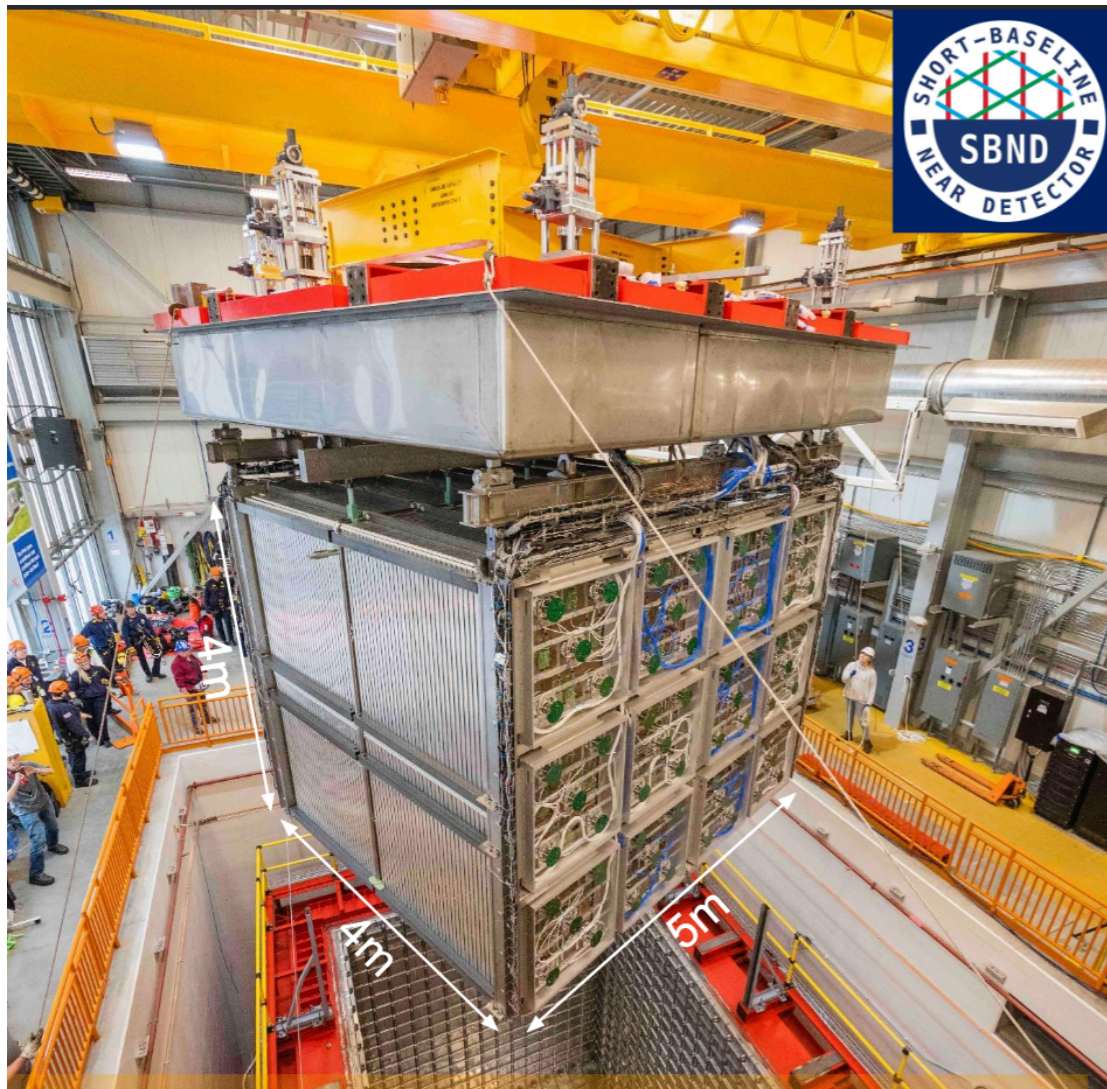




Credit: IHEP, CAS

JUNO and SBND

Particle Physics Annual Meeting
Liverpool, May 2026



Costas Andreopoulos

Motivation

What is the Neutrino Mass Ordering (NMO)?

Neutrino **oscillations** in vacuum **measure mass-squared differences** Δm_{ij}^2 , not absolute masses.

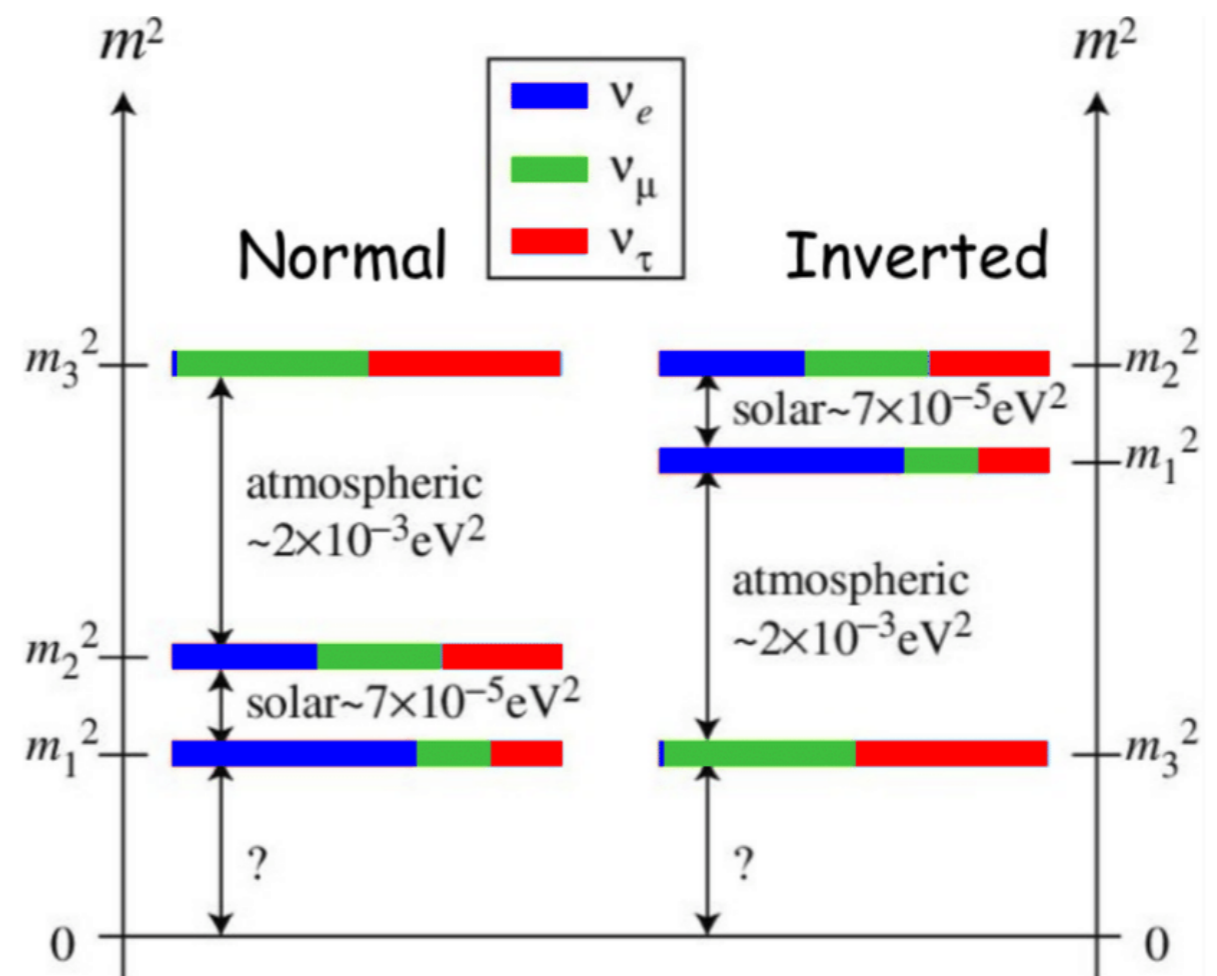
Probabilities depend on terms like $\sin^2(\Delta m_{ij}^2 \frac{L}{4E})$.

They are approximately symmetric in $\Delta m_{ij}^2 \rightarrow -\Delta m_{ij}^2$.

Matter effects and the CP-odd interference term break the degeneracy, but they are sub-leading.

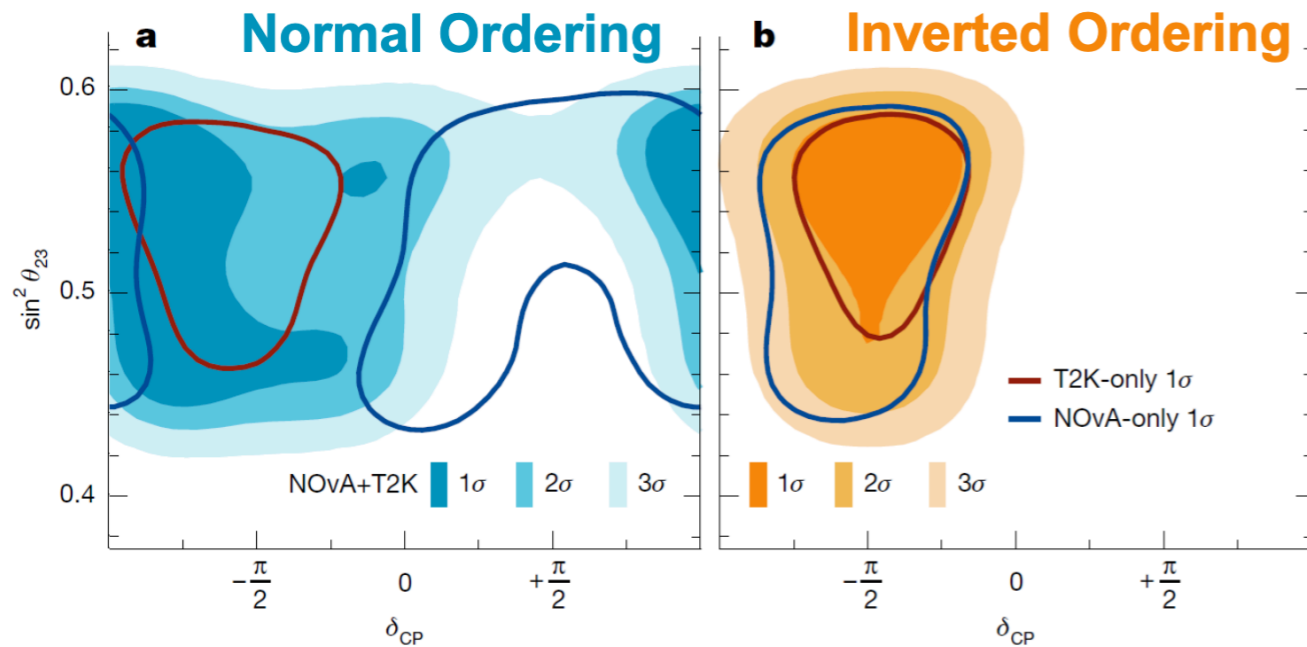
So we know the **splittings** well, but not directly their **sign** - hence the unknown **neutrino mass ordering**.

