Accelerator Neutrinos
–
The Future

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Accelerator Neutrino Experiments

- Introduction.
- LBL Neutrino Program
  - DUNE
  - Hyper K
  - NOνA
  - T2K
- @ the LHC
  - FASER
  - SND

See Josh McFayden's talk tomorrow

- SBL Neutrino Program
  - MicroBooNE
  - SBN
  - SBND
  - $JSNS^2$
- Further Future: NuSTORM
- Outlook

Neutrinos

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

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

- 2nd lightest 2nd most abundant particle.
- Three known active neutral flavours, each corresponding to a charged lepton flavour.
- Interact via weak force: NC (via Z^0 exchange), CC (via $W^\pm$ exchange).
- They have mass and "oscillate":
  - Produced in flavour states $\nu_{e\text{-}\mu\text{-}\tau}$, travel in mass states $\nu_{1\text{-}2\text{-}3}$.
  - Flavour changes as a function of energy and distance travelled.
- ***Neutrino experiments are responsible for 10% of the physics papers published by HEP experiments in the last CG round and 3 of the top 10 most cited are neutrino papers.***

Neutrinos: What we know

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{\mu1} & U_{\tau1}\\ U_{e2} & U_{\mu2} & U_{\tau2}\\ U_{e3} & U_{\mu3} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

PMNS Matrix

Atmos. + Accel.

React. + Accel.

Solar + Reactor.

c_{ij} = Cos θ_{ij}, s_{ij} = Sin θ_{ij}

- Oscillation described by 3 mixing angles, 2 Mass splittings & 1 phase.
- For two neutrino oscillation in a vacuum: (approx valid in many cases):

Can be same flavour (disappearance) or different (appearance)

$$P(\nu_x \rightarrow \nu_y) = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2(\mathrm{eV}^2)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

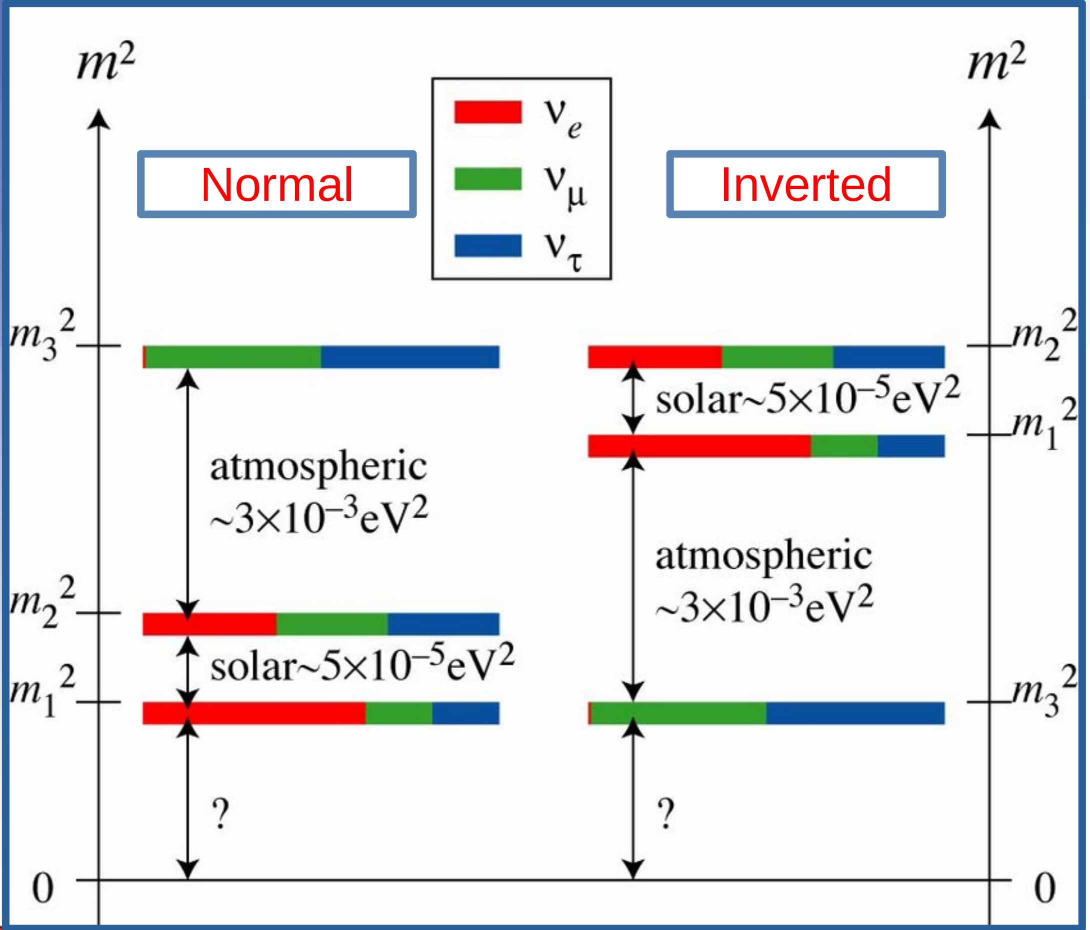
Just handles the units.

Controls frequency defines experimental parameters

Neutrinos: What we know

without SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

Neutrinos: What we Wish we Knew



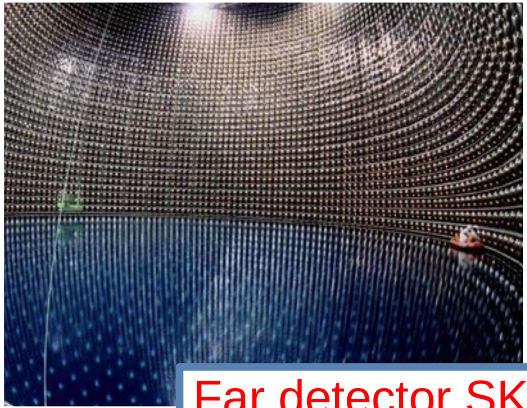
- Do neutrinos violate CP? $\delta^{CP} \neq 0$.
- How are neutrino masses ordered?
- What is the origin of neutrino mass?
- Are there undiscovered neutrinos?
- Octant of θ_{23} – max?
- More precise measurements & X sections.
- *Their own anti-particle?*
- *What is the absolute neutrino mass?*

Long Baseline Neutrino Experiments

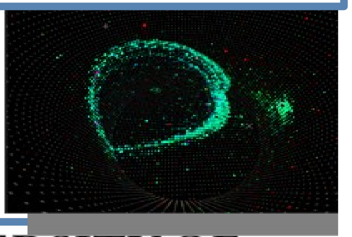
- Multiple experiments, utilising different technologies and teams, with different experimental constraints (L/E etc) are vital to successful measurements.
  - Different energies and baselines can resolve the degeneracies between mass hierarchy & δ_{CP} and/or the octant of θ_{23} & δ_{CP}.
  - Important to study possible systematics correlations between them.
  - Just like at the LHC.
- The UK are highly visible across almost all LBL Accelerator Neutrino Experiments.
- Clear benefit/impact for UK.

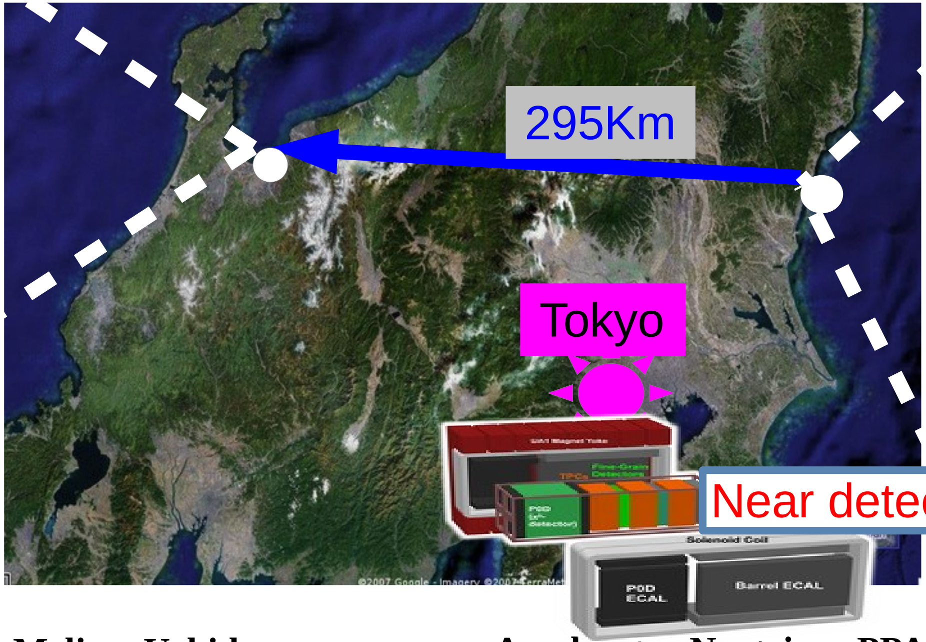
T2K

- 11 UK institutions and >98 UK members.
- UK leadership in beam and target, deputy technical coordinator, ND upgrade, detector HW, calibration, analysis, fitting, cross-sections, SW, computing and DAQ.



Far detector SK





JPARC

T2K-UK/Super-K-UK Recent Highlights and Future Plans

- Major upgrades to proton & neutrino beams (recently reached 800kW 1st time).
  - high-power beam targetry; proton beam modelling (final focus section); optical transition radiation beam monitor.
- New ND280 Upgrade Detectors installed.
  - SuperFGD R&D and construction; DAQ and software integration for new detectors; detector calibration algorithms and implementation.
- New analyses within T2K and jointly with other experiments.
  - T2K oscillation analyses for 2024 and cross-section measurements with near detector; T2K+NOνA joint analysis; T2K+Super-K (beam + atmospheric) joint analysis.
- Super-K Gd neutrino tagging entering physics analyses.
  - UK leadership in detector calibration.
- T2K to continue as Hyper-K starts; sharing/transitioning of responsibilities in negotiation.

T2K Joint Fits

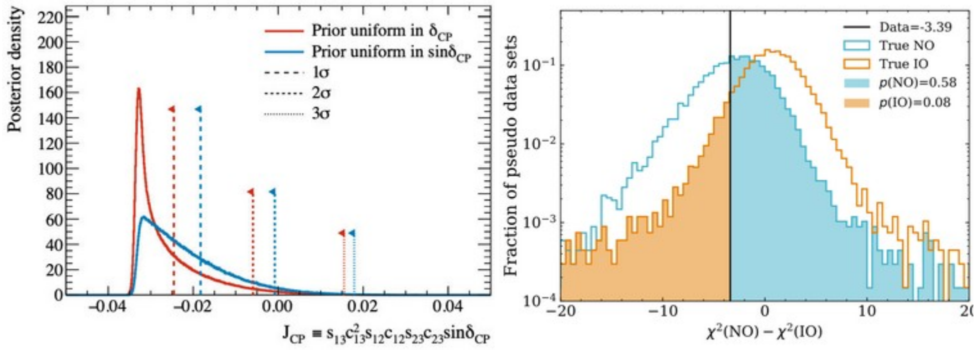
T2K - SK

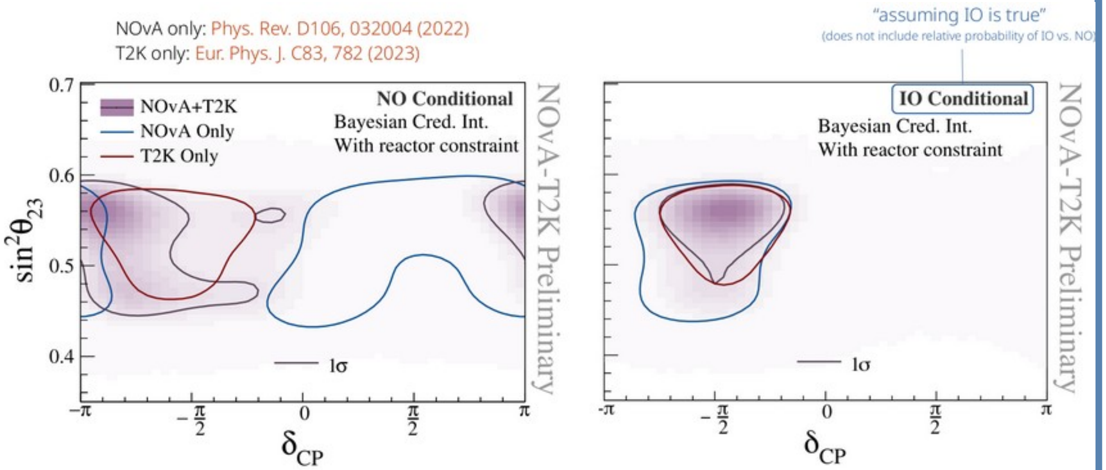
T2K - NOνA

T2K – sensitive to δ_{CP} not to mass order;
SK – good constraint on mass order not δ_{CP}.

T2K – measurements isolate impact of CP;
NOνA – more sensitivity to mass ordering.

ArXiV: 2405.12488





- CP conserving value of Jarlskog invariant excluded at ~2σ.
- Normal Ordering is preferred.
- (Both individually prefer NO and δ_{CP} ~-π/2. T2K prefer upper octant – SK prefer lower.)

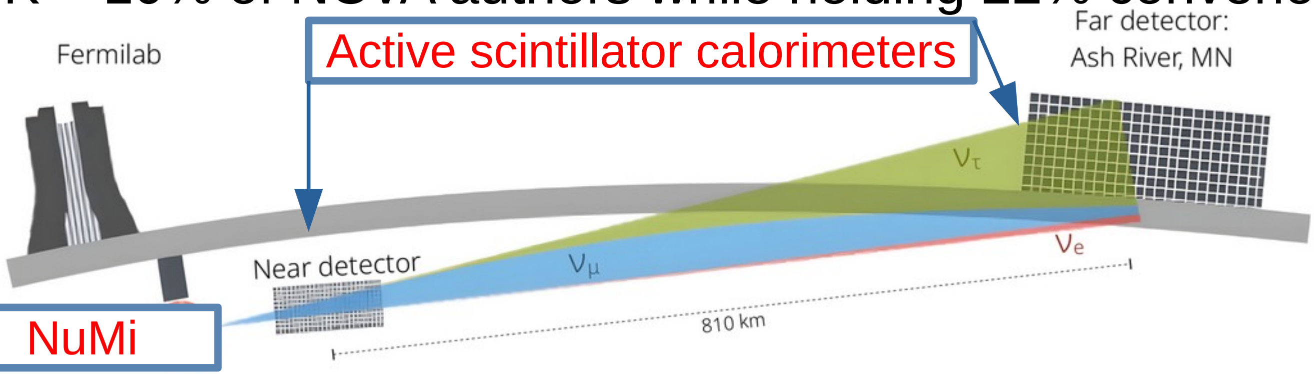
- Yield strong constraint on Δm^2_{32}
- Weakly prefer IO or NO depending on which reactor constraint is applied.
- Favour CP violation in IO (CPC outside 3σ intervals).

Mach3 used for all joint analyses

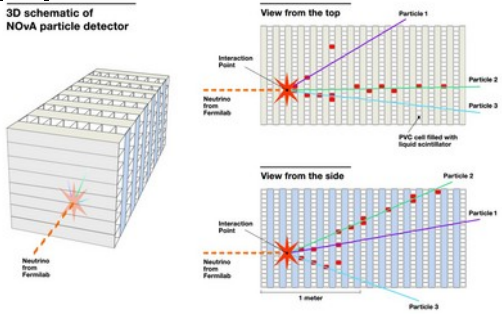
NOvA

- 3 UK institutions, >10 UK members.
- Leadership in analysis, IB chair, beam, reconstruction SW.
- UK ~ 10% of NOvA authors while holding 22% convenorship positions.

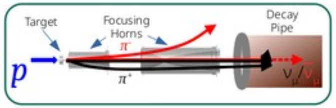
Active scintillator calorimeters



NuMi

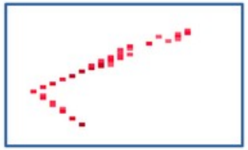


1. Make a beam of ν_μ

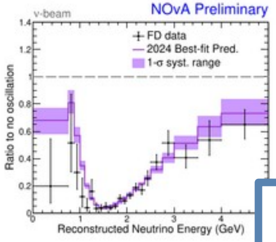


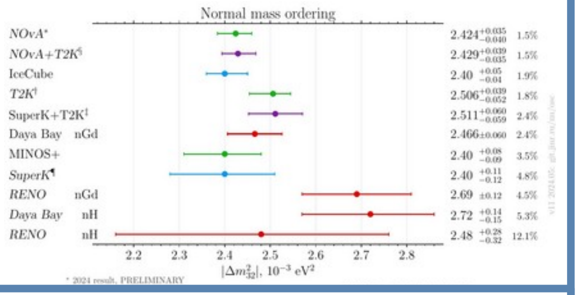
>900kW
Just approved – 1 MW

2. Select ν_μ and ν_e candidates at both detectors



3. Interpret E_ν distributions





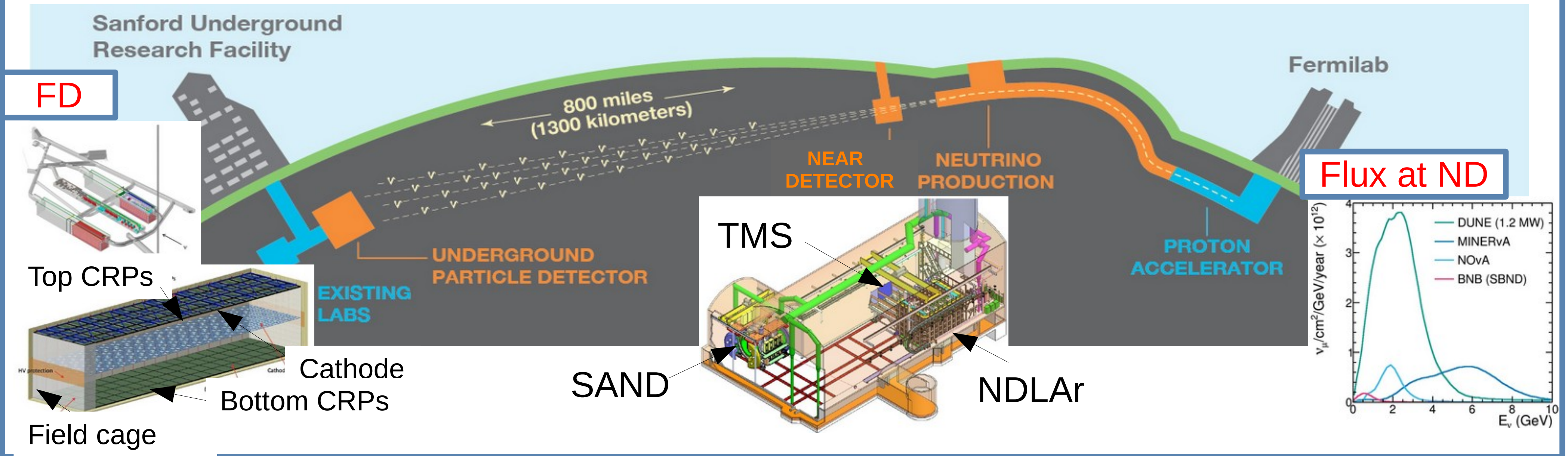
Gr8 precision on Δm^2_{32} (1.5%).
Most precisely known PMNS param!

NOνA – Recent Highlights & Outlook

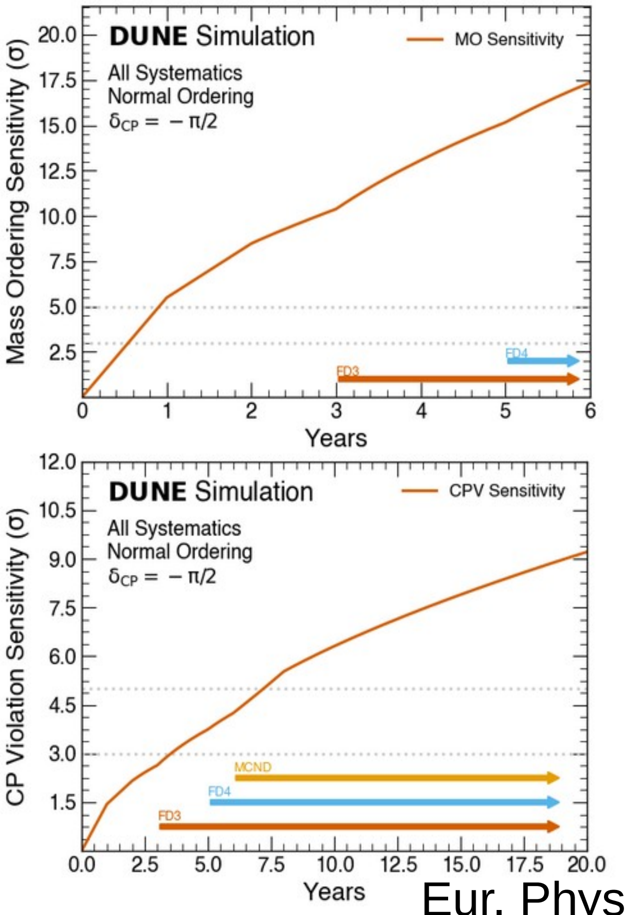
- First new NOνA neutrino oscillation measurement since 2020:
  - Doubled neutrino-mode dataset with 10 years of neutrino & antineutrino data.
  - Updated simulation, including improved light response model and neutron propagation uncertainty.
  - New low-energy ν_e candidate sample.
  - Most precise single-experiment measurement of Δm^2_{32} (1.5%).
  - Data favours region where matter, CP violation effects are degenerate.
- Strong synergy with reactor measurements:
  - Constraint on θ_{13} enhances Upper Octant preference (69% odds).
  - Constraint on Δm^2_{32} enhances Normal Ordering preference (87% odds).
- Compelling future prospects from NovA:
  - Goal: doubling of antineutrino data before 2027 – crucial to clarify MO/CPV.
  - Test beam constraints on energy scales expected in near term.
  - BSM oscillations, ν interactions, atmospheric and astrophysics, non-beam BSM…

DUNE

- 19 UK institutions and >170 UK members.
- The UK is the largest contributor to DUNE after the host country, the US.
- UK Leadership in: APA HW, DAQ, proton target and RF cavities for LBNF 1.2 MW, Pandora reconstruction, Near Detector, Physics, Calibration, ProtoDUNE and DUNE Phase II FD and ND, as well as several senior leadership and ex-spokes.



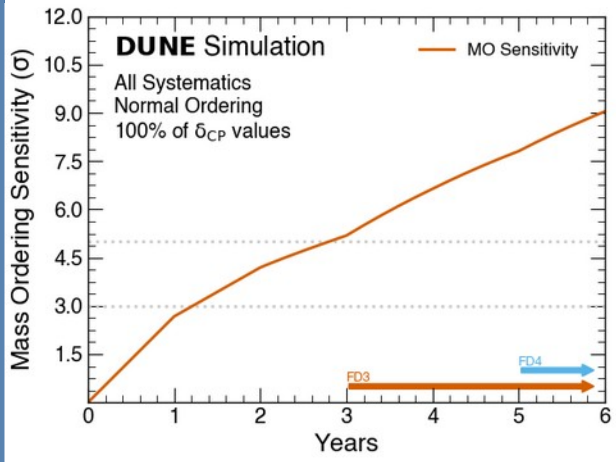
DUNE Physics

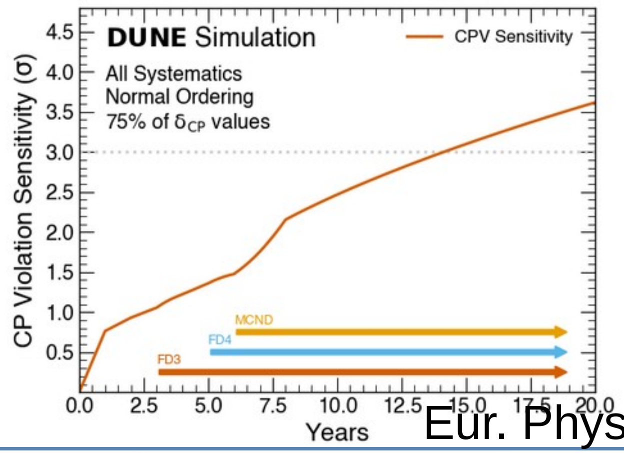


- For best-case oscillation scenarios, DUNE has:
  - >5σ mass ordering sensitivity in 1 year.
  - >3σ CPV sensitivity in 3.5 years.

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

DUNE Physics





- For best-case oscillation scenarios, DUNE has:
  - >5σ mass ordering sensitivity in 1 year.
  - >3σ CPV sensitivity in 3.5 years.
- For worst-case oscillation scenarios, DUNE has >5σ mass ordering sensitivity in 3 years.
- In long term, DUNE can establish CPV over 75% of δ_{CP} values at >3σ.

Arrows indicate assumed staging scenario.

