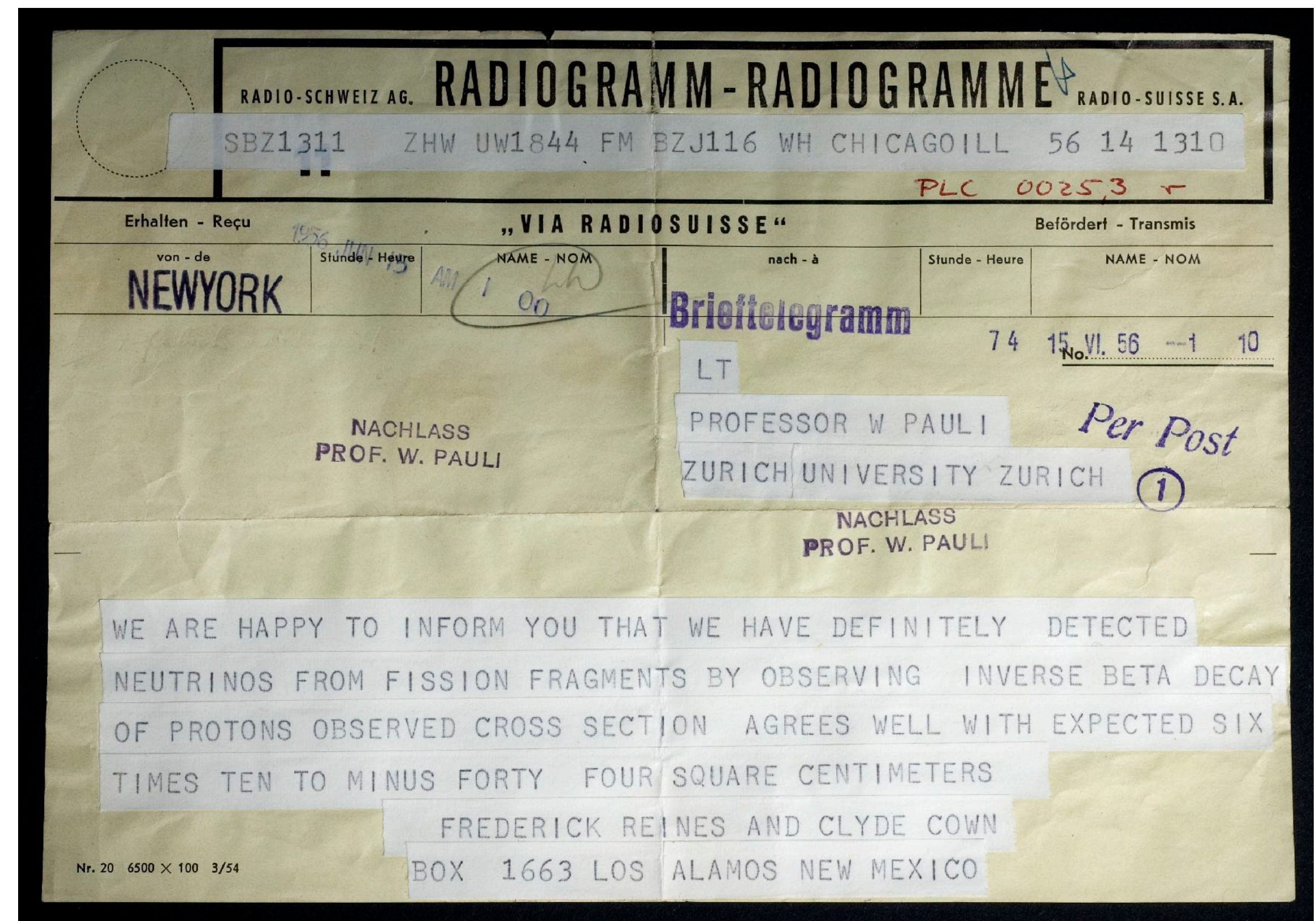


Accelerator Neutrino Experiments

Dave Newbold
PPAP, 16th July 2026

Neutrino discovery announced 70y ago ->



More Later...

- In this talk, I cover oscillation phenomena
 - Neutrino physics is a wide field, see Cheryl's talk (and Mark's, *and Dan's?*) for the rest
 - See also UK overview talk by Rhiannon Smith-Jones at IOP HEPP 2026

805

UNIVERSITY OF CALIFORNIA, IRVINE

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO

DEPARTMENT OF PHYSICS

IRVINE, CALIFORNIA 92717

August 24, 1989
Bitnet: FREINES@UCIVMSA
Tel: (714) 856-7036

Dr. Taiji Yamanouchi
Director's Office
Fermilab
P.O. Box 500,
Mail Station 105
Batavia, IL 60510

Dear Dr. Yamanouchi:

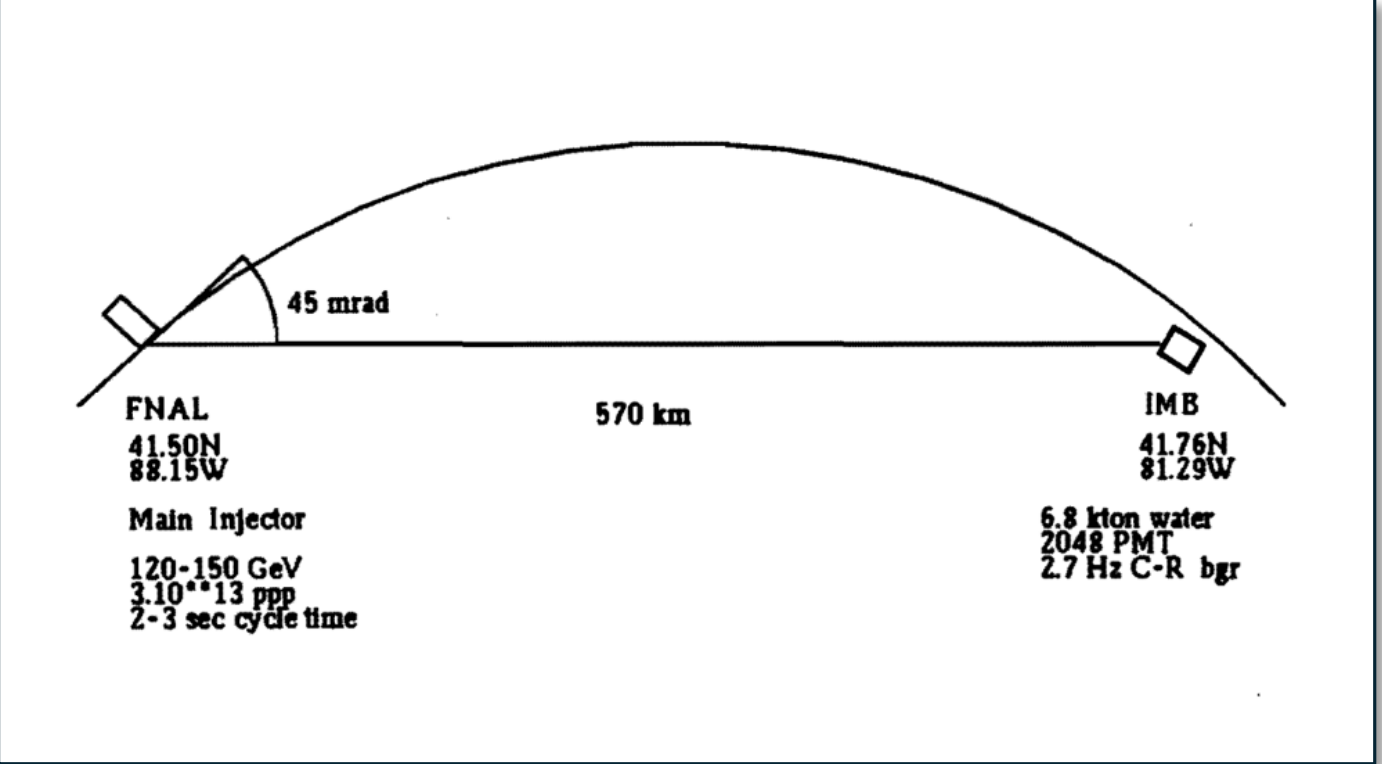
Enclosed is a letter of intent for: "A long baseline oscillation experiment using the high intensity neutrino beam from the Fermilab main injector and the IMB water cerenkov detector."

The contact person for this experiment is:

Wojciech Gajewski
Physics Department
University of California, Irvine
Irvine, CA 92717
Bitnet: WGAJEWSK@UCIVMSA
Tel: (714) 856-6403

Sincerely,
F. Reines
Frederick Reines
Spokesman for IMB Collaboration

FR:deo



THE LETTER OF INTENT FOR A LONG BASELINE OSCILLATION EXPERIMENT USING THE HIGH INTENSITY NEUTRINO BEAM FROM THE FERMILAB MAIN INJECTOR AND THE IMB WATER CERENKOV DETECTOR.

R. Becker-Szendy, C.B. Bratton, R. Cady, D. Casper, S.T. Dye, W. Gajewski, M. Goldhaber, T.J. Haines, P. Halverson, T.W. Jones, D. Kielczewska, W.R. Kropp, J. Learned, J.M. LoSecco, S. Matsuno, C. McGrew, L. R. Price, F. Reines, J. Schultz, H.W. Sobel, L.R. Sulak, R. Svoboda, F. Wittel.

The University of California, Irvine
Boston University
Brookhaven National Laboratory
Louisiana State University
Cleveland State University
The University of Hawaii, Manoa
University College, London
Warsaw University
The University of Notre Dame
The University of Maryland

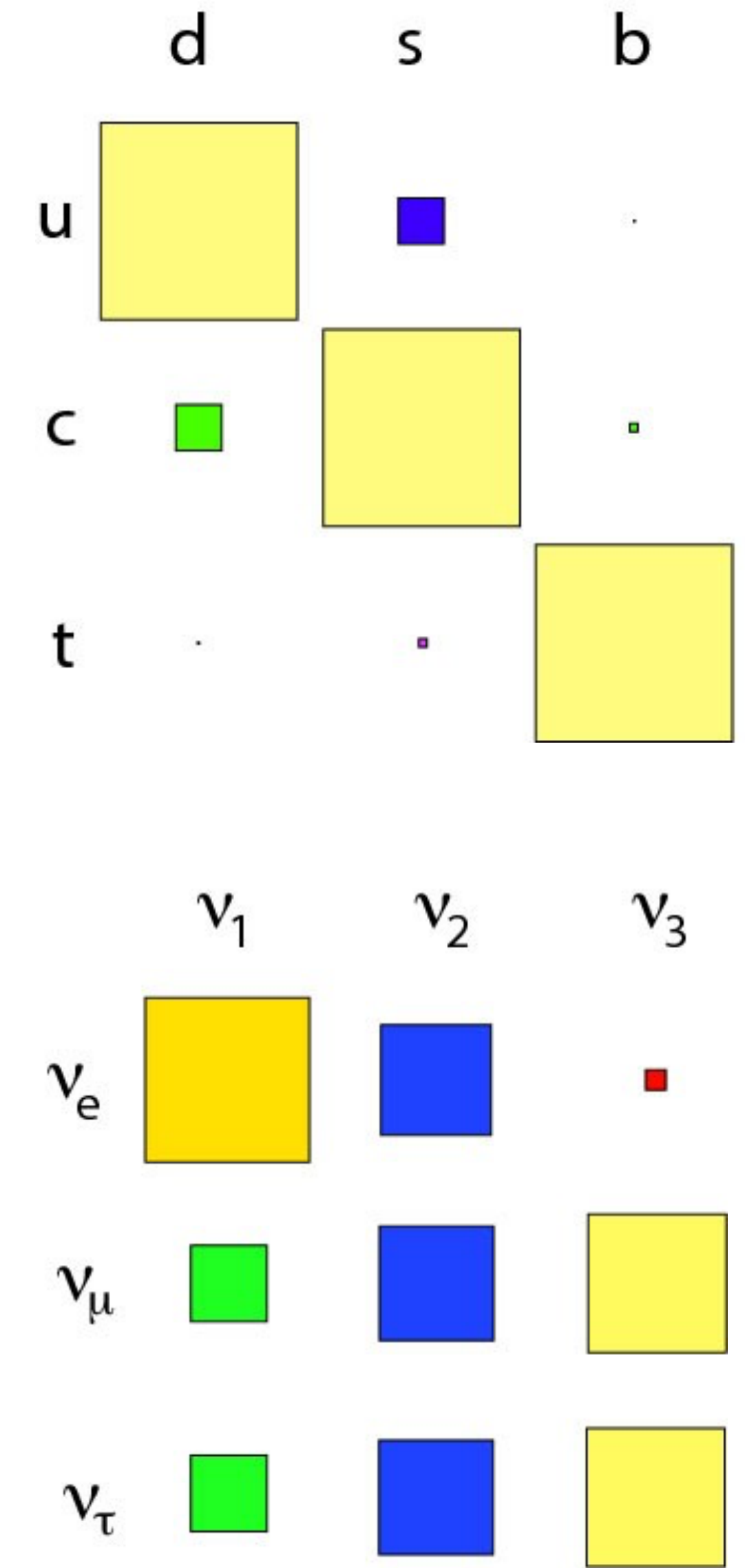
ABSTRACT

We propose to study muon neutrino oscillations by detecting neutrinos produced by the Fermilab Main Injector in the IMB detector, some 581 km distant. Interactions span the energy range 1-50 GeV. We are able to detect muon neutrino disappearance of more than a few percent down to a mass range of $\delta m^2 \sim 10^{-3} \text{ (eV)}^2$, a

Last proposal from Fred was to Fermilab to build a long-baseline neutrino experiment in 1989

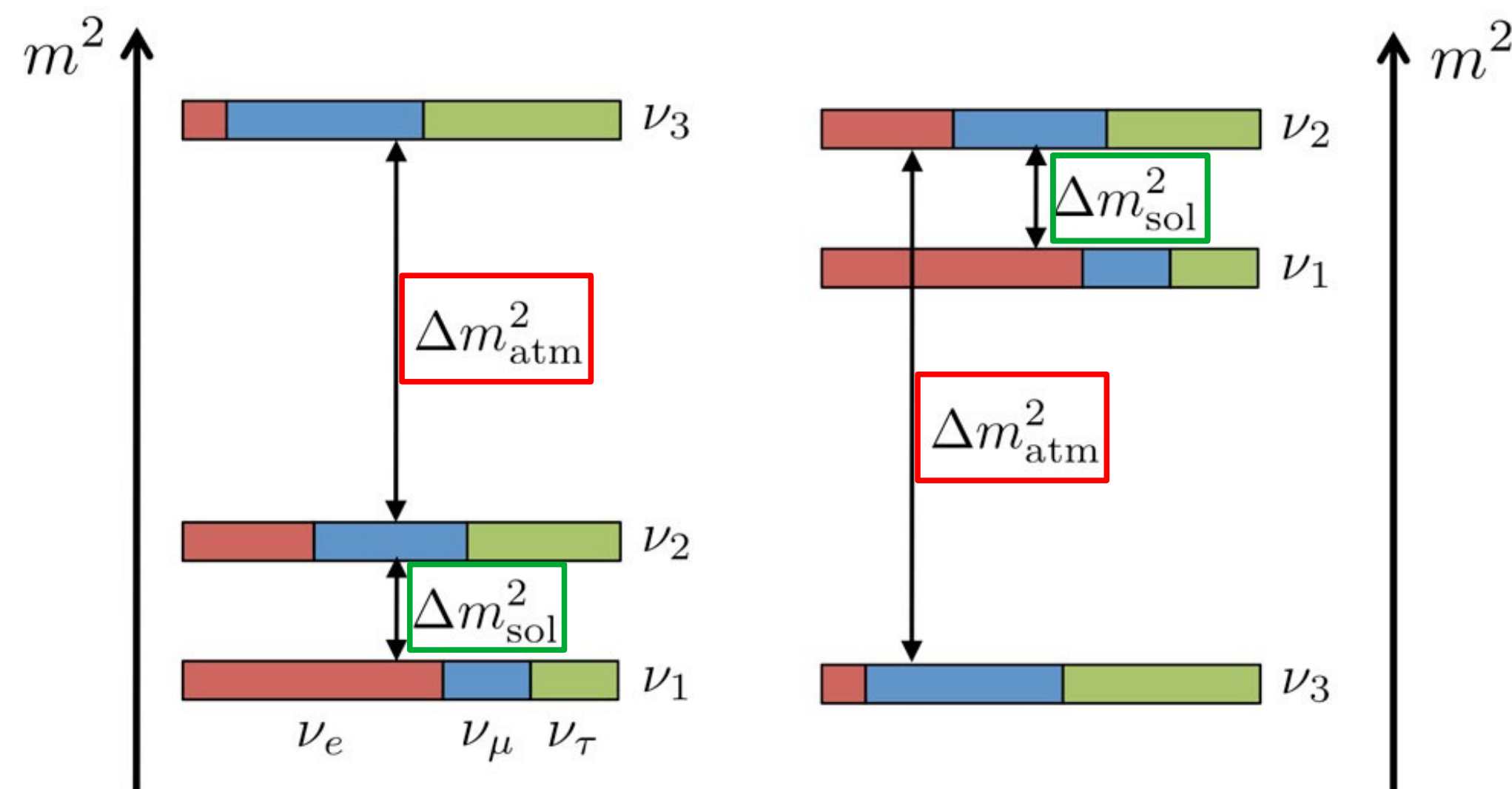
What we Know

- The first era:
 - Neutrinos exist and interact with expected cross-sections
 - Neutrinos undergo flavour oscillations $\rightarrow$ non-zero mass
 - All solar and atmospheric phenomena accounted for
 - Direct evidence of new physics, no get-out clause
 - Three light active neutrino flavours
 - All phenomena / problems / anomalies accounted for by three-flavour mixing
 - Two large mixing angles
 - At least two (very different) non-zero masses
- Last $\sim$ ten years (post-Daya Bay)
 - μ - τ symmetry is not exact
 - θ_{13} is significant, neutrino CP violation is possible and can be measured
 - *Almost* all experimental observations currently consistent with Λ_{CDM}



Mixing Parameters: 2026

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



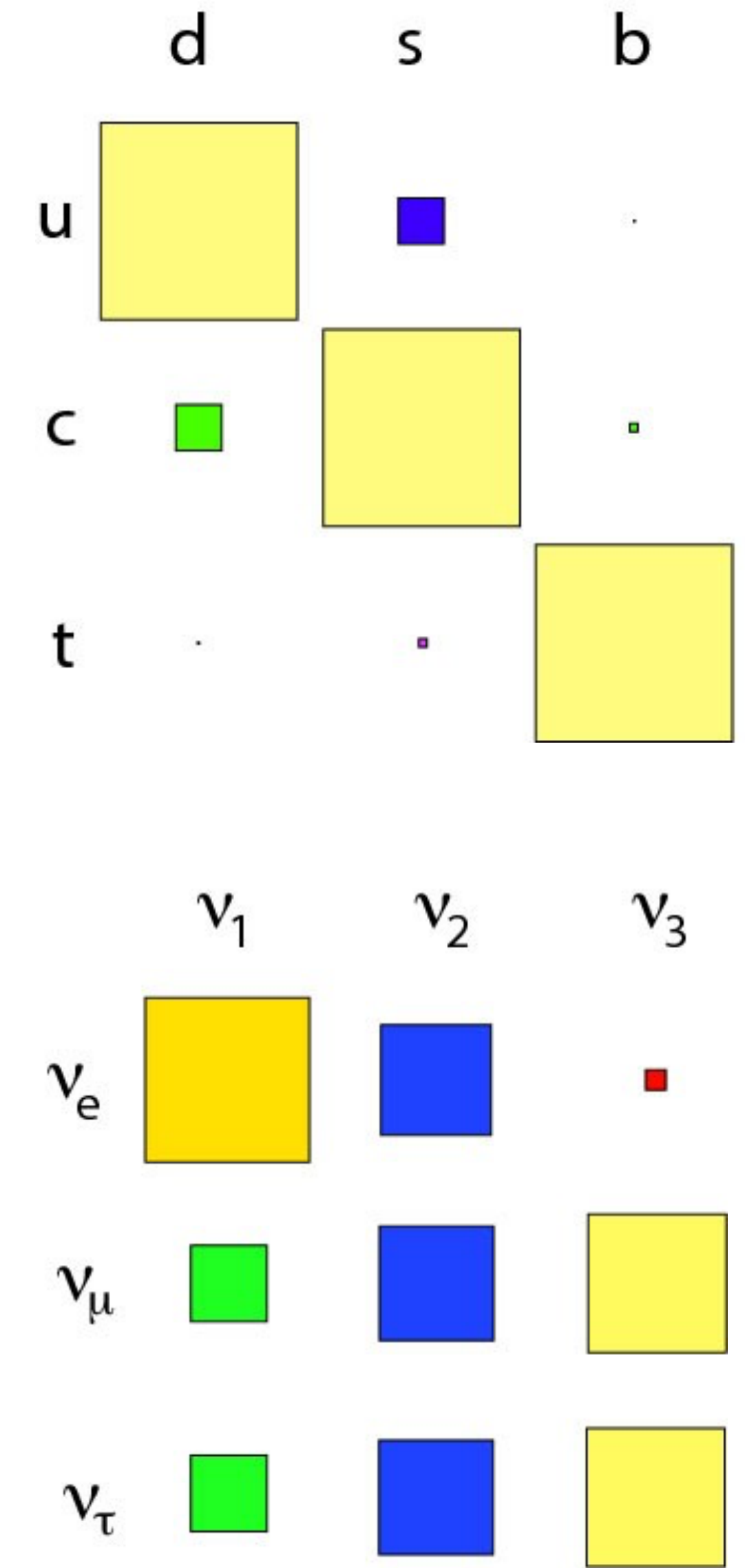
mass ordering

Solar, reactor with $L \sim 50$ km
Atmospheric
Accelerator long-baseline
Reactor with $L \sim 2$ km

Majorana parameters
not measurable
through oscillation

What we Don't Know

- And would like to...
 - The hierarchy of mass states – normal or inverted ordering?
 - The existence and degree of CP violation – is it maximal?
 - The size and octant of θ_{23} – is it maximal?
 - Quantum nature of neutrinos – is there Majorana content?
 - Whether additional sterile and / or heavy neutrinos exist
 - Whether PMNS is even unitary or if there is underlying symmetry
 - And why PMNS and CKM matrices are wildly different
 - What all of this is telling us about new physics
- The field is rich in *known unknowns*
 - If history guides us, there will also be *unknown unknowns* (discoveries)
 - And perhaps some *unknown knowns* (from tensions in current data)



Why Accelerator Neutrinos?

$$P(\nu_l \rightarrow \nu_{l'}) = \sum_j |U_{l'j}|^2 |U_{lj}|^2 + 2 \sum_{j>k} |U_{l'j} U_{lj}^* U_{lk} U_{l'k}^*| \cos\left(\frac{\Delta m_{jk}^2}{2p} L - \phi_{l'l;jk}\right)$$

$$P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'}) = \sum_j |U_{l'j}|^2 |U_{lj}|^2 + 2 \sum_{j>k} |U_{l'j} U_{lj}^* U_{lk} U_{l'k}^*| \cos\left(\frac{\Delta m_{jk}^2}{2p} L + \phi_{l'l;jk}\right)$$

$$\phi_{l'l;jk} = \arg\left(U_{l'j} U_{lj}^* U_{lk} U_{l'k}^*\right)$$

- ν (and $\bar{\nu}$) are free - so why pay more?
 - ν where you want, when you want, through what you want
 - Suppress backgrounds, utilise matter effects
 - Known baseline, known composition (ish)
 - Near detectors can measure beam before oscillation
 - CP conjugation at the flick of a switch (ish)
 - Can operate above μ / τ threshold
 - With decent energy resolution

$P(\nu_e \rightarrow \nu_e)$ solar / reactor disappearance

$P(\nu_e \rightarrow \nu_\mu)$ needs focussed muon beam

$P(\nu_\mu \rightarrow \nu_e)$ accel / atmos appearance

$P(\nu_\mu \rightarrow \nu_\mu)$ accel / atmos disappearance

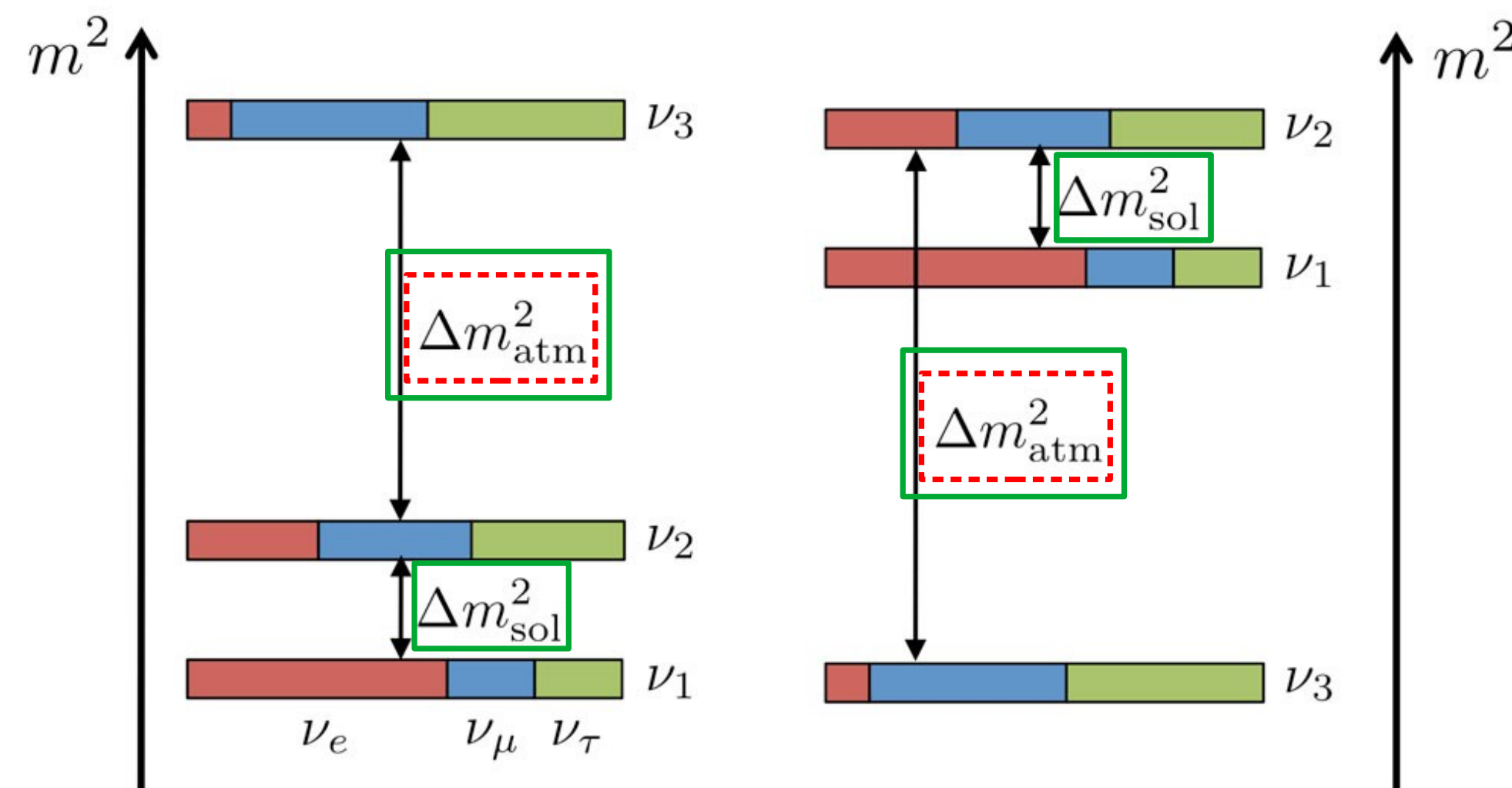
+ C.C.

