The DUNE Experiment

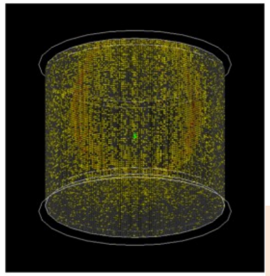
Nikolina Ilic on behalf of DUNE Canada

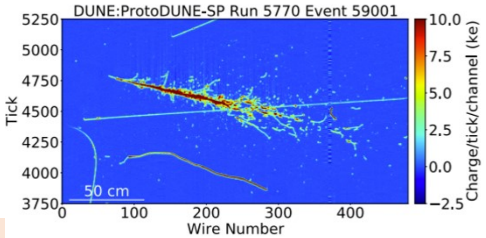
Institute of Particle Physics & University of Toronto

CAP 2023, Fredericton

Why are on both DUNE & Hyper-K?

- Effect on matter on neutrino oscillations complicates some measurements
- Matter does not have same effect on neutrino and anti-neutrino oscillations – complicates CPV measurement
- Possible strategies:





Small oscillations length (~300 km) = insignificant matter effects
Off axis beam gives high flux at oscillation maximum, narrow energy range

Hyper-Kamiokande

Large oscillations length (~1000 km) = significant matter effects
On axis beam gives wide range of neutrino energy – differentiate CPV effects from matter effects through energy dependence

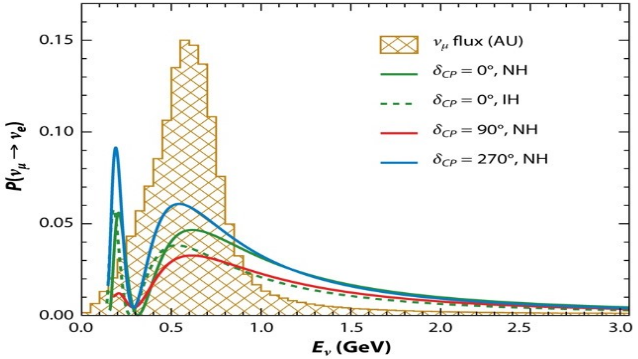
v

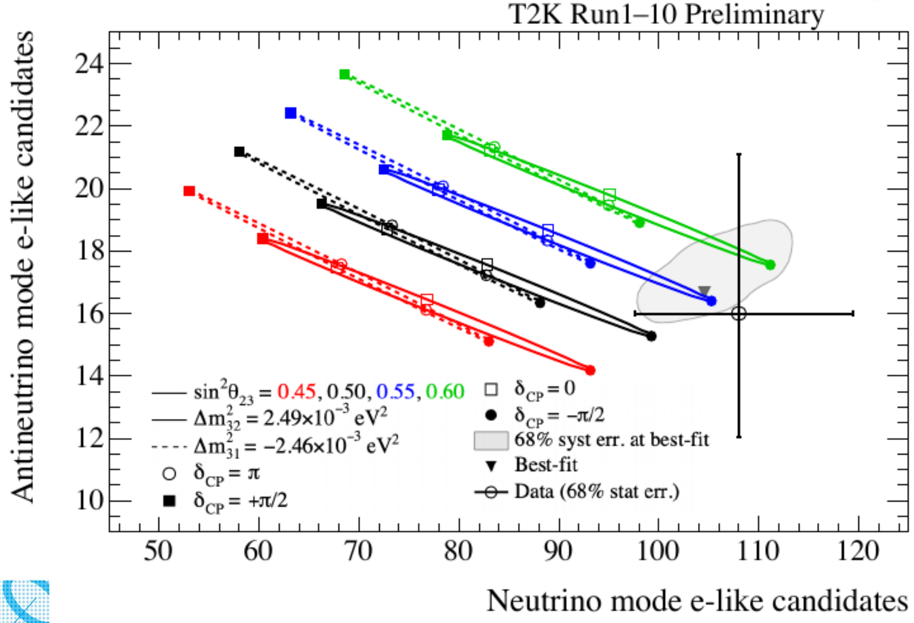
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Why are on both DUNE & Hyper-K?

- Count ν_e events in neutrino mode (x axis), and count ν_e in antineutrino mode (y axis)
- Ellipses represent effect of $\delta_{CP,}$ Matter effect splits the NH and IH ellipses about y=x, $\sin^2\theta_{23}$ moves ellipses along y=x

Getting as many neutrinos at one energy at possible to maximize event rate





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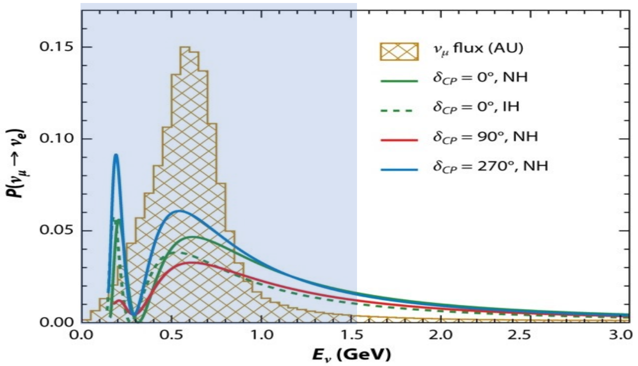
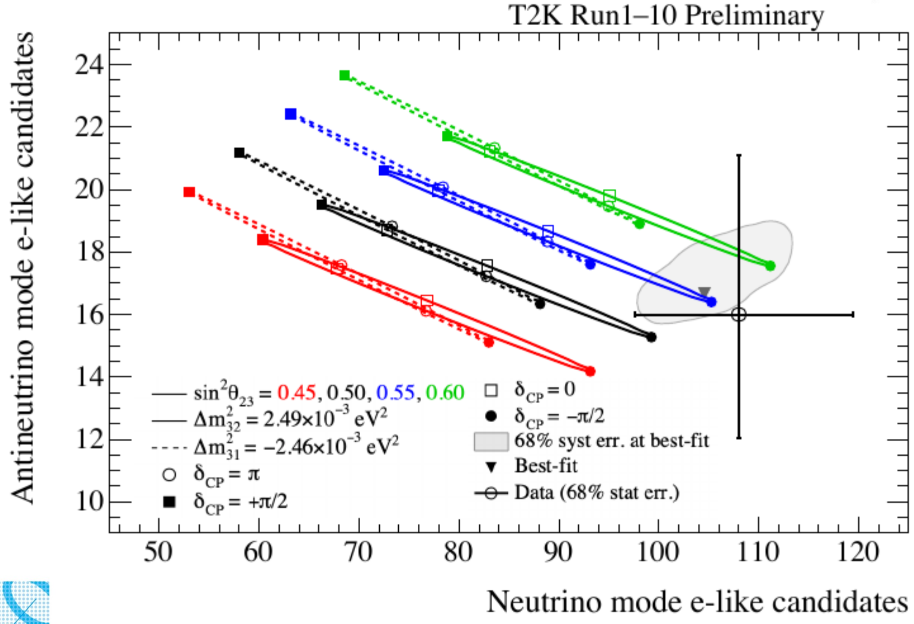
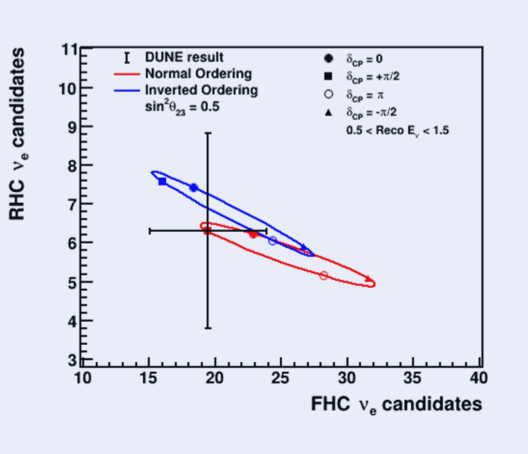
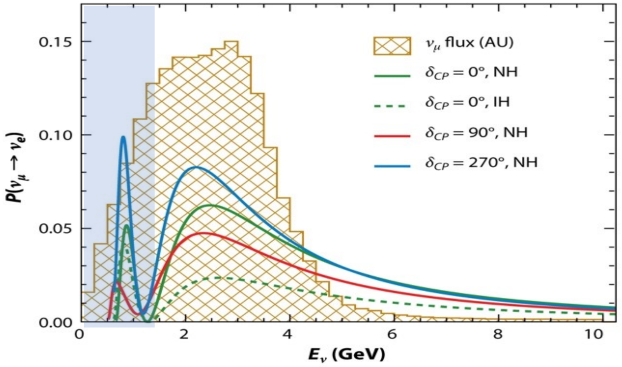




Hyper-Kamiokande

Detector optimized for higher energies





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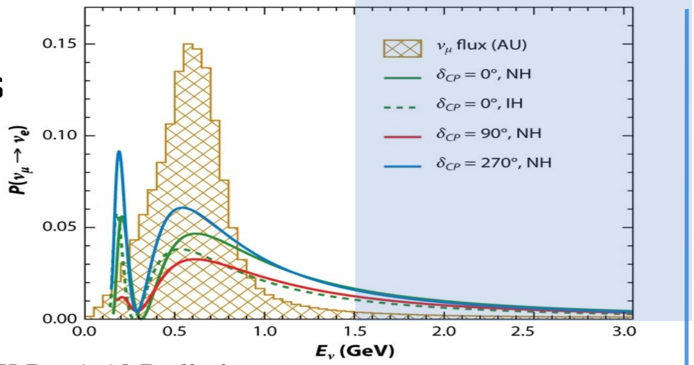

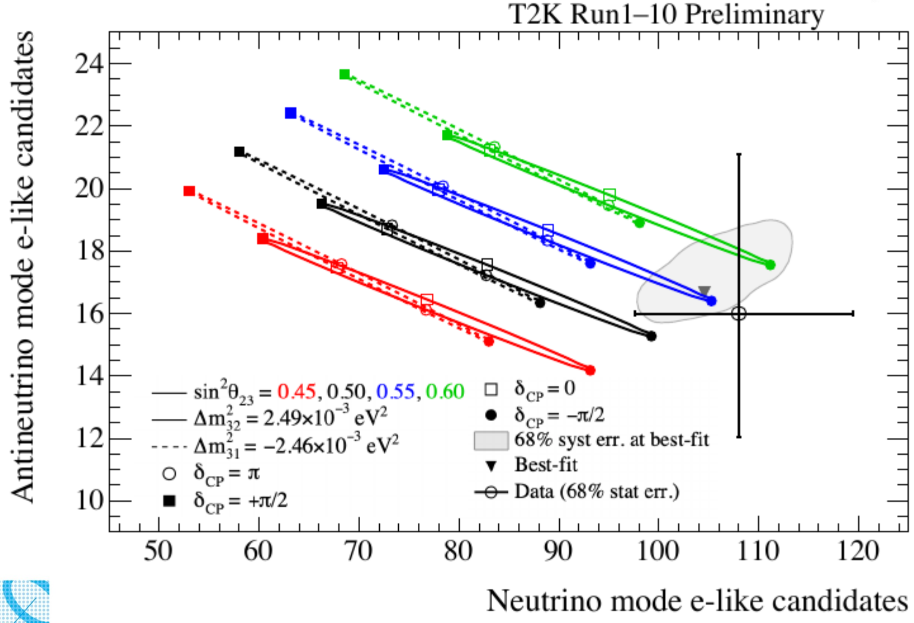

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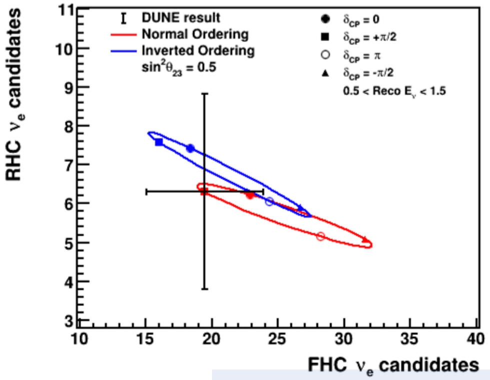

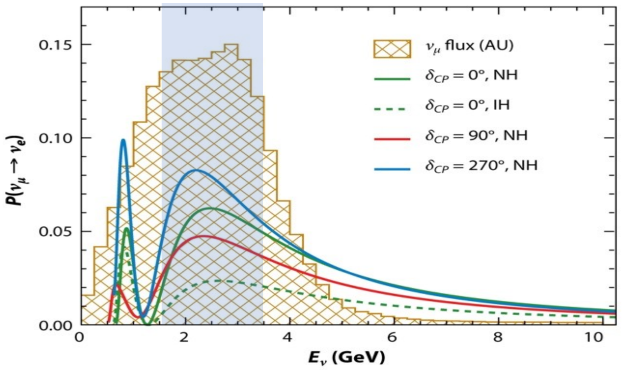

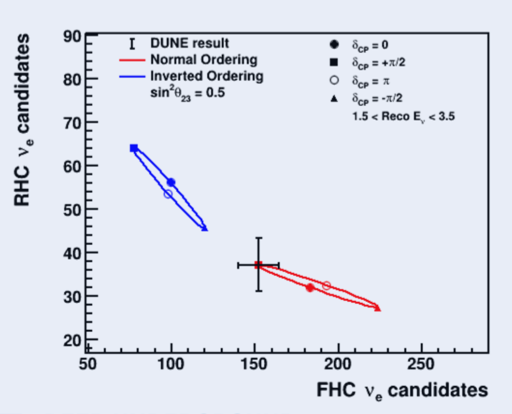

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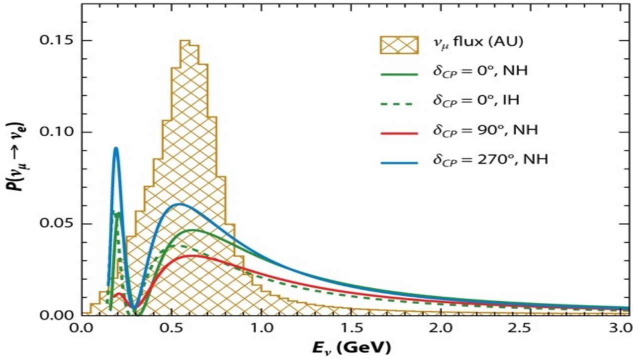

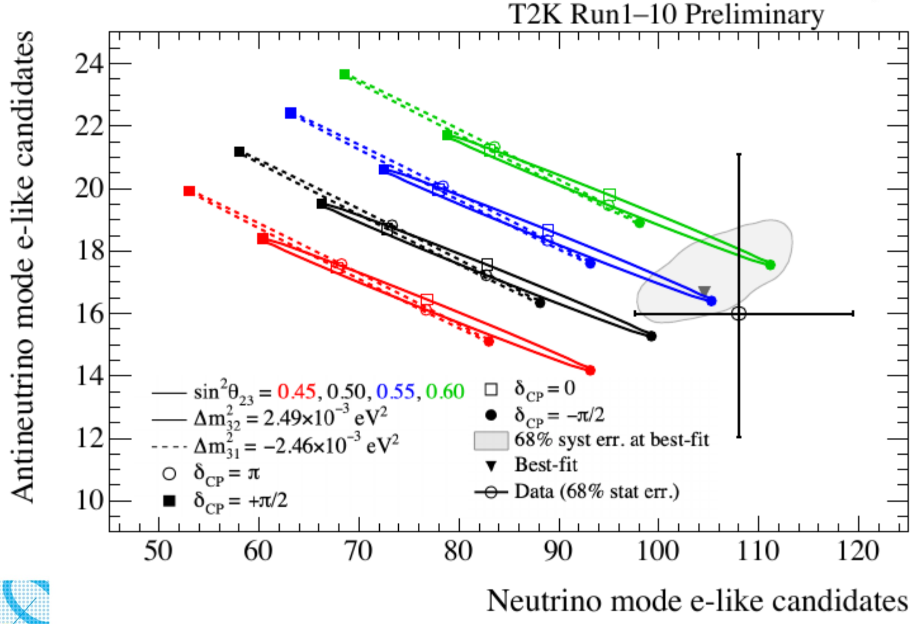

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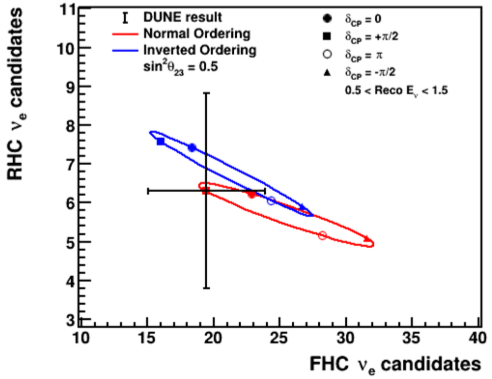

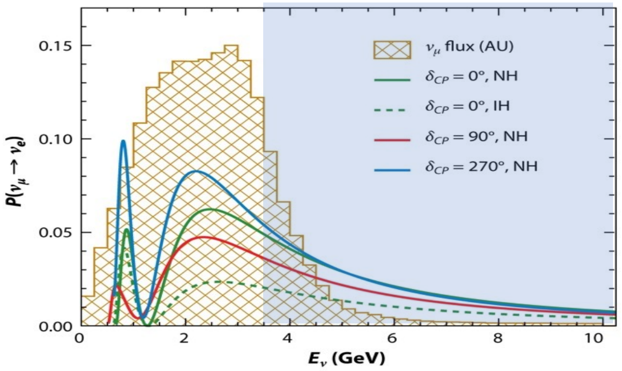

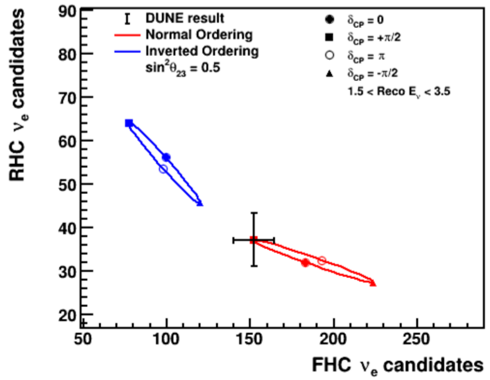

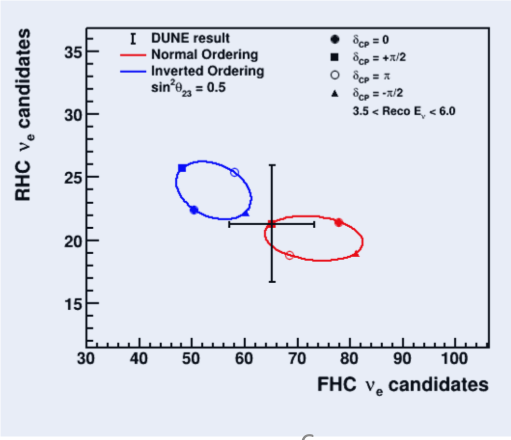

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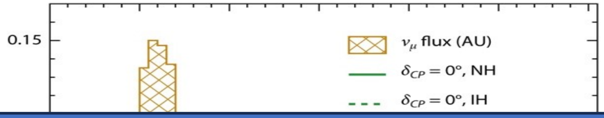
Getting as many neutrinos



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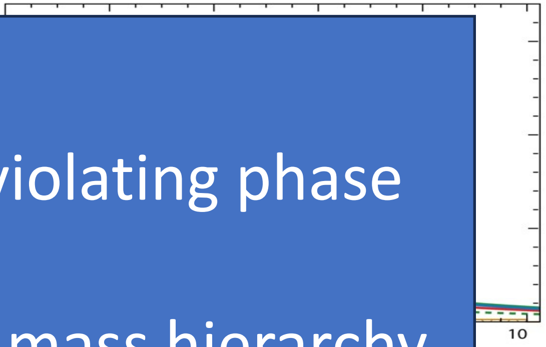
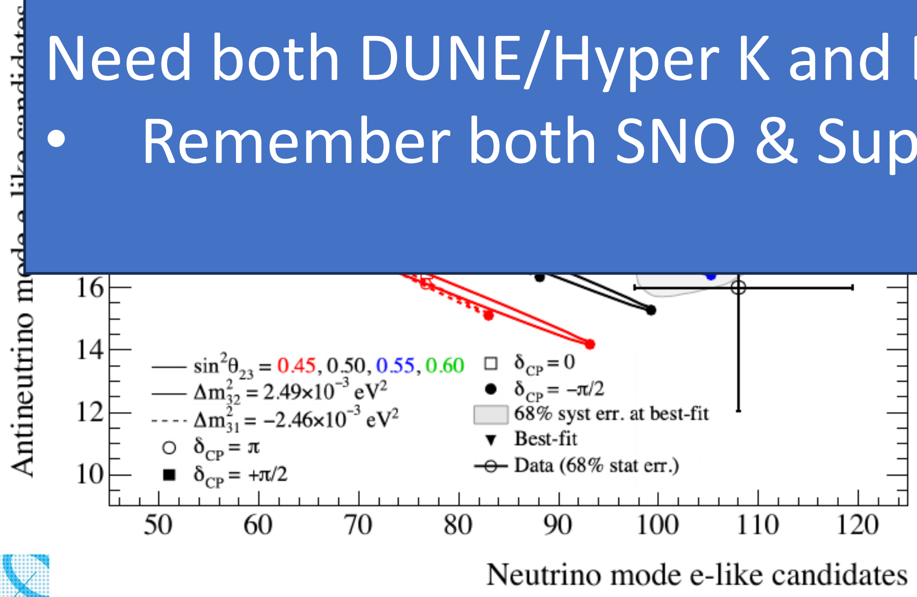


DUNE will be able to determine mass hierarchy regardless of CP violating phase

Need both DUNE/Hyper K and DUNE to characterize the δ_{CP} and mass hierarchy
- Remember both SNO & Super K got Nobel prize for neutrino oscillations



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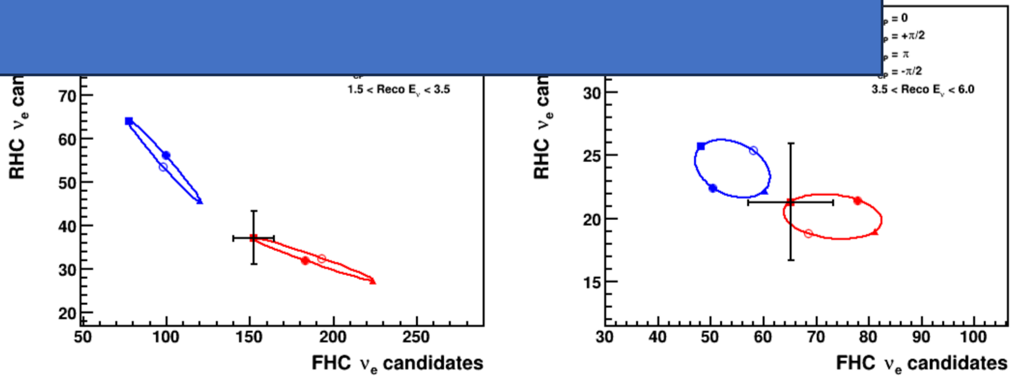


DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE: A general purpose detector

Tau neutrino appearance

Atmospheric & Solar neutrinos ($^8B/hep$)

- additional probe to neutrino properties and BSM
- DUNE can identify first hep neutrinos
- verify the standard solar model, measure sun's core temperature, characterize neutrino floor, resolve tension between global solar neutrino measurements & KamLAND, characterize MSW affect, measure matter profile of the earth

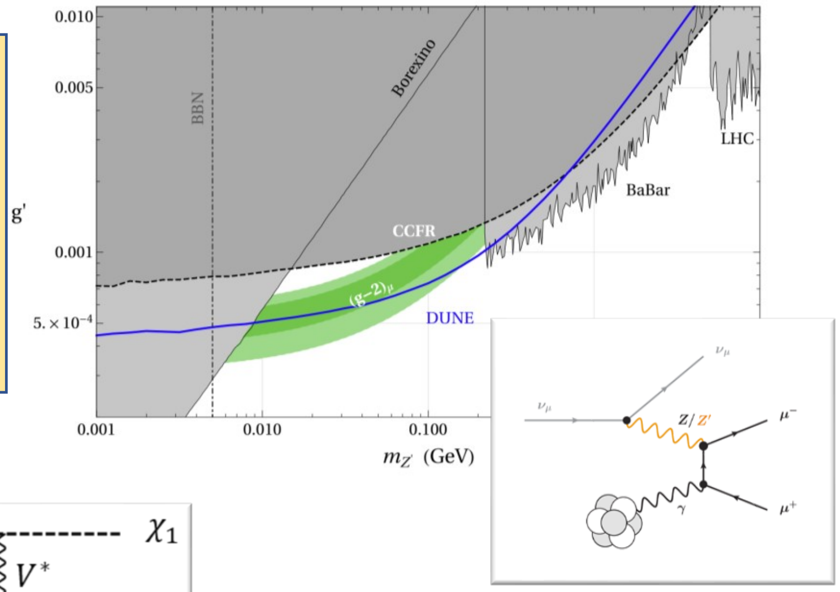
Supernova neutrinos: Core collapses expected to occur few times per century (at 10-15 kpc), ~ 10^{58} of ~ 10 MeV ν emitted for few seconds.

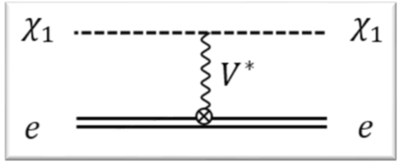
- Test astrophysical theories, probe new physics
- HK sees $\bar{\nu}$, DUNE sees $\bar{\nu}$ - ($\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$)

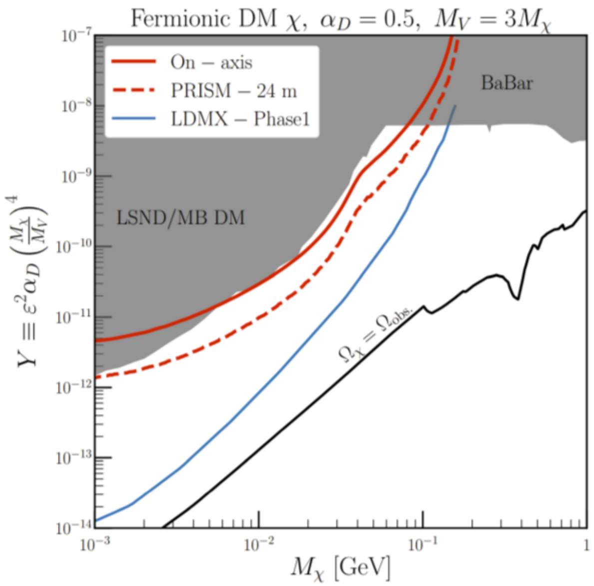
Beyond standard Model

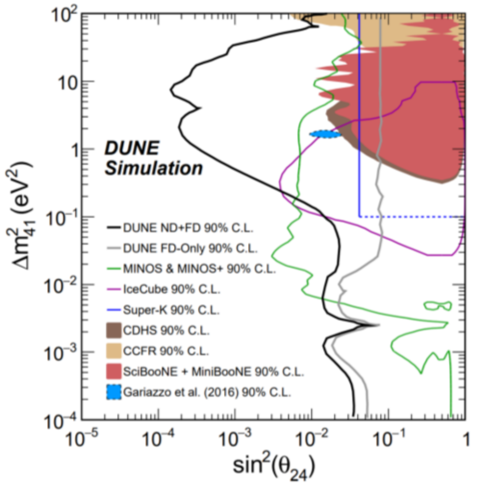
- Light Sterile ν (could explain short baseline/ gallium/reactor anomalies, hints of CKM non-unitarity and LFV)
- Neutrino tridents (Z' in gauged $L_\mu - L_\tau$ can explain g-2/B-anomalies)
- Non-standard interactions (could explain B-anomalies)
- Dark Matter, Heavy Leptons, Non-PMNS unitarity, Lorentz violation…

Proto Decay, Baryon Number Violation



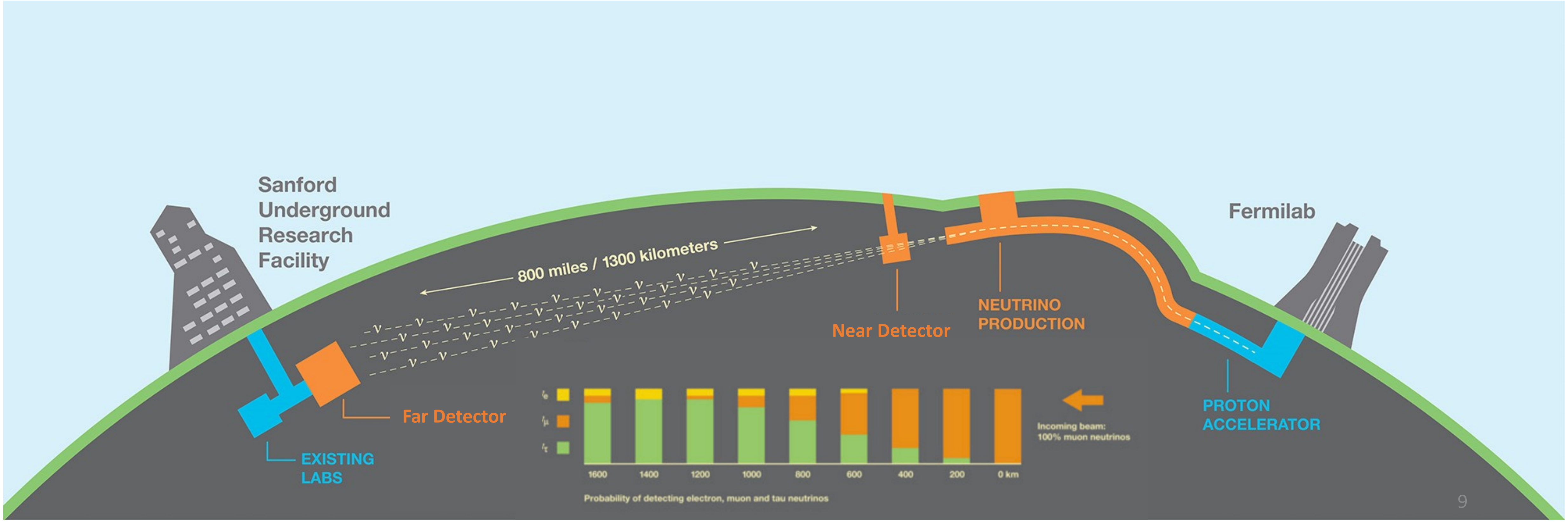






LBNF DUNE Facility

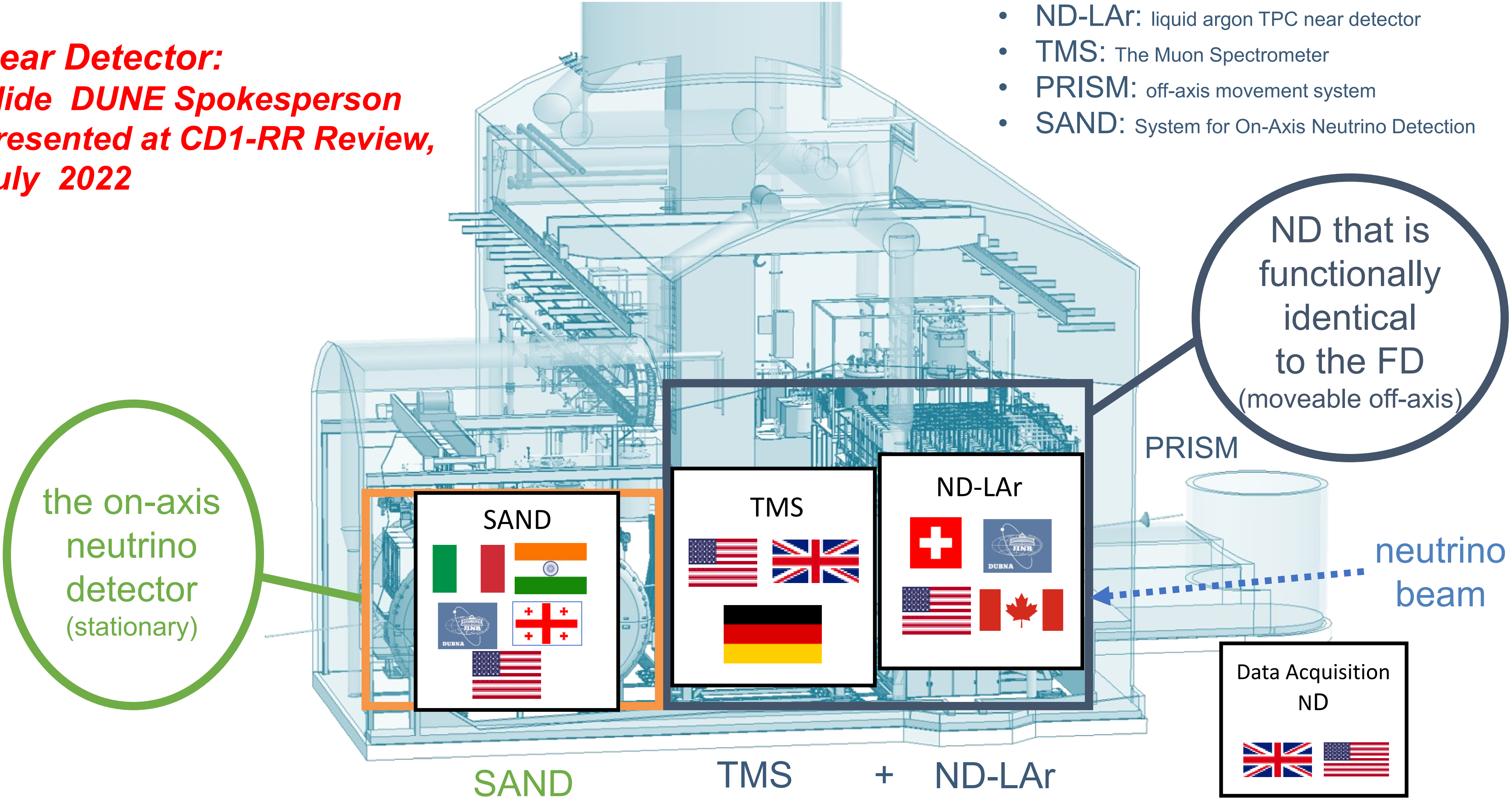
- 1-6 GeV muon neutrinos/antineutrinos from high-power proton beam (1.2 MW – upgradable to 2.4 MW)
- Near detector measures fluxes & constrains systematics (100s of millions of neutrino interactions)
- Far Detector is a Liquid Argon Time Projection Chambers (LAr TPC) – fine granularity



Near Detector:

Slide DUNE Spokesperson presented at CD1-RR Review, July 2022

- ND-LAr: liquid argon TPC near detector
- TMS: The Muon Spectrometer
- PRISM: off-axis movement system
- SAND: System for On-Axis Neutrino Detection



the on-axis neutrino detector (stationary)

SAND

TMS

ND-LAr

ND that is functionally identical to the FD (moveable off-axis)

PRISM

neutrino beam

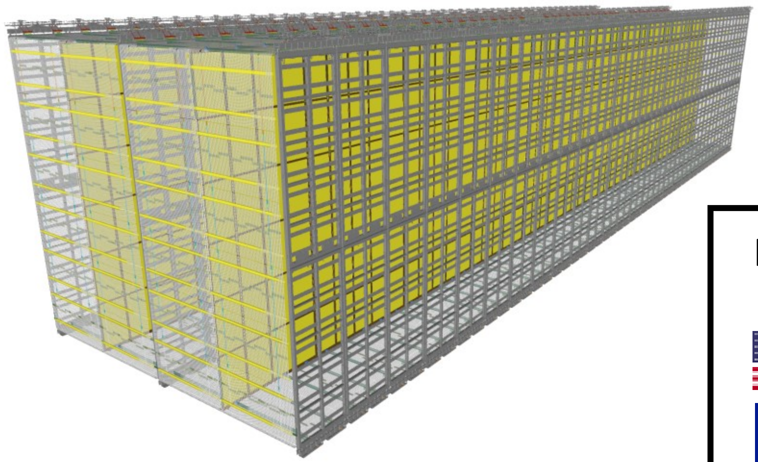
Data Acquisition ND

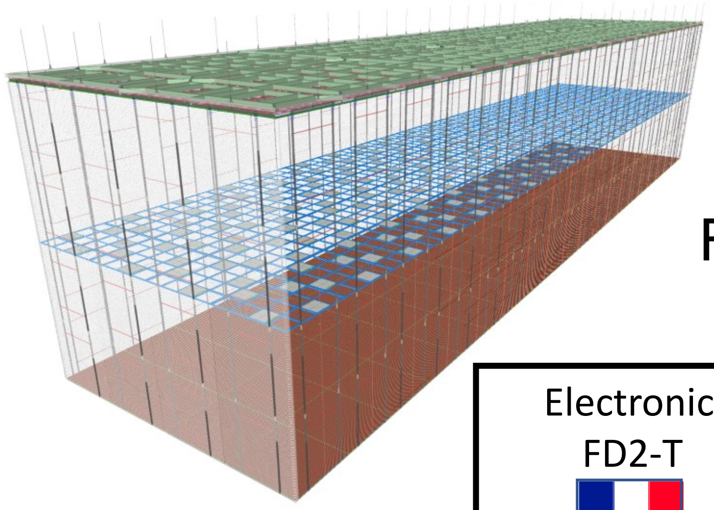
SAND

TMS + ND-LAr

Far Detector:
Slide DUNE Spokesperson presented at CD1-RR Review, July 2022

- Multiple international partners have invested significant resources





our partners are getting ready to send detectors and detector components

High Voltage
FD1, FD2
🇺🇸 CERN
🇫🇷

Anode Plane Assemblies - FD1
🇬🇧 🇺🇸

Photon Detection
FD1, FD2
🇧🇷 🇮🇹 🇪🇸
🇨🇿 🇫🇷 🇺🇸
🇵🇾 🇨🇴

Electronics
FD2-T
🇫🇷

Charge Readout Planes - FD2
🇫🇷 🇺🇸
CERN

Data Acquisition
FD1, FD2
🇬🇧 🇺🇸
CERN 🇨🇦
🇮🇱

🇺🇸 TPC Electronics
FD1, FD2-B

CALCI
FD1, FD2
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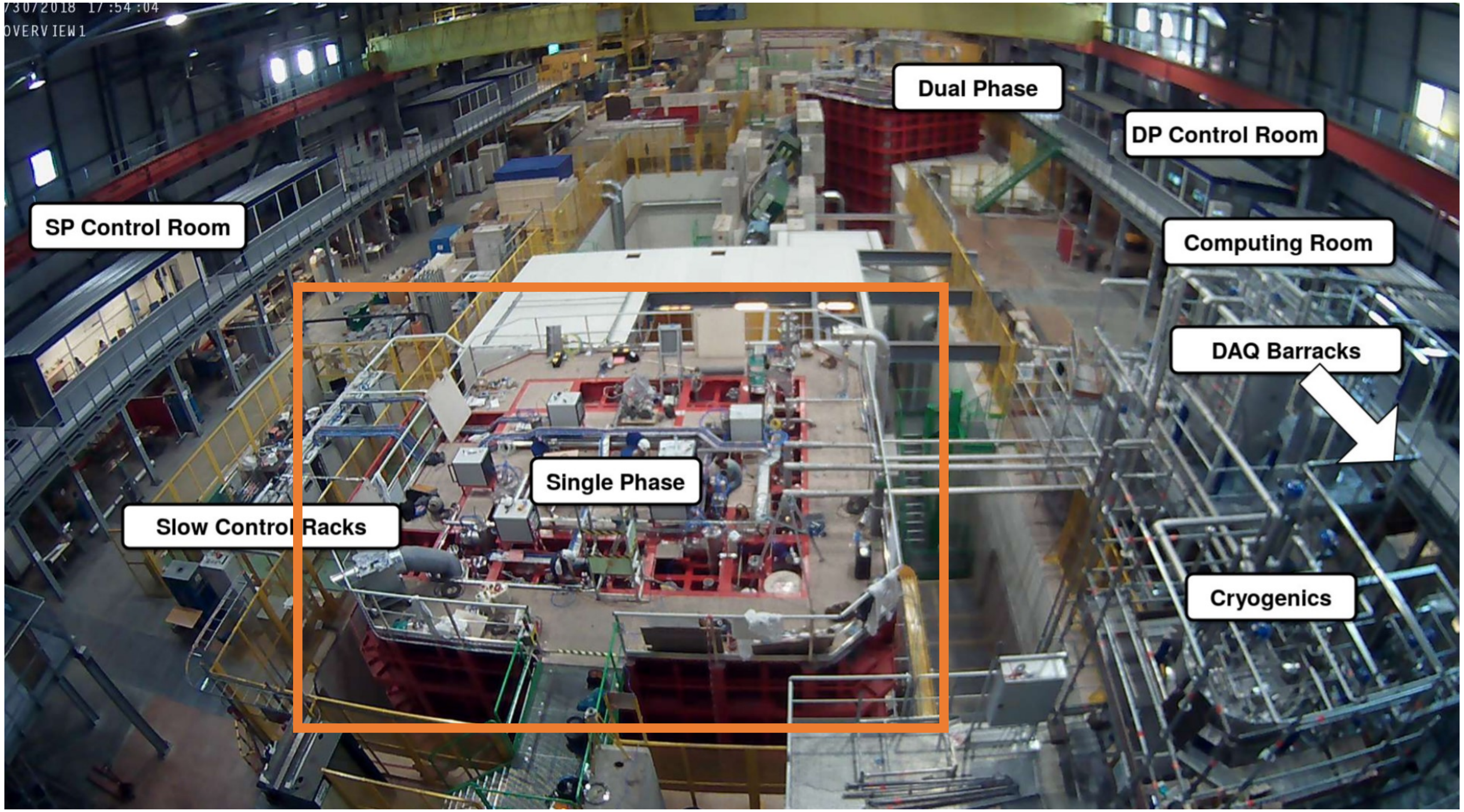
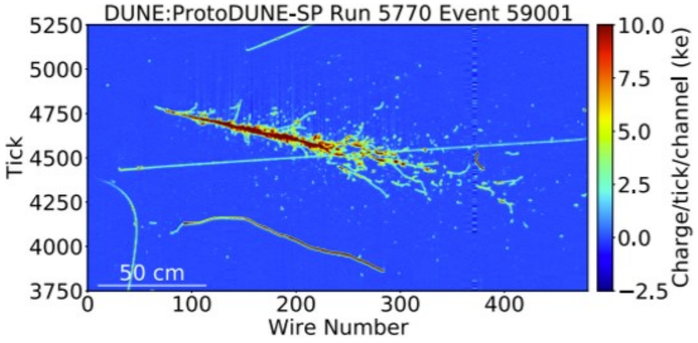
🇺🇸

Gina Rameika, CD1-RR Review, July 2022

ProtoDUNE



- At CERN neutrino platform, have built 2 prototypes, 1/20th the size of planned DUNE (15K sense wires)
- Collected hadron data 2018-2020, excellent performance!
  - 99.7% of electronics responsive, 99% HV uptime, high purity
- Will run again this year with vertical drift design!