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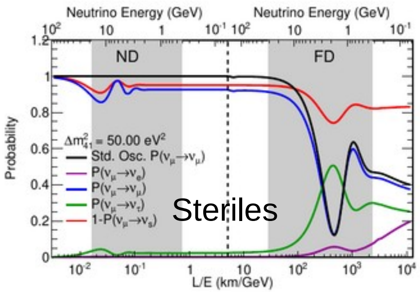
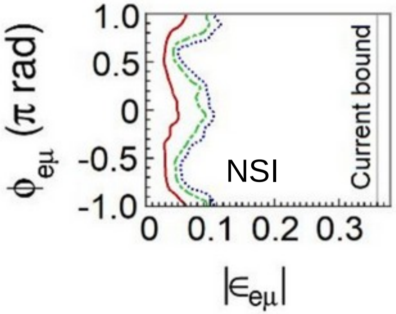
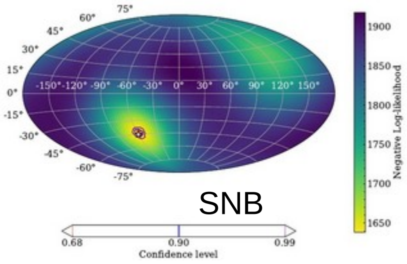
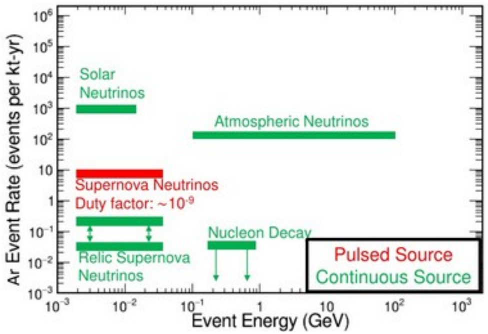
DUNE Physics



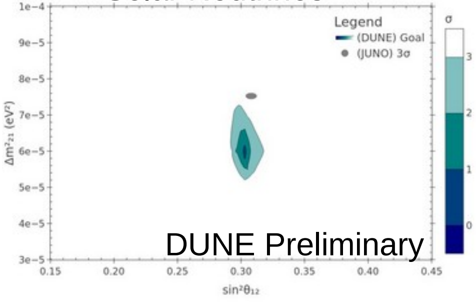




- Broad range of L/E at ND and FD → search for non-SM oscillations.
- High statistics neutrino and antineutrino measurements → search for CPT violation.
- Very large matter effect → uniquely sensitive to some NSI.
- FD will observe atmospheric, solar, and supernova neutrinos.
- Proton decay.
- Excellent sensitivity to 8B solar neutrinos above ~10 MeV, and discovery sensitivity to the hep solar flux (despite a large neutron background at low E).

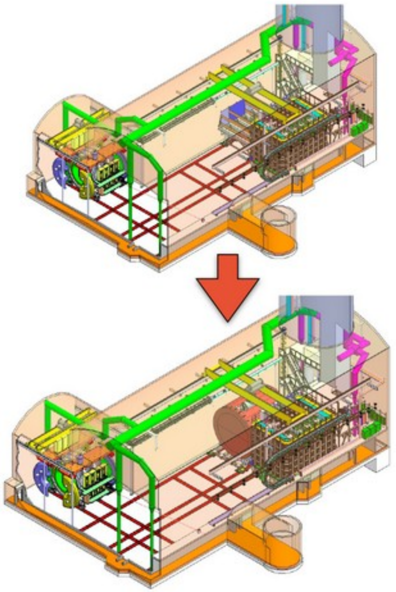


Solar Neutrinos



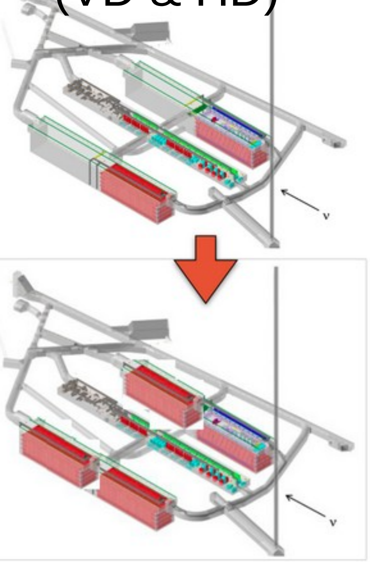
The 2 Phases of DUNE (not an upgrade)

Near Detector (ND)



Far Detector (FD)

(VD & HD)

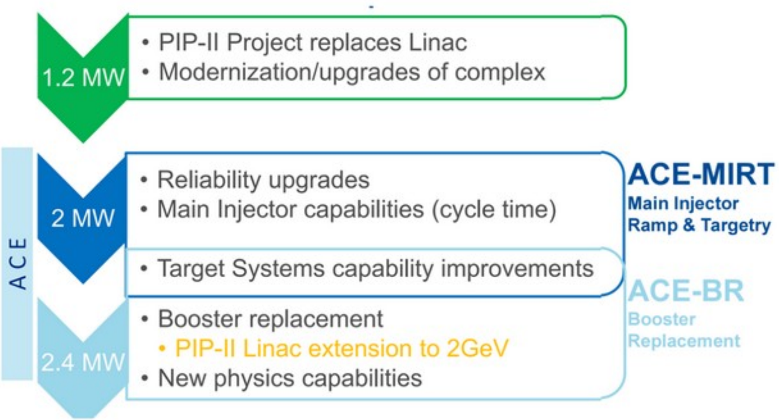


Phase I

- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- **Beam:** 1.2 MW beam line (PIP-II)

Phase II

- **FD:** 2 additional modules (total: 4 x 17 kt LAr-equivalent)
- **MCND:** ND-LAr+ND-GAr (with PRISM) + SAND
- **Beam:** > 2 MW beam line (ACE Upgrades)



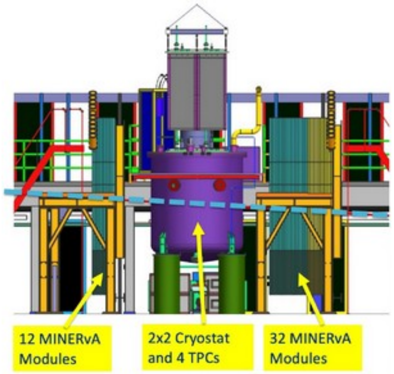
Parameter	Phase-I	Phase-II	Impact
FD mass	20 kt fiducial	40 kt fiducial	FD statistics
Beam power	up to 1.2 MW	>2 MW	FD statistics
ND configuration	ND-LAr, TMS, SAND	ND-LAr, ND-GAr, SAND	Systematics

**Non-Argon options currently under consideration for Phase-II near and far detectors not shown*

The LBNF facilities at both the near and far sites support Phase-II beam and detectors from the beginning (part of Phase-I scope) — simplifying Phase-II implementation

Significant UK involvement or leadership

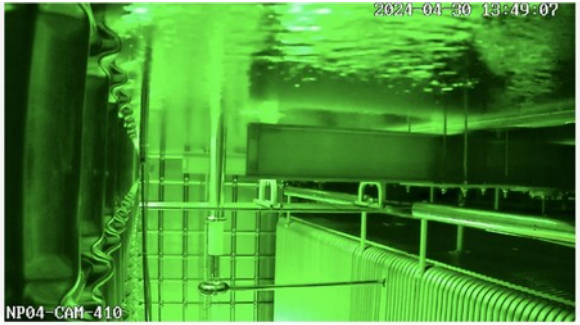
DUNE Recent Milestones

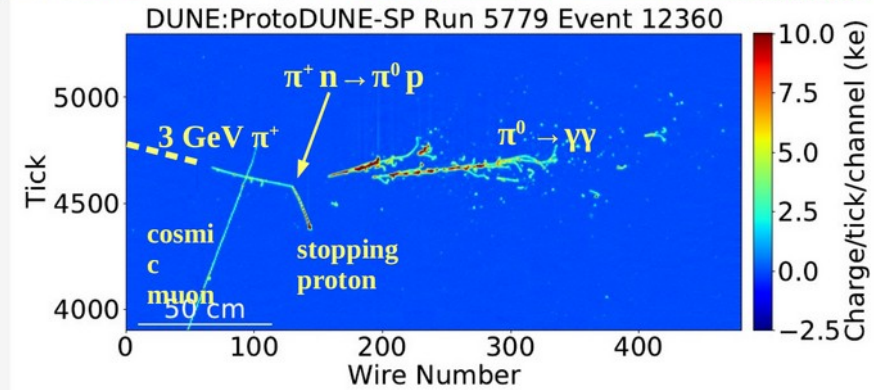


- **Far site** excavation complete, cryostat warm structure to be installed 25-26.
  - FD installation in 2026-27.
  - Purge and fill with argon in 2028.
  - Physics in 28-29. Beam physics with ND 2031.
- **ND-LAr 2x2 prototype**: DUNE's 1st detector in a ν beam.
  - Pandora NDLAr 2x2 (native 3D SW).
  - Support build, calibration, operations.
- Recent signing of Construction MOU, RRB (resource rev. board) approval & P5.
- UK projects PIP-II and Target funded to completion and largely on schedule.
- The DUNE-UK projects: APA, Recon. & Computing approved and DAQ in progress.

ProtoDUNE and CERN Neutrino Platform

The CERN Neutrino Platform is CERN's undertaking in neutrino physics at particle accelerators worldwide, as recommended by the 2013 European Strategy for Particle Physics. Including Icarus, Baby MIND and ProtoDUNE.





ProtoDUNE

- Successful prototype of horizontal drift at CERN Neutrino Platform in 2018 (ProtoDUNE-SP).
- ProtoDUNE-HD completed filling 30th April, running since May, with beam from 20th June.
- LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025.

DUNE The Future

- All Phase-II elements are essential to realise DUNE’s full physics potential, as strongly endorsed by P5 and ESPP.
- Significant progress towards defining a baseline for Phase-II FD & ND.

Detector requirements and concepts are being developed. Key R&D goals have been identified, prototyping plans underway.

– **FD** Module 3 and Module 4 (Module of Opportunity).

Module 4 – ARIADNE and SoLAR

NDGAr

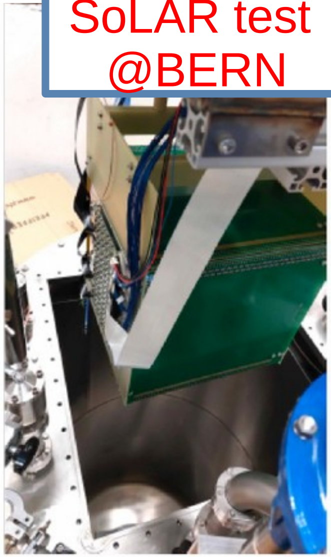
- Pixel readout Qpix and SAMPA ASIC.

A DUNE Phase-II White Paper nearing completion,will be made public soon.

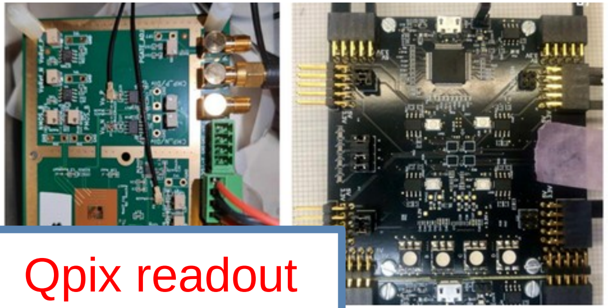
- FD3 cryostat installation could start in 2029, with FD3 filling in 2034. ND-GAr and FD4 would follow after that.

ARIADNE 1-ton Test @Liverpool

SoLAR test @BERN



TOAD



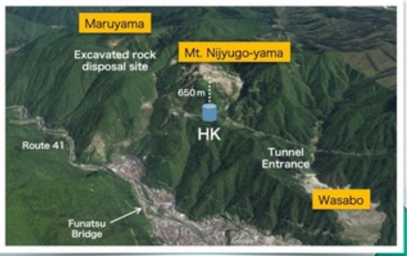
Qpix readout

• All Phase-II elements are e
physics potential, as strong

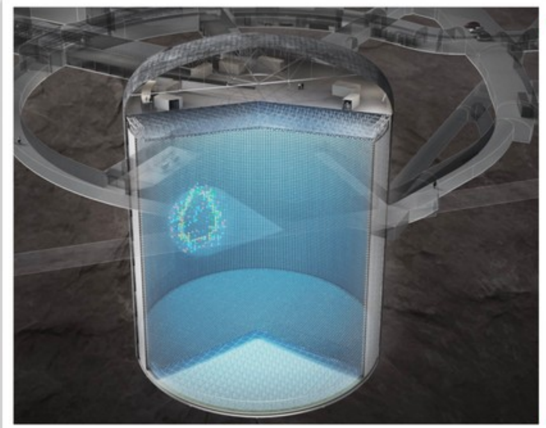
Hyper-K

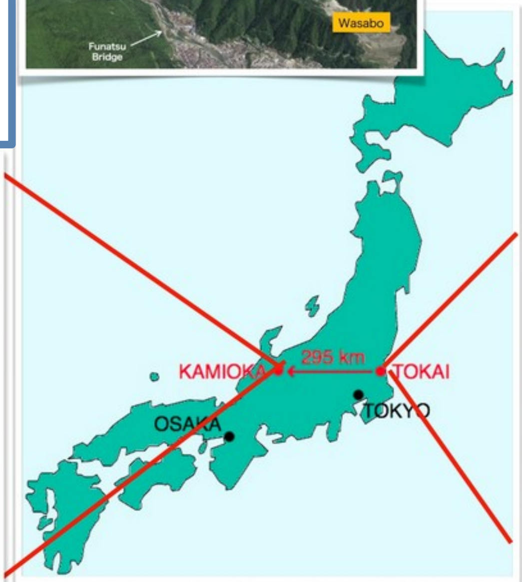
- 9 UK Institutes and > 90 UK members.
- UK leadership in DAQ, Calibration, Analysis, Computing, Outer Detector, Beam components, International Spokesperson and several committee leads I.e. Speakers'' Board, Pub Board, EDI, Outreach...

650 metres (2,130 ft) under the peak of Nijuugo Mountain

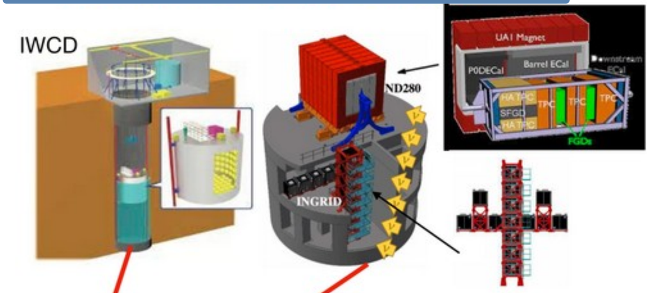


Hyper Kamiokande (FD)
295 km baseline,
188 kton WC detector

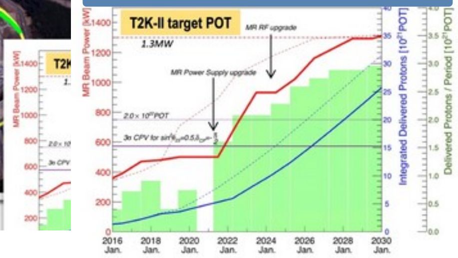




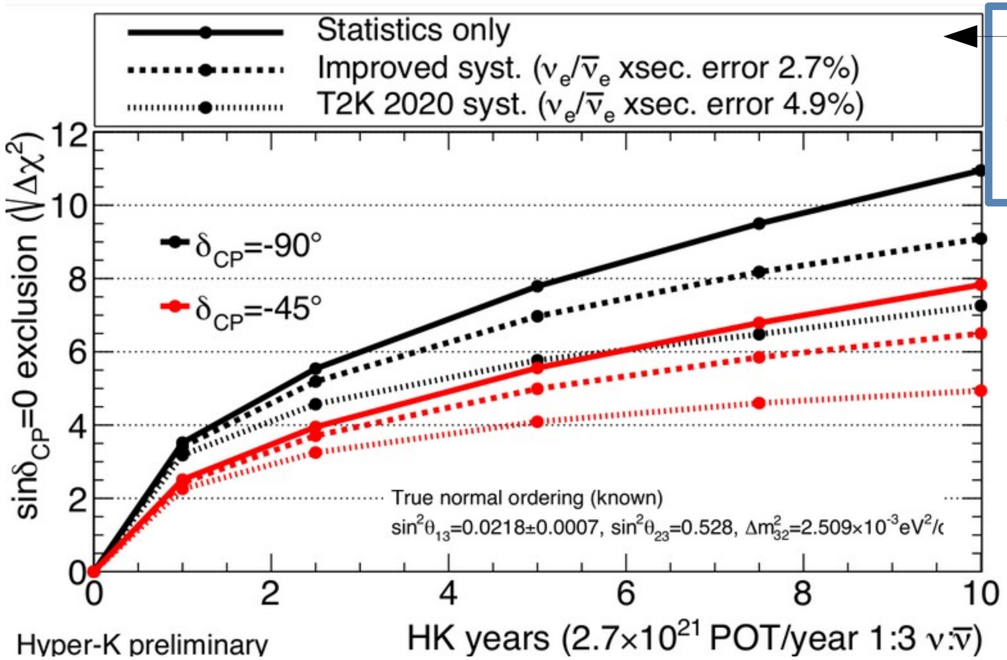
Near Detector suite



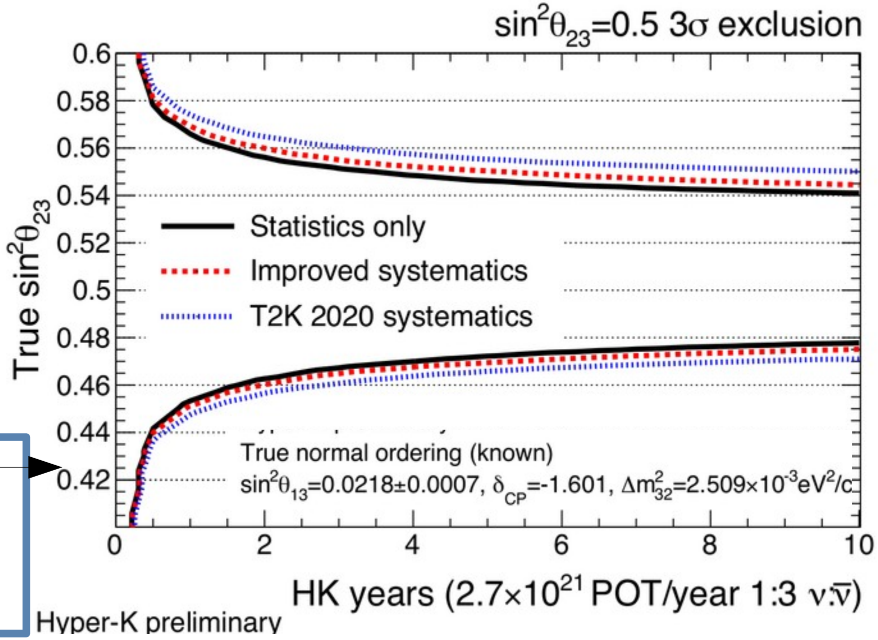
1.3 MW
Beam @ JPARC



Hyper-K Physics



Sensitivity to exclude sin δCP=0 for a 1.3MW beam running 1:3 with ν:ν (best current estimate). HK-years for true δCP=− π/2 and δCP=−π/4

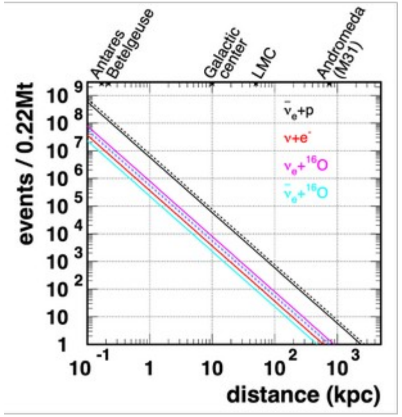


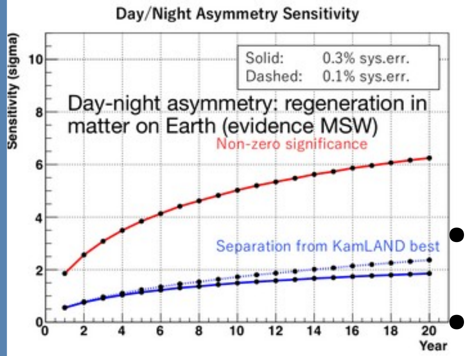
$\sin^2(\theta_{23})$ = 0.5 exclusion sensitivity

For a true value of $\sin^2(\theta_{23})$,

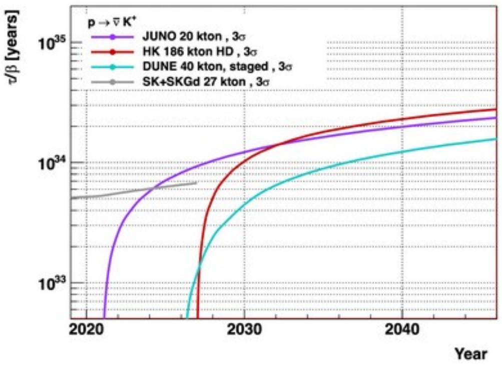
how much can they exclude $\sin^2(\theta_{23})$ = 0.5?

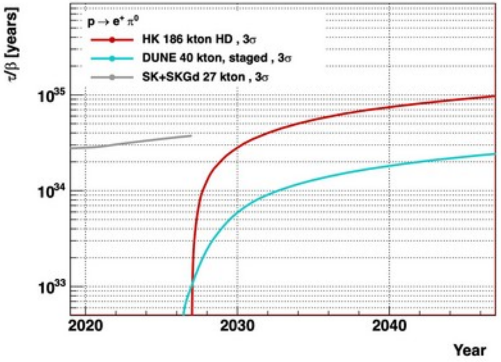
Hyper-K Physics



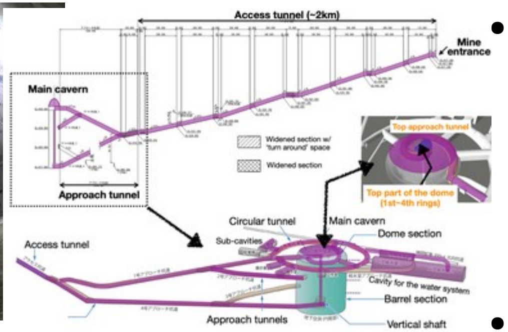


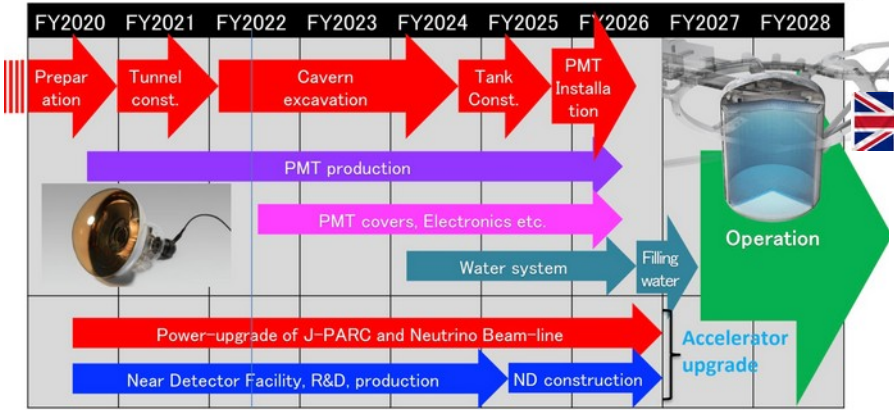
- Sensitive to neutrinos from core-collapse supernova and integrated relic supernova neutrino background.
- Solar Neutrino physics including day night asymmetry and upturn.
- Proton decay searches made possible by scale and design → Only realistic chance of achieving $\tau(p \rightarrow e^{+}+\pi^{0}) > 10^{35}$ years.
- Astro-neutrinos and dark matter.
- Atmospheric neutrinos (MO determination).
- ....





Hyper-K Recent Highlights and Major Plans

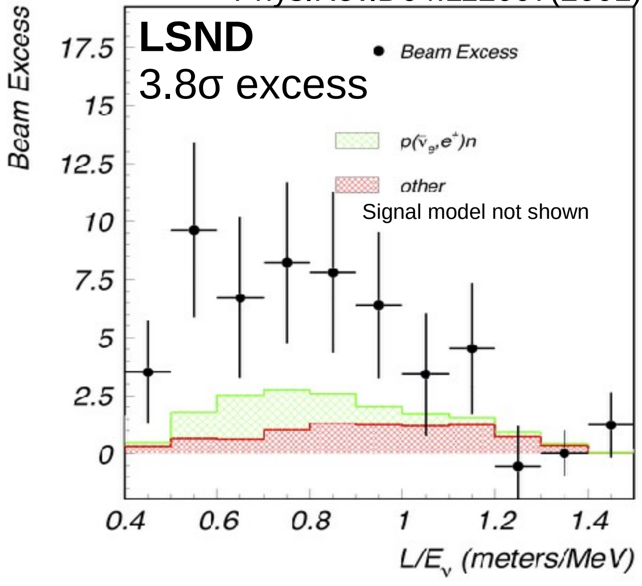




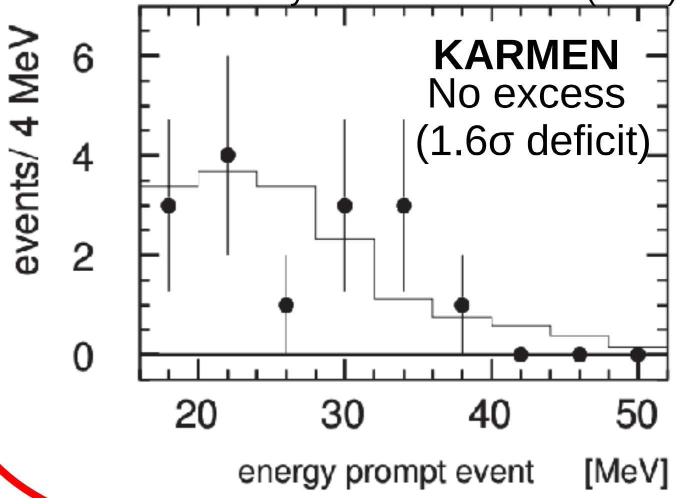
- Far Site Access tunnel excavation complete. Approach, circular tunnel and dome excavation completed. Main cavern excavation has started on-time. Barrel section ongoing.
  - To be completed Autumn 24.
- Construction of 258 kton volume water Cherenkov detector tank → Oct 24 - Oct 25.
- Outer detector 8 cm PMTs with WLS plates, and electronics, production ongoing.
- Inner detector PMT production, covers and electronics ongoing and on target.
- Major near detector upgrades: ND280++ in 2028+.
  - Including upgrading the ECaL → replace all the MPPC's and electronics.
- Operation on target for Dec 2027 start.

