DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

ugr Universidad de Granada

The Deep Underground Neutrino Experiment (DUNE)

Overview and Physics Potential

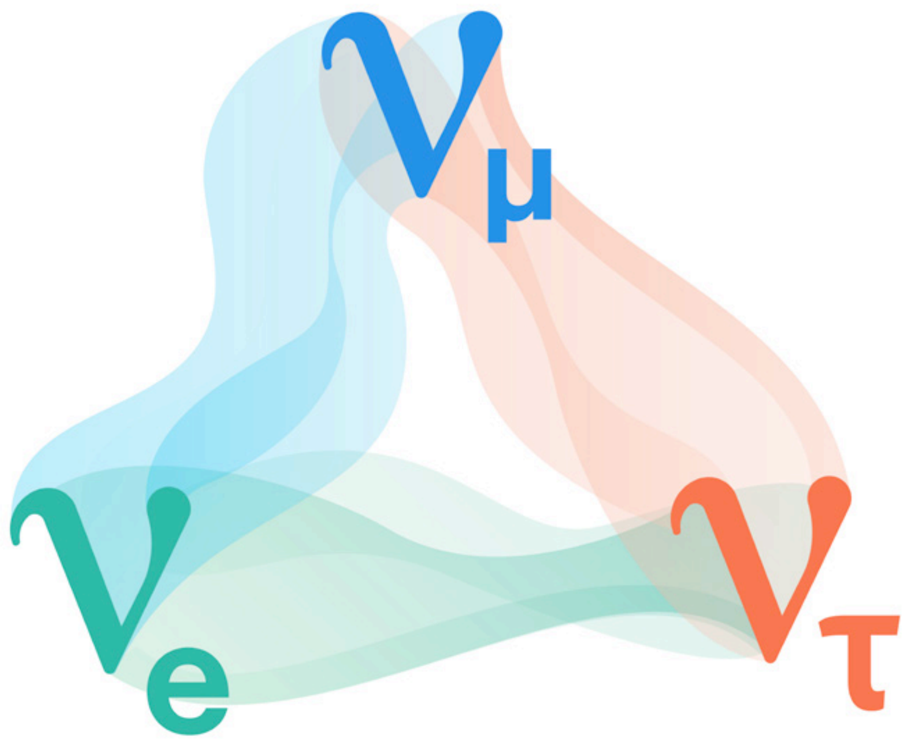
Marciana 2025 - Lepton Interactions with Nucleons and Nuclei

Patricia Sanchez-Lucas
on behalf of the DUNE Collaboration

Isola d’Elba, 25 June 2025

Briefly on Neutrino Physics …. what we know so far

- Neutrinos: one of the most abundant particles in the Universe
- They carry threes flavours (ν_e, ν_μ, ν_τ)
- Different sources and broad energy range (meV -EeV)
- Flavour oscillations have been observed
- Neutrinos have mass
- Oscillations only sensitive to Δm^2



Flavour States | **Mixing PMNS Matrix** | **Mass States**

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

Briefly on Neutrino Physics …. what we know so far

- PMNS Parameterisation: 3 mixing angles (θ_{12}, θ_{13}, θ_{23}) and 1 CP-violating phase (δ_{CP})

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

ATMOSPHERIC + ACCELERATOR SECTOR

REACTOR SECTOR

SOLAR SECTOR

2-flavour appearance probability

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L(km)}{E(GeV)}\right)$$

Interplay between neutrino energy and travel distance

→ Different experiments, Different sensitivities

Briefly on Neutrino Physics …. what we know so far

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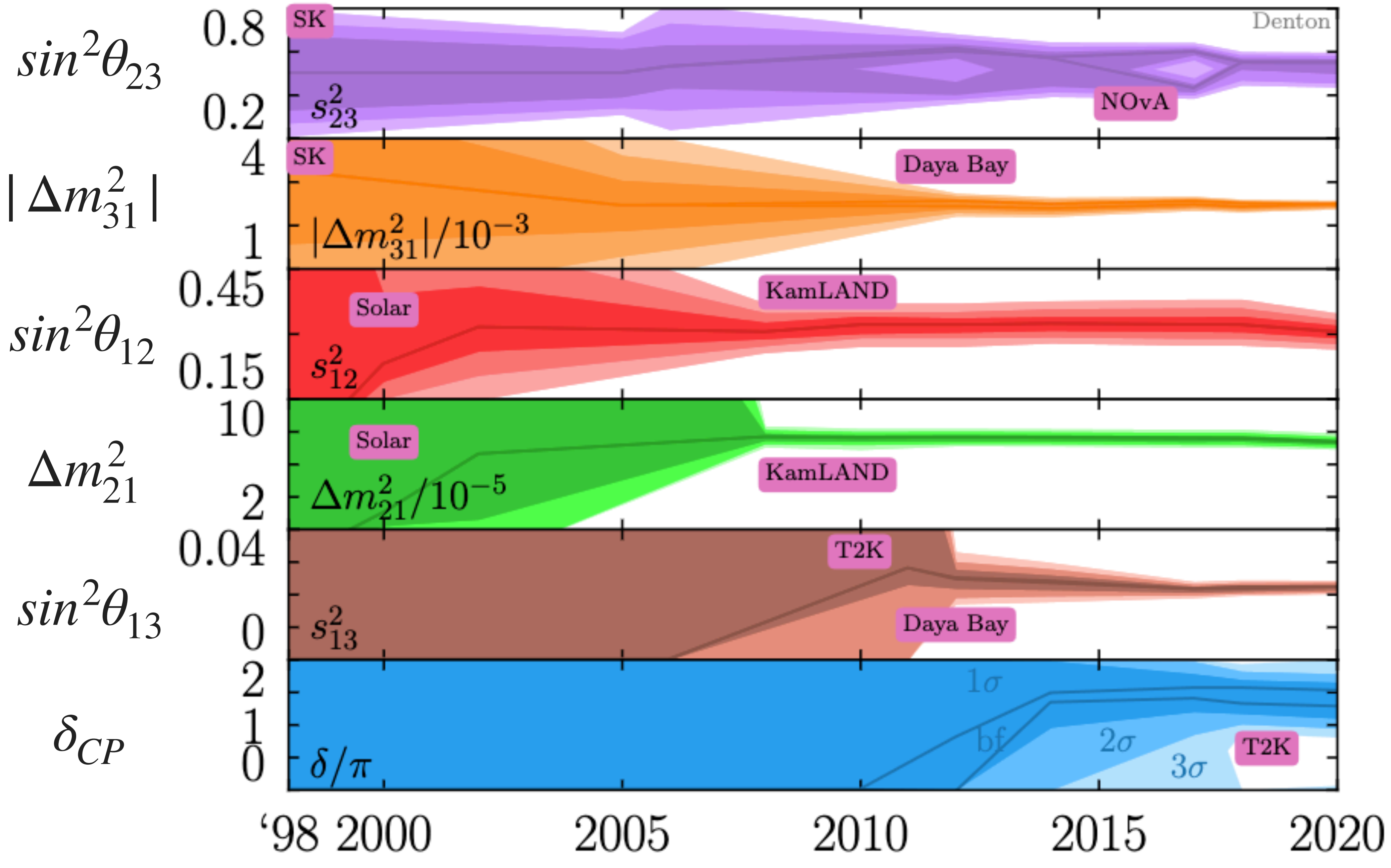
P. Denton, arXiv:2212.00809



M. Tortola, Neutrino2024

parameter	best fit ± 1σ	3σ range	
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	2.7 %
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NO)	$2.51^{+0.02}_{-0.03}$	2.43–2.58	1.0 %
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (IO)	$2.41^{+0.03}_{-0.02}$	2.34-2.49	
$\sin^2\theta_{12}/10^{-1}$	$3.04^{\pm}0.16$	2.57–3.55	5.4%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23–6.04	3-4%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	4.27–6.03	
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	2.03–2.38	2.6%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04–2.38	
δ/π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00	10-15%
δ/π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87	

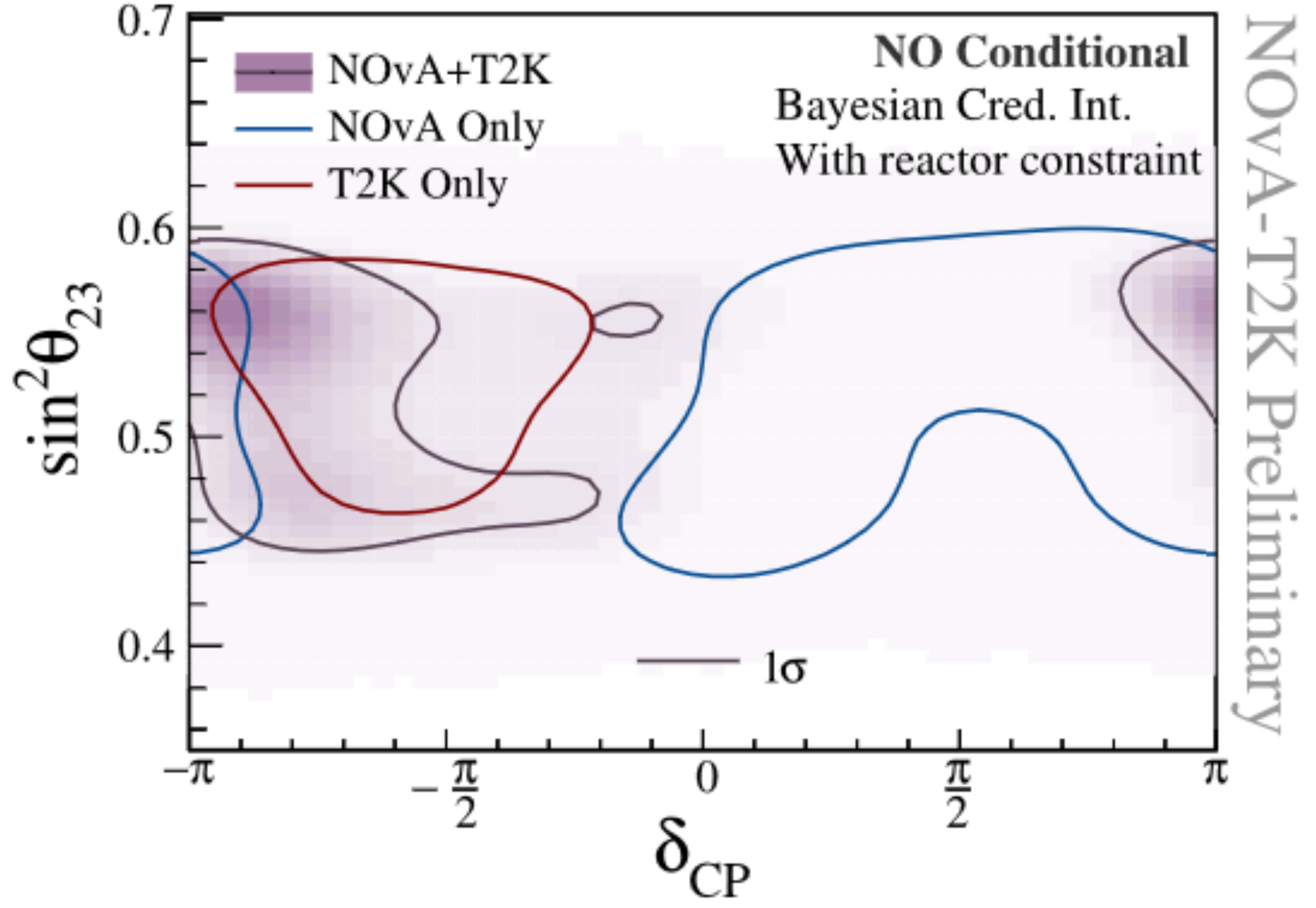
Known parameters: $\theta_{12}, \theta_{23}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{31}|$

Unknown parameters: Mass ordering (sign of Δm^2_{31}) and δ_{CP}

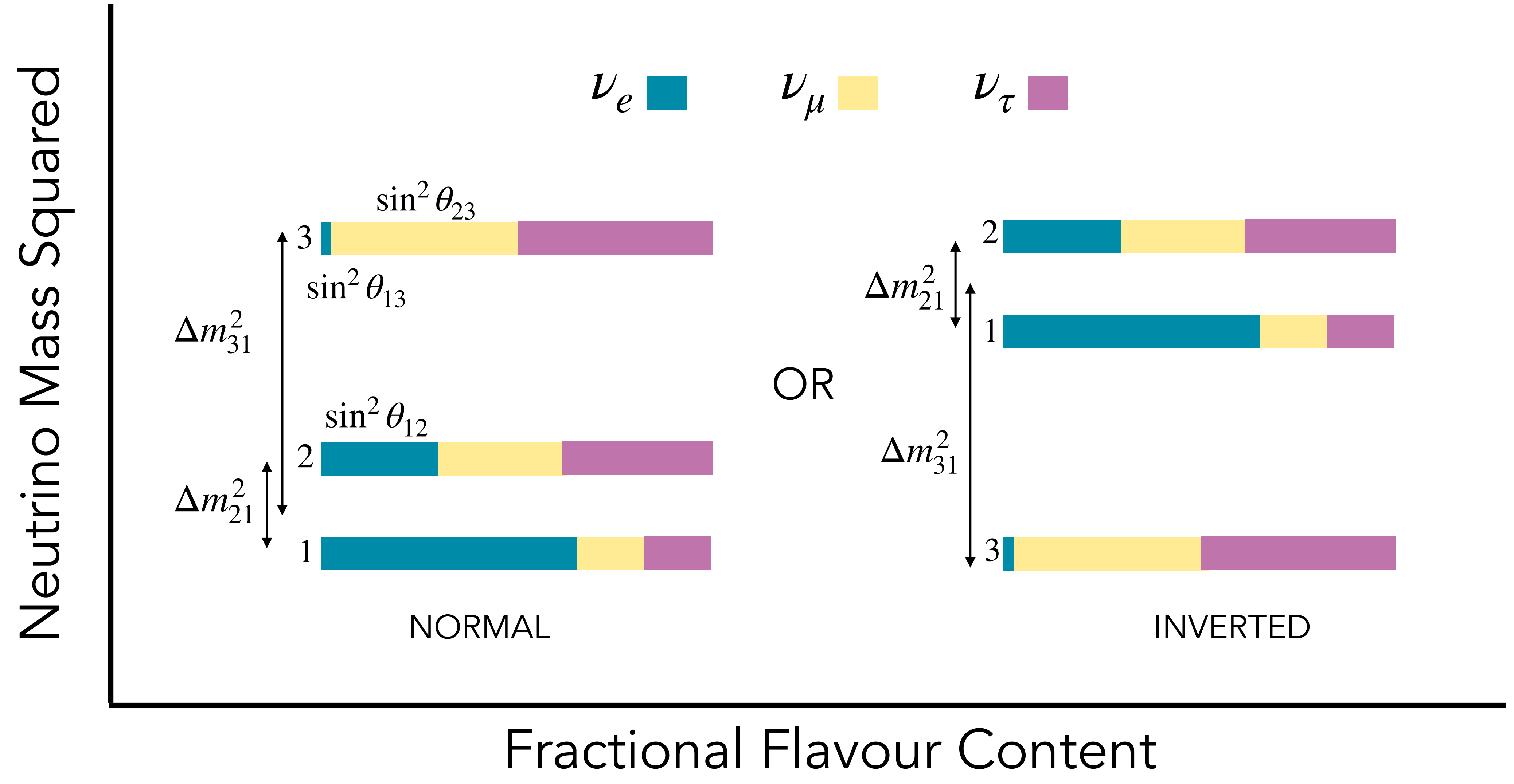
Briefly on Neutrino Physics …. what we certainly don't know yet

- Neutrino nature (Dirac vs Majorana)
- The absolute neutrino mass scale
- Neutrino mass generation mechanism
- Neutrino mass ordering (normal/inverted)
- CP violation - $\delta_{CP?}$

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)



- Some tension in the value of δ_{CP} for NO



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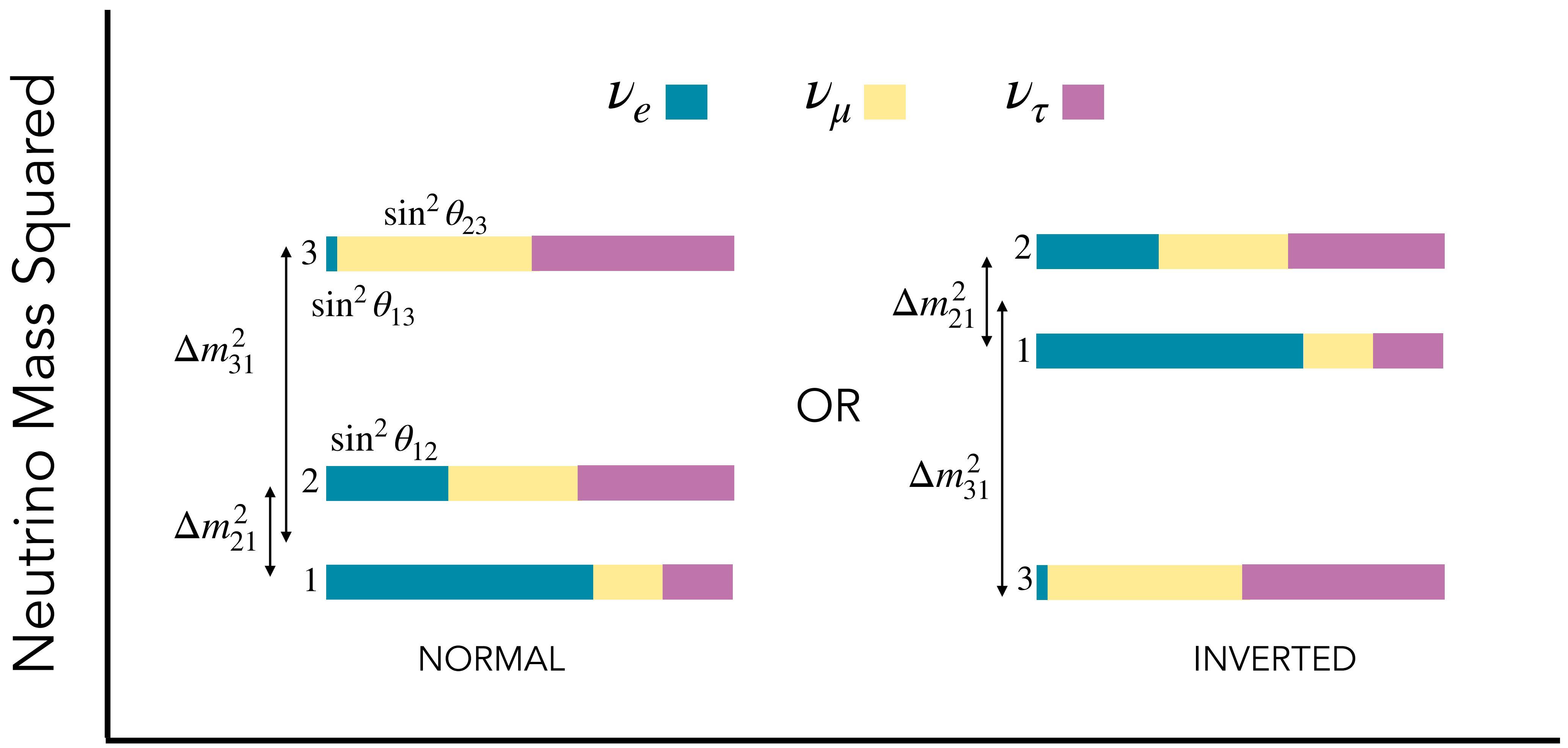
DUNE MAIN GOALS



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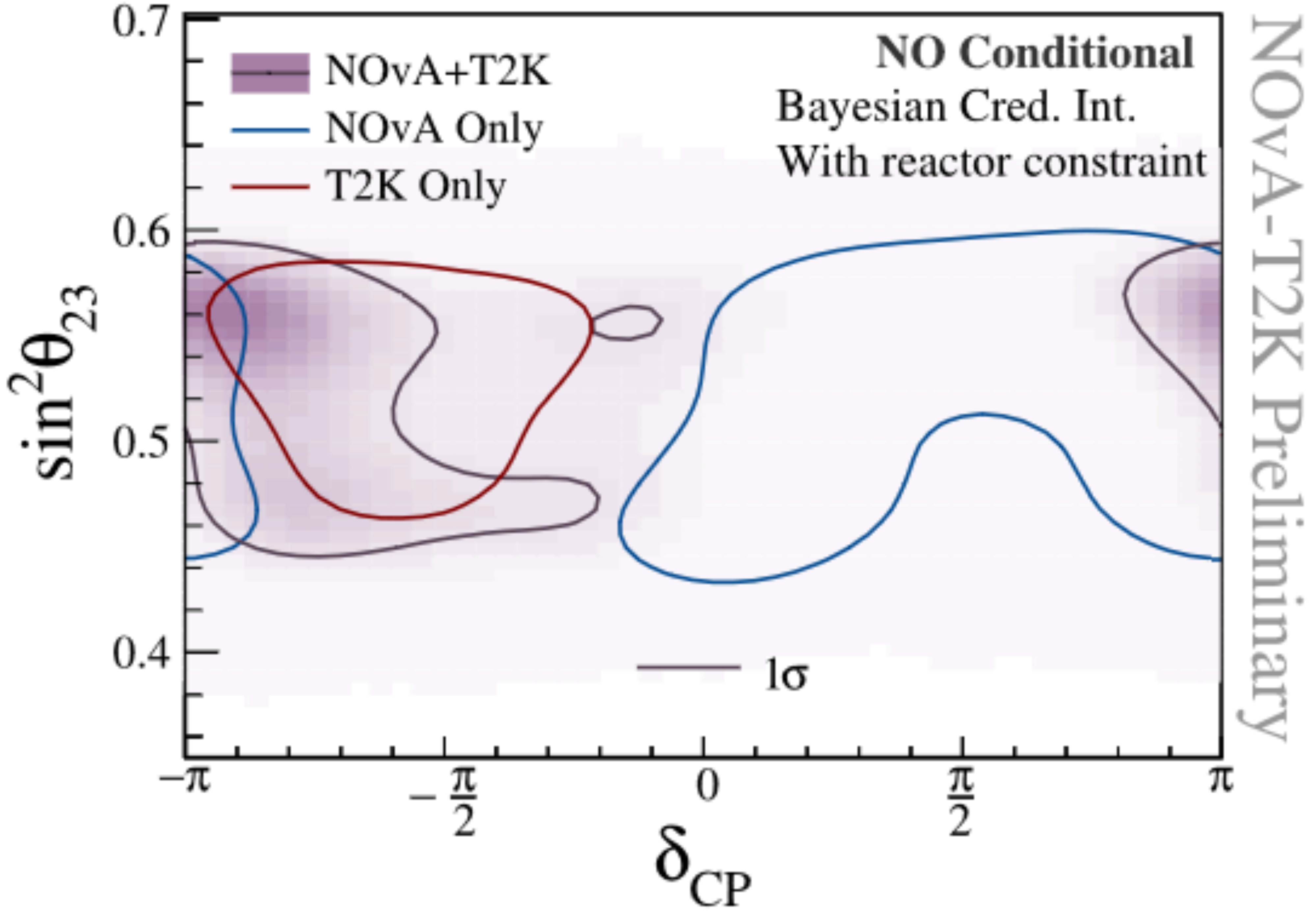

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DUNE in a nutshell

Long-Baseline Neutrino Oscillation Experiment

① Muon neutrino beam

- 1.2 MW beam power
- Upgradeable up to 2.4 MW

② Near Detector (ND)

- 574m from the beam
- Unoscillated flux monitoring (energy spectra & composition)
- νAr cross-section measurements

③ Massive Far Detector (FD)

- 1300 km from the ND
- Measurement of oscillated neutrinos
- Technology: LArTPC

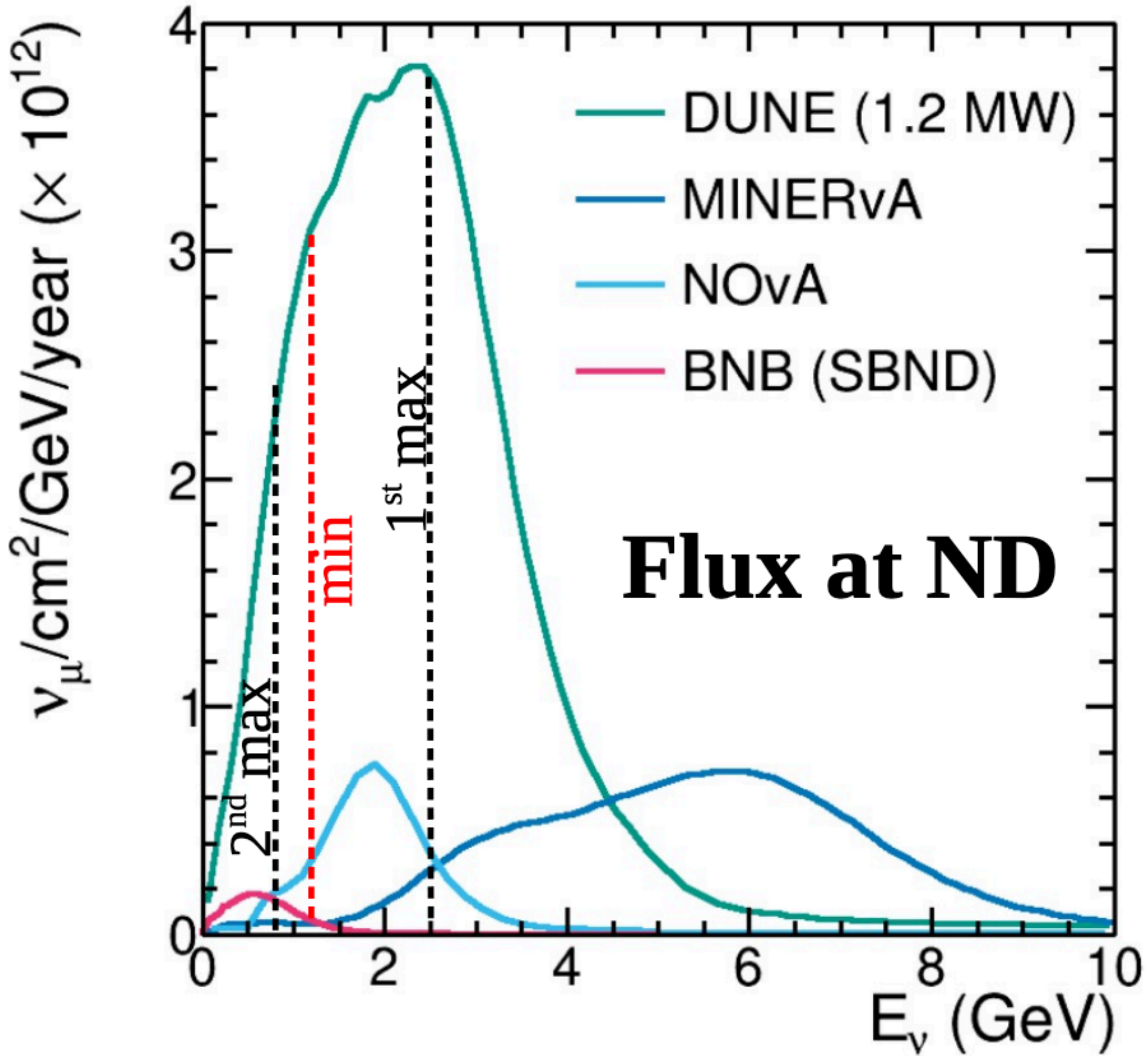
DUNE beam and oscillation probability

Precision measurements of the parameters that govern:

$P(\nu_\mu \longrightarrow \nu_e)$

$P(\bar{\nu}_\mu \longrightarrow \bar{\nu}_e)$

- Very high flux peaked at 2.5 GeV neutrino energy
- Coverage of first and second oscillation maximum
- Neutrino and Anti-neutrino mode
- With 1300 km baseline, the oscillation probability has a strong **dependence on both δ_{CP} and mass ordering**
- The access to several maxima is crucial to resolve the degeneracy



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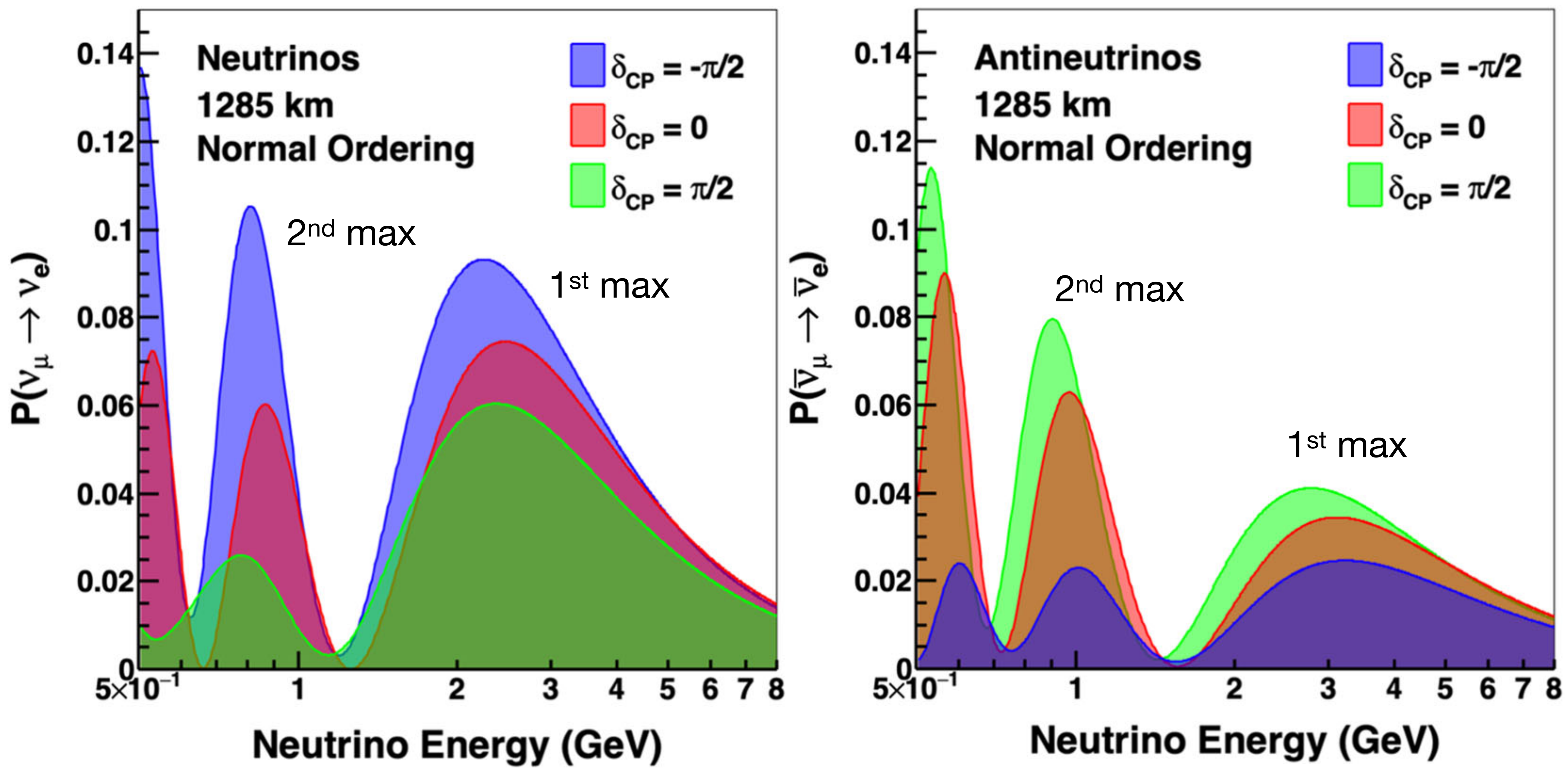


