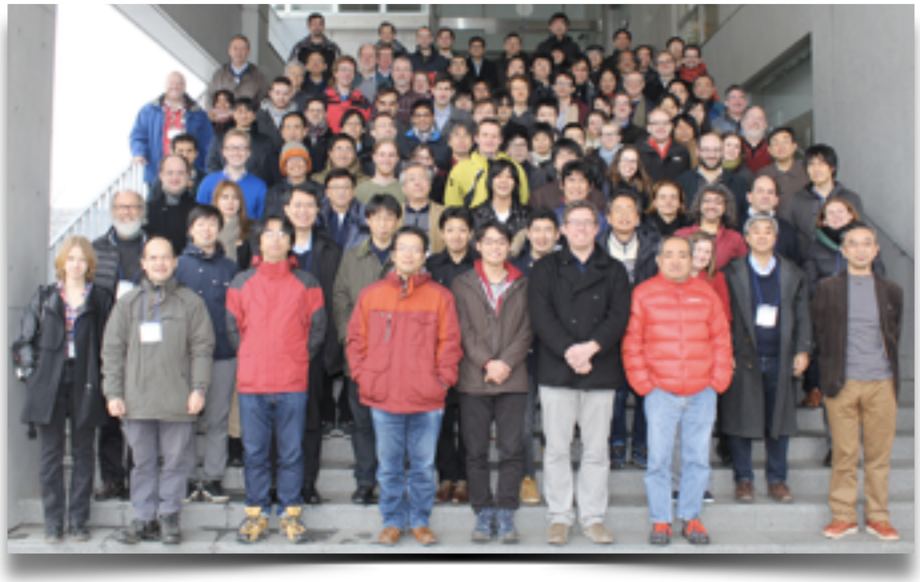
Hyper-K Strategy for Controlling Systematic Uncertainties

Sam Short
for the Hyper-K Collaboration



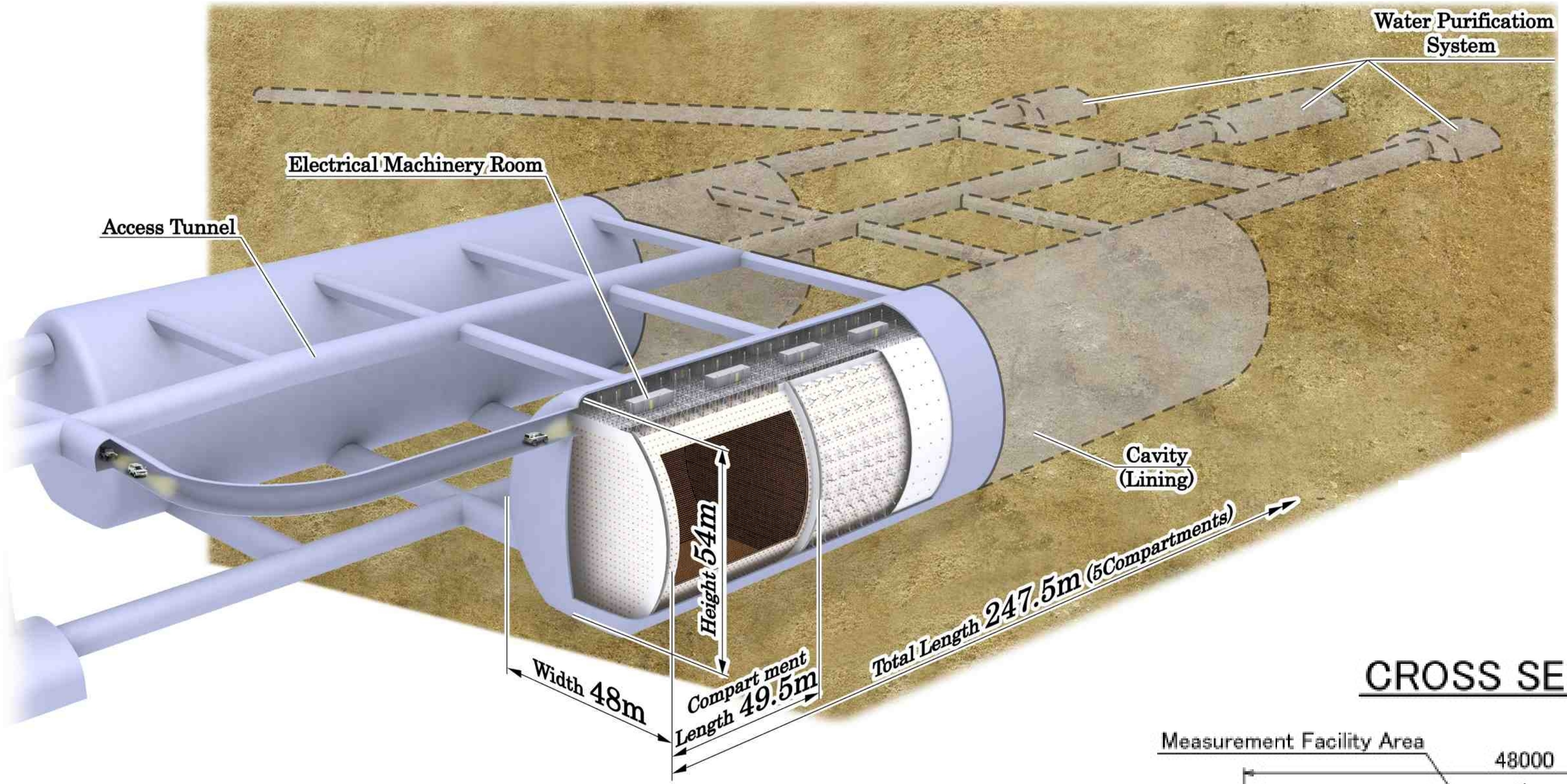
NNN15
29 October 2015

Outline

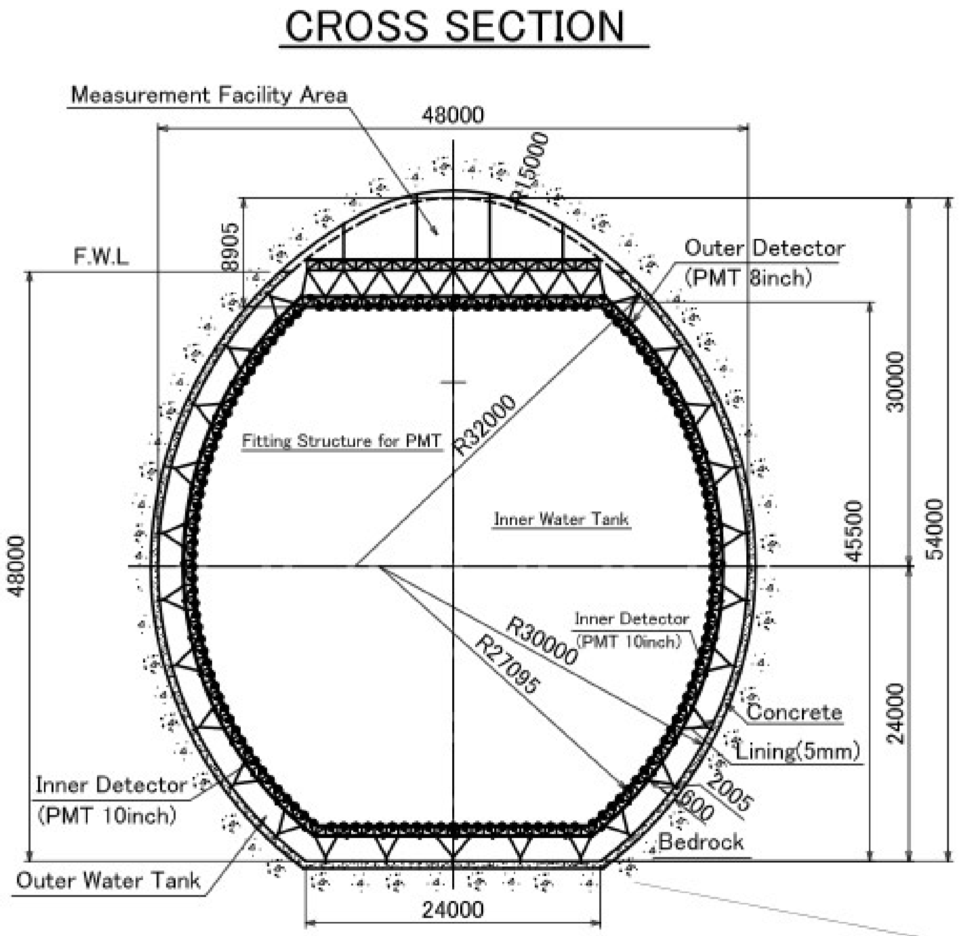
- An Introduction to Hyper–K
- Flux uncertainties
- Interaction model uncertainties
- Near and intermediate detectors

Hyper Kamiokande

Hyper Kamiokande

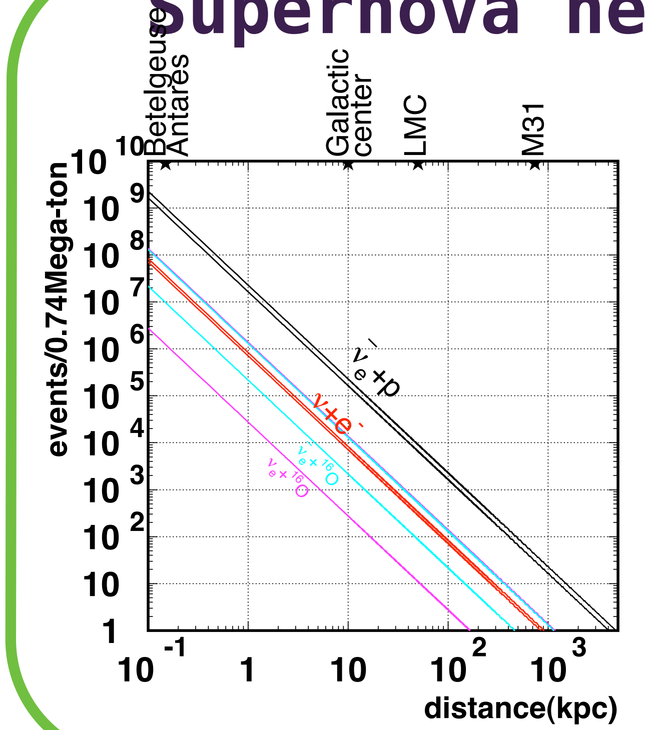


- ~1 mega tonne total mass (0.52 Mt fiducial mass)
- 295 km and 2.5° off-axis from J-PARC neutrino beam
- Segmented design
- 99,000 (20inch) PMTs
- 20% photo-coverage

