DUNE: Science and Status

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Caltech

for the DUNE collaboration

Fermilab Joint Experimental-Theoretical Physics Seminar
August 2, 2019

Neutrino oscillations

Three neutrino flavors

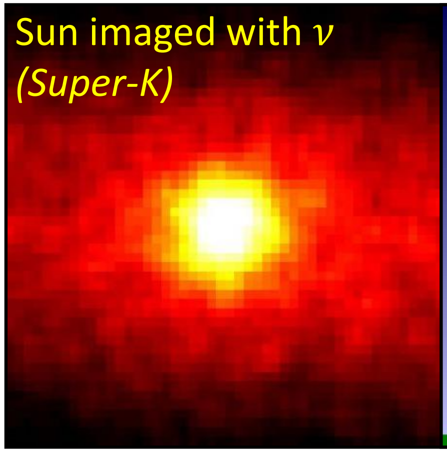
ν_e ν_μ ν_τ

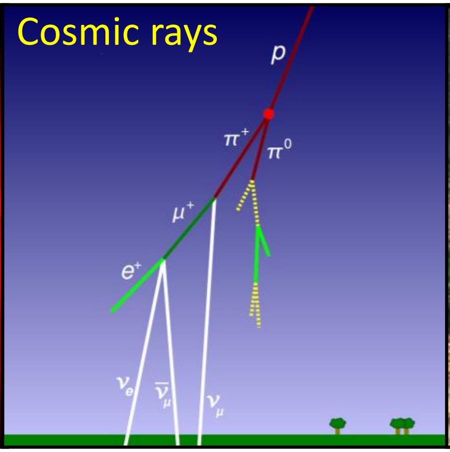
$P(\nu_\alpha \to \nu_\beta)$ depends on…

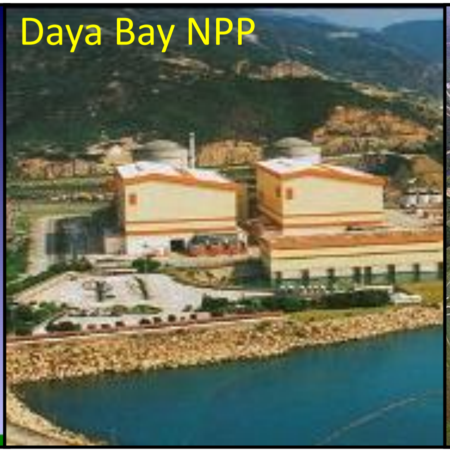
mixing matrix U_{PMNS}
mass-squared splittings Δm^2_{ij}

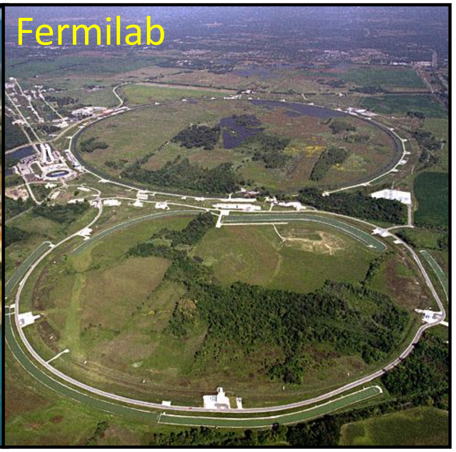
Observed using…

solar, atmospheric, reactor, and accelerator ν sources

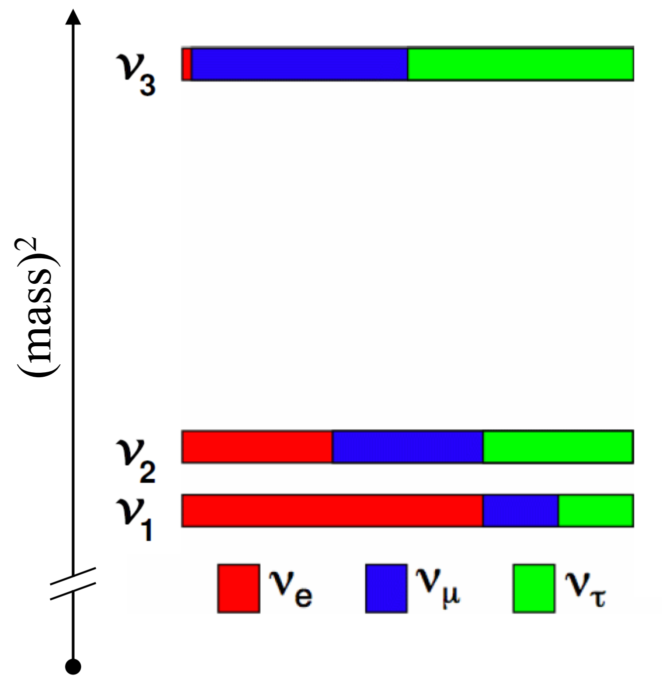


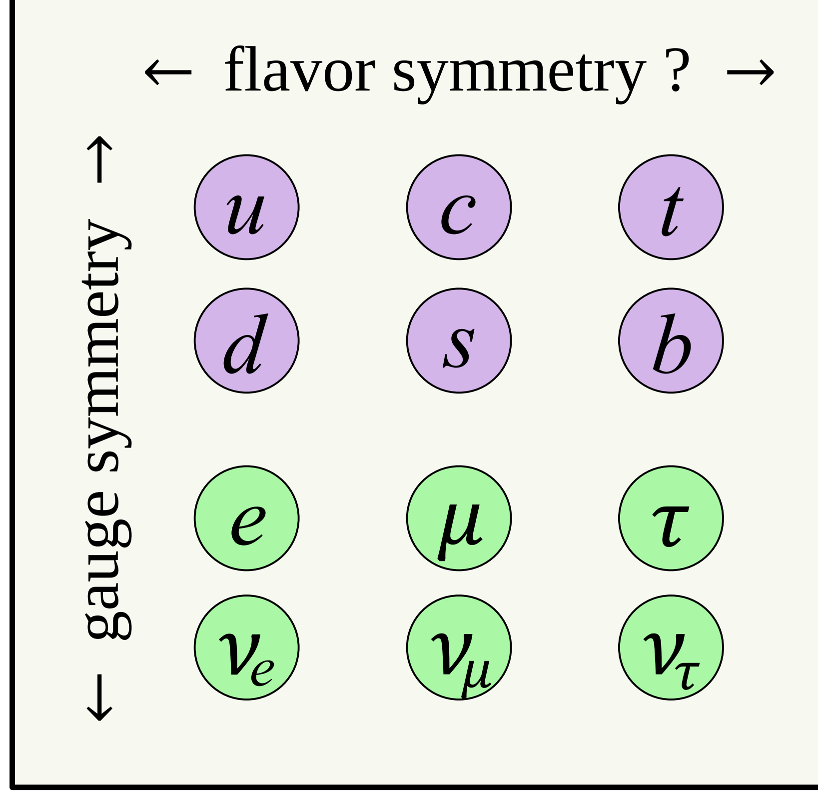




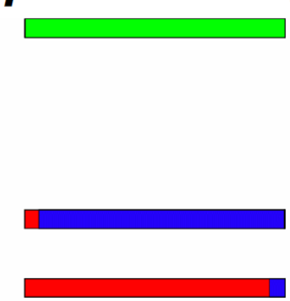


Flavor structure

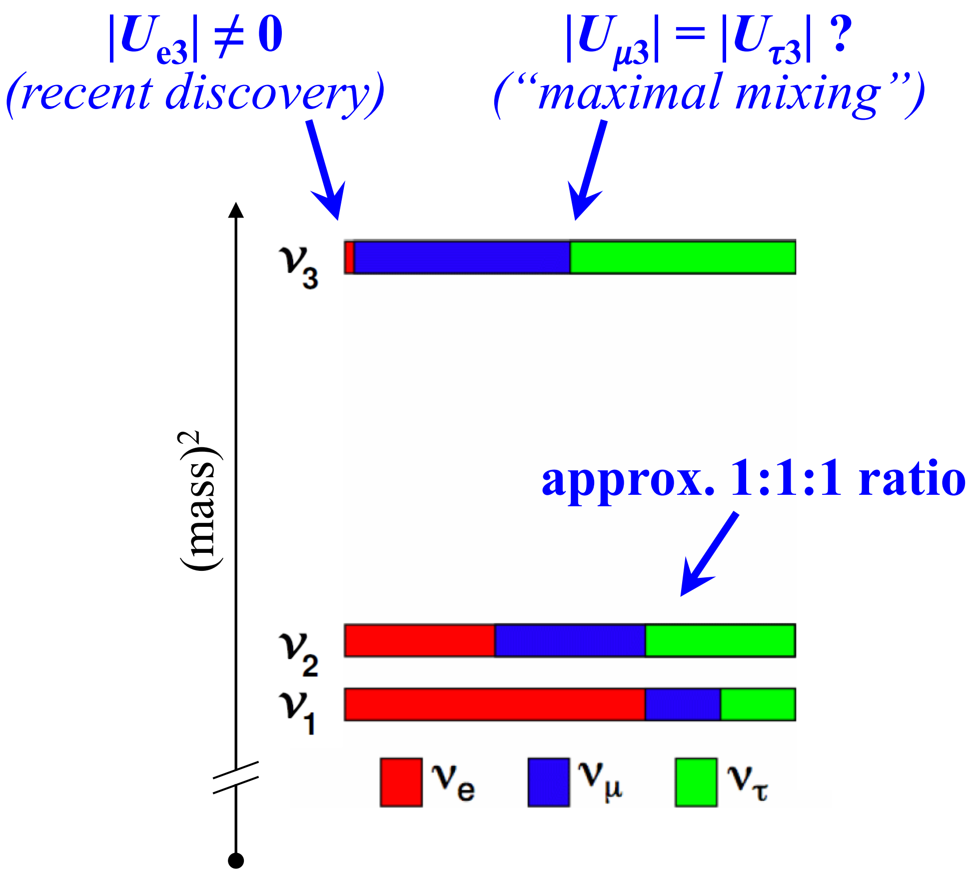


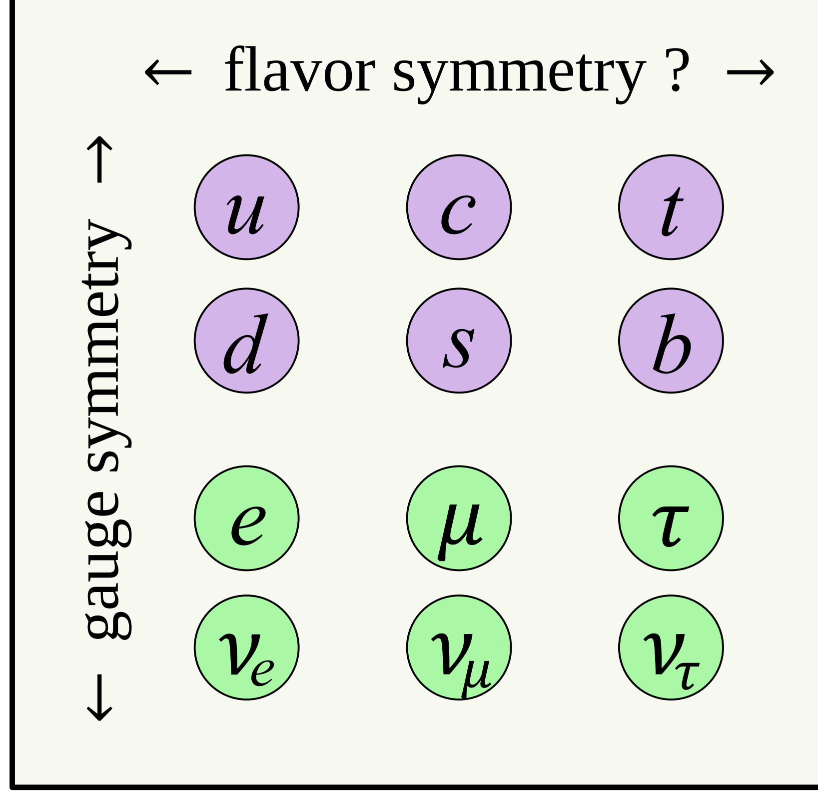


quark mixing:



Flavor structure

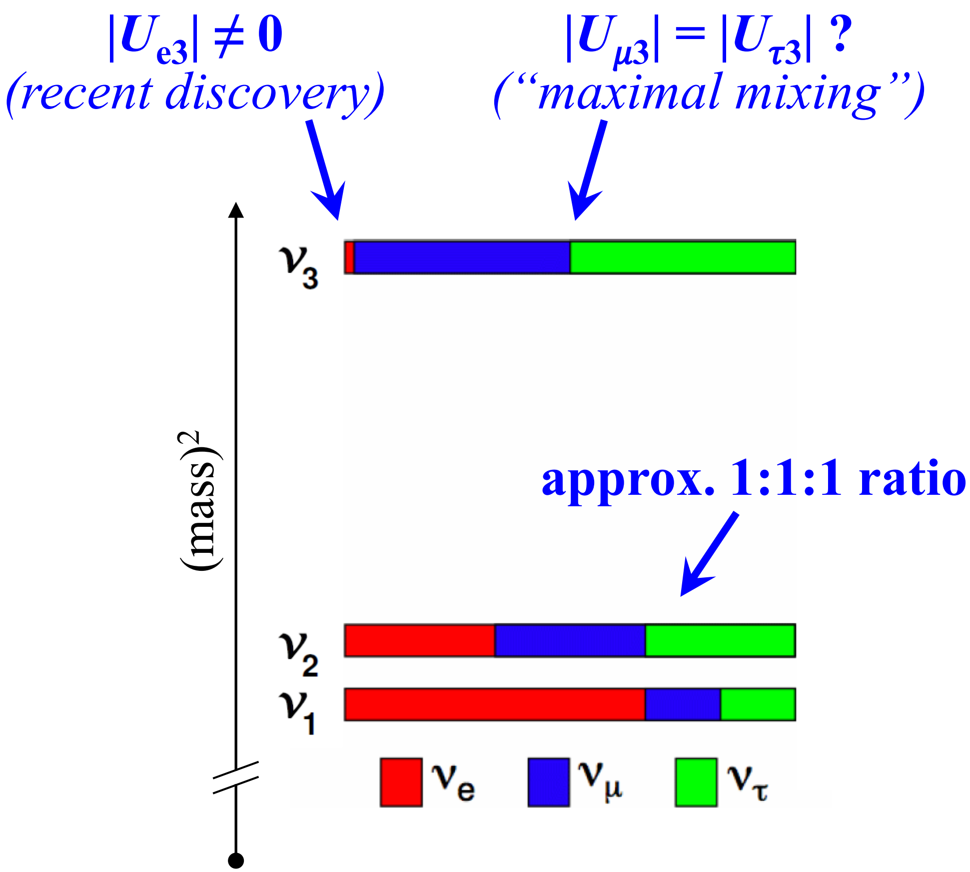




What **flavor symmetry** can produce this pattern of mixings and masses, and how is that symmetry broken?

More broadly: what are the **dynamical origins** of fermion masses, mixings, and *CP* violation?

Flavor structure



Experimental question:

★ $\sin^2\theta_{23} \neq 0.5$?

Non-maximal mixing?
If so, which way does it break?

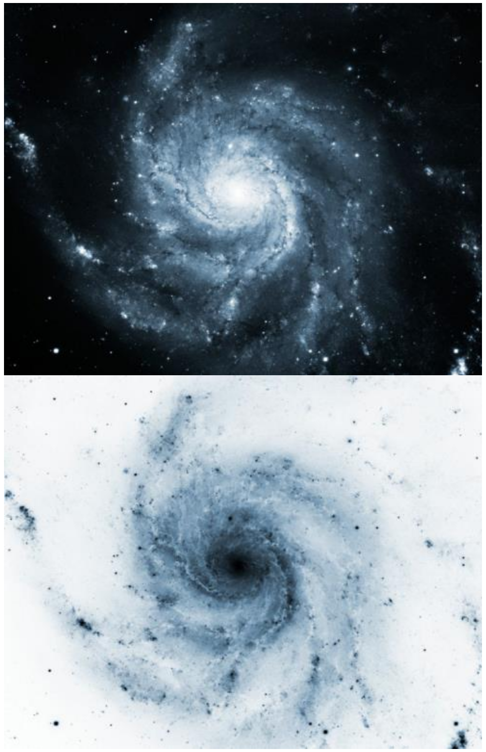
Standard parametrization of PMNS matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP violation

New source of *CP* violation required to explain baryon asymmetry of universe

part-per-billion level of matter/antimatter asymmetry in early universe



Neutrino *CP*v **allowed in νSM**, but not yet observed

…due so far to the experimental challenge, not physics!

Leptogenesis[1] is a workable solution for the baryon asymmetry, but need to first **find *any* leptonic (neutrino) *CP*v**

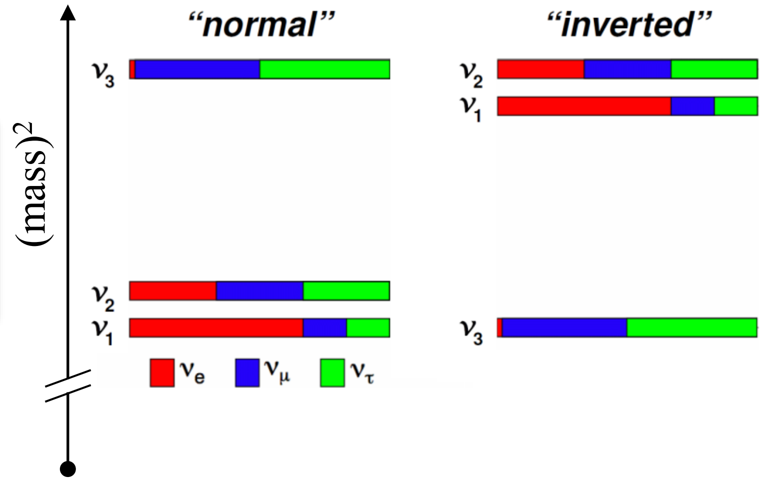
★ $\sin\delta \neq 0$?

Leptonic CP violation?

[1] M. Fukugita and T. Yanagida (1986); rich history since then.

ν mass ordering

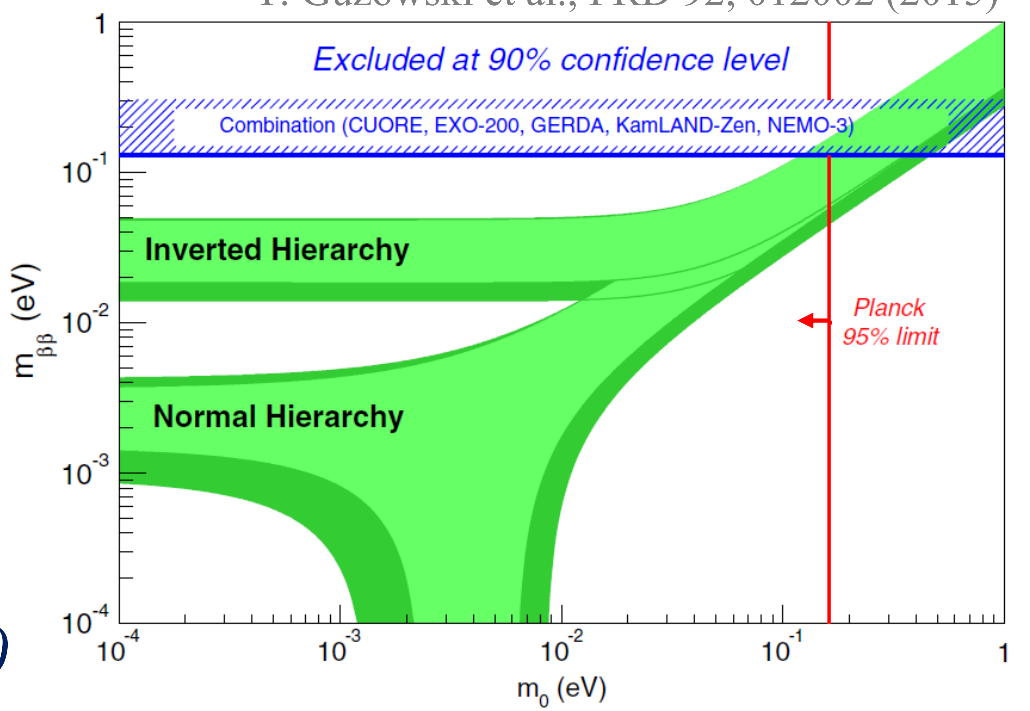
★ Are the electron-rich states ν_1 & ν_2 **heavier or lighter** than ν_3 ?



