THE HYPER-K NEAR DETECTOR PROGRAMME

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FOR THE HYPER-K PROTO-COLLABORATION

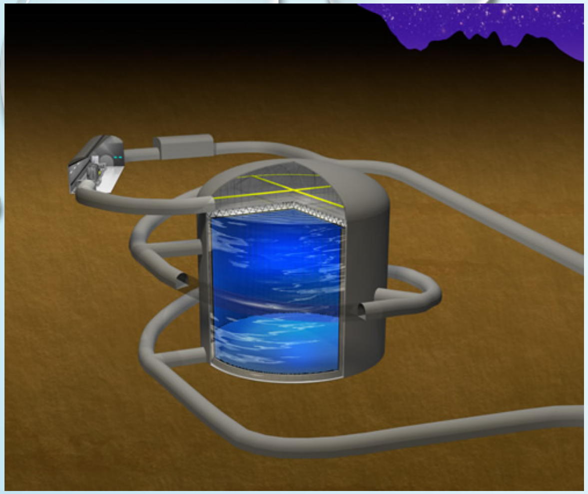
TAUP 2017, SUDBURY

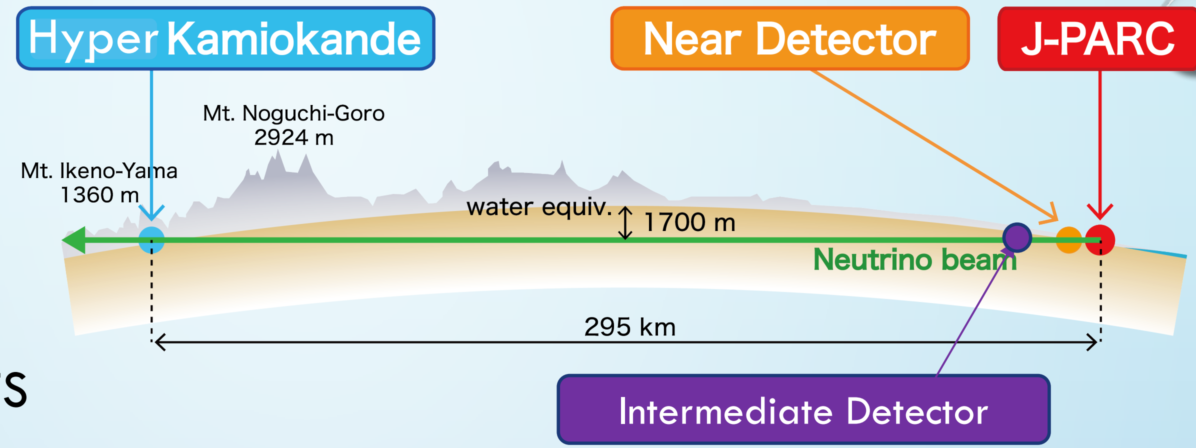
OVERVIEW

- THE HYPER-K PROJECT
- WHY DO WE NEED NEAR DETECTORS?
- ND280 AND POTENTIAL UPGRADES
- AN INTERMEDIATE WATER CHERENKOV DETECTOR – E61
- OTHER DETECTOR TECHNOLOGIES
- SUMMARY

Related Talks:
Mark Scott (Tuesday 2nd Neutrino session) The latest T2K results on neutrino oscillations and neutrino-nucleus interactions
Hidekazu Tanaka (Wed 1st Neutrino session) Hyper-Kamiokande
Seon-Hee Seo (Wed 1st Neutrino session) The 2nd Hyper-Kamiokande detector in Korea
Hiroyuki Sekiya (Wed 2nd Neutrino session) The Super-Kamiokande Gadolinium Project
Takatomi Yano (Wed 2nd Neutrino session) Astroparticle Physics in Hyper-Kamiokande

HYPER-K





- PHYSICS MEASUREMENTS
  - LEPTONIC CP VIOLATION
  - MASS ORDERING
    - FROM ATMOSPHERIC NEUTRINO OSCILLATIONS
    - + 2ND TANK IN KOREA
  - PRECISION OSCILLATION PARAMETER MEASUREMENT
  - PROTON DECAY SEARCH
  - ASTROPHYSICAL MEASUREMENTS
    - SOLAR NEUTRINOS
    - SUPERNOVA BURST
    - SUPERNOVA RELIC NEUTRINOS

WHY NEAR DETECTORS?

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})}$$

$$\propto \frac{\sigma^{\nu_e}/\sigma^{\nu_\mu}}{\sigma^{\overline{\nu_e}}/\sigma^{\overline{\nu_\mu}}}$$

Beam ν event rate @ Hyper-K

Oscillation Probability

Neutrino Flux

Interaction Cross-section

Detector Efficiency

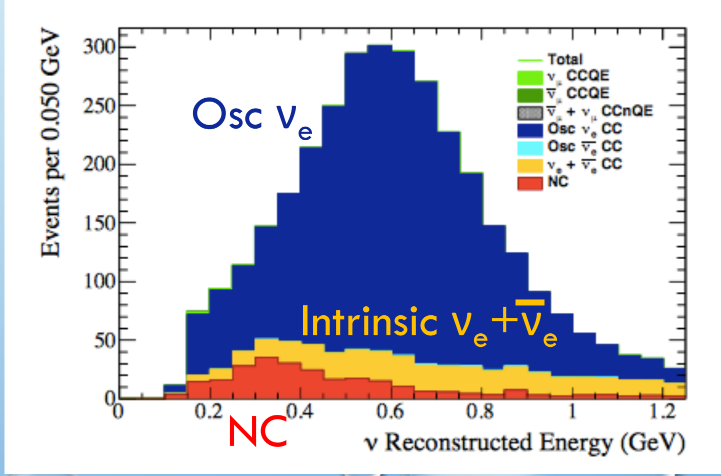
Detector Fiducial Mass

Near Detector Requirements:

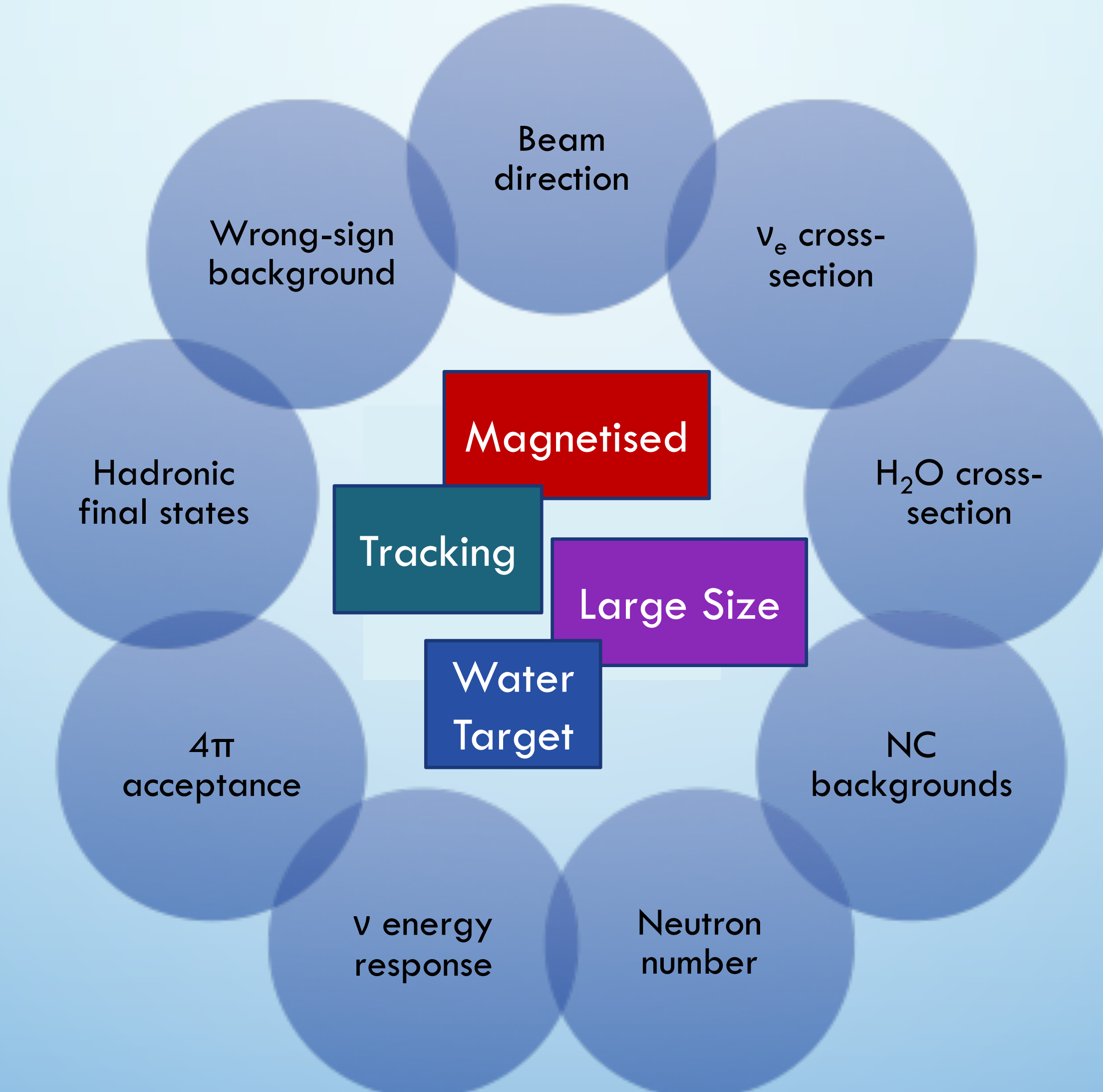
- Measure CC0π (& CC1π) interactions - signal channel in Hyper-K
- Intrinsic ν_e component of beam from muon and kaon decays (background for appearance signal)
- Wrong-sign CC processes (background in the CP-violation measurement)
- Maximise cancellation of systematic uncertainties in extrapolation to far detector event rate prediction (due to angular acceptance, target nuclei, energy range)

