MW-Power Proton Beams for Neutrino Experiments

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21st Rencontres du Vietnam
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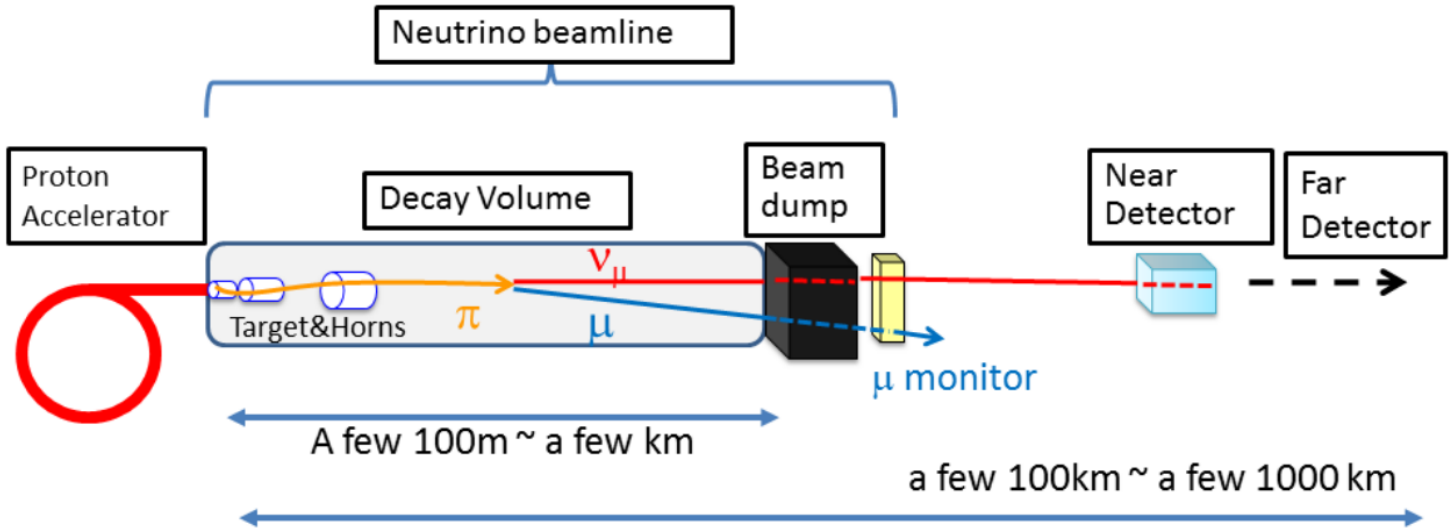
Outline

- Conventional Neutrino Beam Production
- Current and Near-Future Conventional Neutrino Beamlines
  - J-PARC neutrino beamline (current T2K, future HK)
  - Fermilab NuMI (current NOvA, past others), LBNF (future DUNE)
  - Current Status and Future Prospects
- Some Technological Challenges
  - Intercepting Devices:
    - Instrumentation
    - Targets
  - Maintenance of Irradiated Components

Producing a Conventional Neutrino Beam



- High-energy, high-intensity proton beam from an accelerator
  - Neutrino flux is directly proportional to number of protons
- Protons incident on a long target produce hadrons: π's, K's, etc
- Outgoing hadrons are sign selected + focused in electro-magnetic focusing "horns"
- Hadrons decay in long decay volume: $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$, ...
  - Change horn polarity to switch between primarily ν_μ's and $\bar{\nu}_\mu$'s
- Charged decay products can be monitored using a hadron or muon monitor then stop in shielding, earth
- ν's continue on to near and far detectors for measurements

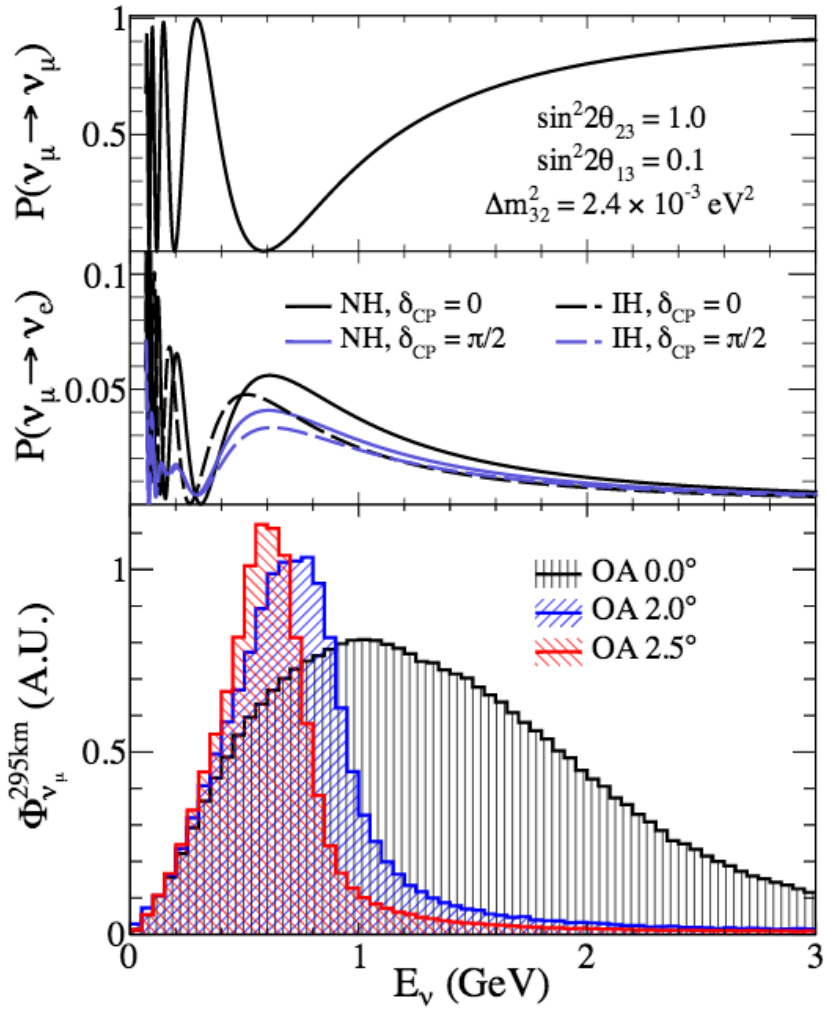
Off-Axis Beam Concept

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

    $$E_\nu = \frac{(1-(m_\mu/m_\pi)^2)E_\pi}{1+\gamma^2\theta^2}$$

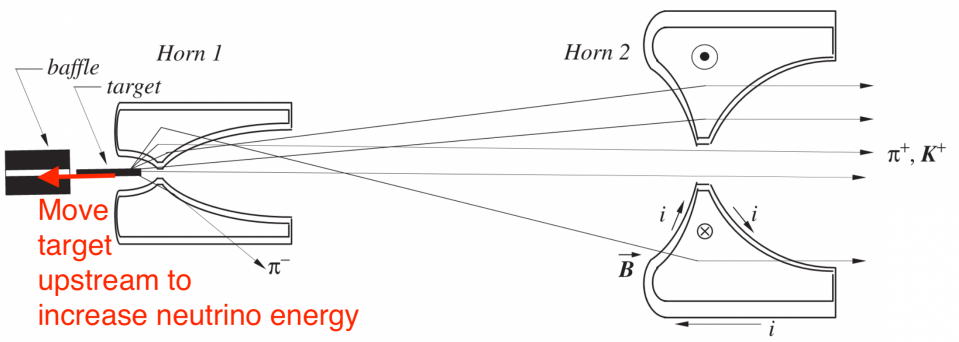
  - So, an "off-axis" beam gives a smaller range of neutrino energies
- Many experiments use an off-axis beam to select a neutrino flux with a peak energy near the oscillation maximum

J-PARC Flux + Osc. Prob.



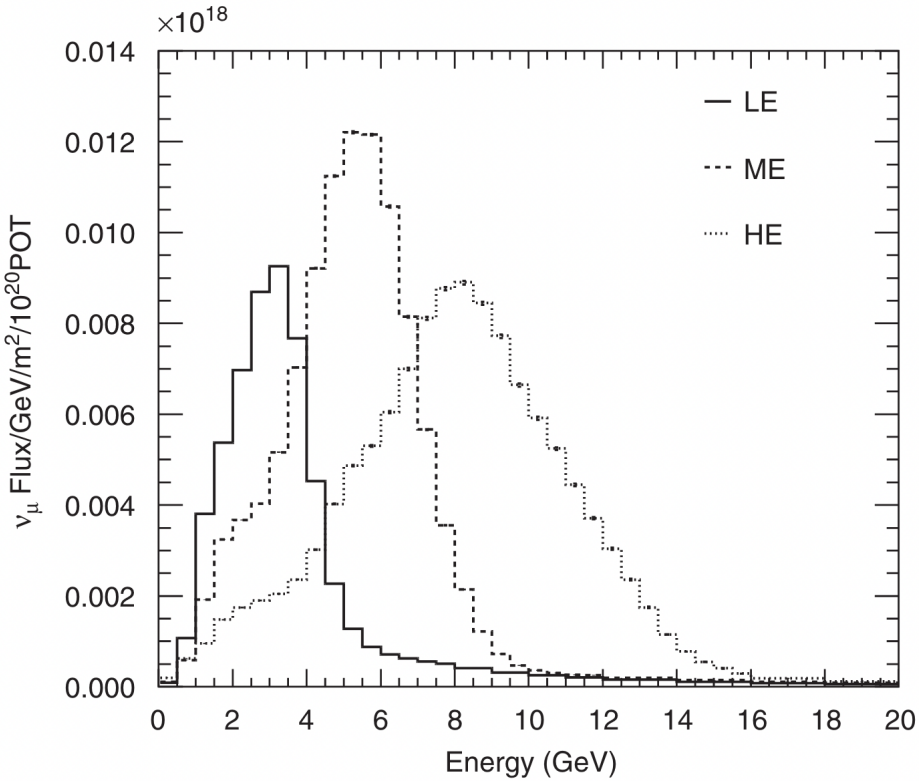
- Install detectors off-axis from the center of the neutrino beam to select the energy
- Precise understanding of the neutrino beam direction essential

NuMI Adjustable 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

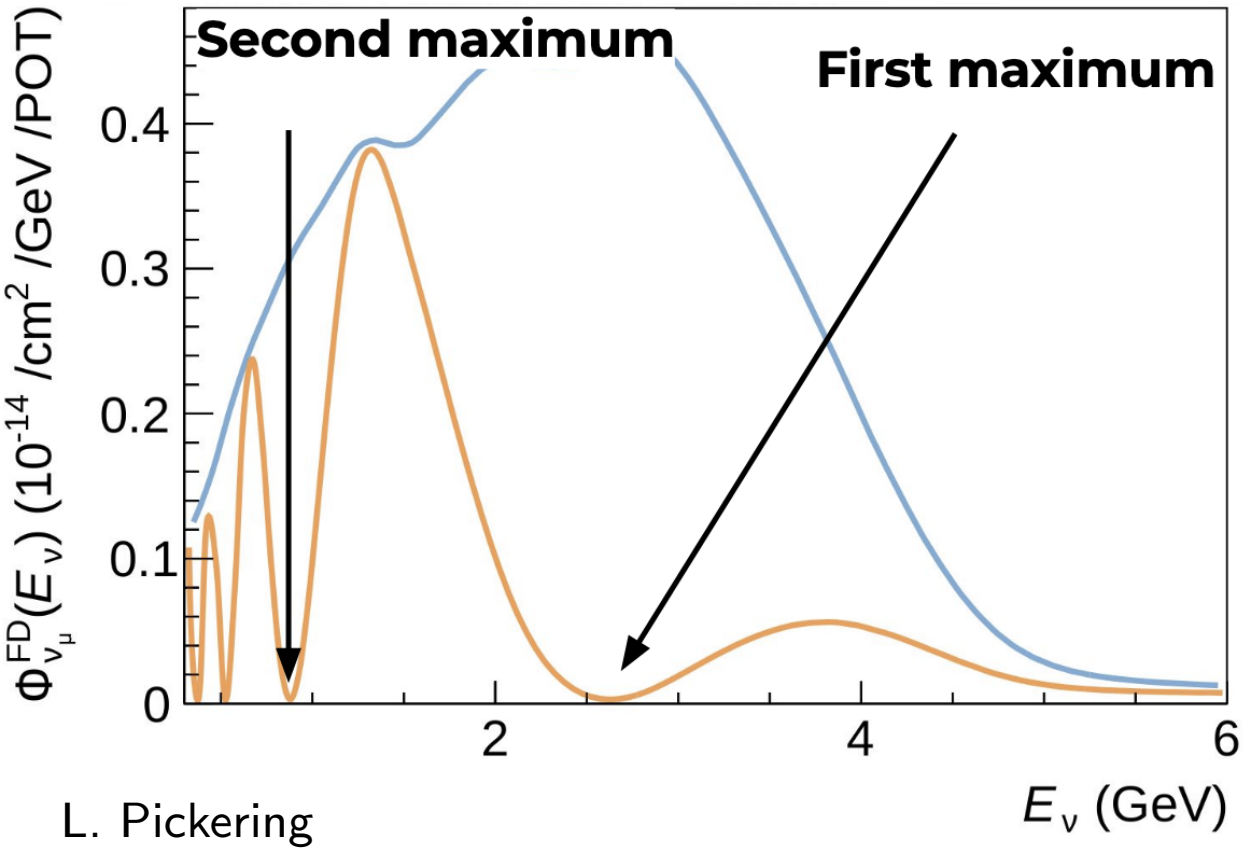
Flux at NuMI Near Detector



Nucl. Instrum. Meth. A 568 (2006)

LBNF On-Axis Flux

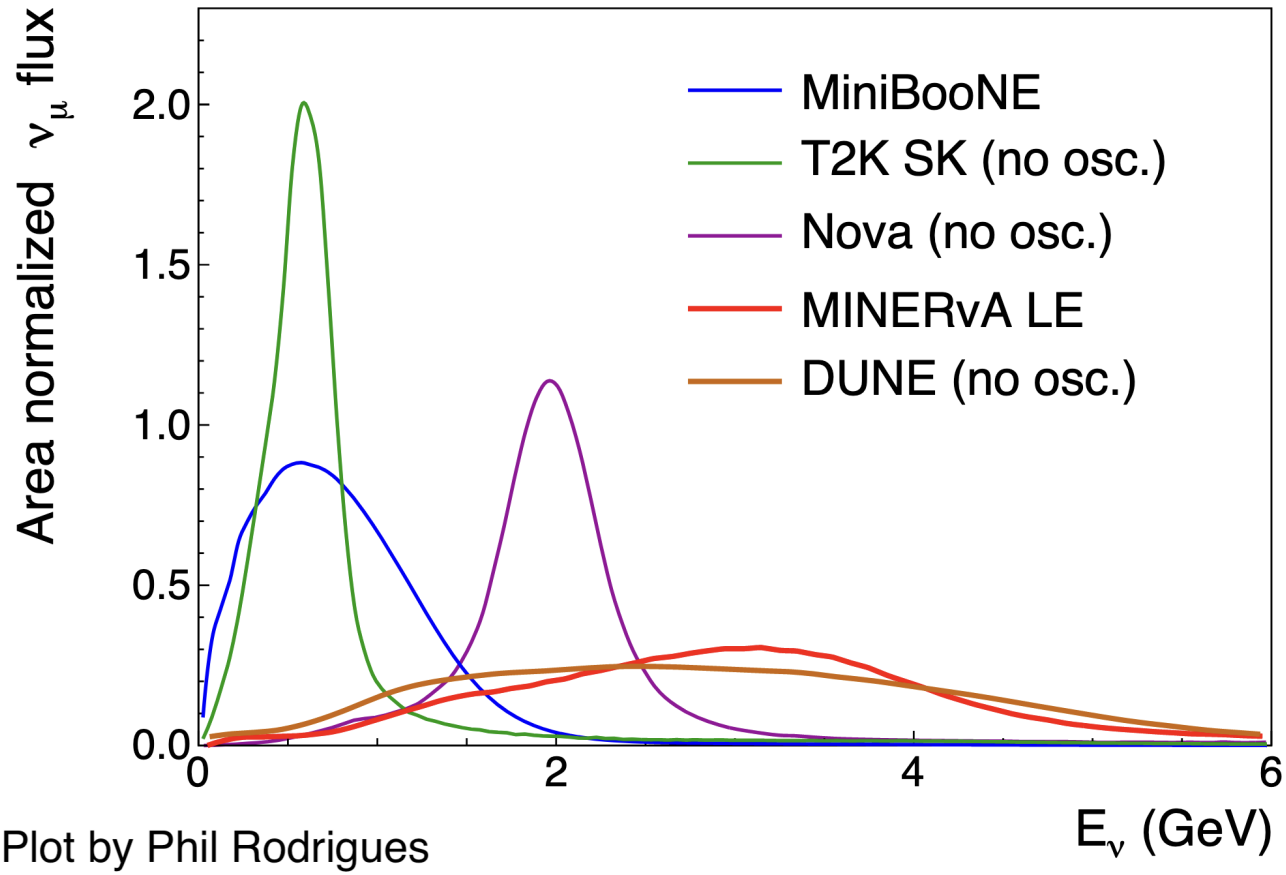
LBNF/DUNE flux and oscillation probability



