Future (Long Baseline) Neutrino Near Detectors

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International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN 2019)

November 7-9 2019, Medellín, Colombia

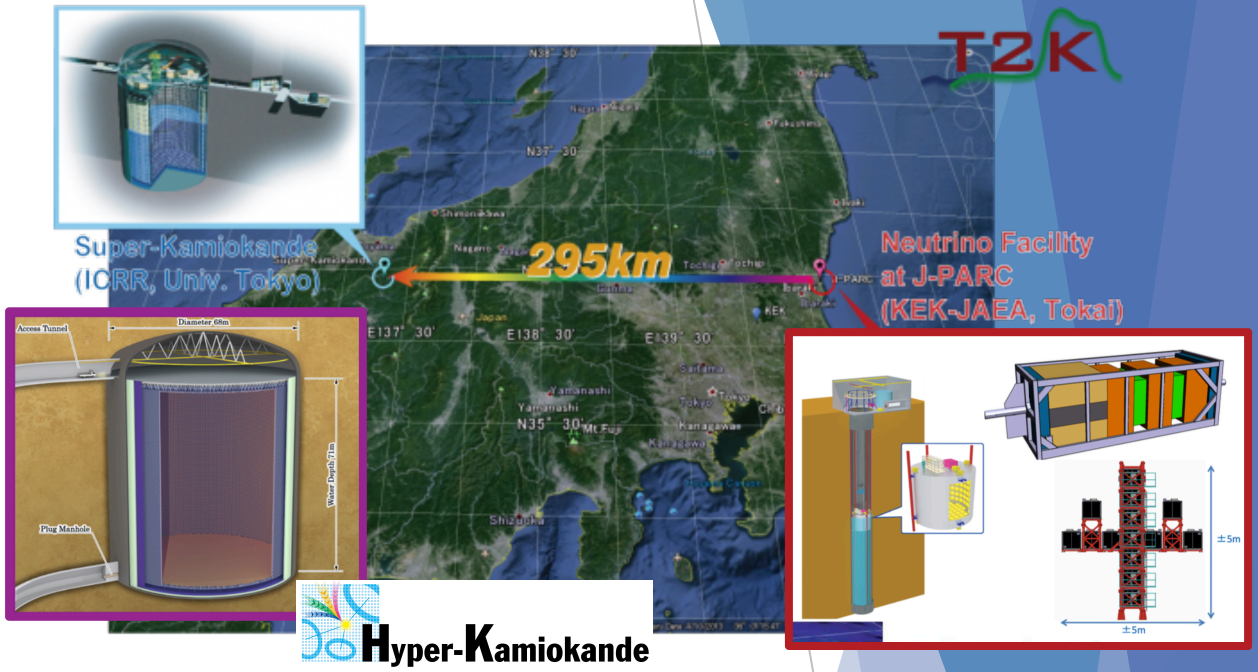
Motivation

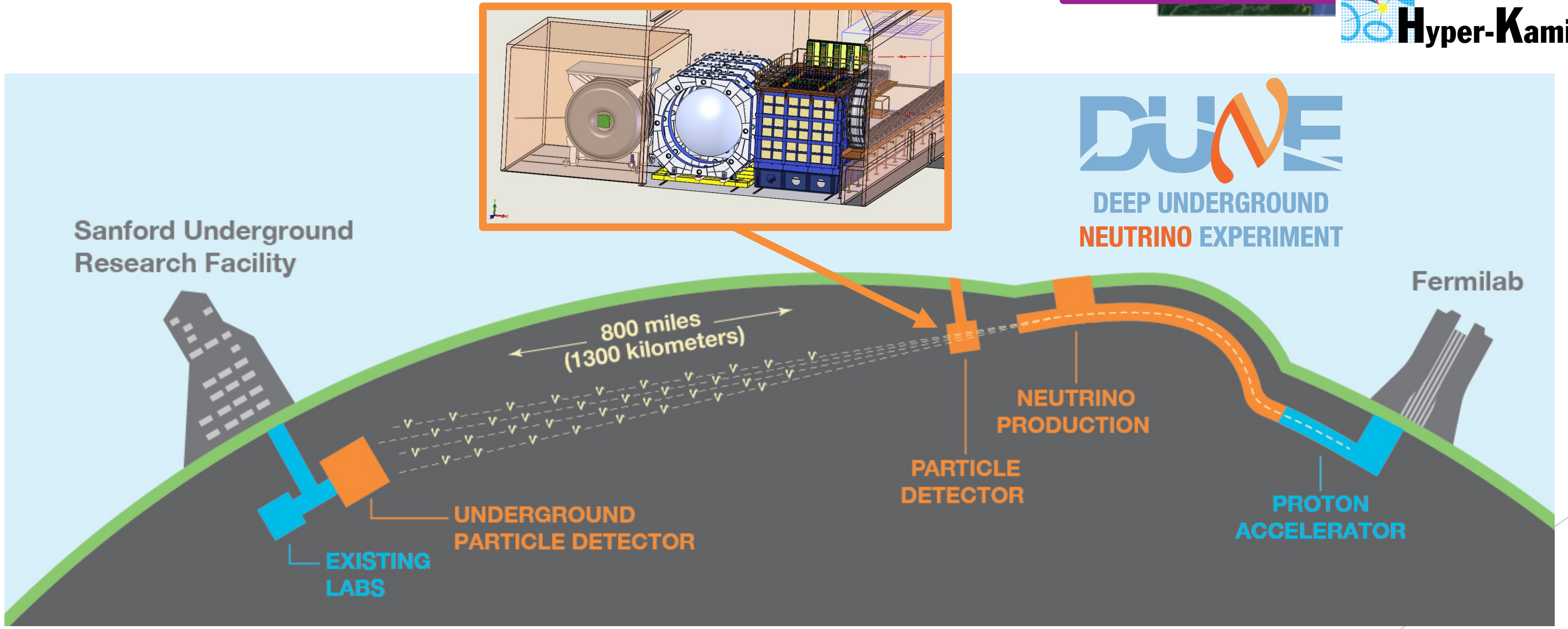
- In long-baseline neutrino oscillation experiments, near detectors play an essential role in:
  - Characterizing the intensity and energy spectrum of the neutrino beam, prior to modification by oscillations
  - Precisely measuring the flavor composition of the (anti)neutrino beam
  - Reducing systematic uncertainties by measuring event rates, kinematics, and cross sections
- These detectors also enable a rich physics program beyond long baseline oscillations:
  - Measurement of neutrino interaction cross sections and nuclear effects on multiple target nuclei
  - Sensitivity to Beyond Standard Model (BSM) physics, e.g., non-standard interactions, sterile neutrinos, dark photons, heavy neutral leptons, other exotic particles, and dark matter

Physics Opportunities in the Near DUNE Detector hall (PONDD) workshop: https://indico.fnal.gov/event/18430/

Future long-baseline neutrino experiment near detectors

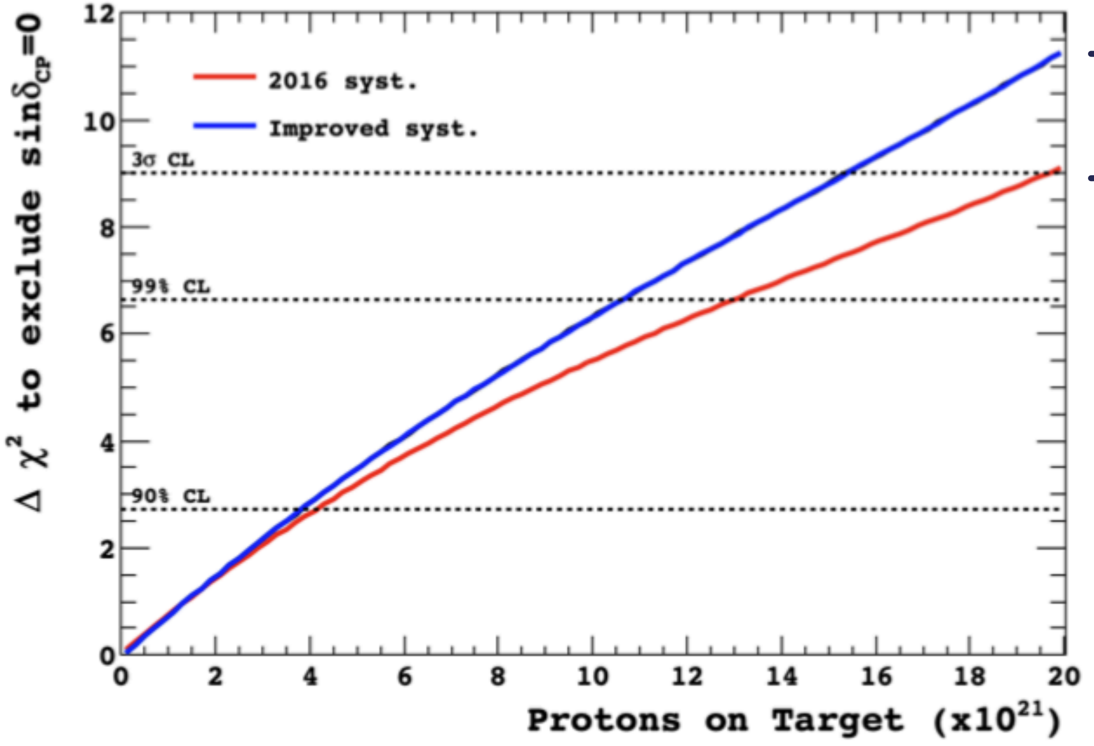
- T2K-II (upgrade of near detector)
- Hyper-Kamiokande
- DUNE





T2K → T2K-II

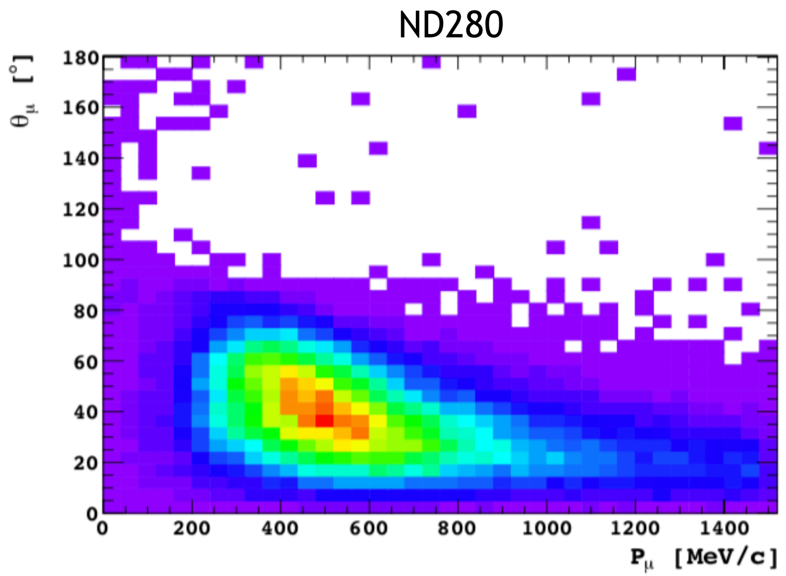
- T2K will reach its approved 7.8×10^{21} POT by 2021
- T2K-II is proposed to extend the T2K run to collect $>10 \times 10^{21}$ POT by 2025 (Phase-I approval received)
  - Goal: exclude CP conservation at 3σ for a large range of δ_{CP} values, if neutrino mass ordering is known
  - With higher statistics, physics reach is enhanced by reducing systematic uncertainties from current level (~6%) to 4% or lower → requires upgrades to near detector



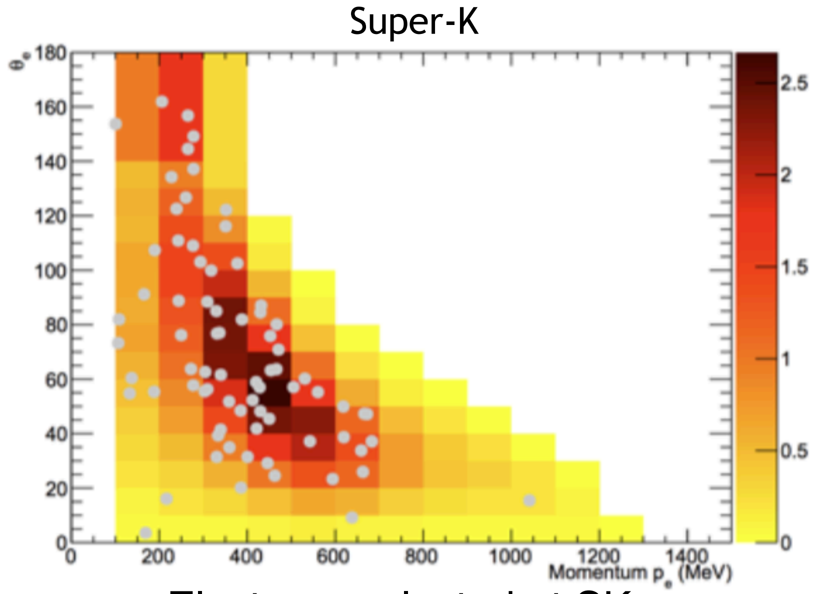
Expected sensitivity improvement for maximal CP violation ($\delta_{CP} = -\pi/2$) and normal mass ordering

