Latest and Near-Future Highlights from DUNE

Alessandro Minotti – Università di Milano-Bicocca

on behalf of the DUNE Collaboration

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

BCVSPIN Conference
Particle Physics and Cosmology in the Himalayas
9-13 Dec 2024
Kathmandu, Nepal

UNIVERSITA' DEGLI STUDI DI MILANO
BICOCCA

Present and Future of Neutrino Physics

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

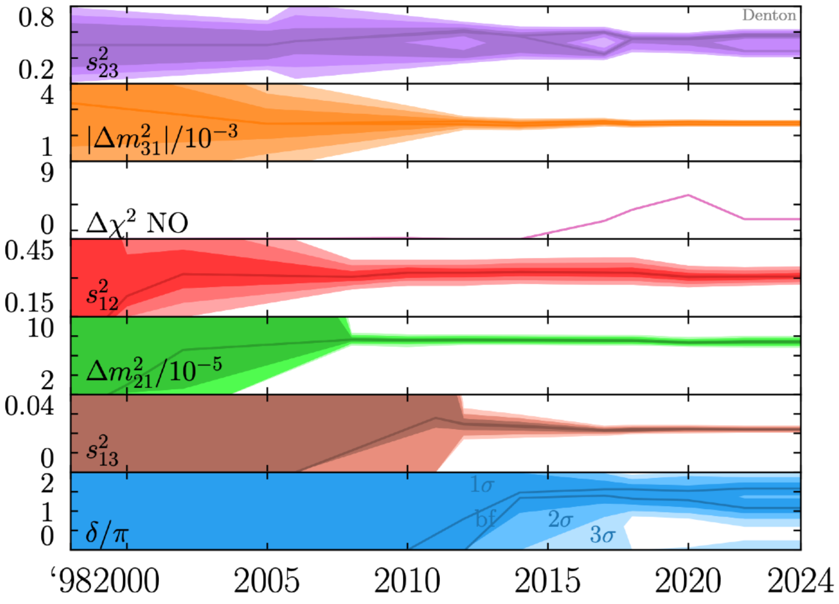
Atmospheric Sector

Reactor/Accelerator Sector

Solar Sector

Majorana Phases

[arXiv:2212.00809](https://arxiv.org/abs/2212.00809)

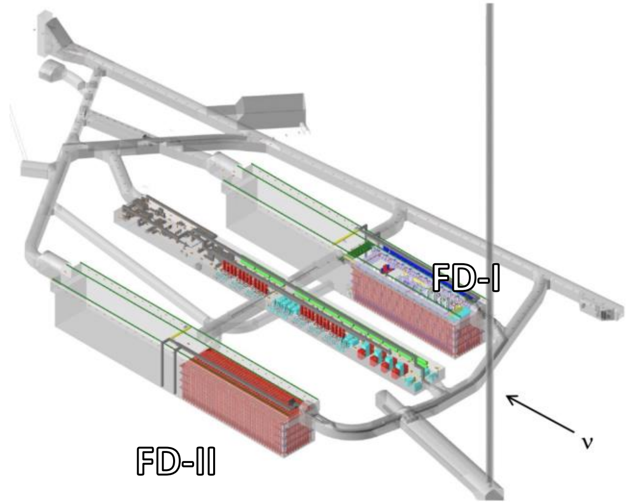


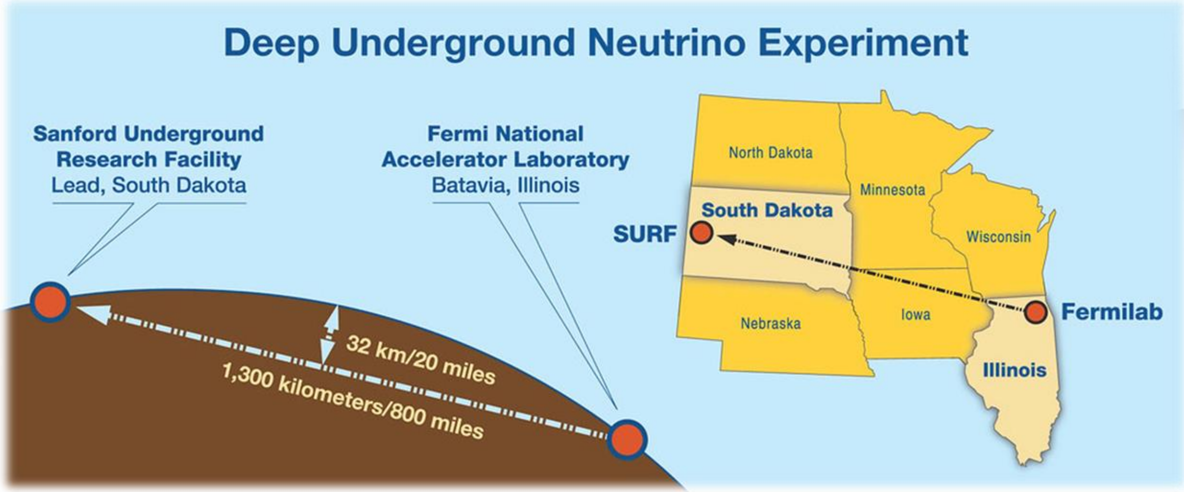
- Neutrino physics is entering the precision era
- The remaining parameters hold the key to break the Standard Model and unlock fundamental conundrums
  - CP-violation in the leptonic sector (δ_{CP})
  - Neutrino masses (nature, order, scale)
  - Octant of ϑ_{23} ($\vartheta_{23} \gtreqless 45^o$?)

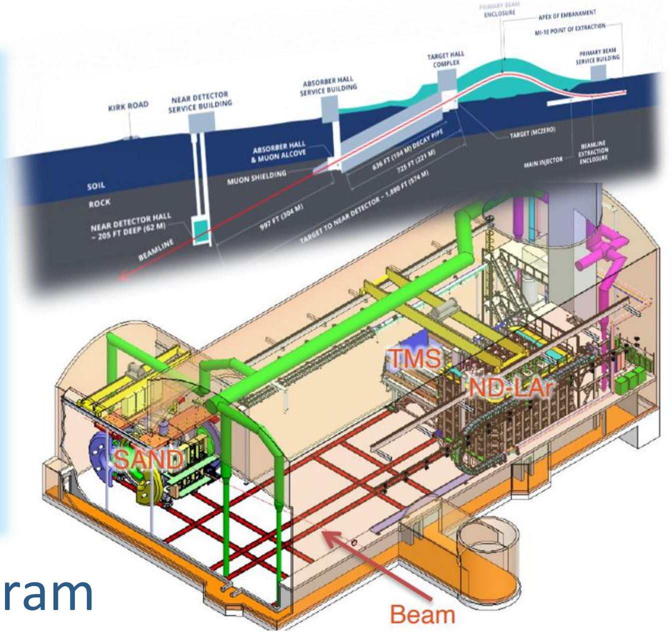
→

  - Matter-antimatter asymmetry
  - Mass scale problem
  - New fundamental symmetries

The Deep–Underground Neutrino Experiment







- A large mass, high precision, Deep-Underground accelerator Neutrino Experiment (DUNE)
  - ○ Powerful wide-band ν (and ν̅) beam w/ long baseline

    1.2 MW proton beam, upgradable to 2.4 MW
  - ○ Near detector complex for beam characterization

    movable (NDLAr, TMS) + on-axis (SAND) detectors
  - ○ Huge far detector w/ superior PID capability

    4 X 17kt total mass LArTPCs, 1.5 km underground

..for a wide physics program

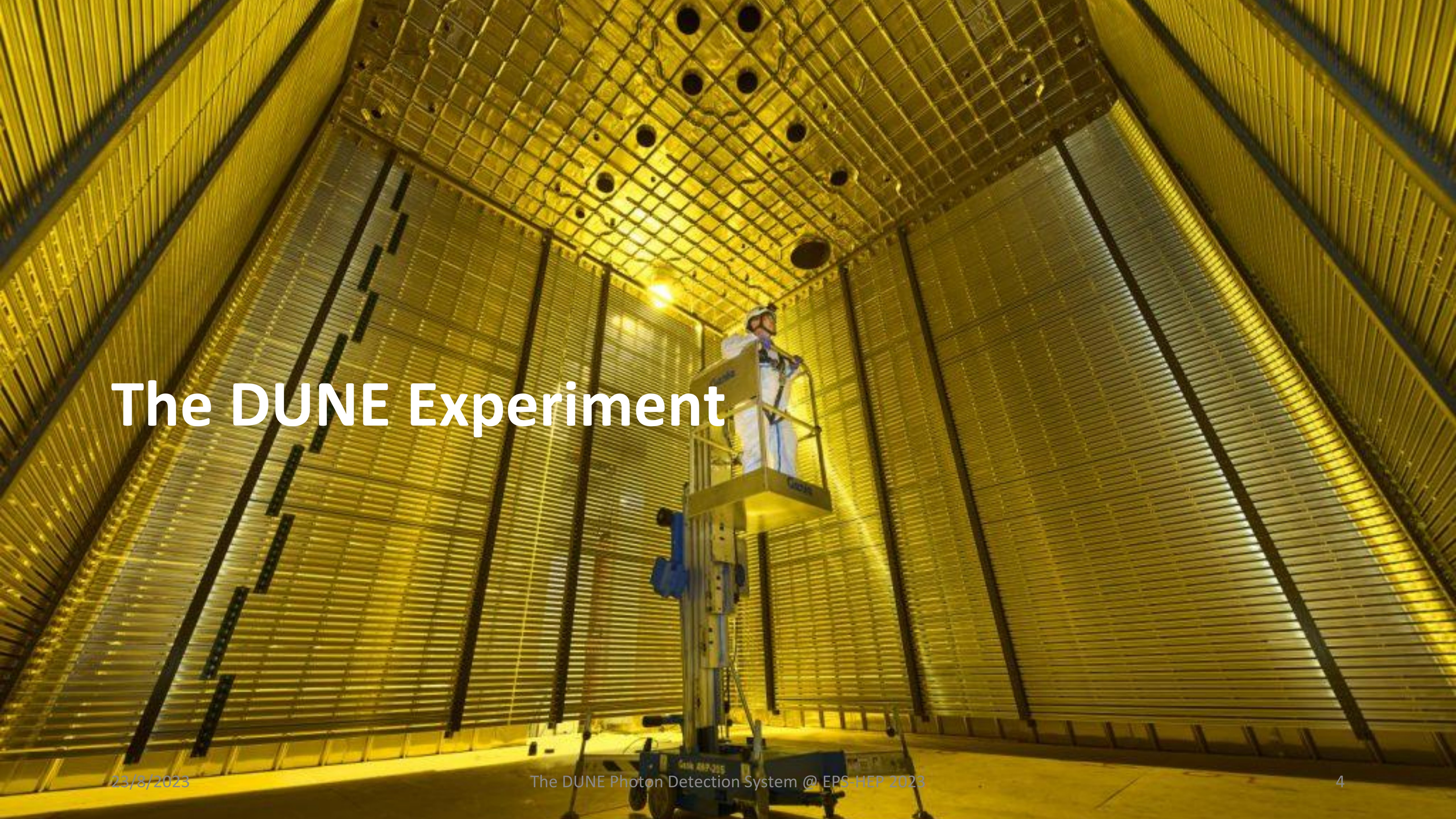
- ○ Discovery of lepton Yukawa sector missing parameters

  ν mass ordering, CP-violating phase δ_{CP}
- ○ Measurement of PMNS parameters

  octant of ϑ_{23}, Δm^2_{13}, *precision measurement of* δ_{CP}
- ○ Physics with natural ν sources

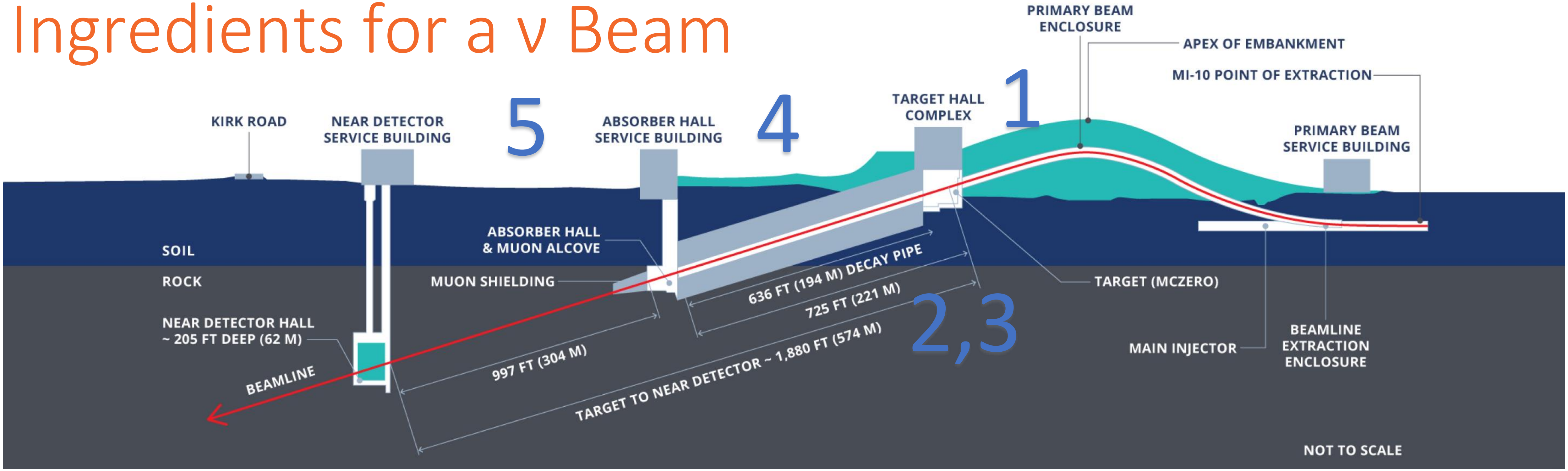
  1^{st} *observation of HEP, galactic SN bursts & SNNB,* ϑ_{12}
- ○ BSM physics

