Status of the DUNE experiment

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on behalf of the DUNE collaboration
NuFact 2021
Sept. 6th 2021

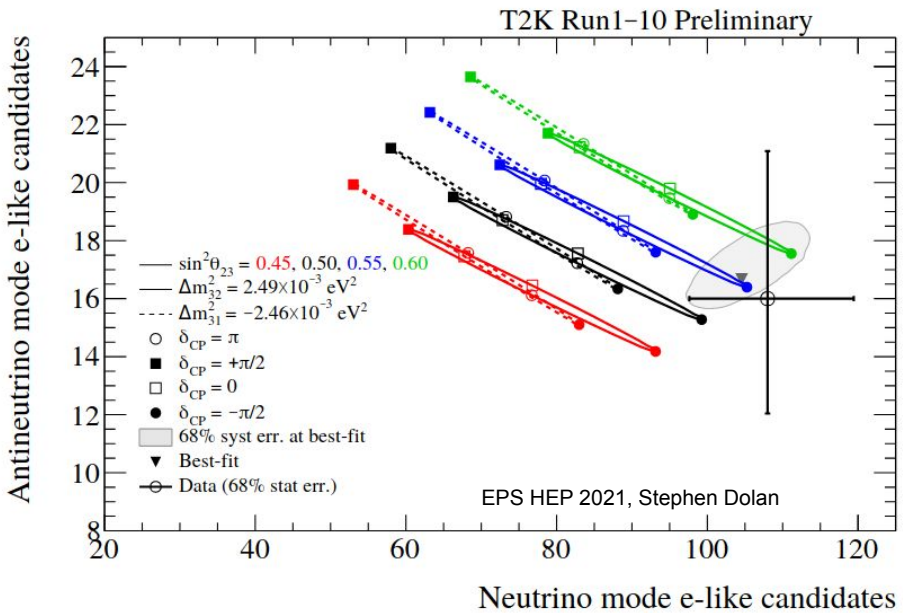

Stony Brook University
DUNE

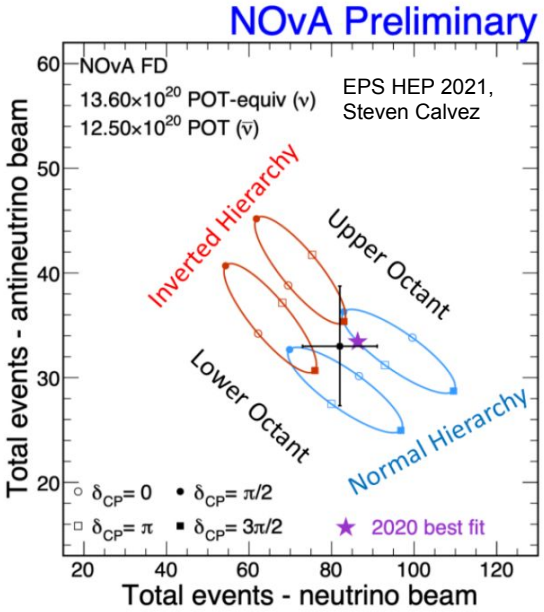
Important questions to be answered

- Facts about neutrino oscillation that we know
  - Neutrinos interact in flavor states and propagate in mass states→ oscillation nature
  - All three mixing angles measured non-zero→ room for a CP violation phase measurement
- Key questions to be answered by DUNE long-baseline program
  - How well do we know about the CP violation phase? $\delta_{CP} = 0$ or not?
  - What is the mass hierarchy? Normal or inverted?
  - How well can we disentangle the octant of θ_{23} degeneracy?

What we know from current long-baseline experiments?

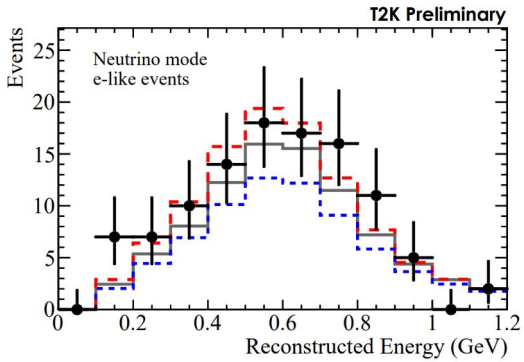
- T2K (Ciro's talk an hour ago) and NovA (Dan's talk half an hour ago) have great sensitivity to the CP violation measurement → not enough to conclude, yet

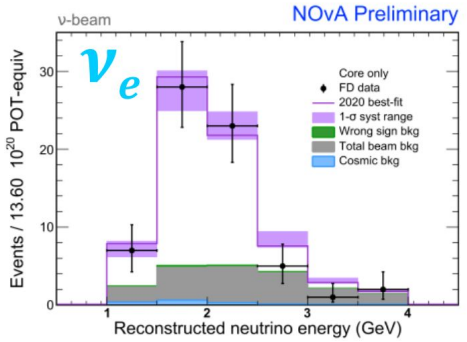




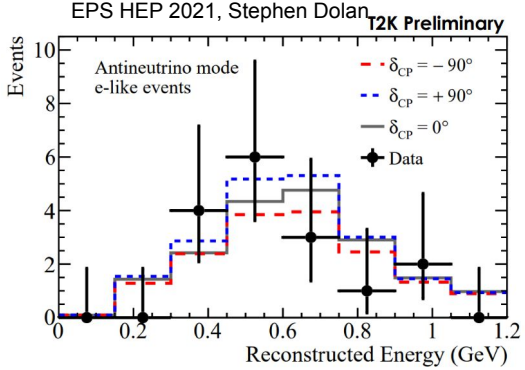
What we know from current long-baseline experiments?

- NOvA and T2K are off-axis-> narrow flux peak intentionally
- Bi-event plot presenting almost the full power of T2K and NOvA, but not for those with capability of spectral measurement
- DUNE to utilize a wide-band beam mapping out more than 1 oscillation period -> spectrum experiment





EPS HEP 2021, Stephen Dolan



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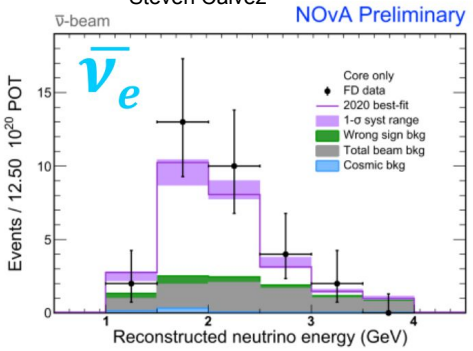
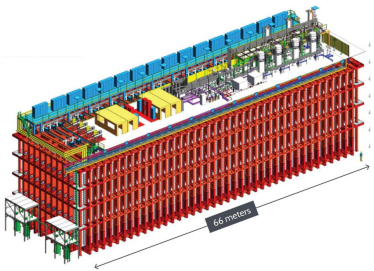
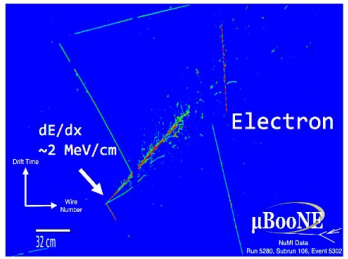
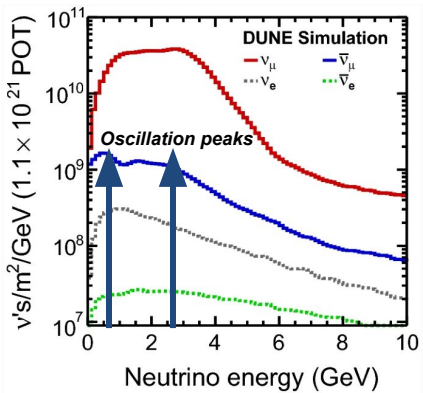


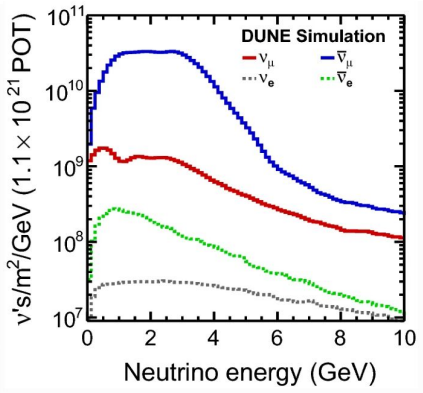
One-slide DUNE



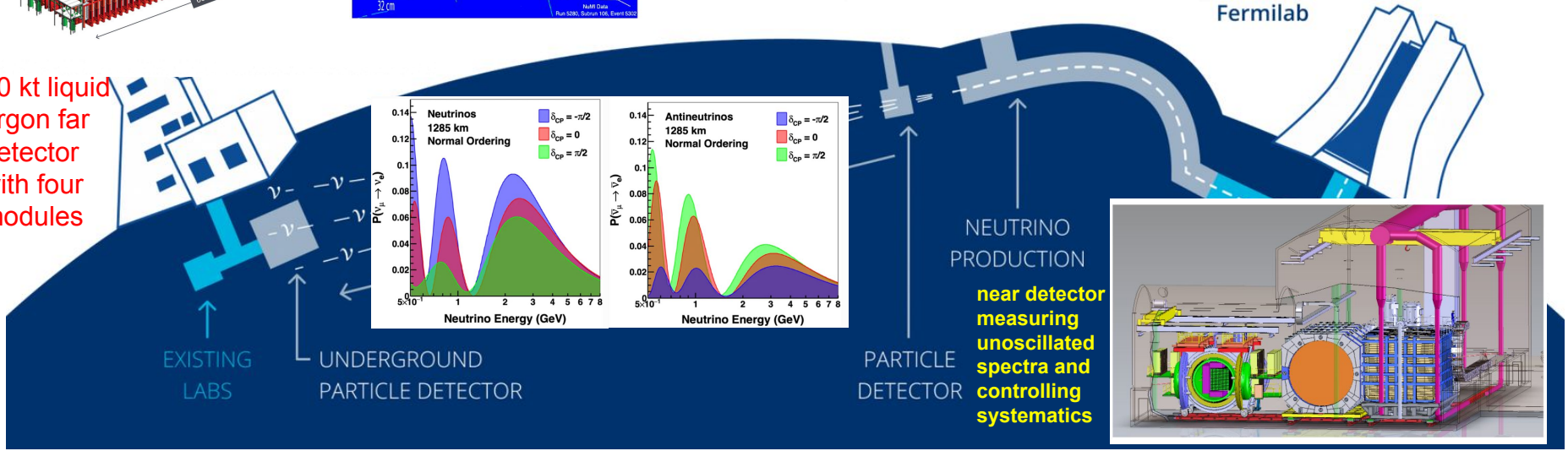


Broad band neutrino and antineutrino beam





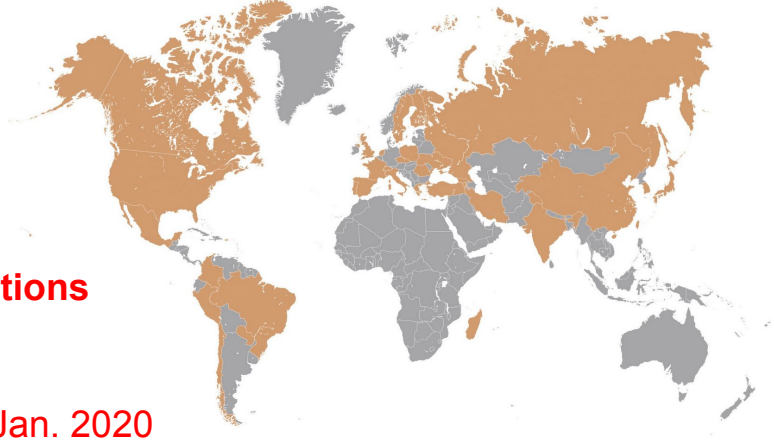
70 kt liquid argon far detector with four modules



