DUNE: Science & Status

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for the DUNE Collaboration

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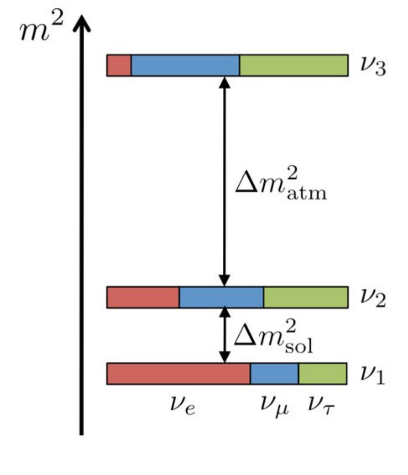
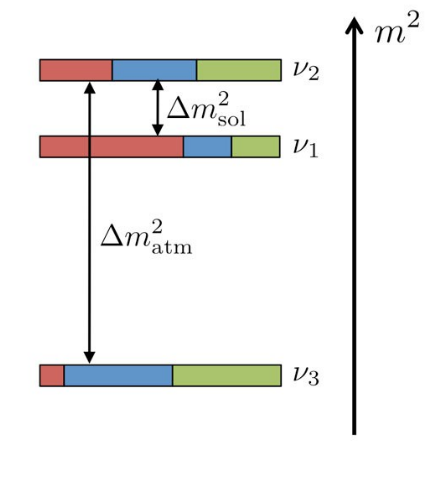
Long-baseline neutrino oscillations: unknown PMNS parameters

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

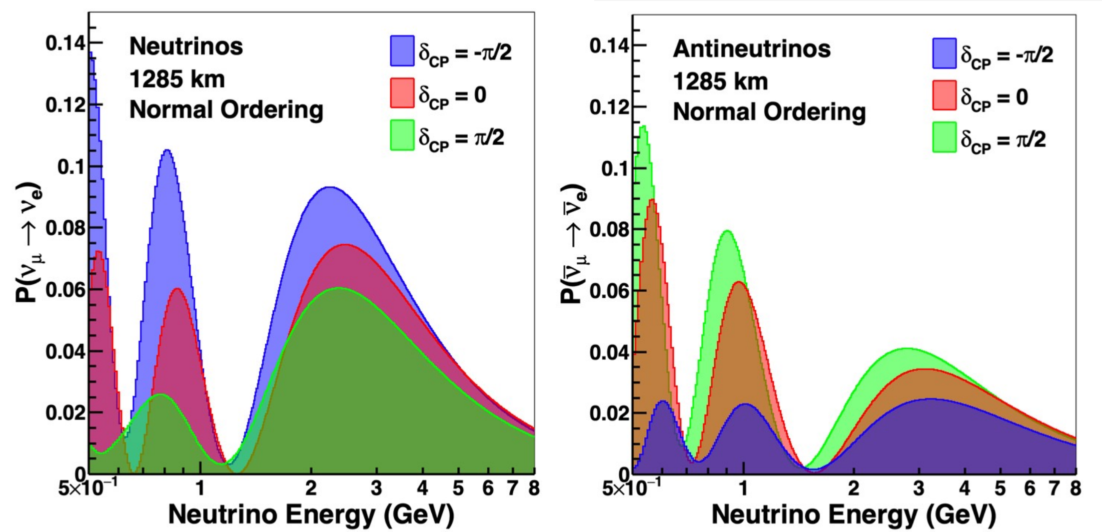
- Goals for next generation experiments:
  - Determine the neutrino mass ordering
  - Measure δ_{CP} and determine if CP is violated
  - Determine the octant of θ_{23}





Long-baseline neutrino oscillations: Is the 3-flavor model correct?

- Measure neutrino and antineutrino oscillation as a function of L/E
- Does the three-flavor model describe the data?
    - If yes: measure the mixing angles, mass splittings, and CP phase
    - If no: characterize the new physics
- Need for a global program: different energies, matter effects, systematics, etc.



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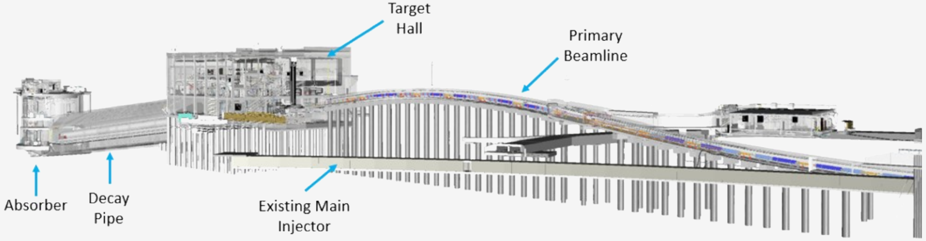
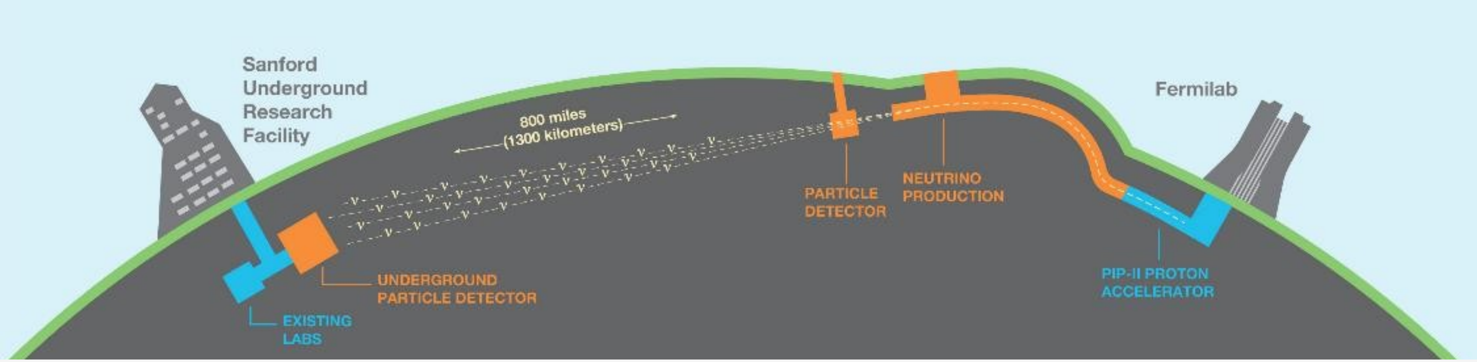
Long-baseline oscillations as part of a broad physics program

- Large, sensitive underground detectors are excellent to:
  - Observe supernova burst neutrinos
  - Measure solar and atmospheric neutrinos
  - Search for new physics (nucleon decays, cosmogenic dark matter, etc.)
- Intense beams with capable near detectors are excellent to:
  - Search for new physics produced in the beamline
  - Search for new physics in rare interactions (i.e. neutrino tridents)

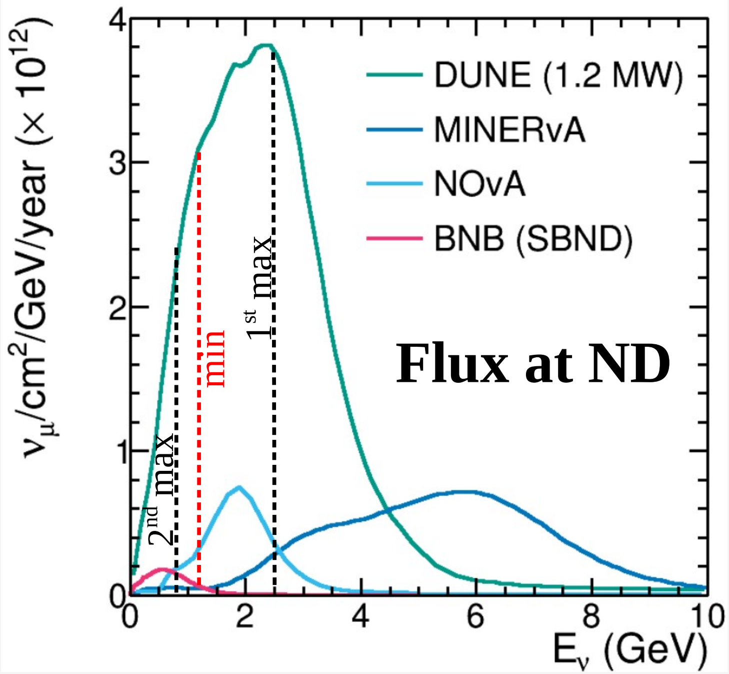


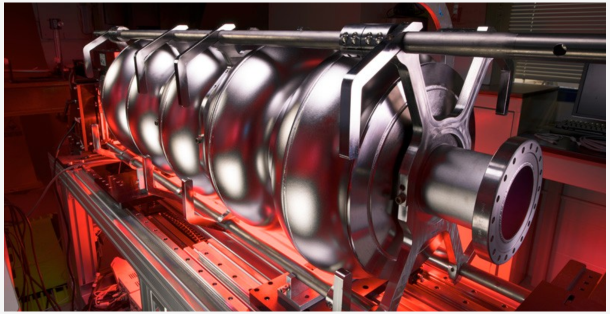


- Wideband (anti)neutrino beamline with >2MW intensity
- Underground, modular LArTPC Far Detector with ≥40 kt fiducial mass
- Movable LArTPC Near Detector with muon spectrometer and separate on-axis detector
- Global collaboration of >1400 scientists and engineers

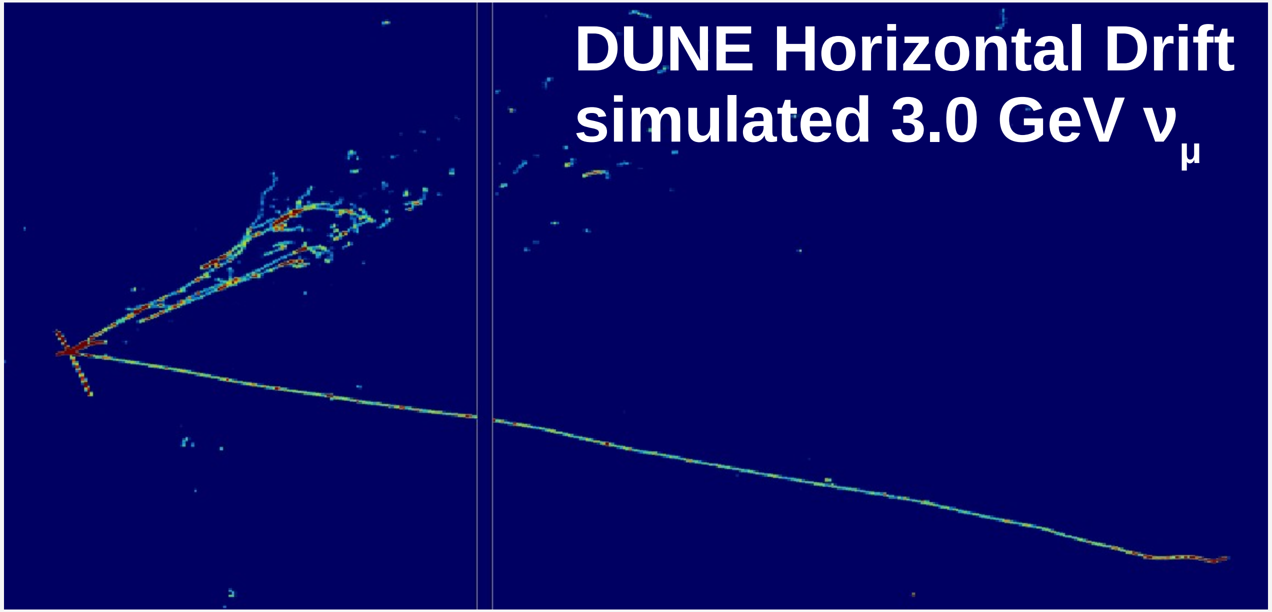
LBNF beamline: world-leading intensity

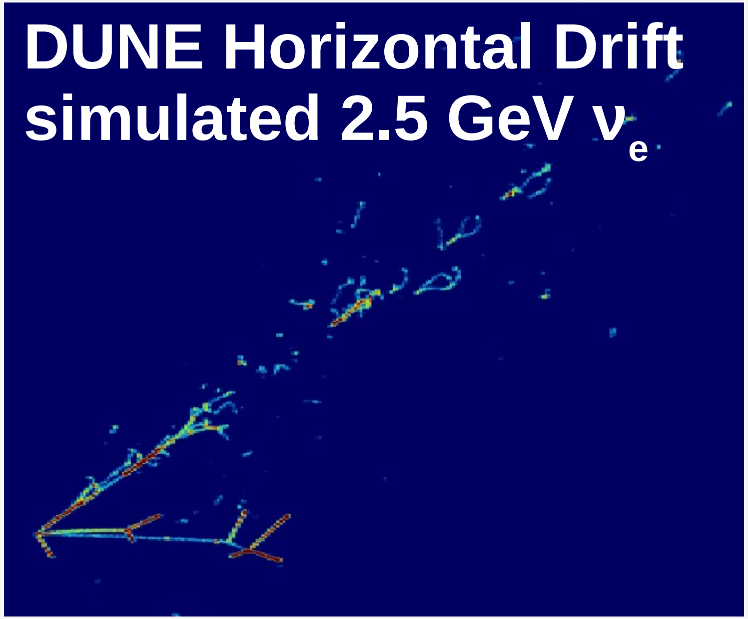
- Very high flux between oscillation minimum and maximum, with coverage of second maximum
- ACE-MIRT upgrade enables >2MW beam by ~doubling frequency of spills, and can be achieved before operations begin