DUNE collaboration. Eur. Phys. J. C (2020) 80:978

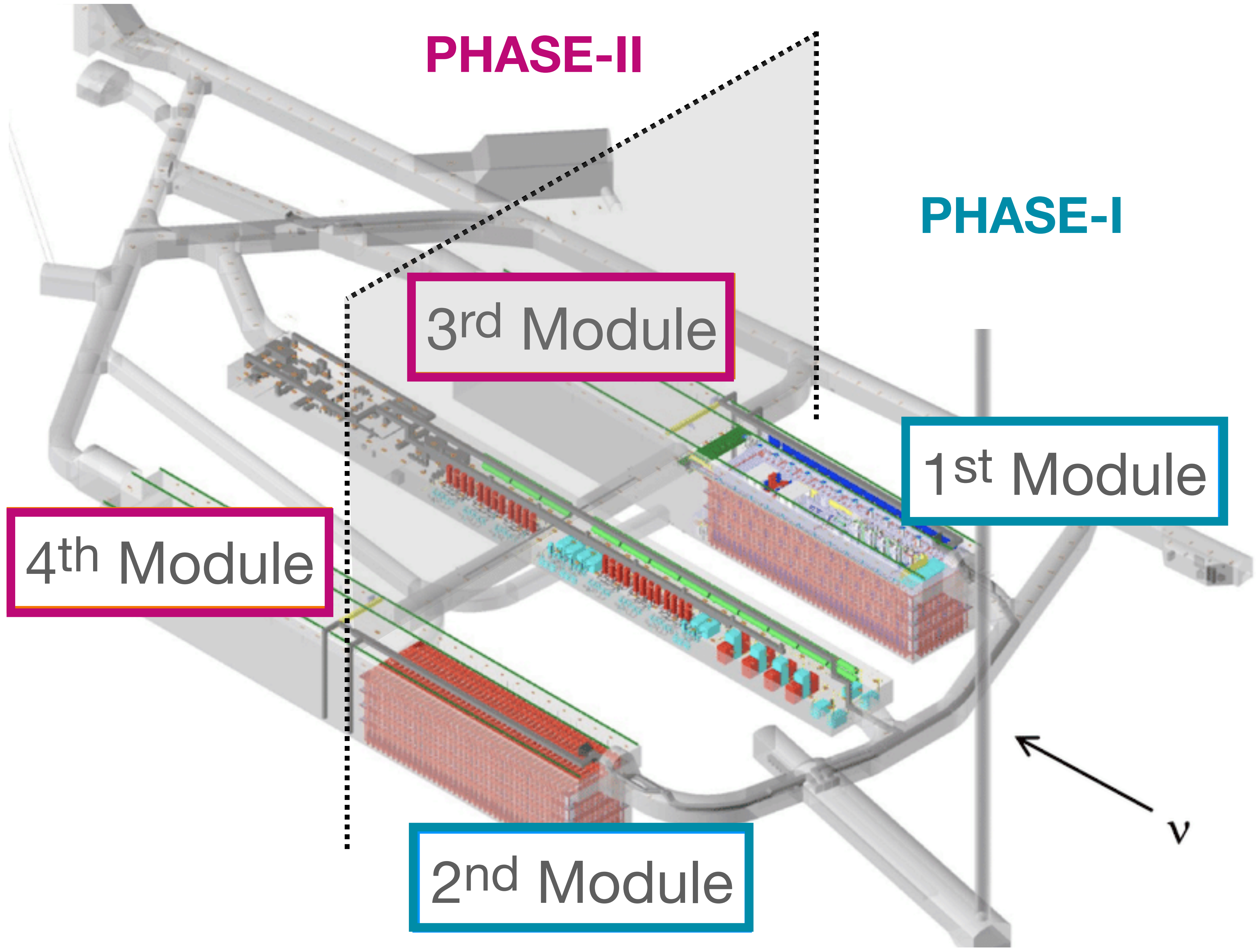
DUNE Phase Approach

PHASE-I

- **Full Near and Far site facilities**
- 1.2 MW upgradable neutrino beamline
- Far Detector (FD): Two LArTPCs modules (17 kt each)
- Near Detector (ND): three detectors including a LArTPC and a temporary muon spectrometer

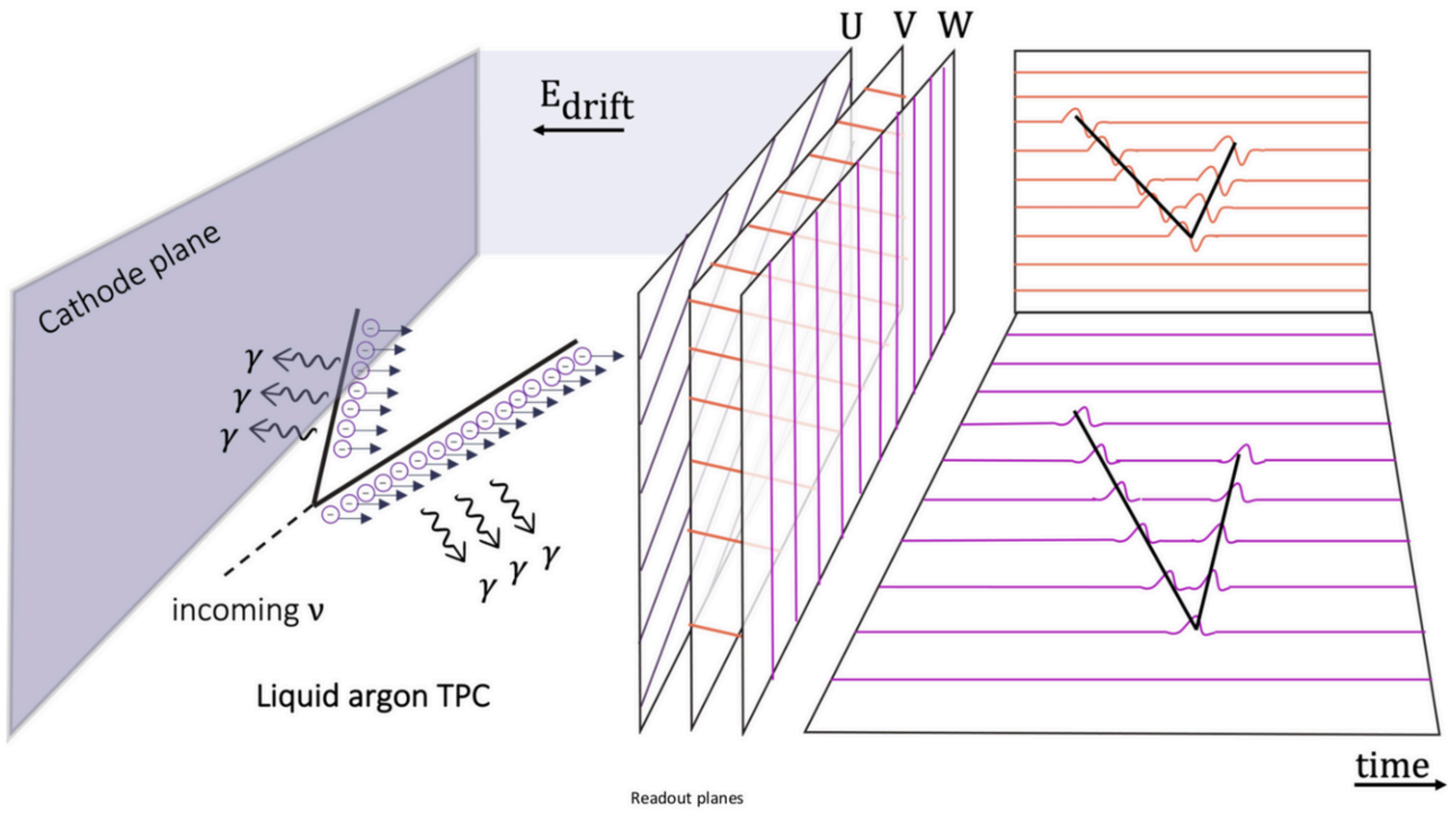
PHASE-II

- Beamline upgrade to > 2MW
- Two additional FD modules (four in total for 70 kt)
- A more capable ND



Overview of the Far Detector Site at SURF

Working principle of LArTPC



Example of single phase & horizontal drift (wp.lancs.ac.uk)

Interactions in a LArTPC

two signals proportional to the energy

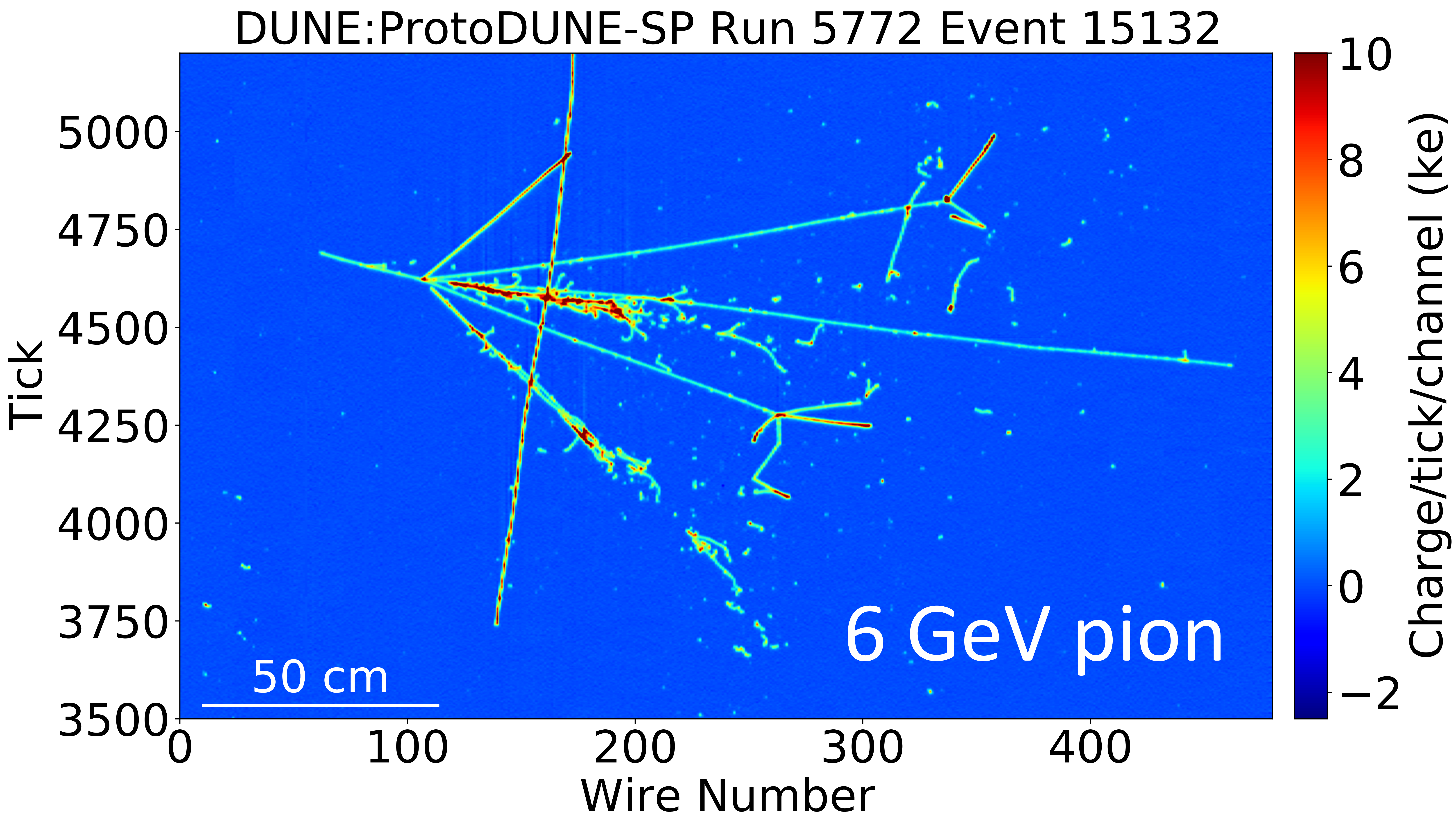
ionisation electrons	scintillation photons
~27000 e^-/ MeV	~24000 γ / MeV

For 500V/cm drift field

drifted and collected in charge readout planes → **Precise tracking and calorimetry**

observed by the photon detection system → **t_0 and complementary calorimetry**

LArTPC images



- Spatial resolution ~mm
- Time resolution 14 ns

ProtoDUNE-SP (JINS 15 (2020) P12004)

The LArTPC technology provides **excellent imaging capabilities** over large detector volumes

⇩

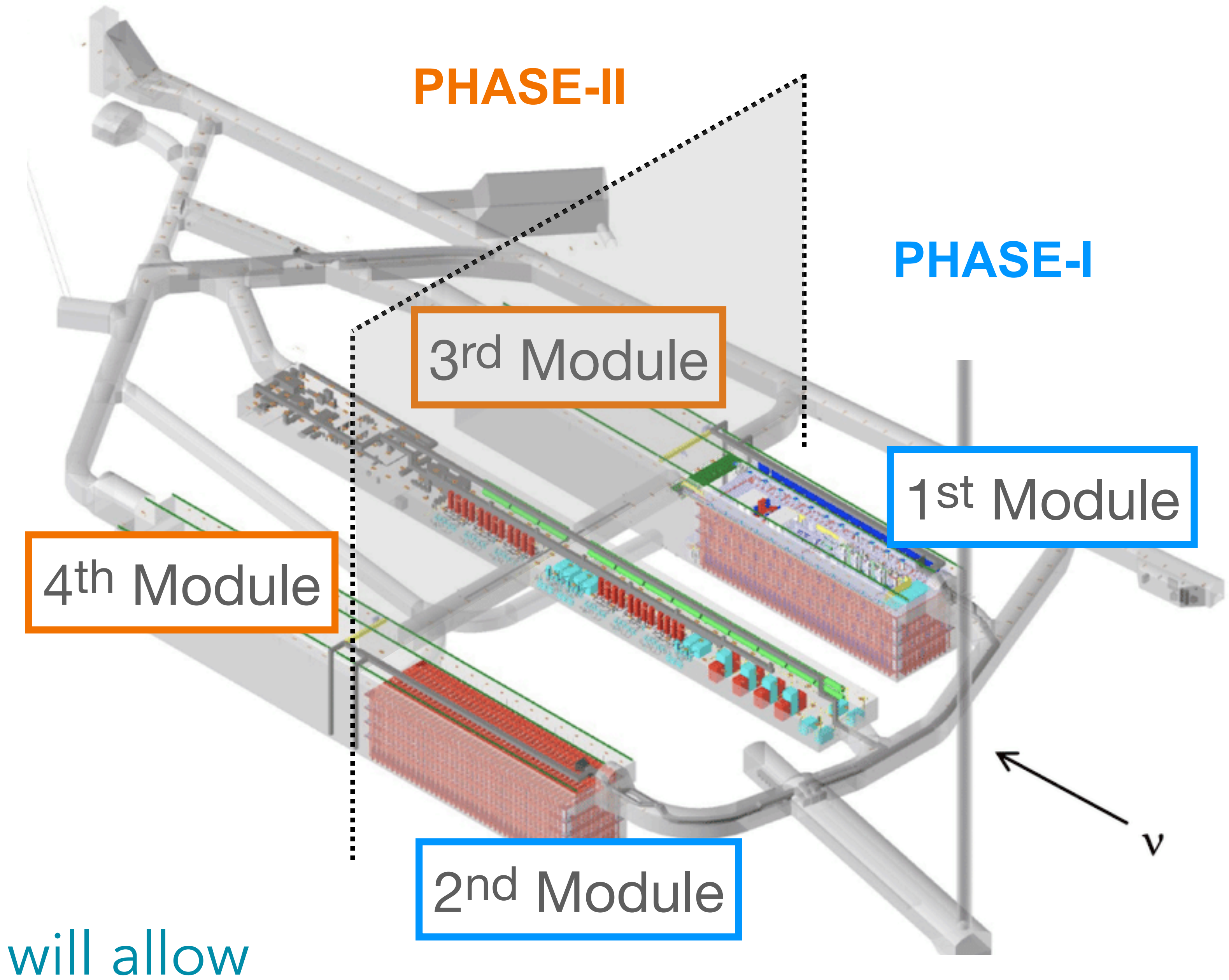
High-quality particle ID and energy reconstruction

The DUNE Far Detector (FD)

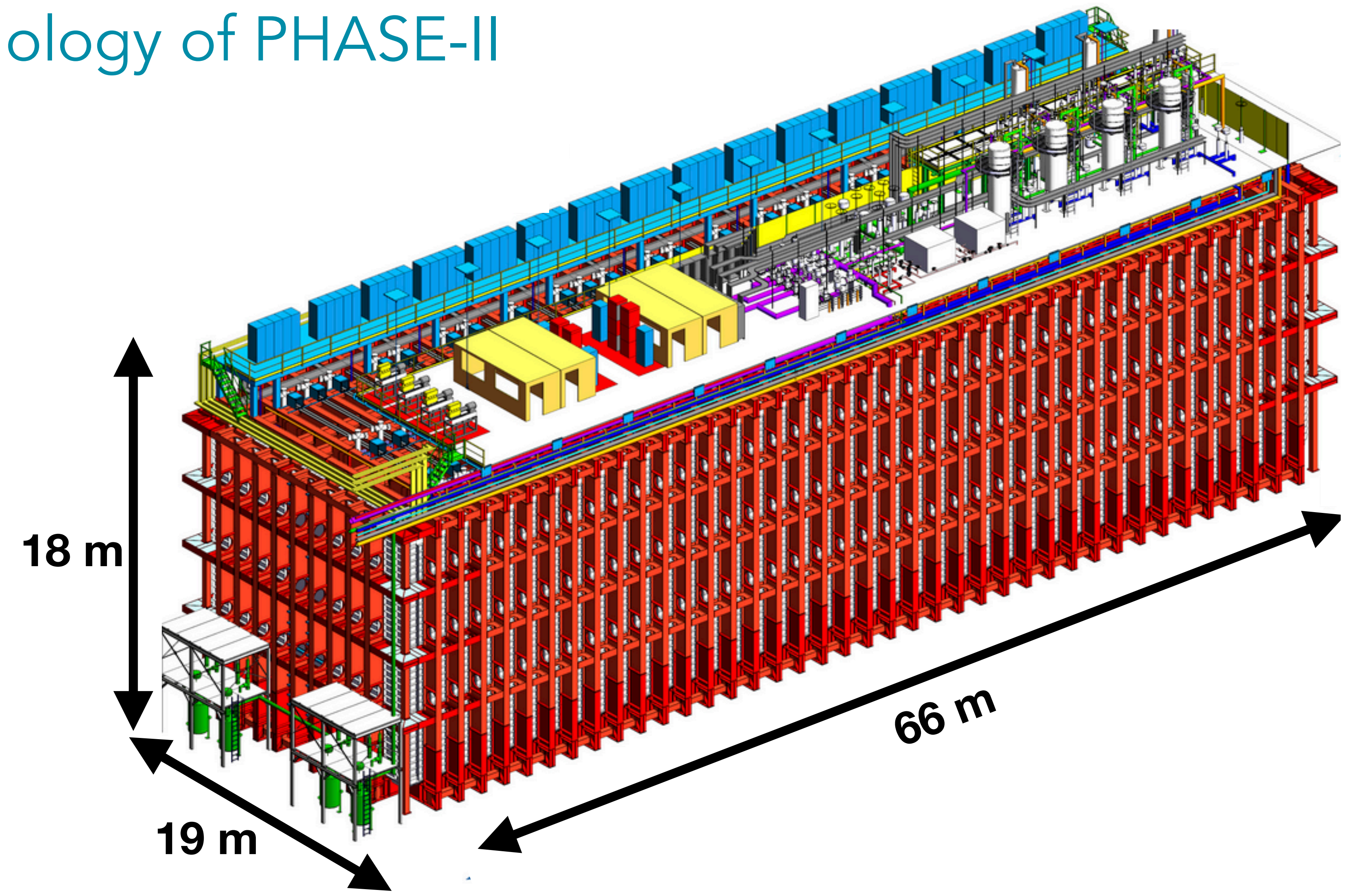
A massive 70 kt detector deployed in 4 modules

- Sanford Underground Research Facility (SURF)
- 1300 km apart from ND
- 1500 m underground (4300 m.w.e.)
- 4 modules in two different 2 caverns

  - Modules 1, 2 and 3: **LArTPCs**
  - Module 4: **Module of Opportunity**
    - └→ Different technologies under consideration

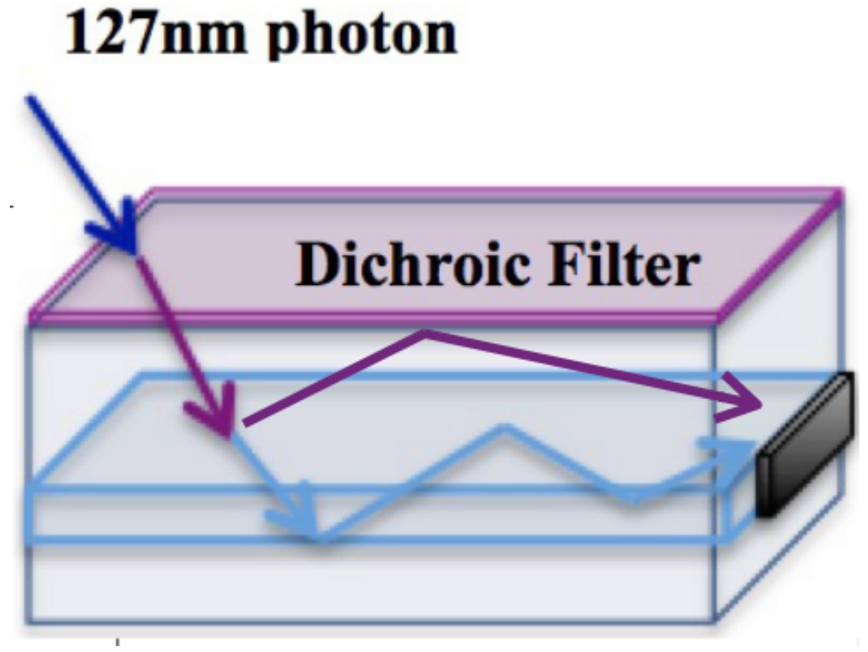


The phased approach will allow improvements in the technology of PHASE-II

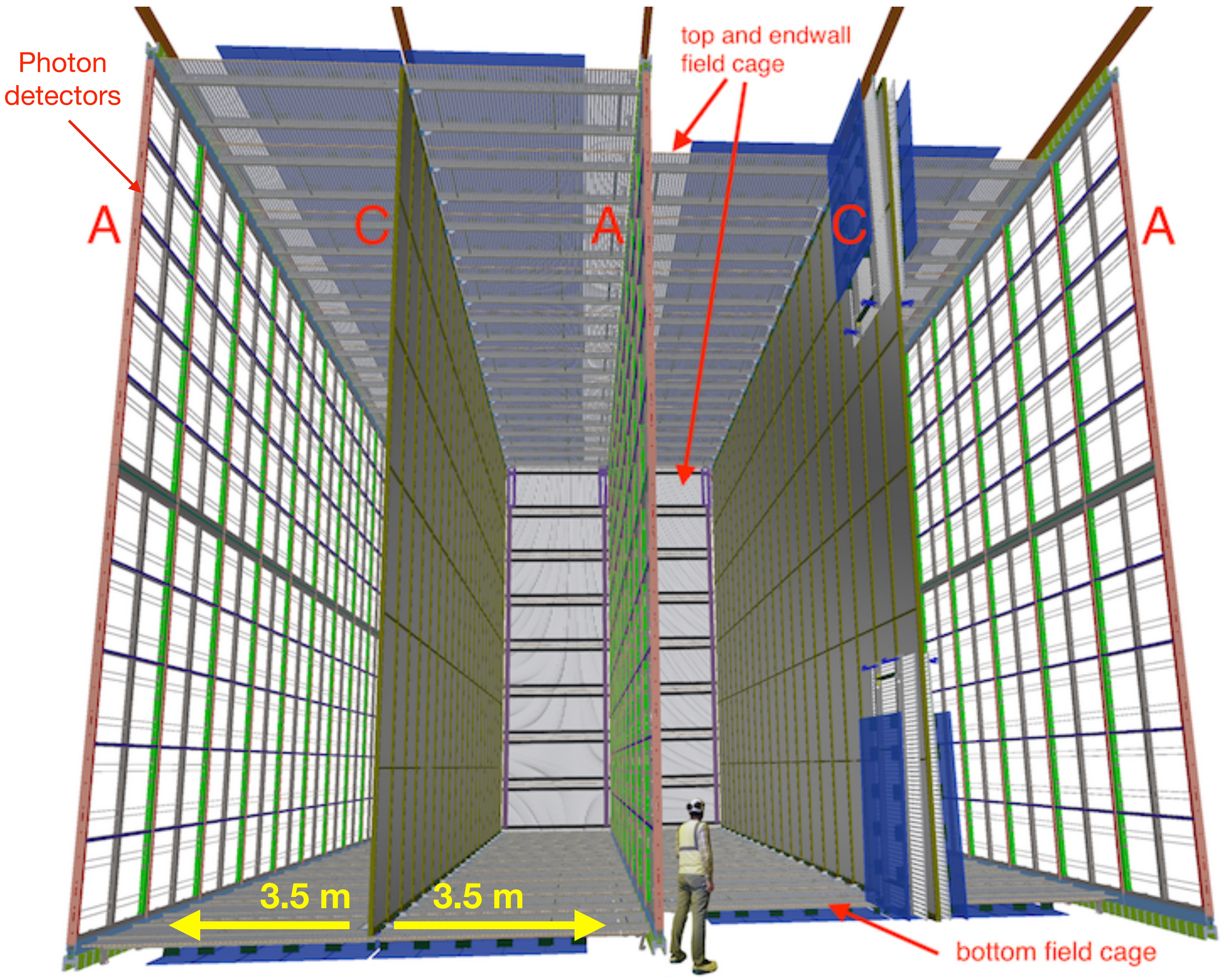


Far Detector Horizontal Drift (FD-HD)

- **Long-stablished and validated technology**
- TPC size: 12m x 14m x 58.2 m
- 4 horizontal drift regions (3.5 m)
- Drift Voltage 500 V/cm
- Vertical cathode and anode planes
- Photon detectors on the anode planes
- Photon detection based on X-Arapucas

