Studying neutrinos with DUNE

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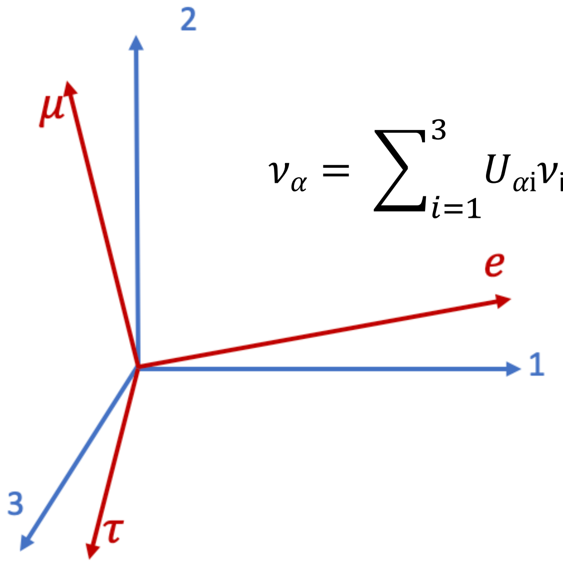
Neutrino oscillation is a window to Beyond Standard Model Physics but difficult to study

- Neutrino oscillation
  - three flavor (ν_e, ν_μ, ν_τ) and three mass (ν_1, ν_2, ν_3) eigenstates related via the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix
  - non-zero neutrino mass
  - difficult to study due to extremely low interaction cross sections (~ 10^{-44} cm^2)

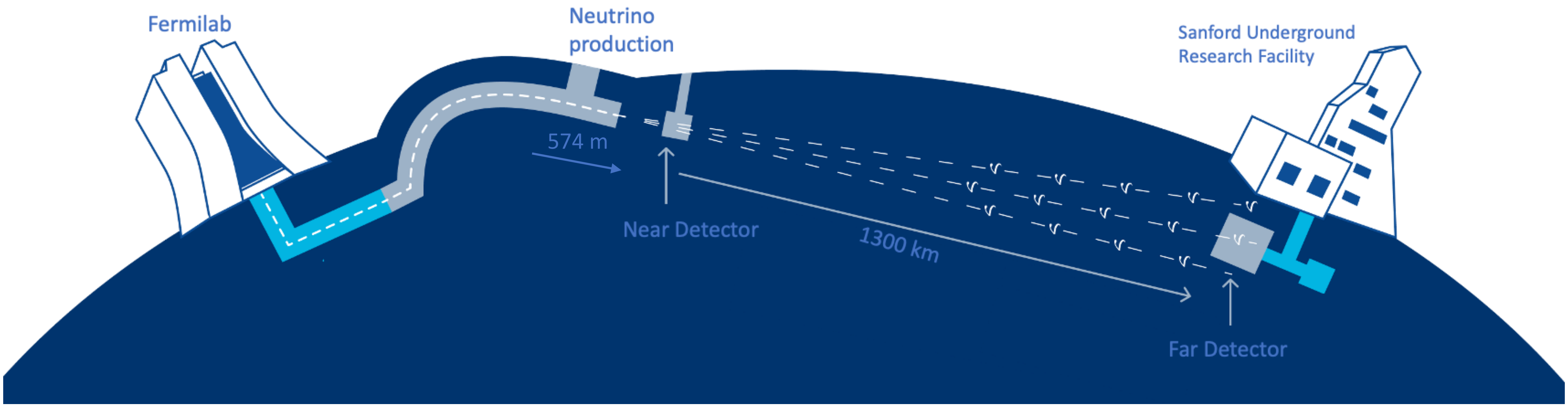


$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i \quad (\alpha = e, \mu, \tau)$$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left[-i\frac{\Delta m^2_{ji}}{2}\frac{L}{E}\right]$$

Oscillation probability from flavor α to β

DUNE will measure $\nu_\mu/\bar{\nu}_\mu$ beam oscillation to $\nu_e/\bar{\nu}_e$ using 1300 km baseline



DUNE will focus on a broad range of physics goals

ν_μ oscillation physics

- Measure oscillation parameters
- Resolve neutrino mass ordering
- Measure amount of CP violation in leptons

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Oscillation probability from flavor α to β

NO : $m_1 < m_2 < m_3$

IO : $m_3 < m_1 < m_2$

Neutrino mass ordering

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

CP violation

DUNE will focus on a broad range of physics goals

ν_μ oscillation physics

- Measure oscillation parameters
- Resolve neutrino mass ordering
- Measure amount of CP violation in leptons

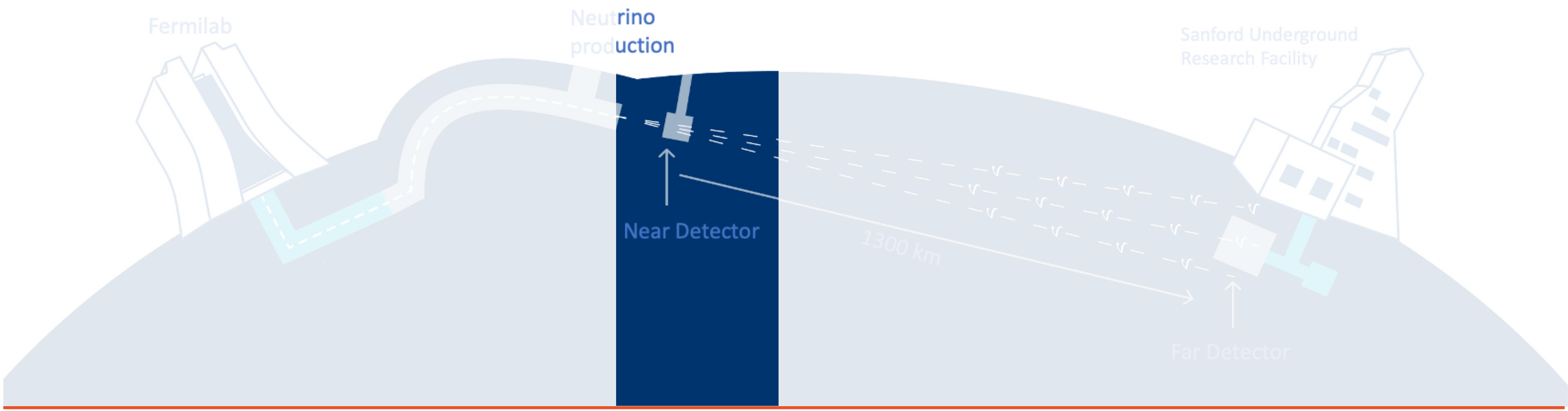
Other primary physics goals

- Search for Proton decay
- Measure ν_e flux from Supernova explosion

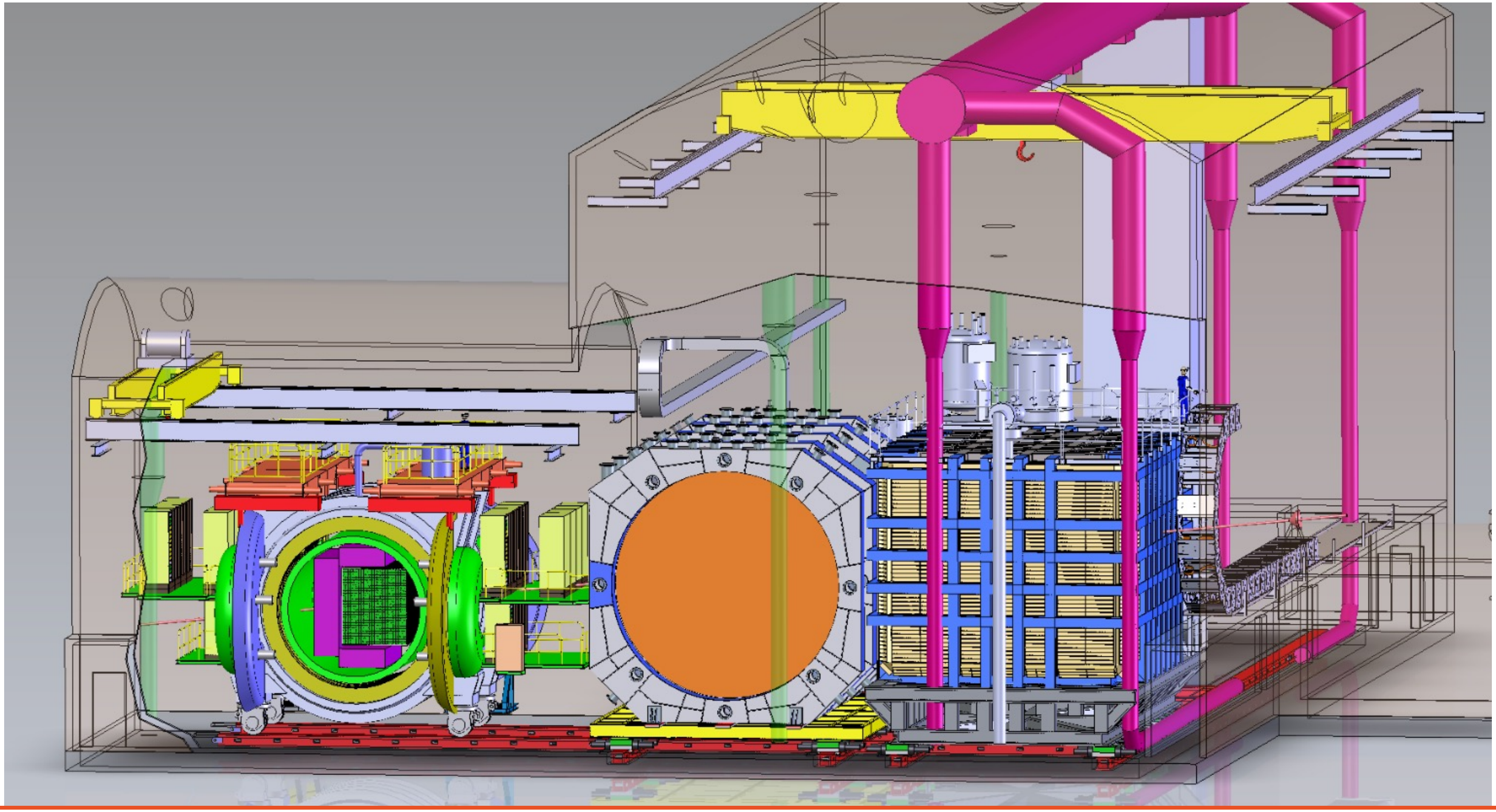
Secondary physics goals

- Atmospheric/Solar neutrino science
- ν-N interaction physics using Near Detector
- …

