Deep Underground Neutrino Experiment - Physics and Technology

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Warsaw High Energy Physics Seminar

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Lancaster University

DUNE

Neutrino Mixing & Oscillation

- Neutrinos have non-zero mass
- Mass states are not the same as the flavor states; flavor states may be written as linear combination of mass states (and vice versa) using a mixing matrix

$\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau$
are the flavor states

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

$\nu_k = \nu_1, \nu_2, \nu_3$
are the mass states

- Oscillation probability depends on the mixing angles, Δm^2 (mass differences), and L/E (baseline/energy)

2 neutrino case:

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

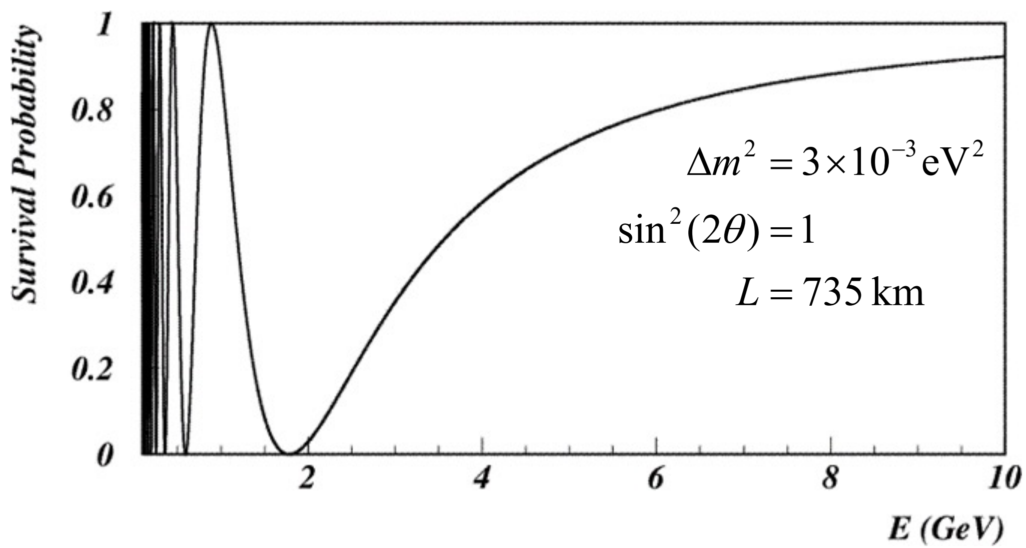
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Simplified neutrino oscillations

$$\nu_\mu \longrightarrow \nu_1, \nu_2 \longrightarrow \nu_\mu \text{ or } \nu_\tau$$

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences



Matter Effects

- Simplified treatment: two neutrinos only

In vacuum

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

in matter

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_m)\sin^2\left(\frac{\Delta m_m^2 L}{4E}\right)$$

$$\text{with } \sin(2\theta_m) = \frac{\sin(2\theta)}{\sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}}$$

$$\Delta m_m^2 = \Delta m^2 \sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}$$

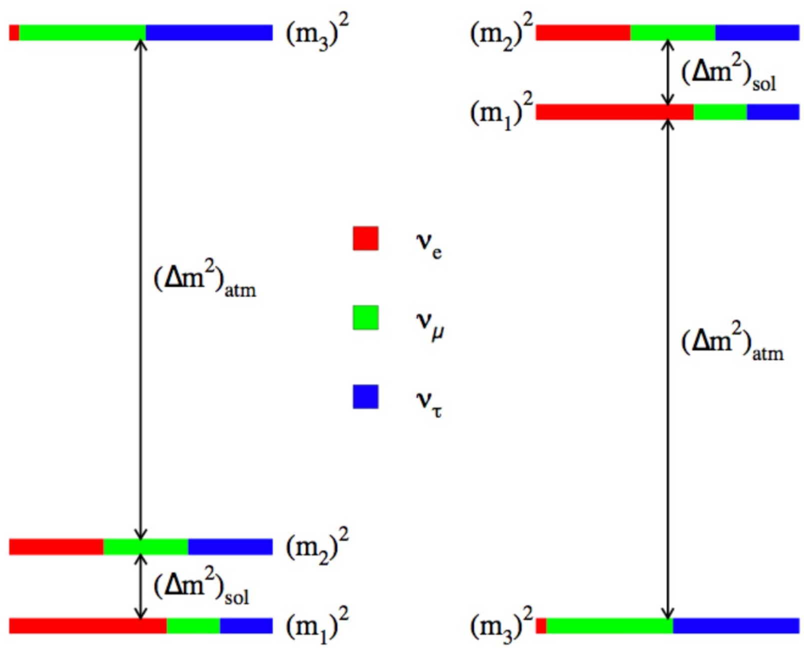
$$A = \pm\frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

- Matter modifies oscillation probability
  - Sign of mass difference matters (opposite for anti-v)
  - Larger effect at higher energies and longer baseline

Mass Ordering

Neutrino mass “ordering” or “hierarchy” (sign of Δm^2_{23}) is unknown.

Normal ordering



Inverted ordering

$$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\ \text{eV}^2$$
$$|\Delta m^2_{32}| \approx 2.5 \times 10^{-3}\ \text{eV}^2$$

PMNS Matrix

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle \quad \Rightarrow \quad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **$\theta_{23} \approx 45^o$**
- ν_μ disappearance
- Octant unknown (new symmetry?)

- **$\theta_{13} \approx 10^o$**
- ν_e appearance in ν_μ beam or reactor neutrino experiments

- Large uncertainty in δ_{CP} (CP violation?)

- θ_{12} **$\approx 35^o$**
- Solar neutrinos

Three flavour oscillations

Appearance

θ₁₃ dependence | Octant Sensitivity | CP odd phase

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \times \left(1 \pm \frac{2a}{\Delta m_{31}^2}(1-s_{13}^2)\right)$$ Leading term

$$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Conserving

$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\frac{aL}{4E}(1-2s_{13}^2)$$ Matter effect

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Violating

$$+4s_{12}^2 c_{13}^2(c_{12}c_{23} + s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta)\sin^2\Delta_{21}$$ Solar term

ν vs. $\bar{\nu}$ sign change

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_{..}}$ $a = 2\sqrt{2}G_F n_e E$

Disappearance

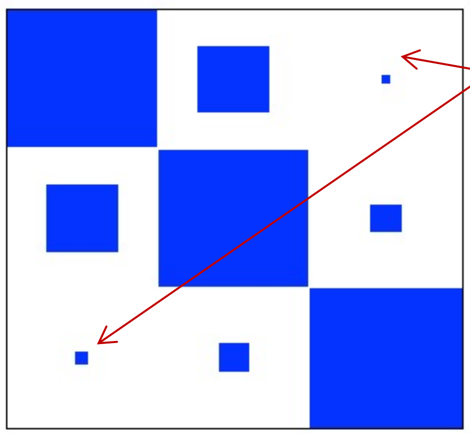
θ₂₃ dependence | Octant Sensitivity

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23}\right)\cdot\sin^2\frac{\Delta m_{32}^2 \cdot L}{4E_\nu}$$

$$P_{PMNS}(\bar{\nu}_\mu \to \bar{\nu}_\mu) = P_{PMNS}(\nu_\mu \to \nu_\mu)$$ Test of CPT

CP violation neutrinos vs. quarks

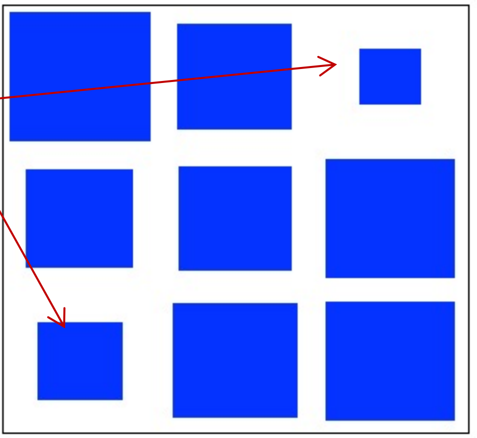
CKM matrix



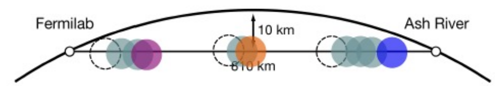
The CP violation phase
At the most off-diagonal elements

CPV can be ~1000 bigger in neutrino sector.

PMNS matrix



T2K & NOvA



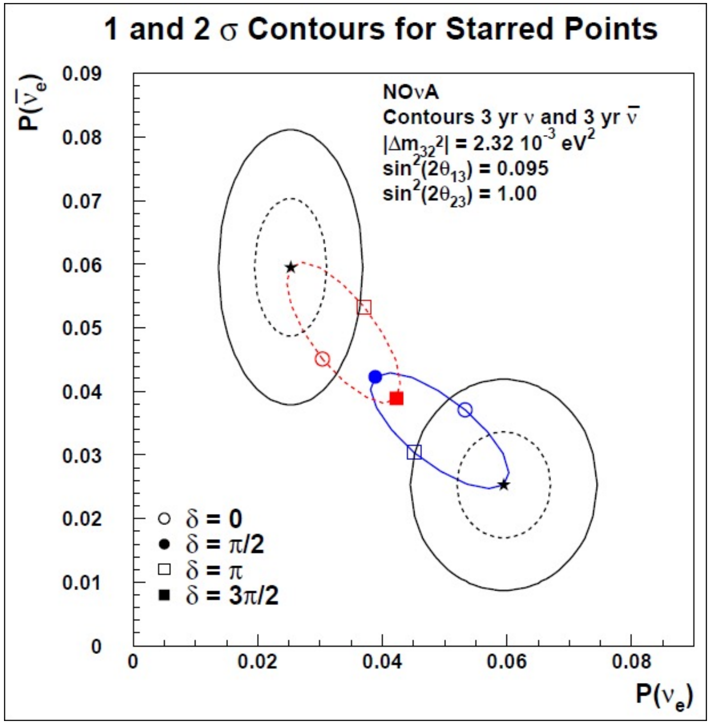
- Neutrino Beam from j-parc
  - Beam power 50 – 550 kW
  - Peak at ~600 MeV
  - Baseline 295 km
- Far Detector
  - Super-Kamiokande
  - 40 kton water Cherenkov

- Neutrino Beam from Fermilab
  - Beam power ~650 kW
  - Peak at ~2 GeV
  - Baseline 810 km
- Far Detector
  - 14 kton liquid scintillator
  - mineral oil