6 GeV electron

DUNE

CANADA

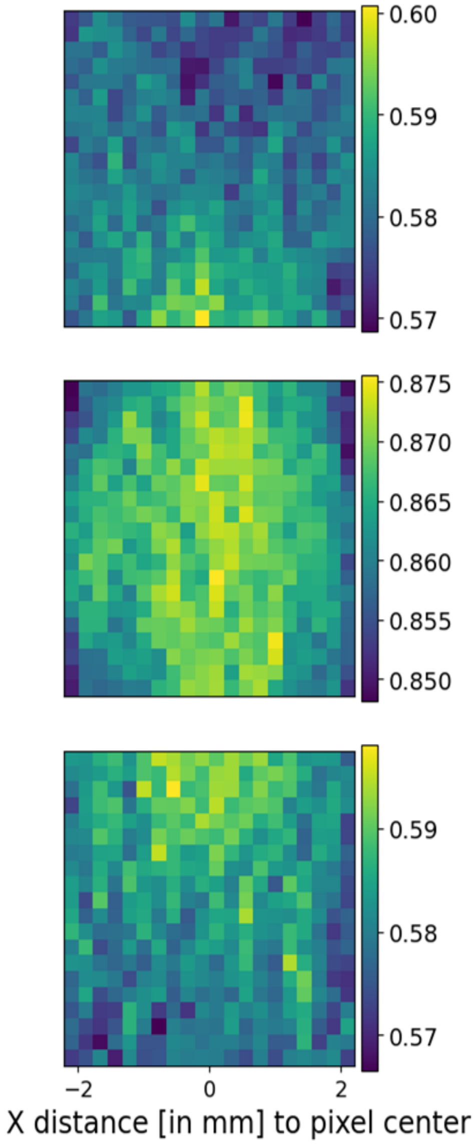
YORK
UNIVERSITÉ
UNIVERSITY

INSTITUTE OF
PARTICLE
PHYSICS

UNIVERSITY OF
TORONTO

Université
de Montréal

Near Detector



DUNE Near Detector

- 4 modules already tested in Bern with comics –several detectors, will be tested with neutrino beam this year at Fermilab
- York characterized detector response of ArgonCube 2x2 prototype
- Repurposed MINERva simulation for DUNE ND

Deborah Harris
(faculty)

Rowan Zaki
(PhD student)

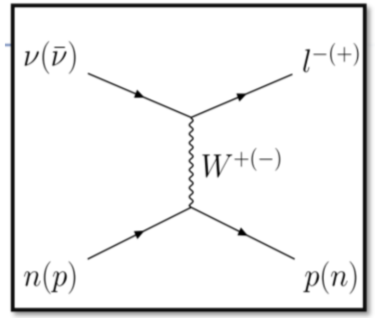
Noe Roy
(PhD student)

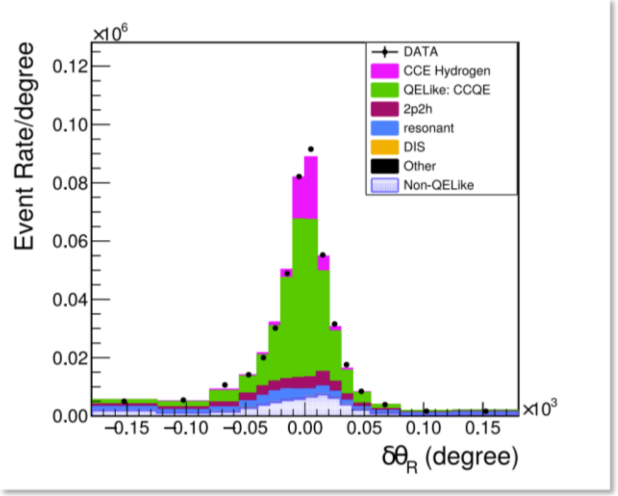
Cross Section Measurements, Modelling & Computing

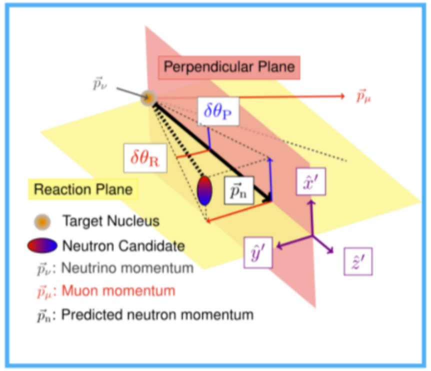
Balint Radics
(faculty)

Tejin Cai,
postdoc

- Propagation of systematic uncertainties in oscillation analysis
- DUNE Computing: Production Coordination (T. Cai is production manager) and Interactive Analysis Facility
- Neutrino Interactions modelling: measurements of anti-neutrino elastic scattering on protons







Data Acquisition (DAQ)

UNIVERSITY OF TORONTO

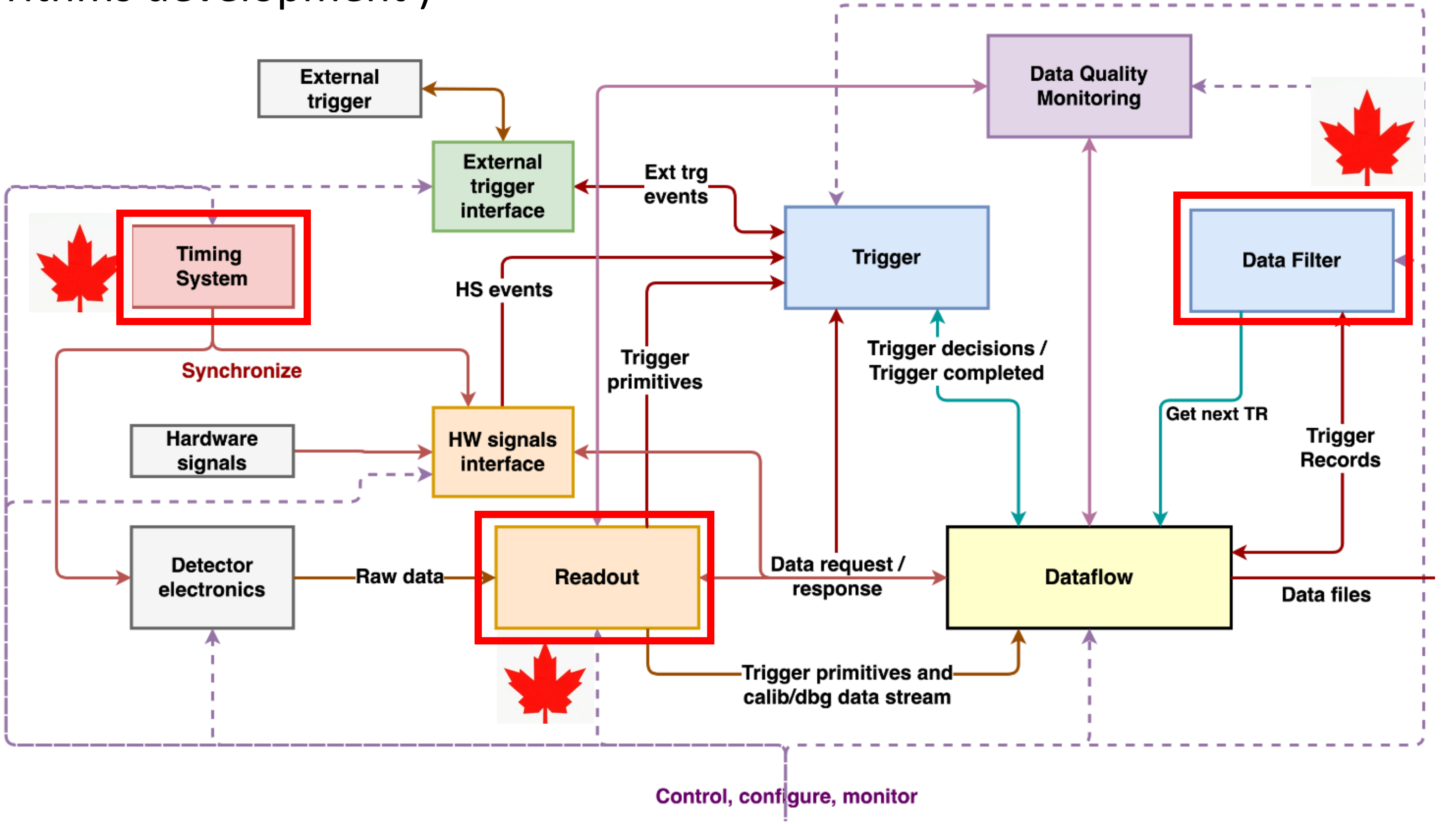
Université de Montréal

U of Toronto is optimizing sensitivity to wider energy ranges

- Supernova neutrinos (readout & SSD selection)
- Solar neutrinos (Region of Interest Algorithms development)
- Tau neutrinos

Hardware/software work

- Timing – hit finding firmware development with Montreal engineers
- Readout – commissioning/testing high performance servers and readout cards
- Data Filter – higher level algorithm design – entirely U of Toronto and Montreal (through MRS) responsibility



Data Acquisition (DAQ) & Computing

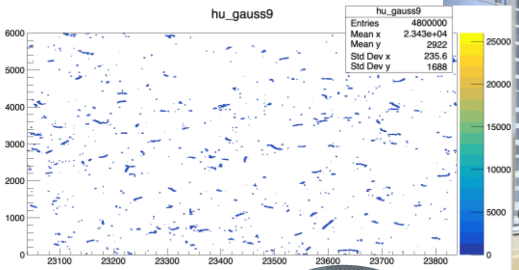
- Ilic is on DUNE DAQ Management board, signed MoU for DAQ
- Contributing 8% to DAQ FD hardware + ProtoDUNE (CFI JELF/ORF/U of T.)
- Significant computing resources for MC production through Digital Resource Alliance Grant
- Passed FDR in March! Ilic was main editor

Nikolina Ilic (faculty)

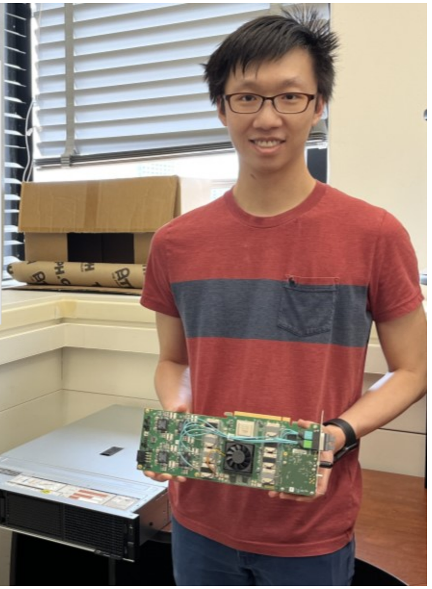
Danaisis Vargas (Postdoc)

At CERN: DAQ testing/integration in ProtoDUNE

- For the last 4 years, postdoc was one of few people based at CERN responsible for all hardware/software & integration/commissioning activities



William Dallaway
(PhD Student)



Mathew Man
(PhD Student)

U of Toronto lab: testing high performance servers with FELIX

- tests on several server/SSD/adapter combinations to ensure DUNE can handle readout requirements, servers were shipped to CERN in March, students are going there for commissioning

Summary & Outlook

APAs being tested at Daresbury Laboratory, UK; one 2.3m x 6.3m APA is shown

- DUNE will have a large physics program: unprecedent sensitivity to neutrino mass hierarchy, CP violation; a rich atmospheric, solar, and supernova neutrino program; sensitivity to many BSM signals
- ProtoDUNE ran smoothly and performed well, this year will run again to test vertical drift technology
- Excavation over half done, detector construction underway
- MOUs signed, including by Canadians, committing to hardware and manpower for many DAQ components
- TRDs completed: JINST 15 (2020) 08, T08008, T08009, T08010, FERMILAB-PUB-20-025-ND), ***CD1-RR Review passed***
- In November, Anode Plane Assembly (APA) test lift was successfully completed at SURF demonstrating that largest detector components can be successfully moved
- Far detector expected to take physics data in late 2020s
- Neutrino beam expected on similar time scale
- Canadian contributions to ND, DAQ, Computing, Neutrino Interactions

DUNE Collaboration is 1,402 collaborators from 206 institutions in 37 countries including CERN

OUR HQP

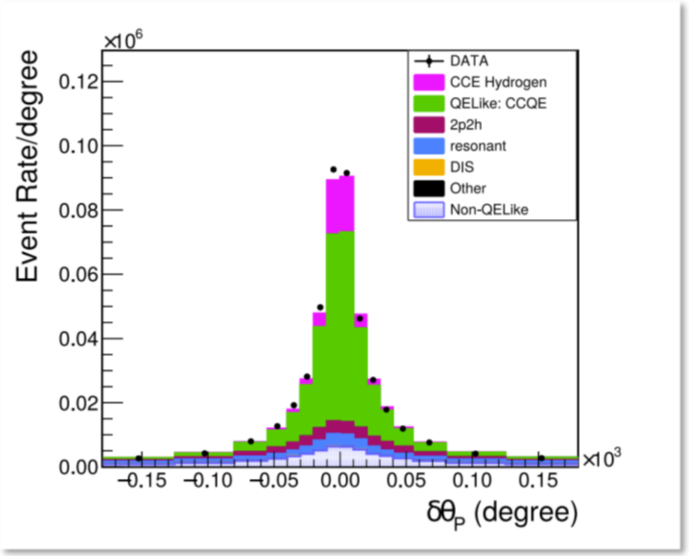
Y/UT	Name	Position	Start Date
Y	Tejin Cai	Postdoc	July 2021
UT	Danaisis Vargas	Postdoc	March 2022
Y	Noë Roy	Postdoc	June 2022
Y	Faiza Akbar*	Postdoc	March 2023
Y	Rowan Zaki	PhD Student	January 2020
UT	Matthew Man	PhD Student	September 2020
Y	Rituparna Banerjee	Masters Student	January 2022
Y	Maria Mehmood	Masters Student	September 2022
Y	Anna Federova	PhD Student	September 2023

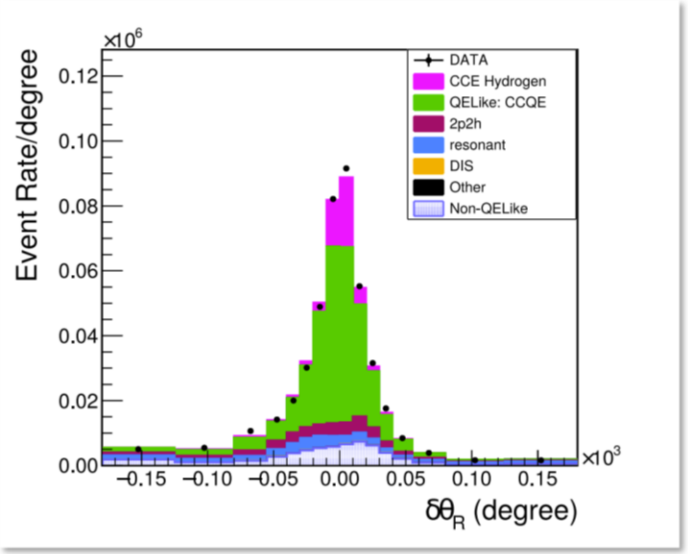
JOIN US! contact Nikolina.Ilic@cern.ch

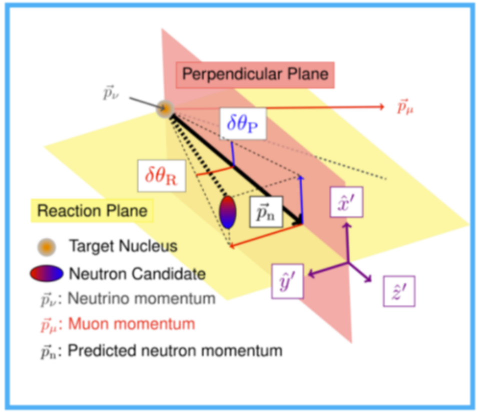
BACKUP

From Noe Roy

Deviation angles measurement







Data and Monte-Carlo distribution of the deviation angles

Elastic scattering on **H** centered on 0 with little deviation

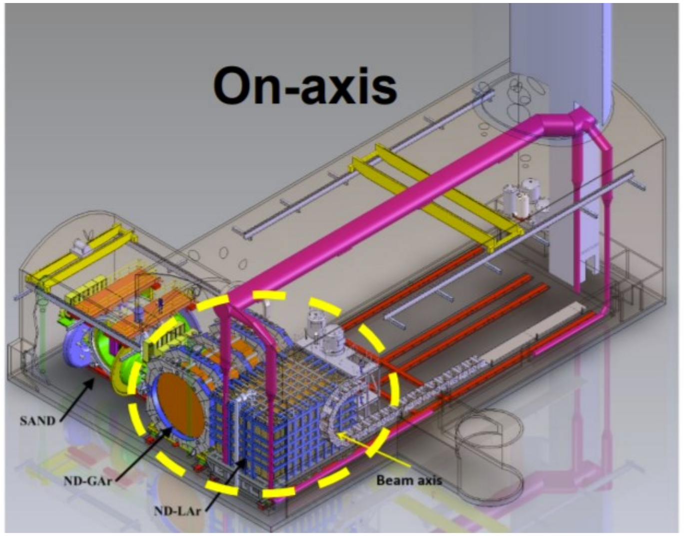
Quasi elastic scattering (**QE-Like**) on **Carbon**: Centered on 0 with some smearing

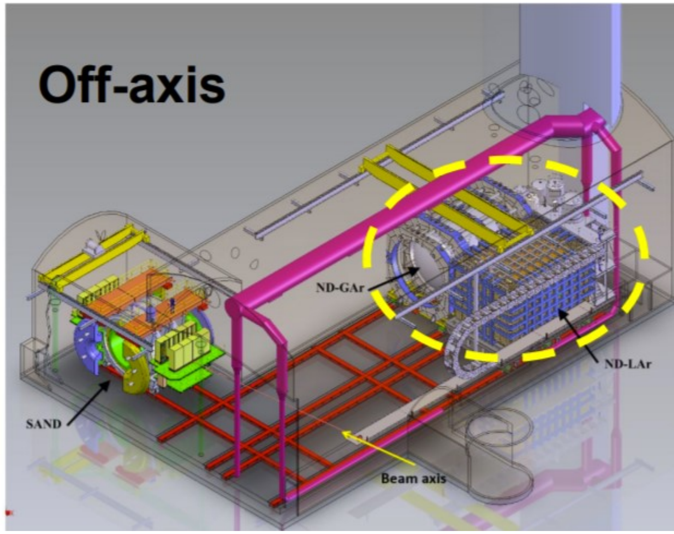
Other type of background (not simple scattering)

Clear difference between H and C scattering but signal/background ratio is not good, need to get smarter !

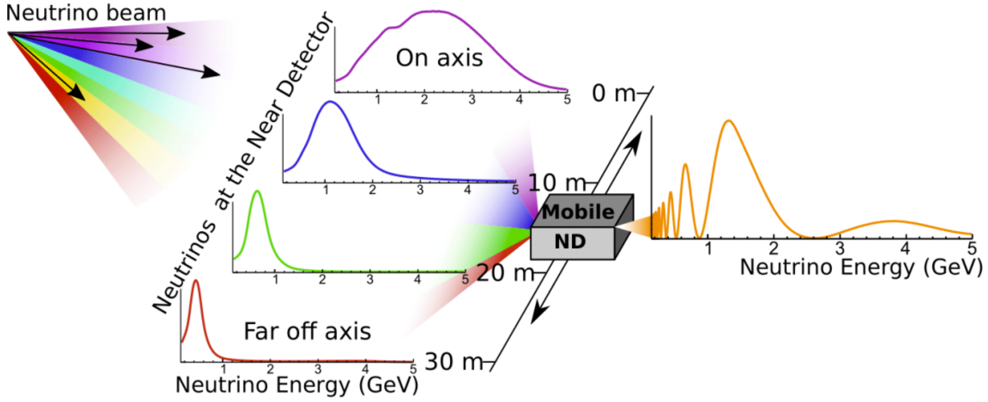
DUNE Near Detector

- **ND-LAR:** liquid argon TPC with muon spectrometer (TMS) 50t fiducial mass, modular detector with pixel readout to reduce pileup
  - Similar to FD to characterize beam flux and neutrino interactions
- **ND-GAr**: Gaseous argon detector
  - surrounded by ECAL and muon system in magnetic field
  - good tracking resolution, can study low-p_T ν Ar interactions
- **SAND**: System for on-Axis Neutrino Detection
  - Inner tracker & ECAL in magnetic field serve as beam monitor
- **PRISM** for ND-LAr/GAr: Precision Reaction-Independent Spectrum
  - Can measure flux at different off-axis angles,

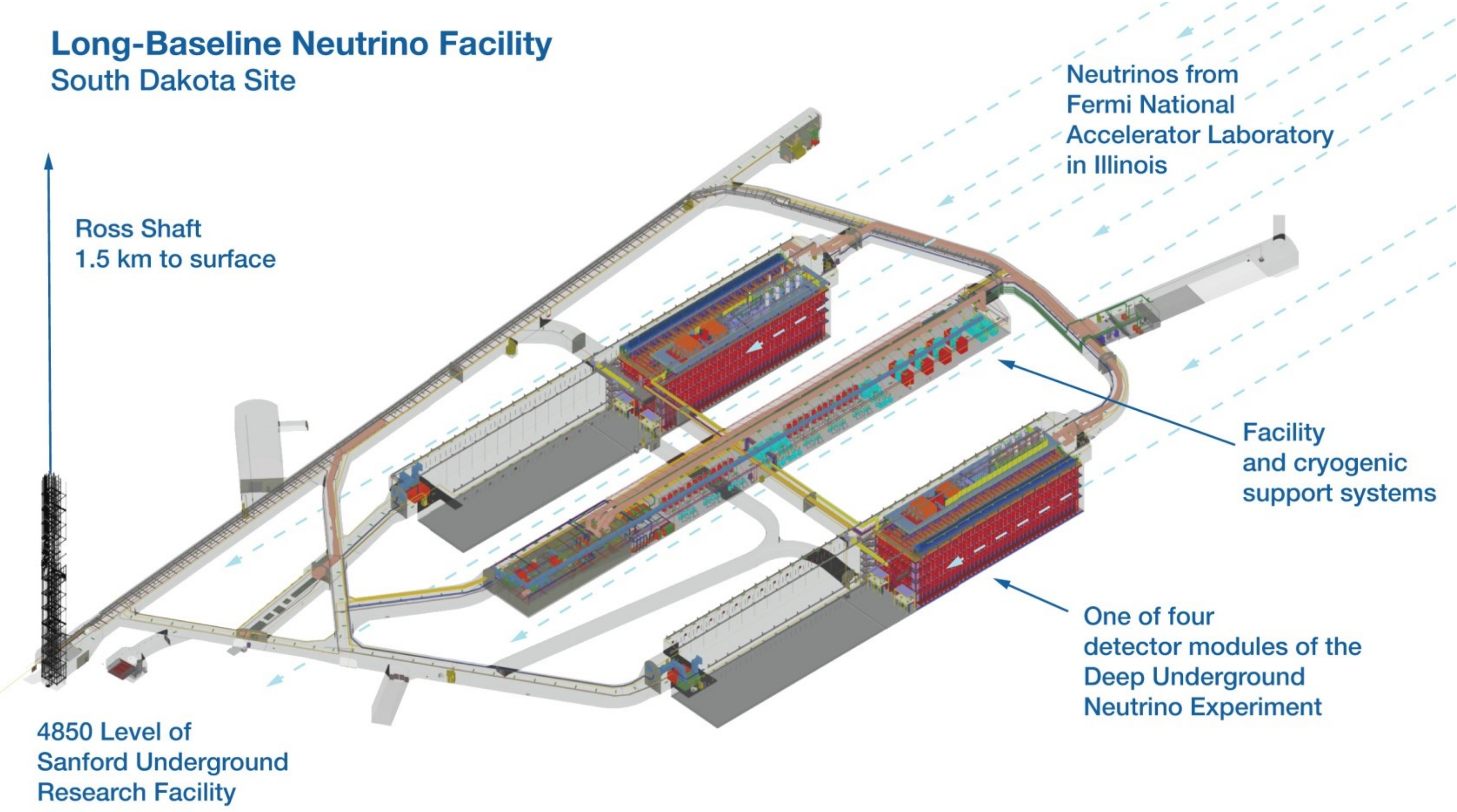




DUNE PRISM



DUNE Far Detector



- 4 Far Detector modules in cryostats (15.1m wide x 14 m high by 62 m long) containing 17 kt of LAr mass

Phase I

- 1st module - Single Phase (SP), horizontal drift, LAr Time Projection Chamber (LArTPC) Installed mid 2020s
- 2nd module - SP vertical drift LAr TPC
- ND: NDLAr+TMS+SAND
- 1.2 MW beam power

Phase II

- 3rd / 4th module - to be defined
- ND-GAR
- up to 2.4 MW beam power

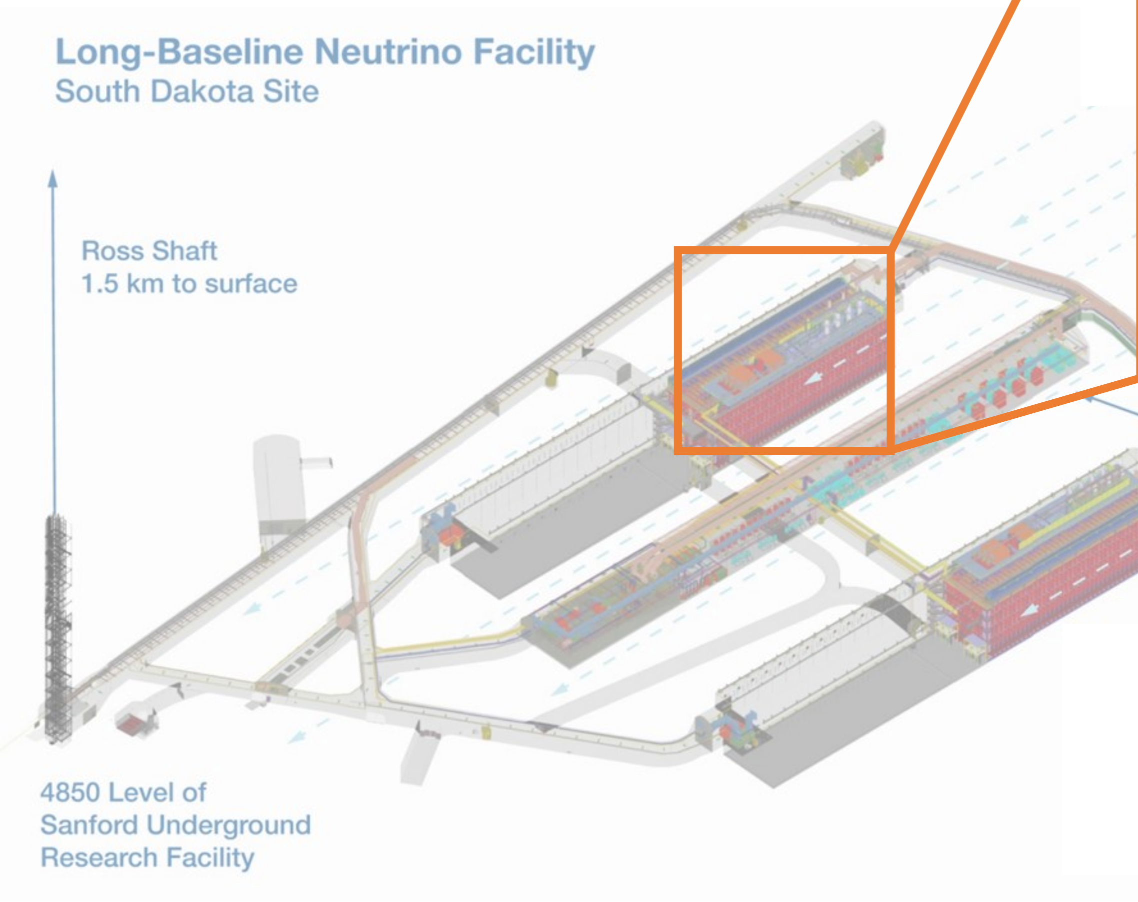
Excavation over half completed

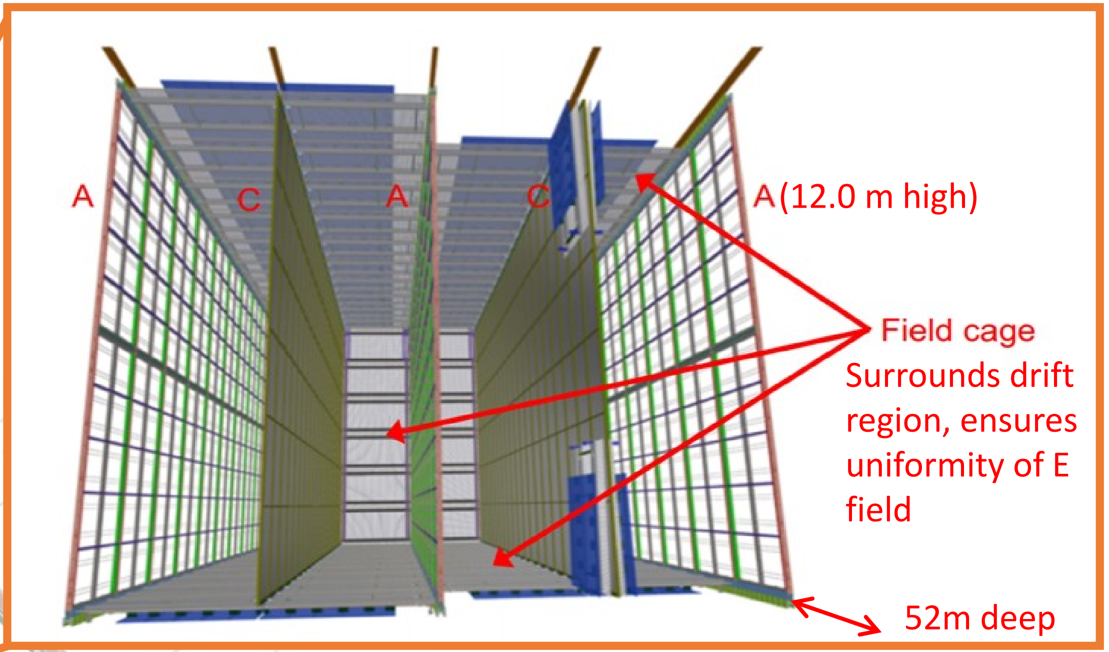
Canadian Support of DUNE-Canada

- NSERC “Project Grant”
  - Submitted by all DUNE-Canadian participants
  - Pays student and postdoc salaries
  - Originally 3 years, extended to 4th year because of pandemic
  - Current grant expires April 1, 2024
  - Will submit new grant November 1, 2023

- NSERC CFI Grant for DUNE DAQ
  - PI: Nikolina Ilic
  - 547k CAD Awarded
- NSERC CFI Grant for Near Detector Prototyping
  - Co-PI’s: Claire David and Deborah Harris
  - 125k CAD Awarded
- Compute Canada Grant
  - Coordinated by Nikolina Ilic
  - Other DUNE and ATLAS Computing folks also contributed

DUNE 1st Module





(12.0 m high)

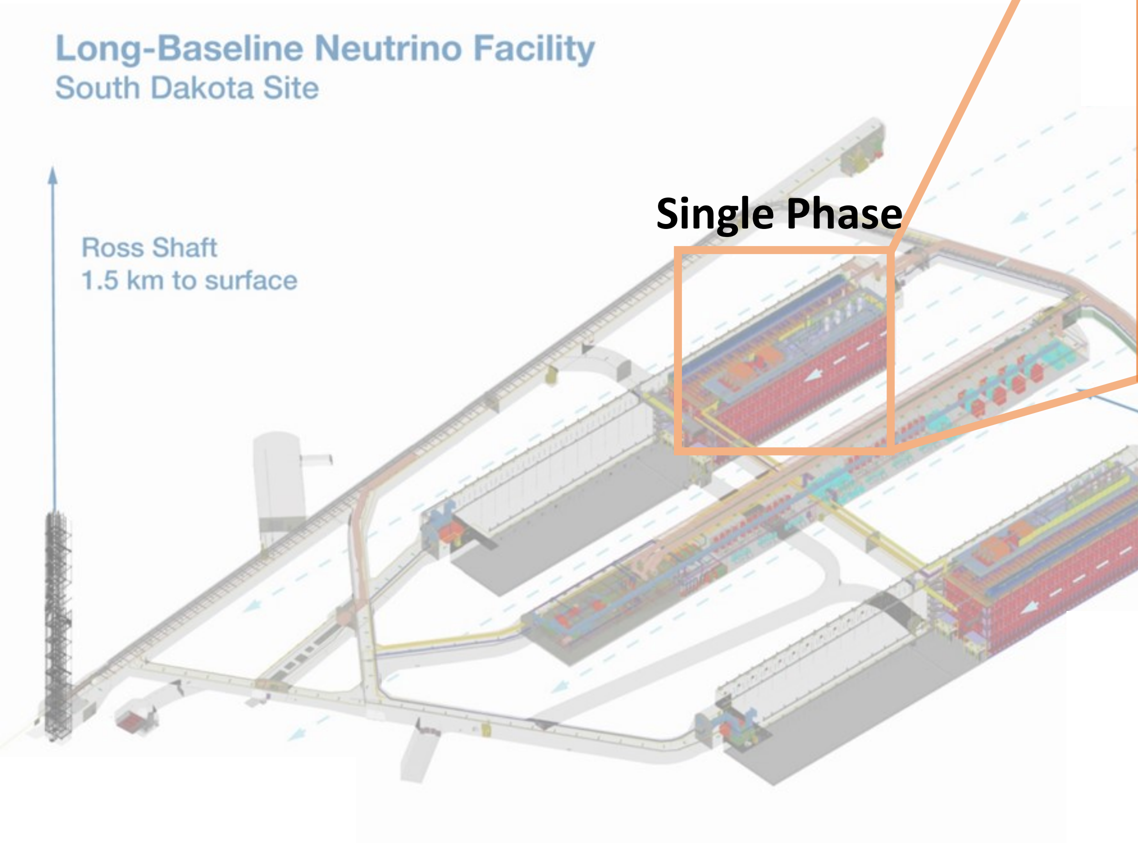
Field cage

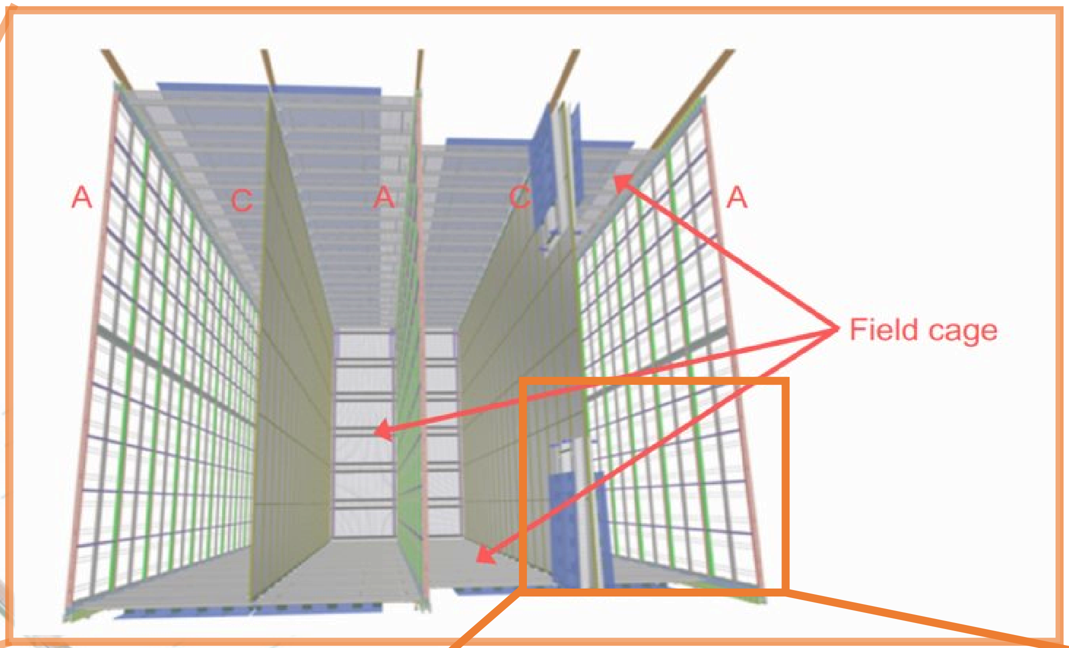
Surrounds drift region, ensures uniformity of E field

