Status of LBNF/DUNE

Gina Rameika
DUNE Co-spokesperson

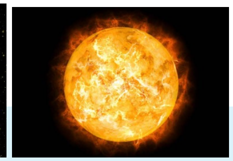
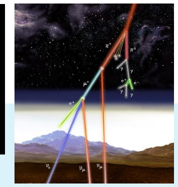
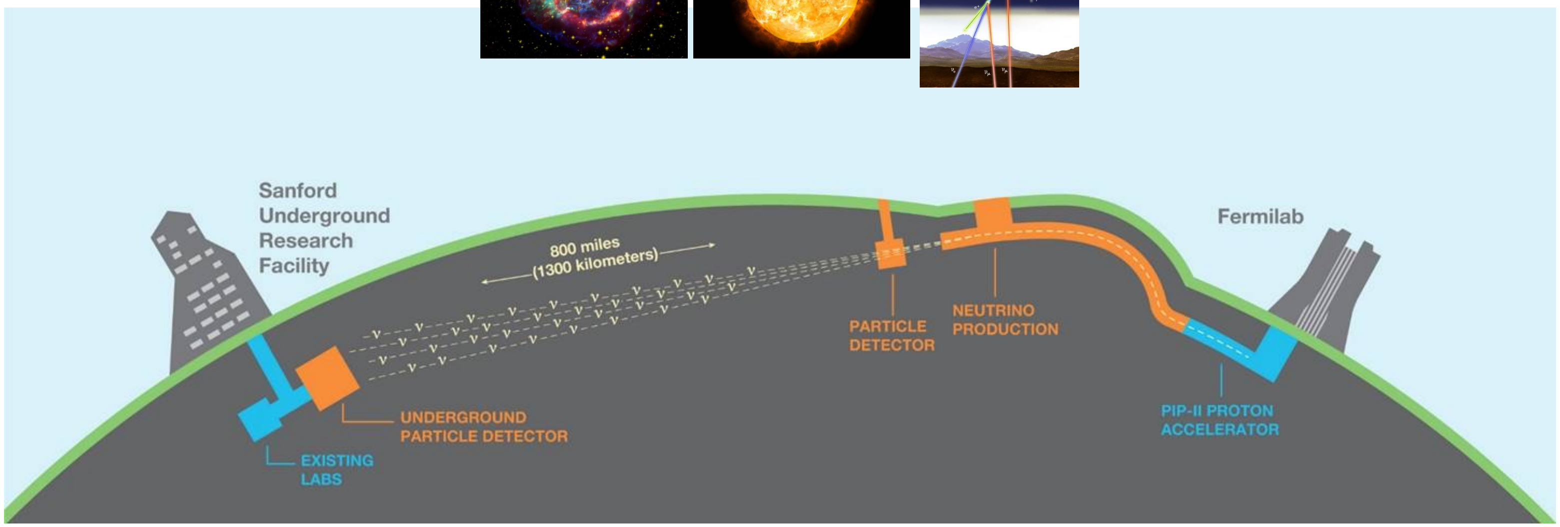
PAC Meeting
21 June 2022

Outline

- Introduction to DUNE
- Status of DUNE
- Status of LBNF
- Summary

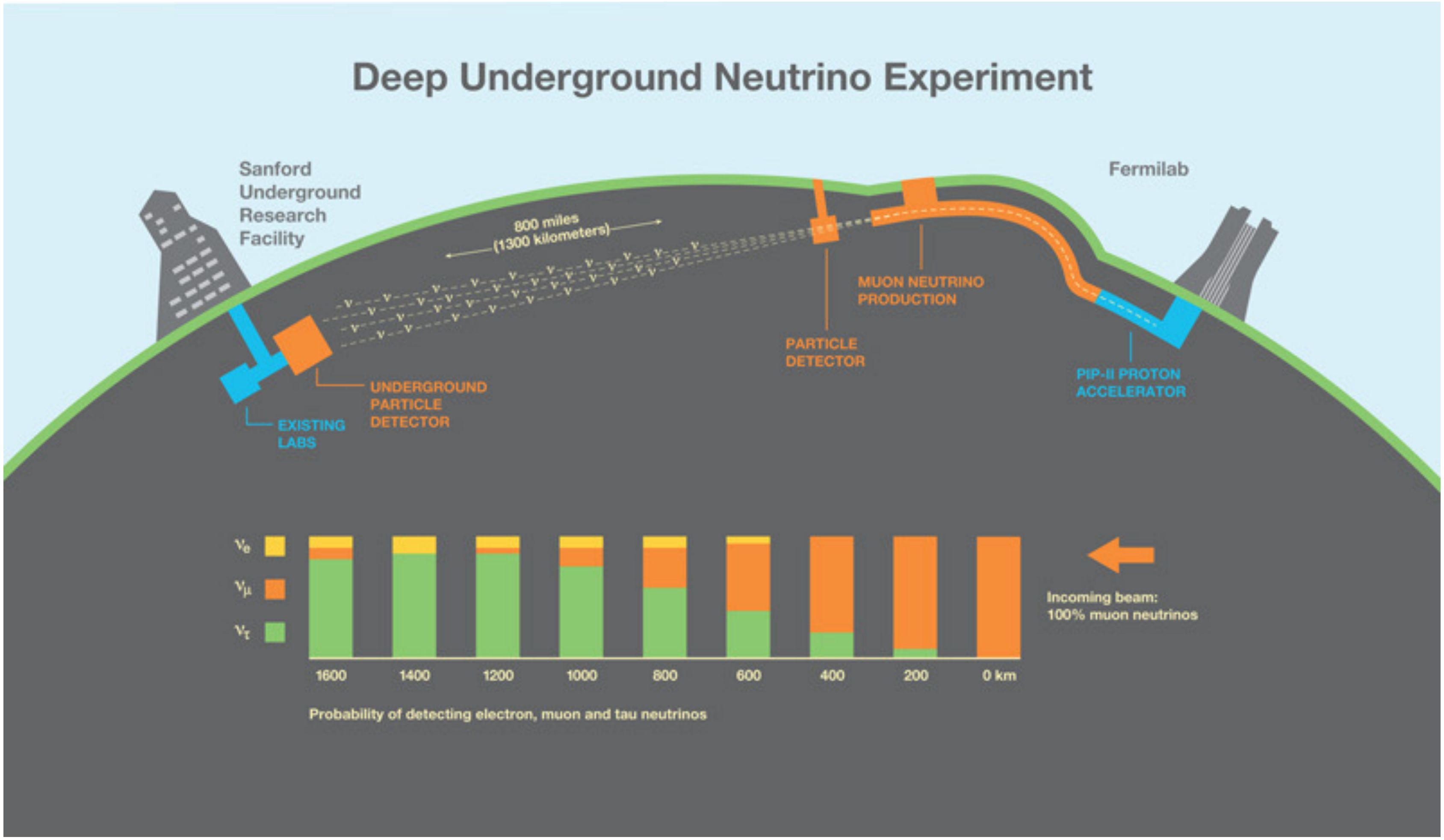
- Lot's of additional slides for FAQs

DUNE Physics Goals

- Unambiguous, high precision measurements of Δm^2_{32}, δ_{CP}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ in a single experiment
- Discovery sensitivity to CP violation, mass ordering, θ_{23} octant over a wide range of parameter values
- Sensitivity to MeV-scale neutrinos, such as from a galactic supernova burst
- Low backgrounds for sensitivity to BSM physics including baryon number violation

Neutrino oscillations in DUNE

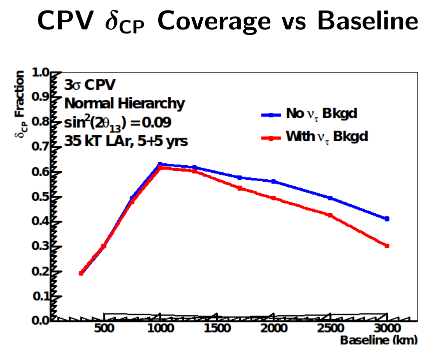


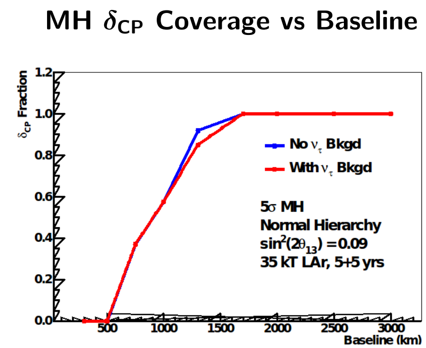
At the Near Detector we measure the rate, composition and spectrum of the neutrino beam before oscillations

At the far detector we measure ν_μ ($\overline{\nu_\mu}$) disappearance and ν_e ($\overline{\nu_e}$) appearance

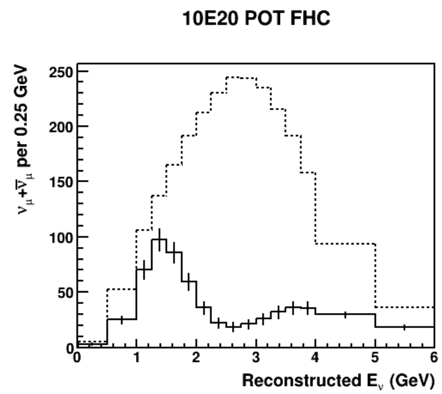
Why is this the best configuration for the experiment

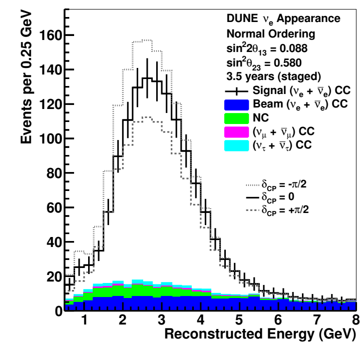
- Baseline is optimized



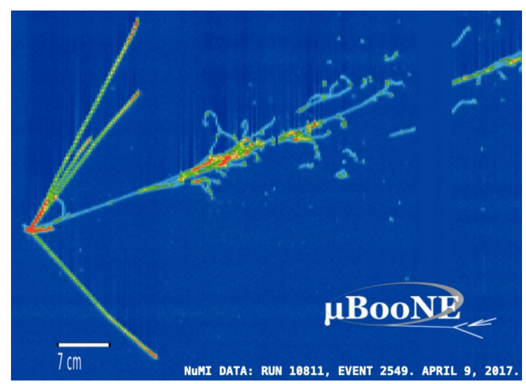


- Beam spectrum covers the oscillation curve



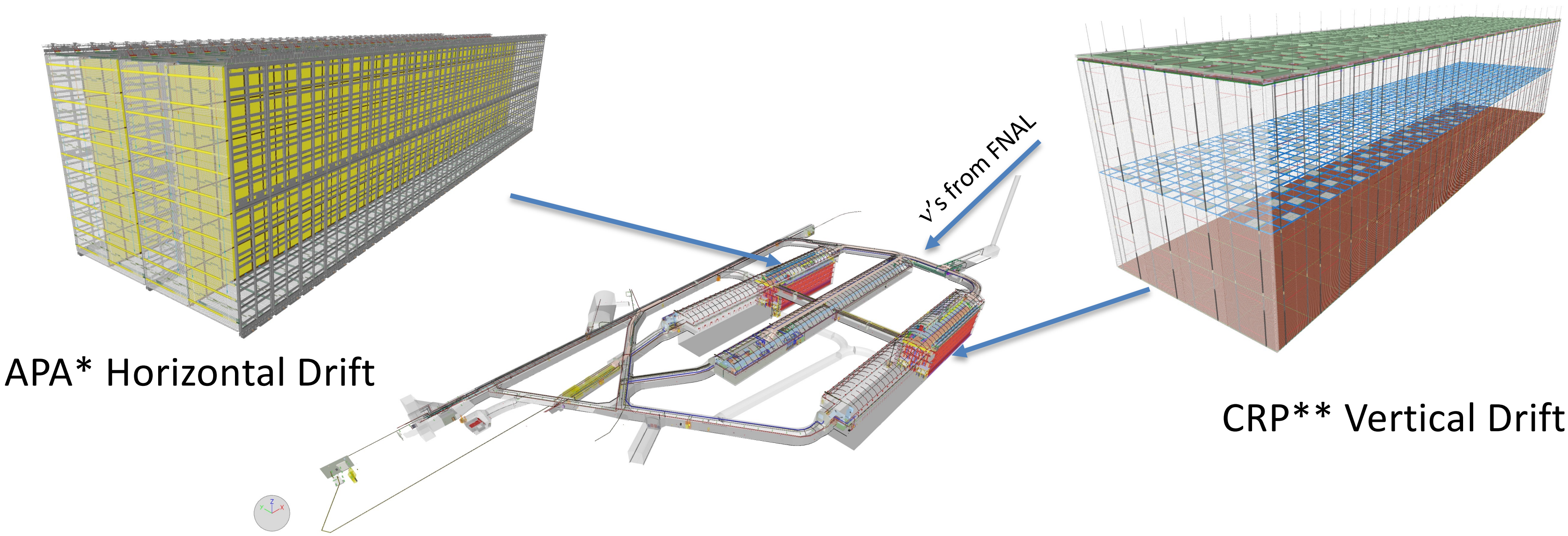


- Detector Technology enables precise energy reconstruction



DUNE – Phase 1

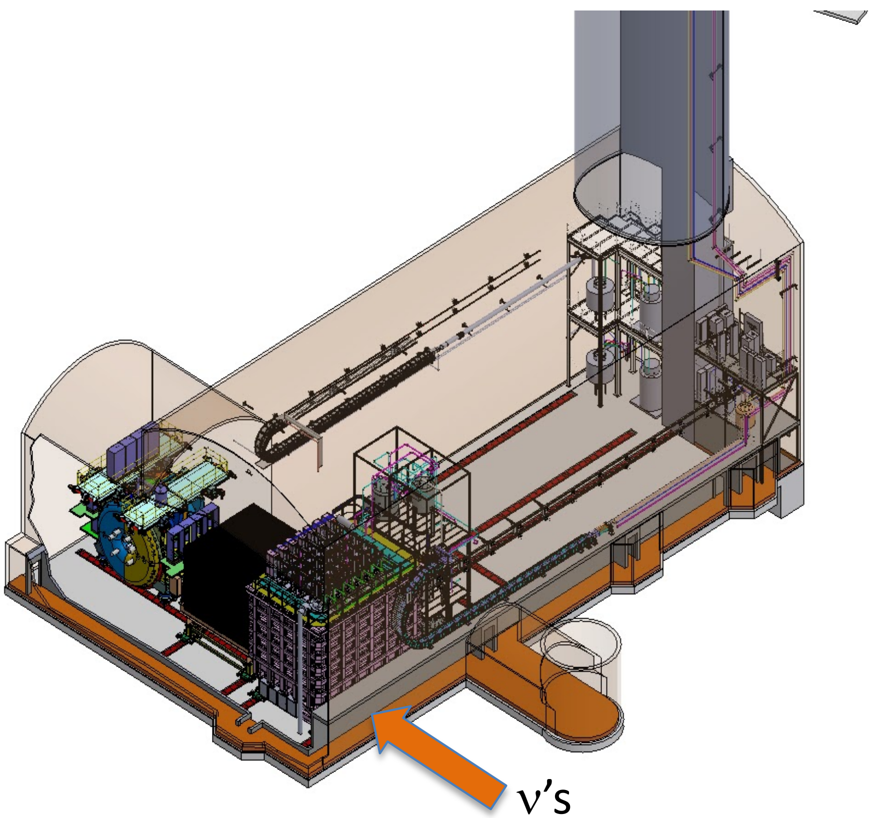
- LBNF will provide caverns for 4 detector modules at SURF
  - 1st detector to be installed in NE cavern has horizontal drift (like ICARUS and MicroBooNE)
  - 2nd detector will go into SE cavern and has vertical drift (capitalizing on elements of the dual phase development)



Note : DUNE Science begins when FD1 is filled and turned on and recording tracks

*Anode Plane Assemblies
**Charge Readout Planes

DUNE – Phase 1

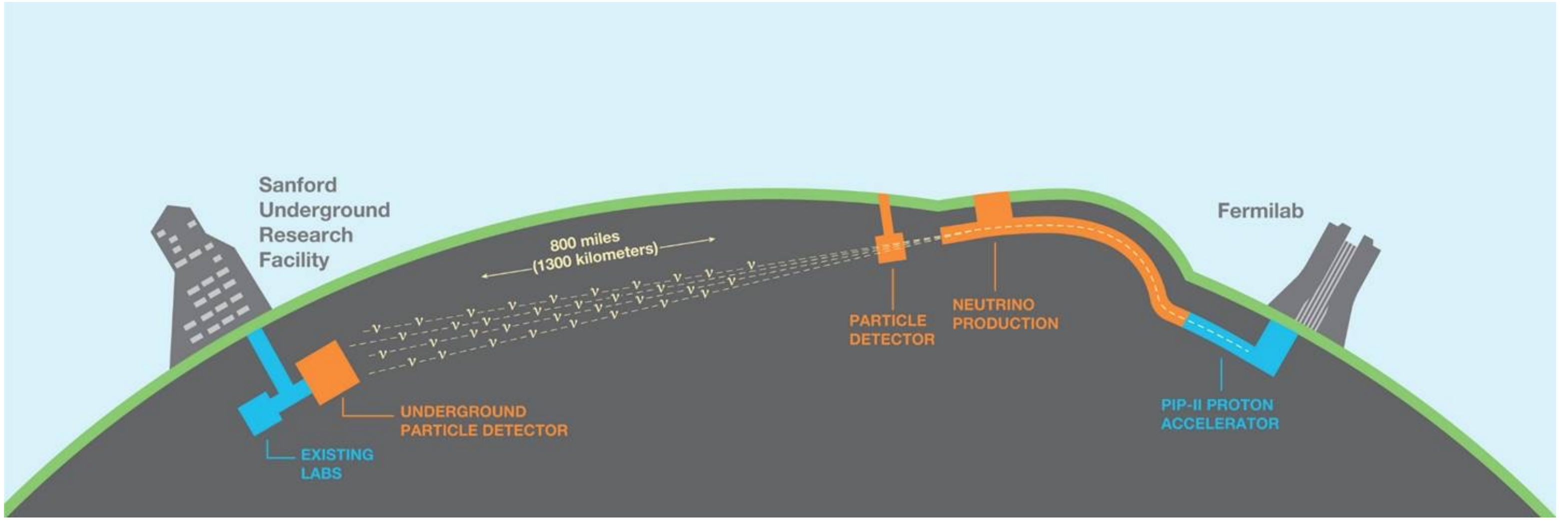


- Near Detector Complex houses a set of detectors that work in concert with each other to predict the far detector spectrum and monitor the beam stability.
- These include
  - A liquid argon TPC (ND-LAr) plus a Muon Spectrometer (TMS) ; these can move off-axis (PRISM system)
  - An on-axis beam monitor (SAND) ; SAND will also make precision measurements of multiple channels of neutrino interactions, leading to more control of systematics

Definitions

- DUNE Phase I (accomplished with LBNF/DUNE-US and PIP-II projects and international partners)
  - Two far detectors : 1 HD + 1 VD
  - Near detector = NDLAr + TMS + SAND + PRISM movement
  - 1.2 MW beam power from PIP-II
- DUNE Phase II (or upgrade paths)
  - Additional mass at Far Detector
  - A more capable near detector (MCND) (could replace)TMS
  - Increased beam power (up to 2.4 MW) provided by Booster replacement