T2K-II (ND280 Upgrade)

- One of the main limitations of the T2K ND280 data used in oscillation analyses so far is that they mainly cover the forward region, while the far detector (Super-K) has 4π acceptance
  - Introduces model dependencies when extrapolating to the full phase space
  - Neutrino-nucleus cross sections are not well known → need near detector upgrades to reduce associated systematic uncertainties



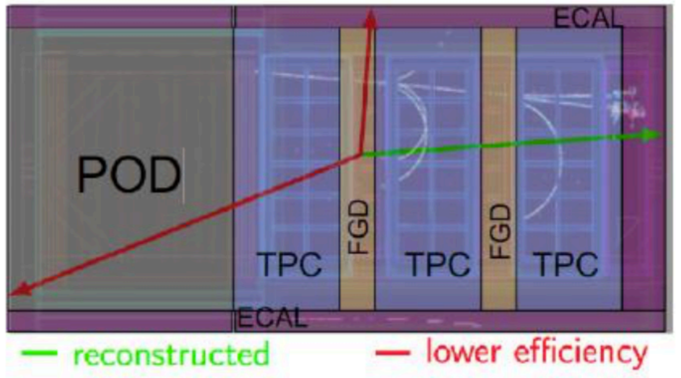
Muons selected at ND280



Electrons selected at SK

ND280 Upgrade

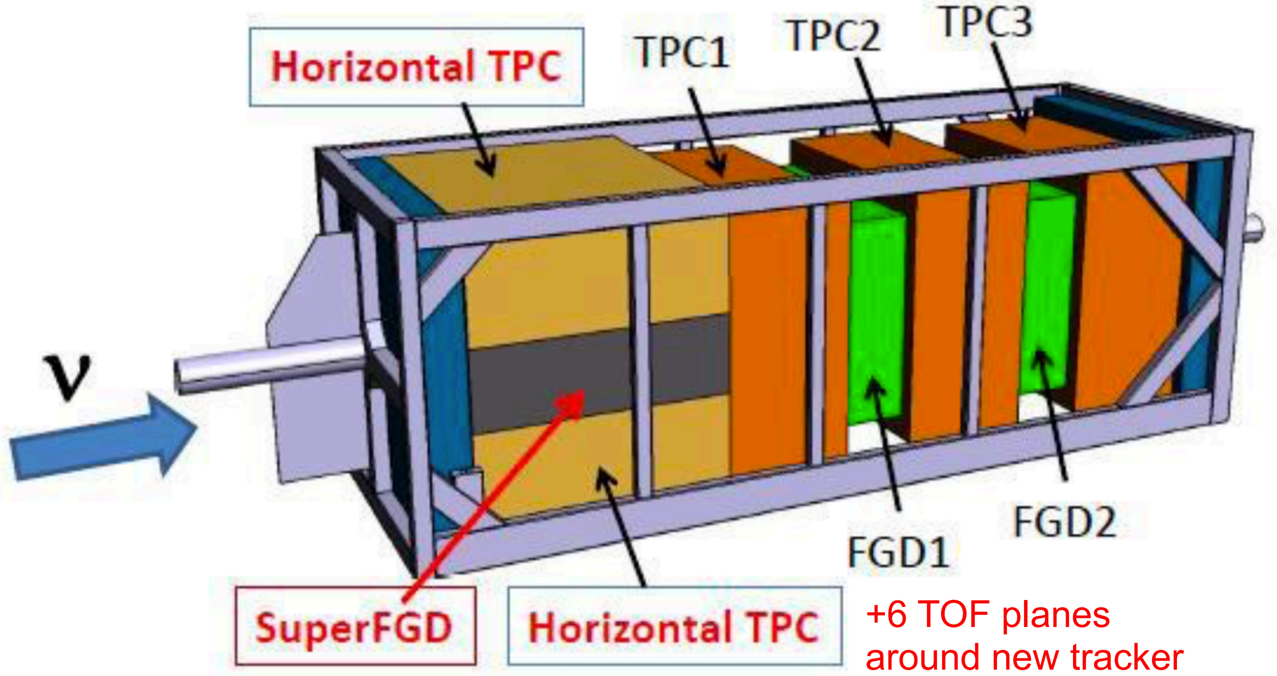
Current ND280



Good acceptance only for forward-going tracks

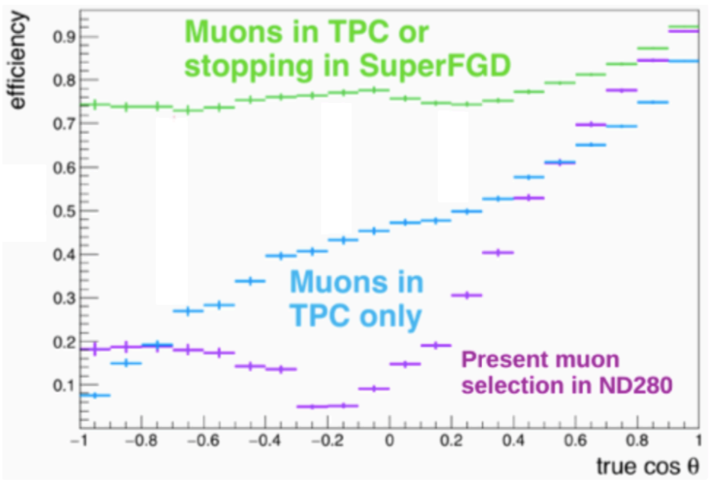
Replace P0D

Upgraded ND280

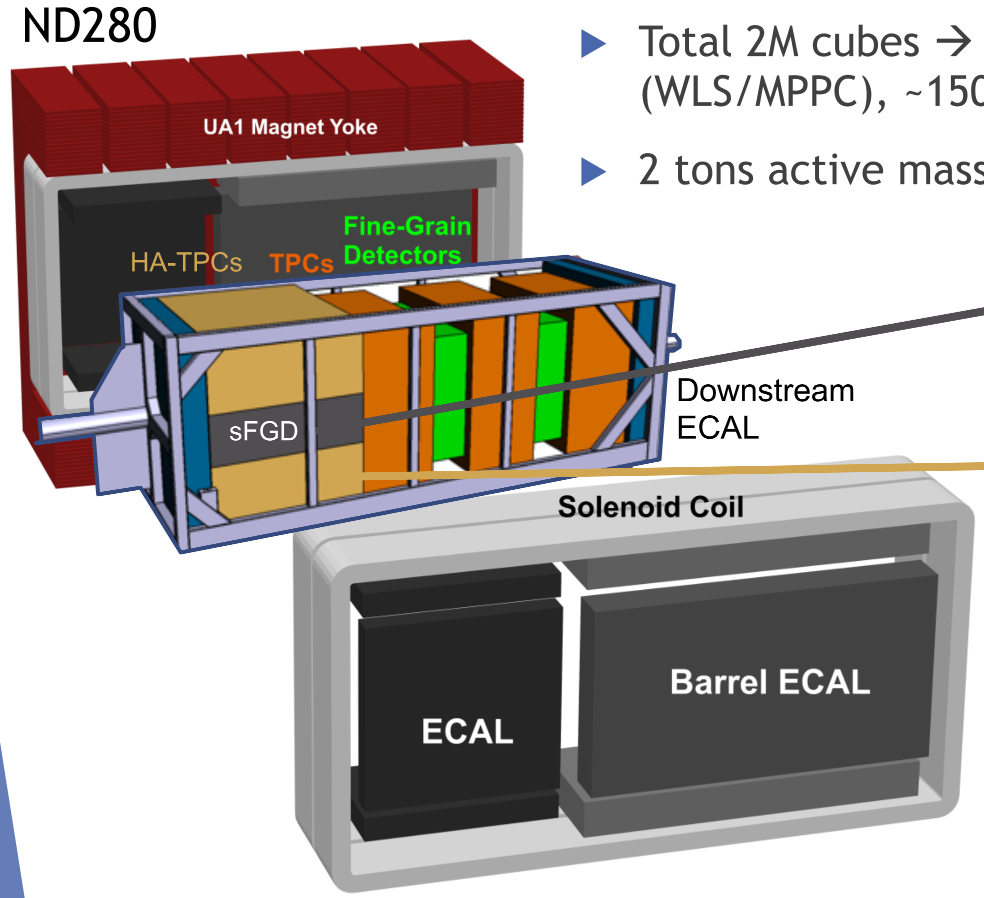


See arXiv:1901.03750 [physics.ins-det] for more details

- Measure neutrino interactions over full phase space
- Improve
  - Detection of low energy protons and pions (reduce threshold)
  - Electron/gamma separation
  - Measurement of neutrons in antineutrino interactions
- Reduce backgrounds (better track ID using TOF)



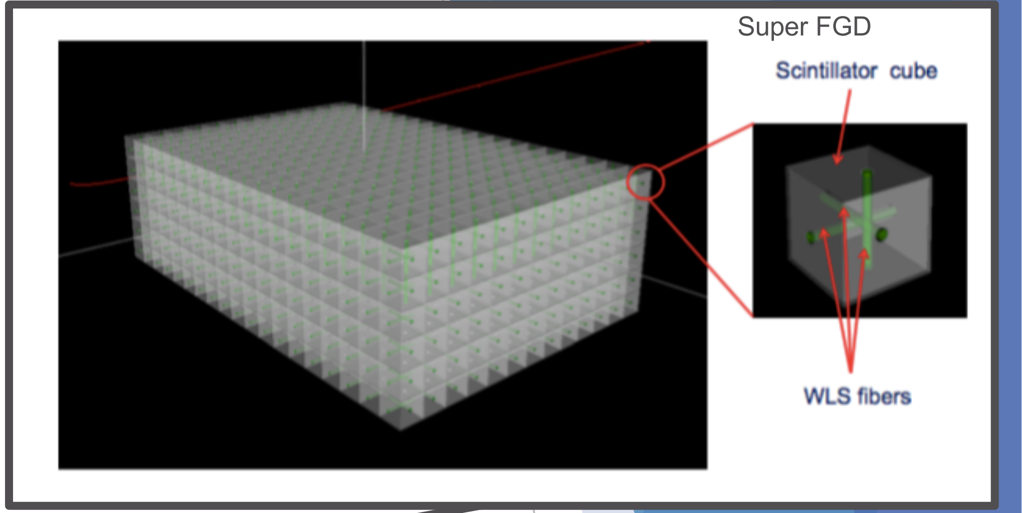
ND280 Upgrade Details



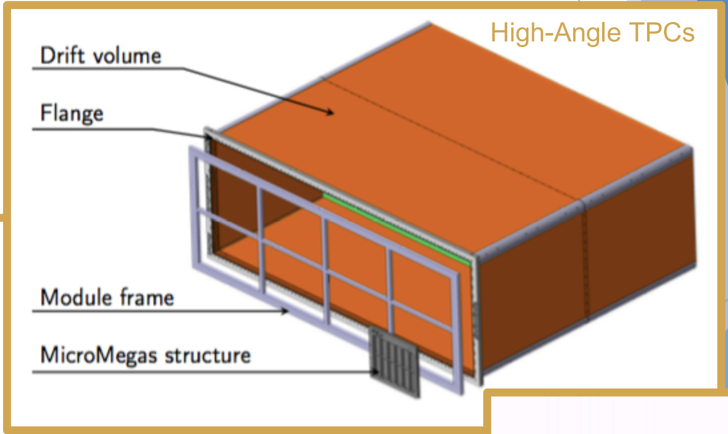
Super Fine Grained Scintillator Detector

- 200 x 200 x 60 cm^3 volume
- 1 x 1 x 1 cm^3 scintillator cubes with 3 orthogonal fibers for 3D readout
  - Injection molding, chemical reflector cover
- Total 2M cubes → 60k readout channels (WLS/MPPC), ~150ps timing resolution
- 2 tons active mass

