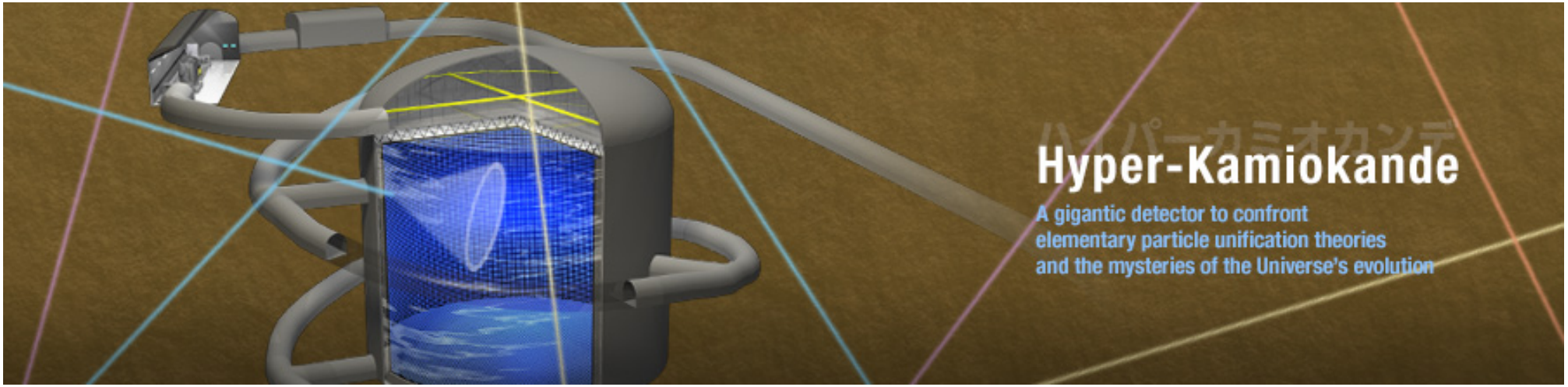
Nagoya University
Institute for Space–Earth Environmental Research

# Near Detectors for Hyper Kamiokande

- Motivation and goals of Near Detectors
- Physics impact on HyperK
- Intermediate Water Cherenkov Detector (IWCD)
- Off-axis spanning measurements
- Neutron-tagging with Gd

Steve Playfer (on behalf of HyperK and E61)
ICHEP, Seoul, 6th July 2018




## An 8x larger version of Super K in a new cavern in Kamioka mine

250 kTon detector (water)

L = 295km

JPARC Beam 1.3MW

$E_\nu$ = 600 MeV

Construction from 2019

Start of operations 2026

Main goals (within 10 years)

- CP violation in $\nu$ oscillations with Long Baseline Beam + Atmospheric neutrinos
  (Talks by Ishitsuka, Bravar)
- Proton decay
  (Talk by Yokoyama)
- Astrophysical $\nu$
  (Talk by Shimizu)

*Steve Playfer, ICHEP 2018, Seoul*

# Motivation for Near Detectors

- To measure the product of the unoscillated neutrino flux ($N_\nu$) times cross-section ($\sigma_\nu$) as a function of $E_\nu$, off-axis angle, horn current (F/B) and $\nu$ flavour ($\nu_e/\bar{\nu}_e/\nu_\mu/\bar{\nu}_\mu$)

- To predict the expected event rates in HyperK as a function of the oscillation parameters. Uncertainties in these predictions enter as systematic errors on HyperK measurements.

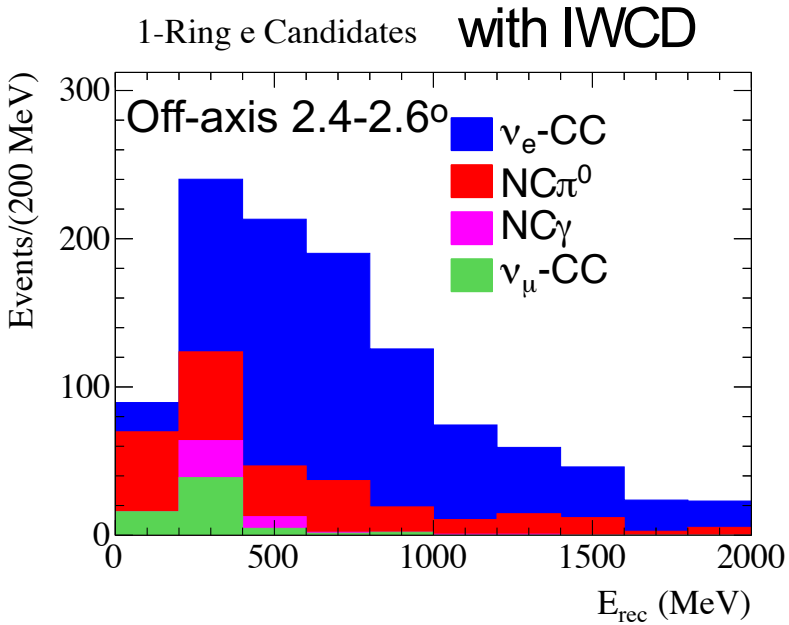
- To measure the properties of $\nu$ interactions, their detector signatures and final state particles
  - Essential information for LBL accelerator $\nu$
  - Important input to p decay (atmospheric $\nu$ backgrounds)
  - Improves reconstruction of atmospheric $\nu$

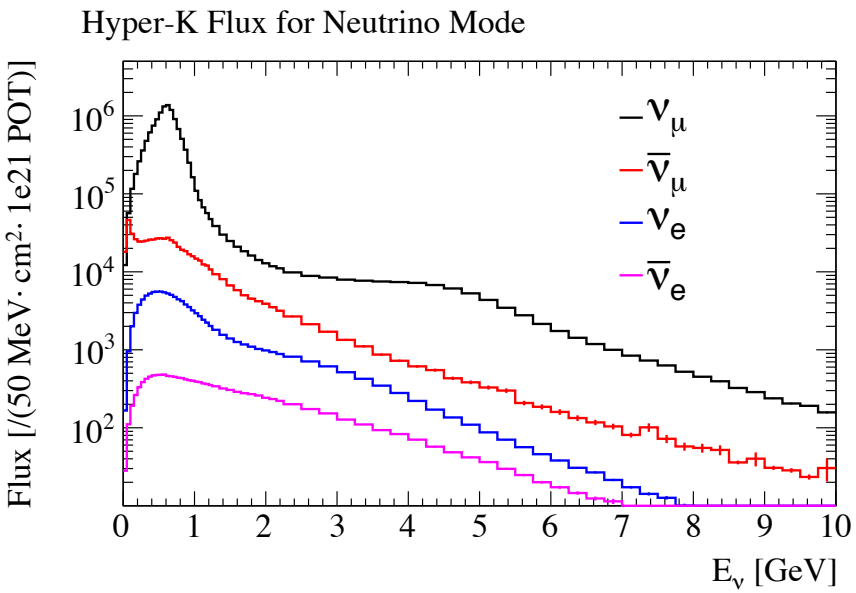
- The differences between the near and far detectors should be minimized.