Neutrino oscillations in DUNE

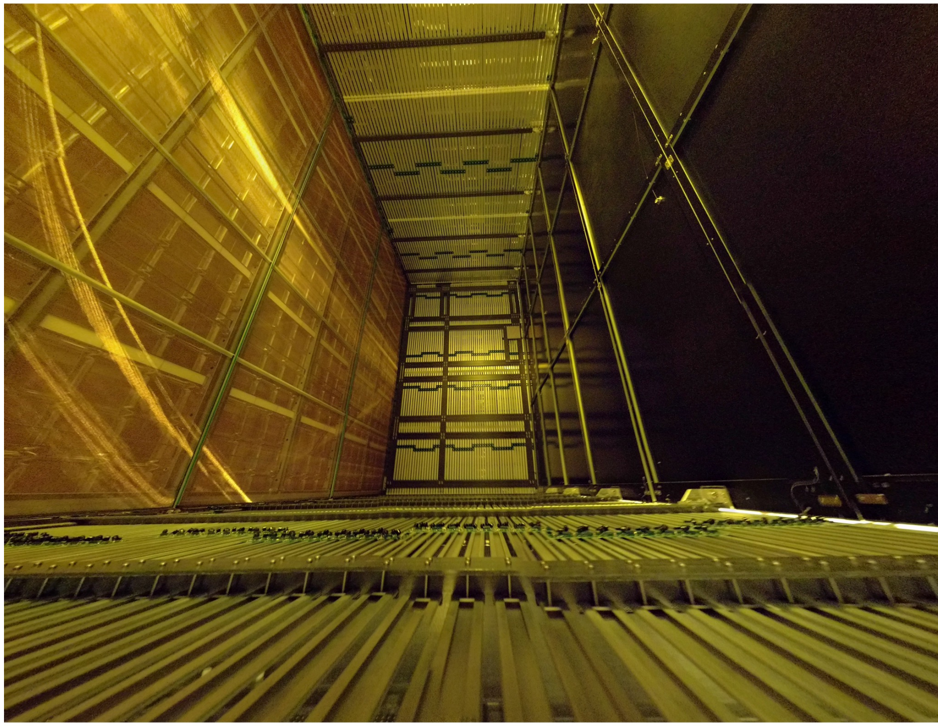


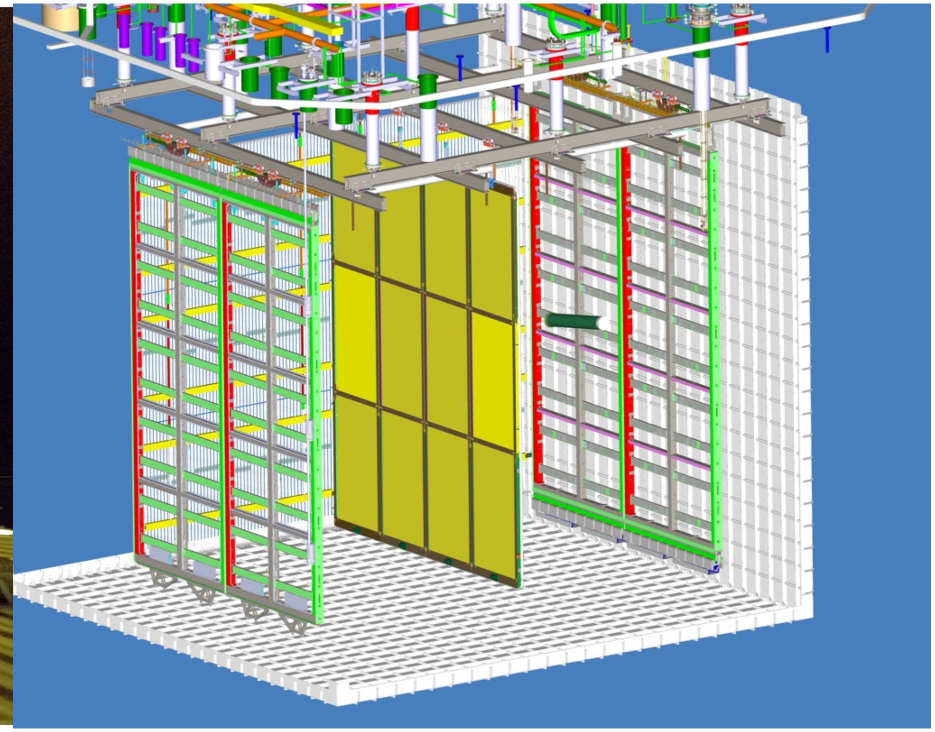
- The DUNE neutrino oscillation program is **exceptional** due to several key features of the experiment and facility design :
  - The **1300 km baseline** between Fermilab and SURF location for the far detectors enables an unambiguous measurement of the neutrino mass ordering (mass hierarchy)
  - The detector's on-axis location provides for a **wide-band energy spectrum of neutrinos** to be seen in the near and far locations enabling detailed fitting of the oscillation parameters
  - The **liquid argon detector technology** enables precise reconstruction of the neutrino interactions
  - The Near Detector complex at Fermilab will support near detectors that will provide **unprecedented control of systematic uncertainties** in the prediction of the un-oscillated neutrino flux

Status of DUNE

- Far Detectors
  - Designs are quite mature and prototyping activities are in full swing at CERN neutrino platform
  - The Far Detector and Cryogenics sub-project (FDC) is planning to be ready for CD-2 in 2023
- Near Detectors
  - Work continues on prototyping the LarTPC modules for the 2x2 demonstration in the NuMI beam
  - Collaboration decision on the inner tracker for SAND has led to an updated Consortium organization with focus on designs for the Straw Tube Tracker (STT) and a liquid argon target volume (GRAIN)
  - Designs will mature over the next two years

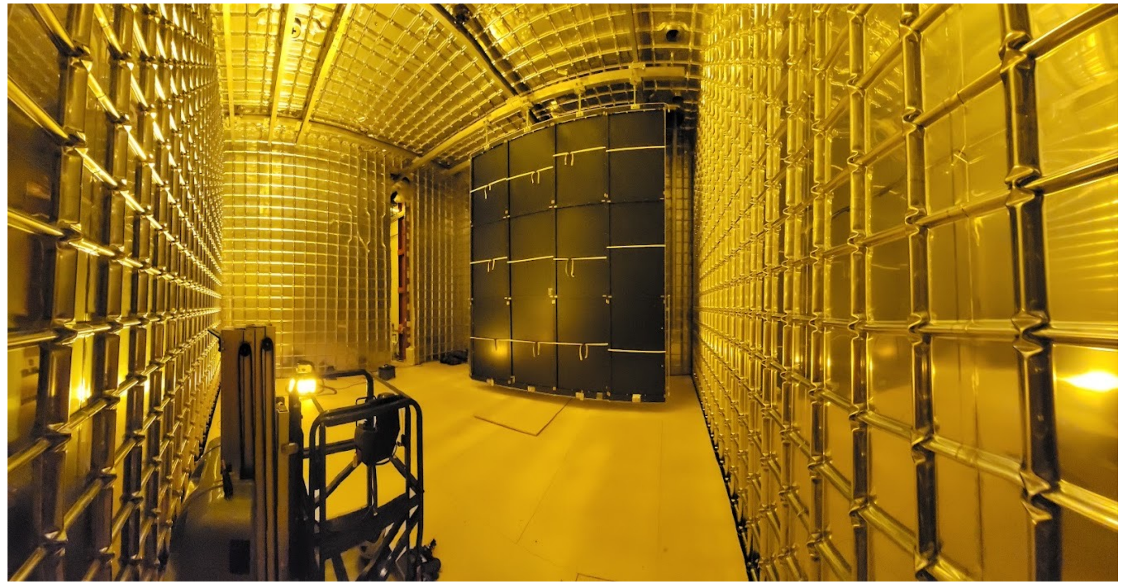
ProtoDUNE-I (HD) –> ProtoDUNE-II (HD)





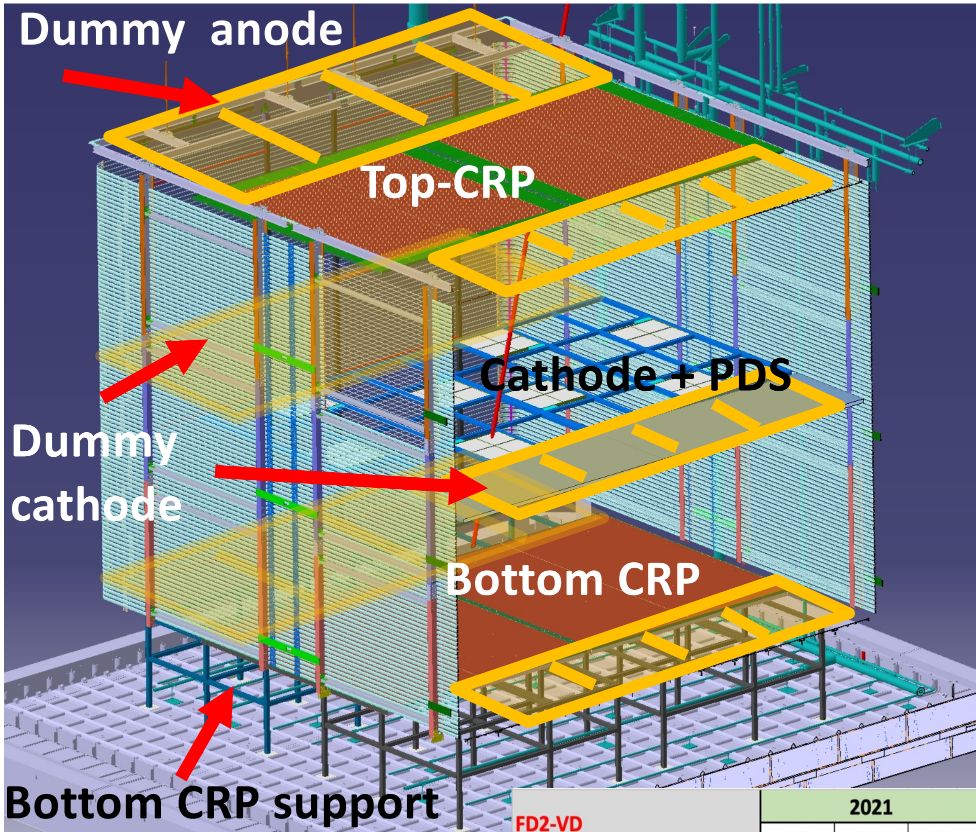
- ProtoDUNE I consisted of two drift volumes each with 3 APAs, for a total of 6; this enabled a full demonstration of deployment with upstream, downstream and middle modules of field cages
- ProtoDUNE II will reduce in size to two volumes with only two APAs each; one side will be deployed with upside down APAS to mimic the bottom of the double decker layers that are in DUNE

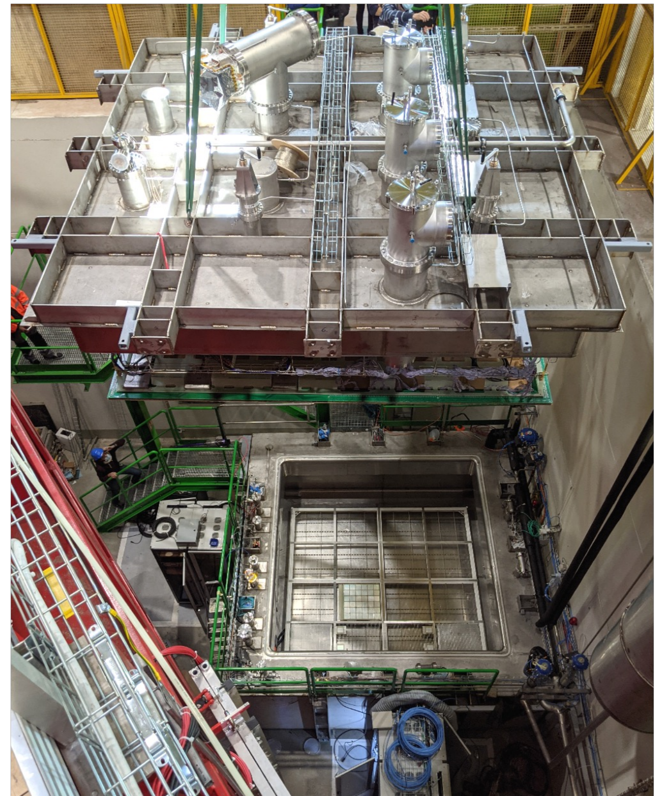
ProtoDUNE-II HD assembly



ProtoDUNE-HD-Module 0	2022										2023						
	March	April	May	June	July	August	September	October	November	December	January	February	March	April	May	June	July
Detector Installation																	
Close TCO and Fill Cryostat																	
Detector Operation (Cosmics)																	
Detector Operation (Beam)																	
FD1 Cold Box Tests																	
APA #1																	
APA #2																	
APA #3																	
APA #4																	

ProtoDUNE – Vertical Drift





FD2-VD	2021			2022				2023				2024		
	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
NP02 HV test														
Cold-box prep														
CB Refurbishment														
CB Dry Run														
Cold-box runs														
CRP #1														
CRP #2														
CRP #3														
CRP #4														
Module-0 components				production										
Module-0 installation							inst.							
Module-0 closing/operation								cleaning/TCO/CRYO				OPS		

Fermilab DUNE

Contributions

2020 Update of the European Strategy for Particle Physics

European Strategy Update

Major developments from the 2013 Strategy

B. The existence of non-zero neutrino masses is a compelling sign of new physics. The worldwide neutrino physics programme explores the full scope of the rich neutrino sector and commands strong support in Europe. Within that programme, the Neutrino Platform was established by CERN in response to the recommendation in the 2013 Strategy and has successfully acted as a hub for European neutrino research at accelerator-based projects outside Europe. ***Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).***

Collaboration Demographics

International Collaboration

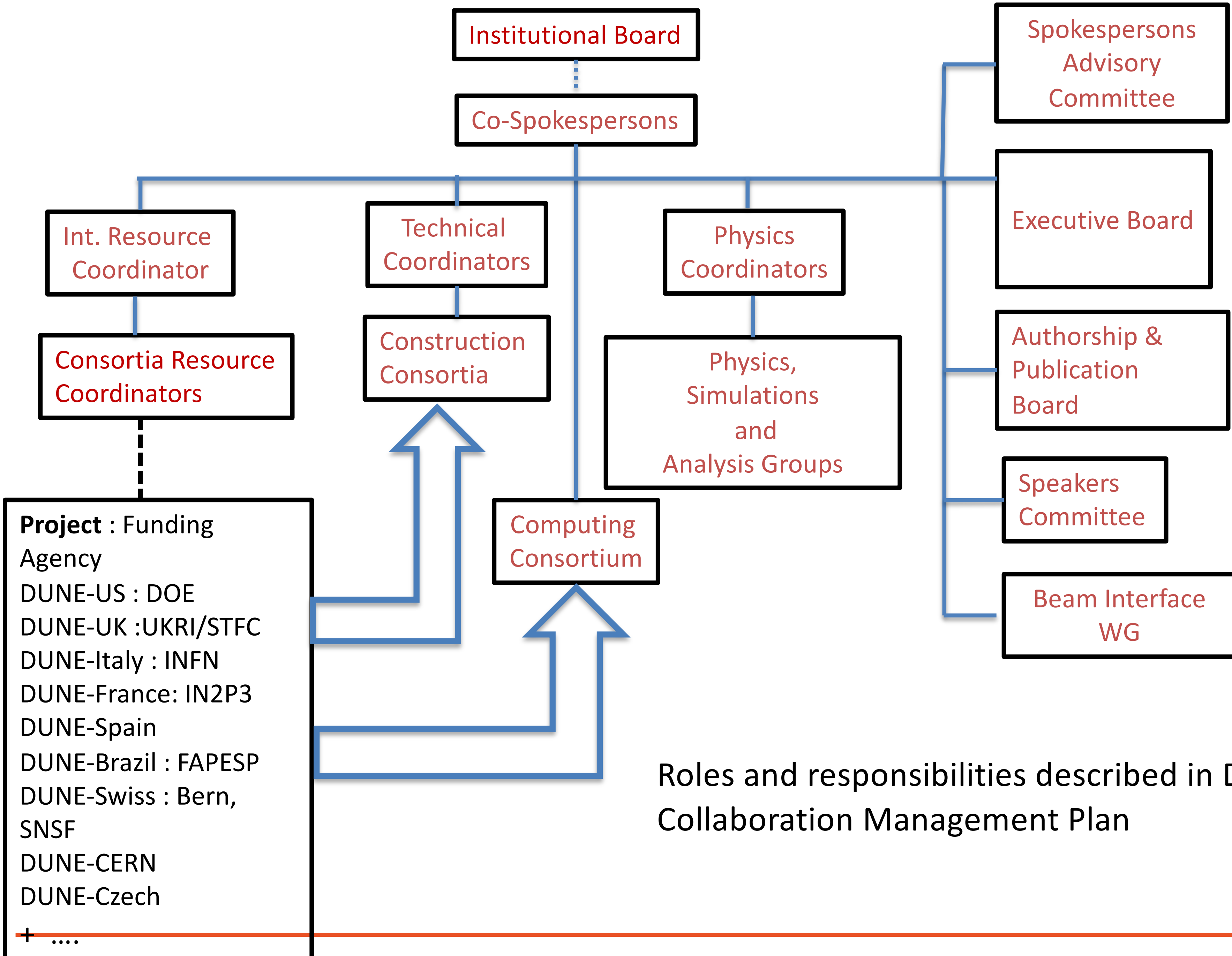
Position	In Collaboration		Effort on DUNE	
	2021	2020	2021	2020
Faculty	654	676	195	200
Post Docs	249	240	79	77
Graduate Students	324	319	109	104
Engineers, CP	164	158	54	67

DUNE-US

Position	In Collaboration		Effort on DUNE	
	2021	2020	2021	2020
Faculty	291	298	85	90
Post Docs	127	123	37	35
Graduate Students	143	146	44	38
Engineers, CP	88	85	35	41

2021 effort reporting just completed.
Effort reporting topics are completely aligned with Collaboration Organization, hopefully leading to more meaningful and accurate results