LArTPC: flavor & energy reco over a broad range of topologies

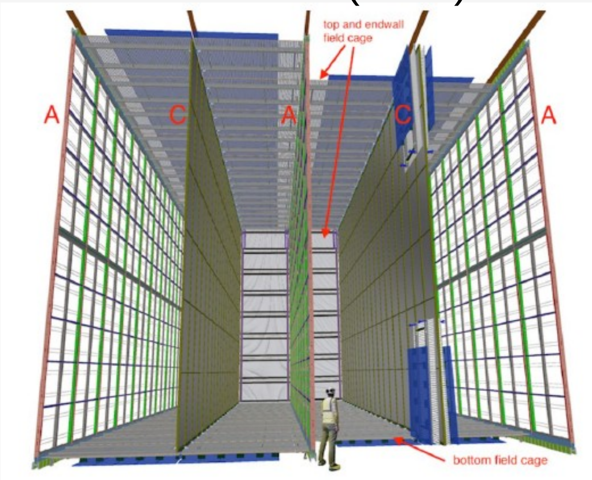




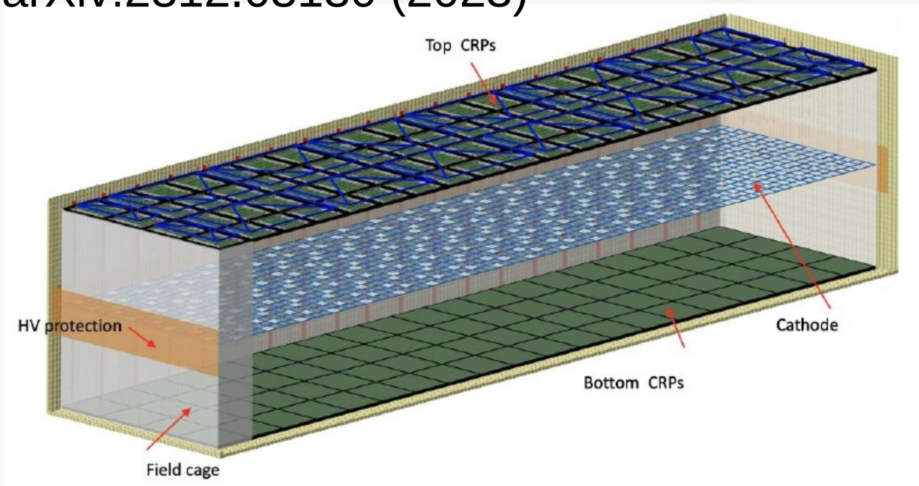
- 60% of interactions at DUNE energy have final state pions → LArTPC enables precise hadron reconstruction
- Excellent e/μ and e/γ separation

Far detector: two readout technologies

JINST 15 T08010 (2020)



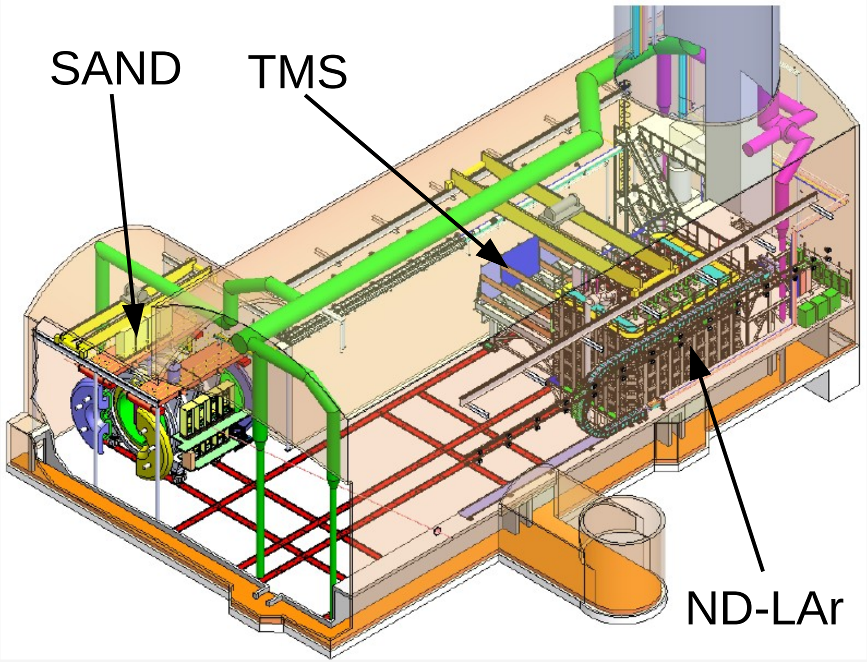
arXiv:2312.03130 (2023)



- Horizontal drift (HD, left) using wire readout planes, four drift regions
- Vertical drift (VD, right) using two 6.25m drift regions and central cathode
  - Simpler to install → first DUNE FD module will use vertical drift
  - VD is baseline design for modules 3 and 4

Near detector: systematic constraints for precision physics

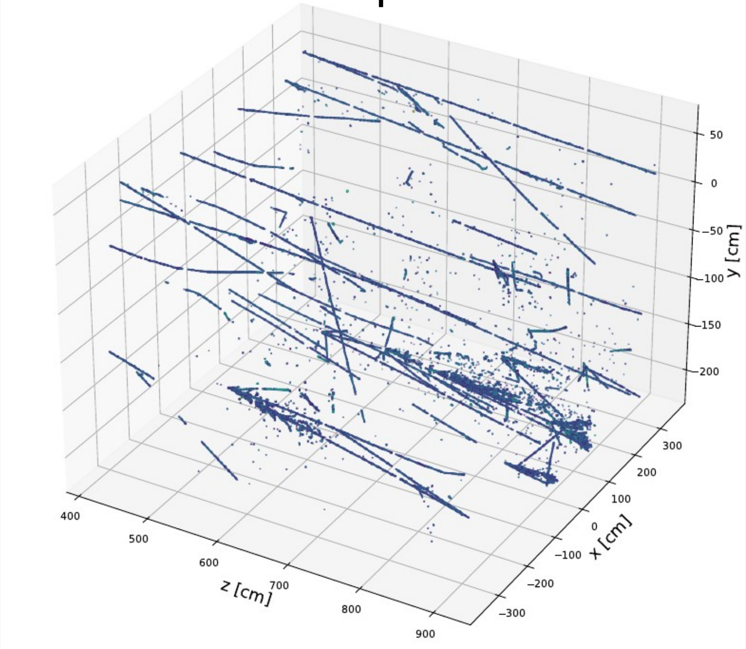
- Main purpose: enable prediction of Far Detector reconstructed spectra
- Movable detector system: LArTPC with muon spectrometer
- Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
- Same target, same technology → inform predictions of reconstructed E_ν in Far Detector



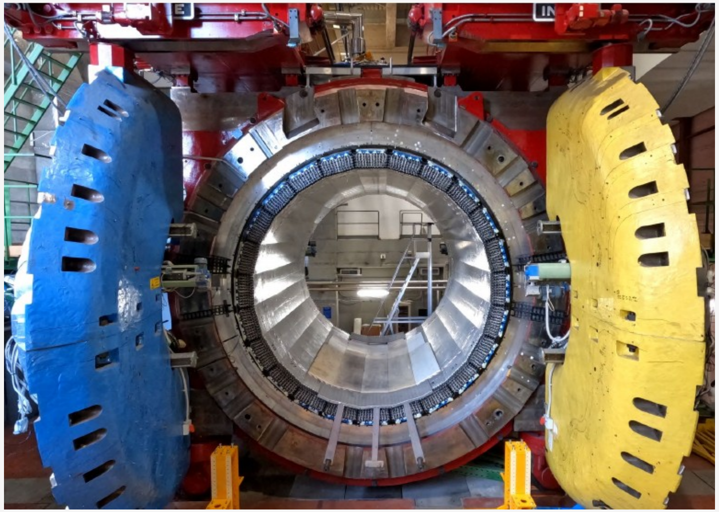
Unique challenge for ND: pile-up

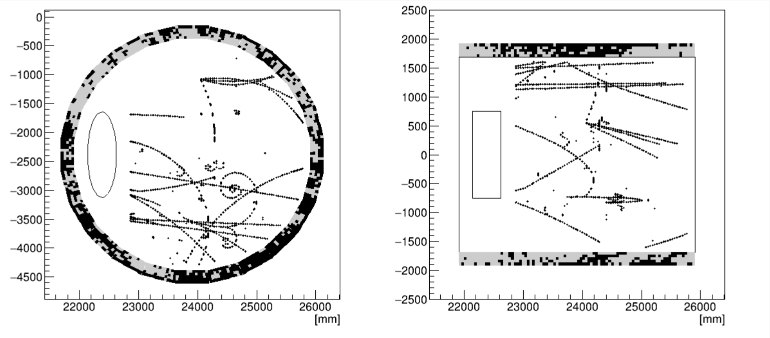
- Neutrino pile-up: very high rate at near site motivates pixelated readout and optical modularity
- Pixel readout: Natively 3D information in raw data, for resolving activity that would overlap in 2D projections
- Optical modularity: For charge-light matching, to allow association of detached energy (e.g. from neutrons)

One beam spill at ND-LAr



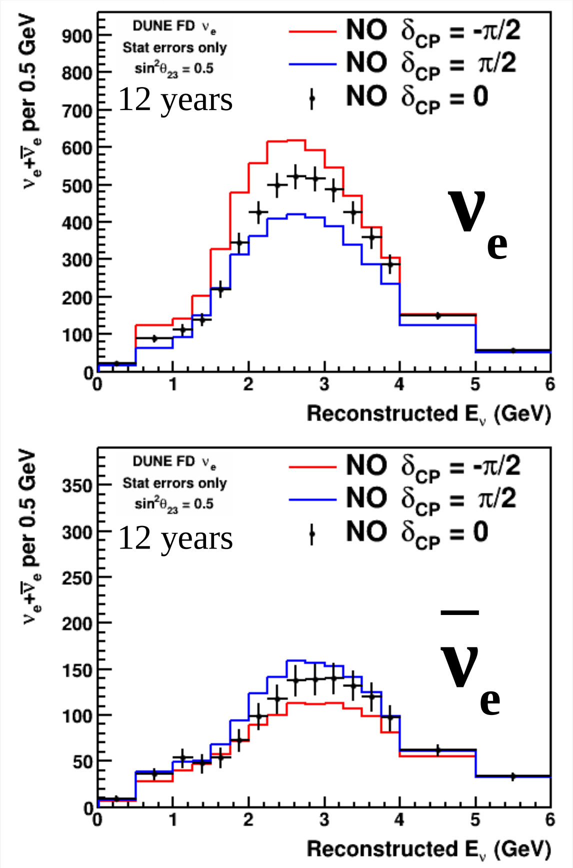
SAND: on-axis detector using KLOE magnet and calorimeter





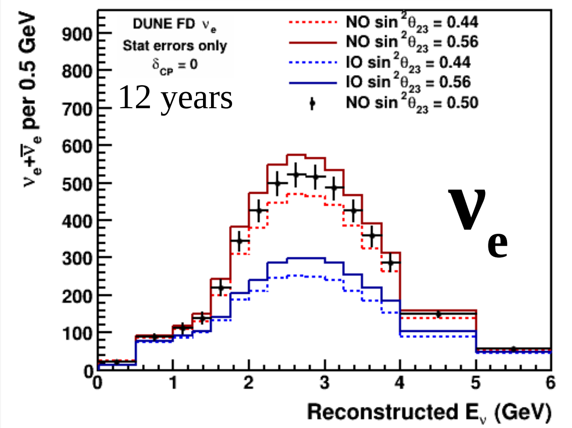
- Fixed component of ND repurposes existing solenoid magnet and ECAL from KLOE
- Plan is to build a collider-like detector in a neutrino beam: low-density tracker surrounded by calorimetry in magnetic field
- Fine-grained, particle-by-particle reconstruction with very low rescattering, excellent for highly exclusive neutrino-nucleus measurements
- Being (carefully) taken apart at Frascati for the move to the US

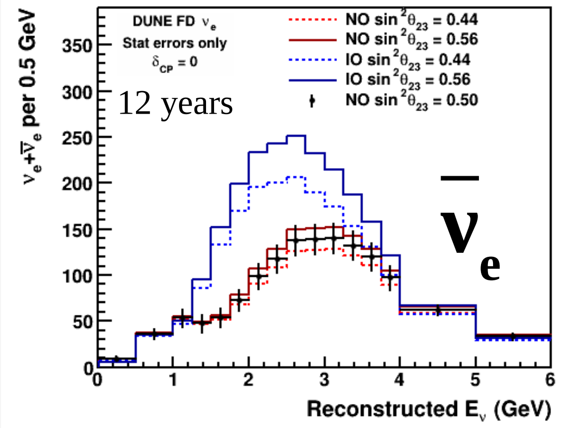
Far Detector energy spectra are sensitive to CP violation