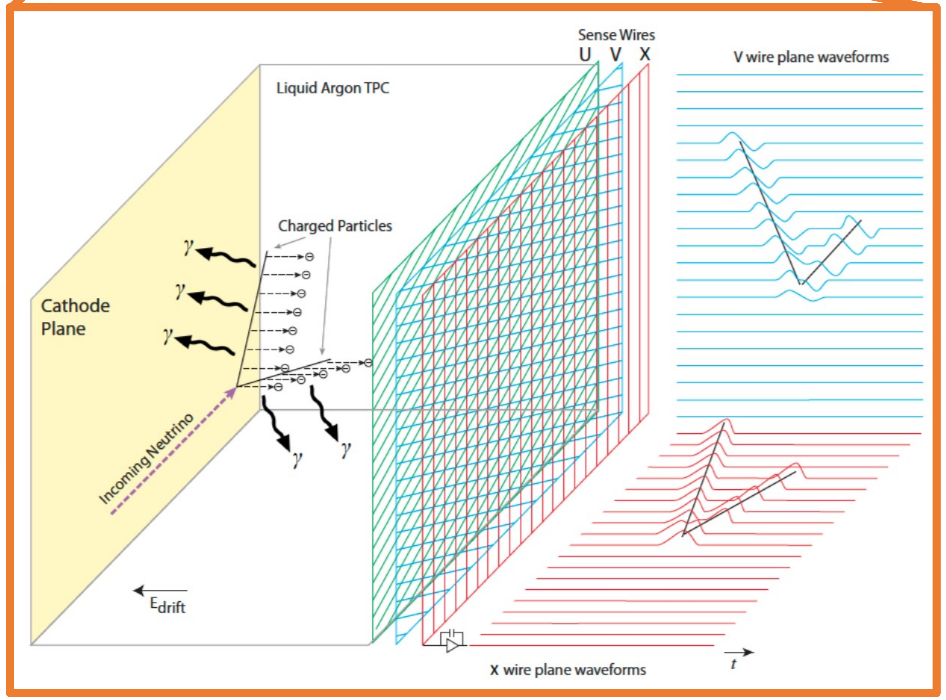
52m deep

1st module will be Single Phase (SP), LAr TPC.
Divided into 4 sections

DUNE 1st Module

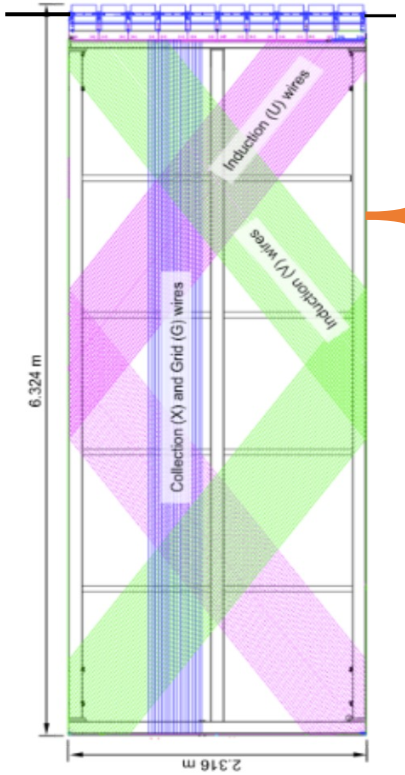


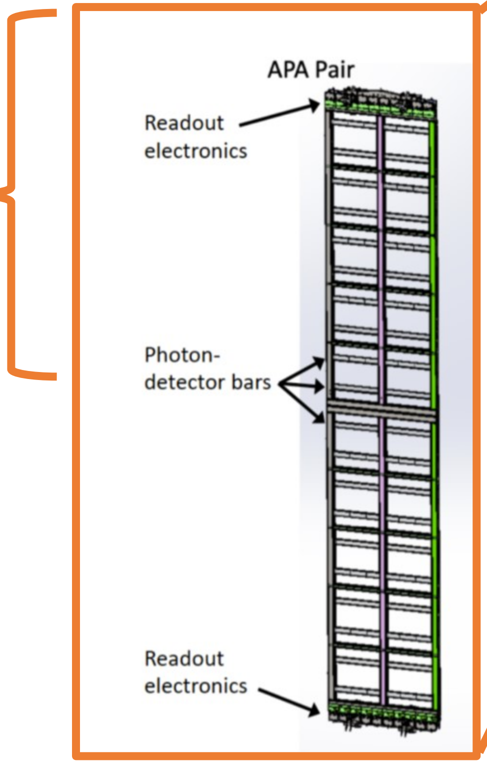


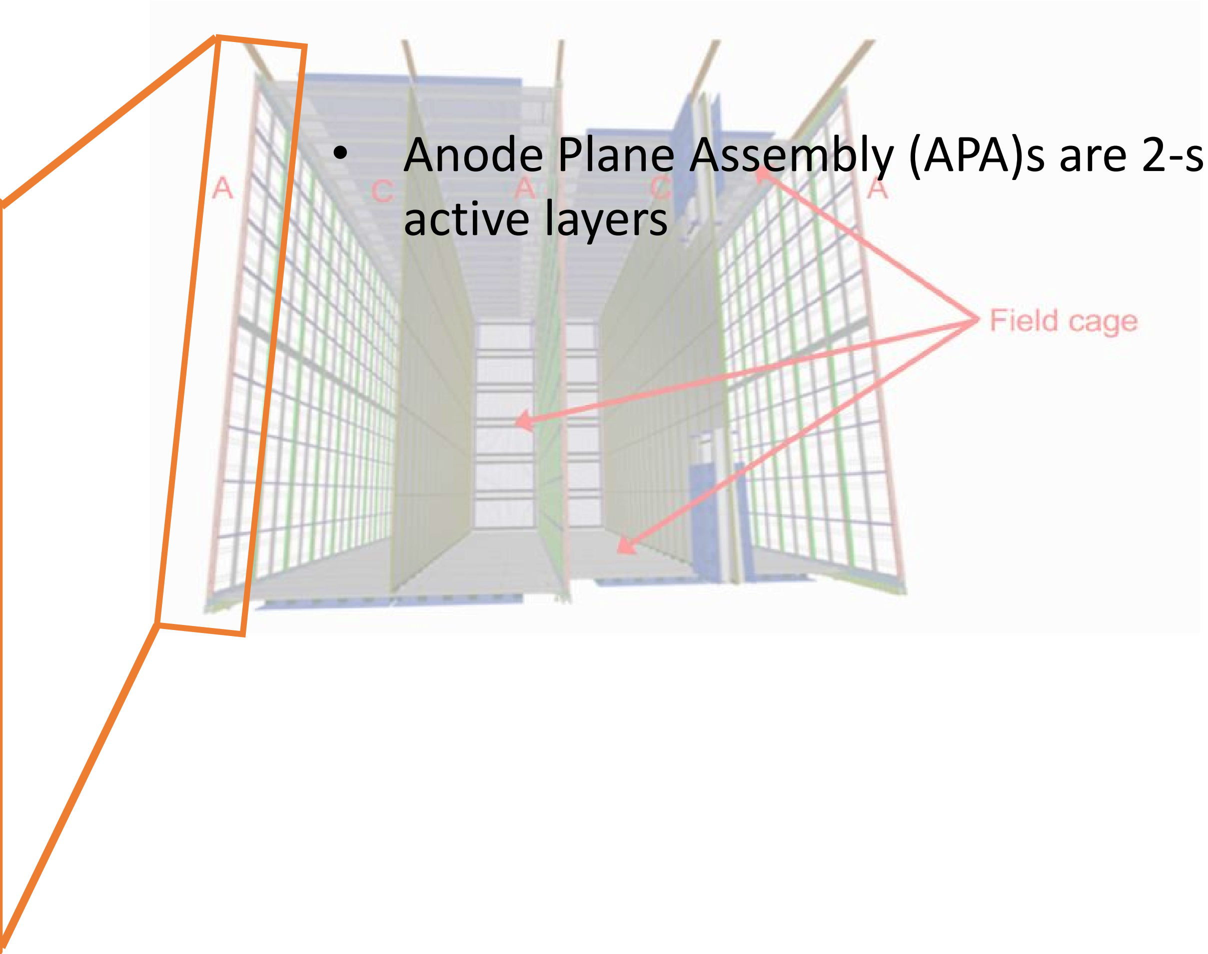


- 3D image of neutrino interactions with mm resolution
  - 3.5m drift region, E field of 500 V/cm, Cathode HV 180 kV
- LAr is good scintillator ⇒ provide t_0 (non-beam trigger)

DUNE 1st Module

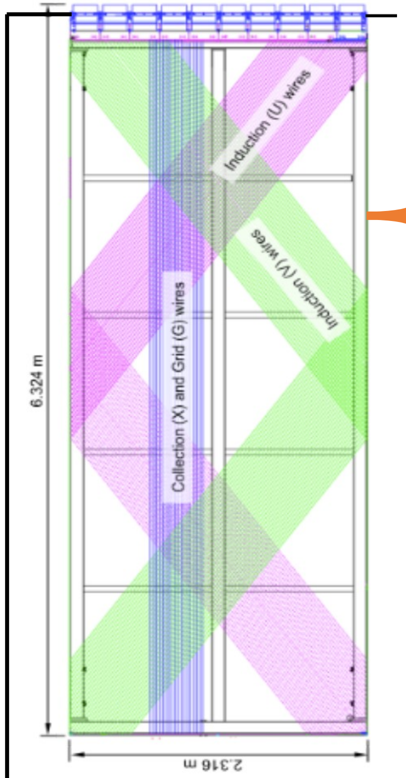


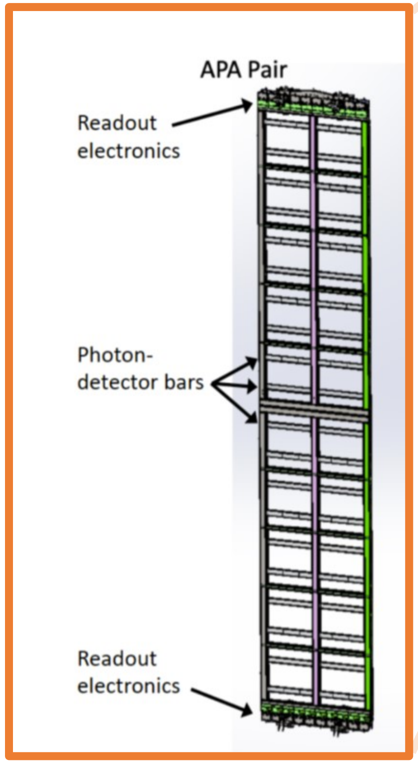


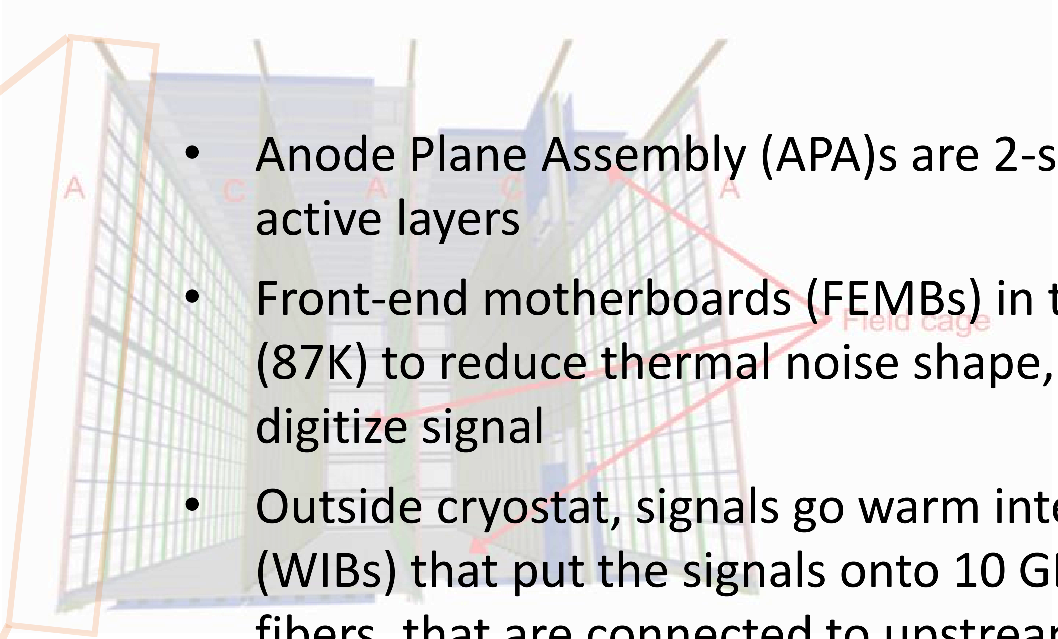


- Anode Plane Assembly (APA)s are 2-sided, with 3 active layers

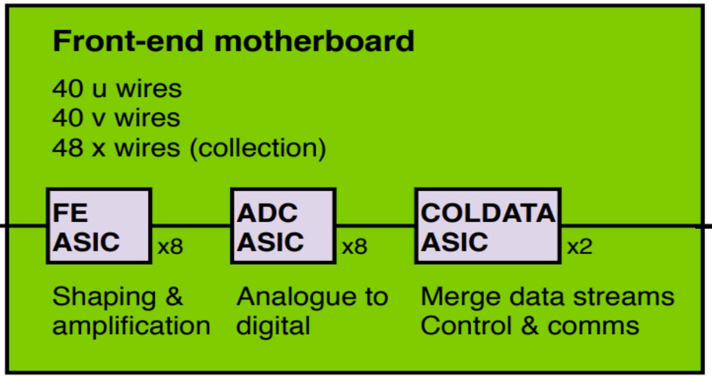
DUNE 1st Module







- Anode Plane Assembly (APA)s are 2-sided, with 3 active layers
- Front-end motherboards (FEMBs) in the cryostat (87K) to reduce thermal noise shape, amplify, digitize signal
- Outside cryostat, signals go warm interface boards (WIBs) that put the signals onto 10 GB optical fibers, that are connected to upstream DAQ



Front-end motherboard

40 u wires
40 v wires
48 x wires (collection)

Shaping & amplification

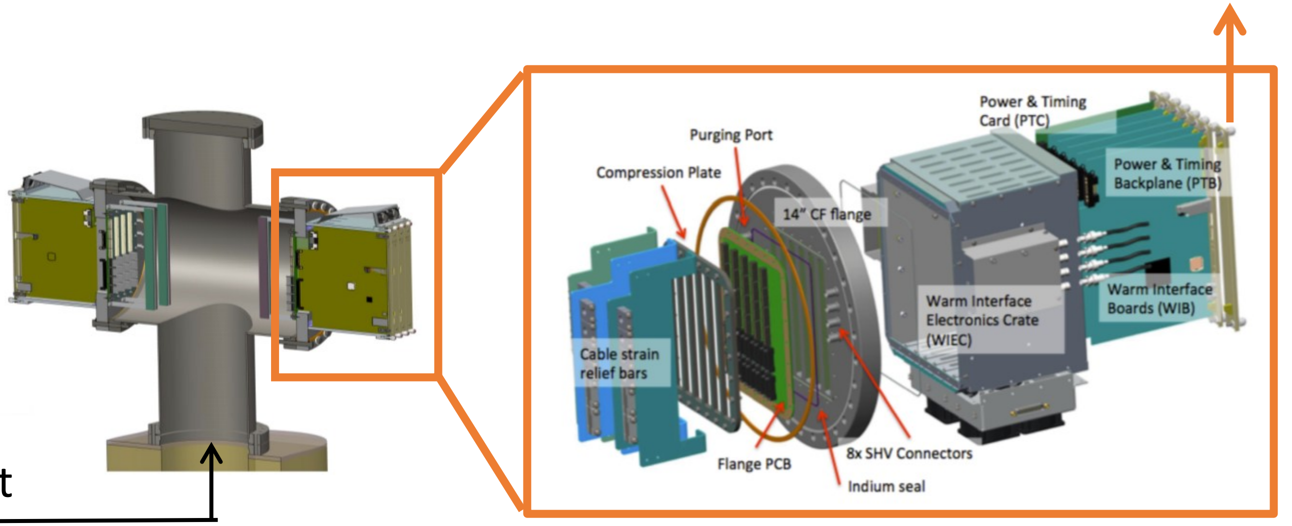
Analogue to digital

Merge data streams
Control & comms

x 20 per APA

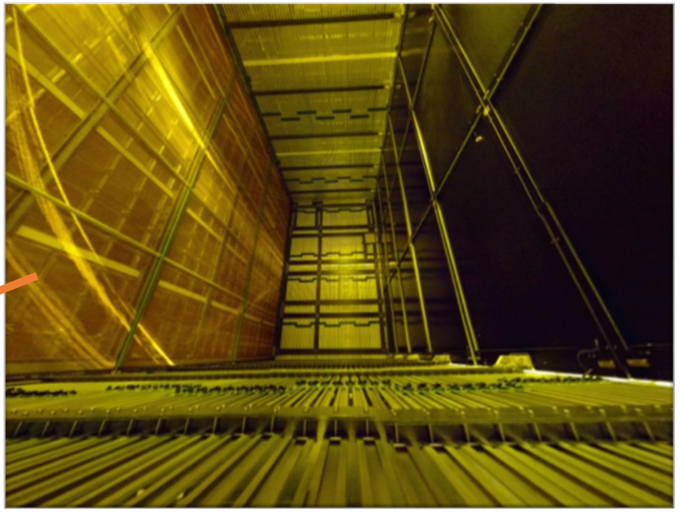
Outside Cryostat

DAQ

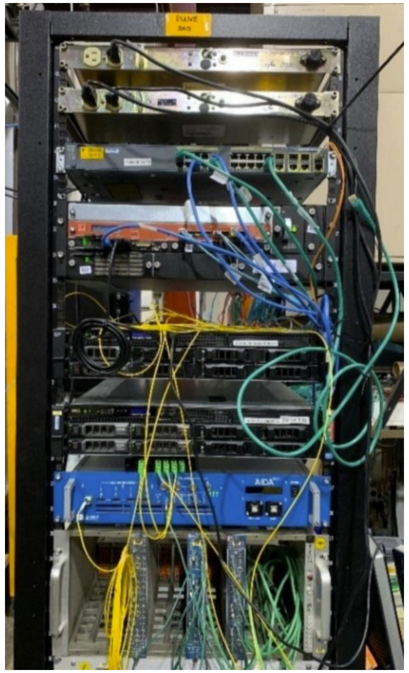


ProtoDUNE

APA

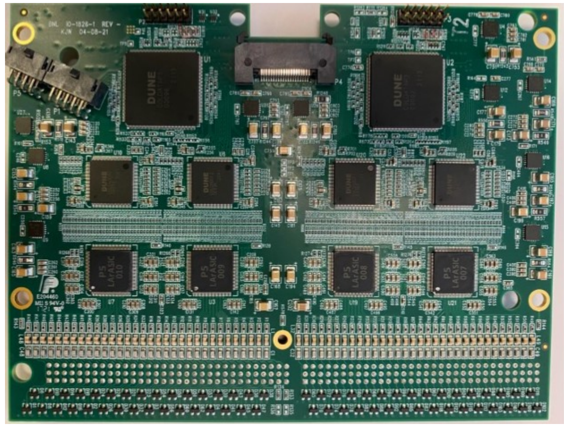


ProtoDUNE SP Drift Region

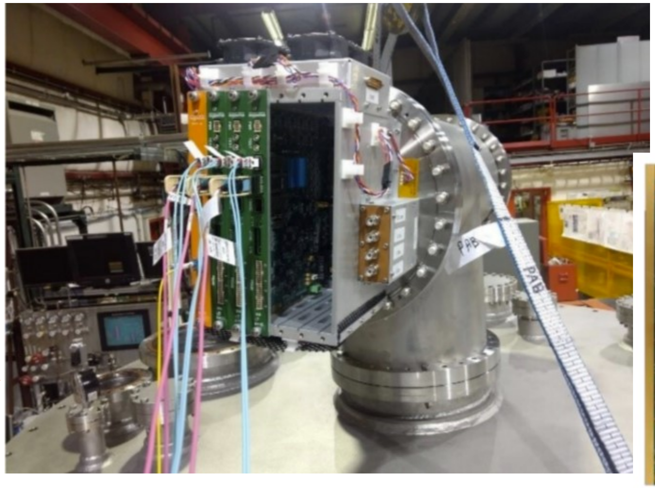


DAQ

FEMB



Outside Cryostat



WIB

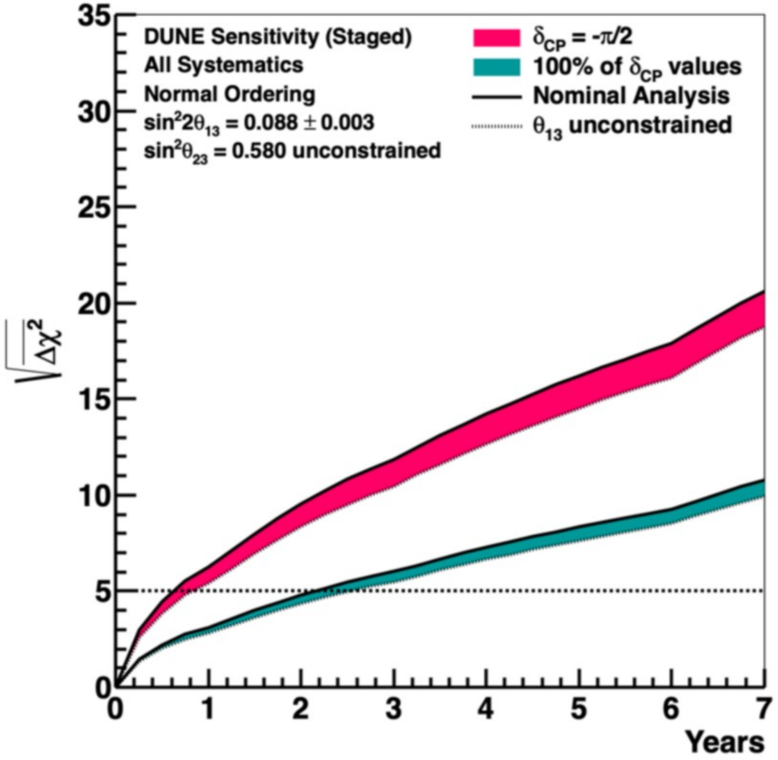
Digital Resource Alliance Grant

- **HPC allocations**
  - **360** core years on the **cedar-compute** system
  - **50** TB of project storage on the **cedar-storage (Cedar)** system
  - **250** TB of dCache storage on the **cedar-storage (Cedar)** system
- Allocation from **April 3, 2023**, and is valid until the **end of April 1, 2024**.
- Providing these resources to your research group costs roughly **$54,659**.

- Nikolina Ilic and Leslie Groer (U of Toronto) working on making sure these resources available to DUNE members at large
- Ability for non-Canadian institution members to have DRA accounts
- Oscillation fitting framework (“Mach-3”) runs on these accounts

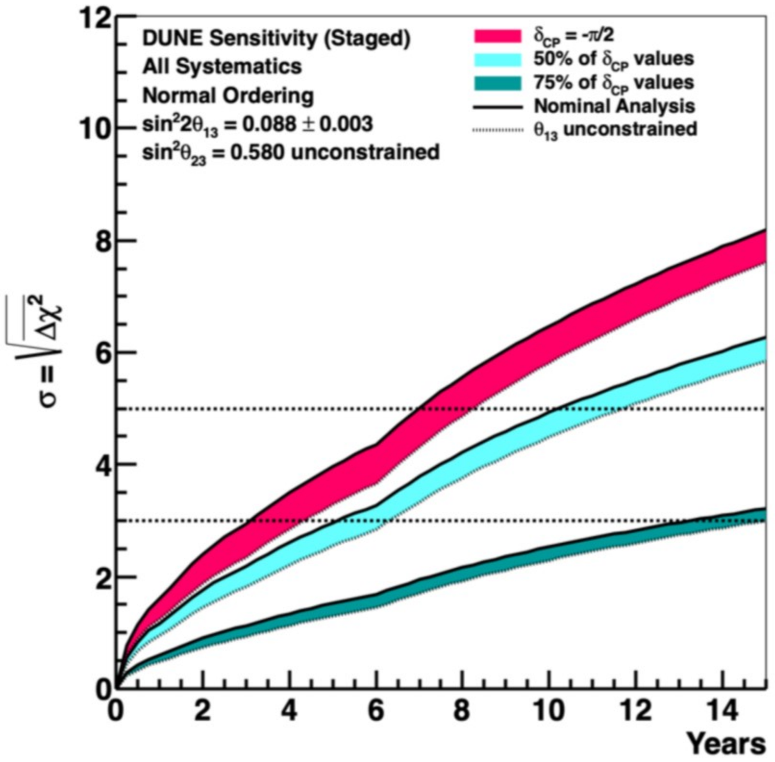
Motivation: Mass Ordering and CP violation

Mass Ordering Sensitivity



- 5σ sensitivty after 2 years of running

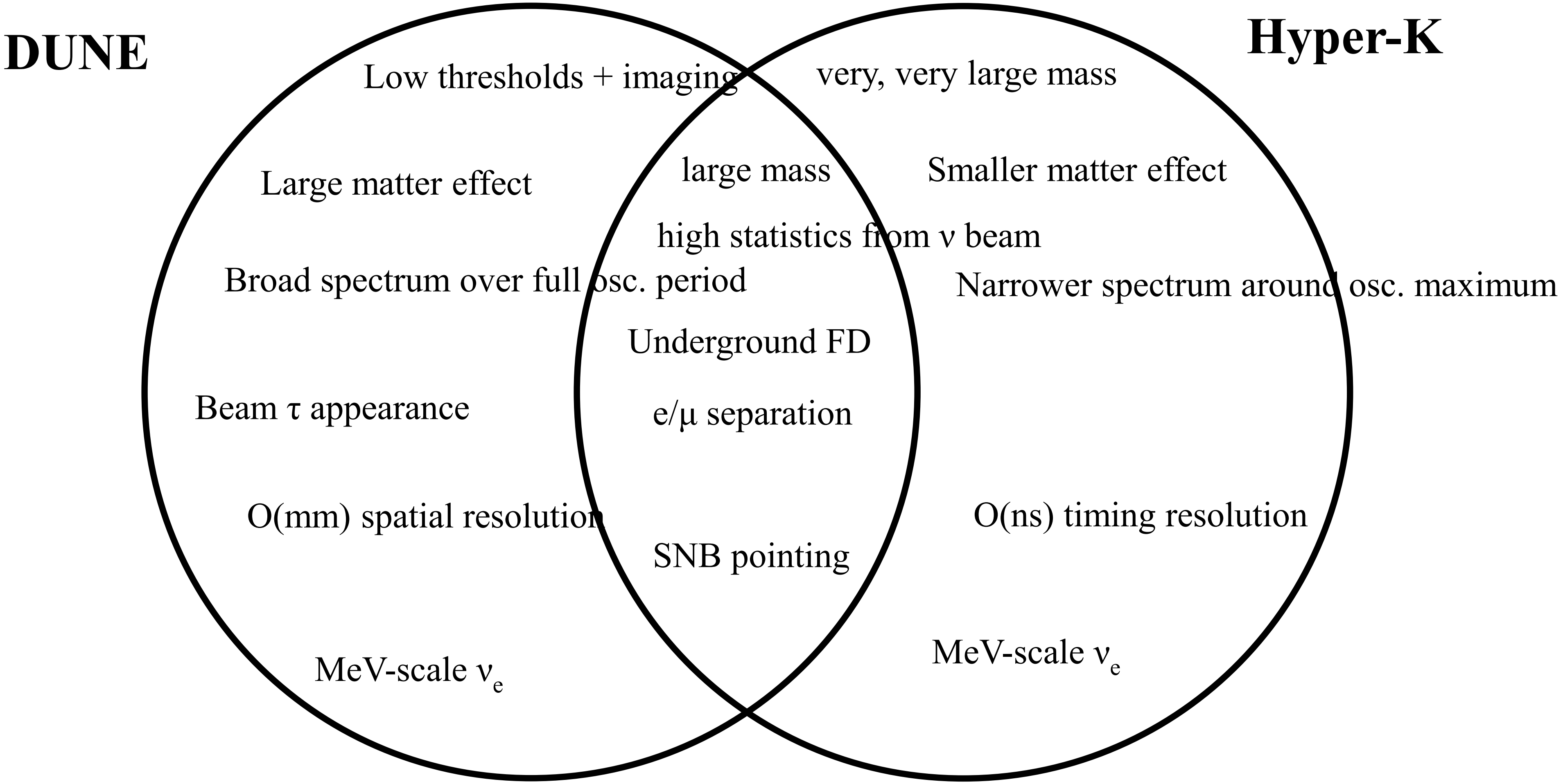
CP violation Sensitivity



- 5 σ sensitivity after 10 years of running for 50% of δ_{CP} values

+ High precision measurement of $\Delta m^2_{32}, \delta_{CP}, \sin^2\theta_{23}, \sin^2 2\theta_{13}$

Complementarity



DUNE

Low thresholds + imaging

Large matter effect

Broad spectrum over full osc. period

Beam τ appearance

O(mm) spatial resolution

MeV-scale ν_e

large mass

high statistics from ν beam

Underground FD

e/μ separation

SNB pointing

Hyper-K

very, very large mass

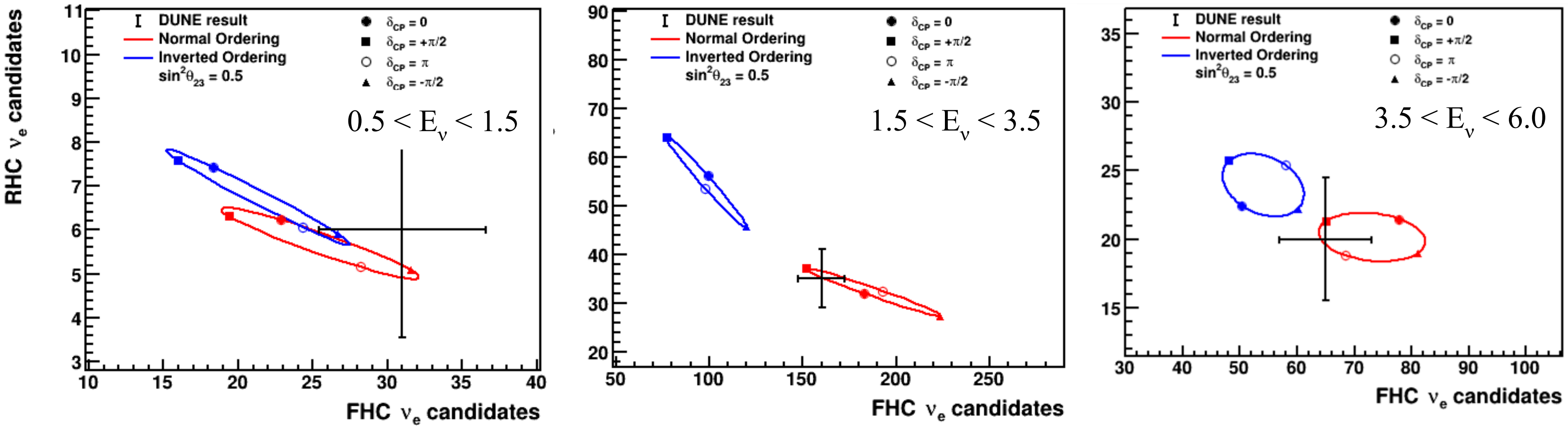
Smaller matter effect

Narrower spectrum around osc. maximum

O(ns) timing resolution

MeV-scale ν_e

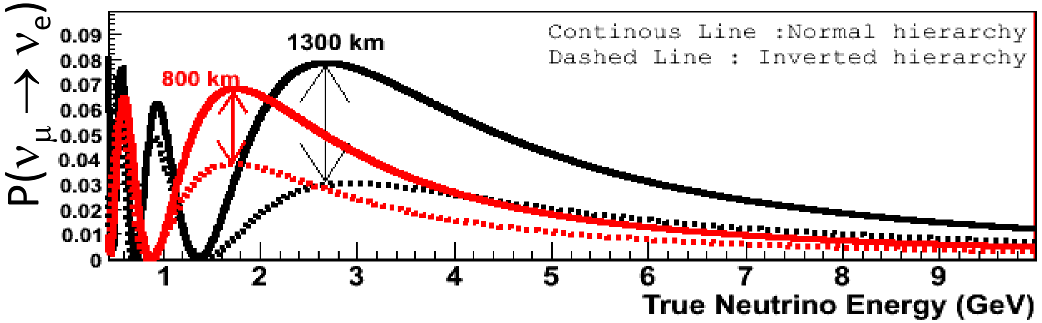
With Phase I only, DUNE is not sensitive to new physics



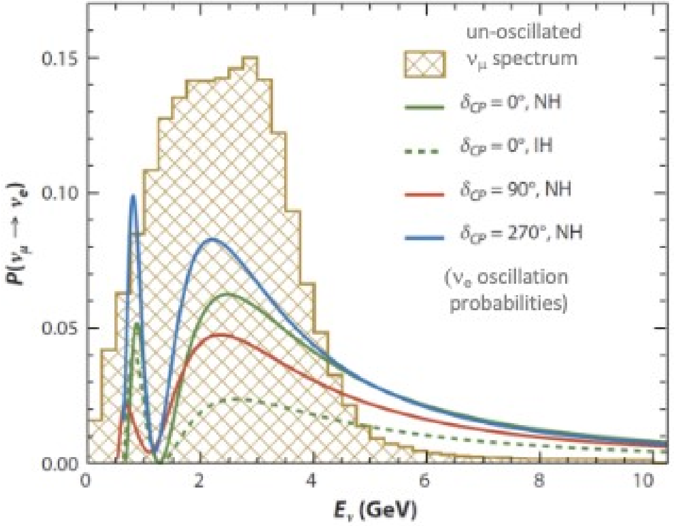
- Phase I statistical uncertainties do not permit this kind of new physics search – the data are consistent at 1σ with three-flavor oscillations for the same effect
- We have a fantastic opportunity to really push the three-flavor model, but it requires DUNE Phase II **and** Hyper-K

Why Is This the Best Configuration for the Experiment?

- neutrino baseline is optimized
  - *1000-1500 km is the optimal distance for MO, CP*
  - *1300km is in a “sweet spot” for this physics

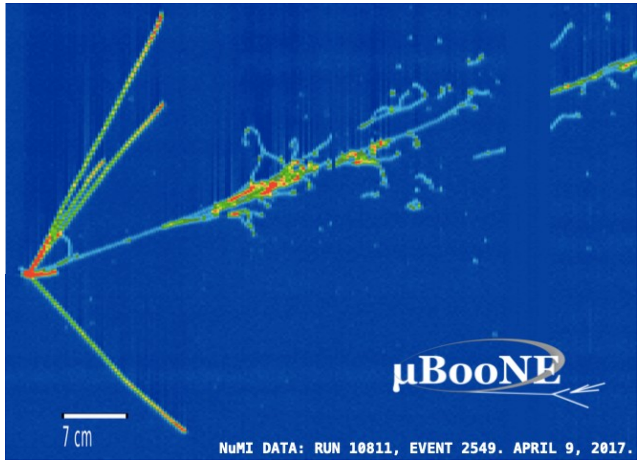


- beam spectrum covers the full neutrino oscillation curve
  - *this is not a counting experiment*
  - *enables detailed fitting of the ν oscillation parameters*



other ν LBL experiments probe shorter baselines, narrow band beam, not LAr TPC

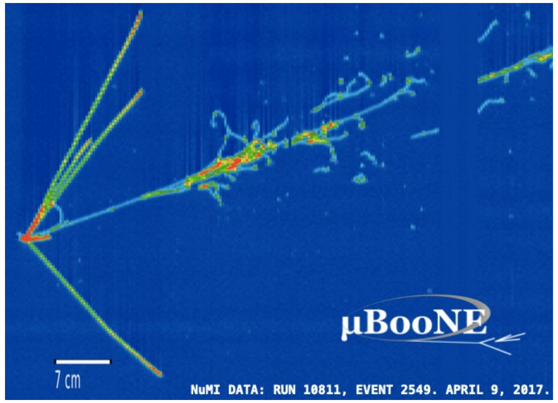
- LAr TPC is a game-changer
  - *enables precise reconstruction of the entire neutrino interaction*

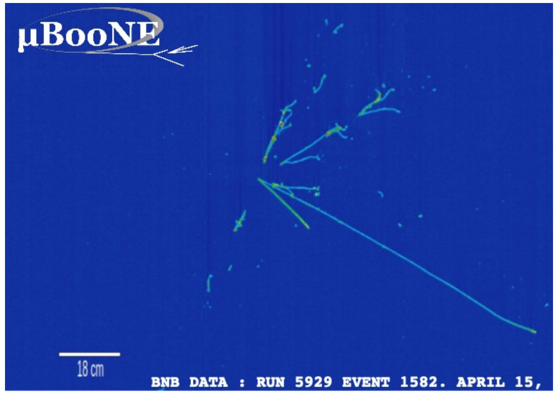


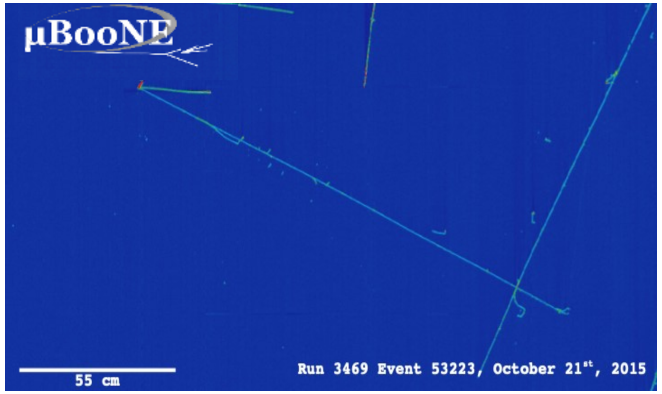
Why Liquid Argon?

- This really sets DUNE apart. Can see the hadronic side the interaction. This means that we can measure both the hadronic and leptonic parts of the ν event with extremely high precision leading to much better event classification & determination of E_ν.