DUNE Collaboration Organization



Roles and responsibilities described in DUNE Collaboration Management Plan

International DUNE Detector Construction Consortia

Near Detectors

ND-LAr

SAND

Data Acquisition
FD1, FD2, ND

Far Detectors

Anode Plane Assemblies - FD1

Charge Readout Planes - FD2

High Voltage
FD1, FD2

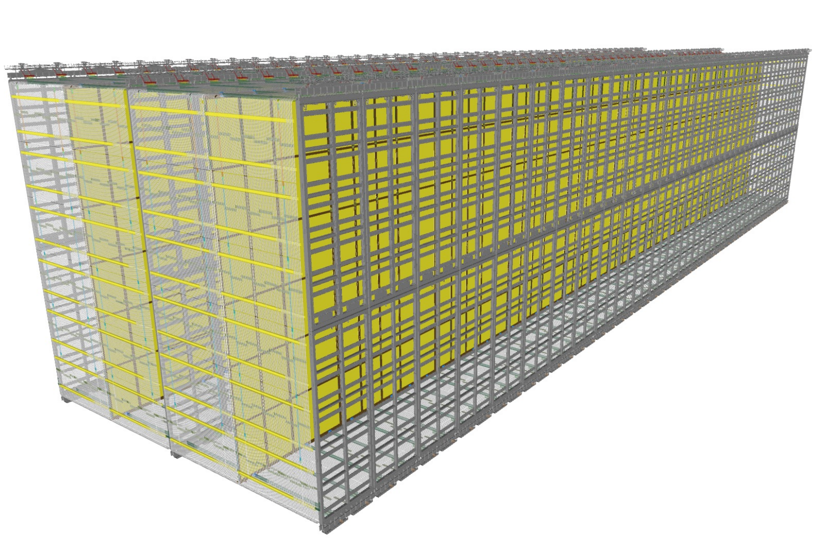
TPC Electronics
FD1, FD2-B

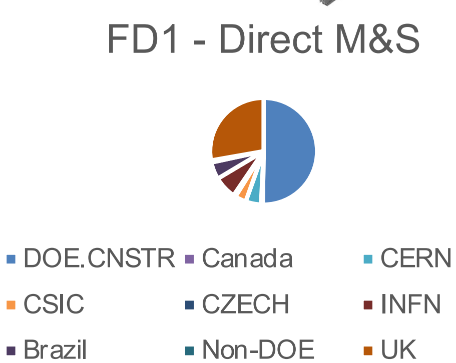
Electronics
FD2-T

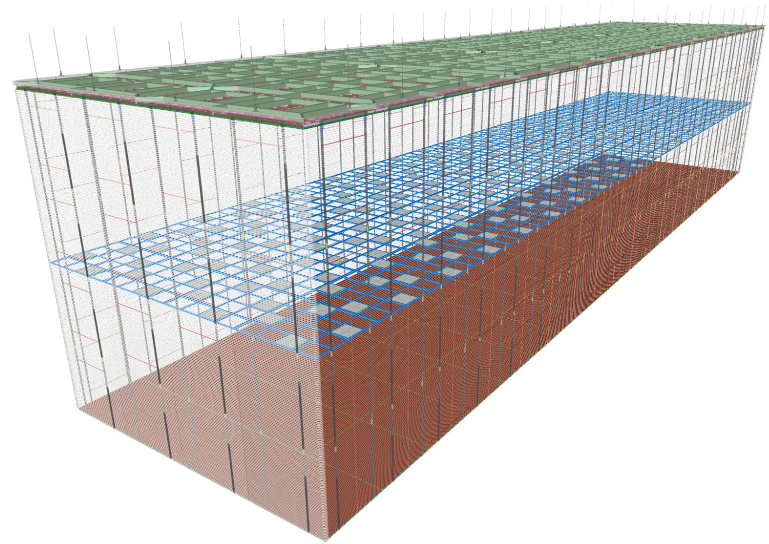
CALCI
FD1, FD2

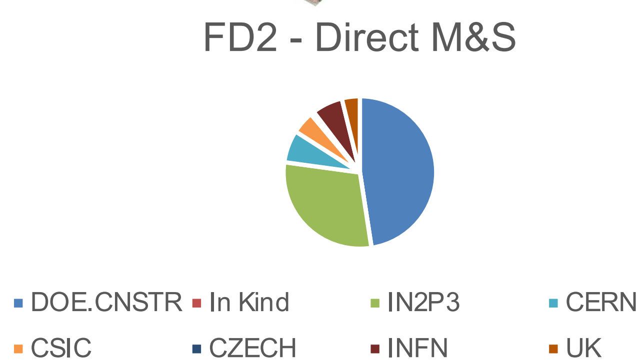
Photon Detection
FD1, FD2

International Contributons

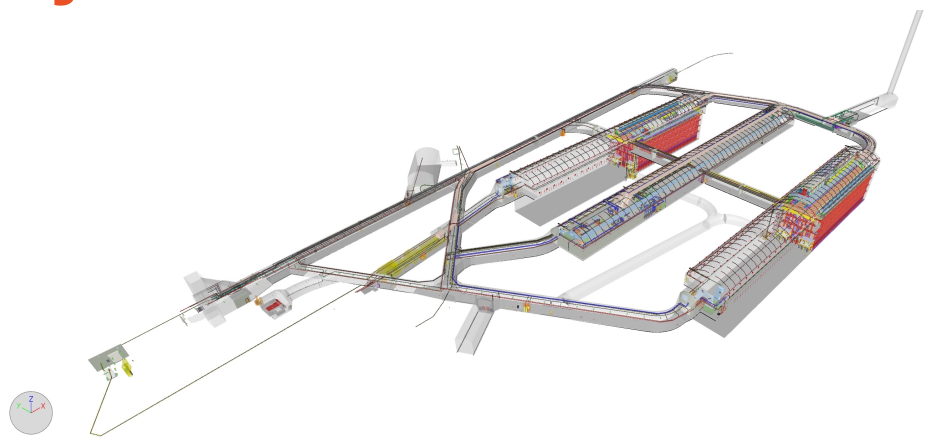


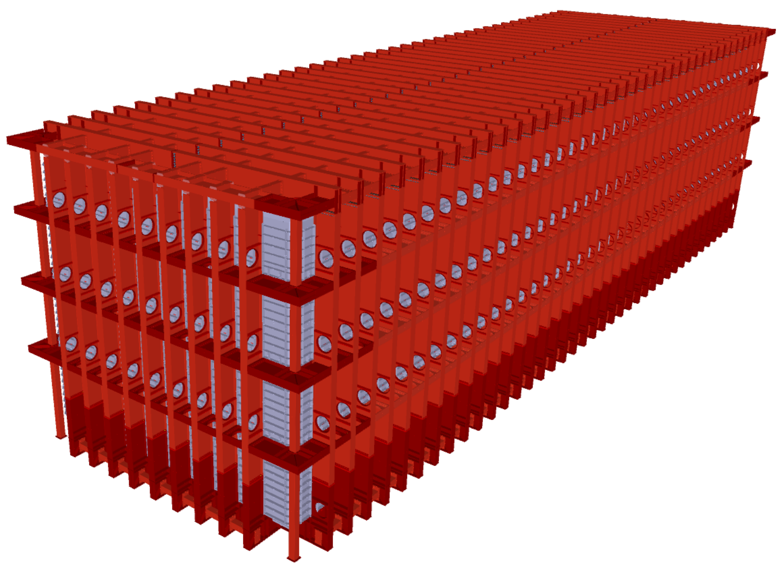


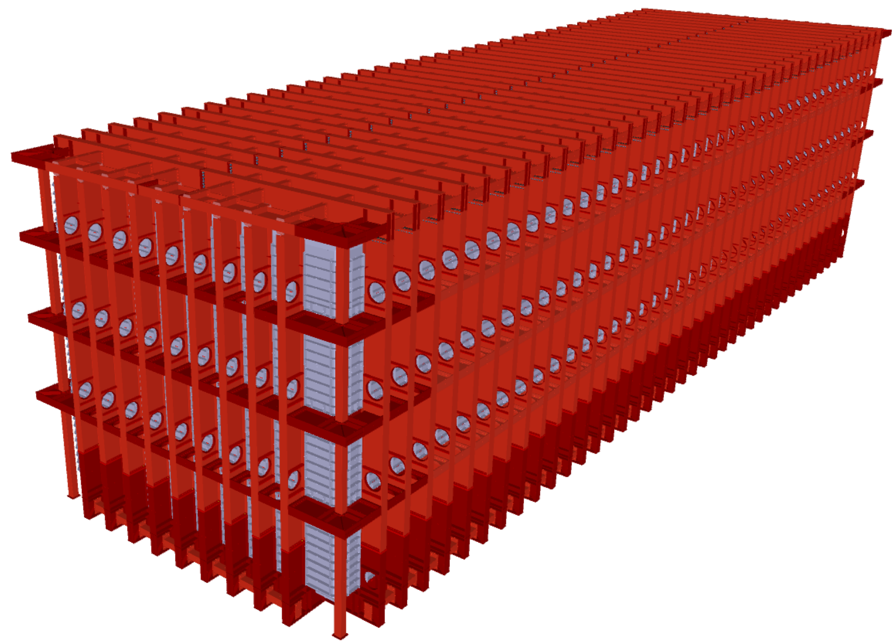




Two Cryostats for the facility

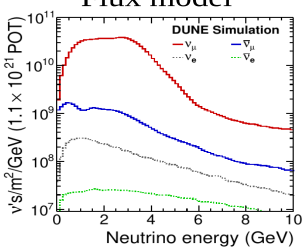




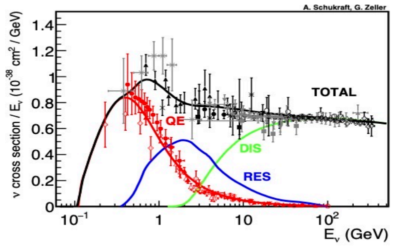


Key components of the long-baseline oscillation analysis

Flux model



X



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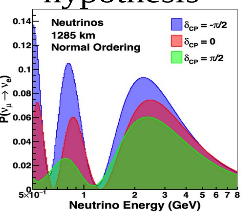
Oscillation hypothesis



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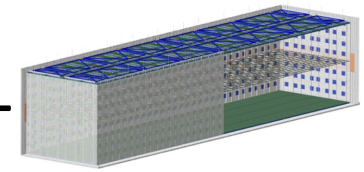
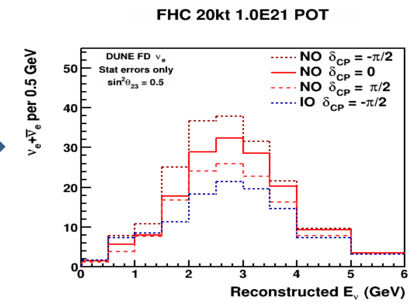
Detector Model

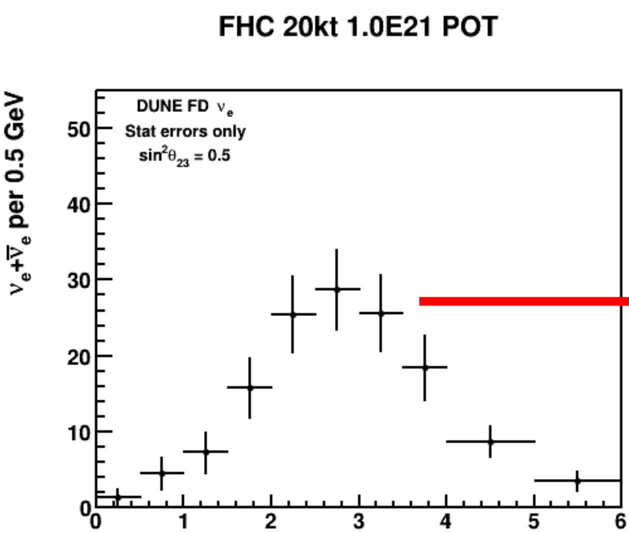


Use simulations to predict spectrum at far detector



Eventually do the experiment and collect data

Fit the data to the prediction to extract an unknown parameter



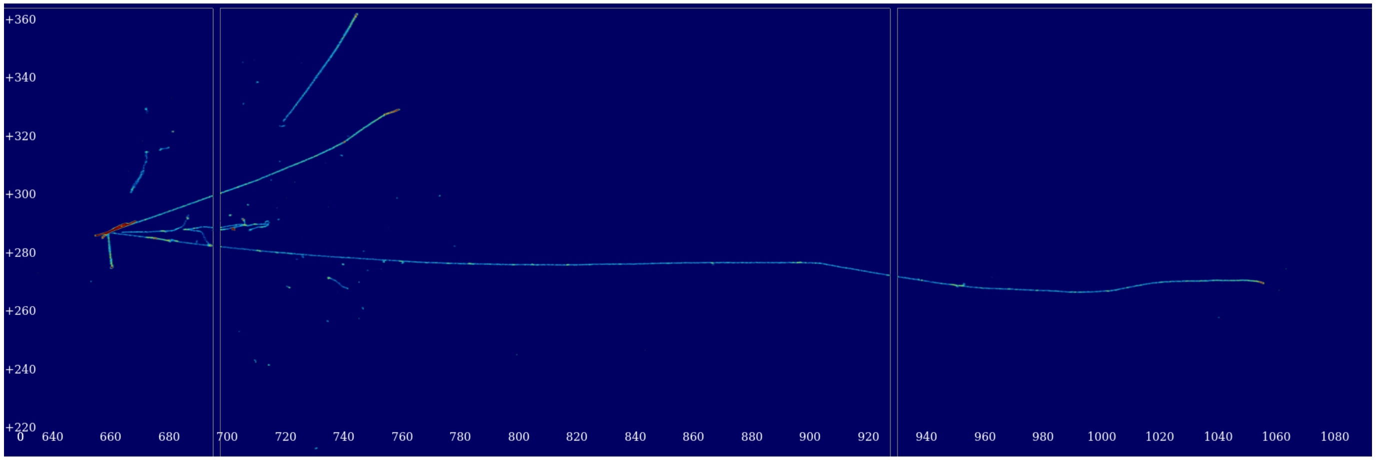
Reconstructed ν energy

$$\Delta\chi^2(\delta_{CP}) = 2\sum_{i}^{N_{bins}}\left[N_i^{pred}(\delta_{CP}) - N_i^{obs} + N_i^{obs}\ln\left(\frac{N_i^{obs}}{N_i^{pred}(\delta_{CP})}\right)\right]$$

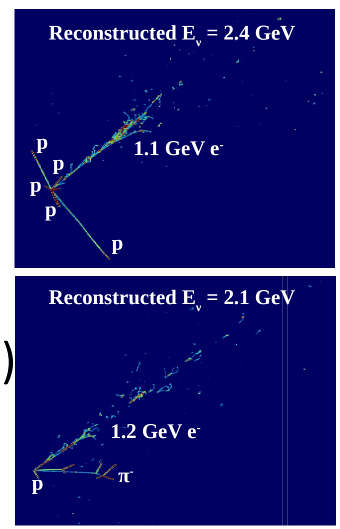
How do we make the prediction?

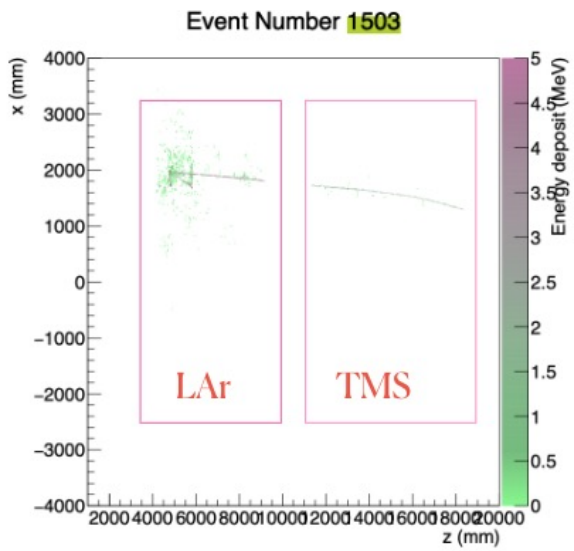
Important role of ND

- Far detector events come in all shapes and sizes; in general within a well defined fiducial volume they are fully contained; never-the-less they are challenging to reconstruct as there are missing particles (neutral) which led to mis-reconstructed energy



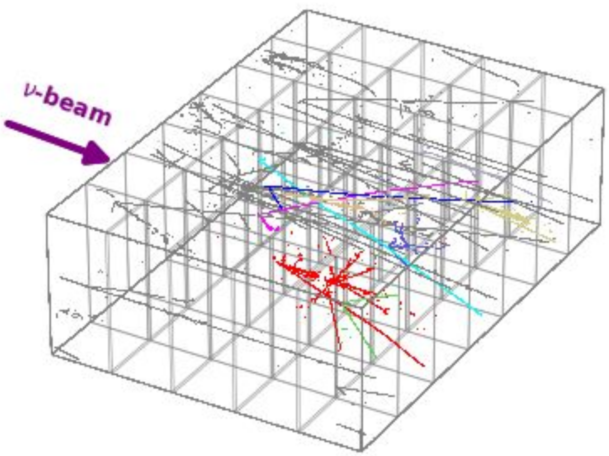
By having a ND functionally same as FD, we get equivalent reconstructed E_ν
(Left : True 2.5 GeV ν)

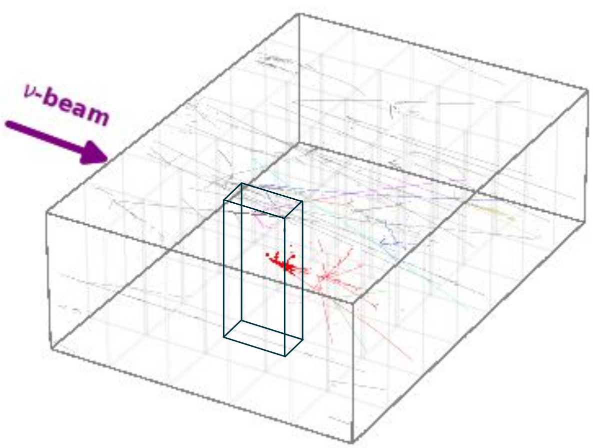




But we can't build a ND of similar size as the Far Detector,
we measure the muons with a supplementary muon monitor

Complications in the Near Detector





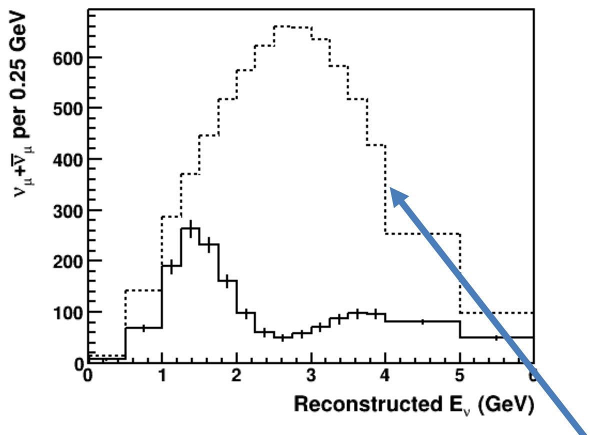
- Due to the high intensity of the 10μs spill the neutrino interactions "pile-up" on themselves, making it difficult to reconstruct individual interactions
- This problem is mitigated by constructing the detector in modules to minimize overlaps
- Pixel readout and modular light collection are used to match tracks and light to individual events

PRISM technique in Long Baseline data taking and analysis :

Traditionally : use on-axis near detector to PREDICT an un-oscillated spectrum at the Far Site

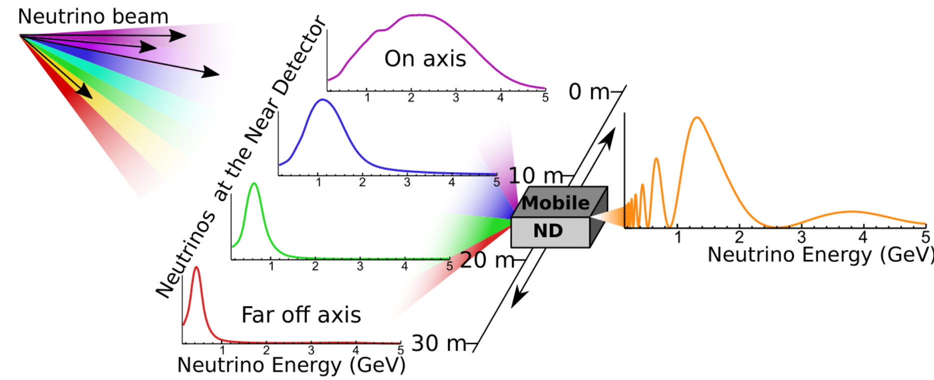
FD DATA

27E20 POT FHC

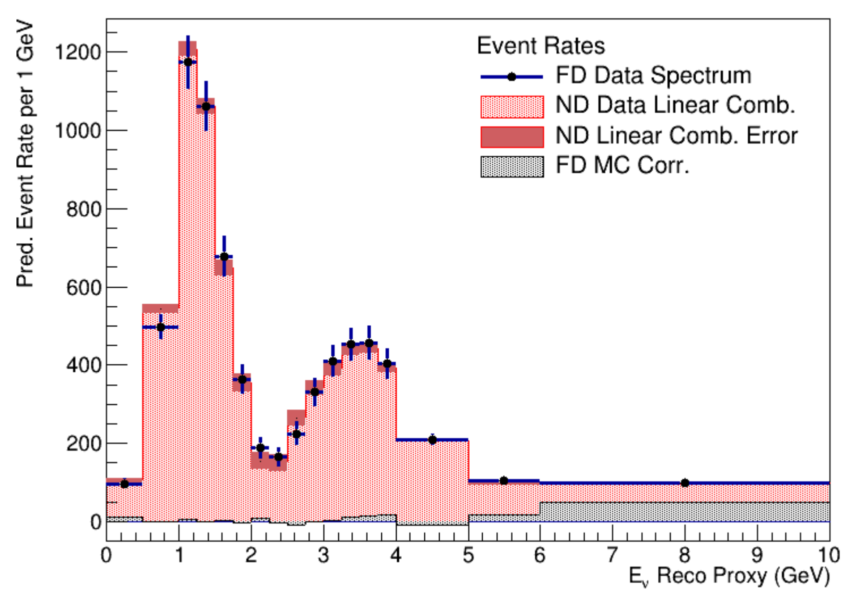


Un-oscillated MC prediction ~ on-axis near detector spectrum

DUNE PRISM



PRISM FD Prediction



Fermilab DUNE

The Near Detector Challenge

- In February 2022, DOE/HEP gave guidance to the DUNE-US Near Detector sub-project that the DOE contribution to the Near Detector would be capped at $200M, including all costs to date ($23M as of March 2022)
- Additionally, the estimate to complete needed to be separated into what is needed to deliver threshold KPPs, and objective KPP's, such that there would be 50% scope contingency (~$90M) in the objective KPP
- The sub-project has addressed these constraints by defining the threshold KPP as the capability to monitor the neutrino beam such that far detector data could be collected and deemed stable for physics analysis; and that this can be achieved with the muon spectrometer (TMS), the downstream component of the LArTPC detector
- The liquid argon TPC itself is in objective scope, and the sub-project and the DUNE collaboration are working together to find a way to "stay in the cost box"