  neutrino anomalies, proton decay, dark matter, …

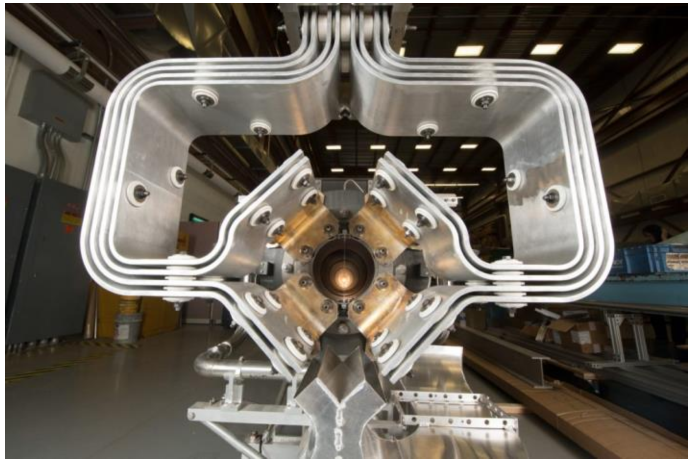


The DUNE Experiment

Ingredients for a ν Beam

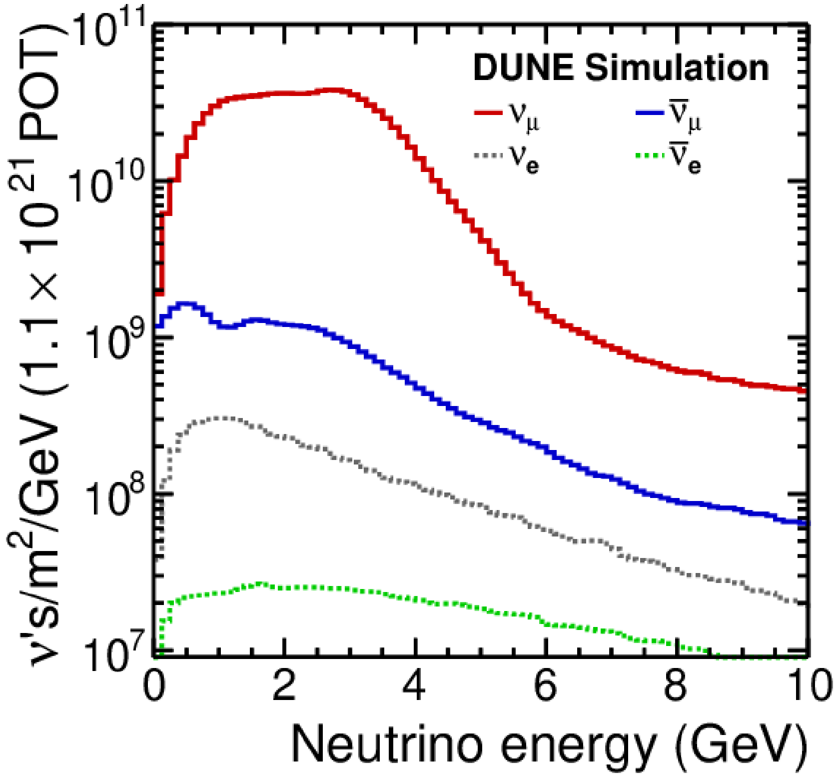


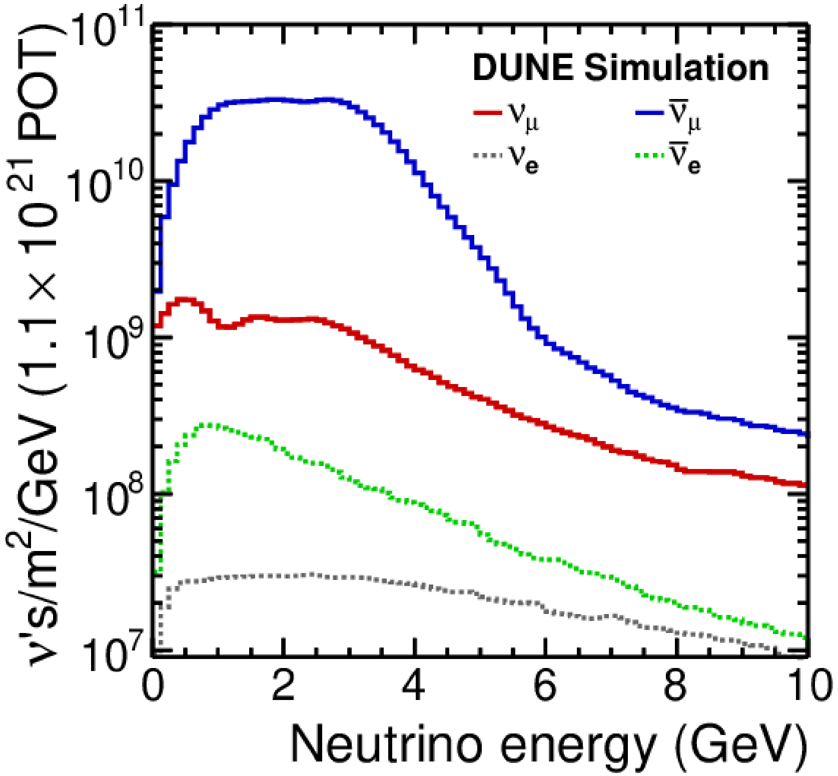
1. Point an intense (MW) proton beam towards SURF
2. Smash those high-energy (~120 GeV) protons onto a graphite target → π, K
3. Focus positive (negative) π, K, by means of a 1 MW focusing horn with forward (reverse) current polarity
4. Let them decay and absorb remaining charged particles (μ)
5. You got an (anti)neutrino beam

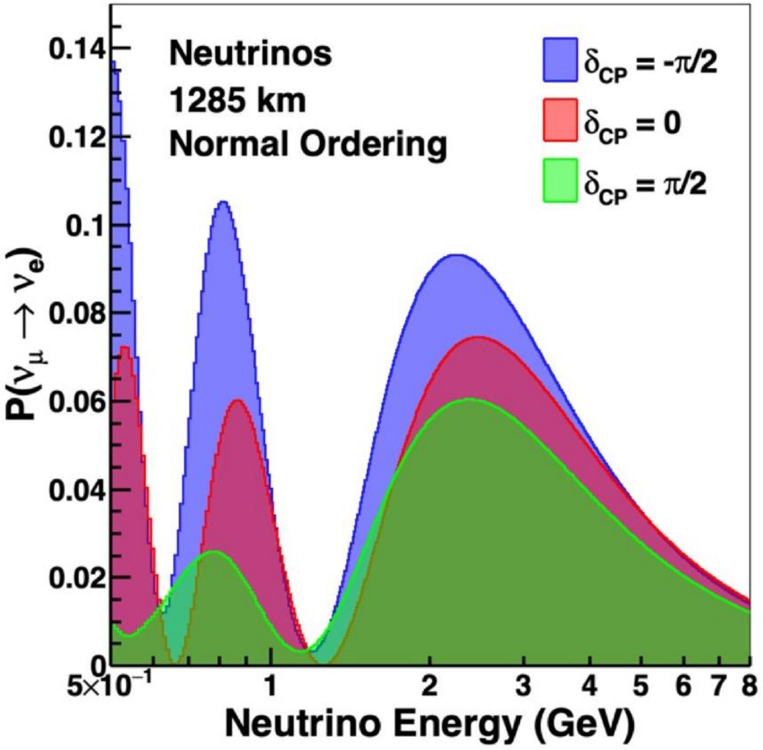


The Long Baseline Neutrino Facility (LBNF)

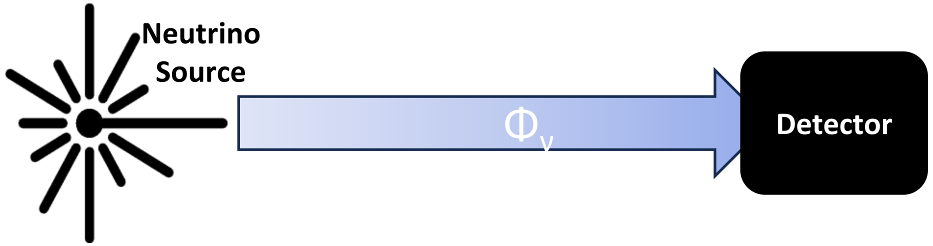
- LBNF produces a pure, wide-band beam: energy covers two oscillation peaks
  - Slightly different dependence from the involved parameters in the two peaks → enhances sensitivity
- 1.2 MW and 1.1 × 10^{21} POT/year in Phase-I





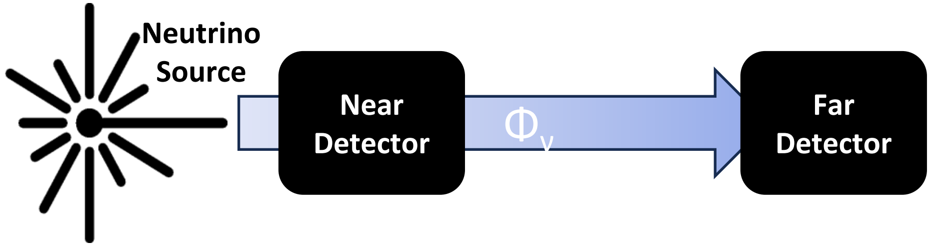


Purpose of a Near Detector



$$\underset{\text{What we get}}{N(E_{rec})} = \int \overset{\text{Flux}}{\underset{\text{What we want}}{\Phi(E_\nu)}} \times \overset{\text{Cross-Section}}{\sigma(E_\nu)} \times \overset{\text{Acceptance}}{\varepsilon(E_\nu)} \times \overset{\text{Smearing Matrix}}{D(E_\nu \rightarrow E_{rec})} dE_\nu$$

- Observed ν rate is measured as a function of the reconstruction energy, which is connected to E_ν by a smearing matrix (detector response, neutrino interactions)

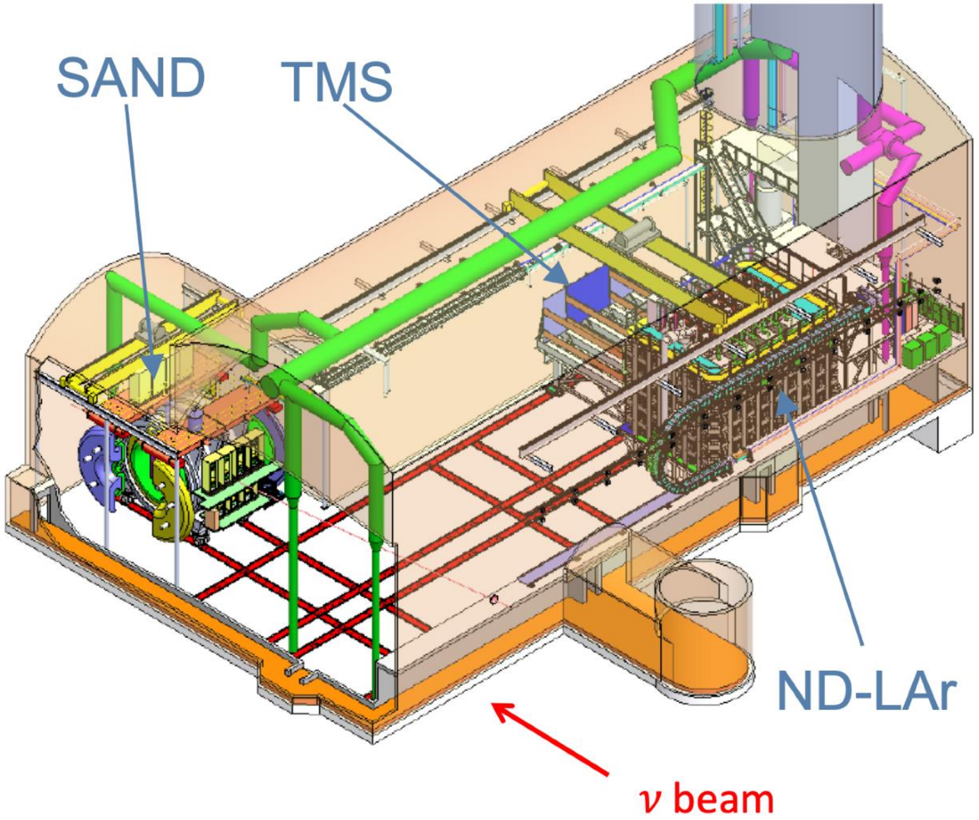


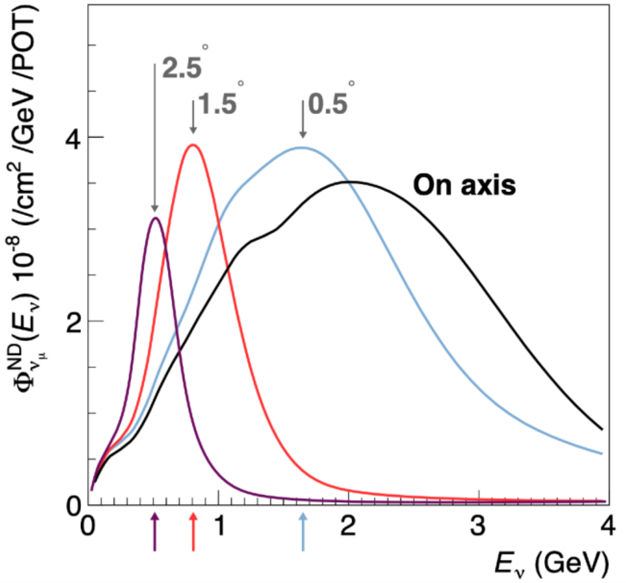
$$\frac{N_{far}(E_{rec})}{N_{near}(E_{rec})}$$

