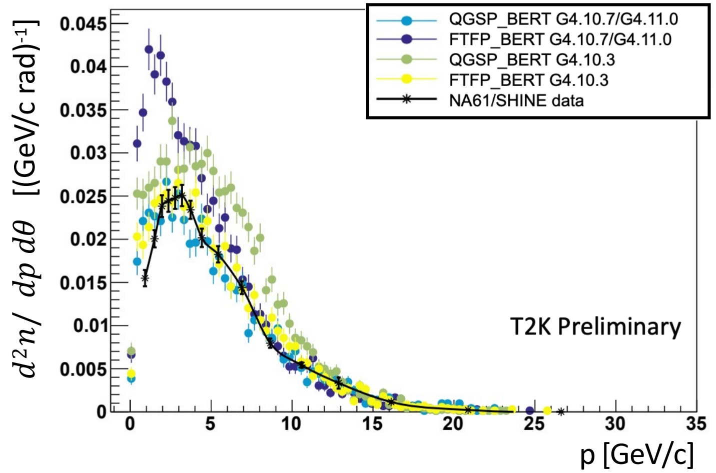


Flux prediction uncertainties vs neutrino energy in the neutrino mode for T2K, at the far detector.

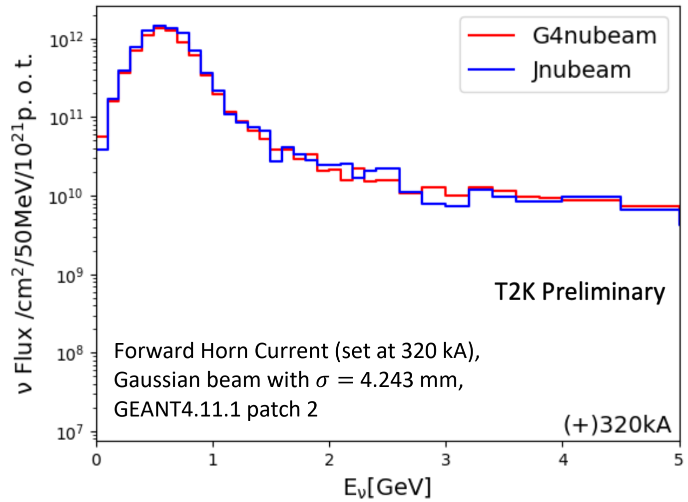
First 320 kA release: hardware related errors amplified.

GEANT4 Framework – G4JNUBEAM

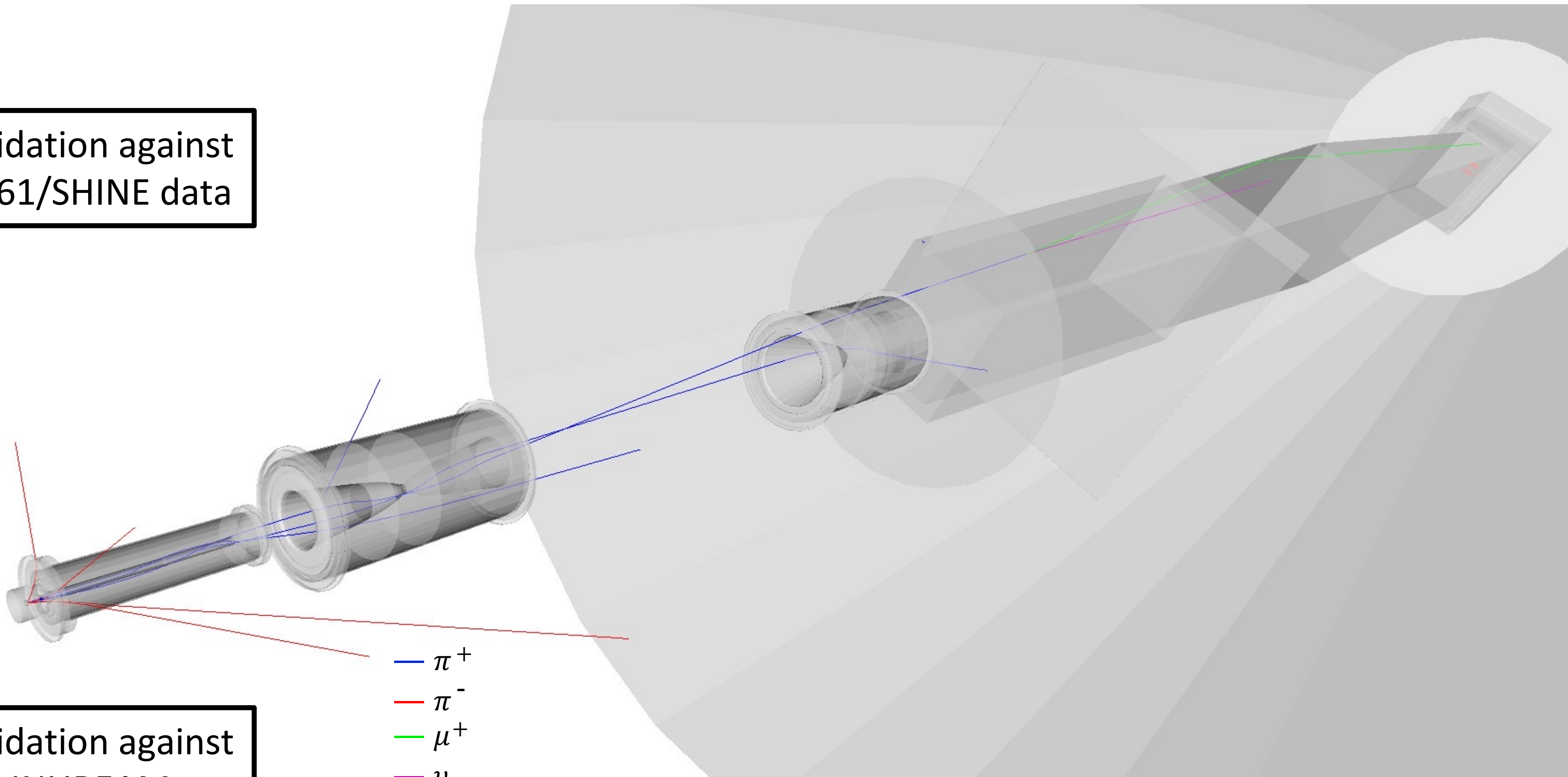
Under development: Monte Carlo simulation based on GEANT4, aiming to describe the physical processes from proton interactions in the target to the decay of hadrons and muons producing neutrinos.