JINST 13 (2018) 02006

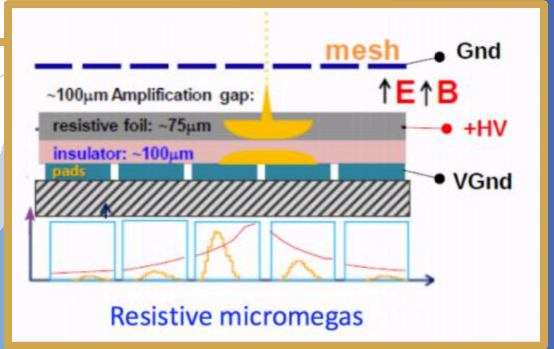


arXiv:1901.03750 [physics.ins-det]



High-Angle TPCs

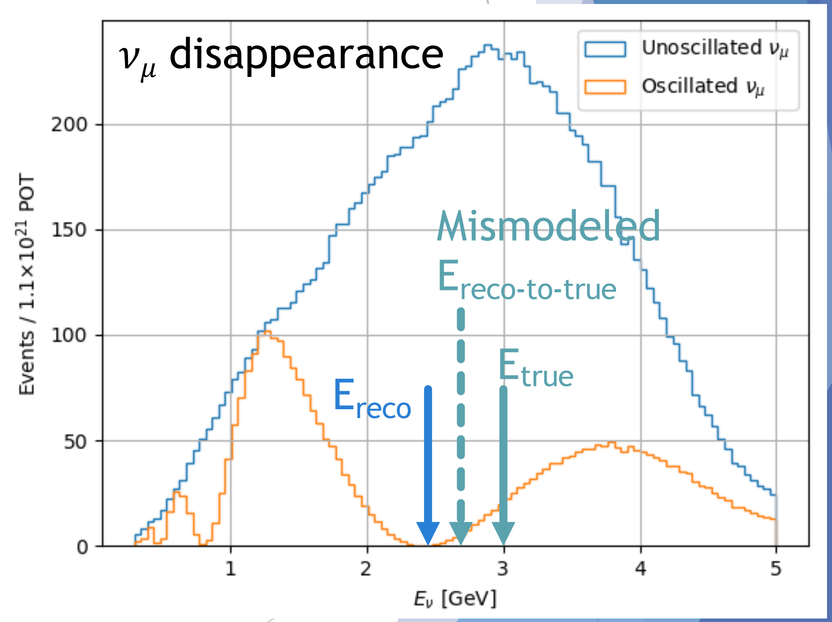
- Resistive bulk Micromegas
- Charge-sharing → lower pad density
- No spark protection needed



Next Generation: DUNE & Hyper-K
A need for even better detectors and techniques

$$\frac{dN_\nu^{\text{det}}}{dE_{\text{rec}}} = \int \underbrace{\phi_\nu^{\text{det}}(E_\nu)}_{\text{Flux}} \cdot \underbrace{\sigma_\nu^{\text{target}}(E_\nu)}_{\text{Cross section}} \cdot \underbrace{T_{\nu_\mu}^{\text{det}}(E_\nu, E_{\text{rec}})}_{\text{Detector response}} \, dE_\nu$$

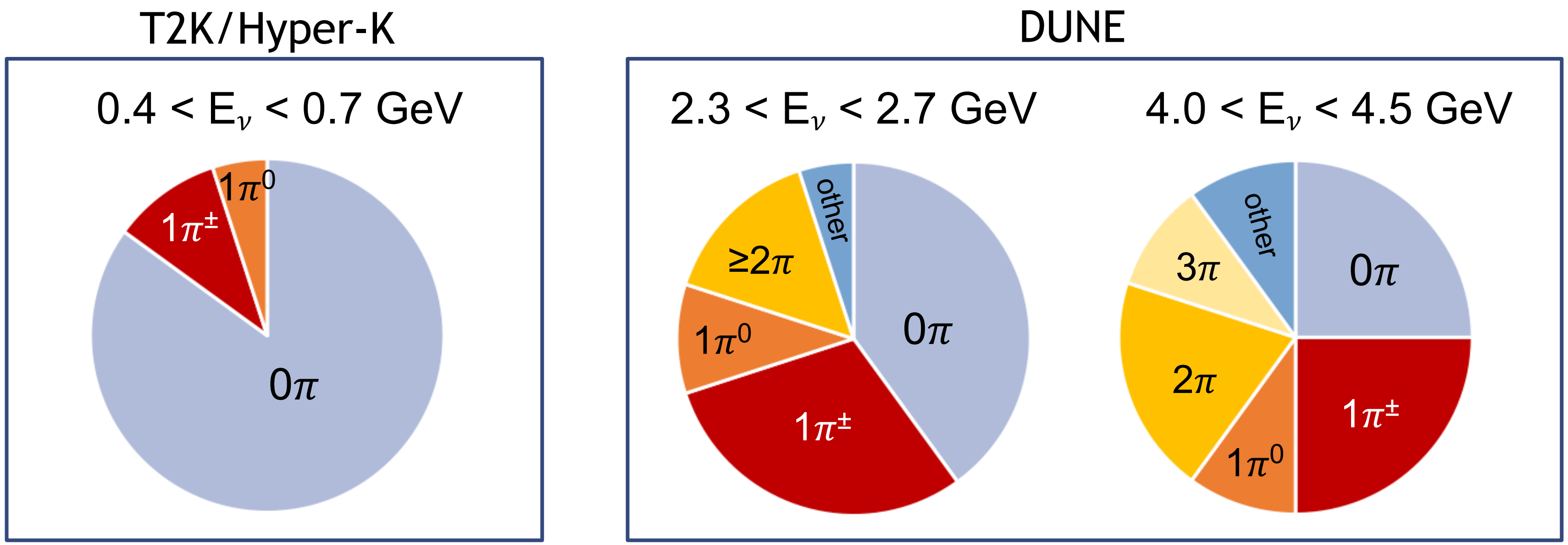
- Detectors measure flux times cross section, with smearing, biases, and inefficiencies due to detector effects
  - In reality, we cannot factorize flux, cross section, and detector response – there are no simple cancellations
  - Fluxes at near and far detectors differ
  - Relationship of $E_{reco} \rightarrow E_{true}$ depends on poorly understood neutrino interaction models and on detector response
    - Reconstructed energies can feed down into oscillation dip, biasing measured oscillation parameters



Requires something better than functionally identical near detectors.

Cross section uncertainties

- Impact the final state particles and kinematics → amount of energy visible in the detector
- CC0π modeling uncertainties have been significantly reduced in recent years, thanks to a lot of theoretical work
  - But still large uncertainties in 1π, 2π, DIS, nuclear effects, etc.

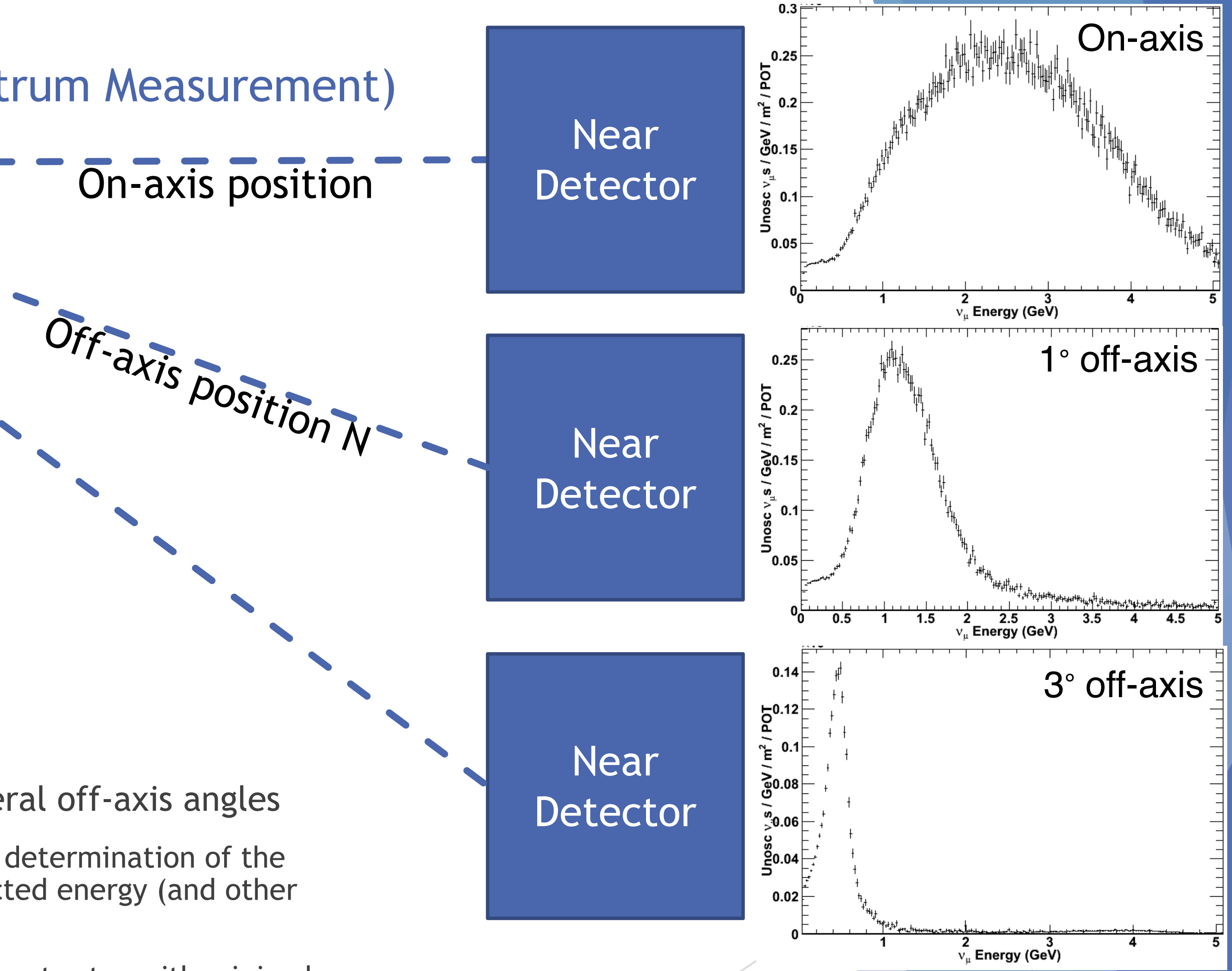


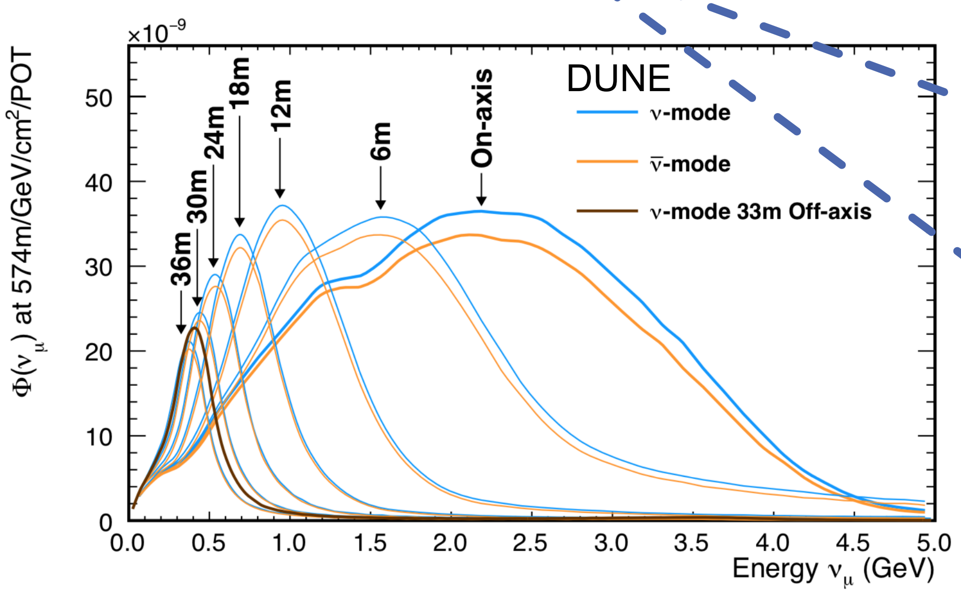
- At typical T2K/Hyper-K neutrino energies, most (~85%) events do not have pions
- By contrast, at DUNE energies, pions are created in a *large fraction of events*

Need highly capable near detectors and a way to disentangle flux, cross sections, and detector response.

