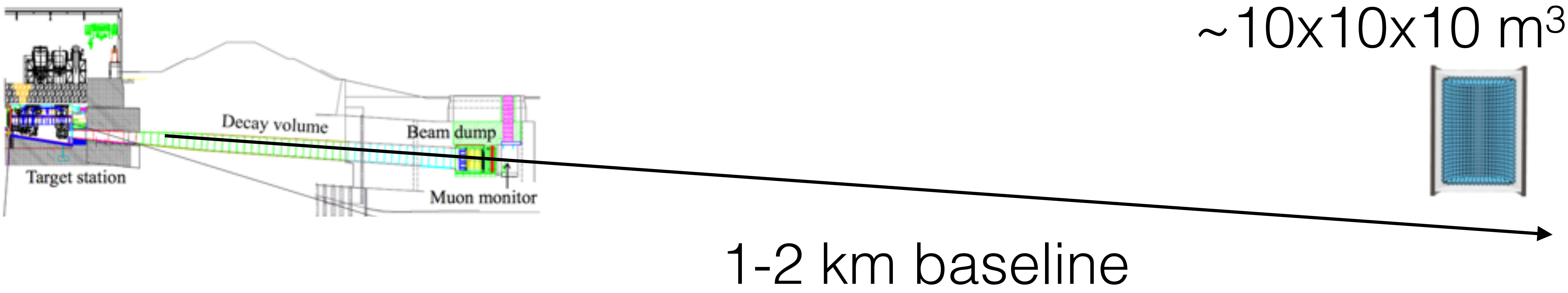
Intermediate Water Cherenkov Detector for Hyper-K

Mark Hartz for the HK Near Detectors Working Group

Intermediate Water Cherenkov Detector



- 1 kton scale water Cherenkov detector
  - Contain muons up to 1 GeV or more with >100 ton fiducial volume
- 1-2 km baseline
  - Avoid significant event pile-up in the detector
  - Beam is nearly a point source (same as Hyper-K)

Features/Limitations

- Features (for generic detector):
  - Same target nuclei as the far detector
  - 4π coverage to match the far detector
  - Large fraction of active mass in the detector
  - Direct measurement of intrinsic ν_e and NC backgrounds
  - Good e/μ and e/π^0 separation
- Limitations (for generic detector):
  - No charge identification
  - No direct detection of below Cherenkov threshold particles

Systematic Error Reduction

Current T2K systematic error model

	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	3.9	3.3	2.5	3.1	1.6
SK Final State & Secondary Interactions	1.5	2.1	2.5	2.5	3.5
ND280 Constrained Flux & Cross-section	2.8	3.3	3.0	3.3	2.2
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.5	3.0	1.5
NC Other Cross-section	0.8	0.8	0.2	0.3	0.2
Total Systematic Error	5.1	5.2	5.5	6.8	5.9
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.1	4.0	0.8

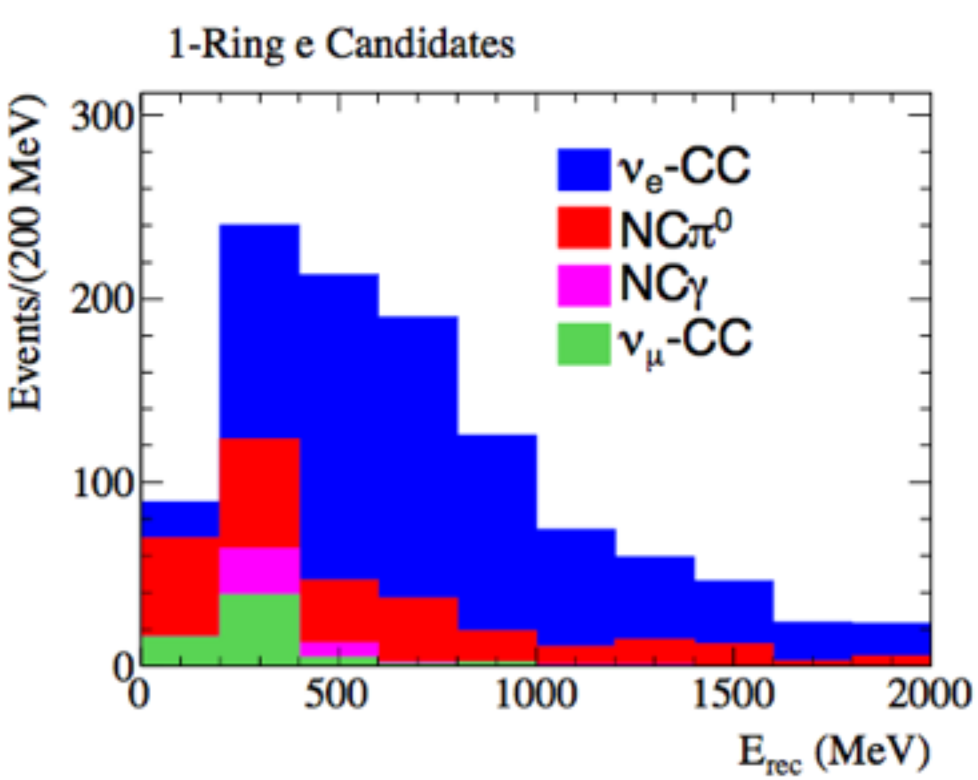
Benefit from identical nuclear targets in near and far detectors (also identical spectra if possible)

Need pure, high statistics samples of ν_e(bar) in near detectors. Error on ratio important since ν_μ candidates are measured in near detector.

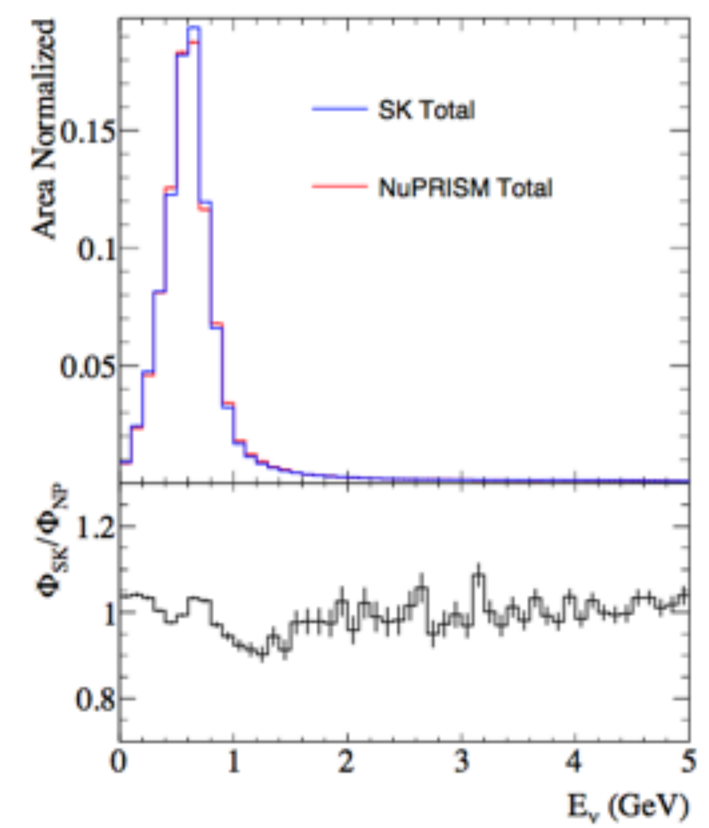
Direct measurement of the intrinsic ν_e and NC backgrounds

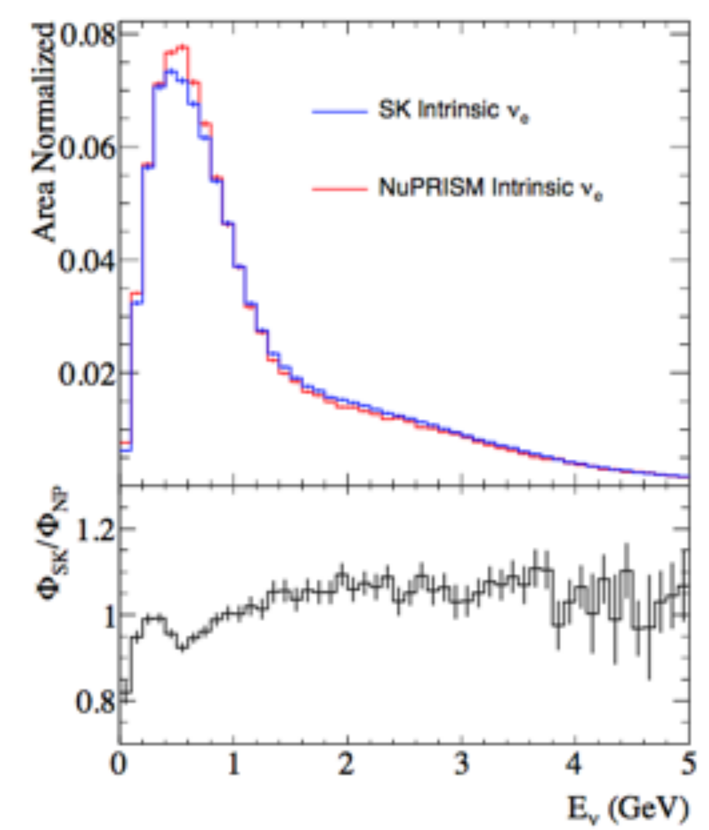
Direct Background Measurement

- Total neutrino and intrinsic ν_e and fluxes are nearly identical in the intermediate and far detectors
- Can measure the intrinsic+NC background directly in the intermediate detector