Validation against NA61/SHINE data



Validation against JNUBEAM



Neutrino fluxes at the near detector

Outlook

The J-PARC Neutrino Facility provides the neutrino beam for the T2K experiment.

- 30 GeV protons from J-PARC acceleration interact with a carbon target producing hadrons and muons, which are focused/de-focused using three magnetic horns. These particles decay and produce a neutrino beam.
- Since January 2010, T2K has accumulated 4.14×10^{21} protons on target.

To precisely predict the neutrino fluxes at the near and far detectors, a simulation based on FLUKA and GEANT3 describing all the physical processes producing neutrinos is used (currently being upgraded to GEANT4).

- Due to the large uncertainties in hadronic production models, external data is used to constrain predictions.
- Total current flux errors are around $\sim$5% near the flux peak, which were previously reduced from $\sim$10% with replica target data from the NA61/SHINE experiment.

Systematic uncertainties can be limiting in HyperK-era, we need to improve both cross section and flux systematics.

- Using future hadron production measurements will help reduce further the flux uncertainties and constrain more interactions.
- In preparation for HyperK, beamline components are currently being upgraded.

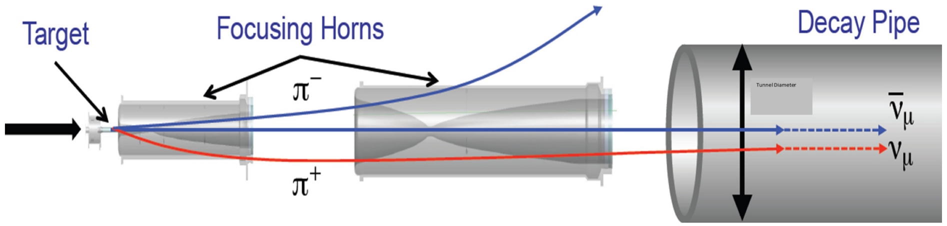
References

- [1] N. Abgrall et al. (The NA61/SHINE Collaboration), Phys. Rev. C 84, 034604.
- [2] N. Abgrall et al. (The NA61/SHINE Collaboration), The European Physical Journal C, 76(2), 1-49 (2016).
- [3] N. Abgrall et al. (NA61/SHINE), Nucl. Instrum. Meth. A 701, 99 (2013).
- [4] N. Abgrall et al. (The NA61/SHINE Collaboration), The European Physical Journal C (2016) 76: 617.
- [5] N. Abgrall et al. (The NA61/SHINE Collaboration), Eur.Phys.J.C 79 (2019) 2, 100.
- [6] T. Eichten et al., Nucl. Phys. B 44 (1972).
- [7] J. V. Allaby et al., High-energy particle spectra from proton interactions at 19.2 GeV/c, Tech. Rep. 70-12 (CERN, 1970).
- [8] I. Chemakin et al., Phys. Rev. C 77, 015209 (2008).

