Deep Underground Neutrino Experiment

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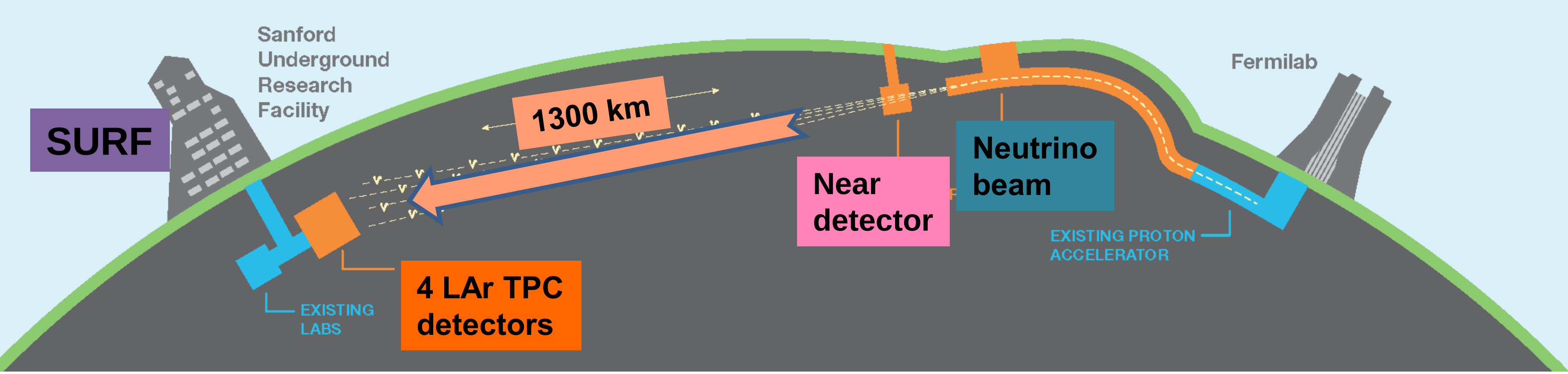
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

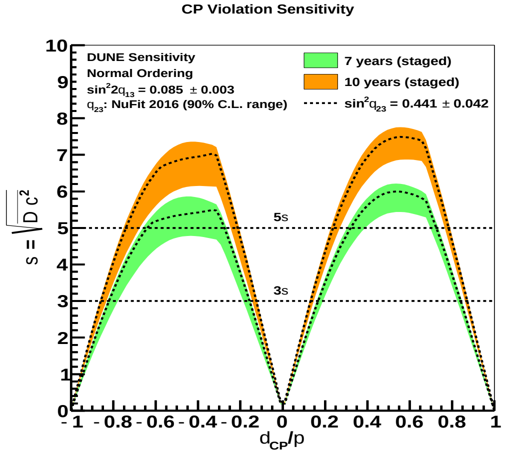
FZU Institute of Physics of the Czech Academy of Sciences

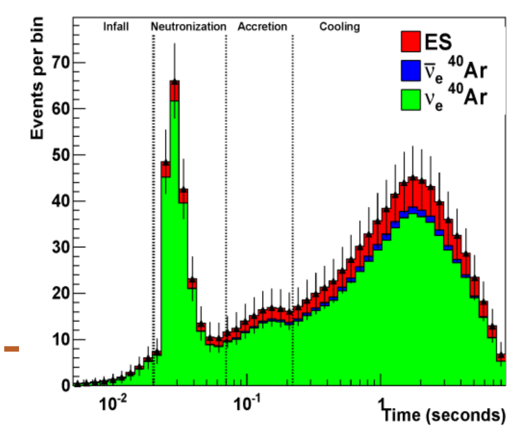
DUNE

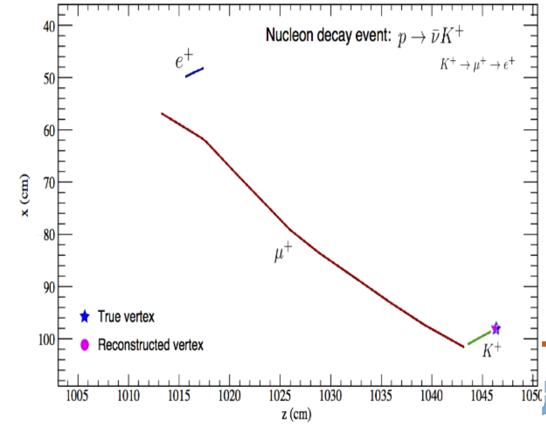
DUNE – Deep Underground Neutrino Experiment



- 40 kt fiducial mass liquid-argon TPC Far Detector.
- Located at SURF's – depth of 1478 m, with 1300 km baseline.
- Hybrid Near Detector located 575 m from neutrino source.
- Wide-band neutrino beam (~ GeV range).
- Physics topics: CPV, supernova neutrinos, proton decay, and more







DUNE – Collaboration

Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Finland, France, Gergia, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, The Netherlands, Paraguay, Peru, Poland, Portugal, Romania, Russia, Spain, South Korea, Sweden, Switzerland, Turkey, UK, Ukraine, USA

DUNE/LBNF Project

DUNE

❑ **Deep Underground Neutrino Experiment**

Main physics goals:

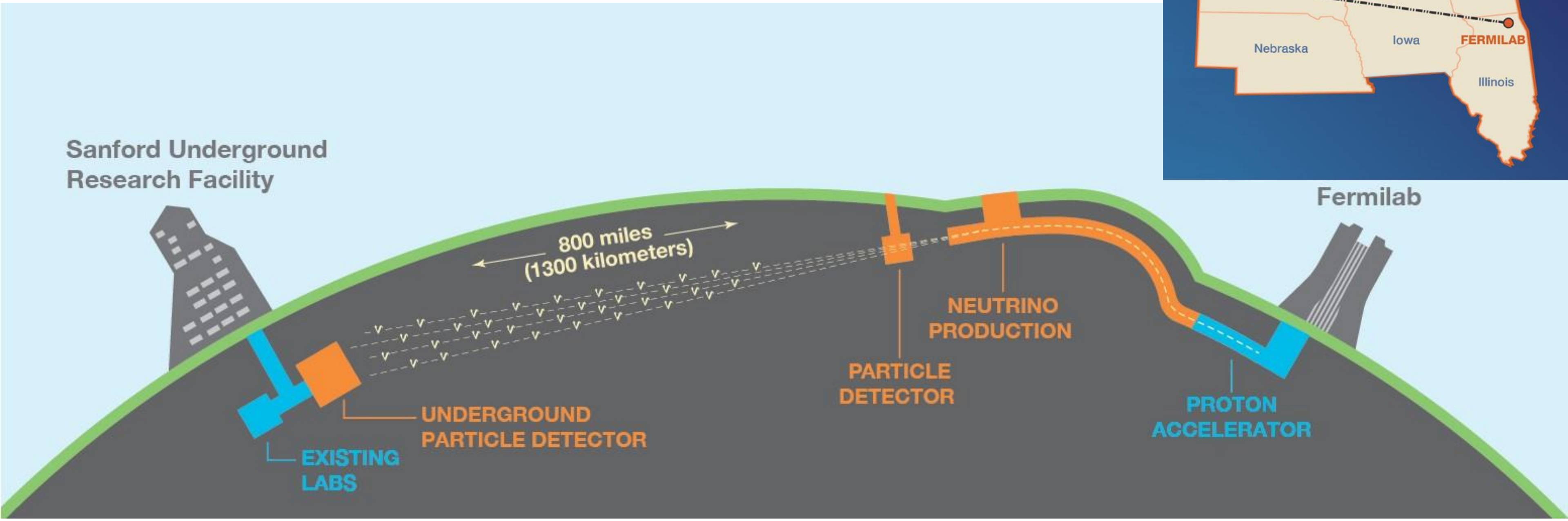
- Measuring neutrino oscillation parameters via an accelerator-based neutrino beam δ_{CP}, mass ordering θ_{23} and its octant
- Searching for proton decay
- Measuring neutrino flux of a supernova core collapse

LBNF

❑ **Long-Baseline Neutrino Facility**

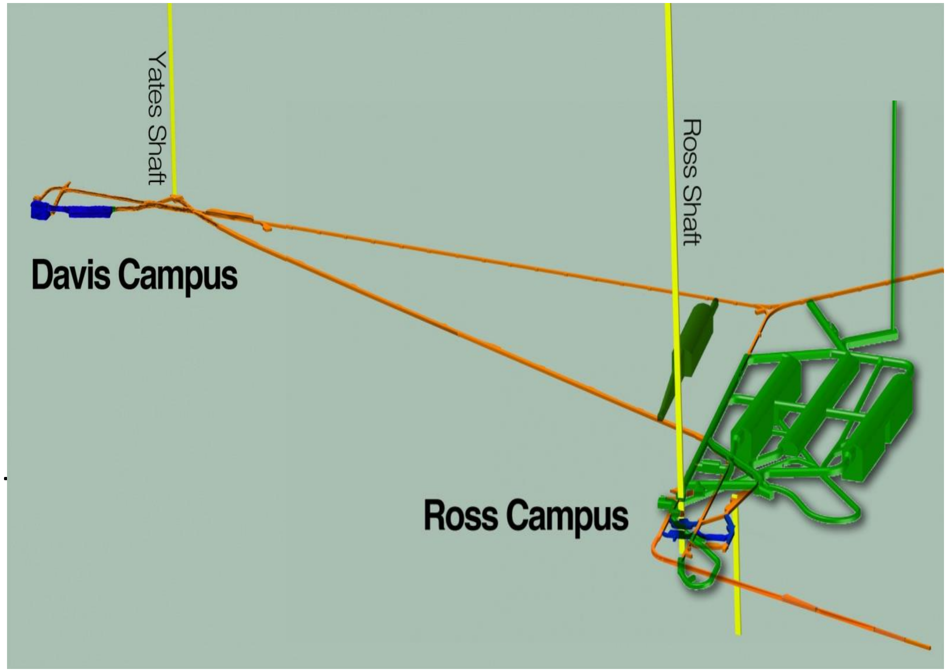
Infrastructure supporting the DUNE detectors:

- Neutrino beam
- Far site facilities
- Near site facilities
- Cryogenic systems



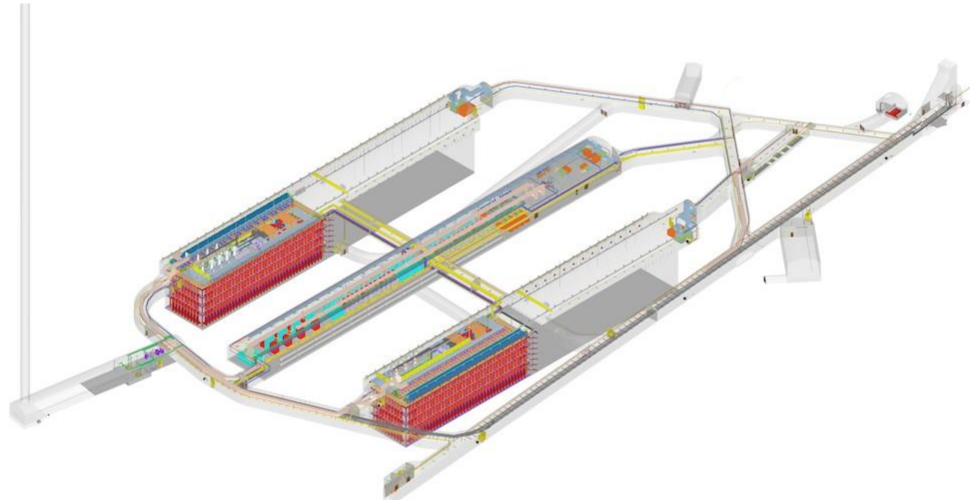
Far Site – SURF (Sanford Underground Research Facility)

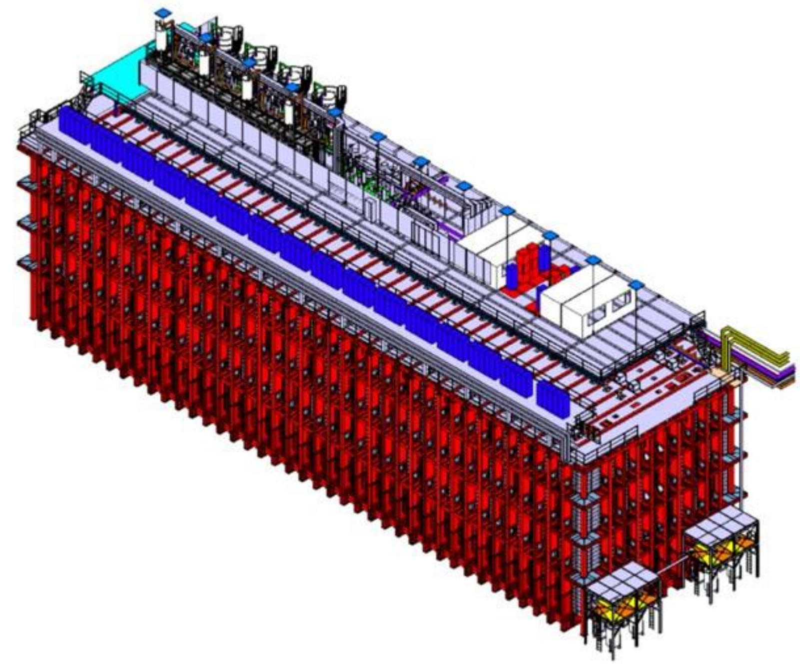
- Gold mine repurposed into underground laboratory
- Deepest laboratory in the US (1.5 km underground)
- Two main campuses
  - Davis Campus - Homestake Experiment, LUX (LZ), MAJORANA, …
  - Ross Campus - DUNE, possibly future ton-scale 0ν2β experiment,…



DUNE Far-site Facility

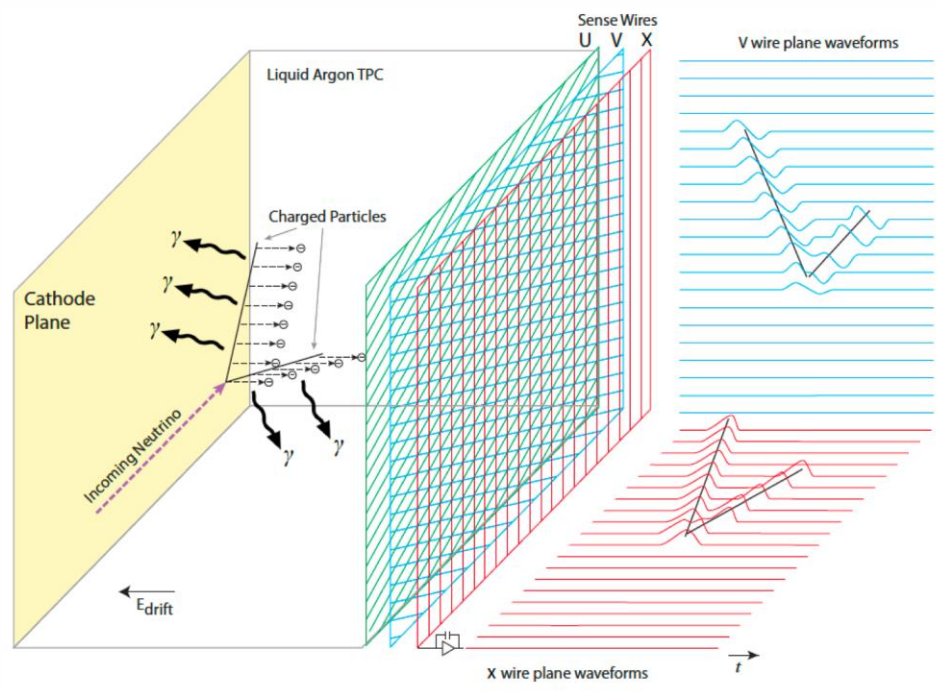
- 3 main caverns
  - 4 detector halls in 2 caverns
  - 1 support cavern (cryo + DAQ)
- Detectors based on LarTPC technologies
  - Same cryostat dimensions (62m x 19m x 18m)
  - 17 kt total LAr mass (70kt total)
  - 10 kt total LAr mass (40kt total)
- Detectors installed in staged approach over several years
  - 2 of them before beam starts





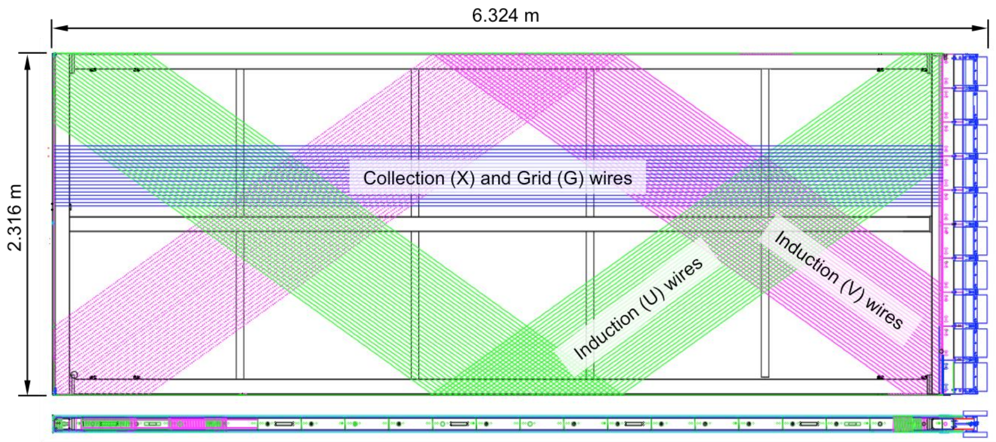
DUNE Far Detectors – Single-Phase LarTPC Option

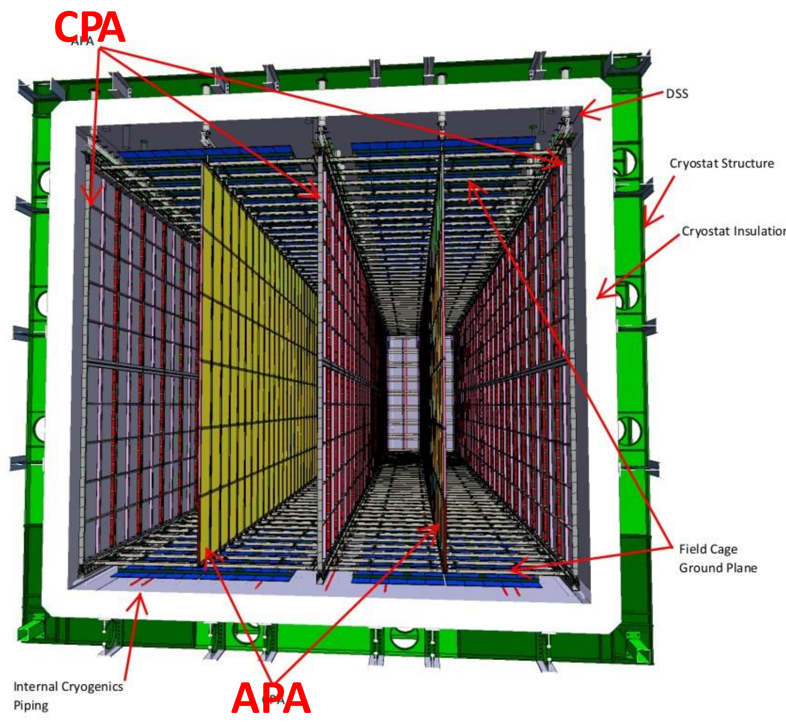
- Liquid Argon Time Projection Chamber
- Charged particles produce ionization charge and scintillation light
- Electric field across TPC volume
  - Ionization electrons drifted towards anode readout plane
  - Charge signal induced on readout plane
  - DUNE SP: 2D projection of ionization read out from 3 planes of wires, time is 3rd dimension
- 2 out of 4 detector modules confirmed to use this technology, including the first one



- No signal amplification → Require low noise electronics

DUNE Far Detectors – Single-Phase LarTPC Option



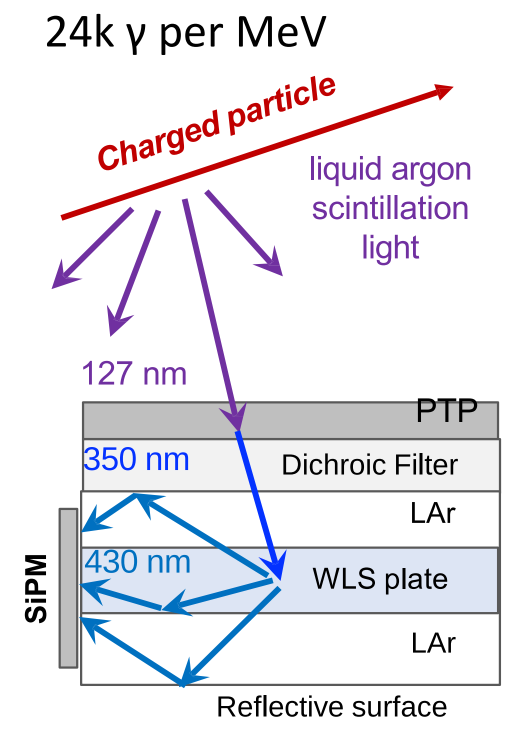


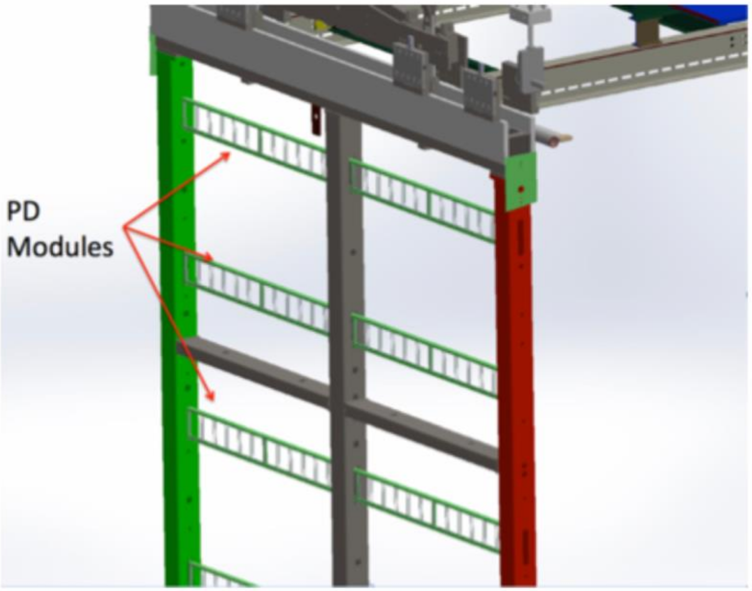
- ❑ Anode wires wrap around frame to allow two drift volumes (Anode Plane Assembly, APA)
- ❑ 4 wire layers (outermost acts as shield) with 5 mm pitch
- ❑ Drift distance: 3.5 m
- ❑ E = 500 V/cm ⇒ Cathode voltage: -180 kV
- ❑ 150 APAs per detector module: 384,000 channels

