Event Reconstruction and Analysis in Water Cherenkov Detectors with Machine Learning

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ILANCE
International Laboratory for Astrophysics, Neutrino and Cosmology Experiments

What are Neutrinos ?

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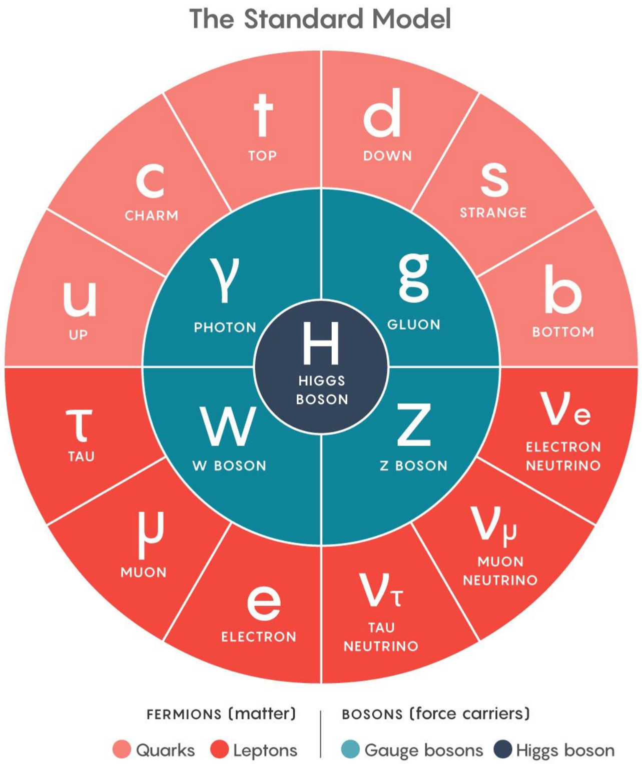


- Neutrinos are mysterious

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Flavour" (interaction) state

Mass eigenstate

- Chargeless lepton : only interacts via the weak interaction : hard to observe
- Impressively low mass compared to other particles : less than 2eV for neutrinos vs 0.511MeV for the electron

Why is neutrino oscillation important to study ?