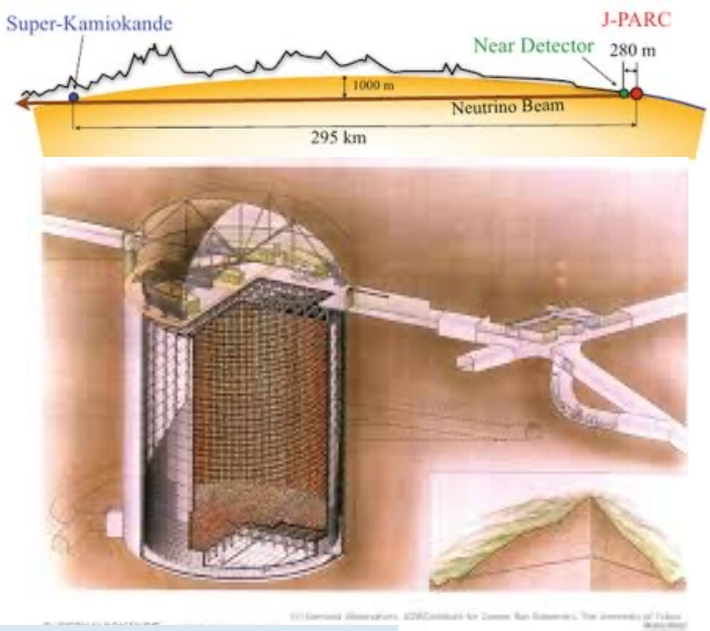
The take-away

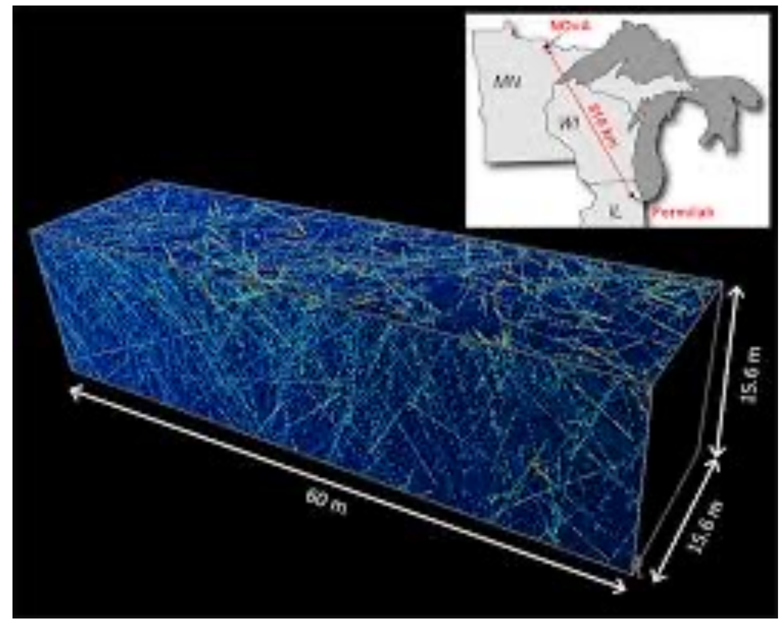
- Far detectors → statistics
- Near detectors → control systematics
- Statistics + controlled systematics → **Precision** Physics

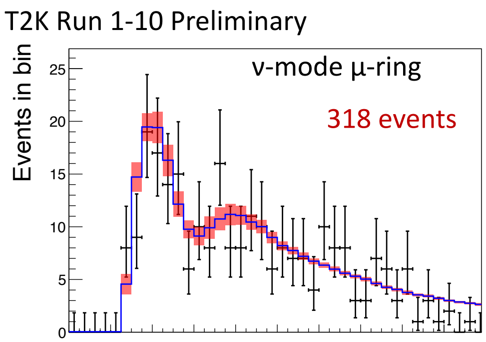
What physics results will we have before DUNE?

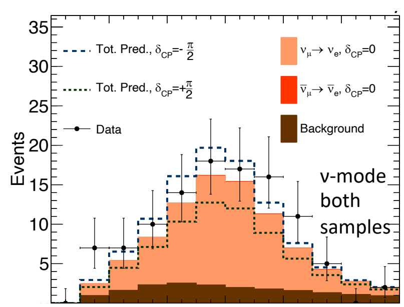
- T2K and NOvA cannot reject the CP conservation hypothesis definitively and will not precisely measure δ_{CP} , but they can give indications that CP is violated
- Mass ordering is not resolved with T2K or NOvA, but the joint fit may have some sensitivity
- The Jiangmen Underground Neutrino Observatory in China (JUNO) is expected to come on line in the next few years
  - Follow-on experiment to Daya Bay
  - 20 kTon liquid scintillator, 700-m underground, detecting reactor anti-neutrinos
  - Goal is precision measurements of θ_{12}, Δm^2_{21}, Δm^2_{32} and neutrino mass ordering to 3-4σ with 6 years of data taking
  - With 10 years of data taking, they report sensitivity to past core-collapse supernova, and sensitivity to proton decay.
  - JUNO's success is based on achieving exquisite energy resolution, acknowledged by its proponents to be **extremely challenging**.

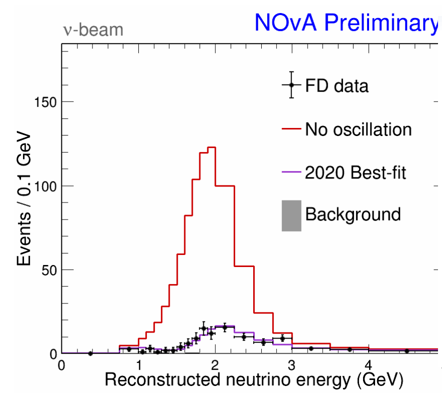
T2K & NOvA Neutrino 2020*

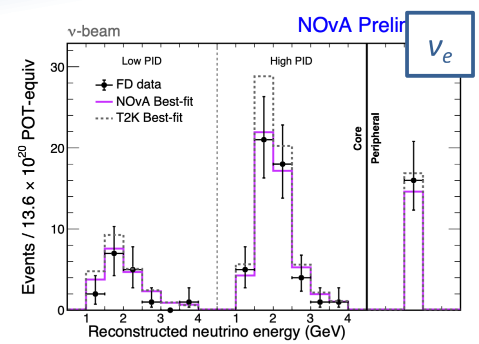








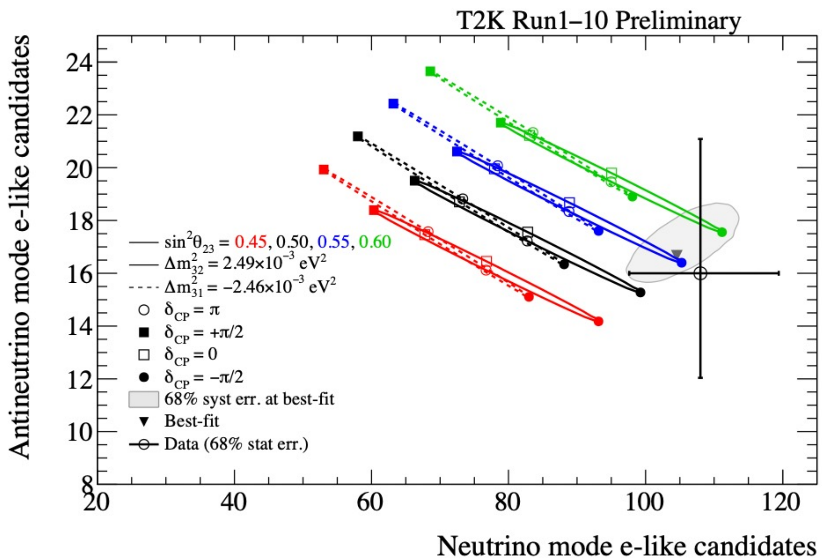


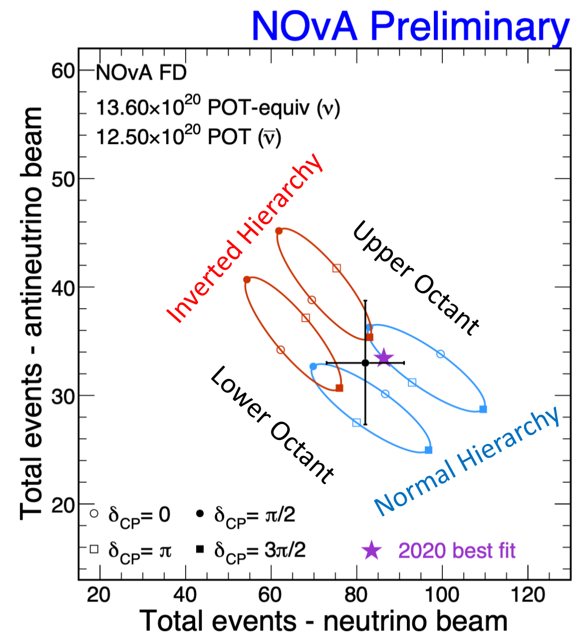


*Neutrino 2022 updates did not include new data ; new analyses were presented

Both experiments will remain statistics limited for their remaining run time

Summer 2020 -> present





- T2K and NOvA continue operations and updated results are expected this summer
  - Two sets of results have different best fit but are not in significant tension
- Both experiments have worked on advanced analysis packages
- The experiments are working on a joint analysis, aiming for later this year
- T2K is installing an upgraded Near Detector and adding new samples to their fit

Hyper-Kamiokande Experiment: A Snowmass White Paper

Contributed Paper to Snowmass 2021

J. Bian,[1] F. Di Lodovico,[2] S. Horiuchi,[3] J. G. Learned,[4] C. Mariani,[3,*] J. Maricic,[4]
J. Pedro Ochoa Ricoux,[1] C. Rott,[5,6] M. Shiozawa,[7,8,9] M. B. Smy,[1] H. W. Sobel,[1], R. B. Vogelaar[3]
(on behalf of the Hyper-Kamiokande Collaboration)
[1] *Department of Physics and Astronomy, University of California Irvine, Irvine CA 92697-4575, USA*
[2] *King's College London, Department of Physics, Strand Building, Strand, London, United Kingdom*
[3] *Center for Neutrino Physics, Virginia Tech, Blacksburg, Virginia 24061, USA*
[4] *Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA*
[5] *Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA*
[6] *Department of Physics, Sungkyunkwan University, Suwon 16419, Korea*
[7] *University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory, Kamioka, Japan*
[8] *University of Tokyo, Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo Institutes for Advanced Study, Kashiwa, Japan*
[9] *University of Tokyo, Next-generation Neutrino Science Organization, Kamioka, Japan*
(Dated: March 7, 2022)

arXiv:2203.02029v1 [hep-ex] 3 Mar 2022

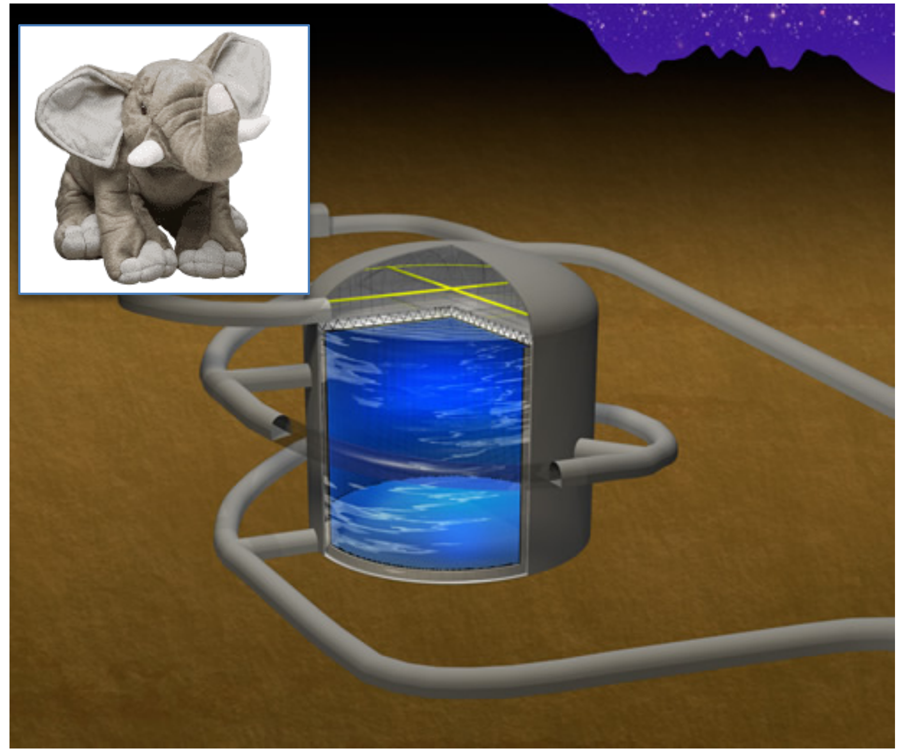
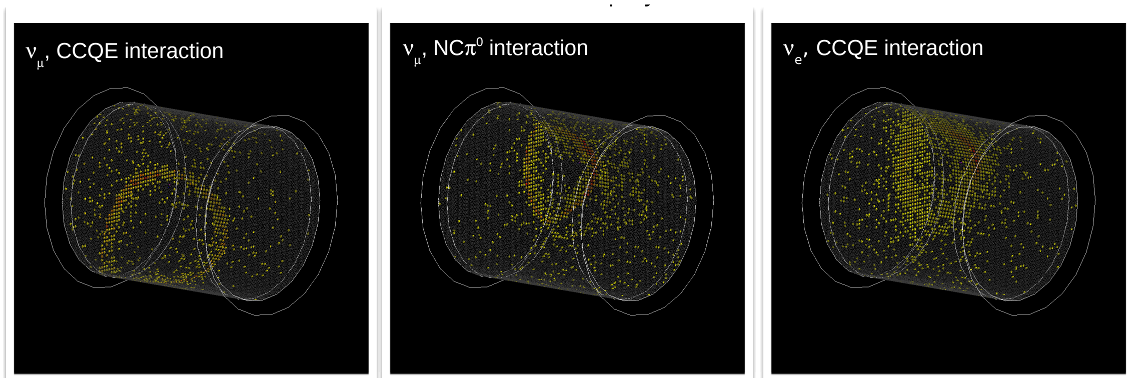


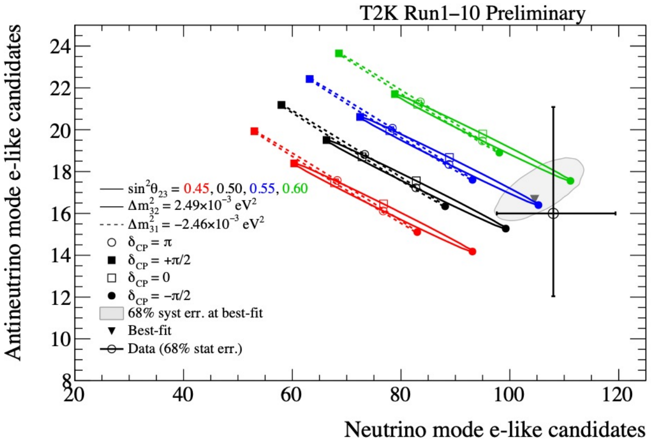
FIG. 1. Illustration of the Hyper-Kamiokande first cylindrical tank in Japan.

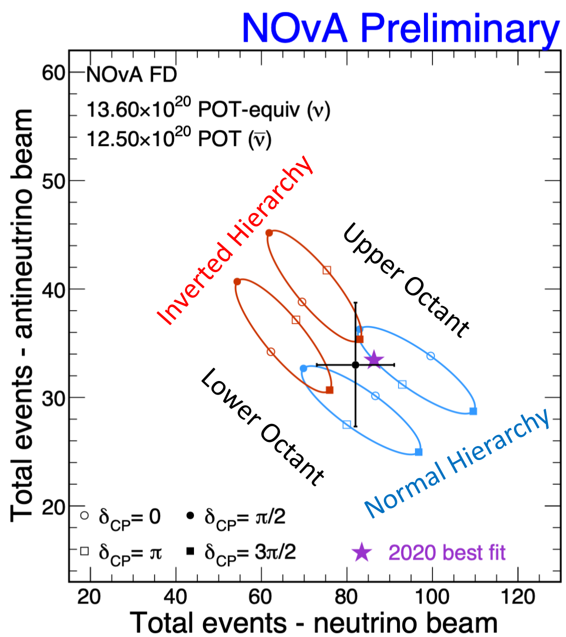
Data taking expected to start in 2027
260 kTon (5x total SK; 8x FV)

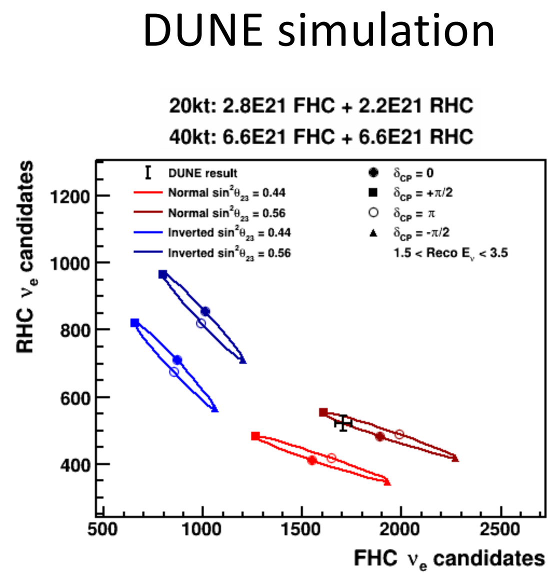
Science program includes :
Accelerator neutrino oscillations,
atmospheric neutrinos, solar and supernova neutrinos, searches for nucleon decay



http://www.hyper-k.org/doc/Hyper-K_FPCP2015.pdf







In Hyper-K only the error bars will shrink

In NOvA these ellipses will always touch each other

In DUNE we have unique Separation of the mass ordering …..

