Neutrino flux predictions from the J-PARC beam

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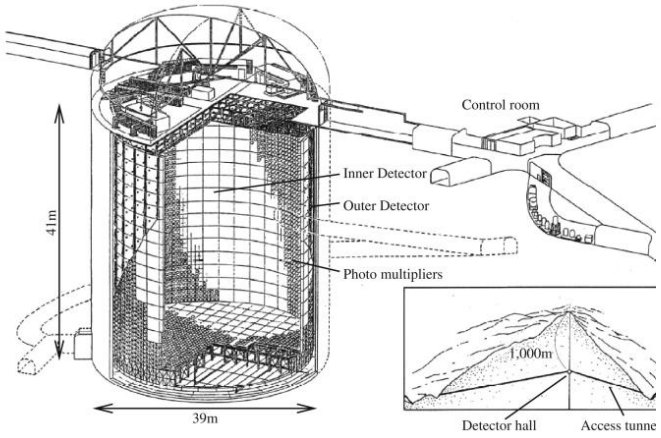
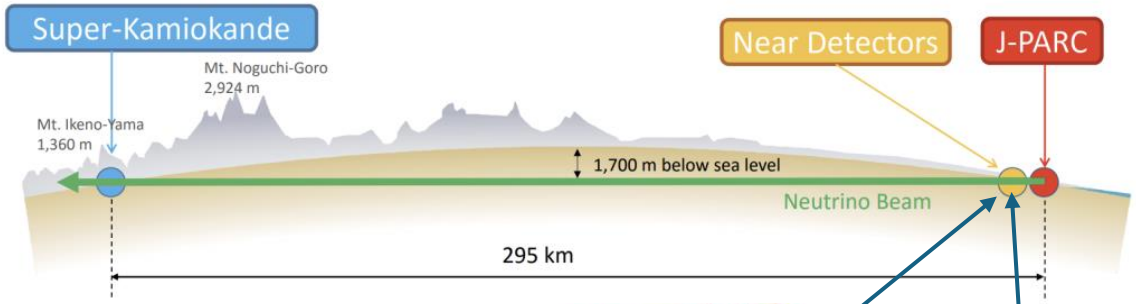
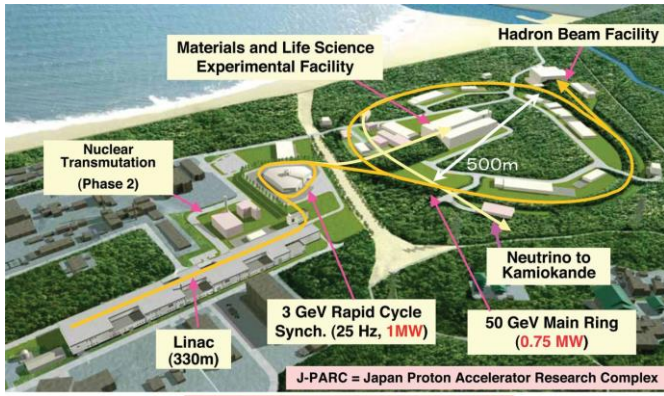
T2K Experiment

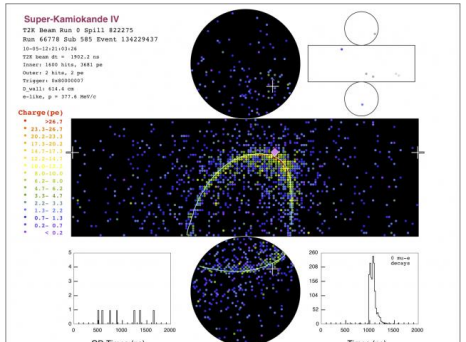
- Long baseline accelerator neutrino oscillation experiment in Japan
- Neutrino/Antineutrino beam created at J-PARC with 30 GeV proton beam
- Detected 280 m downstream (unoscillated) at the near detectors and 295 km away (after oscillations) by Super Kamiokande via Cherenkov radiation



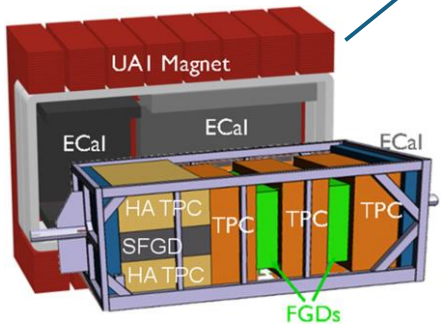


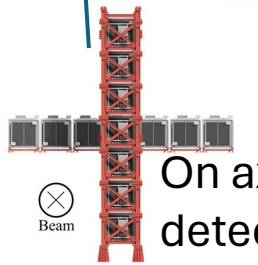


Joint Project between KEK and JAEA



Upgraded near detector suite
2.5 degrees off axis

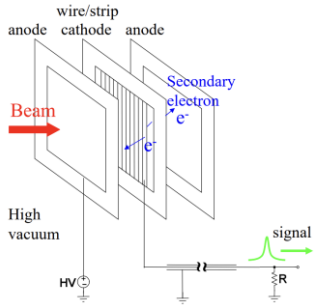




On axis neutrino detector

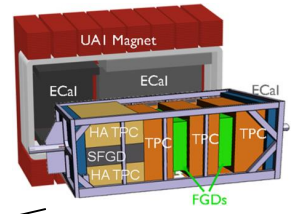
Neutrino Beam Production

CT, SSEM, Horn current, etc.
➔ Input for flux Monte Carlo



Segmented Secondary Emission Monitor (SSEM): Proton beam profile

Optical Transition Radiation Monitor (OTR)



Pions decay along decay volume via $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\overline{\nu_{\mu}}$

To ND/SK

Final Focusing Magnets

30 GeV Proton Beam

3 Focusing Horns

$\pi^{\pm}$

$\overline{K}^{\pm}$

$\nu_{\mu}/\overline{\nu_{\mu}}$

2.5°

$\mu^{\pm}$

Current Transformer: # of protons

Collimator

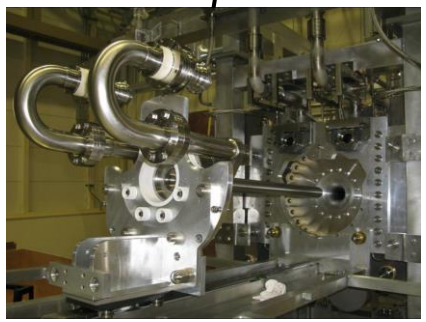
Target

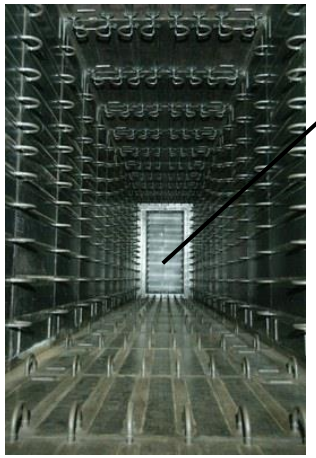
$\pi^{\mp}$

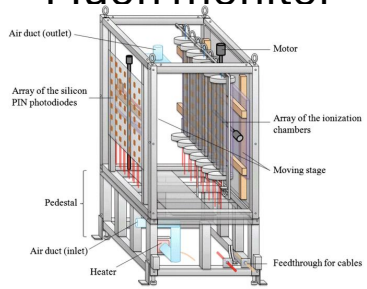
Wrong sign pions are defocused

Beam Dump

Muon monitor







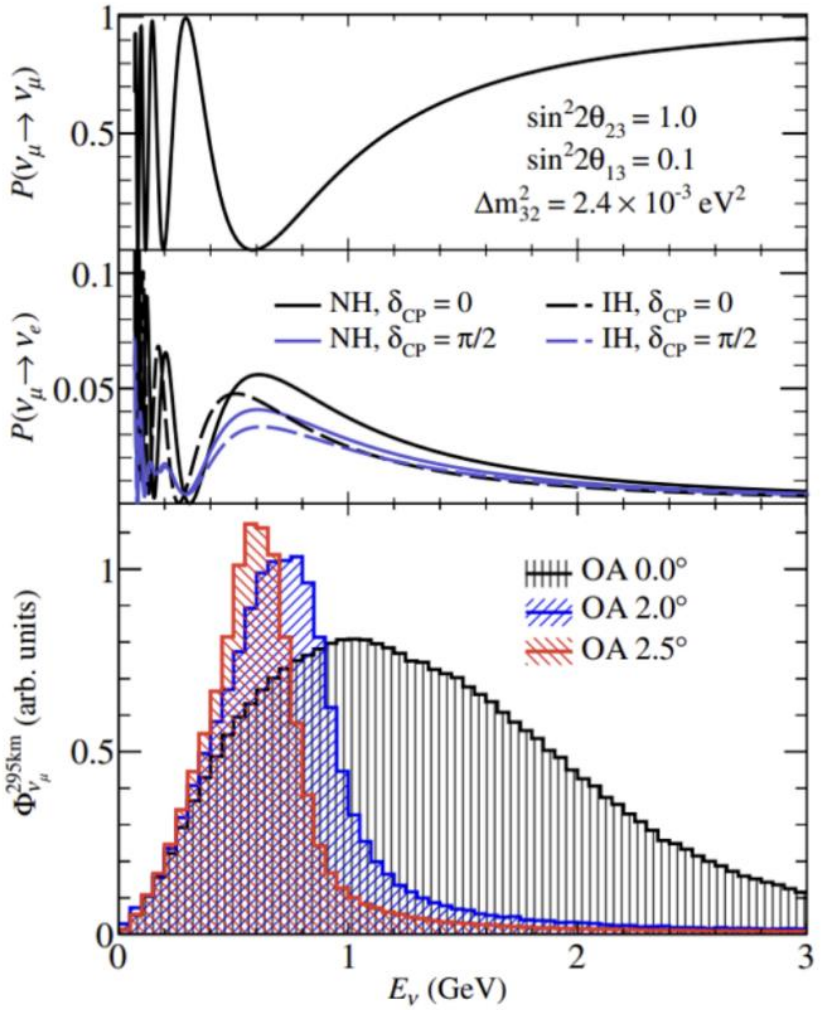
Off Axis Method

- SK is located 2.5 degrees off beam axis
- We can restrict neutrino energy to near oscillation maximum
- Main interaction at 0.6 GeV is CCQE
- Off axis angle (and thus neutrino beam direction) must be well controlled