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric Δm^2_{32}

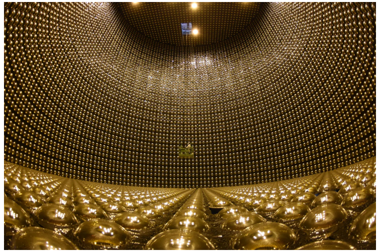
solar Δm^2_{21}

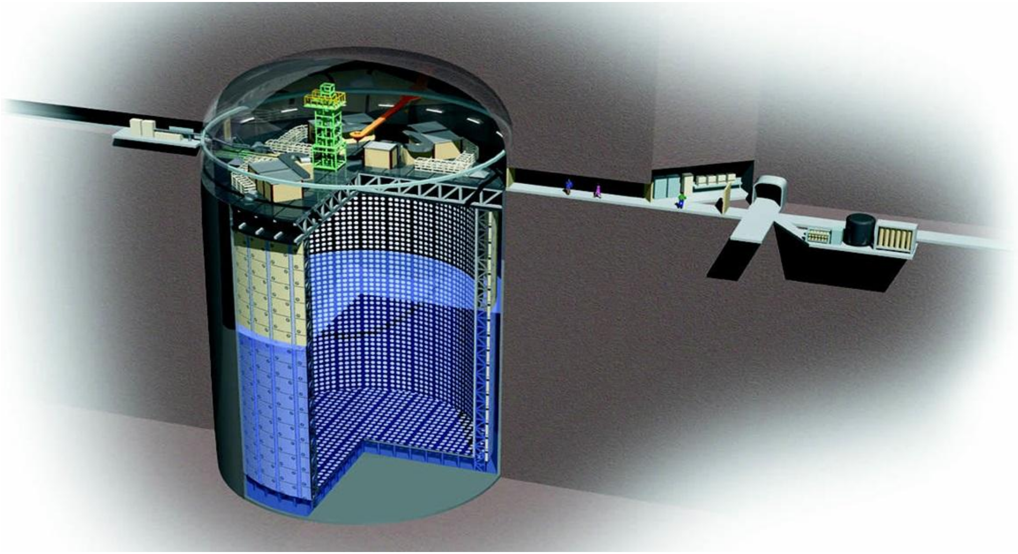
accelerators

reactors

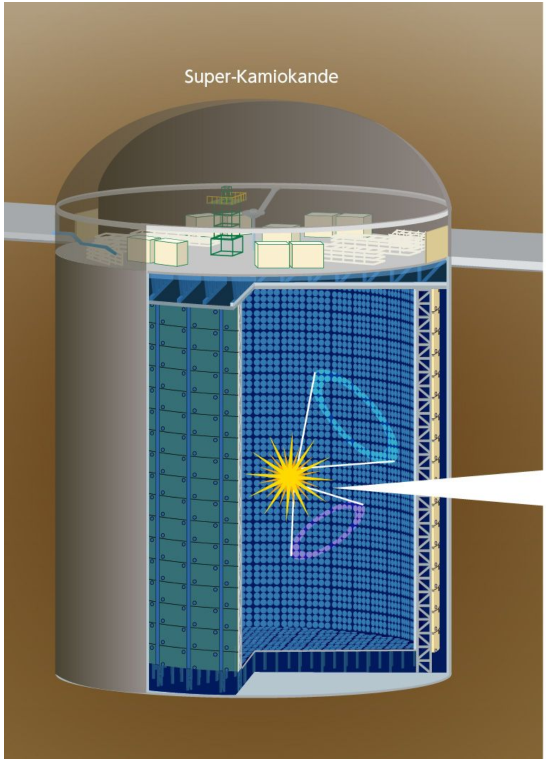
- CP violation for leptons: Matter antimatter asymmetry
- Mass ordering is still unknown
- Neutrinos and neutrino experiments are important inside and outside particle physics too : proton decay, cosmology (CMB, Dark matter searches), astrophysics (SuperNovae)

Neutrino experiments in Japan



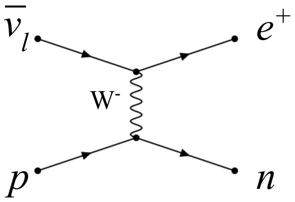


A focus on Water Cherenkov detectors

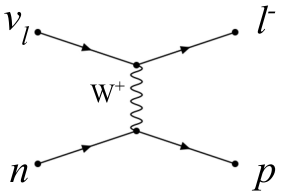


- Uses light to indirectly detect particles, via the Cherenkov effect
- The neutrinos will interact via different processes :