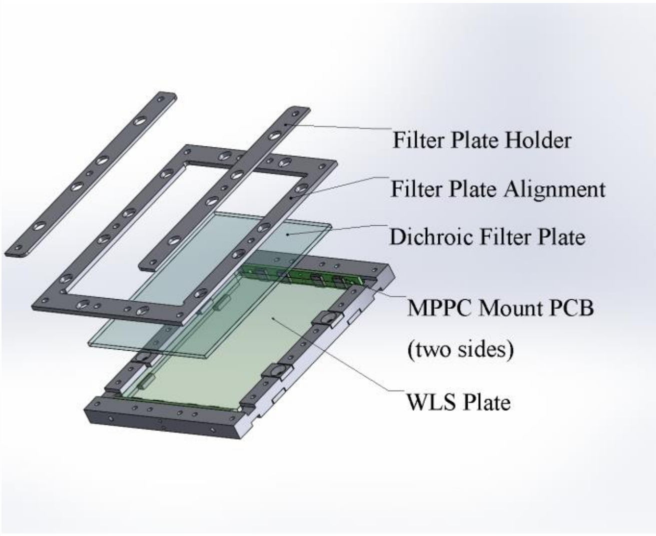
Single Phase Photon Detection system

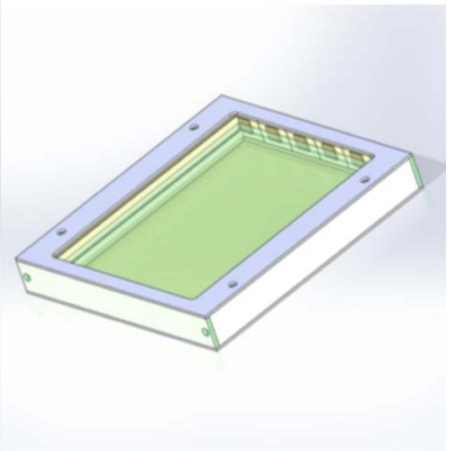
Provides T_0 for each event, fiducializing nucleon-decay, SNB resolution

- X-ARAPUCA “light trap”
  - Increase active area of SiPM
  - Dichroic filter + wavelength shifter
  - Highly reflective interior
  - Acrylic guides shifted light to SiPMs
- 6000 supercells of 48.8 cm x 10 cm x 0.8 cm
- Inserted in APA frames





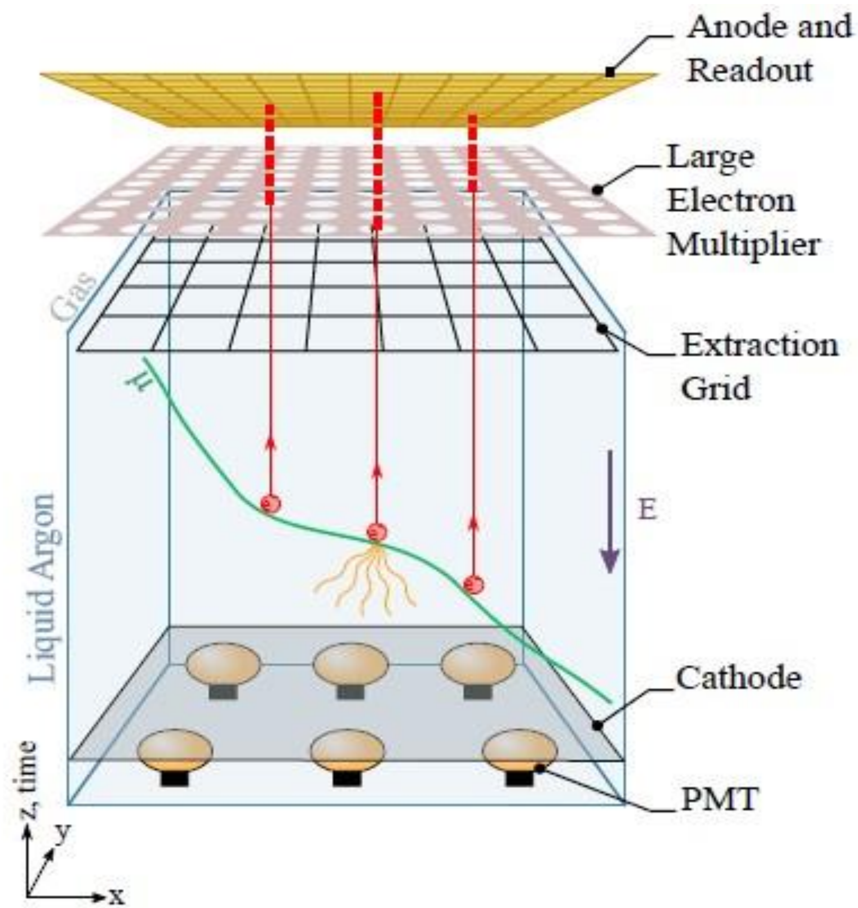




DUNE Far Detectors – Dual-Phase LarTPC Option

- LAr target
- GAr readout
  - benefit from charge multiplication in gas

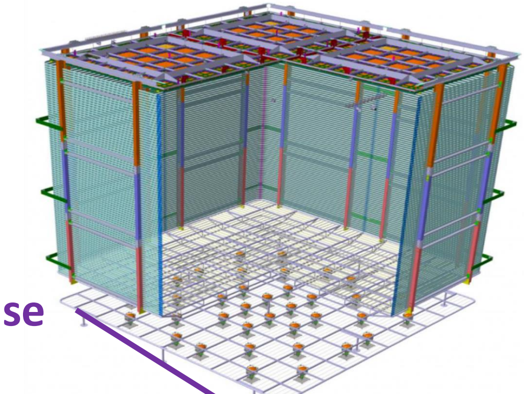
- Large ~12m vertical drift
  - E = 500 V/cm ⇒ Cathode voltage: -600 kV
- Ionization extracted and further amplified in Gas
- LEM electron amplifier
- Anode collection and read-out planes
- Photon readout
  - TPB-coated PMTs of 20 cm diameter



DUNE FarDet prototyping ProtoDUNE-SP/DP

Two ~1kt Lar TPCs in a charged particle test beam and cosmics, at CERN Neutrino Platform

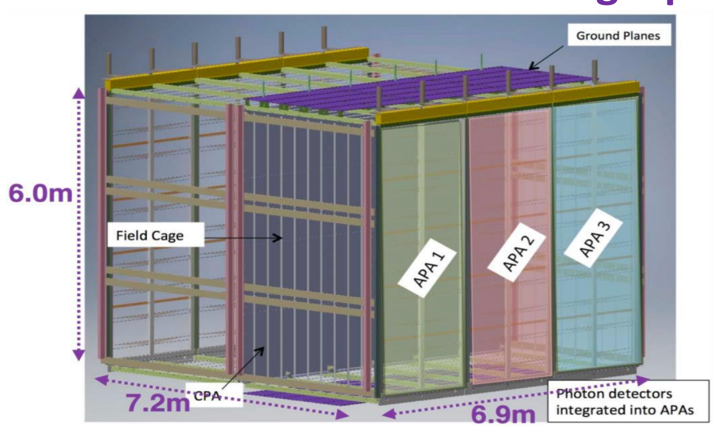
- Goals:
  - Collect test beam data to measure the response of DUNE readout technology to different particles
  - Test production and installation methods
  - Use data to validate the detector designs

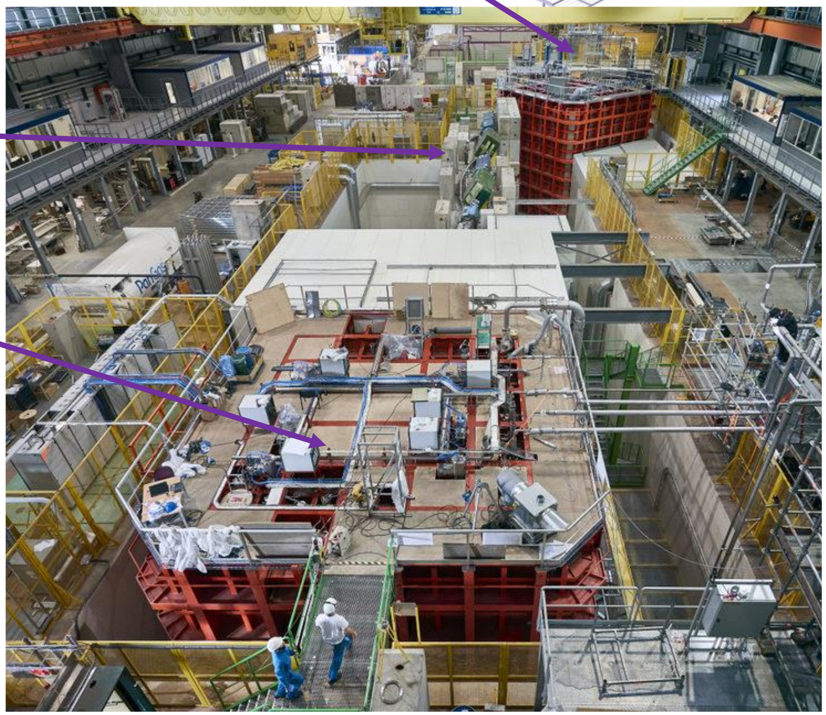


Dual phase

Beamline

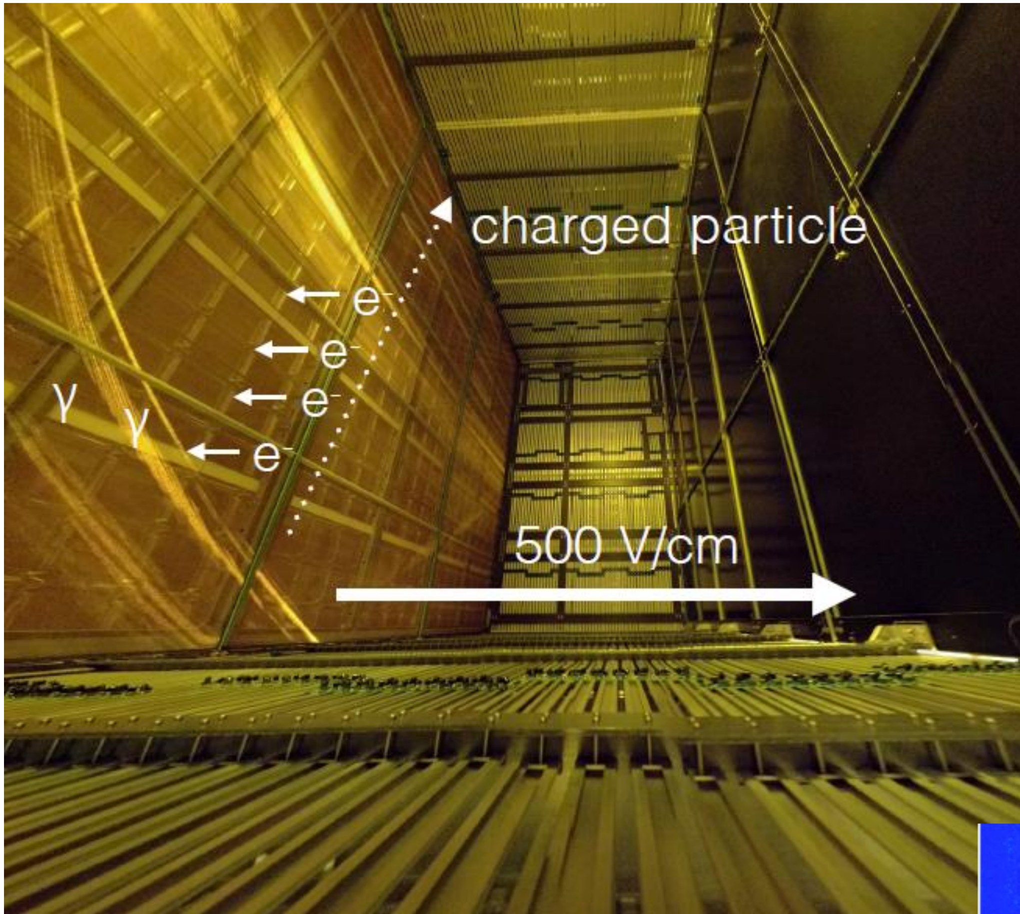
Single phase

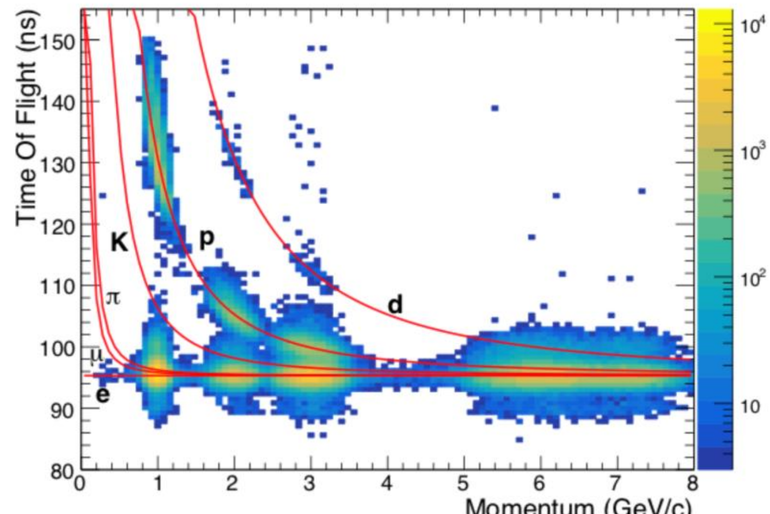


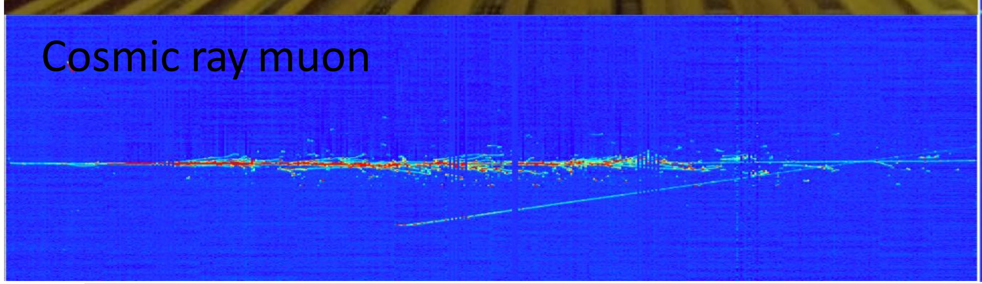


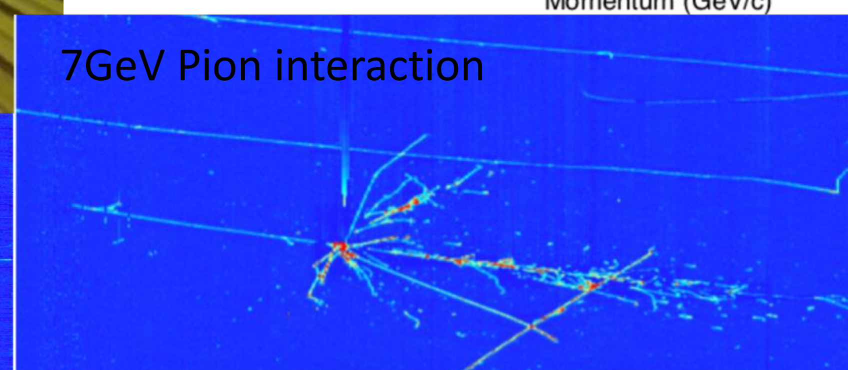
ProtoDUNE Single-phase

- ❑ Currently taking cosmic data
- ❑ Beam data taken in fall of 2018:
  - ➢ Pions, protons, positrons, kaons
  - ➢ Momentum 0.3 – 7 GeV
- ➢ First publication coming soon!