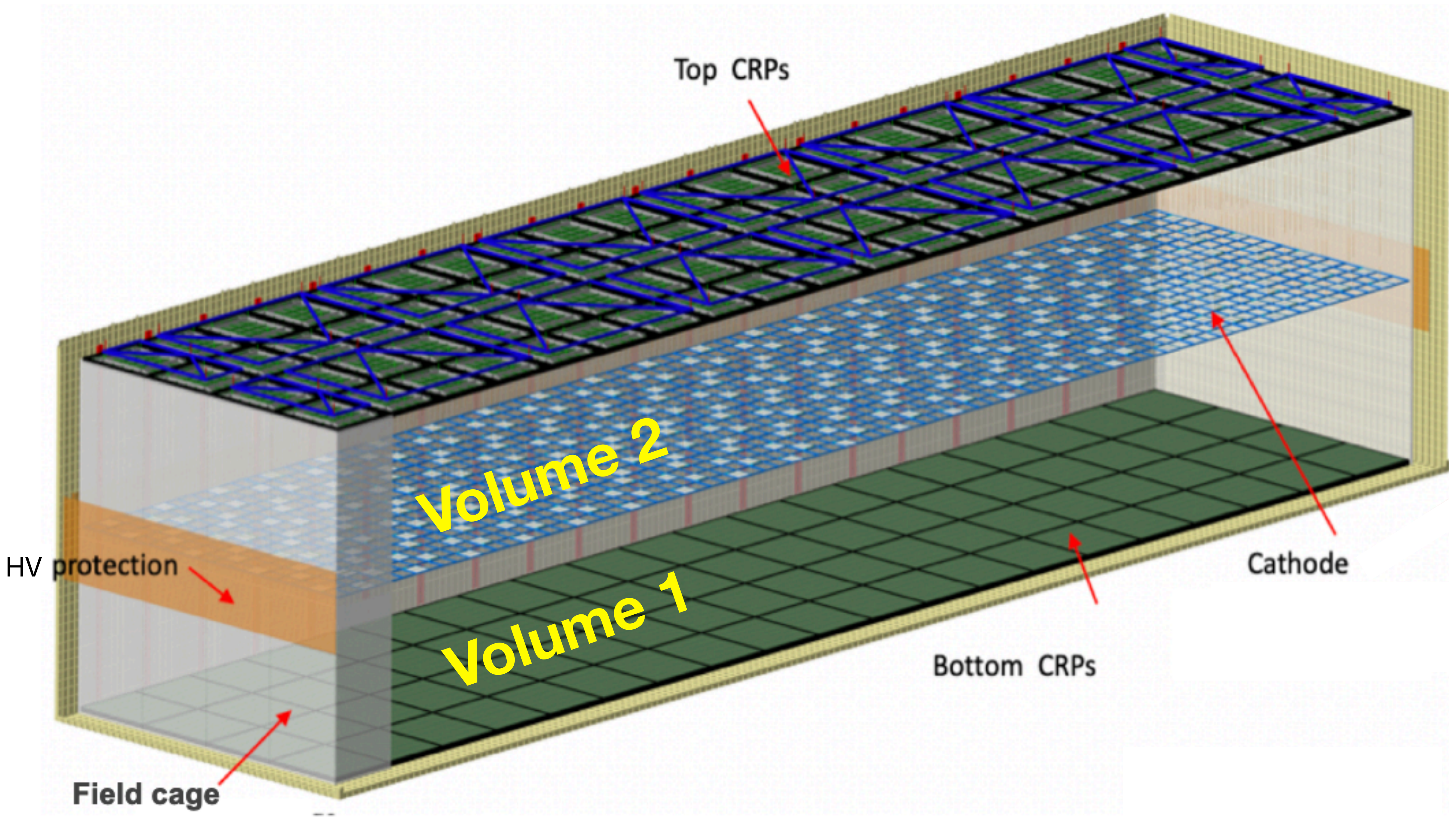


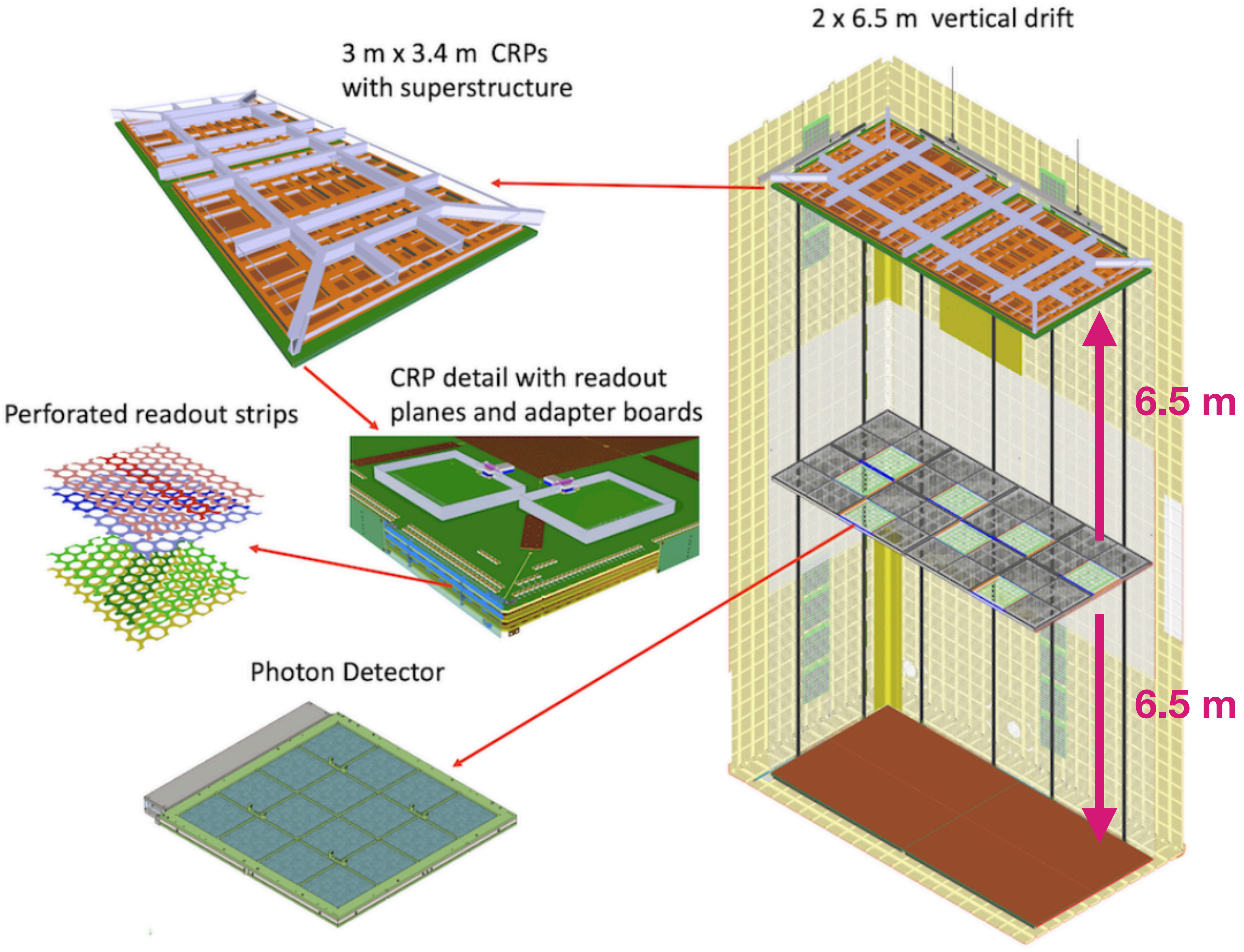
X-Arapuca: very high reflective photon trap with SiPMs



DUNE. JINST 15 (2020) T08010

Far Detector Vertical Drift (FD-VD)

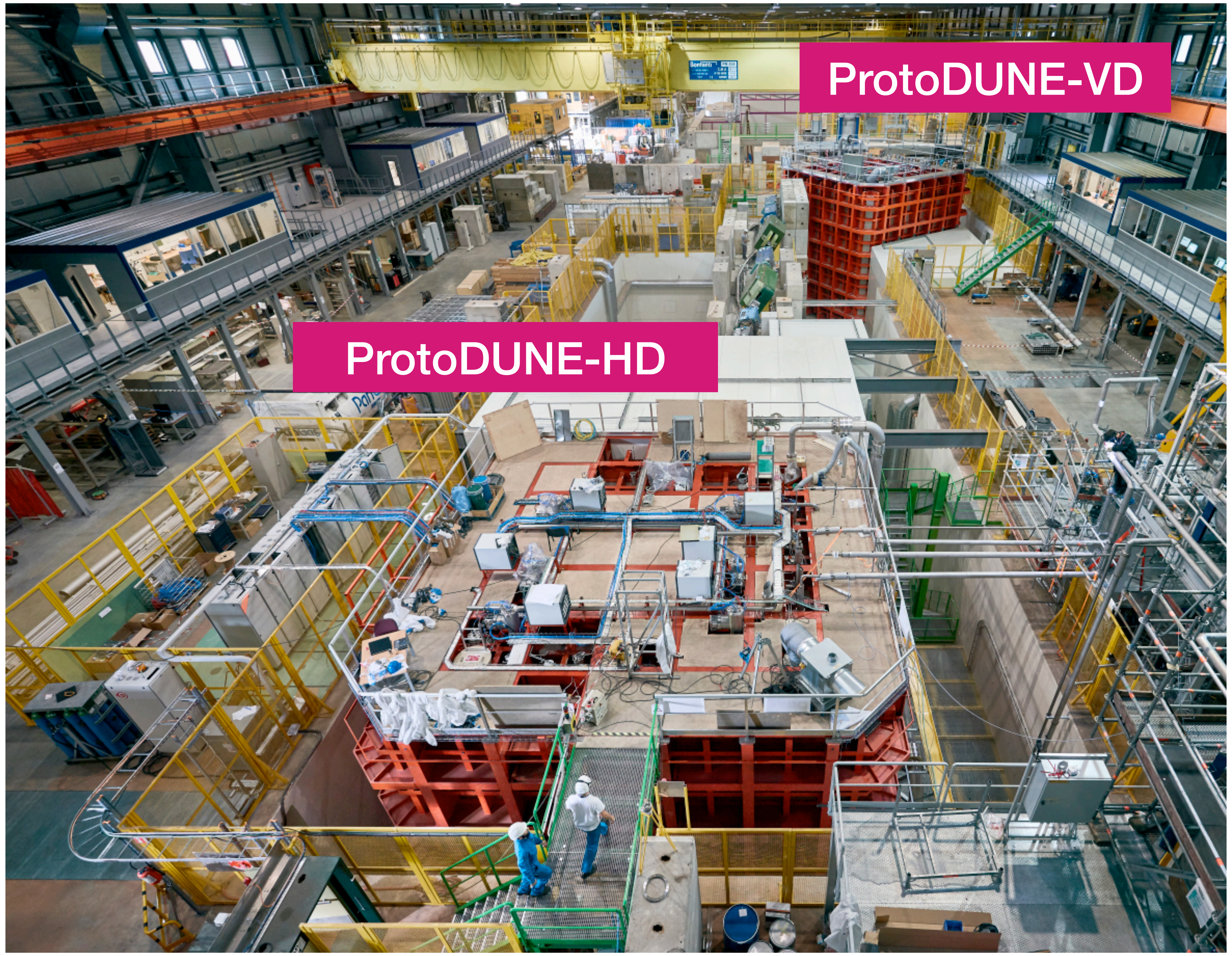




DUNE. JINST 19 (2024) 08 T08004

- 2 volumes separated by a cathode plane
- 2 anode planes (top & bottom)
- 6.5 m drift distance (drift field 450 V/cm)
- Simpler construction
- PCB-based charge readout
- Photon detectors on the cathode plane and membrane walls

ProtoDUNEs at CERN (HD & VD)



The first run of the ProtoDUNEs (2018-2020) led to the single phase technology for the PHASE-I

- Size: 800 t LAr total (1/20 of a total FD module)
- Real-size readout elements (APA, PDS, CRP,…)
- Successful run in 2018 - 2020:

DUNE. JINST 15 (2020) P12004

NEW Runs:

- ProtoDUNE-HD run in summer 2024: ✅

Goal: Test upgraded components in their final design and take more beam data

- ProtoDUNE-VD run in summer 2025: ⌛

Goal: Test the VD concept for the first time at large scale

DUNE: Near Detector (ND) - Phase I

- **Main Goal**: constrain uncertainties for oscillation measurements

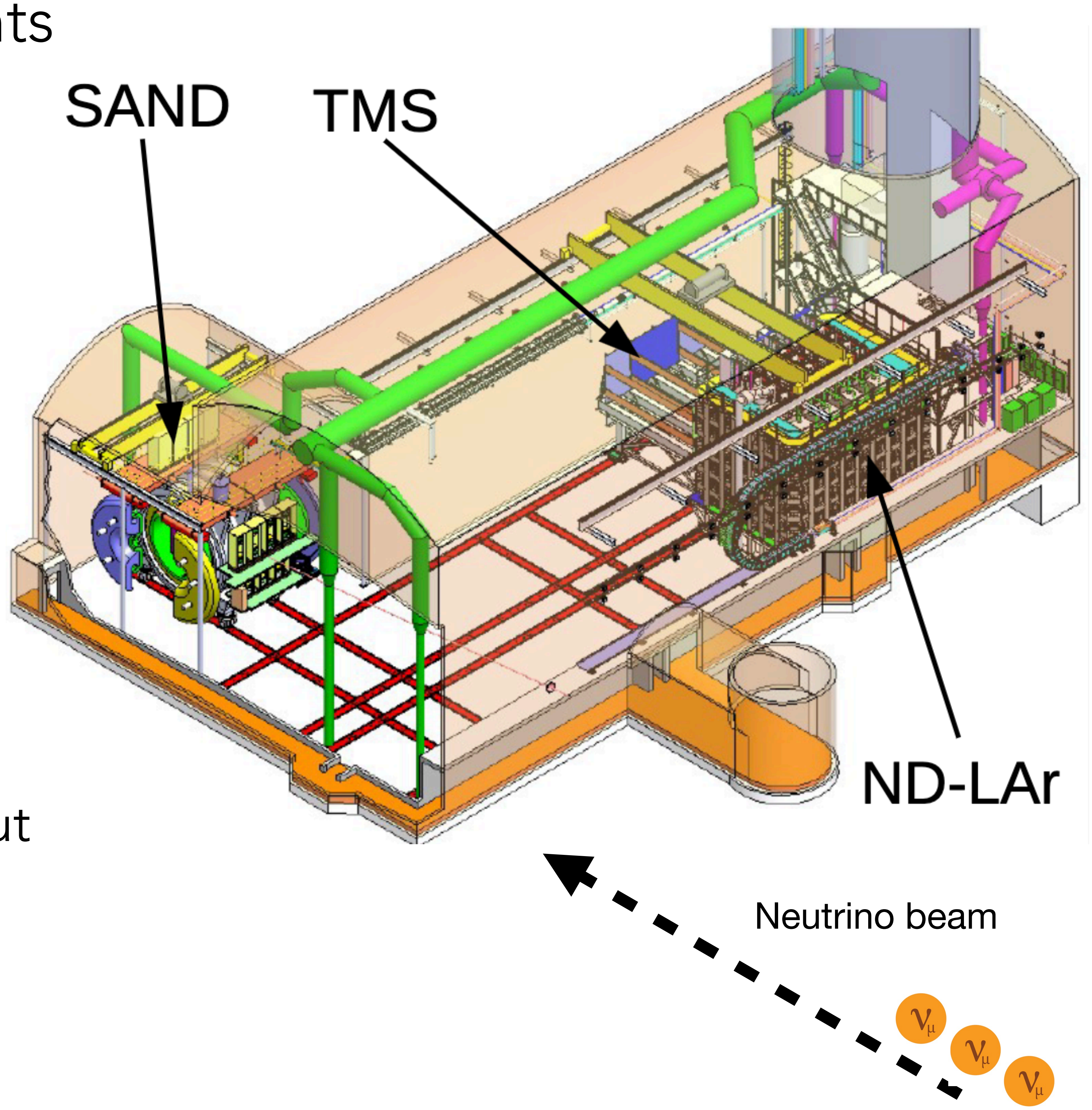
  - Un-oscillated neutrino flux monitoring
  - ν-Ar cross section measurements
  - Enable the prediction on neutrino spectra at FD
  - Three different detection systems on and off axis:

1) Liquid Argon Detector (50t FV)
   - Primary target, same technology as FD + pixelated readout

2) Temporary muon spectrometer (TMS)
   - Measure muons escaping the first detector

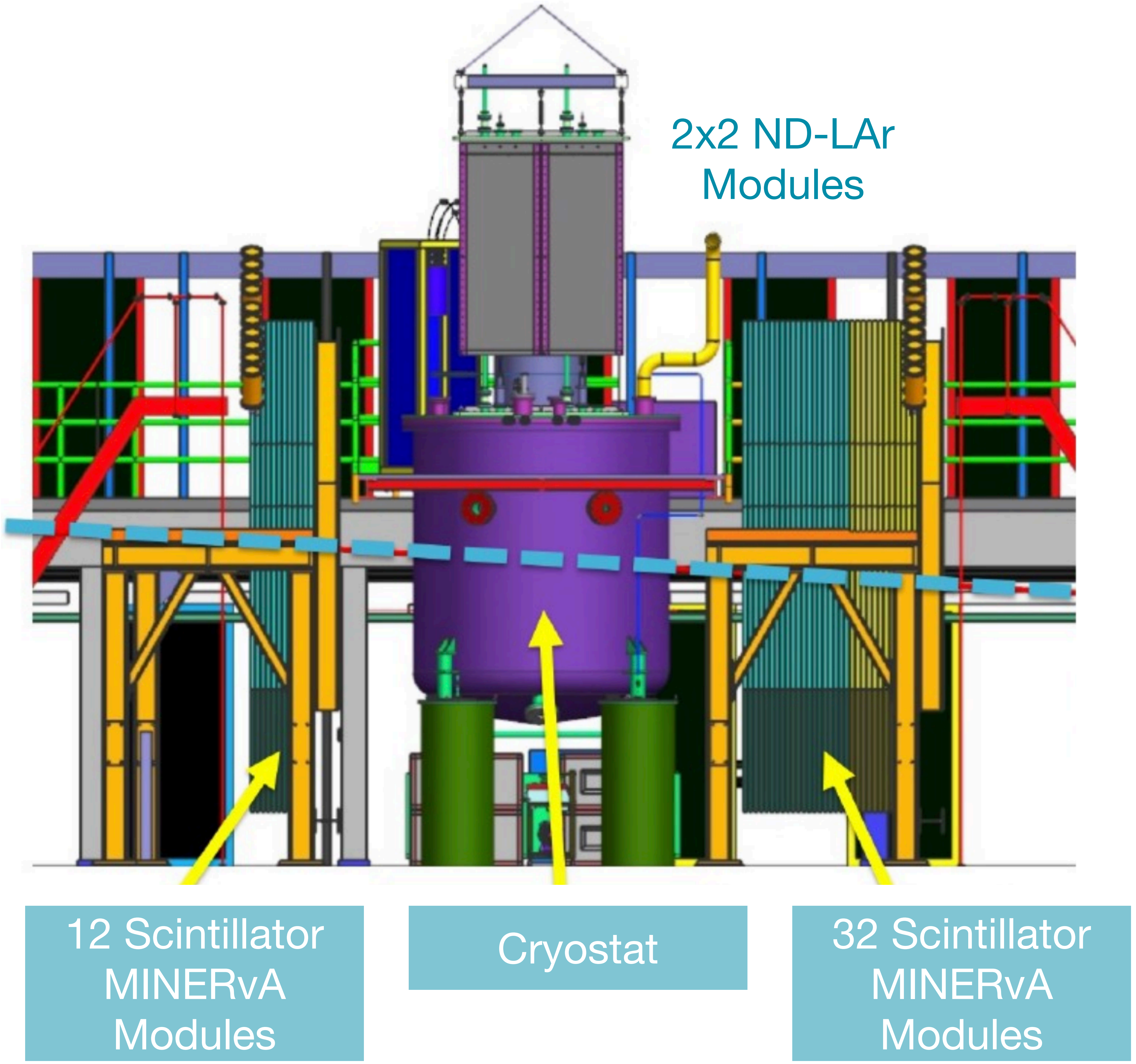
3) SAND (tracker surrounded by an electromagnetic calorimeter and magnet)
   - Control and monitor of the neutrino beam

574m from the beam & 60m underground



DUNE. Instruments 5 (2021) 4, 31

ProtoDUNEs at Fermilab (ND)



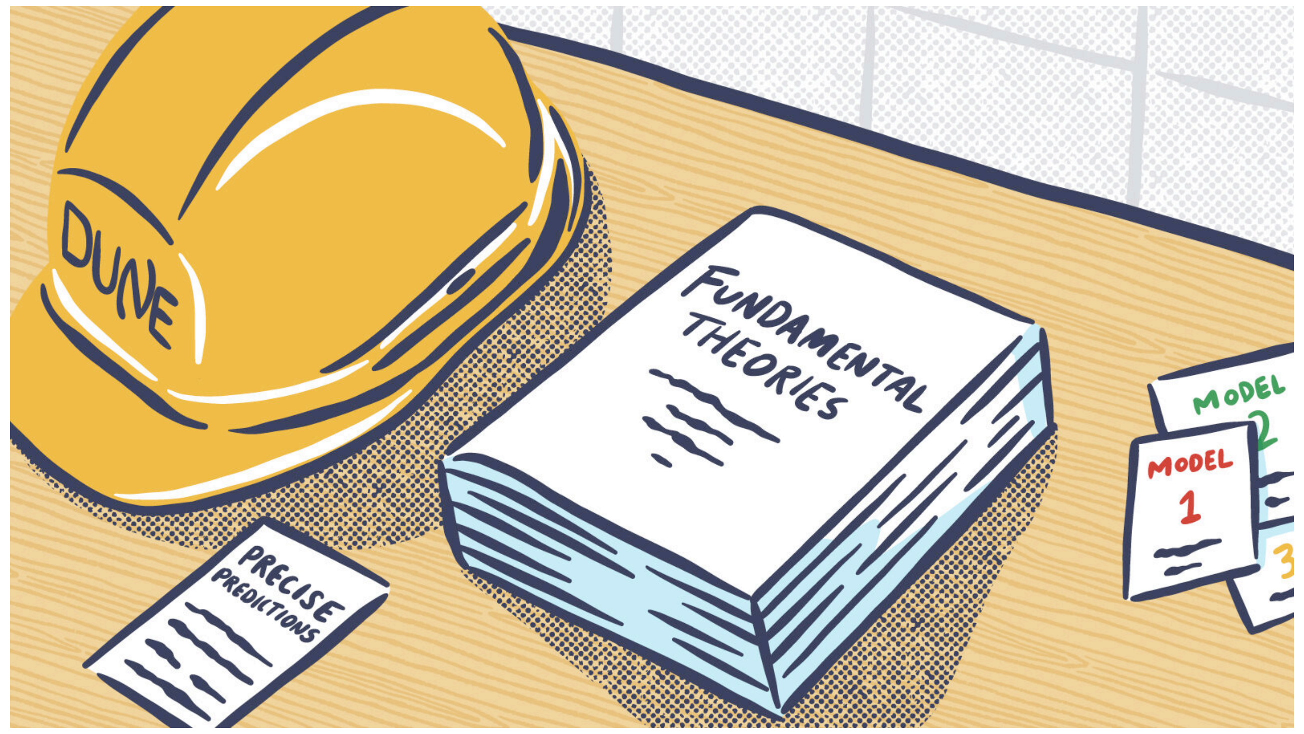
2x2 ND-LAr Demonstrator

- Mid-scale module size: 0.7x0.7x1.4 m^3
- Pixelated charge readout (LarPix)
- 2x2 modules integrated in a neutrino beam (NuMi)
- Re-purposed MinervA scintillator modules to mimic the role of the TMS
- Successful commissioning of July 2024
- 4.5 days of beam data before NuMi damaged
- Calibrations runs until NuMi gets back (2027?)

DUNE Physics Programme

Neutrino Beam Physics

- 5σ measurement of the neutrino mass ordering
- Discovery potential for CP violation
- Precision measurements of neutrino mixing parameters



symmetrymagazine.org

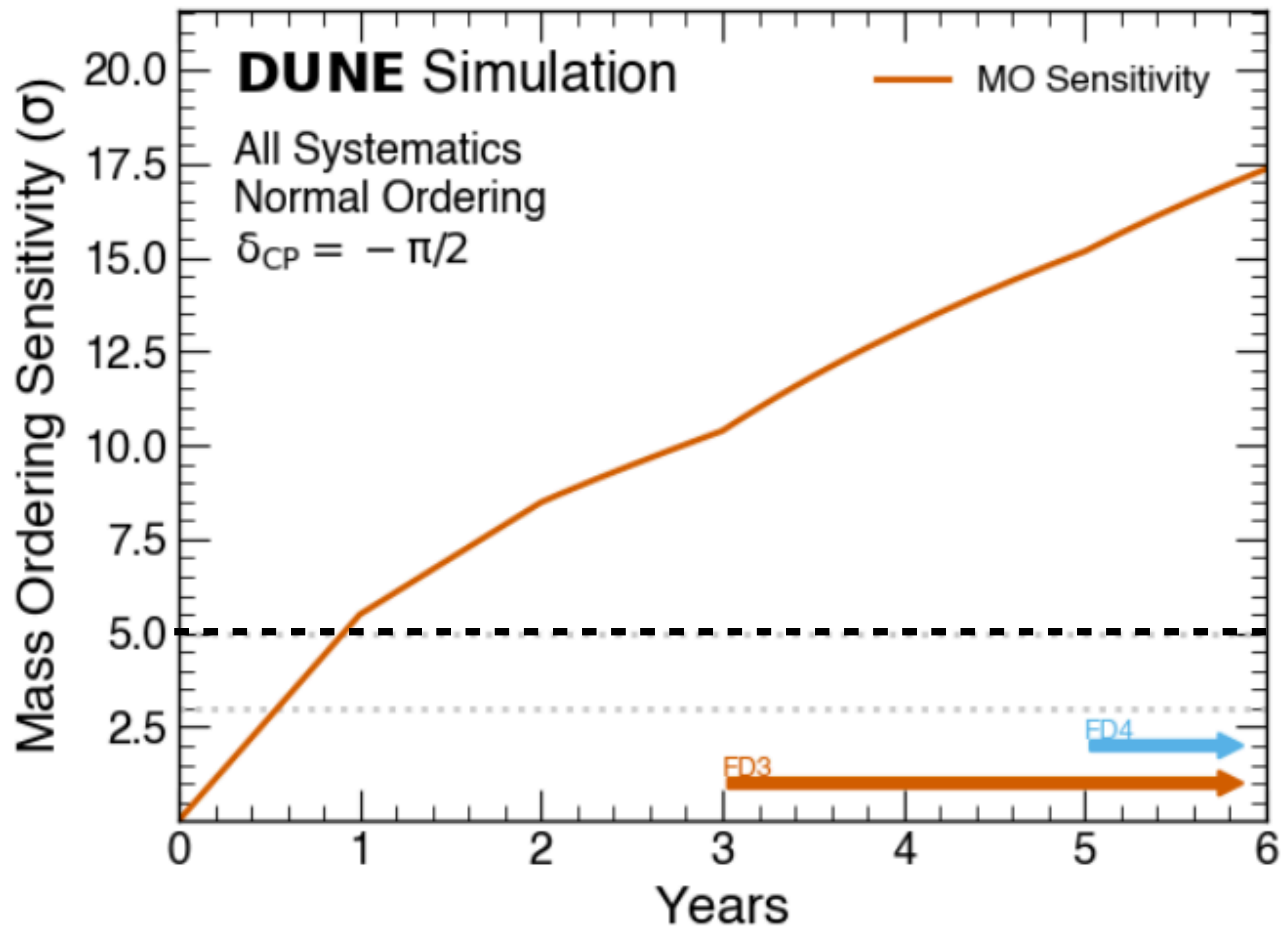
No Beam Physics

- Low energy neutrinos (supernova and solar)
- Proton Decay search $p \to K^+\bar{\nu}$
- Physics beyond SM

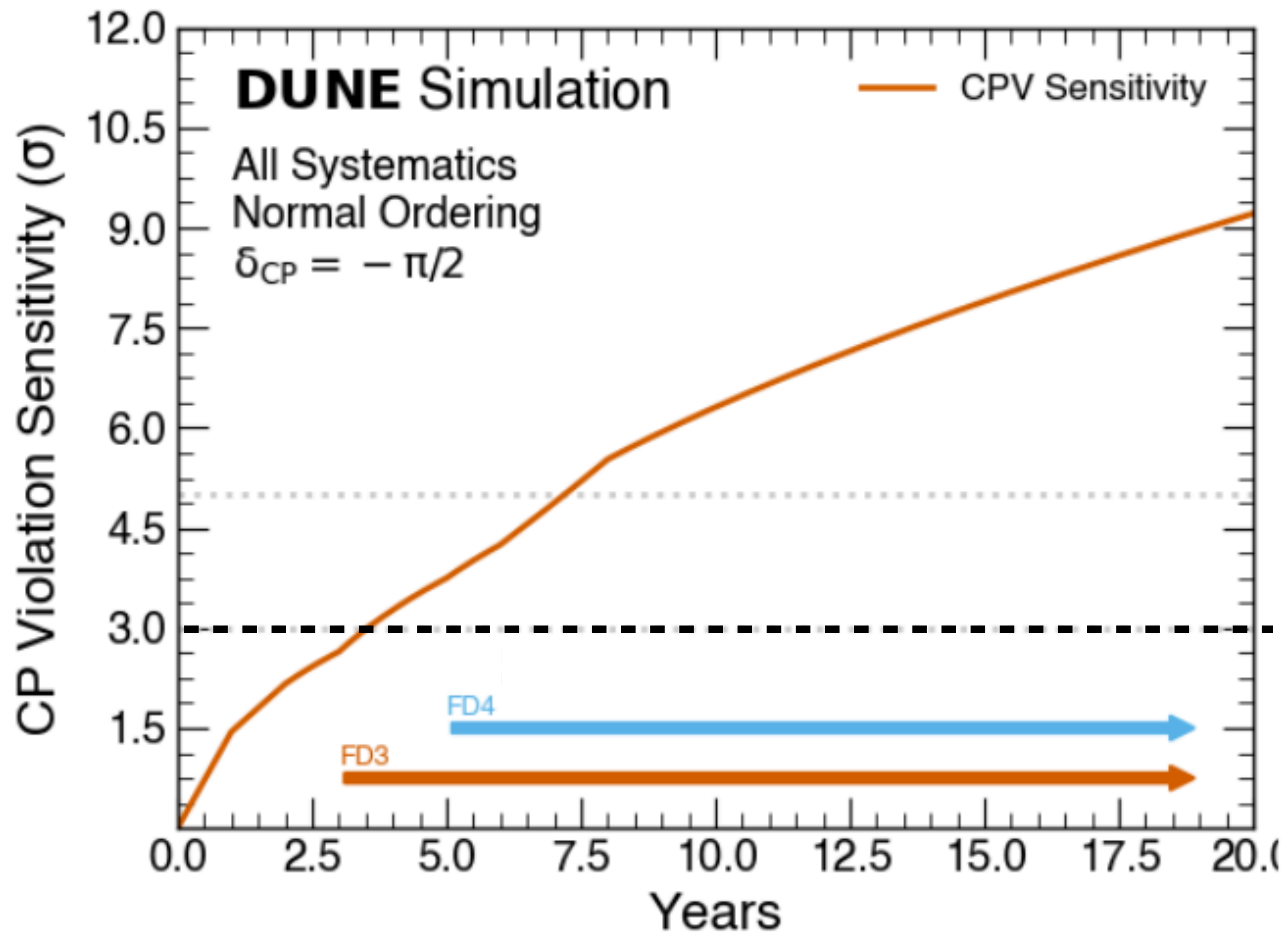
symmetrymagazine.org

DUNE sensitivity to mass ordering and δ_{CP}

Mass Ordering



CP Violation



Best case scenario (δ_{CP} = -π/2)

> 5σ mass ordering sensitivity in 1 year

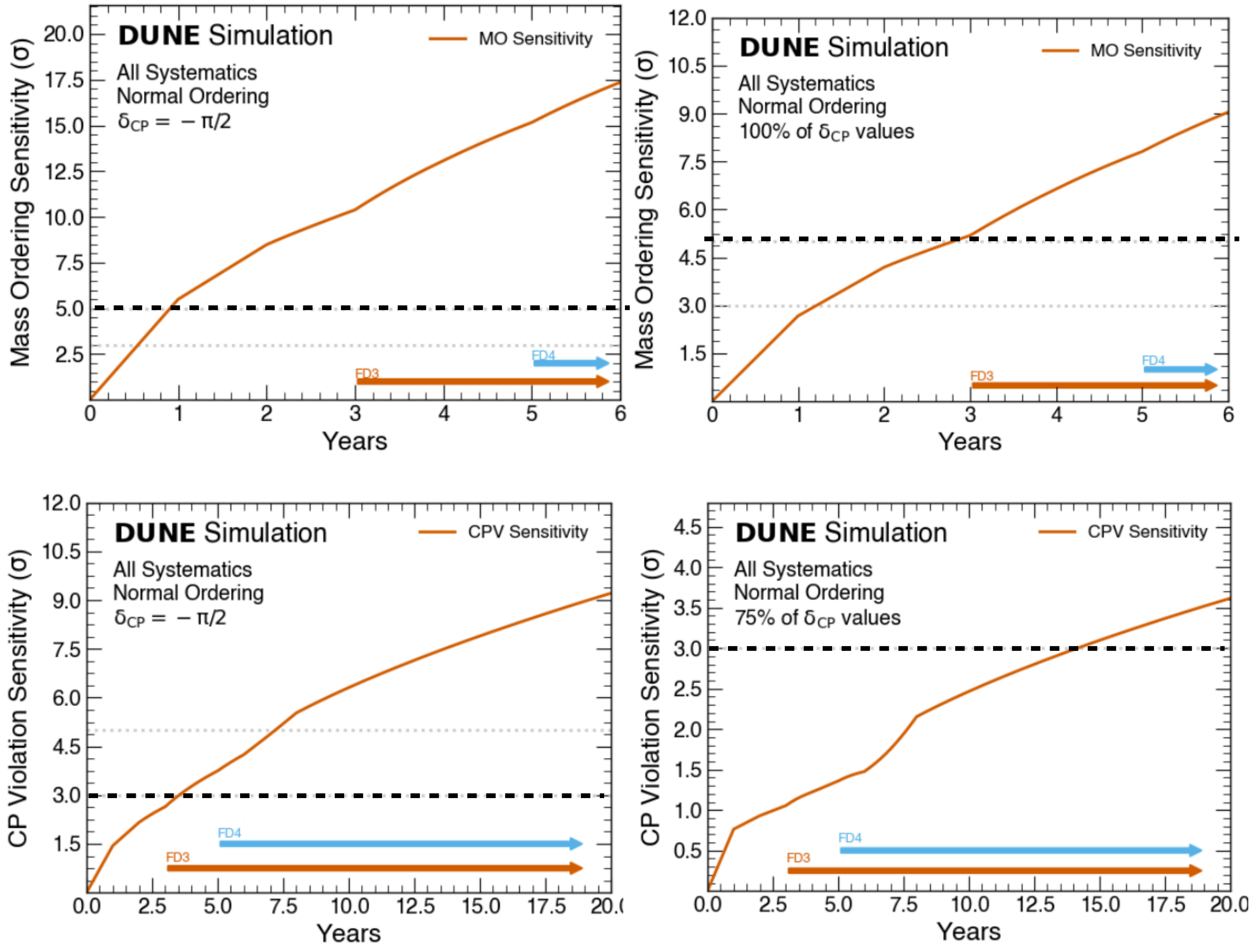
> 3σ CPV sensitivity in 3.5 year

DUNE Collaboration. EPJC 80, 978 (2020)   DUNE Collaboration. Neutrino 2024

DUNE sensitivity to mass ordering and δ_{CP}

Mass Ordering

CP Violation



Best case scenario (δ_{CP} = -π/2)