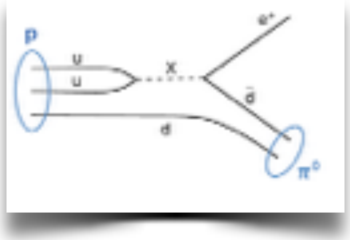


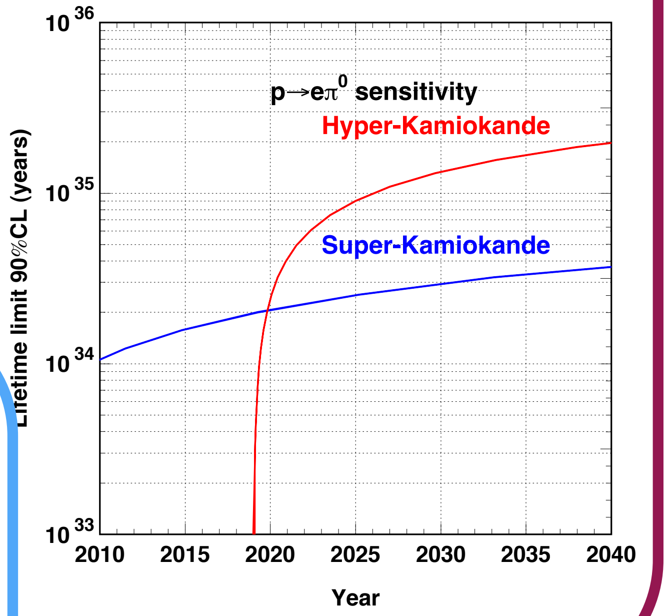
Physics with Hyper-K

Supernova neutrinos

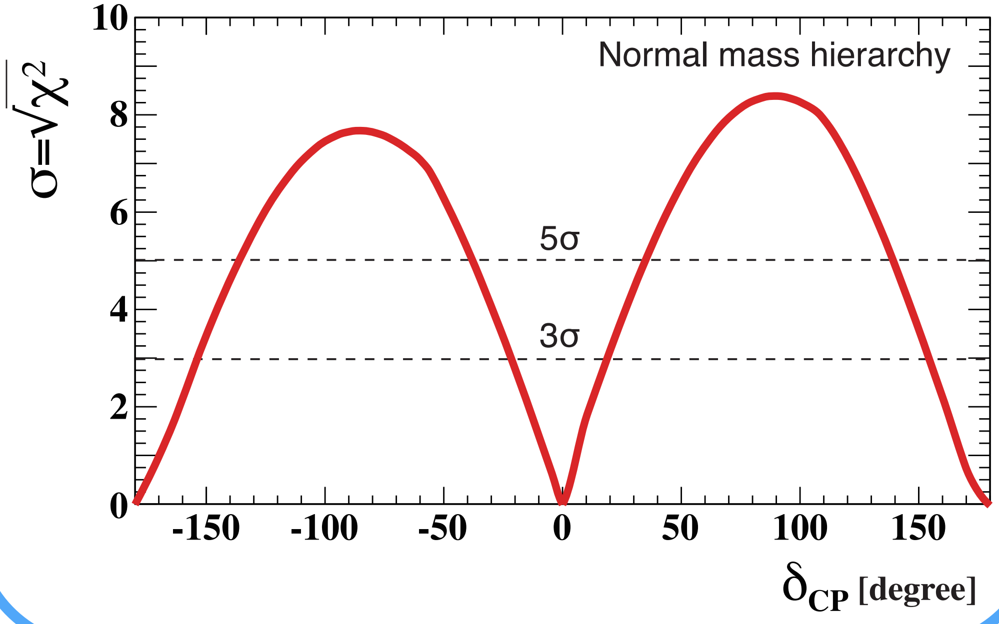


Nucleon decay searches

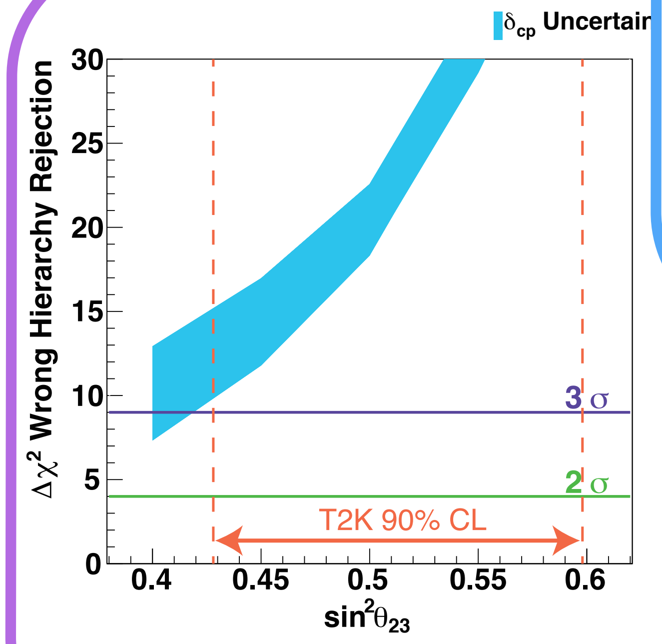


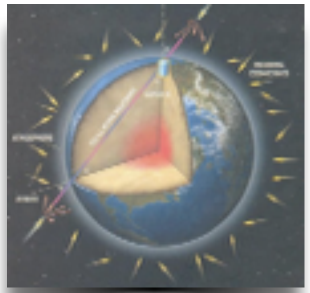


Long baseline accelerator neutrinos

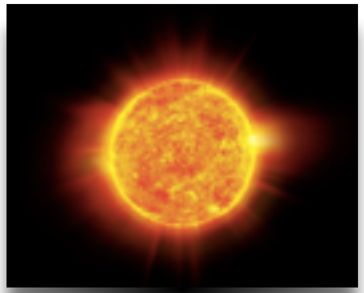


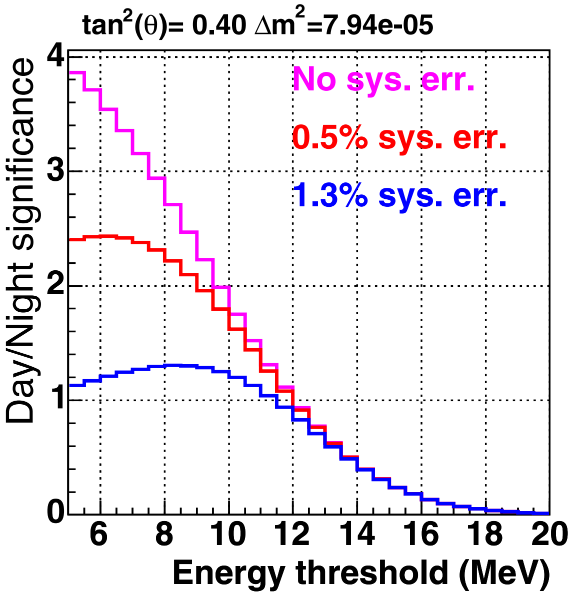
Atmospheric neutrinos



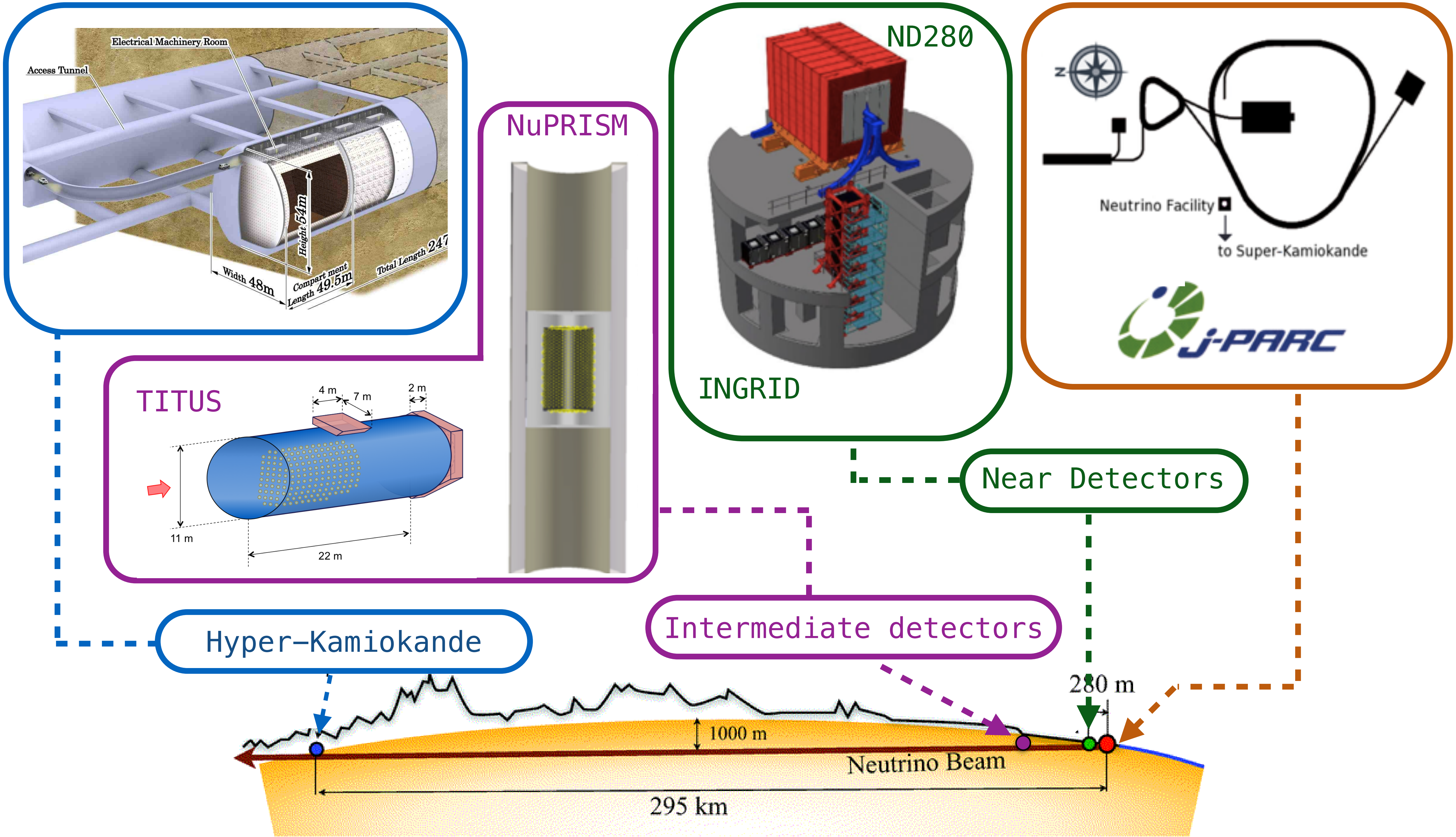


Solar neutrinos





Tokai2HyperKamiokande



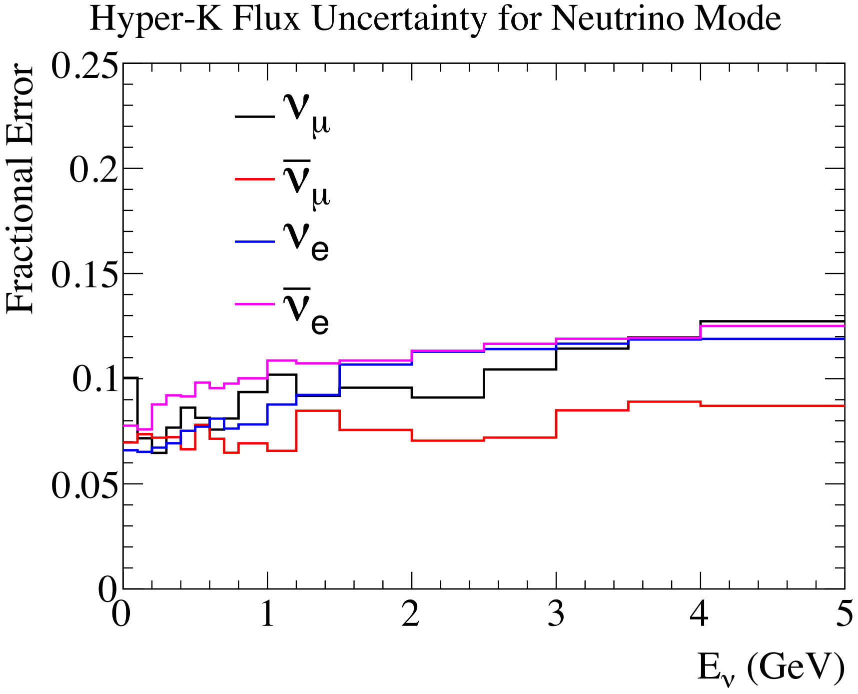
Hyper–Kamiokande

Intermediate detectors

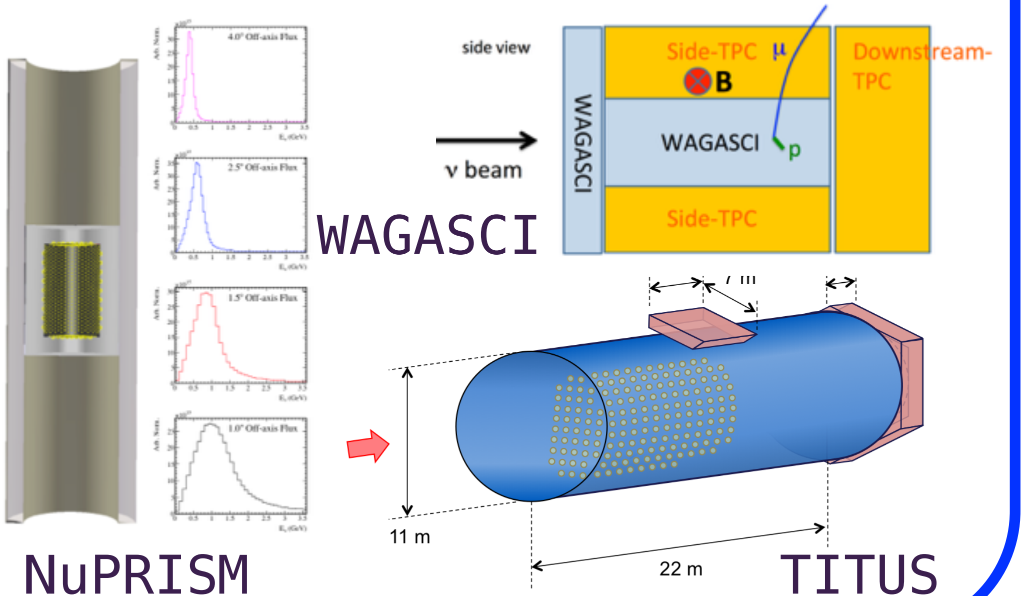
Near Detectors

Sources of Systematic Uncertainty

Neutrino Flux



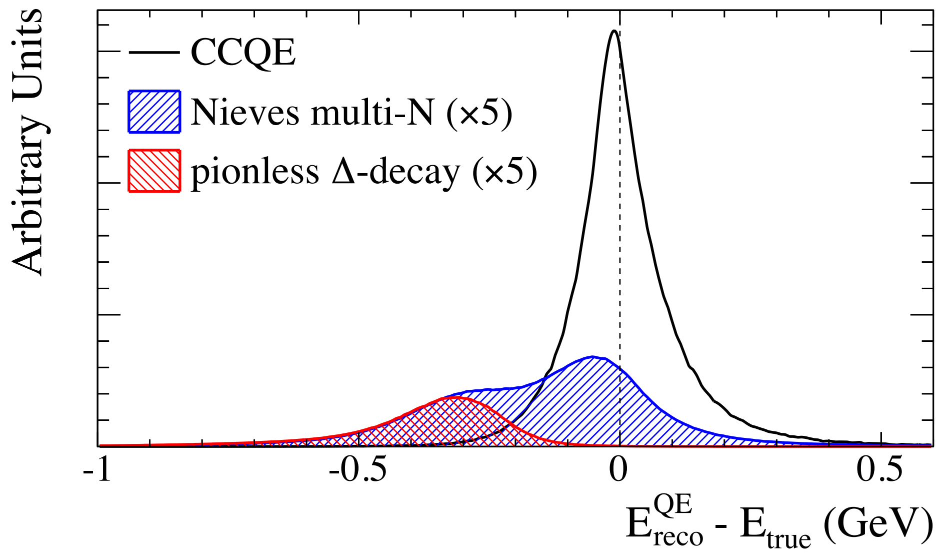
Near/Intermediate Detector Response



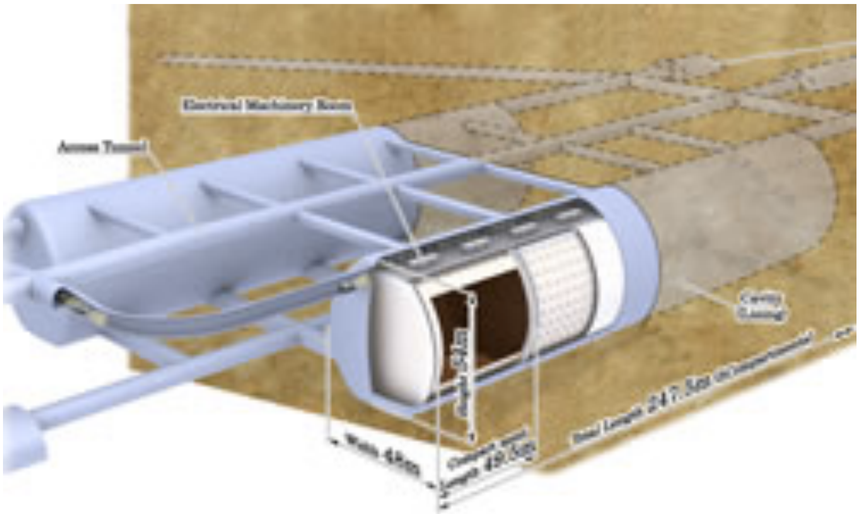
WAGASCI

NuPRISM

TITUS



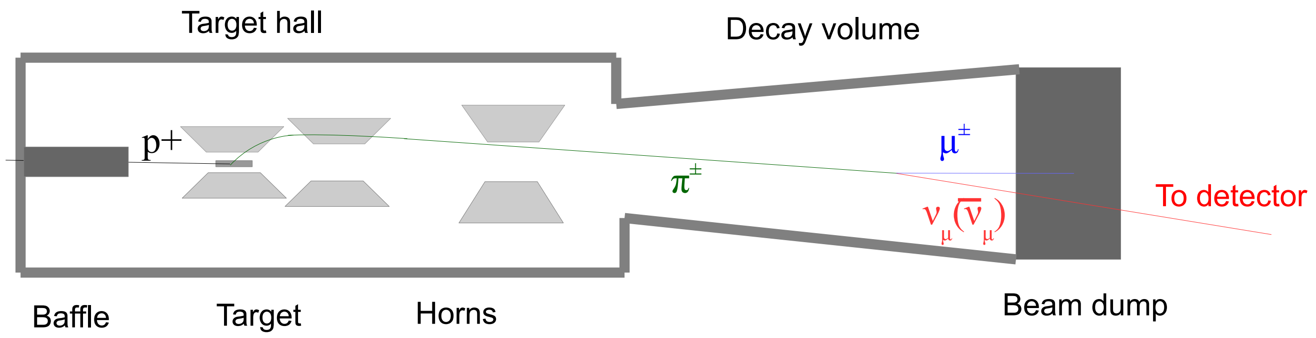
Neutrino Interactions



Far Detector Response

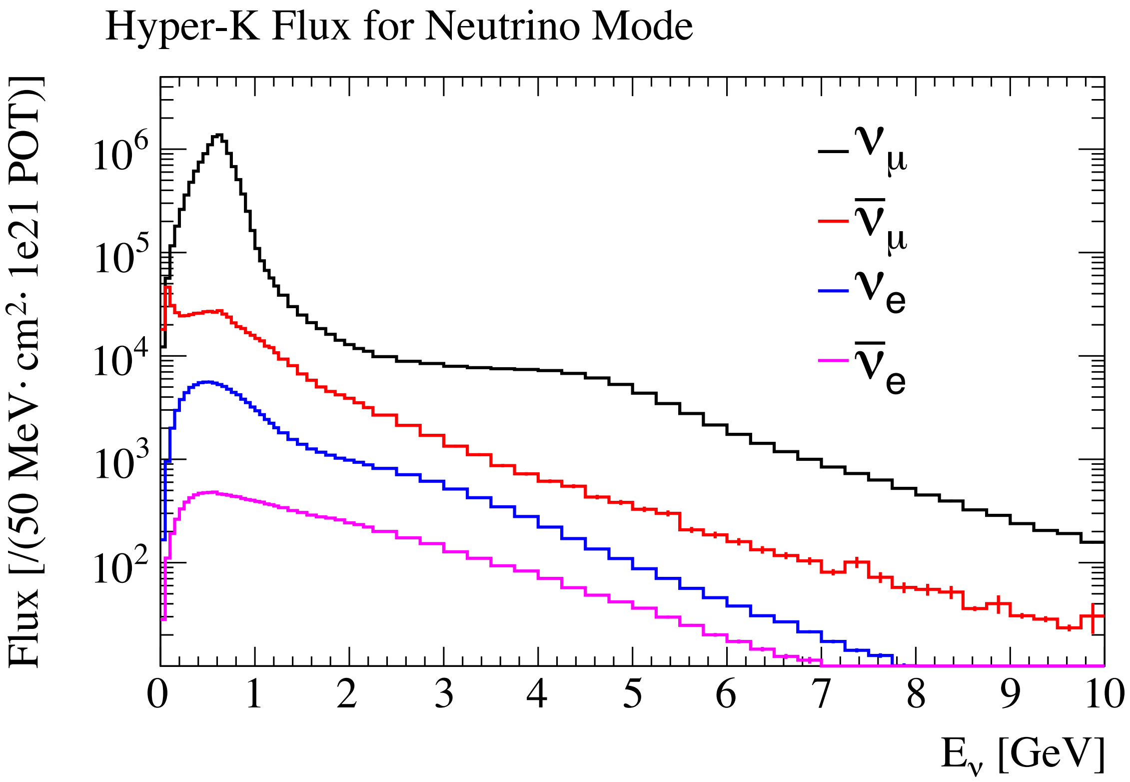
Neutrino Flux

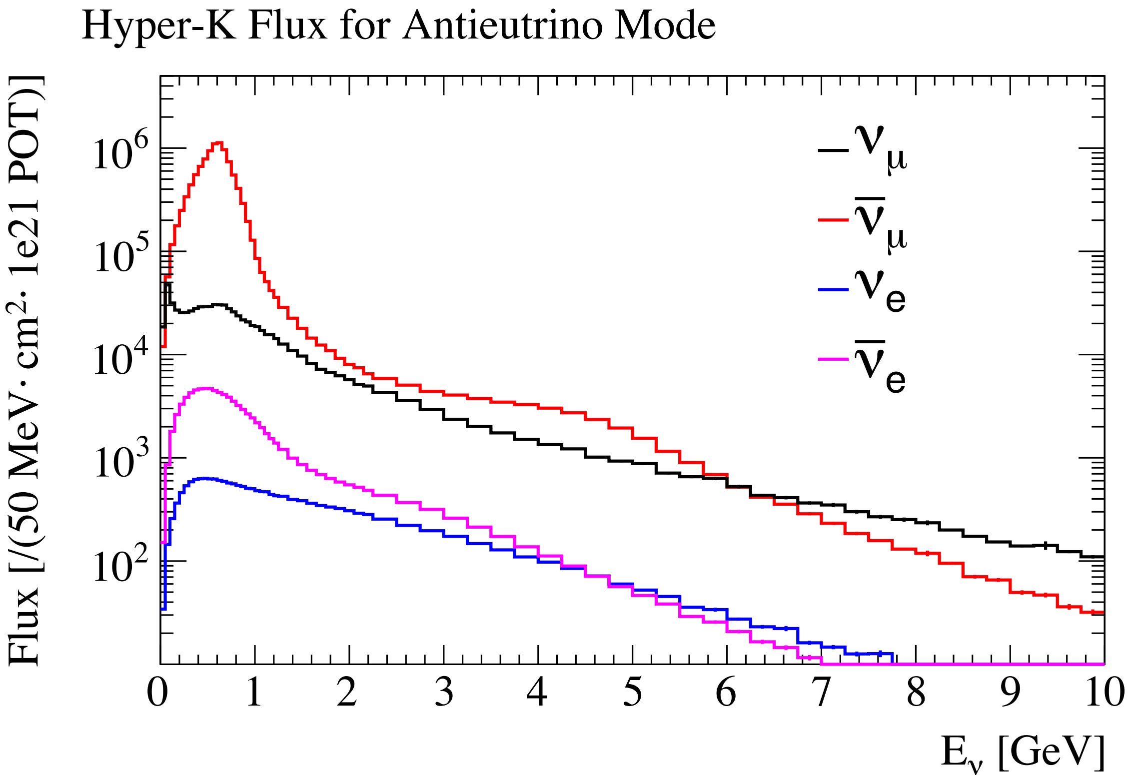
Neutrino Flux Prediction



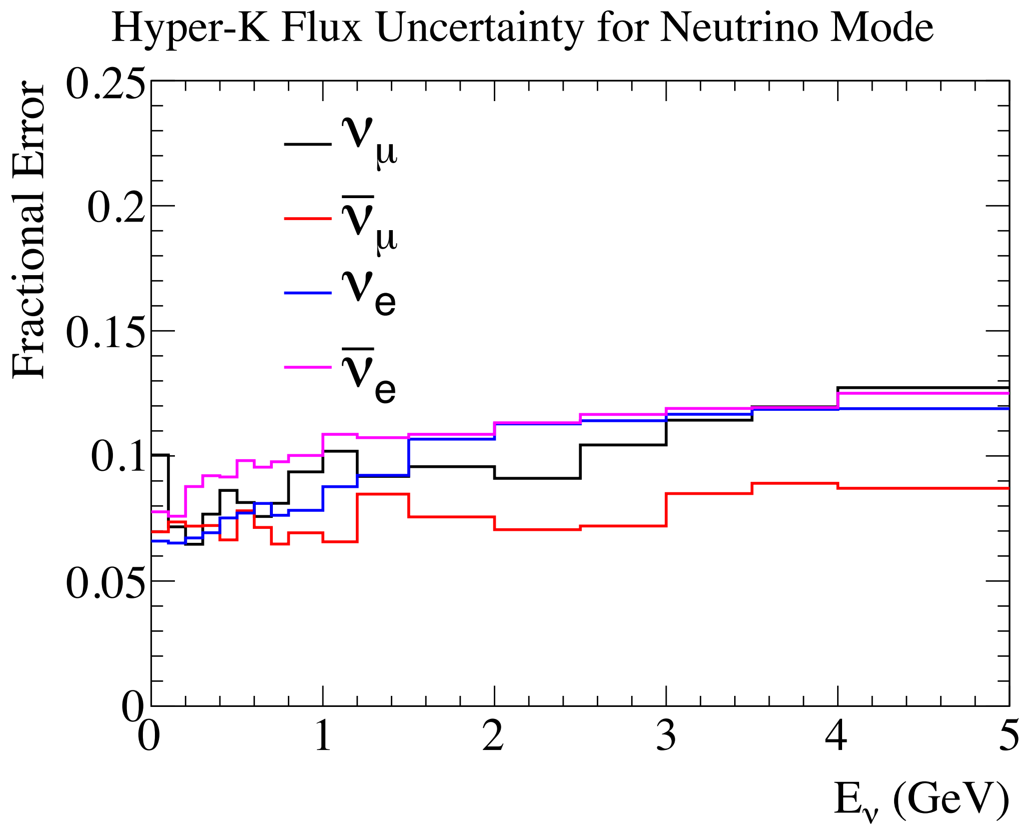
Data driven flux model:

- Proton beam monitor measurements
- Horn field measurements
- Beam-line component alignment measurements
- NA61/SHINE hadron production measurements



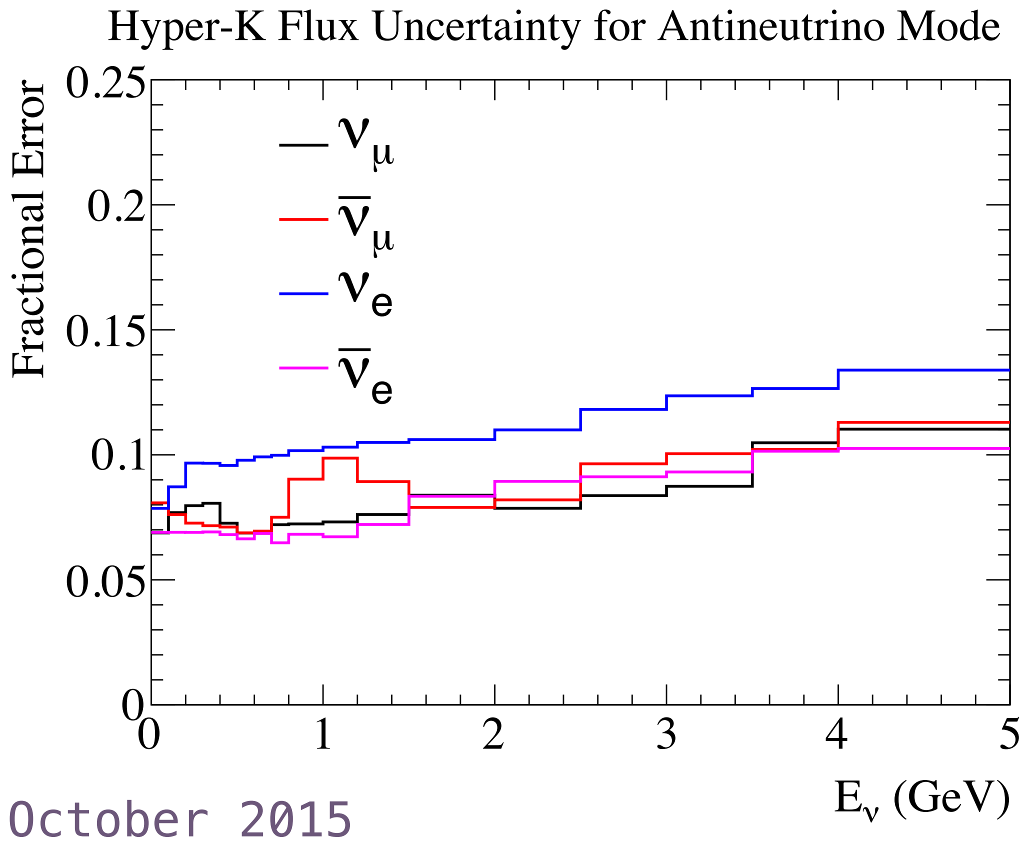


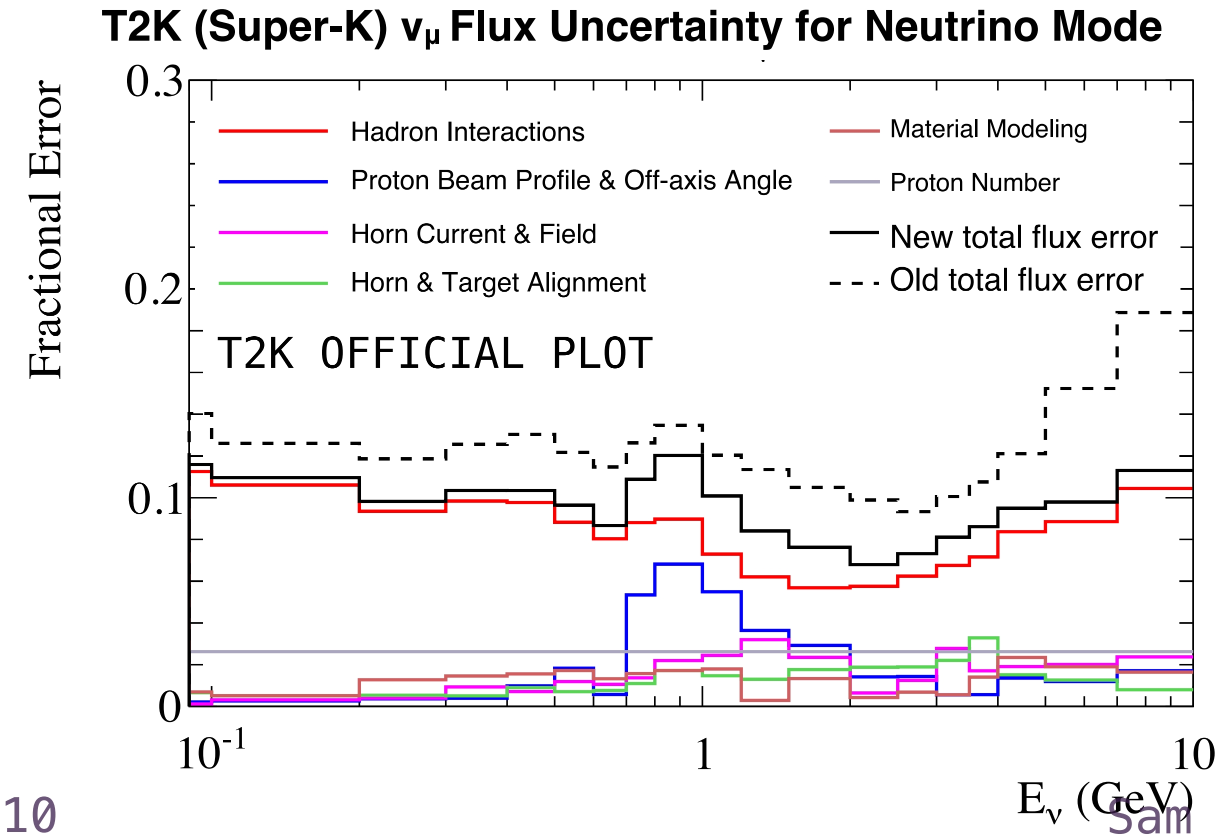
Neutrino Flux Uncertainty


Hyper-K Flux Uncertainty for Neutrino Mode

Uncertainties considered:

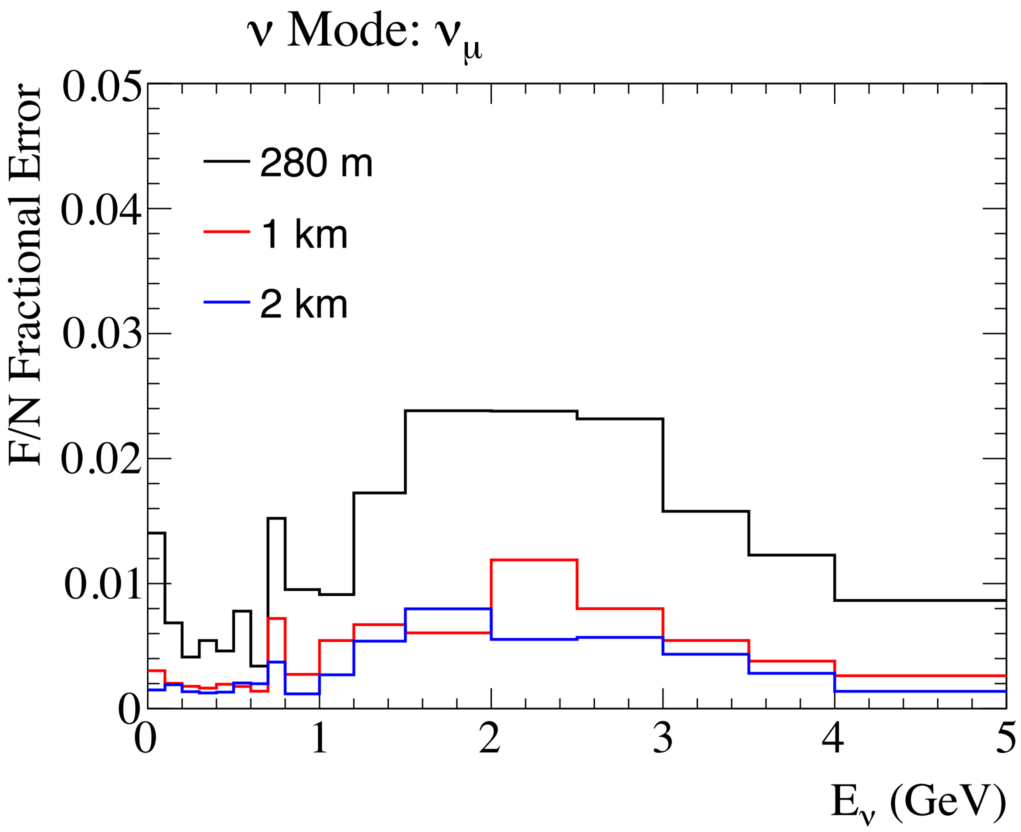
- Hadron interactions
- Proton beam profile and off-axis angle
- Horn current and field
- Horn and target alignment
- Material modelling
- Proton number

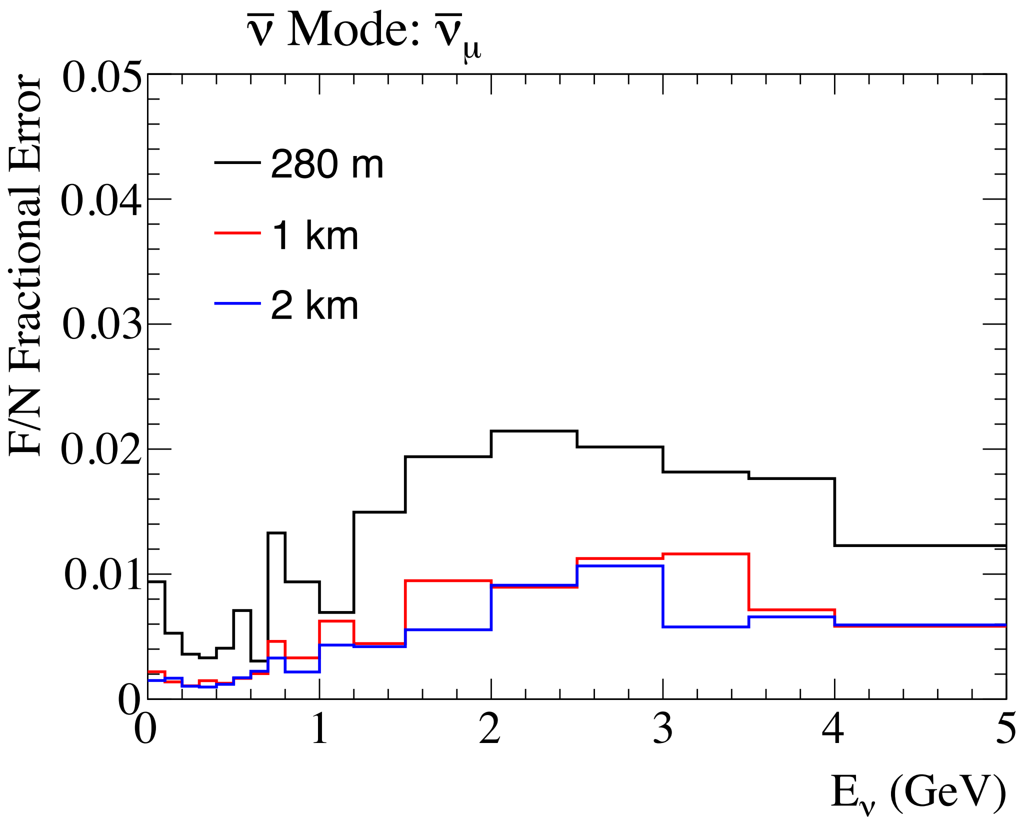

Hyper-K Flux Uncertainty for Antineutrino Mode


T2K (Super-K) ν_μ Flux Uncertainty for Neutrino Mode

Near/Far Flux Uncertainty

- At 280m: source is not point-like → near/far ratio not flat
- At 1km, 2km: ratio is flatter → better cancellation of flux uncertainties
- Uncertainty <0.5% for intermediate (1km and 2km) detectors
- Uncertainty <1% around peak region (0.6GeV) for 280m detector (T2K ND280)





Wrong Sign Background

- In antineutrino mode neutrinos contribute 20% to the event rate

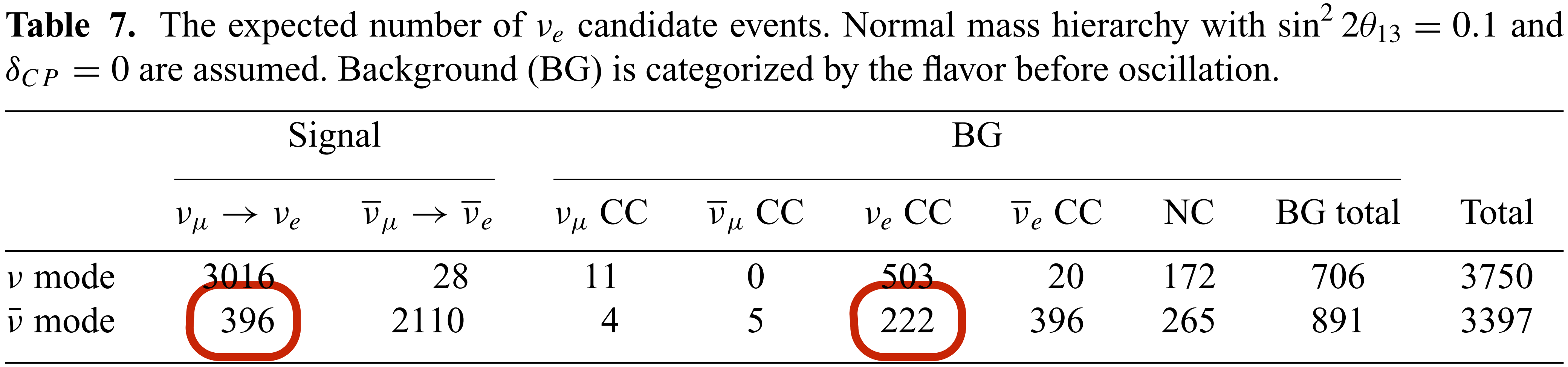
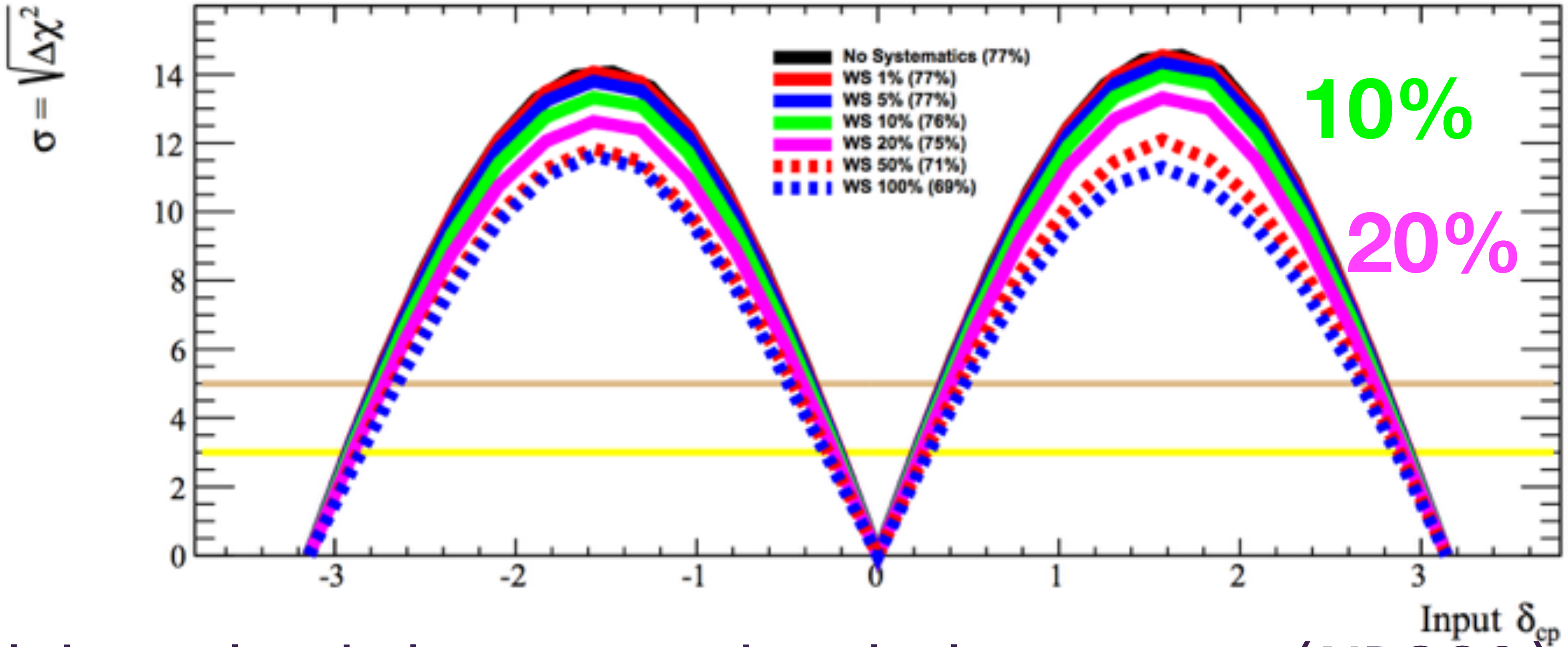


Table 7. The expected number of ν_e candidate events. Normal mass hierarchy with $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed. Background (BG) is categorized by the flavor before oscillation.

	Signal		BG						
	$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG total	Total
ν mode	3016	28	11	0	503	20	172	706	3750
$\bar{\nu}$ mode	396	2110	4	5	222	396	265	891	3397

- <10% normalisation uncertainty is necessary to have negligible impact on CP-Violation sensitivity



- Achieved with magnetised detector (ND280)

Intrinsic ν_e Background

- Intrinsic beam ν_e contributes ~15–20% to the event rate

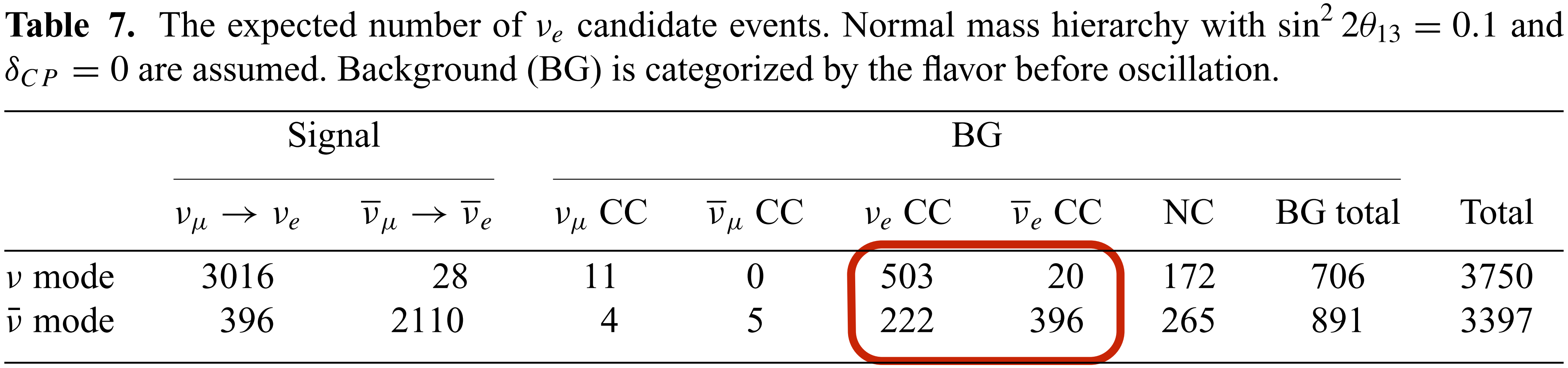
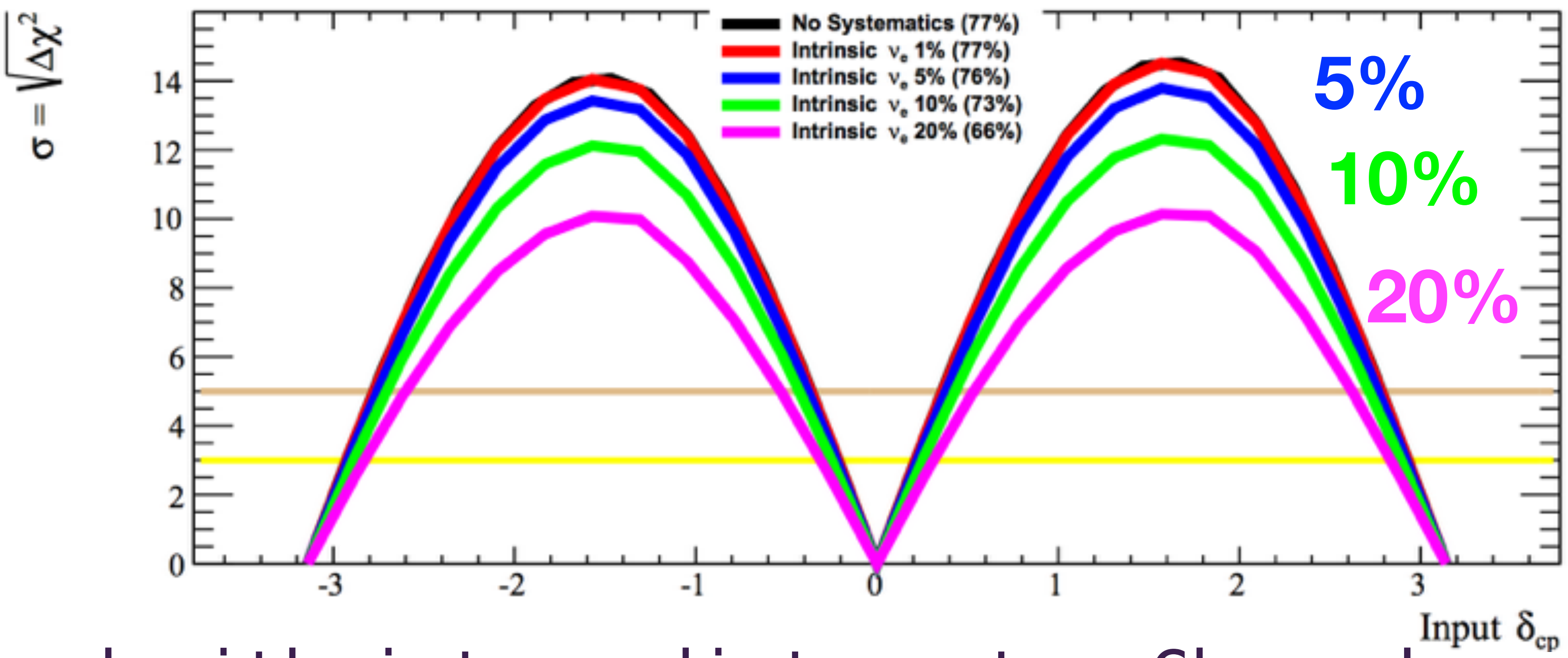


Table 7. The expected number of ν_e candidate events. Normal mass hierarchy with $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed. Background (BG) is categorized by the flavor before oscillation.