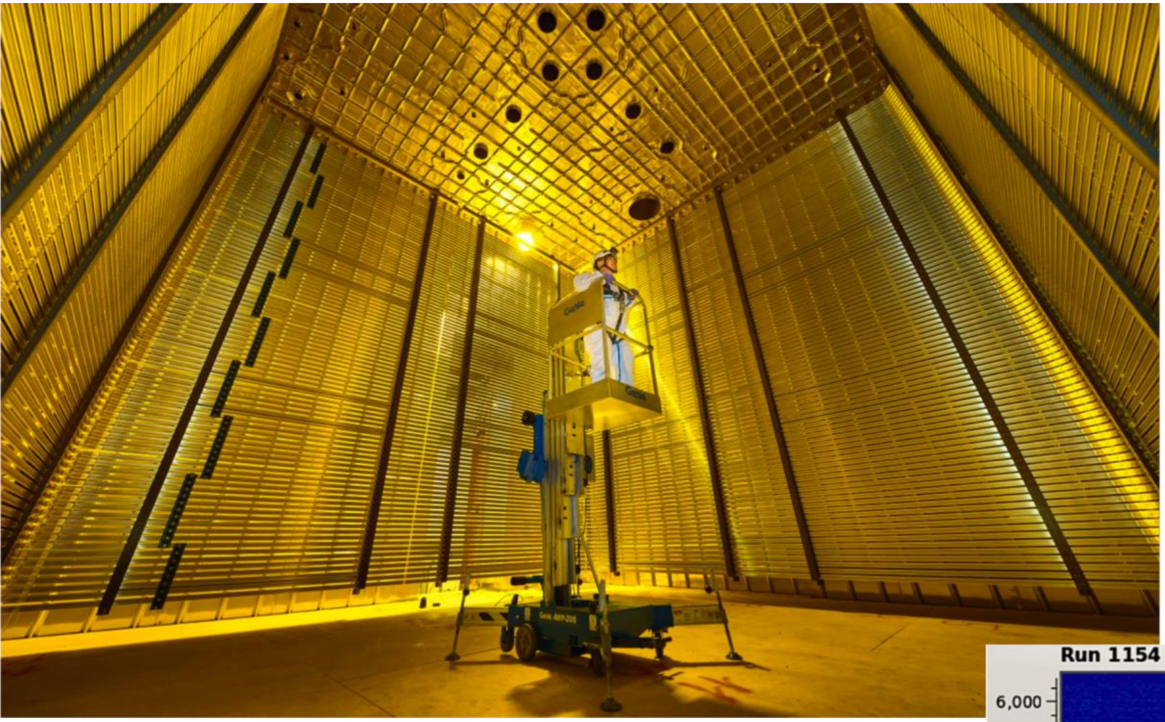




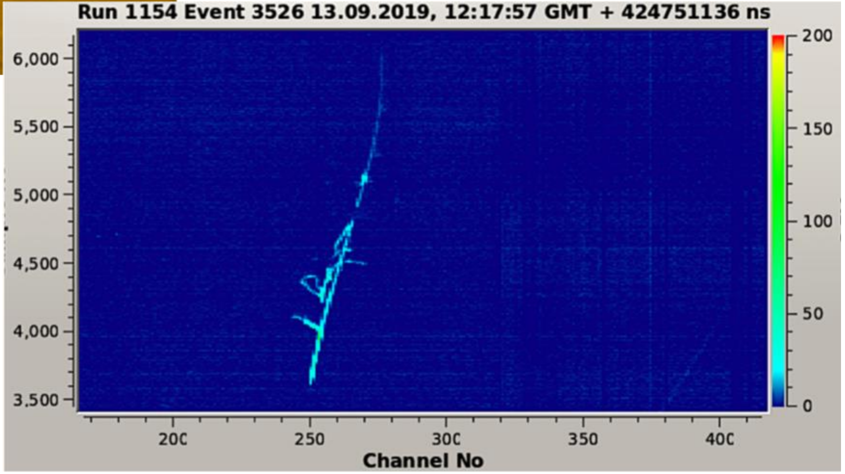


ProtoDUNE Dual-phase

Currently taking cosmic data

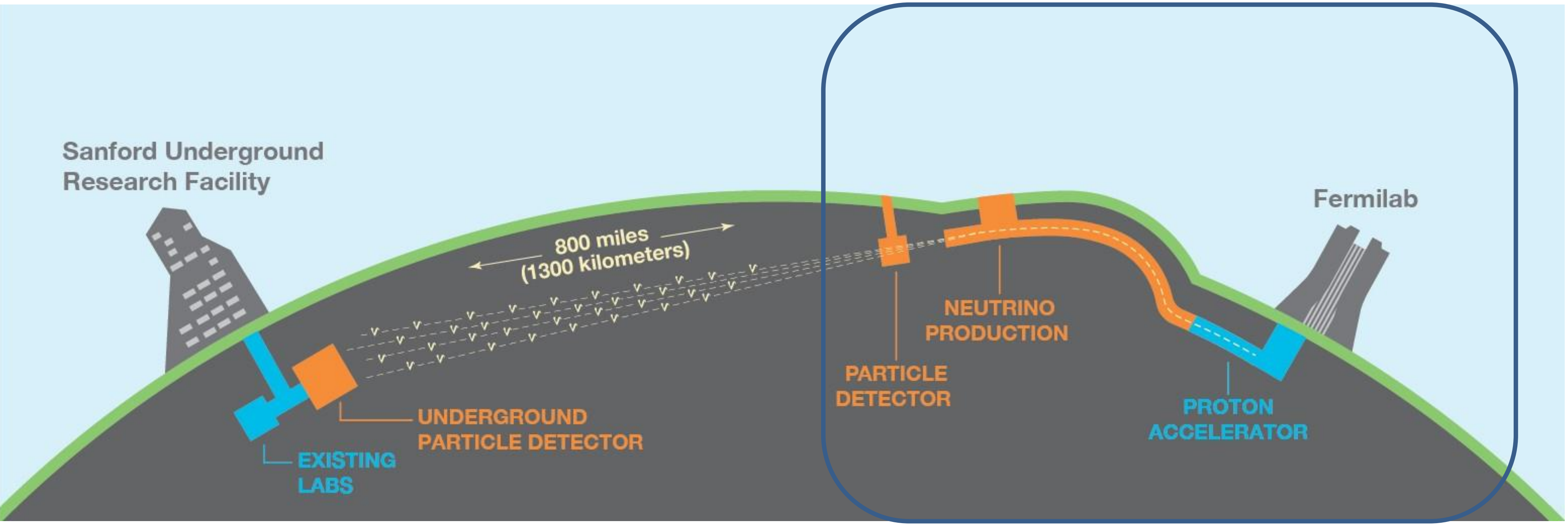


Inside the cryostat

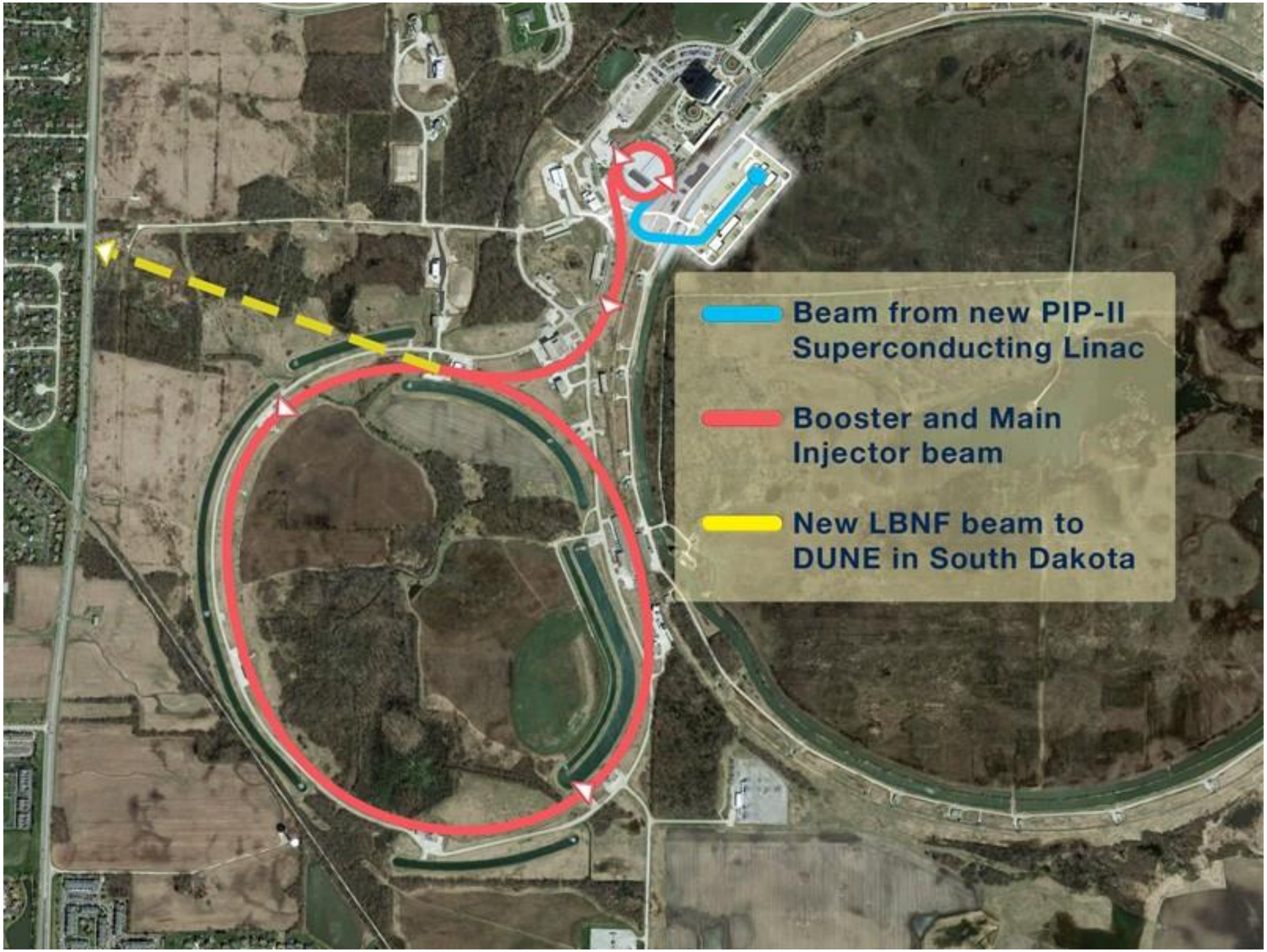


Track made by a cosmic-ray muon observed in the dual-phase detector.
The ionization released by the muon track in liquid argon.

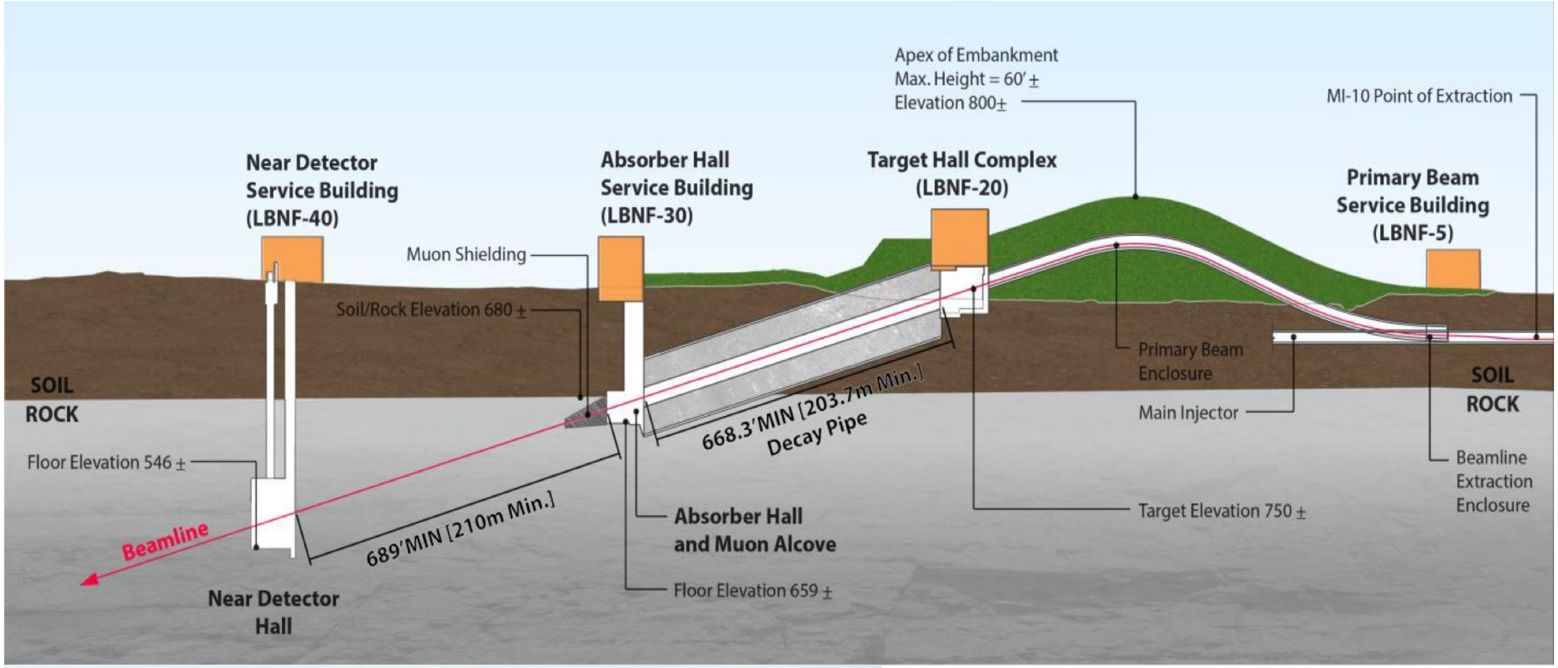
Near Site – Fermi laboratory



Near Site – FNAL accelerator complex



Near Site – LBNF beam line

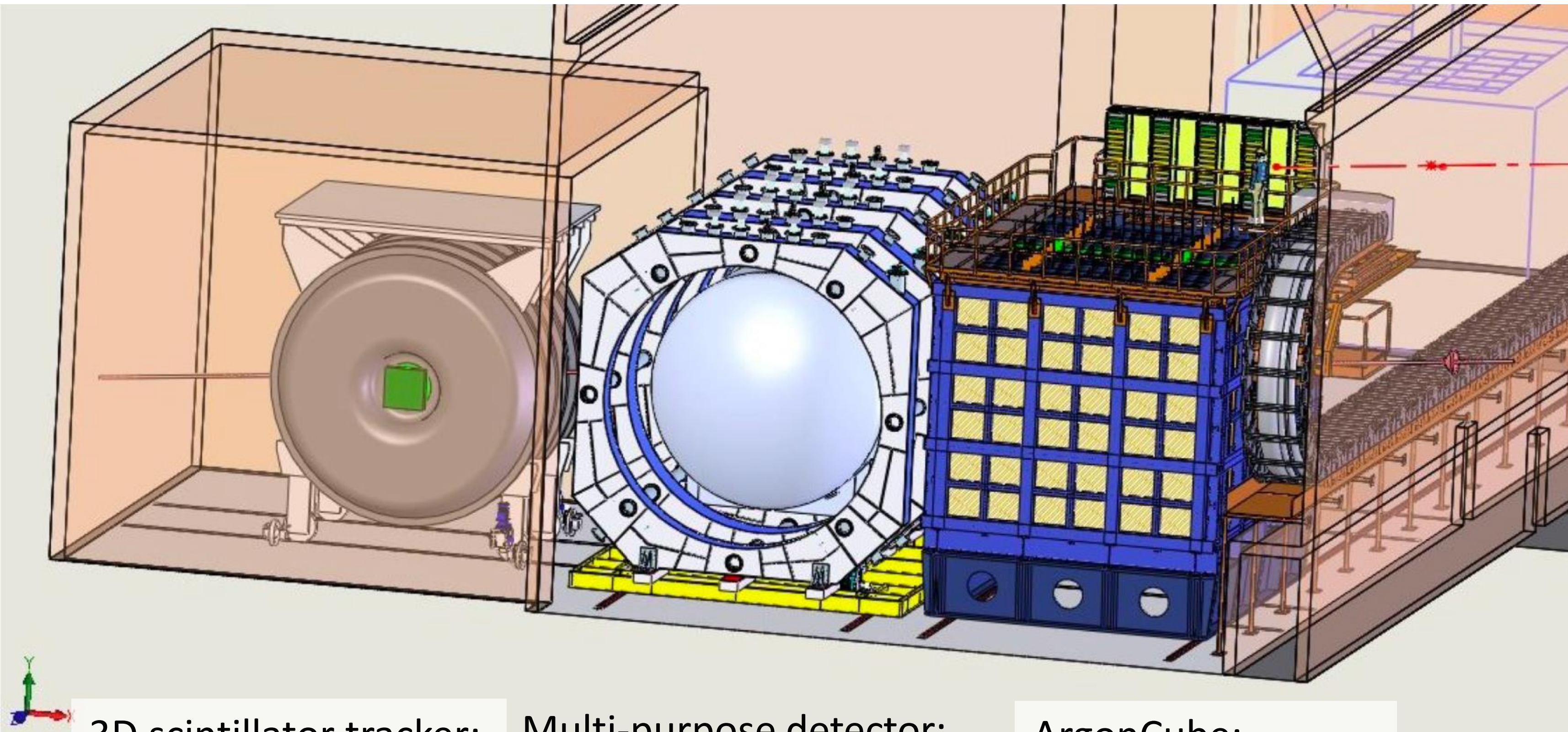


- A new neutrino beam from Fermilab to SURF
  - 1.2 MW proton beam
  - 10^{21} POT/year
  - Oriented 5.8° down
  - Wide band neutrino beam ν_μ / $\overline{\nu_\mu}$

- A PIP-II (Proton Improvement Plan II) aims to increase intensity of proton beam via a 800-MeV superconducting RF linac

Near Site – Near detector

- Composite detector
- Goal: constrain flux and cross-section systematic uncertainties
- Can also measure 10 million neutrino interactions per year



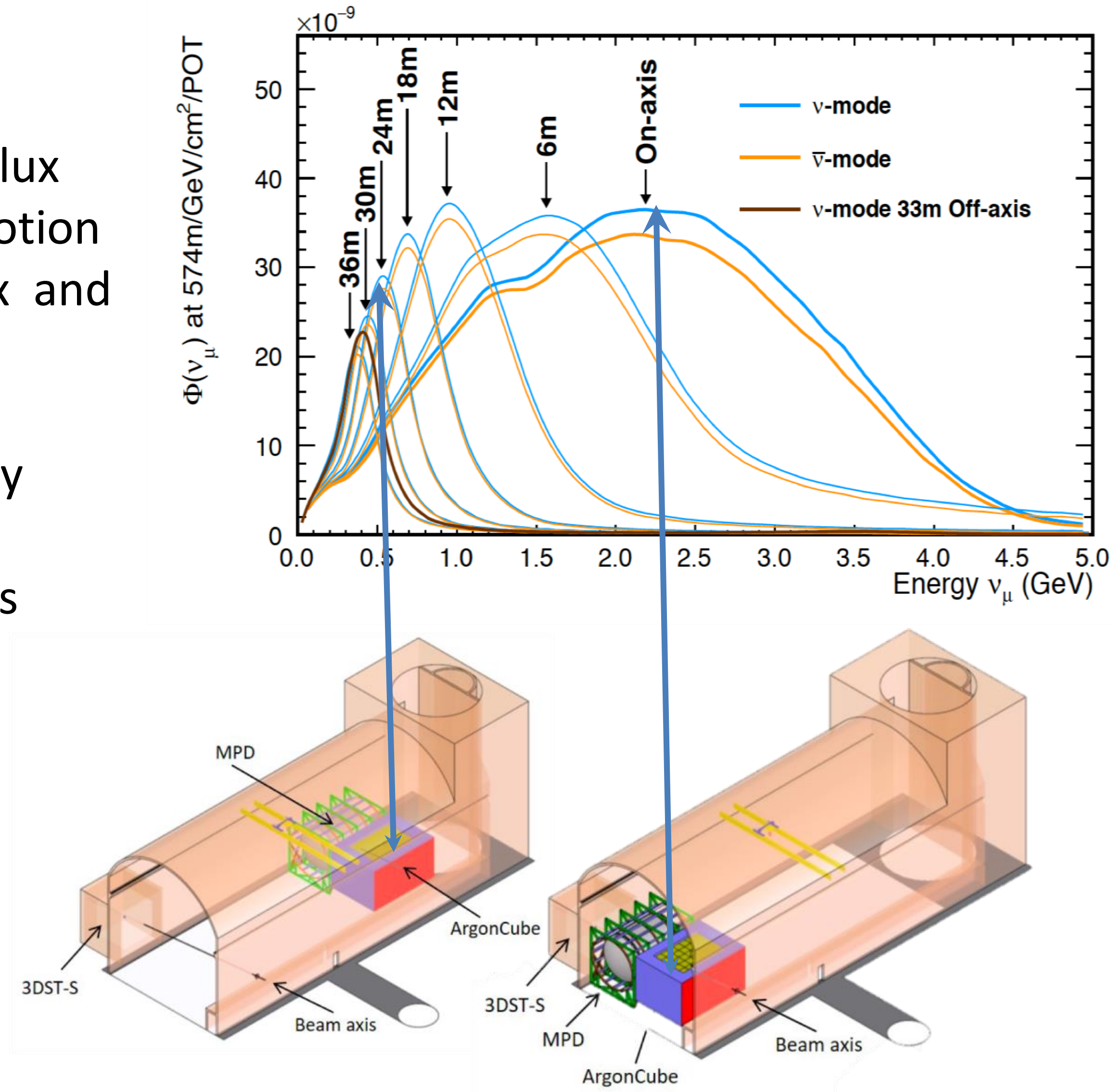
3D scintillator tracker:
On-axis beam monitor

Multi-purpose detector:
High pressure gaseous
argon with magnet

ArgonCube:
Lar TPC

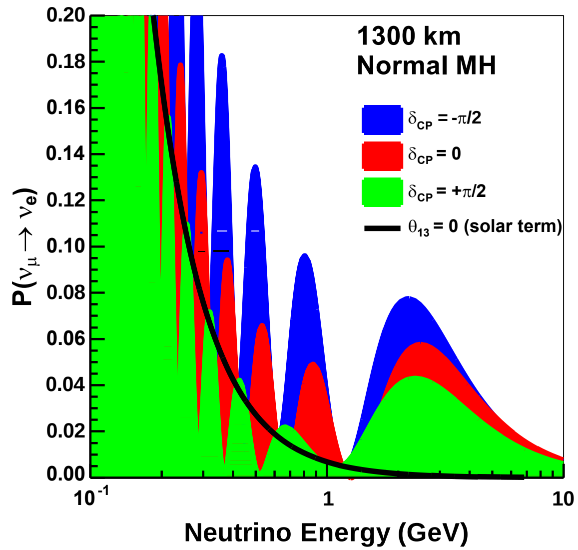
Near Detector – DUNE Prism

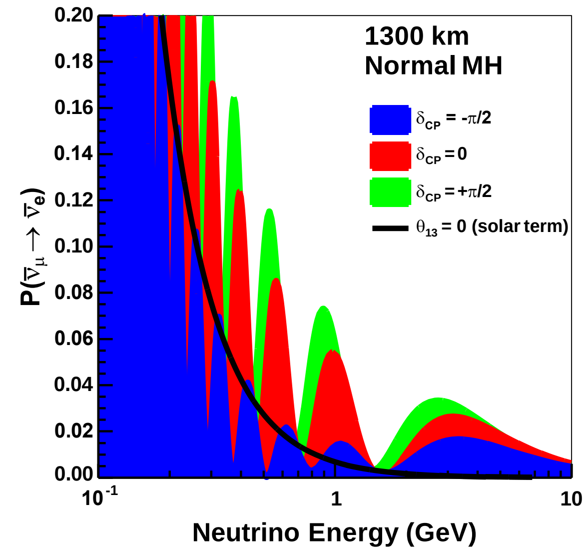
- ArgonCube and MPD on rails
  - move off axis to sample flux
  - 30m off axis proposed motion
  - Allows to deconvolve flux and cross section
- 3DST-S does not move
  - Beam monitor for stability
- Allows to measure new flux
  - Deconvolve flux and cross section



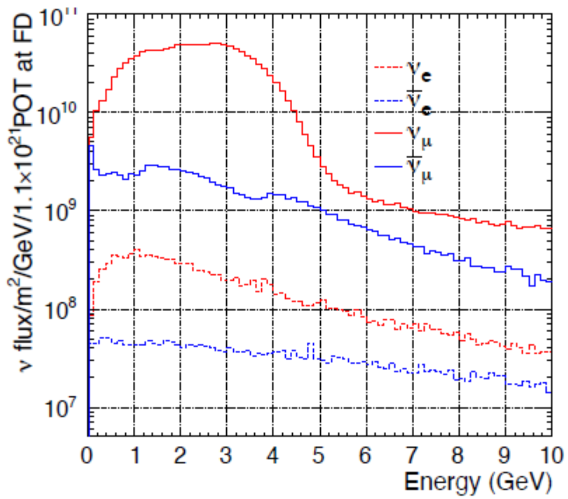
Physics – Neutrino beam

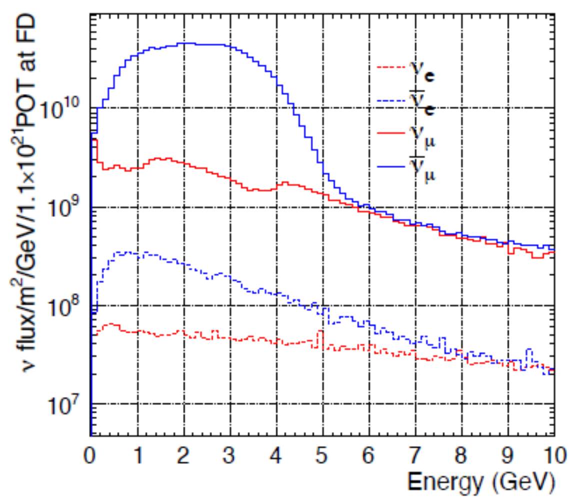
- Horn-based on-axis wide-band neutrino beam
  - Allows sensitivity to first and second oscillation maxima