500 ton x 1e21 POT

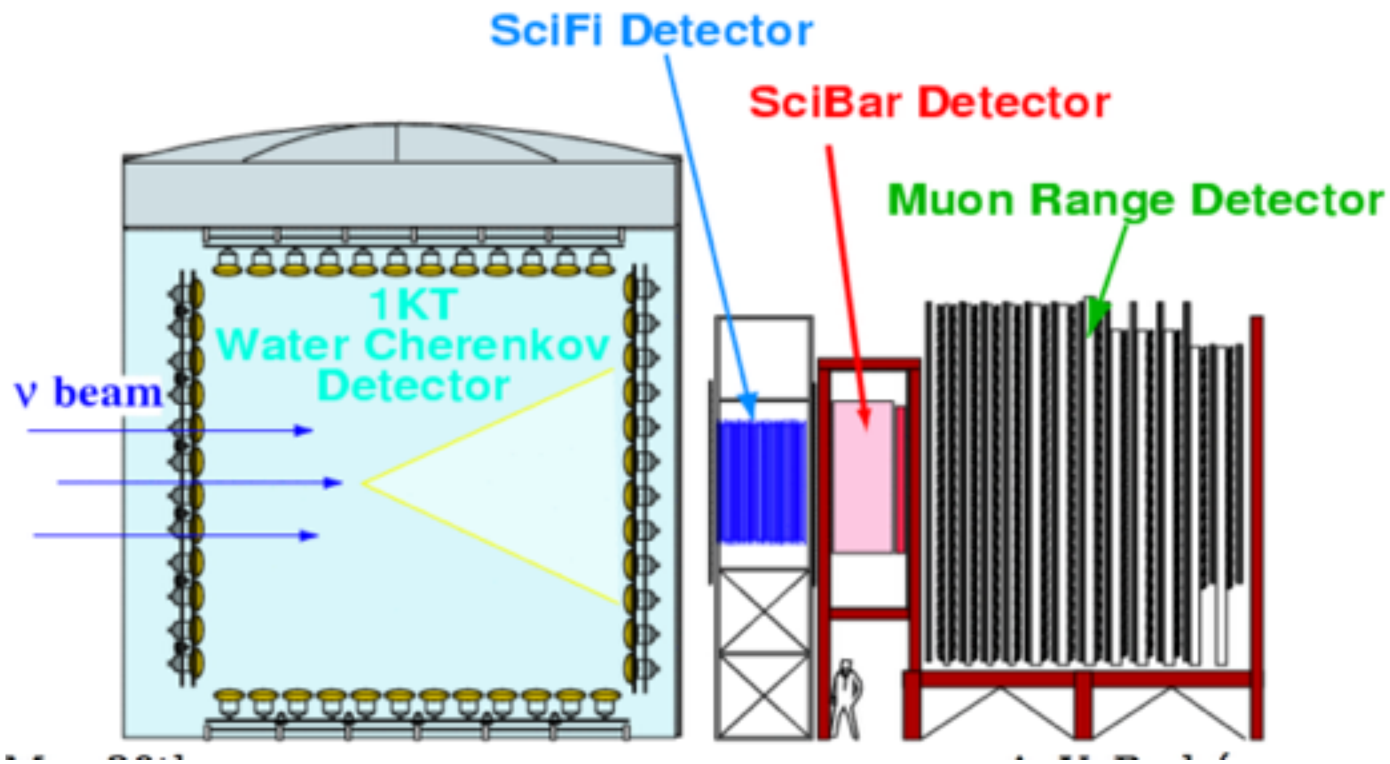




Previous (Proposed) Detectors

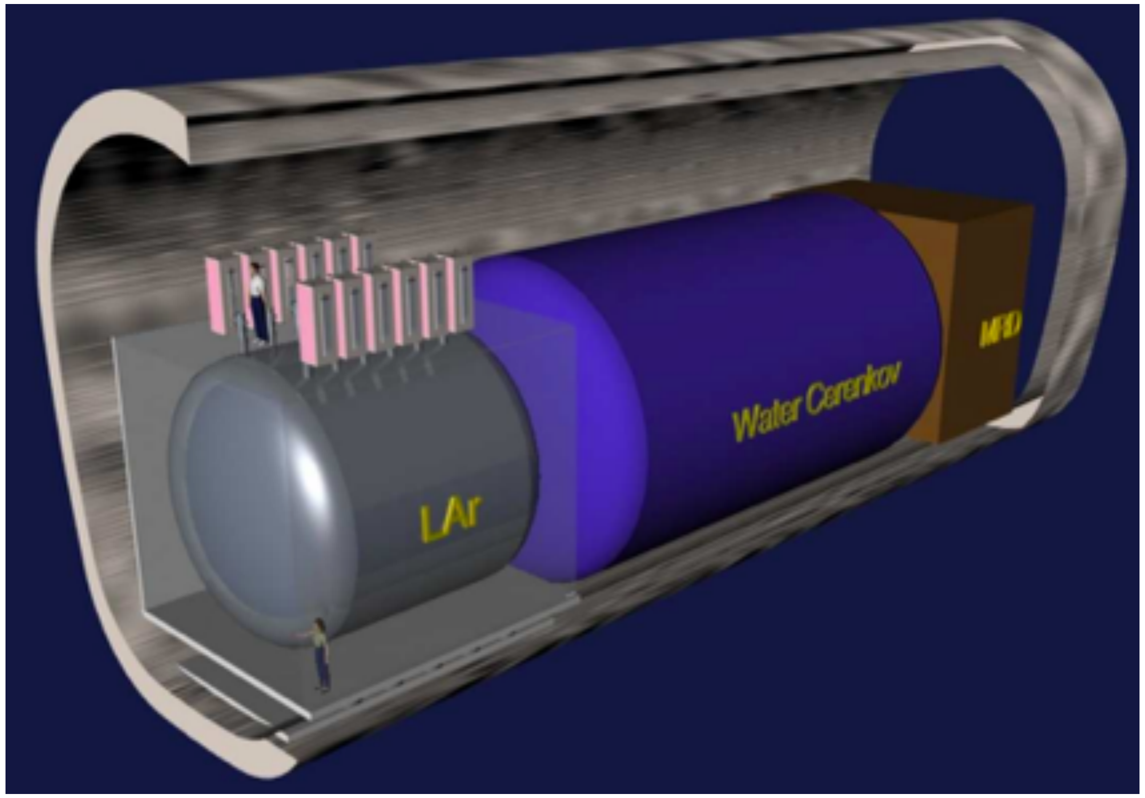
K2K 1 Kiloton Detector:

- 20 inch diameter PMTs
- 40% photo-coverage
- Achieved 0.3% mis-ID rate of muons as electrons



T2K 2 km Detector

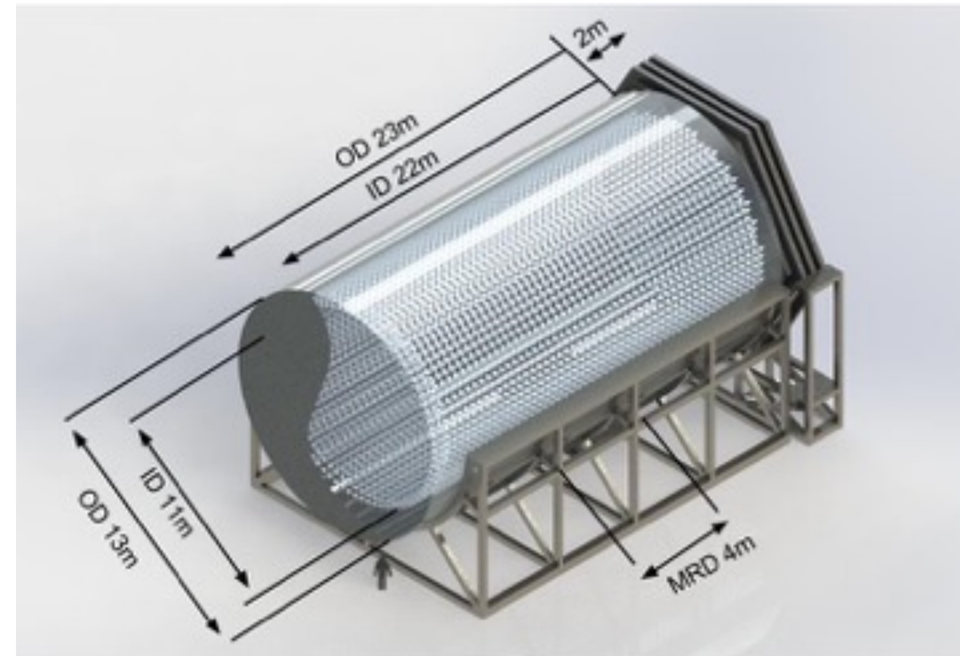
- Proposed for T2K
- Potential site at 1.8 km (same direction as Tochibora)
- Improved performance with smaller (8 inch) PMTs -> finer granularity



Current Detector Proposals

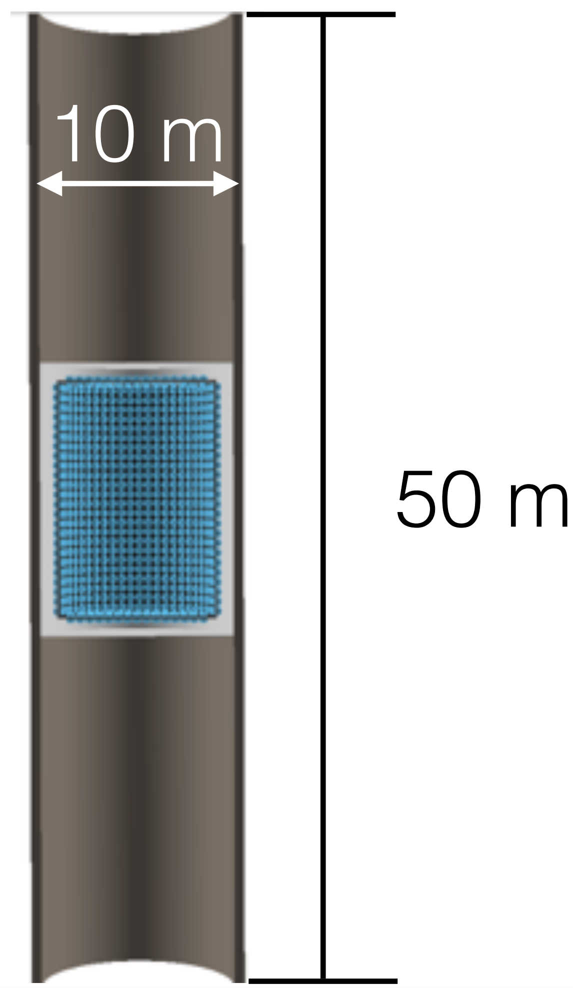
TITUS

- Located 2.5° off-axis in same direction as Tochibora at 1.8 km
- Gd-loading for neutron detection
- Magnetized muon range detector
- Long geometry for high momentum muon containments



NuPRISM

- Tall detector covers 1.0°-4.0° off-axis angles for studying energy dependence of neutrino interactions
- Located at 1-1.2 km baseline



Process for a single detector design with off-axis spanning coverage and Gd-loading is started

Current Detector Proposals

TITUS: the Tokai Intermediate Tank for the Unoscillated Spectrum

C. Andreopoulos *[15], F.C.T. Barbato[3], G. Barker[17], G. Barr[9], P. Beltrame[13], V. Berardi[2], T. Berry[11], A. Blondel[14], S. Boyd[17], A. Bravar[14], F.S. Cafagna[2], S. Cartwright[16], M.G. Catanesi[2], C. Checchia[4], A. Cole[16], G. Collazuol[4], G.A. Cowan[13], T. Davenne[12], T. Dealtry[7], C. Densham[12], G. De Rosa[3], F. Di Lodovico[10], E. Drakopoulou[13], P. Dunne[1], A. Finch[7], M. Fitton[12], D. Hadley[17], K. Hayrapetyan[10], R.A. Intonti[2], P. Jonsson[1], A. Kaboth*[11], T. Katori[10], L. Kormos[7], Y. Kudenko[6], J. Lagoda[8], M. Laveder[4], M. Lawe[7], P. Litchfield[1], A. Longhin[4], L. Ludovici[5], W. Ma[1], L. Magaletti[2], M. Malek[16], N. McCauley[15], M. Mezzetto[4], J. Monroe[11], T. Nicholls[12], M. Needham[13], E. Noah[14], F. Nova[12], H.M. O'Keeffe[7], A. Owen[10], V. Palladino[3], D. Payne[15], J. Perkin[16], S. Playfer[13], A. Pritchard[15], N. Prouse[10], E. Radicioni[2], M. Rayner[14], C. Riccio[3], B. Richards[10], J. Rose[15], A.C. Ruggeri[3], R. Shah[9], Y. Shitov †[11], C. Simpson ‡[9], G. Sidiropoulos[13], T. Stewart[12], R. Terri[10], L. Thompson[16], M. Thorpe[12], Y. Uchida[1], D. Wark*[9], M.O. Wascko[1], A. Weber §[12], and J.R. Wilson[10]

arXiv:1606.08114 [physics.ins-det]

Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline

S. Bhadra,[24] A. Blondel,[3] S. Bordoni,[5] A. Bravar,[3] C. Bronner,[9] J. Caravaca Rodríguez,[5] M. Dziewiecki,[23] T. Feusels,[1] G.A. Fiorentini Aguirre,[24] M. Friend,[4,*] L. Haegel,[3] M. Hartz,[8,22] R. Henderson,[22] T. Ishida,[4,*] M. Ishitsuka,[20] C.K. Jung,[11,†] A.C. Kaboth,[6] H. Kakuno,[25] H. Kamano,[13] A. Konaka,[22] Y. Kudenko,[7,‡] M. Kuze,[20] T. Lindner,[22] K. Mahn,[10] J.F. Martin,[21] J. Marzec,[23] K.S. McFarland,[15] S. Nakayama,[18,†] T. Nakaya,[9,8] S. Nakamura,[12] Y. Nishimura,[19] A. Rychter,[23] F. Sánchez,[5] T. Sato,[12] M. Scott,[22] T. Sekiguchi,[4,*] M. Shiozawa,[18,8] T. Sumiyoshi,[25] R. Tacik,[14,22] H.K. Tanaka,[18,†] H.A. Tanaka,[1,§] S. Tobayama,[1] M. Vagins,[8,2] J. Vo,[5] D. Wark,[16] M.O. Wascko,[6] M.J. Wilking,[11] S. Yen,[22] M. Yokoyama,[17,†] and M. Ziembicki[23]
(The nuPRISM Collaboration)

arXiv:1412.3086 [physics.ins-det]

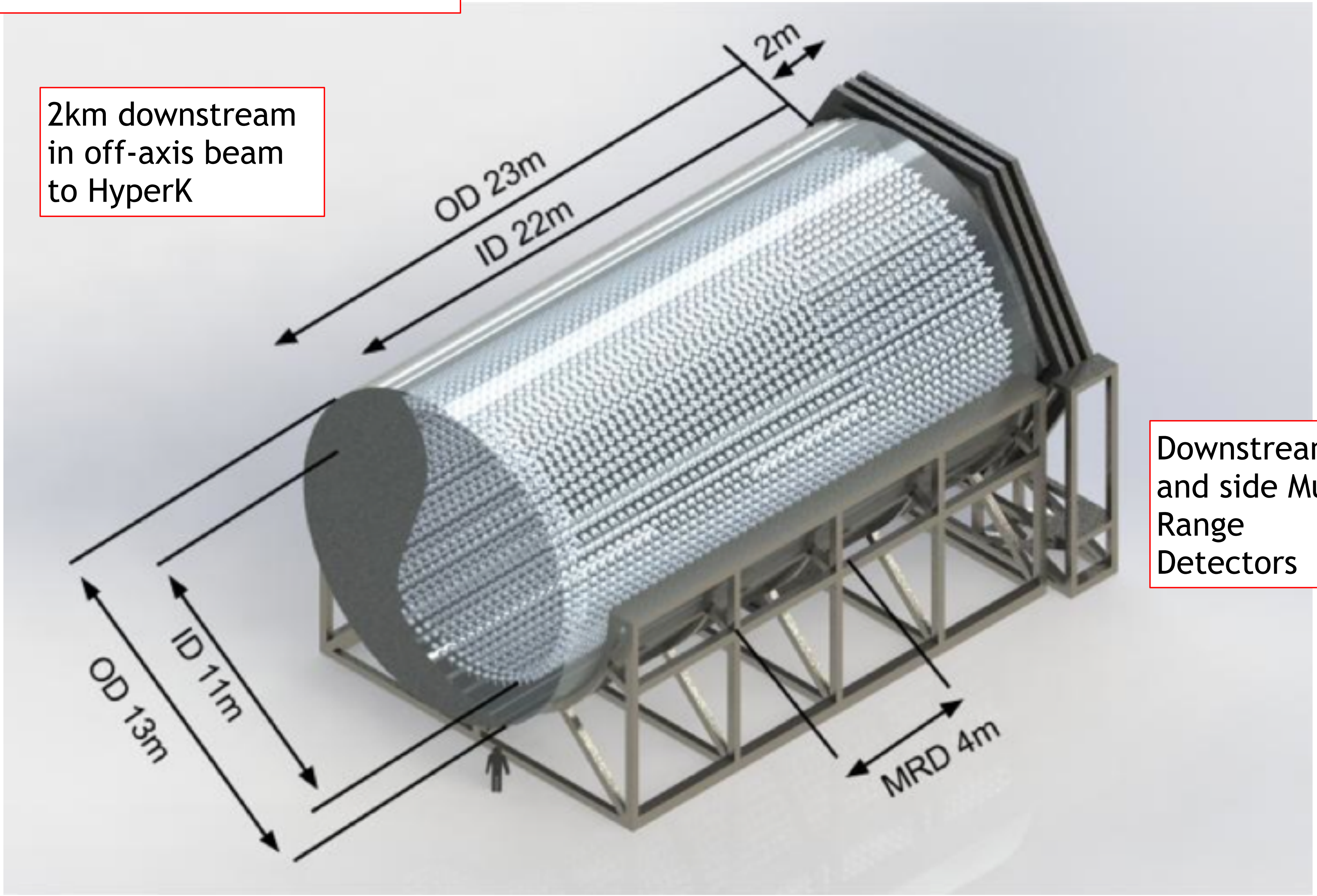
TITUS Detector

11m diameter
22m length
40% photo-coverage (~3k 12” PMTs)
2kt Gd-loaded Water Cerenkov