Short-Baseline Neutrino Experiment Anomalies

Phys.Rev.D64:112007(2001)



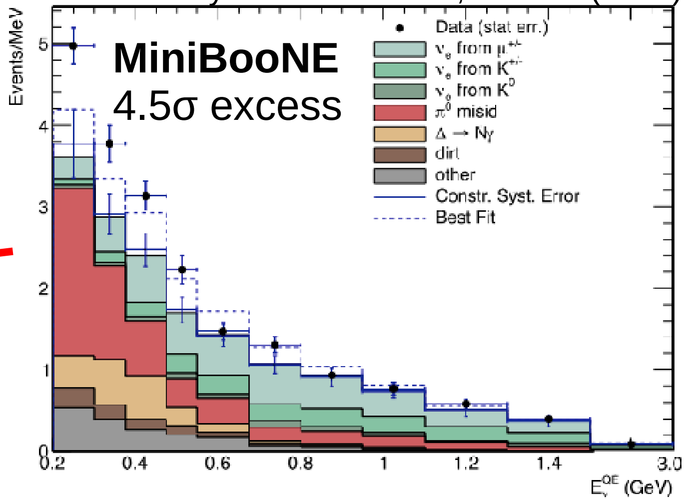
Phys.Rev. D65 112001 (2002)



μ decay-at-rest

π decay-at-rest

Phys. Rev. Lett. 121, 221801 (2018)



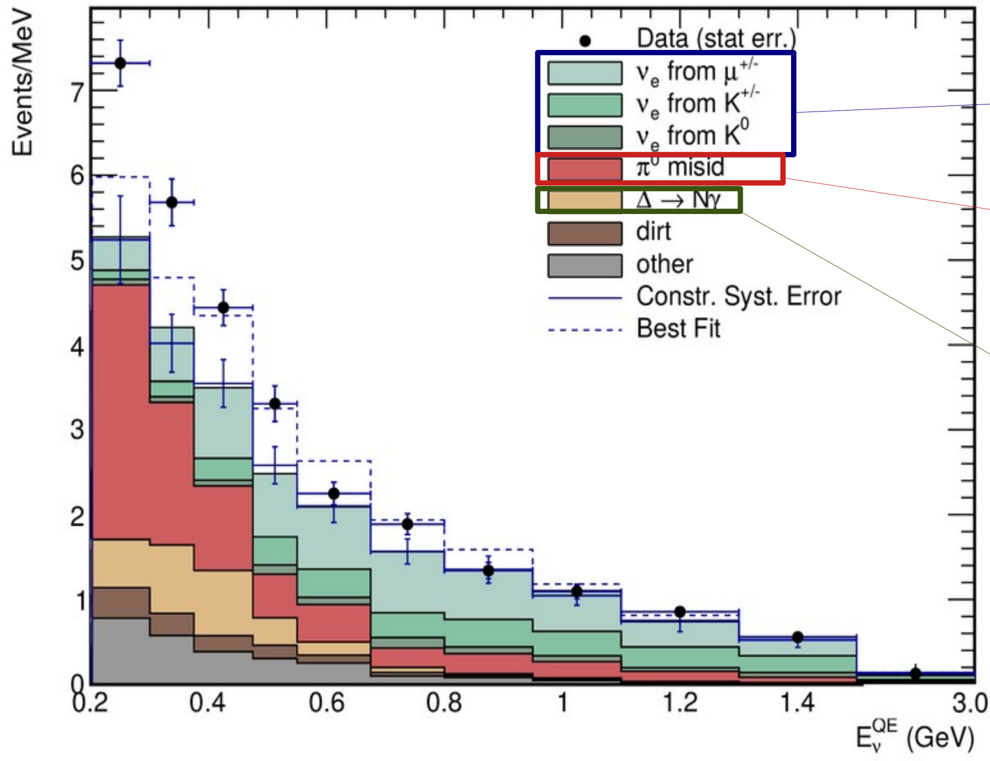
π decay-in-flight

Definitive test of short baseline ν_e appearance requires new experiments and detector technology:

→ enter the **SBN** programme.

The MiniBooNE Low Energy Excess

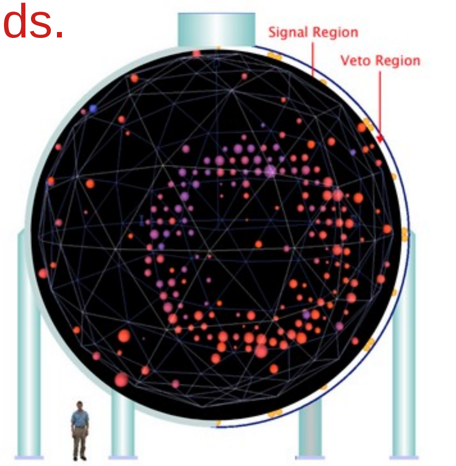
MiniBooNE Electron-like selection has a lot of photon backgrounds.



Flux?

Mis-ID'd pi-zero background (measured in-situ).

Mis-ID'd photon background?



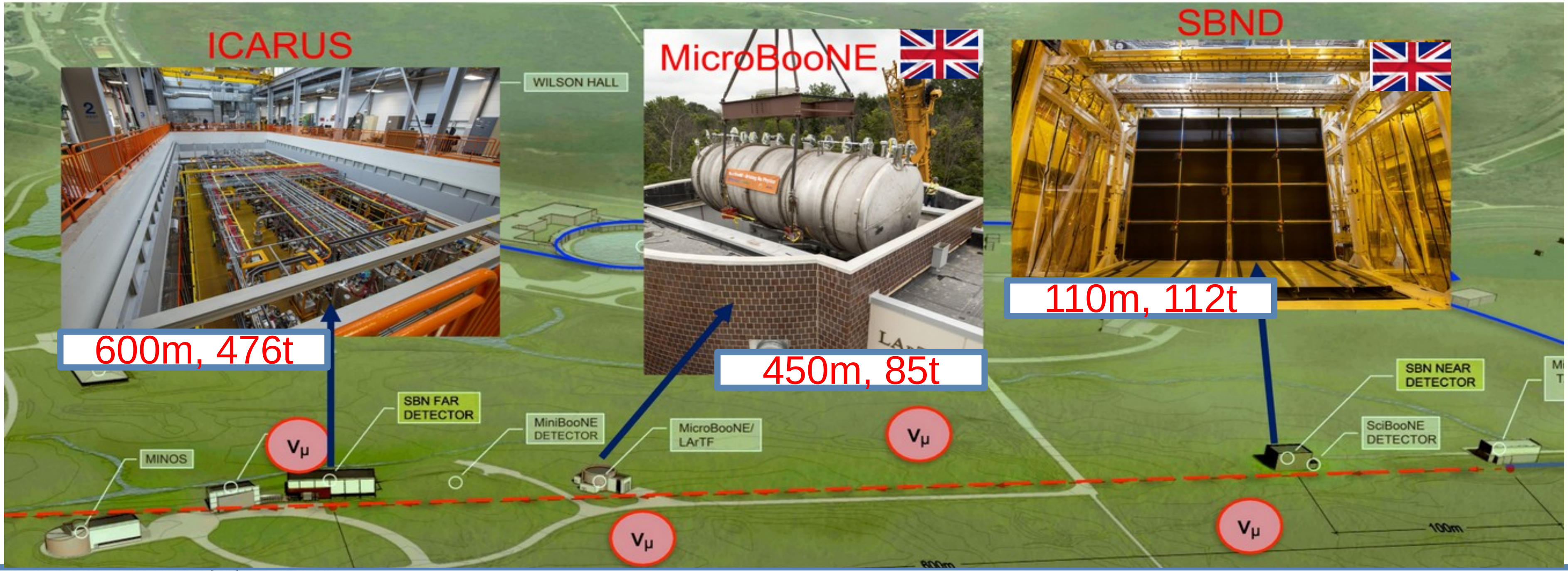
Event display: MiniBooNE collaboration

Or real electron neutrino appearance?

Sees 4.5σ excess in neutrino mode, 4.7σ in antineutrino mode.

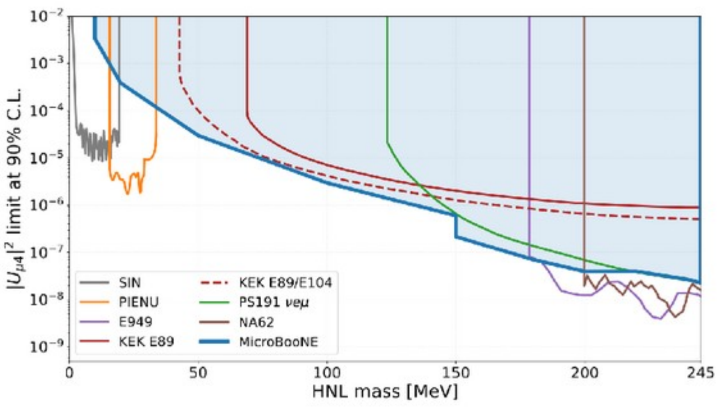
FNAL SBN Programme

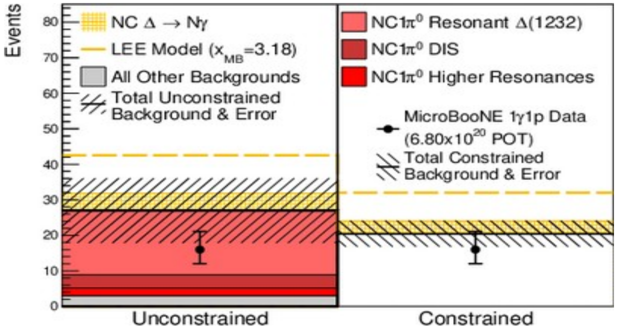
- 11 UK institutions and >90 UK members.
- MicroBooNE – UK spokesperson, Physics Coordinator, many conveners.
- SBND – UK led construction of key elements, including 50% of wire planes and all APA, UK Physics Coordinators, IB chair, Executive Committee members, many conveners.



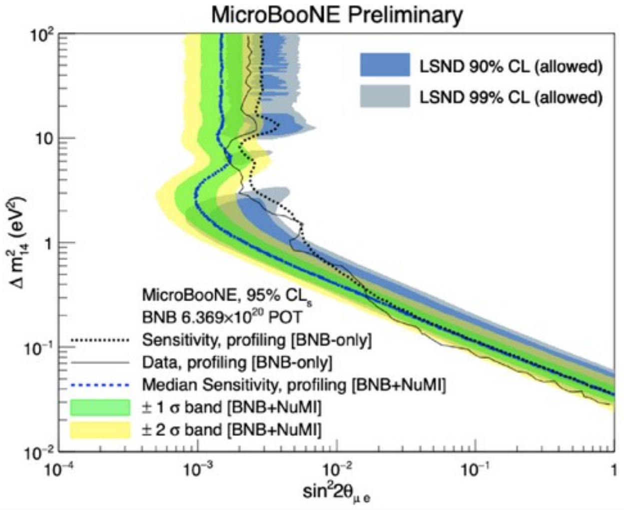
MicroBooNE

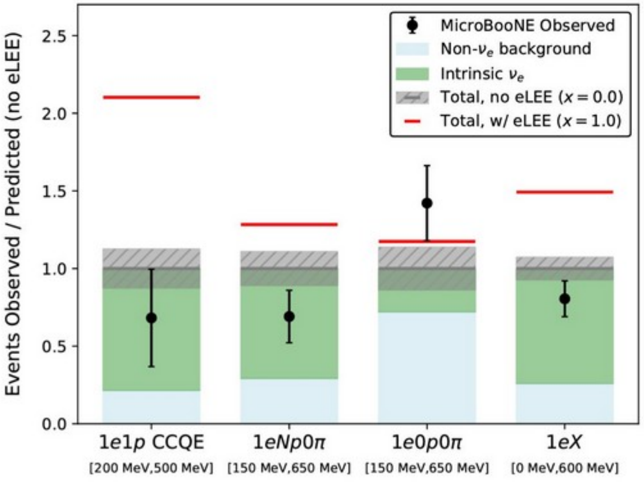
- Photon-like: explanation of LEE disfavoured at 94.8% CL.
- Electron-like: Results consistent with nominal ν_e rate expectations from BNB → no excess of ν_e events observed. Reject the hypothesis that simple charged current ν_e fully explains the MiniBooNE excess at >97% CL in all analyses.
- Joint sterile 3+1 analyst with BNB + NuMI allows enhances sensitivity.
- Most stringent constraints on $|U_{\mu}^4|^2$ for 34 < mHNL < 175 MeV.
- **Next 5-15 yrs → precision measurements: X sections, rare and BSM processes.**





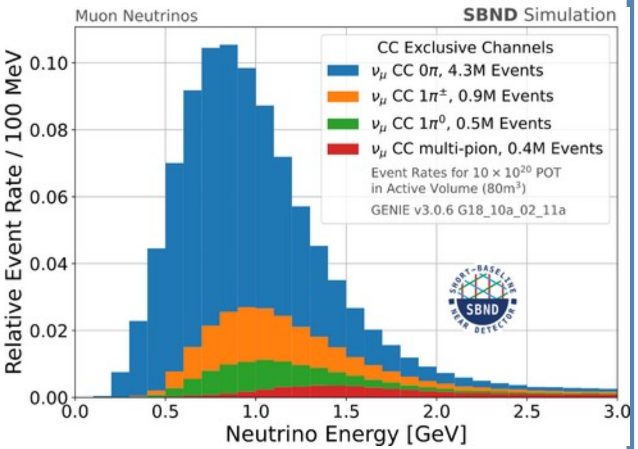
	$1\gamma 1p$
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	4.88
LEE ($x_{MB} = 3.18$)	15.5
Data	16

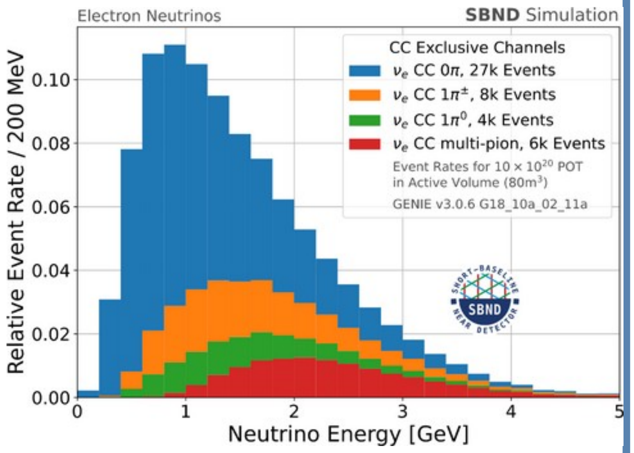




SBND

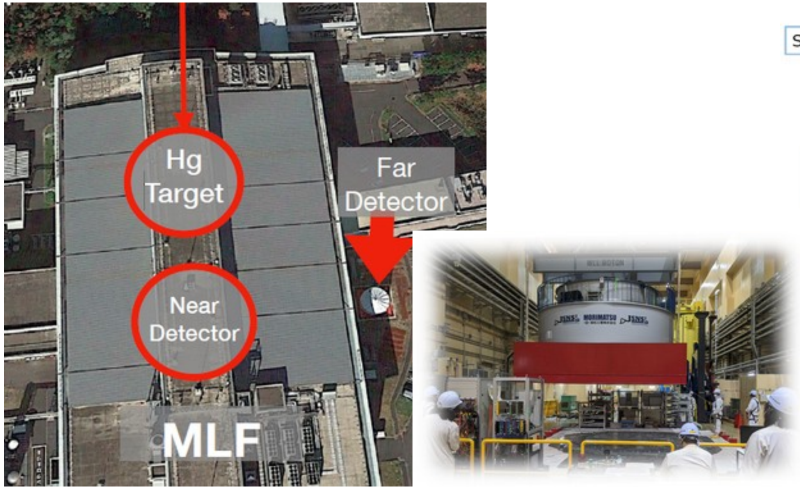
- SBND experiment installation finished and is commissioning.
- The highly-capable LArTPC detector technology + close proximity to the BNB target + resulting high statistics = enables a wide variety of measurements.
- SBND-PRISM provides a unique opportunity to probe different neutrino fluxes within the same stationary detector.
- SBND expects approximately 2 million ν_μ CC and 15,000 ν_e CC interactions per year, and will collect beam neutrino data over the course of a ~3 year run.
- Will record an order of magnitude more neutrino–argon interactions (GeV) than currently available.
  - Common channels: multi-dimensional differential measurements.
  - Rare channels:~ SBND can make measurements that are limited in other existing experiments (NC N_p 1_γ, ν_e elastic scattering, $\bar{\nu}_\mu$ CCQE hyperon production, $K^+ + \Lambda^0$).

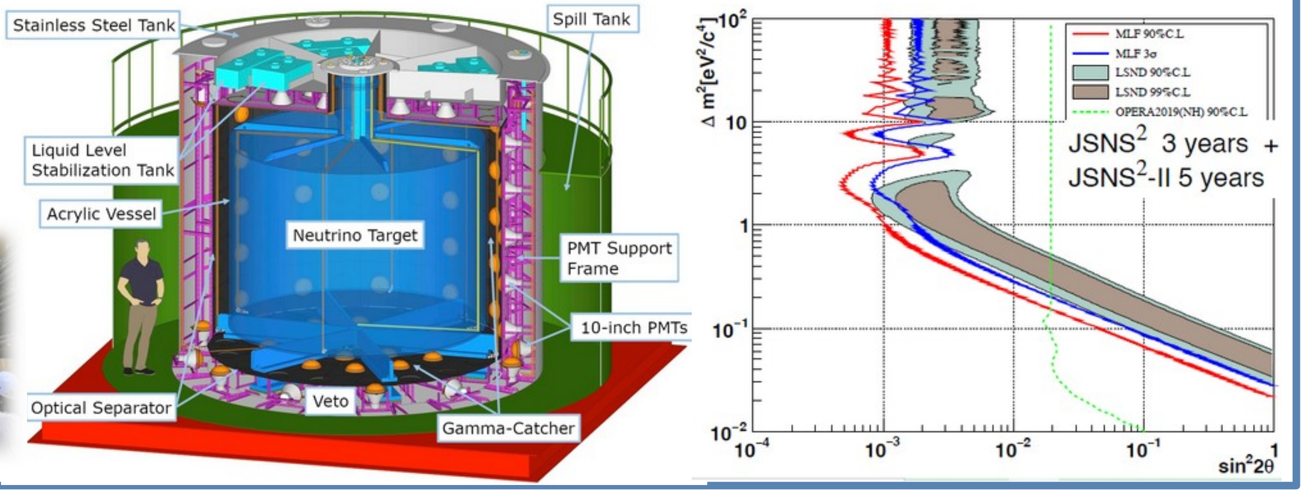




JSNS^2

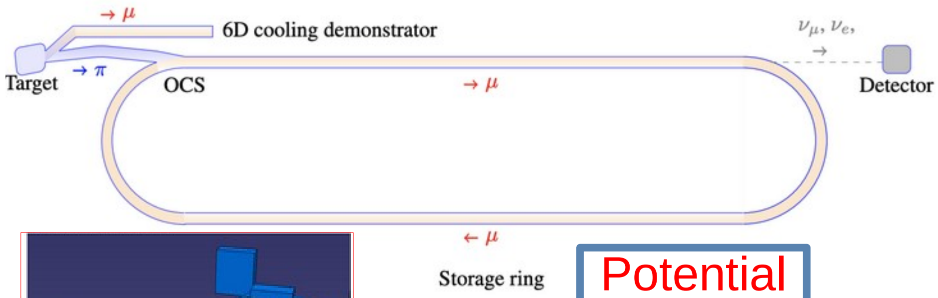
- 23 international institutions, 1 UK institution (of only 4 non Asian).
- 1MW, 3GeV pulsed proton beam @JPARC MLF. ND (24 m baseline) – 17 tonnes Gd-LS w/ 10% DIN; FD (48 m baseline) – 32 tonnes Gd-LS w/ 10% DIN.
- Far detector construction began in 2021, data taking expected in the 2024-2025 run period.
- With 1 MW x 3 years observed POT (currently acquired 42.5%), cover the majority of the LSND observation region at 90% CL. UK supplied 2 LED calibration sources.



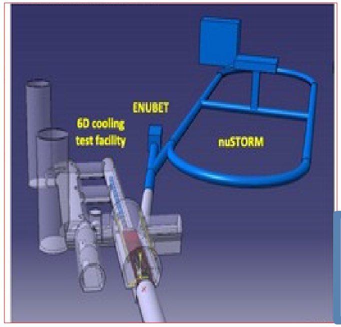


NuSTORM

- UK leadership and 15 UK institutes involved. **5-15 year timescale!**
- NuSTORM → neutrino beams from muon decay in a storage ring → beam with well defined spectrum. → cross-sections with %-level precision necessary for LBL programme.
- Muons in the 1–6 GeV/c momentum range, relevant to LBL experiments.
- Step towards a muon collider, proof of concept for muon storage rings, a test for beam monitoring and magnets.
- Could combine with ENUBET to mutual benefit.

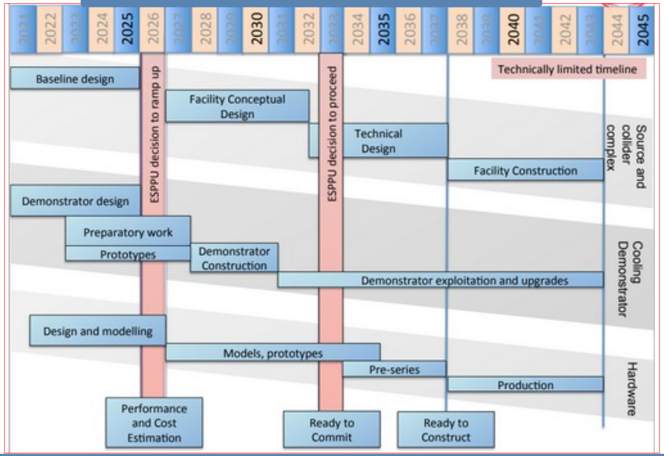


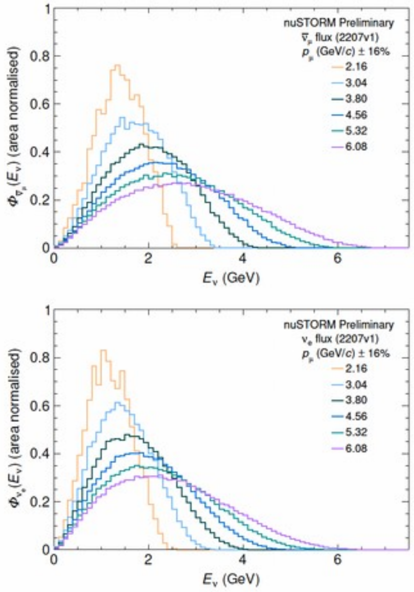
Potential design



Potential Layout

Rough timeline





Flux simulation

PPAP Roadmap 2021

The 2020 ESPP update **identifies experimental neutrino physics as a high priority area** in the quest to address the shortcomings of the Standard Model. In the next **20 years the key questions for neutrino physics are measuring the parameters that govern neutrino mixing,** establishing whether the neutrino is its own anti-particle (i.e. whether neutrino is a Majorana or Dirac particle), measuring the absolute masses of neutrino states and **understanding whether a sterile neutrino could contribute to anomalies in oscillation data observed by some experiments.**

PPAP Roadmap 2021

Recommendation 6.1: The UK should maintain its leading role in long-baseline neutrino oscillation experiments. Exploitation of the currently running experiments should be supported. In the next 10-20 years the main priority will be on measuring the CP-violating phase of the mixing matrix and the neutrino mass ordering with the long-baseline programmes in Japan and USA. The UK should continue to engage with both programmes. In particular, it should maintain its leading involvements in LBNF/DUNE.

Recommendation 6.2: To extract the most physics out of the long-baseline neutrino experiments the UK should build on its existing expertise to pursue a complementary programme of precision measurements of neutrino interaction cross-sections and neutrino fluxes. In addition, recently emerged opportunities of detecting collider neutrinos, that allow measuring neutrino cross sections at energies where they are currently unconstrained, should be pursued.

PPAP 2024 – So what's new

- Strong and diverse progress towards all our PPAP 2021 neutrino physics goals!
- T2K – Upgrades complete. Data taking at high intensity continues. Joint analyses with both NoνA and SuperK.
- Hyper-K – is now an official approved part of the STFC programme. Construction ongoing and on target.
- NovA – Double the dataset and several joint analyses.
- DUNE – Construction ongoing and on target. UK project funded. International project: signing of the Construction MOU, RRB approvals and P5.
- MicroBooNE – 1st search for LEE steriles & HNLs published, analysis factory...
- SBN (FNAL) and JSNS – data taking begins soon.
- NuSTORM – Solve multiple problems in an exciting way over the next 5-15 yrs.

Accelerator Neutrinos 2029-2039

- Strong UK involvement in 9 accelerator neutrino experiments. There is strength in this diversity.
- Large collaboration LBL experiments are enhanced, supported by and parallel to smaller collab SBL (and beyond) experiments.
  - More bang for our buck!
- Precision measurements of cross sections, rare processes and BSM phenomena vital for the next 10-15 years.
- Long-baseline experiments also need capable near detectors to attain physics goals and maiximise cost benefit and glitzy results.
- Strong UK expertise in targetry, SW, HW, electronics, DAQ and design (and leadership) should be maintained through ongoing projects and support.
  - visibility/outreach → public excitement/funding (avoid the brain drain).
- Field which really does perform → high impact publications / media reports and more...!
- BUT – we need to support these measurements with a strong theory component and cross section modelling→ neutrino theorists and phenomenologists.

Thank you!

Back-up Slides...

Many Thanks To

- Yoshi Uchida
- Dave Wark
- Francesca Di Lodovico
- Jeff Hartnell
- Anna Holin
- Kirsty Duffy
- Simone Peteers
- Sowjanya Gollapinni
- Stefan Soldner-Rembold
- Gary Barker
- Jarek Nowak
- Patrick Dunne

plus many more...