LAr → TPC



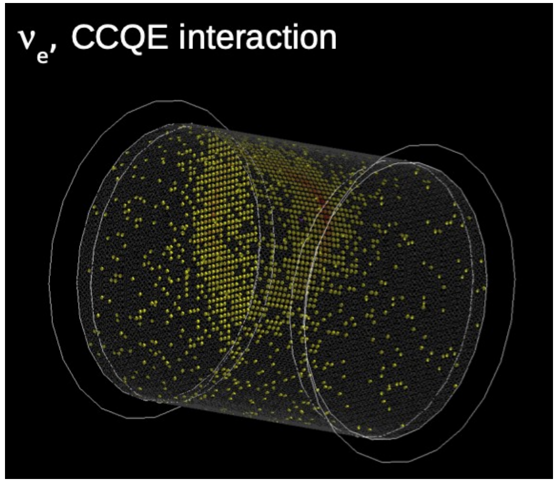




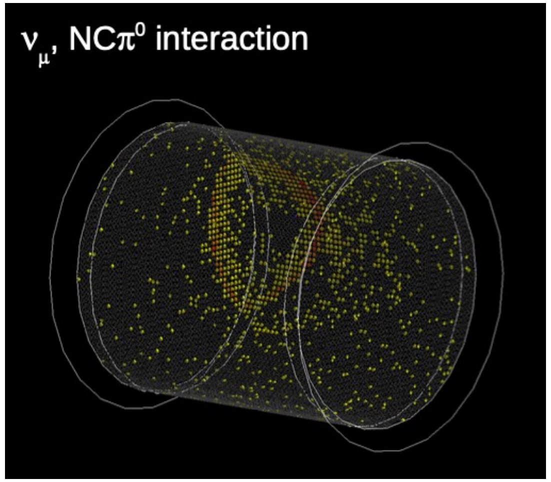
DUNE far detector has unmatched capability

Water → Cerenkov

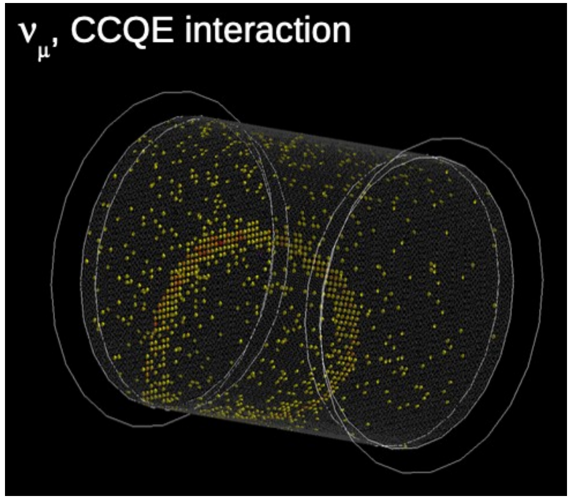
ν_e, CCQE interaction



ν_μ, NCπ^0 interaction

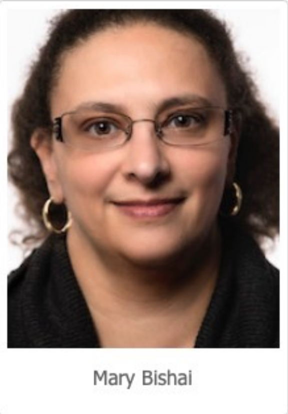


ν_μ, CCQE interaction



LAr also a fertile playground for AI/ML

DUNE Collaboration


Mary Bishai

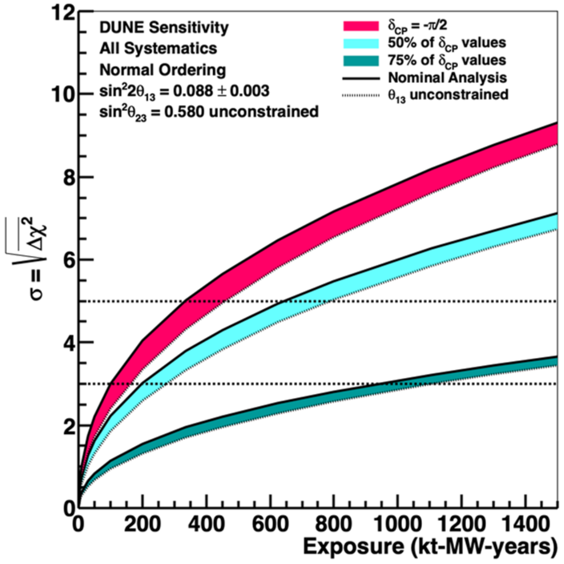

Sergio Bertolucci

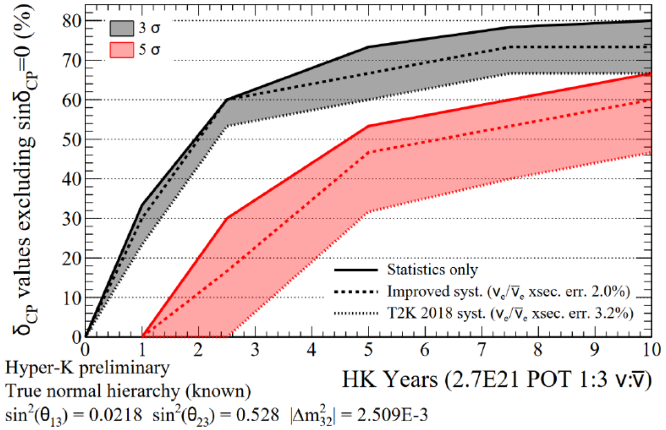
DUNE Co-Spokespeople

- DUNE has attracted the world
- DUNE Science Collaboration is currently 1,402 collaborators from 206 institutions in 37 countries including CERN

DUNE Collaboration meeting at CERN, January 2023

When will CP violation be established?





- DUNE can establish CP violation at 3σ in 4 years (if δ_{CP} = 90°), or 6 years (δ_{CP} = 45°), or 14 years (if δ_{CP} = 22°), or establish that CP is **not** violated (if δ_{CP} = 0°)
- DUNE can establish CP violation at 5σ in 7 years (if δ_{CP} = 90°), or 10 years (δ_{CP} = 45°), or ~16 years (if δ_{CP} = 30°)
- With current T2K systematics, and assuming that J-PARC turns on at full power, Hyper-K can establish CP violation at 3σ in 1 year (if δ_{CP} = 90°), or 2 years (δ_{CP} = 45°), becoming systematically limited around δ_{CP} = 30°
- With “improved” systematics, 3σ reach goes out to ~24°
- For 5σ, depending on systematics Hyper-K can establish CP violation for δ_{CP} = 45° between 6-13 years, and becomes limited between 35-45°
- Hyper-K reach assumes that the mass ordering is determined externally

DUNE ν_e and ν_e spectra can distinguish MO in Phase I

Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

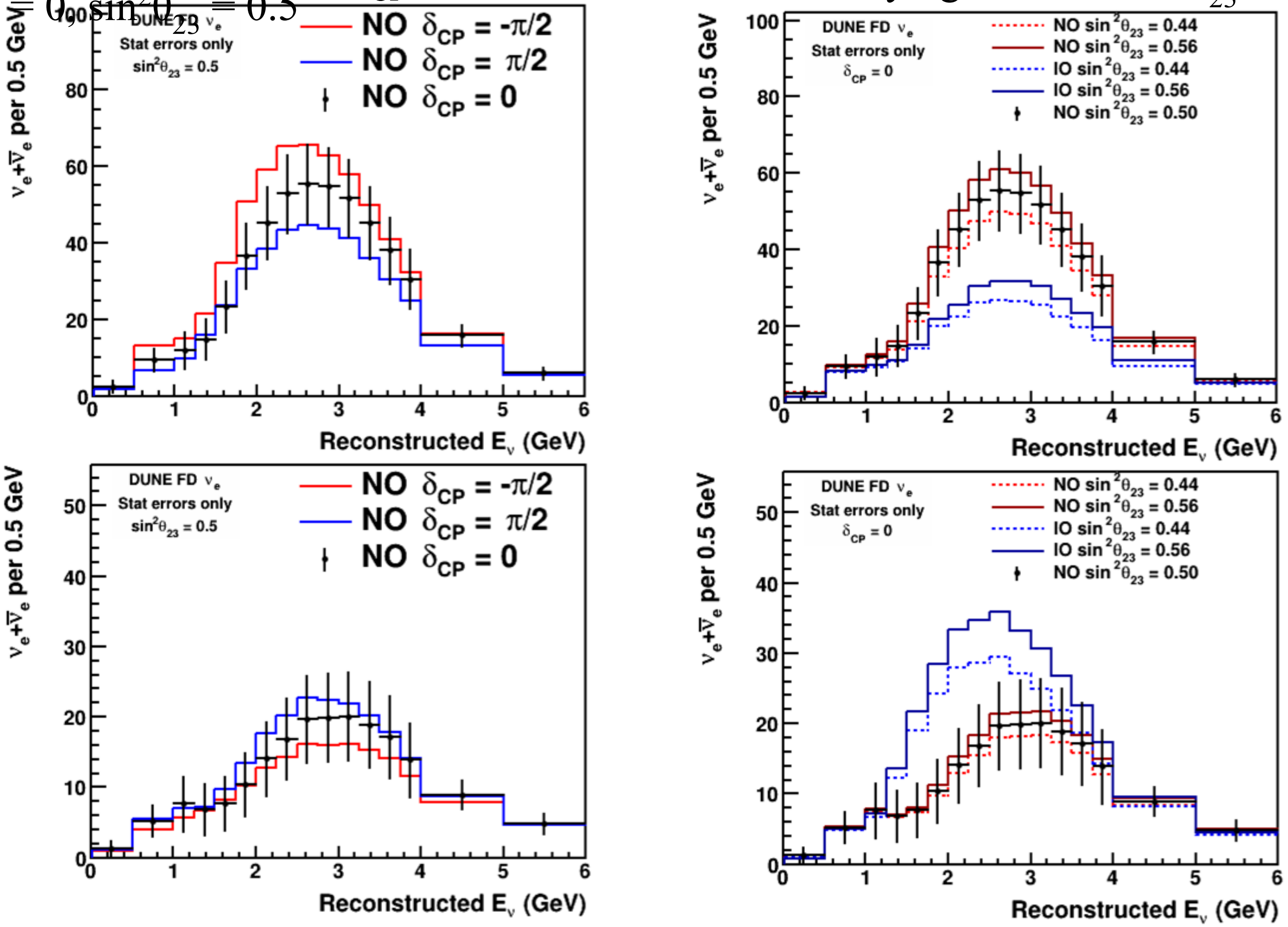
Varying δ_{CP}

Varying MO and $\sin^2\theta_{23}$

Neutrino mode

Phase I

Antineutrino mode



DUNE ν_e and ν_e spectra can measure δ_{CP}, θ_{23} octant in Phase II

Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

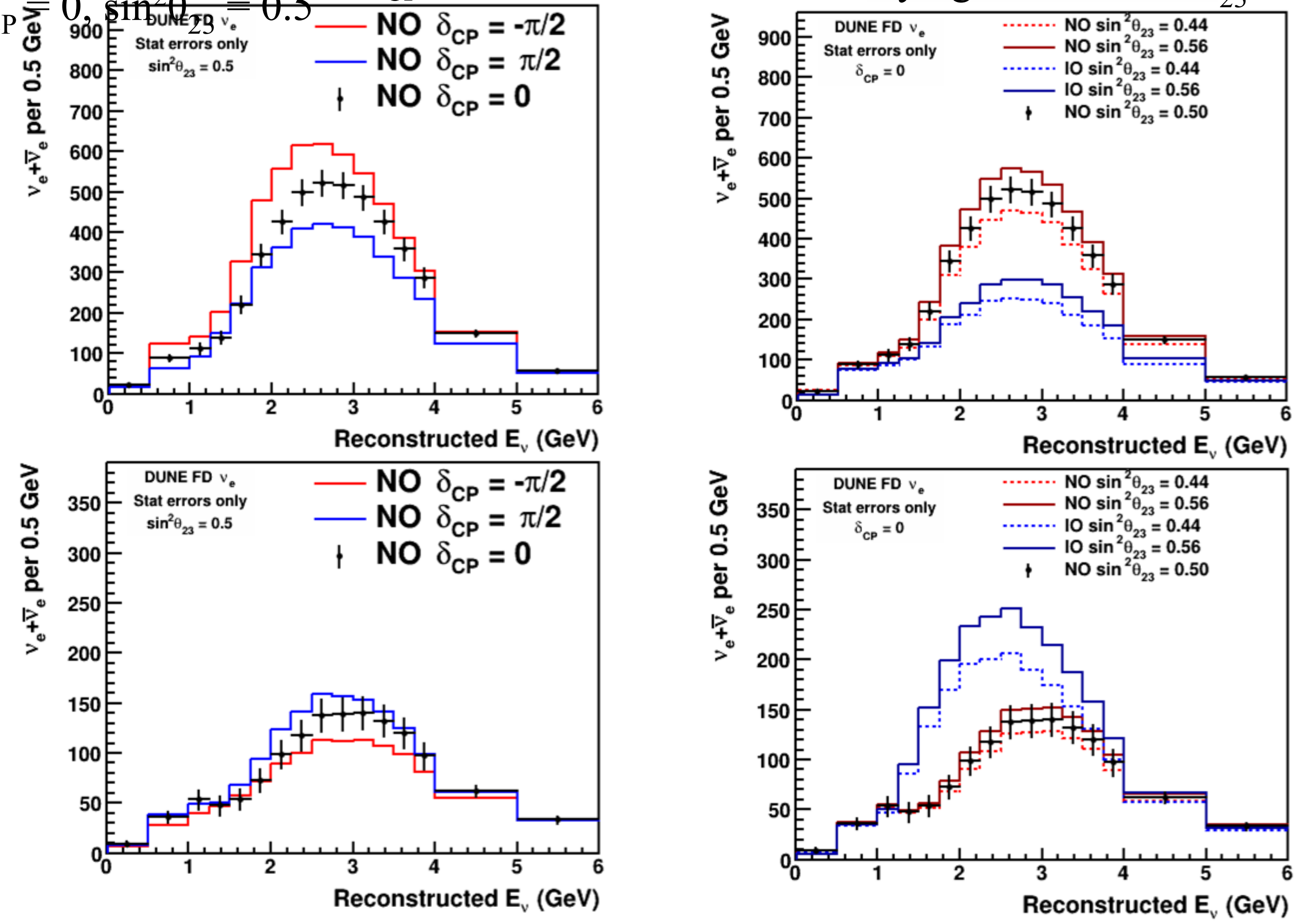
Varying δ_{CP}

Varying MO and $\sin^2\theta_{23}$

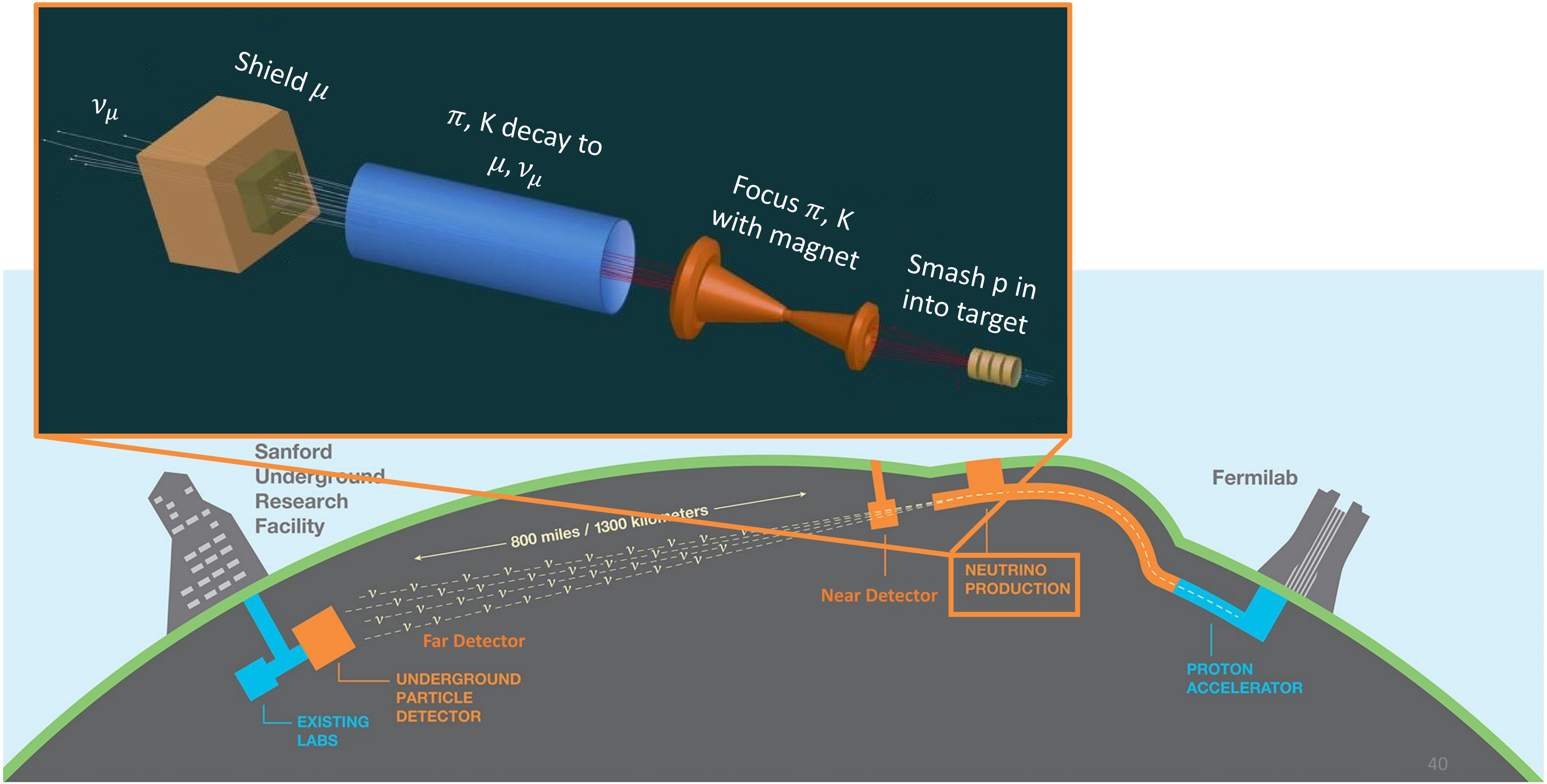
Neutrino mode

Phase II

Antineutrino mode

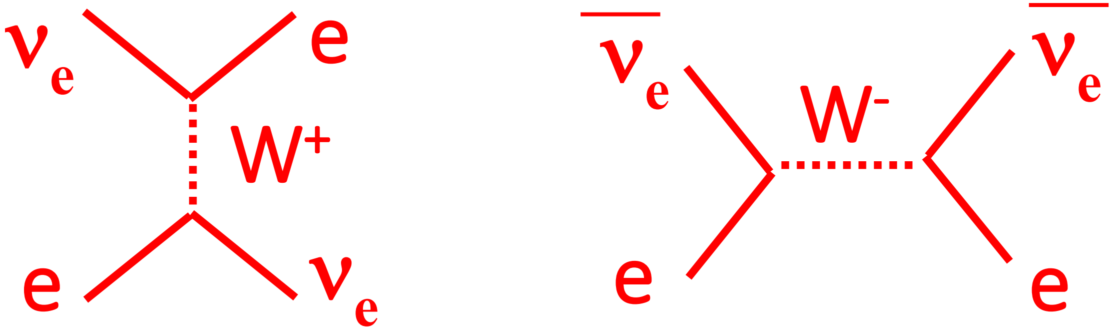


LBNF DUNE Facility



DUNE Sensitivity to Mass Ordering and CP violation

- In DUNE, L = 1300km, lots of chances to interact with matter!
- Since matter acts differently on ν_e and $\bar{\nu}_e$, there is asymmetry in $\mathrm{P}(\nu_\mu \rightarrow \nu_\mathrm{e})$ versus $\mathrm{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Sign of asymmetry depends on mass ordering!

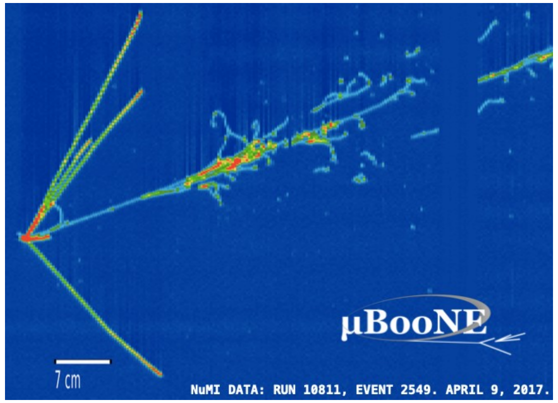


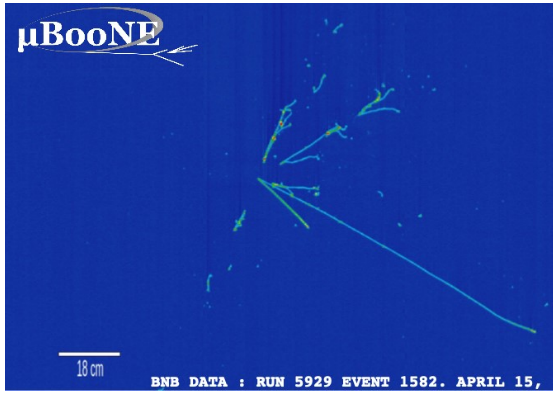
- This complicates CP measurement, BUT matter effects and direct CP violation have different *E* and *L* dependences – and DUNE can get CP violation as function of E!

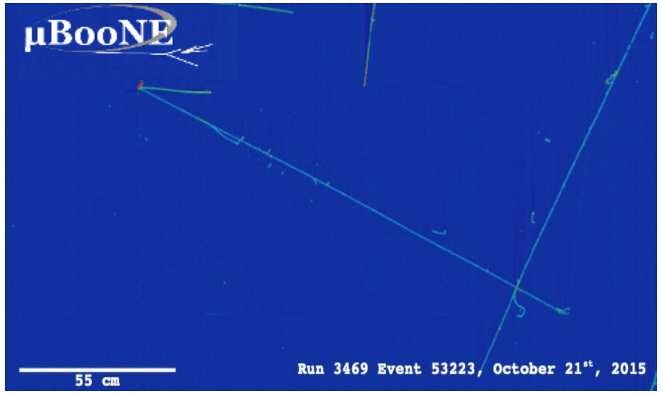
Why Liquid Argon?

- This really sets DUNE apart. Can see the hadronic side the interaction. This means that we can measure both the hadronic and leptonic parts of the ν event with extremely high precision leading to much better event classification & determination of E_ν.

LAr → TPC

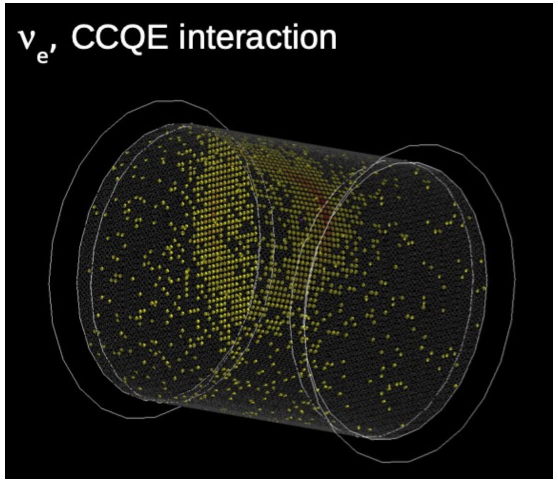


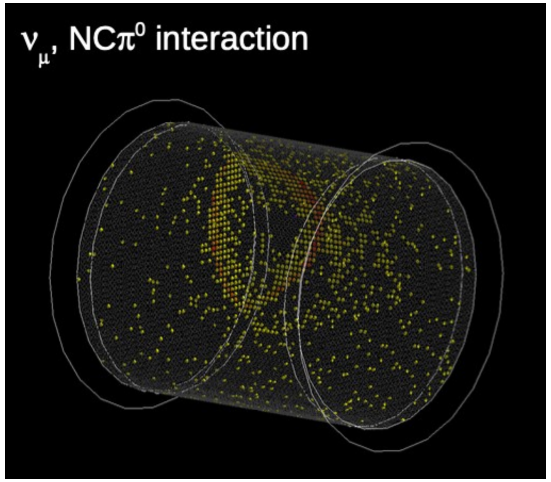


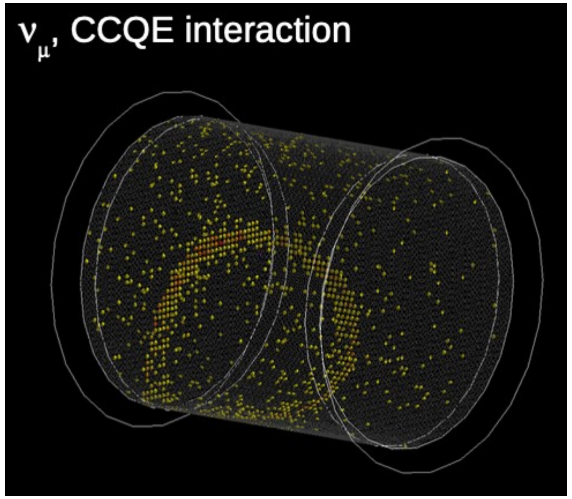


DUNE far detector has unmatched capability

Water → Cerenkov

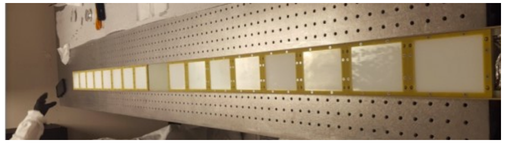


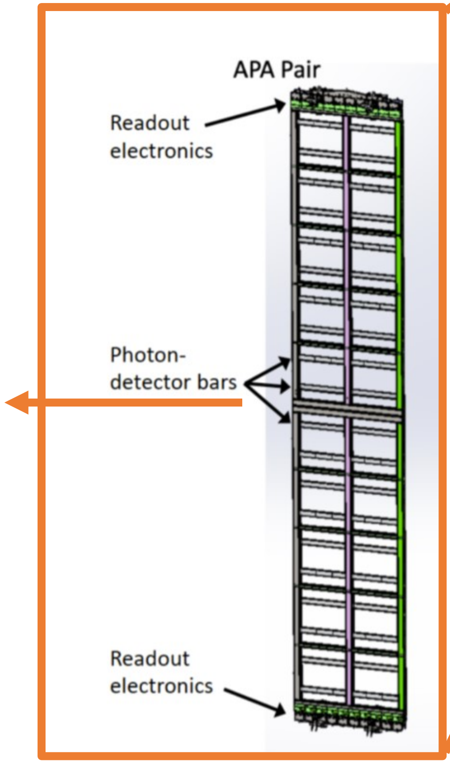


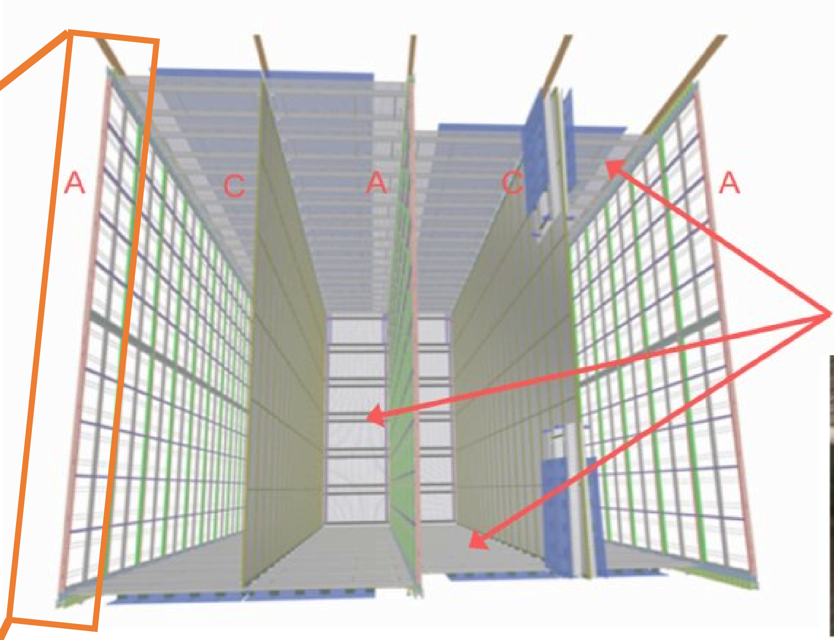


LAr also a fertile playground for AI/ML

DUNE 1st Module



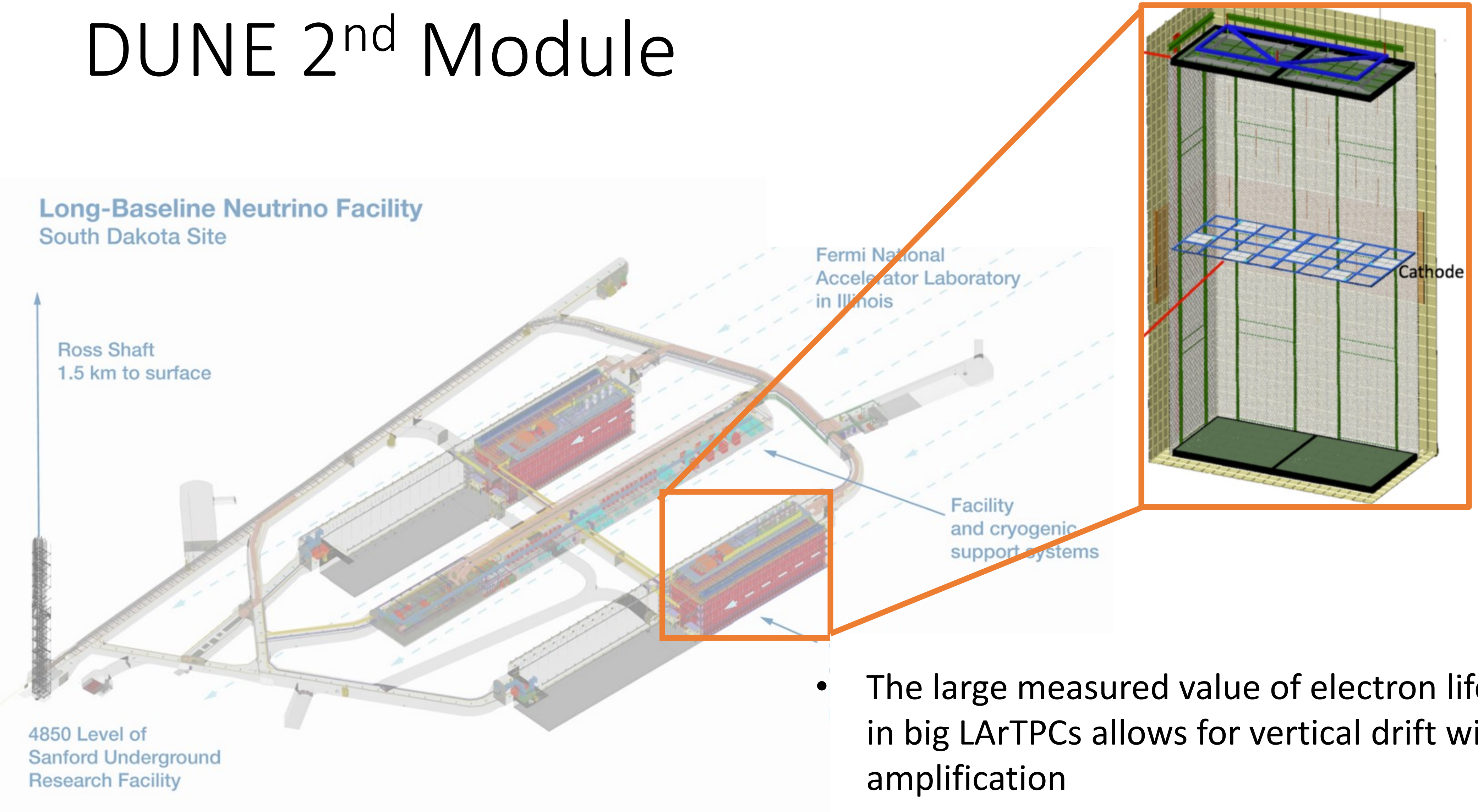




aluminum with white polyethylene caps on the ends to prevent discharges

- Photon detection provides time of interaction, and can serve to identify backgrounds, non-beam physics trigger (Supernova, proton decay, etc.)
- Photons collected by X-ARAPUCAs
  - layers of dichroic filter and wavelength-shifter
- Signals sent to feedthroughs in roof of cryostat, merged with APA data at DAQ

DUNE 2nd Module

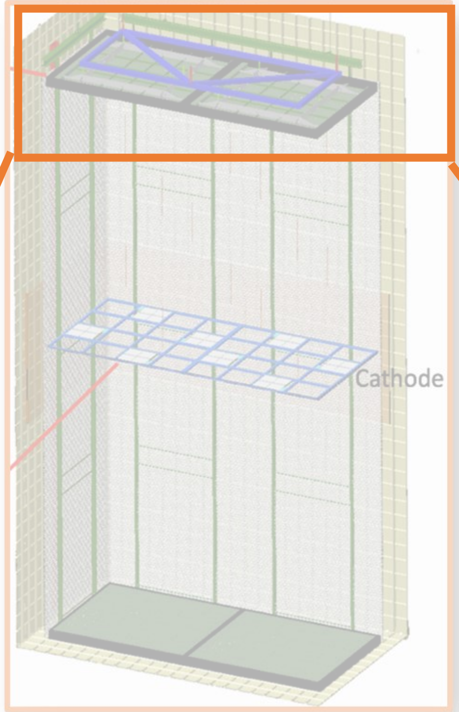


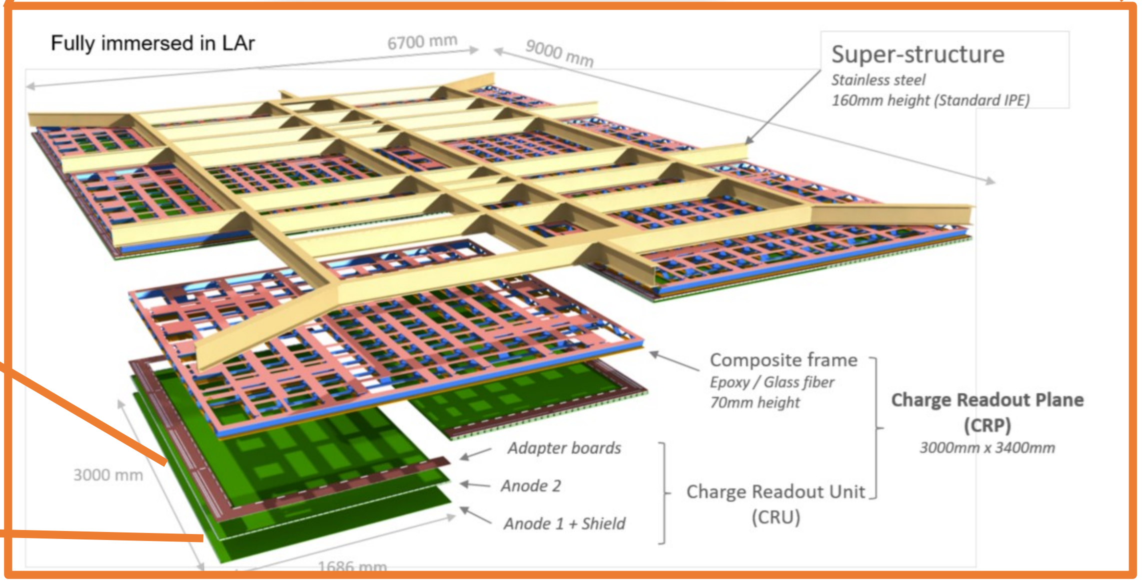
- The large measured value of electron lifetime (> few ms) in big LArTPCs allows for vertical drift without signal amplification

- Ionized charges drift vertically, read out on horizontal PCB anode and cathode planes (two 6.5 m drift volumes). E field 450 V/cm
- This design simplifies construction/installation and reduces cost

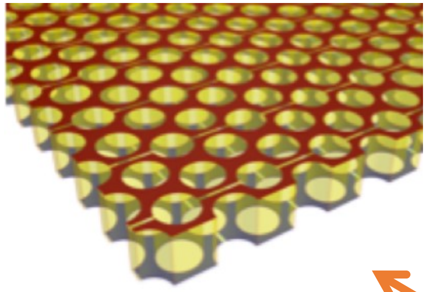
DUNE 2nd Module

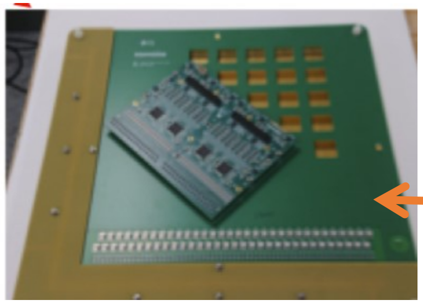
- Charge Readout Plane (CRP) consists of anodes made from two double-sided perforated PCBs (3.2 mm thick), and steel frame. Perforated PCBs have holes so electrons can go to collection strips. Emersed in LAr
- Top CRPs suspended from cryostat roof using superstructure, bottom CRPs supported by posts





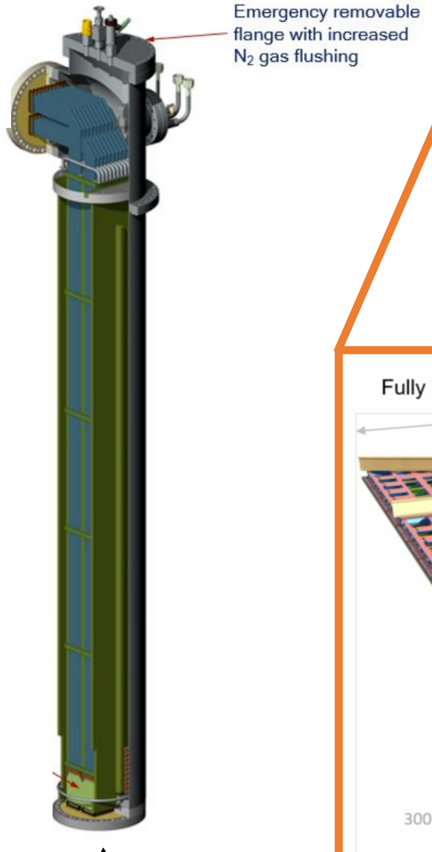
- Anode 1 (facing drift volume) has a copper guard plane to absorb unexpected discharges. Anode 2 has induction plane strips facing the drift volume, and collection plane strips on the reverse side
- 3 of electrode strips segmented at 5 mm pitch and set at different angles to give different projections

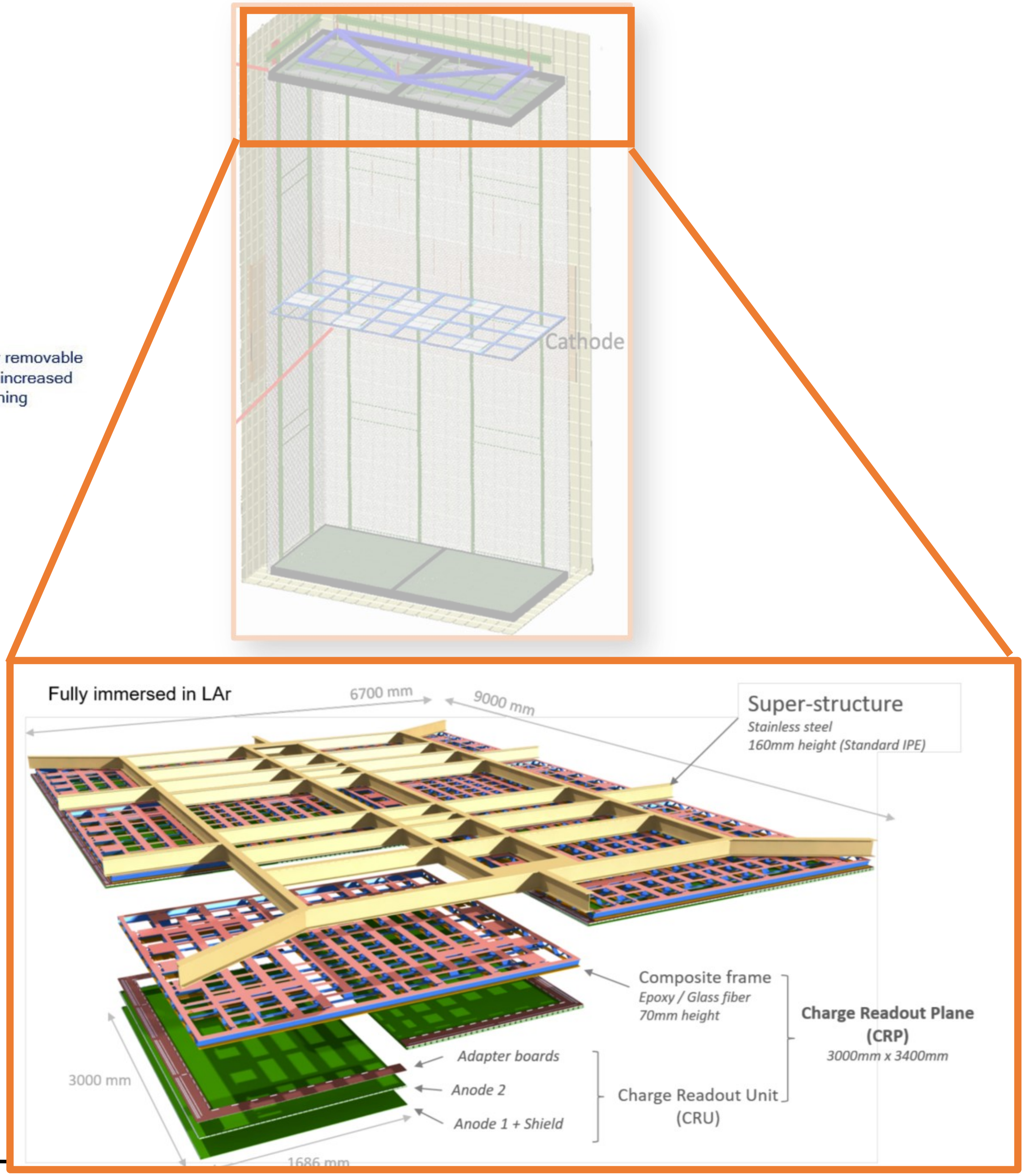




DUNE 2nd Module

- Charge Readout Plane (CRP) consists of anodes made from two double-sided perforated PCBs (3.2 mm thick), and steel frame. Perforated PCBs have holes so electrons can go to collection strips. Emersed in LAr
- Top CRPs suspended from cryostat roof using superstructure, bottom CRPs supported by posts
  - Signals from bottom CRP readout like the APAs in horizontal drift detectors
  - Signals from top CRP collected by Signal Feedthrough Chimneys (SFC), which are pipes that penetrate the cryostat. SFCs are filled with nitrogen gas and sealed by ultra-high vacuum flanges