TITUS

Tokai Intermediate Tank for the Unoscillated Spectrum

2km downstream in off-axis beam to HyperK



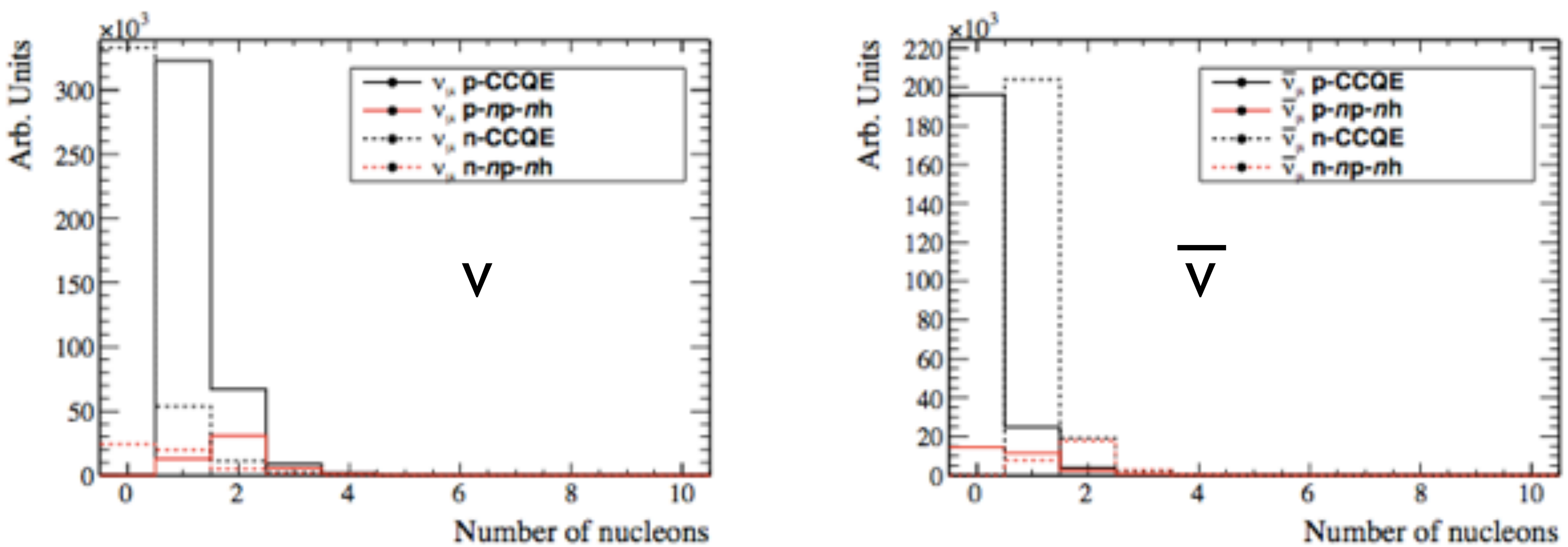
Downstream and side Muon Range Detectors

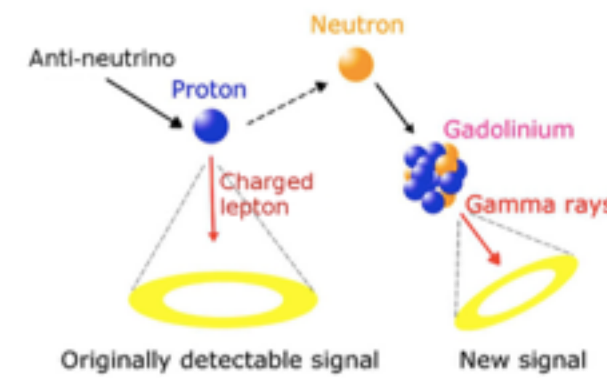
TITUS Motivation and Strategy

- Water-target detector to minimize errors due to different target than far detector
- Ability to separate the final states as in ND280 (neutrino/antineutrino and different interaction modes)
- Minimize the contribution to errors due to the flux, remove dependence from external measurements
- Full 4π coverage and full spectrum
- Current detector optimized for Hyper-Kamiokande but optimal for T2K-II too.

Gd Doping

- 0.1% $Gd_2(SO_4)_3$ allows tagging of final state nucleons
  - ν_μ CCQE: $\nu_\mu + n \rightarrow \mu^- + p$ 0 neutrons 74% → 83%
  - $\bar{\nu}_\mu$ CCQE: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ 1 neutron 61% → 73%

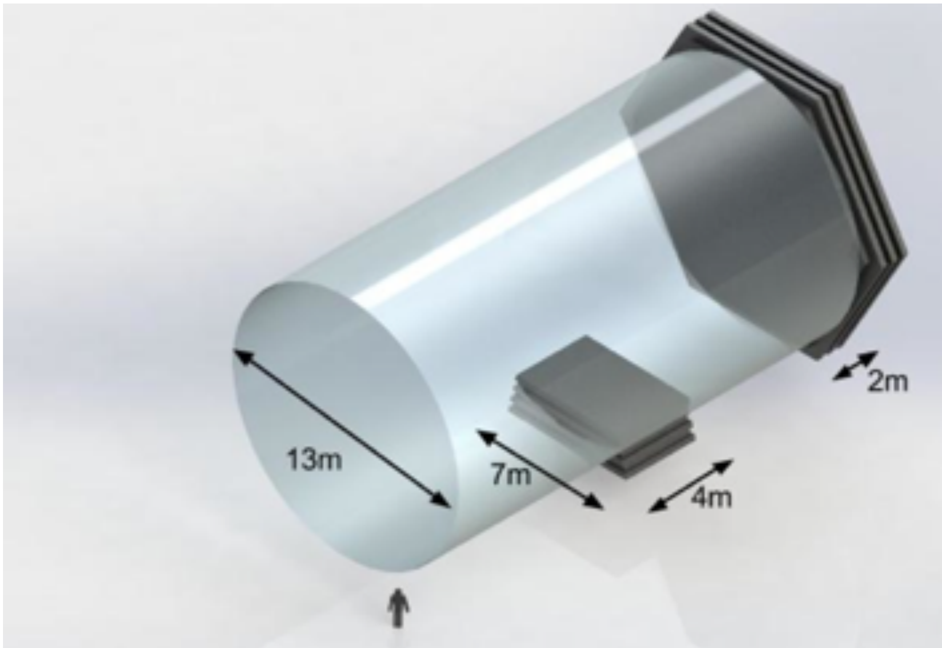


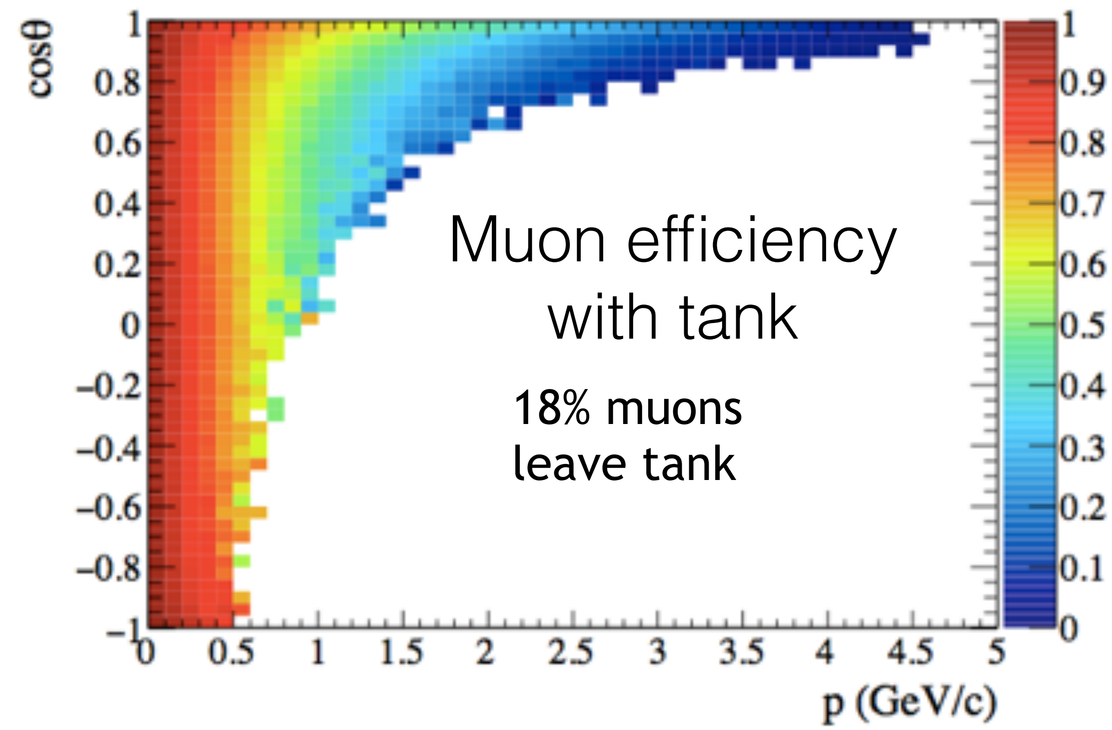


GENIE v2.8.0 simulations of neutrino/antineutrino interactions with C target

- Clear n signals can be modified by nuclear effects: re-scattering, charge exchange, and absorption in the nuclear media
- Statistical information remains – powerful approach for H_2O
- Cross section measurements

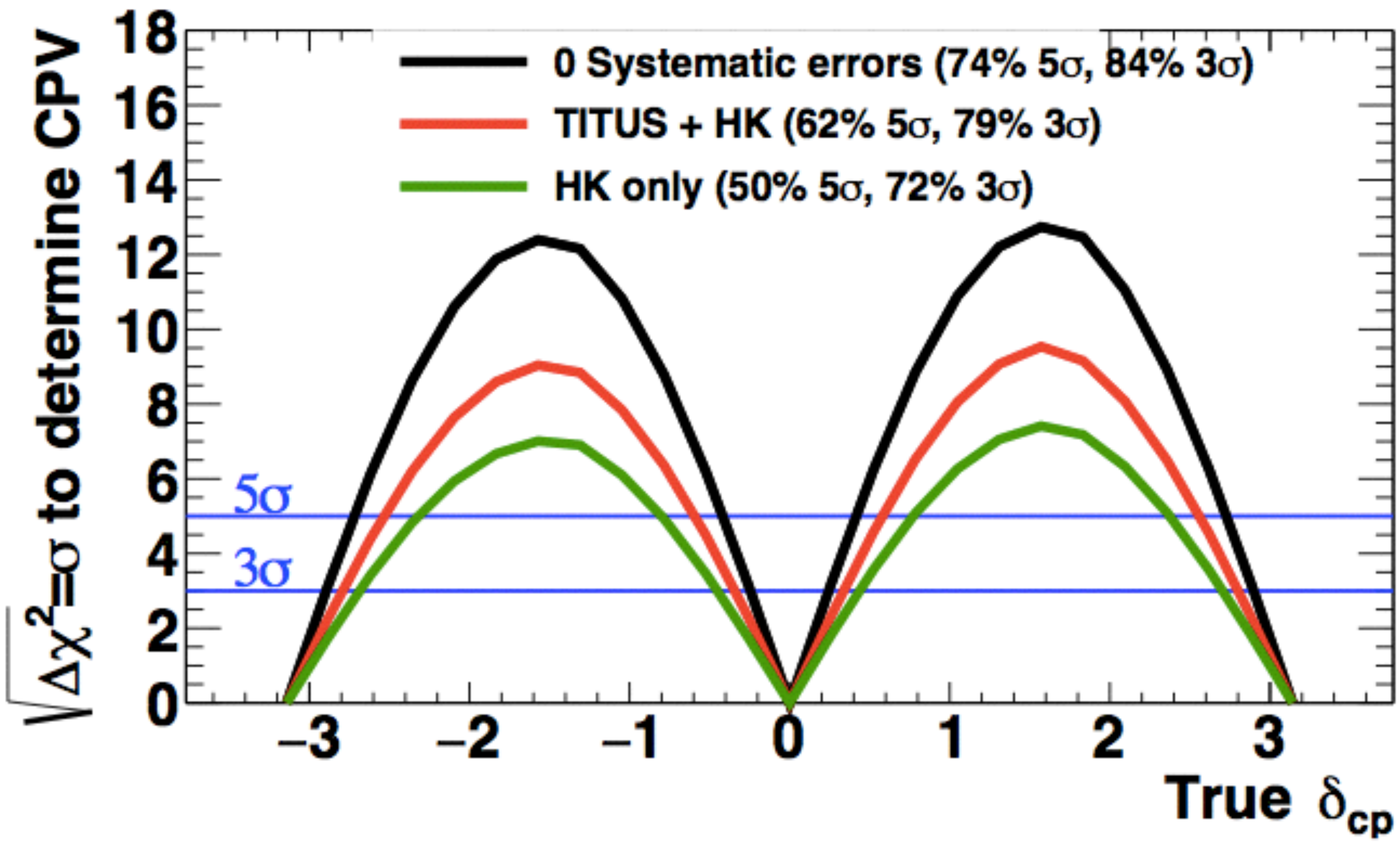
Magnetized Muon Range Detector





- Magnetised iron tracking detector with a 1.5T field
  - 13m radius, 2m thickness downstream
  - Optimise first 3 layers for 0.6GeV beam peak with double scintillator planes and 10cm air gaps
- Measures charge of muons exiting tank (95% charge reconstruction efficiency)
- Range out forward muons -> 2GeV
- Calibrate Gadolinium Technique
- Smaller Side MRD to probe high Q^2 phase space