PRISM

(Precision Reaction Independent Spectrum Measurement)



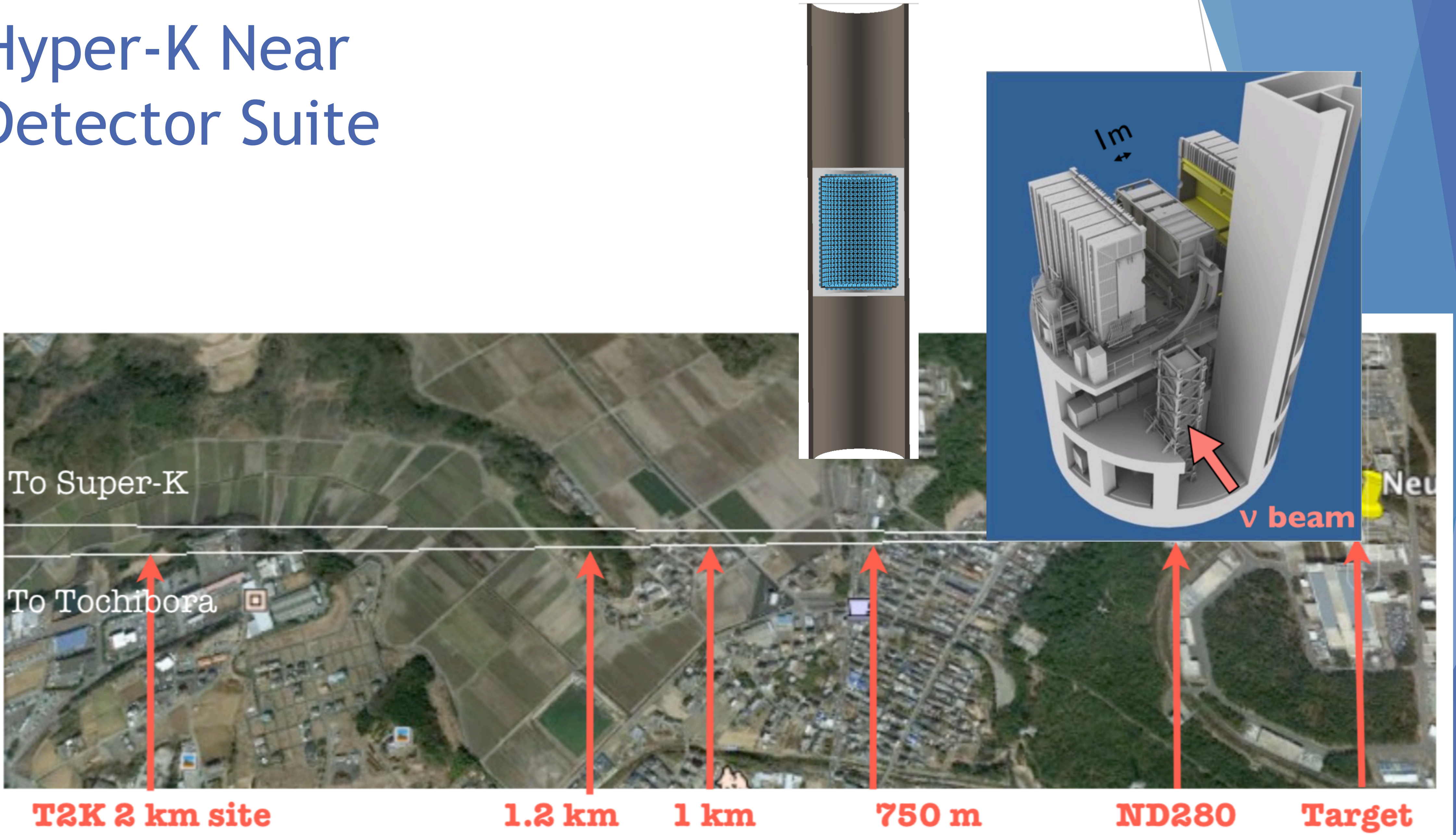


- New technique: PRISM
  - Use near detector data collected at several off-axis angles
    - Narrow energy bands allow experimental determination of the relationship between true and reconstructed energy (and other observables)
    - Data-driven predictions of far detector event rates with minimal cross section model dependence
  - Just need a movable near detector!

Next-Generation Near Detector Needs

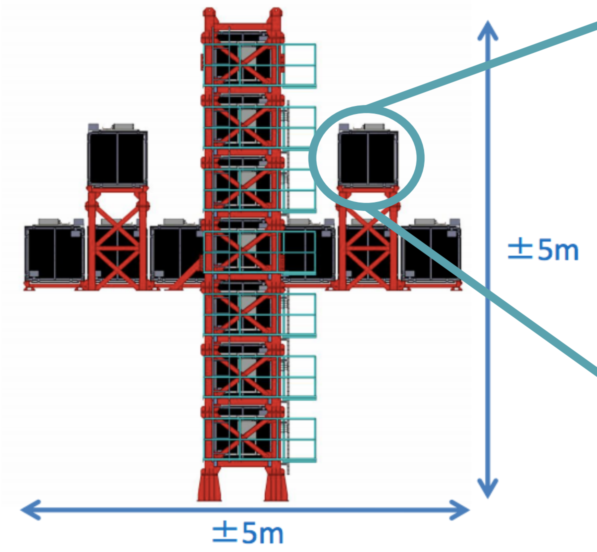
- Monitor beam direction and stability on-axis
- Measure details of neutrino interactions in as much detail as possible
- Disentangle flux, cross sections, detector effects
- Understand $E_{reco} \rightarrow E_{true}$ relationship

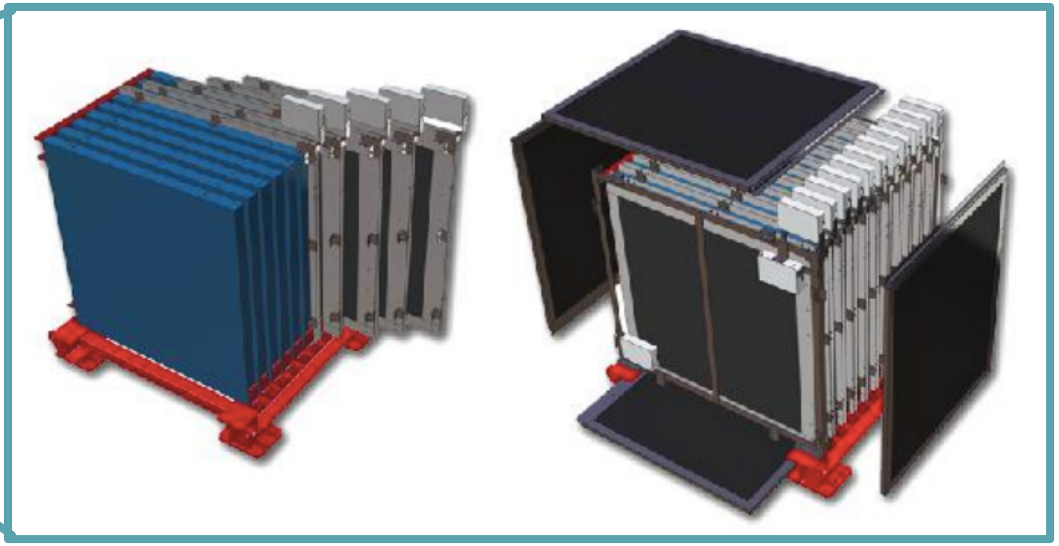
Hyper-K Near Detector Suite



Hyper-K Near Detector Suite

INGRID

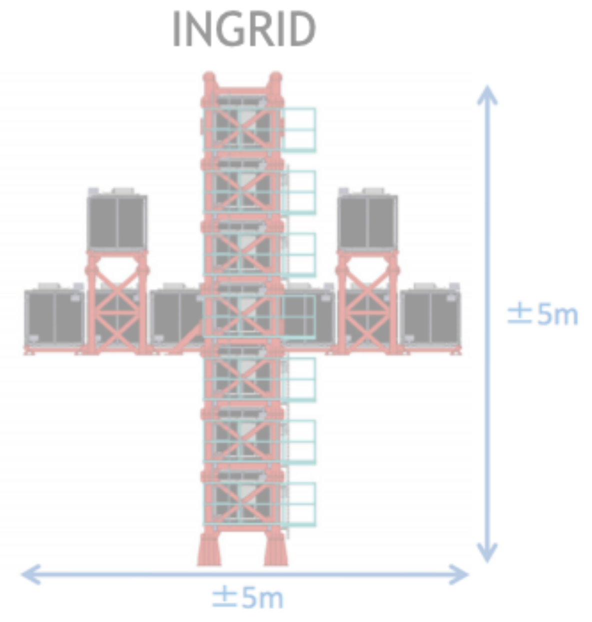


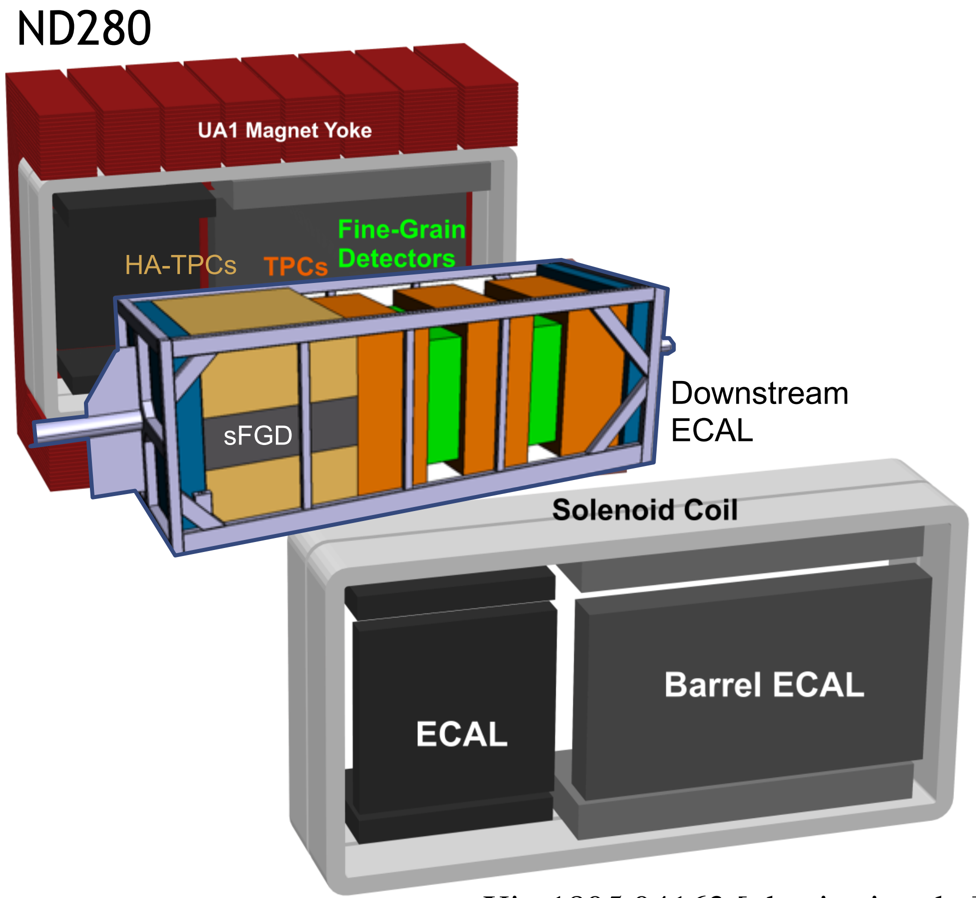


NIM A 694, 211-223 (2012)

- INGRID (exists in T2K, to be upgraded for Hyper-K)
  - On-axis beam direction measurement and beam monitoring
    - Monitor event rate to ensure stable beam operation
    - Measure beam direction with <0.25 mrad accuracy
  - 14 modules: iron + scintillator layers (7 tons target mass per module)