L. Pickering

- LBNF/DUNE uses an on-axis beam for wide energy range
- Wide energy spectrum allows DUNE experiment to observe multiple oscillation maxima

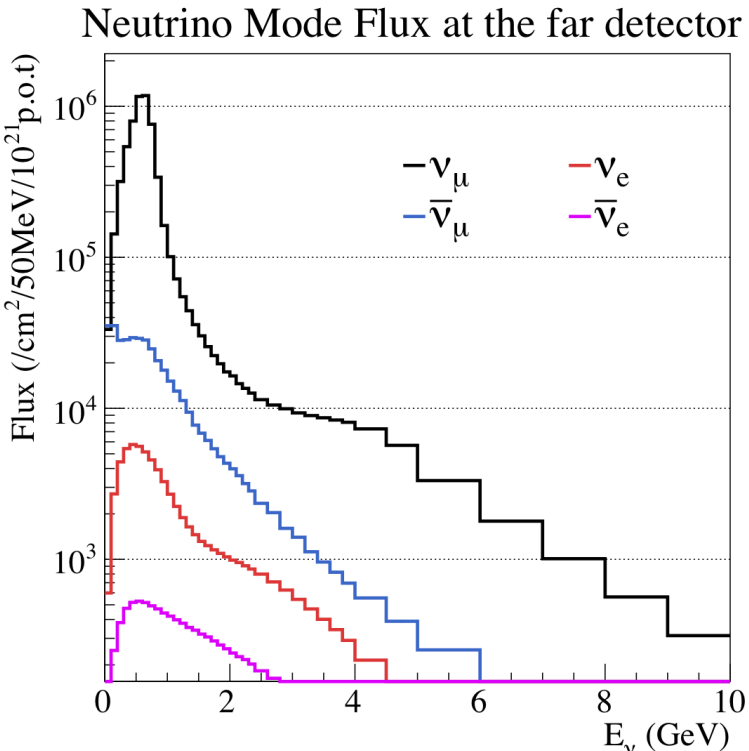
Example Accelerator Neutrino Fluxes

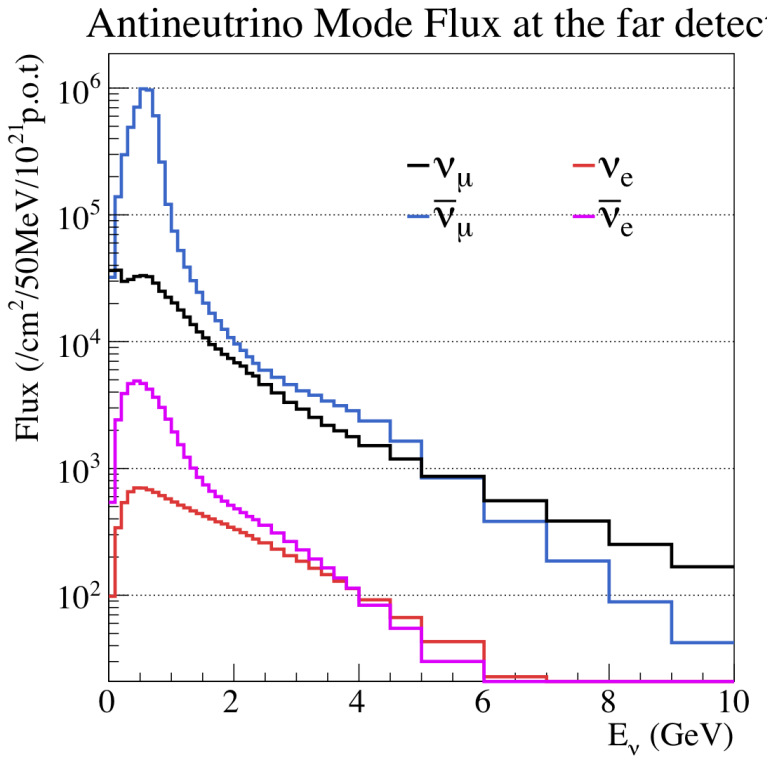


Plot by Phil Rodrigues

- 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

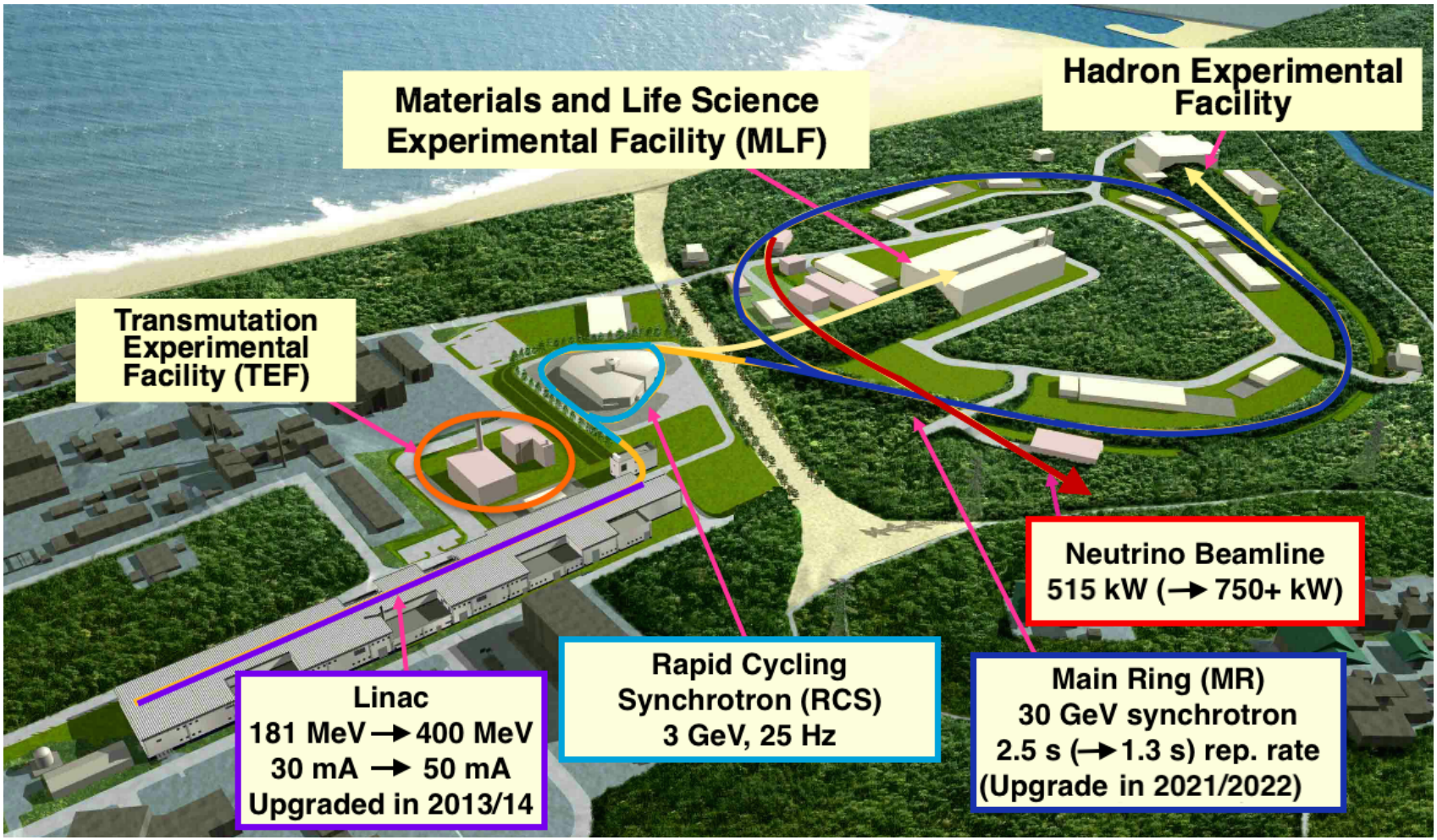
Example: J-PARC Neutrino Flux





- Relatively pure beam of right-sign ν_μ or $\bar{\nu}_\mu$
  - 2$\sim$3% wrong-sign background at flux peak energy
  - $<$1% ν_e contamination at flux peak energy
- To precisely predict the flux:
  - Precisely understand proton beam + all beamline components
  - Constrain hadron interactions inside + outside the target
    - Dedicated hadron production measurements, like NA61/SHINE experiment @CERN, ... etc

Japan Proton Accelerator Research Complex – J-PARC Proton Source

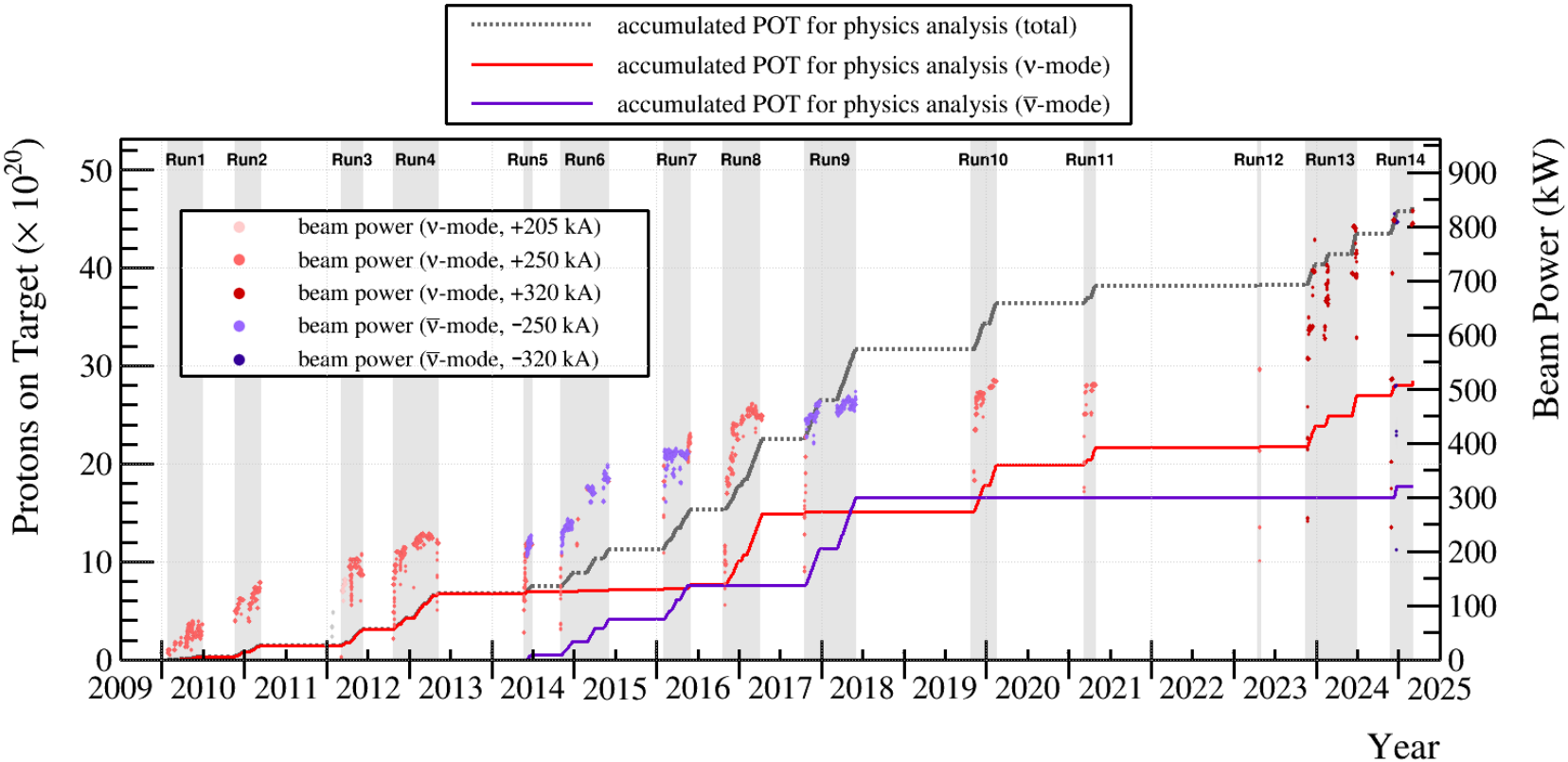


- Accelerates proton beam to 30 GeV by:
  - 400 MeV Linac (linear accelerator) $\rightarrow$ 3 GeV RCS (Rapid Cycling Synchrotron) $\rightarrow$ 30 GeV MR (Main Ring Synchrotron)

Fermi National Accelerator Laboratory – Fermilab Proton Source

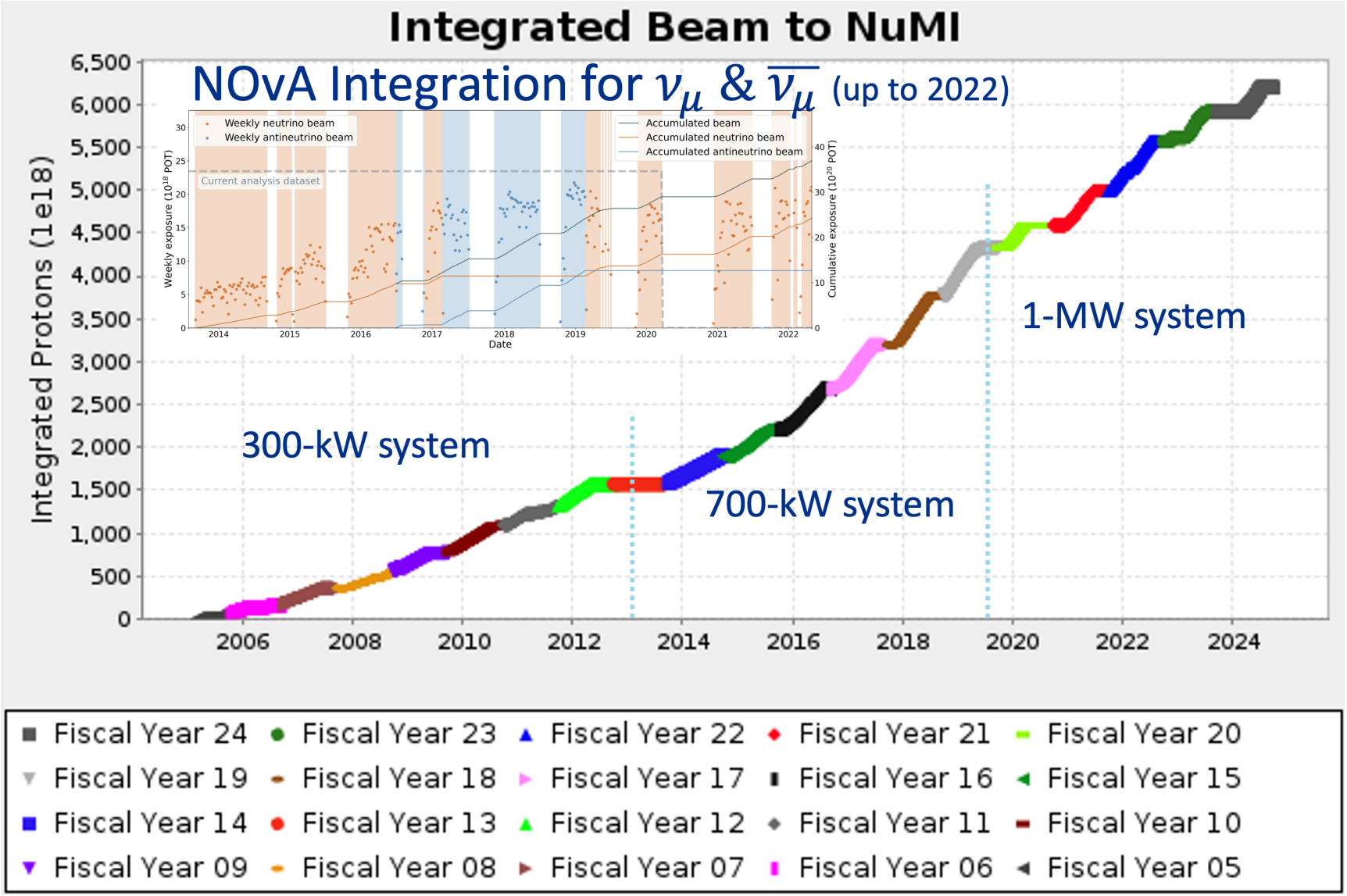
- 120 GeV Main Injector proton beam for NuMI
- 60∼120 GeV, 1.2 → 2.4 MW beam for LBNF/DUNE

J-PARC Neutrino Beam Operation History



- T2K commissioning from 2009∼, physics data-taking from 2010∼
- Gradually ramped up proton beam power
  - From a few kW → record ∼830 kW continuous operation in 2025
- Upgraded horn power supplies in 2022: 250kA → 320kA
- Periods of both ν-mode and $\bar{\nu}$-mode running
- Have accumulated 2.85×10^{21} ν-mode + 1.77×10^{21} $\bar{\nu}$-mode POT

NuMI Beam Operation History



- NuMI operation since 2005, significant upgrades in 2013 and 2019
- Record >1MW beam power operation achieved in June 2024!