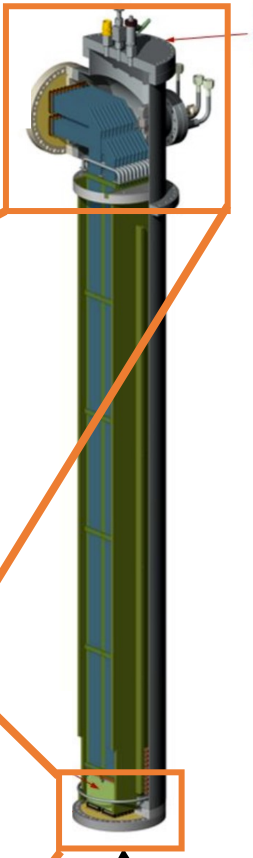
In/Out Cryostat

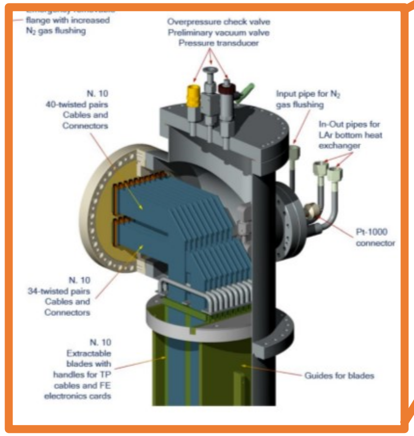
DUNE 2nd Module

- Signals from bottom CRP readout like the APAs in horizontal drift detectors
- Signals from top CRP collected by Signal Feedthrough Chimneys (SFC), which are pipes that penetrate the cryostat. SFCs are filled with nitrogen gas and sealed by ultra-high vacuum flanges

- Analog FE cards on the PCB of the cold feedthrough side of PCB hosts connectors for flat cables from anodes

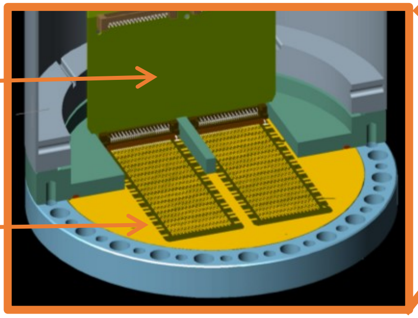
Warm Signal Feedthrough

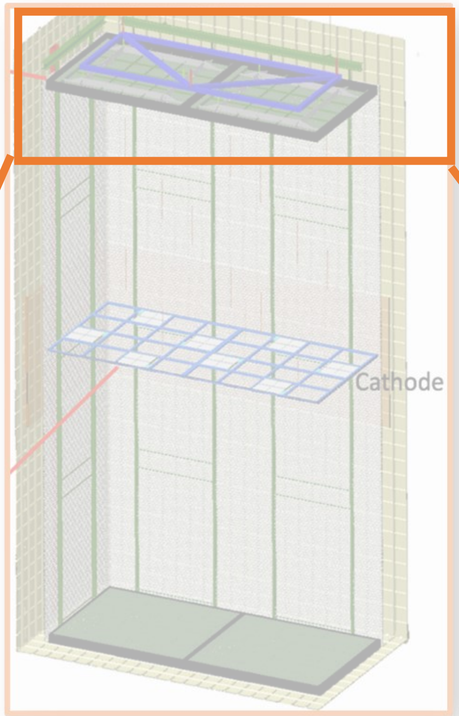


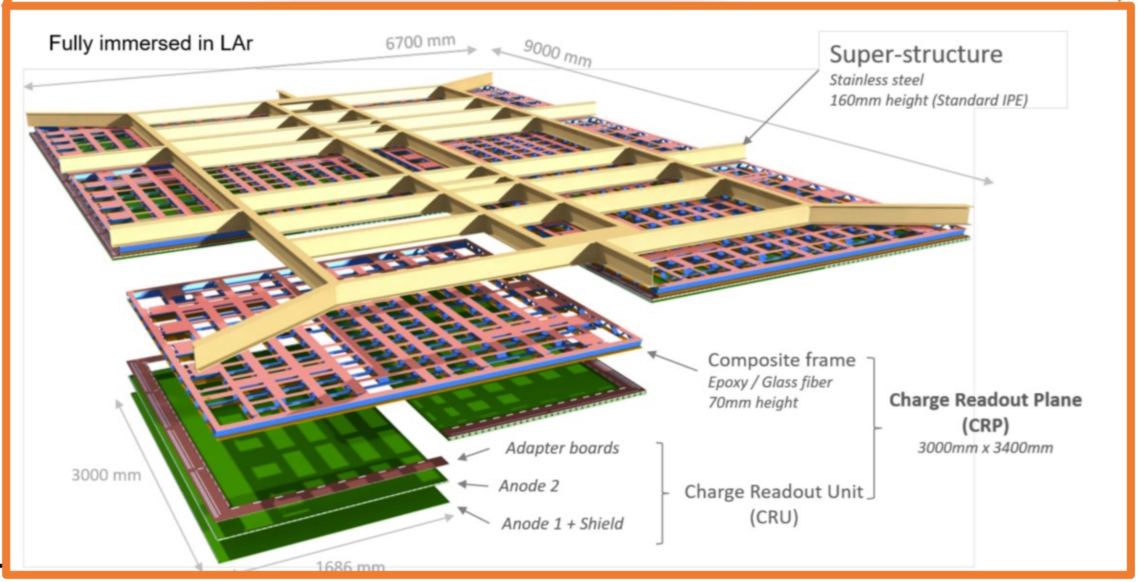


Cold FE Analogue Acquisition Card

Cold Signal Feedthrough

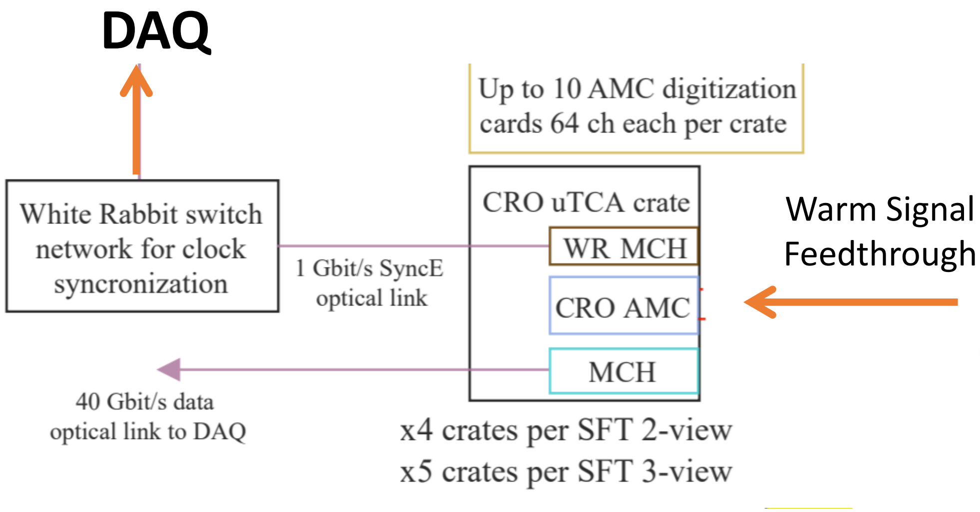






In/Out Cryostat

DUNE 2nd Module



DAQ

White Rabbit switch network for clock syncronization

1 Gbit/s SyncE optical link

40 Gbit/s data optical link to DAQ

Up to 10 AMC digitization cards 64 ch each per crate

CRO uTCA crate

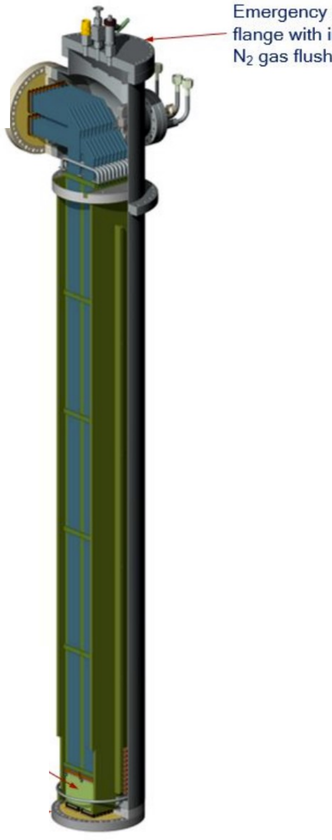
WR MCH

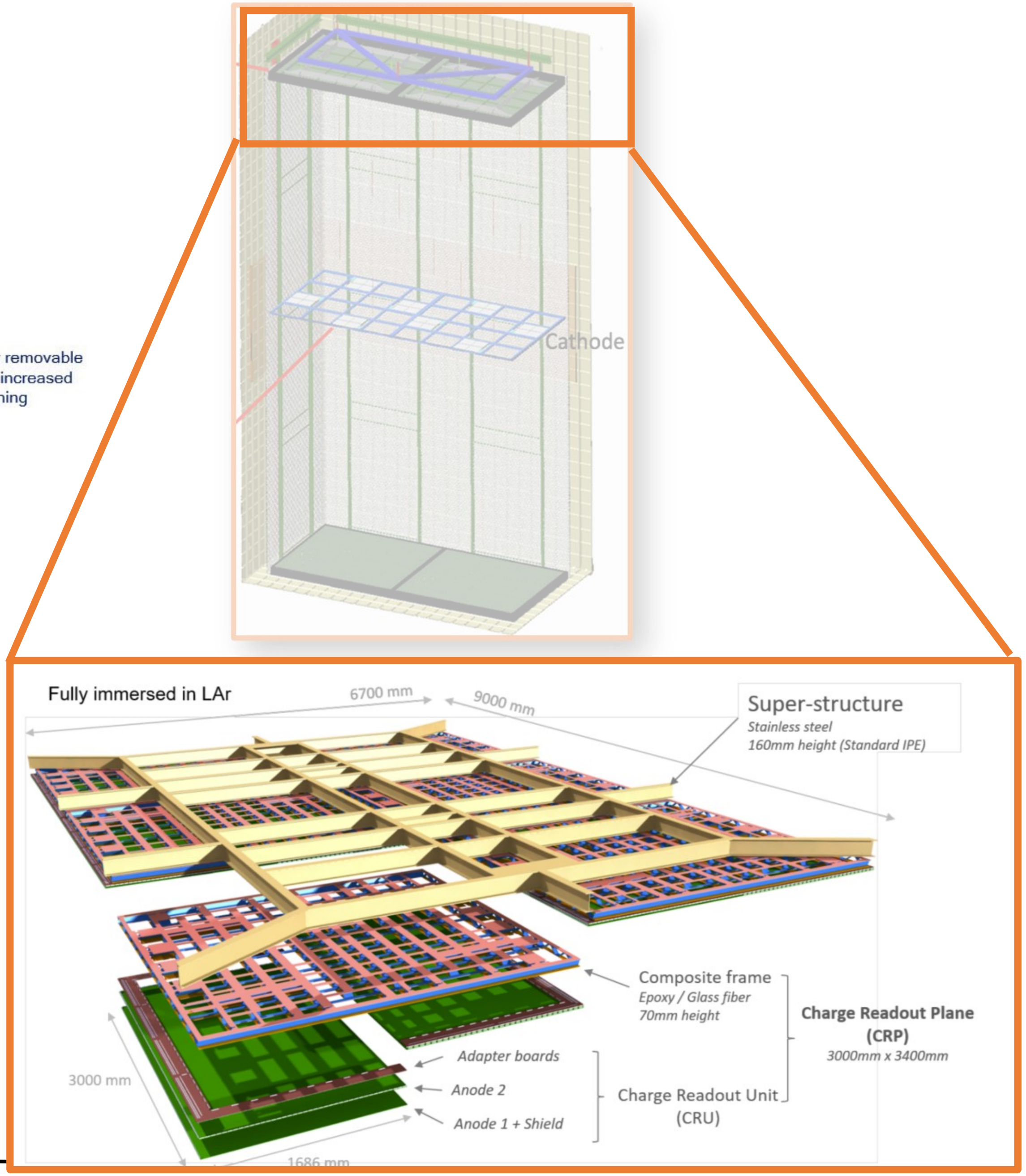
CRO AMC

MCH

x4 crates per SFT 2-view
x5 crates per SFT 3-view

Warm Signal Feedthrough





In/Out Cryostat

- Each SFT chimney sends data to Micro Telecommunications Computing Architecture (µTCA) crate, containing AMC cards.

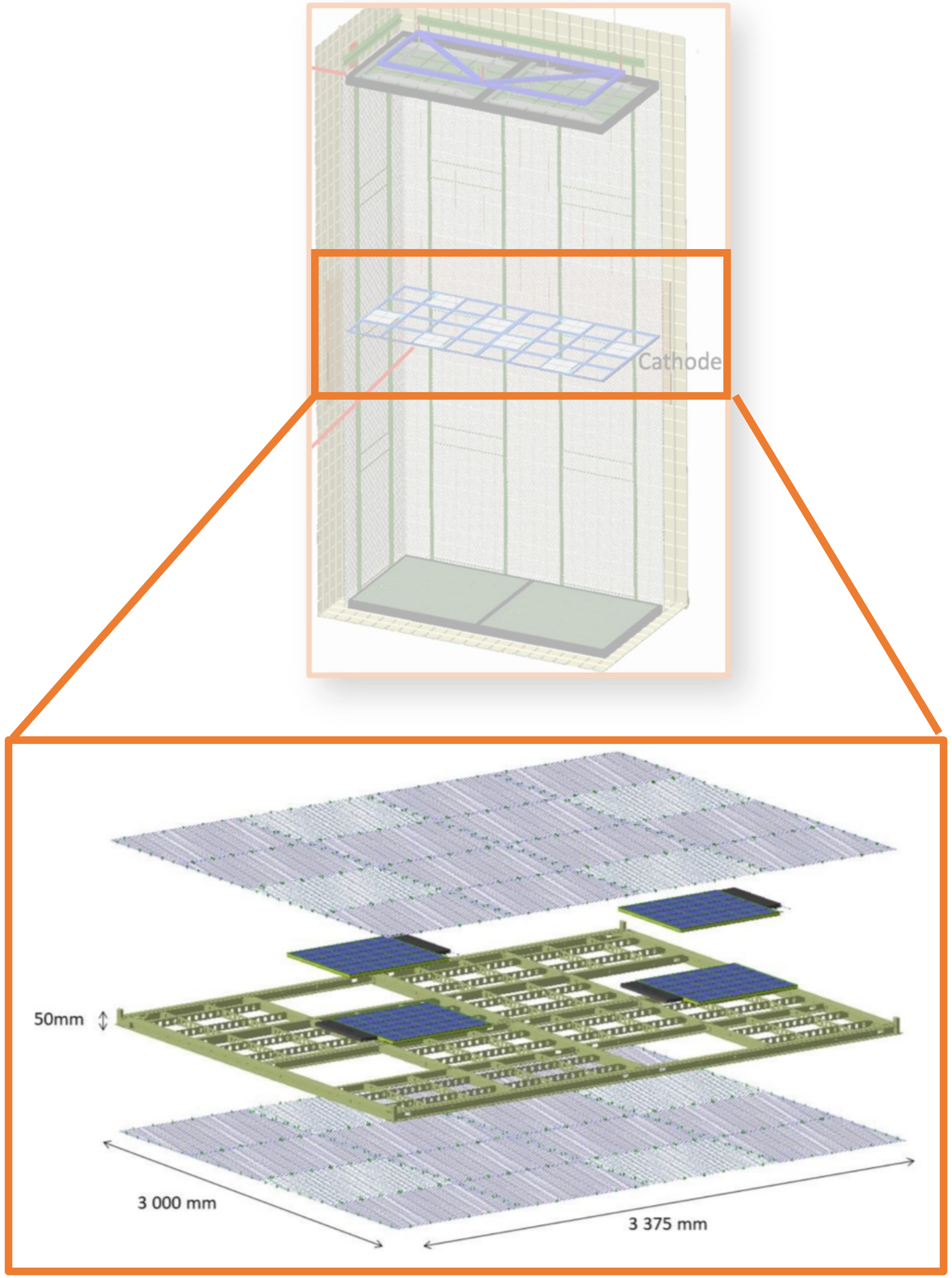
- AMC cards read and digitizes signal and sends to White Rabbit switch and DAQ via optical fiber. AMCs have ADC chips and FGPA (Alterra6 Cyclone V)

DUNE 2nd Module

- Cathode modules mounted on fiber reinforced plastic (FRP) frames. Hangs from top support structure and held at −294 kV (a challenge!)

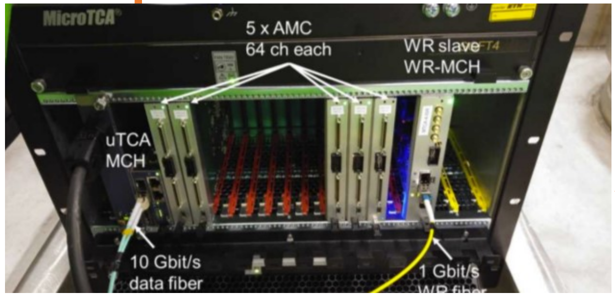
- Although CRP is perforated, opaque to light and therefore PDs can't be installed at anode. Thus each cathode module holds 4 double-sided X-ARAPUCA PD modules, exposed to top and bottom drift volumes. Frame has openings for PDs (blue)
  - Wavelength-shifted photons converted to electrical signals by 160 SiPMs that sit around perimeter of module

- Challenge: converting electrical signals to optical signals in LAr- R & D on the way to identify cold transceiver solutions operating at LAr temperature



Prototypes

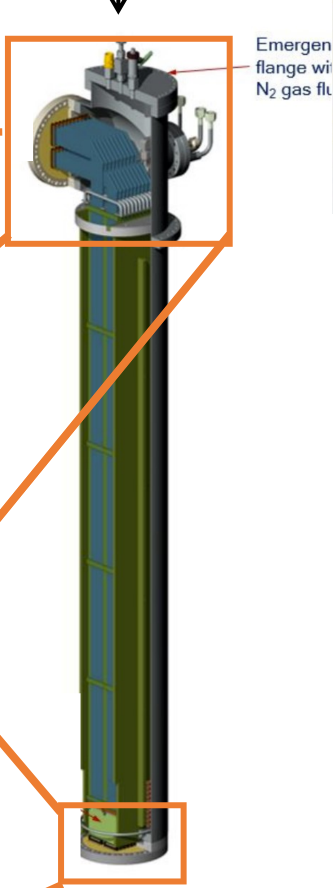
DAQ



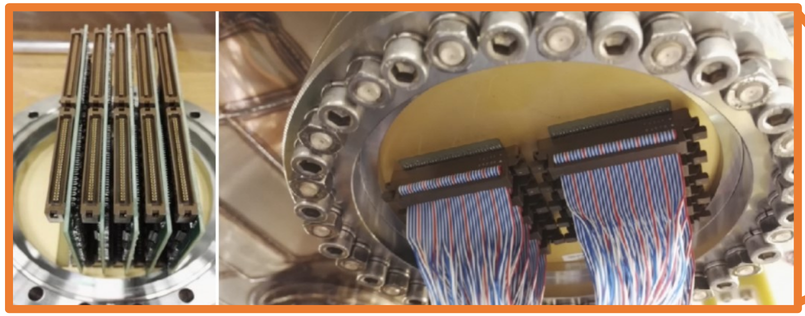
μTCA with AMCs

Vertical Drift Chamber

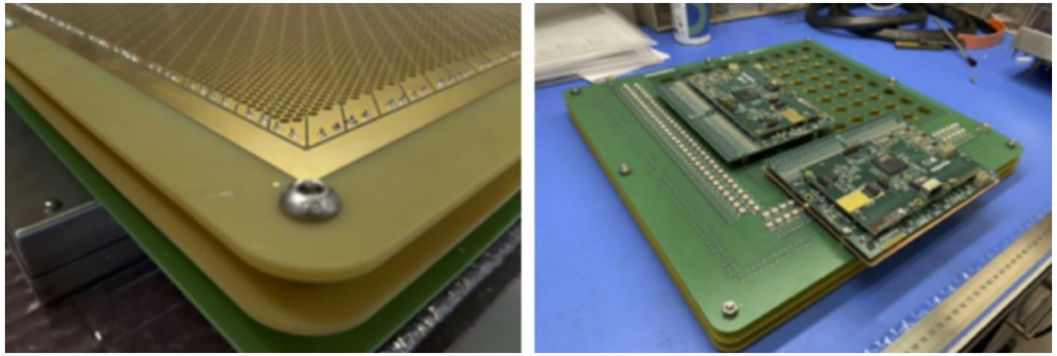
(from ProtoDUNE)



Warm Signal Feedthrough



Cold FE Analogue Acquisition Card

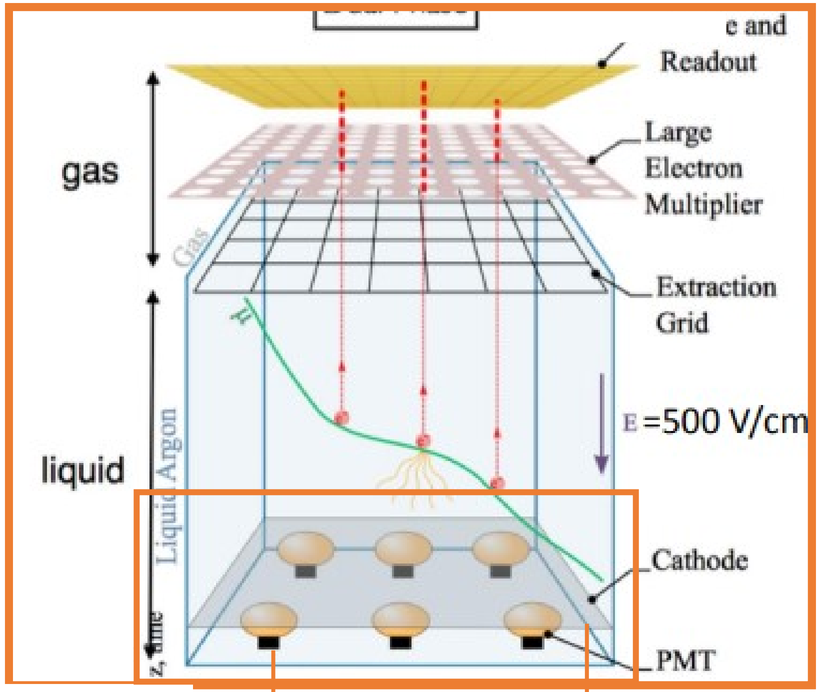


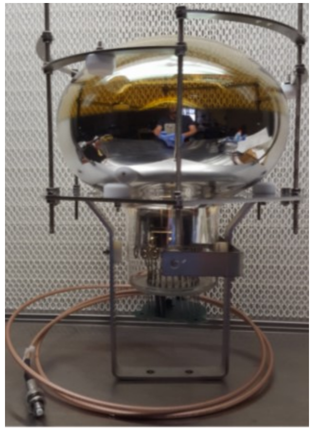
ANODE & Cold FEMBs

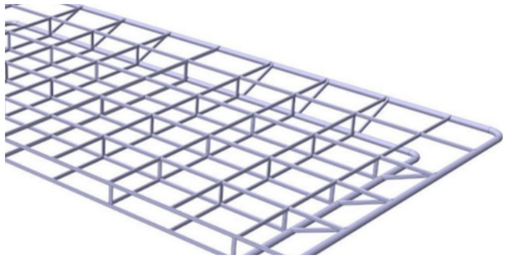
(from test stand)

Dual Phase

- 1 PMT (Hamamatsu R5912- MOD20) per m^2 anchored to bottom of cryostat
- PMT coated with tetra-phenyl butadiene (TPB) to provide wavelength shifting to read out 127 nm light from LAr
- The stainless steel cathode plane (eighty 3 m × 3 m modules) held at – 600 kV located 2 m above the bottom of the cryostat







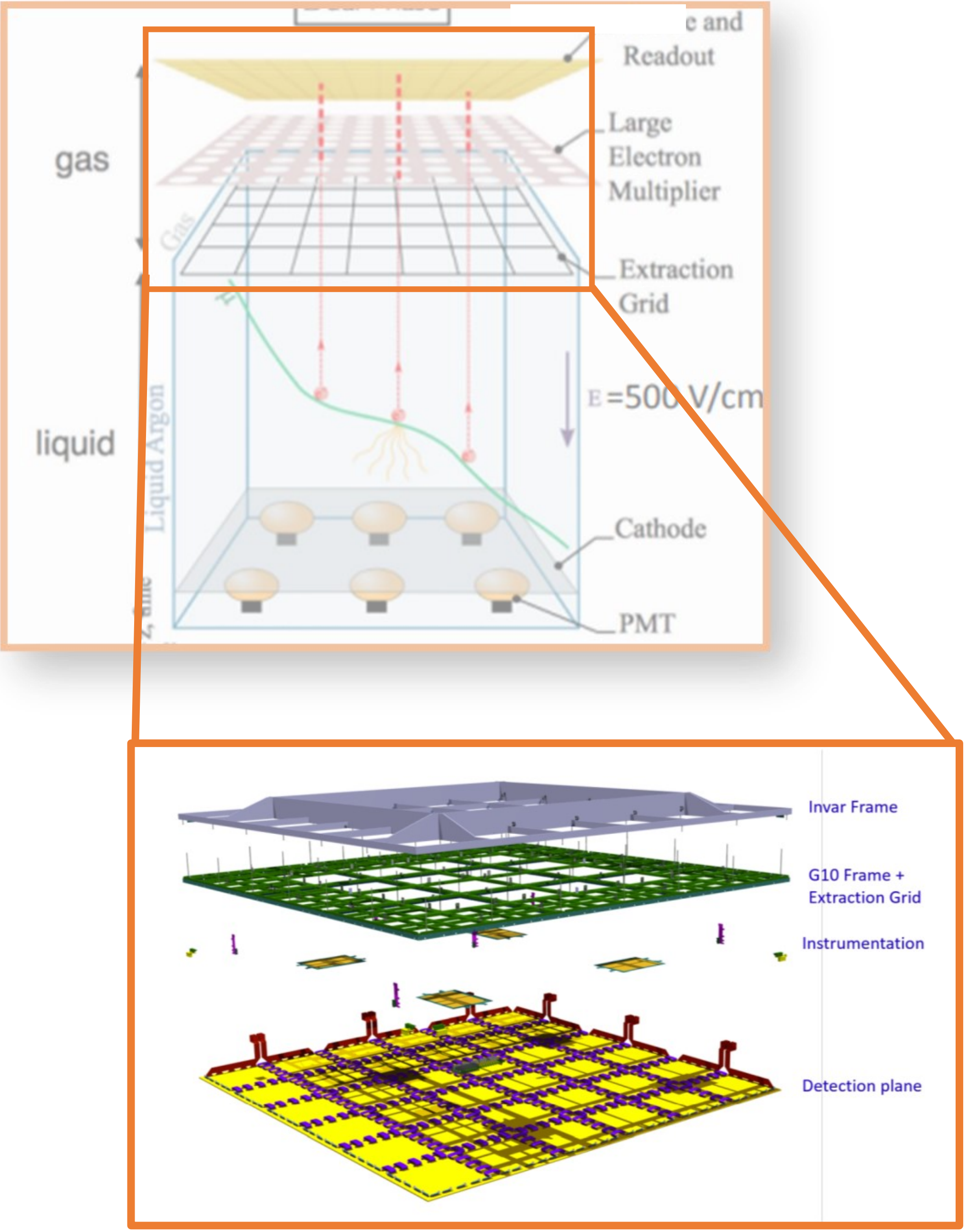
Dual Phase

- Charge readout plates (CRPs) are three layer sandwich (extraction grid, LEM, Anodes) sandwich that perform the collection, amplification and readout of charges

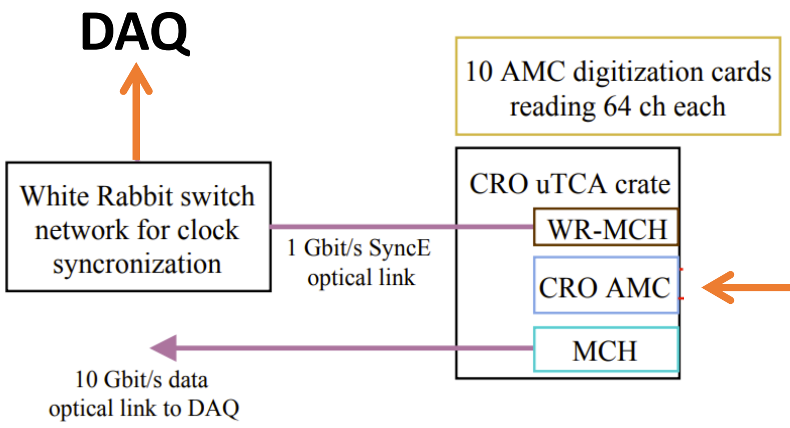
- LEMs and anodes form the detection plane, attached to the fiberglass grid (G10 Frame)

- LEM: is a 1 mm-thick, 50×50 cm^2 copper-clad PCB with electrodes on top and bottom. It contains holes of 500 µm diameter, through which electrons undergo amplification

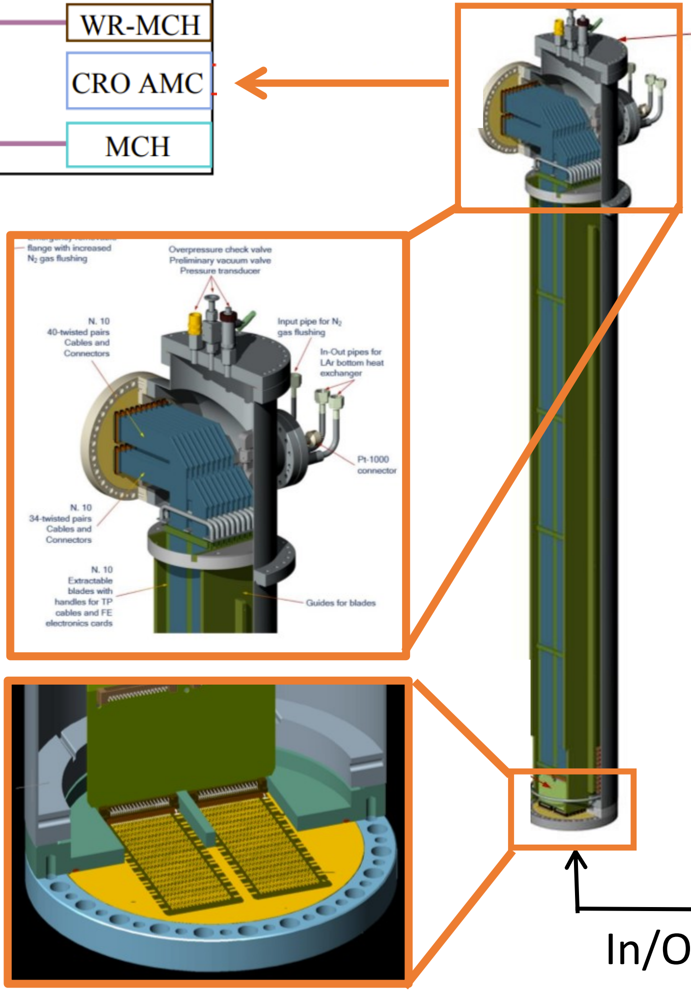
- Anode: 2D PCB with gold-platted copper strips that provide x and y views of event (moving toward 3). Pattern of readout strips optimized so that charge is evenly spilt between both views

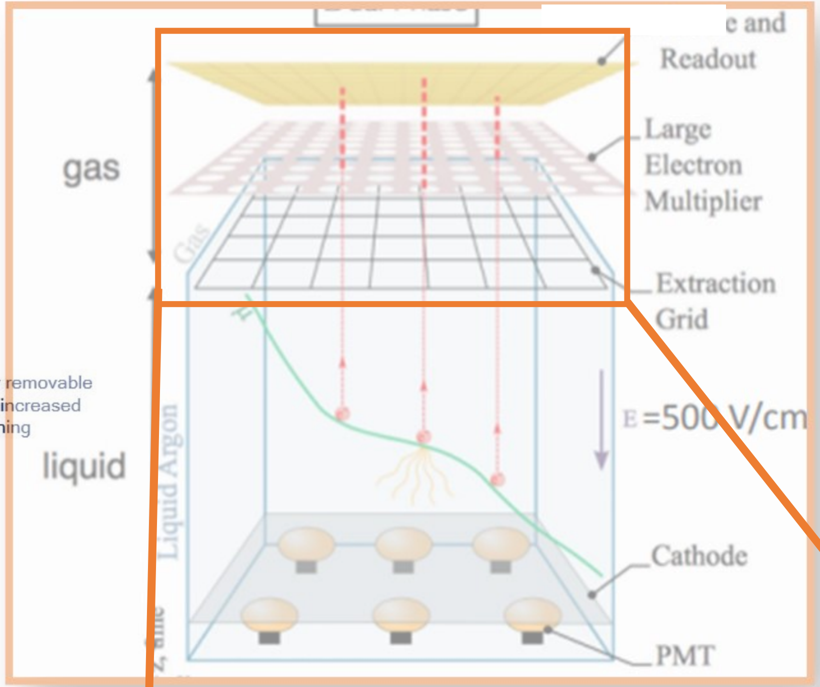


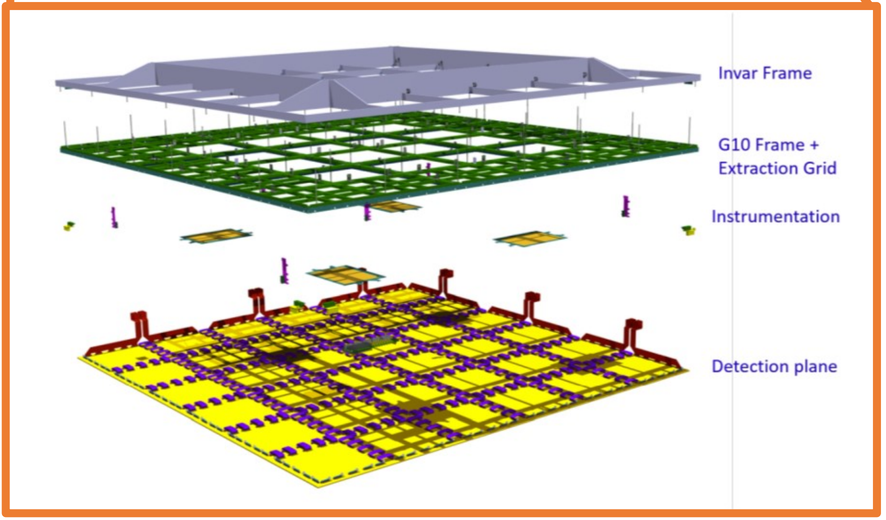
Dual Phase



- Same readout as Single Phase Vertical Drift

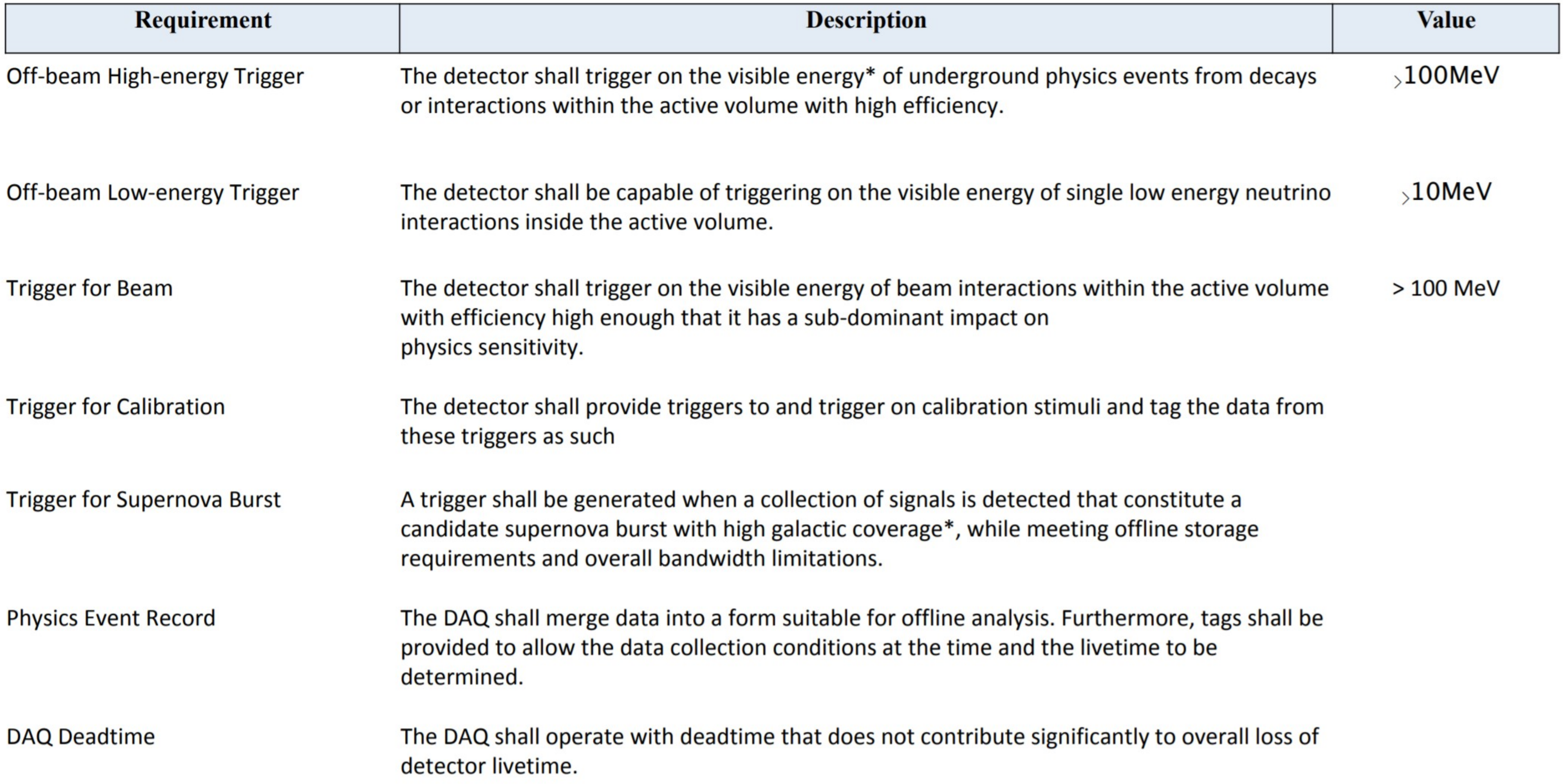






In/Out Cryostat

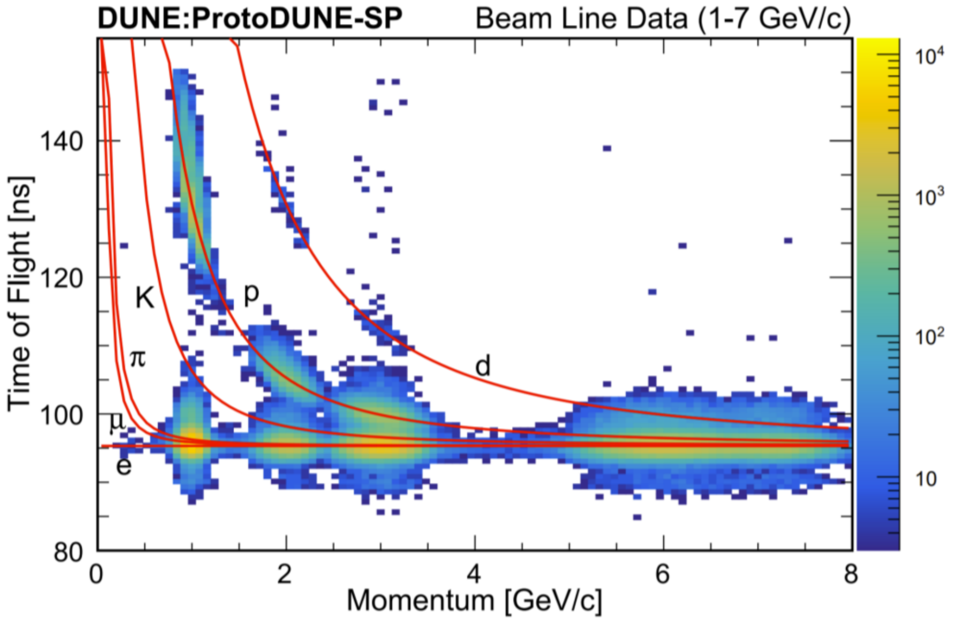
DUNE Readout Requirements



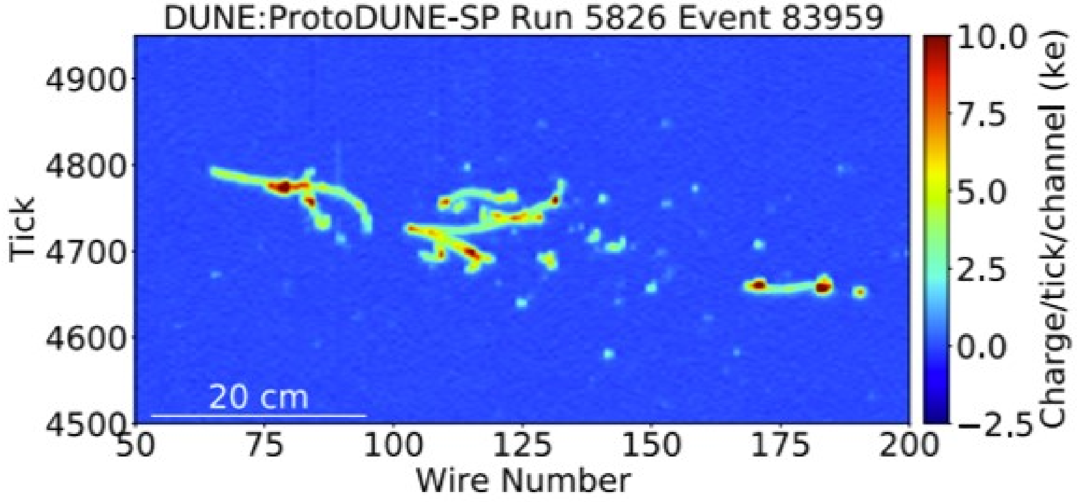
Requirement	Description	Value
Off-beam High-energy Trigger	The detector shall trigger on the visible energy* of underground physics events from decays or interactions within the active volume with high efficiency.	>100MeV
Off-beam Low-energy Trigger	The detector shall be capable of triggering on the visible energy of single low energy neutrino interactions inside the active volume.	>10MeV
Trigger for Beam	The detector shall trigger on the visible energy of beam interactions within the active volume with efficiency high enough that it has a sub-dominant impact on physics sensitivity.	> 100 MeV
Trigger for Calibration	The detector shall provide triggers to and trigger on calibration stimuli and tag the data from these triggers as such	
Trigger for Supernova Burst	A trigger shall be generated when a collection of signals is detected that constitute a candidate supernova burst with high galactic coverage*, while meeting offline storage requirements and overall bandwidth limitations.	
Physics Event Record	The DAQ shall merge data into a form suitable for offline analysis. Furthermore, tags shall be provided to allow the data collection conditions at the time and the livetime to be determined.	
DAQ Deadtime	The DAQ shall operate with deadtime that does not contribute significantly to overall loss of detector livetime.	