$P(\nu_X \rightarrow \nu_\tau)$ tau detection challenging

$P(\nu_\tau \rightarrow \nu_X)$ no primary tau beams

Mixing Parameters: Future

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



mass ordering

Reactor with L ~ 50 km (JUNO)

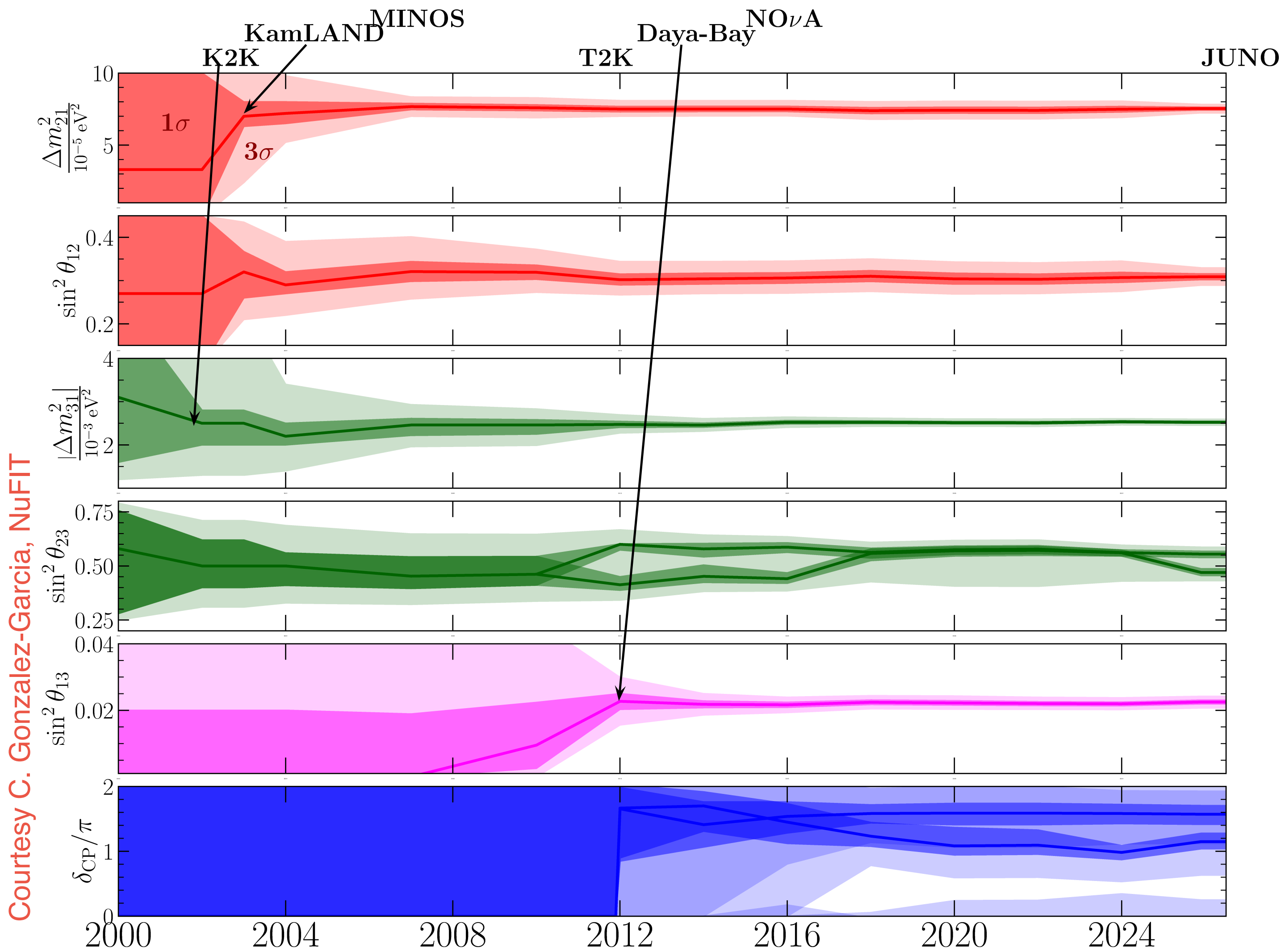
Atmospheric

Accelerator long-baseline

Reactor with L ~ 2 km

- Accelerator long-baseline experiments are the best way to measure θ_{13} , δ_{CP}
- Complementary with reactor neutrinos on θ_{13} , Δm^2_{31}
- Complementary with atmospheric on θ_{23}

Timeline of Measurements



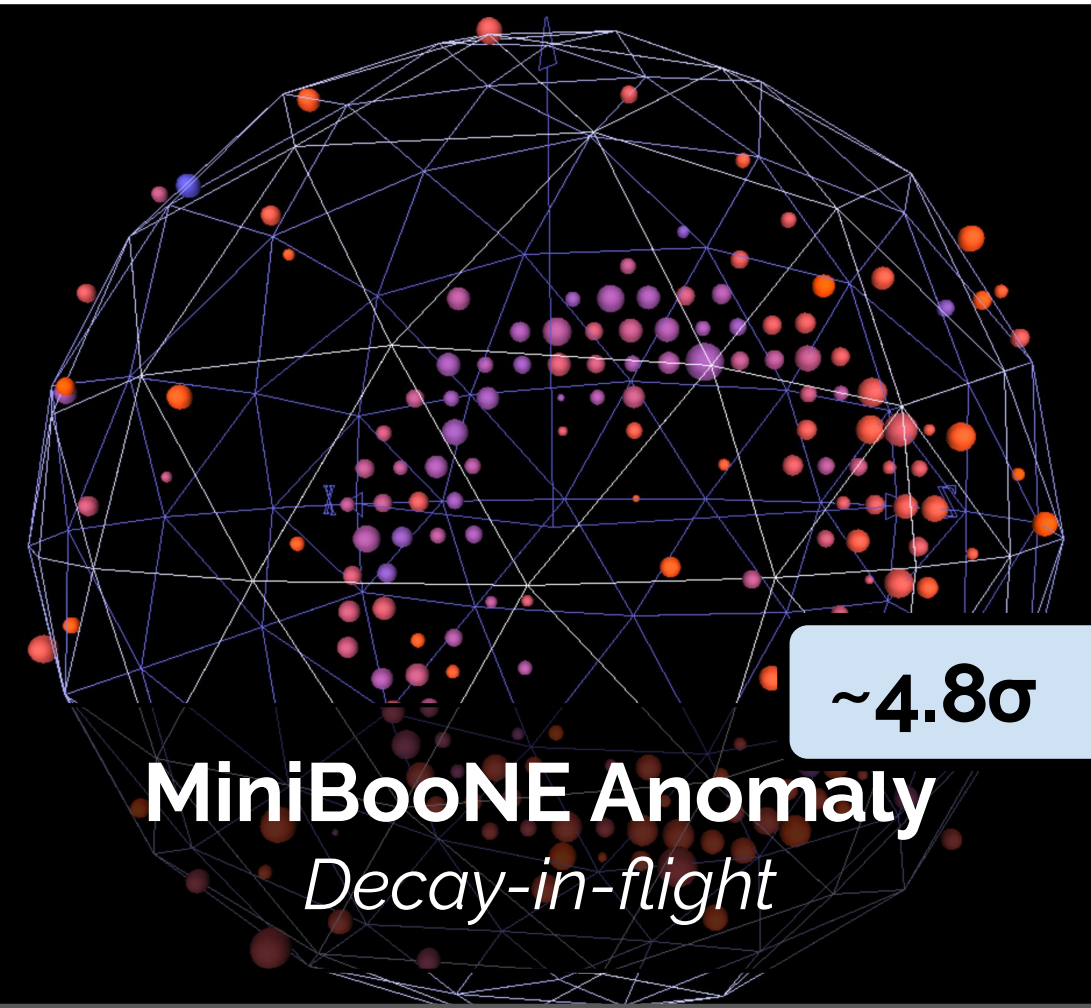
NuFIT 6.1 (2025)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 1.5$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC23 without SK atmospheric data	$\sin^2 \theta_{12}$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \rightarrow 0.3295$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \rightarrow 0.3295$
	$\theta_{12}/^\circ$	$33.76^{+0.42}_{-0.41}$	$32.54 \rightarrow 35.03$	$33.76^{+0.42}_{-0.41}$	$32.54 \rightarrow 35.03$
	$\sin^2 \theta_{23}$	$0.470^{+0.017}_{-0.014}$	$0.432 \rightarrow 0.587$	$0.555^{+0.013}_{-0.016}$	$0.437 \rightarrow 0.590$
	$\theta_{23}/^\circ$	$43.27^{+1.0}_{-0.82}$	$41.11 \rightarrow 50.02$	$48.15^{+0.75}_{-0.92}$	$41.40 \rightarrow 50.21$
	$\sin^2 \theta_{13}$	$0.02249^{+0.00057}_{-0.00057}$	$0.02070 \rightarrow 0.02420$	$0.02261^{+0.00056}_{-0.00056}$	$0.02091 \rightarrow 0.02433$
	$\theta_{13}/^\circ$	$8.62^{+0.11}_{-0.11}$	$8.27 \rightarrow 8.95$	$8.65^{+0.11}_{-0.11}$	$8.31 \rightarrow 8.97$
	$\delta_{CP}/^\circ$	207^{+23}_{-20}	$114 \rightarrow 405$	283^{+24}_{-28}	$202 \rightarrow 347$
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.537^{+0.094}_{-0.10}$	$7.236 \rightarrow 7.823$	$7.537^{+0.094}_{-0.10}$	$7.236 \rightarrow 7.822$
	$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.521^{+0.026}_{-0.018}$	$+2.454 \rightarrow +2.592$	$-2.500^{+0.024}_{-0.023}$	$-2.569 \rightarrow -2.430$

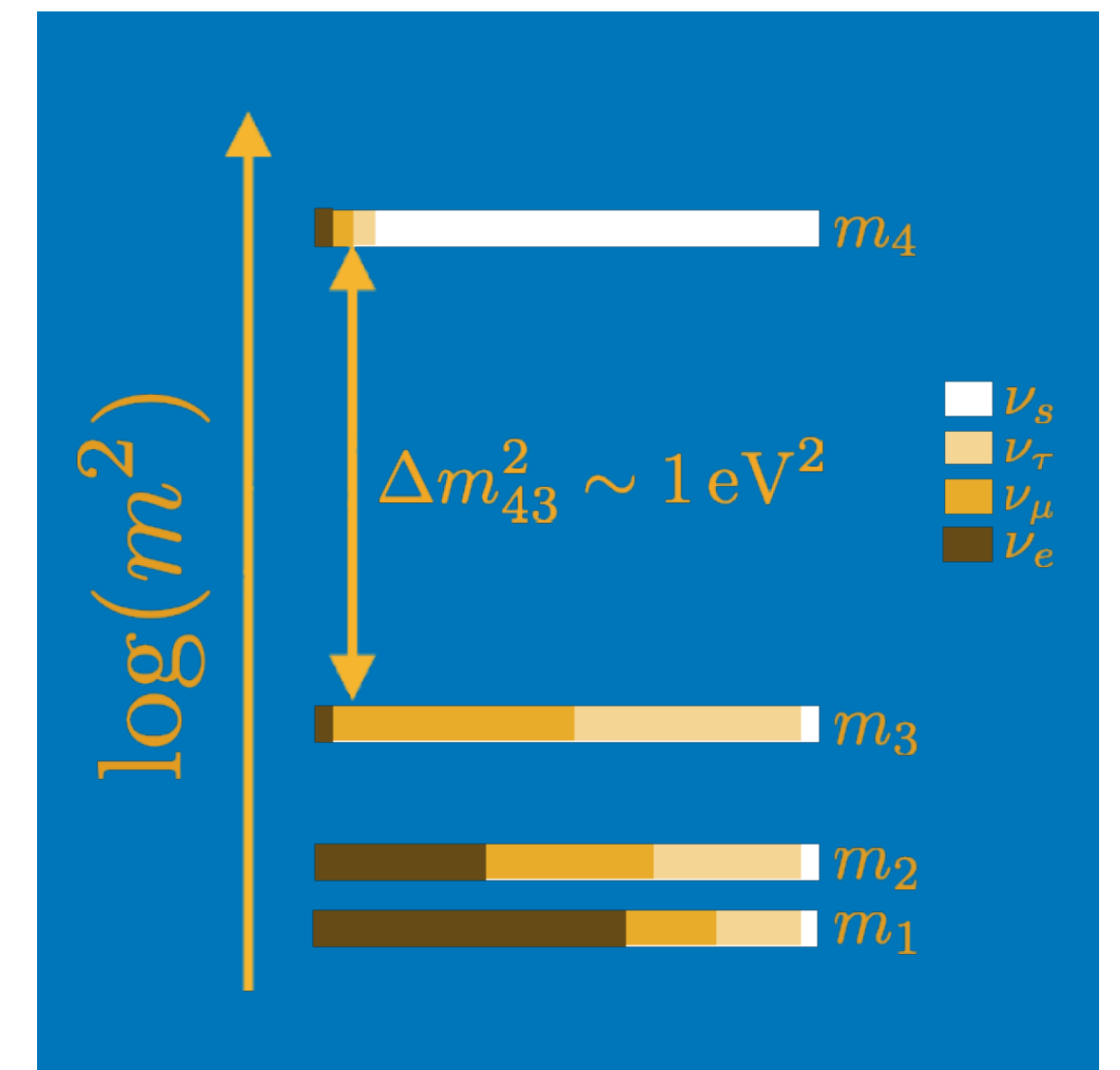
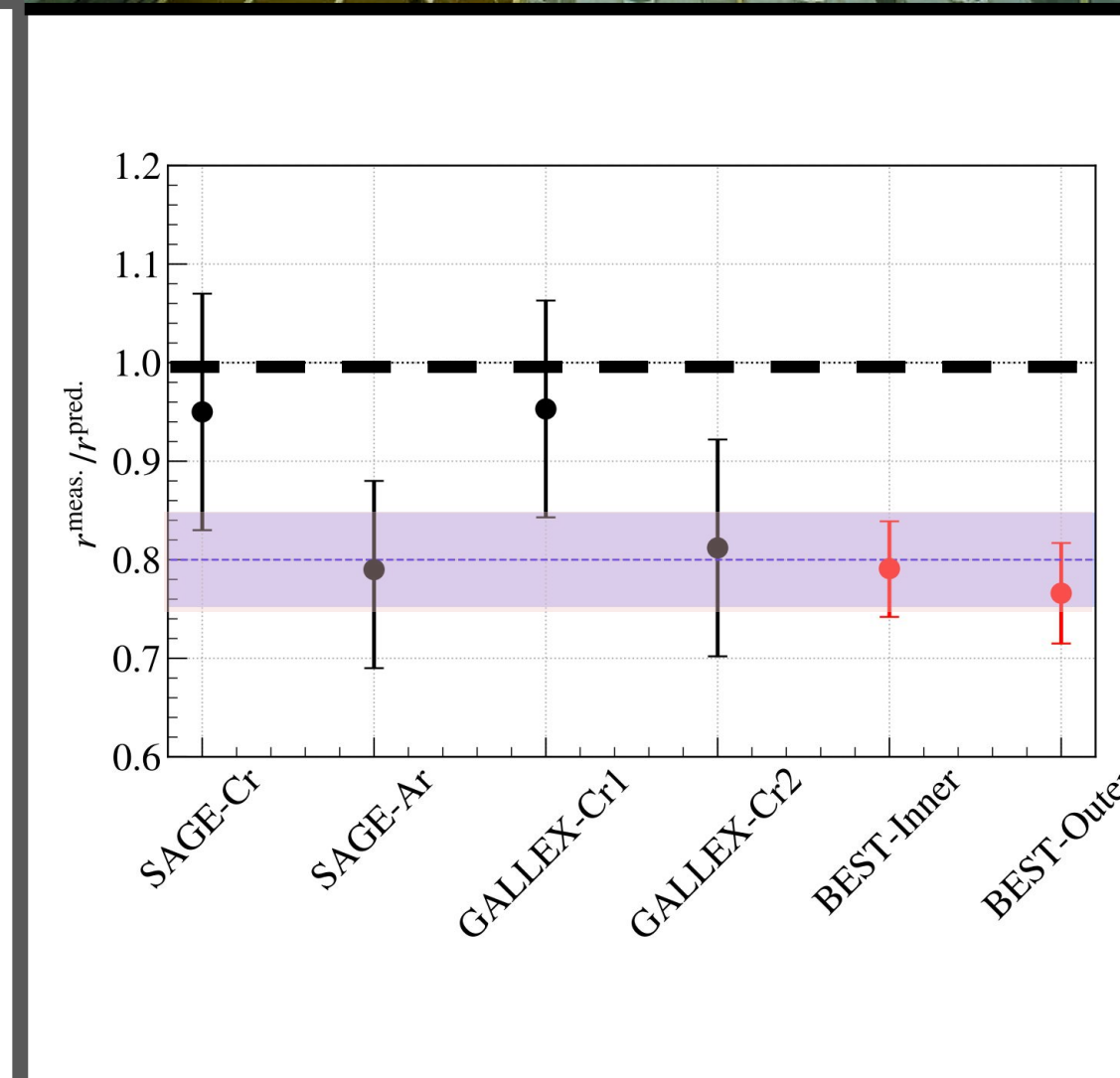
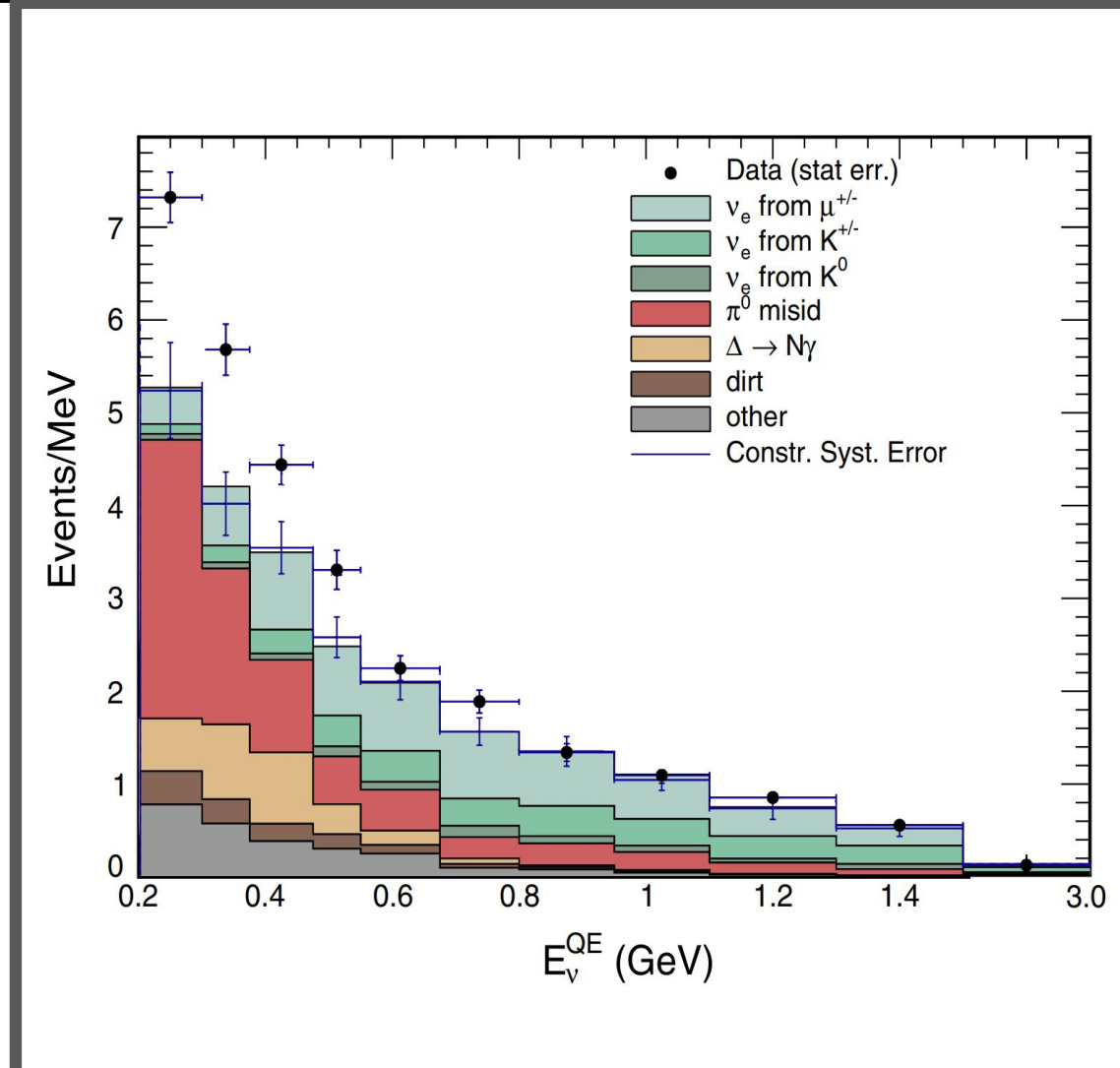
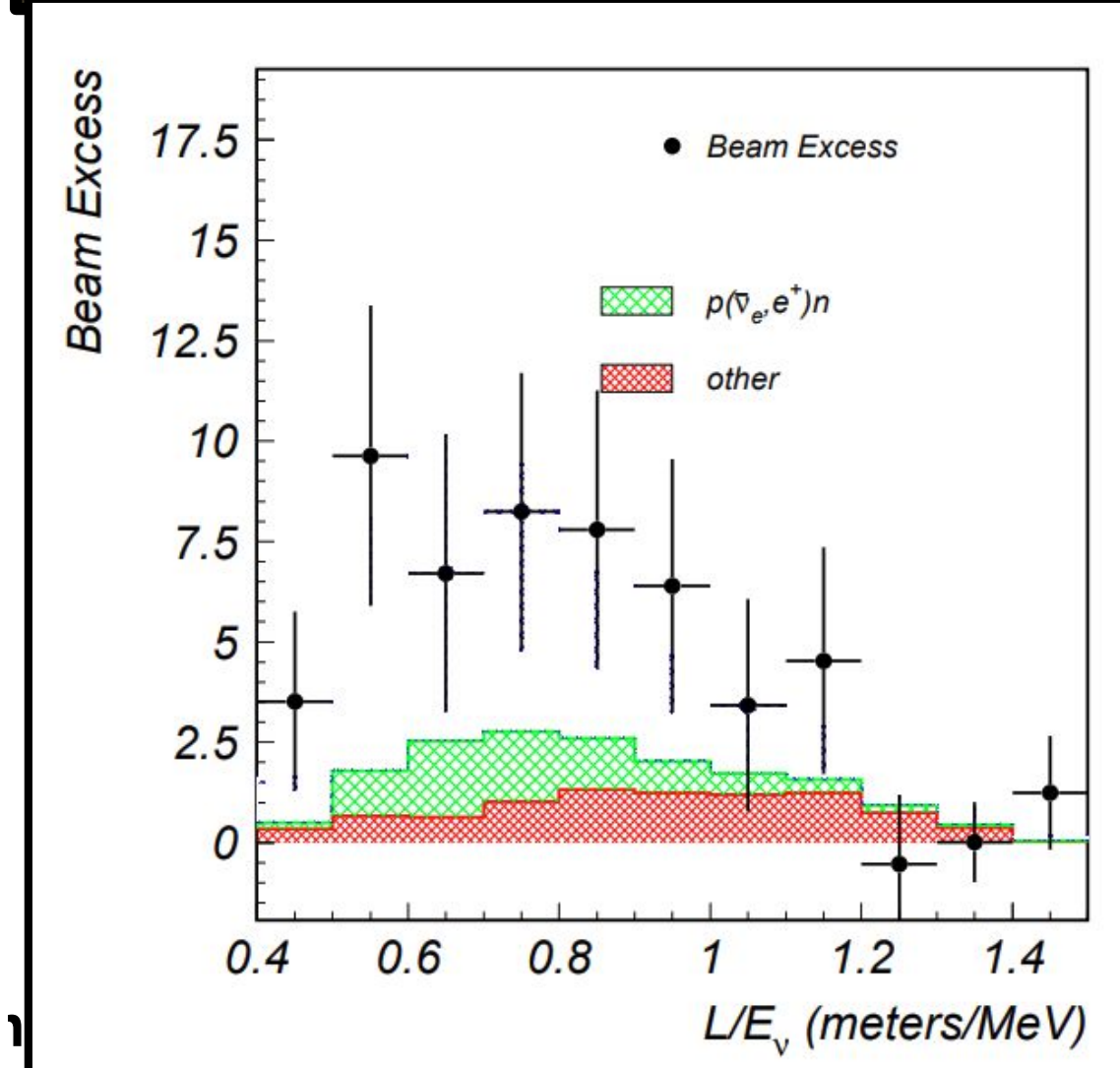
Hyper-K
2028