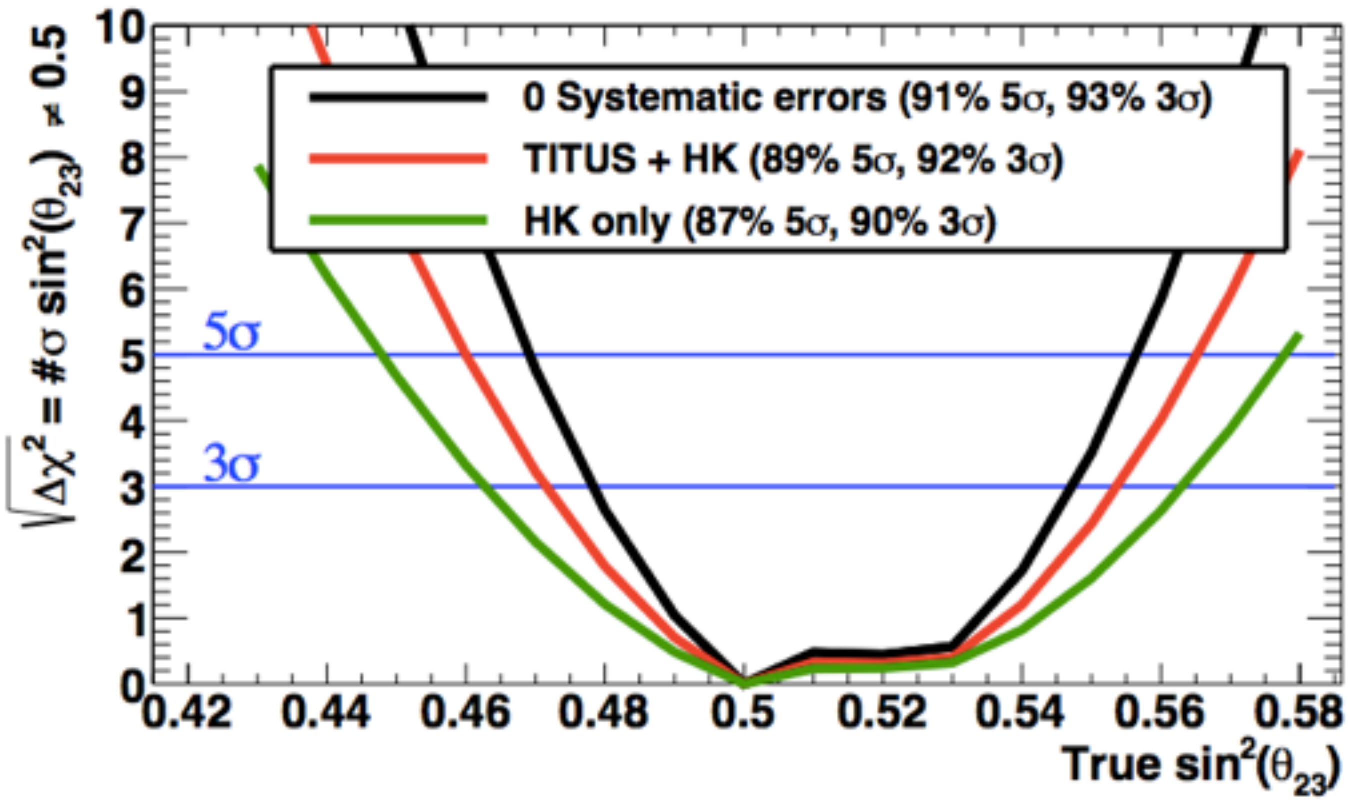
HK δ_{cp} Sensitivity with TITUS

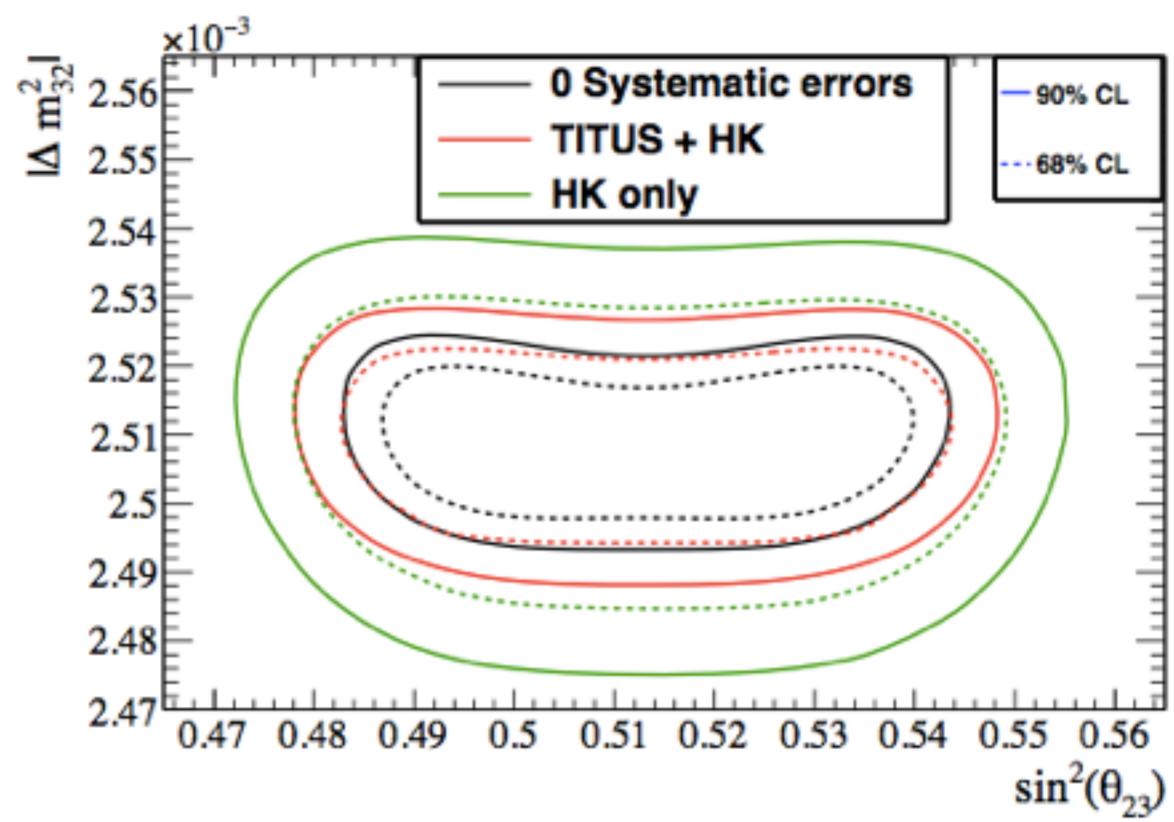


1.3MW beam, 1:3 POT ratio for ν:ν-bar beams.
Hyper-K and TITUS can determine CP violation at the 5σ level for 62% of δ_{cp} space and can provide a 3σ measurement for 79%

See arXiv:1606.08114 for more details

HK Atm. Param. Sensitivity with TITUS





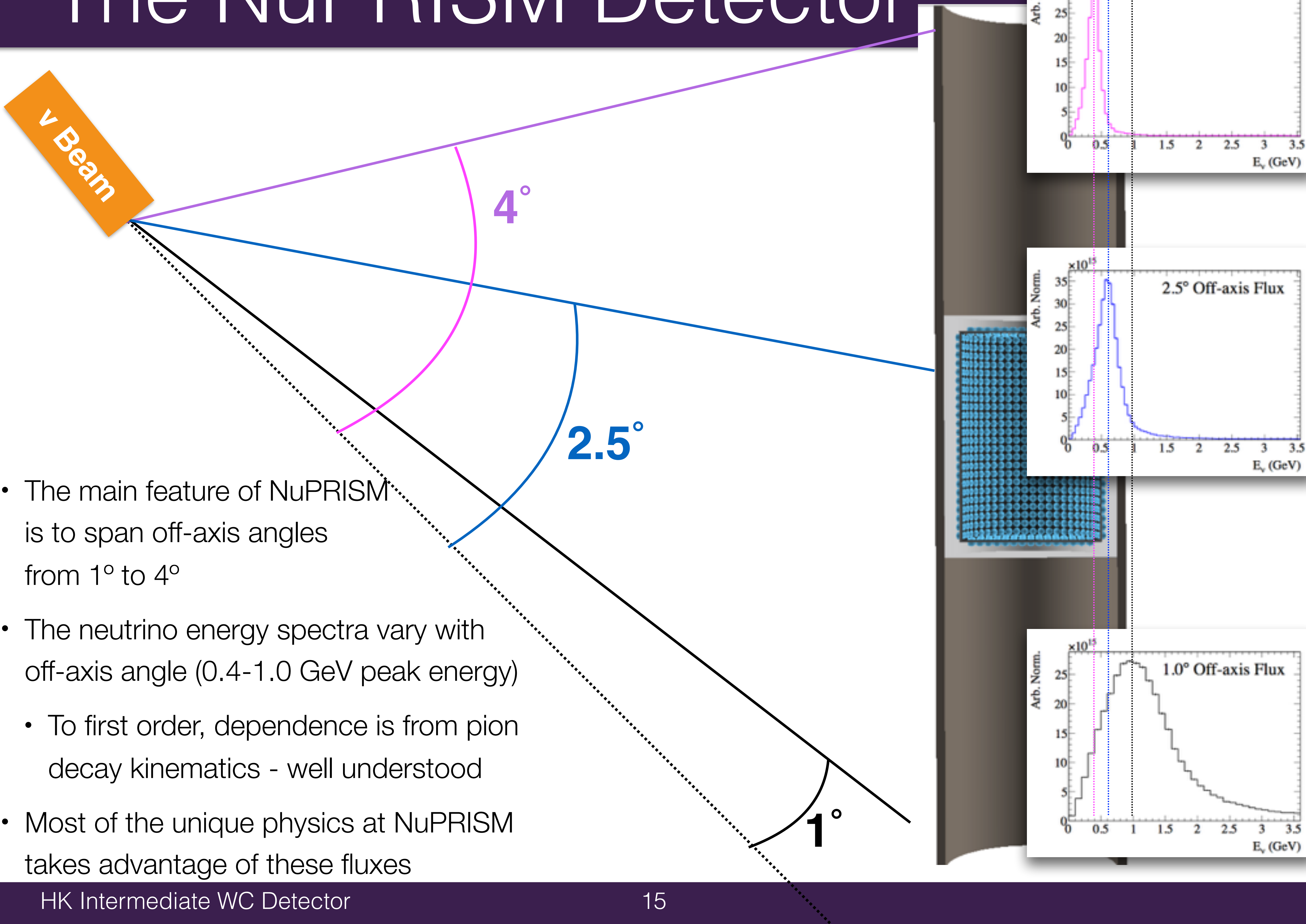
1.3MW beam, 1:3 POT ratio for ν:ν-bar beams.

TITUS samples greatly improve the sensitivity to the 23 sector parameters.

TITUS sensitivity studies use a simple fast reconstruction algorithm. Expect significant improvement after updating to fiTQun reconstruction.

See arXiv:1606.08114 for more details

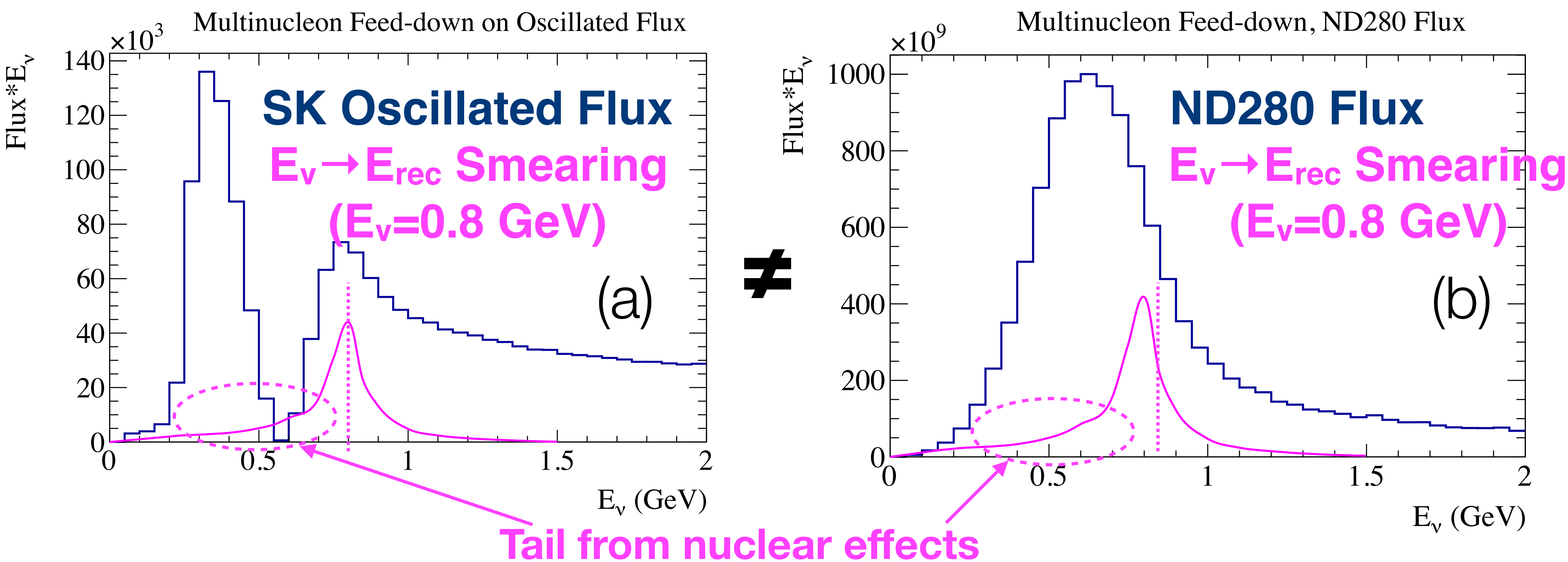
The NuPRISM Detector



- The main feature of NuPRISM is to span off-axis angles from 1° to 4°
- The neutrino energy spectra vary with off-axis angle (0.4-1.0 GeV peak energy)
  - To first order, dependence is from pion decay kinematics - well understood
- Most of the unique physics at NuPRISM takes advantage of these fluxes

