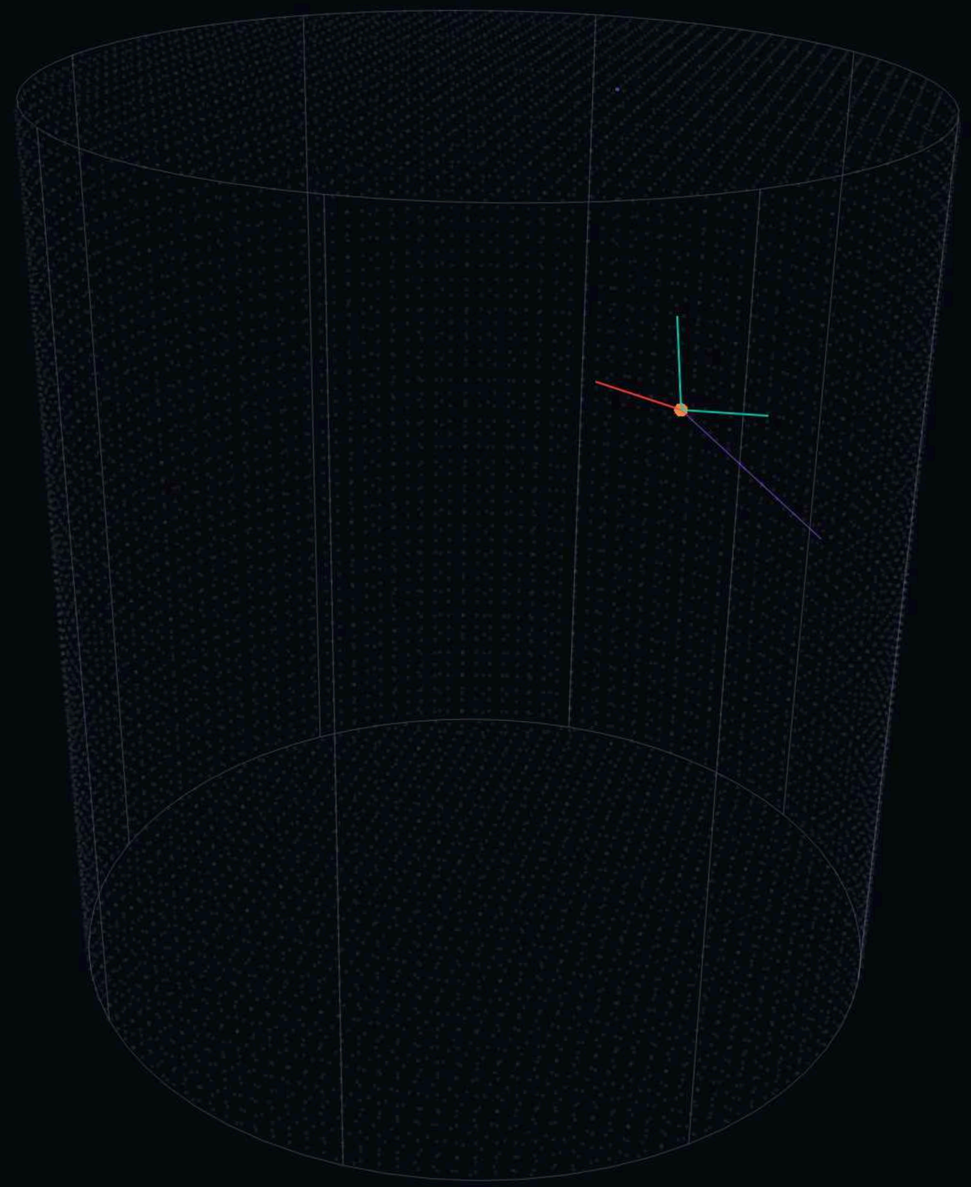
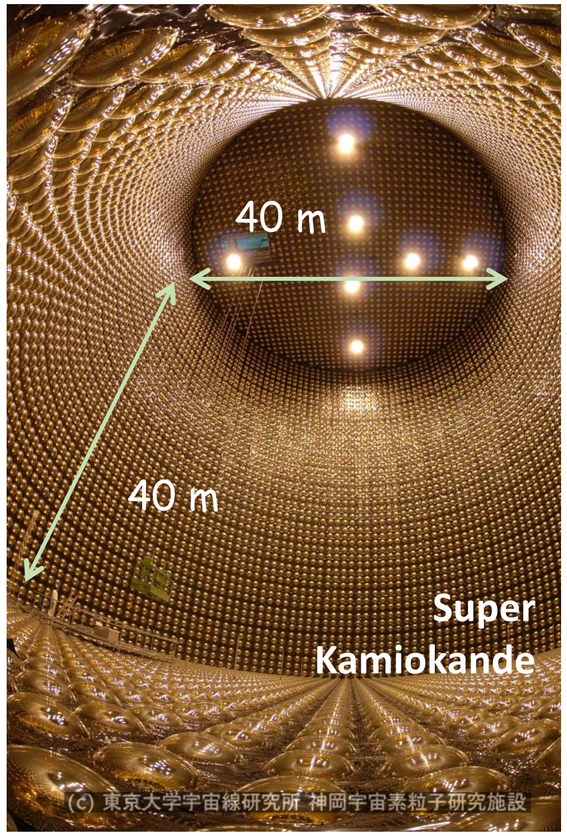
Nu 11 :
Upgrade of the Reconstruction Algorithms