> 5σ mass ordering sensitivity in 1 year

> 3σ CPV sensitivity in 3.5 year

Worst case scenario (δ_{CP} ≠ -π/2)

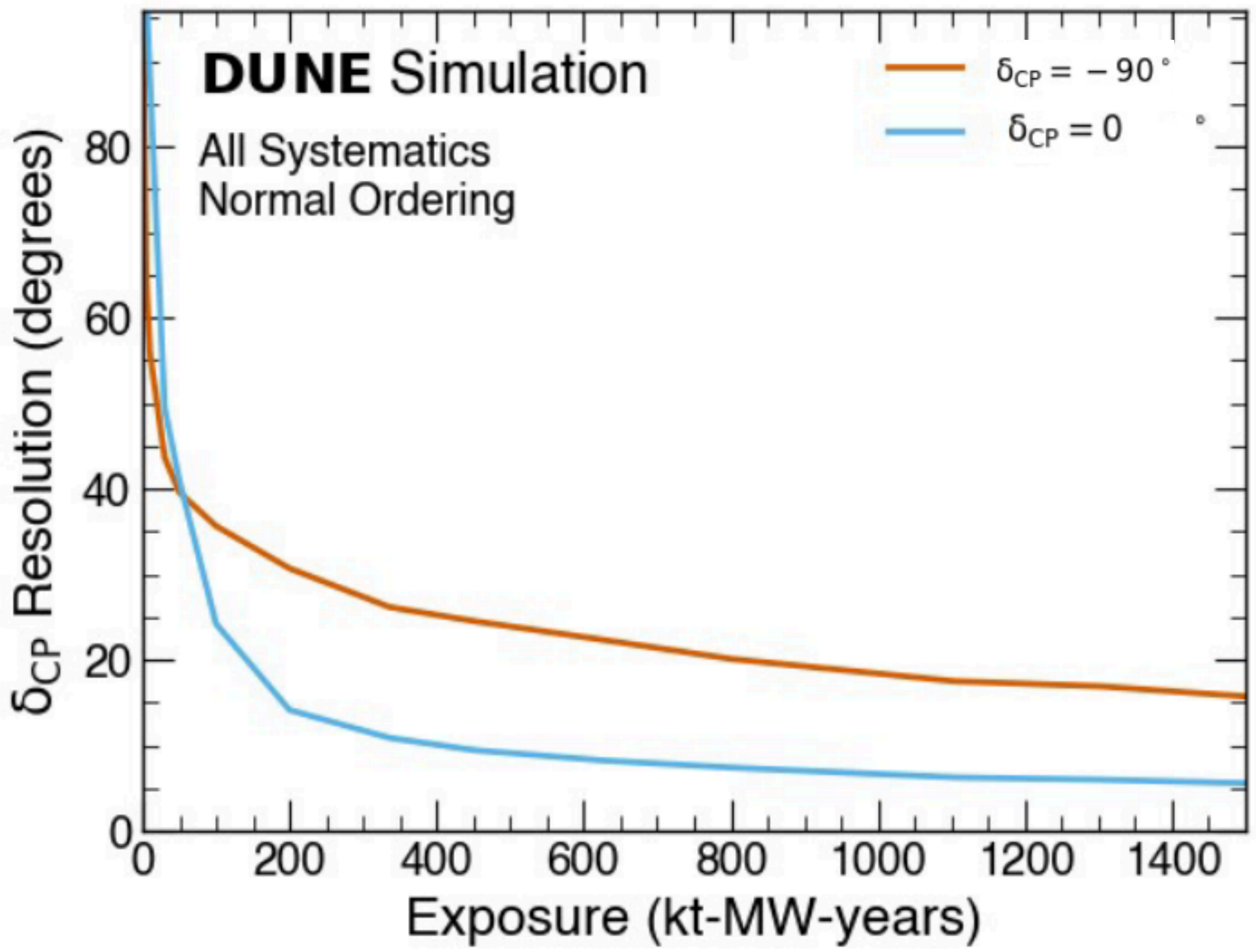
> 5σ mass ordering sensitivity in 3 year

> 3σ CPV sensitivity in ~13 year

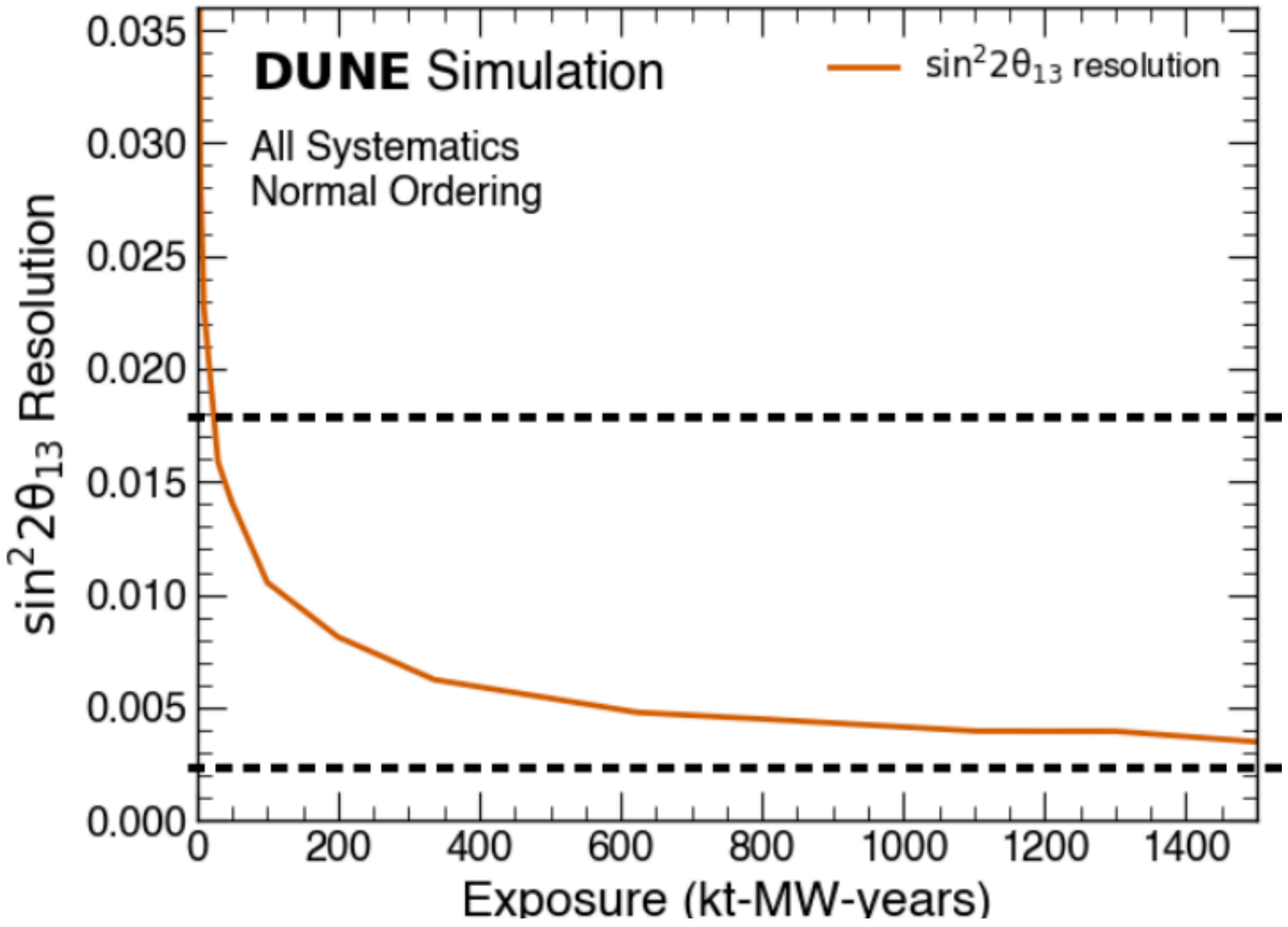
DUNE Collaboration. EPJC 80, 978 (2020) DUNE Collaboration. Neutrino 2024

DUNE High Resolution Measurements

DUNE Collaboration. Neutrino 2024
DUNE Collaboration. EPJC 80, 978 (2020)



Ultimate precision of 6° - 16° in δ_{CP}



For long-baseline experiments, word-leading precision in θ_{13}

Low Energy interactions in LAr

- DUNE will observe natural neutrinos produced by a supernova burst and the Sun
- Liquid Argon target gives unique sensitivity to **MeV-scale electron neutrinos**

1. Charge-current interactions on Ar

$$\nu_e + {}^{40}Ar \longrightarrow {}^{40}K^* + e^- \qquad (E_\nu > 1.5\text{ MeV})$$

$$\bar{\nu}_e + {}^{40}Ar \longrightarrow {}^{40}Cl^* + e^+ \qquad (E_\nu > 7.5\text{ MeV})$$

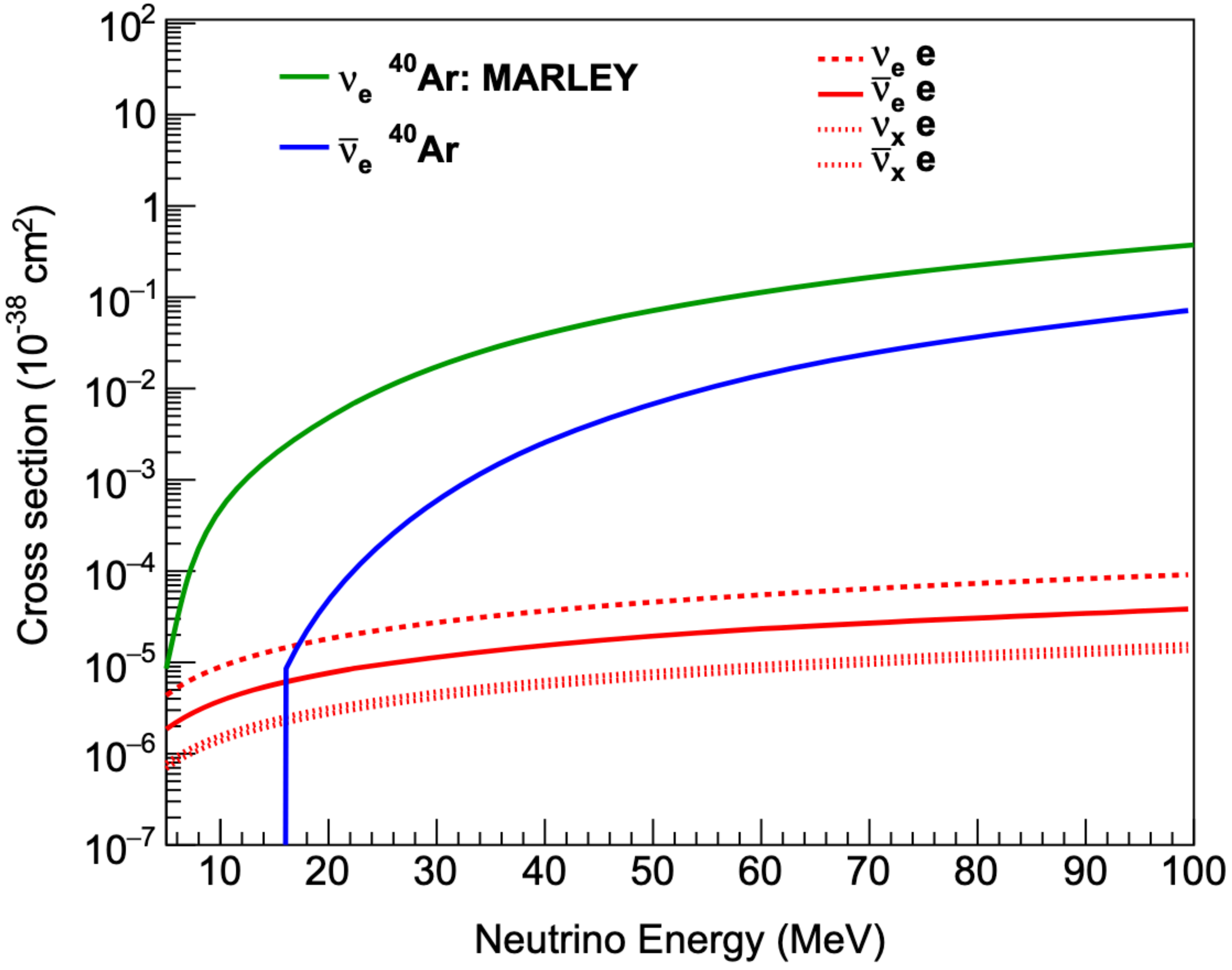
2. Elastic scattering on electrons

$$\nu_x + e^- \longrightarrow \nu_x + e^- \qquad \text{(pointing capabilities)}$$

3. Neutral current interactions on Ar

$$\nu_x + {}^{40}Ar \longrightarrow \nu_x + {}^{40}Ar^* \qquad \text{(potential)}$$

Complementary to Hyper-K & Juno that predominantly see $\bar{\nu}_e$ via inverse beta decay



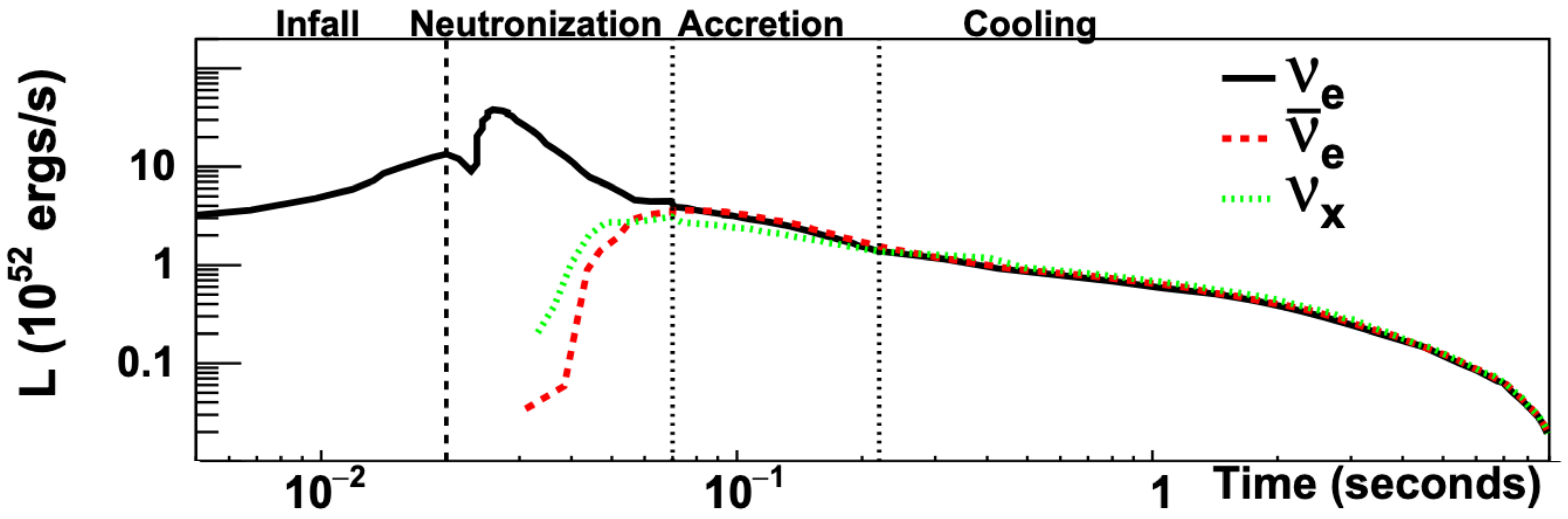
DUNE Collaboration. EPJC 81, 423 (2021)

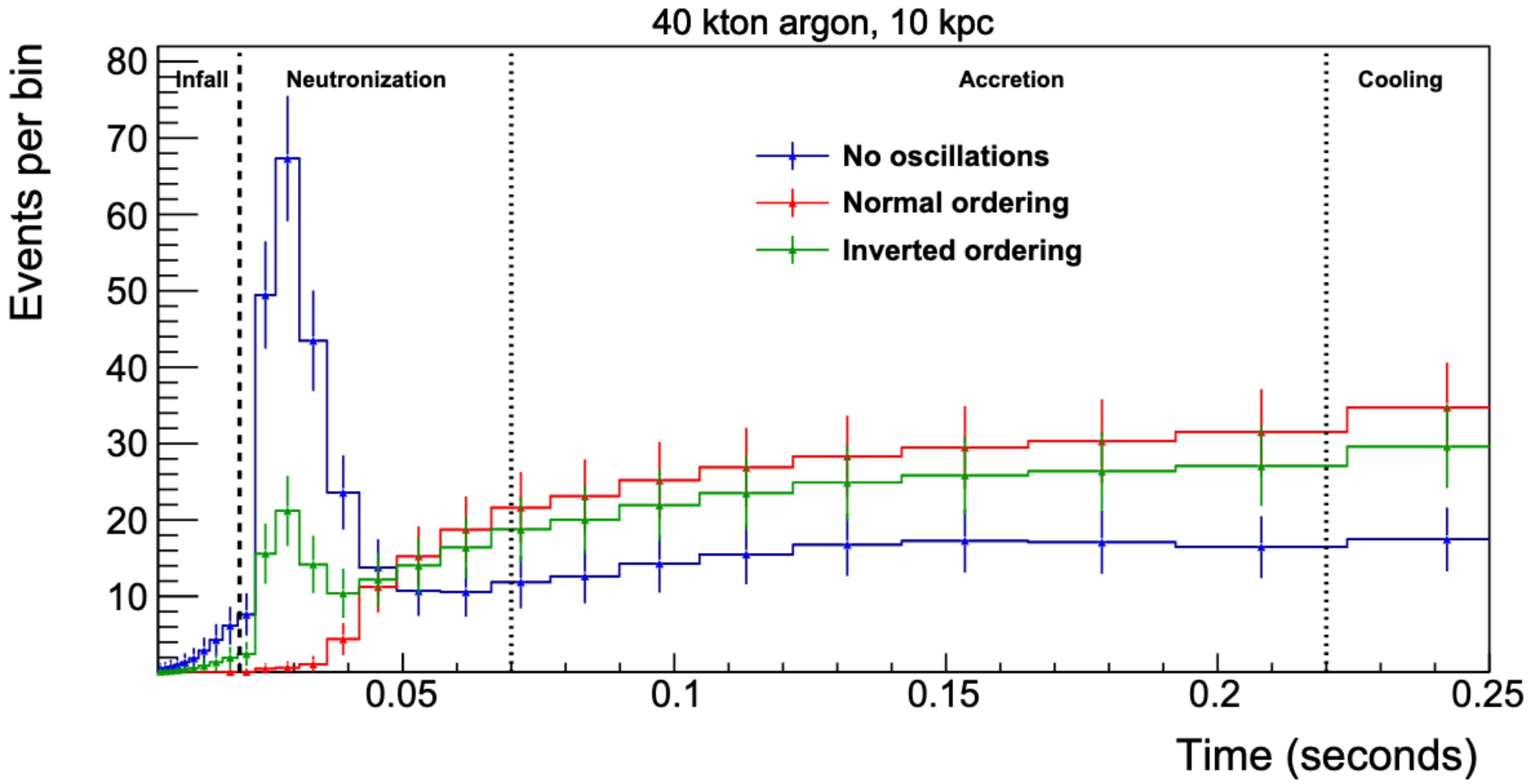
Neutrinos from a Supernova Burst in DUNE

- **Supernova Burst (SNB)** are a huge source of neutrinos of all flavours in ~10 sec
- 1-3 SNB per century in our Galaxy (10 kpc)
- Time and energy spectra of these neutrinos will provide information about:

  Supernova physics: Core collapse mechanism, SN time evolution or black hole formation

  Neutrino physics: flavour transformation, absolute mass and other properties as the magnetic moments



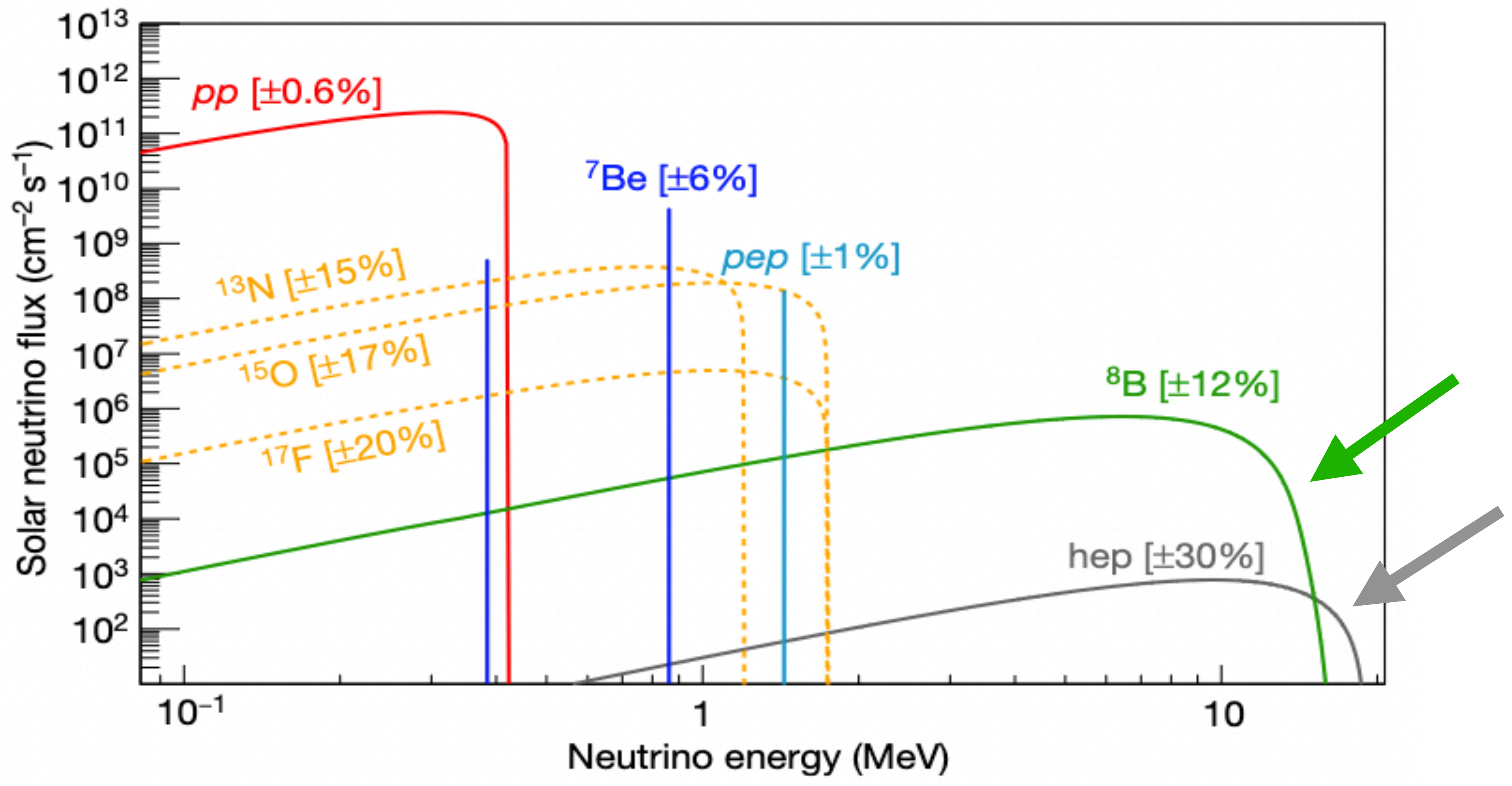


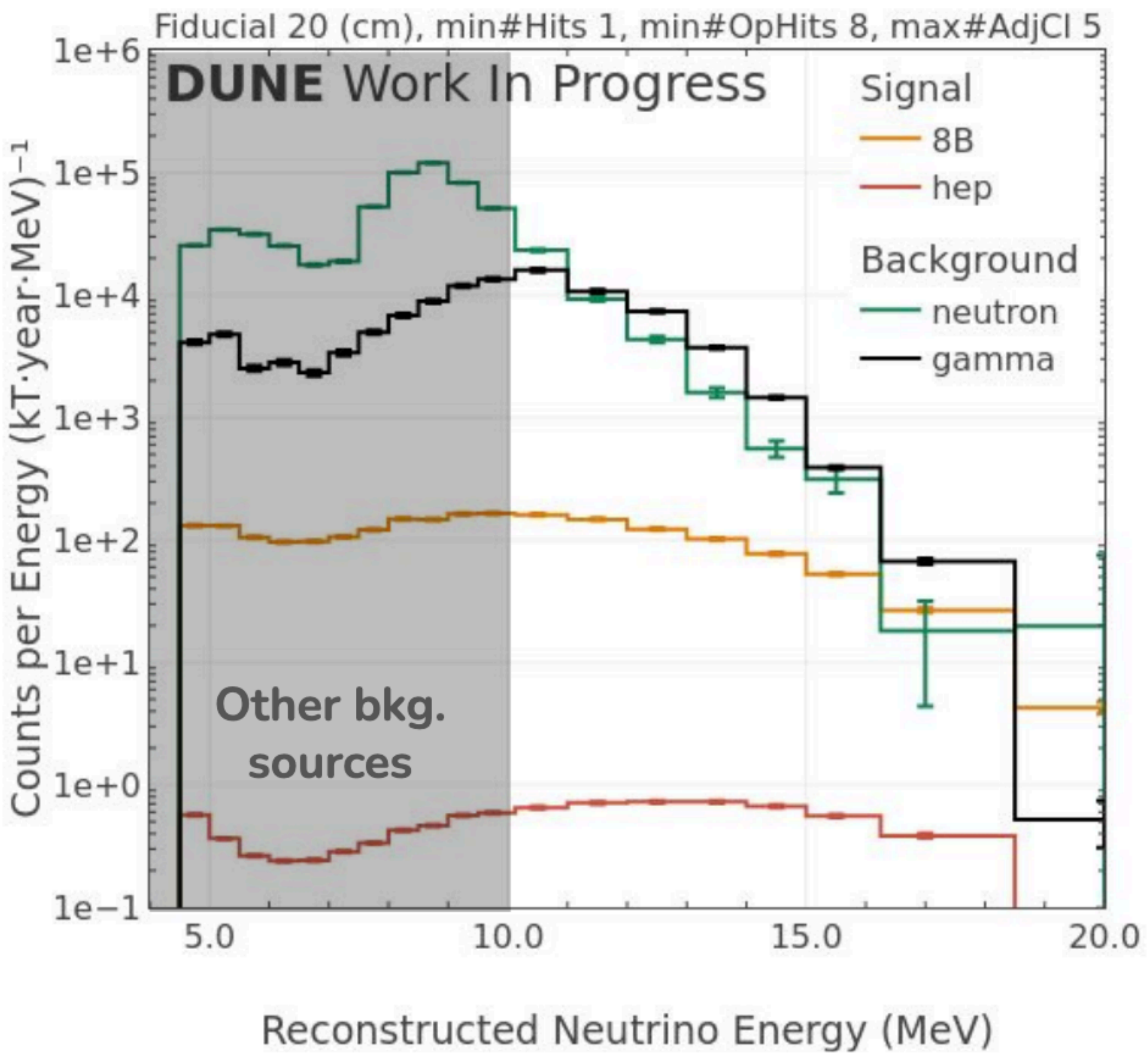
DUNE Collaboration. EPJC 81, 423 (2021)

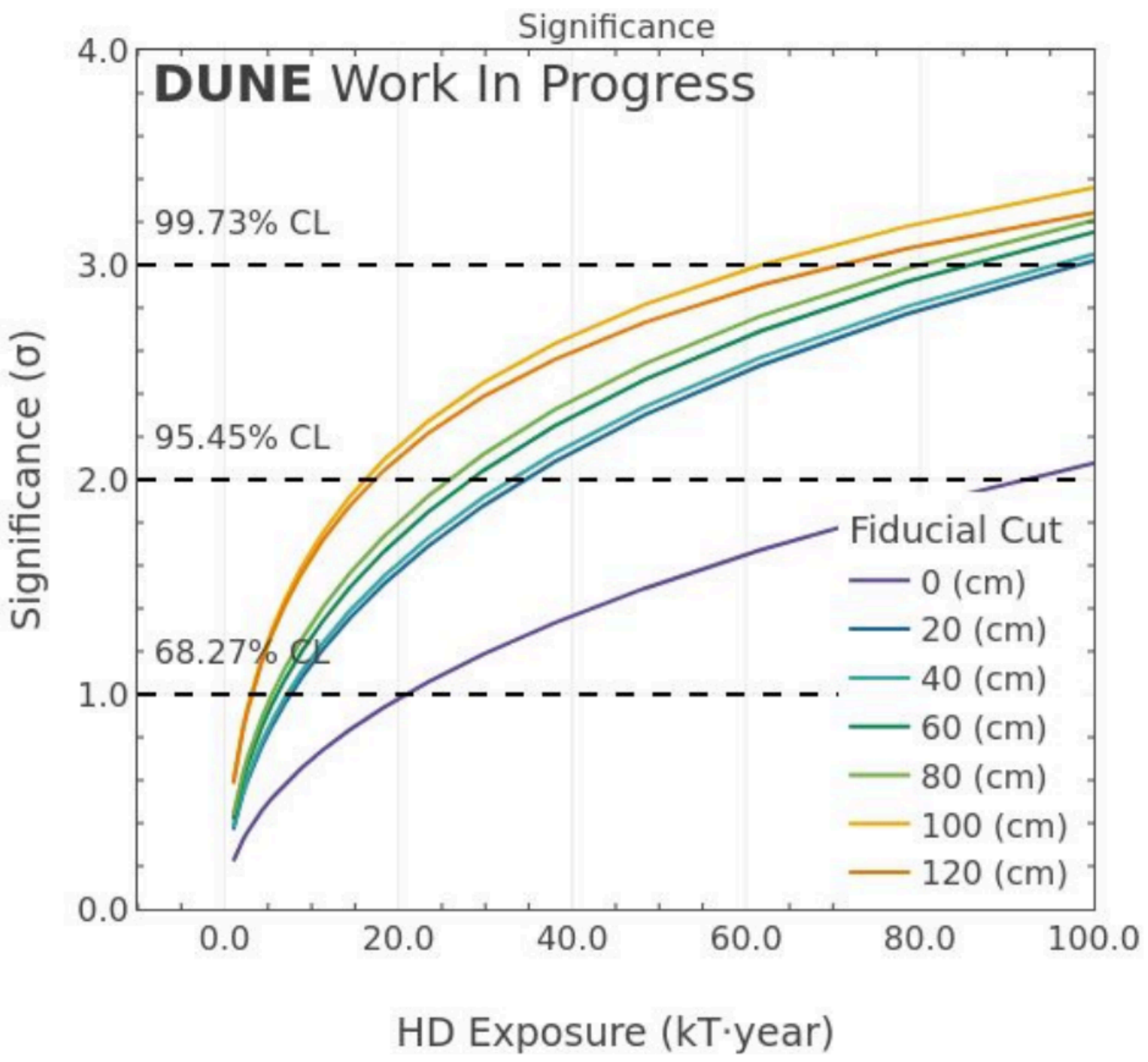
Bonus:

DUNE will participate in SN early warning systems for multi-messenger astronomy since neutrinos arrive at Earth first

Solar neutrinos in DUNE







- DUNE will record plenty of solar neutrinos
  ~ several events/day/kt
- Despite a large neutron background at low energies, DUNE will have **sensitivity to ^{8}B** solar neutrinos above 10 MeV
- Discovery potential for hep neutrinos as well
- DUNE can improve upon existing solar oscillation measurements via day-night asymmetry induced by matter effects
- **On-going full DUNE study:** including a dedicated trigger & flash matching for fiducialization

Proton decay searches in DUNE

DUNE will be an excellent detector to perform nucleon decay searches:

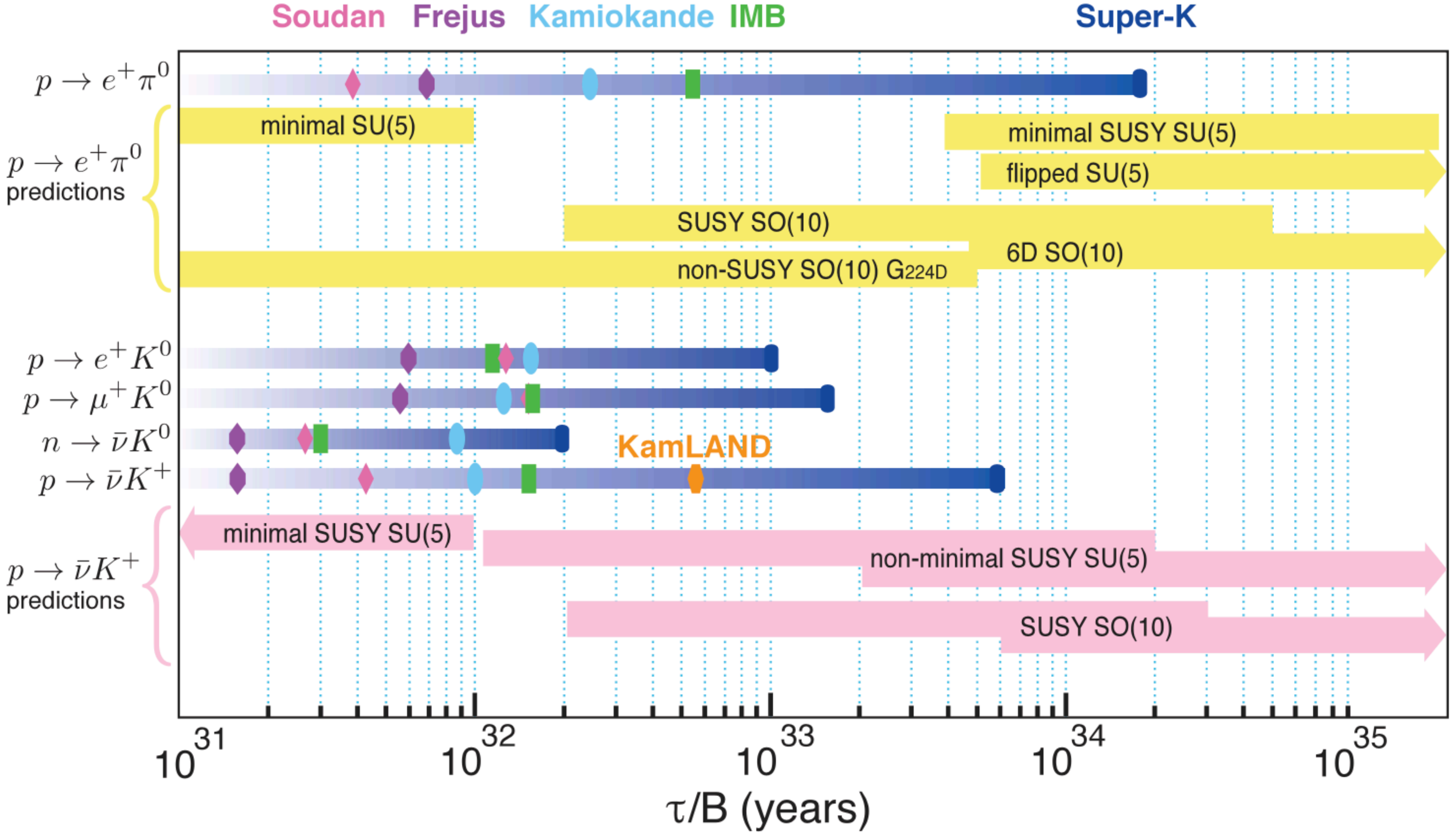
- Underground location
- Very large fiducial mass
- Imagine capabilities

Main signature channel in DUNE:

$$p \longrightarrow K^+\bar{\nu}$$

LArTPC allow for the observation of the entire decay channel

Main background for this channel in DUNE are **atmospheric neutrinos**



- Non-SUSY GUT —> dominant channel $p \to e^+\pi^0$
  (Super-K stringent limits ~10^{34} years)
- SUSY GUT models —> dominant channel $p \to K^+\bar{\nu}$

DUNE Collaboration. arXiv: 2002.03005

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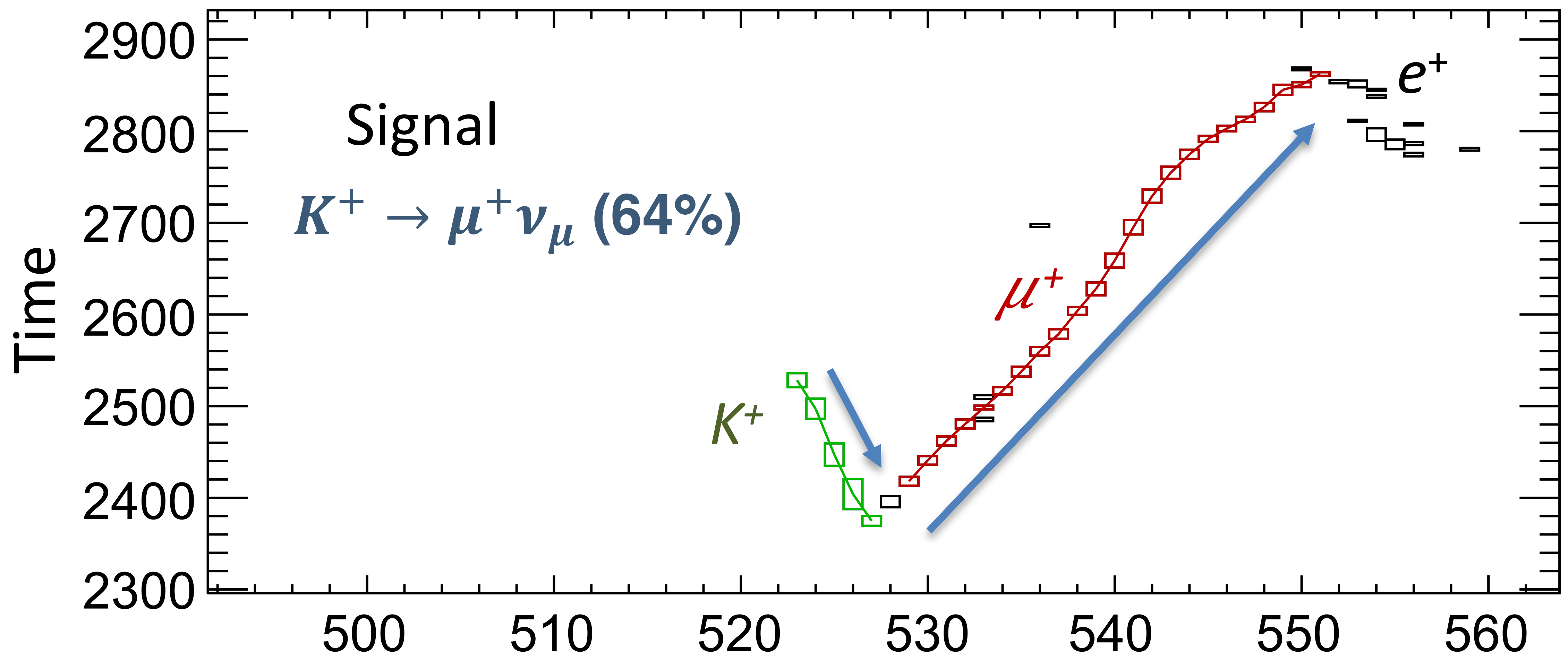


- **DUNE can image the three particles**
- K^+ typically below Cherenkov threshold
- Hyper-K can identify this channel by timing (μ & e) and the observation of the muon
- DUNE sensitivity comparable to Cherenkov detectors:

$$\tau/\mathrm{Br}\,(p \rightarrow \bar{\nu}K^+) > 1.3 \times 10^{34}\ \text{years}$$

for 400 kt · year at 90% CL

DUNE Collaboration. arXiv: 2002.03005

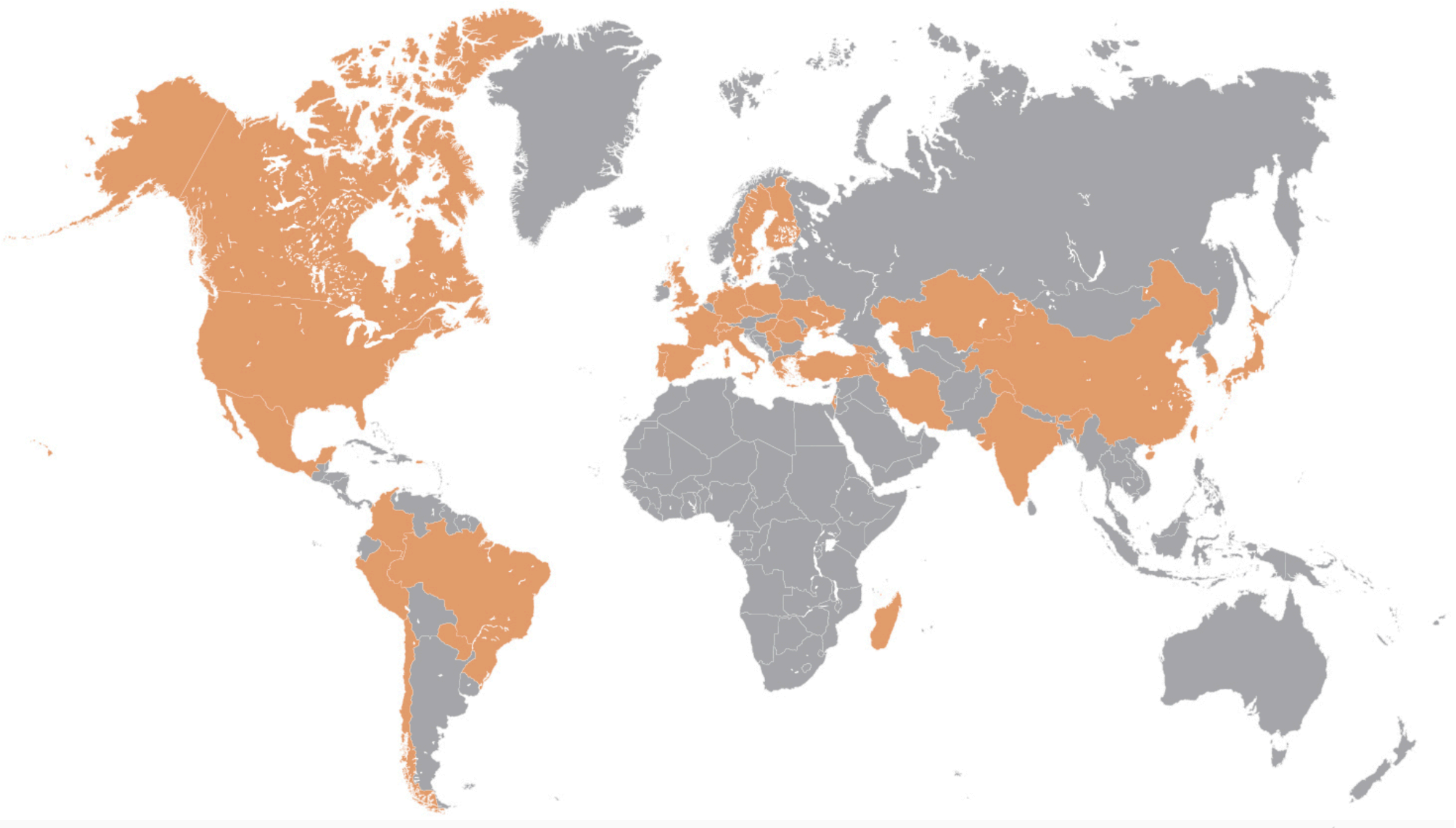
Status and timeline

- Far site excavation complete ✅
- Building & Site Infrastructure ongoing
- Cryostat installation by January 2026
- Far Detector Installation by Mid 2027
- Physics by the end of 2029
  - solar, atmospheric and astrophysics neutrinos
- Beam physics with near detector by 2031
  - full physics scope

Time line

The DUNE Collaboration

- More than 1400 collaborators
- More than 200 institutions
- Moran than 35 countries (plus CERN)



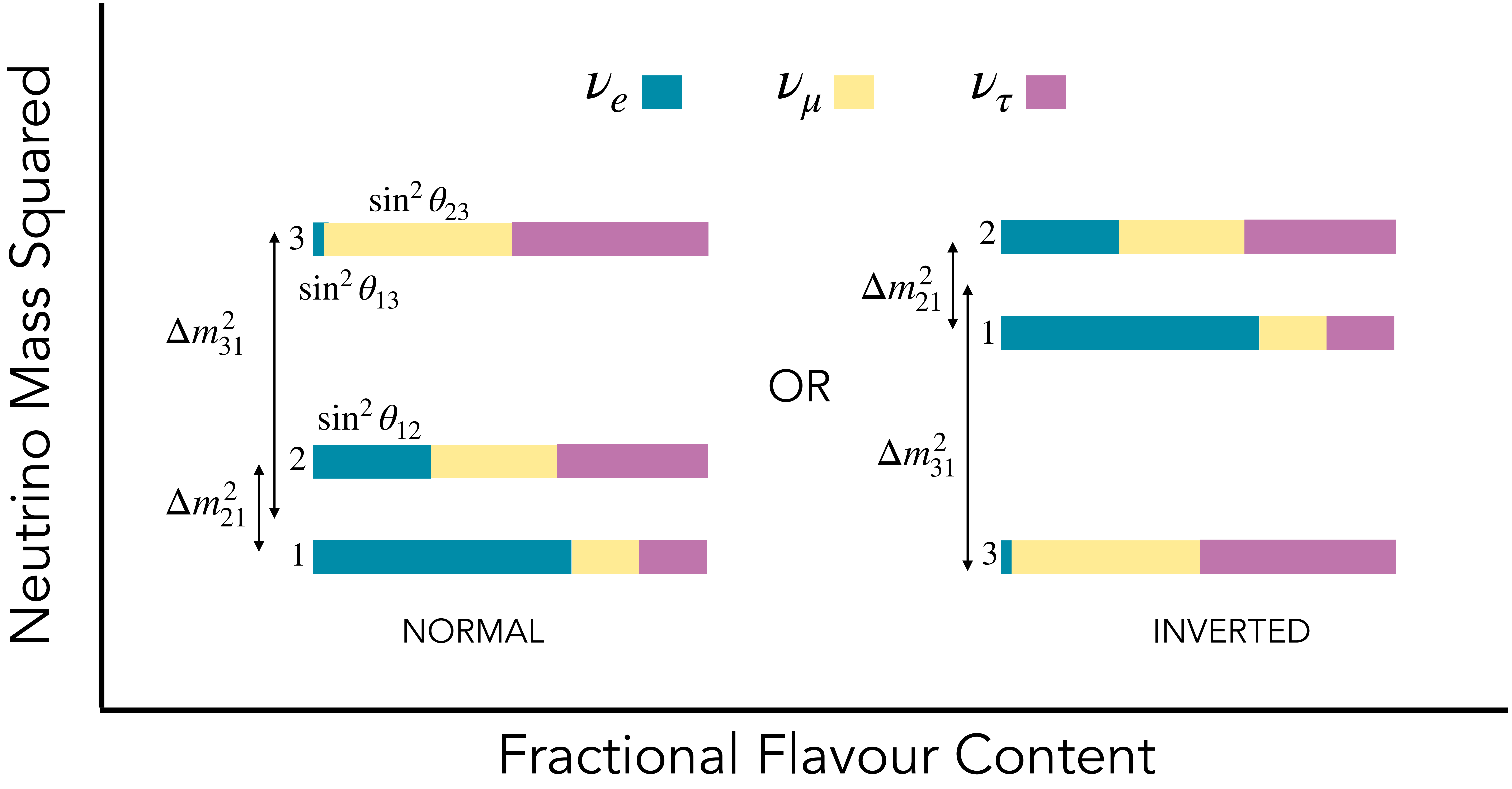
Summary

- DUNE is a long-baseline oscillation experiment + neutrino observatory

  Mass ordering & δ_{CP}, MeV-scale natural neutrinos and proton decay & BSM

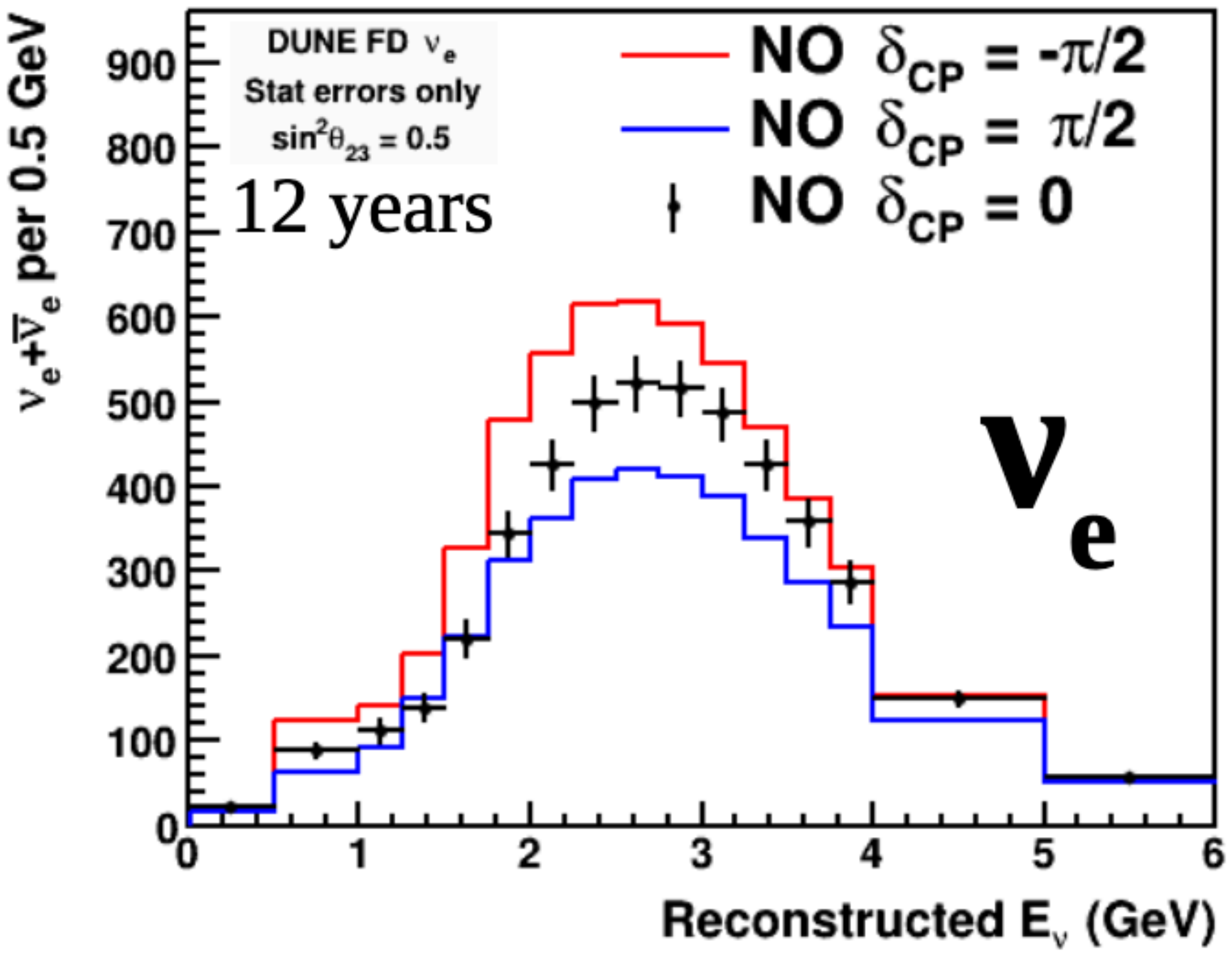
- Prototyping program very active and successful
- Construction work ongoing
- Start of Science by the end of this decade

Back Up

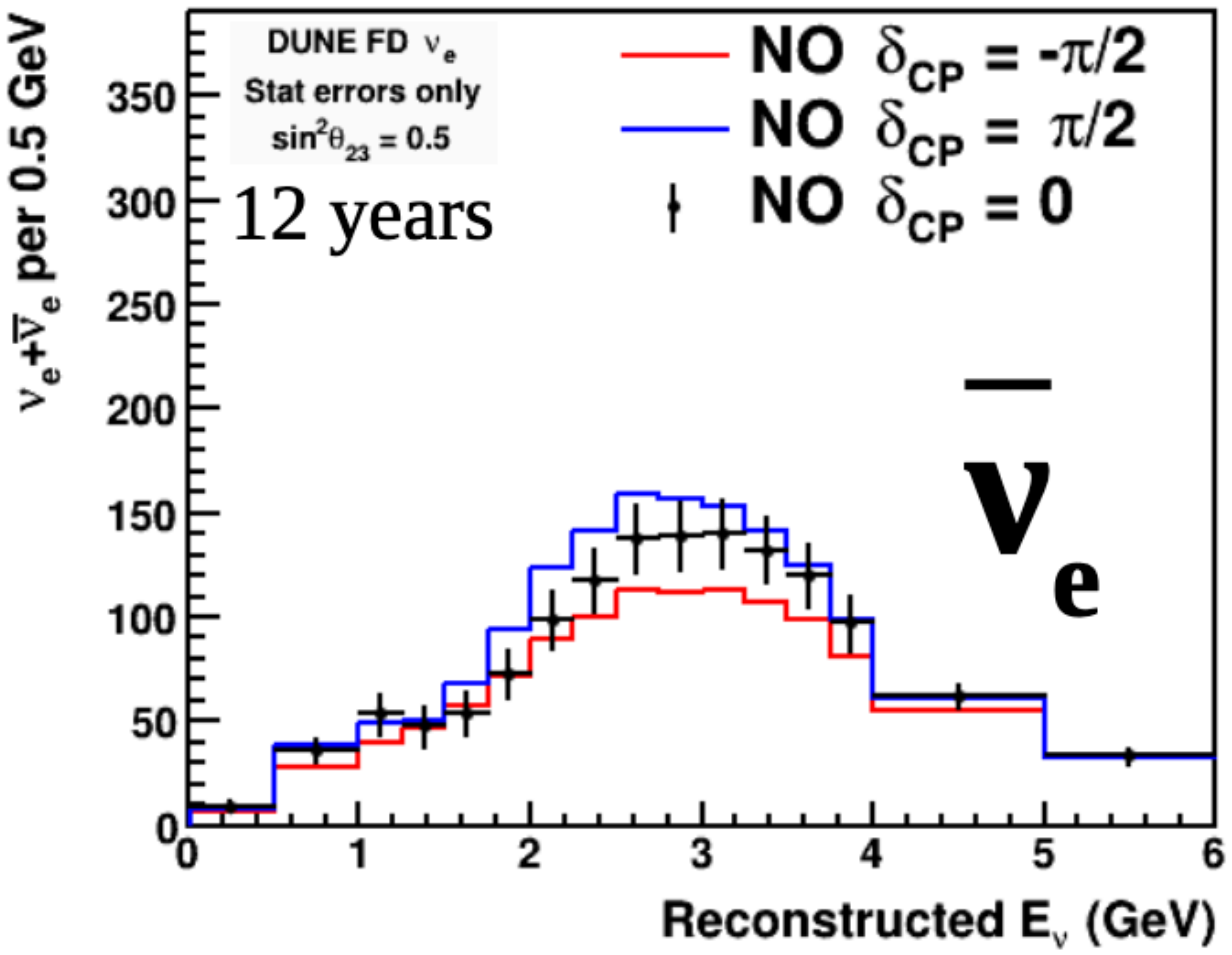

Neutrino Mass Squared
ν_e
ν_μ
ν_τ
$\sin^2\theta_{23}$
3
$\sin^2\theta_{13}$
Δm^2_{31}
$\sin^2\theta_{12}$
2
Δm^2_{21}
1
NORMAL
OR
2
Δm^2_{21}
1
Δm^2_{31}
3
INVERTED
Fractional Flavour Content

FD energy spectra are sensitive to CP violation

$P(\nu_\mu \longrightarrow \nu_e)$



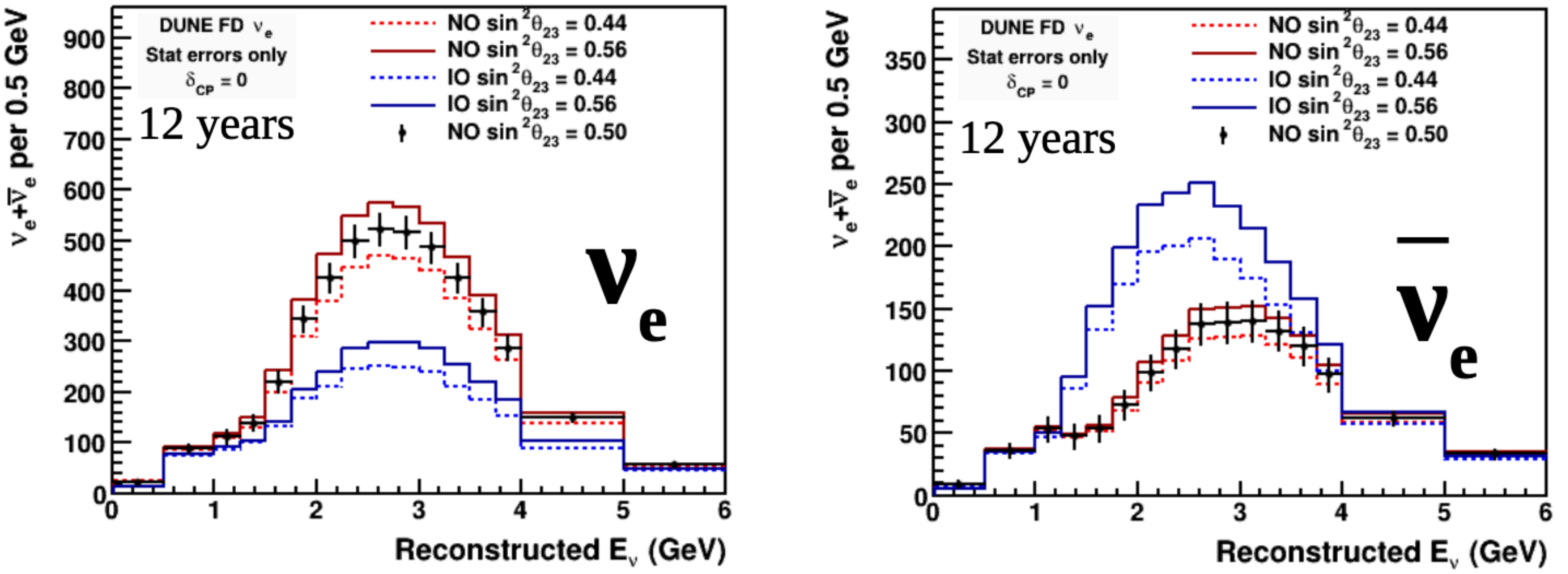
$P(\bar{\nu}_\mu \longrightarrow \bar{\nu}_e)$