Far-reaching implications for such a simple question:

- **$0\nu\beta\beta$** and **Majorana nature of ν**
- Experimental approach to and interpretation of m_β
- **Cosmology** and **astrophysics**
- **Theoretical frameworks** for flavor and mass generation

P. Guzowski et al., PRD 92, 012002 (2015)



Notice:

An inverted ordering implies **<1.5% mass degeneracy**.

→ *Would hint at…??* *(cf.: π^+/π^0)*

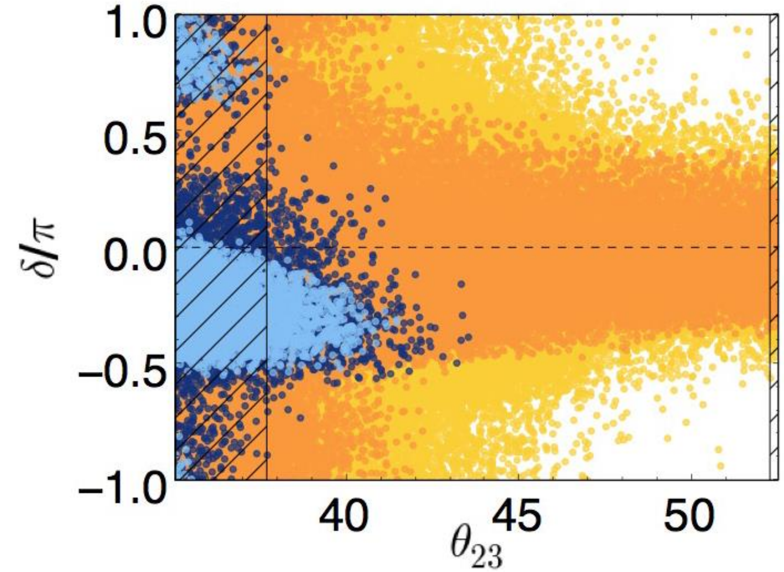
Flavor: A core problem for 21st century particle physics

Flurry of theoretical work.

Emphasis on genuine predictive power.
Explicit connections between low energy observables and leptogenesis.

Often **immutable preferences** for **mass ordering** and $\boldsymbol{\mu/\tau}$ **asymmetry**

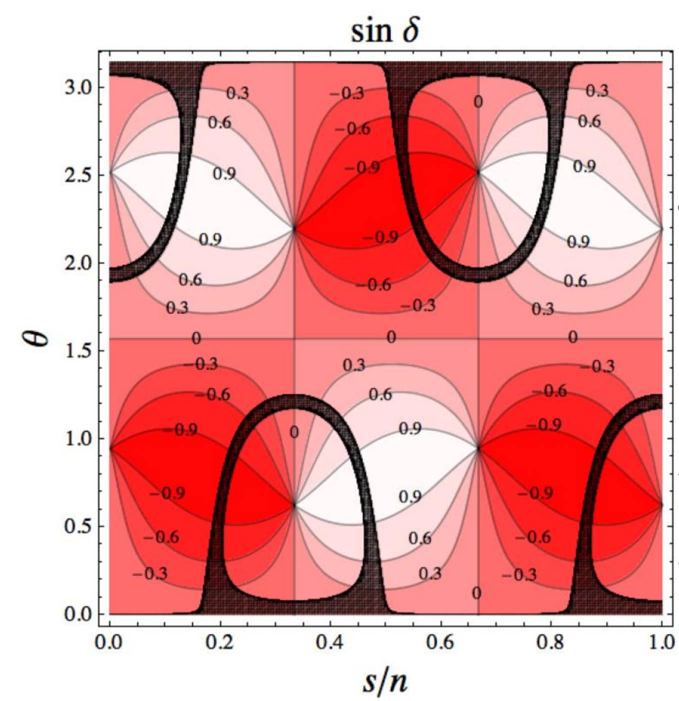
★ **Need precision PMNS measurements**



Di Bari, Marzola, Re Fiorentin
Nucl. Phys. B **893**, 122 (2015)

tan β	Output			
5	θ^q_{12}	13.027°	θ^l_{12}	34.3°
	θ^q_{13}	0.1802°	θ^l_{13}	8.67°
	θ^q_{23}	2.054°	θ^l_{23}	45.8°
	δ^q	69.18°	δ^l	-86.7°
	y_u	2.92×10^{-6}	Δm^2_{21}	7.38×10^{-5} eV^2
	y_c	1.43×10^{-3}	Δm^2_{31}	2.48×10^{-3} eV^2
	y_t	5.34×10^{-1}		
	y_d	4.30×10^{-6}	y_e	1.97×10^{-6}
	y_s	9.51×10^{-5}	y_μ	4.16×10^{-4}
	y_b	7.05×10^{-3}	y_τ	7.05×10^{-3}

Björkeroth, de Anda,
de Medeiros Varzielas, King
JHEP **06**, 141 (2015)



Hagedorn, Meroni, Molinaro
Nucl. Phys. B **891**, 499 (2015)

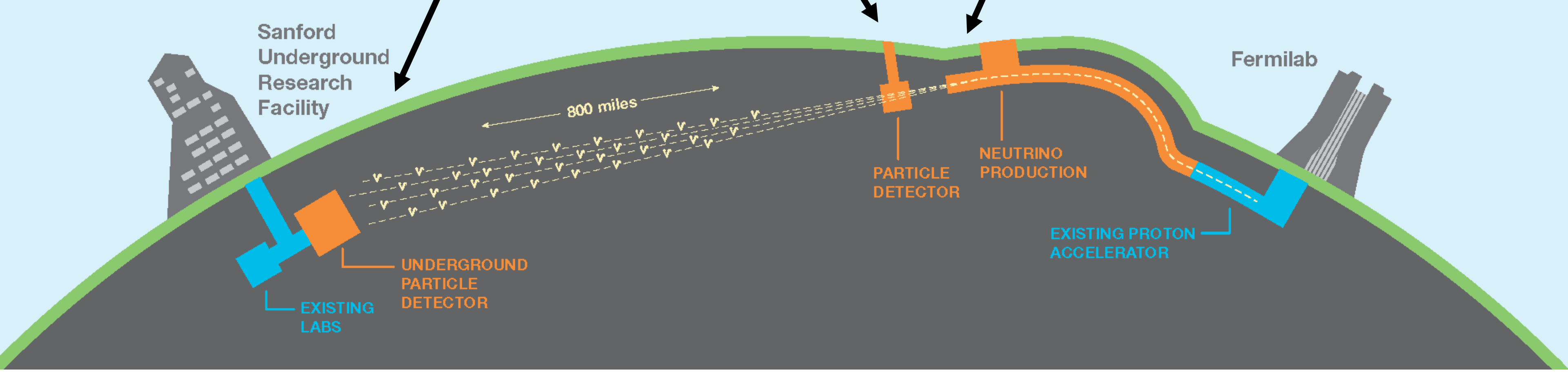
DEEP UNDERGROUND NEUTRINO EXPERIMENT

A next generation experiment for **neutrino science, supernova physics,** and **physics beyond the Standard Model**

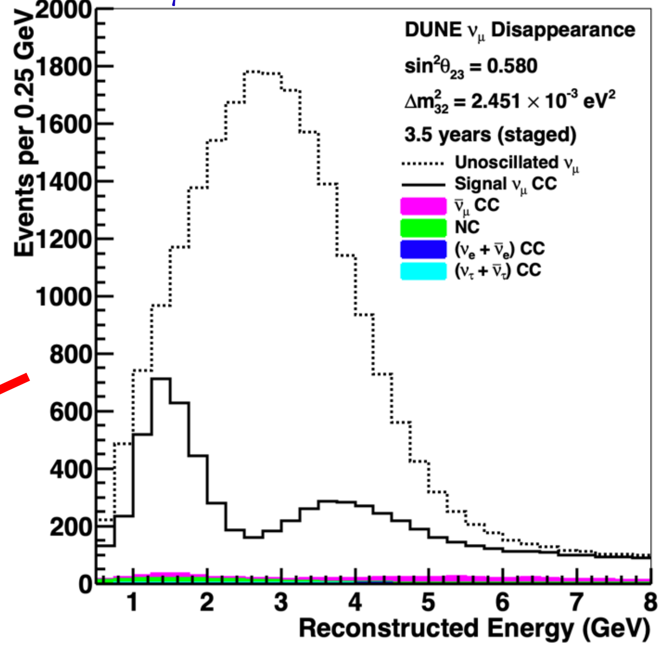
Far Detector
(measure oscillated flux)

Near Detector
(essential systematics control)

Initial beam: ν_μ or $\bar{\nu}_\mu$
(selectable)



ν_μ "disappearance"