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2(\Delta m_{ij}^2 \frac{L}{4E}) + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin(\Delta m_{ij}^2 \frac{L}{2E})$$

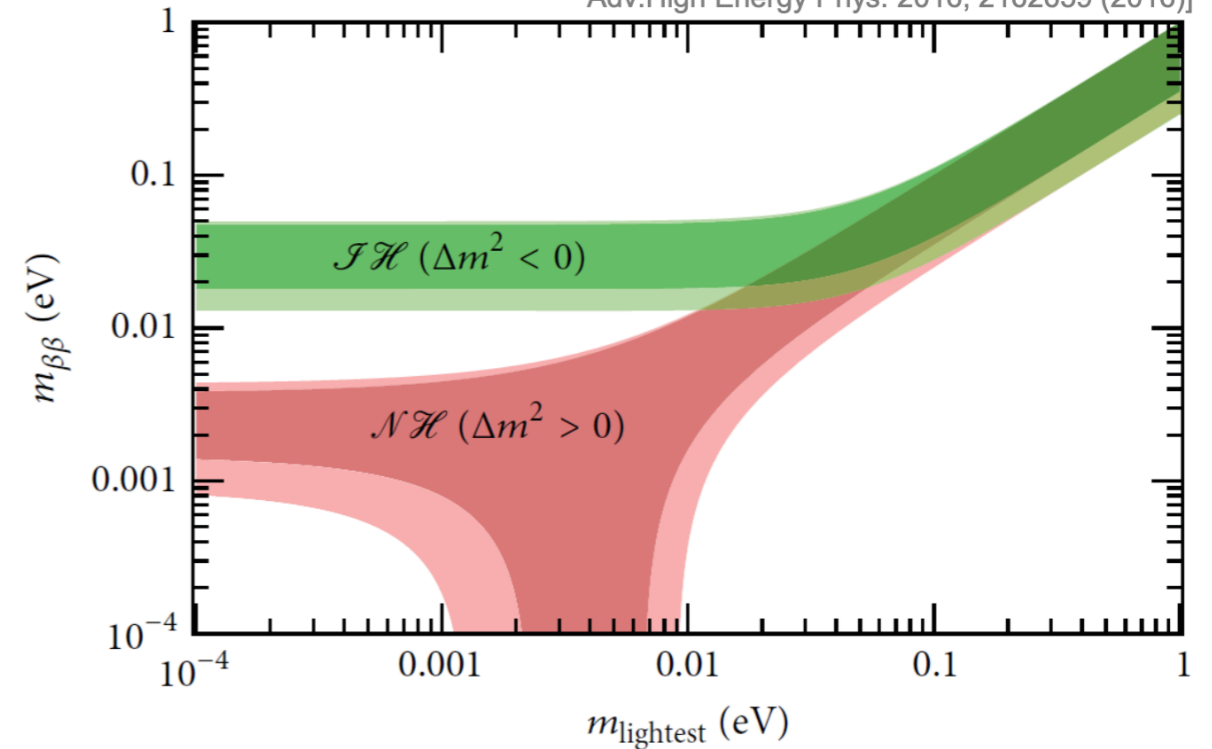


Why NMO matters?

[T2K and NOvA, Nature 646, 818 (2025)]



[Dell'Oro, Marcocci, Viel, and Vissani, Adv.High Energy Phys. 2016, 2162659 (2016)]



Essential input for leptonic CP violation searches

CP violation is already extremely challenging to measure; an unknown NMO introduces degeneracies with the CP phase, matter effects, and oscillation parameters.

Key to interpreting neutrinoless double beta decay

The expected effective Majorana mass range depends strongly on whether the ordering is normal or inverted, shaping discovery reach and exclusion power.

Anchor for absolute neutrino mass constraints

NMO fixes the minimum possible value of $\sum m_\nu$, providing essential context for cosmological limits on neutrino mass.

Crucial for supernova neutrino physics

Flavour conversion in dense stellar matter depends on the ordering, affecting the expected ν_e , $\bar{\nu}_e$, and heavy-flavour signal at Earth.

Gateway to a complete three-neutrino picture

NMO is one of the remaining unknowns in the standard oscillation framework; resolving it turns precision measurements into consistency tests of the paradigm.

JUNO

Jiangmen **U**nderground **N**eutrino **O**bservatory
In the Guangdong–Hong Kong–Macao Greater Bay Area



A massive (20 kton) liquid scintillator detector
the **largest ever built**

With **extreme radiopurity and energy resolution.**

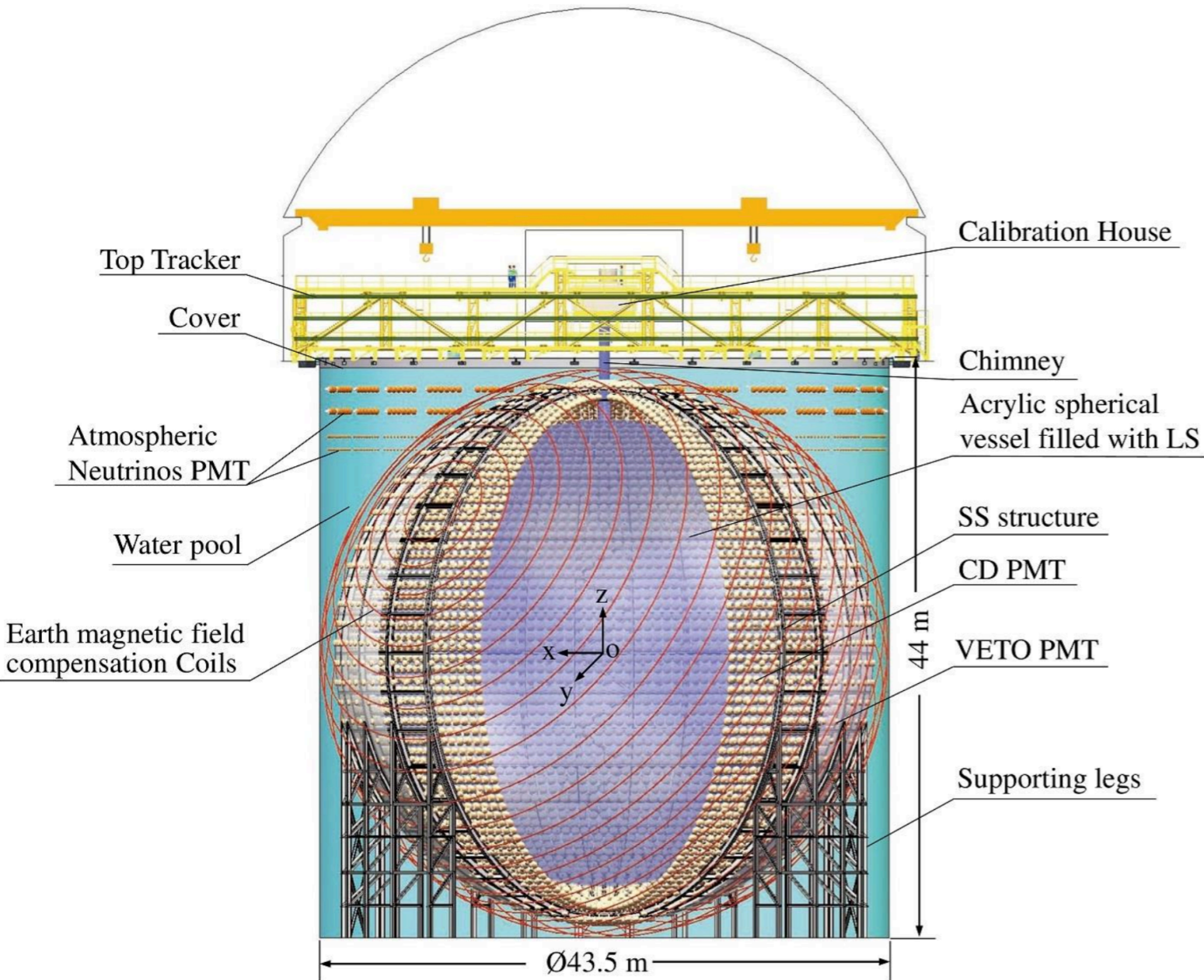
700 m underground

53 km away from the Taishan and Yangjiang
nuclear power plants **in south China**

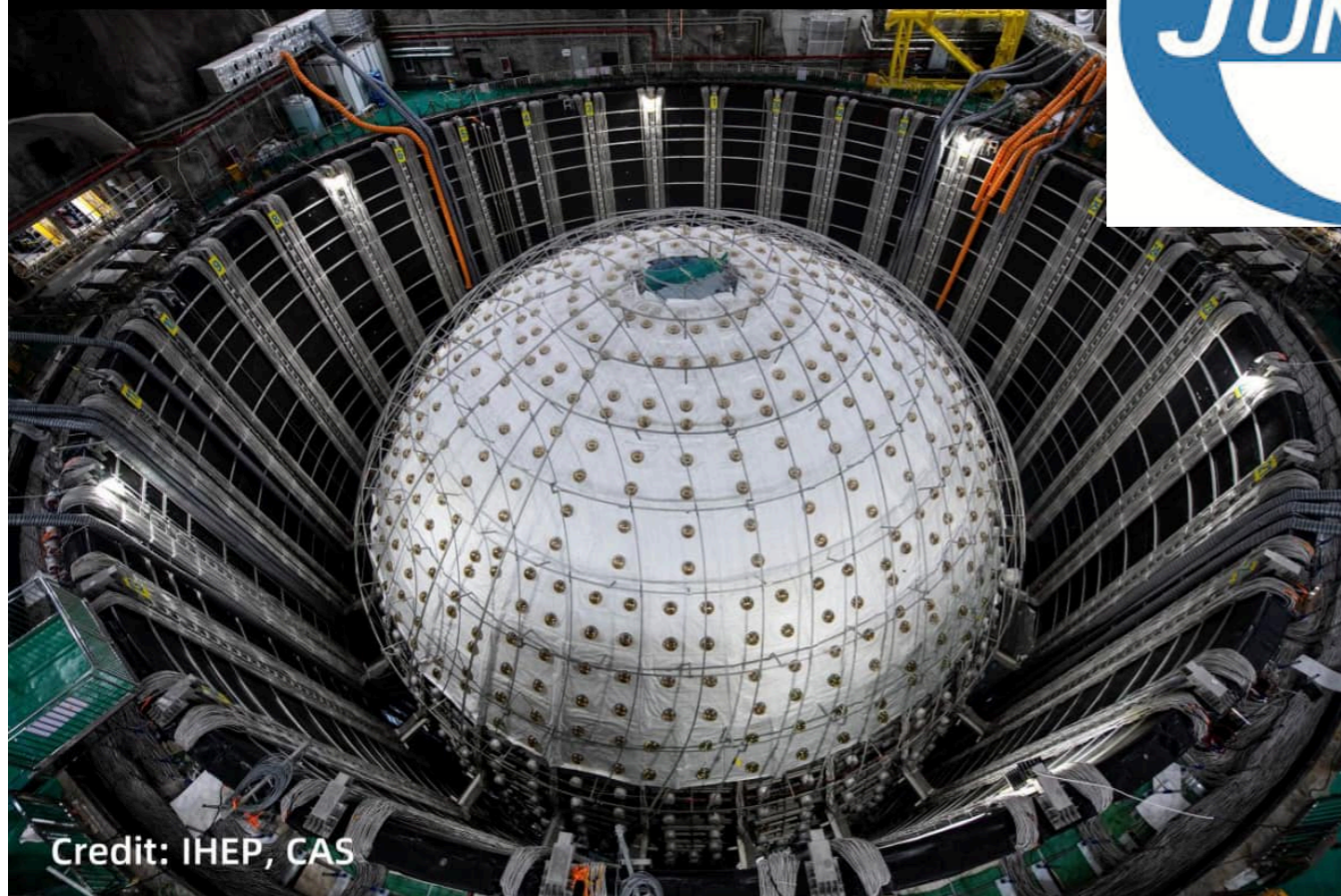
An observatory with **uniquely rich physics program:**