DUNE
2030

Short-Baseline Anomalies

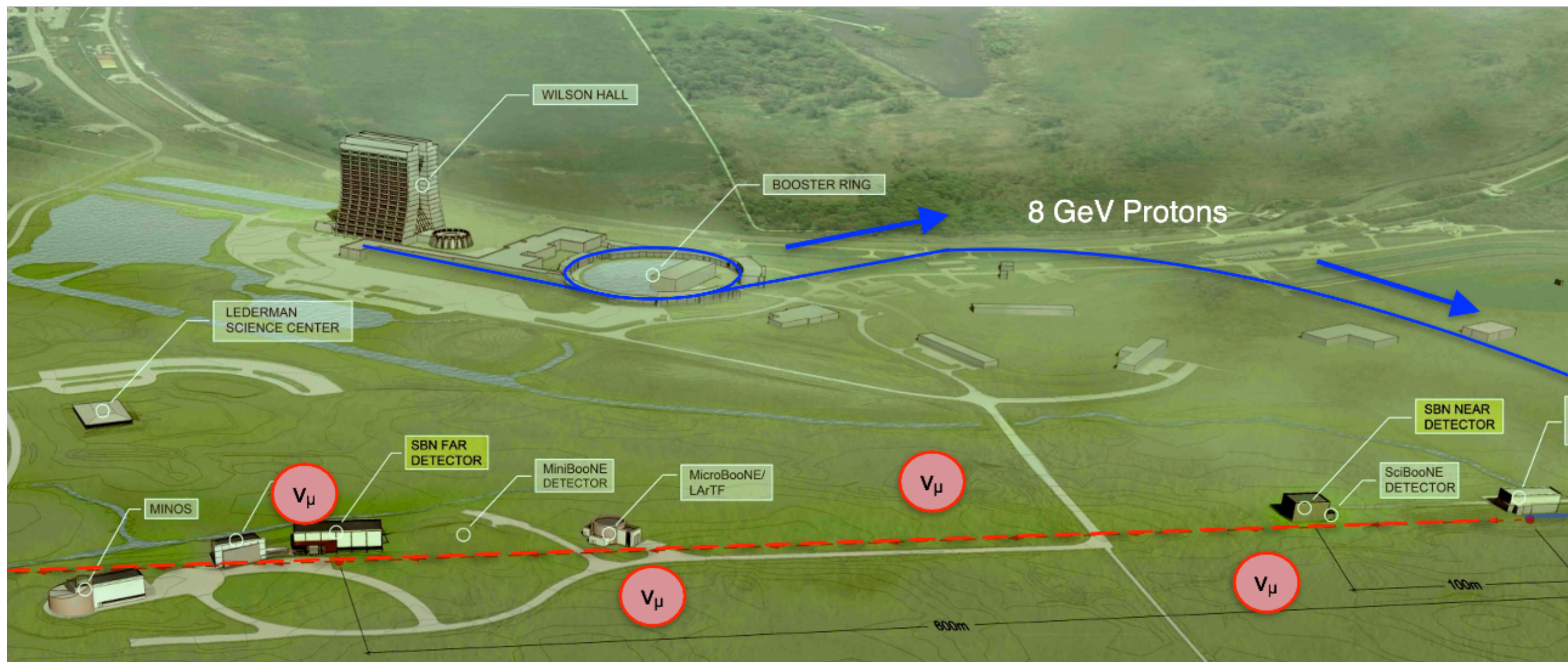


- Several observations independently consistent with oscillations at $\Delta m^2 \approx 1 \text{ eV}^2$
- Previous 'reactor anomaly' resolved by new flux models



Courtesy M. Ross-Lonergan

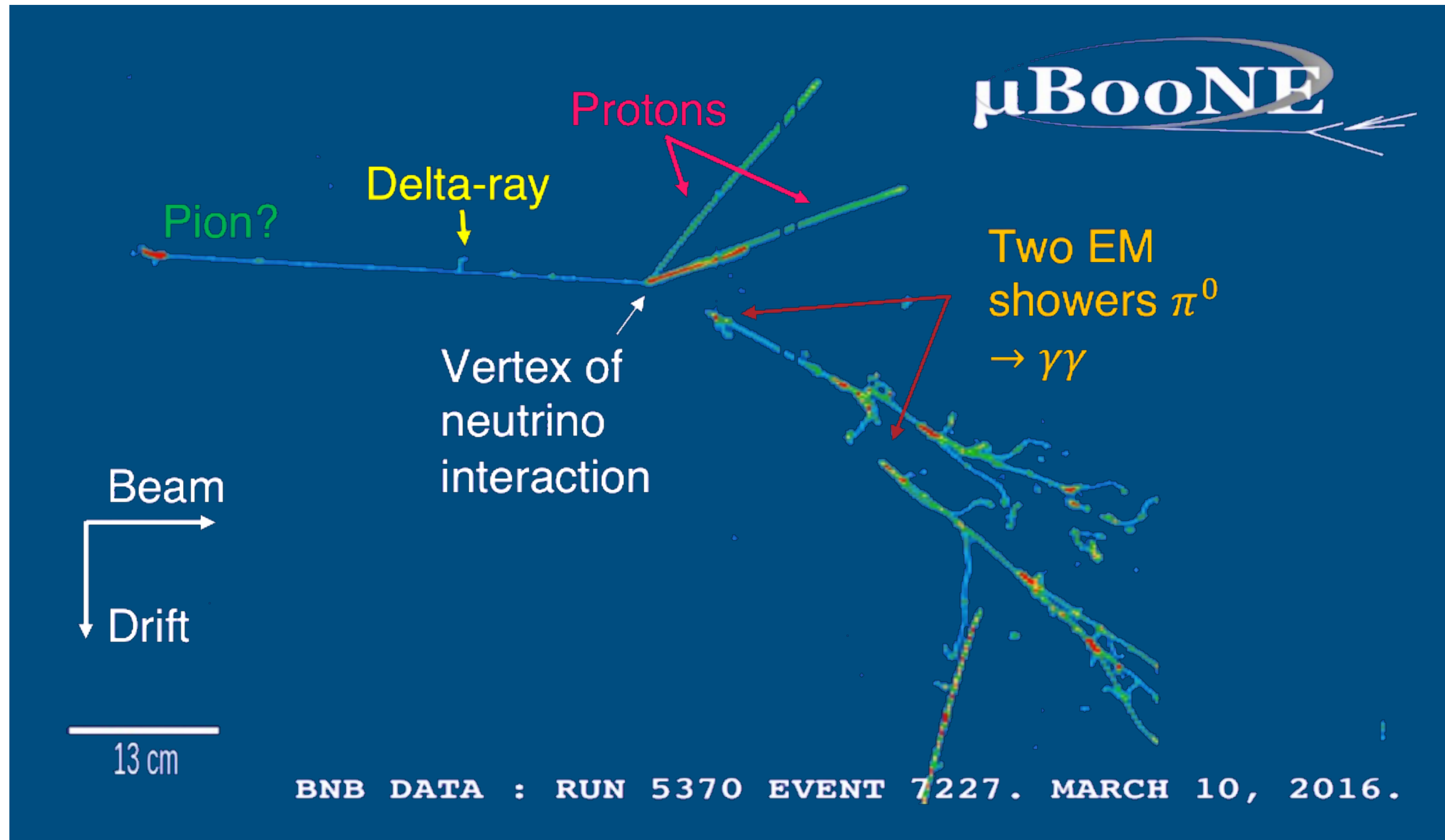
FNAL Short-Baseline Programme



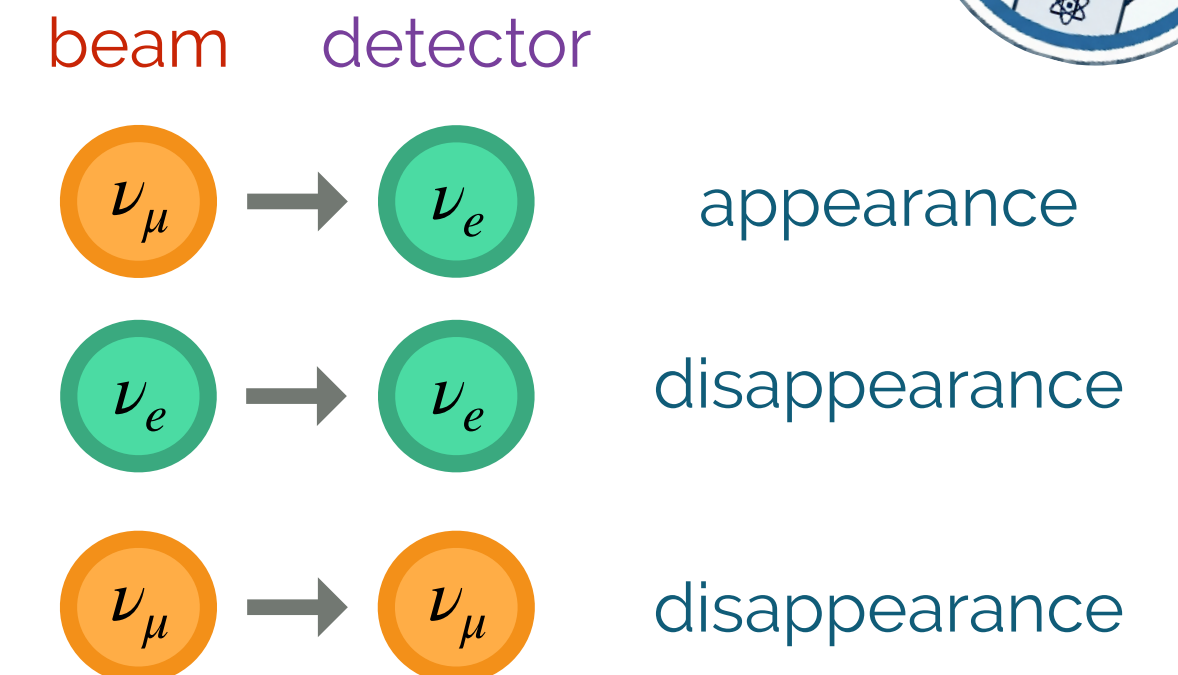
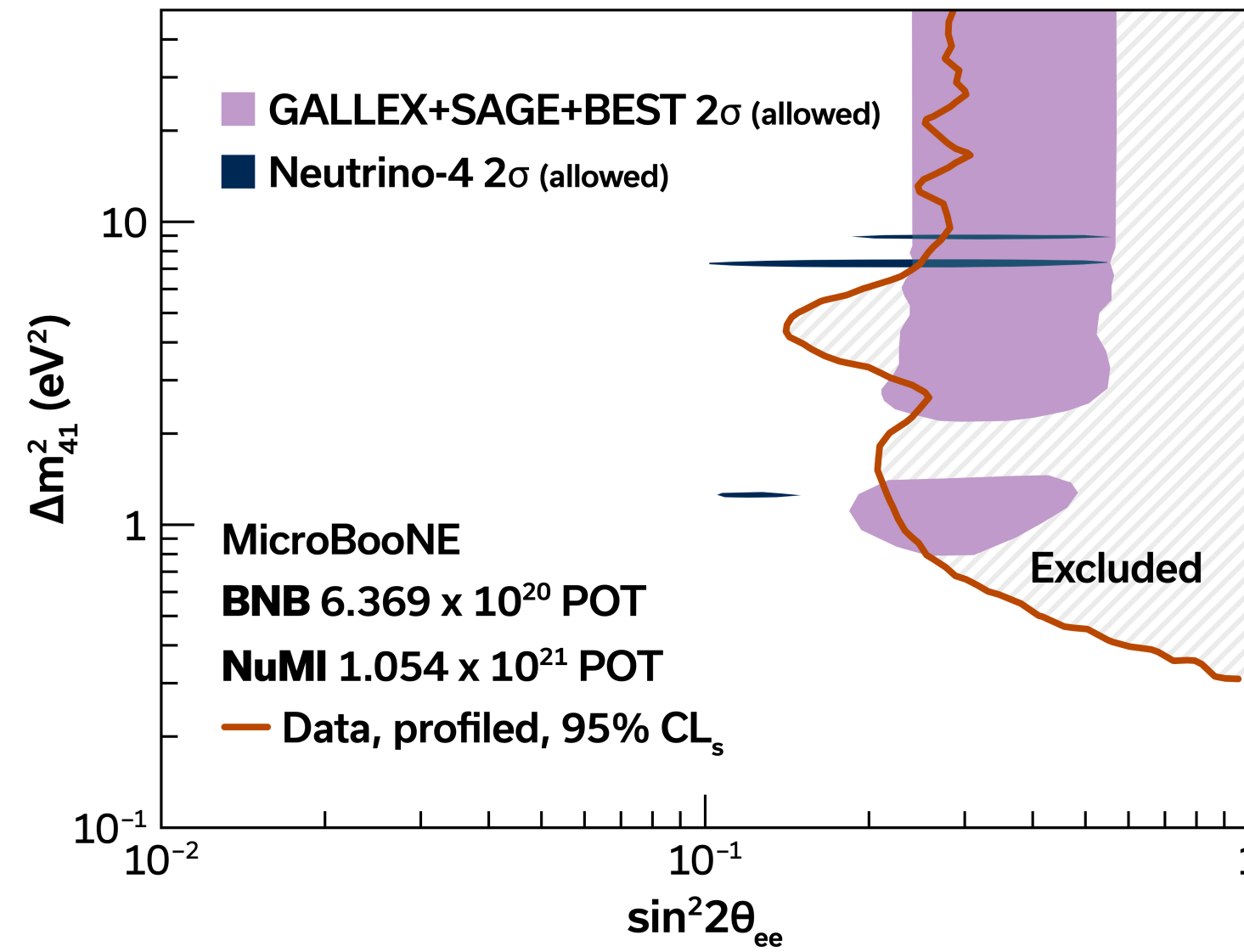
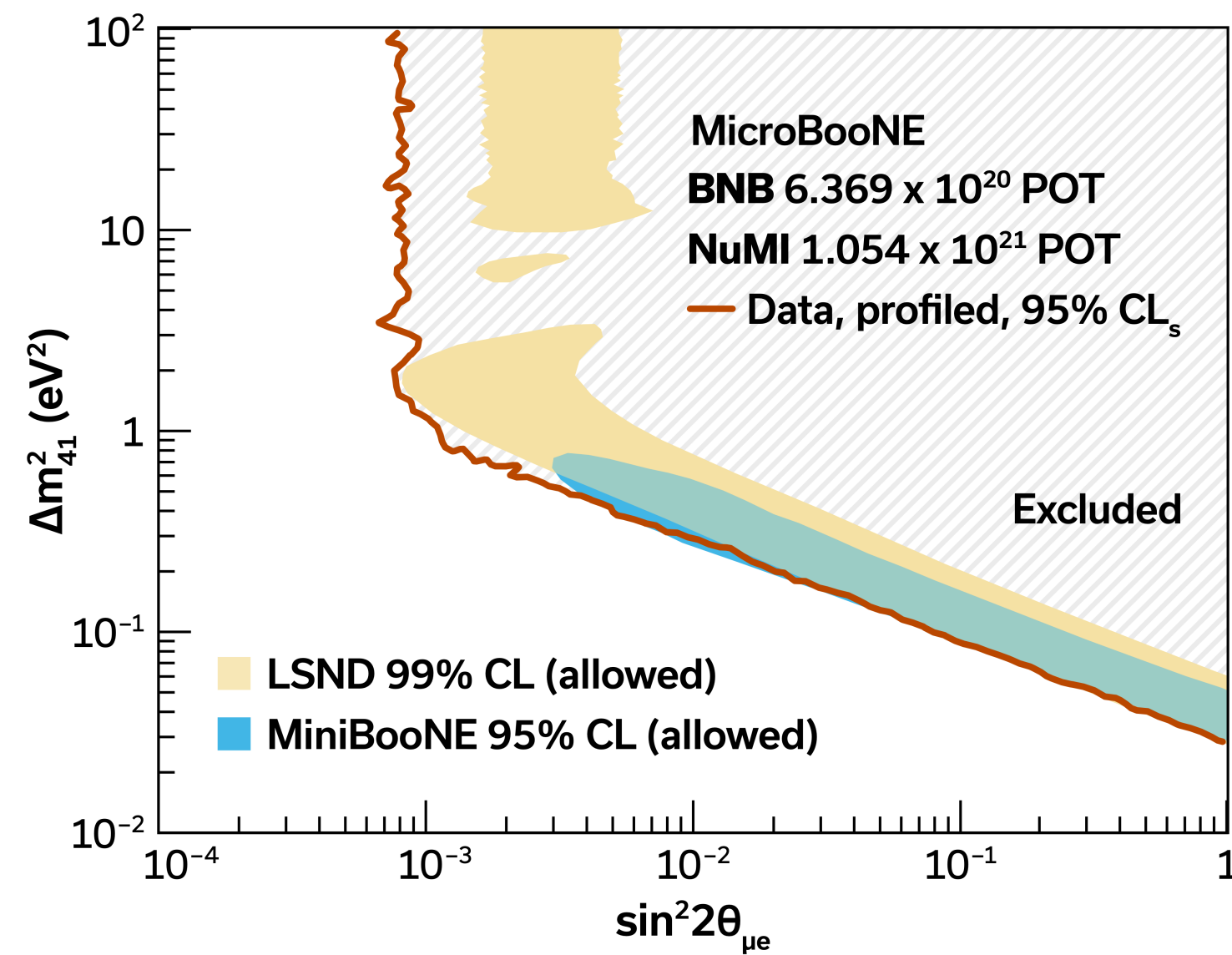
- $L \sim 600 \text{ m}, L/E \sim 1 \text{ km/GeV}$
- Investigate short-baseline anomalies
 - ν_μ disappearance, ν_e appearance in single detectors
- Direct Search for BSM signatures in production / interaction
- Measure neutrino cross sections (-> DUNE)
- Develop and demonstrate LAr TPC technology (-> DUNE)



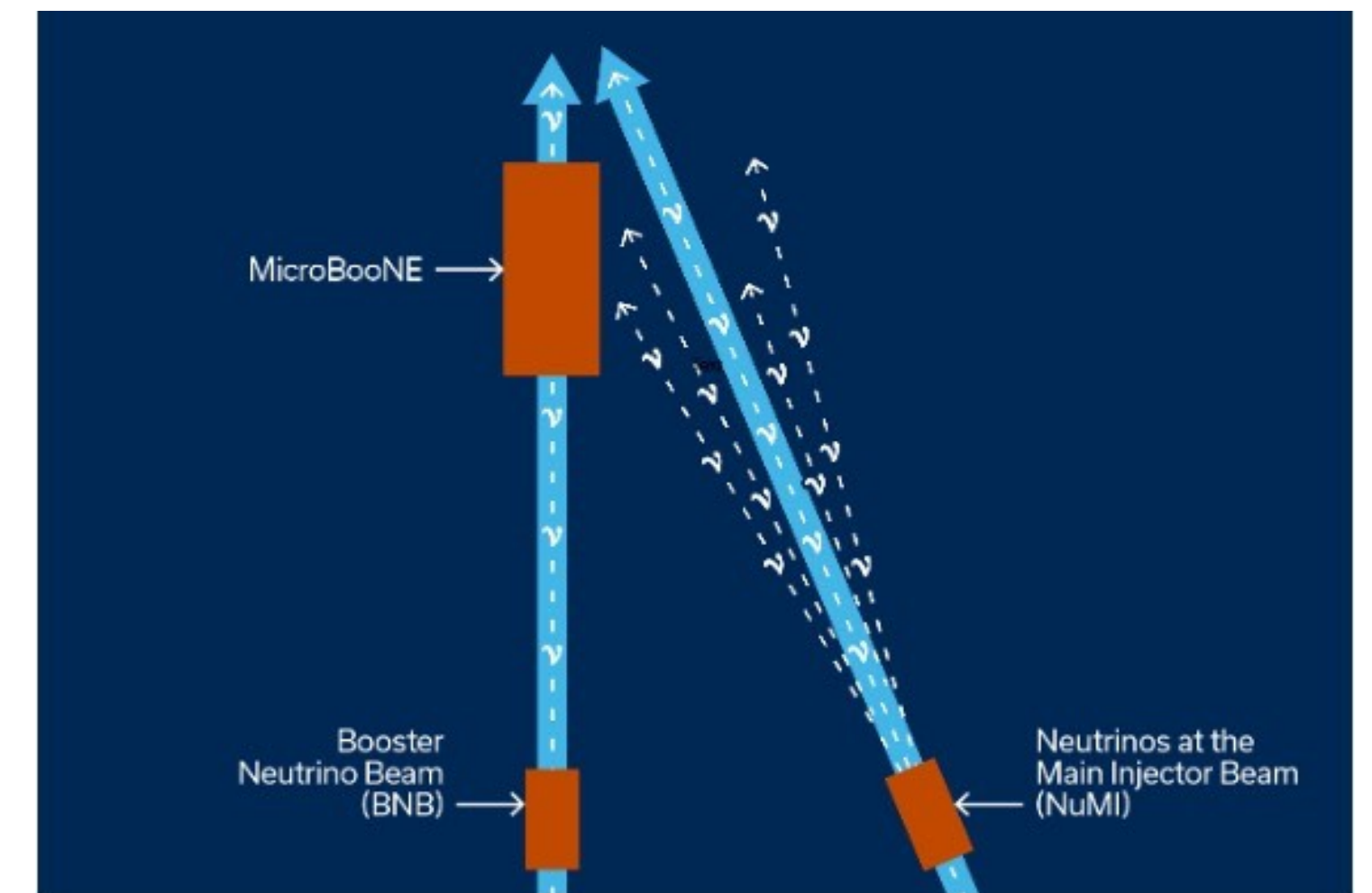
LAr TPC Event in MicroBooNE



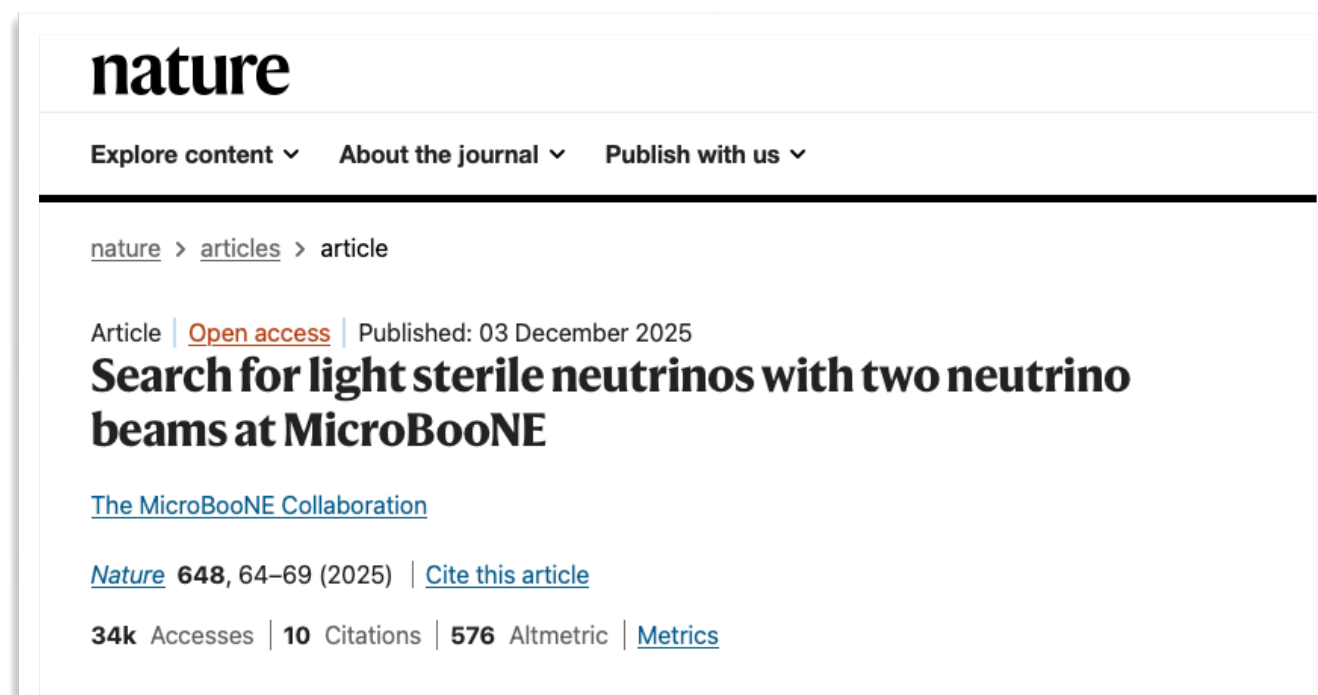
MicroBooNE Results 2026



‘Two beam’ approach mitigates cancellation effects

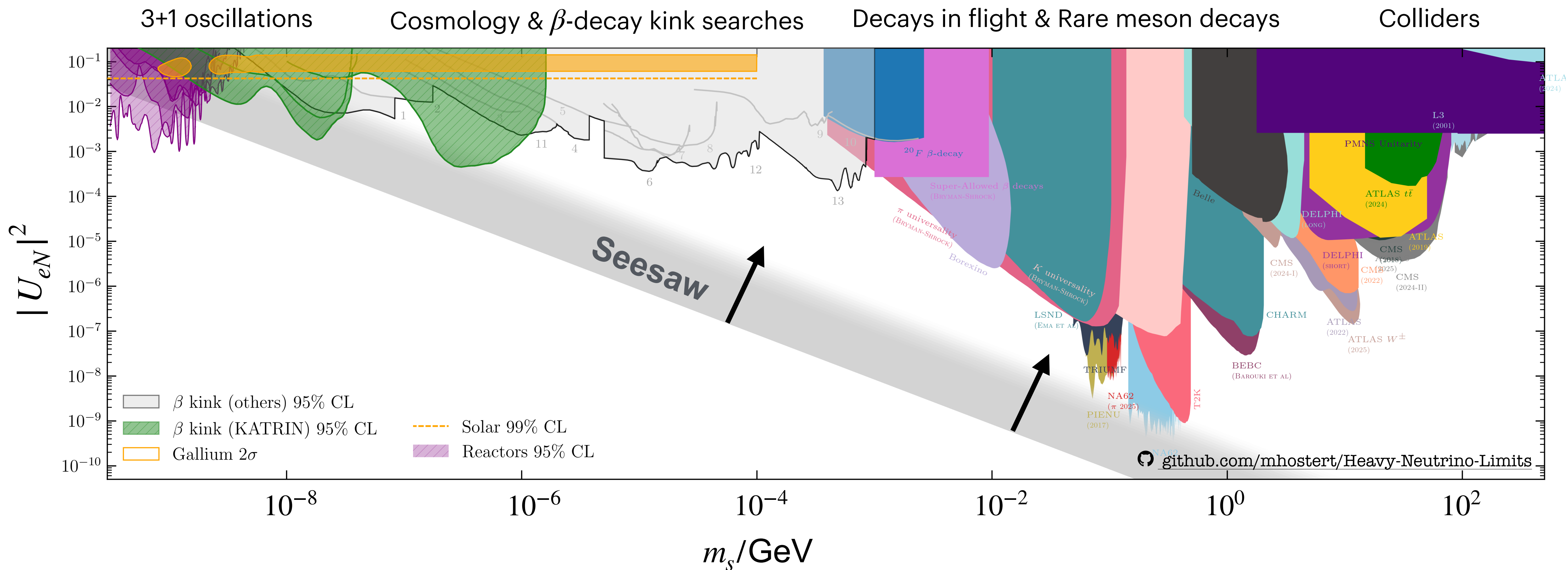


Nature 648 64-69 (2025)



- ‘3+1’ ν_s hypothesis appears ruled out
- So what’s the explanation?