THE NEAR DETECTOR COMPLEX

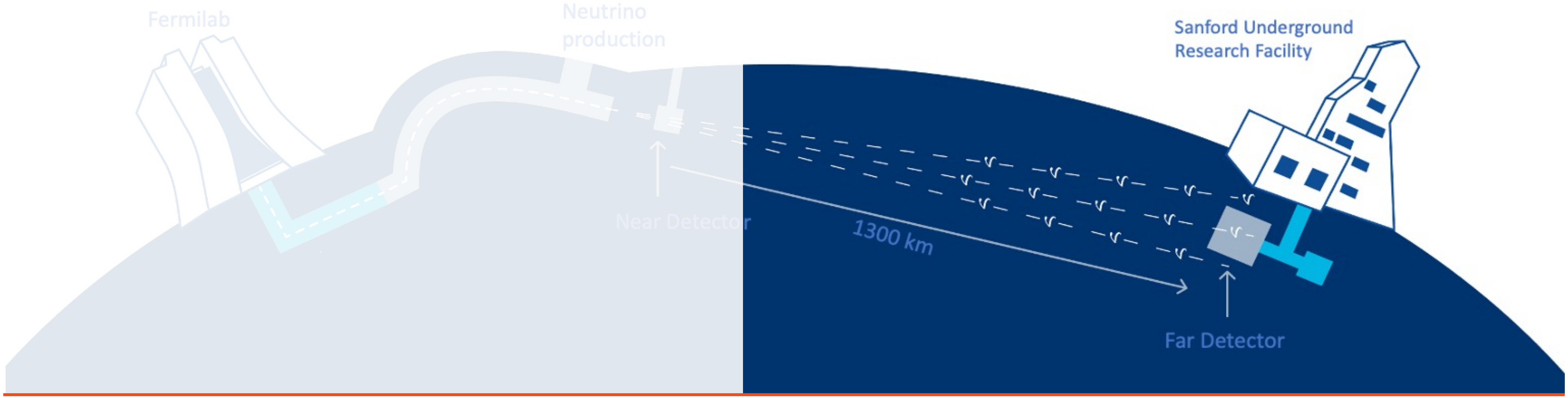


The Near Detectors will constrain effects of cross section, flux, and detector energy response to enable the oscillation physics