From Super-K Towards Hyper-K

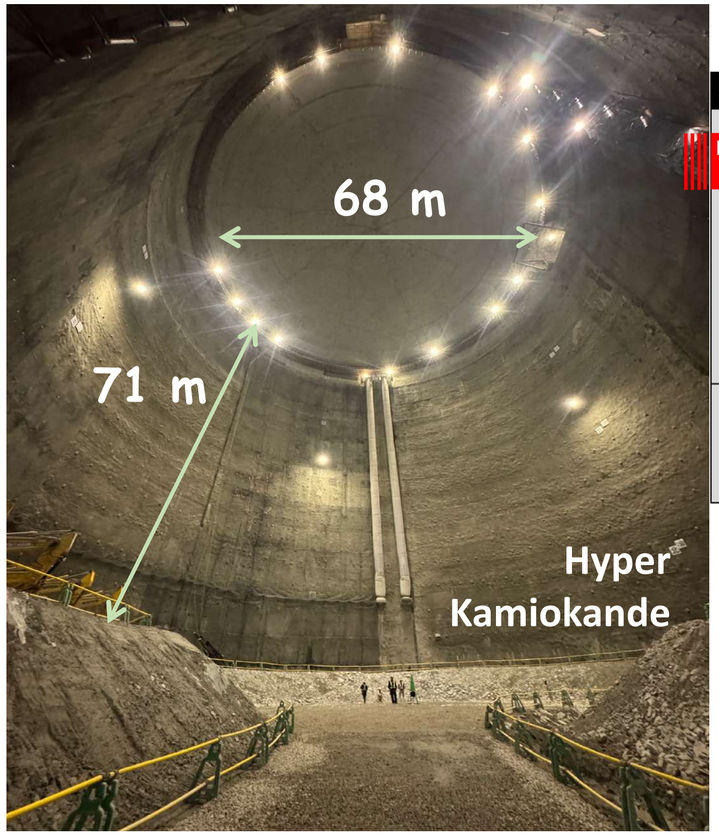


On behalf of Nu 11
PI : Masaki **Ishitsuka** (TUS) | Benjamin **Quilain** (LLR/ILANCE IN2P3)

