Update on DUNE physics

IN2P3 Scientific Council 2-3-2026

A.Meregaglia (LP2i Bordeaux)

Introduction

What we know

- Neutrinos of **3 families** have been detected and **oscillations** between the families were observed.

- The three **mixing angles** and the two **mass splittings** have been measured with precision at the **few percent level**.

- **Neutrino masses** are the first and so far only manifestation of physics **beyond the Standard Model** in particle physics experiments.

2015 NOBEL PRIZE IN PHYSICS

Takaaki Kajita and Arthur B. McDonald
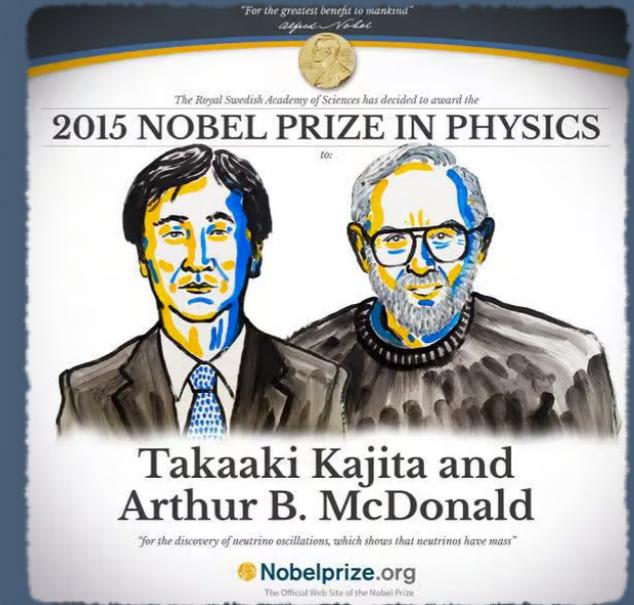
	Ref. [181] w/o SK-ATM	
NO	Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$
$\theta_{12}/°$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.72^{+0.18}_{-0.23}$	$4.06 \to 6.20$
$\theta_{23}/°$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.203^{+0.056}_{-0.059}$	$2.029 \to 2.391$
$\theta_{13}/°$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$
$\delta_{CP}/°$	197^{+42}_{-25}	$108 \to 404$
$\frac{\Delta m^2_{21}}{10^{-5}~eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{32}}{10^{-3}~eV^2}$	$2.437^{+0.028}_{-0.027}$	$2.354 \to 2.523$
IO	$\Delta\chi^2 = 2.3$	
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$
$\theta_{12}/°$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.78^{+0.16}_{-0.21}$	$4.12 \to 6.23$
$\theta_{23}/°$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.219^{+0.060}_{-0.057}$	$2.047 \to 2.396$
$\theta_{13}/°$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
$\delta_{CP}/°$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}~eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{32}}{10^{-3}~eV^2}$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

from PDG (2023)

Introduction

What we do not know

- The **absolute** value of their **masses**.

- Whether neutrinos are **Dirac or Majorana fermions**.

- The **mass ordering** (normal or inverted).

- Whether the **charge-parity (CP) symmetry** is violated in the lepton sector.

- Whether the **three-neutrino framework** is complete and the PMNS matrix is unitary.
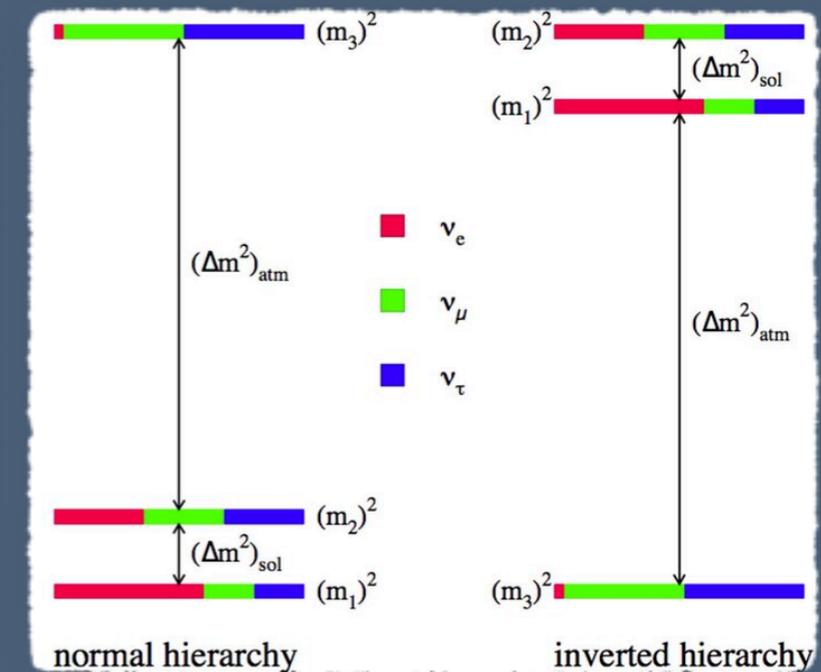
Introduction

Neutrino: one of the least known elementary particles

What we do not know

- The *absolute* value of their *masses*.

- Whether neutrinos are *Dirac or Majorana fermions*.

- The *mass ordering* (normal or inverted).

- Whether the *charge-parity (CP) symmetry* is violated in the lepton sector.

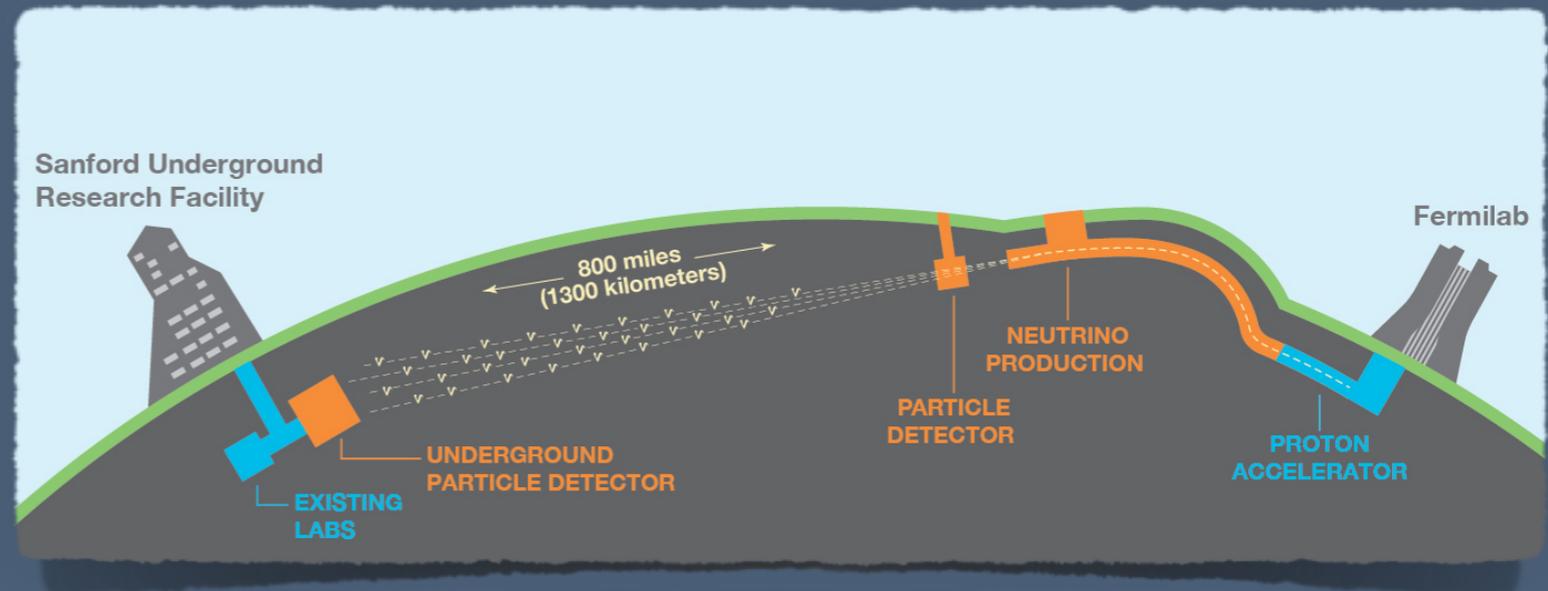- Whether the *three-neutrino framework* is complete and the PMNS matrix is unitary.

Likely measured in the next 10 years with critical contributions from Long Baseline experiments
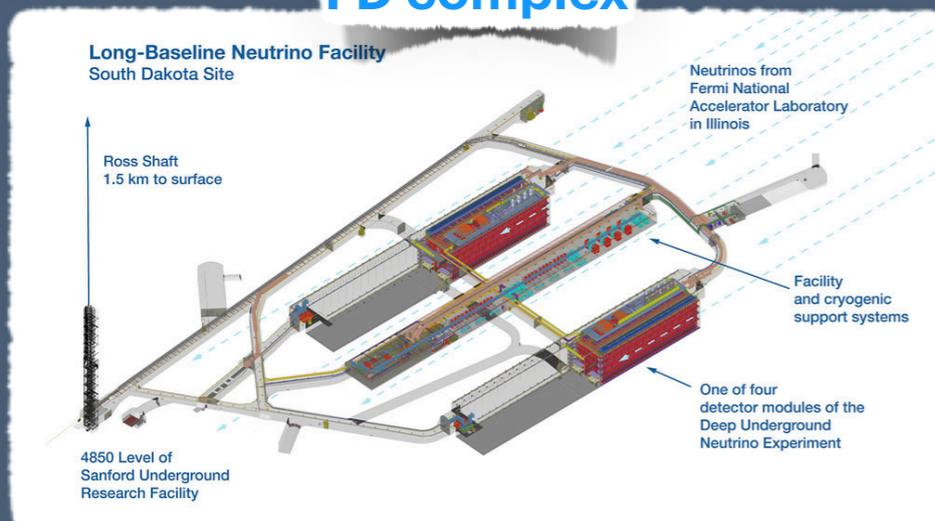
Long Baseline Experiments

- The precise study of oscillations with Long Baselines (LBL) is a **privileged tool** to investigate both standard and non-standard neutrino properties.

- The **main goals** of current and future LBL experiments are the **search for CPV** in the neutrino sector, the **determination of the neutrino mass ordering**, and the **precise measurement** of the phase δ_{CP} and of the so called "atmospheric" parameters (θ_{23} and Δm^2_{32}).

- T2K and NOVA are providing accurate measurements of neutrino oscillations and new tests of the standard PMNS oscillation paradigm, observed for the first time ν_e appearance in a ν_μ beam, and yielded first hints of CP-symmetry violation.

- The **next generation experiments**, Hyper-Kamiokande (HK) in Japan and the Deep Underground Neutrino Experiment (**DUNE**) in the US, represent the **forefront of this endeavour**.
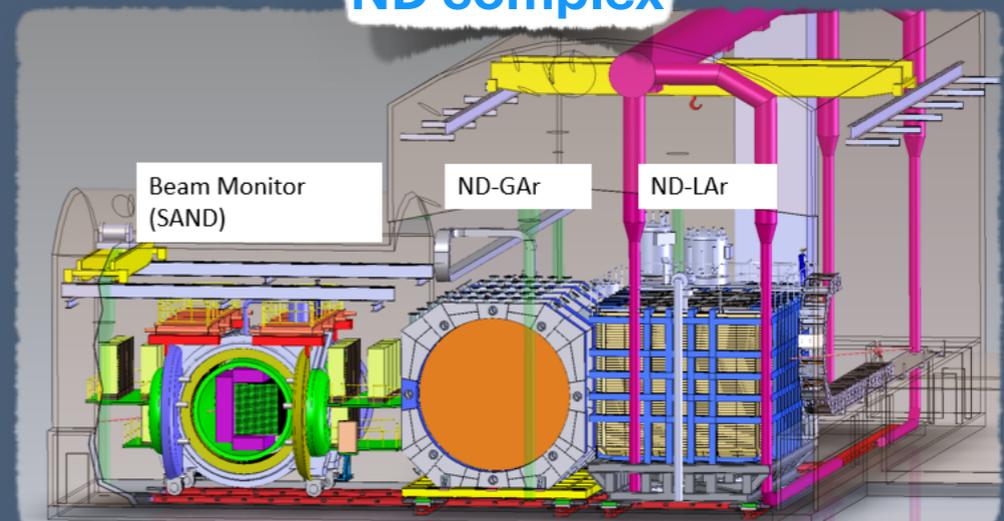
DUNE

- DUNE is a *long baseline neutrino oscillation experiment* with a baseline of 1300 km.

- The neutrino beam will be produced at *Fermilab* and detected in the *SURF* (Sanford Underground Research Laboratory) underground facility (1500 m overburden).

- The experiment consists of a 1.2 MW proton beam upgradable to more than 2 MW, a near detector complex (at about 570 m from the target), and more than *40 kton far detector* (staged approach).
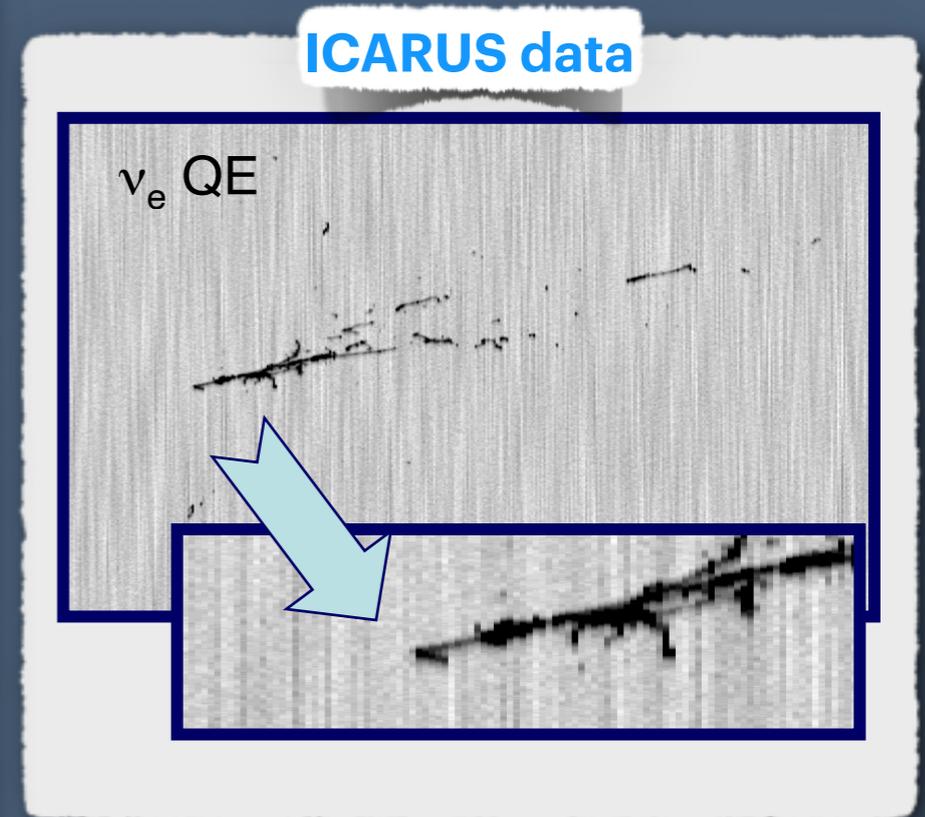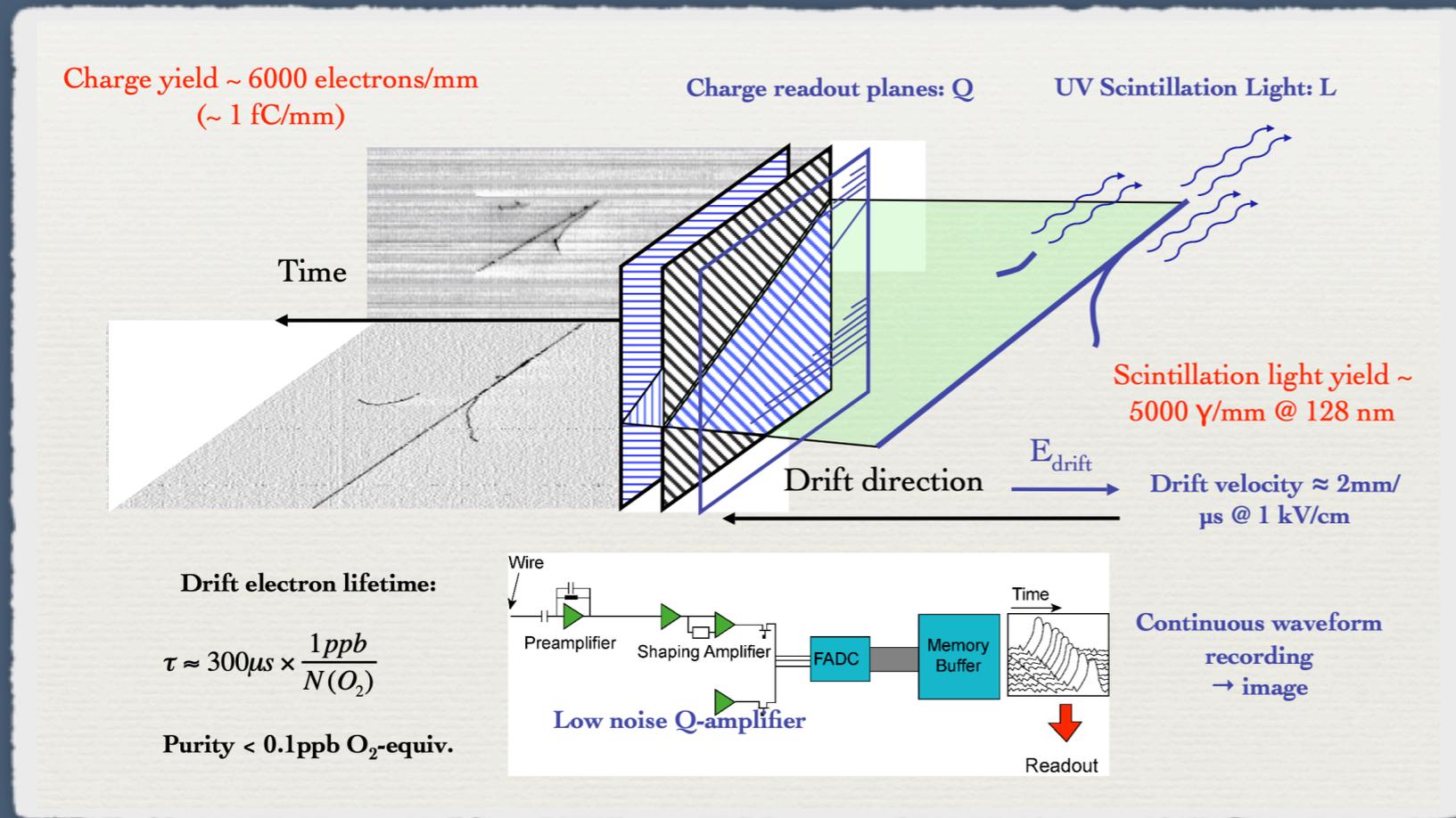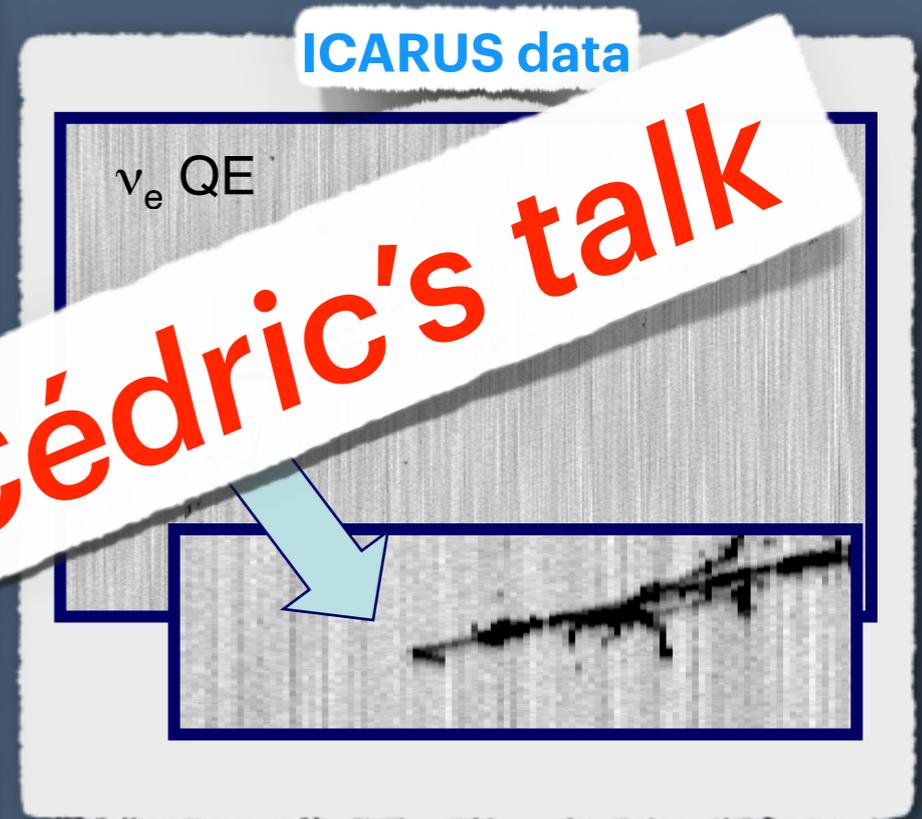
FD complex

ND complex

DUNE FD technology

Charge yield ~ 6000 electrons/mm (~ 1 fC/mm)

Charge readout planes: Q

UV Scintillation Light: L

Time

Scintillation light yield ~ 5000 γ/mm @ 128 nm

E_{drift}

Drift direction

Drift velocity ≈ 2mm/µs @ 1 kV/cm

Drift electron lifetime:

$$\tau \approx 300\mu s \times \frac{1\,ppb}{N(O_2)}$$

Purity < 0.1ppb O_2-equiv.