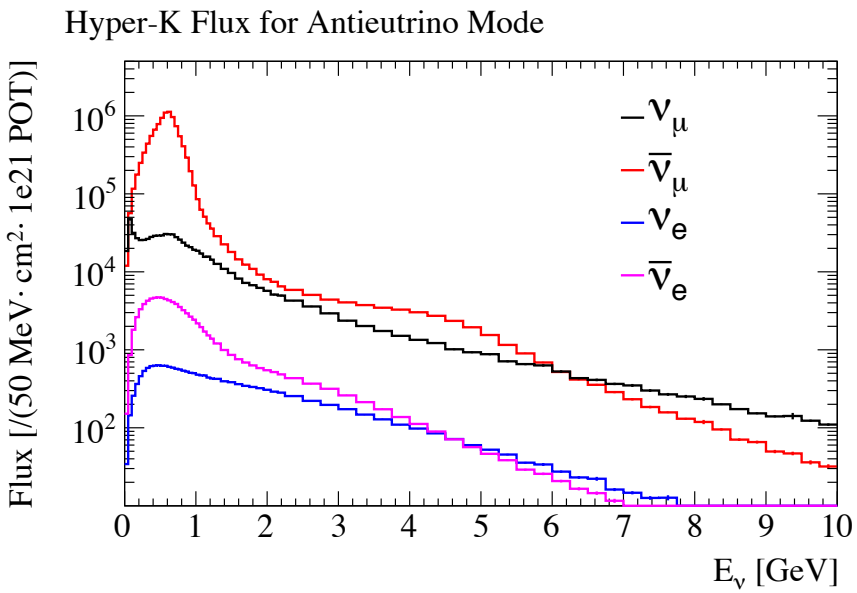
# Unoscillated Beam Flux

- Need unoscillated $\nu_\mu$ rate ($\nu_\mu$-CC) from 1-ring $\mu$ candidates
- Need intrinsic $\nu_e$ component ($\nu_e$-CC ~1%) from 1-ring e candidates
- Can calculate beam composition from hadronic interactions to 5% accuracy (see backup)
- Intermediate Water Cherenkov Detector (IWCD) measure CC 1e events to ~3% (stat.)

HyperK study with IWCD



# Neutrino Interactions

- Quasielastic Charged Current (CCQE) production of e or $\mu$
- Separate out samples with additional $\pi^+$ (and $\pi^0$,p)
- Model additional contributions to the CC $0\pi$ sample from multi-nucleon (2p2h), resonant processes, Neutral Current (NC), $\bar{\nu}$ background, and final state interactions (FSI)
- Targets water(O), scintillator(C)

They differ by a few %

- For appearance need $\sigma(\nu_e)$

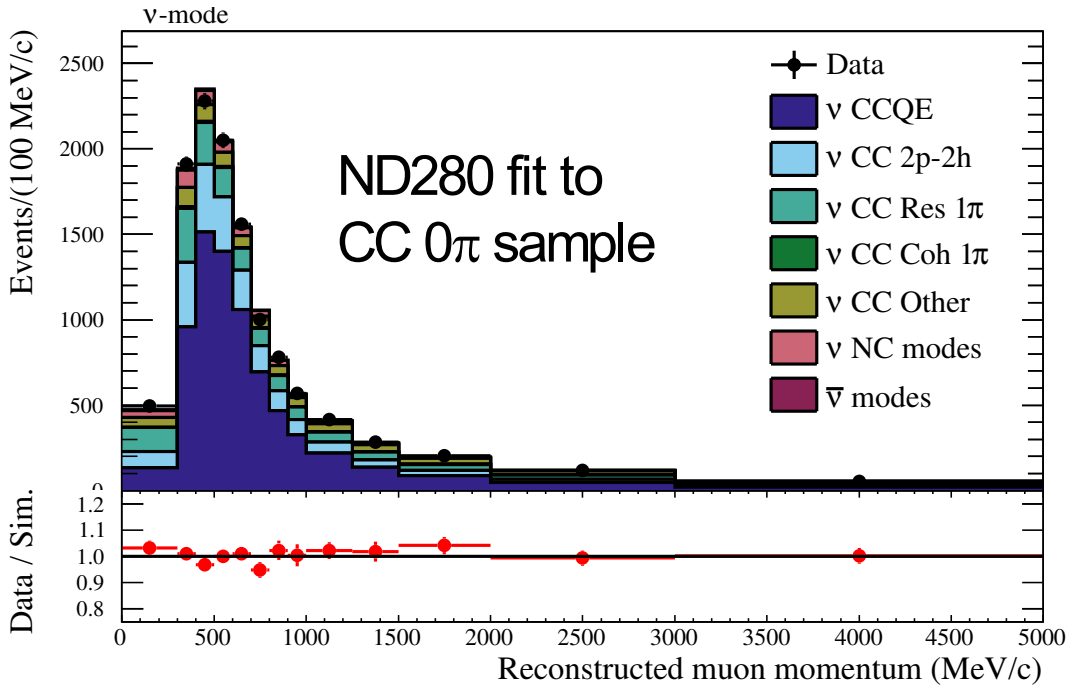
but beam is only ~1% $\nu_e$

Plan is to measure $\sigma(\nu_e)/\sigma(\nu_\mu)$

- Currently T2K measures

$\sigma(\nu_\mu)$ and uses theory to relate CCQE rates for $\mu$ and e

(T2K talks by Wilkinson/Hadley/Zito)



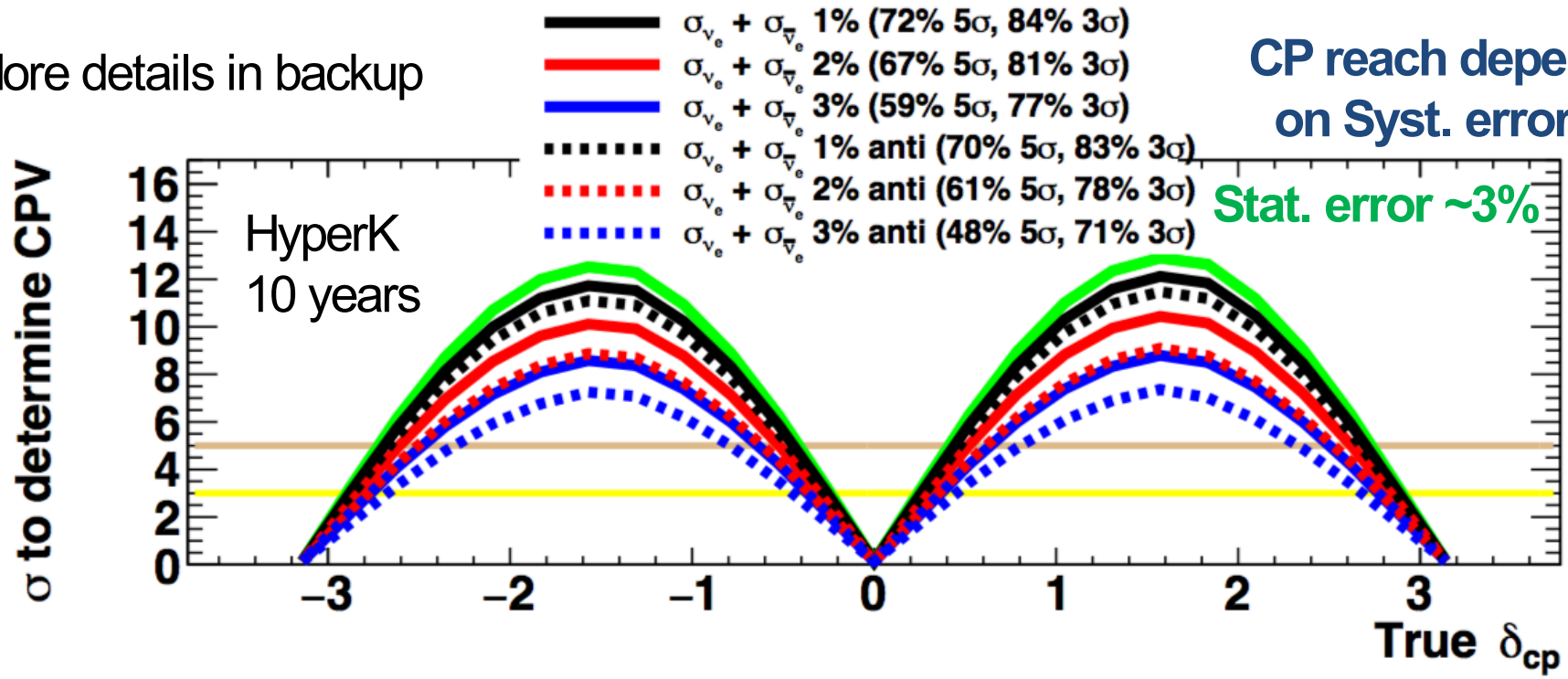

*Steve Playfer, ICHEP 2018, Seoul*

# Systematics aimed for by HyperK

| HK design report arXiv:1805.04163 | | Flux & ND-constrained cross section | ND-independent cross section | Far detector | Total |
|---|---|---|---|---|---|
| $\nu$ 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% |

More details in backup

CP reach depends on Syst. errors!