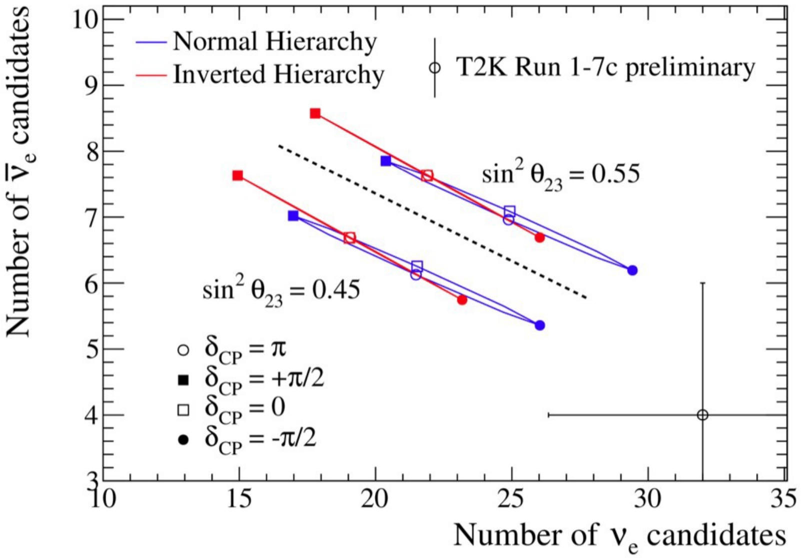
Principle of CP violation measurements

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e)$$

NOvA



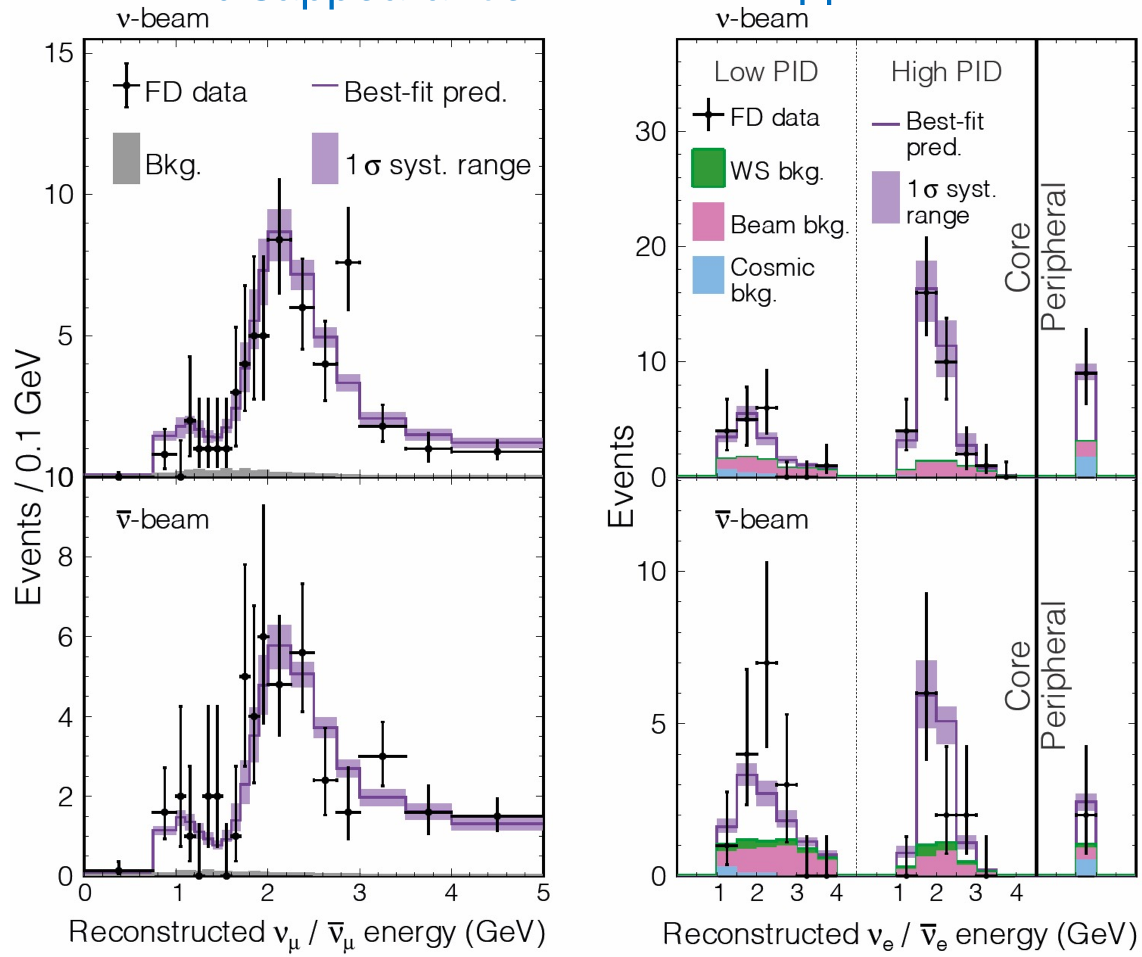
T2K



NOvA oscillation results

Muon Neutrino disappearance

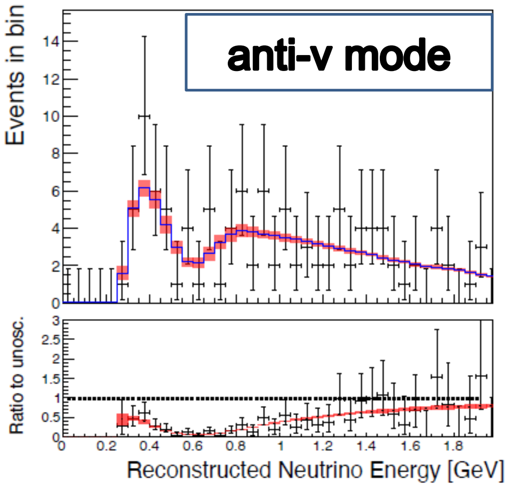
Electron Neutrino Appearance

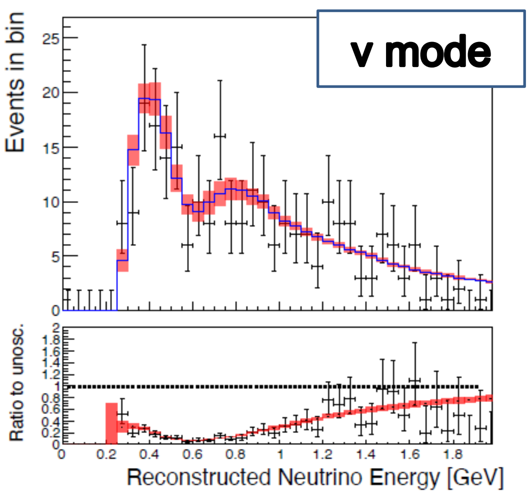


>4σ evidence of $\bar{\nu}_e$ appearance

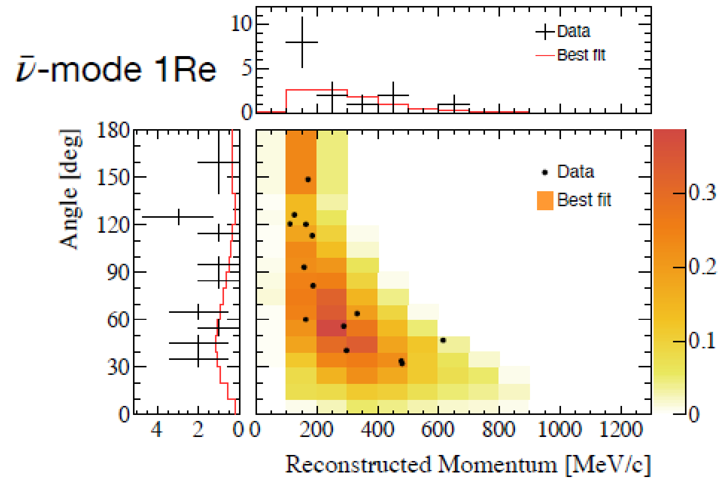
T2K oscillation results

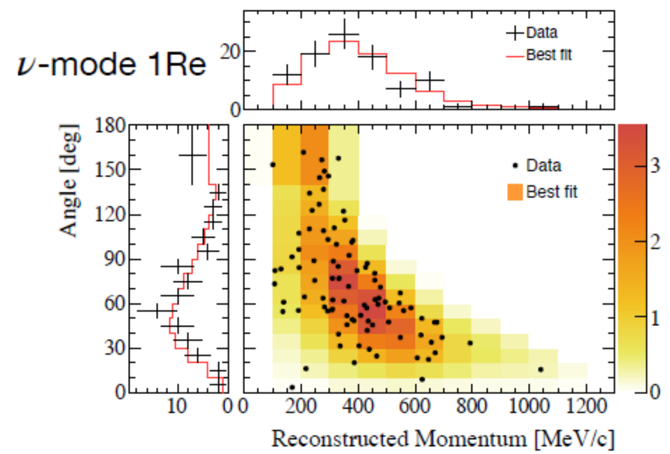
Muon Neutrino disappearance



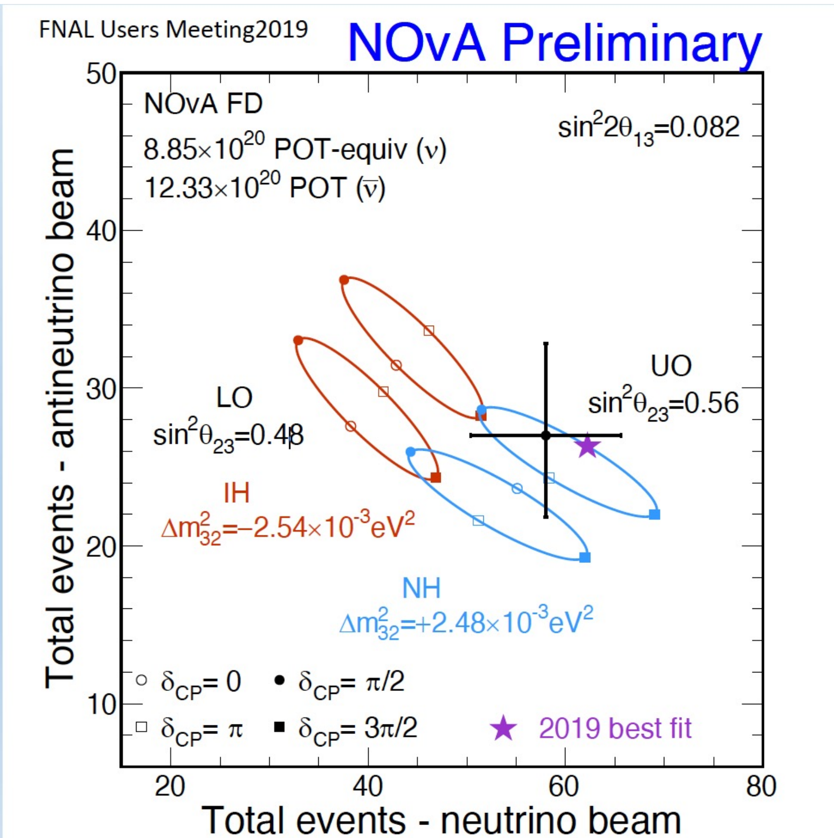


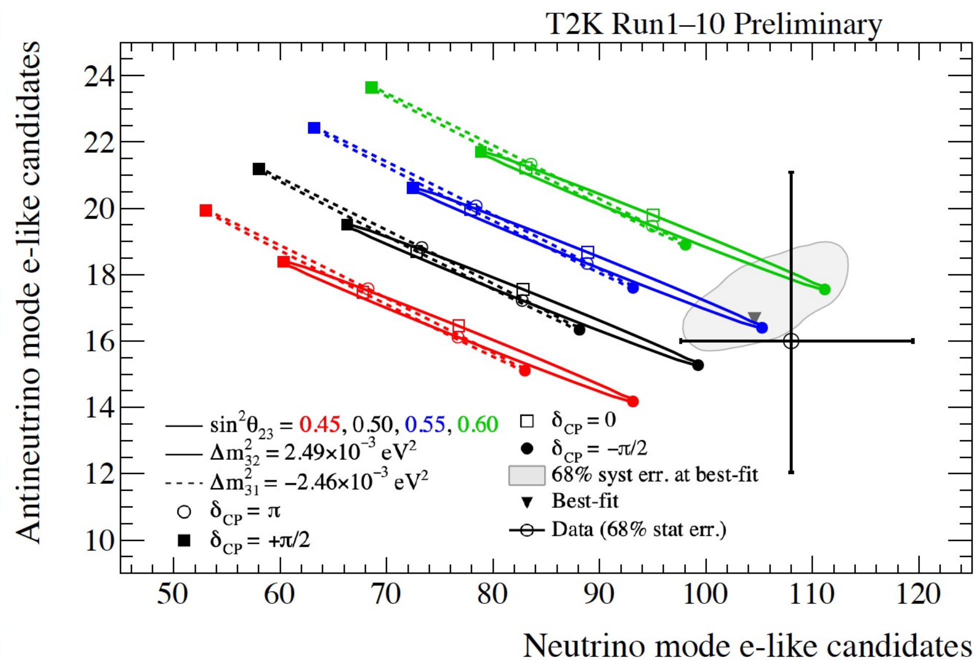
Electron Neutrino Appearance



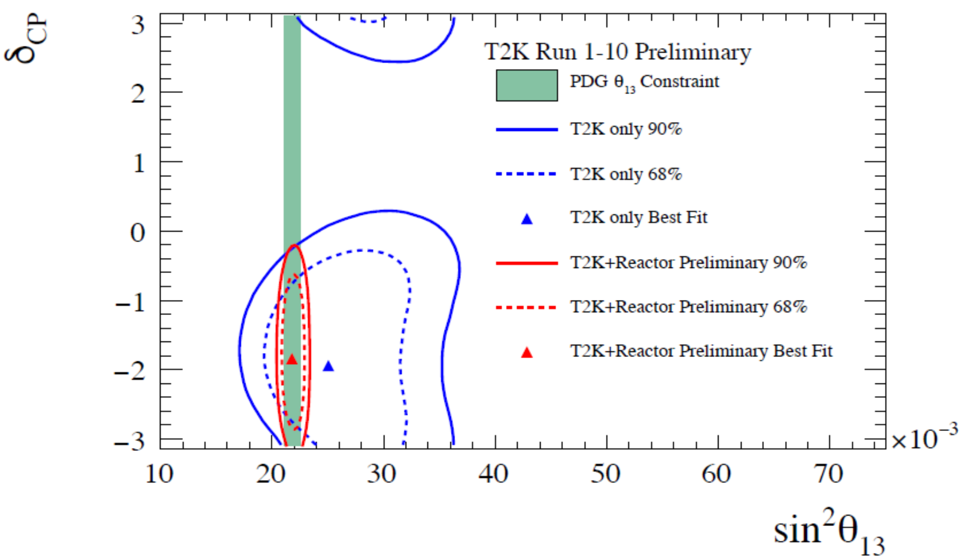


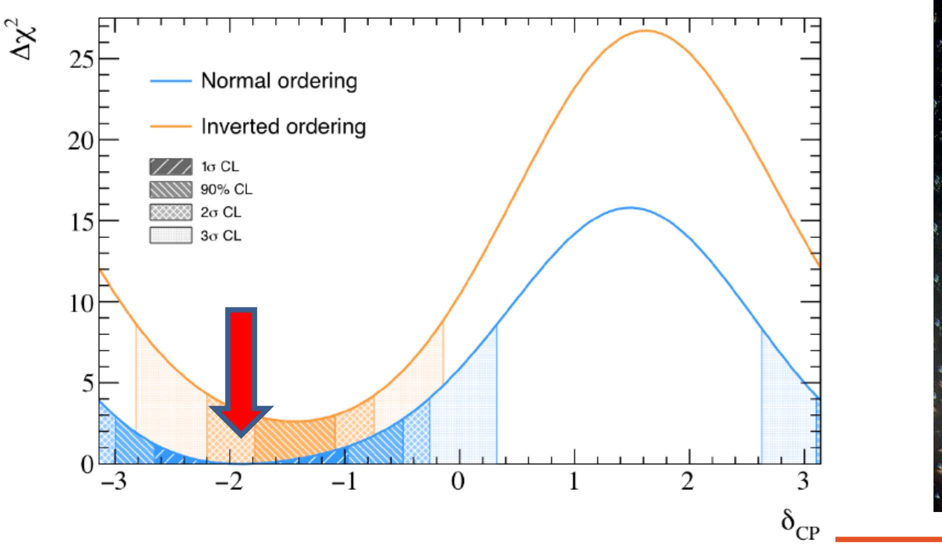
T2K & NOvA


FNAL Users Meeting2019
NOvA Preliminary
NOvA FD
8.85×10^20 POT-equiv (ν)
12.33×10^20 POT (ν̄)
sin²2θ13=0.082
LO
sin²θ23=0.48
UO
sin²θ23=0.56
IH
Δm²32=−2.54×10⁻³eV²
NH
Δm²32=+2.48×10⁻³eV²
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
2019 best fit
Total events - antineutrino beam
Total events - neutrino beam


T2K Run1–10 Preliminary
sin²θ23 = 0.45, 0.50, 0.55, 0.60
Δm²32 = 2.49×10⁻³ eV²
Δm²31 = −2.46×10⁻³ eV²
δCP = π
δCP = +π/2
δCP = 0
δCP = −π/2
68% syst err. at best-fit
Best-fit
Data (68% stat err.)
Antineutrino mode e-like candidates
Neutrino mode e-like candidates