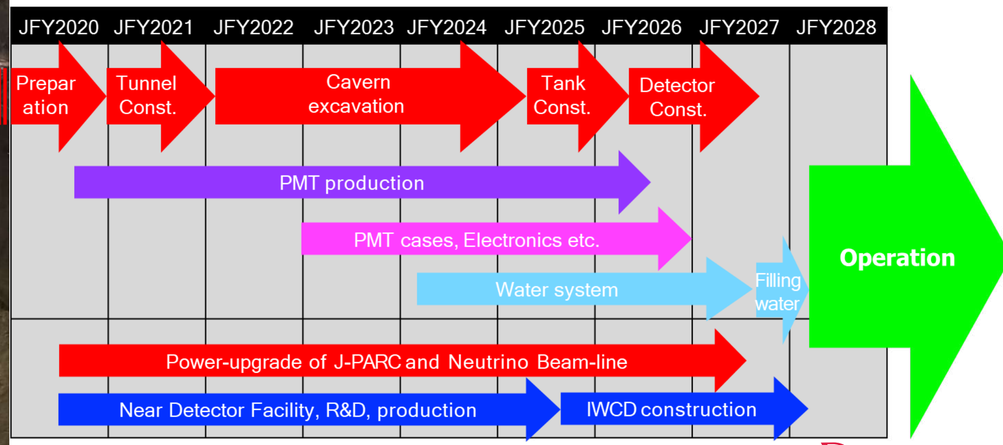
From Big To Huge



Fid. Mass
x 8



Timetable



Data Taking !

	1996 - today	*2028 -*
Inner Volume / Fiducial Mass	32 kton / 22.5 kton	217 kton / 188 kton
ID PMTs	~11k	~20k
Photo Coverage	40%	20% (x2 efficiency)

News

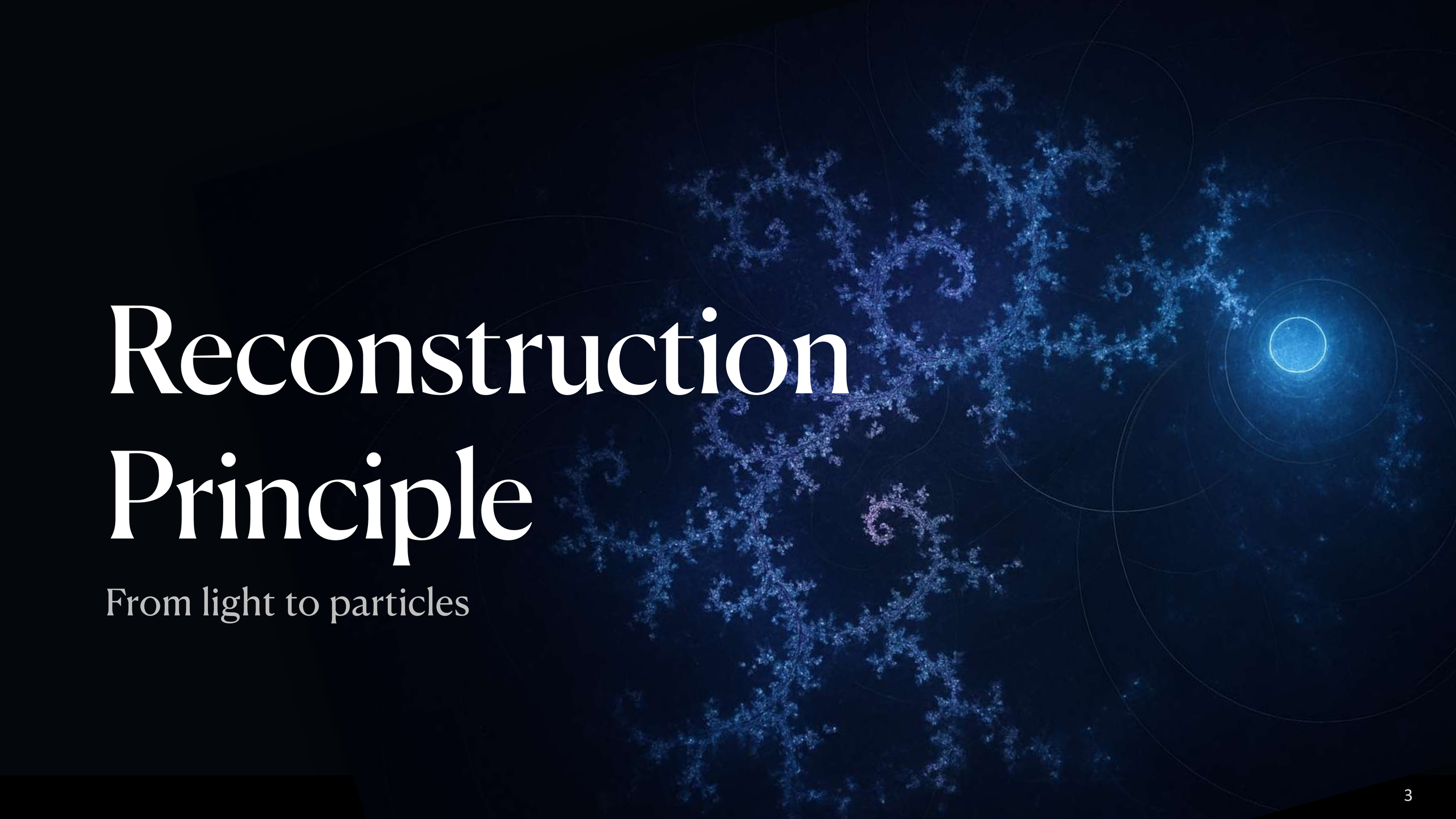
31 Jul. 2025 Construction and Development