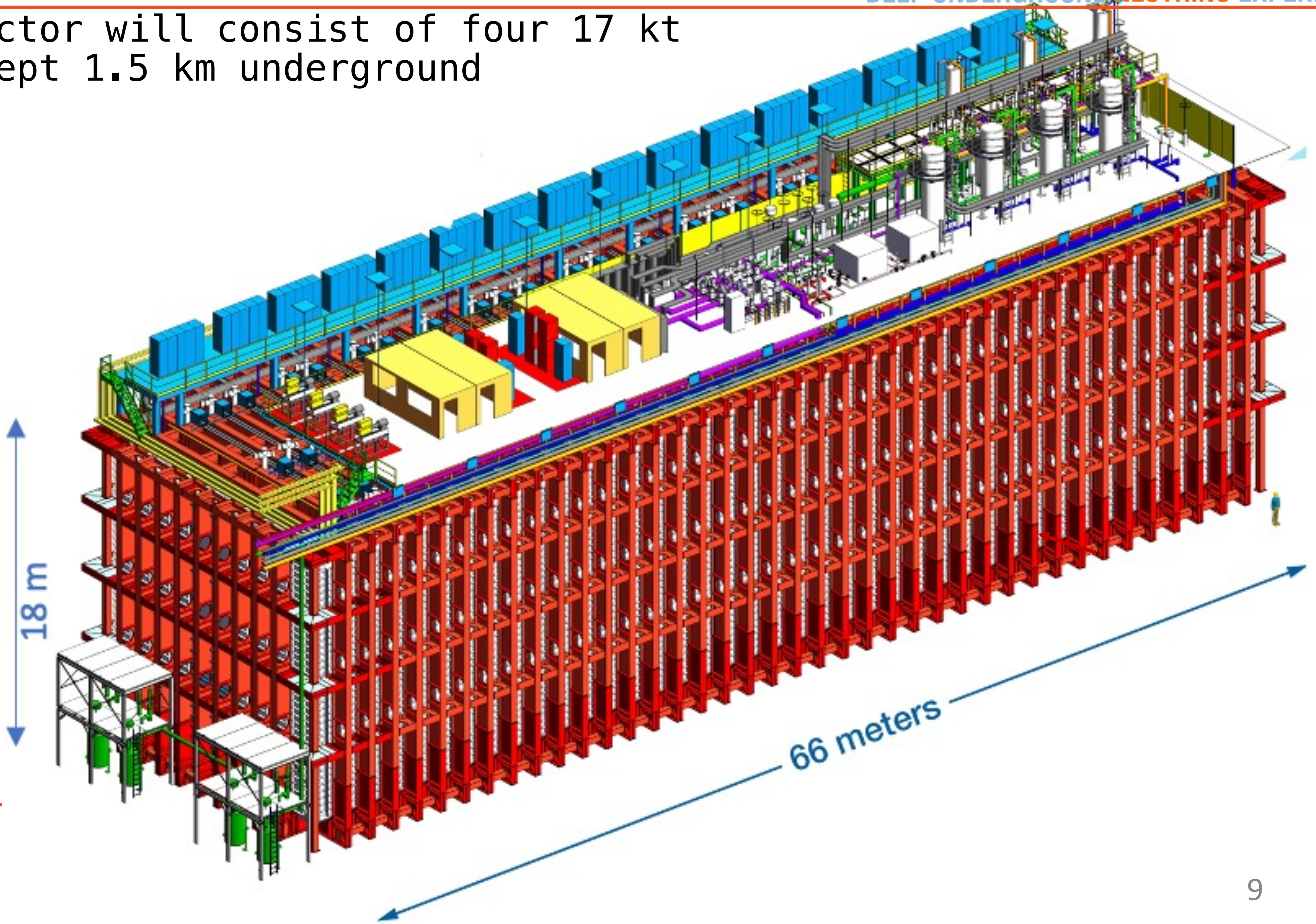


DUNE Near Detector complex

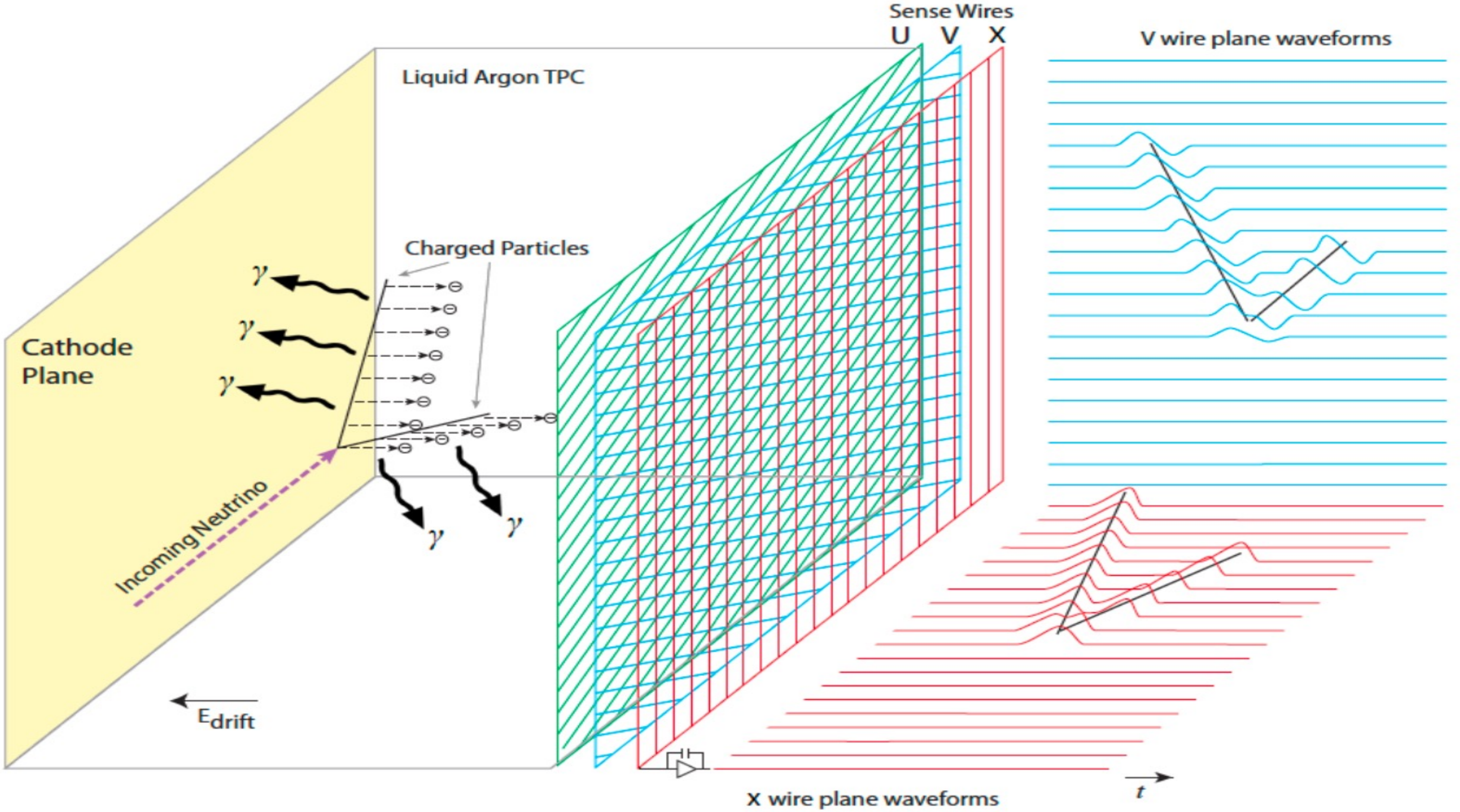
THE FAR DETECTORS



DUNE Far Detector will consist of four 17 kt LAr modules kept 1.5 km underground



Liquid Argon Time Projection Chambers (LArTPC) allow imaging of particle interactions with sub cm resolution



Working principle of LArTPC

ProtoDUNE : An extensive R&D program at CERN to develop the Far Detector technology using two ~800 ton LArTPC detectors

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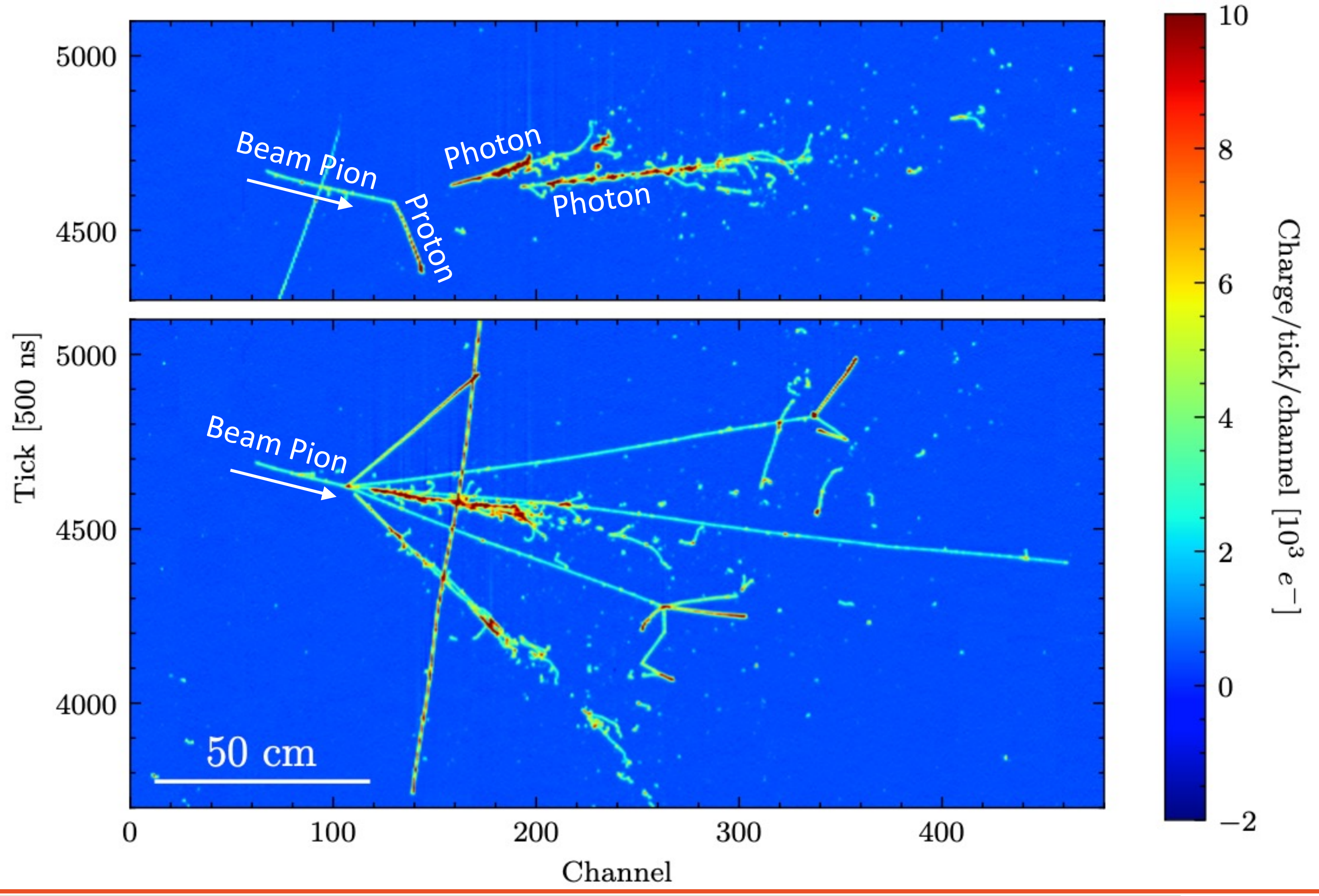
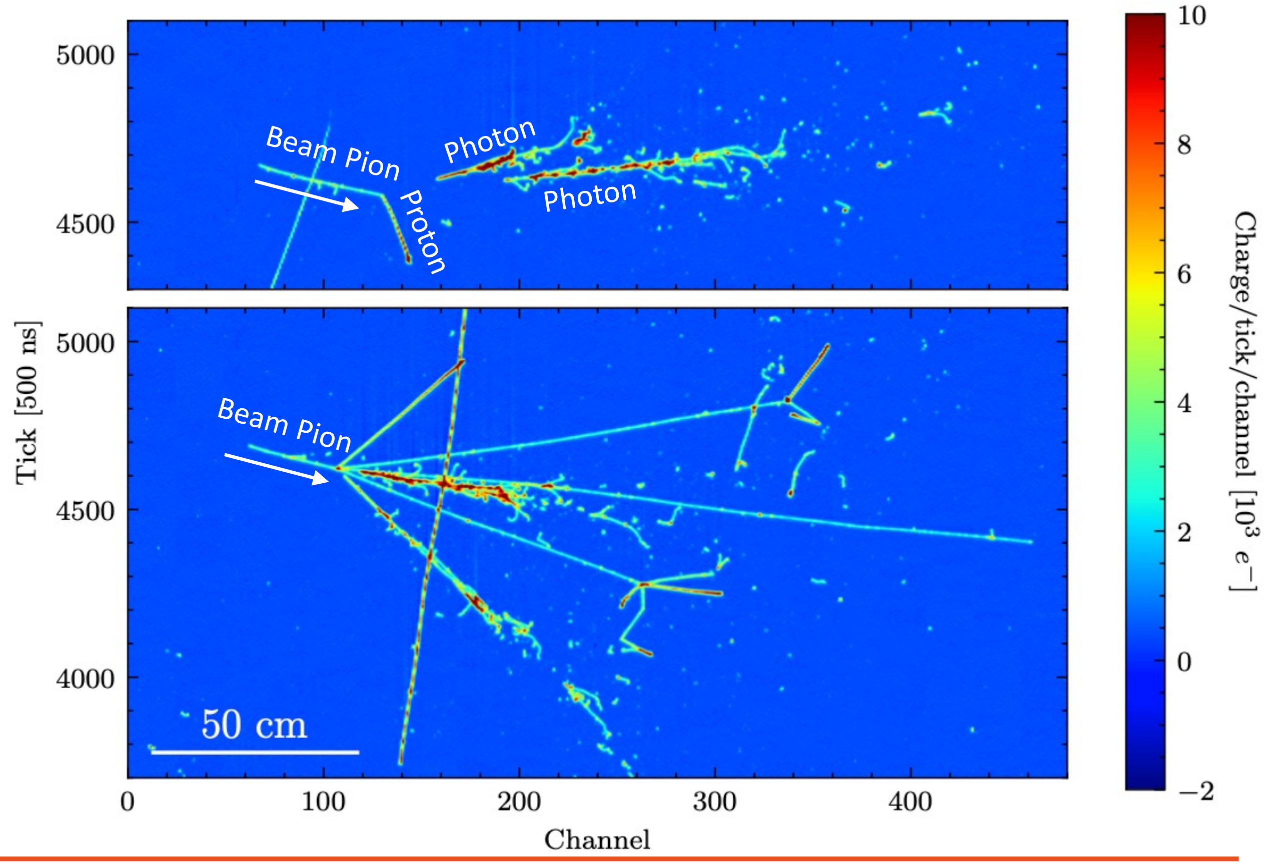
Example events from 2 GeV and 6 GeV beam π^+ beam interaction from ProtoDUNE I data