- Polarity of horn current selectable
  - ν_e ($\overline{\nu_e}$) appearance
  - ν_μ ($\overline{\nu_\mu}$) disappearance





Physics – Neutrino Oscillation

Neutrino energy spectra

- Neutrino and antineutrino running modes:

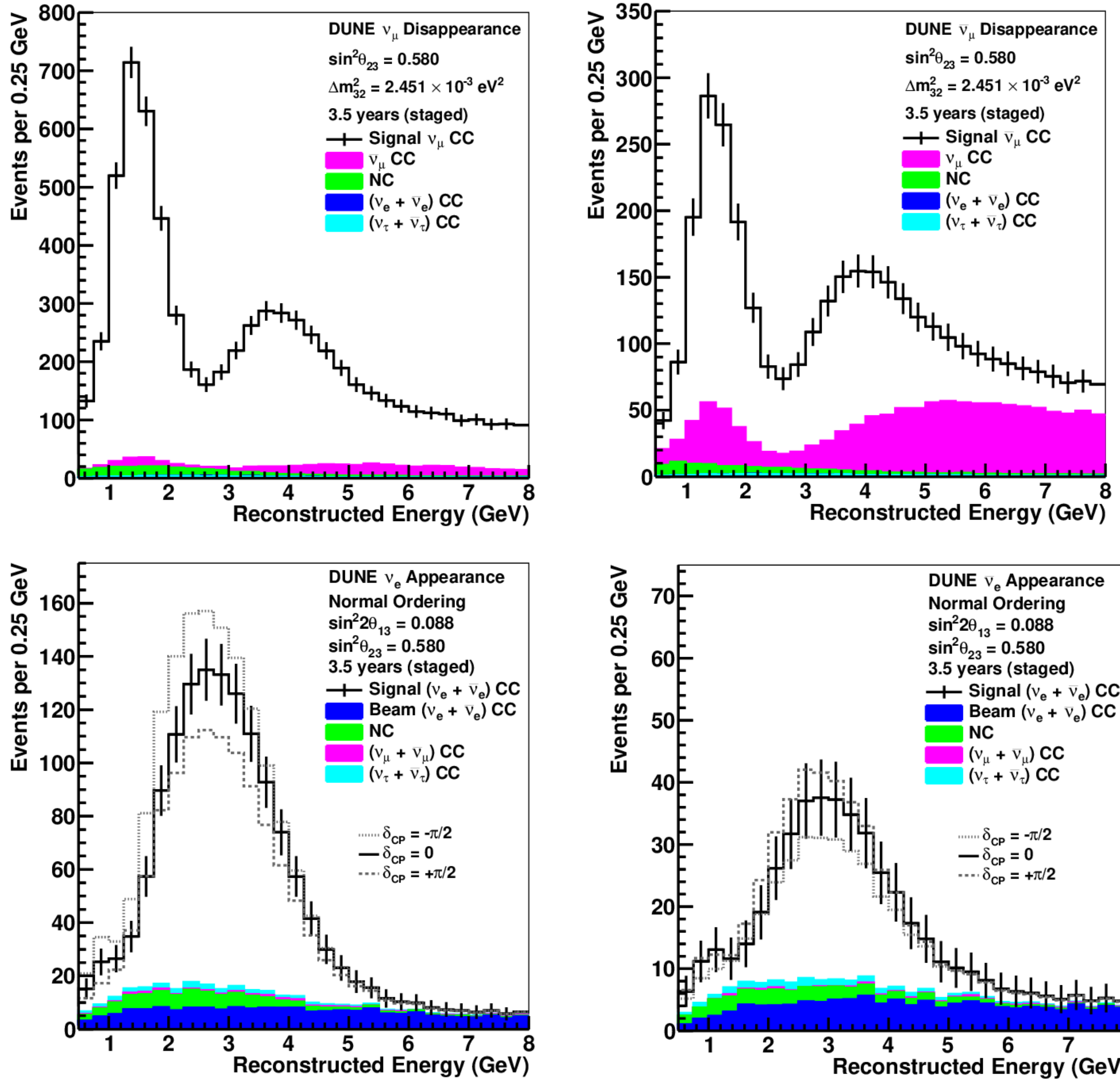
- ν_μ ($\overline{\nu}_\mu$) disappearance
- ~ 10,000 events in 7 years

- ν_e ($\overline{\nu}_e$) appearance
- ~ 1,000 events in 7 years

Staged = realistic time estimation of the detector deploying and the beam power intensity

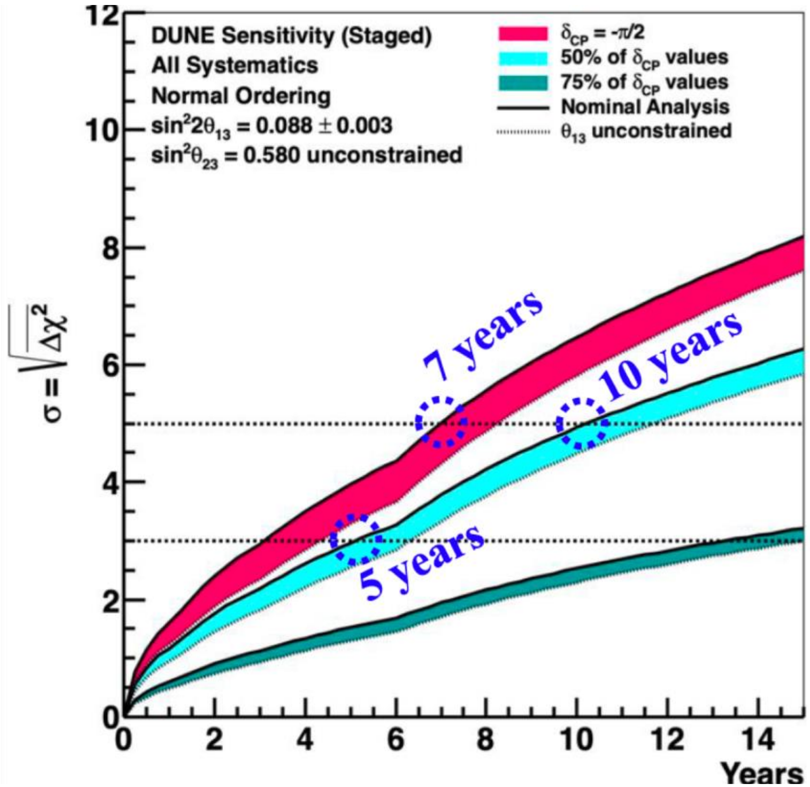
Neutrino mode

Anti-neutrino mode

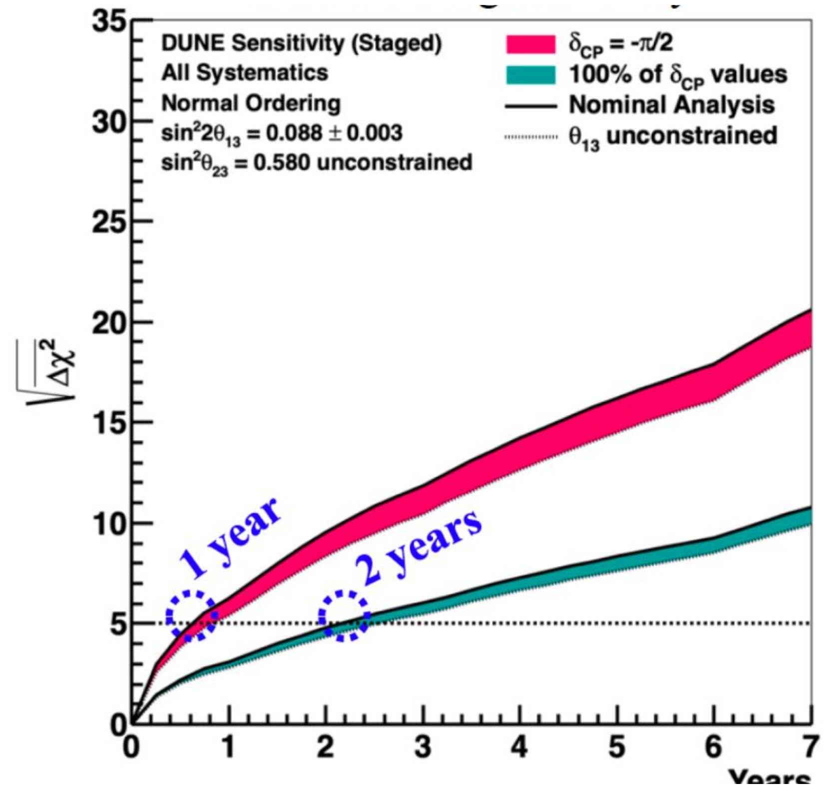


Physics – Neutrino Oscillation

CP violation sensitivity



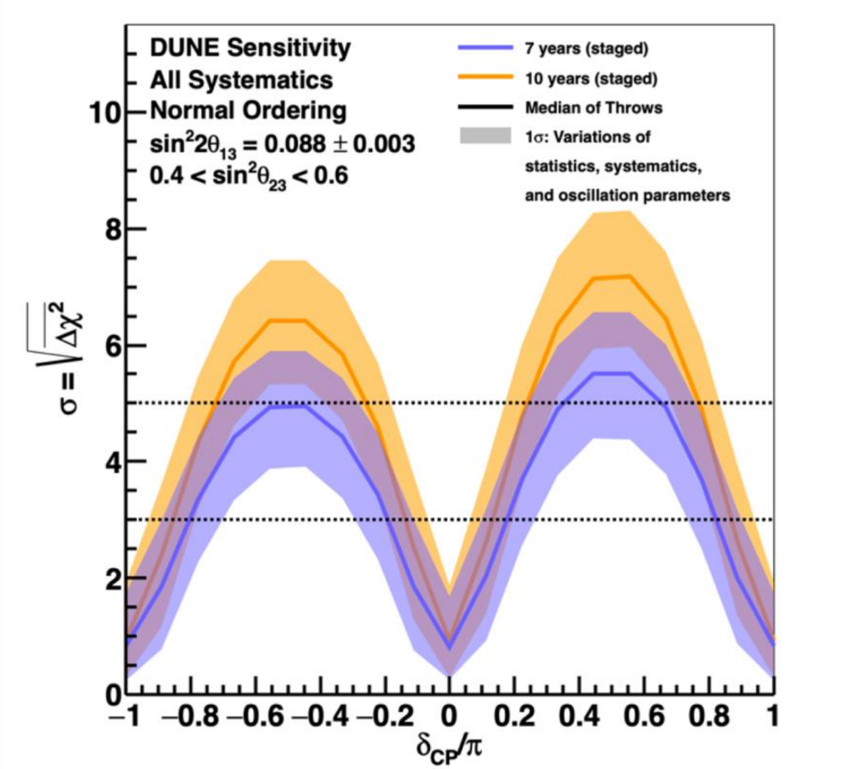
Mass ordering sensitivity



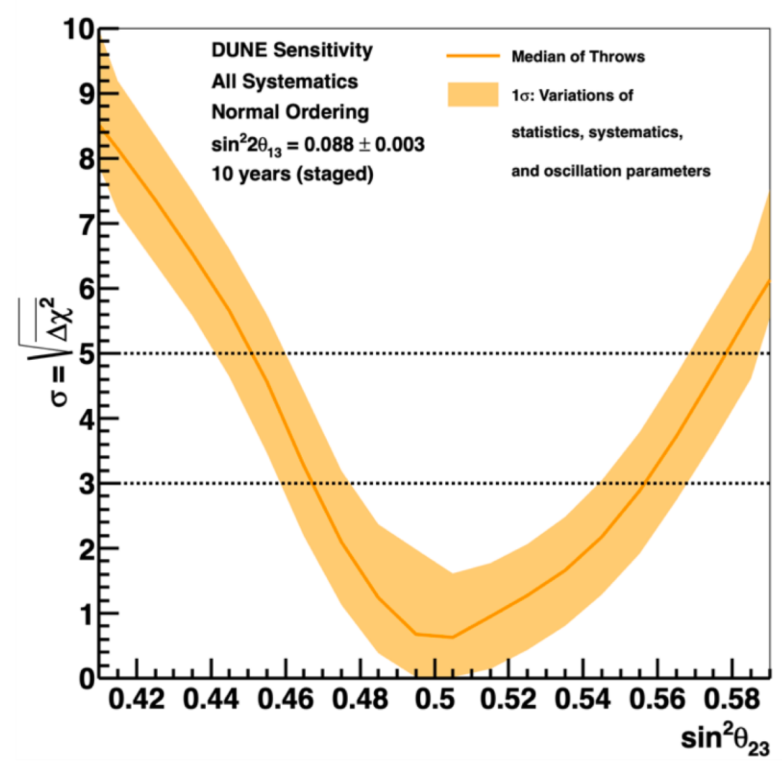
- 5σ sensitivity to mass ordering after 2 years of beam running (for any value of δ_{CP})
- 5σ sensitivity to 50% of δ_{CP} values after 10 years of beam running

Physics – Neutrino Oscillation

CP violation sensitivity (7/10y)

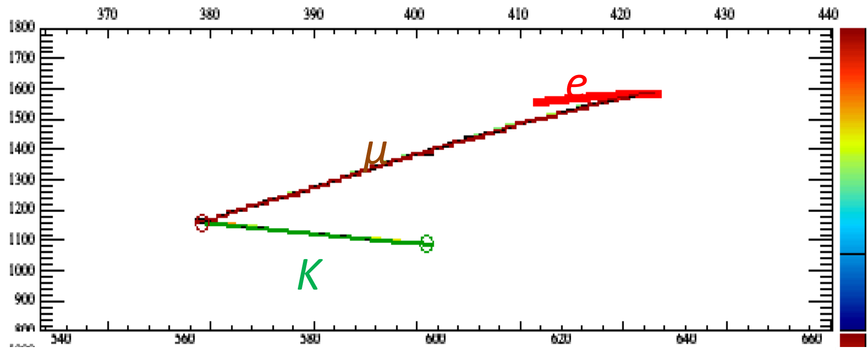


Octant determination at 10 years

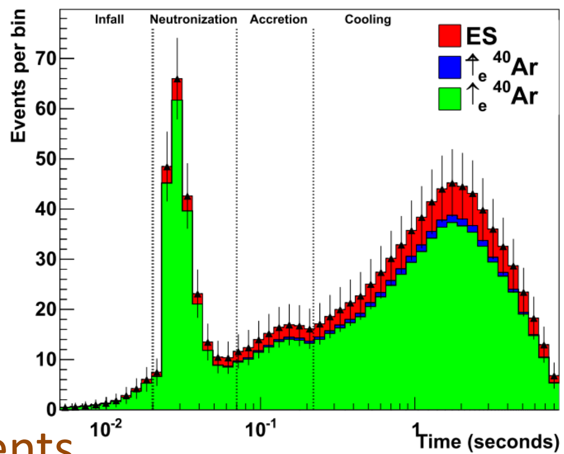


- ❑ Measurement of multiple PMNS parameters in a single experiment
- ❑ θ_{23} octant at 5σ possible

DUNE – Non-oscillation Physics



- Large mass of FD enables:
  - Proton decay searches
    - Golden channel in LArTPCs: $p \rightarrow K + \overline{\nu}$
  - Supernova core-collapse flux sensitivity
    - LArTPCs uniquely sensitive to ν_e flux



- Large flux enables precision cross-section measurements

- Both Near and Far detectors have sensitivity to BSM physics
  - Non-standard interactions
  - Sterile neutrinos
  - Dark Matter, Extra dimensions, SUSY,...

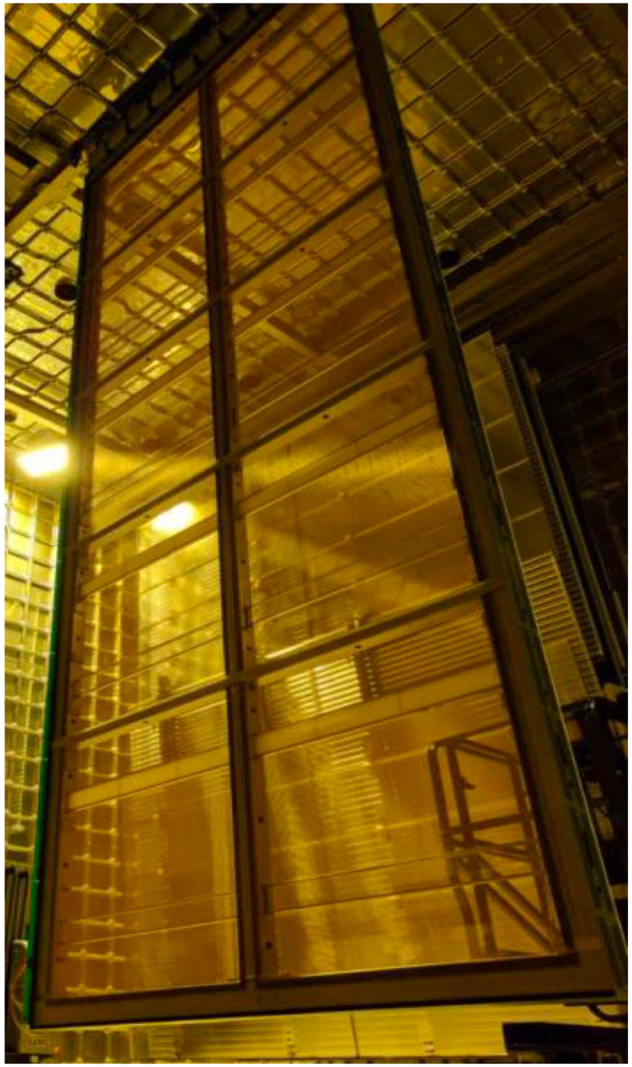
DUNE – Timeline & Milestones

Milestones

- ❑ 2018: LBNF Far Site Pre-excavation
- ❑ LBNF Near Site Groundbreaking – Nov 19
- ❑ PIP-II groundbreaking – May 19

FarDet DUNE modules

- ❑ 2024: Start installing first module (SP)
- ❑ 2025: Start installing second module
  - ➢ DUNE physics data starts with atmospheric neutrinos!
- ❑ 2026: Beam operational at 1.2 MW
  - ➢ Total fiducial mass of 20 kt
  - ➢ DUNE physics data taking with beam starts!
- ❑ Following add third/fourth FD module
  - ➢ final fiducial mass of 40 kt
- ❑ 2030+: Upgrade to 2.4 MW beam



DUNE – Summary

Deep Underground Neutrino Experiment (and LBNF)

- is expected to break new ground in the understanding of neutrinos and their role in the Universe.
- is an international collaboration with an ambitious and rich physics program
  - Precision oscillation parameter measurements
  - CP violation
  - Supernova physics
  - BSM physics
- Well on its schedule
  - Major milestone: final TDR for Far Detectors completed
  - Working on details of the near detector
  - LBNF's excavation of far site will start in the next months
  - Production of first major FD module component starts this year
  - Success through the Prototypes at CERN

Back Up

DUNE – Timeline & Milestones

Milestones

- ❑ 2018: LBNF Far Site Pre-excavation
- ❑ LBNF Near Site Groundbreaking – Nov 19
- ❑ PIP-II groundbreaking – May 19

FarDet DUNE modules

- ❑ 2024: Start installing first module (SP)
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  - ➢ DUNE physics data starts with atmospheric neutrinos!
- ❑ 2026: Beam operational at 1.2 MW
  - ➢ Total fiducial mass of 20 kt
  - ➢ DUNE physics data taking with beam starts!
- ❑ 2027: Add third FD module
  - ➢ Total fiducial mass of 30 kt
- ❑ 2029: Add fourth FD module
  - ➢ Total fiducial mass of 40 kt
- ❑ 2032: Upgrade to 2.4 MW beam

ProtoDUNE-SP I run

- ❑ 2019: CRT cosmics runs
- ❑ Jan/Feb: 2020 Xe- doping cosmics runs
- ❑ Apr 2020 decommissioning

ProtoDUNE-SP II run

- ❑ Summer 2020: module construction
- ❑ Summer 2021: installation 3-4 APAs module into cryostat
- ❑ 2021/2022: start beam test data taking
- ❑ 2022 physics at ProtoDUNE Single II