https://arxiv.org/pdf/1606.08114.pdf

Predicted ν_e spectrum @ Hyper-K

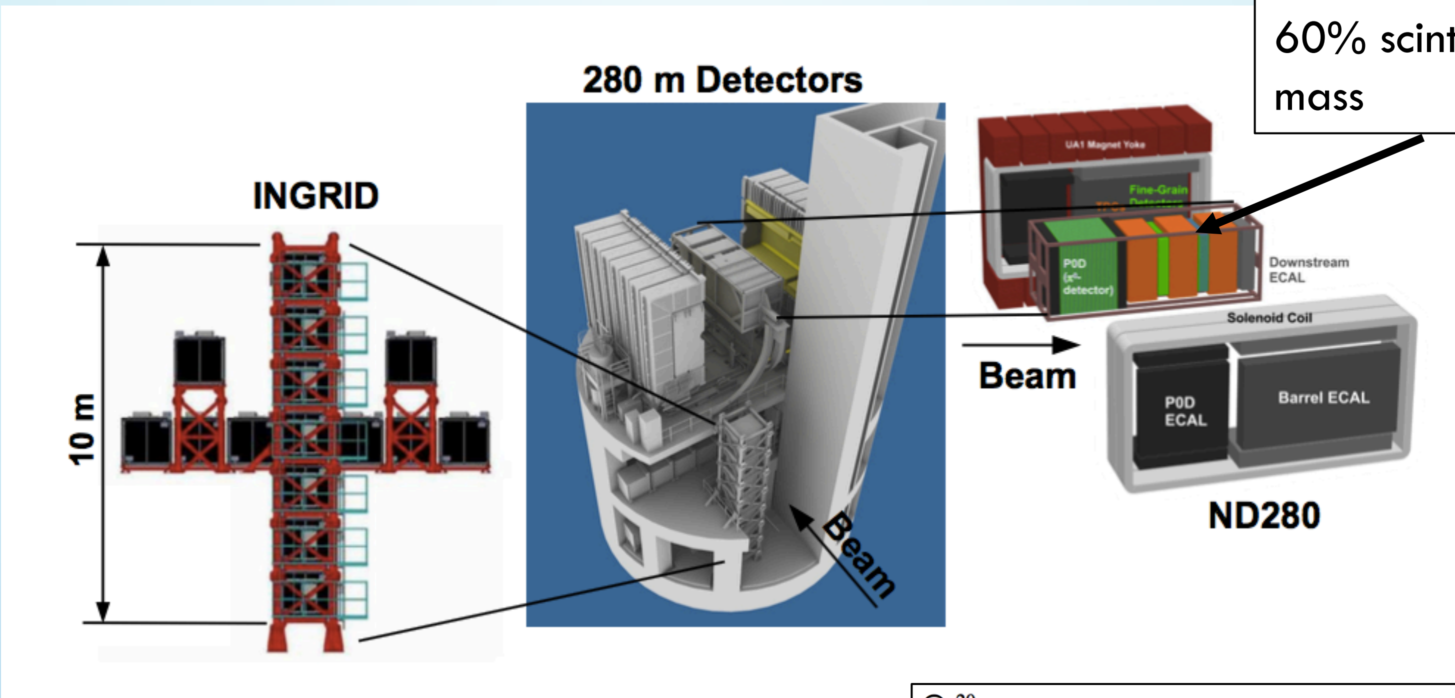


DETECTOR OPTIONS

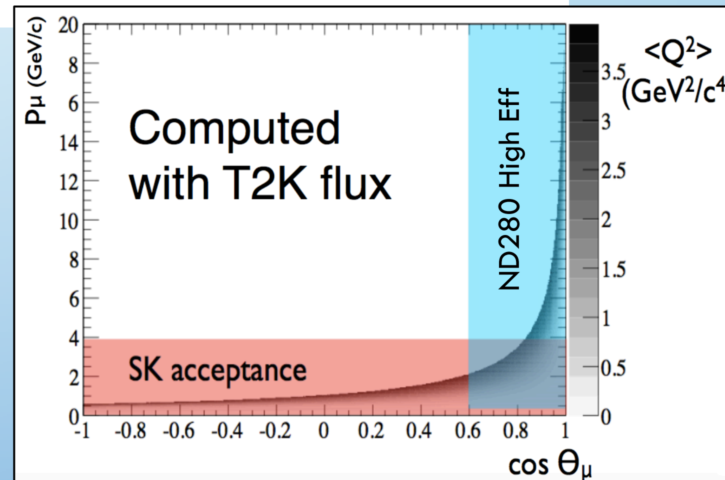


T2K NEAR DETECTORS

FGD2 40% water, 60% scintillator by mass



Source of uncertainty	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC
Flux and common cross sections				
(w/o ND280 constraint)	10.8%	10.9%	11.9%	12.4%
(w/ ND280 constraint)	2.8%	2.9%	3.3%	3.2%
Unconstrained cross sections	0.8%	3.0%	0.8%	3.3%
SK	3.9%	2.4%	3.3%	3.1%
FSI + SI(+ PN)	1.5%	2.5%	2.1%	2.5%
Total				
(w/o ND280 constraint)	11.9%	12.2%	13.0%	13.4%
(w/ ND280 constraint)	5.1%	5.4%	5.2%	6.2%