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

FD energy spectra are sensitive to CP violation

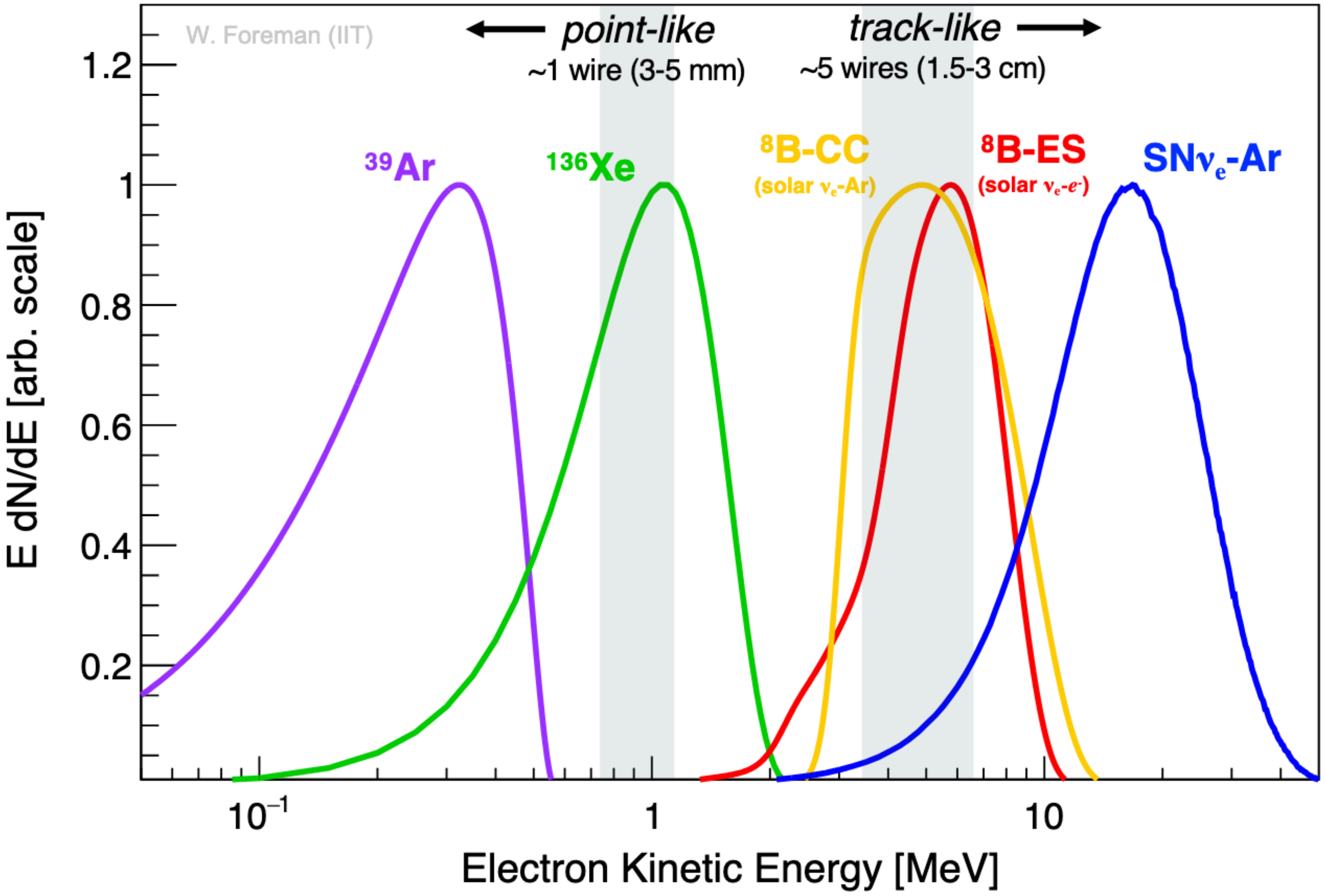
$P(\nu_\mu \longrightarrow \nu_e)$ $P(\bar{\nu}_\mu \longrightarrow \bar{\nu}_e)$



If the mass ordering is normal, DUNE will measure a much larger enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance

DUNE Collaboration. Neutrino 2024

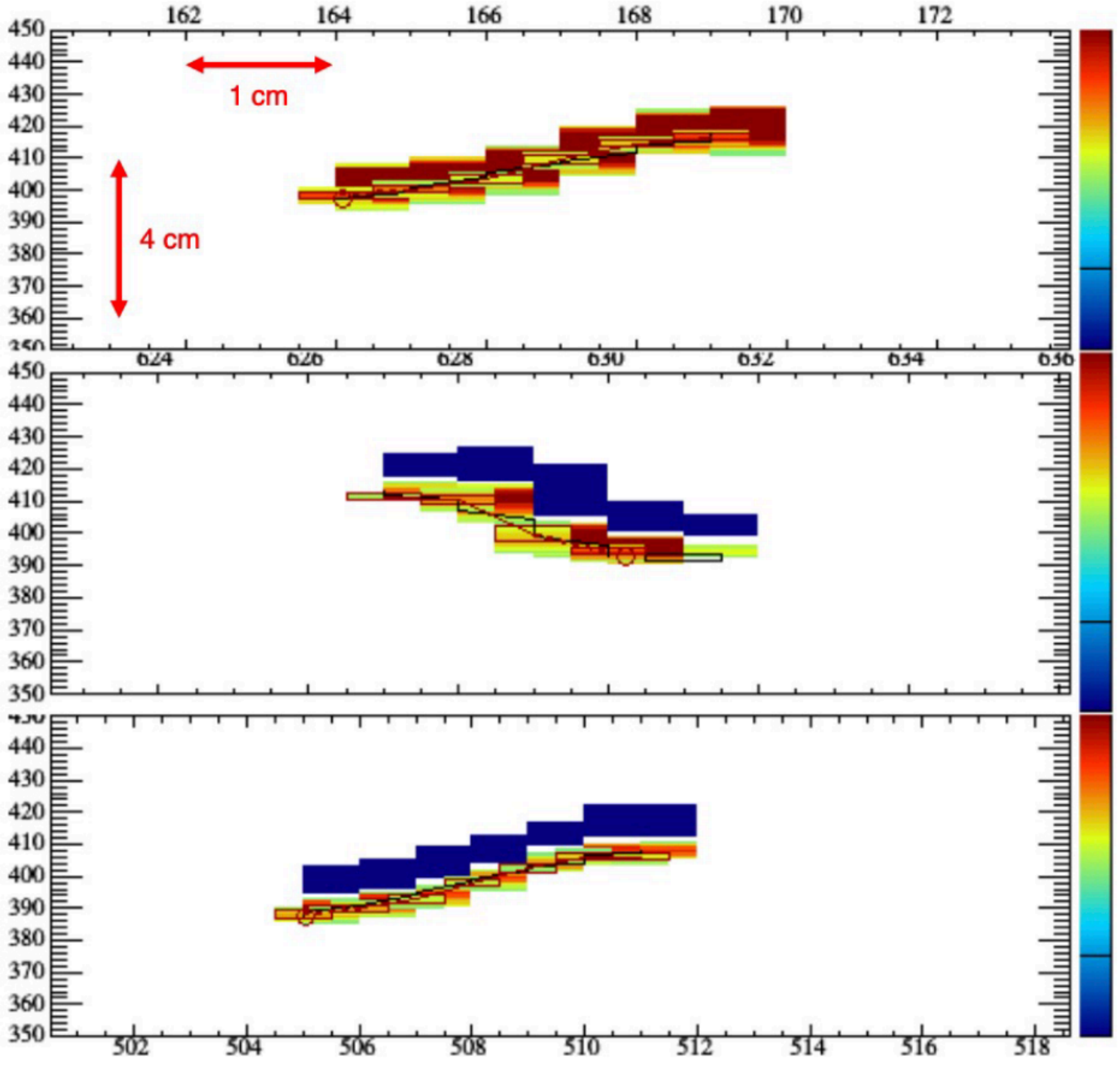
Low Energy interactions in LAr



arXiv: 2203.00740

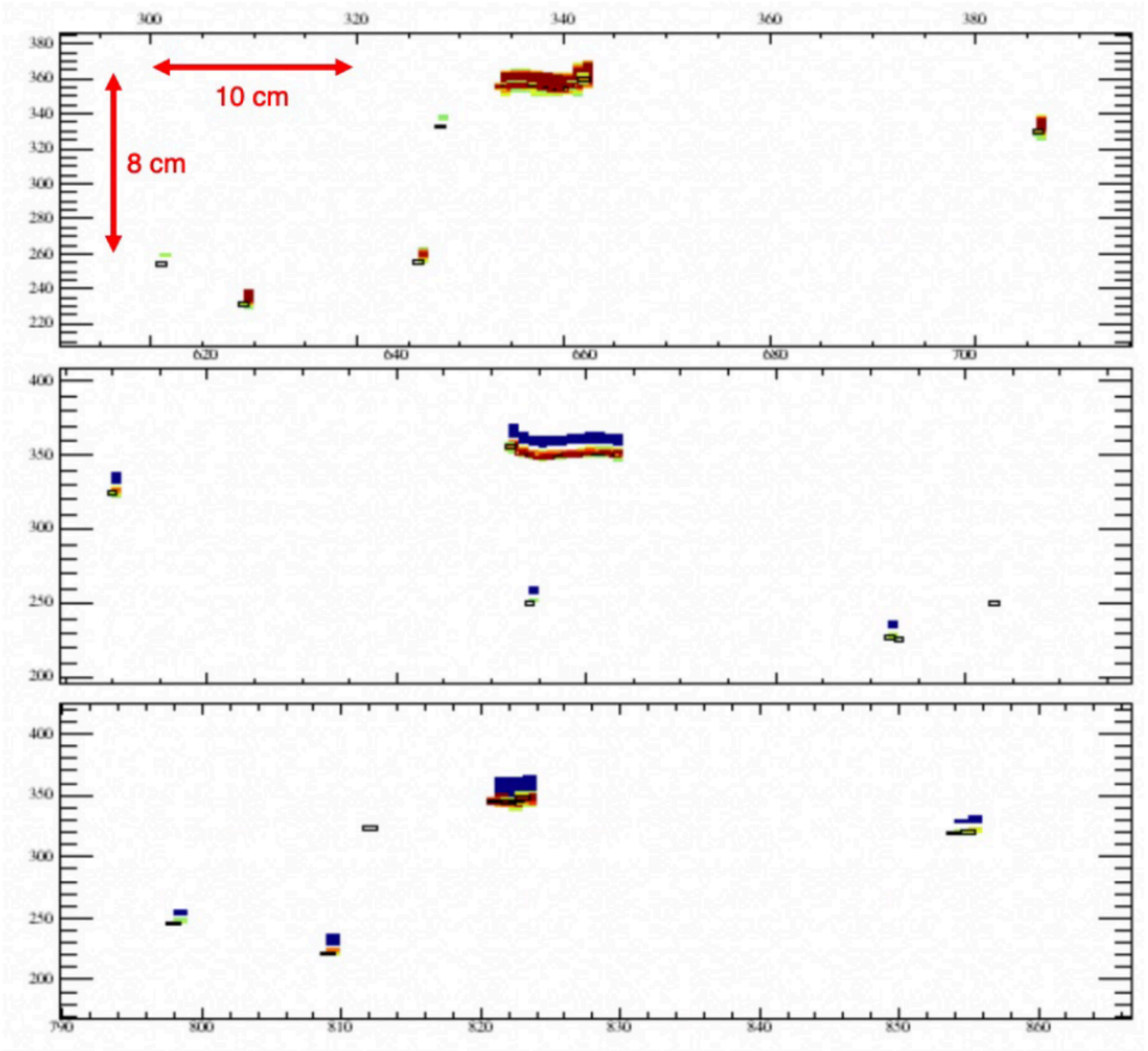
Low Energy interactions in LAr

ν - e$^-$ ES event (10.25 MeV e$^-$)



Topology: isolated electron track

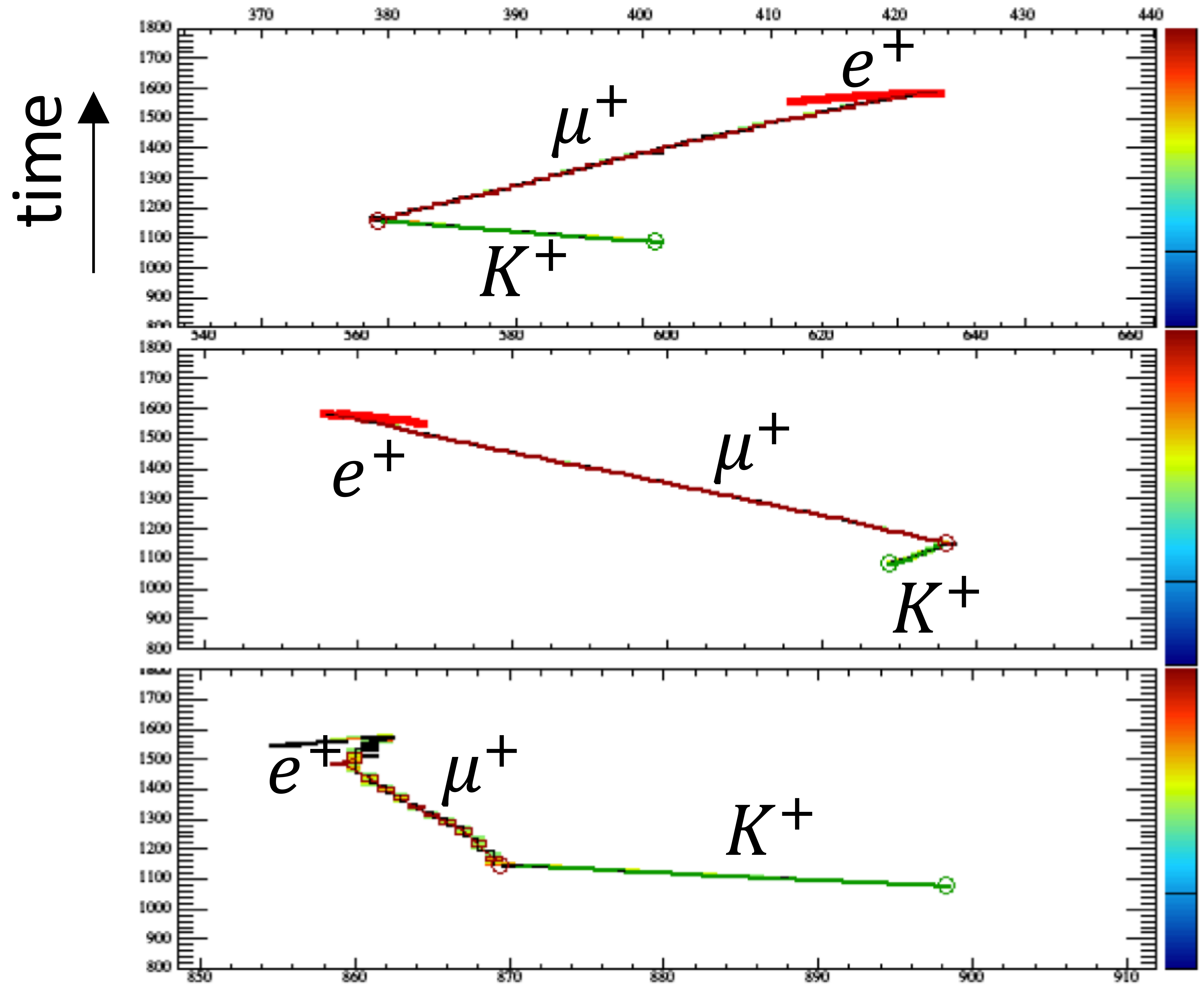
ν_e CC event (20.25 MeV ν_e)



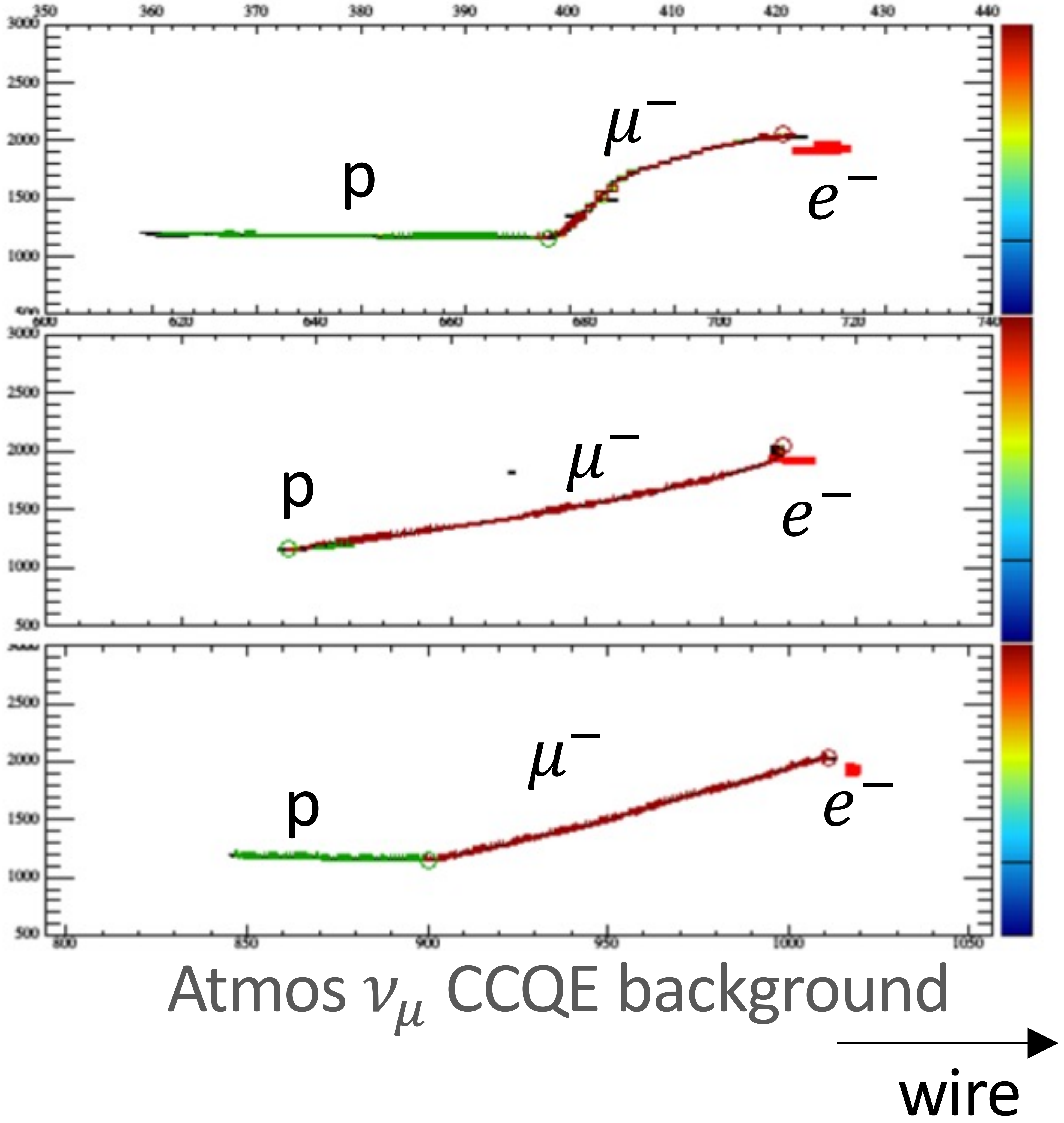
Topology: electron track + blips from the gammas

Proton Decay Background in DUNE

The main background for the p —>$K^+\nu$ channel are the atmospheric neutrinos (very similar signature)



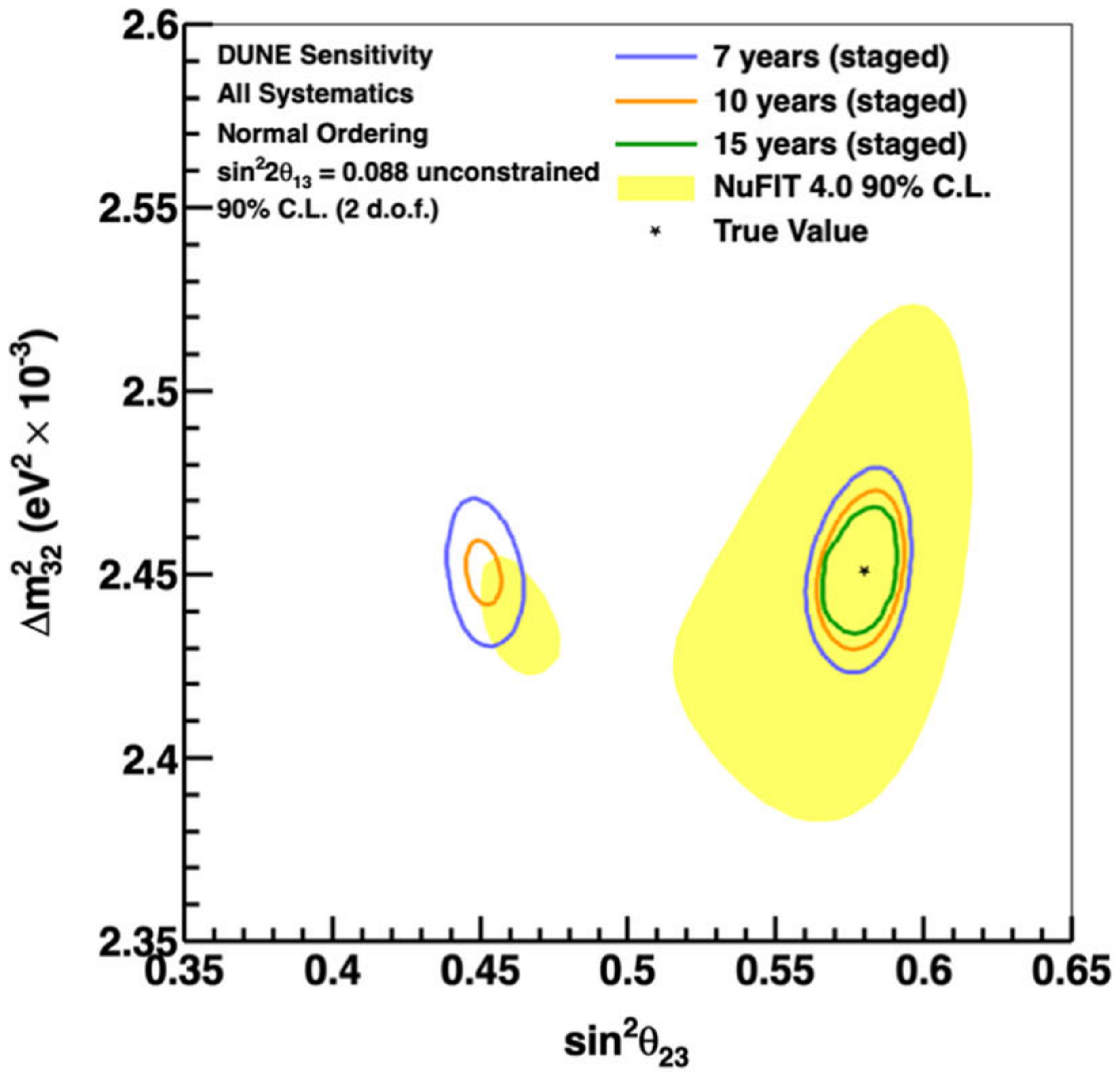
Proton decay event



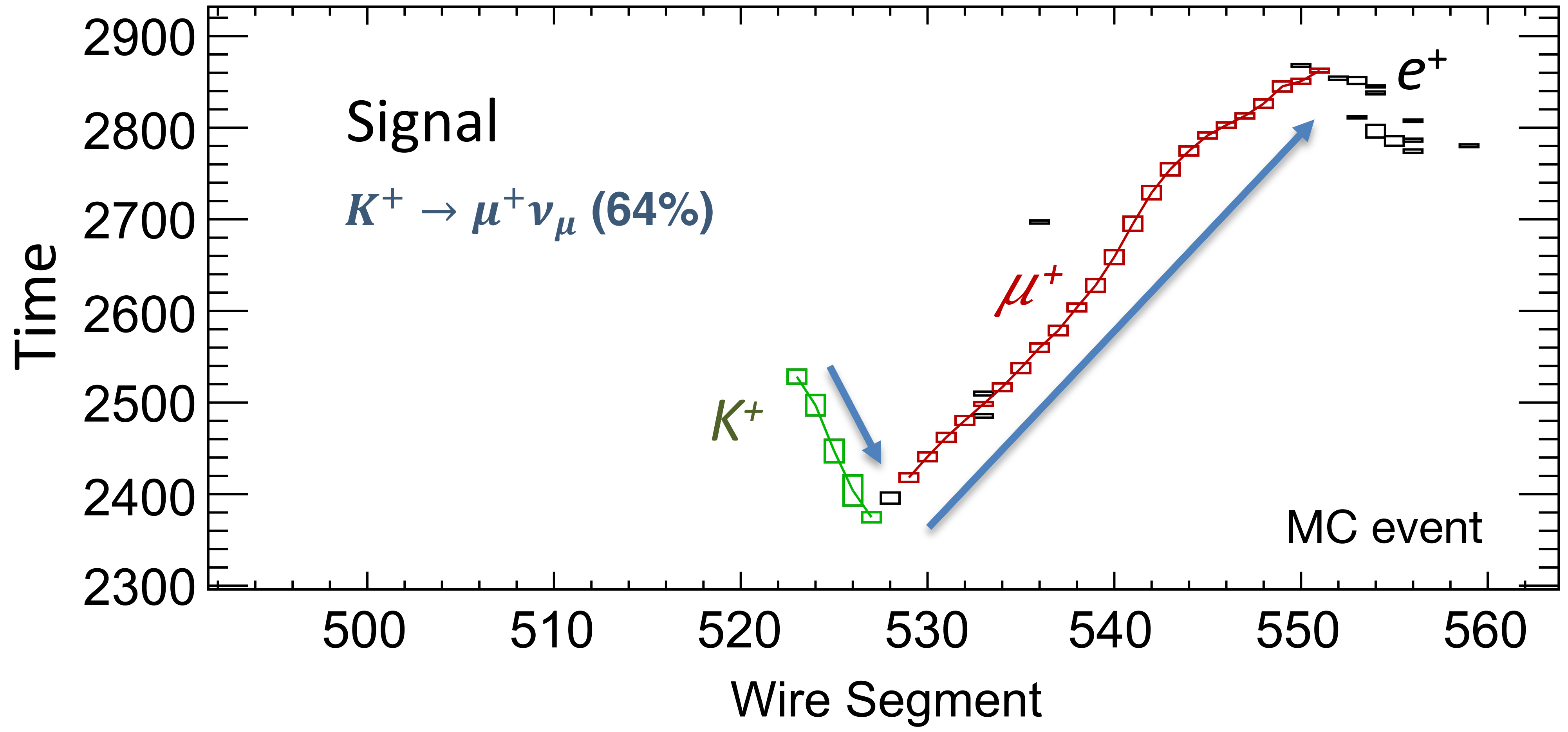
Atmos ν_μ CCQE background

Additional Physics Program in DUNE

- Precise measurement of oscillation parameters with $P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu)$
- Proton decay (through Kaon identification) $p \rightarrow K^+ \bar{\nu}$
- Detection of neutrinos from core-colapse supernovae (~5 MeV)
- Detection of solar neutrinos (~10 MeV)



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



DUNE: Near Detector (ND) - Phase II

- **Main Goal**: constrain uncertainties for oscillation measurements

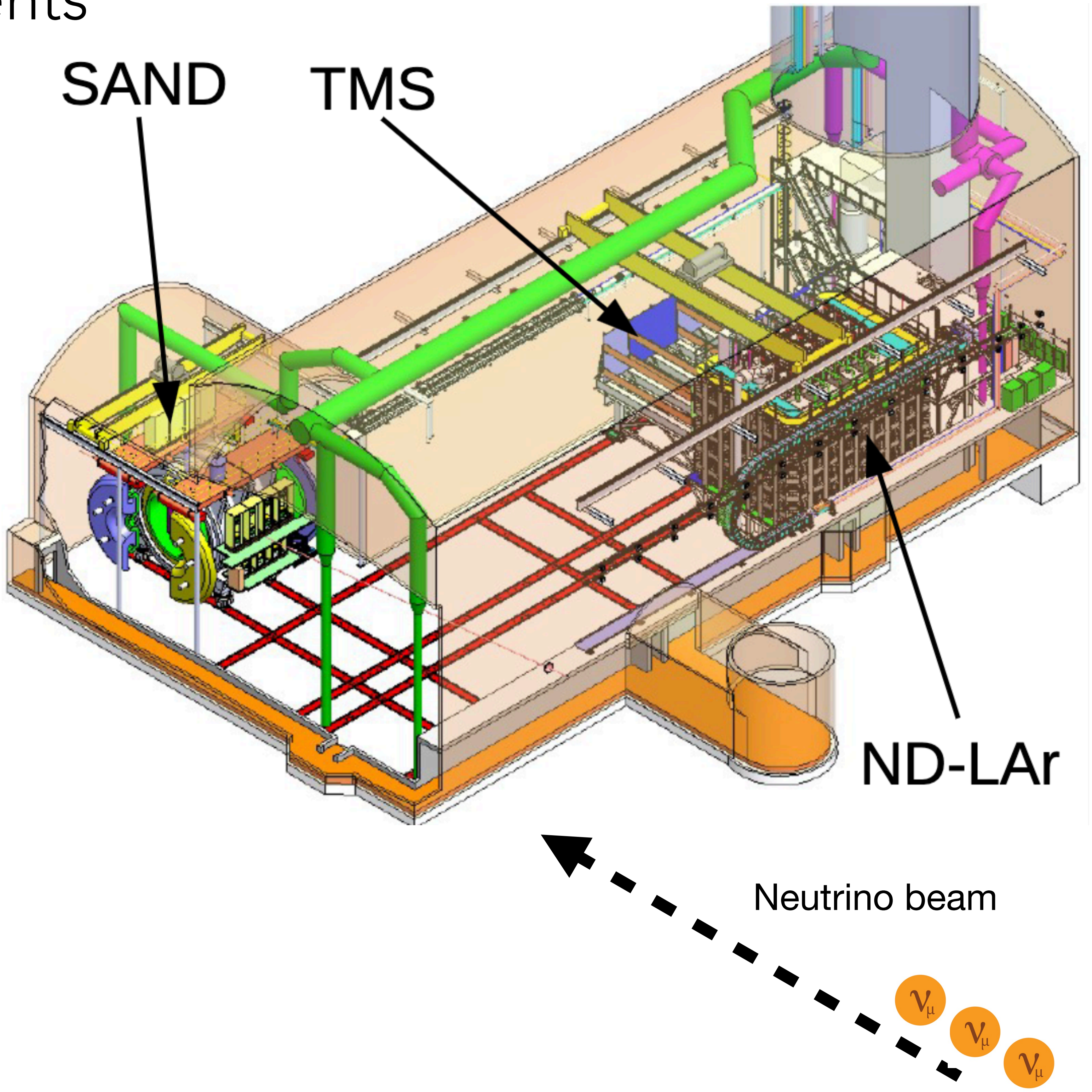
  - Un-oscillated neutrino flux monitoring
  - ν-Ar cross section measurements
  - Enable the prediction on neutrino spectra at FD
  - Three different detection systems on and off axis:

    1) Liquid Argon Detector (50t FV)
       - Primary target, same technology as FD

    2) Gas Argon High Pressure Detector
       - Detect escaping muons + wider physics programe