T2K -> Hyper-K :

Same baseline

Same beam spectrum

Same detector technology

From NoVA -> DUNE :

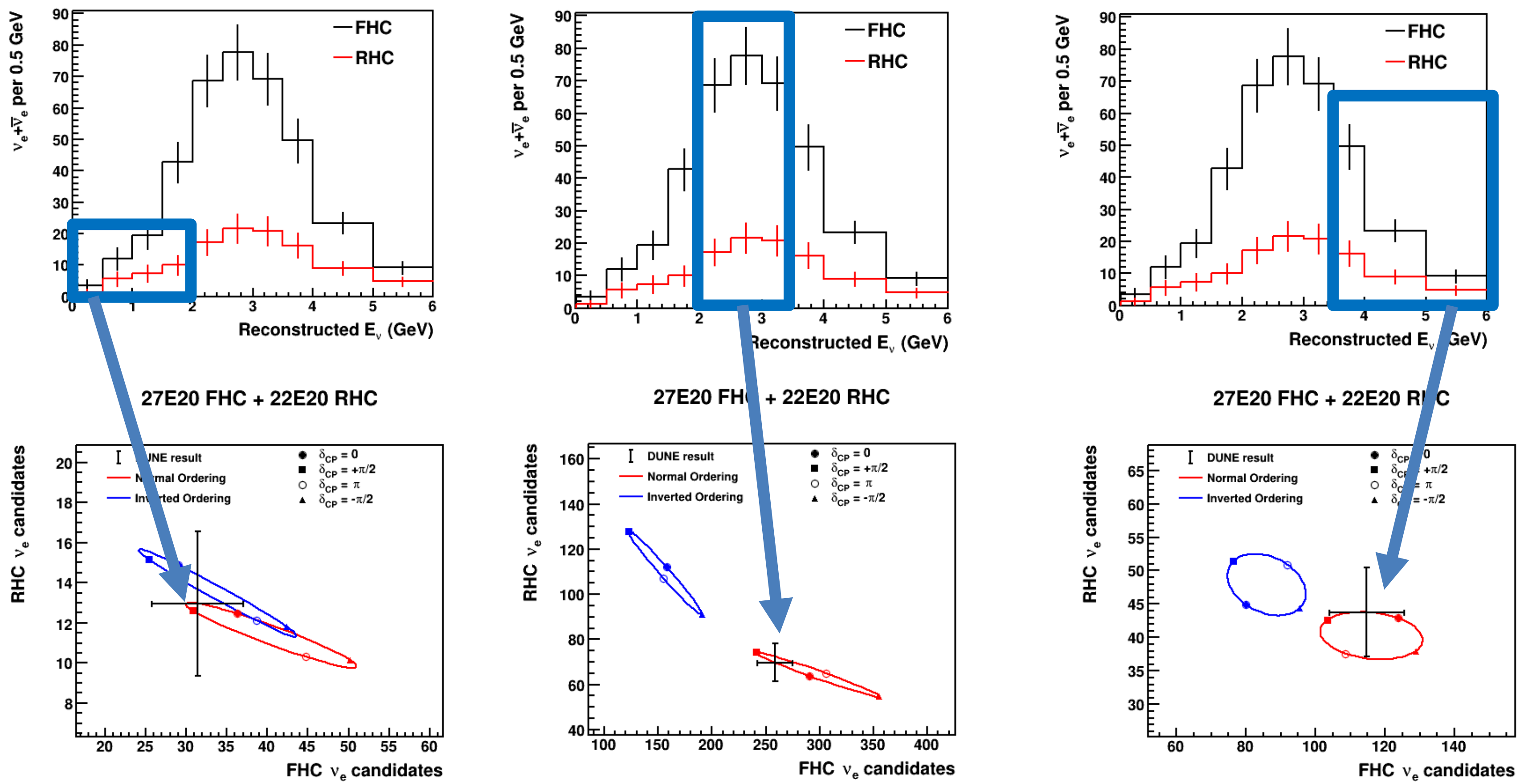
Longer baseline

Wideband beam

Precision detector event reconstruction

..... DUNE : enhanced by the wide-band beam

→ spectrum shape carries information → proper energy reconstruction is essential

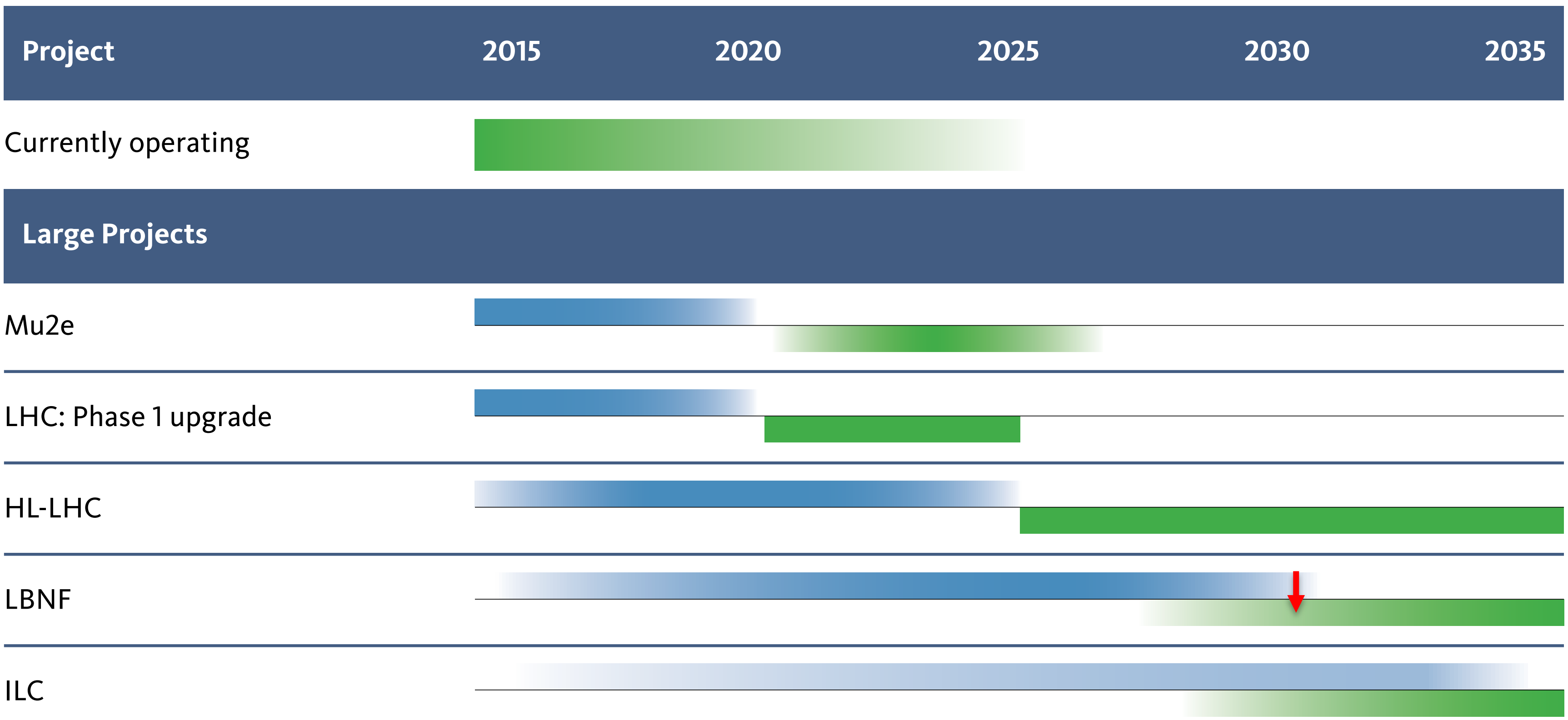


Metric of Capability

- kTon-MW-years is a metric of capability
- In 2015, P5 said to show capability to accumulate an exposure of 120 kTon-MW-years in the 2035 time-fram
- The intent was to evaluate the proton beam power, the detector mass and the timescale :
  - Mass -> 20kT
  - Proton Power -> 1.2 MW
  - Time frame -> 5years
- This would be achievable with a beam start in ~2030

Math to reach 120kT-MW-yrs

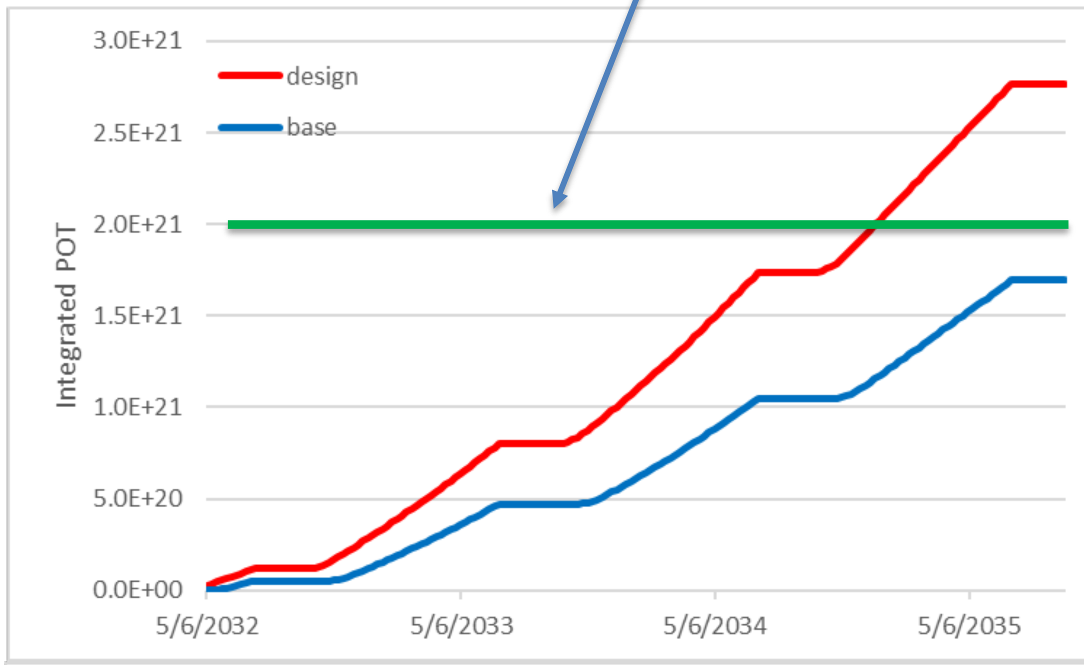
- ~>20 kT operating BEFORE first beam neutrinos
  - Needs 6 MW-yrs
- 1.2 MW in 3 year ramp-up
- 6 – 1.2 = 4.8; 4.8/1.2 = 4 yrs
- 1st neutrinos in ~2030 -> 120 kT-MW-yrs by 2037



Proton power ramp-up

- The base assumes uptimes for :
  - PIP – II = 90%
  - Recycler, MI = 85%
  - Switchyard 120 = 10%
  - LBNF beamline = 70%

1.2MW @ 100% efficiency=
2e21 pot/year



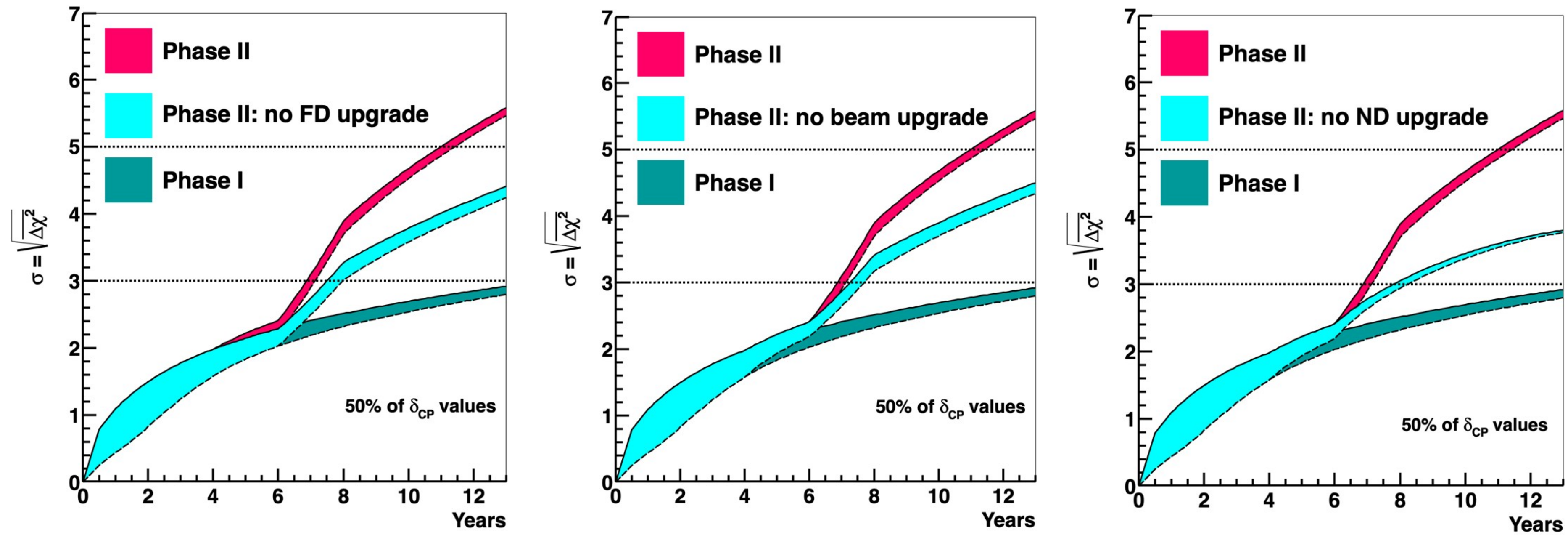
This 3-yr ramp-up is equivalent to
one year of operation at 1.2MW from Day 1

Physics sensitivities are always based on the integrated POTs

Comparison of DUNE with the "competition"

- DUNE and Hyper-K
  - Very different parameters in approach to accelerator oscillations:
    - Baseline, beam spectrum and detector technology
  - Observation of supernova in different channels (ν_e-bar vs ν_e)
  - Searches for nucleon decay are in different detection channels
  - Very different systematics in the two experiments
  - Complimentary verification of important science measurements is essential
- Experiments with sensitivity to the mass ordering
  - JUNO, IceCube, KM3Net, along with NOvA and T2K, will try to measure the mass ordering, but the results depend on the kindness of nature
- DUNE is the only experiment that is guaranteed to independently measure the mass ordering and δ_{CP} in the same experiment
- DUNE will make precision measurements of the full PMNS framework!
- We look forward to emerging results over the coming decade !

Evolution of DUNE

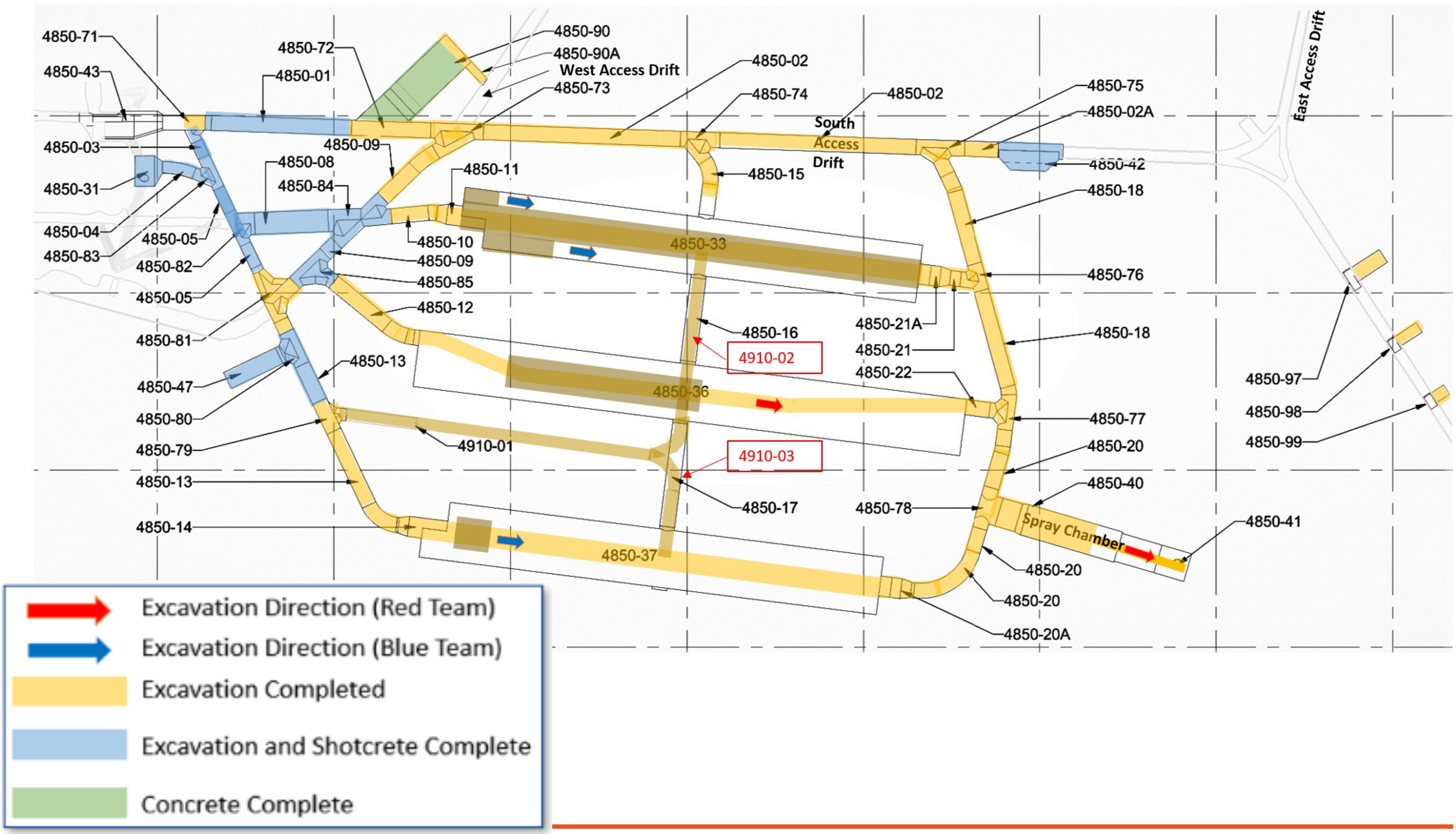


- Three components : detector mass, improved systematics, beam power
- Each ~ worth a factor of 2 in sensitivity (2 statistical, 1 systematics)
- We look forward to discussions at Snowmass and with P5

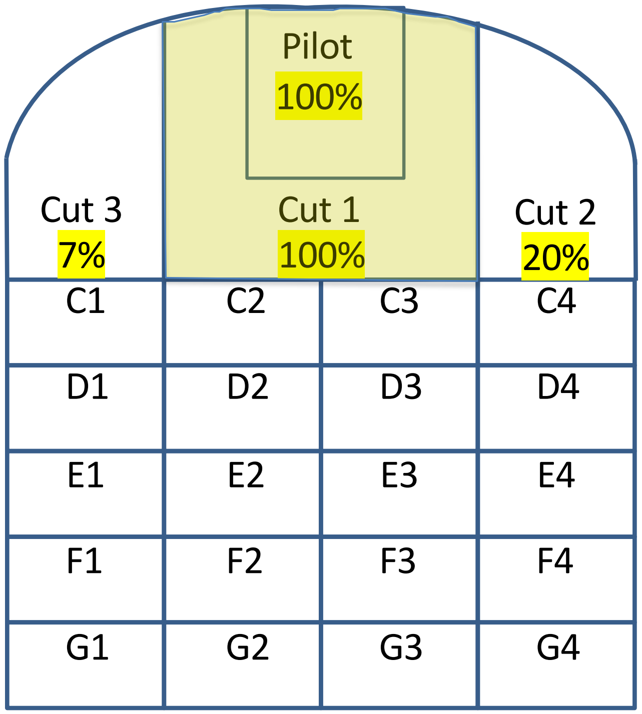
Status of LBNF

Far Site

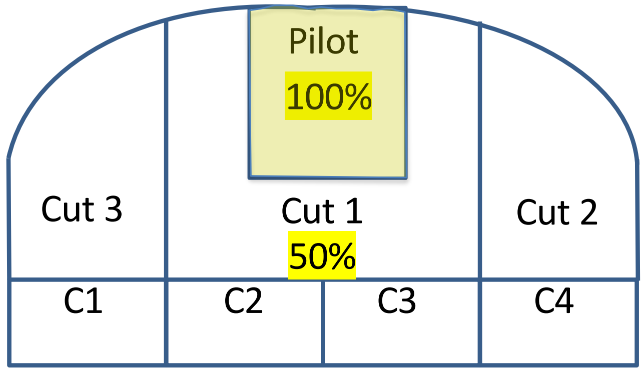
Total Excavated Rock (In-Situ YD³) to Date 30.4% as of 13 Jun 2022

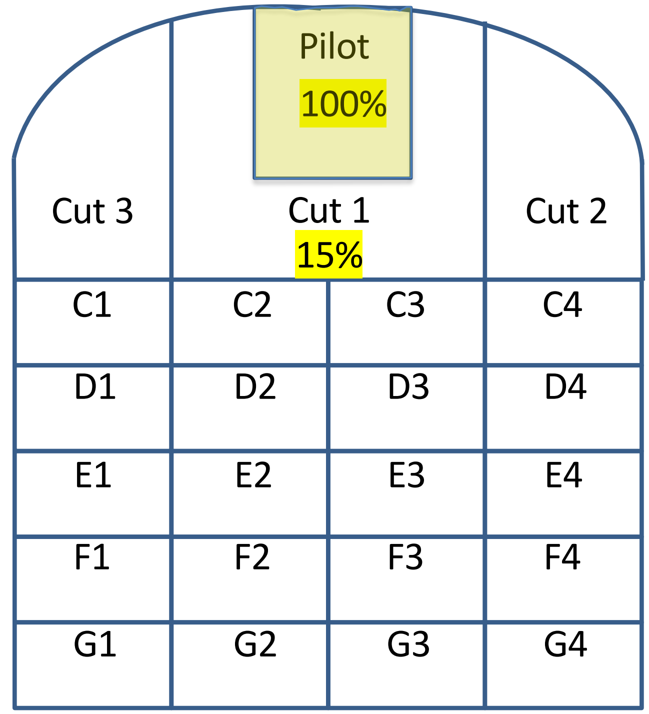


Cavern Excavation Completion Percentage (as of 13 June)