*Visible energy = deposited energy in the active volume as ionization and/or scintillation
*Galactic coverage = SBN probability-weighted efficiency, integrated over the physical extent of the Milkyway

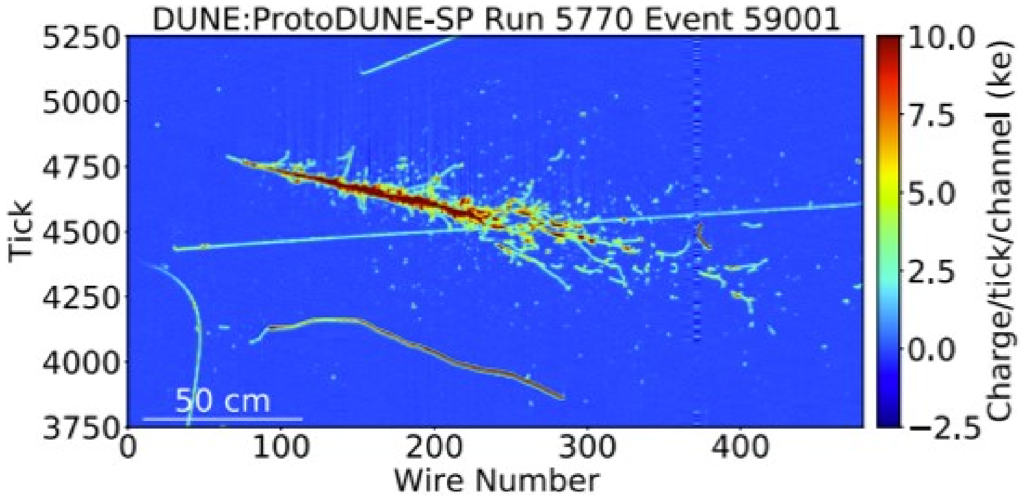
ProtoDUNE SP Performance



- Excellent performance!
- Low noise: Noise charge of ~ 550 (650) e^- on collection (induction) wires -> HALF of the maximum allowed noise
- 99.7% of the 15360 TPC electronics responsive, 99% HV uptime, high purity



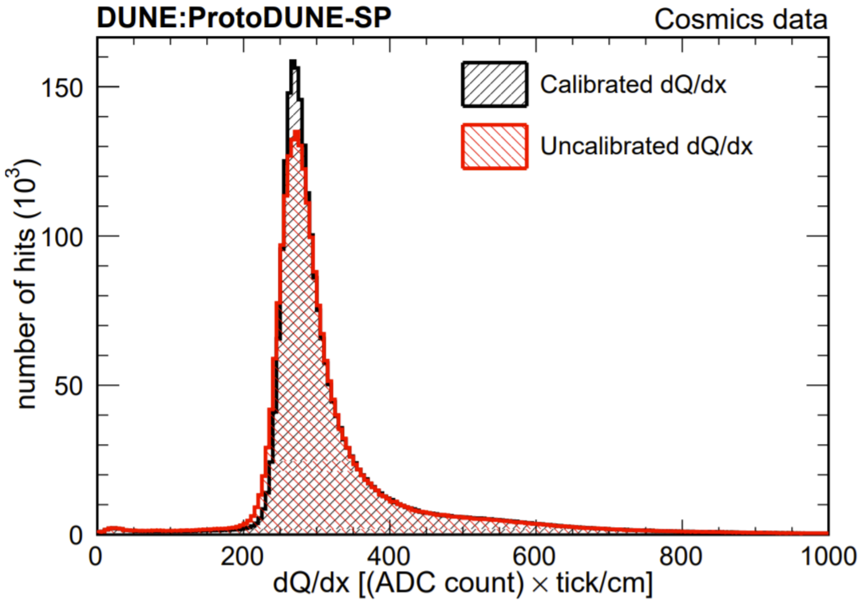
0.5 GeV electron

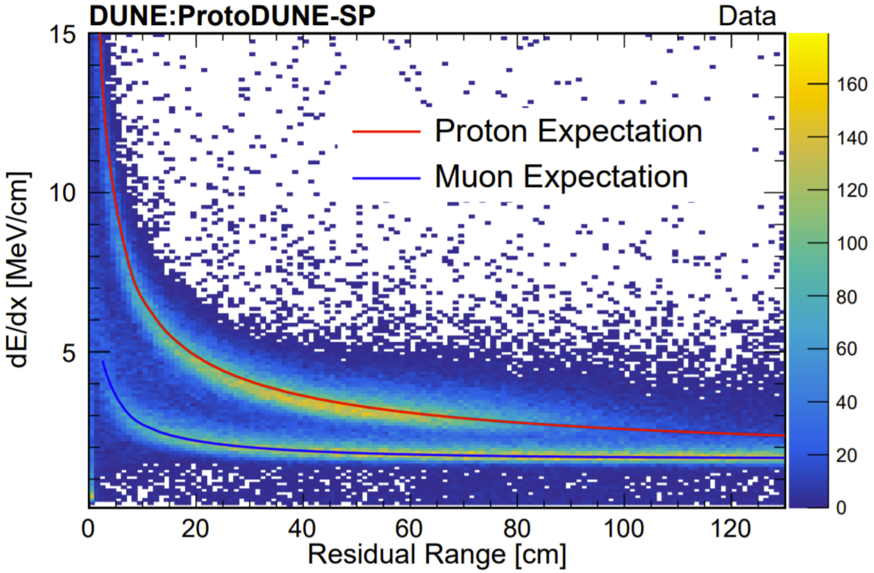


6 GeV electron

ProtoDUNE SP Performance

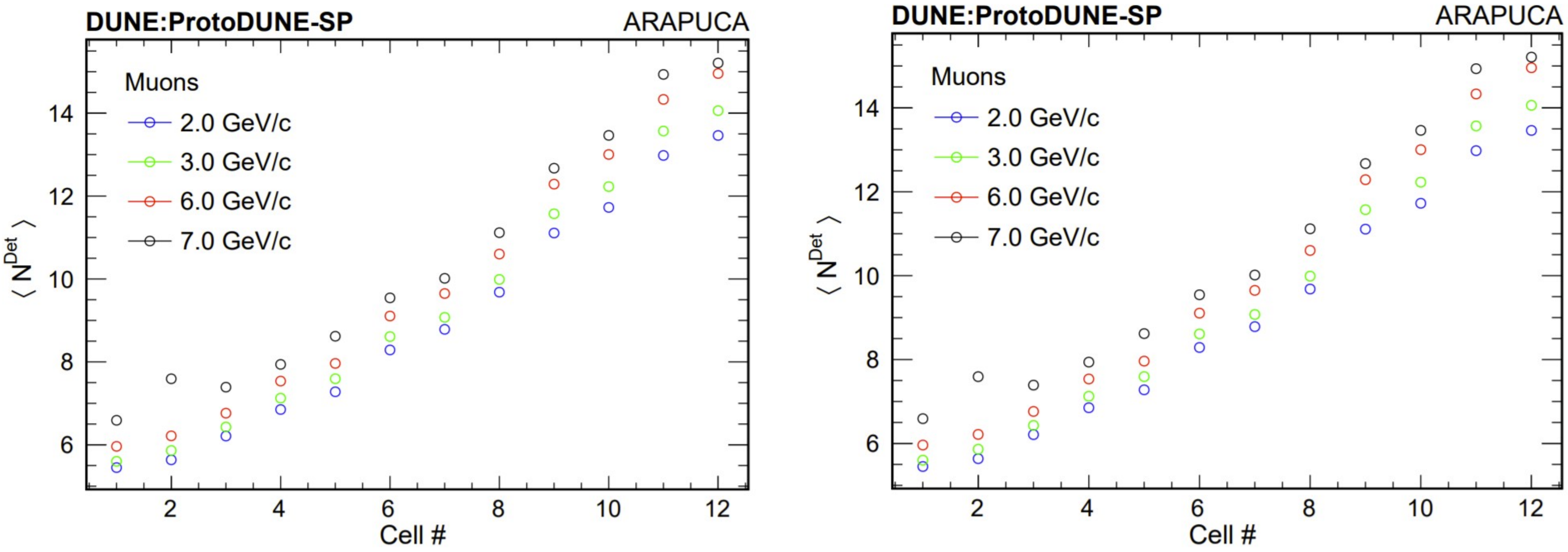
- Charge deposited along track converted energy loss (dE/dx) using stopping cosmic ray muons
- Calibration constants derived and applied to beam particles (muons, pions, protons, positrons)
- Charge deposition per unit length (dQ/dx) affected by space-charge effect, recombination effect, electron attenuation, diffusion, electronics gain variation
- Detector response calibration is based on cosmic muons – shows good results for test beam protons and muons
- High quality of ProtoDUNE-SP demonstrated by excellent proton-muon separation





ProtoDUNE SP Performance

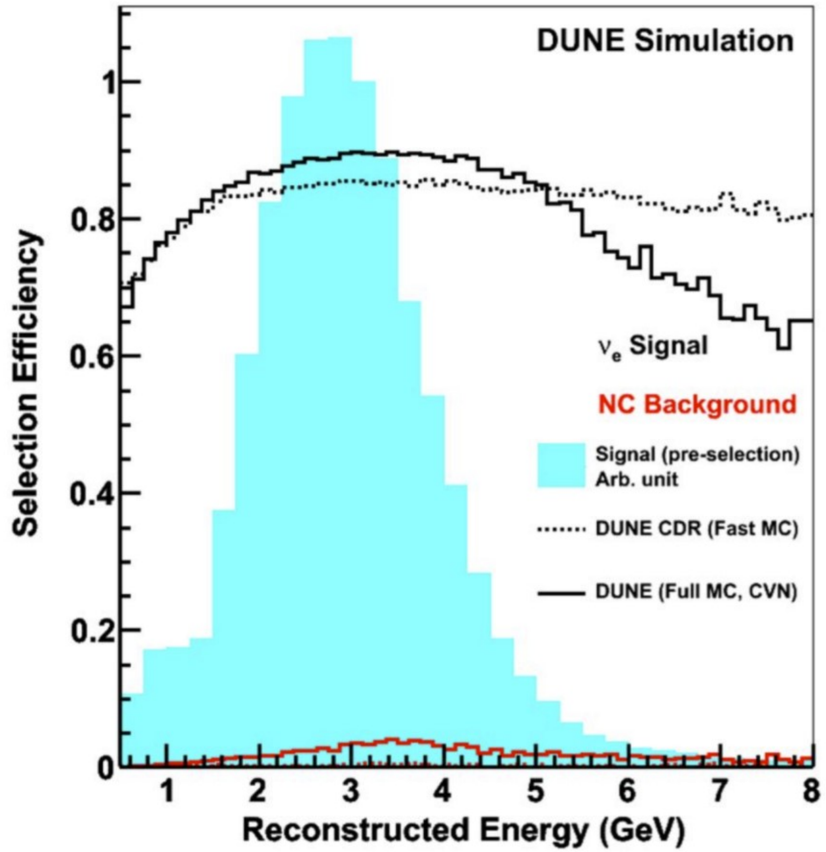
- Photon system performed well

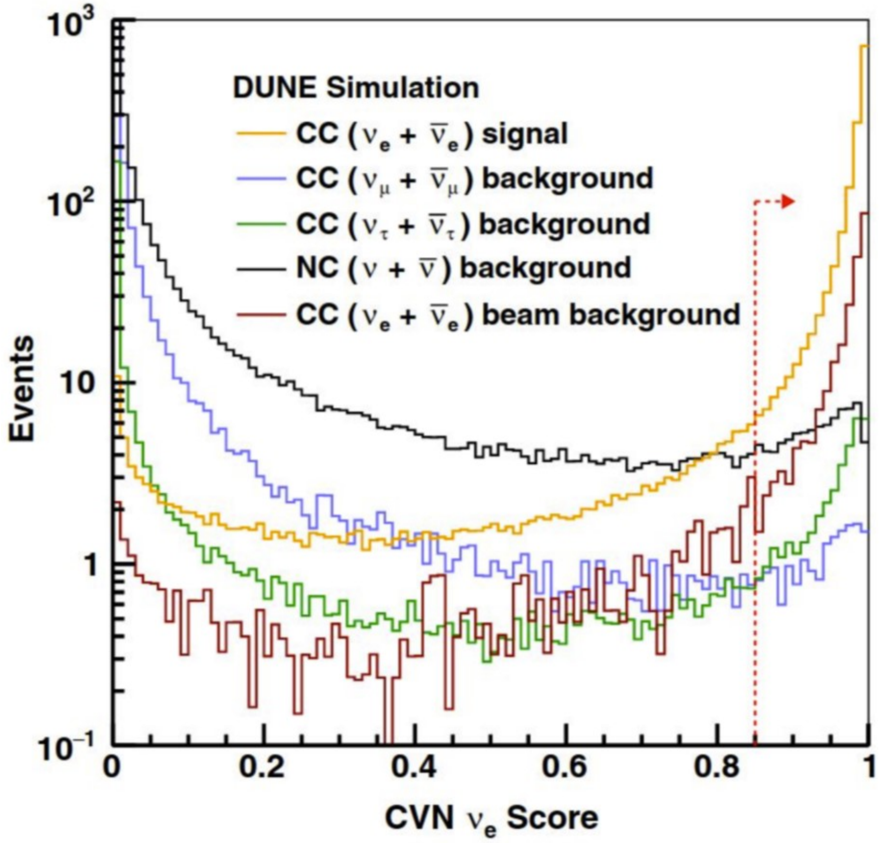


average number of detected photons with beams at different momenta

DUNE Far Detector Event Reconstruction

- Many Algorithms being explored: 2D clustering per plane, 3D hit clustering, convolutional visual networks

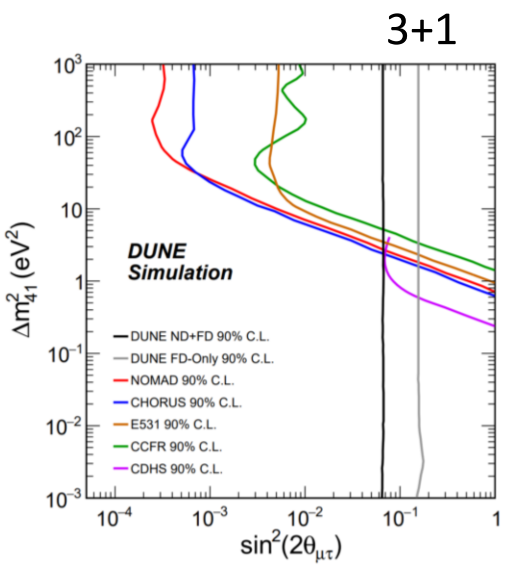




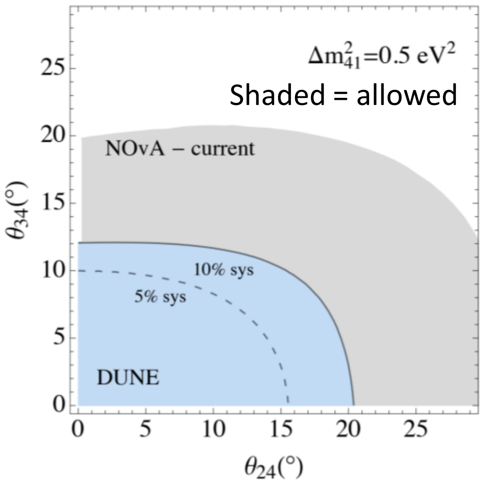
Sensitivity to Sterile Neutrinos

Case 1 ($\Delta m^2_{14} \sim 0.1 - 1\ eV^2$): slow light-sterile neutrino oscillations, underdeveloped in ND, averaged out in FD

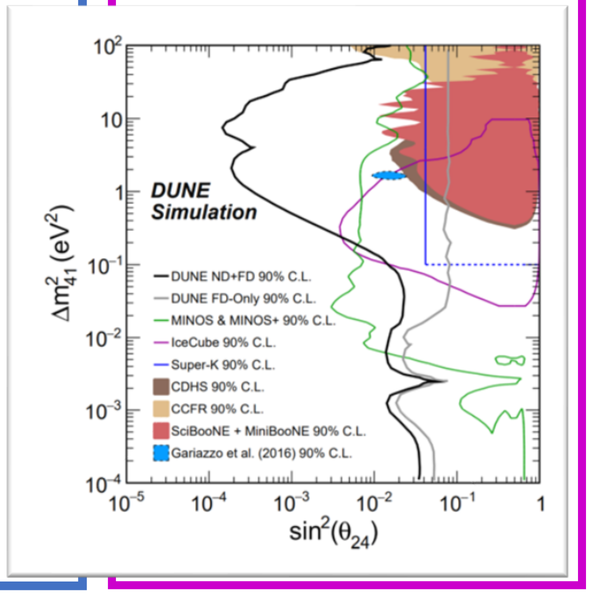
$\Delta m^2_{14} > 0.1\ eV^2$ (LSND)
$> 0.5\ eV^2$ (reactor)
Arxiv:1901.08330v1



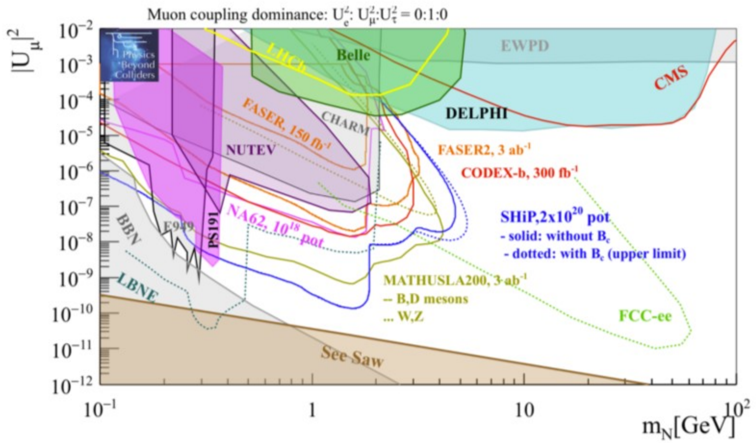
arXiv:1707.05348v1



Case 2 ($\Delta m_{14} > 1\ eV^2$) : light-sterile oscillation frequency matches ND distance.
Preferred by LSND & MiniBoone anomalies & DANSS & NEOS : arXiV: 1803.10661v1 (2018)



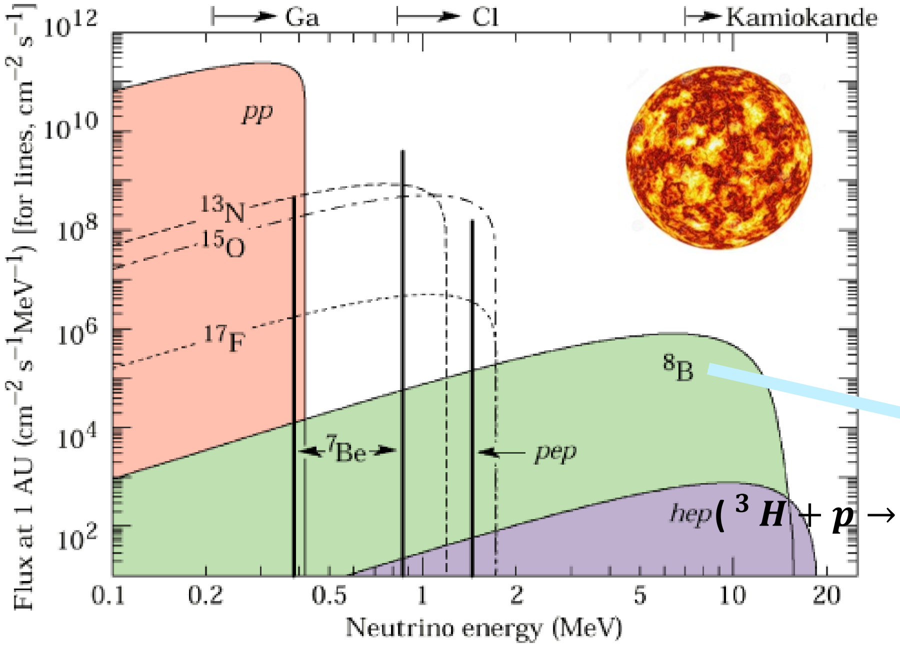
Case 3 ($\Delta m^2_{14} > 100\ eV^2$) : fast sterile neutrino oscillations, averaged out in ND and FD (same as PMNS non-unitarity from heavy neutrinos)



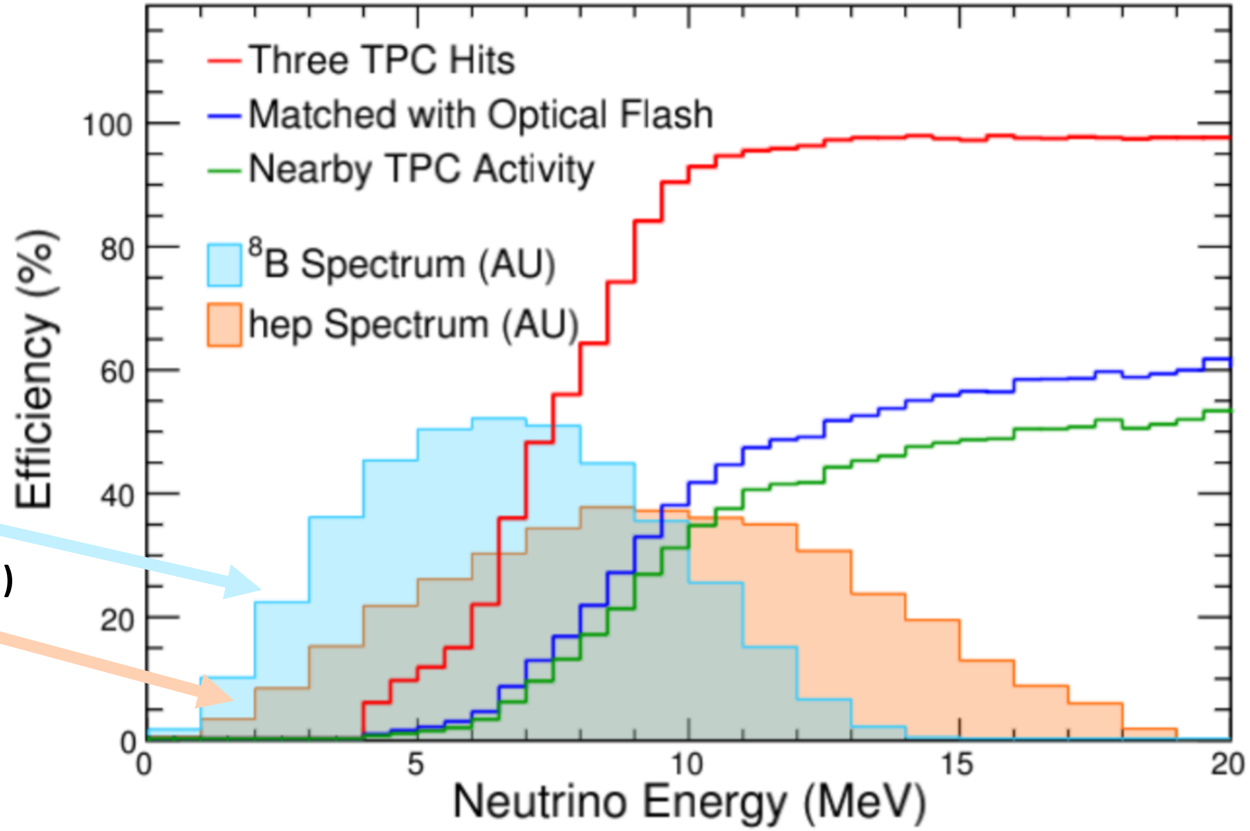
10^{-3}eV 10^{-2}eV 10^{-1}eV eV KeV MeV GeV 100 GeV

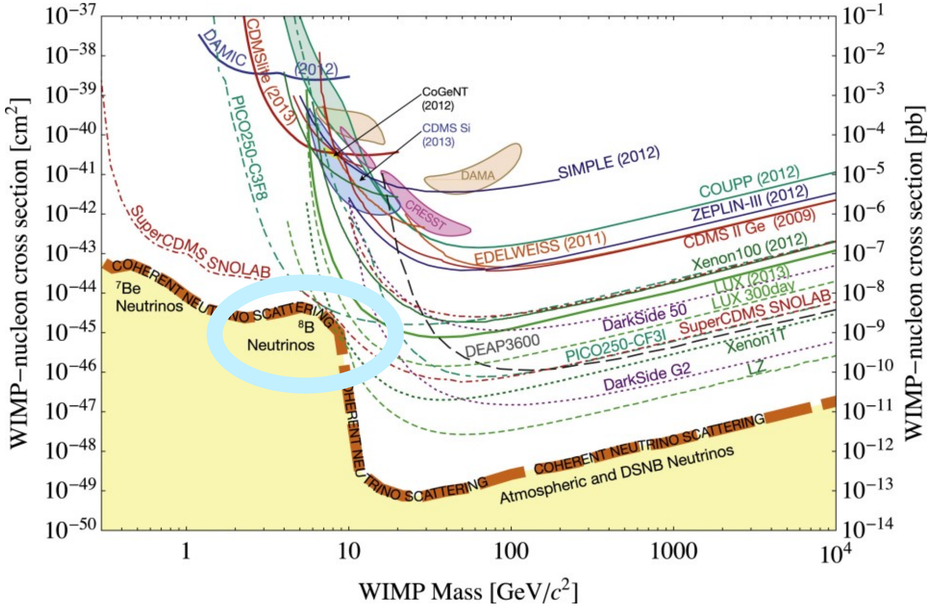
Extra Neutrino mass

Solar Neutrinos



$hep(^3H + p \rightarrow {}^4H + e^+ + \nu_e)$

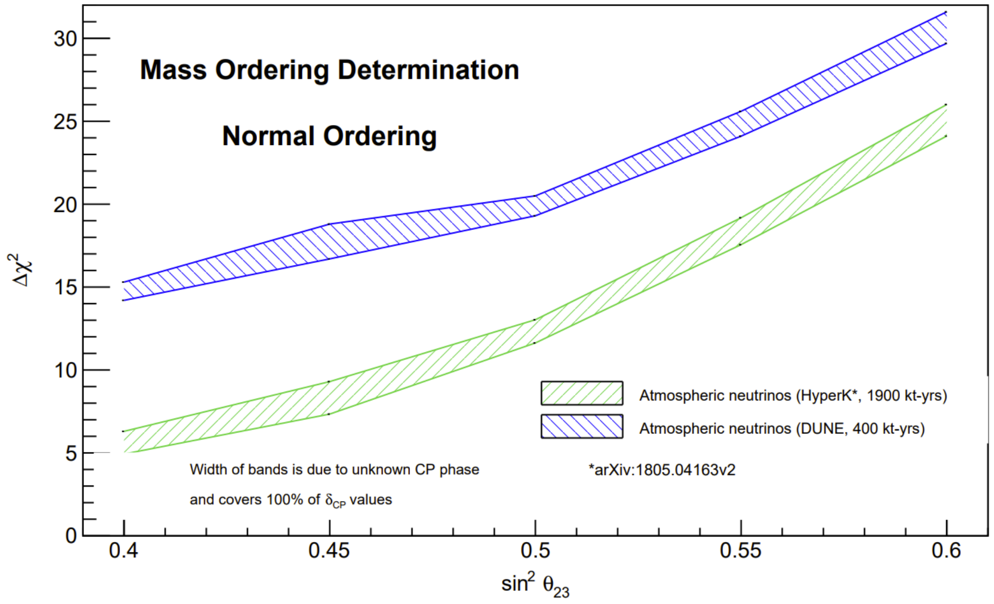




- DUNE can measure solar neutrinos to help verify the standard solar model, measure sun’s core temperature, characterize neutrino floor, resolve tension between global solar neutrino measurements & KamLAND (arXiv:1808.08232), characterize MSW affect

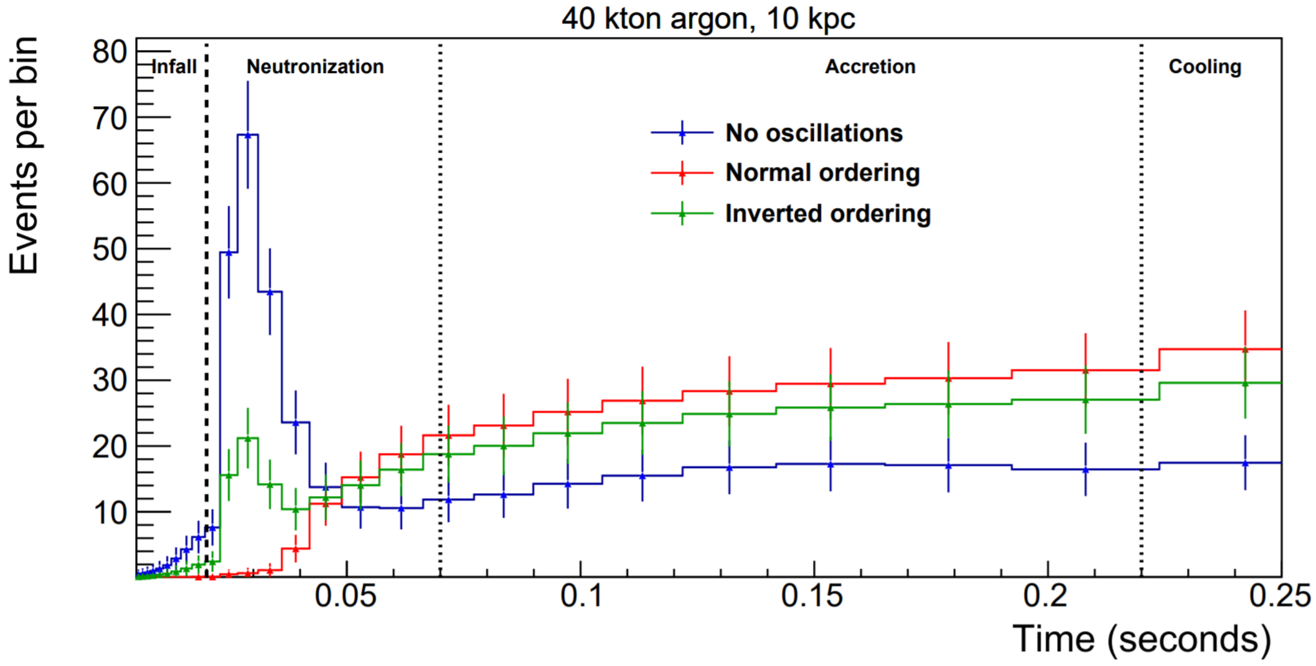
Atmospheric & SuperNova Neutrinos

- Can use atmospheric neutrinos to extract neutrino properties



- Core collapses expected to occur few times per century (at 10-15 kpc): test astrophysical theories, probe new physics
- When massive star collapses to neutron star/black hole, ~ 10^{58} of ~ 10 MeV ν emitted for a few seconds.
- DUNE sensitive to ν_e supernova neutrinos- this is unique among supernova neutrino detectors for the next decades. Tracks can indicate direction of supernova

$$\nu_e +^{40}\mathrm{Ar} \rightarrow e^- +^{40}\mathrm{K}^*$$



Non Standard Interactions

DUNE will improve current constraints on τe and μe, the magnitude of the NSI relative to standard weak interactions, by a factor of 2 to 5.

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2/2E & \\ & & \Delta m_{31}^2/2E \end{pmatrix} U^\dagger + \tilde{V}_{\rm MSW}$$

$$\tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon_{ee}^m & \epsilon_{e\mu}^m & \epsilon_{e\tau}^m \\ \epsilon_{e\mu}^{m*} & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m \\ \epsilon_{e\tau}^{m*} & \epsilon_{\mu\tau}^{m*} & \epsilon_{\tau\tau}^m \end{pmatrix}$$

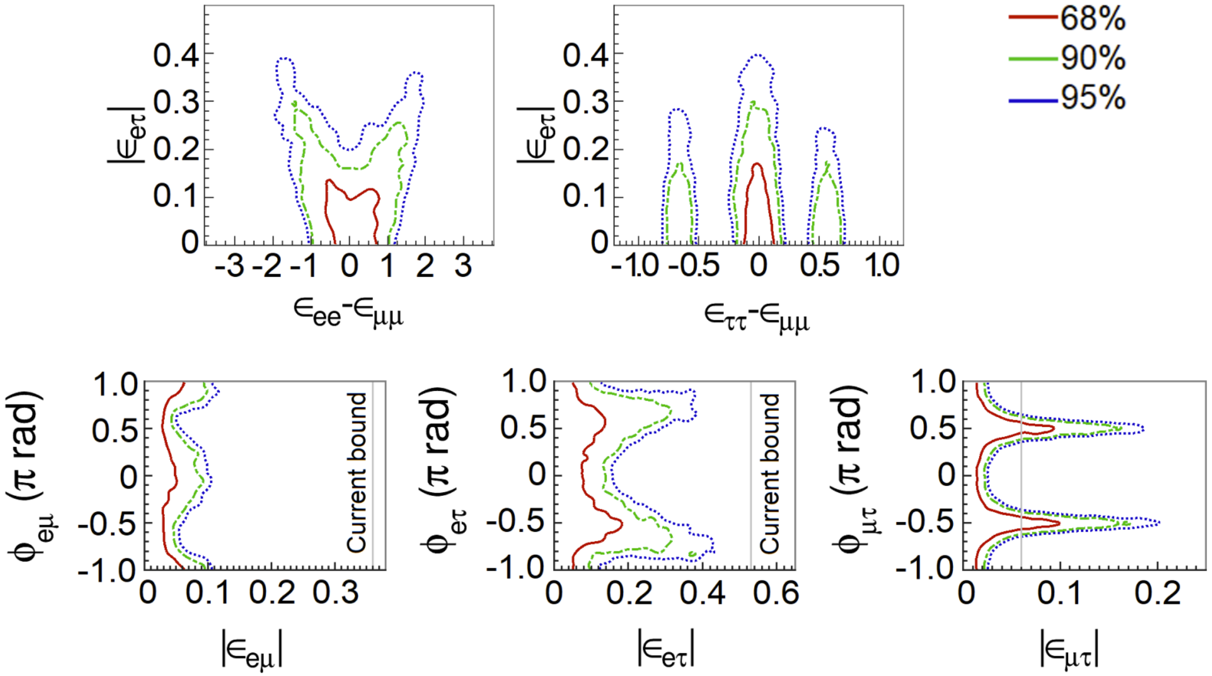


Figure 8.7: Allowed regions of the non-standard oscillation parameters in which we see important degeneracies (top) and the complex non-diagonal ones (bottom). We conduct the analysis considering all the NSI parameters as non-negligible. The sensitivity regions are for 68% CL [red line (left)], 90% CL [green dashed line (middle)], and 95% CL [blue dotted line (right)]. Current bounds are taken from [397].