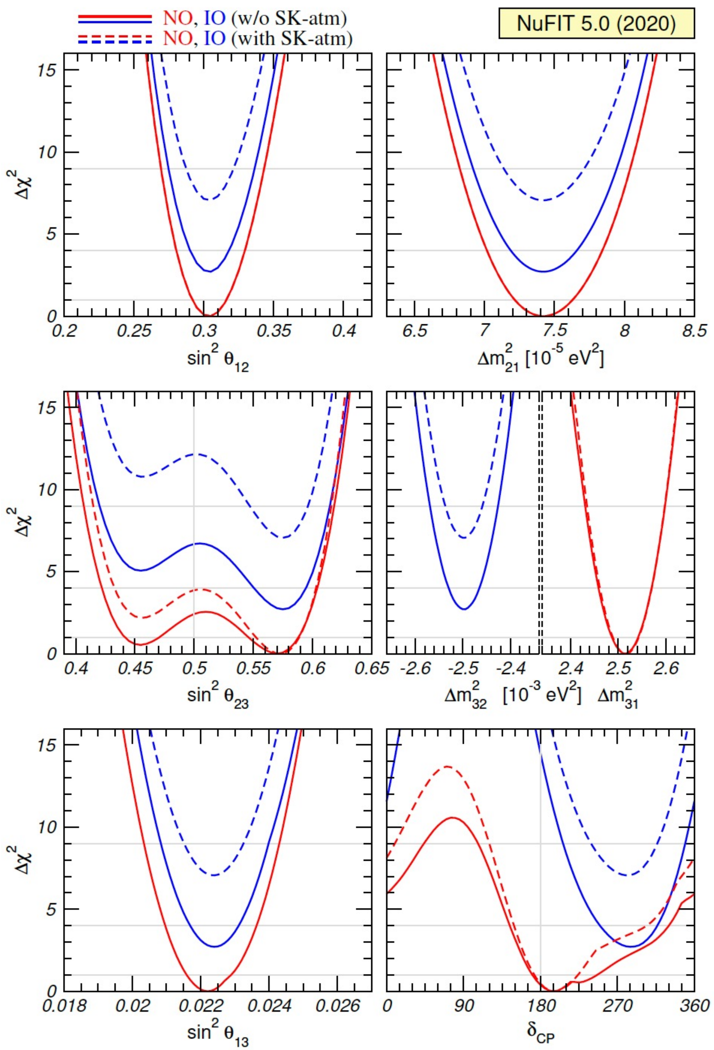
T2K Appearance Results





δ_{CP}

Current Knowledge (NuFit 5.0)



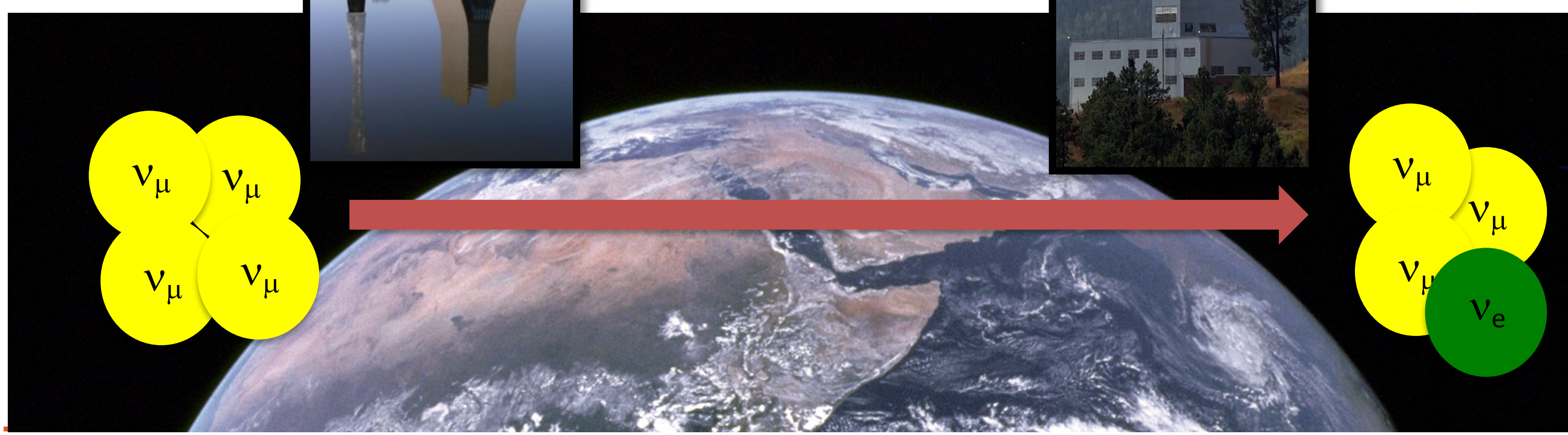
- Sign of larger mass splitting unknown; some preference for normal ordering
- θ_{23} octant unknown; some preference for upper octant
- δ_{CP} unknown; significant regions of possible phase space excluded at 3σ
- Currently running long-baseline experiments: T2K & NOvA
  - Recent result from T2K: *Nature* **580,** 339–344 (2020).
  - Latest result from NOvA: *Phys.Rev.Lett.* 123 (2019) 15, 151803

Esteban, Gonzalez-Garcia, Maltonil, Schwetz, Zhou [JHEP 09 (2020) 178]

Long-Baseline Experiment

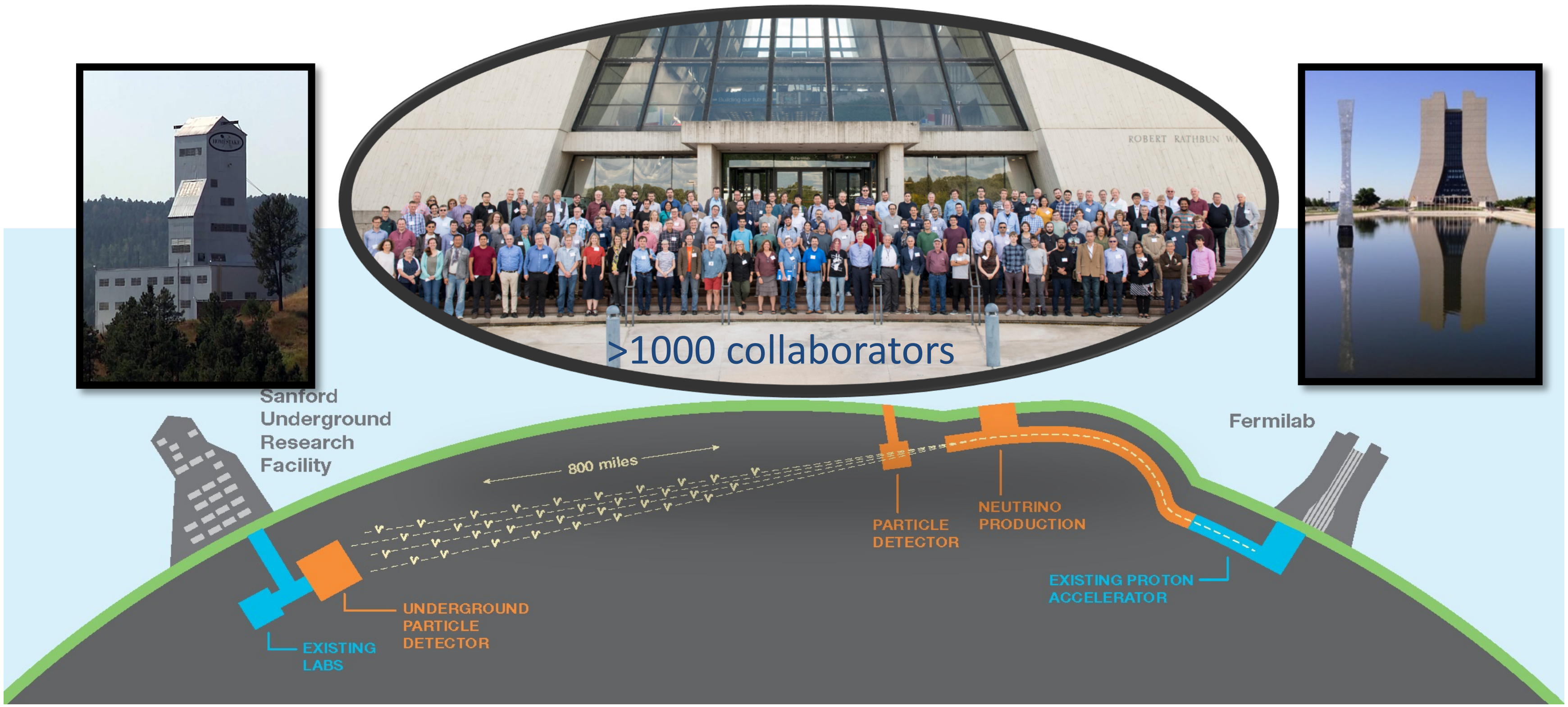
"Muon" neutrino beam created at accelerator complex → Composition of neutrino beam measured by near detector → Neutrinos travel 100s of kilometers through the Earth → Composition of neutrino beam after oscillation measured by far detector → Neutrino spectra analyzed to extract oscillation parameters

Two operational modes make either neutrino or antineutrino dominated beam



DUNE

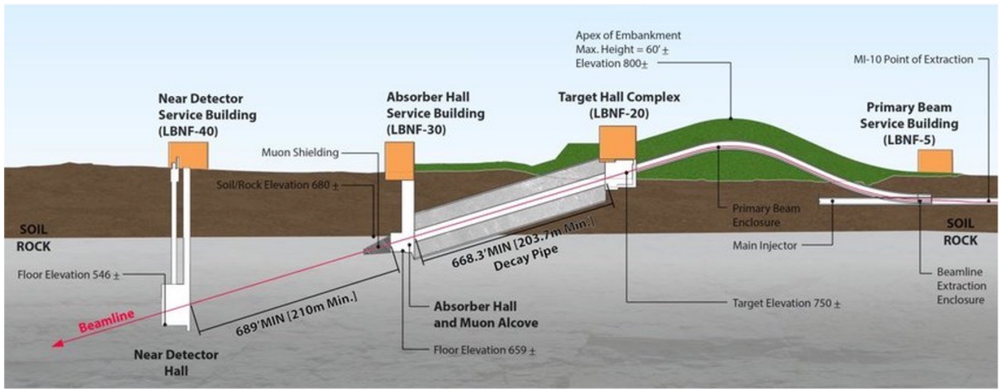
Measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km to measure mass ordering, CP violation, and neutrino mixing parameters in a single experiment. Large detector, deep underground allows sensitivity to rare processes and low-energy physics.

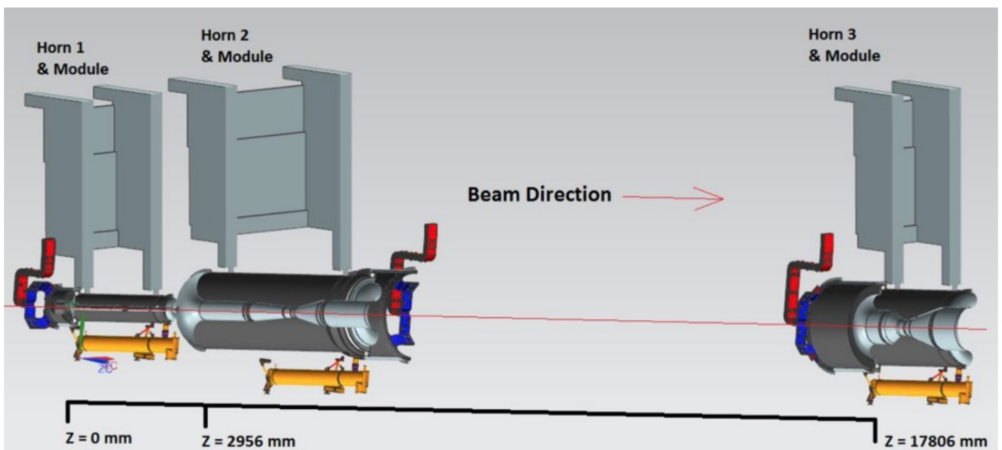


The DUNE Collaboration

- World-spanning community
- Draws on years-long experience of LAr-TPC based neutrino experiments
  - > 1300 collaborators
  - > 200 institutions & CERN
  - 33 countries