- If δ_{CP} ~ $-\pi/2$, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance

Far Detector energy spectra are sensitive to CP violation

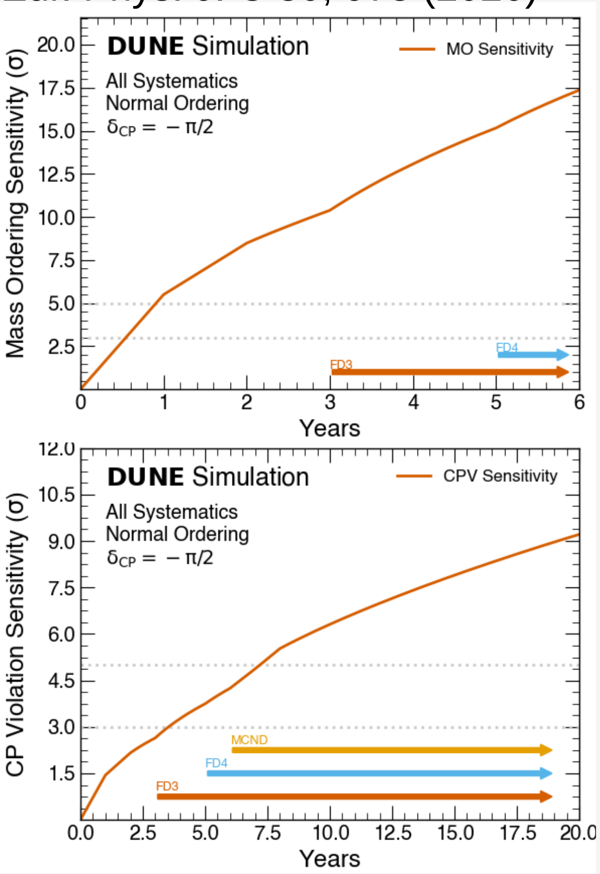




- If δ_{CP} ~ $-\pi/2$, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- If the mass ordering is normal, DUNE will measure a *much larger* enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- MO, δ_{CP}, and θ_{23} all affect spectra with different shape → additional handle on resolving degeneracies
- If new physics is present, there may be no combination of MO, δ_{CP}, and θ_{23} that fits data

MO & CPV significance if nature is kind

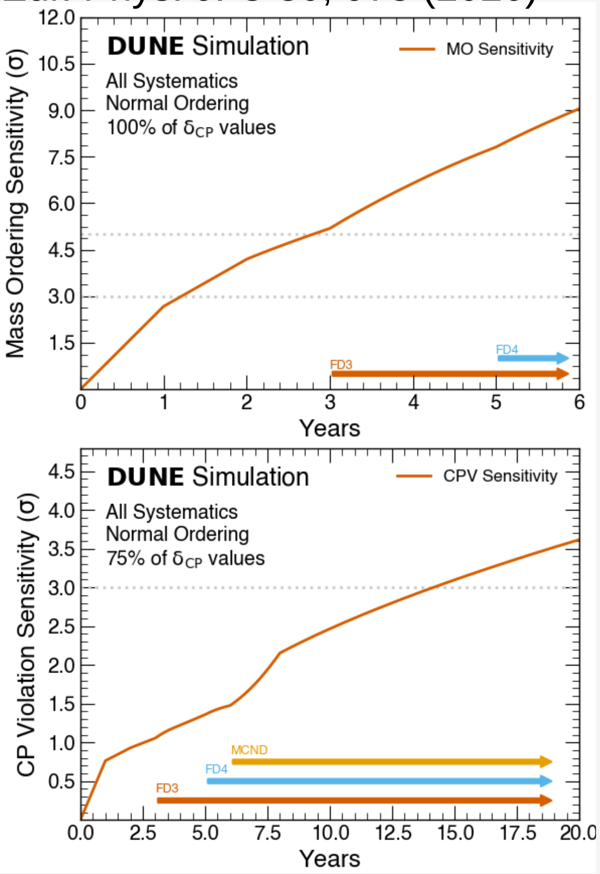
Eur. Phys. J. C 80, 978 (2020)



- For best-case oscillation scenarios, DUNE has
  - >5σ mass ordering sensitivity in 1 year
  - >3σ CPV sensitivity in 3.5 years

MO & CPV significance if nature is unkind

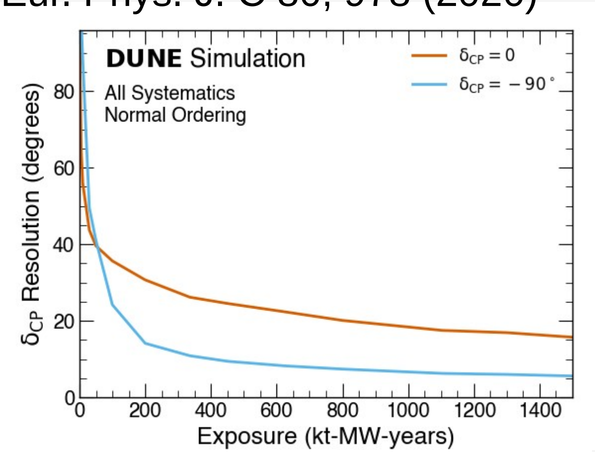
Eur. Phys. J. C 80, 978 (2020)

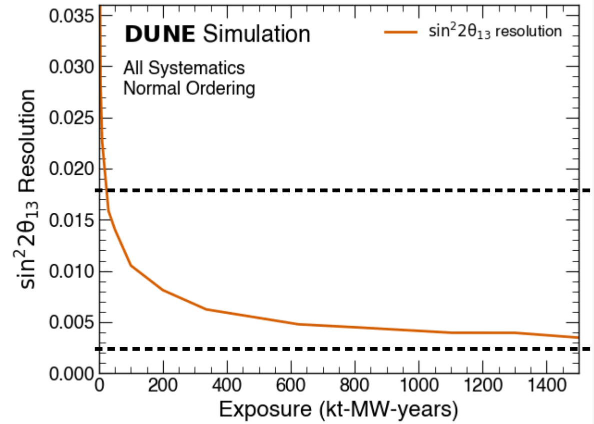


- For best-case oscillation scenarios, DUNE has
  - >5σ mass ordering sensitivity in 1 year
  - >3σ CPV sensitivity in 3.5 years
- For worst-case oscillation scenarios, DUNE has >5σ mass ordering sensitivity in 3 years
- In long term, DUNE can establish CPV over 75% of δ_{CP} values at >3σ
- Arrows indicate assumed staging scenario

Precision measurements of 3-flavor parameters

Eur. Phys. J. C 80, 978 (2020)



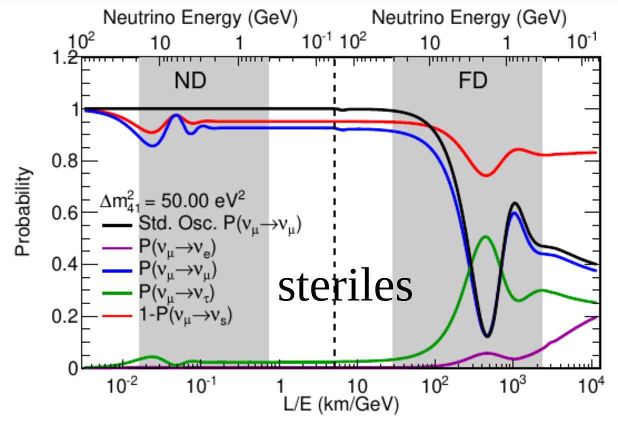


- Ultimate precision 6-16° in δ_{CP}
- World-leading precision (for long-baseline experiment) in θ_{13} and Δm^2 → comparisons with reactor measurements are sensitive to new physics

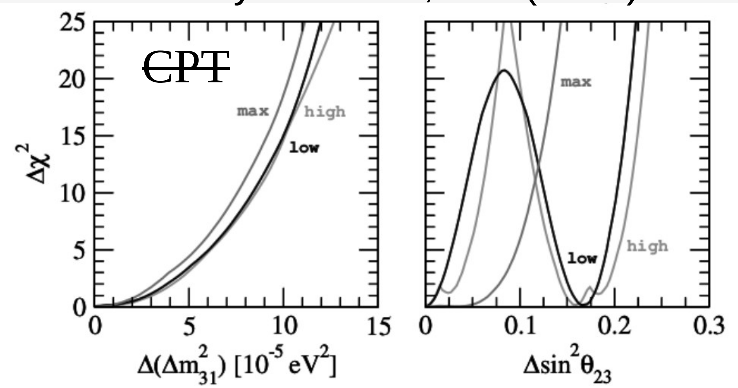
Current NOvA uncertainty

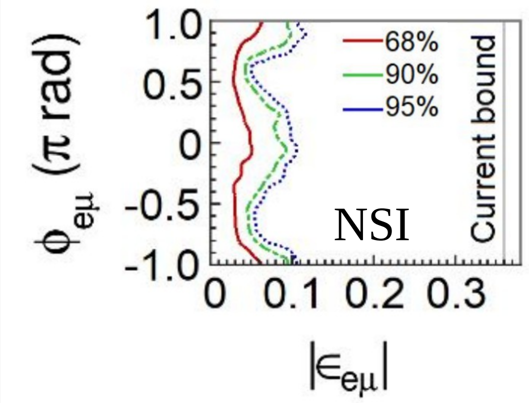
Reactor uncertainty

Beyond three flavors



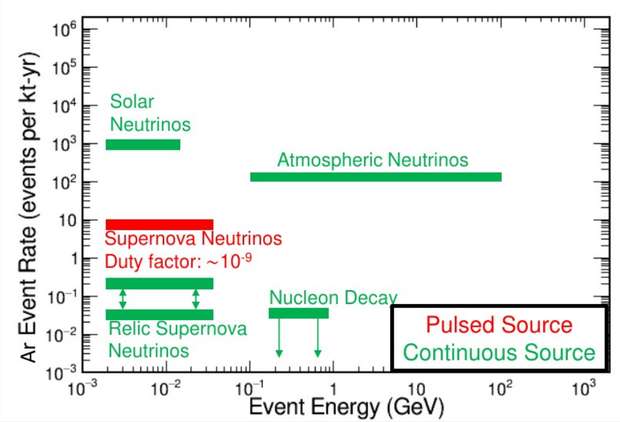
Eur. Phys. J. C 81, 322 (2021)

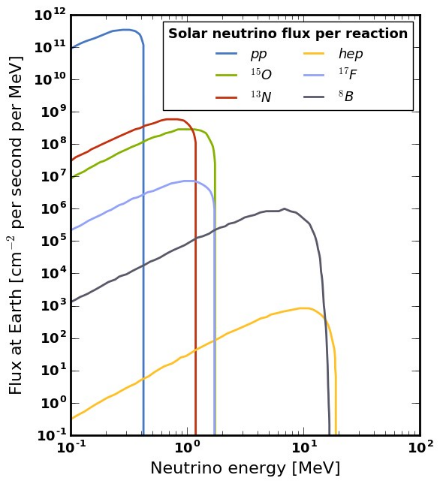


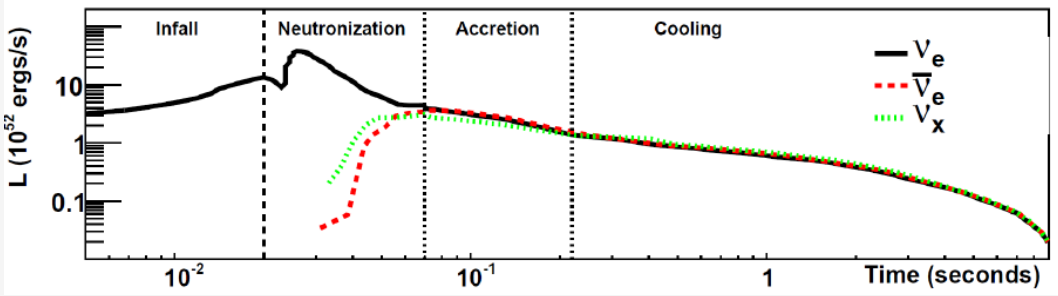


- Broad range of L/E at ND and FD → search for non-SM oscillations
- High statistics neutrino and antineutrino measurements → search for CPT violation
- Very large matter effect → uniquely sensitive to some NSI