Hyper-K Near Detector Suite

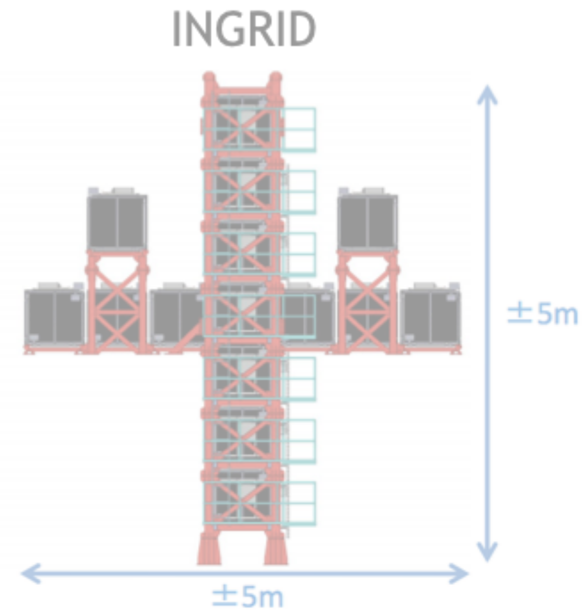


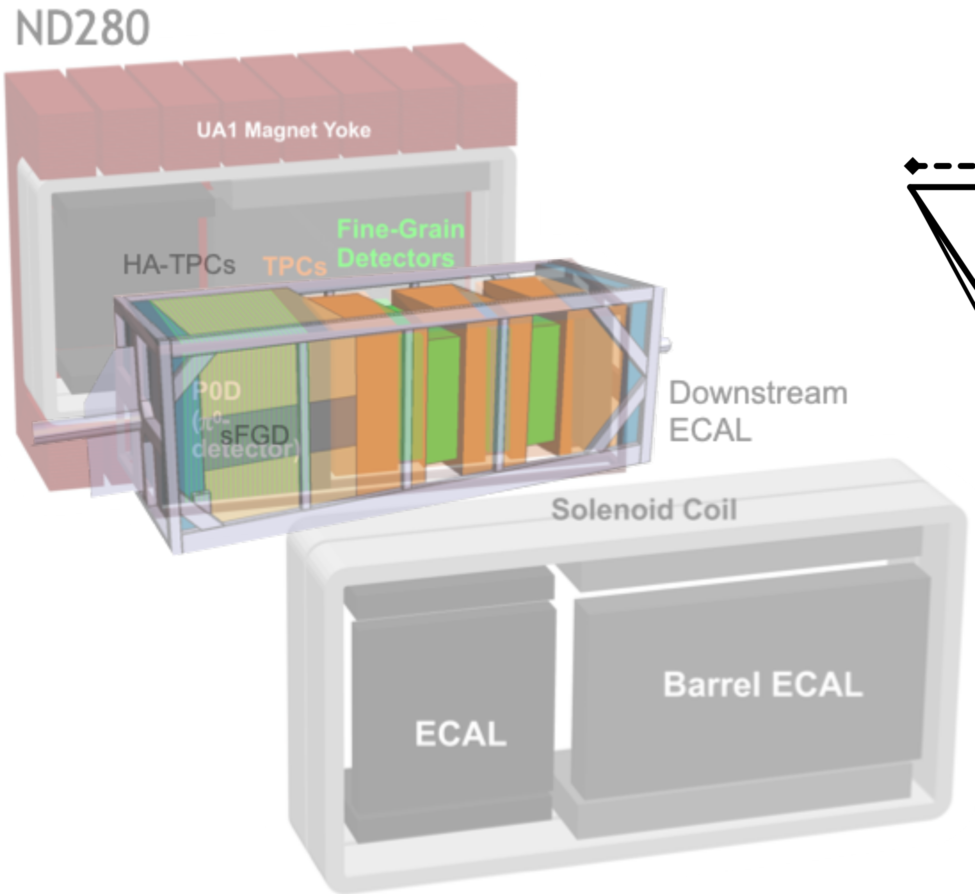


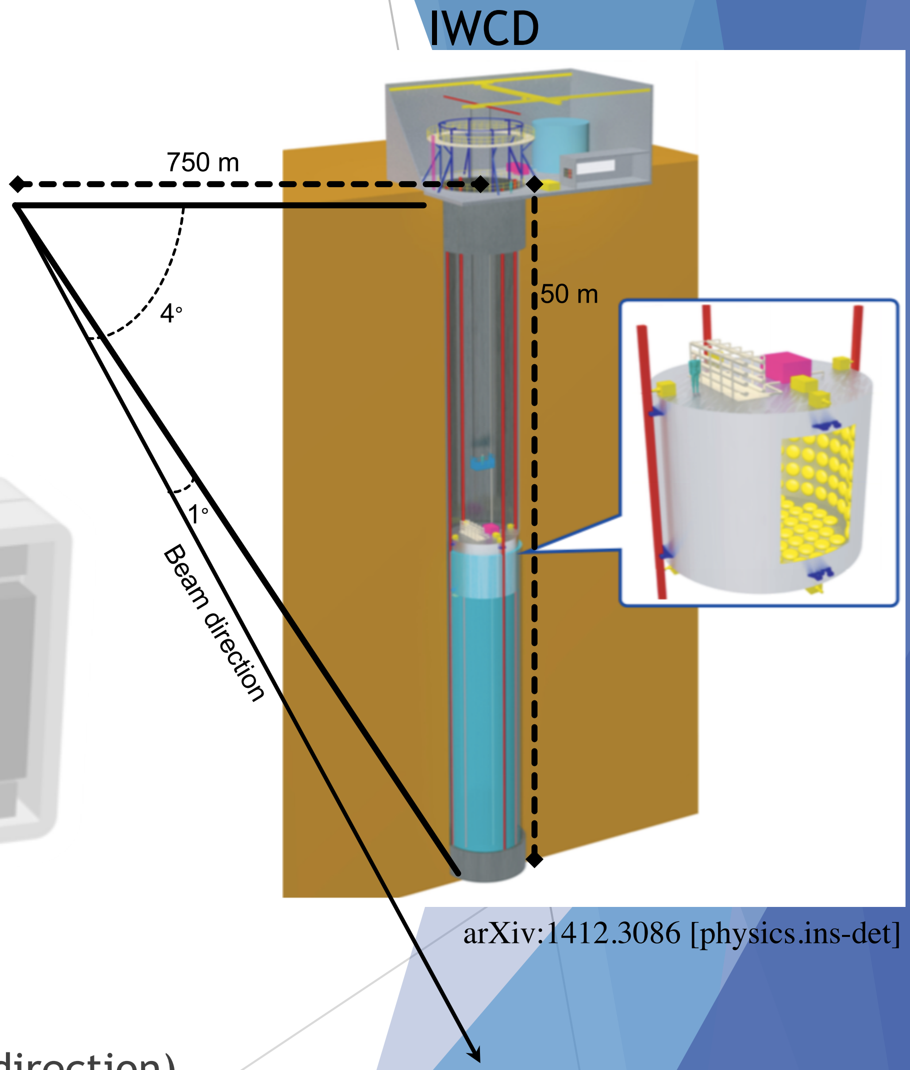
arXiv:1805.04163 [physics.ins-det]

- INGRID
- ND280
  - Off-axis magnetized tracker
  - Charge separation (measure wrong-sign component of beam) & study of hadronic recoil system
  - Detector will be well understood from operation in T2K-II, but additional upgrades likely

Hyper-K Near Detector Suite



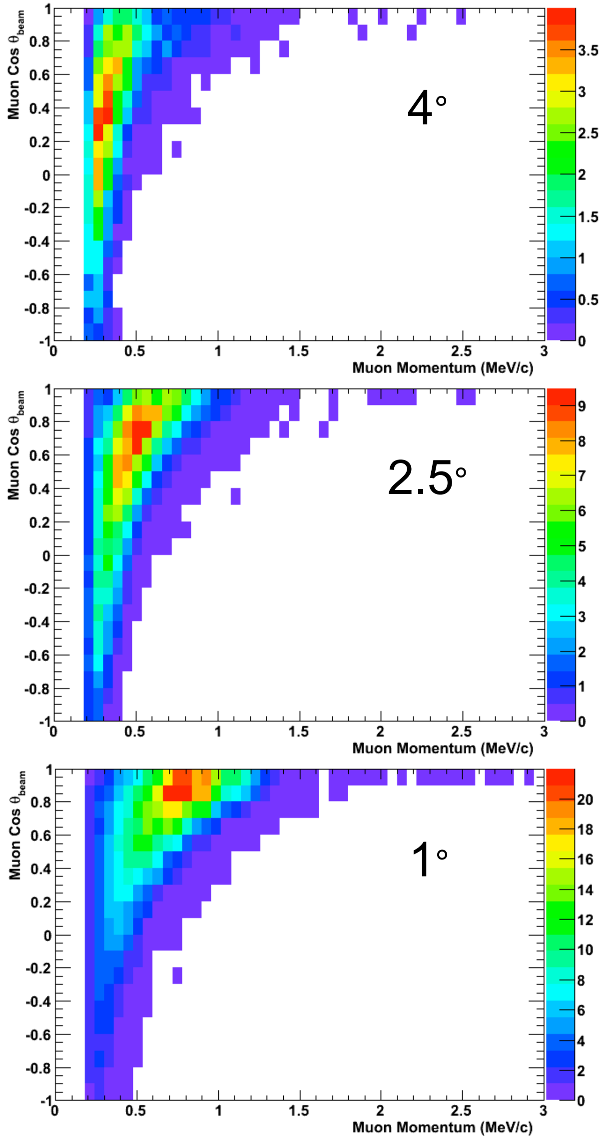


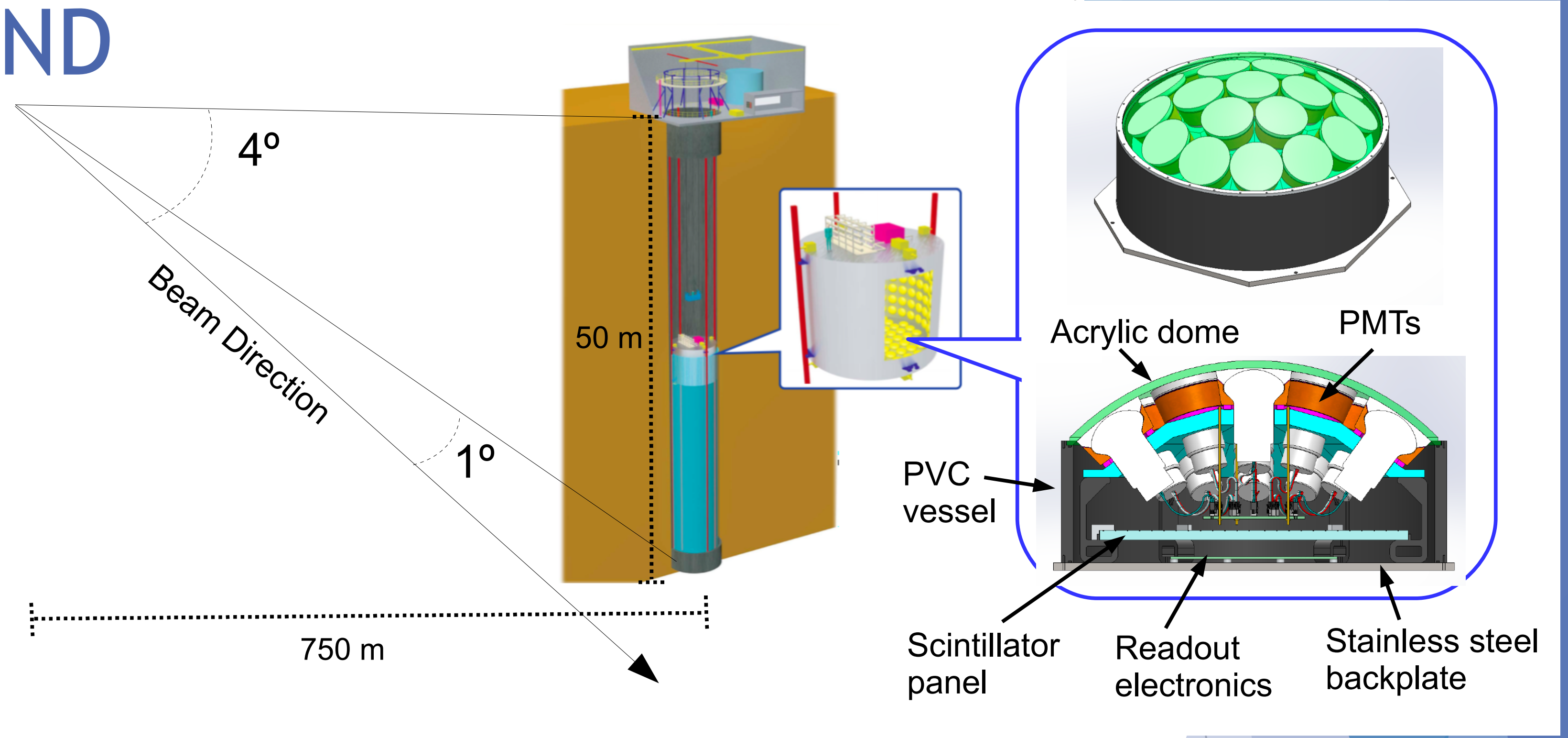


arXiv:1412.3086 [physics.ins-det]