near detector measuring unoscillated spectra and controlling systematics

DUNE collaboration

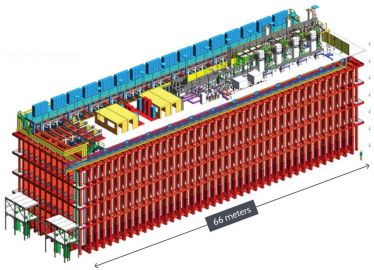
- > 1300 Collaborators
- > 200 institutions
- 33 countries + CERN

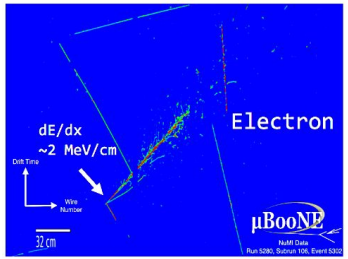


A long list of oral and poster presentations in NuFact2021

Last in-person photo in Jan. 2020

One-slide DUNE





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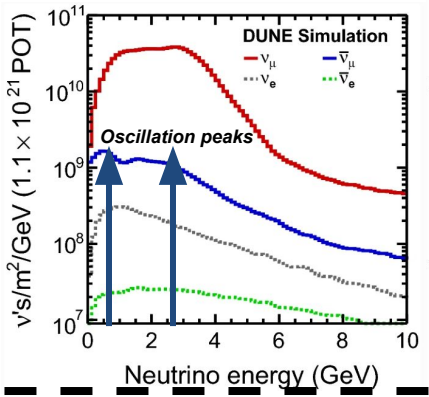

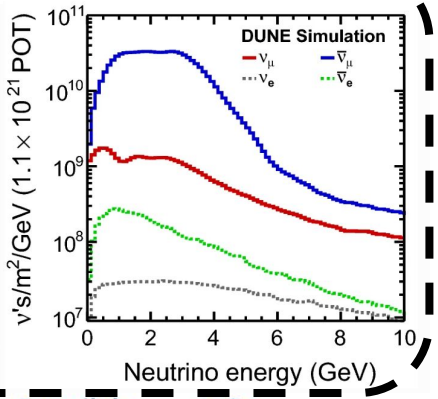

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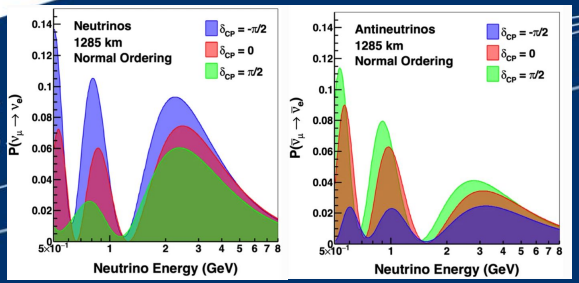


Fermilab

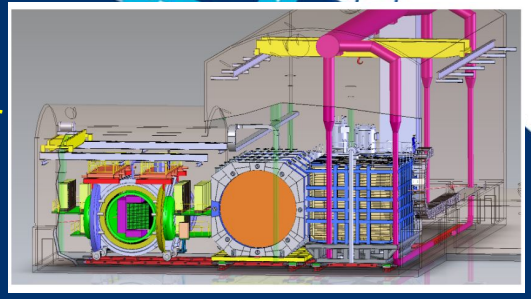
NEUTRINO PRODUCTION

EXISTING LABS

UNDERGROUND PARTICLE DETECTOR

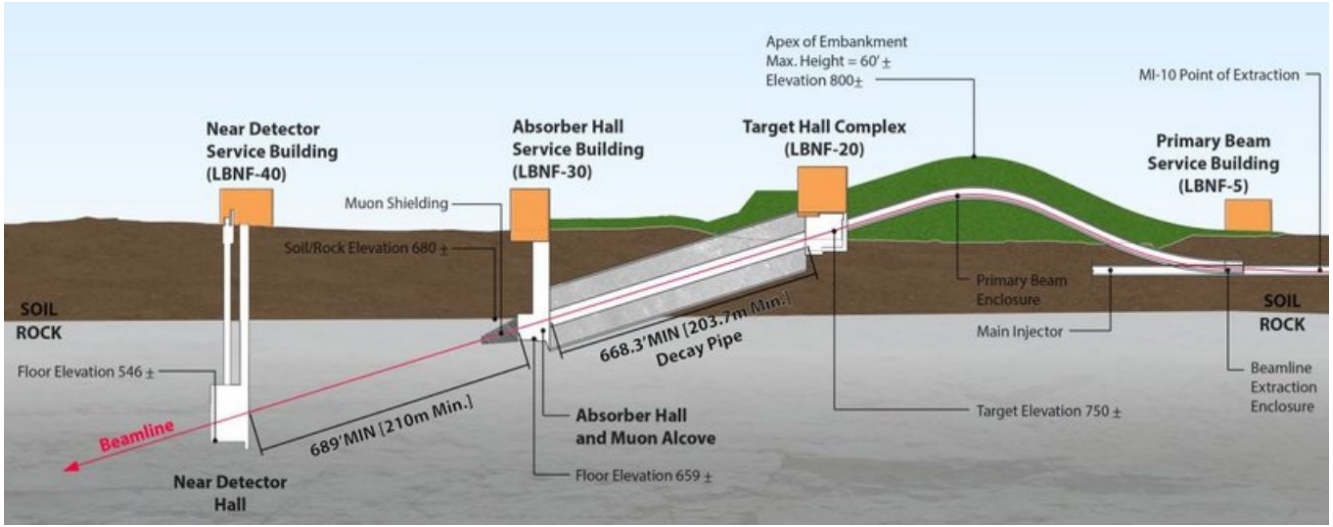
PARTICLE DETECTOR

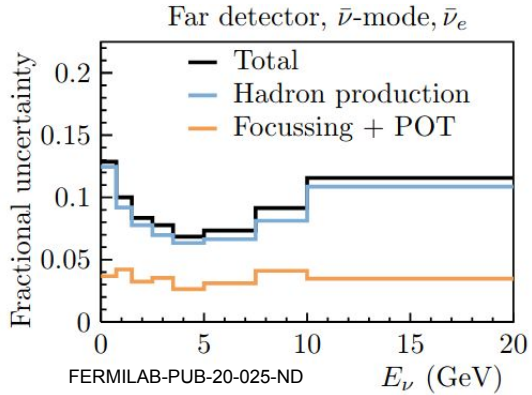
near detector measuring unoscillated spectra and controlling systematics



Beamline

- The Proton Improvement Plan II (PIP-II), an enhancement to the Fermilab accelerator complex, powering the world's most intense high-energy neutrino beam-> **1.2 MW upgradable to 2.4 MW**
- The LBNF beam optimization completed by scanning different horn and target geometries to identify those that produced the optimal sensitivity to the CP violation phase





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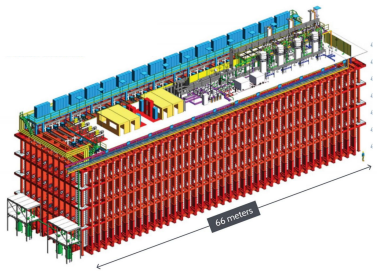