Neutrino beamline upgrades

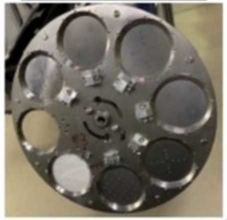
- Replacement of Main Ring power supplies to allow for higher repetition rate from 2.48s to 1.36s
- Several upgrades done on the neutrino beamline to cope with higher beam power
- Horn being operated at 320 kA instead of 250 kA → ~10% increase in the ν flux

New horn PS for 320 kA/1Hz operation

New horns 1 and 2

Increasing cooling capability for the heat generated by beam

New OTR

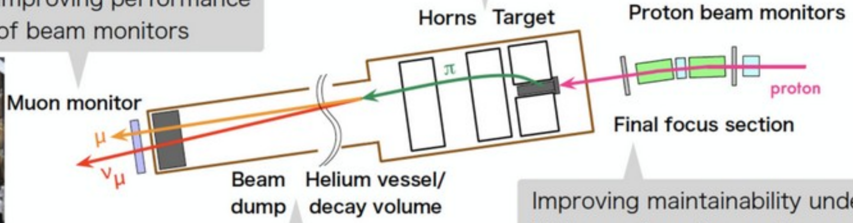


Improving performance of beam monitors

New FVD2 magnet

New target

Improving performance of beam monitors

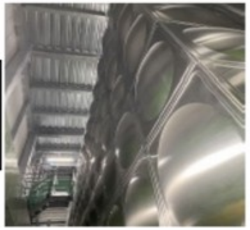


Improving maintainability under higher radio-active environment

Increasing capability of radio-active waste handling

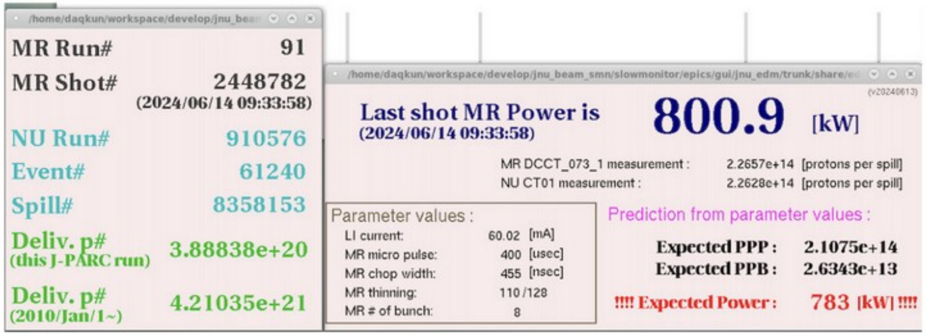
New MUMON Si (Half sensors)

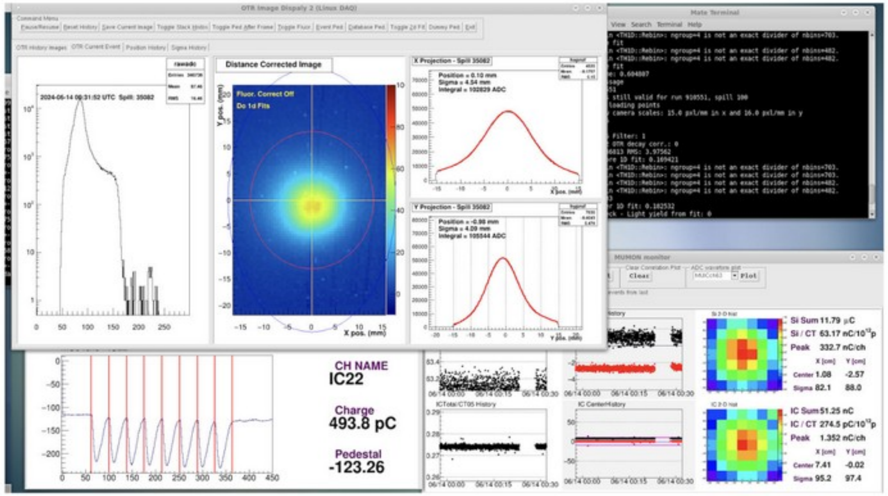
New water tank for radioactive water disposal



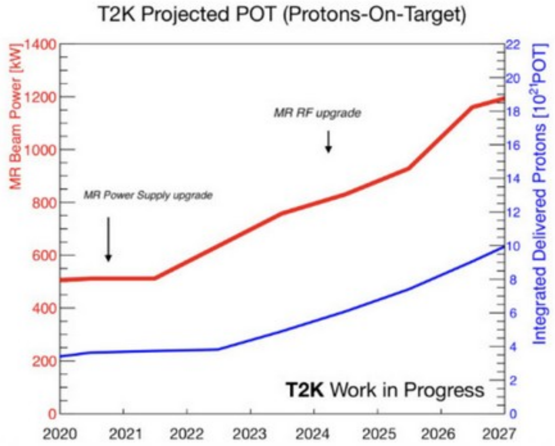
New target cooling system

Towards higher beam power

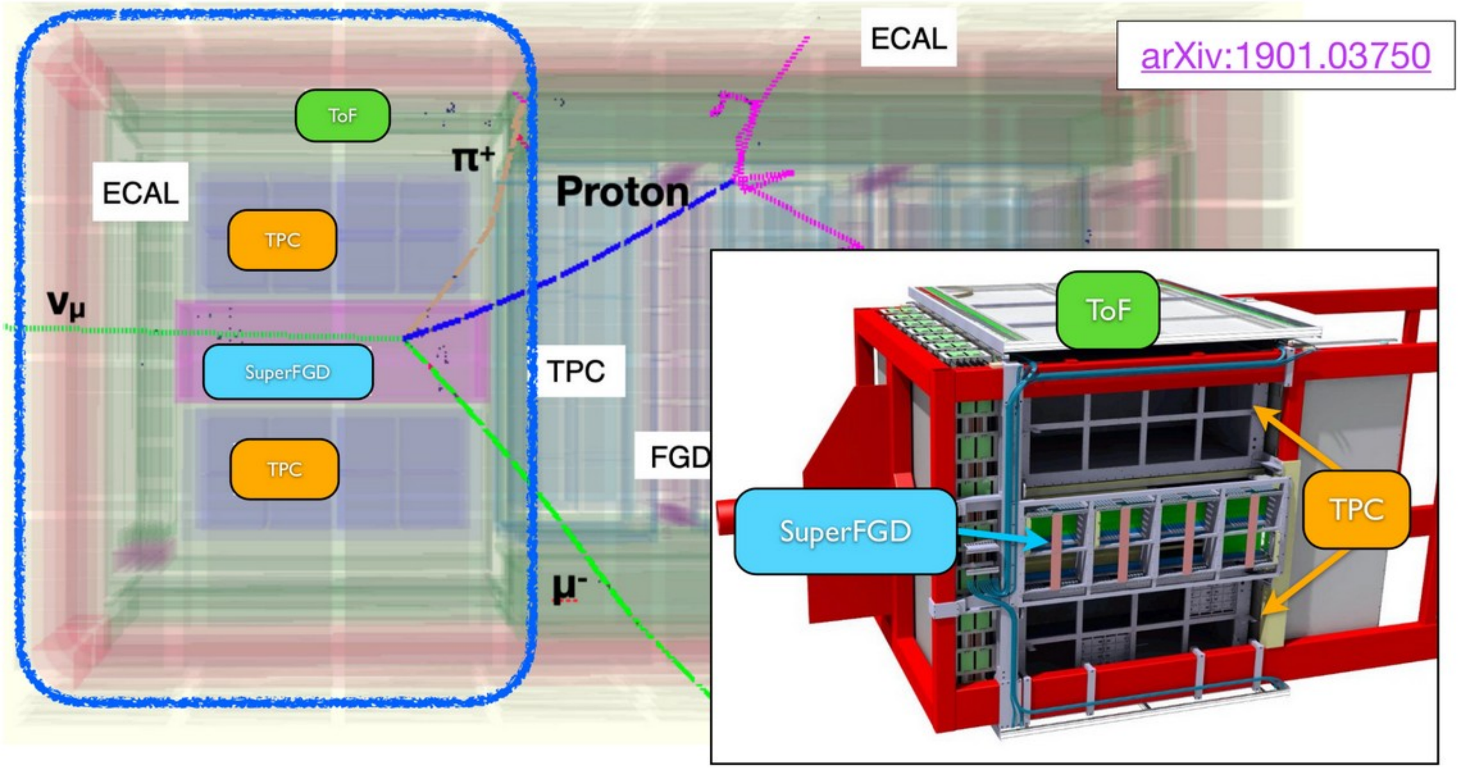




- June 2024 → Beam power increased to 800 kW since last week! (~500 kW before upgrades)
- Steady improvements to reach 1.3 MW by 2027 → increase T2K statistics by a factor of 3 by 2027
- Larger statistics → need to reduce systematic uncertainties → ND280 upgrade

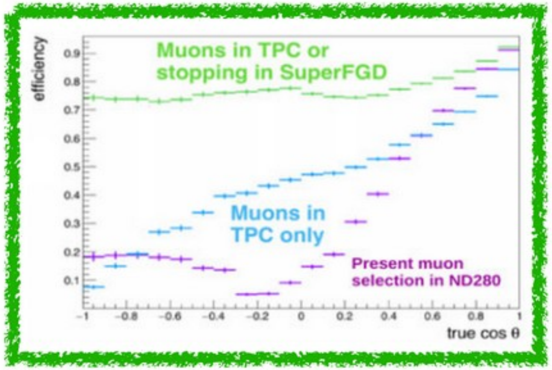


The Near Detector upgrade

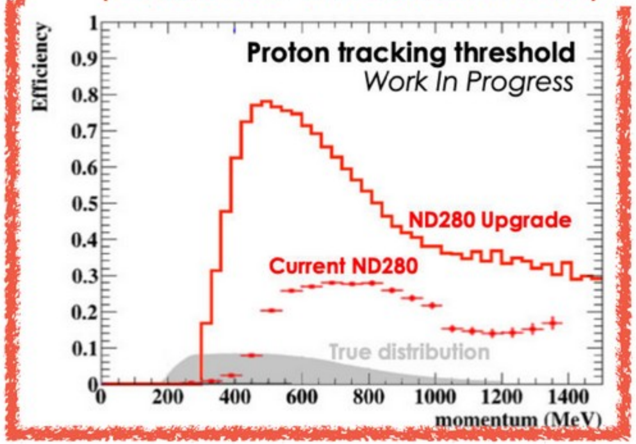


Replace part of the P0D detector (measured NC π^0 production) with
a new scintillator target (SuperFGD), two High-Angle TPCs and six ToF planes

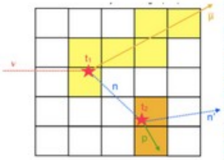
ND280 Upgrade improvements



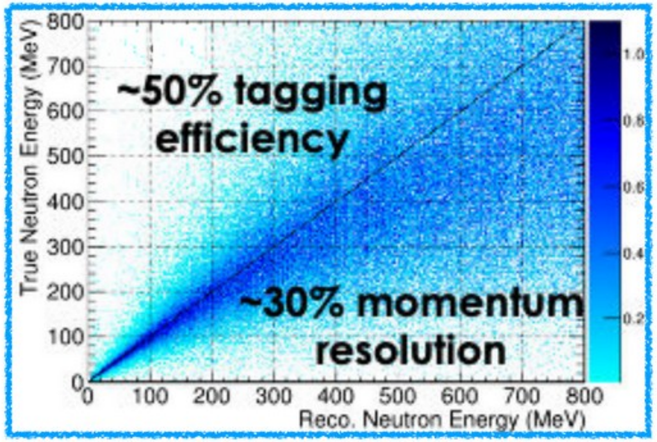
Protons → threshold down to 300 MeV/c
(>500/c MeV with current ND280)



- High-Angle TPCs allow to reconstruct muons at any angle with respect to beam
- Super-FGD allow to fully reconstruct in 3D the tracks issued by ν interactions →lower threshold and excellent resolution to reconstruct protons at any angle
  - Improved PID performances thanks to the high granularity and light yield
- Neutrons will also be reconstructed by using time of flight between vertex of $\bar{\nu}$ interaction and the neutron re-interaction in the detector



$\bar{\nu}_\mu$+p → μ^++n

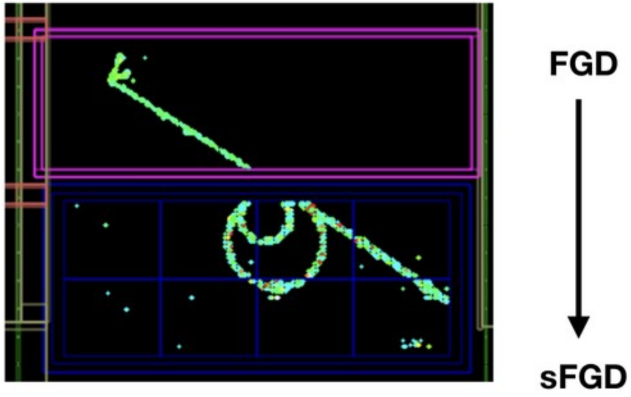


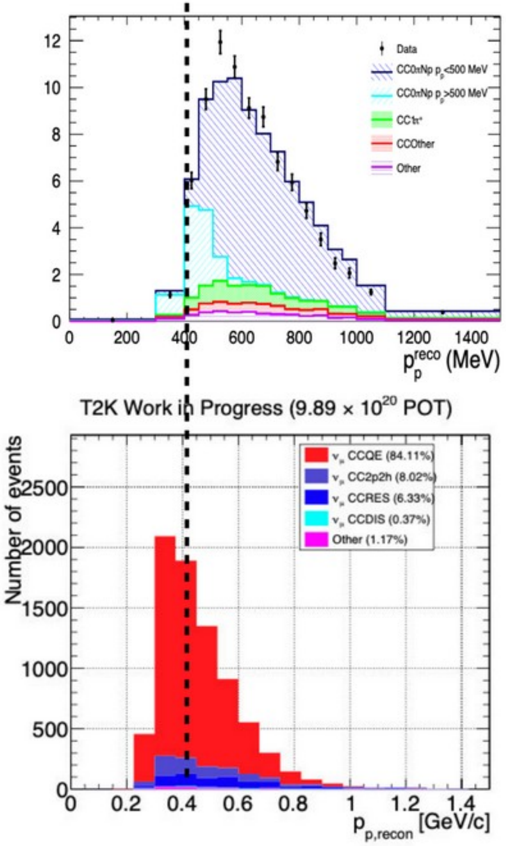
Phys.Rev.D 101 (2020) 9, 092003

L. Kneale, K. Lachner, and W. Li posters

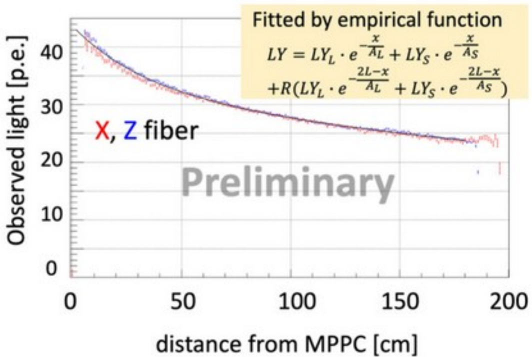
Expected results

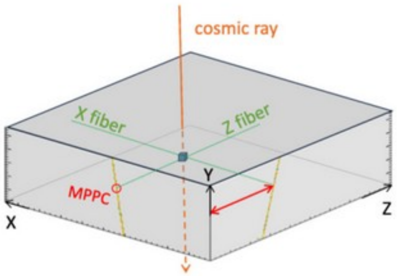
- First physics run with full upgrade currently on-going
- Expect to select 20k ν_μ CC0π interactions in the super-FGD for 1 month of beam
- ~ half of them with a reconstructed proton



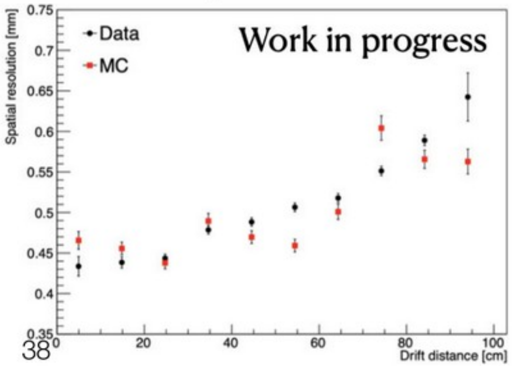


sFGD L.Y. vs distance from MPPC

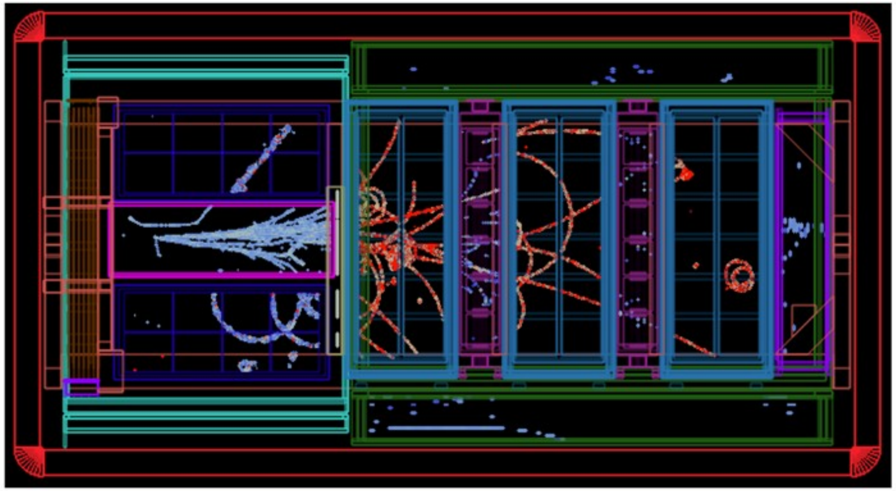


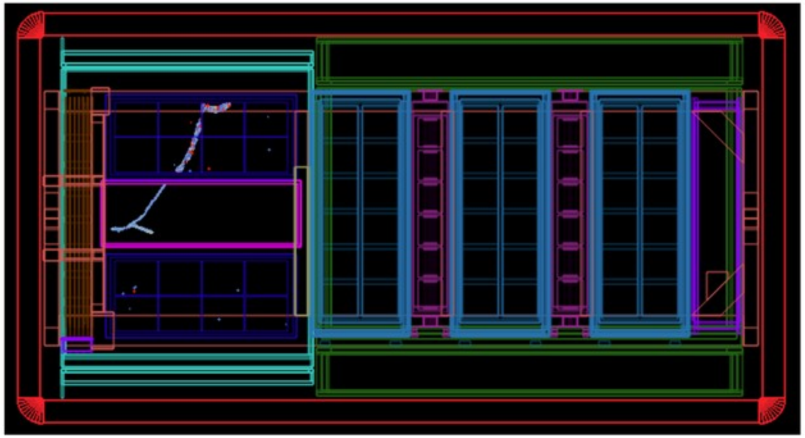


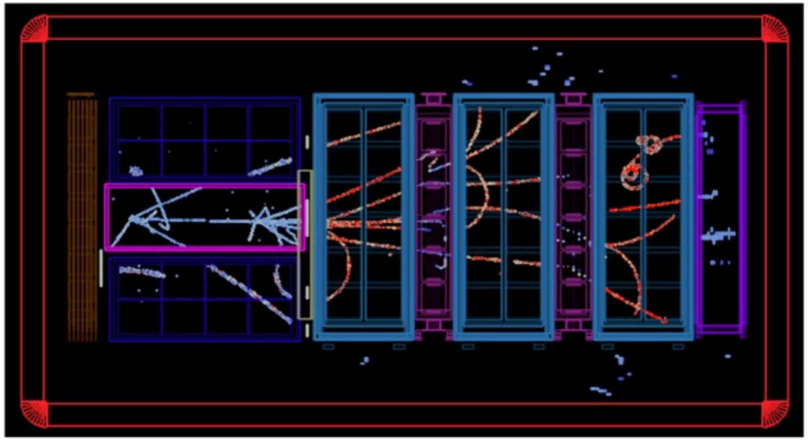
HA-TPC spatial resolution



June 2024: Full upgrade



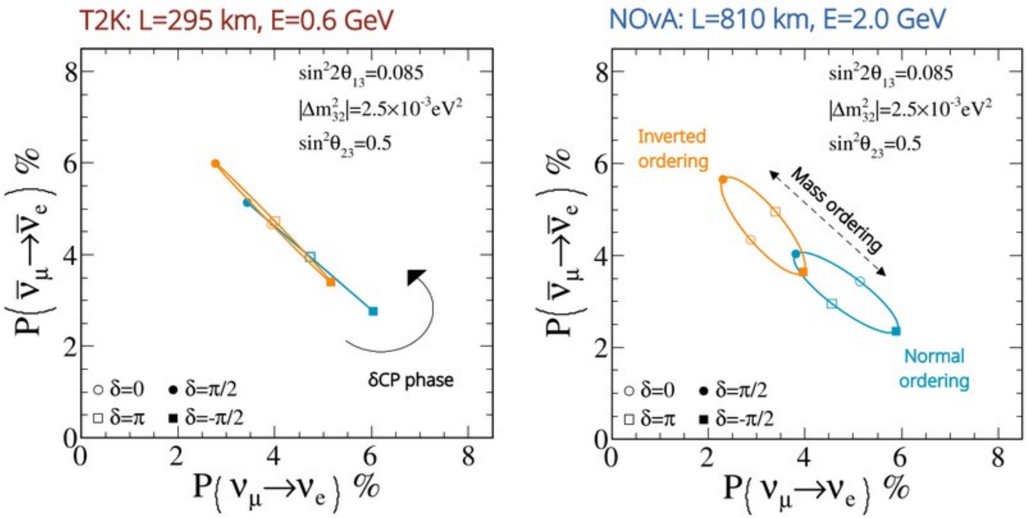




NOvA and T2K are complementary

Compared to T2K*, NOvA has **Higher E_ν**

Larger matter effects



Stronger mass ordering sensitivity;
more δ_{CP} degeneracy

Also...

- More antineutrinos
- More final-state pions

(see overflow slides)

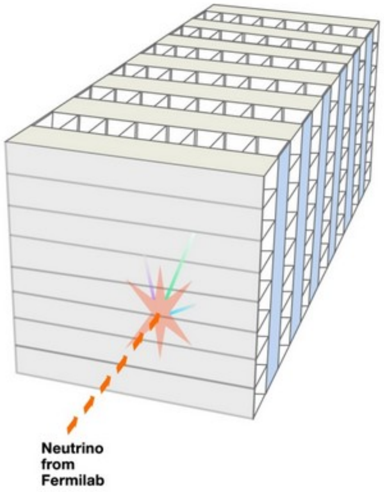
NOvA and T2K are complementary

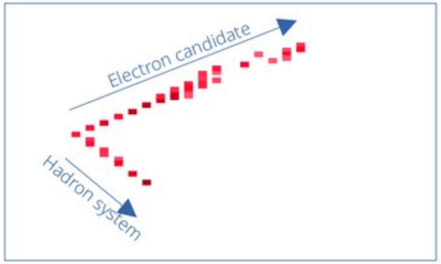
Compared to T2K*, NOvA uses

a different experimental approach

NOvA

active scintillator calorimeters





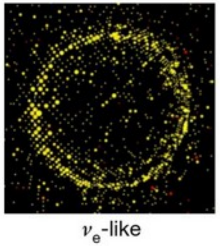
see significant energy from both lepton and hadron systems: "calorimetric" E_ν reconstruction

& functionally equivalent detectors

shared uncertainties mostly cancel

T2K

water Cherenkov FD



see only lepton energy: "kinematic" E_ν reconstruction

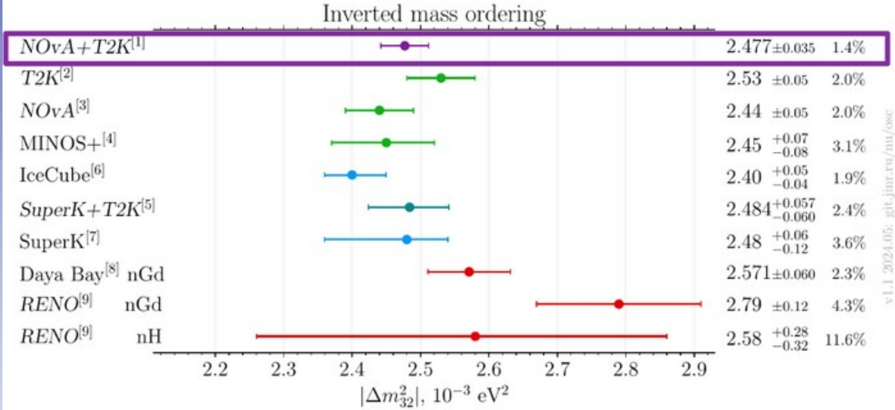
Hybrid gas TPC & scintillator tracker ND

ND+FD shared uncertainties explicitly fitted & constrained via model

NOvA-T2K joint fit: takeaways

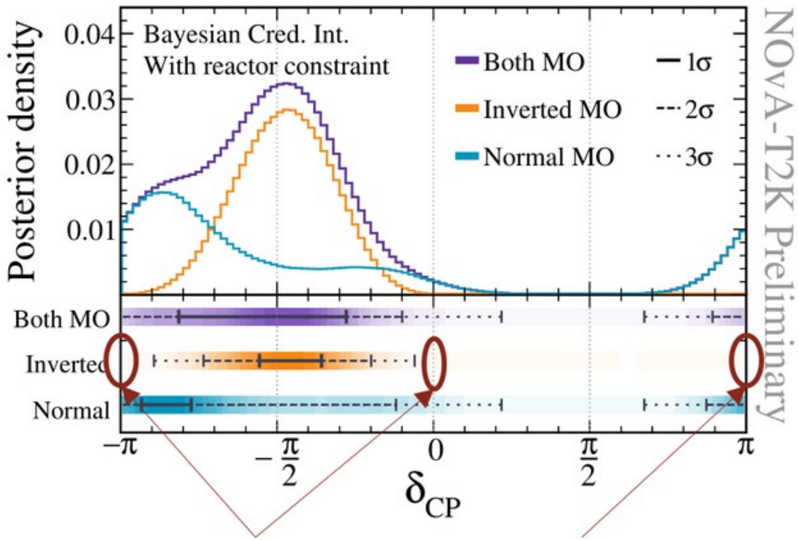
Advancing the precision frontier on $|\Delta m^2_{32}|$

<2% measurement!