Wire

Preamplifier

Shaping Amplifier

FADC

Memory Buffer

Time

Low noise Q-amplifier

Continuous waveform recording → image

Readout

ICARUS data

ν_e QE

- The liquid Argon Time Projection Chamber (*LArTPC*) was proposed by C.Rubbia in 1977, and it is a homogeneous massive target and ionization detector, i.e. an *electronic bubble chamber*.

- Ideal detector for neutrino oscillations, supernovae neutrinos and proton decay search:

  - Large mass, homogeneous detector, low thresholds, exclusive final states

  - Tracking + calorimetry (0.035 X_0 sampling with 5mm pitch)

  - Electron identification, π^0 rejection, particles identification with dE/dx

DUNE FD technology

Charge yield ~ 6000 electrons/mm (~ 1 fC/mm)

Charge readout planes: Q

UV Scintillation Light: L

Time

Scintillation light yield 5000 γ/mm @ ...

Drift direction E_{drift}

Drift electron lifetime:

$$\tau \approx 300\mu s \times \frac{1 ppb}{N(O_2)}$$

Purity < 0.1ppb O_2-equiv.

Wire

Preamplifier Shaping Am...

Readout

ICARUS data

ν_e QE
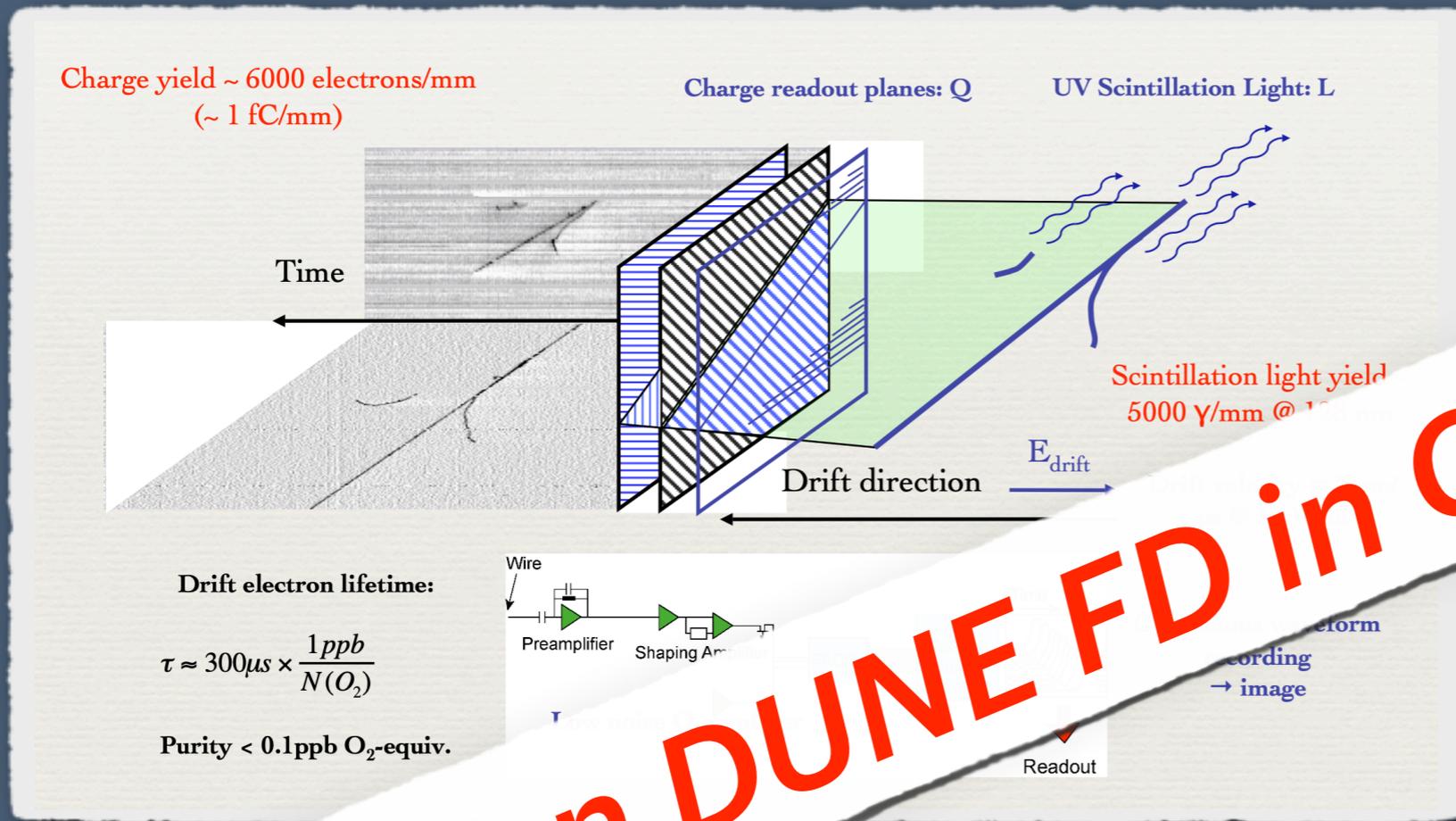
More on DUNE FD in Cédric's talk

- The liquid ... Projection Chamber (*LArTPC*) was proposed by C.Rubbia in 1977, ... homogeneous massive target and ionization detector, i.e. an *electronic* ... *chamber*.

- Ideal detector for neutrino oscillations, supernovae neutrinos and proton decay search:

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  - Tracking + calorimetry (0.035 X_0 sampling with 5mm pitch)

  - Electron identification, π^0 rejection, particles identification with dE/dx

DUNE ND

- DUNE will have a **Near Detector complex critical starting from early physics goals** to reduce flux and cross sections uncertainties and have the most accurate prediction of neutrino spectrum at the Far Detector.

- **System for on-Axis Neutrino Detection (SAND):** On-axis magnetized low-density tracker and calorimeter to control and monitor the neutrino beam on axis.

- **Near Detector Liquid Argon (NDLAr):** Liquid Argon Detector (50t fiducial) with the same target and technology as FD.

- **The Muon Spectrometer (TMS):** detector to measure muons escaping from NDLAr.

- **NDLAr+TMS** are a **movable** detector and exploit the **PRISM technique**: they measure neutrino flux at different angles (i.e. different energies) for a **better extrapolation at the FD reducing the dependency on the accuracy of interaction models**.

SAND

ND-LAr

TMS
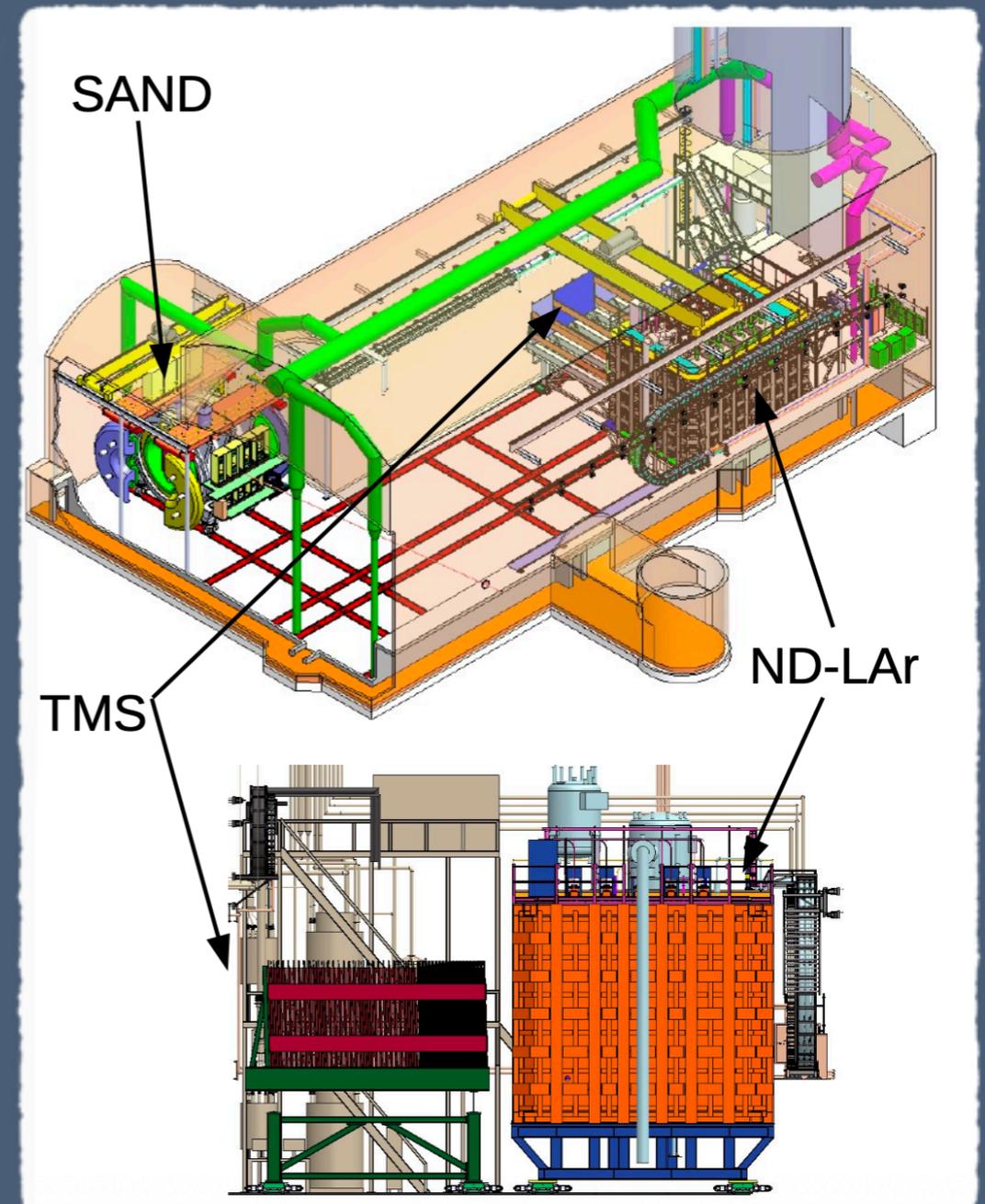
DUNE staged approach

- DUNE follows a **staged approach** which implies the construction of different ND and FD modules and beam upgrades which have been **updated following the P5 report** in 2023 and is made of two phases.

Phase 1

2026 start detector installation - 2029 physics - 2032 beam + ND

- Full near + far site facility and infrastructure.

- Two LArTPC modules (total active mass of about 25 kton).

- Upgradeable 1.2 MW neutrino beamline.

- Movable LArTPC near detector and on axis detector (NDLAr + TMS + SAND).

Phase 2

More detectors and beam upgrade

- Two additional FD modules (more than 40 kton fiducial in total).

- Beamline upgrade to multi MW.

- More capable near detector (including ND-GAr).

DUNE oscillation strategy

- DUNE will measure neutrino spectra in a **wide band beam exploiting the spectral information** and 2nd oscillation maximum.

- DUNE will study $\nu_\mu \rightarrow \nu_e$ oscillations both with neutrinos and antineutrinos.
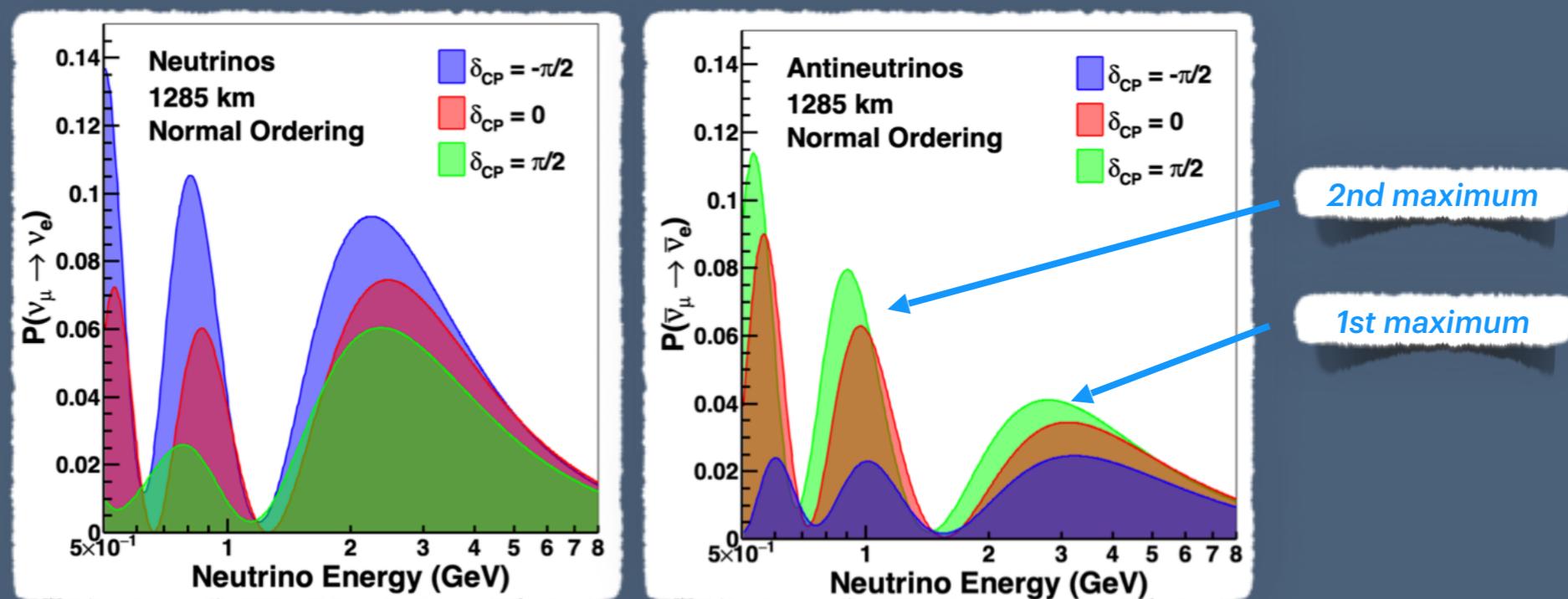
- Wide band beam and long baselines **break the degeneracy between δ_{CP} and matter effects**.

- **DUNE is a unique experiment** enabling searches for CP violation, mass ordering, and three-flavour neutrino phenomenology, including ν_τ appearance, within a single experimental setup, while providing detailed reconstruction of neutrino interaction final states.

CP violation - general considerations

- Typically to measure CP violation the idea is to measure and compare $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ transitions.

Few important considerations

- ***Matter effects and CP are degenerate*** since they both impact neutrino and antineutrino in opposite ways, however matter effects depends on the ordering whereas CP effects do not.

- ***Narrow band*** experiments basically just "***count***" the appeared neutrinos.

- There are therefore solutions with CP conserving phases in one ordering which overlap to CP violating phases in the opposite ordering.

68% syst err. at best-fit	—— $\sin^2\theta_{23} = 0.45$, 0.50, 0.55, 0.60
▼ Best-fit	—— $\Delta m^2_{32} = 2.49\times10^{-3}$ eV^2 (NO)
Data (68% stat err.)	---- $\Delta m^2_{31} = -2.46\times10^{-3}$ eV^2 (IO)

○ $\delta_{CP} = \pi$
■ $\delta_{CP} = +\pi/2$
□ $\delta_{CP} = 0$
● $\delta_{CP} = -\pi/2$

Antineutrino mode e-like candidates

Neutrino mode e-like candidates

T2K from Eur. Phys. J. C (2023) 83 :782
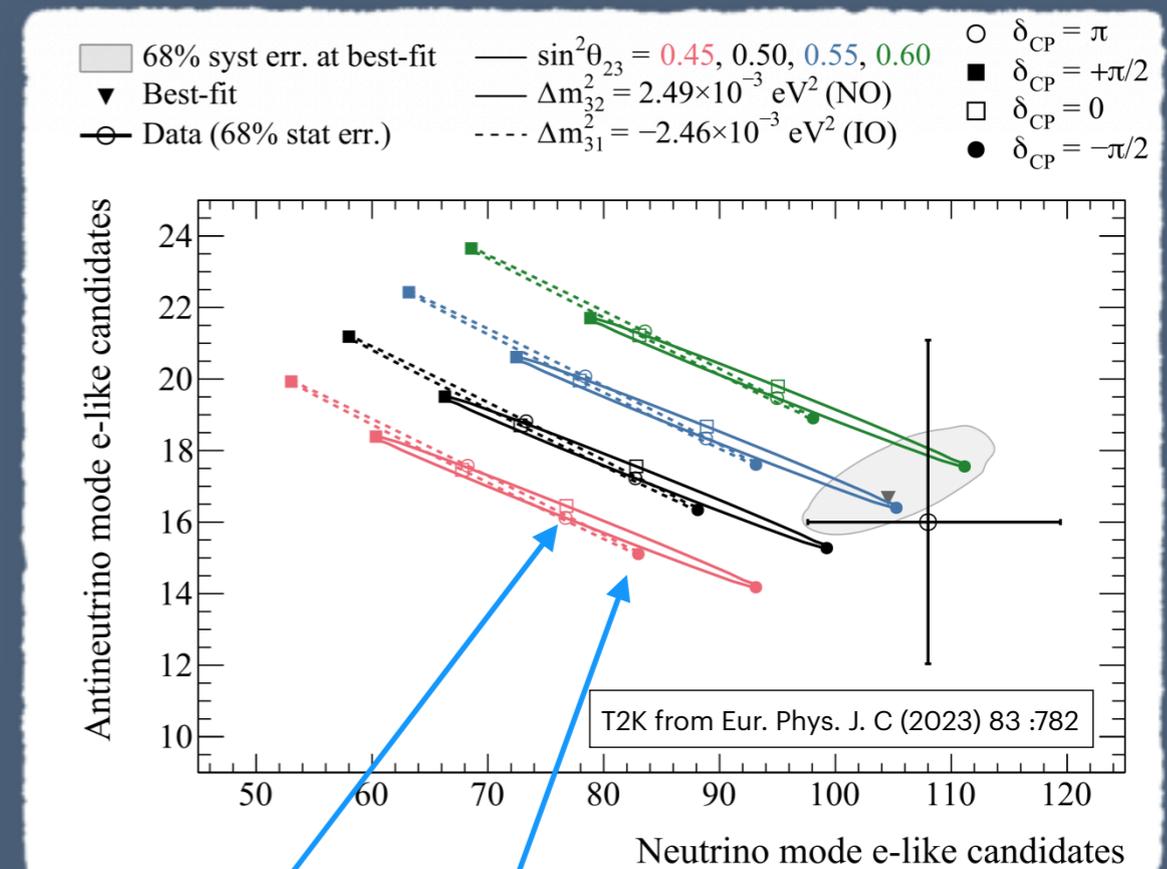
Maximal CP violation IO

CP conserving NO

CP violation - HK

- The next important actor in the search of CP violation will be Hyper-Kamiokande (HK) starting in 2028.

- The experiment uses the same technology as T2K but with an upgraded beamline (factor of about 2 with respect to current beam power of 750 kW) and an increase in mass of a factor of 8.

- The bi-plot is the same with a smaller error.