BACKUP

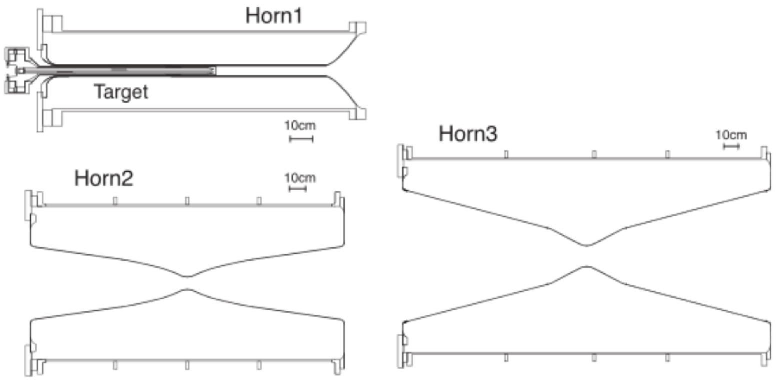
J-PARC Neutrino Beam

The T2K target is 900 mm long graphite rod (around two interaction lengths) placed inside of the first magnetic horn. Graphite is surrounded by a titanium case and temperature is controlled by allowing helium to flow around the target.

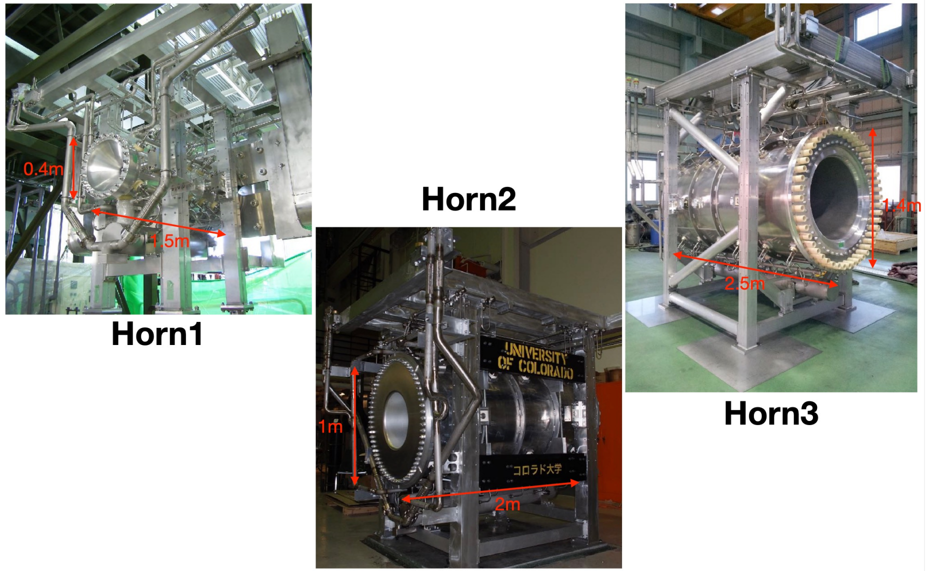


Picture of the T2K target before integration with horn.

Three magnetic horns are used to focus charged particles produced by the interactions of the protons in the target. They generate the magnetic field with a pulsed current of 320 kA.



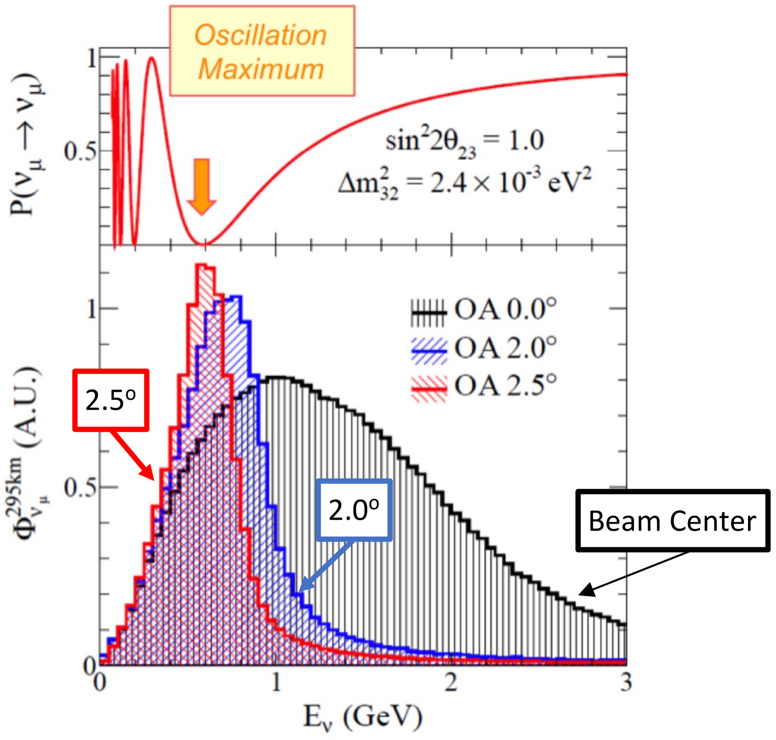
Cross section of three magnetic horns.



Region between the inner and outer conductors.

J-PARC Neutrino Beam (3)

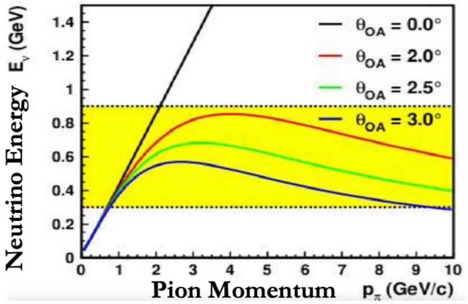
T2K uses an ”off-axis” beam to maximize the effect of the neutrino oscillations.