- A near detector can constrain many of the systematic uncertainties related to the E_ν extrapolation (beam flux and spectrum , ν-Ar interaction and cross-section, detector response, beam fluctuations)
- Also, pursue an independent physics program (cross-section measurements, BSM searches)

The DUNE ND

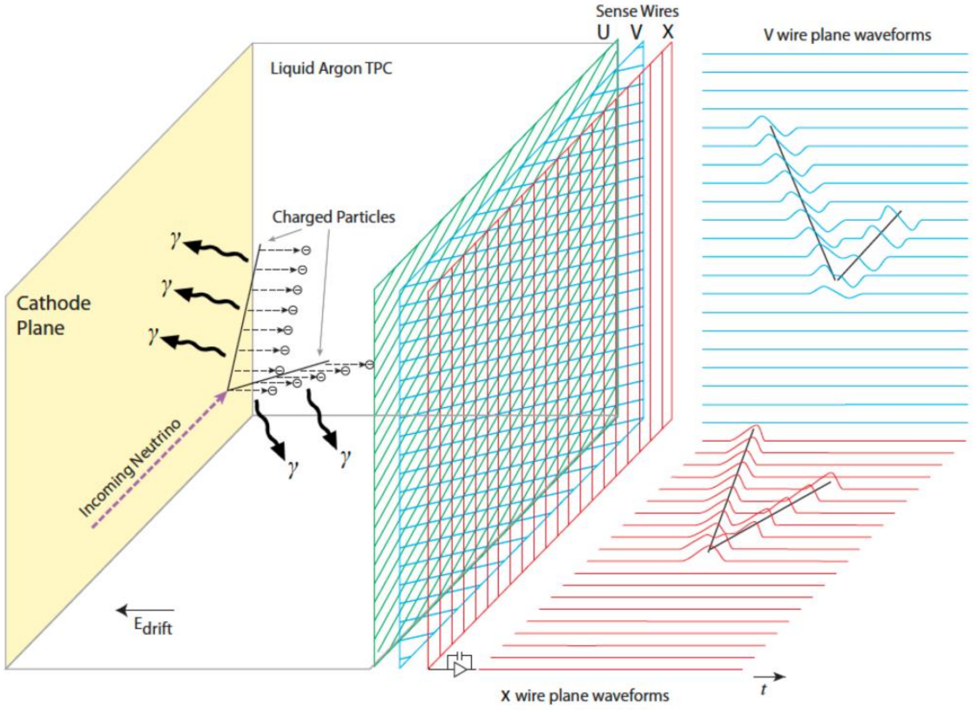
- Three detectors with complementary purposes
  - ND-LAr, same target technology as far detector to maximize ‘cancelation’ of systematics
  - TMS (then ND-Gar) for downstream tracking (PID, high-performance calorimetry)
  - SAND, on-axis magnetized detector for beam monitoring
- Neutrino Pile-up is a challenge
  - Pixelated readout (3D reconstruction)
  - Optical modularity (charge-light matching)
- PRIMS concept: detectors move on-off axis to match oscillated spectrum and construct an energy-dependent model of cross-section and response

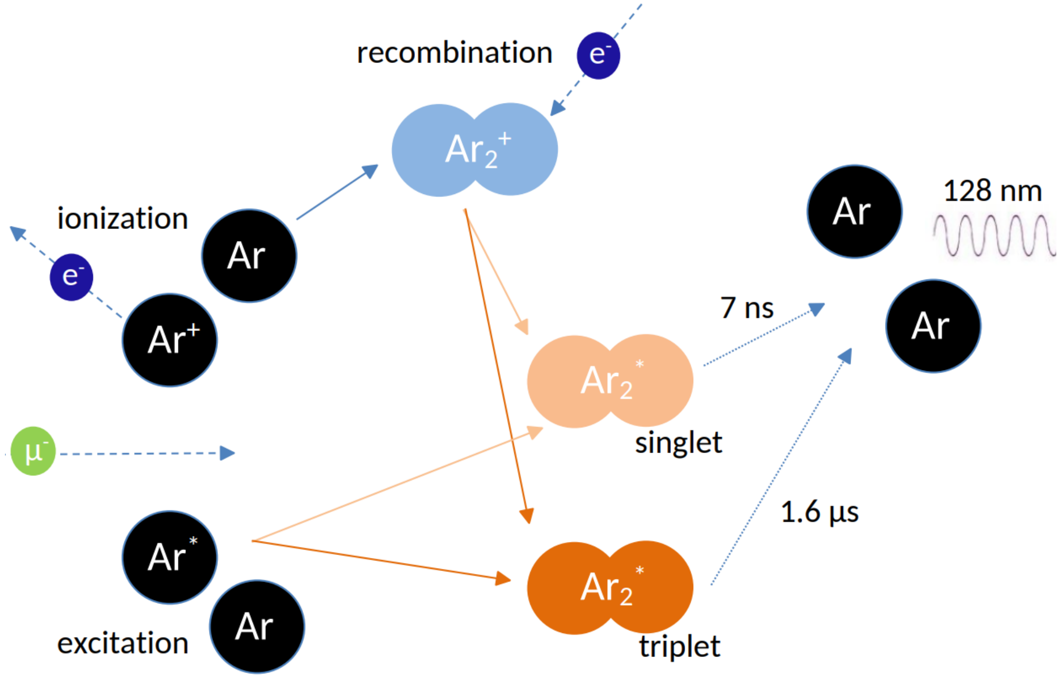


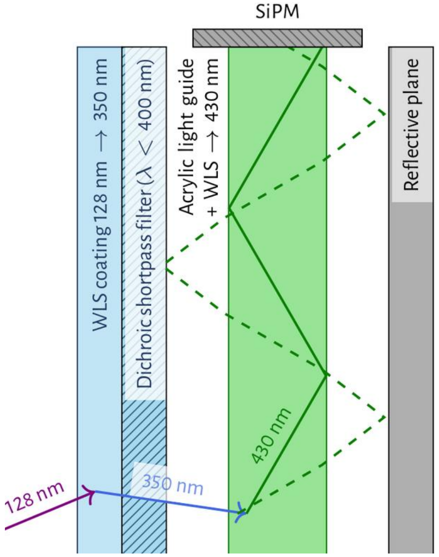


The LArTPC

- A charged particle in liquid argon produces two signals, proportional to its energy deposit:
  - Free electrons; drifted from a cathode to an anodic readout (500 V/cm) inside a field cage
  - Luminescence VUV photons (λ = 128 nm); shifted to UV, trapped and collected by photosensors
- A DUNE Far Detector LArTPC has two systems, one for each of these signals

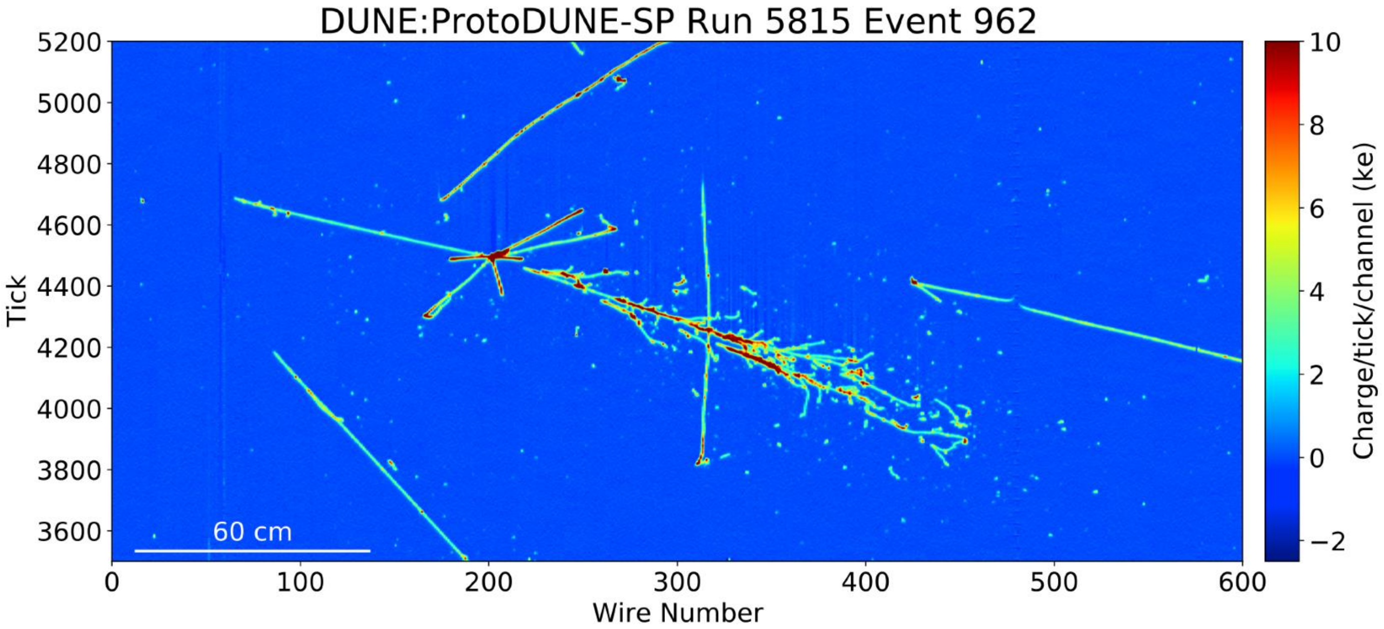




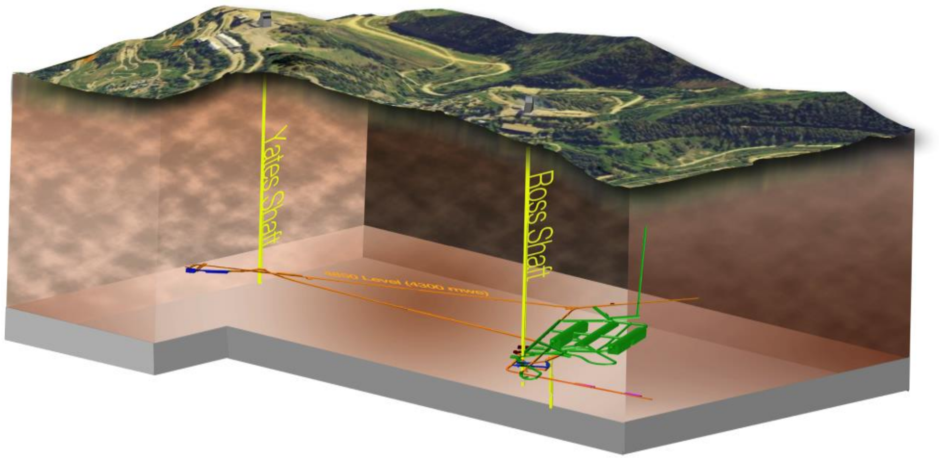


A Song of Charge and Light

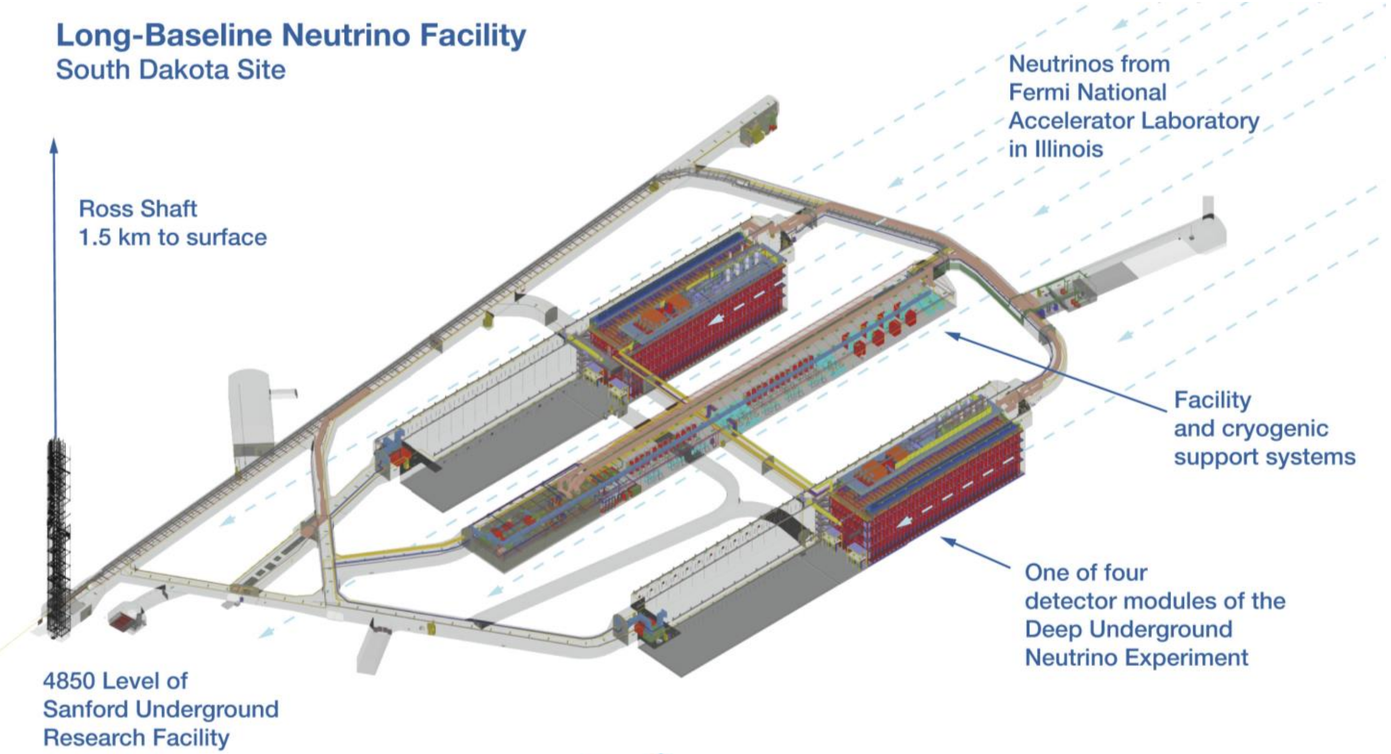
- The charge signal is the true force the LArTPC – visual tracks & showers, like an online could chamber
  - Good energy resolution (42k e/MeV) – 15-20% (10-15%) for quasi-elastic ν_μ (ν_e) interactions
  - Precise mm imaging – best available technology at the kt scale → PID via dE/dx (e/μ & e/γ separation)
- LAr VUV light (λ = 128 nm) is an independent (anticorrelated) signal
  - τ_{fast} = 7ns → provides event t_0, crucial for triggering/locating non-beam events
  - Can enhance calorimetry (40k photons/MeV) and has background rejection capabilities