- HK is excellent at distinguishing between conserving and violating CP phases *provided the mass ordering is known*.
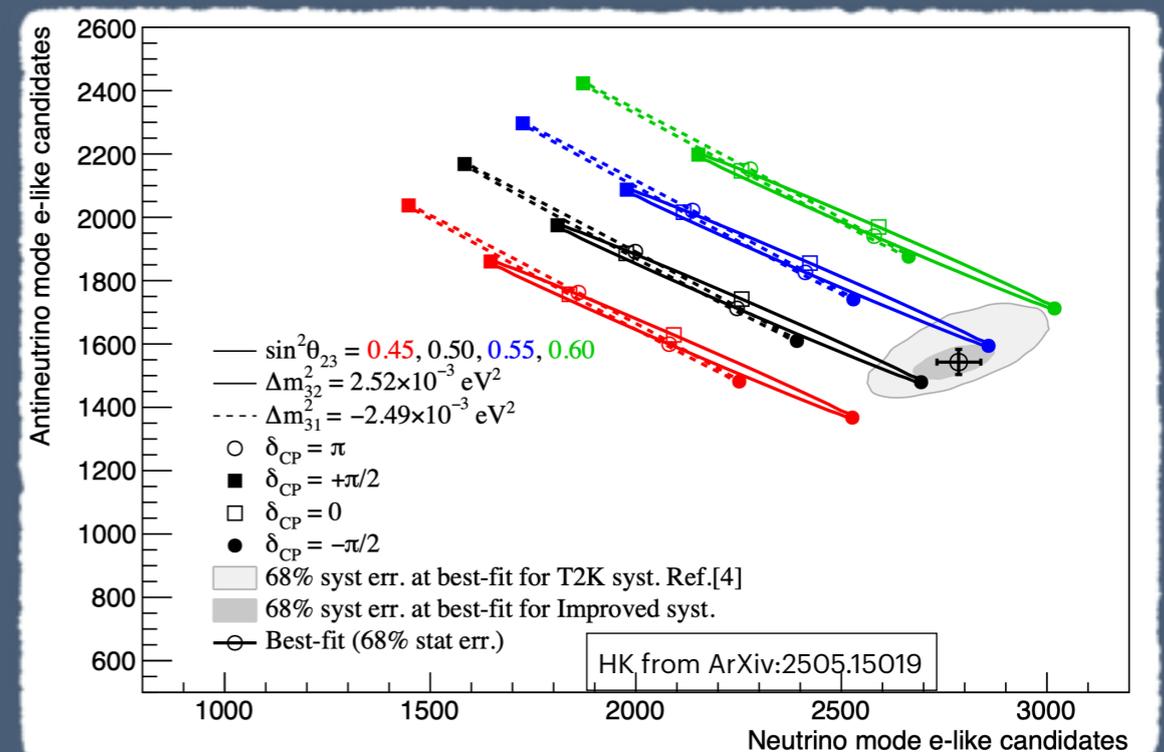
CP violation - DUNE strengths

- The specific **advantages of DUNE** in the search of CP violations are:

  ➡ **Higher energy** (to match the longer baseline) with **larger matter effects**.

  ➡ The use of a **wide band beam** (WBB) which allows for **spectral information** exploitation.

No spectral information
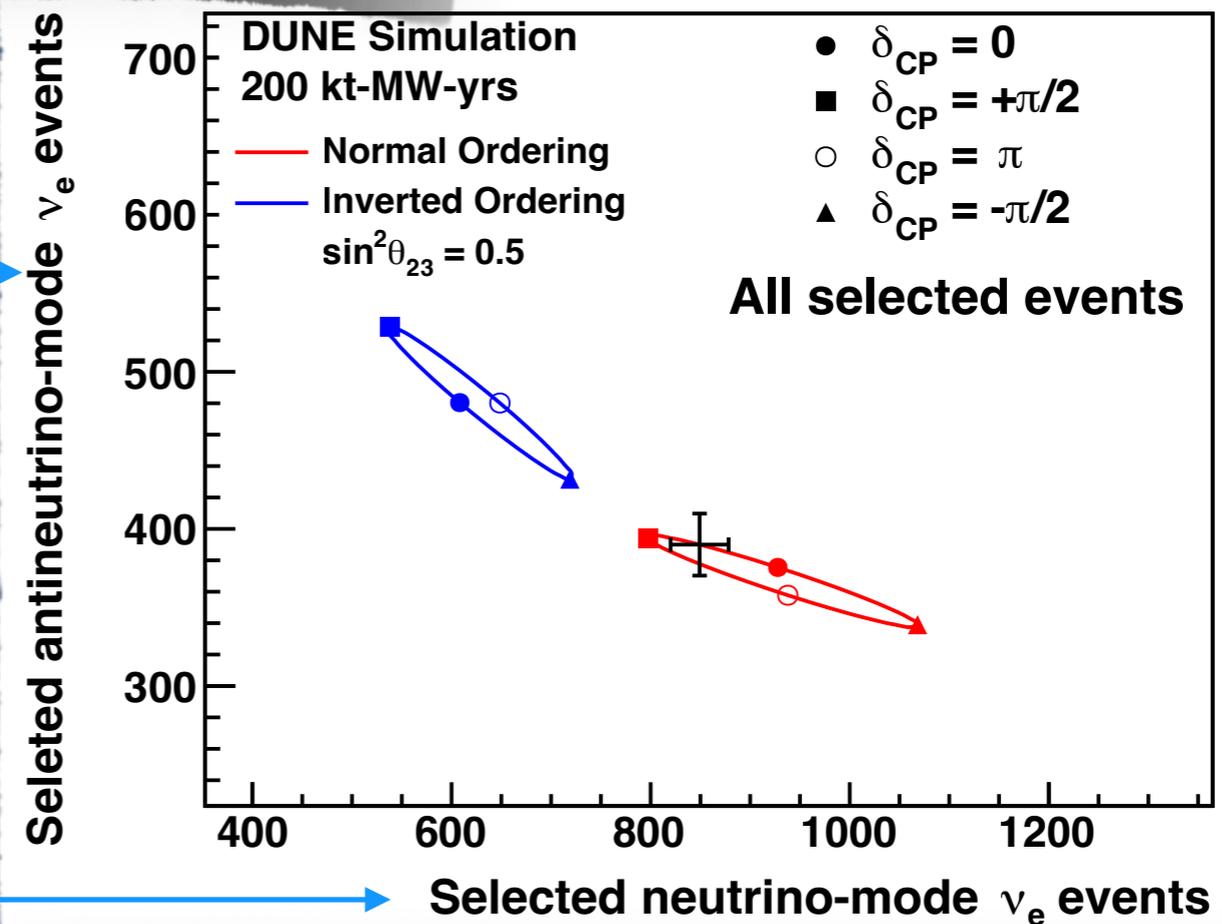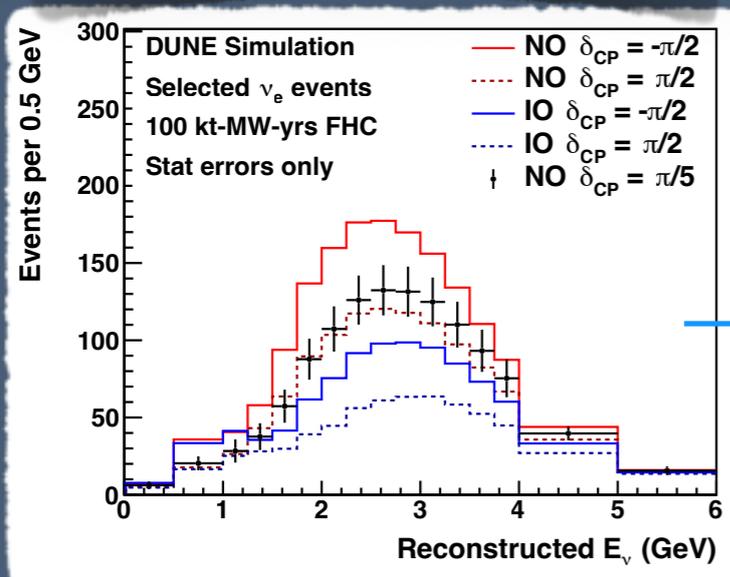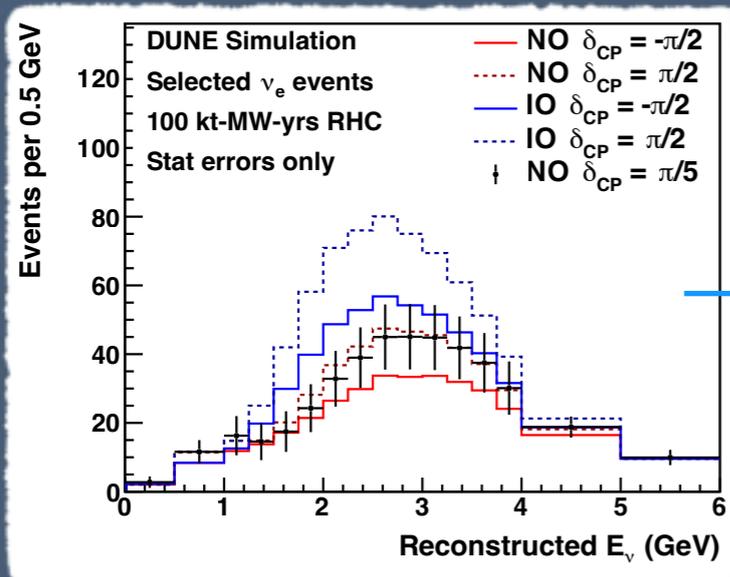
The NH and IH ellipses are well separated and no degeneracy remains

CP violation - DUNE strengths

Spectral information

High L/E
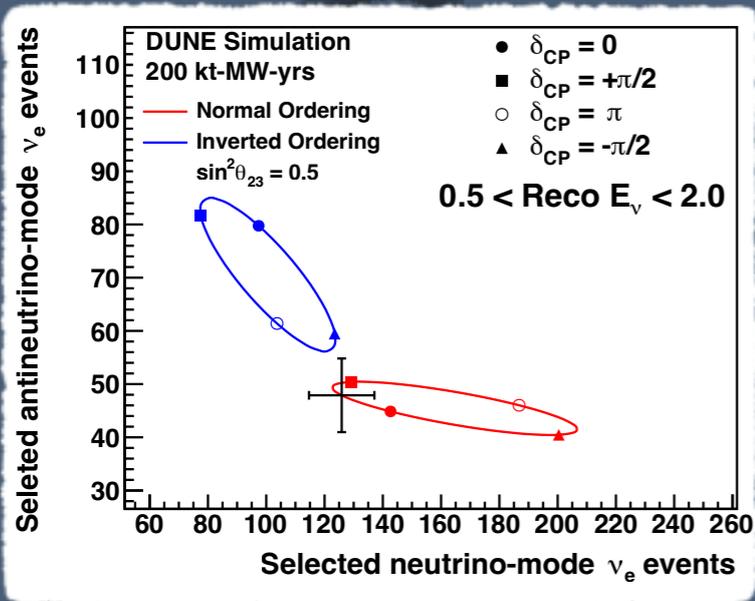
Medium L/E
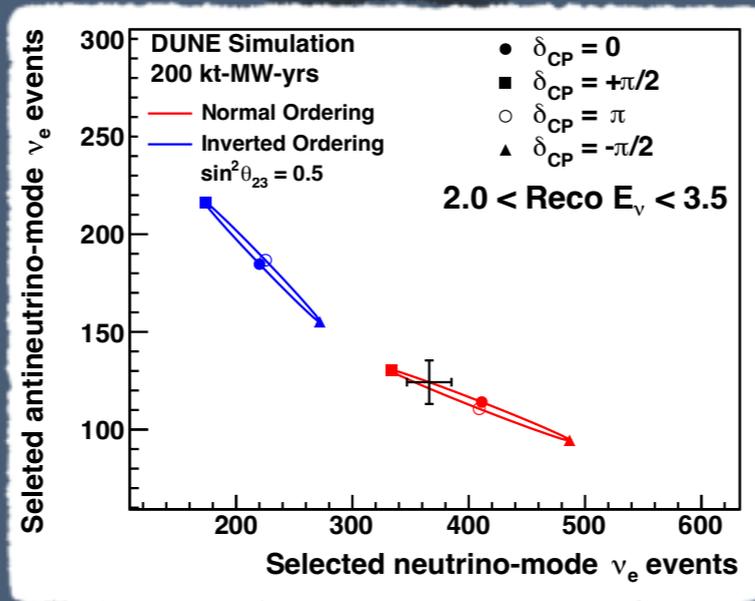
Low L/E
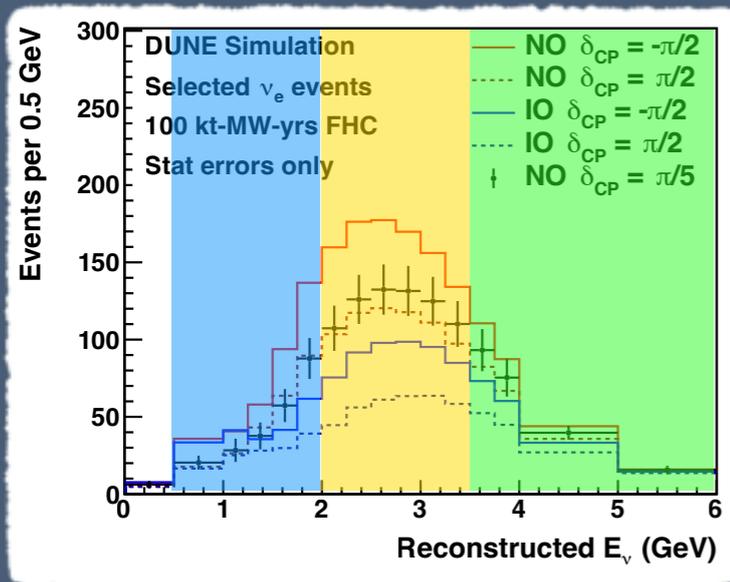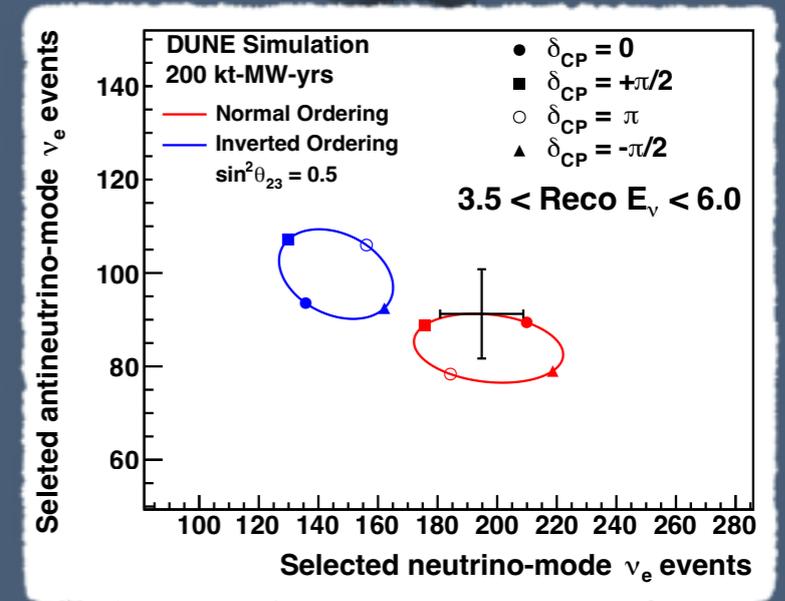
- DUNE can measure oscillation parameters in *several regions of L/E*.

- If 3-flavor PMNS picture is correct, data should prefer the same point in every bin.

- It is likely that *new physics* would distort the result as a function of L/E (DUNE unique sensitivity).