- **reactor** neutrinos,
- **solar** neutrinos,
- **atmospheric** neutrinos,
- **geo-neutrinos**,
- diffuse **supernova** background neutrinos,
- nucleon decay
- dark sector searches

JUNO detector



- Ø43.5 m, H 44 m Water Pool/WP
 - ❖ 35 kt water—Water Cherenkov Detector/WCD
 - Tyvek -----
 - ❖ 5 kt water buffer between WCD and AV
- Stainless Steel Structure/SSS
 - ❖ WCD PMTs viewing outwards
 - 2,404 20" veto PMTs (Micro-Channel Plate/MCP)
 - Tyvek -----
 - ❖ CD PMTs viewing inwards
 - 17,596 20" large PMTs: 4939 dynode + MCP (w/ ×2 photon detection efficiency)
 - 25,587 3" small PMTs (higher dynamic range, calibration for large PMTs; a problem due to the connections: add N₂ into water)
 - ✓ 75%+3% geometrical coverage ← SSS
 - mechanical precision ~3 mm
- Ø35.4 m Acrylic Vessel/AV
 - ❖ 20 kt liquid scintillator—Central Detector/CD
 - Fluorescence emission peak 430 nm (violet-blue)



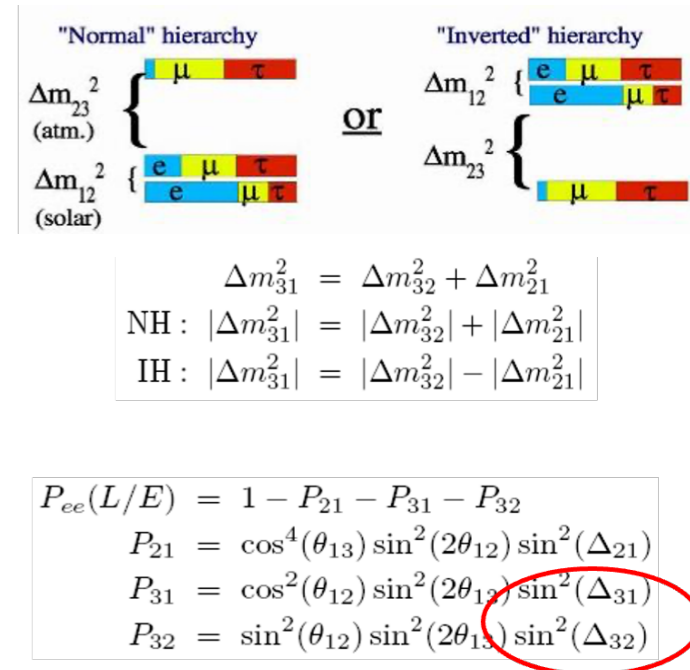
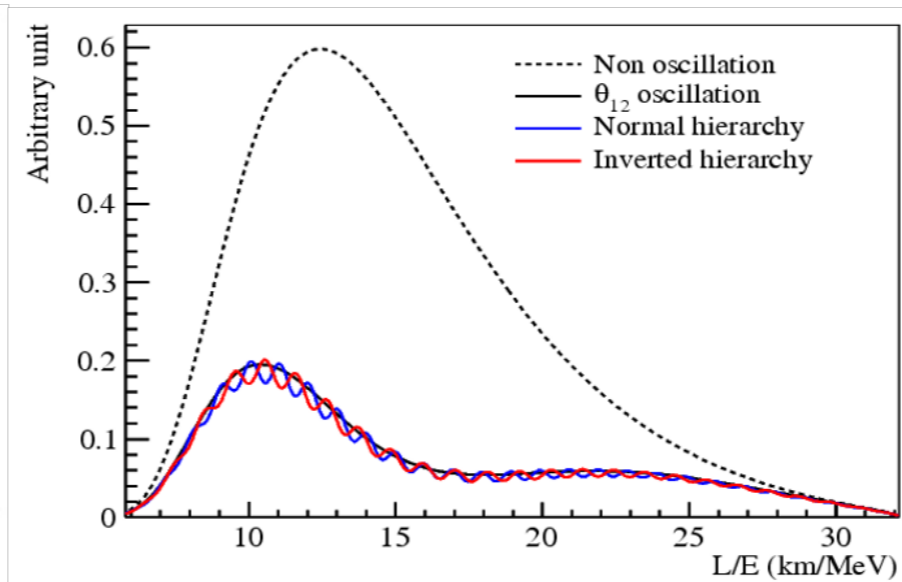
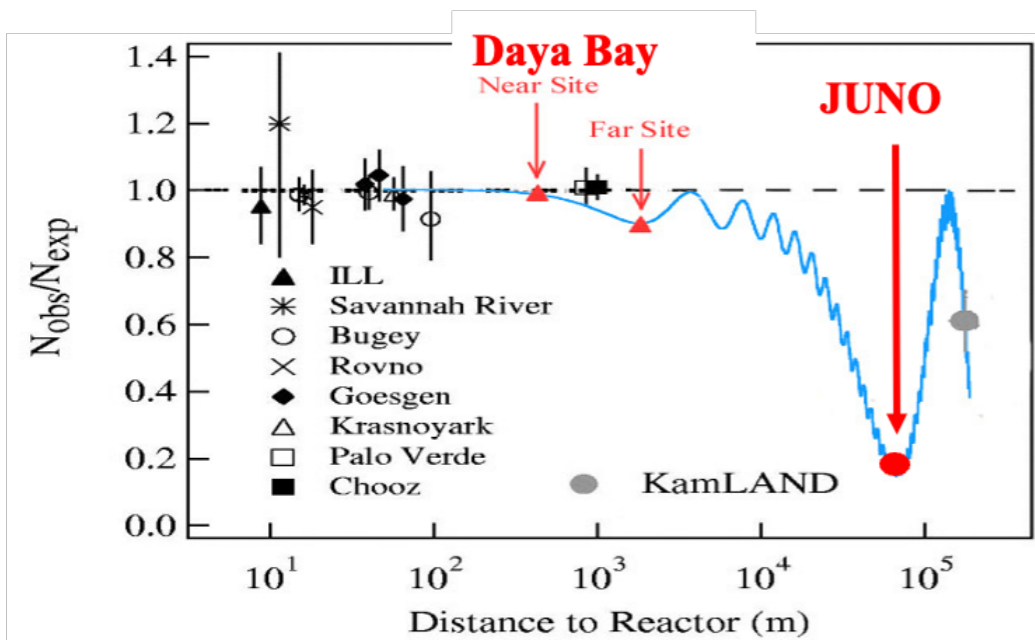
Credit: IHEP, CAS

dit: IHEP, CAS

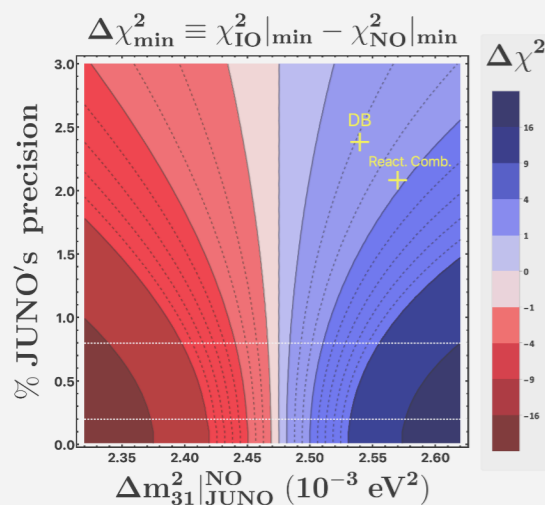
JUNO has superb oscillation sensitivity



JUNO is using a novel technique that exploits the interference between the solar and atmospheric oscillation frequencies,



Using this technique, aiming at a better than $\sim 3\sigma$ NMO determination with ~ 6 year of data



Not the only way to determine the NMO

Combination for JUNO atmospheric and/or external measurements (NOvA, T2K) of Δm_{31}^2 enhances sensitivity.

$\sim 3\sigma$ NMO determination with only ~ 1 year of data is a distinct possibility.

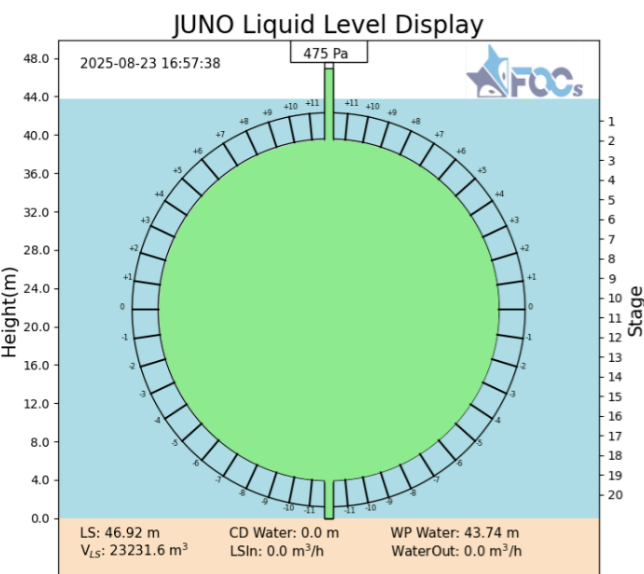
<https://arxiv.org/pdf/2404.08733>

Precision measurements of oscillation parameters

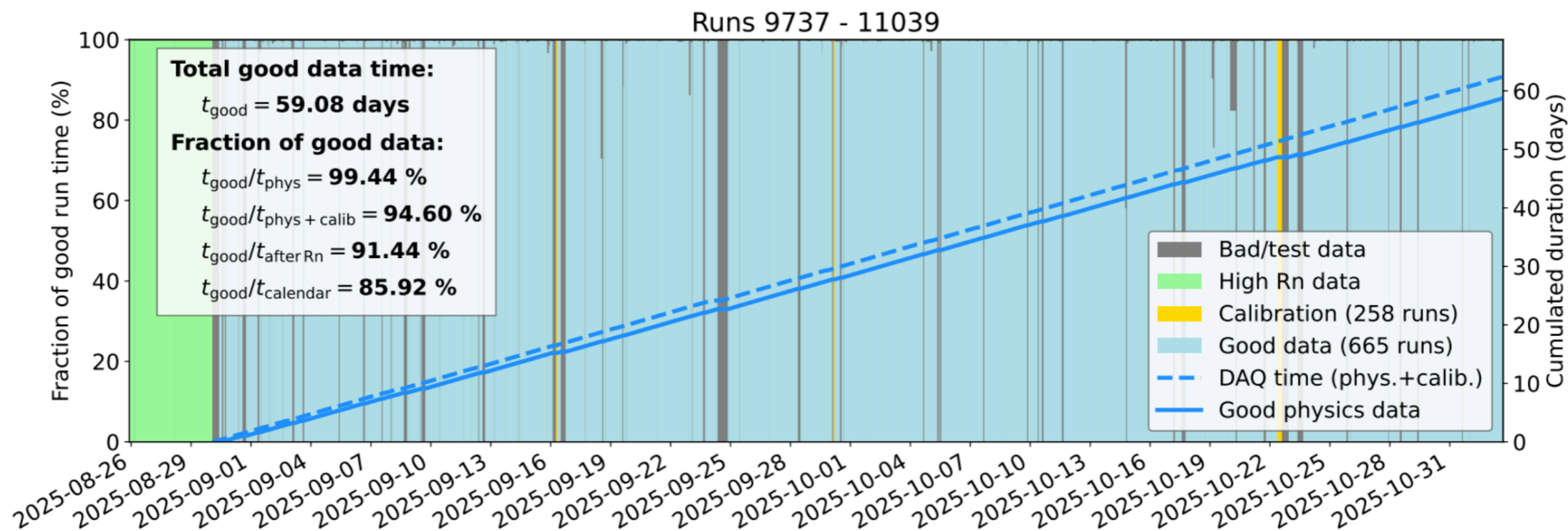
	Central Value	PDG2020	100 days	6 years	20 years
Δm_{31}^2 ($\times 10^{-3}$ eV ²)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm_{21}^2 ($\times 10^{-5}$ eV ²)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2 \theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2 \theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)