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# Overview of Near Detectors at JPARC

- INGRID is an on-axis detector
  Measures beam position to 0.2mrad and monitors flux

- ND280 is an off-axis (2.5°) magnetic detector
  Measures CC production of right and wrong-sign $\mu$ and e
  Being upgraded for T2K2 (Talk by M.Zito)

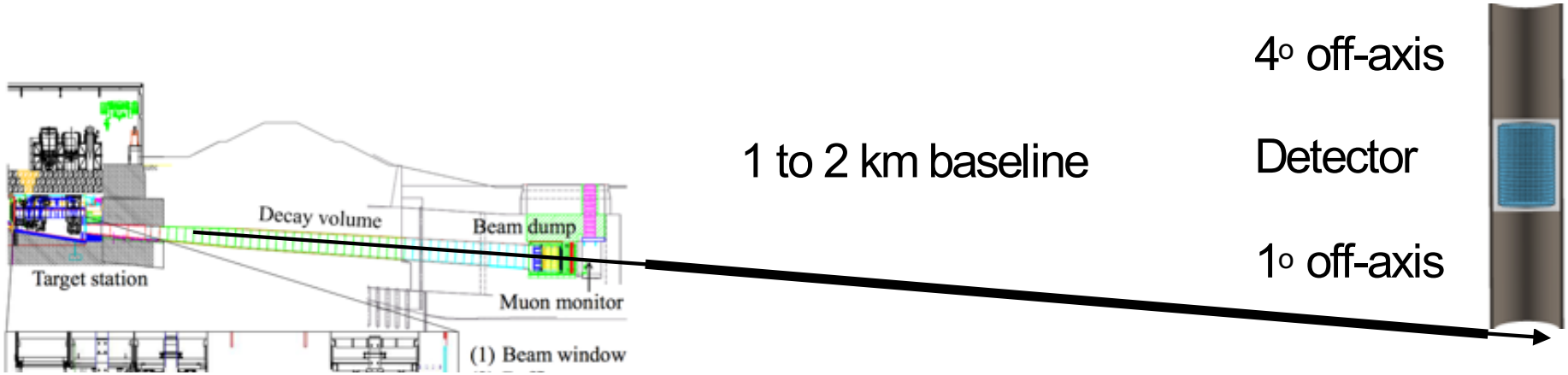
- E61 is a proposed Intermediate Water Cherenkov Detector (IWCD)
  Uses almost identical detector technologies to HyperK
  The subject of the rest of this talk

… and for completeness there are two other near detectors

- WAGASCI/BabyMIND measures $\nu$ cross-sections in water (Talk by A.Blondel)

- NINJA measures $\nu$ cross-sections with nuclear emulsion

# Intermediate Water Cherenkov




~1kTon Water Cherenkov detector

Diameter 8m (Inner Detector), 10m (Outer Detector)
contains charged muons up to ~1GeV with high efficiency

Height 8m to 12m (depends on baseline)
+ several m of water overburden for passive shielding against $\gamma$ and n backgrounds

Moves vertically in 50-100m shaft to scan off-axis beam

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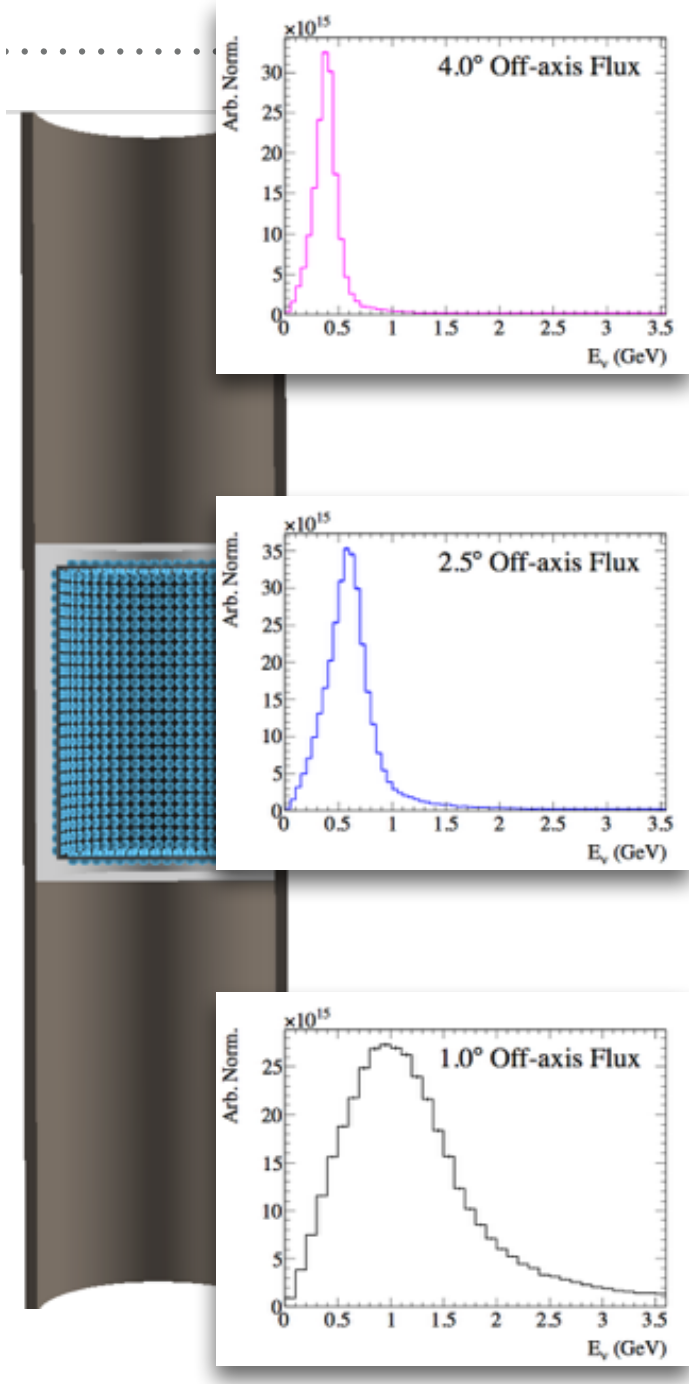
# Off Axis Measurements

- Probe cross-sections and final states as a function of $E_\nu$
- Mean energy varies from 0.4GeV (4°) to 1.0GeV (1°)
- Fraction of $\nu_e$ varies from 0.5% (1°) to 1.5% (4°), with a high energy tail from Kaon decays
- Can use linear combinations of different angles to define "quasi-monochromatic" beams
- Aim for direct measurement of $\sigma(\bar{\nu}_e)/\sigma(\nu_e)$ to few % accuracy
- Take advantage of $4\pi$ coverage of IWCD with same target and similar detection efficiency