CP violation - Sensitivity
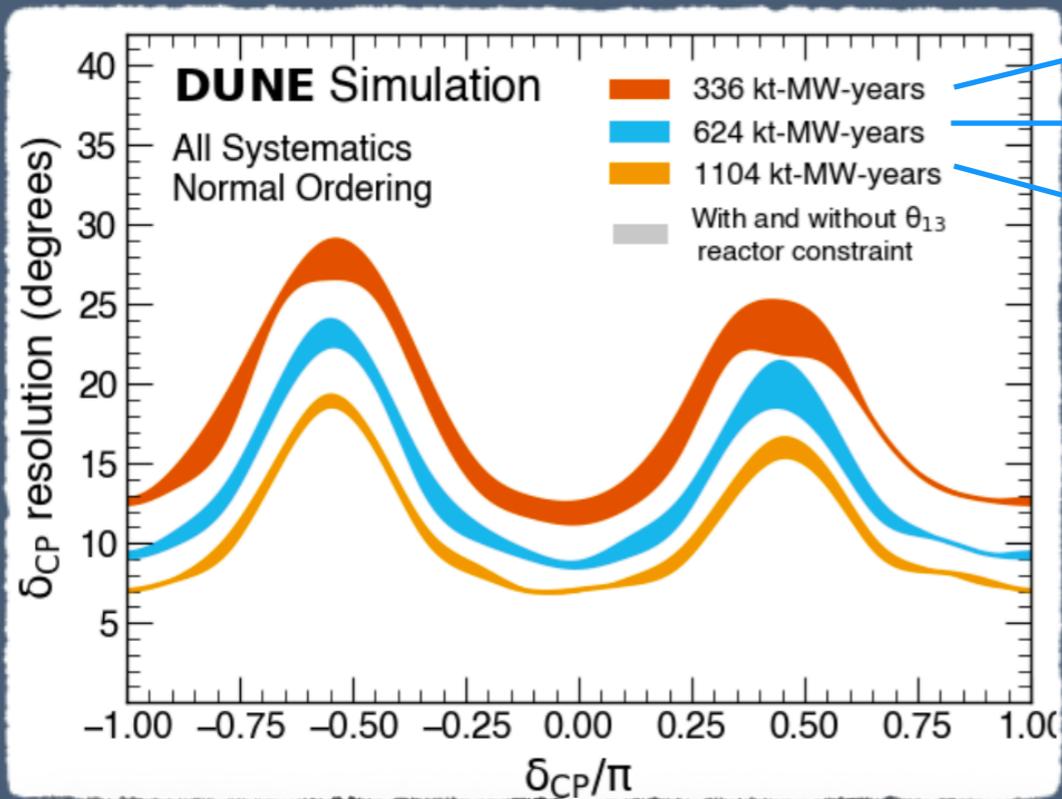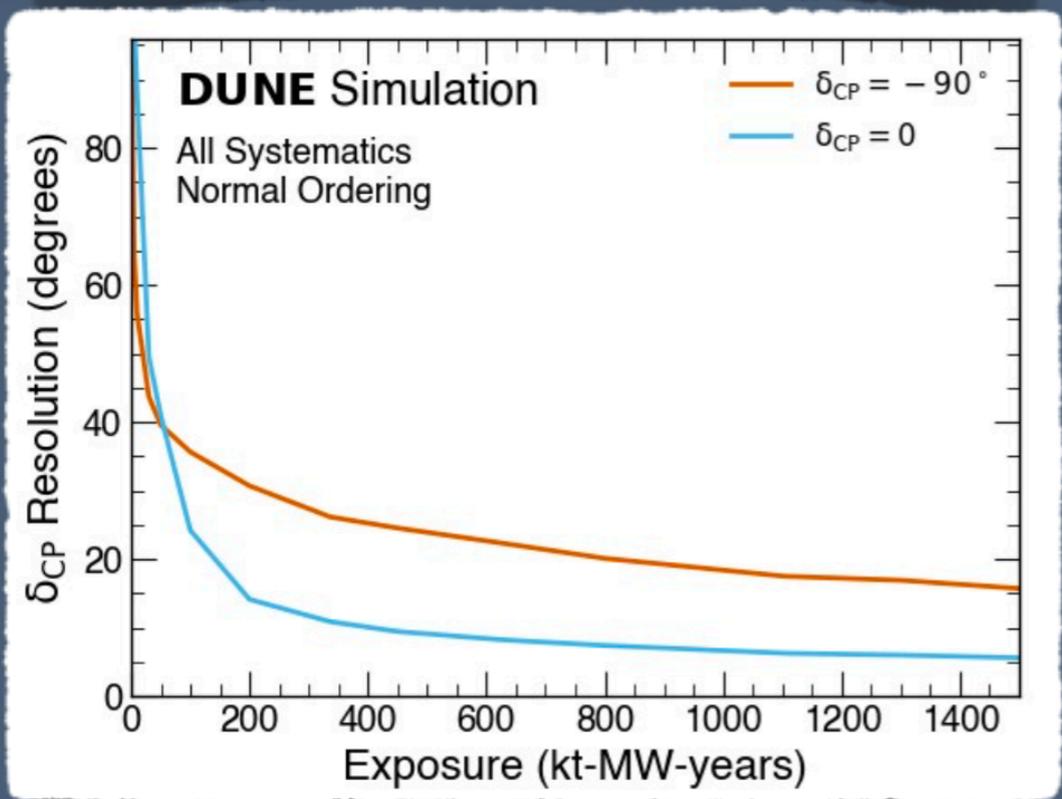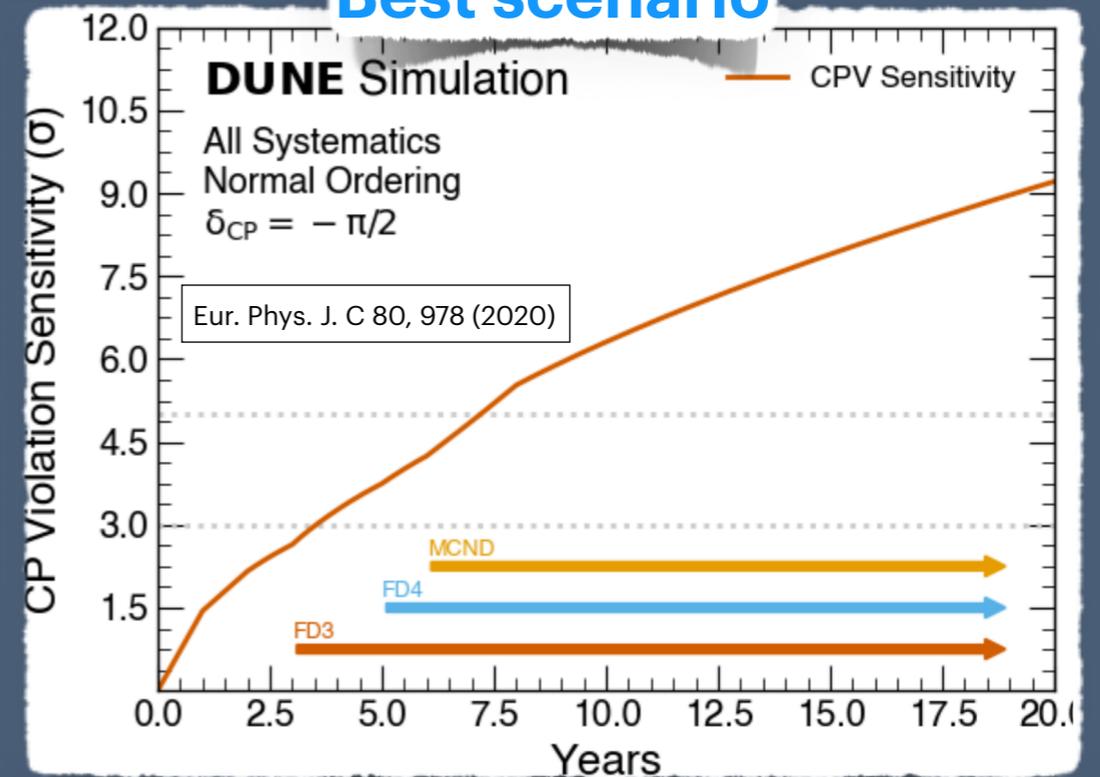
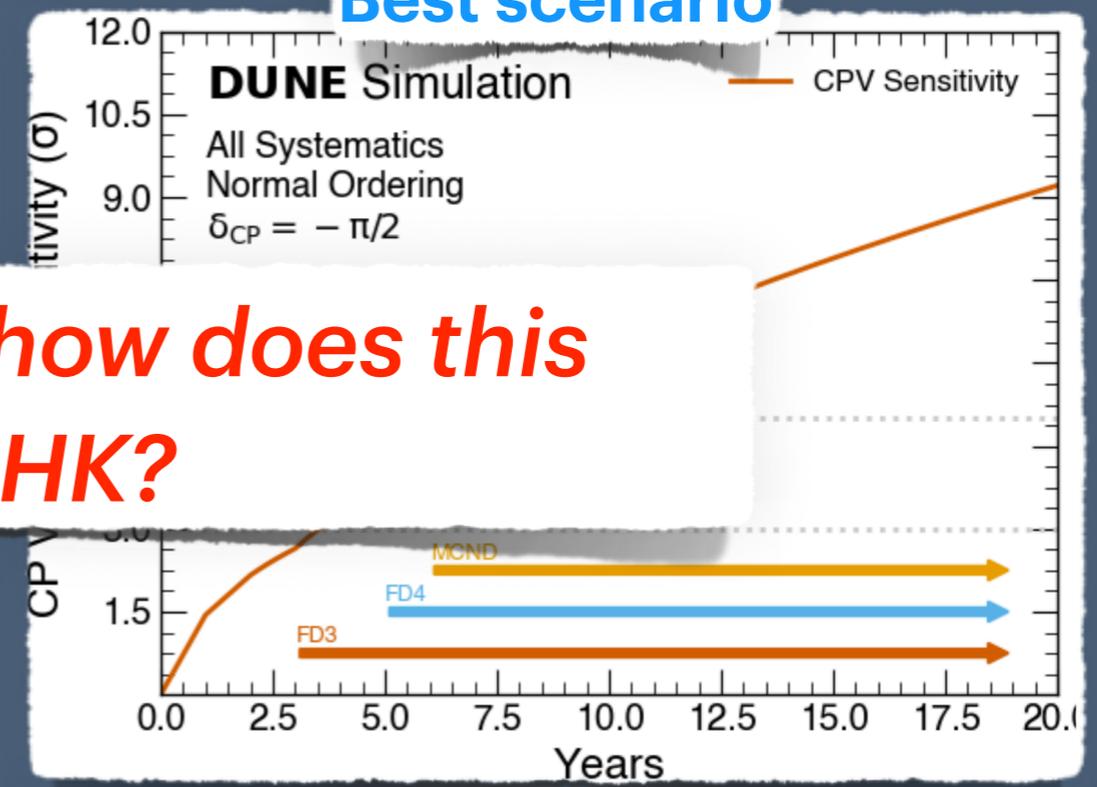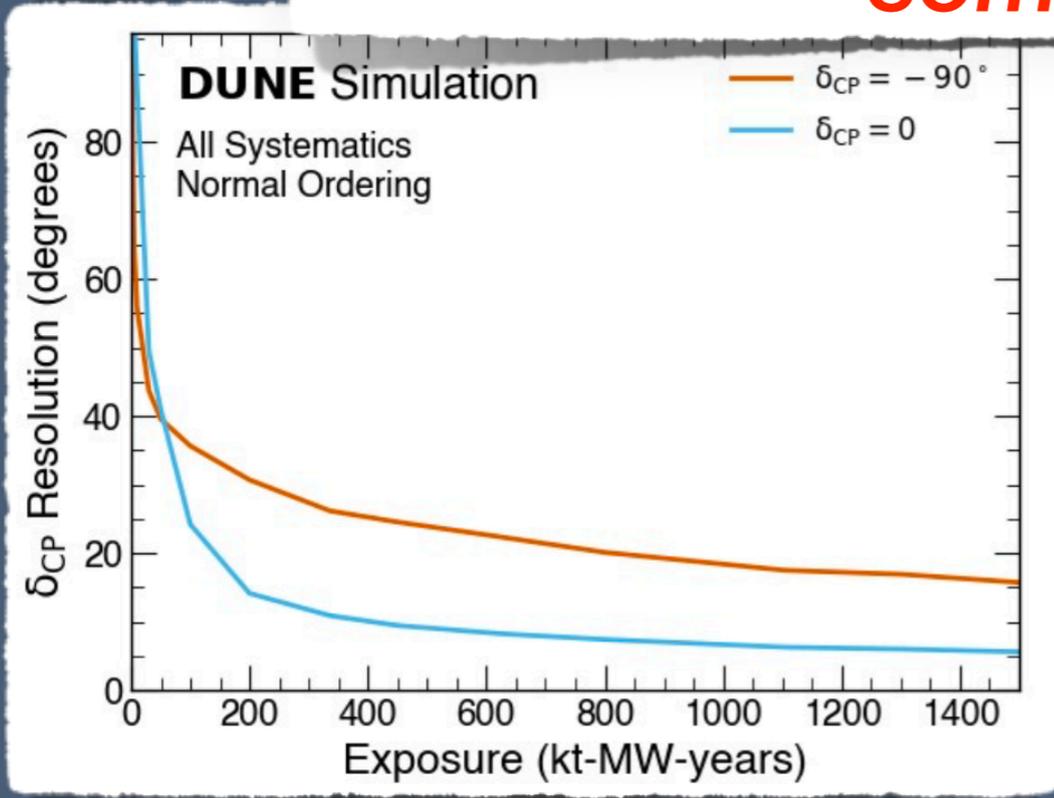
7 years staged

10 years staged

15 years staged

Best scenario

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

DUNE could have >3 σ CPV sensitivity in 3.5 years

CP violation - Sensitivity
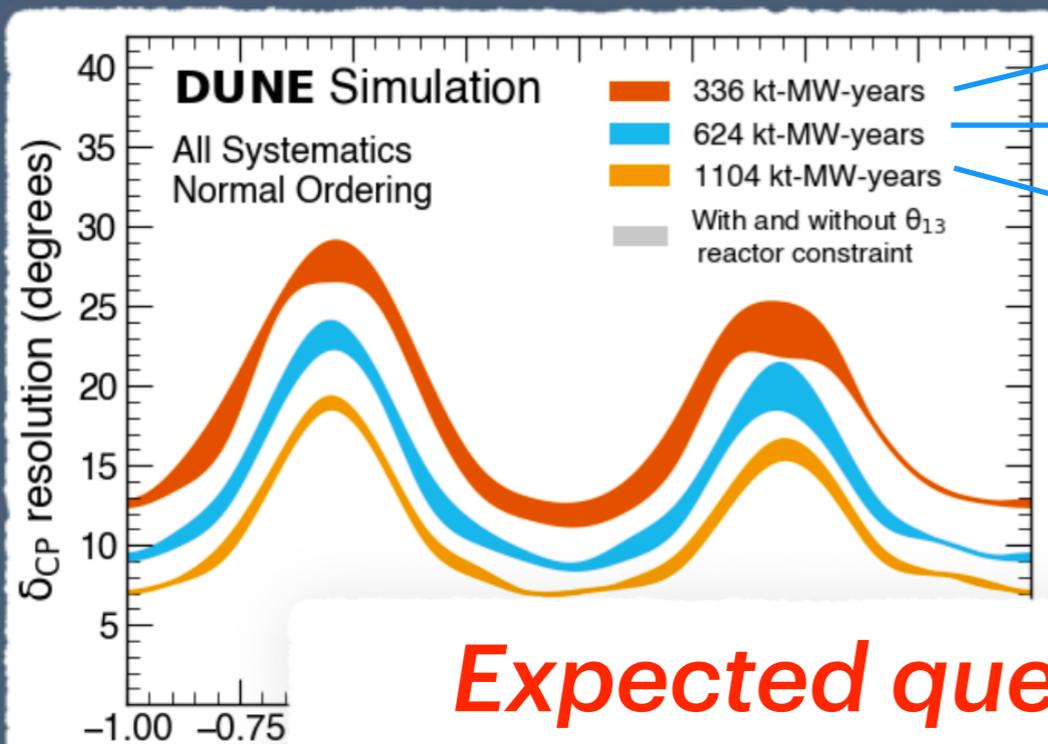
7 years staged

10 years staged
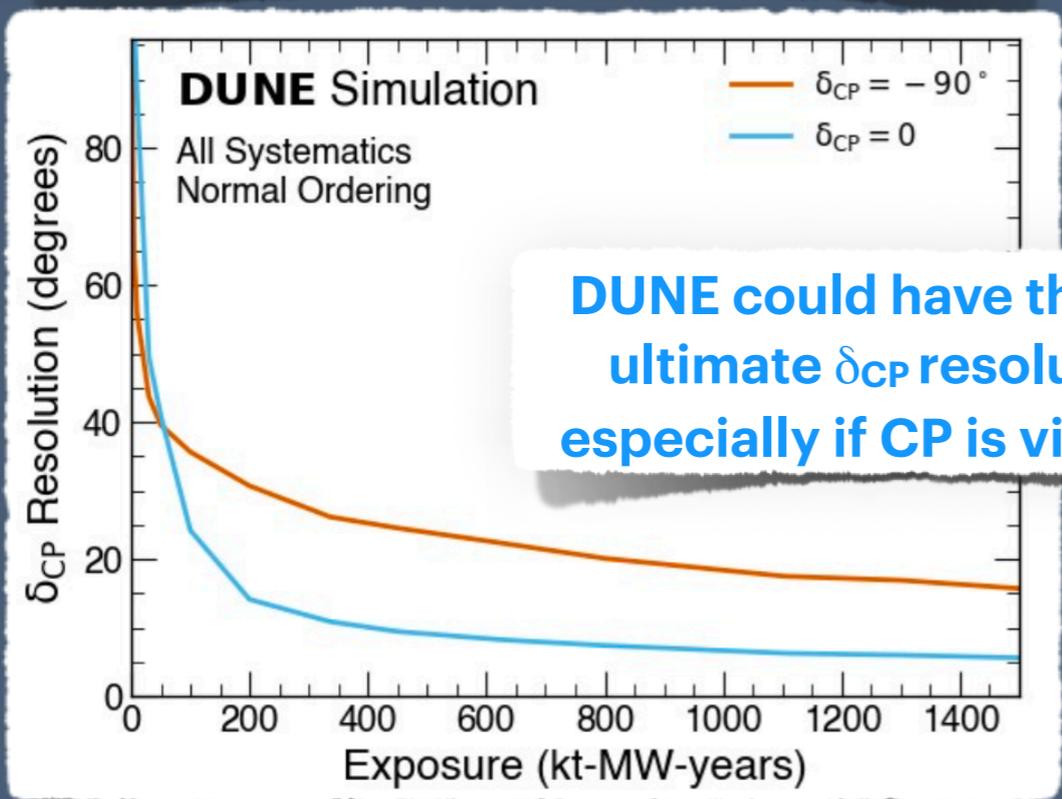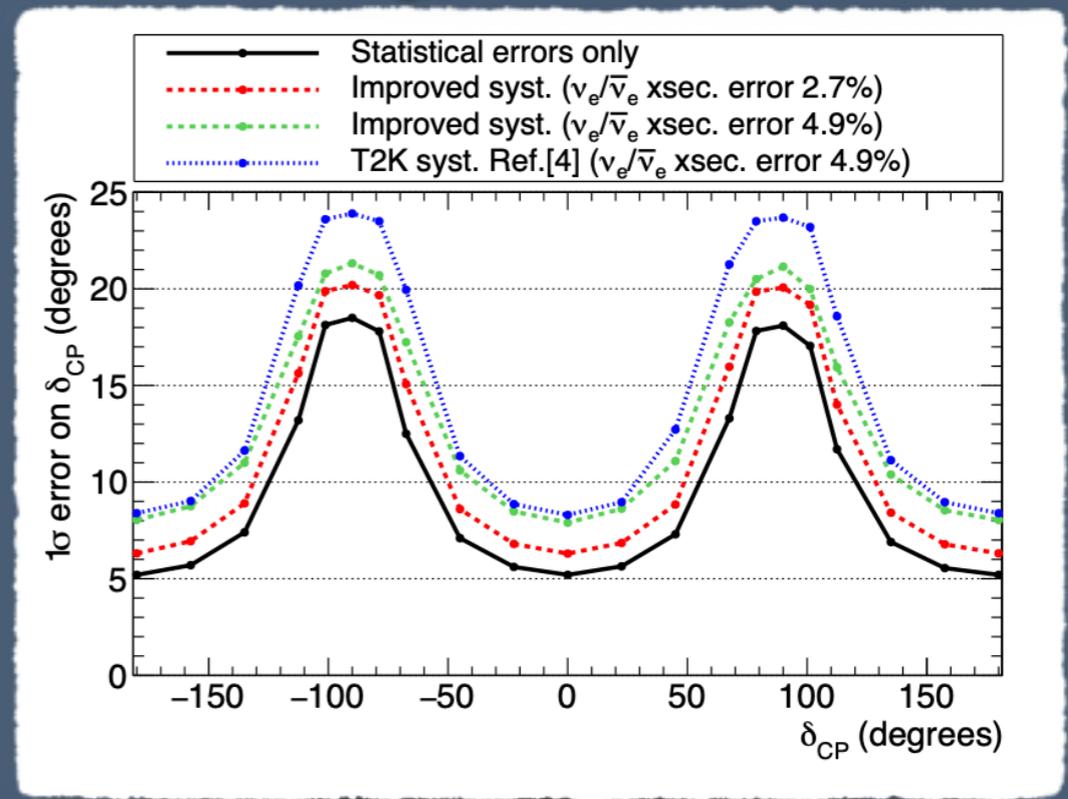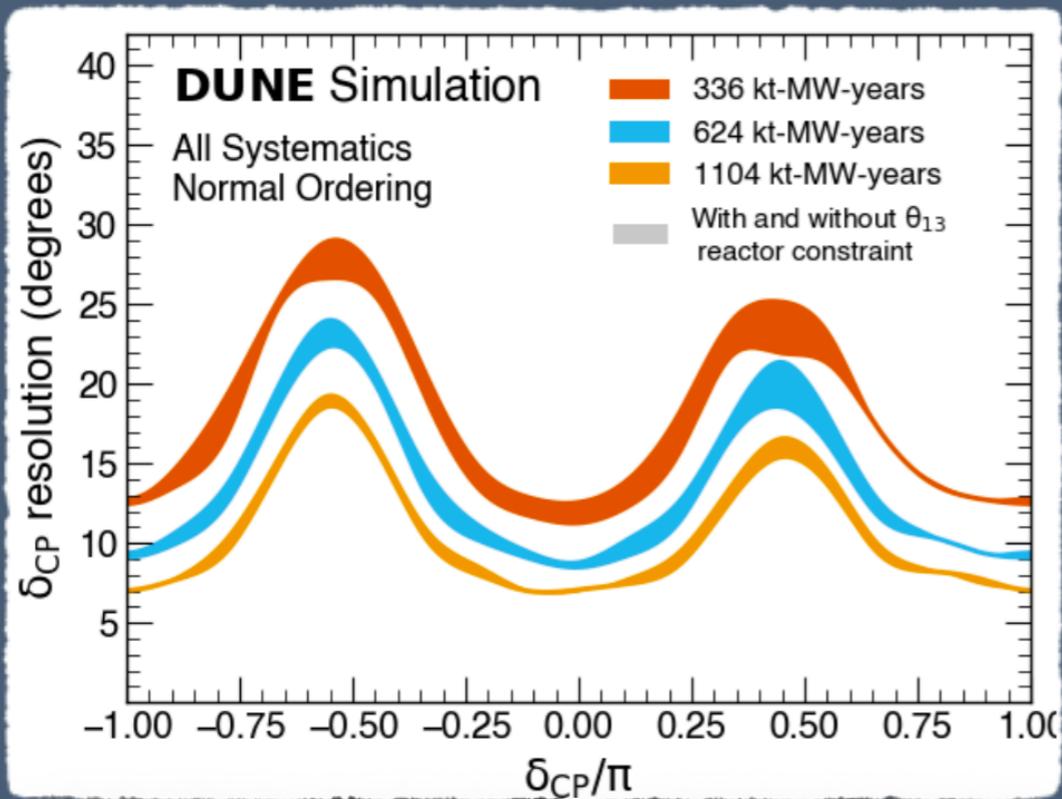
15 years staged

Best scenario

Expected question... how does this compare to HK?