Increasing the Beam Power

How to increase the number of neutrinos produced with a conventional neutrino beam $\rightarrow$ Increase the number of protons !

- Two ways to increase the proton beam power:
  1. Increase the frequency, number of beam spills
     - Increase beam repetition rate
     - Increase number of accelerated bunches by slip-stacking
     - Maximize beam operation time (including timely maintenance of aging infrastructure)
  2. Increase the number of protons per spill
     - Reduce beam instabilities and beam losses (including increasing the energy upstream)
- Of course, after increasing the proton beam power, all components in the neutrino beamline must be able to handle the increased power

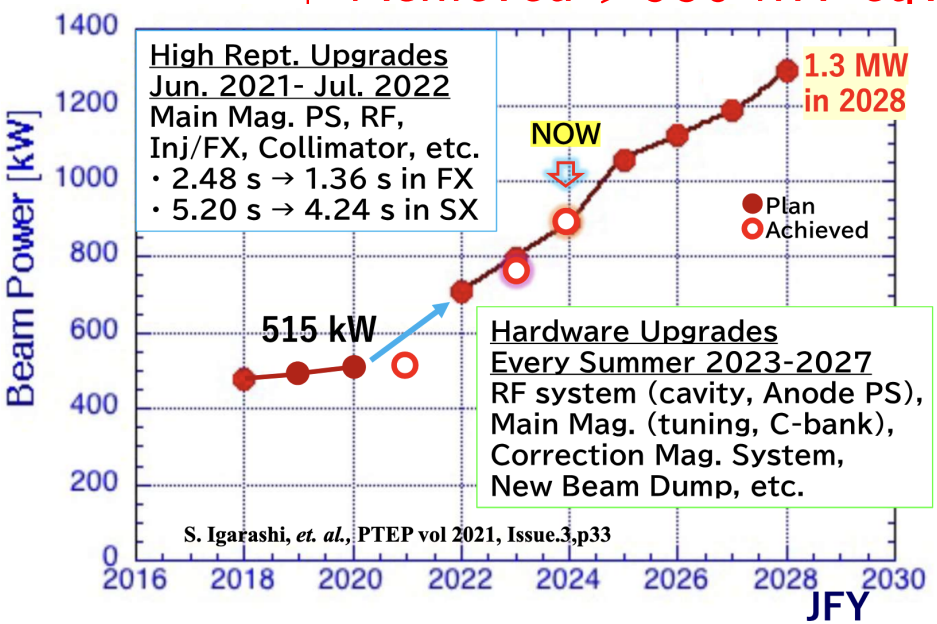
Another way $\rightarrow$ Secondary beamline improvements

- Optimize the target design to increase right-sign hadrons, decrease wrong-sign hadrons
- Optimize the horn focusing (eg increase horn current) for better right-sign hadron focusing, wrong-sign defocusing

Increasing the J-PARC MR Beam Power

- Increasing the J-PARC MR proton beam power in 2 ways:
  - Upgrade PSs + RF to reduce the time between beam spills from 1 spill every 2.48s $\rightarrow$ 1.36s $\rightarrow$ 1.28s $\rightarrow$ 1.16s
  - Improve stability to increase the number of protons per spill from $\sim 2.65 \times 10^{14} \rightarrow 3.2 \times 10^{14}$ 515 kW $\rightarrow$ >800 kW $\rightarrow$ 1.3 MW
- In 2020, J-PARC MR accelerator delivered $\sim 2.65 \times 10^{14}$ protons every 2.48 seconds = 515 kW
- In March 2025, J-PARC MR accelerator delivered $\sim 2.35 \times 10^{14}$ protons every 1.36 seconds = 830 kW

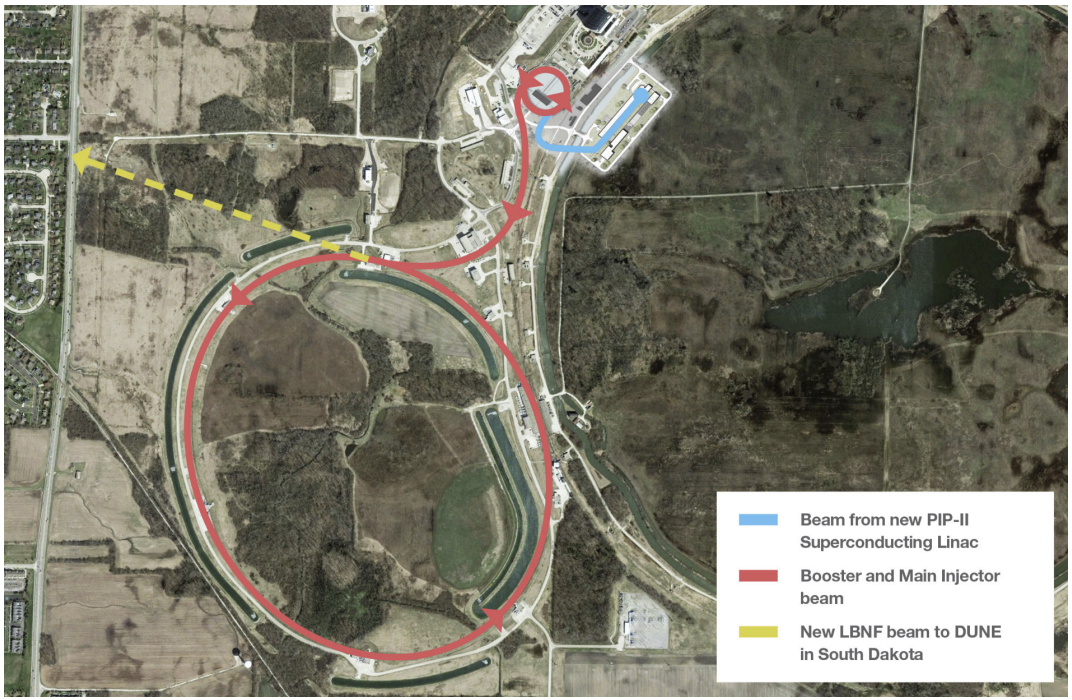
+ Achieved >950 kW eqv. in MR beam test in 2025



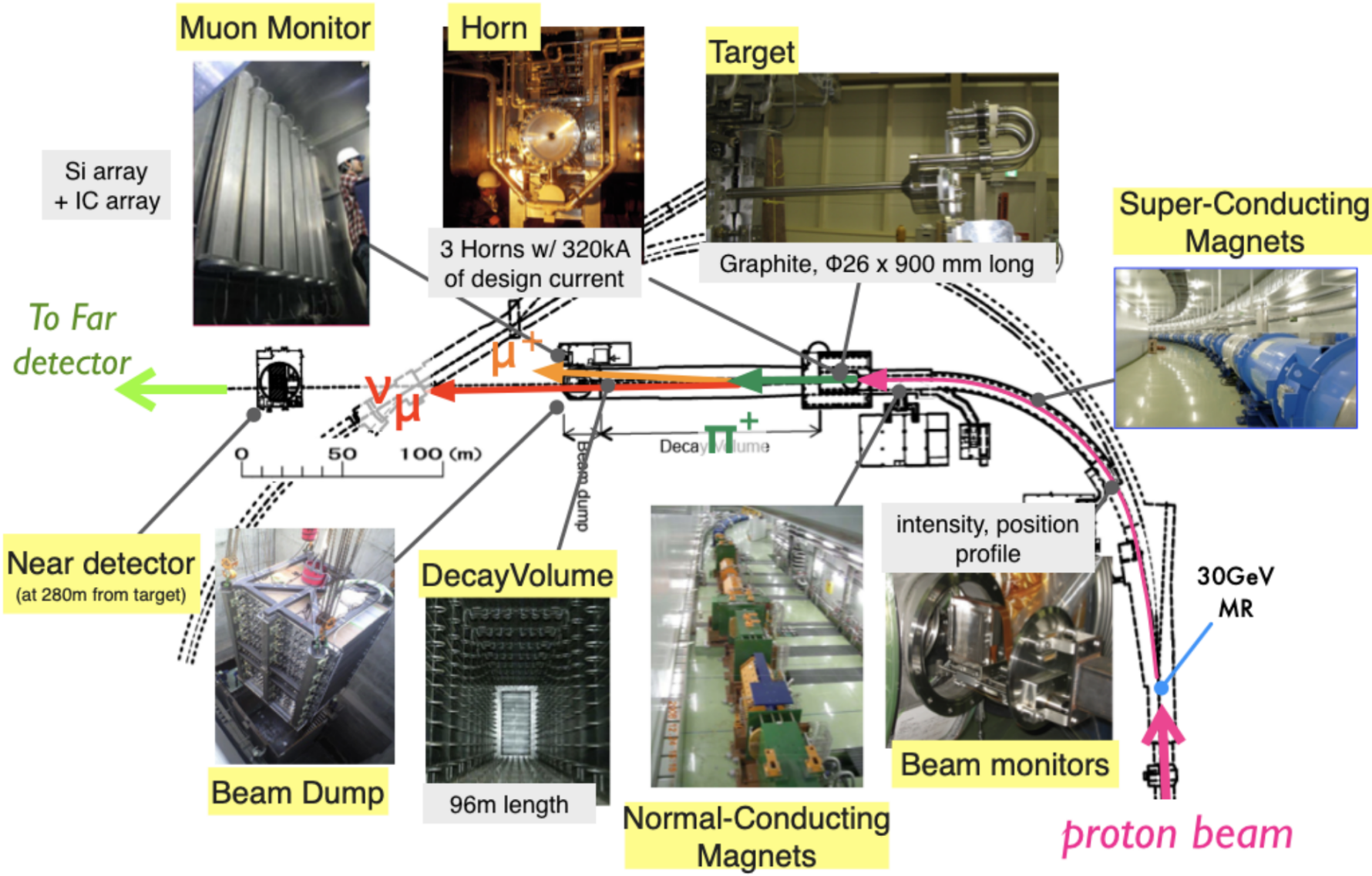
	Achieved	Target
Beam power [MW]	0.5	1.3 (~x3)
# of protons per pulse	2.6×10^{14}	3.2×10^{14} (+30%)
Rep. Time [sec]	2.48	1.16 (~1/2)

Increasing the Fermilab Beam Power

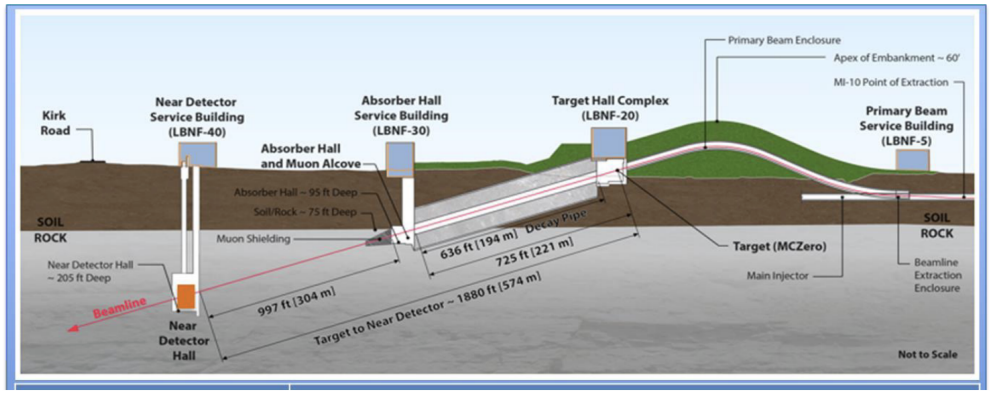
- PIP-II – Proton Improvement Plan II
  - New 800 MeV superconducting RF linac will enable >1MW beam power to LBNF, upgradeable to multimegawatt levels
  - Groundbreaking in 2019, scheduled for completion in 2028
- ACE-MIRT – Accelerator Complex Evaluation - Main Injector Ramp and Targetry R&D
  - Operate the accelerator complex with a faster repetition rate (1.2s $\rightarrow$ 0.65s) and higher beam intensity (5.7e13 $\rightarrow$ 6.5e13 protons/spill) without construction of a new accelerator after PIP-II