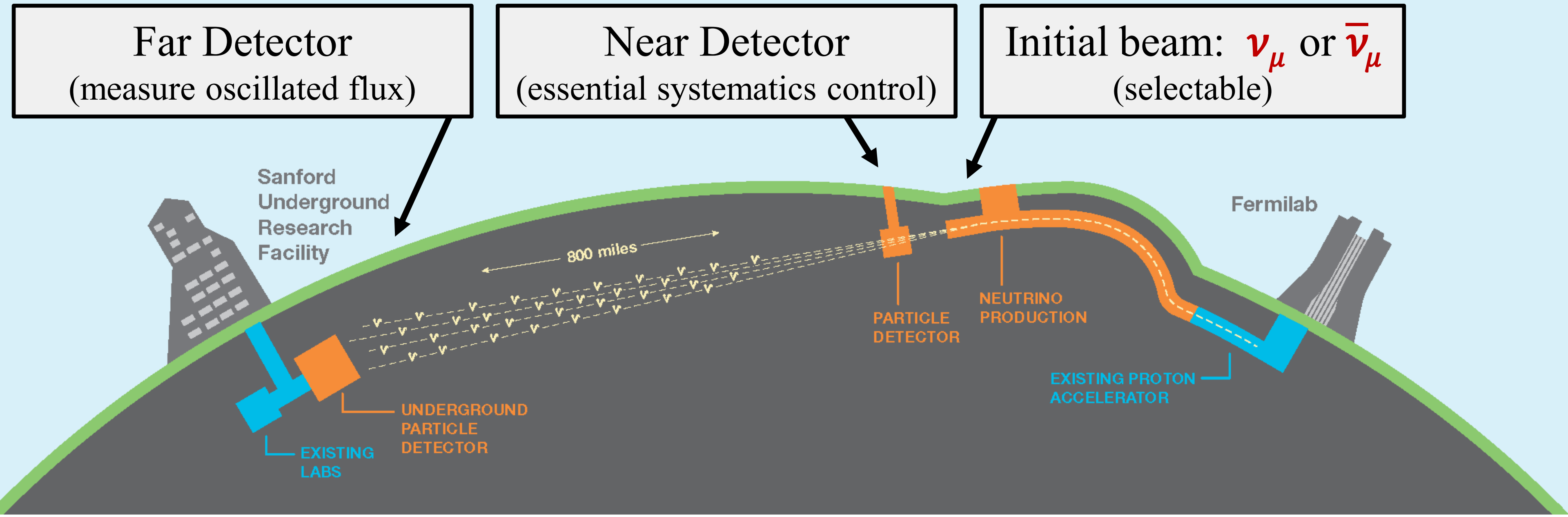


Measure **rate** and **energy spectrum** of

ν_μ and ν_e

$\bar{\nu}_\mu$ and $\bar{\nu}_e$

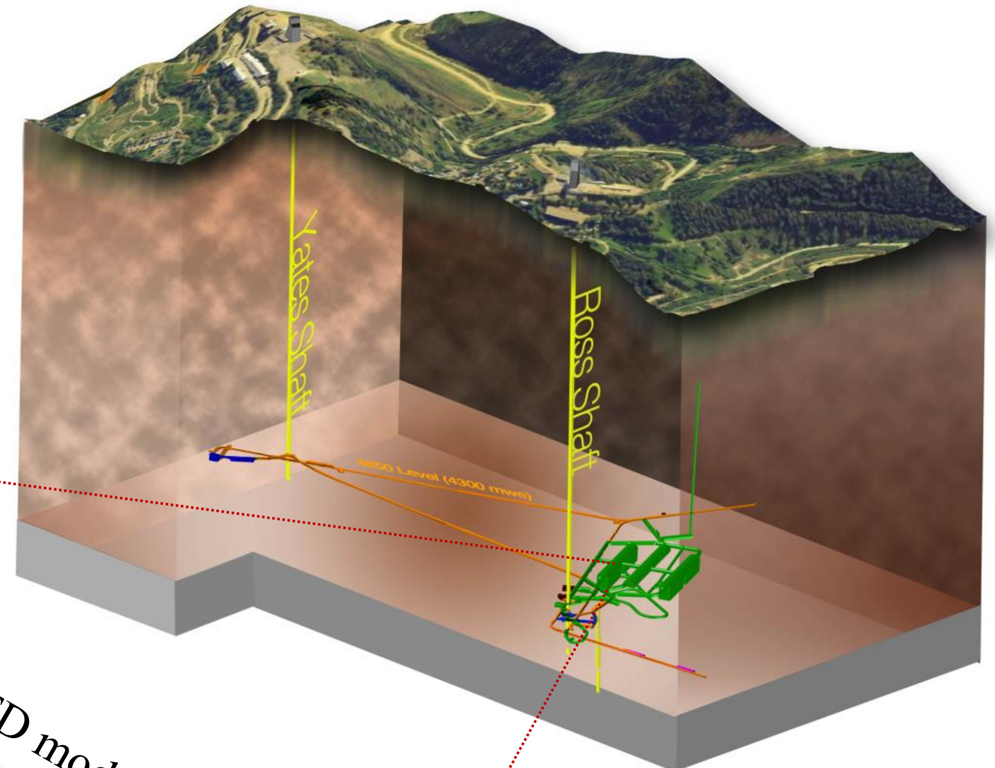
at **Far Detector**



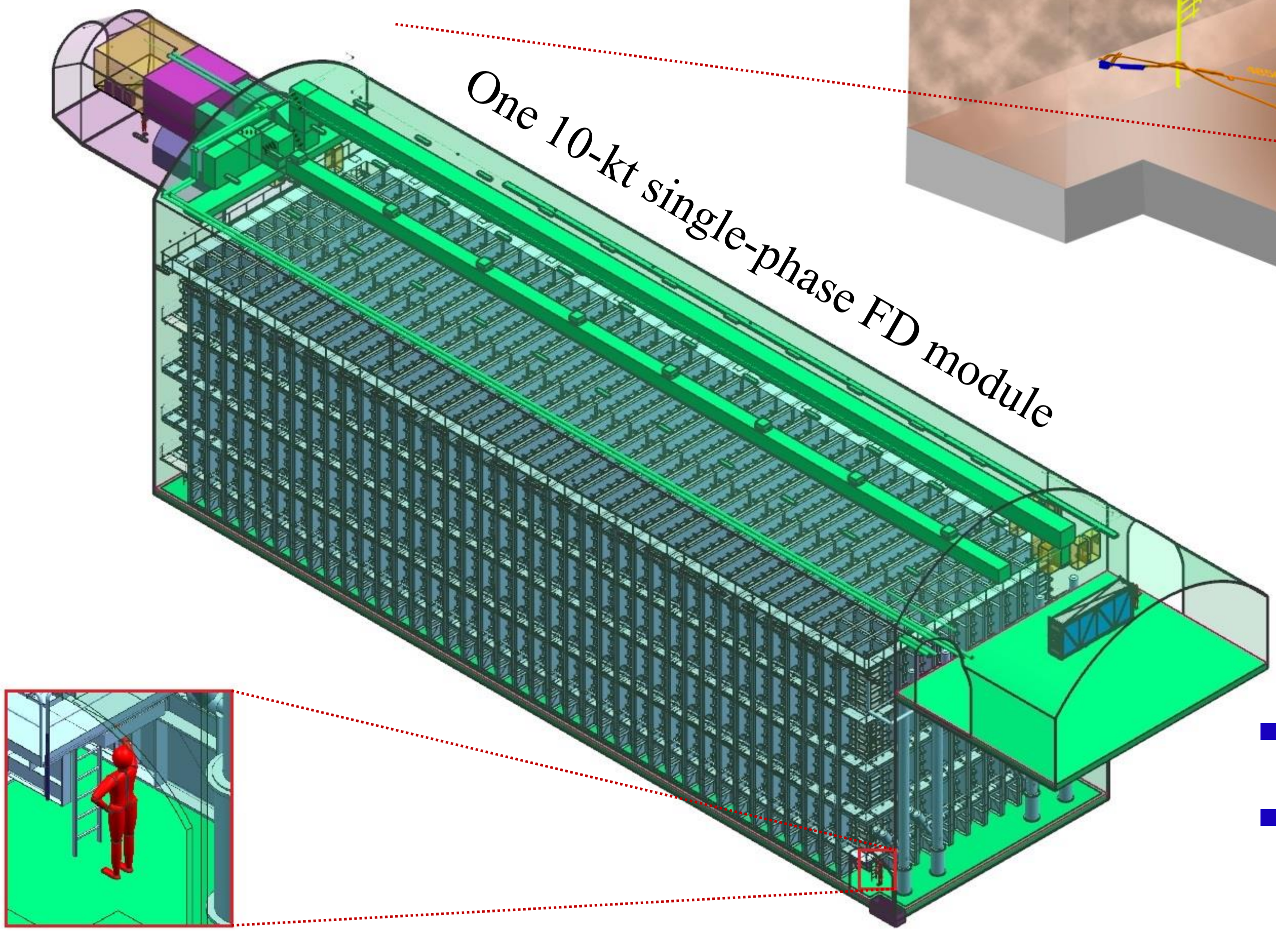
Far Detector

40-kt (fiducial) liquid argon time projection chambers

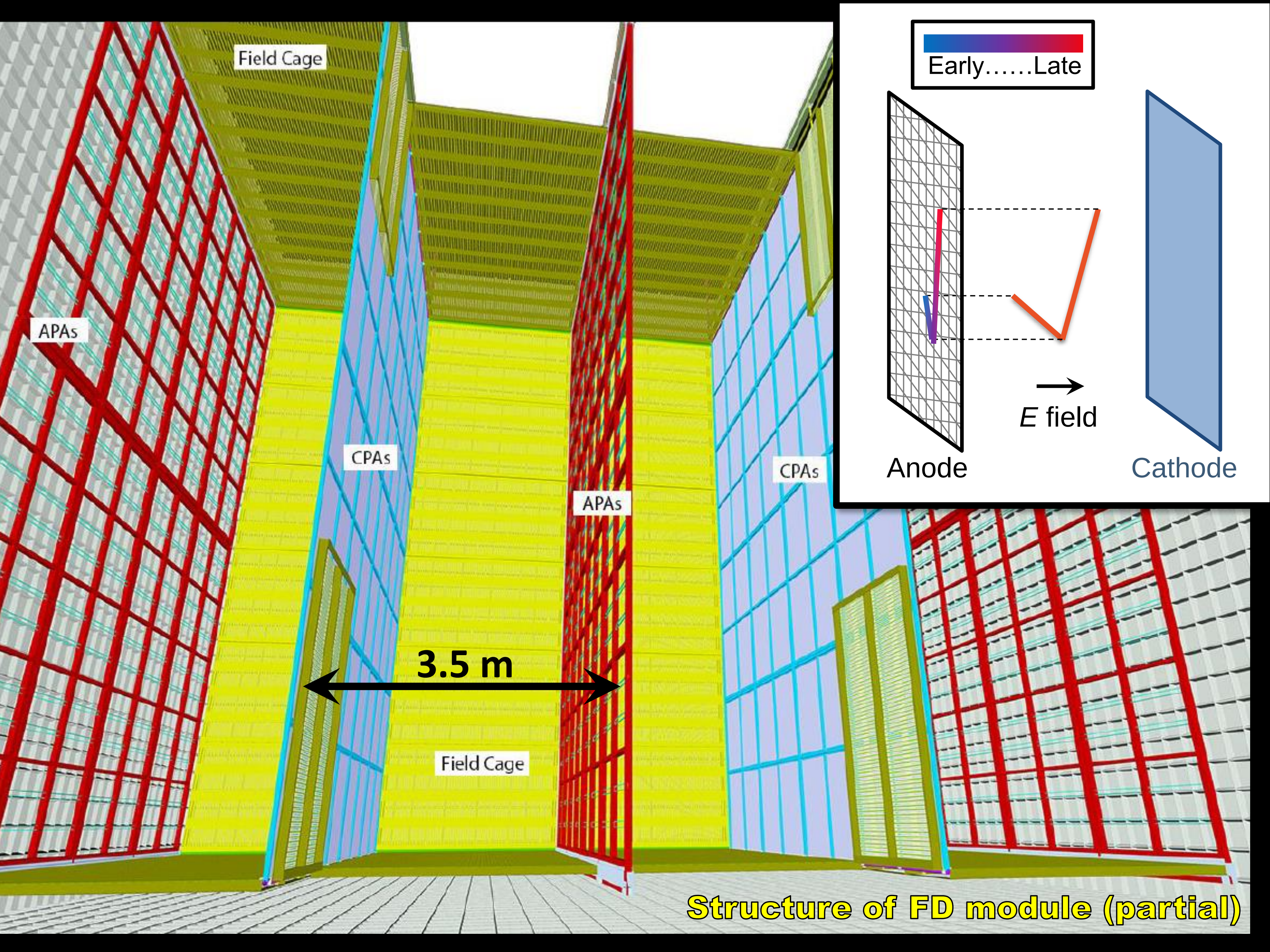
- Installed as four 10-kt modules

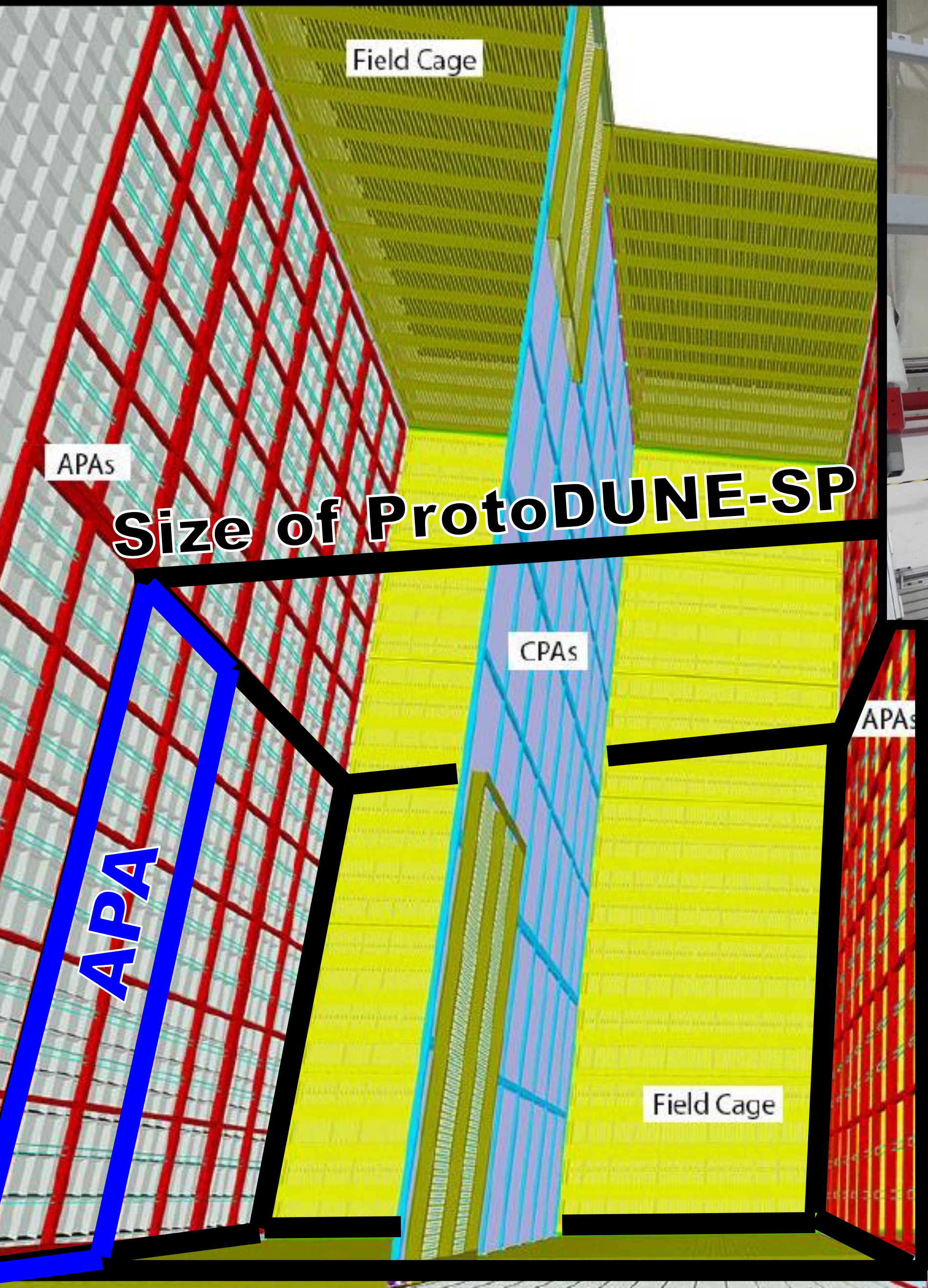


Sanford Underground Research Facility (SURF)

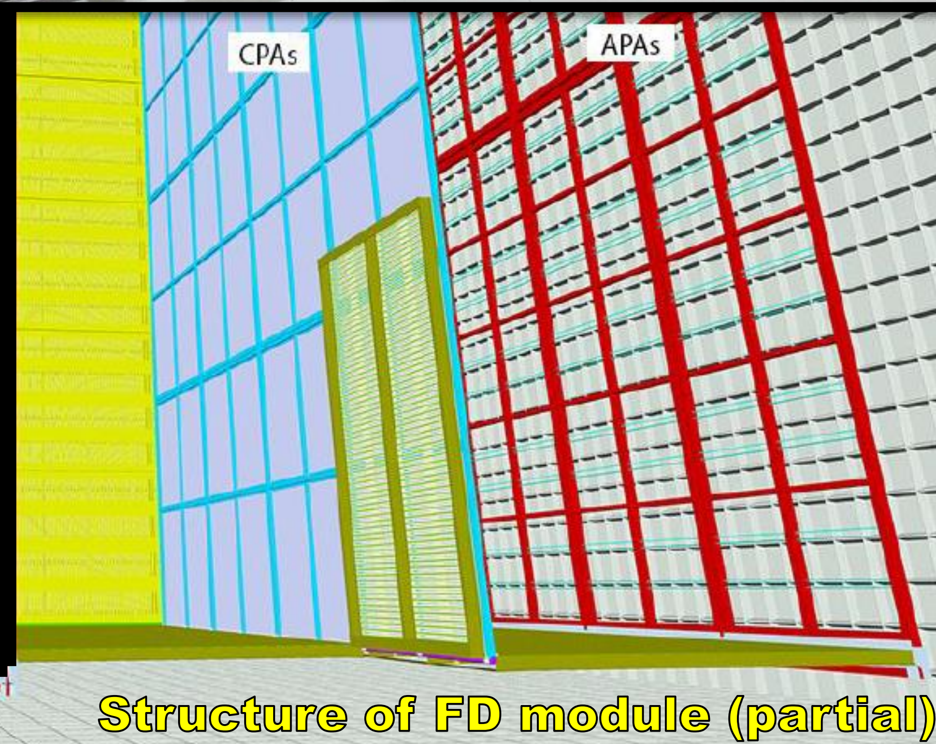


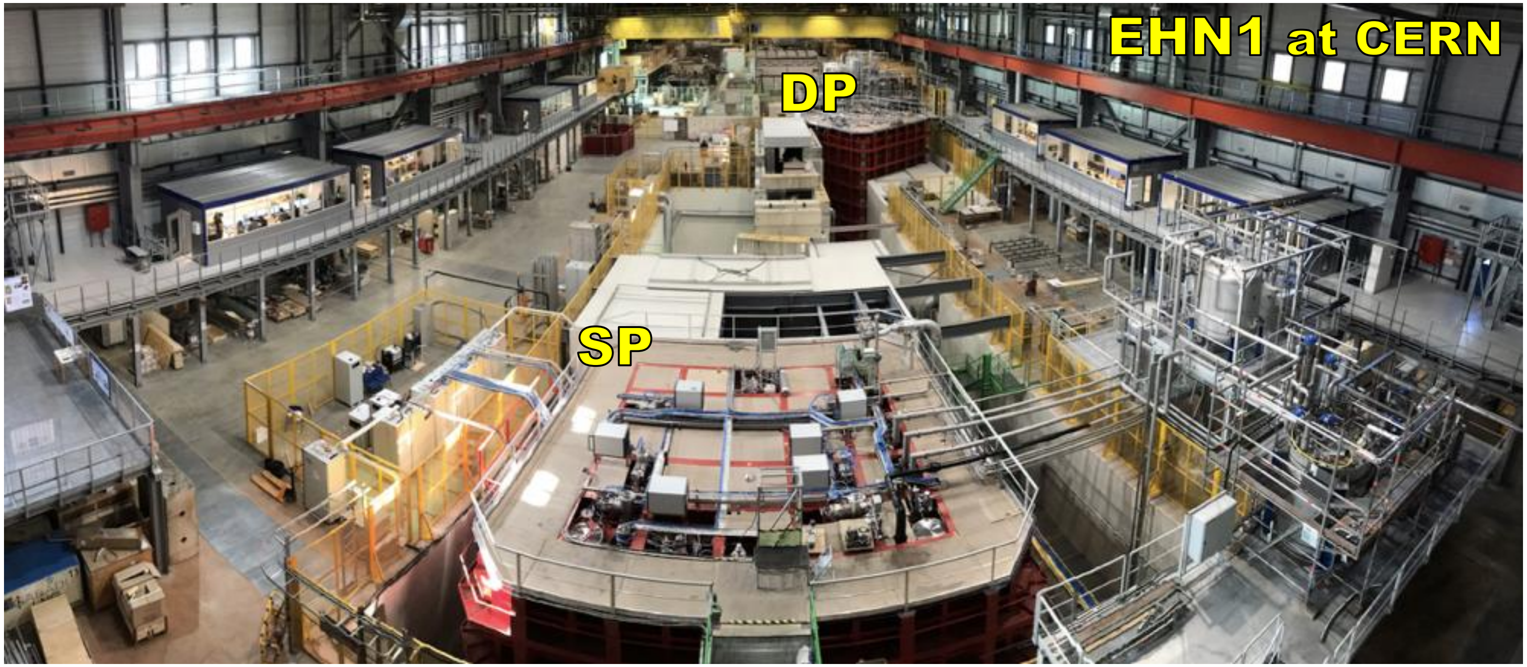
- **4850' level at SURF**
- First module will be a **single phase LAr TPC**


Field Cage
APAs
CPAs
APAs
CPAs
3.5 m
Field Cage
Early……Late
Anode
E field
Cathode
Structure of FD module (partial)

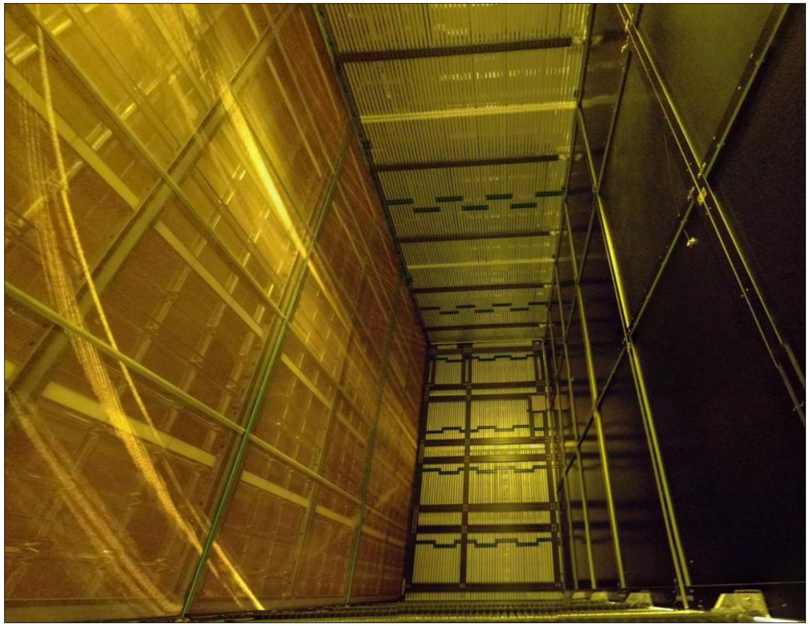

Field Cage
APAs
Size of ProtoDUNE-SP
APA
CPAs
APAs
Field Cage


One Anode Plane Assembly (APA)


CPAs
APAs
Structure of FD module (partial)



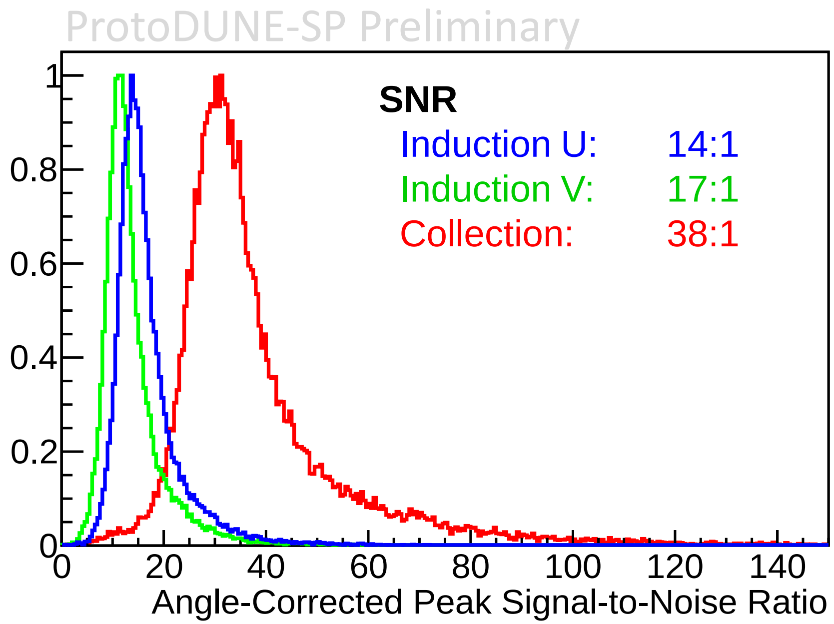
Inside ProtoDUNE-SP

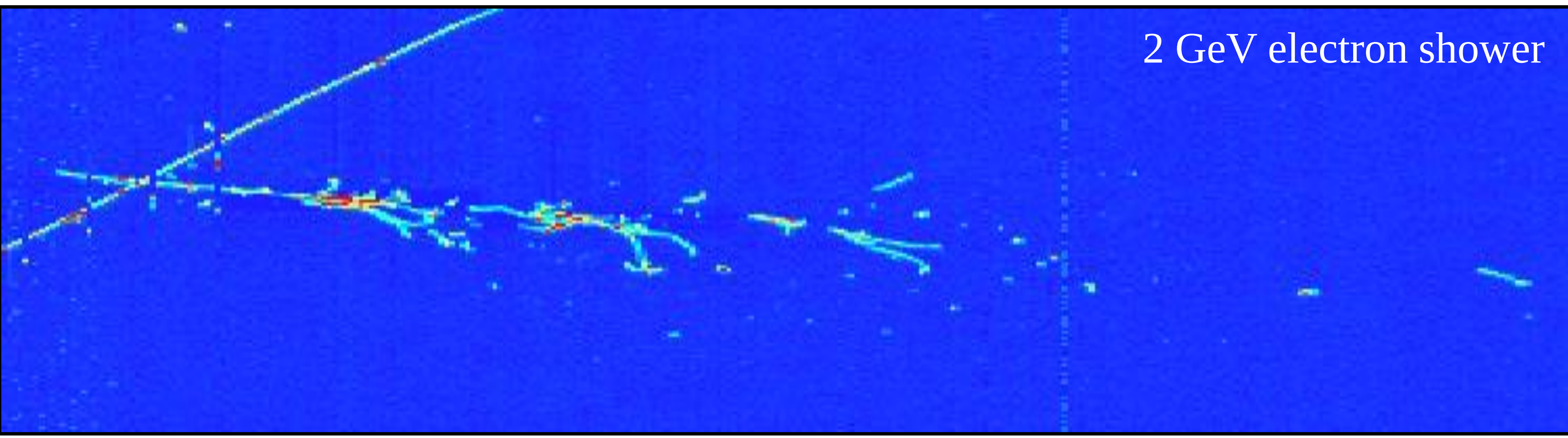


Argon filling of ProtoDUNE-DP (underway now!)