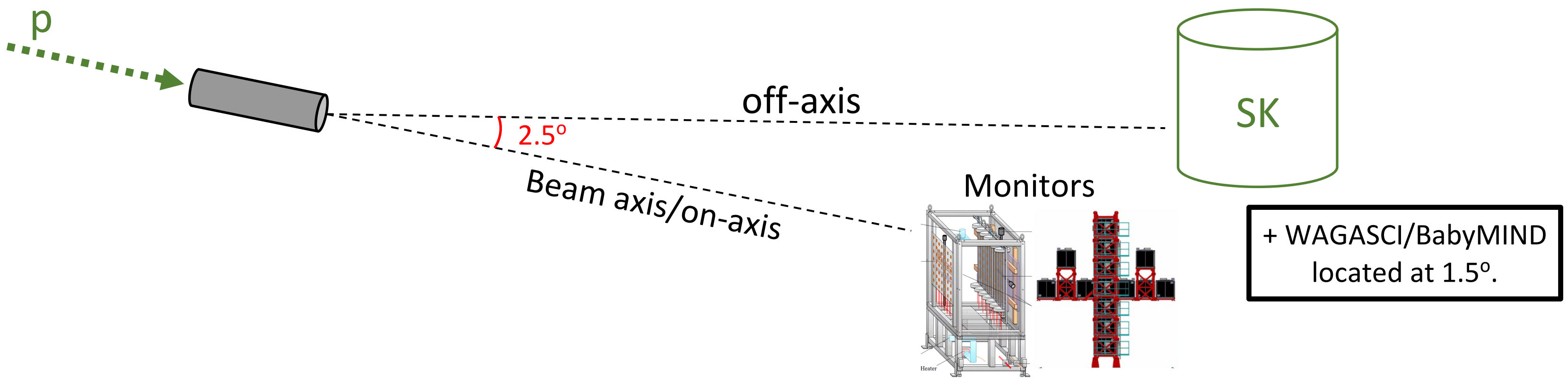
Muon neutrino survival probability and fluxes at far detector for off-axis angles 0.0°, 2.0° and 2.5° [1]

The neutrino’s energy varies according to the outgoing angle due to the pion decay kinematics.

- Creates a smaller range of neutrino energies: narrow band beam peaked at oscillation maximum (600MeV).
- Near and far detector located 2.5 off-axis.
- Easier selection.
- Reduced backgrounds.



Monitor the beam direction within 0.3 mrad.



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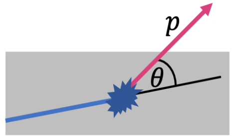
T2K Flux Predictions: Flux Tuning

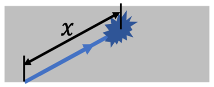
Multiplicity Weights: apply weight based on momentum and direction of outgoing hadron.



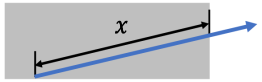
$$weight(p,\theta) = \frac{\left[\frac{d^2 n(p,\theta)}{dp d\theta}\right]_{data}}{\left[\frac{d^2 n(p,\theta)}{dp d\theta}\right]_{MC}}$$

Applied for in-target (using replica target measurements) and out-of-target (thin target measurements) tunings.

Cross-Section Weights: apply weight based on distance travelled through materials before interaction.



$$weight(x) = \frac{\sigma_{data}}{\sigma_{MC}} e^{-\rho(\sigma_{data}-\sigma_{MC})x}$$