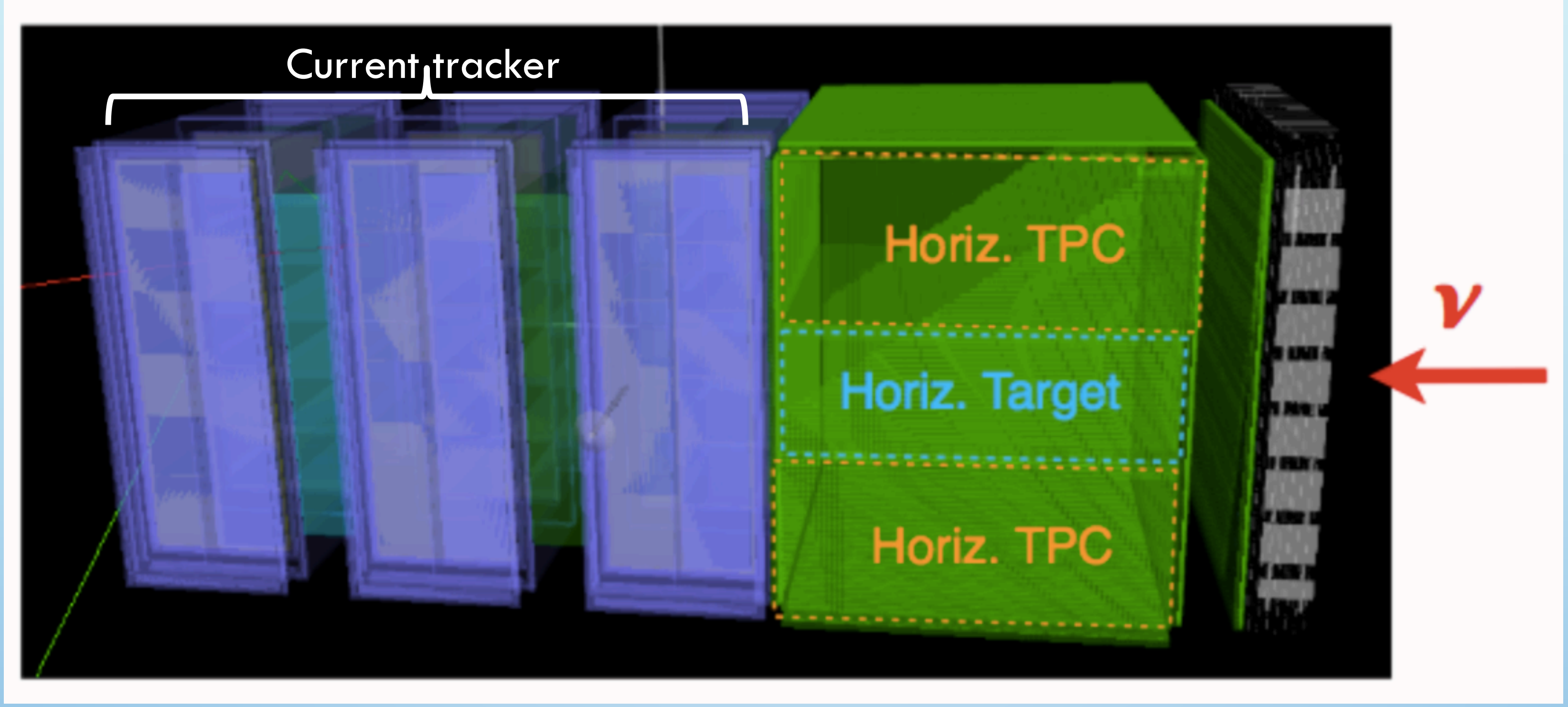


 Phys. Rev. Lett. 118, 151801 (2017), arXiv:1704.06409 [hep-ex].

ND280 UPGRADES

Official T2K project since Feb 2017

Goal: reduce total systematic uncertainty in neutrino event rate in presence of oscillations at far detector to better than 4% by increasing angular acceptance

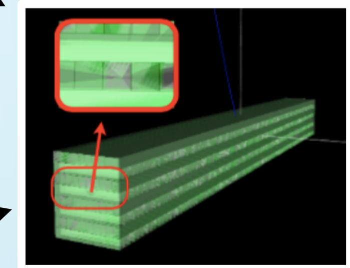


Current tracker + rotated TPCs and neutrino target detector + time of flight around new target

- Increases target mass from 2.2 to 4.3 tonnes

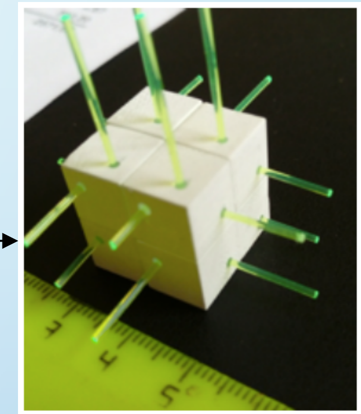
Submitted EOI at CERN, Jan 2017 (CERN SPSC-EOI-015)

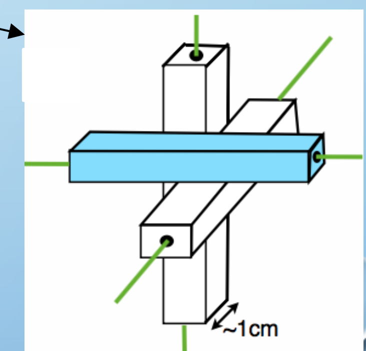
NEUTRINO TARGET DETECTOR

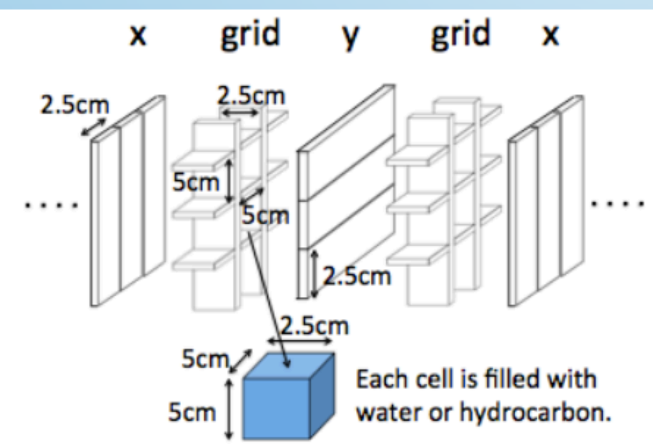


- T2K FINE-GRAINED DETECTOR (FGD) = 1CM THICK XY EXTRUDED TIO2-COATED SCINTILLATOR BARS + MPPC READOUT
  - CAN ACCOMMODATE PASSIVE WATER TARGET REGION
  - LOW EFFICIENCY FOR VERTICAL TRACKS
- TRACKING FIBRE DETECTOR?
- SUPER FGD?
- 3D FGD – BARS IN XY & Z DIRECTIONS? (25% AIR)
- WAGASCI-LIKE? (WATER-IN, WATER-OUT)

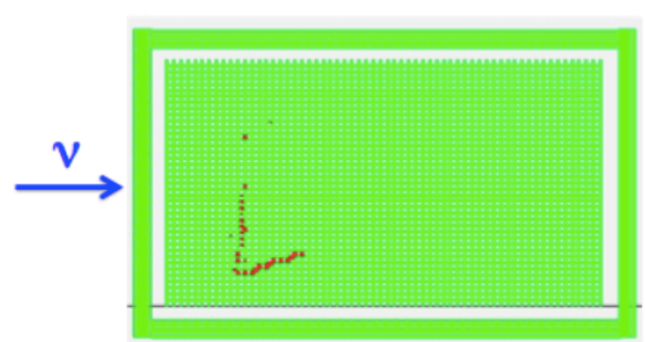
arXiv:1707.01785





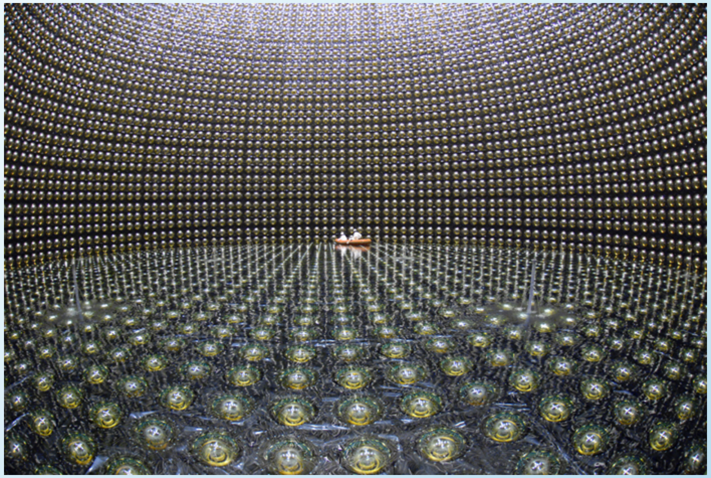


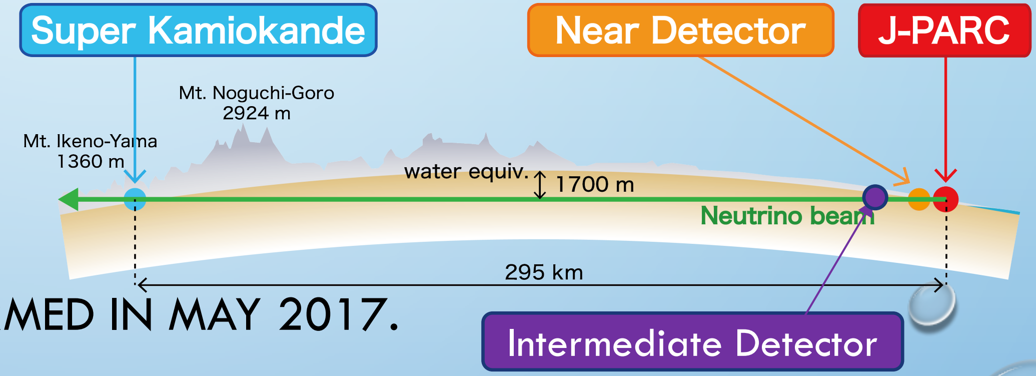
JPS Conf. Proc. 8, 023003 (2015)