DUNE could have >3 σ CPV sensitivity in 3.5 years

CP violation - Sensitivity

DUNE could have the best ultimate δ_{CP} resolution, especially if CP is violated.
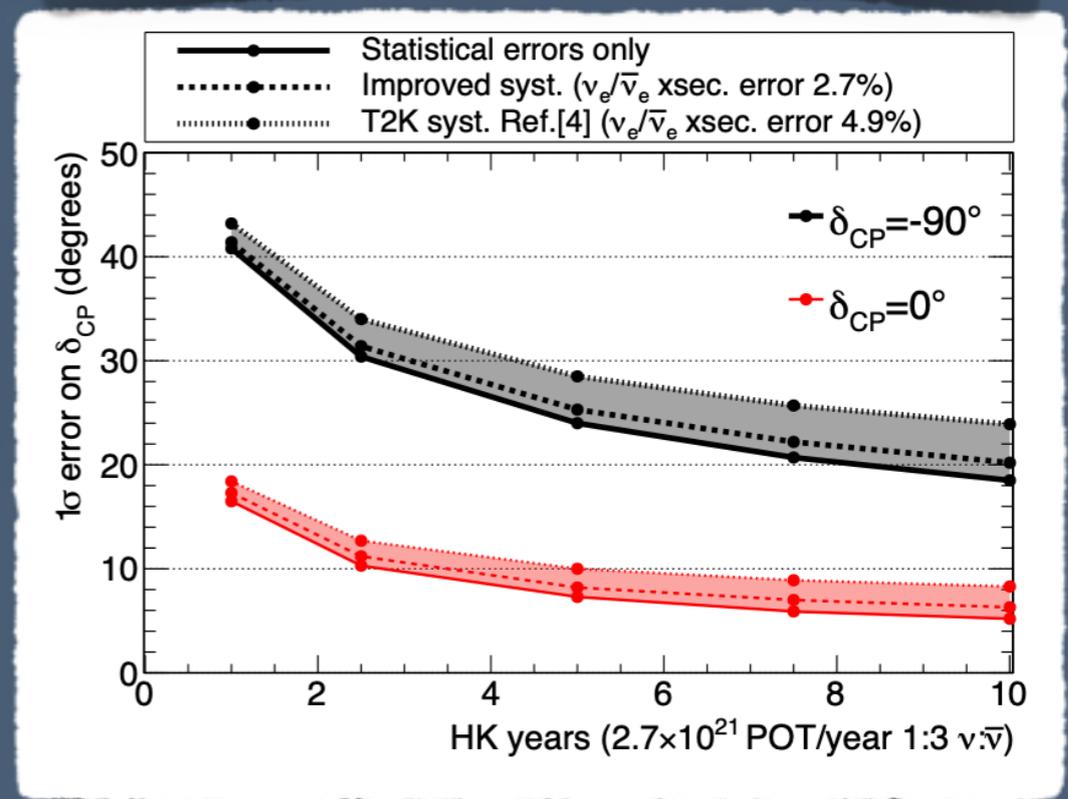
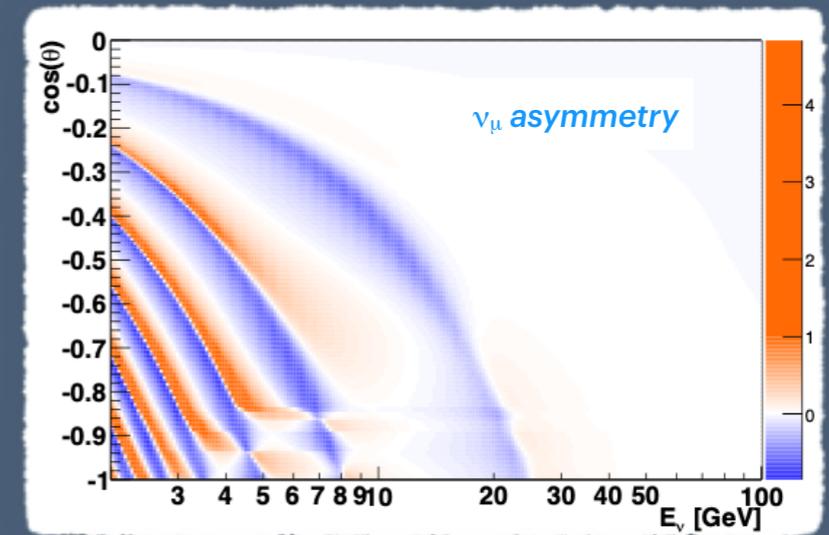# Mass ordering - general considerations

- There are several ways to tackle the mass ordering:

  - *Atmospheric neutrinos:* exploit measurements over a wide range of energies and baselines (zenith angles), comparing the observed patterns with expectations for normal and inverted ordering.

    e.g. SK, ORCA →

  - *Reactor neutrinos:* measure with very high precision the frequency of the wiggles related to Δm^2_{31} in $\overline{\nu}_e$ oscillations.

    e.g. JUNO →
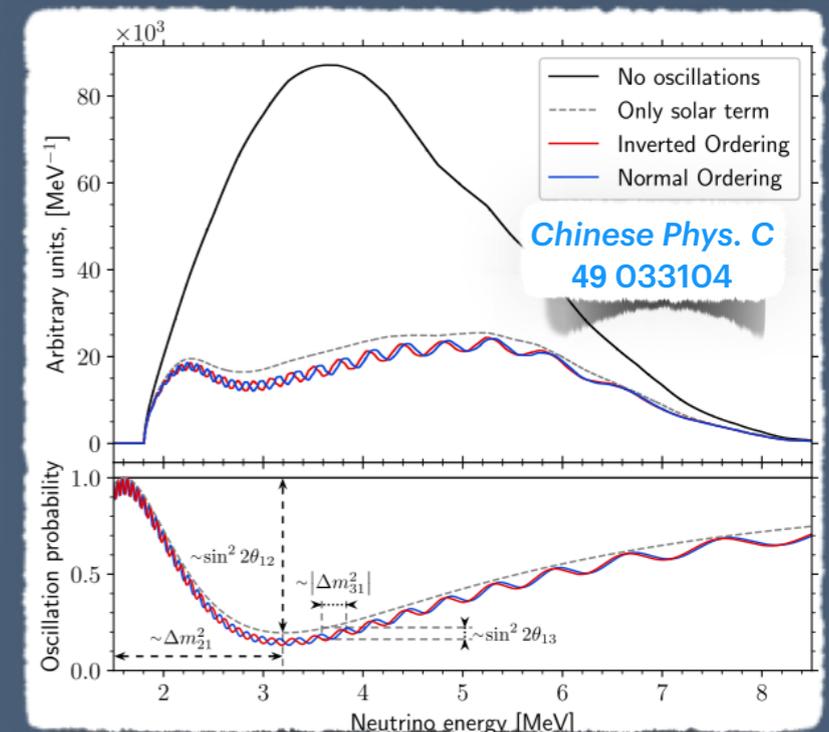
  - *Long-baseline accelerator experiments:* exploit the enhancement or suppression of ν_e appearance induced by matter effects.
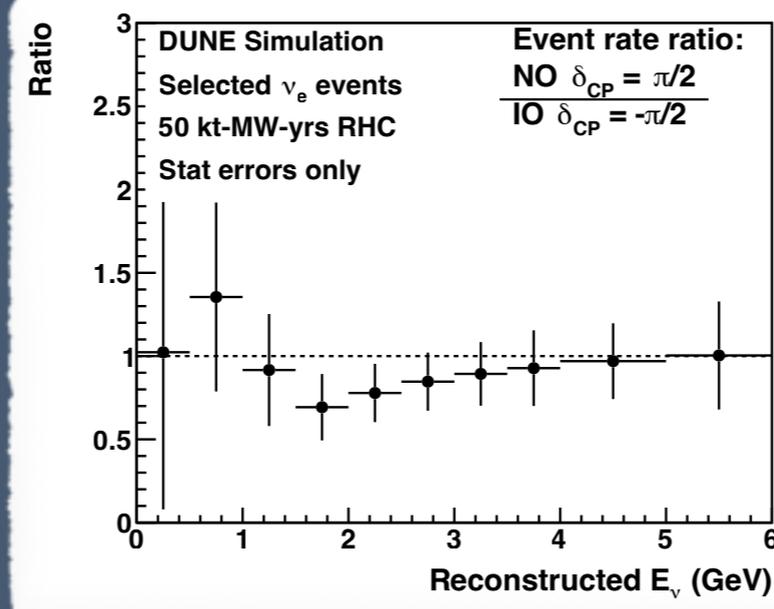
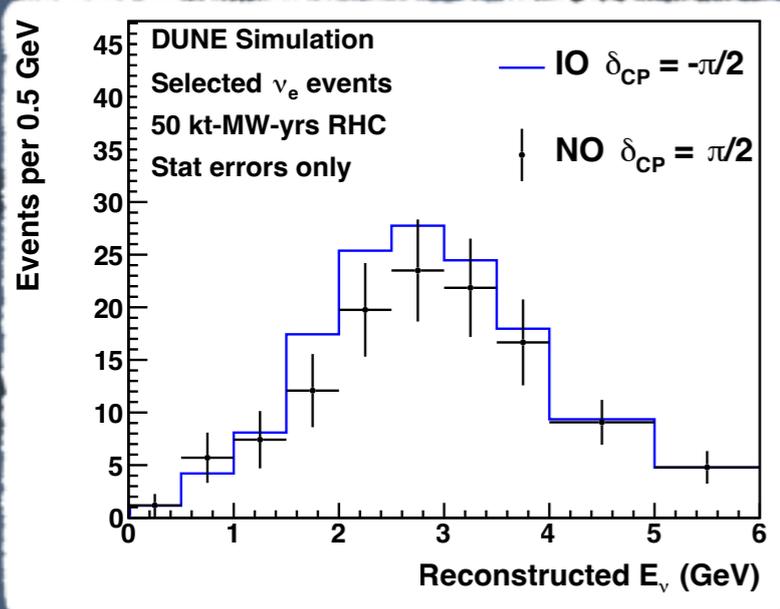   *e.g. DUNE*

ν_μ *asymmetry*

Chinese Phys. C 49 033104

Mass ordering - DUNE

- DUNE is the **only experiment** that measures the mass ordering by **separately** measuring $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations.

- The exploitation of the spectral information is crucial.

Neutrinos
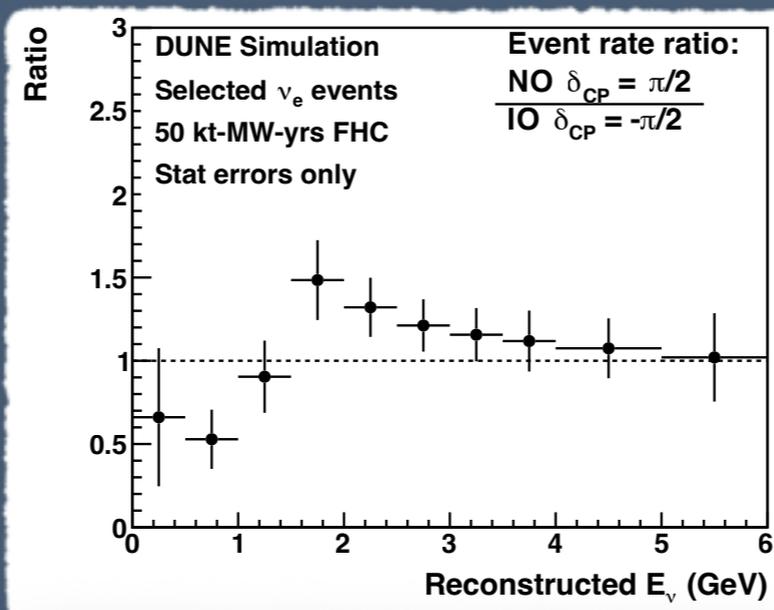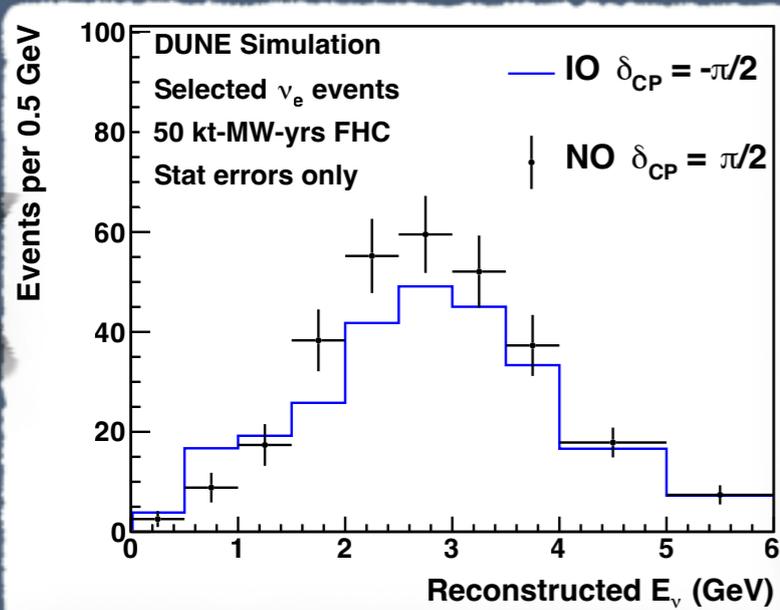
Antineutrinos

*Statistics corresponding to an excess of about 5σ*

40-50% differences in 0.5-2 GeV region, with opposite sign in FHC and RHC

Worst scenario with CPV and matter effect in opposite directions

Mass ordering - DUNE

- Although DUNE's mass ordering sensitivity depends on true oscillation parameters, *DUNE will measure mass ordering no matter what*.

- In the *favourable* scenario, DUNE surpasses *5σ in less than 1 year*, but even in the most *pessimistic* scenario, DUNE reaches *more than 5σ in about 5 years*.

Although starting later DUNE is the only experiment that will reach 5σ without combination with other experiments and regardless of the true ordering.
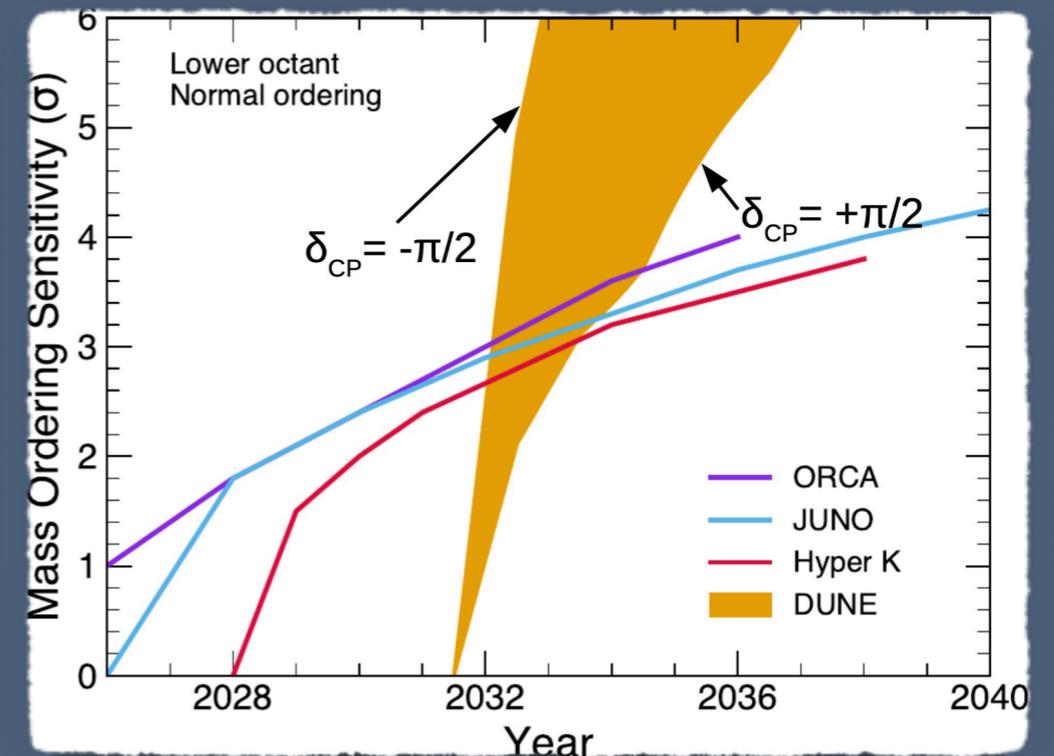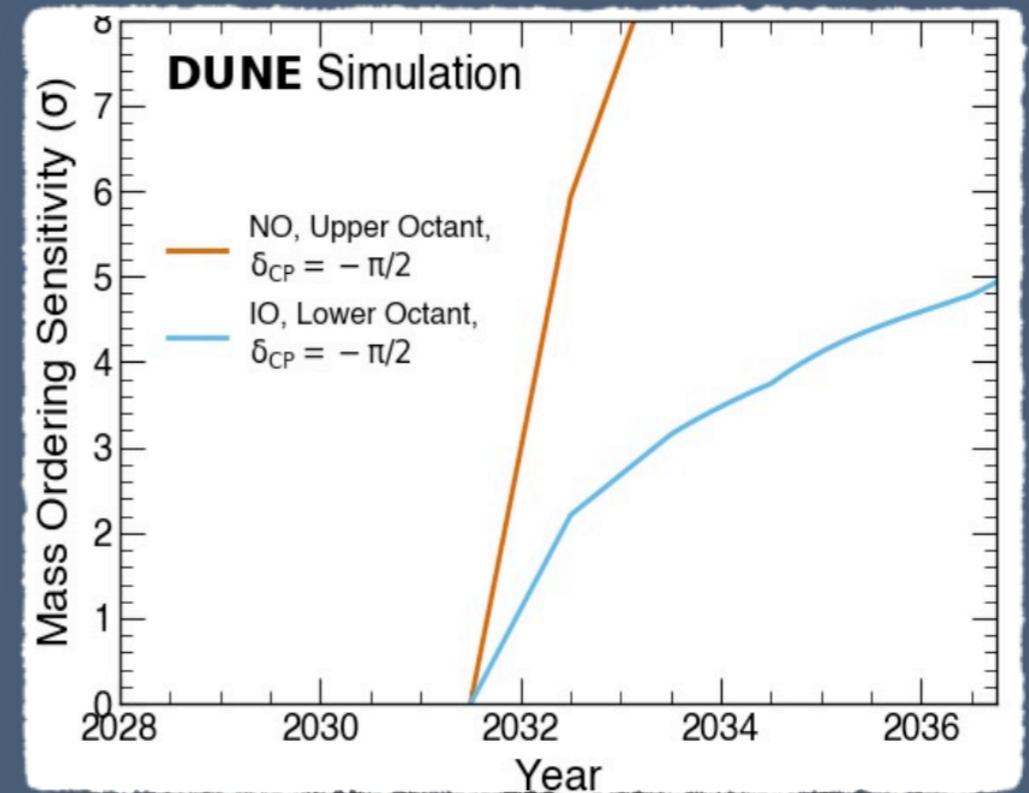
Solar neutrino

- The possibility to study solar neutrinos in DUNE has been boosted by the work on detecting low energy events as demonstrated with radiological events in ProtoDUNE.

- Separate precision measurements of neutrino-mixing parameters and the ^{8}B flux could be made using two channels and the day-night effect.
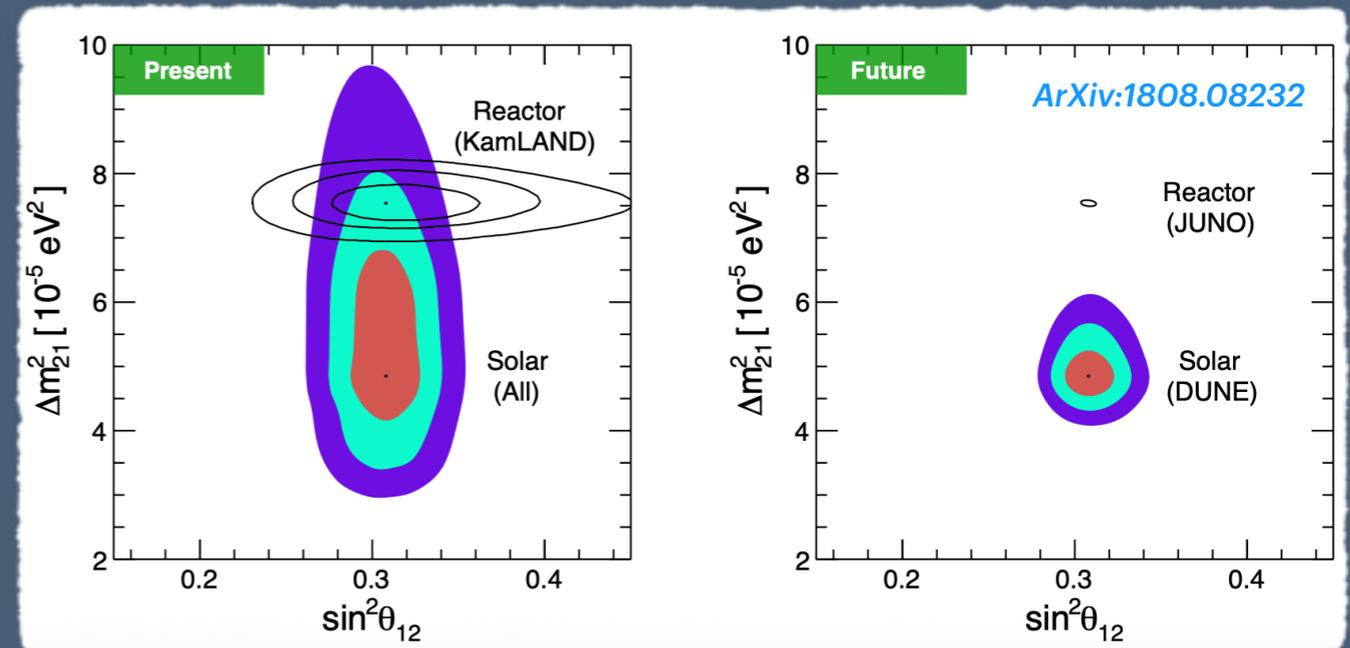
Best precision on solar given by DUNE alone with two caveat: a threshold at 5 MeV and a shielding to reduce low energy background (work in progress)

CC channel: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

**ES channel**: $\nu_x + e^- \rightarrow \nu_x + e^-$ (pointing)

	10 MeV Threshold	5 MeV Threshold
CC	1300	117000
ES	1400	33000

Shielding increasing

Threshold decreasing

3 flavour paradigm

- DUNE will have a unique opportunity to test the **PMNS unitarity** and confirm the three flavour paradigm.