Sterile Neutrino 3+1 Limits

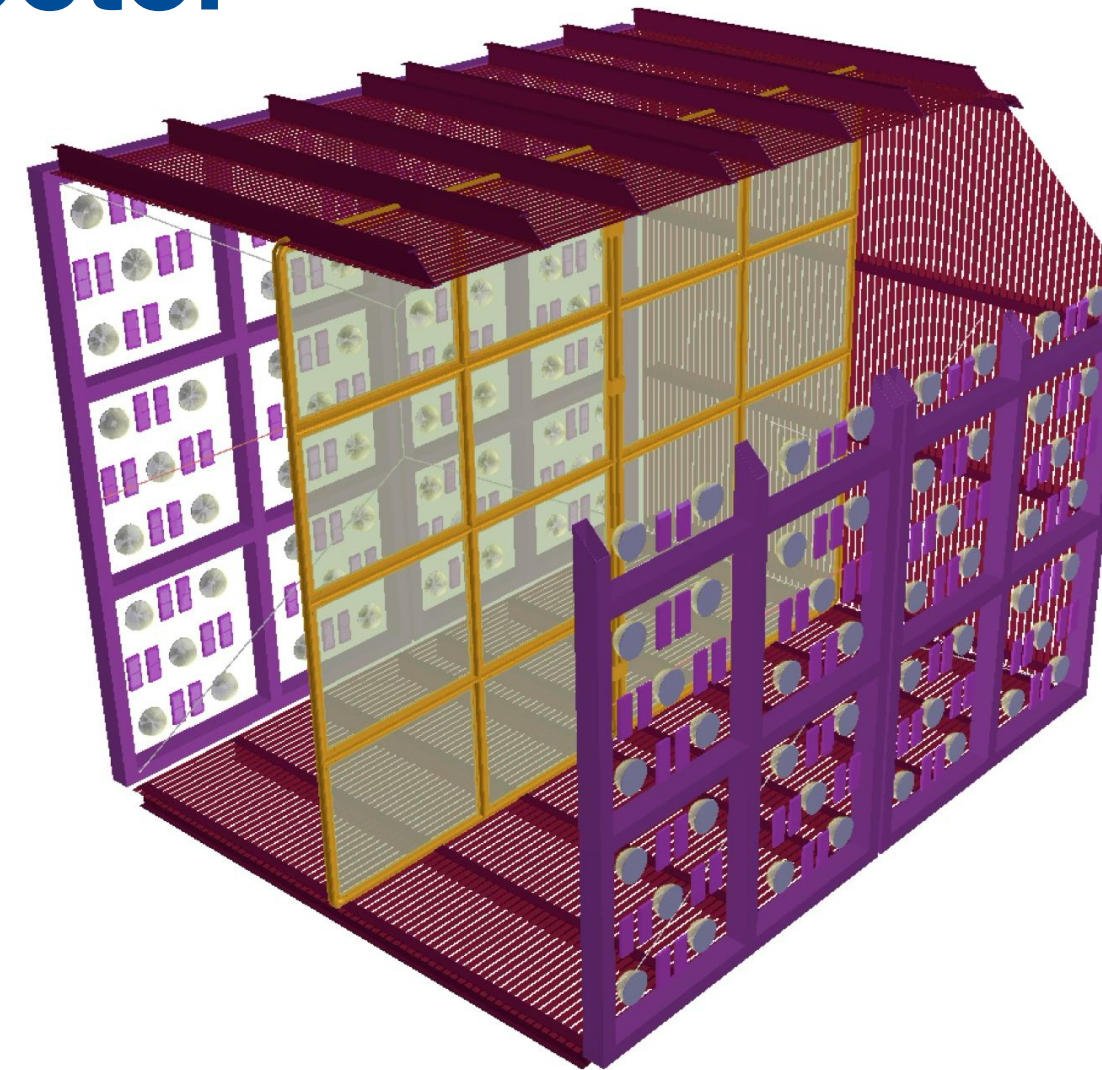


E. Fernández-Martínez, M.González-López, J. Hernández-García, MH, J. López-Pavón, [10.1007/JHEP09\(2023\)001](https://arxiv.org/abs/10.1007/JHEP09(2023)001)

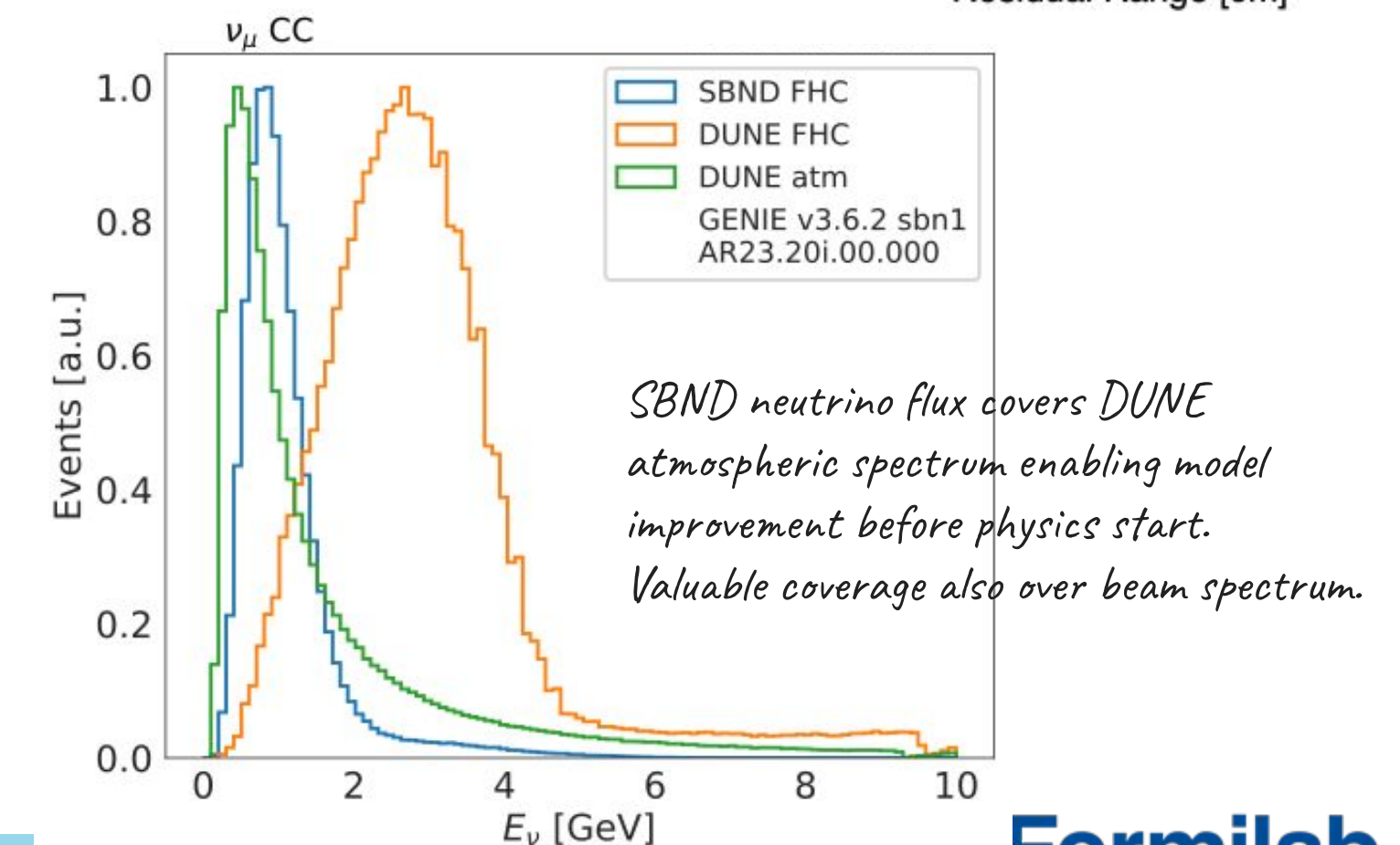
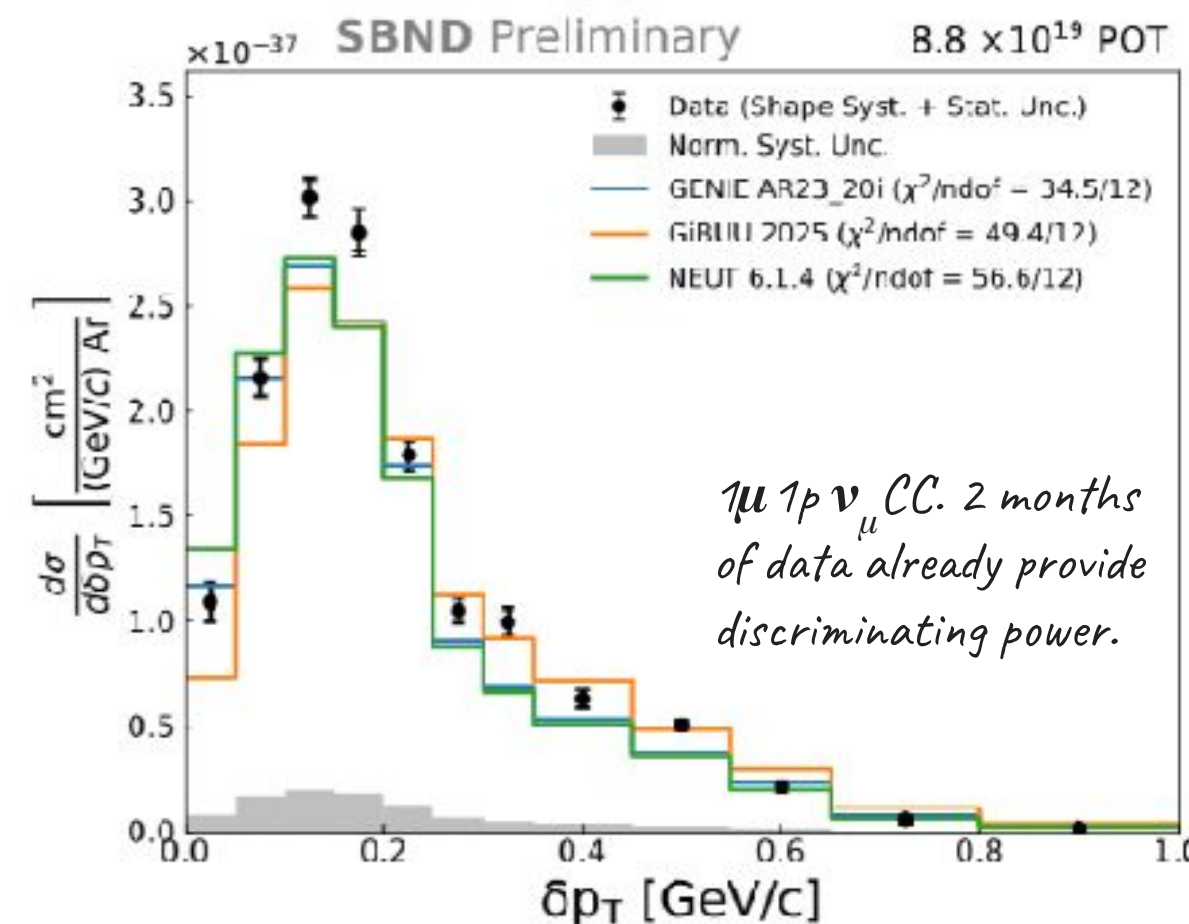
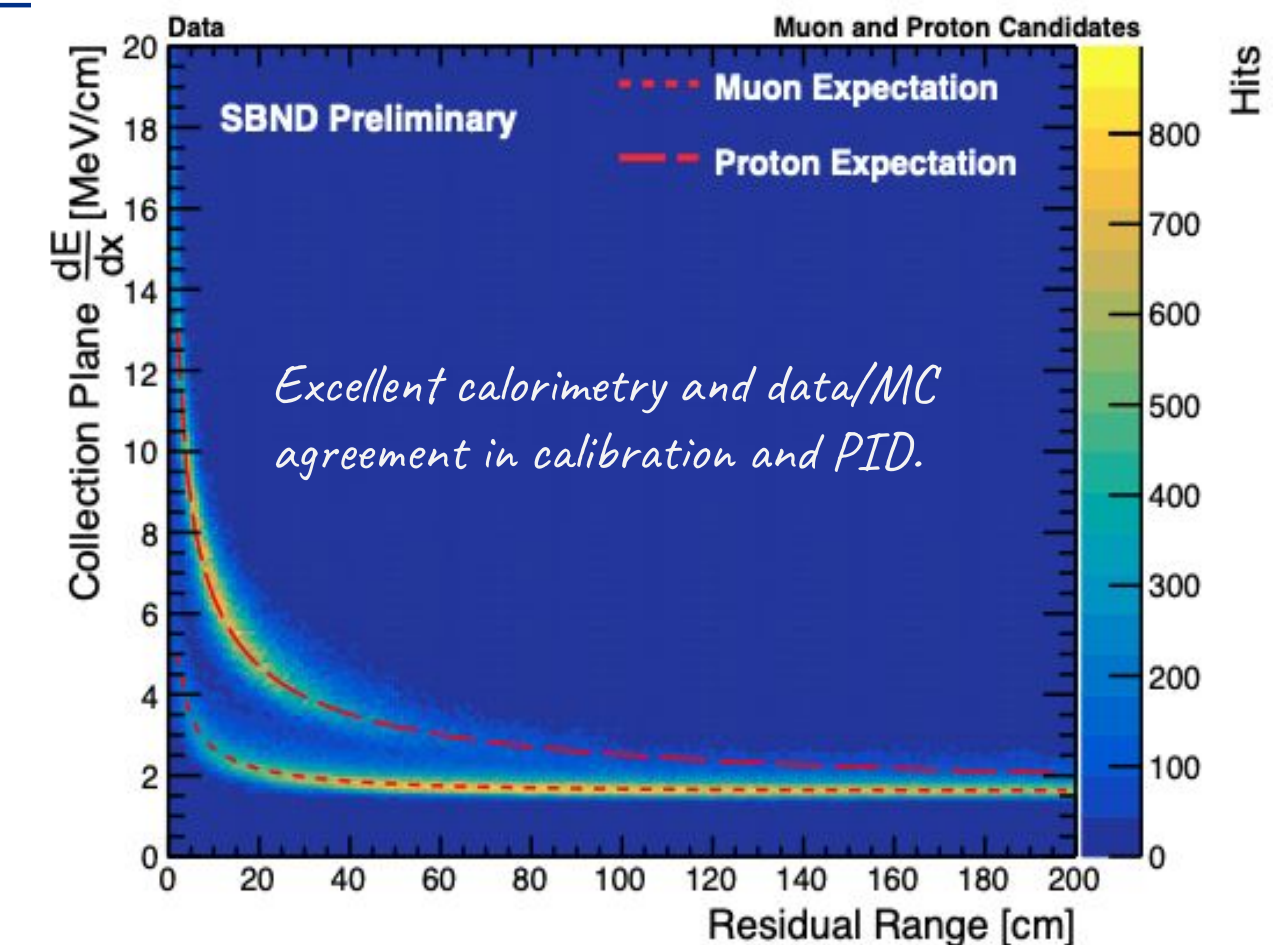
SBN

SBND: The SBN Near Detector

- Began operation in 2024. Run 2 completed in June. Large UK contributions to construction.
- A sample of ~6M ν -argon interactions collected. ~10x MicroBooNE dataset.
- Building on predecessor's experience + excellent detector performance, first papers coming <2 years after start of data taking. With systematics already lower than previous best.
- Observable PRISM effect.
- An important opportunity to develop Pandora on ν data
- As part of SBN will perform a comprehensive study of short-baseline oscillation phenomena



Two time projection chambers
Total dimension: 4m x 4m x 5m
Total active Ar mass: **112 tons**

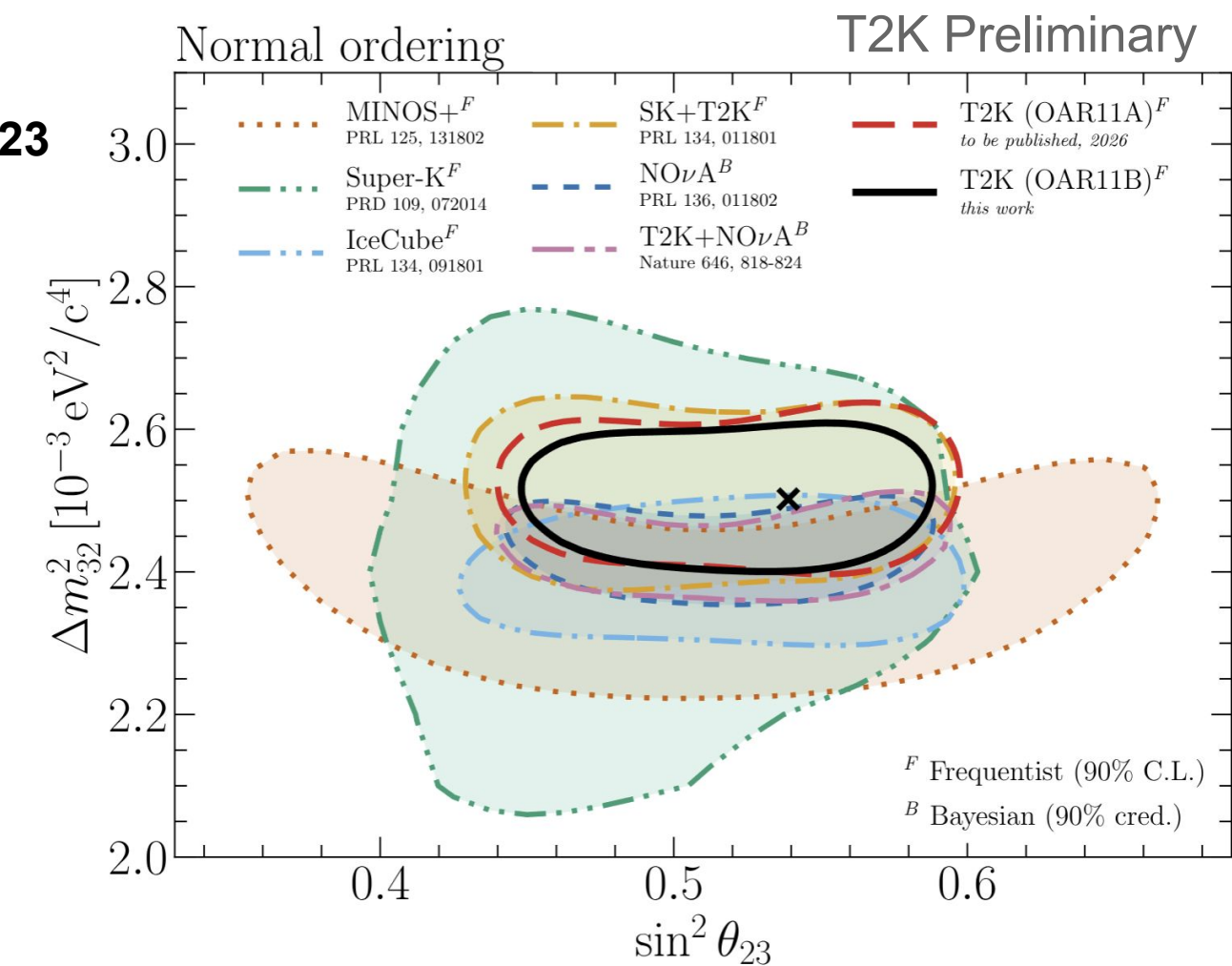
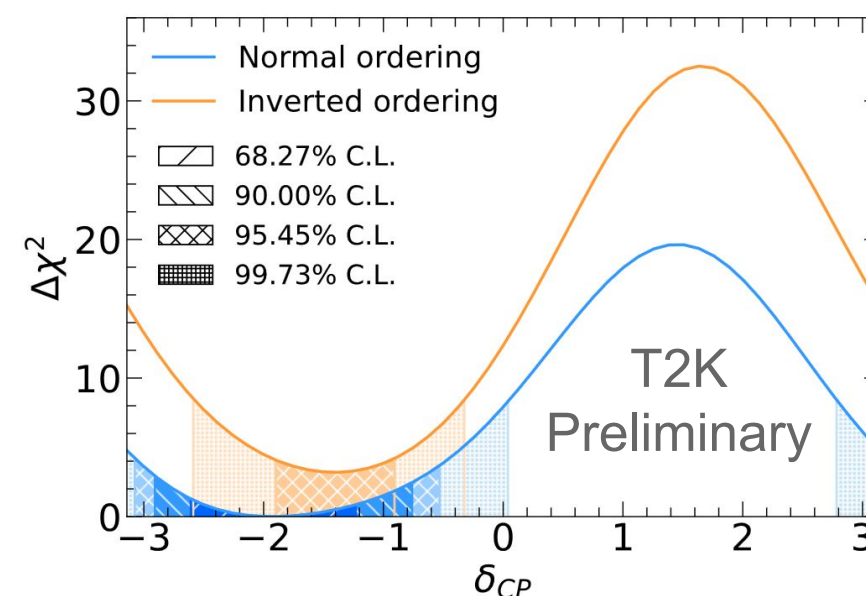


Formilab

Current Long-Baseline Experiments: T2K

T2K provides competitive constraints on δ_{cp} , Δm^2_{32} , θ_{13} , θ_{23}

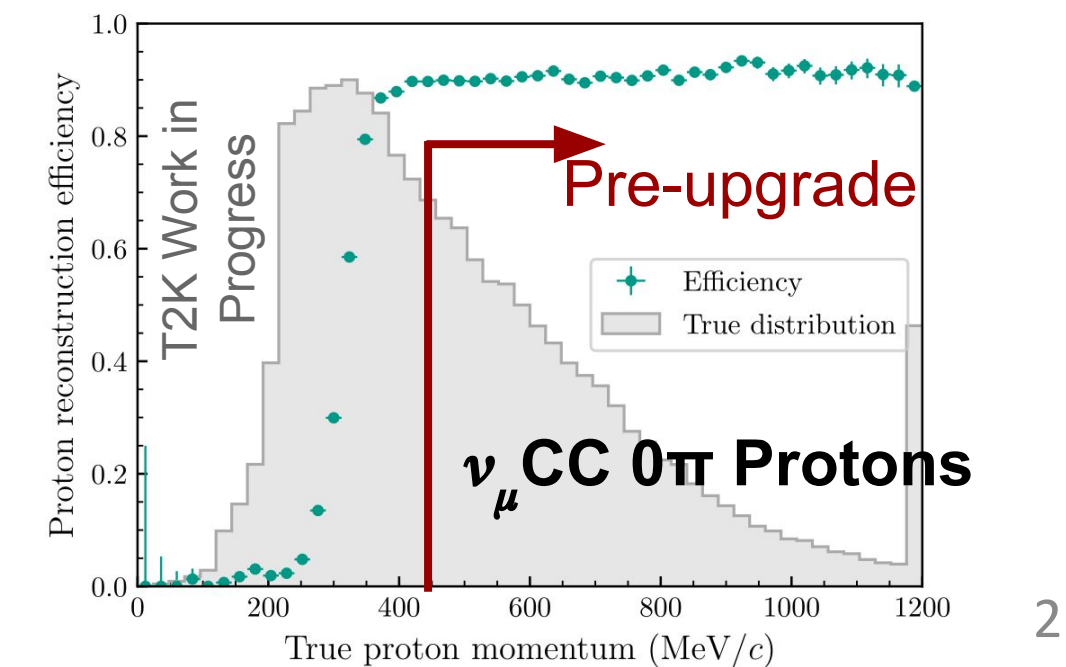
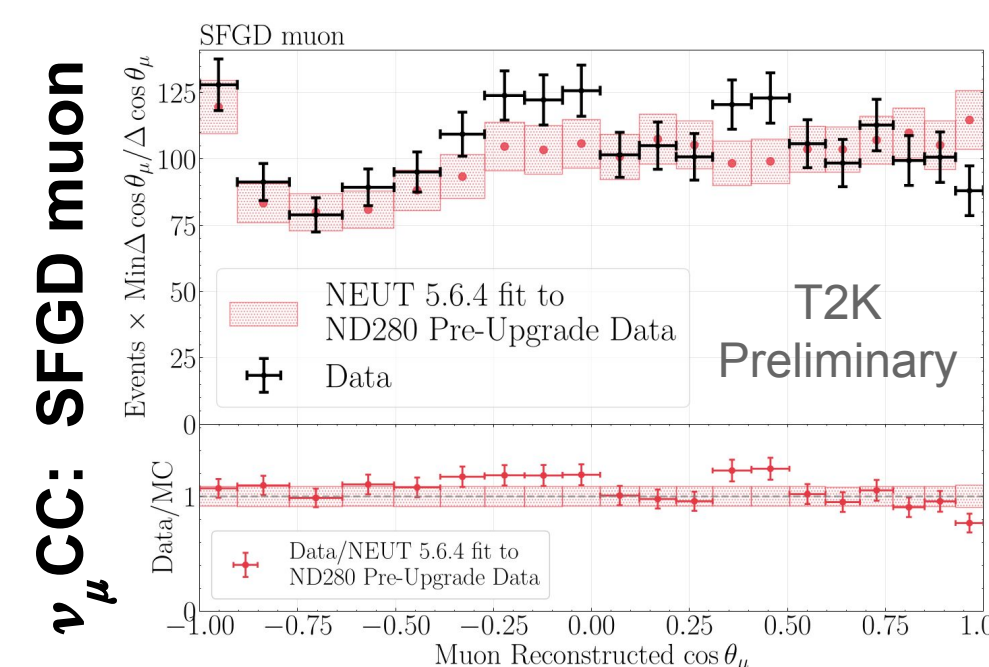
- T2K **excludes CP-conservation at the 95% CL**
- Weak preference for **NO**
(Posterior: 78% T2K, 90% T2K+SK)
- Weak preference for **θ_{23} upper octant**
- Continued collaboration between
T2K & SK and **T2K & NOvA**
[P.R.L. 134 011801](#) [Nature 646, 818-824 \(2025\)](#)



- The biggest improvement in the latest T2K result ([@ Neutrino 2026](#)) is due to the improved interaction model
- Interaction model errors still dominate total systematics error (still statistics limited, but increasingly important)

