Spatiotemporal Machine Learning for Atmospheric Neutrino Interactions in JUNO

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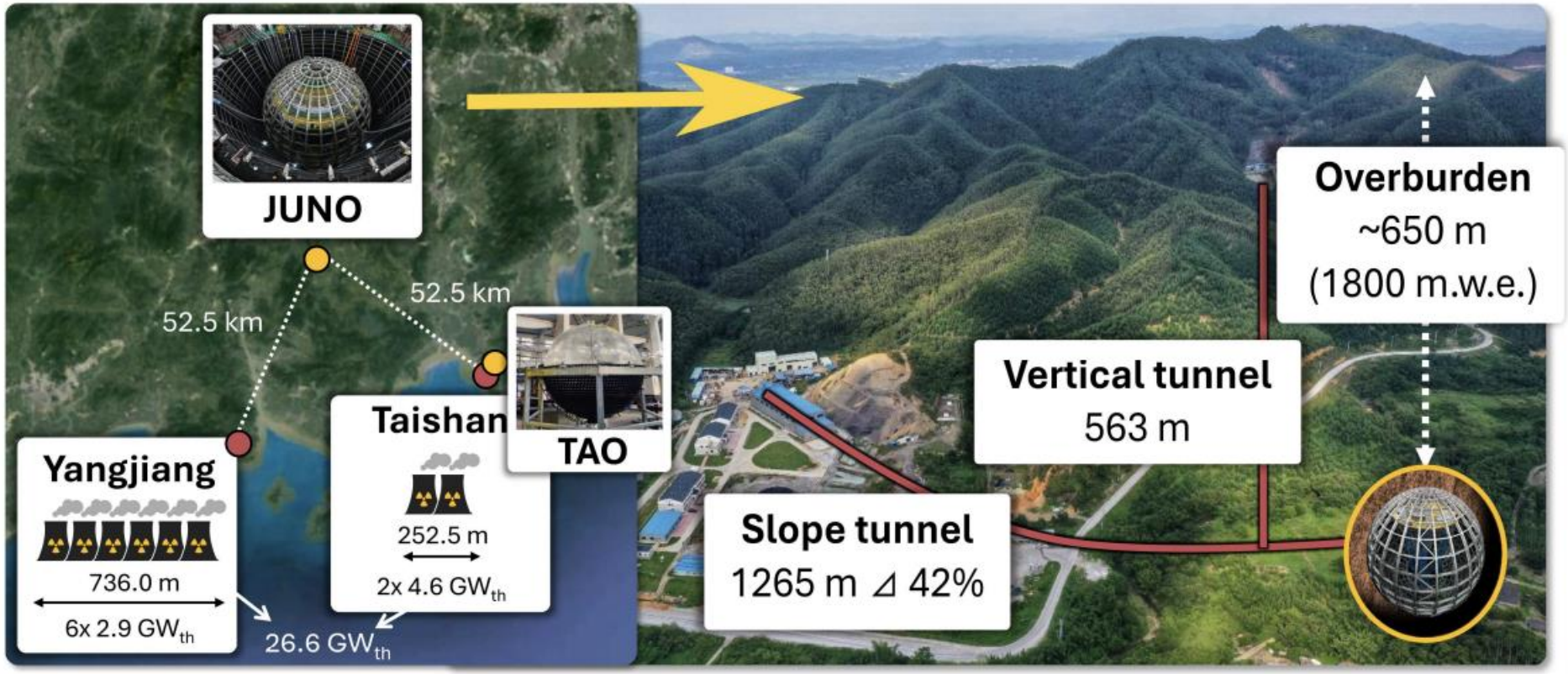
Supervisors: Prof. Costas Andreopoulos & Prof. Xianguo Lu

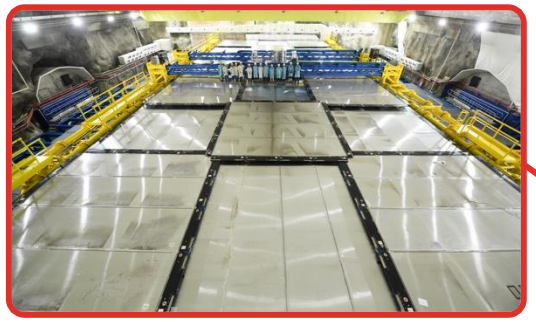
JUNO Experiment

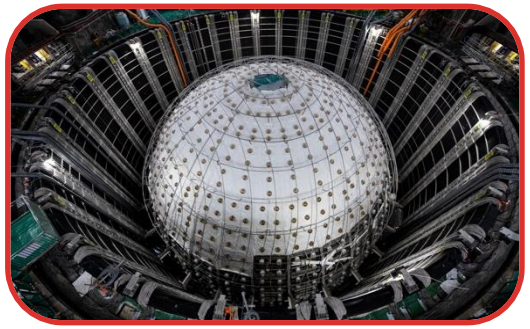
- **J**iangmen **U**nderground **N**eutrino **O**bservatory (JUNO) is a next-generation multi-purpose, 20 kton Liquid Scintillator (LS) detector



JUNO Detector

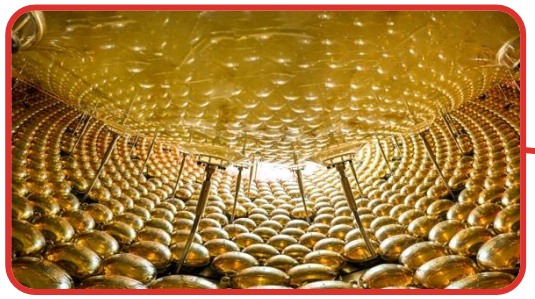
Top Tracker
3 plastic scintillation layers
~650m rock overburden



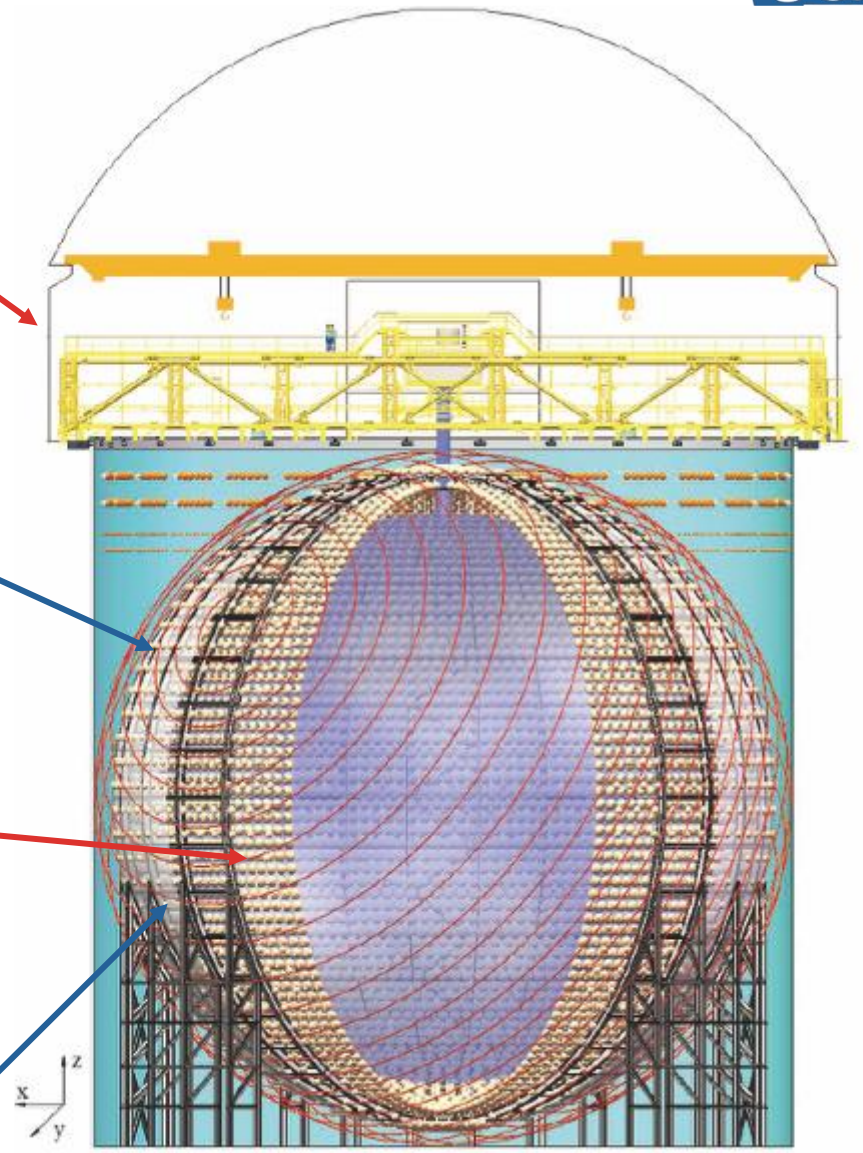


Outer Cherenkov Detector
35 kton of ultrapure water
>2500 20-inch PMTs

PMTs
17,596 20-inch + **25,600** 3-inch



Acrylic Vessel
17.7m radius
20 kton of liquid scintillator
LAB + PPO + bis-MSB + BHT