2 neutrino oscillation probability

$$P(\nu_\alpha \to \nu_\beta) \approx \frac{1}{4}\sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{21}}{4E}L\right)$$

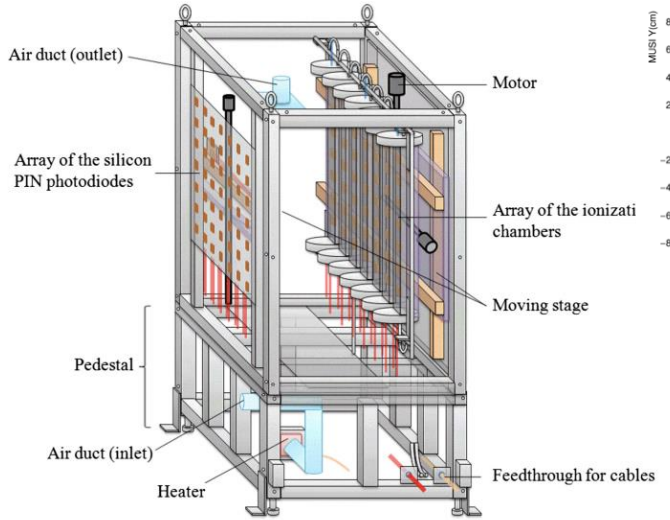
$$\approx \frac{1}{4}\sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2_{21}[\mathrm{eV}]}{E[\mathrm{GeV}]}L[\mathrm{km}]\right)$$

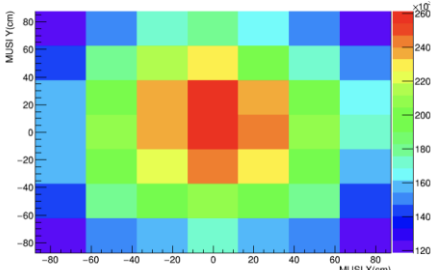


Beam Monitors

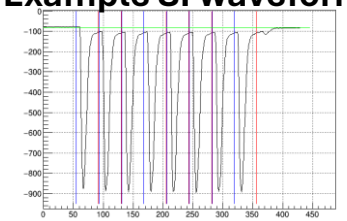
Muon Monitor:

- Located just downstream of the beam dump
- Measures muons created coincident with neutrinos
- Provides spill-by-spill measurement of beam direction
- Beam direction measured within 0.3 mrad





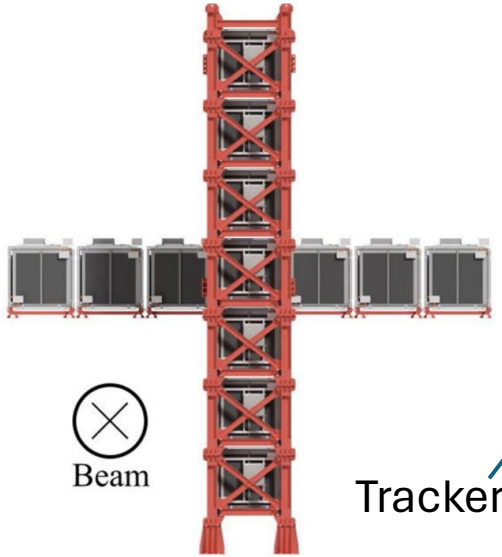
Example SI waveform



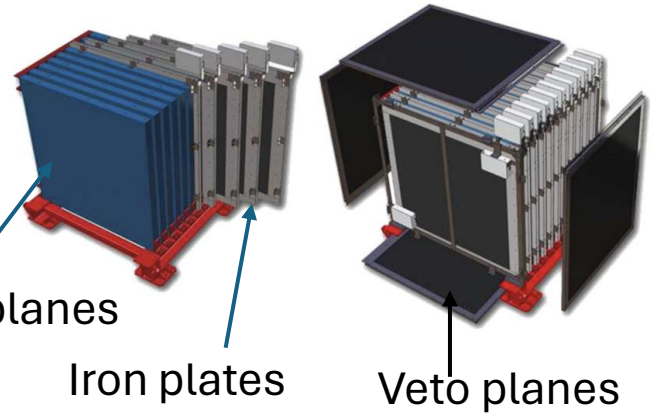
- 7x7 grid of Si PIN photodiodes and ionization chambers
- For >1 MW beam intensity, new sensor development is underway to replace Si sensors

INGRID:

- On axis neutrino detector
- Provides day-by-day measurement
- Measures beam direction, stability, intensity
- Modules consists of iron plates and scintillators in a “+” shape
- Constrains flux for simulation

