

Systematics in Next Generation Oscillation Experiments

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MICHIGAN STATE
UNIVERSITY

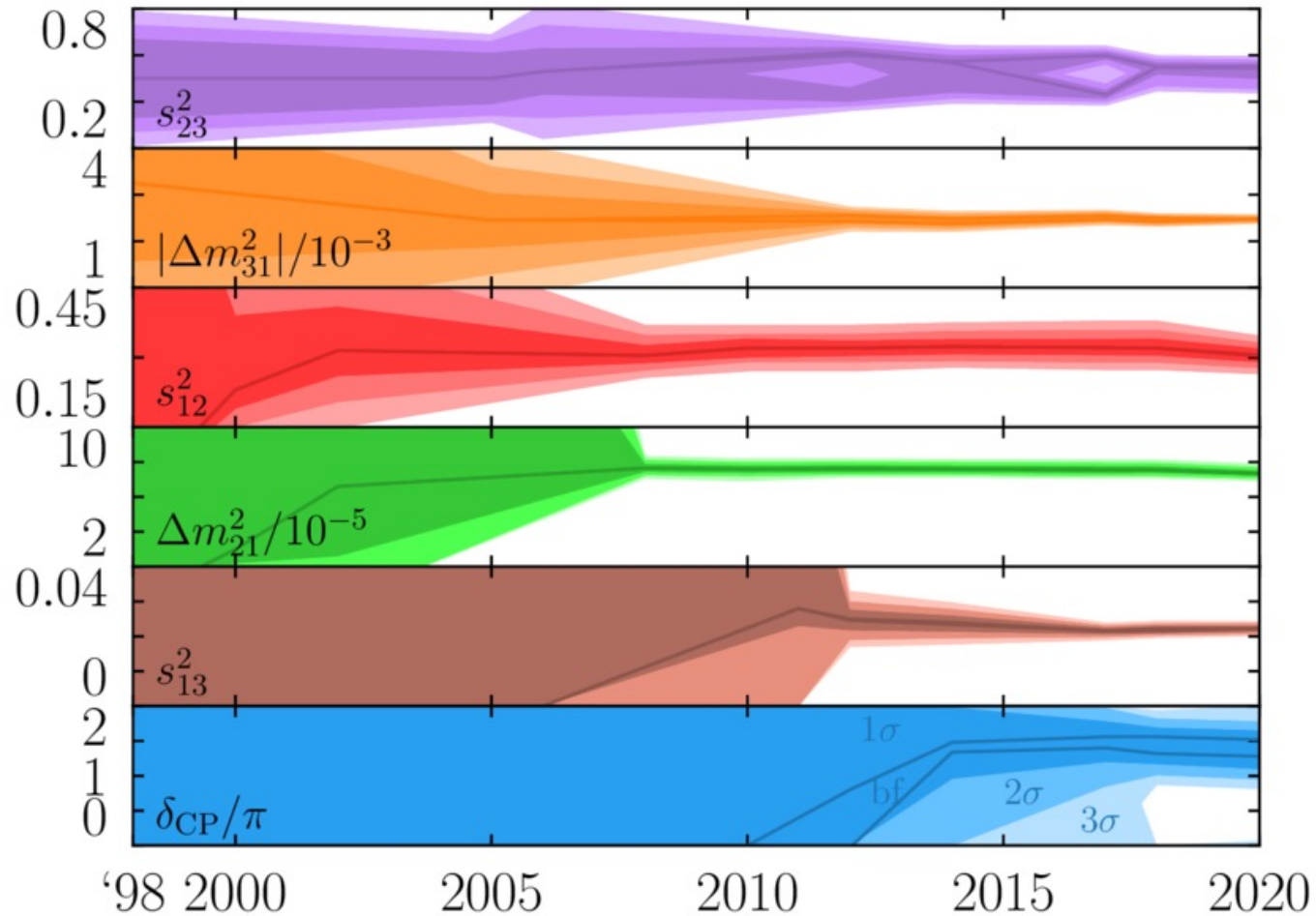


U.S. DEPARTMENT OF
ENERGY

Office of Science

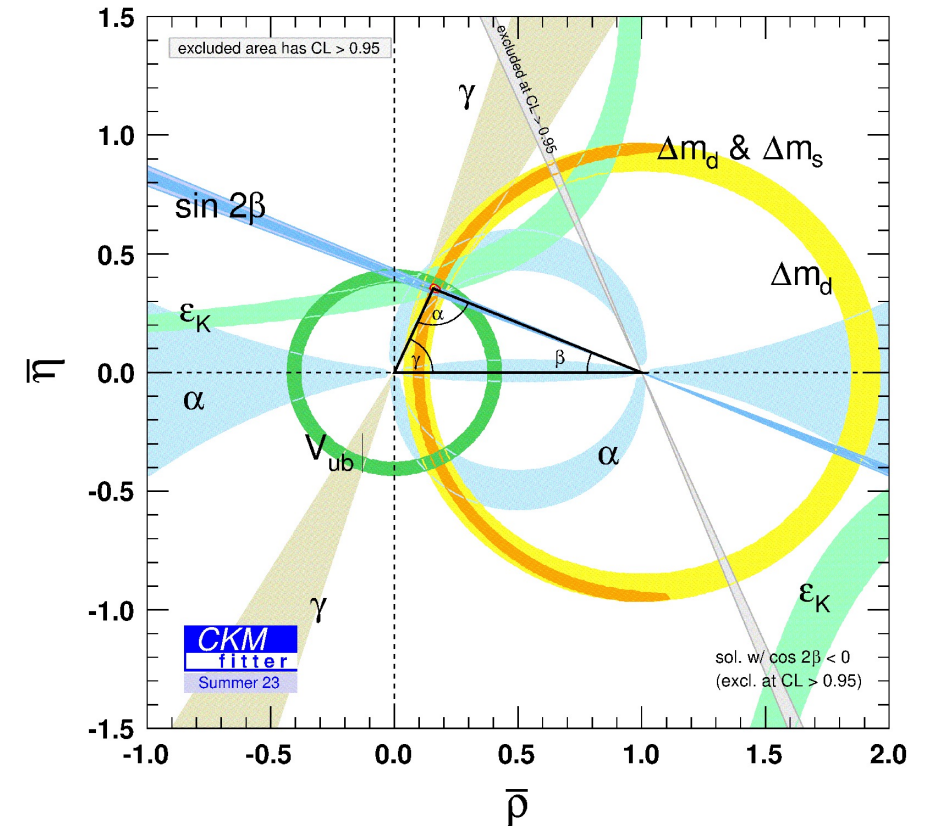
An Age of Precision

Where we are...



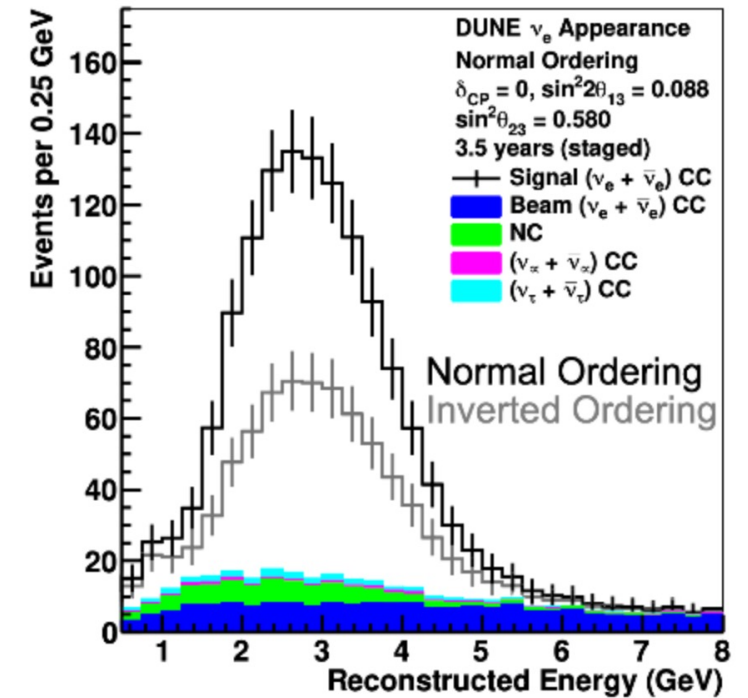
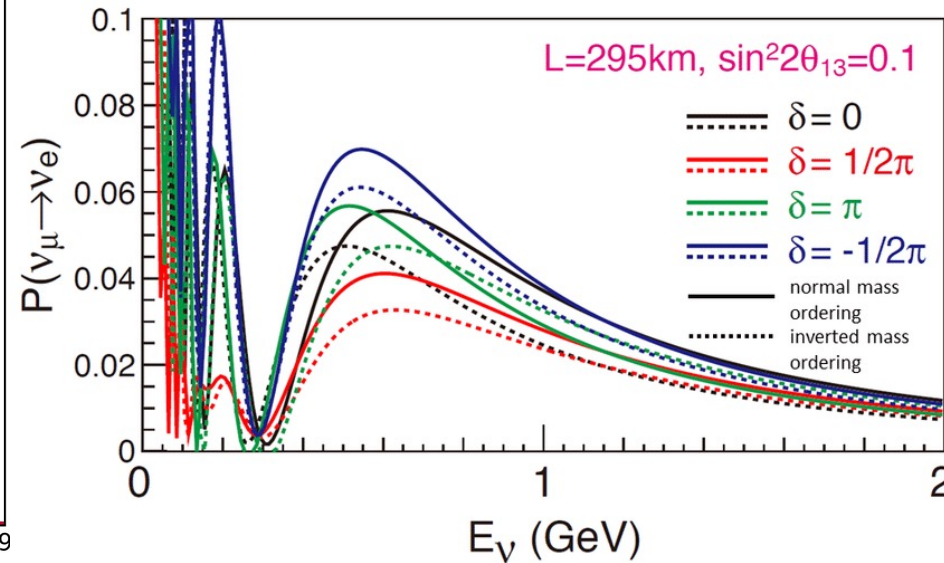
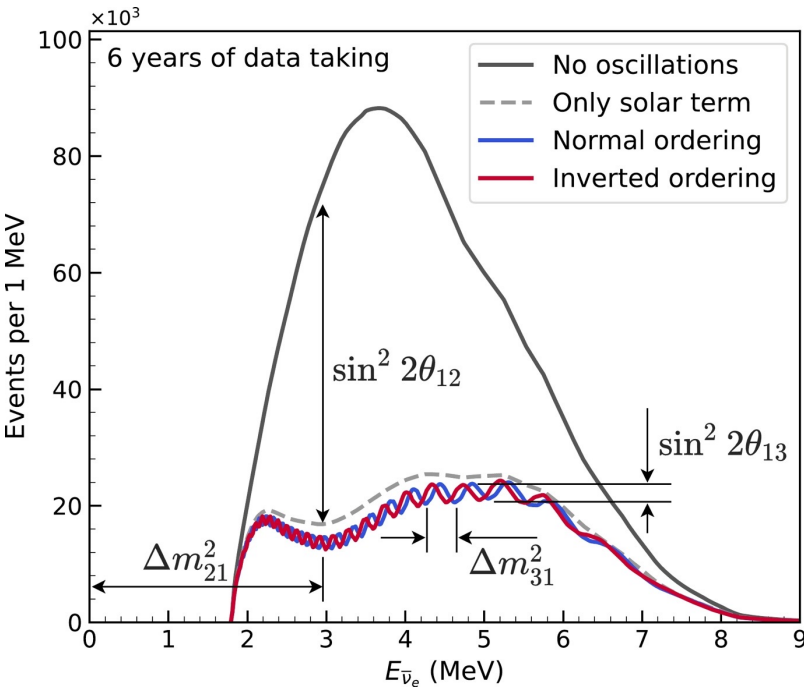
arXiv:2212.00809

...where we want to get



CKM Unitarity Triangles
Eur. Phys. J. C 2005, 41, 1–131.

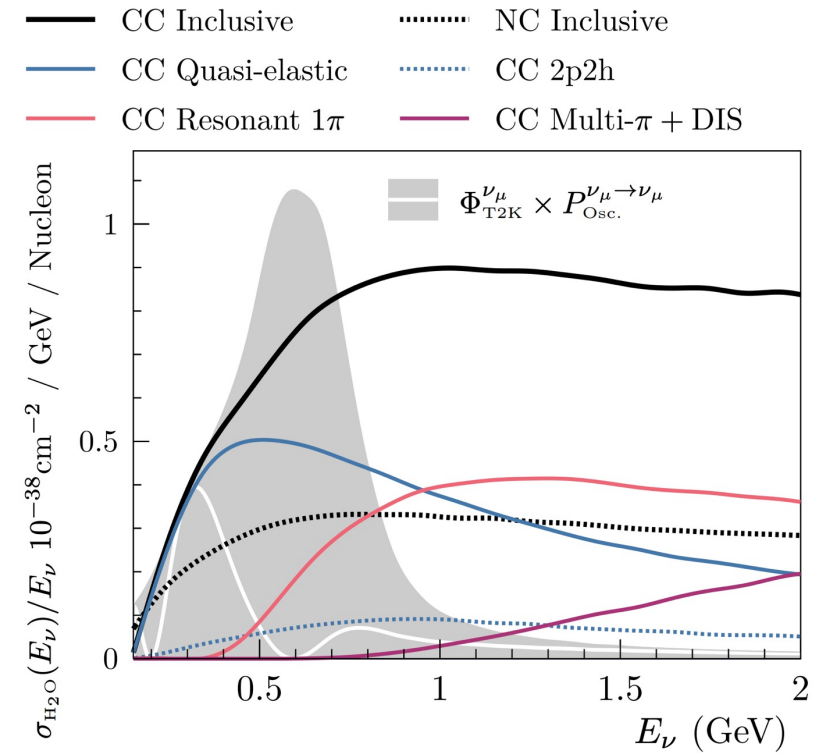
The Next Generation



Measuring Oscillations

Not a pure probability measurement, in spectra predictions mixing effect is convolved with **flux**, **interaction**, **detector** modeling

$$R = \Phi \times \sigma \times \epsilon \times P(\nu_\alpha \rightarrow \nu_\beta)$$



$$L = \underbrace{[L_{Flux} \otimes L_{xsec} \otimes L_{Det}]}_{\text{Near Detector}} \otimes L_{PMNS}$$

Far Detector

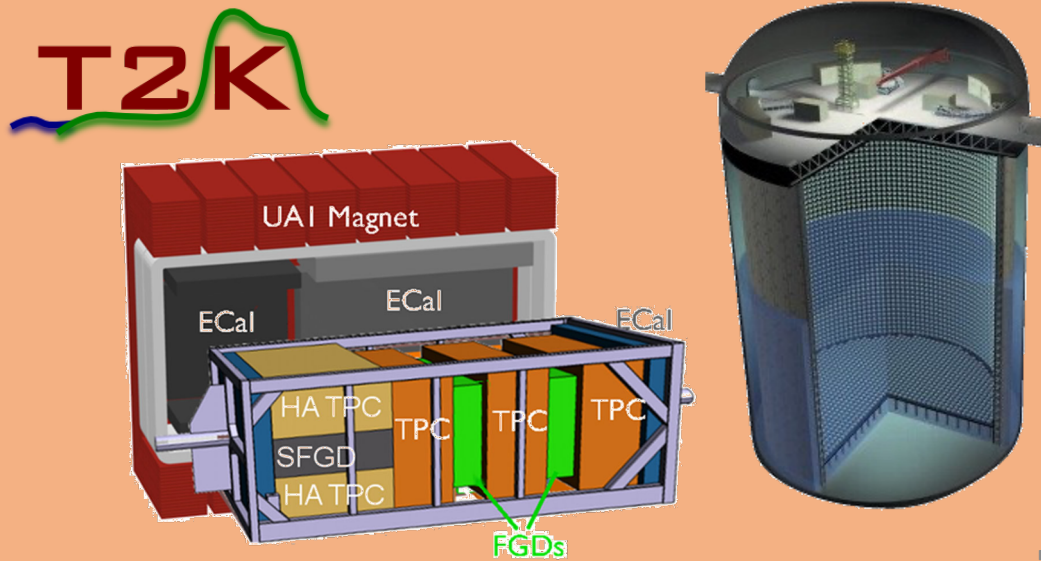
Approaches to Systematics

Model Driven

Use data to constrain systematic models – Can help you understand underlying physics

Need adequate model freedoms to describe data

Significant risk of model dependent bias in results



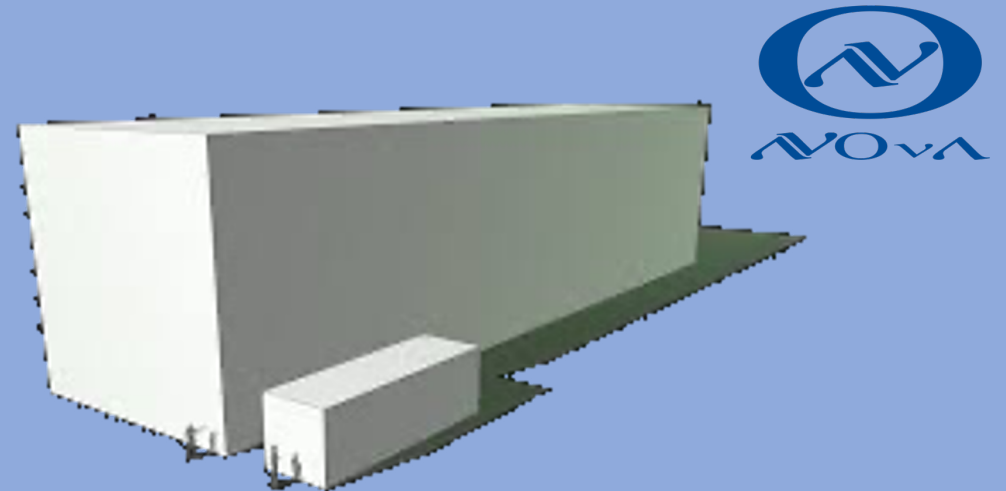
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Data Driven

Use data from one detector to more directly make predictions for a functionally identical or similar

Avoids model dependencies

Still need to understand any possible differences between very similar detectors like size, flux, or geometry

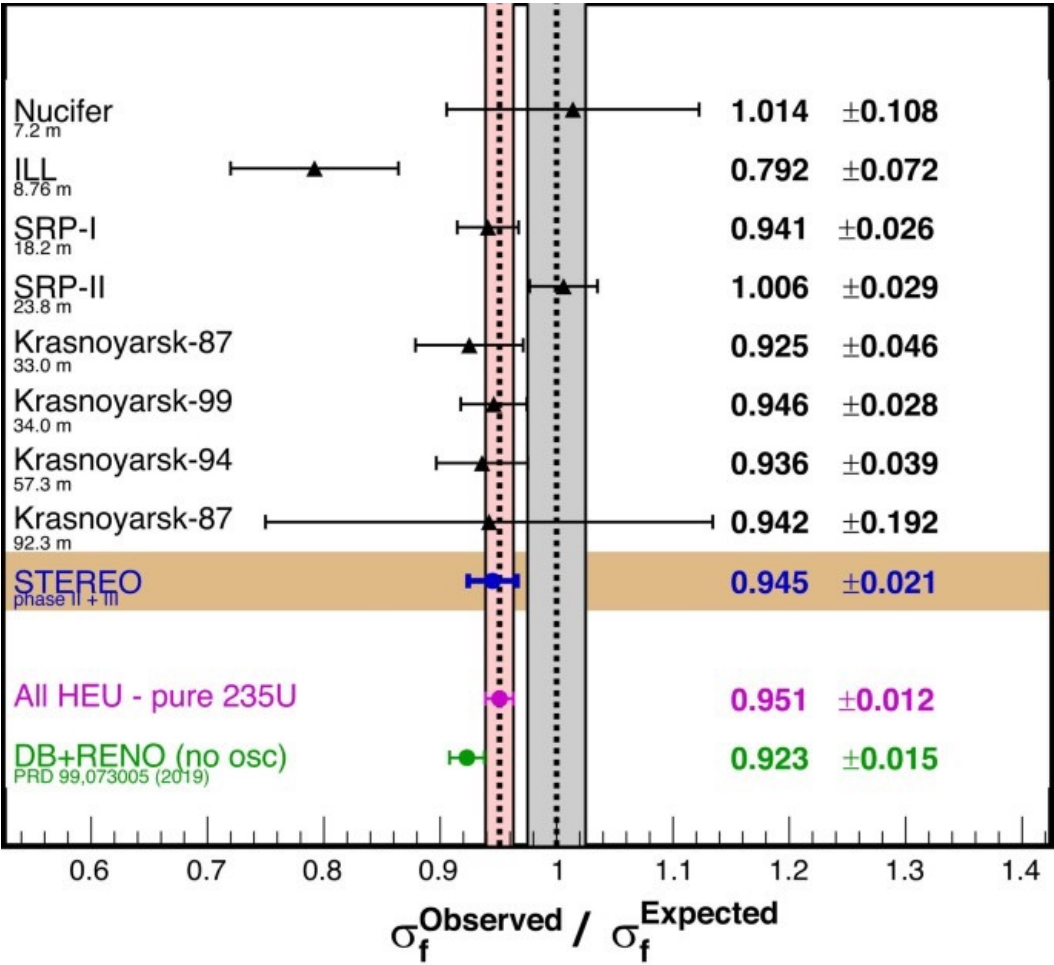
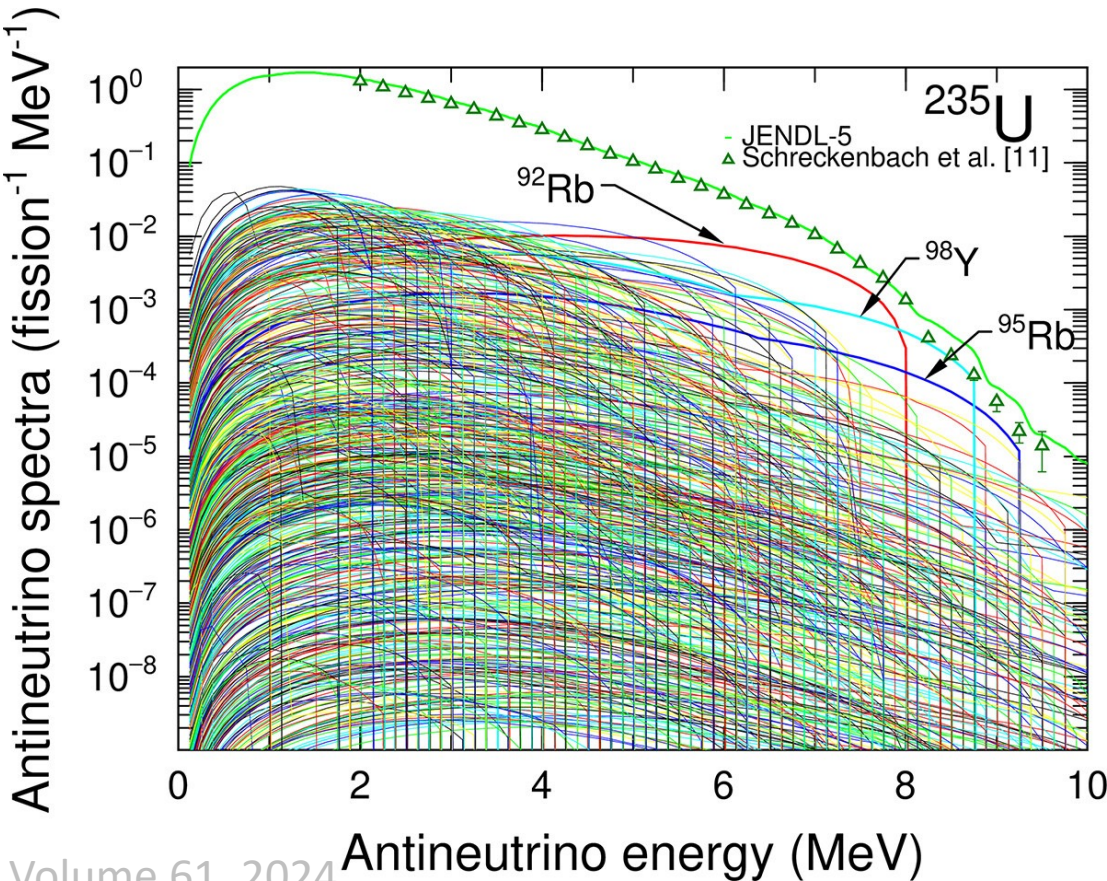


General Considerations for Neutrino Experiments

Neutrino Sources: Nuclear

Reactors

Many contributing beta decay processes each with fine structure. Models have significant discrepancy

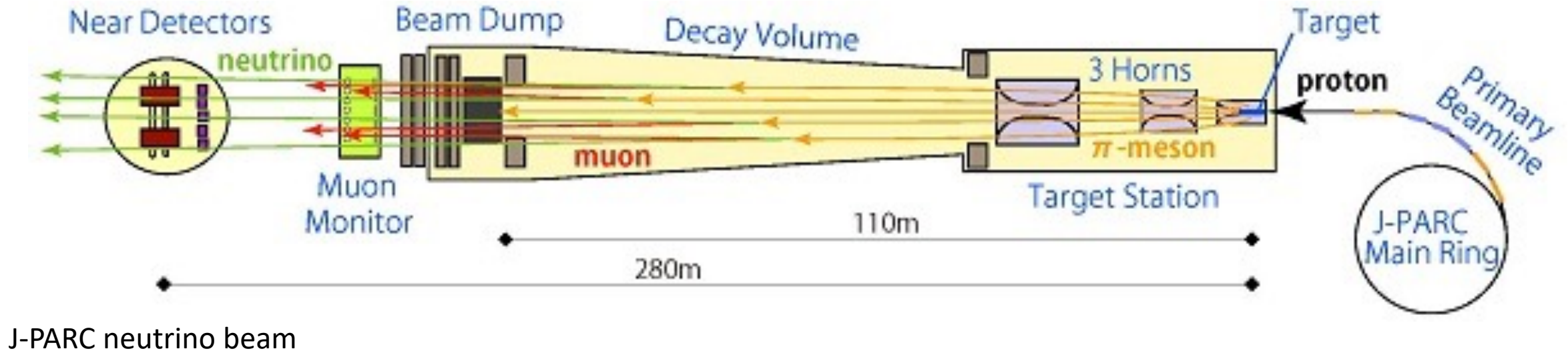


Nature volume 613, pages257–261 (2023)

Neutrino Sources: Hadron Decays

Beam and Atmospheric

Hadronic production processes and secondary interactions are biggest contribution to flux uncertainty