Natural neutrino sources at DUNE FD





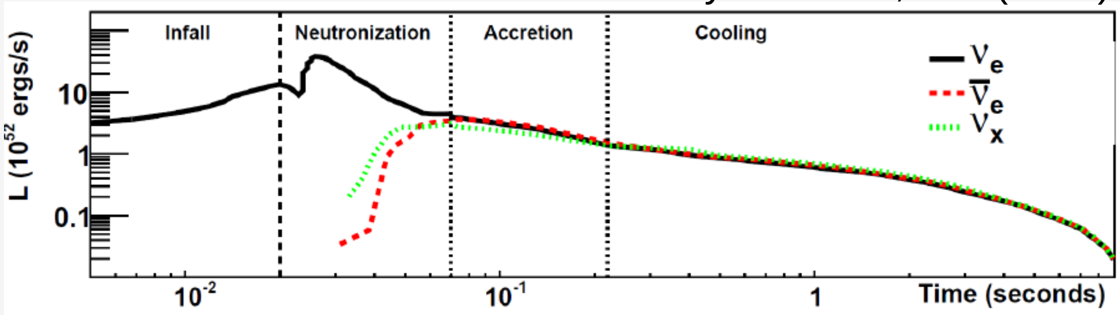


- DUNE FD will observe atmospheric, solar, and supernova neutrinos
- Argon target gives unique sensitivity to MeV-scale electron neutrinos
  - $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ ($E_\nu > 1.5$ MeV)
  - $\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$ ($E_\nu > 7.5$ MeV)
  - $\nu_x + e^- \rightarrow \nu_x + e^-$ (pointing)
- Highly complementary to other experiments (Hyper-K, JUNO) that predominantly see $\bar{\nu}_e$ via IBD

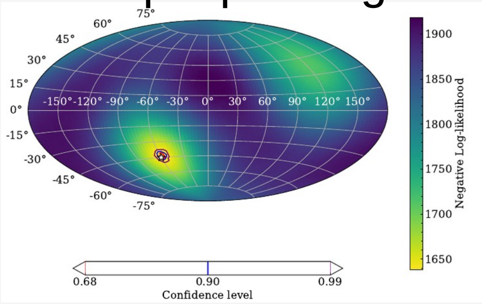
Particle & astrophysics with supernova burst neutrinos

- DUNE will observe ~thousands of neutrino interactions from a galactic supernova burst
- Time and energy spectra are sensitive to core collapse mechanism and stellar evolution
- Unique ability to observe neutronization burst, and determine neutrino mass ordering
- Channel tagging ν+e → ν+e enables ~5° pointing resolution (40 kt, 10 kpc)

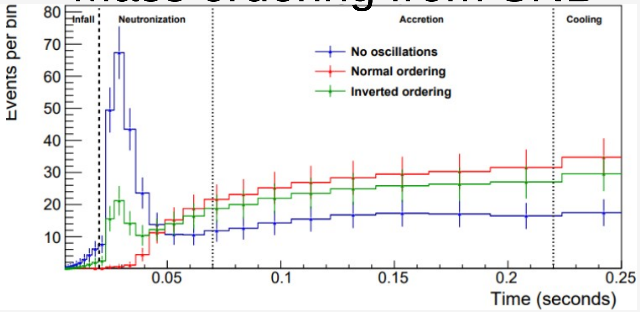
Eur. Phys. J. C 81, 423 (2021)



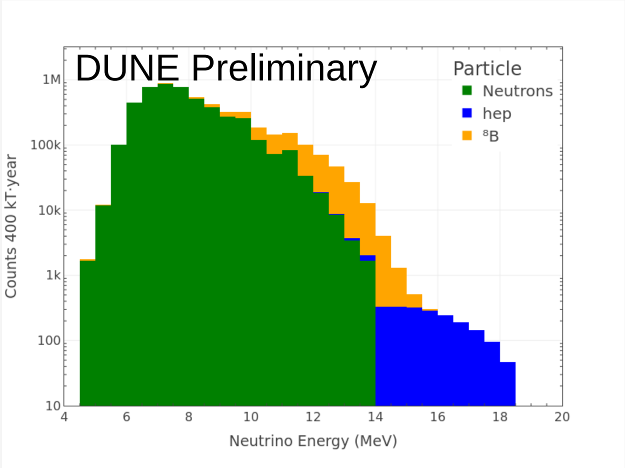
Example pointing

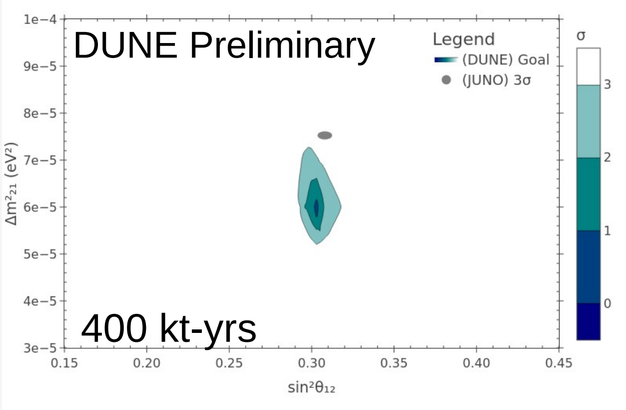


Mass ordering from SNB



DUNE sensitivity to solar neutrinos

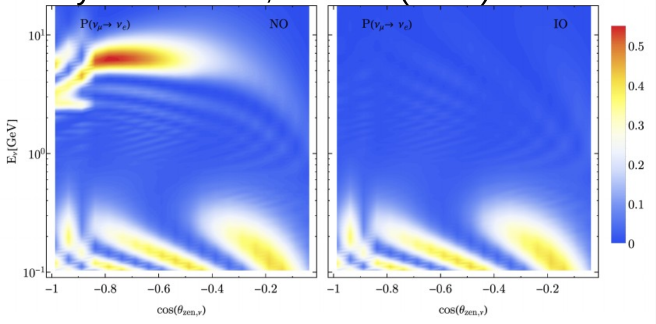


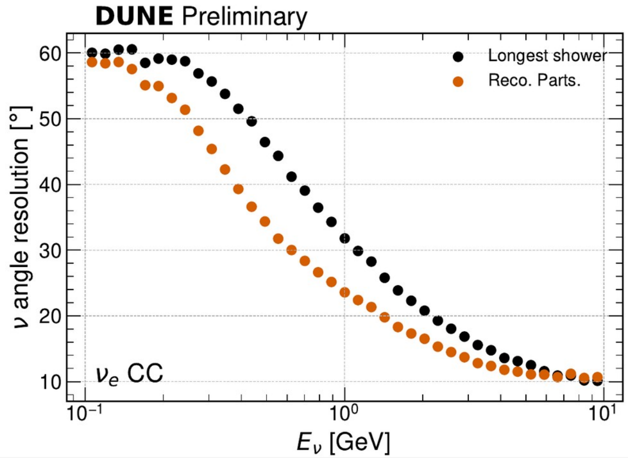


- Despite a large neutron background at low energies, DUNE has excellent sensitivity to ^{8}B solar neutrinos above ~10 MeV, and discovery sensitivity to the hep solar flux
- DUNE can improve upon existing solar oscillation measurements via day-night asymmetry induced by matter effects → comparison with JUNO
- Current analysis assumes dedicated trigger and flash matching (needed for fiducialization)

Atmospheric neutrinos: angle reconstruction including hadrons

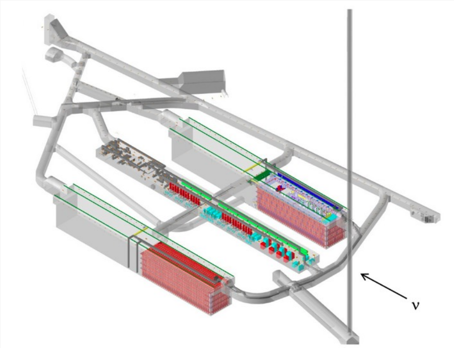
Phys. Rev. X 13, 041055 (2023)

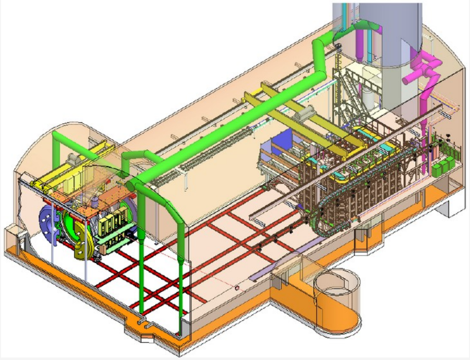




- Atmospheric neutrinos will be DUNE's first data; aim to combine with long-baseline
- Including reconstructed hadrons substantially improves angle resolution, especially at lower neutrino energies
- Potential to extend to low energies has been studied phenomenologically, see Phys. Rev. Lett. 123, 081801 (2019)
- DUNE analysis in progress

DUNE construction: Phase I





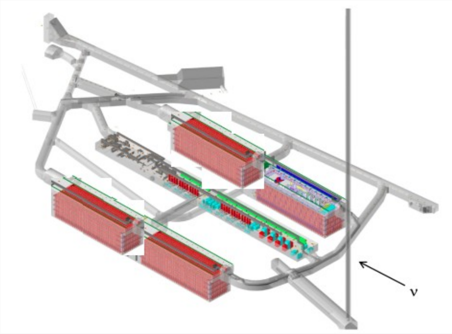
- Full Near and Far Site facility
- Two LArTPC modules (VD & HD), each 17 kt Ar
- 1.2 MW upgradeable neutrino beamline
- Movable LArTPC ND+muon catcher, SAND

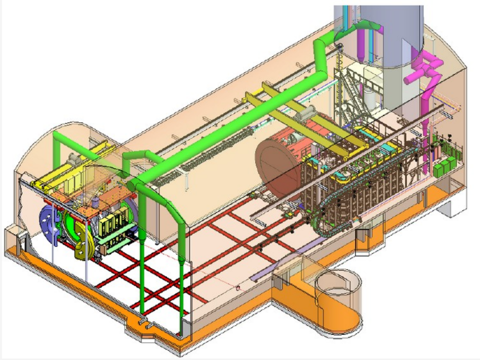
Completing Phase I is highest priority in P5 report:

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

b. The first phase of DUNE and PIP-II to open an era of precision neutrino measurements that include the determination of the mass ordering among neutrinos.

DUNE construction: Phase II





- Two additional FD modules
- Beamline upgrade to >2MW (ACE-MIRT)
- More capable Near Detector (ND-GAr)

P5 report endorses FD3, ACE-MIRT, and MCND in the next decade, and R&D toward FD4

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

b. A re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind

Recommendation 4: Invest in a comprehensive initiative to develop the resources—theoretical, computational, and technological—essential to realizing our 20-year strategic vision. This includes an aggressive R&D program that, while

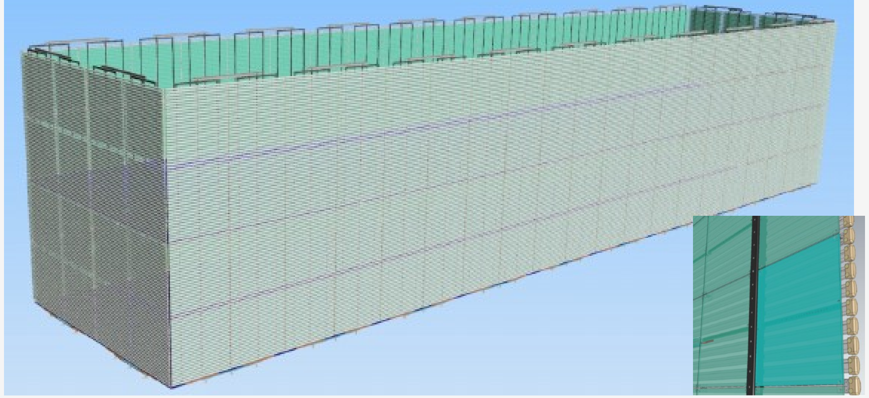
e. Conduct R&D efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping

Building DUNE: construction schedule

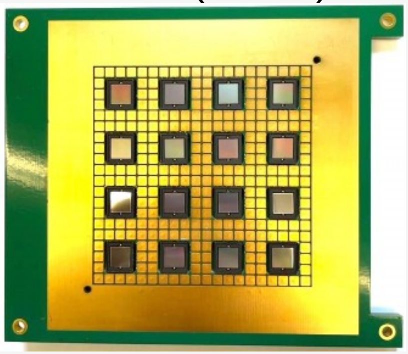
- Far site excavation is complete
- Next: Building & Site Infrastructure work until mid-2025
- Cryostat warm structure is on its way to US from CERN to be installed in 2025-26
- Far Detector installation in 2026-27
- Purge and fill with argon in 2028
- Physics in 2028 or early 2029
- Beam physics with Near Detector 2031

Phase II FD: additional mass + opportunities to expand physics reach

Improved light collection for FD3 (APEX)