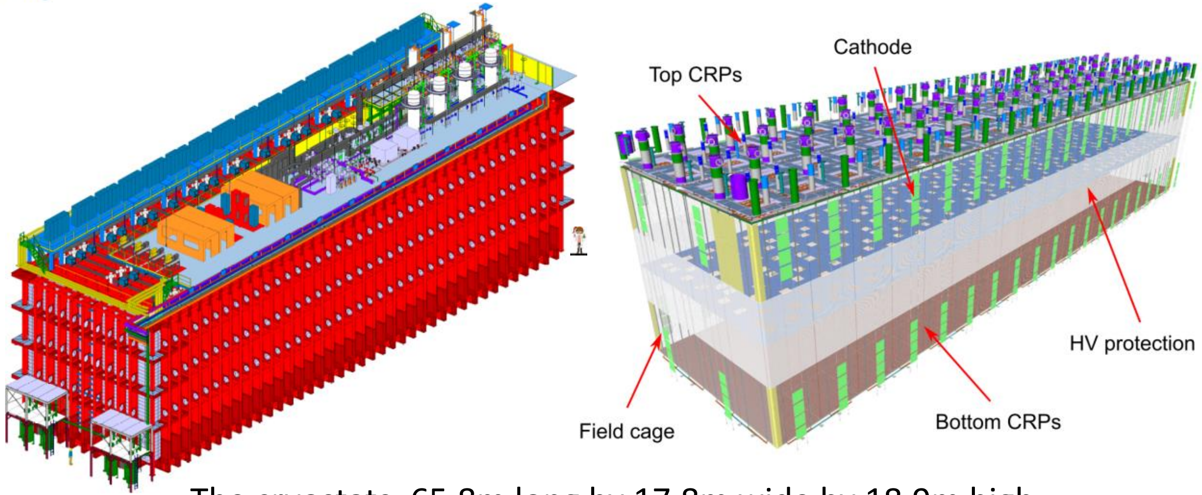


The DUNE FD Complex



- 4 chambers, each can host a 17 kt LArTPC (≳10 kt fiducial volume, 40kt total)
- Possibility to mix different types of detector
- Phase-I foresees 2 different LArTPC
  - FD-I – horizontal drift
  - FD-II – vertical drift
- 2 additional modules (& upgraded ND) in Phase-II

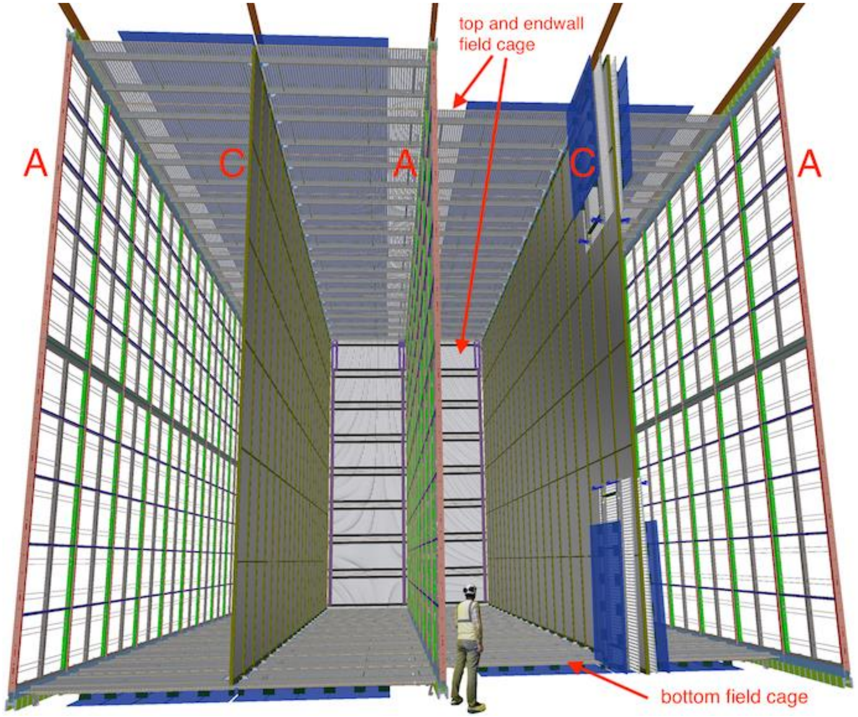




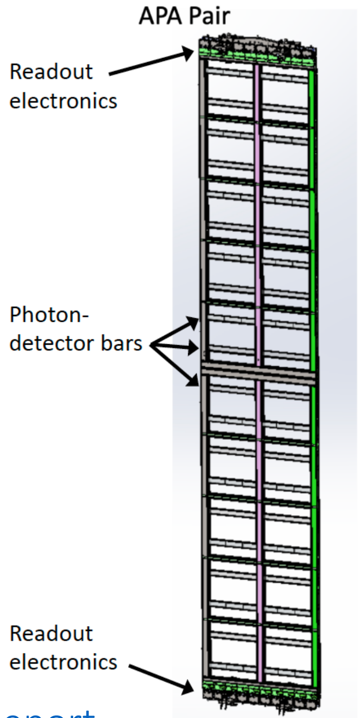
The cryostats: 65.8m long by 17.8m wide by 18.9m high

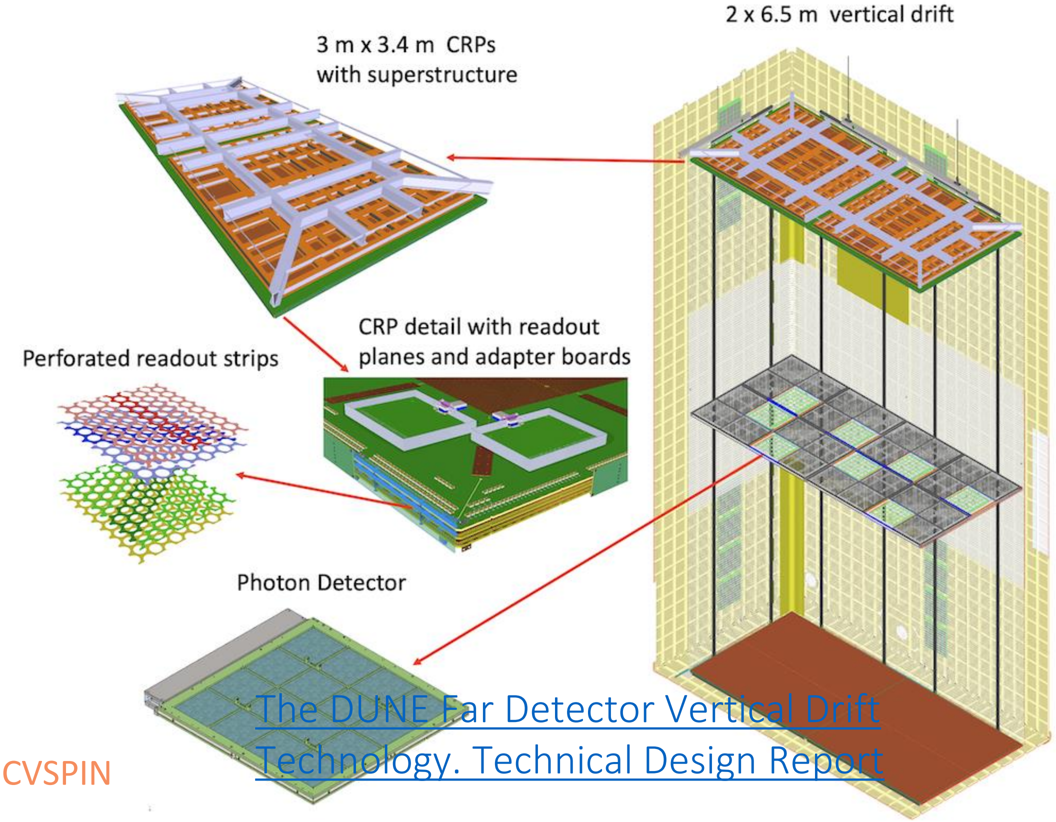
FD-I and -II

- Horizontal drift – well-established technology
  - 150 6 X 2.3m^2 Anode Plane Assembly (APA) with wire charge readout
  - 1500 X-ARAPUCA light trap bars inside APAs
  - 4 X 3.5m drift (180 kV, 500 V/cm, 1.6mm/μs)
- Vertical drift – cheaper, simpler, longer drift
  - 160 3 X 3.4m^2 Charge Readout Planes (CRP)
  - 750 X-ARAPUCA modules inside the cathode (with power-over fiber) and on the field cage, Xe doping?
  - 2 X 6.5m drift (294 kV, 450 V/cm)



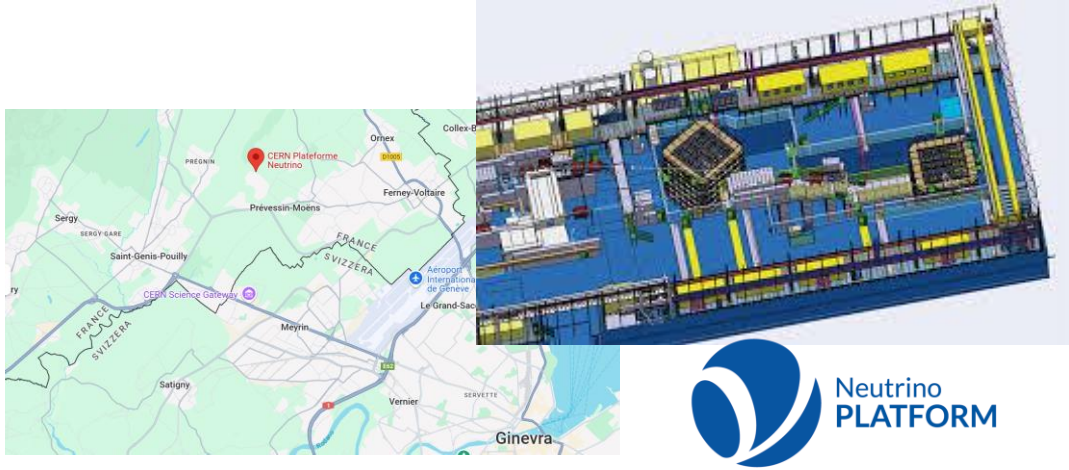
DUNE Far Detector Technical Design Report





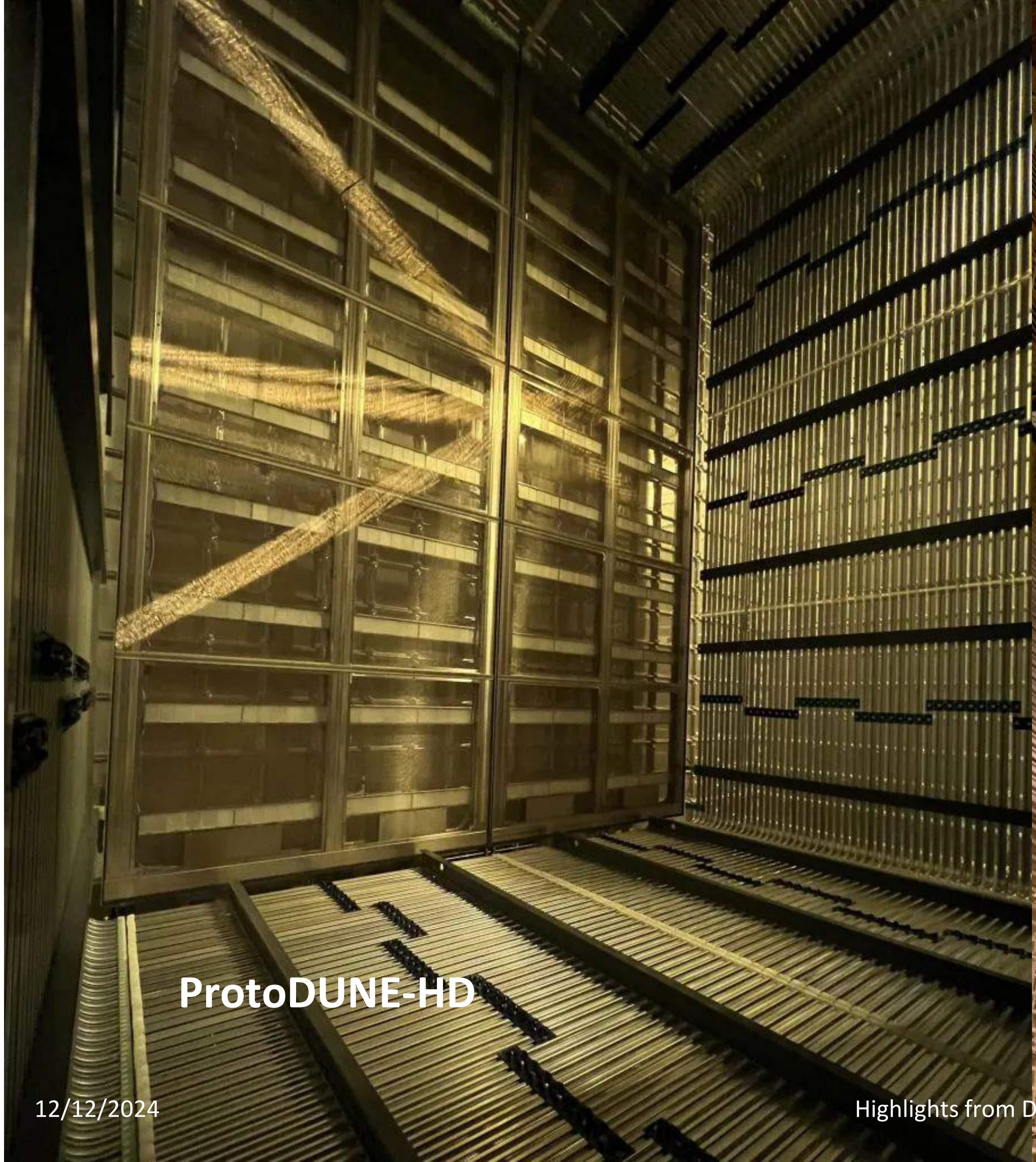
The DUNE Far Detector Vertical Drift Technology. Technical Design Report