For beams, horn current and field have impact too as well as beamline geometry

Hadron production

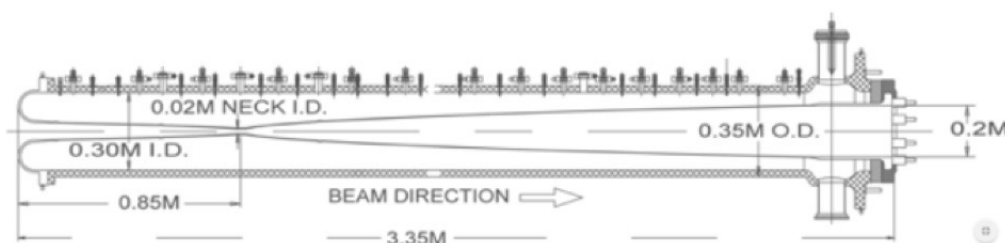
[See Lu Ren's talk from Wednesday](#)



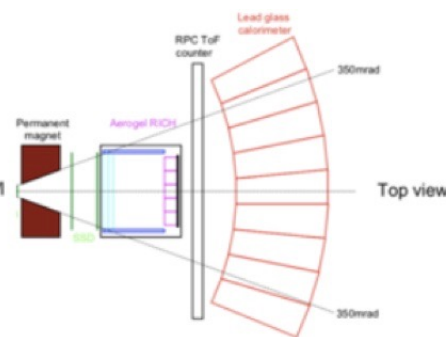
Detailed measurements of hadrons exiting fixed targets in proton beam at different energies

Mix of thin-target and replica-target measurements
Reduces T2K flux uncertainty from ~10% to ~5%

EMPHAT!C

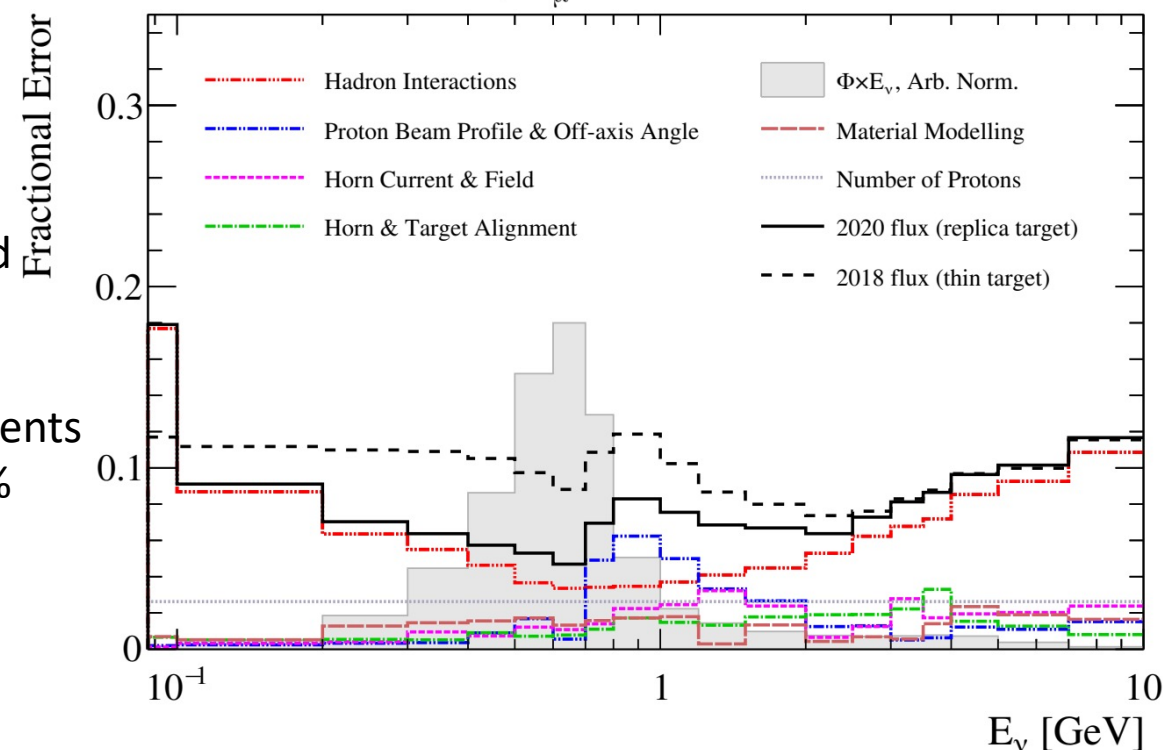


NuMI Horn 1



EMPHATIC

FD: Neutrino mode, ν_μ

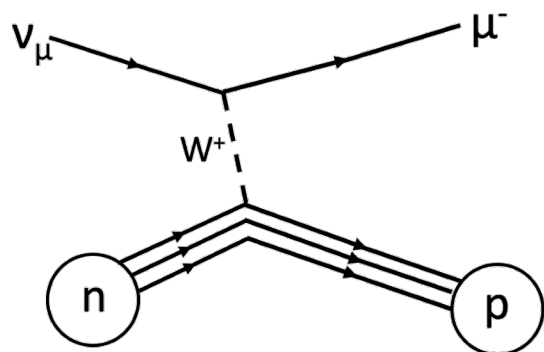


Also makes hadron measurements

Will make first measurement of hadrons exiting neutrino beam focusing horn

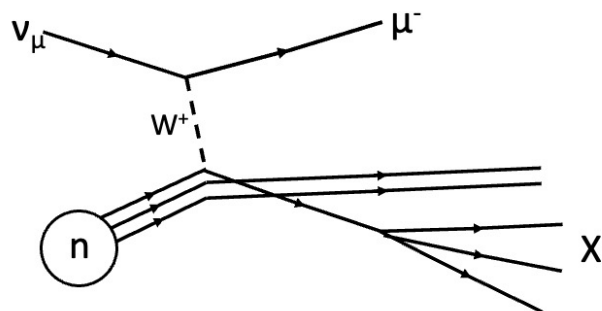
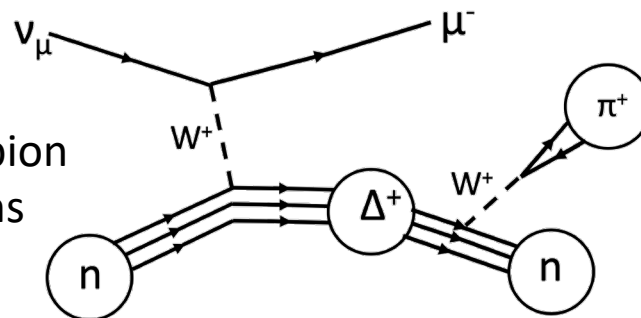
Interaction modeling

Each interaction mode has different relationship between neutrino energy and final-state kinematics

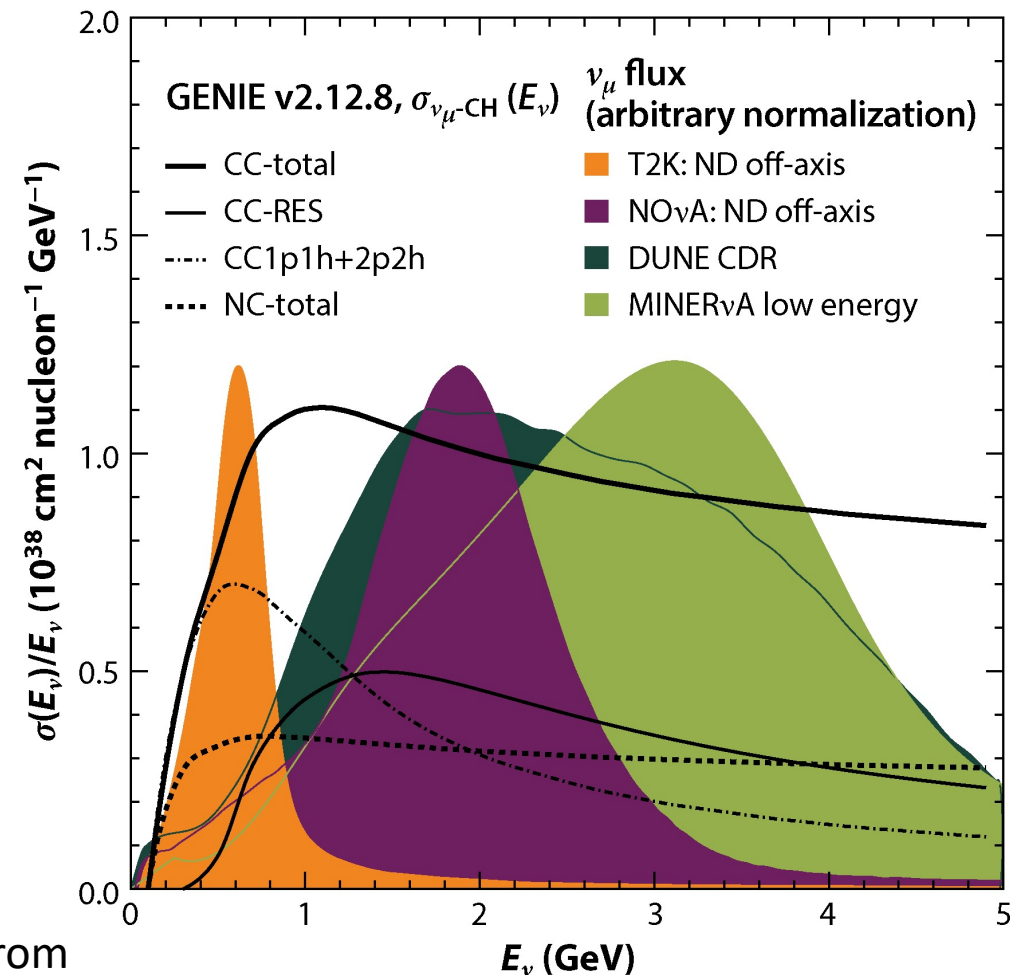


CCQE and Multinucleon Knockout
Recent measurements seem to disfavor dipole form factor model

We cannot yet accurately model pion kinematics in resonant interactions



Hadronization models and tools from collider world may not accurately describe relatively low- W systems
Are our corrections sufficient?



[3] [Ann.Rev.Nucl.Part.Sci. 68 \(2018\) 105-129](#)

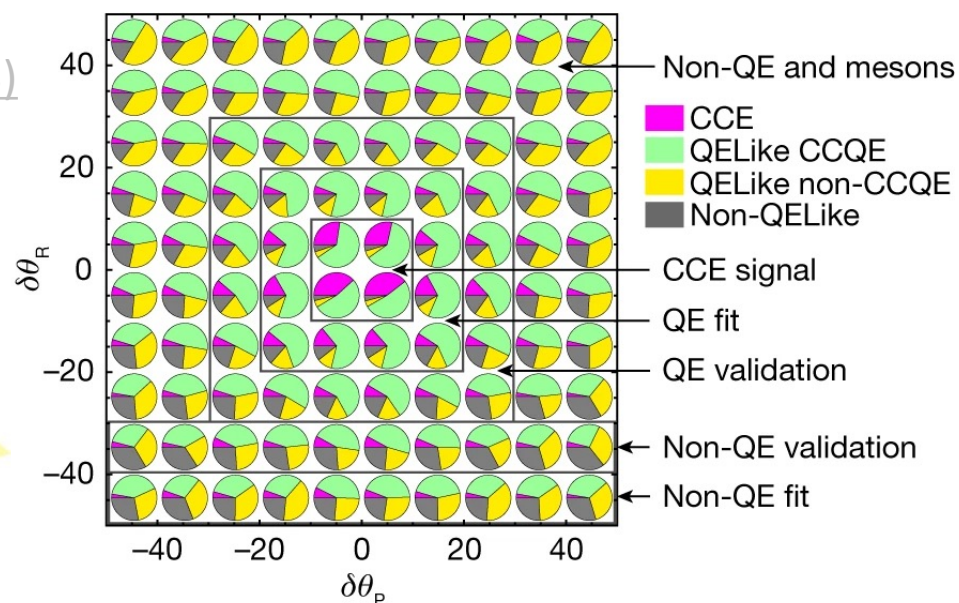
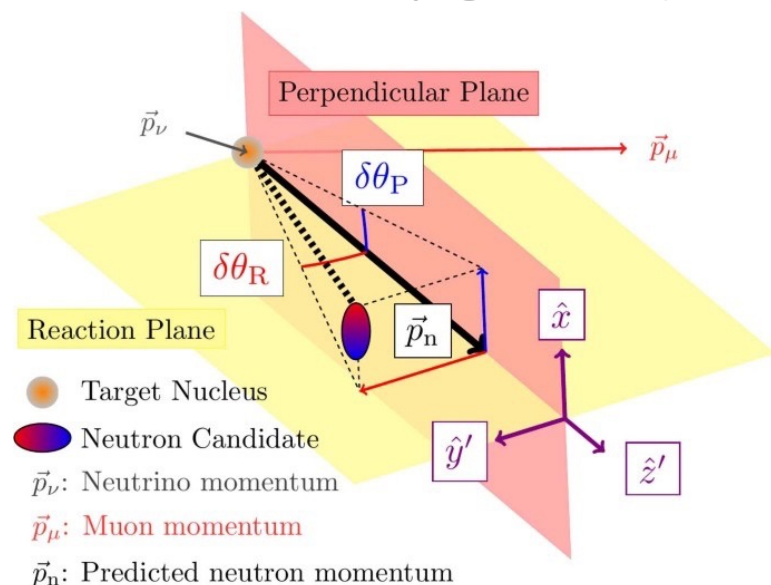
A complicated nuclear environment

Interactions often take place in the complicated nuclear environment

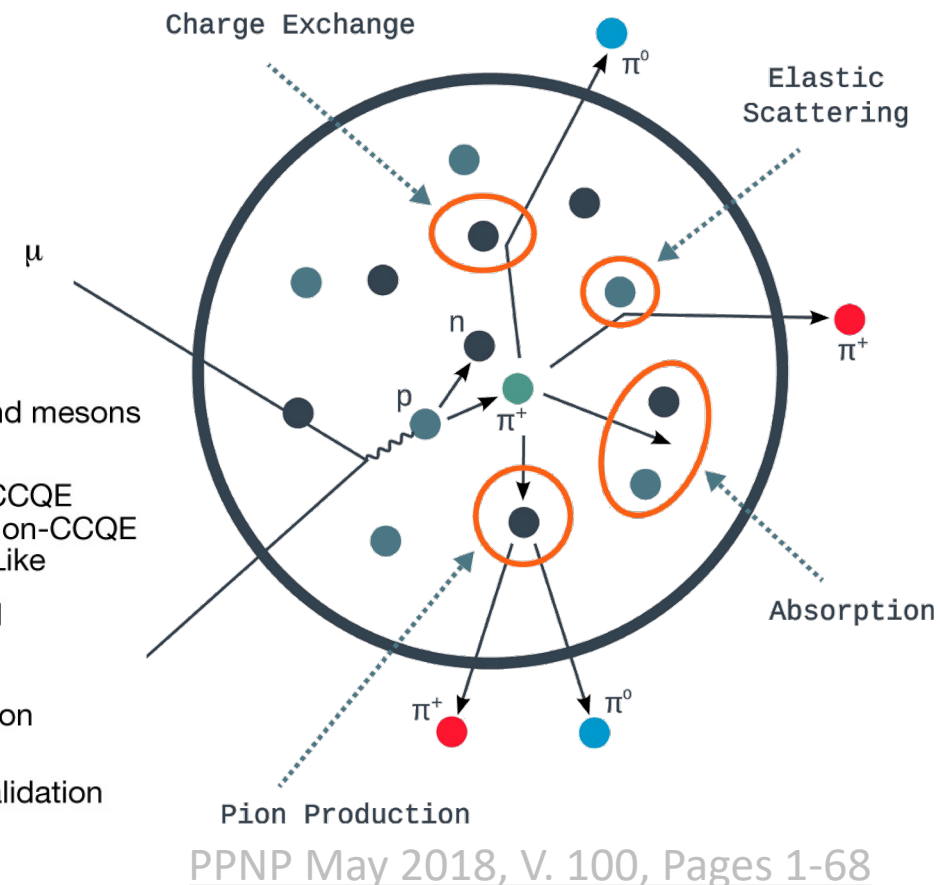
Ground state impacts cross section and available energy in non-trivial ways, need to go beyond PWIA

Final State interactions can alter FS-topology and kinematics introducing irreducible backgrounds and smearing energy

Nature volume 614, pages48–53 (2023)



Can use TKI to probe nuclear effects and even separate out free proton interactions



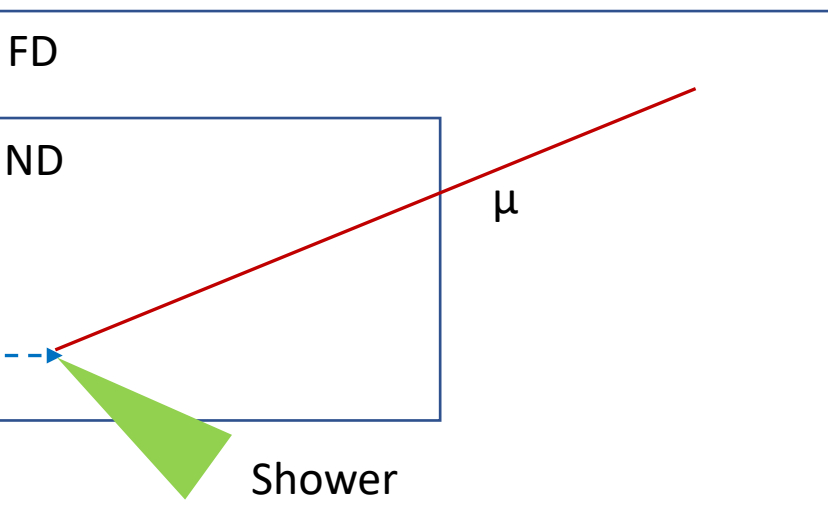
PPNP May 2018, V. 100, Pages 1-68

Detector Systematics

Need to understand how particles and different interaction topologies look in our detectors

Understand how particles propagate and deposit energy in the detector, and how accurately we can record it electronically

Geometry can play a big roll in near-to-far acceptance differences, as well as reconstruction efficiencies and fiducial volume mass uncertainties



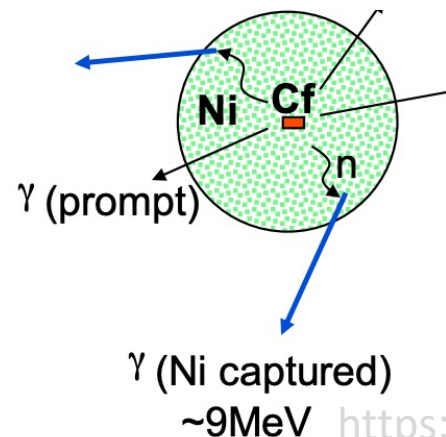
ND may not contain all events large FD can

Physical surveys and crossing tracks useful for assessing geometry

Develop control samples for specific systematics

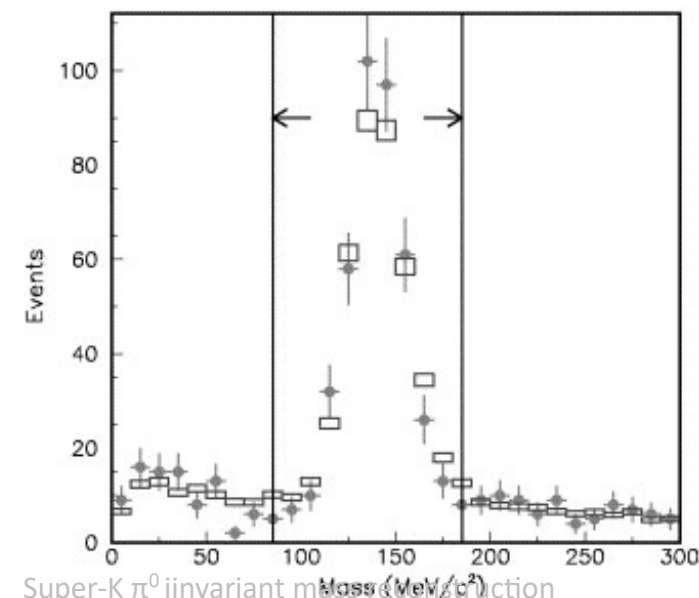
- Stopping particles
- Through-going cosmics
- Standard candles and decays

Energy scale is very important. Independent measures as well as calibration sources can be used to assess this



<https://arxiv.org/abs/1307.0162>

Invariant Mass 2R e-like

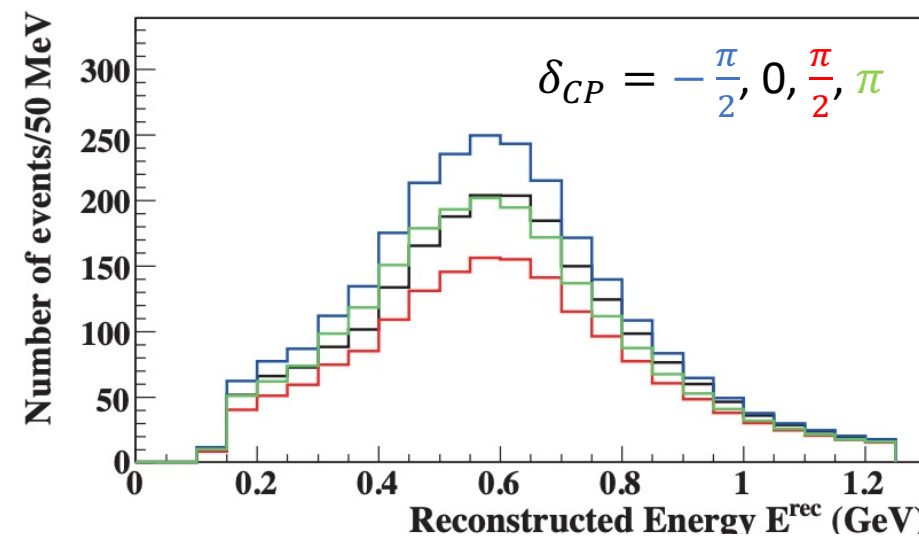


Super-K π^0 invariant mass reconstruction

[https://doi.org/10.1016/S0168-9002\(03\)00425-X](https://doi.org/10.1016/S0168-9002(03)00425-X)

How systematics impact oscillations

Neutrino mode: appearance

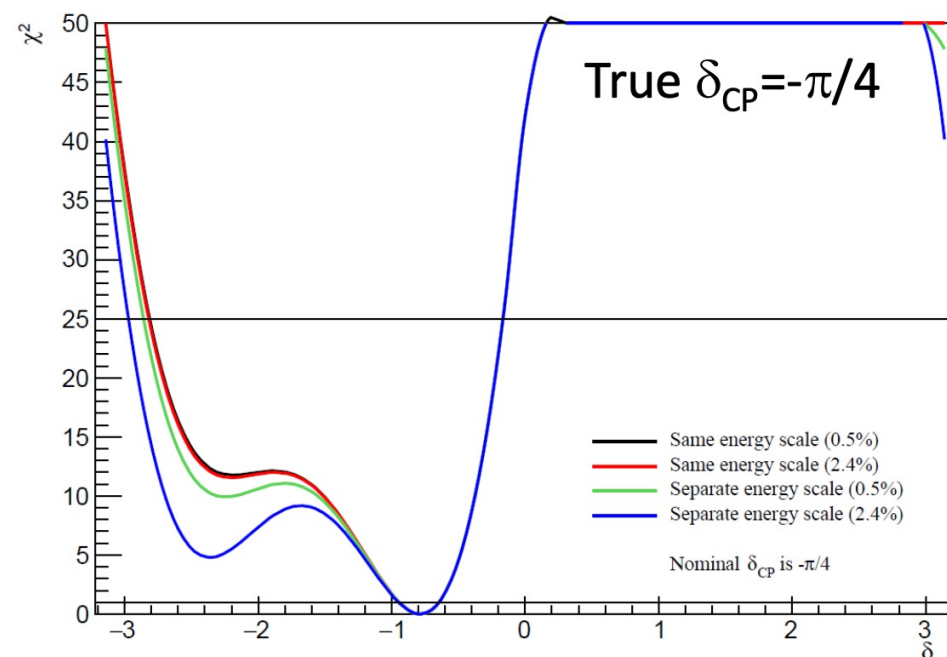


Example from Hyper-K

If ν_e and ν_μ energy scales are not similar, and we don't understand the ν_e energy scale well we bias appearance shape

For CP-conserving values of δ_{CP} there are subtle shape changes from subdominant terms in the oscillation