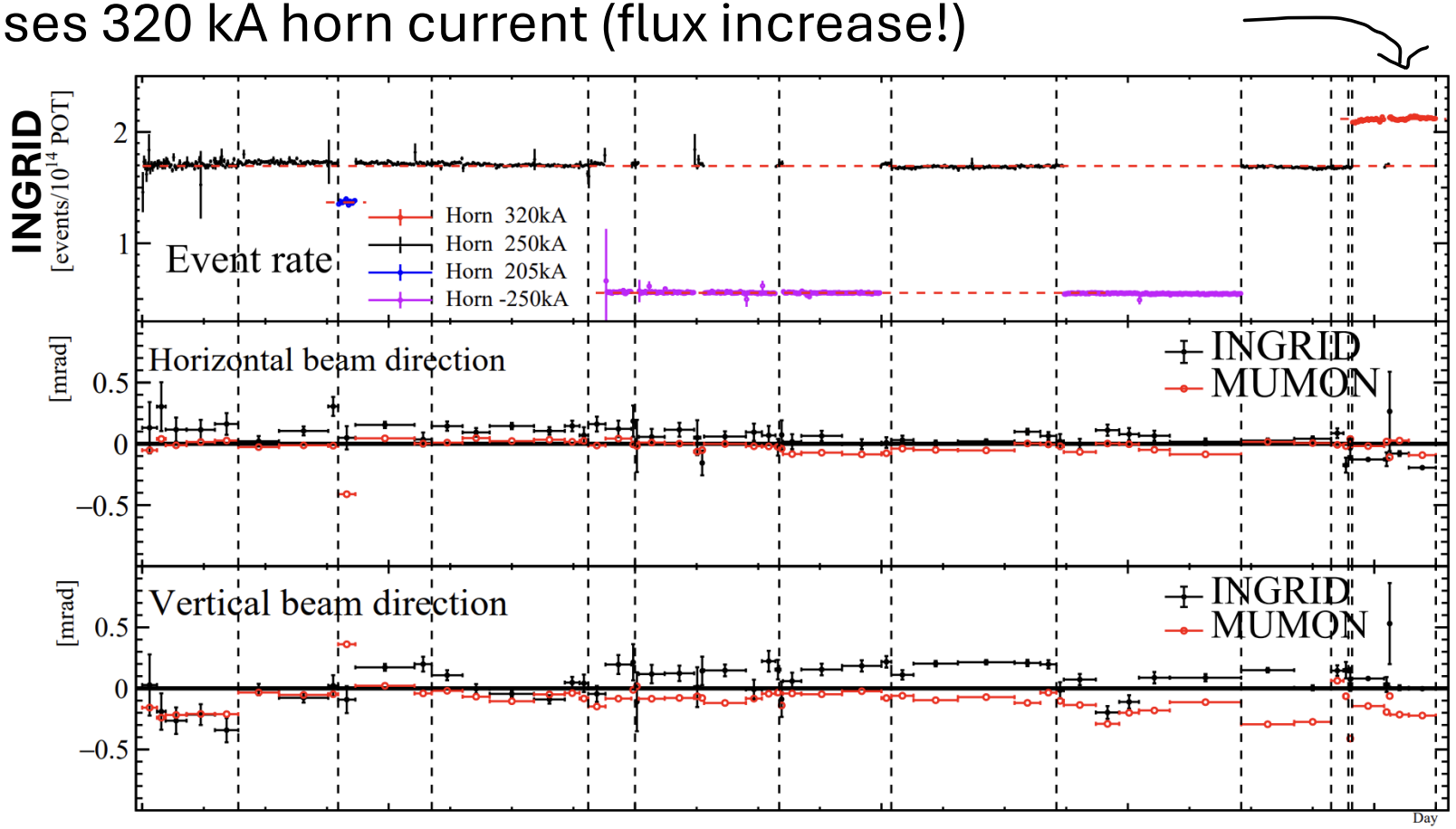


Inside an INGRID module



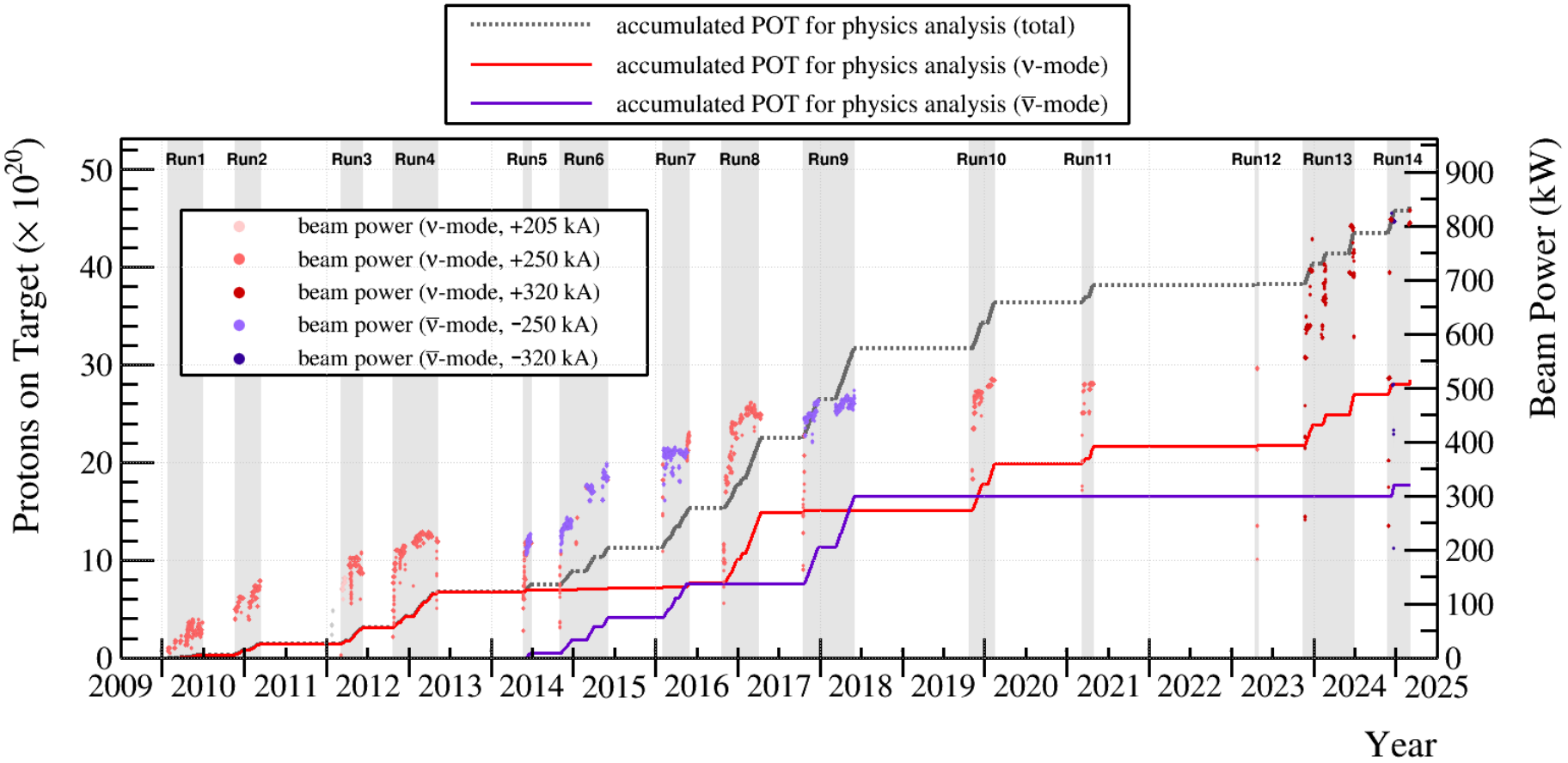
Beam Stability

- Beam direction is stable within $\pm$0.5 mrad
- Run 13 uses 320 kA horn current (flux increase!)



Beam History

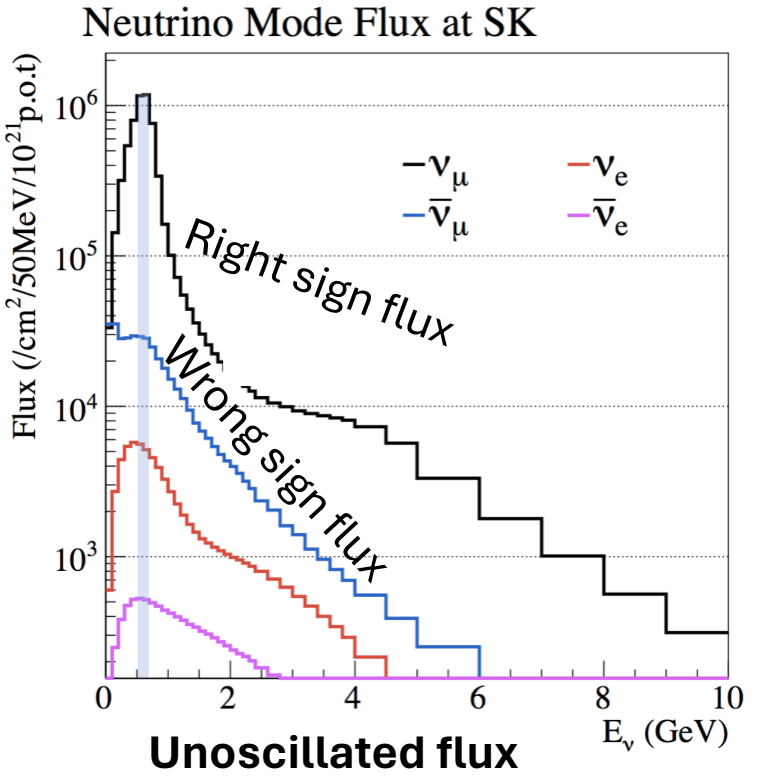
- Total accumulated POT: 4.62×10^{21} (ν mode: 2.85×10^{21}/ $\bar{\nu}$ mode: 1.77×10^{21})
- Run 13 and Run 14 use 320 kA horn current
  - (~10% ν flux increase! + decrease in wrong sign component)



Flux Prediction Purpose

- For oscillation analysis we compare event rates:
- $N_{\nu_e}^{SK} = \mathrm{P}_{\nu_\mu \to \nu_e} \times \Phi_{\nu_\mu}^{SK} \times \sigma_{\nu_e}^{SK} + \mathrm{P}_{\nu_e \to \nu_e} \times \Phi_{\nu_e}^{SK} \times \sigma_{\nu_e}^{SK}$
- $N_{\nu_\mu}^{SK} = \mathrm{P}_{\nu_\mu \to \nu_\mu} \times \Phi_{\nu_\mu}^{SK} \times \sigma_{\nu_\mu}^{SK} + \mathrm{P}_{\nu_e \to \nu_\mu} \times \Phi_{\nu_e}^{SK} \times \sigma_{\nu_e}^{SK}$
- $N_{\nu_{\mu/e}}^{ND280} = \Phi_{\nu_{\mu/e}}^{ND280} \times \sigma_{\nu_{\mu/e}}^{ND280}$

➔We need to have a strong prediction on flux to constrain oscillation parameters



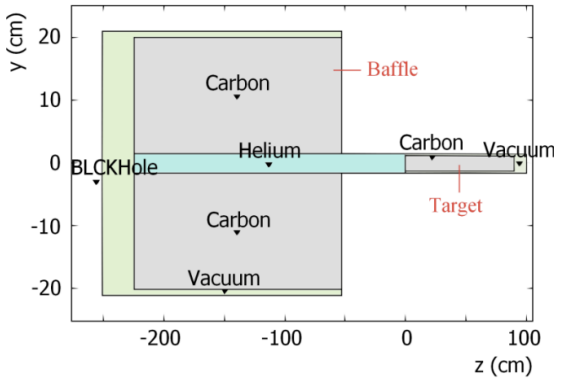
Unoscillated flux

JNUBEAM

- GEANT3 based simulation using GCALOR for hadron interactions
- FLUKA is used to simulate region around target, and particles exiting region are fed into JNUBEAM
- Comparing physics lists in FLUKA leads to different predictions on flux depending on hadron production

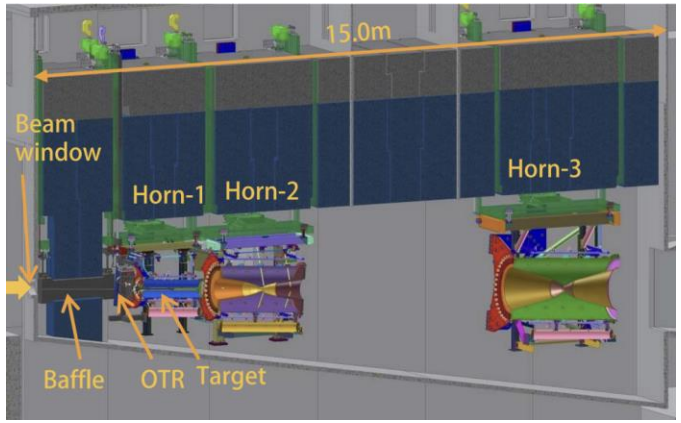
➔We need to constrain hadron production with external experiment