First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform
(https://arxiv.org/pdf/2007.06722.pdf)

DUNE activites @Nikhef

- At Nikhef, we are working on
  - Improving event reconstruction performance of the LArTPC detectors
  - Understanding and validating EM shower response using ProtoDUNE data
  - ProtoDUNE II construction and operation



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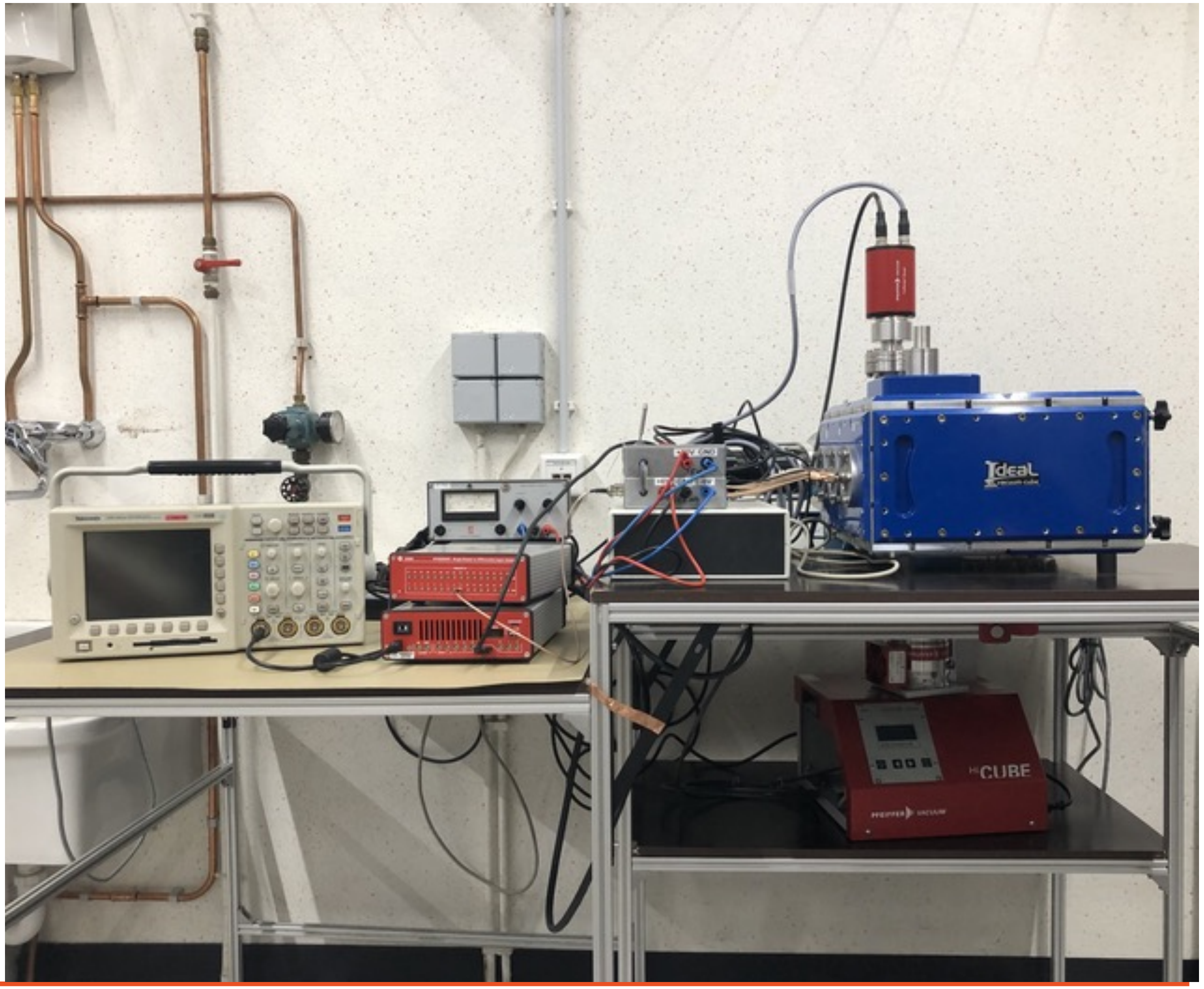
  - Understanding and validating EM shower response using ProtoDUNE data
  - ProtoDUNE II construction and operation
  - Dedicated setup to characterize detector components interaction with scintillation light for LAr/LXe experiments



Summary

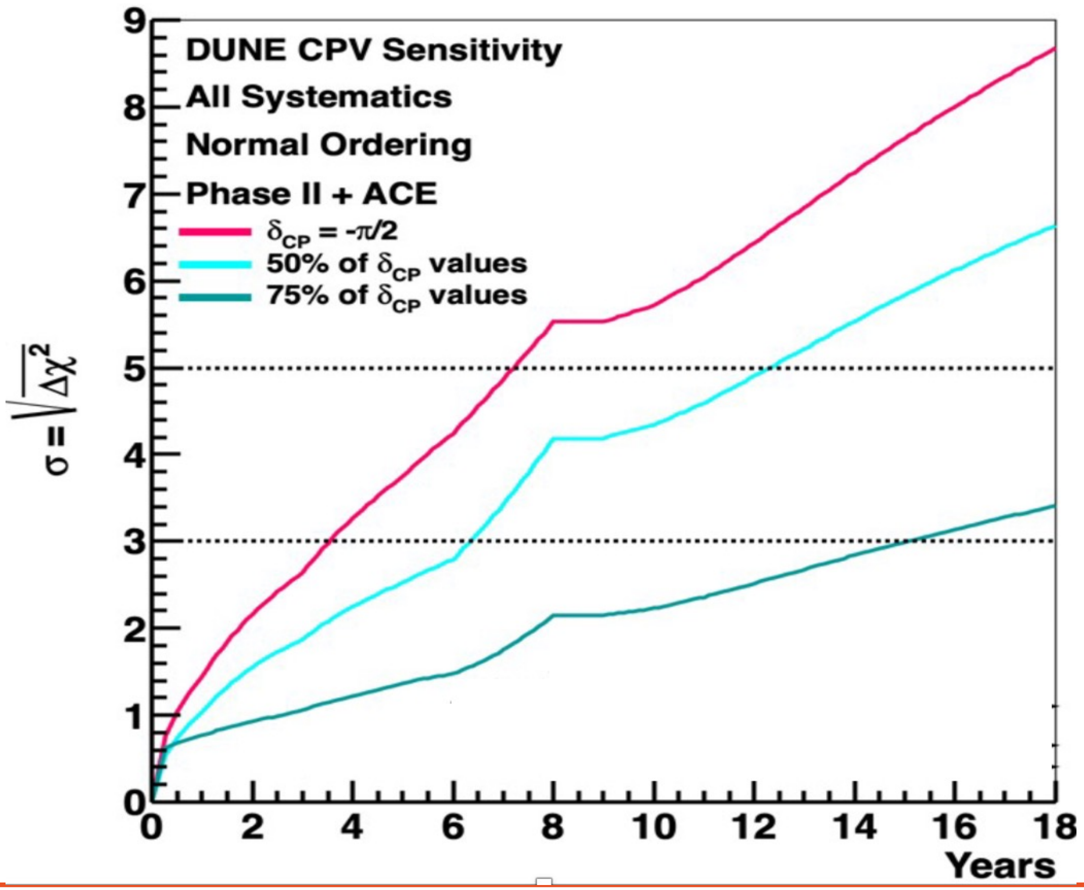
- DUNE is an upcoming neutrino oscillation experiment that
  - will answer fundamental questions about neutrinos with precision measurement of $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$ oscillations
  - has a broad range of physics goals possible due to intense neutrino beam and complex detector technology
  - has an extensive R&D program running at CERN for developing the DUNE Far Detectors

2024	2028	2031
ProtoDUNE II run	First two FD modules are operational	Beam and ND complex are ready

Thank You

Backup

CP violation sensitivity



Assuming certain construction timeline

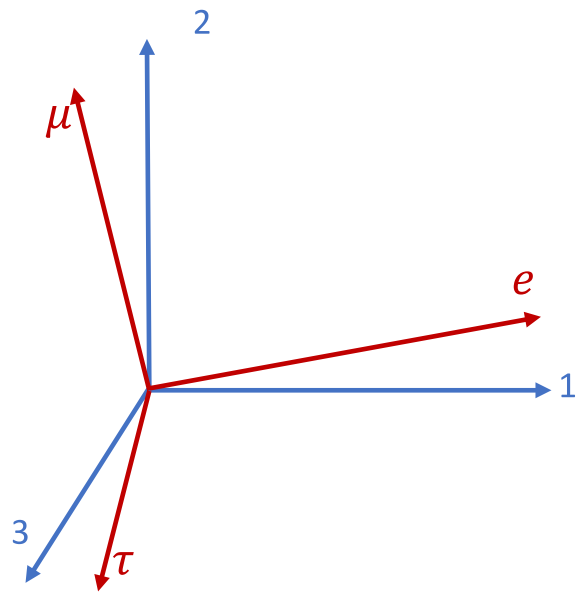
Neutrino oscillation experiments measure the PMNS matrix elements via appearance/disappearance of different flavors.