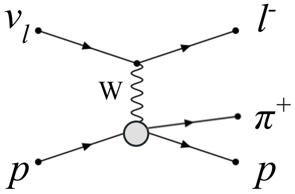
IBD



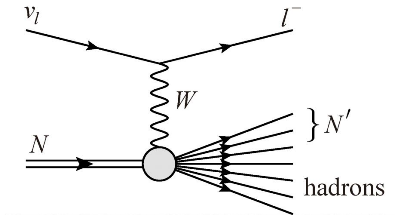
CCQE



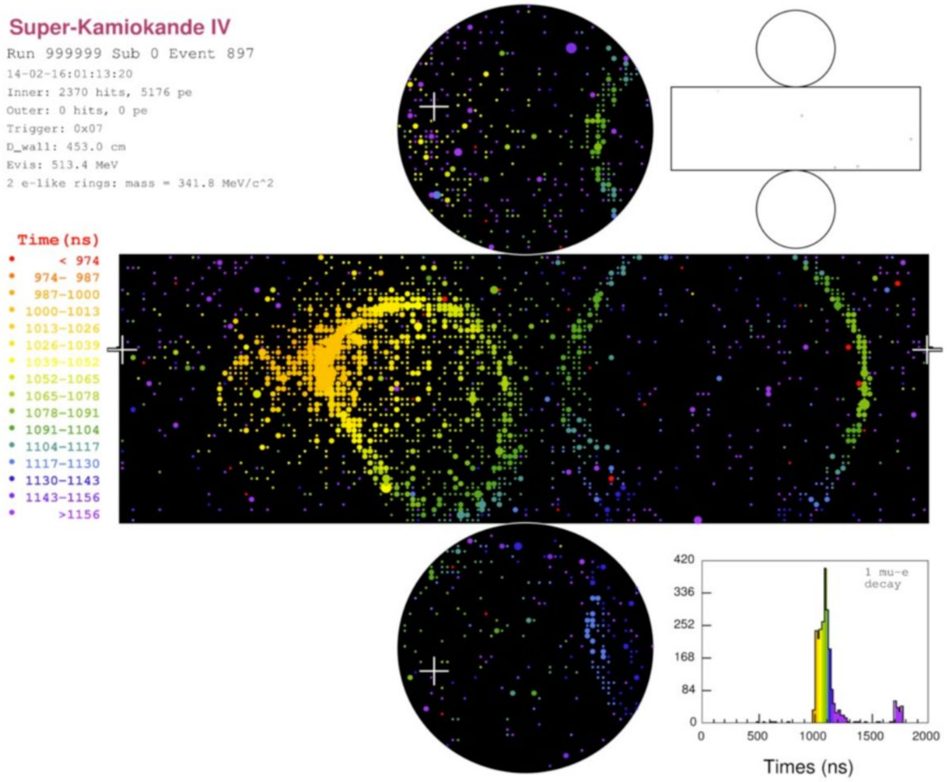
CC RES



CC DIS



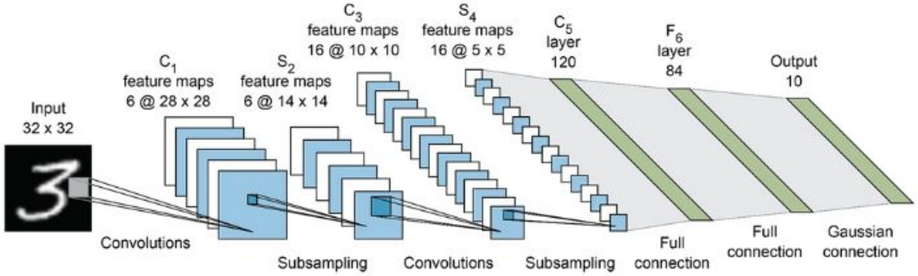
How do we understand what we see in the detector ?

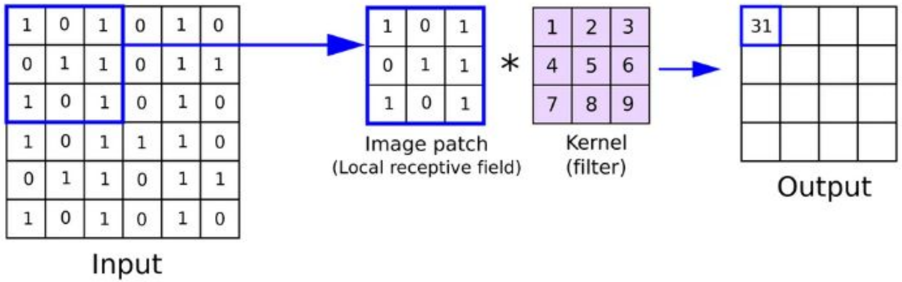


- The detector acts like a giant camera only giving us charge and time information
- **Reconstruction methods** have been developed to recover the physics variables:
  - What particles ? Electron, photon, muon, pion…
  - What energy ? Position of origin in the detector ? Impact angle ?
- They are traditionally based on maximum likelihood estimation, based on what we know about the underlying processes. (FitQun)

Machine Learning based reconstruction

- ML has seen an extreme rise of popularity and research effort in the past 5-6 years : some algorithms from Machine and Deep Learning can be adapted to neutrino detectors.