JUNO Detector

Top Tracker

lastic scintillation ers

rock overb

17,596 20-inc

Excellent Energy Resolution

78% Photocoverage

~3% per MeV

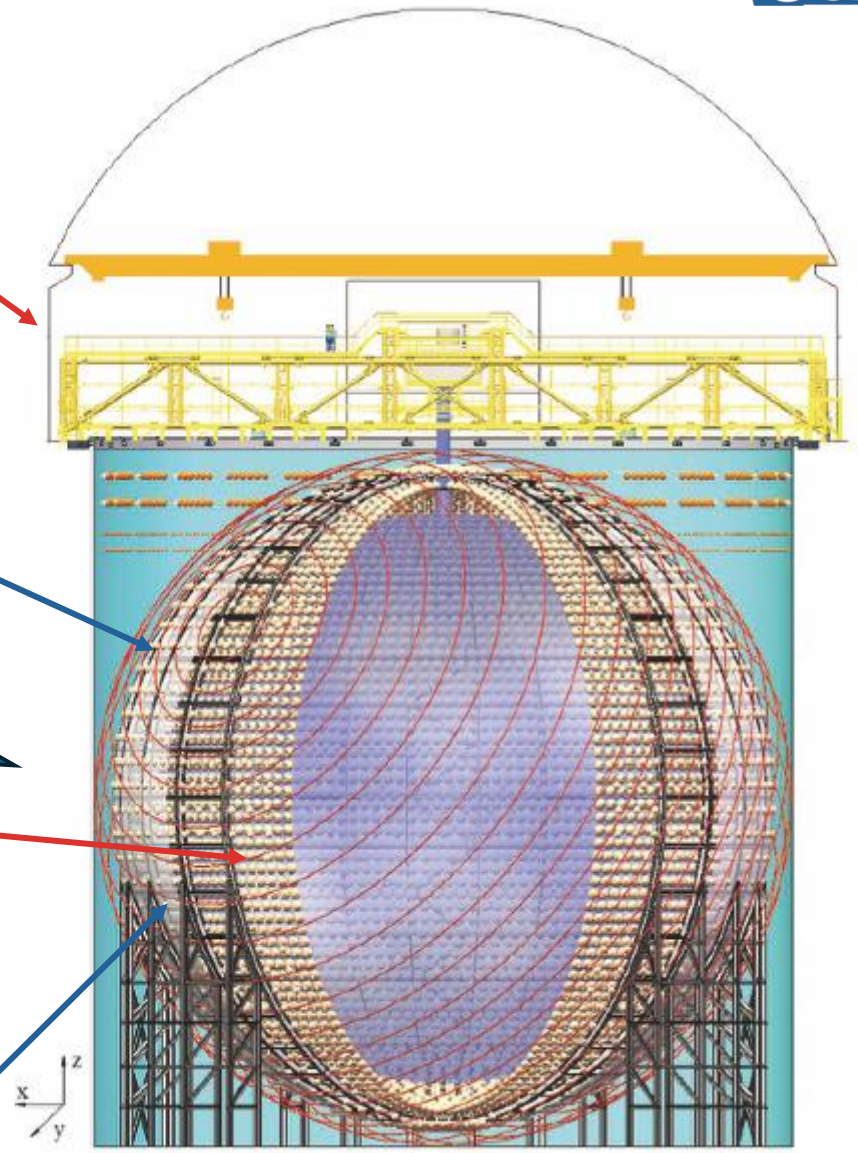
~1300 p.e. per MeV

Acrylic Vessel

17.7m radius

20 kton of liquid scintillator

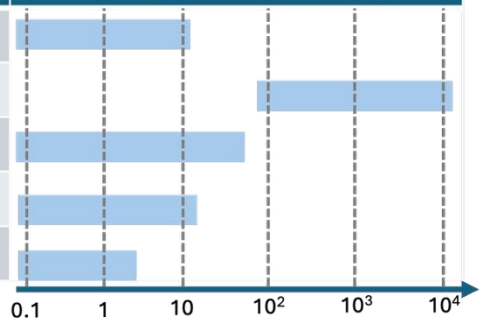
LAB + PPO + bis-MSB + BHT

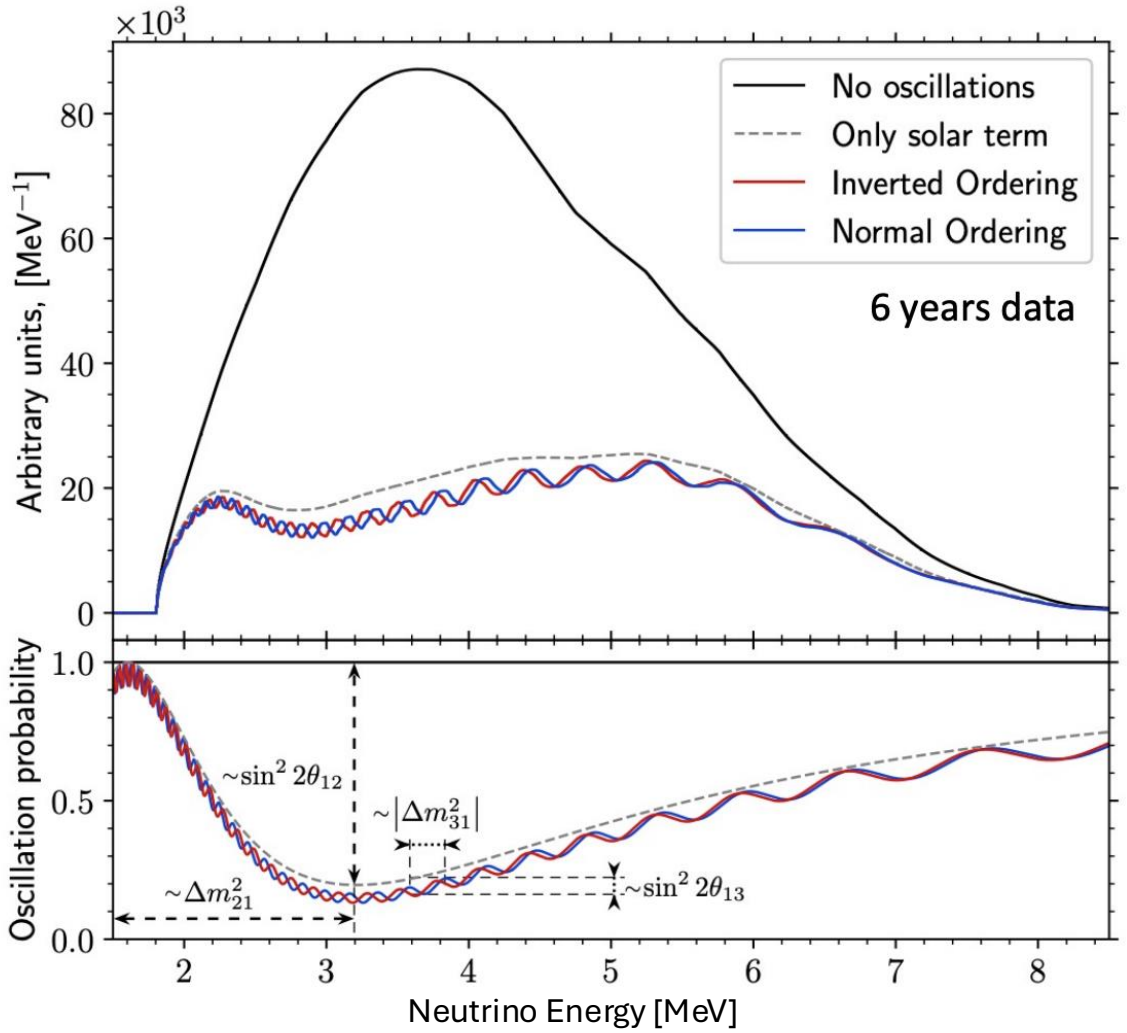


Physics Programme

- NMO with **3σ** significance in **6 years**
- Precision of oscillation parameters
  - **<0.5%** for $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} in **6 years**