-> Pontecorvo–Maki–Nakagawa–Sakata matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\Delta m{i_1}^2 = {m_i}^2 - {\mathrm{m}_1}^2$

$$P(\nu_\alpha \to \nu_\beta, t) = \left| \sum_i U_{\beta \mathrm{i}} U_{\alpha i}^* \exp\left(-i \frac{\Delta m_{i12} t}{2E} \right) \right|^2$$



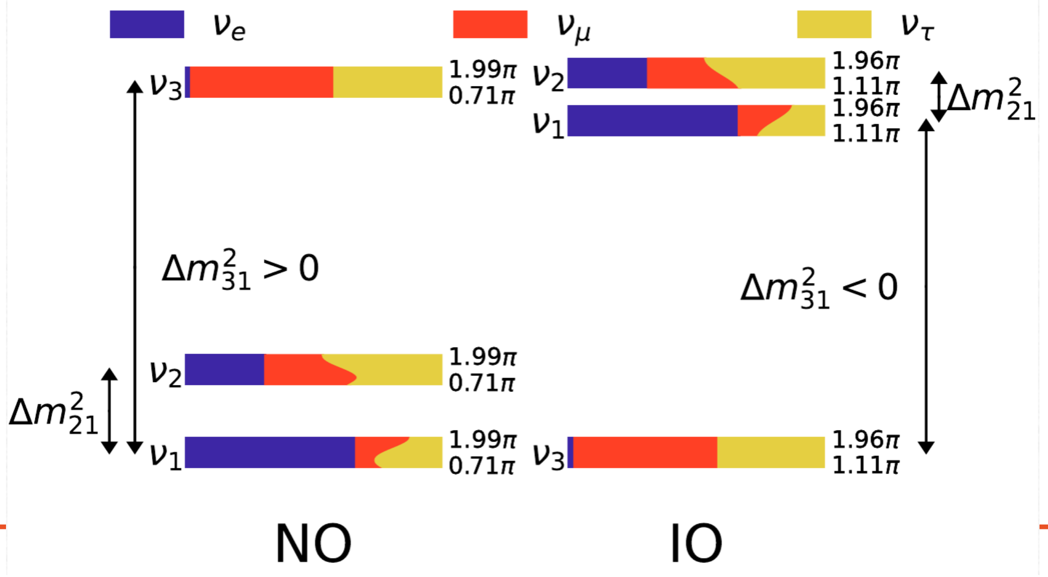
$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix} \qquad |V_{\mathrm{CKM}}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

CP violation in lepton sector can be studied from differences in oscillation between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Accelerator/Reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}}$$

3 Mixing angles: c_{ij}, sij ($\cos\theta_{ij}$ and $\sin\theta_{ij}$)

1 CP violation term δ



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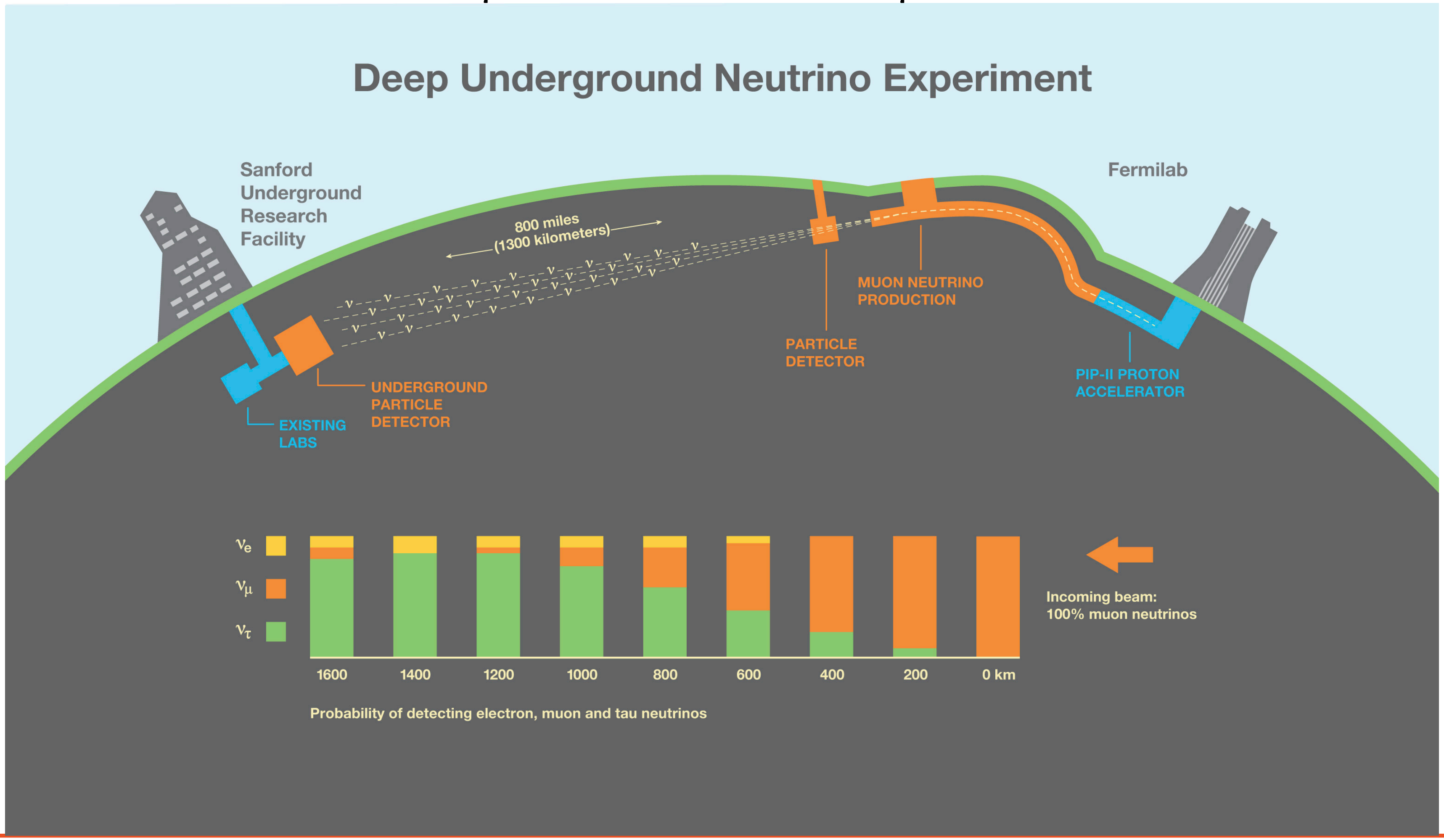


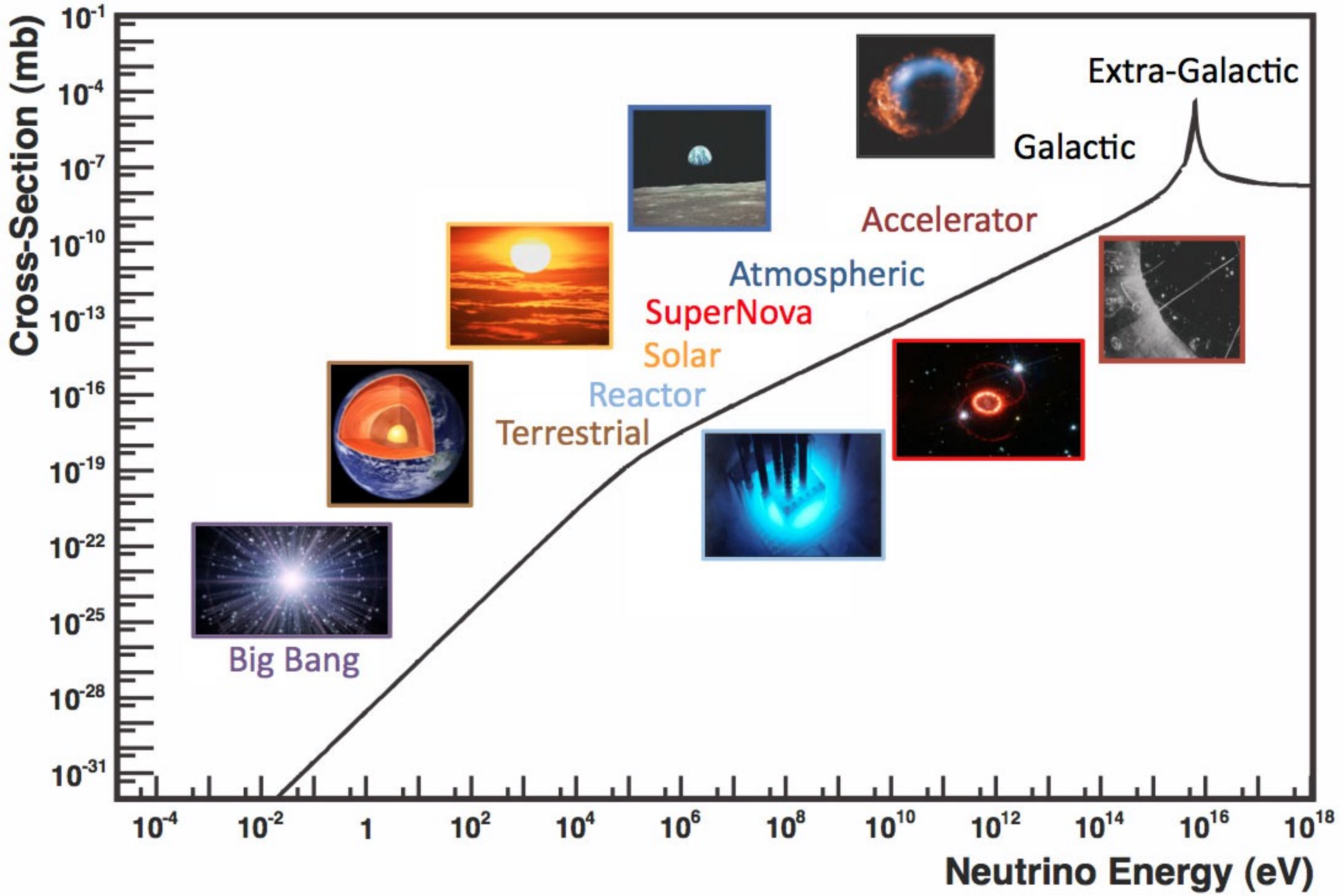
Current best fit values

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

DUNE:
Target resolution of ~0.005 on $\sin^2\theta_{23}$ *and* $\sin^2 2\theta_{13}$