Tau Neutrino

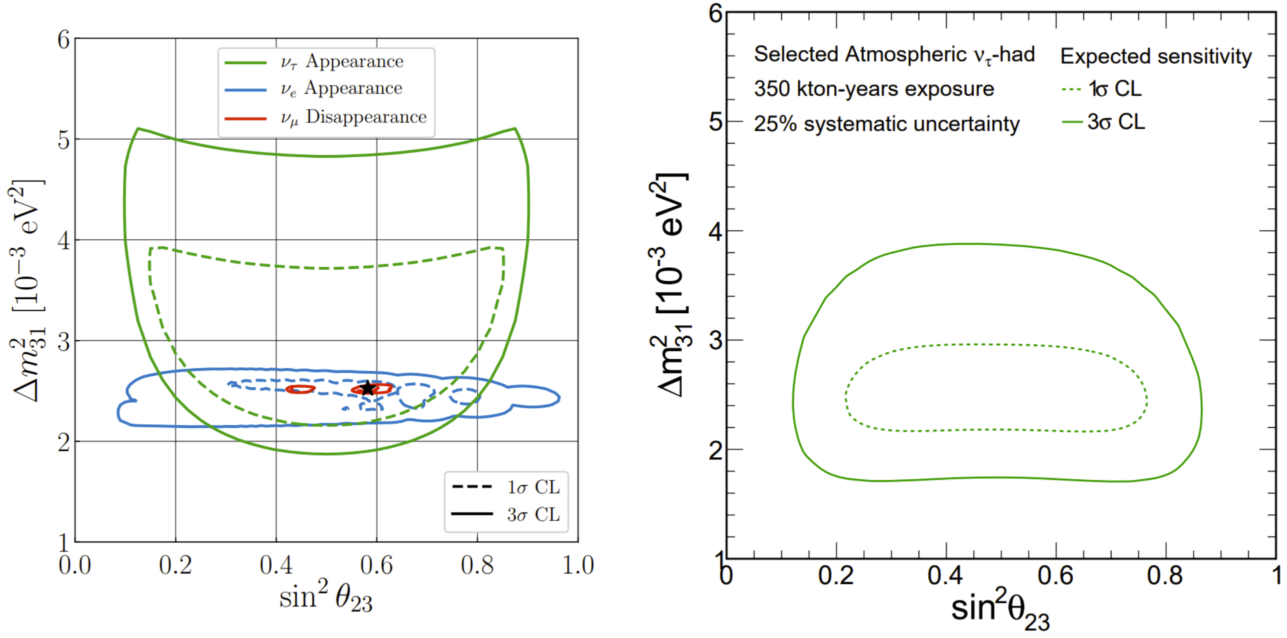


Figure 8.26: The 1σ (dashed) and 3σ (solid) expected sensitivity for measuring Δm^2_{31} and $\sin^2\theta_{23}$ using a variety of samples. Left: The expected sensitivity for seven years of beam data collection, assuming 3.5 years each in neutrino and antineutrino modes, measured independently using ν_e appearance (blue), ν_μ disappearance (red), and ν_τ appearance (green). Adapted from Ref. [498]. Right: The expected sensitivity for the ν_τ appearance channel using 350 kton-years of atmospheric exposure.

Proton Decay

- The 90% CL limit of a bound neutron lifetime is 6.45 × 1032 years for a 400 kt · year exposure. The corresponding limit for the oscillation time of free neutrons is calculated to be 5.53 × 108 s. This is approximately an improvement by a factor of two from the current best limit, which comes from Super–Kamiokande
- With a 30% signal efficiency and an expected background of one event per Mt · year , a 90% CL lower limit on the proton lifetime in the p → K+ν channel of 1.3 × 10^34 years can be set, assuming no signal is observed over ten years of running with a total of 40 kt of fiducial mass. This calculation assumes constant signal efficiency and background rejection over time and for each of the FD modules.

(from TDR)

Dark Matter

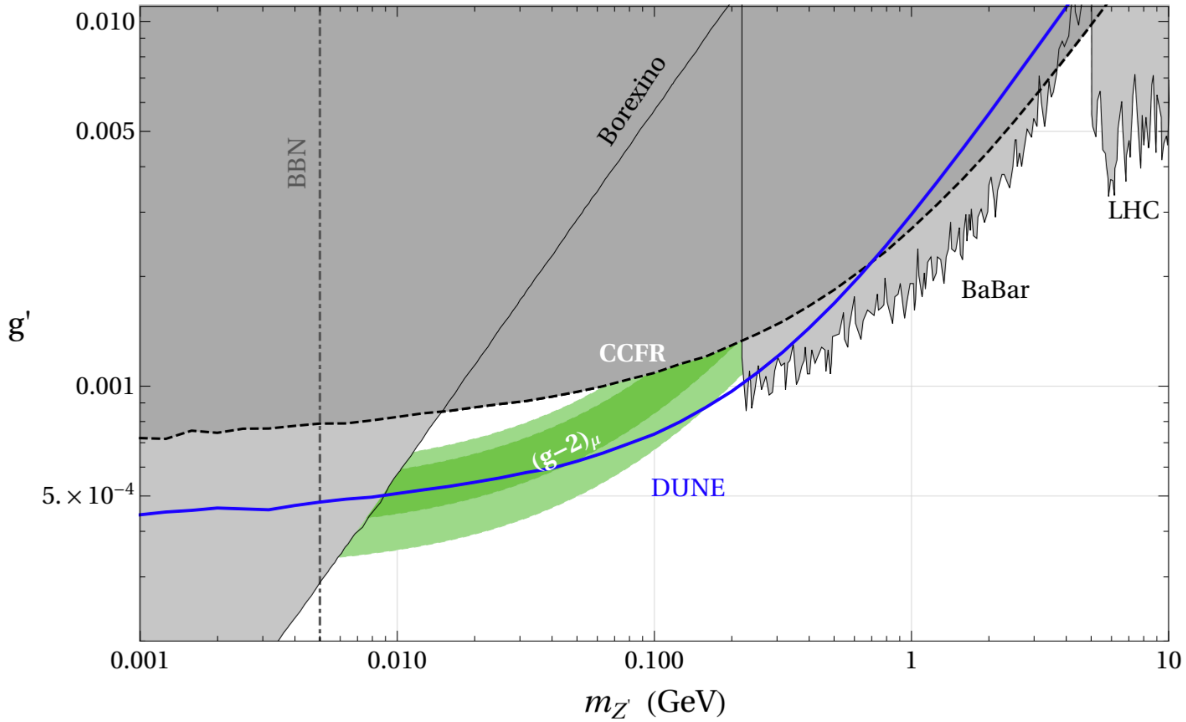
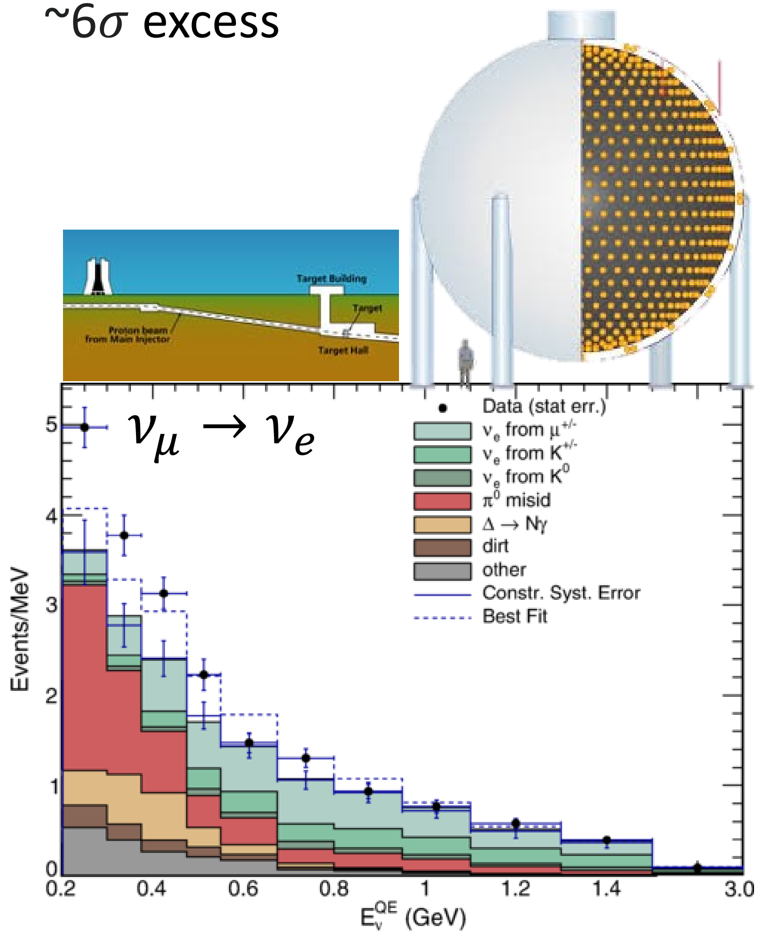


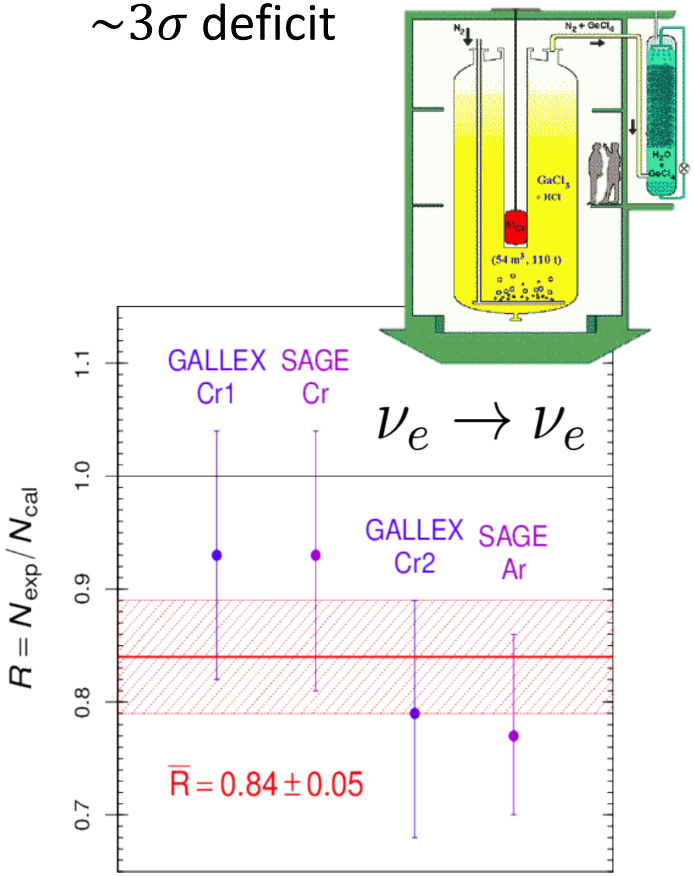
Figure 8.15: Existing constraints and projected DUNE sensitivity in the $L_\mu - L_\tau$ parameter space. Shown in green is the region where the $(g-2)_\mu$ anomaly can be explained at the 2σ level. The parameter regions already excluded by existing constraints are shaded in gray and correspond to a CMS search for $pp \to \mu^+\mu^- Z' \to \mu^+\mu^-\mu^+\mu^-$ [444] ("LHC"), a BaBar search for $e^+e^- \to \mu^+\mu^- Z' \to \mu^+\mu^-\mu^+\mu^-$ [445] ("BaBar"), precision measurements of $Z \to \ell^+\ell^-$ and $Z \to \nu\bar{\nu}$ couplings [446, 441] ("LEP"), a previous measurement of the trident cross section [434, 436] ("CCFR"), a measurement of the scattering rate of solar neutrinos on electrons [447, 448, 449] ("Borexino"), and bounds from big bang nucleosynthesis [450, 451] ("BBN"). The DUNE sensitivity shown by the solid blue line assumes a measurement of the trident cross section with 40% precision.

Modern Neutrino Mysteries?

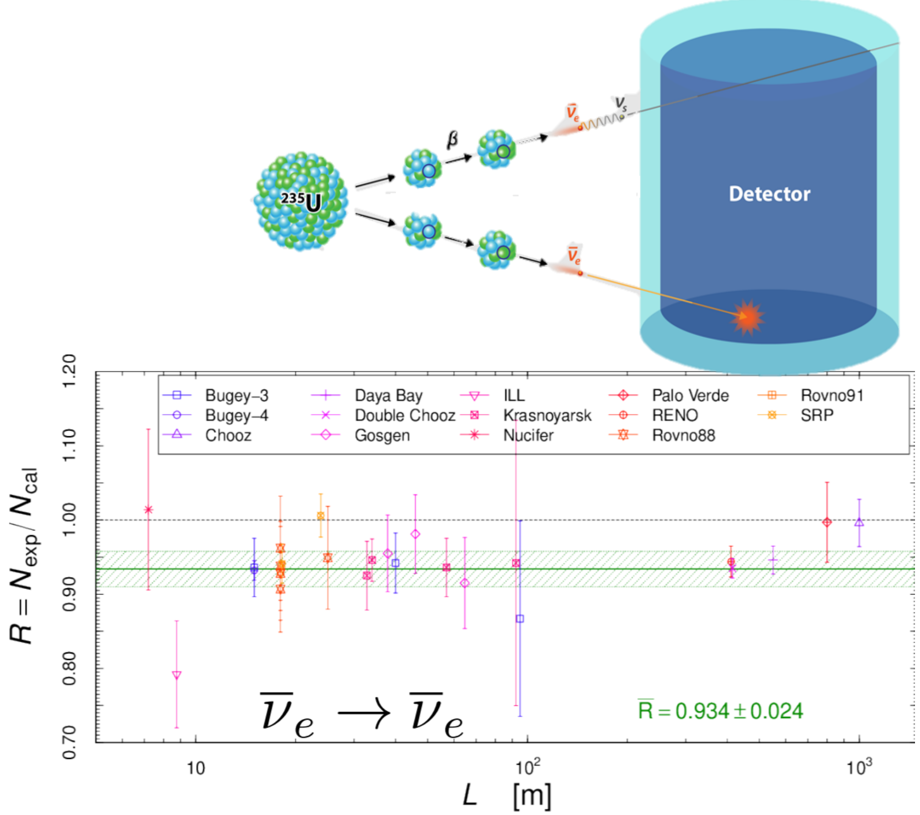
MiniBooNE & LSND
~6σ excess



Gallium anomaly
~3σ deficit



Reactor anomalies
~3σ deficit



Extra Neutrino Searches & NSI

$\mathcal{L} = \mathcal{L}_{SM} + \dots$

$+\ \delta\mathcal{L}^{d=5}$

Neutrino mass generation (if mass hierarchy too big, naturally get light 3ν), but other dimensions suppressed – and get no observable phenomena at energies we can reach (**Seesaw I/II/III**)

$+\delta\mathcal{L}^{d=6}$

Non Standard Neutrino Interactions (NSI)
Minimal Unitarity violation (MUV)
After EW symmetry breaking ->PMNS non-unitarity induced by mixing with heavy neutrinos. Implies breaking lepton universality and lepton flavor violation
(**inverse or linear seesaw**)

$$H = \frac{1}{2E}\left[U_{\mathrm{PMNS}}\begin{pmatrix}0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^{\dagger}_{\mathrm{PMNS}} + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

$+\delta\mathcal{L}^{d=8}$

NSI – strong matter effects. Not sensitive at Colliders, but are at neutrino facilities

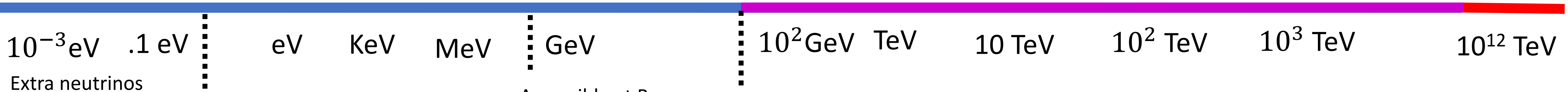
$+\delta\mathcal{L}^{d=9}$

Dark photon & extra neutrino motivated by LNSD/ MiniBoone

$$P^{\mathrm{SBL}}_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$+\ \phi$

Add new Scaler - Radiative models. (some type 1 radiative models have NSI, all type II radiative models don't have NSI)



10^{-3}eV .1 eV eV KeV MeV GeV 10^2GeV TeV 10 TeV 10^2 TeV 10^3 TeV 10^{12} TeV

Extra neutrinos can participate in oscillations

accessible at osc. Exp

Accessible at B-factories

Accessible at LHC

Parameterizations for Extra Neutrinos Searches

3x3 active ν Active-heavy mix

$$\mathcal{U} = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Active-sterile mix Sterile-heavy mix

$\epsilon, \alpha, \eta, \theta$ can be related to each other: arXiv:1609.08637v3

R allowed at % level since it can only be probed at osc exp.

If sterile ν would participate in neutrino oscillations – ie: $P_{\alpha\beta}$ depends on $\mathcal{U}$

3+1, 3+N scenarios : $\theta_{14}, \theta_{24}, \delta_{14}$

$$\mathcal{U} = \begin{pmatrix} c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \cdots & \cdots & \begin{array}{c} c_{13}c_{24}s_{23} \\ -s_{13}s_{14}s_{24}e^{i(\delta_{14}-\delta_{13})} \end{array} & c_{14}s_{24} \\ \cdots & \cdots & \cdots & c_{14}c_{24}s_{34}e^{-i\delta_{34}} \end{pmatrix}$$

arXiv:1901.08330v1

Direct Heavy Neutrino Searches at LHC

Here N is not unitary – 2 common parametrizations

Triangular

$$\boldsymbol{N} = (I - \alpha)U$$

$$\alpha \downarrow \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix} \qquad U \downarrow \text{Unitary PMNS}$$

Hermitian

$$\boldsymbol{N} = (I - \eta)U'$$

$$\eta \downarrow \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta^*_{e\mu} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta^*_{e\tau} & \eta^*_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix}$$

10^{-3}eV .1 eV | eV KeV MeV | GeV | 10^2GeV TeV 10 TeV 10^2 TeV 10^3 TeV 10^{12} TeV

Extra neutrinos can participate in oscillations

accessible at osc. Exp

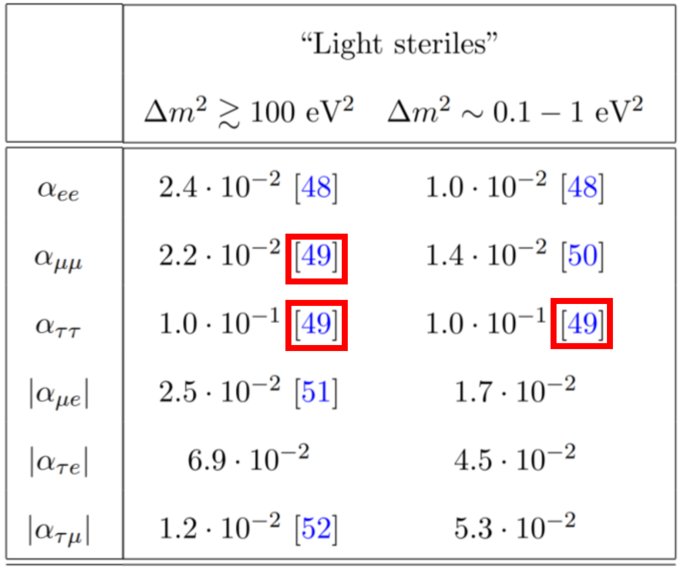
Accessible at B-factories

Accessible at LHC

Limits on Extra Neutrinos

For neutrinos with masses below the electroweak scale, best limits from oscillation data. BUT most future experiments (DUNE) won’t add too much here (see arXiv:1609.08637v3) – maybe Hyper-K can?

arXiv:1609.08637v3



	“Light steriles”	
	$\Delta m^2 \gtrsim 100$ eV^2	$\Delta m^2 \sim 0.1 - 1$ eV^2
α_{ee}	$2.4 \cdot 10^{-2}$ [48]	$1.0 \cdot 10^{-2}$ [48]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-2}$ [49]	$1.4 \cdot 10^{-2}$ [50]
$\alpha_{\tau\tau}$	$1.0 \cdot 10^{-1}$ [49]	$1.0 \cdot 10^{-1}$ [49]
$\|\alpha_{\mu e}\|$	$2.5 \cdot 10^{-2}$ [51]	$1.7 \cdot 10^{-2}$
$\|\alpha_{\tau e}\|$	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\|\alpha_{\tau\mu}\|$	$1.2 \cdot 10^{-2}$ [52]	$5.3 \cdot 10^{-2}$

48: Buggy

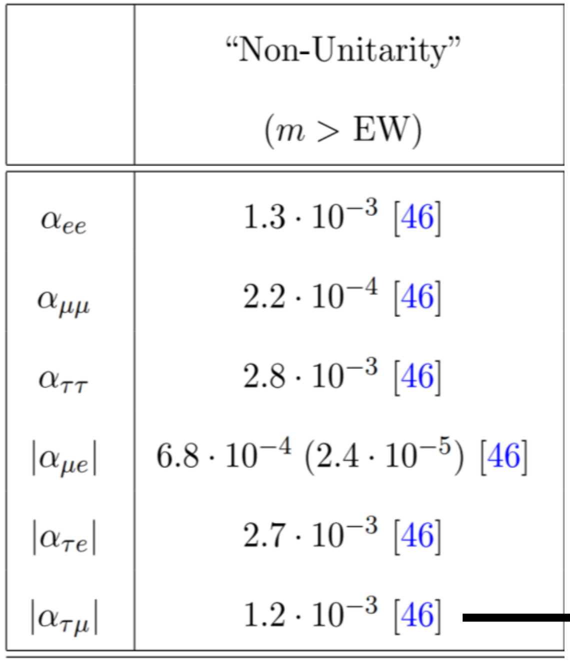
49: SuperK atmospheric

51/52: Nomad

50: Minos

PMNS non-unitarity bounded at per mil level from Lepton Universality, Lepton Flavor Violation EW observables, (B-factories ,MEG, LHC)

arXiv:1609.08637v3

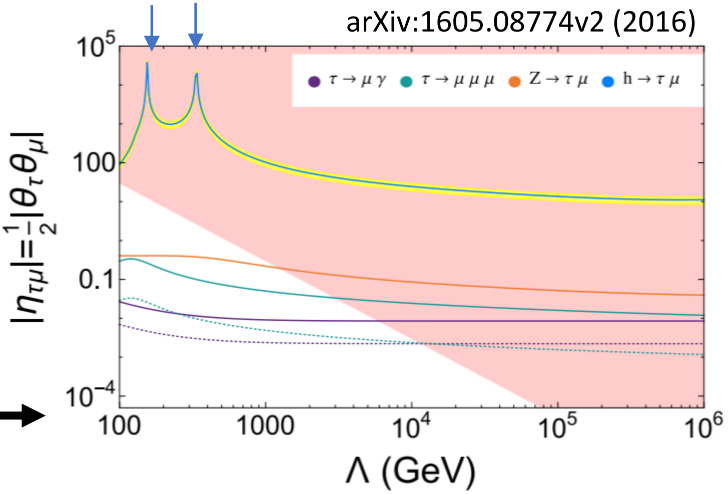


	“Non-Unitarity” $(m >$ EW$)$
α_{ee}	$1.3 \cdot 10^{-3}$ [46]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$ [46]
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$ [46]
$\|\alpha_{\mu e}\|$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$ [46]
$\|\alpha_{\tau e}\|$	$2.7 \cdot 10^{-3}$ [46]
$\|\alpha_{\tau\mu}\|$	$1.2 \cdot 10^{-3}$ [46]

LFV: best limits from $\alpha \to \gamma\alpha$ & $\alpha \to 3\beta$ for 3 extra neutrino model

$H \to \tau\mu$ has small preference for non zero (arXiv:1502.07400, arXiv:1508.03372)

arXiv:1605.08774v2 (2016)



10^{-3}eV .1 eV

Extra neutrinos can participate in oscillations

eV KeV MeV

accessible at osc. Exp

GeV

Accessible at B-factories

10^2GeV TeV 10 TeV 10^2 TeV 10^3 TeV 10^{12} TeV

Accessible at LHC

Lepton Flavor Violation & non Unitarity of PMNS

arXiv:1407.6607v2 [hep-ph] 6 Aug 2014

$$\Gamma_{W,\alpha} = \sum_i \Gamma(W \to \ell_\alpha \nu_i) = \frac{G_\mu M_W^3}{6\sqrt{2}\pi} \frac{(NN^\dagger)_{\alpha\alpha} F_W(m_{\ell_\alpha})}{\sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}}$$

$$F_W(m_{\ell_\alpha}) = \left(1 - \frac{m_{\ell_\alpha}^2}{m_W^2}\right)^2 \left(1 + \frac{m_{\ell_\alpha}^2}{m_W^2}\right) .$$

$$R_{\alpha\beta}^W = \sqrt{\frac{\Gamma_{W,\alpha} F(m_{\ell_\beta})}{\Gamma_{W,\beta} F(m_{\ell_\alpha})}} = \sqrt{\frac{(NN^\dagger)_{\alpha\alpha}}{(NN^\dagger)_{\beta\beta}}}$$

arXiv:1605.08774v2, 21 Dec 2016

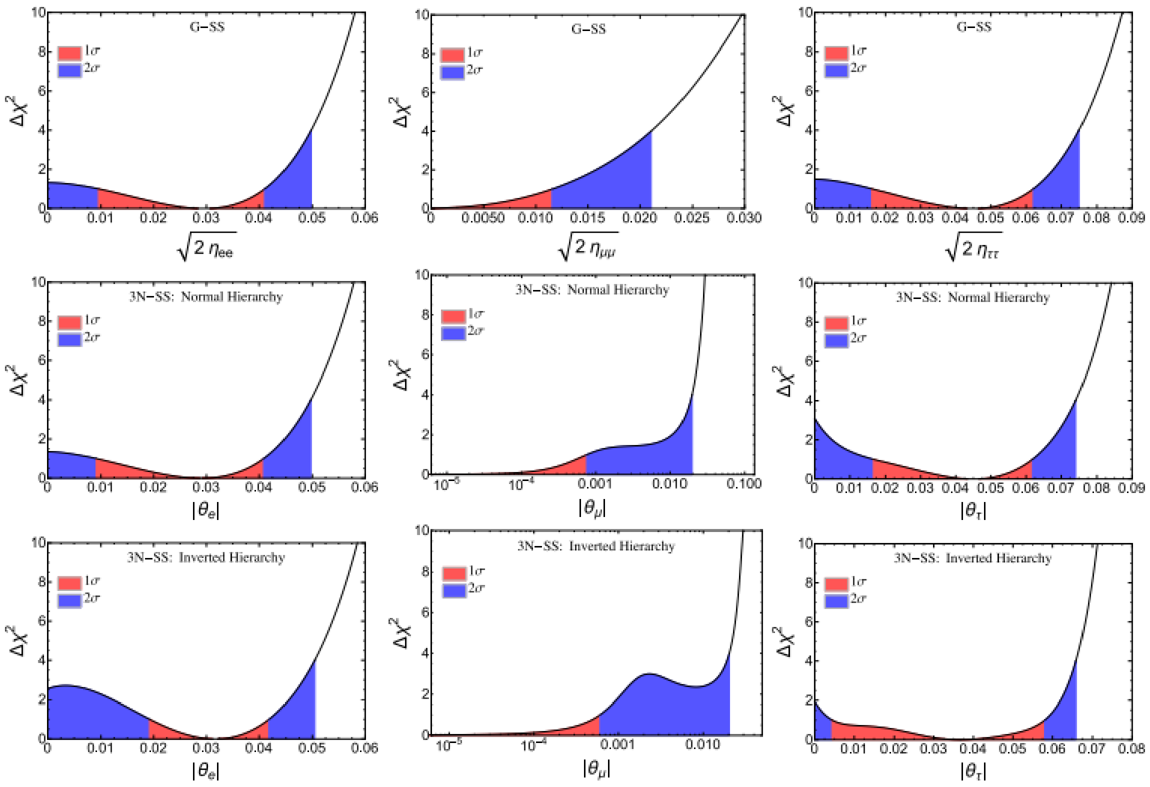


FIG. 3: $\Delta\chi^2$ profile minimized over all fit variables except for one θ_α (or $\sqrt{2\eta_{\alpha\alpha}}$) in the case of the G-SS) at a time. The upper panels are for the G-SS, and the middle and lower panels for the 3N-SS for a normal and inverted hierarchy respectively.

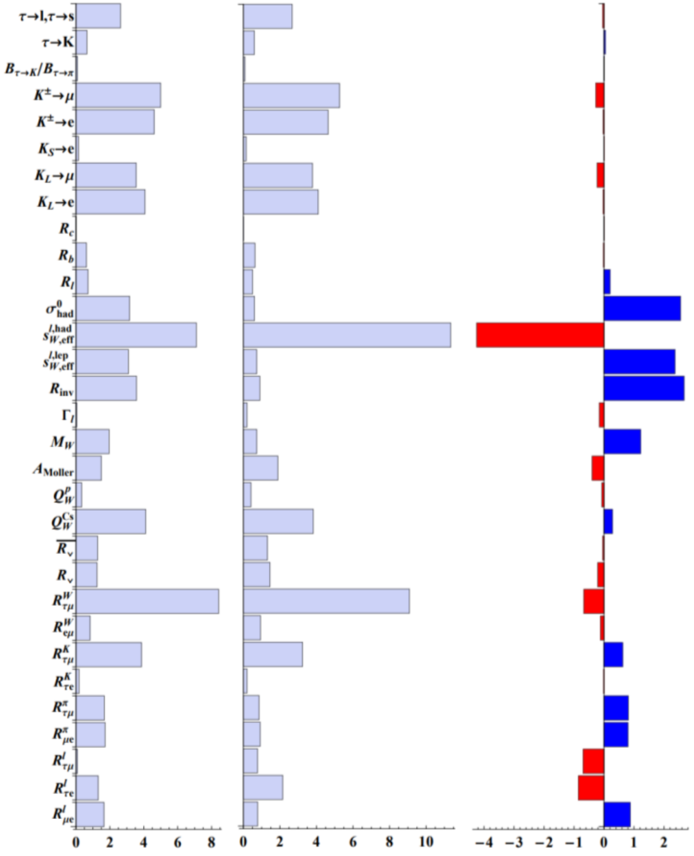
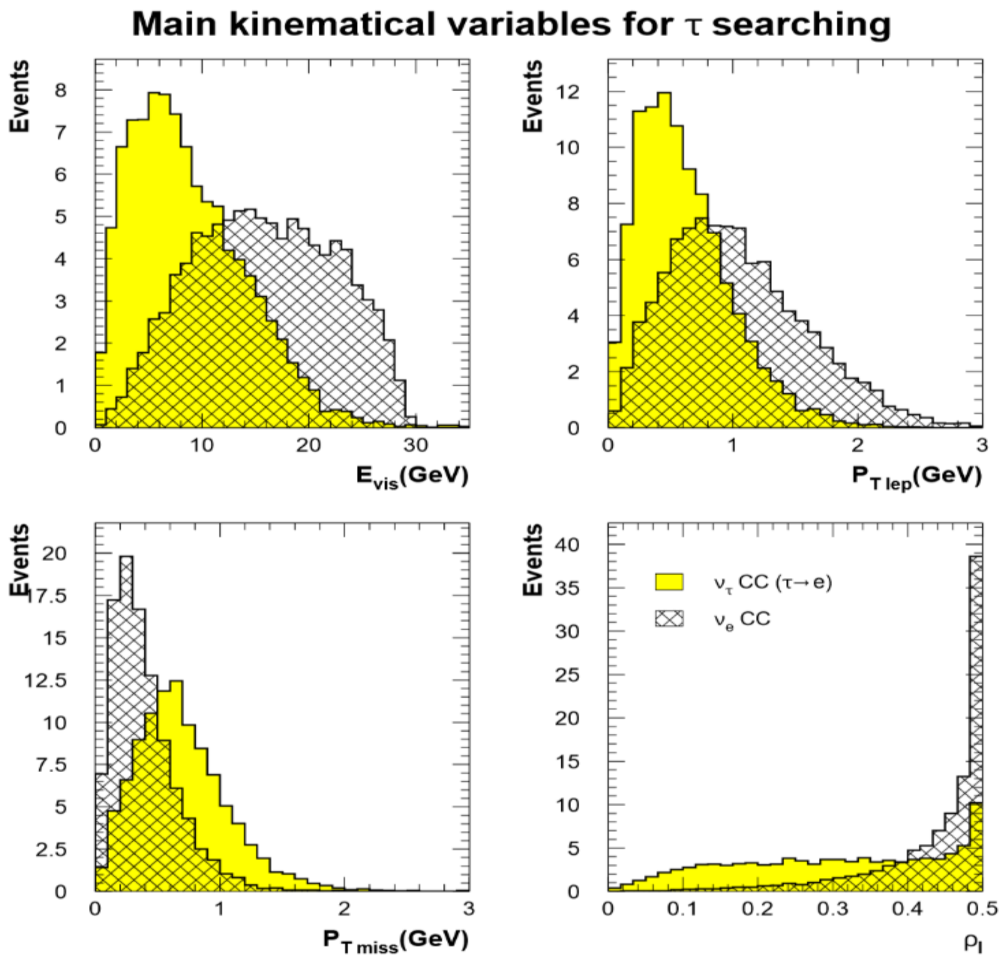


Figure 1: Individual contributions to the total χ^2 from the considered observables. The left column shows the SM and the middle column the MUV scheme with best-fit parameters. The right column shows $\chi_i^2(SM) - \chi_i^2(MUV)$ for the observable i. The positive blue (negative red) bars indicate an improvement (worsening) of the MUV scheme best fit compared to the SM.

Tau Neutrinos in DUNE

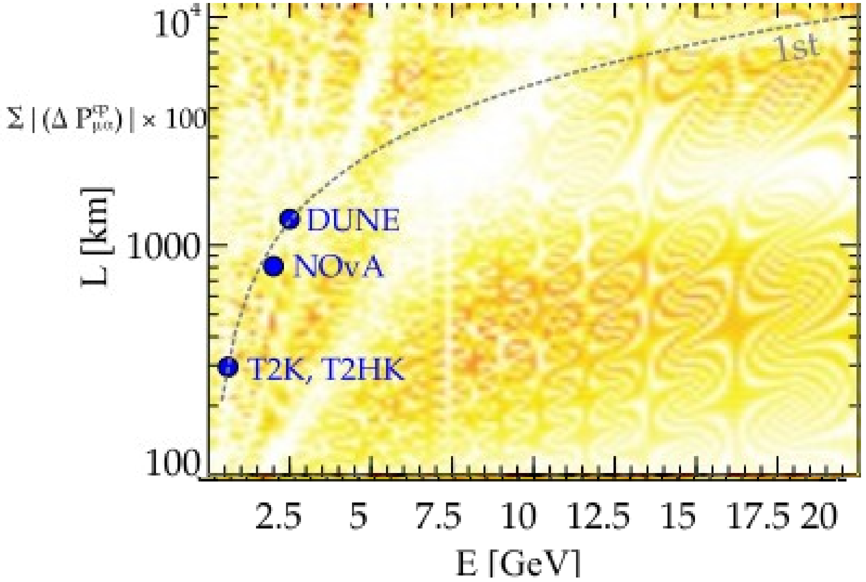


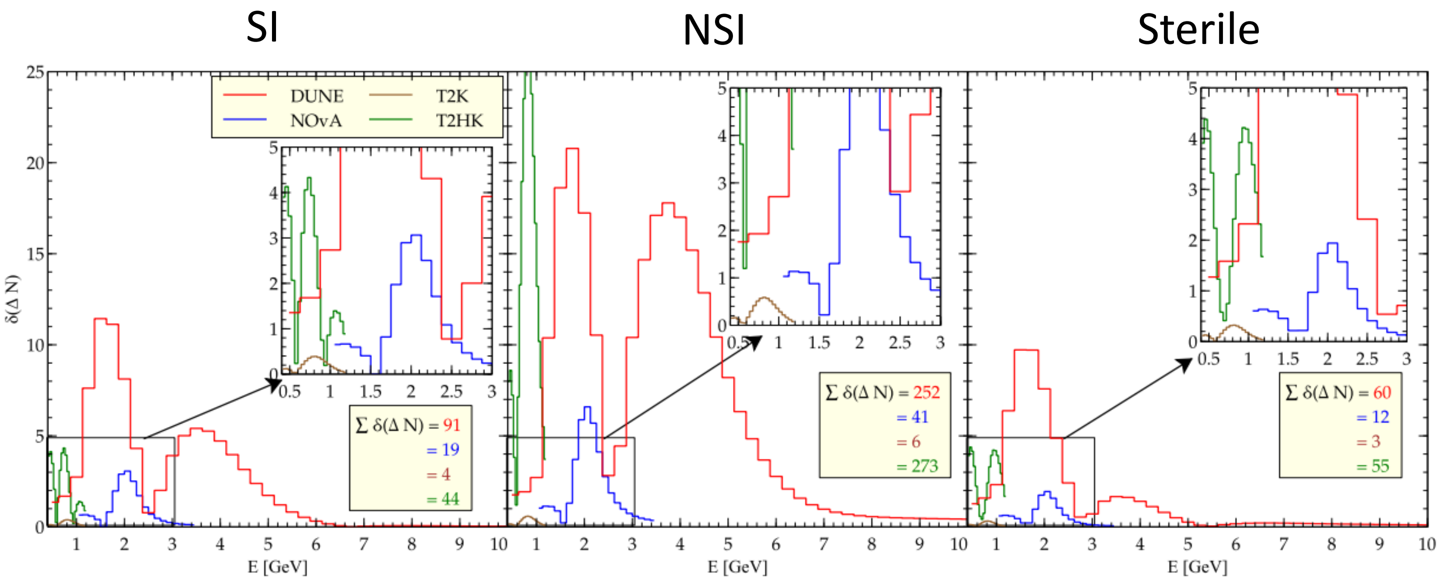
$$\rho = \frac{P_T^{lepton}}{P_T^{lepton} + P_T^{hadron} + P_T^{miss}}$$

The discriminating power of E_{vis}, P_T, P_T^{miss}, ρ between ν_τ induced interactions, represented by the filled yellow distributions, and the ν_e background events represented by the hashed distribution.