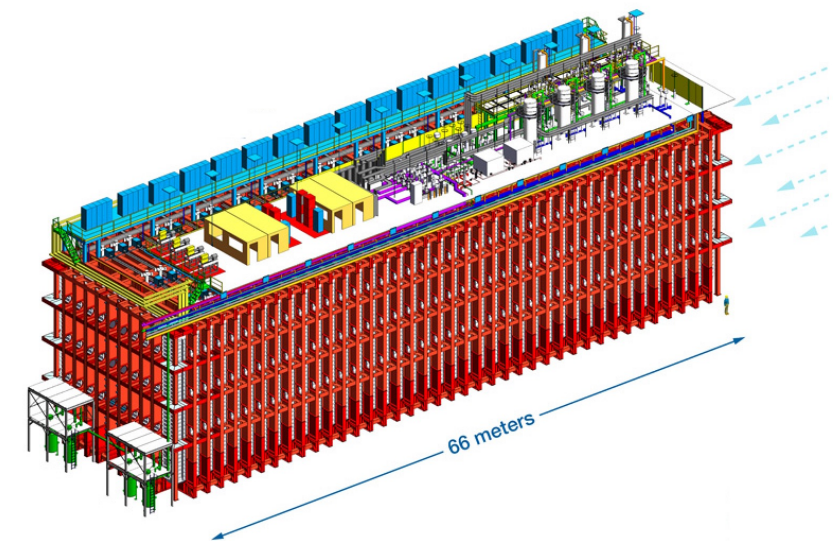
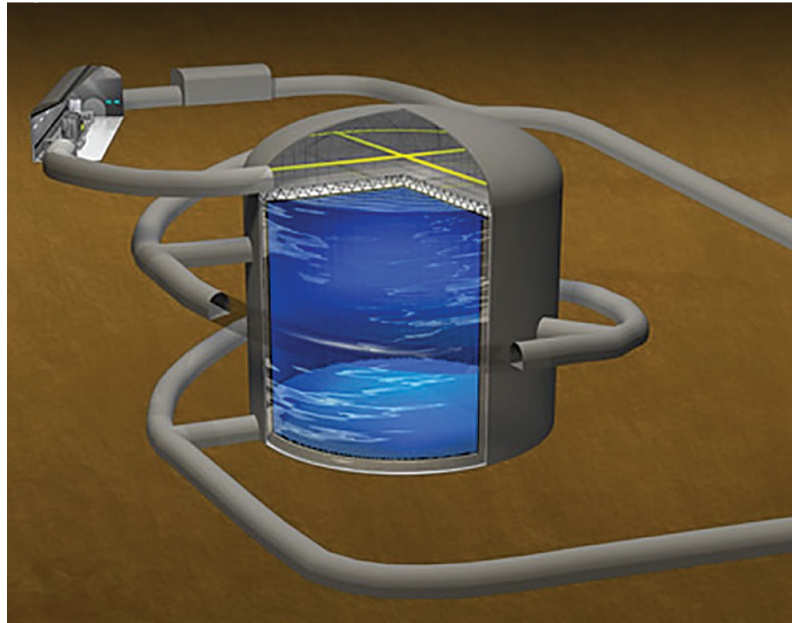
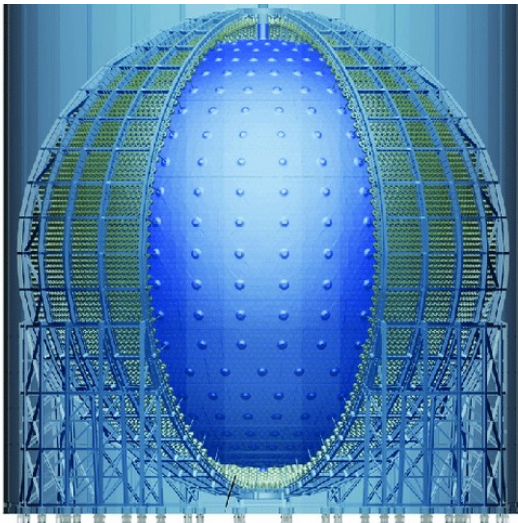
A bias in the energy scale results in inability to exclude false minima in the constraint and determine correct octant



The Next Generation



Reactor, Atmospheric, Solar	Narrowband Sub-GeV Beam, Atmospheric, Solar	Broadband Multi GeV beam, Atmospheric, Solar
Inverse Beta Decay	Mostly quasielastic	Broad mix of QE, RES, SIS, DIS
20 kt Liquid Scintillator	170 kt Water Cherenkov	2-4 x 17 kt LAr-TPC





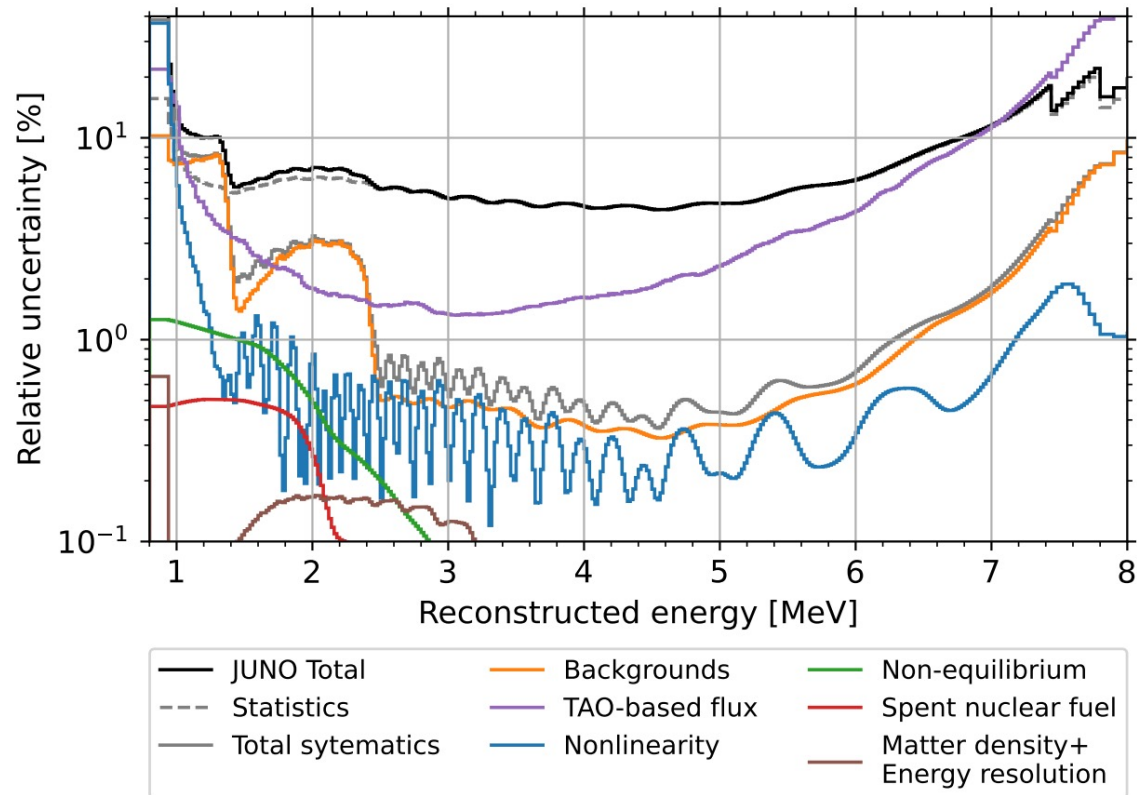
● Guangzhou

[See Prof. Xiaonan Li's talk for more details](#)

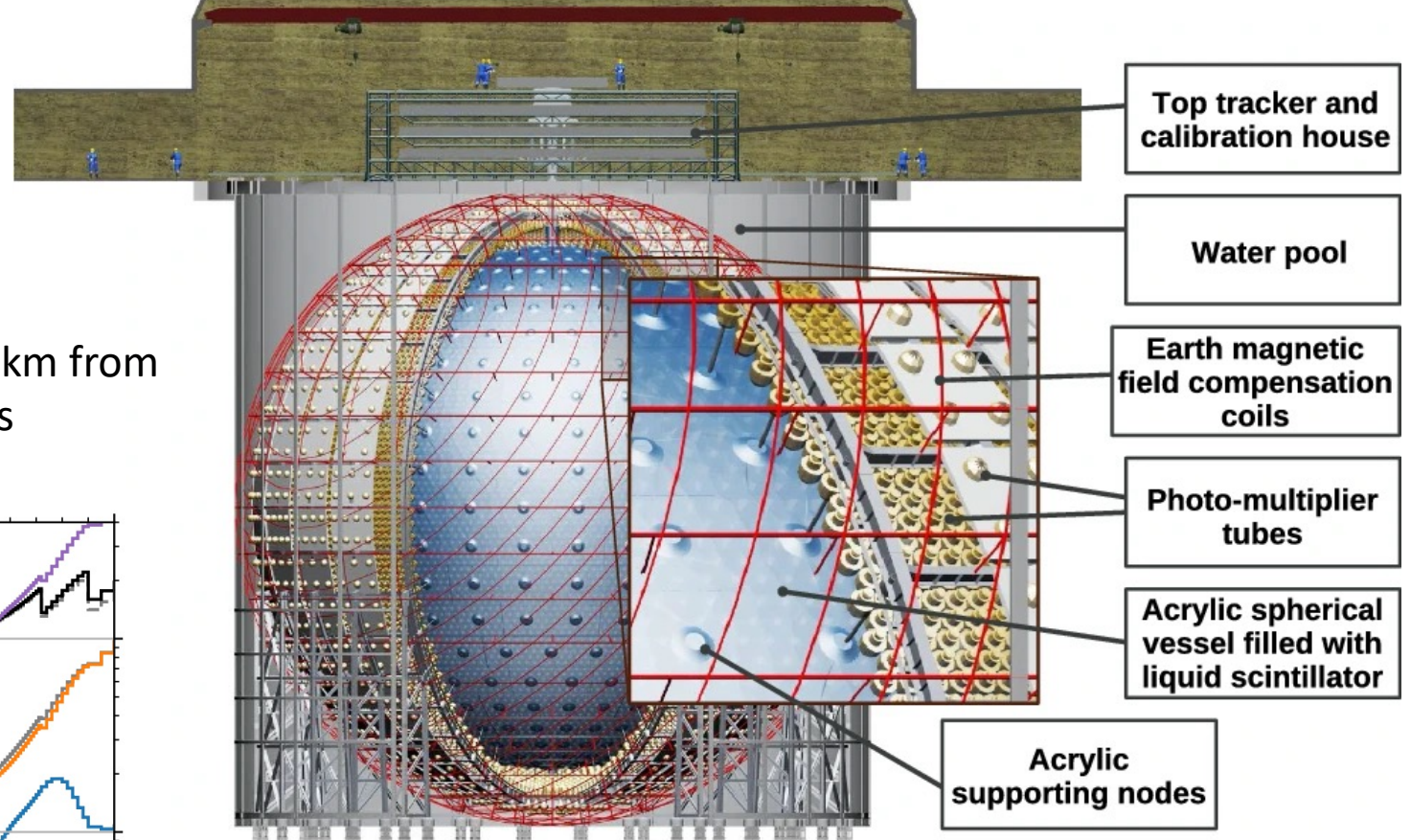




20 kt LS detector at 52.5 km from two nuclear power plants



<https://arxiv.org/pdf/2405.18008>



3% / $\sqrt{E}$ energy resolution
 17,612 20" PMTs
 25,600 3" PMTs
 77% total photocathode coverage

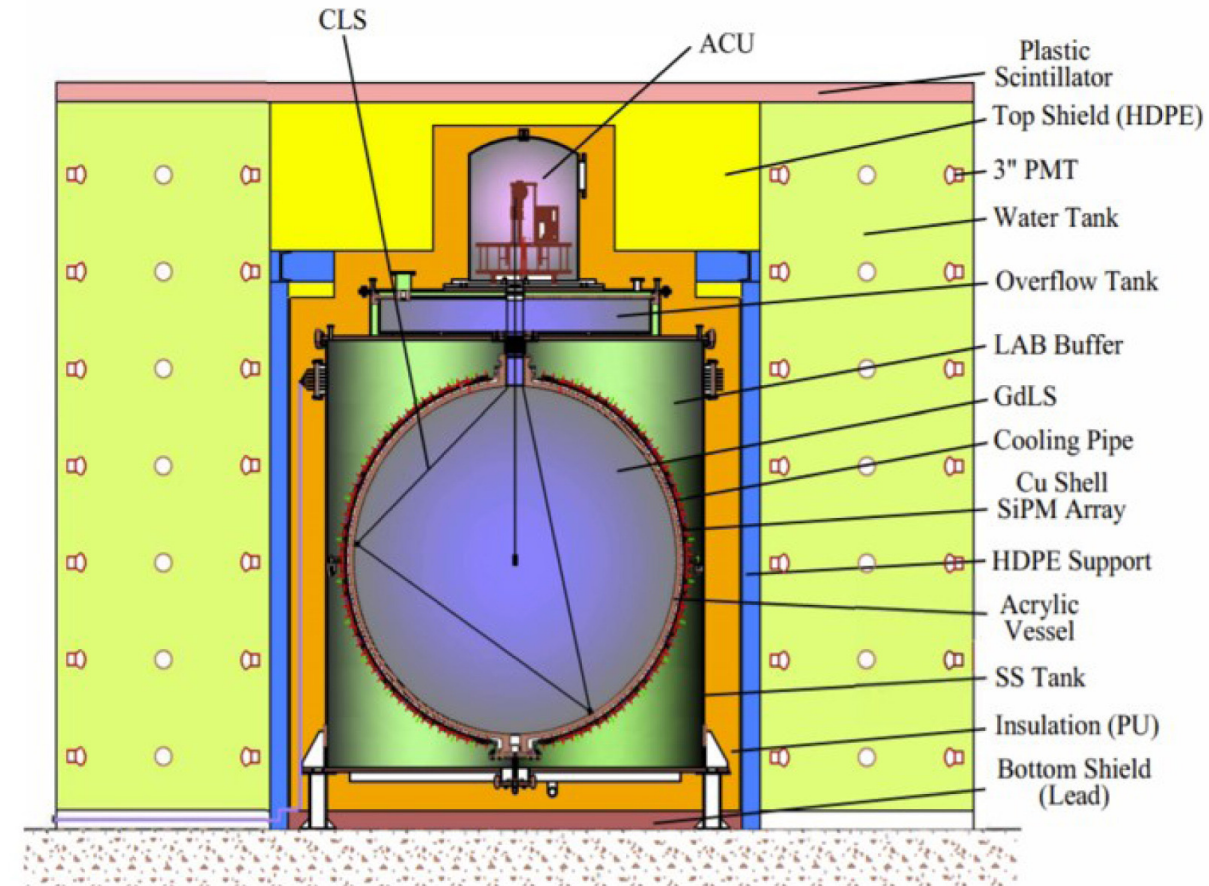
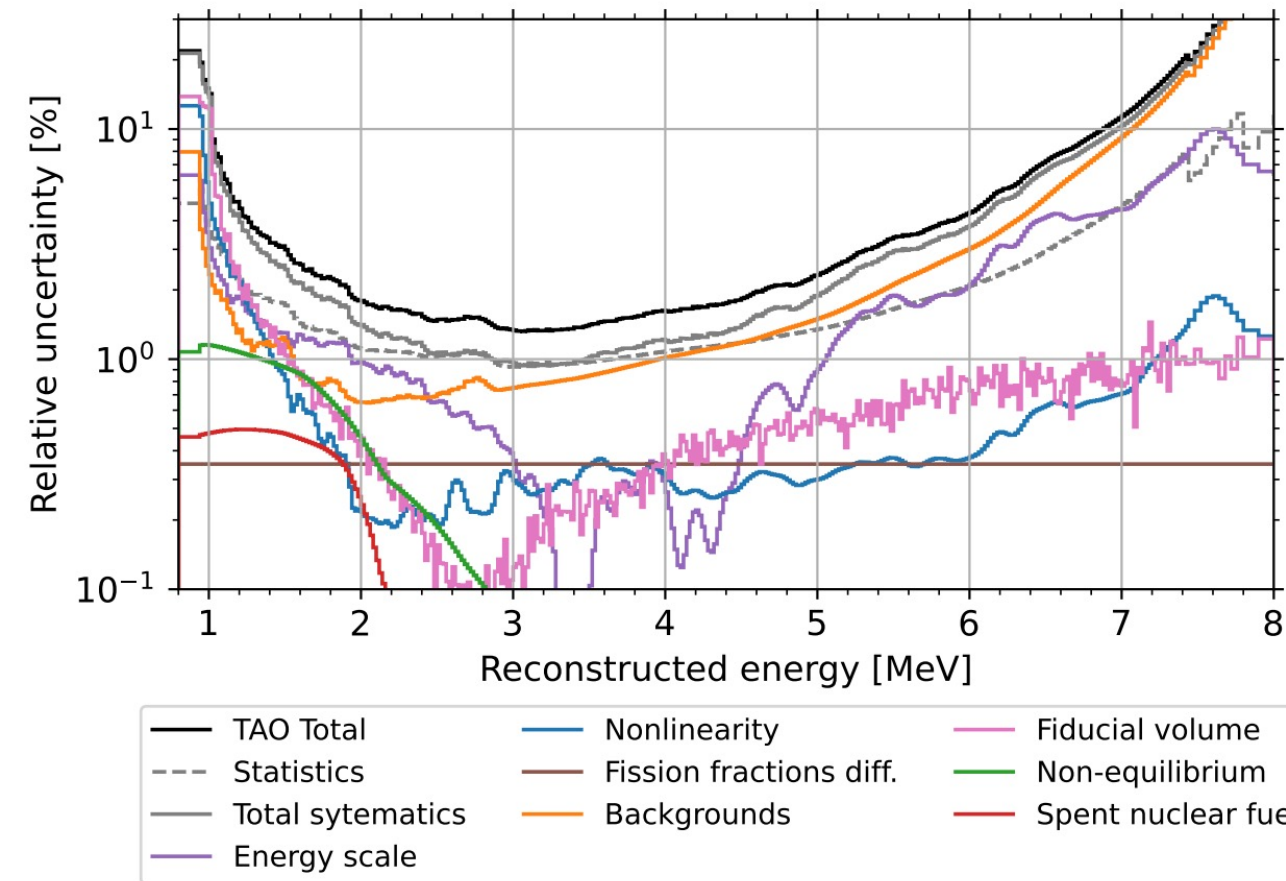
Cosmic ray tracker and outer WC det reduce backgrounds

Mix of PMTs helps validate systematics



JUNO-TAO

44 m from reactor
Will measure fine structure in spectrum
with high statistics and
1% uncertainty on spectra at 3 MeV



<https://arxiv.org/pdf/2405.18008>

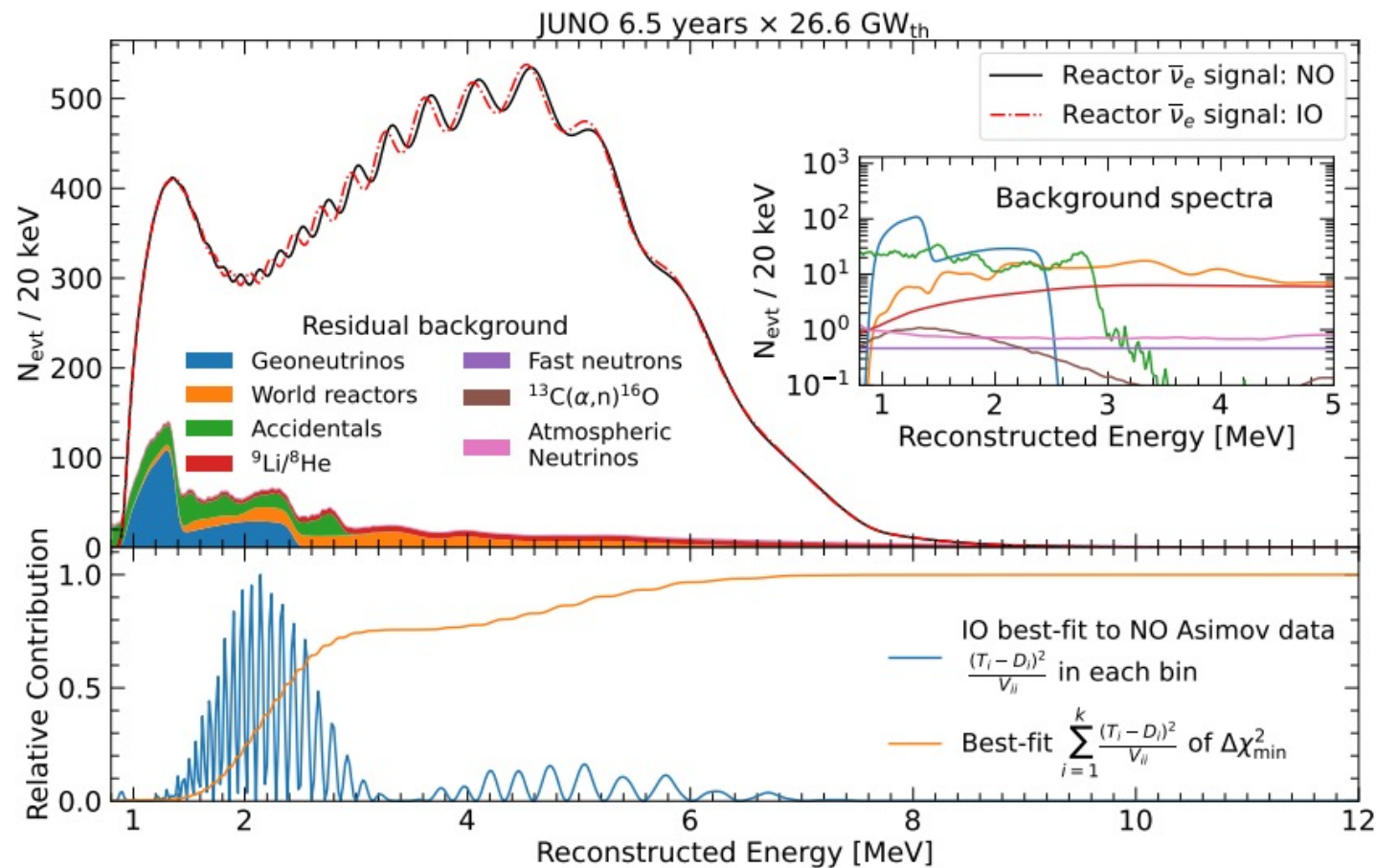
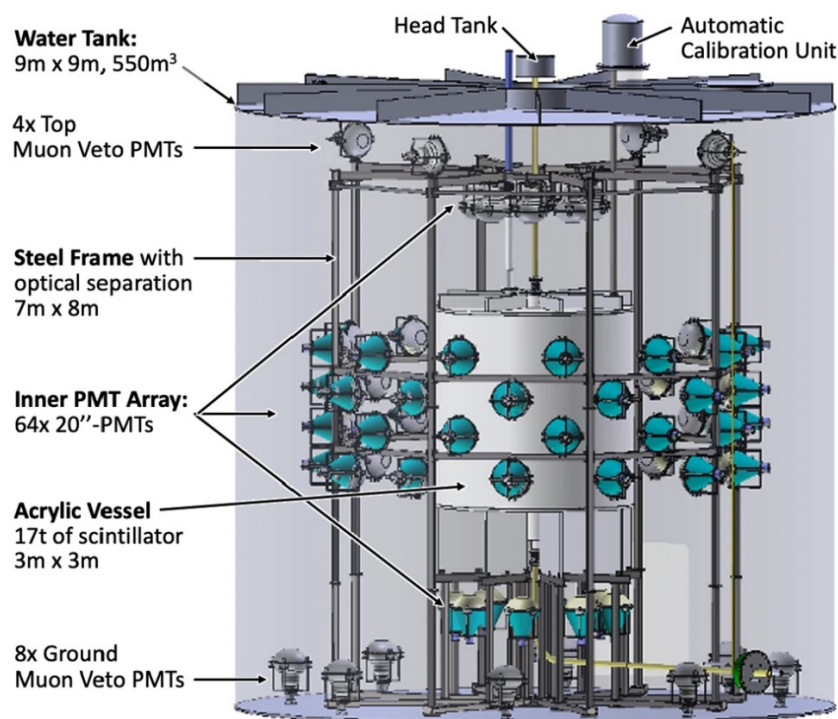
Doped with Gd to increase n-capture
Helps account for acceptance difference due to smaller size



Lower stats at far detector lead to larger backgrounds

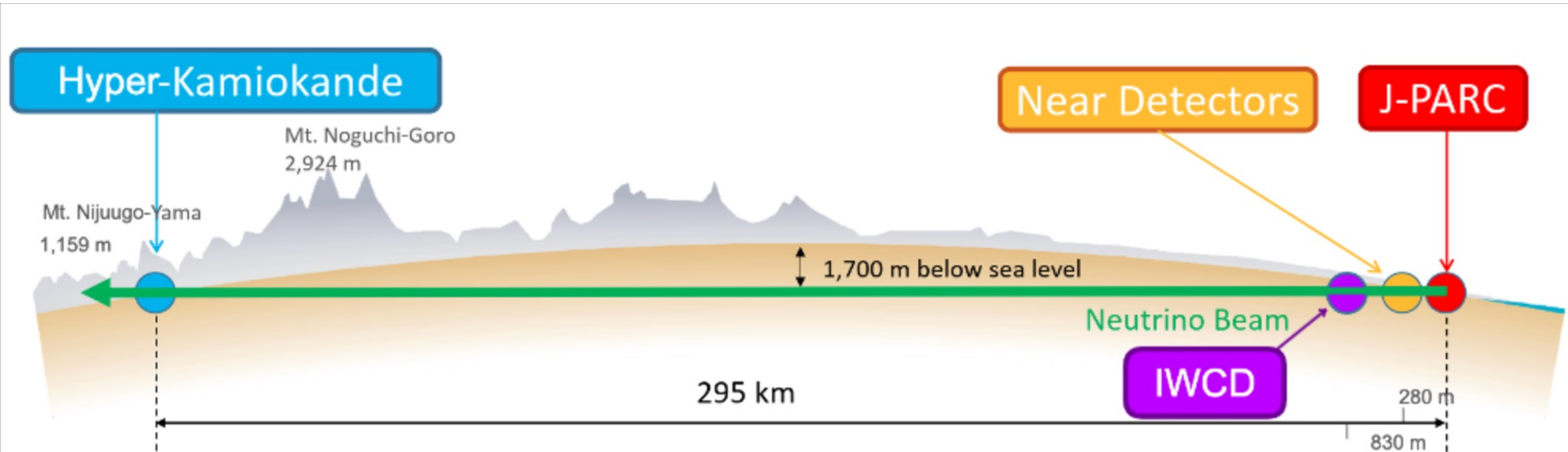
Radiopurity of LS is monitored with dedicated OSIRIS detector