- Measurements θ_{13} obtained from long-baseline (ν_e appearance) and reactor experiments ($\overline{\nu}_e$ survival) are only equivalent if unitarity is assumed.
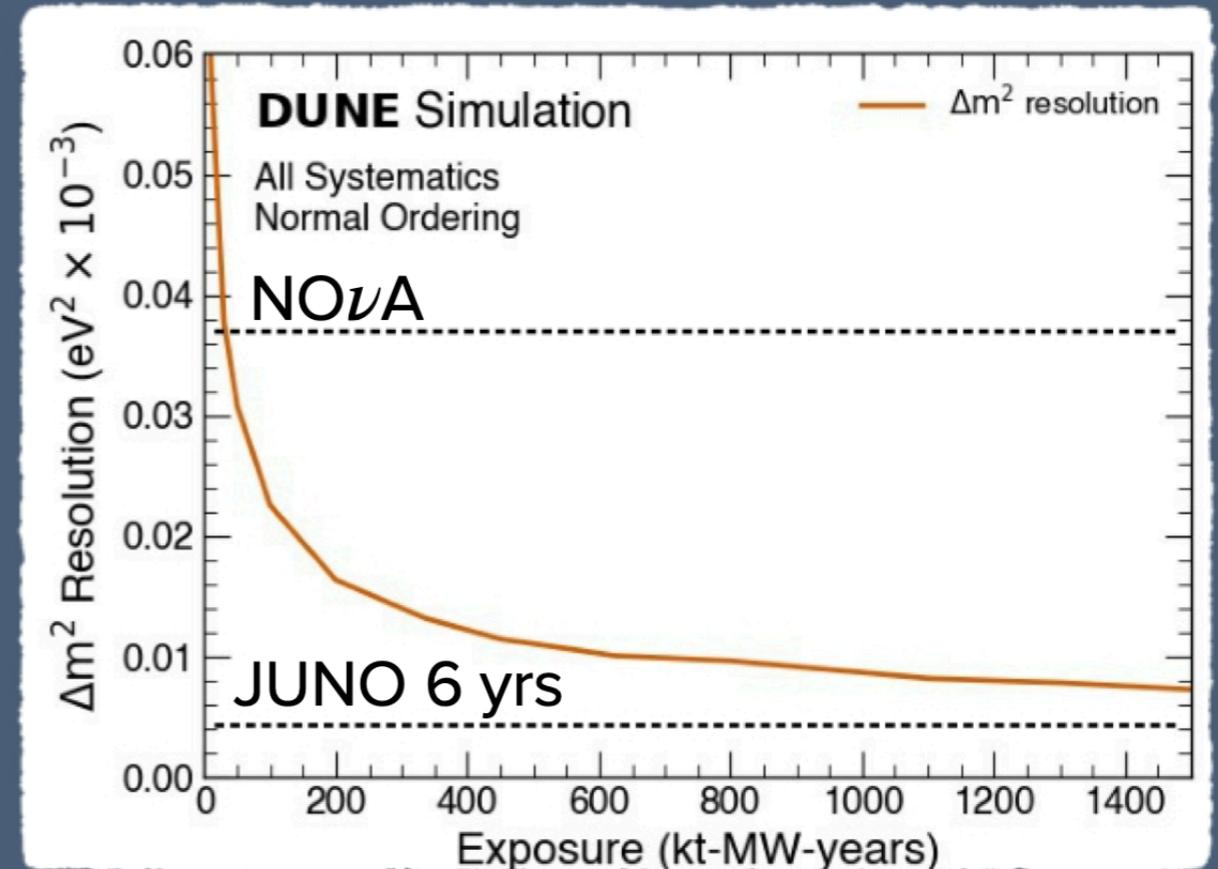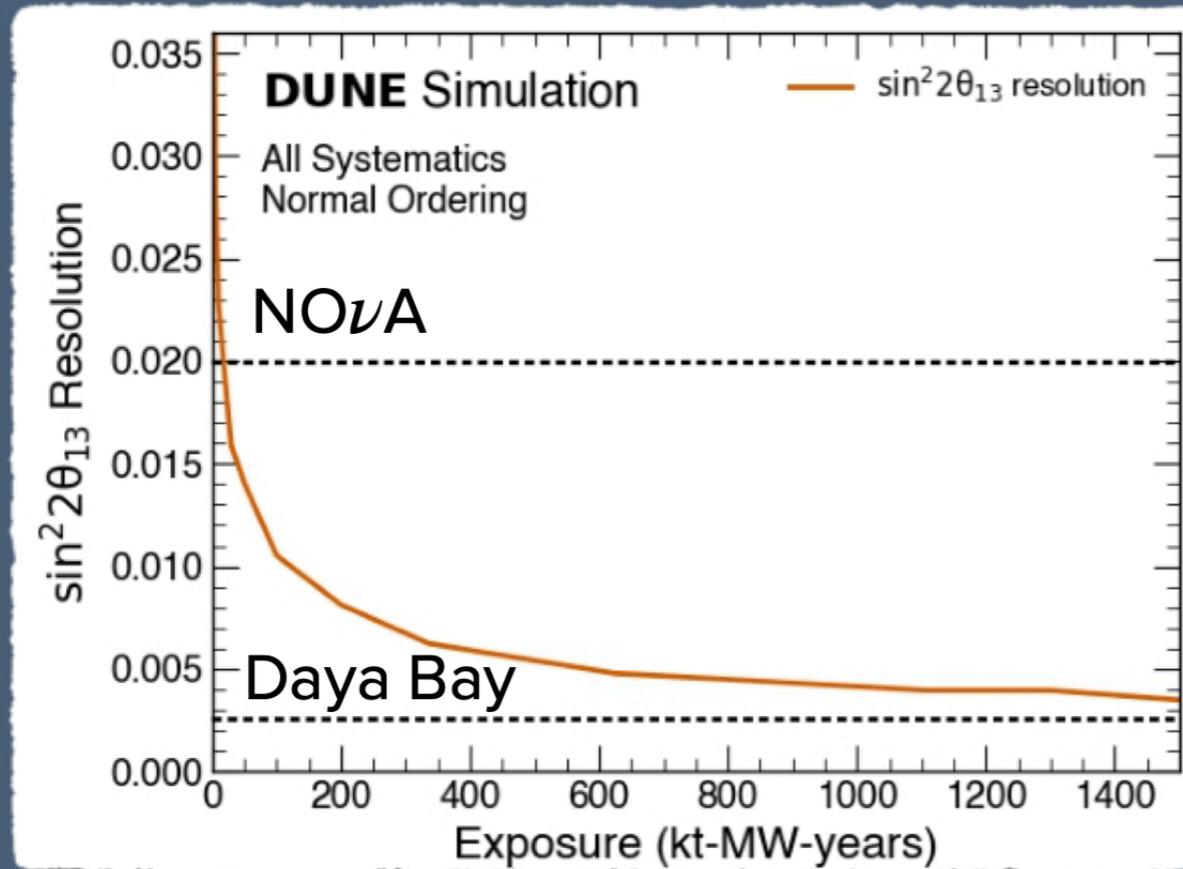
DUNE approaching world leading measurements on θ_{13} and Δm^2_{atm}

3 flavour paradigm

- Another opportunity of DUNE to test unitarity is directly *measure 3-flavor oscillations*.

- Thanks to the high-energy proton beam with on-axis detector, DUNE has substantial flux above the 3.5 GeV ν_τ CC threshold and could therefore *observe* ν_τ *appearance*.

- Imaging capabilities of DUNE's LArTPCs makes it possible to *reconstruct complex τ final states kinematically*.

- ML-driven reconstruction based on hierarchical graph neutral network being pursued.
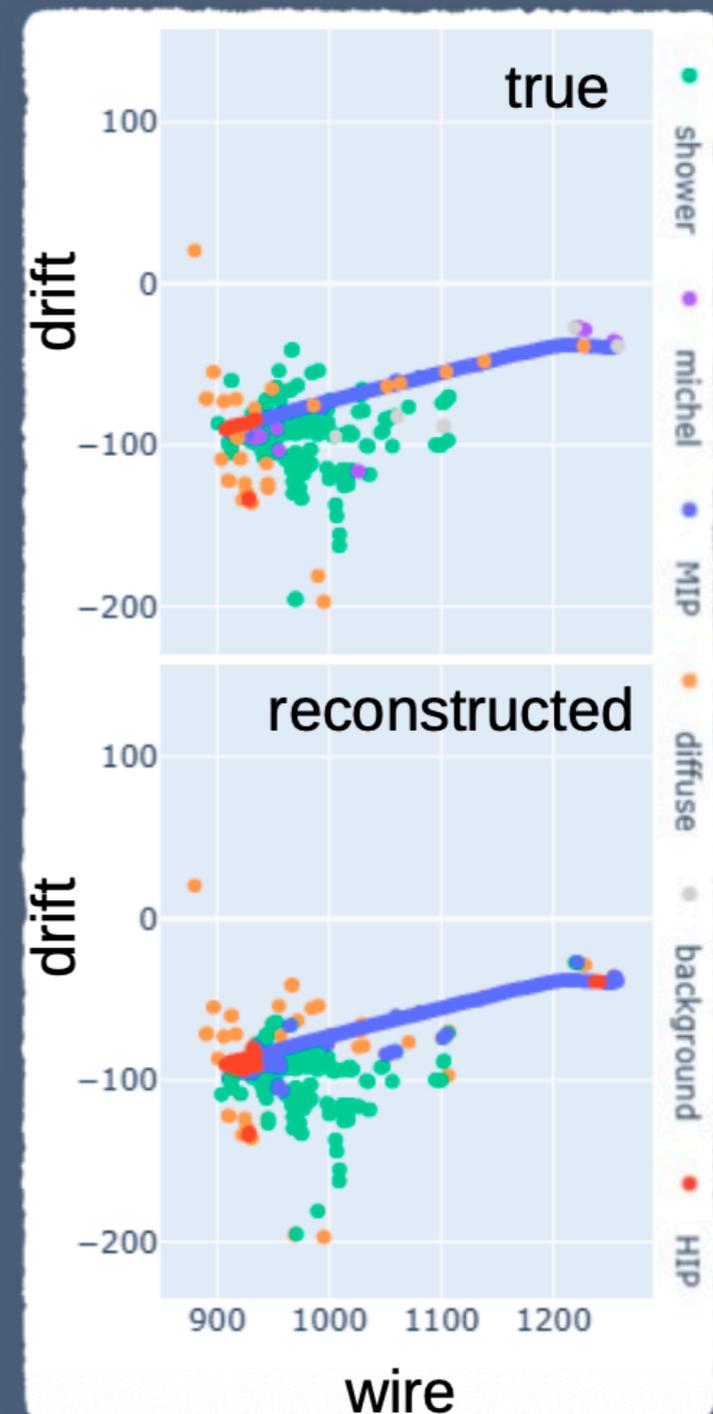
Atmospheric neutrinos

- Atmospheric neutrinos will be **first DUNE data** (between 2029 and 2032) and will be important for commissioning the detector and for physics studies.

Sub-GeV Atmospheric Neutrinos

DUNE FD 400 kt yr exposure
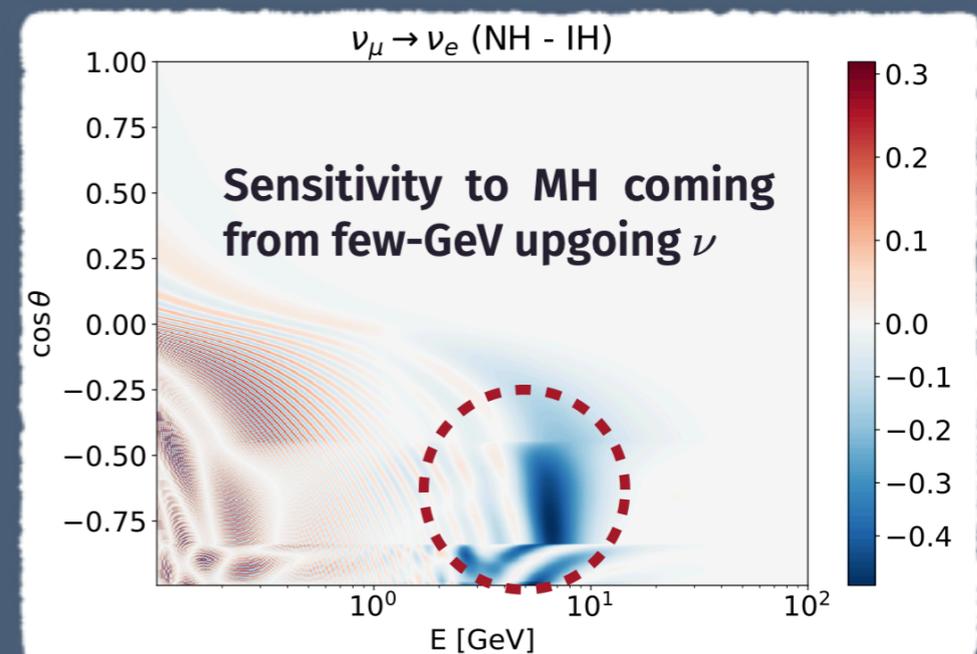NuWro ν event generator
Assuming $\sim 15^\circ$ resolution
30 MeV p KE threshold
Phys. Rev. Lett. 123, 081801

Joint fit — CC$-1p0\pi$ — CC$-2p0\pi$ — CC$-0p0\pi$
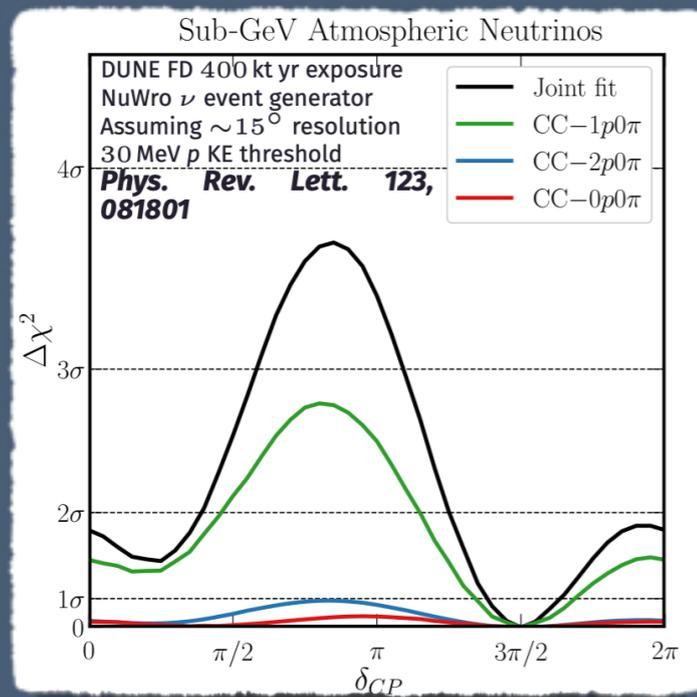
- DUNE analysis in progress, with joint fit framework in place.

- Sub-GeV neutrinos could **exclude several values of CP** phases beyond 3σ.

- GeV neutrino could give a first measurement of **mass ordering complementary to beam** measurements.

$\nu_\mu \to \nu_e$ $(\delta_{CP}, \frac{\pi}{2} - 0)$

Sensitivity to δ_{CP} coming from sub-GeV upgoing ν

$\nu_\mu \to \nu_e$ (NH - IH)

Sensitivity to MH coming from few-GeV upgoing ν
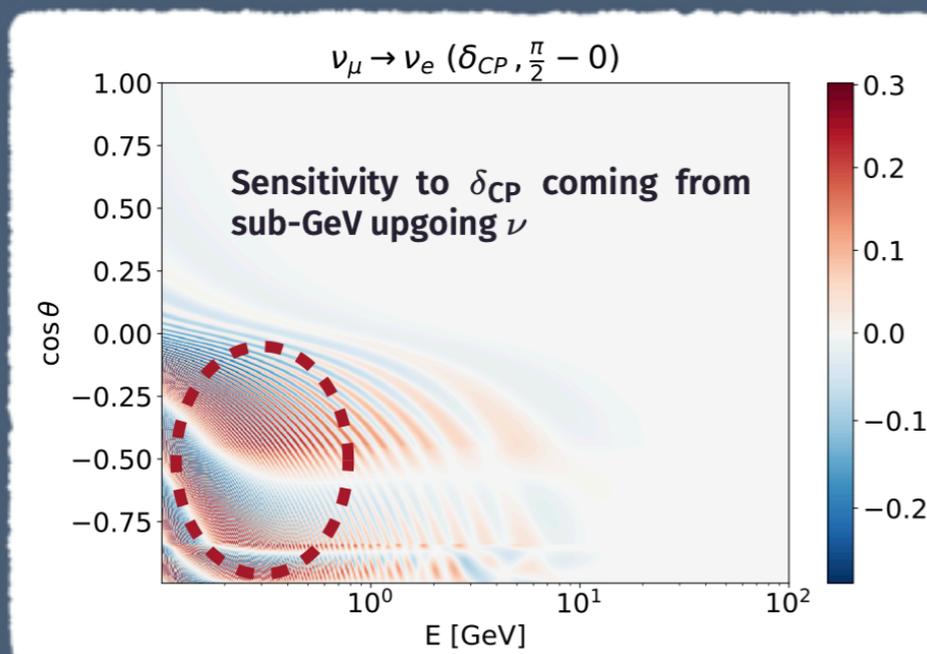
BSM

- DUNE is sensitive to some specific oscillation modes.

- ***Sterile neutrinos*** can be tackled thanks to the large range of L/E (wide-band beam and ND/FD and atmospheric neutrinos).
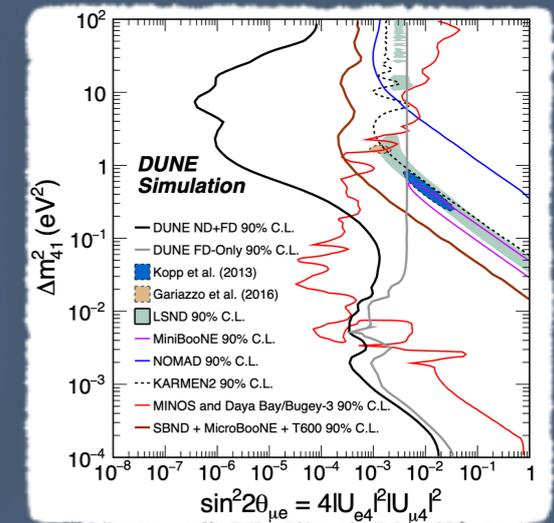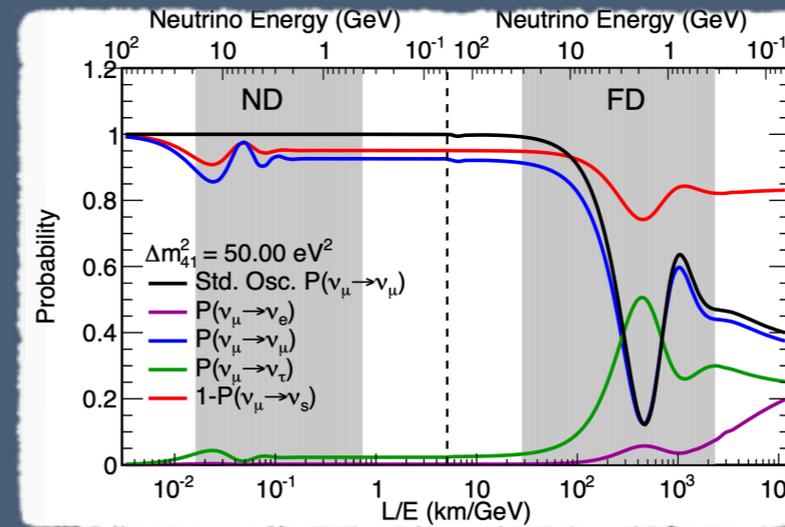
- Precise measurements of neutrinos and antineutrinos could give the ***best limits on CPT violation***.