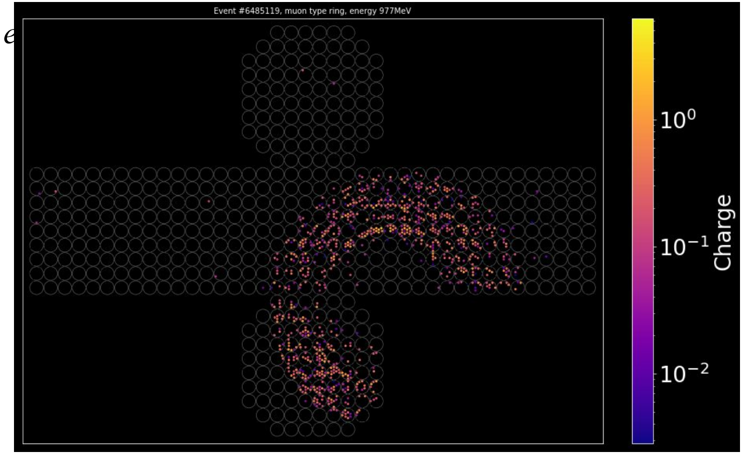
\+ Much better performances than traditional methods

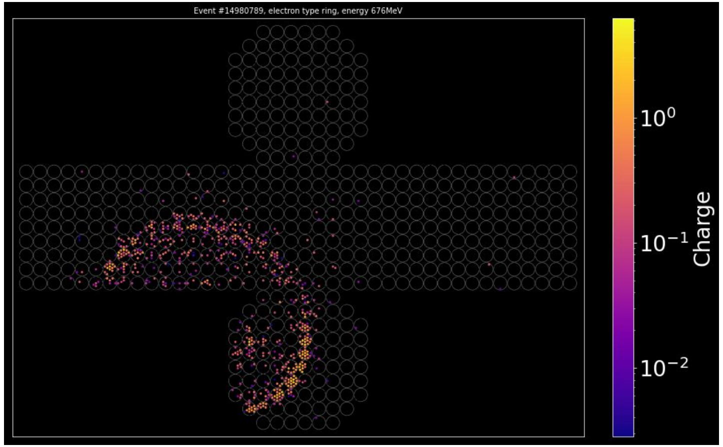
\+ No physics knowledge required

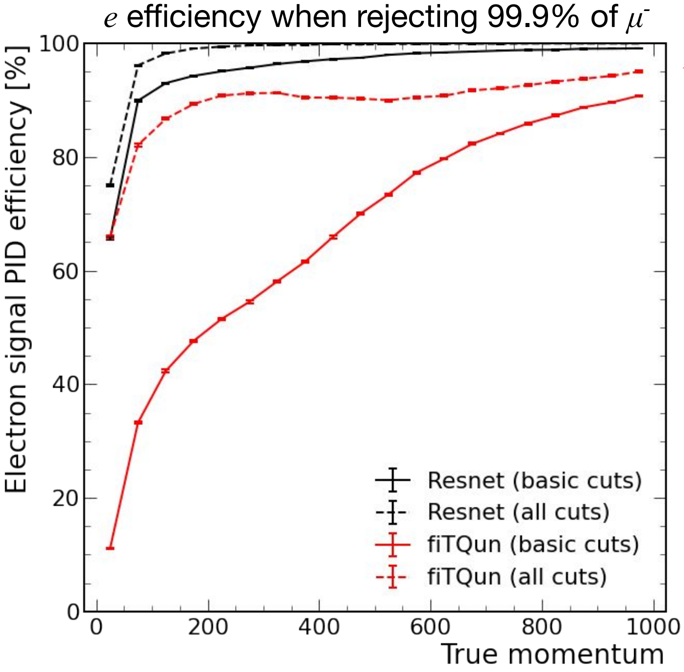
\- With current architectures, hard to estimate the uncertainty and the bias in the predictions