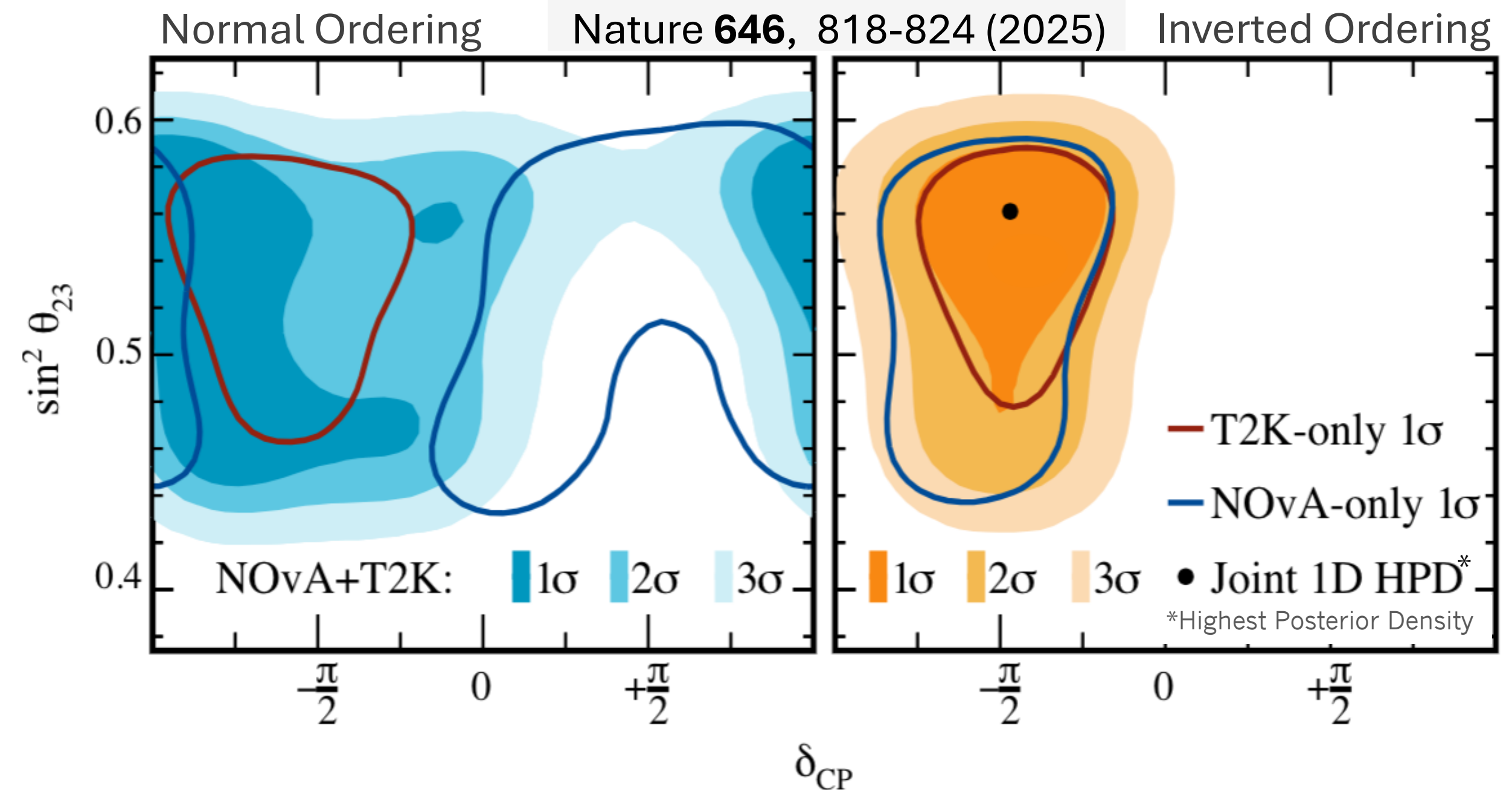
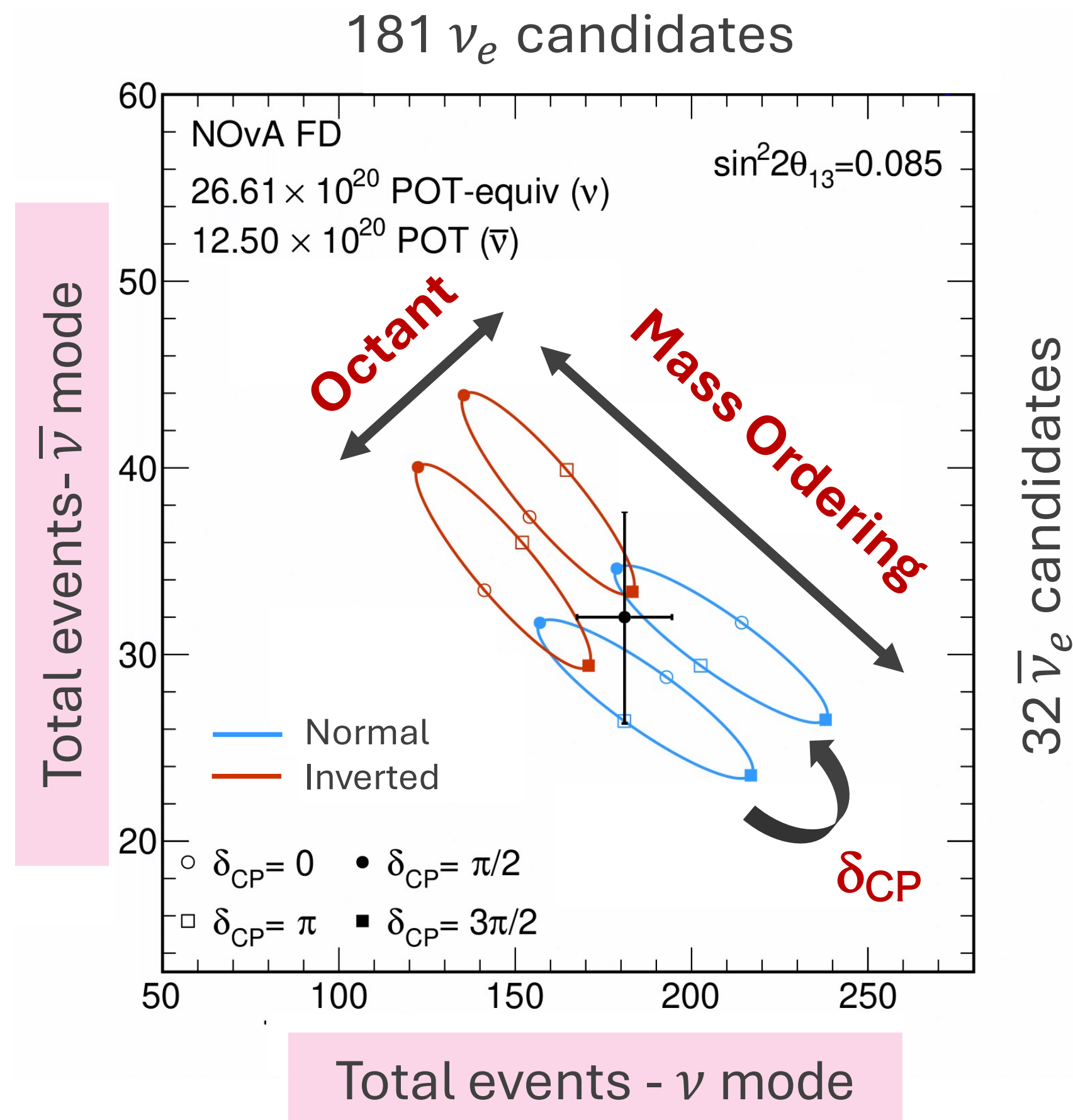
ND280 upgrade - designed to provide precision constraints of neutrino interaction models

- **First analysis level (ν_μ CC inclusive) data** and **detector systematics** were showcased at Neutrino 2026
- **MC studies for exclusive channels** presented to demonstrate physics capabilities expected from the first analyses



$L = 295 \text{ km}$, $E = 0.6 \text{ GeV}$, 2.5° off-axis

Current Long-Baseline Experiments: NOvA

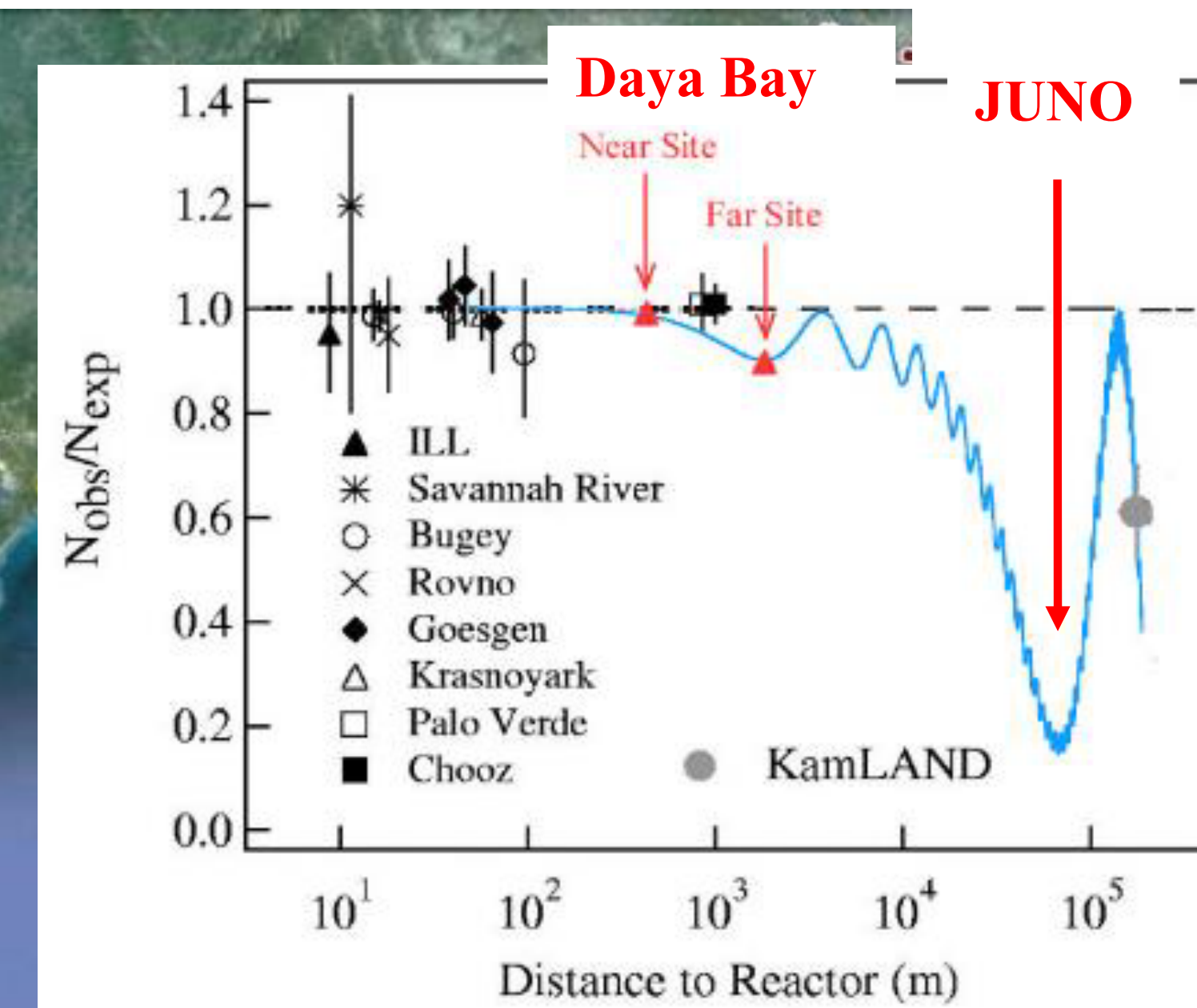
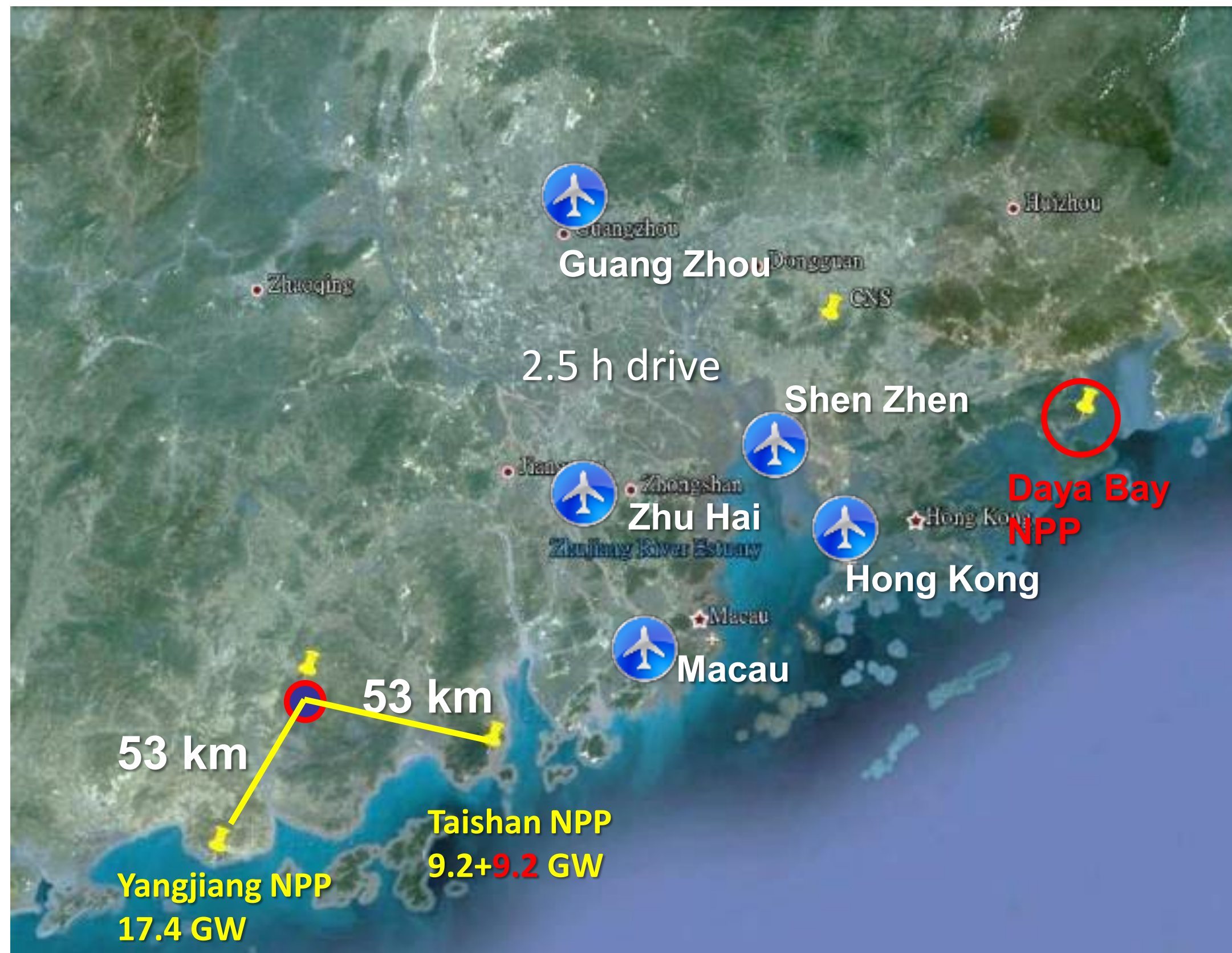


- T2K and NOvA best fits individually favour NO
 - But for different values of δ_{CP}
 - Combined fit (weakly) favours IO!

$L = 810$ km, $E = 1.8$ GeV, 0.8° off-axis

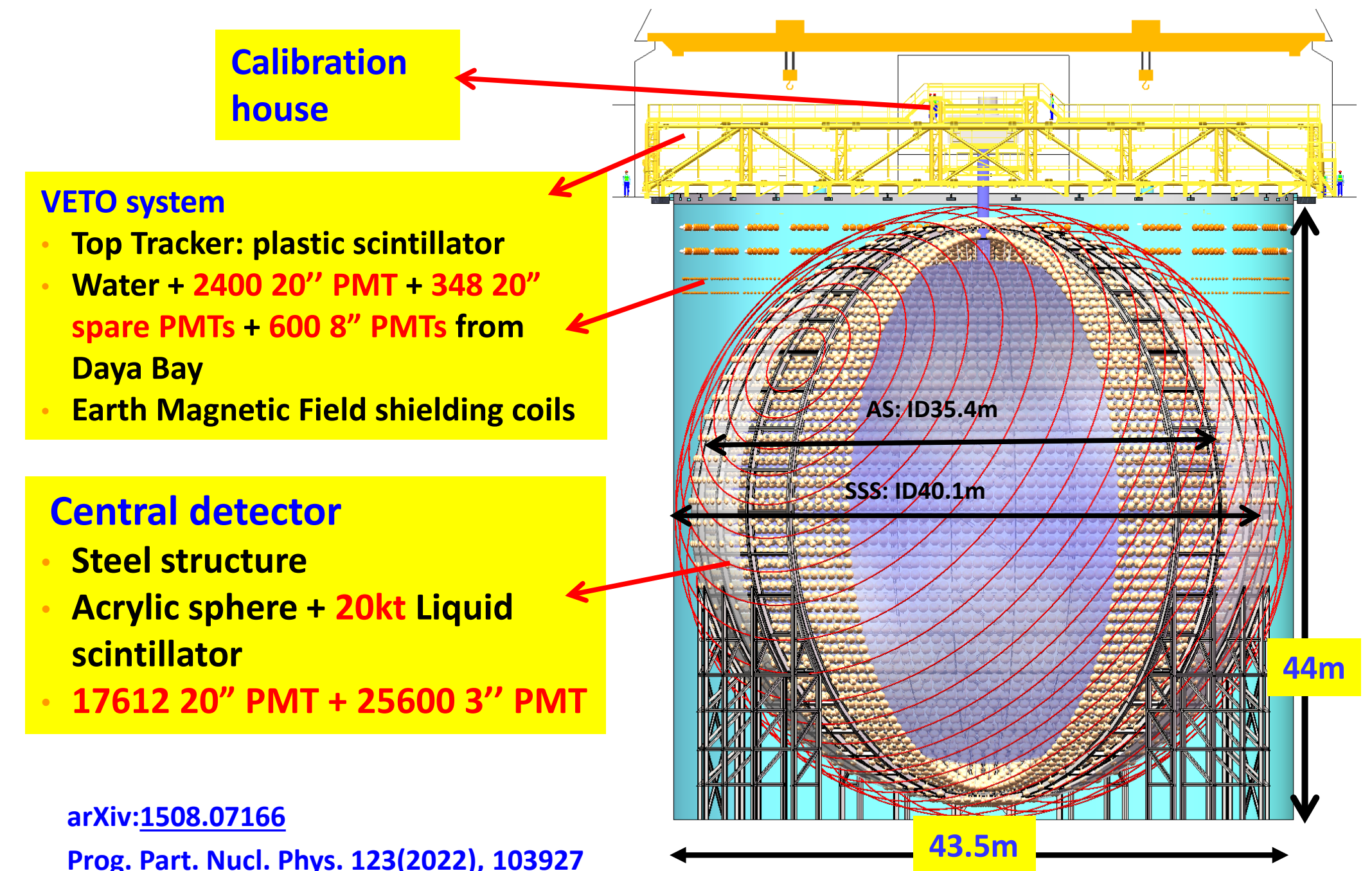
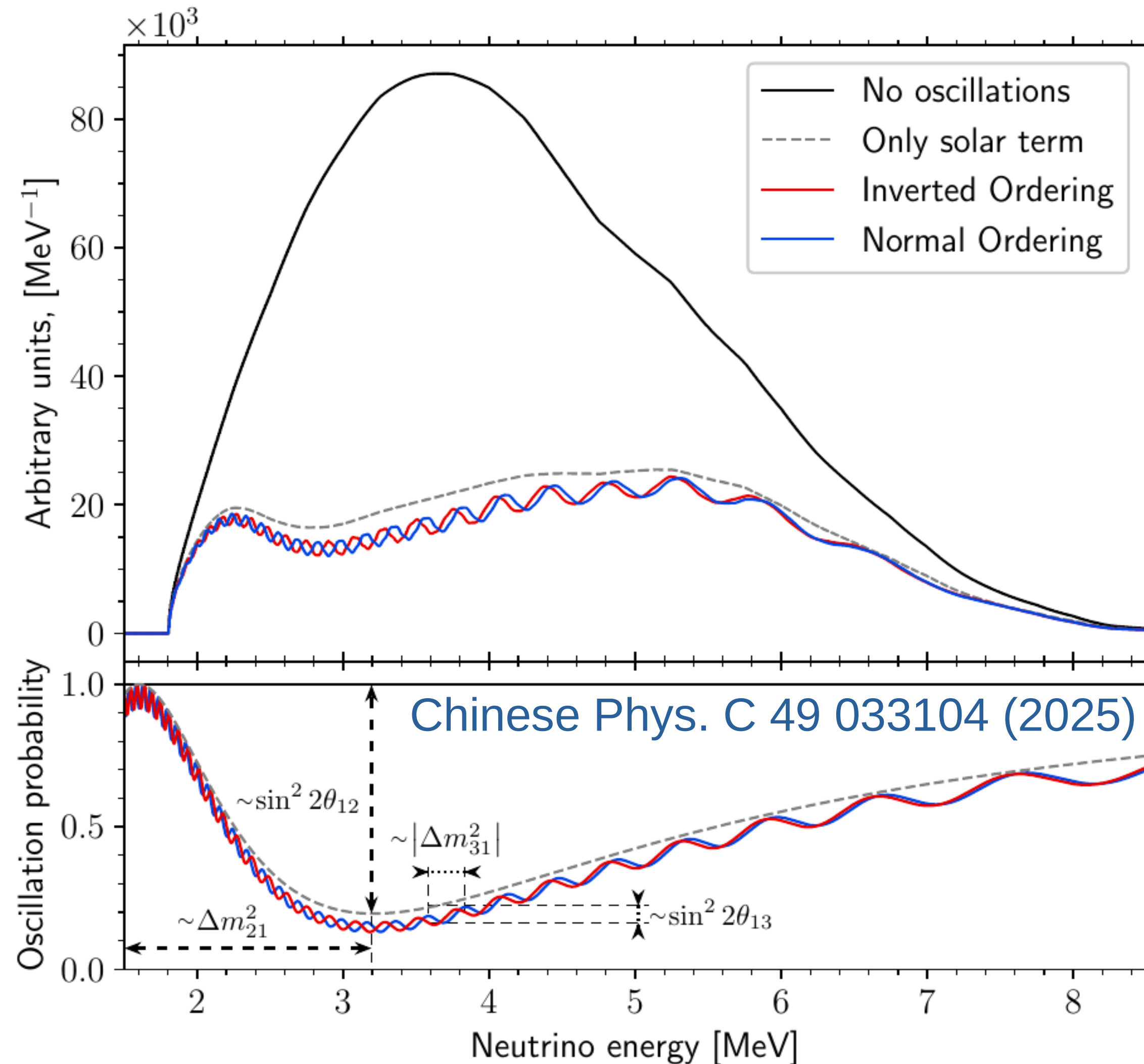
New: JUNO

- Use reactor neutrinos to determine the mass ordering (sign of Δm^2_{32}), independent of matter effects and CP phase δ
- Equal distance to two reactor power plants for doubling the ν flux



Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011;
 Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen,
 PRD78:111103,2008; PRD79:073007,2009

JUNO

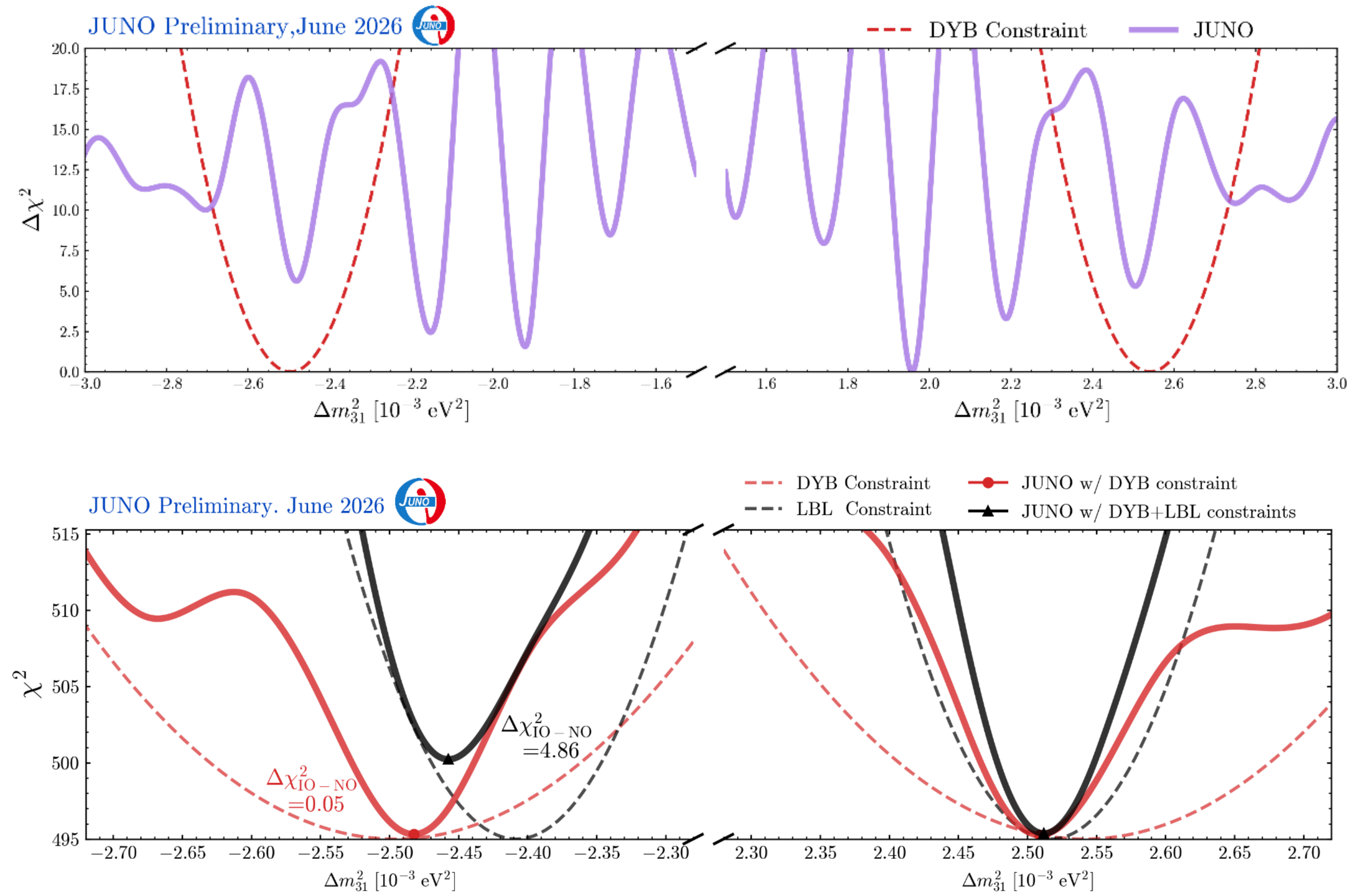
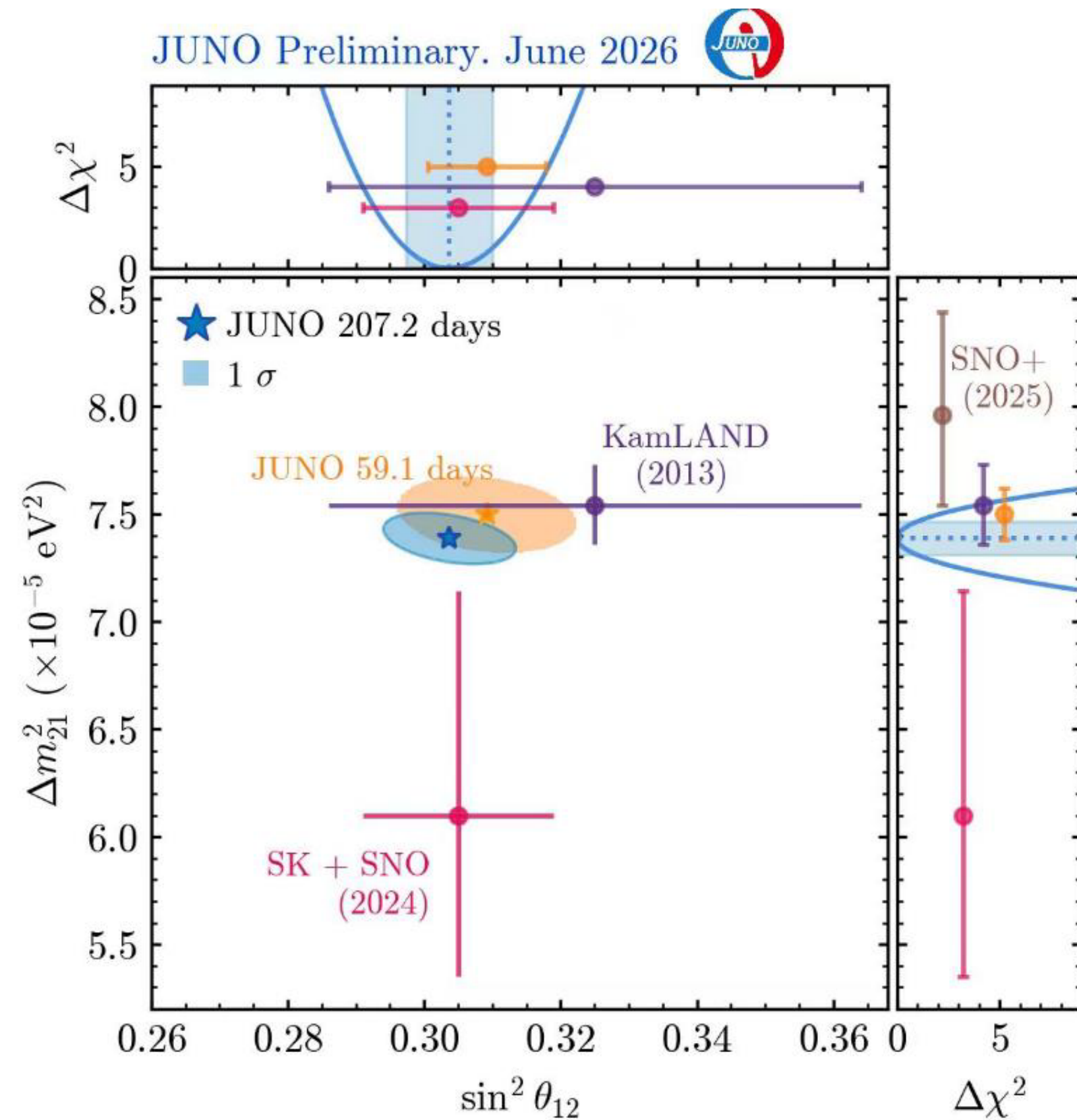