INTERMEDIATE WATER CHERENKOV

- MEASURE CROSS SECTION ON H_2O DIRECTLY
- 4Π ANGULAR ACCEPTANCE
- CHERENKOV PID:
  - pure ν_μ-CC, ν_e-CC and NCπ^0 samples
- CONTAIN MUONS ~0.6GEV (UP TO 1.2MEV)
- 0.7-2KM DOWNSTREAM TO REDUCE PILE-UP
- OFF-AXIS SPANNING TECHNIQUE
- NEUTRON TAGGING





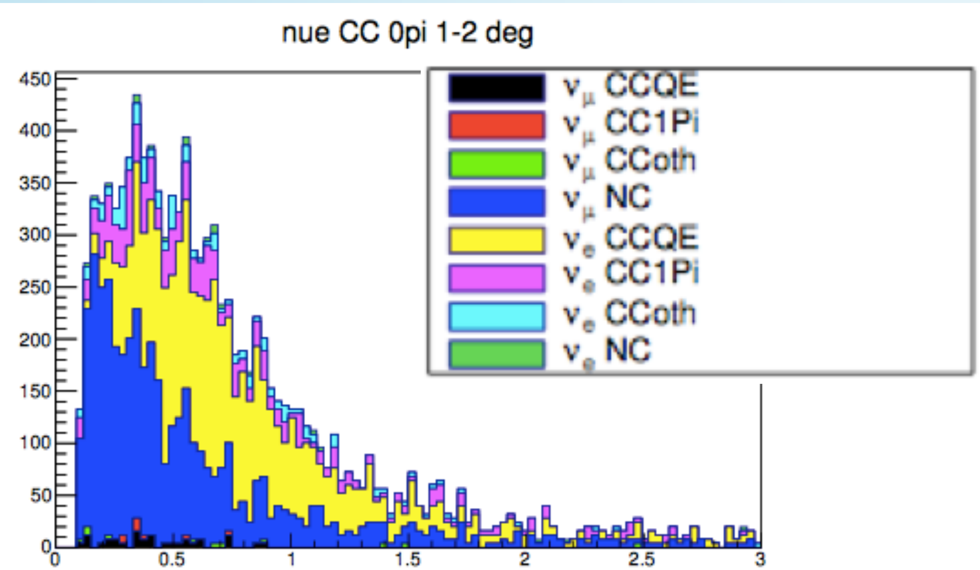
INTERNATIONAL COLLABORATION FORMED IN MAY 2017.

- J-PARC E61 EXPERIMENT
- STAGED APPROACH: 1ST PHASE 1KTON WC ON SURFACE

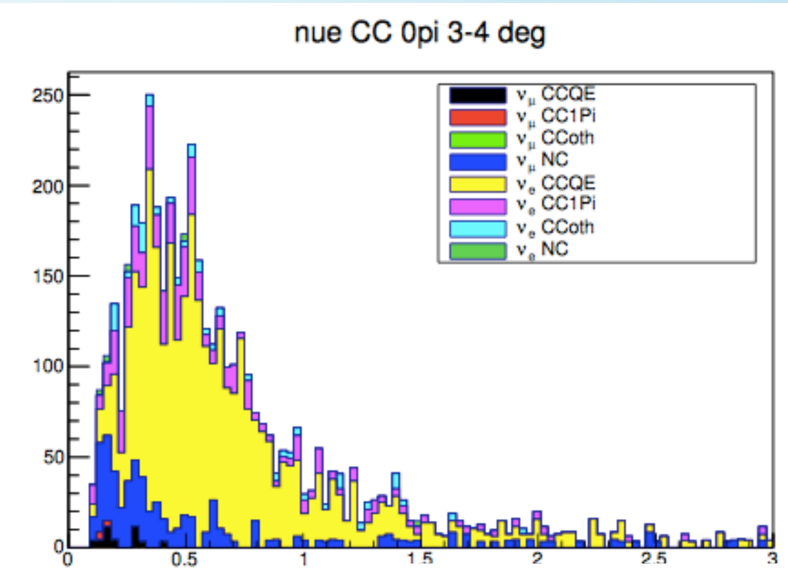
NU-E CROSS SECTION

10^{21} POT exposure

1kTon WC @ 1km angle	N (ν_eCC0π) selected	Sample Purity
1-2degrees	11.2k	54%
2-3degrees	6.9k	71%
3-4degrees	4.6k	80%