$\sin^2 2\theta_{12}$, Δm_{21}^2 , $|\Delta m_{32}^2|$, leading measurements in 100 days; precision $< 0.5\%$ in 6 years

Towards the first results

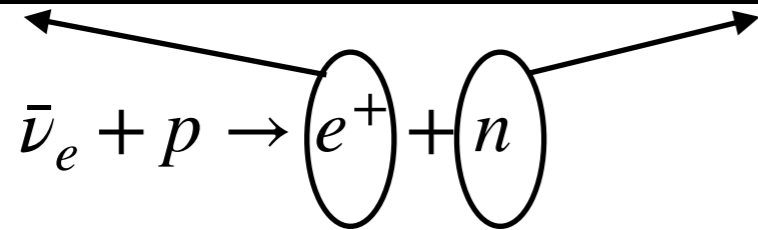
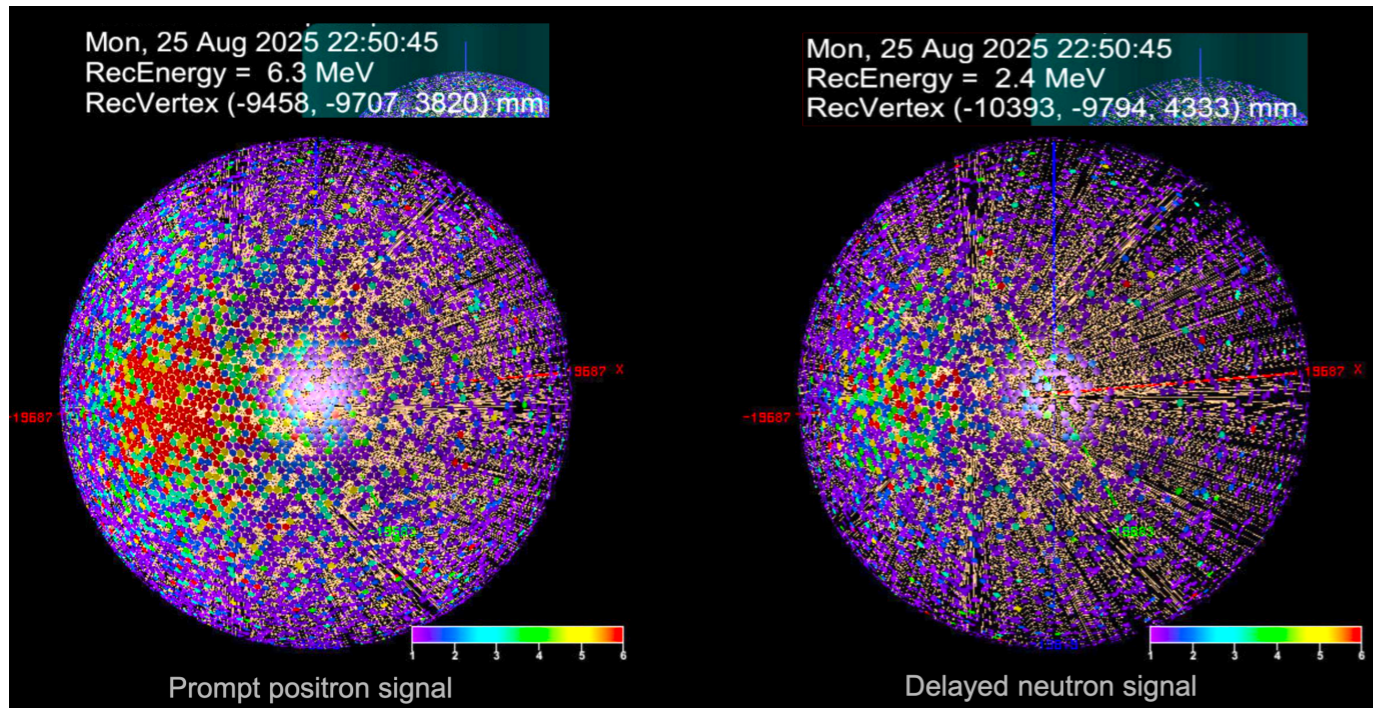


- ❑ 2025/08/22 (22:12): LS filling completed; water in CD fully replaced by LS
- ❑ 2025/08/23 (14:00): Detector calibration began
- ❑ 2025/08/26 (05:30): Start of physics data taking
 - ❖ LS in CD: 23,231.6 m³
 - ❖ Water in WP: 41,225.1 m³
- ❖ Data set used for First Result: 08/26–11/02 (69 calendar days)
 - ❑ Detector uptime > 97.8%
 - ❑ Physics-quality data: 59.1 days



Excellent detector performance - arXiv:2511.14590

First JUNO reactor events



Antineutrinos ($\bar{\nu}_e$) Candidates Summary

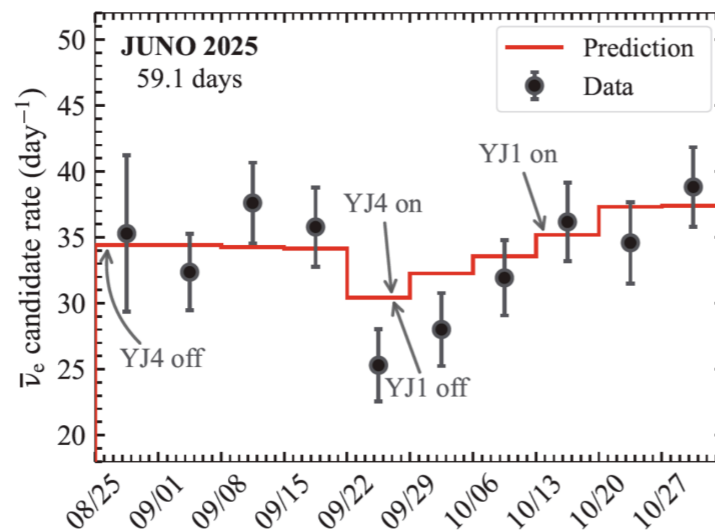
DAQ live time (days)	59.1	
$\bar{\nu}_e$ candidates	2379	~ 40 cpd
Selection Efficiencies (%)		
	ϵ	σ_{rel}
Fiducial volume	80.6	1.6
PMT flasher rejection	>99.9	negligible
μ veto	93.6	negligible
Multiplicity	97.4	negligible
Prompt-delayed coinc.	95.1	0.13
Total efficiency (ϵ_{tot})	69.9	1.6
$\bar{\nu}_e$ signal (cpd¹)		
w/o ϵ_{tot} corrected		33.5 ± 1.7
w/ ϵ_{tot} corrected		47.9 ± 2.6
Non-oscillated $\bar{\nu}_e$		150.9 ± 2.7
Backgrounds (cpd)		
	Pre-fit	Best-fit
$^9\text{Li}/^8\text{He}$	4.3 ± 1.4	3.9 ± 0.6
Geoneutrinos	1.2 ± 0.5	1.4 ± 0.4
World reactors	0.88 ± 0.09	0.88 ± 0.09
$^{214}\text{Bi}-^{214}\text{Po}$	0.18 ± 0.10	0.20 ± 0.10
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	0.04 ± 0.02	0.04 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.05 ± 0.05	0.07 ± 0.05
Atmospheric neutrinos	0.08 ± 0.04	0.07 ± 0.04
Accidentals ($\times 10^{-2}$)	4.9 ± 0.3	4.9 ± 0.3

~ 6 cpd

Neutrino rate follows reactor operations in real time.

Reactor real-time monitoring

Sensitive to single core at 50 km (8 cores, 27 GWth)



* Background subtracted

S/B ~ 5

First JUNO physics results

Dominant distortion driven by θ_{12} and Δm_{21}^2 .

Backgrounds under control.