Phys. Lett. B780 (2018) 631–637
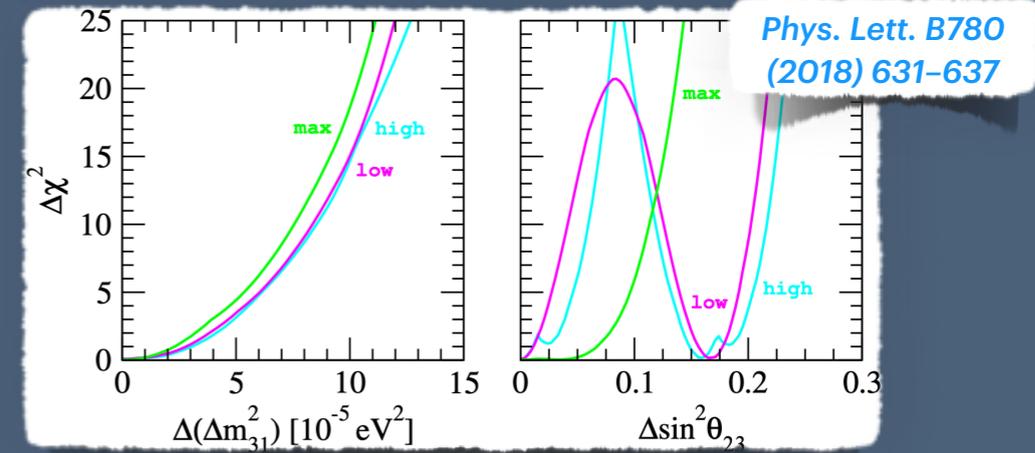
- Large matter effects and three-flavour sensitivity allow DUNE to search for ***non-standard interactions***.
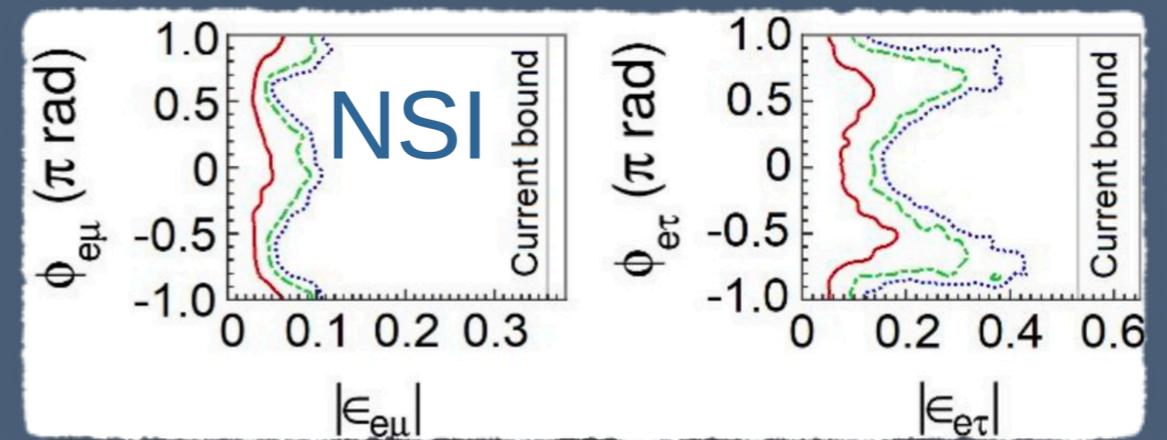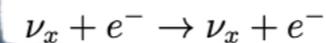
Supernova

- Time and energy profile of SNB neutrino flux is rich in supernova astrophysics.

- Flux includes all neutrino flavours but *only DUNE measures* ν_e thanks to the Ar target.

- DUNE is uniquely sensitive to mass ordering via SNB detection.

- About 5° pointing resolution thanks to ES channel depending on SNB location (40 kton 10 kpc)

- DUNE supernova program starts at the moment FD1 is turned on. Reach extends beyond the Milky Way with additional modules.

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

$$\overline{\nu}_e + {}^{40}\mathrm{Ar} \to e^+ + {}^{40}\mathrm{Cl}^*$$

$$\nu_x + e^- \to \nu_x + e^-$$
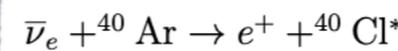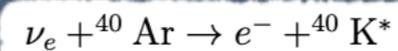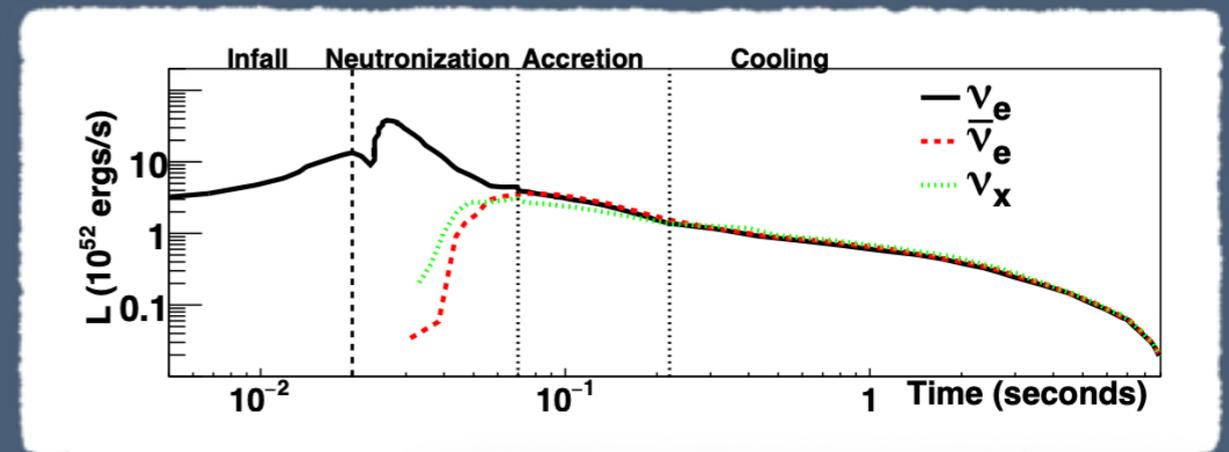
	ν_e	$\overline{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)
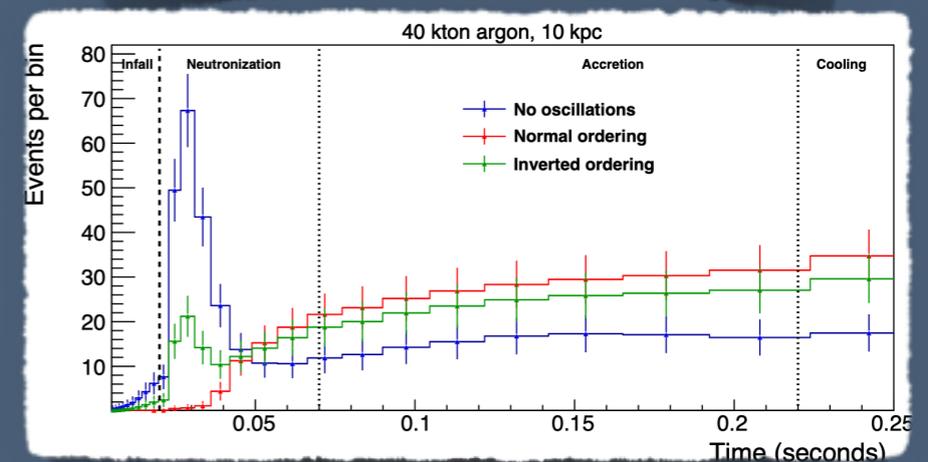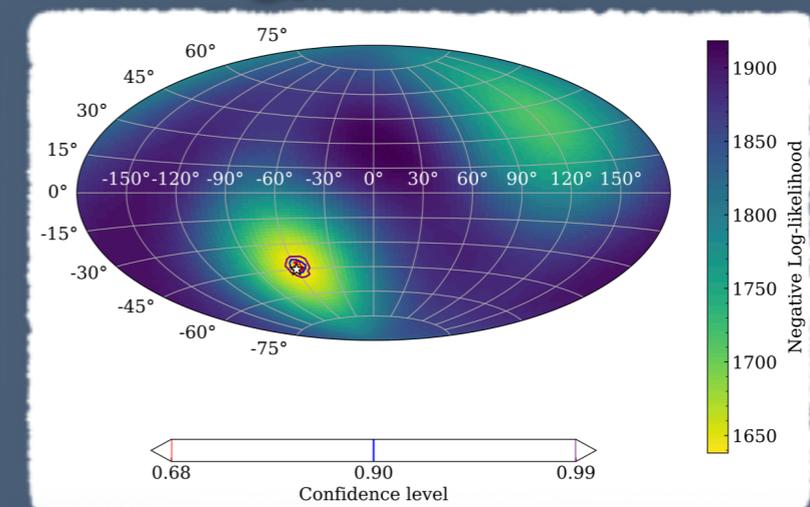
Proton decay

- DUNE will be an *excellent detector to perform nucleon decay searches* considering the underground location, the very large fiducial mass, and the millimetric size imaging capabilities.

- The *golden channel* would be

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

The main background for this channel in DUNE are atmospheric neutrinos.

The 90% CL lower limit (400 kton-year exposure) is

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

DUNE sensitivity comparable to larger water Cherenkov detectors

3 particles reconstruction

Signal
$K^+ \rightarrow \mu^+ \nu_\mu$ (64%)

2021 J. Phys.: Conf. Ser. 2156 012153

$p \rightarrow \bar{\nu} K^+$
- JUNO 20 kton , 3σ
- HK 186 kton HD , 3σ
- DUNE 40 kton, staged , 3σ
- SK+SKGd 27 kton , 3σ
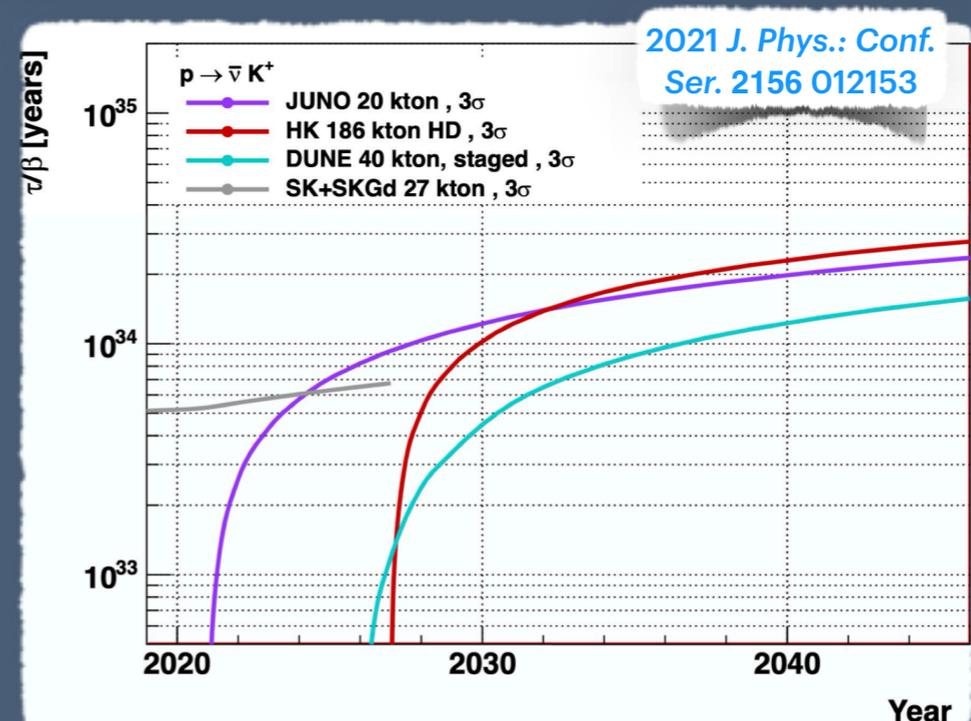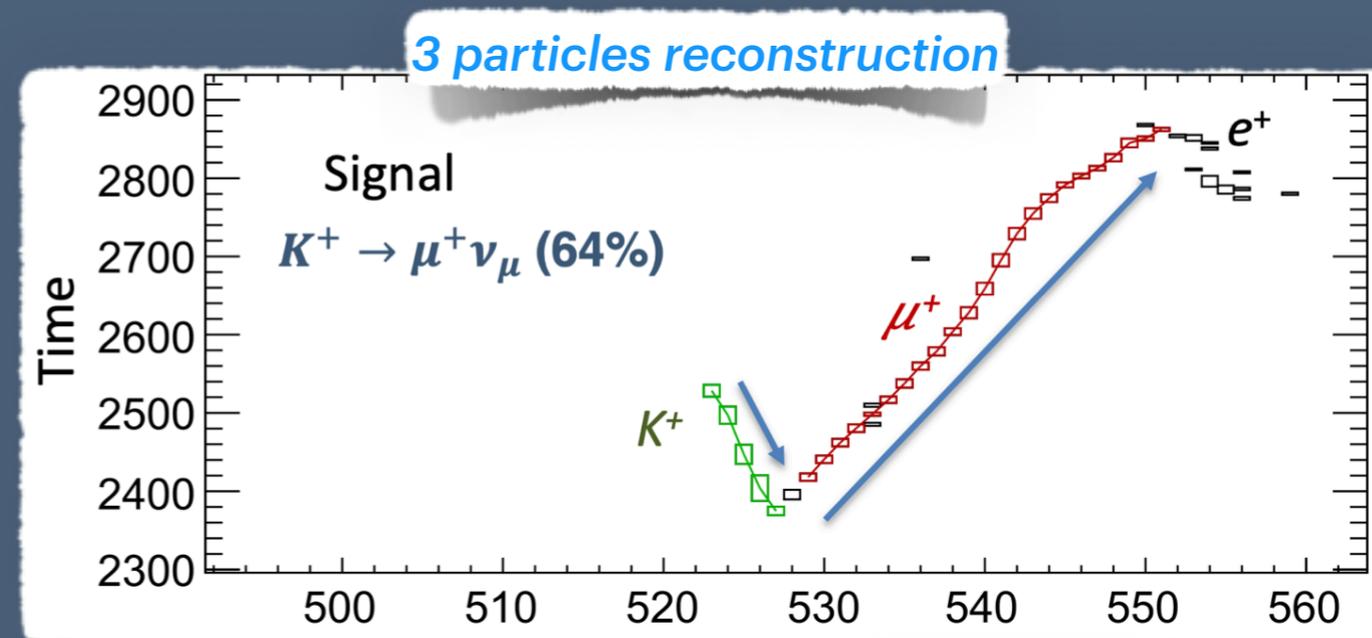
IN2P3 contributions

- There is a *large implication of IN2P3 groups in various critical topics*.

Physics analysis

- APC ➔ Atmospheric, sterile and supernova neutrinos, and systematics studies.
- LAPP ➔ Solar neutrinos.
- IJCLab ➔ Low energy events.
- IP2I ➔ LBL neutrinos and energy reconstructions.
- LP2iB ➔ LBL neutrinos and energy reconstructions.
- LPSC ➔ LBL sensitivity, low energy showers (GeV) , PID and ML.

CERN prototypes analysis

- APC ➔ Neutrino events, pion energy reconstruction, and PDS related analyses.
- LAPP ➔ Data reconstruction and analysis leader.
- IJCLab ➔ Data reconstruction (incl. PDS), processing & simulation, detector calibration.
- IP2I ➔ Online analysis and hadronic interactions.
- LP2iB ➔ Validation of data/MC response.
- LPSC ➔ CRP related studies.

Computing/software

- IP2I ➔ Management of data at CC Lyon and responsible in the computing consortium for data and MC production.

Energy resolution/LBL oscillations

- Work ongoing to understand the best way to reconstruct EM showers (*IP2I and LP2I*).

From IP2I

- Work started in parallel to select showers in PDVD data and improve PID in general with the DUNE AI/ML workflow SPINE (*IJCLab and LPSC*).

From LPSC

- Deployment on LPSC HPC platform of a framework to estimate DUNE LBL sensitivity implementing oscillation analysis with GUNDAM with updated systematics and VD performances (*LPSC*).

- Study of the impact of CRP gaps, implementation of correct geometry and tuning of charge recovering based on PDVD data (*LP2I*).
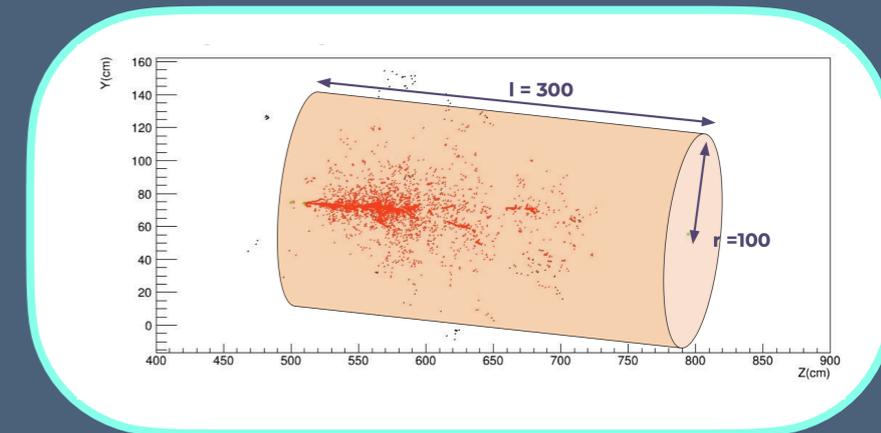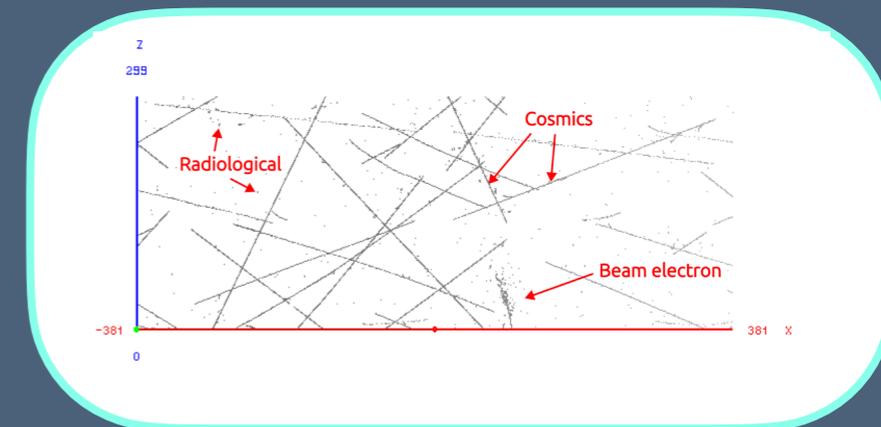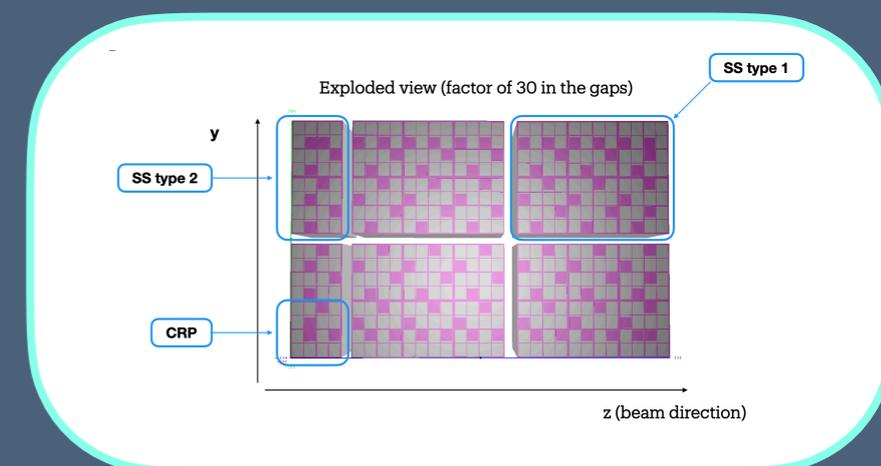
From LP2I

Atmospheric neutrinos

- The study of atmospheric neutrinos is a primary topic for DUNE and France is well visible and recognized on this (*effort driven by APC*).

- The **first paper on atmospheric neutrino reconstruction** has been released [*arXiv:2601.05697*] (co-lead by *APC*).

- In addition studies on **sterile neutrino searches** were performed (*APC*).

- The study of atmospheric neutrinos includes the reconstruction of vertex (*APC*) with impacts also on beam events .