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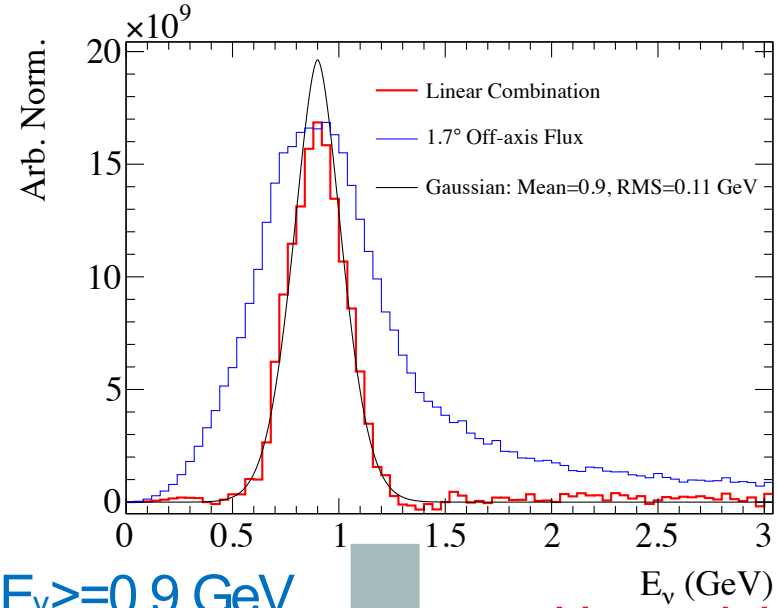
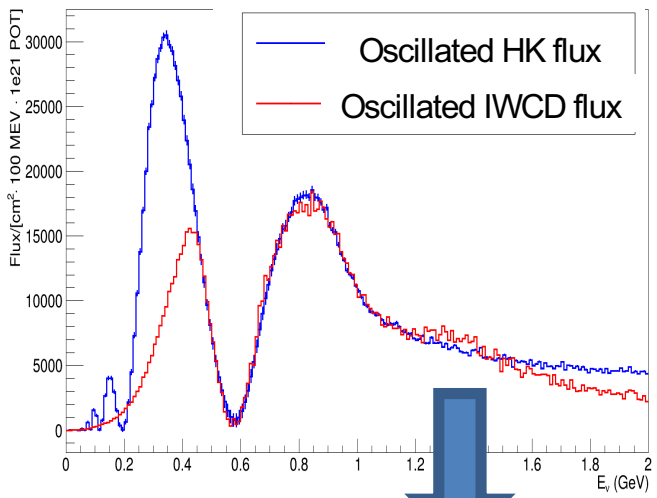
# HyperK Predicted $\nu_\mu$ from IWCD




$\sin^2\theta_{23} = 0.48$

$\Delta m_{32}^2 = 2.41\times10^{-3}$

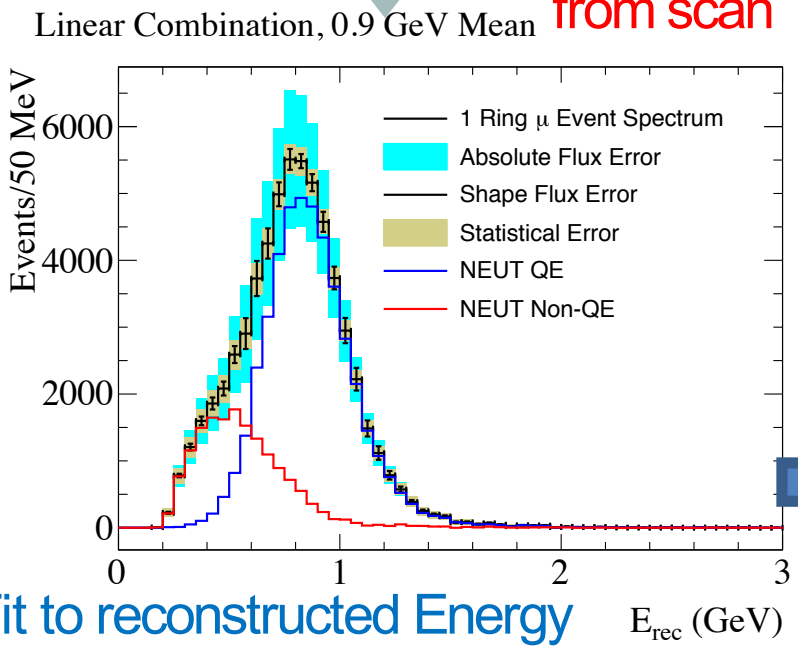
$\langle E_\nu \rangle = 0.9$ GeV

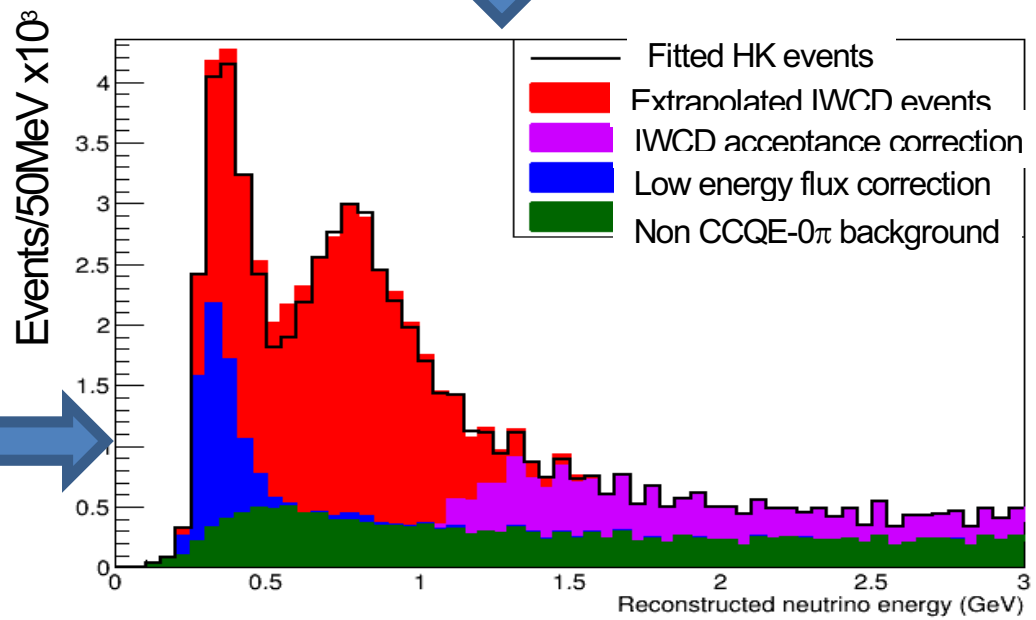
Off-axis 1.7°

Use weighted Spectrum from scan

Fold in $E_{rec}$ as a function of $E_\nu$

Correct for IWCD acceptance




Fit to reconstructed Energy

Gives non-CCQE component

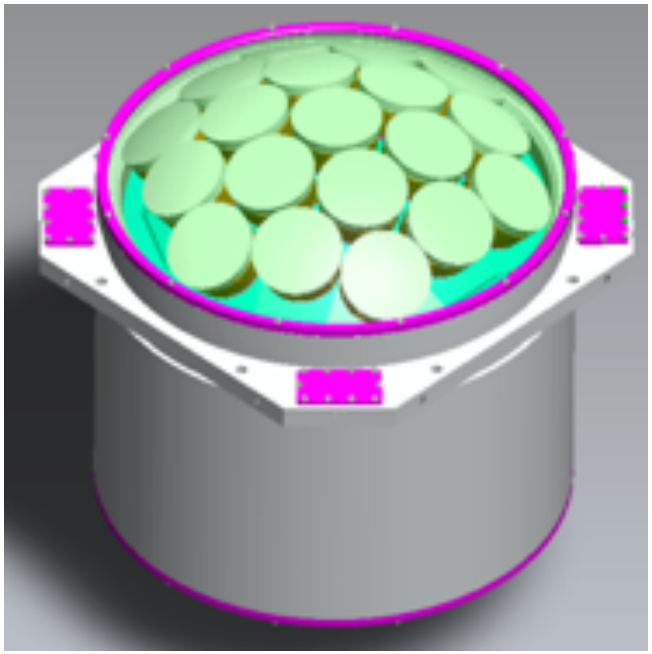
# Multi-PMT Photosensors

Need fine-grained photodetectors
(scale down from 20” PMTs in HyperK)

Build modules with 19 x 3” PMTs facing inwards
(and add some PMTs facing outwards)