- INGRID
- ND280
- Intermediate Water Cherenkov Detector (IWCD)
  - PRISM concept: spans a range of off-axis angles (1°→4° from beam direction)

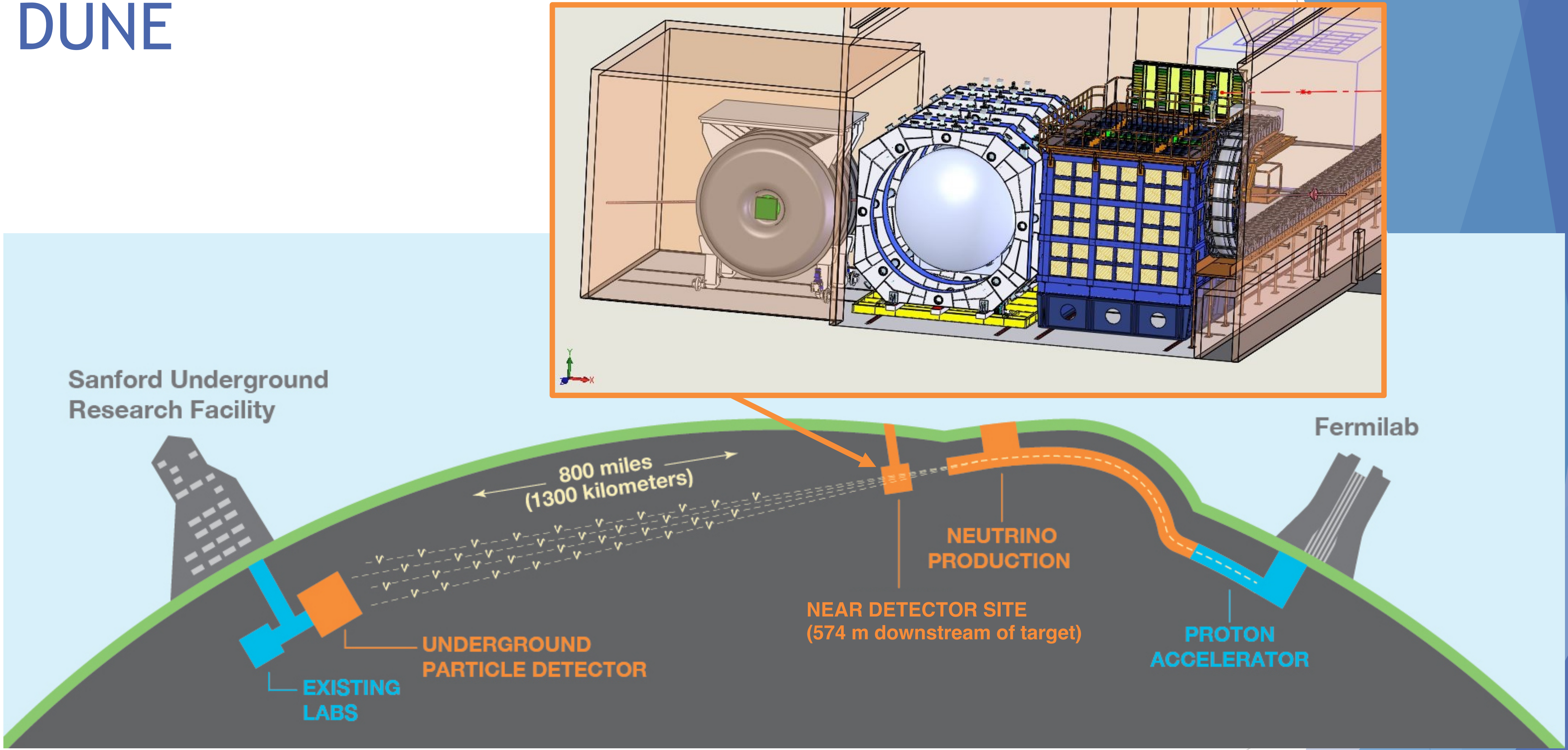
PRISM at Hyper-K ND



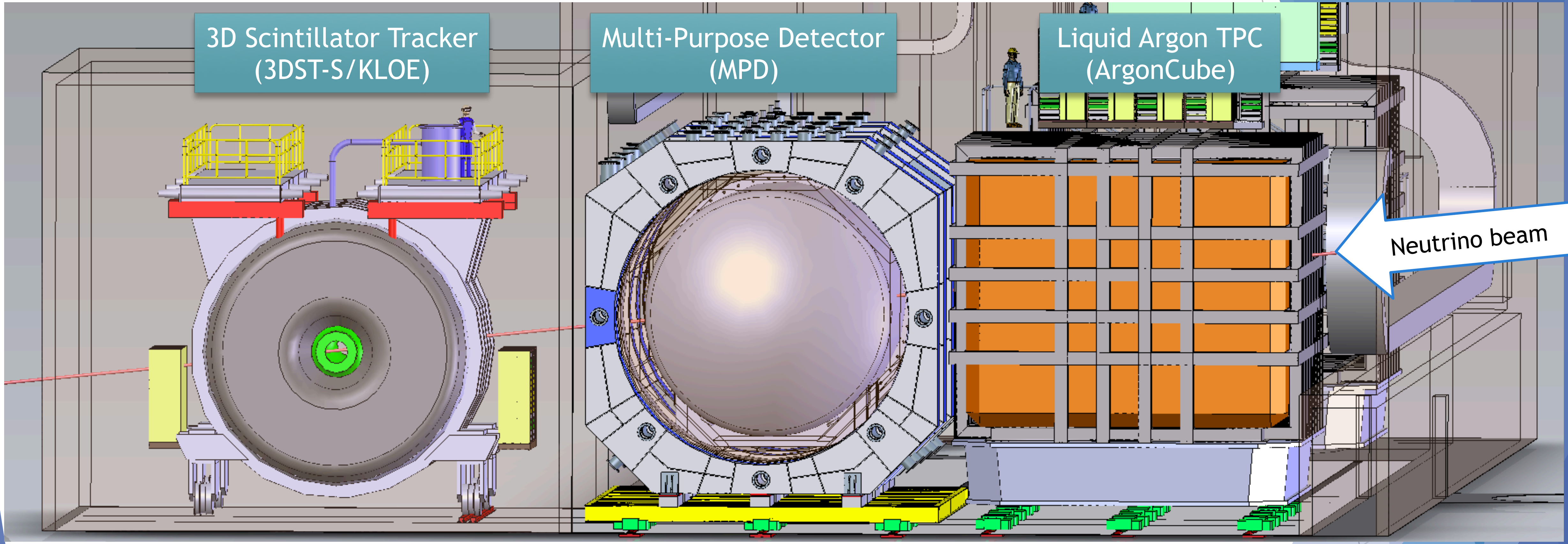


- Neutrally buoyant detector can be moved to different off-axis positions by changing water level in shaft
- 1-kton scale WC detector (dimensions) located 750m from target
  - Multi-PMT photosensors with excellent spatial (80 mm) and timing (1.6 ns FWHM) resolution
  - Same target nucleus (water) as far detector
- Possibility to load water with Gd for neutron multiplicity measurements

DUNE


Sanford Underground
Research Facility
800 miles
(1300 kilometers)
Fermilab
NEUTRINO
PRODUCTION
NEAR DETECTOR SITE
(574 m downstream of target)
PROTON
ACCELERATOR
UNDERGROUND
PARTICLE DETECTOR
EXISTING
LABS

DUNE Near Detector Suite



Three main detector components, working together:

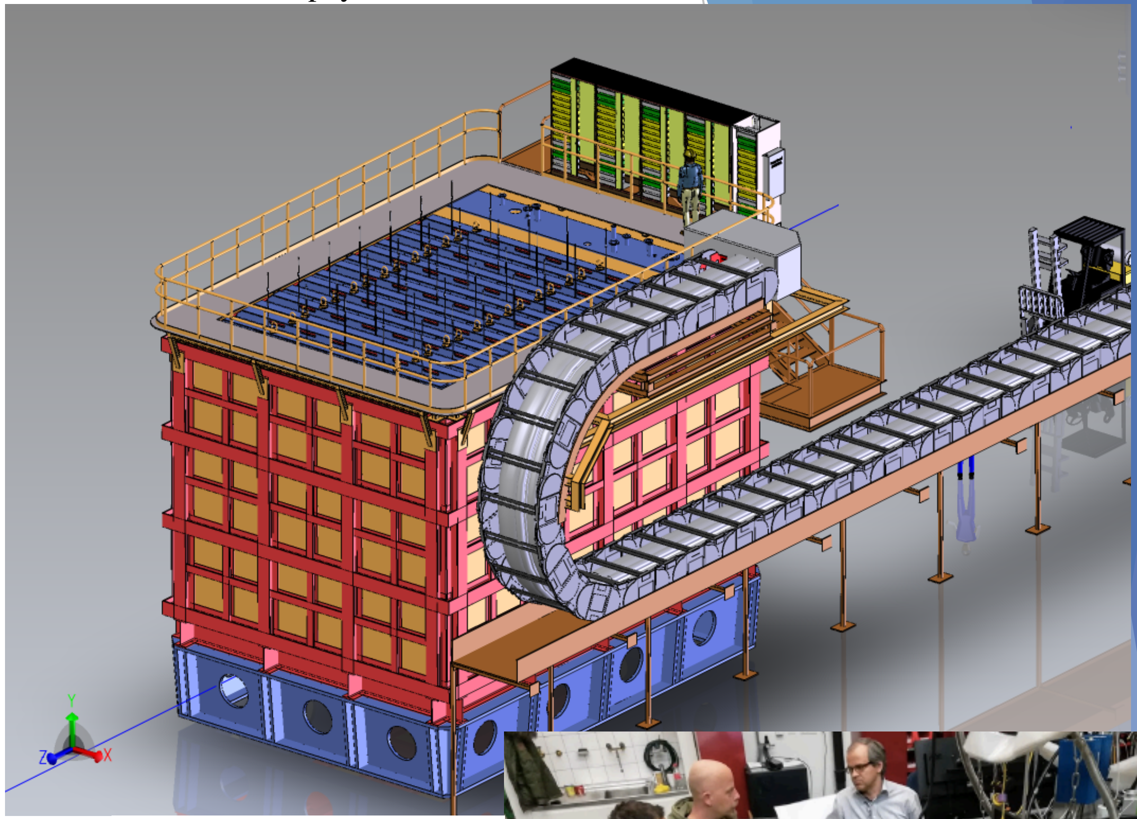
1. Liquid argon detector (ArgonCube)
2. Magnetized downstream tracker with gaseous argon target (MPD)
3. On-axis flux monitor with neutron detection capability (3DST-S+KLOE)

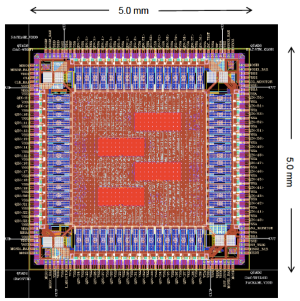
} LAr and GAr systems can move to off-axis fluxes (PRISM)

LArTPC: ArgonCube

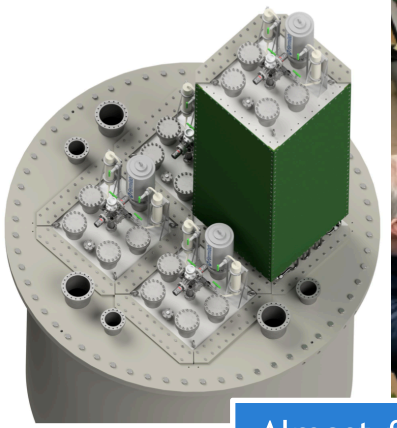
- Modular liquid argon TPC detector
  - 35 modules, each (1m x 1m x 3.5m) w/50cm drift (50kV max HV at cathodes)
  - Pixel readout to accommodate high event rate (>5 interactions/module/spill)
    - 12 million pads (2 billion voxels)
    - Readout via custom-designed low-power ASIC (LArPix)
  - Active volume
    - 5m in beam direction x 3m tall (hadronic shower containment) 7m transverse (eliminates need for side muon catcher)
  - Active mass ~150 tons (50 ton fiducial, 3m x 2m x 6m)