Excavation of the Colossal Cavern for Hyper-Kamiokande Completed

A 3D virtual tour of Hyper-Kamiokande released

2026.2.3 Topics *Link*

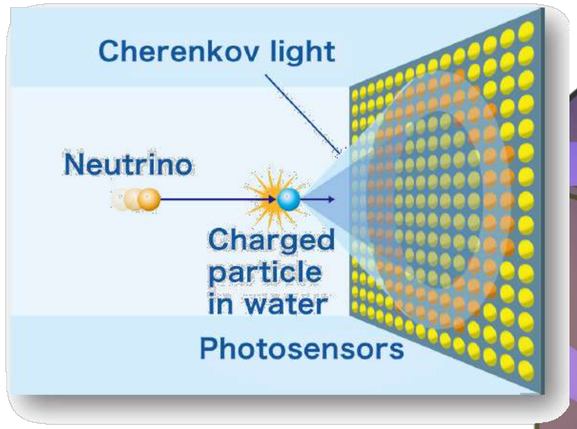
Sensitivity of the Hyper-Kamiokande experiment to neutrino oscillation parameters using acceleration neutrinos, Hyper-Kamiokande Collaboration,
arXiv:2505.15019 *Link*

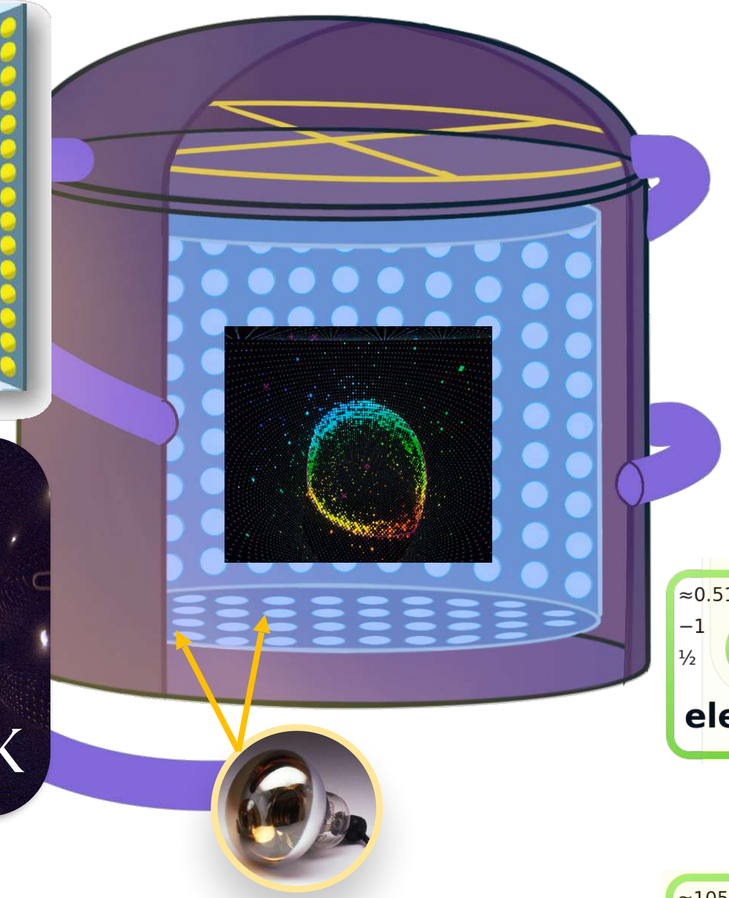


Reconstruction Principle

From light to particles

Detecting & Reconstructing Events

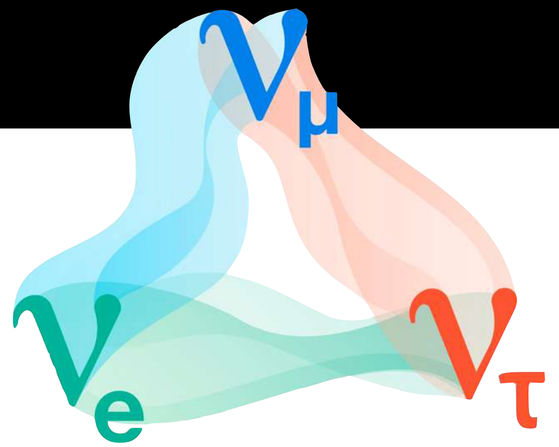




One PMT Features

« Geometry »
- ❖ Position
- ❖ Orientation

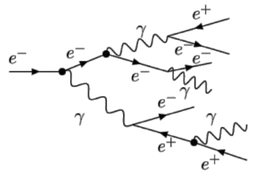
« Event »
- ❖ Charge
- ❖ Time

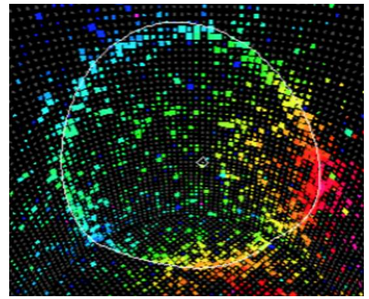


Oscillations L/E

$$\mathbb{P}\left(\nu_\mu \to \nu_e\right) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

≈0.511 MeV/c²
−1
½
e
electron

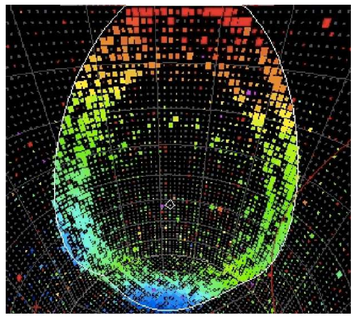




≈105.66 MeV/c²
−1
½
μ
muon

μ^-

Different behaviors



Different particules

Different ring patterns

Reconstruction Soft.