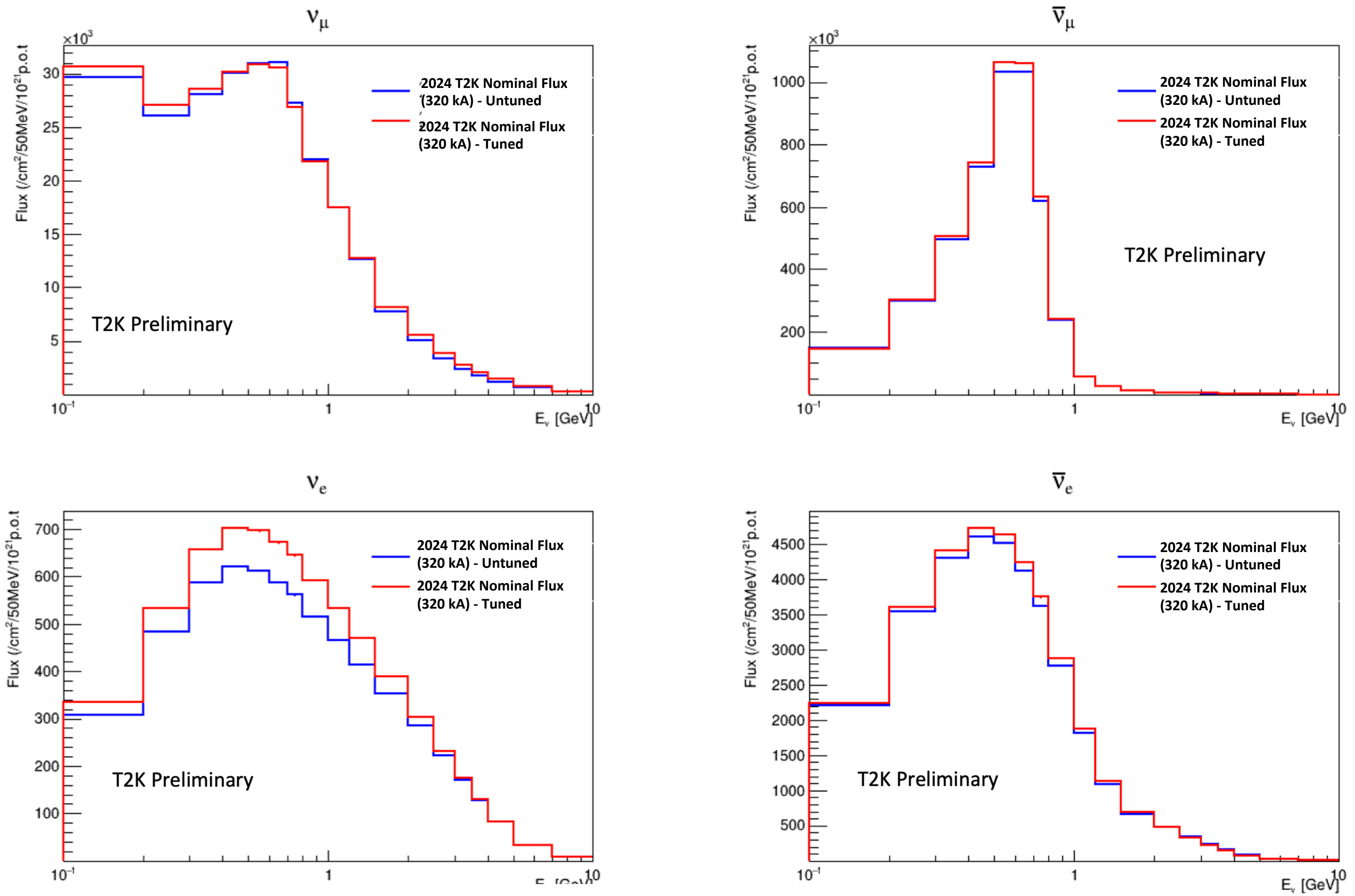


$$weight(x) = e^{-\rho(\sigma_{data}-\sigma_{MC})x}$$

Applied for out-of-target tuning (thin target measurements).

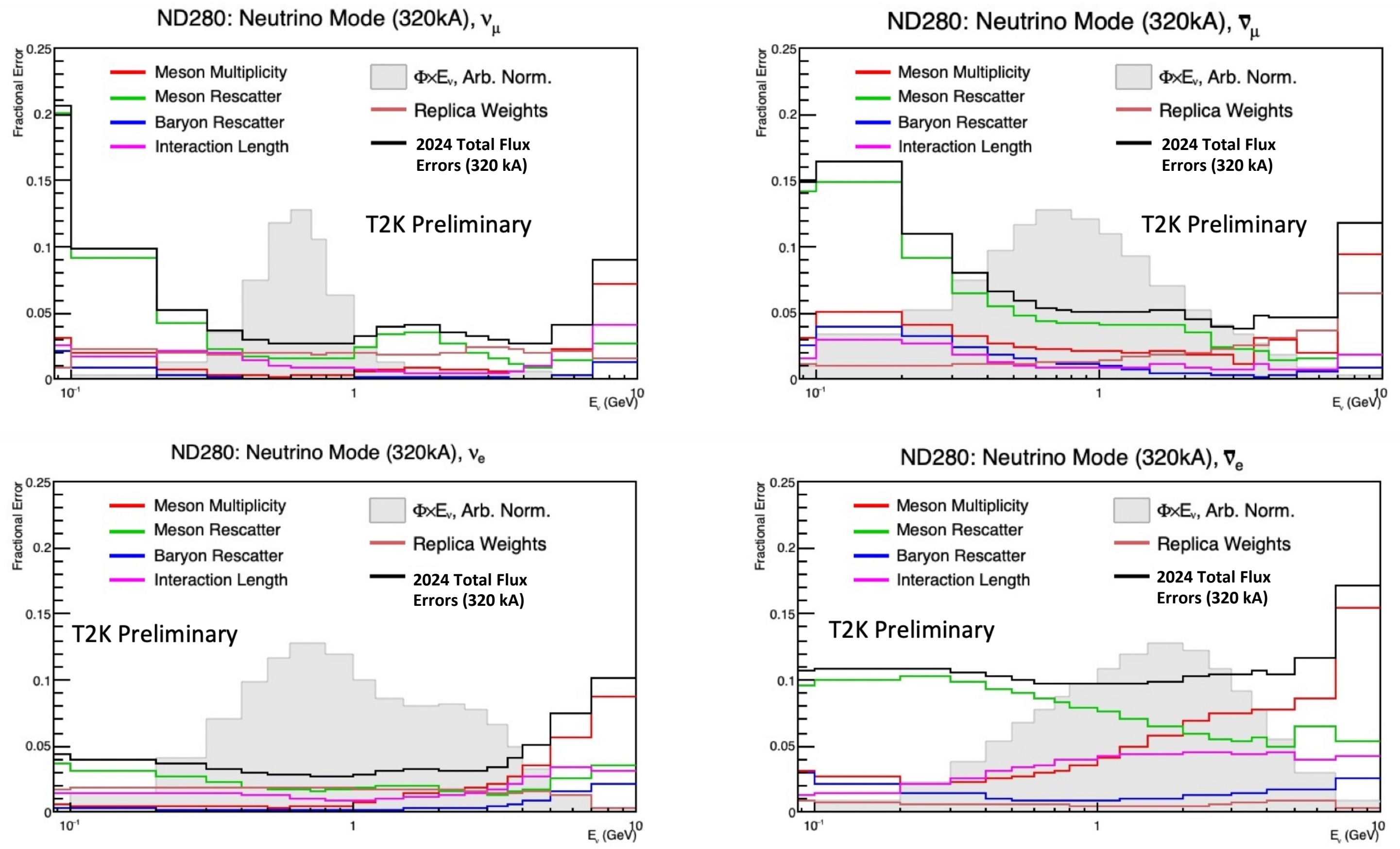
NuInt 2018 – The T2K Flux Prediction (T. Vladisavljevic) (more detail)