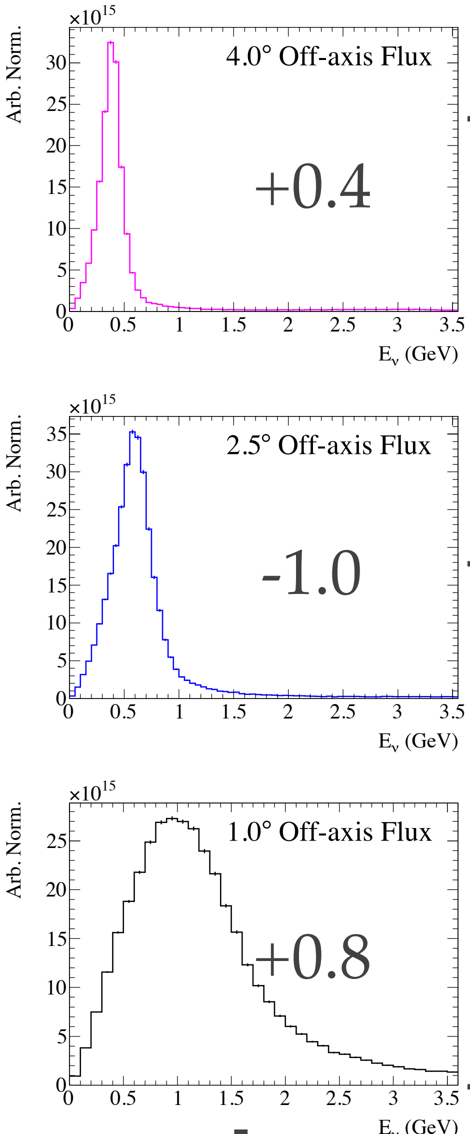
NuPRISM Motivation

- The primary feature of NuPRISM is to address the fact that the near and far detectors have different spectra (due to oscillations)

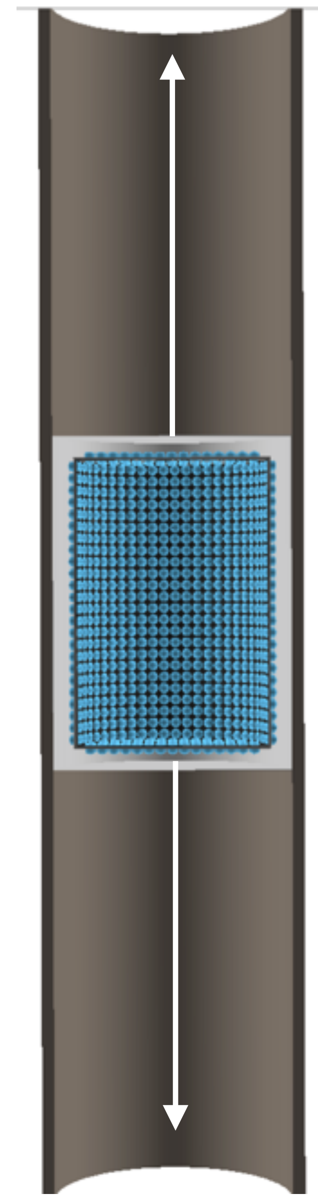


- Nuclear effects that have a small effect in the near detector (right) can have a large effect in the far detector (left)