Sensitivity to Extra Neutrinos and NSI

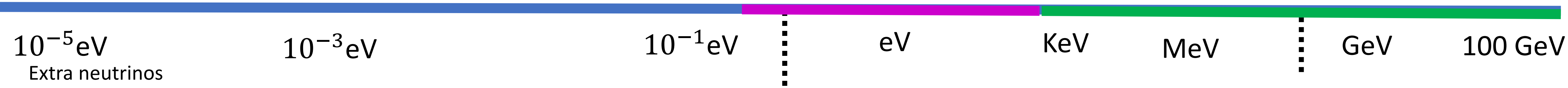
Darker regions = larger amount of non-unitarity in sterile
Can’t probe non-unitarity at better than 6%





$$\delta[\Delta N^{CP}_{\alpha\beta}] = [\Delta N^{CP}_{\alpha\beta}](\delta_{13} = \pi/2) - [\Delta N^{CP}_{\alpha\beta}](\delta_{13} = 0)$$

- NSI with matter gives rise to NSI at source and/or detector (arXiv:0807.1003v3). Bounds on source & detector NSI an order of magnitude more strict than matter NSI. DUNE can probe matter (dim 8), Hyper – K source & detector NSI (dim 6)
- NSI can be probed with supernova neutrinos in Hyper-K : arXiv:1907.01059v2

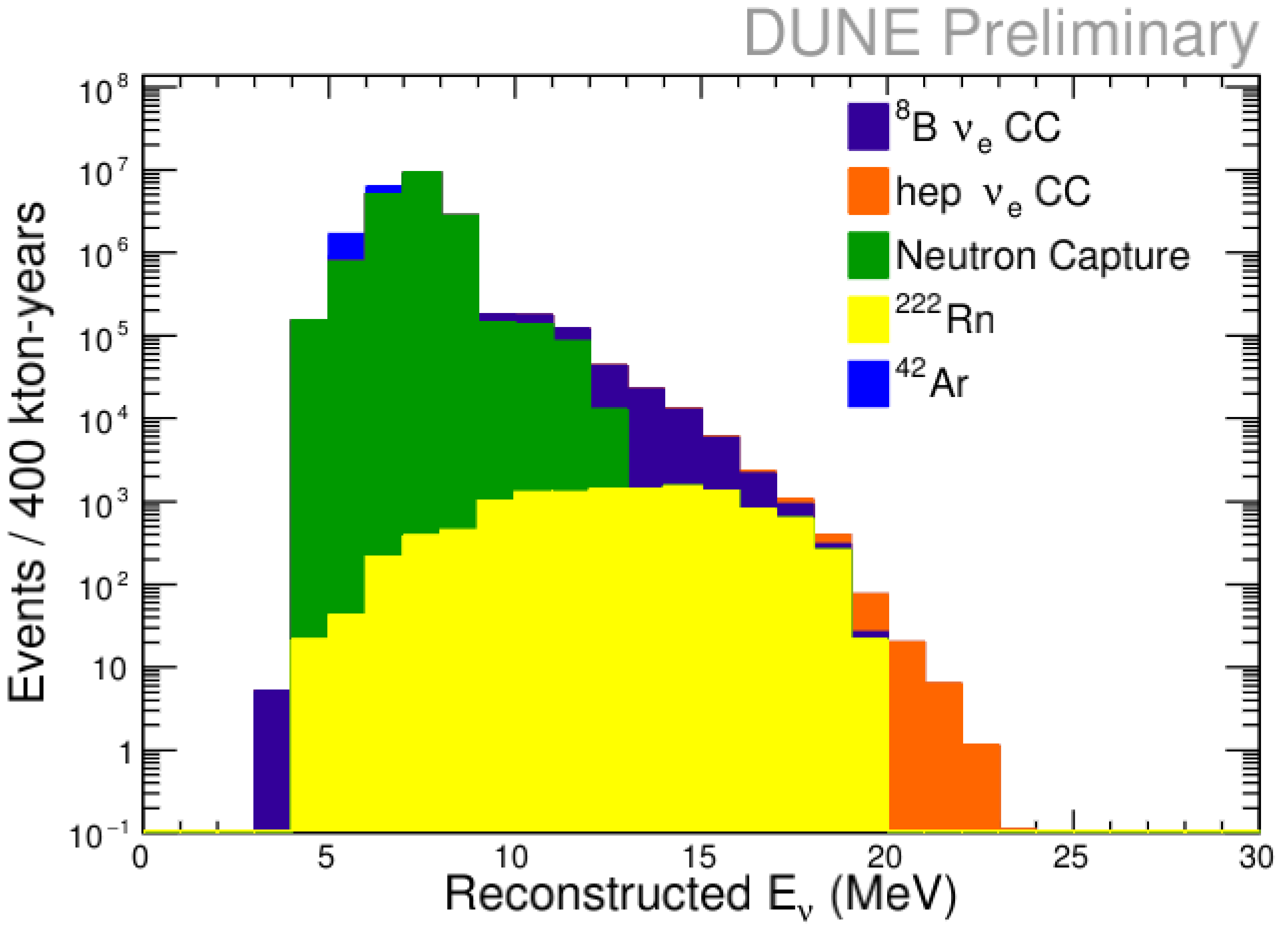

10^{-5}eV
10^{-3}eV
10^{-1}eV
eV
KeV
MeV
GeV
100 GeV

Extra neutrinos can participate in oscillations

accessible at osc. Exp

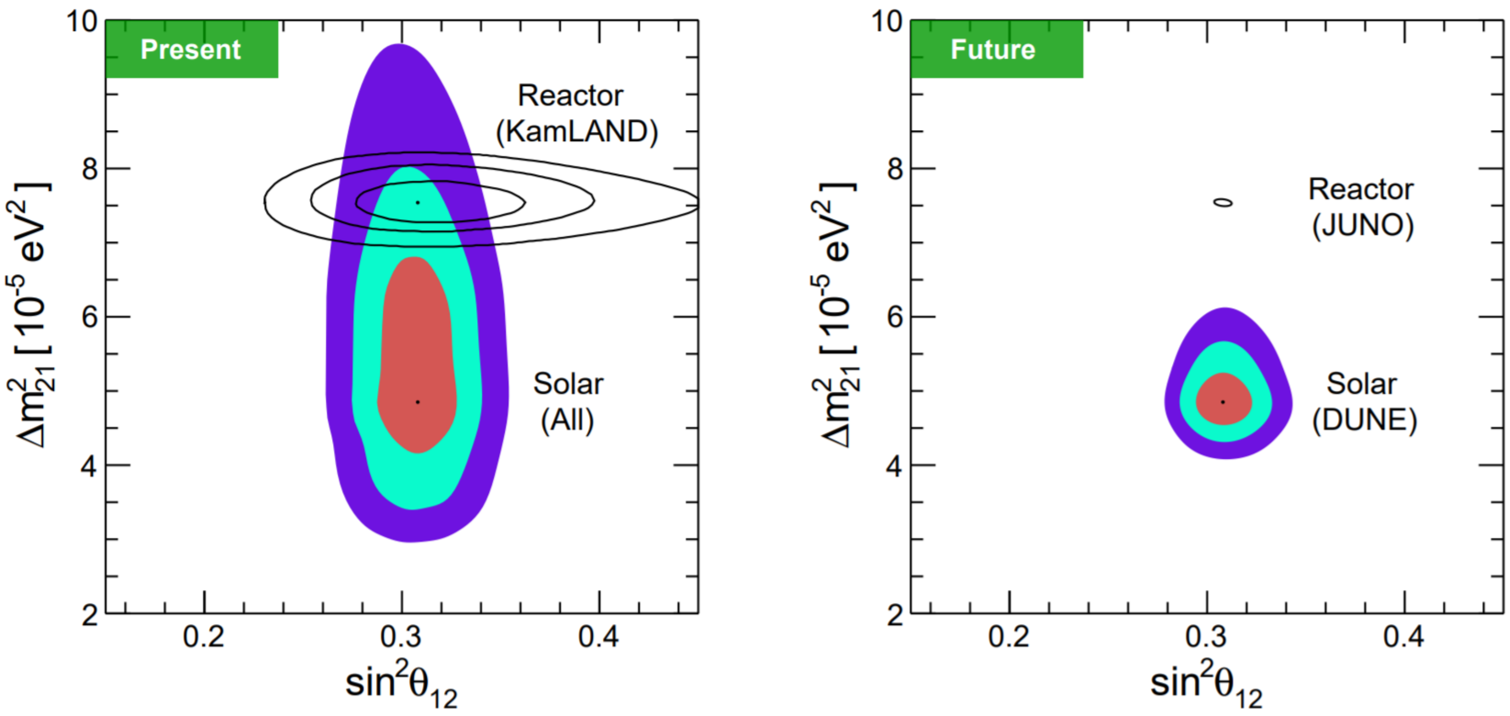
Accessible at B-factories

Solar Neutrino Backgrounds

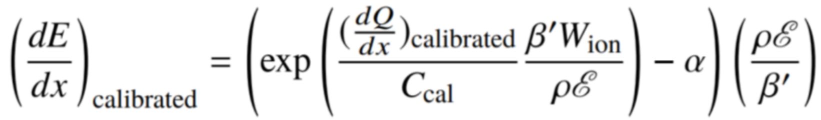


DUNE as the Next-Generation Solar Neutrino Experiment

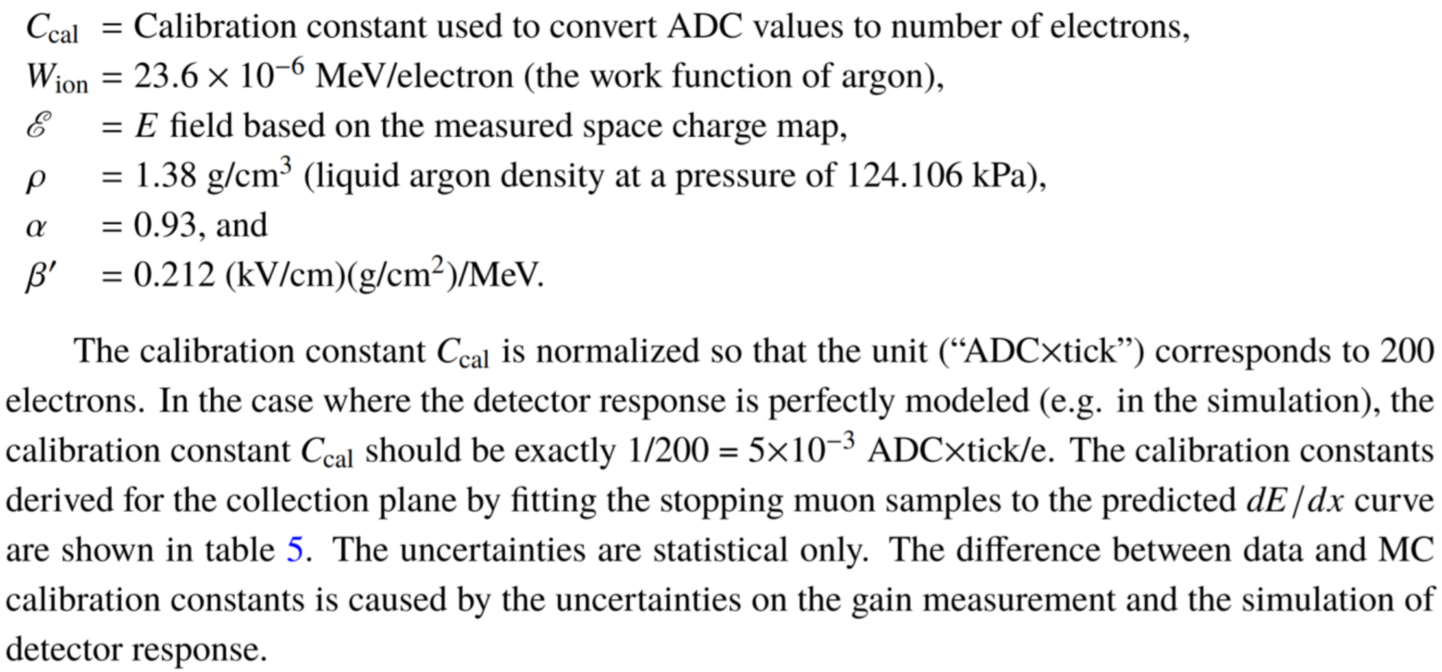
- https://arxiv.org/pdf/1808.08232.pdf



ProtoDUNE calibration



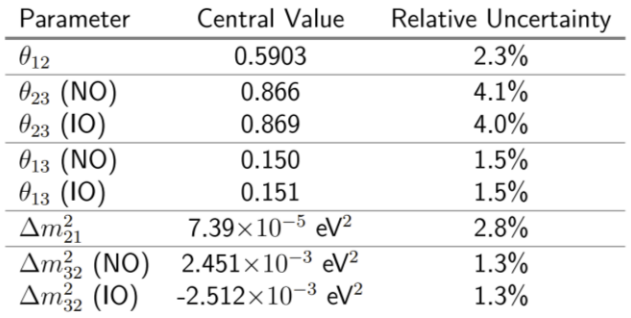
$$\left(\frac{dE}{dx}\right)_{\text{calibrated}} = \left(\exp\left(\frac{(\frac{dQ}{dx})_{\text{calibrated}}}{C_{\text{cal}}}\frac{\beta' W_{\text{ion}}}{\rho\mathscr{E}}\right) - \alpha\right)\left(\frac{\rho\mathscr{E}}{\beta'}\right)$$



C_{cal} = Calibration constant used to convert ADC values to number of electrons,
W_{ion} = 23.6×10^{-6} MeV/electron (the work function of argon),
$\mathscr{E}$ = E field based on the measured space charge map,
ρ = 1.38 g/cm^3 (liquid argon density at a pressure of 124.106 kPa),
α = 0.93, and
β' = 0.212 (kV/cm)(g/cm^2)/MeV.

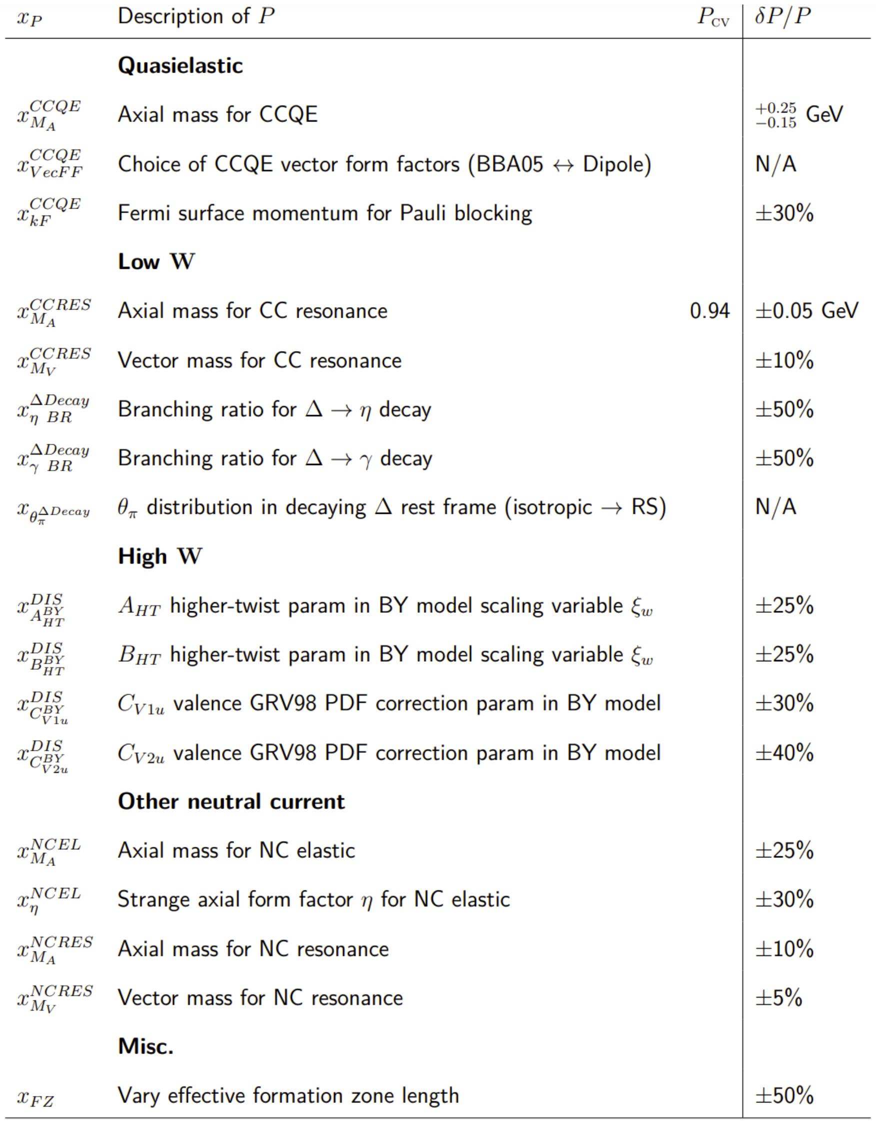
The calibration constant C_{cal} is normalized so that the unit ("ADC×tick") corresponds to 200 electrons. In the case where the detector response is perfectly modeled (e.g. in the simulation), the calibration constant C_{cal} should be exactly 1/200 = 5×10^{-3} ADC×tick/e. The calibration constants derived for the collection plane by fitting the stopping muon samples to the predicted dE/dx curve are shown in table 5. The uncertainties are statistical only. The difference between data and MC calibration constants is caused by the uncertainties on the gain measurement and the simulation of detector response.

From DUNE Physics TDR



Parameter	Central Value	Relative Uncertainty
θ_{12}	0.5903	2.3%
θ_{23} (NO)	0.866	4.1%
θ_{23} (IO)	0.869	4.0%
θ_{13} (NO)	0.150	1.5%
θ_{13} (IO)	0.151	1.5%
Δm^2_{21}	7.39×10^{-5} eV^2	2.8%
Δm^2_{32} (NO)	2.451×10^{-3} eV^2	1.3%
Δm^2_{32} (IO)	-2.512×10^{-3} eV^2	1.3%

Table 5.1: Central value and relative uncertainty of neutrino oscillation parameters from a global fit [2, 3] to neutrino oscillation data. Because the probability distributions are somewhat non-Gaussian (particularly for θ_{23}), the relative uncertainty is computed using 1/6 of the 3σ allowed range from the fit, rather than the 1σ range. For θ_{23}, θ_{13}, and Δm^2_{31}, the best-fit values and uncertainties depend on whether normal mass ordering (NO) or inverted mass ordering (IO) is assumed.



x_P	Description of P	$P_{\rm CV}$	$\delta P/P$
	Quasielastic		
$x^{CCQE}_{M_A}$	Axial mass for CCQE		$^{+0.25}_{-0.15}$ GeV
x^{CCQE}_{VecFF}	Choice of CCQE vector form factors (BBA05 ↔ Dipole)		N/A
x^{CCQE}_{kF}	Fermi surface momentum for Pauli blocking		±30%
	Low W		
$x^{CCRES}_{M_A}$	Axial mass for CC resonance	0.94	±0.05 GeV
$x^{CCRES}_{M_V}$	Vector mass for CC resonance		±10%
$x^{\Delta Decay}_{\eta\ BR}$	Branching ratio for $\Delta \rightarrow \eta$ decay		±50%
$x^{\Delta Decay}_{\gamma\ BR}$	Branching ratio for $\Delta \rightarrow \gamma$ decay		±50%
$x_{\theta_\pi^{\Delta Decay}}$	θ_π distribution in decaying Δ rest frame (isotropic → RS)		N/A
	High W		
$x^{DIS}_{A^{BY}_{HT}}$	A_{HT} higher-twist param in BY model scaling variable ξ_w		±25%
$x^{DIS}_{B^{BY}_{HT}}$	B_{HT} higher-twist param in BY model scaling variable ξ_w		±25%
$x^{DIS}_{C^{BY}_{V1u}}$	C_{V1u} valence GRV98 PDF correction param in BY model		±30%
$x^{DIS}_{C^{BY}_{V2u}}$	C_{V2u} valence GRV98 PDF correction param in BY model		±40%
	Other neutral current		
$x^{NCEL}_{M_A}$	Axial mass for NC elastic		±25%
x^{NCEL}_{η}	Strange axial form factor η for NC elastic		±30%
$x^{NCRES}_{M_A}$	Axial mass for NC resonance		±10%
$x^{NCRES}_{M_V}$	Vector mass for NC resonance		±5%
	Misc.		
x_{FZ}	Vary effective formation zone length		±50%

Table 5.4: Neutrino interaction cross-section systematic parameters considered in GENIE. GENIE default central values and uncertainties are used for all parameters except $x^{CCRES}_{M_A}$. Missing GENIE parameters were omitted where uncertainties developed for this analysis significantly overlap with the supplied GENIE freedom, the response calculation was too slow, or the variations were deemed unphysical.

Uncertainties

Prefit uncertainties on flux and cross section parameters are at the level of ~10%. These uncertainties become constrained in the fit, especially by the ND.

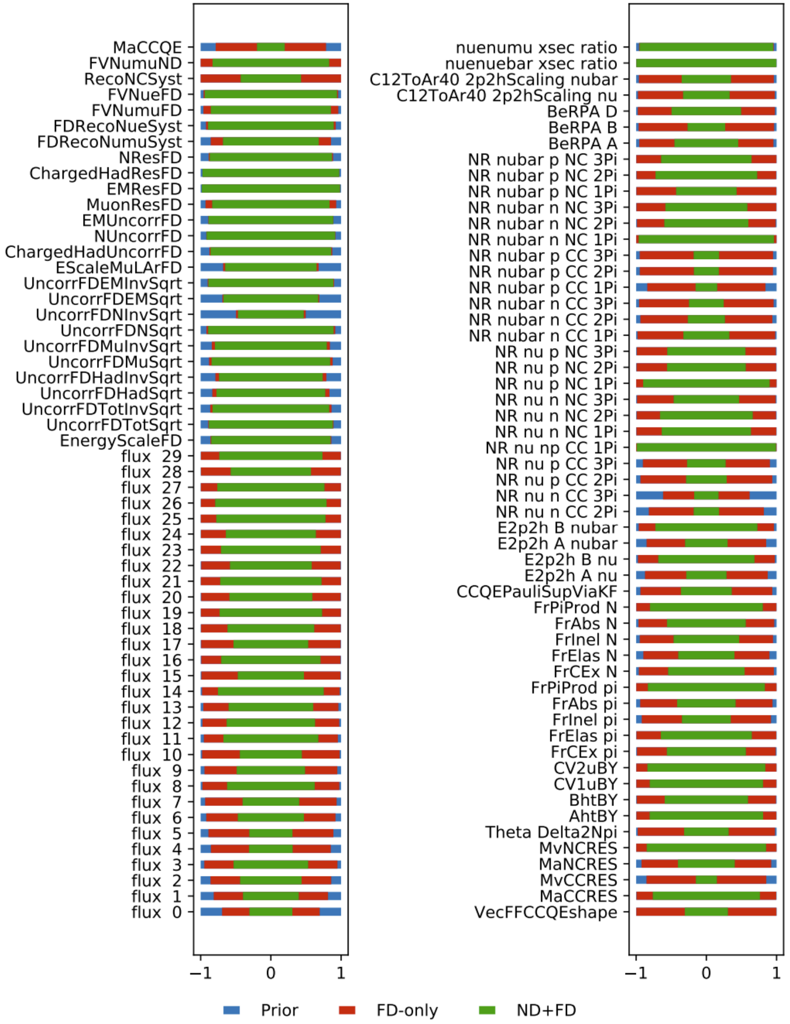


Figure 5.34: The ratio of post-fit to pre-fit uncertainties for various systematic parameters for a 15-year staged exposure. The red band shows the constraint from the FD only in 15 years, while the green shows the ND+FD constraints. Systematic parameter names are defined in Table 5.12.

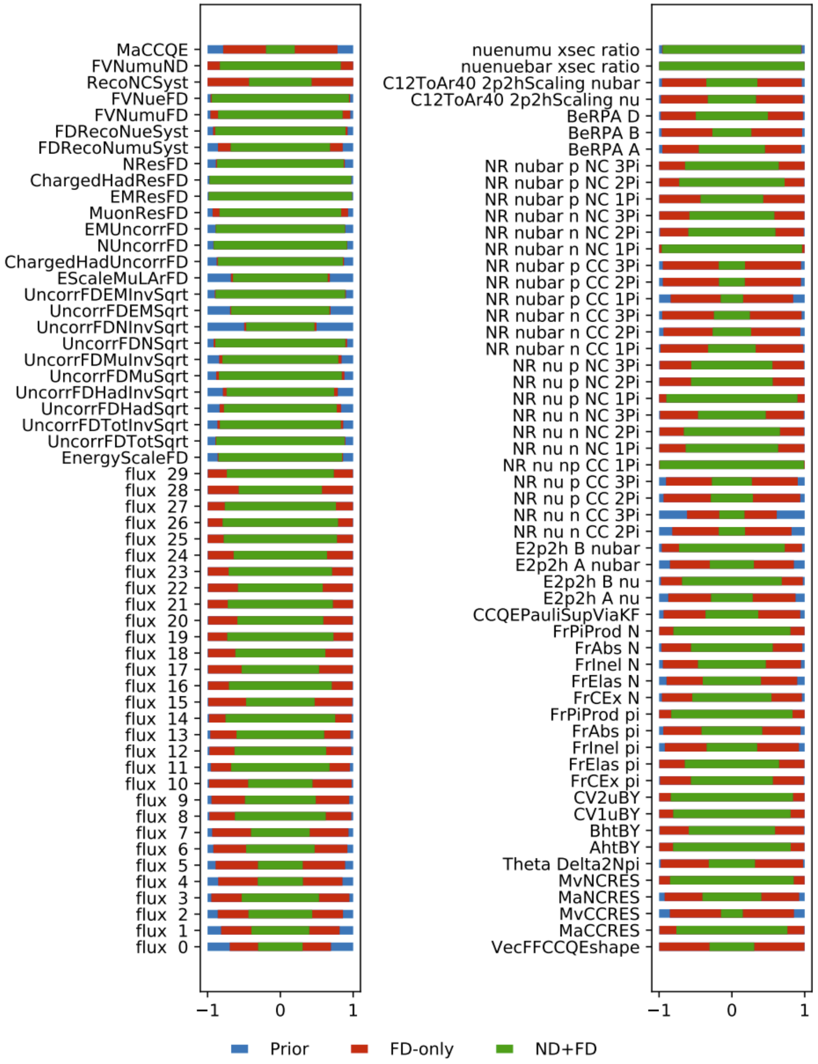


Figure 5.34: The ratio of post-fit to pre-fit uncertainties for various systematic parameters for a 15-year staged exposure. The red band shows the constraint from the FD only in 15 years, while the green shows the ND+FD constraints. Systematic parameter names are defined in Table 5.12.

SuperNova Neutrinos

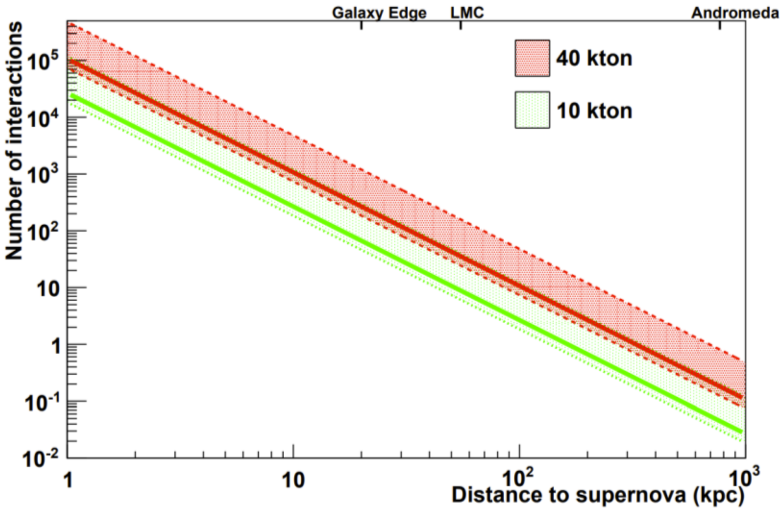
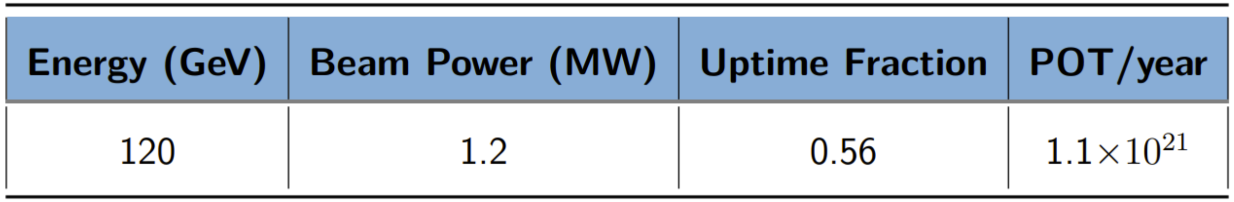


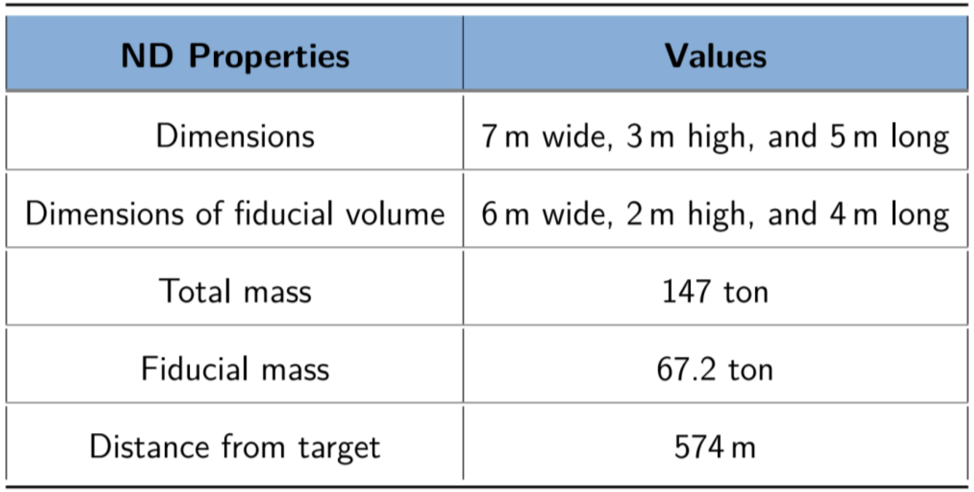
Figure 7.7: Estimated numbers of supernova neutrino interactions in DUNE as a function of distance to the supernova, for different detector masses (ν_e events dominate). The red dashed lines represent expected events for a 40-kton detector and the green dotted lines represent expected events for a 10-kton detector. The lines limit a fairly wide range of possibilities for "Garching-parameterized" supernova flux spectra (Equation 7.1) with luminosity 0.5×10^{52} ergs over ten seconds. The optimistic upper line of a pair gives the number of events for average ν_e energy of $\langle E_{\nu_e} \rangle = 12$ MeV, and "pinching" parameter $\alpha = 2$; the pessimistic lower line of a pair gives the number of events for $\langle E_{\nu_e} \rangle = 8$ MeV and $\alpha = 6$. (Note that the luminosity, average energy and pinching parameters will vary over the time frame of the burst, and these estimates assume a constant spectrum in time. Oscillations will also affect the spectra and event rates.) The solid lines represent the integrated number of events for the specific time-dependent neutrino flux model in [249] (see Figures 7.1 and 7.2; this model has relatively cool spectra and low event rates). Core collapses are expected to occur a few times per century, at a most-likely distance of around 10 to 15 kpc.

BSM Simulation Assumptions



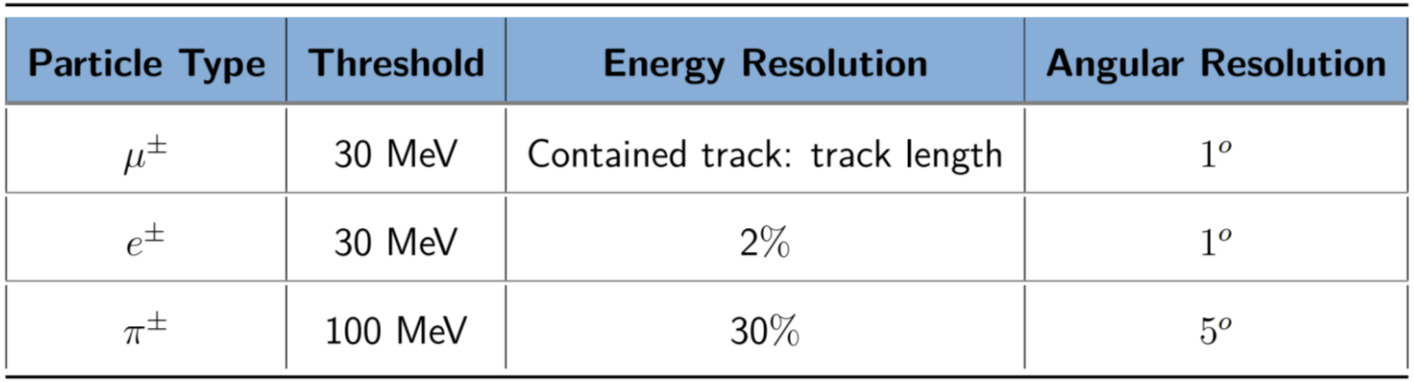
Energy (GeV)	Beam Power (MW)	Uptime Fraction	POT/year
120	1.2	0.56	1.1×10^{21}

Table 8.2: ND properties used in the BSM physics analyses.



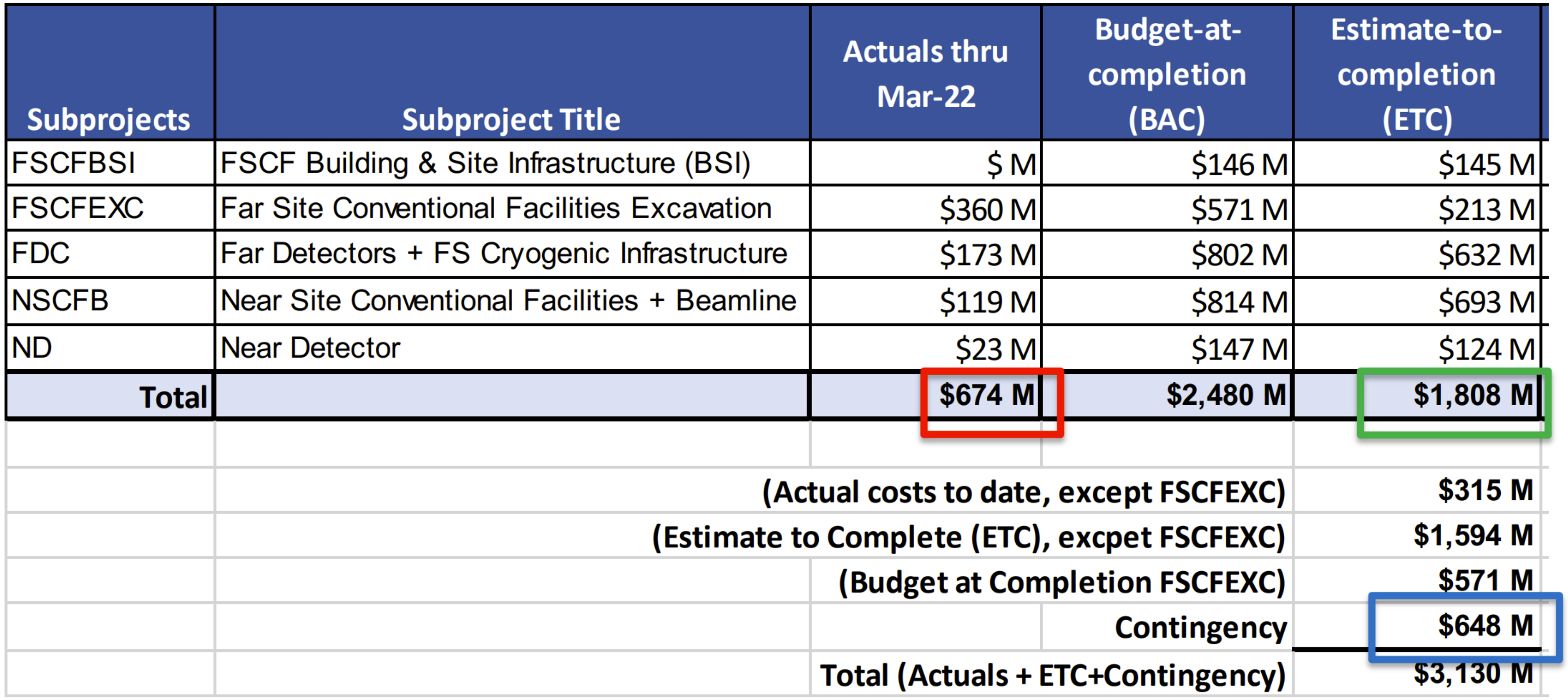
ND Properties	Values
Dimensions	7 m wide, 3 m high, and 5 m long
Dimensions of fiducial volume	6 m wide, 2 m high, and 4 m long
Total mass	147 ton
Fiducial mass	67.2 ton
Distance from target	574 m

Table 8.3: FD properties used in the BSM physics analyses.



Particle Type	Threshold	Energy Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained track: track length	1^o
$e^{\pm}$	30 MeV	2%	1^o
$\pi^{\pm}$	100 MeV	30%	5^o

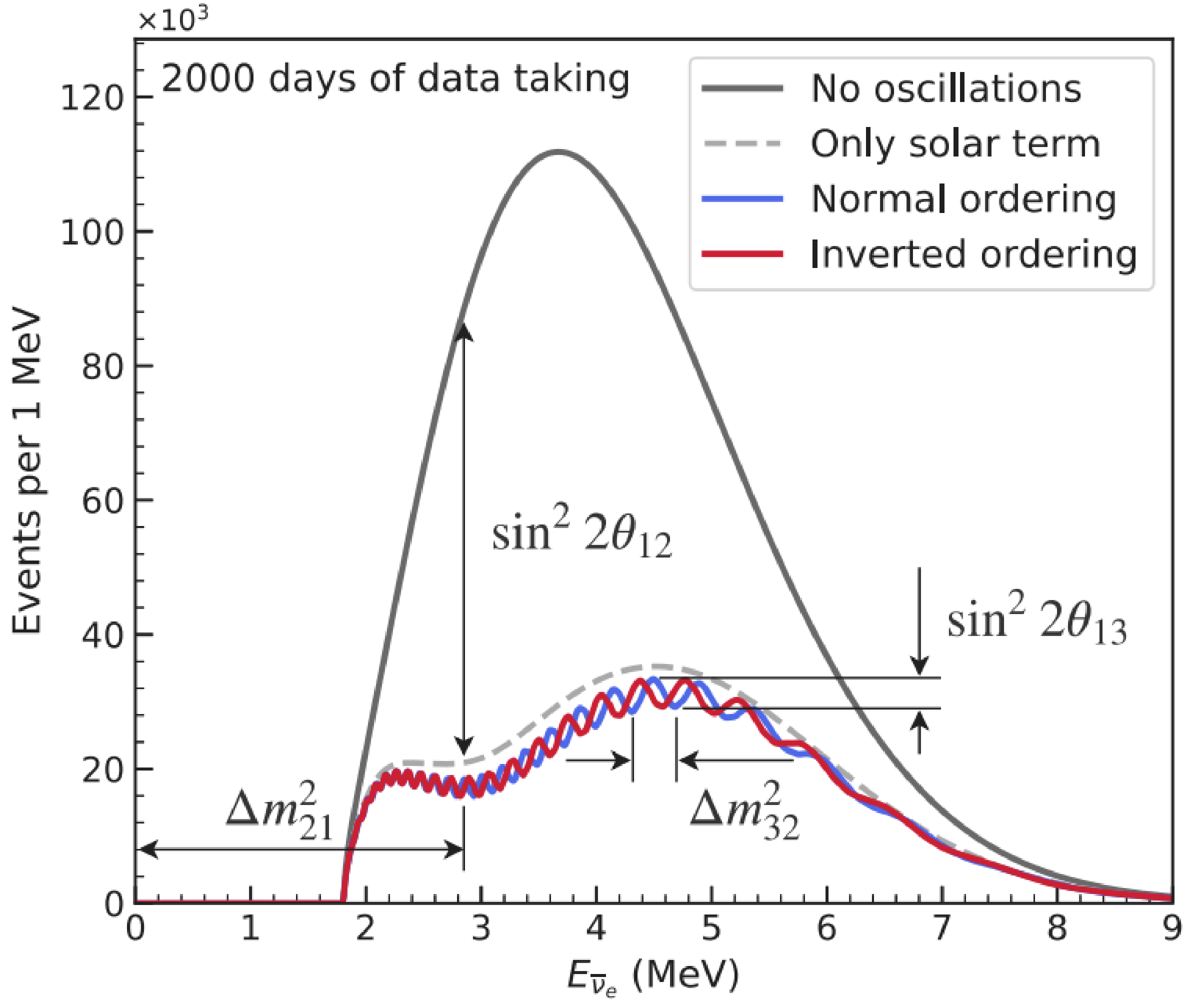
LBNF/DUNE Cost Phase I



Subprojects	Subproject Title	Actuals thru Mar-22	Budget-at-completion (BAC)	Estimate-to-completion (ETC)
FSCFBSI	FSCF Building & Site Infrastructure (BSI)	$ M	$146 M	$145 M
FSCFEXC	Far Site Conventional Facilities Excavation	$360 M	$571 M	$213 M
FDC	Far Detectors + FS Cryogenic Infrastructure	$173 M	$802 M	$632 M
NSCFB	Near Site Conventional Facilities + Beamline	$119 M	$814 M	$693 M
ND	Near Detector	$23 M	$147 M	$124 M
Total		**$674 M**	**$2,480 M**	**$1,808 M**
			(Actual costs to date, except FSCFEXC)	**$315 M**
			(Estimate to Complete (ETC), excpet FSCFEXC)	**$1,594 M**
			(Budget at Completion FSCFEXC)	**$571 M**
			Contingency	**$648 M**
			Total (Actuals + ETC+Contingency)	**$3,130 M**

Total Project Cost = Actuals + Estimate to Complete + Contingency

JUNO



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