The CERN Prototypes

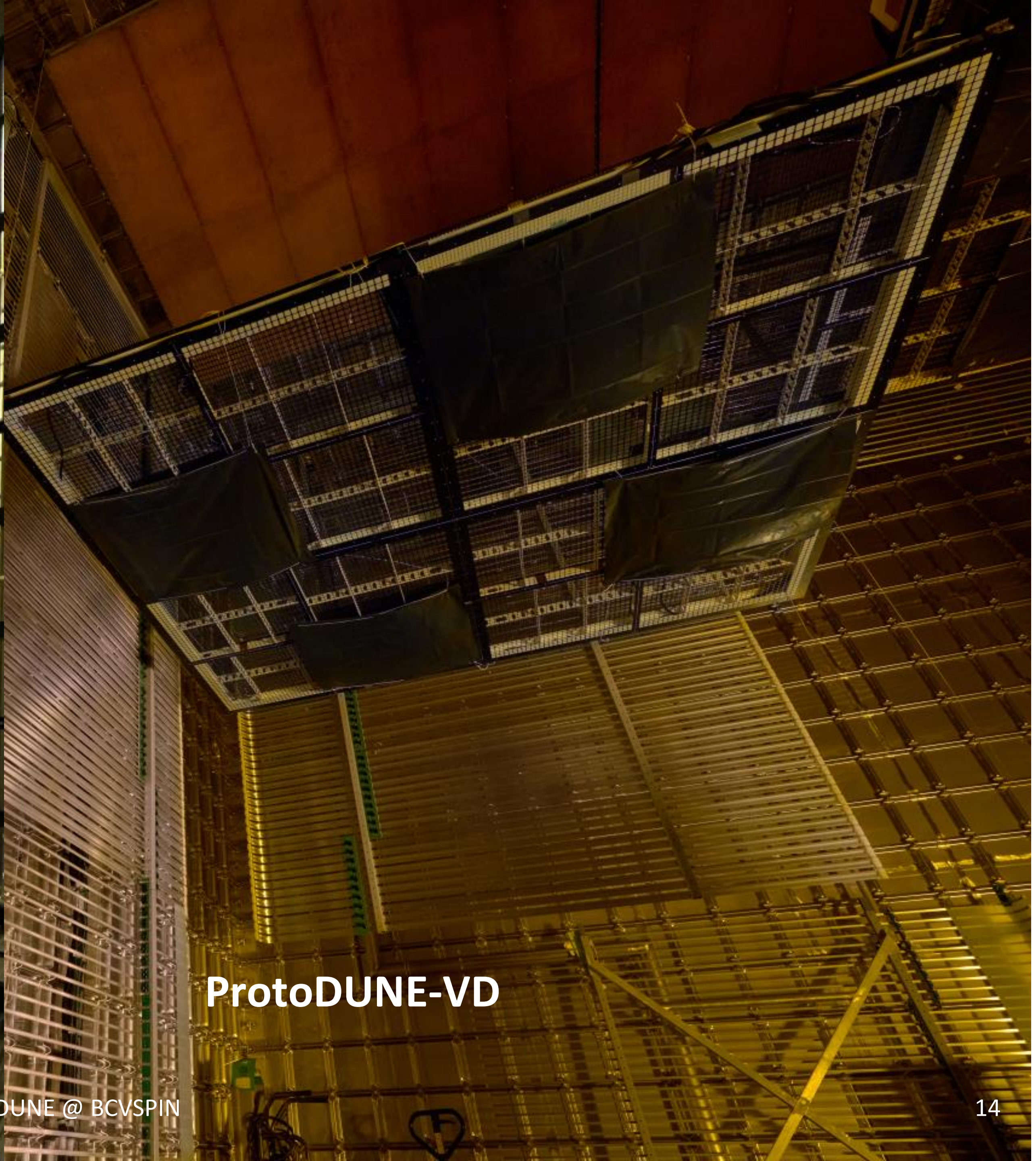


Neutrino PLATFORM

- Two 6 X 6 X 6 m^3 Module-0 at the CERN Neutrino Platform, CERN hadronic beam in the North Area
- ProtoDUNE Phase-I (2016-20)
  - Successfully demonstrated the horizontal drift technology, reaching or exceeding DUNE specifications
  - Several analyses ongoing (h-Ar cross-sections, calibrations, detector response)
- ProtoDUNE Phase-II (2020-)
  - Two modules, an upgraded horizontal and a vertical drift, constructed
  - Run-II of the HD ended last Friday! Run-I for the VD starting in early 2025 (with transferred argon)



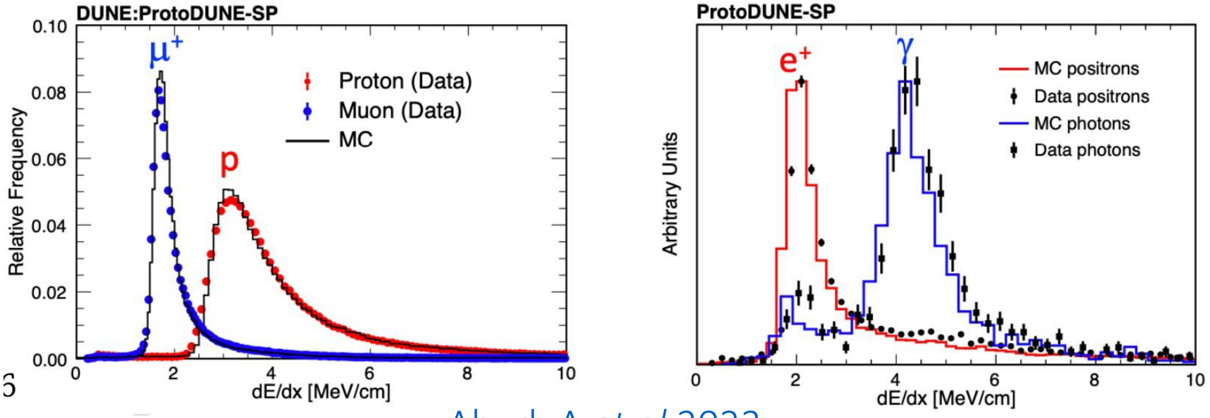
ProtoDUNE-HD



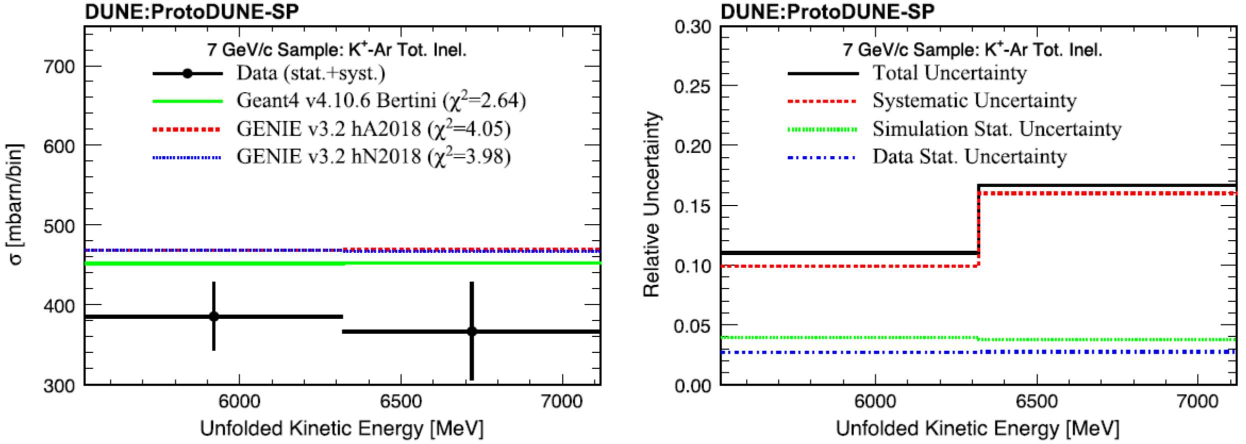
ProtoDUNE-VD

Highlights of ProtoDUNE Runs

- Beam (0.3-7 GeV hadrons, 4×10^6 triggers) & cosmics collected in ProtoDUNE-HD (formerly -SP)
  - ○ High ε_{reco} (~100%) & beam particle ID (~80%), excellent e/γ and μ/p separation
  - ○ First measurement of K-Ar inelastic cross-section
  - ○ Xenon doping run (20 ppm) to test light yield increase
  - ○ ARAPUCA established as photon detection technology
- Current Phase-II establishing Module-0(s)
  - ○ Underpinned DUNE FD final designs with production and methods
  - ○ Beam data will allow to complete/improve hadron cross-section measurements on Argon



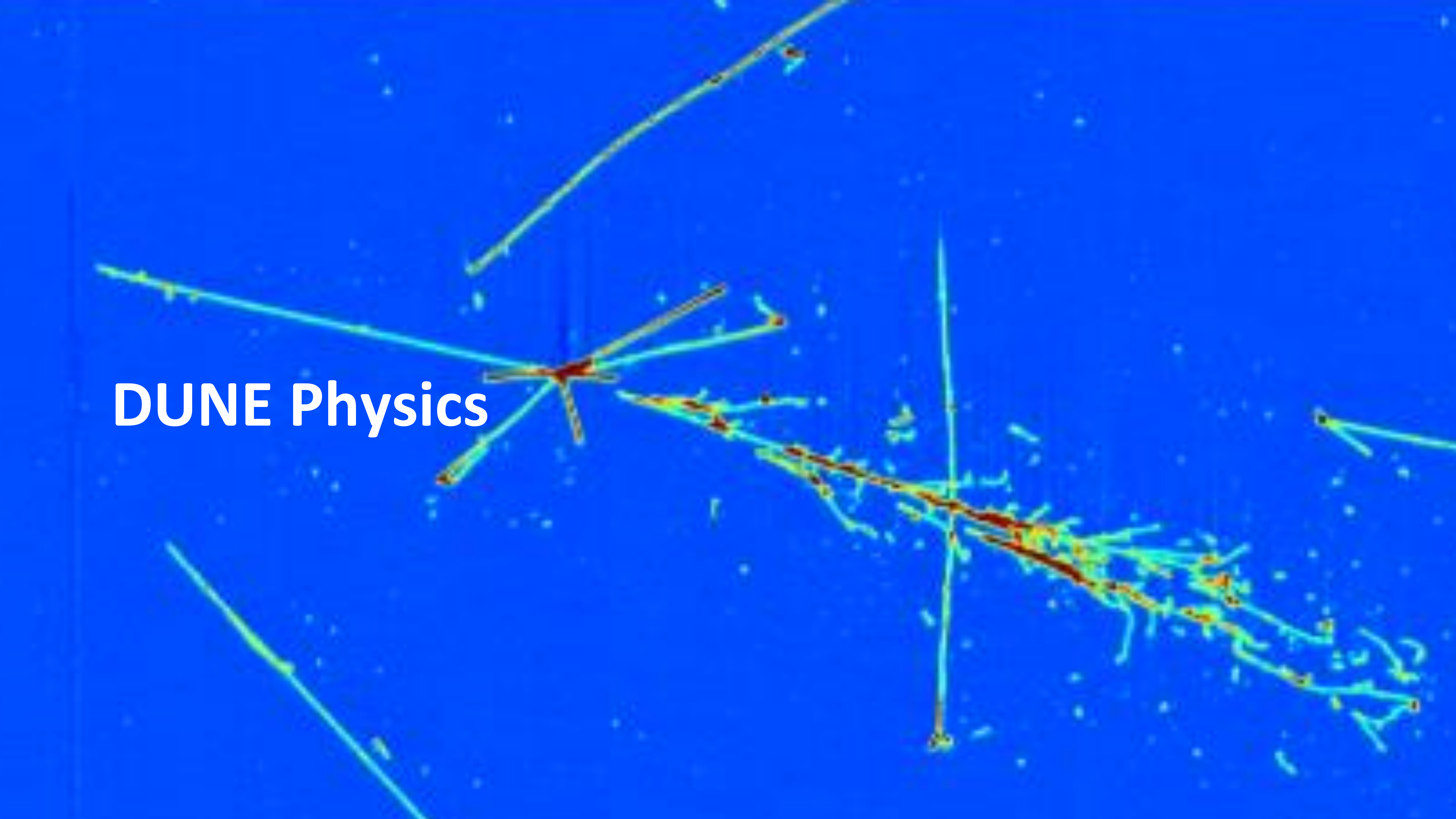
[Abud, A *et al* 2023](#)
[*EPJC* **83**, 618](#)



B. Abi *et al* 2020 *JINST* **15** P12004

Abud, A. *et al* 2024 *PRD, 110*(9), 092011.