Geometry in FLUKA



JNUBEAM imports particles exiting FLUKA region

JNUBEAM includes detailed geometry, horn system and magnetic fields



NA61/SHINE

- Data taken with T2K thin target and replica target

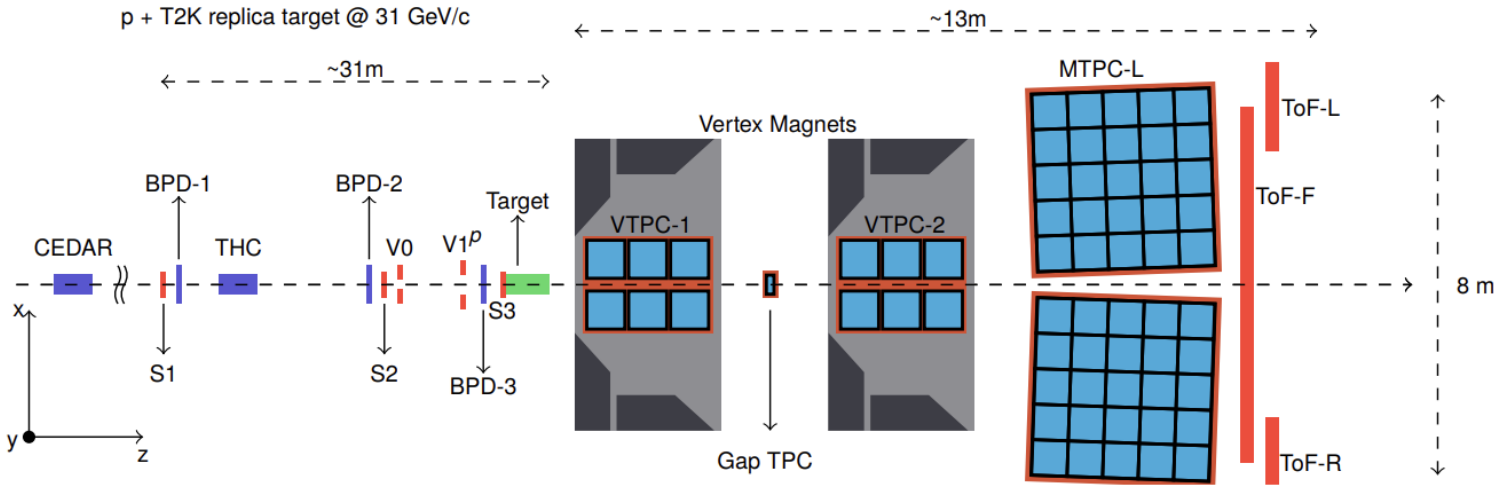
Thin target [2 cm]: thin graphite target

Replica target [90 cm]: replica of T2K graphite target

➔We can tune the flux from JNUBEAM based on this data

NA61 2007 thin-target dataset
Phys. Rev. C 84, 034604 (2011)
Phys. Rev. C 85, 035210 (2012)
NA61 2009 thin-target dataset
Eur. Phys. J. C 76, 84 (2016)
NA61 2009 replica-target datase
Eur. Phys. J. C 76, 617 (2016)
NA61 2010 replica-target datase
Eur. Phys. J. C 79, 100 (2019)

NA61/SHINE w/ replica target top view



Data taking runs

Beam + Graphite target	Mom (GeV/c)	year	Data	POT ($\times 10^6$)
p+TT	31	2007	$\pi^{\pm}, K^{+}$	0.7 (pilot run)
p+TT	31	2009	$\pi^{\pm}, K^{\pm}, K^0_S, p$	5.4
p+T2K RT	31	2007	$\pi^{\pm}$	0.2 (pilot run)
p+T2K RT	31	2009	$\pi^{\pm}$	2.8
p+T2K RT	31	2010	$\pi^{\pm}, K^{\pm}, p$	10

Flux Tuning

In target interactions:

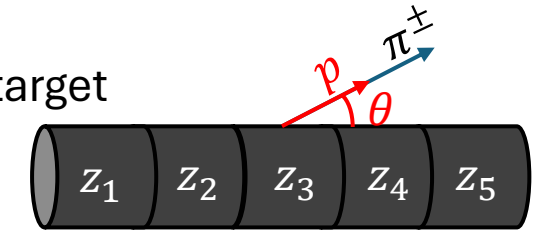
- Apply weights based on NA61/SHINE replica target data

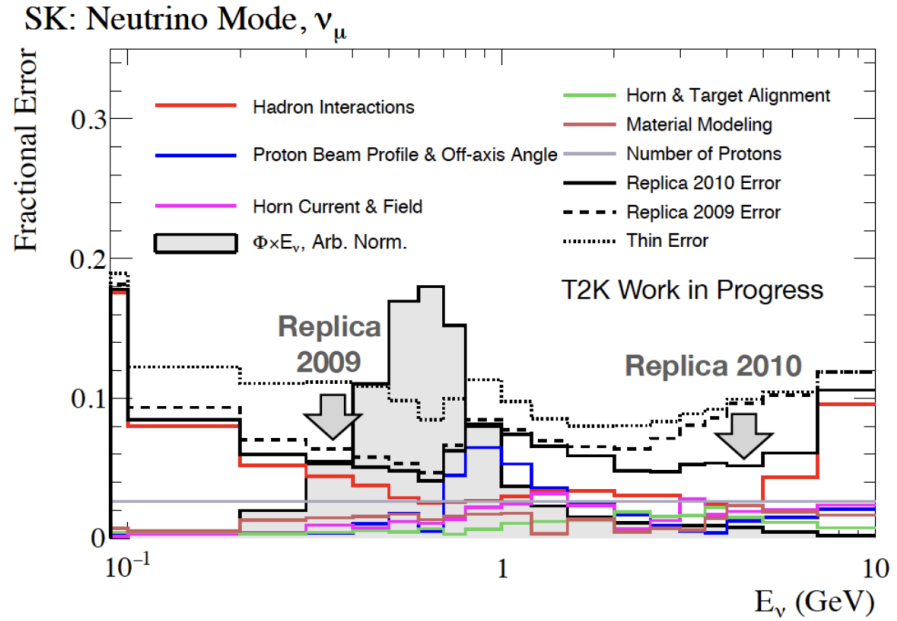
Out of target interactions:

- Low momentum interactions on materials other than graphite
- Large uncertainties, loosely constrained by current data sets
- Active area of development