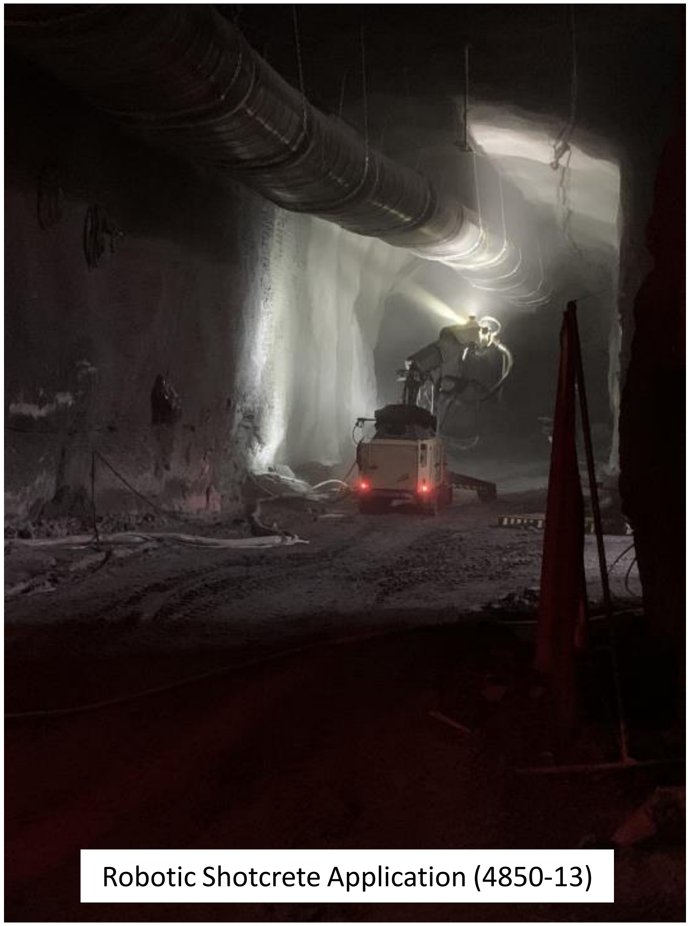
North Cavern



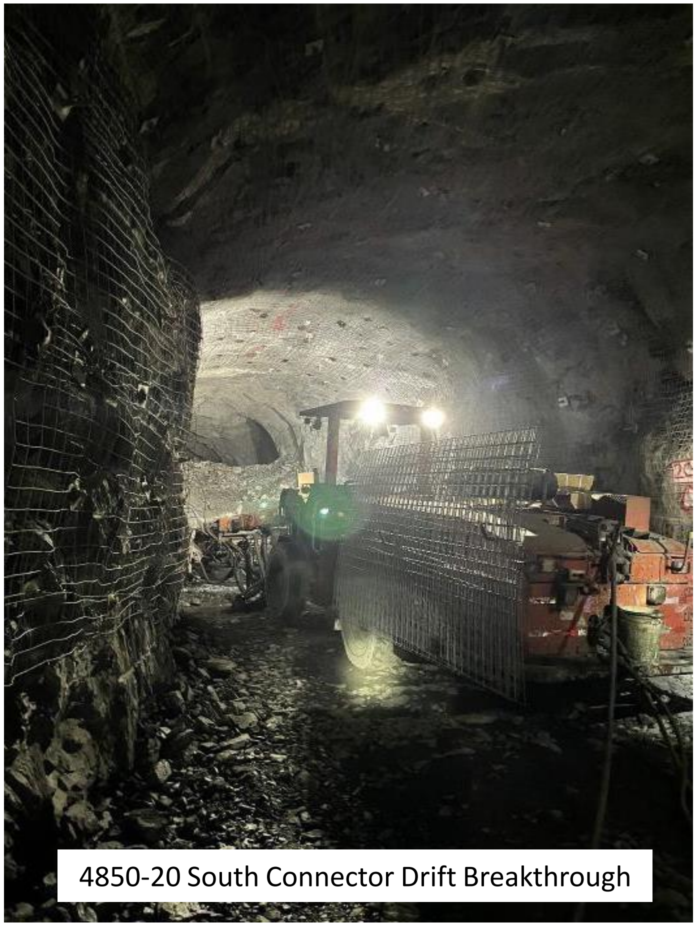


South Cavern

Excavation Progress – Supporting Access Drifts


Robotic Shotcrete Application (4850-13)

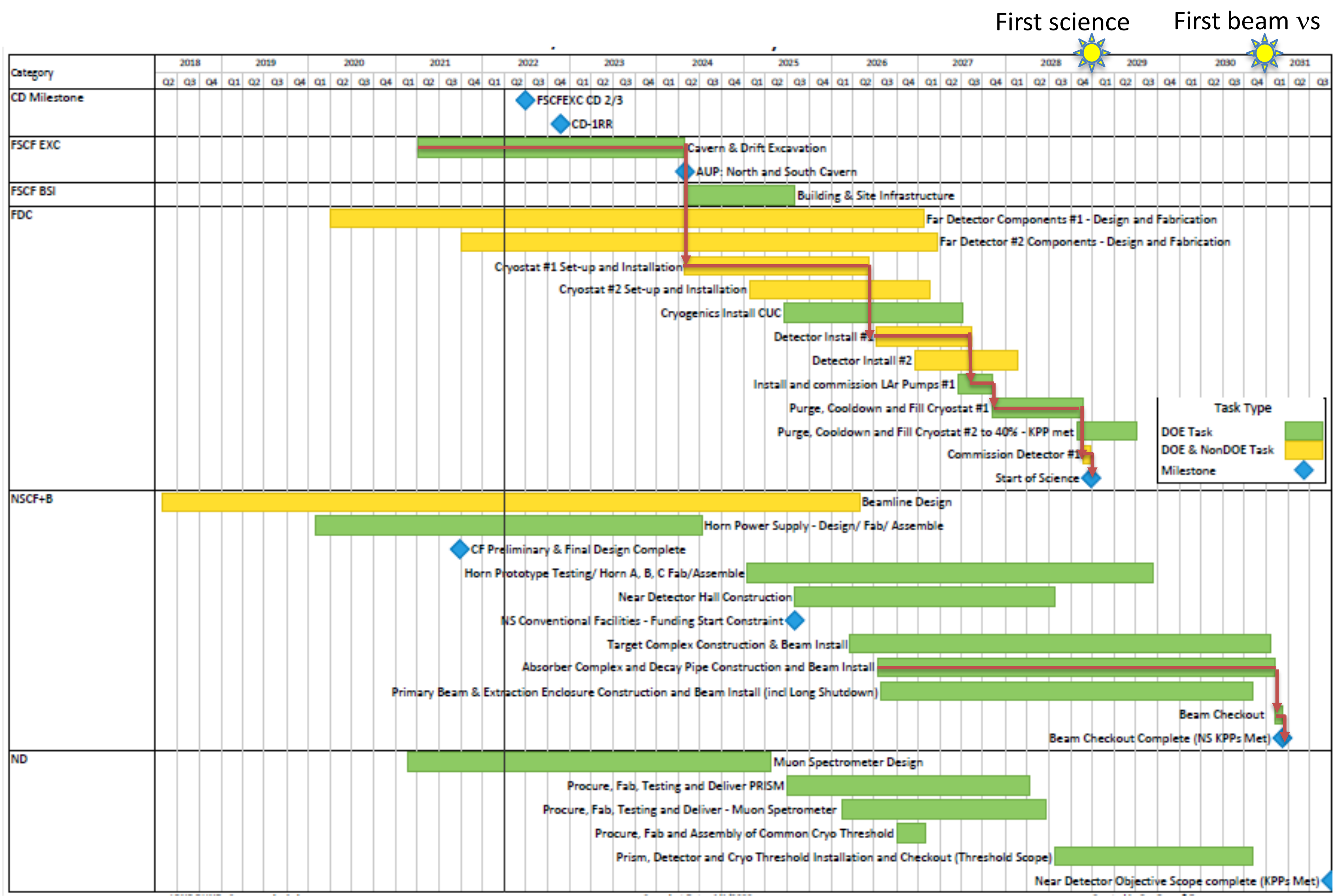

4 CY LHV Mucker moving through expanded drift


4850-20 South Connector Drift Breakthrough

Upcoming Project Reviews

REVIEW/MEETING	PROJECT PLANNED DATE
LBNF/DUNE-US CD-1RR Director's Review	23-27 May 2022 ✅
LBNF/DUNE-US CD-1RR DOE IPR	11-15 July 2022
FSCF-BSI CD-2/CD-3 Directors Review (includes also CD-3a for FDC and NSCF+B)	20-22 September 2022
FSCF-BSI CD-2/CD-3 DOE IPR (includes also CD-3a for FDC and NSCF+B)	15-17 November 2022

Schedule Summary With Critical Paths through Start of Science (FD1) and Beam-on



Notes:
- March 2022 reporting cycle
- Based on "CD-1RR" profile

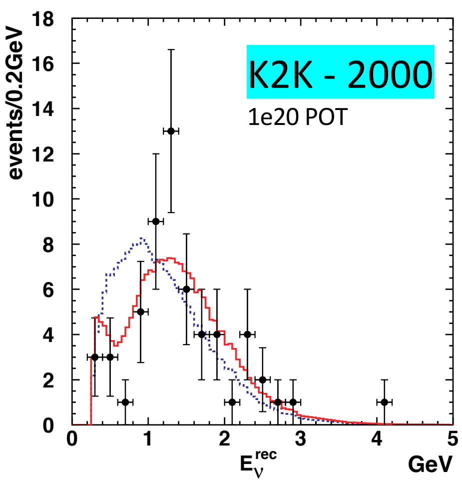
Summary

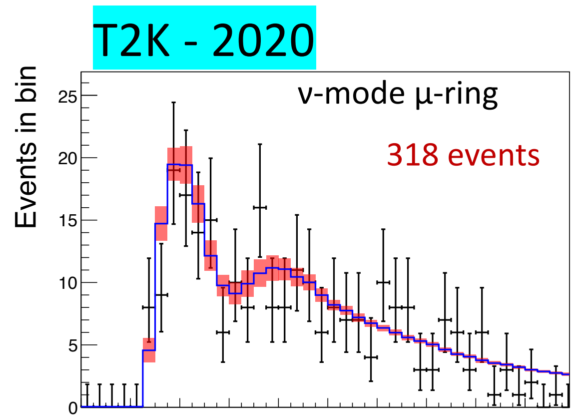
- The 2014 P5 model for an international effort to explore the neutrino sector and more, hosted in the United States, has found reality in the LBNF/DUNE enterprise.
- The commitments of international partners to the facilities of PIP-II and LBNF and the DUNE detectors are very significant; the 2nd cryostat from CERN has enabled the realization of the Phase 1 program with 2 far detector modules – each of which has ~50% contributions from non-DOE sources and a capable Near Detector complex with major contributions from international partners.
- DUNE will be a best-in-class experiment that will make precision measurements of neutrino parameters, be able to detect supernova neutrinos, search for nucleon decay and physics beyond the standard model.
- DUNE is unique in its approach to making these measurements, with its key features being the long-baseline, wide-band beam and liquid argon detector technology.
- The facilities provided by LBNF are world class and provide opportunities for decades of discovery beyond what we even contemplate today.
- There is **no competition** that can rival this **capability**.

DUNE Collaboration Meeting May 2022

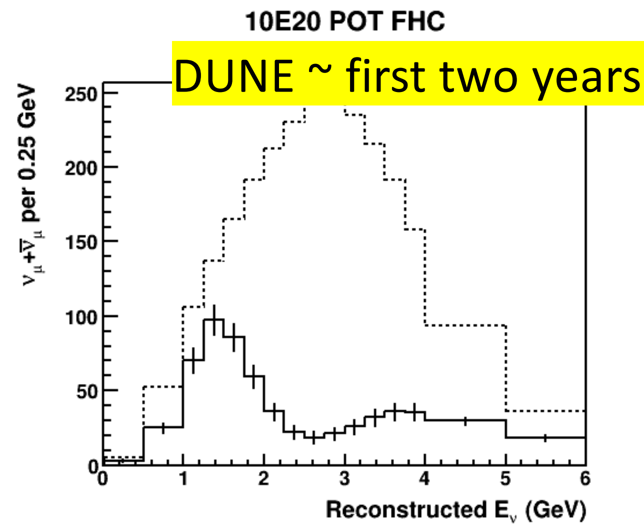
Backup Material for FAQs

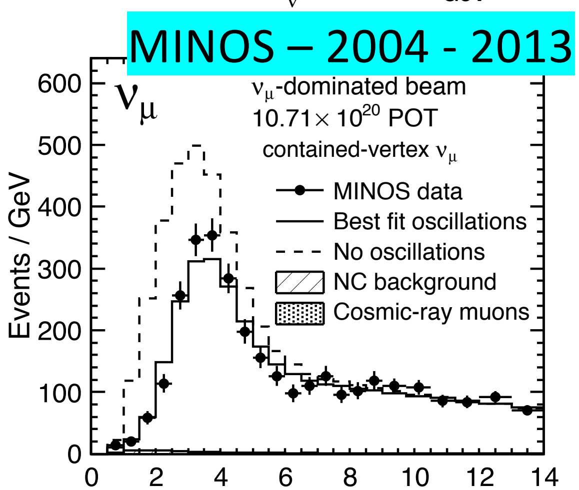
ν_μ disappearance

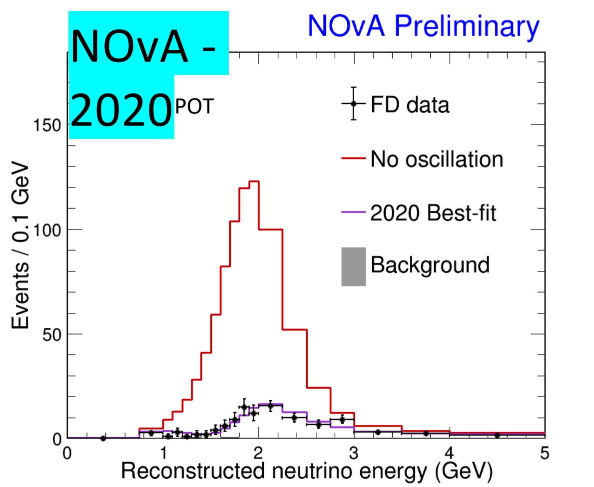




DUNE is a 3rd generation ν_μ disappearance experiment

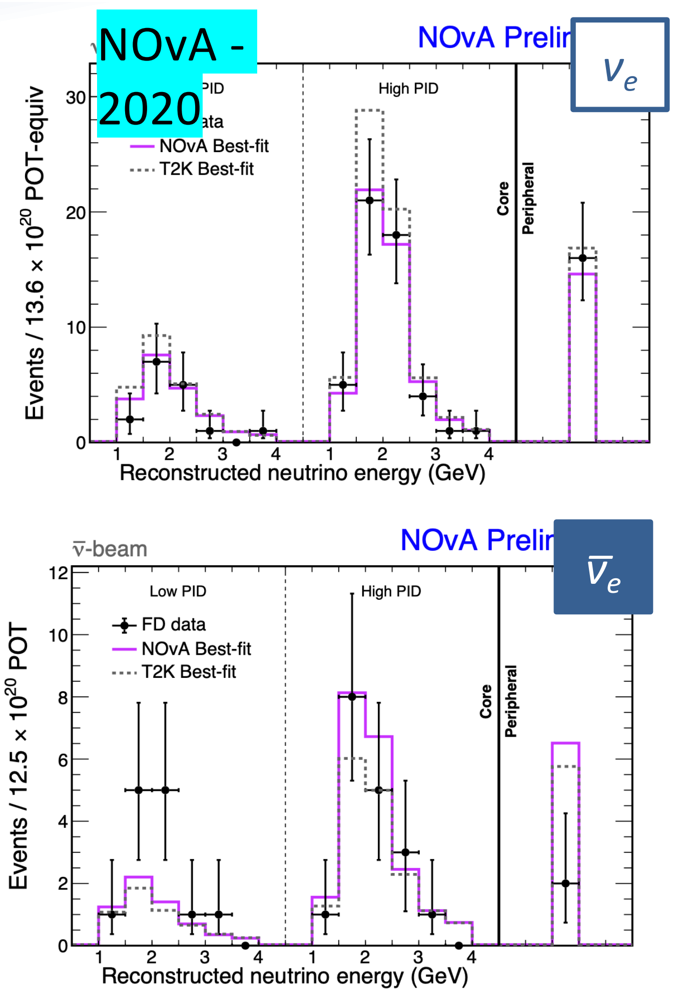


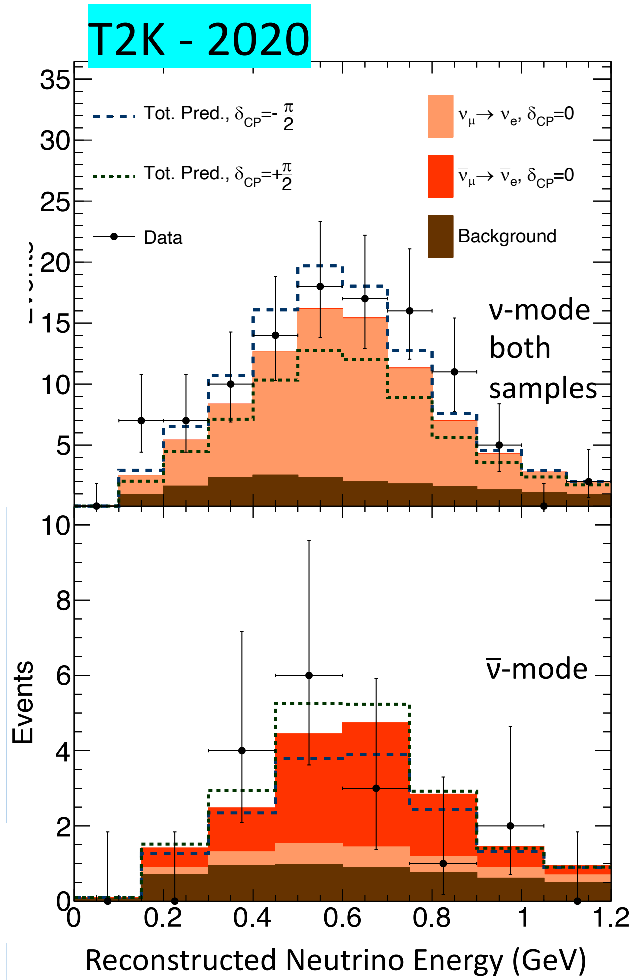




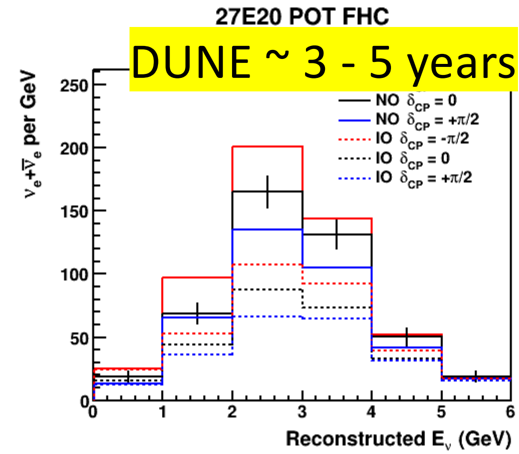
Unprecedented precision achievable in small amount of running time

ν_e appearance





DUNE is a 2nd generation accelerator ν_e appearance experiment



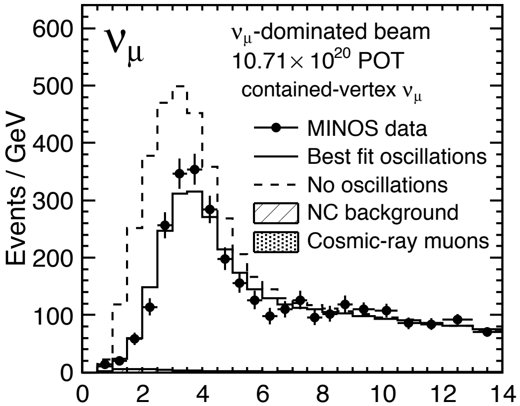
with unique capability to determine the mass ordering

Why 1300 km baseline?