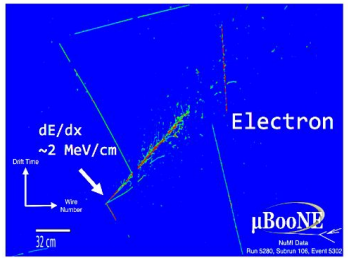

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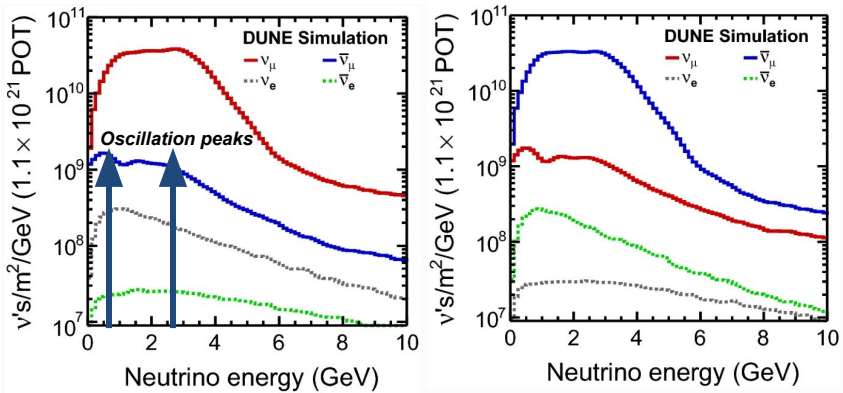
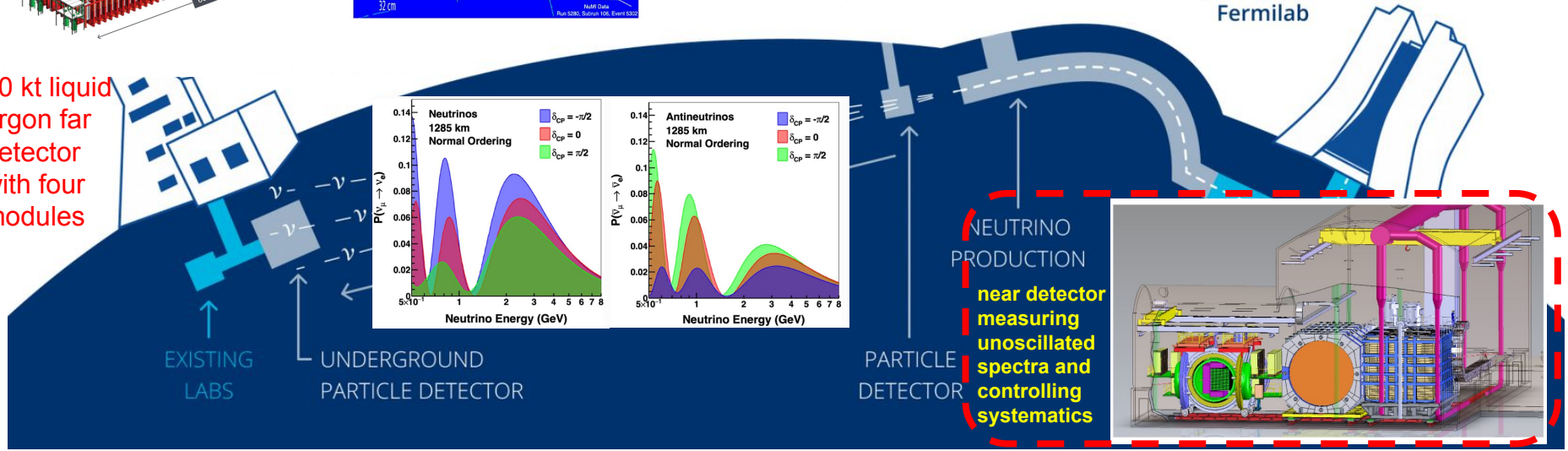


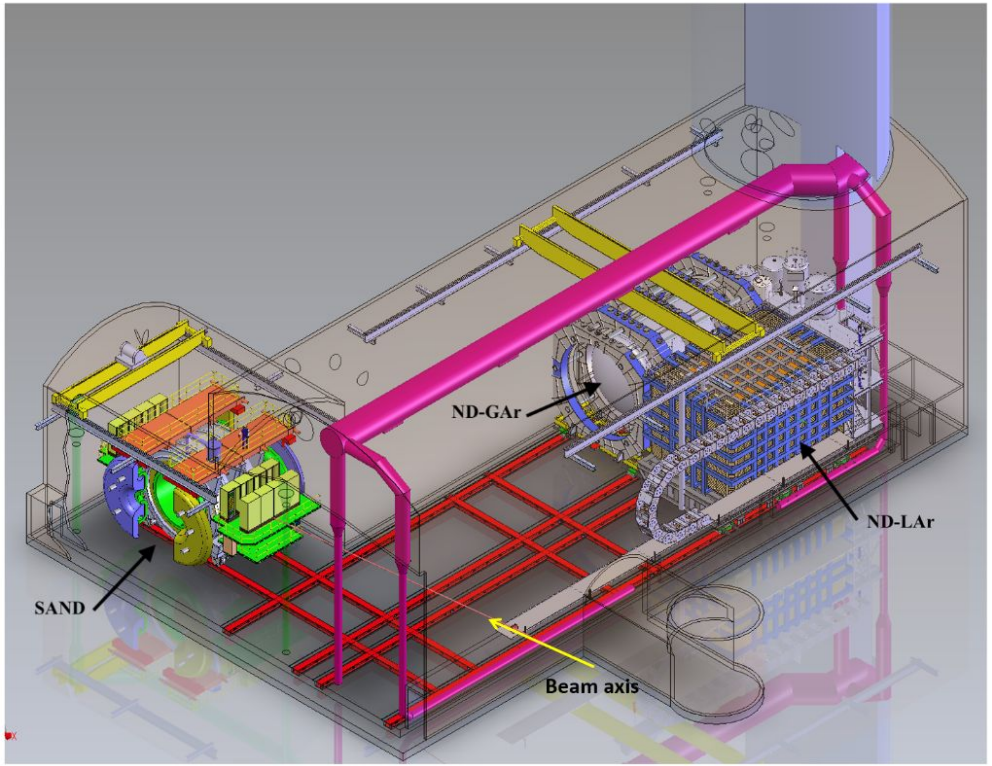
70 kt liquid argon far detector with four modules



DUNE near detectors (ND)

ND CDR: arXiv:1606.09550

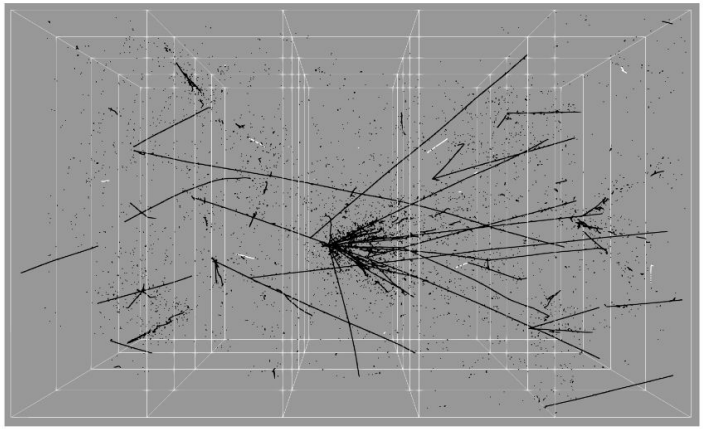
- ND to constrain the cross section, flux, and energy response independently as good as possible
  - Multiple methods for measuring neutrino fluxes: target independent
  - Better detail in neutrino interaction than the far detector (FD): same target material but better phase space coverage, particle ID, energy reconstruction etc.
  - Capable to measure events in a similar way to the FD: similar technology
- A hybrid detector with three components: A liquid argon TPC, a gaseous argon TPC and an on-axis detector



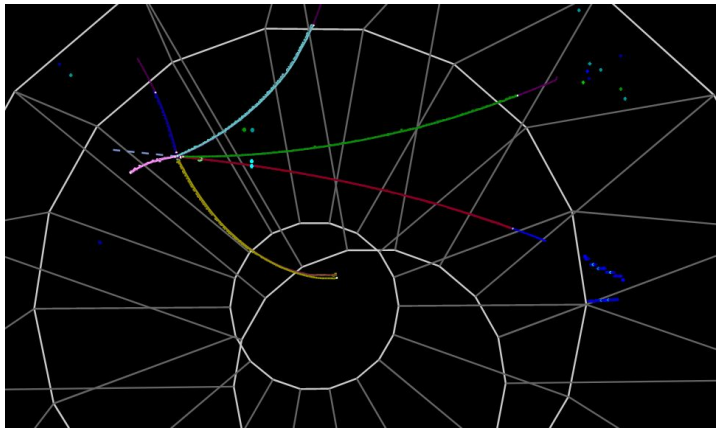
DUNE ND LAr and GAr

- LAr: Primary target, with 50t fiducial mass divided into 35 optically separated modules
  - Charge readout: a novel pixelated anode
  - Light readout: rejection of unassociated charge signals (pile-up)
- GAr: Extending the capabilities of the ND v-Ar interaction detection
  - Measuring the momentum and sign of charged particles exiting ND LAr
  - As a target, extending charged particle measurement capabilities to lower energies than achievable in the far or near LAr detectors

A full spill in LAr

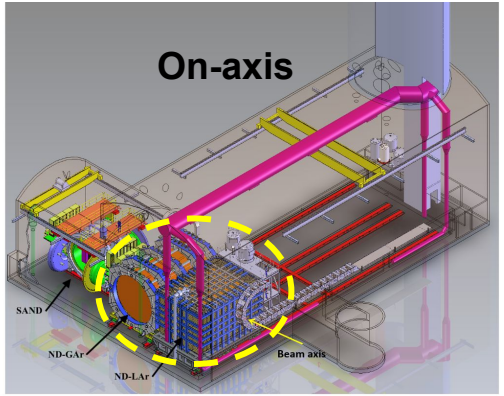


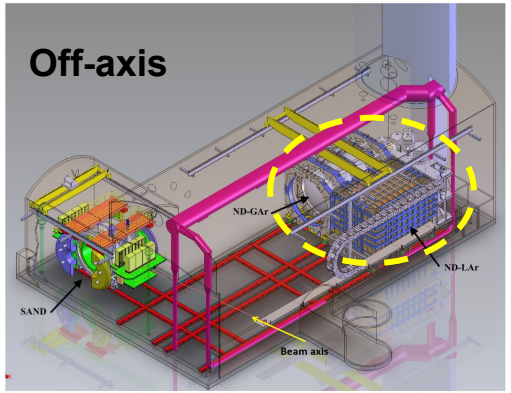
ν_μ CC with five protons in GAr



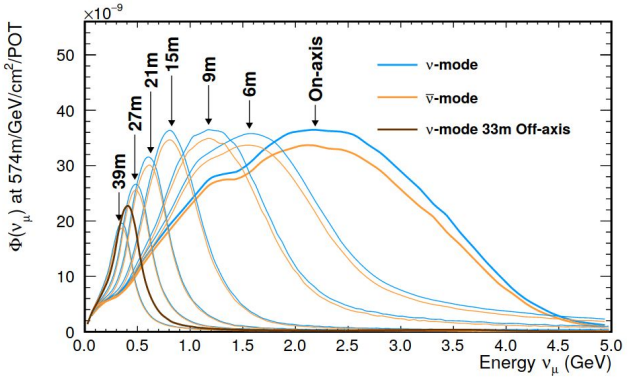
DUNE PRISM

- Moving LAr and GAr off-axis-> Sampling the neutrino flux
  - Mapping between the true and reconstructed neutrino energy within the near detector→ Constructing Mono-energetic beam
  - A direct way of extrapolating near detector measurements to the far detector→ Reducing the model dependence on the neutrino interaction cross section