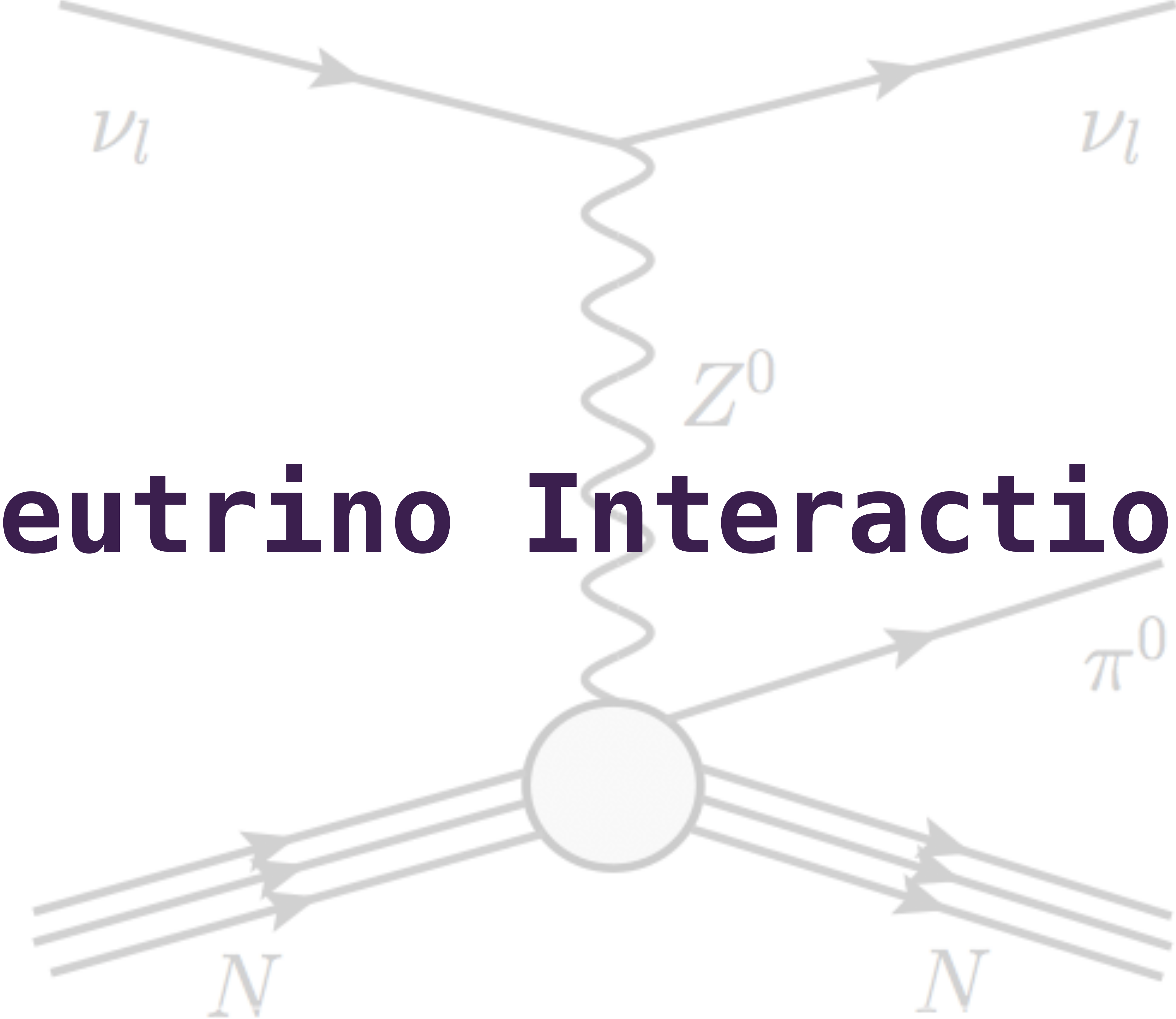
	Signal		BG						
	$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG total	Total
ν mode	3016	28	11	0	503	20	172	706	3750
$\overline{\nu}$ mode	396	2110	4	5	222	396	265	891	3397

- <5% normalisation uncertainty is necessary to have negligible impact on CP-Violation sensitivity



- Achieved with intermediate water Cherenkov detector

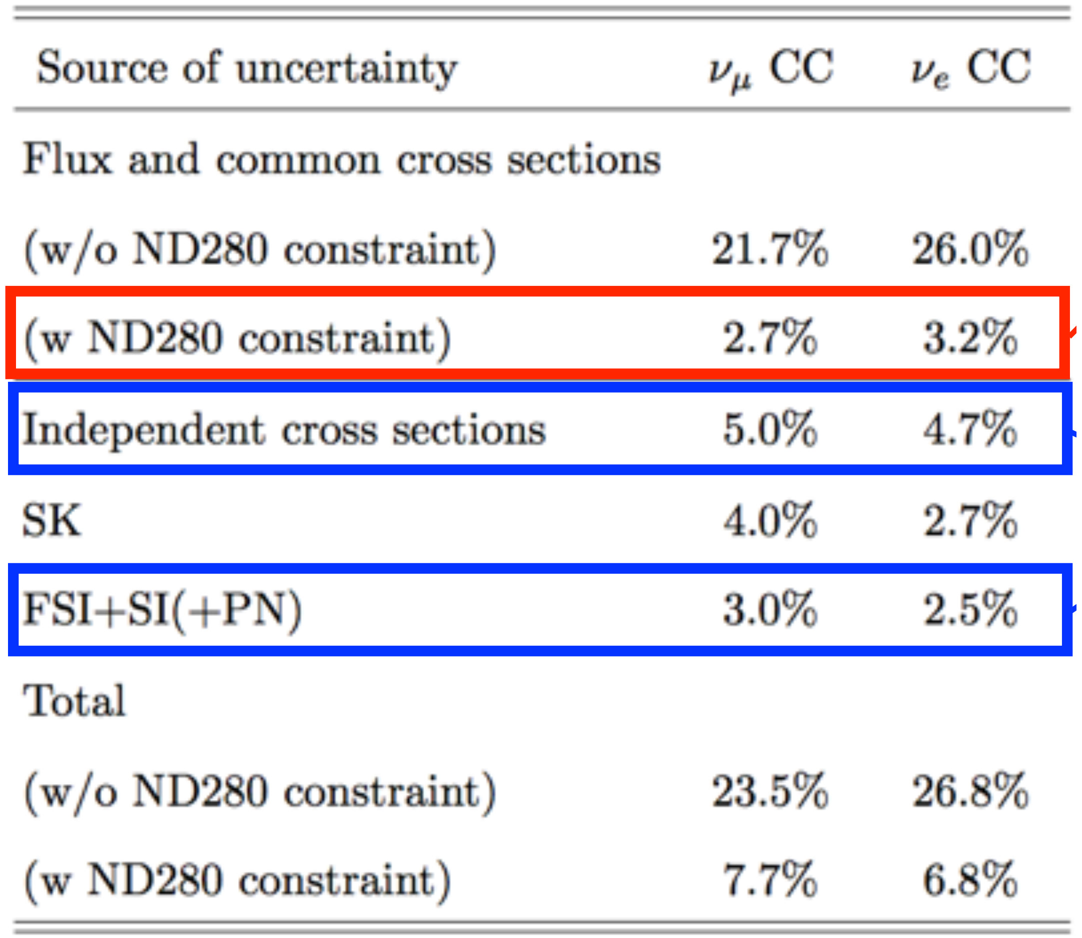
Neutrino Interactions



Interaction Model Uncertainties

Use T2K approach:

- **Data driven:** External neutrino, electron and pion scattering data
- **Uncertainties:** Modelled by varying the underlying model parameters and ad-hoc parameters
- **Fit** to near detector data to constrain flux and interaction model uncertainties to ~3%



Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI+SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%

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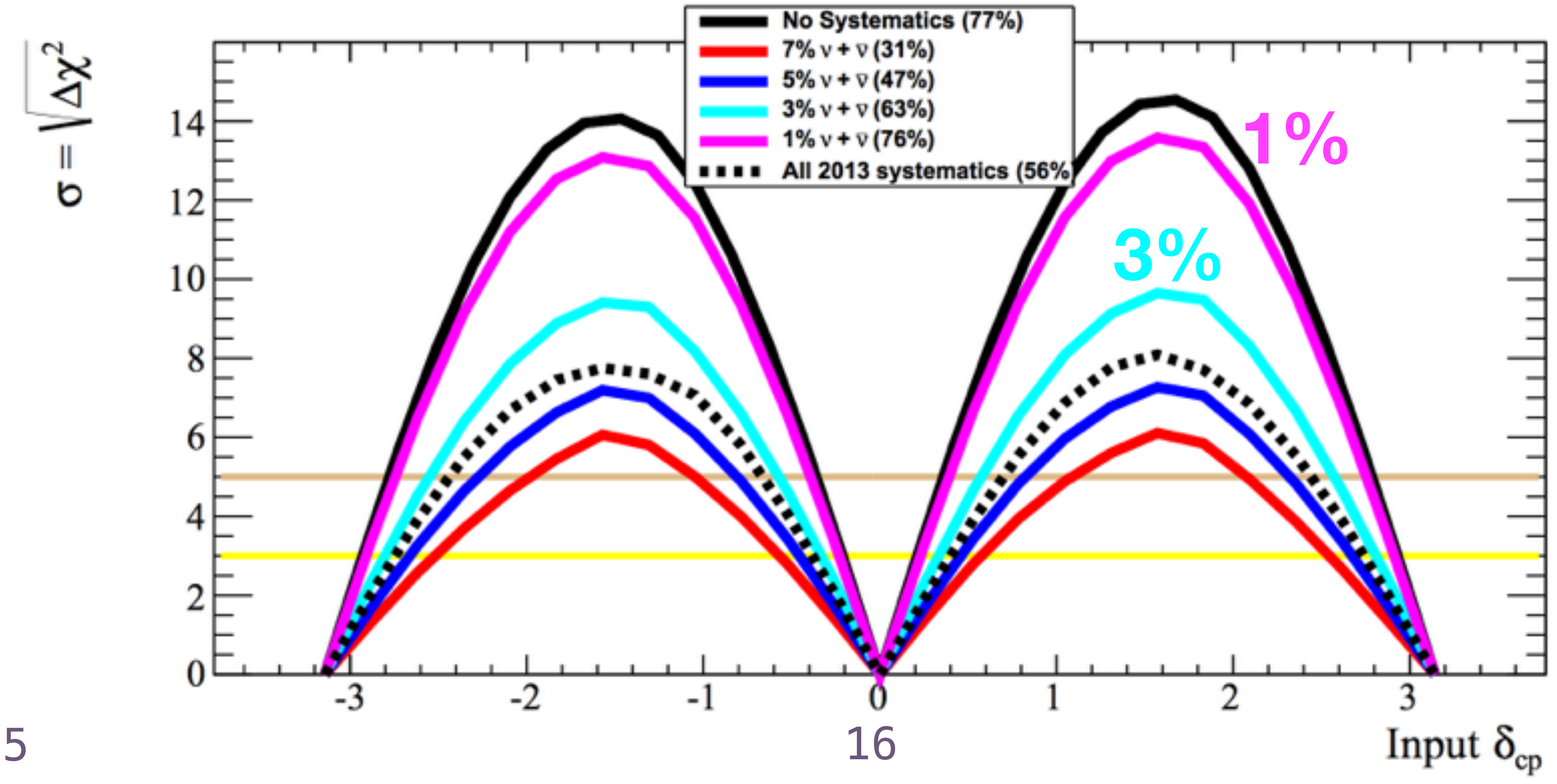
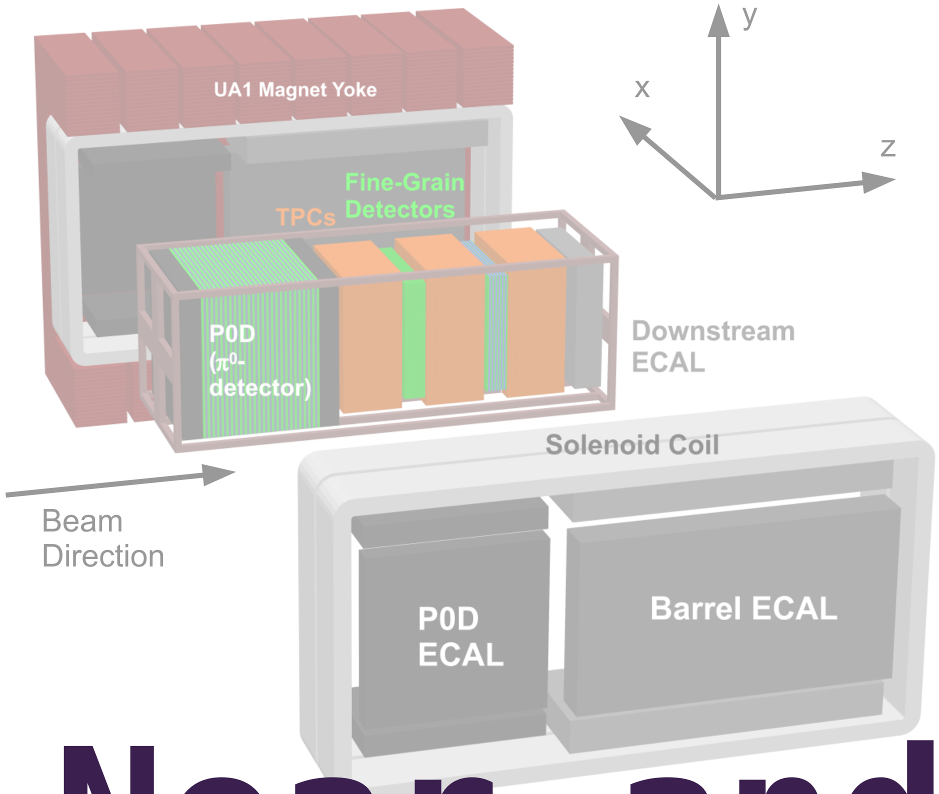
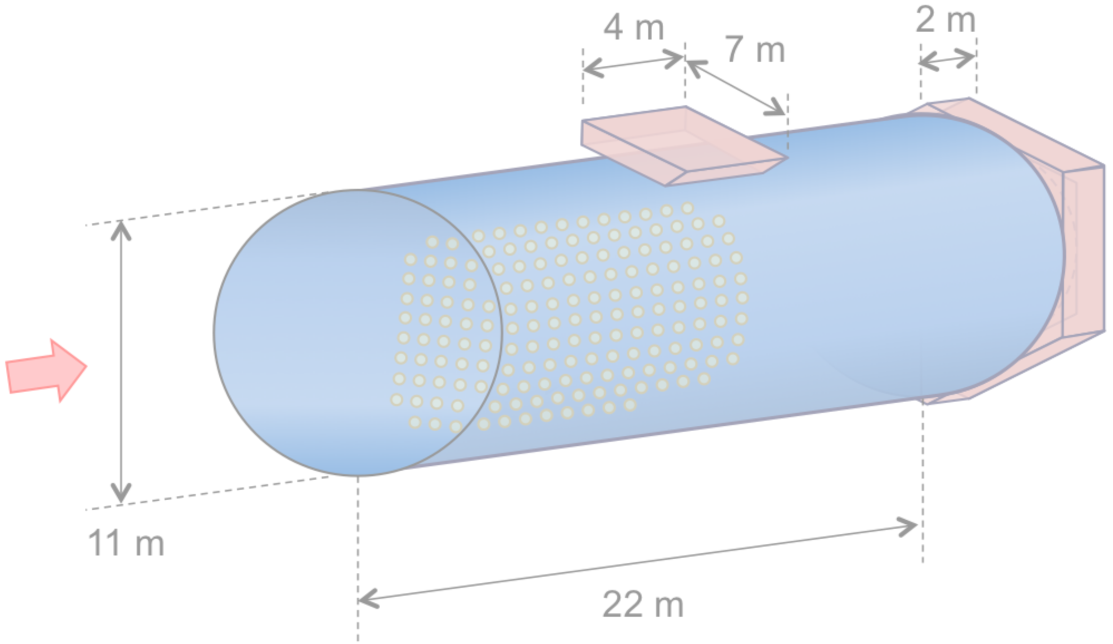
$\nu_e/\bar{\nu}_e$ Cross-Sections

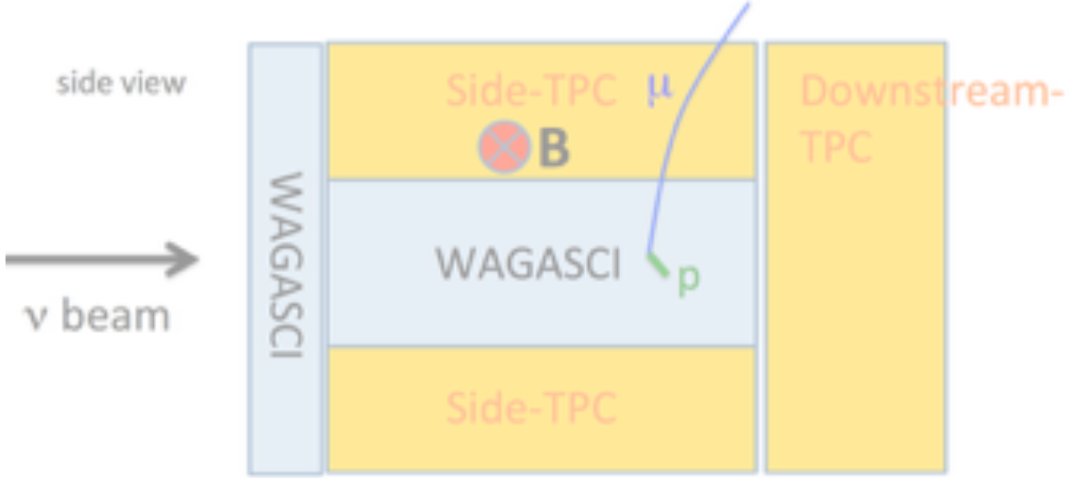
- Measure ν_μ, $\bar{\nu}_\mu$ rates in near detectors
- To predict ν_e, $\bar{\nu}_e$ rates at far detector need to correct for cross-section difference
- **Problem:** no precision measurements of ν_e, $\bar{\nu}_e$ cross-sections at energies of interest
- **Sensitivity study:** assign ν_e, $\bar{\nu}_e$ cross-sections uncorrected normalisation systematic parameters
- Need: <1–2% uncertainty to minimise impact on CP-Violation discovery sensitivity