Reconstructed energy

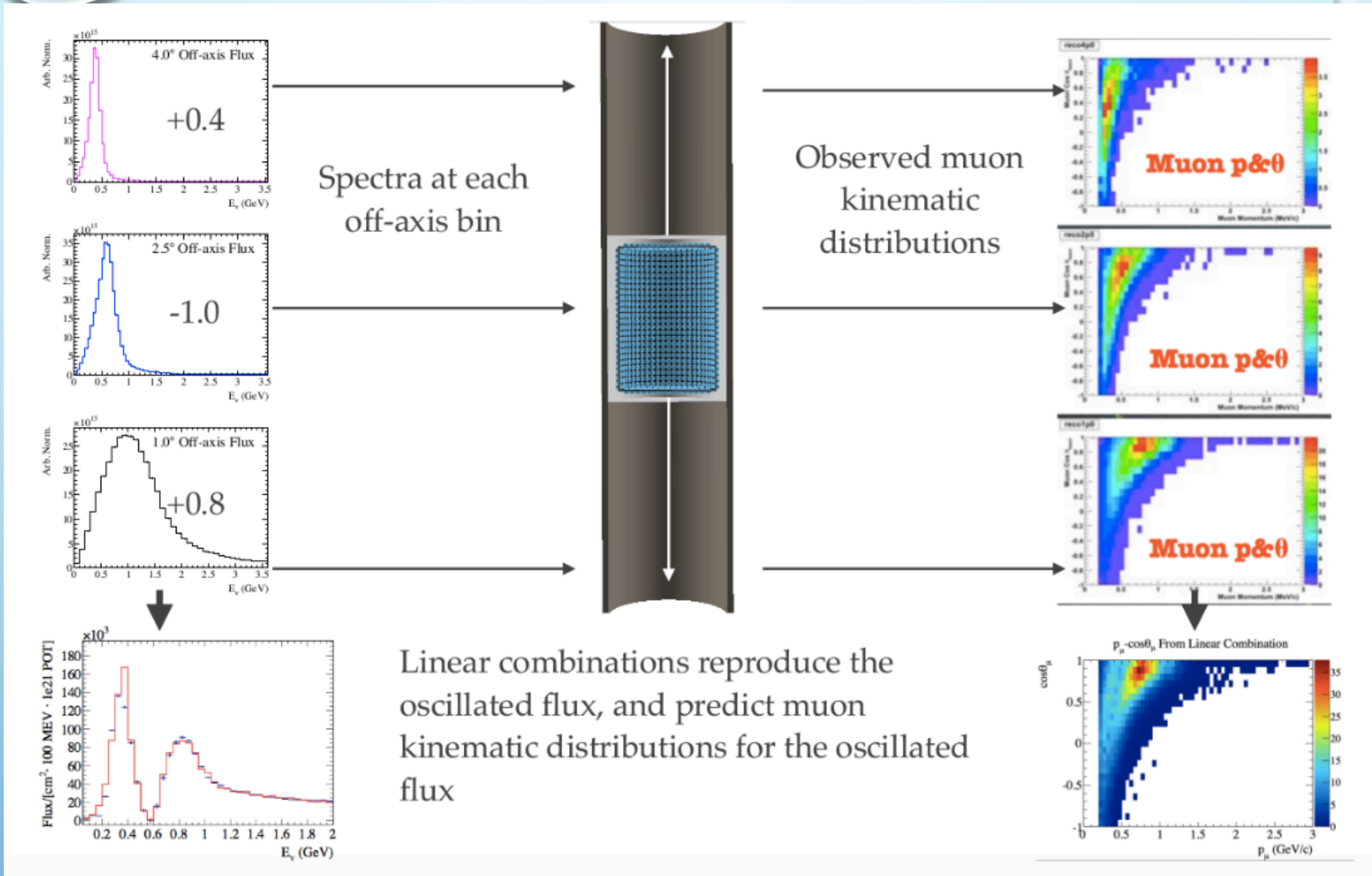


Reconstructed energy

Select one ring – electron-like events

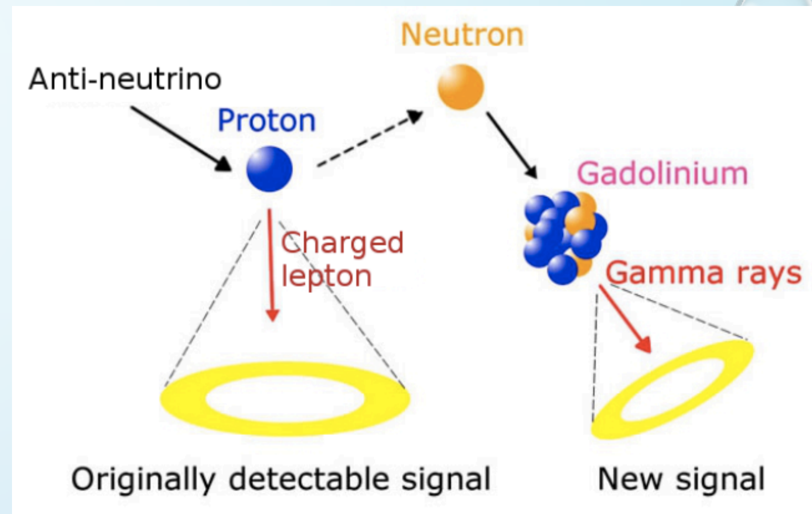
Increased nu-e purity at higher angles – larger contribution from Kaon parents

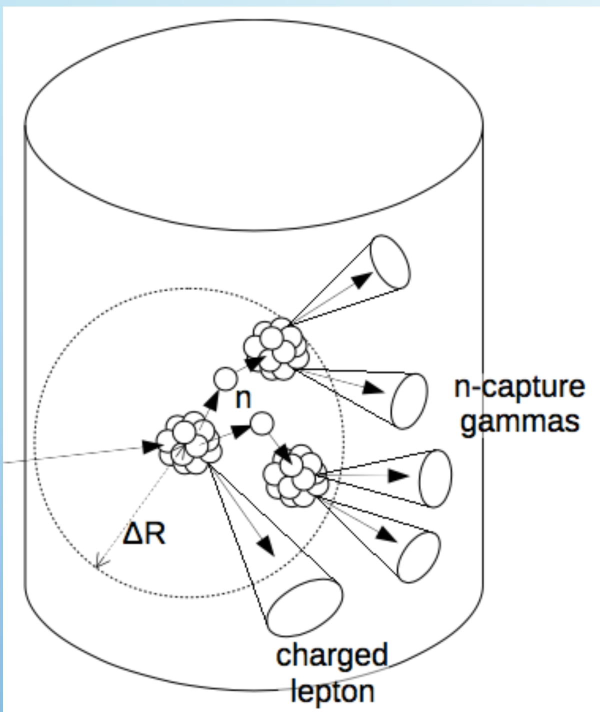
OFF-AXIS SPANNING



NEUTRON CAPTURES

0.2% Gadolinium Sulphate (0.1% Gd)
Captures ~90% neutrons → ~8MeV of gammas
~25μs capture time
(cf~200μs & 2.2MeV γ from capture on H)





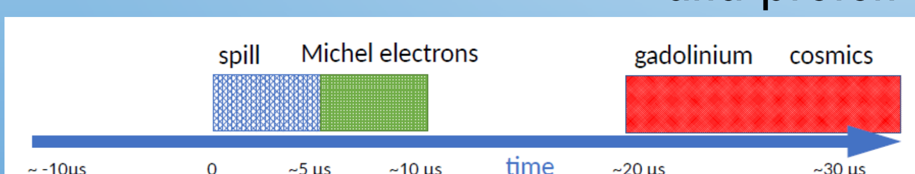
Neutron tagging gives us:

- Statistical separation of interaction modes
- $\nu_\mu : \overline{\nu}_\mu$ separation:

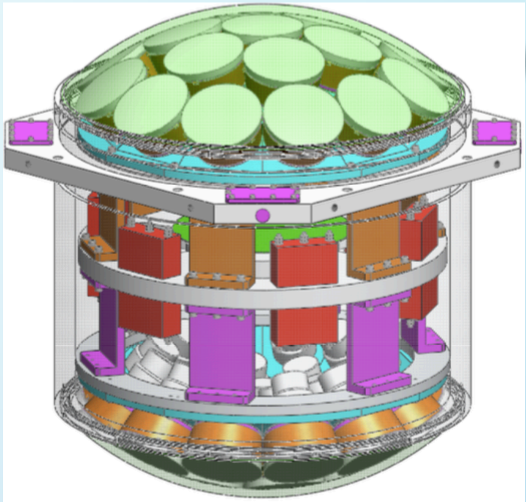
Charged Current Quasielastic (CCQE):

ν_μ :	$\nu_\mu + n \rightarrow \mu^- + p$	0 neutrons
$\bar{\nu}_\mu$:	$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$	1 neutron

- Measurement of neutron multiplicity
  - Large model uncertainties feed into atmospheric and proton decay measurement uncertainties