[arXiv:1508.07166](https://arxiv.org/abs/1508.07166)

Prog. Part. Nucl. Phys. 123(2022), 103927

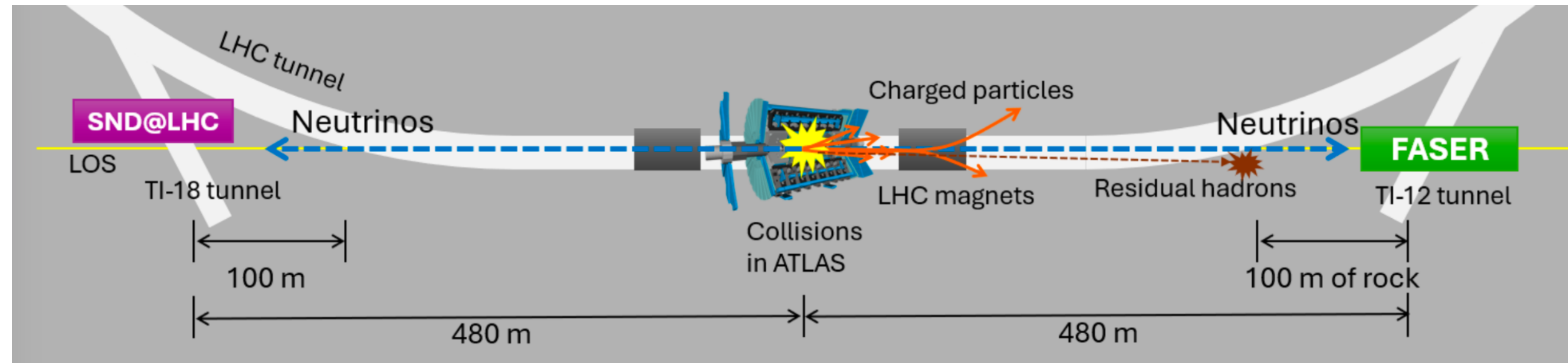
- Extraction of Δm_{23}^2 requires exceptional control of systematics
 - Notably, energy resolution and calibration across the entirety of the detector volume

JUNO Results 2026



- Headline: NO preferred at $\sim 2\sigma$ via comparison with LBL measurements

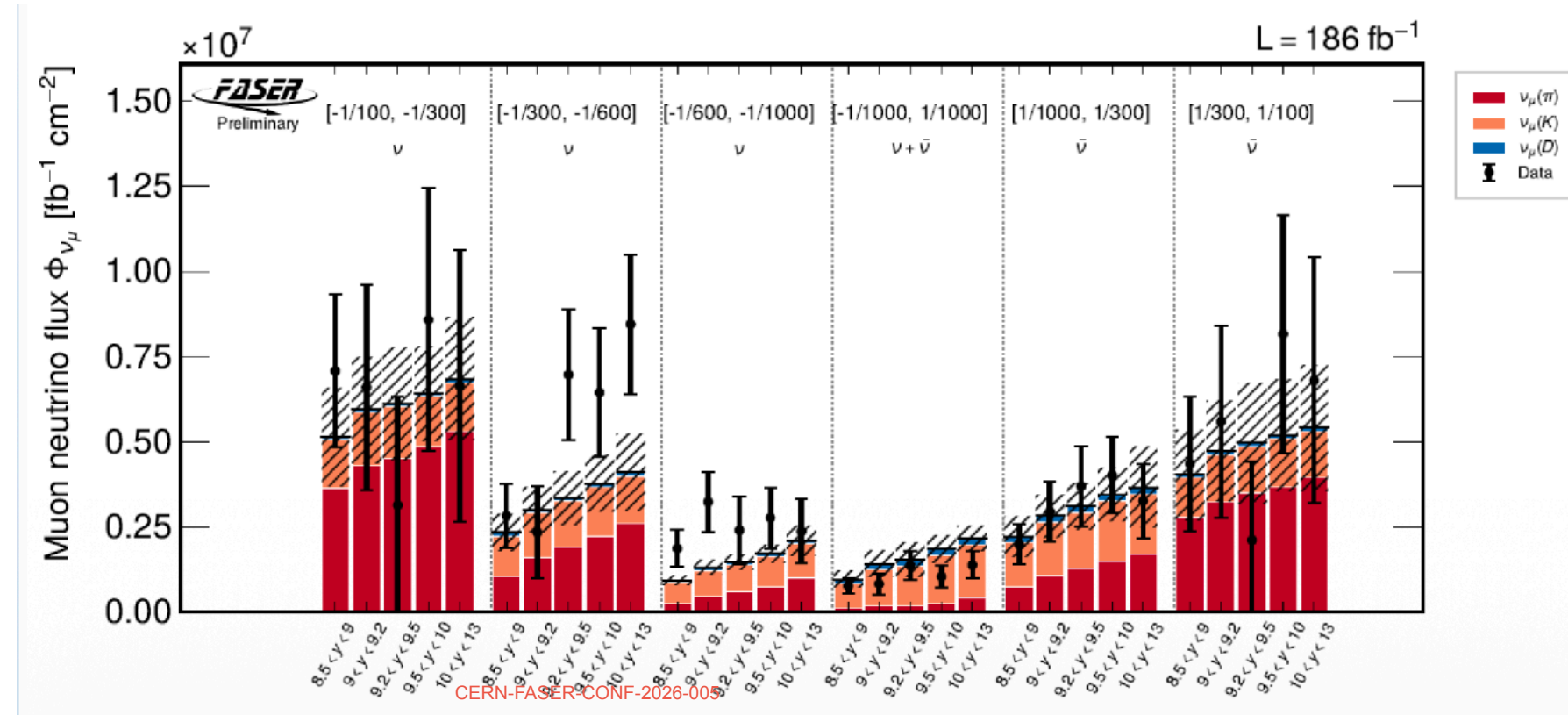
LHC Neutrinos



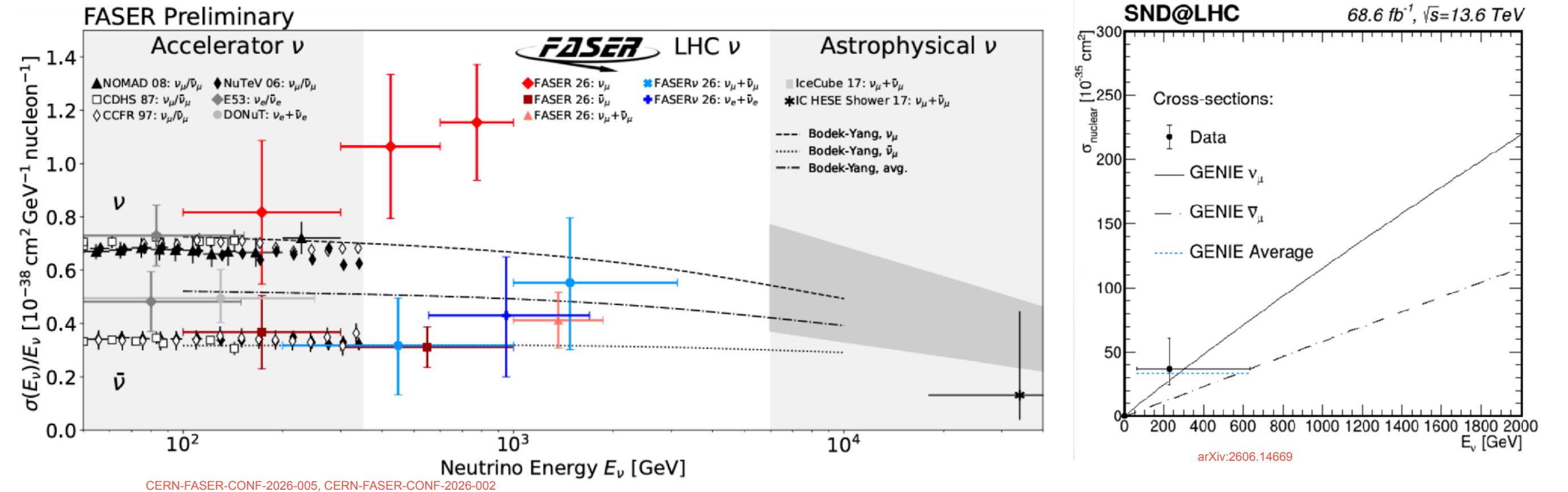
- FASER (on-axis) and SND@LHC (off-axis) experiments probe an unexplored neutrino energy regime
 - Broad physics programme at the interface of collider physics, neutrino physics and astroparticle physics.
 - Both use a combination of a neutrino target with emulsion films and a downstream spectrometer.
- Cross sections
 - DIS for all flavours (LFV); tau neutrinos; non-standard interactions; nuclear PDFs.
- Flux measurements
 - Forward QCD (low-x PDFs, intrinsic charm, saturation)
 - Astroparticle physics (prompt atmospheric neutrinos, cosmic-ray muon puzzle).

Recent Highlights

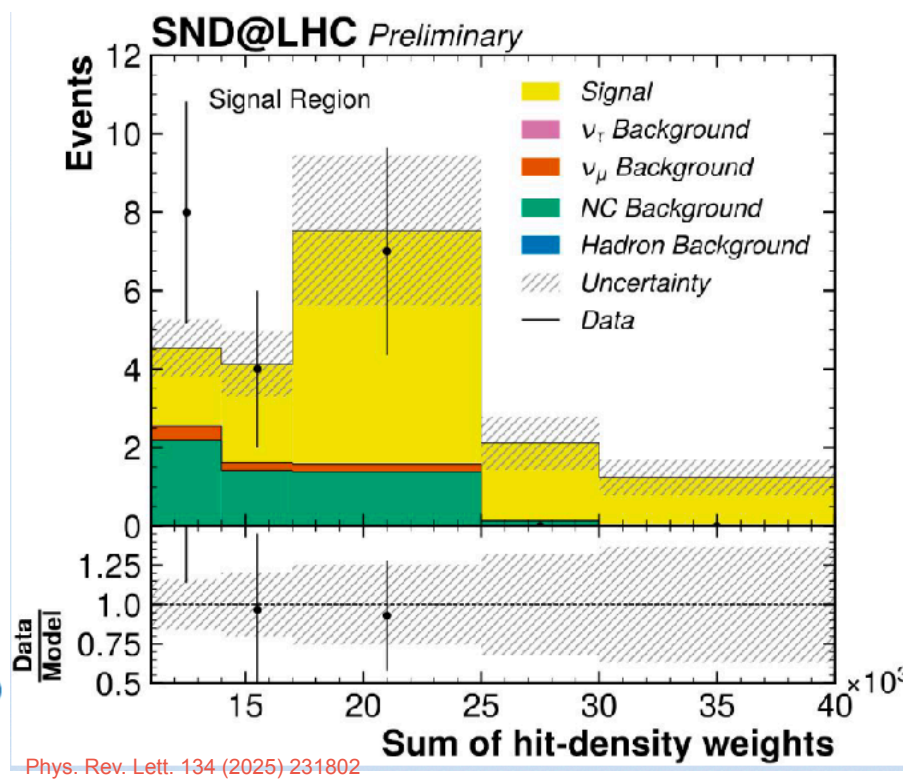
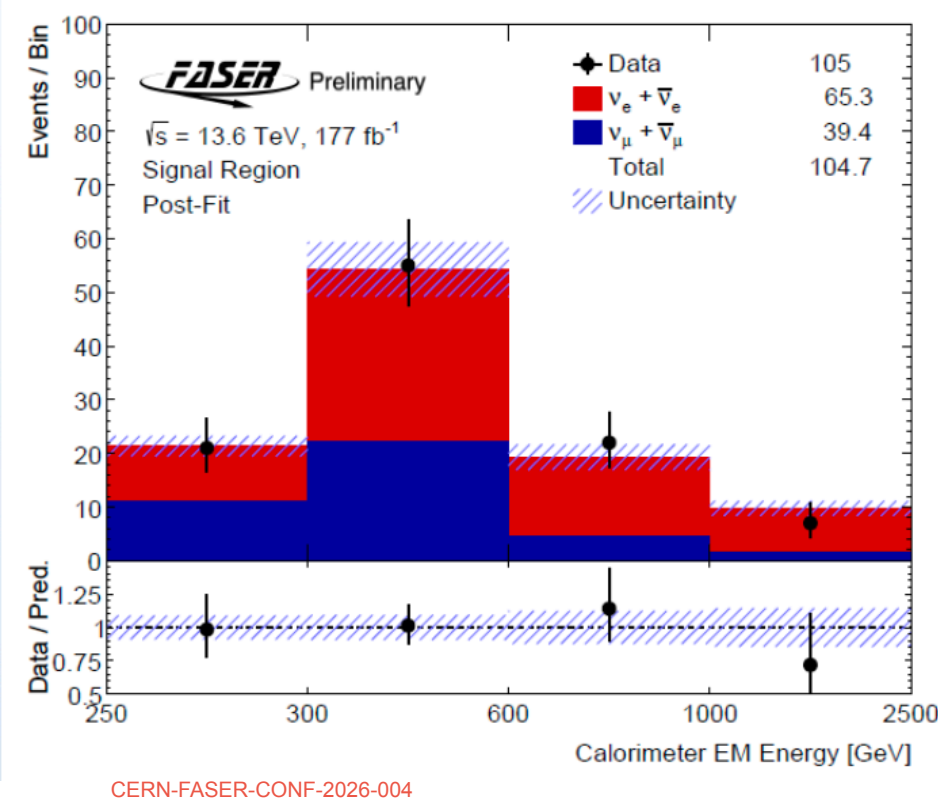
Flux measurements