Neutrinos are produced in a variety of physical processes with energy from meV to EeV

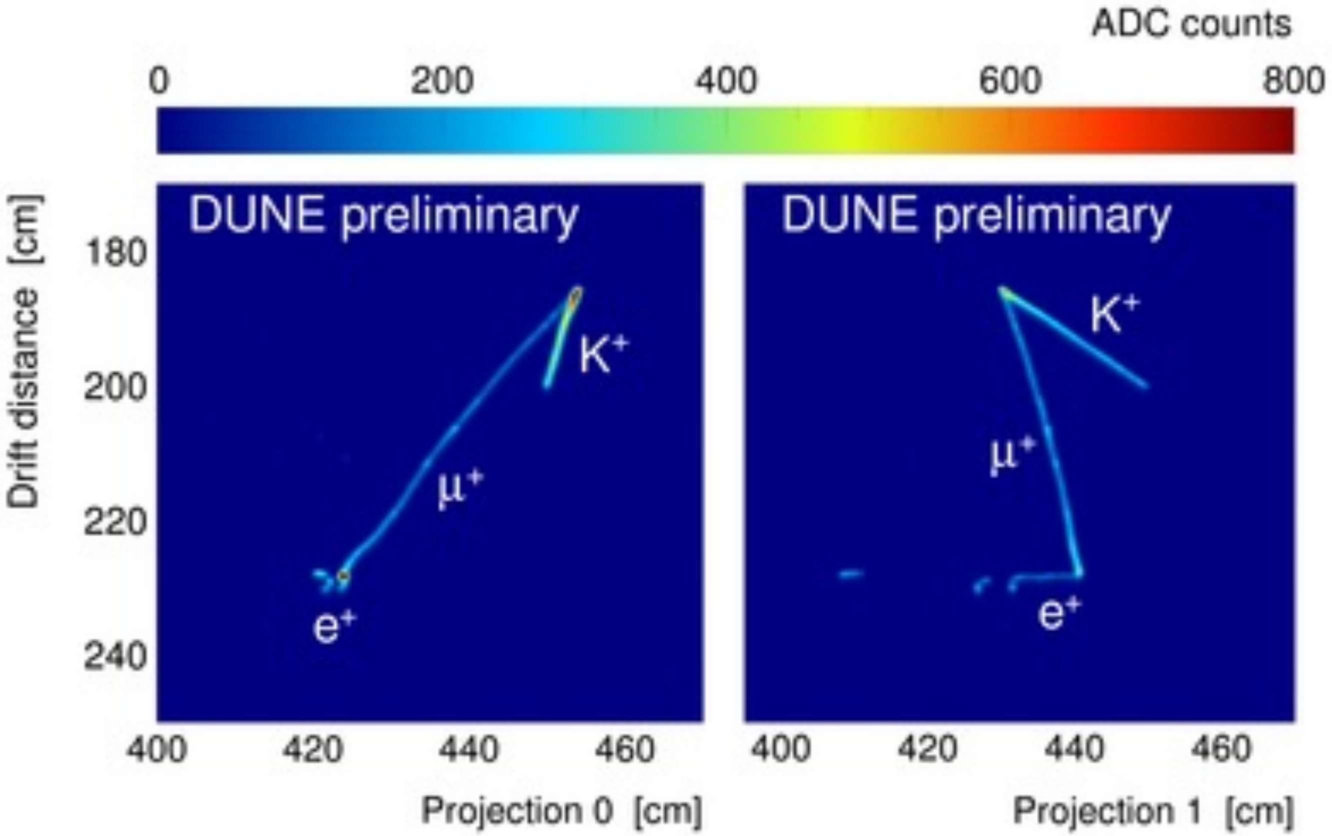
- Sources for neutrino oscillation experiments
  - Solar
  - Atmospheric
  - Reactor
  - Accelerator



DUNE will focus on a wide range of physics goals

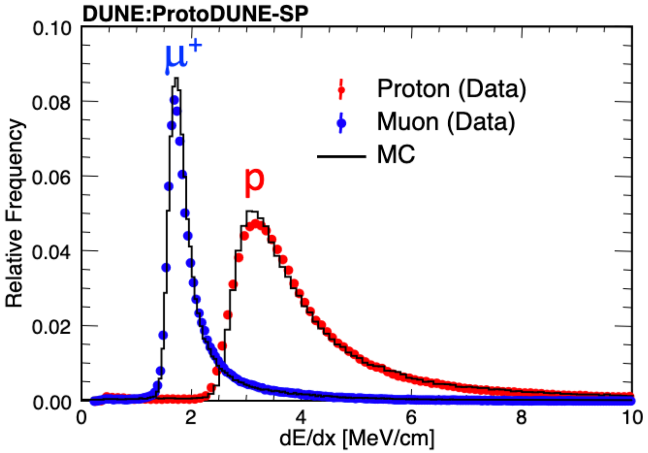
Other primary physics goals

- Look for Proton decay
- Measure ν_e flux from Supernova explosion

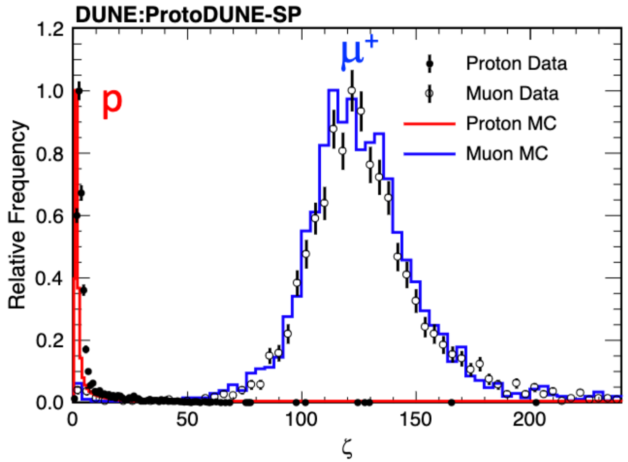


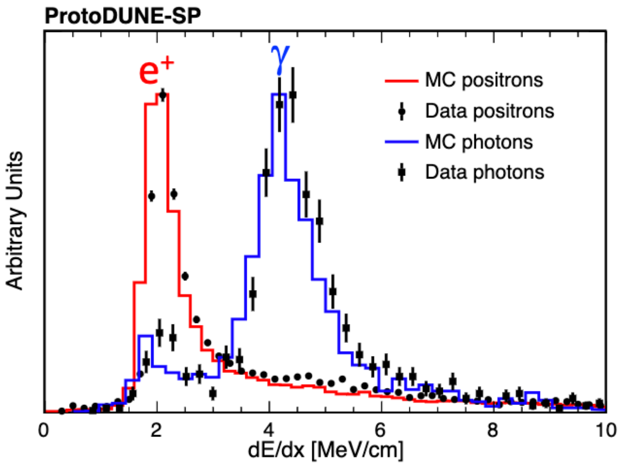
Proton Decay via $p \to K^+ + \bar{\nu}, K^+ \to \mu^+ + \nu_\mu$

dE/dx measurements



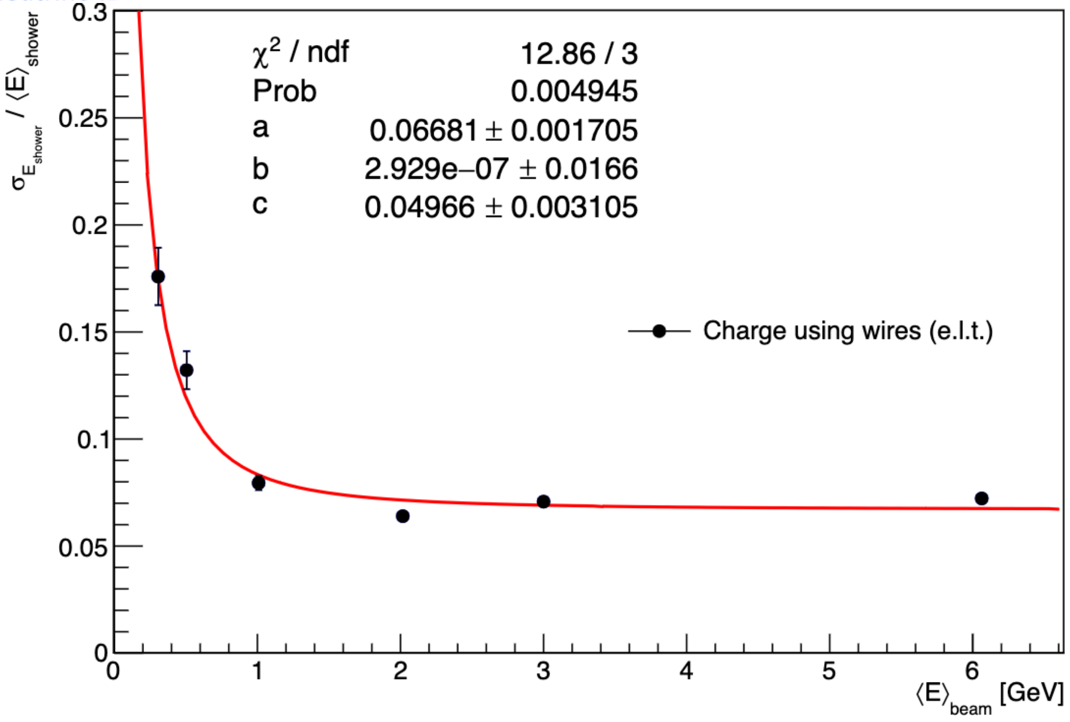
Precise dE/dx leads to excellent μ/p separation