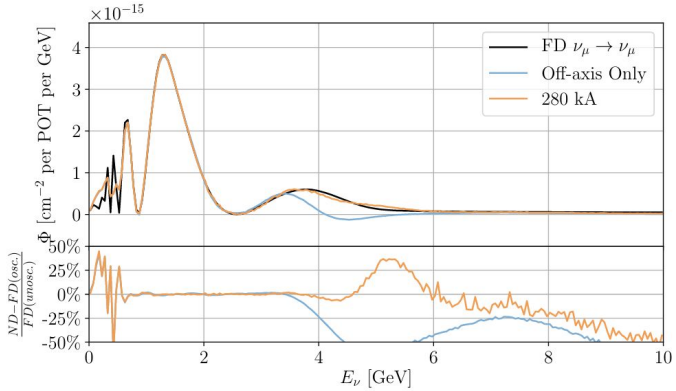




ND flux for different off-axis locations

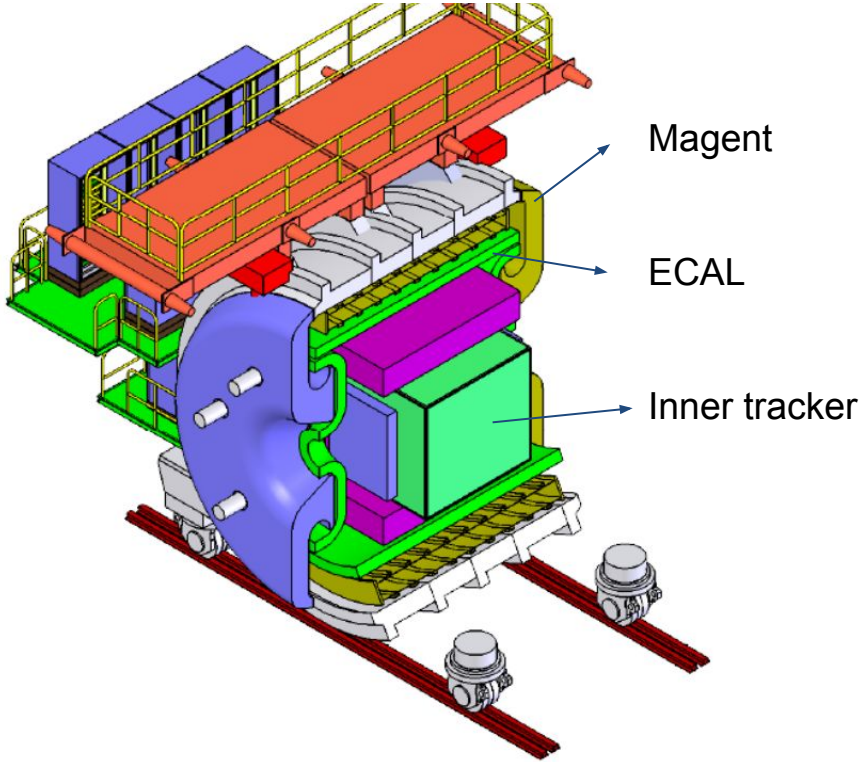


FD oscillated flux matching



DUNE ND SAND (System for on-Axis Neutrino Detection)

- On-axis permanently
  - Monitoring the beam stability
  - Providing absolute flux measurement
  - A different target material to validate the neutrino interaction modeling
- KLOE magnet + ECAL + inner tracker + LAr target
  - A Superconducting magnet + electromagnetic calorimeter re-purposed from the KLOE experiment

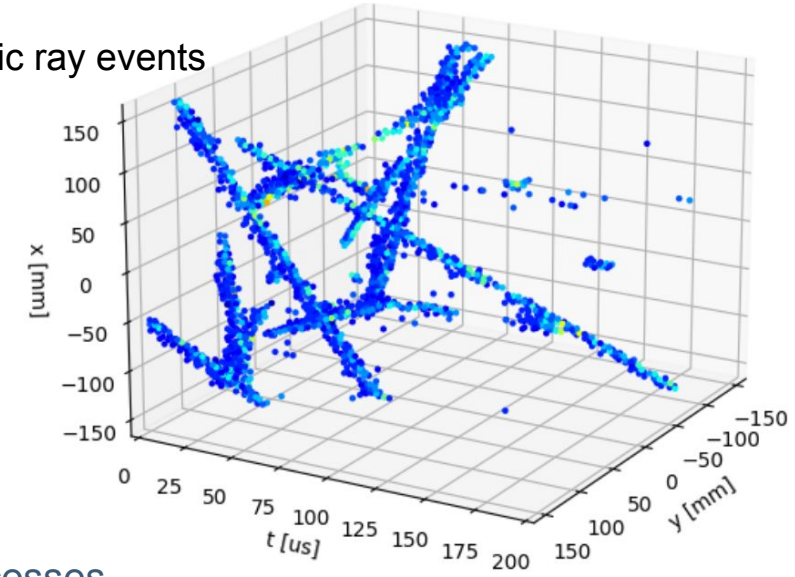


DUNE ND prototyping

- ND LAr demonstrator program
  - SingleCube Demonstrator
    - Validating integrated performance of charge and light readout
  - ArgonCube 2x2 Demonstrator
    - Verifying technical readiness of the ND LArTPC module design
    - Including Minerva components with NuMI beam to form ProtoDUNE-ND
  - Full-scale Demonstrator
    - Providing an engineering validation of the full-scale production, assembly and testing processes

The 2x2 cryostat and cryogenics system at the Univ. of Bern

Cosmic ray events



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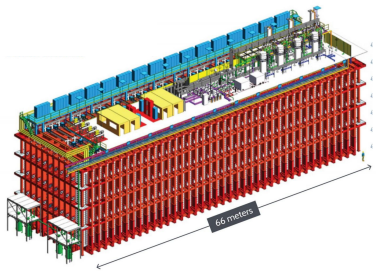
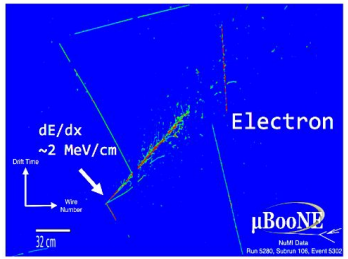
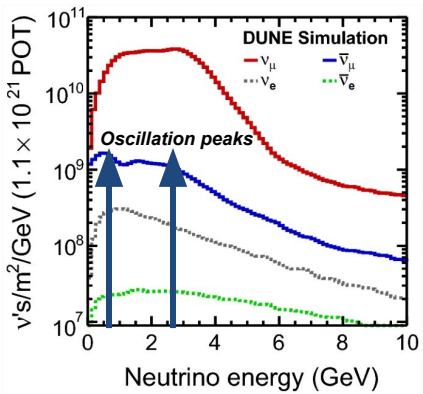
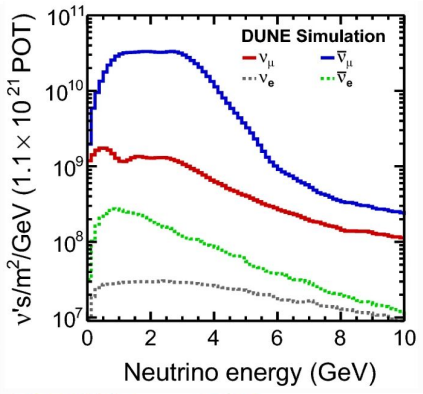




Neutrino mode



Antineutrino mode



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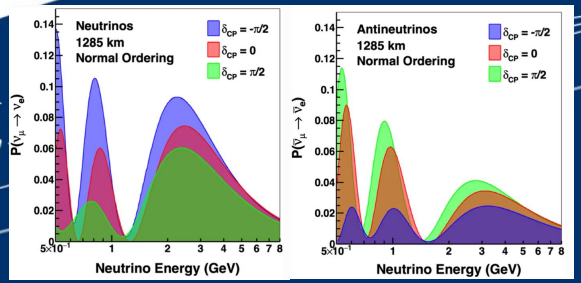

Fermilab

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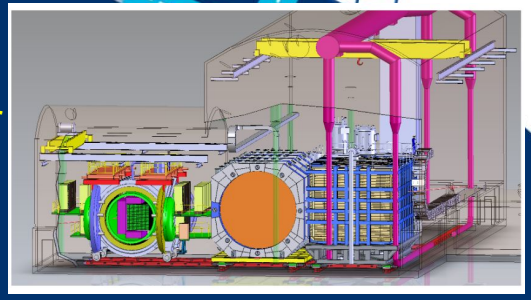
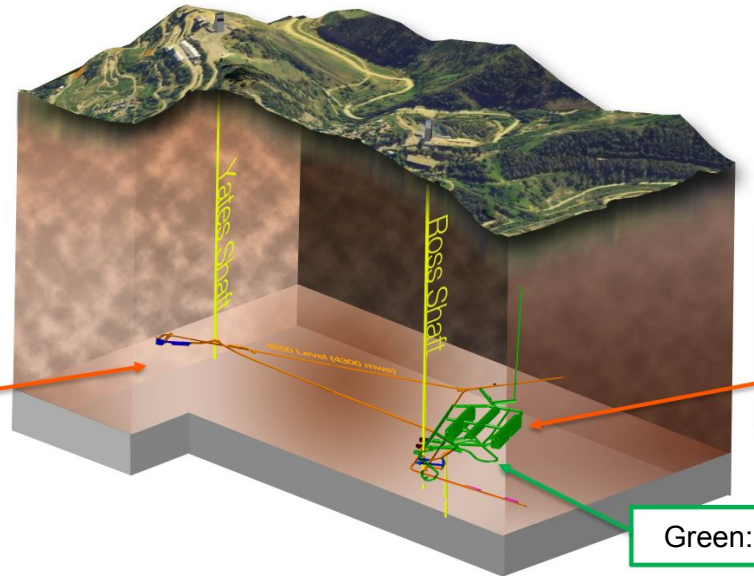


At SURF (Sanford Underground Research Facility)

- Gold mine repurposed into underground laboratory
- Deepest laboratory in the US:
  1.5 km underground
  - Three main caverns: 4 detectors halls in 2 cavers and 1 support cavern
  - Excavation started
  - FD first module installation mid-2020's



Davis Campus:
- LUX
- Majorana demo.
- LZ ...

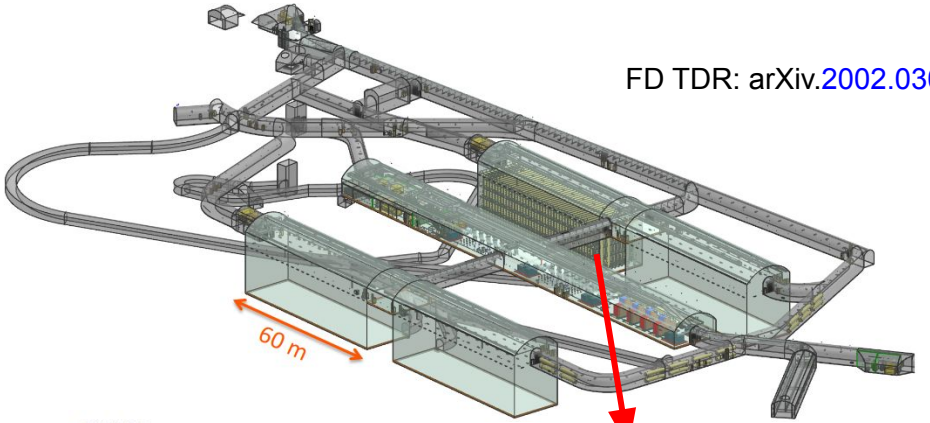
Ross Campus:
- CASPAR
- DUNE ...