DUNE Physics



Long-Baseline Oscillation Physics

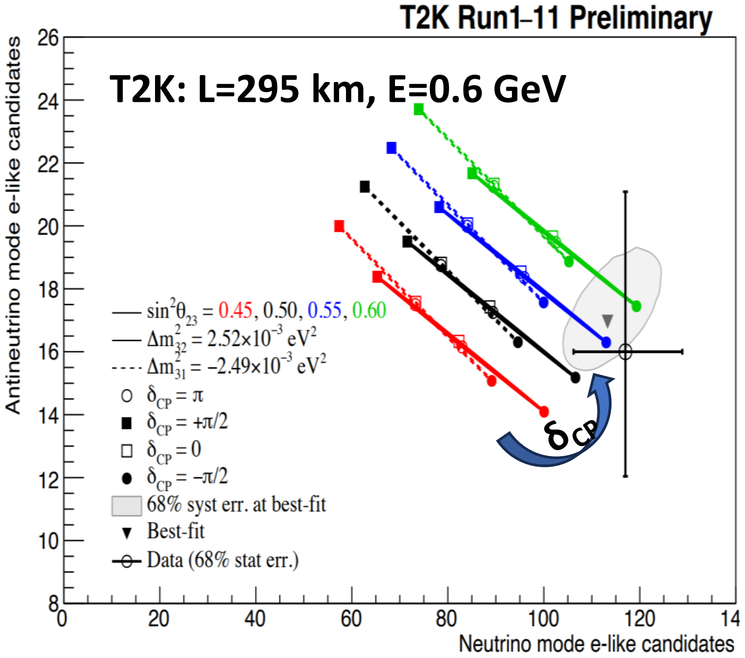
- ν_μ oscillation in matter is sensitive to matter effect, δ_{CP}, octant of ϑ_{23} → can measure all these parameters, but the effects mix up!
- Long-baseline and high statistics are crucial to break current degeneracy
  - ○ DUNE takes advantage of the longest (1300 km) baseline in accelerator neutrino history
  - ○ ν_e & $\overline{\nu}_e$ yields are order of magnitude increases relative to NOvA, T2K
  - ○ Control of systematics is crucial (ND)

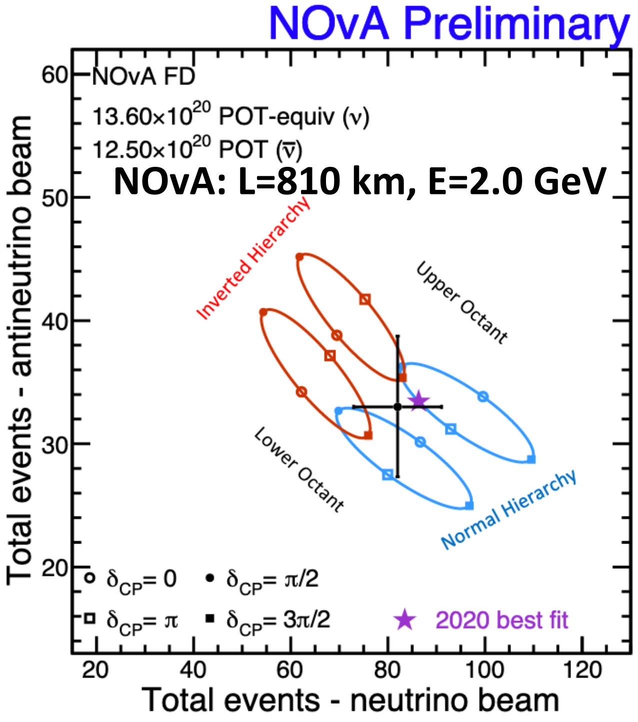
$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12} \times \frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31} \times \frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

Coherent forward scattering on e$^-$ ($a = G_F N_e/\sqrt{2}$)

CP violation (δ_{CP})

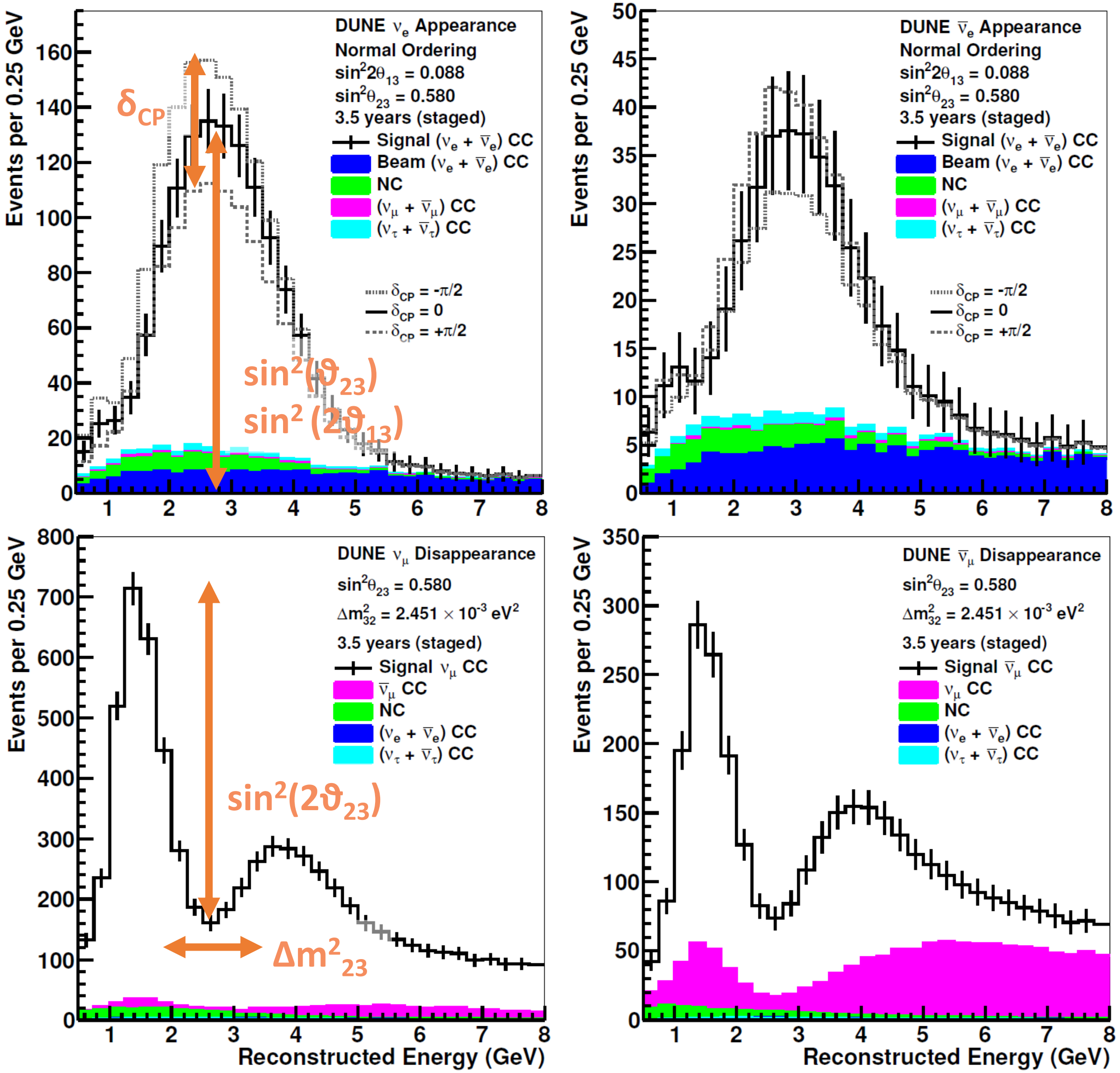
$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{E_\nu}$$





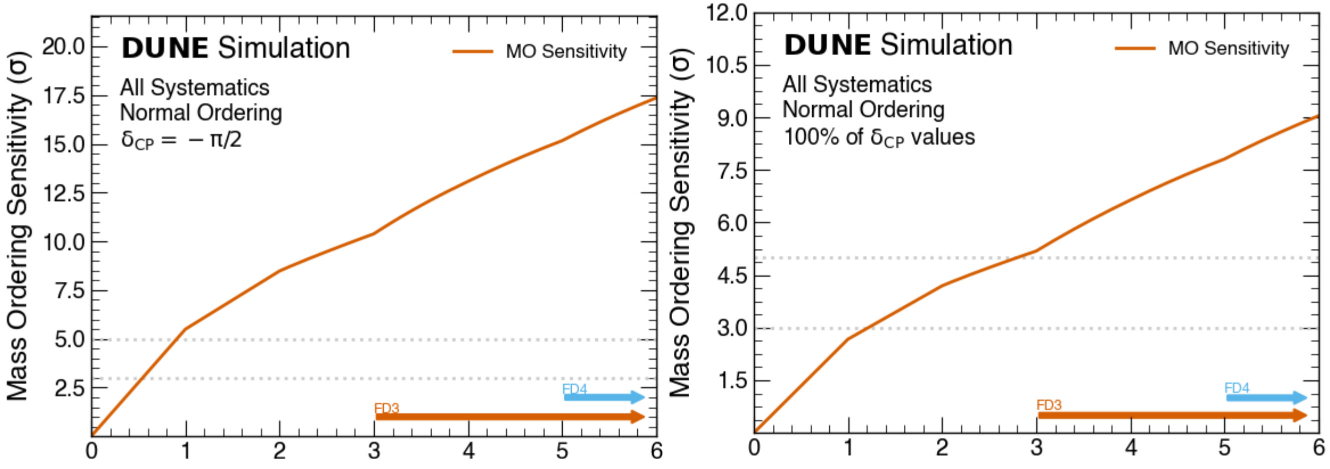
Oscillation Physics in DUNE

- High flux between oscillation min (1.27 GeV) & max (2.54 GeV); coverage of 2nd max (0.80 GeV)
- If $\delta_{CP} \simeq -\pi/2$, DUNE will measure an enhancement (reduction) in $\nu_e(\bar{\nu}_e)$ appearance
- If the mass ordering is normal, DUNE will measure a much larger enhancement (reduction) in $\nu_e(\bar{\nu}_e)$ appearance
- Different parameters affect spectra in different ways → handle on resolving degeneracies
- If new physics is present, there may be no combination of mass ordering , δ_{CP}, and θ_{23} that fits data



Sensitivity to Oscillation Parameters

- Sensitivity goals depend on nature kindness
- For best-case scenarios, DUNE has
  - ○ > 5 σ mass ordering sensitivity after 1 year
  - ○ > 3 σ δ_{CP} sensitivity in 5 years
- For worse-case scenarios, DUNE has
  - ○ > 5 σ mass ordering sensitivity in 3 years
- In the long run, DUNE can establish CPV over 75% of δ_{CP} values at > 3 σ