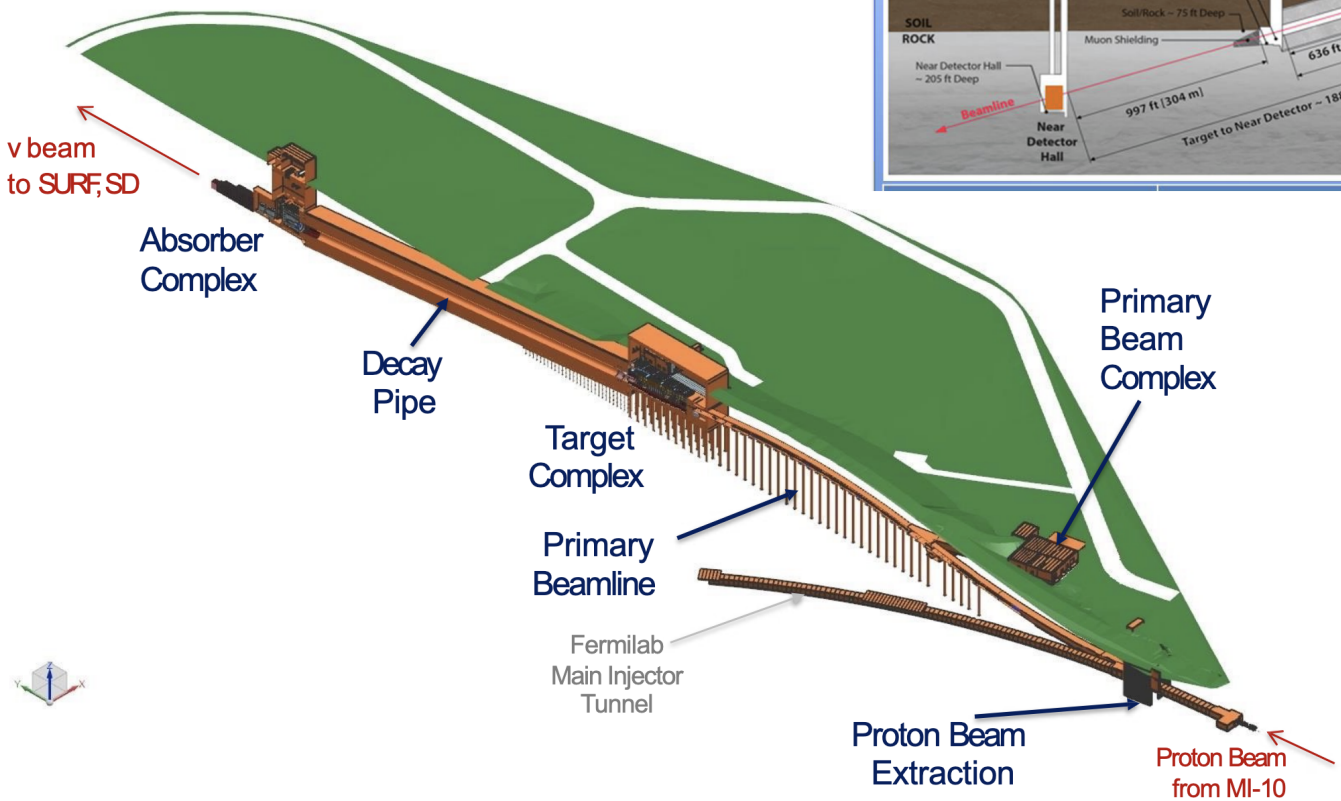
J-PARC Neutrino Beamline



LBNF Beamline



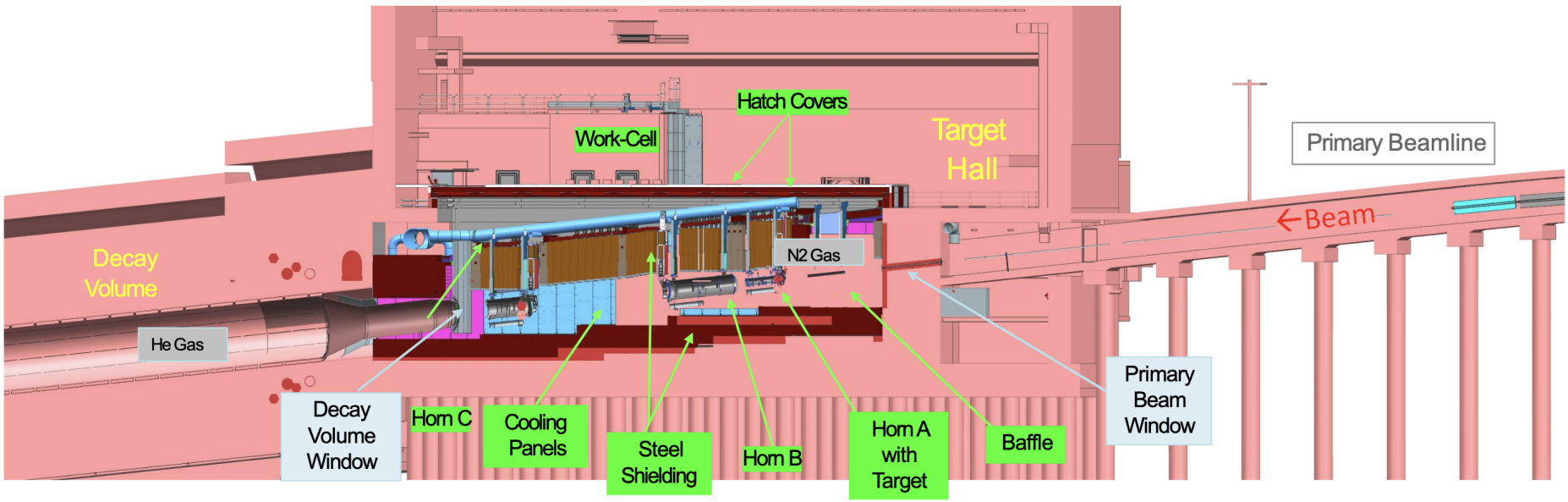
LBNF Near Site



S. Ganguly, NBI2024

- LBNF primary beamline built on a hill – minimize excavation for secondary beamline, decay volume, near detectors, ...

Target Complex: Target Hall and Chase



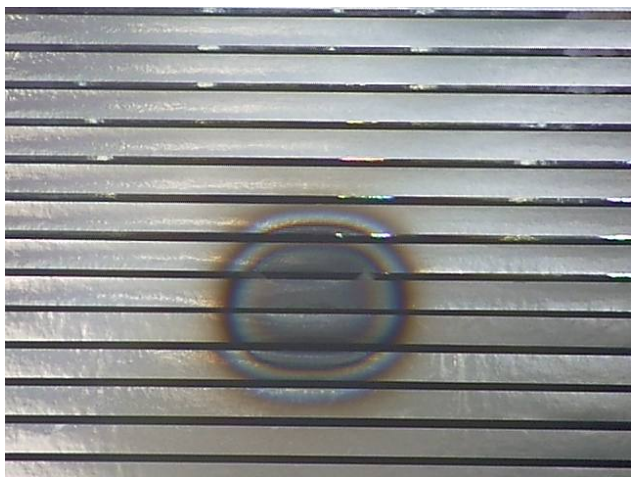
S. Ganguly, NBI2024

- Secondary beam – monolithic (segmented) target, 3 focusing horns
- Various secondary beamline parameters designed and optimized using genetic algorithm

J-PARC Beam Profile Monitor Upgrades

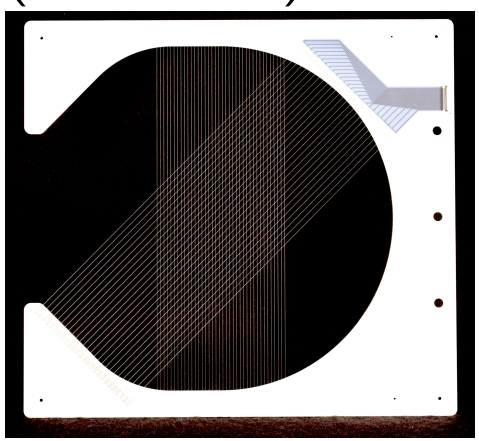
- Proton beam profile is measured by series of foil-based SSEMs
  - Each monitor causes 0.005% beam loss – only use for beam tuning
  - Most downstream one is near the target – can be used continuously
- Concern with degradation of foils, increase of beam loss/component irradiation with increasing beam power
- US/Japan joint R&D for lower loss monitor (WSEM) – 1 in use now
- Non-destructive profile monitor – Beam Induced Fluorescence Monitor (BIF) – developed, prototype installed, tested
  - Upgrading towards full working monitor now

S. Cao, PASCOS 2024

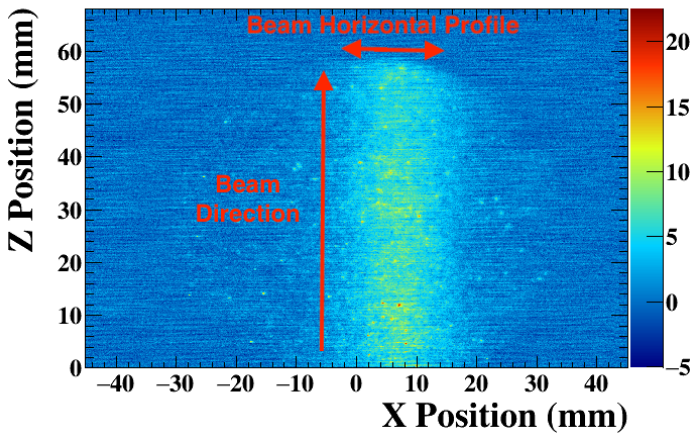


SSEM after $\sim 3.2 \times 10^{21}$ Incident Protons

WSEM @J-PARC (FNAL-like)

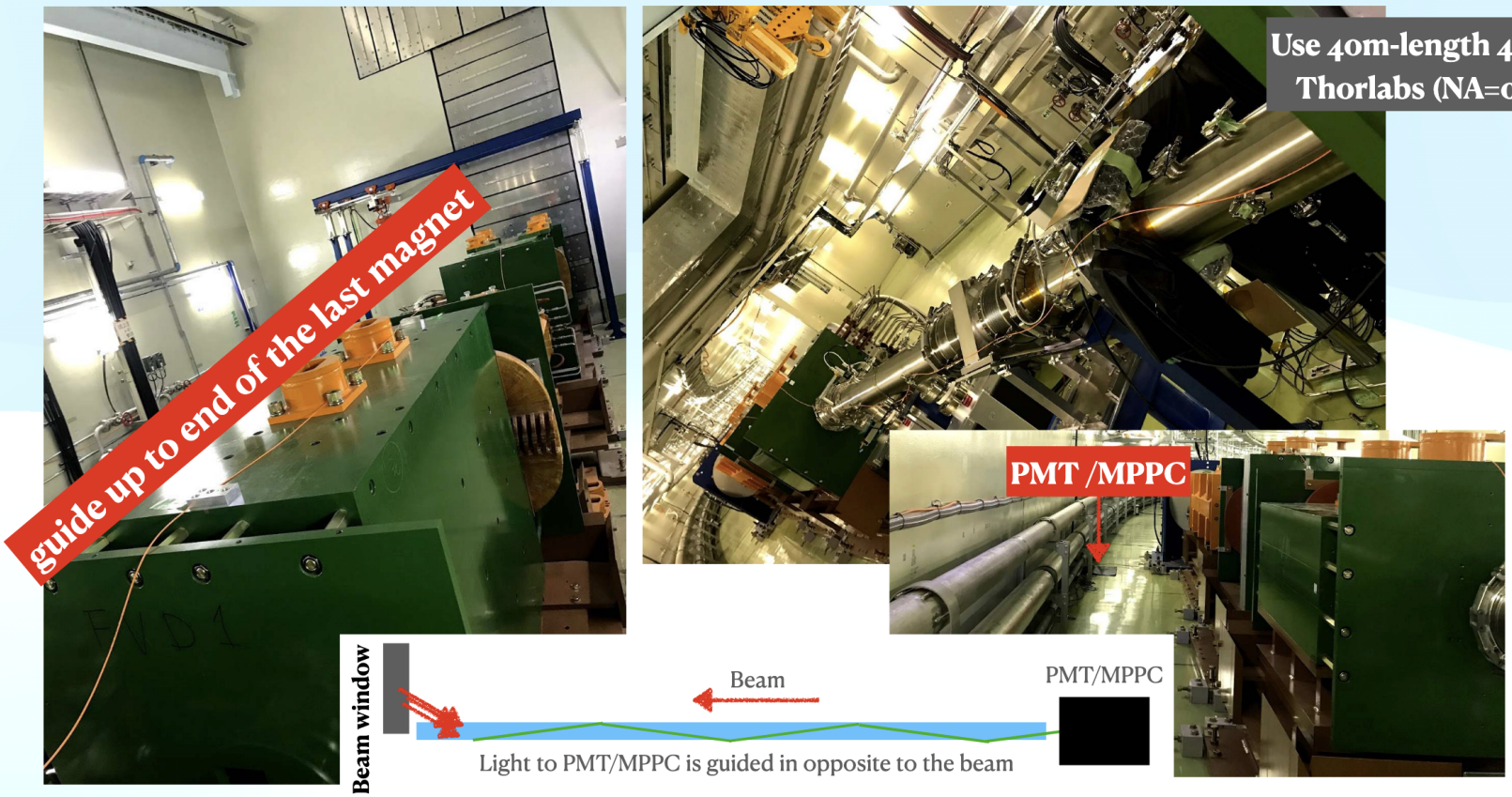


Beam profile measured by BIF @beam test



J-PARC O-BLM Development

Instrument 37m of the final focusing section



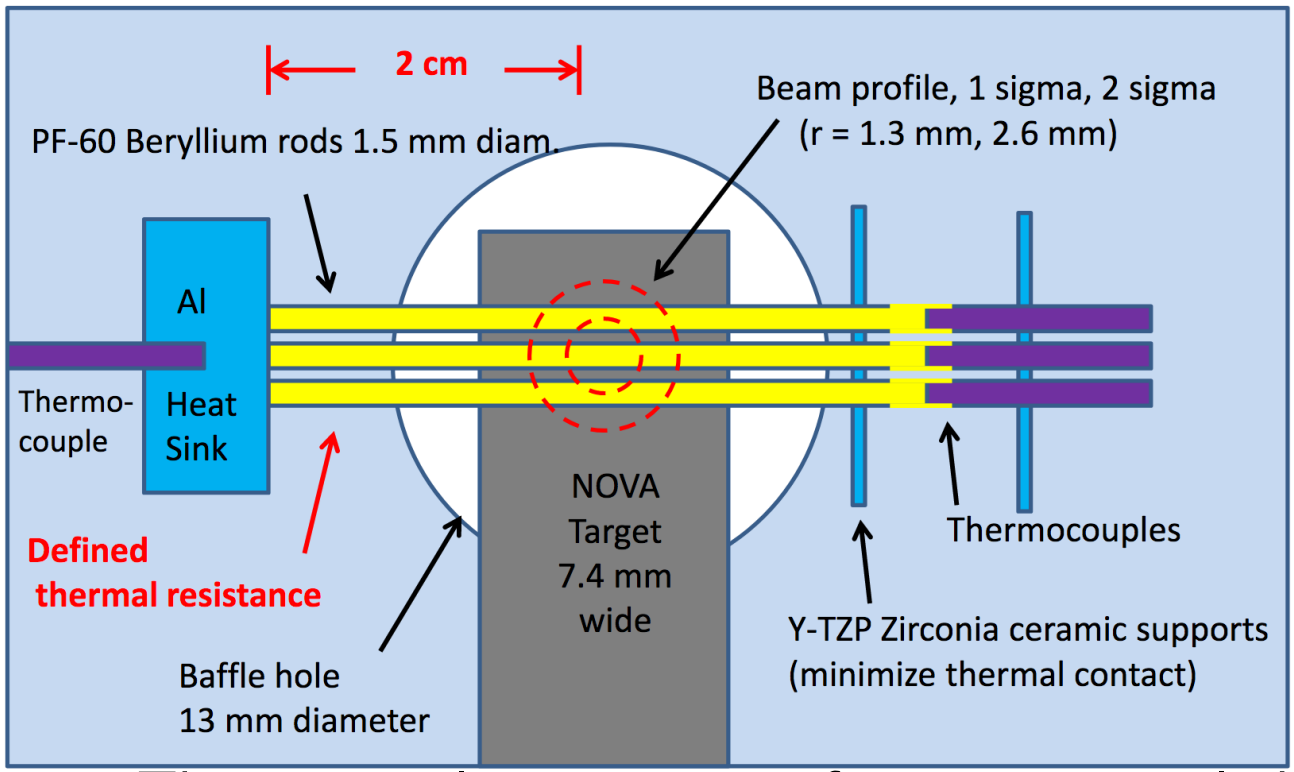
S. Cao, PASCOS 2024

- Development and testing of optical fiber as simple, robust beam loss monitor at J-PARC

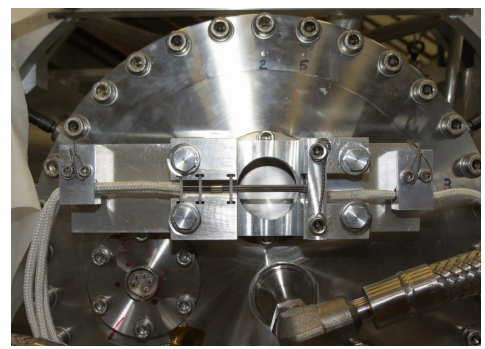
Fermilab "Hylen Device" Principle and Design

Beryllium rods, near upstream window of target, to watch beam position

(not to scale; also baffle drawn behind target, although it is actually in front)

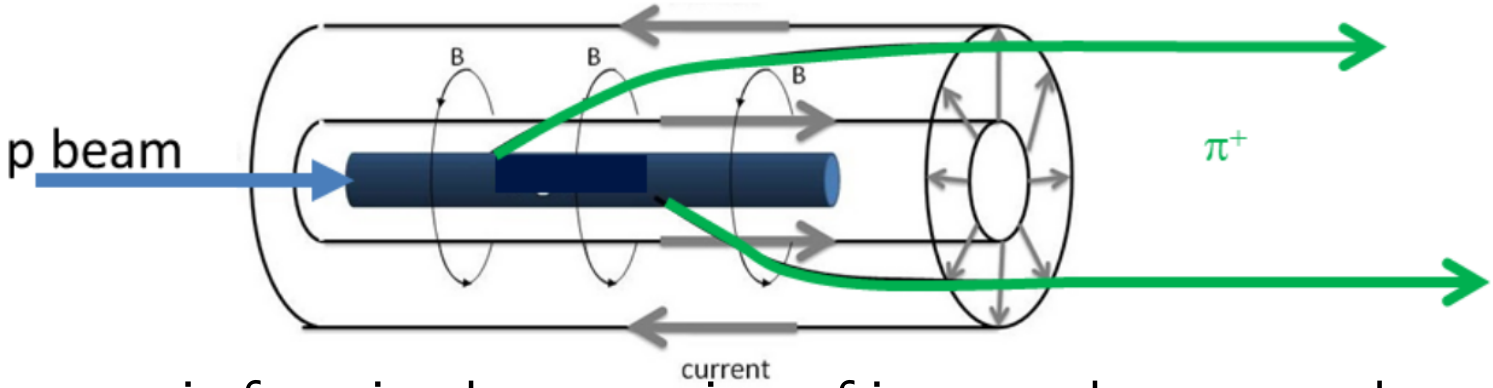


J. Hylen, "Thermal Position Monitor", NBI2014



- Thermocouples upstream of target as simple beam profile monitor – 3 rod Be version in use at NuMI, 5 rod Al version planned for LBNF
- ΔT (Rod - Sink) $\propto$ (beam power deposition in rod)
  $\rightarrow$ Coarse profile derived from ratio of ΔT's of the different rods
- Thermocouples same material as the beam window – very robust