ProtoDUNE-DP

- ❑ 2020: commissioning cosmics running
- ❑ 2022 physics at ProtoDUNE Dual

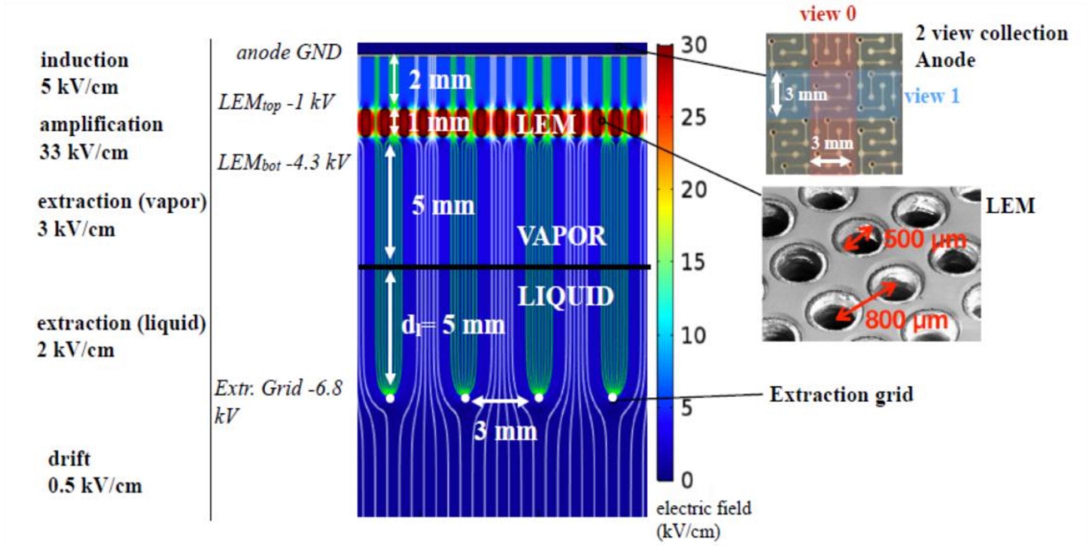
Near Detector

- ❑ 2020 Technical design report

DUNE Far Detectors – Dual-Phase LarTPC Option

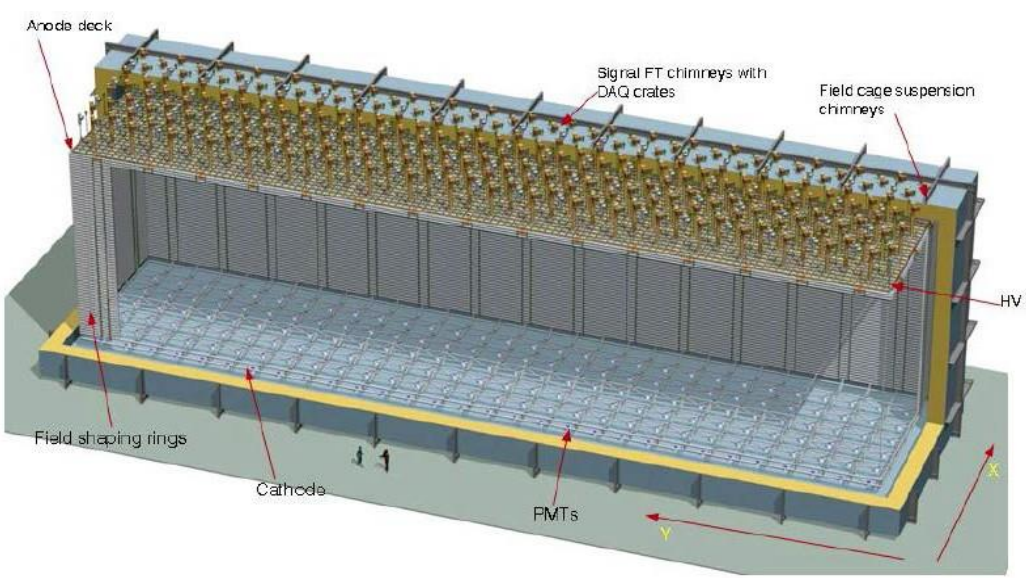
DUNE-DP charge readout

- ❑ Charge readout plane (CRP)
  - ➢ Extraction grid
  - ➢ LEM
  - ➢ Anode readout - strips
    - ▪ 3 mm pitch
  - ➢ 3m x 3m
  - ➢ 80 CRPs in total (153, 600 channels)



- ❑ Drift distance: 12 m
- ❑ E = 500 V/cm ⇒ Cathode voltage: -600 kV

- ❑ Photon readout
  - ➢ TPB-coated PMTs of 20 cm diameter
  - ➢ 1 PMT/m2: 720 PMTs total



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Two ~1kt Lar TPCs in a charged particle test beam and cosmics, at CERN Neutrino Platform

- Goals:
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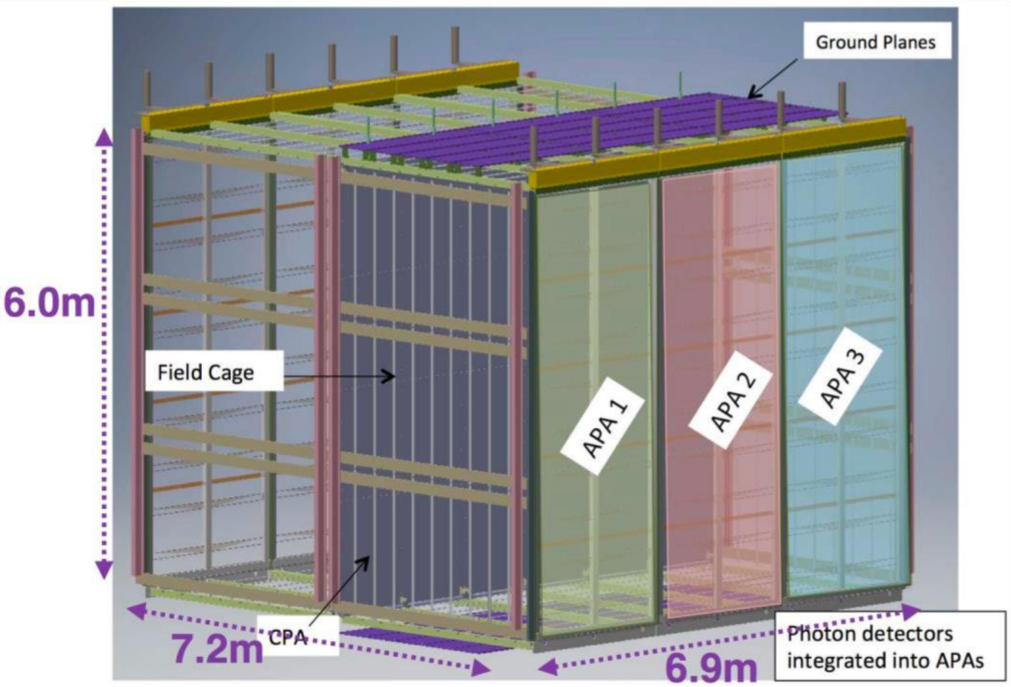
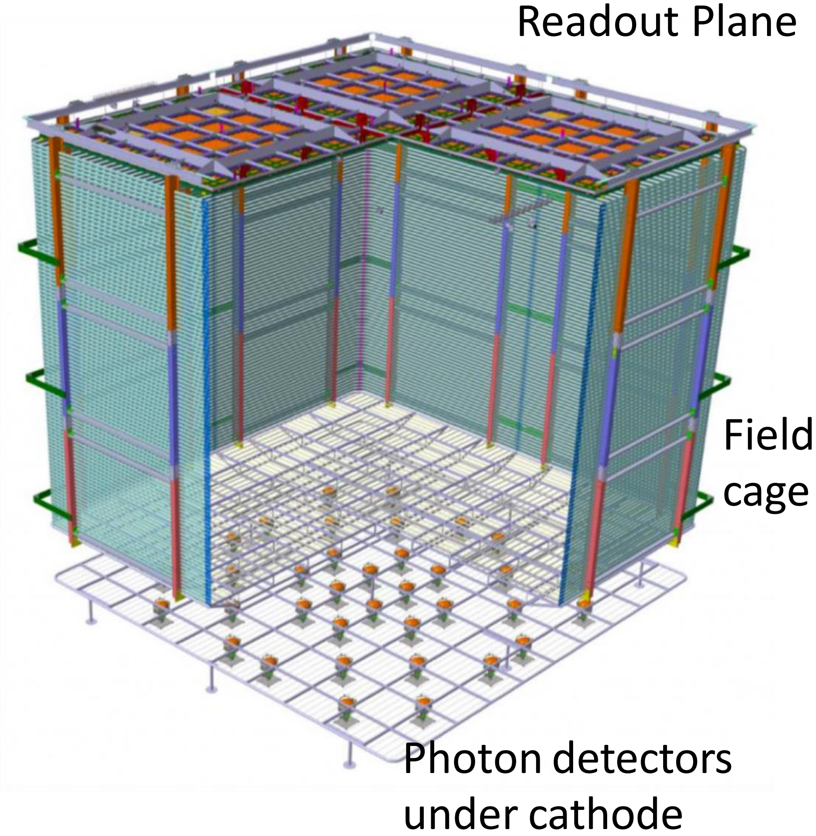
ProtoDUNE Detectors

Single-phase

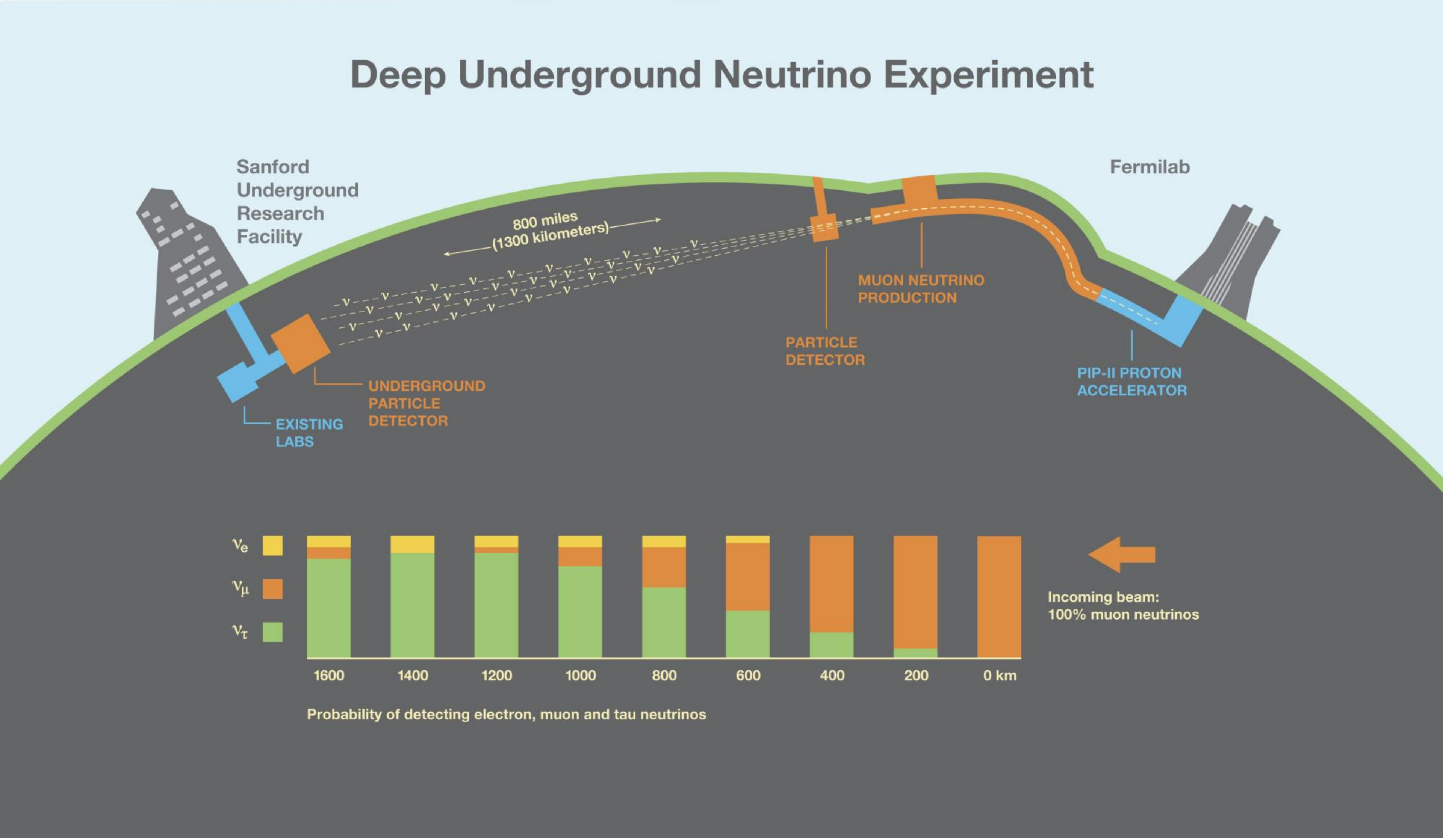


Dual-phase



Far Site – SURF (Sanford Underground Research Facility)

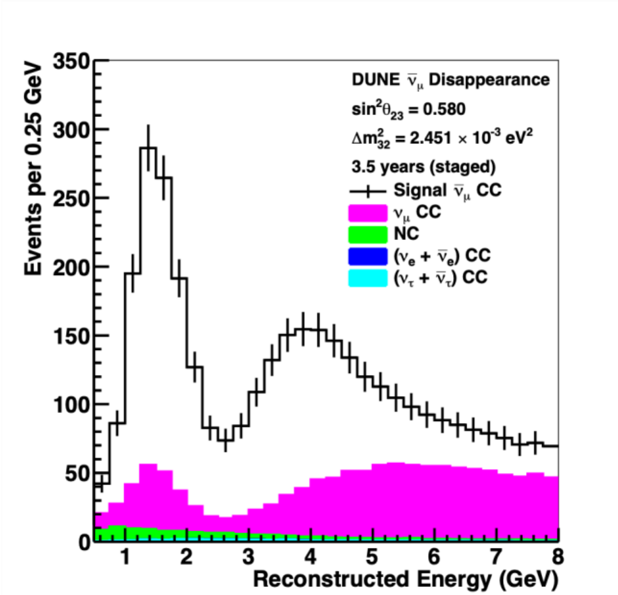
DUNE – Physics



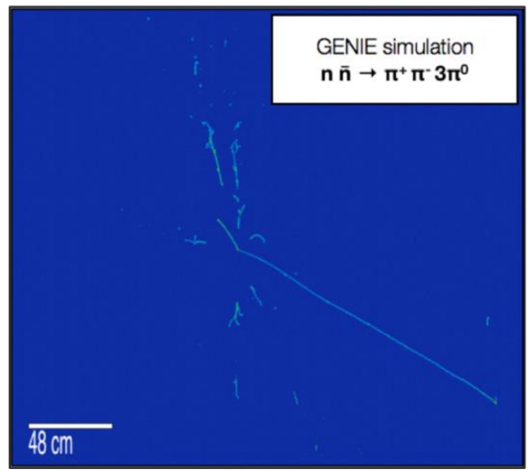
DUNE – Physics Motivation

- Rich neutrino physics programme for DUNE

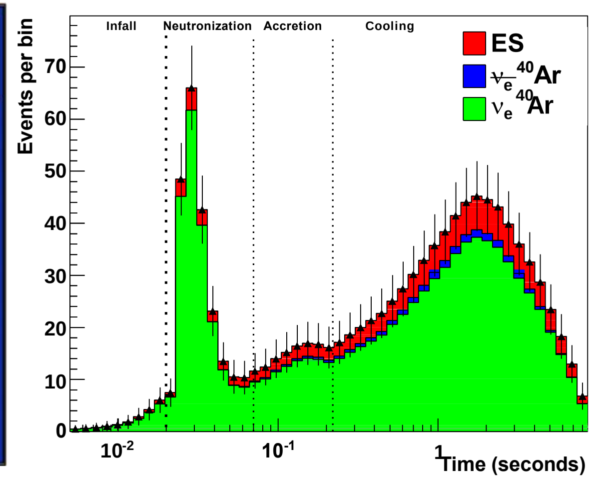
Long baseline neutrino physics



Nucleon decay

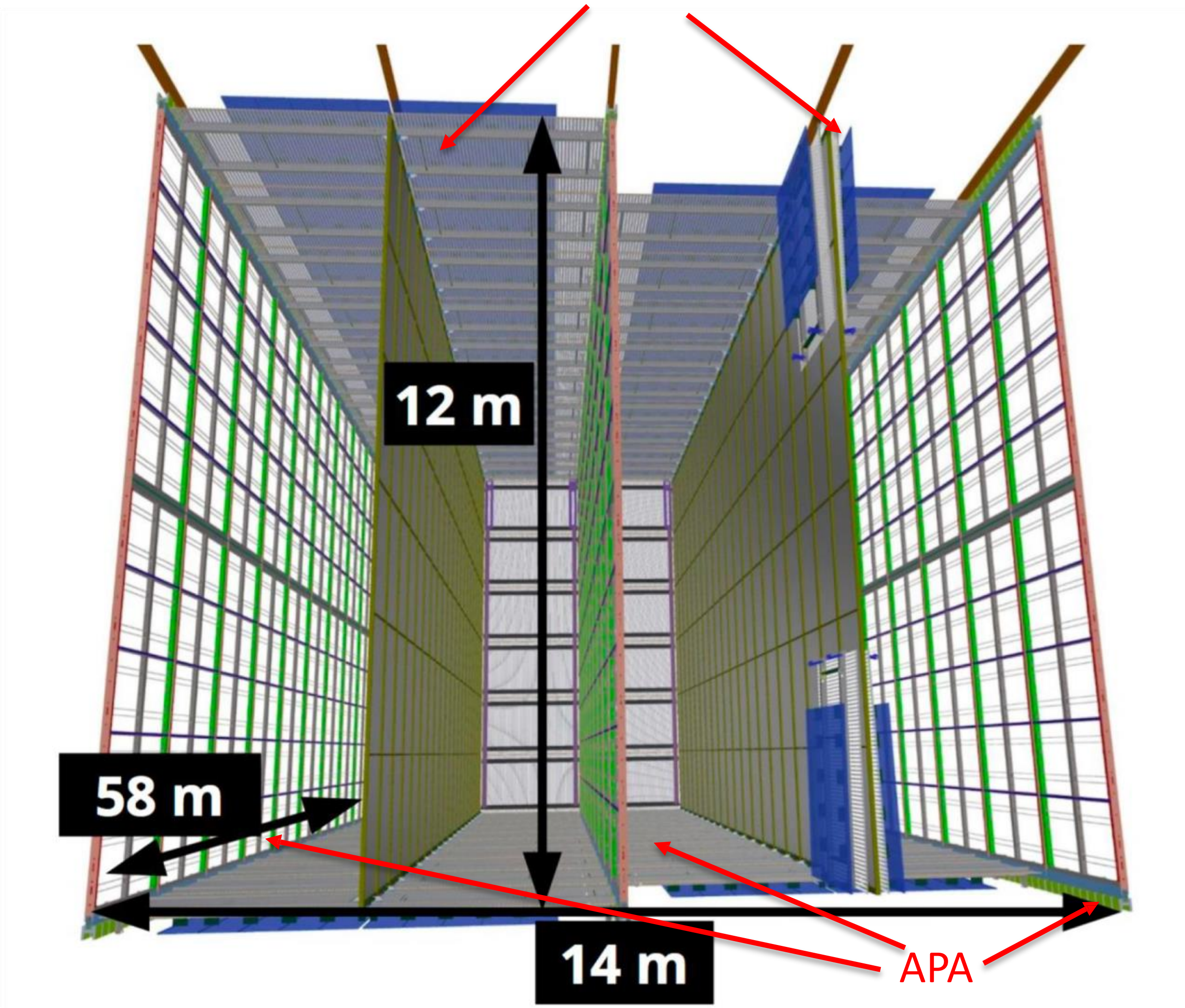


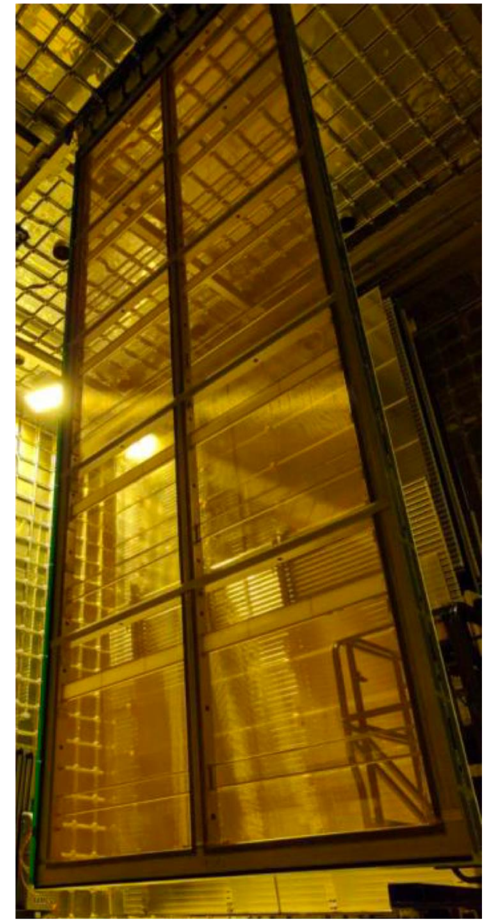
Astroparticle physics



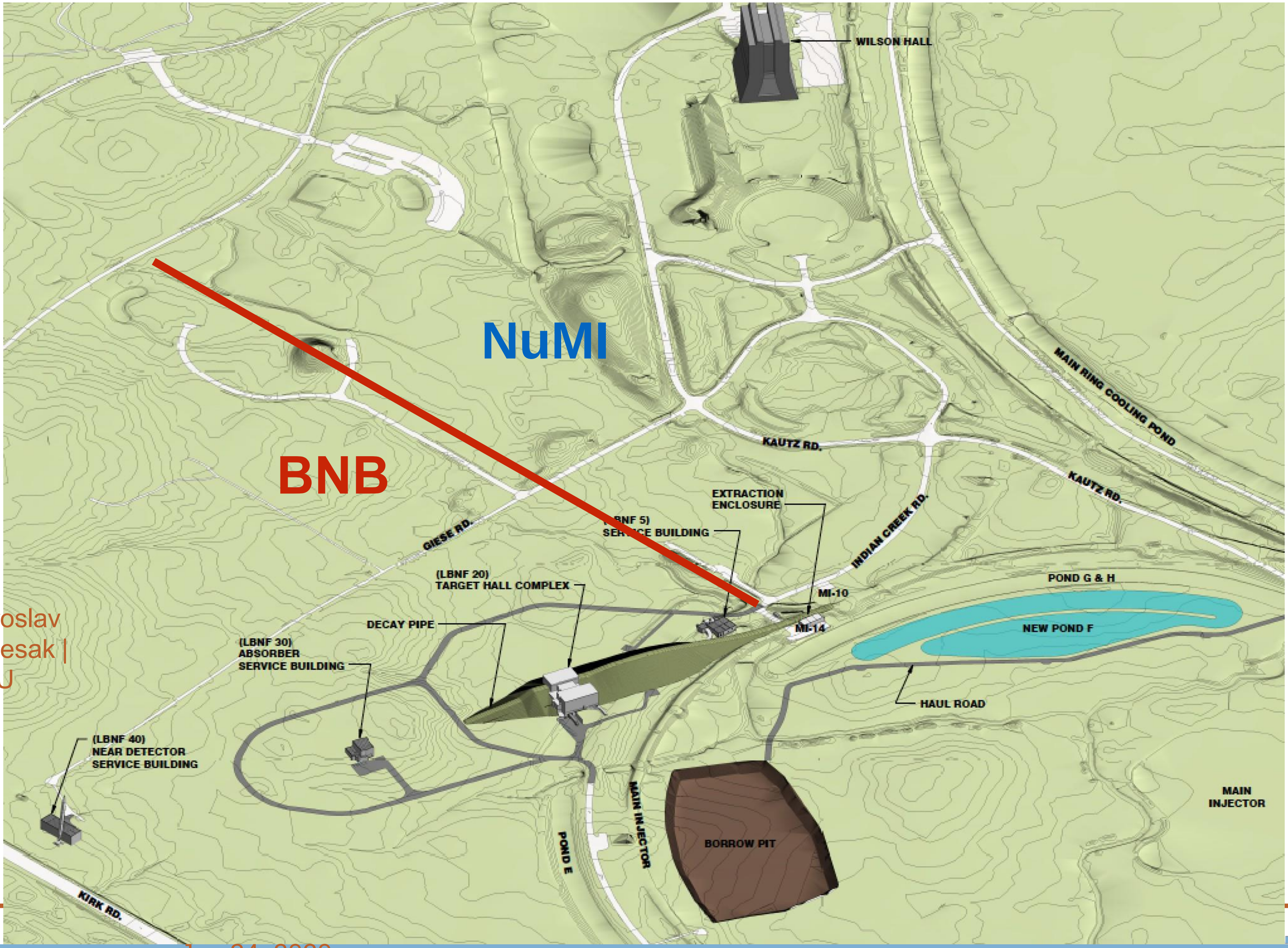
- …to name but a few! See DUNE TDR for more! [link to TDR]