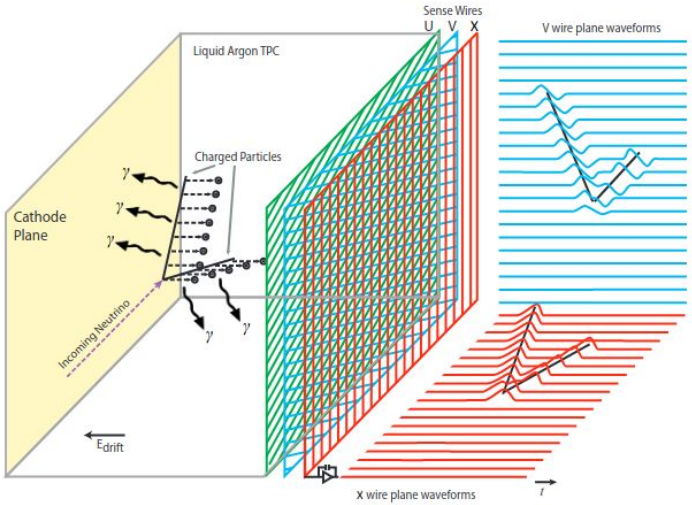
Green: new construction

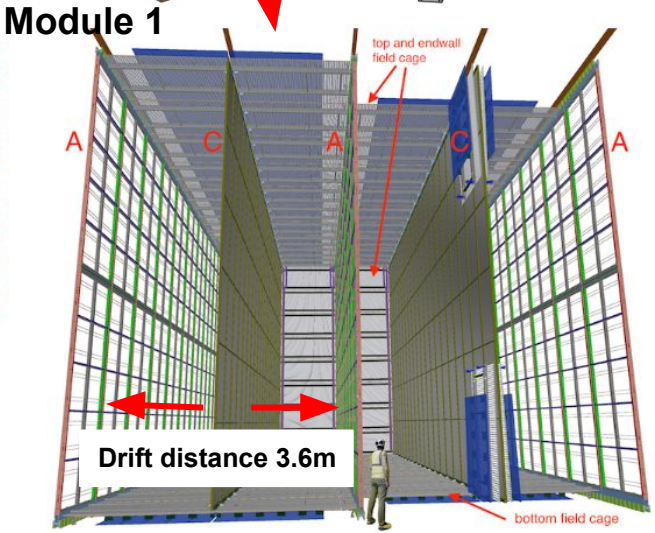
DUNE far detector

FD TDR: arXiv.2002.03005

- Four 17kt modules
  - Module 1, 2 and 3: Liquid Argon TPC
  - Module 4: Module of Opportunity
- Module 1 technology: 3.6 m horizontal drift with vertical anode and cathode planes and photon detector
- Module 2 technology: 6.5 m vertical drift with horizontal PCB (Printed Circuit Board) anode and cathode planes and photon detector

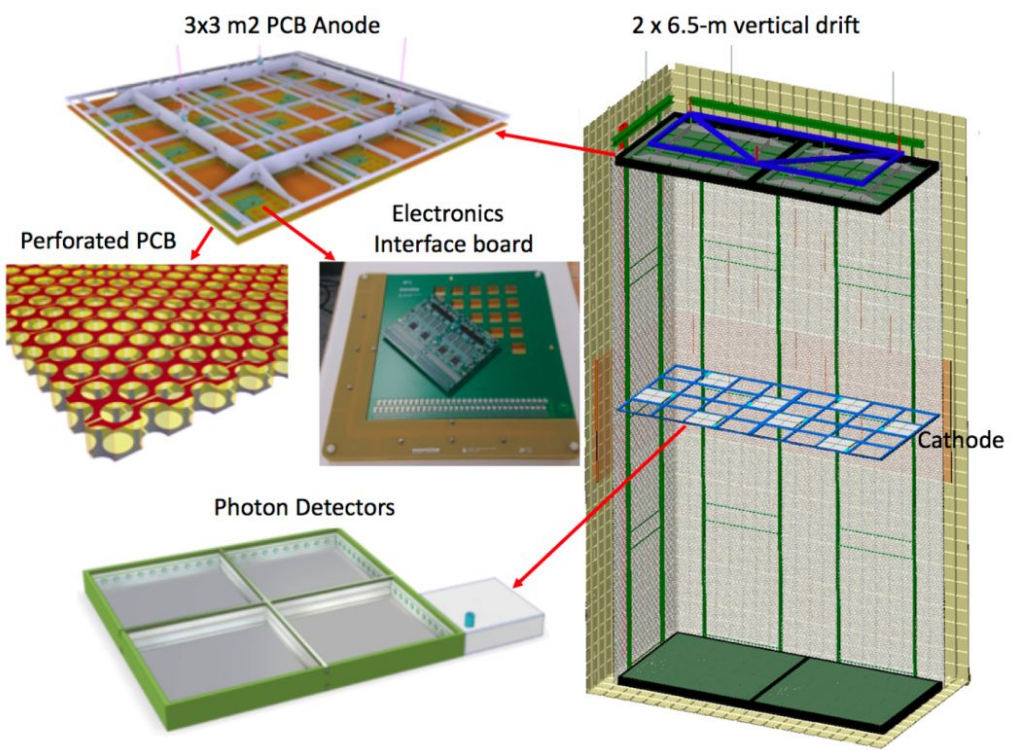






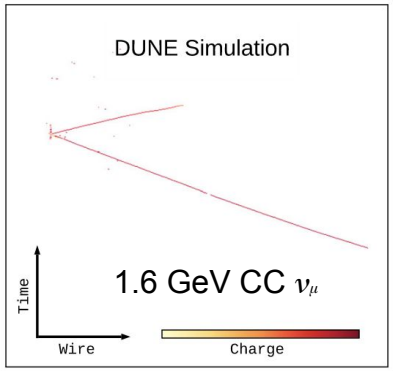
FD module 2: vertical drift

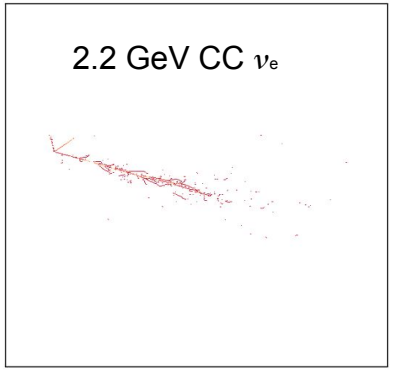
- ProtoDUNE used to demonstrate that electron lifetimes of tens of ms are achievable
- Charge readout:
  - Drift along vertical direction and cathode plane in the middle
  - Readout on strips etched on PCBs
  - Two induction and one collection readout
  - Electronics for top drift volume accessible
  - Cathode near -300 kV for a drift field of 450 V/cm

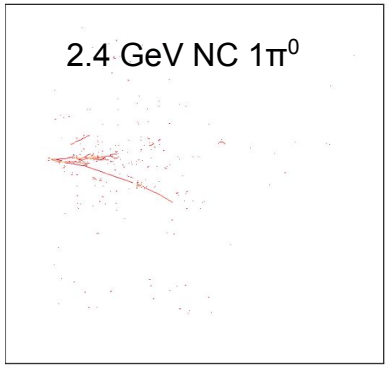


DUNE far detector event reconstruction

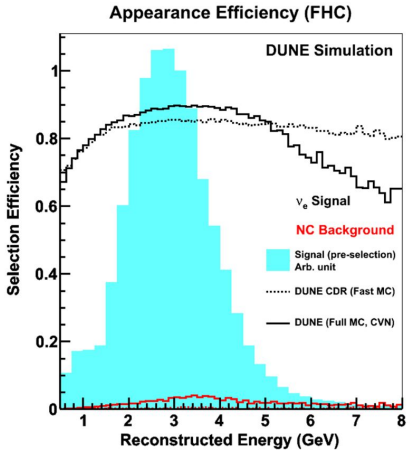
- Various complimentary algorithms
  - 2D clustering on each plane → 3D
  - Direct 3D hit clustering
  - Deep-learning (convolutional visual network)
- Tracks based on range (contained) or multiple Coulomb scattering (exiting)
- Showers based on calorimetry
- > 90% peak efficiency for both muon and electron neutrinos

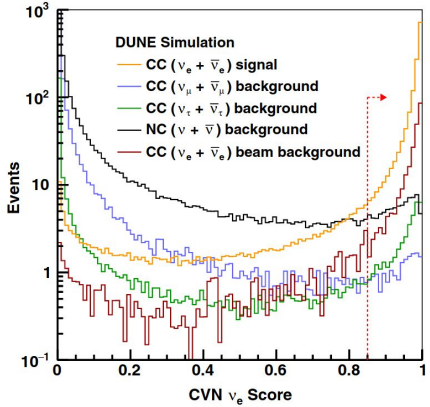






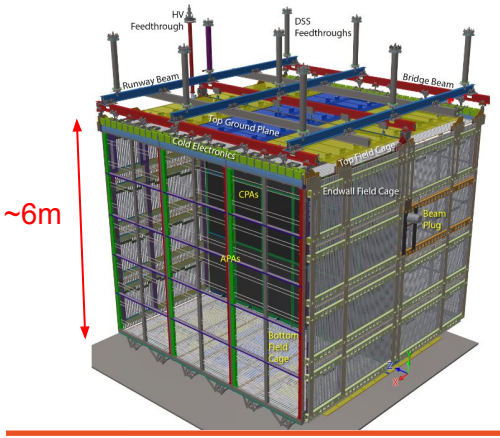
Phys. Rev. D 102, 092003 (2020)