Replica target method: segment target

➔ Apply weight based on p, θ, z_i on particles exiting target





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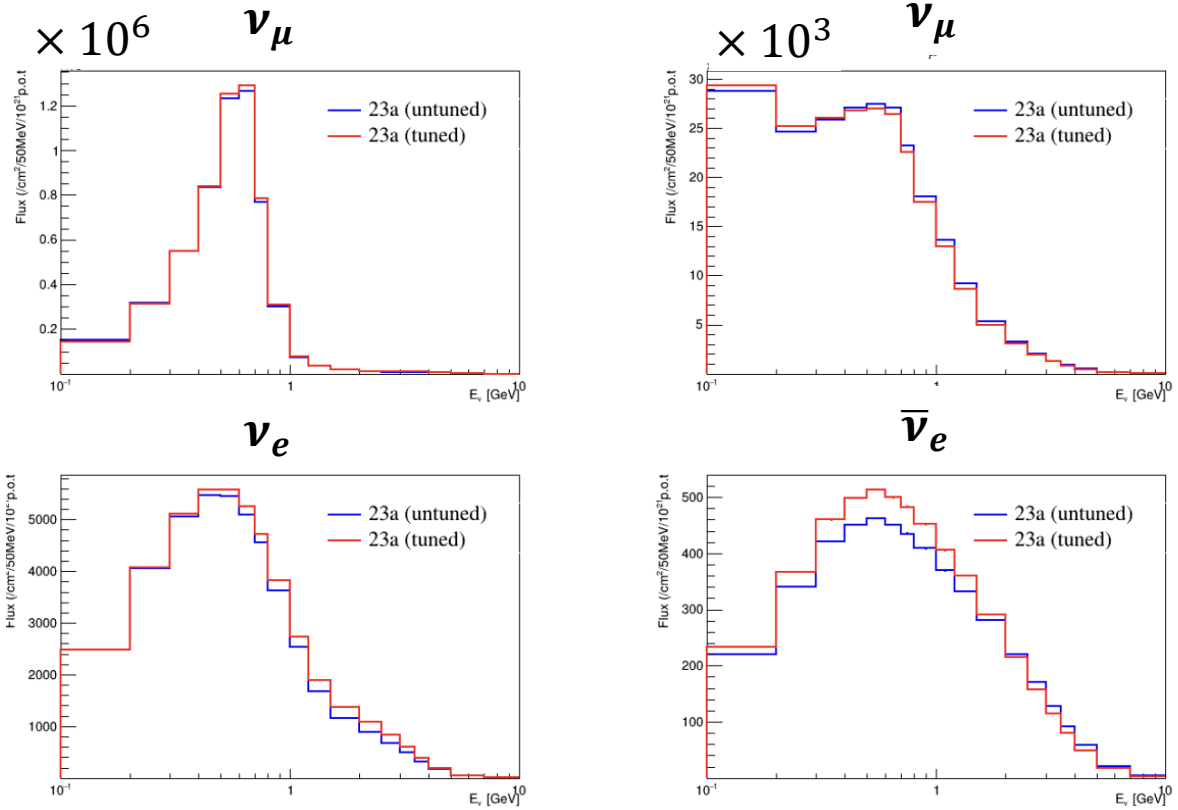
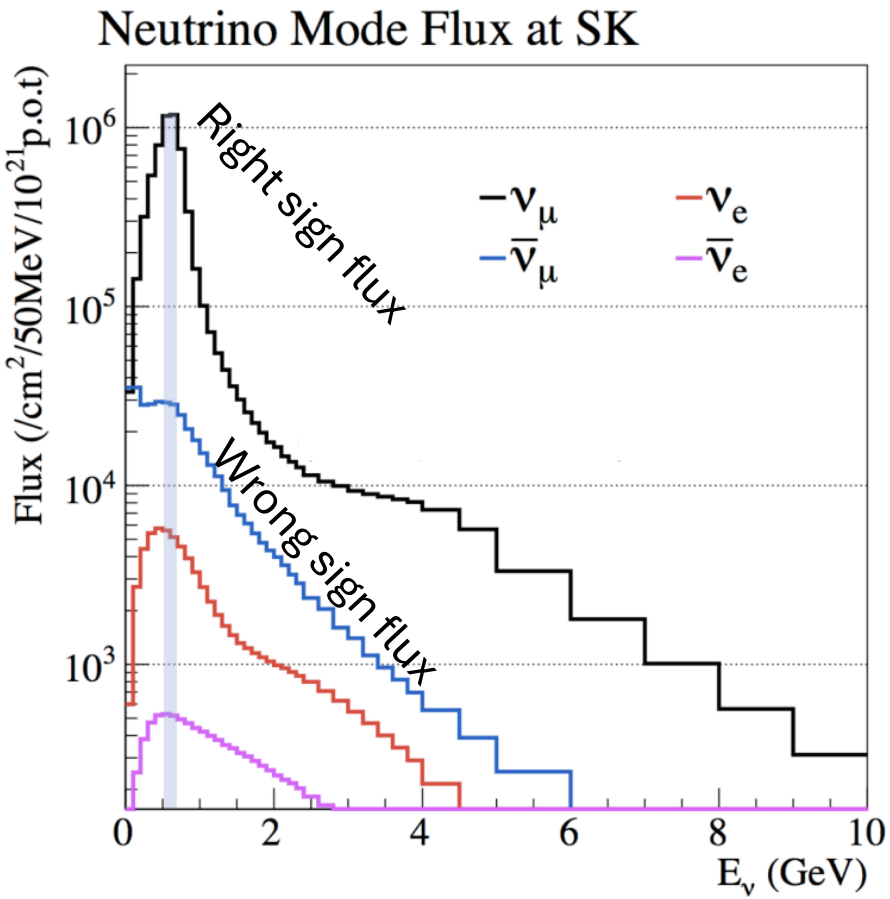
Flux Tuning