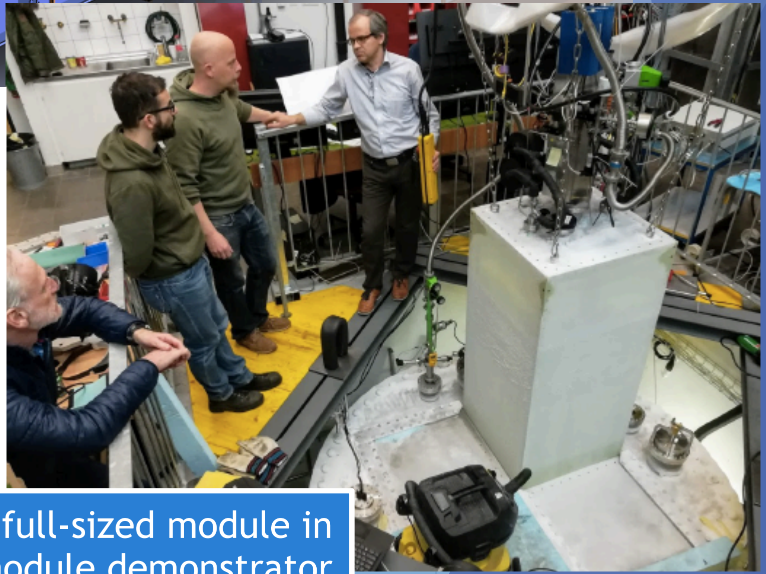
arXiv:1908.10956 [physics.ins-det]





LArPix-v2
64 channels, 25 mm^2

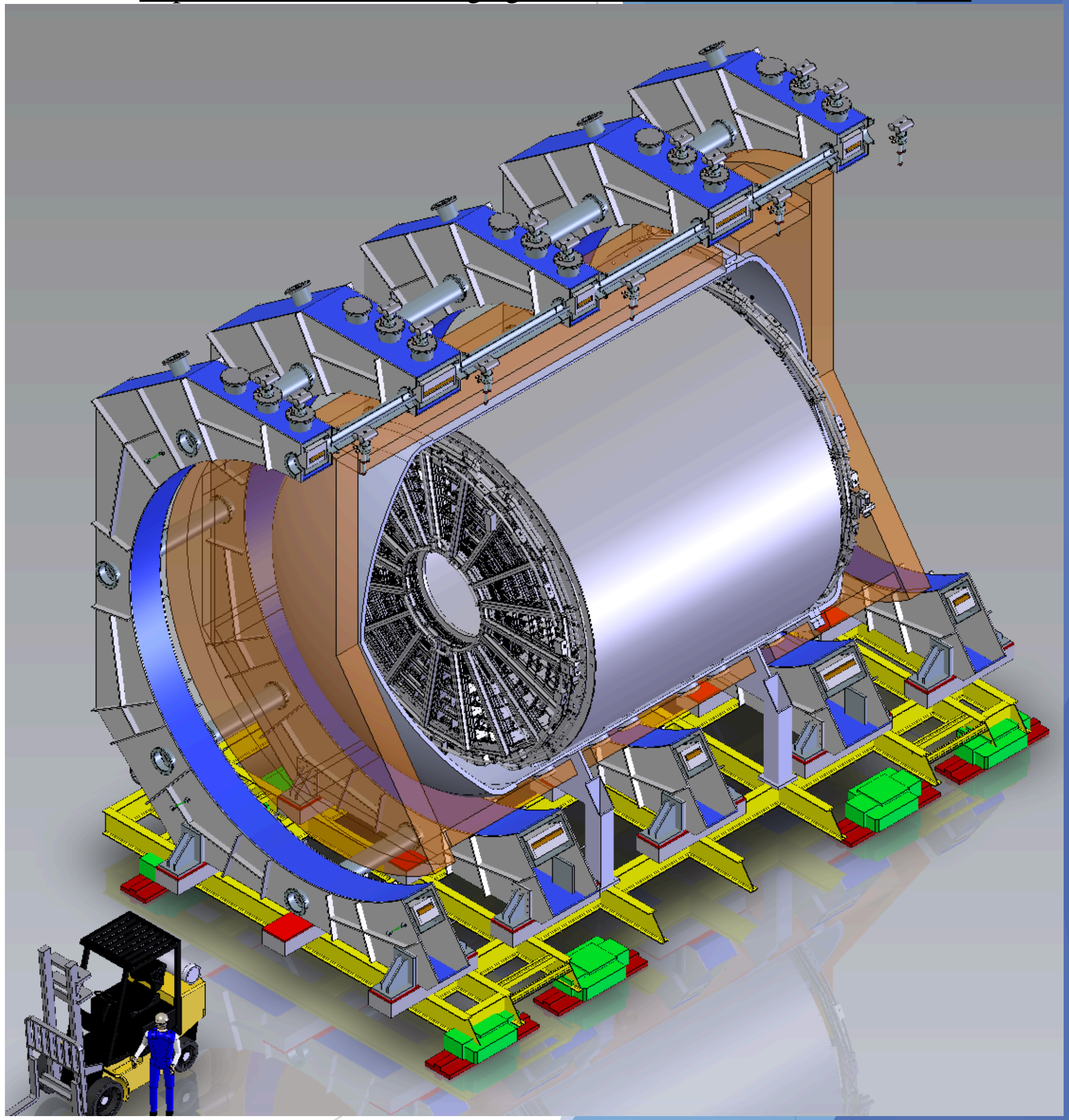




Almost-full-sized module in 2x2 module demonstrator

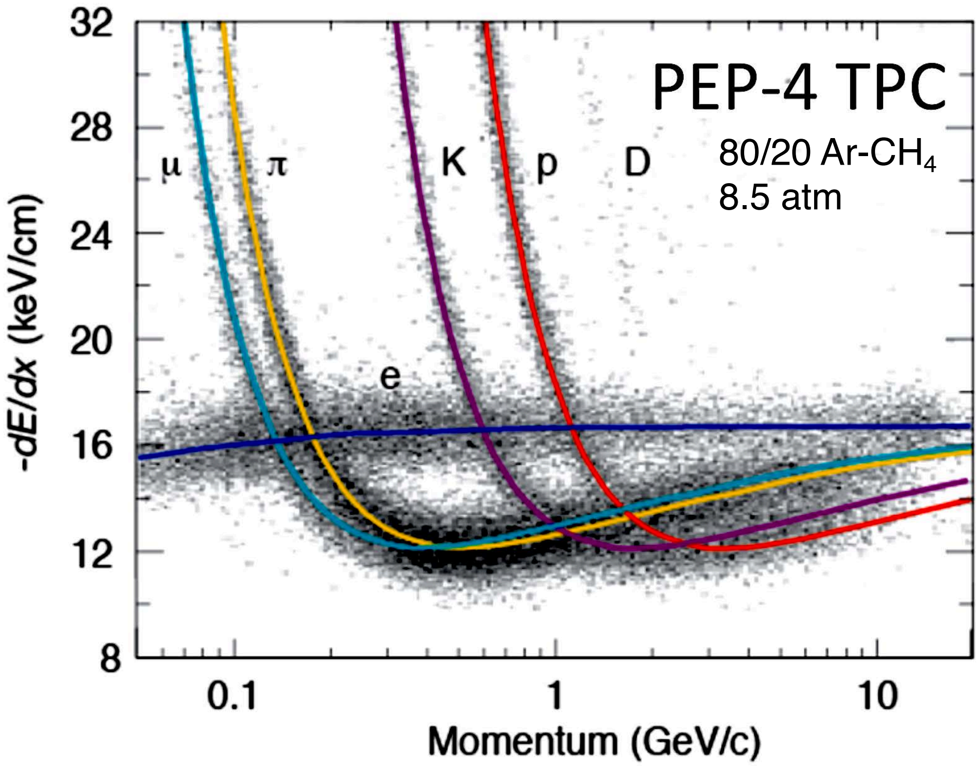
Multi-Purpose Detector (MPD)

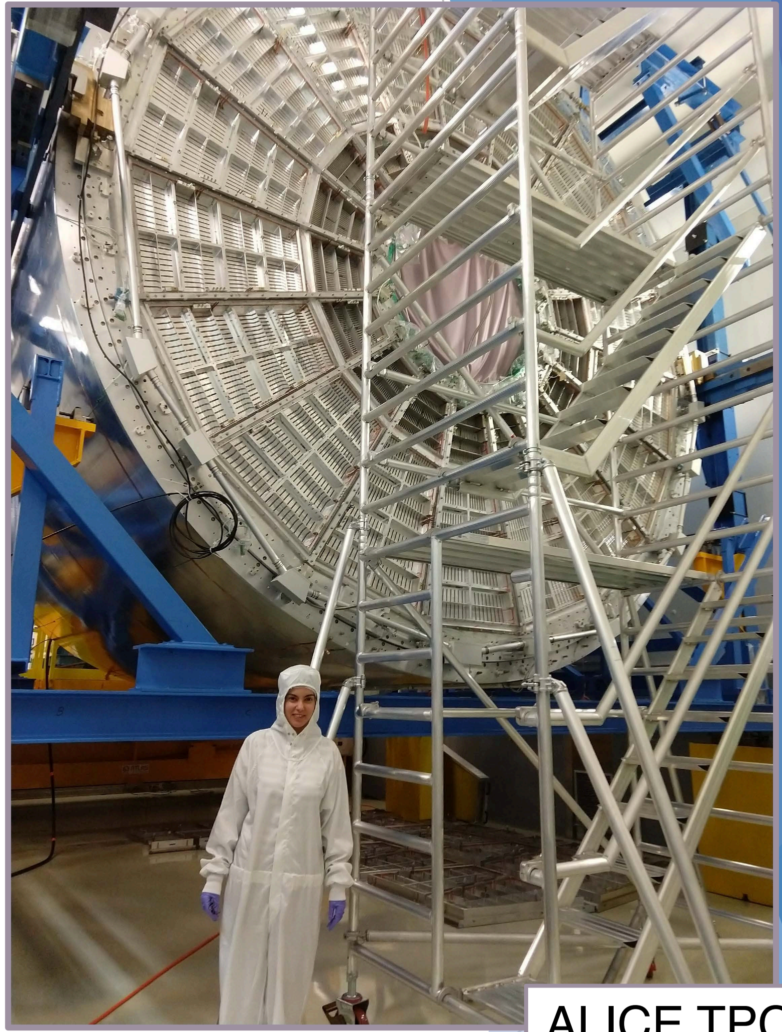
http://docs.dunescience.org/cgi-bin/ShowDocument?docid=12388



- Magnetized high-pressure (10 atm) gaseous argon TPC + surrounding EM calorimeter + muon tagger
  - Gaseous TPC: fully active low-density tracker
  - ECAL: event t_0 + π^0 reconstruction + neutron detection
  - Muon tagger: μ/π separation
  - Open-geometry superconducting magnet (design in progress) with 0.5 T central field
- Provides muon spectrometry for muons leaving LAr
  - LAr event containment
- Provides an independent, statistically significant event sample on Ar gas, with
  - Sign selection and flavor tagging
  - Full 4π coverage
  - Very low tracking thresholds
  - Essentially no secondary interactions

High-Pressure Gas TPC (HPgTPC)