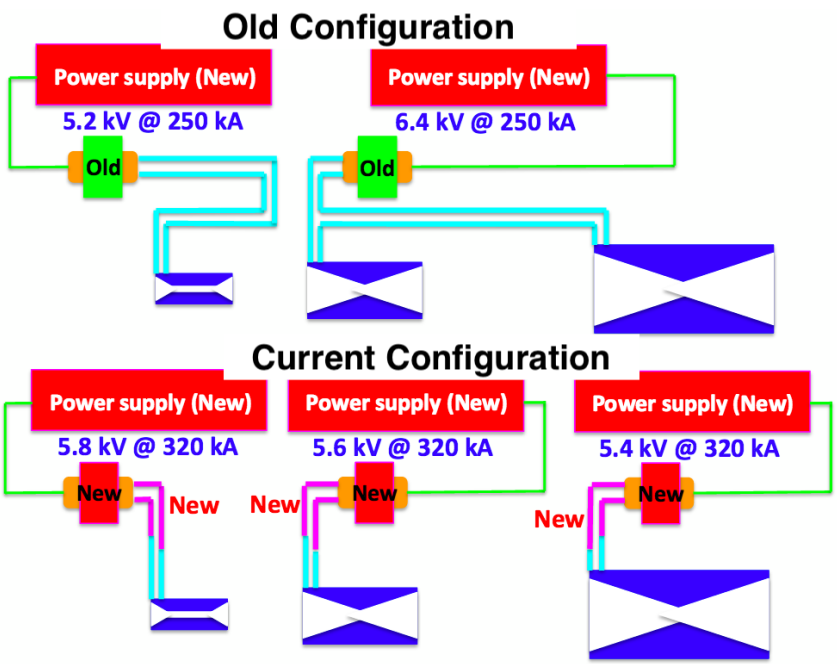
Electromagnetic Focusing Horns

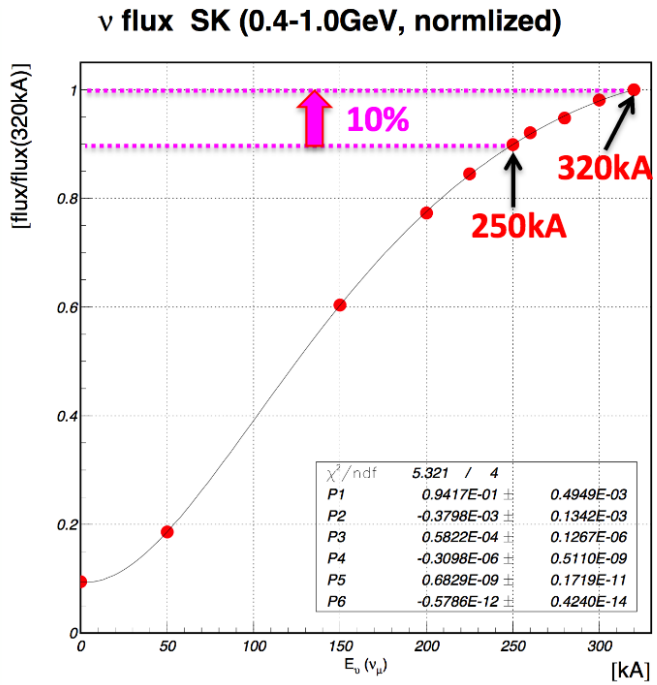


- Electromagnetic focusing horn consists of inner and outer conductor
  - Large magnetic field between conductors achieved by flowing high current down one conductor and back along the other
- Pions of the correct sign traveling between two conductors are focused
  - Sign of focused pions chosen based on direction of flowed current
- Horn conductors cooled by water spray between 2 conductors
- Huge currents supplied by striplines – stripline cooling is one important consideration
  - Horn 2 striplines are particularly susceptible to impinging particles defocused by horn 1
- NuMI uses 2 horn configuration; J-PARC, LBNF use 3 horns

J-PARC Horn Upgrades

- At J-PARC, upgraded 2 $\rightarrow$ 3 power supplies (+ new striplines, transformer) in 2022 to increase horn current from $\pm$250kA $\rightarrow$ $\pm$320kA
  - $\sim$10% increase in right-sign neutrino flux, 5$\sim$10% decrease in wrong-sign neutrino flux
- Horn 2 striplines are particularly susceptible to impinging particles defocused by horn 1 – cooling upgrade essential
  - Upgraded, water cooled striplines installed in 2022

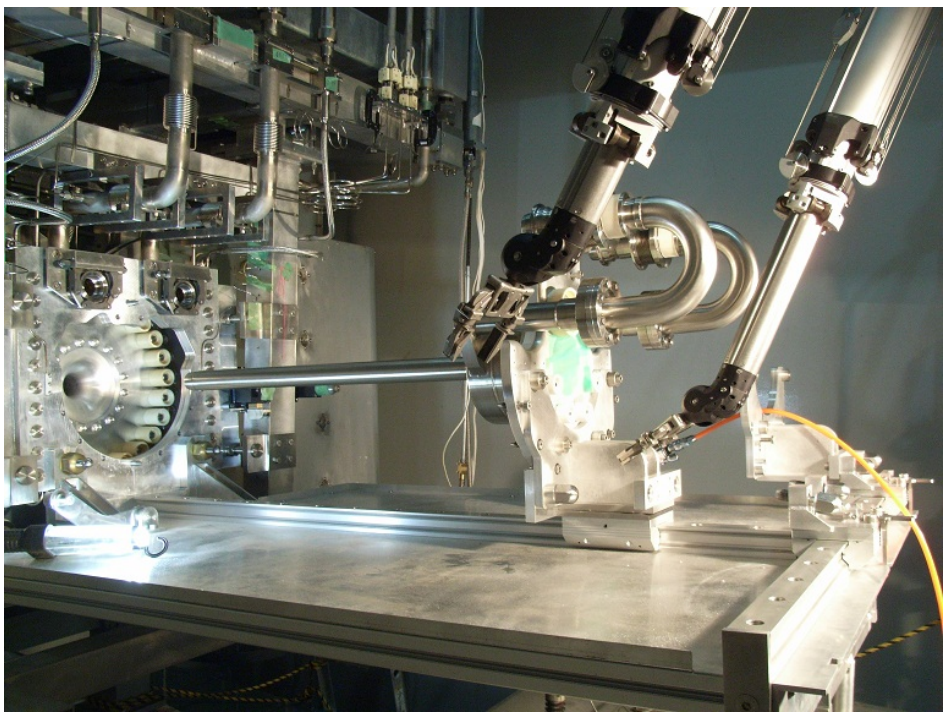




Flux Improvement @ 320 kA

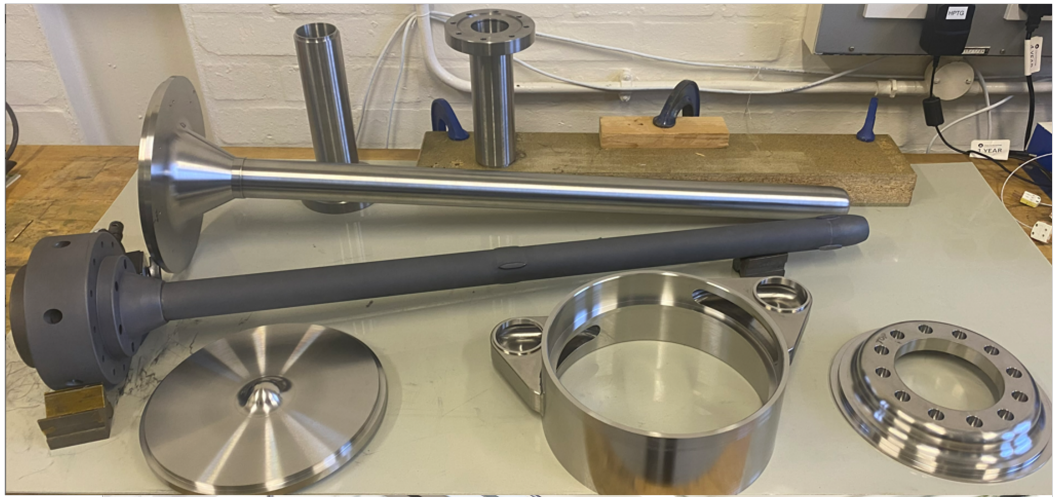
J-PARC Neutrino Production Target

- J-PARC neutrino production target consists of a 91.4cm long (1.9 interaction length) monolithic carbon target installed in the 1st horn
- Cooled by He gas – increase of cooling capacity (He flow rate) for higher power underway now
- New J-PARC target for 1.3MW developed and ready for installation in summer 2026 (RAL)



- Studies to establish new target types to further maximize number of produced neutrinos are also ongoing
  - Possible to decrease forward-going wrong-sign component by new target design
  - Higher-density and/or hybrid materials, longer targets

J-PARC 1.3MW Target



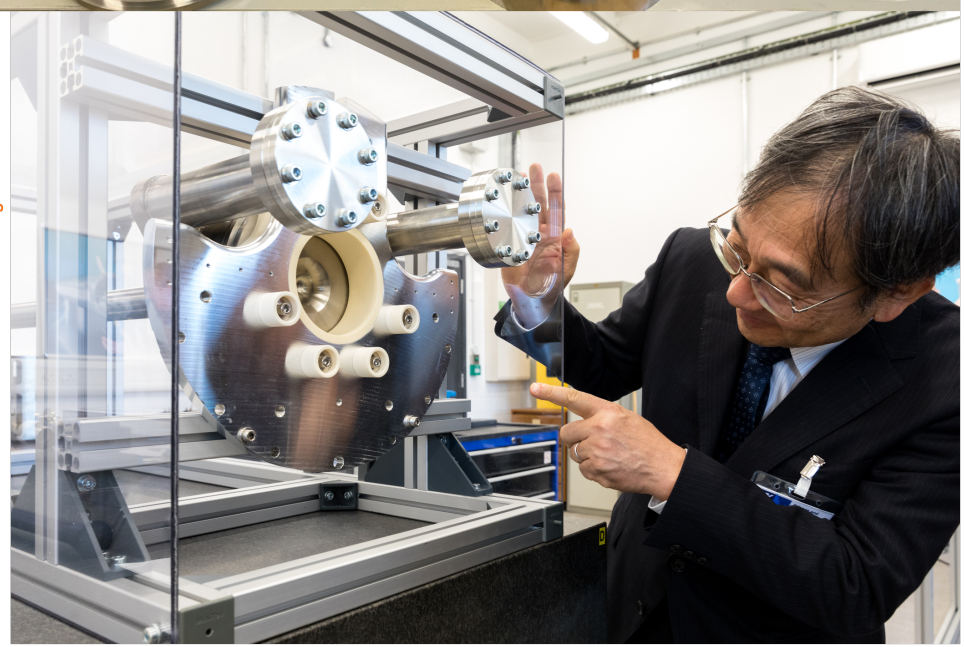


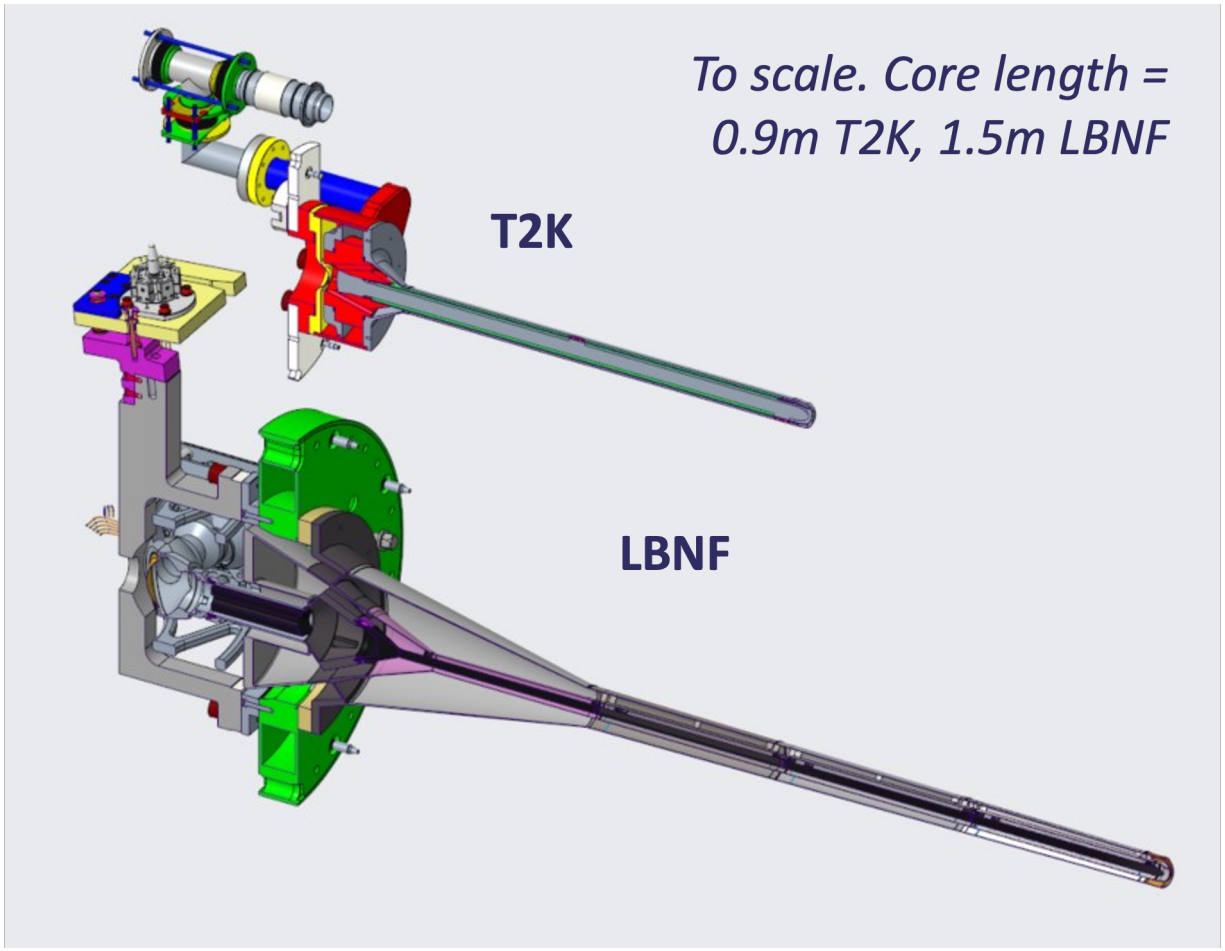
Image © STFC John Dawson

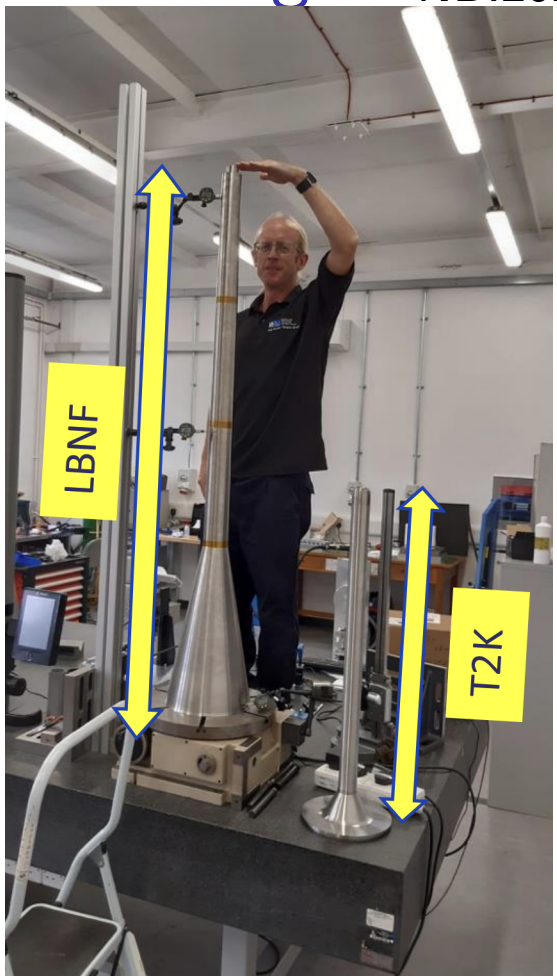
SuperK Spokesperson Professor Nakahata Masayuki inspects the first 1.3 MW capable neutrino production target manufactured at RAL.