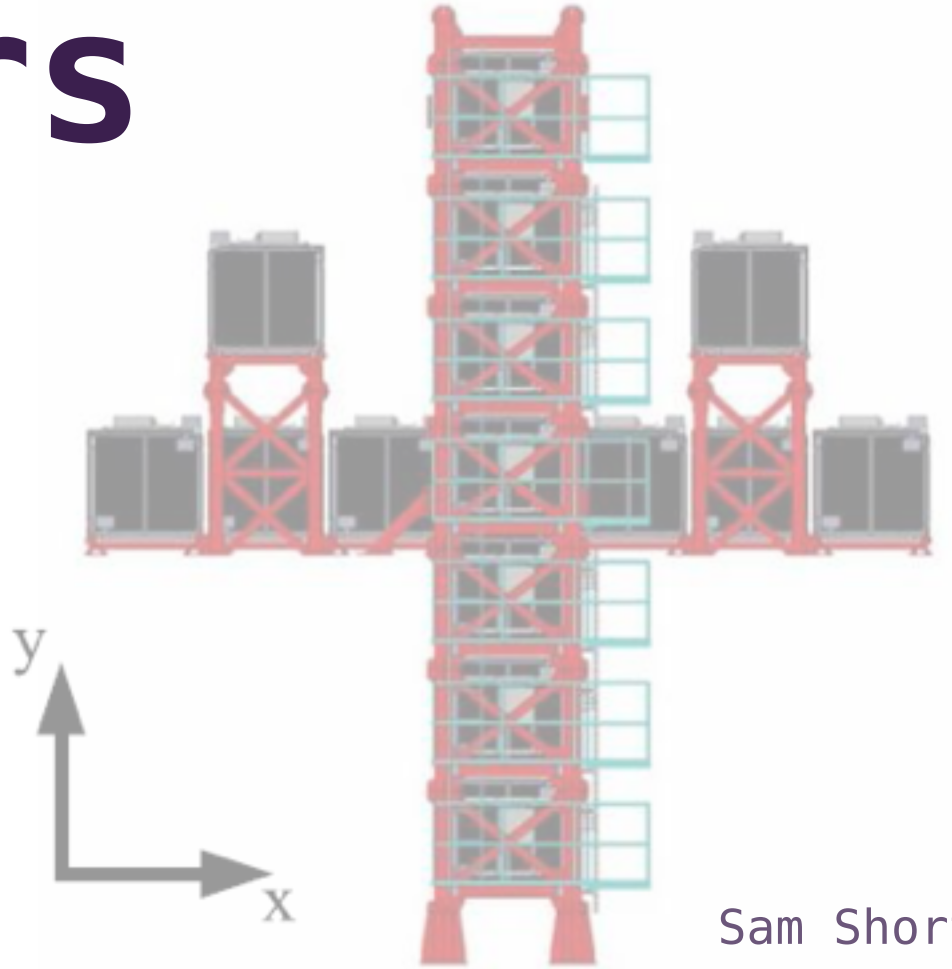


Near and Intermediate Detectors





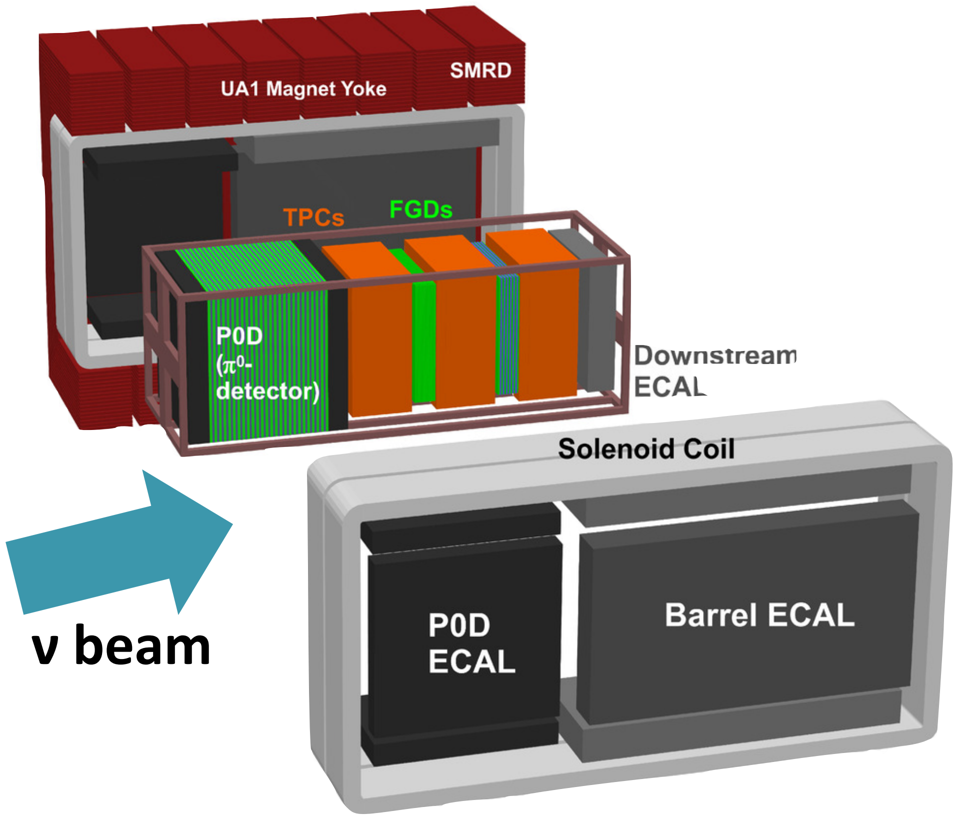


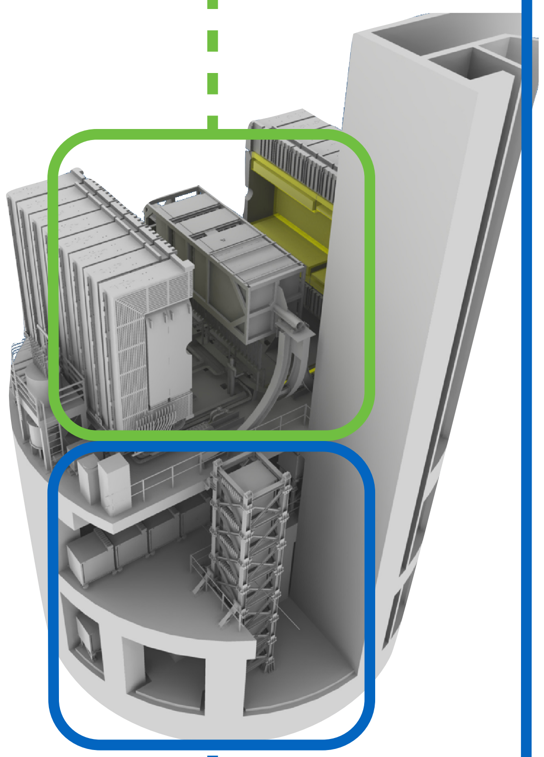


T2K Near Detector Suite

Off-Axis: ND280

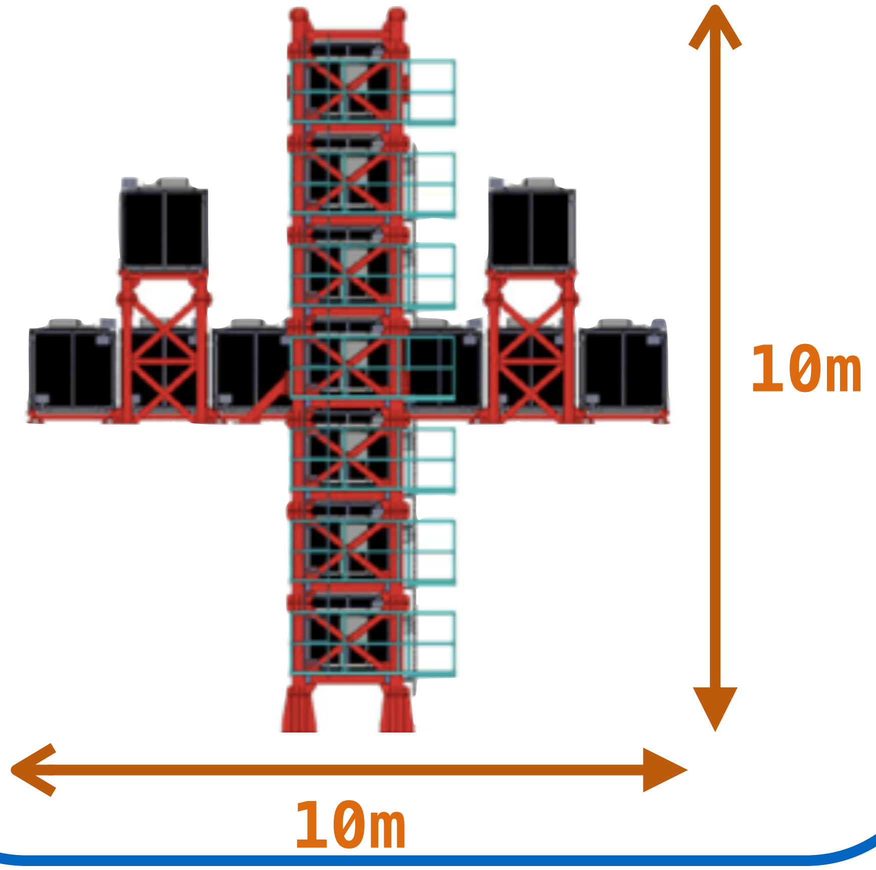
- Characterises beam before neutrino oscillations
- Targets: water, carbon, lead and argon
- Measures neutrino cross-sections





On-Axis: INGRID

- 16 iron/scintillator module
- 1 scintillator tracking module
- Monitors beam centre, profile and neutrino flux



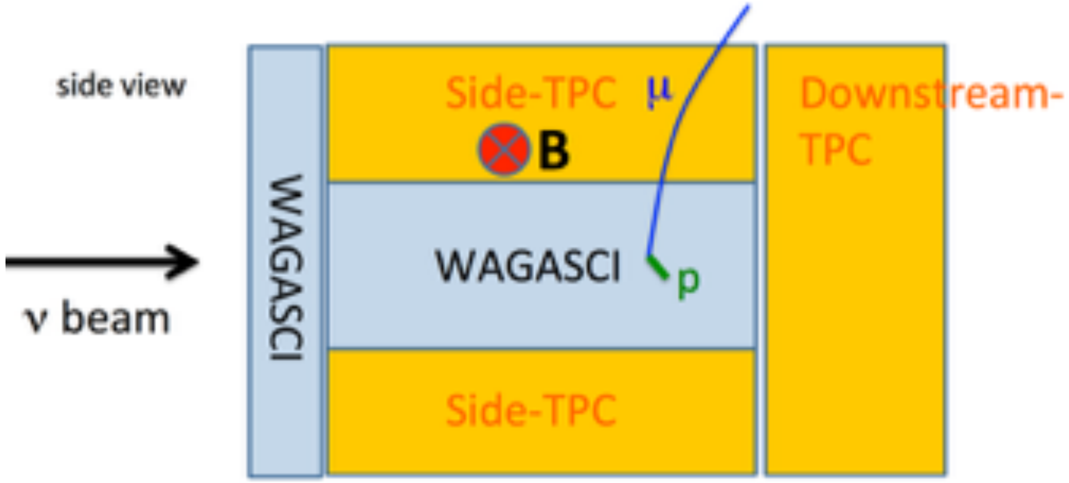
Potential T2K Near Detector Upgrades

Inside UA1 magnet:

- **FGD2: H_2O → D_2O**
  Neutrino interaction properties on quasi-free neutron in deuterium (via subtraction with data taken with H_2O)
- **Using water-based liquid scintillator**
  Detailed reconstruction of hadronic system
- **High pressure TPC (He, Ne, Ar)**
  Study A-dependence of cross-sections and final state interactions

Outside UA1 magnet:

- **Scintillating tracking detector with water and plastic targets surrounded by range detectors**
  Measure muon momentum over large range of angles and water/CH cross-sections



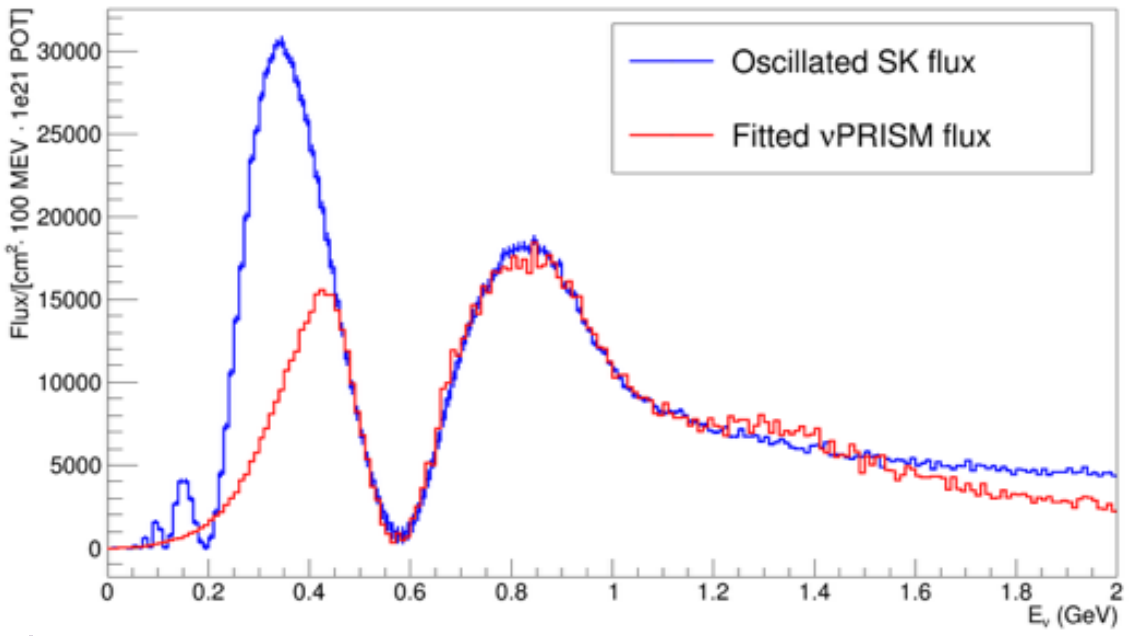
Hyper-K Intermediate Detector: NuPRISM

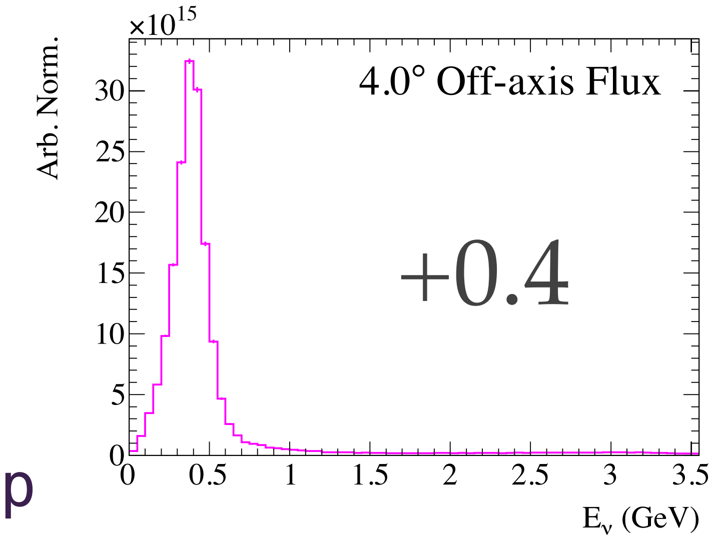
- Experimental method to remove uncertainties of neutrino interactions from oscillation analyses

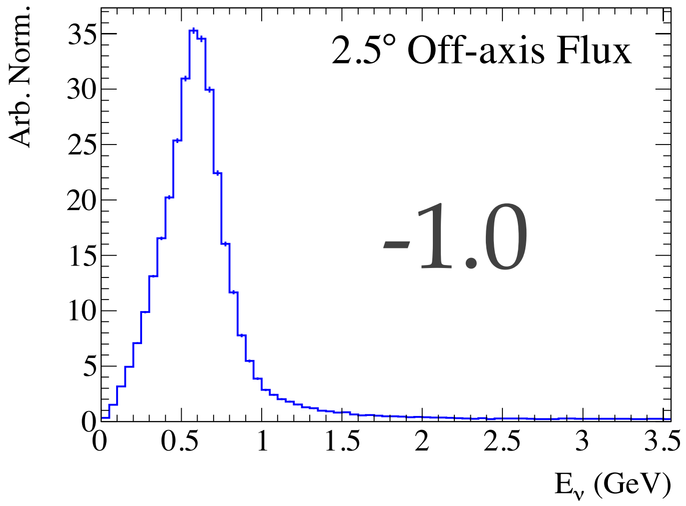
- Covers 1-4° off-axis angle range

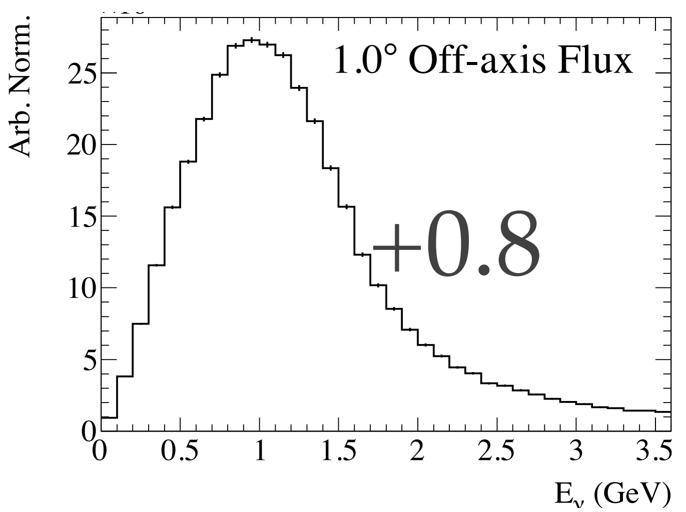
- Initial design: inner detector moves up and down in **water** filled pit

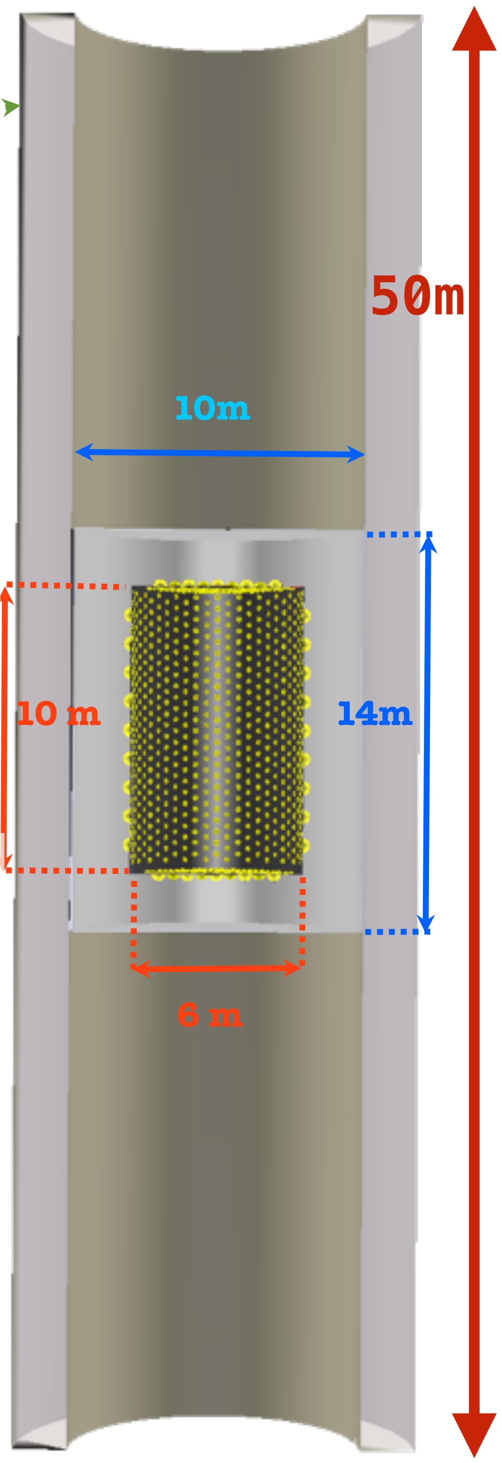
- **Linear combinations reproduce and predict muon kinematic distributions for the oscillated flux**







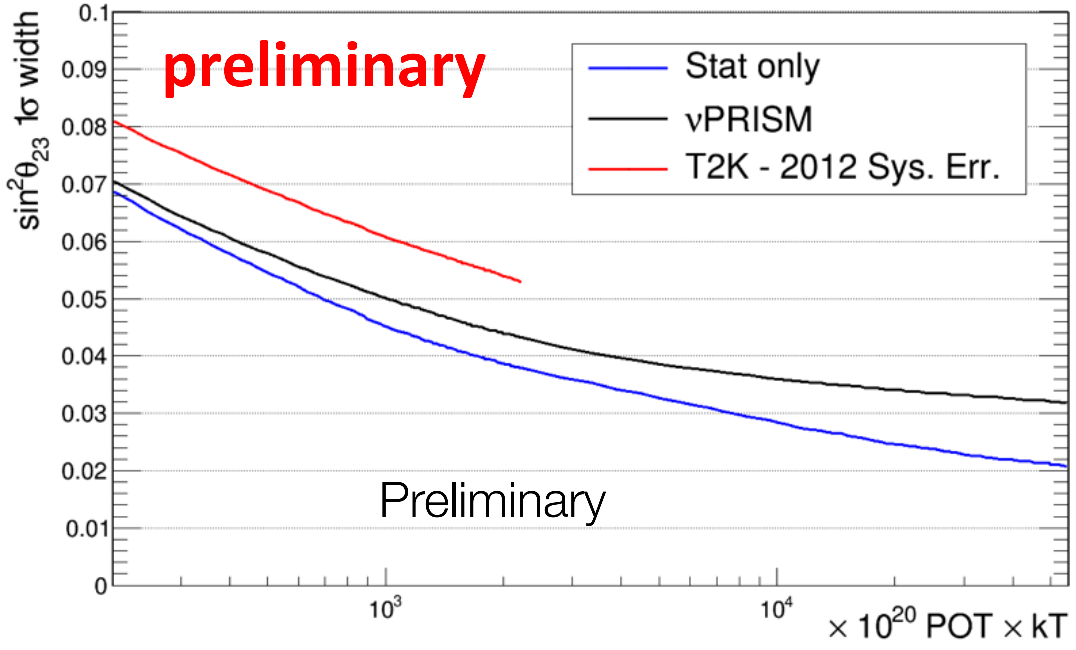


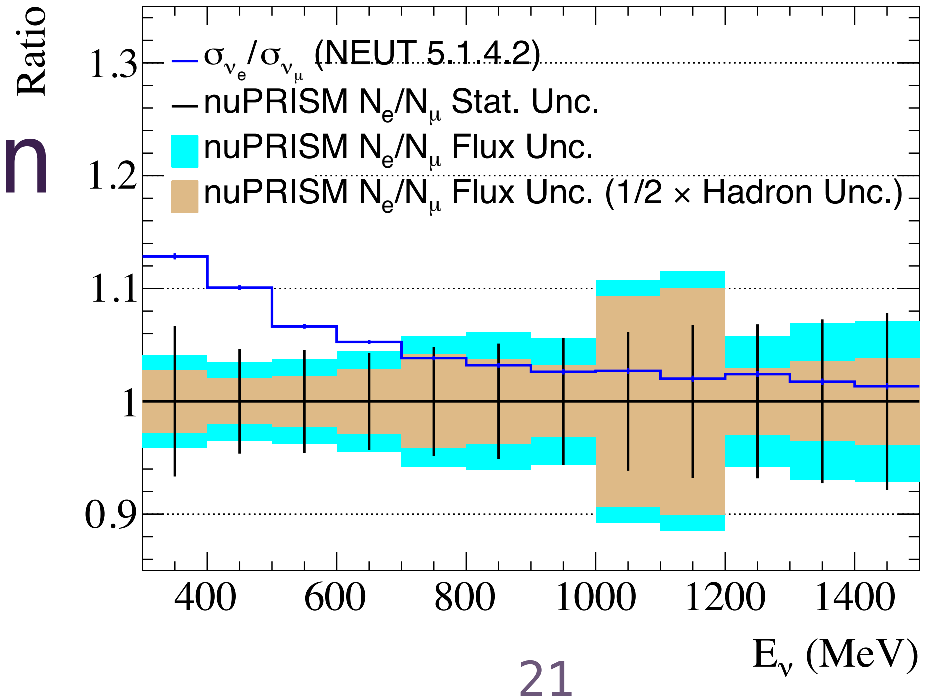


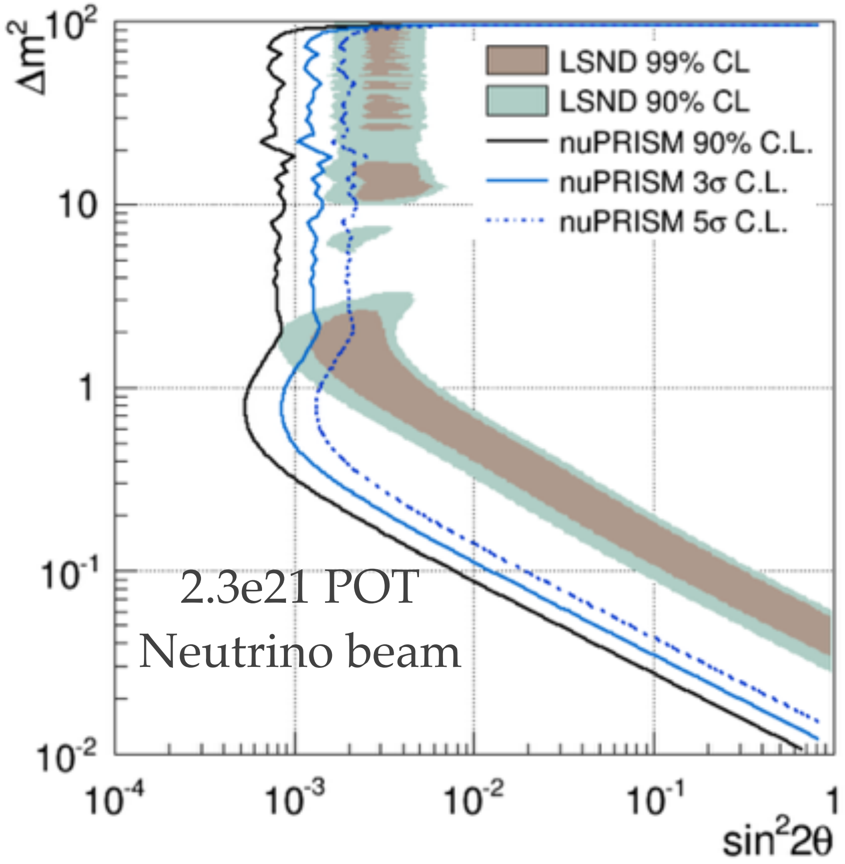
NuPRISM Studies

- **ν_μ disappearance analysis** 4% systematic error using T2K ND280, using NuPRISM reduces to 1%
- Short baseline **ν_e** appearance (sterile neutrino search)
- Cross-section measurements