DUNE Far Detectors – Single-Phase



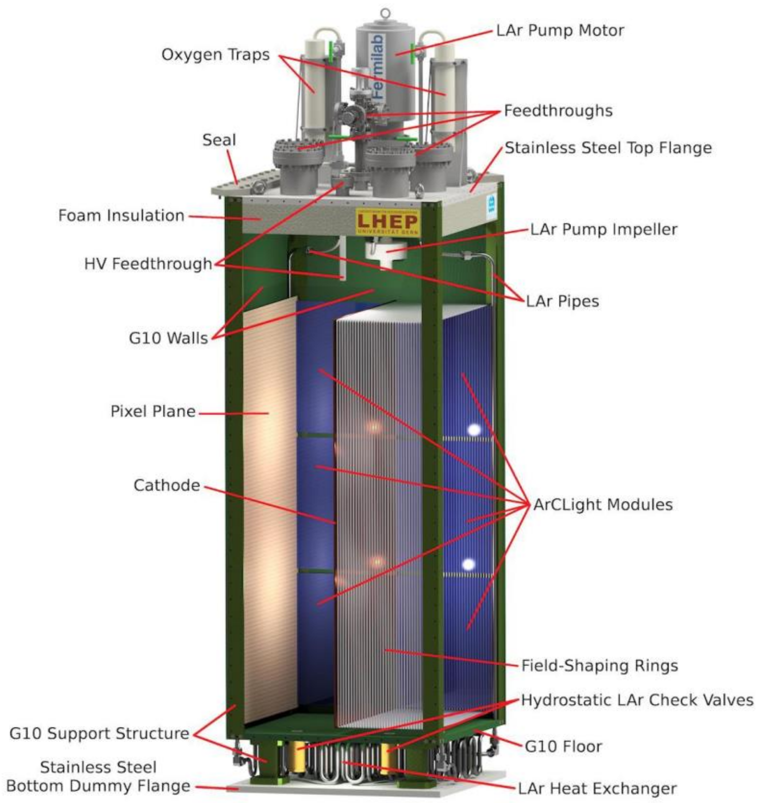


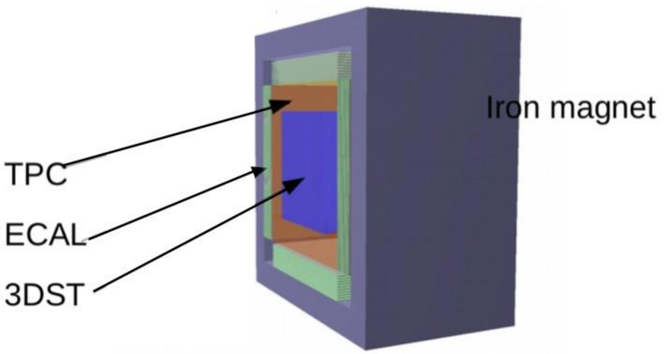
Near Site – Beam line

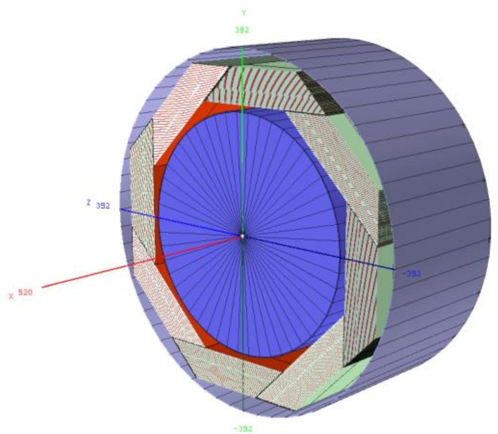


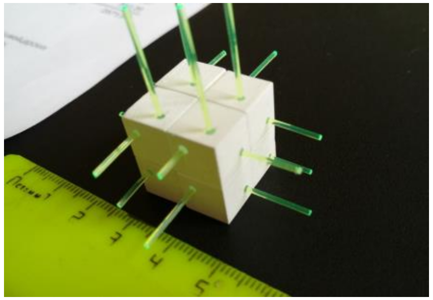
Near Site – Near detector

- Goal of near detector
  - Constrain flux and cross-section systematic uncertainties
  - Can also measure 10 million neutrino interactions per year
- Concept for near detector
  - LArTPC (ArgonCube)
  - Multi-purpose detector (MPD)
  - Beam monitor (3D scintillator tracker spectrometer, 3DST-S)



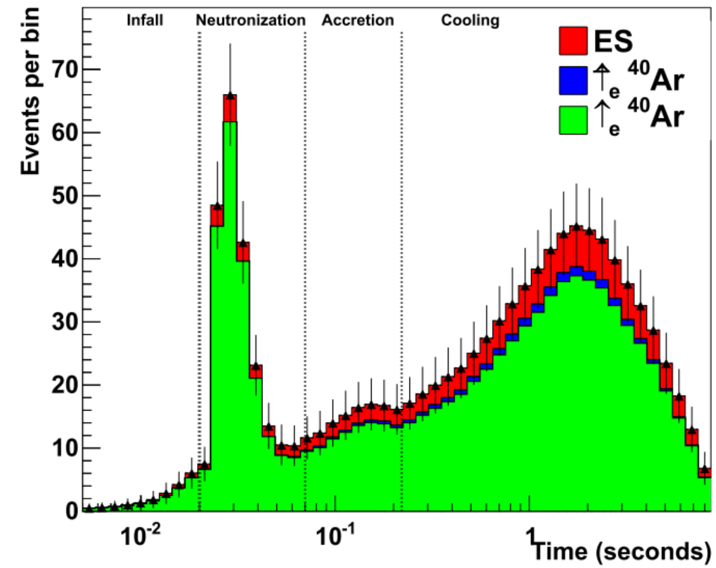




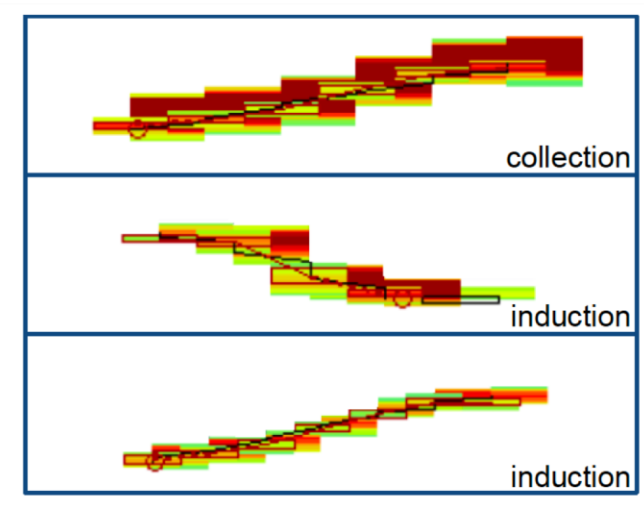


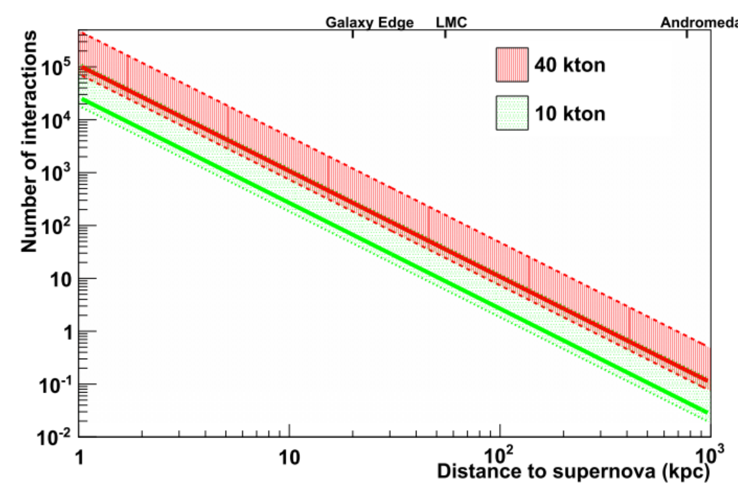
DUNE – Physics – Supernova Neutrinos

- ❑ Large mass of Far detector gives sensitivity to supernova spectrum
- ❑ LAr has unique sensitivity to ν_e flux from core collapse

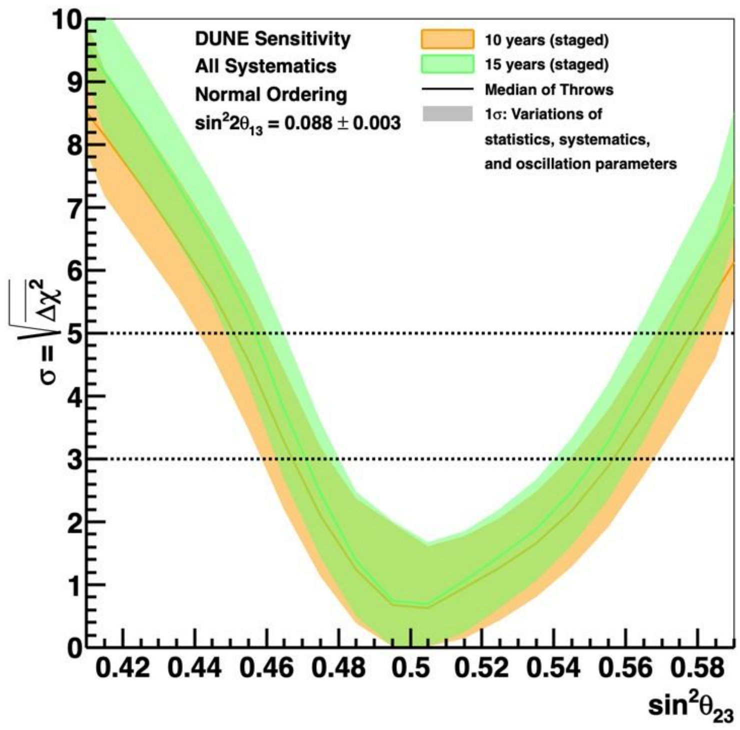


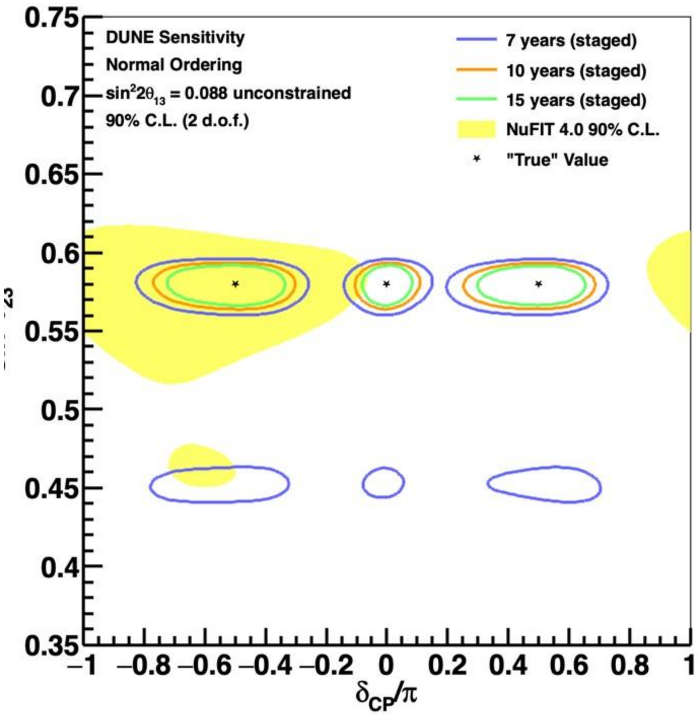
10.25 MeV electron (simulated + reconstructed)





Physics – Neutrino Oscillation





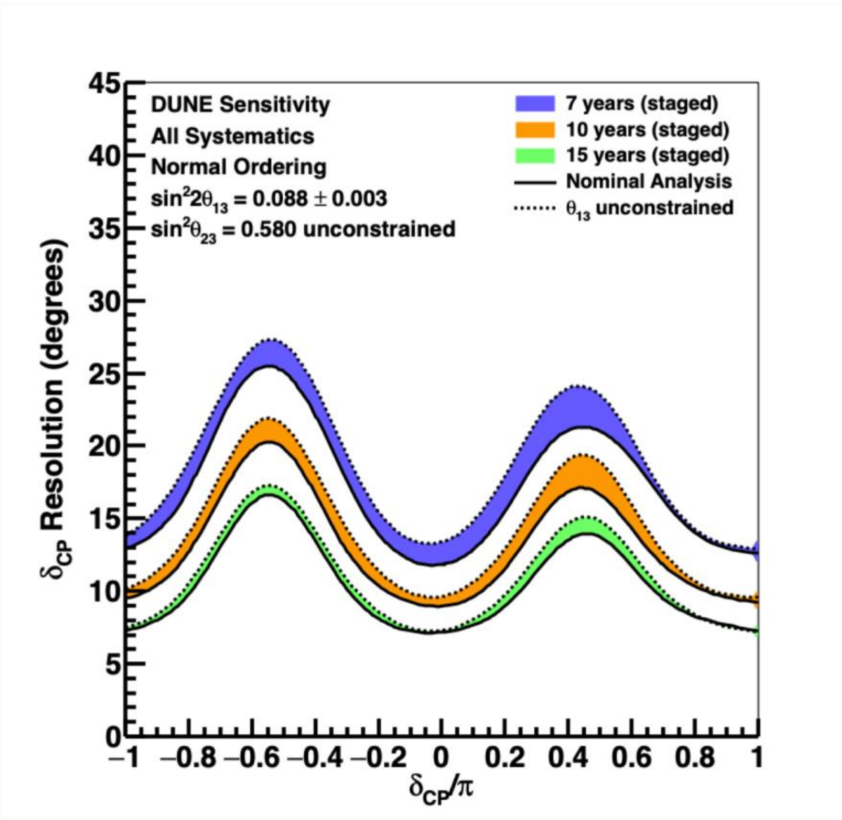
θ_{23} octant at 5σ possible

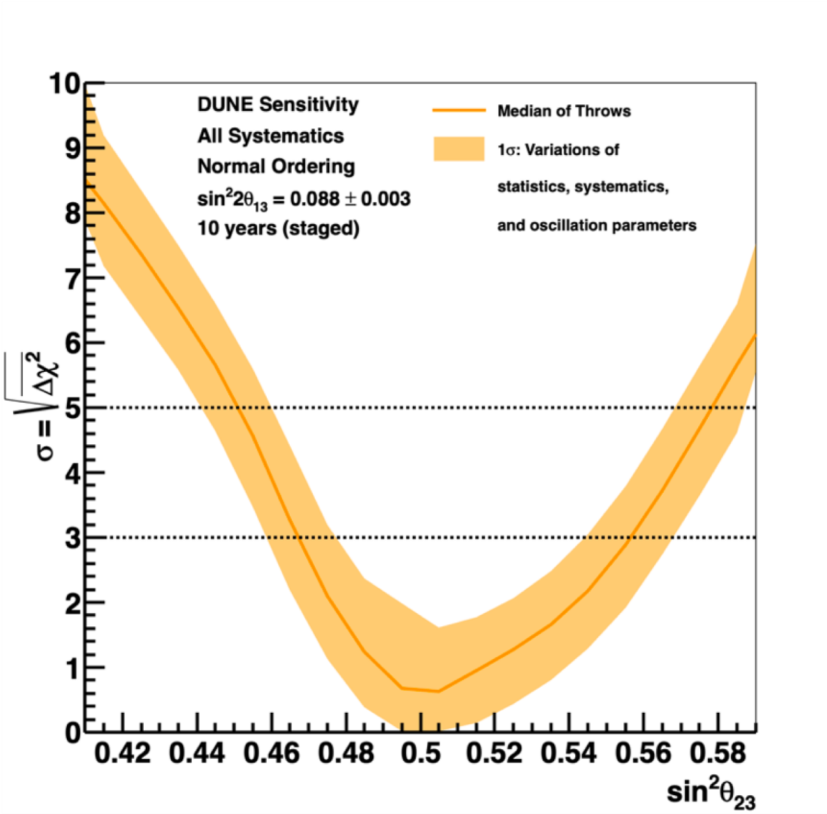
Simultaneous measurement without external constraints

Physics – Neutrino Oscillation

CP violation sensitivity

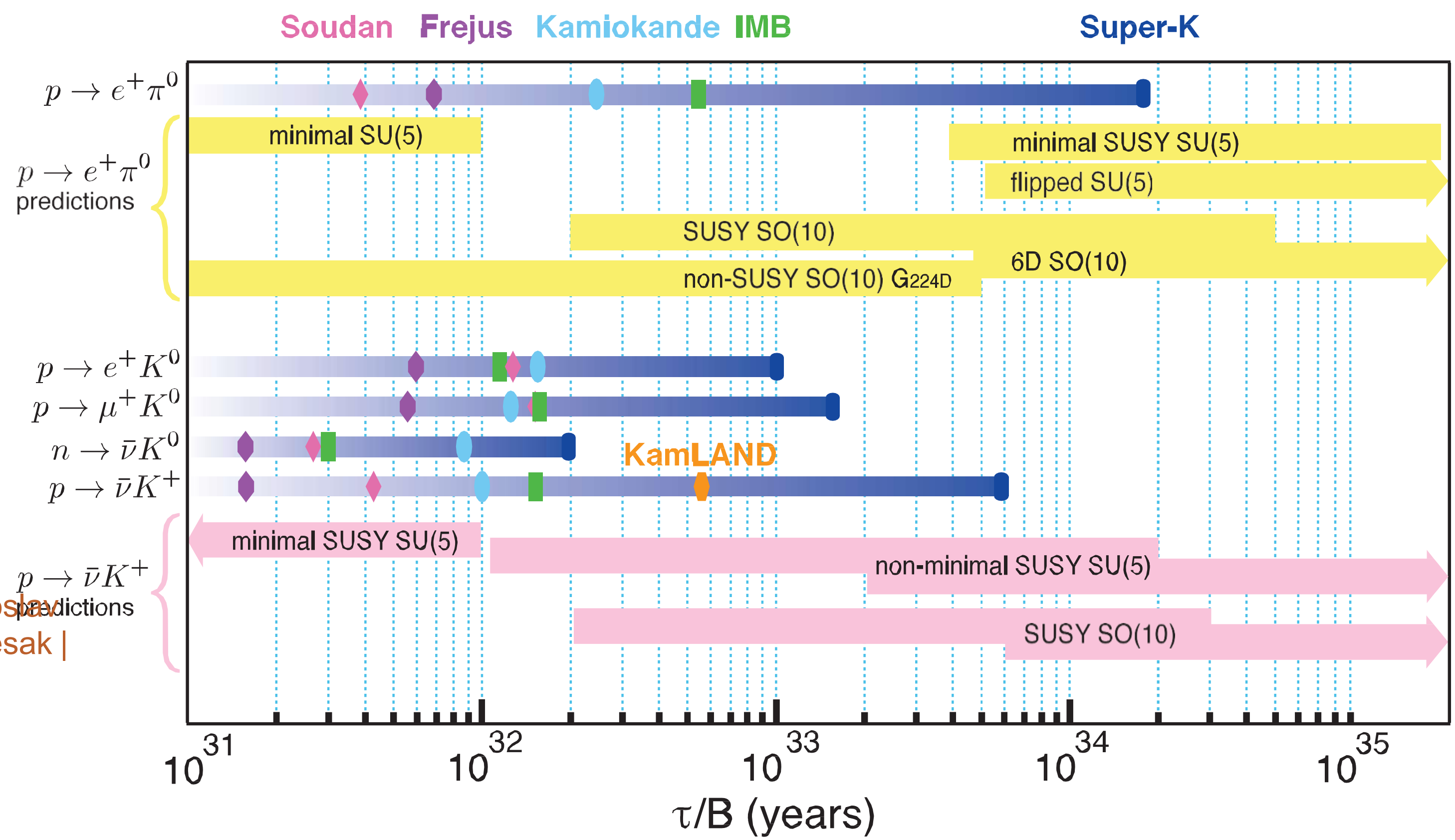
Octant determination at 10 years





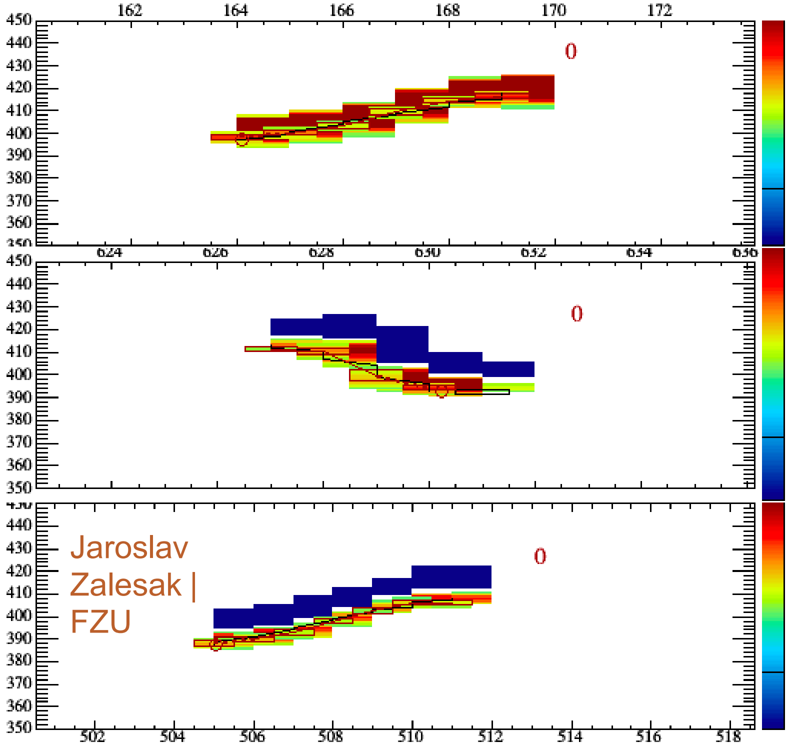
- Measurement of multiple PMNS parameters in a single experiment