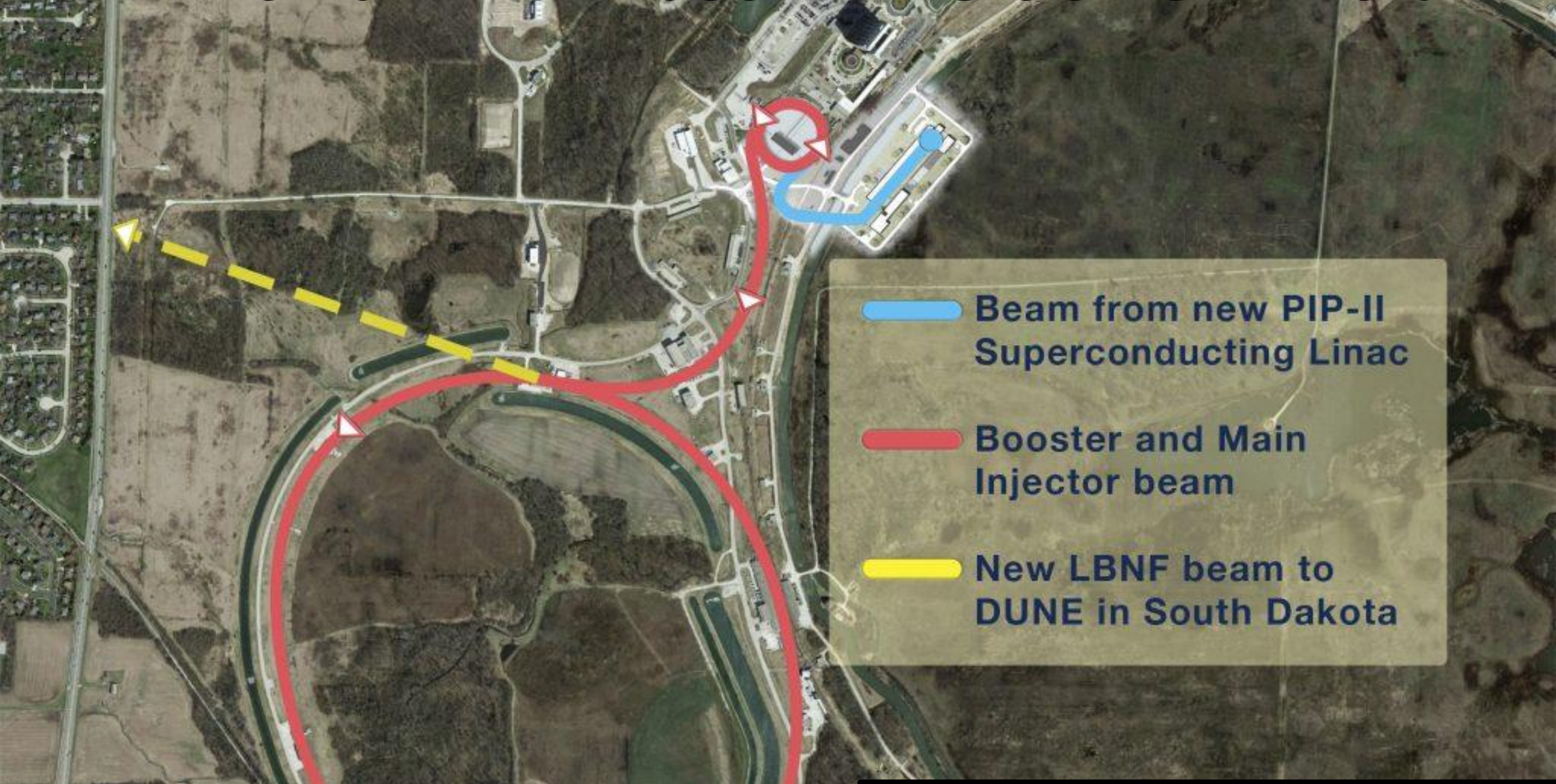
Performance

- **Stable operation at design voltage**
  → 180 kV
- **Excellent LAr purity**
  >5 ms e^- lifetime. Req: >3 ms.
- **Excellent signal-to-noise** →
- **Excellent light yield and linearity** in photon detector systems
- **0.5 – 7 GeV/*c*** beam data collected last Fall (e, π, p, K)





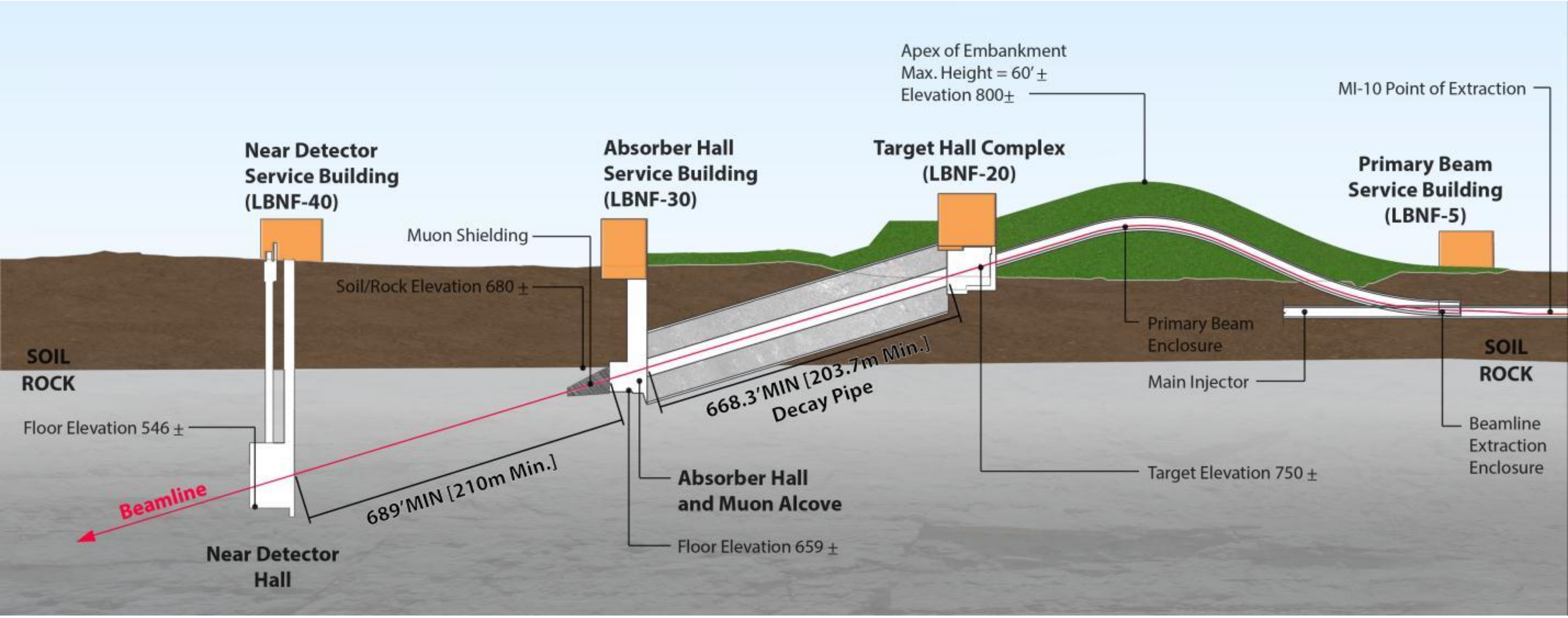
PIP-II and LBNF beamline at Fermilab



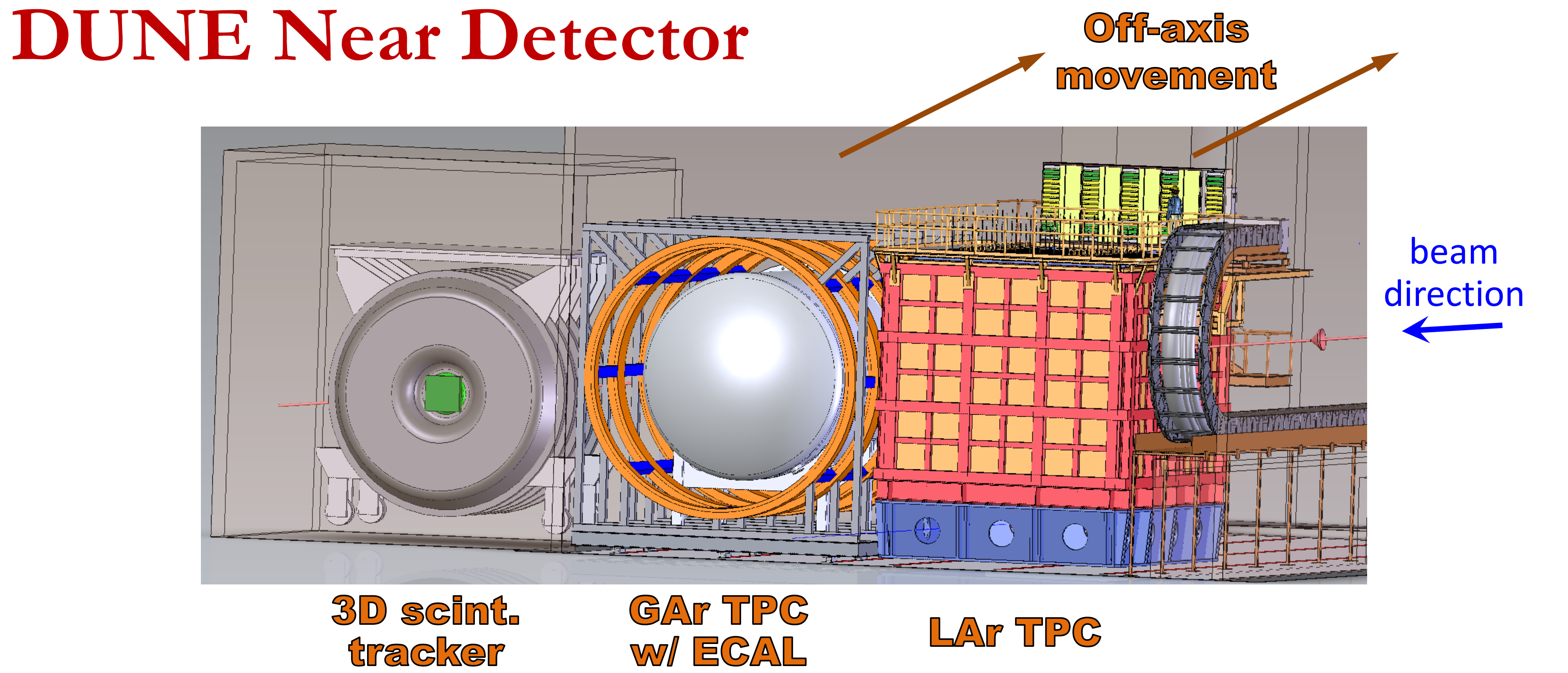
PIP-II groundbreaking: March 15, 2019

Long Baseline Neutrino Facility (LBNF)

- DOE/Fermilab hosted project with international participation
- **Horn-focused beamline** similar to NuMI beamline
  - 60 – 120 GeV protons from Fermilab's Main Injector
  - 200 m decay pipe at -5.8° pitch, angled at South Dakota (SURF)
  - Initial power 1.2 MW, upgradable to 2.4 MW



DUNE Near Detector



Coherent design that draws from experience of current and past long-baseline oscillation experiments

LAr TPC: Matches basic **FD technology**. Core ν-Ar (and ν-e) samples.

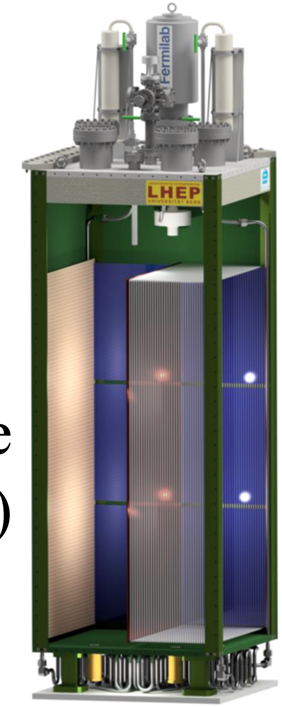
GAr TPC w/ ECAL: Magnetized. ν-Ar events with **low-threshold tracking, 4π acceptance**. Provides spectrometry for muons exiting LAr.

DUNE-PRISM: Off-axis movement of Ar detectors to **vary incident neutrino spectrum.**

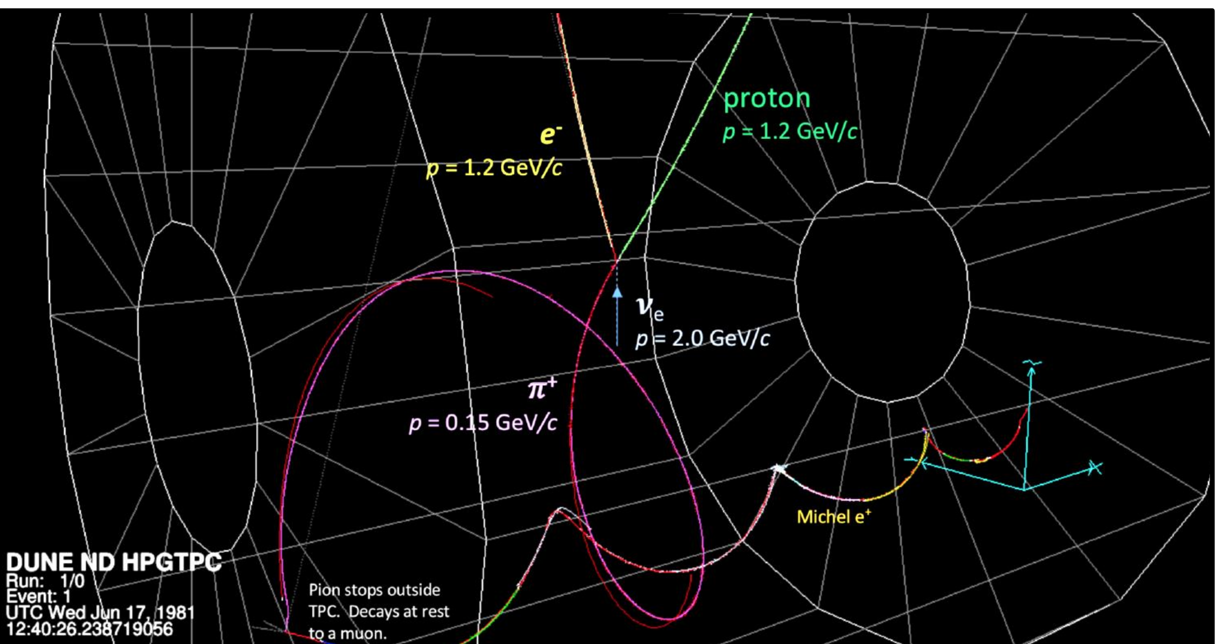
3DST: **Fast beam monitoring** in fixed on-axis position.

ArgonCube (LAr TPC)
2-by-2 demonstrator

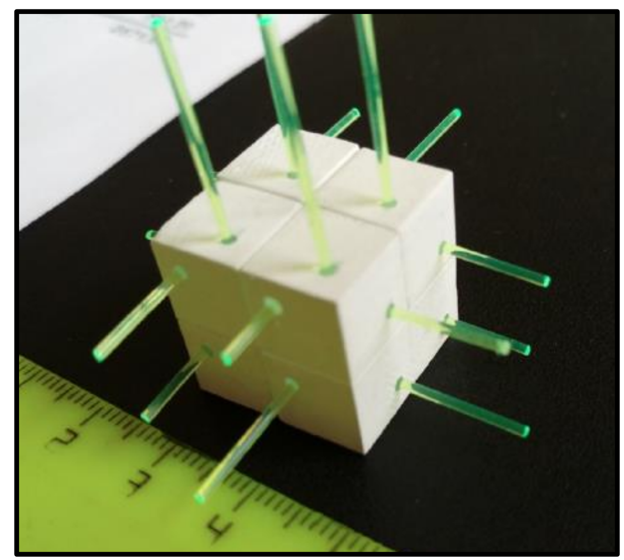
An ArgonCube module
(0.7 m × 0.7 × 1.8 m)



Simulated GAr TPC event with reconstruction

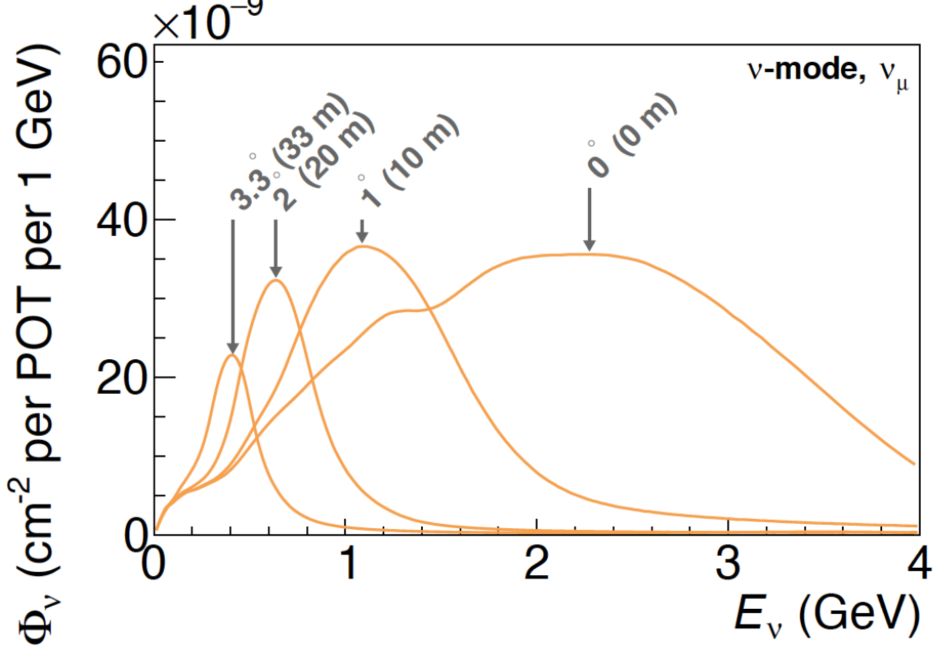


3DST detector elements

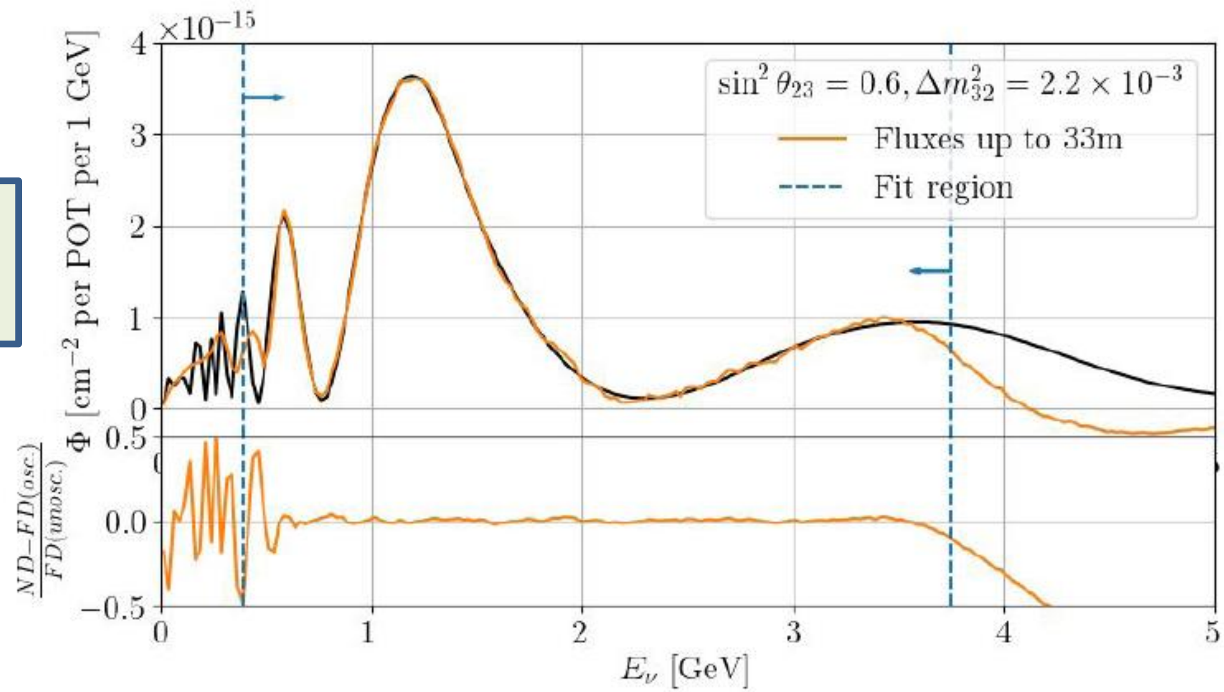


DUNE-PRISM

- **Vary the incident neutrino spectrum** by moving off-axis
- Break cross section model degeneracies
- Linearly combine off-axis samples to craft **"arbitrary" neutrino spectra**
  - *- narrow Gaussian spectra*
  - *- FD-like oscillated spectra*



Unprecedented reduction in XS model dependence



Updated Sensitivity Analysis

In the **DUNE Technical Design Report:**

Major overhaul of all of DUNE's physics sensitivity calculations.

Showing key results today.