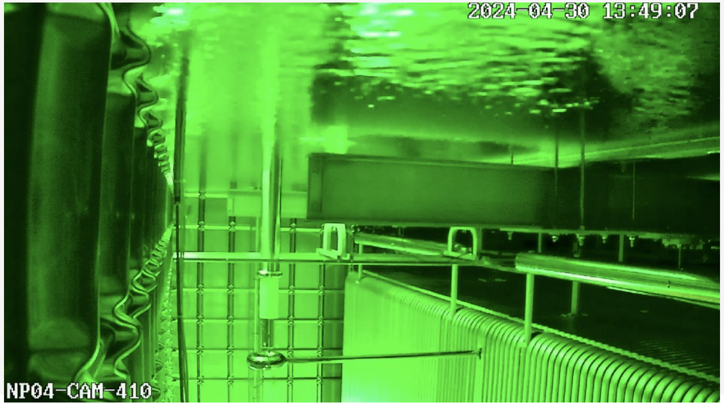


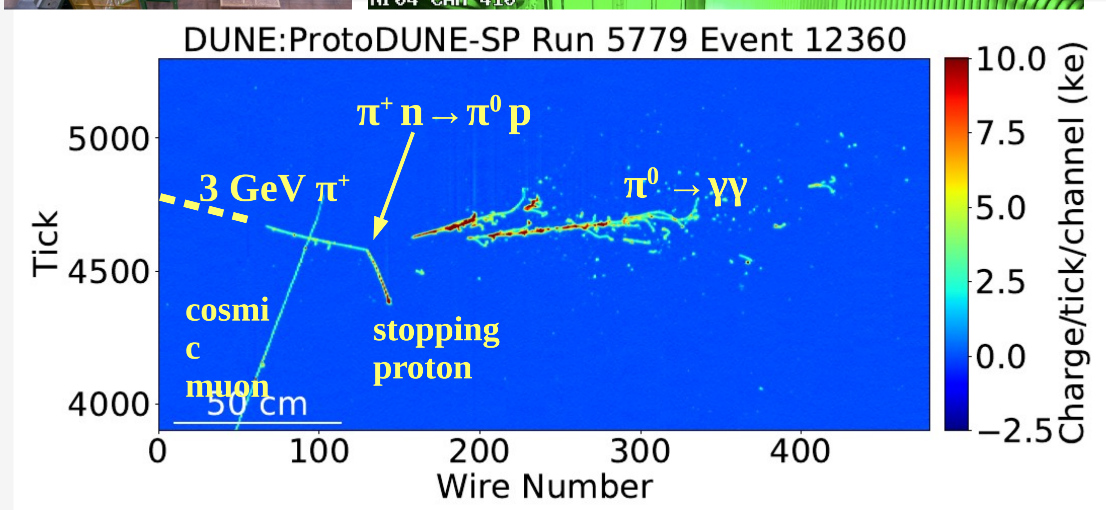
Prototype for possible FD4 readout (SoLAr)



- Vertical Drift module is the baseline design for Phase II FD modules
- Pursuing low-hanging improvements to light collection for FD3, including Aluminum Profiles with Embedded X-ARAPUCA, essentially integrating light detectors into field cage
- FD4 is the “Module of Opportunity”, and more ambitious designs are being considered, including pixel readout, integrated charge-light readout, low background modules, and non-LAr technologies

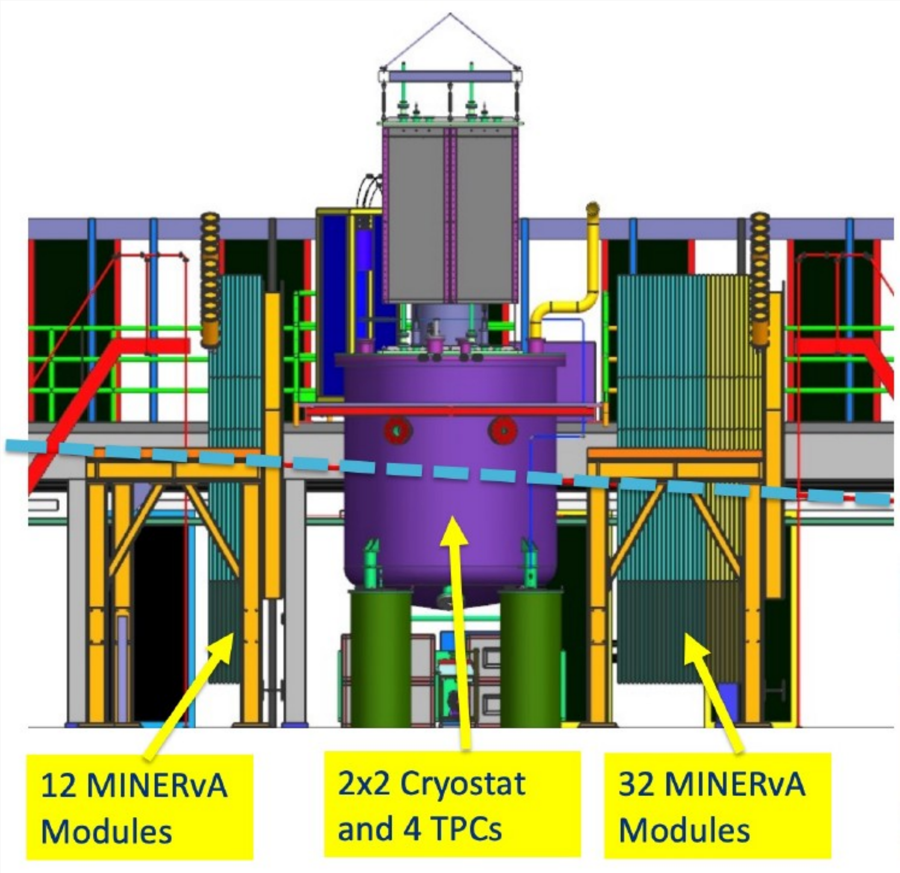
ProtoDUNE: preparing for second runs





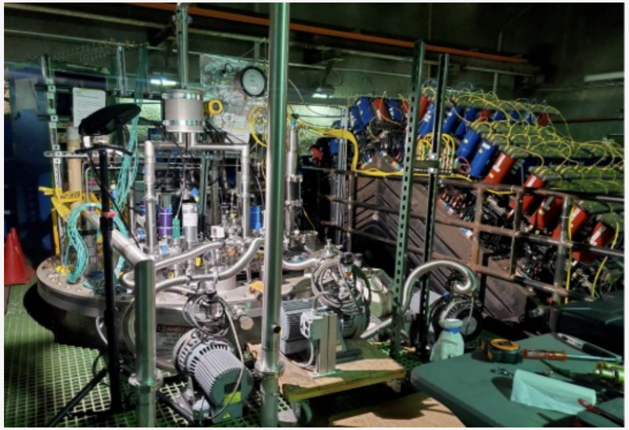
- Successful prototype of horizontal drift at CERN Neutrino Platform in 2018 (ProtoDUNE-SP)
- ProtoDUNE-HD completed filling 30th April, running since May, with beam turning on at 6pm tomorrow evening
- LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025

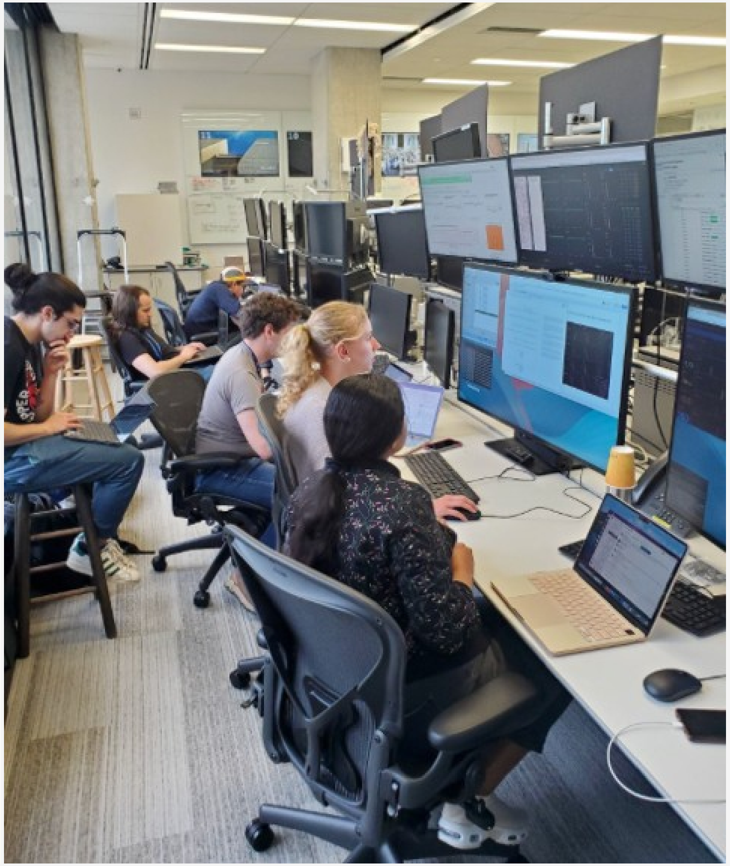
ND-LAr 2x2 prototype: DUNE's first detector in a neutrino beam



- Individual ND-LAr prototype modules have been operated with cosmics at Bern
- "2x2" is a four-module integration test in the Fermilab NuMI beam
- Re-purposed MINERvA scintillator and calorimeter planes mimic the role of TMS in the DUNE ND
- Will demonstrate reconstruction with natively 3D readout in a neutrino beam with similar event rate to DUNE

ND-LAr 2x2 prototype: towards data





- Detectors installed inside cryostat
- Cooling and argon filling is complete
- Currently undergoing cold commissioning
- Monitored with 24-hour shifts since early June

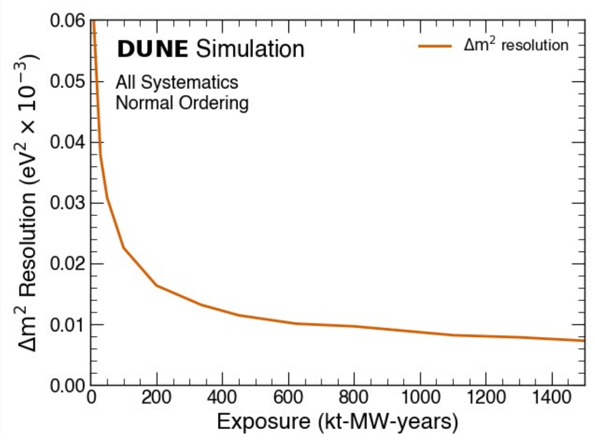
Summary

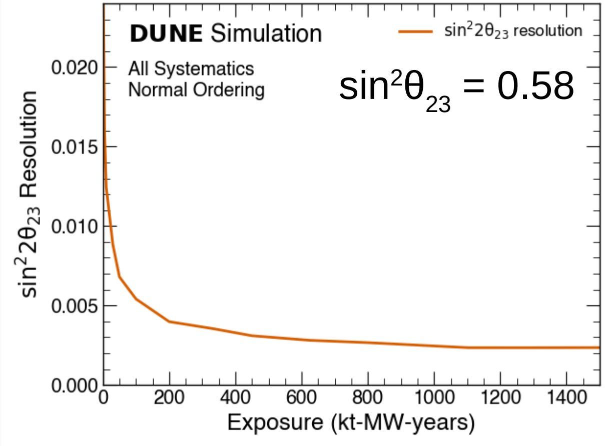
- DUNE is a long-baseline oscillation experiment and neutrino observatory
  - Unique and complementary reach in oscillations, MeV-scale neutrinos, and BSM searches
- DUNE has an active prototyping program, with excavation complete and components under construction → start of science in this decade
- See also 33 DUNE posters!