- The identification of neutrinos and antineutrinos via the Michel electron tagging is under study to improve the sensitivity to mass ordering (*APC*).
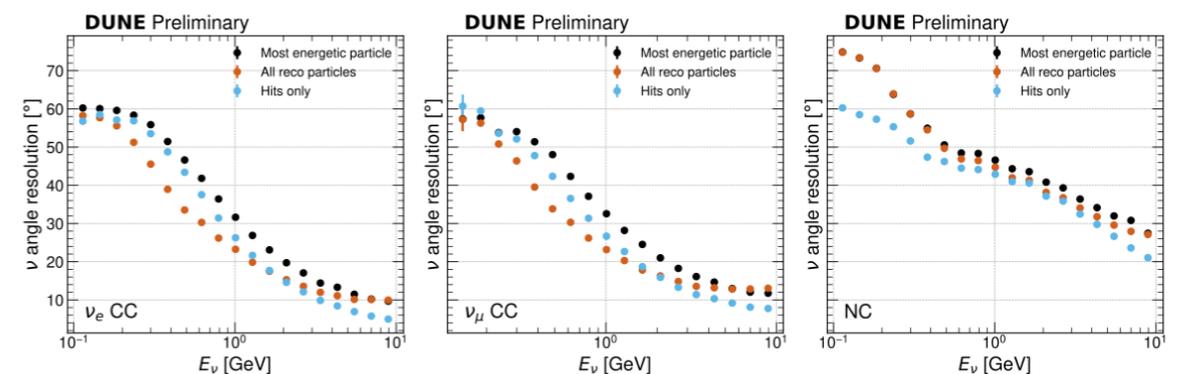
From arXiv:2601.05697

Solar neutrinos

- The study of solar neutrino has also started in France, initiated at *LAPP*.

- The evaluation of background in particular neutrons and cosmogenic backgrounds was carried out and the sensitivity estimated in the current situation and with shielding (*LAPP*).
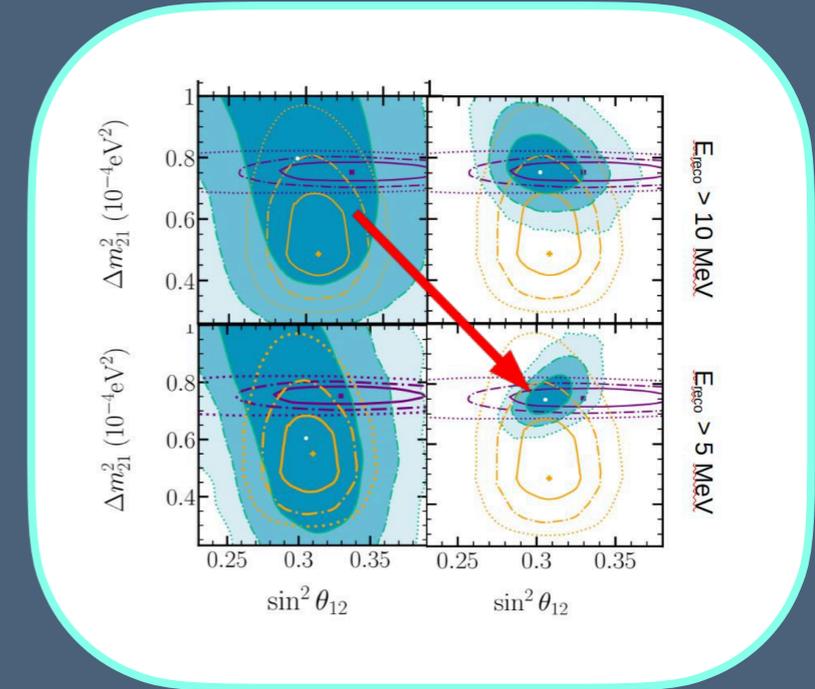
From LAPP

- Calibration at low energy is critical for solar neutrinos but also for SuperNova neutrinos. This work is ongoing in connection with the calibration team, using radiologicals (*IJCLab and LAPP*), and Michel electrons (*IJCLab*).
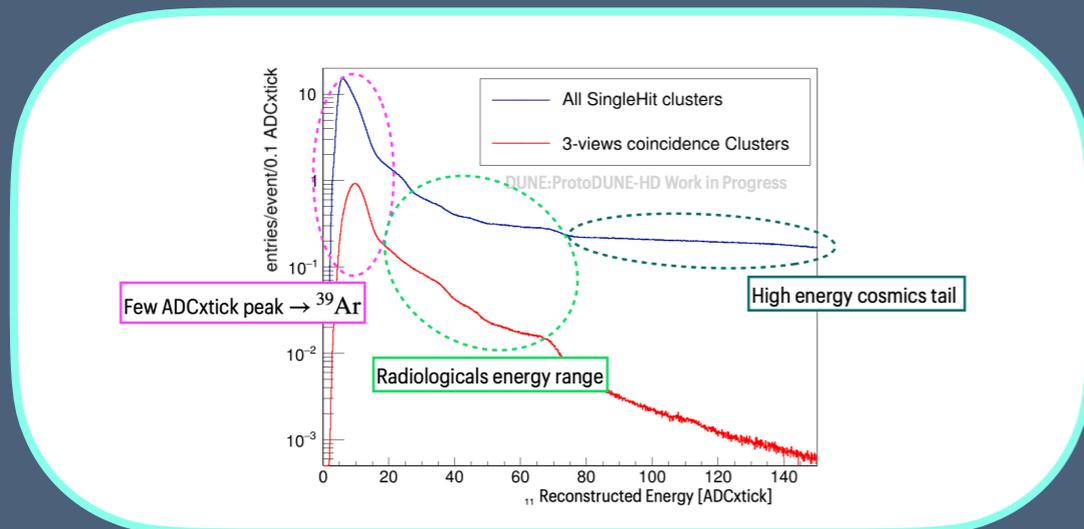
Systematics for atmospherics and LBL

- The assessment of systematic is a topic transverse to different WGs (LBL, ANOA, FD Sim/Reco, Calibration) on which France has always been involved (*effort driven by APC*).

- A new framework for FD systematics has been developed (presented@LBNC in October 2025) and is being improved (*APC*).

- The beam data on ProtoDUNE will be analyzed to evaluate systematics on energy reconstruction (*APC*).

Framework for FD systematics studies, ANOA+LBL

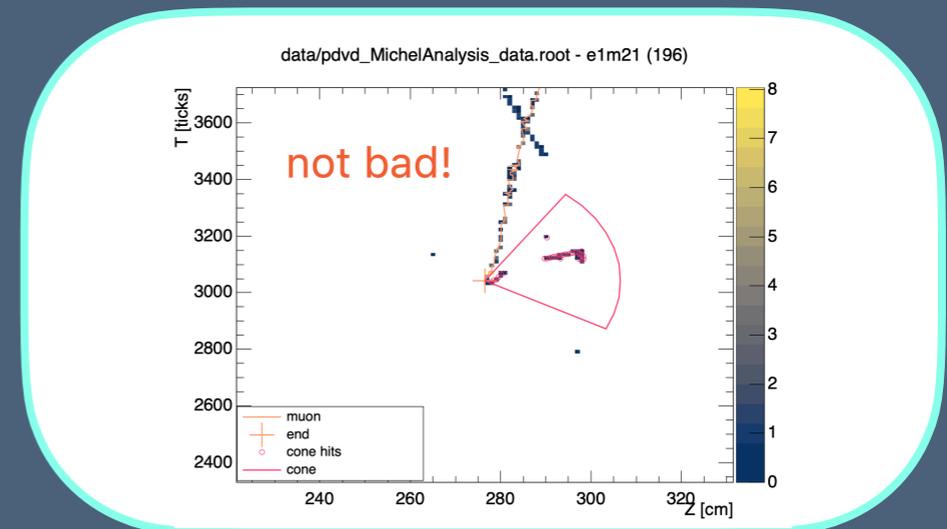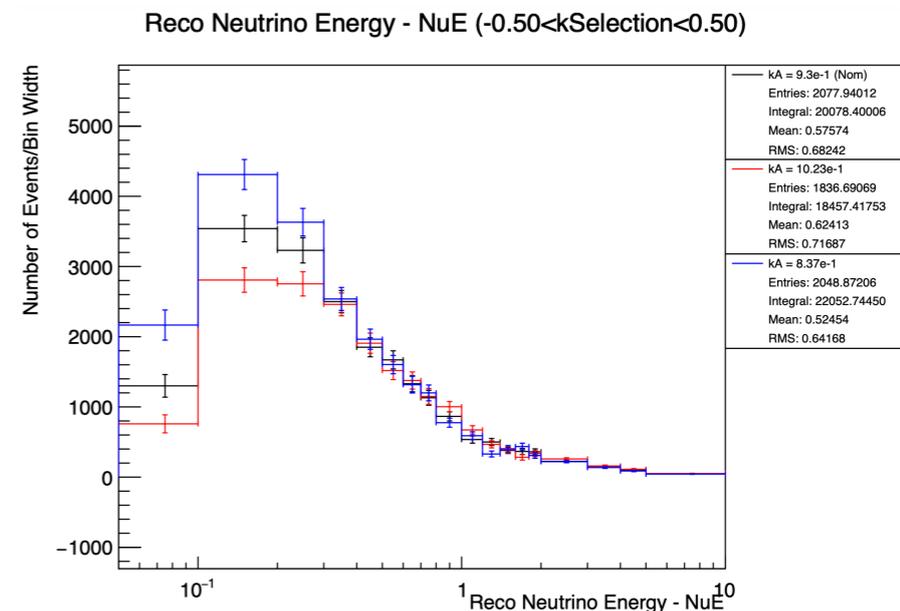|	
Identify relevant physical effects / parameters	✅ List compiled, can be completed and modified
Re-spin detector simulation and reco on existing MC	✅ Code available (can be improved) CAFs have been produced
Impact on observables (Ereco θreco … ⇒ CAFs)	✅ CAF comparison tool ready, easily configurable
Input for fitters (covariance matrix as first try)	◯ In progress (preliminary matrices have been produced)
Implementation in OA	❌

Details on wiki page

Reco Neutrino Energy - NuE (-0.50<kSelection<0.50)

kA = 9.3e-1 (Nom)
Entries: 2077.94012
Integral: 20078.40006
Mean: 0.57574
RMS: 0.68242

kA = 10.23e-1
Entries: 1836.69069
Integral: 18457.41753
Mean: 0.62413
RMS: 0.71687

kA = 8.37e-1
Entries: 2048.87206
Integral: 22052.74450
Mean: 0.52454
RMS: 0.64168

From APC

ProtoDUNE and Coldbox analysis

- France is heavily involved in ProtoDUNE, co-leader of the Data Reconstruction and Analysis working group, and development of dedicated tools (LARDON) systematically used during prototyping (*LAPP*).

- A lot of work is done to assure the correct data readability and utilization (*IP2I*).

- France is also involved in the Data Production (*IJCLab and IP2I*).

- Analysis performed in the VD coldbox (PDS, charge) will be extended to PDVD (*APC and LAPP*).

- Work on the transparency of CRPs as a function of the voltage and the reconstructed charge as a function of the track angle (*LAPP and LPSC*), will be validated on PDVD.

- First studies on PDVD and PDHD data were presented (*IJCLab and LAPP*).

- First neutrino-Argon interactions seen in DUNE (*APC*).

From APC

Candidate event with a neutrino in NP02

View 2 channel
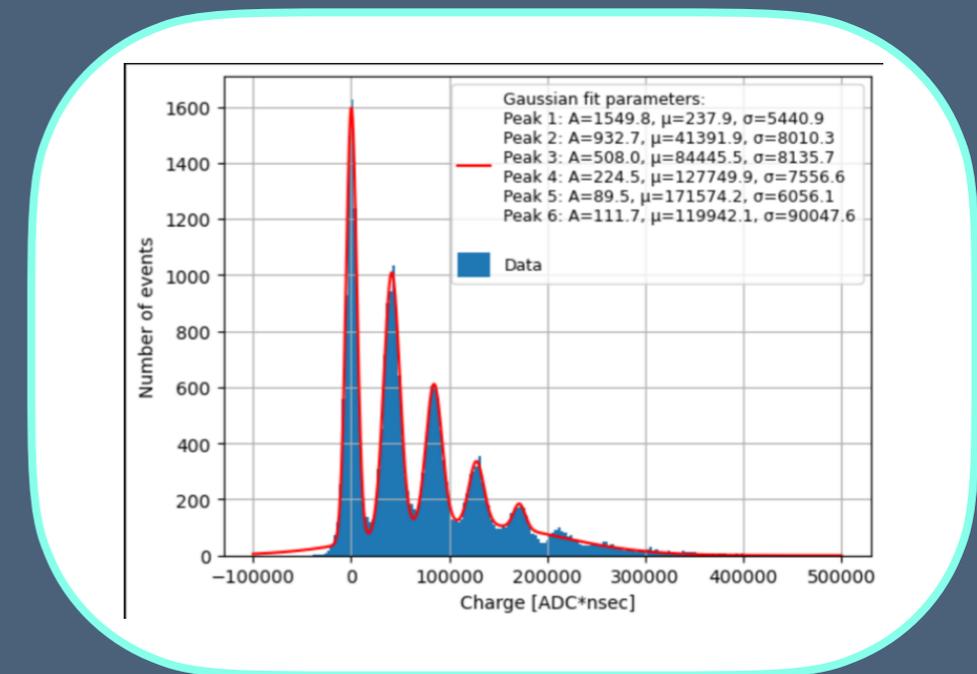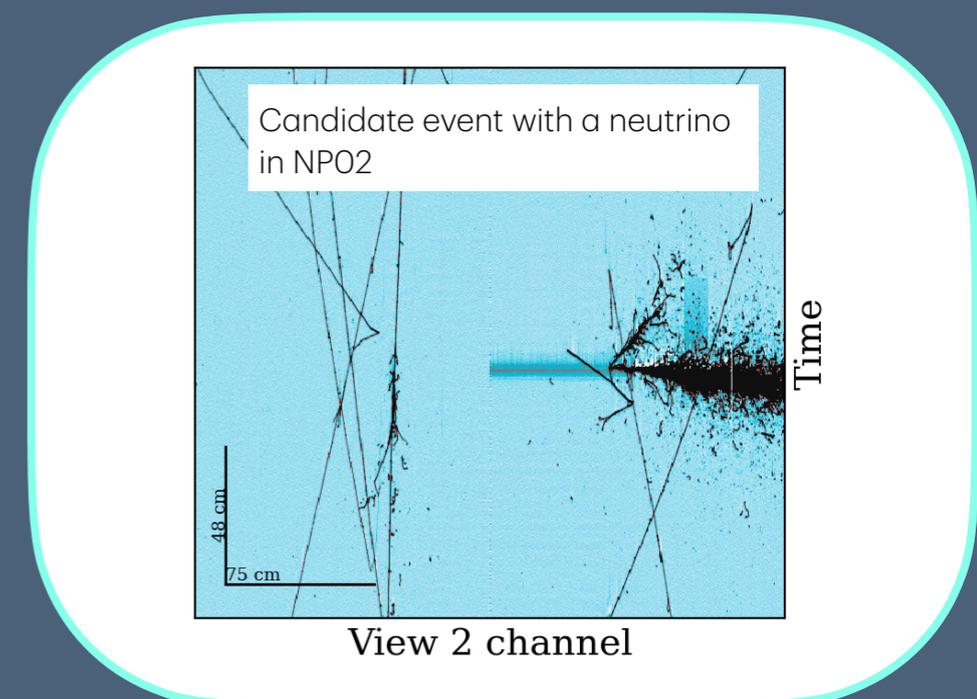
Conclusions

- The DUNE physics case, already assessed in previous CS in 2018 and 2021. Its importance was restated and **supported by the new P5 and European Strategy outcomes**.

- DUNE is designed to **test the three-flavor paradigm** and search for new physics in neutrino oscillations.

- If the three-flavor picture is correct, DUNE will make **very precise measurements of its parameters**, leveraging spectral information to break degeneracies.

- DUNE has qualitatively **superior ability to determine the neutrino mass ordering** definitively.

- DUNE has unique capabilities to run a **rich physics program without beam**.

- There is a **large implications of IN2P3 groups in the physics analysis**, **analysis of CERN prototypes** (only real data before first FD operation) and **computing/software efforts**.

- Strong IN2P3 efforts for a timely operation of the first FD module (see Cédric's talk).

BackUp

ACE MIRT

- An increase in **beam power to > 2 MW is a primary requirement for DUNE** to achieve its P5 physics goals.

- Fermilab has in place an **Accelerator Complex Evolution (ACE)** plan to realize the beam power required. It will be delivered in two phases:

1. The first phase known as **ACE-Main Injector Ramp and Targetry (ACE-MIRT)**, will raise the beam power to just beyond 2 MW by reducing the cycling time in the Main Injector (MI) from 1.2 sec to 0.7 sec (available since 2031 !)

2. Phase two is the **replacement of the Booster and an extension of the Linac to 2 GeV (ACE-BR)**, which will eventually allow the beam power to rise to 2.4 MW.

- While the ACE-MIRT upgrade is primarily motivated by DUNE science, ACE-BR targets a broader physics program at FNAL, serving as a robust and reliable platform for the future.
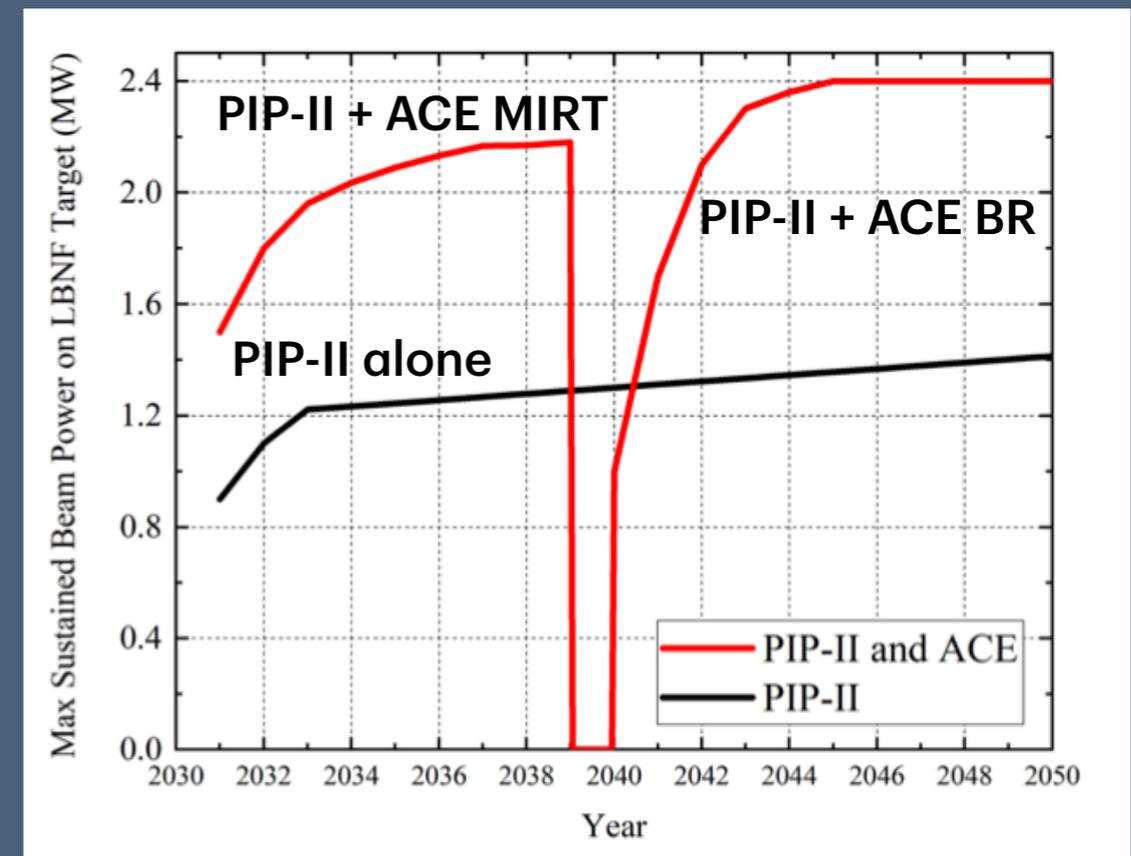
Octant degeneracy

- The θ_{23} angle is currently known with $\sin^2\theta_{23}$ roughly between 0.41 and 0.62 at 3σ.

- DUNE can measure $\sin^2\theta_{23}$ with 3σ precision in the range ~0.48–0.55, allowing a determination of the θ_{23} *octant*.

- $\nu_\mu \to \nu_\mu$ disappearance depends on $\sin^2 2\theta_{23}$, while $\nu_\mu \to \nu_e$ appearance depends on $\sin^2\theta_{23}$; combining both channels helps resolve the octant degeneracy.