Key event types

ν_μ CC

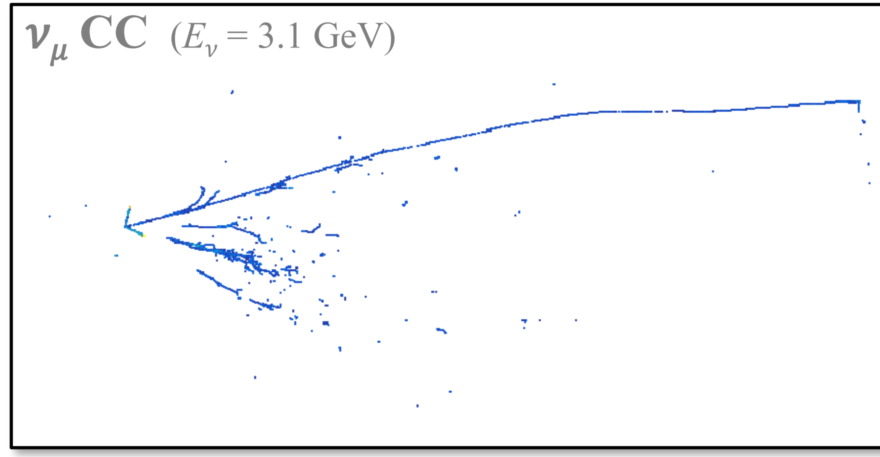
tags: long muon track,
decay electron at end

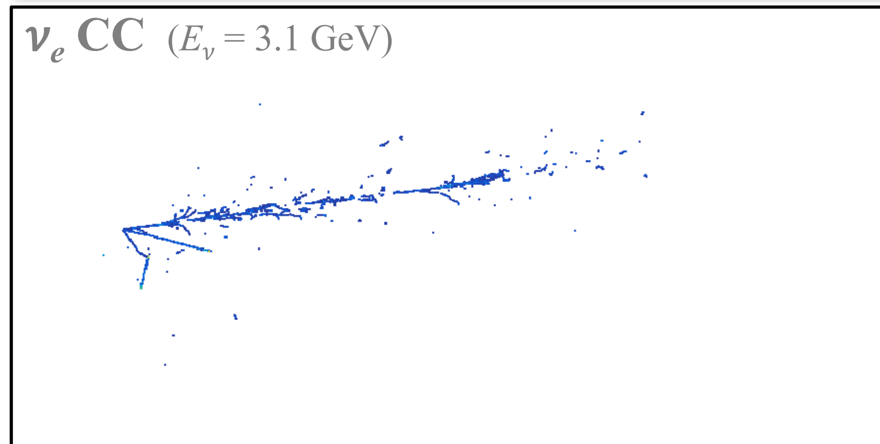
ν_e CC

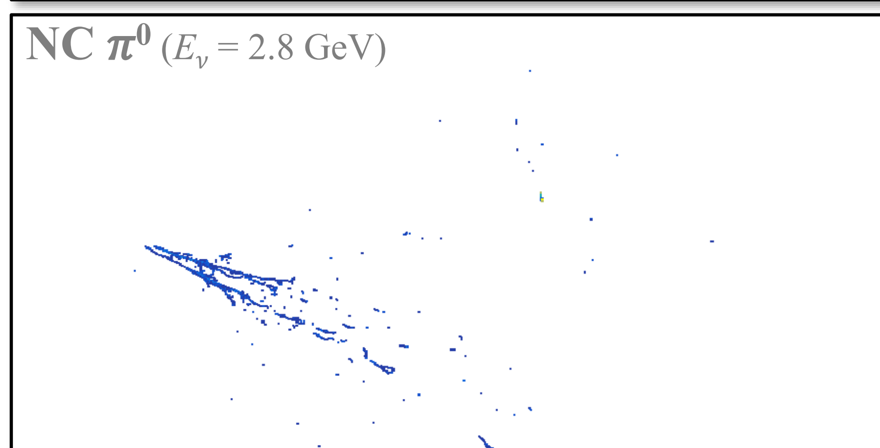
tags: primary electron
(EM shower)

ν NC (with π^0) → *background!*

tags: multiple EM showers,
photon conversion gaps,
dE/dx at shower start

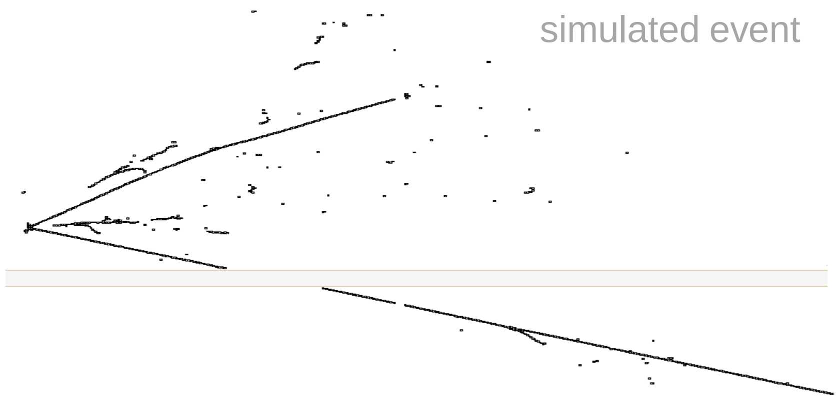






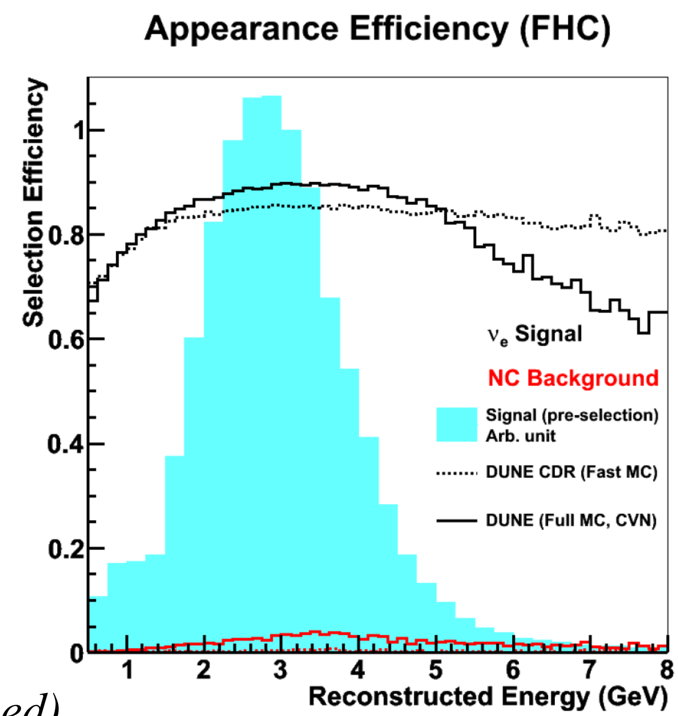
simulations

FD event samples



Fully automated FD simulation, reconstruction, and event selection

- Detailed **G4 LBNF flux predictions**
- **G4 detector sim + electronics response**:
  - *Draws fruitfully from other LAr experiments via LArSoft framework*
  - *ProtoDUNE data → validation!*

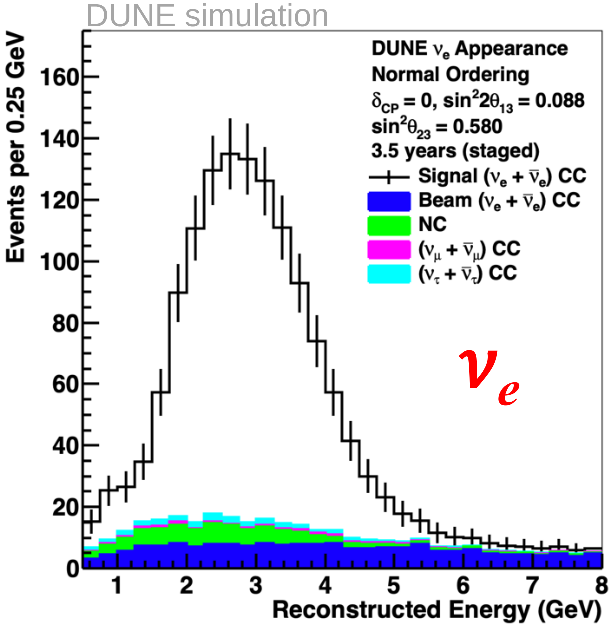


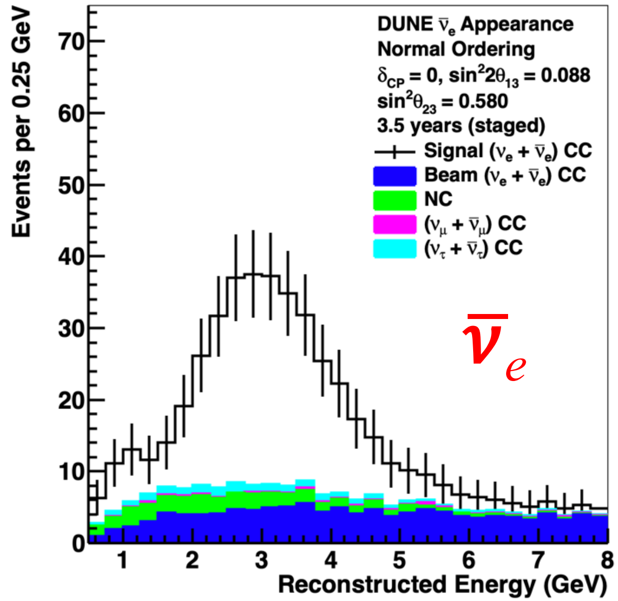
Event selection / reconstruction

- **Convolutional neural network selection**
  - *Based initially on NOvA's "CVN" selection*
- **Energy reconstruction:**
  Muons by range *(or multiple Coulomb scattering)*
  Electrons *and* ***hadronic showers by calorimetry***

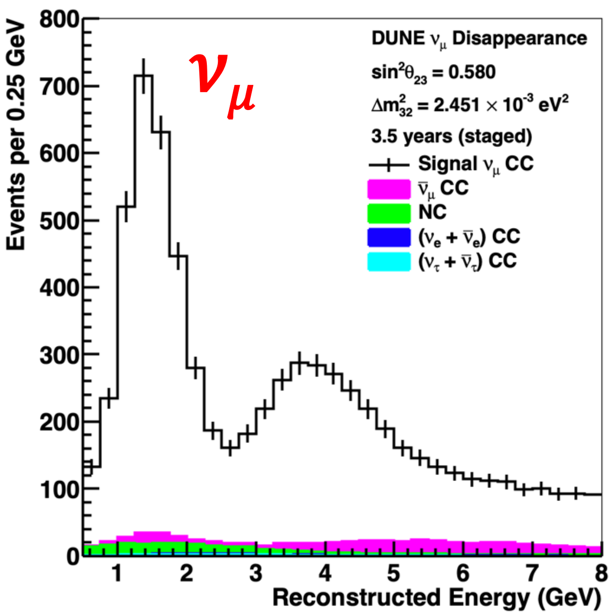
Avg. resolutions ν_e **CC**: 13%
ν_μ **CC**: 18% *(20% if μ uncontained)*

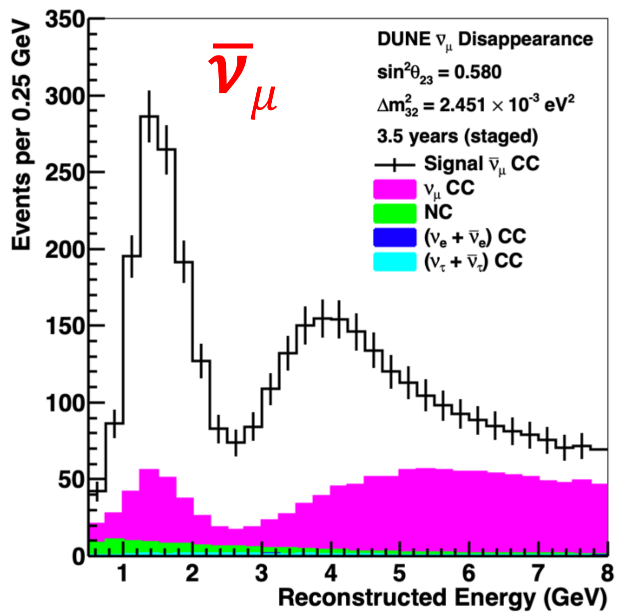
Selected FD samples at 7 years





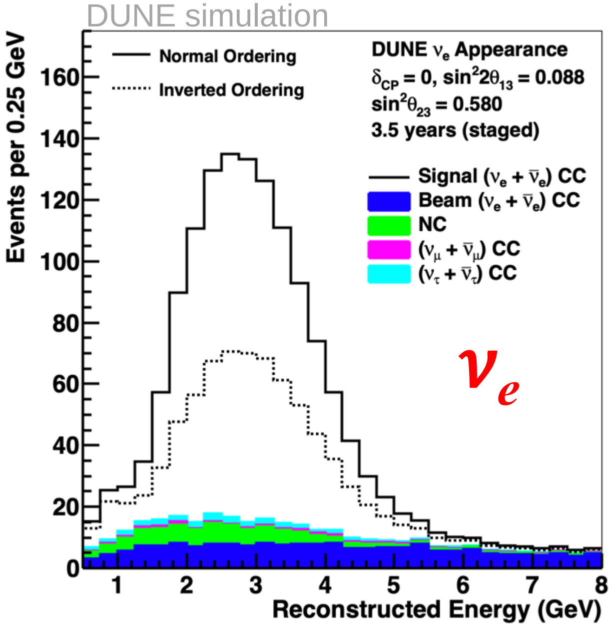
~1,000 $\nu_e / \bar{\nu}_e$ appearance events in 7 years!

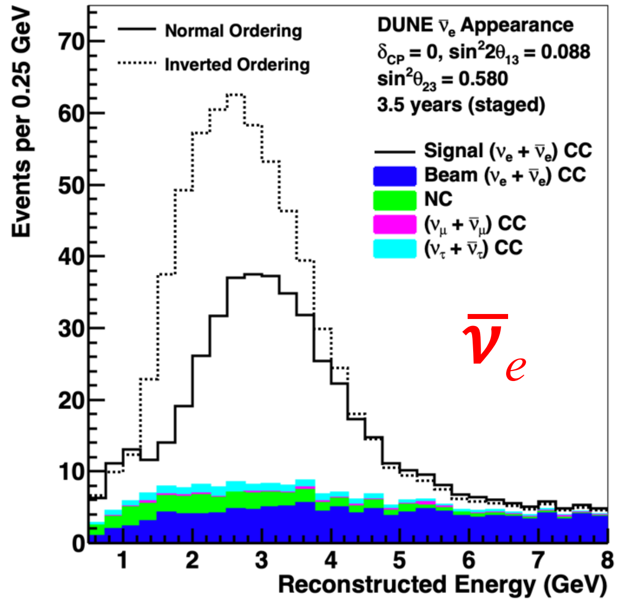




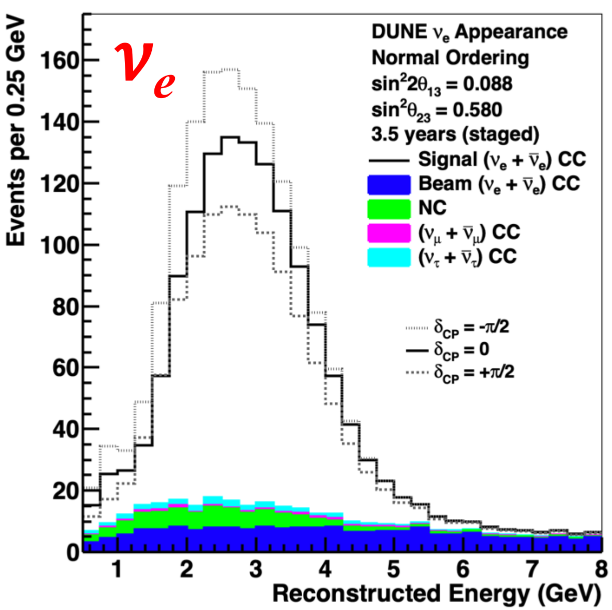
~10,000 $\nu_\mu / \bar{\nu}_\mu$ events

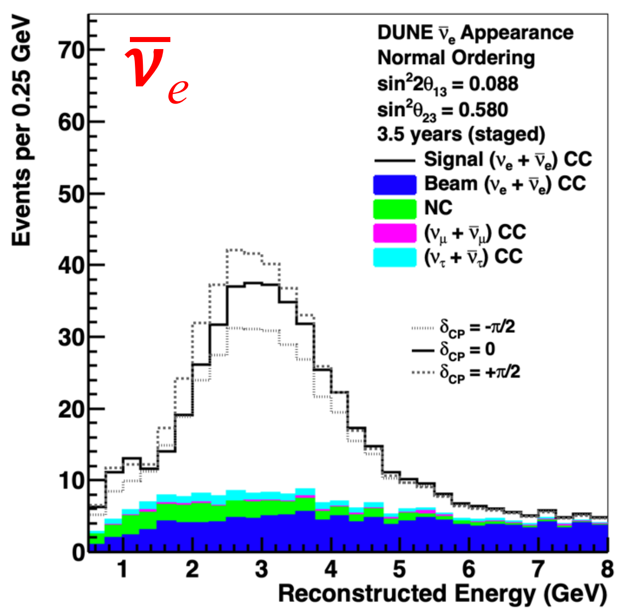
Selected FD samples at 7 years





variation with **mass ordering**





variation with $\boldsymbol{\delta_{CP}}$

Sensitivity calculations

- **Simultaneous ND+FD fitting framework**

  Framework ported from NOvA ("CAFAna") and extended for DUNE case

- G4 simulation of **LAr ND events** with parametrized reconstruction included in the fit

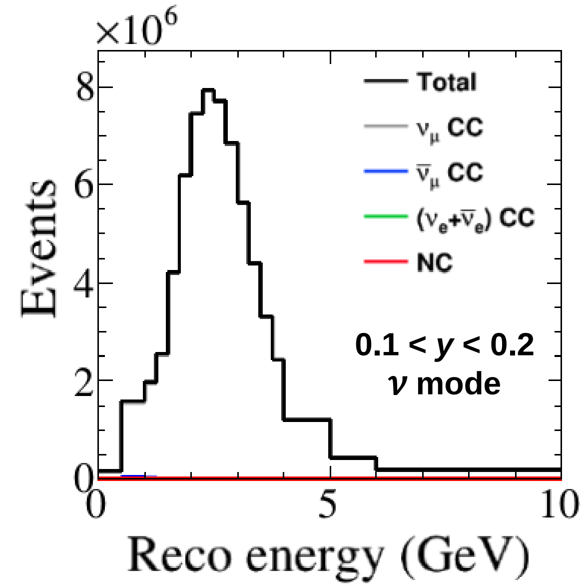
  ND samples binned in $E_{\nu,\mathrm{rec}}$ and y_{rec}

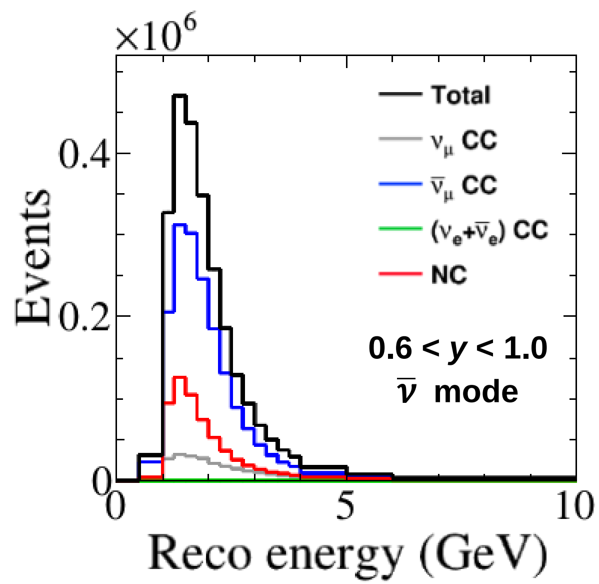
- **Exposure and staging assumptions**
  - Technically limited schedule:

    1.2 MW × 20 kton at start
    1.2 MW × 30 kton after 1 yr
    1.2 MW × 40 kton after 3 yr
    2.4 MW × 40 kton after 6 yr

  - Equal $\nu / \bar{\nu}$ running
  - 56% operations up-time

Example ND LAr samples (7 yr)