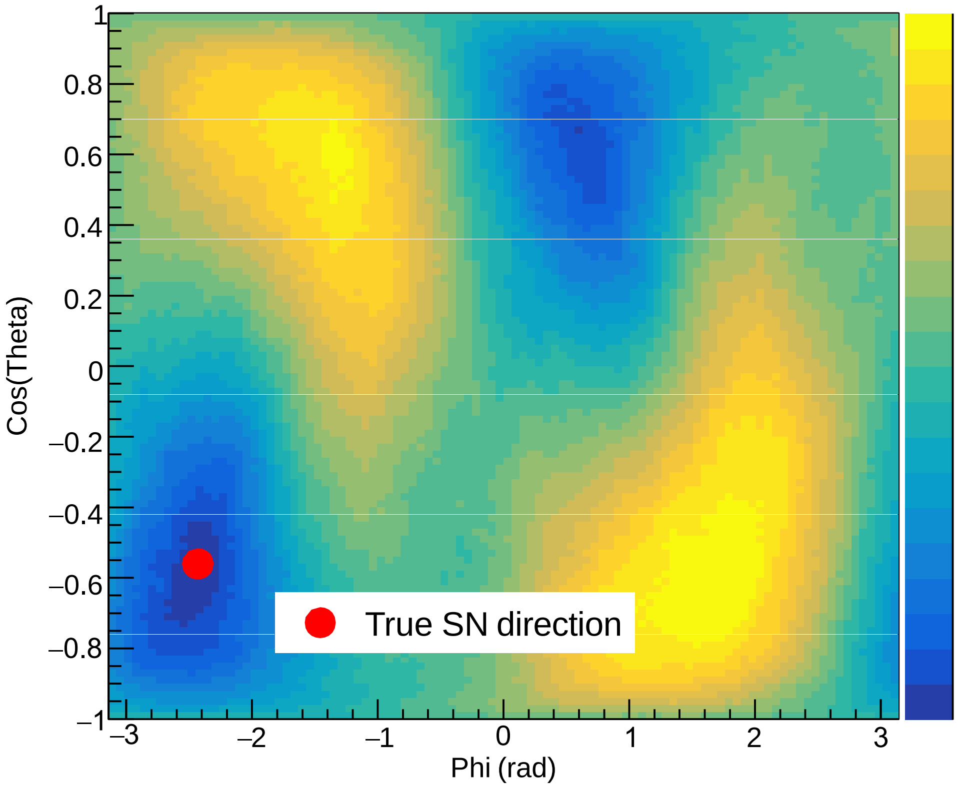
Nucleon decay



Jaroslav Zalesak | FZU

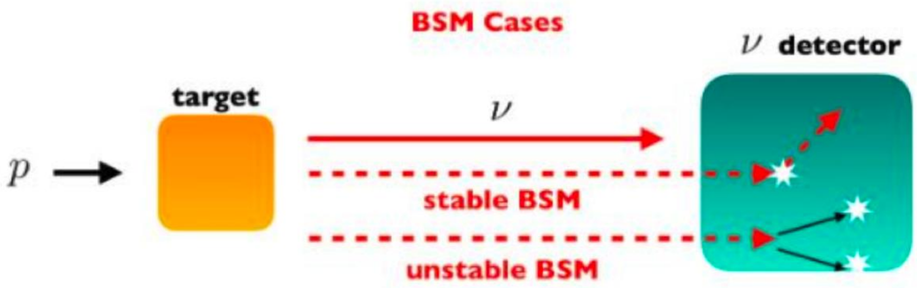
Supernova pointing

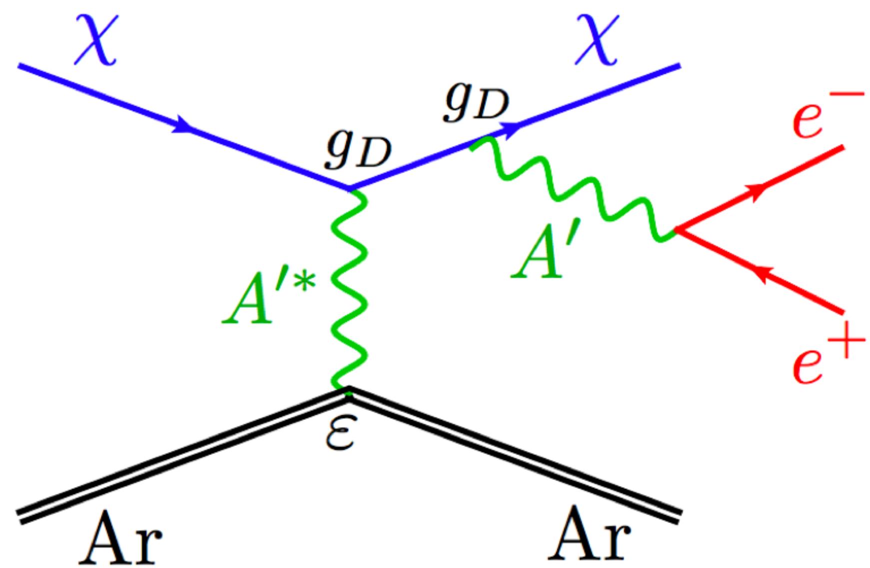




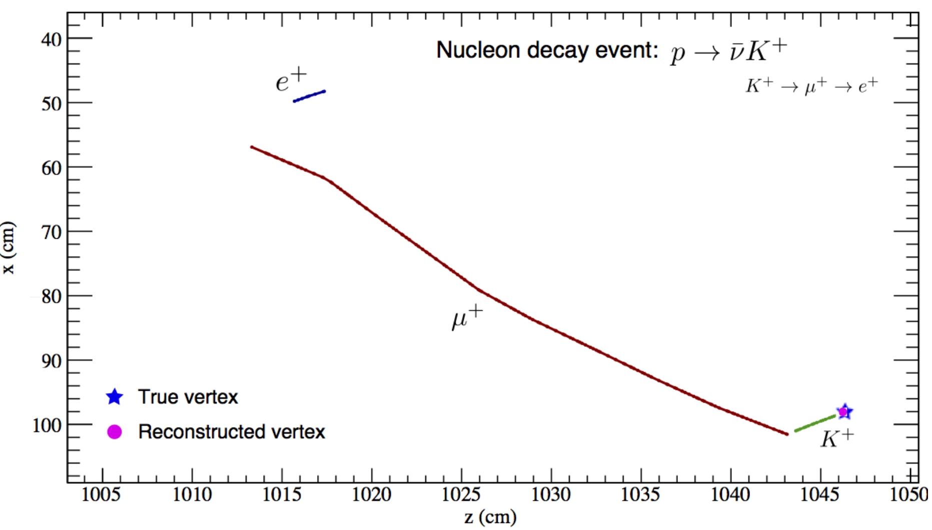
DUNE – BSM Physics

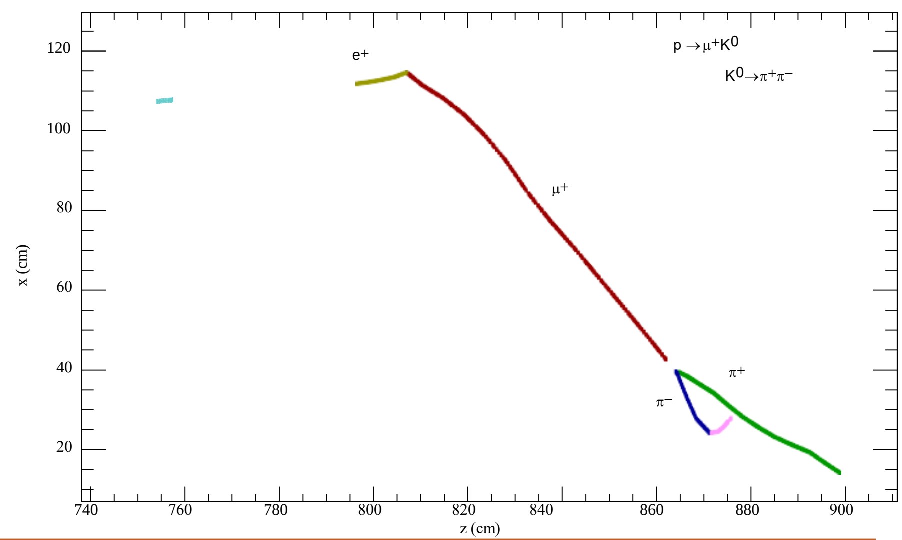
❑ Beyond Standard Model





❑ Nucleon Decays





GENIE – Neutrino Interaction Experiment

At the time of the technical design report (TDR) writing, the DUNE simulation uses a version in the v2 series of the GENIE generator, which includes empirical comprehensive models, based on home-grown hadronic simulations (AGKY model [71] for neutrino-induced hadronization and INTRANUKE/hA model [72] for hadronic re-interactions) and nuclear neutrino cross sections calculated within the framework of the simple relativistic Fermi gas model [73]. Several processes are simulated within that framework with the most important ones, in terms of the size of the corresponding cross section at a few GeV, being: (1) quasi-elastic scattering, simulated using an implementation of the Llewellyn Smith model [74], (2) multi-nucleon interactions, simulated with an empirical model motivated by the Lightbody model [75] and using a nucleon cluster model for the simulation of the hadronic system, (3) baryon resonance neutrino-production simulated using an implementation of the Rein-Sehgal model [76], and (4) deep-inelastic scattering, simulated using the model of Bodek and Yang [77]. These comprehensive models, as well as the GENIE procedure for tuning the cross section model in the transition region, have been used for several years and are well understood and documented [70]. The actual tune used is the one produced for the analysis of data from the MINOS experiment and, as was already known at that time, it has several caveats as it emphasizes inclusive data and does not address tensions with exclusive data. The future DUNE simulation will be done using the v3 GENIE Generator where improved models and tunes are available. Details of improved models in the v3 GENIE Generator are discussed in ??.

Neutrino Oscillation/Transition

$$\begin{array}{l} P(\nu_\mu \to \nu_e) \\ P(\bar{\nu}_\mu \to \bar{\nu}_e) \end{array} \approx \underline{\sin^2(2\theta_{13})}\,\underline{\sin^2(\theta_{23})}\, f^{\pm}(\underline{L, E}, \Delta m^2_{31})$$

$$+ \left\{\underline{\cos\delta_{CP}}\cos\frac{\Delta m^2_{31}L}{4E} \mp \underline{\sin\delta_{CP}}\sin\frac{\Delta m^2_{31}L}{4E}\right\}$$

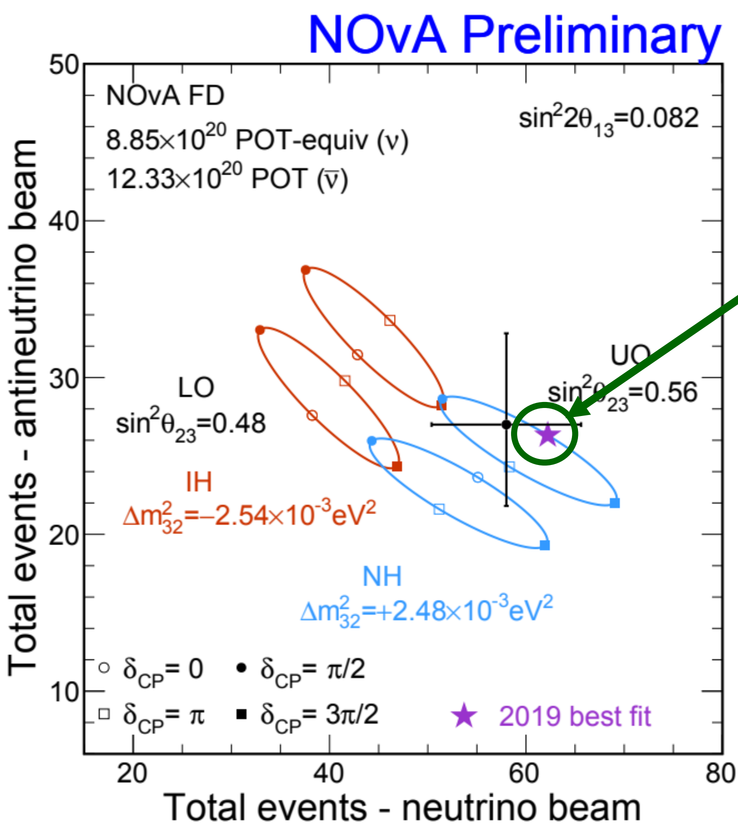
$$\times\; 2\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin(\theta_{13})\, g^{\pm}(L, E, \Delta m^2_{31}, \theta_{12}, \theta_{23})$$

± neutrino mode

± anti-neutrino mode

- The **baseline** (L = 810 km) and **neutrino beam energy** (E = 2 GeV) place our detector at the first $\nu_\mu \to \nu_e$ oscillation peak.
- **$\sin^2 2\theta_{13}$**: the leading term in this equation has already been measured.
- **$\sin^2\theta_{23}$**: we get information about the θ_{23} octant from the leading term.
- **δ_{CP}**: we have sensitivity to the CP-violating phase angle.
- **mass hierarchy**: depending on the sign of Δm^2_{31} ($\sim \Delta m^2_{32}$), the oscillation probability is either enhanced or suppressed.

Oscillation results



Best fit:

(all systematic uncertainties, Feldman-Cousins corrections are applies)

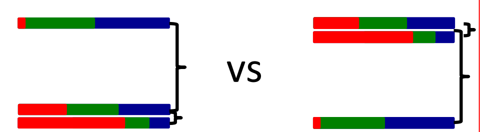
$$sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$$

$$\Delta m^2_{32} = +2.48^{+0.11}_{-0.06} \times 10^{-3}\ eV^2/c^4\ (NH)$$

$$\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi$$

[Feldman-Cousins corrected significances]

IH UO Disfavored 1.8σ	NH UO 2019 best fit	
IH LO Disfavored 2σ	NH LO Disfavored 1.6σ	LO Disfavored 1.6σ
IH Disfavored 1.9σ		



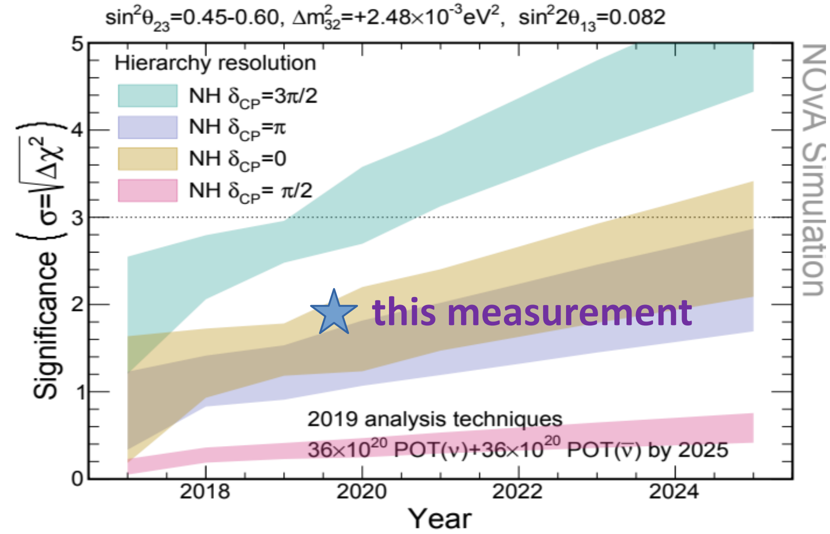
NH preferred by 1.9σ

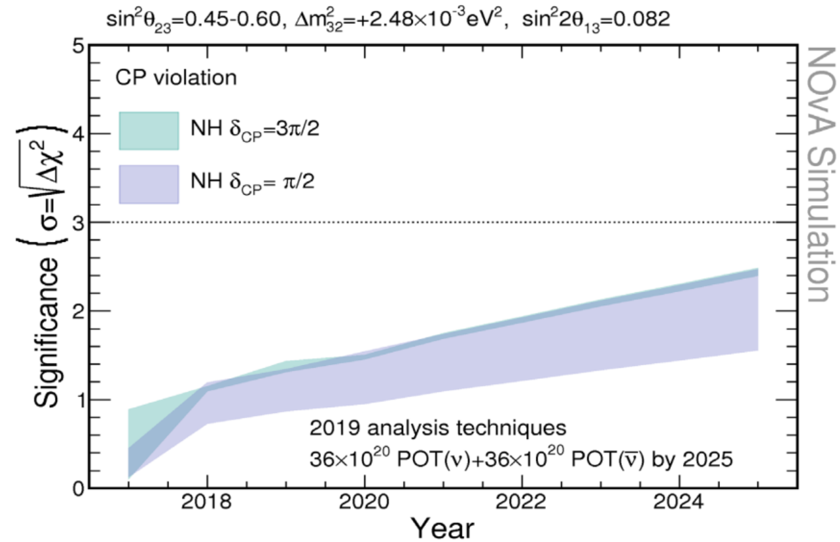
$$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$$

All values of δ allowed at 1.1σ

NOvA Future

- ❑ Currently running in neutrino mode
  - ➢ Run plan: **50%:50% in ν:anit-ν**
  - ➢ NOvA approved to run **until 2025**
  - ➢ **Beam upgrades** an important part of story!
- ❑ With current analysis, expect:
  - ➢ **3-5σ sensitivity to hierarchy** with favorable parameters
  - ➢ **Possible >2σ sensitivity to CP violation**
- ❑ Anticipating improvements in simulations that should extend reach
  - ➢ **Test Beam** / improved det. response model
  - ➢ **GENIE 3.0** / improved cross section models





