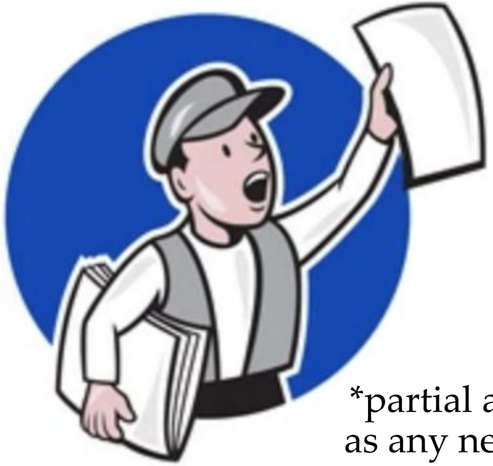
The University of Manchester



*partial and biased as any news report!

Long Baseline Neutrinos*

Dr. Elena Gramellini, The Future of HEP, March 27th 2024, Aspen

ν physics: what we know…

$\theta_{12}, \theta_{13}, \theta_{23}$ ✓
$\Delta m^2, \delta m^2$ ✓
N_ν ✓
δ_{CP}
Octant θ_{23}
sign(Δm^2)
α_1, α_2
m_x

Precision era (< 10%)

N Active: 3 ν

Neutrino Oscillations: 1st evidence of BSM

ν physics: …and what we don't!

Parameter	Status	
$\theta_{12}, \theta_{13}, \theta_{23}$	✓	Precision era (< 10%)
$\Delta m^2, \delta m^2$	✓	
N_ν	✓ ✗	N Active: 3 ν N sterile, NSI?
δ_{CP}	✗	Getting there…
Octant θ_{23}	✗	
$\mathrm{sign}(\Delta m^2)$	✗	
α_1, α_2	✗	No information
m_x	✗	Upper limits

ν physics: …and what we don't! — Can be explored @ LBL

- $\theta_{12}, \theta_{13}, \theta_{23}$ ✓
- $\Delta m^2, \delta m^2$ ✓
- N_ν ✓ ✗
- δ_{CP} ✗
- Octant θ_{23} ✗
- $\text{sign}(\Delta m^2)$ ✗
- α_1, α_2 ✗
- m_x ✗

Precision era (< 10%): $\theta_{12}, \theta_{13}, \theta_{23}$; $\Delta m^2, \delta m^2$

N_ν → N Active: 3 ν; N sterile, NSI?

Getting there…: δ_{CP}; Octant θ_{23}; $\text{sign}(\Delta m^2)$

α_1, α_2 → No information

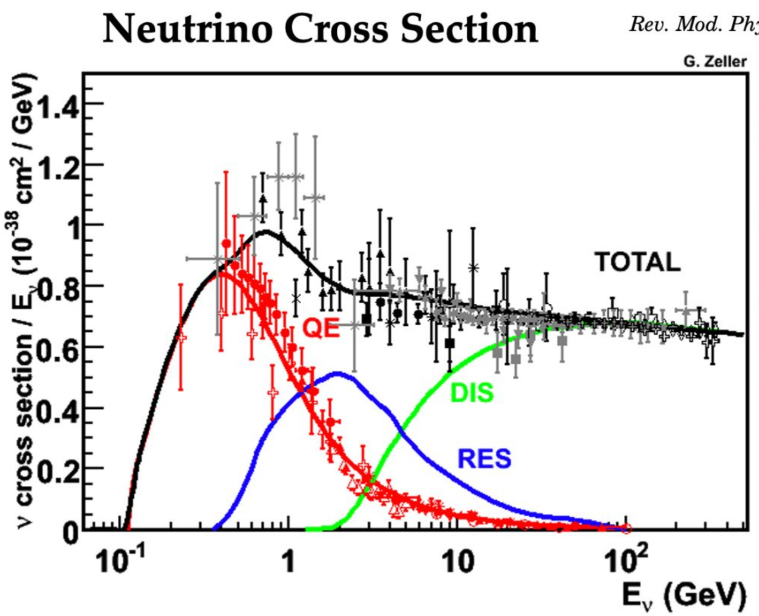
m_x → Upper limits

Experimentally, neutrinos are difficult

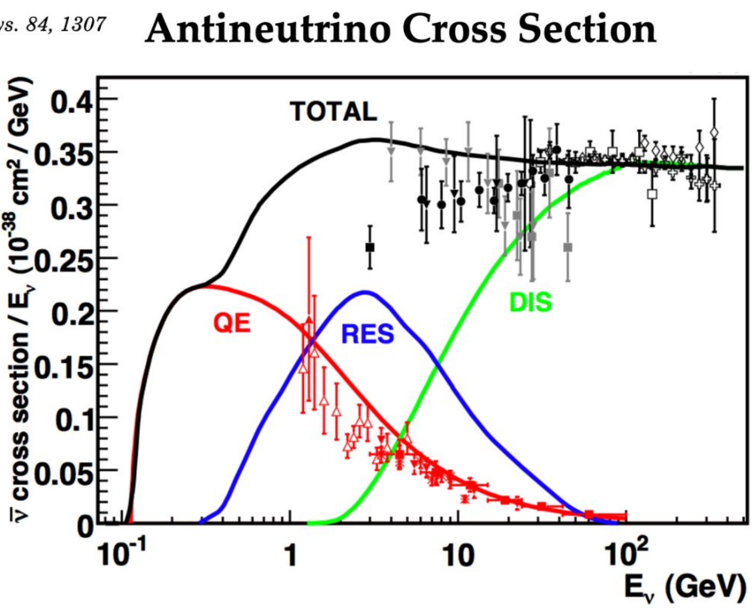
Neutrinos are the most abundant massive particle in the universe, and one of the least understood.
They are neutral: we can't directly detect them. We can study them only if they interact, but…

Experimentally, neutrinos are difficult

Neutrinos are the most abundant massive particle in the universe, and one of the least understood.
They are neutral: we can't directly detect them. We can study them only if they interact, but…

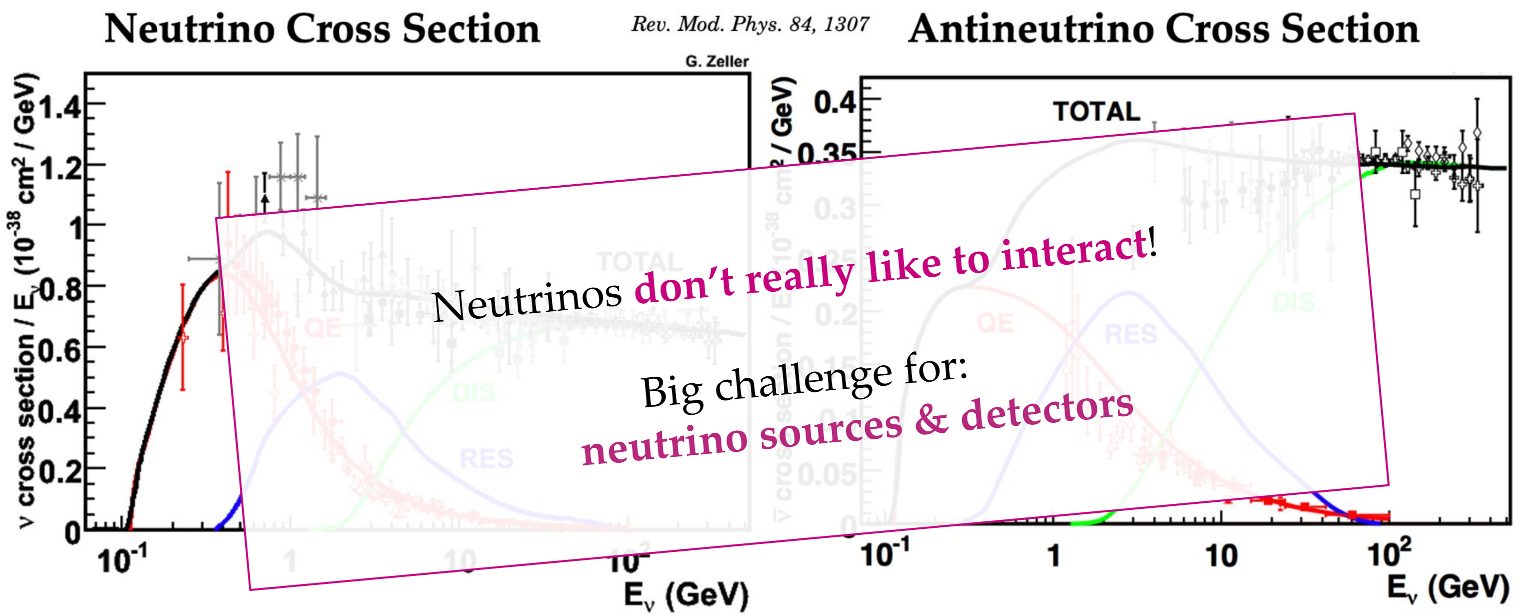


Rev. Mod. Phys. 84, 1307



Experimentally, neutrinos are difficult

Neutrinos are the most abundant massive particle in the universe, and one of the least understood.
They are neutral: we can't directly detect them. We can study them only if they interact, but…



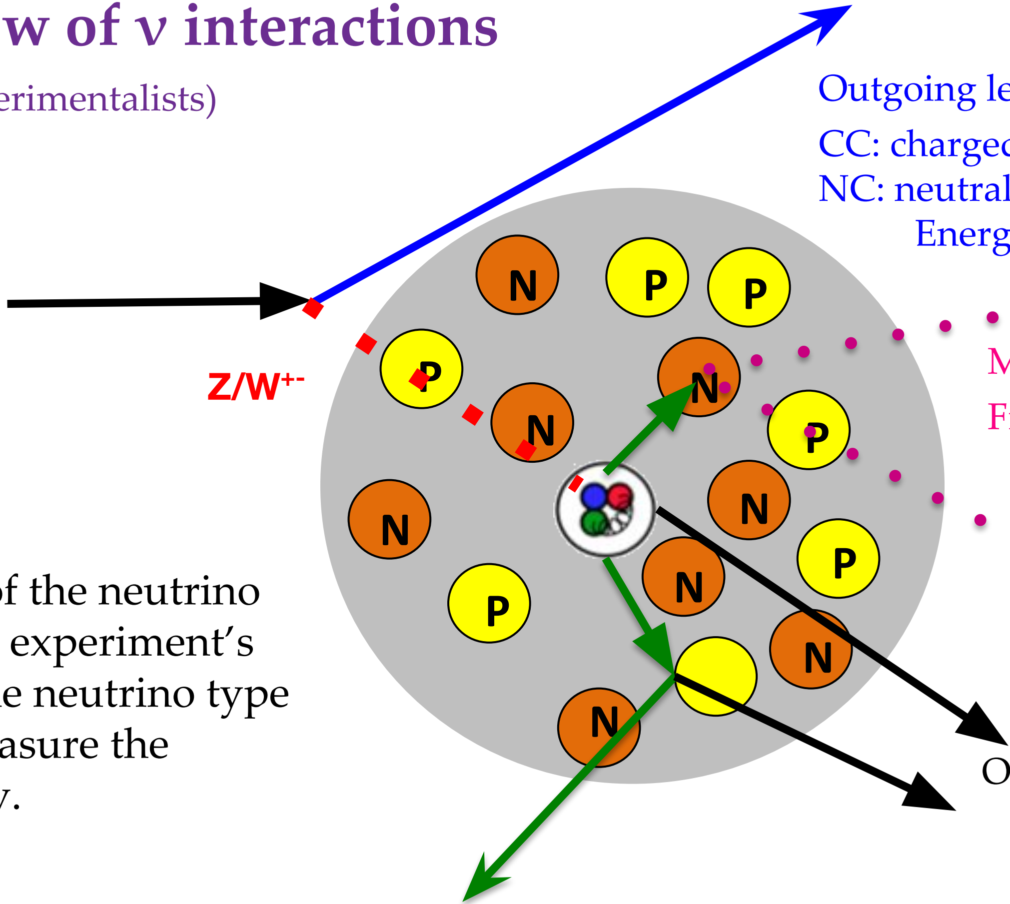
A simplified view of ν interactions

(and of our jobs as experimentalists)

Incoming ν:

Flavor unknown

Energy unknown



Outgoing lepton:

CC: charged lepton

NC: neutral lepton

Energy: measure

Mesons:

Final State Interactions

Energy? Identity?

Outgoing nucleons:

Visible?

Energy?

From the products of the neutrino interactions, it is the experiment's job to understand the neutrino type (ν_e, ν_μ, ν_τ) and to measure the neutrino **true** energy.

Neutrino Oscillations and CP violation

Flavor $\quad \nu_\mu \to \nu_e \quad \nu_\mu \to \nu_\mu \quad$ Mass

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

CP violation

$$c_{ij} = \cos\theta_{ij};\ s_{ij} = \sin\theta_{ij}$$

$\theta_{12}, \theta_{13}, \theta_{23}$	✓
$\Delta m^2, \delta m^2$	✓
N_ν	✓ ✗
δ_{CP}	✗
Octant θ_{23}	✗
sign(Δm^2)	✗

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E}$$
$$(+)-\Big[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}$$
$$\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\Big]$$
$$+\ (\text{CP-even, solar, matter effect terms})$$

Neutrino Oscillations and CP violation

We try to tease out the asymmetry in oscillation probability for the appearance channel:
highly degenerate problem w/ other free parameters

$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

Parameter	Status
$\theta_{12}, \theta_{13}, \theta_{23}$	✓
$\Delta m^2, \delta m^2$	✓
N_ν	✓ ✗
δ_{CP}	✗
Octant θ_{23}	✗
sign(Δm^2)	✗

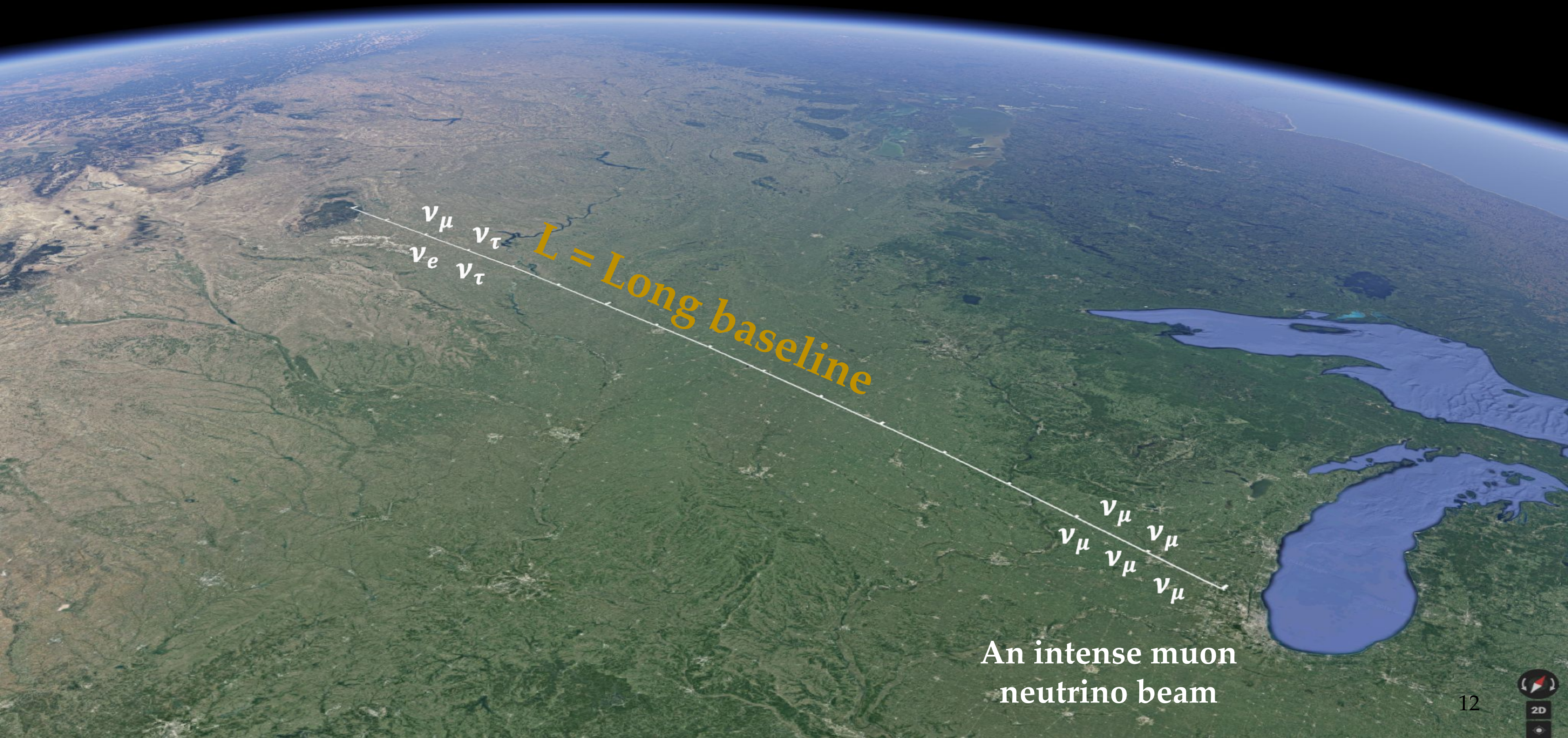
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E}$$
$$(+)-\Big[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}$$
$$\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\Big]$$
$$+\ (\text{CP-even, ~~solar, matter effect~~ terms})$$

MANCHESTER 1824 The University of Manchester

CP violation 101

via ν-oscillations

***STEP 1**: Making a beam*



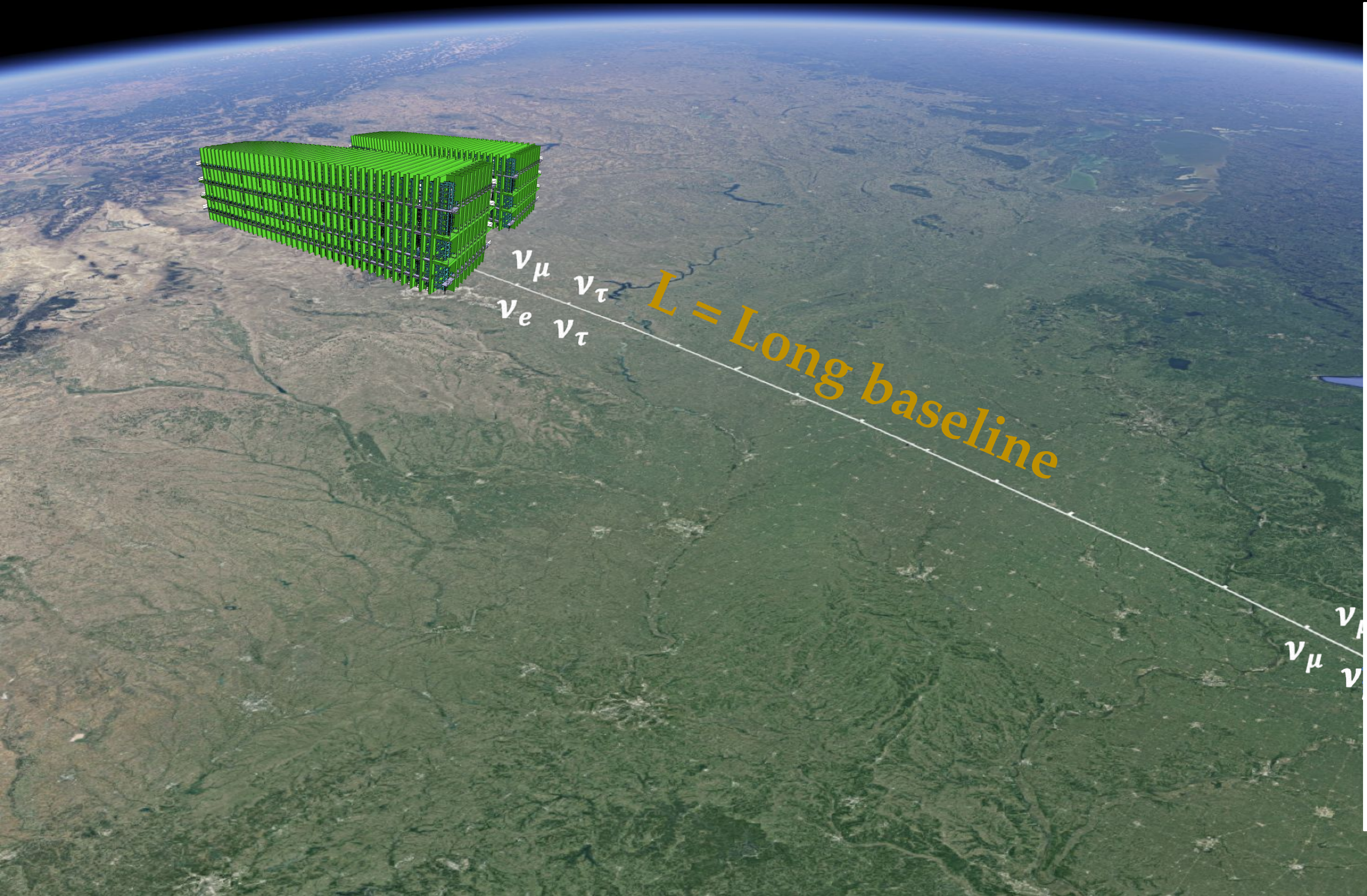
CP violation 101
via ν-oscillations

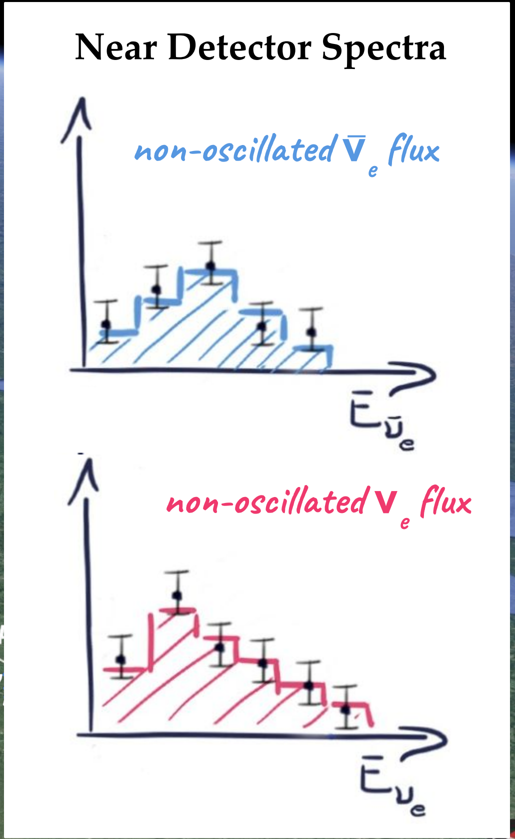
***STEP 1**: Making a beam*
***STEP 2**: Checking twice*

CP violation 101

via ν-oscillations

***STEP 1**: Making a beam*
***STEP 2**: Checking twice*

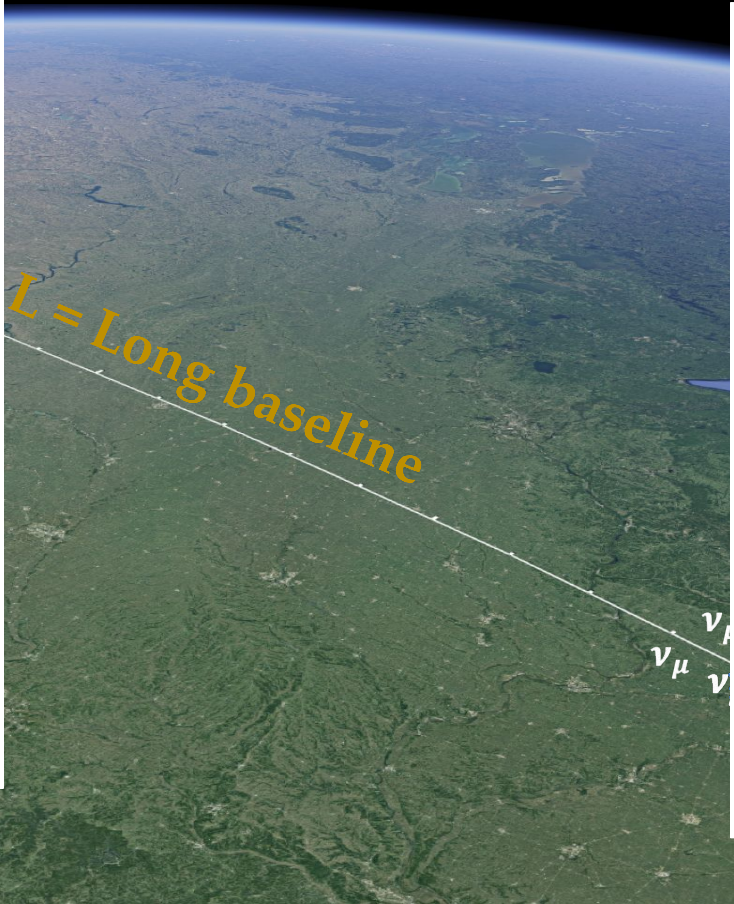


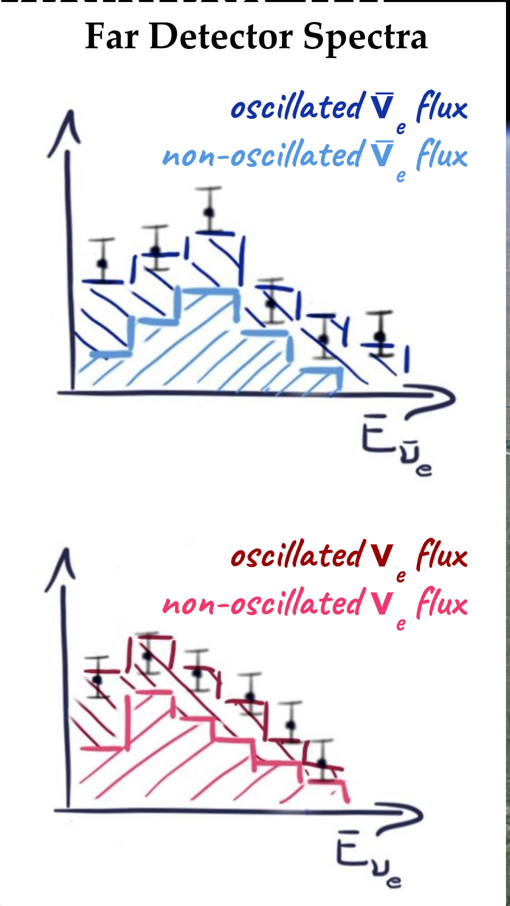


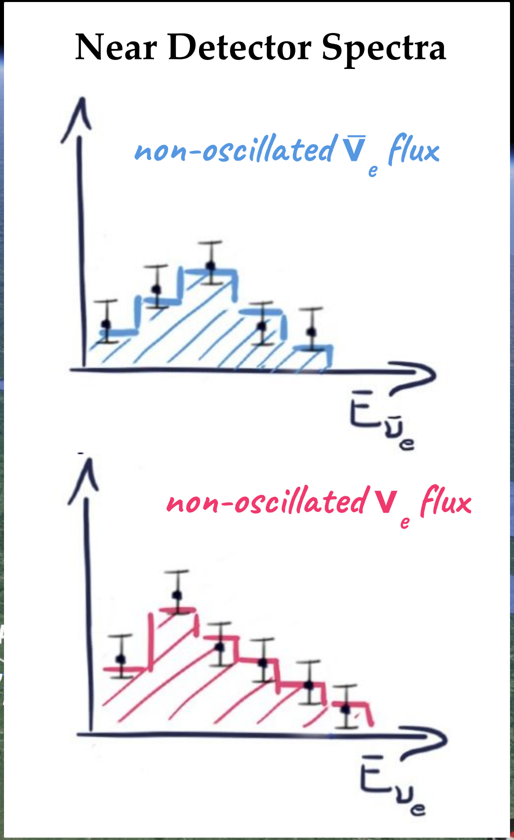
CP violation 101

via ν-

***STEP 1**: Making a beam*
***STEP 2**: Checking twice*



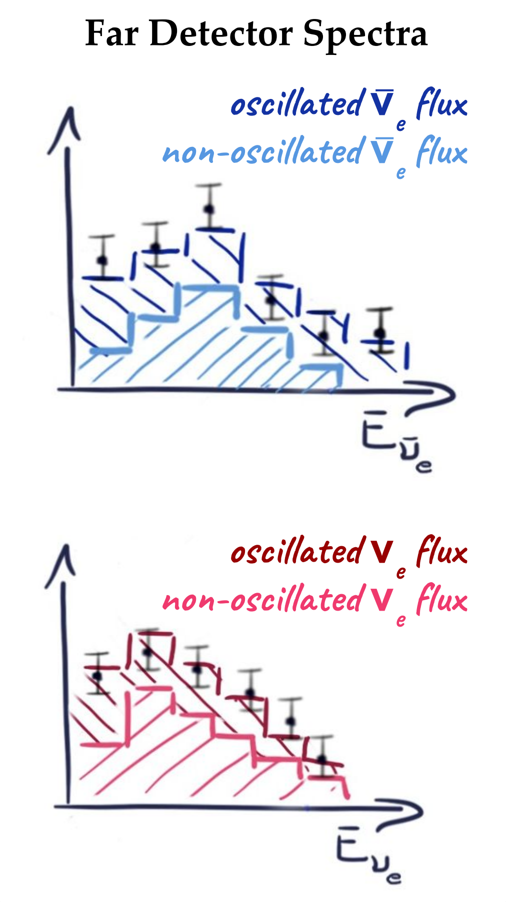


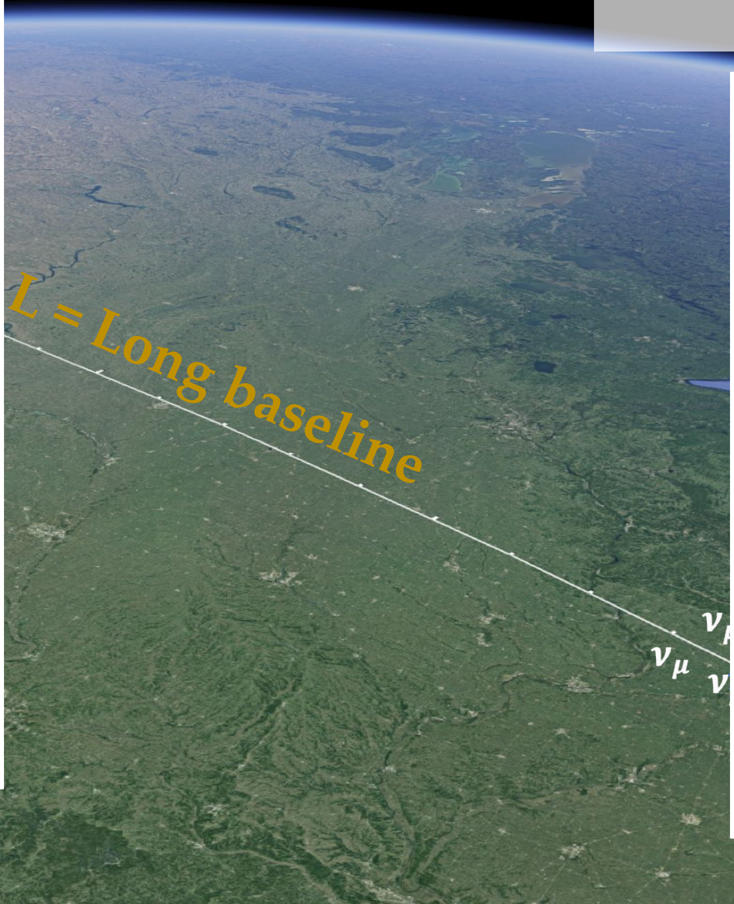


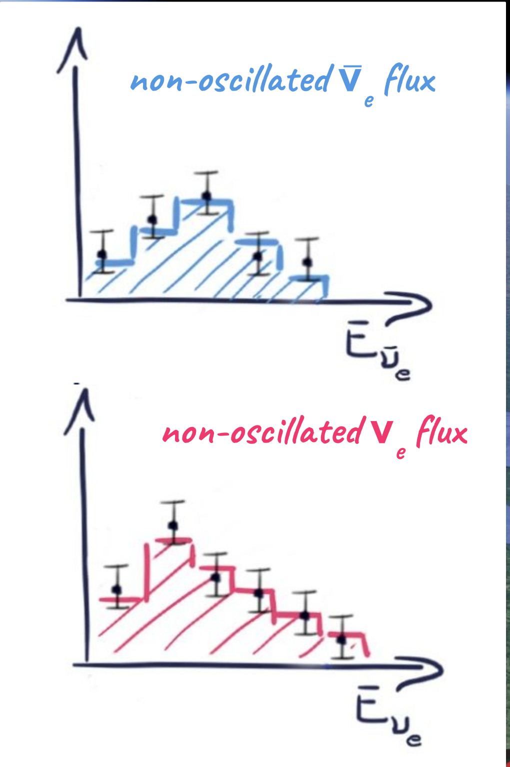
CP violation 101

via ν-

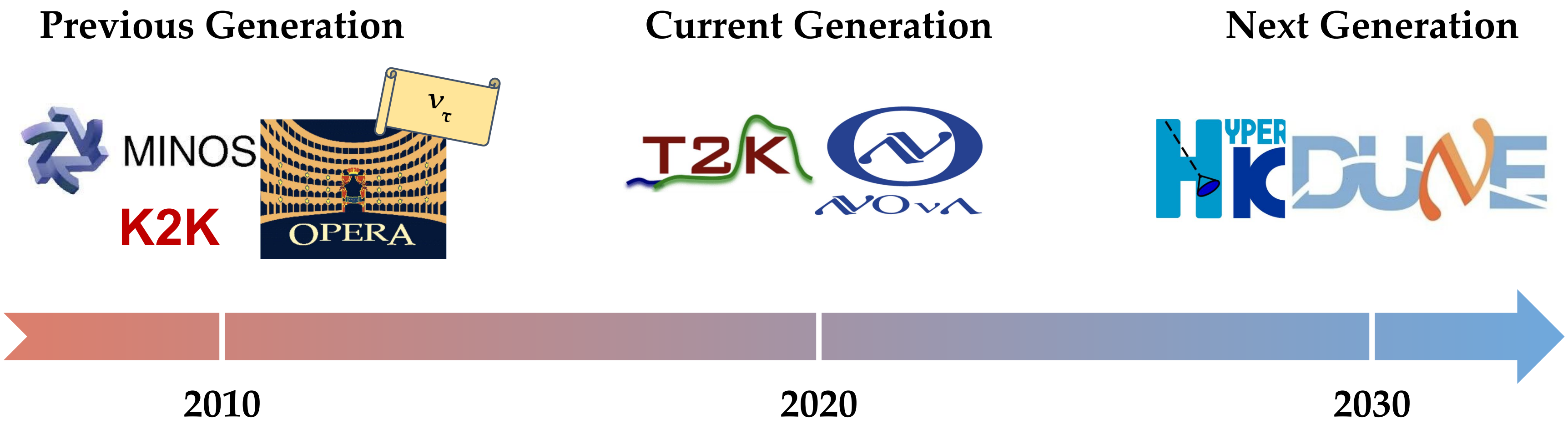
STEP 1: *Making a beam*
STEP 2: *Checking twice*
STEP 3: *Gonna find out if ν_e & $\bar{\nu}_e$ oscillate differently*







A timeline of long baseline accelerator neutrinos



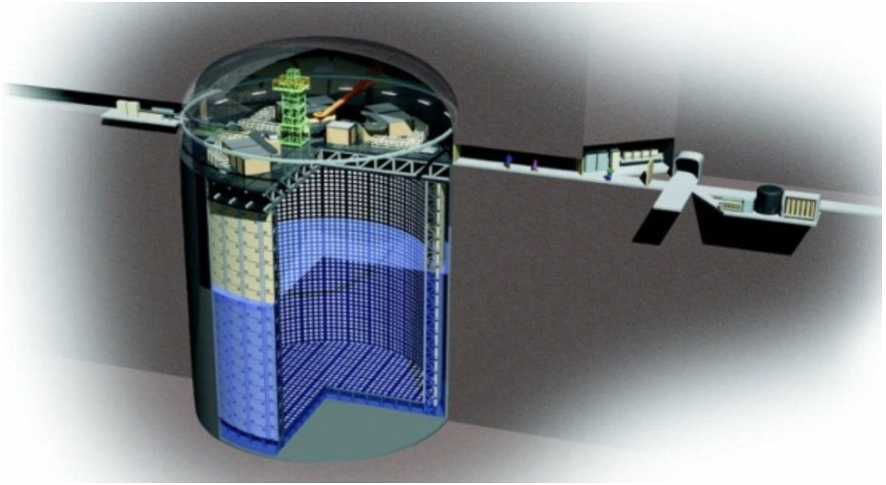
Courtesy of Z. Vallari

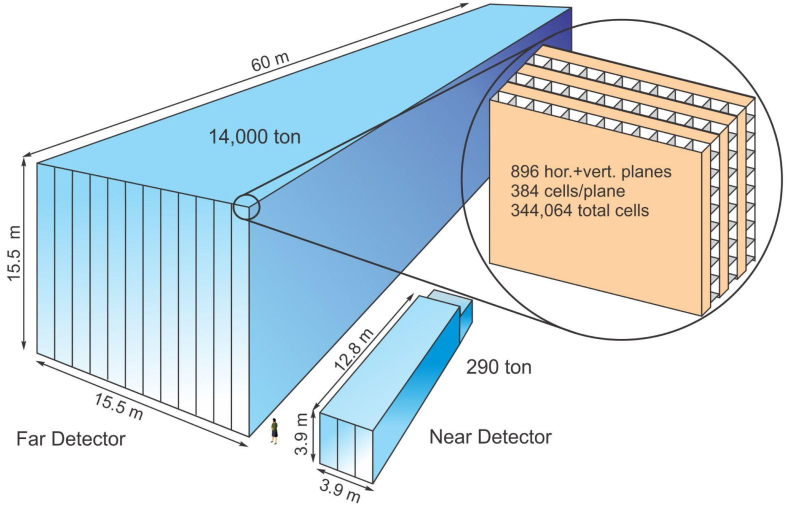
A timeline of long baseline accelerator neutrinos

Courtesy of Z. Vallari

MANCHESTER 1824 The University of Manchester

Current Big Players: T2K & NOvA





T2K

- Water Cherenkov 55 kton (FD), several ND
- L = 295 km, E = 0.6 GeV
- Shorter baseline → greater impact on δ_{CP} (30%)
- "Low energy" → mainly QE interactions

NOvA

- Mineral Oil Scintillator both ND and FD
- L = 810 km, E = 2 GeV
- Longer baseline → greater impact on mass ordering due to bigger matter effect (19%)
- Mixture of QE + 2p2h + RES + DIS

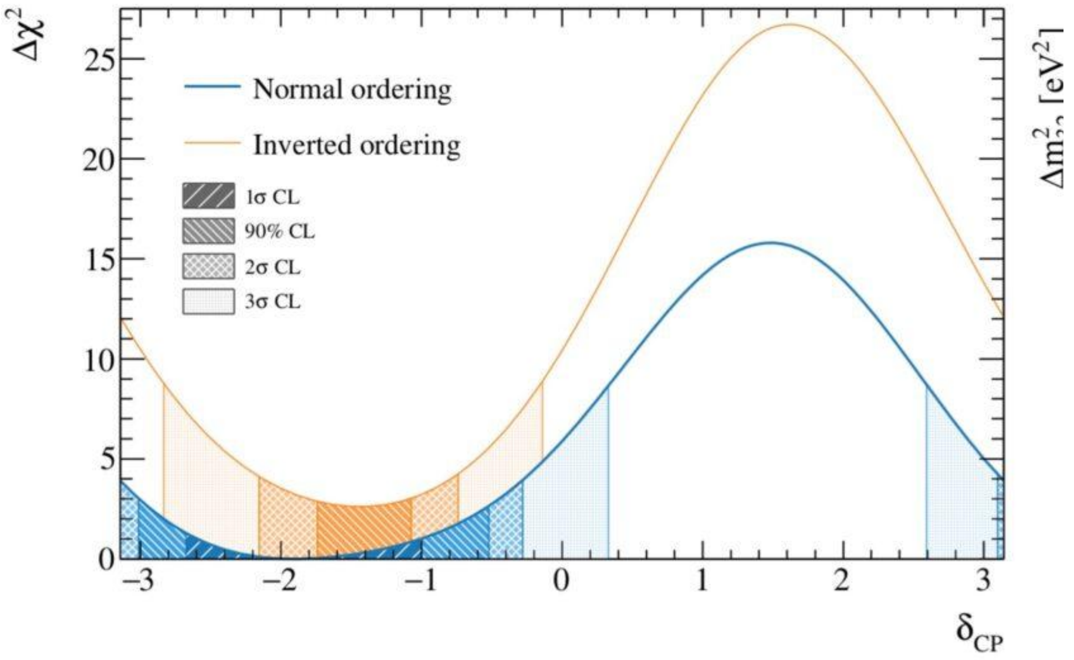
MANCHESTER 1824 The University of Manchester

Oscillations and CP violation: T2K

Eur.Phys.J.C 83 (2023) 9, 782
Nature 580, 339–344 (2020)

New updated result! 3.6 E21 POT

- World-leading constraints on δ_{CP}
- O(100) ν_e events in FD
- Improvements: new selections and more data from ND, improved flux prediction through hadron production; bayesian and frequentist inference.
- Favor: NO and UP, ~maximally CP violating phase. Excludes delta δ_{CP}=0, π >than 90% CL.
- θ_{13} consistent with the reactor experiments.

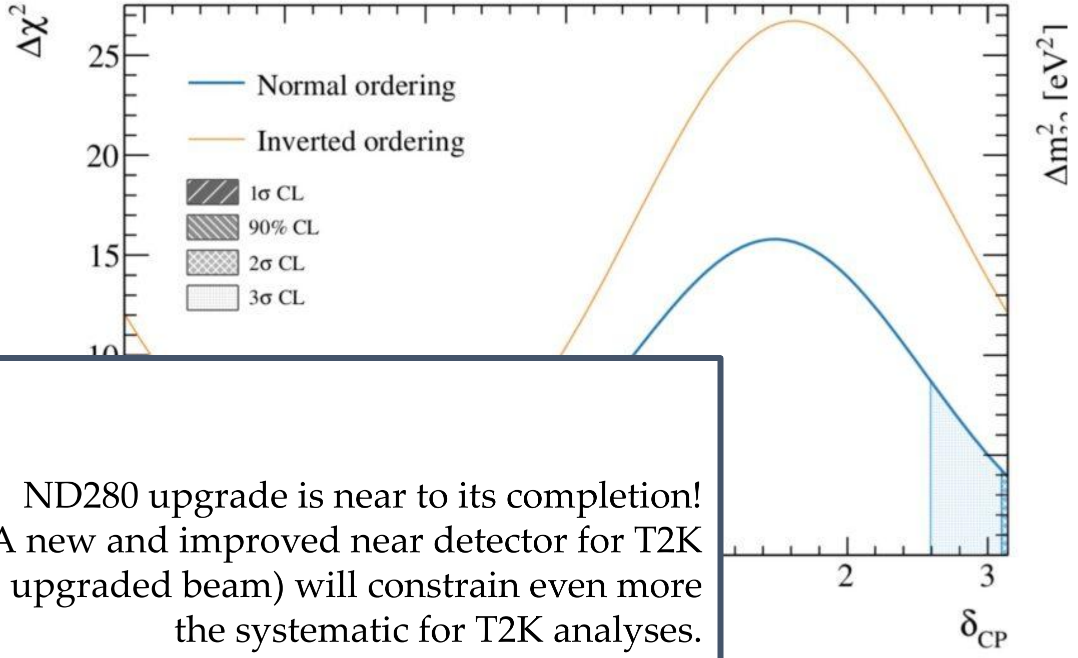


Oscillations and CP violation: T2K

[Eur.Phys.J.C 83 (2023) 9, 782](#)
[Nature 580, 339–344 (2020)](#)

New updated result! 3.6 E21 POT

- World-leading constraints on δ_{CP}
- O(100) ν_e events in FD
- Improvements: new selections and more data from ND, improved flux prediction through hadron production; bayesian and frequentist inference.
- Favor: NO and UP, ~maxi violating phase. Excludes π >than 90% CL.
- θ_{13} consistent with the rea experiments.

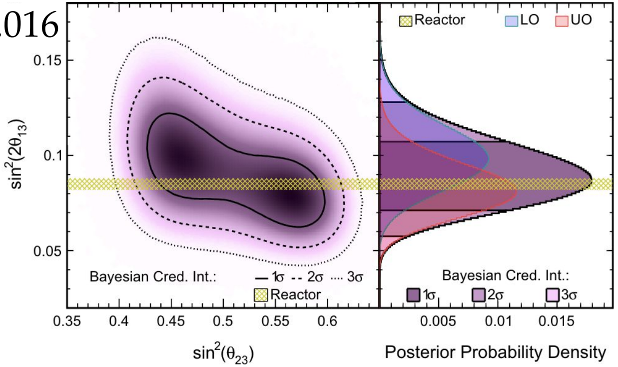


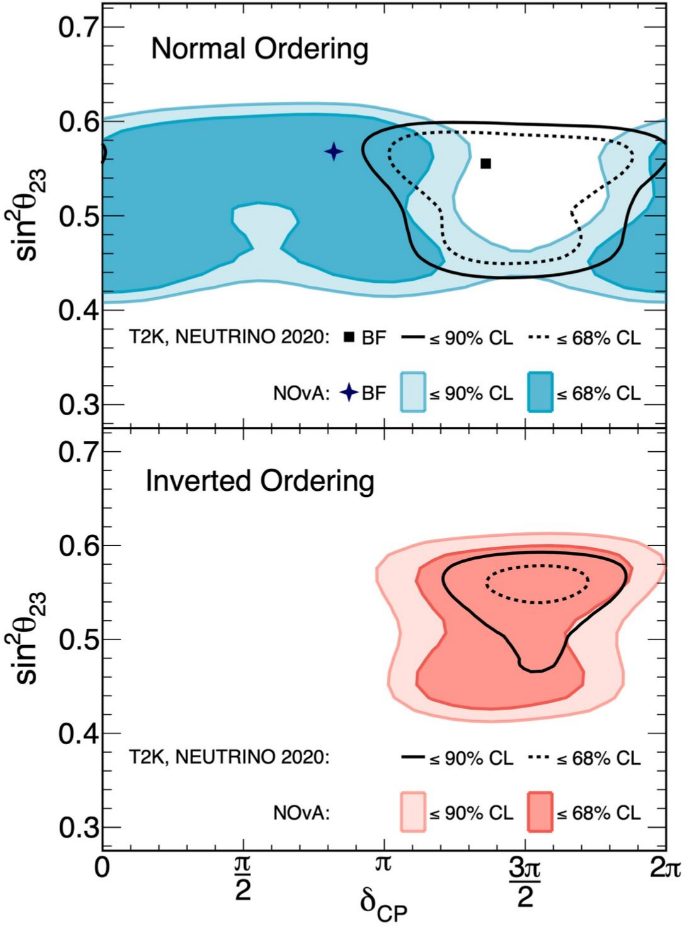
ND280 upgrade is near to its completion!
A new and improved near detector for T2K (and upgraded beam) will constrain even more the systematic for T2K analyses.

Oscillations and CP violation: NOvA

- Exclude $\delta_{CP}=\pi/2$ at $>3\sigma$ (IO). Less strong constraint on δ_{CP} in the NO, but disfavors region around $\delta_{CP}= 3\pi/2$
- Weak preference for NO, UO
- θ_{23} still consistent with 45°
- O(70) ν_e events in FD

- New Bayesian analysis: improved statistical interpretations of the results. Consistent w/ frequentist fit.
- $\sin^2(2\theta_{13}) = 0.085{+0.020}{-0.016}$ good agreement with the reactor experiments





PRD 106.032004, Arxiv 2311.07835

Joining forces: the NOvA-T2K joint fit

Scope: resolving degeneracies

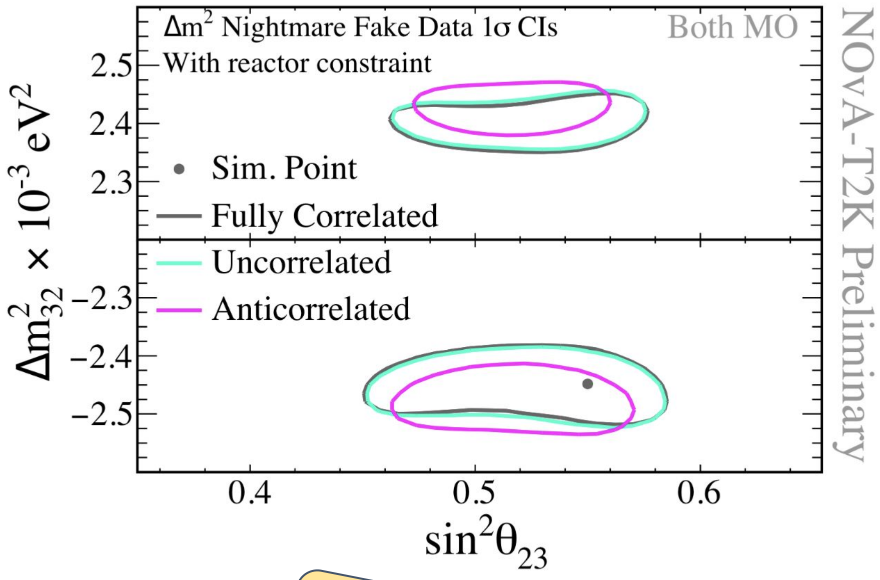
<u>This is a preliminary result</u>

- The experiments have different analysis approaches driven by contrasting detector designs
  → combination is far from trivial

- Challenge: When? What? How? to correlate common physics parameters between the two experiments.
  - Flux & detector models → uncorrelated
  - XS model → there will be dragons:
    even if energy is different and model used are different, the underlying processes are the same.

  Post-hoc strategy: we can learn from this!

Paper in preparation, material from FNAL W&C.



The University of Manchester

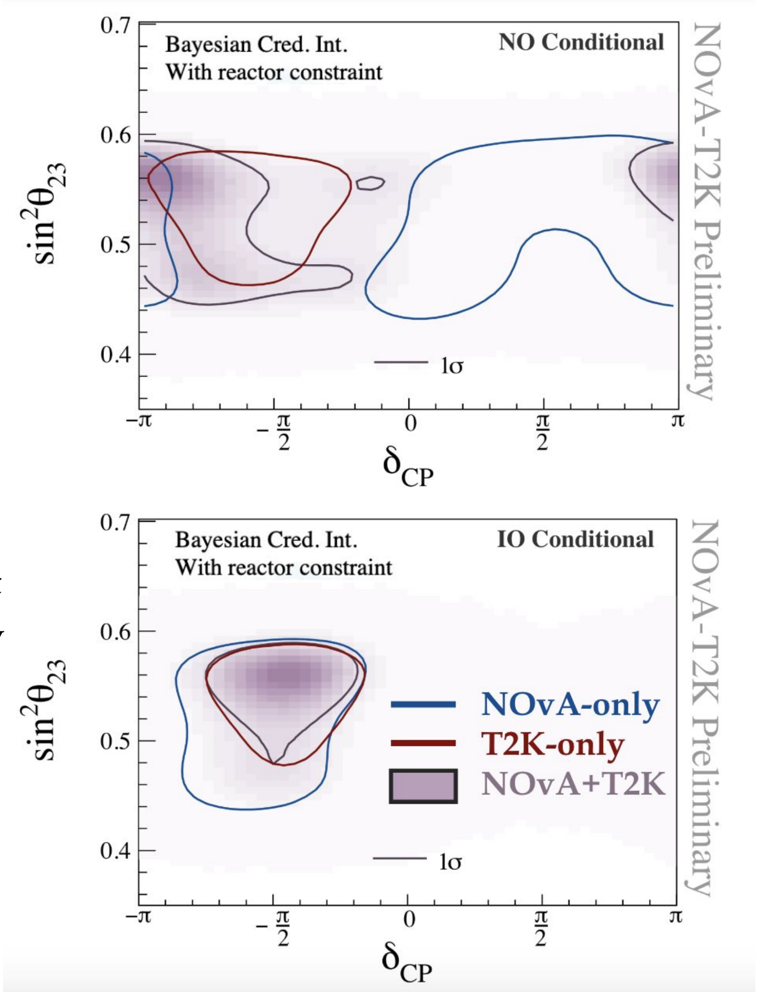
Joining forces: the NOvA-T2K joint fit

Scope: resolving degeneracies

<u>This is a preliminary result</u>

- Simultaneous compatibility of NOvA and T2K datasets.
- Very strong constraint on $|\Delta m_{32}|$
  Mass Ordering preference remains inconclusive.
  → Individual experiments prefer Normal Ordering
  → Small preference for the Inverted Ordering in the joint fit
  → Reverts to a weak NO preference when adding Daya Bay

- $\delta_{CP} = \pi/2$ lies outside 3-sigma credible interval for both MO.
- NO permits a wide range of permissible δ_{CP} , while CP conserving values for the IO falls outside the 3-sigma range.



Paper in preparation, material from FNAL W&C.

Where we are: a snapshot of current results (w/o atmo constraints)

without SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

Up to 2022 published data

www.nu-fit.org

JHEP09(2020)178

Where we are: a snapshot of current results (w/ atmo constraints)

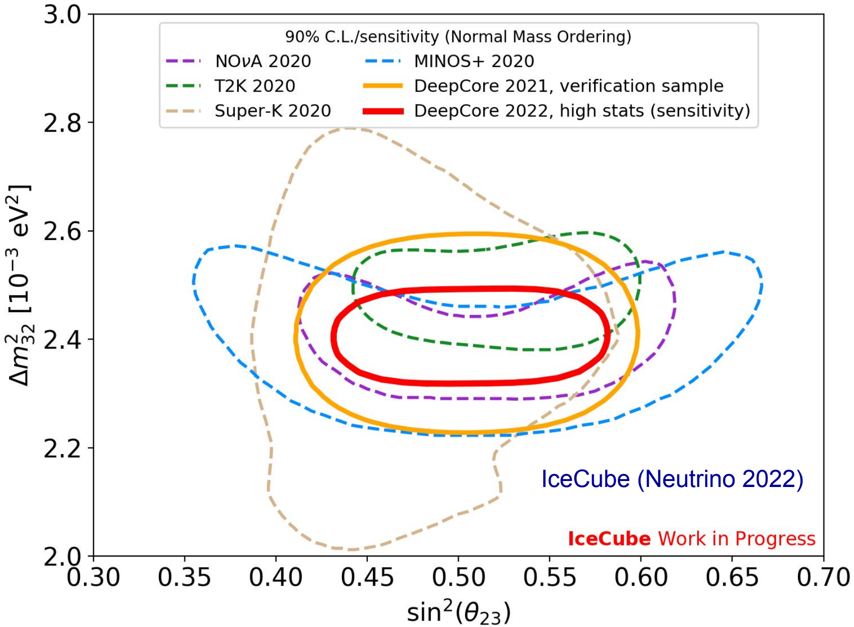
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

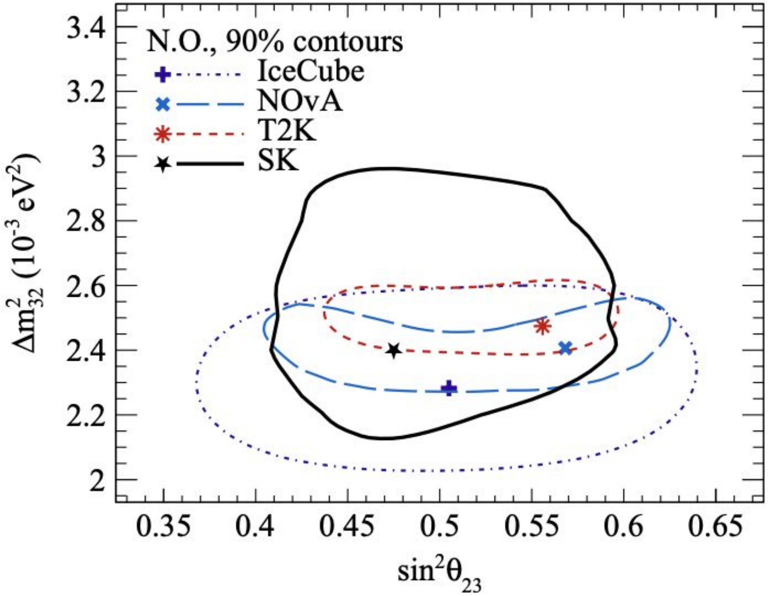
Up to 2022 published data

www.nu-fit.org

JHEP09(2020)178

Atmospheric Neutrinos: θ_{23} Δm^2_{23}





IceCube DeepCore:
Best projected atmospheric neutrino results, current data is consistent with LBL accelerators

SuperK:
Data favors first octant for θ_{23} & NH at ~ 2σ
δ_{CP} best fit agrees with that of T2K
Constraining power over θ_{13} consistent with LBL results

MANCHESTER 1824

The University of Manchester

Escaping the 3-neutrino paradigm & hunting down anomalies…

How can anomalies arise?

$\theta_{12}, \theta_{13}, \theta_{23}$	✓
$\Delta m^2, \delta m^2$	✓
N_ν	✓ ✗

Precision era
(< 10%)

N Active: 3 ν
Sterile?

"PMNS+" matrix

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

$+ \; \nu_X \qquad . \quad . \quad . \quad . \qquad + \; \nu_4$

The existence of a 4th, sterile neutrino would arise as a deviation from the predicted 3-flavor oscillation pattern at a baseline corresponding to the appropriate Δm^2.

How can anomalies arise?

$\theta_{12}, \theta_{13}, \theta_{23}$ ✓
$\Delta m^2, \delta m^2$ ✓
N_ν ✓ ✗

Precis... (<...

N A... Sterile?

The **assumption of unitarity** is the reason why studying ν_τ is crucial

The existence of a 4th, sterile neutrino would arise as a deviation from the predicted 3-flavor oscillation pattern at a baseline corresponding to the appropriate Δm^2.

"PMNS+" matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ + \\ \nu_X \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & . \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & . \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & . \\ . & . & . & . \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ + \\ \nu_4 \end{pmatrix}$$

Elena Gramellini | elena.gramellini@manchester.ac.uk

Recent Results: NOvA sterile searches

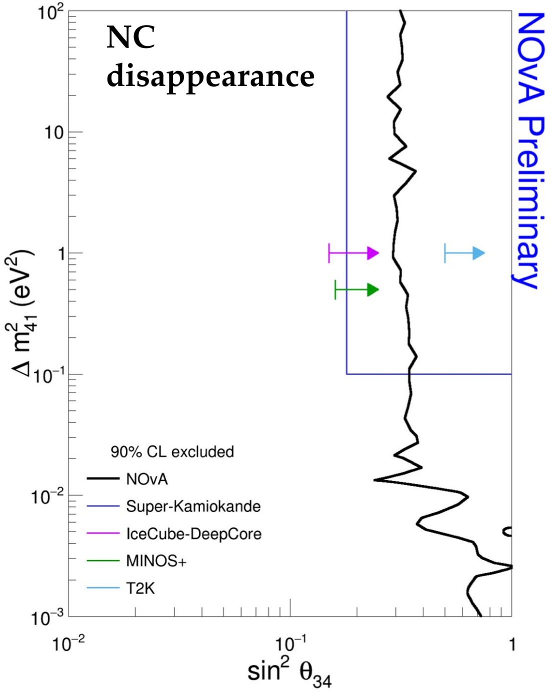
Search for 3 + 1 active-to-sterile ν oscillation in many channels.

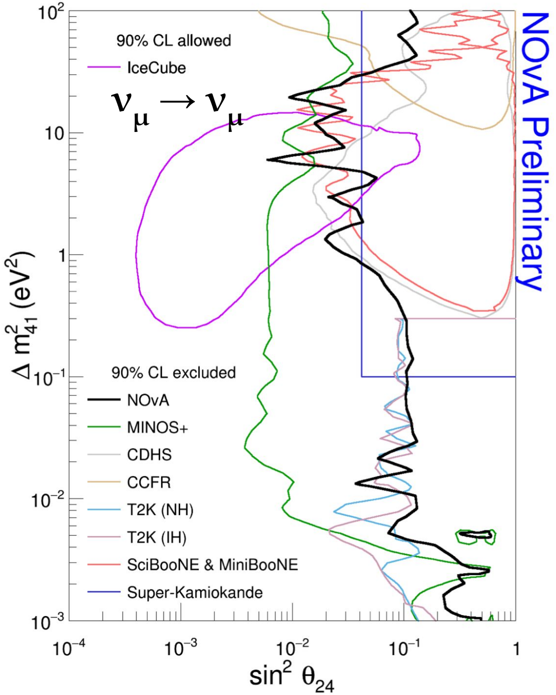
ND and FD searches
Neutral Current search: oscillation in ND is governed by sterile parameters.

Oscillations at FD:
access to θ_{24}, θ_{34}, δ_{24}

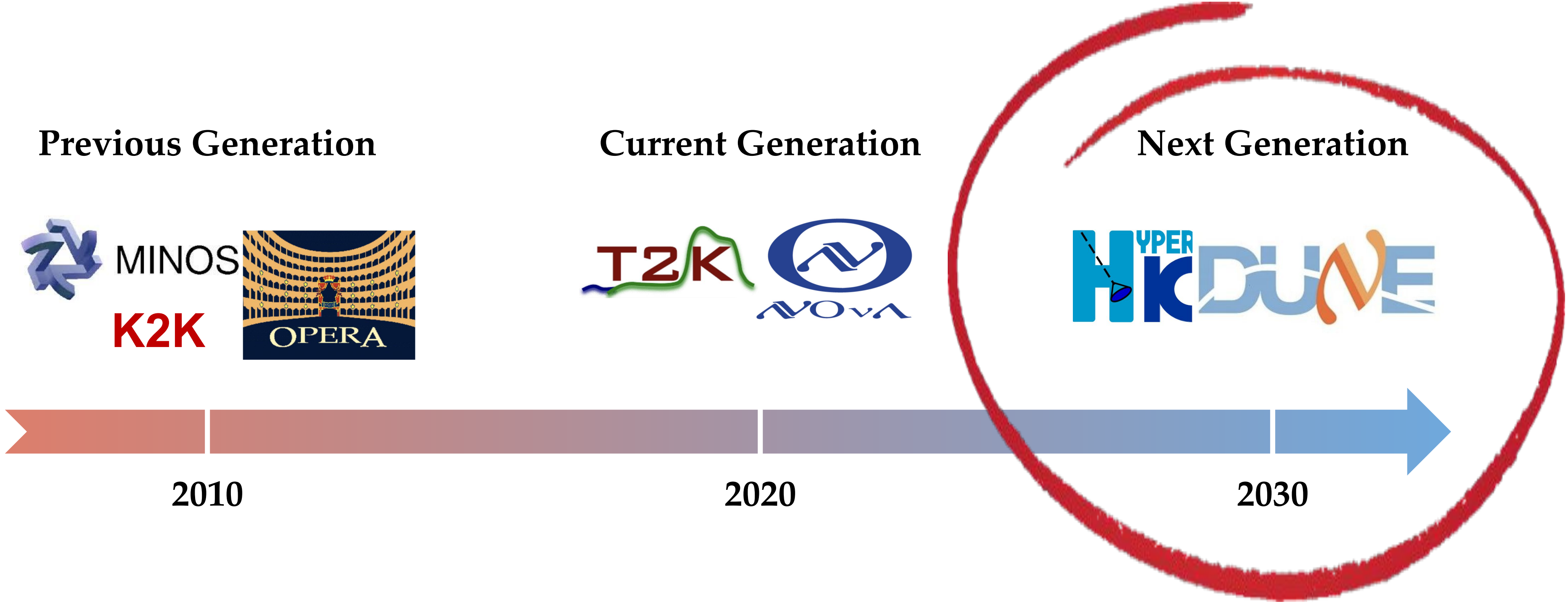
NOvA data shows no evidence for sterile neutrinos under 3+1 model.

- Limits on θ_{24} are competitive around $\Delta m^2_{41} = 10$ eV^2



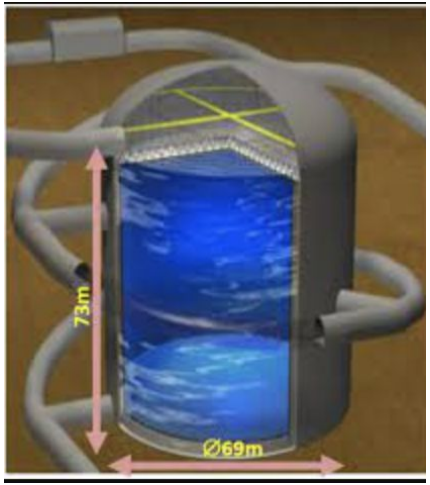


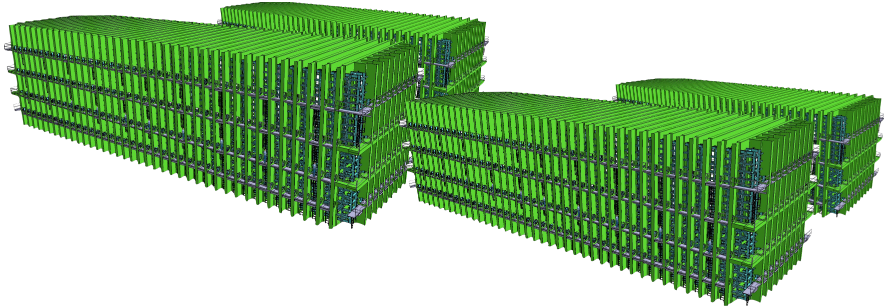
A timeline of long baseline accelerator neutrinos



Courtesy of Z. Vallari

Future Big Players: HyperK & DUNE





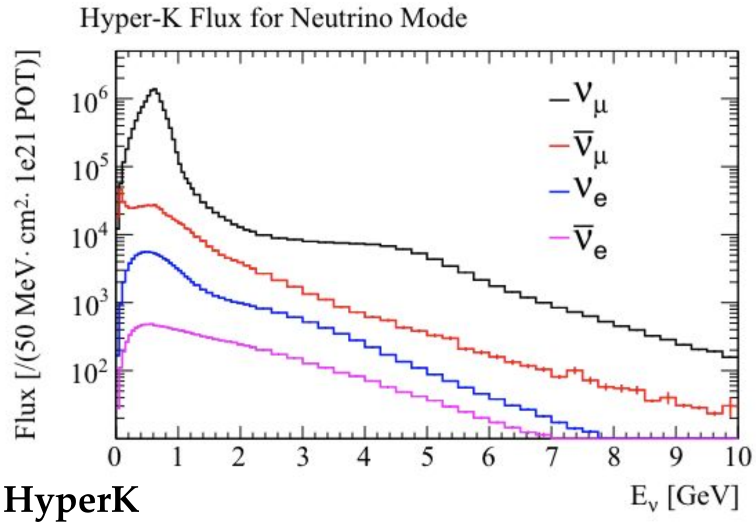
HyperK

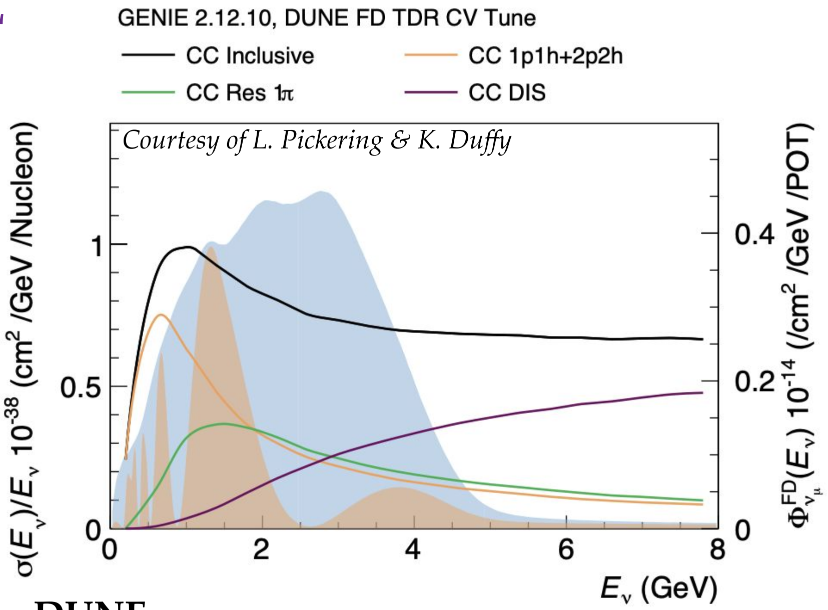
- Water Cherenkov 5xSK (FD), upgraded ND
- L = 295 km, E = 0.6 GeV
- Shorter baseline → greater impact on δ_{CP}
- "Low energy" → mainly QE interactions

DUNE

- Liquid Argon Time Projection Chambers
- L = 1200 km, peak E = 2.5 GeV (broad beam)
- Longer baseline → greater impact on mass ordering due to bigger matter effect
- Mixture of QE + 2p2h + RES + DIS

Future Big Players: HyperK & DUNE





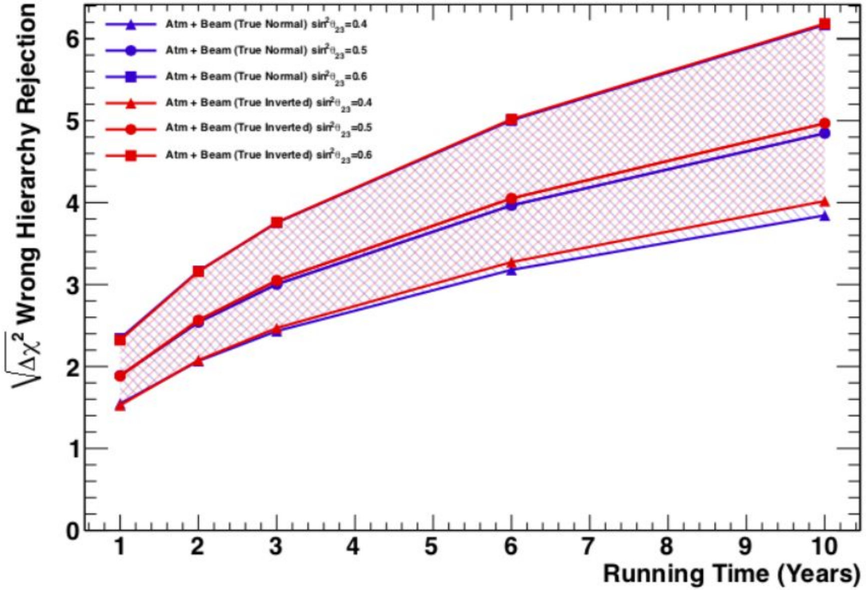
HyperK

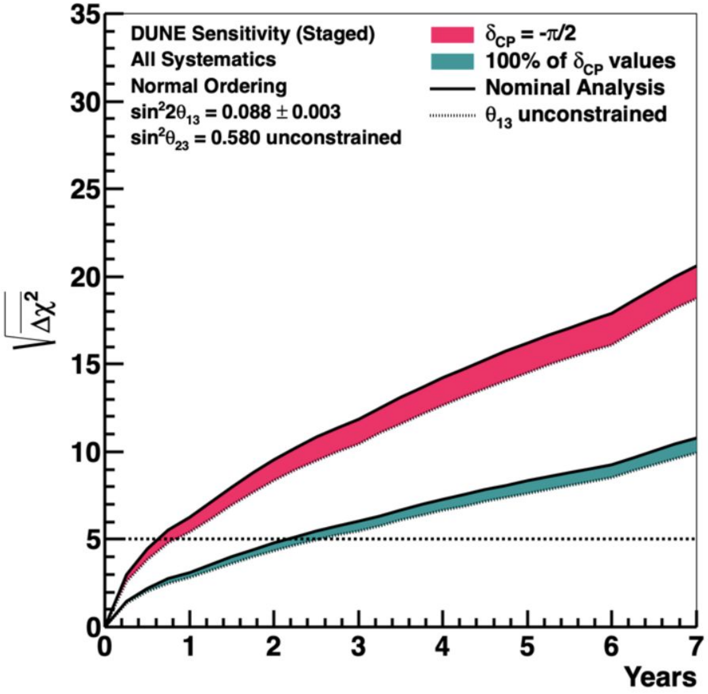
- Water Cherenkov 5xSK (FD), upgraded ND
- L = 295 km, E = 0.6 GeV
- Shorter baseline → greater impact on δ_{CP}
- "Low energy" → mainly QE interactions

DUNE

- Liquid Argon Time Projection Chambers
- L = 1200 km, peak E = 2.5 GeV (broad beam)
- Longer baseline → greater impact on mass ordering due to bigger matter effect
- Mixture of QE + 2p2h + RES + DIS

HyperK & DUNE: sensitivity to mass ordering

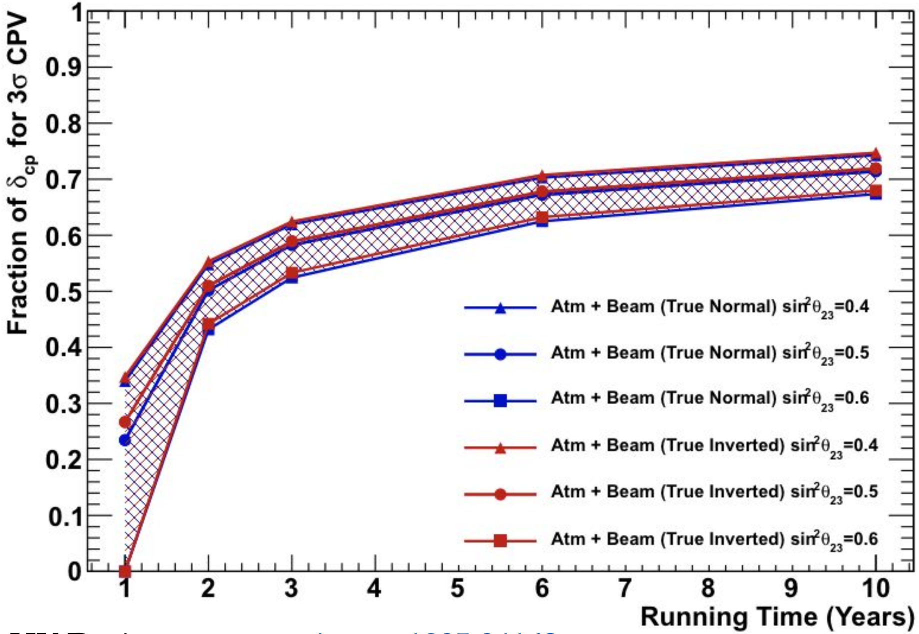


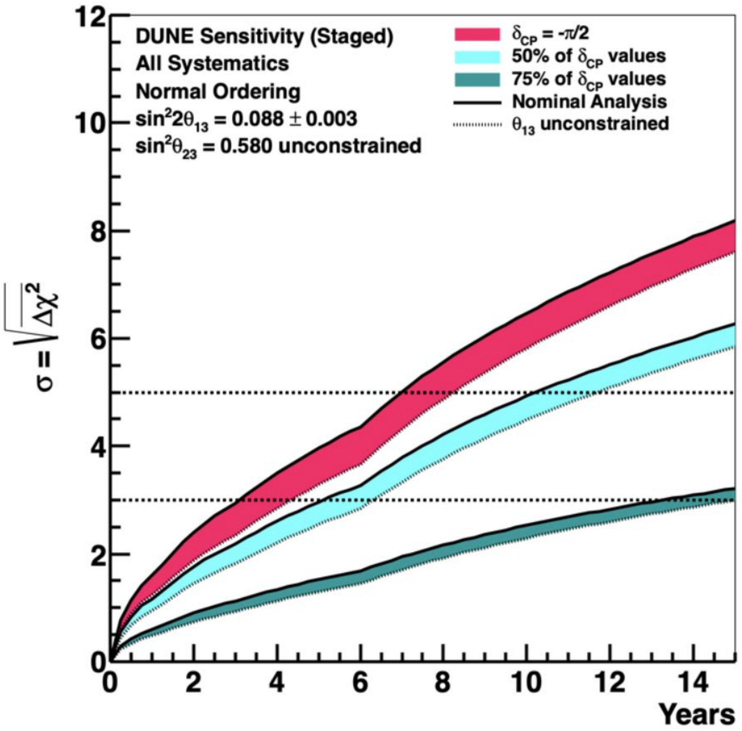


Status & prospects of HK [PoS ICRC2019 (2020) 924]

DUNE TDR [*JINST* 15 (2020) 08, T08008]

HyperK & DUNE: sensitivity to δ_{CP}

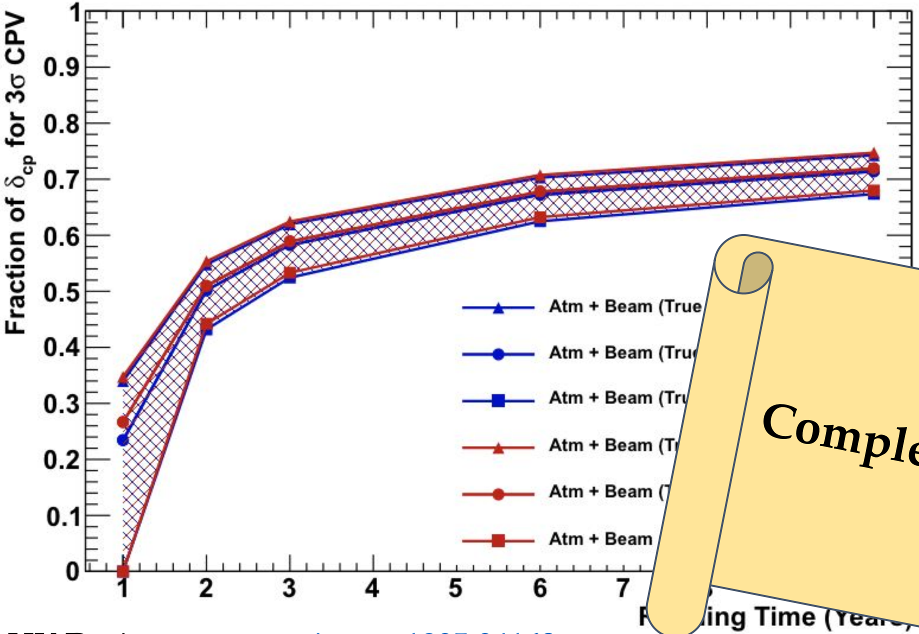


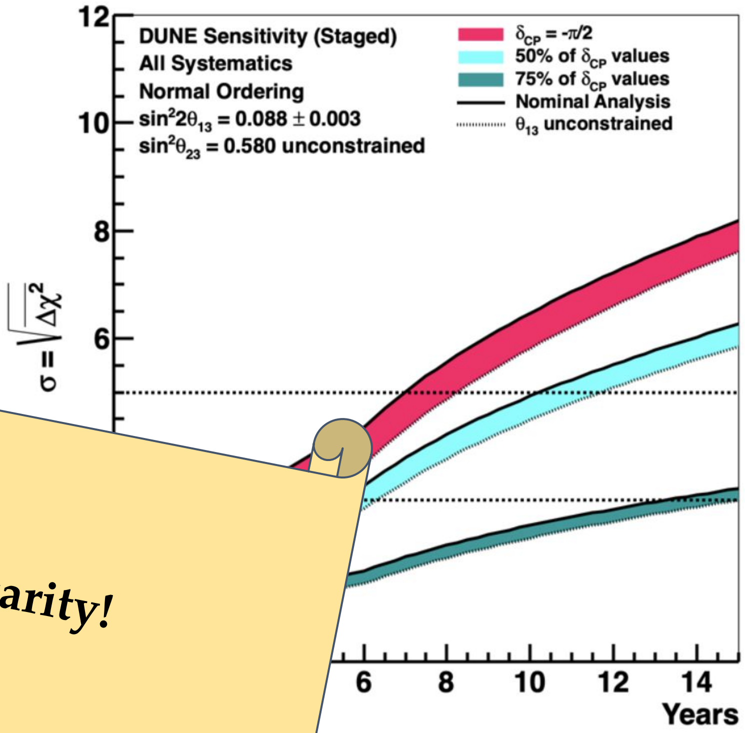


HK Design report [arxiv.org.1805.04163]

DUNE TDR *JINST* 15 (2020) 08, T08008

HyperK & DUNE: sensitivity to δ_{CP}





Complementarity!

HK Design report arxiv.org.1805.04163

TDR *JINST* 15 (2020) 08, T08008

What do we need to make these experiments successful (& better)?

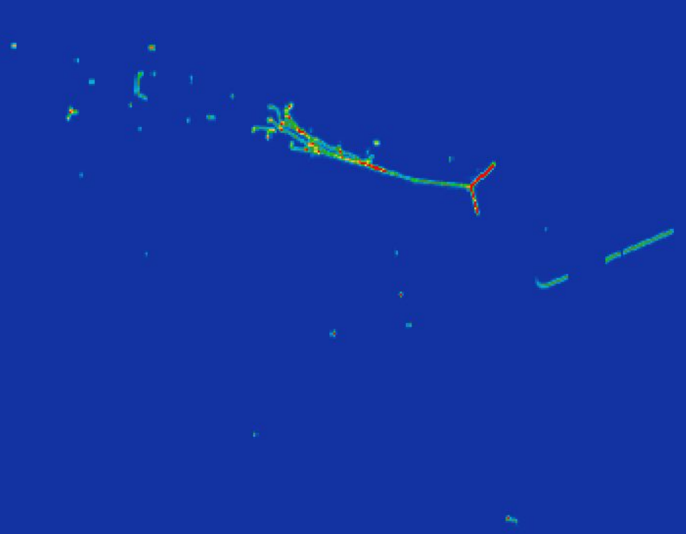
- To know how neutrinos interact → the XS problem
- To know how many neutrinos we get → the flux problem
- Improve our detectors

What do we need to make these experiments successful (& better)?

- **To know how neutrinos interact → the XS problem**
- To know how many neutrinos we get → the flux problem
- Improve our detectors

The importance of **neutrino cross sections**

This is all you see in your detector:
we never see the neutrino directly!

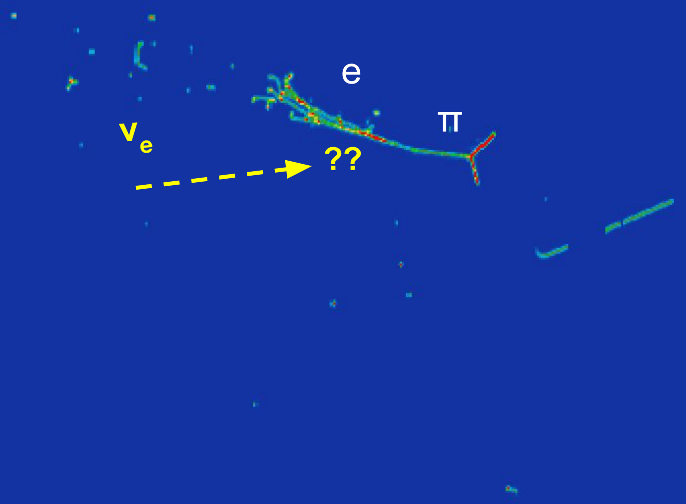


Event display courtesy of μBooNE

The importance of **neutrino cross sections**

This is all you see in your detector: we never see the neutrino directly!

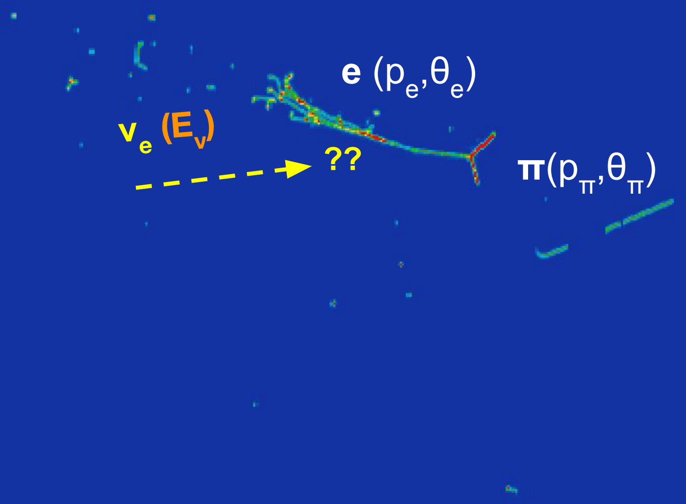
You identify the final state particles to **infer neutrino flavor:** count how many ν_e and ν_μ



Event display courtesy of µBooNE

The importance of **neutrino cross sections**

This is all you see in your detector: we never see the neutrino directly!



You identify the final state particles to **infer neutrino flavor:** count how many ν_e and ν_μ

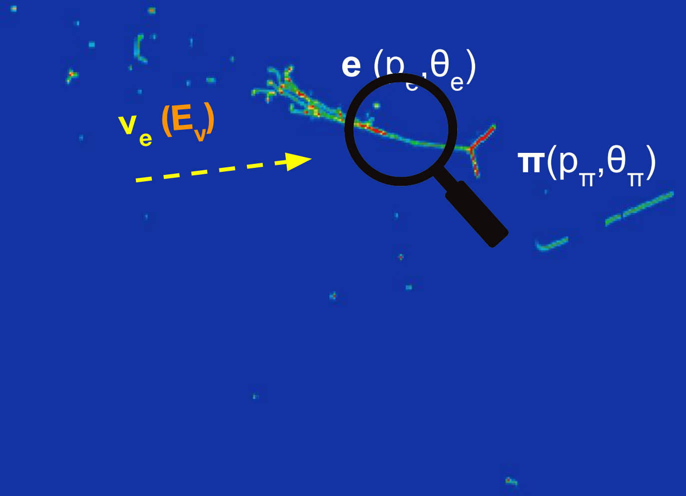
From the reconstructed particles' momenta you **infer neutrino energy:**

$$P(osc) \sim \sin^2(L / E_\nu)$$

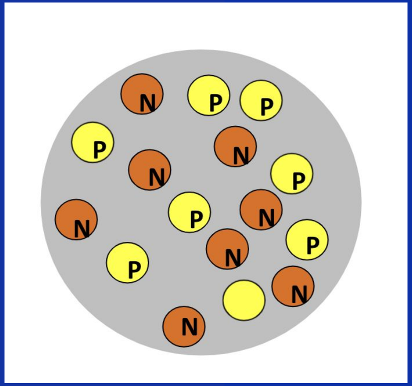
Event display courtesy of μBooNE

The importance of **neutrino cross sections**

This is all you see in your detector:
we never see the neutrino directly!



What gets in between



You identify the final state particles to **infer neutrino flavor:** count how many ν_e and ν_μ

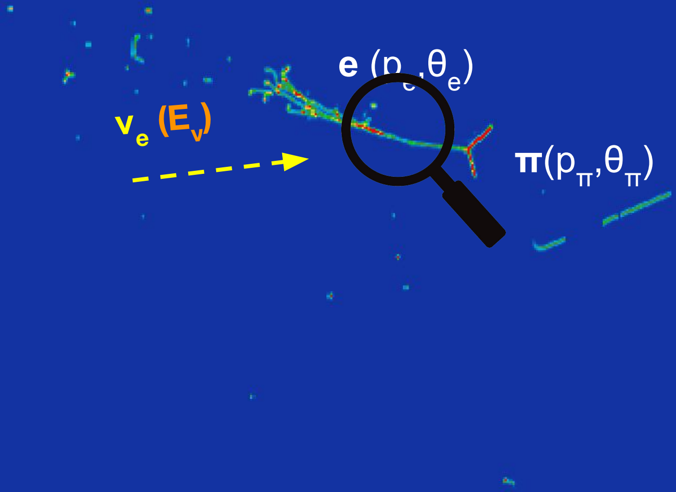
From the reconstructed particles' momenta you **infer neutrino energy:**

$$P(osc) \sim \sin^2(L / E_\nu)$$

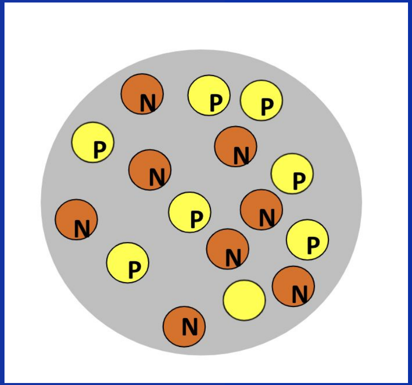
Event display courtesy of μBooNE

The importance of **neutrino cross sections**

This is all you see in your detector:
we never see the neutrino directly!



What gets in between



You identify the final state particles to
infer neutrino flavor:
count how many ν_e and ν_μ

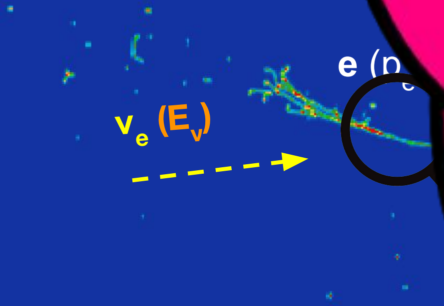
From the reconstructed particles' momenta
you **infer neutrino energy:**

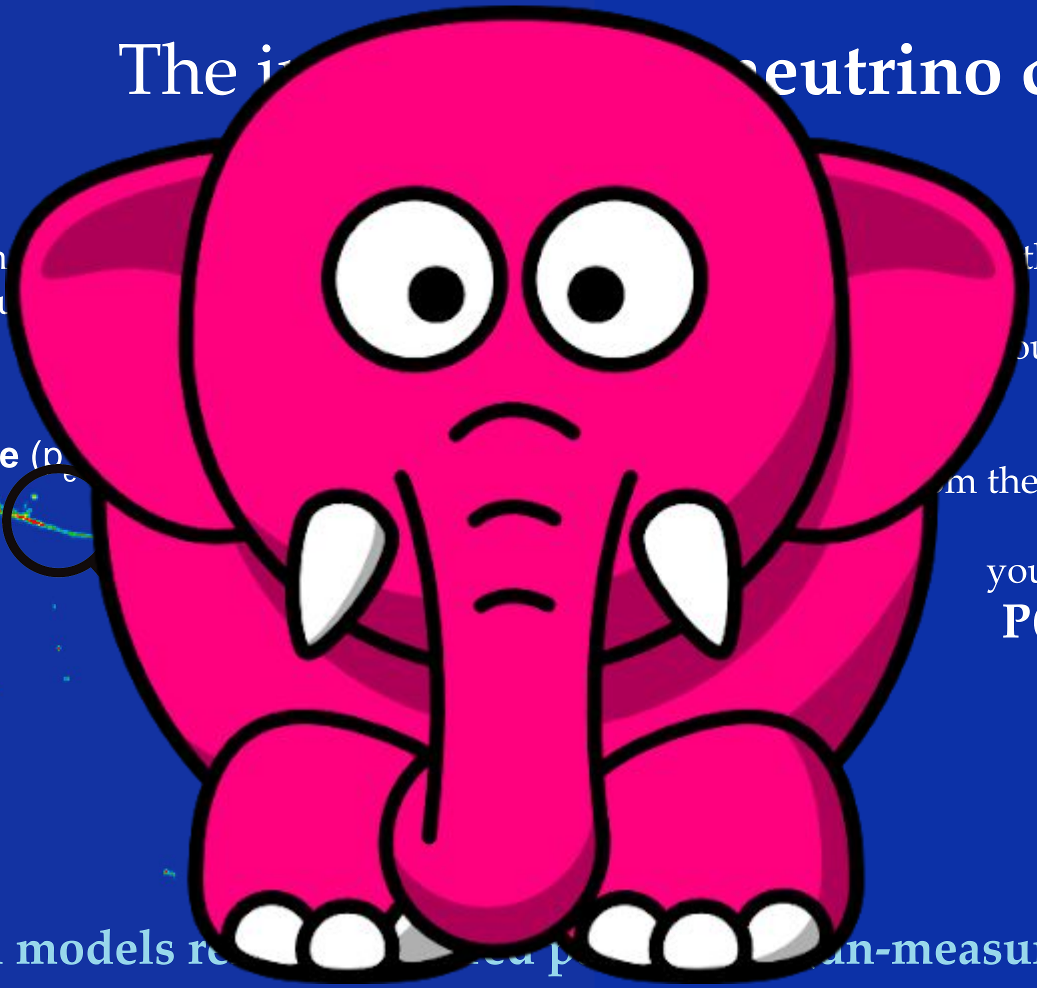
$$P(osc) \sim \sin^2(L / E_\nu)$$

Cross-section models relate measured particles to (un-measurable) neutrinos, need to correctly predict the ν-N interaction make-up as a function of energy

The i eutrino cross sections

This is all you see in
we never see the neu





the final state particles to
infer neutrino flavor:
ount how many ν_e and ν_μ

m the reconstructed particles' momenta
you **infer neutrino energy:**

$P(osc) \sim \sin^2(L / E_\nu)$

Cross-section models re ed p n-measurable) neutrinos,
need to correctly predict the ν-N interaction make-up as a function of energy

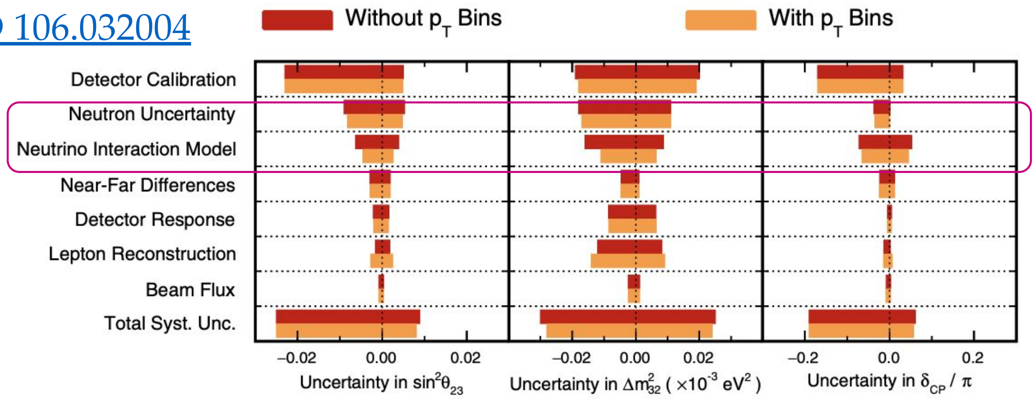
How does this feeds back into neutrino "new" physics? CP Violation @ long baseline

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

T2K, Nature 2020

"uncertainty on the ν_e and $\bar{\nu}_e$ cross-sections… [is] the 2nd largest single source of systematic uncertainty in the CP asymmetry measurement."

NOvA PRD 106.032004



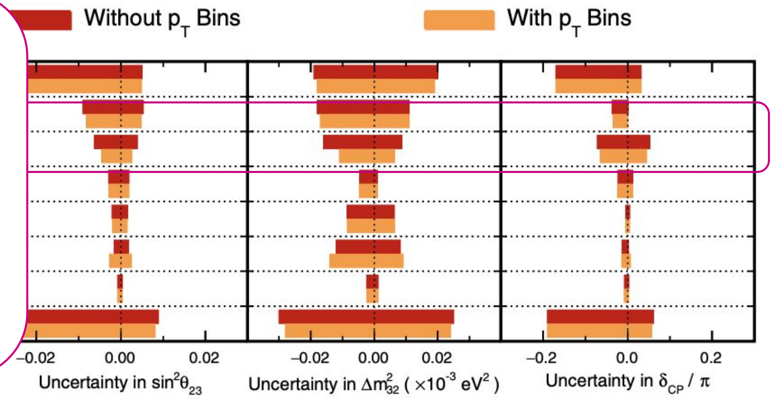
How does this feeds back into neutrino “new” physics? CP Violation @ long baseline

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

T2K, Nature 2020

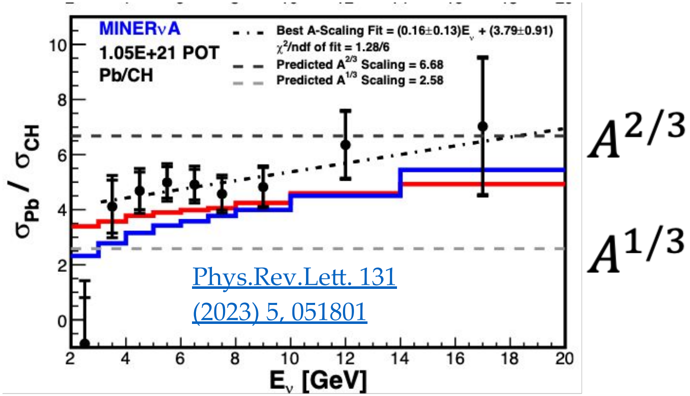
“uncertainty on the ν_e and $\bar{\nu}_e$ cross-sections… [is] the 2nd largest single source of systematic uncertainty in the CP asymmetry measurement.”

DUNE/HyperK
CP violation uncertainty budget is extremely stringent.
We need to do better than this!



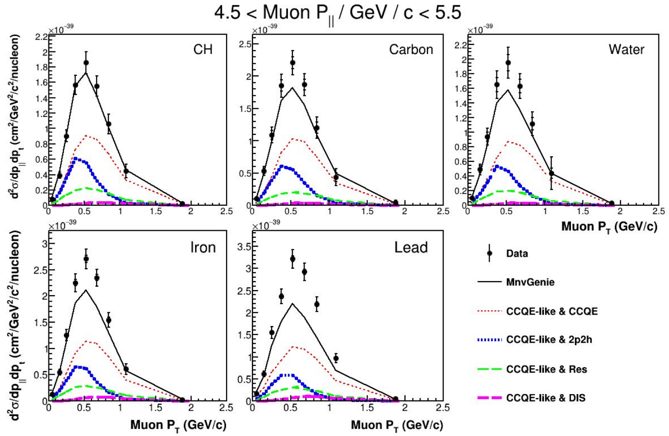
Neutrino Interactions: Measurements on Different Nuclei

Neutrino-induced coherent π^+ production in CH, C, Fe, and Pb at <E_ν>~6GeV
A-scaling not known: important for extrapolation to different nuclei.



Phys.Rev.Lett. 131 (2023) 5, 051801

Simultaneous measurement of muon neutrino quasielastic-like cross sections on CH, C, water, Fe, and Pb as a function of muon kinematics. We need models that can predict cross sections on Argon from wealth of measurements on other nuclei (plastic and iron, especially). See that current models do NOT predict cross section ratios for Lead.

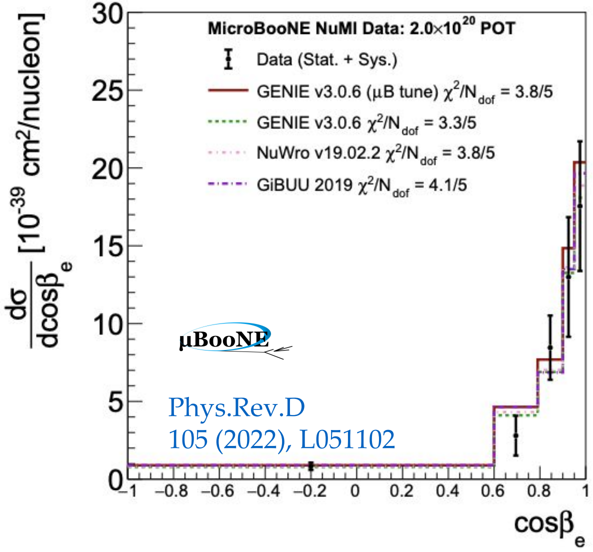


Phys.Rev.Lett. 130 (2023) 16, 161801

Neutrino Interactions: ν_e CC XS on Ar

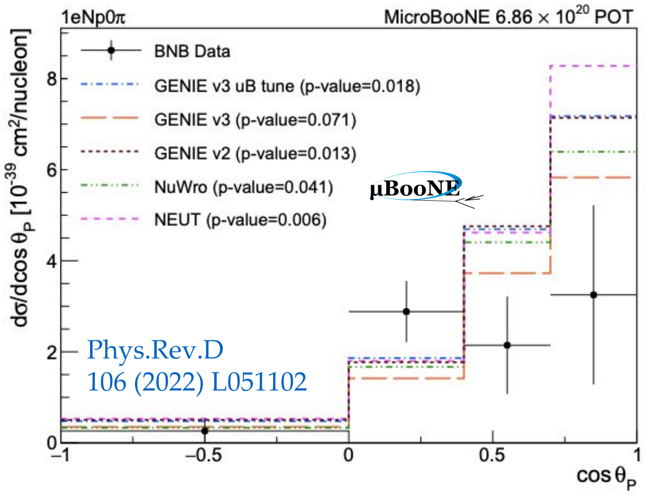
Inclusive XS generally ask for minimal requirements in the final state: just the charged lepton. They are standard candle, a “catch-all” for models.

First measurement of inclusive ν_e and anti ν_e CC in MicroBooNE



Exclusive XS explore specific final states → sensitive to targeted portions of the ν-N model (e.g. QE & MEC modeling and fermi motion).

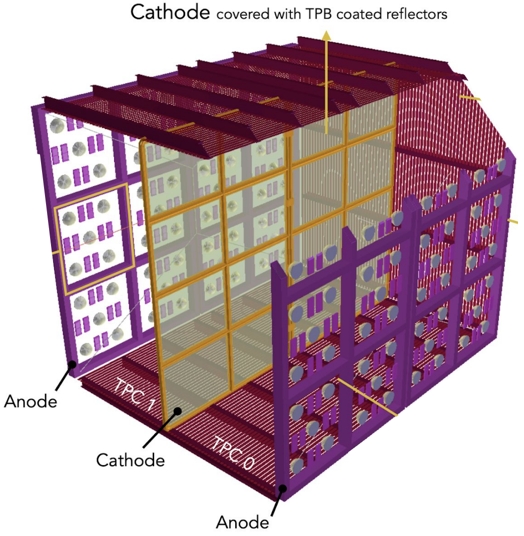
Differential XS measurement of charged current ν_e interactions w/ final-state pions.



Neutrino Interactions: SBND

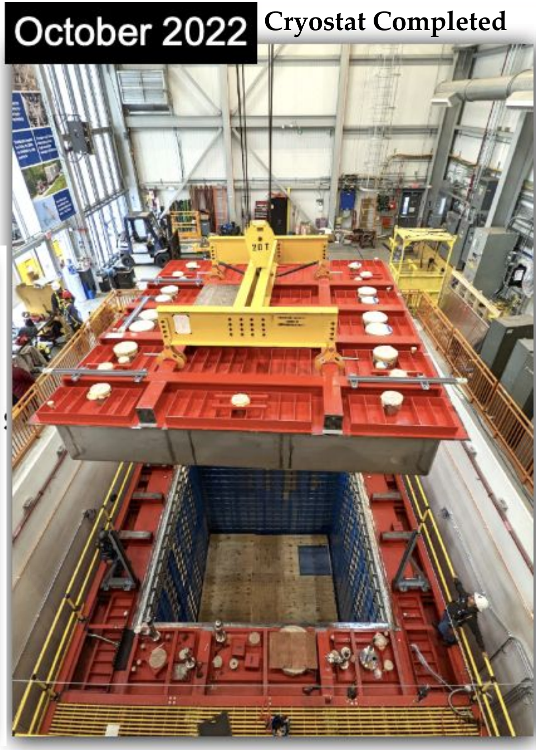
Unprecedented understanding of neutrino interactions on argon: 5000 ν events per day, 1.2M ν_μ & 12k ν_e CC events per year: vital input to DUNE

A near detector for SBN, broad programme of BSM searches.
Installation in the cryostat: April 2023
Physics commissioning: November 2023 → **ABOUT TO TURN ON!!**



TPC&PDS Completed

Cryostat Completed



MANCHESTER 1824 The University of Manchester

A Word on Neutrino Generators (the unsung heroes of the neutrino interaction world)

Genie

NEUT

NuWro * Wrocław Neutrino Event Generator *

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Continuous improvement of our understanding neutrino interactions comes from the interplay between model development and cross section results.

Aim to perform measurements in a form that is useful for generators, and produce predictions easy to translate into usable observables

MINERvA SBN Program NOvA e4V T2K annie

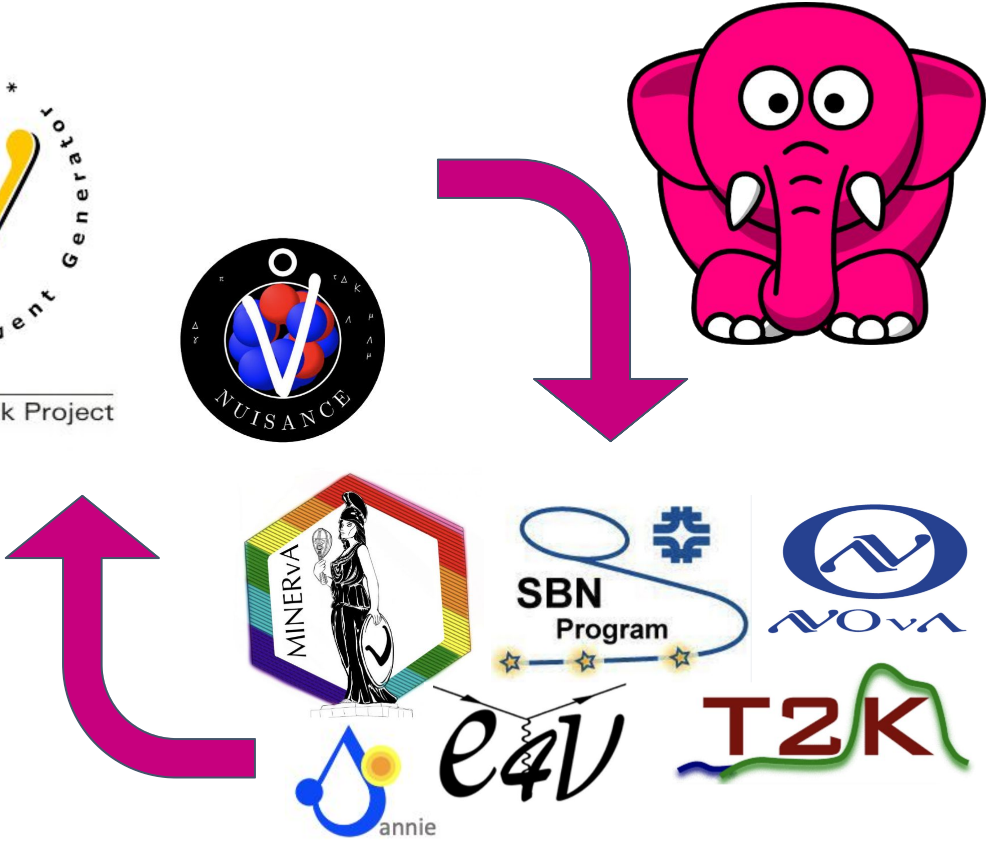
A Word on Neutrino Generators (the unsung heroes of the neutrino interaction world)

Genie

NEUT

NuWro * Wrocław Neutrino Event Generator *

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project



Continuous improvement of our understanding neutrino interactions comes from the interplay between model development and cross section results.

Aim to perform measurements in a form that is useful for generators, and produce predictions easy to translate into usable observables

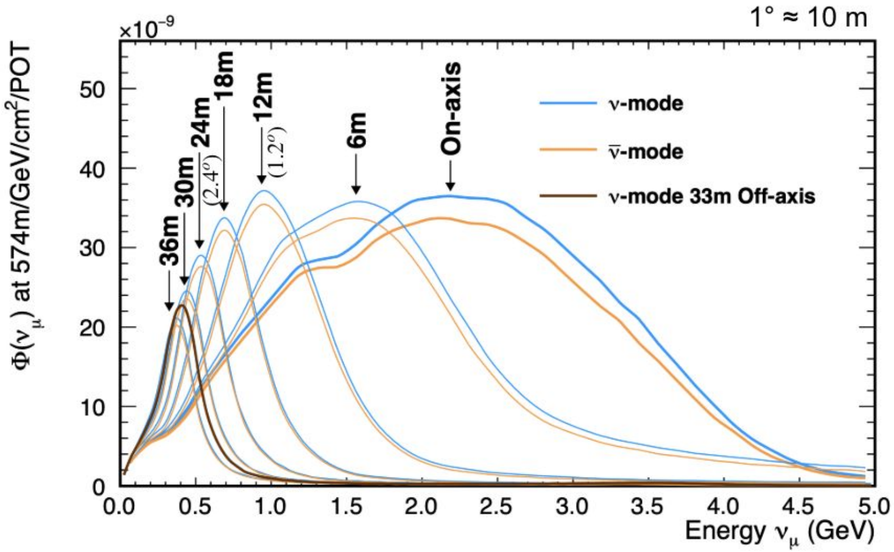
The University of Manchester

What do we need to make these experiments successful (& better)?

- To know how neutrinos interact → the XS problem
- **To know how many neutrinos we get → the flux problem**

Disentangling flux & XS effects in situ: the Prism concept

Neutrino beam "off-axis" effect: moving away from the neutrino beam axis, the observed neutrino energy spectrum narrows and peaks at a lower energy → a movable detector measures the rate of interactions across a continuous range of off-axis angles, allowing to link the neutrino reconstructed energy and true energy in the oscillation analysis.



POWERFUL NEAR DETECTORS

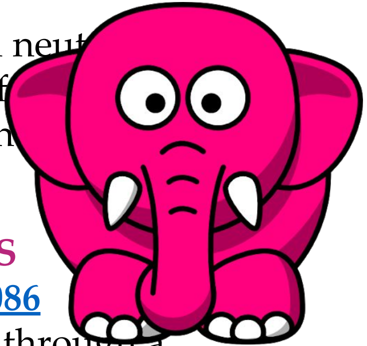
ν-Prism @ JPark arxiv.org.1412.3086
Water Cherenkov detector moves through a cylindrical chamber
1 km downstream of the neutrino target
Scans upto 4 degrees from the neutrino beam axis

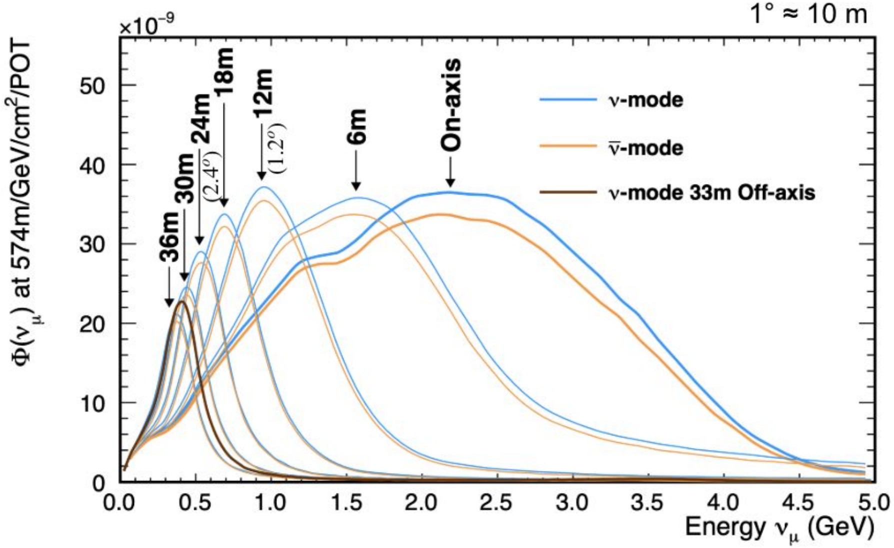
DUNE-Prism arxiv.org.2103.13910
Movable LAr and GAr modules
574 m downstream of the neutrino target
Scans upto 3.2 degrees from the neutrino beam axis

Proof of concept in data coming up w/ SBND-Prism

Disentangling flux & XS effects in situ: the Prism concept

Neutrino beam "off-axis" effect: moving away from the neutrino beam axis, the observed neut
spectrum narrows and peaks at a lower energy → a movable detector measures the rate of
across a continuous range of off-axis angles, allowing to link the neutrino reconstructed en
energy in the oscillation analysis.





POWERFUL NEAR DETECTORS

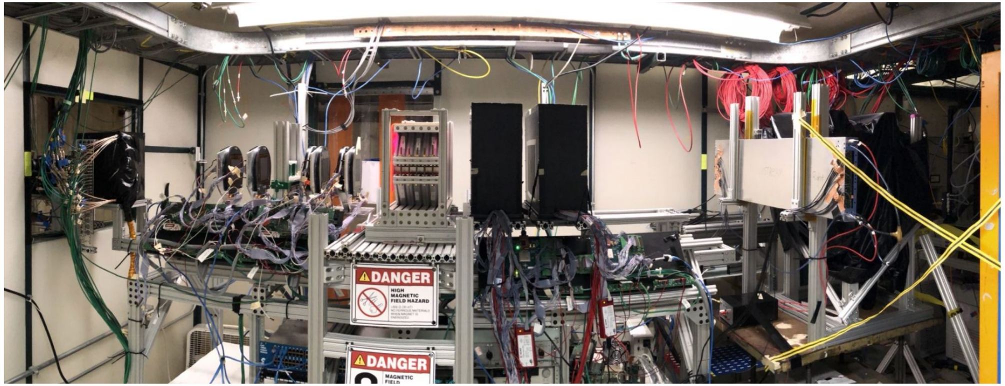
ν-Prism @ JPark arxiv.org.1412.3086
Water Cherenkov detector moves through a cylindrical chamber
1 km downstream of the neutrino target
Scans upto 4 degrees from the neutrino beam axis

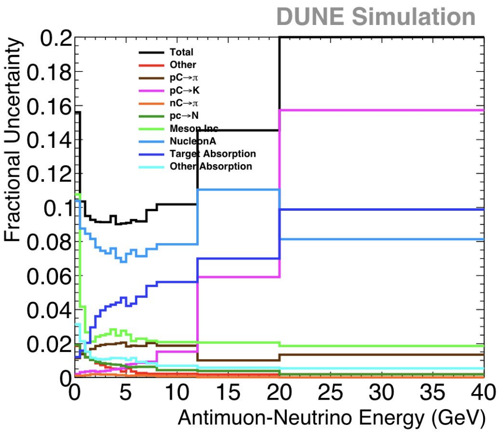
DUNE-Prism arxiv.org.2103.13910
Movable LAr and GAr modules
574 m downstream of the neutrino target
Scans upto 3.2 degrees from the neutrino beam axis

Proof of concept in data coming up w/ SBND-Prism

Constraining neutrino fluxes w/ external data: EMPHATIC

Neutrino flux predictions are constrained w/ hadron production data by experiments measuring the production cross section of the neutrino parents
→ Historically NA61/SHINE.





Increased requirements in precision calls for new experiments:

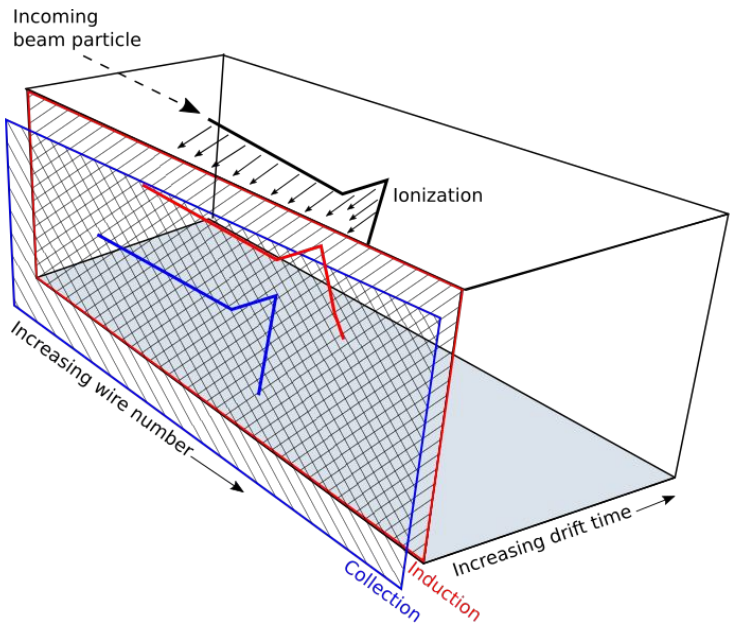
EMPHATIC targets a factor of 2 reduction in ν flux uncertainties. Completed an initial data run with a basic configuration in January, 2022, first HP papers expected soon. Currently done using the NuMI horn… should we do it for DUNE beam too???

arxiv.1912.08841

What do we need to make these experiments successful (& better)?

- To know how neutrinos interact → the XS problem
- To know how many neutrinos we get → the flux problem
- **Improve our detectors**

LArTPC: “Electronics Bubble Chambers”

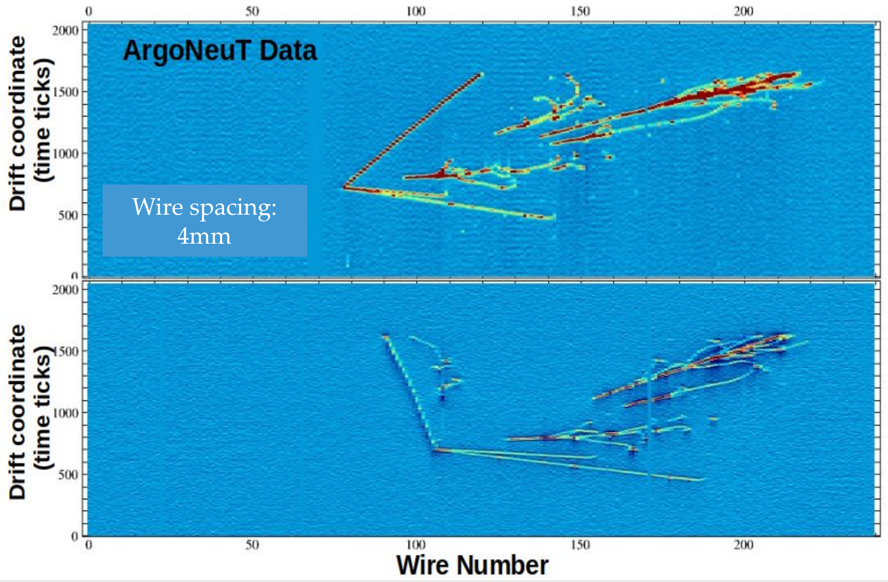


Traditional LArTPCs use sets of wire planes at different angles to reconstruct the transverse position

While we get extremely detailed information about neutrino interactions, in 2D projective readouts, the readout space **DOES NOT coincide w/ the physical space**: highly **anisotropic detectors**.

LArTPC: "Electronics Bubble Chambers"

2D projective readout (wires)



Traditional LArTPCs use sets of wire planes at different angles to reconstruct the transverse position

While we get extremely detailed information about neutrino interactions, in 2D projective readouts, the readout space **DOES NOT coincide w/ the physical space**: highly **anisotropic detectors**.

→ automatic plane matching is difficult, especially for complex topologies.

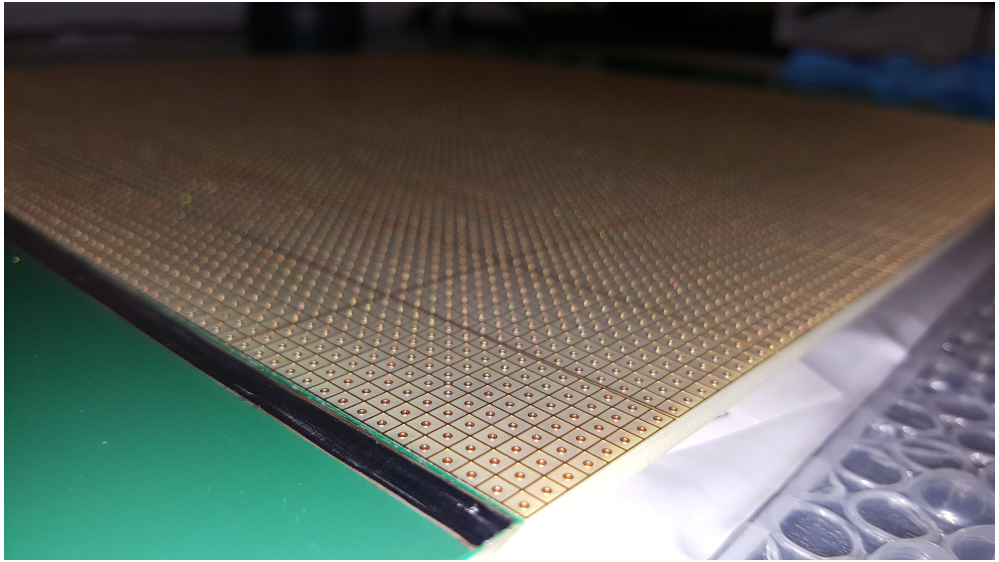
The readout **affects the possibility of maintaining the intrinsic 3D quality of the events.**

LArTPC: Pixels?!?!?

Constructing anode planes with pixels instead of wires can **solve a number of shortcomings** of 2D projective readouts.

More resilient against single point failure and simpler to construct.

Small pixels sizes (4x4 mm^2) provide **comparable spatial resolution**, but the **readout space coincides w/ the physical projected space**



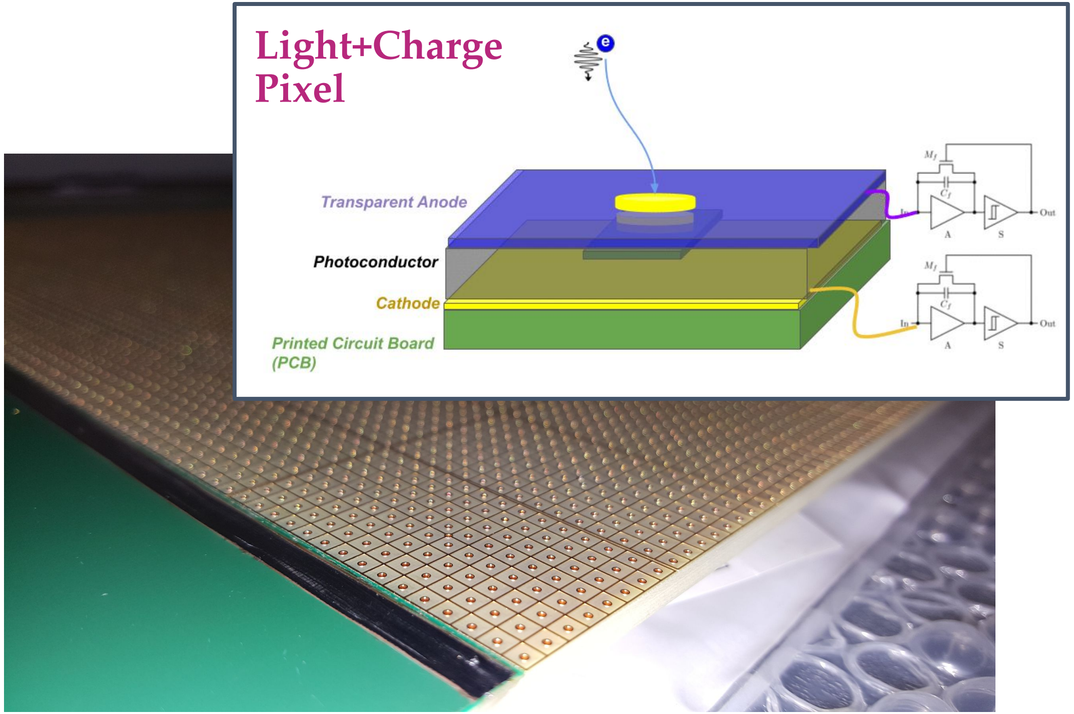
"Pixelizing" a 10kTon DUNE module requires **O(130.0 million) pixels vs O(1.5 million) wires.** Requires **innovation** in readout electronics to meet the **heat load restriction for the increase in the number of channels** → target 50-100 uW/ch w/ < 100 ENC

LArTPC: Pixels?!?!?

Constructing anode planes with pixels instead of wires can **solve a number of shortcomings** of 2D projective readouts.

More resilient against single point failure and simpler to construct.

Small pixels sizes (4x4 mm^2) provide **comparable spatial resolution**, but the **readout space coincides w/ the physical projected space**



"Pixelizing" a 10kTon DUNE module requires **O(130.0 million) pixels vs O(1.5 million) wires.** Requires **innovation** in readout electronics to meet the **heat load restriction for the increase in the number of channels** → target 50-100 uW/ch w/ $<$ 100 ENC

Q-Pix: an “unorthodox solution” to the immense data rate

Q-Pix is a novel **ionization signal capture** and **waveform digitalization** scheme is based on the ”**electronic principle of least action**”:

→ when there’s nothing to do… do nothing!

→ (but be ready to respond properly when signal arrives!)

Hardware solution to the immense data-rate:

→ Estimated Quiescent Data Rate O(50 Mb/s) {as opposed to 4.6 Tb/s}

→ Allows to overcome heatload and to pixelate massive surfaces

Q-Pix offers an innovation in signal capture with a **new approach and measures Time-to-charge: (ΔQ)**

→ **Keeps detailed the waveform typical of LArTPC**, for accurate description of events fundamental to the physics.

→ Attempts to exploit 39Ar to provide an automatic charge calibration (heartbeat)

Q-Pix has started to explore its “real life feasibility” arXiv:1809.10213

MANCHESTER 1824 The University of Manchester

Charge-Integrate/Reset Circuit, CIR: the heart of Q-Pix

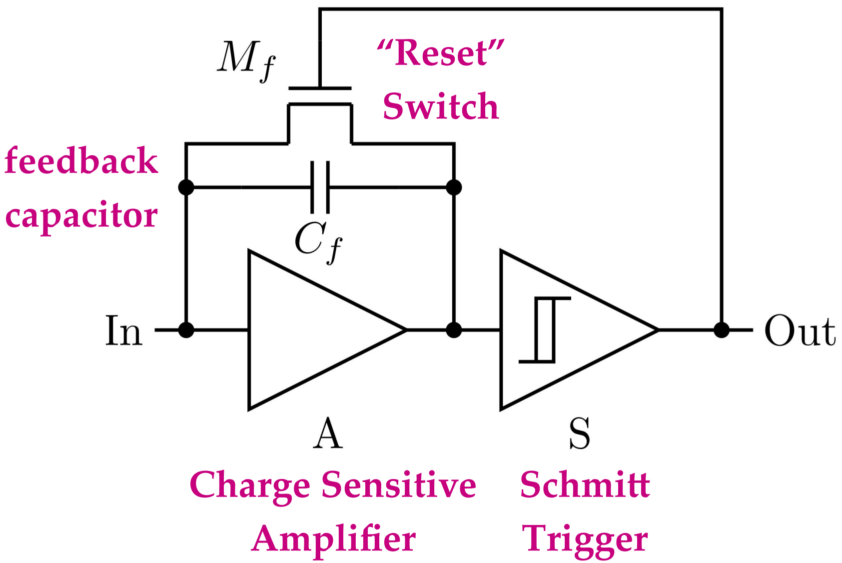
1) The charge sensitive amplifier (CSA) **continuously integrates** incoming signal on a feedback capacitor…

2) … until a **threshold** (V_{th} = threshold/C_f) on the Schmitt trigger is met.

3) When Schmitt trigger fires, it initiates the **reset transition** on M_f which rapidly drains C_f.

3.5) The **reset pulse** is used to **register the value of the local clock**

4) The circuit is **back to baseline** and ready to repeat *ad infinitum.*



Charge-Integrate/Reset Circuit, CIR: the heart of Q-

A hardware zero suppression scheme

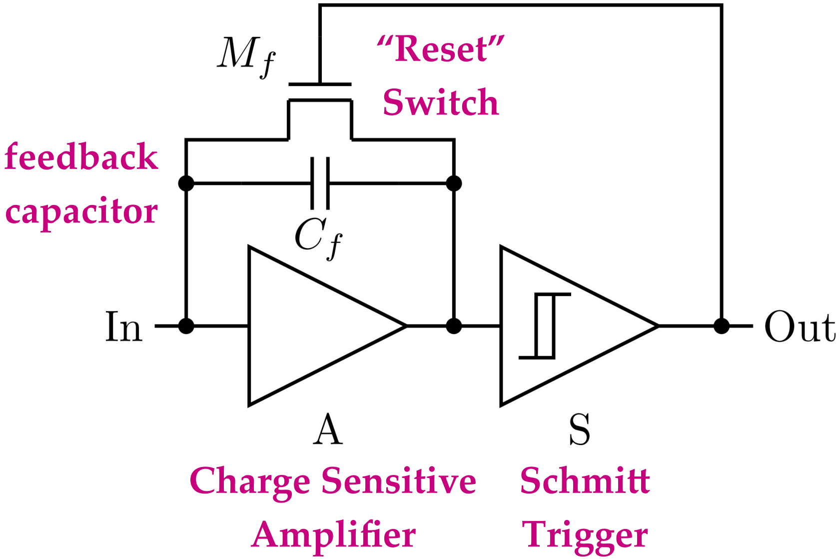
1) The charge sensitive amplifier (CSA) **continuously integrates** incoming signal on a feedback capacitor…

2) … until a **threshold** (V_{th} = threshold/C_f) on the Schmitt trigger is met.

3) When Schmitt trigger fires, it initiates the **reset transition** on M_f which rapidly drains C_f.

3.5) The **reset pulse** is used to **register the value of the local clock**

4) The circuit is **back to baseline** and ready to repeat *ad infinitum.*



The Pixel advantage: on beam neutrino physics

Suitable for DUNE main physics goal!

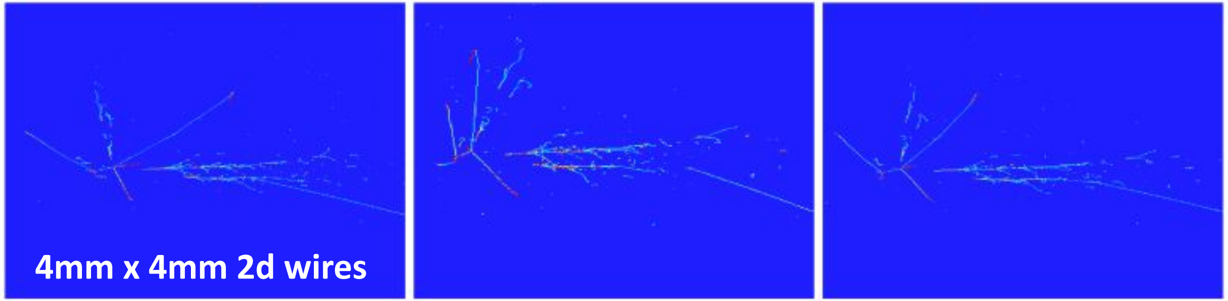
A first attempt to quantify a comparison between 2D and 3D readouts reconstruction performances as been made in JINST 15 P04009.
Event classification for the 3D based readout offers **significant improvement in all physics categories!**

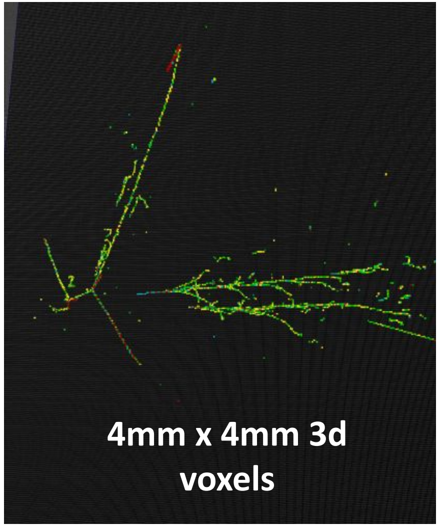
→ νe-CC inclusive: 17% gain in efficiency and 12% gain in purity

→ νμ-CC inclusive: 10% gain in efficiency for 99% purity

→ NCπ^0: 13% gain in efficiency and 6% gain in purity

Such improvements can **lead to significantly shorter experimental run time required to meet desired physics goals!**





The Pixel advantage: low energy

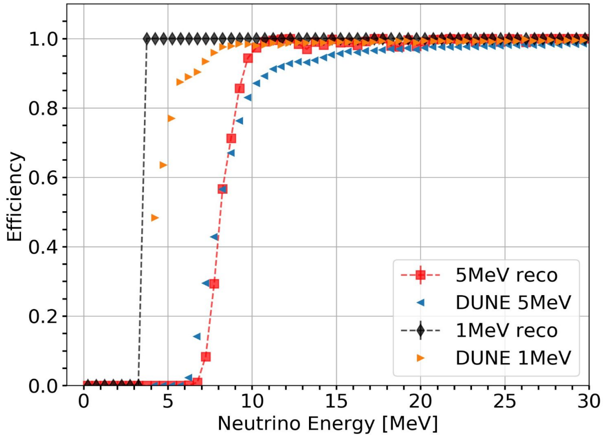
SuperNova Burst: test of low energy events [5-25 MeV]

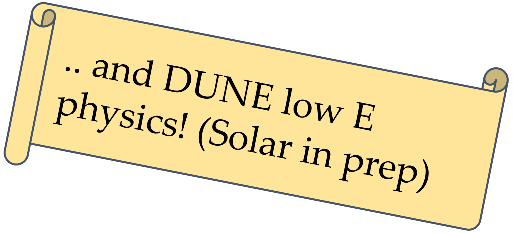
→ significantly enhanced reconstruction efficiency for low energy supernova neutrino events,

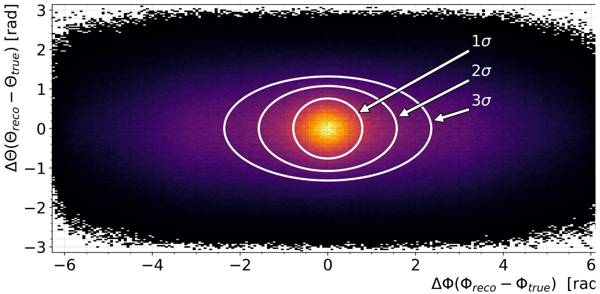
→ high purity & efficiency even with radiological backgrounds,

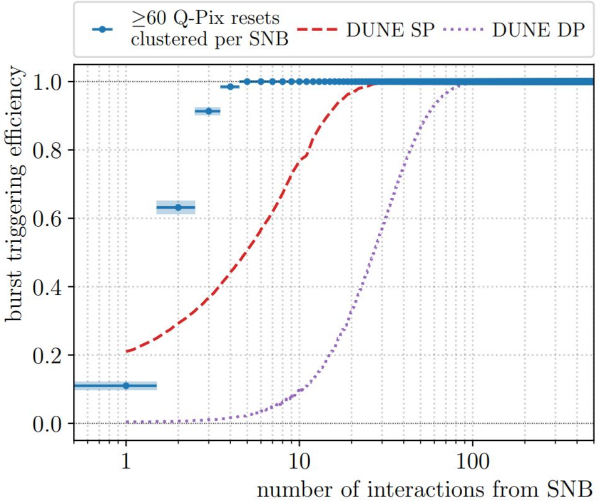
→ the data rate is orders of magnitude (~10^6) less for the same energy threshold and manageable at lower energy thresholds (5.7 MB/s in 10kTon at 147 keV)

→ 3D pixelization: pointing accuracy to < 20 degrees from a single module









Q-Pix: Phys.Rev.D 106 (2022) 3, 032011

MANCHESTER 1824
The University of Manchester

Summing up

My biased and modest view of the distant future

This is a long way to go, but we'll get there!

We are gearing up to measure CP violation in the lepton sector!!!

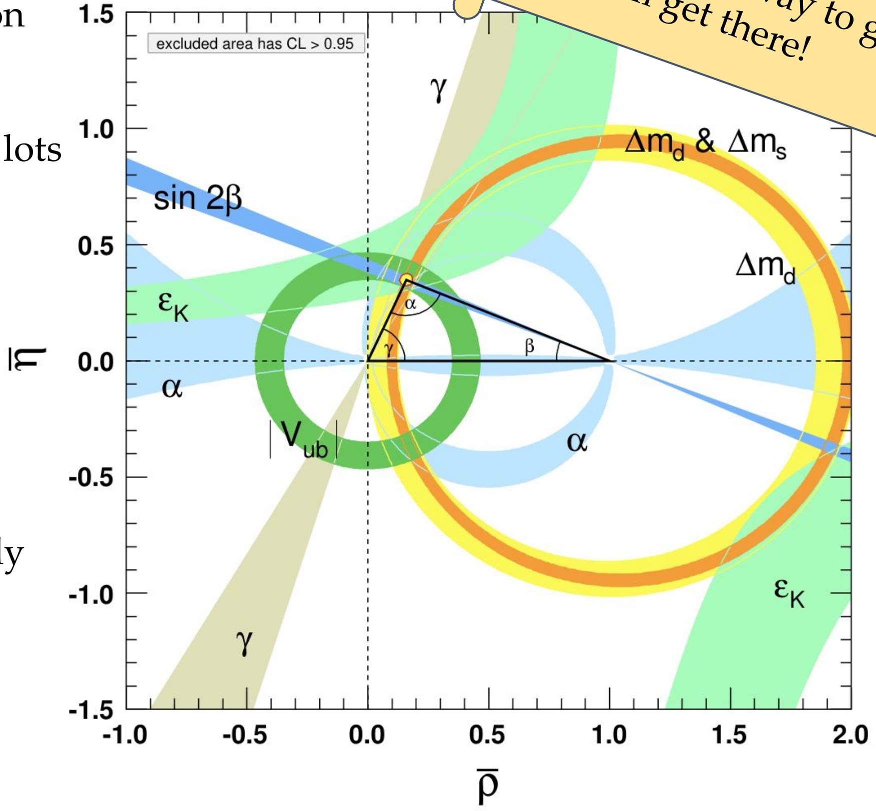
The next decade will be an exciting time for neutrinos: lots of important measurements and opportunities for innovation:

1. Understanding better our neutrino beams
   & ν-nucleus models, with our unsung heroes experiments and theorists.

2. Blue skies ideas for new neutrino oscillation experiments → "the bigger the better" is not going to fly

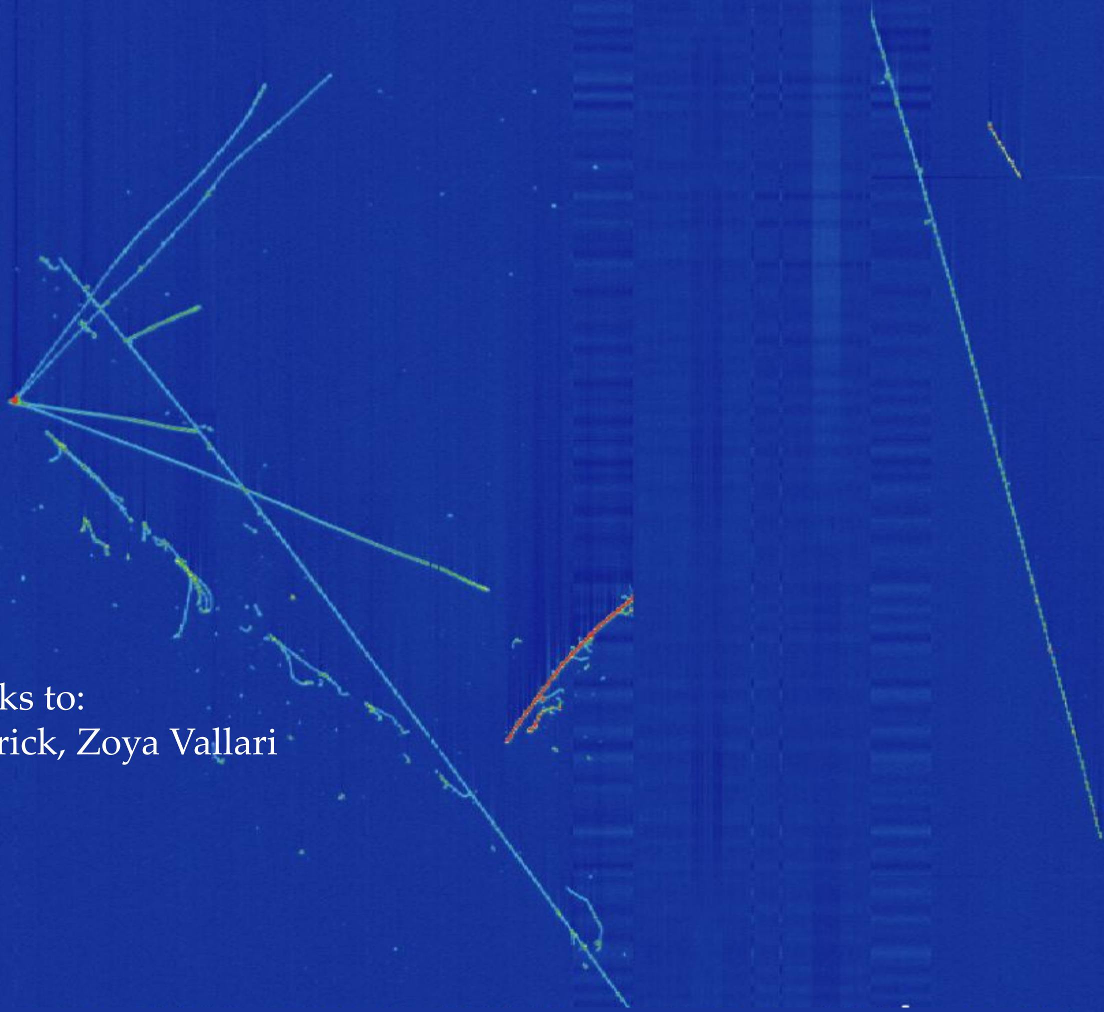
3. THE TAU NEUTRINOS… a double issue:
   - no good source
   - no good detectors

} **FASERν + R&D! R&D! R&D!**



Thank you!

For your help in preparing this talk, special thanks to:
Francesca di Lodovico, Teppei Katori, Anne Norrick, Zoya Vallari

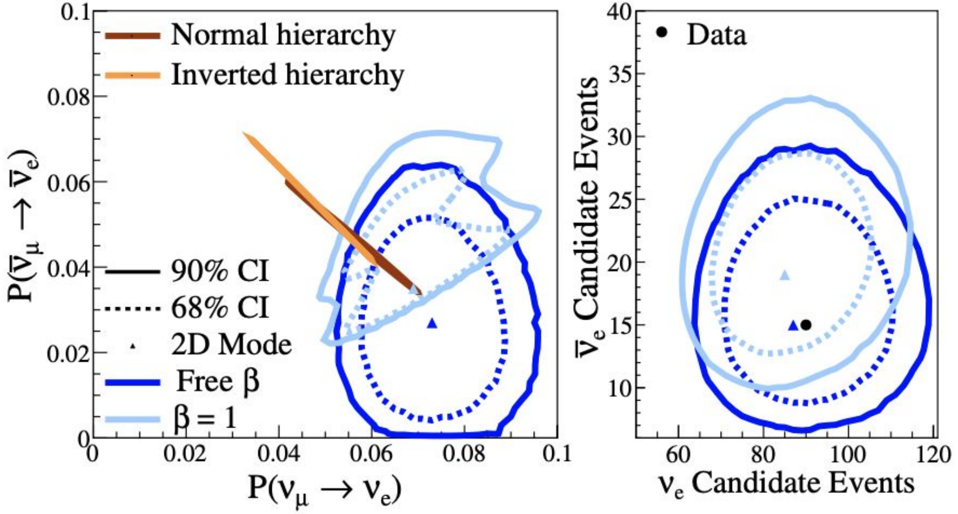


Neutrino Oscillations: T2K test of PNMS matrix

Measurement of electron antineutrino appearance in the antineutrino beam.
15 candidate electron antineutrino events with a background expectation of 9.3 events.

ν_e Bar appearance in a ν_μ Bar beam.
Two analysis frameworks: compare with no ν_e Bar appearance or ν_e Bar appearance as expected from the PMNS model prediction.
In both frameworks, no discrepancy between data and PMNS predictions is found.
No-appearance scenario is disfavored with a significance of 2.4 σ.

PRL 124 (2020) 16, 161802

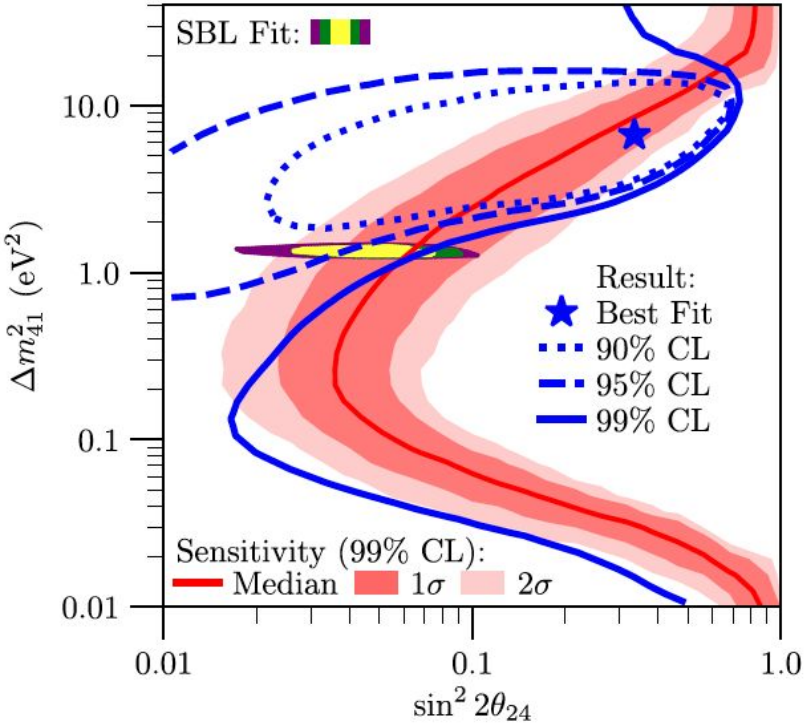


Recent Results: IceCube

Search for 3 + 1 active-to-sterile ν oscillation in many channels.

IceCube: decaying sterile neutrino search
Search for an unstable sterile neutrino by looking for a resonant signal (8 years of atmospheric ν_μ data).

Do not observe evidence for 3+1 neutrinos with neutrino decay
Majority of short-baseline experiment phase space rejected



IceCube, PRL129 (2022) 151801

Jarlskog invariant

The Jarlskog invariant, which controls the size of true CP violation in neutrino oscillation appearance experiments and is useful for quantifying CP violation in a parameterization-independent way

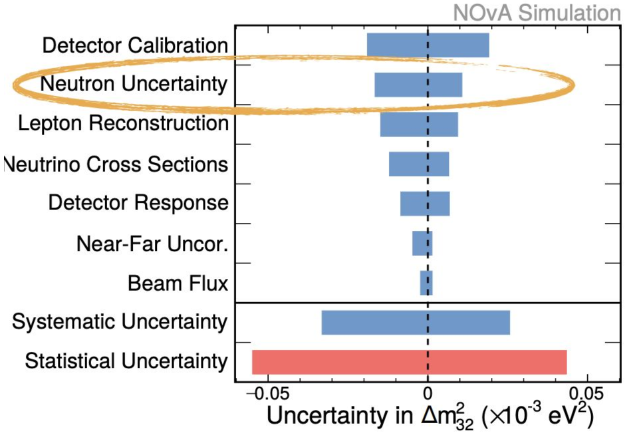
$$J = c_{12} s_{12} c_{23} s_{23} c_{13}^2 s_{13} \sin \delta_{13}$$
$$= \frac{1}{8} \sin 2\vartheta_{12} \sin 2\vartheta_{23} \cos \vartheta_{13} \sin 2\vartheta_{13} \sin \delta_{13}$$

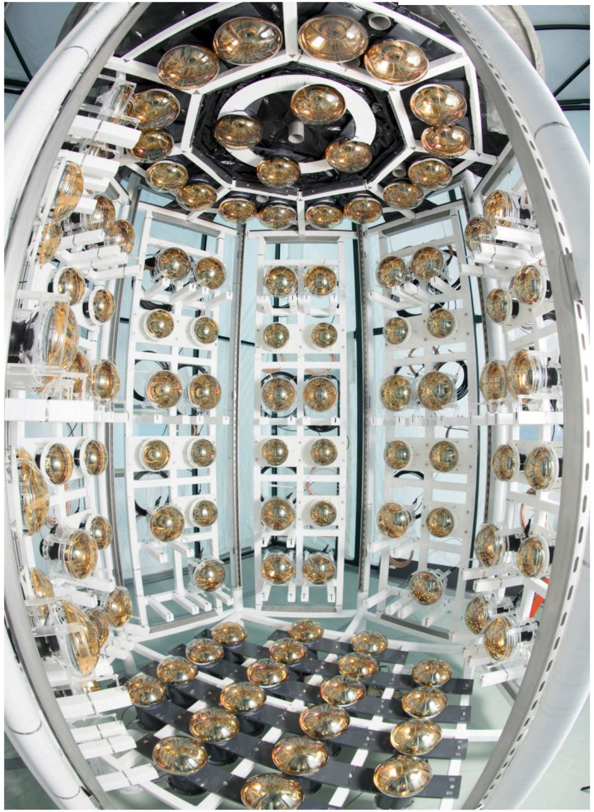
For neutrino propagation in matter, it factorizes into 3 pieces:
the vacuum Jarlskog invariant times two simple two-flavor matter resonance factors that control the matter effects for the solar and atmospheric resonances independently.

MANCHESTER 1824 The University of Manchester

Neutrino Interactions: Annie

Study neutrino-nucleus interactions with a special focus: the neutron yield/multiplicity in neutrino interactions.
Neutrons are a significant systematic uncertainty in long-baseline experiments (missing energy!)

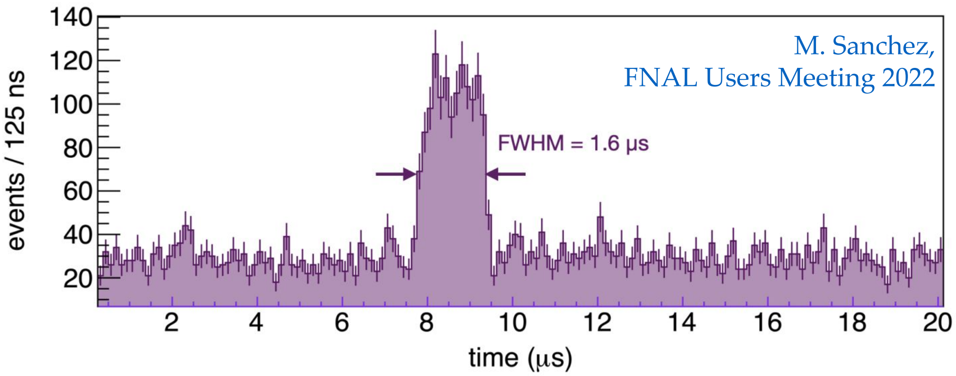




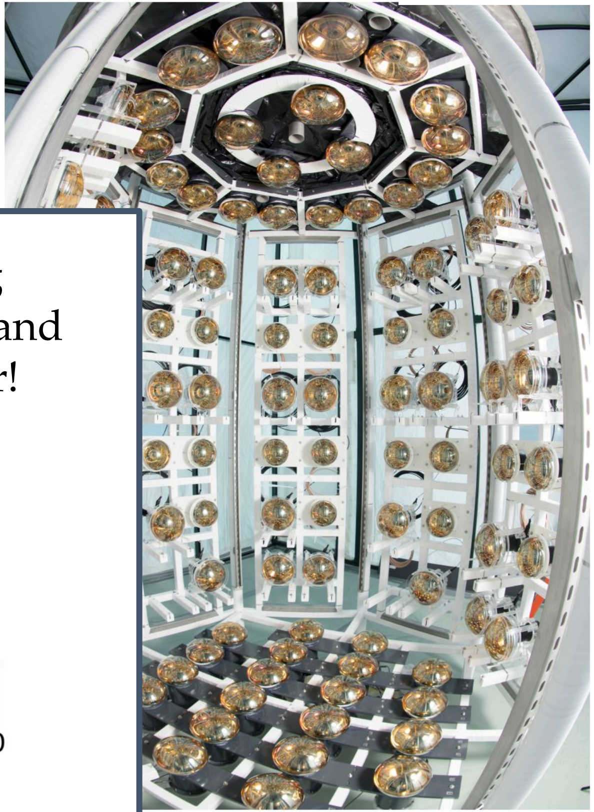
Neutrino Interactions: Annie

Study neutrino-nucleus interactions with a special focus: the neutron yield/multiplicity in neutrino interactions.
Neutrons are a significant systematic uncertainty in long-baseline experiments (missing energy!)

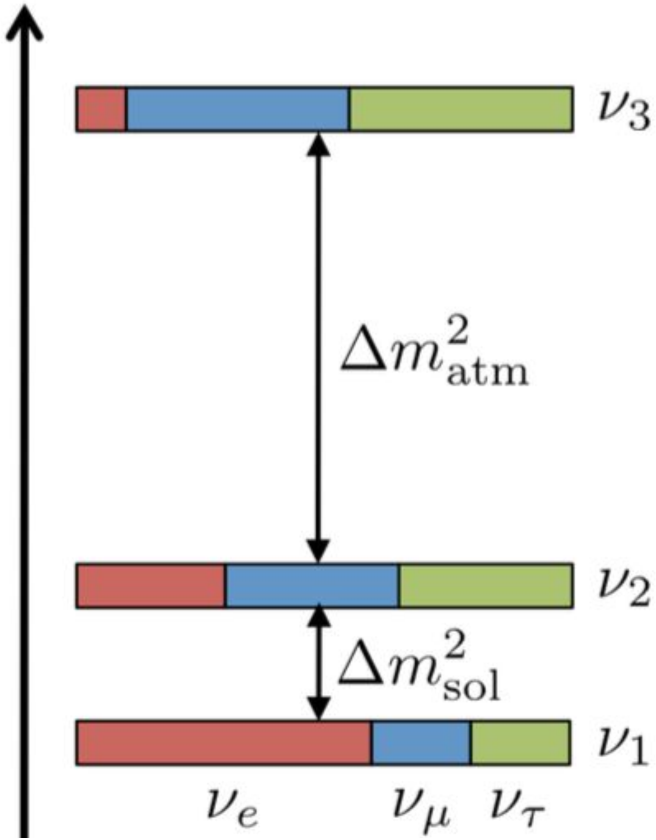
The ANNIE detector is commissioned and taking beam ν data! Observed neutrons from calibration and beam, and ν on LAPPDs for the first time this year!



M. Sanchez,
FNAL Users Meeting 2022

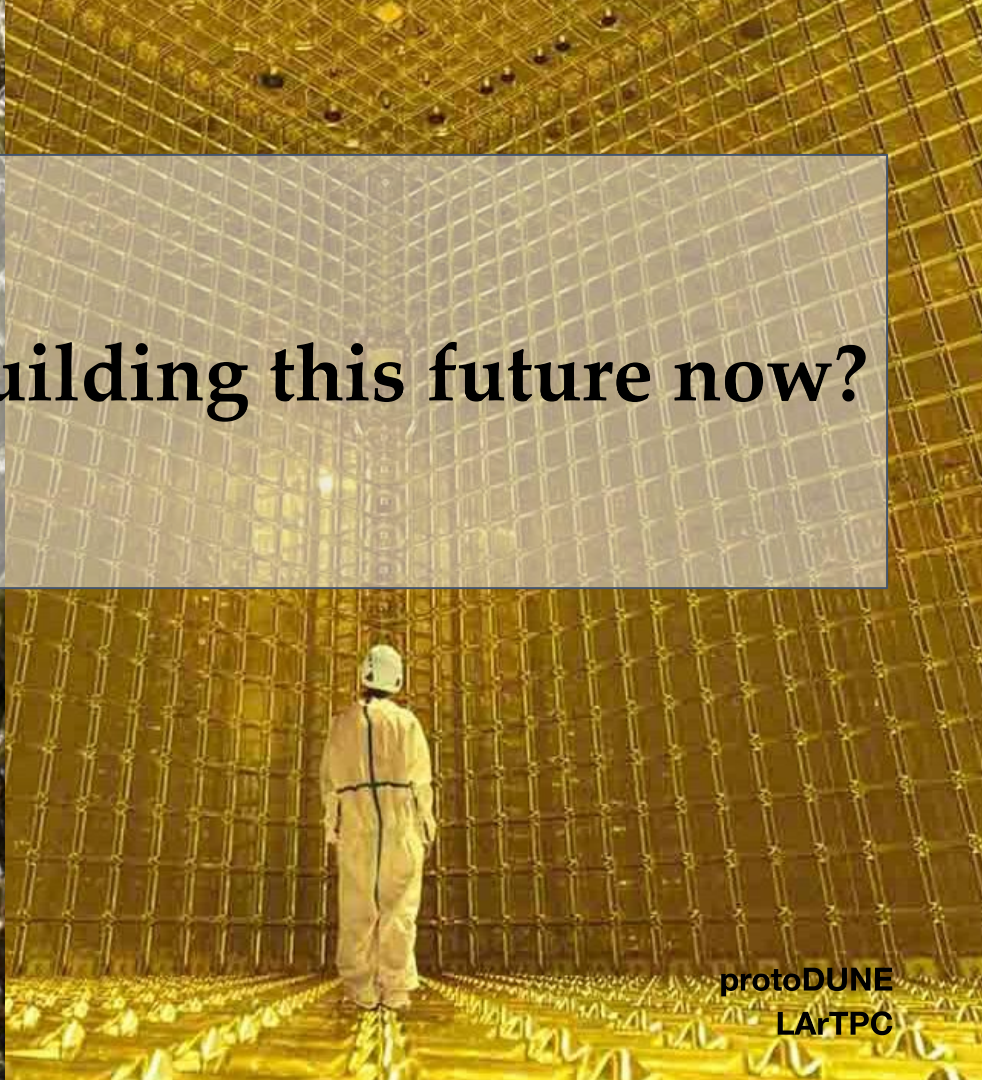


The octant problem in a snapshot



How are we building this future now?

SuperK
Cherenkov detector

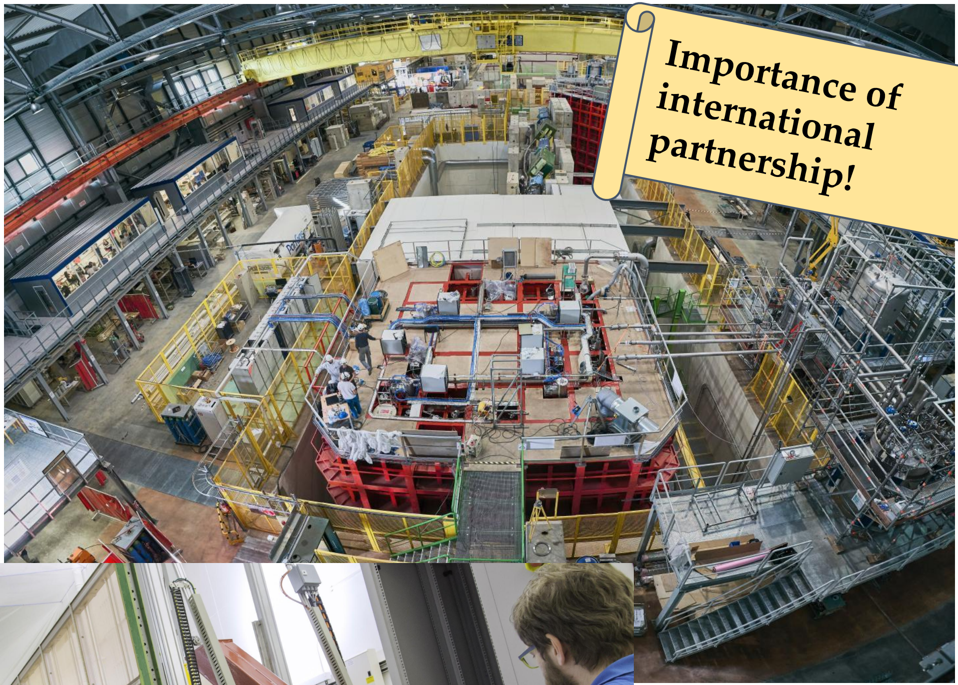


protoDUNE
LArTPC

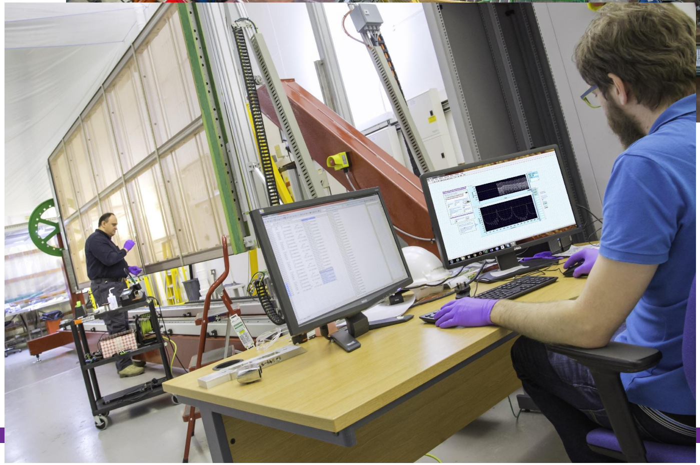
Happening now in DUNE/LBNF

ProtoDUNE programmes @ the **CERN neutrino platform** are demonstrating the viability of the technology for the first two FD modules while performing physics measurements of charged particles in argon.

Great space for R&D for future module of opportunity!



Importance of international partnership!



Happening now in DUNE ND

Importance of international partnership!

UK leadership in:

Physics

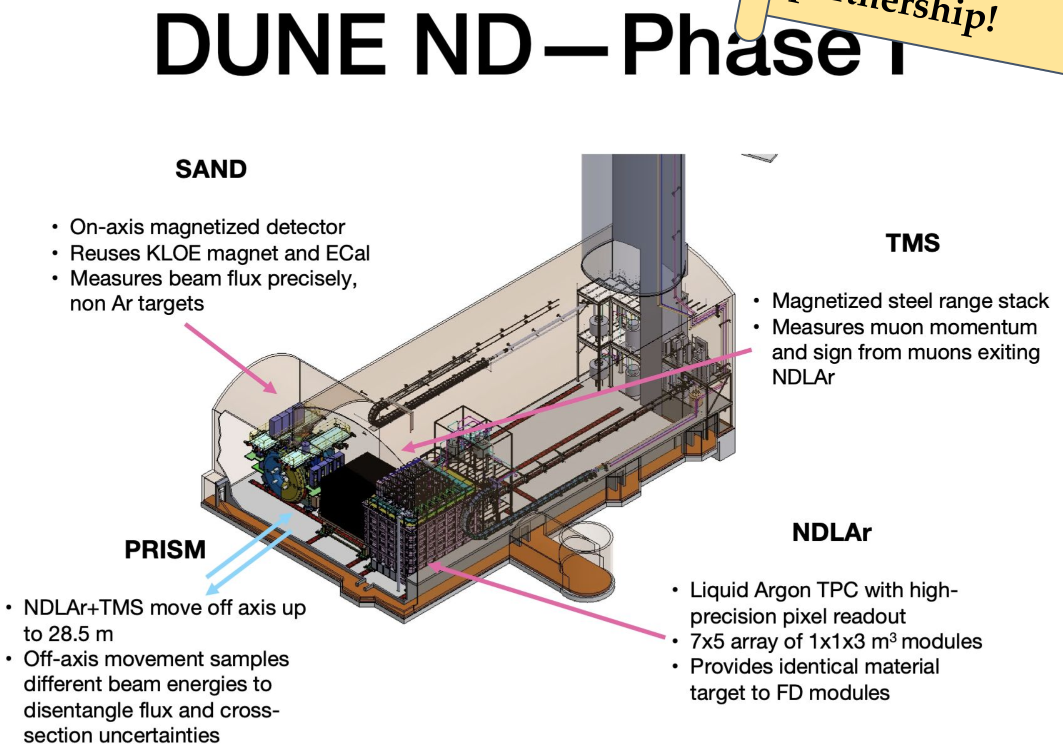
- Studies for design and development
- Impact of ND on oscillation analyses
- Development of PRISM analyses

Phase I

- DAQ support for all detectors
- Reconstruction and simulation
- TMS

Phase II

- Readout development for gaseous argon detector
- High-pressure GAr TPC test stand construction and operation
- Interest in pursuing further construction opportunities for Phase II

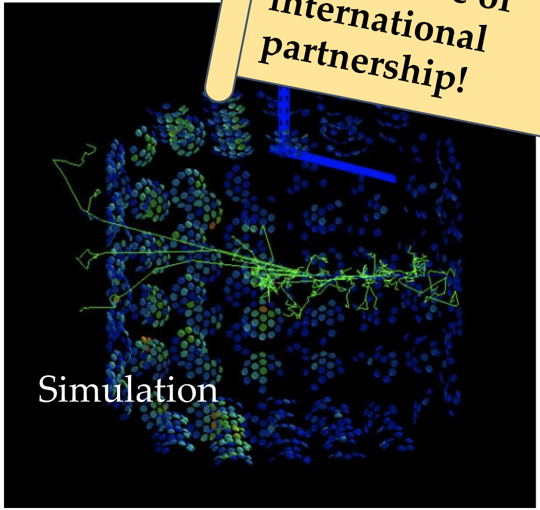


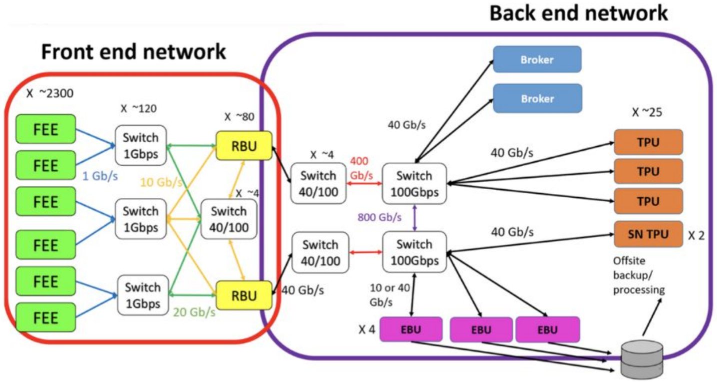
Happening now in Hyper-K

Importance of international partnership!

UK leadership 

- gadolinium-loaded water Cherenkov ND (currently tested in SK)
- sensitivity studies for oscillation physics, focus on ν-PRISM in HK
- DAQ development
- Water monitoring system
- R&D in the light readout
- deliver the primary calibration system of IWCD: laser diffuser + UniConeEx (a quartz cylinder mimicking the Cherenkov light from a muon).





Network reference diagram of the DAQ system for the Hyper-K