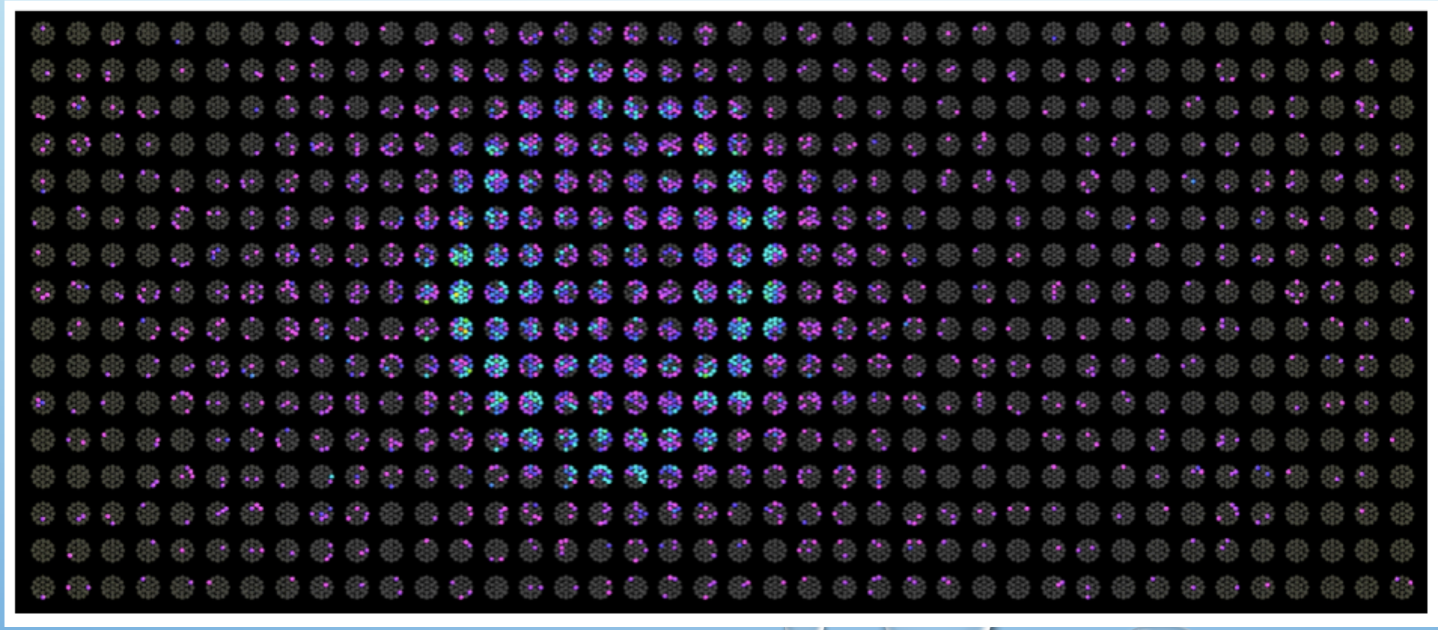


MULTI-PMTS

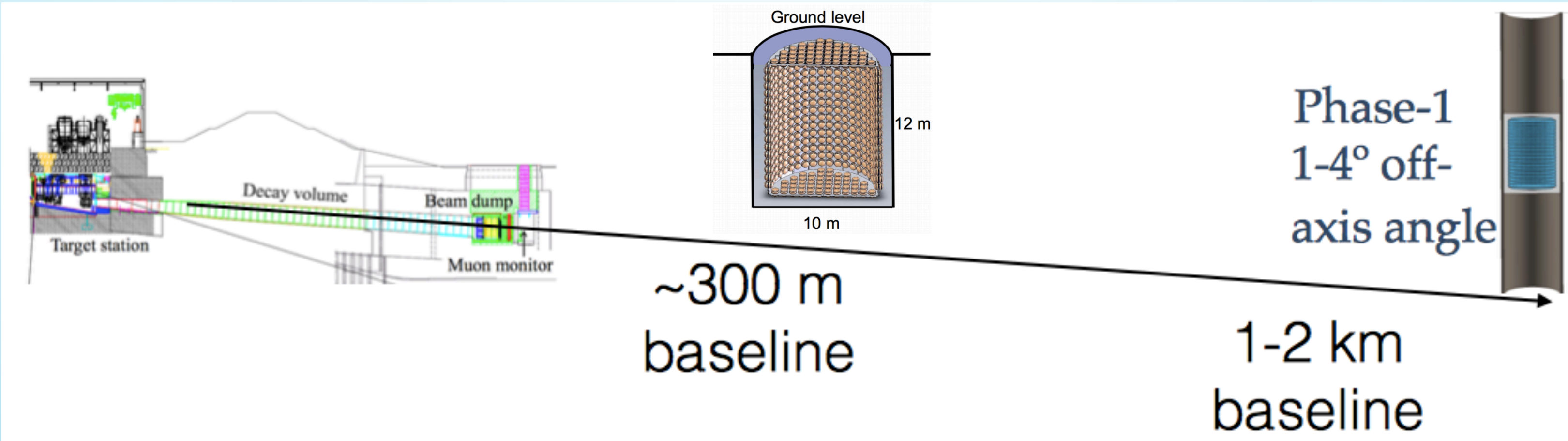


Modular approach to PMT instrumentation.
- Array of small (~3") PMTs.
- Waterproofing, pressure protection, reduced cabling.
- Readout electronics, monitoring, calibration inside.
- Directional information - improved vertex resolution.

Leveraging from KM3NeT/IceCube mPMT design.



WATER CHERENKOV SURFACE DETECTOR



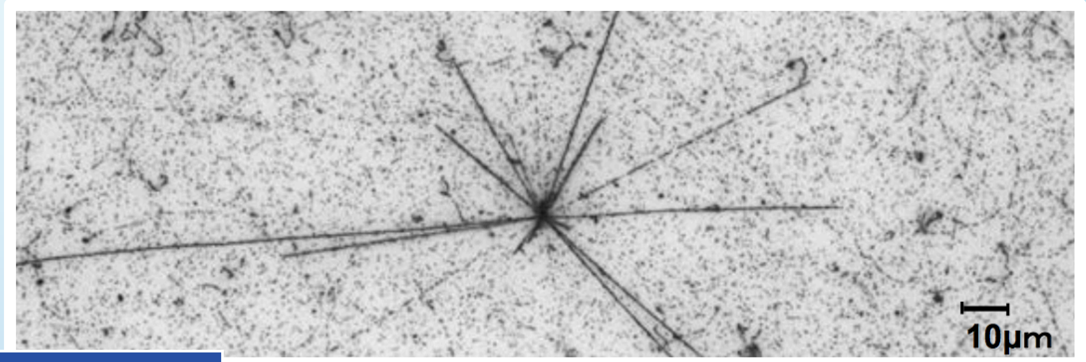
Surface detector goals:

- Demonstrate detector calibration and precision
- ~3% precision measurement of $\sigma_{\nu e}$/ $\sigma_{\nu\mu}$
- Measure neutron multiplicities in neutrino-nucleus interactions
- Test-bed for Hyper-K

OTHER TECHNOLOGIES

HIGH PRESSURE TPC

- Less target mass than scintillator but detect more final state particles
- Investigating range of target gases
- Prototyping underway, beam test planned at CERN