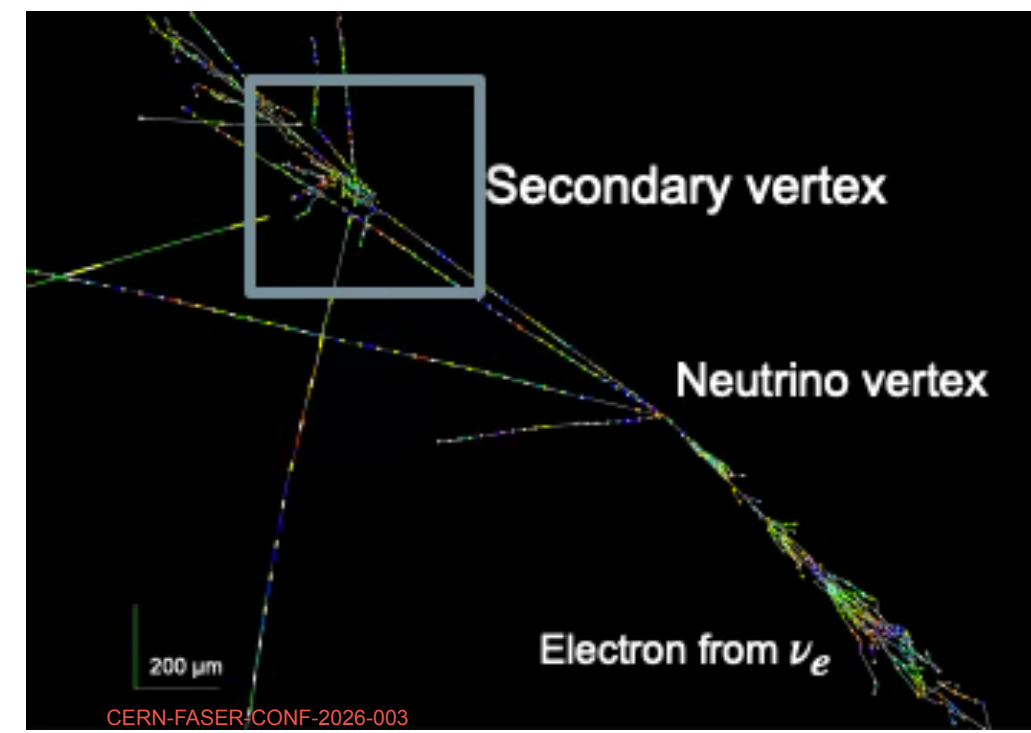
Cross section measurements



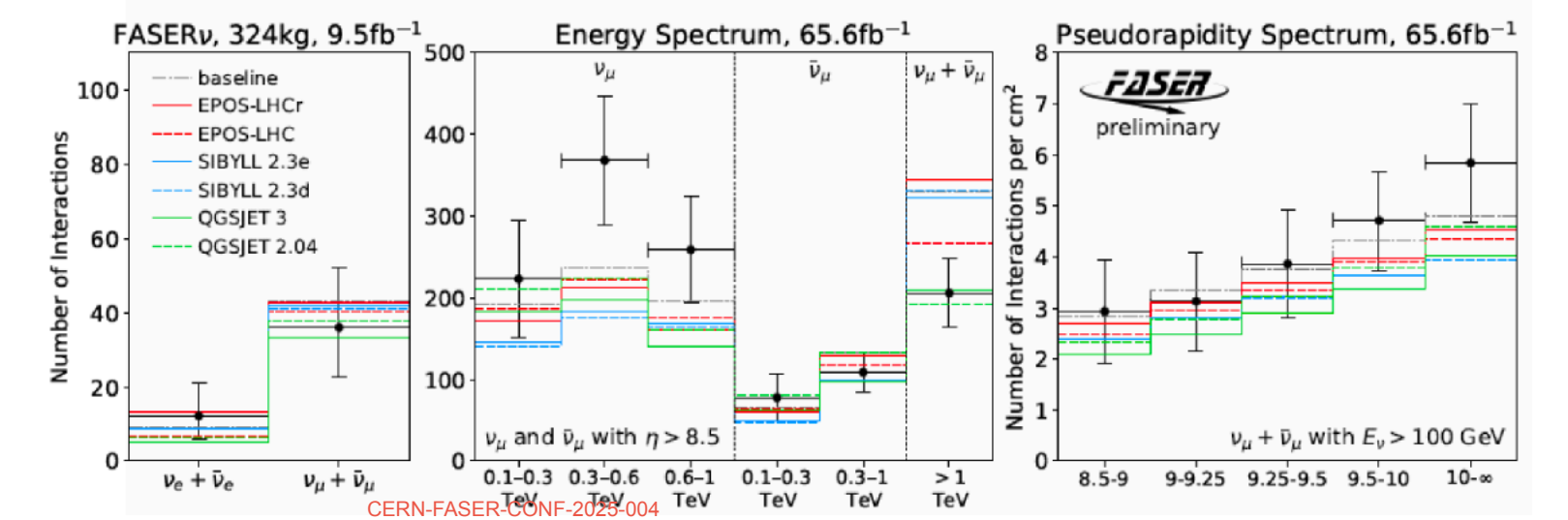
Electron neutrinos in spectrometer



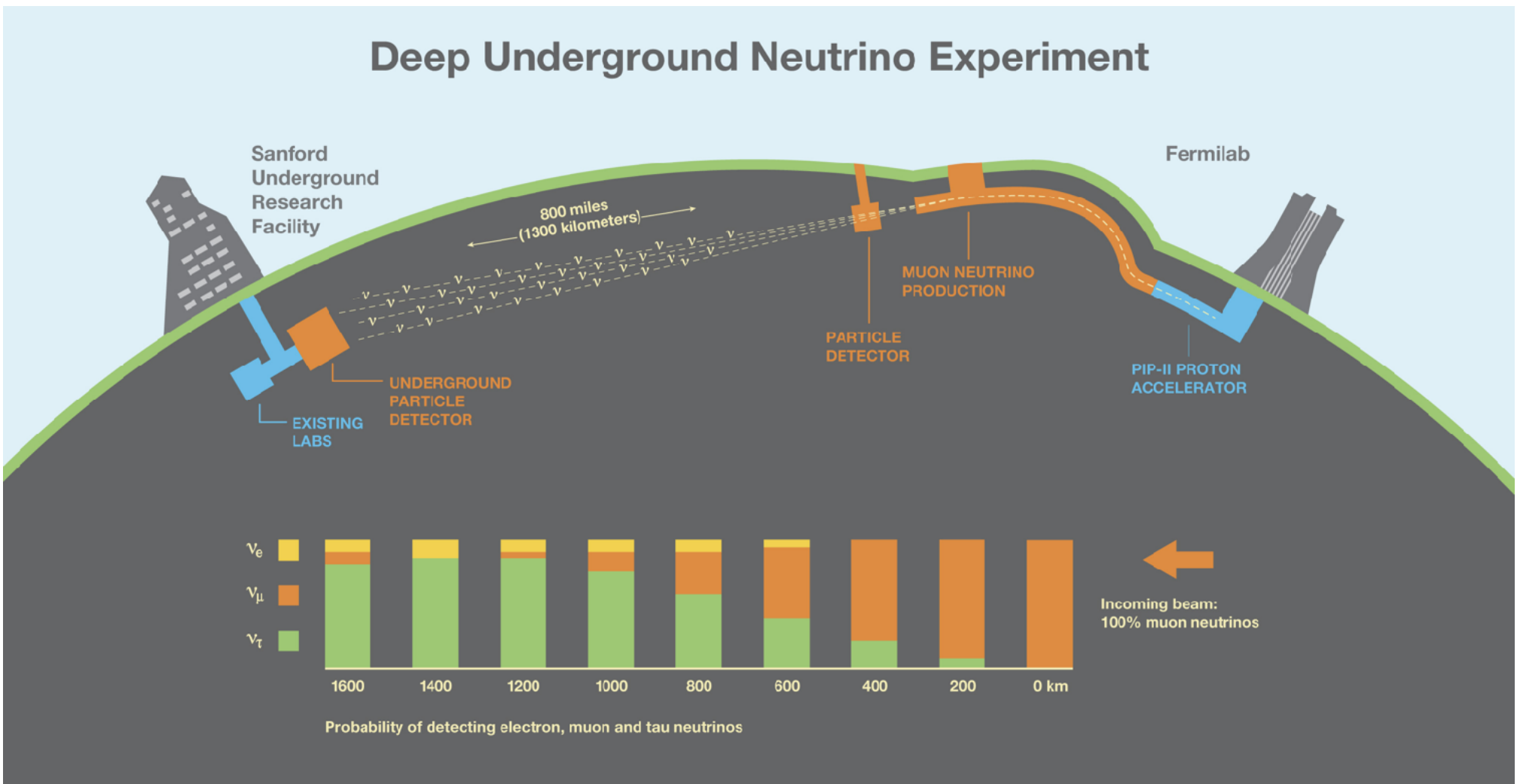
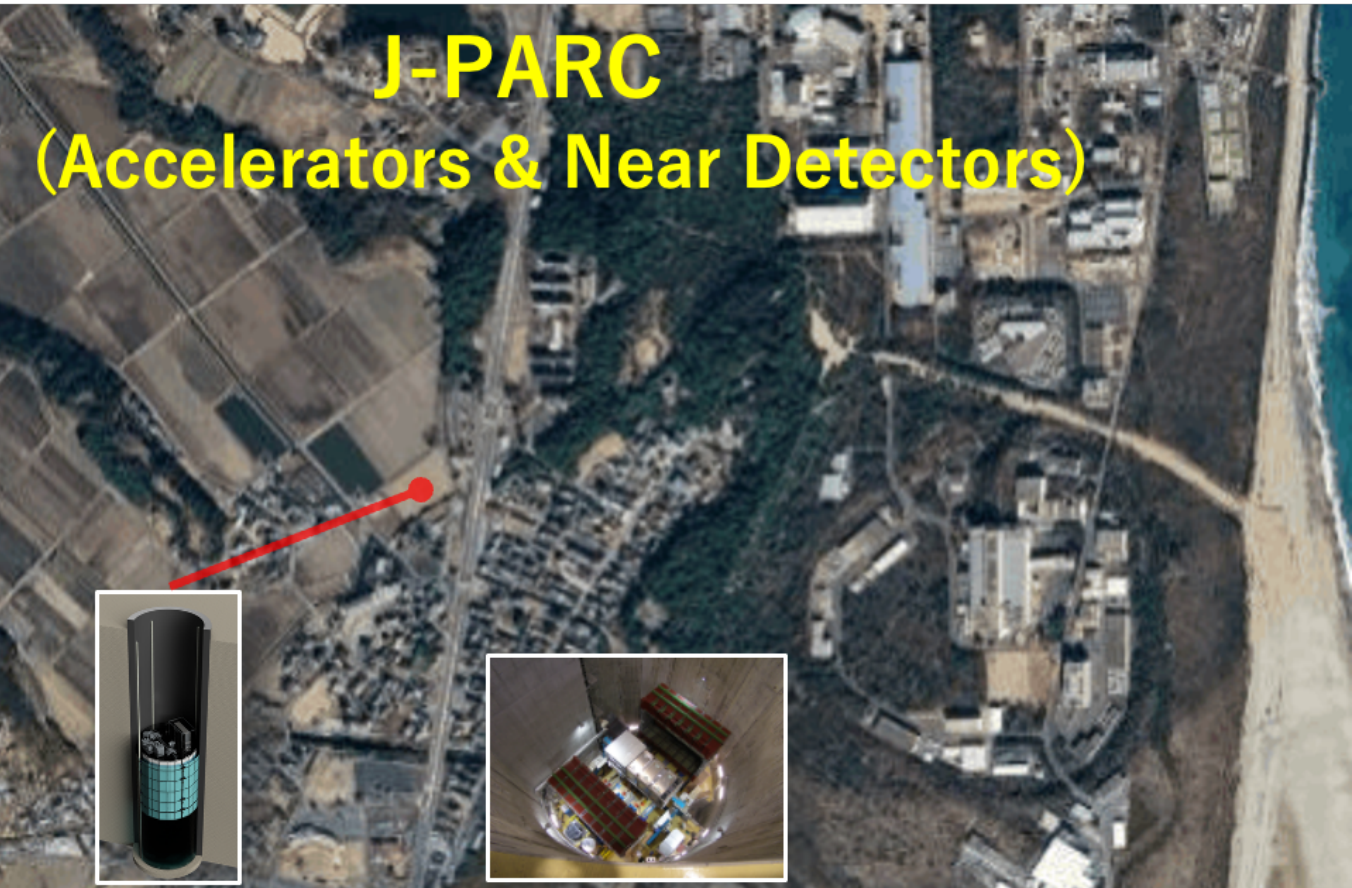
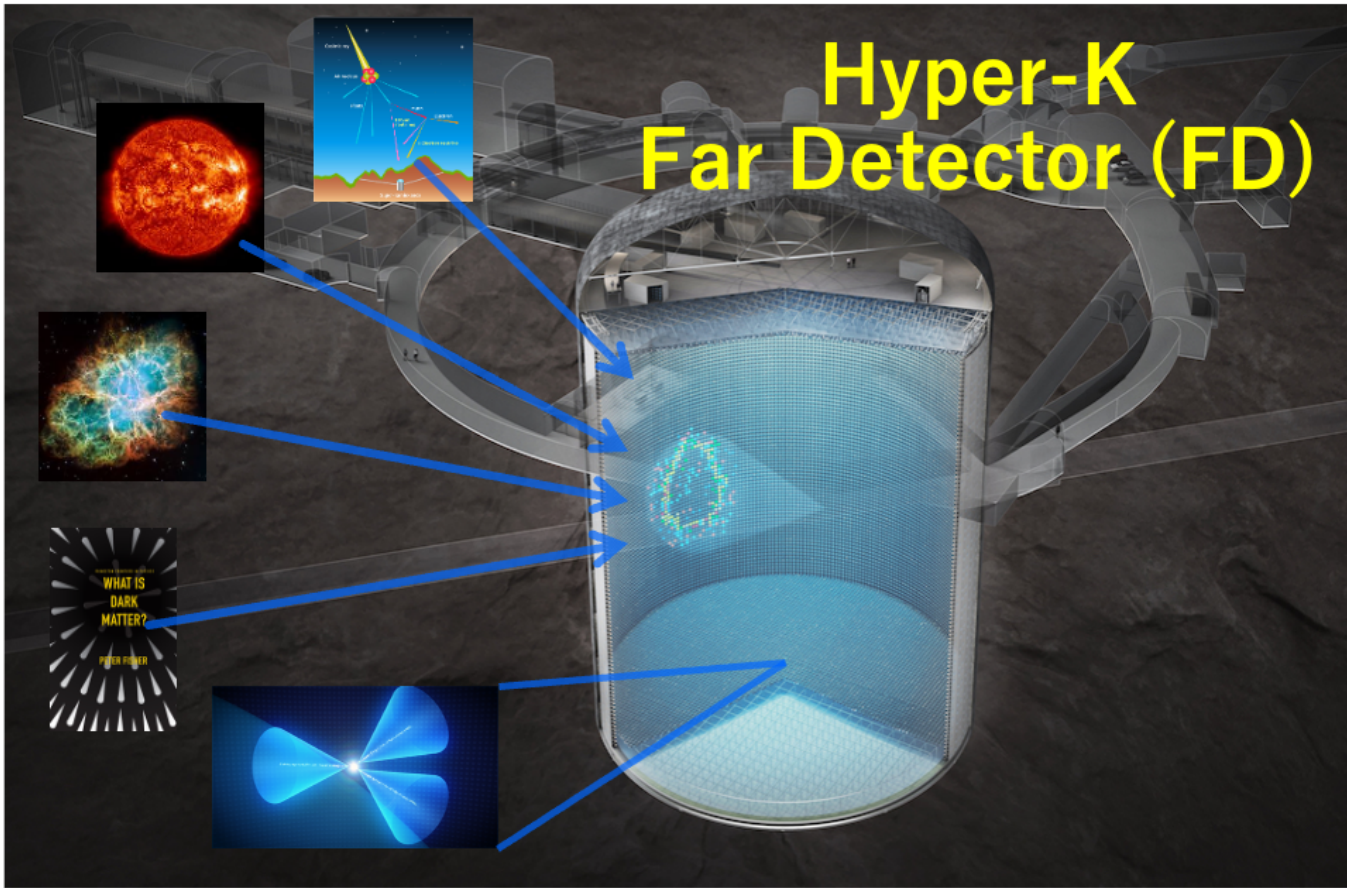
Displaced vertex ID (neutrino-induced charm)



QCD model interpretations



Next Generation LBL: Hyper-K and DUNE



Hyper-K and DUNE

- Hyper-K

- Pushes the proven techniques used by T2K to the limit (20x statistics)
- Beam upgrade to 1.3MW; 295km baseline, 2.5deg off-axis
- Large statistics in narrow-band beam -> excellent measurement of δ_{CP}
- **First beam neutrino data 2028**



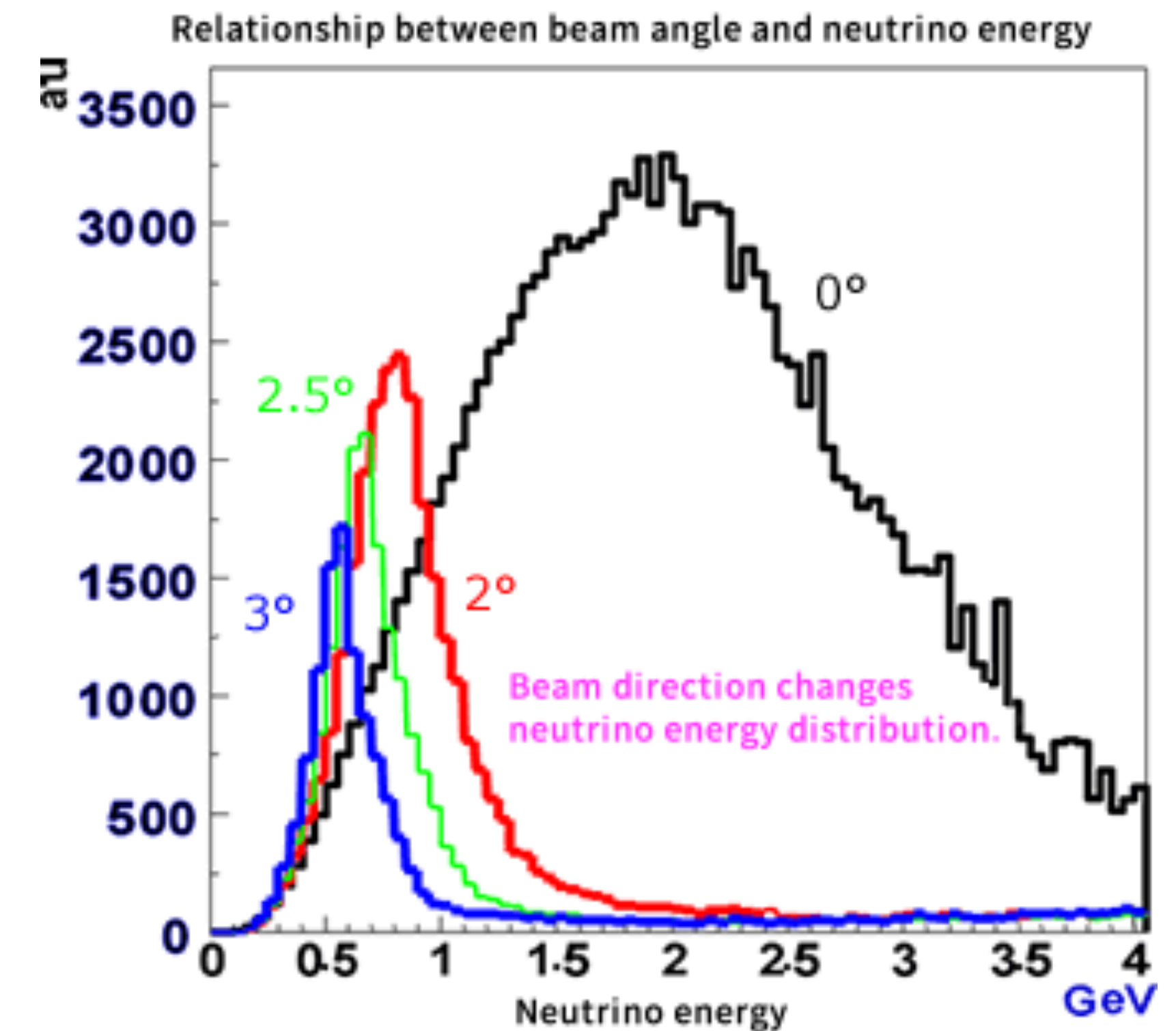
- DUNE

- Builds on practical experience of LAr TPC from Icarus, FNAL SBL
- Beam 1.2MW, 1300km baseline, on-axis (sensitivity to 1st / 2nd maximum)
- Matter effect, excellent reconstruction, robust stand-alone measurements as $\nu_n(E)$
- **First neutrino data 2030, beam from 2031**
- **DUNE Phase-1 followed by a Phase-II detector additions and beam power upgrade**

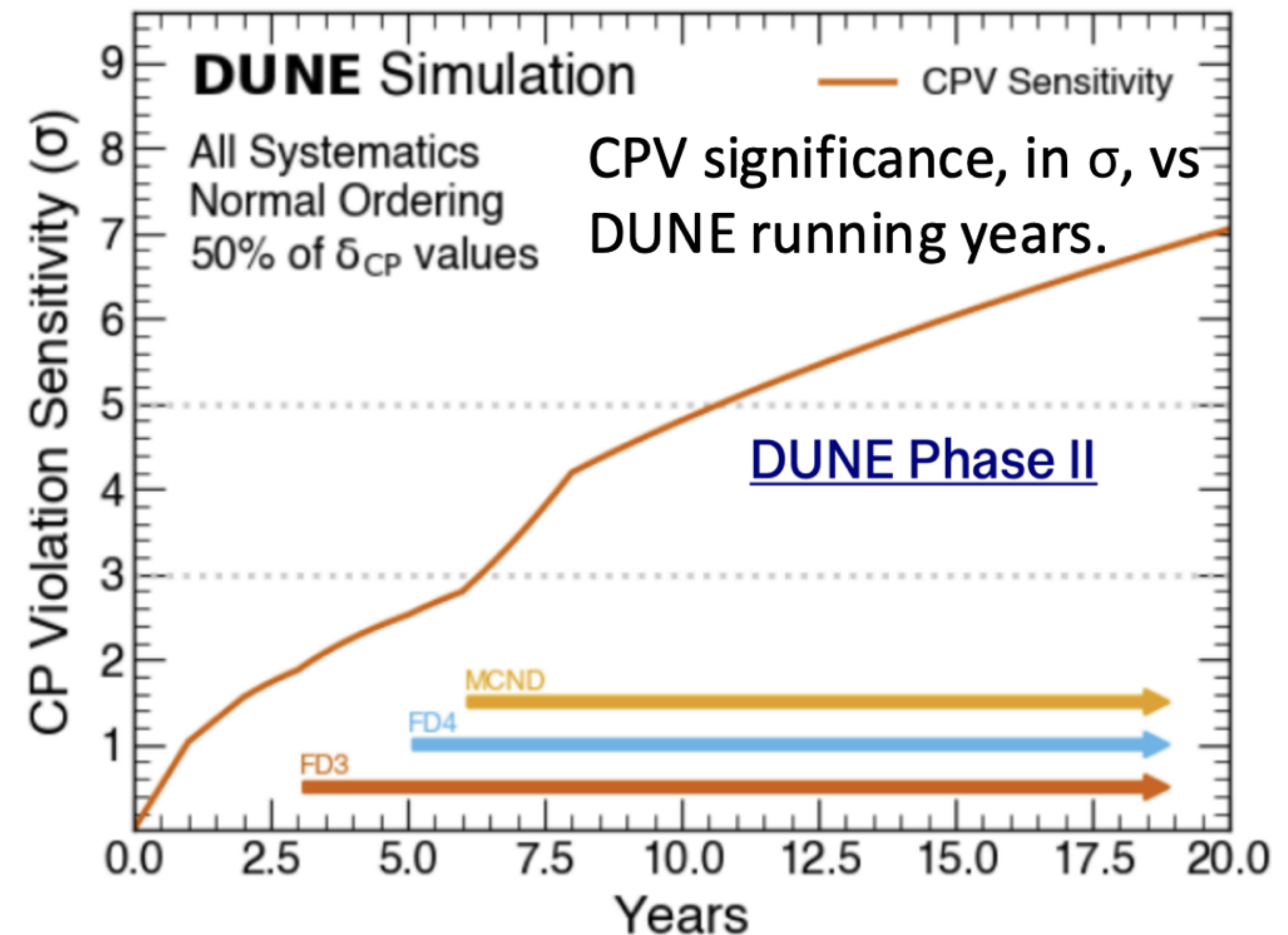
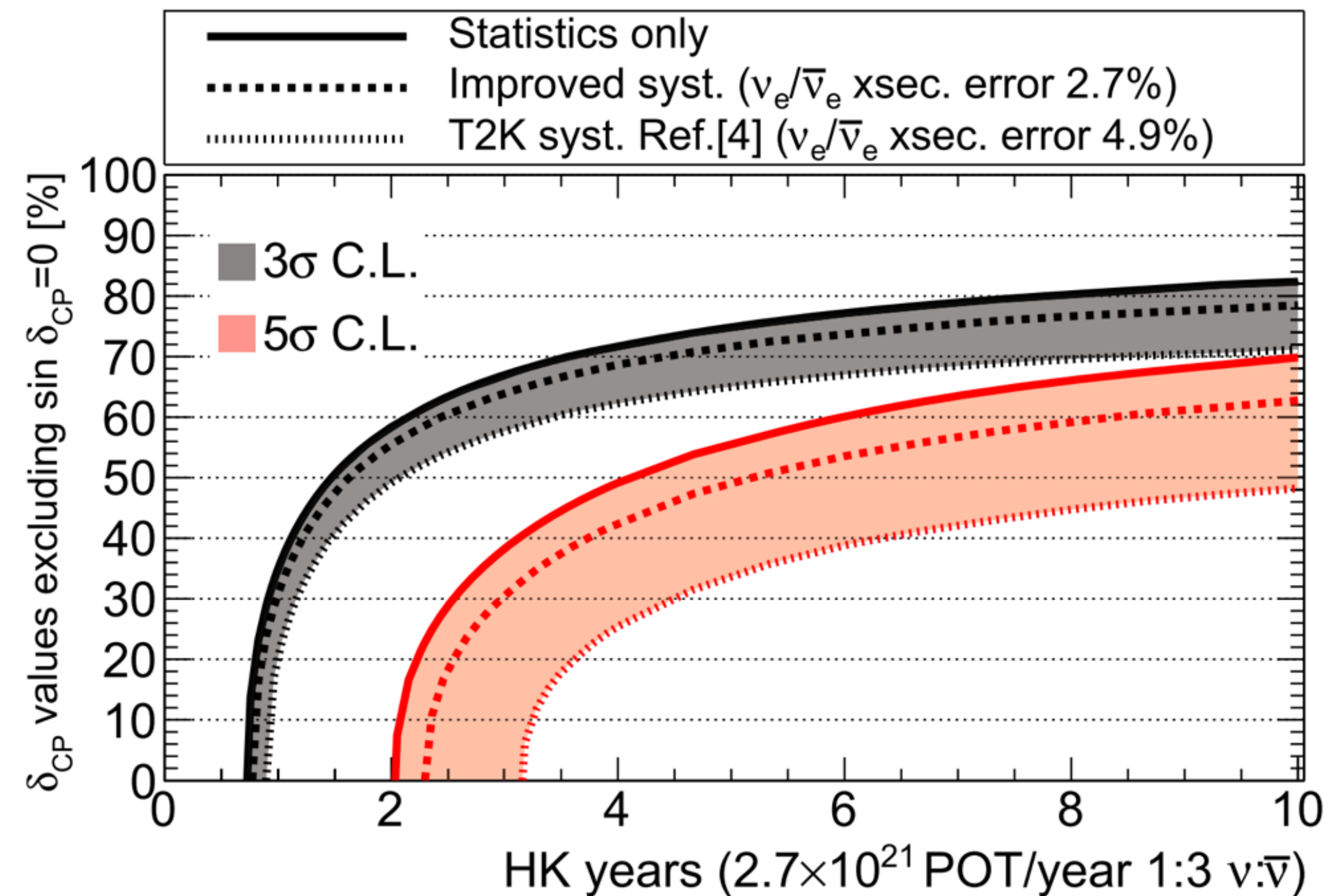


- Hyper-K and DUNE will measure the same parameters, but in very different ways

- Key goals: Definitive mass ordering and δ_{CP} measurements
- In global fits, will result in ~1% precision tests of the three-flavour model
- Requires exceptional control of systematics for ultimate sensitivity -> emphasis on capable near detectors
- Also! Non-beam physics! Atmospheric, astrophysical, solar neutrinos. baryon decay; direct BSM sensitivity (near and far detectors)

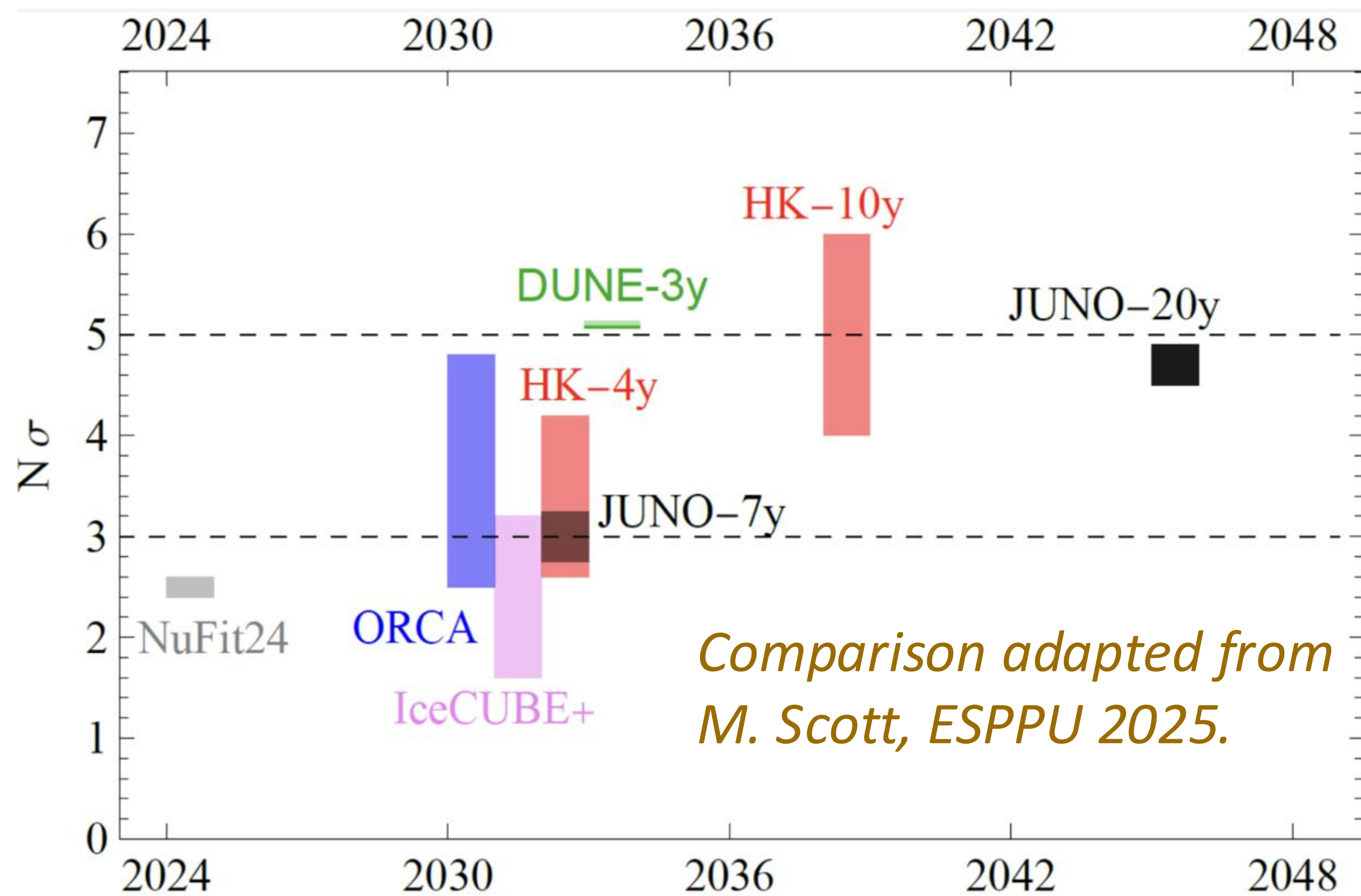


Sensitivities: δ_{CP}

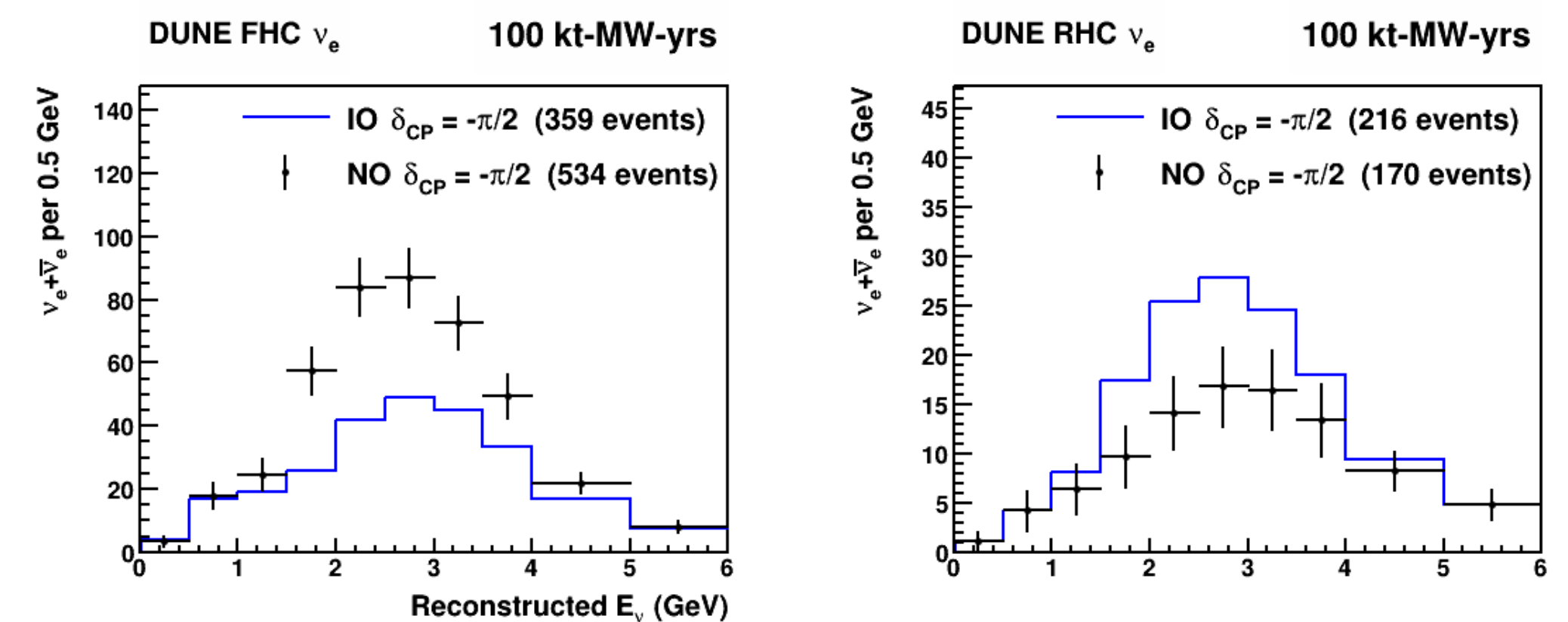


- 5 σ sensitivity for 50% of δ_{CP} range in 5y (HK), 11y (DUNE nominal schedule)
 - HK sensitivity shown here relies on knowledge of MO (from JUNO / DUNE)