≈0.511 MeV/c²
−1
½
e
electron

- Direction
- Energy
- Vertex

≈105.66 MeV/c²
−1
½
μ
muon

- Direction
- Energy
- Vertex

Reconstruction : Tools & Knowledge From Super-K

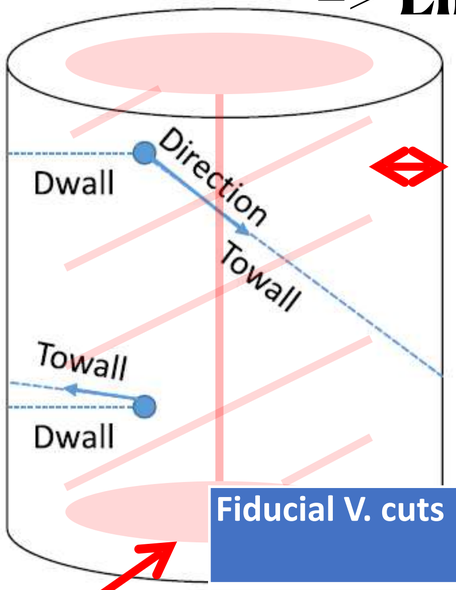
FITQUN

Main reco. software during and after SK IV period

Fiducial Volume Cut

Limited performances close to the edges

=> **Limits statistics**



dwall cut

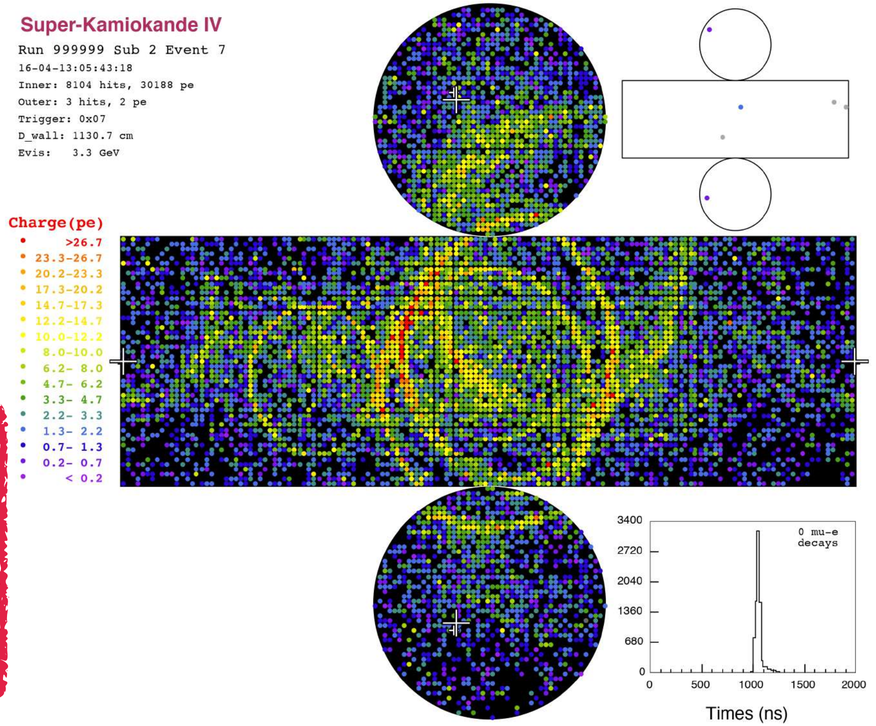
Fiducial volume

Fiducial V. cuts	Super K (cm)	T2K (cm)
Dwall	> 50	> 80
Towall	X	> 170