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Backup Slides

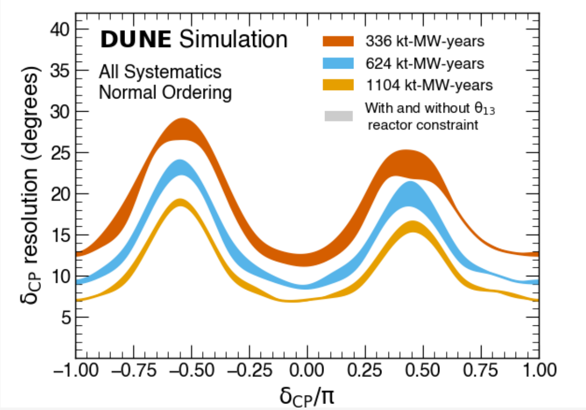
Resolution to disappearance parameters

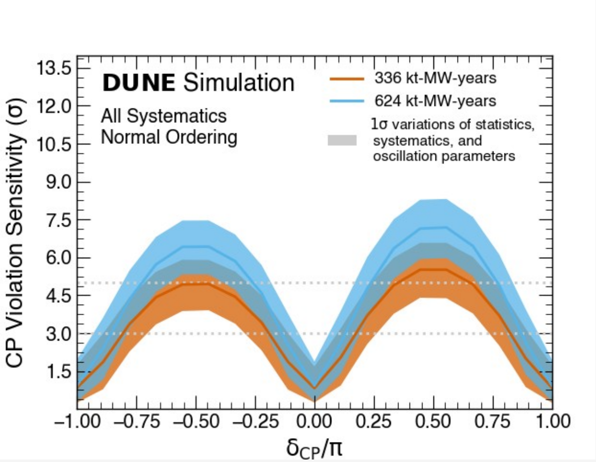




- Δm^2 is measured by location of dip in disappearance spectrum → high rate and on-axis location gives improved sensitivity relative to current LBL experiments
- Comparison with similar JUNO measurement is sensitive to new physics
- Resolution to θ_{23} is complicated; strongly dependent on true parameter values, and correlated with other parameters

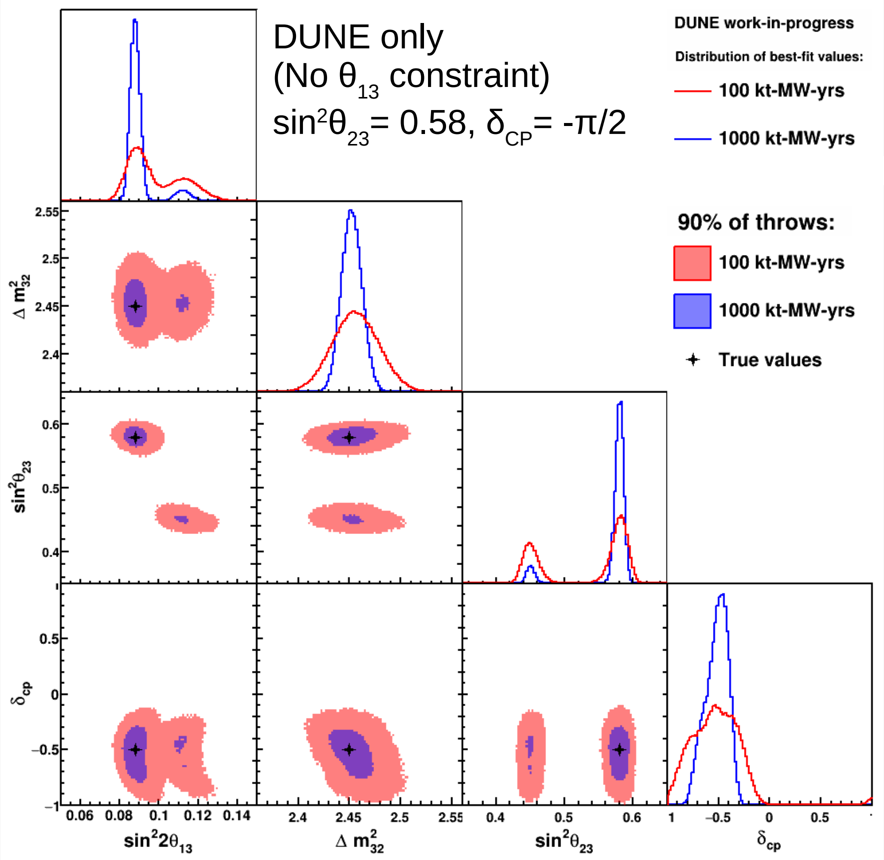
CP violation and δ_{CP} resolution





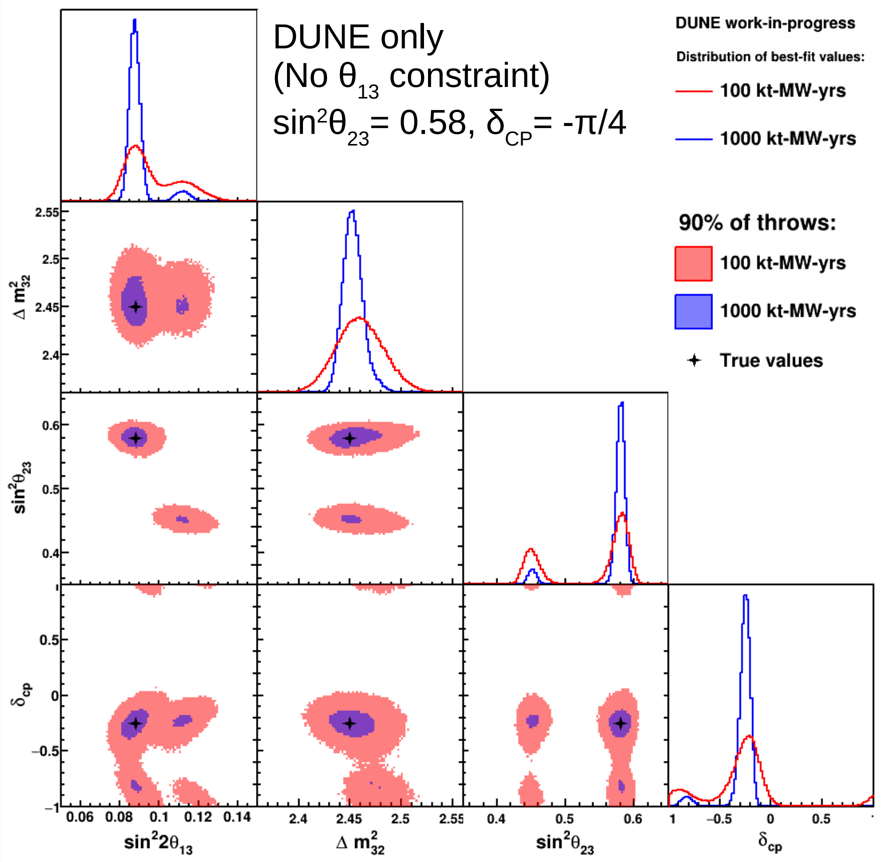
- δ_{CP} resolution is best at 0 and π because appearance at maximum is proportional to $\sin(\delta_{CP})$
- DUNE (and most experiments) typically quote median sensitivities, but statistical fluctuations and systematic uncertainties give a range of possible values shown by the bands

Resolving parameter degeneracies with spectral information



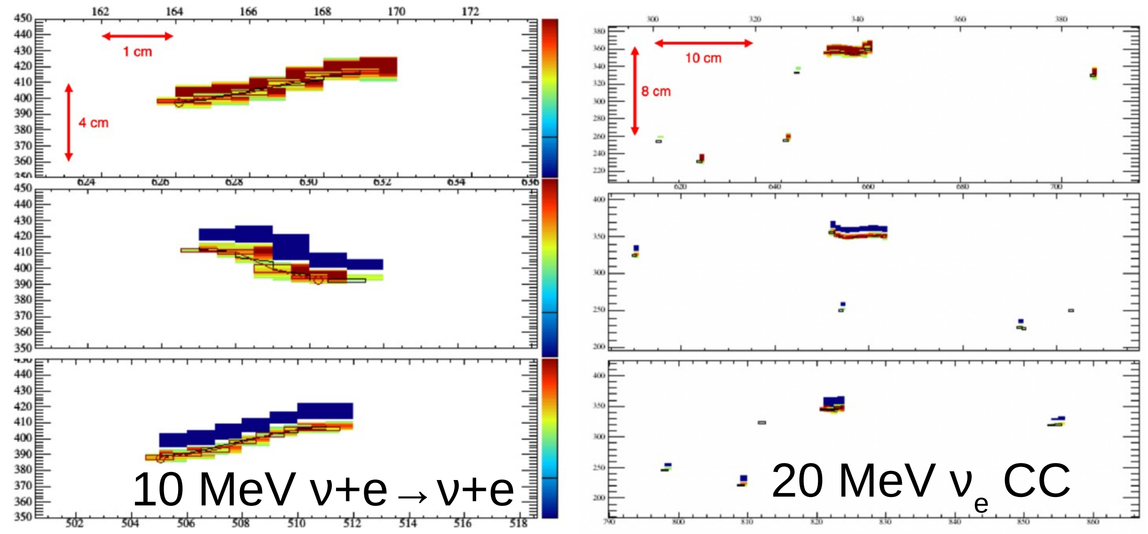
- DUNE resolutions projected into different 2D spaces, for two different exposures
- Degeneracy between θ_{13} and θ_{23} in DUNE data is resolved by reactor θ_{13} data, which resolves θ_{23} octant
- For maximal δ_{CP}, CP conserving values are strongly excluded but resolution is relatively poor

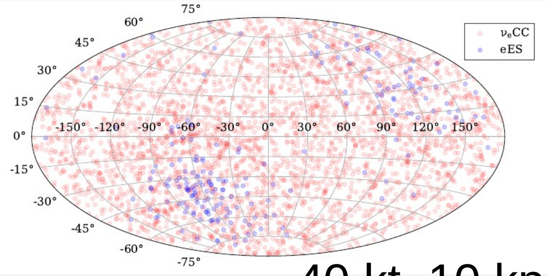
Resolving parameter degeneracies with spectral information



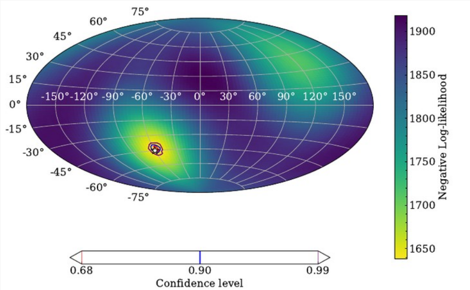
- For non-maximal values of δ_{CP}, an additional degeneracy arises because $P(\nu_\mu \rightarrow \nu_e) \sim \sin\delta_{CP}$ at maximum
- DUNE can largely resolve this using its spectral information
- Combining experiments is challenging → we all need to publish this full 4D space!

Supernova pointing and multi-messenger astronomy



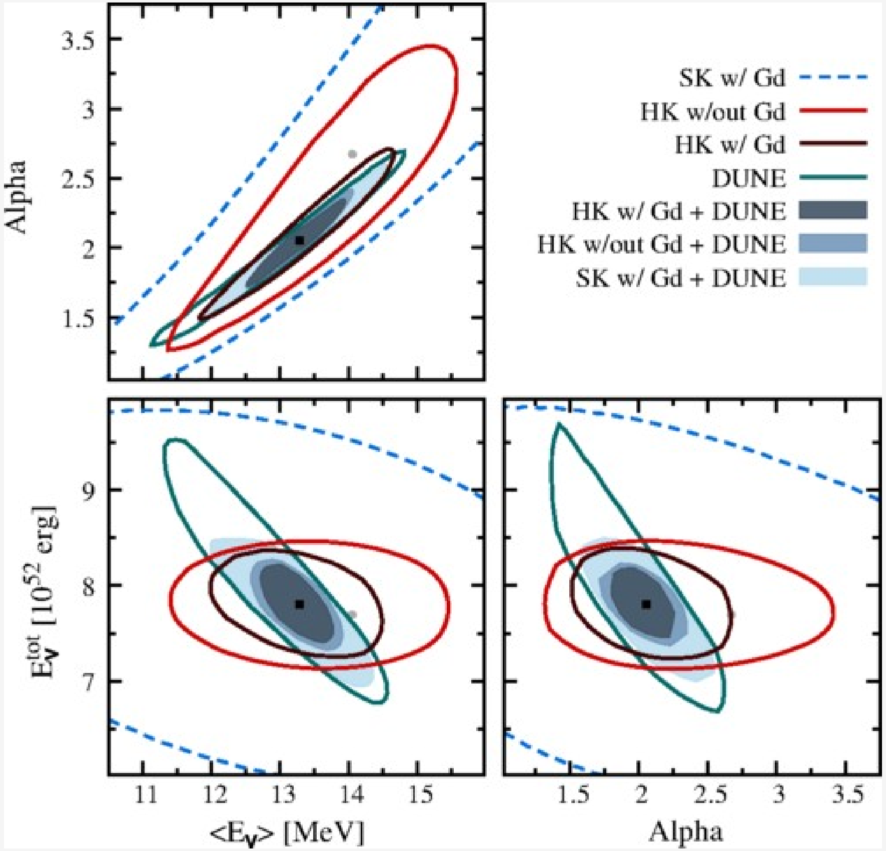


40 kt, 10 kpc



- DUNE can identify elastic scatters by the absence of nuclear de-excitation photons
- Enables pointing resolution as good as ~5° depending on location
- Paper is imminent

Supernova spectral measurements with DUNE + HK data



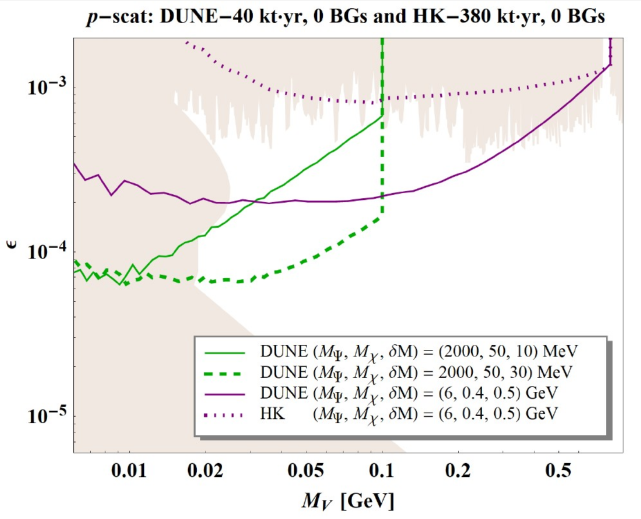
$$\frac{dN_\nu}{dE_\nu}(E_\nu) = A\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