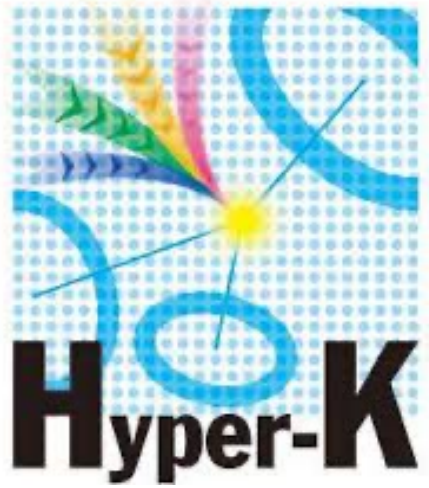
JUNO-OSIRIS





Hyper-Kamiokande

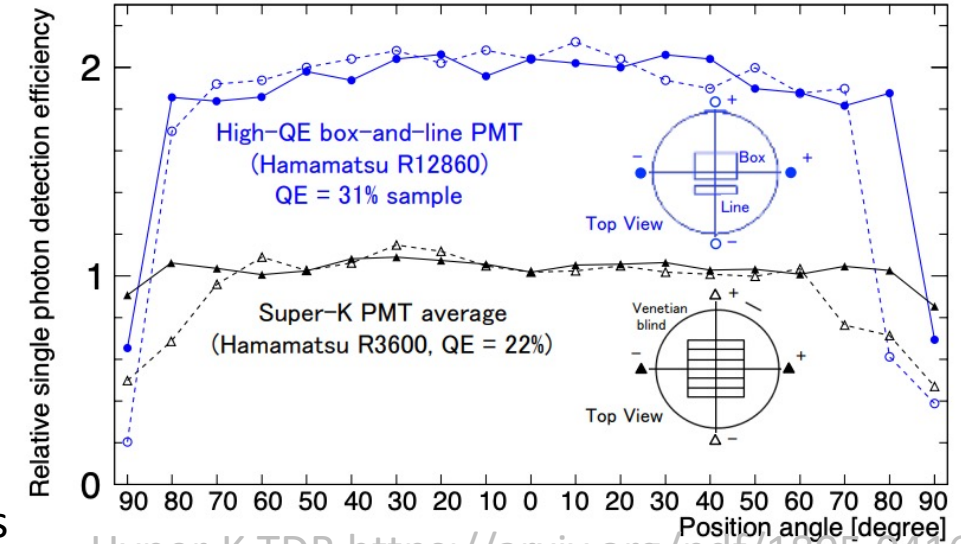




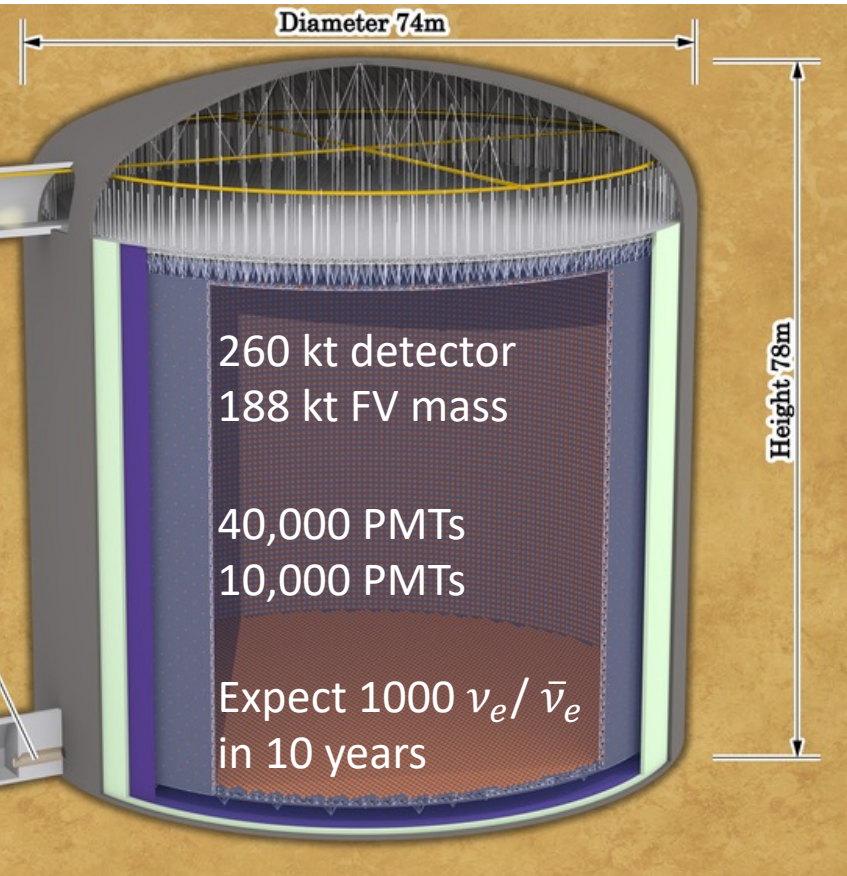
Hyper-K Far Detector

Significant 50cm PMT performance increase from SK
Better QE, timing resolution and charge discrimination

Calibration including light injection, radioactive sources and photogrammetry

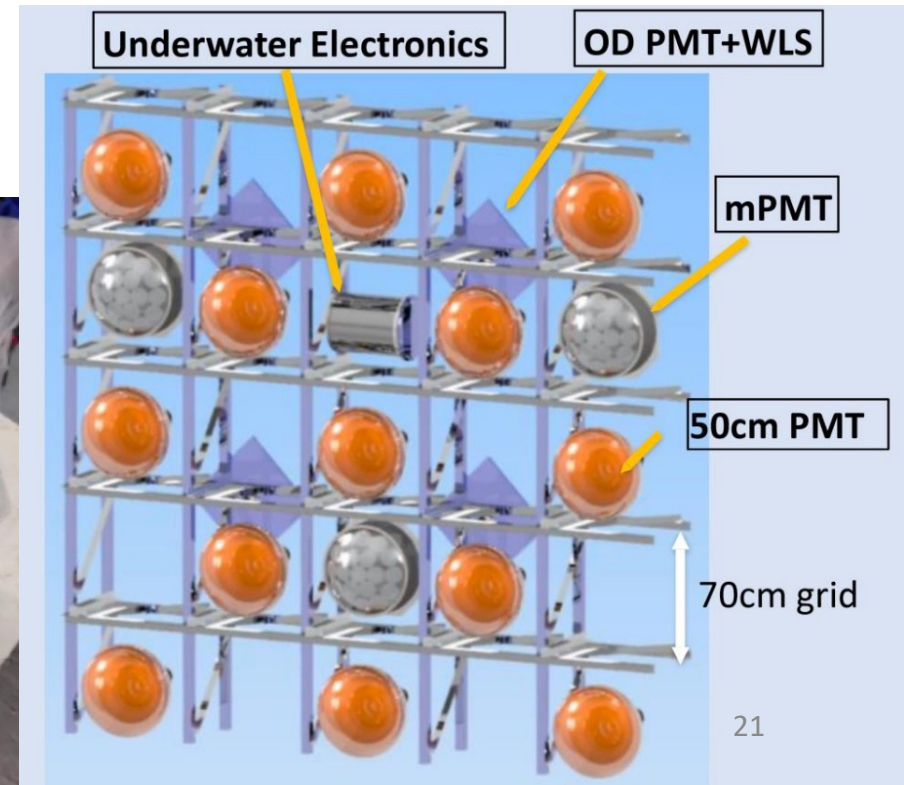
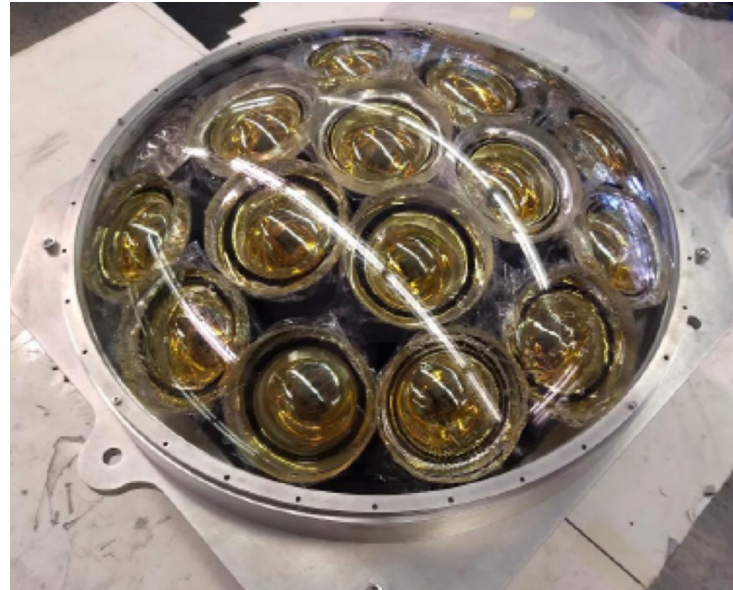


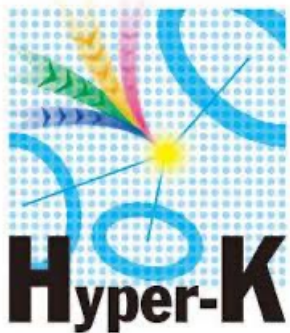
Hyper-K TDR <https://arxiv.org/pdf/1805.04163>



KM3NET/IceCube style multi-PMTs
Better timing and angular resolution.

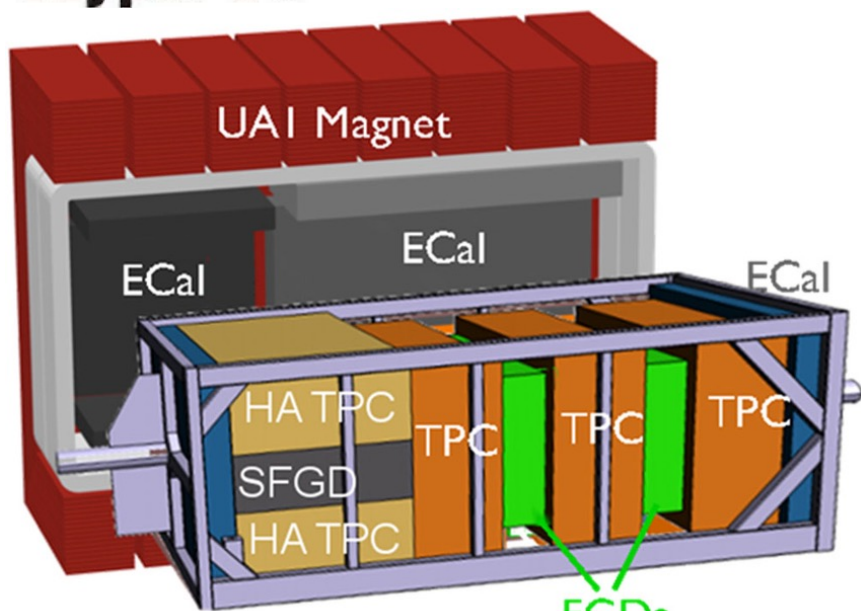
Better ring separation and light-absorption constraint





ND280 Upgrade

Hyper-K will inherit the suite of near detectors from T2K
Including magnetized off-axis detector ND280



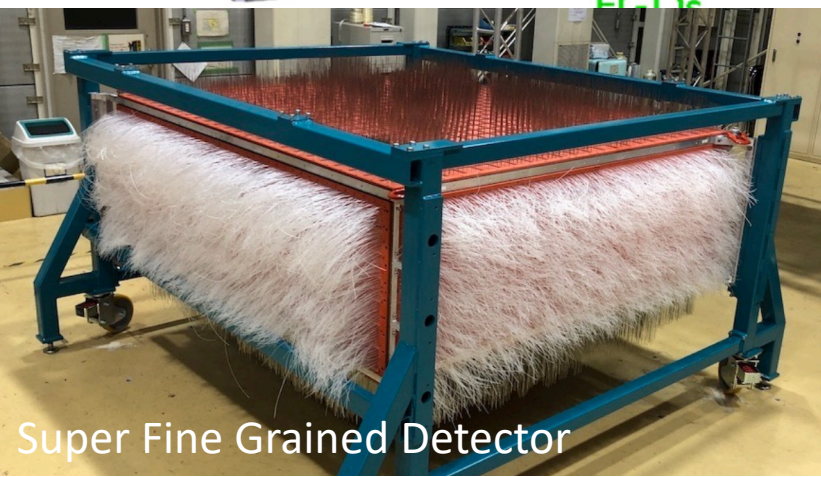
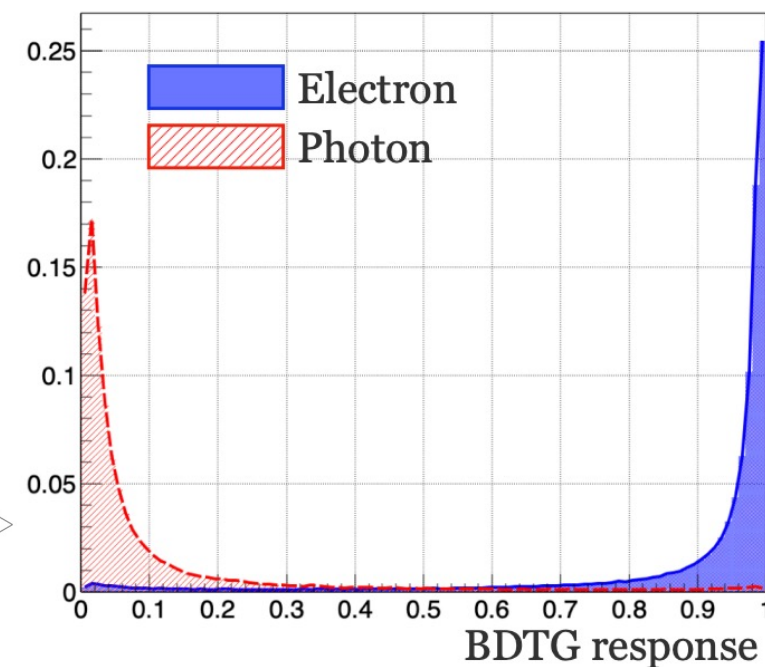
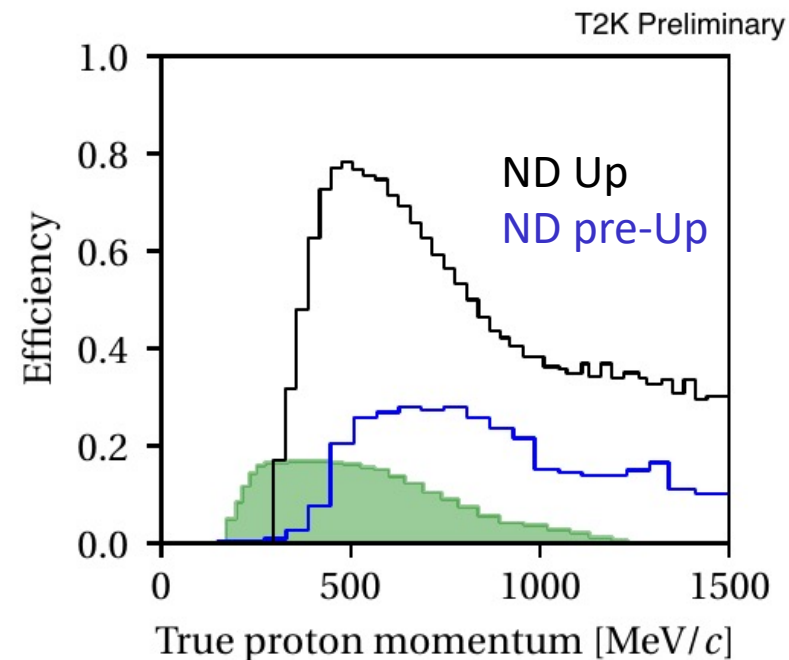
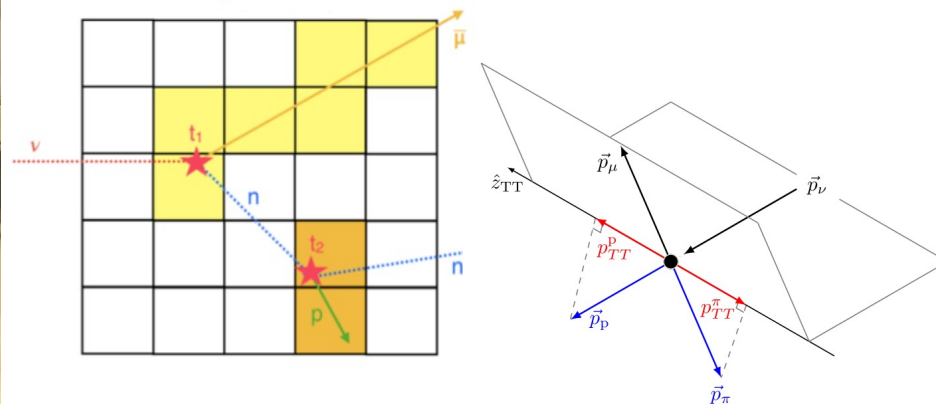
Full 3D readout plastic scintillator target detector SFGD

Improved muon acceptance and hadron efficiencies

Double mass of existing targets

Improved electron-photon discrimination

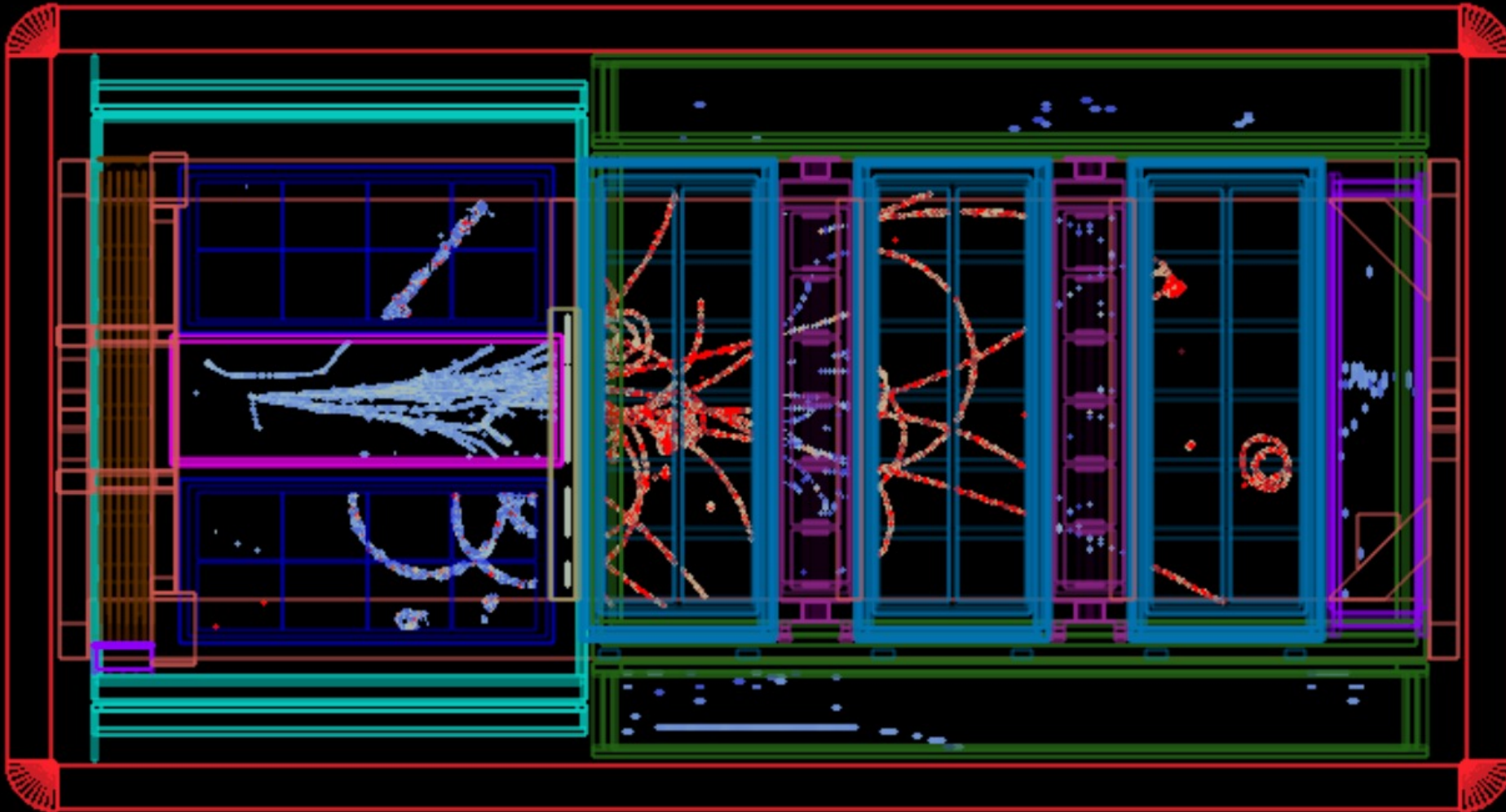
Neutron tagging and kinematics from ToF
Allows more TKI variable measurements

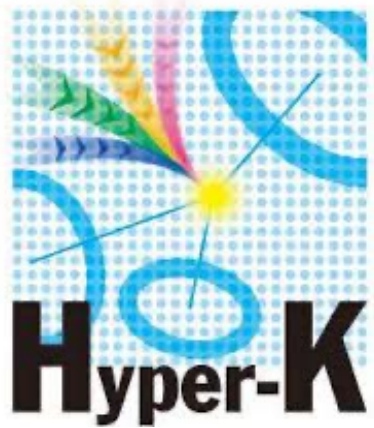


Super Fine Grained Detector

T2K is already taking data in upgraded ND280 at over 750 kW

Event number : 345342 | Run number : 16847 | Spill : 28852 | Time : Fri 2024-06-07 18:29:00 JST | Trigger: Beam Spill





Intermediate Water Cherenkov Detector

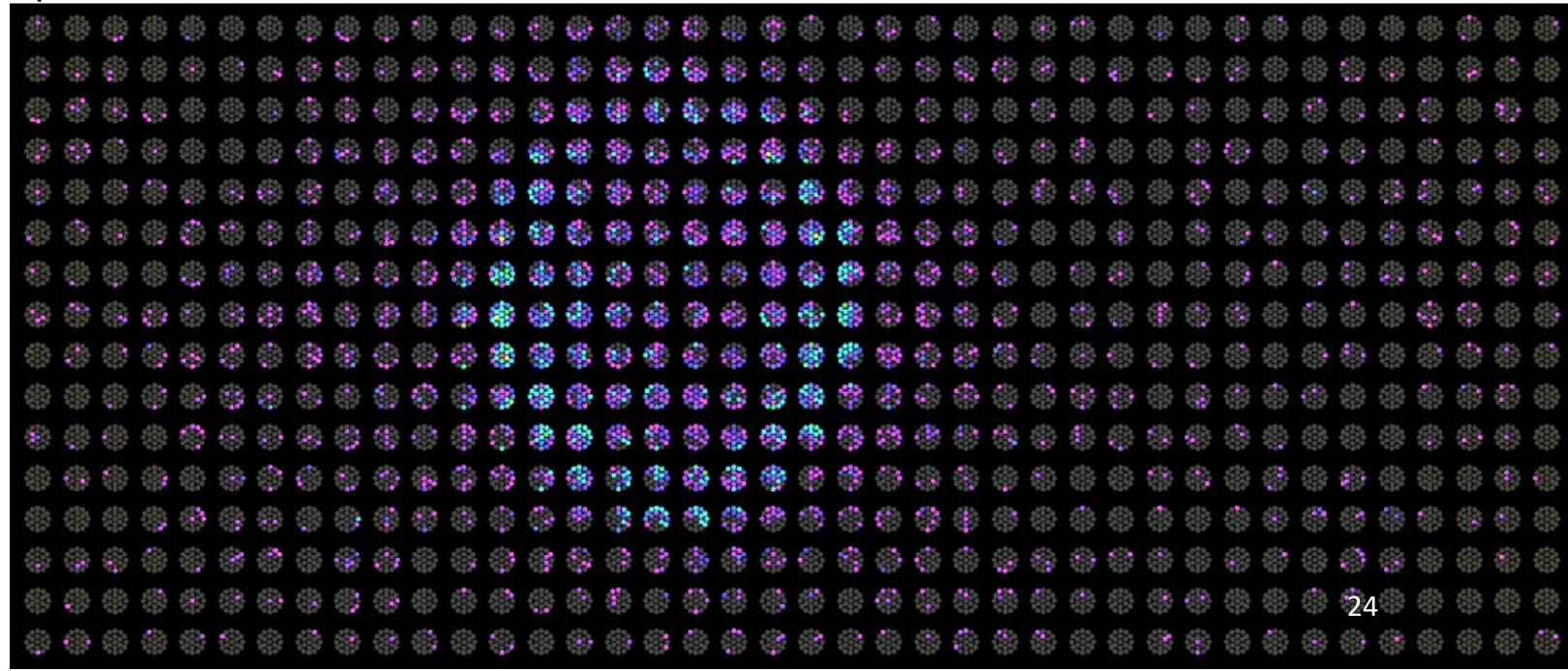
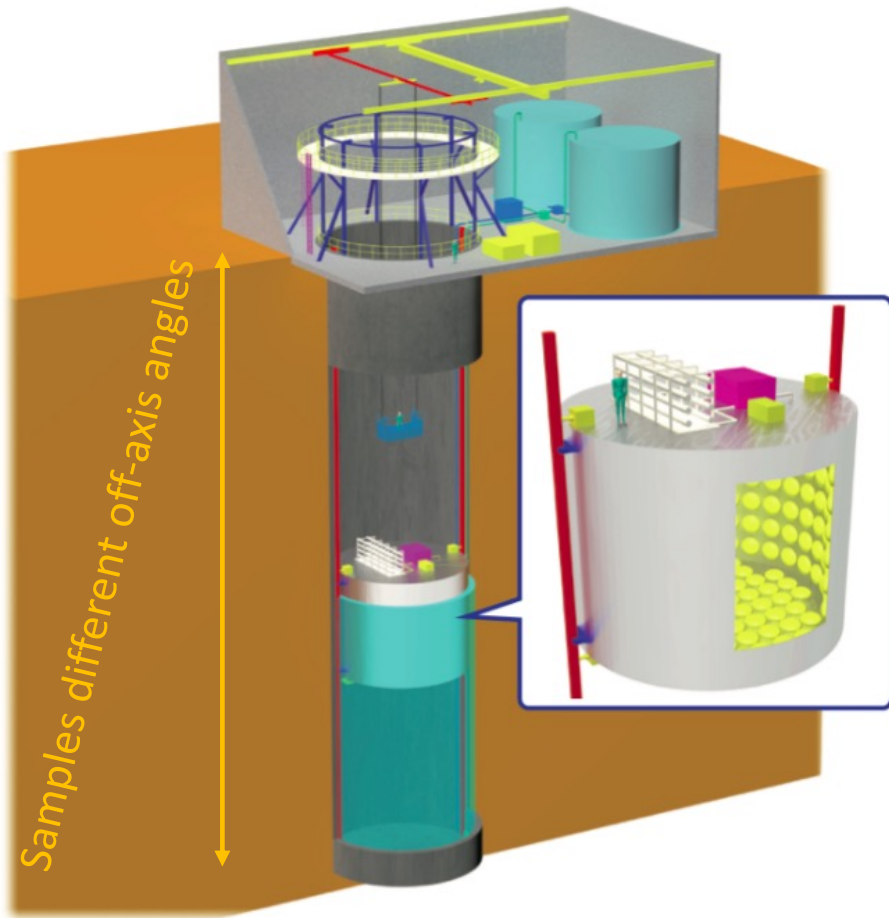
Hyper-K will supplement the existing suite of T2K near detectors with a Water Cherenkov detector at 830 m capable of sampling different off-axis spectra

Same detection principle and target material as HK FD
Benefits from more direct cancellation of systematics