Mild preference for Inverted Ordering but **influenced by θ_{13} constraint**

NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)

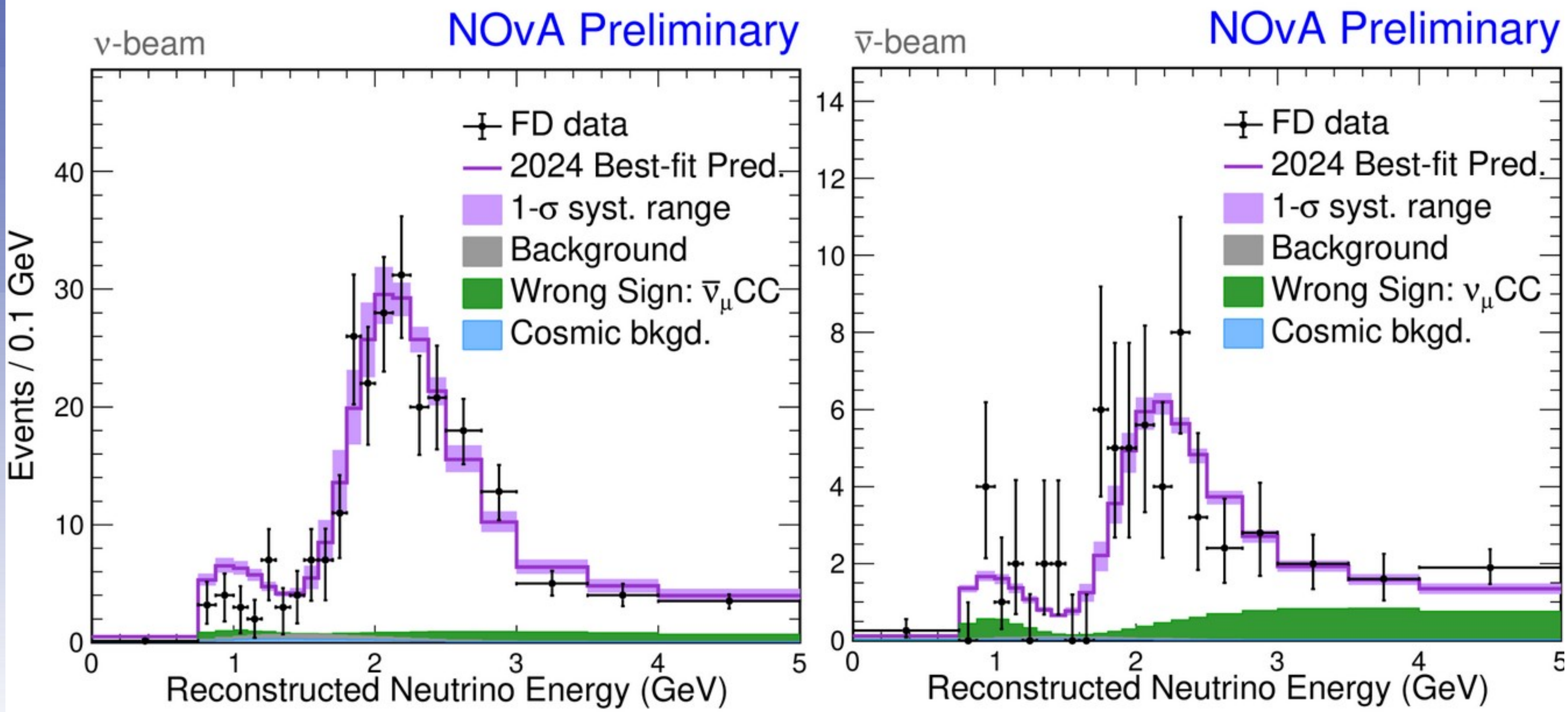


CP-conserving points are *outside* 3σ intervals in IO

Expect CPV *if* ordering is inverted

[1] KEK IPNS seminar, FNAL JETP seminar
[2] Eur. Phys. J. C83, 782 (2023)
[3] Phys. Rev. D106, 032004 (2022)
[5] arXiv:2405.12488
[6] arXiv:2405.02163
[7] Phys. Rev. D109, 072014 (2024)
[9] RENO @ Neutrino 2020 [10.5281/zenodo.3959697]

Far detector observations: ν_μ

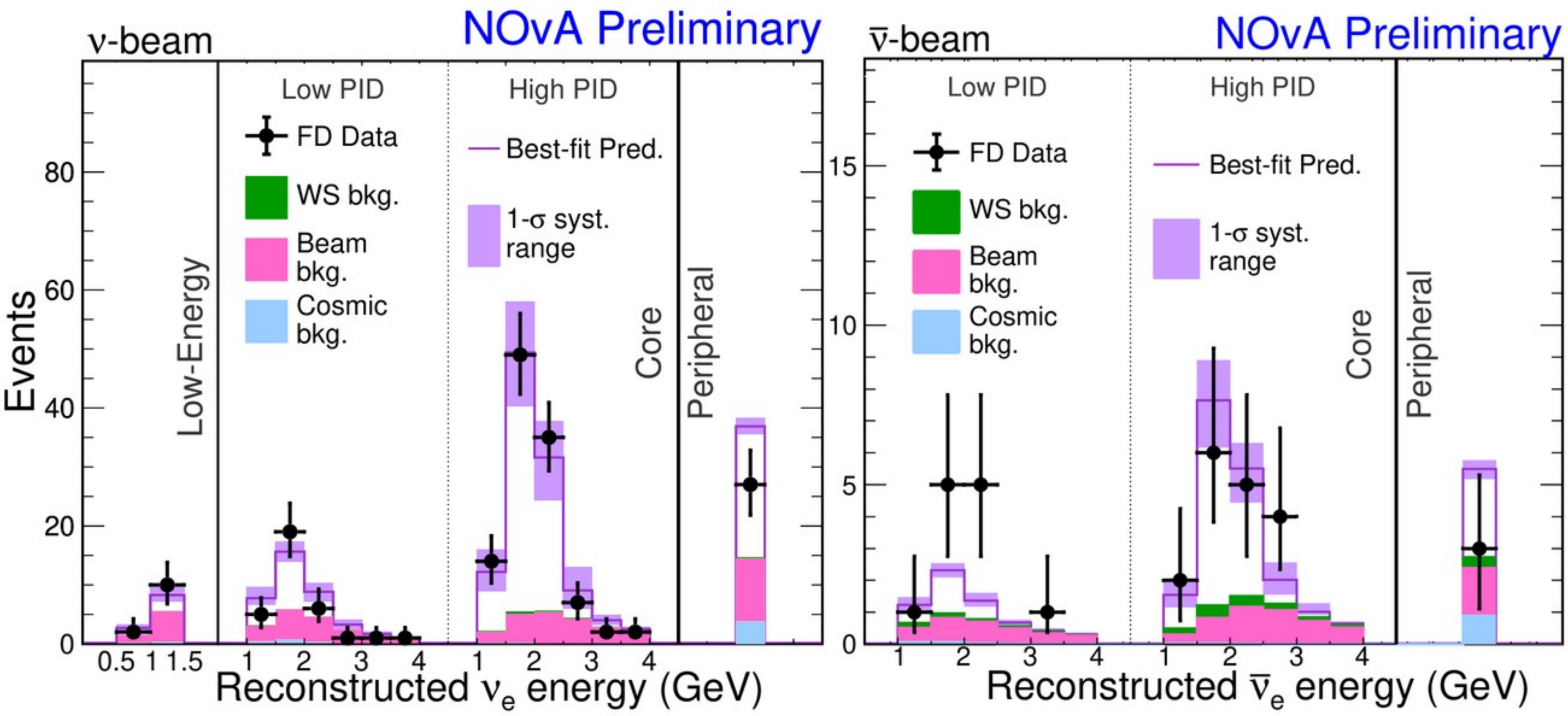


384 ν_μ data candidates
(11.3 background)

106 $\bar{\nu}_\mu$ data candidates
(1.7 background)

3-flavor oscillations describe these data well: Bayesian posterior predictive *p*-value = 0.54

Far detector observations: ν_e



181 ν_e data candidates

	Best fit	Range
Total pred	186.2	119 – 250
Wrong-sign	1.8	1.6 – 2.8
Beam bknd.	53.7	
Cosmic bknd.	6.2	
Total bknd	61.7	61 – 63

32 $\bar{\nu}_e$ data candidates

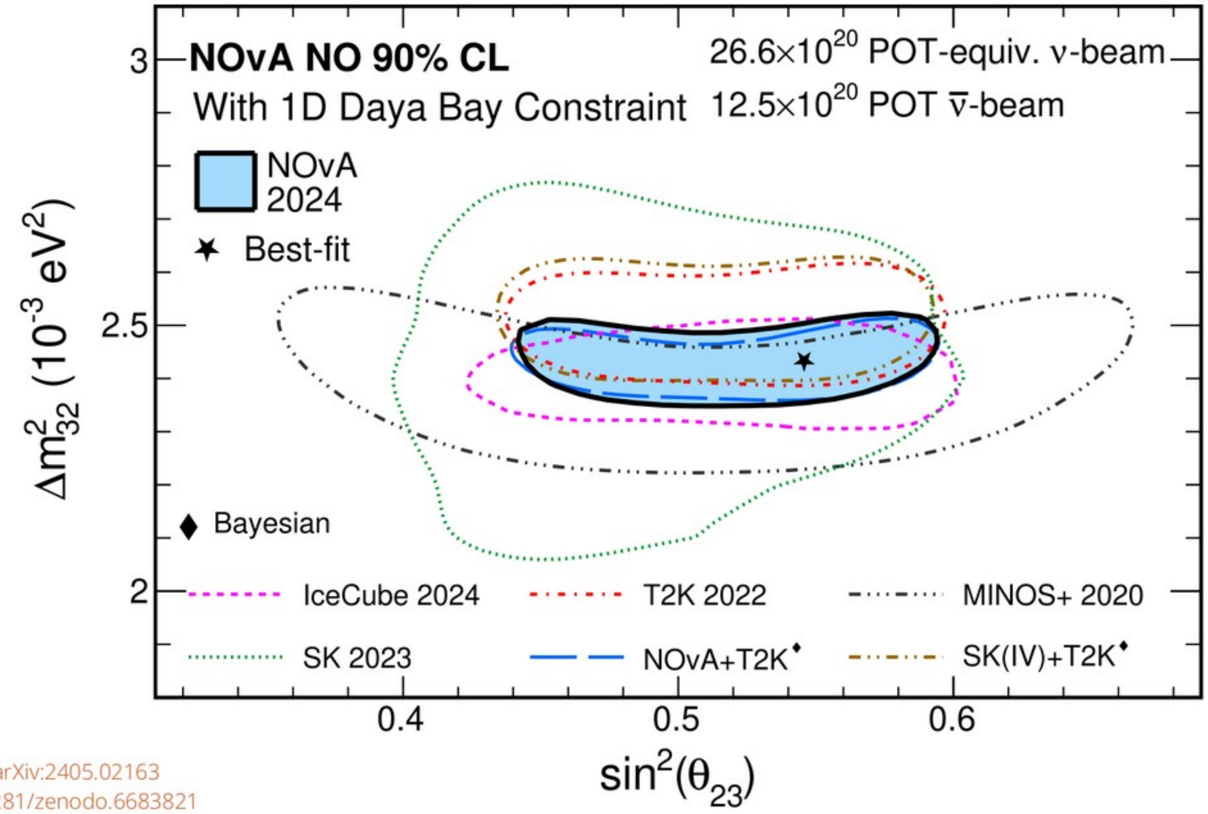
	Best fit	Range
Total pred	30.4	28 – 38
Wrong-sign	2.1	1.0 – 3.2
Beam bknd.	9.0	
Cosmic bknd.	1.1	
Total bknd	12.2	11 – 13

Is $\theta_{23} = 45°$?

Do ν_μ/ν_τ mix equally into ν_3?

$\nu_2 - \nu_3$ sector

NOvA Preliminary

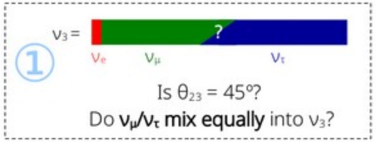


IceCube 2024: arXiv:2405.02163
T2K 2022: 10.5281/zenodo.6683821
MINOS+ 2020: Phys. Rev. Lett. 125, 131802
SK 2023: Phys. Rev. D109, 072014
NOvA+T2K 2024: KEK IPNS seminar, FNAL JETP seminar
T2K+SK 2024: arXiv:2405.12488

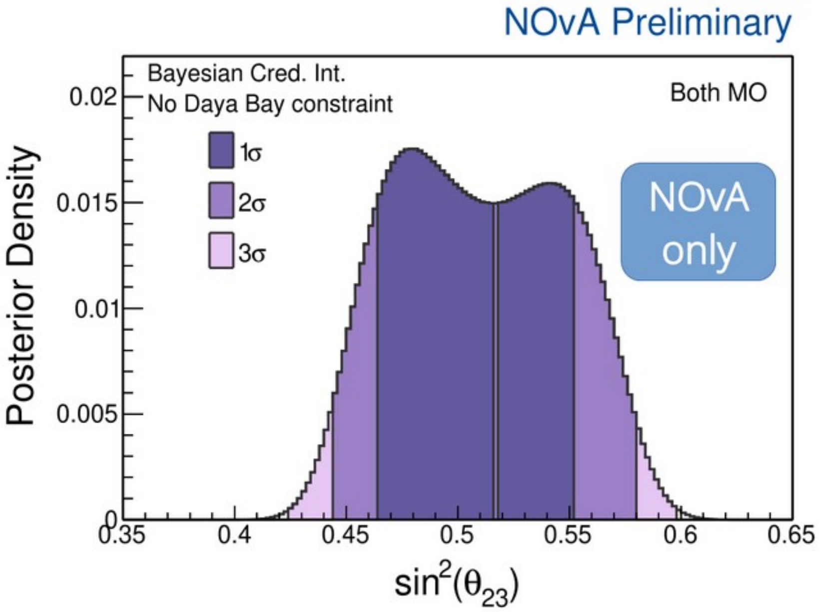
(Frequentist) best fit:

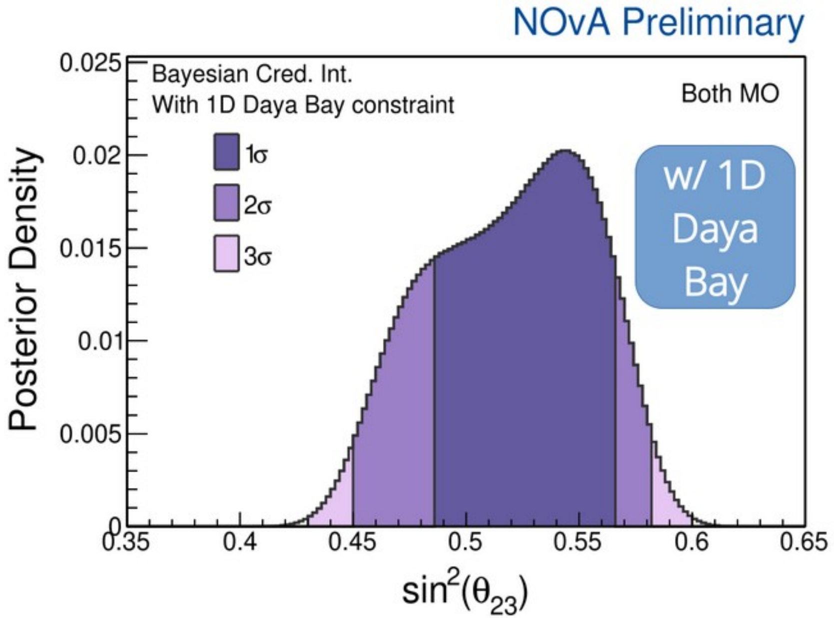
$$\Delta m^2_{32} = \left(+2.433^{+0.035}_{-0.036}\right) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.546^{+0.032}_{-0.075}$$



$\nu_2 - \nu_3$ sector





Mild Upper Octant preference
(69% prob; Bayes factor = 2.2)
emerges from applying reactor constraint
(due to correlation between θ_{13} and θ_{23}, see overflow)

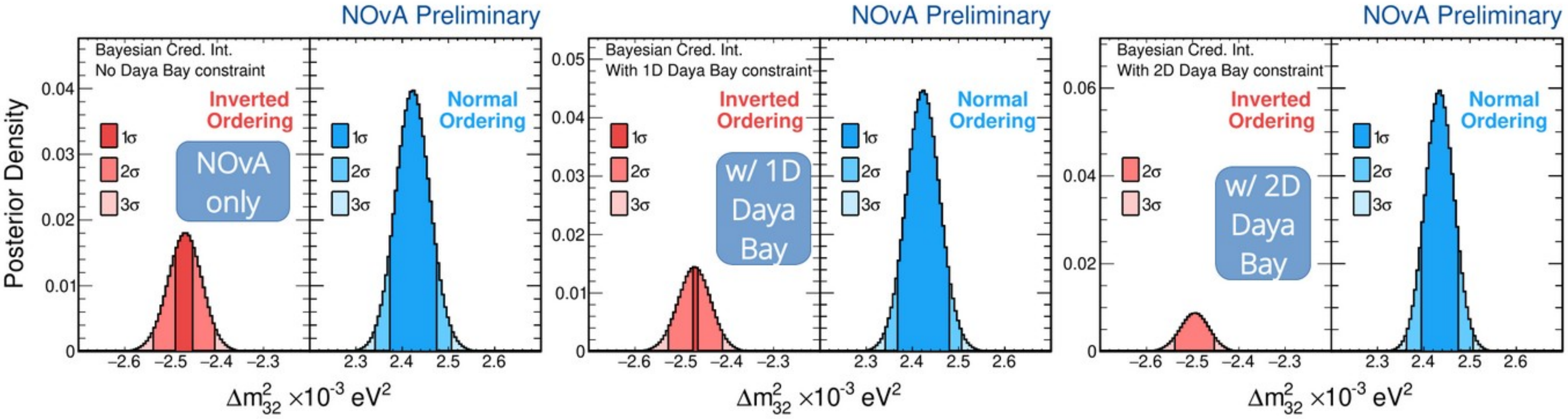
Maximal mixing is allowed at <1σ

② Which way are the neutrino mass states ordered?

Mass ordering and CPV

$\Delta P_{\nu\bar{\nu}} \propto \sin \delta_{CP}$

③ Do neutrinos exhibit CP violation?



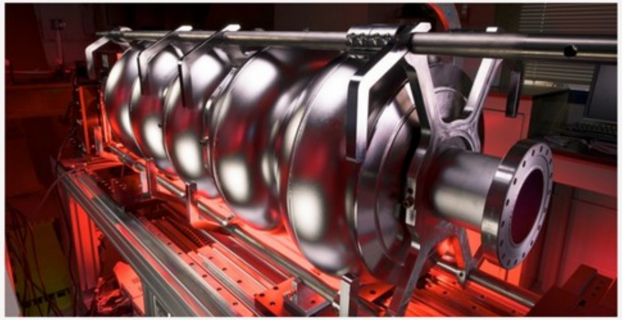
No reactor constraint	Daya Bay $\sin^2 2\theta_{13}$ only	Daya Bay ($\sin^2 2\theta_{13}$, Δm^2_{32})
N.O. preference:	N.O. preference:	N.O. preference:
69% prob. (Bayes factor: 2.2)	76% prob. (Bayes factor: 3.2)	87% (Bayes factor: 6.8)
	Frequentist significance*: 1.4σ	Frequentist significance*: 1.6σ

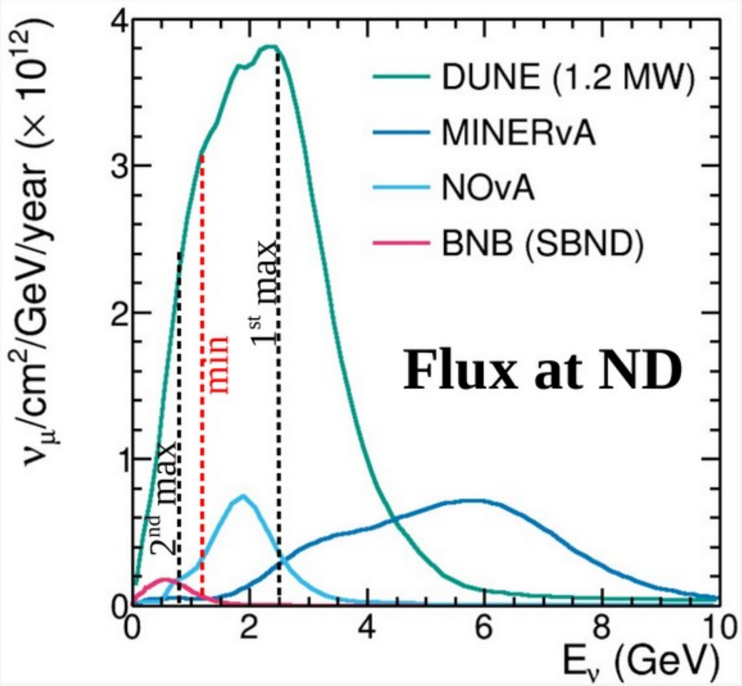
Mass ordering preference strengthened by applying reactor constraint

(not entirely unexpected: e.g., Phys. Rev. D 72: 013009, 2005)

LBNF beamline: world-leading intensity

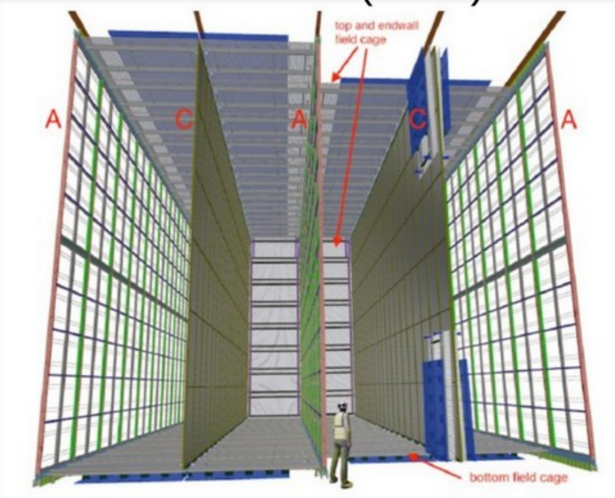
- Very high flux between oscillation minimum and maximum, with coverage of second maximum
- ACE-MIRT upgrade enables >2MW beam by ~doubling frequency of spills, and can be achieved before operations begin



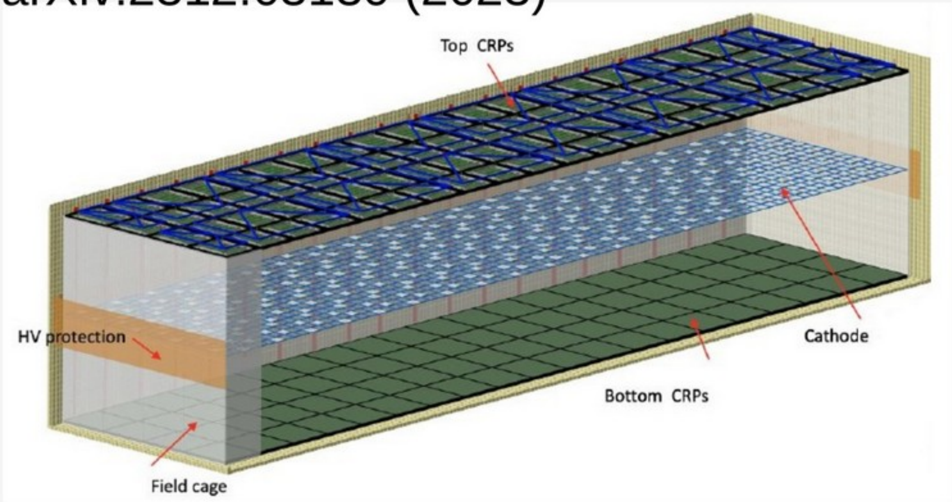


Far detector: two readout technologies

JINST 15 T08010 (2020)



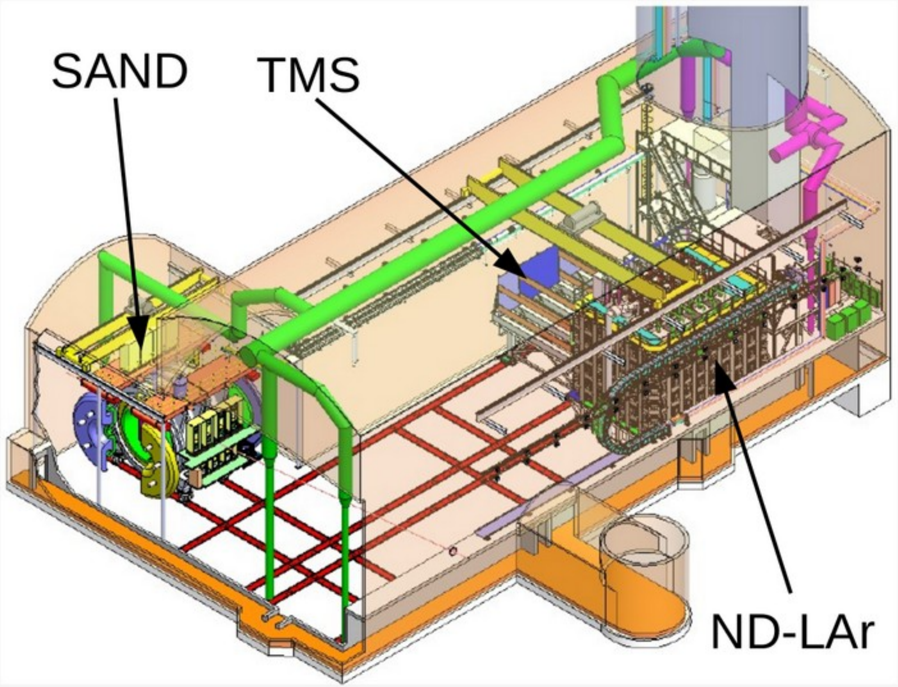
arXiv:2312.03130 (2023)



- Horizontal drift (HD, left) using wire readout planes, four drift regions
- Vertical drift (VD, right) using two 6.25m drift regions and central cathode
  - Simpler to install → first DUNE FD module will use vertical drift
  - VD is baseline design for modules 3 and 4

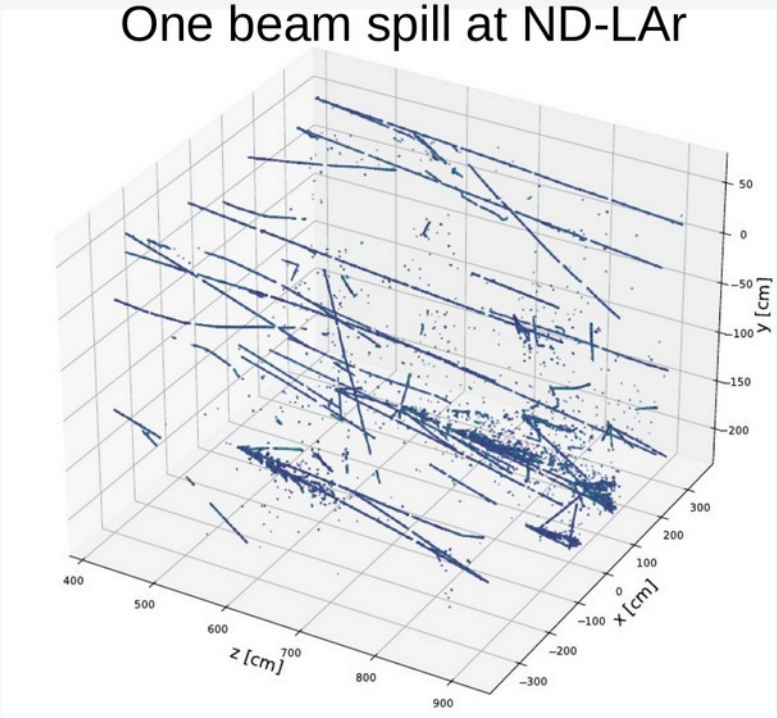
Near detector: systematic constraints for precision physics

- Main purpose: enable prediction of Far Detector reconstructed spectra
- Movable detector system: LArTPC with muon spectrometer
- Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
- Same target, same technology → inform predictions of reconstructed E_ν in Far Detector



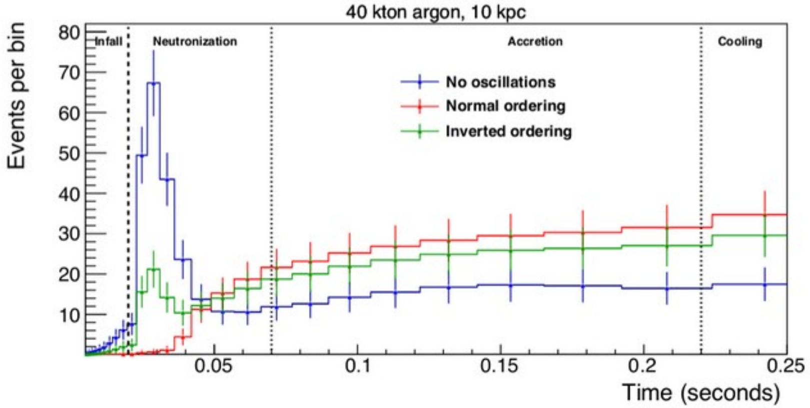
Unique challenge for ND: pile-up

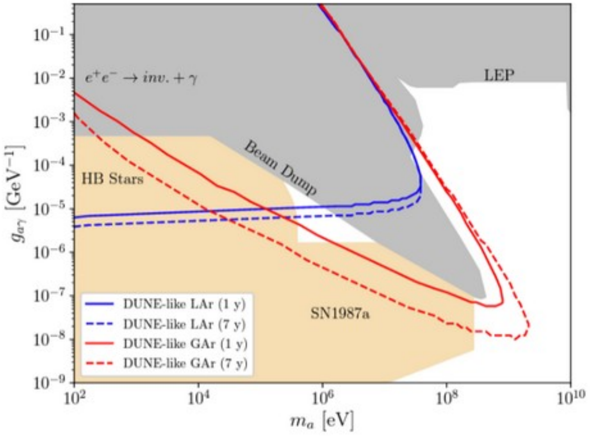
- Neutrino pile-up: very high rate at near site motivates pixelated readout and optical modularity
- Pixel readout: Natively 3D information in raw data, for resolving activity that would overlap in 2D projections
- Optical modularity: For charge-light matching, to allow association of detached energy (e.g. from neutrons)

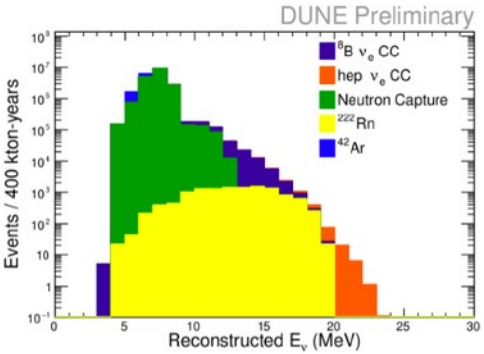


Phase-II Enables Broader Scientific Reach for DUNE

- Phase-II FD mass, as well as potential improvements in energy resolution and background levels, key to improve detection of neutrinos from astrophysical sources in the MeV energy range (e.g. Solar and Supernovae neutrinos)
- FD mass is also crucial for many other BSM searches (e.g. Baryon Number Violation Searches)
- Low-density ND-GAr adds additional unique sensitivity to BSM searches involving neutral particles produced in the beam and decaying in the ND (e.g., Heavy Neutral Leptons, Axion-Like Particles)
- Phase-II improves ν_τ detection capabilities at both ND and FD

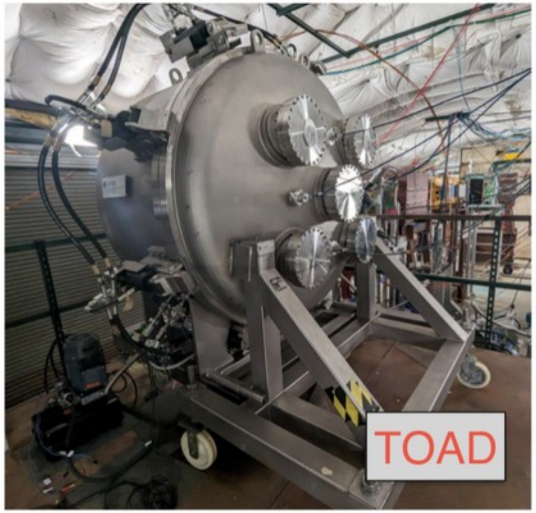


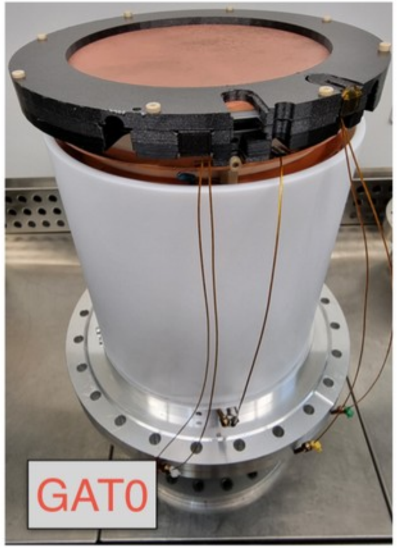


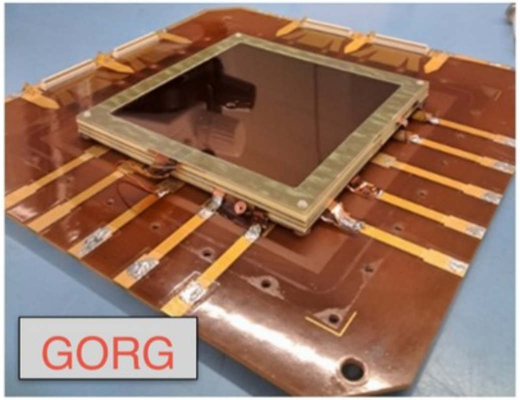


ND-GAr R&D

- Active R&D on both charge and light readout including simulation studies
- GORG (GEMs Over pressurized with Reference Gases), for testing of GEMs in High Pressure: *bench testing complete and getting ready to run at high pressure*
- TOAD (Test stand for Over pressurized Argon Detector), for full electronics Slice Testing of ALICE multi-wire chambers in the FTBF: *Preparing for cosmics and beam data*
- Optical TPC Demonstrator at IGFAE (GAT0): *Investigating the optical gain of ThickGEMs at high pressure; has been benchmarking ThickGEMs at 1 and 1.5 bar in Ar/CF4 mixtures.*

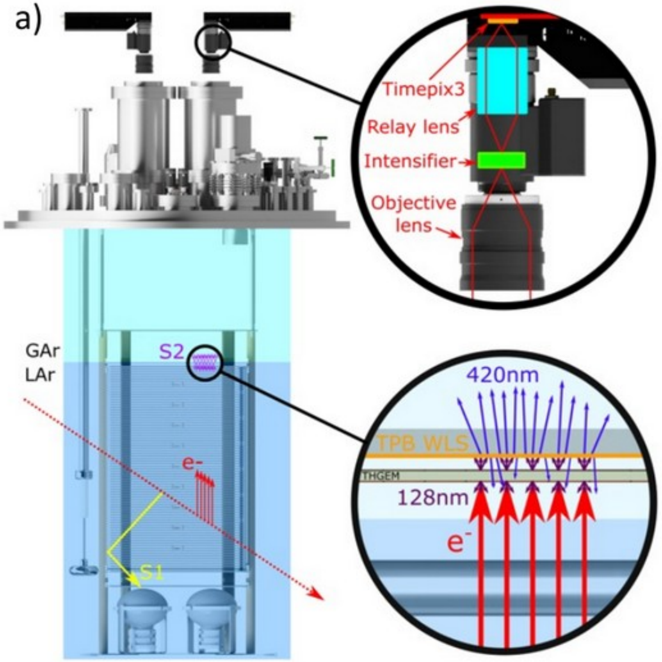


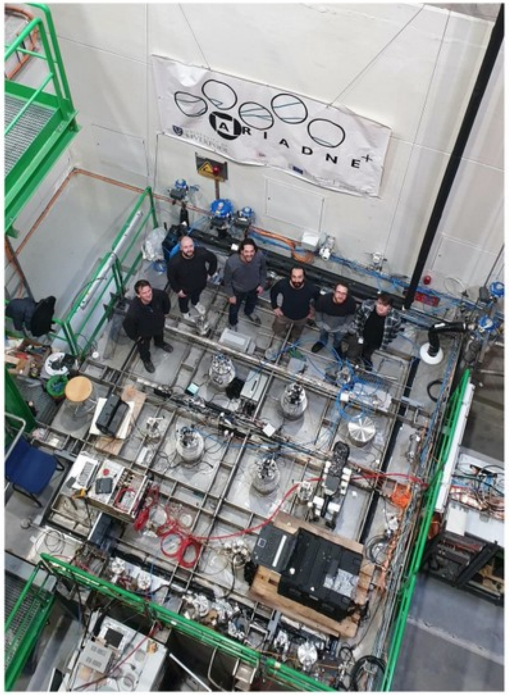




ARIADNE

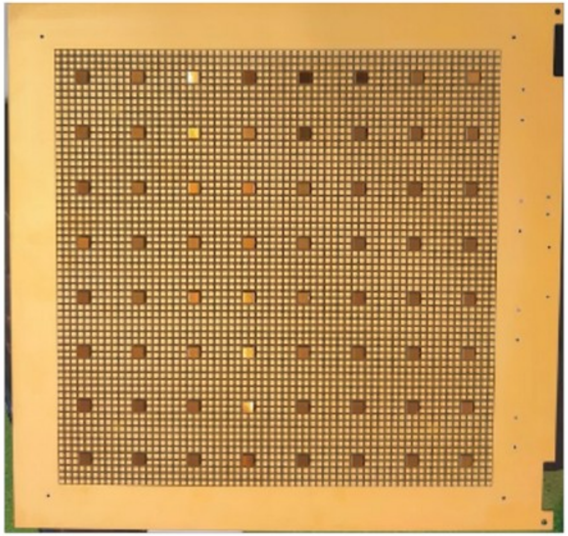
- Optical-based charge readout: S2 light produced in THGEM holes can be captured by fast cameras (eg, TimePIX3) to reconstruct in 3D the primary ionization track
- Successfully prototyped with 1-ton ARIADNE and ARIADNE+

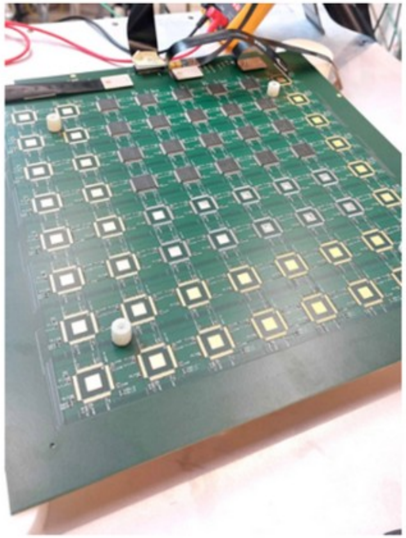




SoLAr

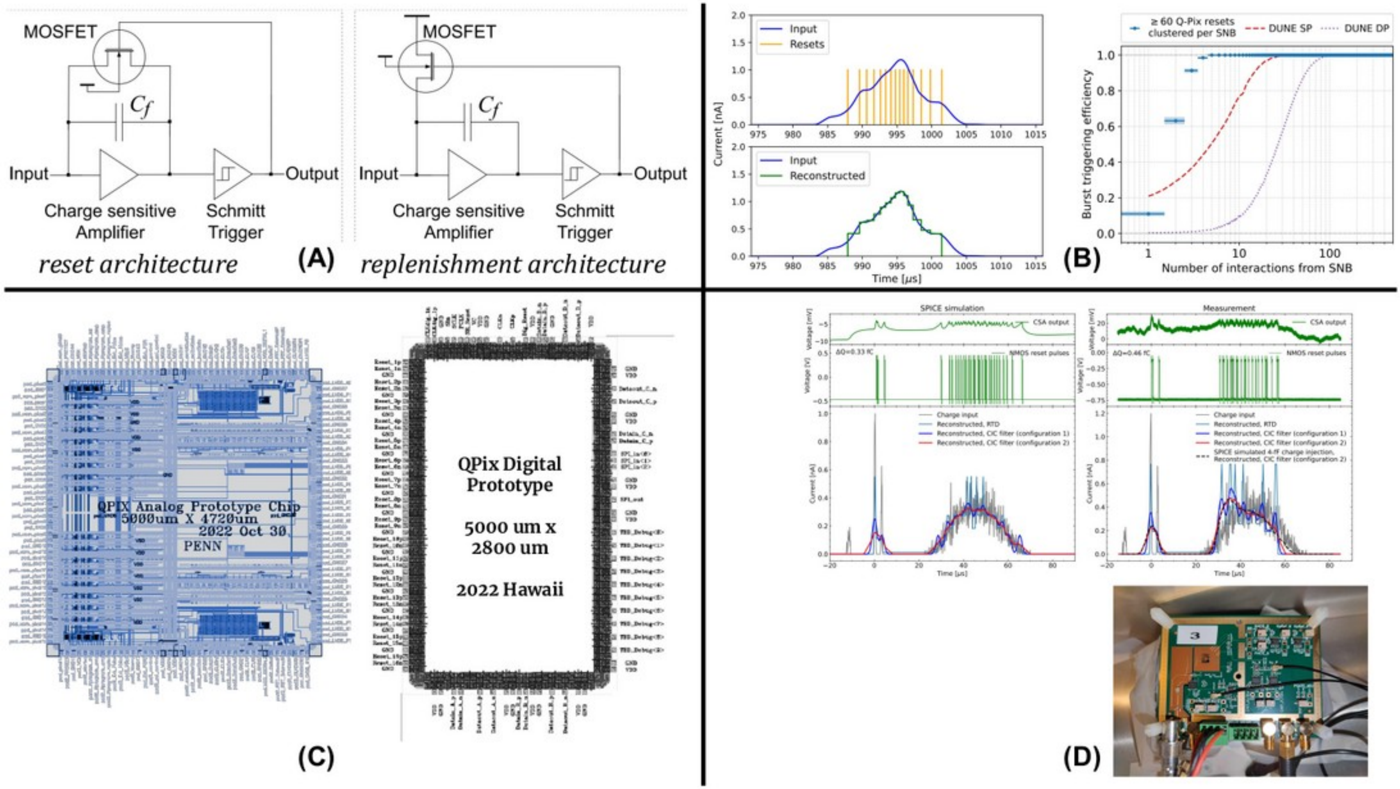
- Integrated array of VUV SiPMs on pixelated anode
- Online localized triggering for dealing with high data rates
- Existing prototypes:
  - *SoLAr v1: 7x7 cm² anode plane, 16 VUV SiPMs, 3.5 mm pitch, 4 LArPix v2a chips*
  - *SoLAr v2: 30x30 cm² anode plane, 64 VUV SiPMs, 4 mm pitch, 20 LArPix v2b chips*





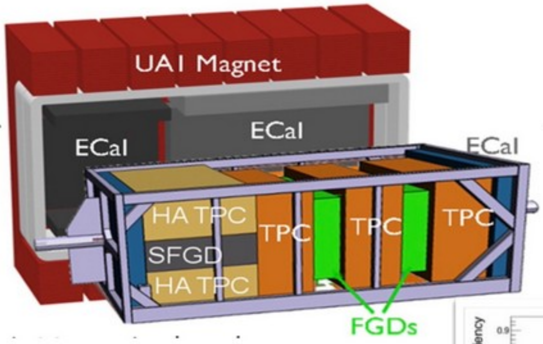
Q-Pix

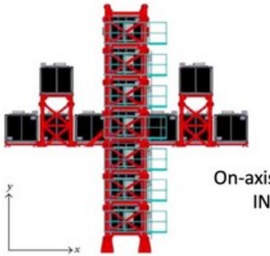
- Self-triggering, low-threshold, high-granularity pixelated readout
- Changes basic quantum of information from traditional “charge per unit of time” data format to time difference between clock captures for a fixed ΔQ → low data throughput
- A number of prototypes are currently under construction and evaluation



Near Detectors

Critical components to precisely understand J-PARC beam and neutrino interactions.

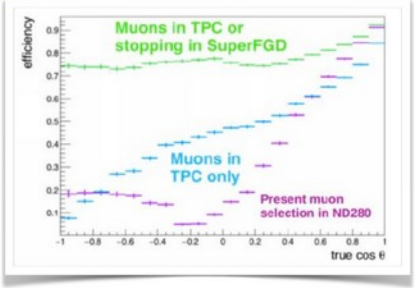




At 280m:

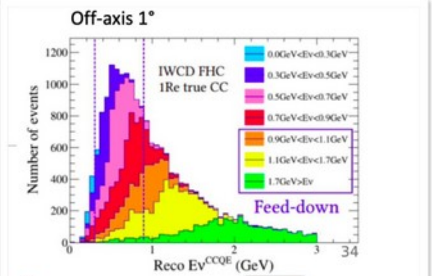
- On-axis detector: measure beam direction, monitor event rate.
- Off-axis magnetised tracker: charge separation (measurement of wrong-sign background), study of the recoil system.
- sFDG, High-Angle TPCs and TOF. Improved:
  - low-energy particles and neutrons reconstruction
  - angular acceptance

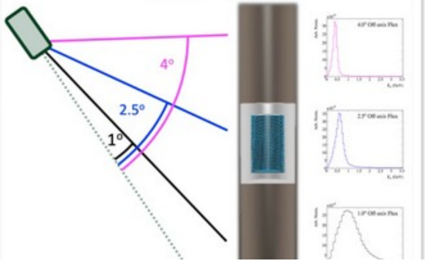
Improved performance on ND280 upgrade.

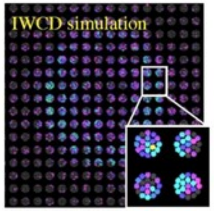


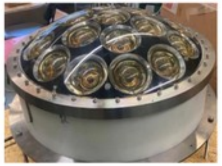
IWCD (~900m):

- Due to pion decay properties, neutrino spectrum varies with offaxis angle
- change off-axis angle ~1° – ~4° to change mean neutrino energy and constrain: $(\sigma(\nu_e)/\sigma(\nu_\mu))/(\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu))$
- ~400 mPMTs (high-granularity and time resolution)









Far Detector

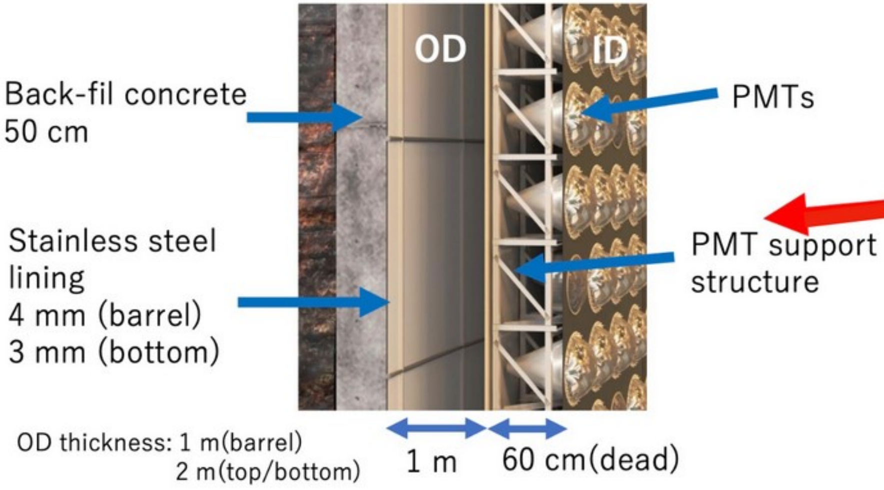
Construction of the water tank, PMT support structure, and infrastructures by Japan

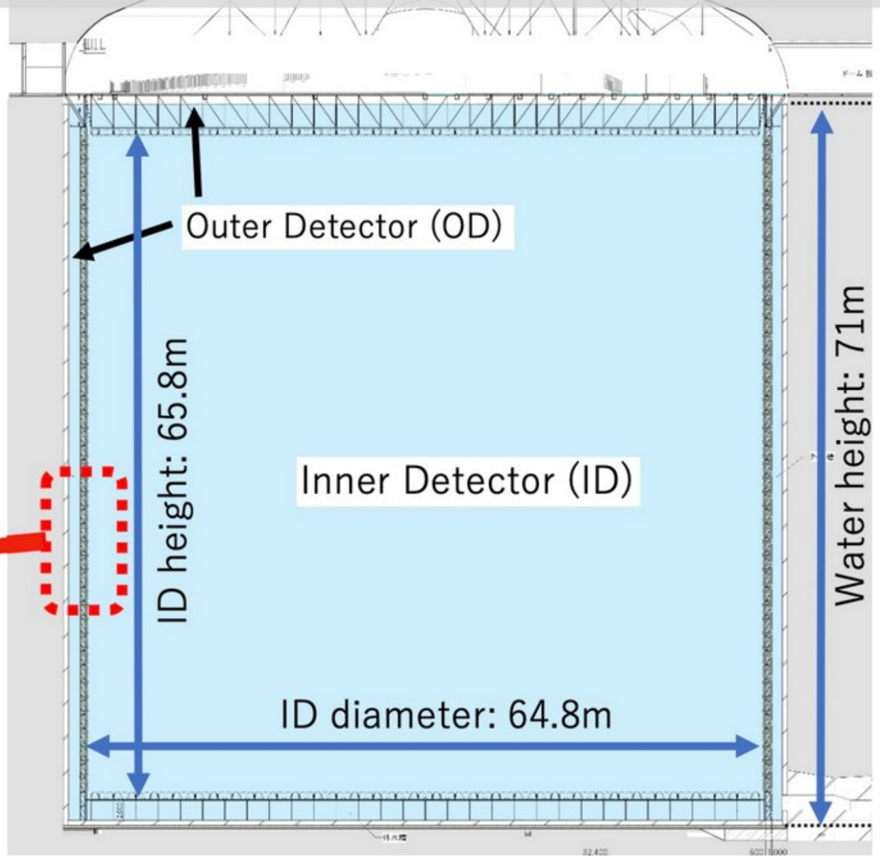
258 kton volume water Cherenkov detector
- 216 kton inner detector (~188 kton fiducial volume)
- 1 m thick outer detector used as a veto region
- Optically separated using high reflectivity Tyvek sheets

Size of the water tank.