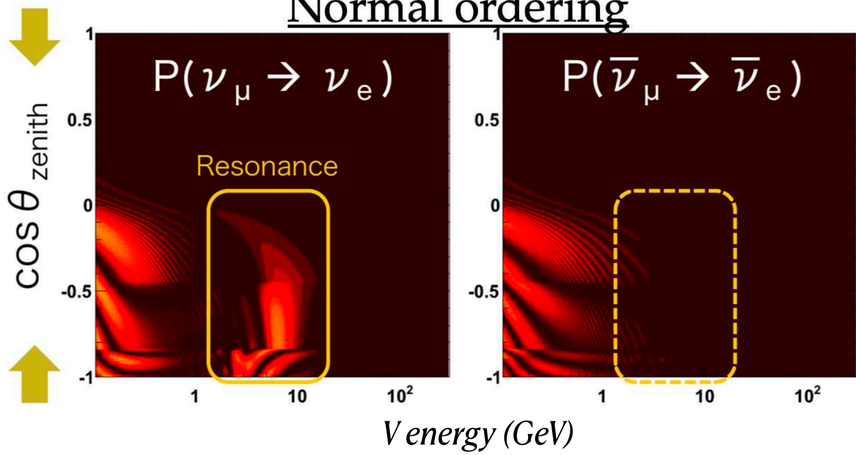
M. Jiang D. Thesis, *T2K, TN465 v1.1,*

Multi rings events

e- like events	fiTQun
First stage	
Multi-ring *e*-like events	
Efficiency	75.7%
Purity	77.8%
Second stage	
Multi-ring True CCν_e events	
Efficiency	56.8%
Purity	58.8%
Multi-ring True CC$\bar{\nu}_e$ events	
Efficiency	68.4%
Purity	30.0%



But MR =>
Most sensity channel
to Mass Ordering



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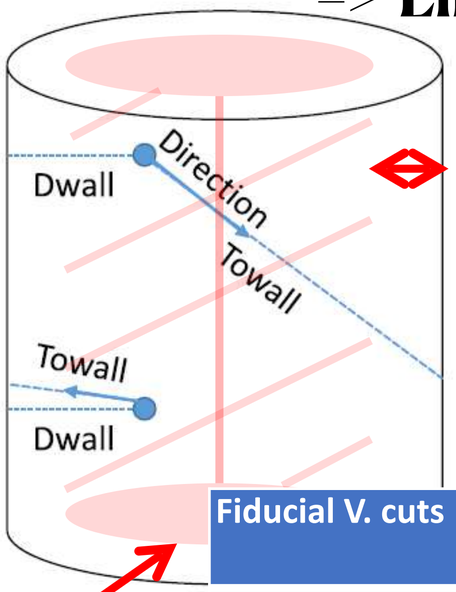