Systematic uncertainties

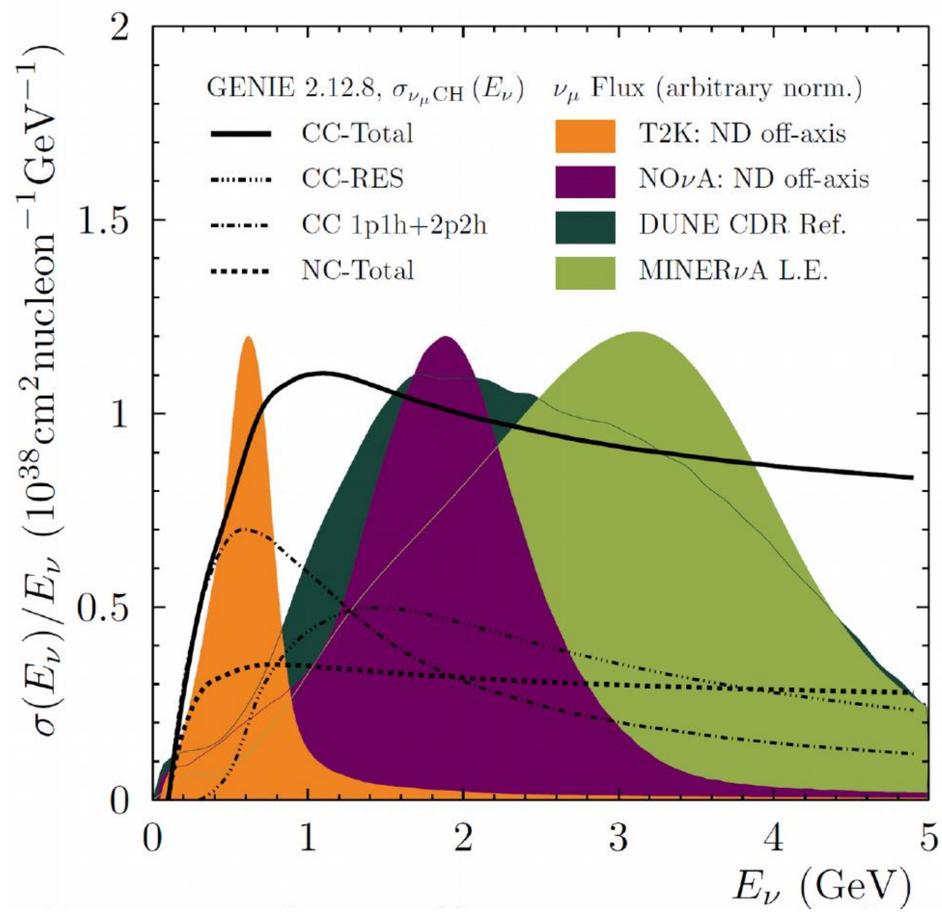
Neutrino interactions

- Extensive suite of **GENIE** model variations (GENIE 2.12.10 with Valencia 2p2h)
- **Heavily augmented** with additional model freedom

  - Theoretical and experimental considerations, including **T2K, NOvA, MINERvA data**

  - **Additions relate to:**

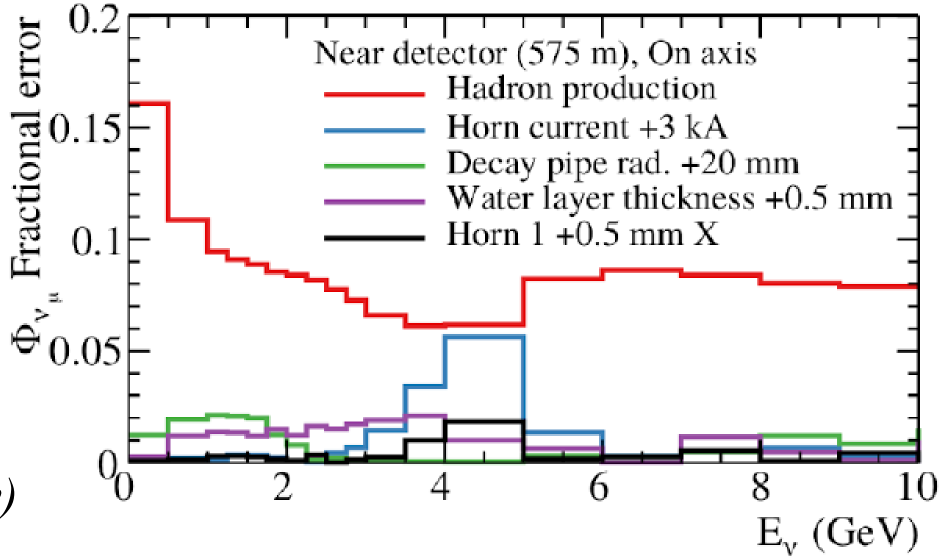
    QE Q^2 dependence
    2p2h strength and E dependence
    Ar/C scaling
    pion multiplicities by channel
    $\nu_e/\nu_\mu/\bar{\nu}_e$ differences
    resonance modeling
    and more



Systematic uncertainties

Neutrino flux

- Uncertainties from **beam transport** and **hadroproduction**
- σ_Φ: 8% at oscillation maximum
  1 – 2% in Near/Far ratio
  (with significant correlations across energy)



Detector response

- **Acceptance** and **energy response** uncertainties
- Post-calibration expectations plus experience from operating experiments.
- *Not yet taking advantage of ND/FD correlations in fits*

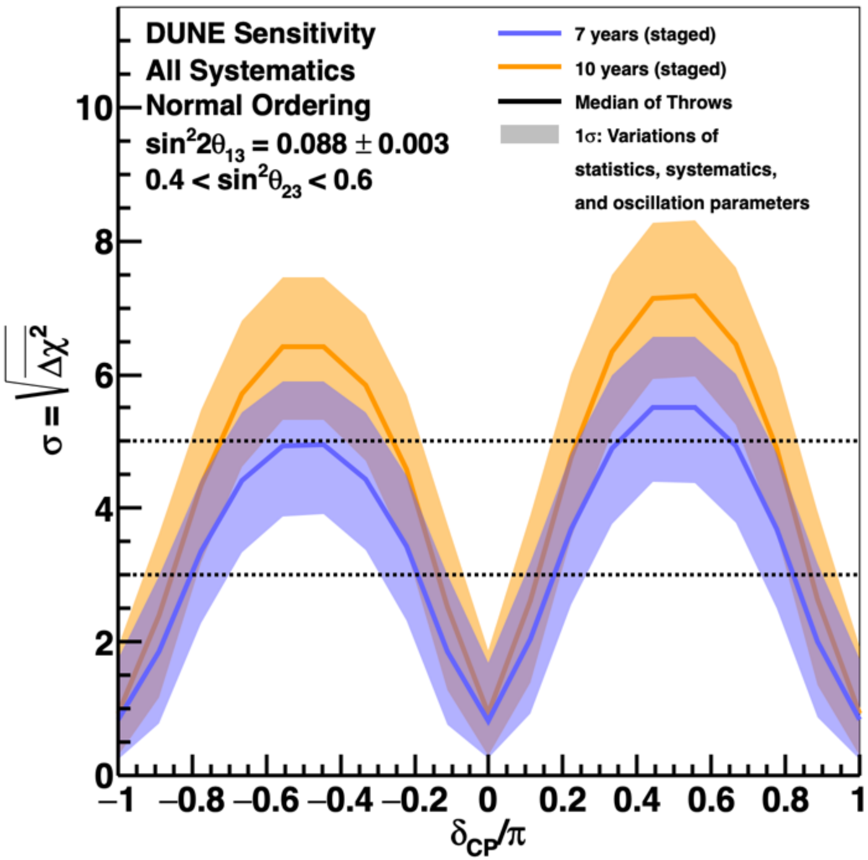
Base energy scale uncertainties

(not shown: allowed variations with energy)

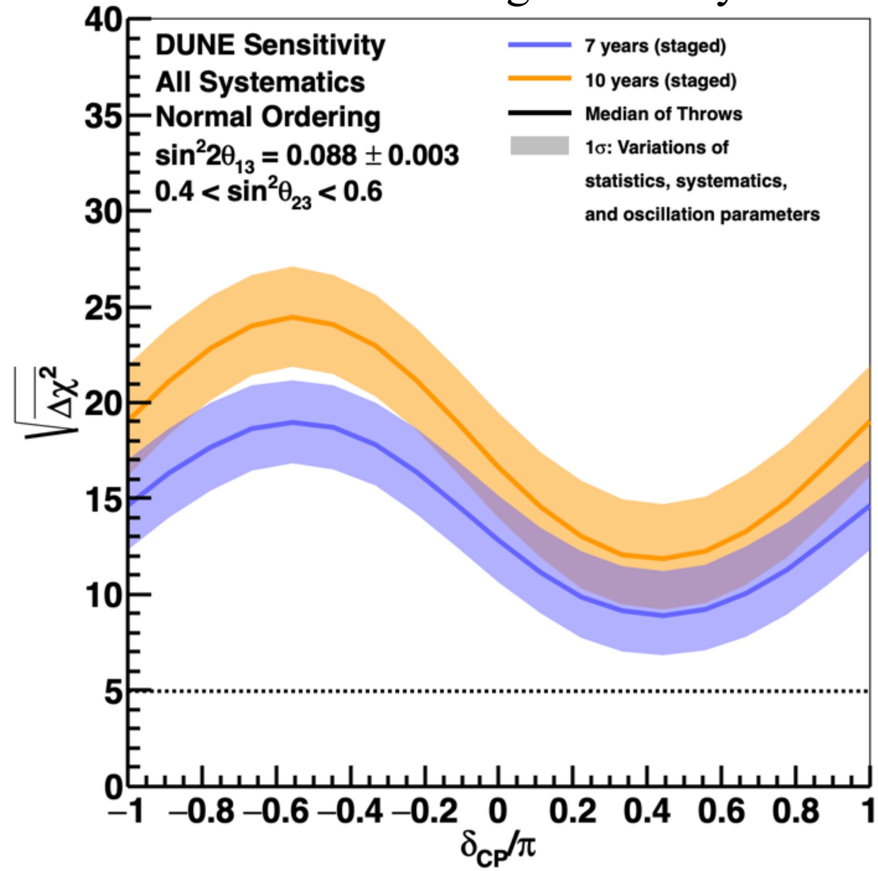
all	2%
μ (range)	2%
μ (curvature)	1%
p, $\pi^\pm$	5%
e, γ, π^0	2.5%
n	20%

CP violation and neutrino mass ordering

*CP*v sensitivity



Mass ordering sensitivity



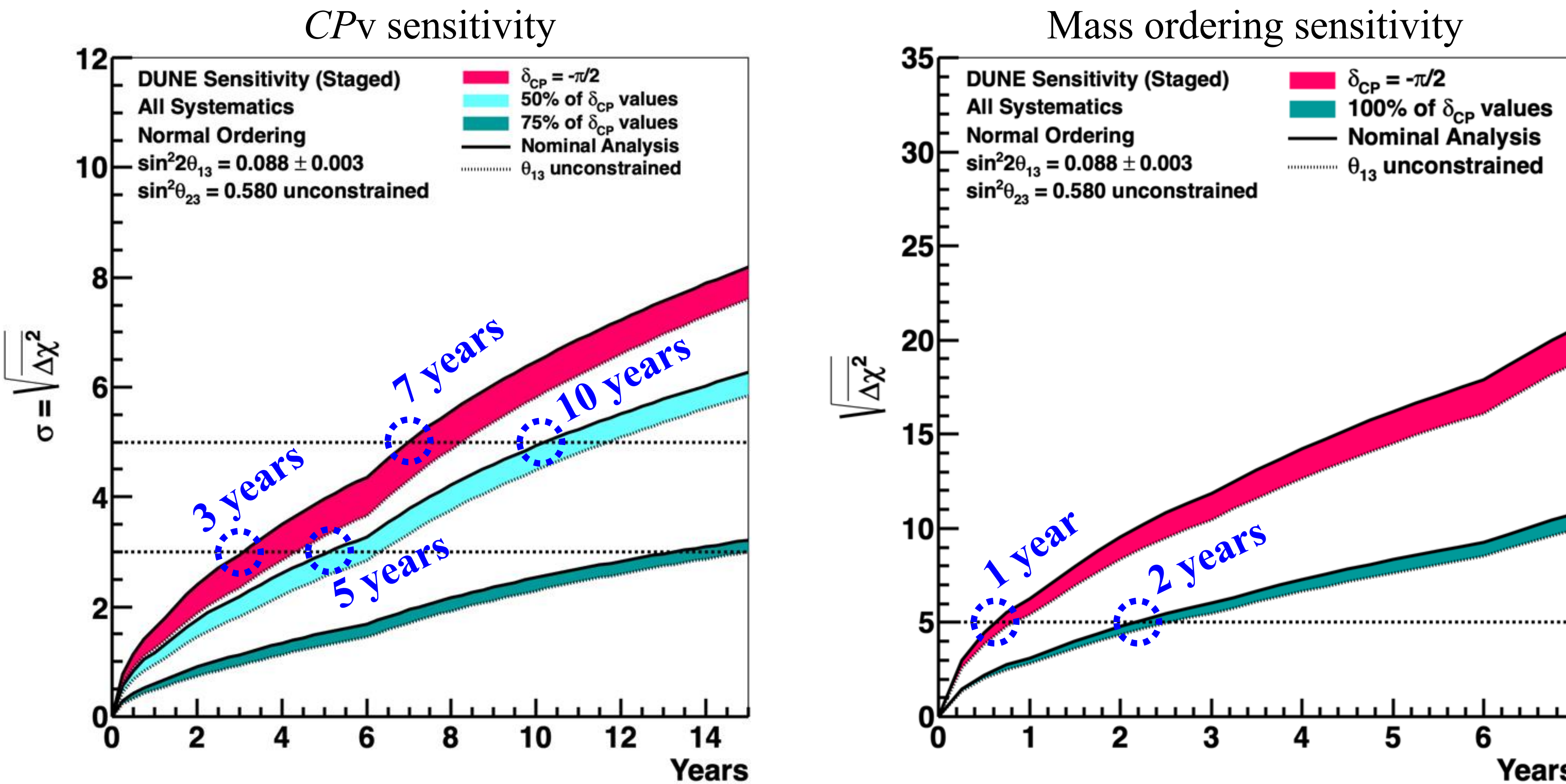
Updated sensitivities!

→ Move quickly to potential ***CP* violation discovery**

→ Rapid, definitive **mass ordering determination**

***>5σ** regardless of any other parameter choices*

Sensitivity versus time

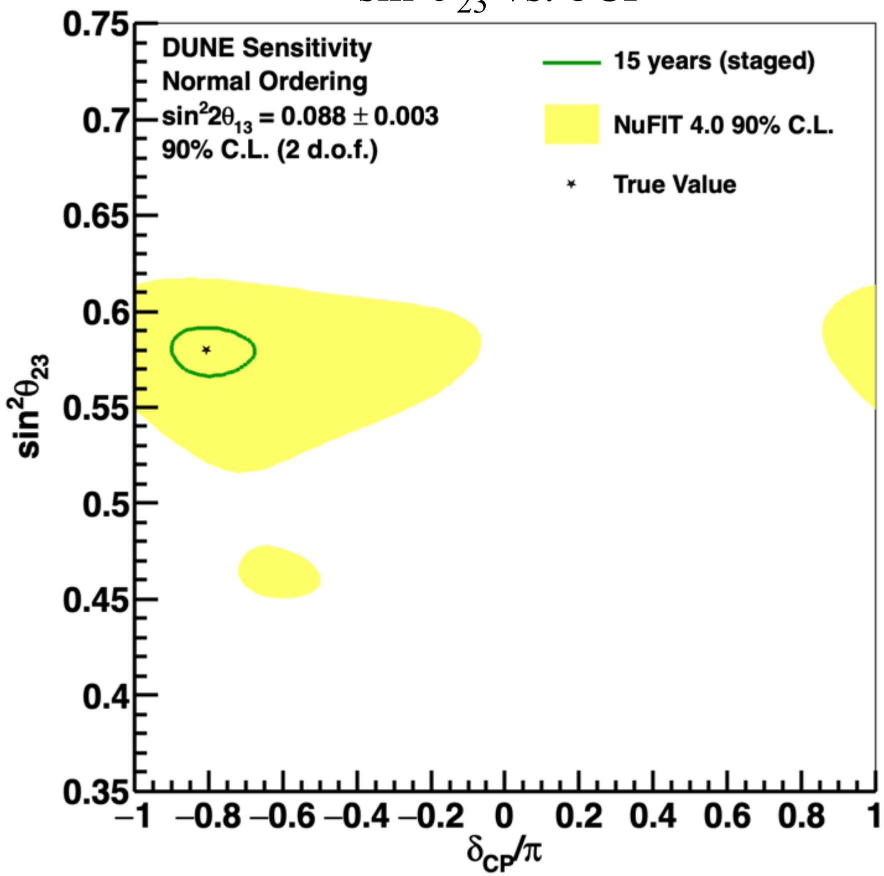


Significant milestones throughout beam-physics program

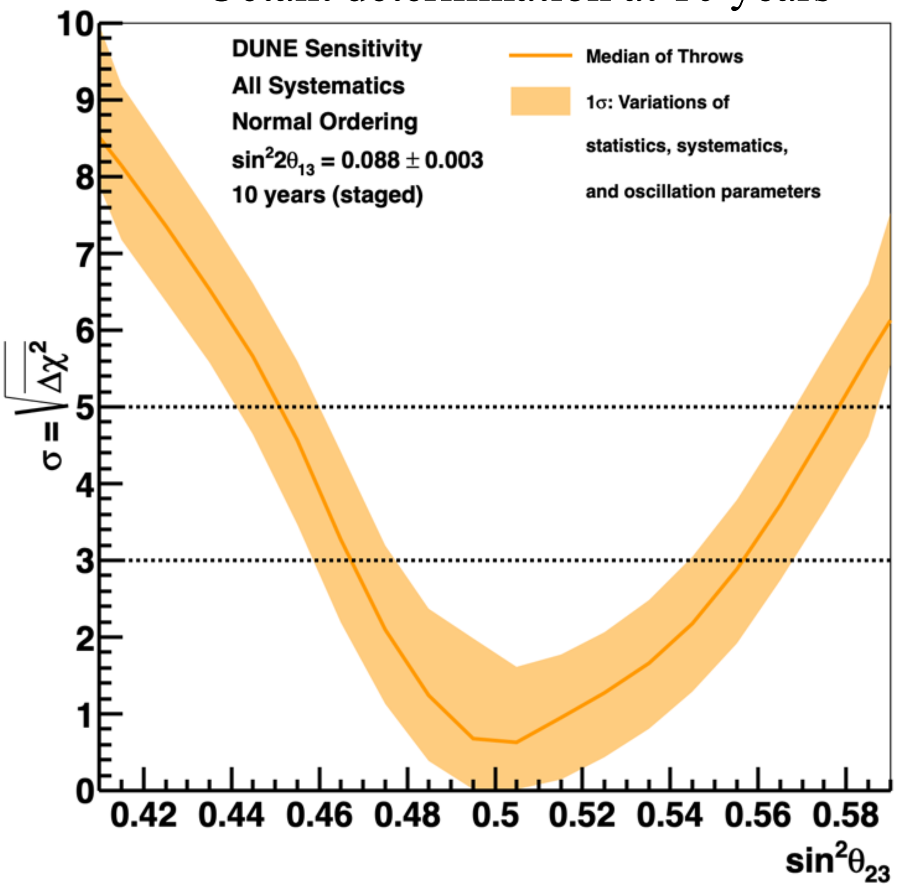
Note: When a choice is called for, **NuFit 4.0 (Nov 2018)** best-fit parameters and/or uncertainties are assumed
JHEP ***01*** *(2019) 106, www.nu-fit.org*