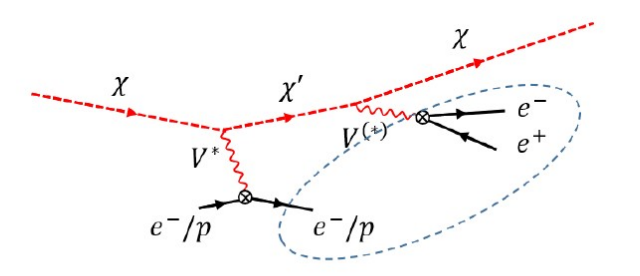
$$A = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}$$

Phys. Rev. D 97, 023019

- Supernova spectrum can be parameterized by average neutrino energy and α
- DUNE and HK measure different fluxes → complementary ability to constrain spectral parameters
- DUNE Phase II (40 kt) shown in figure

BSM searches with the Far Detector





- DUNE Far Detector is sensitive to rare processes (nucleon decay, n-$\bar{n}$ oscillation, etc.) and new physics of cosmogenic origin
- Key strengths of DUNE:
  - Ability to detect low-energy particles (for iBDM, signal is a soft e/p and spatially proximate e^+/e^- pair)
  - Ability to reconstruct direction including hadrons (i.e. for BDM produced in Sun or Galactic Center)

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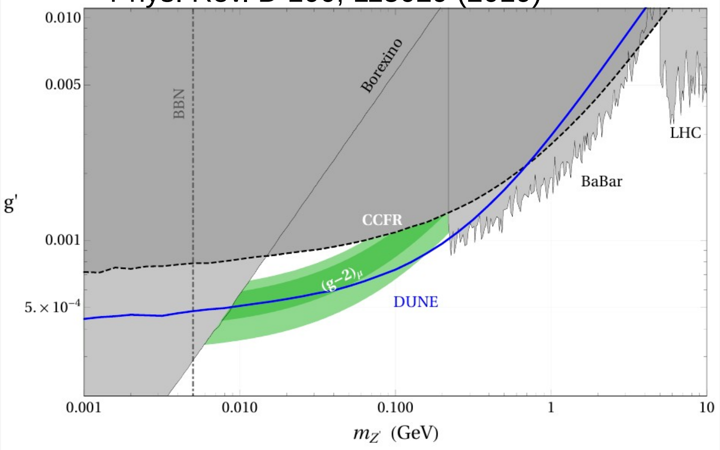
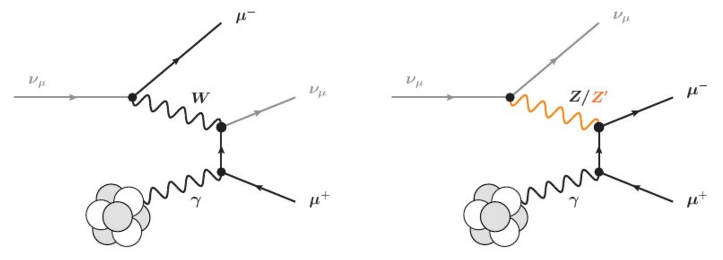
BSM searches with the Near Detector

Phys. Rev. D 100, 115029 (2019)

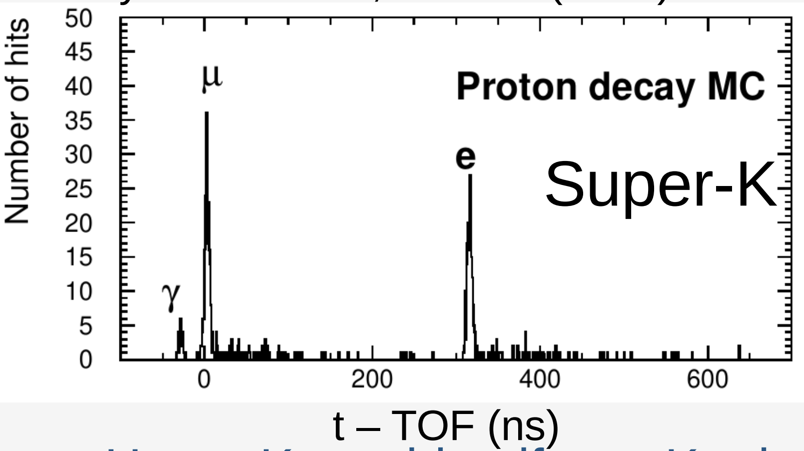


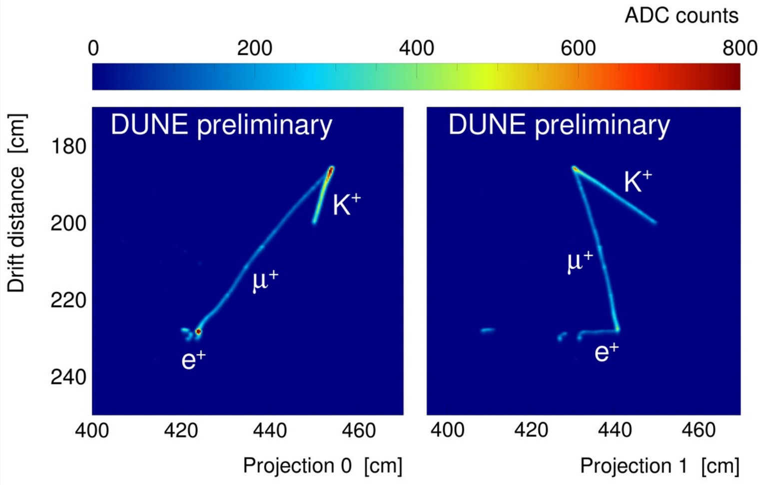


- DUNE Near Detector is sensitive to rare processes in the beamline (HNL, LDM) and to BSM contributions to neutrino interactions (ν tridents)
- Key strengths of DUNE:
  - 120 GeV proton beam and very high intensity
  - LAr ND with 50-70t fiducial mass
  - Low density ND (SAND) → increased S/B for decays in ND volume

Nucleon decay $p \rightarrow K^+\nu$

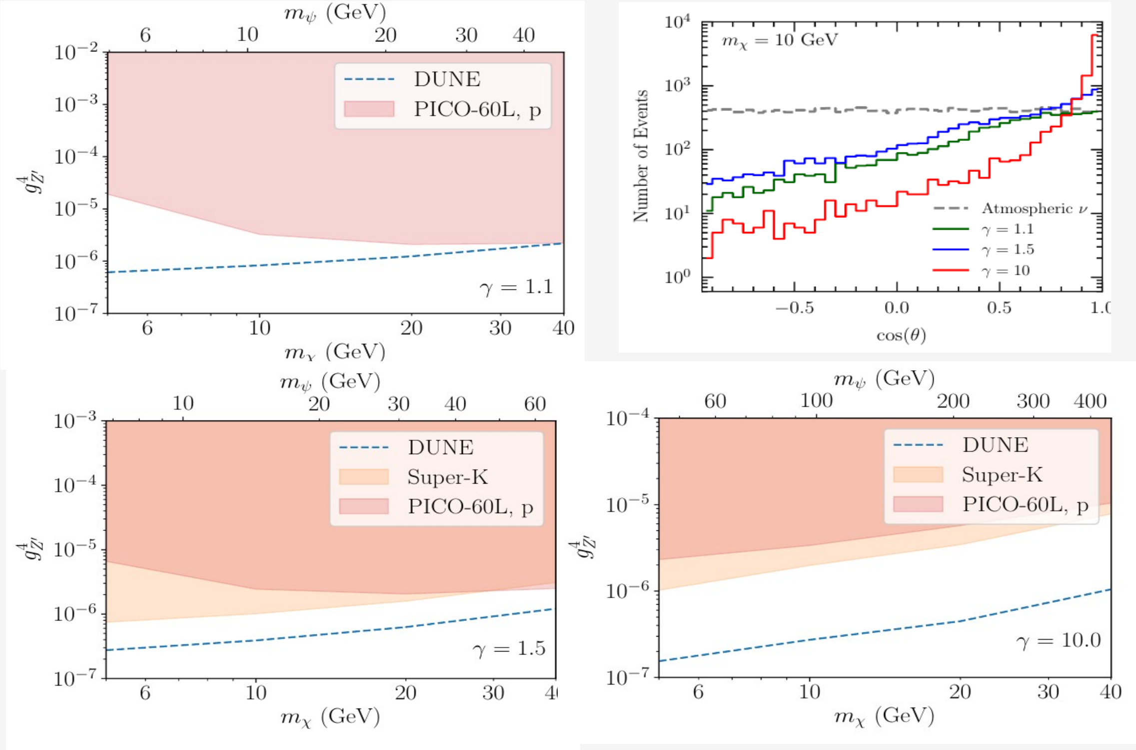
Phys. Rev. D 90, 072005 (2014)





- Hyper-K can identify $p \rightarrow K^+\nu$ by timing, and identification of monoenergetic muon from kaon decay, with sensitivity to $\tau = 3 \times 10^{34}$ yrs
- DUNE can image all three particles, Phase II sensitivity beyond current Super-K limit
- If a signal is observed in Hyper-K it will be valuable to confirm the detection with a very different detector, different backgrounds, etc.

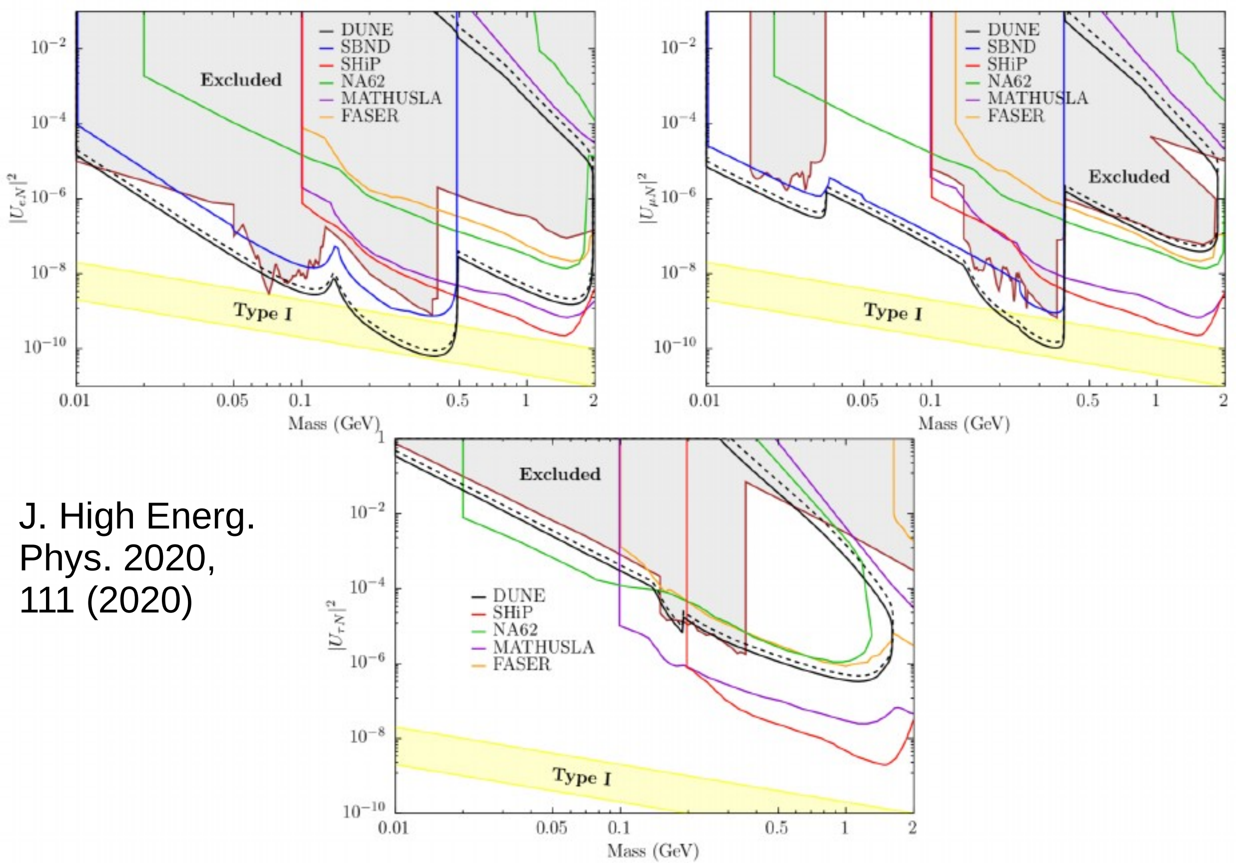
Boosted dark matter from sun via hadronic channels



Phys. Rev. D 103, 095012 (2021)

- χN → χX hadronic processes
- Reconstruct direction in DUNE FD LArTPC, point back to Sun
- Low hadron thresholds are critical → at lower boost factors, SK/HK does not have sensitivity because protons are invisible
- DUNE can surpass current limits from PICO