Tank size	Φ68 m × H 72 m
Water height	71 m
ID volume	216.9 kt
Fiducial volume	188.4 kt
ID surface	19991.1 m^2

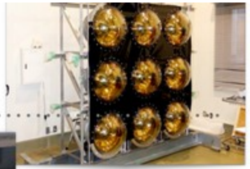
OD=Outer Detector ID = Inner Detector

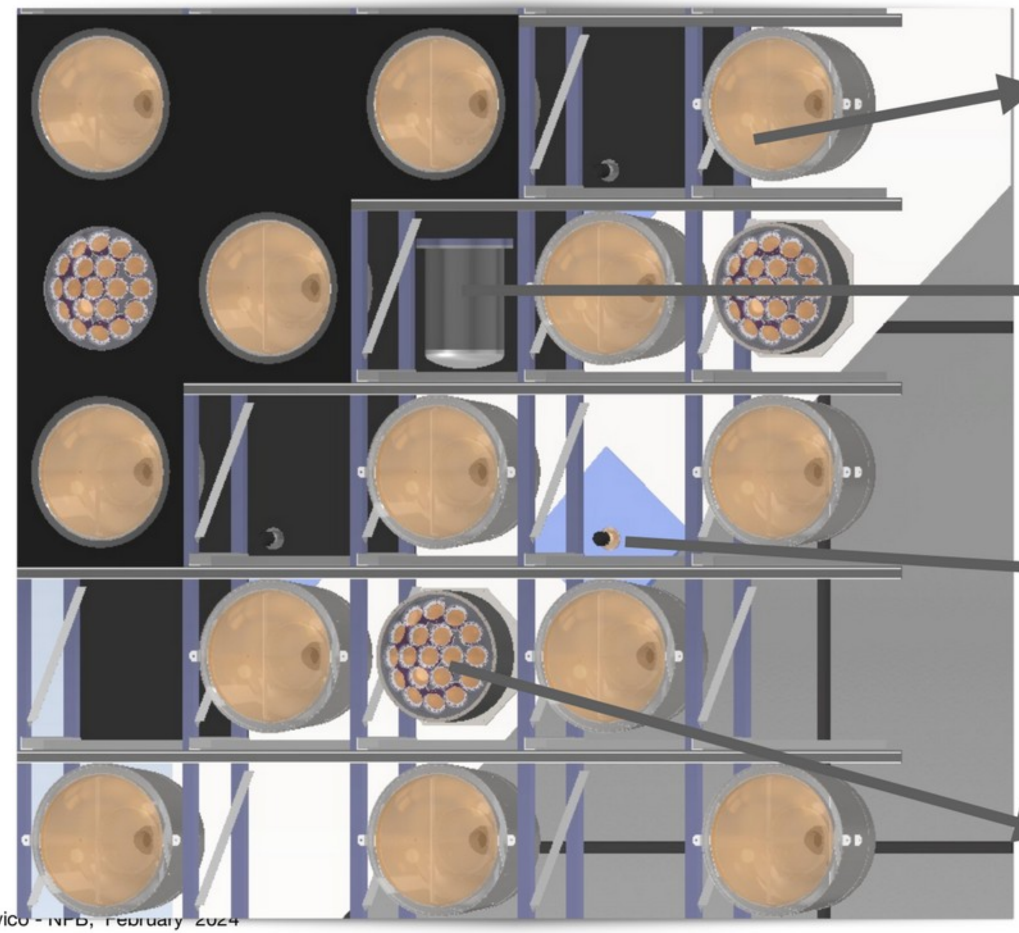




Tank Frame

Mockup (Kashiwa,





50cm PMTs

#20,000

ID+OD Electronics

#~1,000

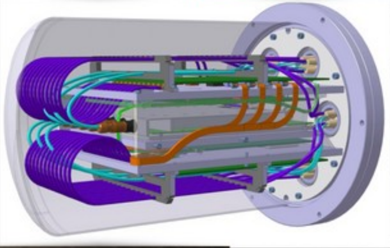
OD

#3,600

mPMTs

#~1,000

Implosion tests ongoing to choose PMT cover.

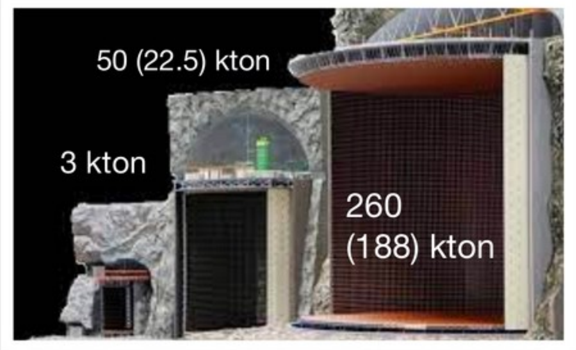


Underwater vessels with electronics boards (ID, ID+OD)

Full OD system includes 3” PMTs, WLS plate and high reflective Tyvek.

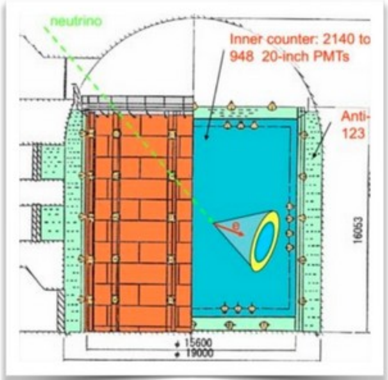
mPMTs provide improved timing and direction resolutions

Three generations of Kamiokande

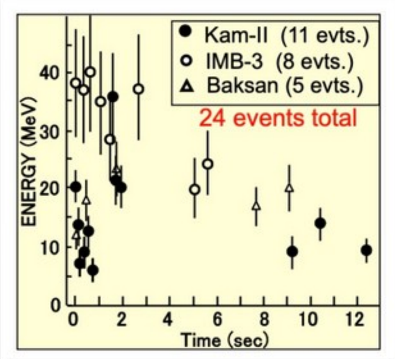


Kamiokande
(1983-1995)

20x



SN1997A

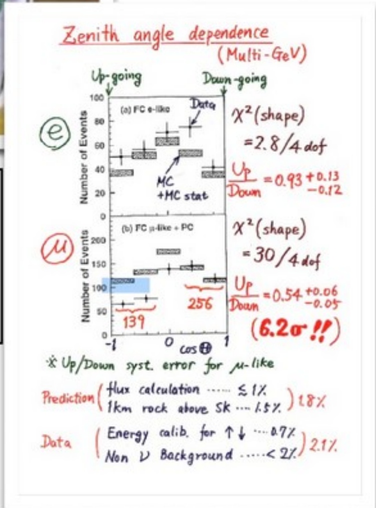


Birth of neutrino astrophysics

Super-Kamiokande
(1996-)

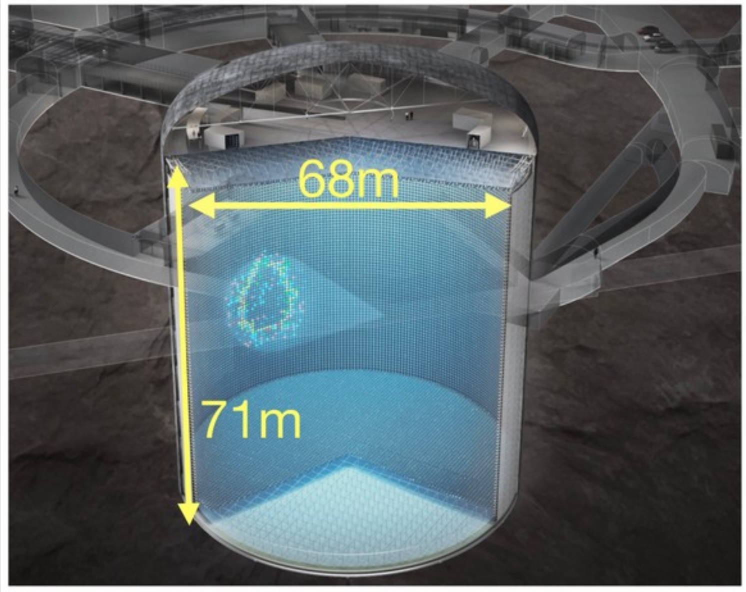
Discovery of neutrino oscillations

Takayama (1998)



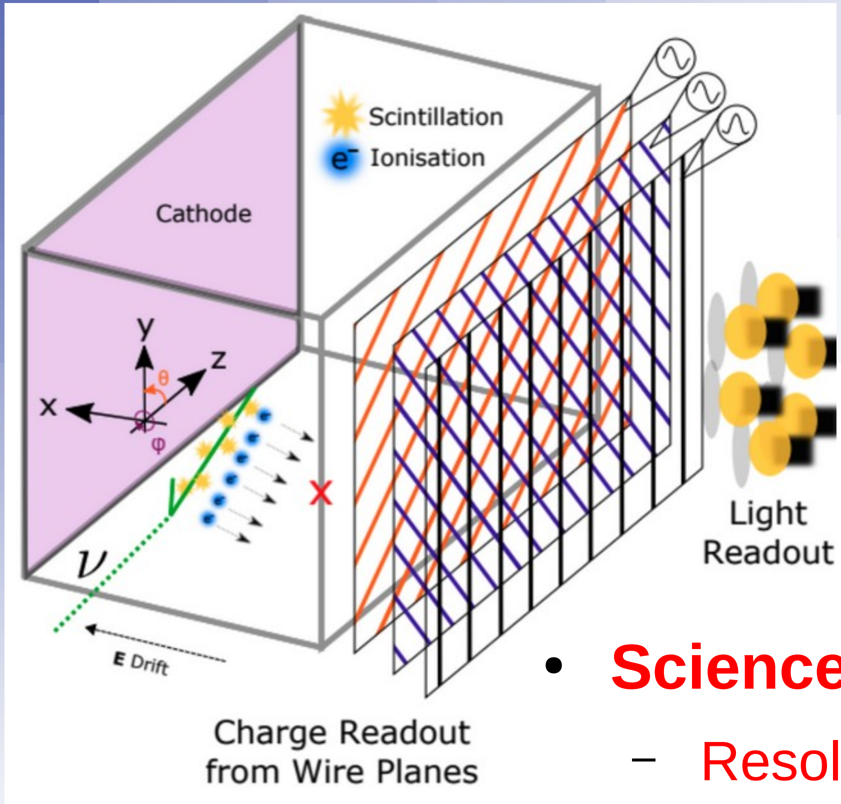
8.4x

Hyper-Kamiokande
(2027-)



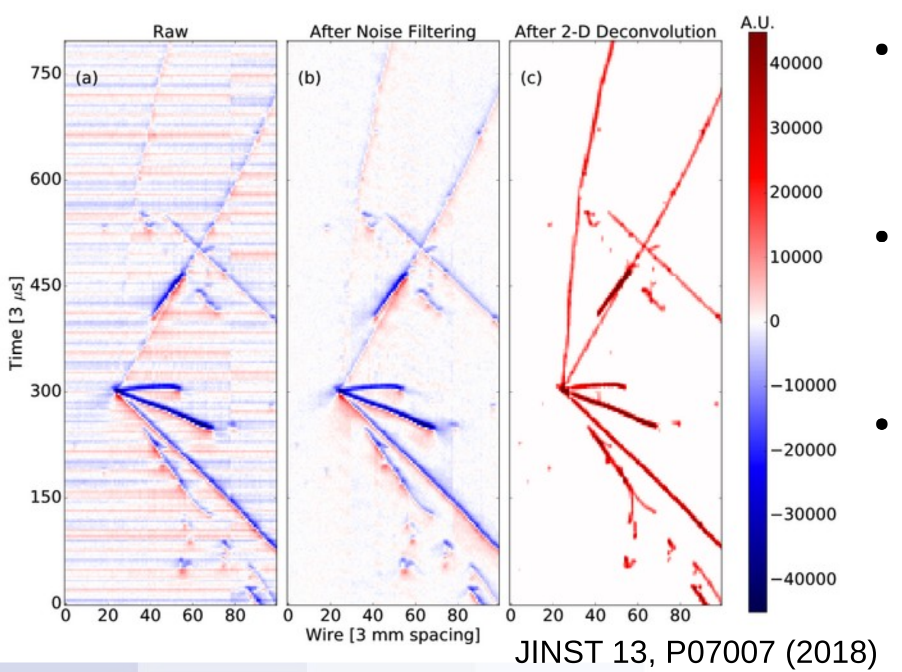
CP, astrophysics, rare decays

MicroBooNE



- Large-scale LArTPC:
  - 85 tonnes (active mass),
  - 8192 wires (3 mm pitch) on 3 planes,
  - 32 8” Cryogenic PMTs,
  - UV laser calibration, Cosmic Ray Tagger.
- Crucial for scaling up to DUNE.
  - Cold electronics: 40:1 signal-to-noise ratio.
  - Gas piston purge: >18 ms electron lifetime.
- **Science goals:**
  - Resolve the nature of miniBooNE’s low-energy excess.
  - Study GeV-scale ν-Ar interactions.
  - LArTPC hardware and software testbed and R&D.

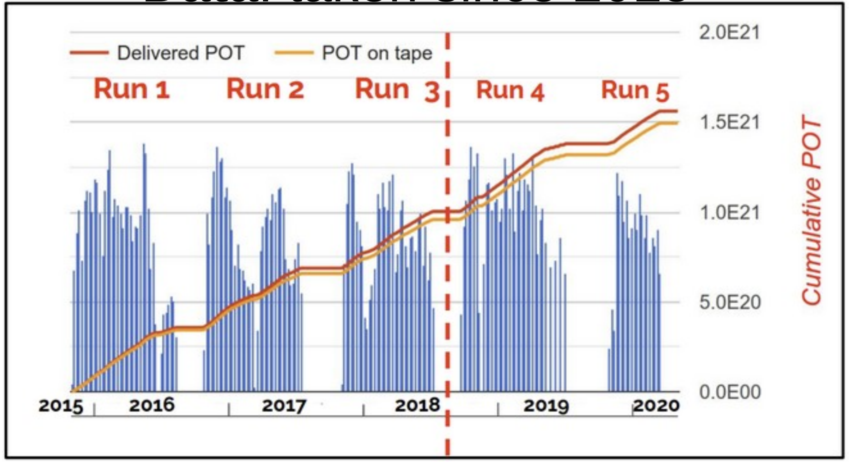
Detector Performance



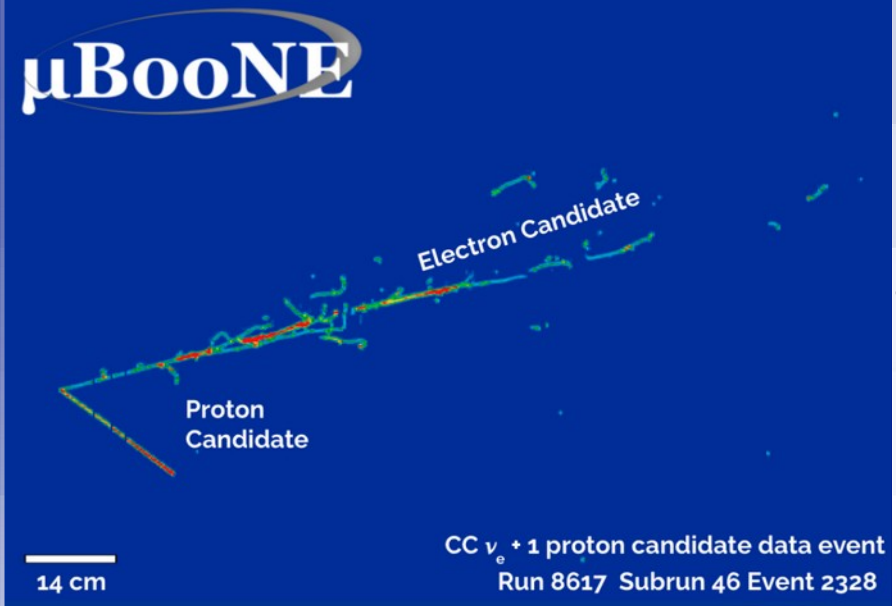
JINST 13, P07007 (2018)

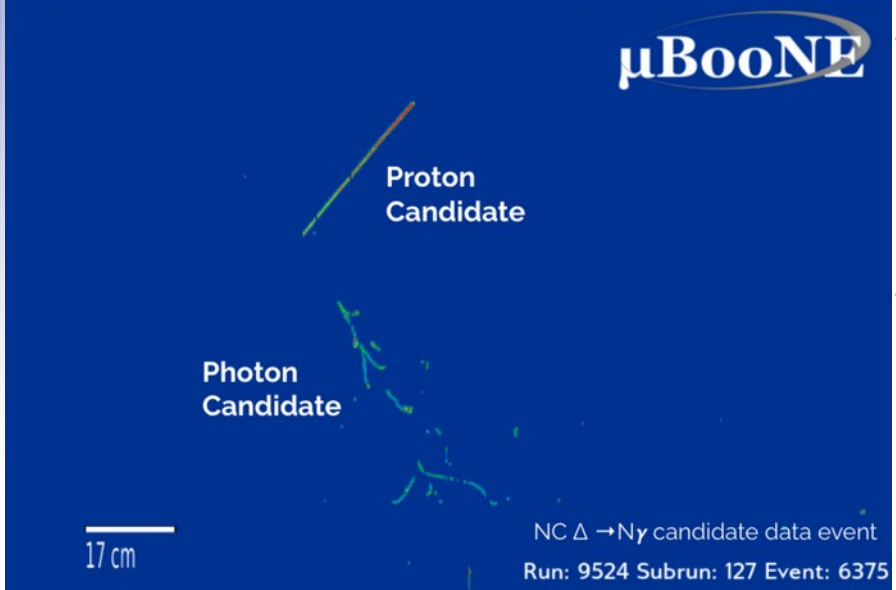
- Data-driven **electric field maps**:
  - UV laser: JINST 15, P07010 (2020),
  - cosmic muons: JINST 15, P12037 (2020).
- **Calorimetric and EM shower calibrations**:
  - JINST 15 P03022 (2020), JINST 15 P02007 (2020),
  - JINST 13 (2018) P07006.
- Longitudinal **diffusion** of ionization e- 's: arXiv:2104.06551

Data: taken since 2015



Advanced signal processing: produces 2D de-convolved waveforms, which represent the number of drift electrons that arrive at each wire as a function of time.





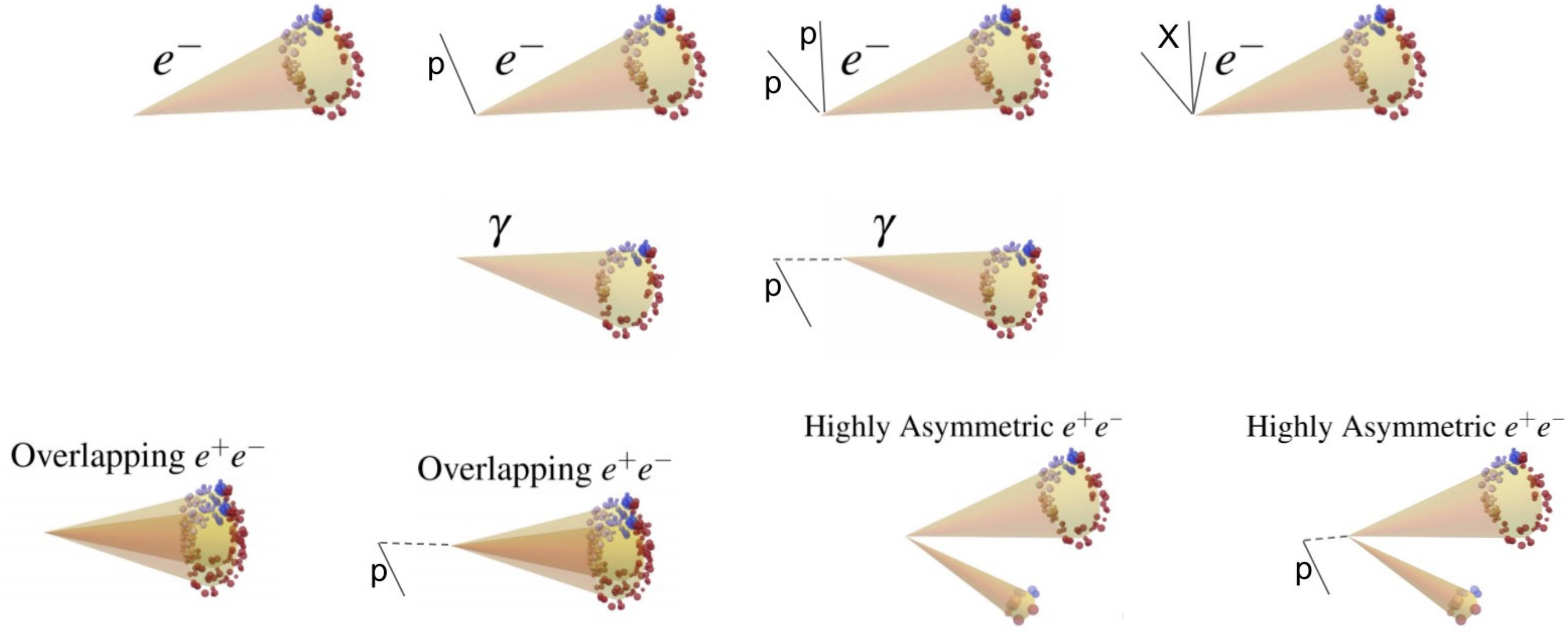
Event Reconstruction

Co-developed 3 fully-automated and independent event reconstruction frameworks - excellent LArTPC resolution:

- **Pandora**
  - Multi Algorithm approach provides robust automated pat-rec.
  - Multiple neutrino cross section results (CC inclusive, CC π^0, CC Np, QE-like, ν_e), BSM searches (HNL, Higgs portal scalar).
  - Eur. Phys. JC78, 82 (2018).
- **Deep Learning (DL)**
  - First of their kind applications in a LAr TPC.
  - PRD 103, 052012 (2021), PRD 103, 092003 (2021),
  - JINST 16, P02017 (2021), PRD 99, 092001 (2019).
- **Wire-Cell**
  - fully 3D, next-generation charge-to-light matching, improved cosmic removal.
  - Phys.Rev.Applied 15 (2021) 6, 064071, JINST 16 (2021) 06, P06043, arXiv:2012.07928 (PRA).

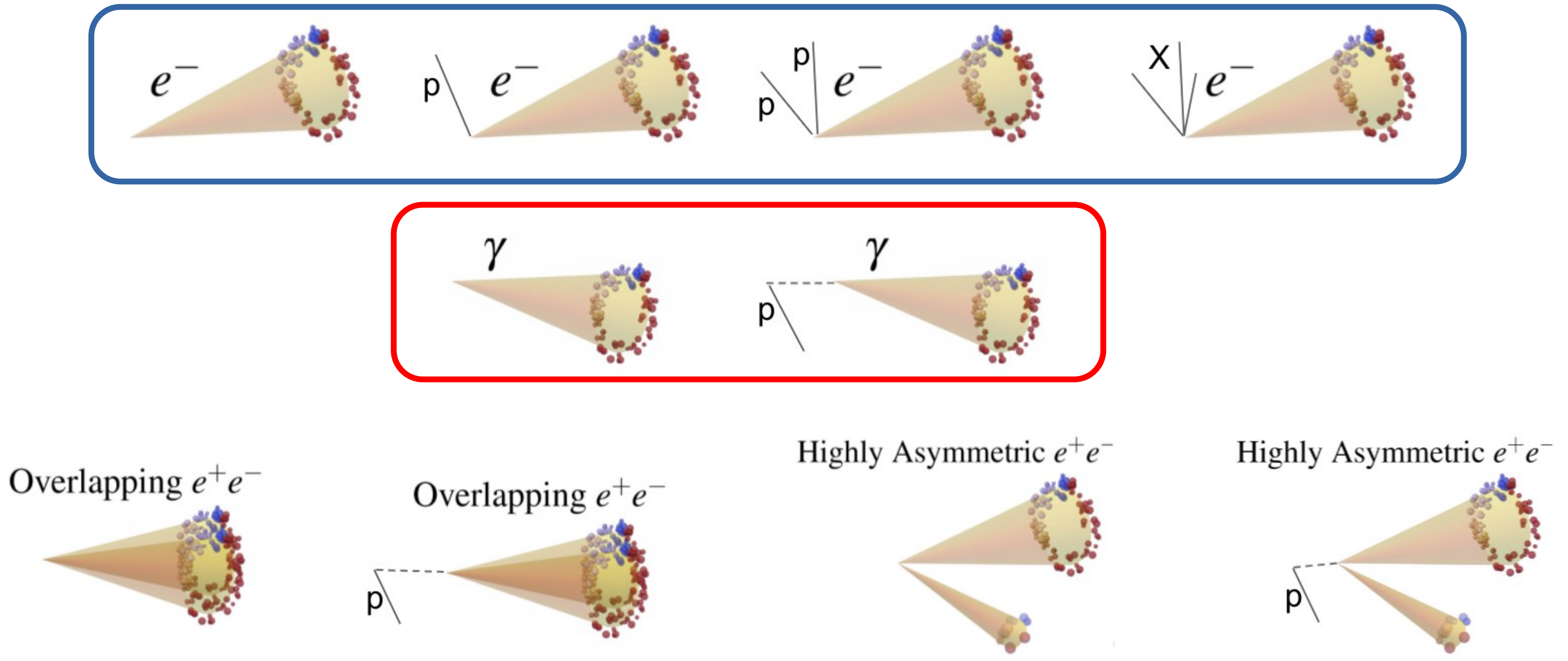
See poster Jingyuan Shi: Comparison Studies

What is the LEE Particle Content?



Credit: Mark R-L

MicroBooNE's First LEE Exploration



Credit: Mark R-L

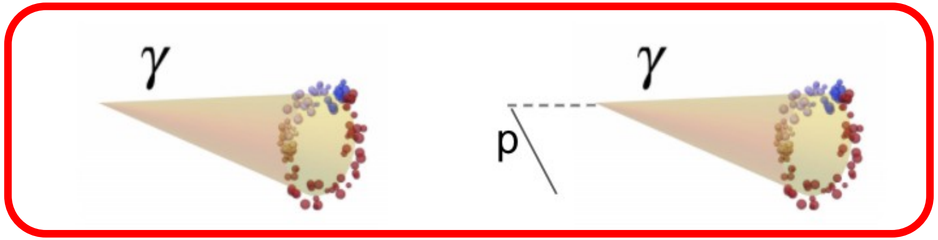
MicroBooNE LEE Exploration so far..