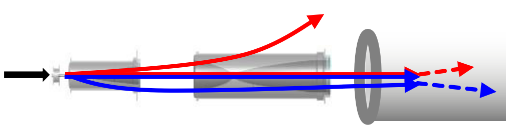
Predictions & Simulations

Geant 4

+

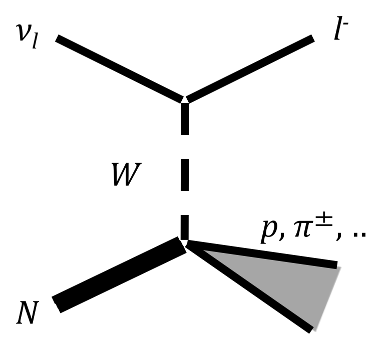
NuMI
PPFX

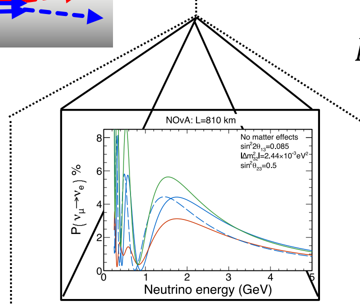
Neutrino flux



GENIE
2.12.2

Neutrino reactions
on detector materials





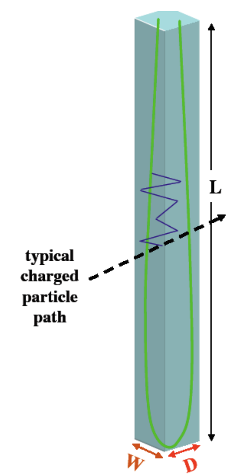
Oscillations

Geant 4

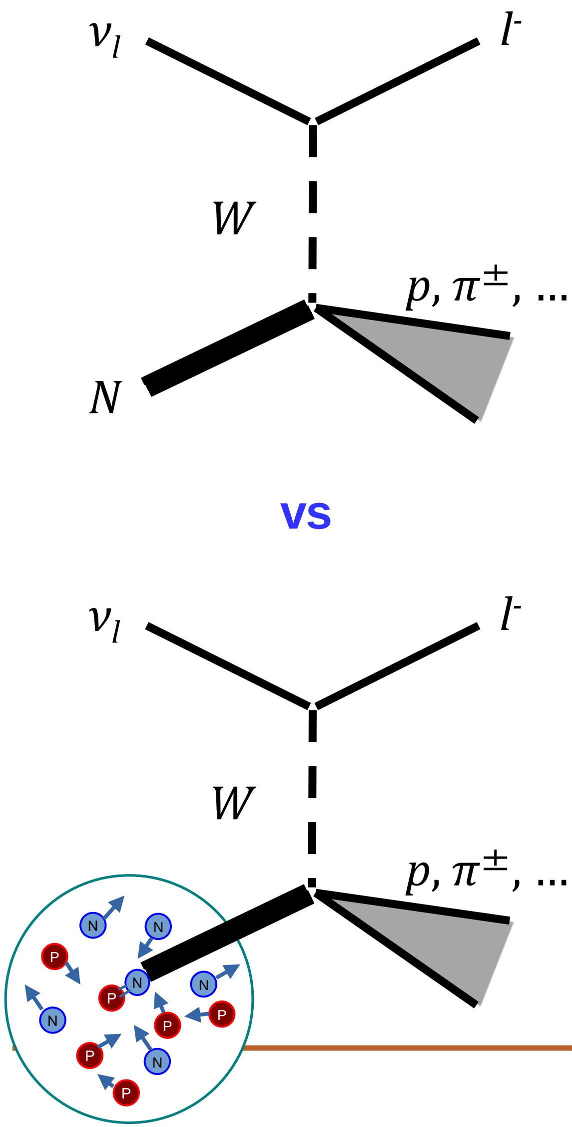
+

Custom readout software

Detector response to charged particles and **light propagation**



Predictions



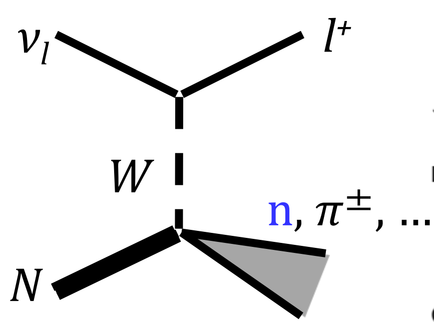
<u>Nuclear physics is important</u> (and *hard*)

Some effects need to be added to GENIE 2.12.2 (our default) *post hoc*

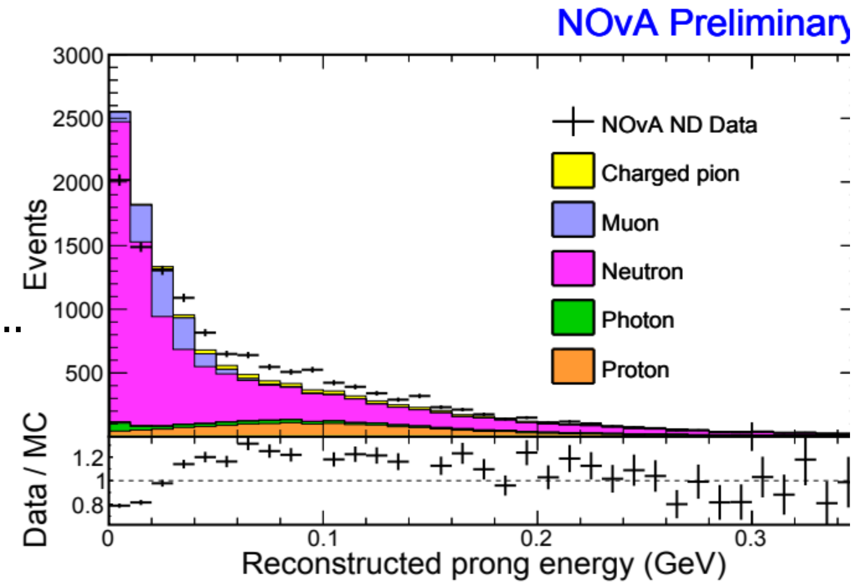
- Elastic-like (no pions produced):
  - Multi-nucleon knockout (short range): tuned empirical model
  - Nuclear charge screening (long range): theory-based corrections†
- Pion production:
  - Empirical correction inspired by observed suppression in data

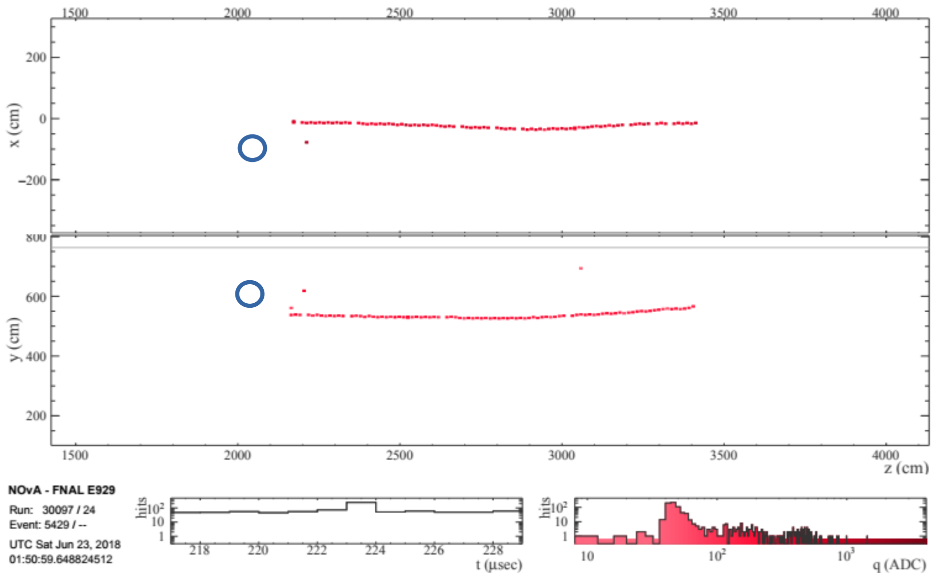
Neutron response

Neutron response is important in ν mode:



neutrons dominate in antineutrino

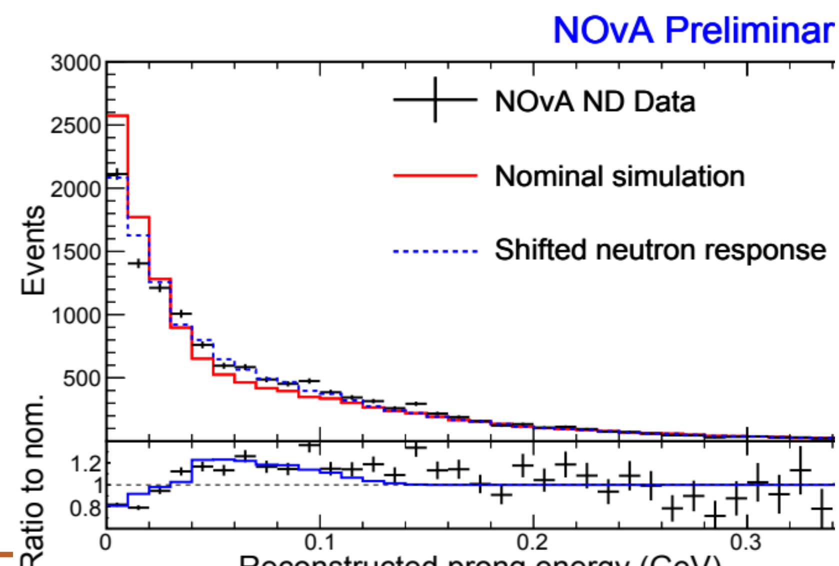




Search for ν QE-like events (μ + no other tracks)

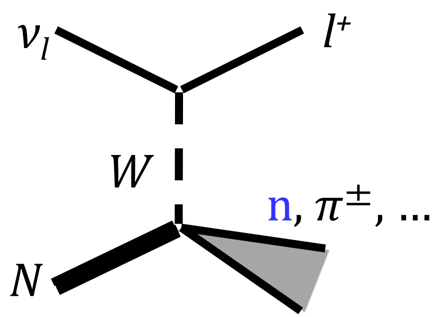
with compact displaced energy deposits...

... and design uncertainty to bound data-simulation difference in observed energy



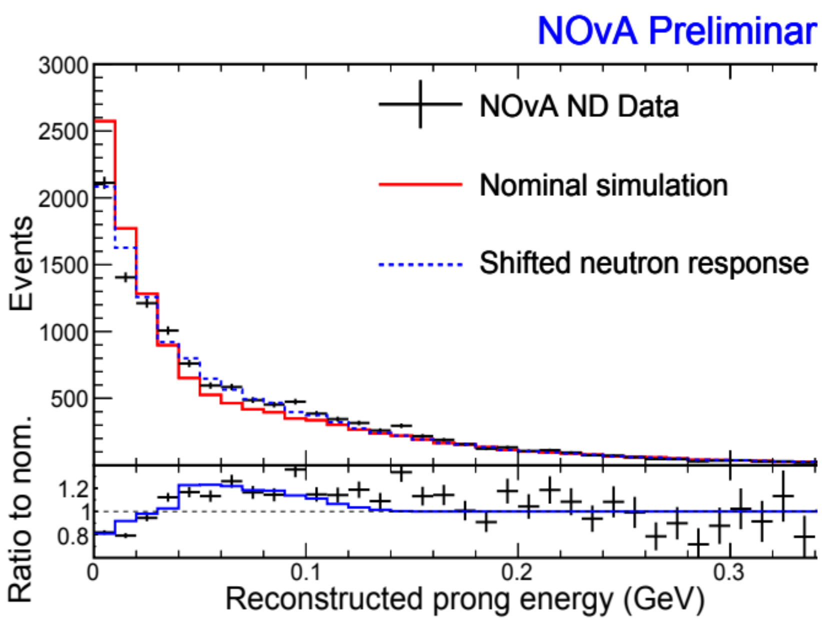
Neutron response

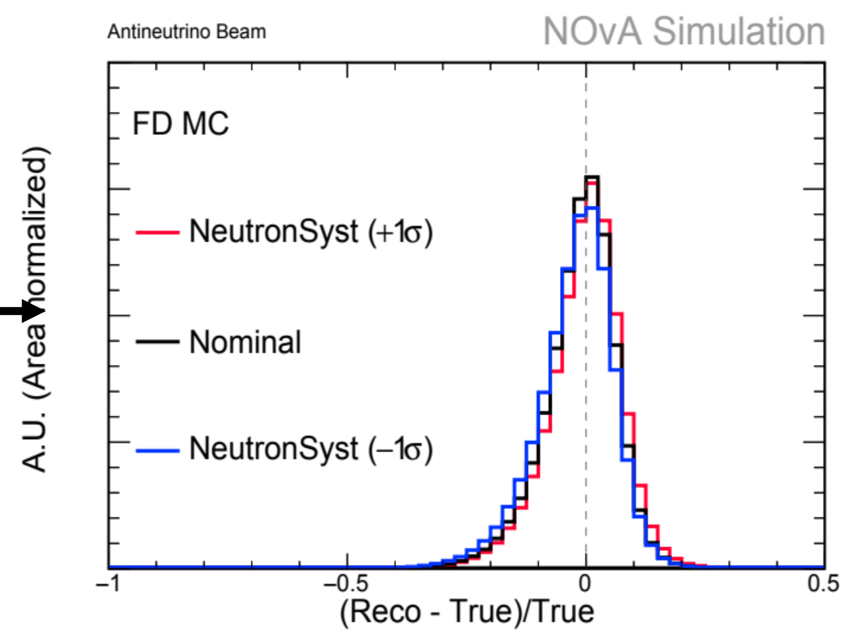
Neutron response is important in ν mode:



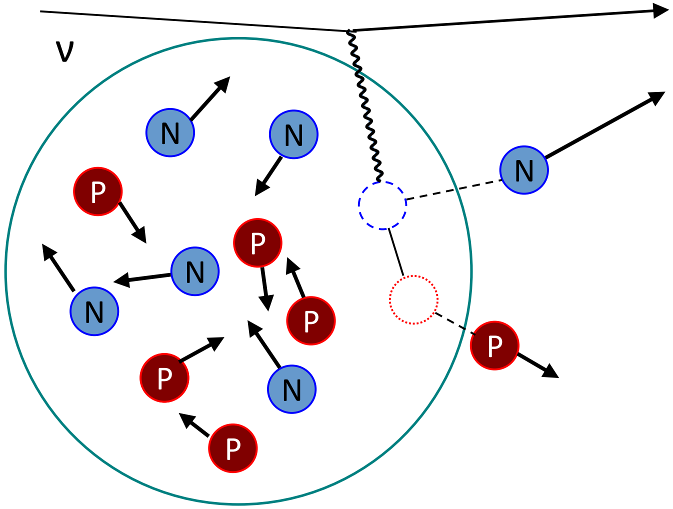
~1% effect shift in mean energy, negligible change to resolution, negligible change to selection efficiencies

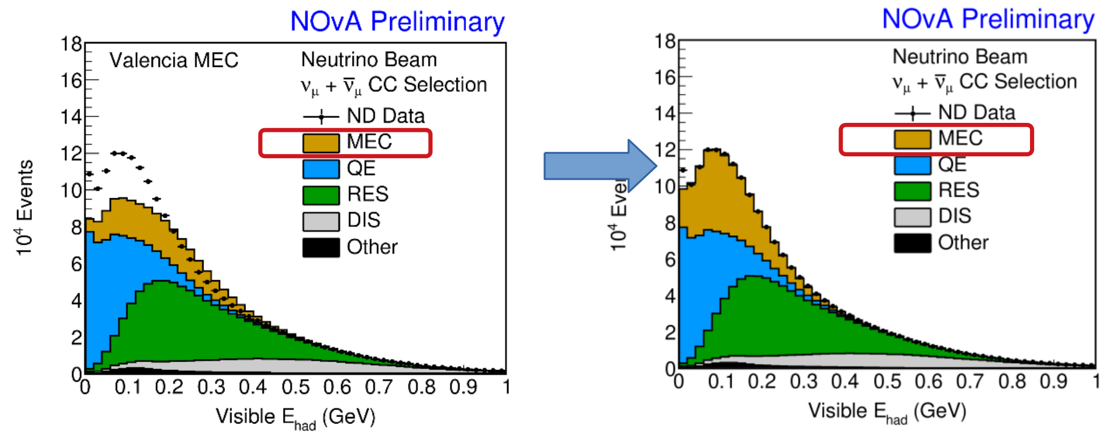
neutrons dominate in antineutrino reactions





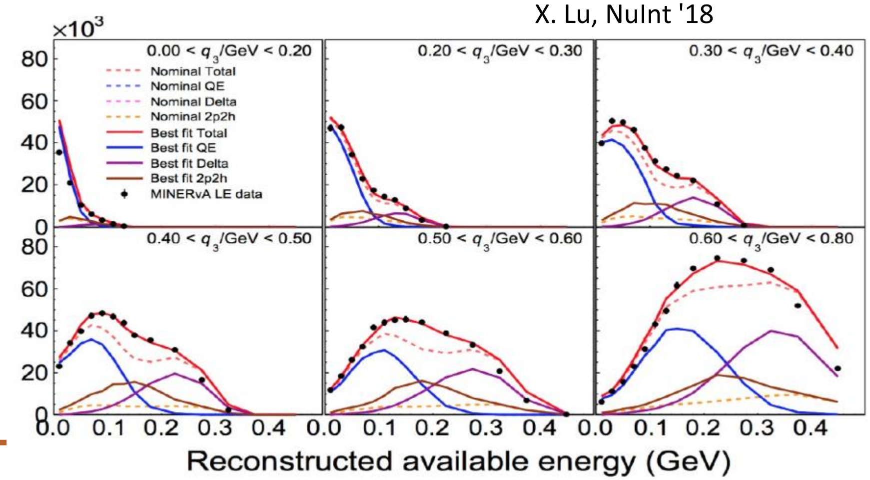
Xsec model tuning: 2p2h





Empirical prediction + uncertainties based on fits to ND data

X. Lu, NuInt '18



"2p2h"

Knock out two nucleons with an elastic-like interaction.

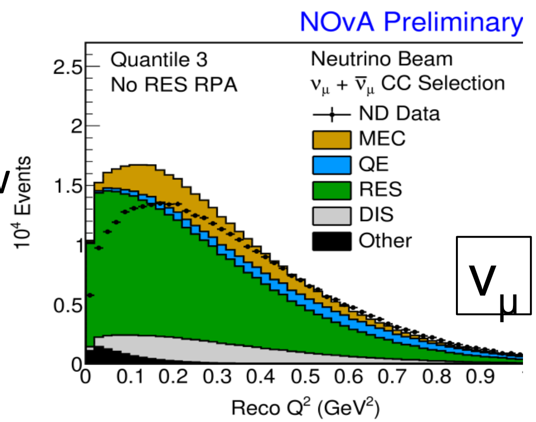
Theory is a work in progress...
employ fits based on empirical model in meantime

Xsec model tuning: pion production

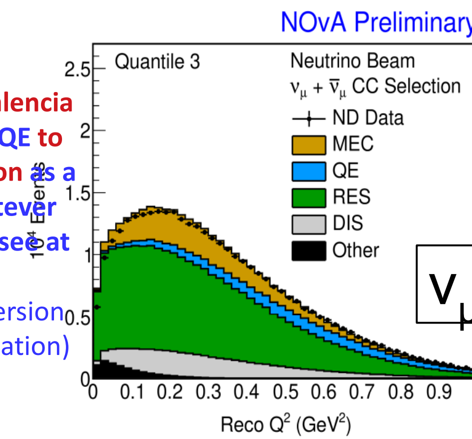
Pion production

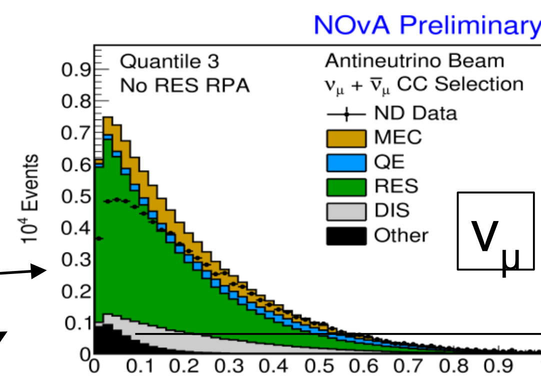
Apparent suppression at low momentum transfer (Q^2) relative to model…

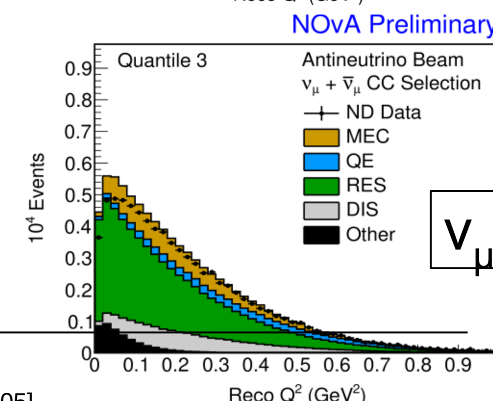
No theory to guide here.
"Adapt" *elastic* long-range correlation model ("RPA")

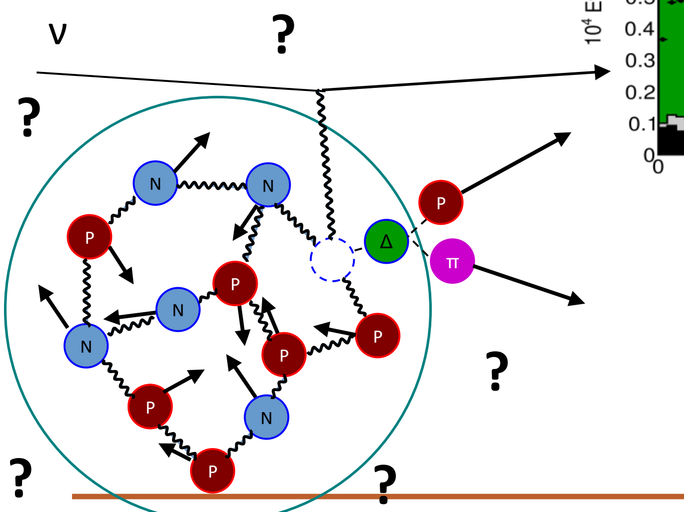


Apply Q^2-based Valencia RPA weight from QE to resonant production as a stand-in for whatever nuclear effect we see at low Q^2
(w/ unmodified version as uncertainty variation)

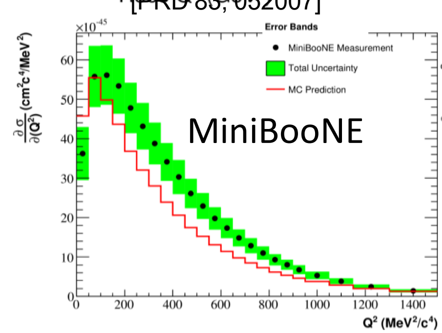




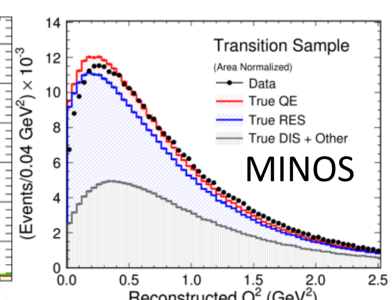




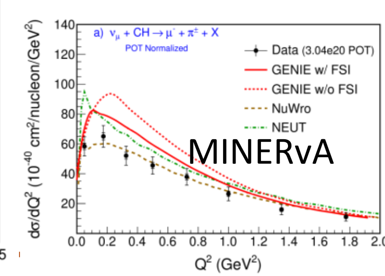
[PRD 83, 052007]



[PRD 91, 012005]



[PRD 94, 052005]



Xsec model tuning: pion production