Neutrino Source	Event Rate
Reactor	60 / Day
Atmosphere	100s / Year
Supernova Burst	5000 at 10 kpc
Sun	2-4 / Year
Earth Crust/Mattle	400 / Year





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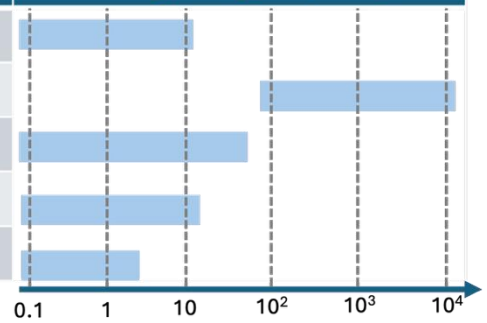
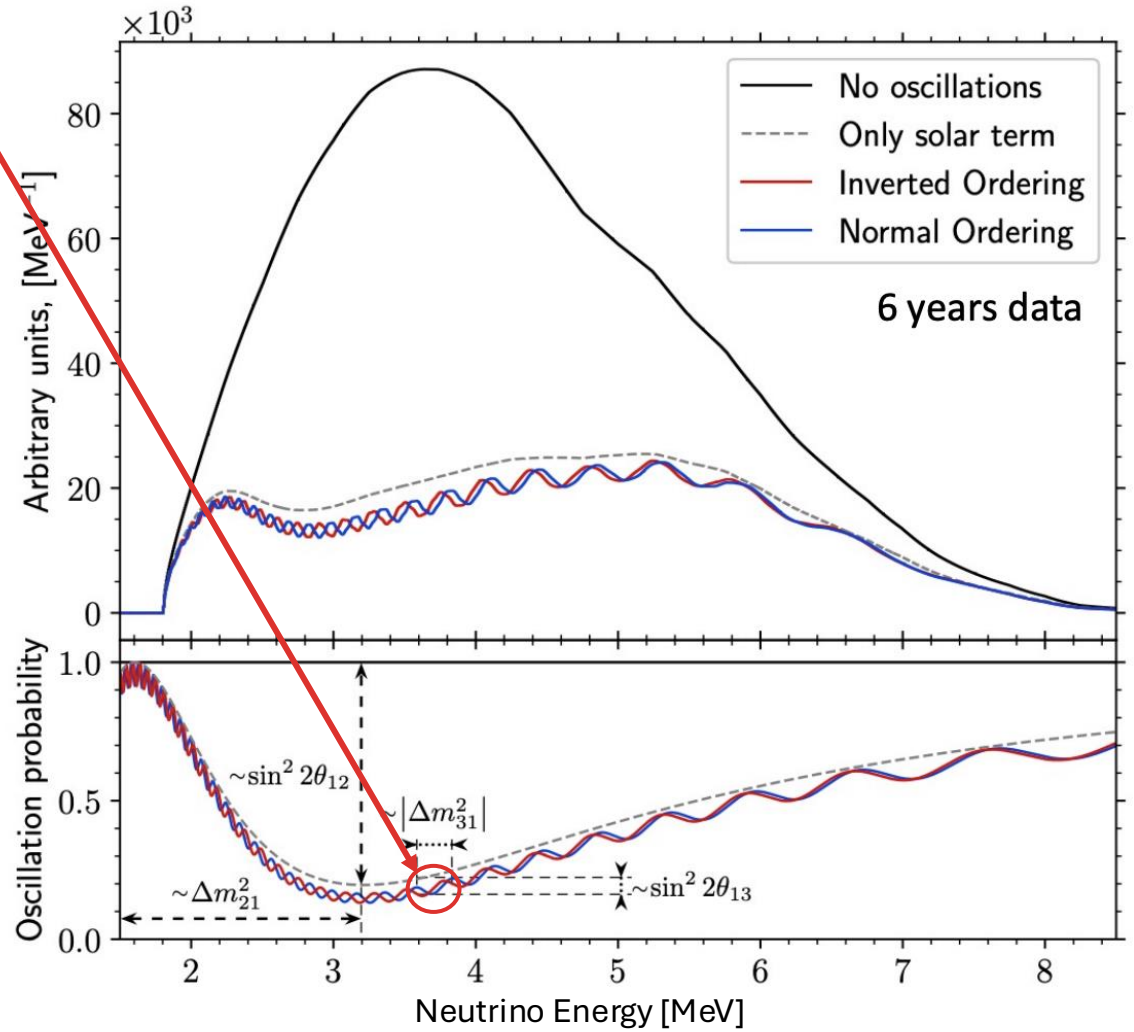
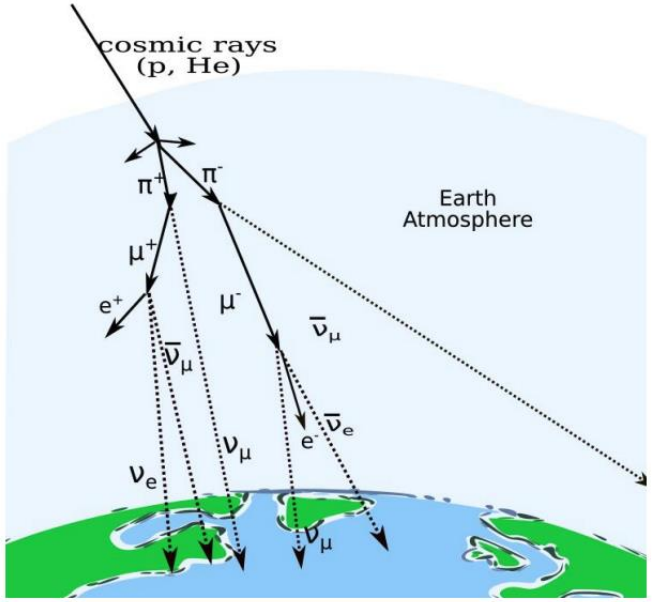
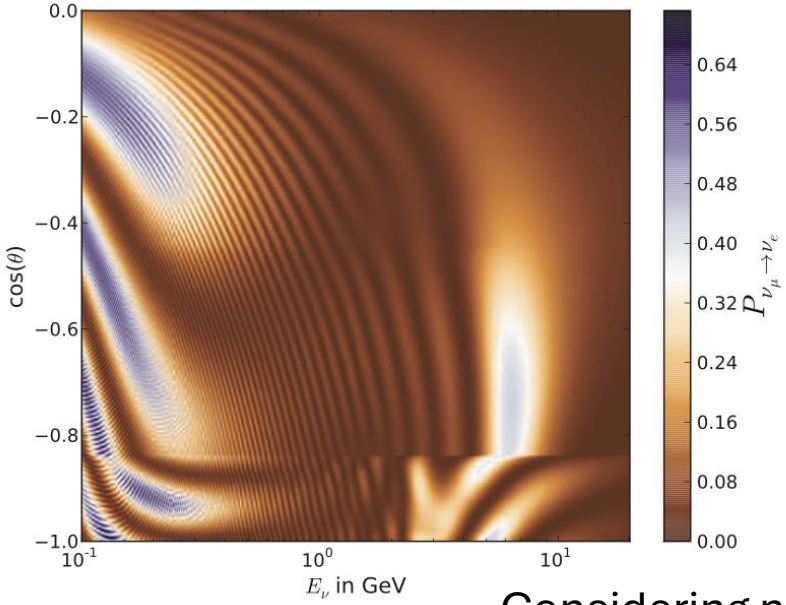