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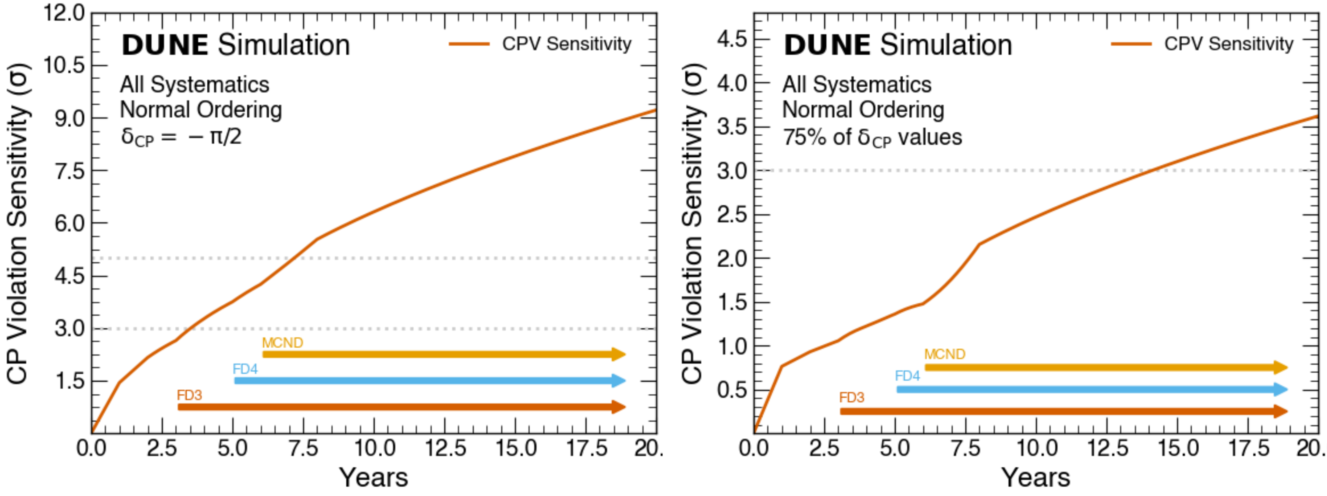
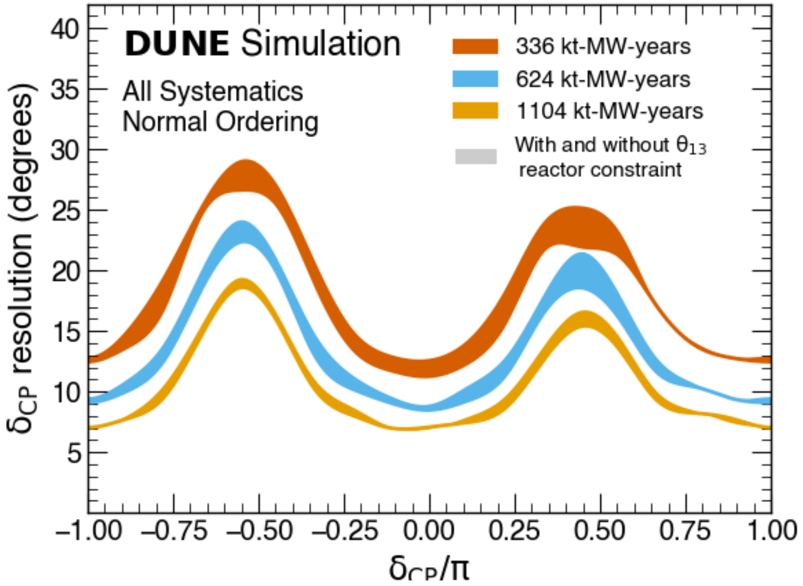
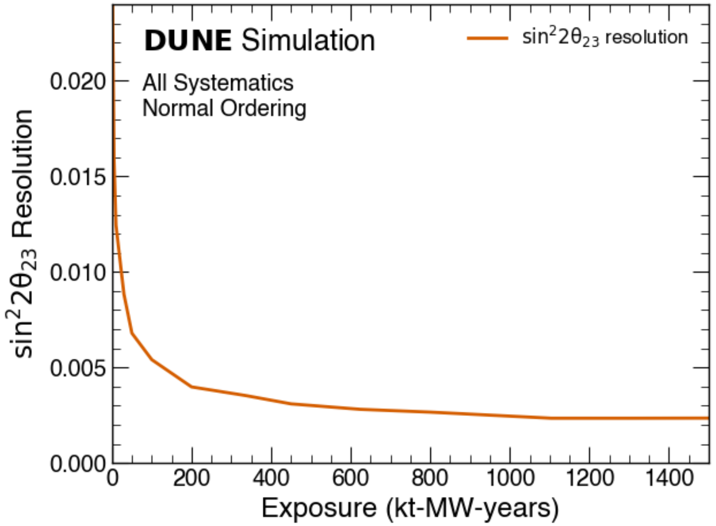


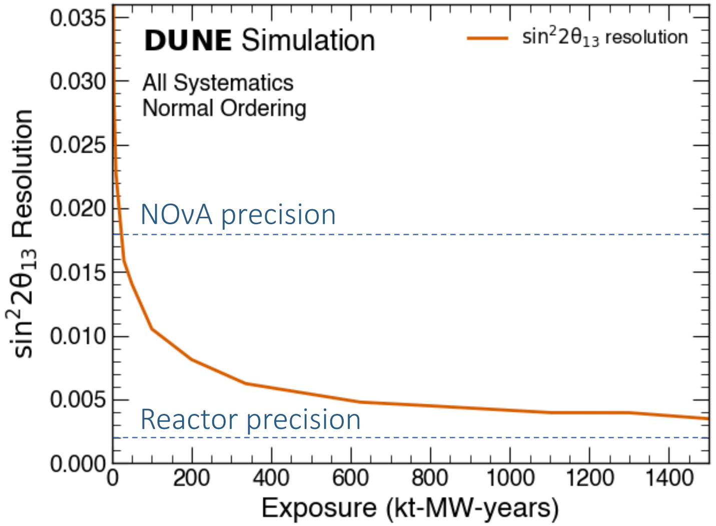
Precision Measurement of Oscillation Parameters

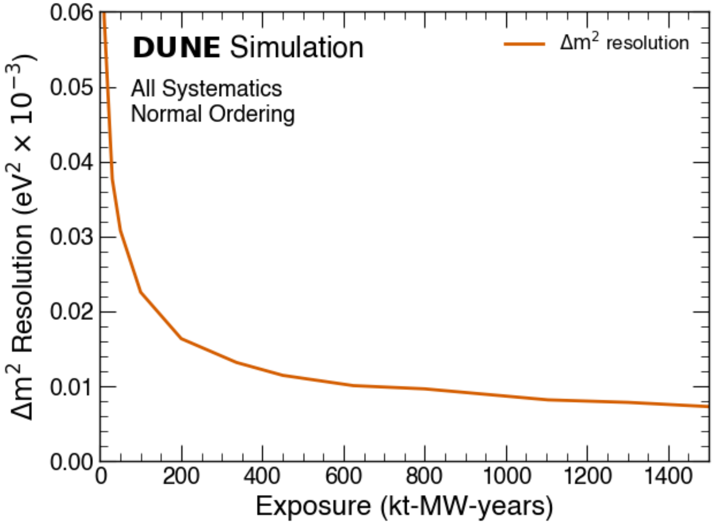
- Best precision for δ_{CP} in the 6-16^{o} range, & the most 'interesting' δ_{CP}
- World leading precision for Δm^2_{23} , ϑ_{23} , and ϑ_{23} for accelerator neutrino experiments
  - ○ Sub-percent precision, DUNE is in the game for the PMNS precision era
  - ○ Comparison with reactor measurements especially powerful to unveil new physics



336 kt-MW-y ≈ 7 years, 1104 kt-MW-y ≈ 15 years

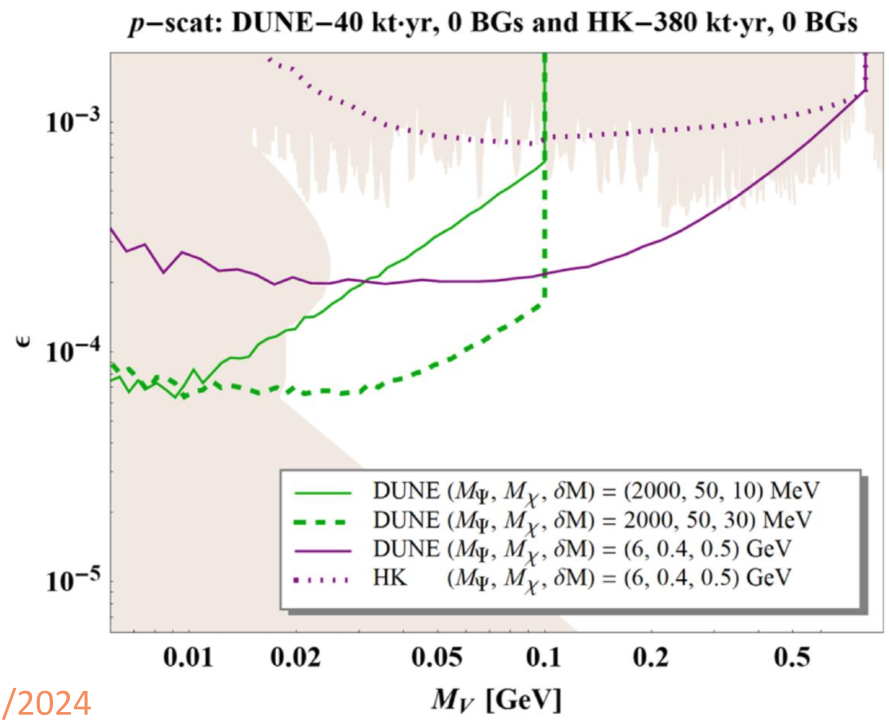


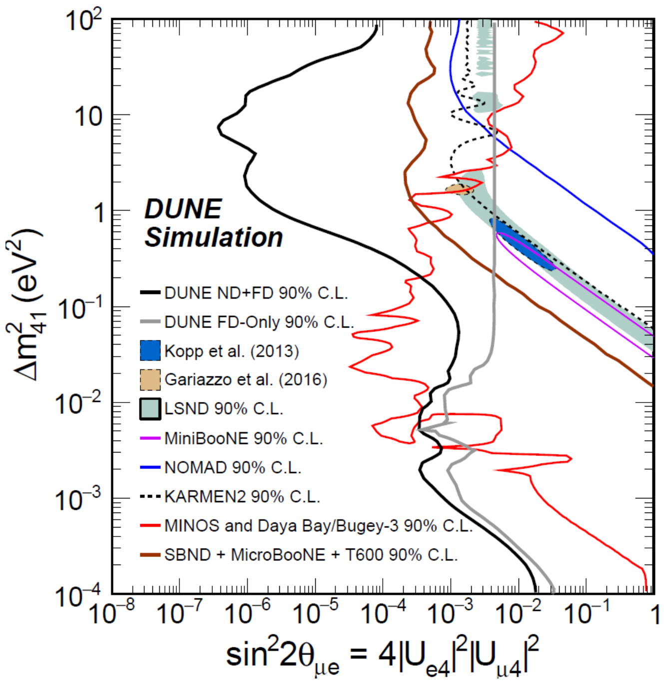




BSM Searches

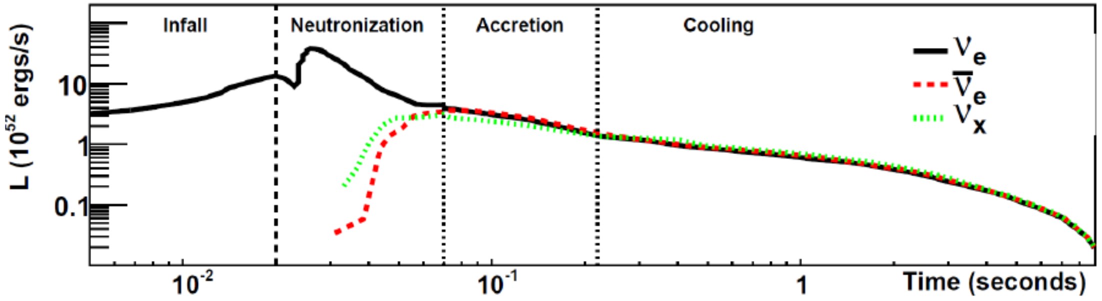
- Huge mass, low threshold and directionality in FD → sensitive to other rare processes
    - E.g., proton decay (best channel p→k$\bar{\nu}$)
- Broad L/E range covered at both ND and FD → new physics (BSM oscillations, CPT violation, NSI)
- High-intensity ν beam → exotic physics @ ND (light DM, HNL), BSM contributions to ν interactions

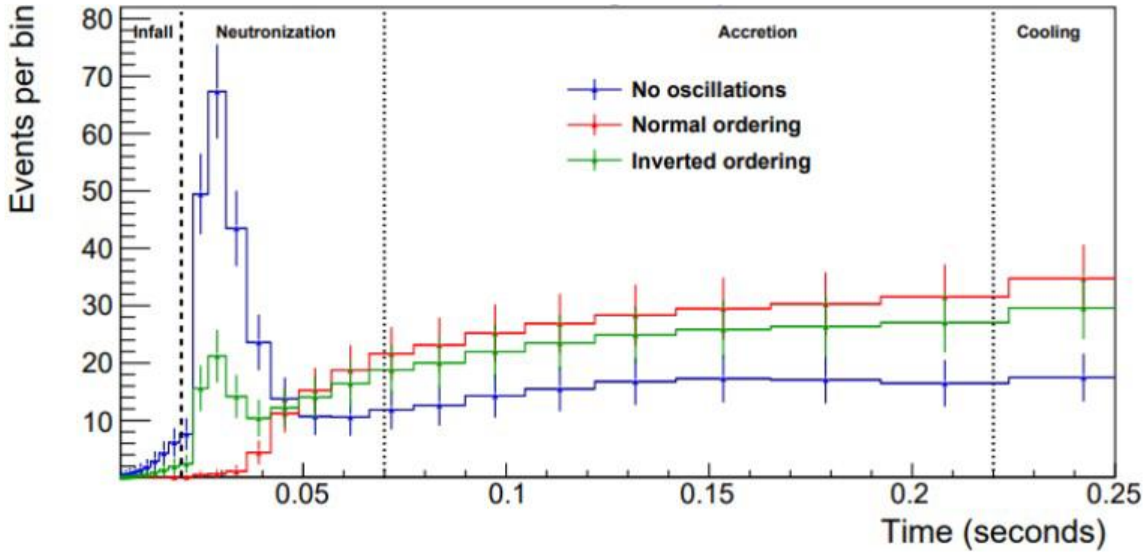


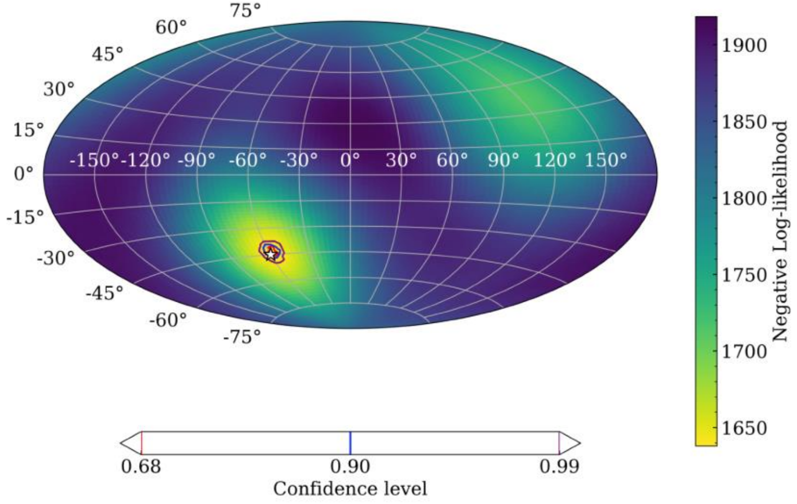


Supernovae

- SN explosion in the center of the MilkyWay
  - ○ $O10^3$ neutrinos in the FD over a few tens of seconds
  - ○ Energy spectrum peaked around 10 MeV, up to 30MeV
- LAr detectors sensitive to the ν_e component
  - ○ DUNE uniquely positioned to study the neutronization burst (first few tens of milliseconds) → mass ordering
- Evolution of the (flavor-dependent) flux & spectrum can be sensitive to astrophysical properties of the supernova and its progenitor
- Pointing resolution of better than 5^{o} (from ν+e → ν+e)