LBNF Neutrino Beam

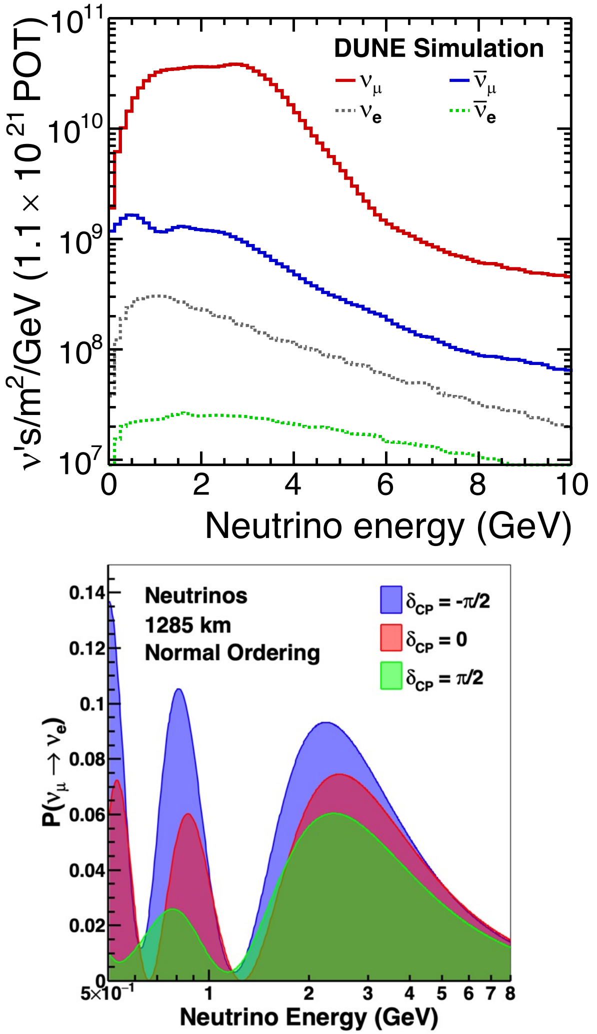




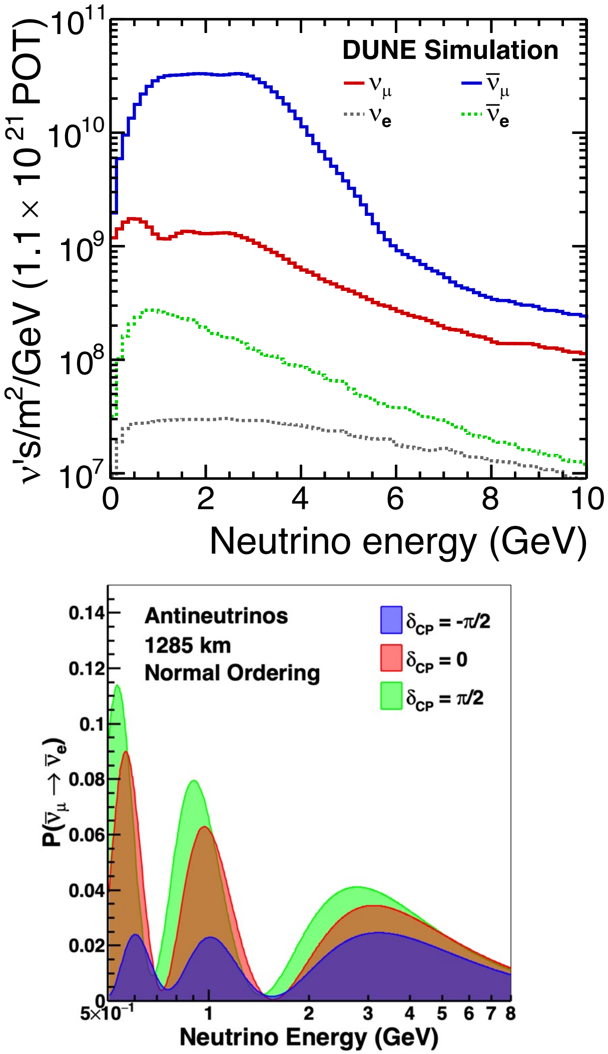
- 120-GeV protons from FNAL accelerator complex
- 5.8 degree vertical bend, to reach SURF
- 1.2 MW beam power, upgradeable to 2.4 MW
- Neutrino beam line designed using genetic algorithm to optimize CP violation sensitivity

Neutrino Flux

Neutrino Mode:

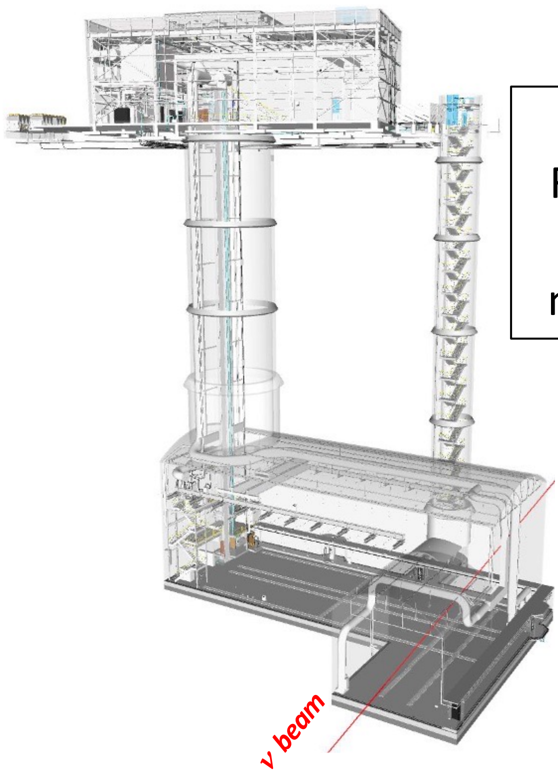


Antineutrino Mode:

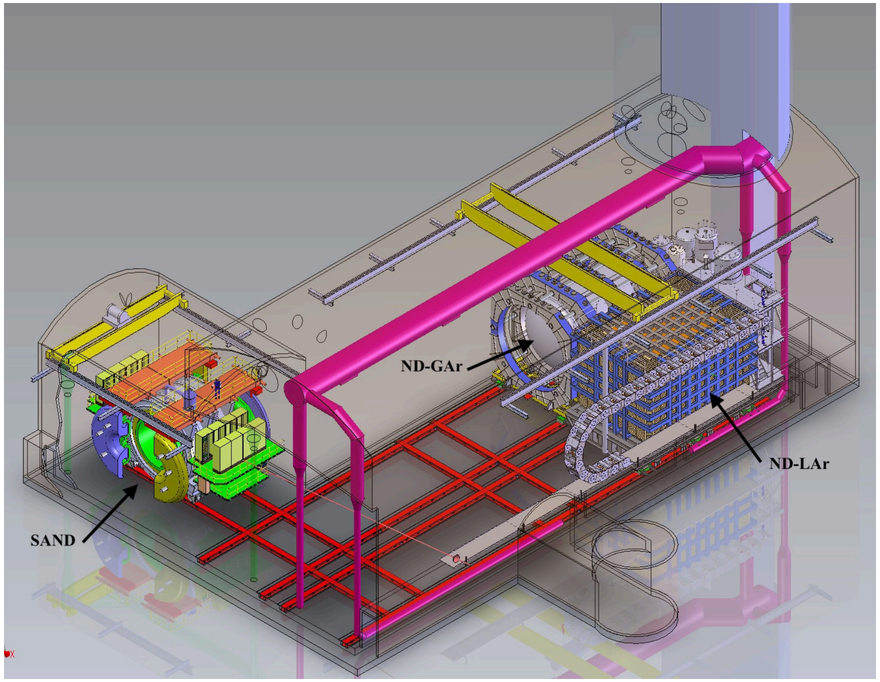


LBNF Near Detector

- Located 574 m from neutrino beam target
- Primary purpose is to constrain systematic uncertainty for the long-baseline oscillation analysis



ND Facility (3D model)



The Near Detector Station

- Multiple complementary systems:

ND-LAr: modular, pixelated charge read-out LAr-TPC (300 ton)

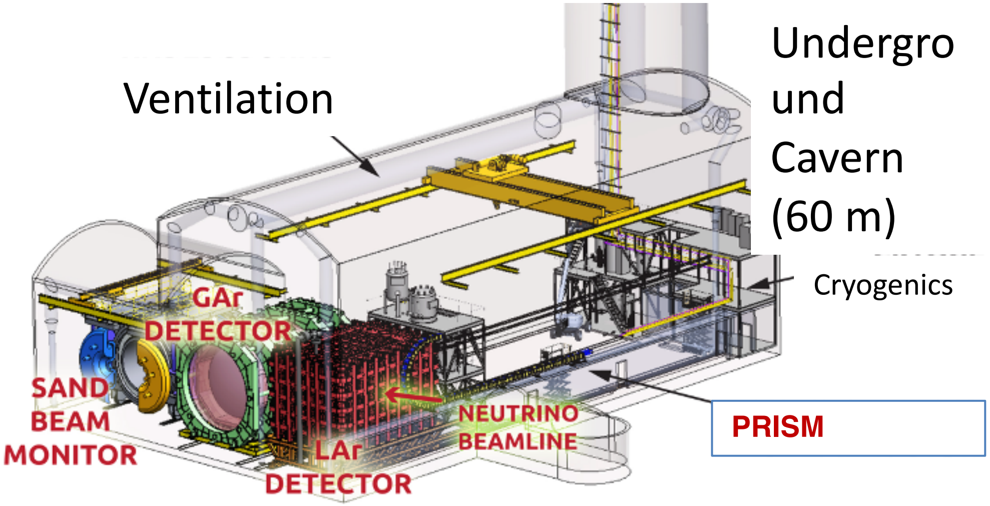
- Primary target
- Most similar to FD

ND-GAr: high-pressure GAr-TPC, surrounded by ECAL and magnet

- intercepts muons escaping LAr-TPC
- Muon spectrometer; nuclear interaction model constraints
- Will come at a later stage. A Temporary Muon Spectrometer (TMS) will be installed at Day 1

SAND: inner tracker surrounded by 100 ton ECal and SC magnet (0.6 T)

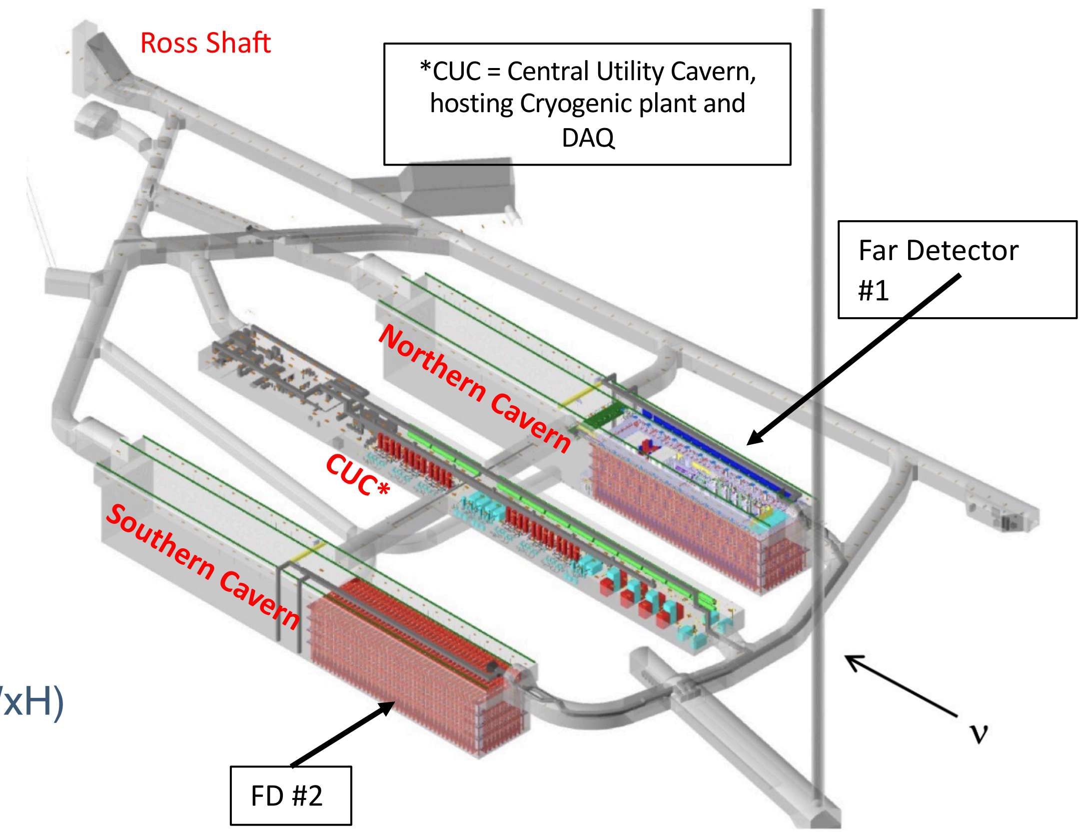
- On-axis beam monitor (spectrum/stability)



PRISM: ND-LAr and TMS/ND-GAr can move up to 30 m Off-axis for beam characterization and lower-energy ν detection

Far Detector Site - SURF

- 4 Detector modules, ~17 kton total volume each
  - Construction in stages
- **FD #1, #2** will be **single-phase (SP) LAr-TPCs,** with Horizontal Drift (HD) and Vertical Drift (VD), respectively
- FD #1 construction starts in mid 2020's
- Maximal cryostat external dimensions: ~ 66 x 19 x 18 m (LxWxH)