Tuned vs untuned flux at 320 kA

Neutrino Mode



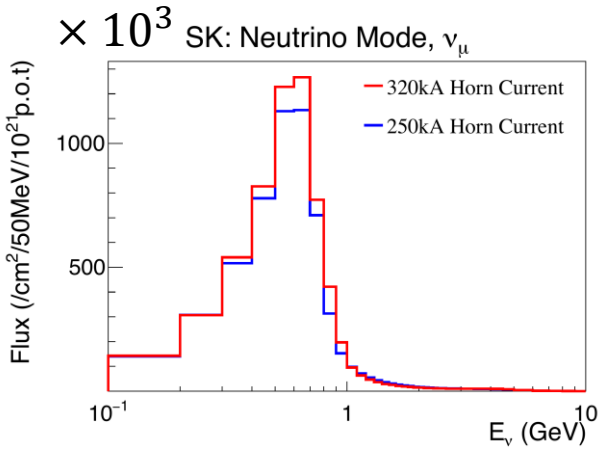


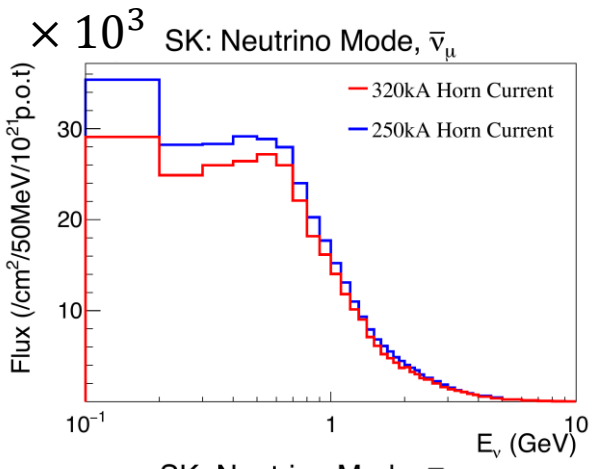
Horn current: 250 kA vs 320 kA

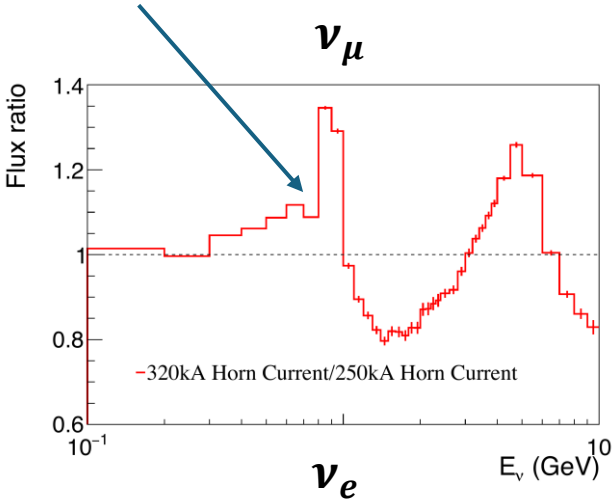
- Effect of horn current

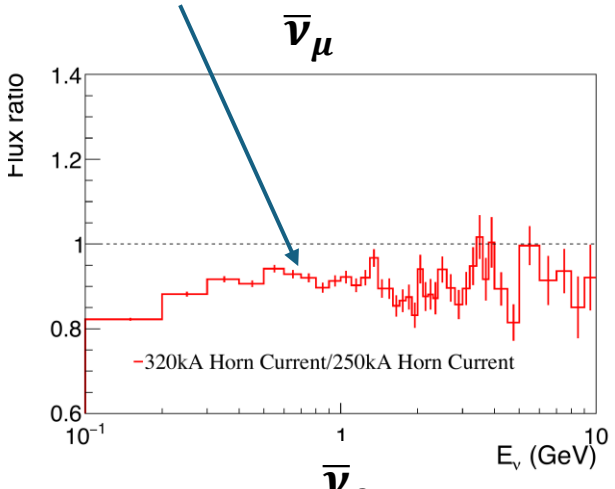
Higher flux at peak energy

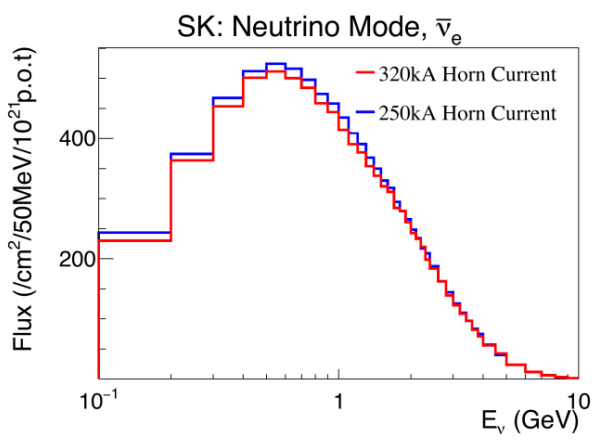
Greater wrong sign suppression

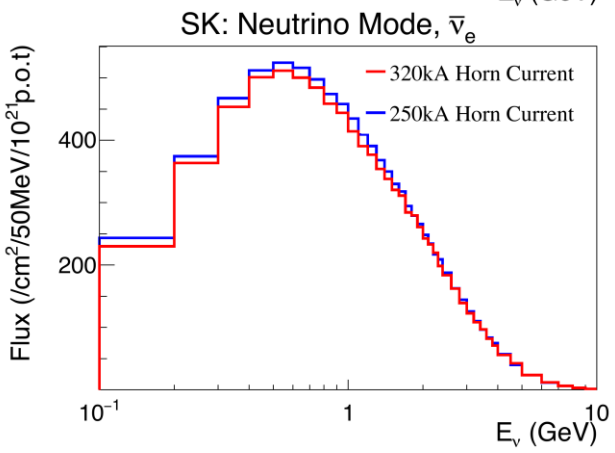


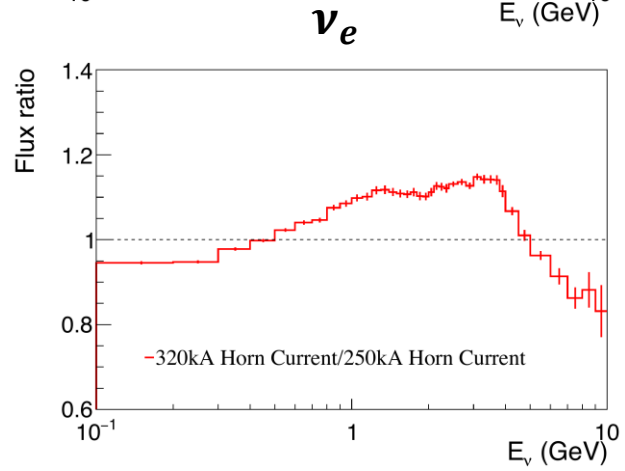


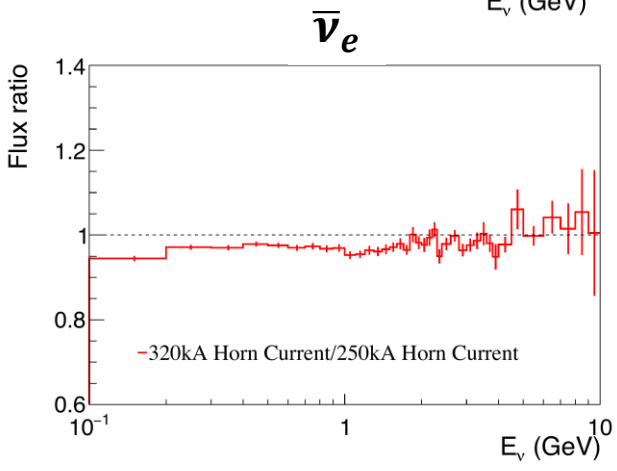








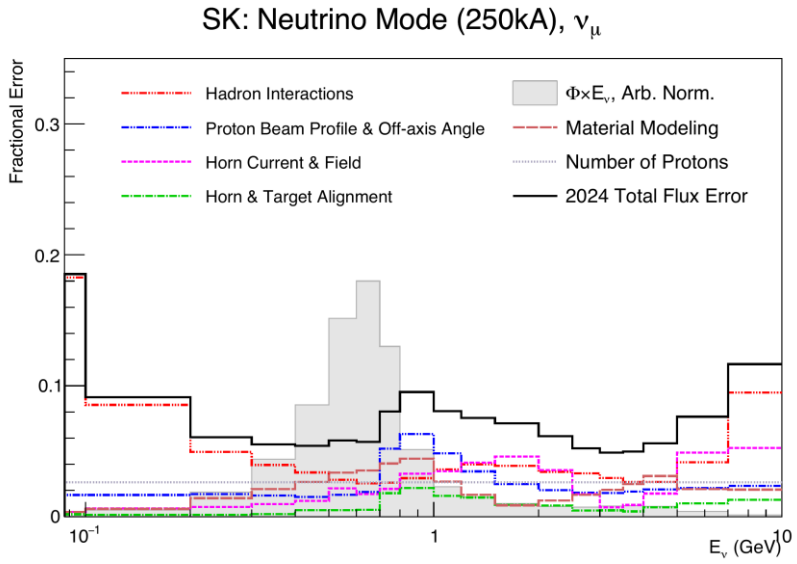


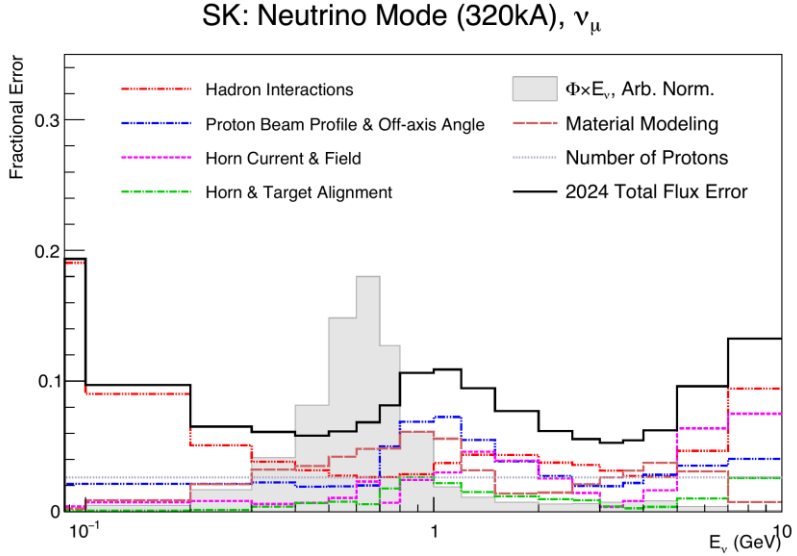


Flux Errors

Dominant errors:

- High/low energies - Hadron interactions: π or K re-scattering
  - ➔Can be reduced with low energy hadron production data: EMPHATIC, low energy NA61 programme
- Flux peak - Material modelling: cooling water distribution added (π absorption/scattering)
- Above peak - Proton beam: may be constrained by INGRID/muon monitor
- Proton beam profile uncertainty proportion are increased at 320 kA
- Improvements to systematics are very important for HK era! Lots of active development



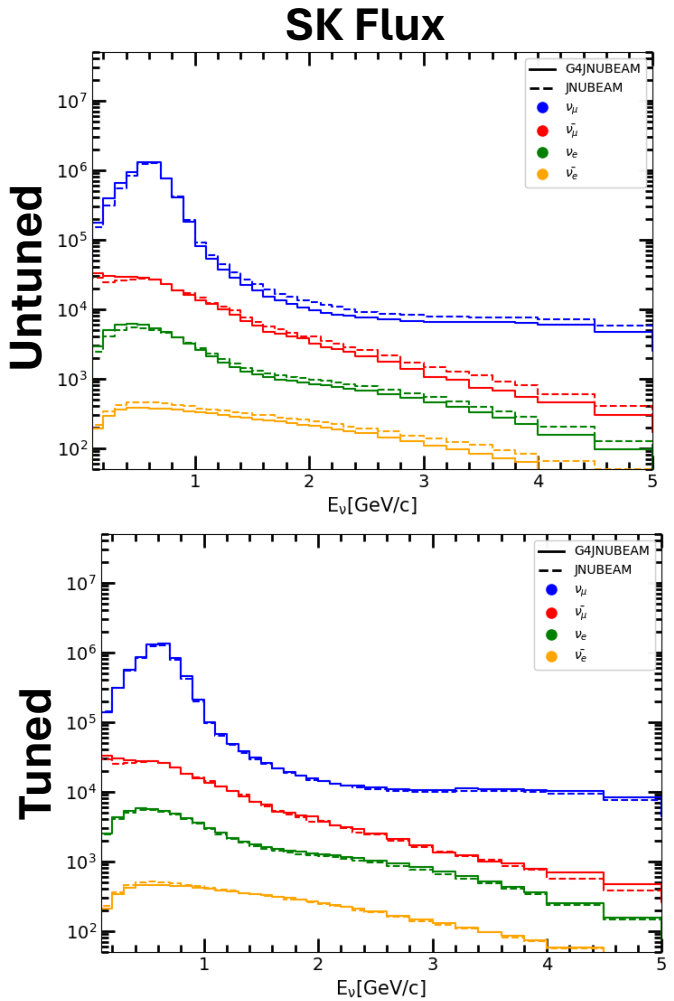


New Developments: G4Jnubeam

- Geant4 based Monte Carlo simulation

➔Goal is to replace outdated Geant3 based Jnubeam

- Agreement with JNUBEAM is now good
- Plan is to generate flux with both Jnubeam and G4Jnubeam



Conclusions

- Predicting flux is important for T2K to constrain oscillation parameters
- Simulation tool JNUBEAM is used to predict flux at ND and SK
- Flux is tuned using NA61/SHINE replica target data
- Horn current increase results in greater flux and wrong sign rejection
- Flux error is no longer dominated fully by hadron interaction uncertainty, now proton beam profile and material modelling become dominant at some energies
- Development on G4JNUBEAM is continuing and now has good agreement with JNUBEAM flux predictions