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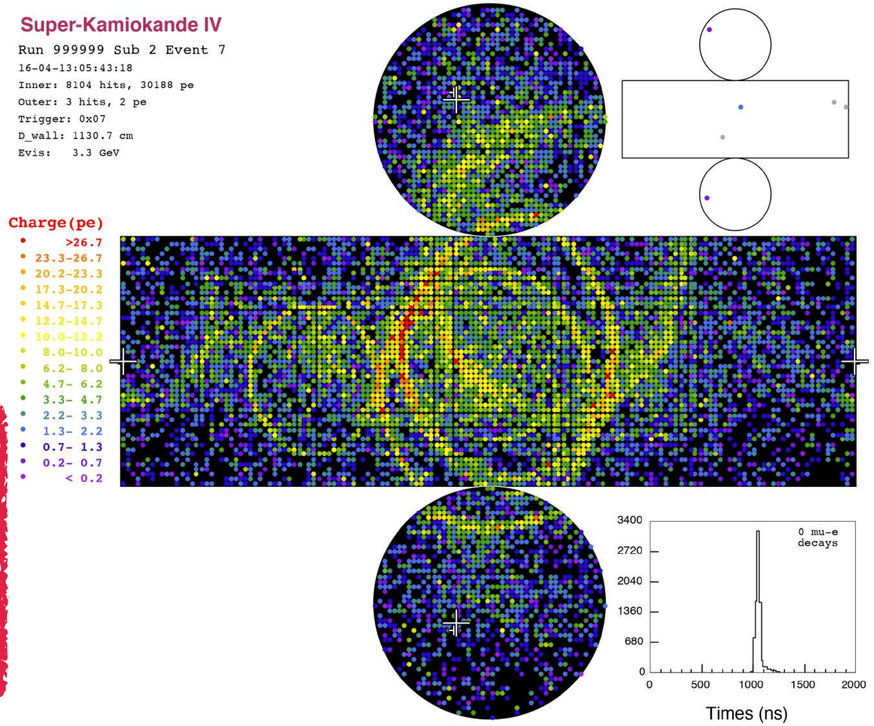


But MR =>
Most sensity channel
to Mass Ordering

Computational Time

~30 seconds / event in **Super K**
~1:30 minute / event in **Hyper K**

(Easiest to address)

Paradigm Shift For Experimental Physics

Heritage :
Likelihood Methods

PMT unhit probability — PMT hit probability — PMT charge pdf — PMT timing pdf

$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_{i}^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_i)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

fiTQun's likelihood

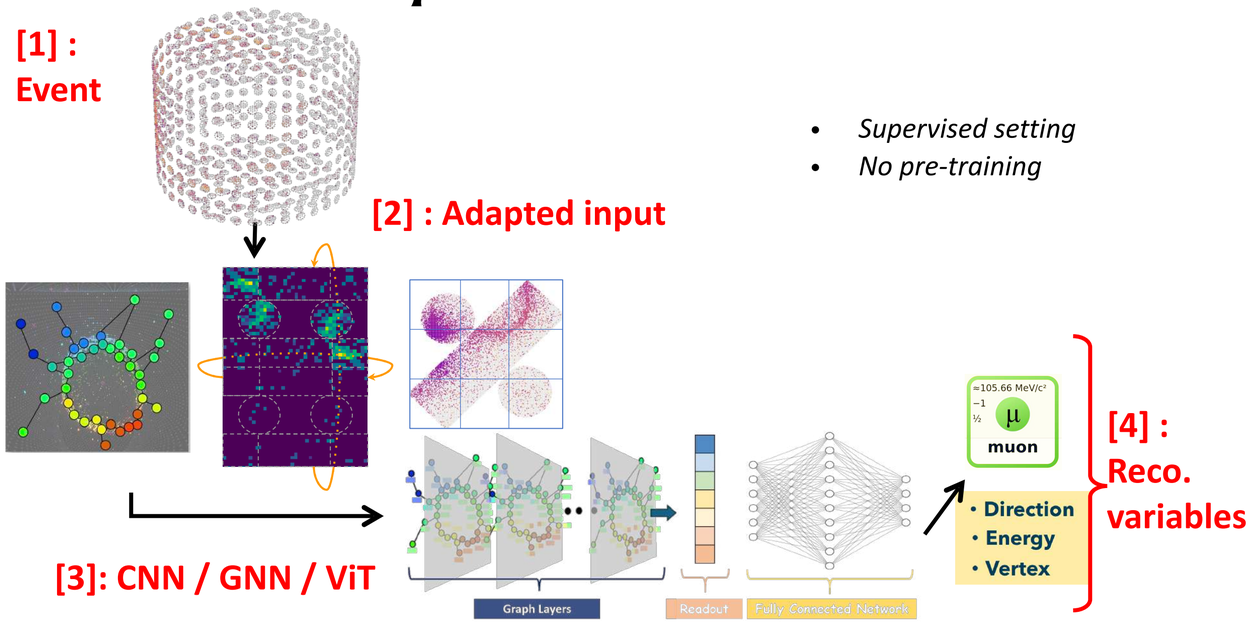
- Physics & Detector **specific** *(SM & Calibration..)*