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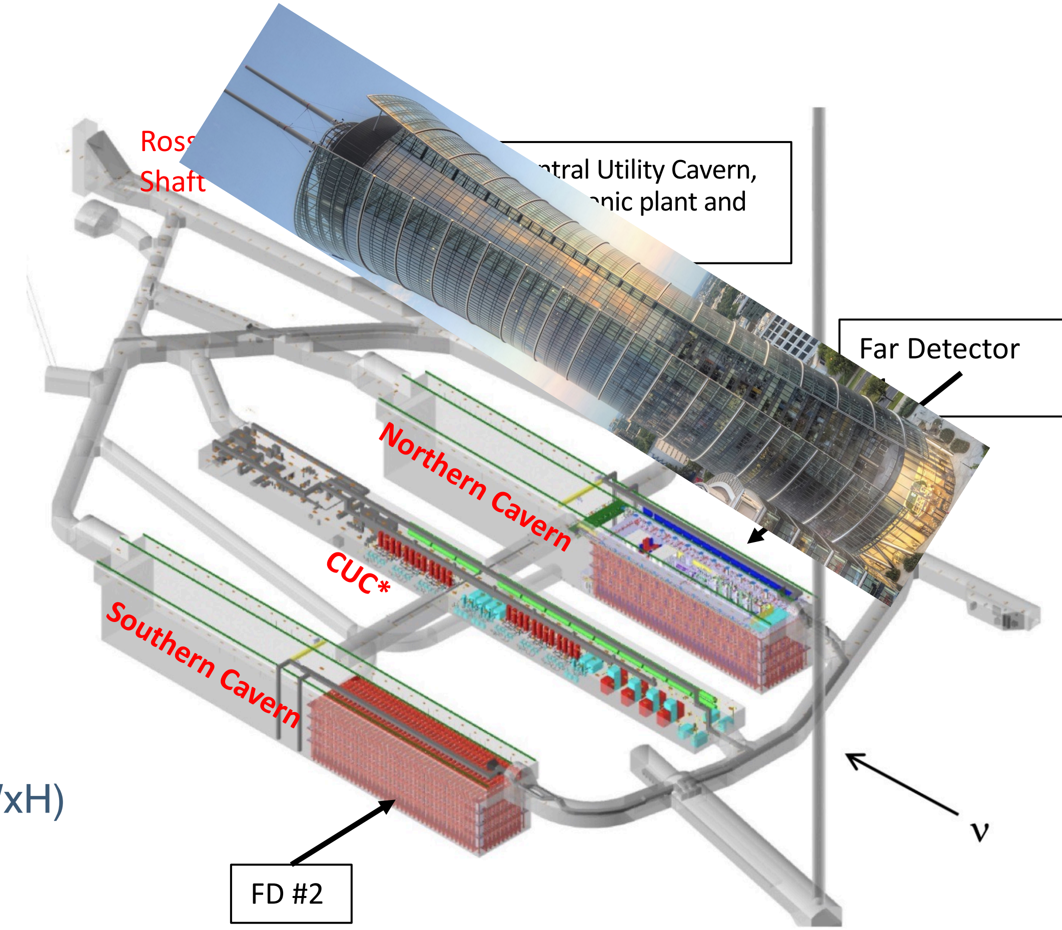
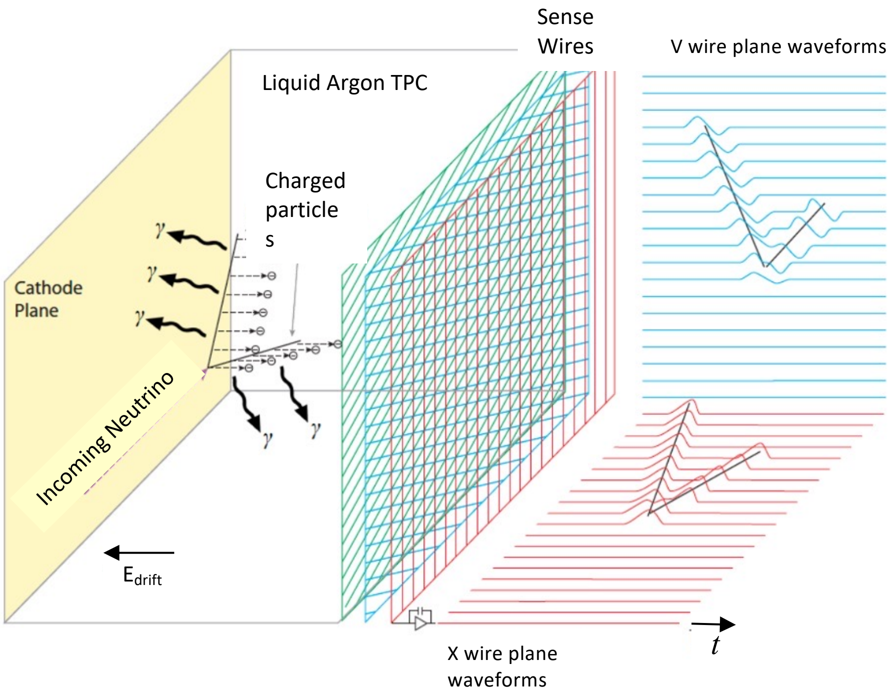


LAr-TPC technology

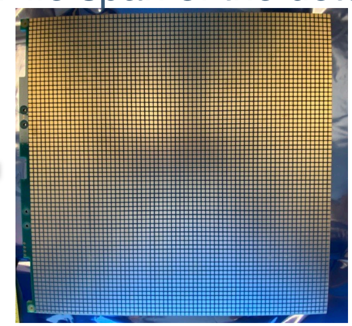
- Charge/light production and collection with wire read-out (HD technology)

- Mature, reliable technology (ICARUS, MicroBooNE)
- Fully compatible with very-long expected life span of the detectors

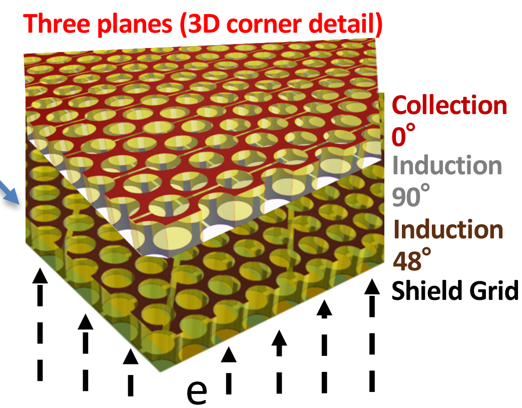


Other read-out solutions:

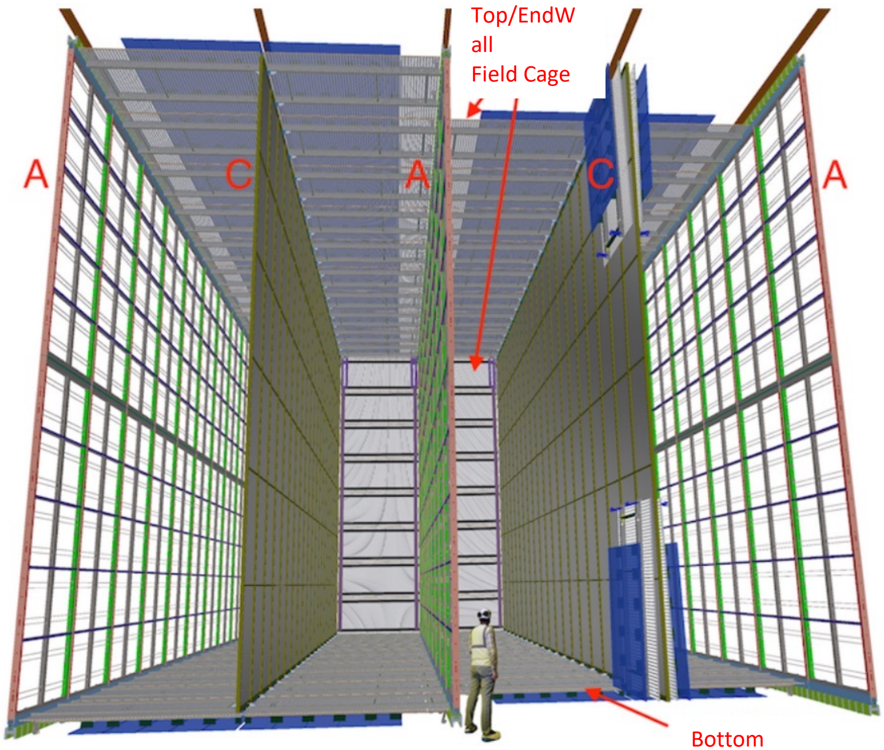
- Pixels (ND LAr-TPC)
- Perforated PCBs (Vertical Drift)



LArPix anode
32 x 32 cm
4.9k pixels

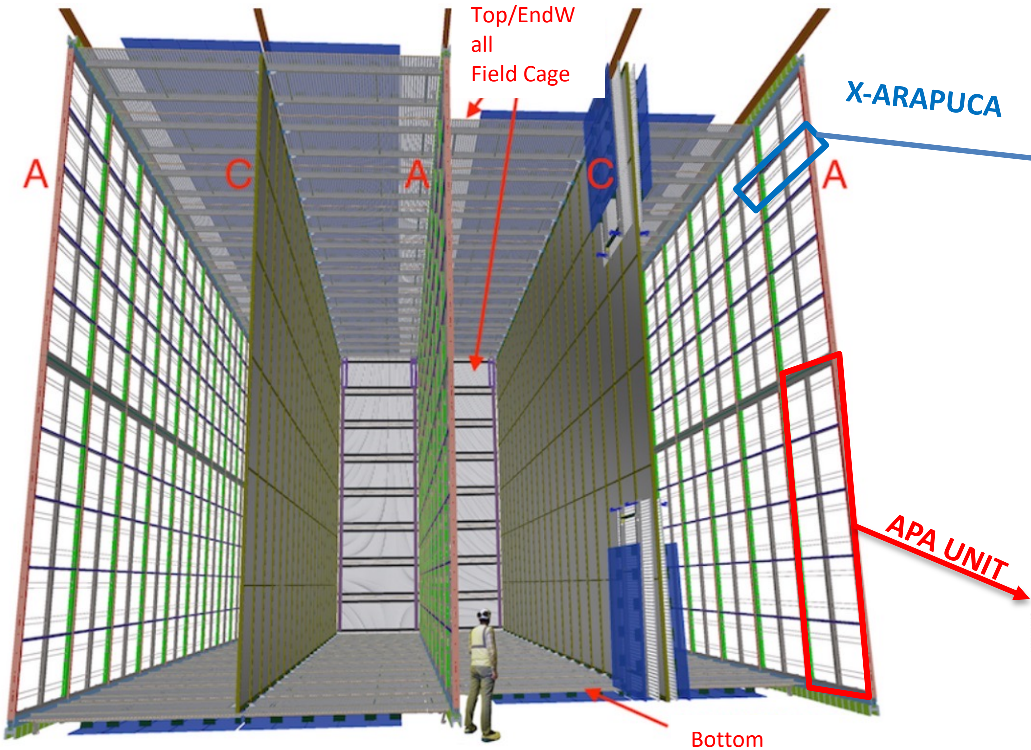


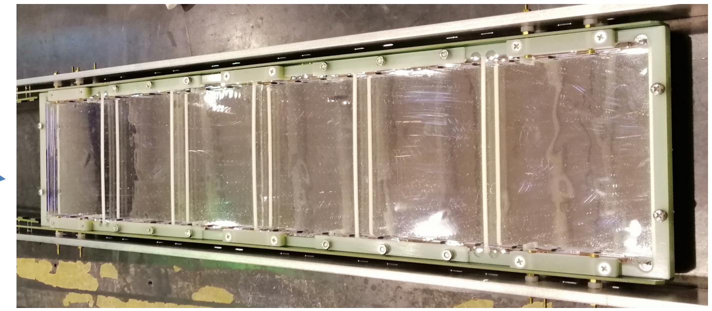
Far Detector #1 (Horizontal Drift)



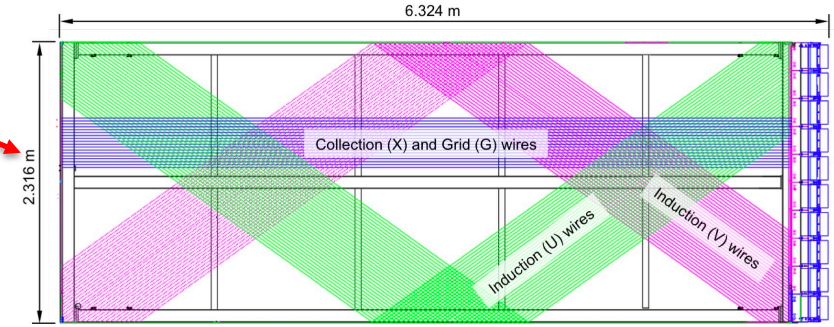
- Structure wholly suspended on roof
- Alternating Anode and Cathode Plane Assemblies (APA – CPA)
  - 4 drift volumes, 3.6 m drift / Electric field = 500 V/cm (HV = -180 kV)
  - High-resistivity CPA for fast discharge prevention
- Anode: 150 APAs, each with 4 wire planes (Grid, 2 x Induction, Collection)
  - Wrapped induction wires
- Photon Detectors: X-ARAPUCA light traps
  - 10 modules / APA
  - Timing
  - Cosmic / SN / BSM event triggering

Far Detector #1 (Horizontal Drift)





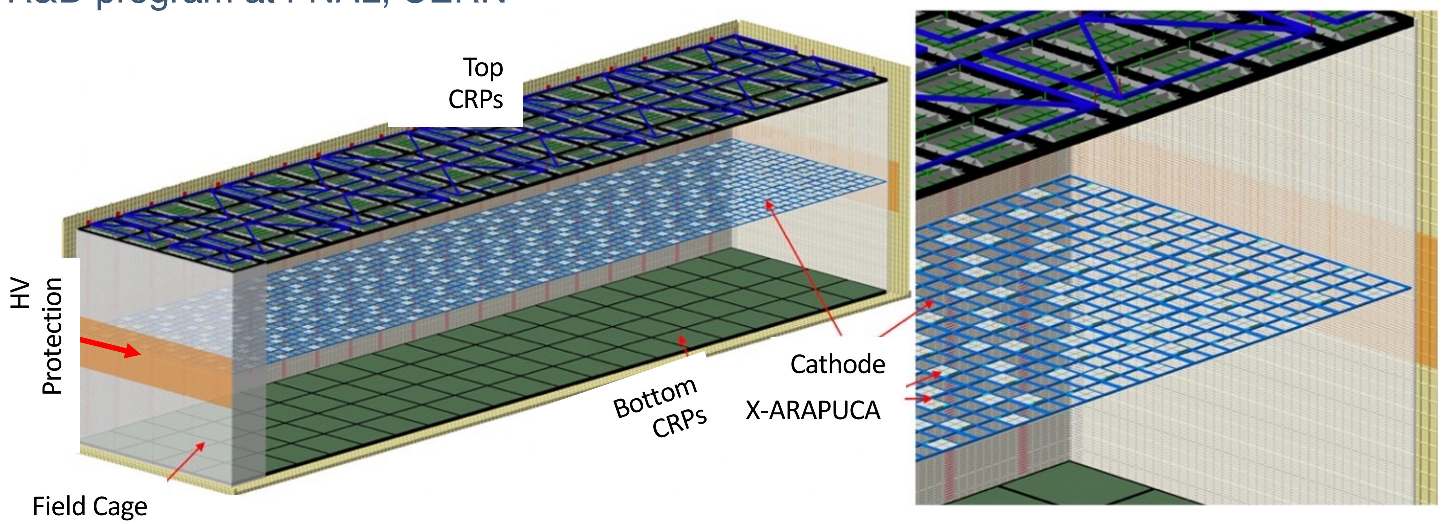
1 SuperCell = ¼ PDS module -- SiPM readout
High-reflectivity inner surfaces
Wavelength-shifting + dichroic filter for light trapping