More finely instrumented with mPMT modules

Large size is self-shielding of OOFV γ background to ν_e

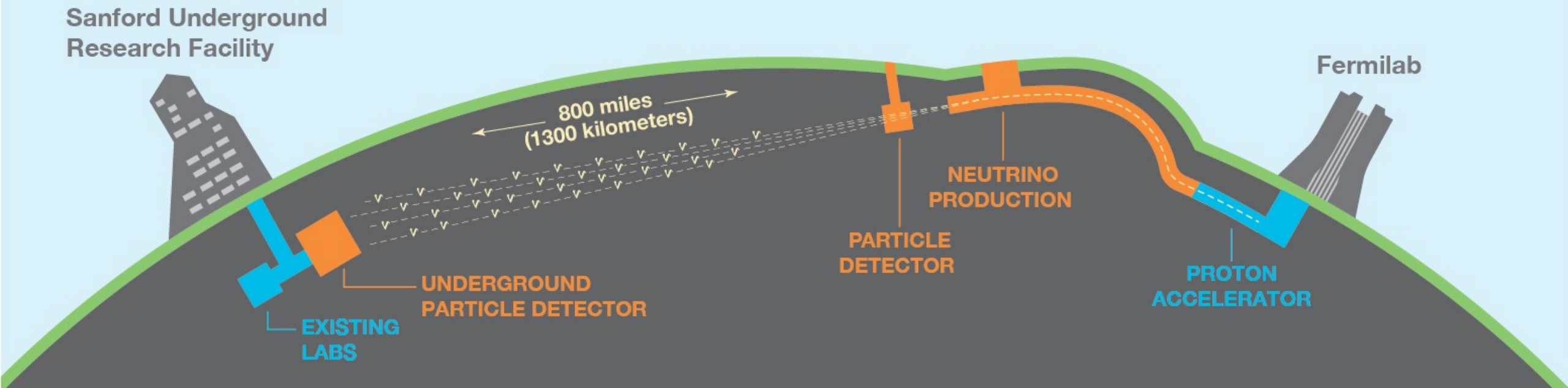
Complimentary sensitivity to ND280 - Much higher ν_e rate to understand ν_e/ν_μ cross section and detection systematics





DEEP UNDERGROUND NEUTRINO EXPERIMENT

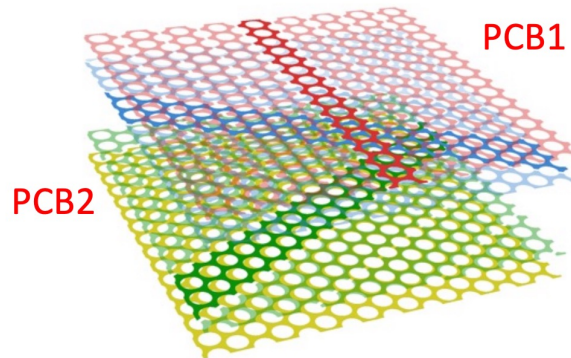
[See Gustavo Valdivieso's talk for more details](#)



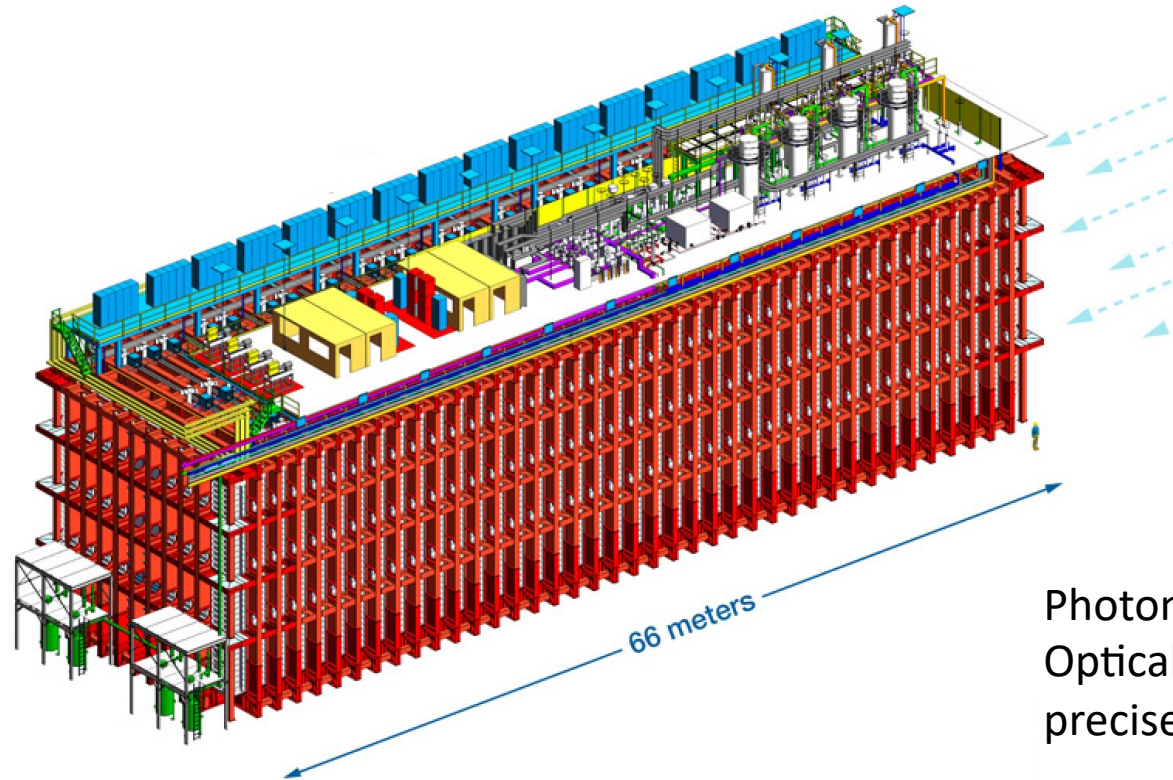
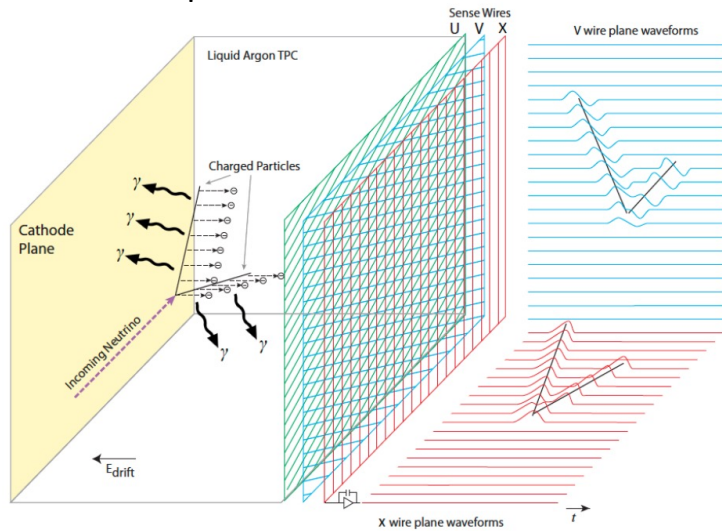
DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Perforated readout strips in Vertical Drift



Wireplane in Horizontal Drift



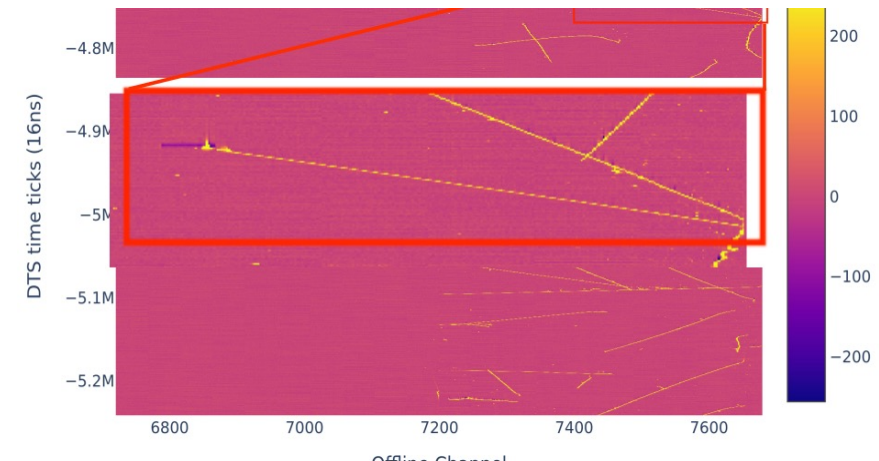
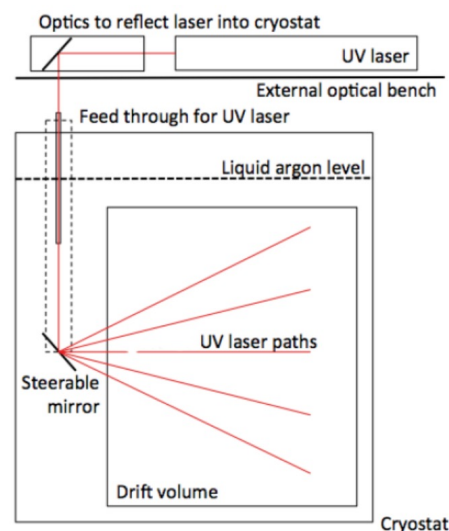
2-4 10 kt FV LAr-TPC detectors

Horizontal Drift:
Wire plane readout

Vertical Drift:
Copper strip charge amplifier
readout planes

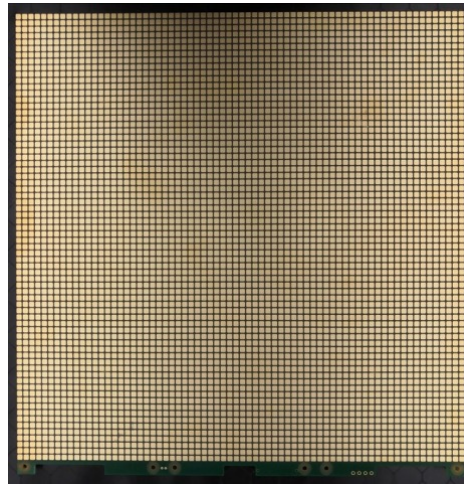
Photon detection system including
Optical X-ARAPUCA detectors provide
precise t_0 for events

Laser ionization calibration system for E-field
uniformity [See talk by José Maneira](#)



DUNE

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

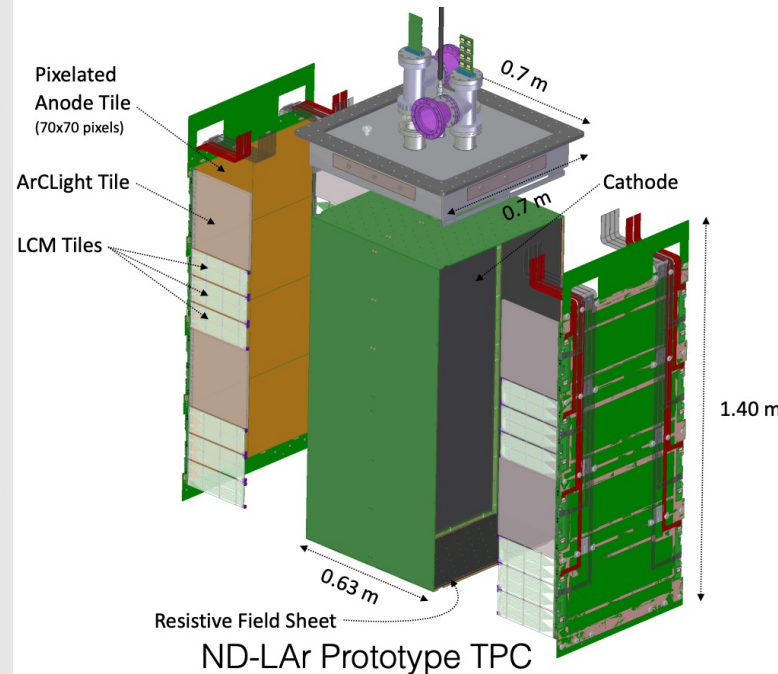
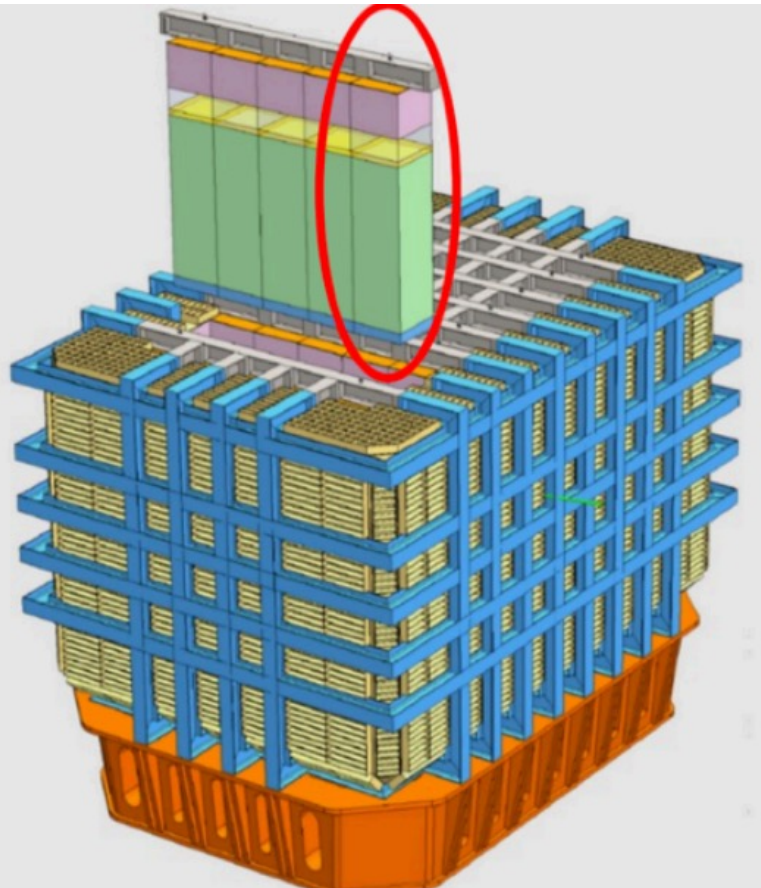
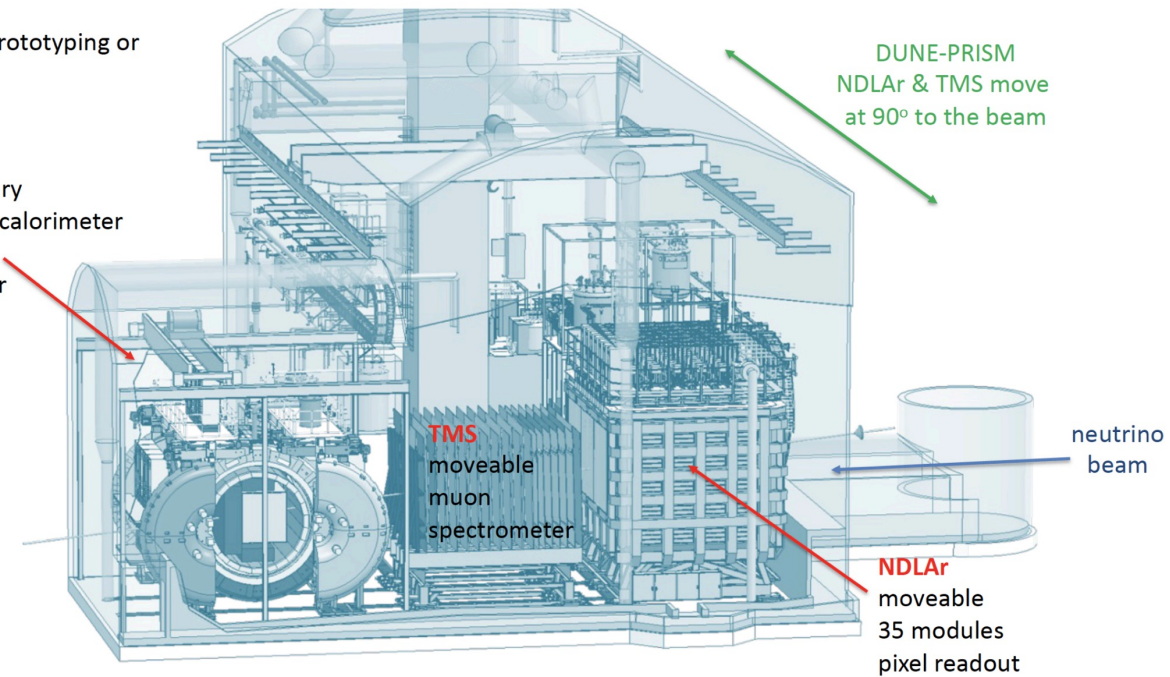


Prototype Pixel readout plane

All systems in prototyping or preparation

SAND

on-axis, stationary
KLOE magnet & calorimeter
Straw Tubes
GRAIN: 1 ton LAr



Movable Segmented LAr-TPC with pixel readout

Segmentation leads to smaller drift lengths and better pile-up separation

TMS muon spectrometer catches forward going muons to account for ND-FD acceptance difference and determine wrong-sign contamination

[See Zoya Vallari's talk](#)

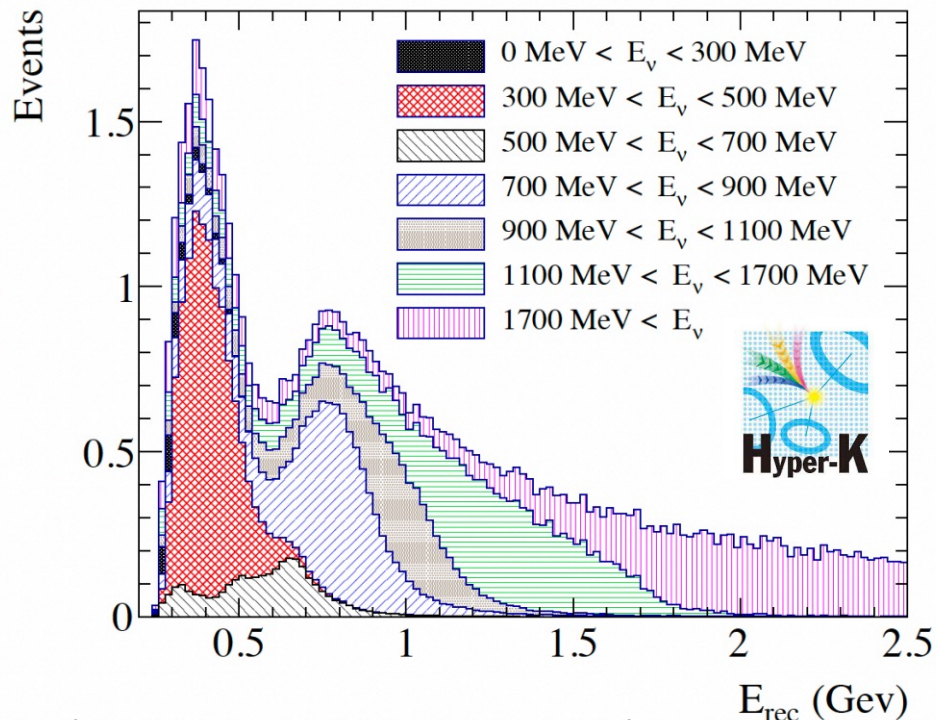
PRISM

PRISM

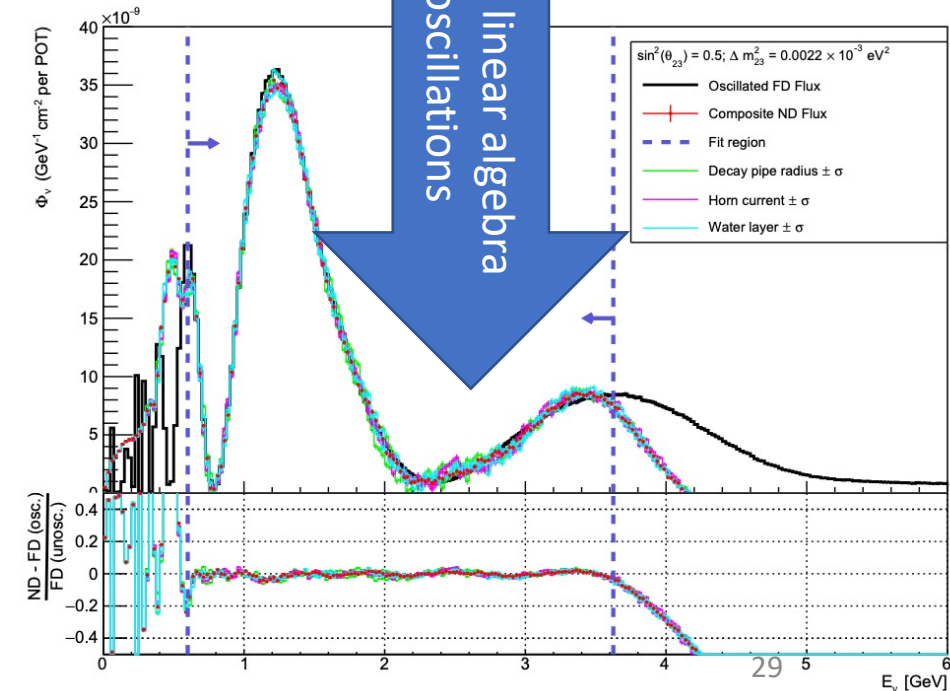
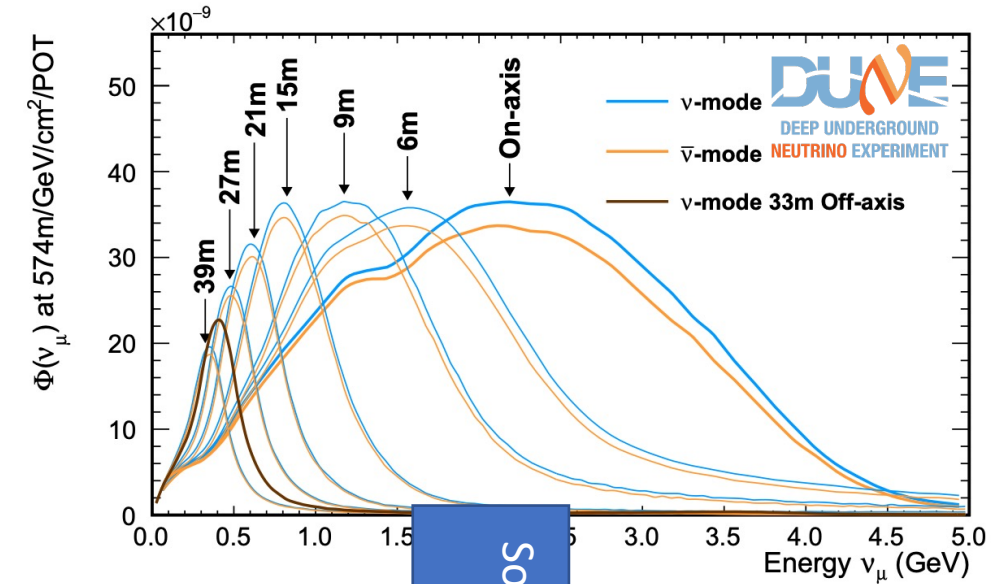
[See Akutsu-san's talk for more details](#)

Predicting amount of neutrino energy which is misreconstructed is model dependent.