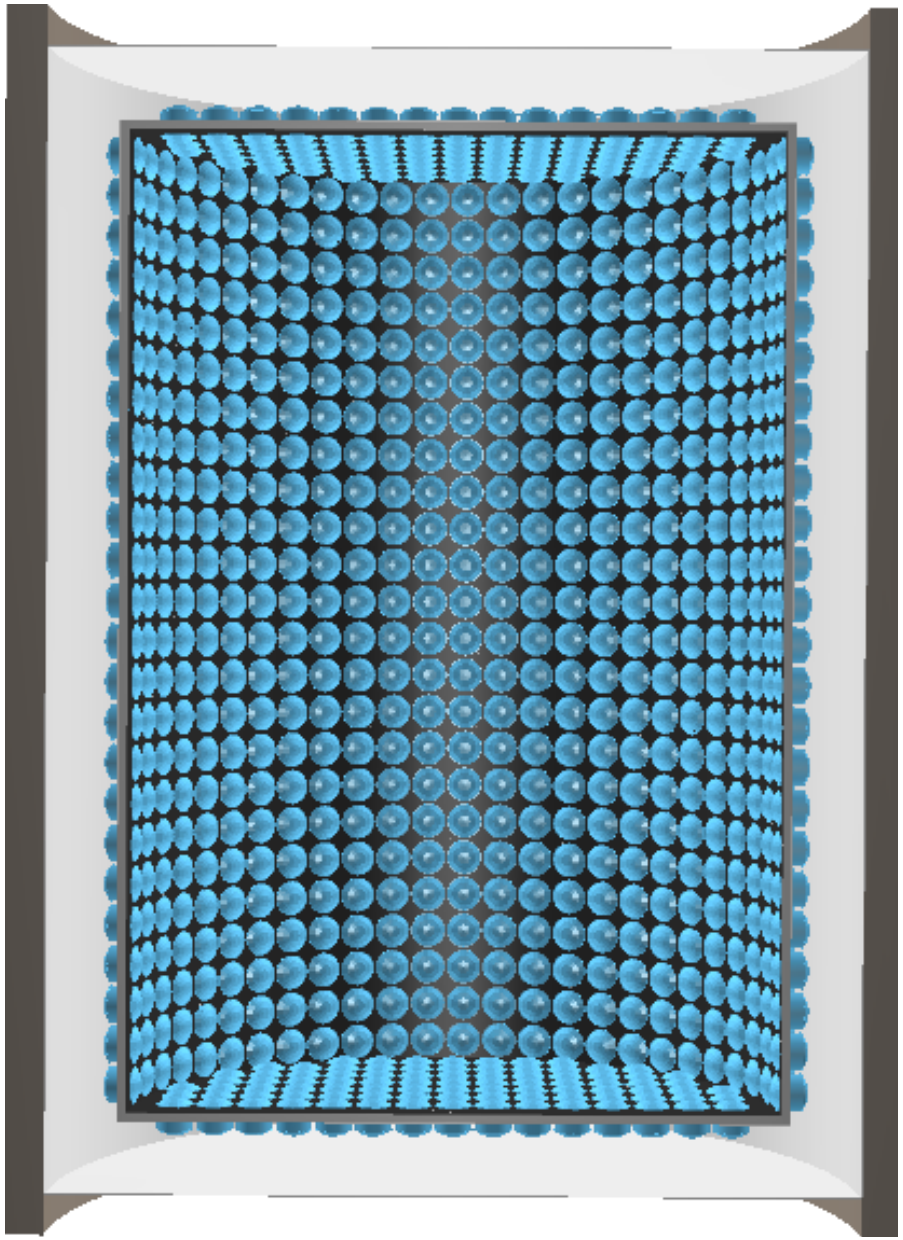
500 to 800 Modules needed to cover ID
(10 to 15k PMTs)

Readout electronics integrated into structure

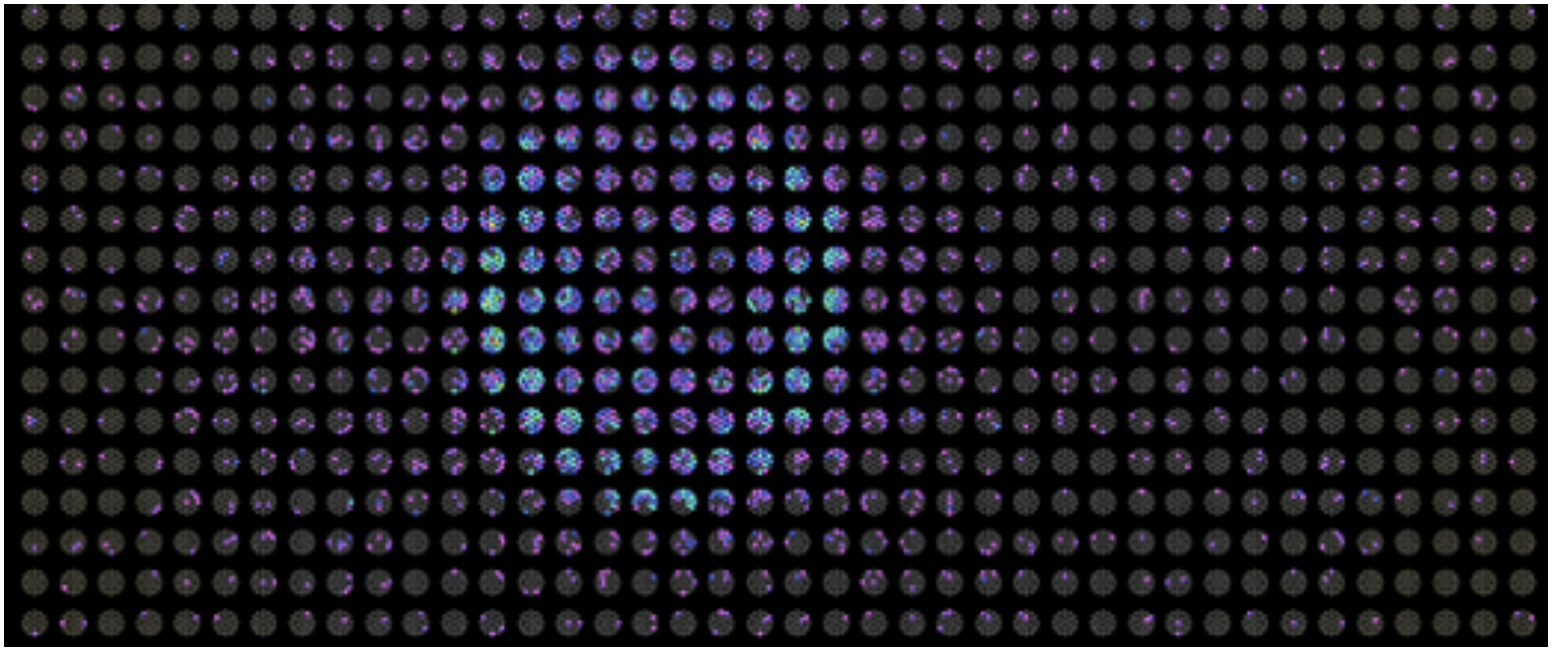


More detailed design in backup

(See Talk by V. Berardi)