Mixing angle θ_{23}

$\sin^2\theta_{23}$ vs. δCP



Octant determination at 10 years

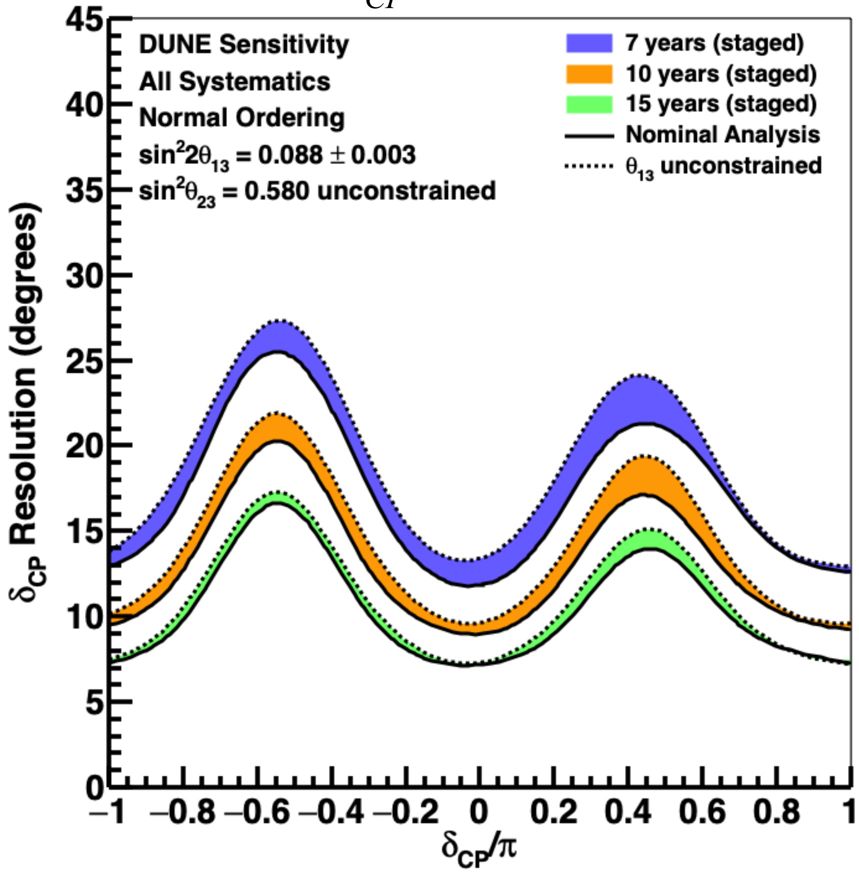


>5σ octant determination possible

(significance depends strongly on true value of θ_{23})

Precision PMNS

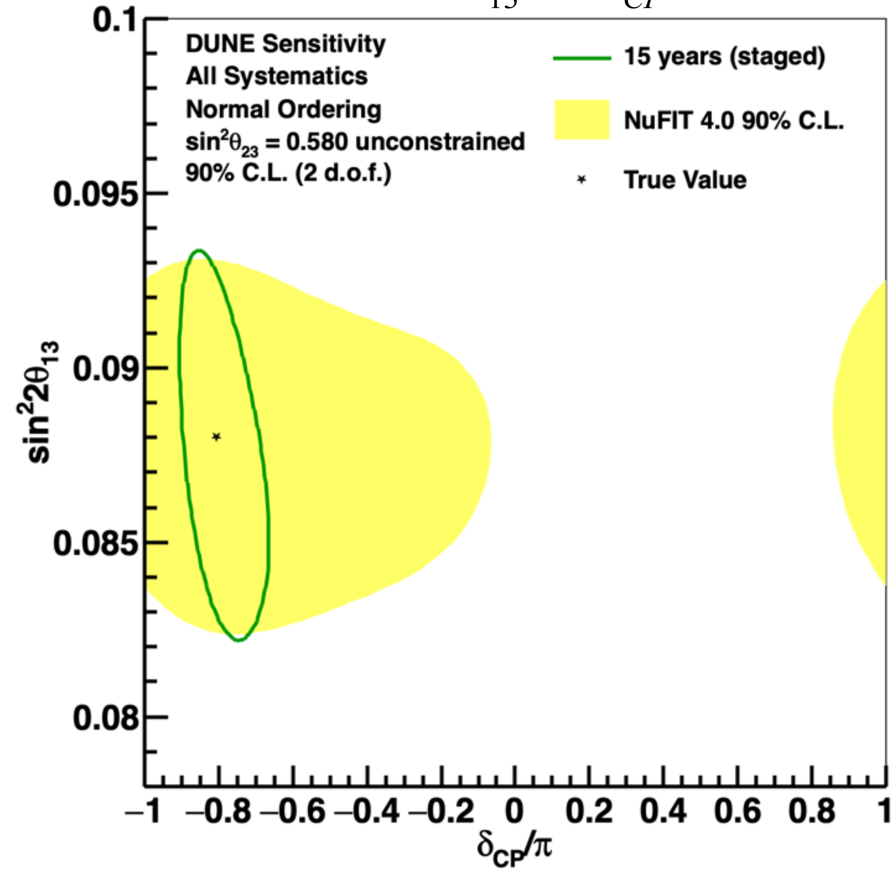
δ_{CP} resolution



δ_{CP} measured to ~7° – 17°

Single-experiment*
precision oscillation measurement!

$\sin^2 2\theta_{13}$ vs. δ_{CP}



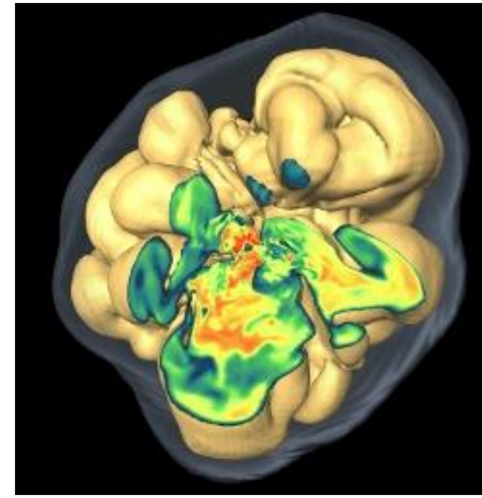
$\sin^2 2\theta_{13}$ resolution: 0.004 ***(4.5%)***

Ultimate **$\sin^2 2\theta_{13}$ precision** competitive with reactor measurements

*solar parameters θ_{12} and Δm^2_{21} are still inputs

Supernova neutrinos

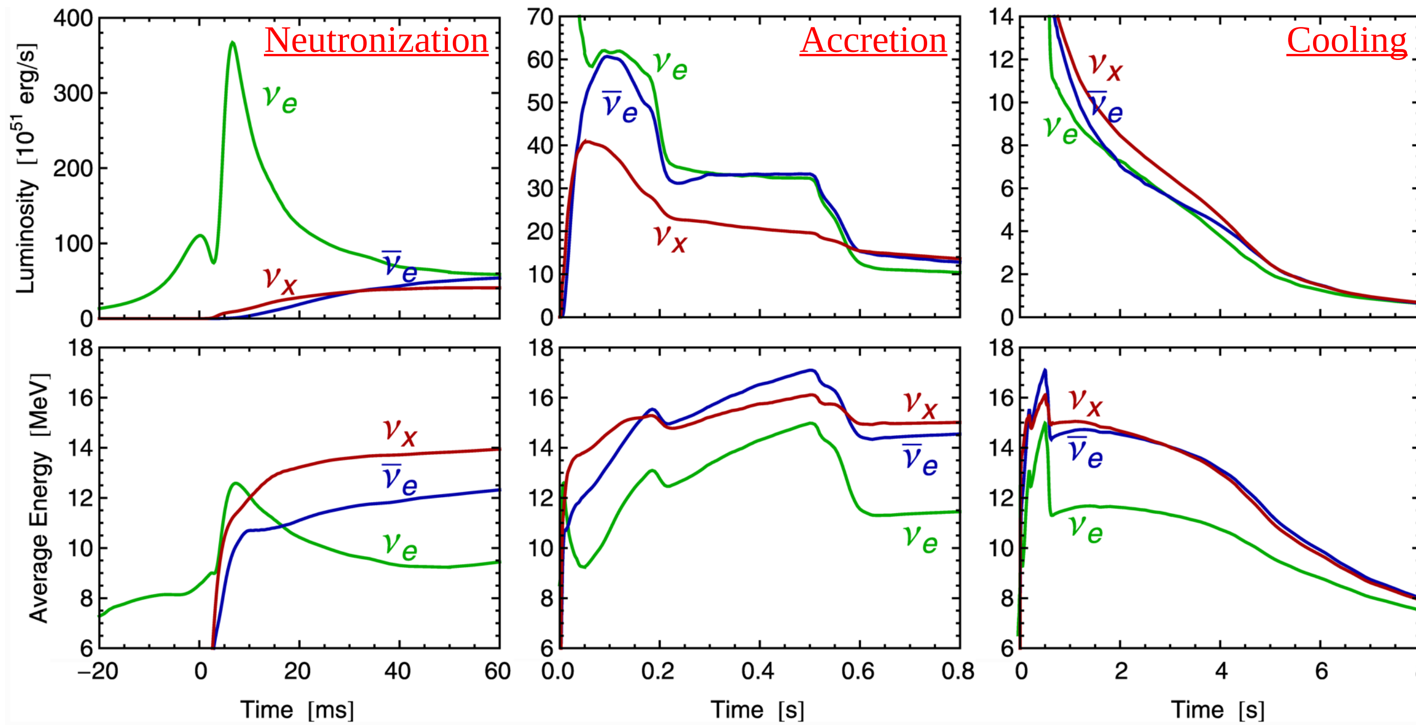
- **99% of energy** released in a core-collapse supernova is **carried away by neutrinos** *(cf.: 0.01% carried away by light)*
- **Rich information** embedded in neutrino signal:
  - **Supernova physics:** core-collapse mechanism, black hole formation, shock stall/revival, nucleosynthesis, cooling, …
  - **Particle physics:** flavor transformations in core, collective effects, mass ordering, nuclear equation of state, exotica



S. Woosley and T. Janka
Nature Physics **1**, 147 (2005)

Argon target:
Unique sensitivity to ν_e flux

DUNE at 10 kpc:
~3000 ν_e events over 10 seconds



Garching model (27 $M_{\odot}$)

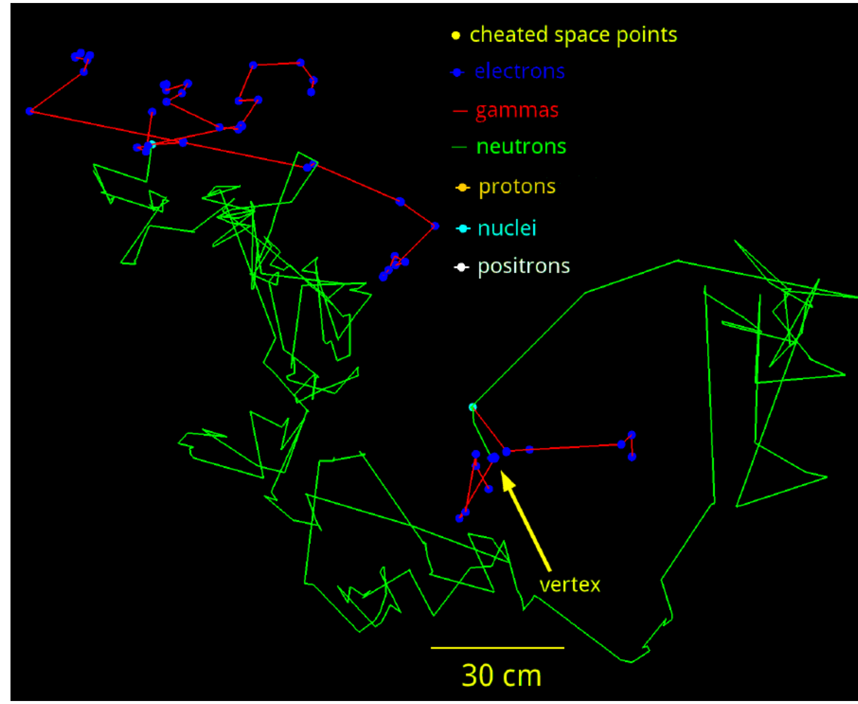
Analysis tools

MARLEY event generator for simulation of primary channel:

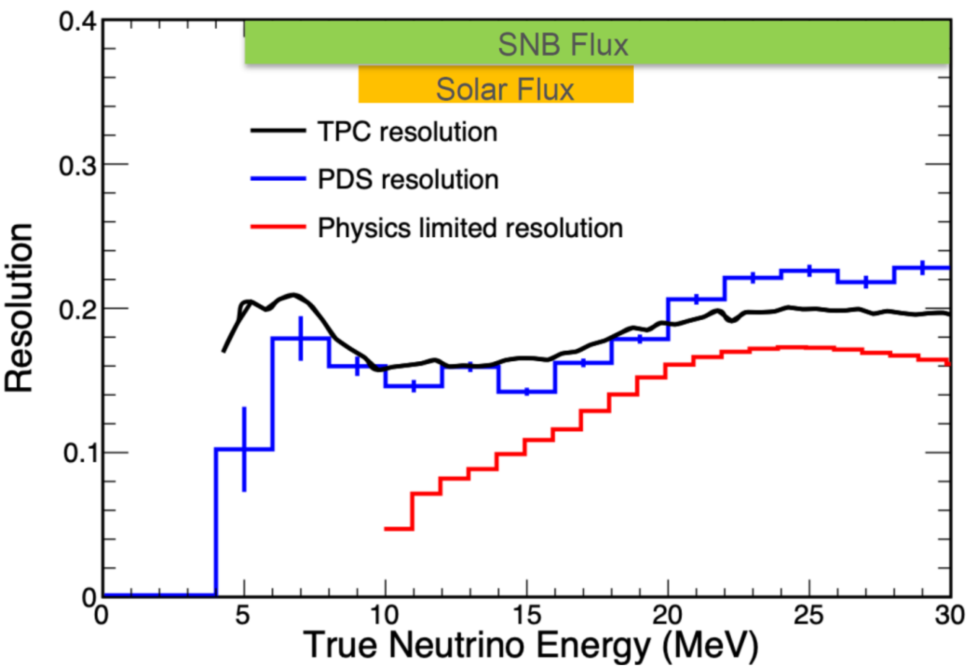
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

includes detailed, data-driven model of the relevant nuclear transitions

MARLEY event



http://www.marleygen.org
S. Gardiner, C. Grant, E. Pantic, and R. Svoboda



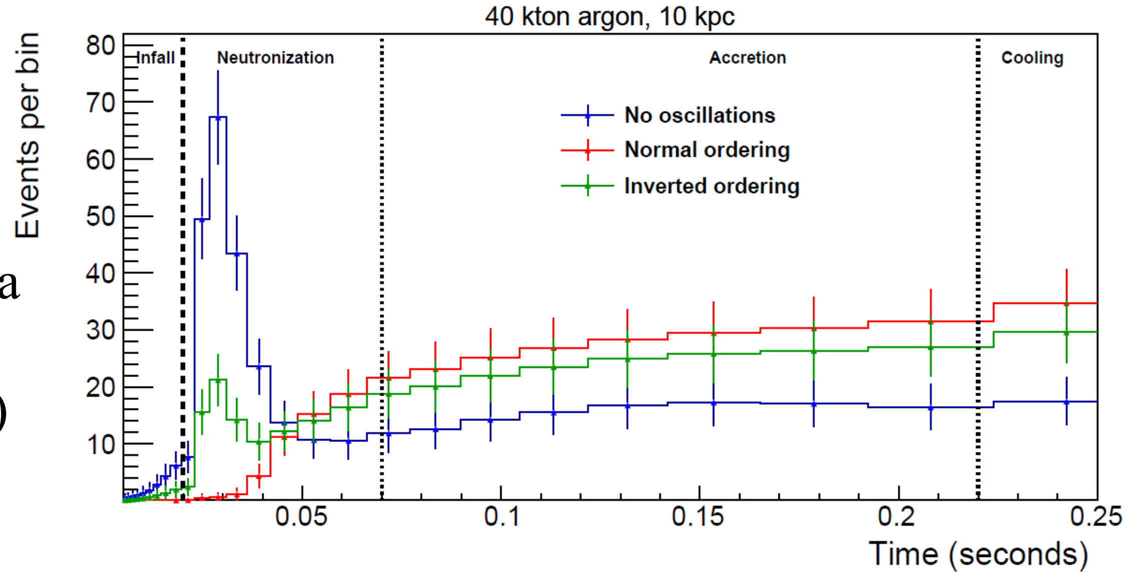
Full detector simulation with **Calorimetric energy reco.**

Using TPC signals with drift correction

Photon-based calorimetry just as good! Incorporated into analyses soon.

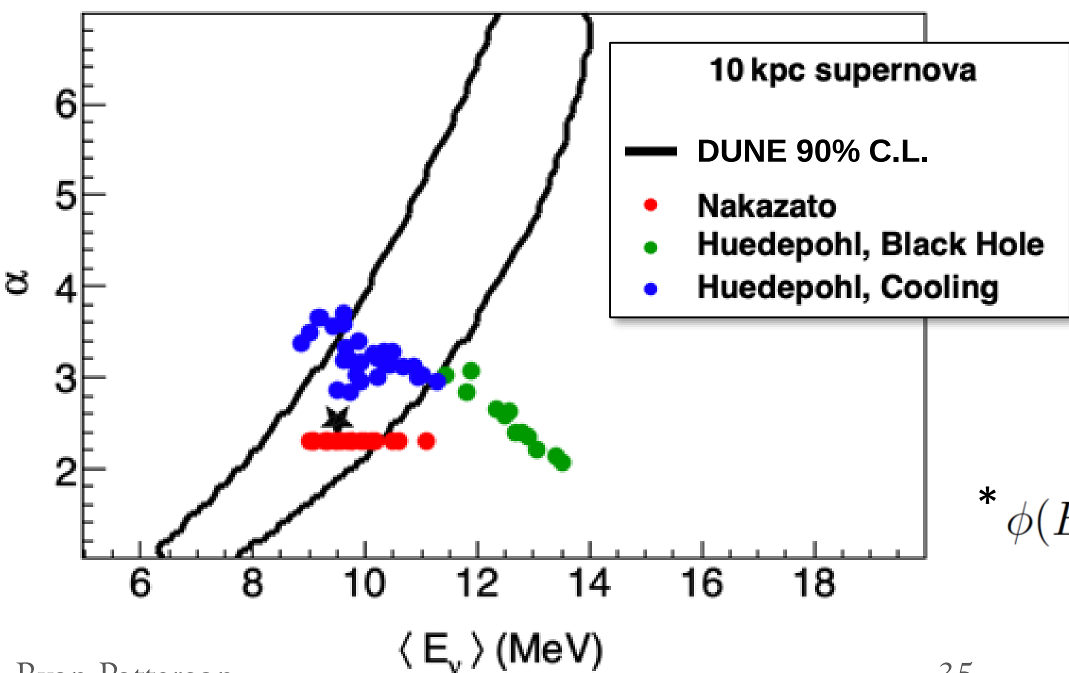
Example observables

Neutrino mass ordering →
signature in neutronization burst



Other νMO signatures in burst data have more theoretical uncertainty (*e.g.*, shock wave, collective effects)

→ ***Leverage beam-based νMO measurement!***



← DUNE sensitivity to **"pinched thermal" spectral parameters***

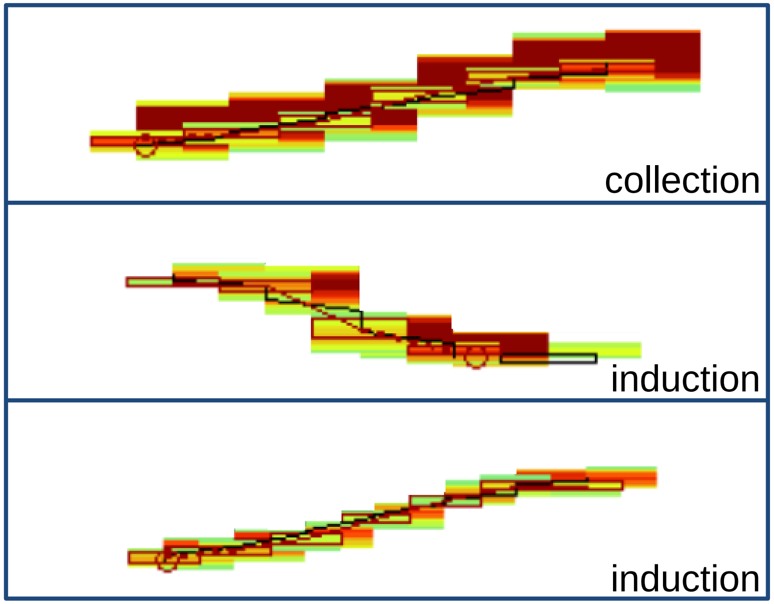
(Only time integrated flux used here!)