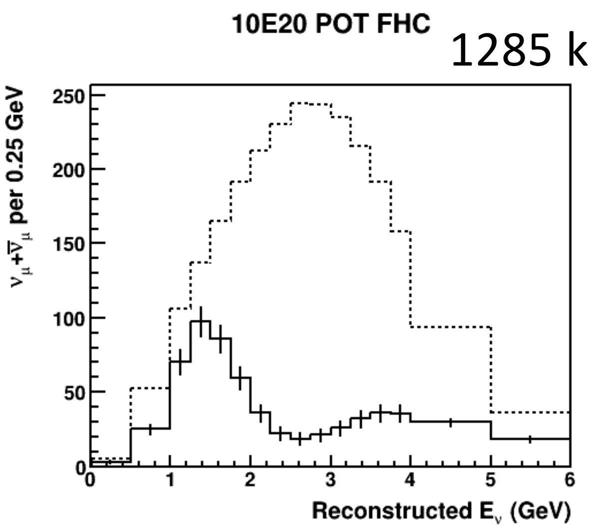
ν_μ disappearance

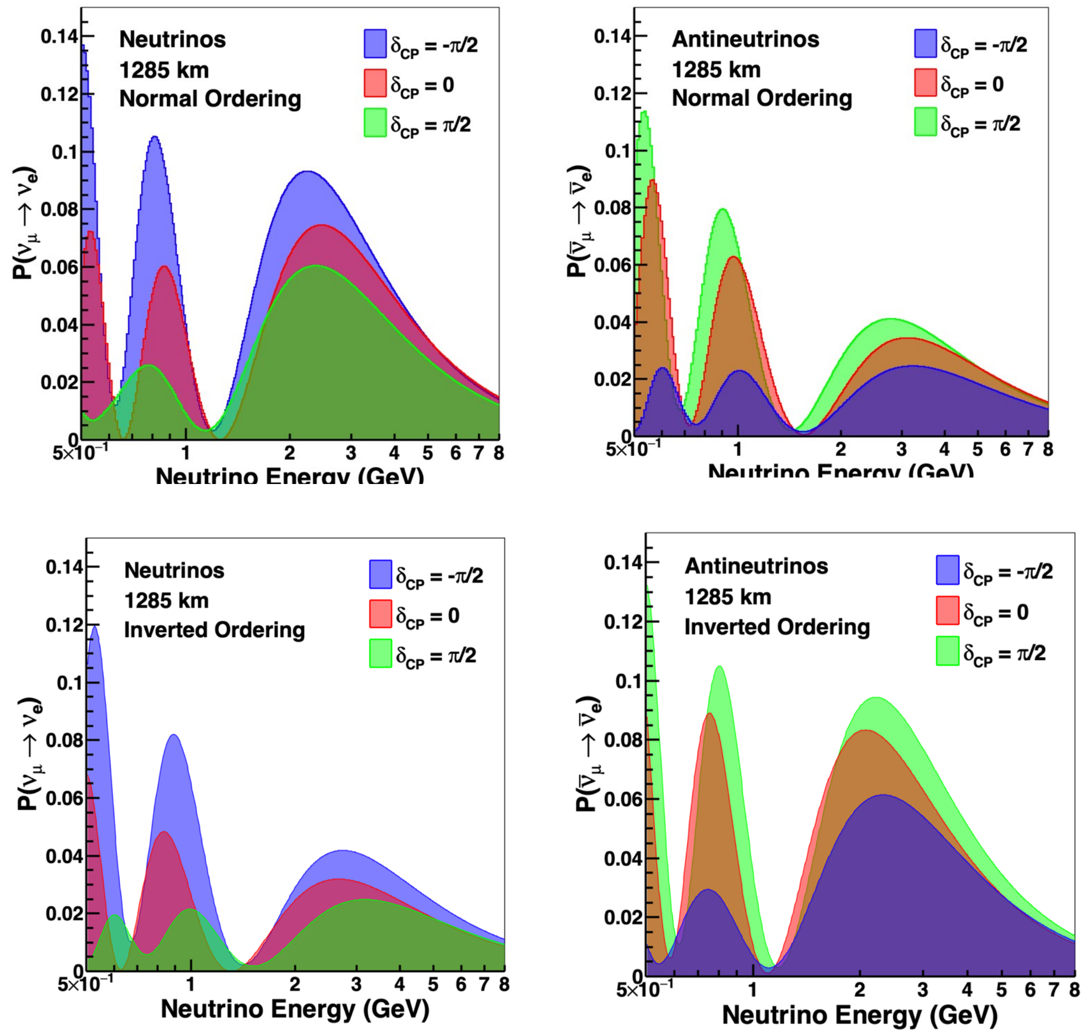
ν_e appearance

735 km

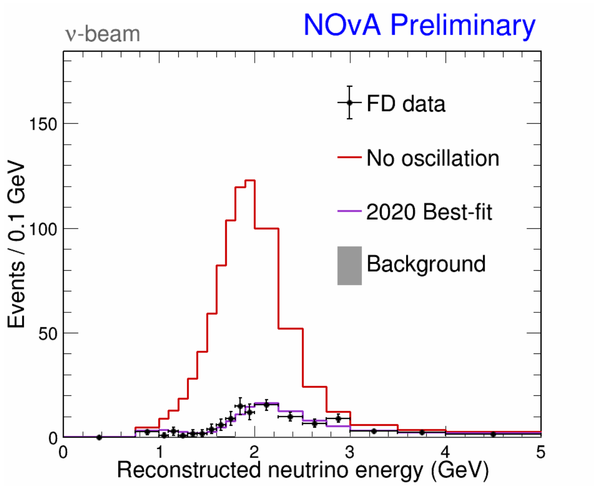


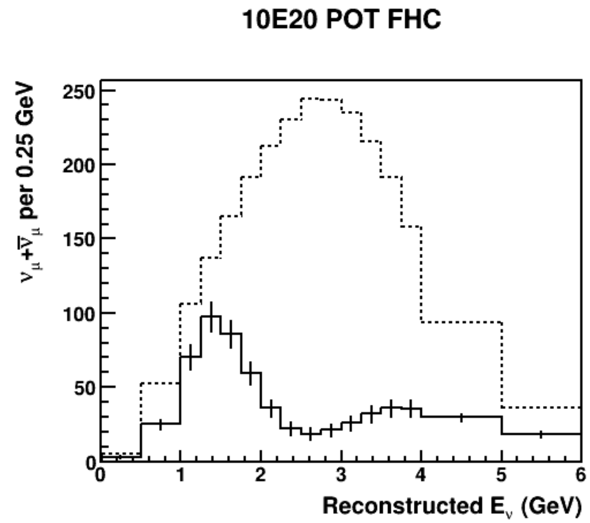
1285 km

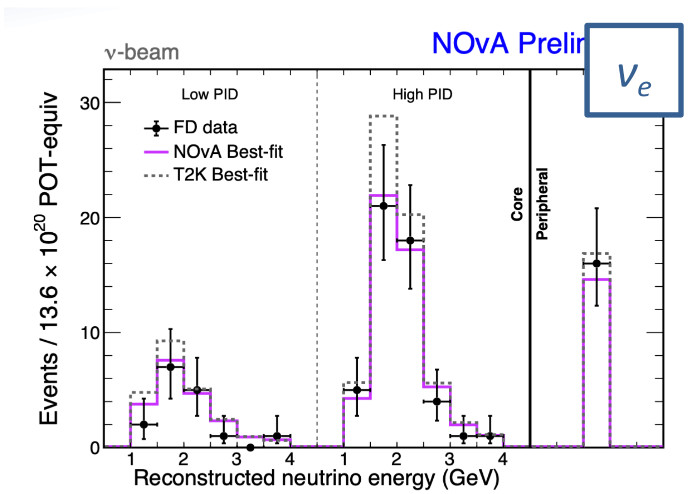




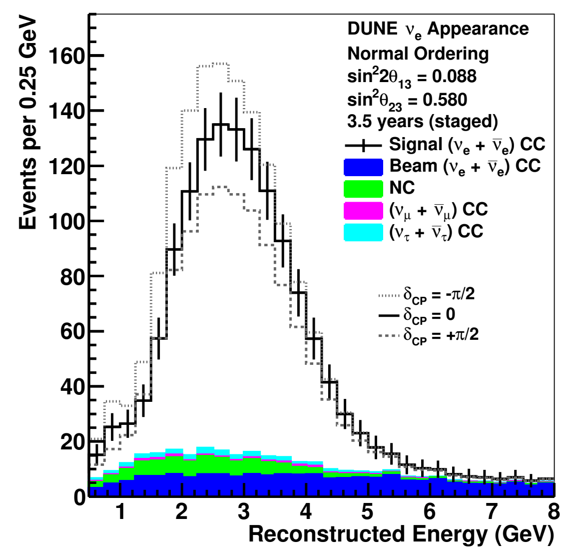
Why wide-band beam?





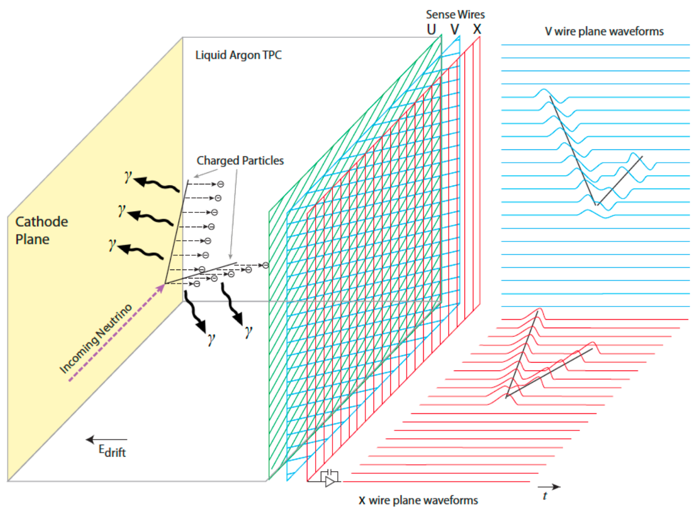


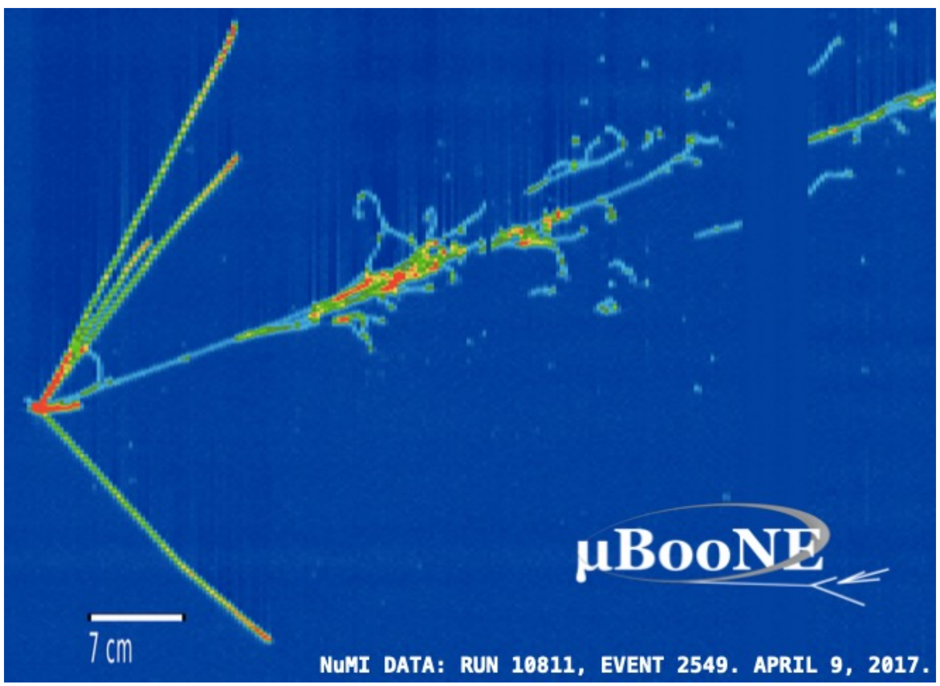
A narrow band beam is essentially a “counting” experiment



The wide band beam can fit the spectrum

Liquid argon basics

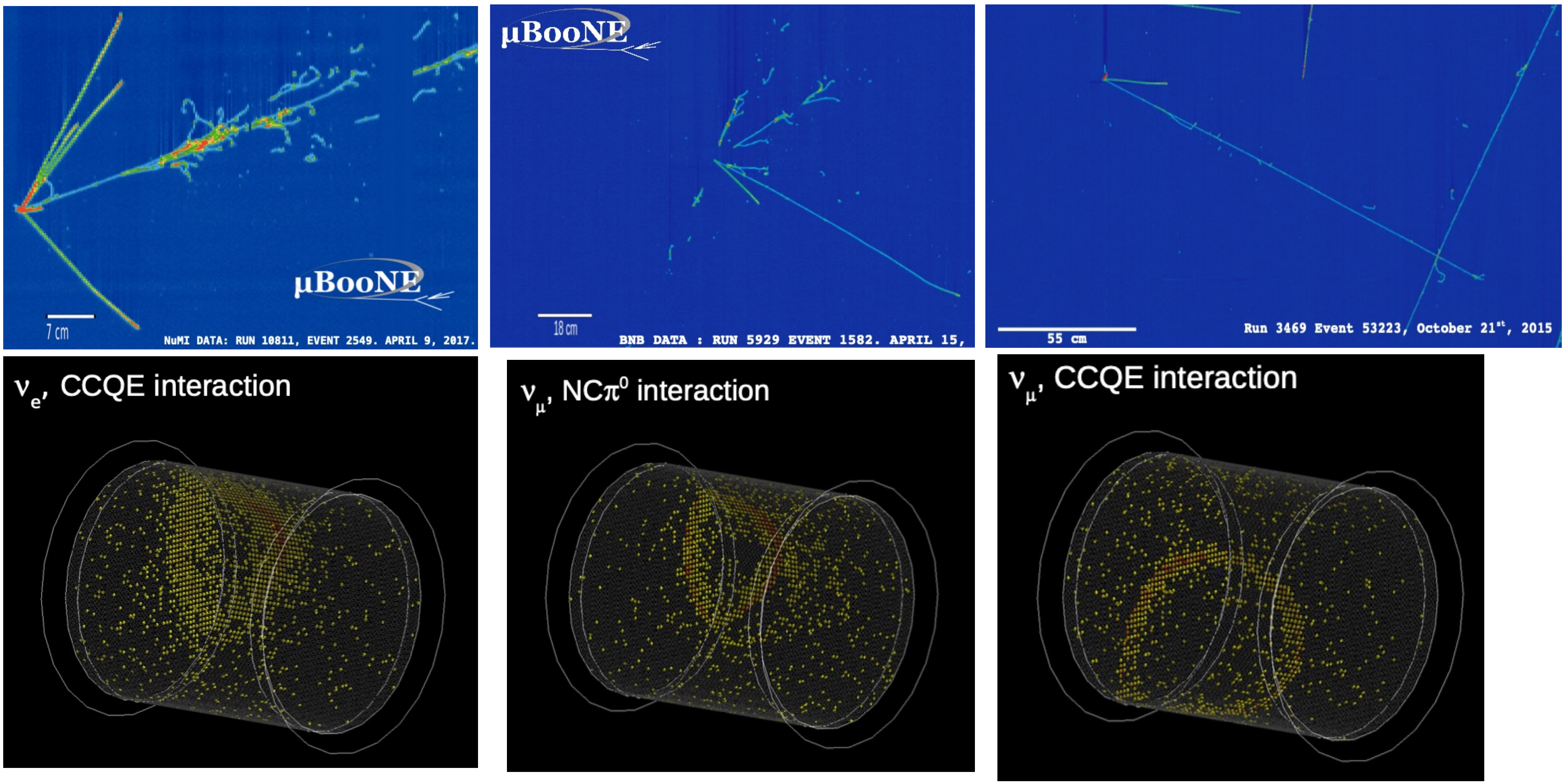




- Drift ionization charge : High Voltage
  - HV power supply and feed-through
  - Cathode Plane
  - Field Cages
    - Resistive dividers
- Collect ionization charge : Sense wires, electronics
  - Anode Planes
  - Front-end amplification, digitization, readout
- Collect scintillation light : wavelength shifters, light guides, light collection electronics

Why liquid argon?

- We can measure both the hadronic and leptonic parts of the event to high precision for energy resolution and particle ID.
- Compare to Water Cherenkov rings

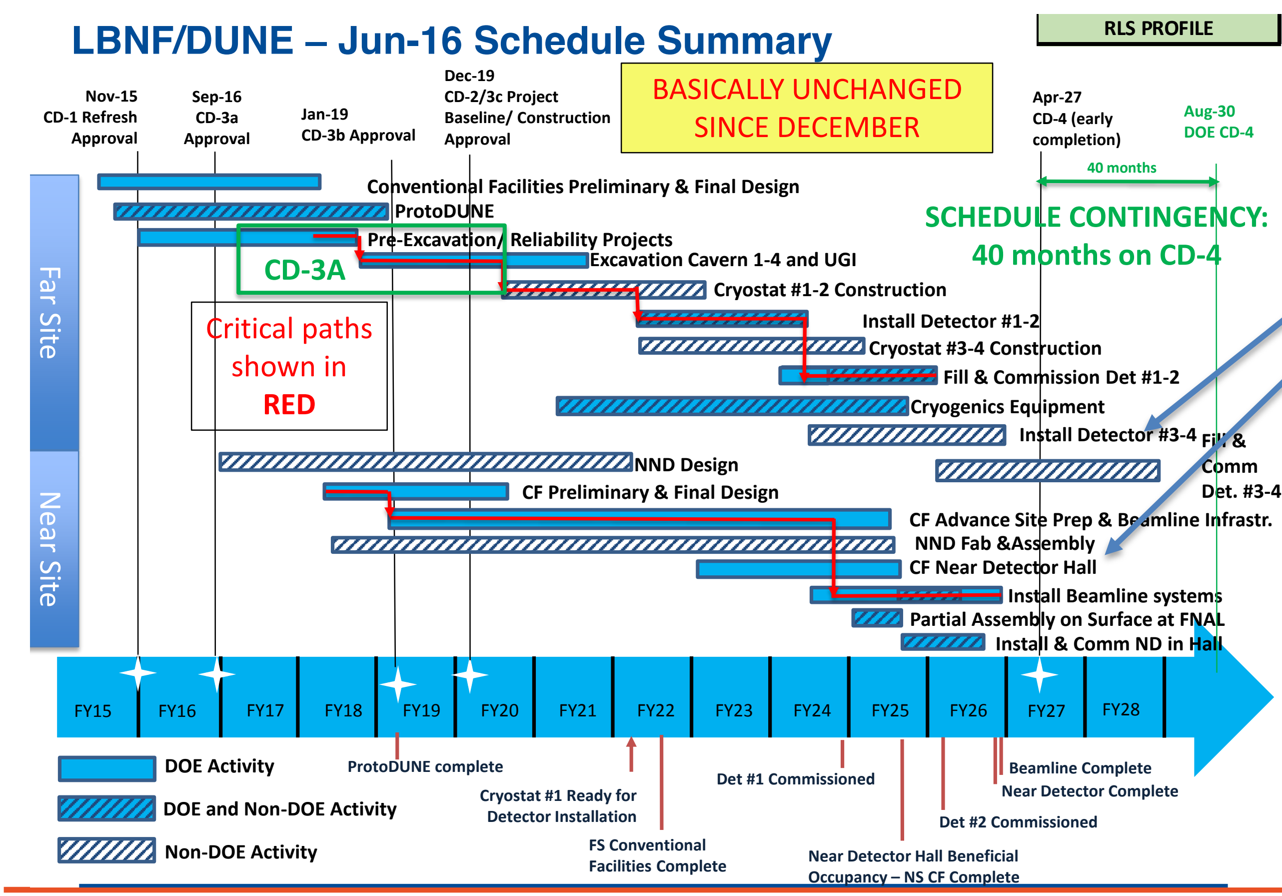


International DUNE Experiment

– Proposed post-P5 (2015)

- 40 kT fiducial mass of LAr in 4 detector modules
- “capable” Near Detector – proposed as a Non-DOE activity
- 1.2 MW proton beam power – PIP-II Project