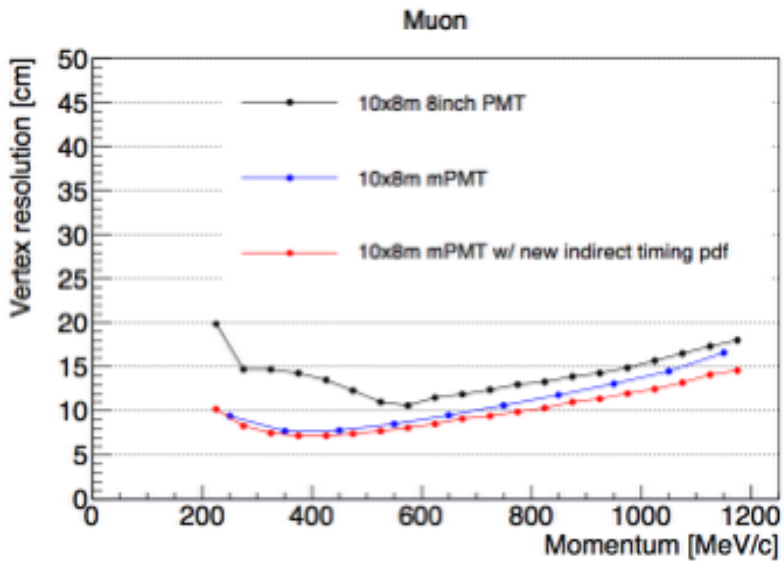
# Reconstruction Performance



Improvement in vertex resolution compared to 8” PMTs

Tuning of event reconstruction ongoing

Also expect better angular resolution and e/$\mu$/$\pi^0$ separation

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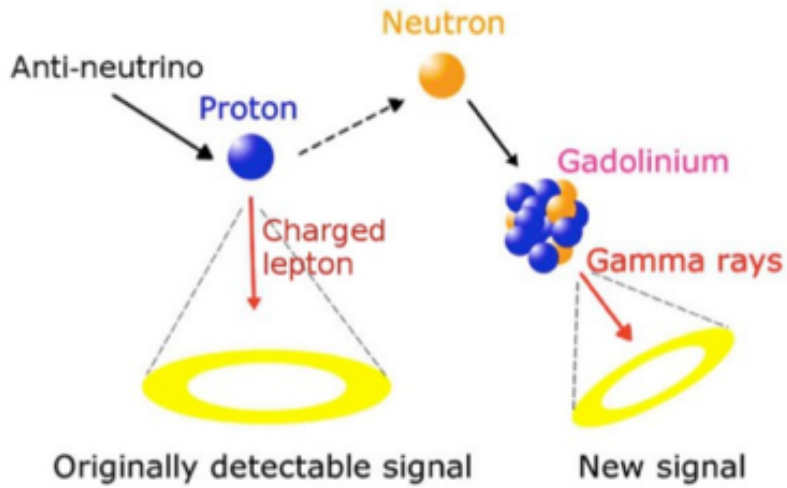
# Neutron Tagging in IWCD

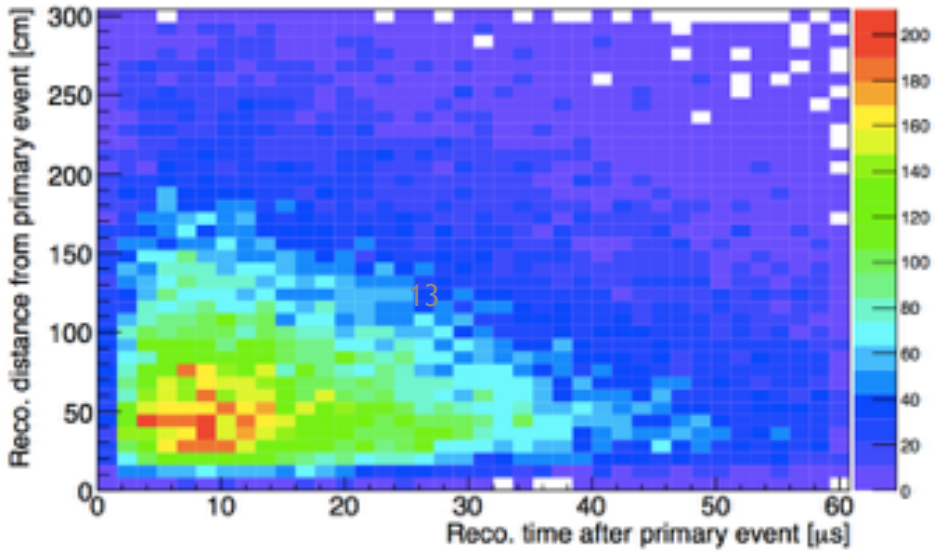
- Load water with 0.2% $Gd_2(SO_4)_3$
  Enhances n capture rate

- Capture time ~10μs, distance ~50cm
- Tagging efficiency ~80% (8MeV γ energy)

- Helps separate $\bar{\nu}$ and $\nu$
- Measures n production in $\nu$ scattering




Simulated neutron capture time and
Reconstructed distance from primary vertex




- Method demonstrated in EGADS

- Planned for SuperK from 2019

(See talks by Simpson/Marti)

- Gd loading is also proposed for HyperK itself

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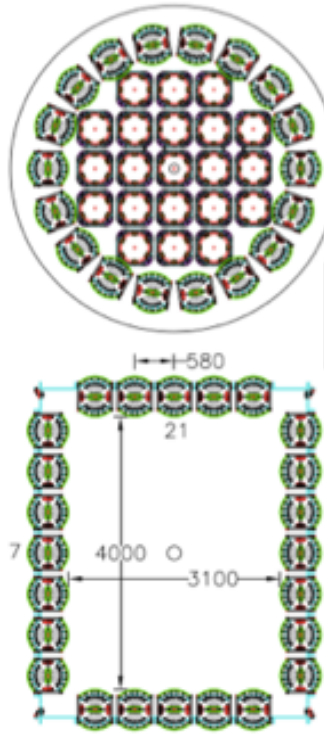
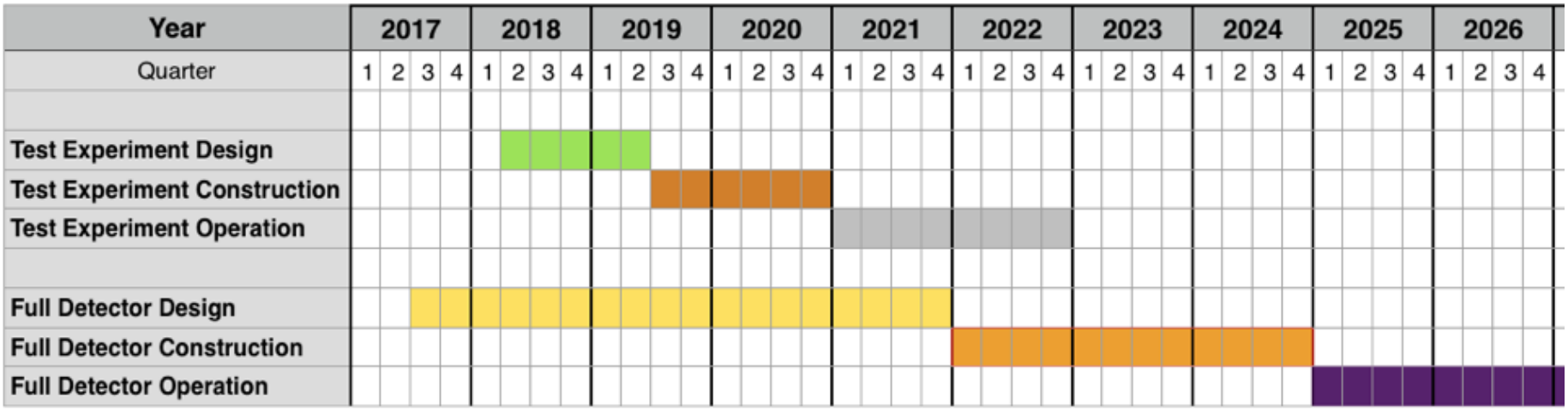
# Beam Test and Schedule




Aim is to test mPMTs and calibration procedures

- Half-size tank, 5m height, 3-4m diameter, ~170 mPMTs
- Charged particle beams (e,$\mu$,$\pi$,p) in the sub-GeV range
- Preferred site Fermilab MCenter or MTest

Schedule for Test Beam and Full IWCD construction

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# *Backup Slides*

# Current T2K systematic errors

TABLE I. Effect of $1\sigma$ variation of the systematic uncertainties on the predicted event rates of the SK samples.