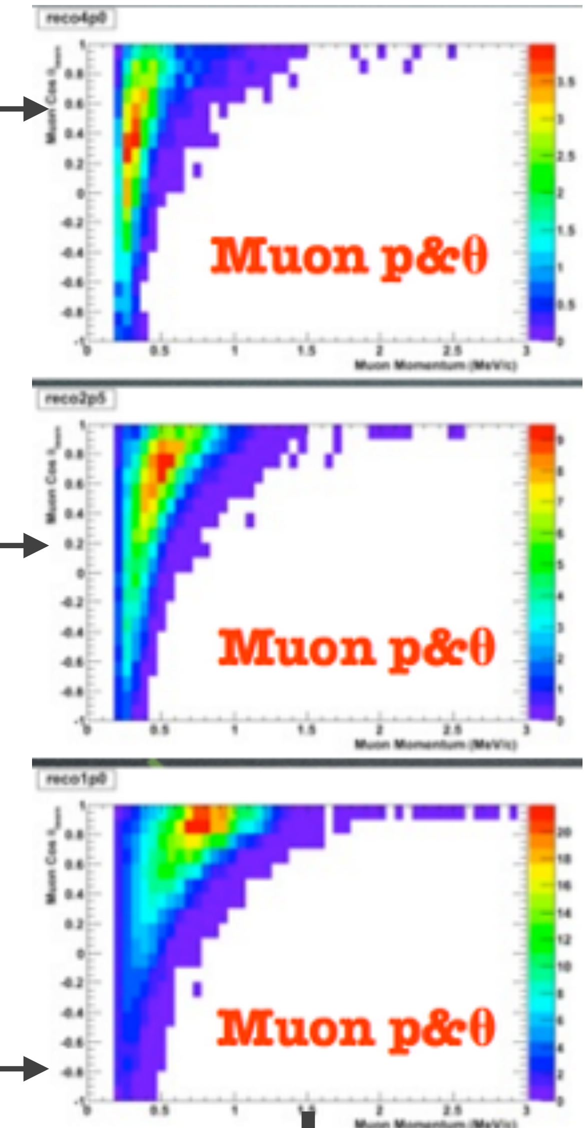
NuPRISM Analysis Method

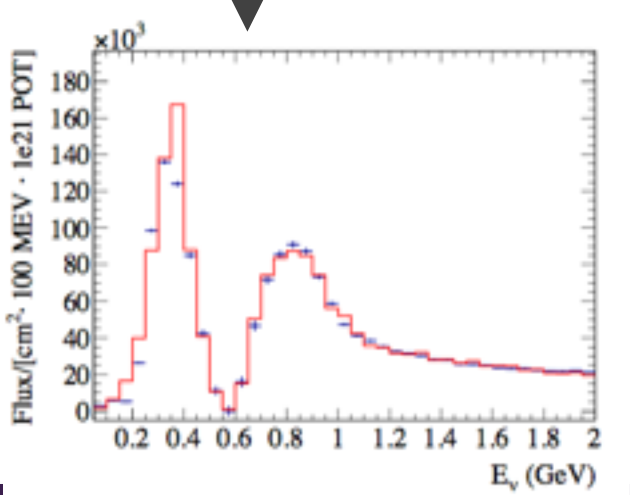


Spectra at each off-axis bin

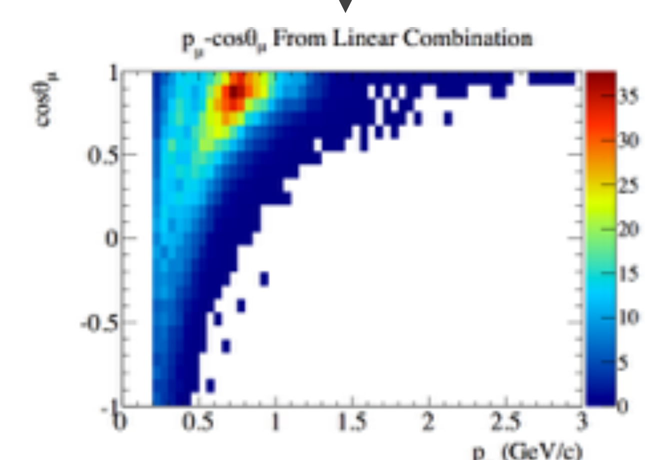


Observed muon kinematic distributions



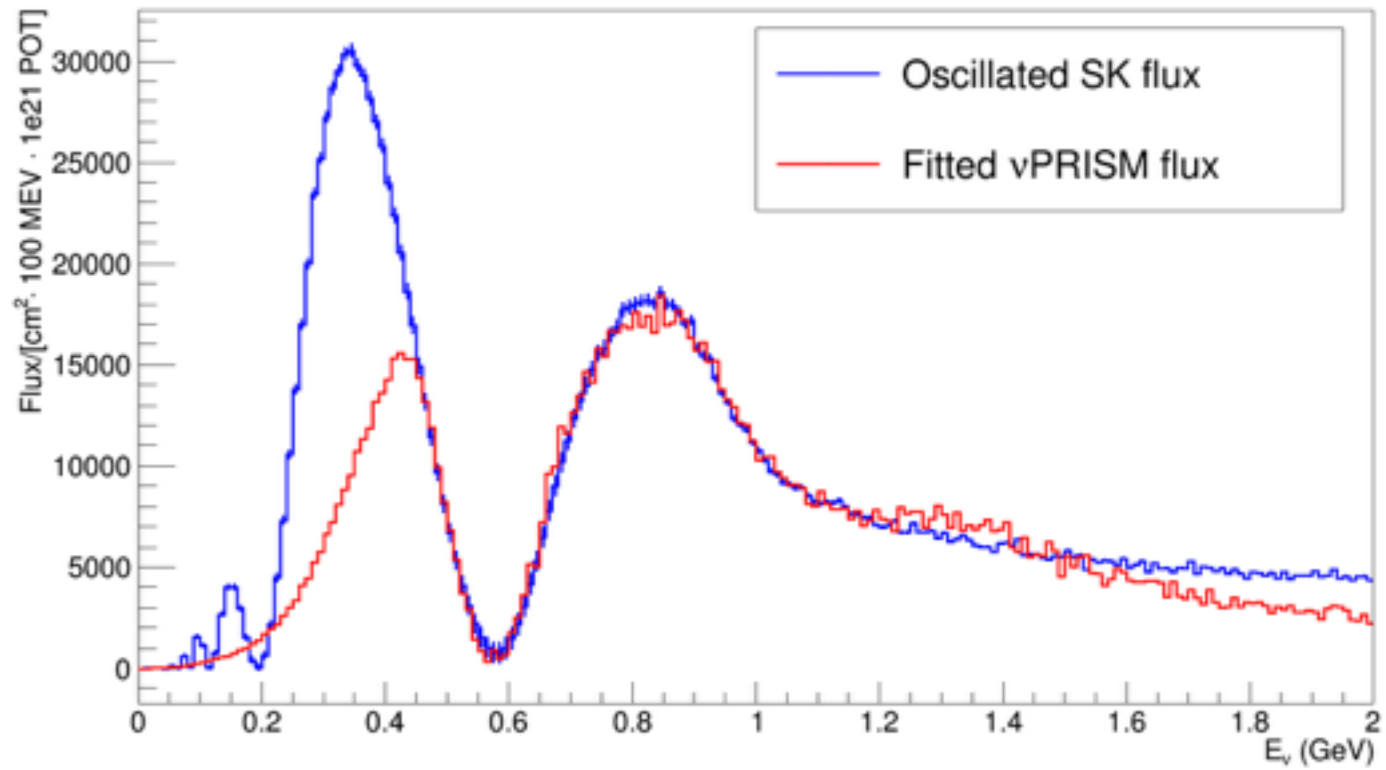


Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux

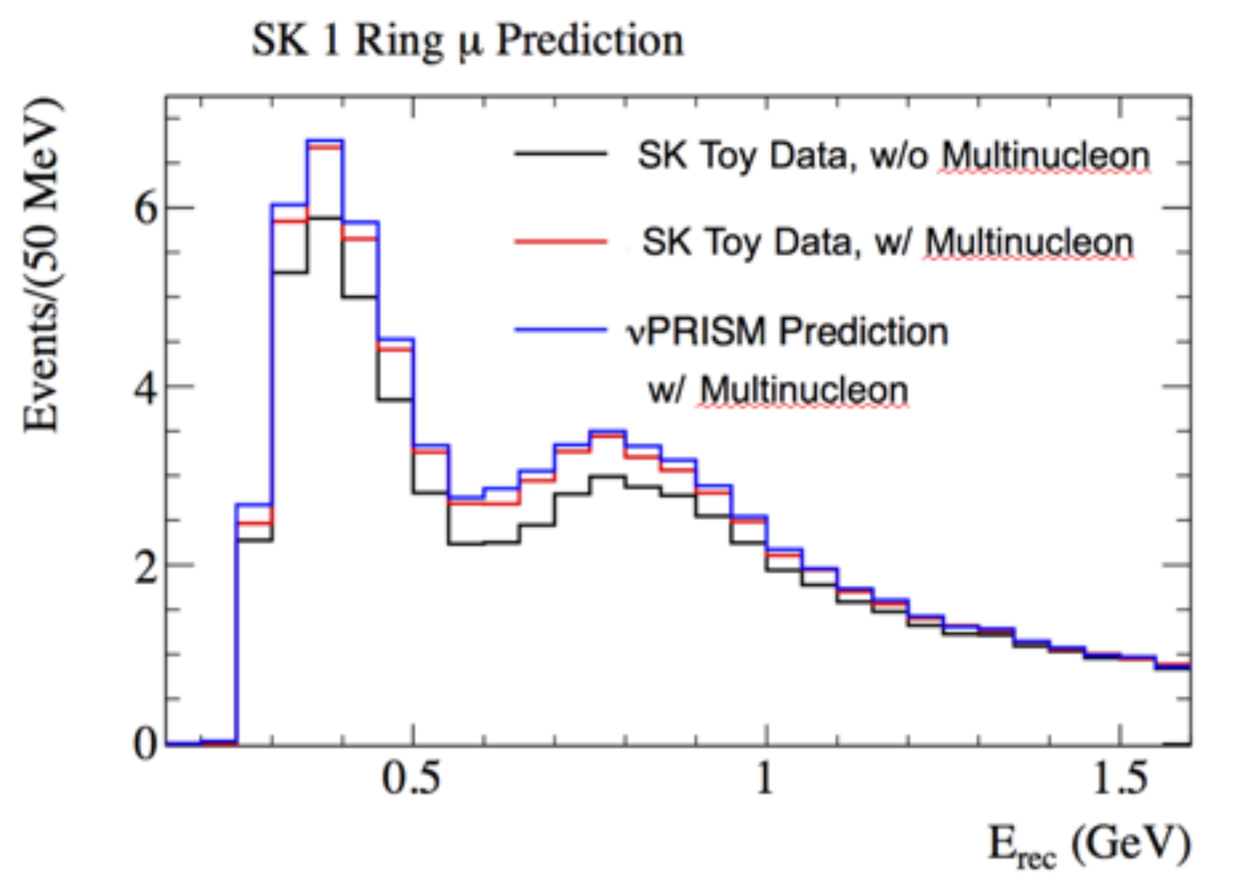


ν_μ Disappearance

- Linear combination of NuPRISM off-axis fluxes reproduces the far detector spectrum with oscillation hypothesis applied



- The linear combination of off-axis NuPRISM measurements are used to predict the reconstructed energy distribution at the far detector

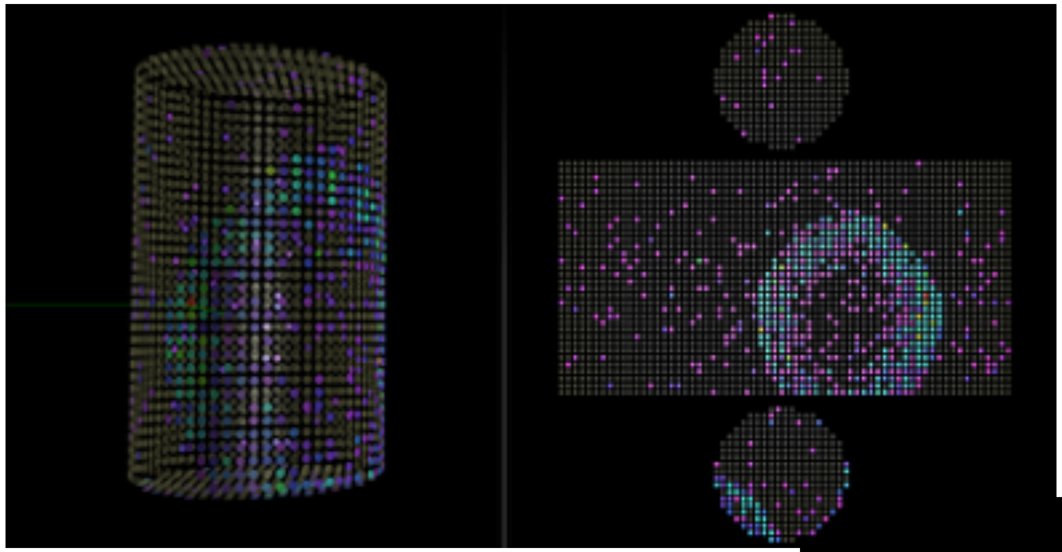


- The **4%** systematic error estimated using the T2K ND280 detector is **reduced to 1% with NuPRISM**

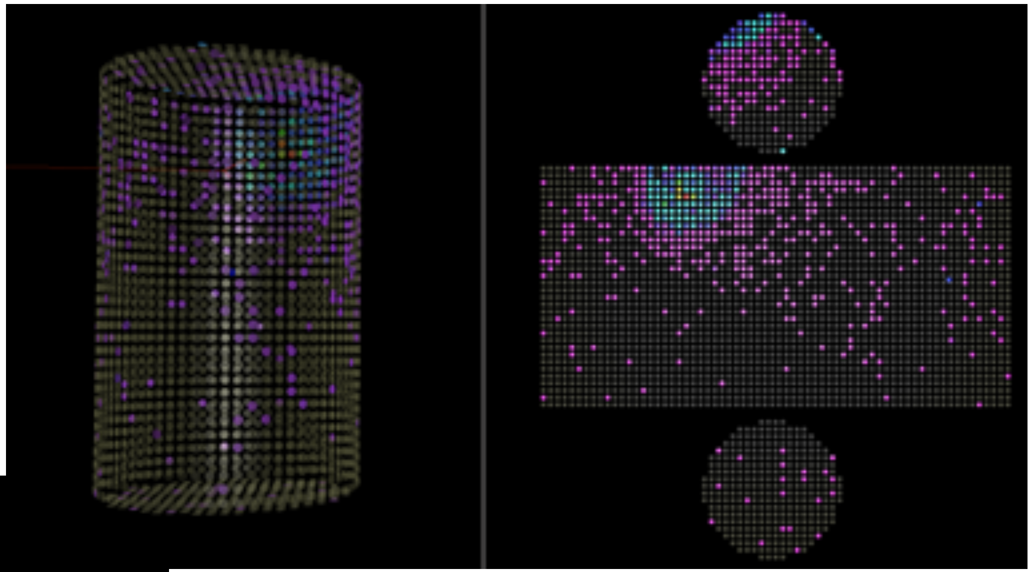
Simulation/Reconstruction

- Originally NuPRISM studies were done with 20 inch diameter PMTs (based on Super-K simulation)
  - Poor electron/muon and electron/π^0 separation
- Have updated to simulation with 40% photo-coverage and 8 inch diameter PMTs using WCSim with fiTQun for reconstruction

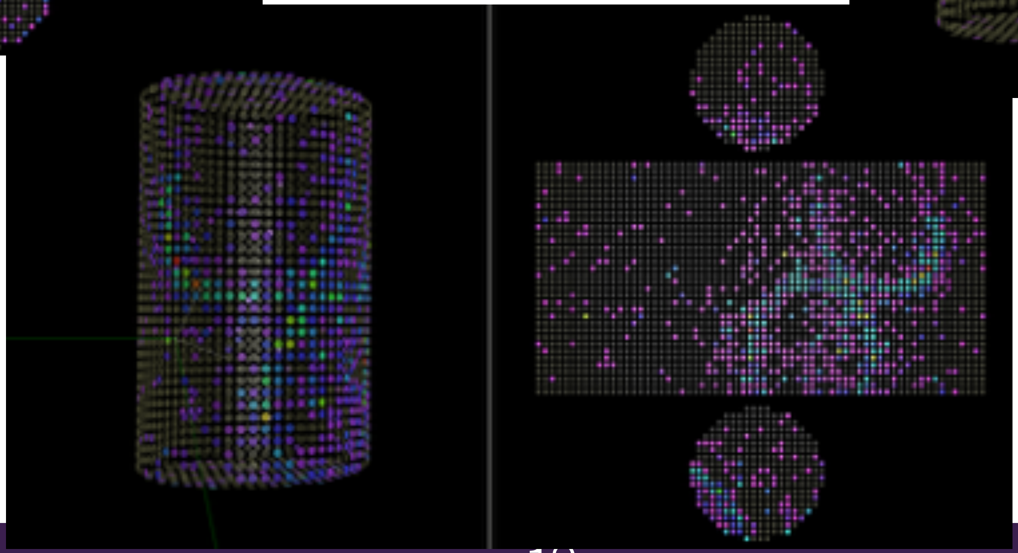
Muon



Electron

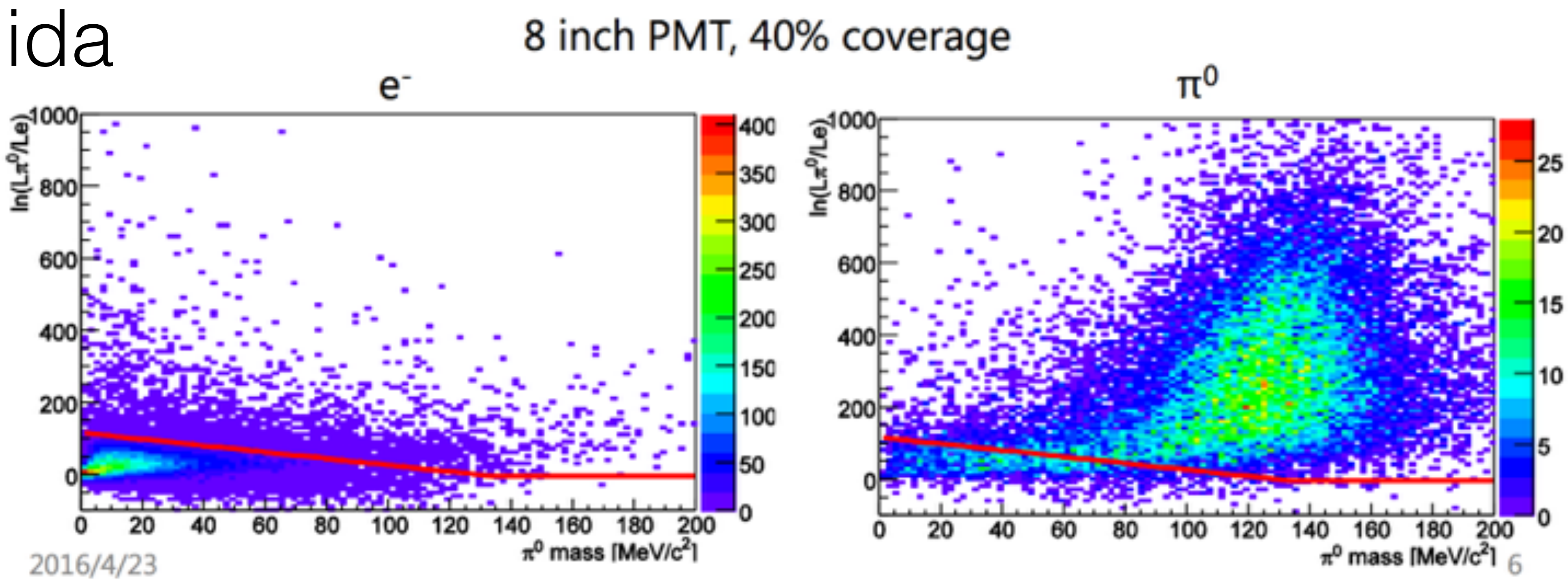


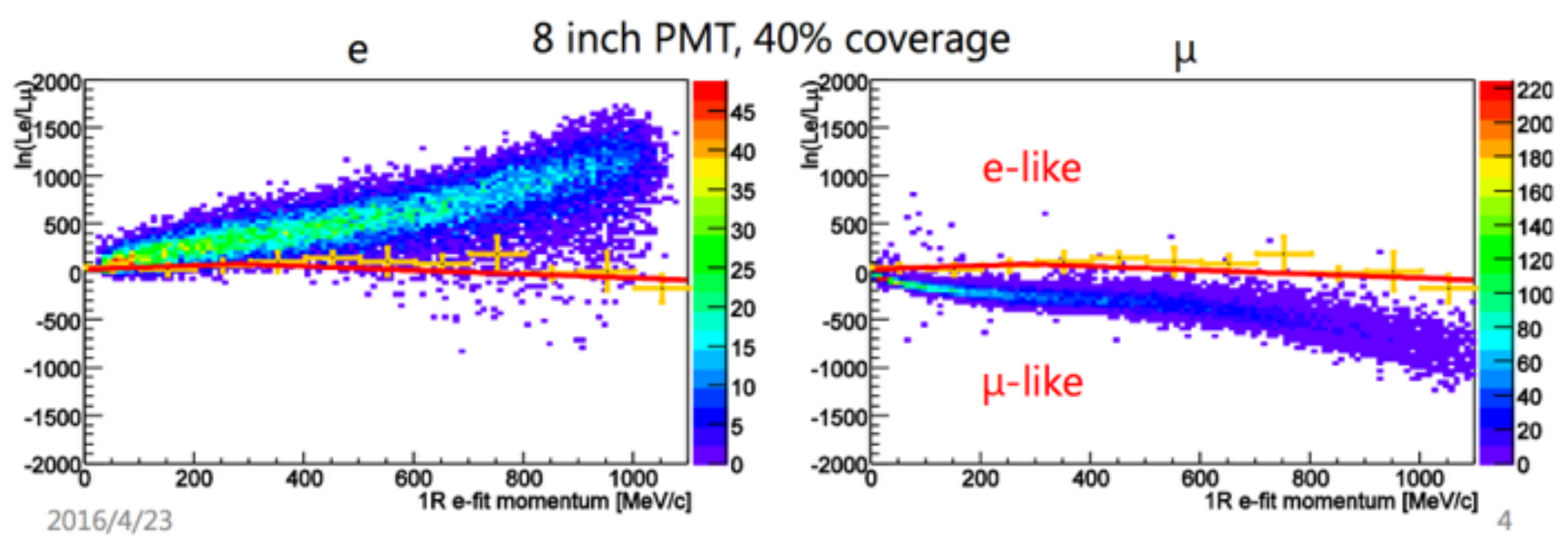
π^0



Particle Identification

T. Yoshida





	e efficiency	μ^- rejection
8″ PMT, 40%	95.4±0.1%	99.59±0.05%
5″ PMT, 40%	95.5±0.1%	99.58±0.05%

	e efficiency	π^0 rejection
8″ PMT, 40%	86.9±0.2%	92.1±0.2%
5″ PMT, 40%	87.9±0.2%	92.7±0.2%