Sensitivities: Mass Ordering

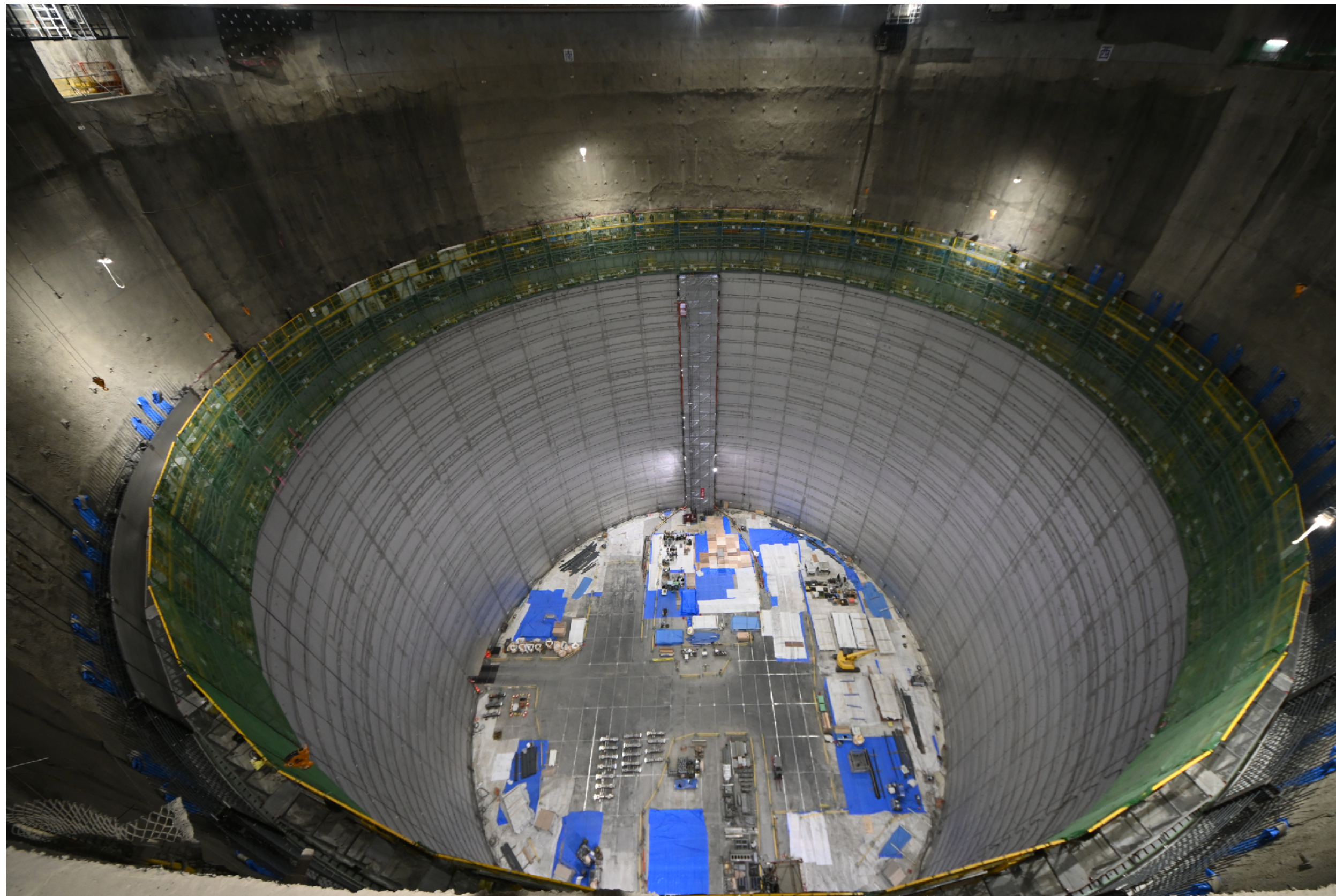


- DUNE gets to 5σ on MO quickly whatever the value of δ_{CP}
 - Long baseline and matter effects
- Potential for $\sim 3\sigma$ measurement via multiple routes before DUNE starts



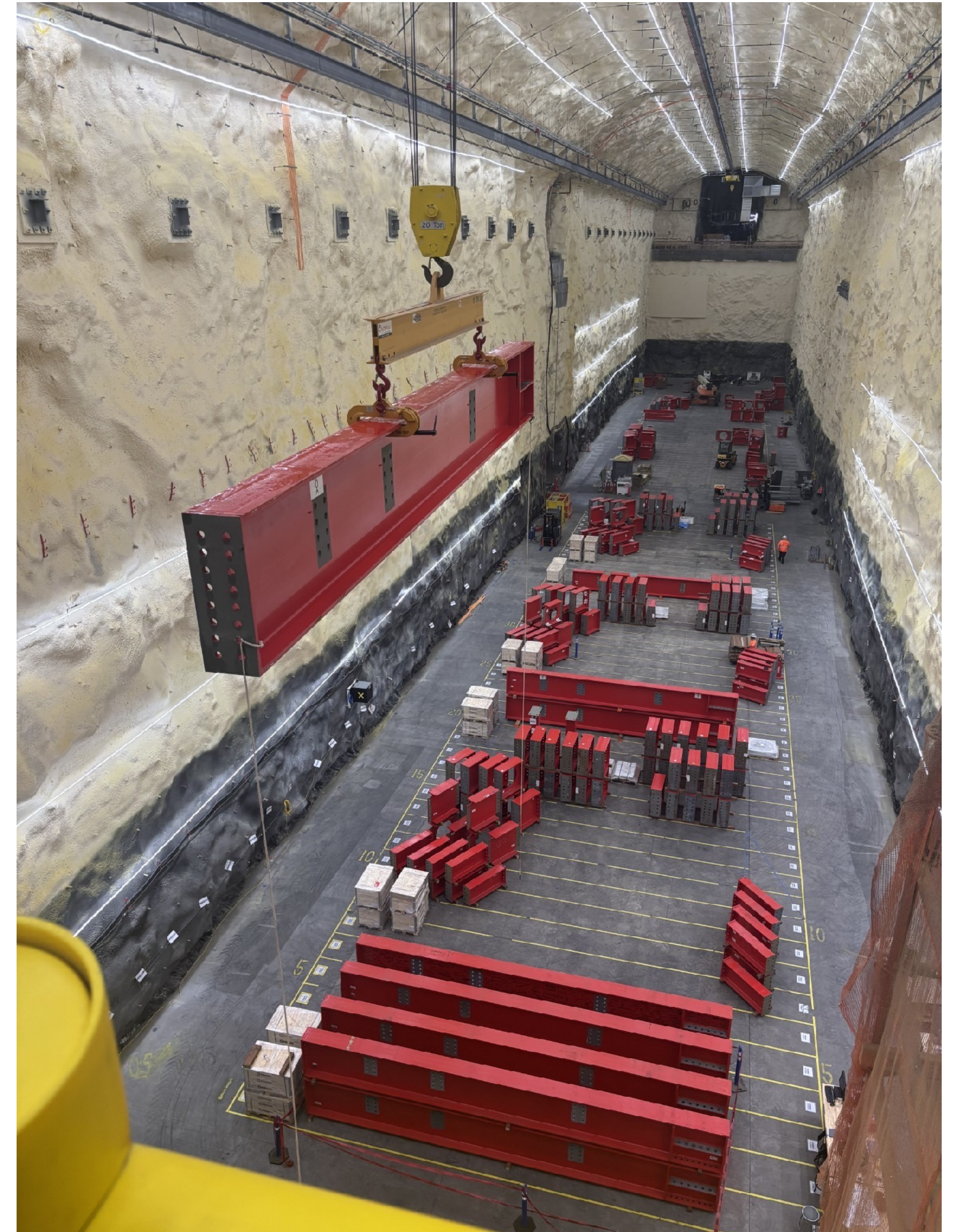
DUNE worst case: CPV – matter effect cancellation

Construction Status



HK Cavern, June 2026

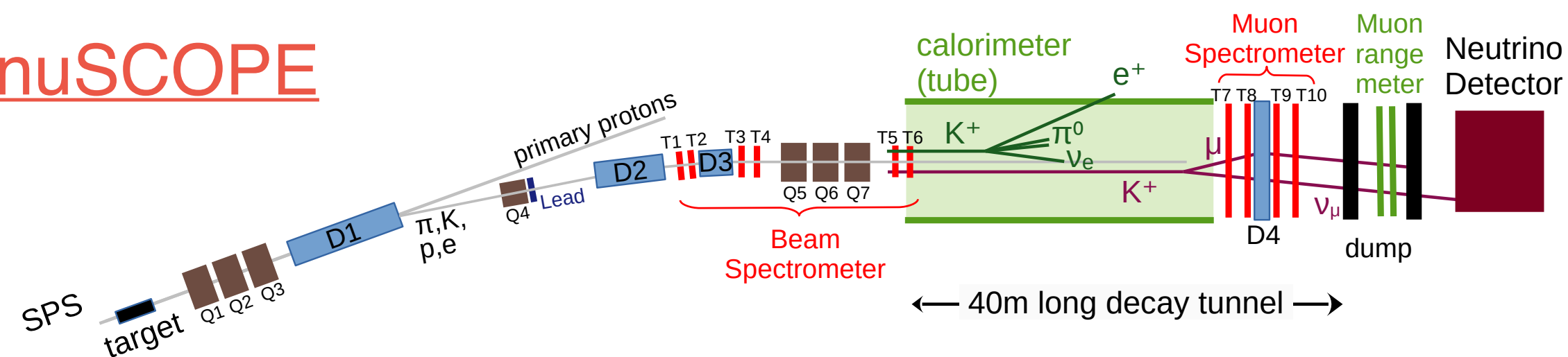
DUNE North Cavern, July 2026



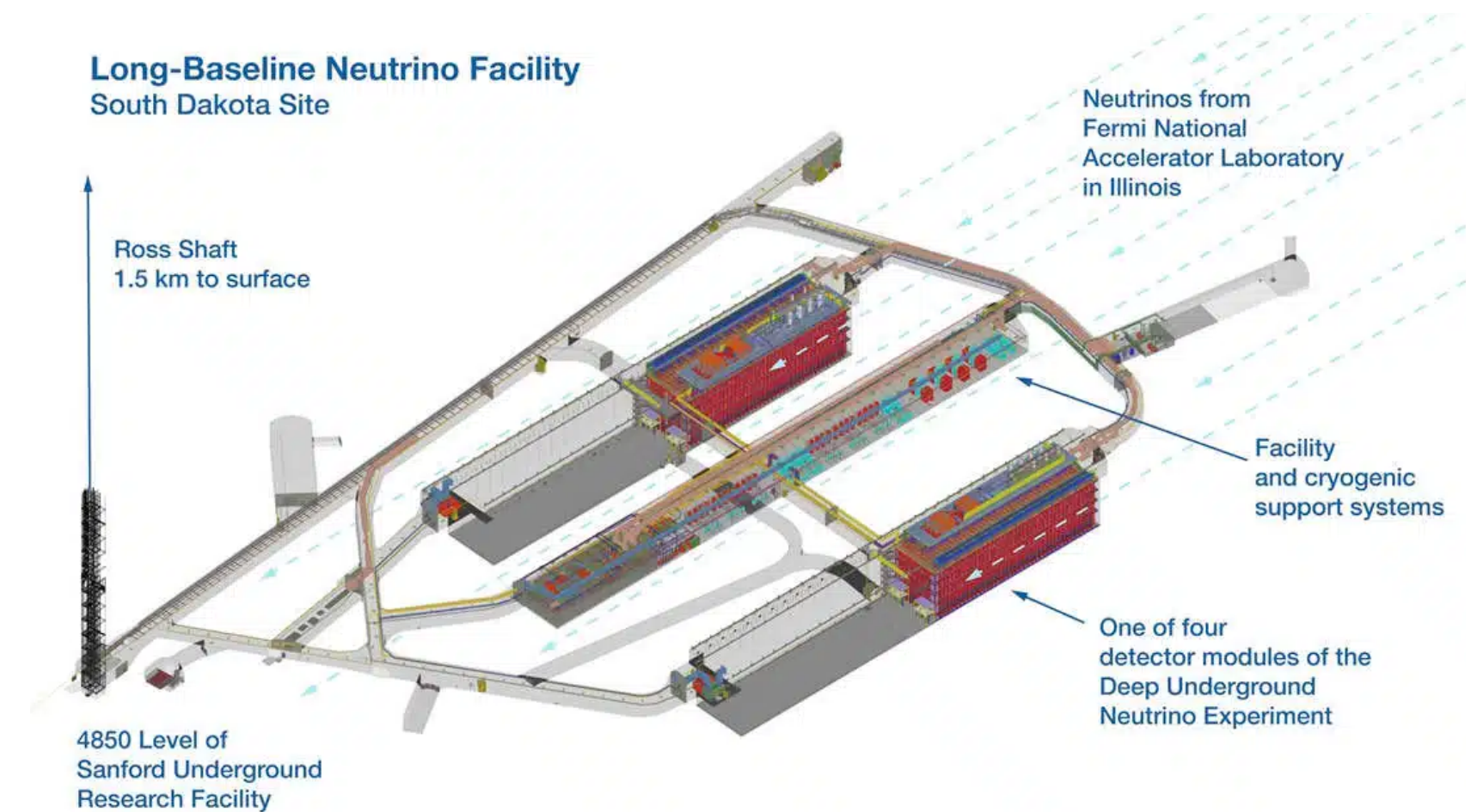
Beyond the Next Generation

- Where to push?
 - DUNE Phase-II R&D (more ν , more mass, lower thresholds)
 - Tagged / known-composition weak-decay beams
 - Leverage new facilities in the long term
- Plenty of ideas and work to do, physics impact in 2030s and 40s

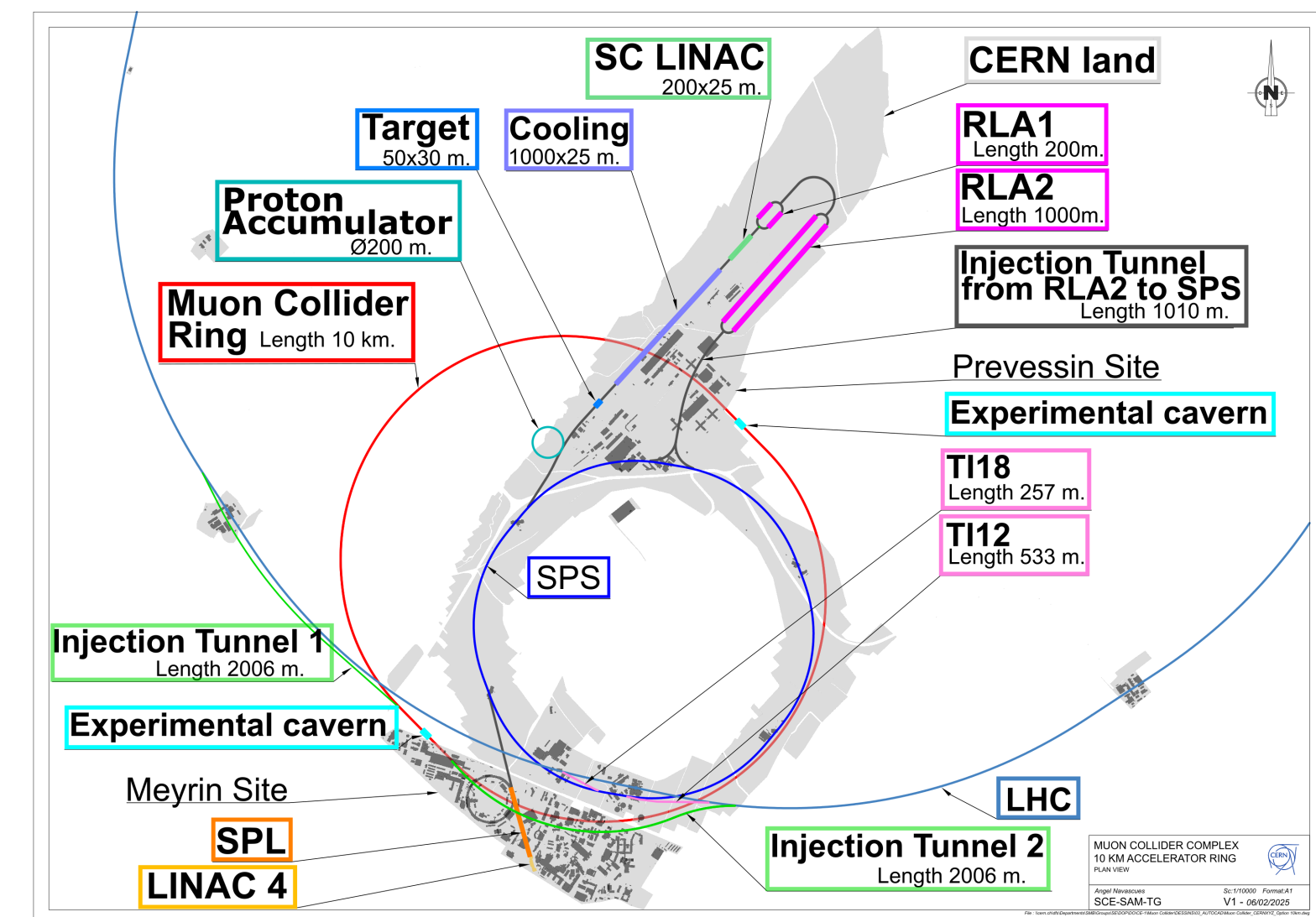
nuSCOPE



nuSTORM



DUNE Phase-II



Summary

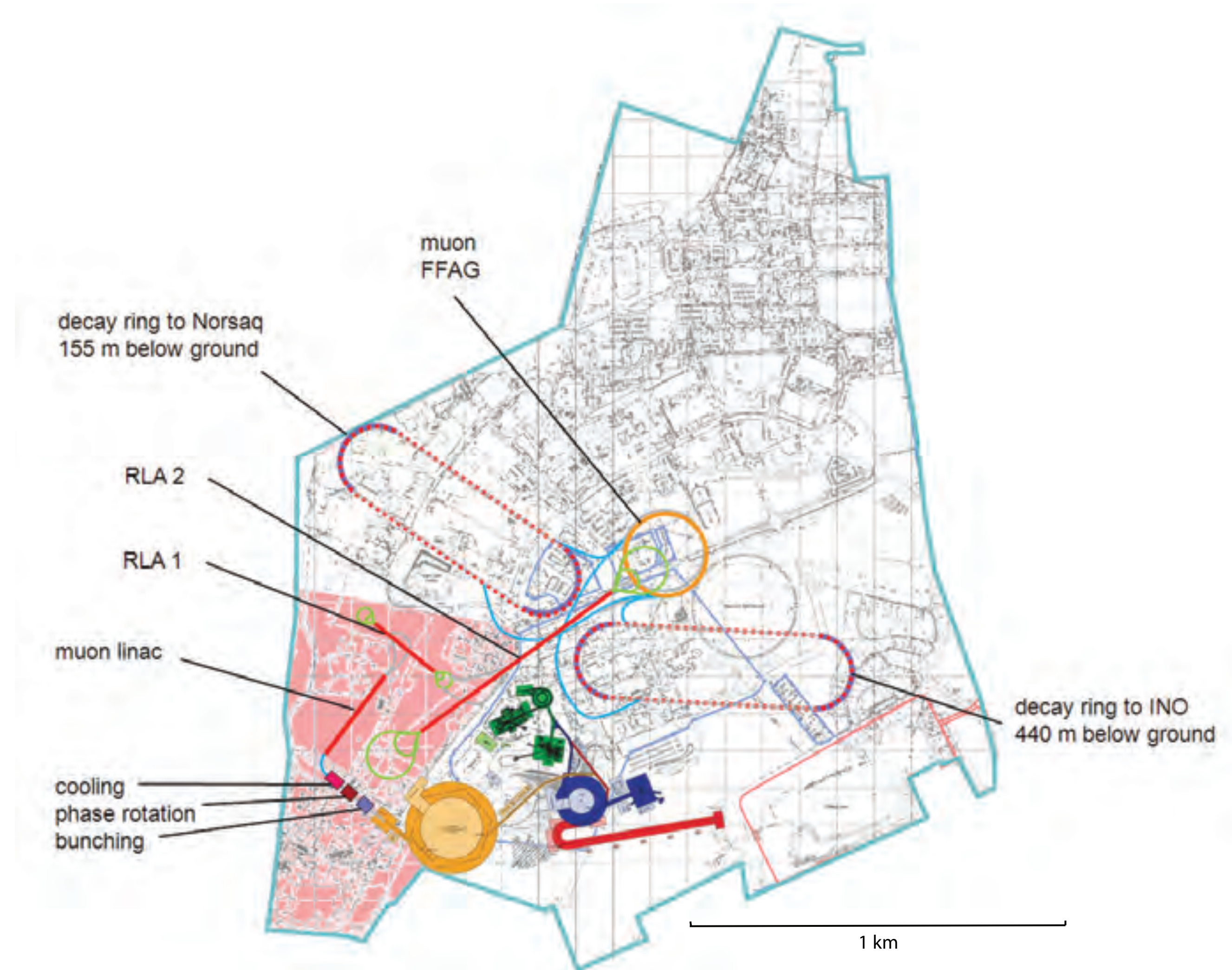
- The first 70 years of neutrino oscillation physics were
 - Demanding; Surprising; Sometimes confusing; Hugely revealing
- By 80th anniversary...
 - Major new results from JUNO, Hyper-K, DUNE, many others
 - We will know the mass ordering and (hopefully) δ_{CP}
- By 90th anniversary...
 - Precision (1%) measurements -> PMNS matrix may be our biggest clue to the new physics
 - Stringent constraints on BSM models and cosmology
- By 100th anniversary...
 - Access to new and even more capable facilities
- A new long-term 'golden era' of neutrino oscillation physics is here – let's get going!

Thoughts on the UK Programme

- The upcoming experiments are in the ‘premier league’
 - Complexity, cost, longevity, collaboration size, *scientific impact*
 - Long-term multi-faceted programmes, delivering on the central agenda of fundamental physics
 - A step change from the experiments of 20 years ago measuring a limited set of parameters
 - Clear strategy, sustained commitment, and long-term planning needed – as for e.g. LHC or SKA
 - The UK is not a ‘customer’ of international projects, it is a long-term provider of core expertise and leadership
 - Essential that future peer review decisions are based on an up-to-date understanding of the situation
- Future investments
 - Punching above our weight – current / past leaders of MINOS, T2K, NOvA, Hyper-K, DUNE, uBooNE, SBND (+ SuperNEMO)
 - Cash will be limited for some time – but need to decide the key investments for the 2030s *soon*
- Priorities
 - Promote the UK’s future leadership in this area of science – the scientific returns are substantial and near at hand
 - Get the theory community motivated and involved, there is a serious gap here in the UK
 - Find ways to provide continuity in our contributions to the future major experiments – even if some creativity is needed
 - Do not ignore long-term R&D! There is much more than can and will be done in the next 70 years!



We used to be More Ambitious



Neutrino Oscillation

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

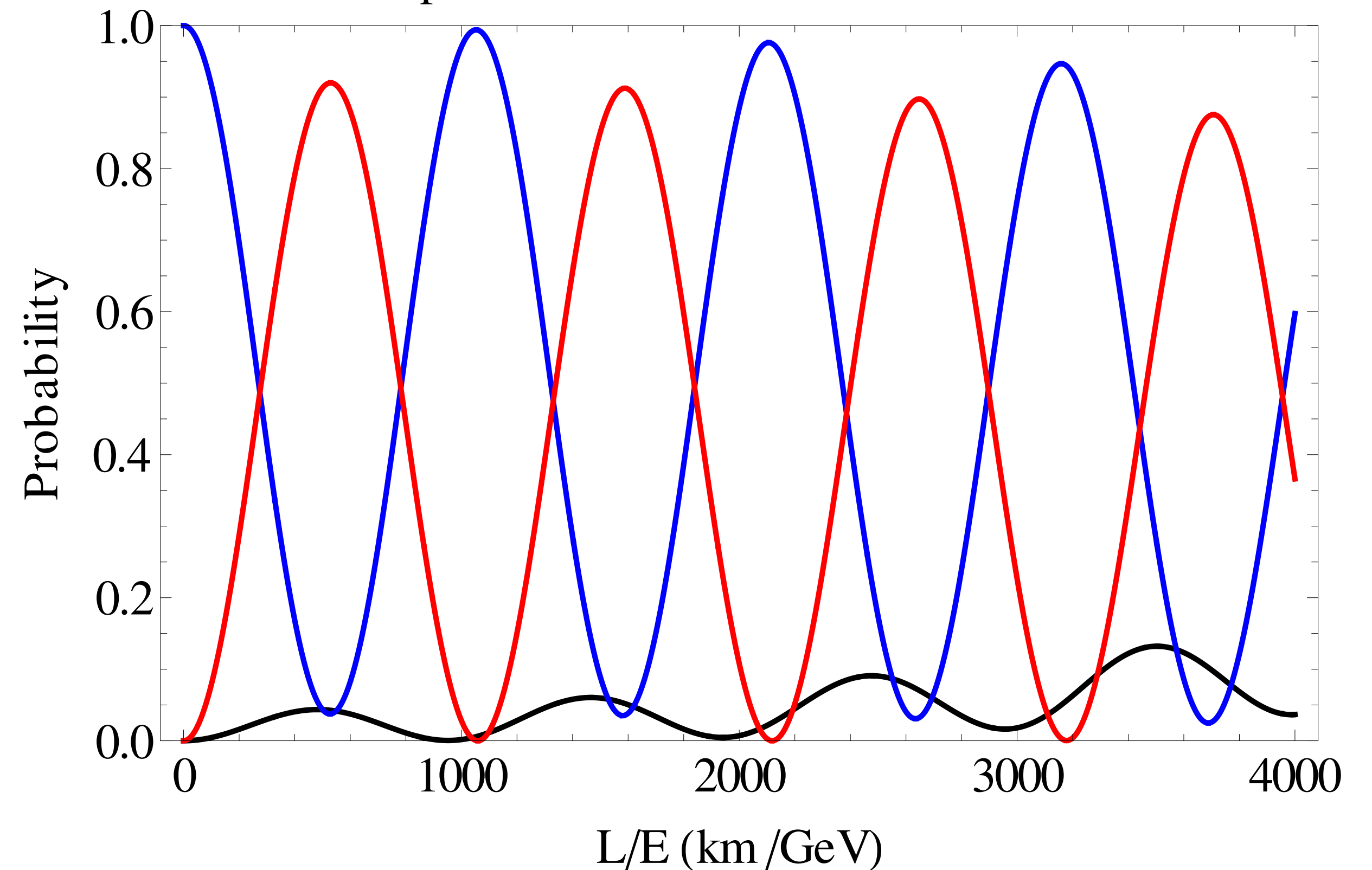
Mixing parameter

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E_\nu} \right)$$

Mass-squared difference

Oscillatory term (time in neutrino frame)

Oscillation probabilities for an initial muon neutrino



DUNE CP Measurement