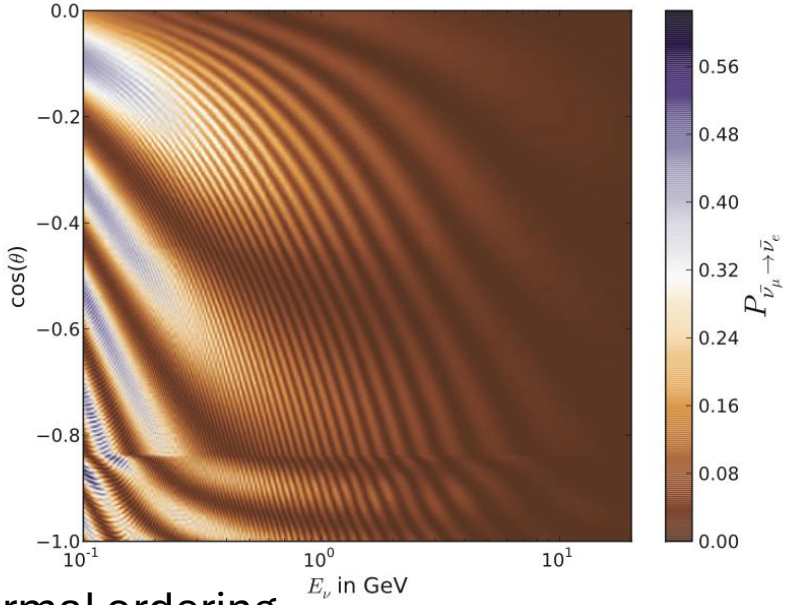


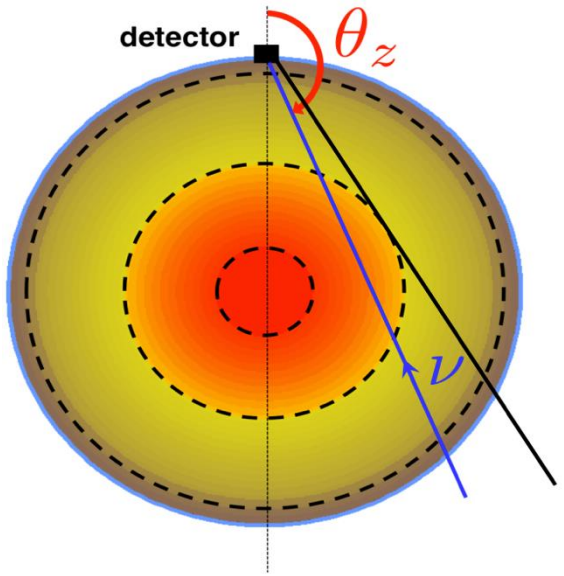
Atmospheric Neutrinos

- Atmospheric neutrinos give insight to NMO through matter effects
- Offers a complementary channel to boost sensitivity
- Oscillation probability, $P = f\left(\frac{L}{E}\right), L \sim \cos\theta$ → Neutrino **flavour, direction** and **energy** are crucial









Considering normal ordering

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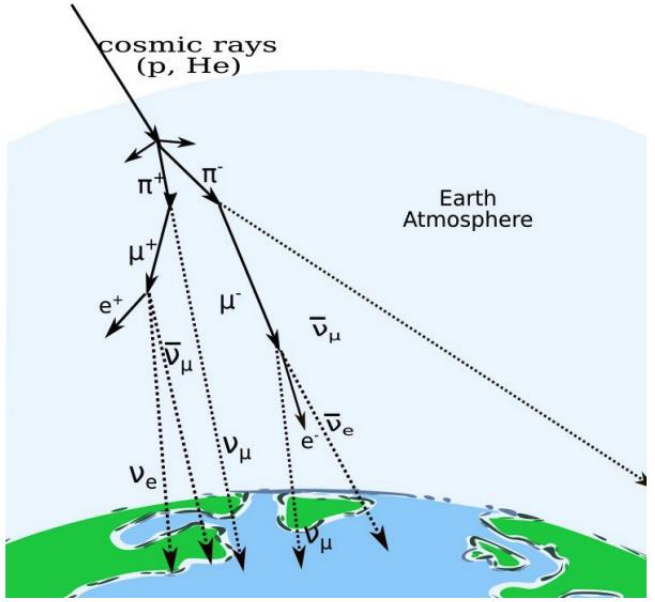
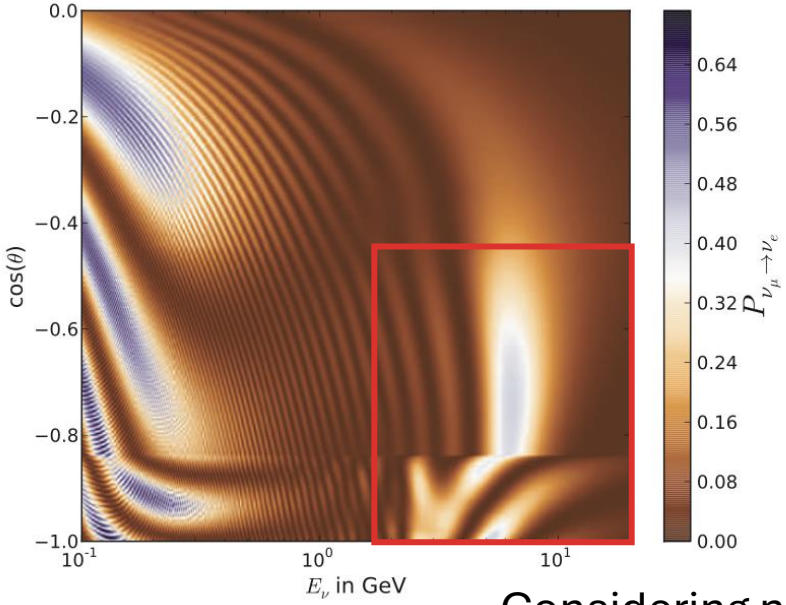
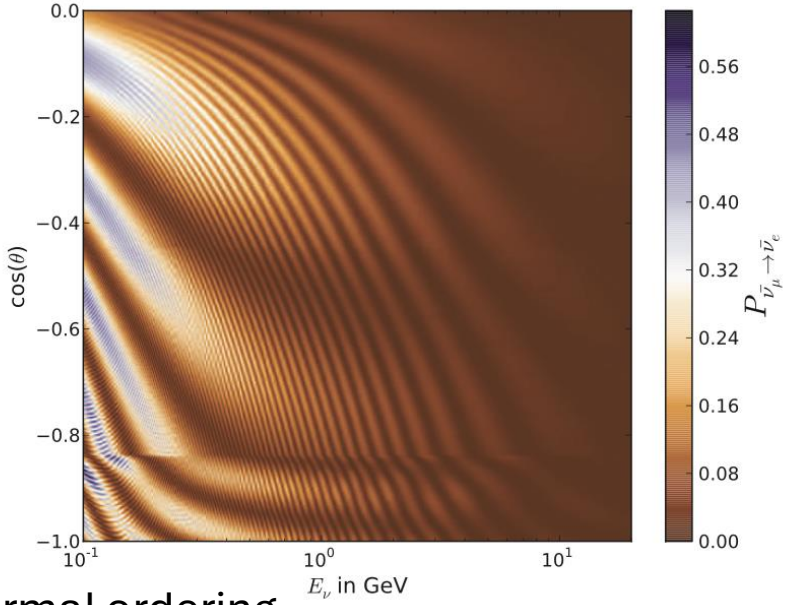
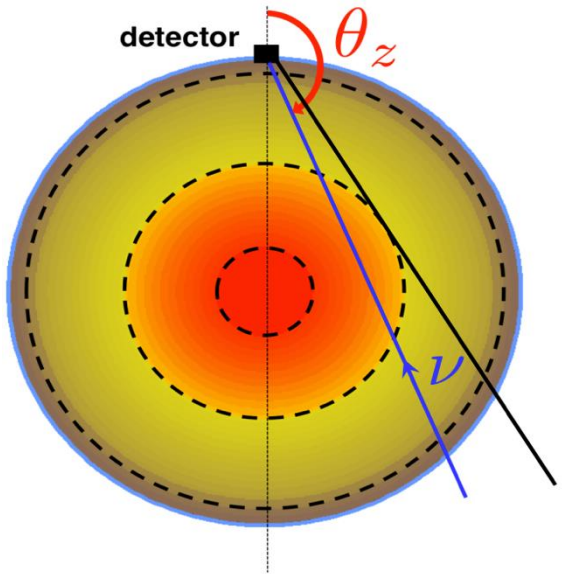






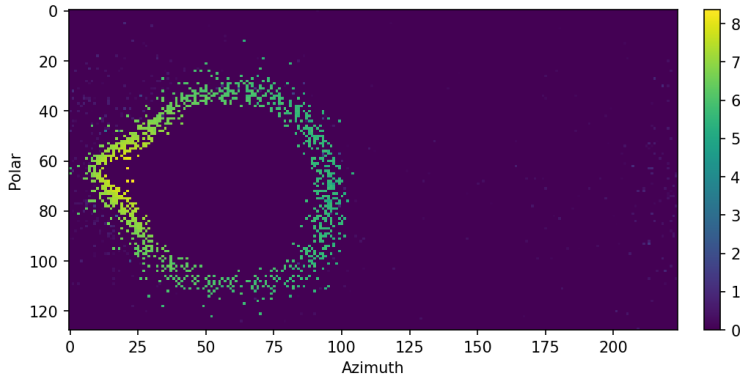


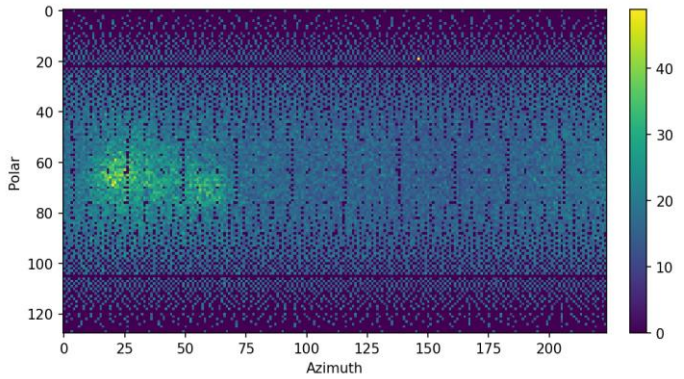
Considering normal ordering

Why Use a Spatiotemporal Method?