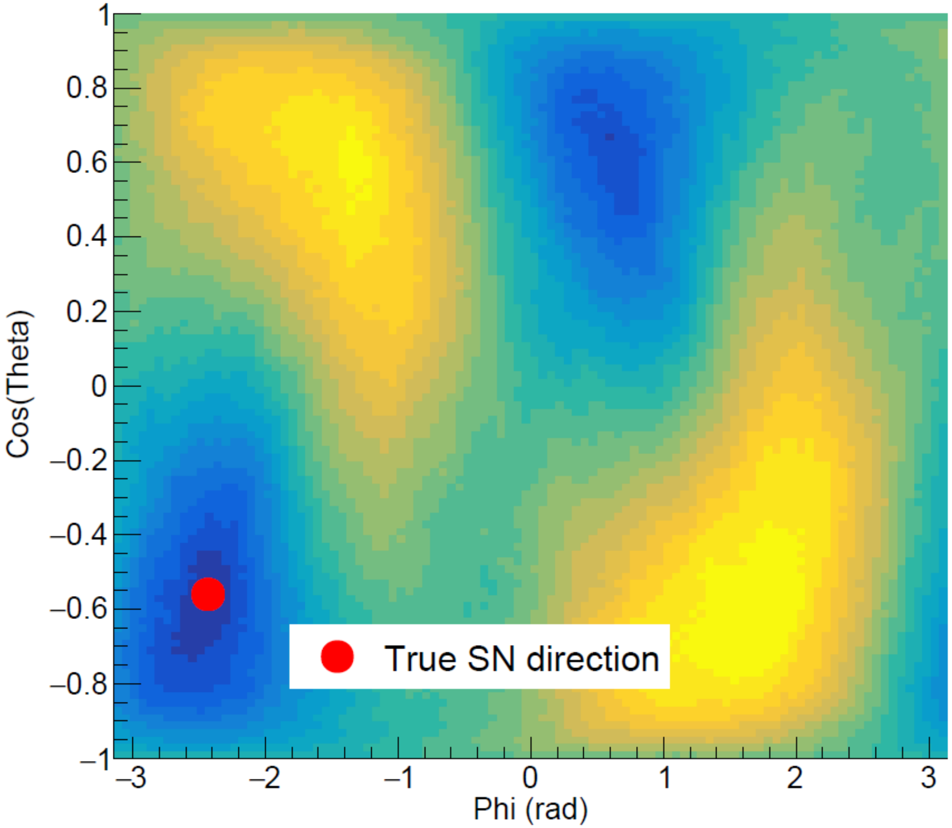
$$^{*}\ \phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu \rangle}\right)^{\alpha} \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu \rangle}\right]$$

Directionality

- **Prompt pointing** to a supernova is highly valuable information to astronomers:
  - Catch **early turn-on** of EM signal
  - Support observation of **optically dim SN**
  - Era of **multi-messenger astronomy**

10.25 MeV electron,
simulated and reconstructed



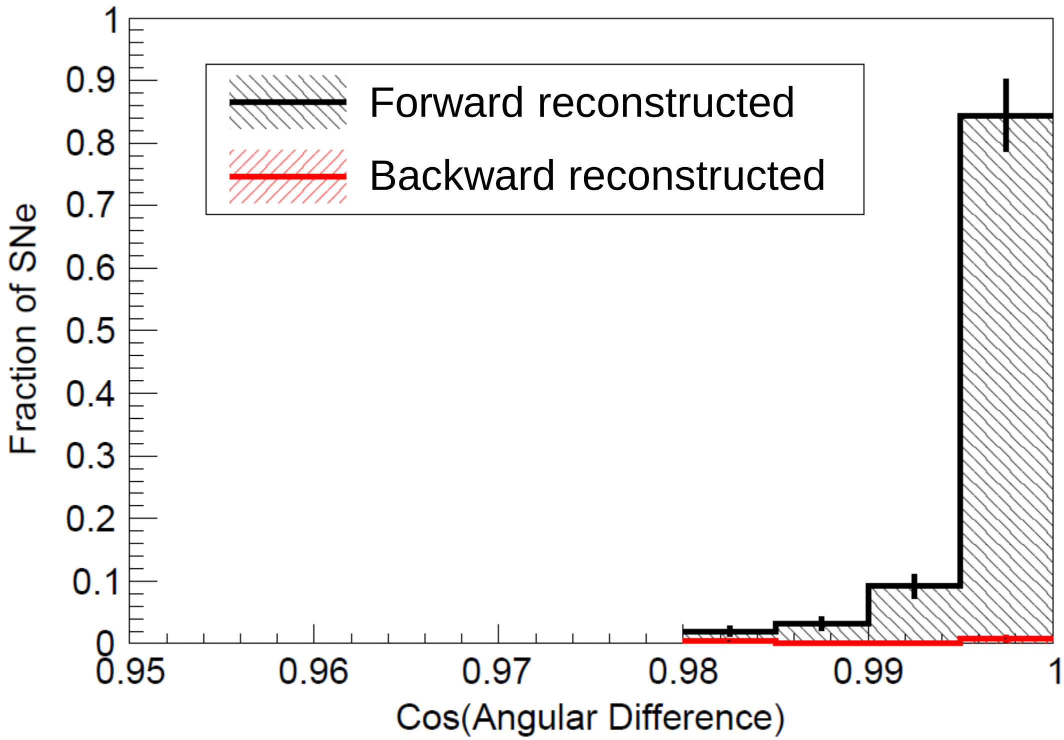


← **Direction likelihood surface** at DUNE for 10 kpc supernova

$\boldsymbol{\nu_e}$ **CC** and $\boldsymbol{\nu + e}$ (elastic scatter) events

Channel tagging can improve this further.

Much better pointing with ES events!
But only ~7% of sample.



← **4.5° pointing resolution**

(10 kpc progenitor)

- Several other **low-energy neutrino measurements** under study
- No time in this talk, but some discussion in Technical Design Report
  - diffuse supernova neutrino background
  - solar neutrinos
  - absolute neutrino mass from SNν
  - Lorentz/CPT violation

Physics Beyond the Standard Model

<u>*Many avenues for searches*</u>

- **Baryon number violation**
  General feature of GUTs. Rich model space.
  Many search modes being explored in DUNE.

Updated simulation/reconstruction/analysis:
More details and more channels in TDR

$p \to K\bar{\nu}$ Tracking and dE/dx for rejection of ν_μ CC background ($p + \mu$ final state)

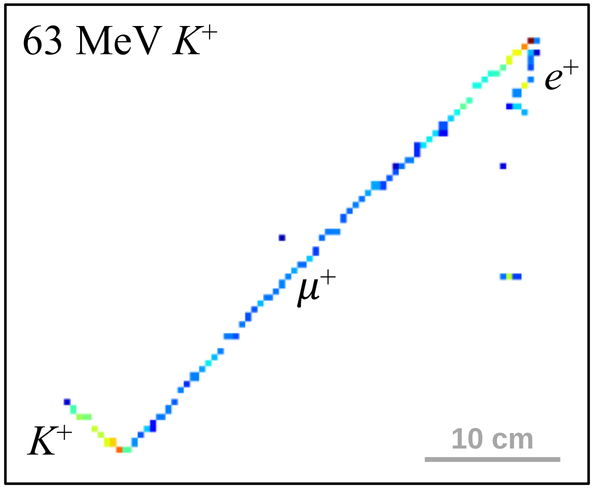
~0.5 bkgnd at 400 kt-yr, 30% signal efficiency
If no signal: **$\tau/B > 1.3{\times}10^{34}$ yr (90% C.L.)**

---

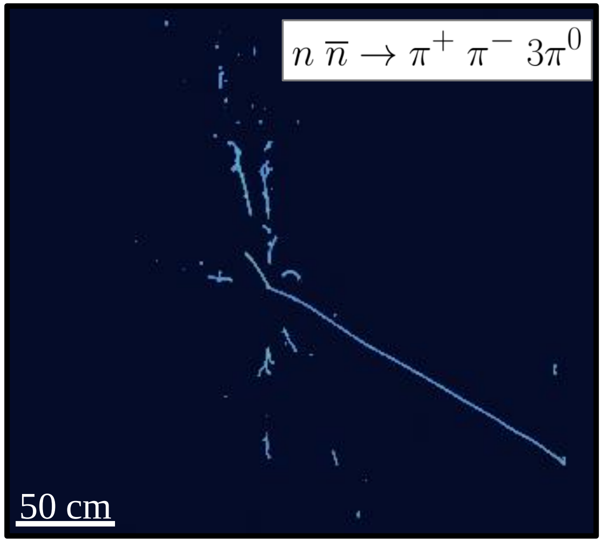
n-$\bar{n}$ osc. Spherical spray of hadrons with $E \approx 2M_n$ and net momentum $\lesssim p_F \sim 300$ MeV

Free-neutron-equivalent sensitivity:
$\tau_{\text{free,osc}} > 5.5{\times}10^{8}$ s (90% C.L.)

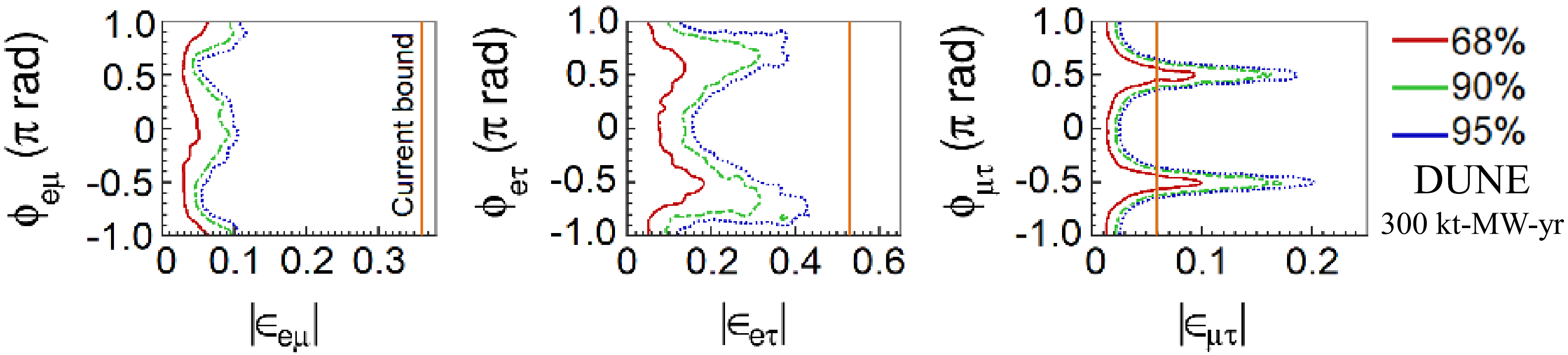
DUNE simulation



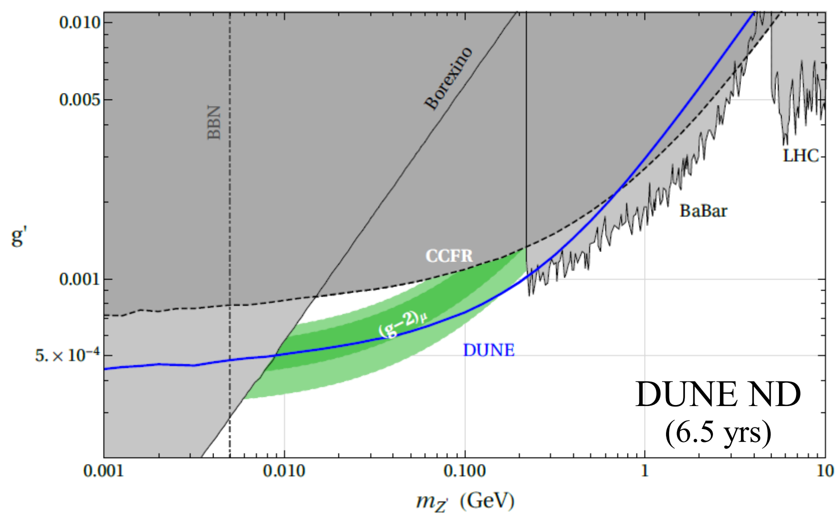
DUNE simulation

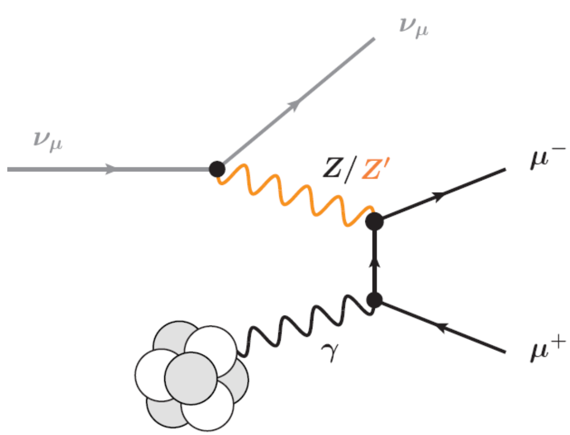


- **Non-standard interactions**
  Observable as modifications to standard matter effects over DUNE's long baseline



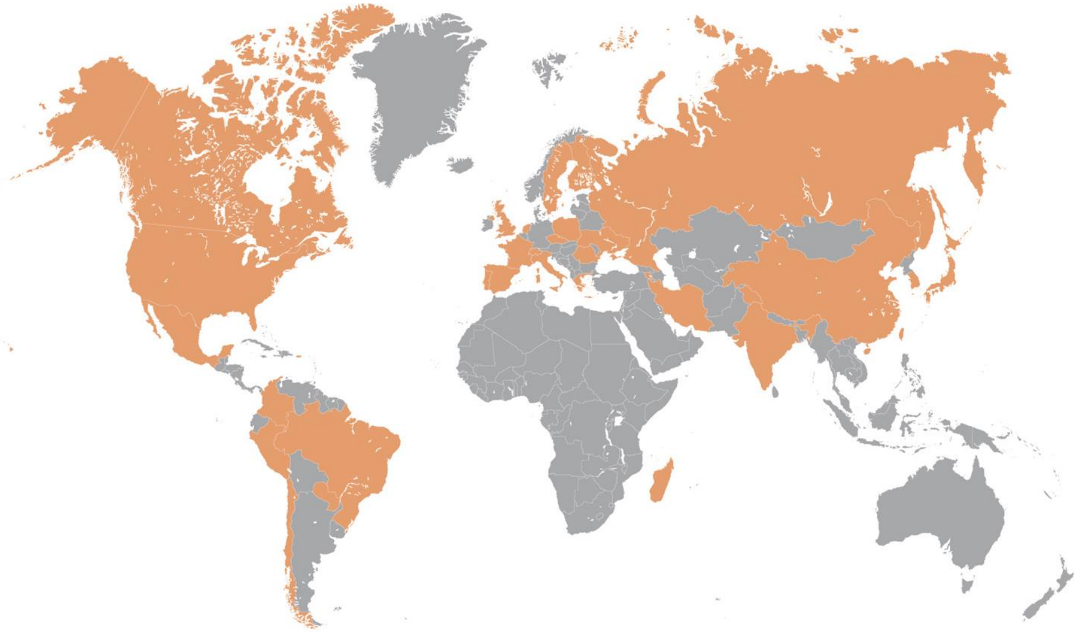
- **Z'-mediated trident interactions**
  Underlying interaction a possible explanation to the muon g−2 anomaly





- **Also:** active-sterile mixing / PMNS non-unitarity / CPTv / heavy neutral leptons / large extra dimensions / dark matter (beam-induced & astrophysical)

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT



An international science collaboration

1106 collaborators from **184 institutions** in **31 countries**

Deep Underground Neutrino Experiment (DUNE)

Technical Design Report

Volume I:

Introduction to DUNE

Technical Design Report

→ Detailed documentation of all **scientific**, **technical**, and **managerial** aspects of DUNE

~2000 pages over five volumes

Submitted last week to **Long Baseline Neutrino Committee** and **Neutrino Costing Group***

**two independent, international committees providing on-going oversight and review*

A major milestone for the collaboration

ND TDR will be a separate step, c. 2020

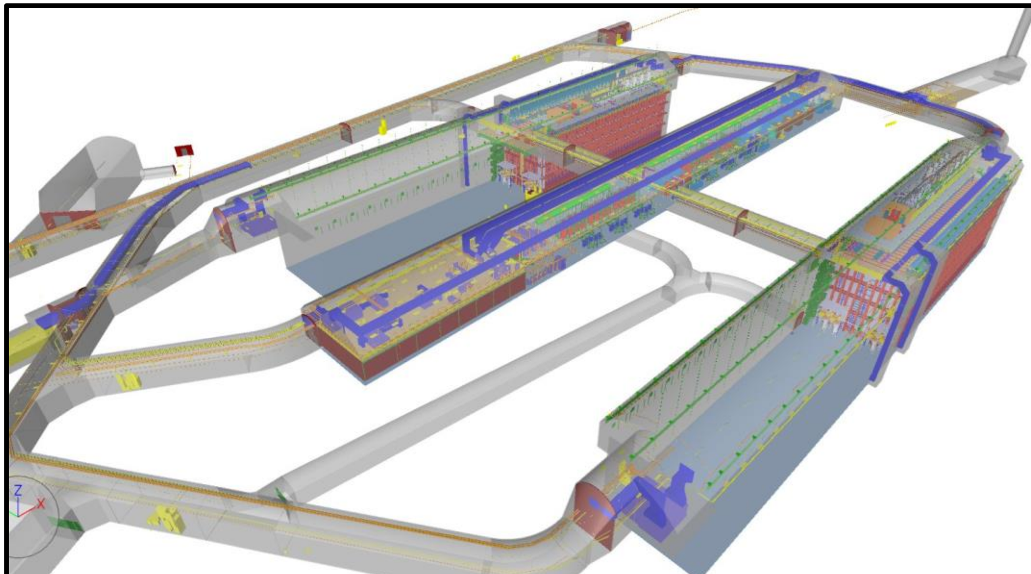
ProtoDUNE-SP/DP operation after CERN LS2 (2021)

→ Will upgrade active detector elements to match final production designs

→ Collect expanded suite of beam data

Far site pre-excavation construction is well underway by contractor

Final design of caverns and supporting infrastructure



Installation timeline to be finalized when the international project is baselined.

c. 2026 estimated start of FD operation

Summary

DUNE: An ambitious **international project** with a **broad physics program**

- Unambiguous ***ν* mass ordering**. **Leptonic *CP*v** at >5σ for most δ_{CP} values
- **Precision PMNS**: a new era for flavor
- Rich physics/astrophysics with **supernova neutrinos**
- Wide-ranging searches for **physics beyond the Standard Model**

❖ **DUNE continues to meet key milestones.**

TDR to be released widely upon conclusion of external reviews.