In addition to NA61 thin target measurements (10.1140/epjc/s10052-016-3898-y) and replica target (10.1140/epjc/s10052-019-6583-0), new data were taken in Summer 2022 (including K_S^0).



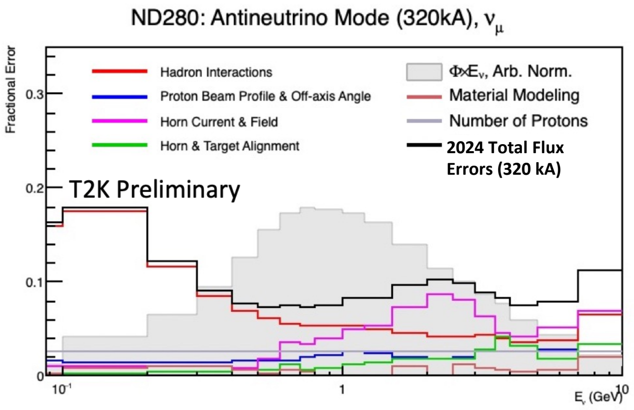
Flux at Super-K Anti-Neutrino Mode

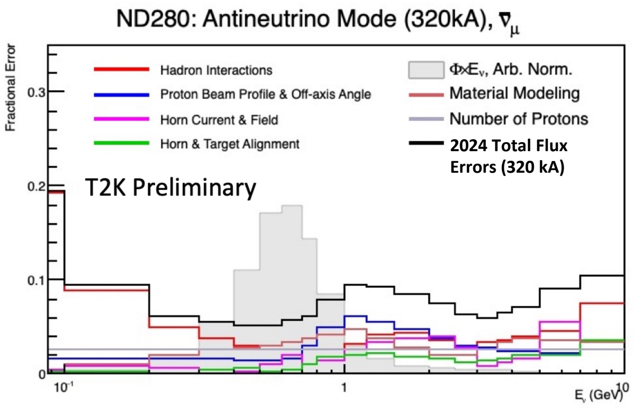
T2K Flux Predictions: Flux Errors (Anti-neutrino mode)

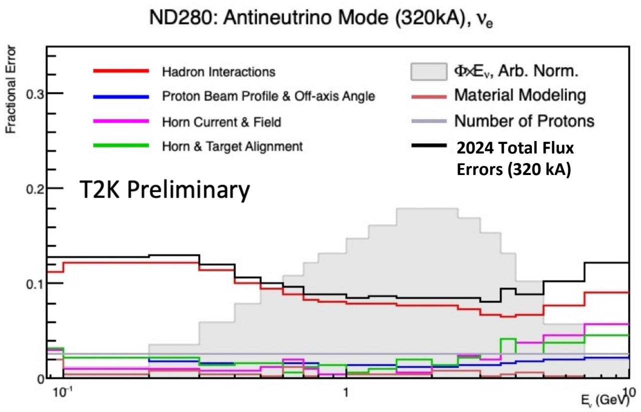


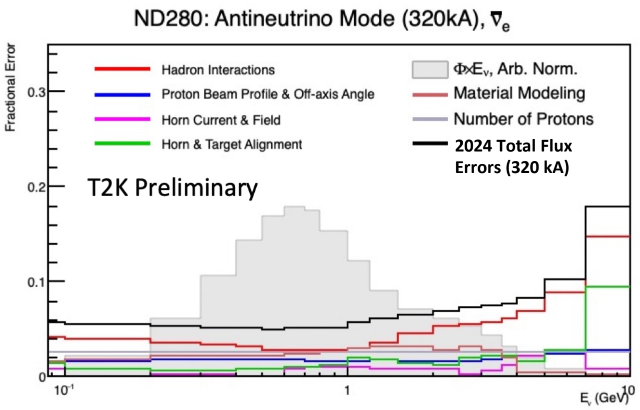
Flux prediction uncertainties vs neutrino energy in the anti-neutrino mode for T2K, at the far detector.