\- Low interpretability

Current results







More than 99.9% efficiency needed for the physics analysis

My work in the WatChMaL group

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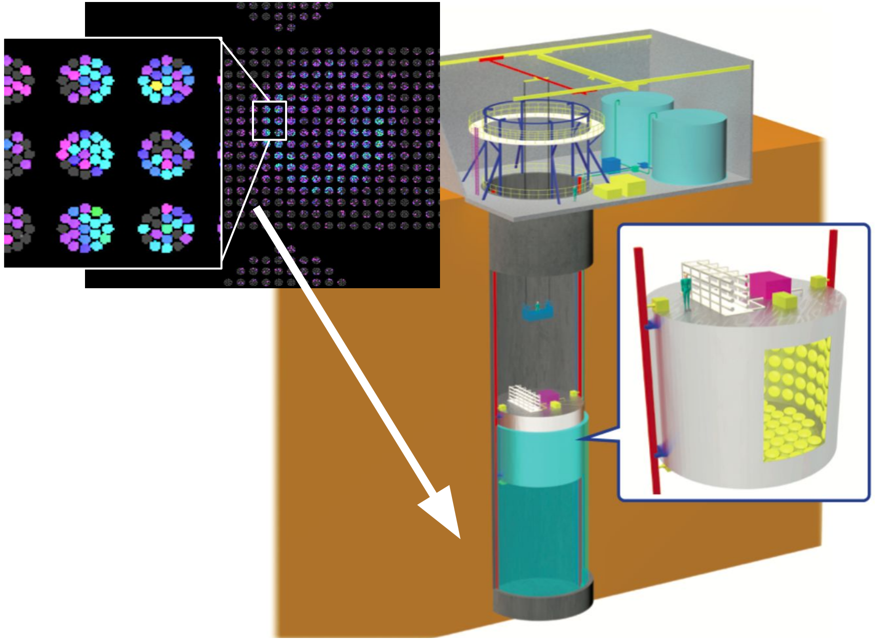
- Trying to improve and extend event classification
- Focused on the IWCD detector, a future detector of the HK experiment
- My goal is to implement ML event labelling within nuPRISM, a physics analysis framework for IWCD.



Hyper-Kamiokande

Conclusion

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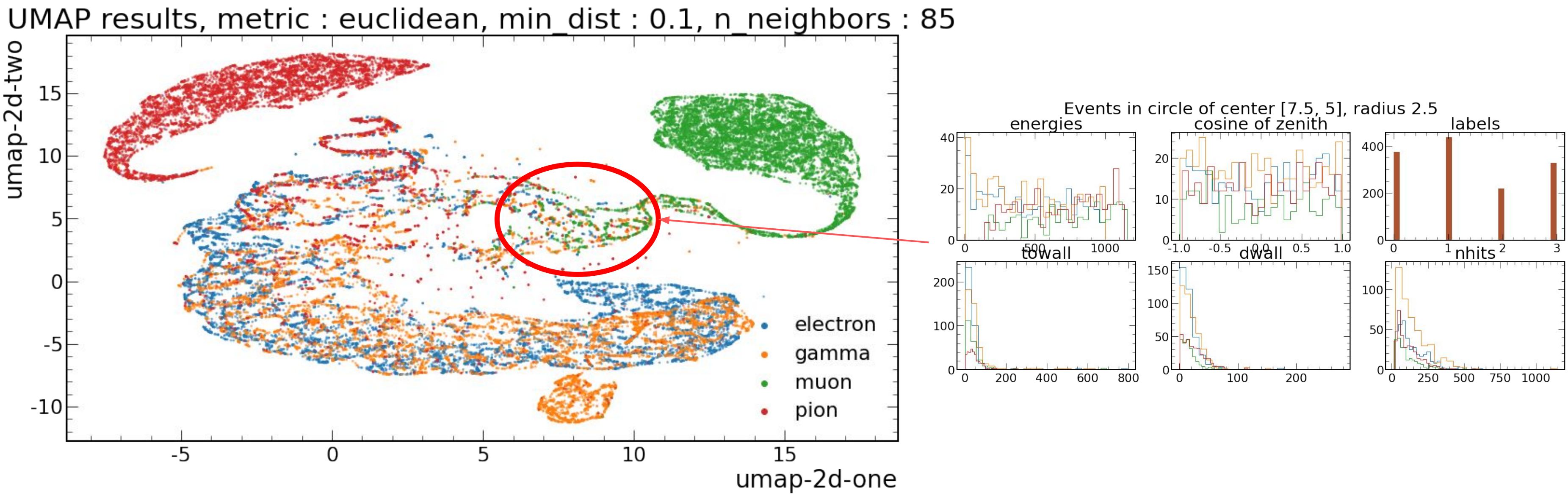
- **ML Reconstruction is a promising way for event reconstruction in neutrino experiments (other experiments like NoVa, US are already using ML based reconstruction in their analysis)**