2560 wires/unit -- Inter-plane distance = 4.75 mm

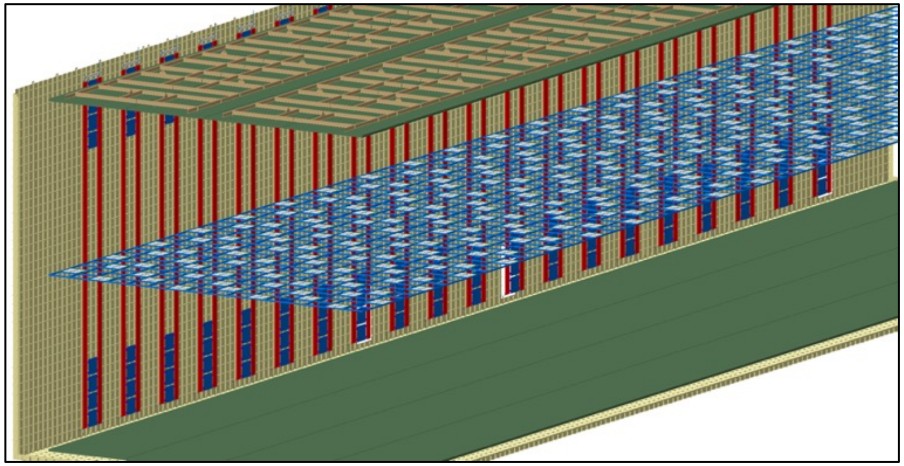
Far Detector #2 (Vertical Drift)

- Single-phase, read-out on cryostat top and bottom
- 2 x 6 m drift ⬄ 300 kV HV on (central) cathode
- Technological challenges on many detector aspects (HV, LAr Purity, Photon Detection,…)
- Strong R&D program at FNAL, CERN
- Dedicated CERN set-up for small-scale tests: 50 liters LAr-TPC
- Large-scale tests of anode and cathode+PD modules in dedicated "cold-box" at CERN by late 2021



Lancaster University DUNE

Far Detector #2 (Vertical Drift)



- 320 X-ARAPUCA 60 x 60 cm^2 on cathode, analog readout
- 320 X-ARAPUCA 60 x 60 cm^2 on cryostat membrane, ~3 m from cathode
  - Enhanced field cage transparency -> 70%

Photon Detection

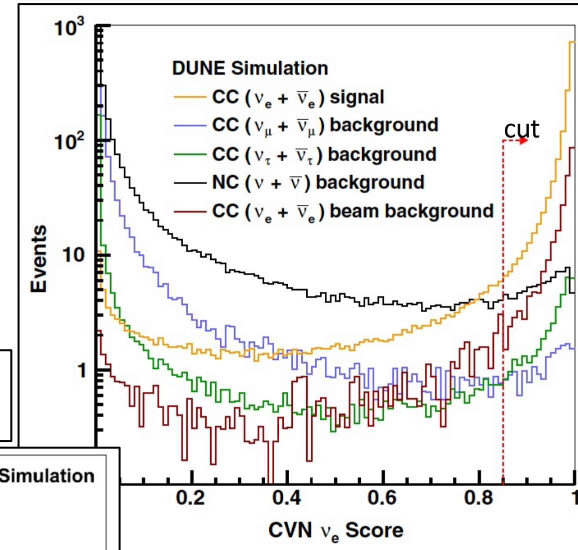
- Based on X-ARAPUCA – “4π” reference design
- SiPM and electronics partially on Cathode: @ 300 kV
- Aggressive R&D program concerning Power-over-Fiber and Signal-over-Fiber technology
- Enhanced scintillation yield by doping with Xenon (tested in ProtoDUNE SP)
- High trigger efficiency down to 10 MeV

Back-up solution foresees fully instrumented membrane, with no detectors on cathode

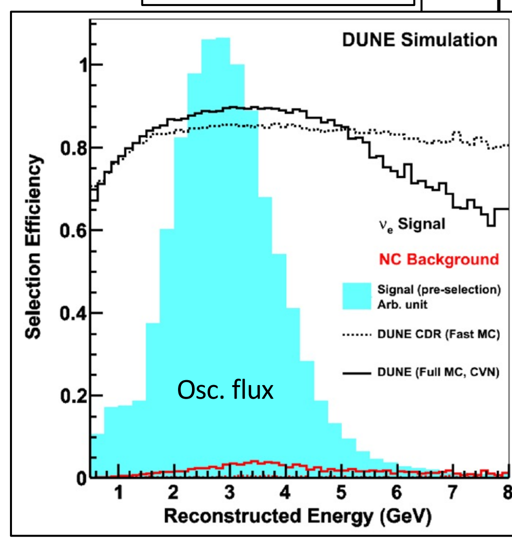
- No losses in physics requirements w.r.t. reference

Neutrino Reco/Identification

- Algorithms trained on Convolutional Neural Networks (CNN)
- Hit identification on 2D views and identification of distinct tracks/showers (clustering) with *Pandora*
  - 3D events produced from matching of 2D hits
- Neutrino event reconstruction from 2D images is the perfect input for machine learning / image analysis techniques
  - CNNs trained on, and aiming to classify, images (TPC views) -> Convoluted Visual Network (CVN)
    - 80-90% recognition efficiency for both ν_μ and ν_e
    - low mis-identification rates



ν-beam mode
3.5 y sim. exposure



- ν_e CNN score (top)
- Resulting ν_e selection efficiency with top cut (left)

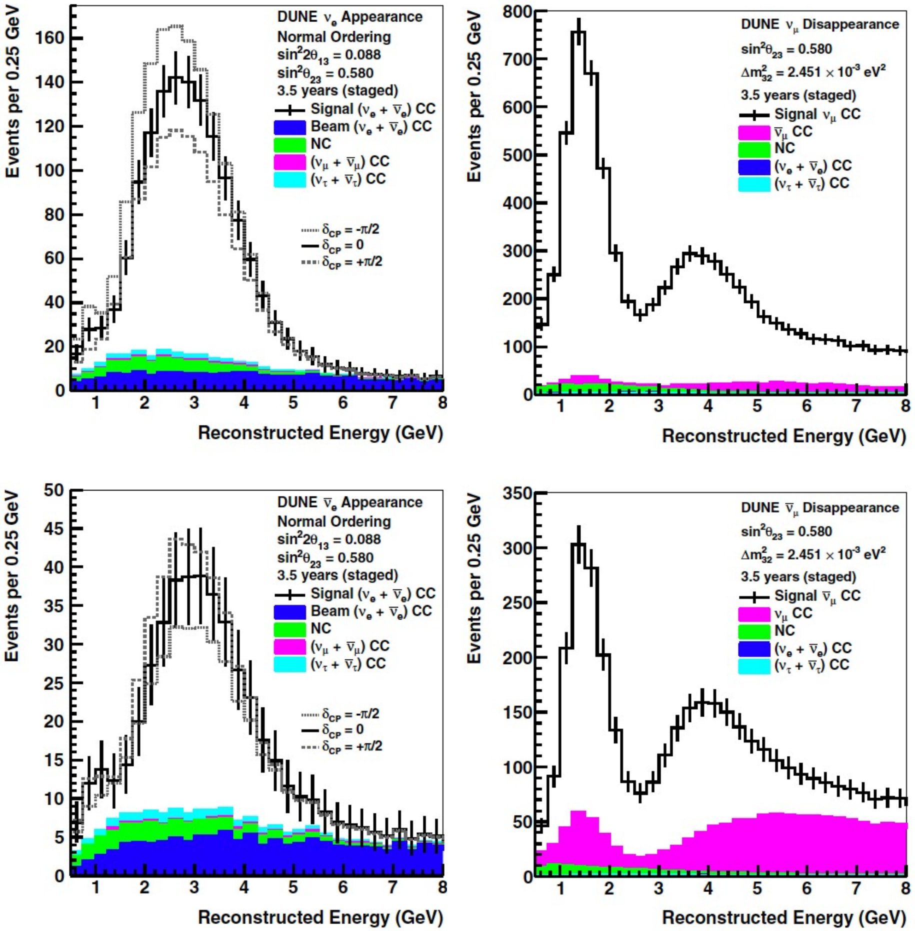
[PRD 102 (2020), 9, 092003](PRD 102 (2020), 9, 092003)

Neutrino Oscillations

- Projected results for $\nu_\mu/\overline{\nu_\mu}$ disappearance and $\nu_e/\overline{\nu_e}$ appearance, assuming:
  - normal ordering
  - 7 staged years (3.5 y ν-beam mode + 3.5 y $\bar{\nu}$-beam mode)

- Measurement and simultaneous fit of oscillation parameters over the four components of FD data
- Sensitivity assessment includes full FD systematics treatment (flux, cross-section, and detector) and ND constraints

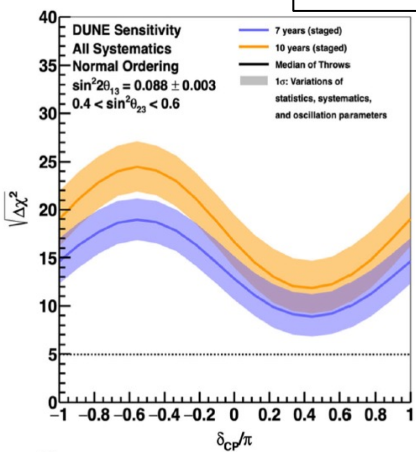
EPJC (2020) 80, 978

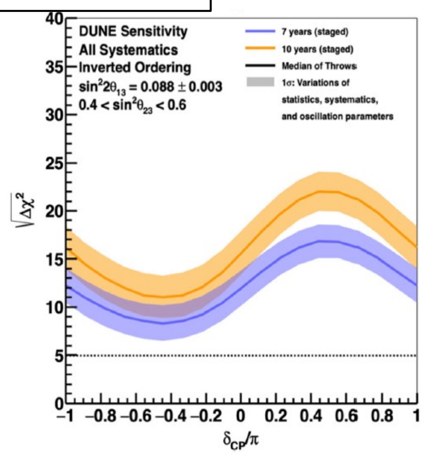


DUNE sensitivity

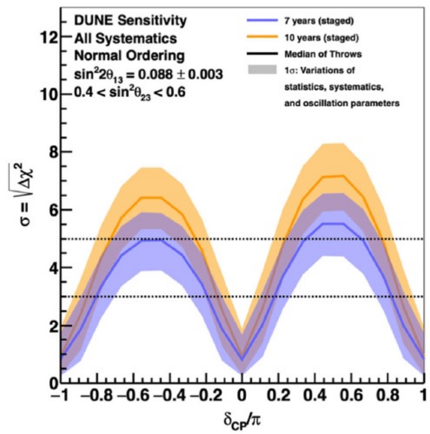
- Assumed staged running as in Technical Design Report (summing ν-beam mode and $\bar{\nu}$-beam mode)
- Potential of CP-violation (δ_{CP}) discovery in 7-10 years (left)
- 2-3 years to unambiguously determine mass hierarchy (NO vs IO, below)

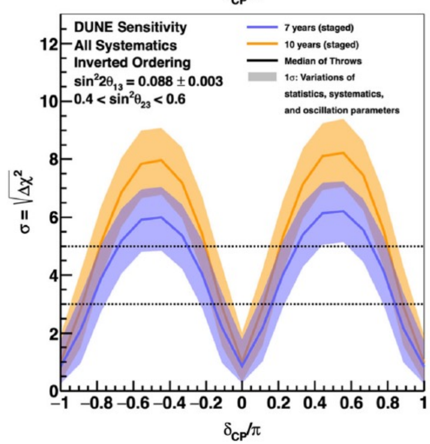
Mass Ordering



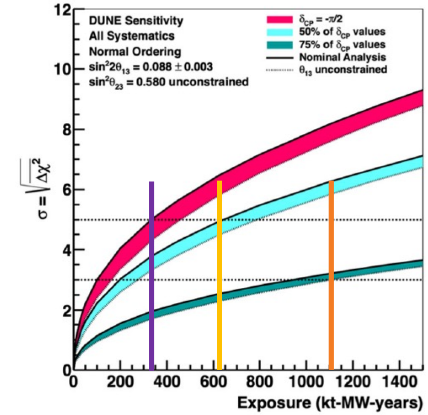


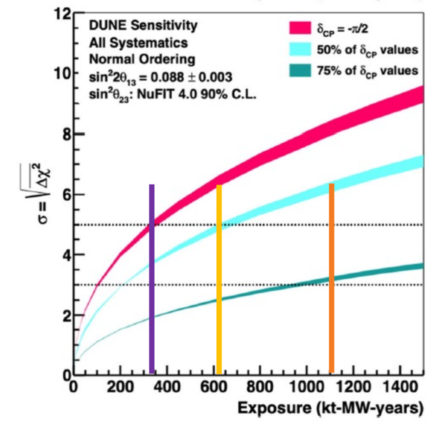
δ_{CP}





[EPJC (2020) 80, 978](https://doi.org/10.1140/epjc/s10052-020-08456-z)





= 7 years (staged)

= 10 years (staged)

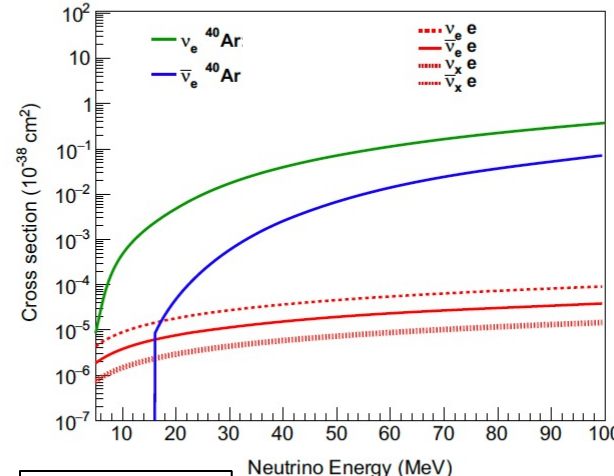
= 15 years (staged)