Sensitivity to Heavy Neutral Leptons produced in beam, decay in ND

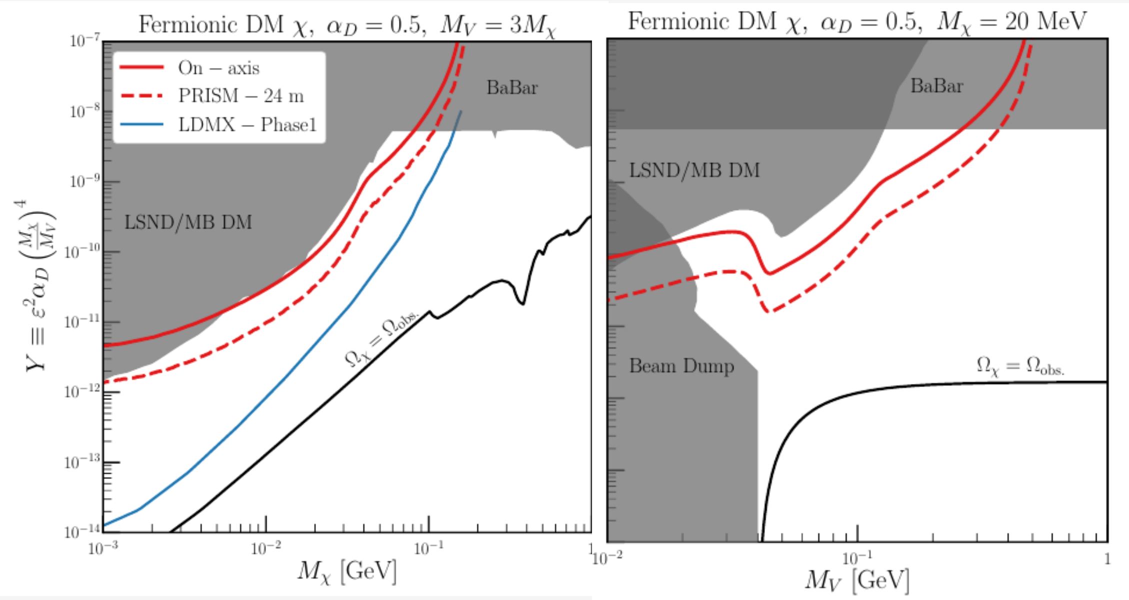


J. High Energ. Phys. 2020, 111 (2020)

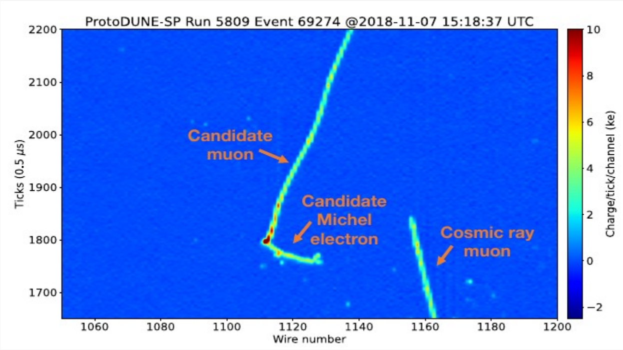
- N → νee, νeμ, νμμ, νπ⁰, eπ, μπ
- Assumes 22 MW-yrs and zero backgrounds
- Reaching zero background not demonstrated, may be possible with ND-GAr

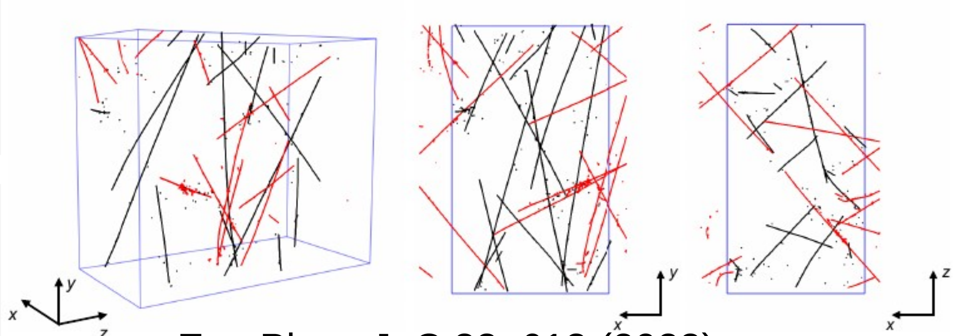
Light dark matter in beamline via χ-e

- $\chi e \rightarrow \chi e$ scattering in ND-LAr, from boosted DM produced in the beamline
- Backgrounds from $\nu e \rightarrow \nu e$ have different spectrum
- DM and ν have different dispersion, and looking at off-axis ND-LAr data improves the statistical separation
- Sensitivity at low mass is potentially world-leading



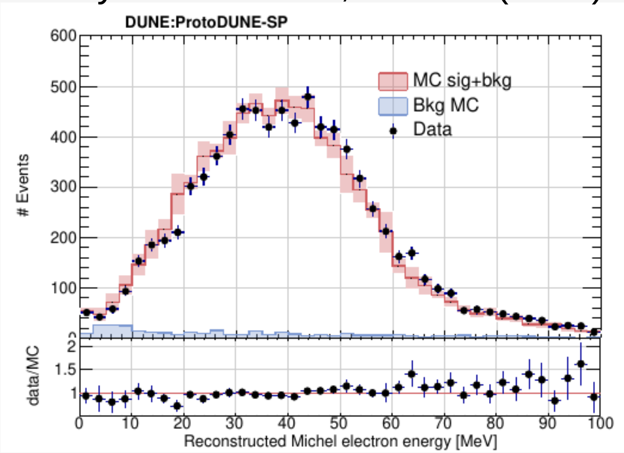
ProtoDUNE-SP: performance papers published in 2023





Eur. Phys. J. C 83, 618 (2023)

Phys. Rev. D 107, 092012 (2023)



- Two ProtoDUNE reconstruction performance papers:
  - Identification and reconstruction of Michel electrons
  - Performance of Pandora for cosmics and beam particles

Accelerator Complex Evolution: Main Injector Ramp & Target

		PIP-II Booster			
Operation scenario	**Present**	**PIP-II**	**ACE (a)**	**ACE (b)**	**units**
MI 120 GeV cycle time	**1.13**	**1.2**	**0.9**	**0.7**	s
Booster intensity	**4.7**	**6.5**			10^{12} p
Booster ramp rate	15	**20**			Hz
MI power	**0.96**	**1.2**	**1.7**	**2.1**	MW
cycles for 8 GeV	**6**	**12**	**6**	**2**	
Available 8 GeV power	30	83	56	24	kW

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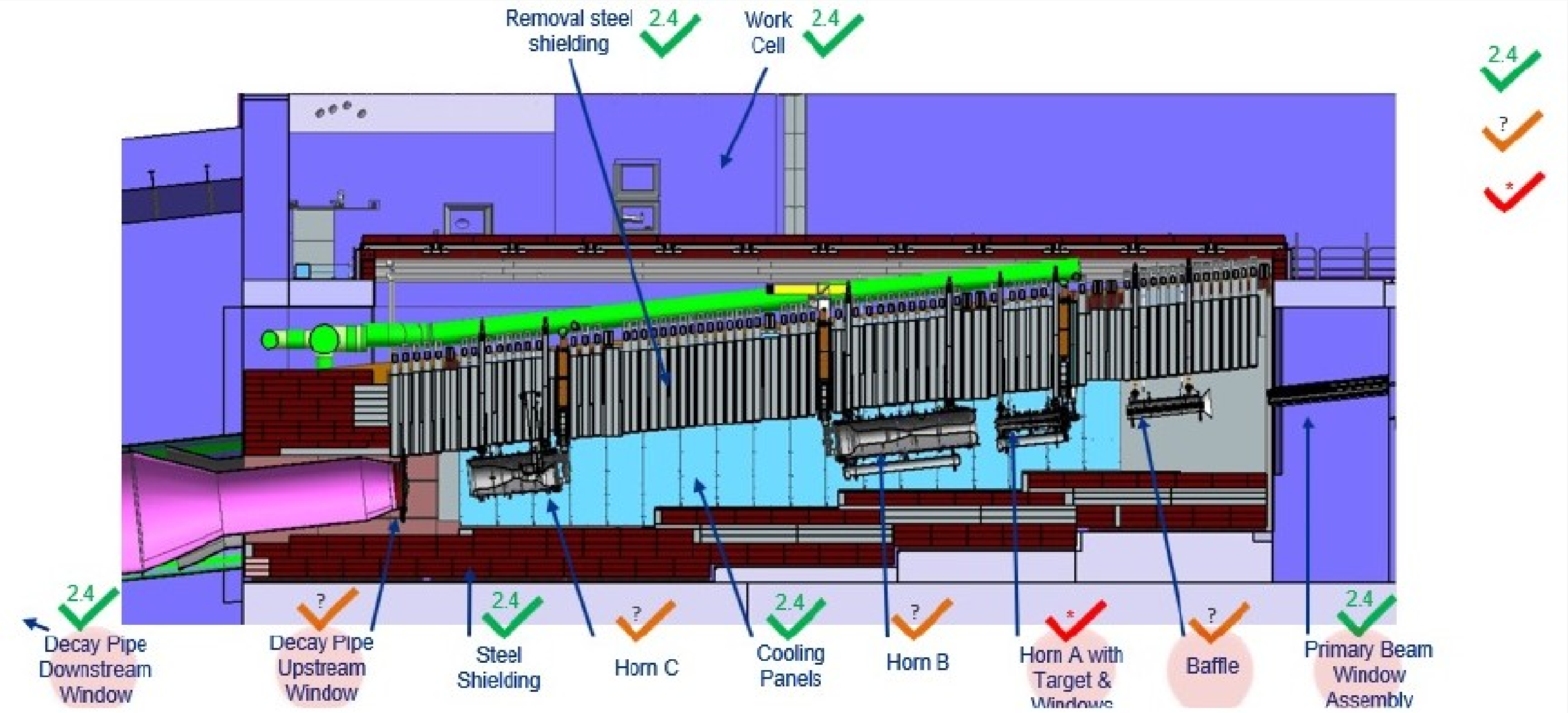
Accelerator Complex Evolution: Main Injector Ramp & Target



- Many beamline components are designed for 2.4 MW
- Others can likely be operated to 2 MW with minor modifications
- Target is the most critical component

P5 report in the US strongly endorses DUNE Phase I & II

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

b. The first phase of DUNE and PIP-II to open an era of precision neutrino measurements that include the determination of the mass ordering among neutrinos.

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

b. A re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind

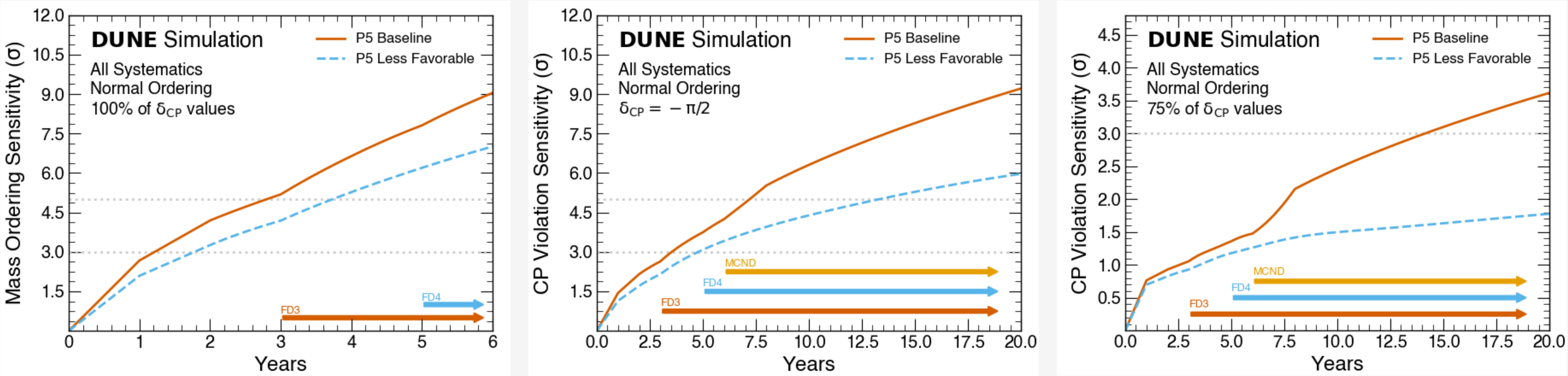
Recommendation 4: Invest in a comprehensive initiative to develop the resources—theoretical, computational, and technological—essential to realizing our 20-year strategic vision. This includes an aggressive R&D program that, while

e. Conduct R&D efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping

Elucidate the Mysteries of Neutrinos

- During the next decade (2024-2034), P5 recommended:
  - Highest priority: Complete DUNE Phase I and begin operations
  - Implement ACE-MIRT accelerator/beamline upgrades before operations begin
  - Design and build FD3 and MCND
  - Perform R&D toward FD4

Importance of maintaining P5 baseline funding scenario



- Less favorable funding scenario includes only FD3, without ACE-MIRT accelerator upgrades, MCND
- Substantial delays to Phase I physics goals (MO and maximal CPV), and elimination of long-term precision program, including CPV over 75% of δ_{CP} values