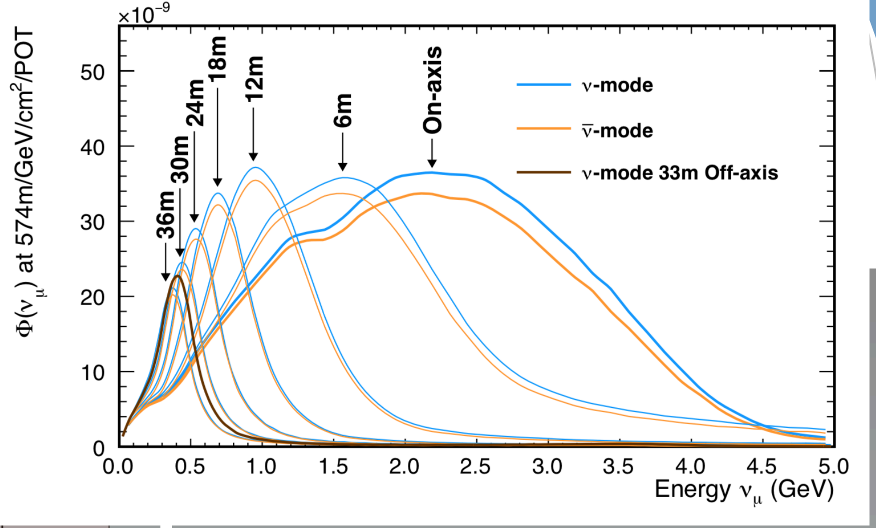




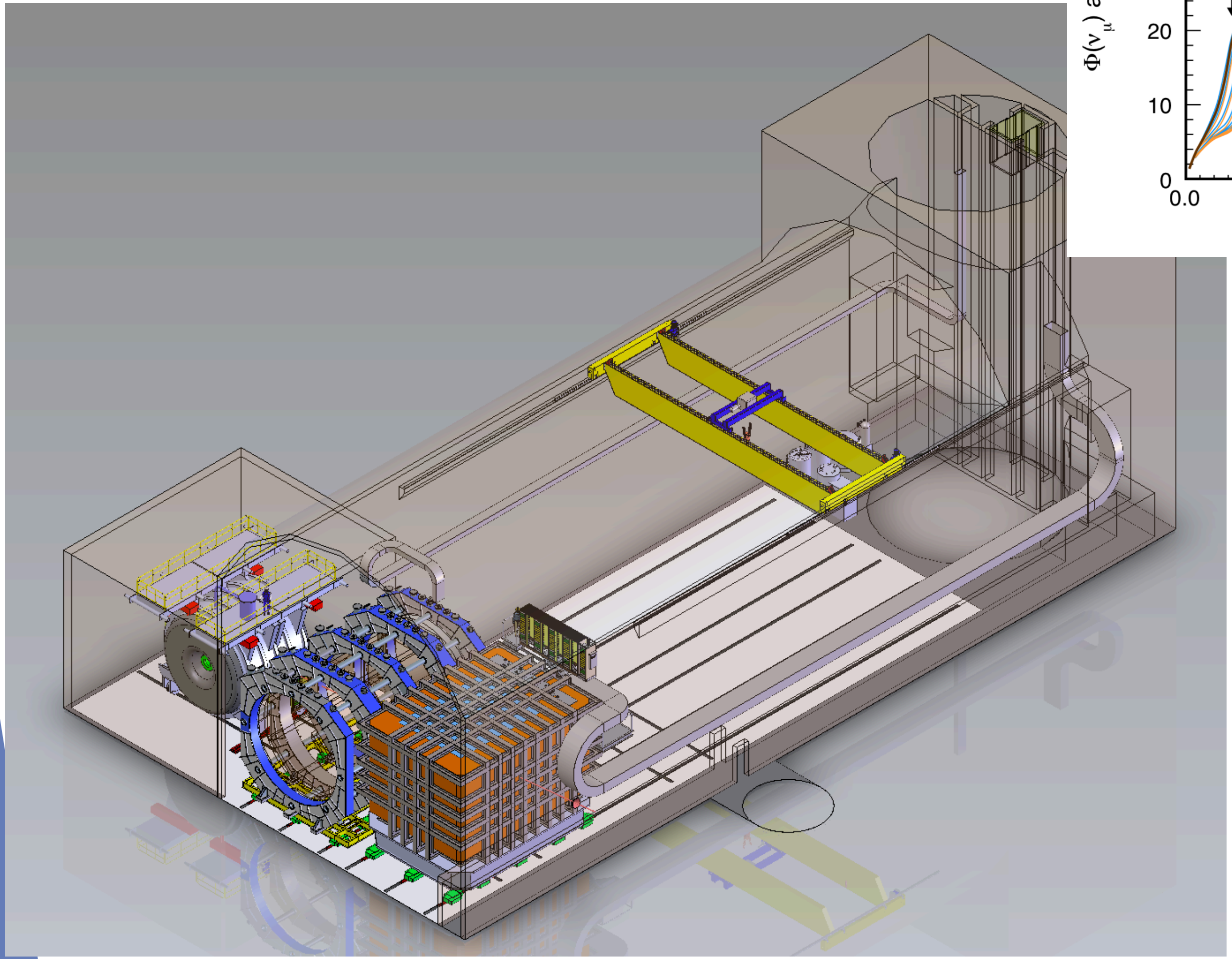
ALICE TPC

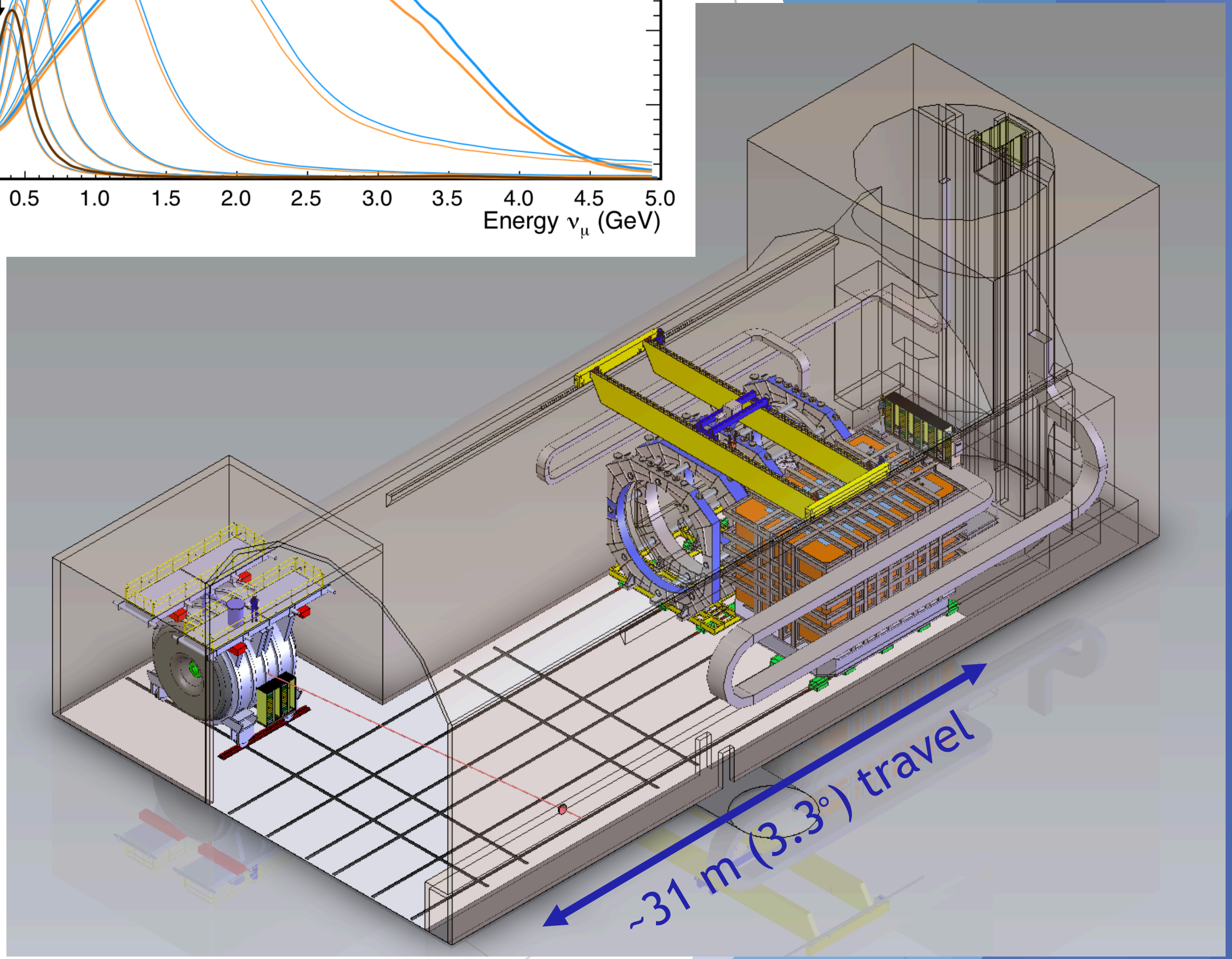
- DUNE gaseous TPC is planned to be a copy of the ALICE TPC
  - MWPC readout chambers now available (ALICE upgrade summer 2019)
  - Well-established technology, vetted detector design
- Expect to achieve ~2% dE/dx resolution

DUNE-PRISM



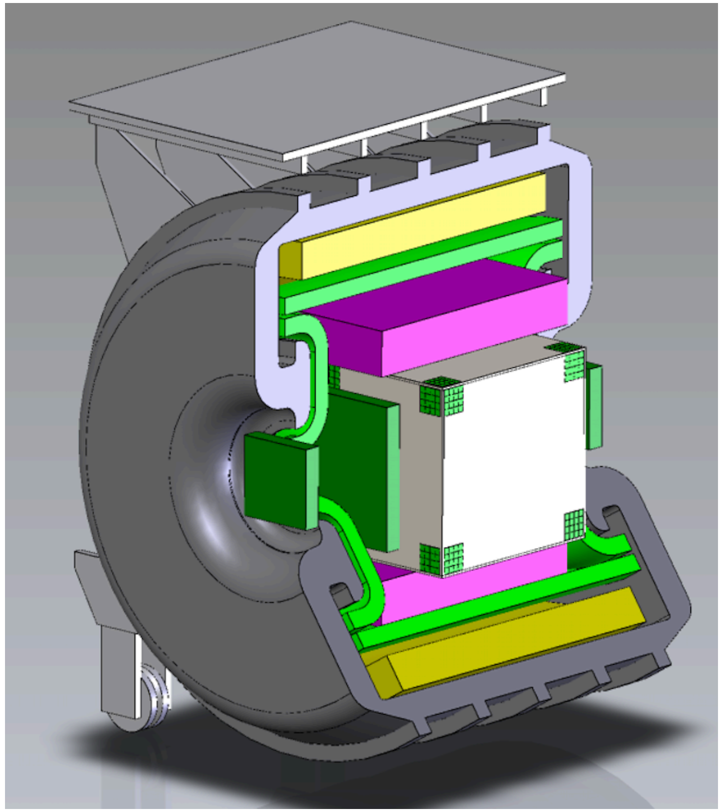
×10⁻⁹
50
40
30
20
10
0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
Energy ν_μ (GeV)
$\Phi(\nu_\mu)$ at 574m/GeV/cm^2/POT
36m
30m
24m
18m
12m
6m
On-axis
ν-mode
$\bar{\nu}$-mode
ν-mode 33m Off-axis





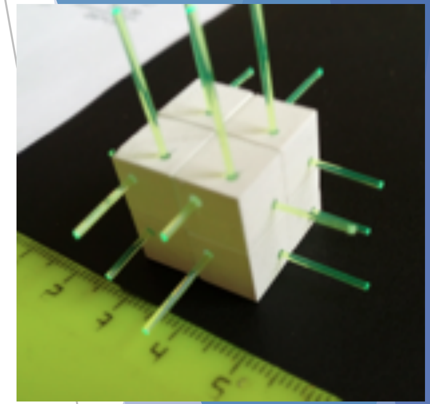
~31 m (3.3°) travel

3D Scintillator Tracker Spectrometer + KLOE (3DST-S+KLOE)



6th DUNE Near Detector Workshop, Sept. 2019
https://indico.fnal.gov/event/21340/

- On-axis beam monitoring & high-stats cross section measurements on CH
- Active target (8t) consisting of 3-dimensional plastic scintillator tracker
  - 1x1x1 cm^3 cubes
- Surrounded by tracking detectors and ECAL in a magnetic field
  - Tracking: atmospheric pressure gaseous TPCs or straw tubes
  - KLOE EM calorimeter (scintillator fiber + Pb)
  - KLOE magnet system
    - 0.6T central field (superconducting magnet)
    - Iron return yoke



DUNE Near Detector Suite

Multi-pronged approach with complementarity among subdetectors

- **Measure neutrino interactions on argon, with extended capability to carbon**
  - LAr detector collects neutrino interactions as seen in the Far Detector (although with different acceptance)
  - MPD (GAr) collects neutrino interactions with sign-selection, very low thresholds, minimal secondary interactions (with full 4π acceptance, as in Far Detector), some neutron detection ability via ECAL
  - 3DST-S+KLOE collects neutrino interactions on CH, with neutron detection capability
- **Measure neutrino energy spectra for different neutrino fluxes via PRISM**
- **Monitor on-axis beam stability**

Summary

- Near detectors play a critical role in long-baseline oscillation experiments
- Next generation experiments will require unprecedented control of systematic uncertainties
  - Neutrino-nucleus interaction modeling
  - Acceptance, fluxes, and $E_{reco} \rightarrow E_{true}$ relationship for near-to-far extrapolations
- Extremely capable detectors and novel ideas for disentangling flux & detector effects at near sites will enable the level of precision needed to measure δ_{CP}

Thank you