NBI2024

- T2K 1.3MW target developed and built at RAL, to be installed in summer 2026

LBNF Target

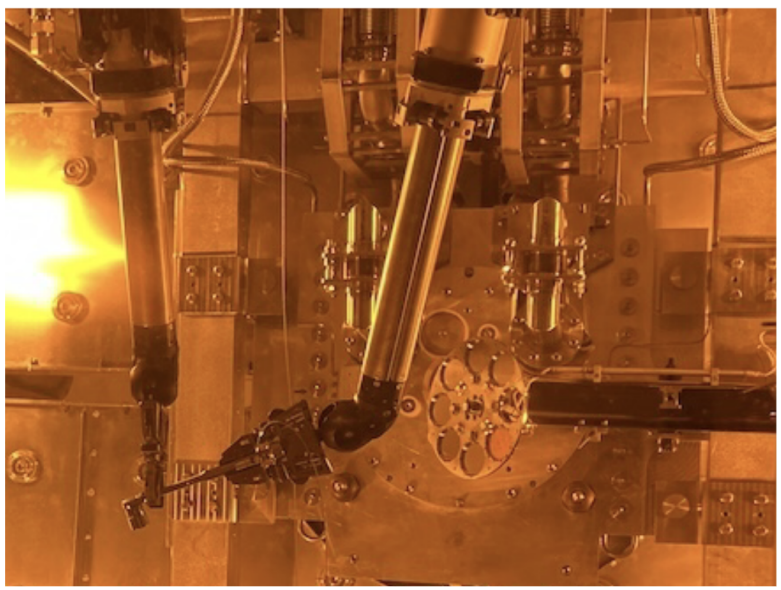




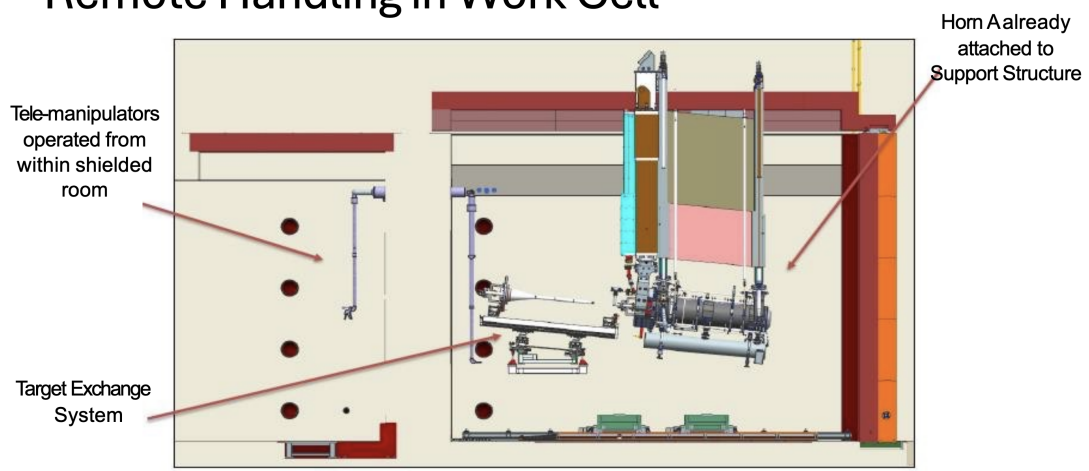
- LBNF target has similar design to T2K one (RAL), but higher density carbon, length increased 0.9m $\rightarrow$ 1.5m
  - Increase in right-sign flux + decrease in wrong-sign flux compared to shorter, lower density target

Remote Maintenance of Irradiated Components

- Components used near the target area of a neutrino production beamline are highly irradiated
  - Any maintenance/replacement of consumable components must be done fully remotely
    - Some components can never be replaced (eg decay volume, beam dump) – must be fully designed to handle final future upgraded beam power (eg beam dump, decay volume designed for 4MW @J-PARC)



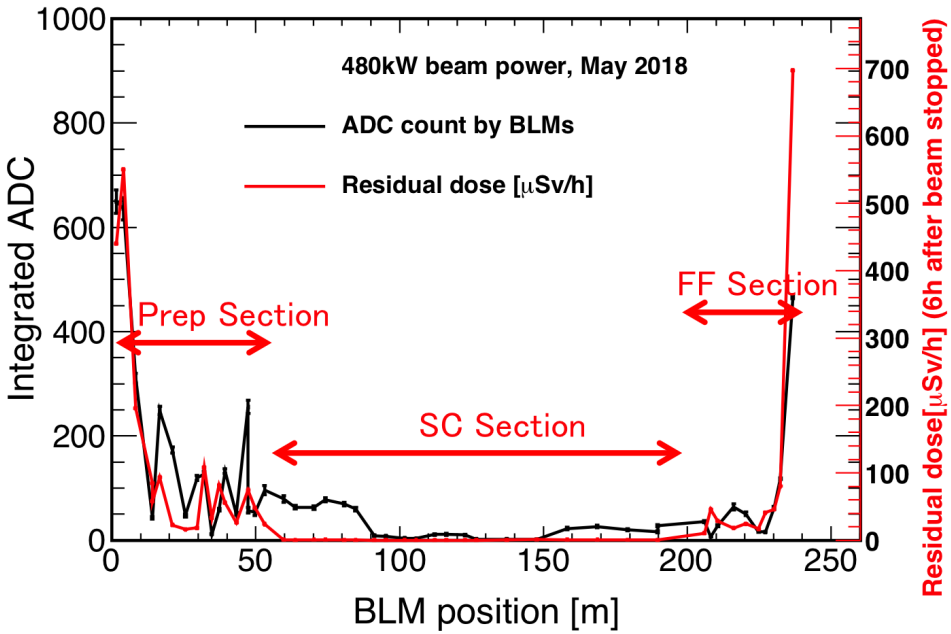
Remote manipulators in use at J-PARC



Planned LBNF remote manipulator cell

J-PARC Primary Beamline Maintenance Scheme Upgrade

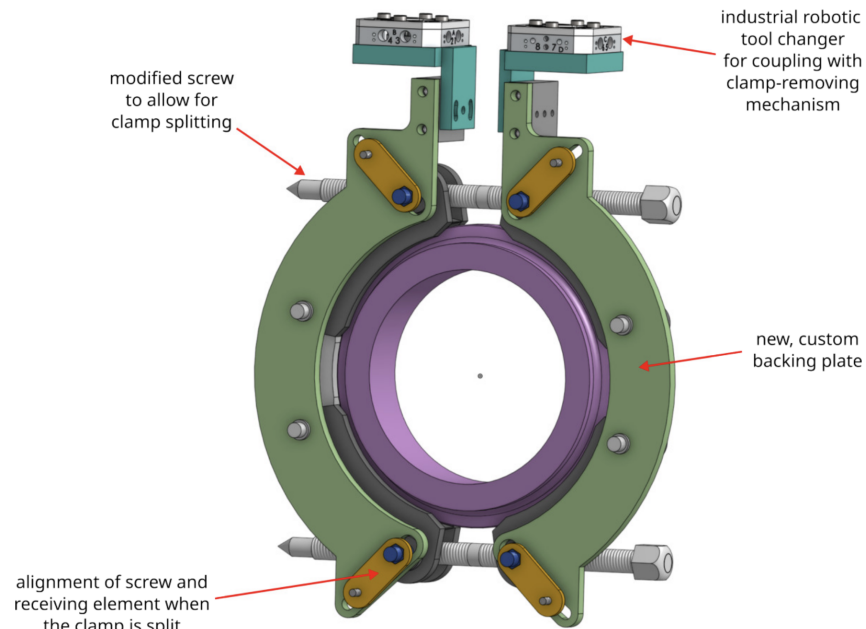
- Residual radiation dose at most downstream end of the J-PARC primary proton beamline is high
  - Due to backscattering from the neutrino production target, beam window, etc
  - Residual dose reaches >1mSv/hr on contact weeks after beam stop, even at 500kW beam power
    - Proportional to integrated POT – will increase with higher beam powers, longer running time



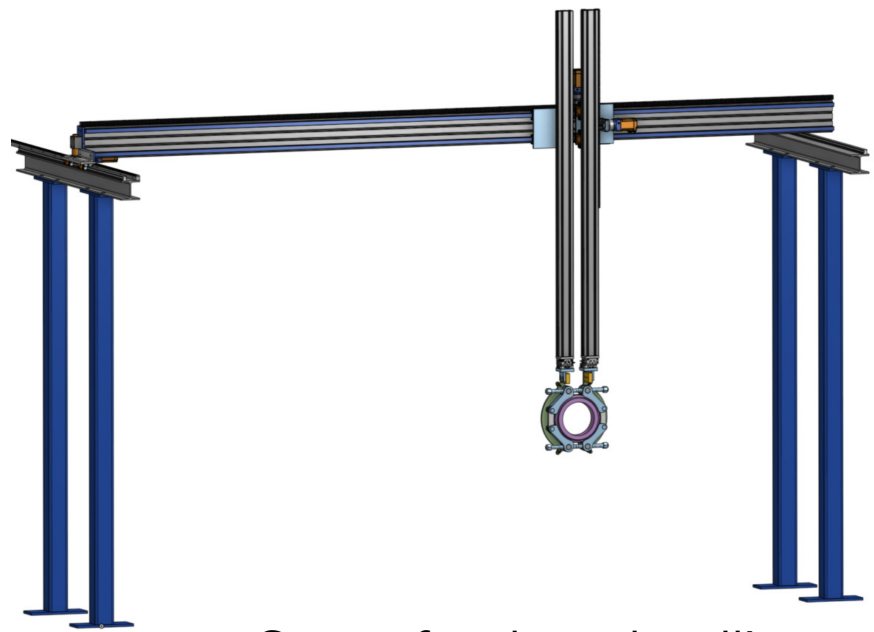
- Hands-on work won't be possible after some years of HK operation
- Long-term upgrade: move to fully remote maintenance scheme

J-PARC Primary Beamline Maintenance Scheme Upgrade

- At J-PARC, always planned for fully remote maintenance scheme at target station
  - Remote handling cell, remote manipulators installed before start of T2K
- Didn't plan for these levels of residual radiation at most downstream end of primary beamline
  - New remote maintenance scheme upgrade under development now for HK

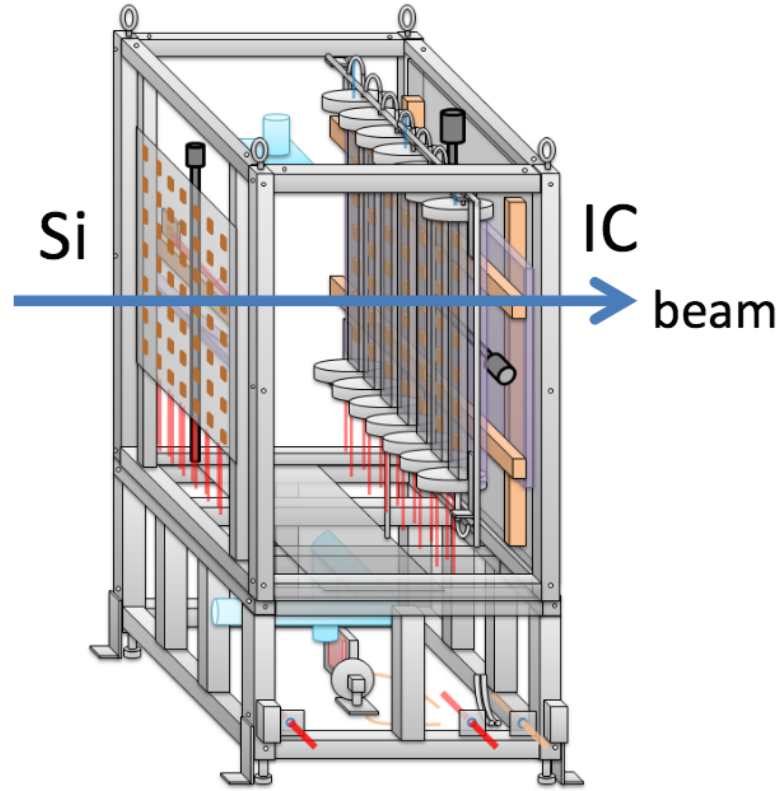


Remote clamp design

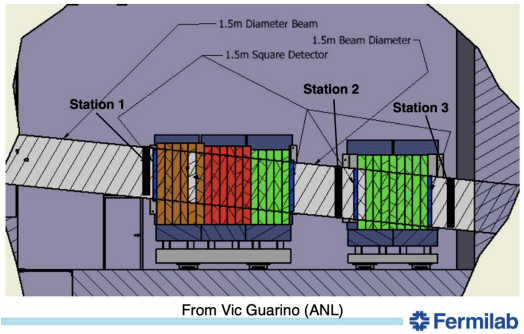

Gantry for clamp handling

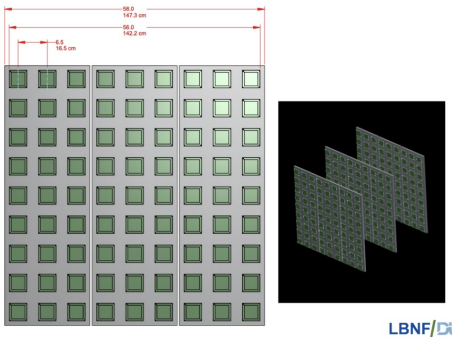
J-PARC Muon Monitoring Upgrades

- Measure tertiary muon beam profile downstream of the decay volume, beam dump ($>\sim$5 GeV muons)
  - Ensure alignment, healthiness of target, horns; proton beam position, angle at target; etc
- 2 redundant measurements of the muon beam profile, position using 7x7 arrays of sensors
  - Ionization chambers (IC)
  - Silicon photodiode sensors (Si)
- Now developing EMT (PMT w/out photocathode) as more robust sensor option
- Also developing MCT (MUMON Current Transformer) for muon sign measurement



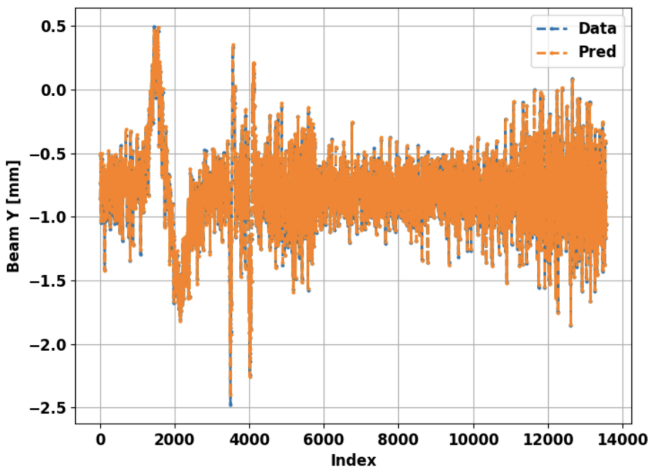
LBNF/DUNE Muon Monitors

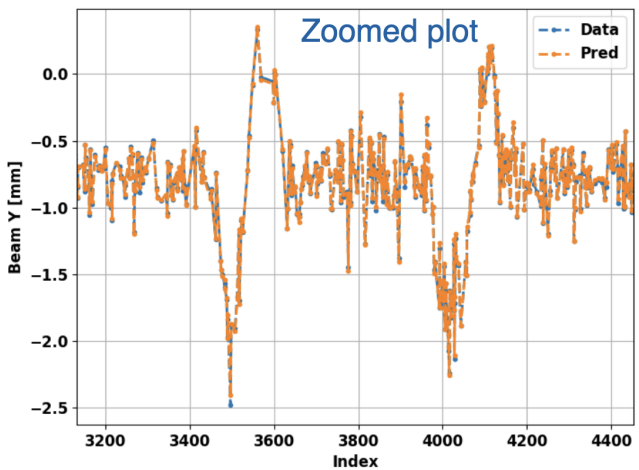




- LBNF has hadron monitor upstream of beam dump for secondary beamline alignment checks
- Multiple muon monitors with different amounts of upstream materials at NuMI and LBNF gives multiple measurements with different muon energies
  $\rightarrow$ Excellent constraint on operational parameters

Extremely precise prediction of NuMI operational parameters using 3x muon monitor information + Machine Learning:





NuFACT2022 (A. Wickremasinghe)

Conclusion

- Now entering an era of >1MW proton facilities for neutrino beam production
  - >1MW beam power established at NuMI in 2024
    - Plan for 1.2 → 2.4 MW for LBNF/DUNE
  - 830kW continuous operation + 950kW eq. beam power achieved at J-PARC in 2025
    - Plan for 1.3MW in 2027

- Need neutrino production beamlines capable of accepting these high-power proton beams
  - Design all beamline components ready for high power
  - Improve/optimize horn and target design to produce the highest quality neutrino beam

Stay tuned for more power (coming soon)!!