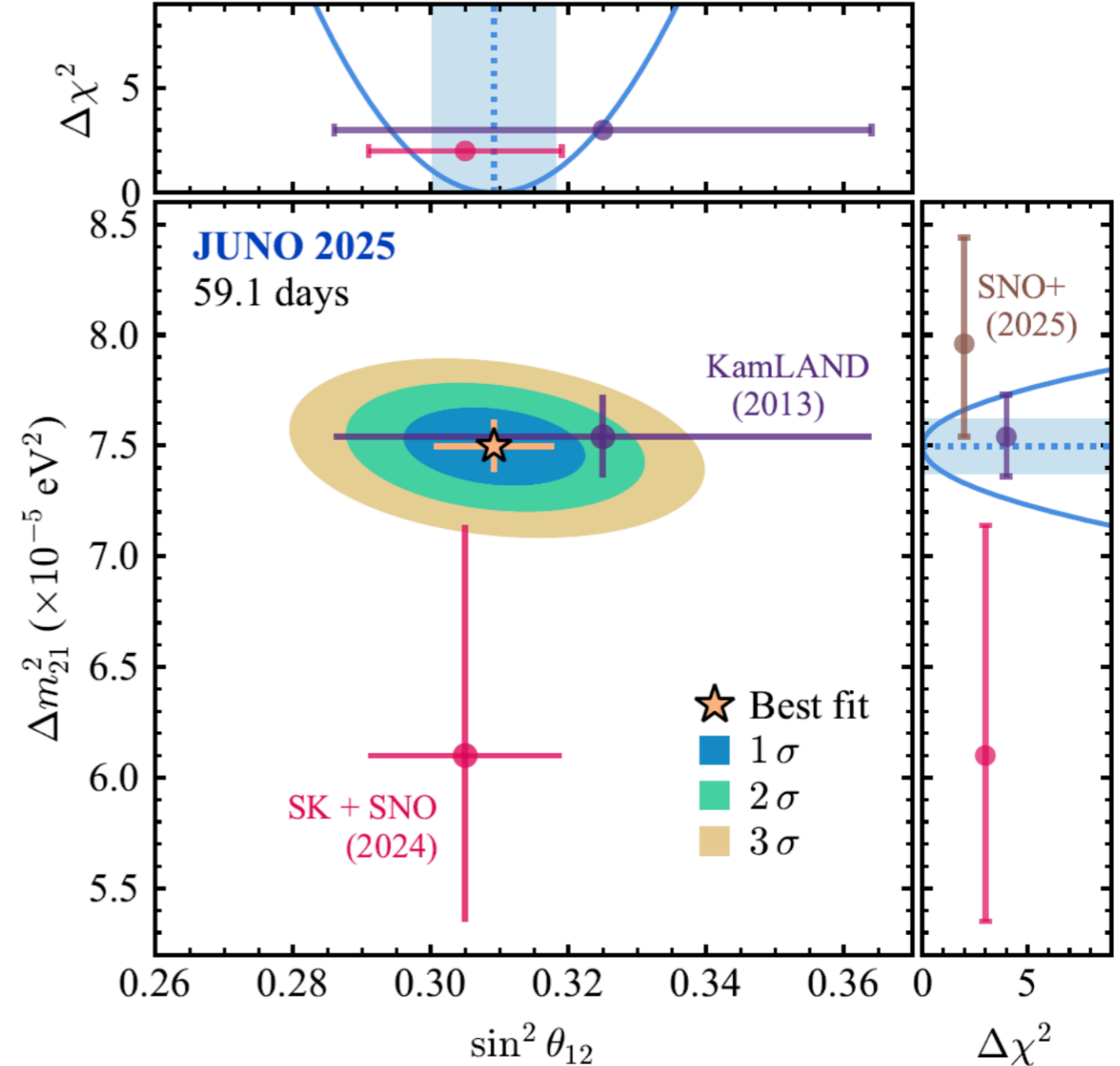
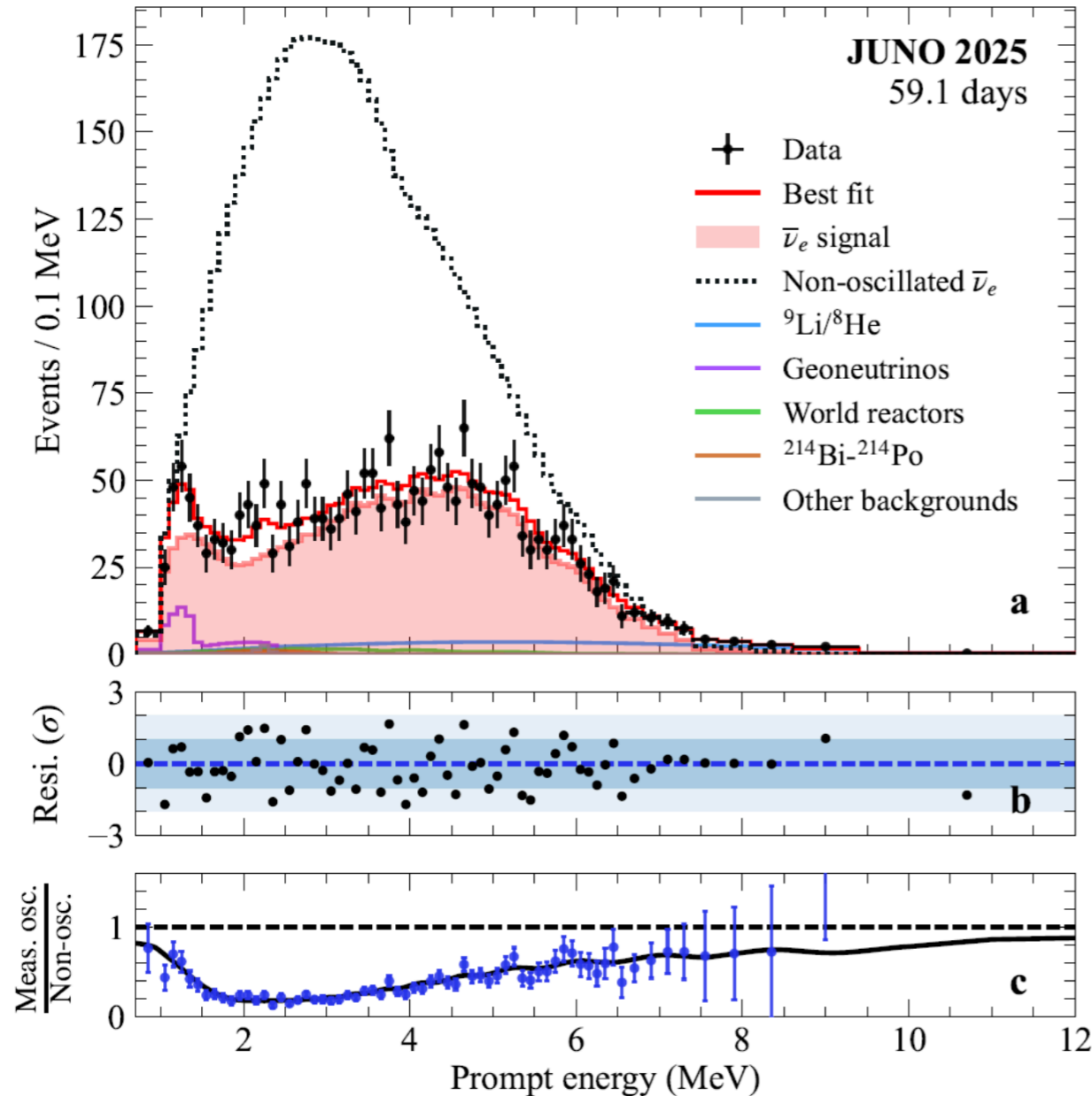
Most precise single-experiment measurement of solar mixing parameters

➤ 1.6× improvement in precision

➤ **With only 59.1 days of data**

First measurement of reactor neutrino oscillations at JUNO, [arXiv:2511.14593](https://arxiv.org/abs/2511.14593)

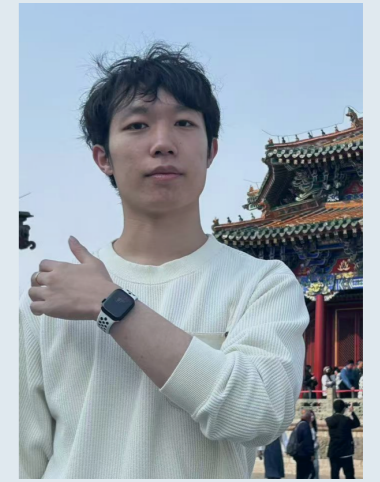
Accepted by Nature



Liverpool at JUNO



Liverpool is a relatively new member of the JUNO Collaboration - one of only two UK groups (w/ Warwick)



JUNO work at Liverpool

- ML-based **neutrino event reconstruction** and classification
- **Physics simulations** - Liverpool-led **GENIE**: <http://www.genie-mc.org>
- **Analysis frameworks** - Liverpool-led **VALOR**: <https://valor-fit.github.io>
- **Atmospheric neutrino** oscillation analysis
 - Aiming to **enhance JUNO NMO** sensitivity
- Other analysis topics under consideration
 - **Dark sector** searches

Team Leader

Prof. Costas Andreopoulos

PhD students:

- Mr **Liam Jones** [2023]
- Mr **Yaoqi Cao** (w/ Warwick) [2024]
- Mr. **Ziou He** (w/ Warwick) [2024]
- Ms **Qianying Yu** [2025]
- Mr **Zekun Yang** [2026]

Masters students:

- Mr **Will Forshow**
- Ms **Kyna Charania** (Computer Science)

Liverpool JUNO ML work

Spatiotemporal (2+1)D Convolutional Model



L. Jones

Why spatiotemporal?

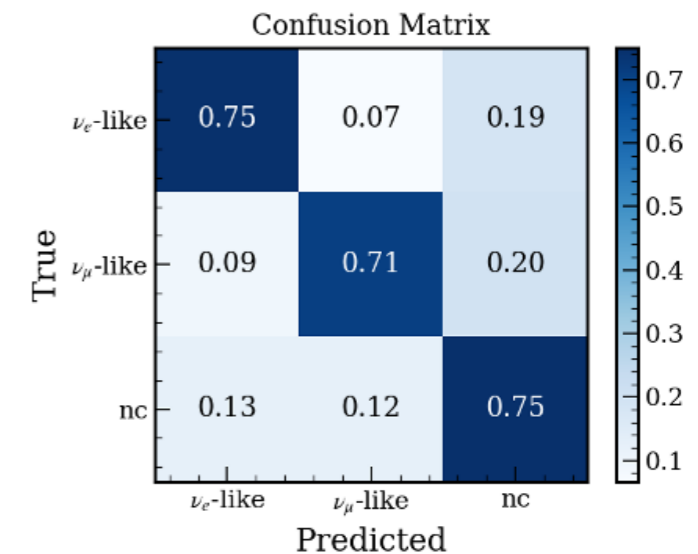
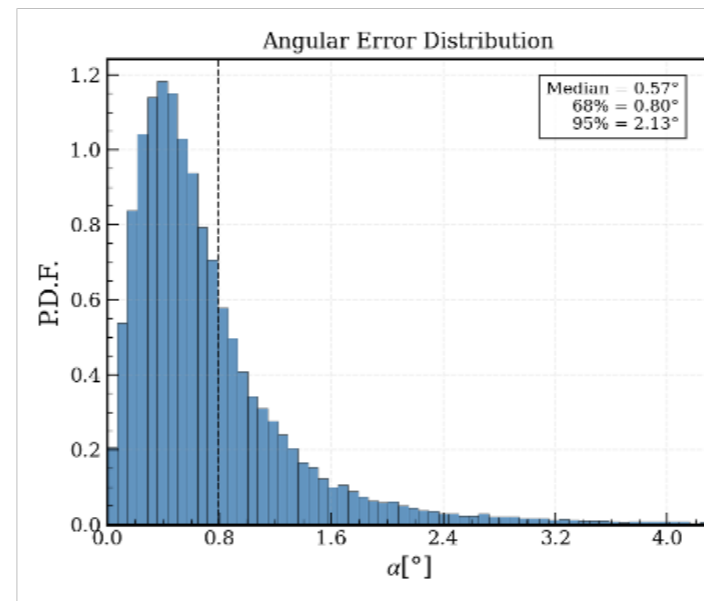
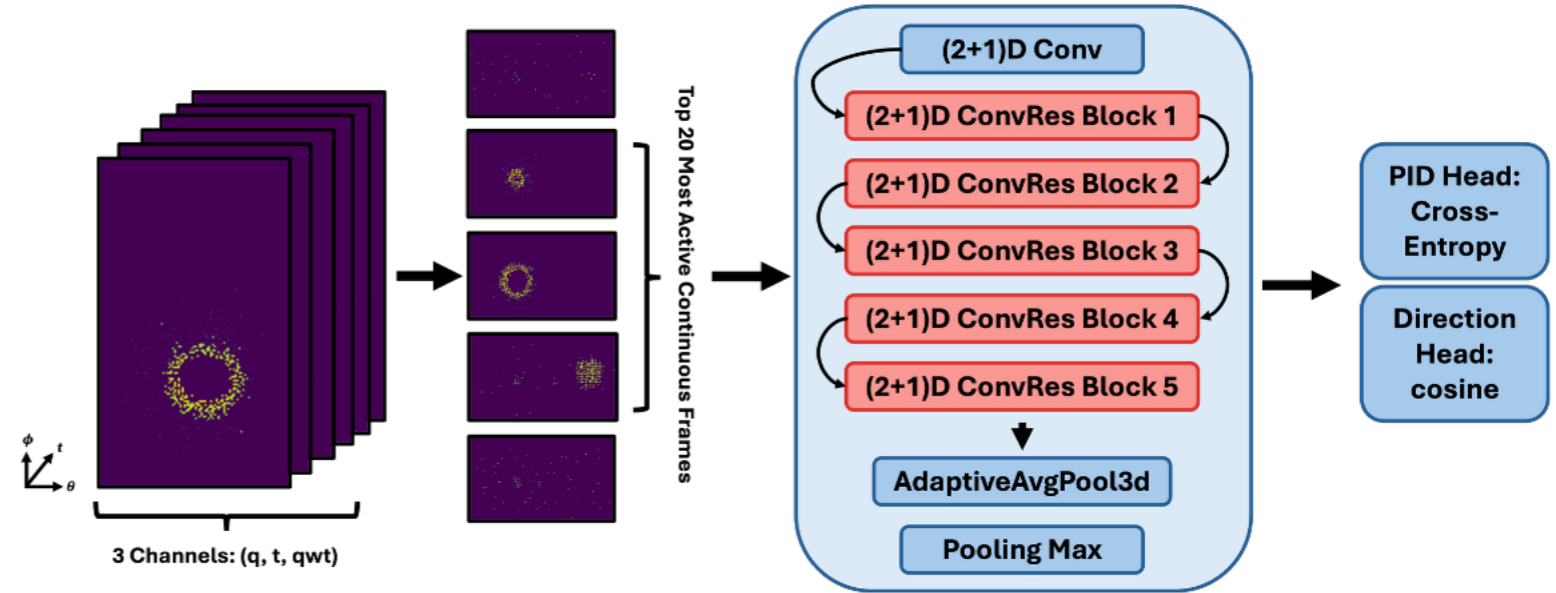
- Handcrafted features discard information
- Raw time/charge allows the model to learn patterns itself