What if we use a linear combination of ND fluxes to create FD flux and minimize interaction model dependence



Predicted true neutrino energy contributions to reconstructed neutrino energy at Hyper-K far detector



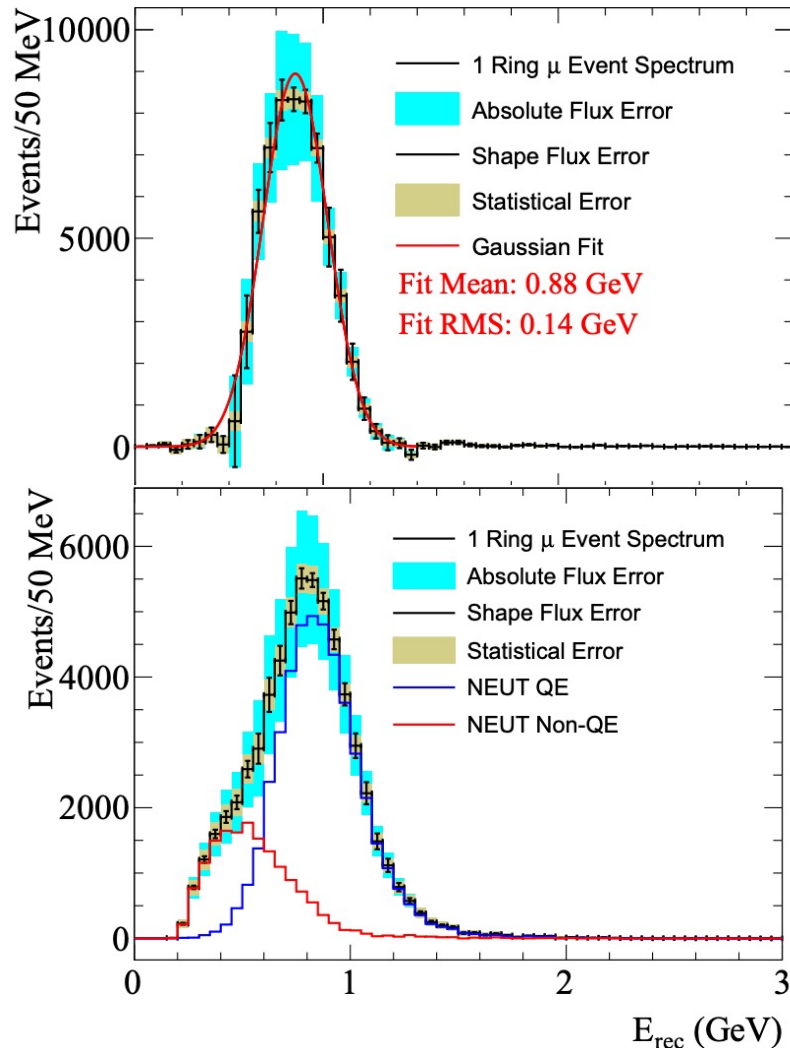
PRISM

[See Akutsu-san's talk for more details](#)



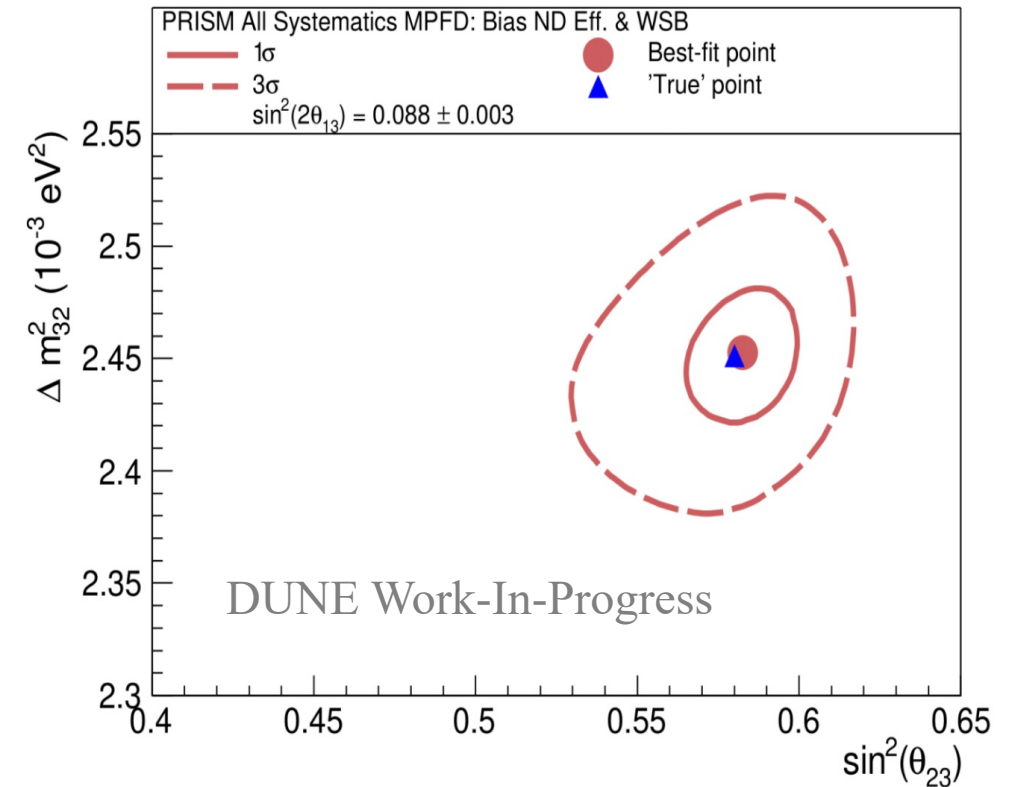
Pseudo-monochromatic neutrino spectra

Linear Combination, 0.9 GeV Mean



<https://arxiv.org/abs/1412.3086>

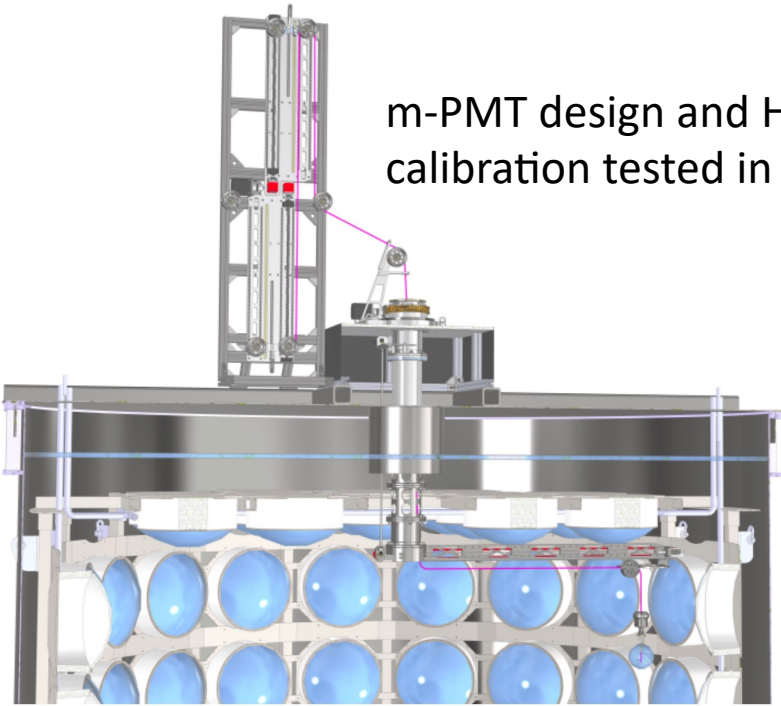
DUNE PRISM analysis sensitivity with wrong interaction model



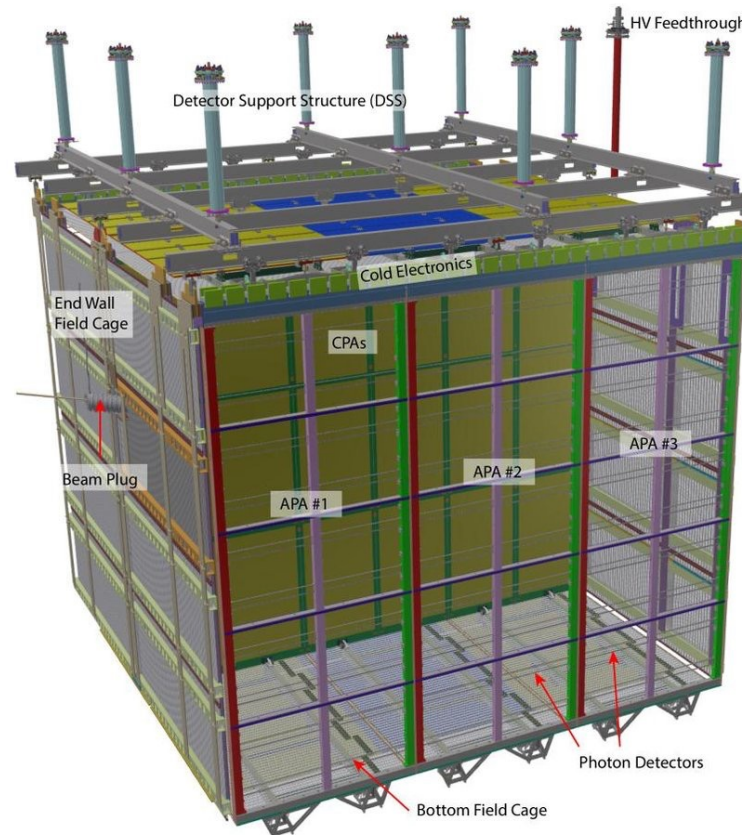
Other measurements

Prototypes

Prototypes in test beams help us understand the detectors we are building.

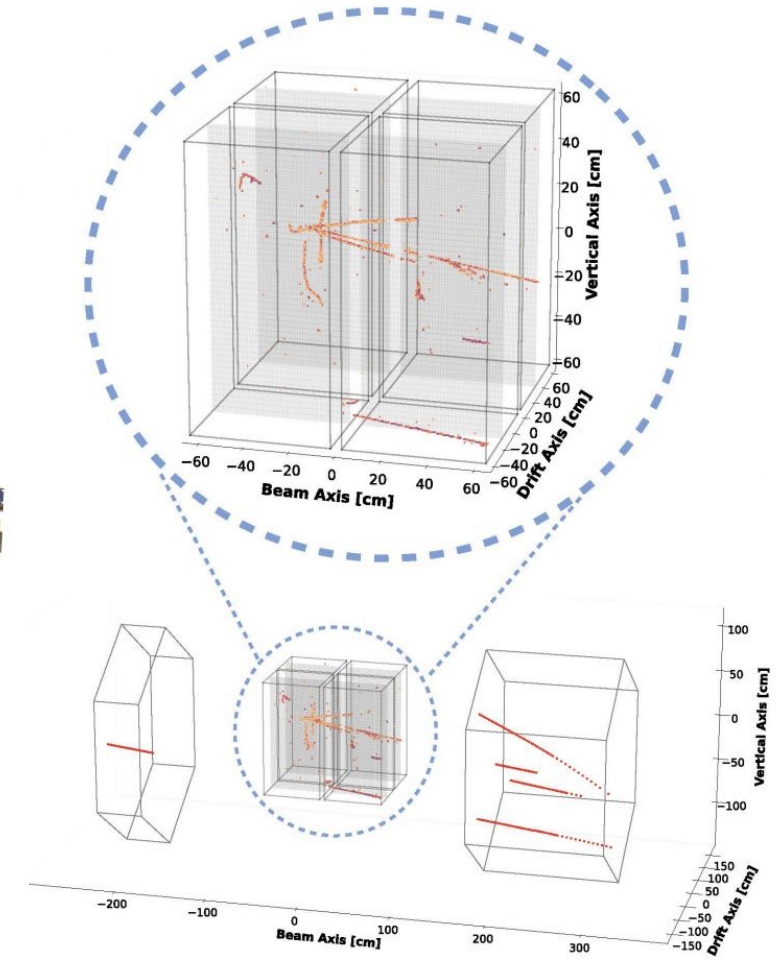


ProtoDUNE and other LAr detectors successfully testing LAr-TPC readout and calibration systems



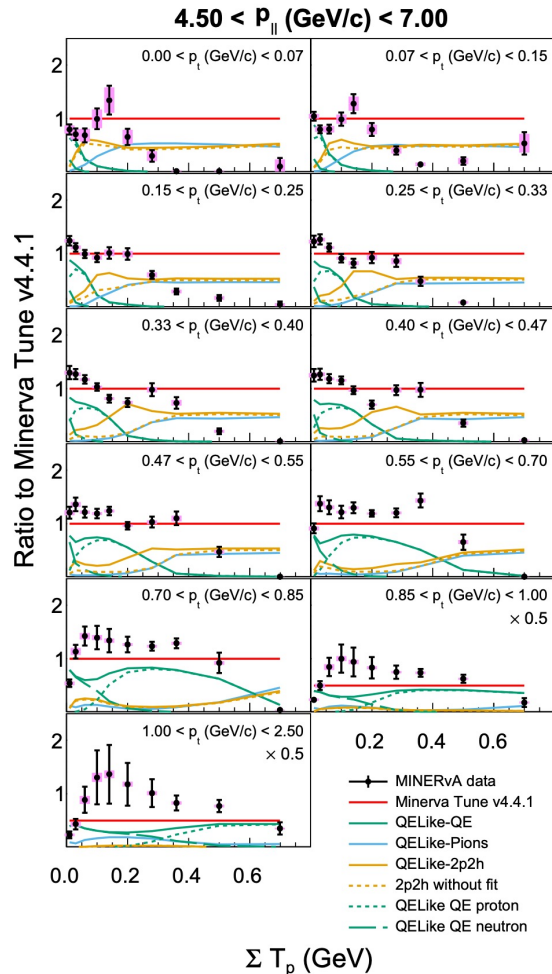
DUNE DEEP UNDERGROUND
NEUTRINO EXPERIMENT

2024-07-11 19:52:24 UTC



External Measurements

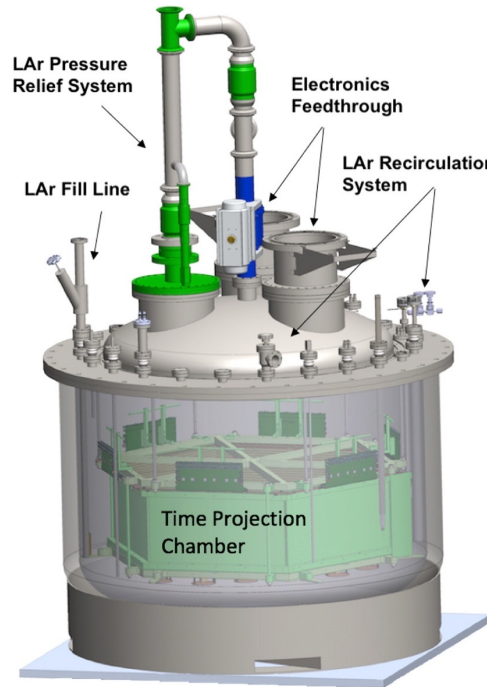
Mix of both neutrino and non-neutrino experiment data can feed into modeling



Healthy cross section community helps keep pushing forward on model development

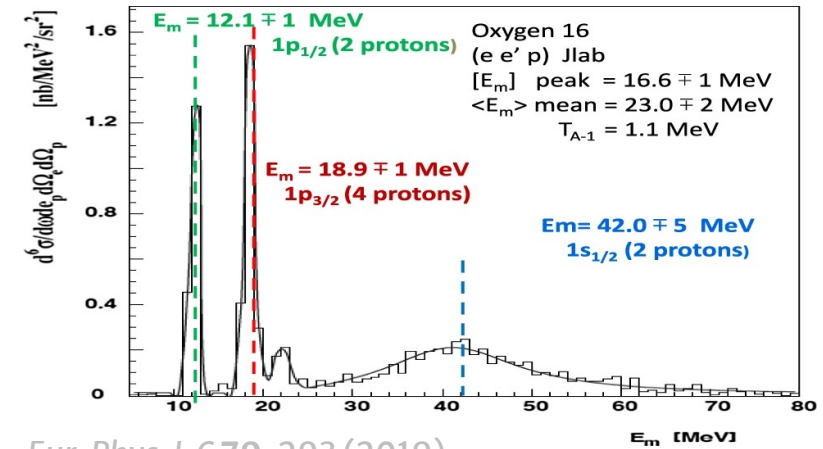
There are non-neutrino experiments which can tell us about both neutrino interactions and the modeling of final state particles

mini-CAPTAIN LAr-TPC in neutron beam at LANSCE

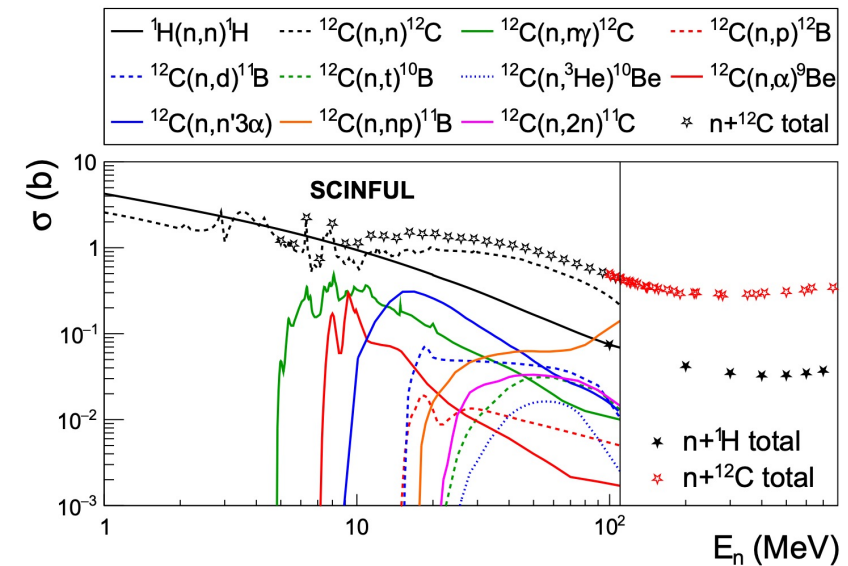


MINERvA 3D lepton-proton correlation measurement

Electron scattering data can help us learn more about the ground state of the nucleus



Eur. Phys. J. C **79**, 293 (2019)



Dedicated neutron scattering experiments at relevant energies

Outlook

Outlook

Next generation experiments will be systematically dominated

- Need robust models and measurements to remain unbiased
- Near detectors are a powerful tool for characterizing our sources
- Prototypes help us understand the performance of these technologies
- External measurements by dedicated experiments are valuable
- Model-independent approaches can reduce our susceptibility to bias

We can do the work now to prepare for the data we will very rapidly collect with these new 10s kt to 100s kt scale detectors and high intensity sources

Obrigado!

Backup

Robustness Studies

“Fake Data Studies”

Test for out-of-model effects which could bias results

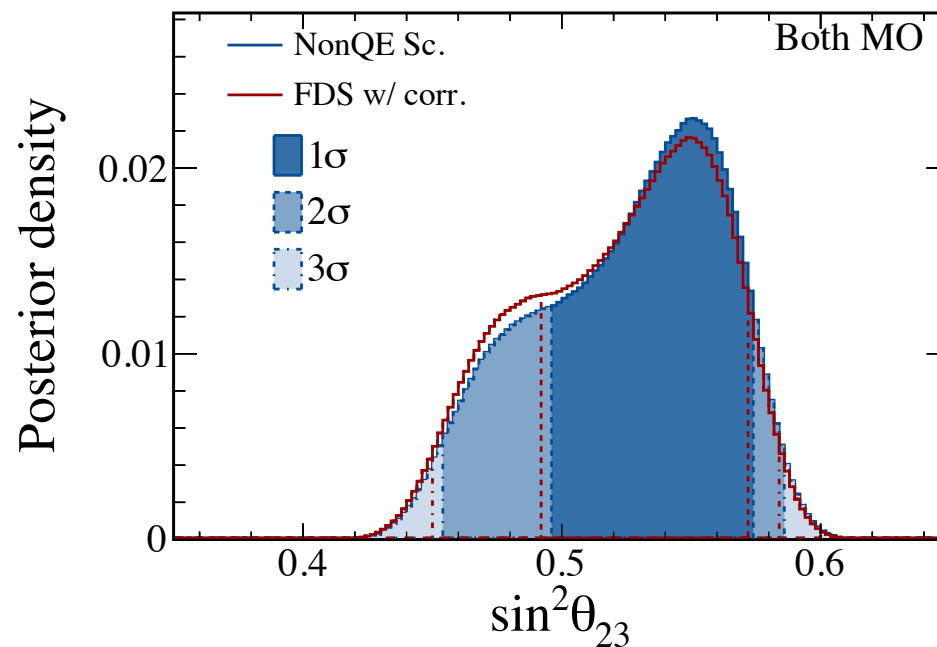
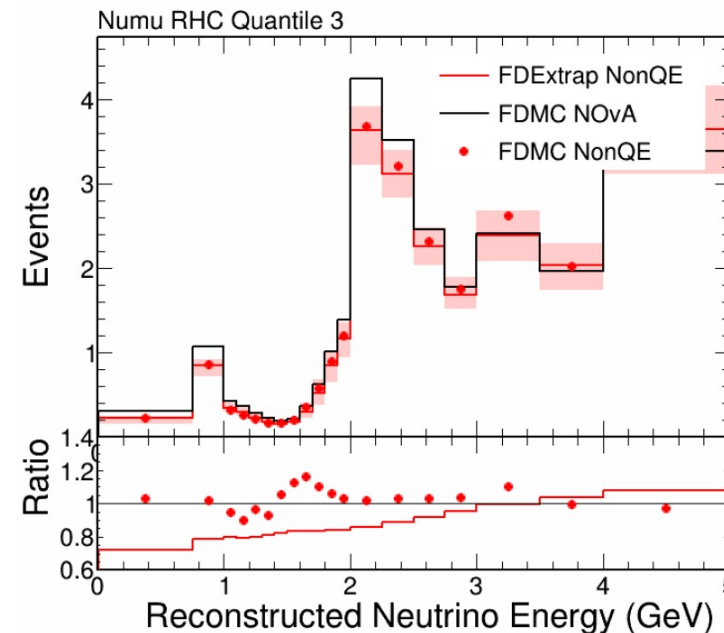
Generate “fake data” – a modified set of the nominal MC to include variations not deliberately included in the uncertainty model

Fit model at ND or use ND tune to predict FD fake data spectra

Check shifts in credible interval positions and sizes are not large relative to systematic uncertainty contribution

Perform this procedure at key several different oscillation parameter combinations of interest

Future experiments may wish to expand this through by testing compatibility with model cloud and not just central values



Example from joint NOvA-T2K analysis based on T2K ND280 CC0 π data

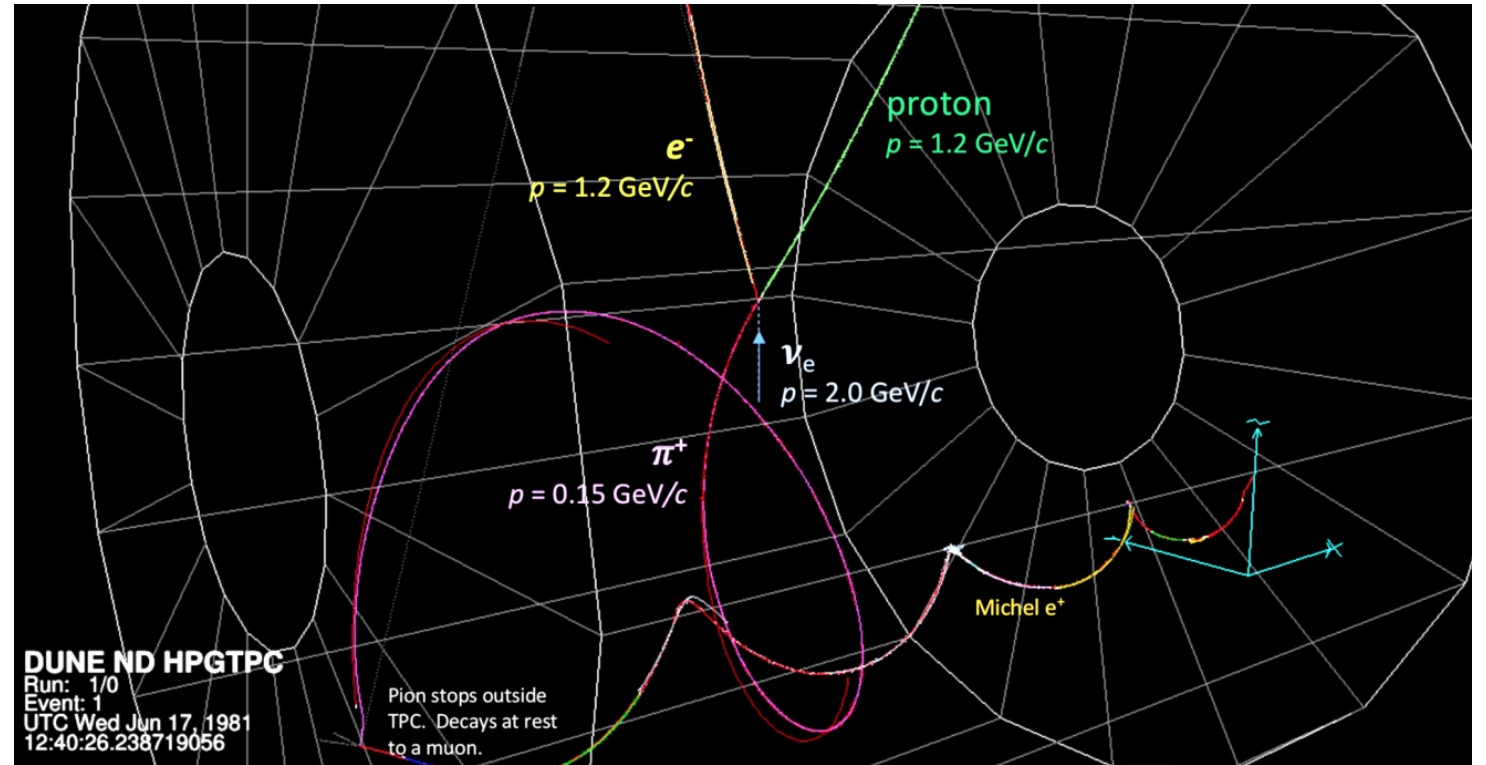
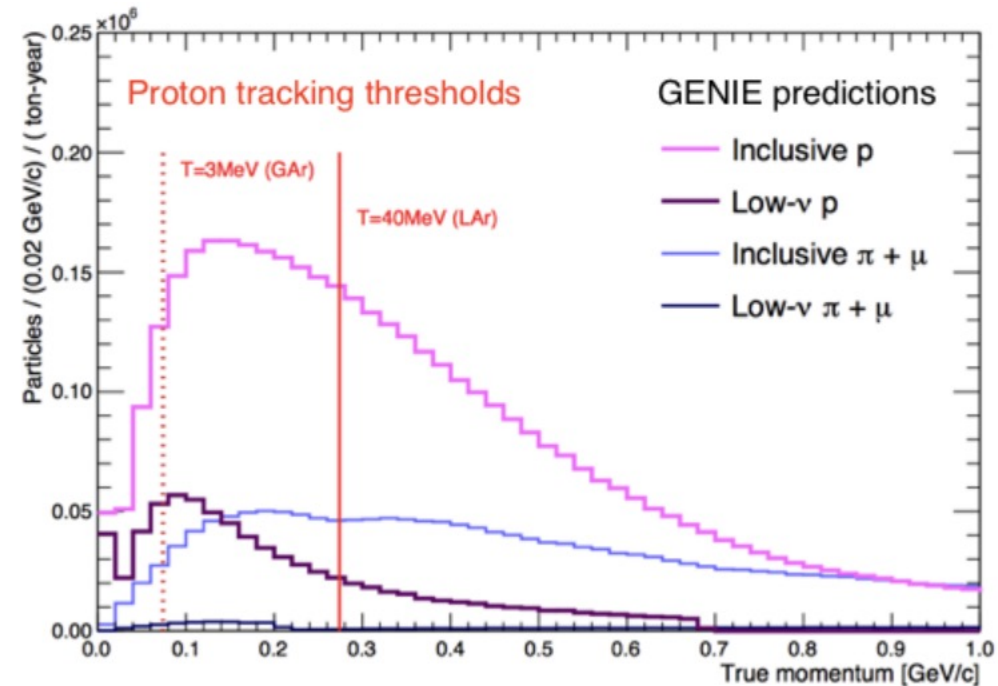
ND-GAr