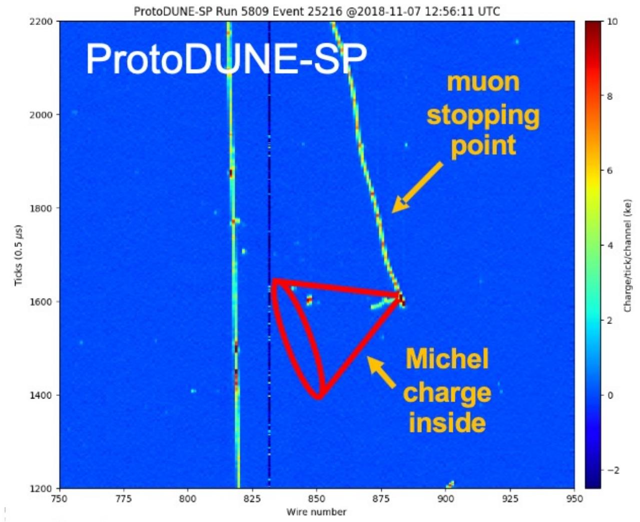
- The calibration constants app test beam particles and yielde data and MC agreements
  - Good μ^+/p separation: crucia cross section measurements
  - Good e/γ separation: crucial DUNE's neutrino oscillation measurements

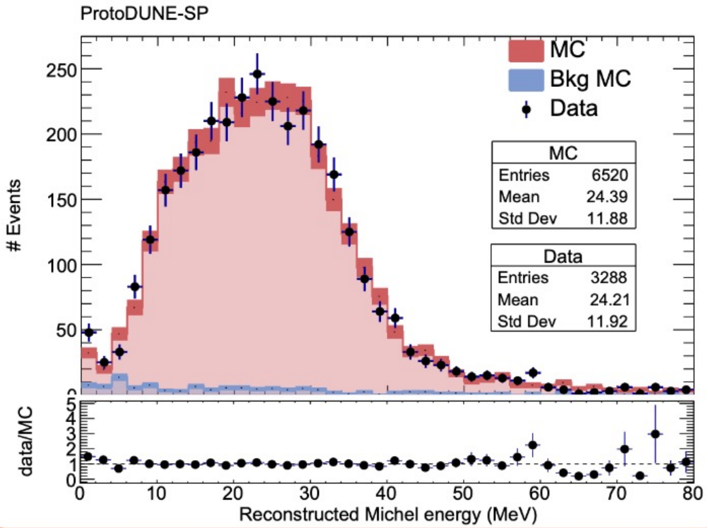
Good e/γ separation crucial for electron neutrino ID



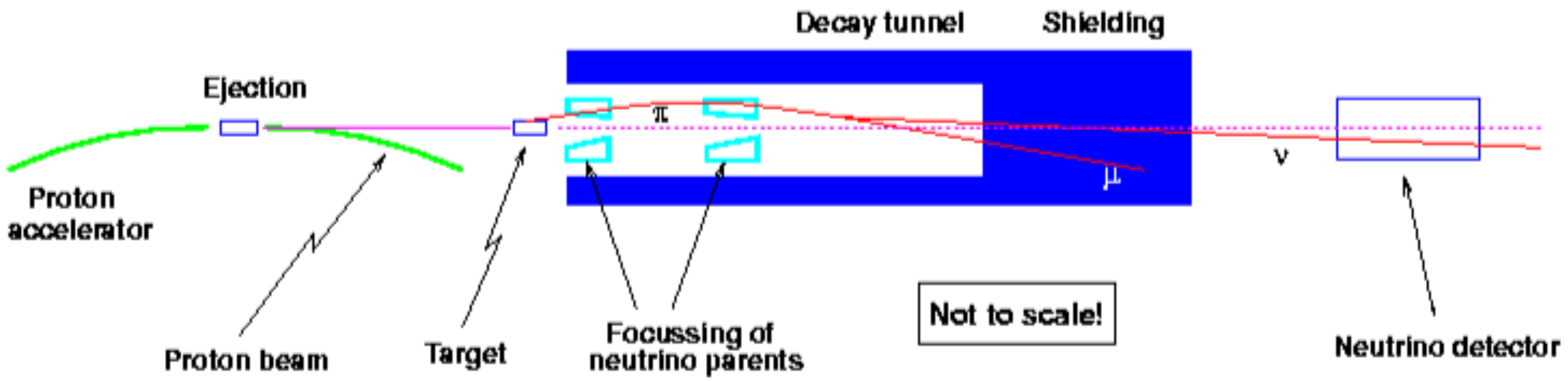
Michel Electron Analysis

- DUNE plans to search for supernova neutrinos (10's MeV) and to measure solar neutrinos (few MeV).
- Michel electrons: a calibration sample to measure detector response to low energy electrons (~10's MeV).
- A cone is defined at the muon end point to include hits produced by Michel.
- The Michel electron selection achieves a 96% purity.
- A good data and MC agreement in reconstructed energy.
- The energy resolution is 26% at 50 MeV.
- Internal note under group review. A paper draft is being composed.





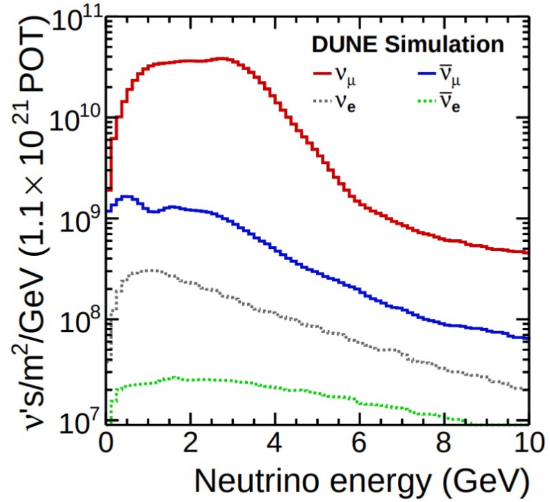
An intense neutrino beam is necessary to probe neutrino oscillations with sufficient precision



~120 GeV

- 4.0×10^{19} neutrinos per year

ν mode

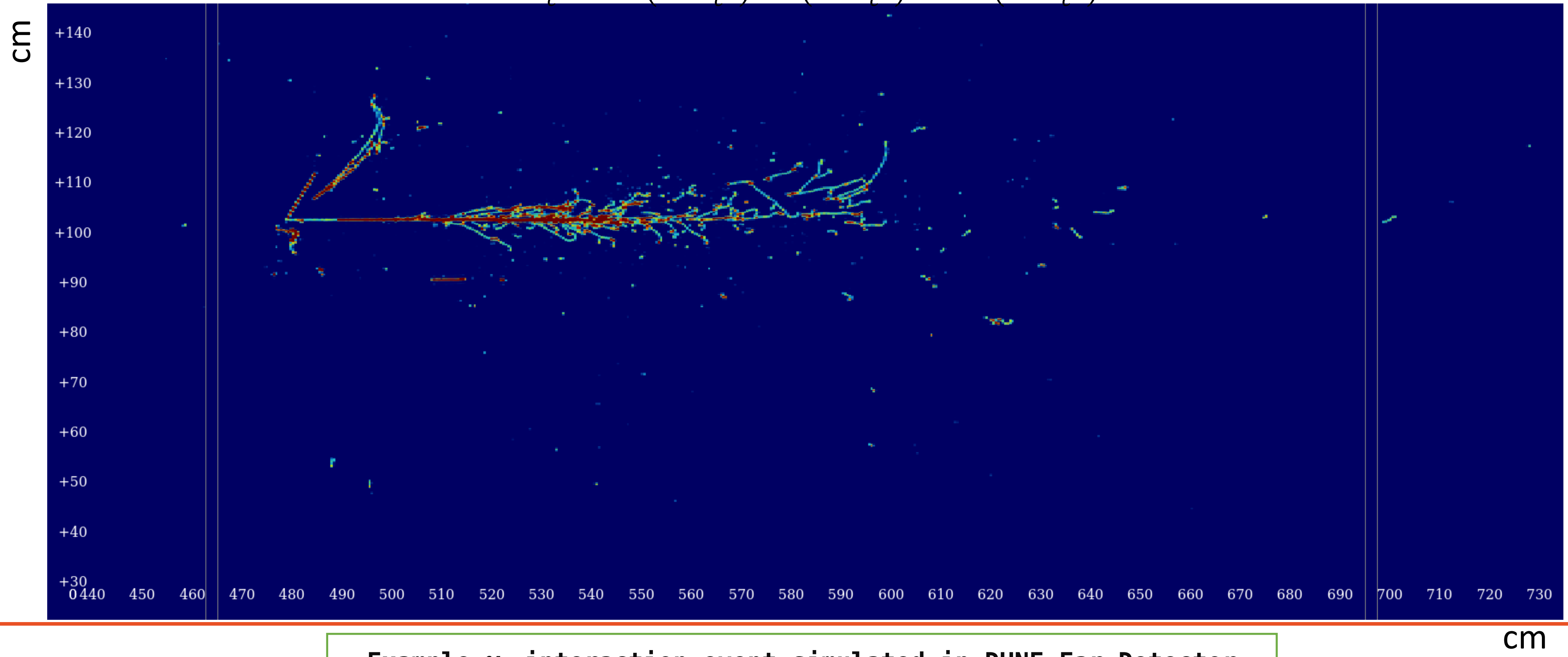


Neutrino energy spectrum in DUNE

Liquid Argon Time Projection Chambers (LArTPC) allow imaging of particle interactions with sub-cm spatial resolution