Architecture

- A (2+1)D convolutional network that separates spatial and temporal convolutions
- Taking the top 20 most active time frames as input

Results

- Strong direction performance for muons
- Correct classification >70% for each class



Liverpool JUNO ML work

Sparse 3D convolution model

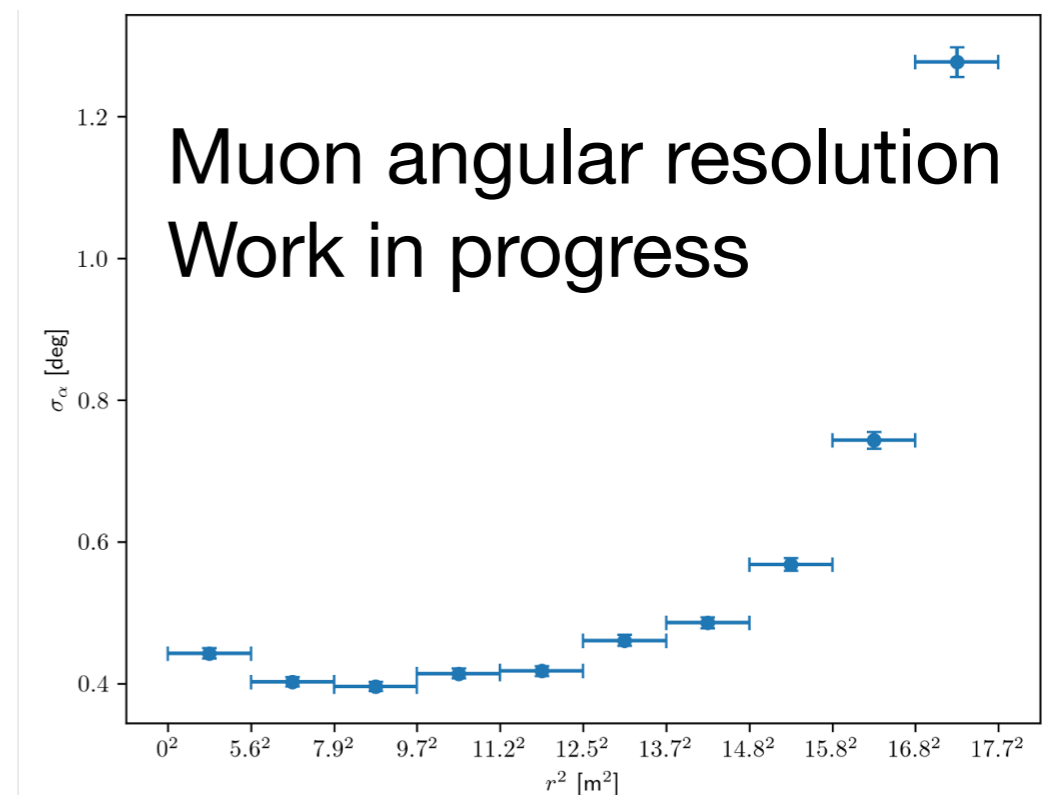
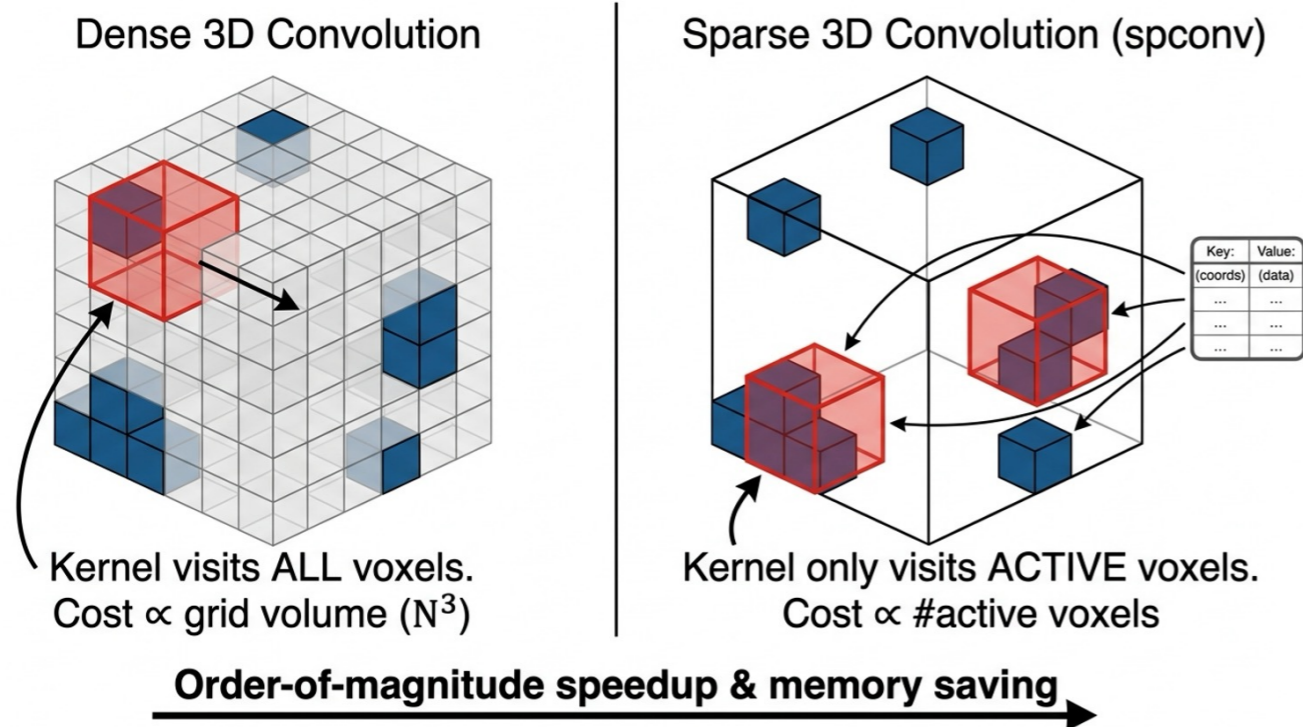
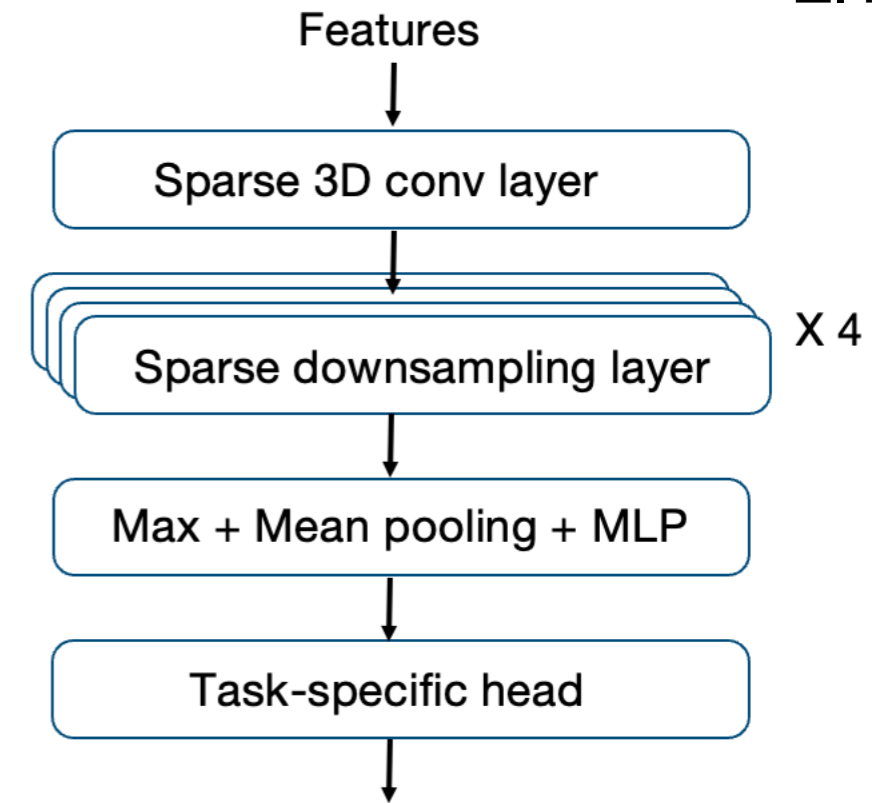
Sparse 3D convolution (spconv):

- Divided 3D space into voxels with configurable grid size. Performs convolution only on active voxels (those with values).
- Uses hash table to index coordinates of active voxels.
- Compute and memory scale with the number of active voxels, not the whole 3D grid volume.

Why spconv? – A Natural Fit for JUNO

- JUNO PMTs are distributed on a sphere: **signals form a sparse spherical point set**. The number of active voxels has ceiling – just the triggered PMTs no more others.