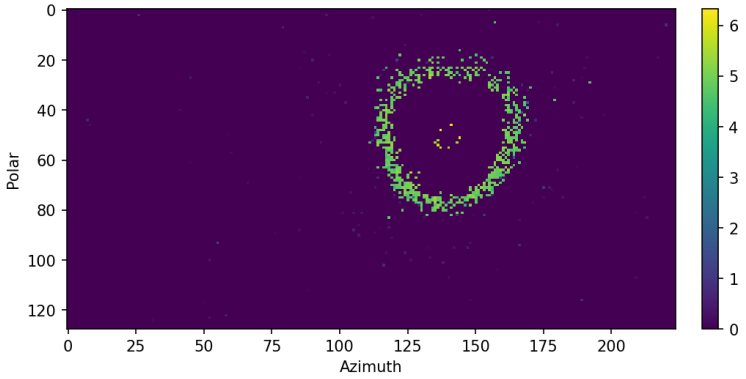
- Handcrafted features throw away information
- Using raw **time/charge** pairs allows the model to decide for itself
- Can capture the highly complex patterns in superpositions of light

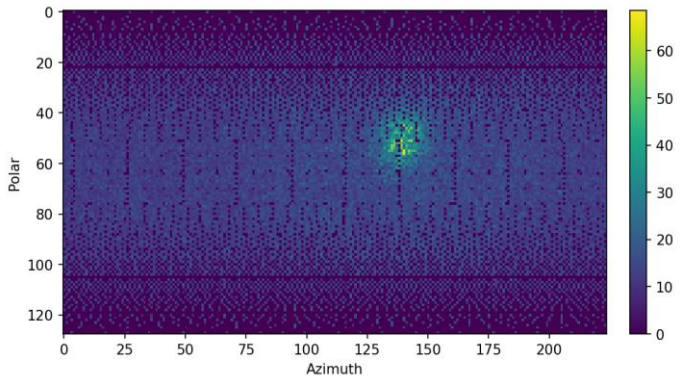
$\nu_\mu - like$



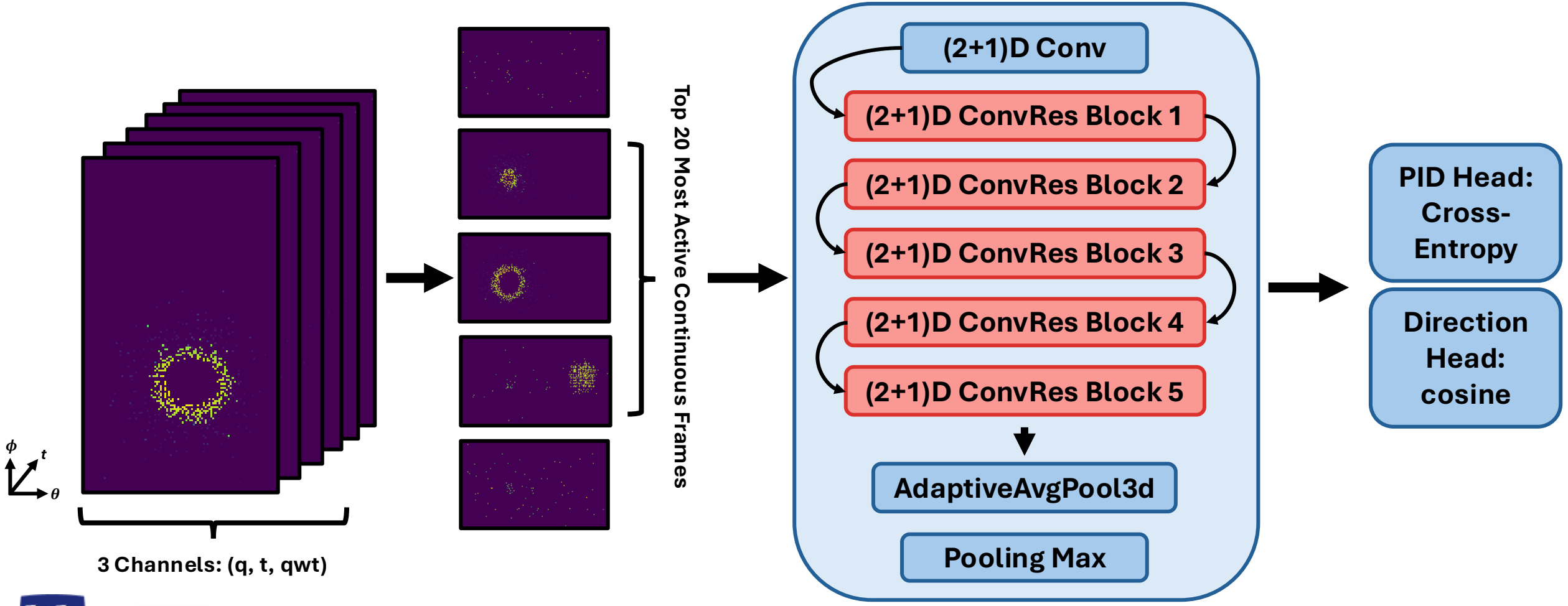


$\nu_e - like$

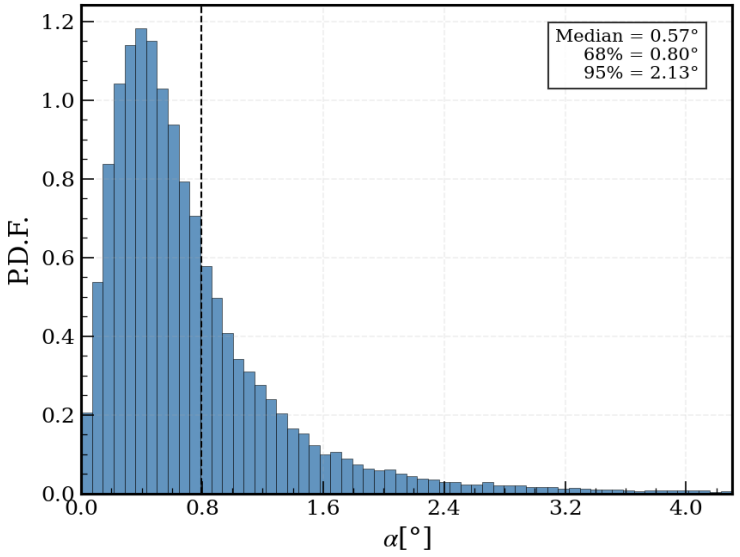


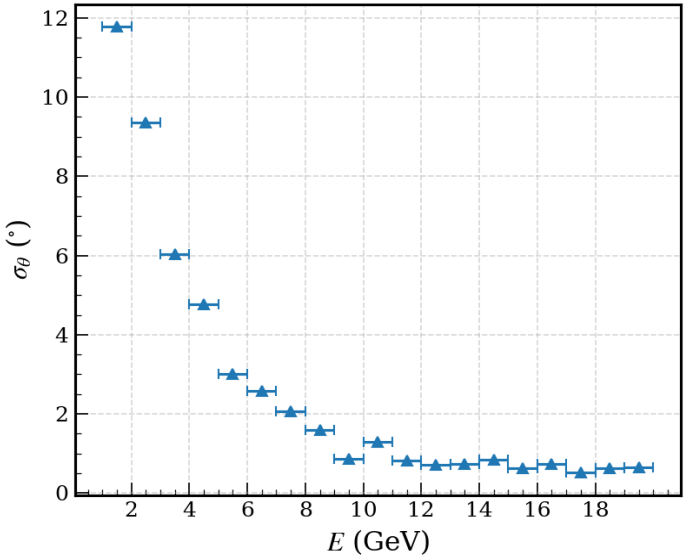