Magnetized High-Pressure gaseous Argon
TPC

Dense enough to collect appreciable statistics

Lower tracking thresholds and more precise
momentum and PID

<https://arxiv.org/pdf/1910.06422>



ND280 Upgrade

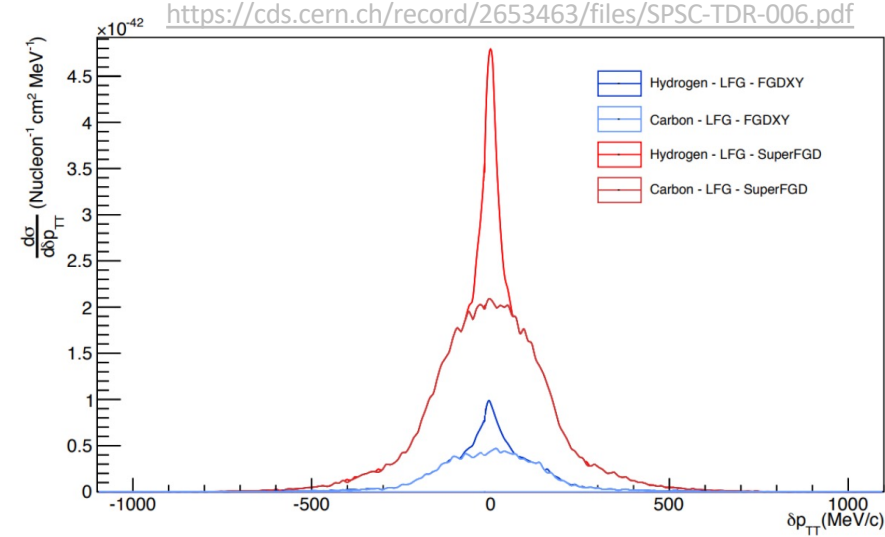
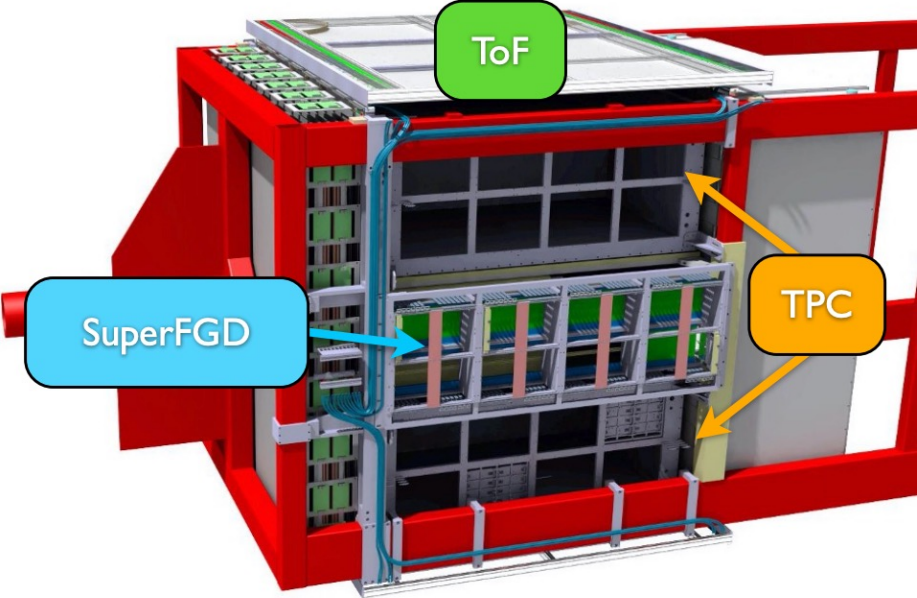
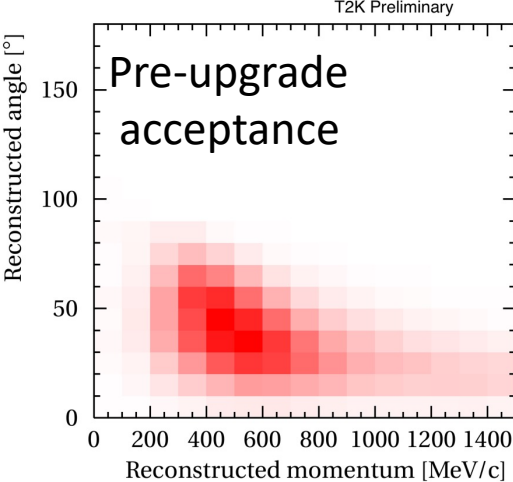
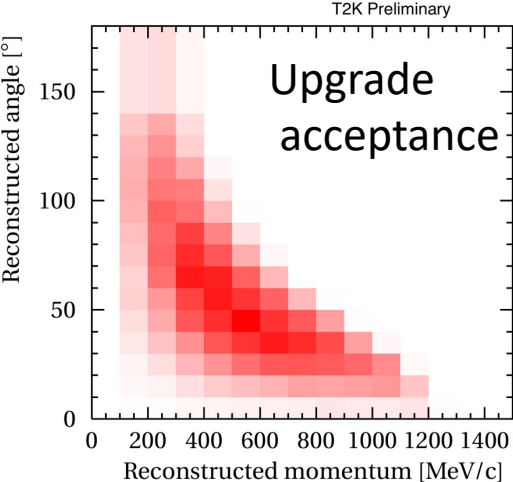
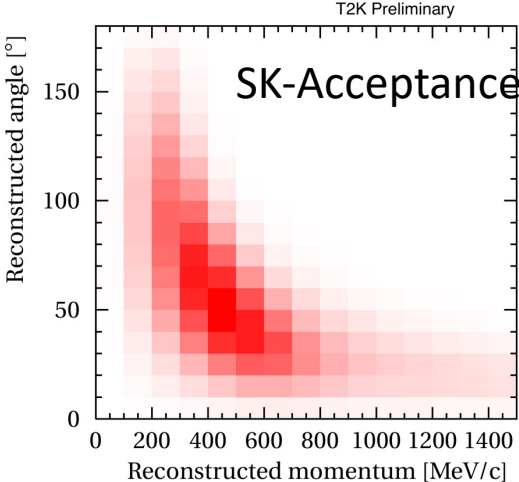


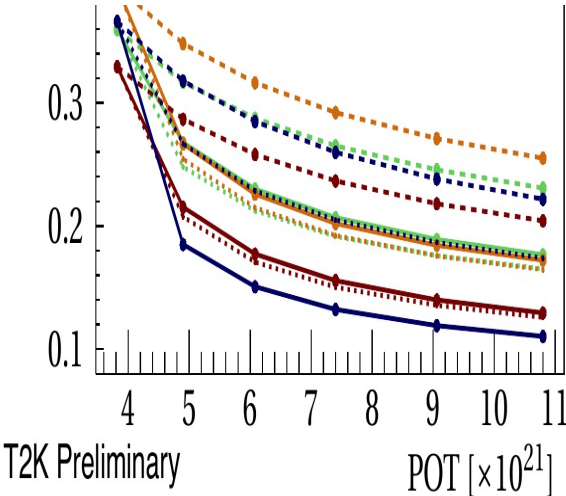
Figure 6.21: Comparison of the ability of a SuperFGD and an FGD XY to measure δp_{TT} . The y-axis reports the CCQE-like cross section within the phase space accessible by the relevant detector. Detector smearing and acceptance effects are applied as described in Sec. 6.5.2.



ND280 now has a much closer match in angular acceptance to WC dets



Improved constraint on Xsec systs



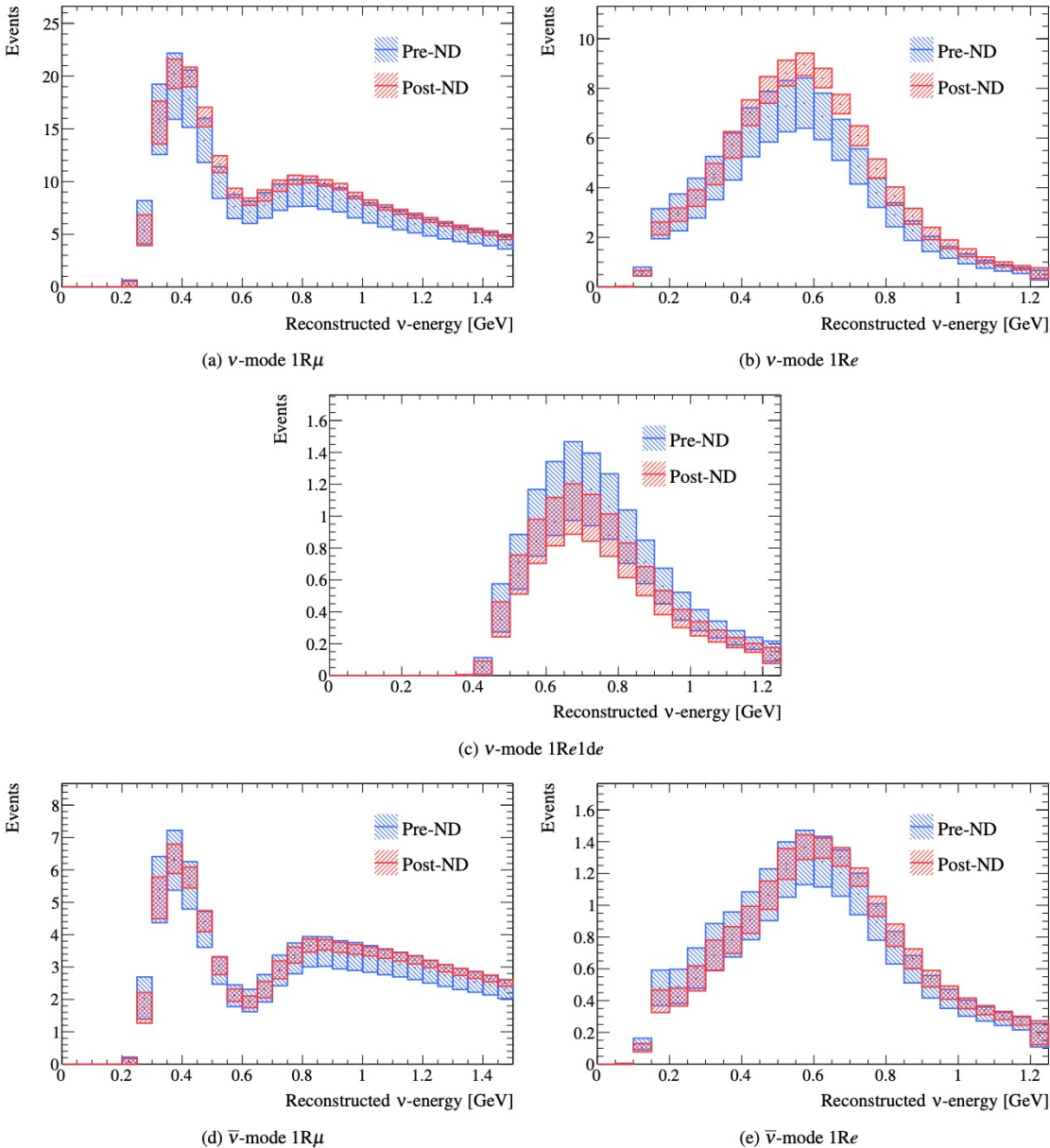
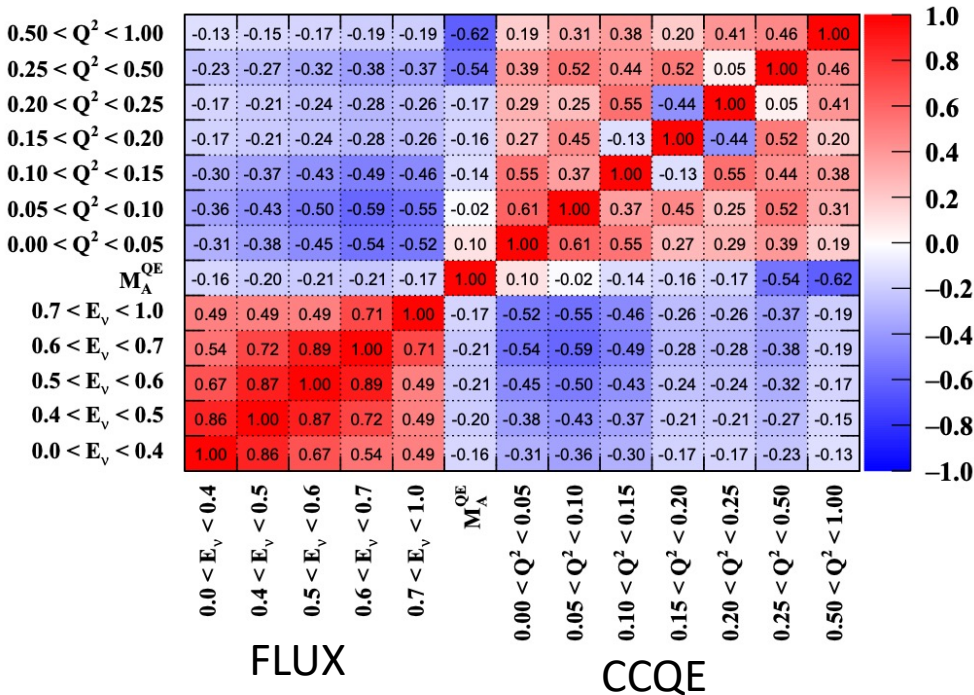
Dashed= pre-upgrade
Dotted=Upgrade muon only
Solid=Upgrade muon + proton

- Nucleon FSI
- M_A^{QE}
- CCQE High Q² norm. 1
- CCQE High Q² norm. 2
- CCQE High Q² norm. 3

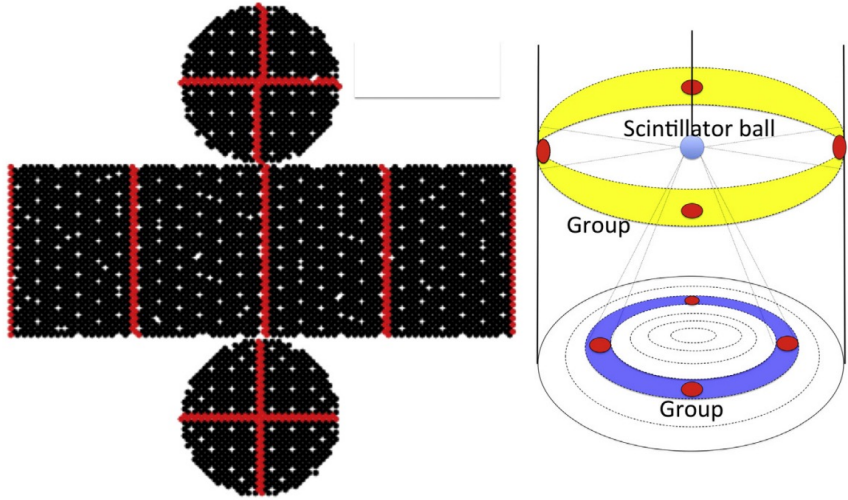
Impact of pre-upgrade ND280 in T2K analysis on Super-K predictions

Sample		Uncertainty source (%)			Flux $\otimes$ Interaction (%)	Total (%)
		Flux	Interaction	FD + SI + PN		
1R μ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)

[Eur. Phys. J. C 83, 782 \(2023\)](#)

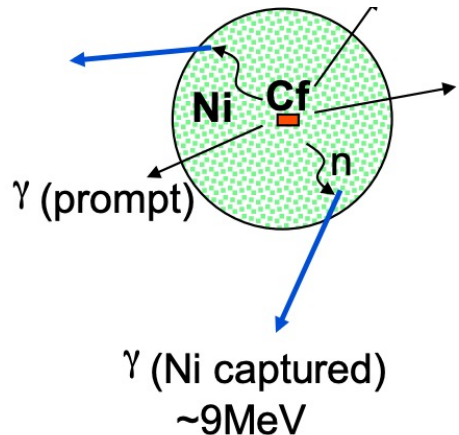


Calibration methods in WC and LS detectors

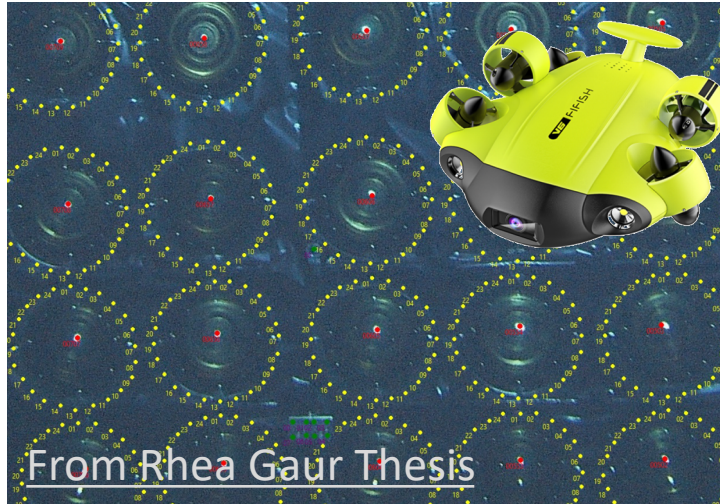


Scintillator used to produce photons in SK
light-injection systems common in scintillator
detectors

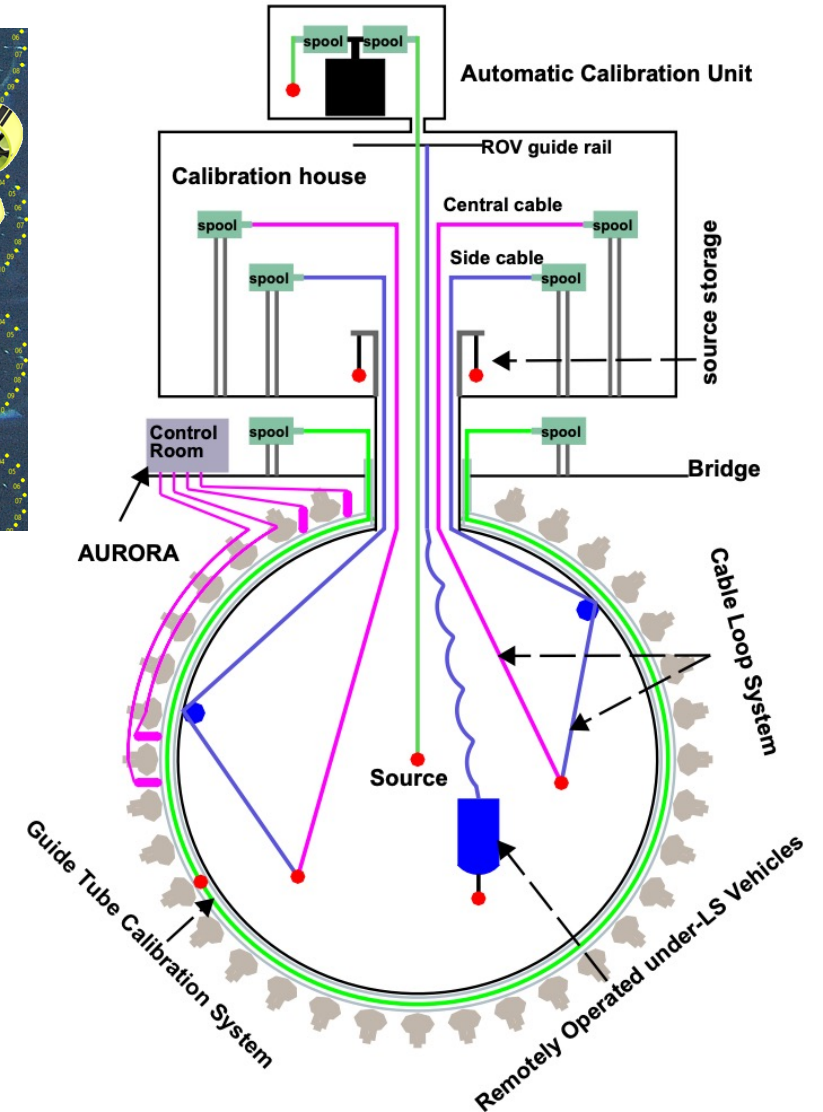
<https://arxiv.org/abs/1307.0162>



Cf source coupled with n-
capture Ni target
Can test prompt+neutron
capture coincidence



Photogrammetry can be used to
measure detector geometry using
underwater survey drones



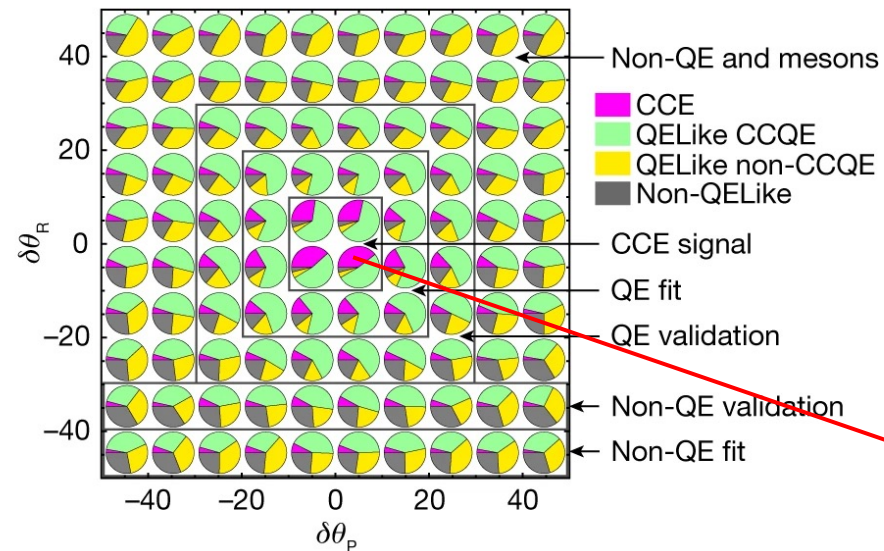
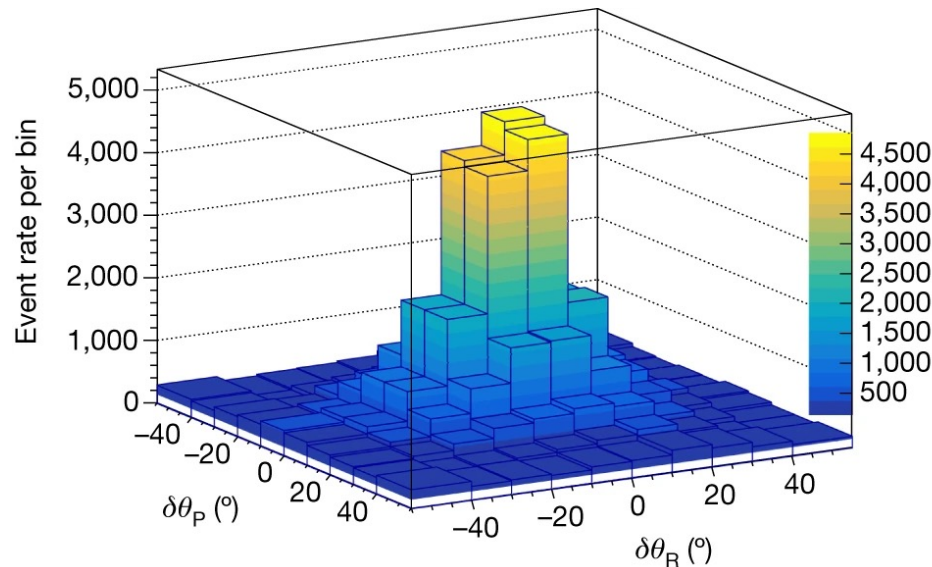
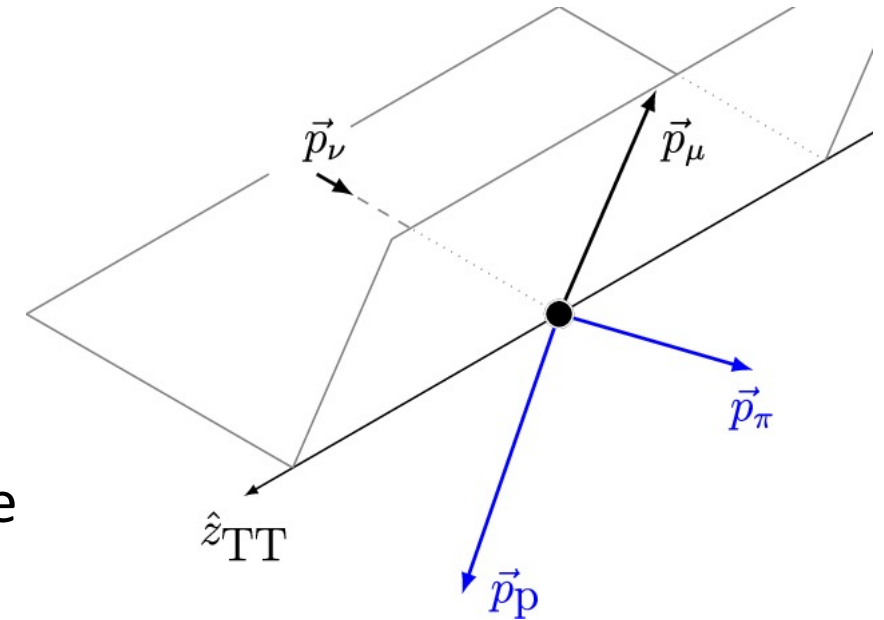
JUNO calibration system uses fixed and cable
movable sources as well as maneuverable
vehicles <https://arxiv.org/pdf/2011.06405>

Free-proton measurements

Exploit FS-kinematic differences between free-proton and nuclear target data

Allows for better understanding of nuclear effects

MINERvA has shown this works,
ND280 Upgrade should have even better performance to resolution and timing