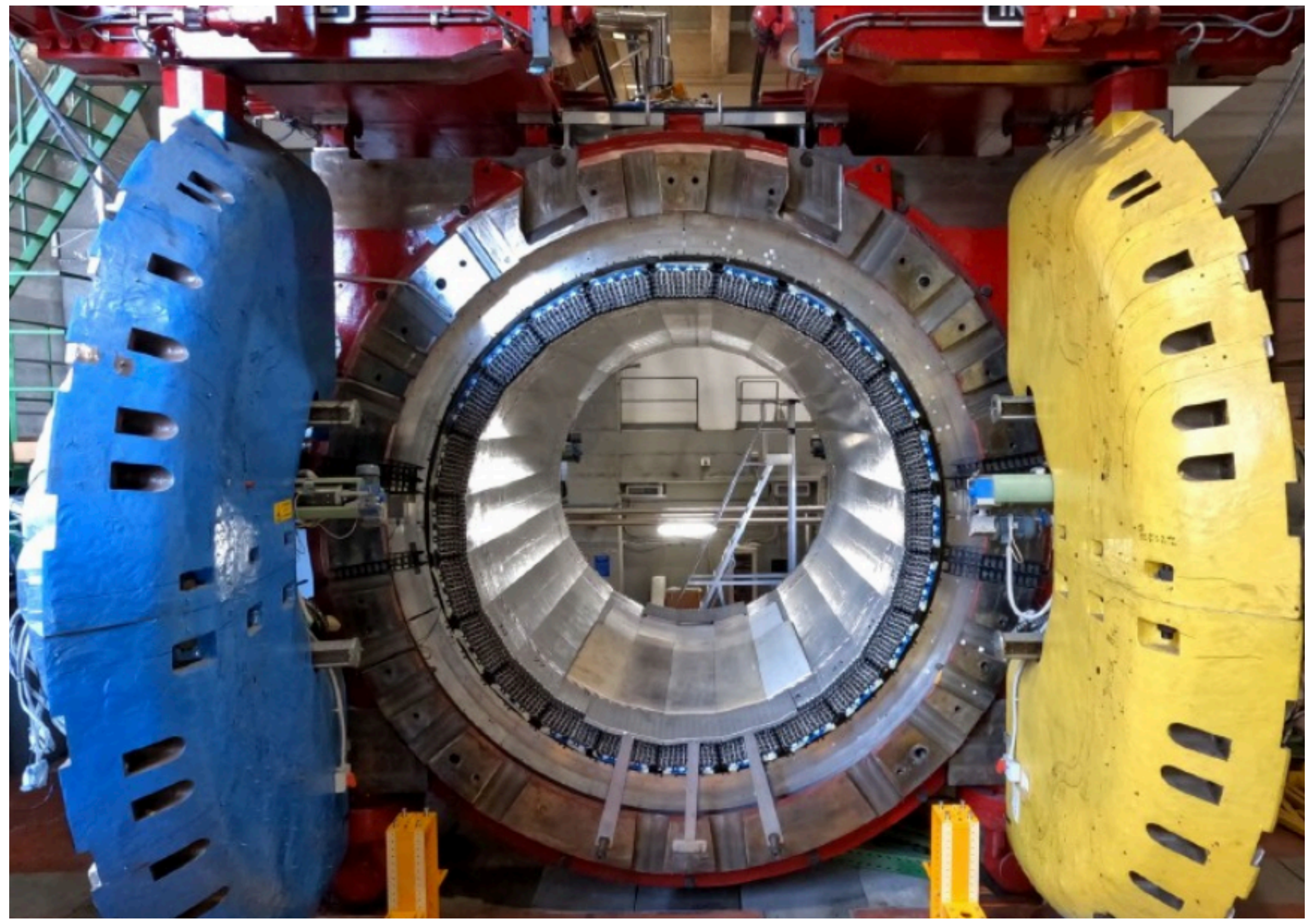
    3) SAND (tracker surrounded by an electromagnetic calorimeter and magnet)
       - Control and monitor of the neutrino beam

574m from the beam & 60m underground



DUNE. Instruments 5 (2021) 4, 31

SAND: on-axis detector (KLOE magnet and calorimeter)



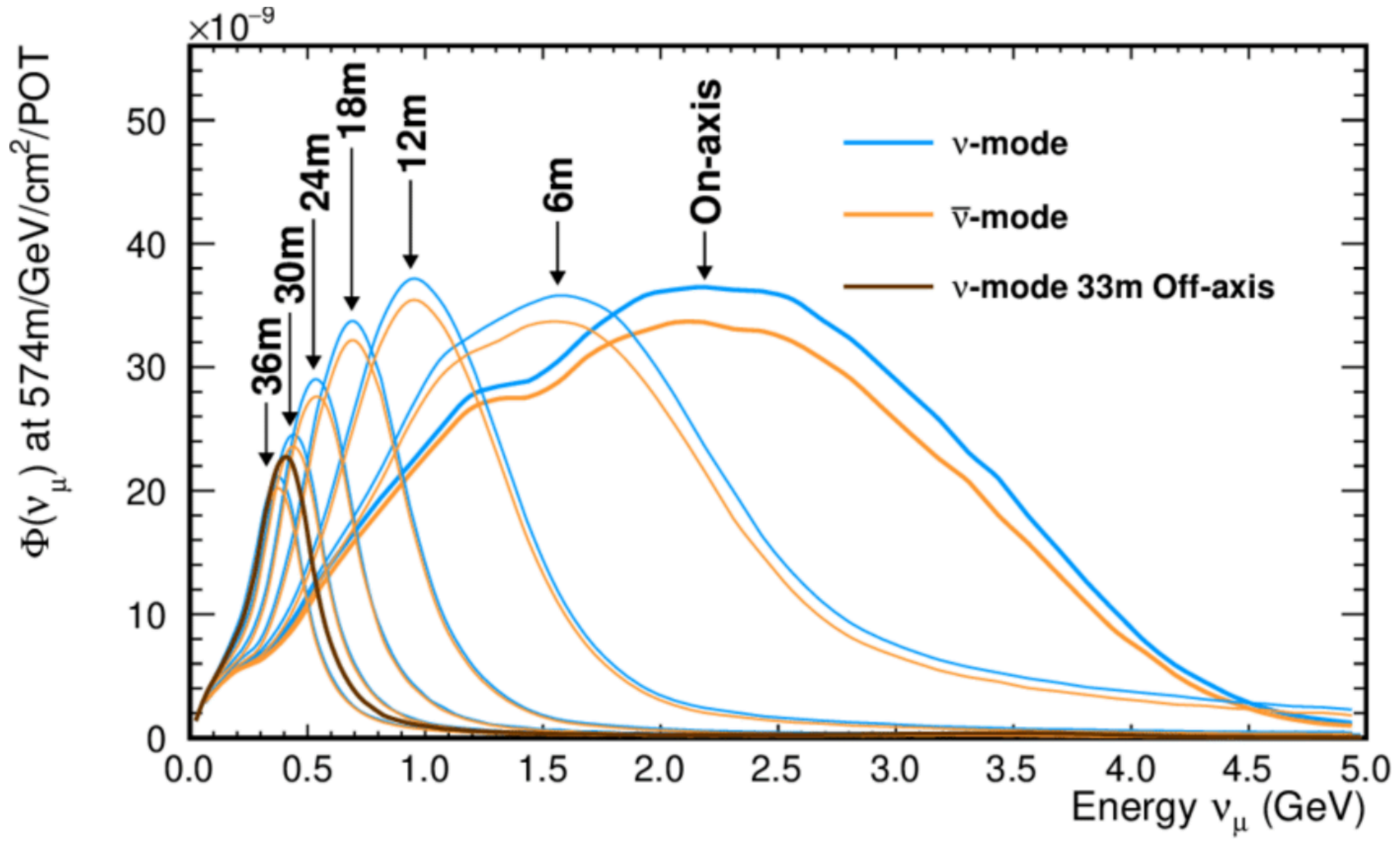
- Fixed component of ND repurposes existing solenoid magnet and ECAL from KLOE
- Plan is to build a collider-like detector in a neutrino beam

  low density tracker surrounded by calorimetry in magnetic field

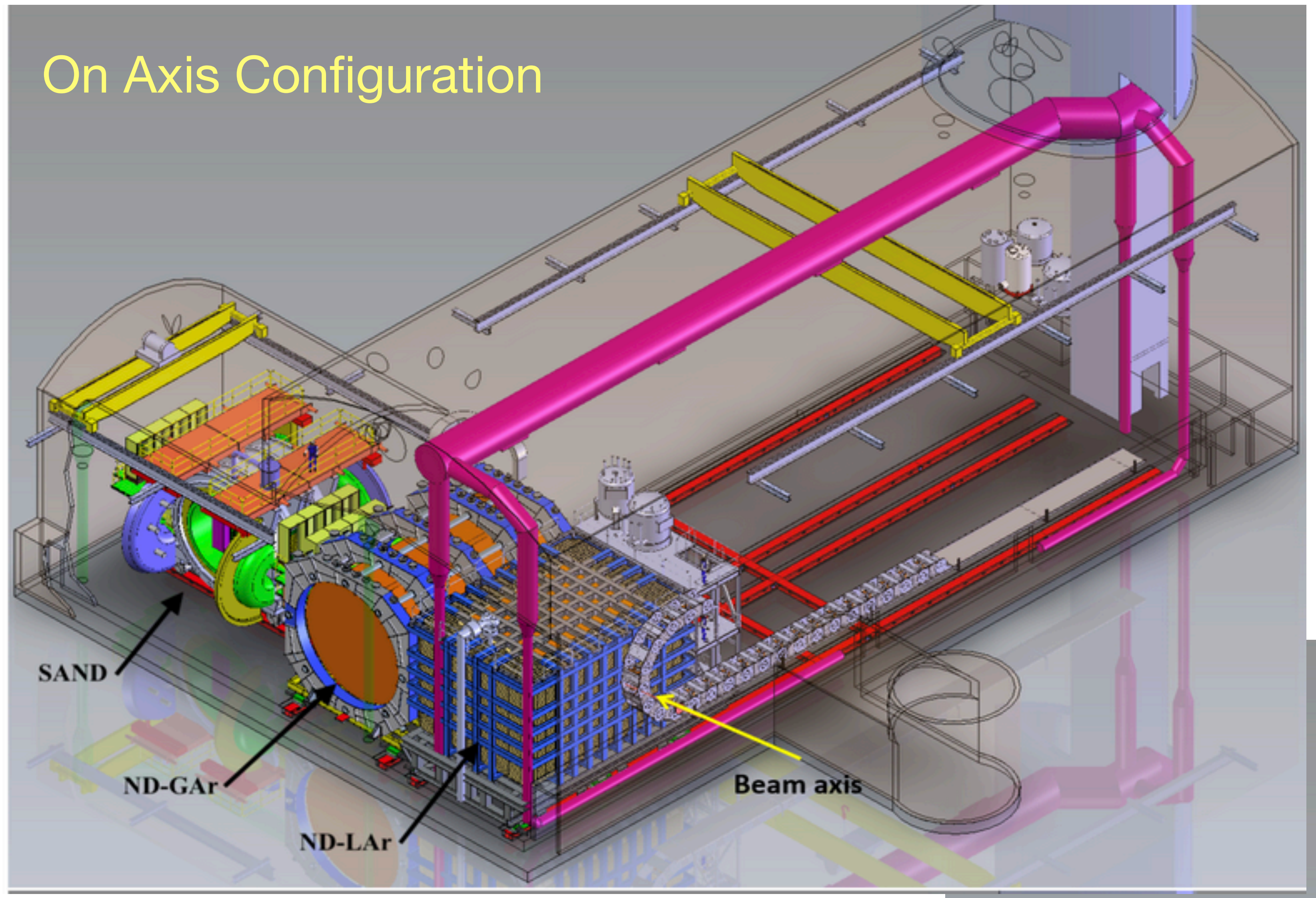
- Fine-grained, particle by particle reconstruction with very low re-scattering, excellent for highly exclusive neutrino-nucleus measurements
- Being taken apart at Frascati for the move to the US

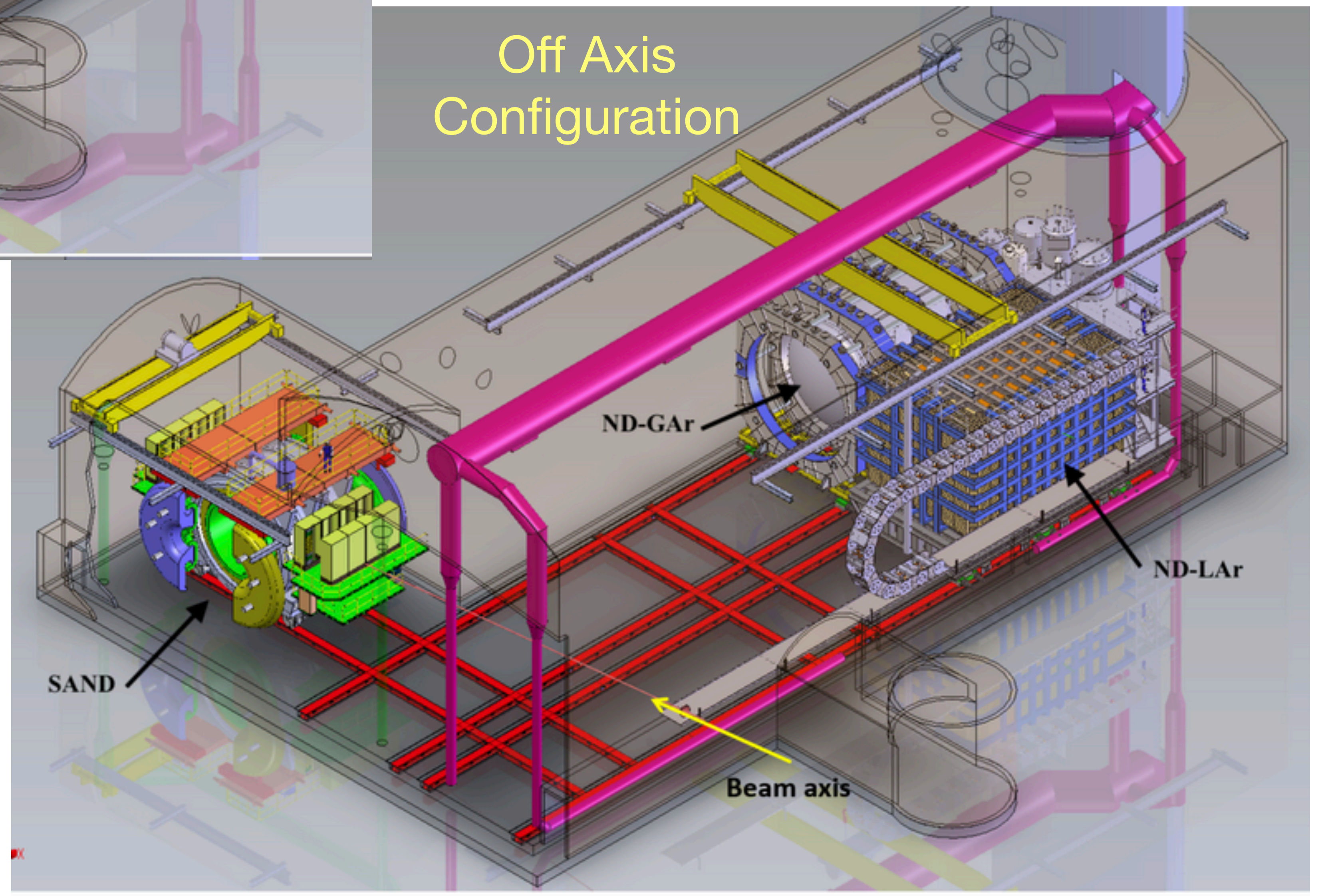
DUNE: Near Detector (ND)

- **Main Goal**: constrain uncertainties for oscillation measurements



The movement system allows for different neutrino energy spectra





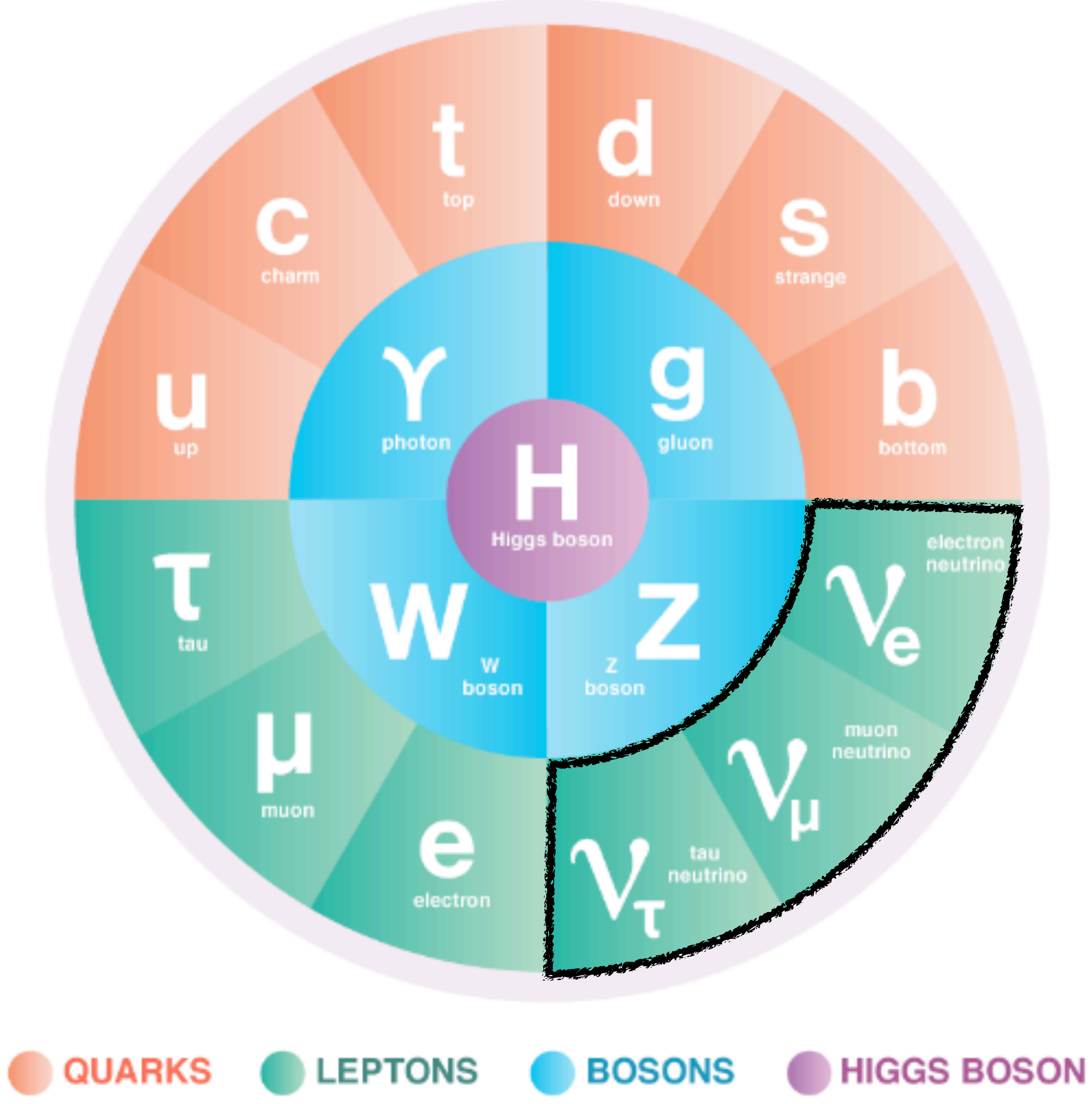
Off-axis measurements reduce cross-section and energy uncertainties

Neutrinos in the Standard Model

Particles of the Standard Model (SM)

- Standard Model leptons
- Neutral charge
- 3 neutrino flavours
- Spin 1/2
- Weak interaction (and gravitational)

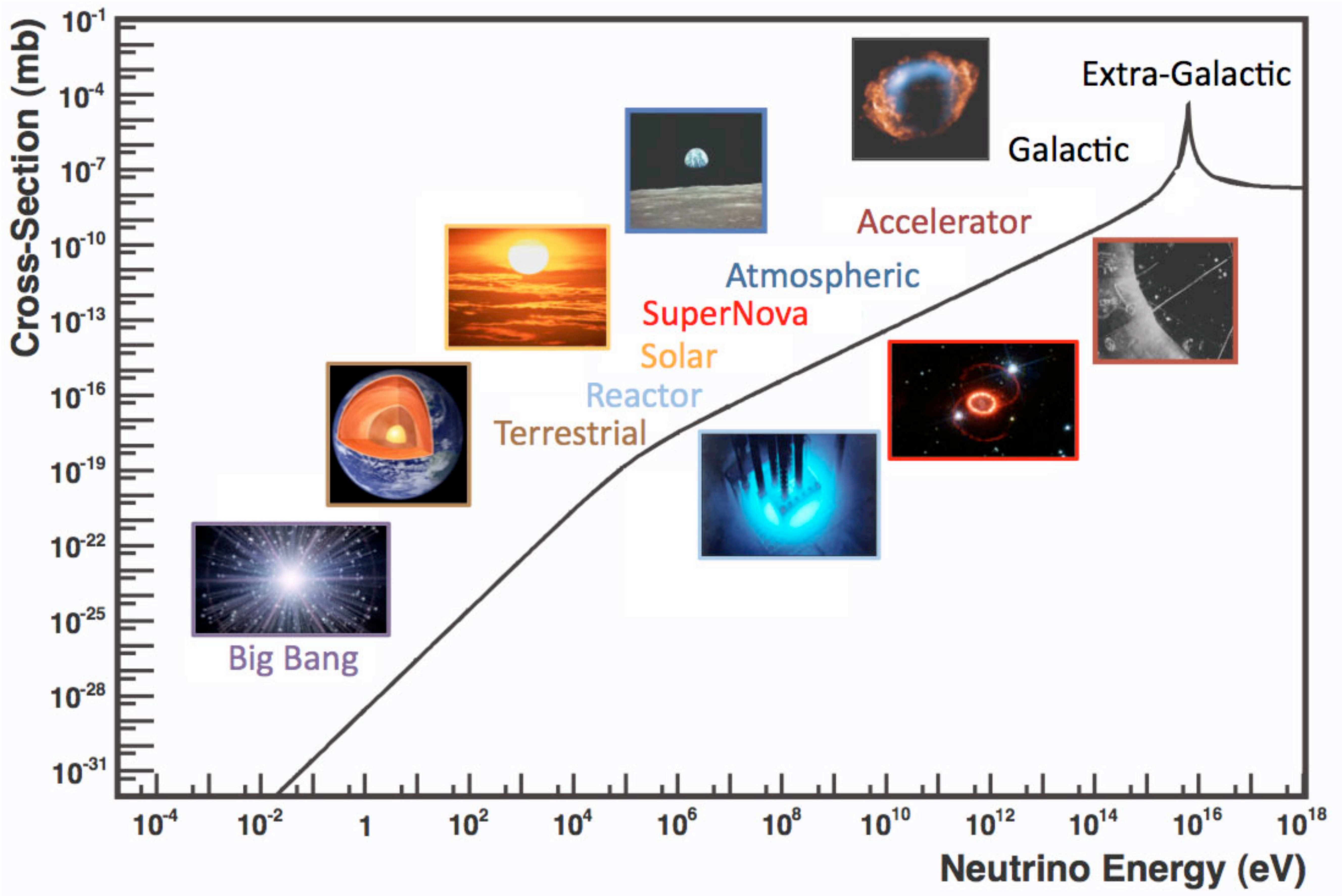
In the SM the lepton number is conserved and neutrinos are massless



symmetrymagazine.org

Neutrino interaction cross-section

- Interaction very very weakly



Cross-section: indication of likelihood of two interacting particles

$$1mb = 10^{-31}cm^2$$

Example:

The cross-section of a 10 MeV photon interacting with an atom is 1b

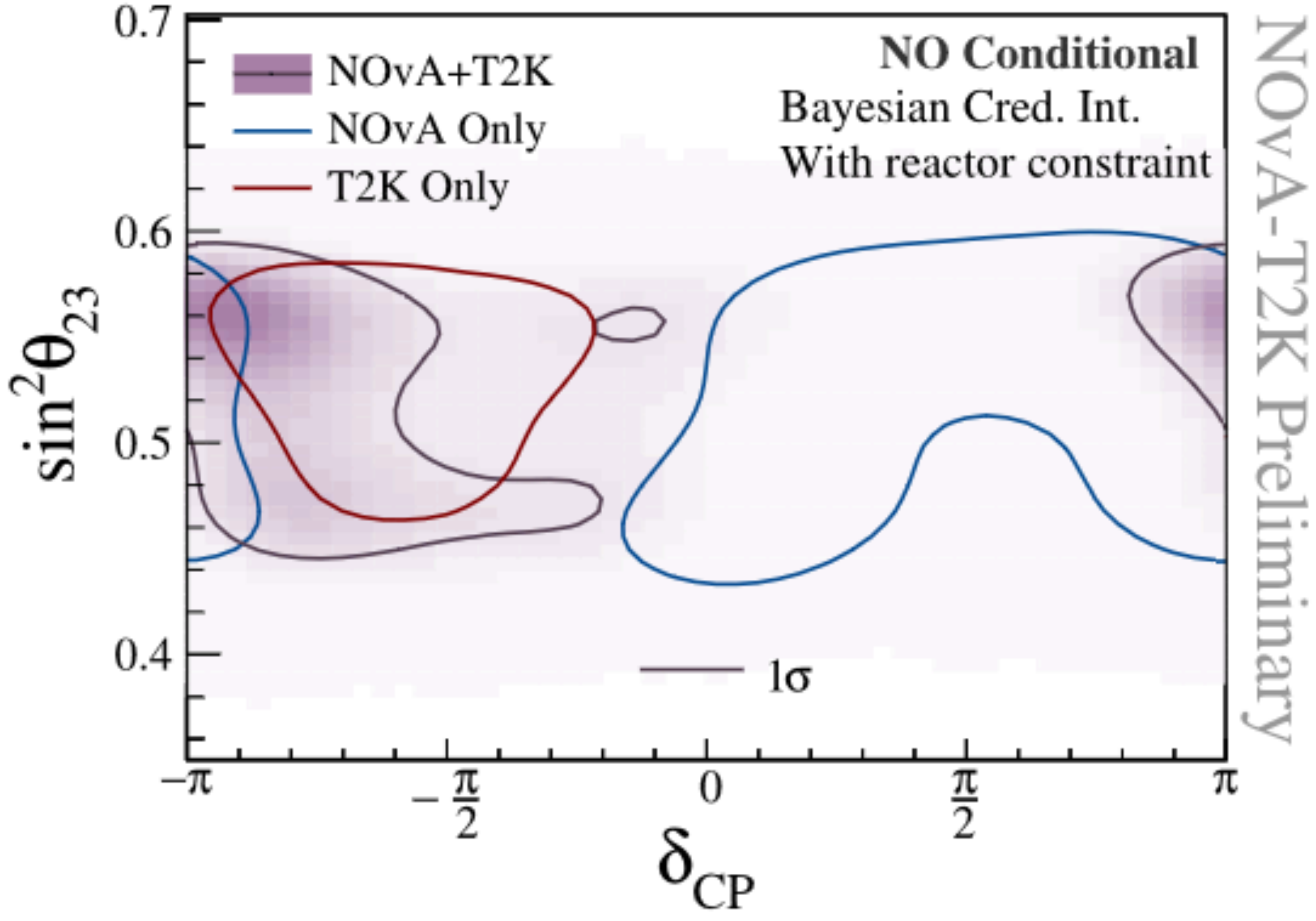
Current knowledge (NOvA & T2K)

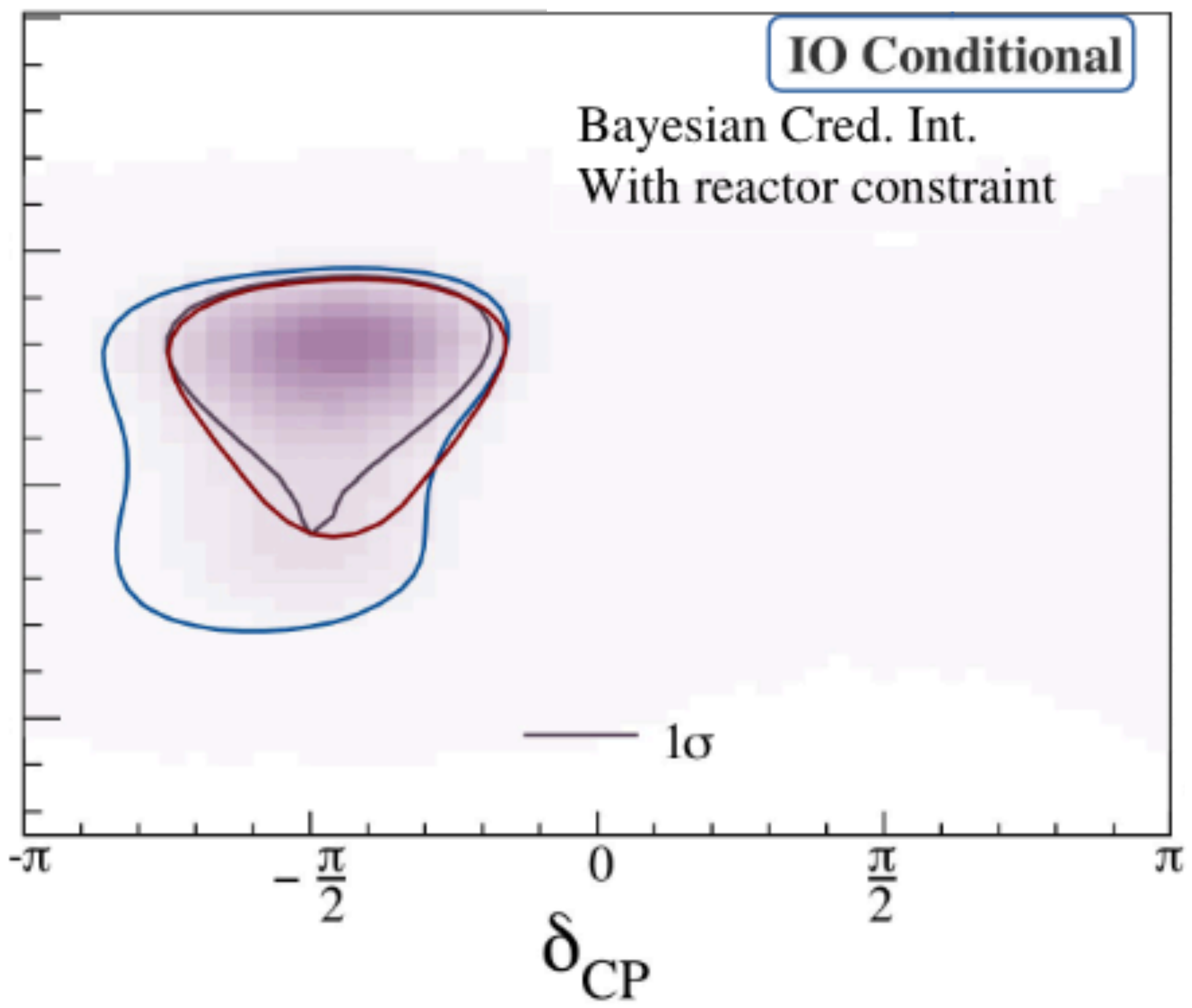
- NOvA + T2K combined results (Neutrino2024)