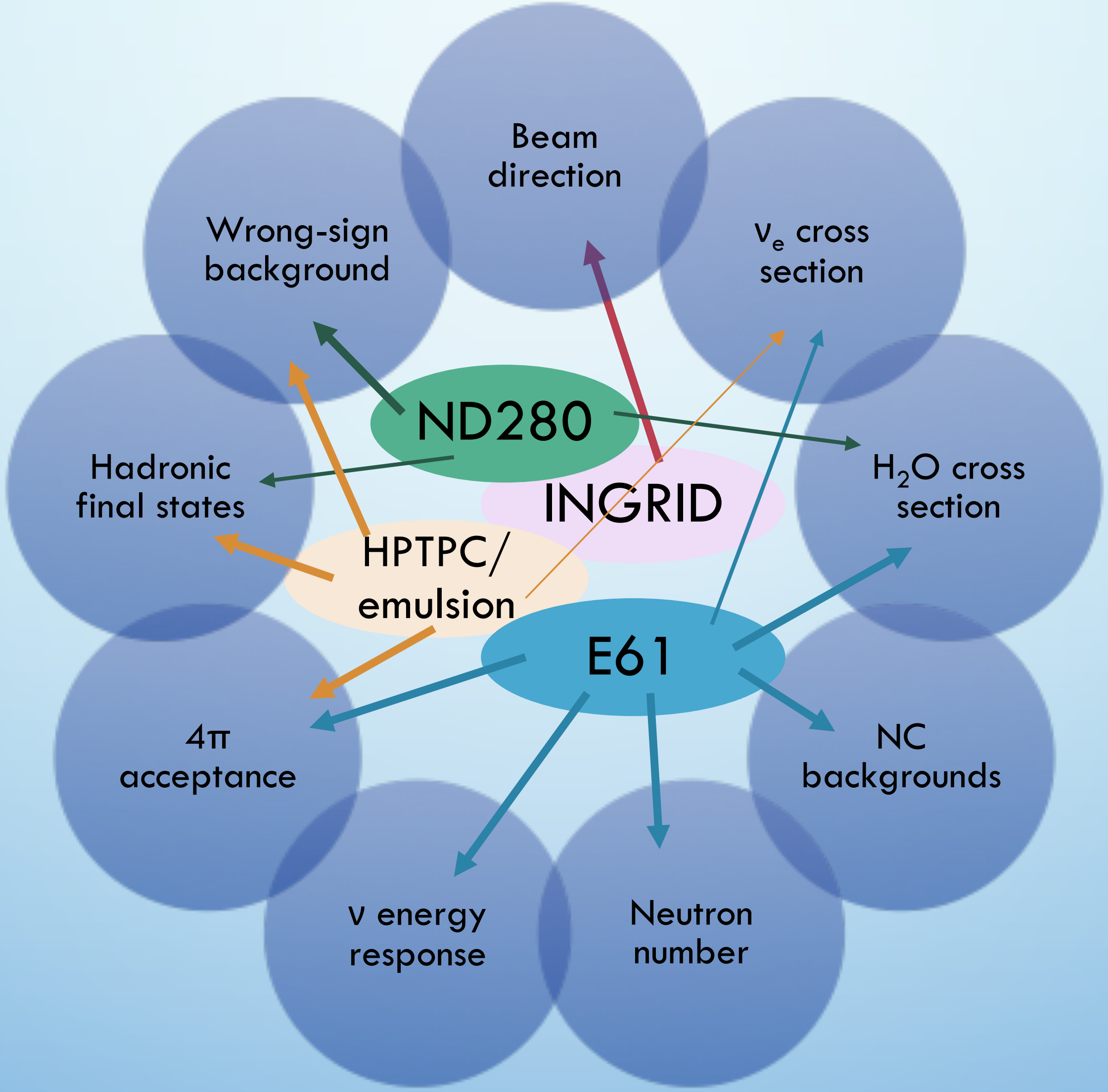


Detector	Proton Energy threshold	Proton Recon Efficiency
ND280	100-500MeV ($\cos\theta > 0.4$)	μ + p ~30%
Wagasci (water in)	125MeV	15%
Wagasci (water out)	12, 30, 45MeV	15% 27%, 55%
HPTPC	>5MeV	Work in progress
Emulsion (water target)	10MeV	84%

EMULSION DETECTOR

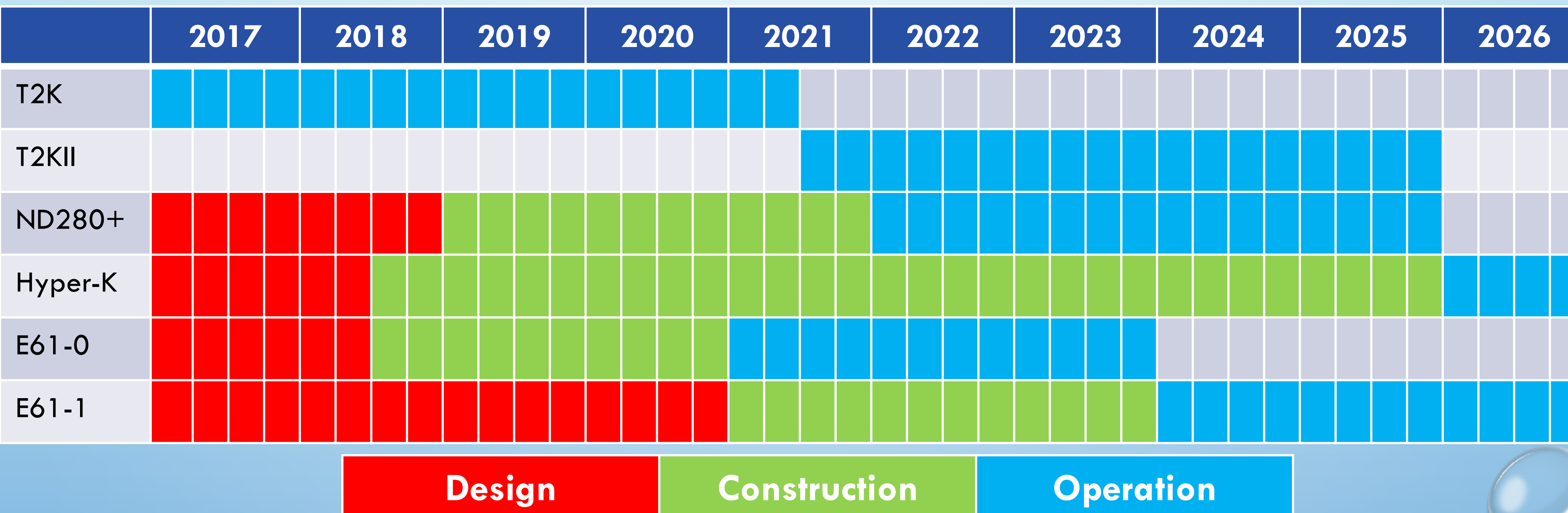
- NINJA collaboration prototyping
- Potential for water target
- Low energy threshold
- ν_e cross section measurement

DETECTOR OPTIONS



SUMMARY

- NEAR DETECTORS VITAL TO CONSTRAIN FLUX AND CROSS SECTION SYSTEMATIC UNCERTAINTIES FOR ACCURATE CP VIOLATION SEARCH
- NO ONE-DETECTOR-FITS-ALL
  - SUITE OF NEAR DETECTORS INCLUDING UPGRADED T2K ND280 + NEW INTERMEDIATE DETECTOR



Thank you to E61(NuPRISM, TITUS), HYPER-K, NINJA, HPTPC, T2K & ND280-upgrade colleagues for slides and plots included in this talk

BACK-UP SLIDES

CROSS SECTION POTENTIAL

Detector	Selection	Nevents	Selection Characteristics
ND280 detector, 280m	$\nu_\mu CC0\pi$	20k	FGD1 (1–3 GeV), $P \approx 72\%$ [51]
ND280 detector, 280m	$\nu_\mu CC1\pi$	6k	FGD1 (1–3 GeV), $P \approx 50\%$ [51]
ND280 detector, 280m	ν_μCC inclusive	40k	FGD1 (1–3 GeV), $P \approx 90\%$[51]
INGRID	ν_μCC inclusive	17.6×10^6	$\epsilon > 70\%$ (1–3 GeV), $P = 97\%$ [191]
HPTPC, $8\,m^3$, 10 bar Ne (CF_4)	ν_μCC inclusive	4.2k (18.4k)	$\epsilon \approx 70\%$, protons > 5 MeV detected
HPTPC, $8\,m^3$, 10 bar Ne (CF_4)	ν_eCC inclusive	80 (450)	$\epsilon \approx 70\%$, protons > 5 MeV detected
WAGASCI	$\nu_\mu CC0\pi$	63k	P=75%, proton reconstruction: $\epsilon \approx$ 15% at 500 MeV, water in; $\epsilon \approx$ 15% at 250 MeV, water out
WAGASCI	$\nu_\mu CC1\pi$	10k	P=50% (protons as above)
WAGASCI	ν_μCC inclusive	75k	P=96% (protons as above)
200kg Water target emulsion off-axis, 280m	ν_μ CC+NC inclusive	10k-20k	4π automated readout proton > 10-30 MeV detected
200kg Water target emulsion off-axis, 280m	ν_e CC inclusive	1k	4π automated readout proton > 10-30 MeV detected
1kton WC 1 km	$\nu_\mu CC0\pi$ (1-2°,2-3°,3-4°)	1682k,1060k,519k	$P \approx 92\%, 95\%, 95\%$
1kton WC 1 km	$\bar{\nu}_\mu CC0\pi$ (1-2°,2-3°,3-4°)	519k,331k,186k	$P \approx 74\%, 77\%, 76\%$
1kton WC 1 km	$\nu_\mu CC1\pi$ (1-2°,2-3°,3-4°)	208k,65k,27k	$P \approx 46\%, 44\%, 31\%$
1kton WC 1 km	$\nu_e CC0\pi$ (1-2°,2-3°,3-4°)	11.2k,6.9k,4.6k	$P \approx 54\%, 71\%, 80\%$
1kton WC 1 km	$\nu NC\pi^0$ (1-2°,2-3°,3-4°)	300k,111k,45k	$P \approx 58\%, 63\%, 60\%$

HYPER-K SENSITIVITY

TABLE XXXVII. Uncertainties for the expected number of events at Hyper-K from the systematic uncertainties assumed in this study.