Z. Yang

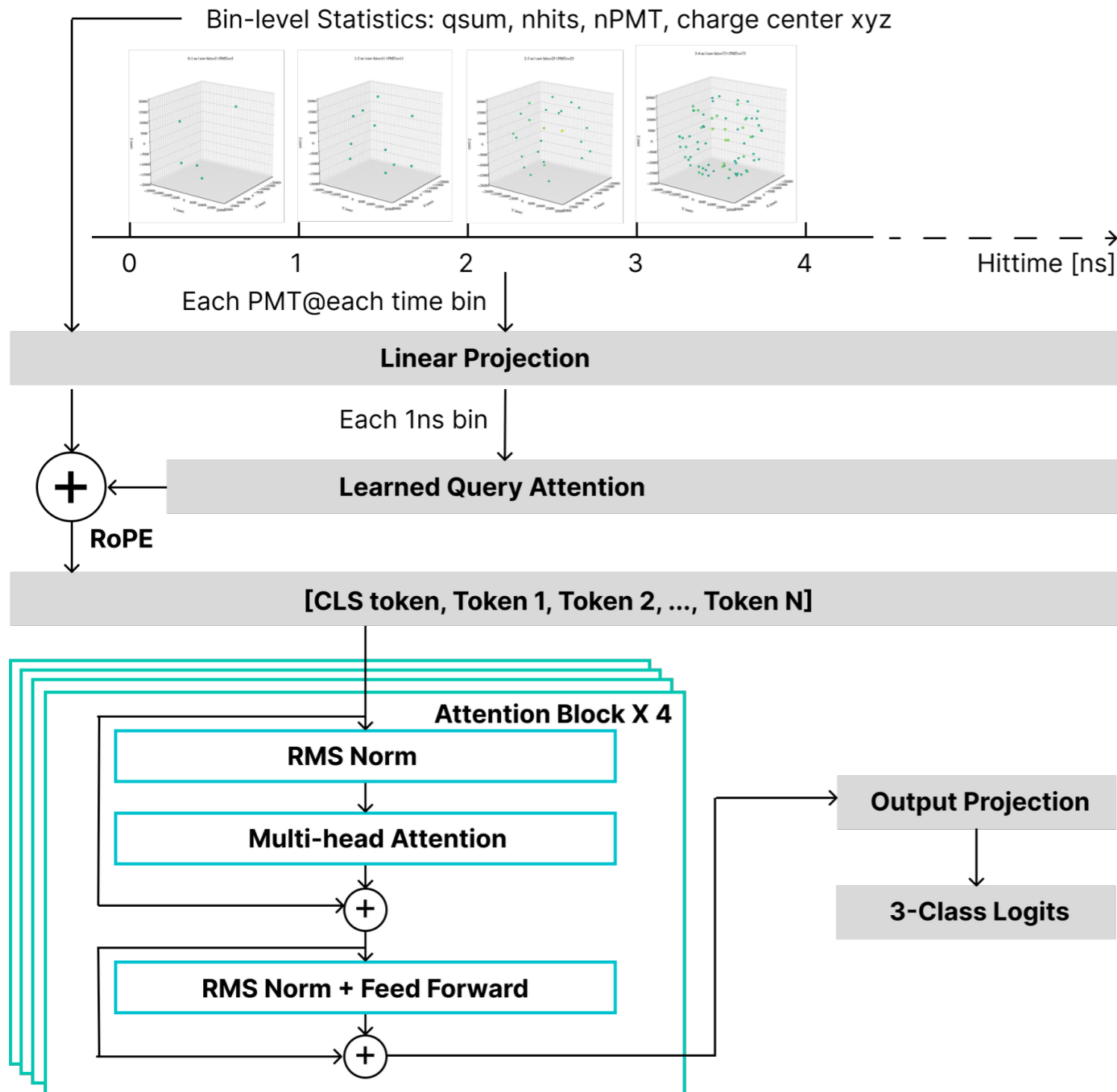


Liverpool JUNO ML work

Transformer-based model



Z. Yang



1. **Group the raw PMT hits into 1ns time bins**: attention blocks just need process $\sim 1k$ time bins, preserving the temporal structure while significantly compressing the sequence length.
2. **Bin-level features contact with tokens**, combining fine-grained hit information with physical summaries.
3. RoPE time encoding.
4. **4 attention blocks** include RMS Norm layer, Multi-head Attention layer, and FFN.

Liverpool JUNO simulation work



Qianying Yu

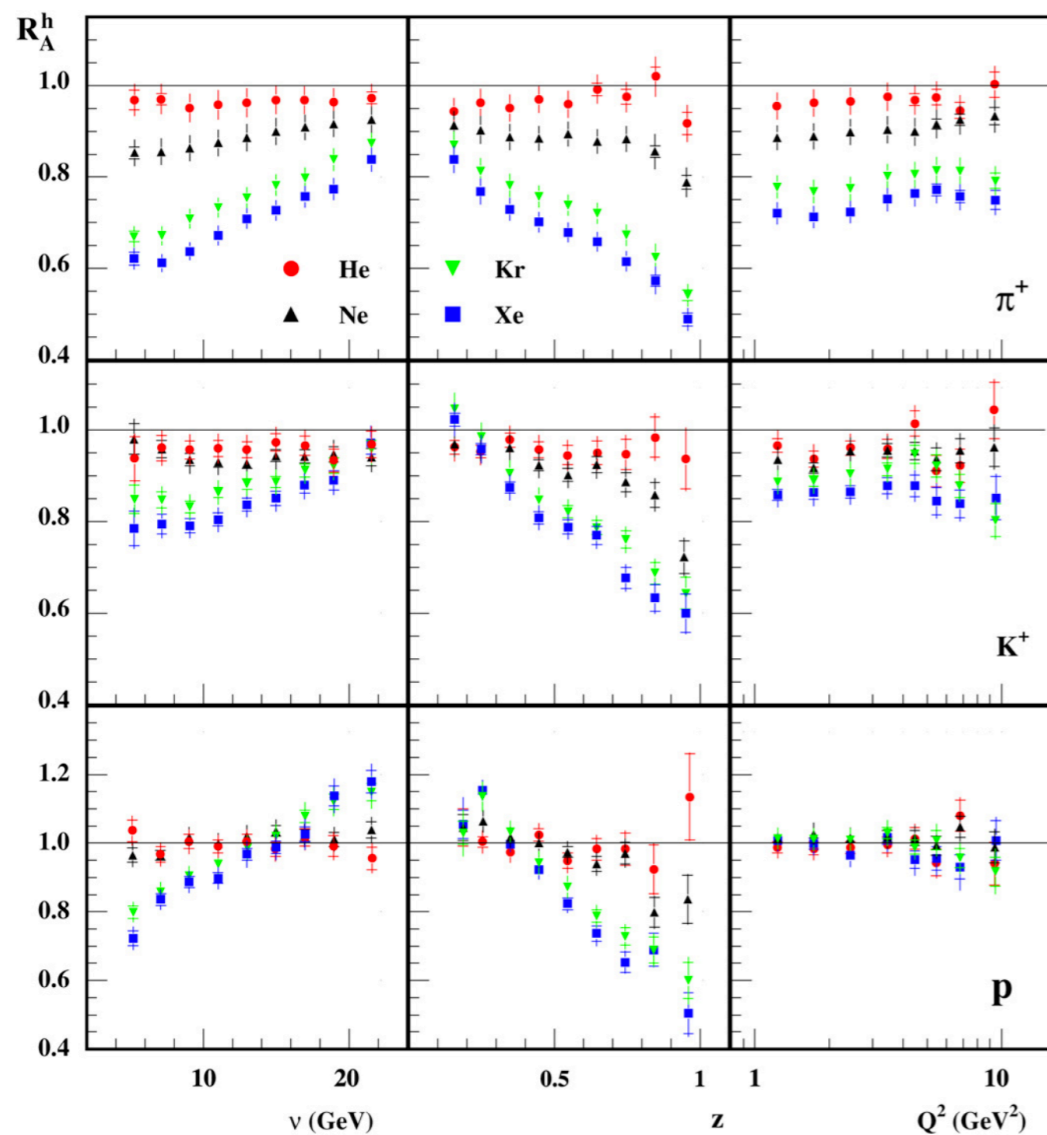
Improving higher energy GENIE simulations.

Looking at **hadron formation in lepton-nucleus interactions**

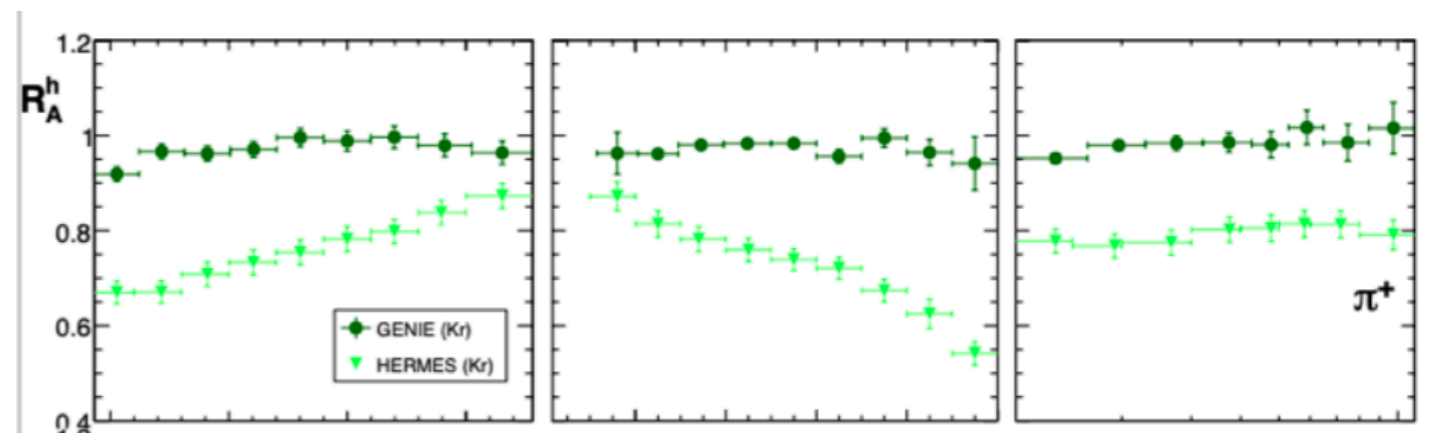
Are hadrons formed late, outside the dense target nucleus environment and therefore experience no intranuclear rescattering?