ν_e Cross Section Measurement

Beam ν_e fraction increases with off-axis angle

Off-axis angle (°)	ν_e Flux 0.3-0.9 GeV	ν_μ Flux 0.3-5.0 GeV	Ratio ν_e/ν_μ
2.5	1.24E+15	2.46E+17	0.507%
3.0	1.14E+15	1.90E+17	0.600%
3.5	1.00E+15	1.47E+17	0.679%
4.0	8.65E+14	1.14E+17	0.760%

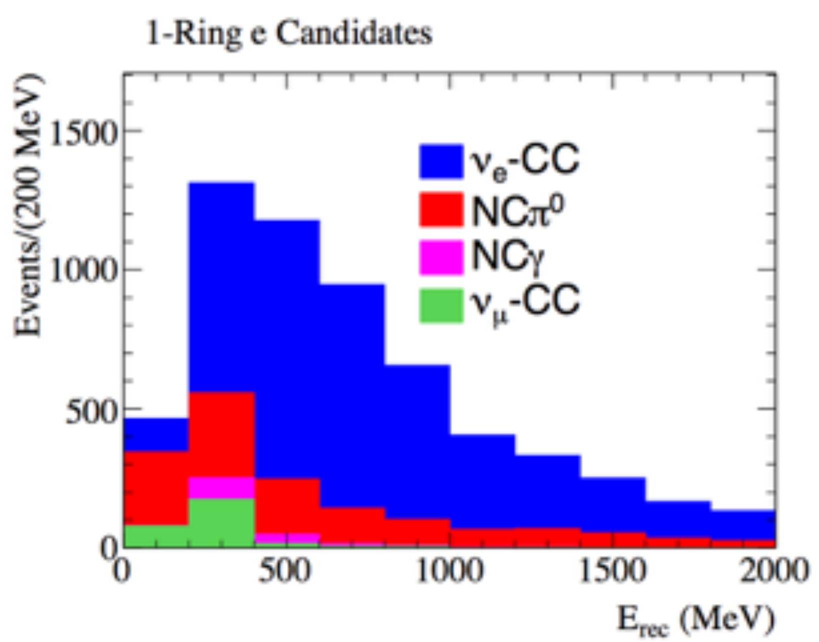


FIG. 24. Selected 1Re candidates in the 2.5-4.0° off-axis range for NuPRISM.

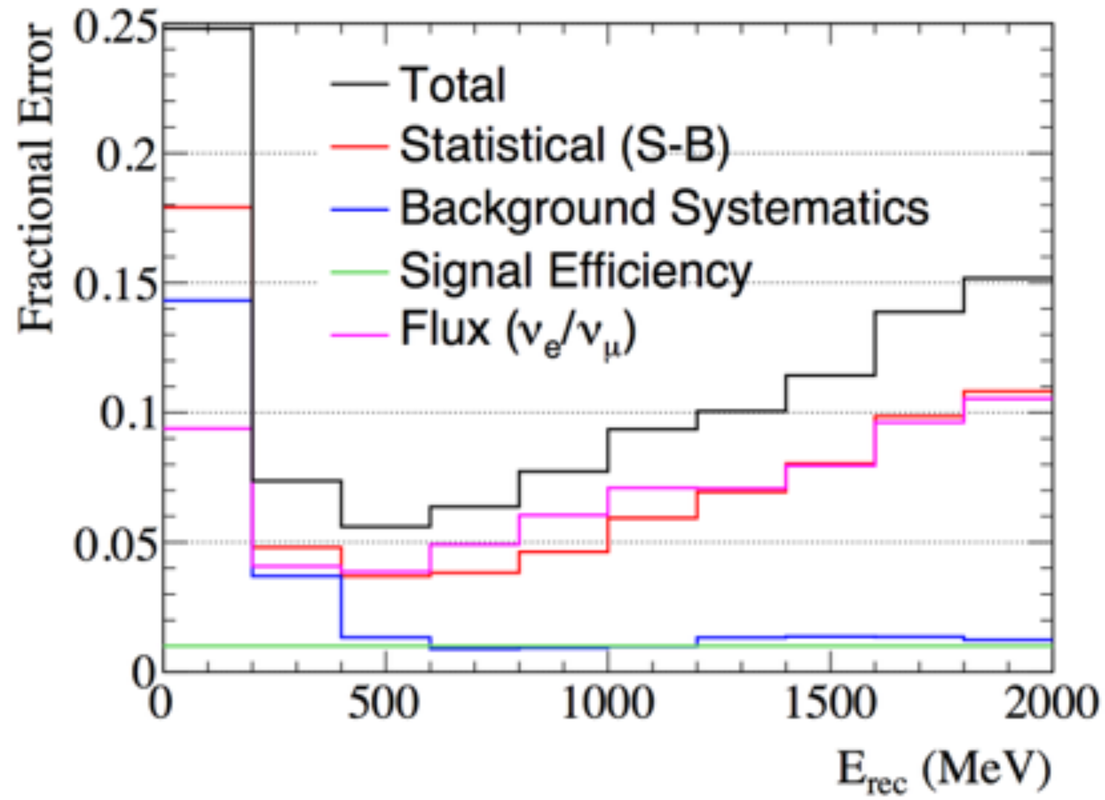
1.5e21 POT exposure at each off-axis position

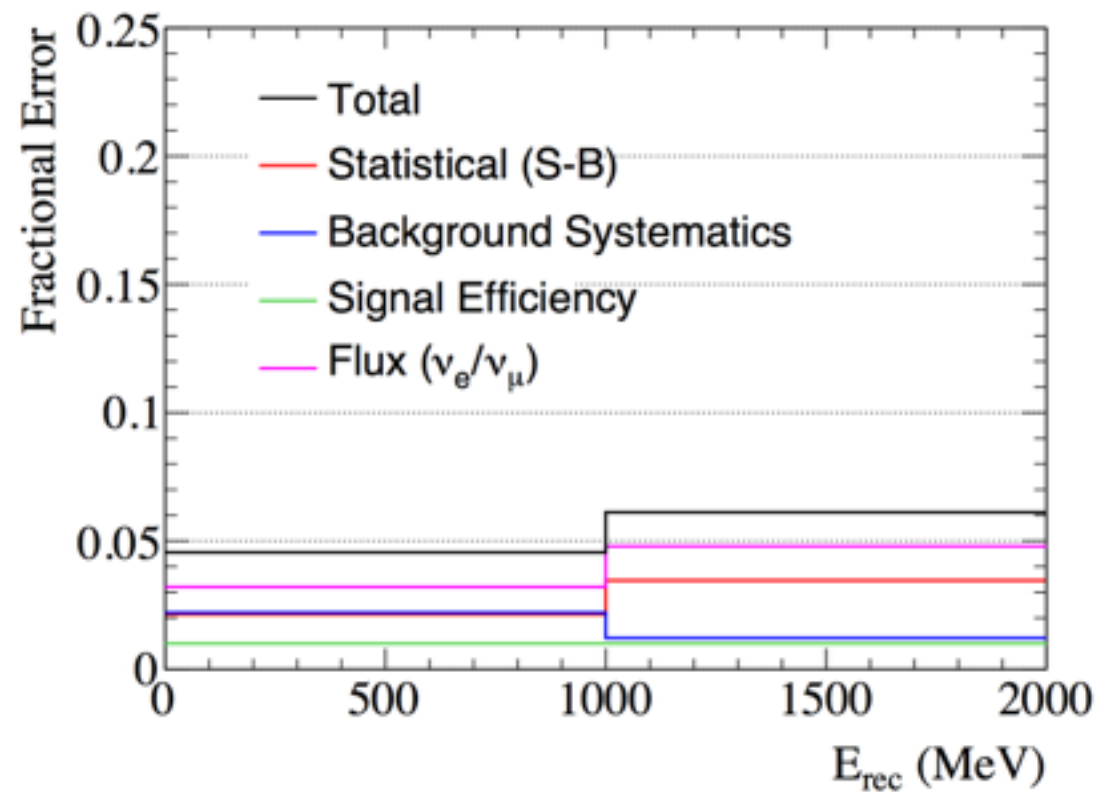
3500 candidate events with 71% signal purity

Aiming for ~3% precision on ν_e/ν_μ cross section ratio

Preliminary Statistical/Systematic Errors

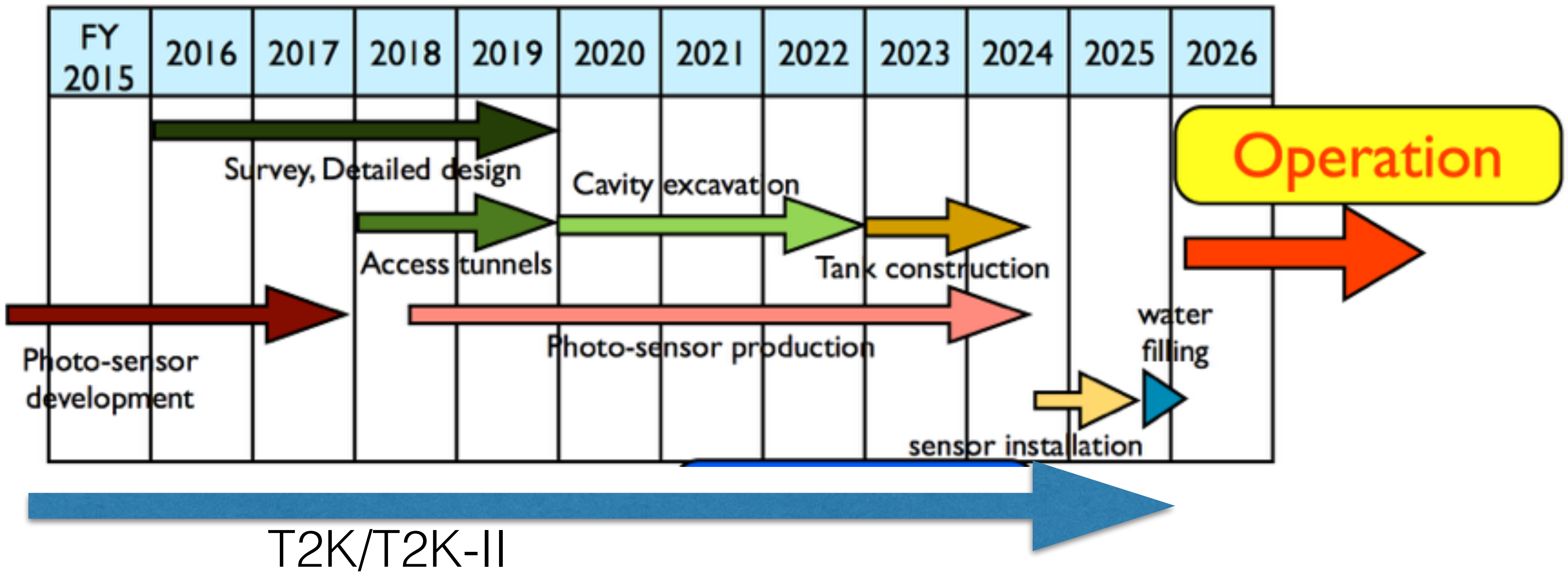
- Systematic errors on the cross section ratio estimated under the following assumptions:
    - Flux systematic errors from T2K model (constant in time)
    - 5% error on muon and NC backgrounds which can be constrained by control samples
    - 50% error on the NC1γ background
    - 1% error on the ratio of the signal efficiencies for ν_e and ν_μ candidates
- Under these assumptions, can achieve <5% error below 1 GeV
- To achieve 3% level:
    - Further reduction of the flux ratio uncertainty needed
    - Higher purity selection