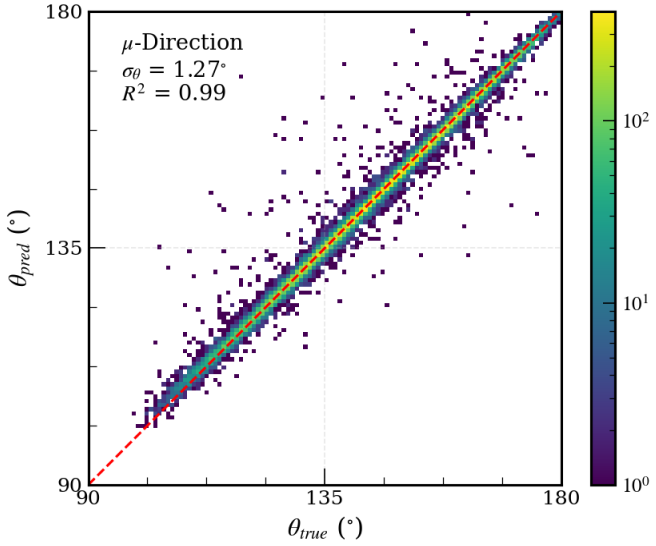
(2+1)D Convolution for Reconstruction

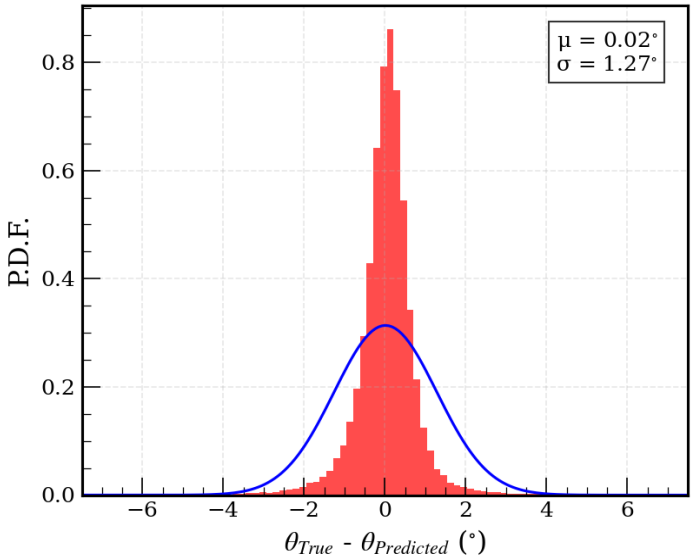


Muon Direction

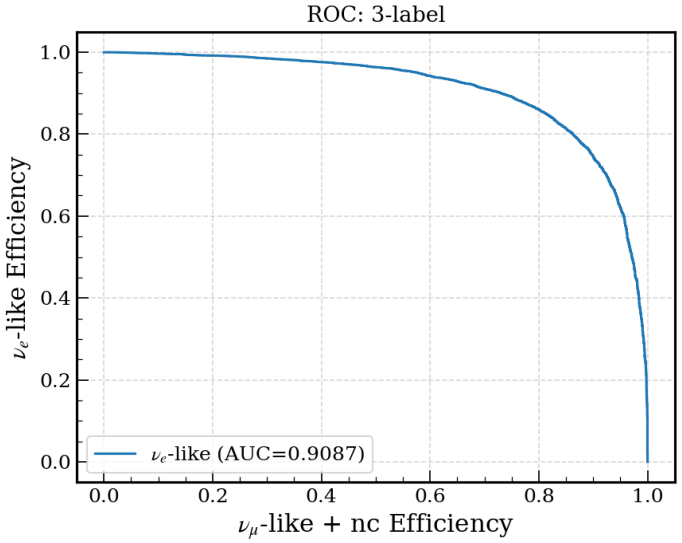


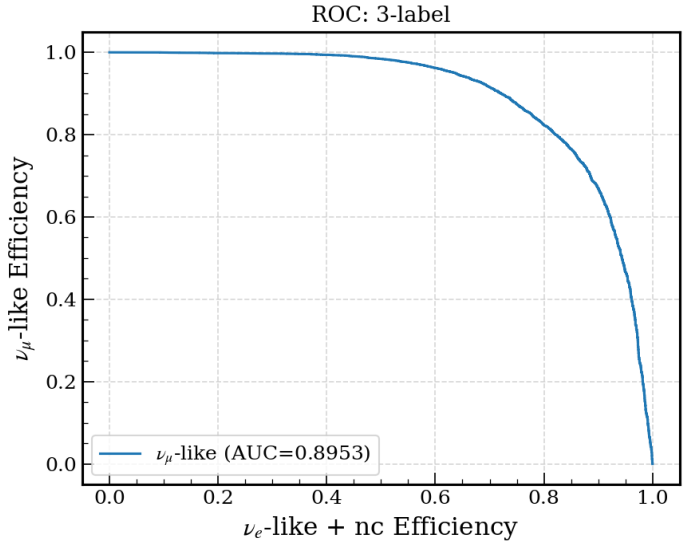


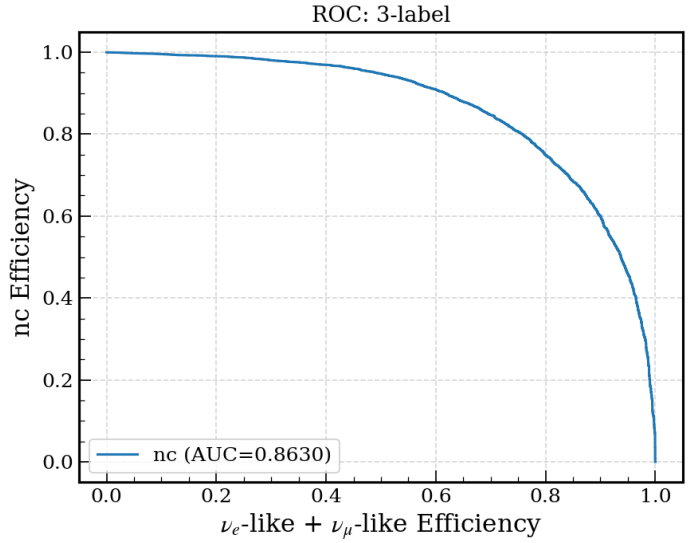


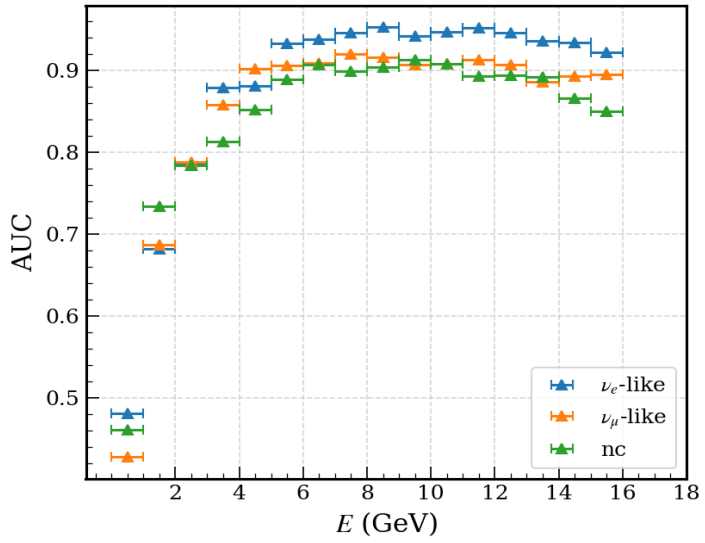


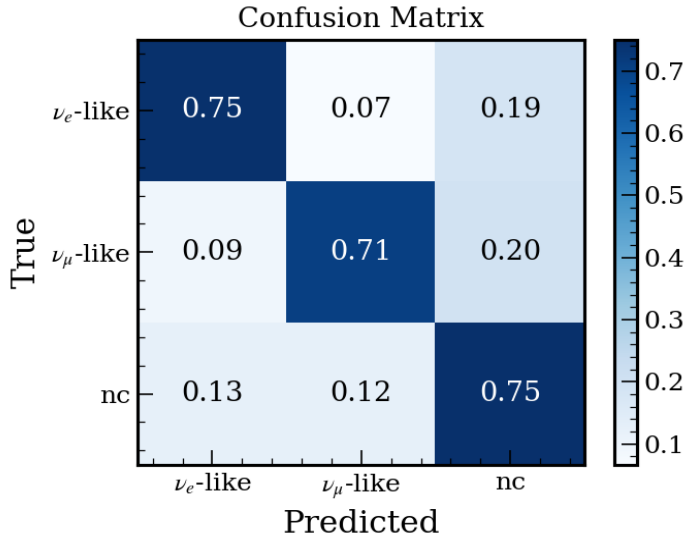
Atmospheric Flavour Classification







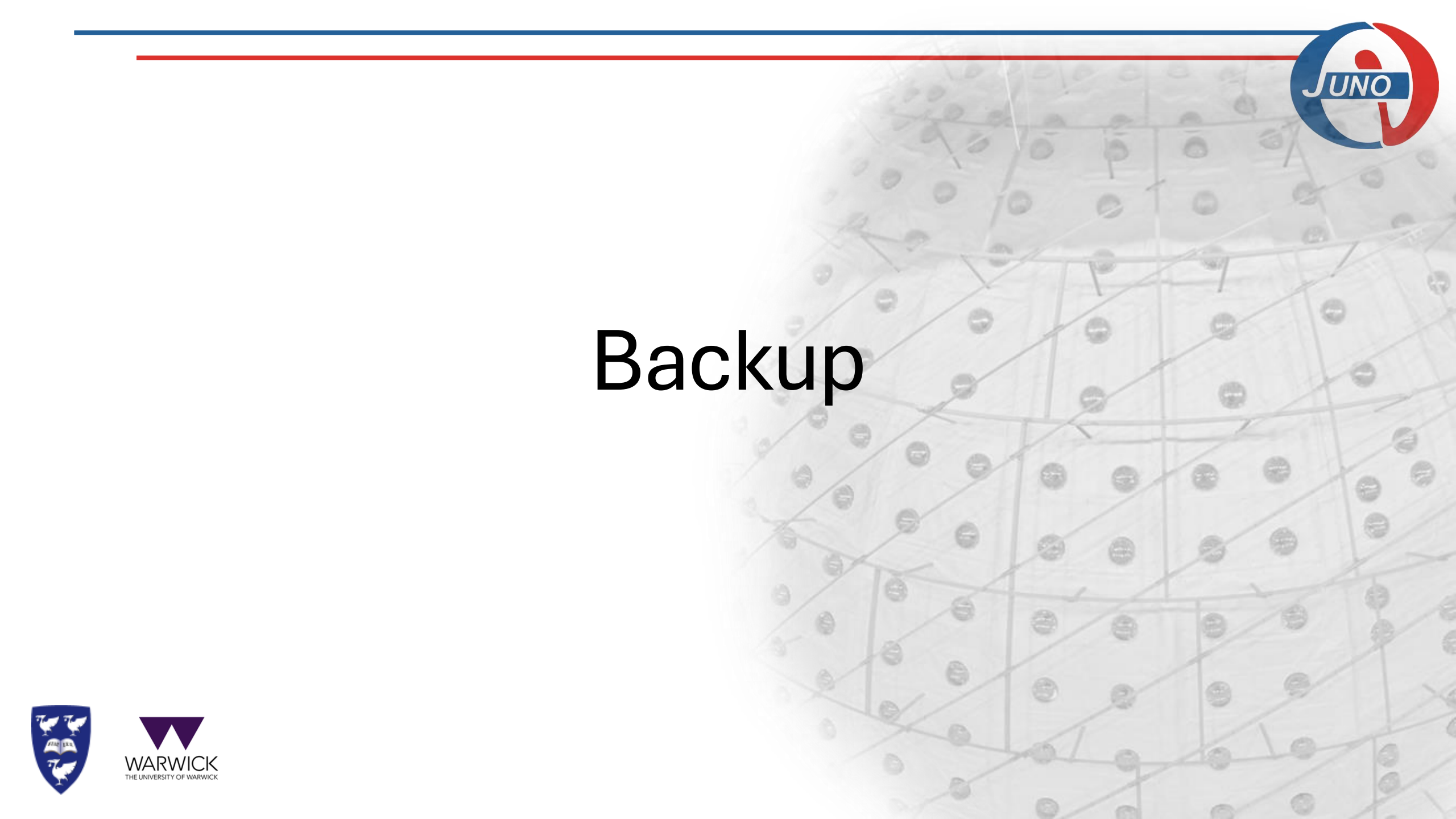