Backup

Flux Errors

- High/low energies - Hadron interactions: π or K re-scattering
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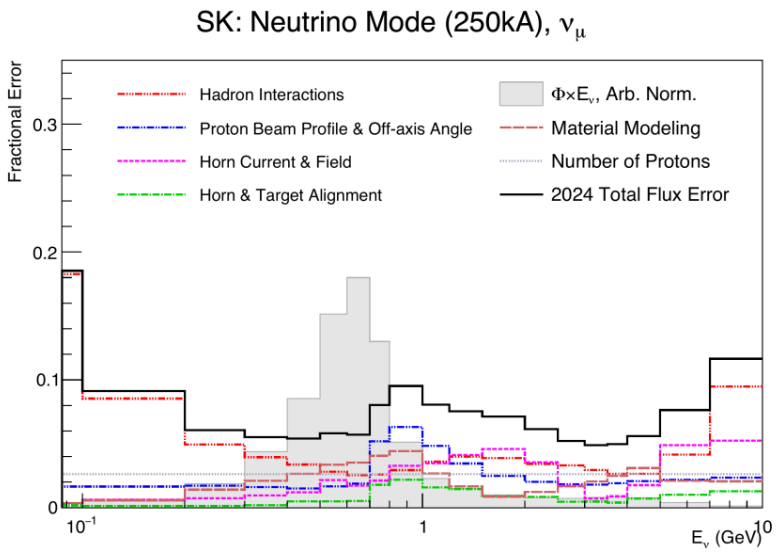
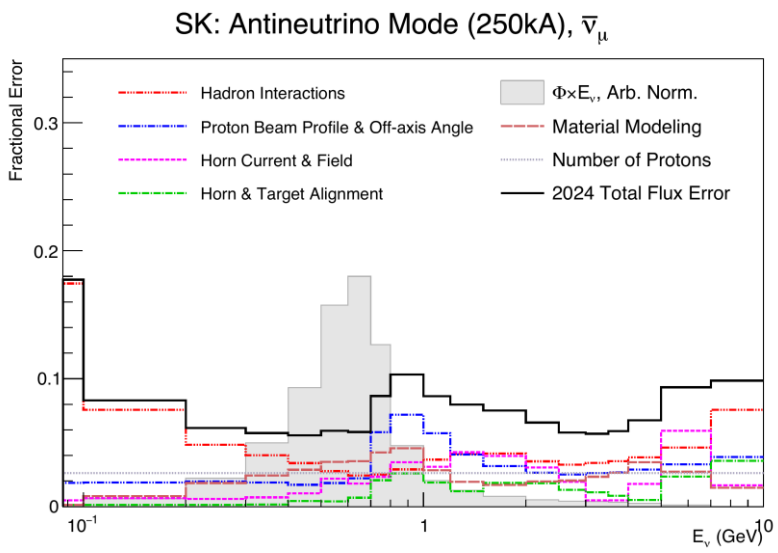
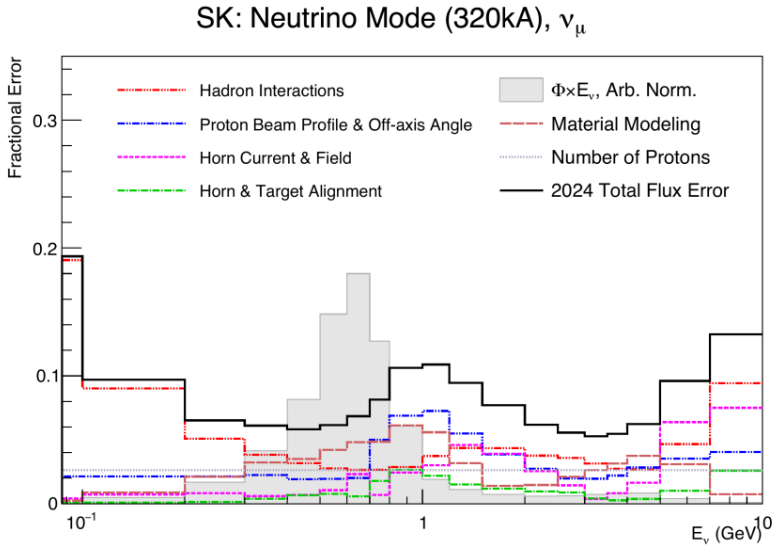
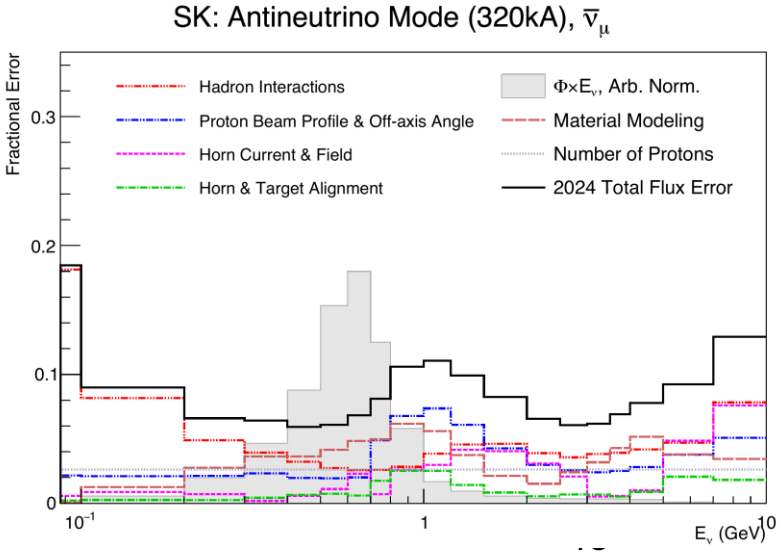
- Flux peak - Material modelling: cooling water distribution added (π absorption/scattering)
- Above peak - Proton beam: may be constrained by INGRID/muon monitor
- Proton beam profile uncertainty proportion are increased at 320 kA

➔Improvements to systematics are very important for HK era! Lots of active development