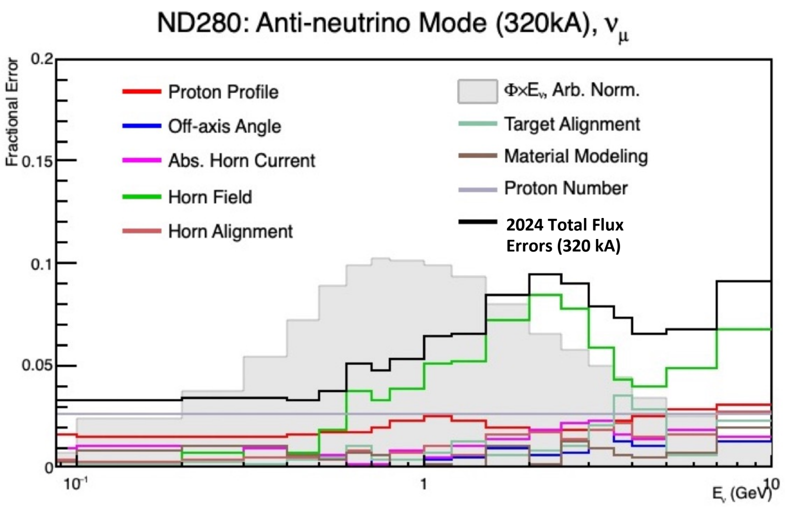
T2K Flux Predictions: Flux Errors (Anti-neutrino mode)