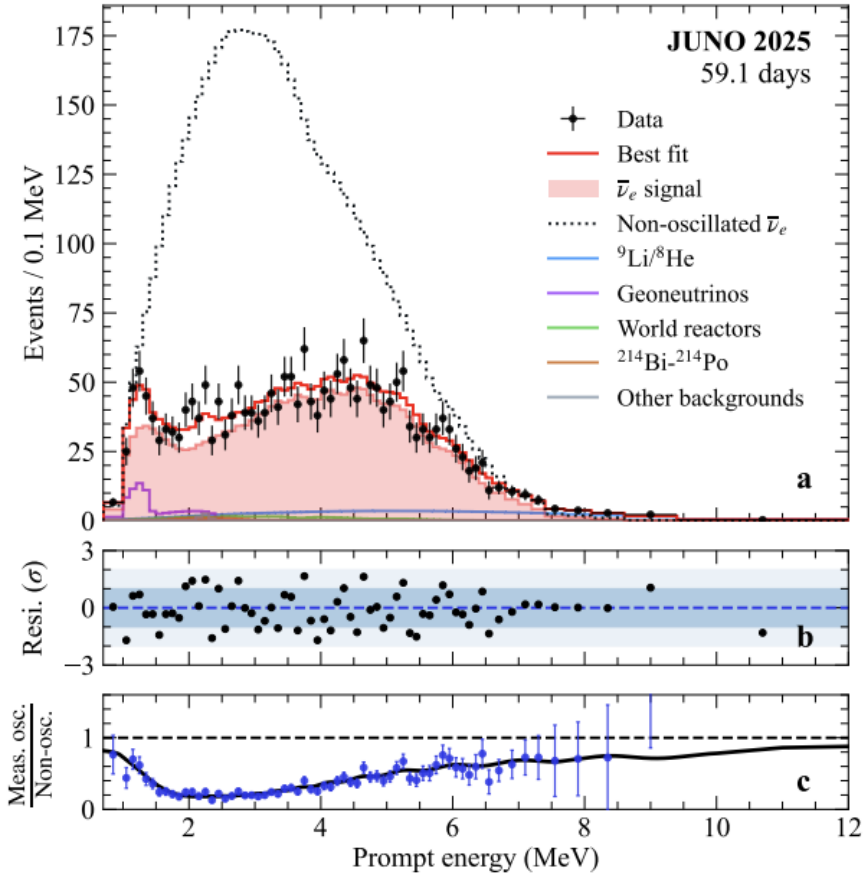
Conclusion

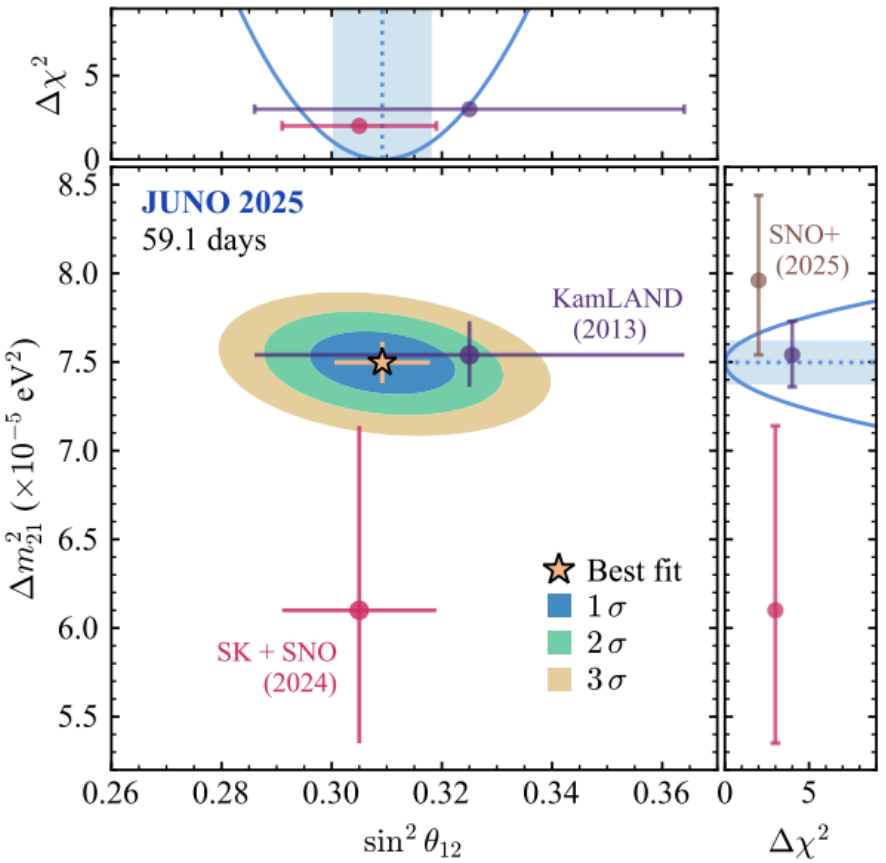
- Summary
  - The first attempt at spatiotemporal learning shows promise
  - For both case low energy events make results worse
  - NC events underperform
- Next Steps
  - Move to atmospheric neutrino direction reconstruction
  - Test auxiliary losses to improve performance
  - Look to real events
  - Extend to 4D spatiotemporal learning