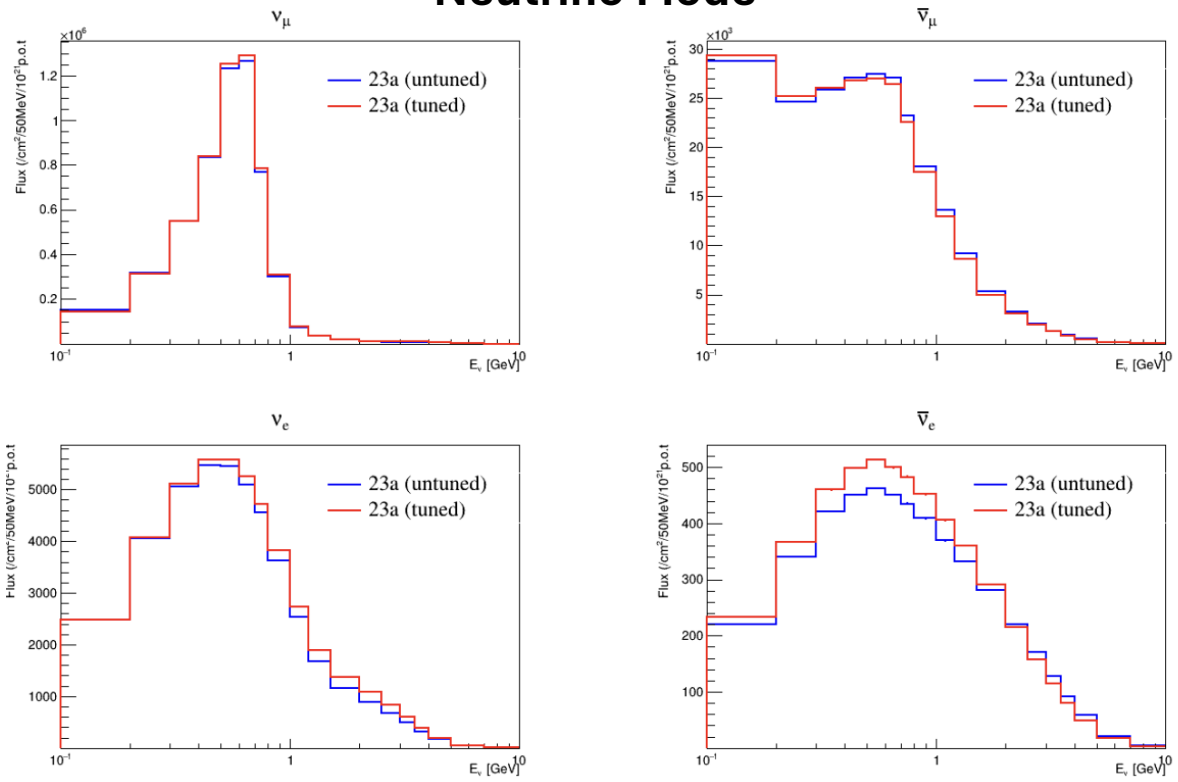




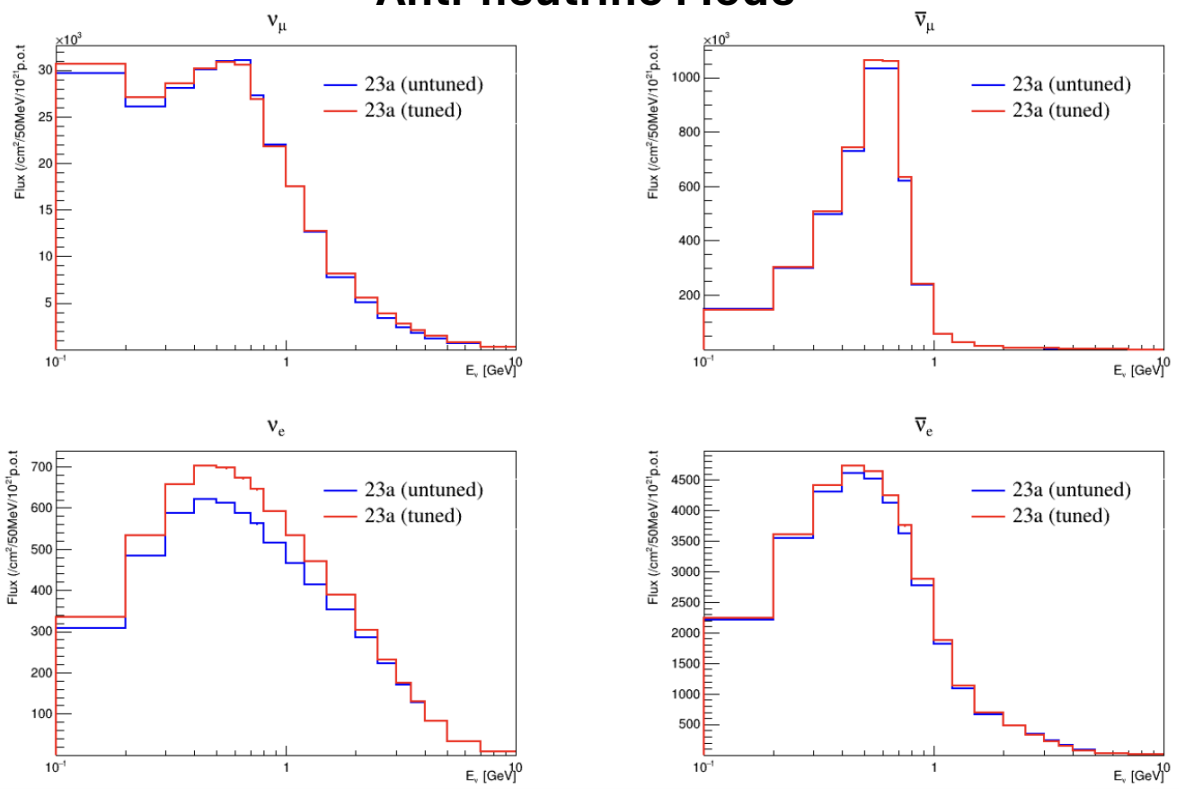
Flux Tuning

Tuned vs untuned flux at 320 kA

Neutrino Mode



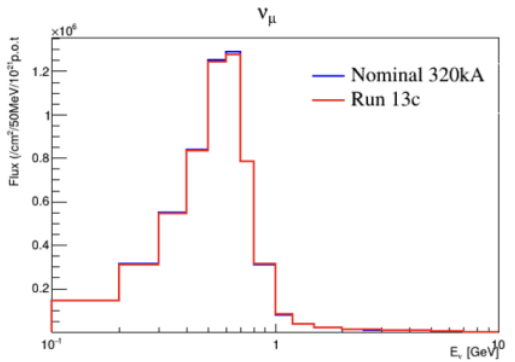
Anti-neutrino Mode

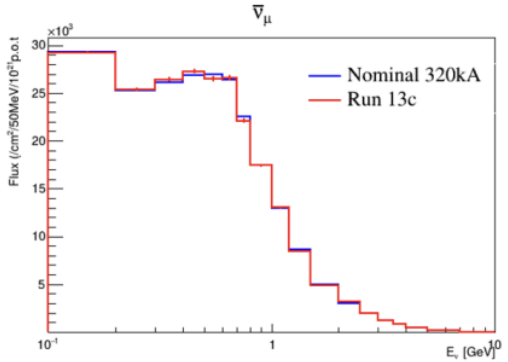


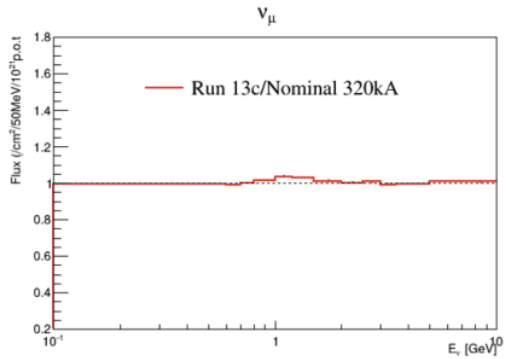
Beam profile inputs

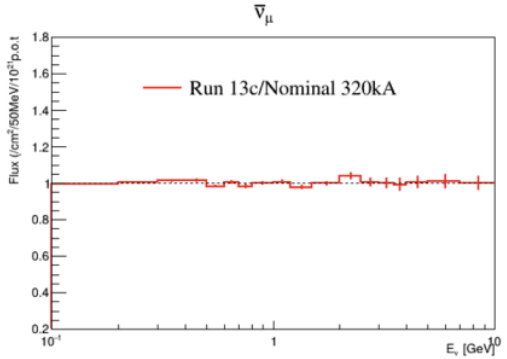
- Proton beam profile is used as input for JNUBEAM
- Generally good agreement with nominal is seen

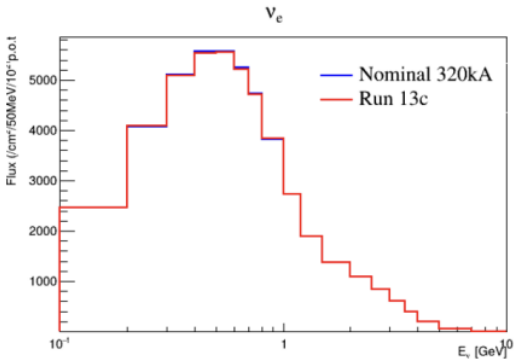
Nominal: Standard beam profile
Run 13c: June 2024

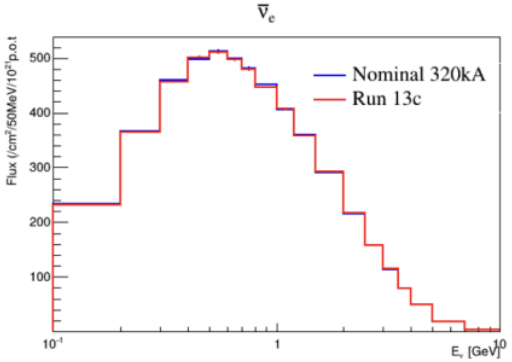


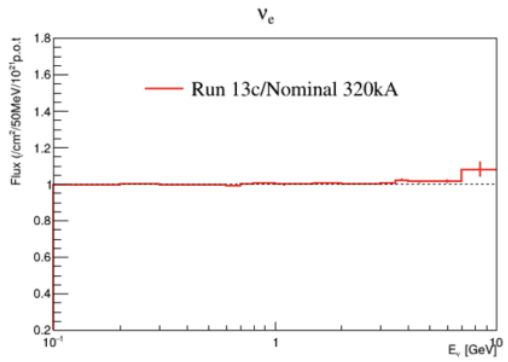


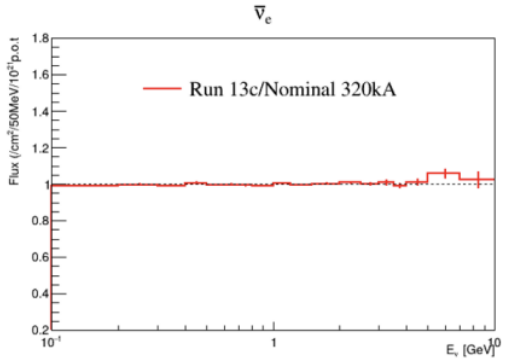








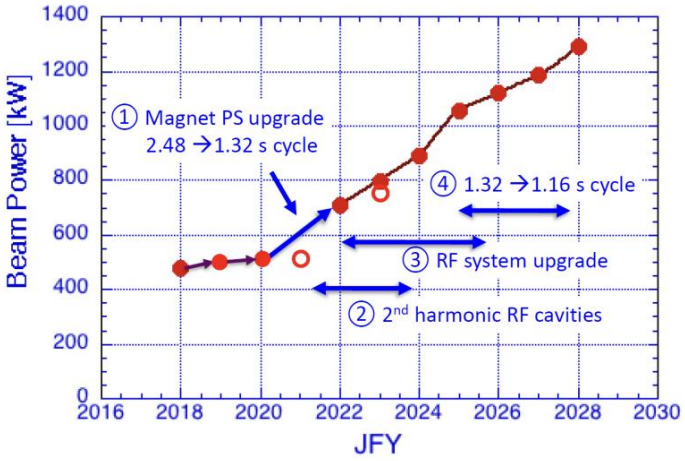




Work Towards HK Era

- Hyper-K expects to start data taking in 2028
- J-PARC is upgrading beam intensity up to 1.3 MW
  - 830 kW beam was received by neutrino beamline in 2025!
  - >1 MW possible with repetition rate upgrade
- Next year: target + horn 1 replacement
  - Current target only rated for up to 900 kW beam
- Construction of IWCD has begun
  - Goal: Measure ν flux at different off axis angles
- Muon monitor will replace Si sensors with radiation resistant EMTs

Upgrade plan of MR



Electron Multiplier Tube (EMT)

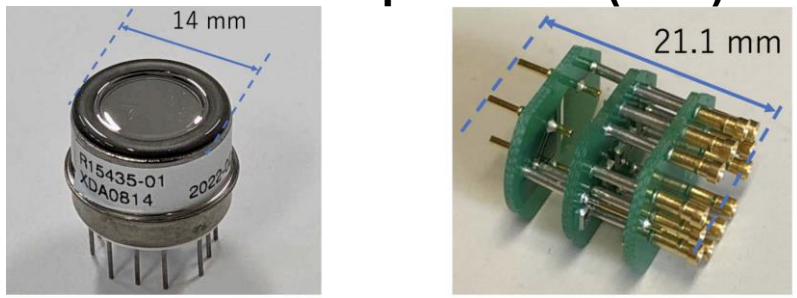


Photo of EMT (left) and bleeder circuit

Intermediate Water Cherenkov Detector(IWCD) site