| Source of uncertainty | 1-Ring $\mu$ | | 1-Ring $e$ | | | |
|---|---|---|---|---|---|---|
| | FHC | RHC | FHC | RHC | FHC 1 d.e. | FHC/RHC |
| SK Detector | 2.40 | 2.01 | 2.83 | 3.79 | 13.16 | 1.47 |
| SK FSI + SI + PN | 2.20 | 1.98 | 3.02 | 2.31 | 11.44 | 1.58 |
| Flux and cross-section (w/ ND280 constraint) | 2.88 | 2.68 | 3.02 | 2.86 | 3.82 | 2.31 |
| Nucleon removal energy | 2.43 | 1.73 | 7.62 | 3.66 | 3.01 | 3.74 |
| $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ | 0.00 | 0.00 | 2.63 | 1.46 | 2.62 | 3.03 |
| NC 1-$\gamma$ | 0.00 | 0.00 | 1.07 | 2.58 | 0.33 | 1.49 |
| NC Other | 0.25 | 0.25 | 0.14 | 0.33 | 0.99 | 0.18 |
| Oscillation parameters | 0.03 | 0.03 | 3.86 | 3.60 | 3.77 | 0.79 |
| Total | 4.91 | 4.28 | 9.60 | 7.87 | 18.65 | 5.93 |

These errors should be reduced for HyperK with more far detector events

These errors should be reduced for HyperK with addition of IWCD

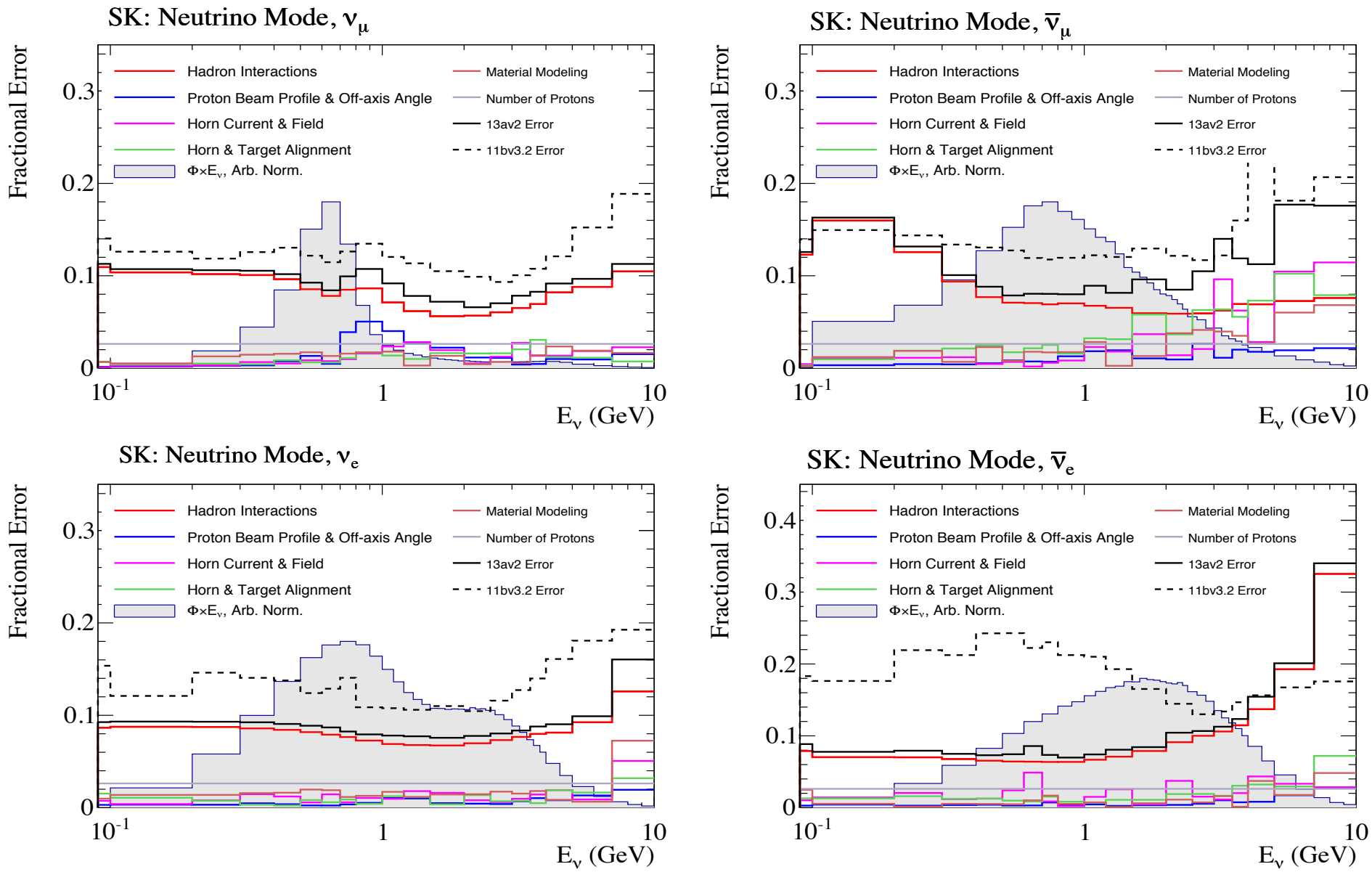
Reduction T2K to HyperK
Total error 5% to 3%

# Beam Flux uncertainties

Integral flux ~5% dominated by hadronic interactions

Proton beam is flat 3% contribution

Horn gives ~10% at high energies



# Uncertainties in predicted $\nu_e$ and $\nu_\mu$ events at HyperK

| | | Flux & ND-constrained cross section | ND-independent cross section | Far detector | Total | T2K2 with ND280 Upgrade |
|---|---|---|---|---|---|---|
| T2K in 2016 | $\nu$ mode | 3.0% | 3.9% | 2.5% | 5.5% | ~4.5% |
| | $\bar{\nu}$ mode | 3.3% | 4.2% | 3.1% | 6.8% | ~5.5% |
| arXiv:1805.04163 HK Design Report | $\nu$ mode | 3.0% | 0.5% | 0.7% | 3.2% | HyperK goals |
| | $\bar{\nu}$ mode | 3.2% | 1.5% | 1.5% | 3.9% | |

- INGRID error on beam direction is more important for HyperK
- IWCD water Cherenkov measurements transfer some uncertainties from ND-independent to ND-constrained
- Far detector understanding is improved by IWCD information on $E_{rec}$ and by large statistics sample of atmospheric $\nu$
- Statistical errors on appearance are ~3% (see next slide)