Backup Slides

Proton Beams for Neutrino Experiments

J-PARC neutrino beamline for the T2K + future HK experiments, etc.

- Running since: 2009
- Beam Energy: 30 GeV
- Beam Power: 800 kW (now) $\rightarrow$1.3 MW (HK)
- Beam Intensity: 2.6E14 ppp $\rightarrow$ 3.2E14 ppp
- Duty cycle: 2.48 s $\rightarrow$ 1.36 s (last year) $\rightarrow$ 1.28 s (this year) $\rightarrow$ 1.16 s (HK)
- Beam Bunches: 8
- Pulse Length: 4.2 μs
- Beam spot size at target: 4 mm

NuMI neutrino beamline @FNAL for the NOνA experiment, etc.

- Running since: 2005
- Beam Energy: 120 GeV
- Beam Power: 865 kW (design) $\rightarrow$ 1.018 MW (now)
- Beam Intensity: 5.7E13 ppp (now)
- Duty cycle: 1.333 s (design) $\rightarrow$ 1.067 s (now)
- Beam Bunches: 588
- Pulse Length: 11 μs
- Beam spot size at target: 1.3 mm $\rightarrow$ 1.5 mm

Proton Beams for Neutrino Experiments

J-PARC neutrino beamline for the T2K + future HK experiments, etc.

- Running since: 2009
- Beam Energy: 30 GeV
- Beam Power: 800 kW $\rightarrow$1.3 MW
- Beam Intensity: 2.6E14 ppp $\rightarrow$ 3.2E14 ppp
- Duty cycle: 2.48 s $\rightarrow$ 1.36 s (last year)$\rightarrow$ 1.28 s (this year) $\rightarrow$ 1.16 s (HK)
- Beam Bunches: 8
- Pulse Length: 4.2 μs
- Beam spot size at target: 4 mm

LBNF neutrino beamline @FNAL for the future DUNE experiment

- Under Design
- Beam Energy: 60-120 GeV
- Beam Power: 1.2 MW $\rightarrow$ 2.4 MW

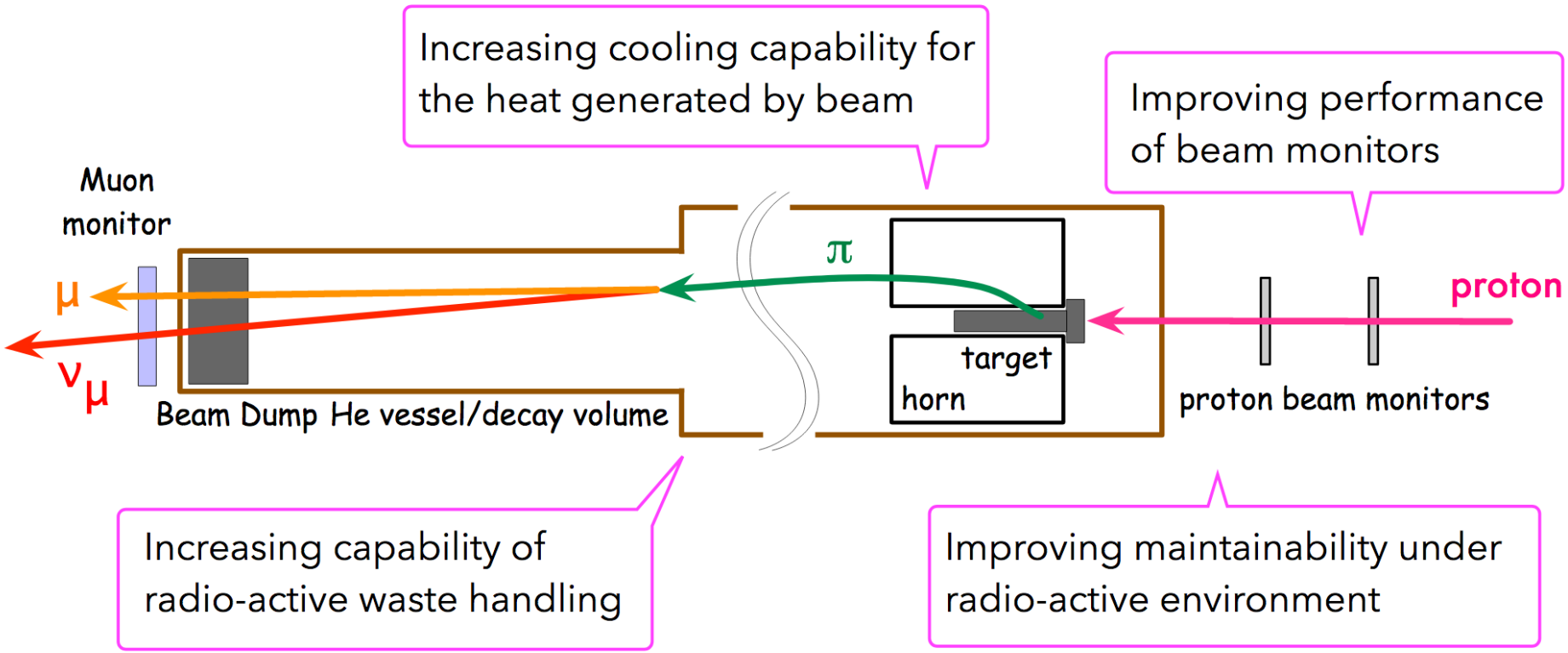
Under Design

J-PARC MR Upgrades Towards 1.3MW

JFY	2020	2021	2022	2023	2024	2025	2026	2027	2028
Event		Long Shutdown ⟷							
FX power [kW]	515	-	>700	800	900	>1000	>1100	>1200	1300
SX power [kW]	55	60–70	>80	>80	>80	>80	~100	~100	~100
Cycle time for Fast Extraction New Magnet PS	2.48s		1.32s	1.32s	1.32s	1.32s	<1.32s	<1.32s	1.16s
	Mass Production Installation/Test ▶								
RF system upgrade			⟷			⟷			
2nd RF system upgrade	⟷								
Collimator system		Add.colli. (3.5kW)							
Injection system FX system	Kicker PS improvement Septa manufacture Test ▶								
Beam Monitors (BPM circuits)	⟷								
SX: Diffuser/Bent crystal/VHF Local shield		⟷							

Prog. Theor. Exp. Phys. 2021, 033G01

J-PARC Neutrino Beamline Upgrades Towards 1.3MW

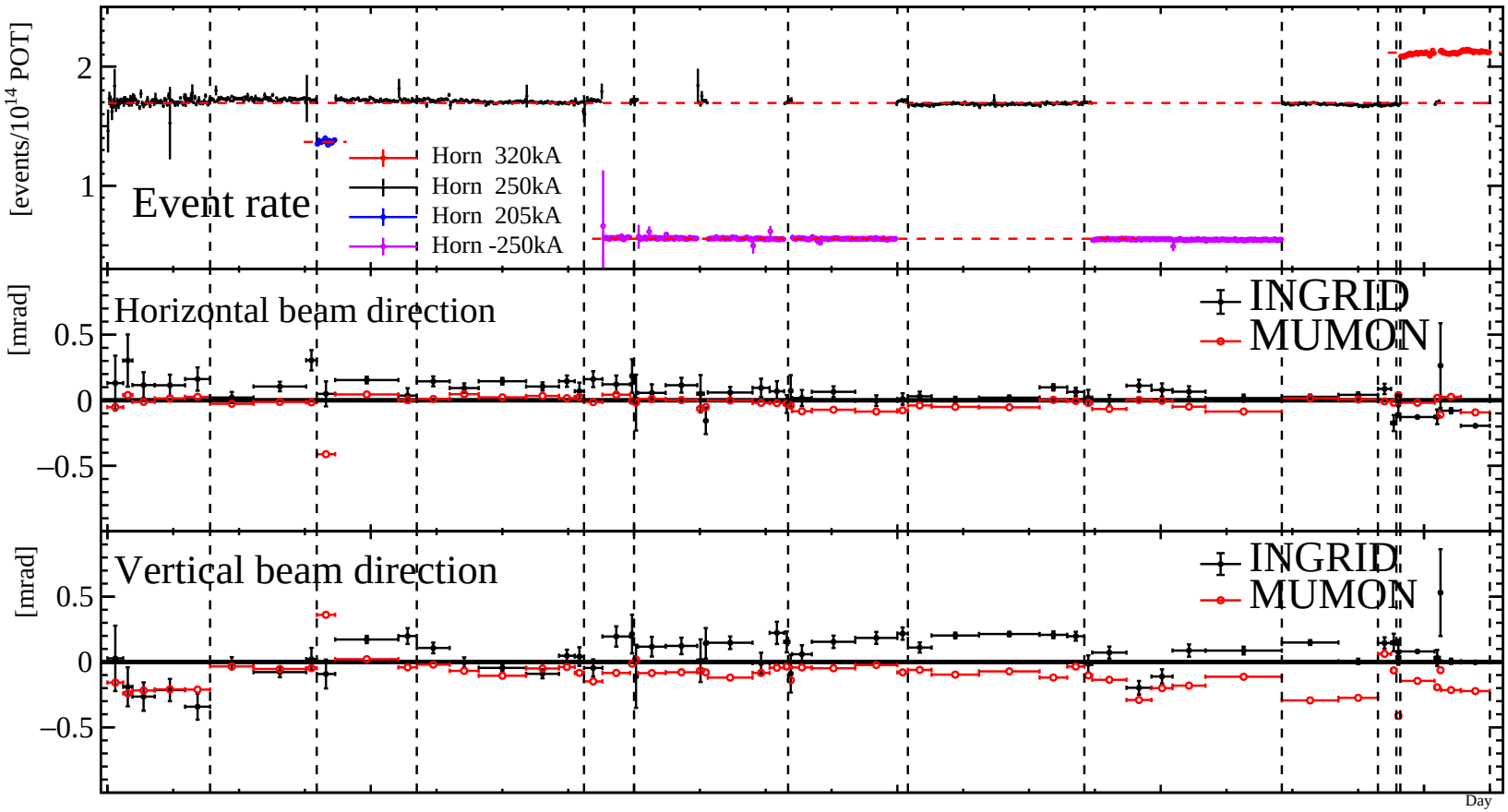


+ Accepting high repetition rate (~1Hz) beam

→ Upgrade DAQ + control system

Technical Design Report : arXiv:1908.05141

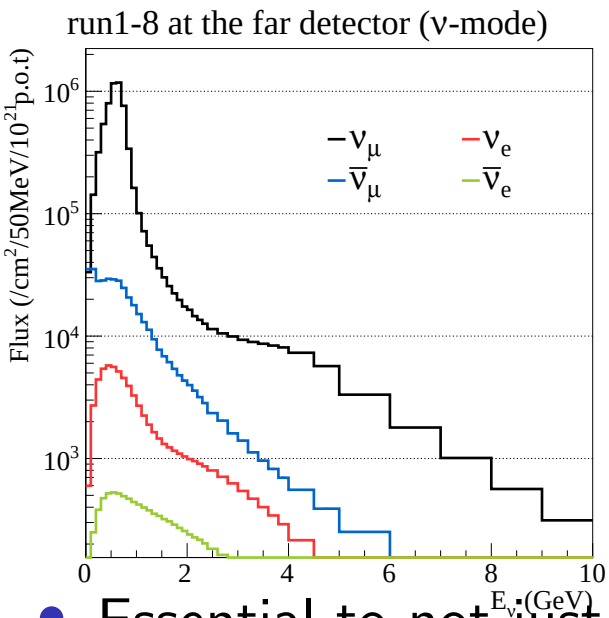
J-PARC Neutrino Beam Stability

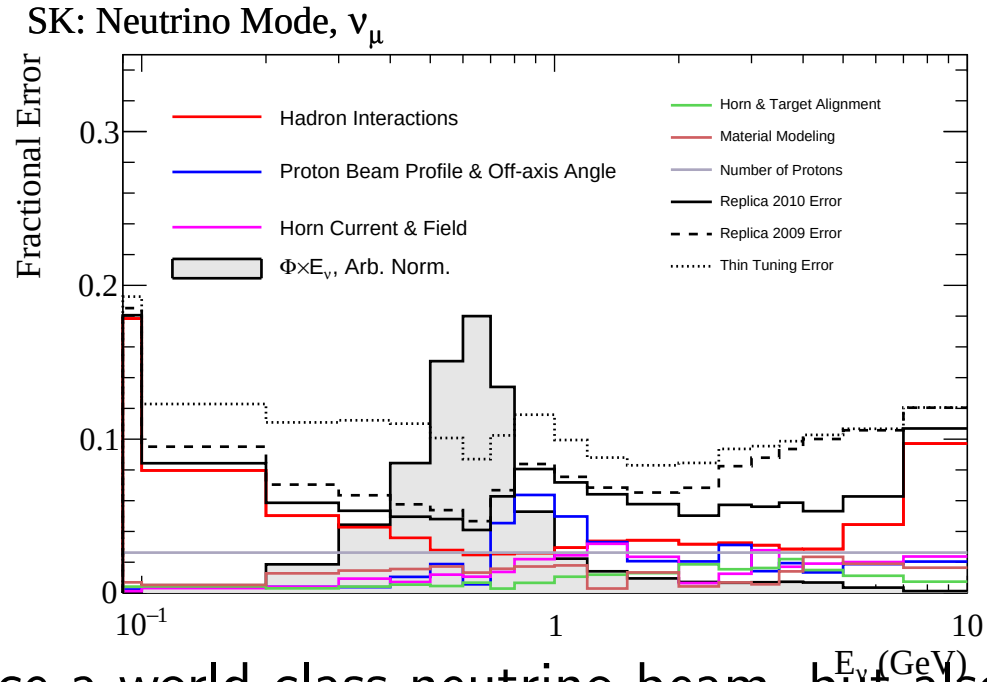


- Good stability of the J-PARC muon beam and neutrino beam position, angle, and event rate over >10 years running