HERMES Collaboration / Nuclear Physics B 780 (2007) 1–27

11

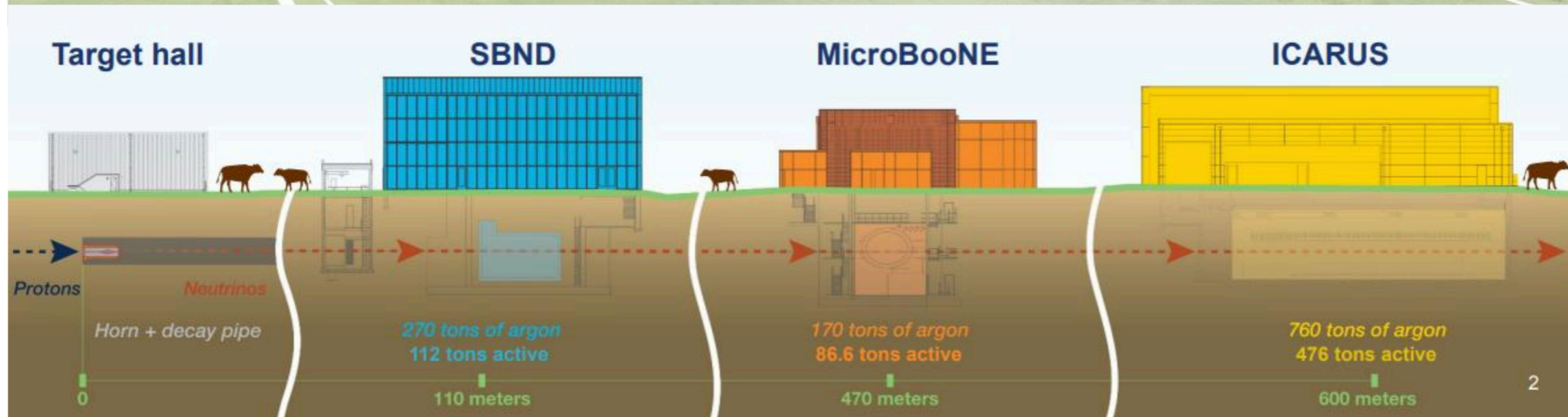
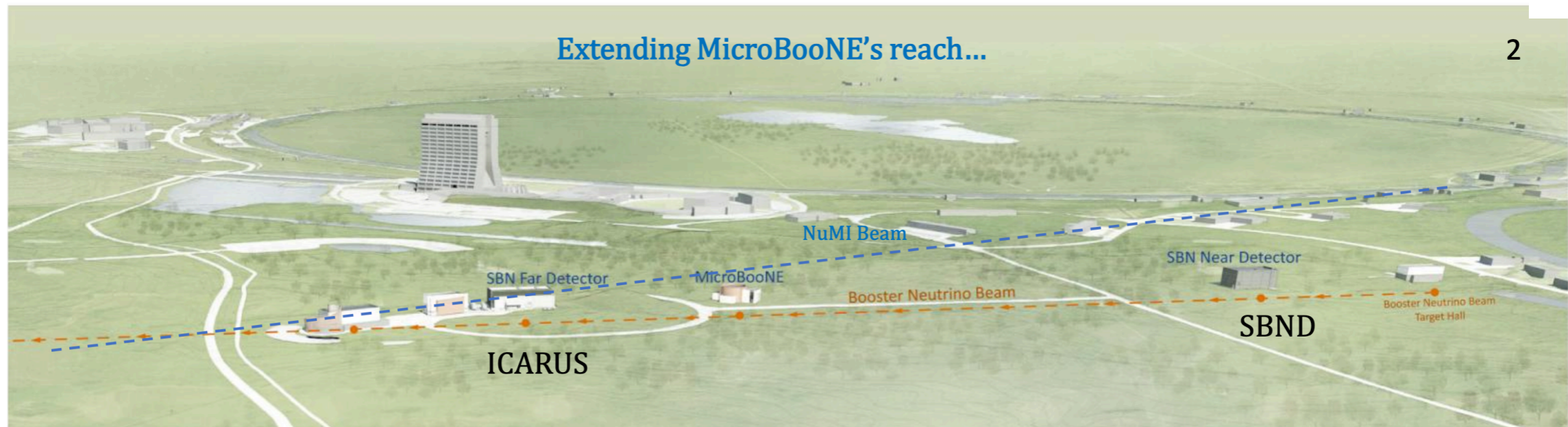


Many pieces of information from HERMES and CLAS



First comparisons with simulation, in collaboration with Ce Zhang, reveal **several issues to address**

SBND and the SBN program



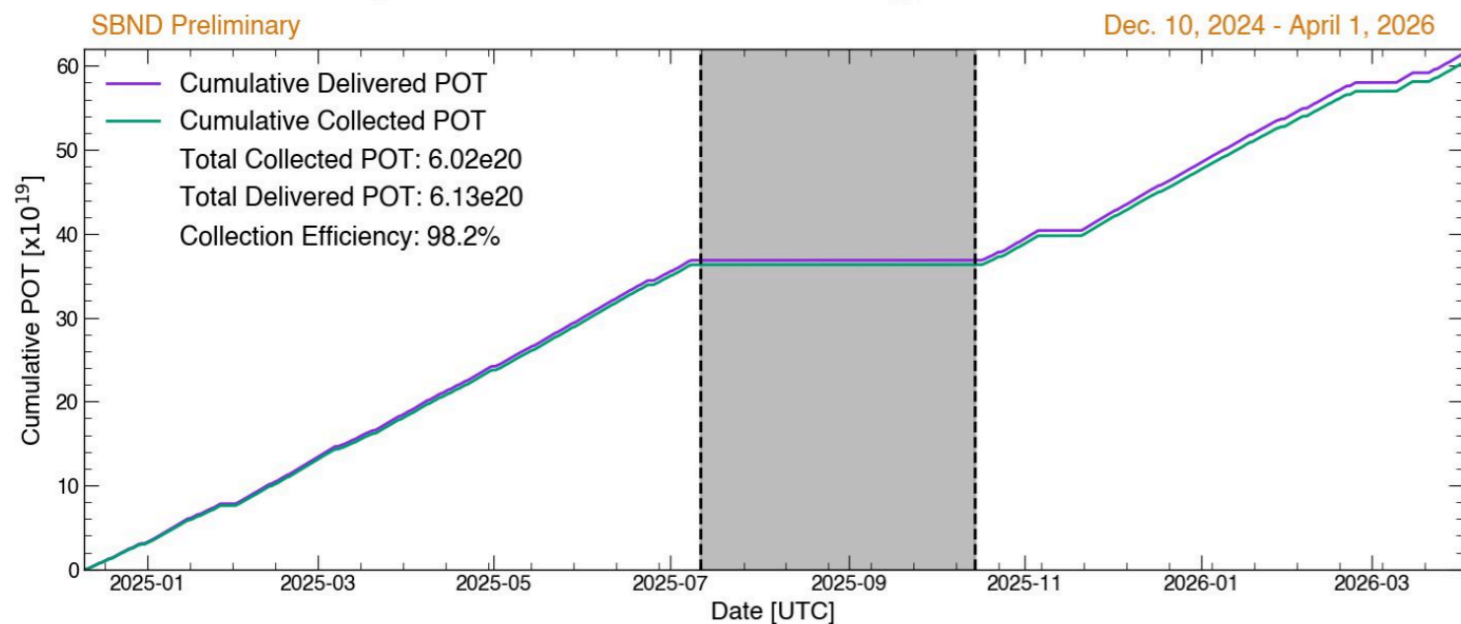
Objectives

- Accept or rule out definitively the short-baseline anomalies
- Precisely measure neutrino-argon interactions in preparation for DUNE
- Search for exotic signatures beyond the Standard Model
- Characterise the performance of LAr detectors for DUNE

SBND Status



SBND Run 1+2 Cumulative POT



FY25: Run 1
7 months
 3.7×10^{20} pot

FY26: Run 2
5 months (so far)
 2.3×10^{20} pot

Steady data-taking for 1.5 yrs

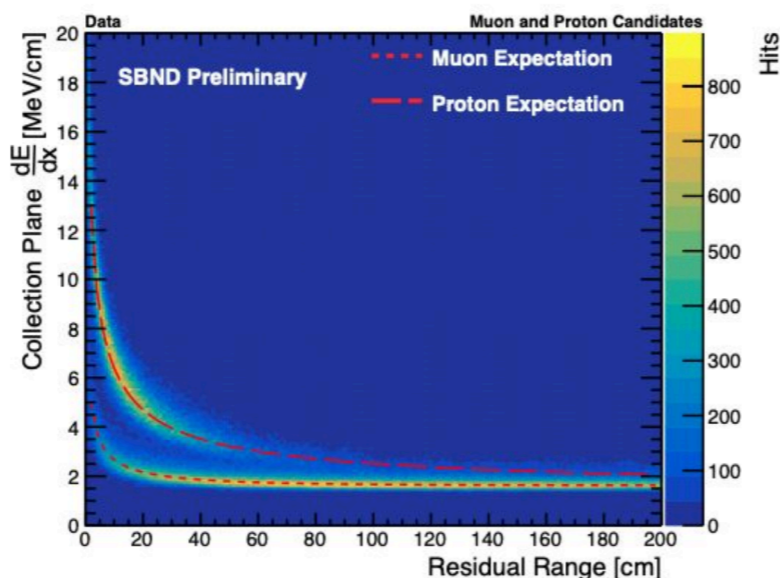
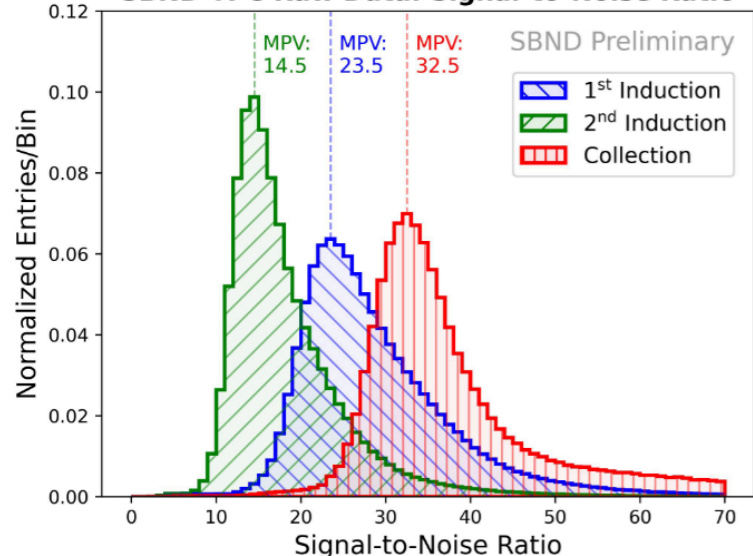
At the end of this run (**June 2026**), SBND will have collected **$\sim 7e20$ POT of data**

This corresponds to about $\sim 4M$ $\nu\mu$ CC, $\sim 30k$ νe CC, and $\sim 2M$ NC interactions in the TPC active volume

Largest neutrino-argon dataset by 10x

The program was approved for a run of $6.6e20$ POT. Planned as a 3-yr run but achieved in 2. A case is made for continuation of running.

SBND TPC Raw Data: Signal-to-Noise Ratio



Excellent detector performance

$>98\%$ data collection efficiency

Best-in-class signal-to-noise performance across the TPC.

$>99\%$ functional channels all with < 3 ADC RMS noise.

Excellent calorimetry and data/MC agreement in calibration and PID

Several physics analyses ongoing

Liverpool at SBND



Academics:

- Costas Andreopoulos (IB)
- Christos Touramanis
- Kostas Mavrokoridis

Research staff:

- **John Plows (contract ended March 2026)**
- Marco Roda
- David Payne

PhD students:

- **Beth Slater (graduated December 2025)**
- Tom Ham (graduated 2023)
- Rhiannon Jones (graduated 2021)

Historically, key contributions and roles to SBND:

Mavrokoridis: TPC Coordinator

Payne: CPA manager, CRT installation manager

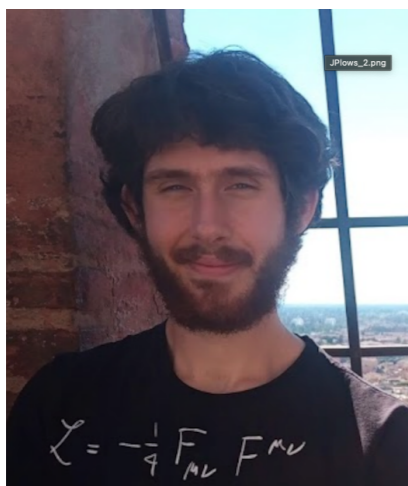
Andreopoulos: Physics Coordinator

Roda: Simulations Coordinator

At the time of leaving, **Plows held the role of SBN Analysis Infrastructure Coordinator**, coordinating the activities of several subgroups

Slater informally led the SBND-PRISM activities

Their recent departure brought the local SBND physics exploitation activities to a halt.



Plows



Slater