$\sin^2\theta_{23}$ sensitivity (T2K, ν mode)

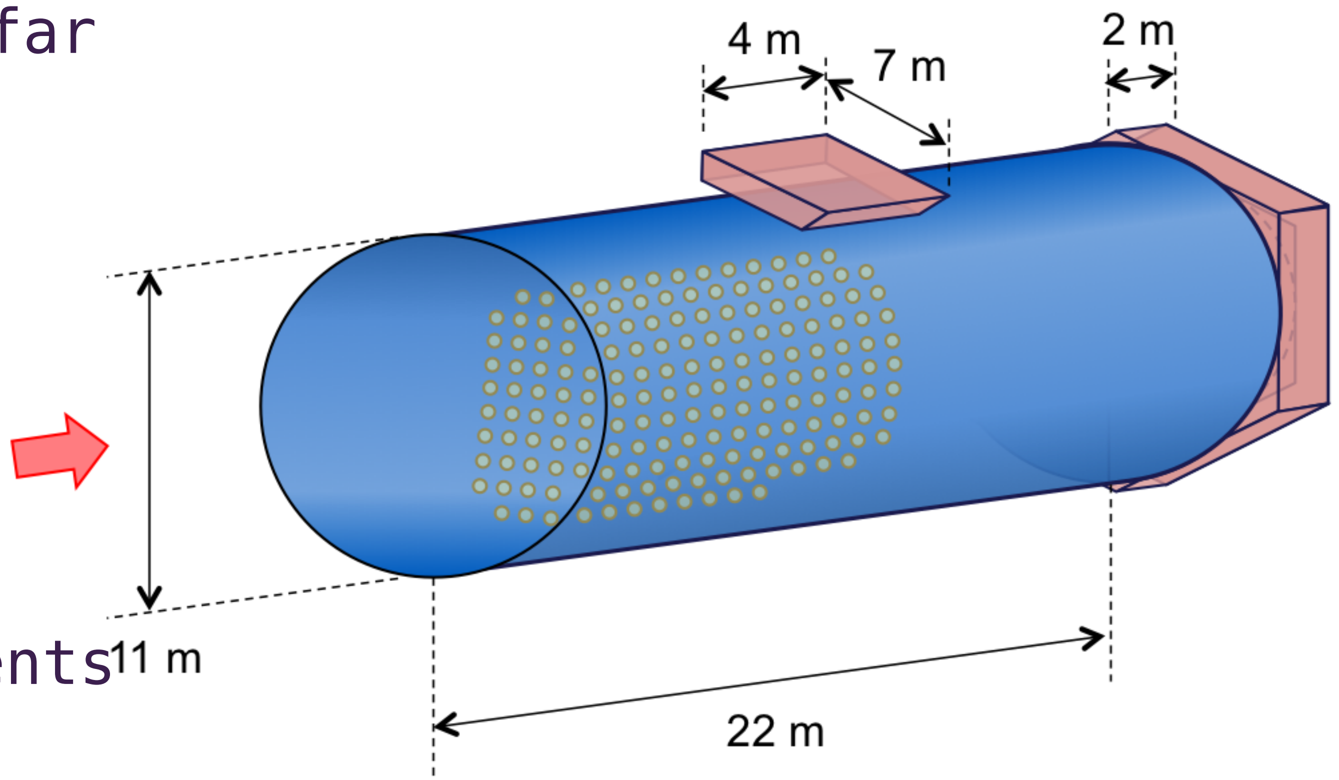






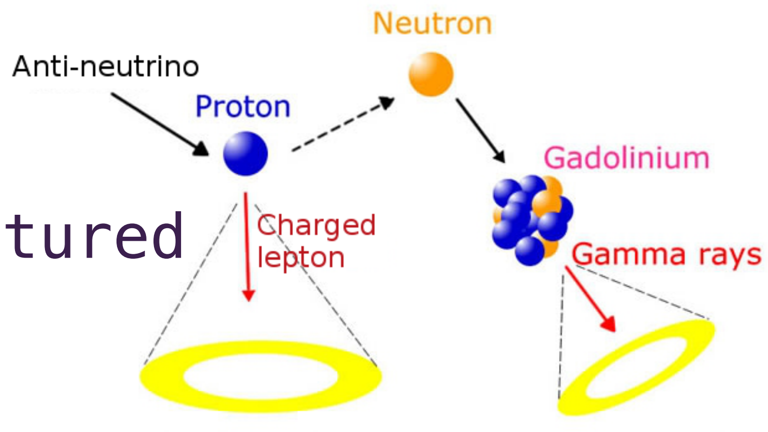
Hyper–K Intermediate Detector: TITUS

- **4π coverage** → mimic coverage at far detector
- **Full magnetised downstream MRD:**
  - Forward scattering muons (momentum < 2GeV) used in oscillation fits
  - Constrain “wrong–sign” components



- **Small magnetised side MRD:**
  - Measure high Q^2 region of phase–space
- **0.1% Gd doping** → ~90% neutrons captured

Phys.Rev.Lett. 93, 171101, 2004



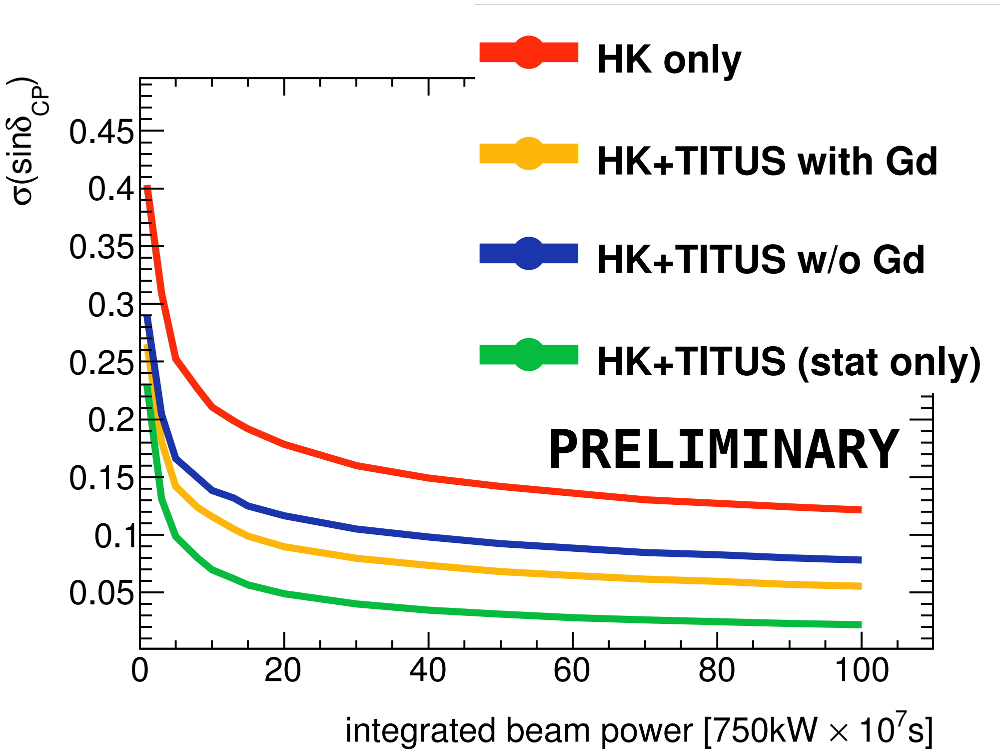
Originally detectable signal

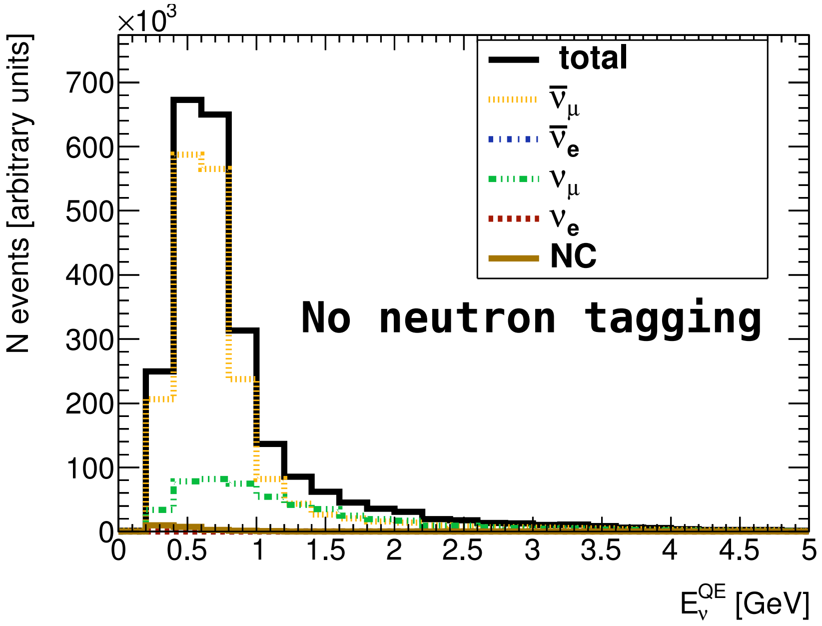
New signal

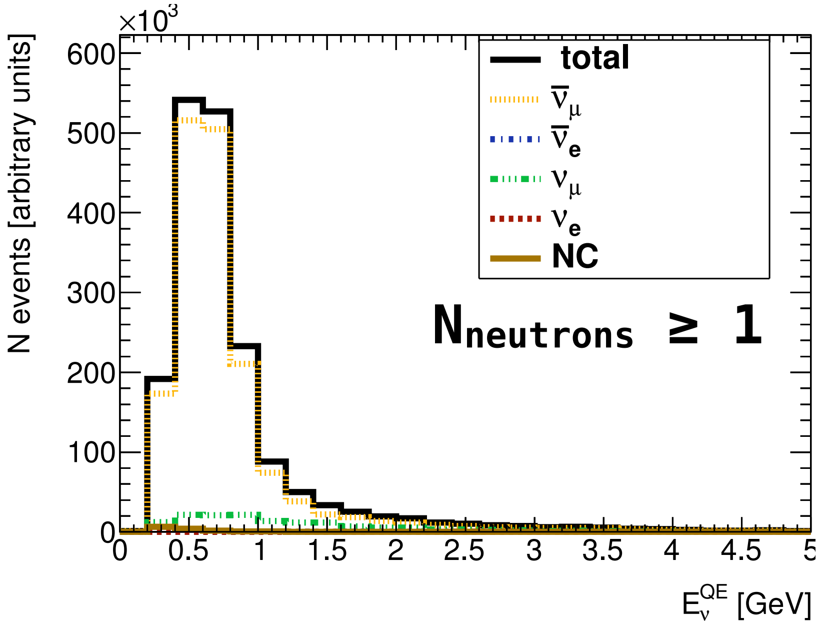
Type	Average number of neutrons
ν_l CCQE	~0
ν_l CC–MEC	~0.2
ν_l NC	~0.5
$\bar{\nu}_l$ CCQE	~1
$\bar{\nu}_l$ CC–MEC	~1.8

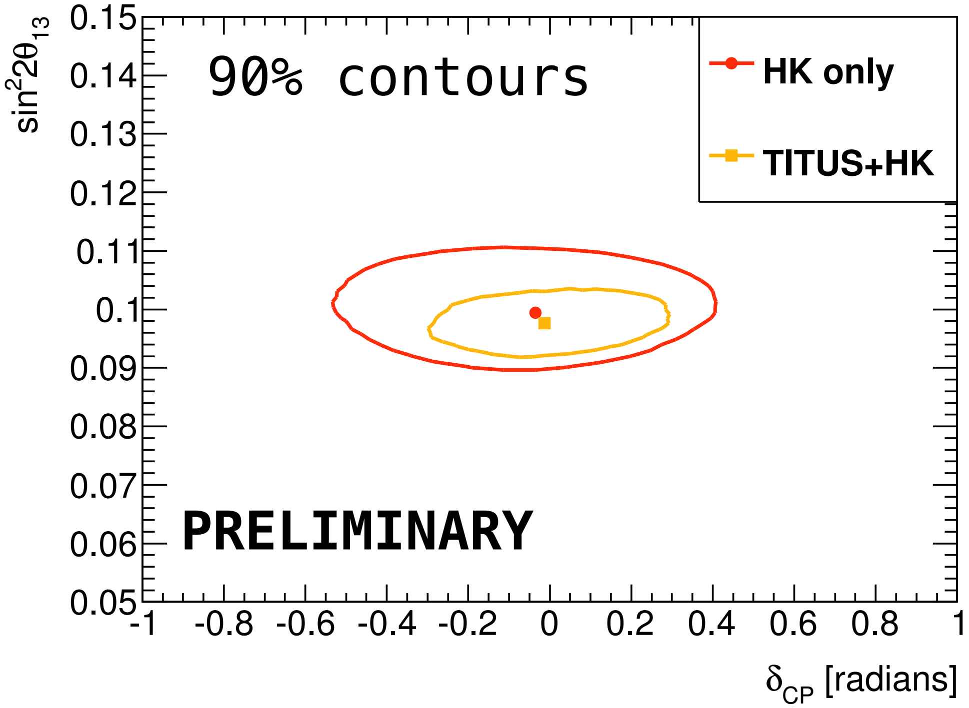
TITUS Sensitivity Studies

- Use Super-K lepton selection and efficiency and detector resolution tables
- Gd enhances CCQE purity:
  (assume 100% efficiency neutron captures on Gd)
  FHC 1Rμ: 74% → 83%
  RHC 1Rμ: 60% → 73%







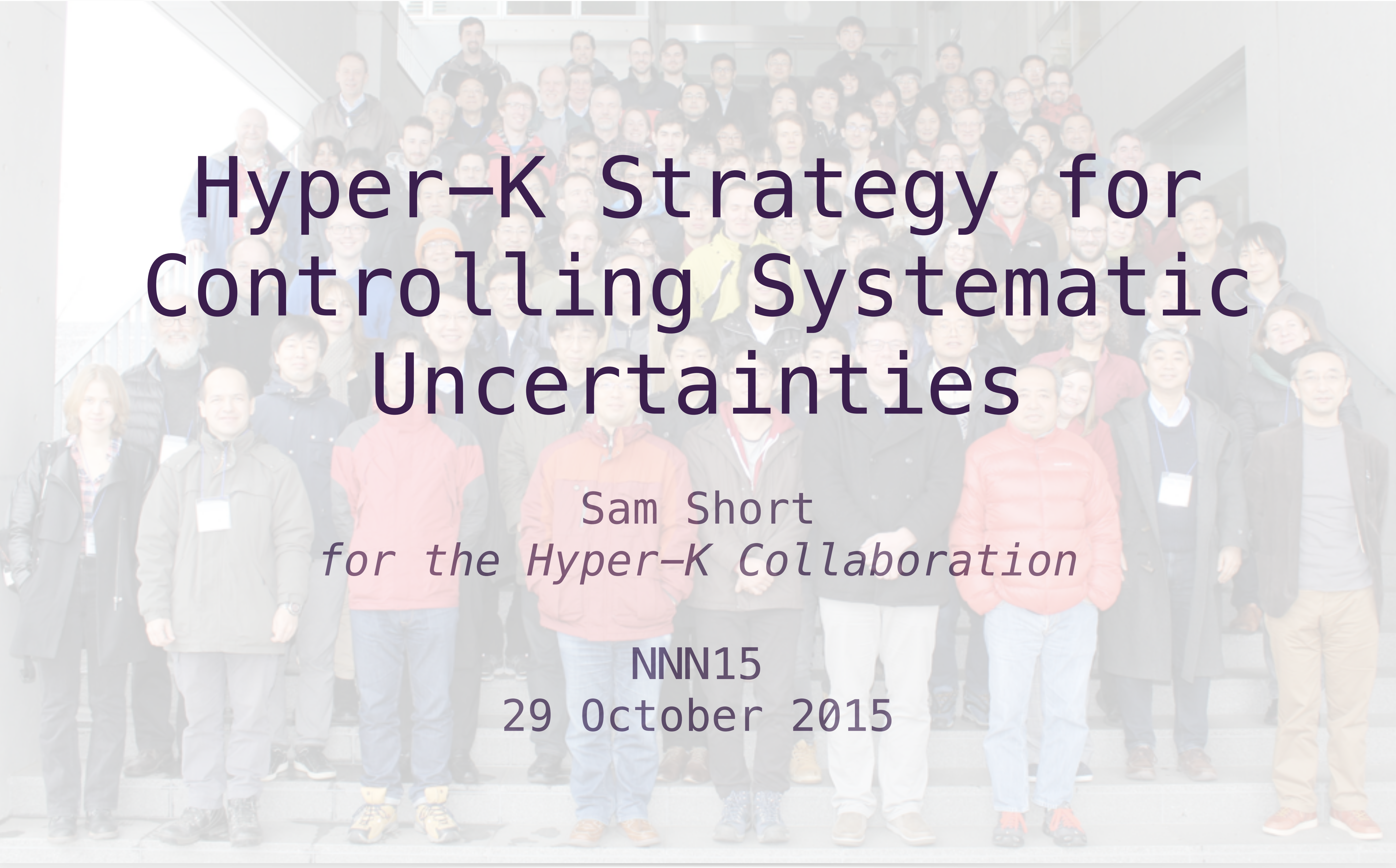


Significantly increase sensitivity to δ_{CP} when include TITUS and neutron tagging to fits

Summary

- Hyper Kamiokande will study:
  nucleon decay and solar, atmospheric, accelerator and supernova neutrino physics
- Require systematic uncertainties to be at the few % level
- Studies ongoing to determine largest sources of systematic errors:
  - Flux uncertainties (data driven measurements)
  - Wrong sign backgrounds (magnetised near detector)
  - Beam contamination (water Cherenkov intermediate detector)
  - Model and (ν_e, $\bar{\nu}_e$) cross-section uncertainties (data driven measurements)

Thanks for listening



Hyper-K Strategy for Controlling Systematic Uncertainties

Sam Short

for the Hyper-K Collaboration

NNN15

29 October 2015

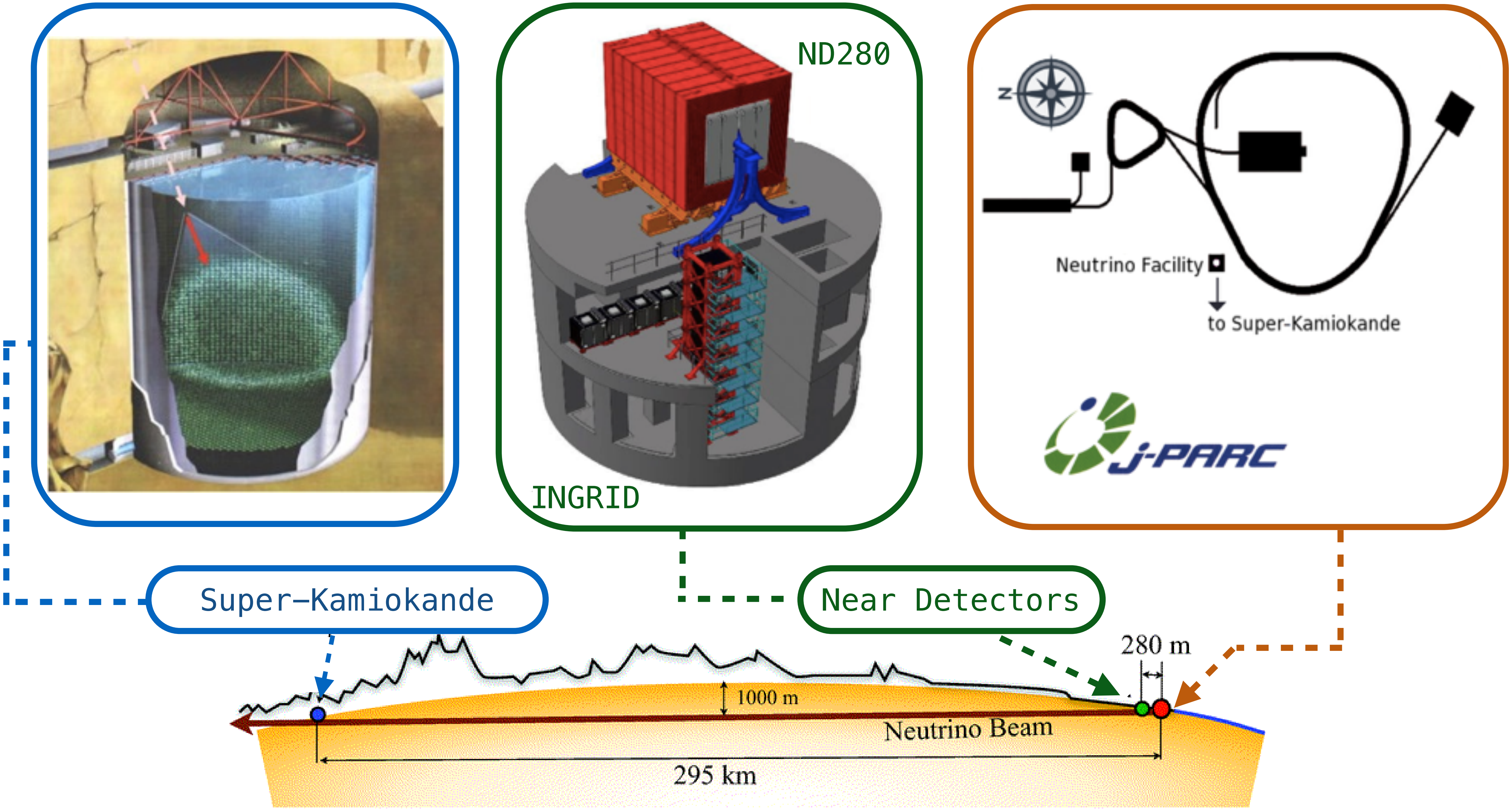
References

- “Physics Potential of a Long Baseline Neutrino Oscillation Experiment Using J–PARC Neutrino Beam and Hyper–Kamiokande” published in PTEP (May 2015)
  arXiv:1502.05199 [hep–ex]