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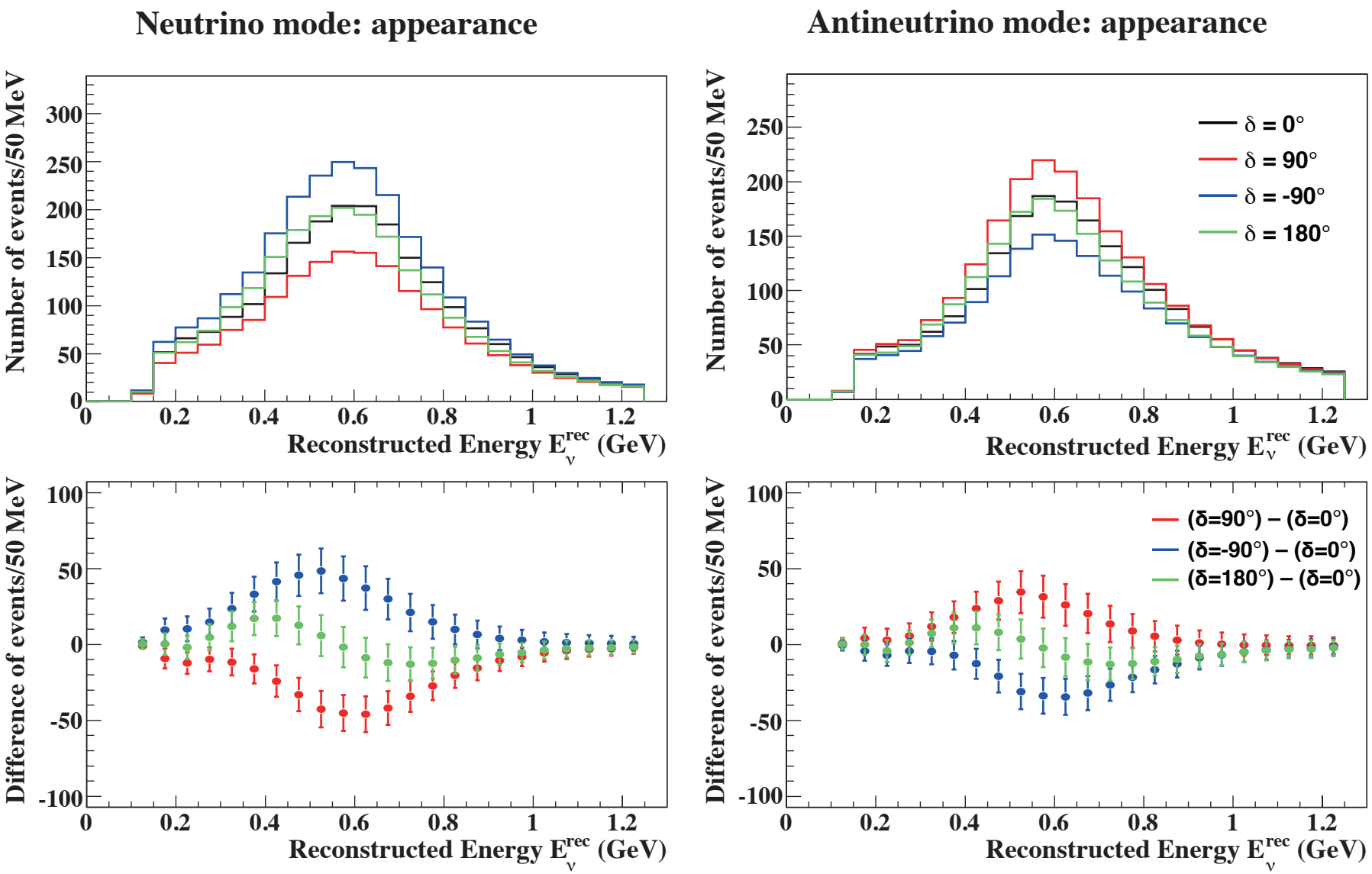
# HyperK statistics after 10 years



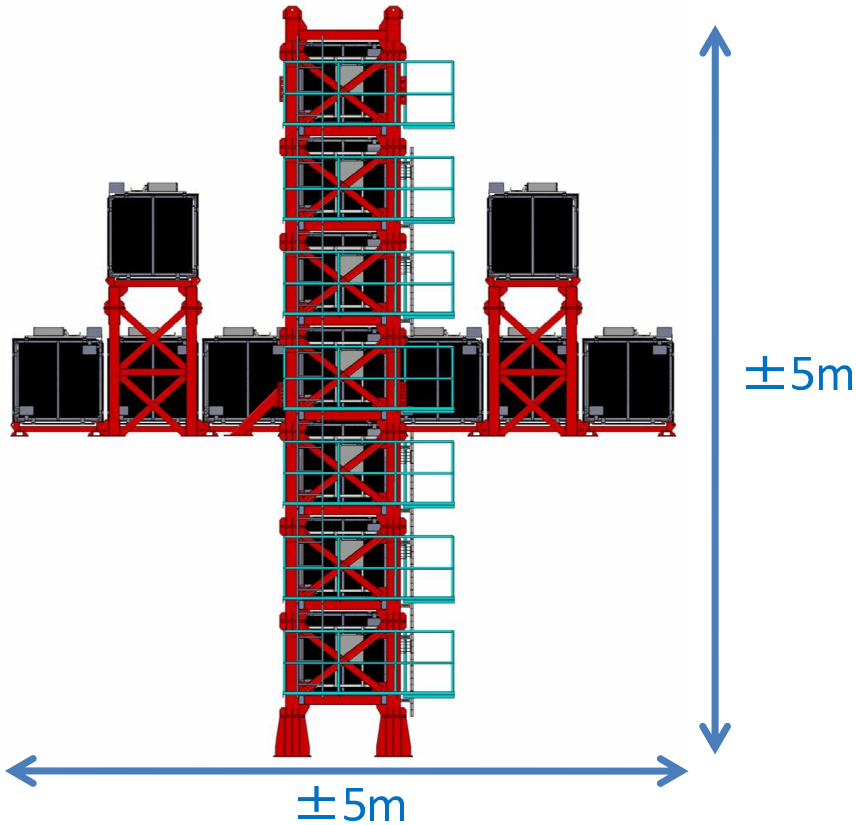
# INGRID on axis detector

Measures H/V beam position

Gives 0.9%(1.7%) systematic
on $\nu$ ($\bar{\nu}$) beam for T2K

Error will increase for HyperK

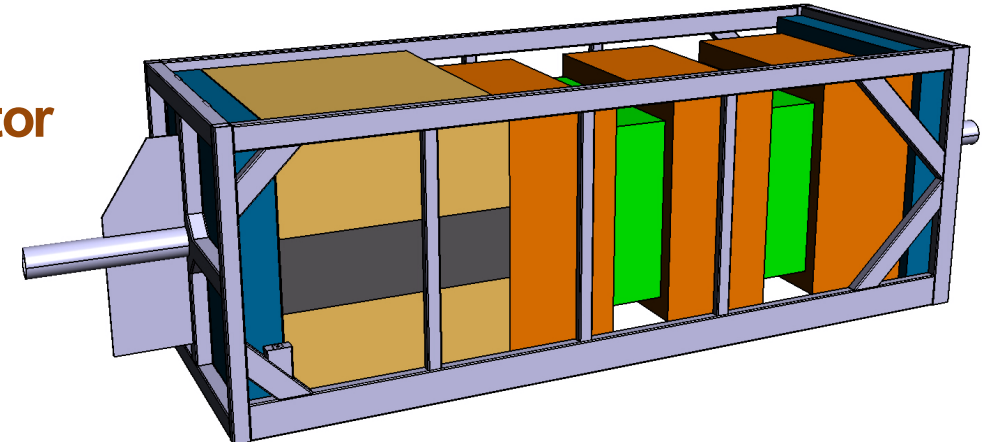
- Beam flux x2 higher.
- Pileup is an issue.
- Detector aging?
- HyperK is not on the same axis as ND280 & SK




Estimate 1.5%(3.6%) systematic
on $\nu$ ($\bar{\nu}$) beam for HyperK, but hope to improve this

# ND280 Upgrade for T2K2

Upgrade ND280
**Scintillator Detector**
**High Angle TPCs**



Existing ND280
Fine-grained Detectors
Tracking TPCs

| Parameter | Current ND280 (%) | Upgrade ND280 (%) |
|---|---|---|
| SK flux normalisation | 3.1 | 2.4 |
| $(0.6 < E_\nu < 0.7$ GeV) | | |
| $MA_{QE}$ (GeV/c$^2$) | 2.6 | 1.8 |
| $\nu_\mu$ 2p2h normalisation | 9.5 | 5.9 |
| 2p2h shape on Carbon | 15.6 | 9.4 |
| $MA_{RES}$ (GeV/c$^2$) | 1.8 | 1.2 |
| Final State Interaction ($\pi$ absorption) | 6.5 | 3.4 |

Overall errors on $\nu_\mu$ flux x $\sigma$ reduced from 2.3% to 1.9% by upgrade

# MULTI-PMT MODULE DESIGN

One mPMT module design being considered: