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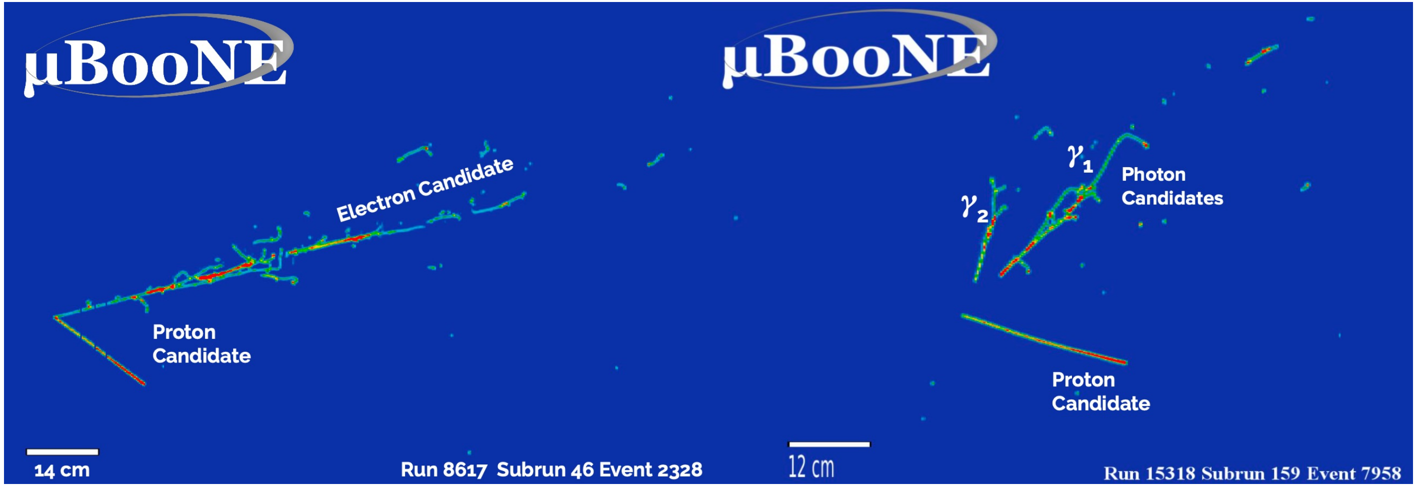
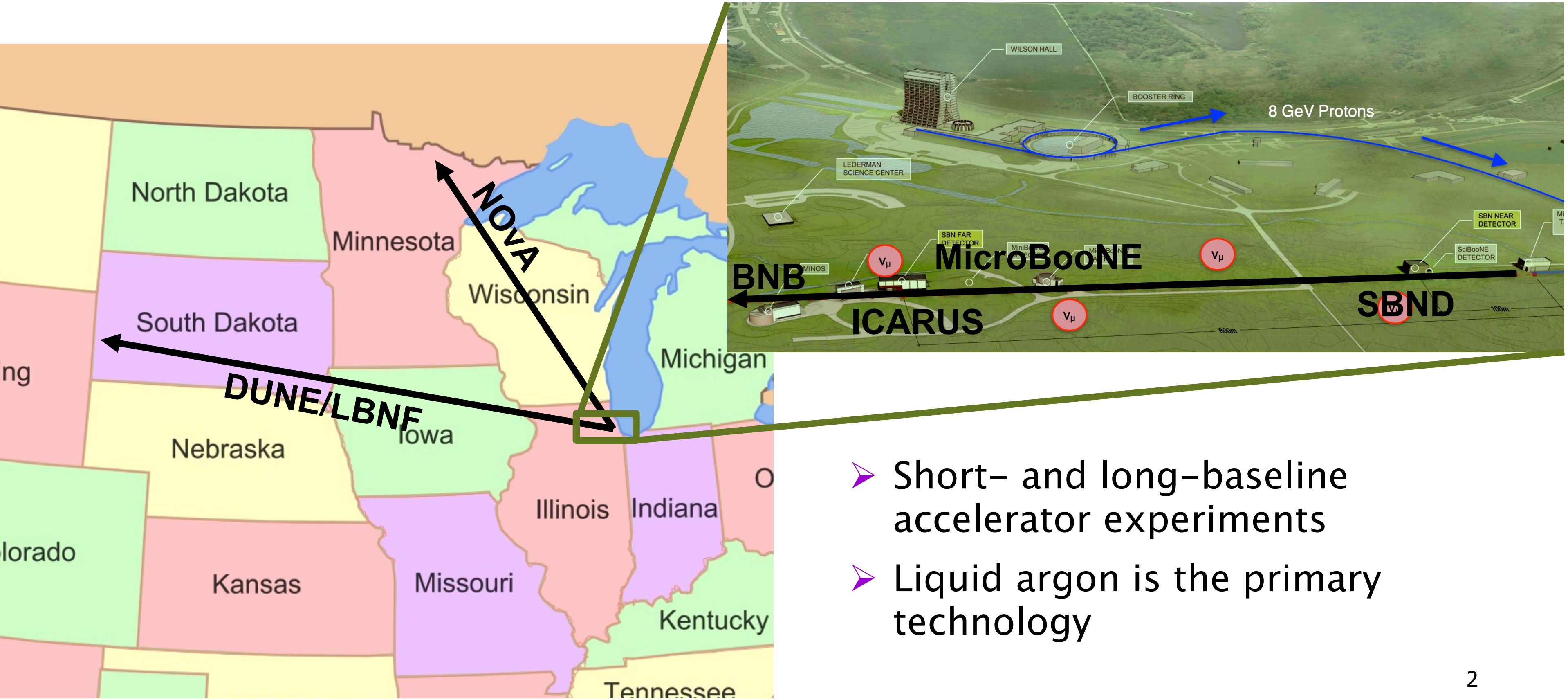
The US and European neutrino programmes



Justin Evans

The US neutrino programme



- Short- and long-baseline accelerator experiments
- Liquid argon is the primary technology

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Oscillations

Flavour | Mass

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

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

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Oscillations

$$\nu_\mu \rightarrow \nu_\mu$$

Flavour

Mass

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

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

Oscillations

$\nu_\mu \rightarrow \nu_e$ $\nu_\mu \rightarrow \nu_\mu$

Flavour Mass

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

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

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Oscillations

$\nu_\mu \rightarrow \nu_e$ $\nu_\mu \rightarrow \nu_\mu$

Flavour 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

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

Oscillations

$$\nu_\mu \rightarrow \nu_e \qquad \nu_\mu \rightarrow \nu_\mu$$

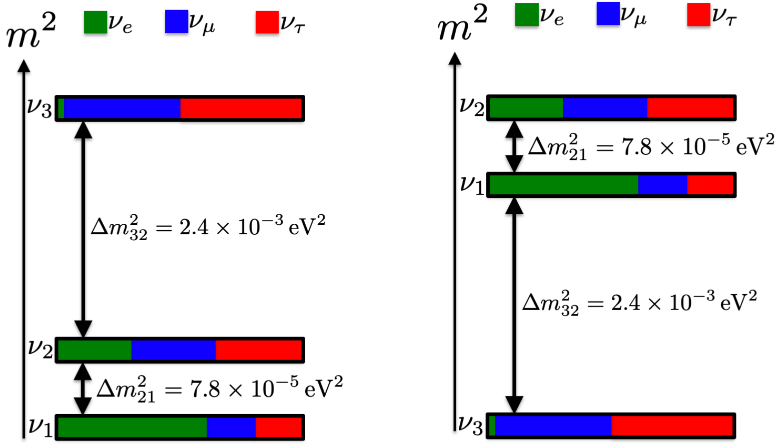
Flavour ... Mass

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

CP violation

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

Mass ordering



Normal ... Inverted

More neutrinos?

Flavour | Mass

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

ν_s ?

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

ν_4 ?

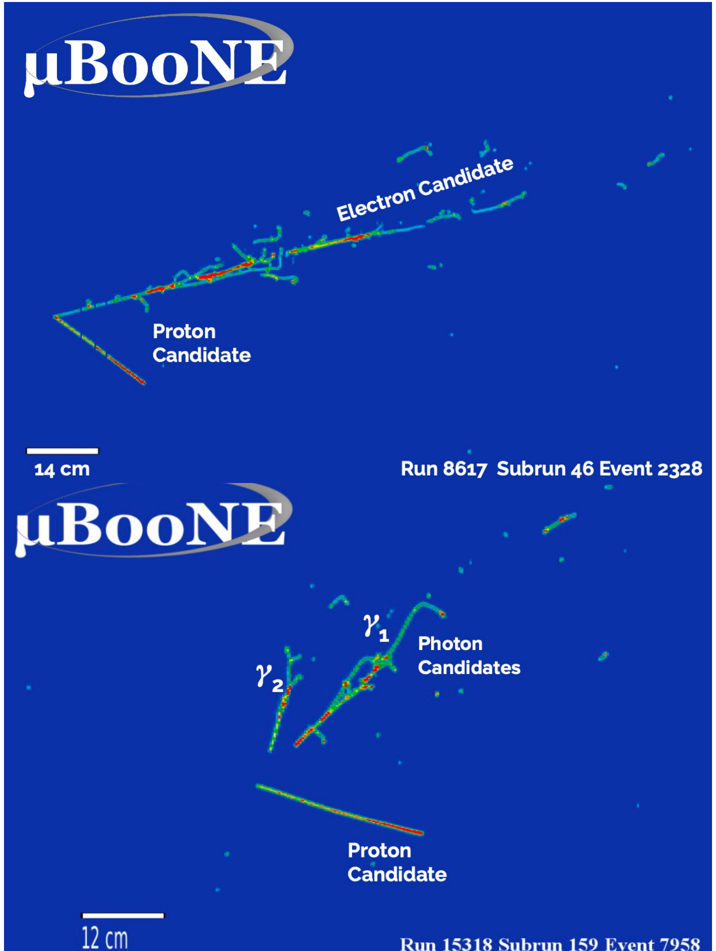
Liquid argon

Unprecedented detail in imaging neutrino interactions

- Including hadronic final state

ν_e, ν_μ, NC, CC separation

Separation of interactions into exclusive final states



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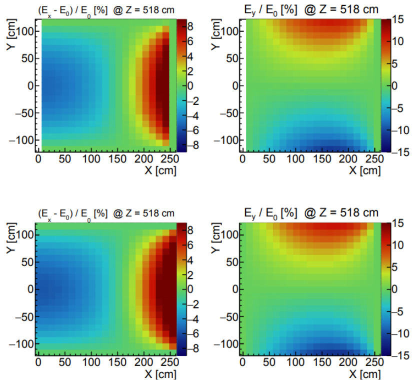
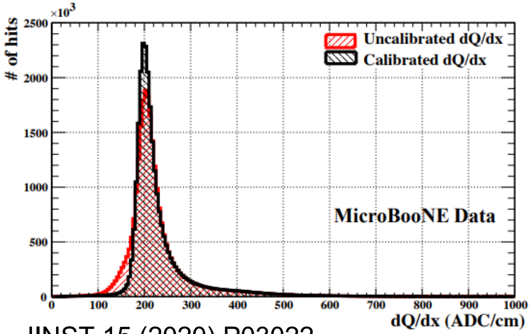
MicroBooNE – pioneering liquid argon

Electric field calibration with lasers and cosmic muons



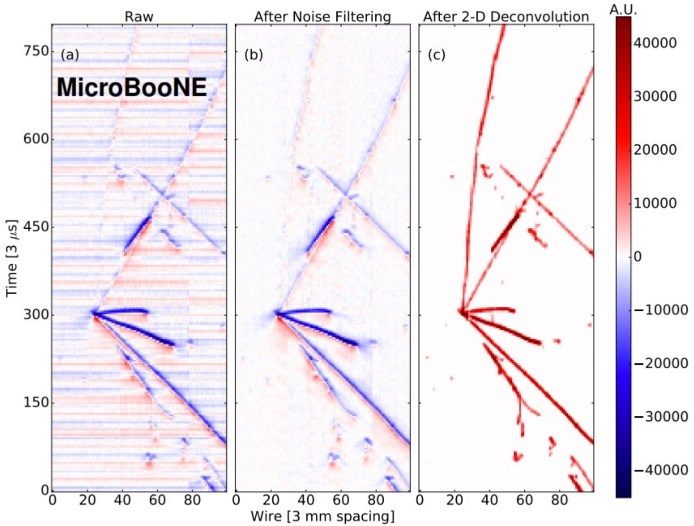
JINST 15 (2020) P07010
JINST 15 (2020) P12037

Calorimetry calibration with crossing muons and π^0 samples



JINST 15 (2020) P03022
JINST 15 (2020) P02007

Signal Processing: From raw signals on wires to 2D reconstructed "hits"



We have made the first complete assessment of systematic uncertainties in a LArTPC arXiv:2111.03556

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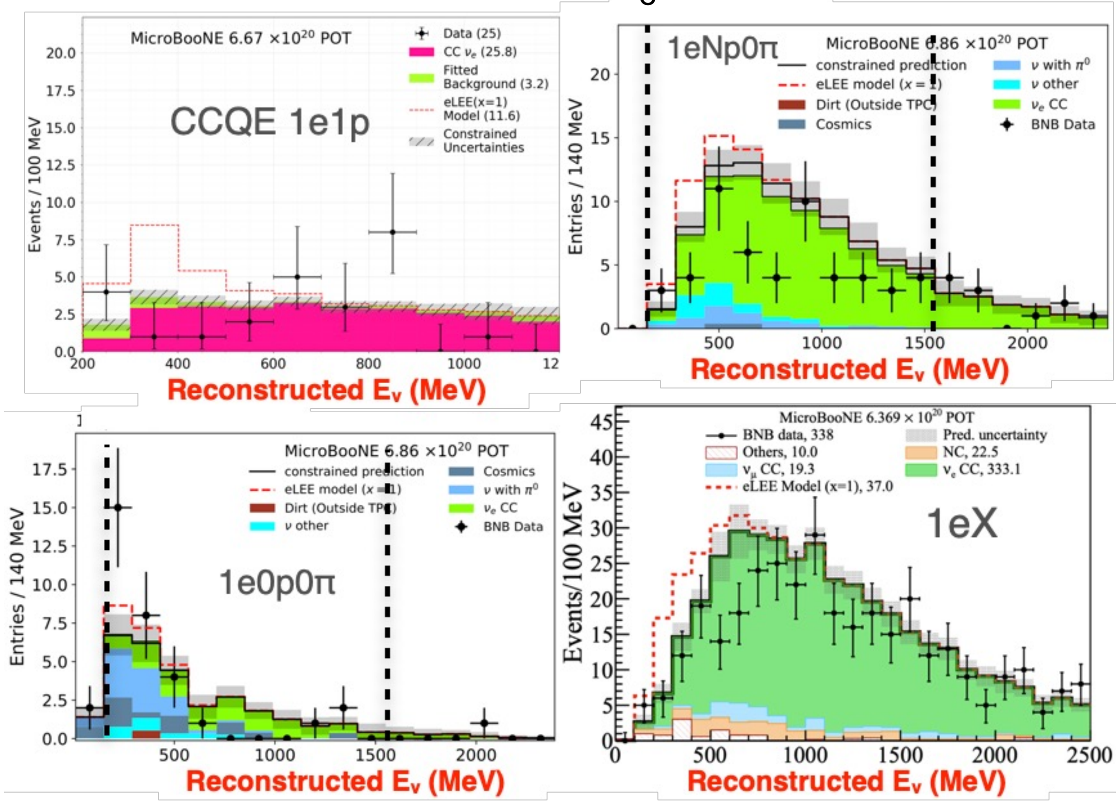
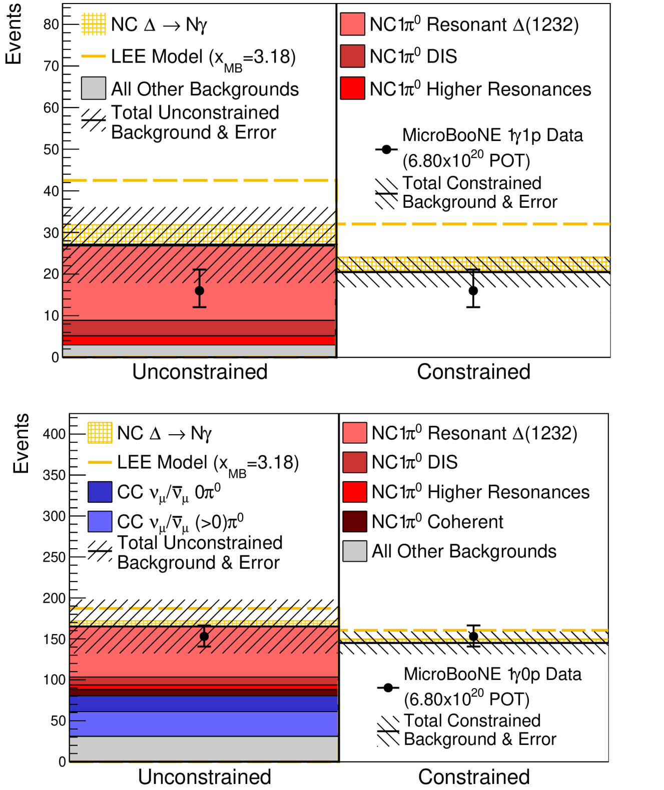
MicroBooNE search for electron-like appearance

Searches in four ν_e final states

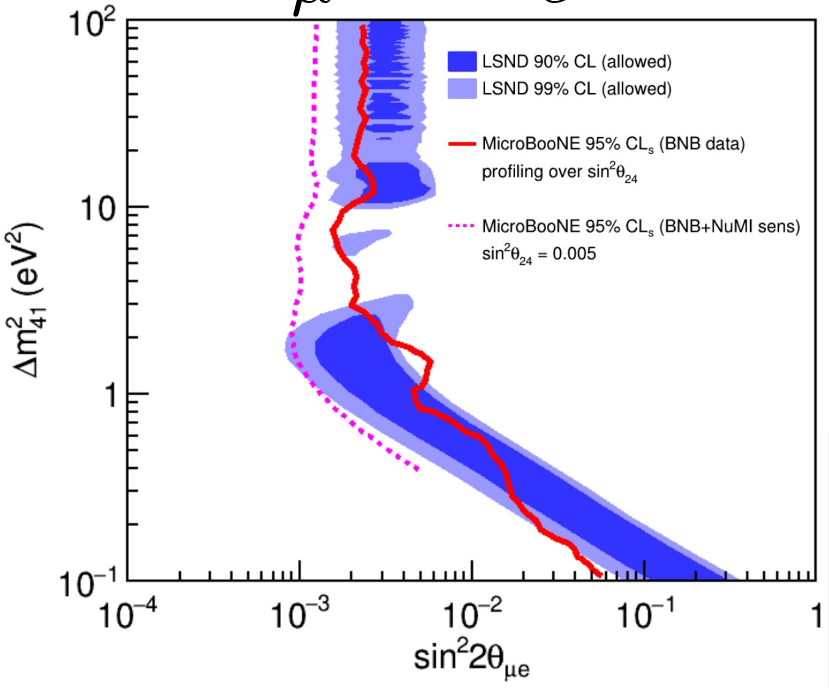


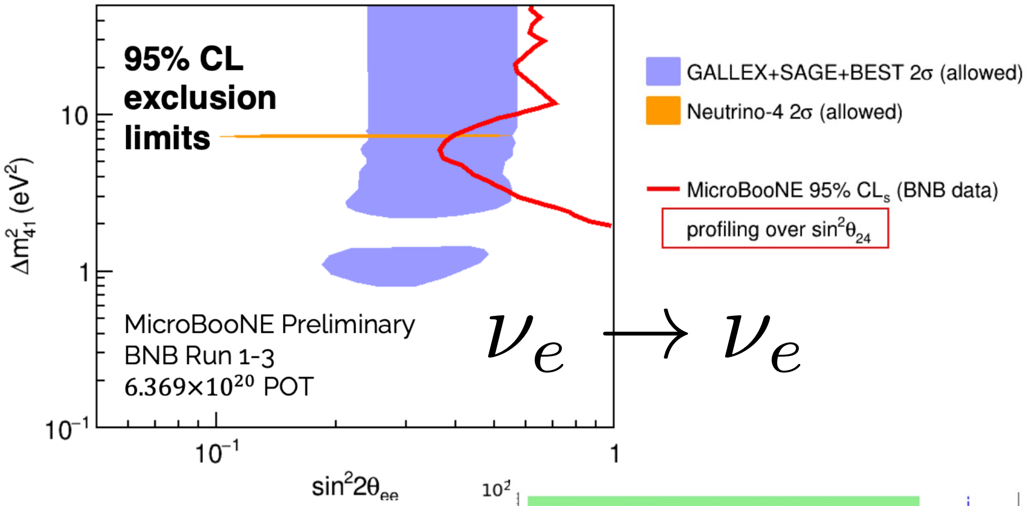
Searches for photon excesses



MicroBooNE constraints on eV sterile neutrinos

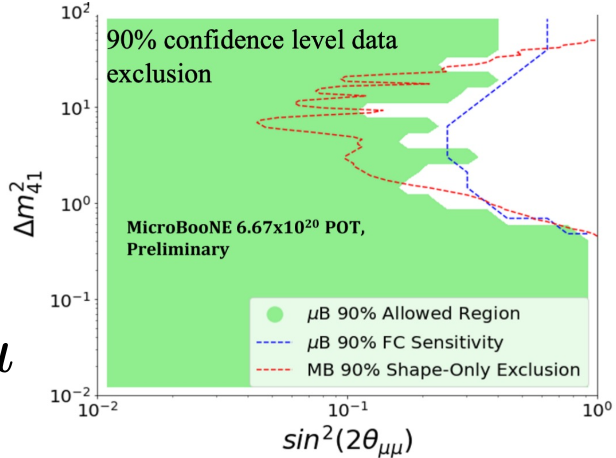
$\nu_\mu \to \nu_e$



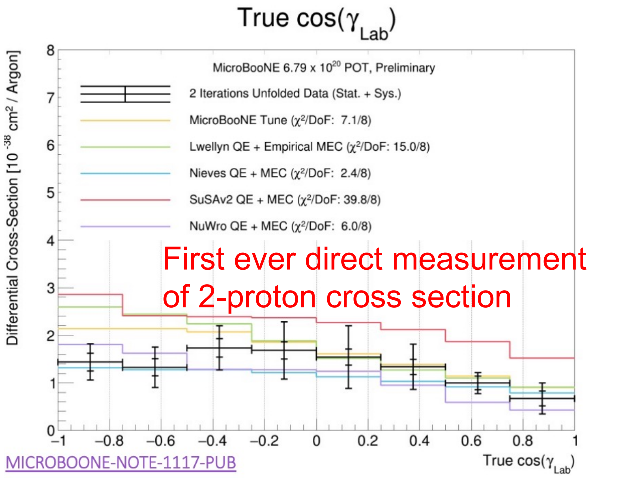


$\nu_e \to \nu_e$

$\nu_\mu \to \nu_\mu$

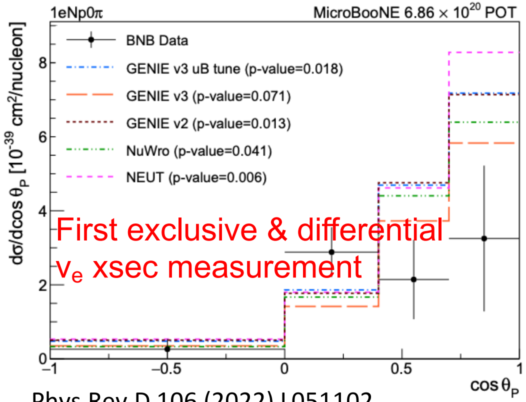


MicroBooNE – Neutrino interactions



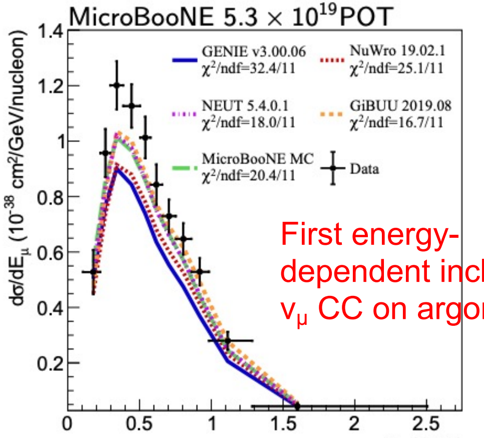
First ever direct measurement of 2-proton cross section

MICROBOONE-NOTE-1117-PUB



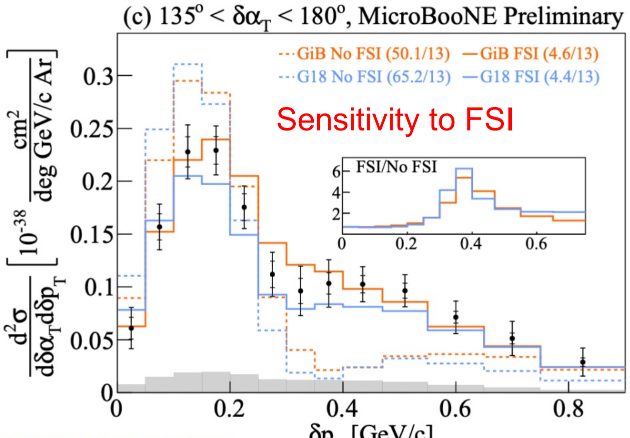
First exclusive & differential ν_e xsec measurement

Phys.Rev.D 106 (2022) L051102



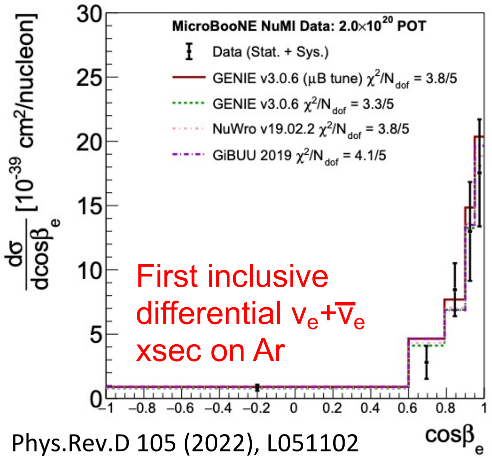
First energy-dependent inclusive ν_μ CC on argon

Phys.Rev.Lett. 128 (2022), 151801



Sensitivity to FSI

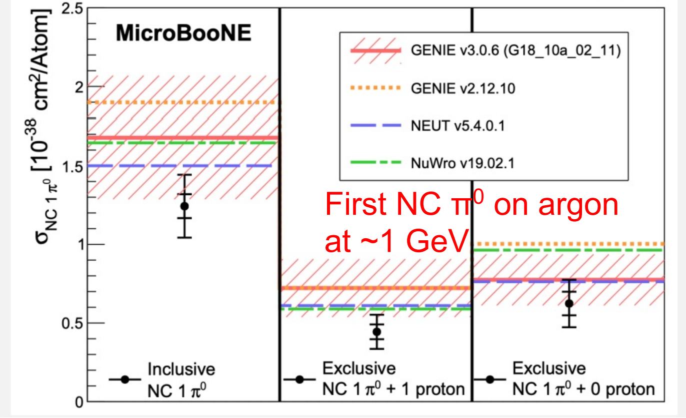
MICROBOONE-NOTE-1108-PUB



First inclusive differential ν_e+$\overline{\nu}_e$ xsec on Ar

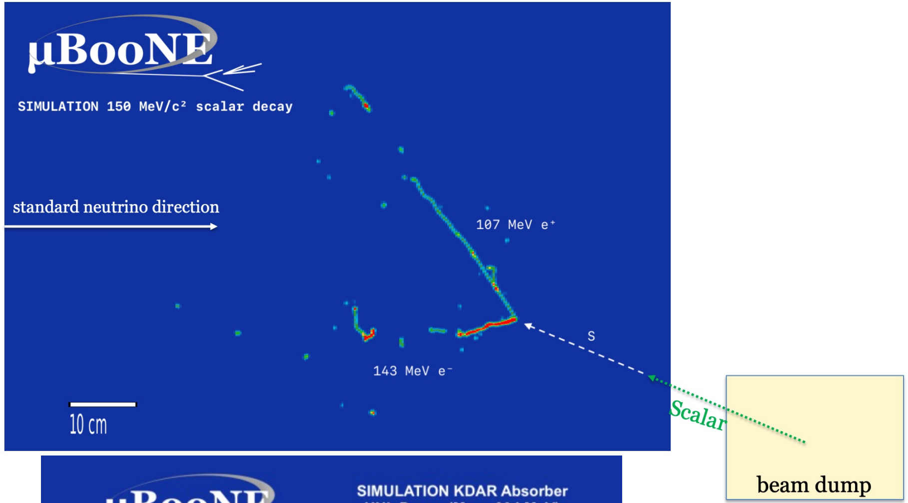
Phys.Rev.D 105 (2022), L051102

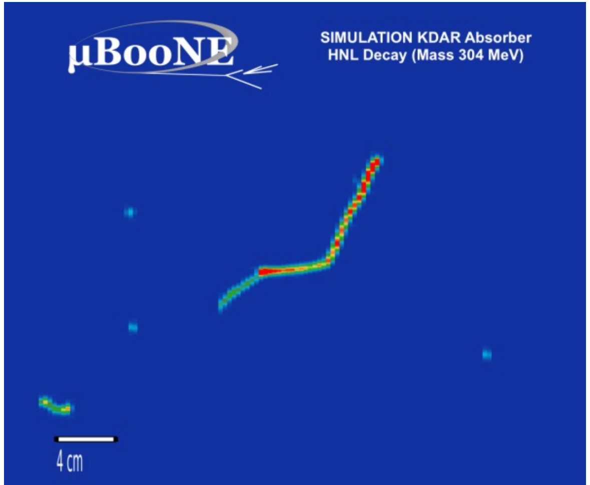
arXiv:2205.07943 [hep-ex]

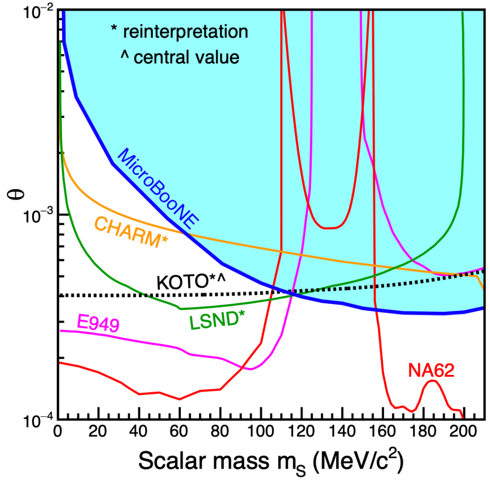


First NC π^0 on argon at ~1 GeV

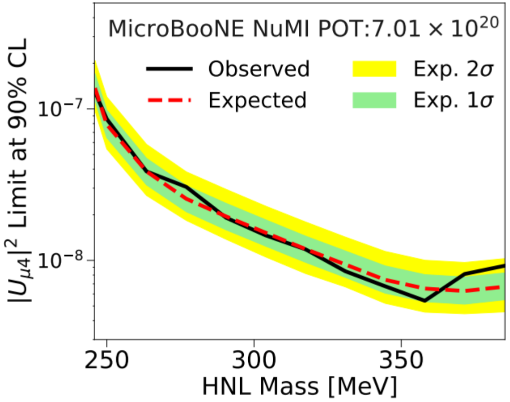
MicroBooNE – a BSM factory





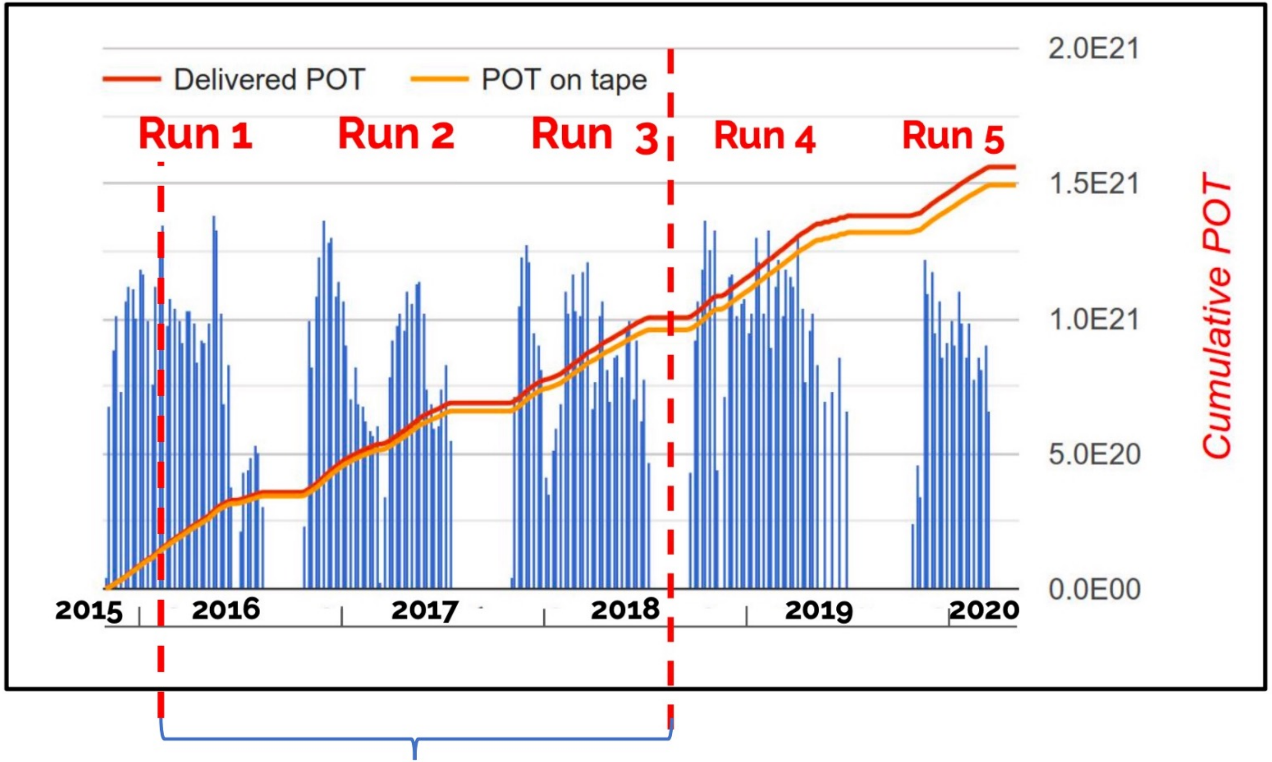


Higgs portal scalar boson search
Phys.Rev.Lett. 127 (2021) 15, 151803



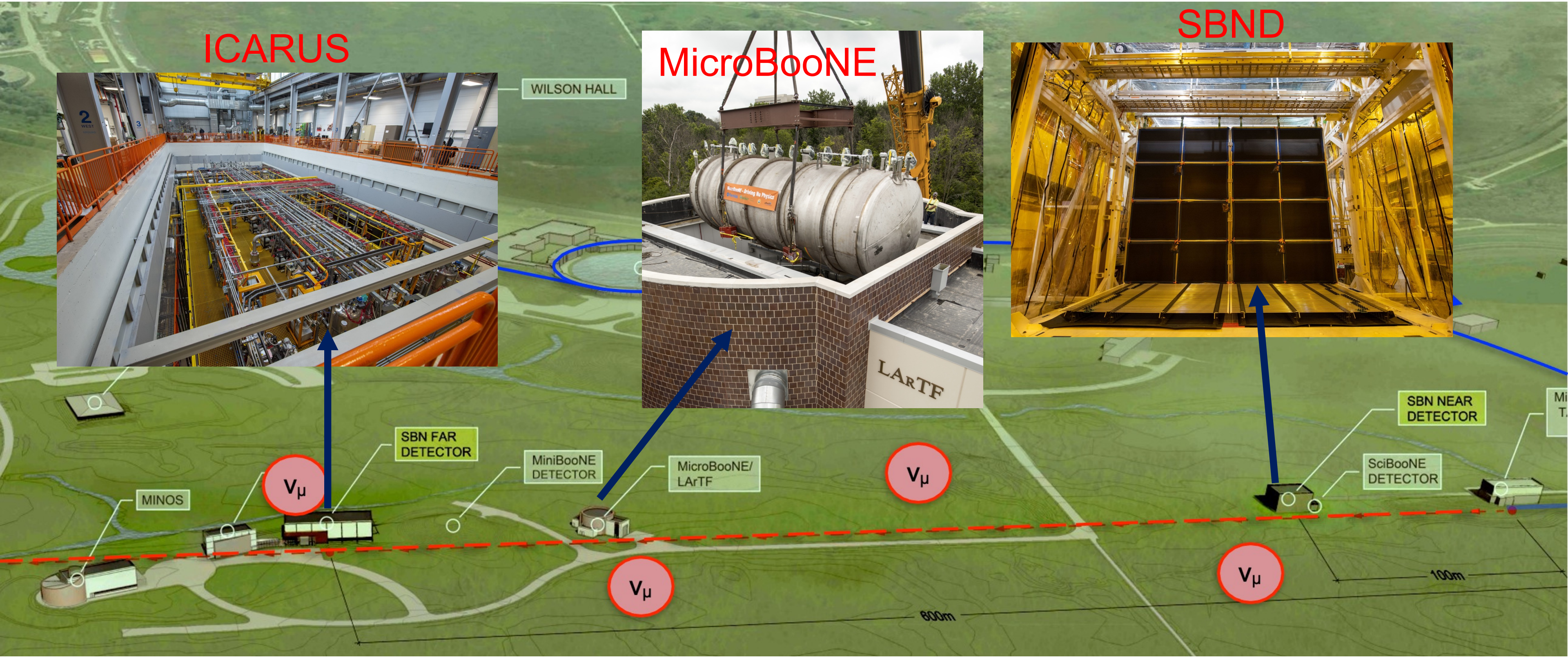
Heavy neutral lepton search
arxiv:2207.03840

MicroBooNE – more to come



This data (~50%) analysed so far

The SBN programme



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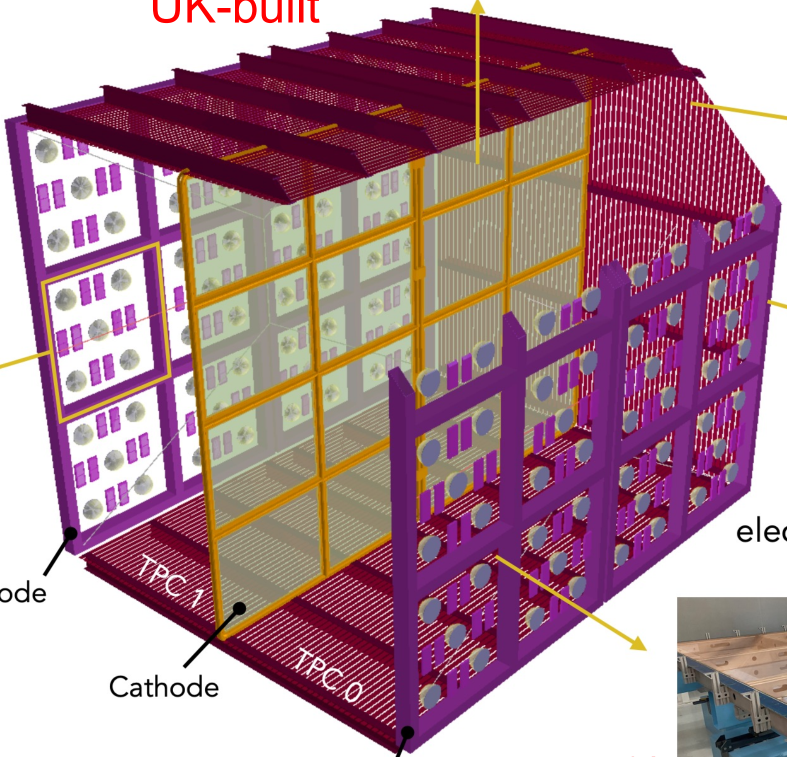
SBND

TPC is complete
Installation into cryostat this winter

2 Time Projection Chambers
for a total of 4m x 4m x 5m

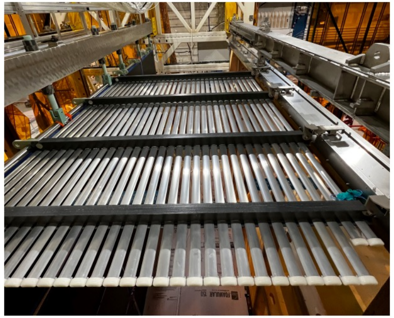
Photo Detection System:
120 PMTs
192 X-Arapucas

Cathode covered with TPB coated reflectors
UK-built

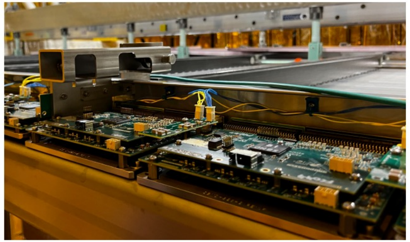


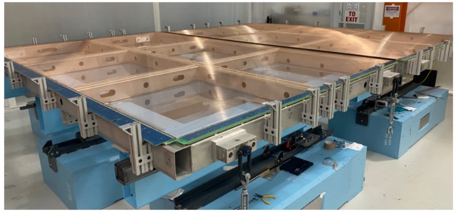
Anode
Cathode
Anode

Field Cage



Cold electronics





Wire Plane
3 readout wire planes
~11000 wires

50% UK-built

SBND physics programme

5000 ν events per day

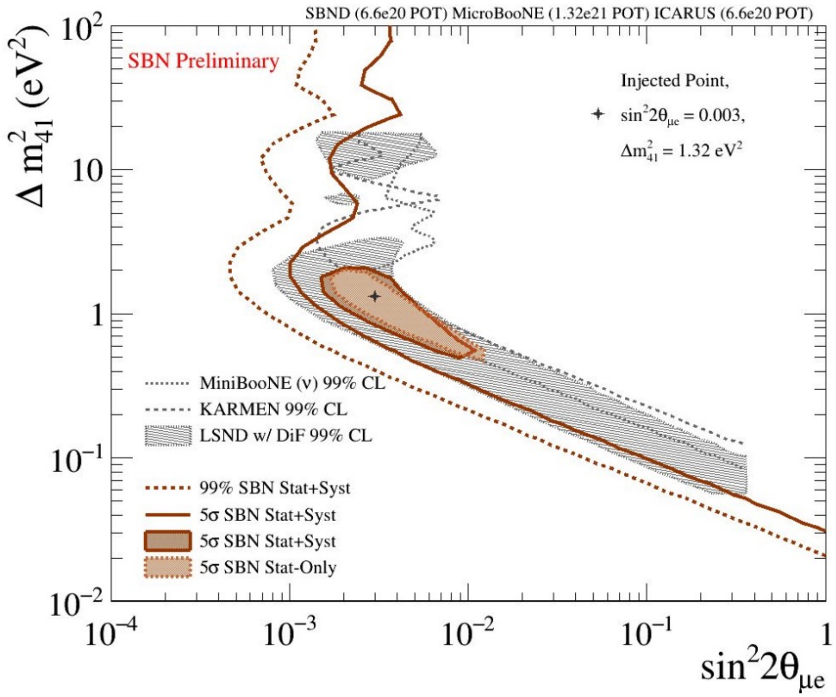
- 1.2M ν_μ & 12k ν_e CC events per year

Unprecedented understanding of neutrino interactions on argon

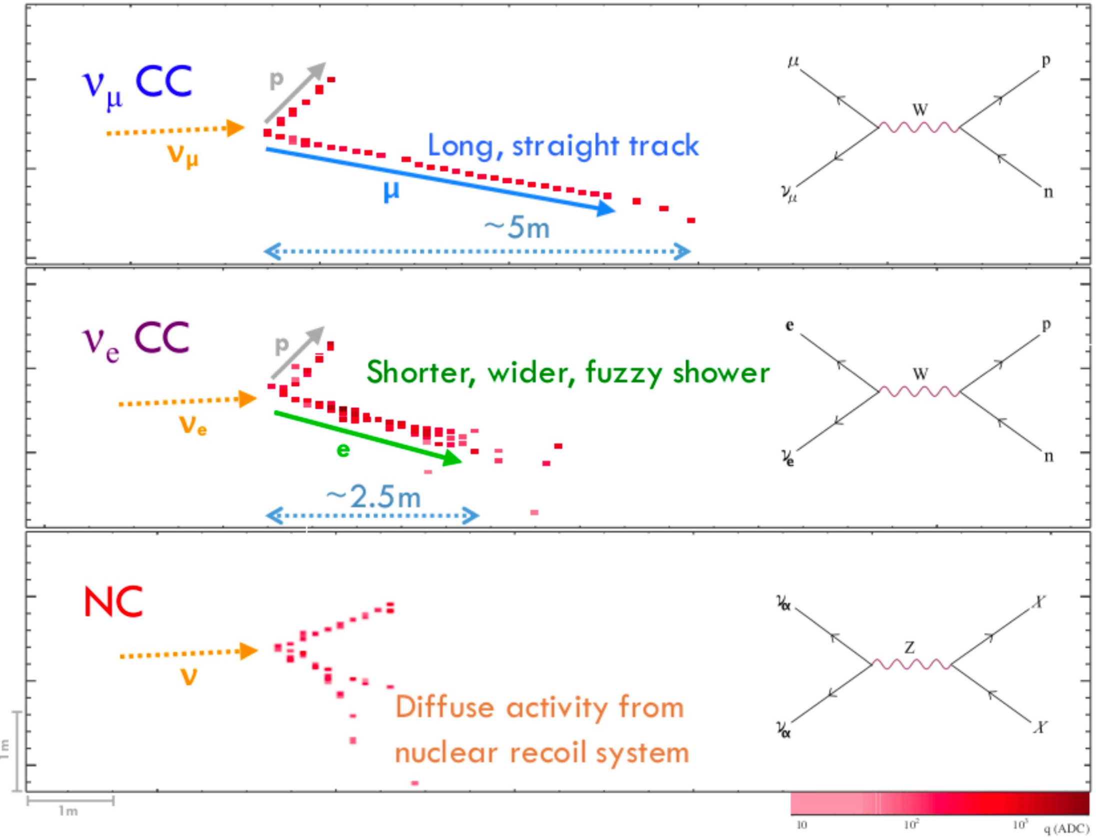
- Argon is a heavy, complex nucleus
- Vital input to DUNE

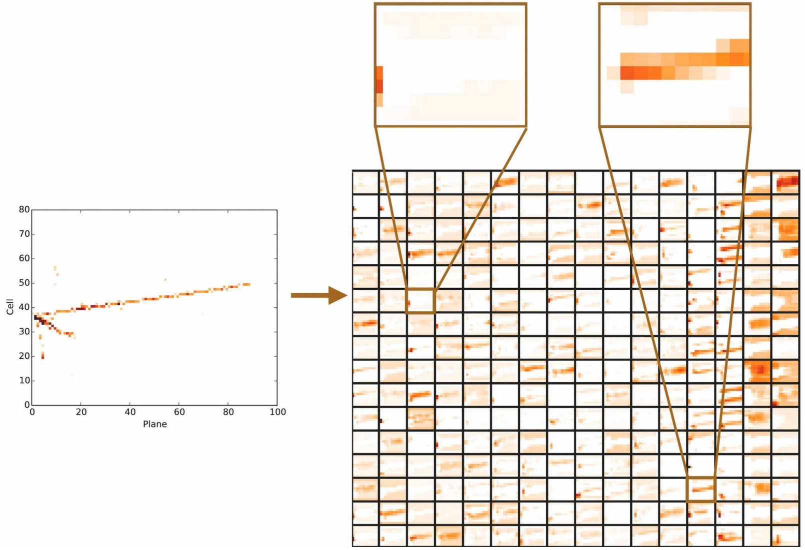
A near detector for SBN

Broad programme of BSM searches



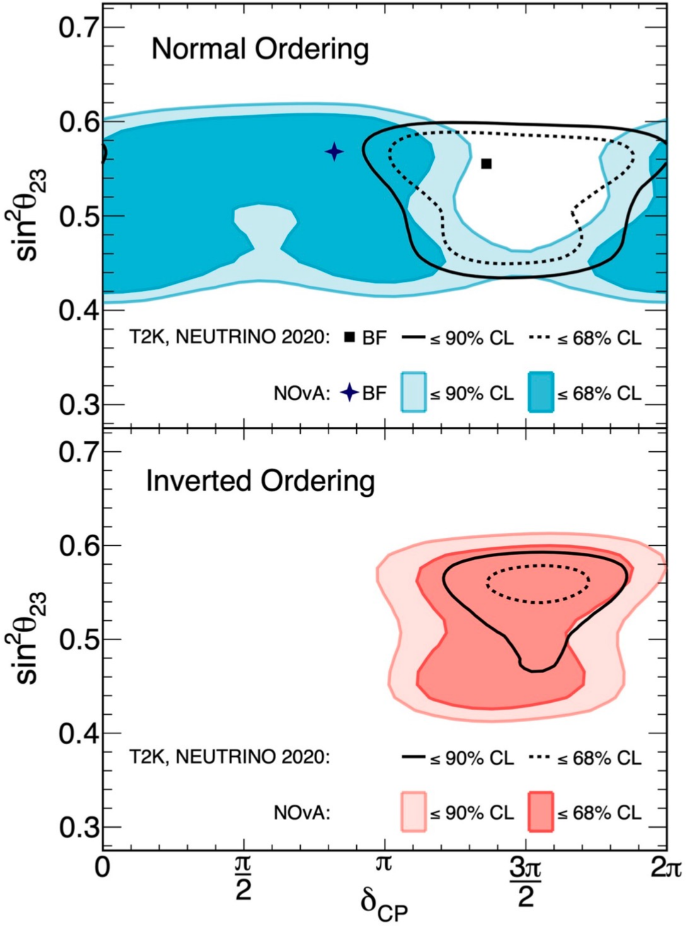
NOvA





- Liquid scintillator low-Z tracking calorimeter
- NuMI ν_μ beam
- Pioneering use of deep learning for image classification in neutrino physics

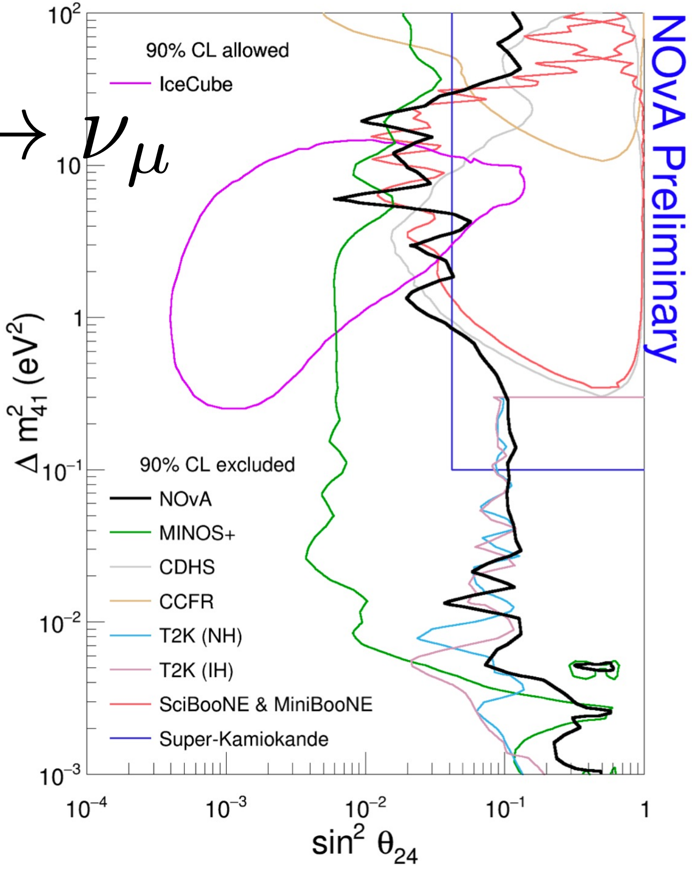
NOvA (and T2K)

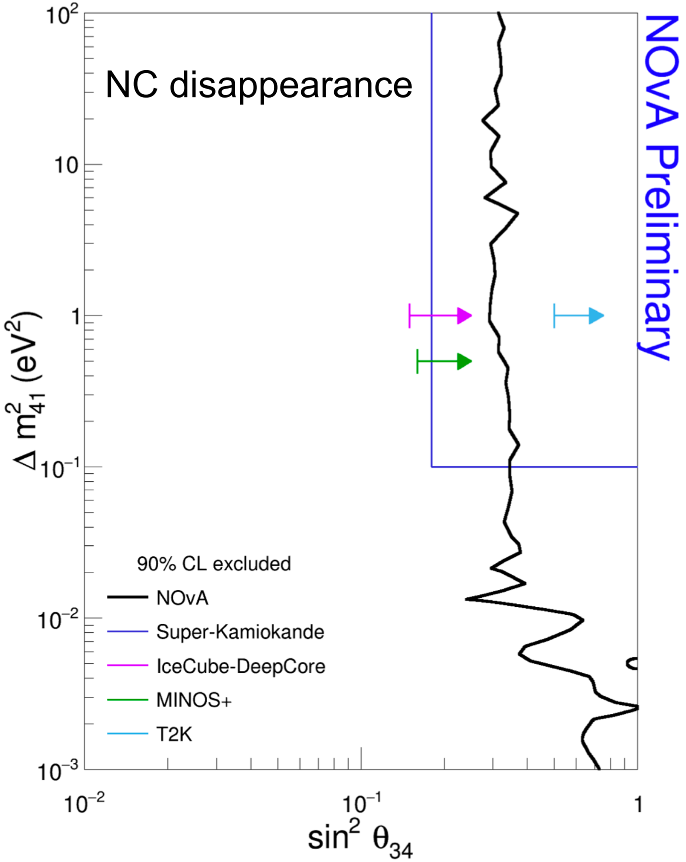


- θ_{23} still consistent with 45°
- No strong preference between mass orderings
- T2K drives a preference for δ_{CP} somewhere around 3π/2
- Joint NoVA–T2K analysis expected in the next few months

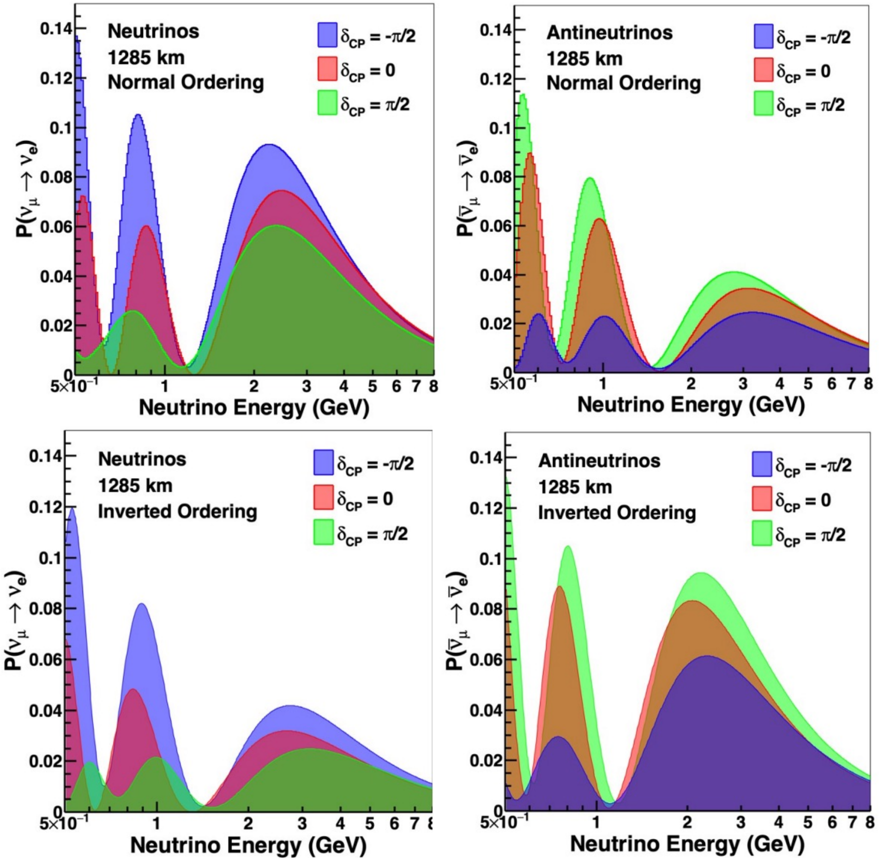
NOvA and sterile neutrinos

$$\nu_\mu \rightarrow \nu_\mu$$



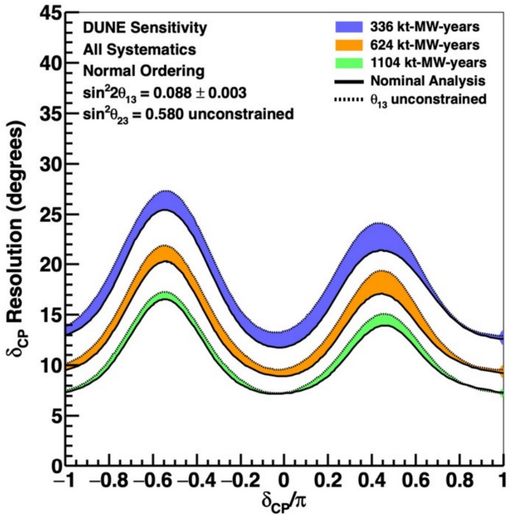


DUNE



Wideband beam enables δ_{CP} and the mass hierarchy to be determined in the same experiment

- Regardless of true values



DUNE physics programme

CP violation

Mass hierarchy

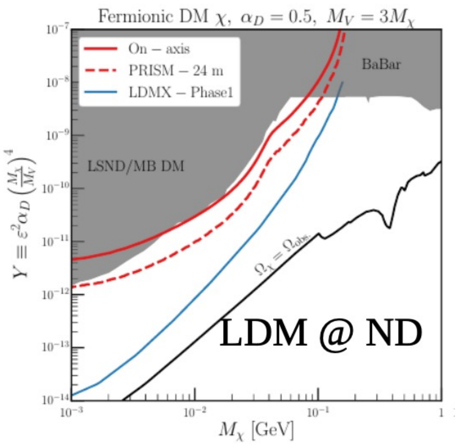
Precision oscillation measurements

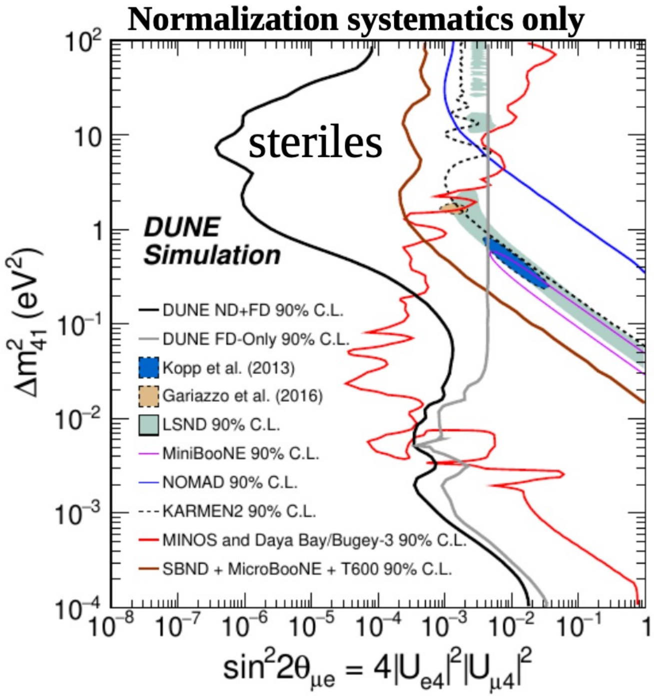
Supernova detection

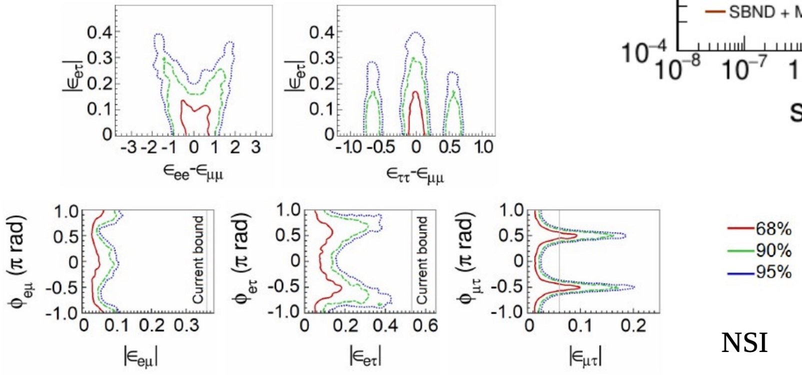
BSM physics

- Sterile neutrinos, dark matter, non-standard interactions, extra dimensions…

Neutrino interaction physics







NSI

UK leadership in DUNE

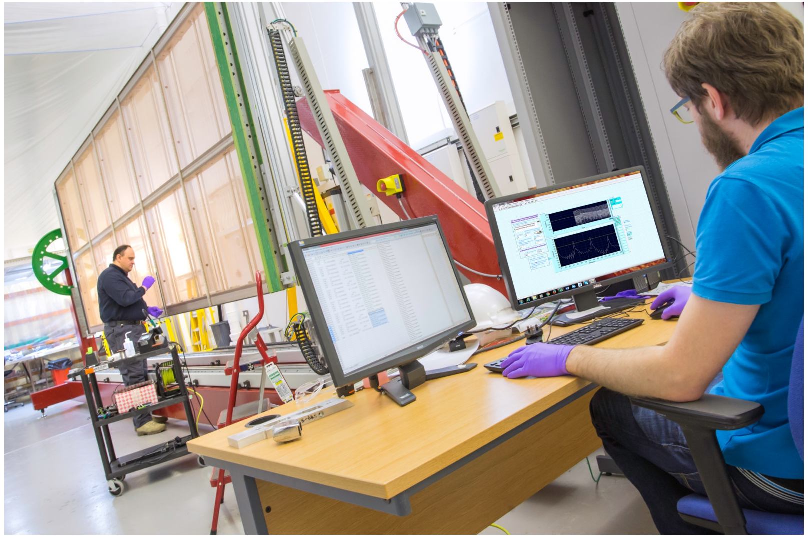
UK is building the majority of readout planes (APAs) for the first 10 kt module

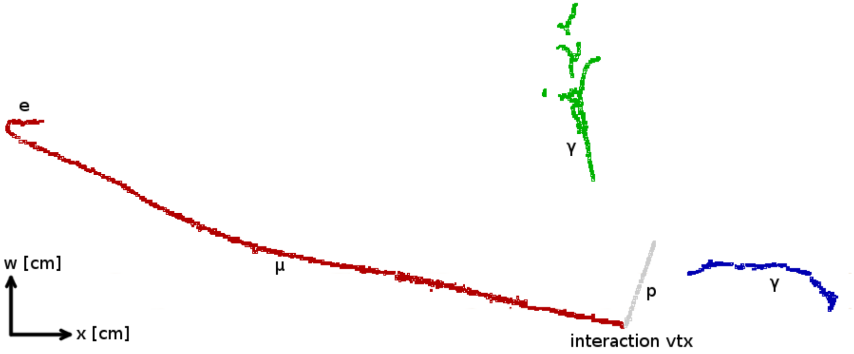
- Major construction factory at Daresbury

UK is providing the DAQ for the first two 10 kt modules

- And contributing to ND DAQ

UK is delivering Pandora reconstruction





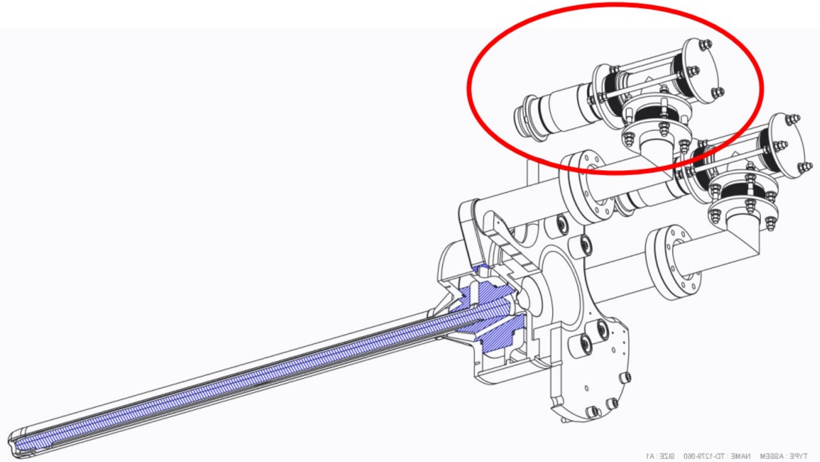
UK leadership in LBNF

Daresbury and RAL are world centres of accelerator expertise

Producing RF cavities for the PIP-II upgrade for the LBNF 1.2 MW beam

- And eventual 2.4 MW goal

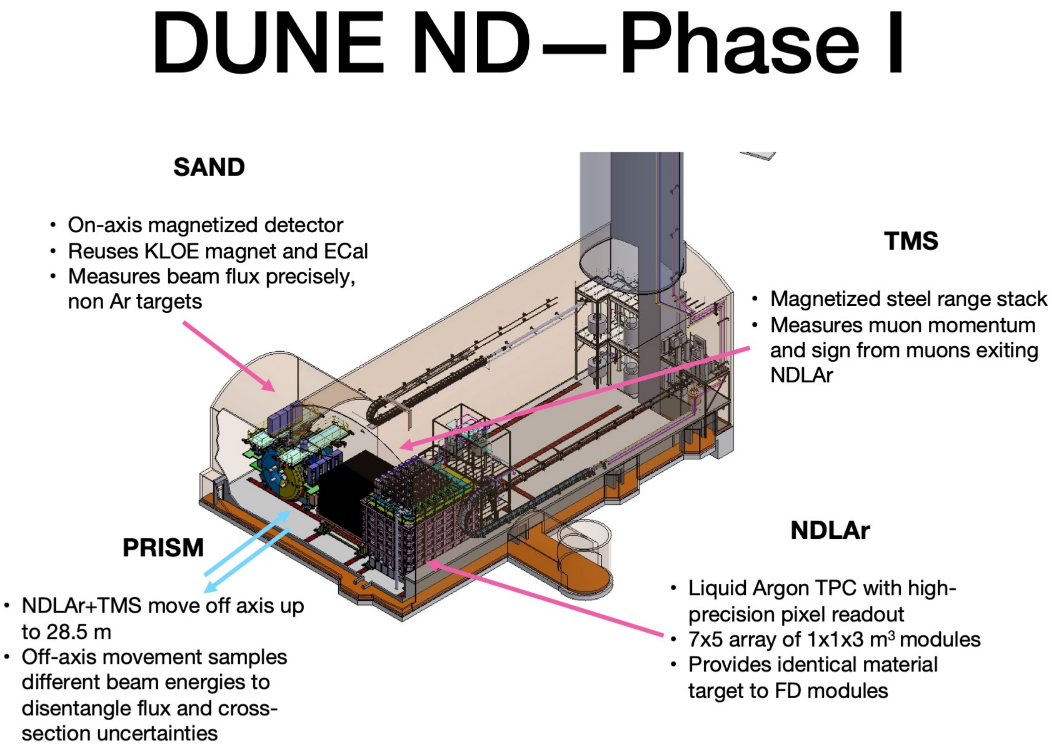
Delivering the LBNF proton target



DUNE near detector

Multi-component near detector

- Highly segmented LArTPC
- Magnetised tracker
- Electromagnetic calorimeter
- Moveable components for off-axis measurements (DUNE-PRISM)



Rich non-oscillation physics programme

- >100 million ν interactions

DUNE near detector

Multi-component near detector

- Highly segmented LArTPC
- Magnetised tracker
- Electromagnetic calorimeter
- Moveable components for off-axis measurements (DUNE-PRISM)

Rich non-oscillation physics programme

- >100 million ν interactions

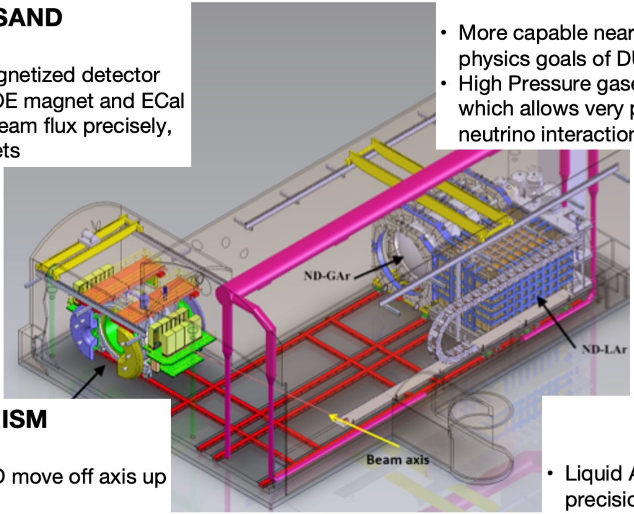
DUNE ND—Phase II

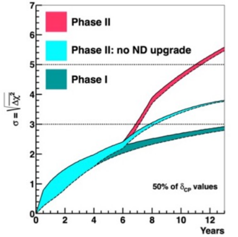
SAND

- On-axis magnetized detector
- Reuses KLOE magnet and ECal
- Measures beam flux precisely, non Ar targets

MCND

- More capable near detector to fulfill ultimate physics goals of DUNE
- High Pressure gaseous Ar detector+ ECal which allows very precise reconstruction of neutrino interactions





PRISM

- NDLAr+MCND move off axis up to 28.5 m
- Off-axis movement samples different beam energies to disentangle flux and cross-section uncertainties

NDLAr

- Liquid Argon TPC with high-precision pixel readout
- 7x5 array of 1x1x3 m^3 modules
- Provides identical material target to FD modules

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DUNE Near Detector – UK Involvement

Physics

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

Phase I

- DAQ support for all detectors, leveraging work from DAQ development for FD modules
- Reconstruction and simulation, leveraging work from development for FD modules
- 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