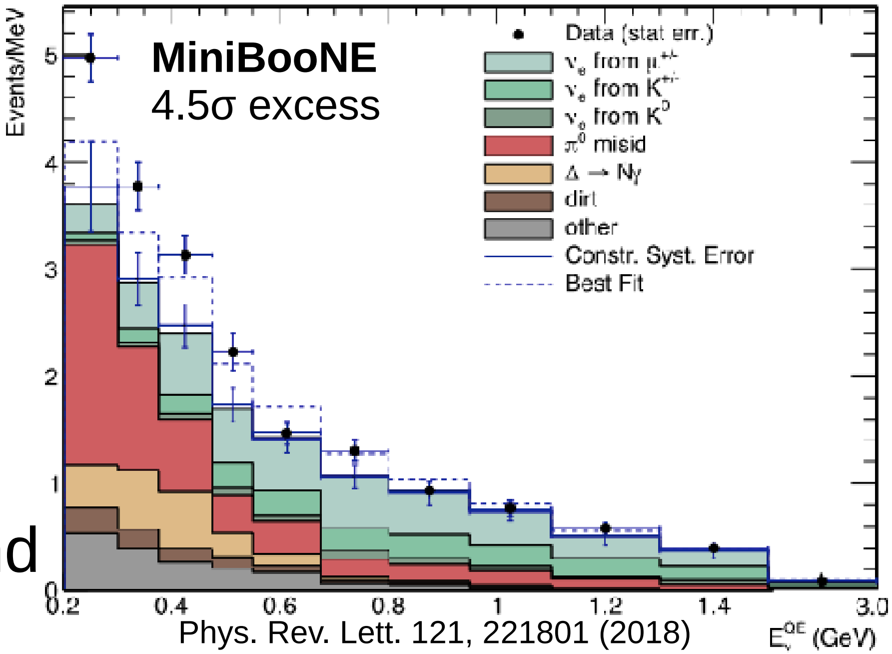
First series of results (1/2 the MicroBooNE data set)

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [2,3]	✔ [2,3]	✔ [1,2,3]	✔ [1,2,3]	✔ [1,2,3]
More complex higgs *					✔ [10]	✔ [10]	✔ [6,10]	✔ [6,10]	✔ [6,10]
Axion-like particle *					✔ [8]		✔ [8]		
Res matter effects	✔ [5]	✔ [5]	✔ [5]	✔ [5]					
SM γ production							✔	✔	✔

*Requires heavy sterile/other new particles also

MicroBooNE's Photon-Like Analysis





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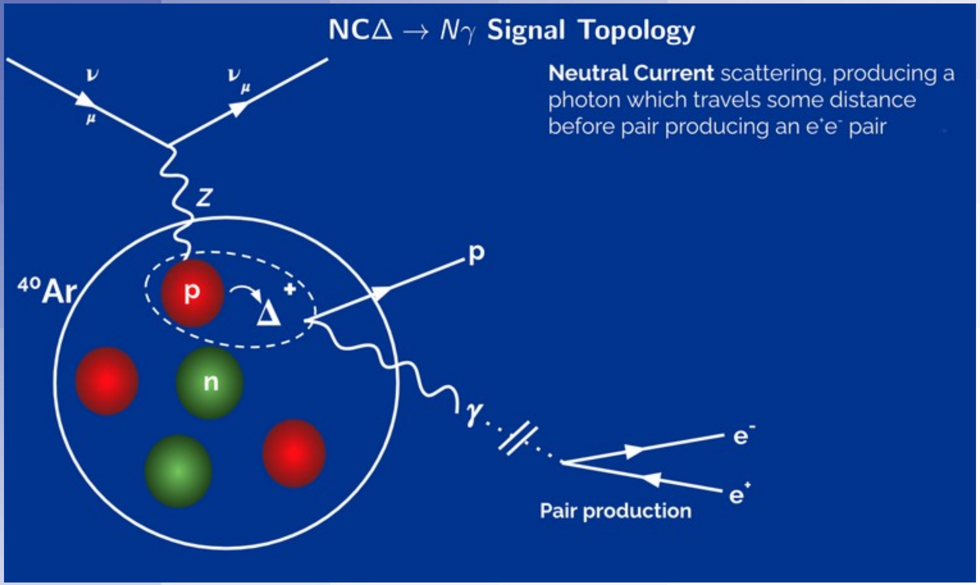
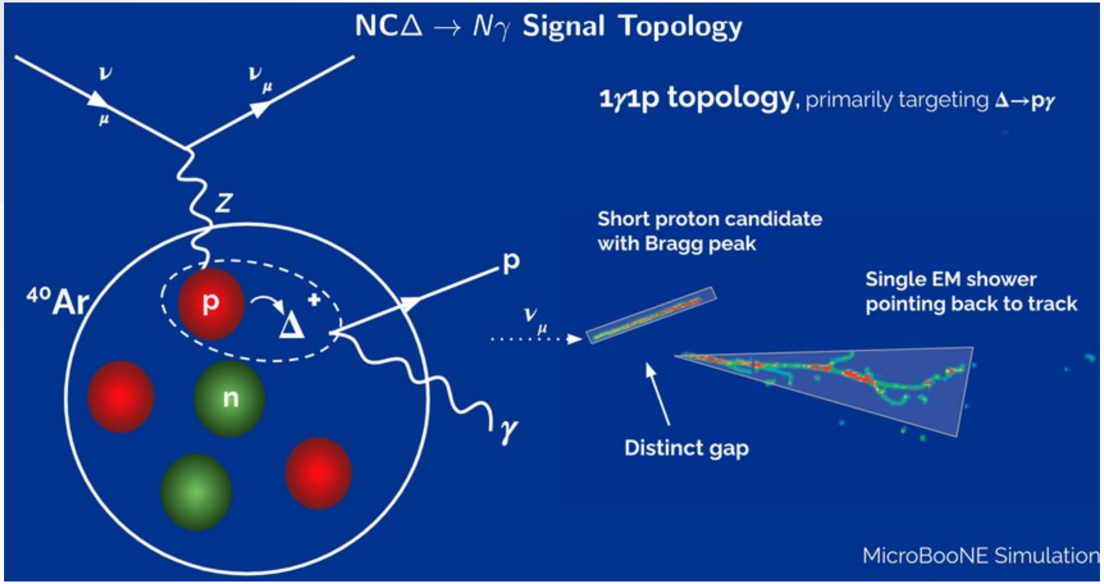
- NCΔ→Nγ is a significant background in the MiniBooNE analysis.
- This process has never been measured in neutrino scattering.
- Multiplying the generator prediction for this by 3.18 resolves the LEE – we can test this alternative model!

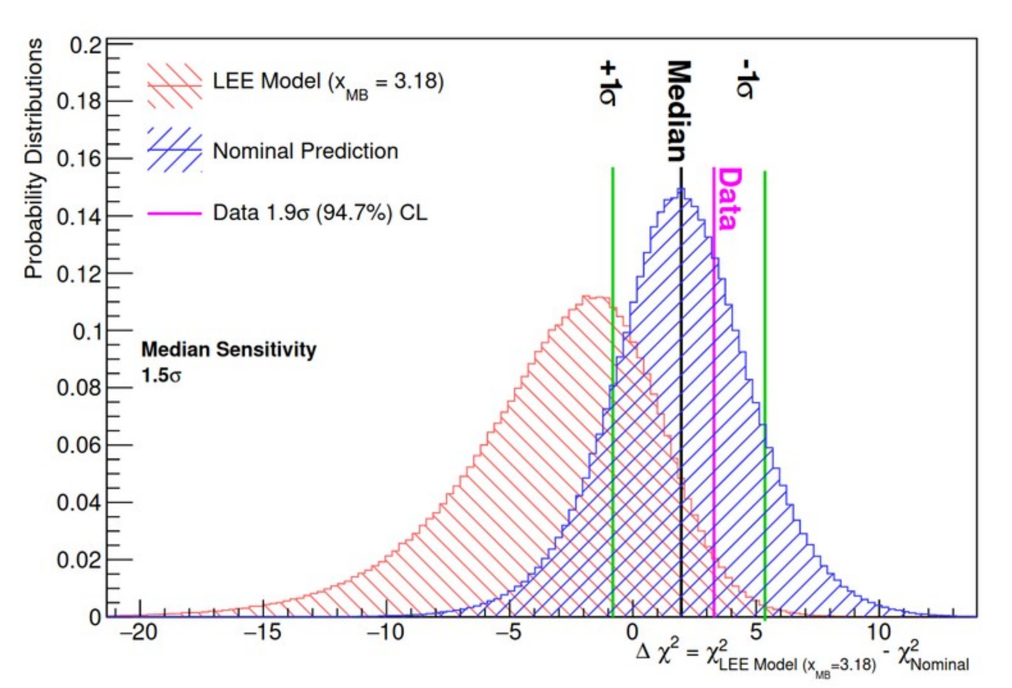
MicroBooNE's Photon Analysis





- Uses two two-photon selections to constrain NCπ^0 background.
- Signal samples are single photon.
- Physics modelled with GENIE v3.0.6 → Berger-Sehgal resonance model.

Well then...



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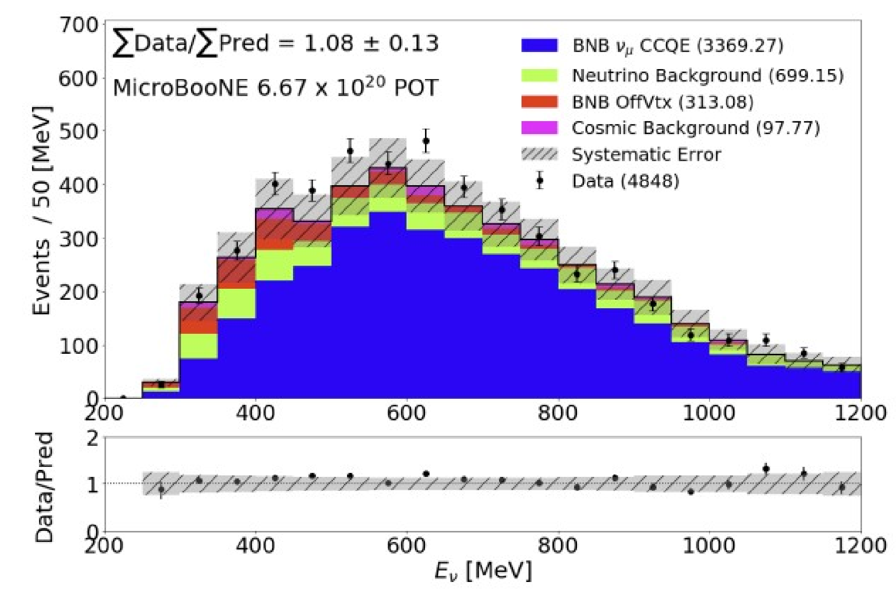
Disfavours the NCΔ→Nγ explanation of **LEE** at **94.8%** confidence level.

	$1\gamma 1p$	$1\gamma 0p$
Unconstr. bkgd.	27.0 ± 8.1	165.4 ± 31.7
Constr. bkgd.	20.5 ± 3.6	145.1 ± 13.8
NC $\Delta \to N\gamma$	4.88	6.55
LEE ($x_{MB} = 3.18$)	15.5	20.1
Data	16	153

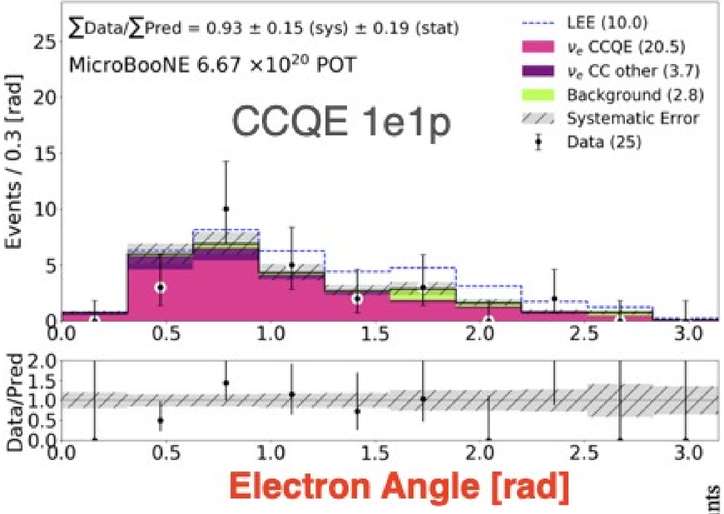
50-fold improvement over prior limit on rate of this interaction.

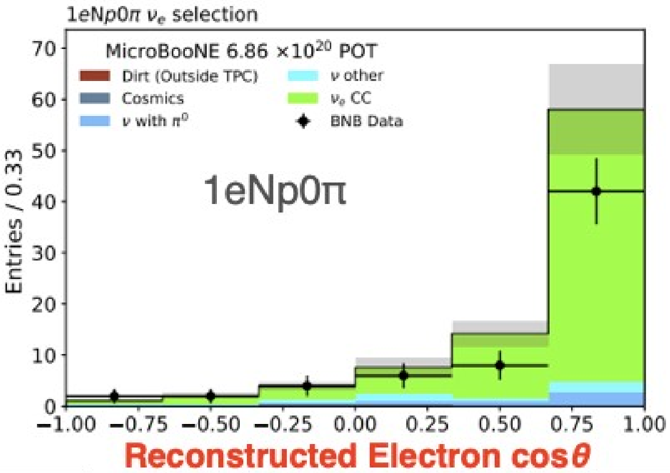
MicroBooNE's Electron-Like Analysis

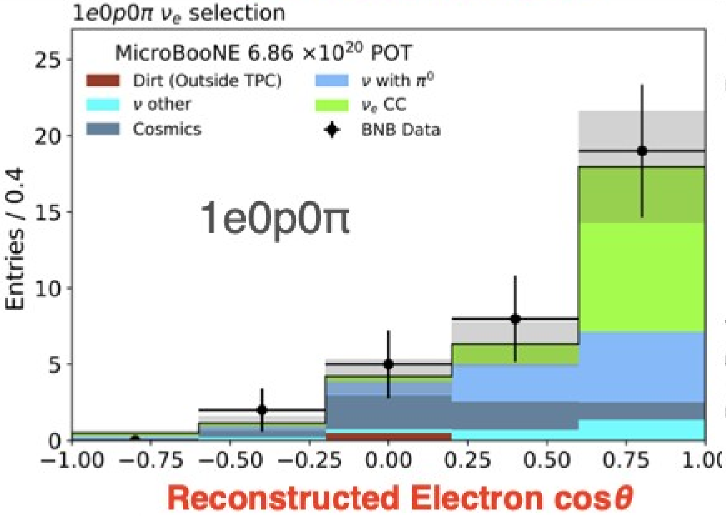


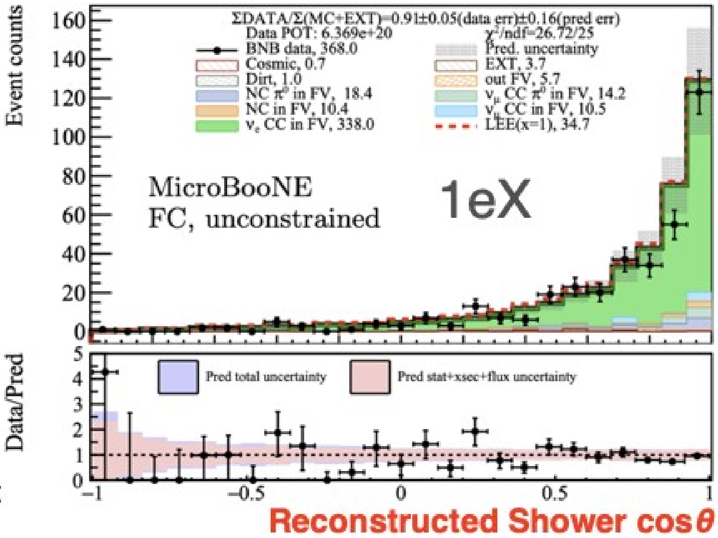
- 3 distinct e-like LEE search analyses:
  - CCQE 1e1p. — PRD arXiv:2110.14080
  - Pionless: 1eNp0π and 1e0p0π. — PRD arXiv:2110.14065
  - 1eX. — PRD arXiv:2110.13978
- Start with high-statistics muon-like samples to make data-driven electron-like prediction.
  - Heavily reduces uncertainties on e-like spectrum.
- Excellent rejection of cosmic-ray and photon shower backgrounds.
- High-statistics auxiliary measurements of π^0 and ν_μ CC events to produce data-driven ν_e estimates with constrained uncertainties.
- **Use unfolded MiniBooNE-like excess to test hypothesis → Not a sterile model!**

Electron-LEE Lepton Angle









Both the leptonic and hadronic kinematics can be studied in the LArTPC.

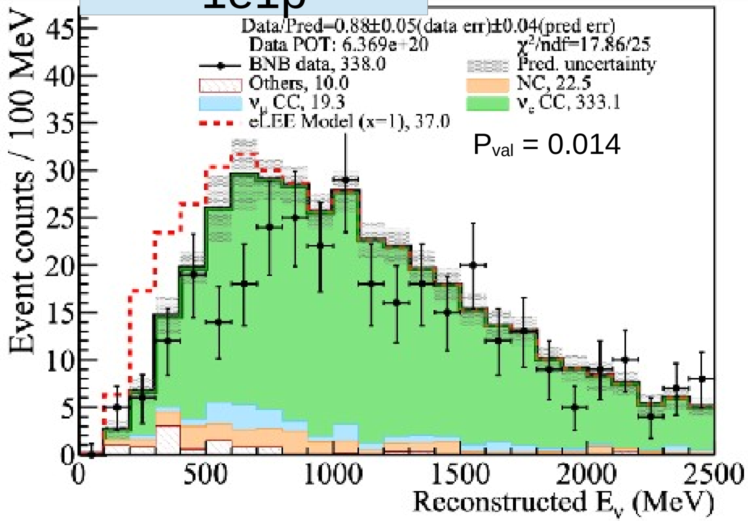
1.7σ deficit in medium energy, forward direction.

Within expectation elsewhere.

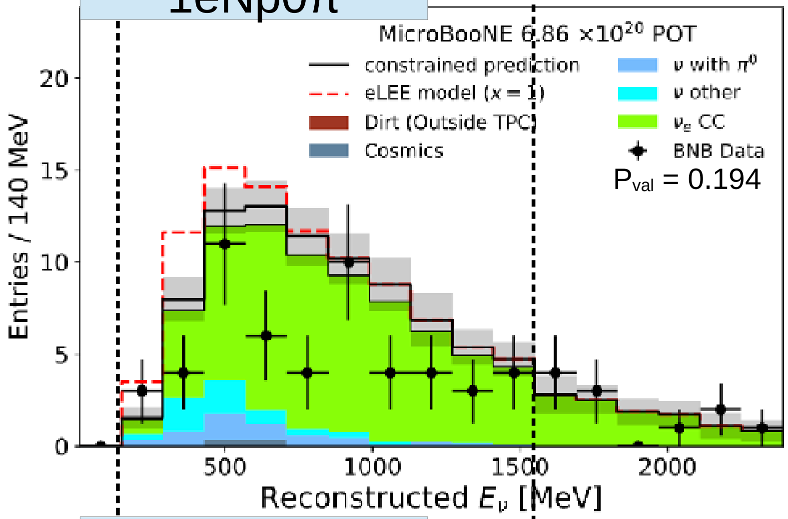
Electron-LEE Neutrino Energy

µBooNE

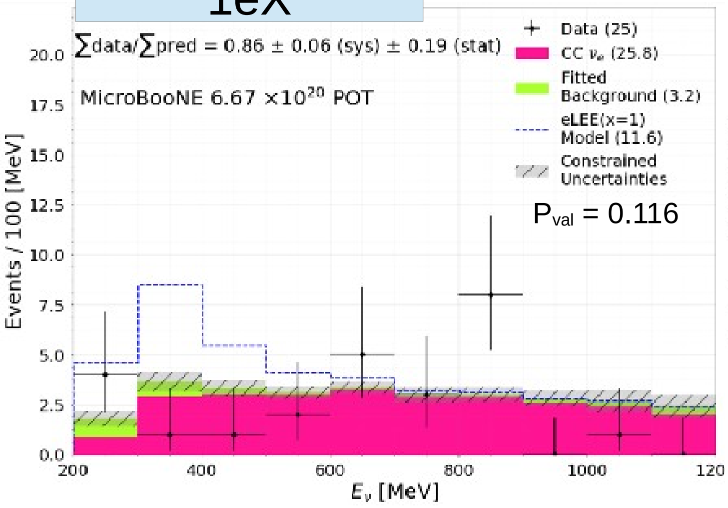
1e1p



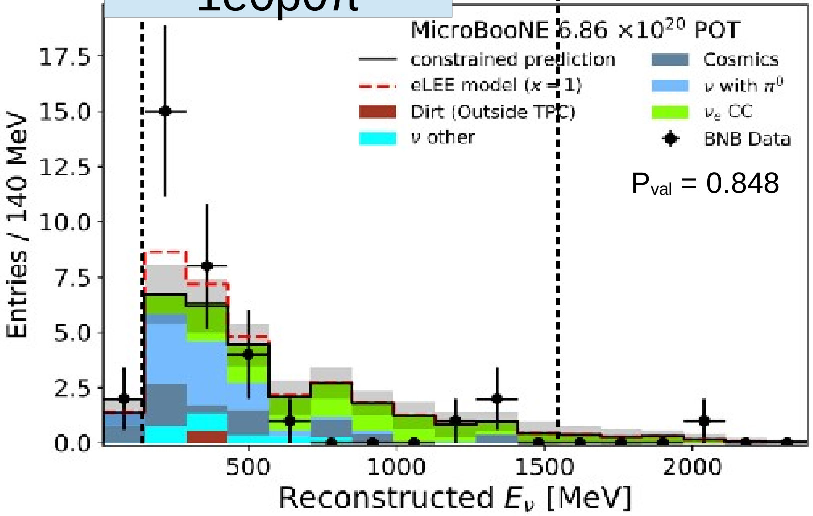
1eNp0π



1eX



1e0p0π



Some tension:

~ 800 MeV in CCQE 1e1p selection, and

~ 150 MeV (& at forward angles) in 1e0p0π selection (bckg. dom.).

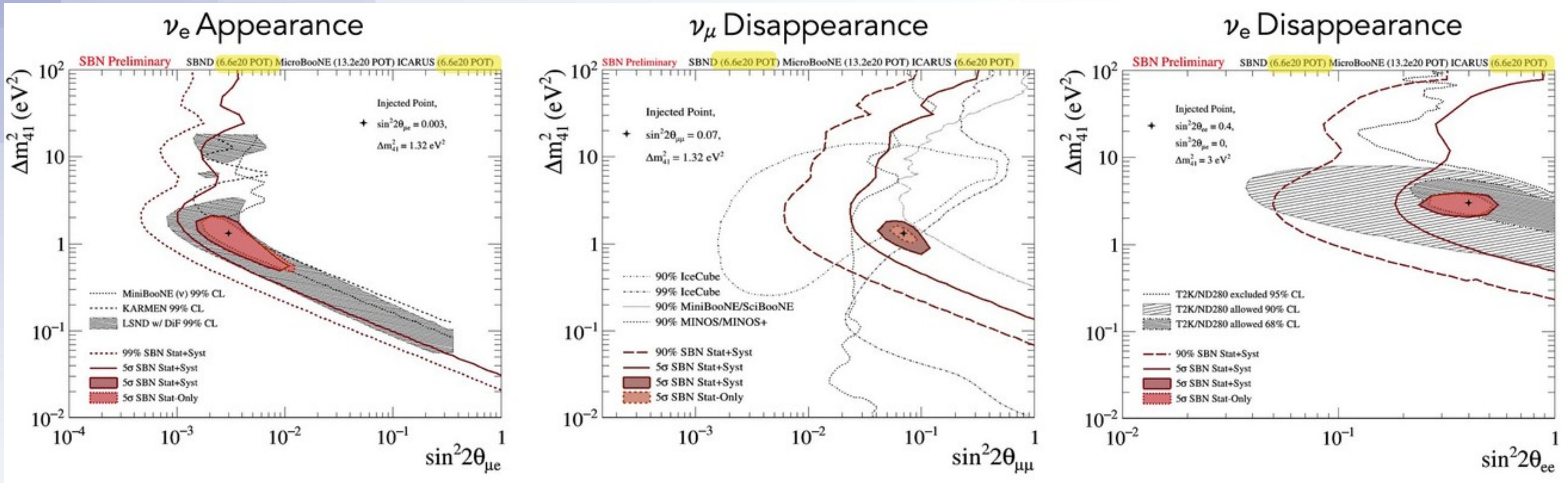
Deficit in 1eNp0π and 1e1p selections at ~400-800 MeV.

SBND Assembly and Installation

- Detector assembly and installation for all components inside the cryostat is complete, and the bottom and north CRT walls are installed.
- The the cabling for all systems from cryostat flanges to readout electronics racks, and in parallel with that on the final parts of cryogenics installation.
- The official end of installation on the 1st of Dec 2023.
- Start LAr fill in January 2024, power up the detector in February and beginning of commissioning.
- First SBND Physics Run from April-July 2024. Expected data will match the MicroBooNE entire dataset.

Sterile Neutrinos and other BSM @ SBND

- SBND contributes to the SBN Program as the near detector, characterizing the beam before eV-scale oscillations set in and thus addressing dominant systematic uncertainties
  - SBN has a unique chance to jointly study ν_e appearance, ν_μ disappearance, and ν_e disappearance



- In addition, SBND will pursue other possible explanations for the MiniBooNE low-energy excess anomaly as well as other beyond Standard Model physics scenarios