Neutrino Flux Errors

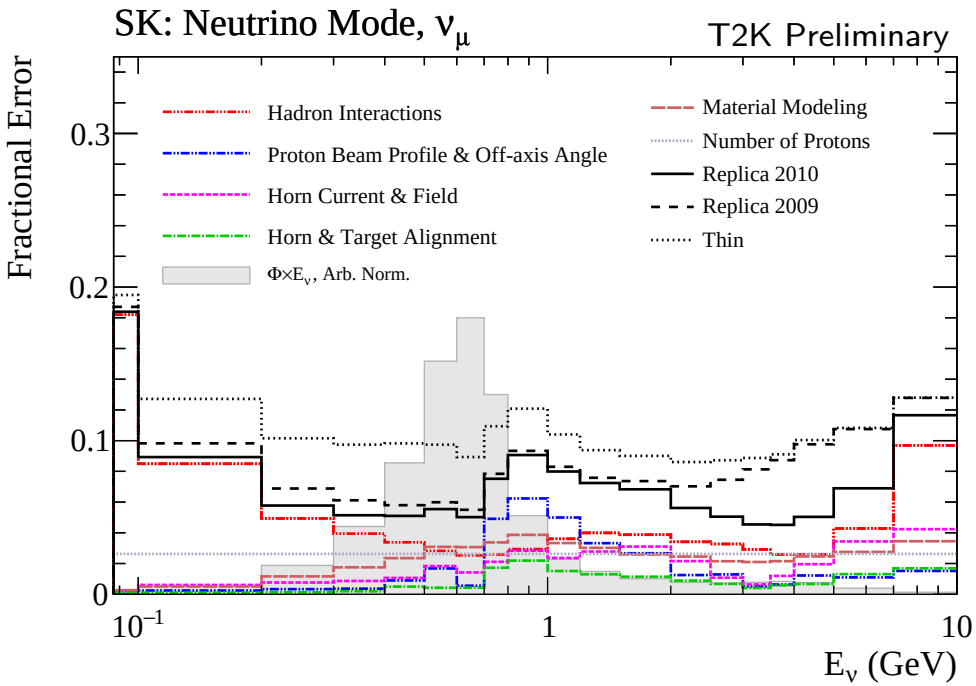
Example predicted T2K flux and errors :

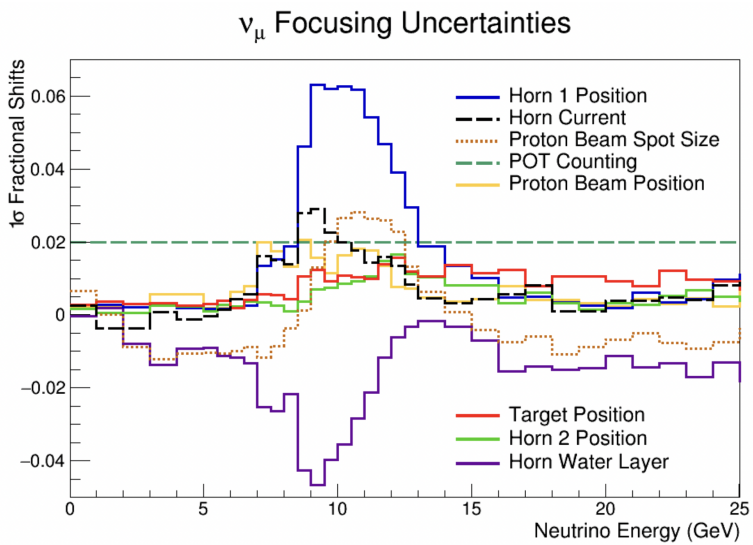




- Essential to not just produce a world-class neutrino beam, but also to precisely understand the neutrino flux
- The ν flux is predicted by simulations which take into account
  - Measured proton beam current, position, angle, profile
  - Measured neutrino beam angle
  - Measured Horn field, alignment
  - Hadron interactions inside + outside the production target
    - External constraints by NA61/SHINE experiment @CERN (in use + future measurements), EMPHATIC experiment @FNAL (future)
- Beamline designed with this in mind

Example Flux Errors



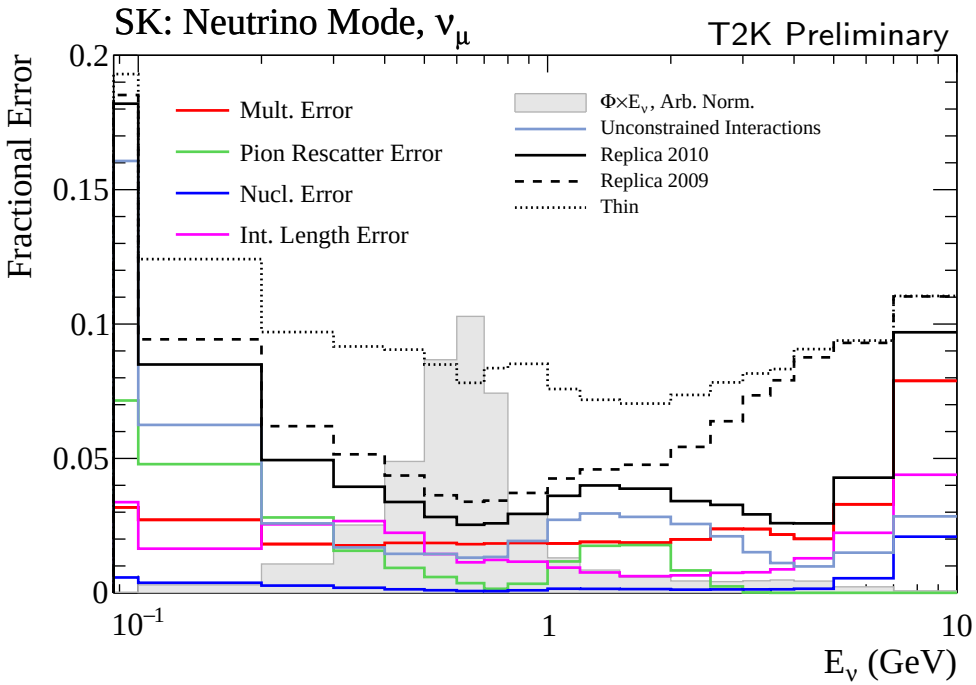


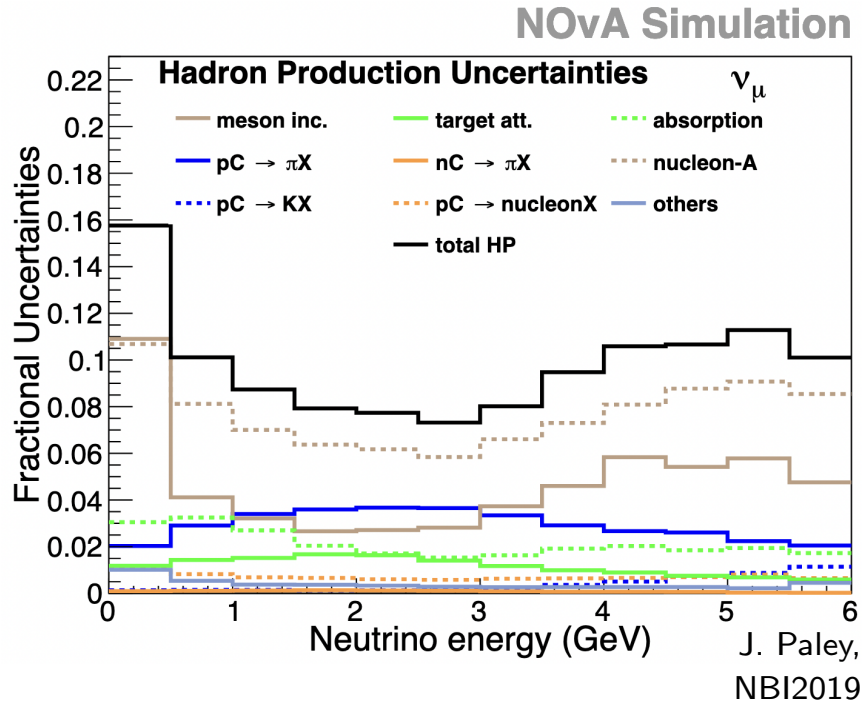
Medium Energy neutrino flux at MINERvA/on-axis detector

A. Bashyal, 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

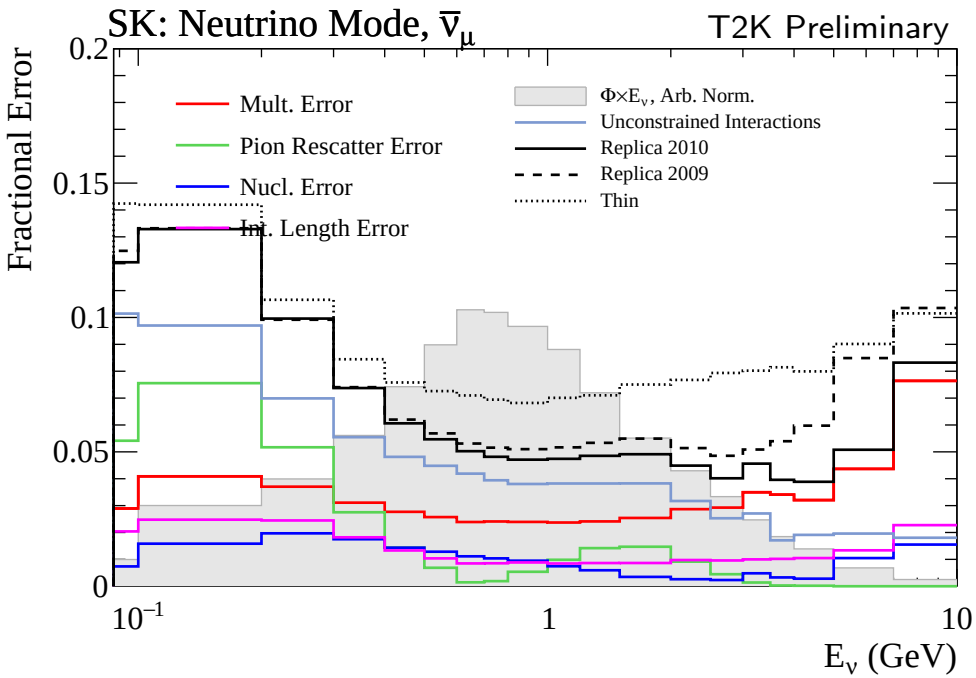
Example Hadron Production Flux Errors

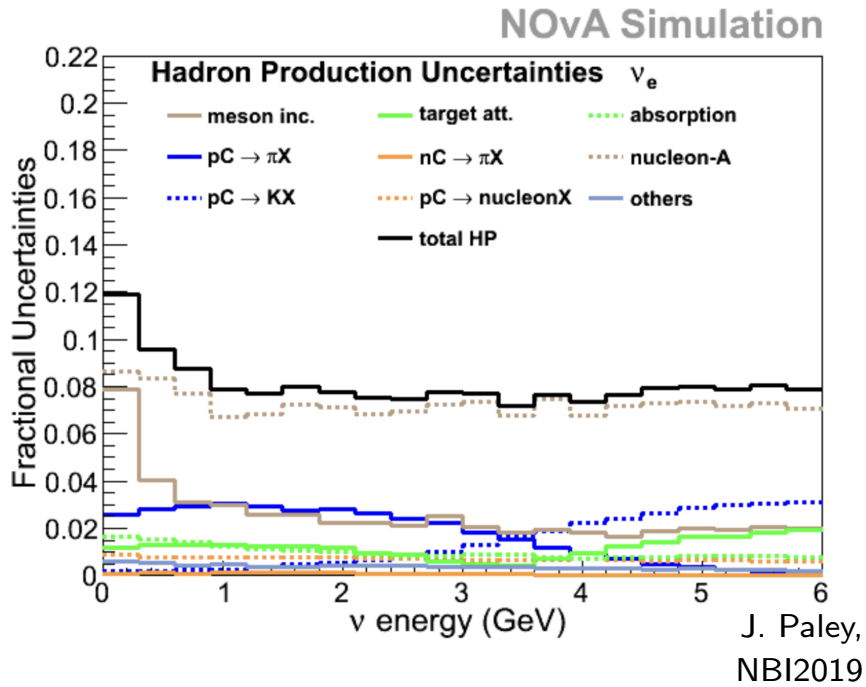




- Hadron production errors are coming from numerous relatively small sources – non-trivial to reduce (although we're working on it!)
- Especially, interactions not constrained by external measurements ("Unconstrained interactions") are becoming important
  - Interaction of low-momentum particles on materials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

Example Hadron Production Flux Errors

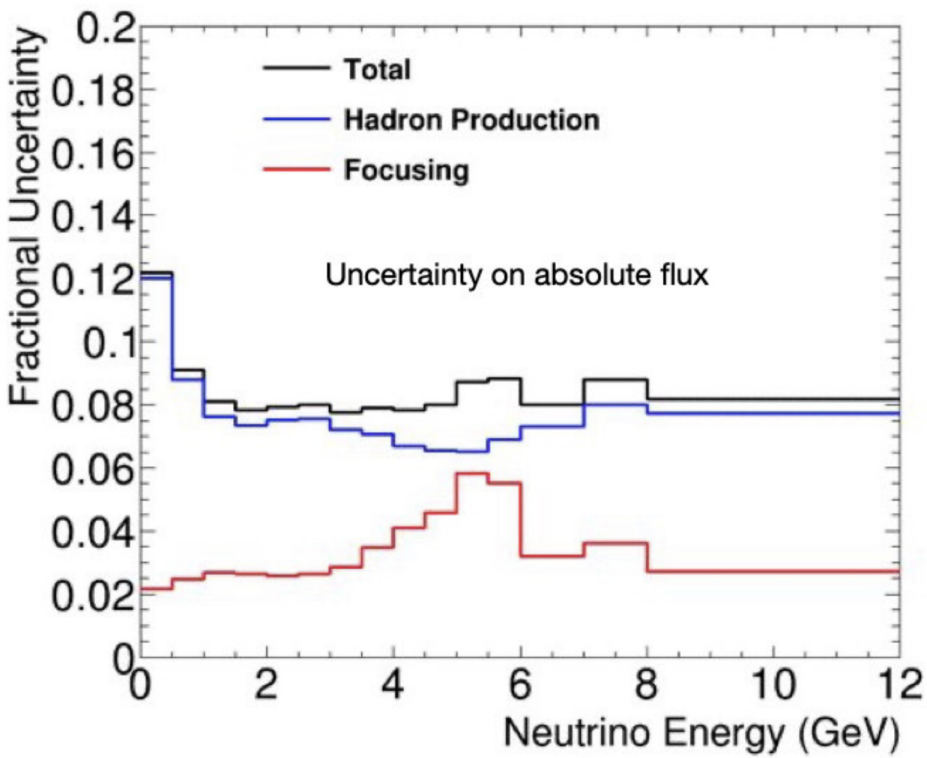




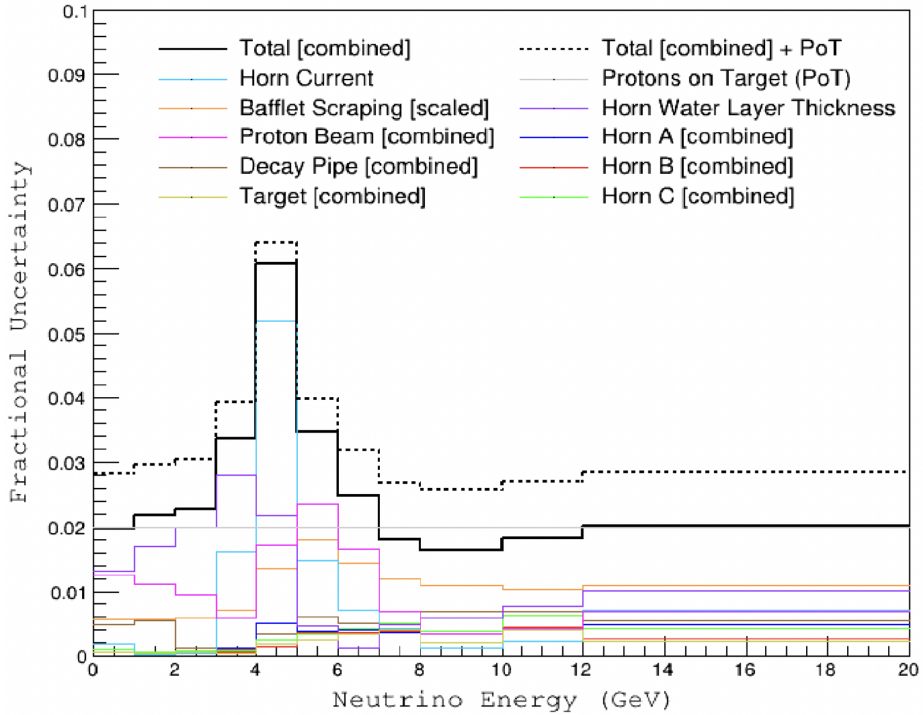
J. Paley, NBI2019

- 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

LBNF/DUNE Flux Errors



Total flux uncertainties



Hardware flux uncertainties

S. Ganguly, NBI2024

- Expected total and hardware-related flux uncertainties for LBNF/DUNE