Hydrogen enriched



JUNO-only systematics

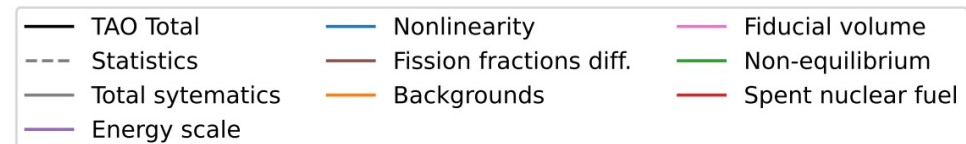
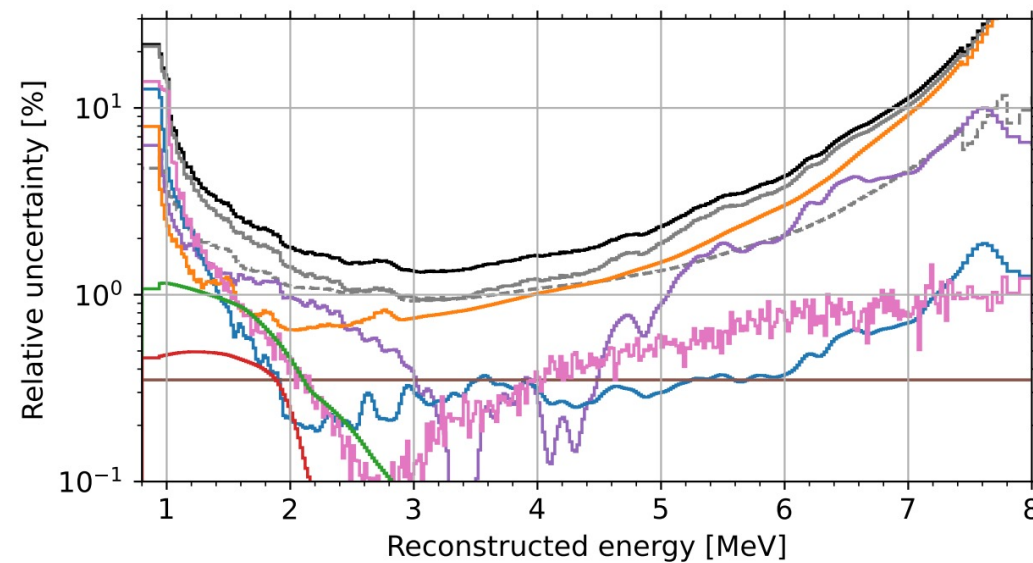
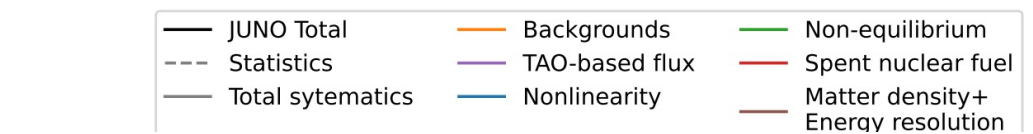
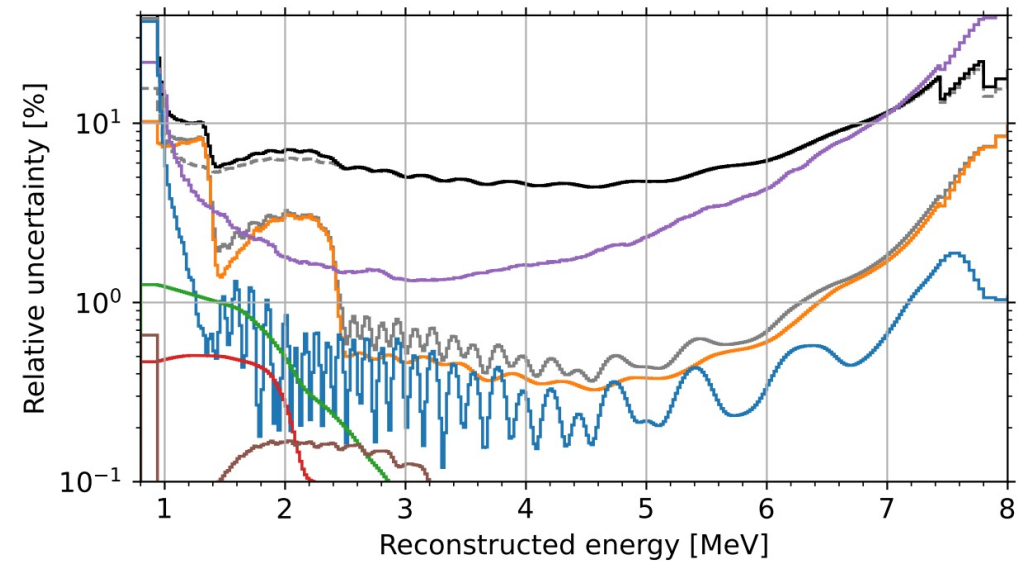
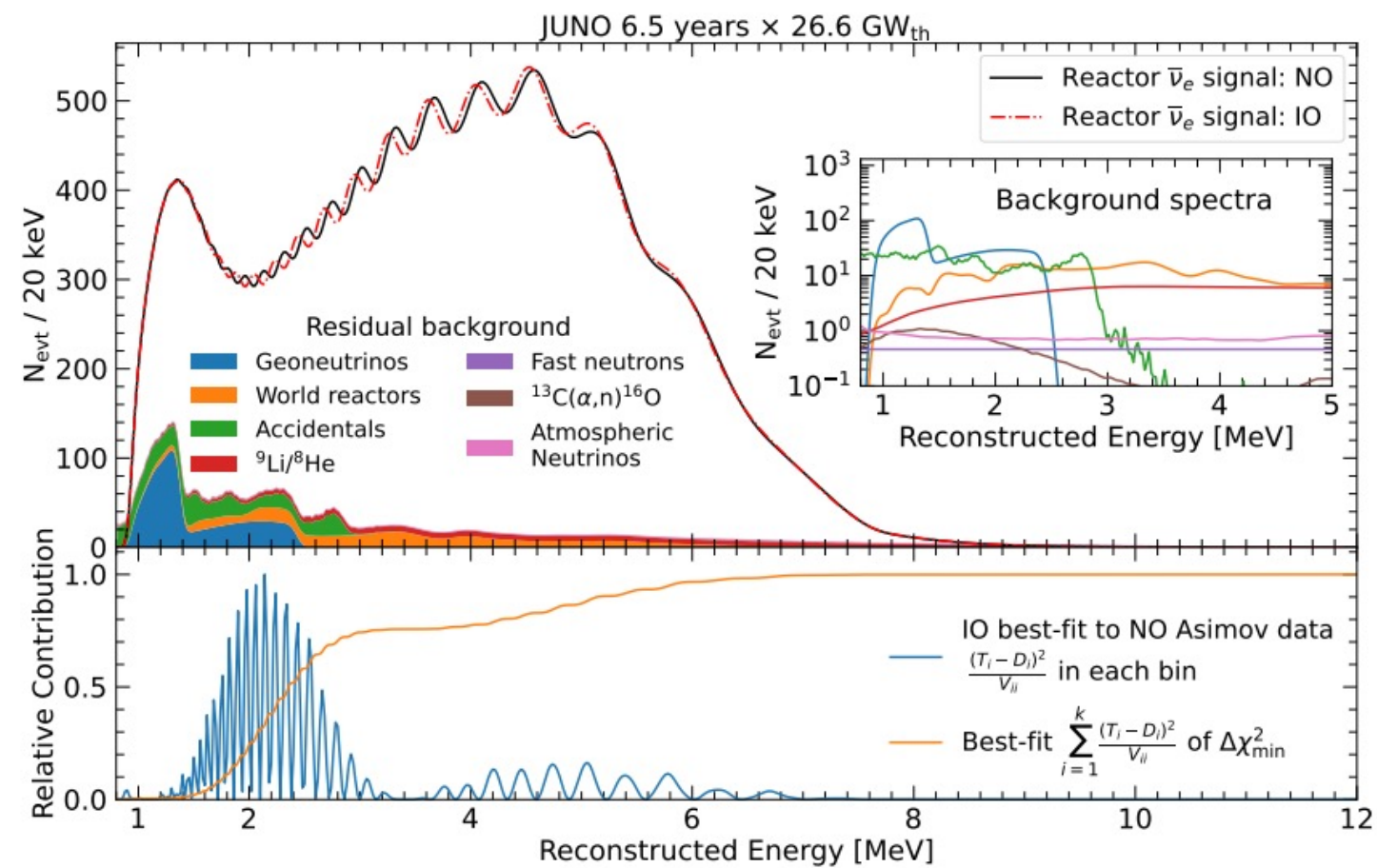
Systematic effect	Number of parameters	Relative uncertainty [%]	
		input	rate
JUNO systematic uncertainty	{13+340}		1.4
$\sin^2 \theta_{13}$	1	3.2	0.13
Matter density (MSW)	1	6.1	0.062
Detector normalization	1	1.0	1.0
Energy resolution	3	0.77, 1.6, 3.3	5.4×10^{-7}
Background rates	{7}		0.96
Accidentals	1	1.0	0.019
$^9\text{Li}/^8\text{He}$	1	20	0.37
Fast neutrons	1	100	0.23
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	1	50	0.058
Geoneutrinos	1	30	0.84
Atmospheric neutrinos	1	50	0.19
World reactors	1	2.0	0.046
Background shape	340		0.033
$^9\text{Li}/^8\text{He}$	(340)	10	0.012
Fast neutrons	(340)	20	0.0026
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	(340)	50	0.0053
Geoneutrinos	(340)	5.0	0.026
Atmospheric neutrinos	(340)	50	0.011
World reactors	(340)	5.0	0.010
IBD spectrum shape uncertainty from TAO	340	1.3 – 45	0.35

TAO-only systematics

Systematic effect	Number of parameters	Relative uncertainty [%]	
		input	rate
TAO	{4+340}		10
Detector normalization	1	10	10
Energy scale	1	0.50	0.0018
Accidentals' rate	1	1.0	0.20
$^9\text{Li}/^8\text{He}$ rate	1	20	1.2
Bin-to-bin	340		0.086
$^9\text{Li}/^8\text{He}$ shape	(340)	10	0.038
Fast neutrons	(340)	0.36 – 5.0	0.016
Fission fractions difference	(340)	0.35	0.023
Fiducial volume	(340)	0.091 – 14	0.072

Systematics in MO sensitivity

Uncertainties	$ \Delta\chi^2_{\min} $	$ \Delta\chi^2_{\min} $ change
Statistics of JUNO and TAO	11.5	
+ Common uncertainty	10.8	−0.7
+ TAO uncertainty	10.2	−0.6
+ JUNO geoneutrinos	9.7	−0.5
+ JUNO world reactors	9.4	−0.3
+ JUNO accidental	9.2	−0.2
+ JUNO $^9\text{Li}/^8\text{He}$	9.1	−0.1
+ JUNO other backgrounds	9.0	−0.05
Total	9.0	



T2K constraint indicative of power of ND280 for constraining Hyper-K samples.

Upgraded ND280 collects roughly double statistics for same POT with higher acceptance better tracking thresholds

<https://arxiv.org/pdf/1805.04163>

TABLE IV. Current systematic uncertainty contributions to the T2K oscillation measurements taken from [91] and [92]

Source of uncertainty	ν_μ <i>CC</i>	ν_e <i>CC</i>	$\bar{\nu}_\mu$ <i>CC</i>	$\bar{\nu}_e$ <i>CC</i>
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%

Right: Expected postfit constraint on systematics relative to priors

<https://arxiv.org/pdf/2002.03005>

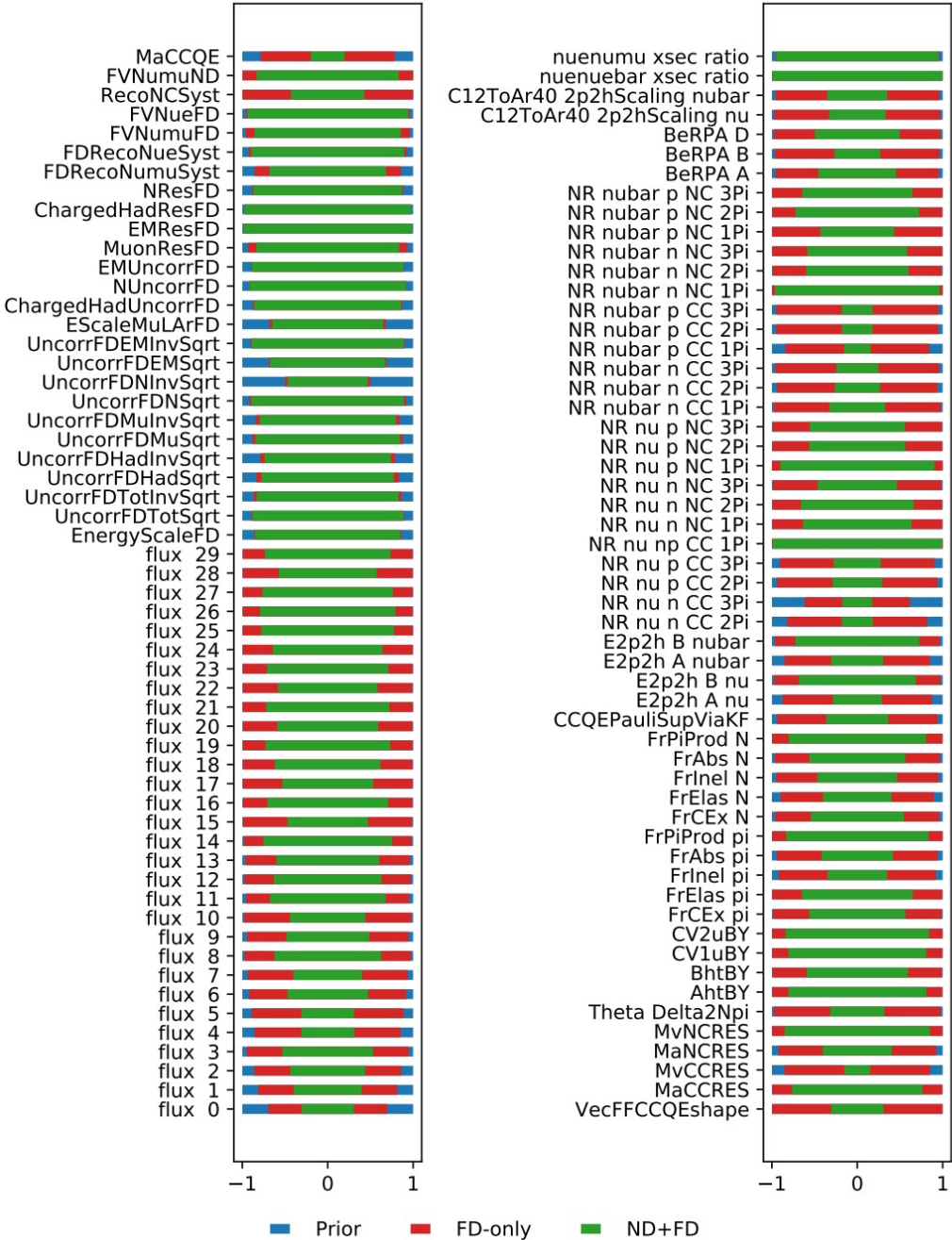


Table 4.1: Primary calibration systems and sources that comprise the nominal DUNE FD calibration design along with their primary usage.

System	Primary Usage
Existing Sources	Broad range of measurements
μ , predominantly from cosmic ray	Position (partial), angle (partial), electron lifetime, wire response, dE/dx calibration etc.
Decay electrons, π^0 from beam, cosmic, atm ν	Test of electromagnetic response model
^{39}Ar beta decays	electron lifetime (x,y,z,t), diffusion, wire response
External Measurements	Tests of detector model, techniques and systems
ArgoNeuT [86], ICARUS [87, 116, 117], MicroBooNE	Model parameters (e.g., recombination, diffusion)
DUNE 35 ton prototype [118]	Alignment and $t0$ techniques
ArgonTUBE [119], MicroBooNE [120], SBND, ICARUS [121], ProtoDUNE [20]	Test of systems (e.g., Laser)
ArgoNeuT [122], MicroBooNE [123, 124, 125, 115, 126, 86], ICARUS [127, 128, 129], ProtoDUNE	Test of calibration techniques and detector model (e.g., electron lifetime, Michel electrons, ^{39}Ar beta decays)
ProtoDUNE, LArIAT [19], CAPTAIN [130]	Test of particle response models and fluid flow models
LArTPC test stands [131, 132, 133, 88]	Light and LAr properties; signal processing techniques
Monitoring Systems	Operation, Commissioning and Monitoring
Purity monitors	Electron lifetime
Photon detection monitoring System	photon detection system (PD system) response
Thermometers	Temperature, velocity; test of fluid flow model
Charge injection	Electronics response
Dedicated Calibration Systems	Targeted (near) independent, precision calibration
Direct ionization via laser	Position, angle, electric field (x,y,z,t)
Photoelectric ejection via laser	Position, electric field (partial)
Neutron injection	Test of SNB signal, neutron capture model
Proposed Radioactive source deployment	Test of SNB signal model

Energy scale impact on δ_{CP} measurement in Hyper-K

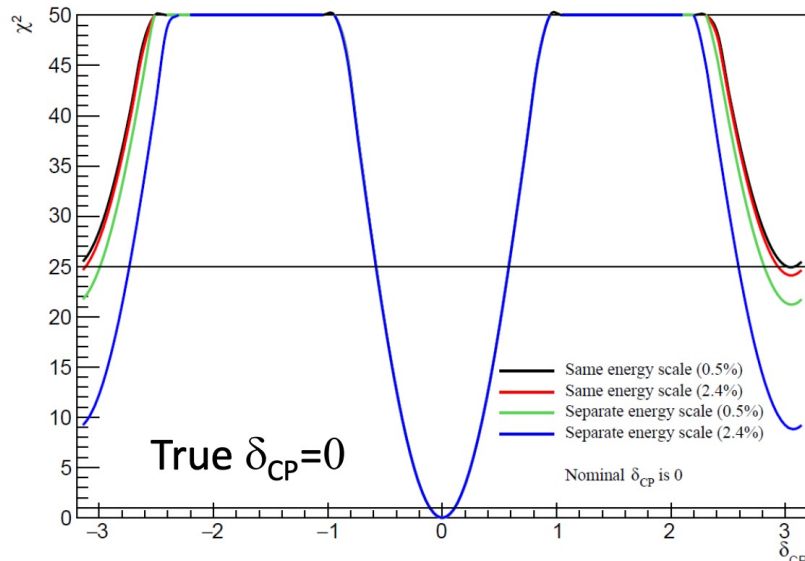
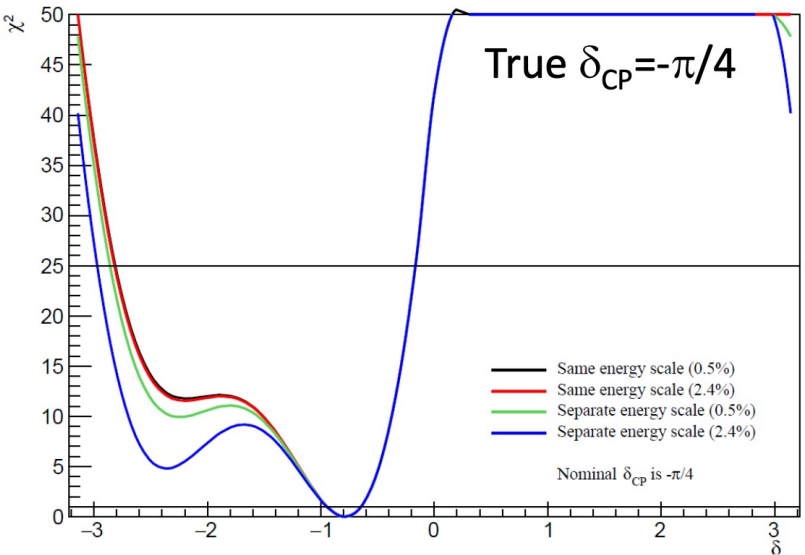
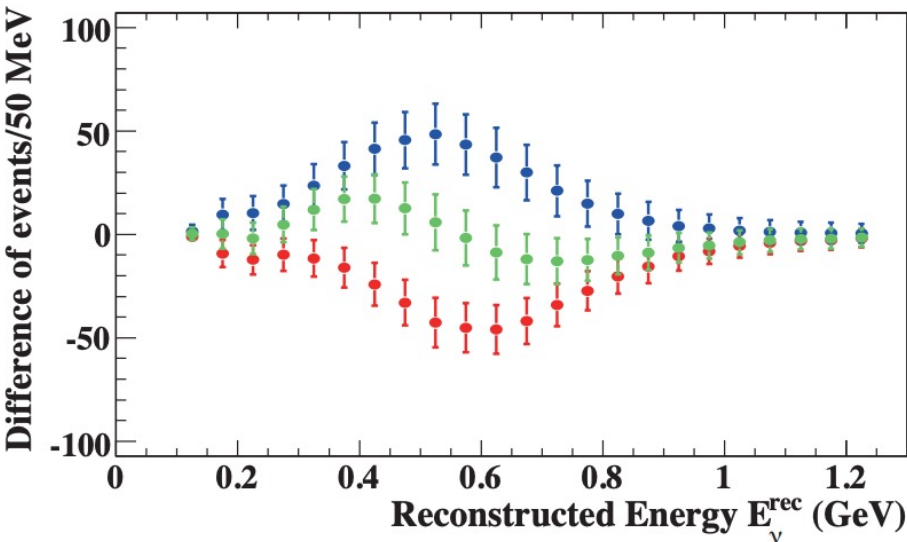
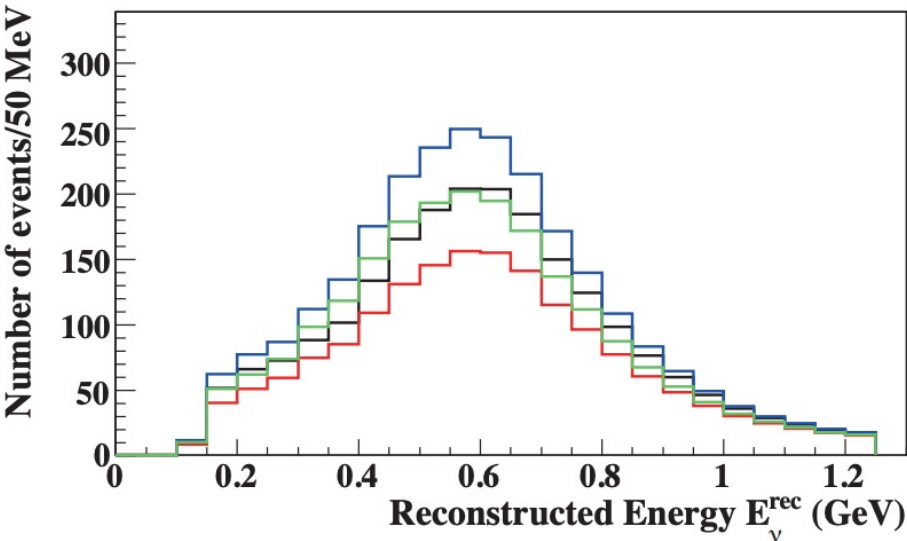
Neutrino mode: appearance

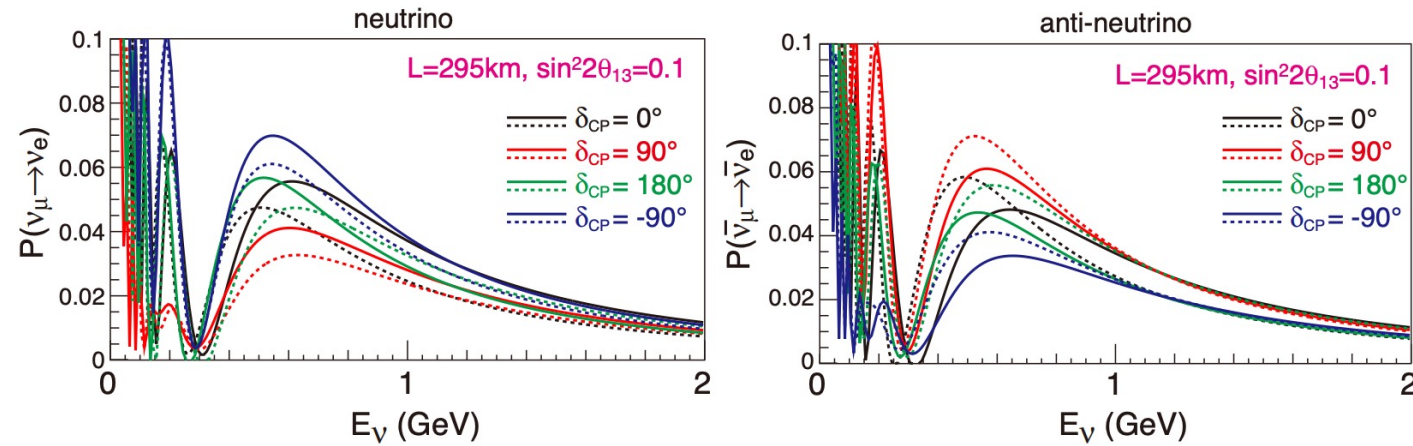
Electron-neutrino and electron-antineutrino candidate predictions for different values of delta.

0 and π have distinguishable spectra, characterized by distortion of the shape induced by $\cos\delta$ terms in the appearance probability

Biases in the reconstructed energy of electron neutrinos can skew bias the shape of this sample and preventing the wrong octant of δ from being excluded due to false minima

This is particularly strong if the muon-neutrino and electron-neutrino energy scales differ but are assumed to be the same





Different contributions from oscillations to Hyper-K electron neutrino appearance

FIG. 129. Oscillation probabilities as a function of the neutrino energy for $\nu_\mu \rightarrow \nu_e$ (left) and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (right) transitions with $L=295$ km and $\sin^2 2\theta_{13} = 0.1$. Black, red, green, and blue lines correspond to $\delta_{CP} = 0^\circ$, 90° , 180° and -90° , respectively. Solid (dashed) line represents the case for a normal (inverted) mass hierarchy.

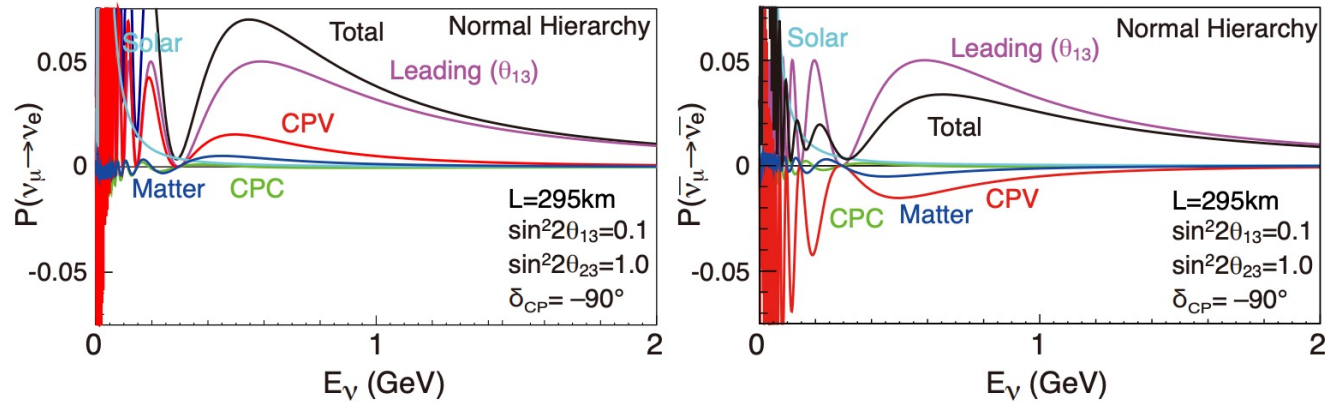


FIG. 130. Oscillation probabilities of $\nu_\mu \rightarrow \nu_e$ (left) and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (right) as a function of the neutrino energy with a baseline of 295 km. $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = -90^\circ$, and normal hierarchy are assumed. Contribution from each term of the oscillation probability formula is shown separately.

Contributions to DUNE's Flux model

Oscillation analysis uses principle component decomposition for flux uncertainties

Select components are shown along with their most analogous underlying systematics