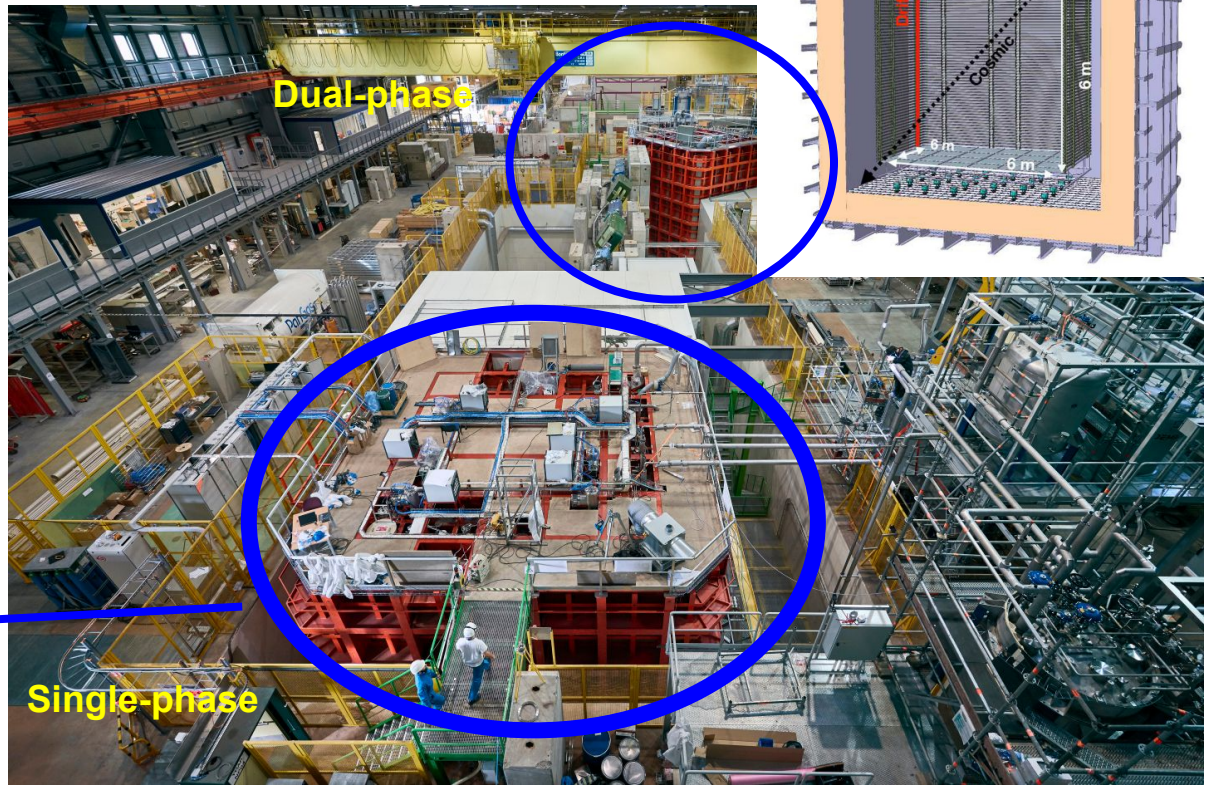




DUNE FD prototyping

- Two kt sale prototypes exposed to the charged particle beam at CERN
  - ProtoDUNE single phase (SP) 2018-2020, **Phase-II in late 2022**
  - Dual phase (DP) 2019-2020

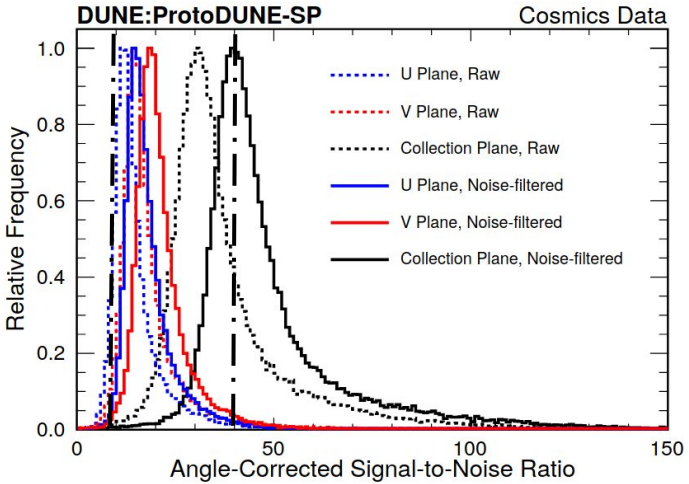


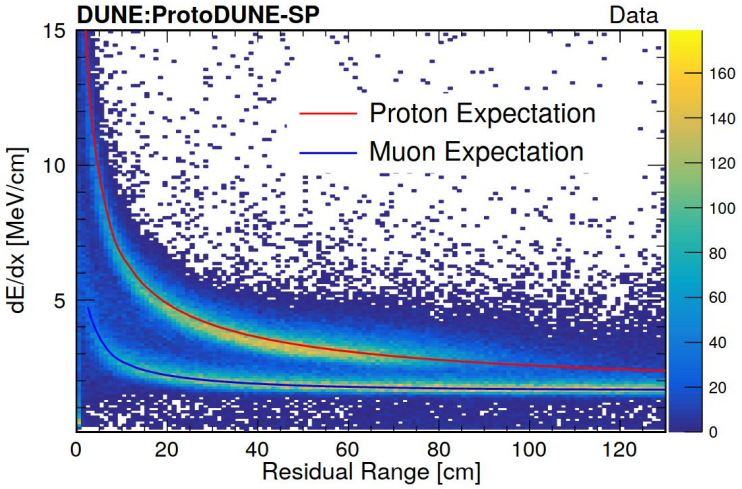


DUNE FD prototyping

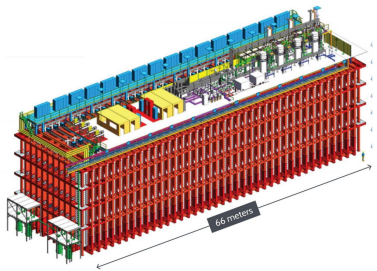
- ProtoDUNE SP aiming at production and installation demonstration, detector performance validation with cosmics and beam charged particles and photon detector demonstration
  - Stability: > 99% HV uptime, > 99% channels alive, high purity (>30 ms e-lifetime for most runs)
  - Low noise: S/N > 10 for induction wires and > 40 for collection wires
  - Test of full analysis chain