Aug 2016 IPR



DOE Activity

DOE and Non-DOE Activity

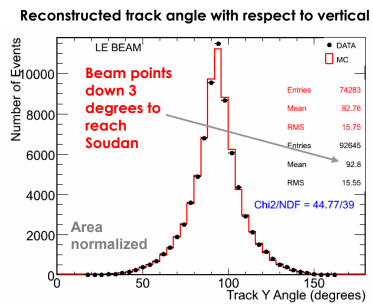
Non-DOE Activity

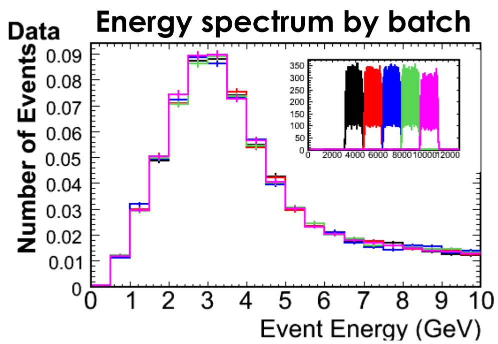
Detector’s 3&4 were never envisioned as part of initial DOE scope;
Near Detector not initially in DOE scope

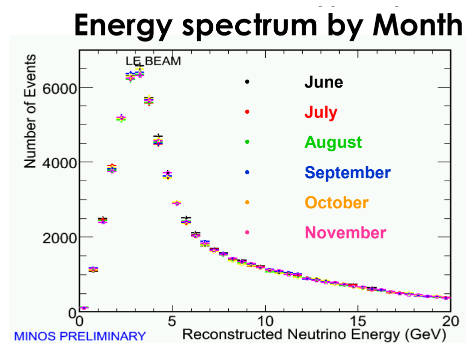
Fermilab DUNE

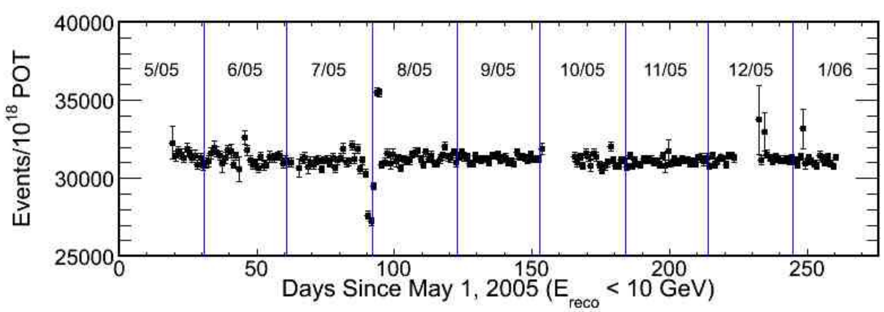
On-Axis Beam Monitoring

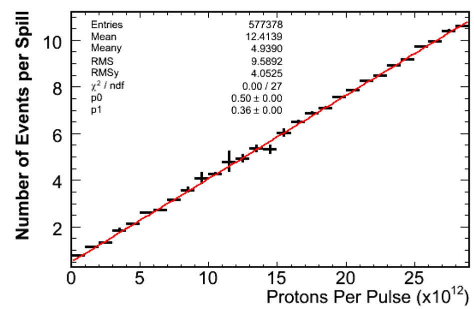
Data examples are from MINOS



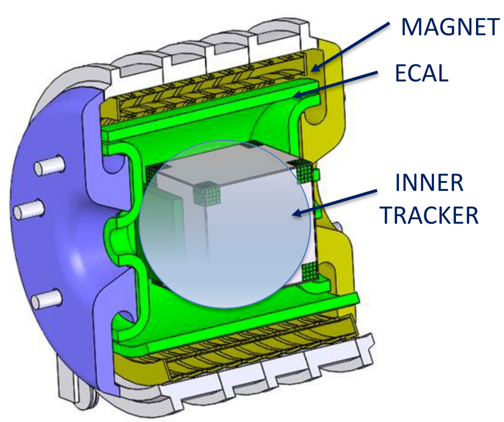


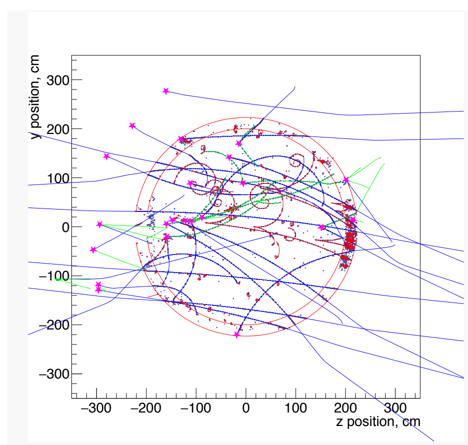


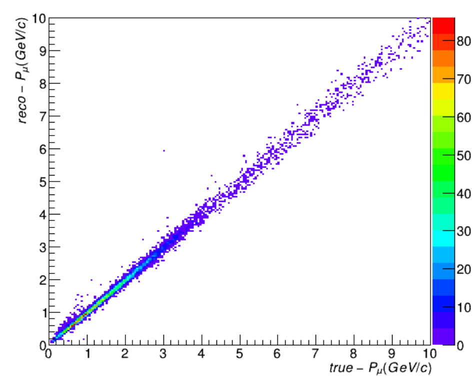




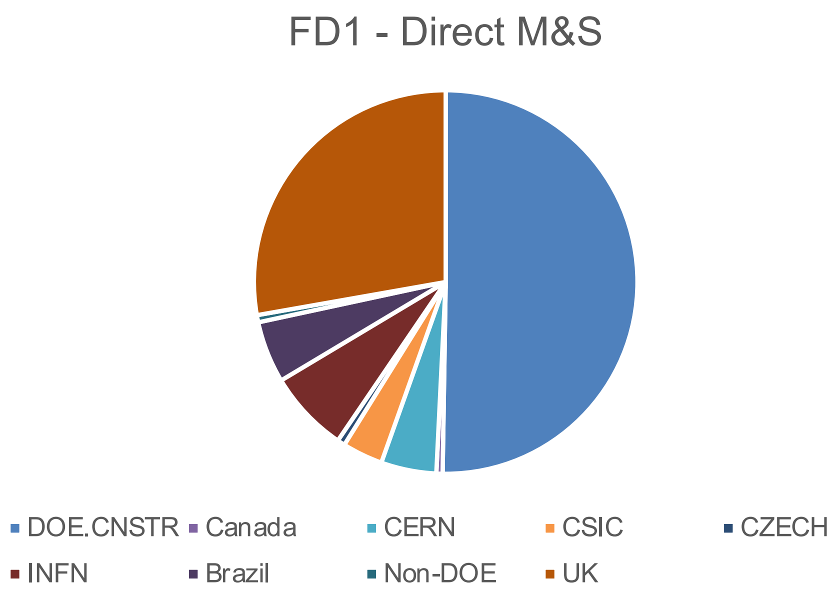
SAND will do this for DUNE

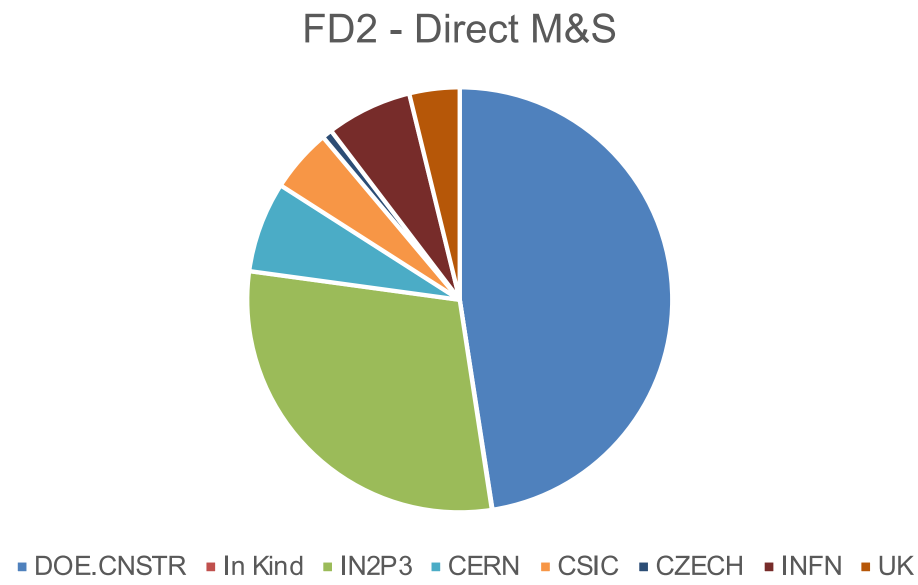


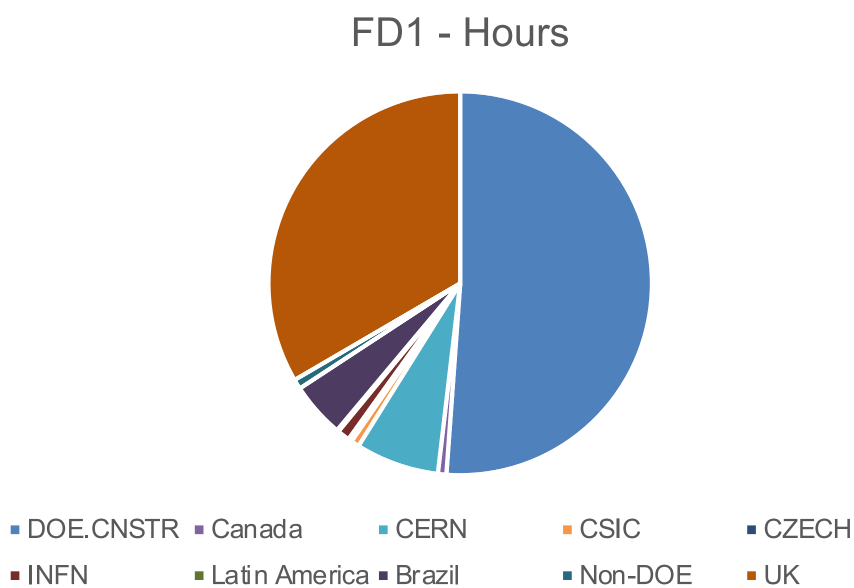


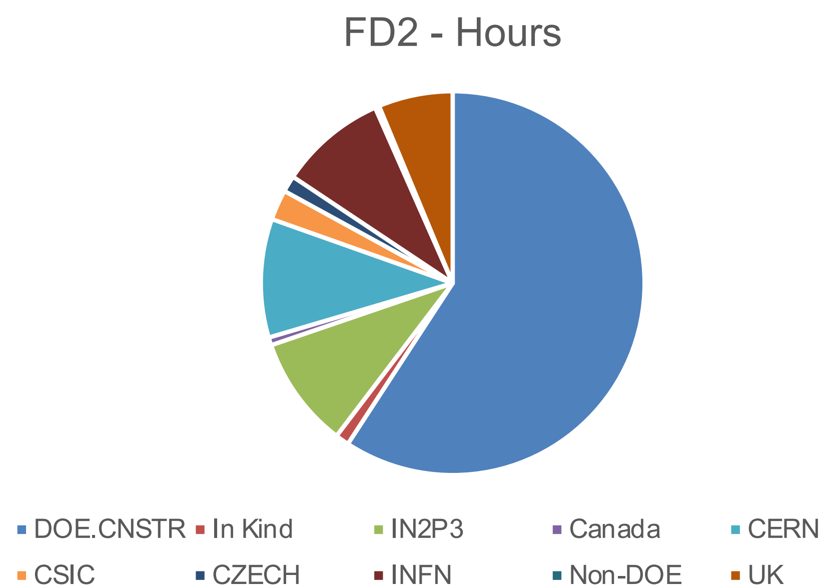


DUNE partner contributions to FD1 and FD2





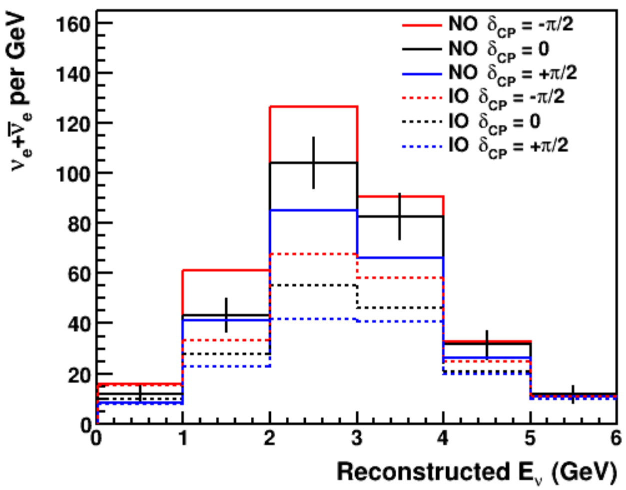




Spring 2035

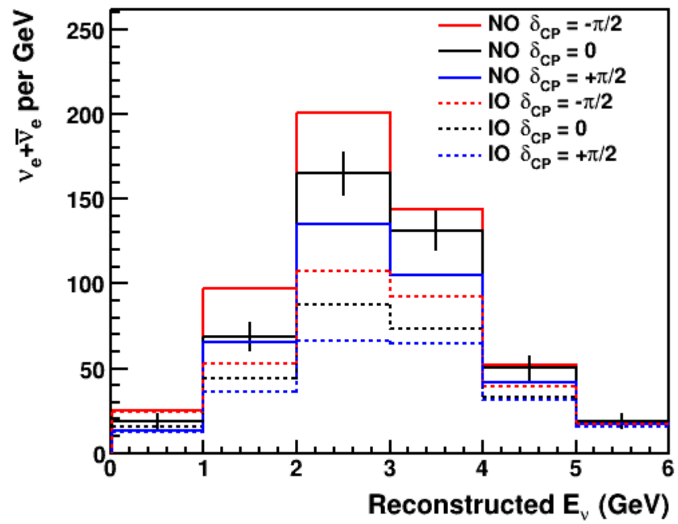
base

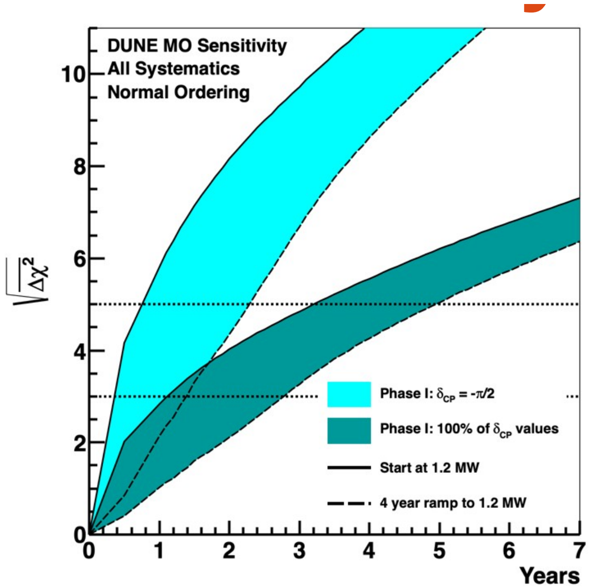
17E20 POT FHC



design

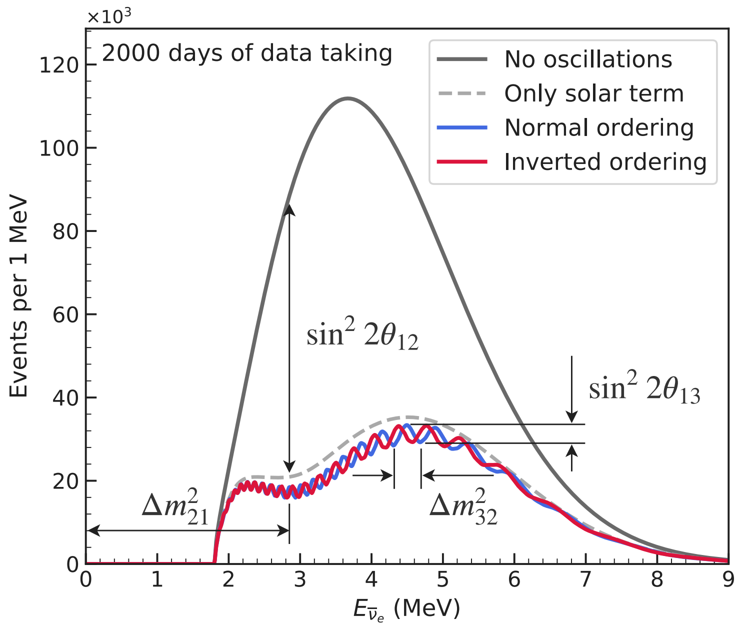
27E20 POT FHC





Only experiment which has > 5σ mass ordering

JUNO



Progress in Particle and Nuclear Physics 123 (2022) 103927

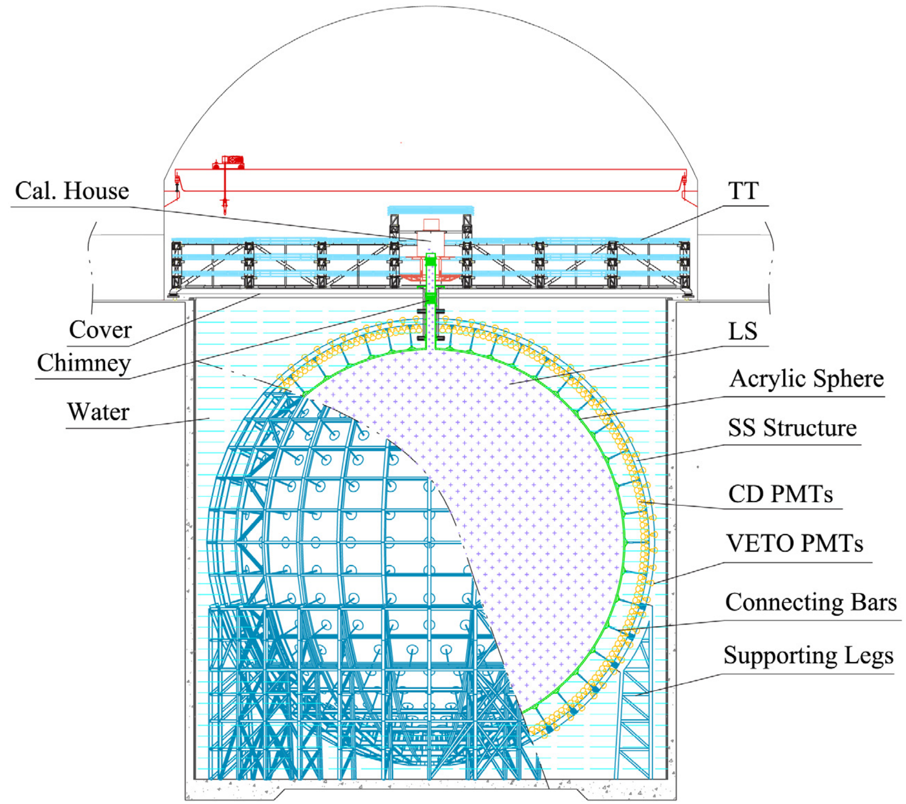
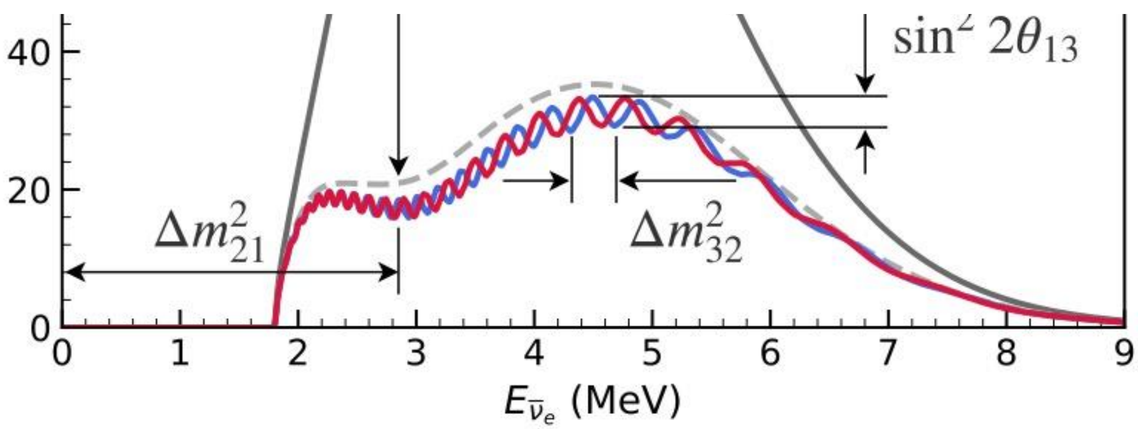


Fig. 3. Schematic view of the JUNO detector.



Only one of these curves is real, and the data needs to be able tell the difference!