Timeline Discussion

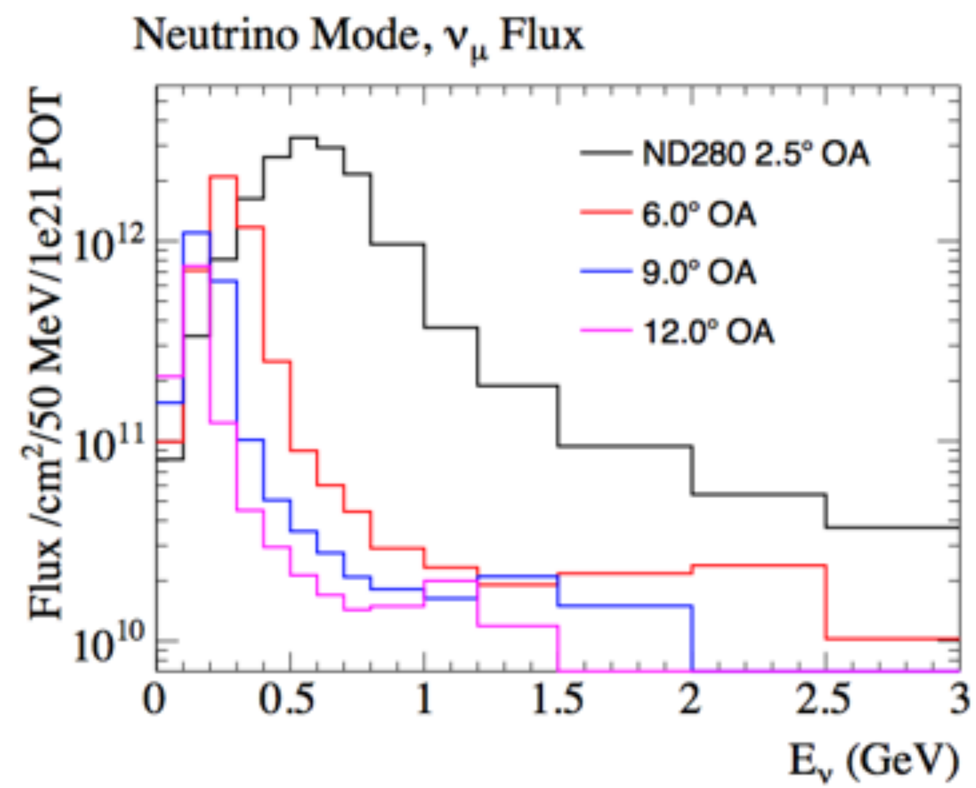
Nominal timeline for HK 1st Tank

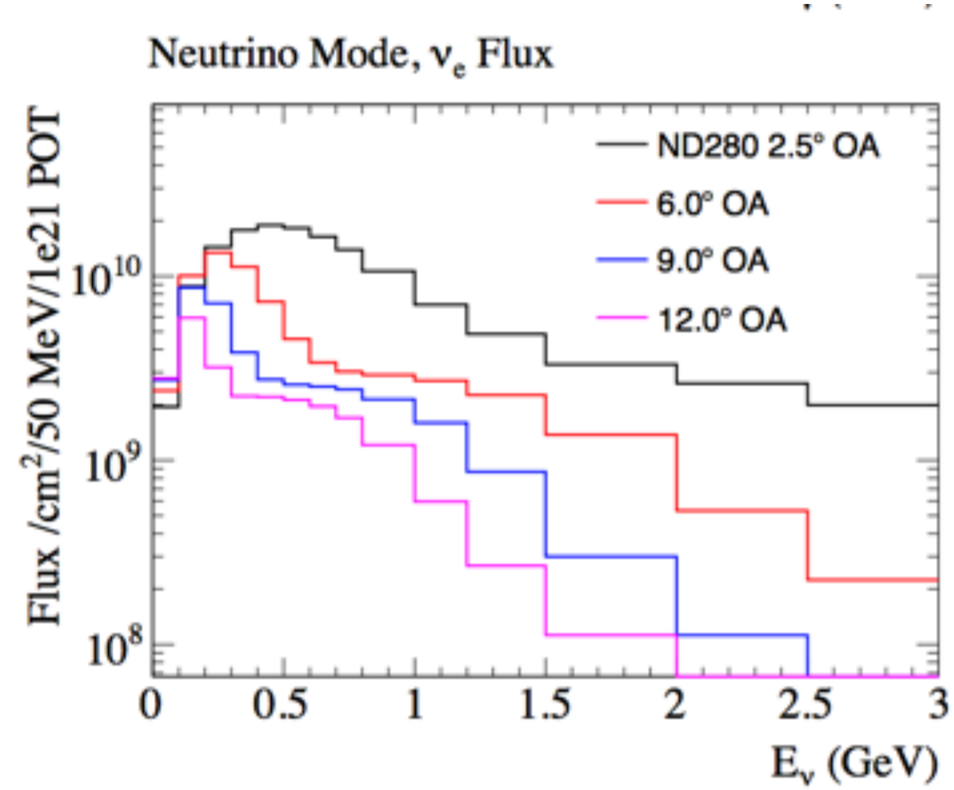


- Hyper-K first tank comes on-line in 2026
- Can benefit from building/operation of intermediate detector before 2026
  - Contribute to systematic error reduction for the T2K/T2K-II program
  - R&D and long-term operation for HK detector technologies
  - Refine the intermediate detector calibration to achieve % level necessary for Hyper-K
  - Begin the Hyper-K experiment with a head-start on systematic error reduction

Initial Phase Option

- Recent consideration of an initial phase for the intermediate detector
  - On the surface at the 280 m near detector site
    - Off-axis angle is ~9°-12°
      - Interesting physics with large off-axis angle beam
    - Can begin operation before excavation of new intermediate detector facility (dominant cost)

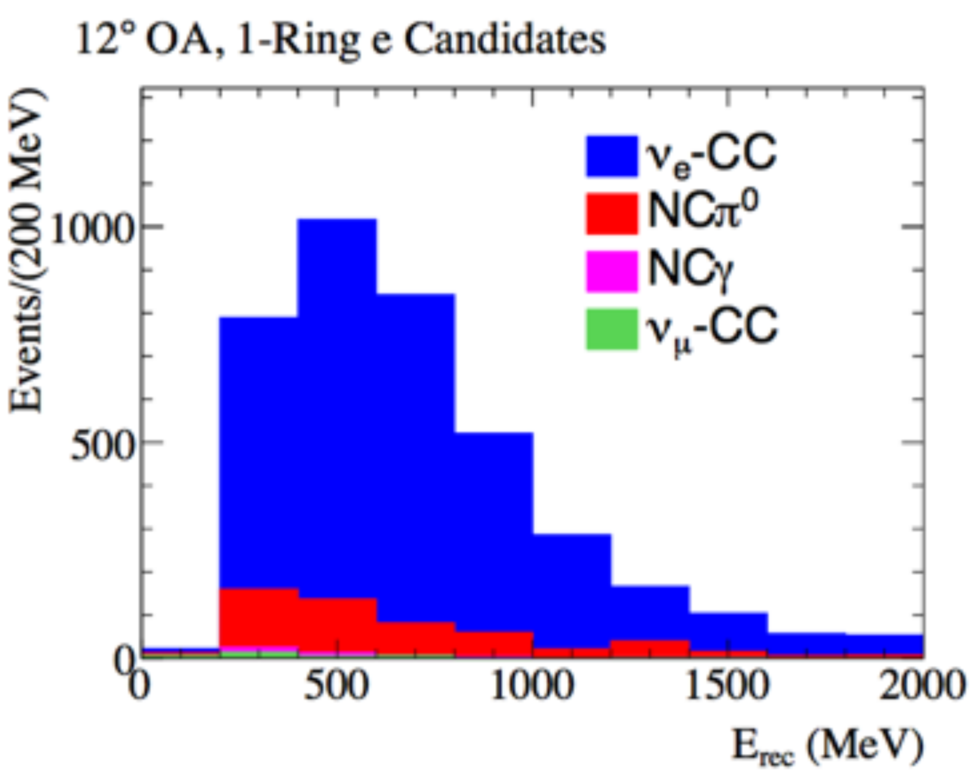


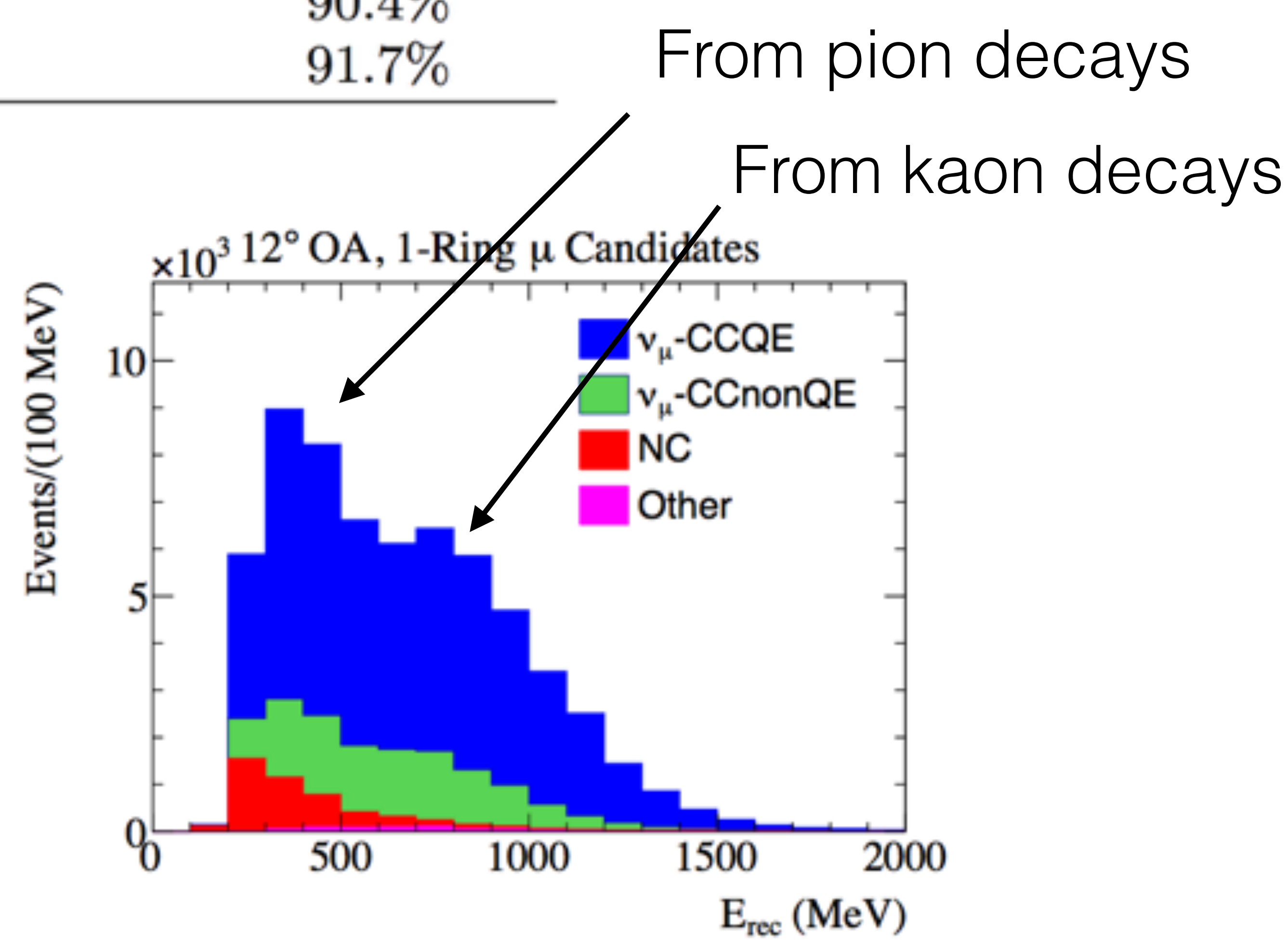


Event Rates in Initial Phase

- Estimate event rates for 300 ton ID, 2e21 protons-on-target

Off-axis Angle	1Re Events ($<$ 1.2 GeV)	ν_e-CC Purity
6°	10626	79.5%
9°	5781	83.5%
12°	3480	86.4%
Off-axis Angle	1Rμ Events	ν_μ-CC Purity
6°	3.33e5	92.7%
9°	1.09e5	90.4%
12°	6.23e4	91.7%





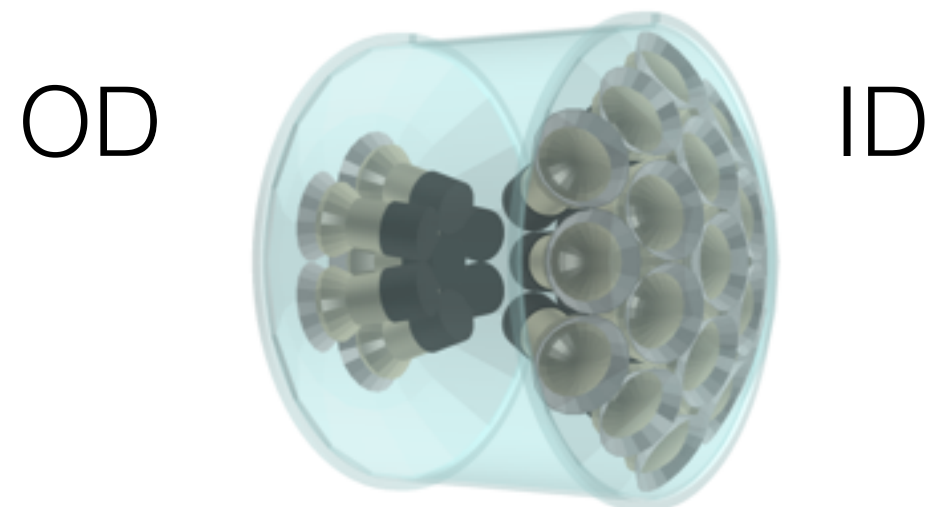
Surface Detector, Further Consideration

- K2K 1 kiloton detector observed low energy background from "sky-shine" neutrinos - needs investigation for surface detector a J-PARC
- Surface location allows for initial operation of the water Cherenkov detector in combination with a BabyMIND
- Have started investigation of available space at the 280 m site

WC Detector R&D

- The intermediate detector provides an ideal location for testing new technologies and systems that will be deployed in Hyper-K
- multi-PMTs are being developed for Hyper-K
  - A version for the intermediate detector is being developed in Canada

19 inward facing 3 inch PMTs
7 outward facing PMTs
Acrylic vessel
In-module electronics



- Testing of calibration systems required to achieve ~1% detector errors
- Long-term operation of in-water electronics

Summary

- An intermediate water Cherenkov detector addresses the most critical systematic errors for Hyper-K
- Two designs have been proposed (TITUS & NuPRISM)
    - Will be merged into a single design that is off-axis angle spanning with Gd-loading
- The Hyper-K and T2K-II programs can benefit from the earliest possible construction and operation of the intermediate detector
    - An initial phase on the surface at 280 m is now being pursued
    - The intermediate detector is an ideal location for testing and long term operation of new technologies and systems that will be deployed in Hyper-K
- **New collaborators are welcome!**