Cosmic Neutrinos

- The DUNE FD will be sensitive to cosmic neutrinos from MeV to tens of GeV in energy
  - Stellar core-collapse supernova (SN) neutrinos
  - Solar neutrinos?
- For a **galactic SN**, DUNE expects to observe up to thousands of ν interactions over the duration of the burst
- High reconstruction efficiency for SN neutrino energy range, 15-20% expected energy resolution with both TPC and PDS

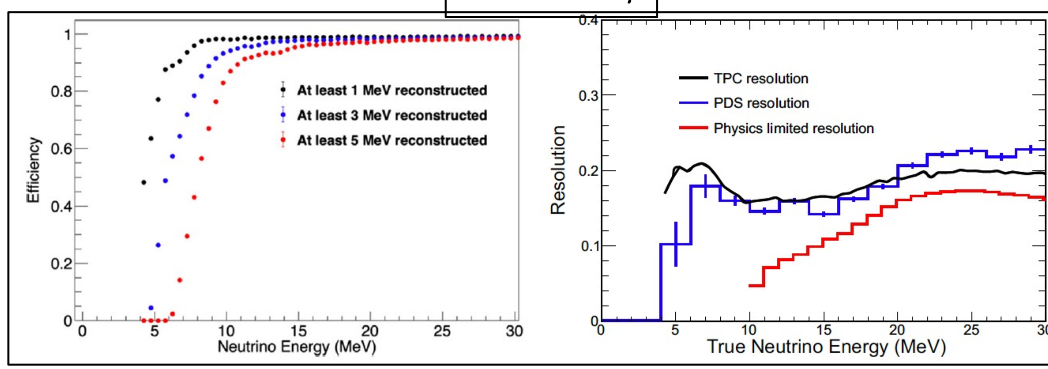
ν_e + ^{40}Ar --> e^- + $^{40}K^*$ *(dominant)*

$\bar{\nu}_e$ + ^{40}Ar --> e^+ + $^{40}Cl^*$



[EPJC (2021) 81, 423](#)

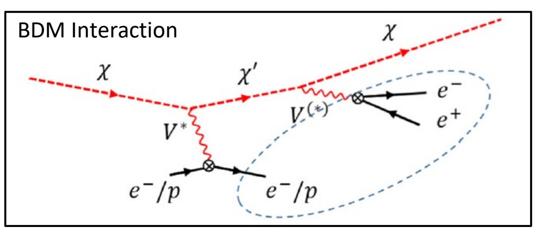
SN sensitivity



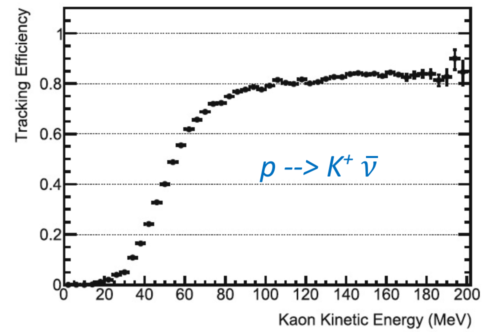
- **Solar neutrino** detection candidates:
  - from ^{8}B, hep (10 < endpoint < 20 MeV)
  - Background limited (detector materials)
  - Feasibility studies underway

BSM Physics

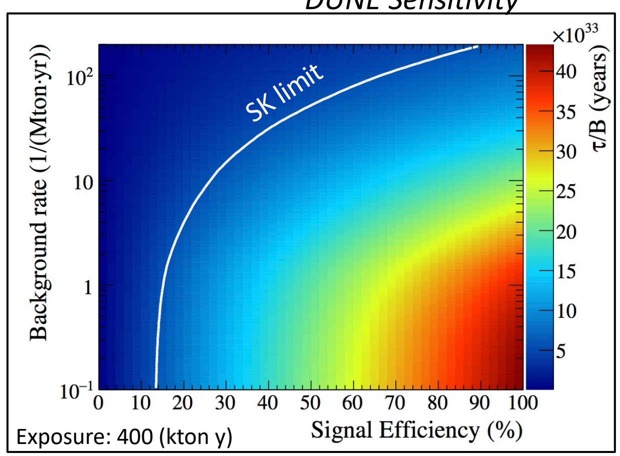
- DUNE can probe several sources of new physics
  - Sterile ν-mixing
  - Non-standard ν interactions
  - Baryon number violation
  - **Nucleon decay**
  - Low-mass Dark Matter (@ ND)
  - **(in-)elastic Boosted Dark Matter - BDM (@ FD)**
  - … [EPJC (2021) 81, 322]

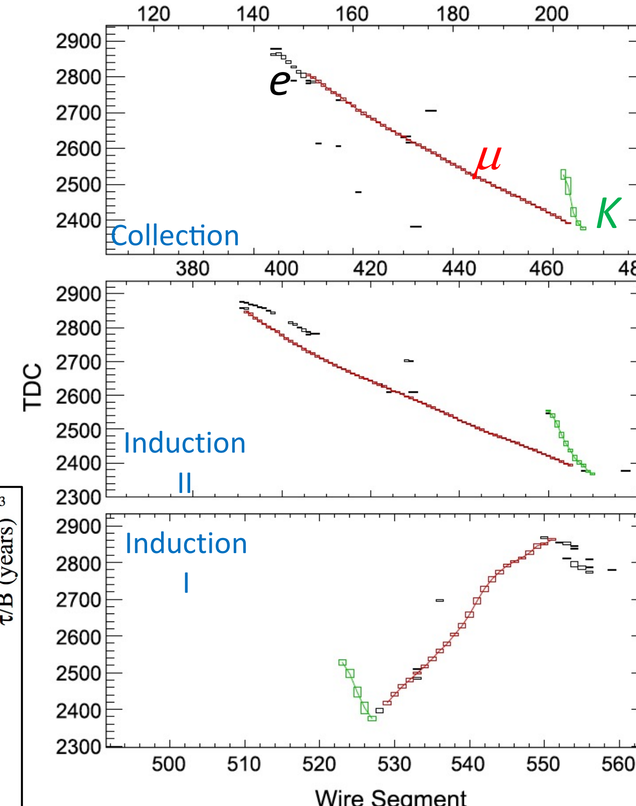


Eff. vs K^+ energy



DUNE Sensitivity

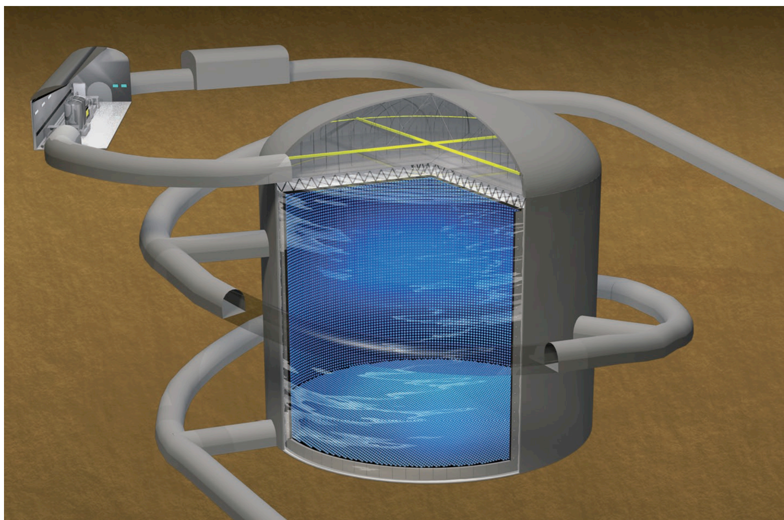




BKG: ν_μ n --> μ^- p , if p is mis-identified as K (atmospheric)

Hyper-KamiokaNDE

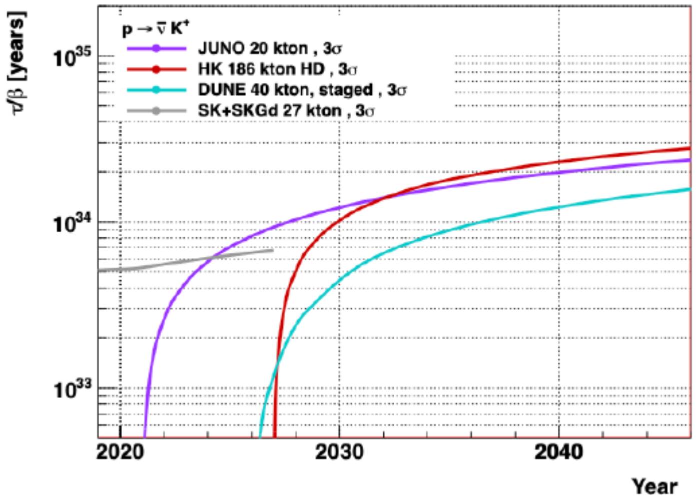
T2K ➔ HyperK



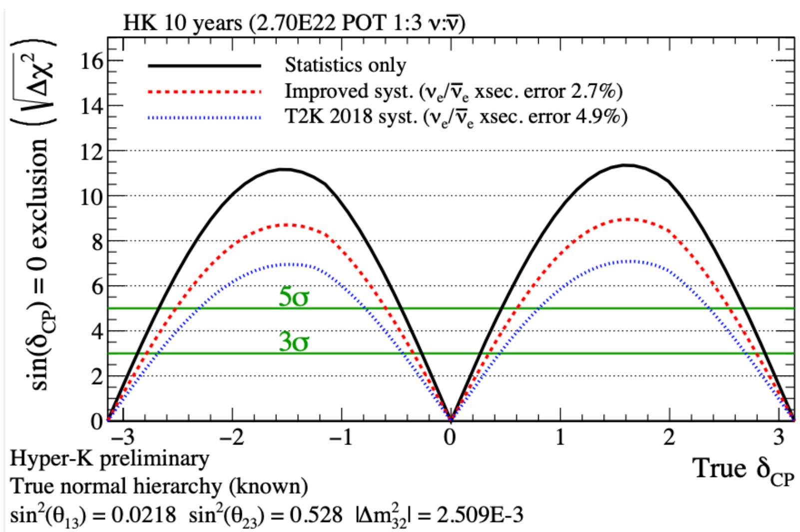
40 kton ➔ 260 kton
22.5 kton ➔ 188 kton (fiducial)

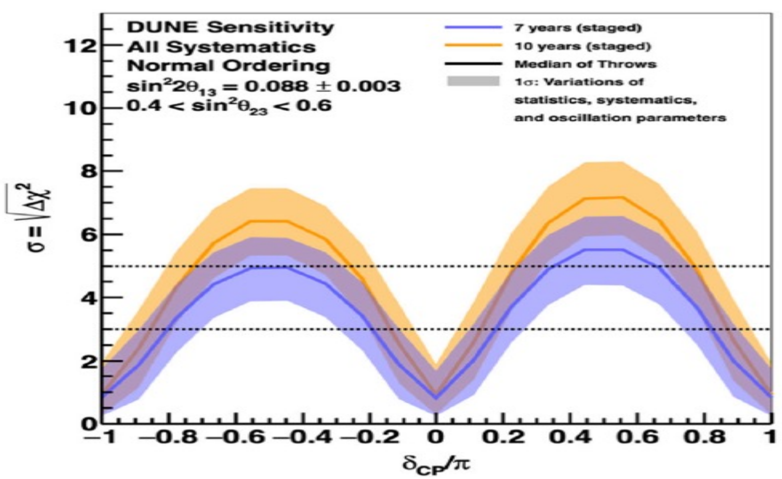
500 kW ➔ 1.3 MW

HyperK Physics



– CP violation
– Supernova
– Relic SN
– Mass hierarchy

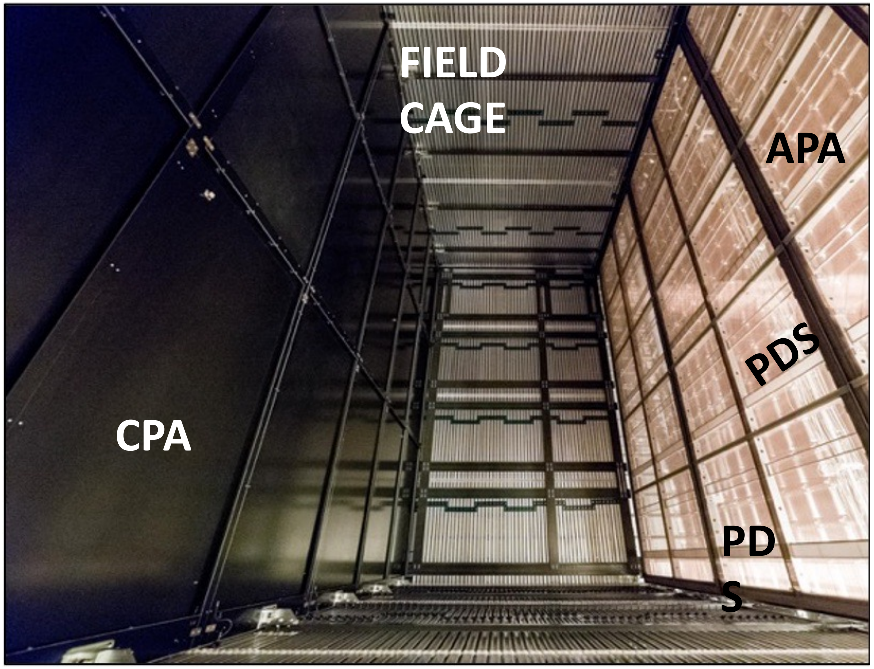




The past and the future – ProtoDUNEs

The past and the future – ProtoDUNEs

- Two ~1 kton prototypes (6 x 6 x 6 m inner dimensions)
- Exposed to Very Low Energy (VLE) charged particle beams at CERN
- Validation of DUNE components design & installation, commissioning and performance study: **FULL-SCALE** prototypes
- **ProtoDUNE-Single Phase (HD)** operated 2018–2020
  - 4-month beam run in late 2018, then cosmics
  - Event reconstruction/identification training
  - R&D site: low-energy calibration (neutron gun), Xenon doping, Higher Voltage tests, …
  - Upcoming Phase-II on beam with HD updated design
- **ProtoDUNE-Dual Phase** operated 2019–2020
  - Development of CRP technology
  - Very High Voltage / large drift studies
  - Evolved into Vertical Drift -> Phase II