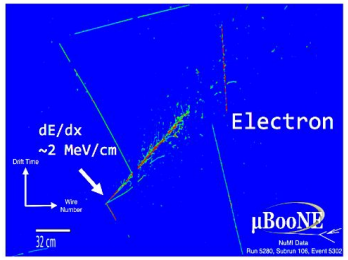
JINST 15 (2020) P12004



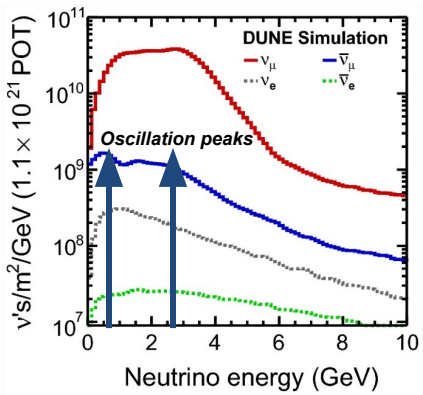


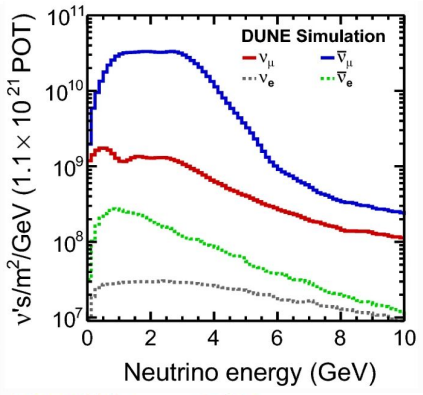
One-slide DUNE



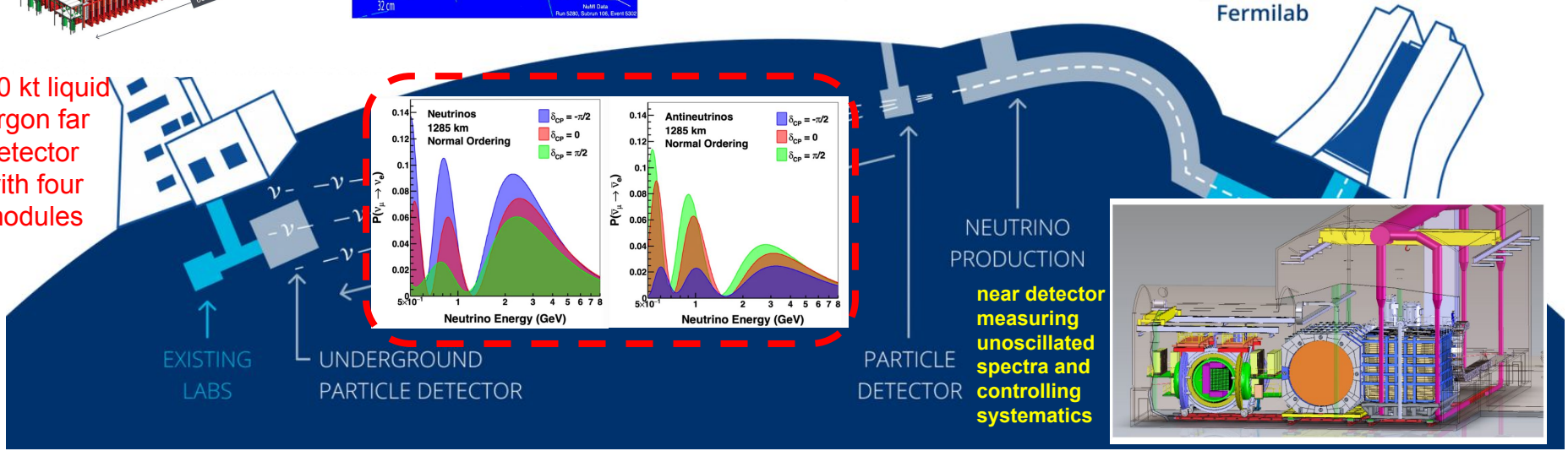


Broad band neutrino and antineutrino beam





70 kt liquid argon far detector with four modules

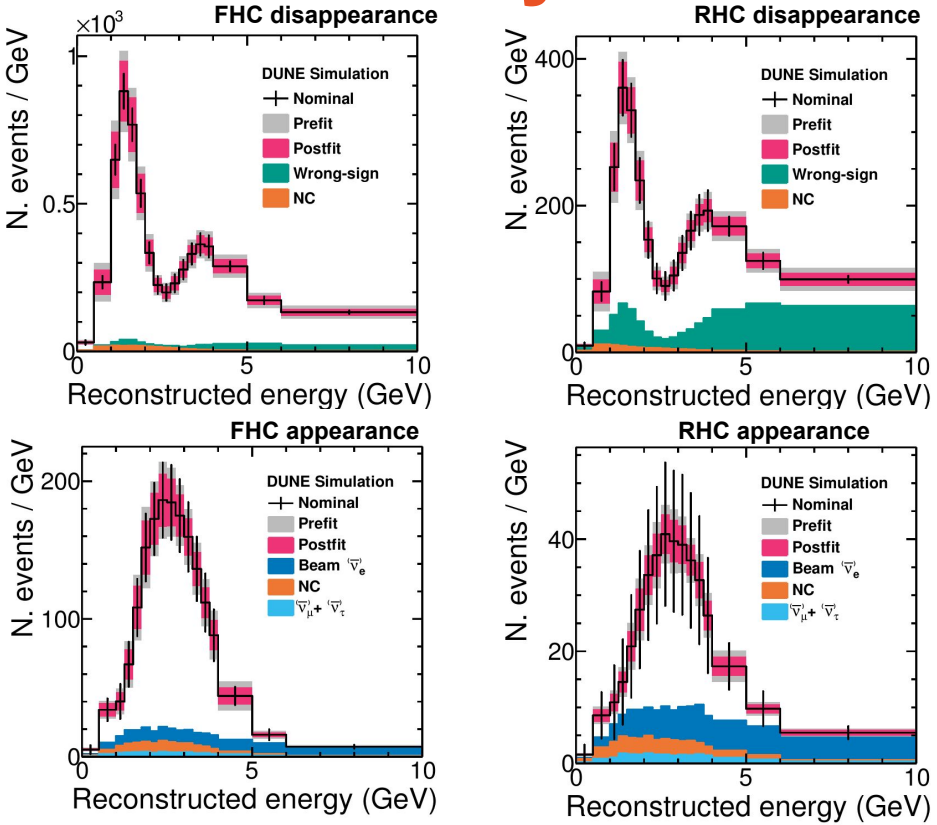


near detector measuring unoscillated spectra and controlling systematics

DUNE long-baseline sensitivity

100 kt-MW-years

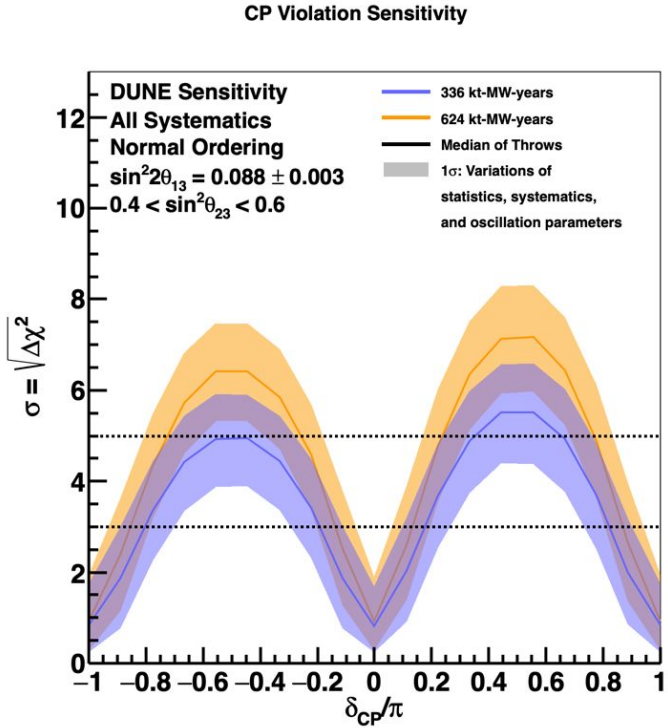
- Simultaneously fitting two disappearance and two appearance samples
- Full treatment of the systematic uncertainties with constraints from ND
- Order of 10,000 and 1,000 events for disappearance and appearance in 7 years

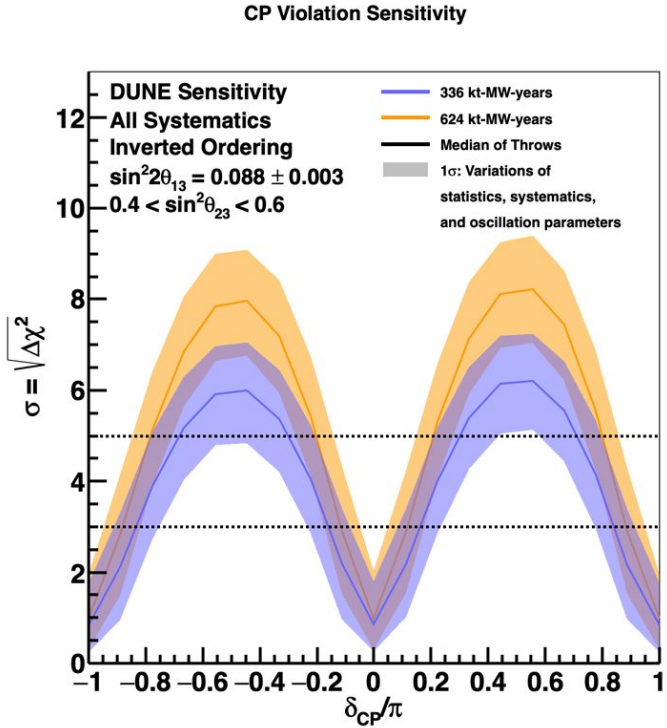


DUNE long-baseline sensitivity

- δ_{CP} sensitivity for normal ordering and inverted ordering

EPJC 80, Article number: 978 (2020)

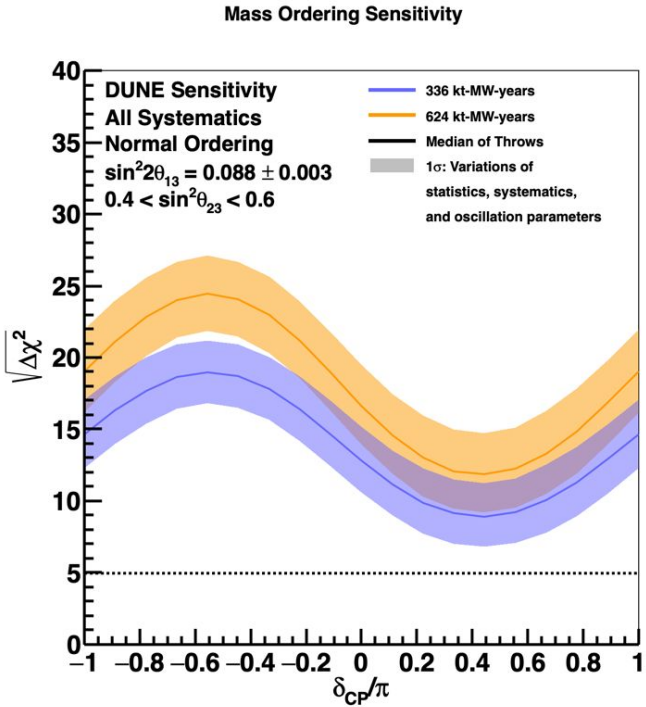


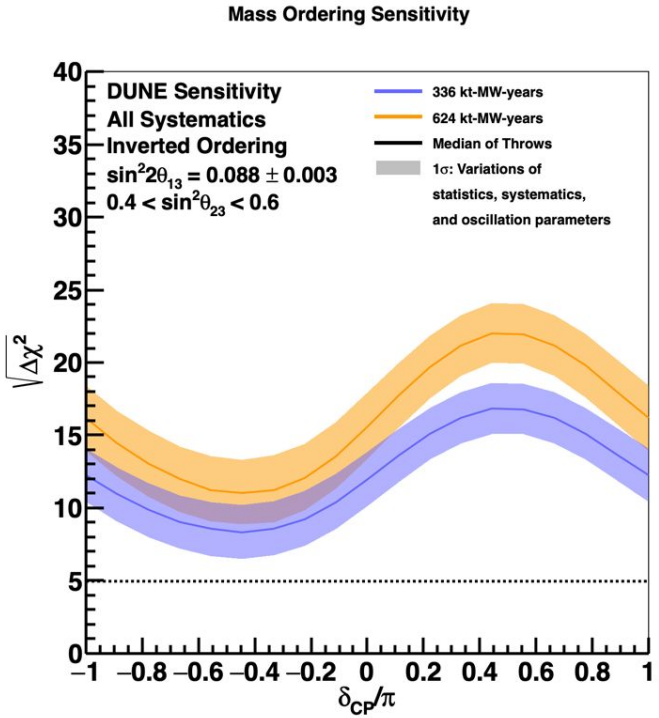


DUNE long-baseline sensitivity

- Mass hierarchy sensitivity

EPJC 80, Article number: 978 (2020)



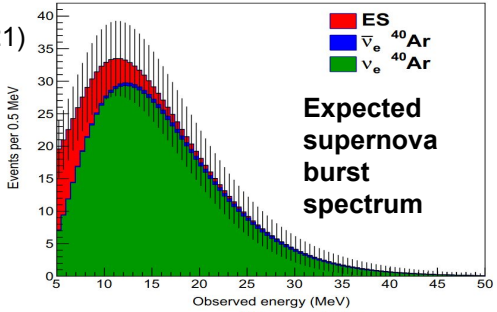


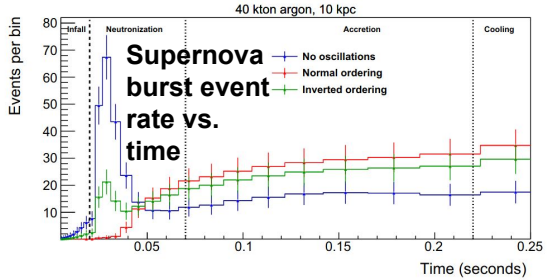
More in Chris Marshall's DUNE long-baseline talk: Sep. 8th 2021, 13:24 CET

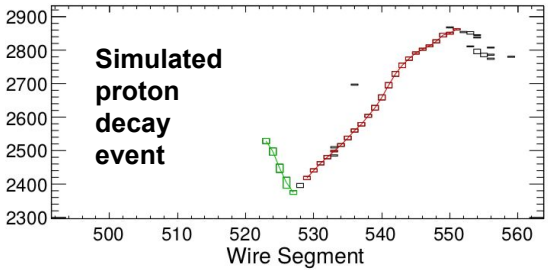
Beyond Long-baseline Neutrino Oscillation

EPJC 81, 423 (2021)

- DUNE covering a broad range of measurements: supernova neutrinos, solar neutrons etc.
- DUNE providing a wide range of BSM measurements
  - Baryon number violation such as proton decay: sensitive to K decay
  - Sterile neutrinos: Combination of ND and FD to boost the sensitivity to the sterile mixing
  - Dark matter: ND to detect the beam-related and FD to detect the external dark matter
  - Non-standard interaction, CPT violation, Non-unitarity of neutrino mixing matrix, neutrino trident at ND etc.
  - More results in EPJC 81 (2021) 4,322, EPJC 81 (2021) 5,423.