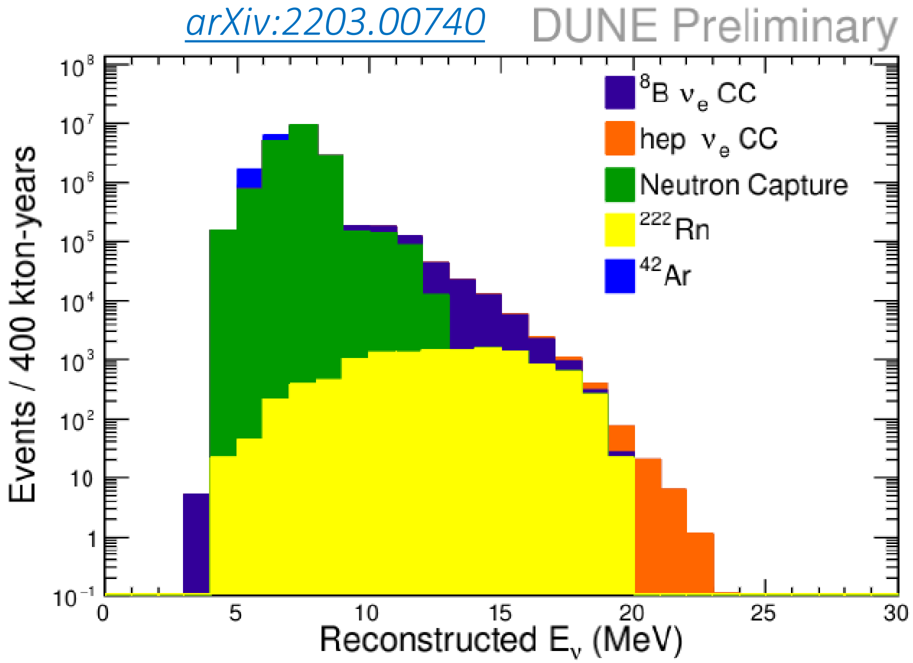




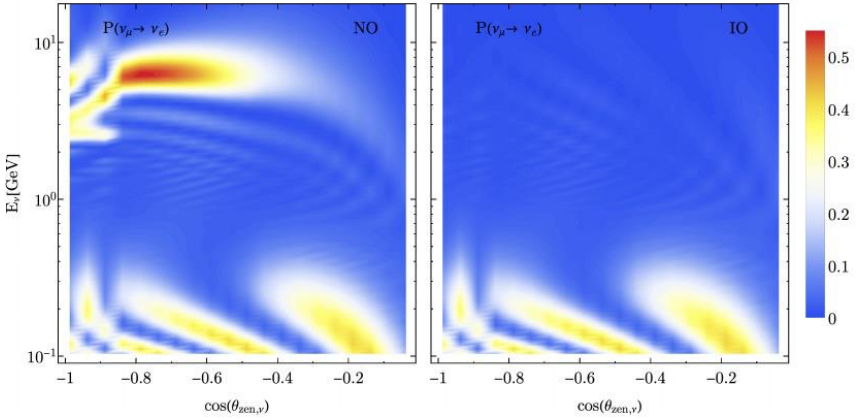
Other Natural Sources

- Solar neutrinos
  - Good sensitivity to ^{8}B neutrinos and discovery potential for hep
  - Can improve day-night asymmetry measurements
  - Background is the main challenge, capability for low-energy physics can be expanded in FD-III,IV
- Atmospheric neutrinos
  - Improved angular resolution with reconstructed hadrons
  - Can combine in the oscillation analysis
- FD-I,II alive before the beam, an opportunity to explore these physics

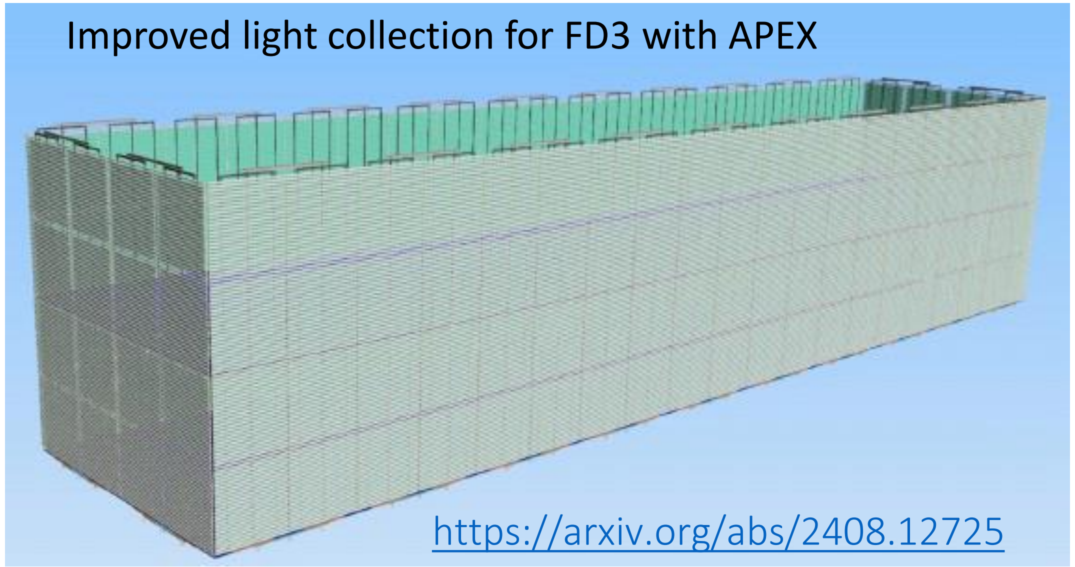
arXiv:2203.00740



Phys. Rev. X 13, 041055 (2023)

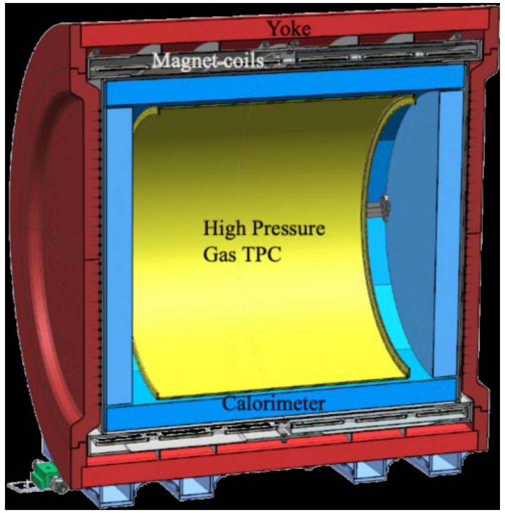


Phase-II of DUNE


Improved light collection for FD3 with APEX

https://arxiv.org/abs/2408.12725

- Two additional modules (40kt total fiducial volume)
  - VD is the baseline design for the Phase II FD modules
  - Phased construction allows to reap off technological developments to expand the physics reach of DUNE (solar and supernova neutrinos, DM, etc.)
  - Pursuing improvements to light collection for FD3
  - For FD4 (the “Module of Opportunity”) more ambitious designs are being considered (pixel readout, integrated charge-light readout, low backgrounds, Xe doping, non-LAr options, etc.)
- More capable Near Detector (ND-GAr) – repurposed KLOE solenoid & ECAL
  - Magnetized high-pressure gaseous argon TPC surrounded by ECAL and μ tagger
  - B field and the ECAL allow for PID and momentum/sign reconstruction
  - Low tracking threshold and uniform acceptance

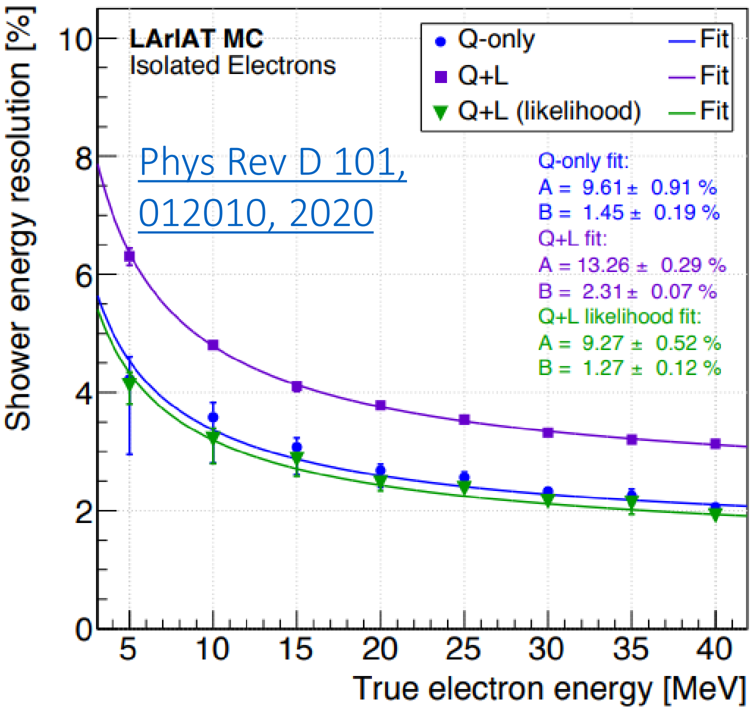


Going Low in Energies

- Strong drive within DUNE to exploit FD Modules 3 and 4 to extend low-energy physics program
  - Improved solar ν and SN physics, SN CEvNS, even $0\nu\beta\beta$ (^{136}Xe doping) and WIMP searches
  - All possible in upgraded FD modules w/o losing sensitivity to neutrino mixing parameters

arxiv:2203.08821
arxiv:2203.14700
arxiv:2203.07501

- These extensions take advantage of enhanced PDS (trigger, PID, calorimetry) → vigorous R&D and design/simulation programs
  - Lower threshold wrt baseline DUNE design (10 MeV → $\mathcal{O}$ 100 keV)
  - Rejection of background (n, Rn, ^{42}Ar, ^{39}Ar) is a major challenge, can be achieved via topology and PSD
  - Better E_{res} via charge + light calorimetry (i.e. with ARAPUCA-style modules and novel VUV SiPMs that are under study)

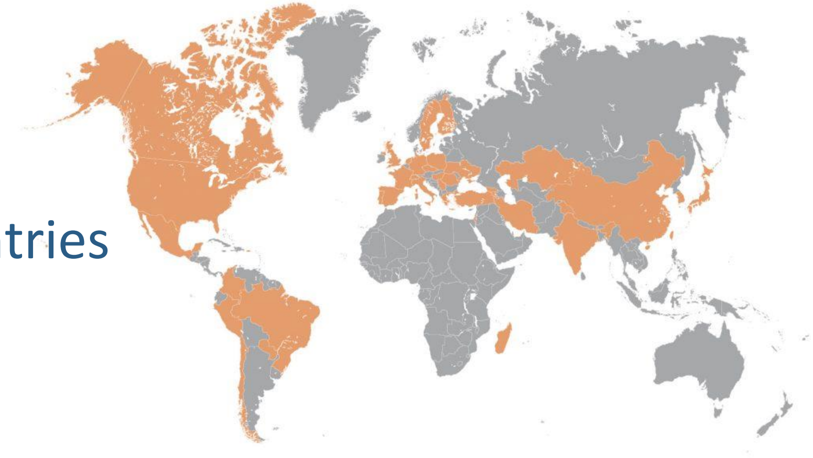


Phys Rev D 101, 012010, 2020

DUNE Timeline

- Far site excavation is complete!
- ‘Til mid-2025 Building & infrastructure works
- 2025-26 cryostat structure installation (recently arrived from CERN)
- 2026-27 far detector installation
- 2028 Purging and Ar filling
- Early 2029 First physics at the far detector
- 2031 Beam physics with ND and two FD modules (total fiducial mass of 20 kt, 1.2 MW beam)
- 2032 One more FD module, for total fiducial mass of 30 kt
- 2034 Another FD module, for total fiducial mass of 40 kt
- 2037 Upgrade to a 2.4 MW beam

The DUNE Collaboration



- Over 1400 collaborators from over 200 institutions in over 30 countries and CERN
- We meet three times a year (CERN, Fermilab, +1 institution)

https://www.dunescience.org/
https://lbnf-dune.fnal.gov/

Conclusions

- DUNE is a next-generation long-baseline neutrino oscillation experiment and neutrino observatory
- It has the potential to deliver ground-breaking results, like the unambiguous determination of the neutrino mass hierarchy, the discovery of CP violation in the leptonic sector, and many more
- DUNE rich scientific programme includes neutrinos of astrophysical origin, as well as BSM searches, both at its ND and FD
- An active large-scale prototype program at CERN validated the technology for the first two, and potentially all four far detectors
- Meanwhile, a rich R&D program is focused on expanding DUNE physics for Phase-II
- DUNE physics starts in this decade, so stay tuned!

Thank you
Grazie