- “A Long Baseline Neutrino Oscillation Experiment Using J–PARC Neutrino Beam and Hyper–Kamiokande”
  arXiv:1412.4673v2 [physics.ins–det]

- “Letter of Intent: The Hyper–Kamiokande Experiment”,
  arXiv:1109.3262v1 [hep–ex]

Tokai2Kamioka Experiment



Super−Kamiokande

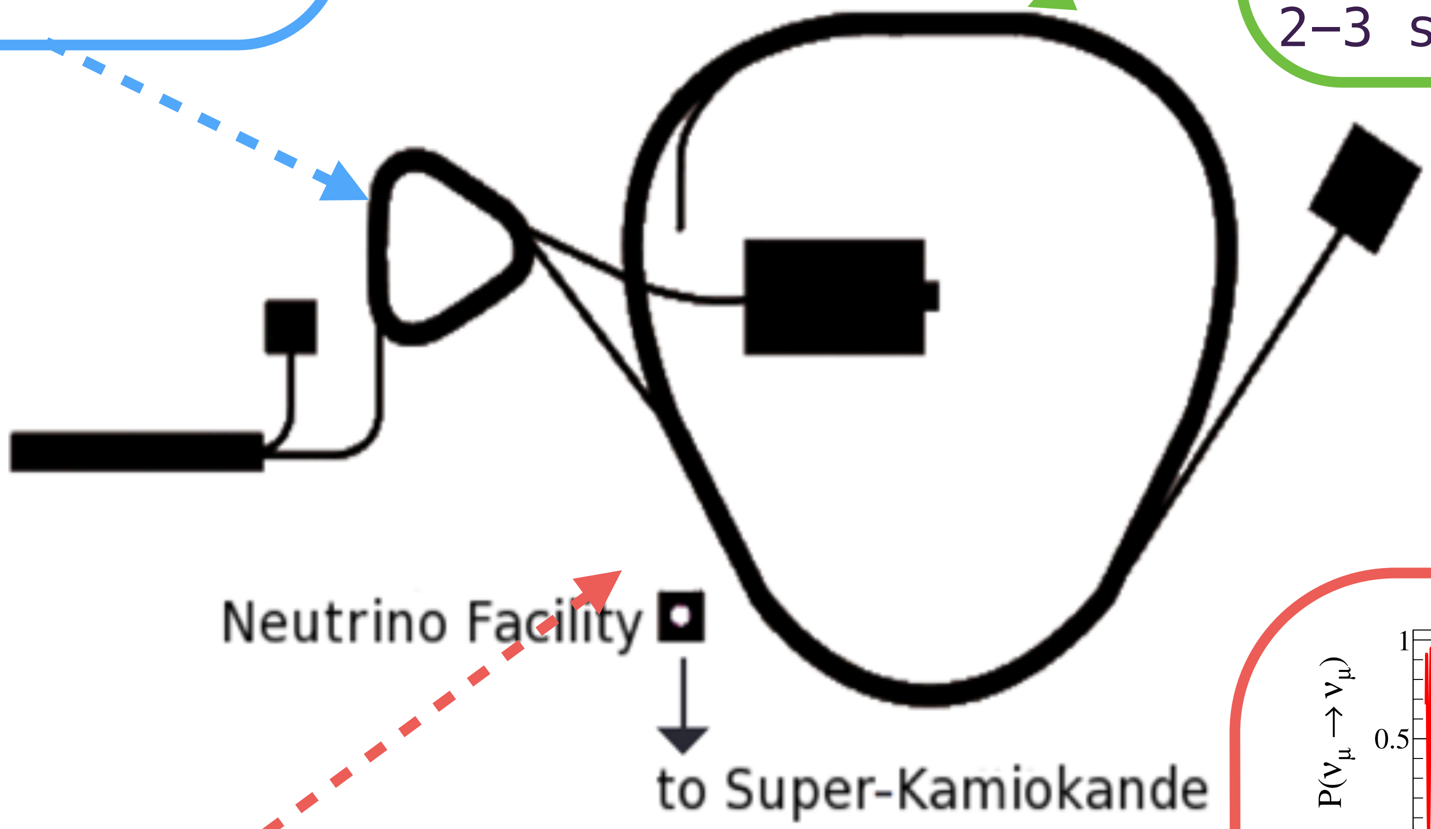
Near Detectors

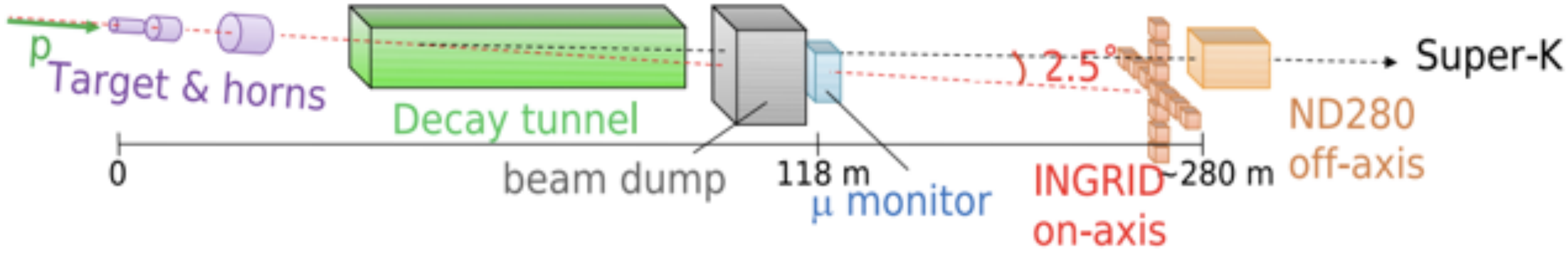
J-PARC Beamline

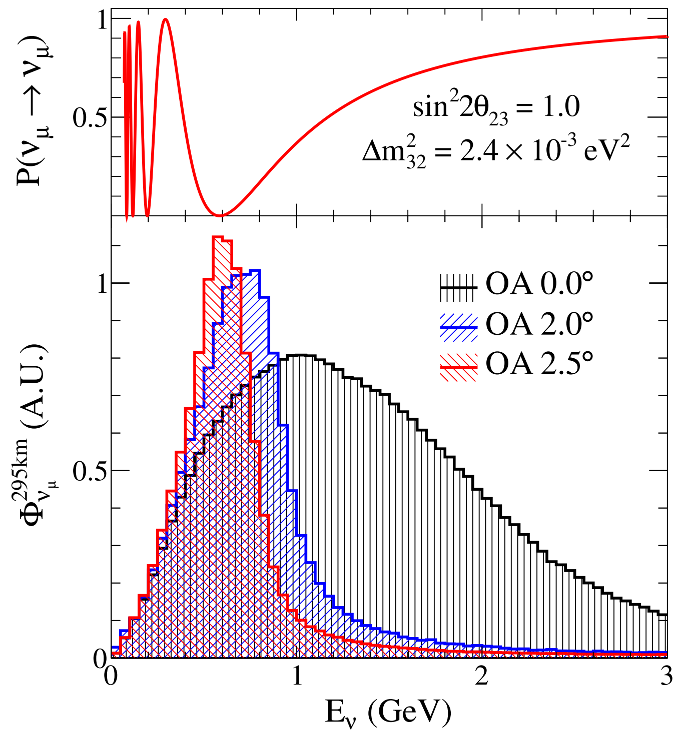
Rapid Cycling Synchrotron:
Accelerate H+ ions to 3 GeV

Main Ring Synchrotron:
30 GeV protons every 2-3 seconds

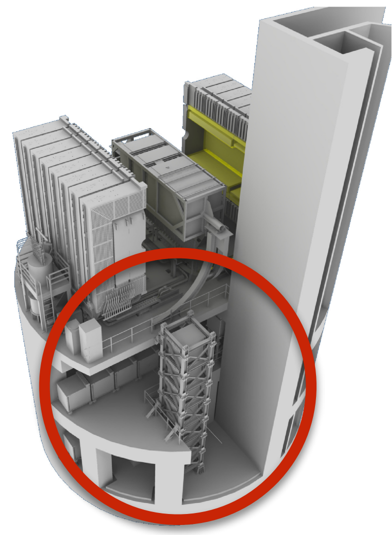
LINAC:
Accelerate H- ions to energy of 400 MeV

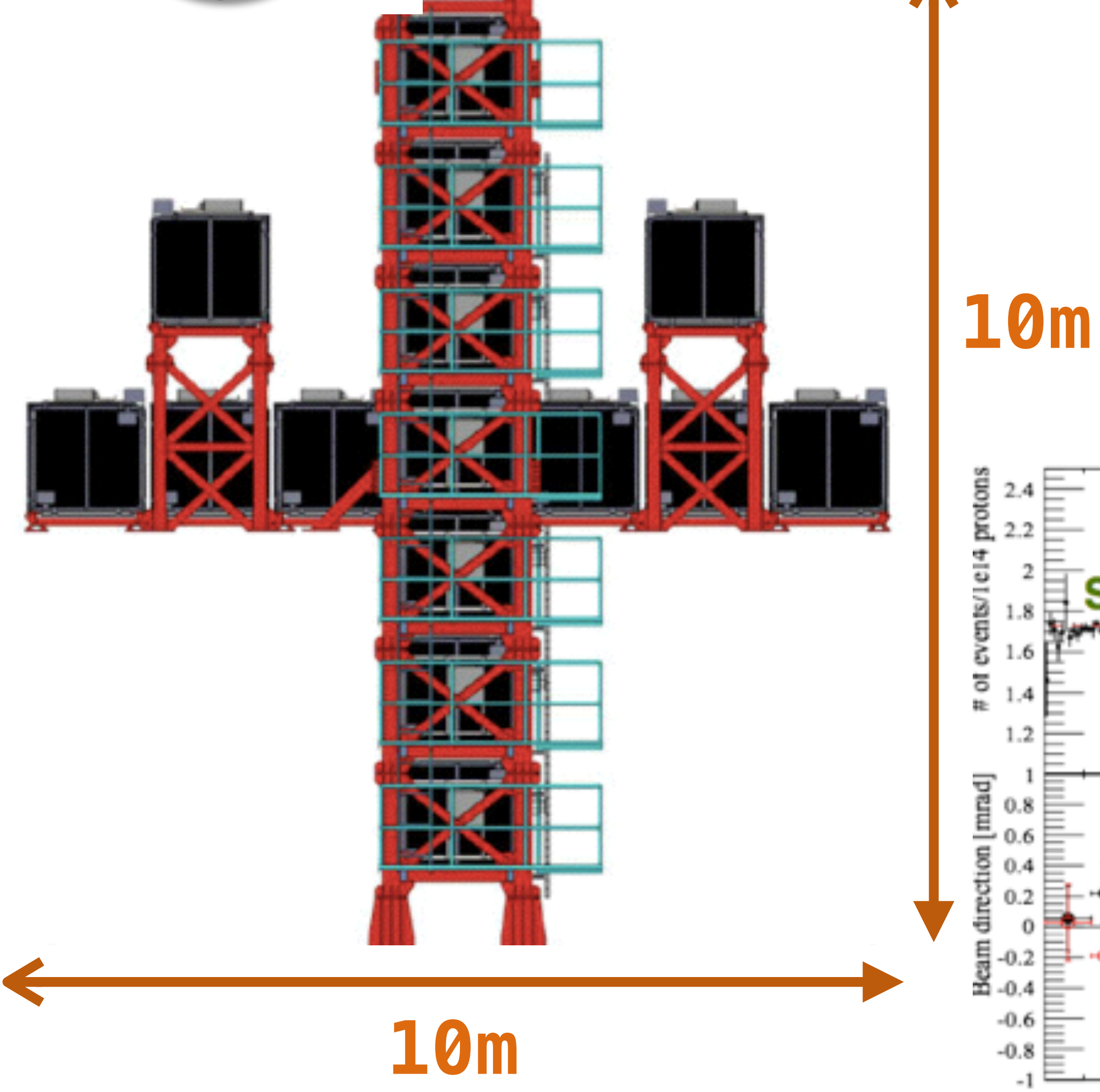






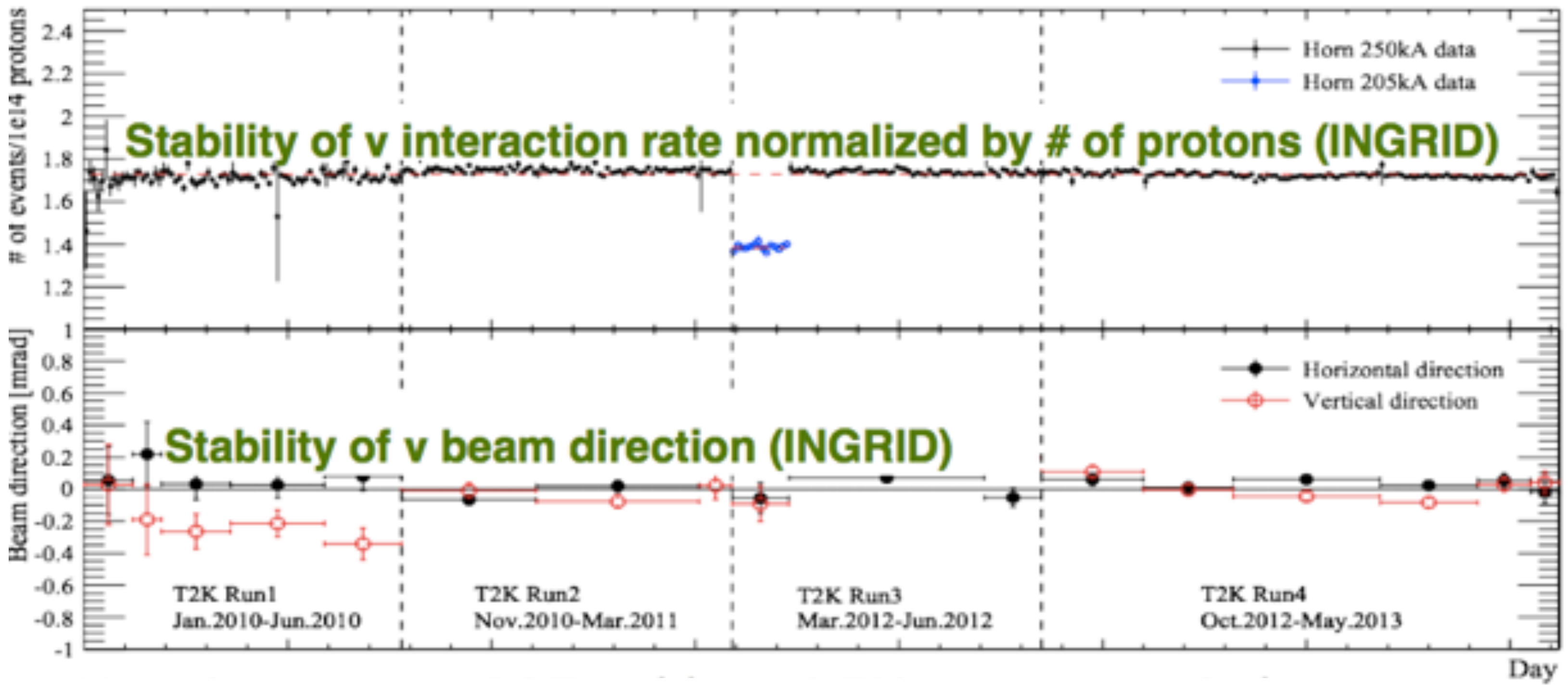
T2K On–Axis Near Detector: INGRID



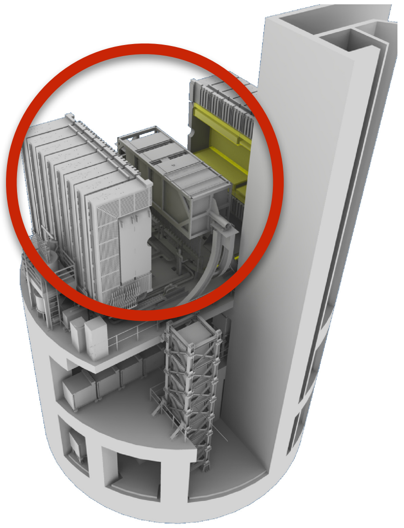


Interactive Neutrino GRID:

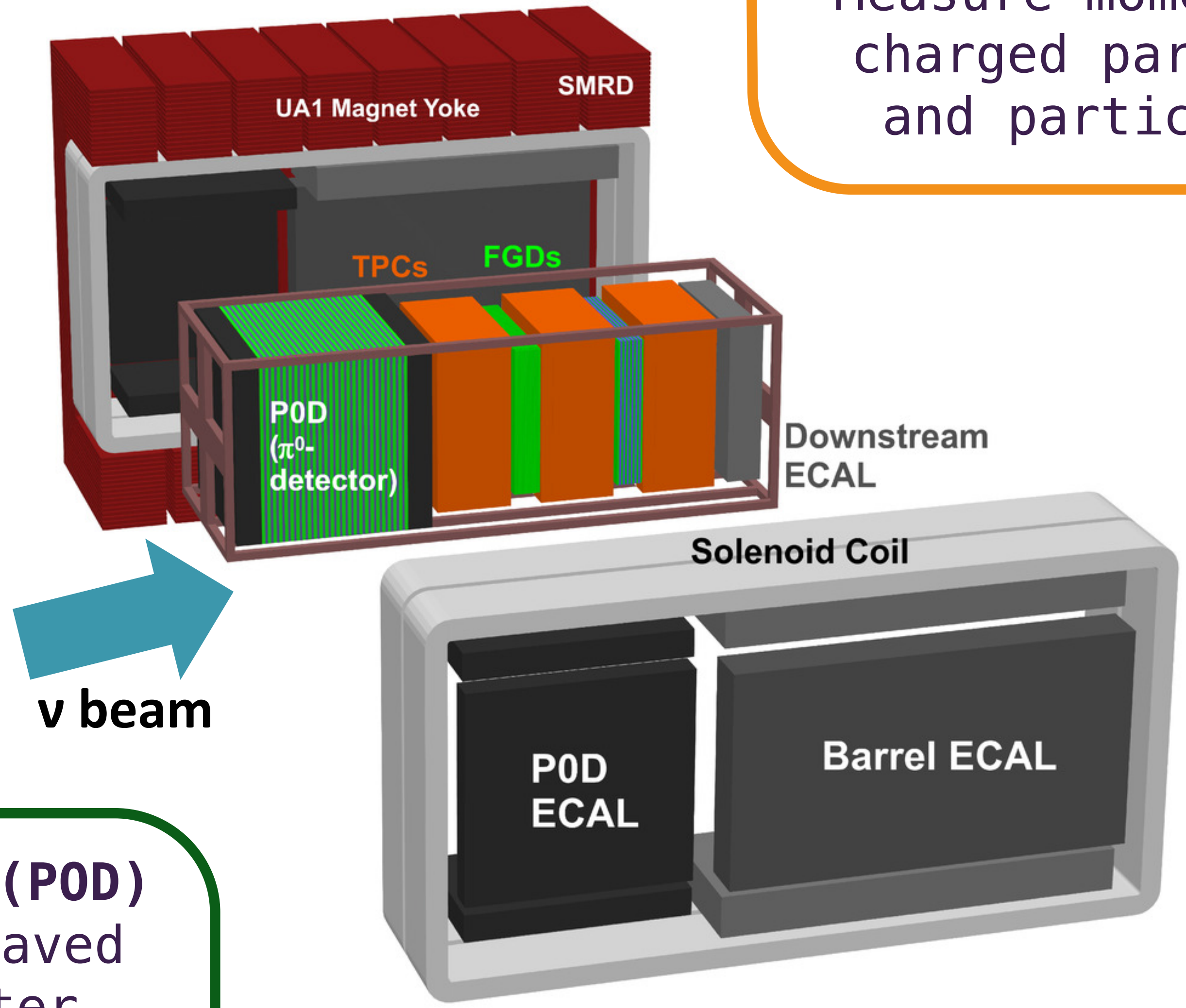
- 280m from target on beam axis
- 16 iron/scintillator module
- 1 scintillator tracking module
- Monitors beam centre, profile and neutrino flux



T2K Off-Axis Near Detector: ND280



Fine Grained Detectors (FGDs)
Provide active targets for neutrino interactions
FGD1: carbon
FGD2: carbon + water



Tracker: FGDs + TPCs
Measure momenta of charged particles and particle ID

Electromagnetic Calorimeter (ECAL)
Plastic scintillator and lead
Aids in PID

Upstream π^0 detector (P0D)
Scintillator interleaved with carbon and water targets