Backup



JUNO First Results



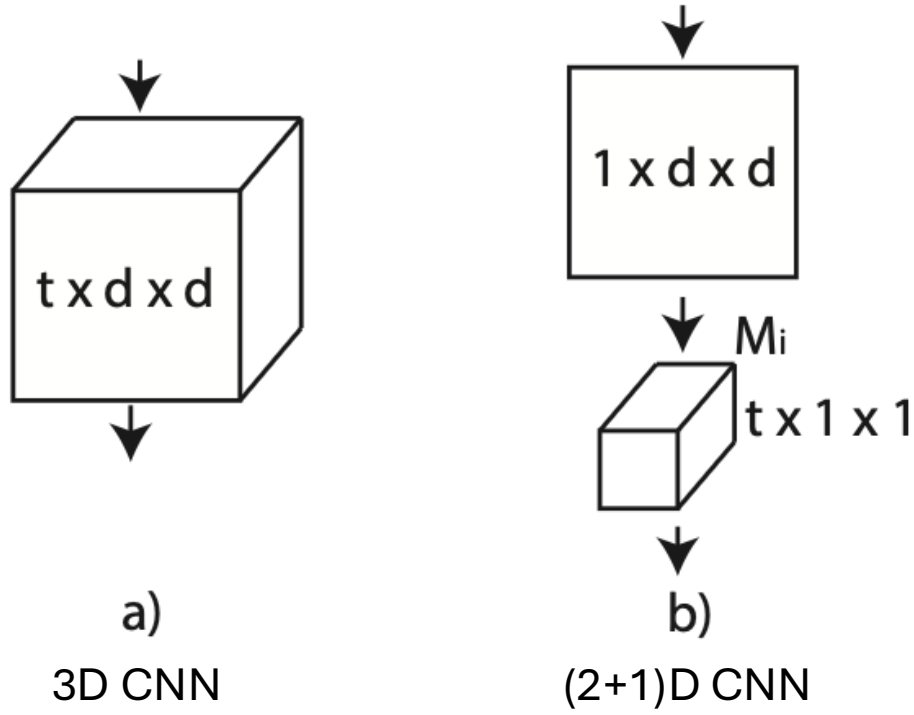


$$\sin^2\theta_{12} = 0.3092 \pm 0.0087$$
$$\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5} eV^2$$

SpatioTemporalConv

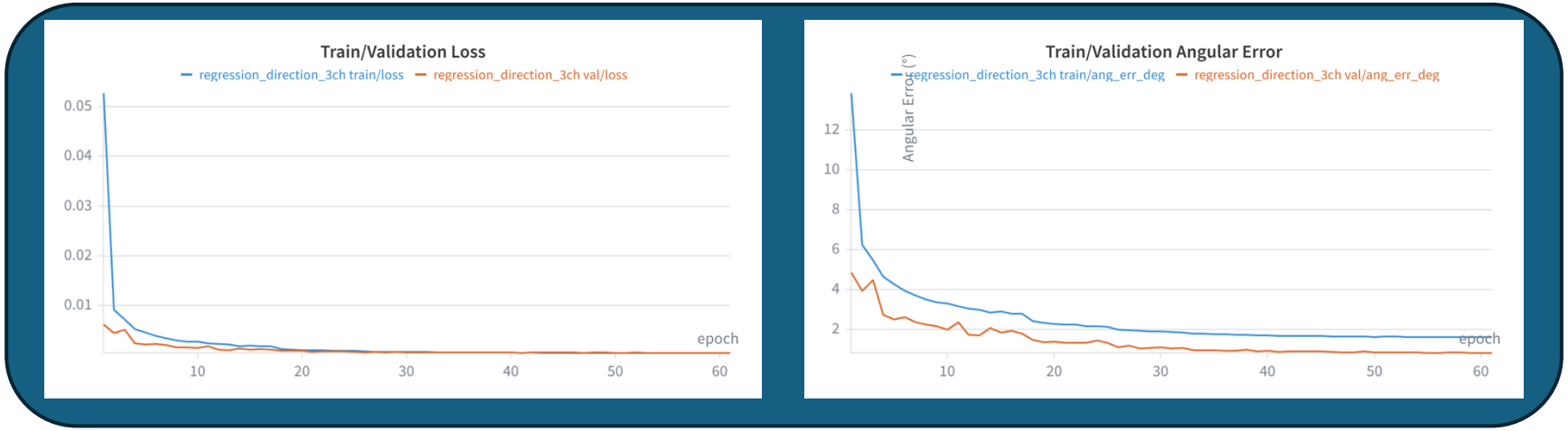
- Instead of a full 3DConv (kernel [kT, kH, kW]) we split the time and space components:
  - **SpatioConv:** Looks at 2D space bins (kernel [1, kH, kW])
  - **TemporalConv:** Looks at 1D space bins (kernel [kT, 1, 1])
- Intermediate channel count (M_i) is chosen to match param count of 3DConv:

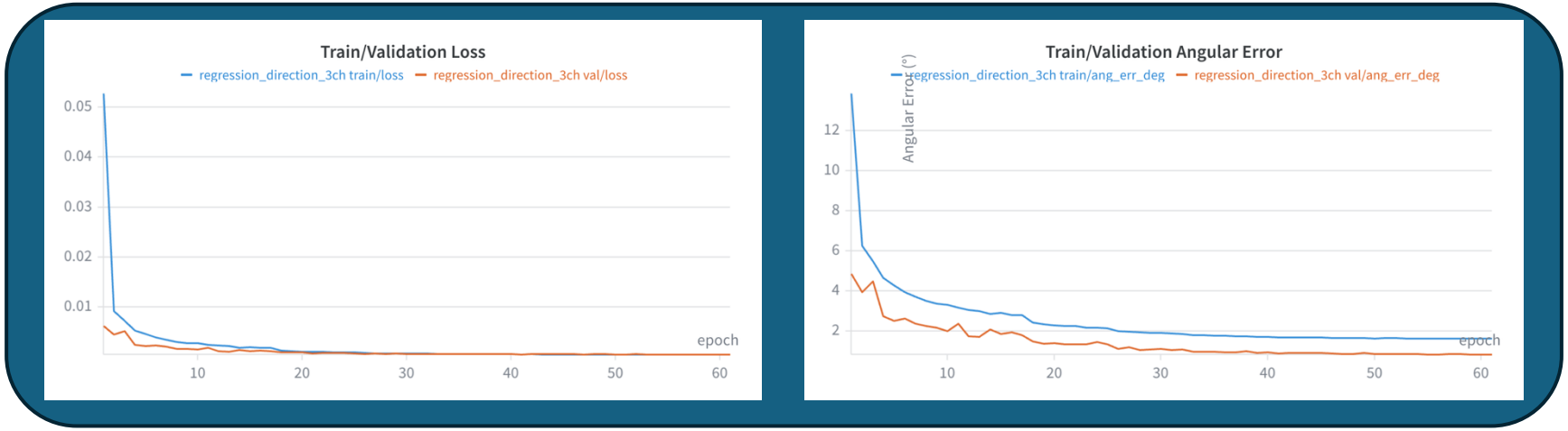
$$M_i = \frac{(kT \cdot kH \cdot kW \cdot C_{in} \cdot C_{out})}{(kH \cdot kW \cdot C_{in} + kT \cdot C_{out})}$$



Training

Muon Direction (40k/10k/40k)





Atmospheric Classification (24k/6k/15k)