		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0%	0.5%	0.7%	3.2%
	Disappearance	3.3%	0.9%	1.0%	3.6%
$\bar{\nu}$ mode	Appearance	3.2%	1.5%	1.5%	3.9%
	Disappearance	3.3%	0.9%	1.1%	3.6%

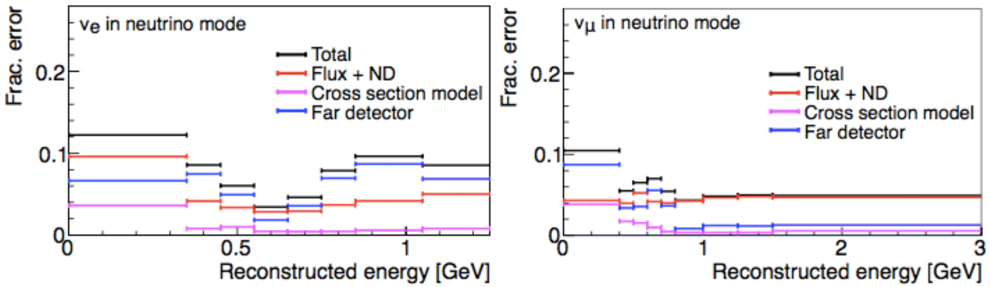


FIG. 130. Fractional error size for the appearance (left) and the disappearance (right) samples in the neutrino mode. Black: total uncertainty, red: the flux and cross-section constrained by the near detector, magenta: the near detector non-constrained cross section, blue: the far detector error.

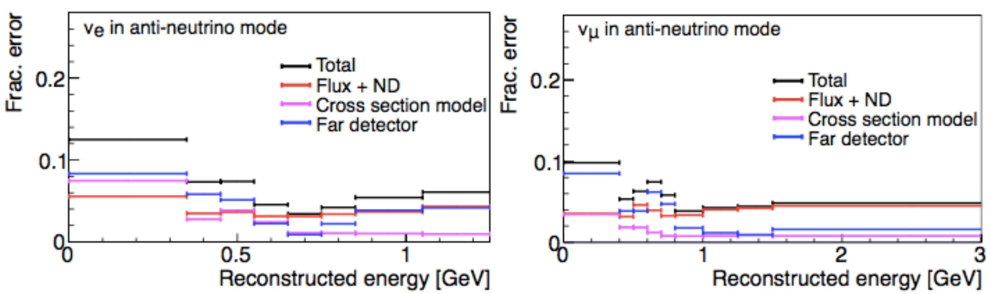
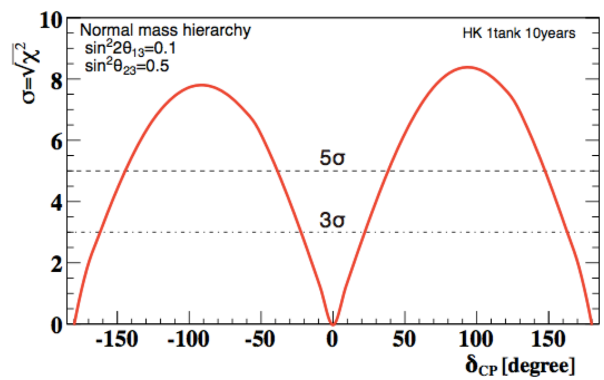


FIG. 131. Fractional error size for the appearance (left) and the disappearance (right) samples in the anti-neutrino mode. Black: total uncertainty, red: the flux and cross-section constrained by the near detector, magenta: the near detector non-constrained cross section, blue: the far detector error.



Expected significance to exclude $\sin \delta_{CP} = 0$ in case of normal hierarchy.

DETECTOR OPTIONS

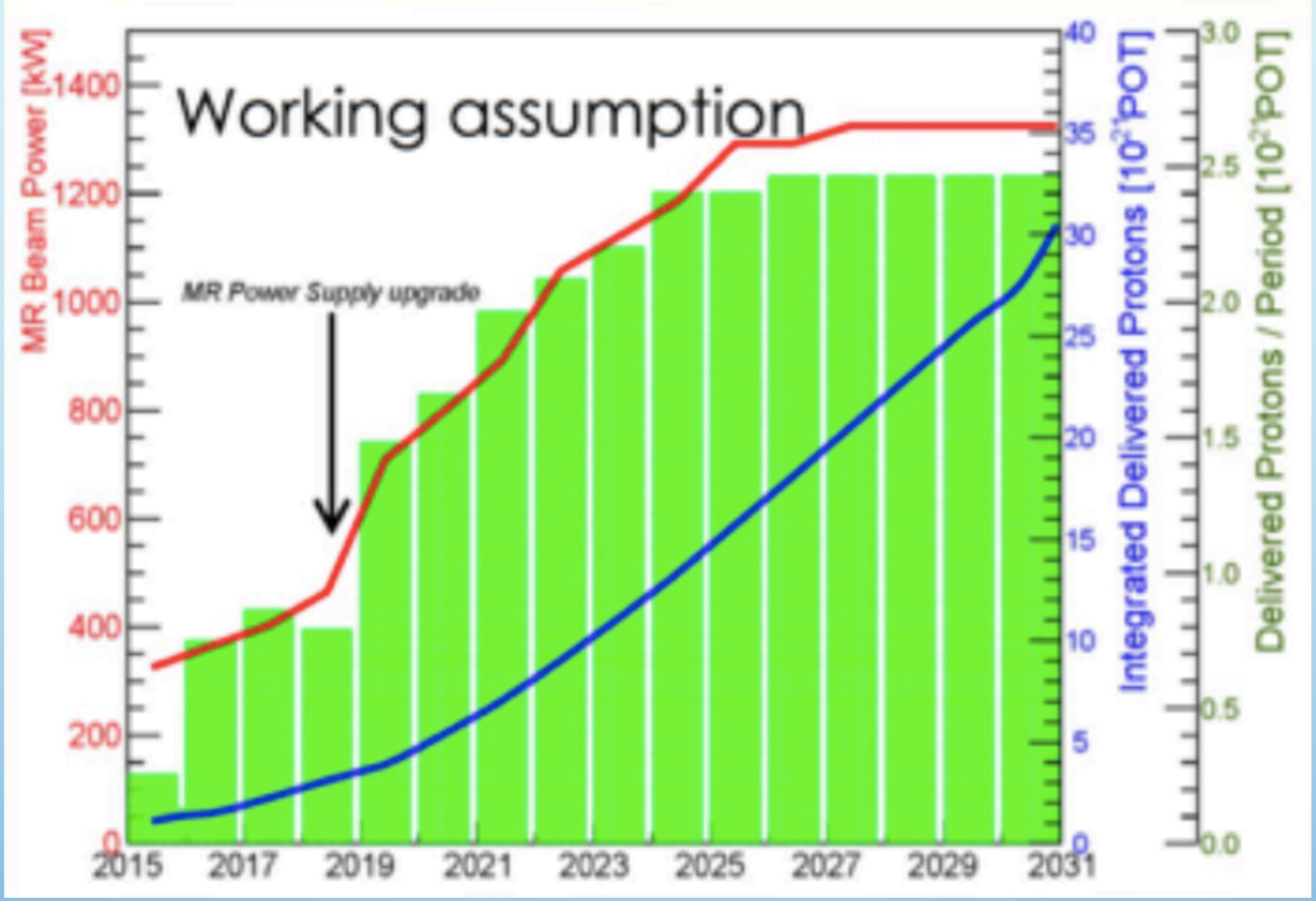
	ν_e x-Sec	4π	H_2O x-sec	NC, ν_e Bg	Neutron # (Gd)	ν Energy response	Wrong sign Bg	Hadronic FS	Beam Dir
INGRID	0	0	0	0	0	0	0	0	5
ND280	2	3	3	2	0	2	5	2	1
ND280 Upgrade (WAGASCI)	2	4	4	2	0	2	5	2	1
HPTPC	0	5	0	1	0	3	3	5	1
nuPRISM style WC	4	5	5	4	3	4	1	1	3
TITUS style WC	4	5	5	4	4	2	3	1	1

5 = Strong*, 0 = no information

Not quantitative!

Each column relates to a systematic uncertainty

T2K-II



Working assumption
MR Power Supply upgrade
MR Beam Power [kW]
Integrated Delivered Protons [10^21 POT]
Delivered Protons / Period [10^21 POT]
0
200
400
600
800
1000
1200
1400
2015
2017
2019
2021
2023
2025
2027
2029
2031
0
5
10
15
20
25
30
35
40
0.0
0.5
1.0
1.5
2.0
2.5
3.0