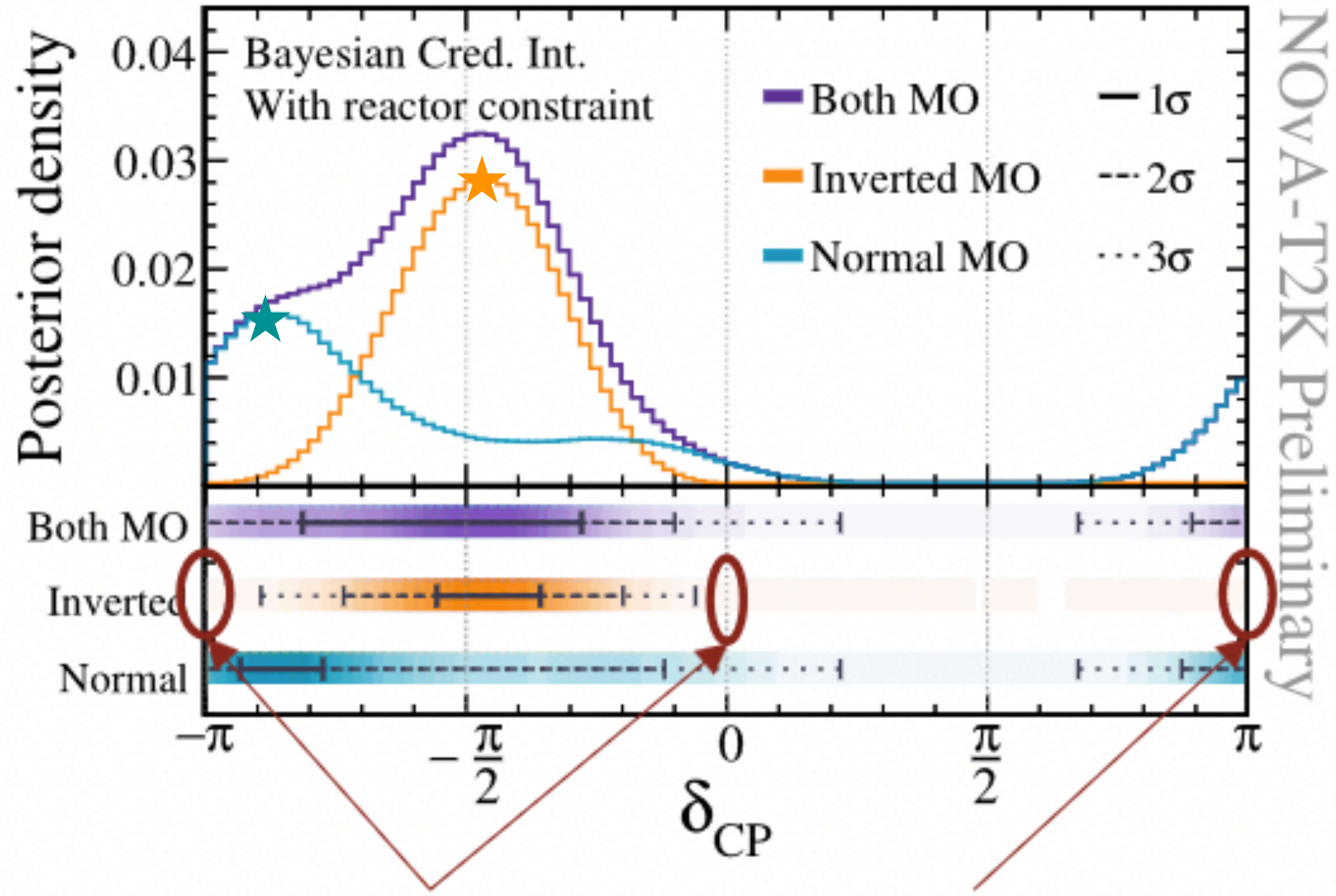
NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)

Some tension in the value of δ_{CP} for NO

Future LBL experiments needed to reach a conclusion







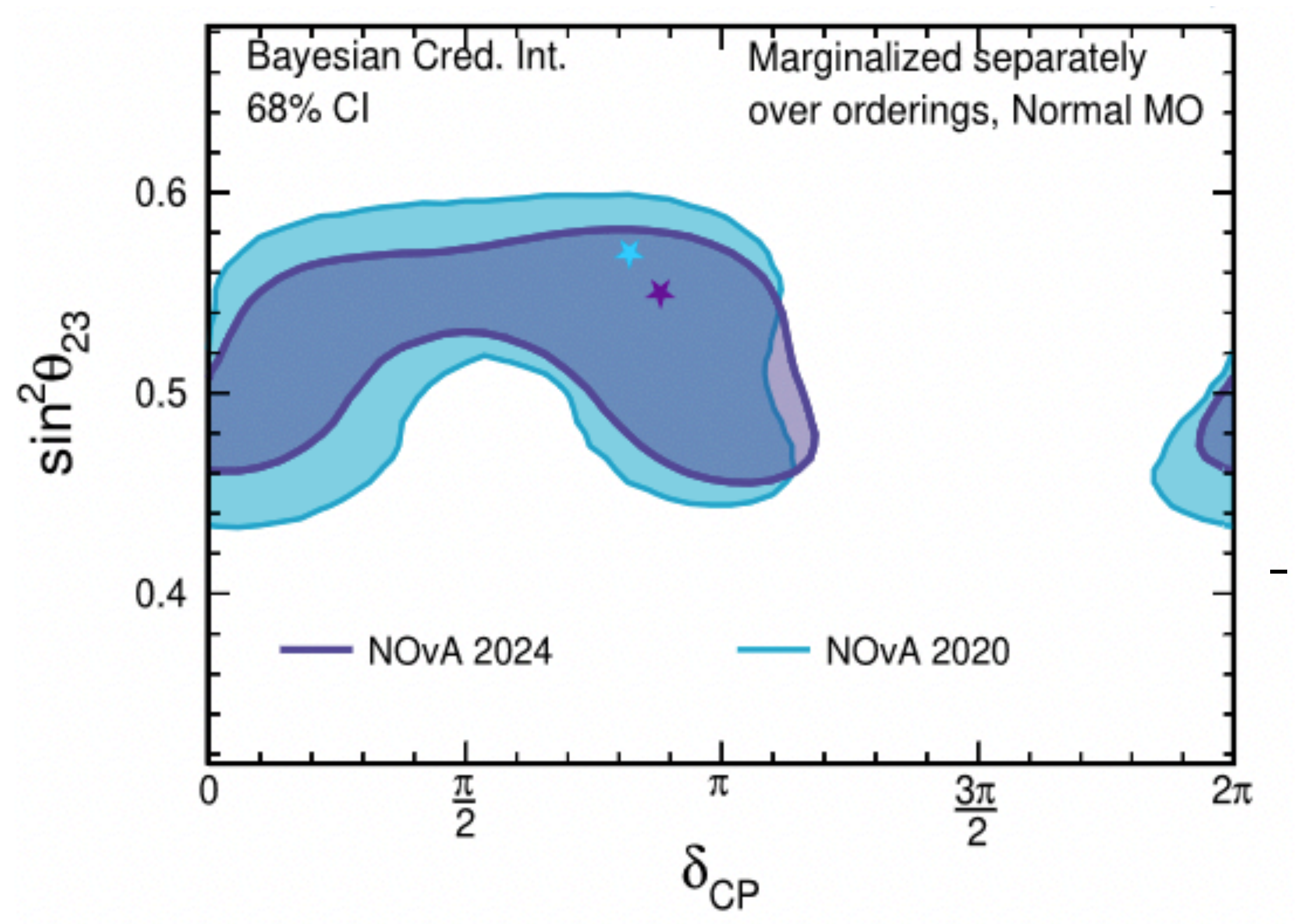
- **NOvA only:**
  - Preference for NO with $\pi/2 < \delta_{CP} < \pi$
  - Different trends NO and IO
- **T2K only:**
  - Preference for NO with $\delta_{CP} \sim -\pi/2$
  - Same trends NO and IO

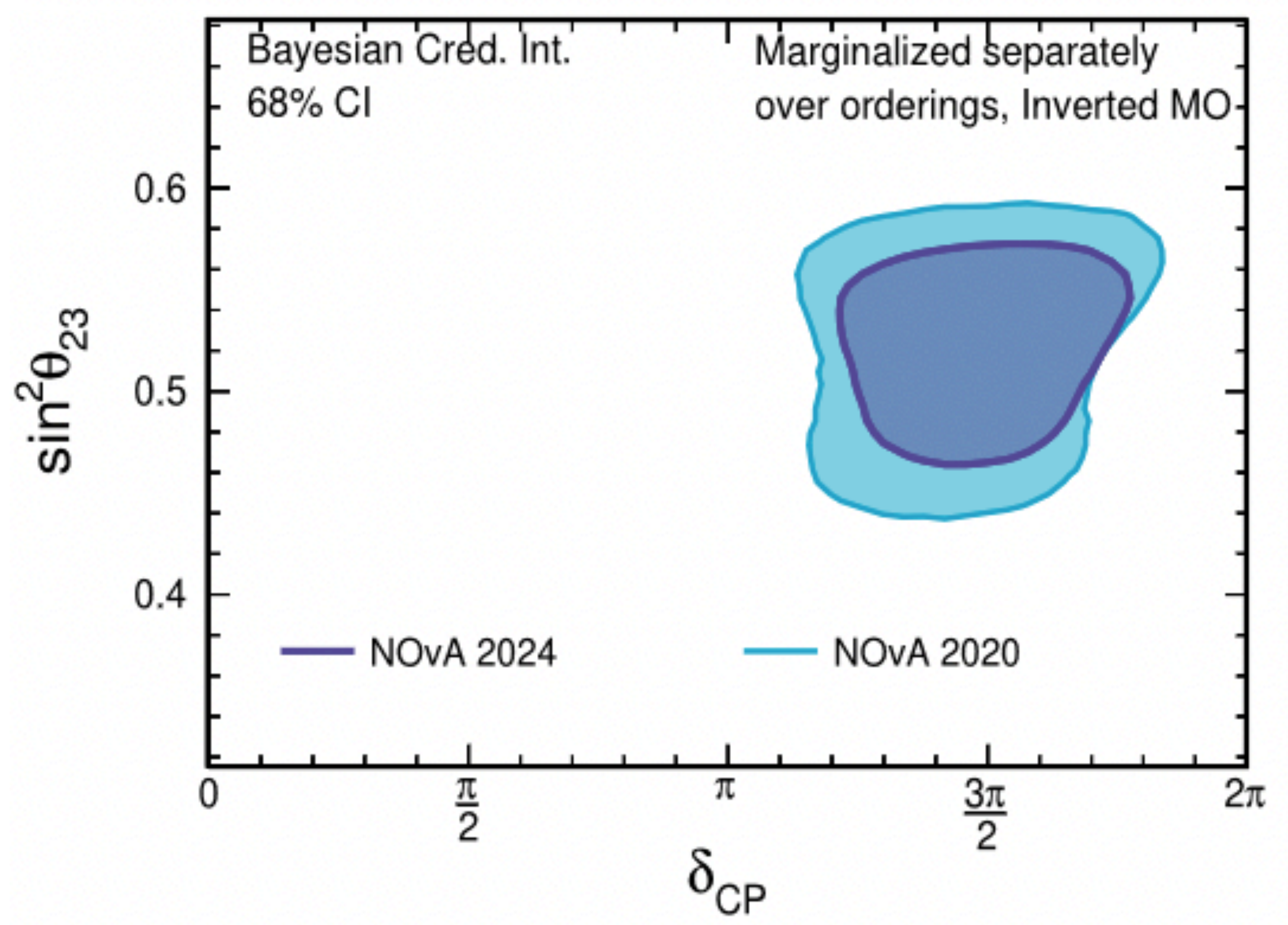
CP-conserving points are *outside* 3σ intervals in IO

Expect CPV *if* ordering is inverted

- **NOvA + T2K combined:** Mild preference for IO

Current knowledge (NOvA & T2K)





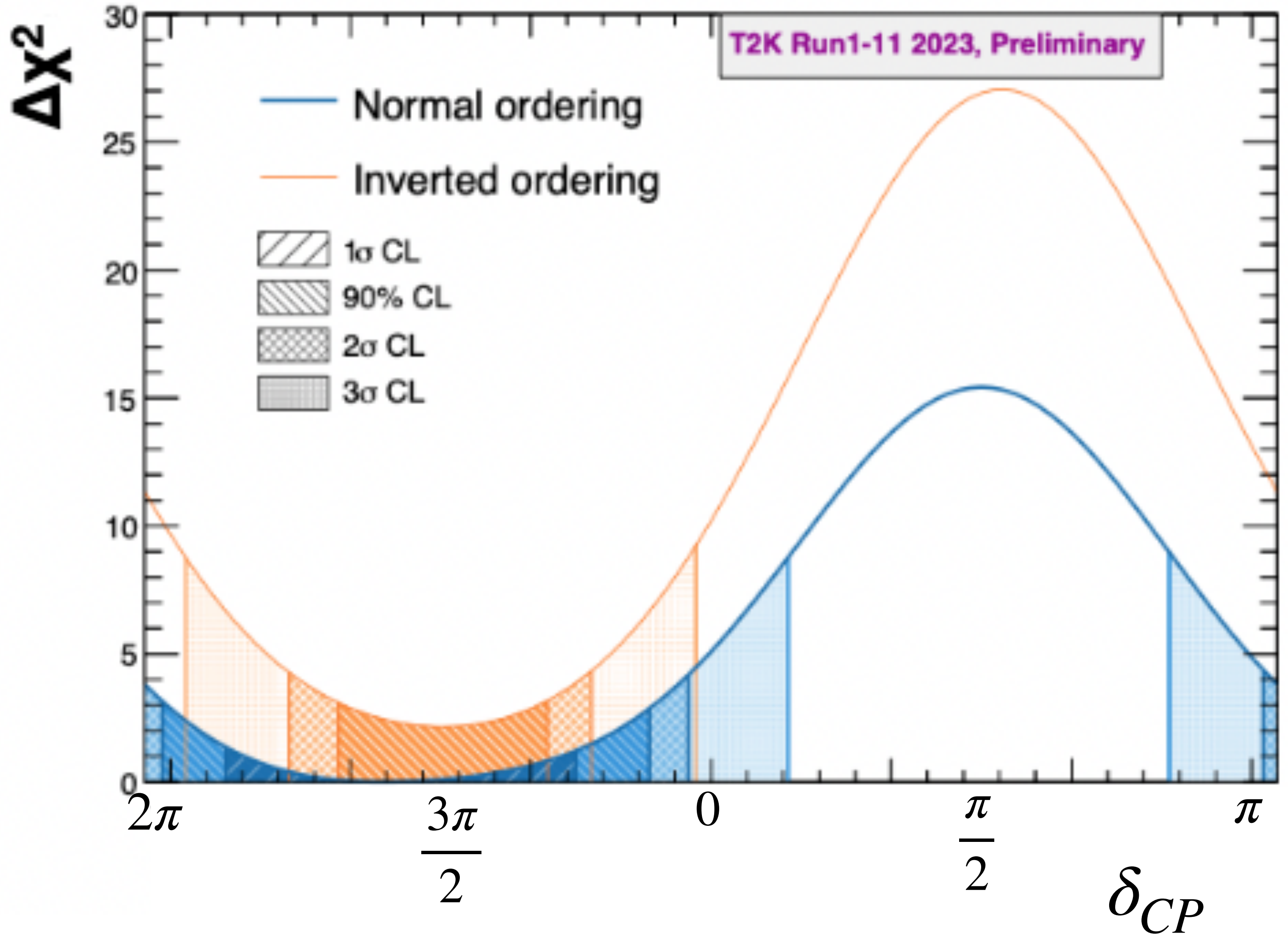
NOvA Preliminary, Neutrino2024

Preference for NO with $\pi/2 < \delta_{CP} < \pi$

- different trends NO/IO

There are hints for CP violation ($\delta_{CP} \neq 0$) from both NOvA and T2K, although with some tension for NO results

T2K Preliminary, Neutrino2024



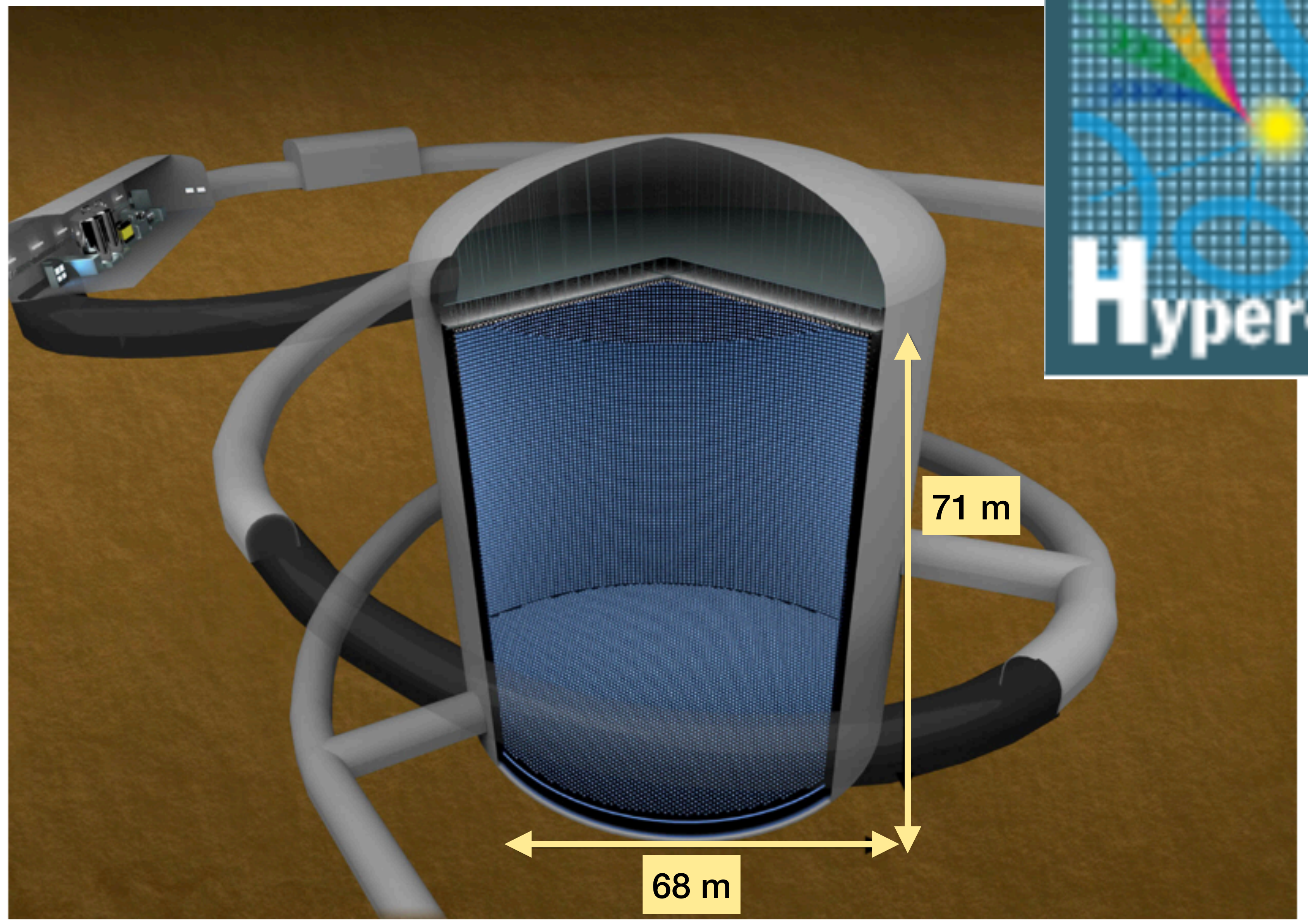
Preference for NO with δ_{CP}~$3\pi/2$, but CP conserving values are within the 2σ interval

- similar trend for NO and IO

Hyper-Kamiokande

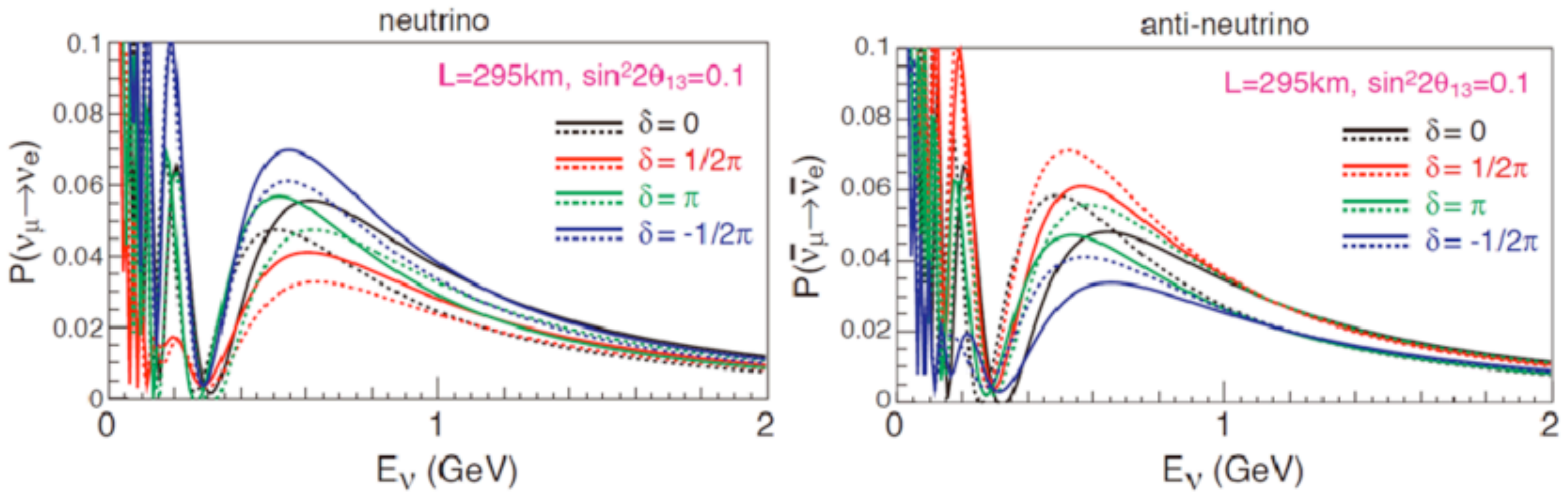
- Natural evolution of Super-Kamiokande (T2K —> T2HyperK)
- **Upgrade:** neutrino beam > 1.3 MW, off-axis angles, larger FD
- **Baseline:** 295 km (same)
- **Fiducial volume:** 200 kton pure water (8 times SK)
- Possibility to add a second FD in Korea (baseline 1100 km)
- Aiming to start operations in 2027

new cavern at Kamioka mine under construction



GOAL: Minimise matter effects + maximise statistics to focus on δ_{CP}

> 5σ CPV sensitivity in 10 years for 60% of the δ_{CP} values



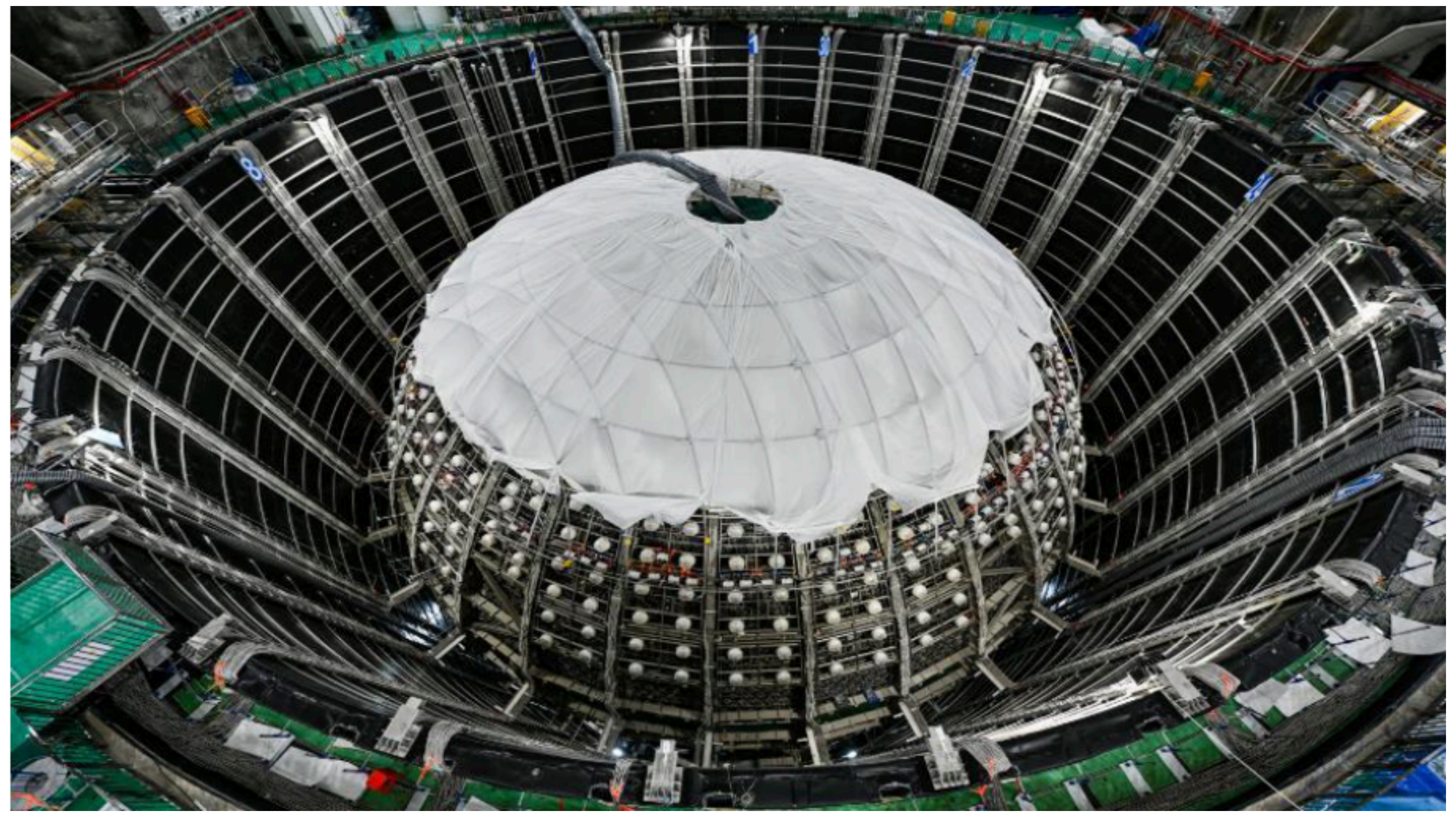
Hyper-K collaboration (Neutrino2024)

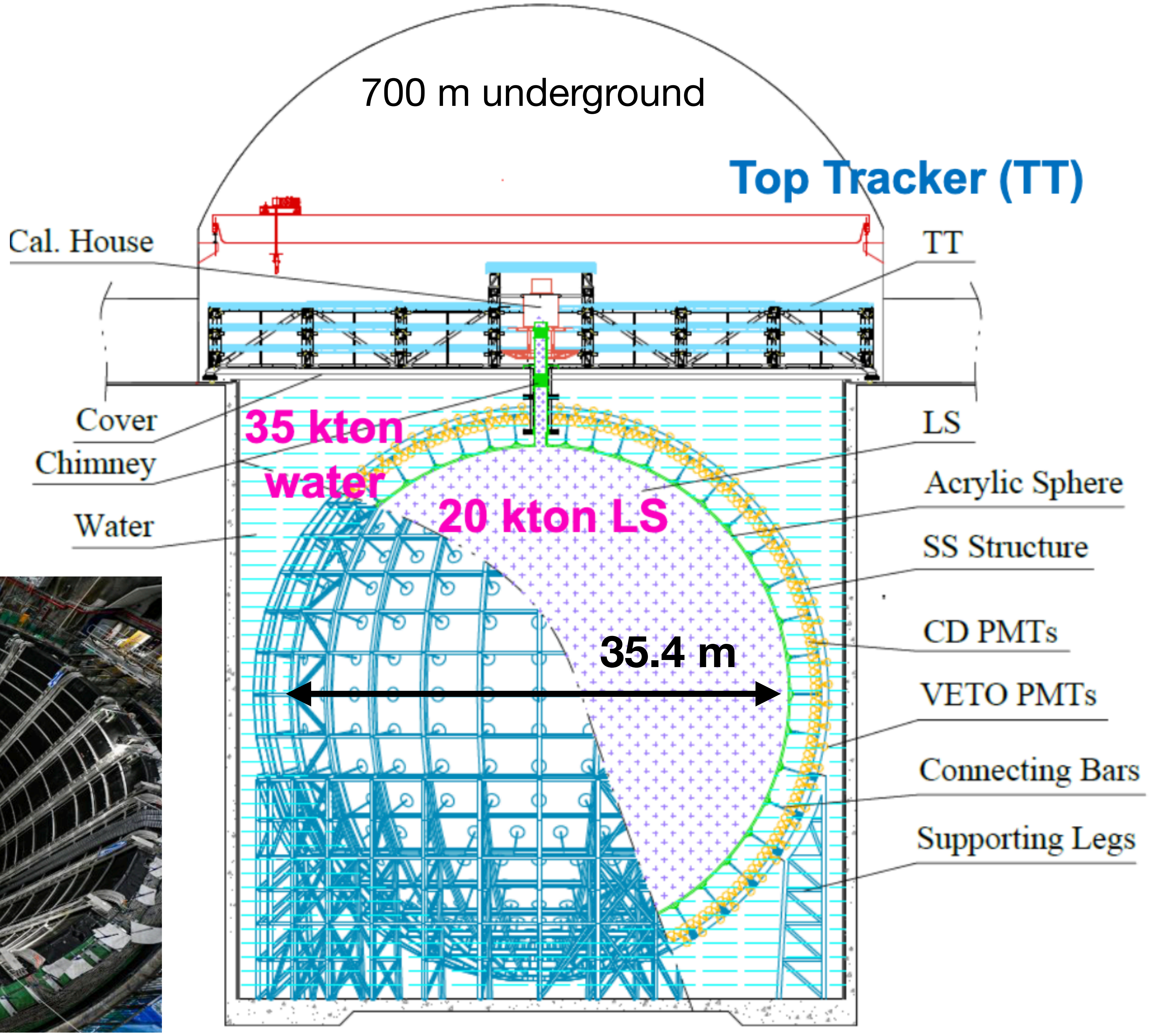
JUNO (Jiangmen Underground Neutrino Observatory)

- Next-generation Large Liquid Scintillator detector (à la KamLAND)
- It is a LBL reactor experiment in China. **Baseline 50 km**
- **Fiducial volume:** 20 kton
- Increased light yield for a better energy resolution (3% at 1 MeV)
- End of the construction + filling in 2024

MAIN GOAL: Mass ordering sensitivity

Design to reach 3σ precision on mass ordering determination after 6 years





JUNO collaboration (Neutrino2024)