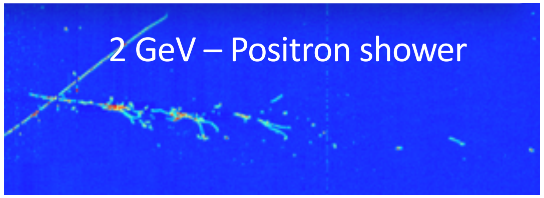


ProtoDUNE SP (HD) drift volume (3.6 m)

ProtoDUNE SP performance - I

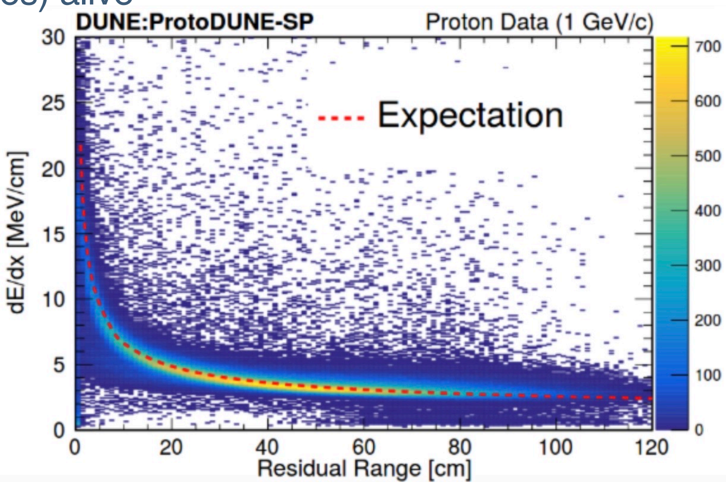
HV / Cryo

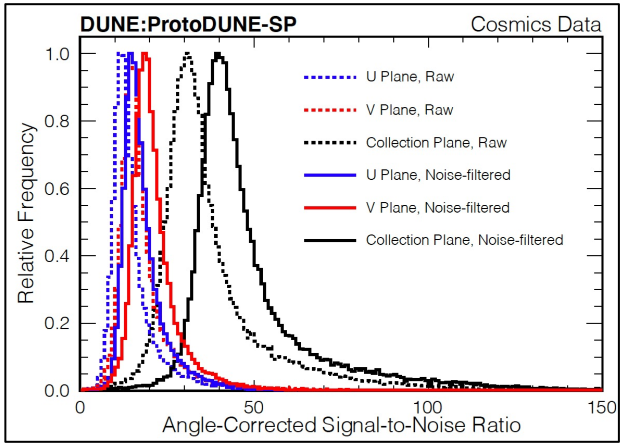
- Very high stability of HV: > 99% up-time
- Purity well above minimal requirements (> 20 ms)



TPC

- > 99% of TPC channels (wires) alive
- SNR far larger than minimal requirements
- Purity and Space Charge corrections flow into calibration & energy reconstruction studies
- Particle tracking enhanced by external Cosmic Ray Tagger (CRT)



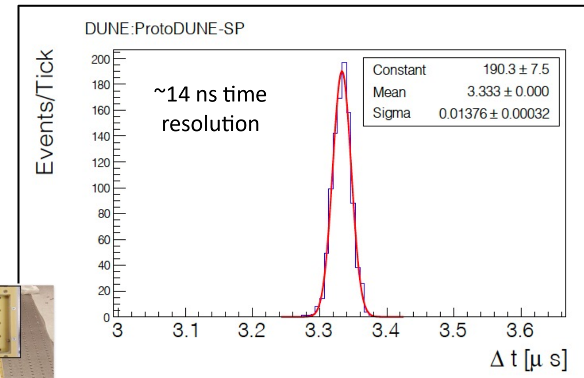


JINST 15 (2020) 12, P12004

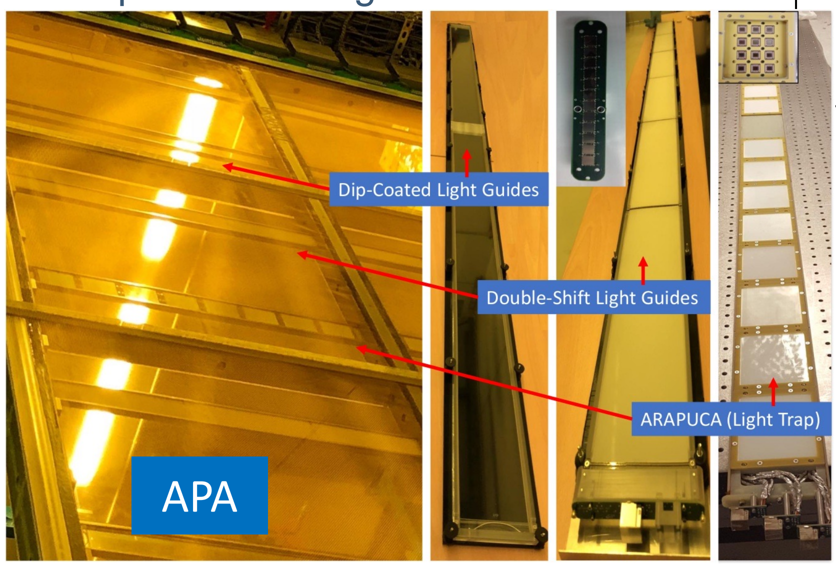
ProtoDUNE SP performance - II

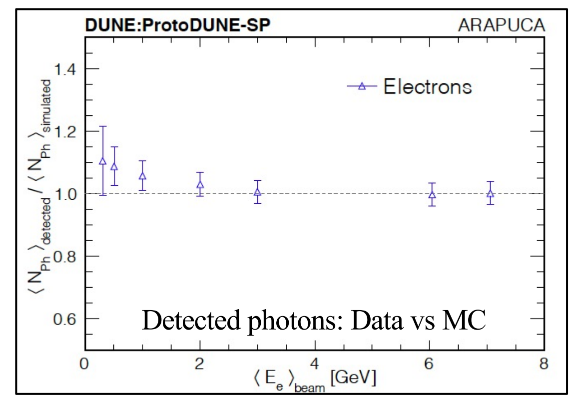
Photon Detection System (PDS)

- 3 technologies based on light-guide modules with WLS (TPB or PTP) read by arrays of SiPM
- Calibration system based on pulsed LED light installed on the cathode



- ARAPUCA technology shows best results (with 2% efficiency based on simulation)
- 1.9 photons/MeV light yield





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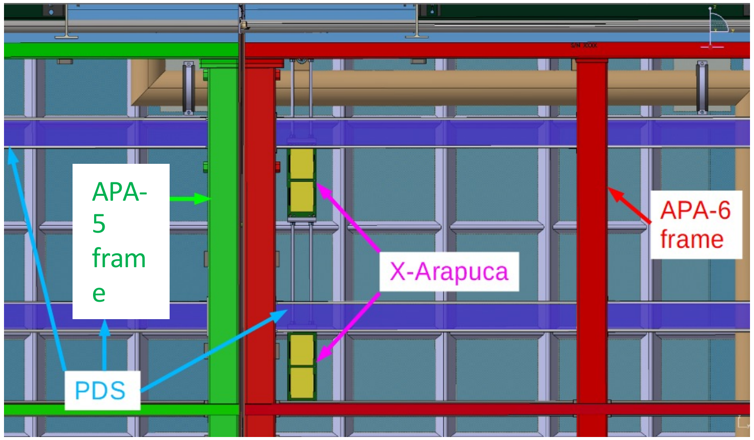
ProtoDUNE SP R&D – Xenon Doping



Location of custom X-ARAPUCAs behind APAs for Xe-doping run

- ~ 20 ppm of Xenon introduced in LAr (~13.5 kg)
- Demonstrated efficient energy transfer from Ar^*_2 to Xe^*_2
- In ProtoDUNE SP, doping also helped recovering light loss due to N_2 pollution (issue with recirculation pump)

Dedicated paper in preparation

- Xenon doping of LAr considered for DUNE, to enhance PDS response
- scintillation light shifted from 128 nm (Ar) to 178 nm (Xe)
  - Photon detectors have higher detection efficiency
  - Shorter pulses -> faster detector response
  - Larger Rayleigh Scattering length -> more uniform response in space (recovering light far from sensors)
- Dedicated studies in ProtoDUNE, with PDS and custom dedicated X-ARAPUCA detectors
  - First successful doping process of a very-large volume LAr-TPC
  - No effect on TPC response
  - Response independent of Drift Field
  - First test of X-ARAPUCA in a large-scale detector

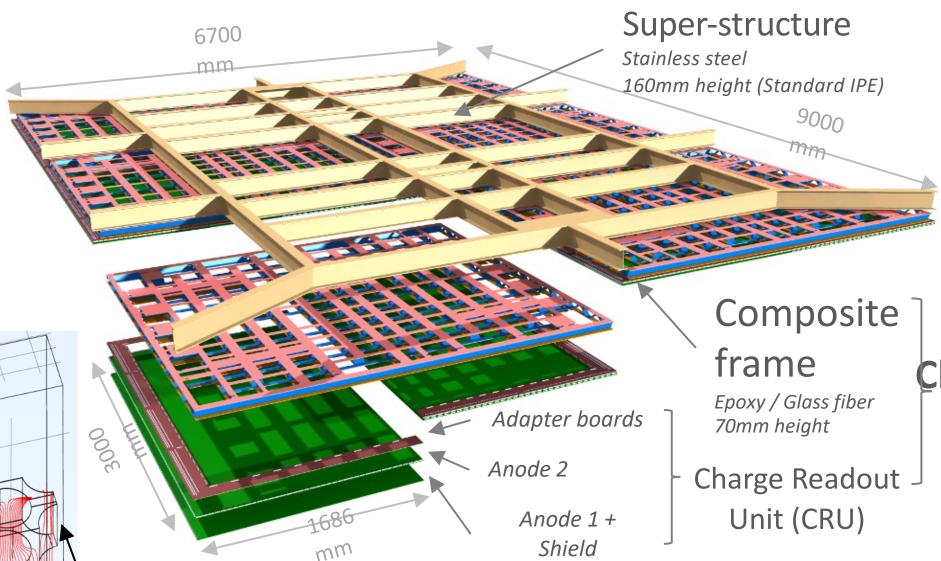
Conclusions and Outlook

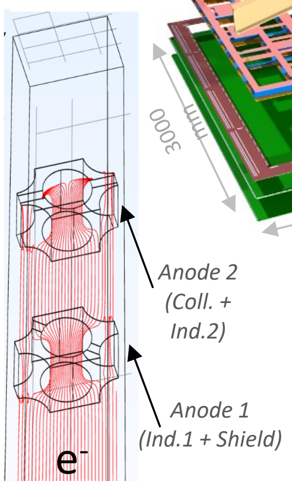
- DUNE: next-gen neutrino experiment, will allow precision neutrino physics measurements:
  - Oscillation parameters, mass hierarchy, CP violation
  - SN burst neutrinos
  - Possibility to probe several BSM channels (sterile ν's, Dark Matter, B violation)
- Beam Line & Near Detector Infrastructure designs under way
- Infrastructure at Far Detector site -> excavation is advancing
- Near Detector technology (multi-station) is defined
  - Design finalization in a few months
- Far detector technology defined for FD #1 (Horizontal Drift)
  - Design validation with “Module 0” in upcoming ProtoDUNE SP Run-II
- Vertical Drift LAr-TPC proposed for FD #2, aggressive R&D program at FNAL and CERN
  - Design validation in ProtoDUNE NP02 with proposed HV test in 2021 and later “Module 0”

Published DUNE TDR Volumes
JINST 15 (2020) T08008/09/10

Thank you!

Far Detector #2 (Vertical Drift)



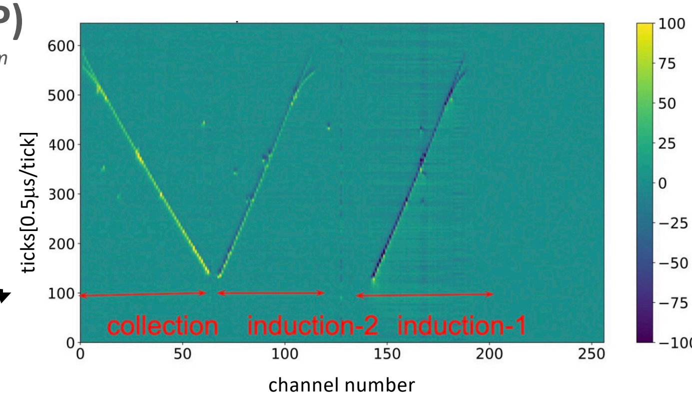


Anode

- Charge Readout Planes from Dual Phase repurposed for VD
- Perforated PCB anode, fully immersed in LAr
- Reference: 3-view design plus shield (2 anodes)

50L test set-up

- 3-view anode: two 35 x 35 cm PCBs, overseeing a 50 cm drift volume.
- Very promising first data (cosmic μ's)



Lancaster University

Analysis Input

- Oscillation parameters: NuFit 4.0 (Nov 2018)
  - http://www.nu-fit.org/?q=node/177
  - True value of θ_{23} has significant impact on sensitivity
- Earth density: 2.848 g/cm^3
- Baseline: 1284.9 km
- Staging assumptions (technically limited schedule)
  - 1.2 MW × 20 kton at start
  - 1.2 MW × 30 kton after 1 yr
  - 1.2 MW × 40 kton after 3 yr
  - 2.4 MW × 40 kton after 6 yr
  - Equal running in neutrino/antineutrino mode
  - Standard "Fermilab year" = 56% accelerator uptime