UA1 magnet: 0.2T magnetic field

Expected Sensitivities

Physics target	Sensitivity	Conditions
Neutrino study w/ J-PARC ν		7.5 MW × 10^7 s
− CP phase precision	$<19^\circ$	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
− CPV discovery coverage	76% ($3\,\sigma$), 58% ($5\,\sigma$)	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
− $\sin^2 \theta_{23}$	± 0.015	$1\,\sigma$ @ $\sin^2 \theta_{23} = 0.5$
Atmospheric neutrino study		10 yr observation
− MH determination	$>3\,\sigma$ CL	@ $\sin^2 \theta_{23} > 0.4$
− θ_{23} octant determination	$>3\,\sigma$ CL	@ $\sin^2 \theta_{23} < 0.46$ or $\sin^2 \theta_{23} > 0.56$
Nucleon decay searches		10 yr data
− $p \rightarrow e^+ + \pi^0$	1.3×10^{35} yr (90% CL UL)	
	5.7×10^{34} yr ($3\,\sigma$ discovery)	
− $p \rightarrow \bar{\nu} + K^+$	3.2×10^{34} yr (90% CL UL)	
	1.2×10^{34} yr ($3\,\sigma$ discovery)	
Astrophysical neutrino sources		
− ^{8}B ν from Sun	200 ν/day	7.0 MeV threshold (total energy) w/ osc.
− Supernova burst ν	170 000–260 000 ν	@ Galactic center (10 kpc)
	30–50 ν	@ M31 (Andromeda galaxy)
− Supernova relic ν	830 ν/10 yr	
− WIMP annihilation at Sun		5 yr observation
(σ_{SD}: WIMP–proton spin-dependent cross section)	$\sigma_{SD} = 10^{-39}$ cm^2	@ $M_{\mathrm{WIMP}} = 10$ GeV, $\chi\chi \rightarrow b\bar{b}$ dominant
	$\sigma_{SD} = 10^{-40}$ cm^2	@ $M_{\mathrm{WIMP}} = 100$ GeV, $\chi\chi \rightarrow W^+W^-$ dominant

Errors for Appearance and Disappearance Analyses

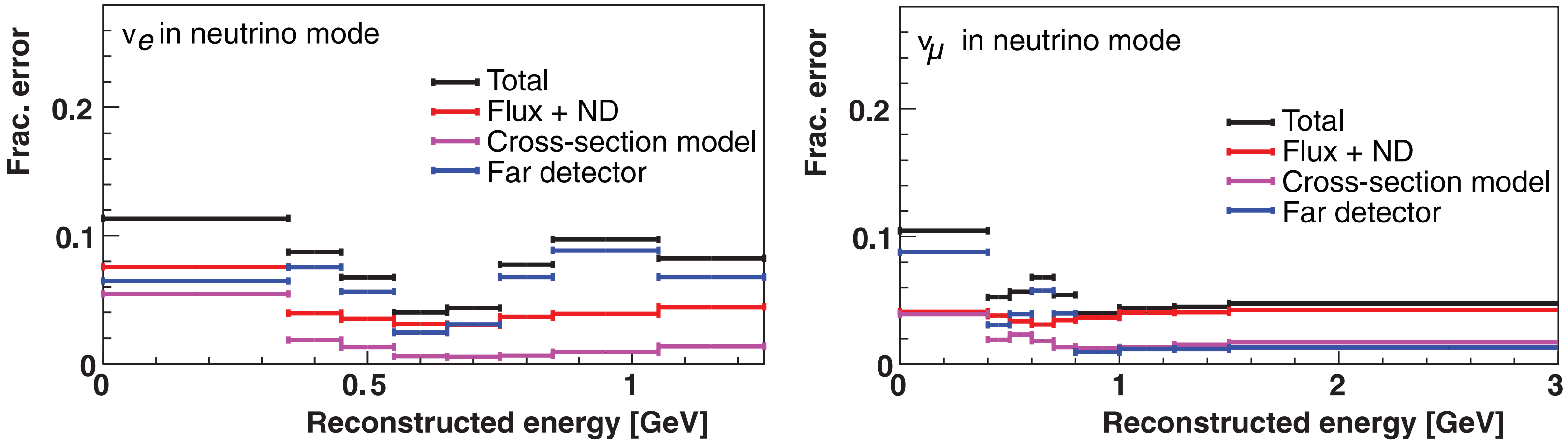


Fig. 15. Fractional error size for the appearance (left) and disappearance (right) samples in the neutrino mode. Black: total uncertainty, red: flux and cross section constrained by the near detector, magenta: near-detector non-constrained cross section, blue: far-detector error.

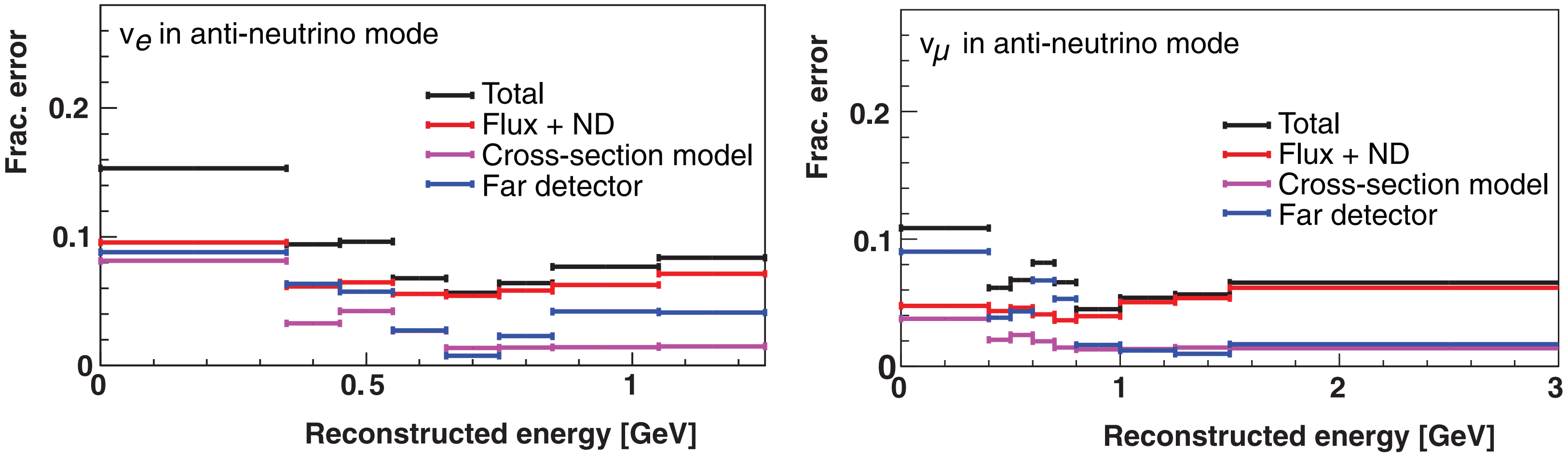
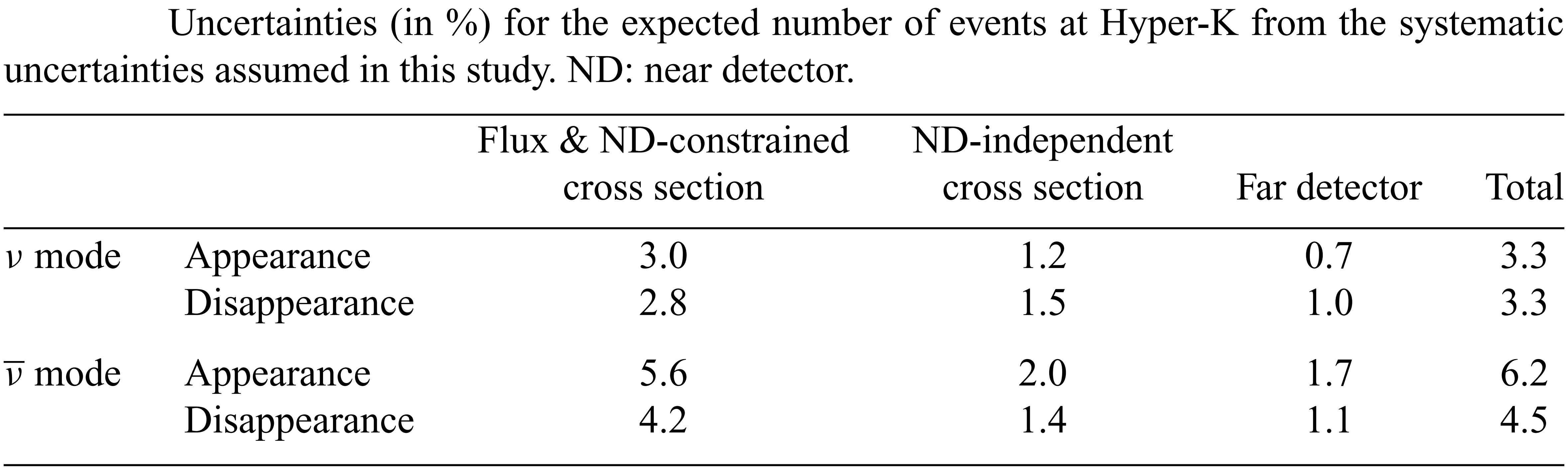


Fig. 16. Fractional error size for the appearance (left) and disappearance (right) samples in the anti-neutrino mode. Black: total uncertainty, red: flux and cross section constrained by the near detector, magenta: near-detector non-constrained cross section, blue: far-detector error.

Hyper–K Uncertainties



Uncertainties (in %) for the expected number of events at Hyper-K from the systematic uncertainties assumed in this study. ND: near detector.

		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0	1.2	0.7	3.3
	Disappearance	2.8	1.5	1.0	3.3
$\overline{\nu}$ mode	Appearance	5.6	2.0	1.7	6.2
	Disappearance	4.2	1.4	1.1	4.5

Expected Sensitivity to CP–Violation

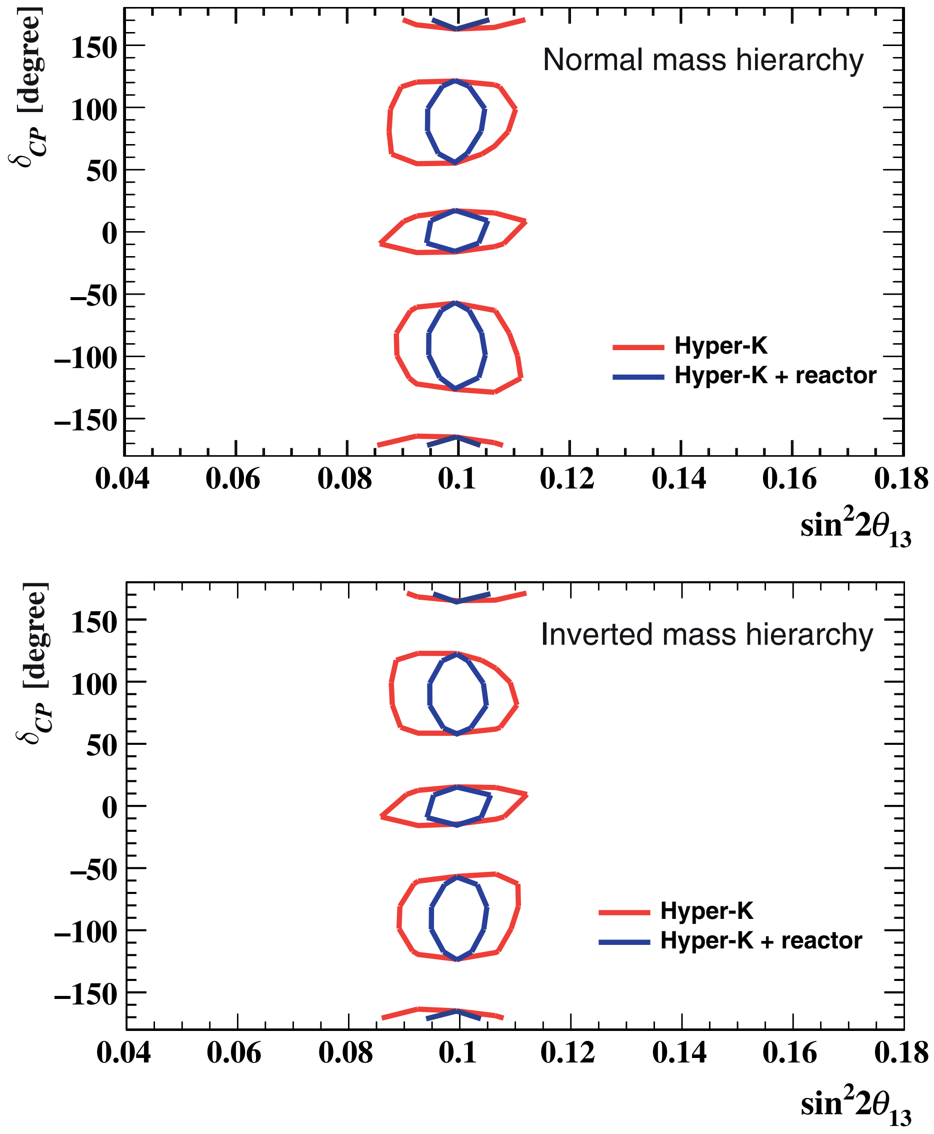


Fig. 18. The 90% CL allowed regions in the $\sin^2 2\theta_{13}$–δ_{CP} plane. The results for the true values of $\delta_{CP} = (-90^\circ, 0, 90^\circ, 180^\circ)$ are overlaid. Top: normal hierarchy case. Bottom: inverted hierarchy case. Red (blue) lines show the result with Hyper-K only (with a $\sin^2 2\theta_{13}$ constraint from reactor experiments).

Excluding DeltaCP = 0

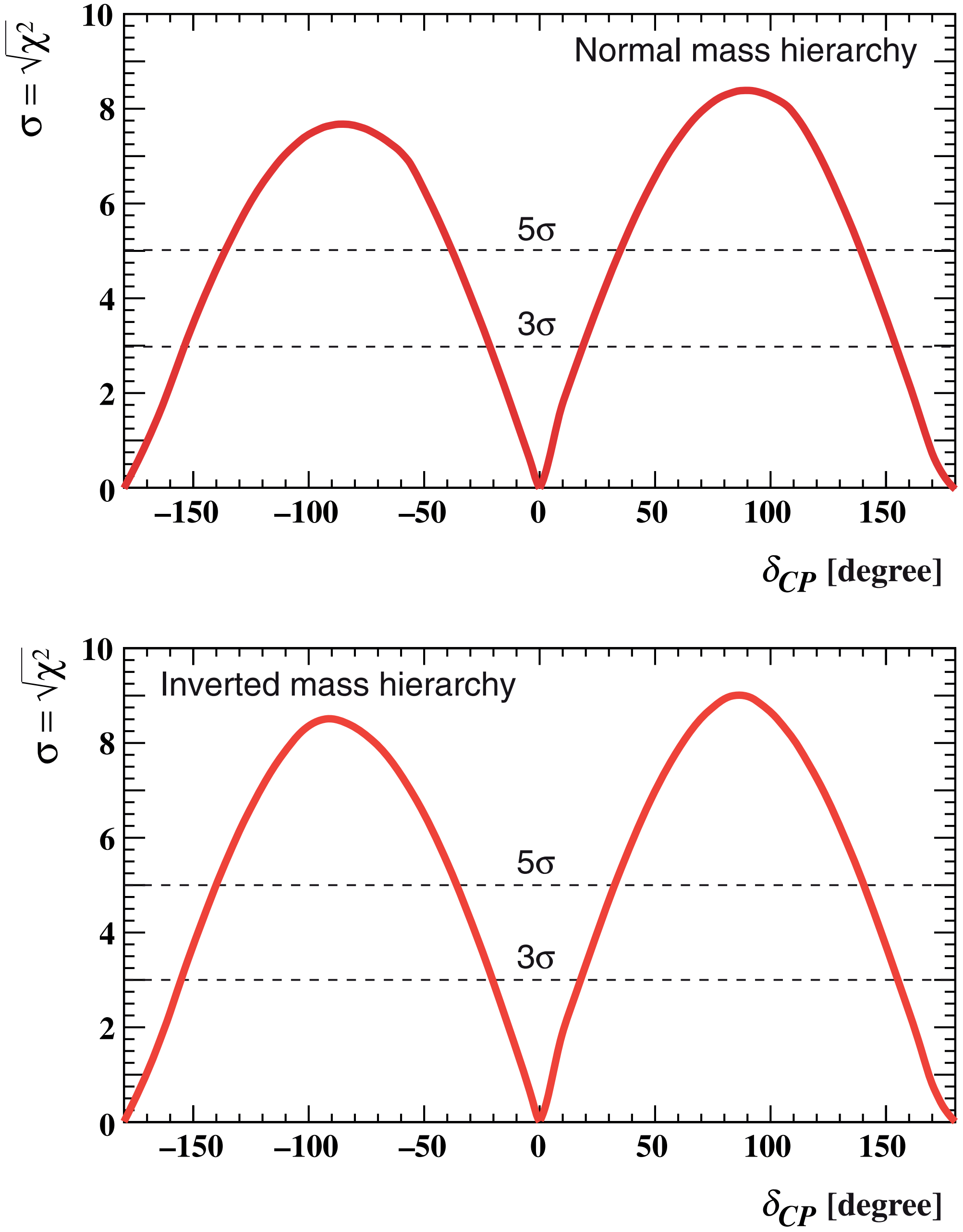


Fig. 19. Expected significance to exclude $\sin\delta_{CP} = 0$. Top: normal hierarchy case. Bottom: inverted hierarchy case.

Atmospheric Sensitivities

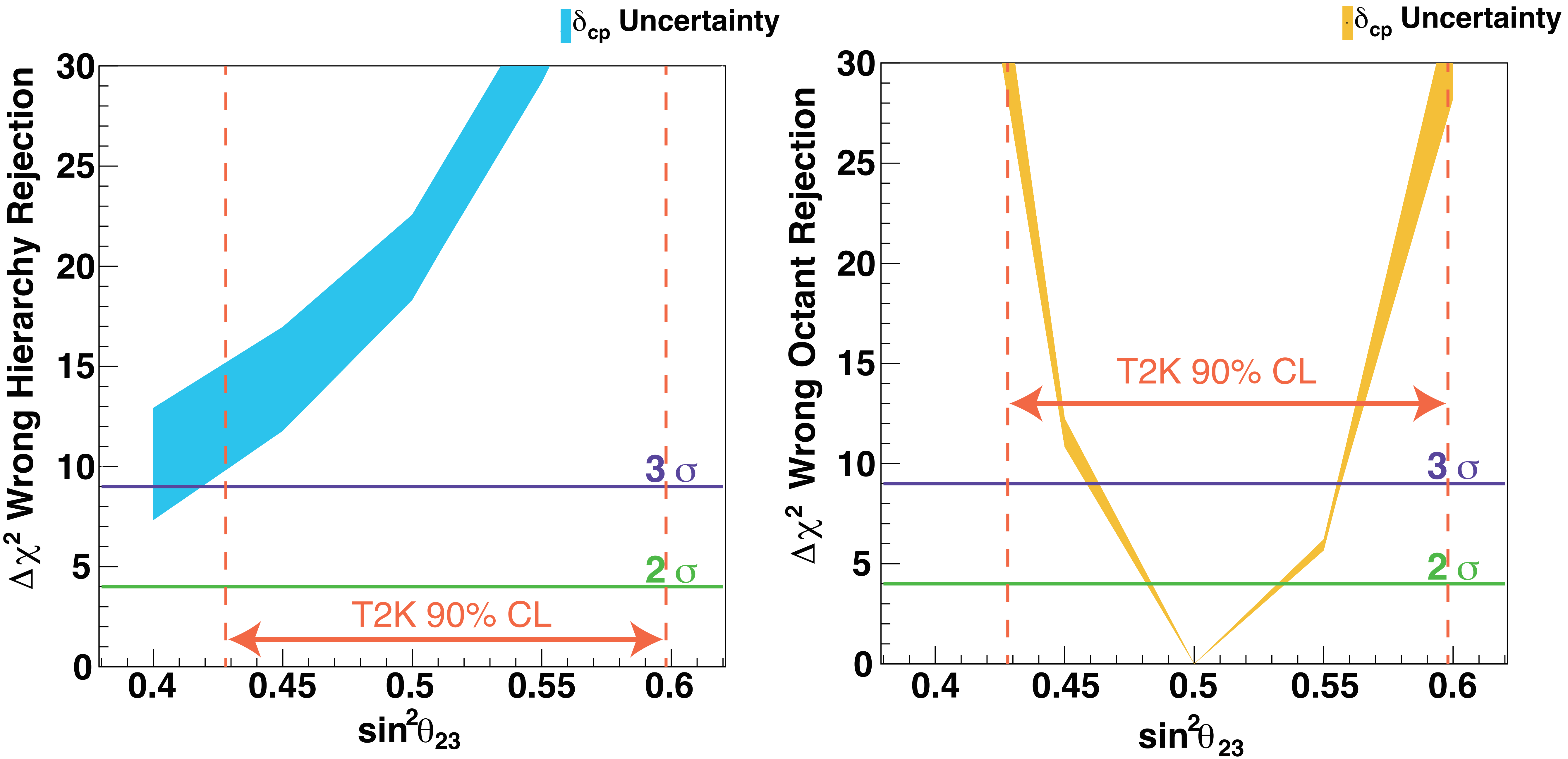


Fig. 25. Atmospheric neutrino sensitivities for a 10 yr exposure of Hyper-K assuming that the mass hierarchy is normal. Top: the $\Delta\chi^2$ discrimination of the wrong hierarchy hypothesis as a function of the assumed true value of $\sin^2\theta_{23}$. Bottom: the discrimination between the wrong octant for each value of $\sin^2\theta_{23}$. The uncertainty from δ_{CP} is represented by the thickness of the band. Vertical dashed lines indicate 90% confidence intervals of $\sin^2\theta_{23}$ from the T2K measurement in 2014 [38].