A $\nu_e\,(4\frac{GeV}{c})$interact with Ar via inelastic resonance (RES)

The decay products are $e^-\,(2.9\frac{GeV}{c})$, $\pi^0\left(0.5\frac{GeV}{c}\right)$, $p\left(0.5\frac{GeV}{c}\right)$ and $n\left(1.2\frac{GeV}{c}\right)$



Example ν_e interaction event simulated in DUNE Far Detector

DUNE timeline

2024

Start of ProtoDUNE II

2028

FD I and II are ready for operation

- ✓ Physics without beamline starts

2031

Beam and ND complex are ready for operation

- ✓ Start of oscillation physics measurement

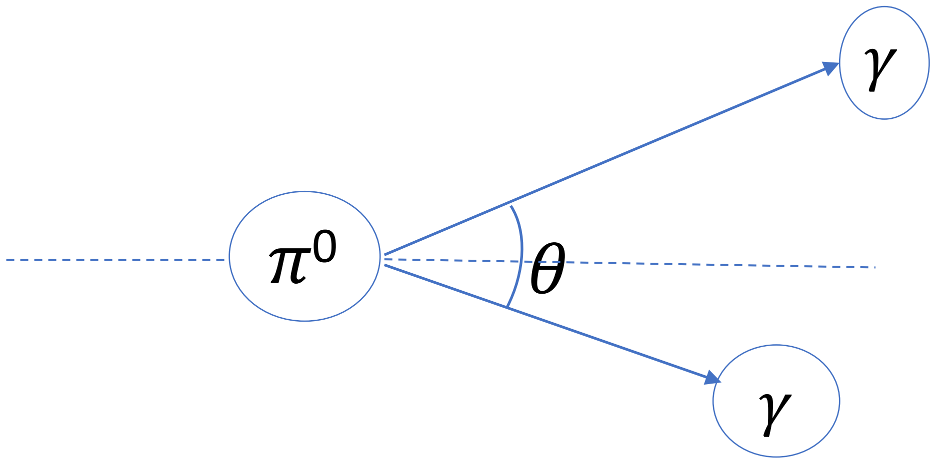
203X -...

Add FD III and IV, upgrade Beam power and complete ND

- ✓ DUNE at full design

DUNE activities @ Nikhef

- π^0 event reconstruction
  - Important background in neutrino flavor identifcation
  - Important candle for validating detector EM shower response



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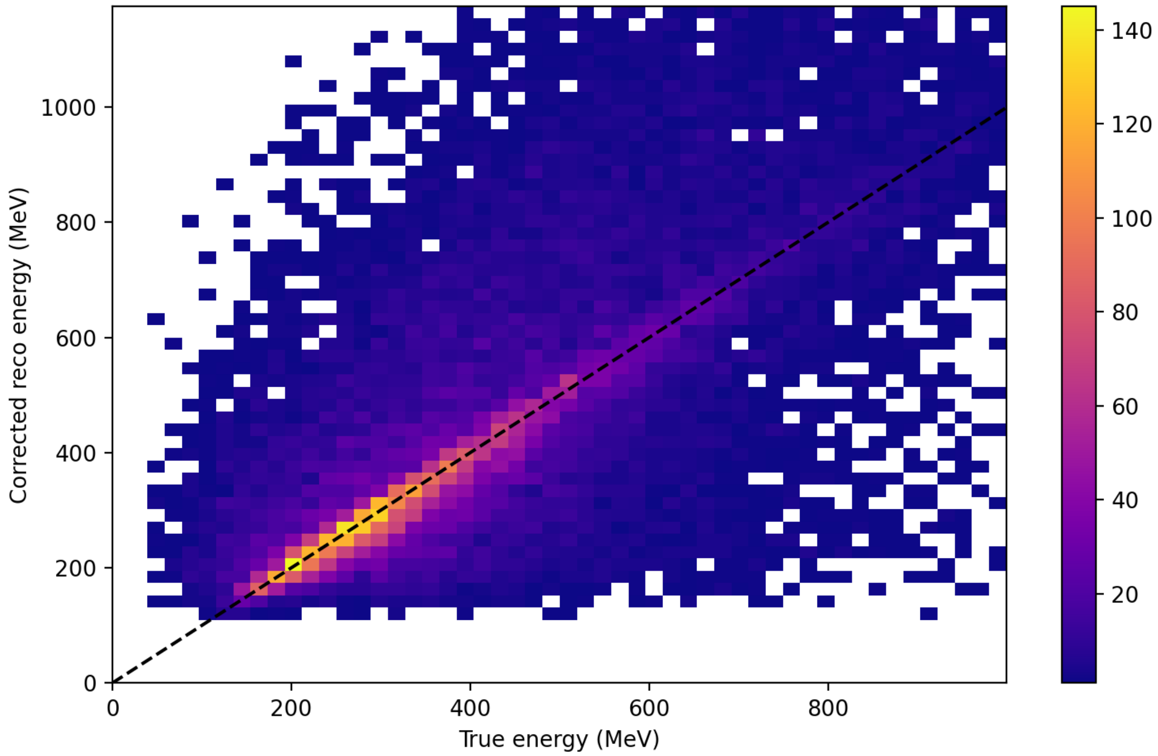
Shower energy reconstruction



$E_{corr} \approx E_{reco} / 0.851$

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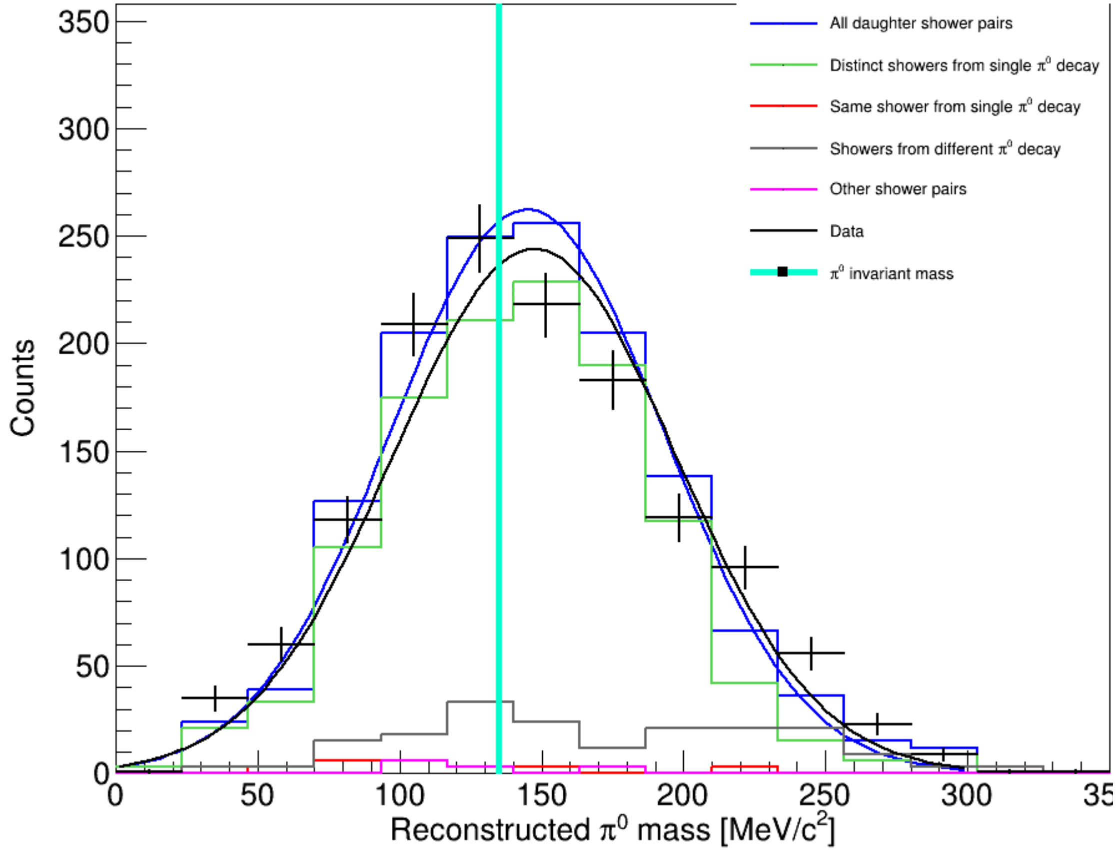

DUNE activities @ Nikhef

- Photon Detection system of DUNE
  - X-Arapuca: light trapping to maximize PDE.