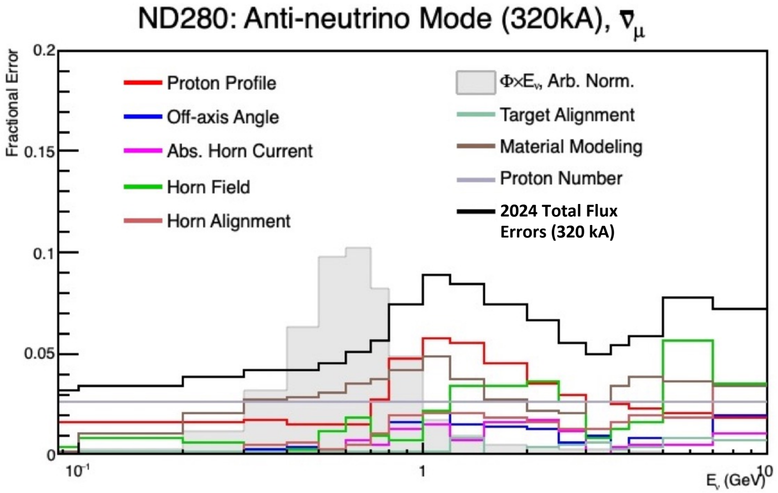








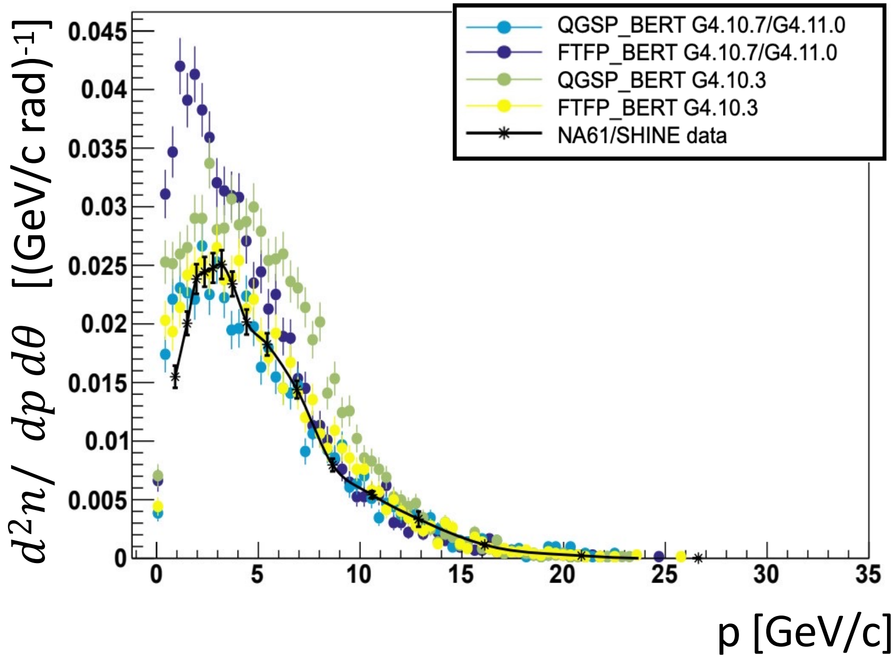




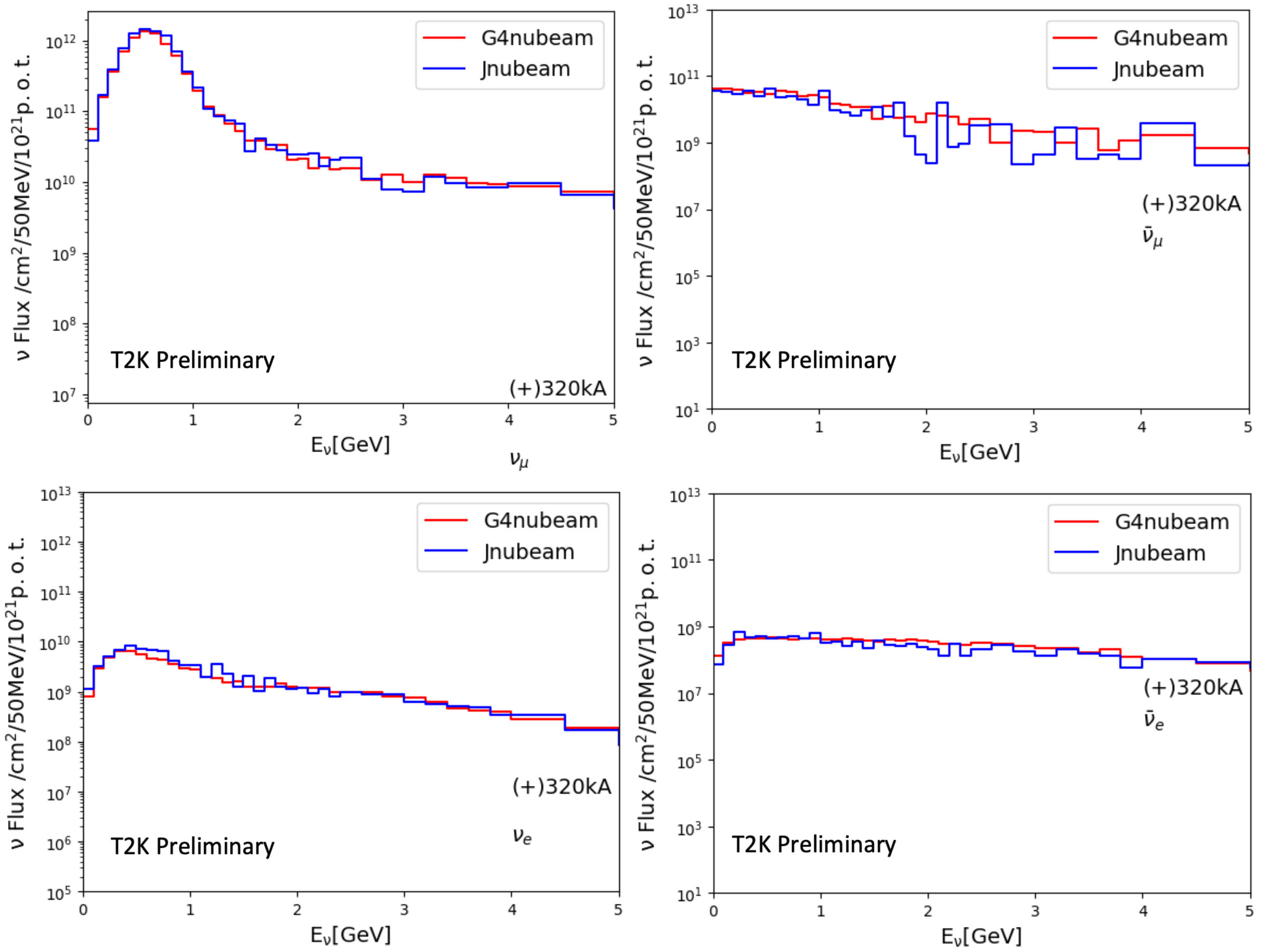
Flux prediction uncertainties vs neutrino energy in the anti-neutrino mode for T2K, at the far detector.

Comparison to NA61/SHINE and JNUBEAM

To validate the results from G4JNUBEAM, simulation of hadrons exiting the target are compared to replica target data (NA61/SHINE 2010) and generated neutrino fluxes compared to JNUBEAM (untuned).



Pion yields from G4JNUBEAM simulations (markers) and NA61/SHINE data (solid line) for Z2 (18-36 cm). (20-40 mRad).



Neutrino fluxes at the near detector

Forward Horn Current (set at 320 kA),
Gaussian beam with $\sigma = 4.243$ mm,
GEANT4.11.1 patch 2