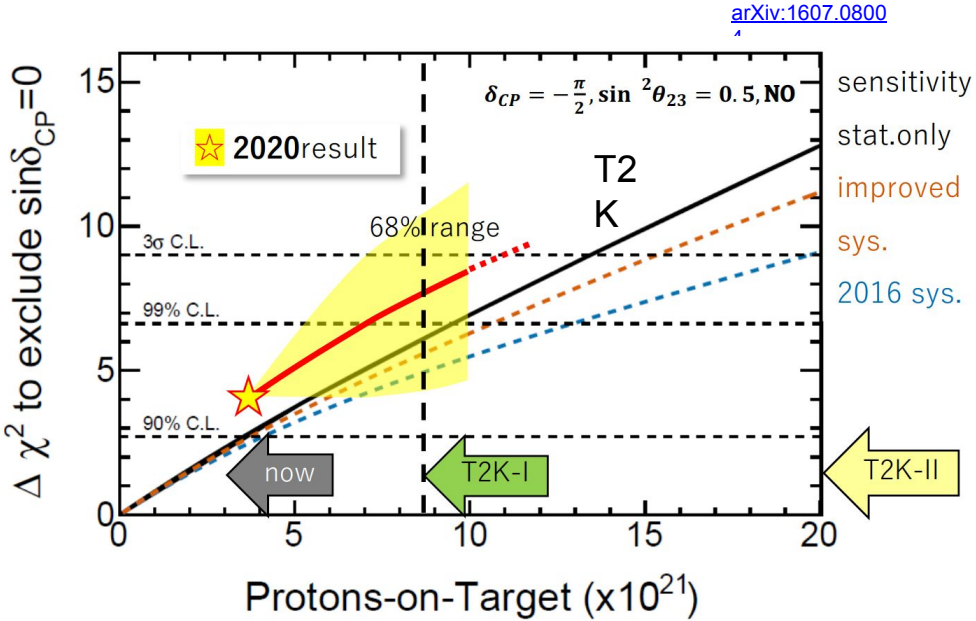
Summary

- DUNE providing a unique opportunity to measure the CP violation and mass hierarchy
  - Broadband high-intensity beam
  - Complex near detector able to disentangle degenerate systematic uncertainties
  - Massive deep-underground far detectors with a very long baseline
- DUNE being working hard toward successful measurements
  - TDR for DUNE FD completed: JINST 15 (2020) 08, T08008, T08009, T08010, FERMILAB-PUB-20-025-ND
  - CDR for DUNE ND completed: FERMILAB-PUB-21-067-E-LBNF-PPD-SCD-T
  - ProtoDUNE as a successful demonstration of technology: JINST 15 (2020) P12004
  - A significant amount of FD and ND prototyping effort
- Plenty of room for additional collaborators

Backups

T2K limitation

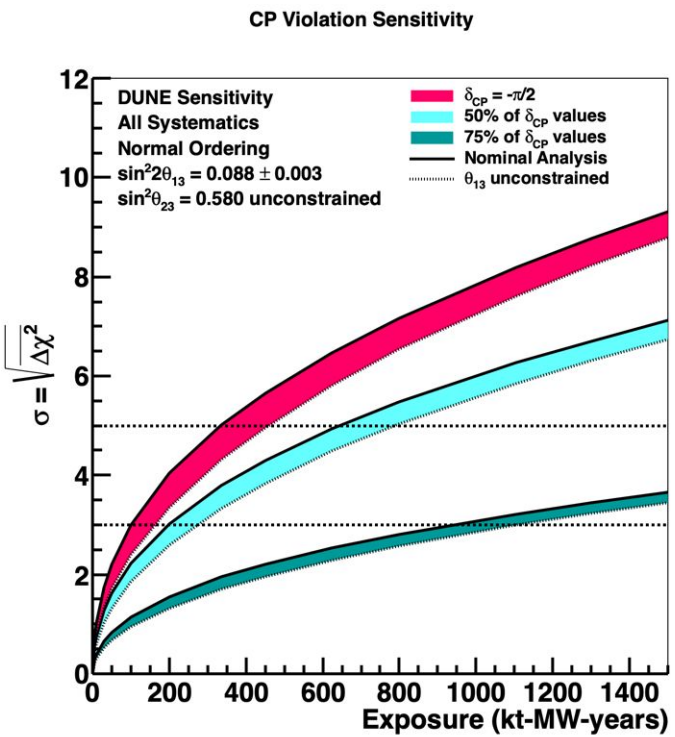
- T2K sensitivity vs. time

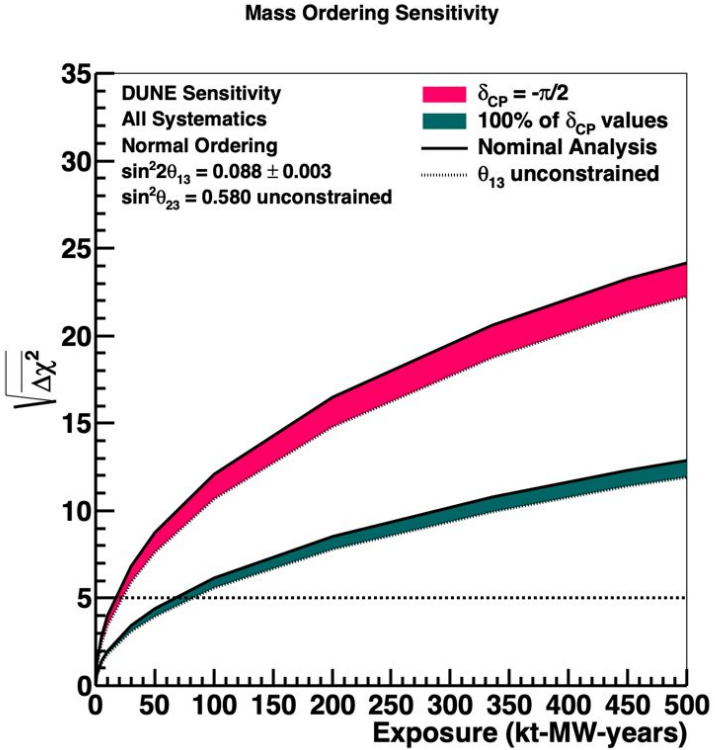


ProtoDUNE detector

TPC configuration	Anode-Cathode-Anode (2 active volumes)
TPC dimensions (active volumes)	6.086 (h) × 3.597 (w) × 7.045 (l) m^3
(instrumented volumes)	5.984 (h) × 3.597 (w) × 6.944 (l) m^3
Total active volume (nominal, at room T)	2 ×154 m^3
Total instrumented LAr mass (87.65 K)	419 t
Number of TPC wire planes	4 (G, U, V, X)
Number of wires (total)	15360 (instrumented)
G: Grid plane	2 × 2880 (non-instrumented)
U: 1st induction plane	2 × 2400 (instrumented, wrapped)
V: 2nd induction plane	2 × 2400 (instrumented, wrapped)
Z: TPC-side collection plane	2 × 1440 (instrumented)
C: Cryostat-side collection plane	2 × 1440 (instrumented)
Wire orientation (w.r.t. vertical)	G: 0°, U: +35.7°, V: −35.7°, X: 0°
Wire pitch (normal to wire direction)	4.79 mm (G, X); 4.67 mm (U, V)
Wire type	Cu-Be Alloy #25, diam. 150 μm
Gap width between planes	4.75 mm
E-Field (nominal) in drift volume	500 V/cm
Cathode plane voltage	−180 kV
Anode plane bias voltages	G: -665 V, U: -370 V, V: 0 V, X: +820 V
Ground mesh	0 V
Max. drift length (Cathode-to-G-plane distance at 87.65 K)	3572 mm
Drift velocity (nominal field, 87.65 K)	1.59 mm/μs
Max. drift time (nominal field, 87.65 K)	2.25 ms

DUNE δ_{CP} sensitivity projection

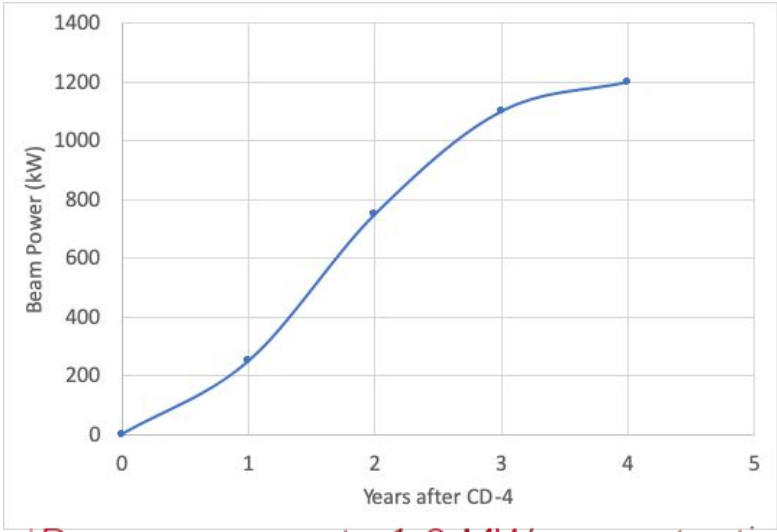




Summary

- Exposure as a function of time depending on details of detector installation schedule, PIP-II beam power ramp-up and accelerator uptime that not fully determined yet
- To avoid dependence on details of the project schedules, DUNE exposure presented in terms of kt-MW-years
- As a reference:
  - Early: 1 calendar year ~ 24 kt-MW-years with 2 FD modules at full nominal intensity of 1.2 MW
  - Long-term: 1 calendar year ~ 96 kt-MW-years with full FD and upgraded 2.4 MW intensity
  - 56% uptime assumed based on historical NuMI operations

PIP-II Nominal Power Ramp-up



*Power ramp up to 1.2 MW can potentially be reduced to 2.5 years

*Power ramp expected to begin before DUNE comes online, such that initial DUNE power is >0