- **Still a lot of work to do to include ML in T2K and SK analysis : multi-ring reconstruction, uncertainty/bias estimation…**

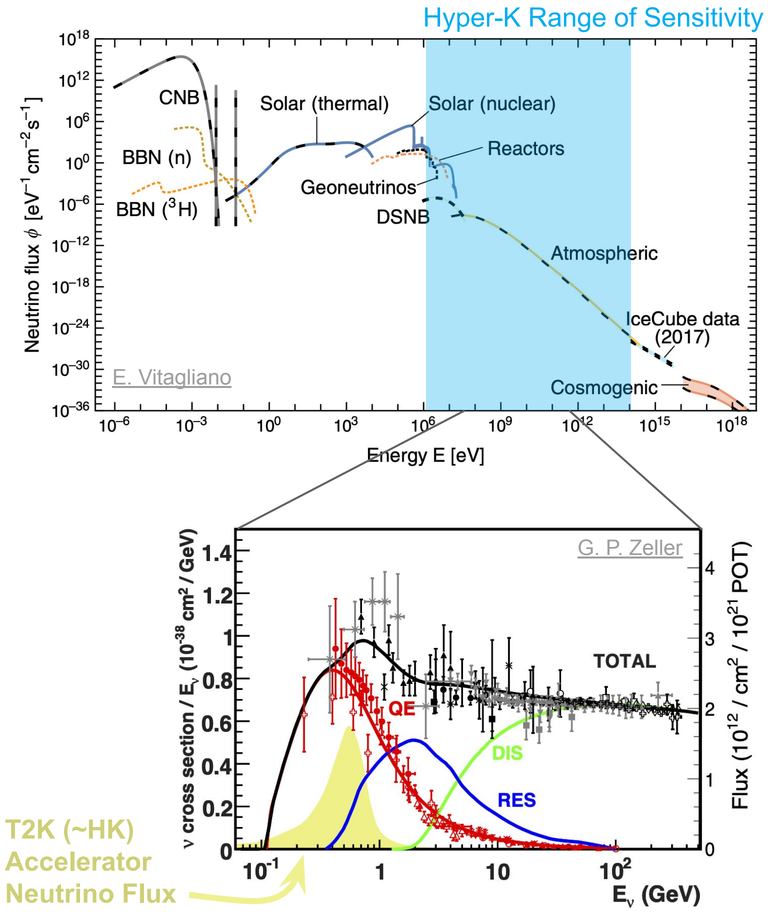
Backup slides

Class separation in latent space

- One of the goals of my internship was to design a ML model able to separate different classes (muon, electron, pion, gamma induced ring) in an abstract latent space



nuPRISM and IWCD in oscillation analysis



- We fit binned Poisson likelihood to the event rate to predict the cross section of muon and electron neutrinos, as well as their ratios
- Will help reduce uncertainties in the oscillation fit at the far detector