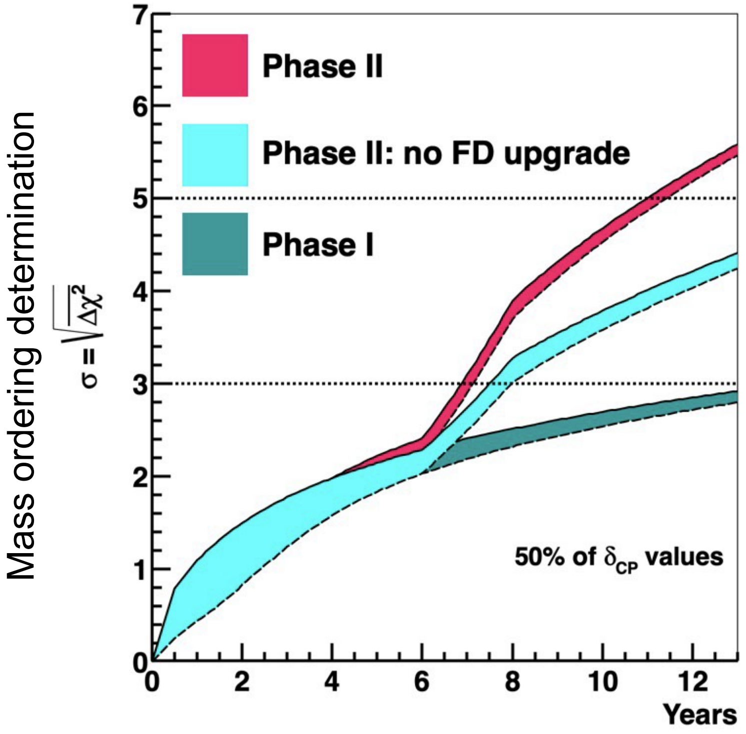
DUNE phase II

The **ultimate** DUNE scope is

- Four far detector TPC modules with up to 70 kt of liquid argon
- A near detector that includes a liquid-argon TPC
- A 1.2 MW beam upgradeable to 2.4 MW

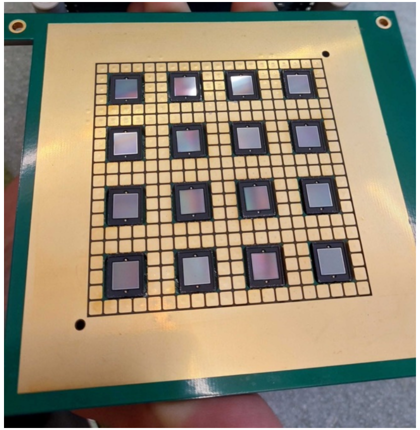
This is needed to achieve the DUNE physics goals as identified by P5

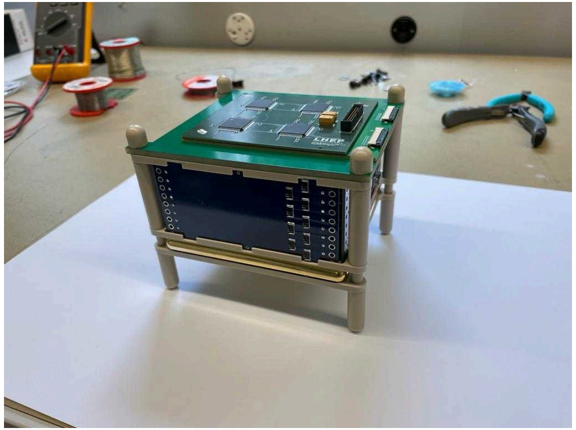
2nd Module of Opportunity workshop in Valencia, 2—4 November



https://arxiv.org/abs/2203.07501

SoLAr pixel collaboration





- UK-led collaboration
- Combine SiPMs and charge readout pads on a single tile
- Extends the DUNE ND pixel concept to the FD
- Can extend FD physics sensitivity to lower energies (solar neutrinos)
- Plan to install a physics prototype in Boulby as part of the SOLAIRE project

CERN Neutrino Platform

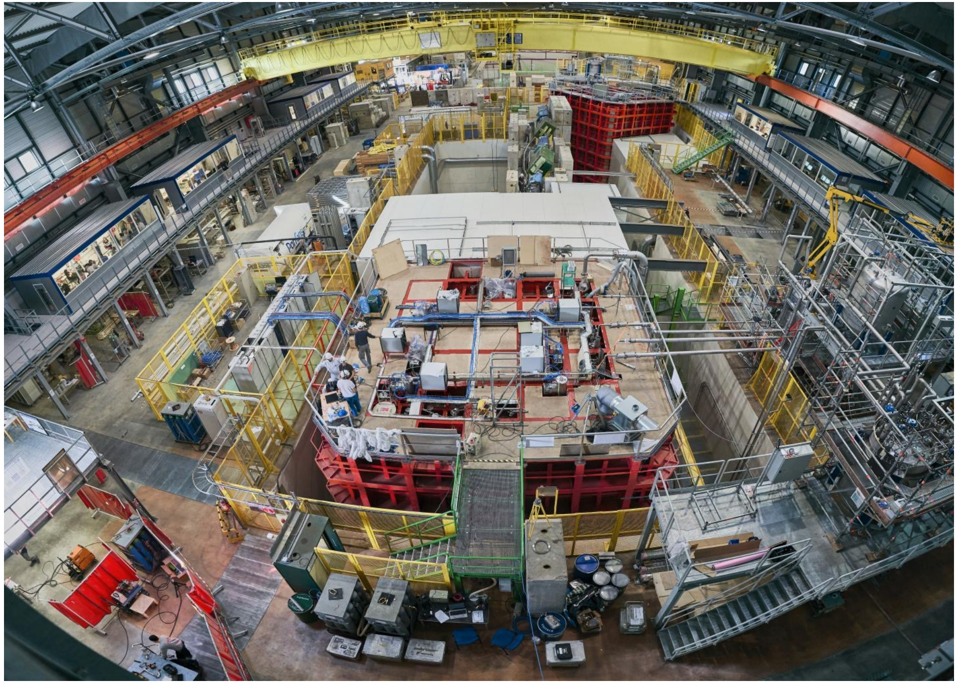
CERN neutrino platform is a vital part of the DUNE programme

ProtoDUNE programmes to demonstrate the technology for our first two FD modules

- And to make physics measurements of charged particles in argon

Significant UK presence at the neutrino platform

- APAs and DAQ provided for ProtoDUNEs



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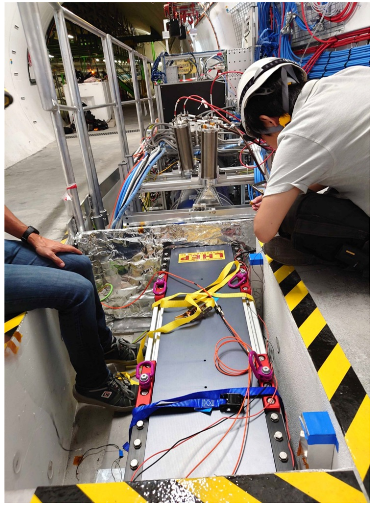
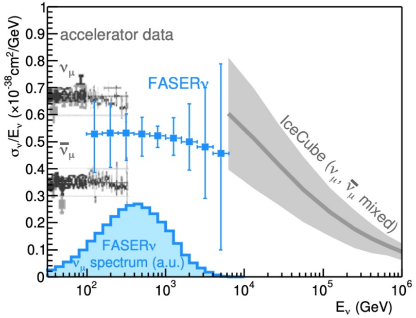
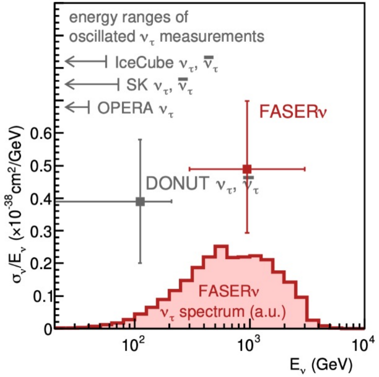
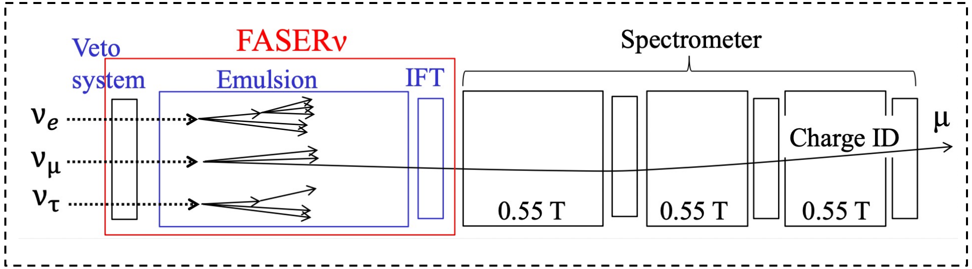
Neutrinos at the LHC: FASERν

- A far-forward emulsion detector: 480 m from ATLAS, 1.3 t of tungsten-emulsion layers, η > 8.8
- LHC run 3 expectations: 1,300 ν_e, 20,000 ν_μ and 20 ν_τ at TeV energies
- TeV-energy cross-section measurements
- Forward particle production to validate underlying hadronic interaction models
- Observation of heavy quark production in ν interactions
- arXiv:2105.06197: First neutrino interaction candidates at LHC from a prototype detector
- UK involved in the silicon strip tracker that interfaces with FASER (Manchester, Liverpool, RHUL, Sussex)









Neutrinos at the LHC: SND@LHC

- 1 tonne detector, 480 m from ATLAS, $7.2 < \eta < 8.4$, ~2,000 neutrino interactions expected
  - More off-axis than FASERnu
- Emulsion-tungsten target region, with downstream muon spectrometer
- ν_e and ν_τ mainly produced in charm decays in ATLAS: enables constraints of charm PDFs
- Also sensitive to feebly interaction DM-type particles produced in LHC collisions
- UK (UCL & IC) contributing to track & vertex reconstruction, and emulsion purchase

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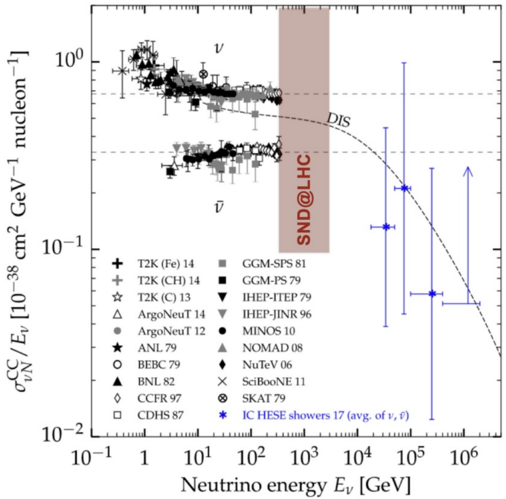

Conclusion

The UK is the leading non-US partner in the US neutrino programme

- Providing major hardware fundamental to DUNE and SBND
- Leading neutrino reconstruction algorithm development with Pandora
- Driving many physics analyses
- Enabling the LBNF and PIP-II MW-beam programmes with proton-target and RF-cavity delivery

CERN Neutrino Platform is integral to the DUNE programme

And the LHC is starting to do neutrino physics!