- Simultaneous fit of 7 reco. variables

vertex position & time, momentum, direction, particle type

- Non-differentiable => Nelder-Mead method to minimise

« Challenger »
Deep Neural Networks



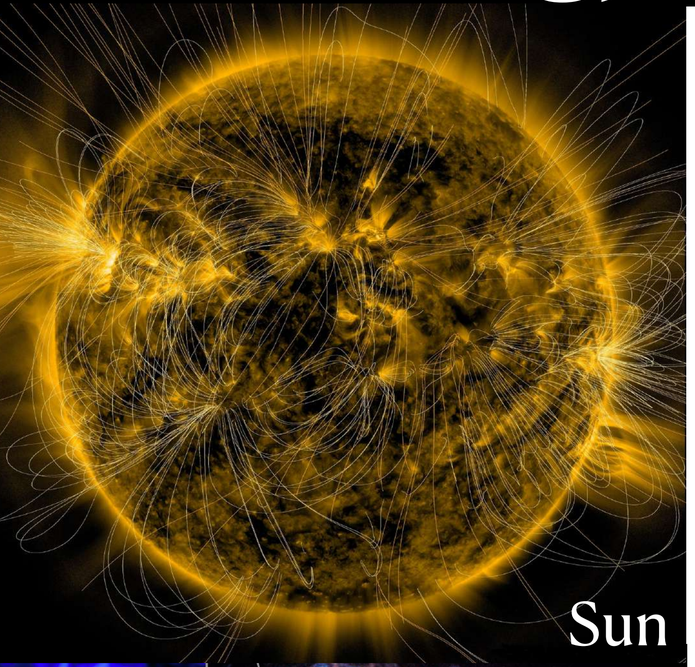
- *Supervised setting*
- *No pre-training*

- **Arbitrary** highly - parametrised function

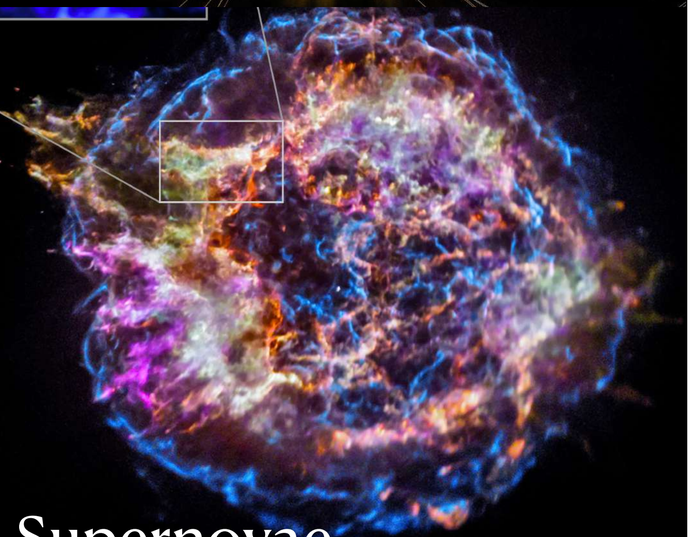
- Sub-differentiable
  => Stochastic Gradient Descent methods

Reconstruction Performances

Low Energy | Previous Status



Sun

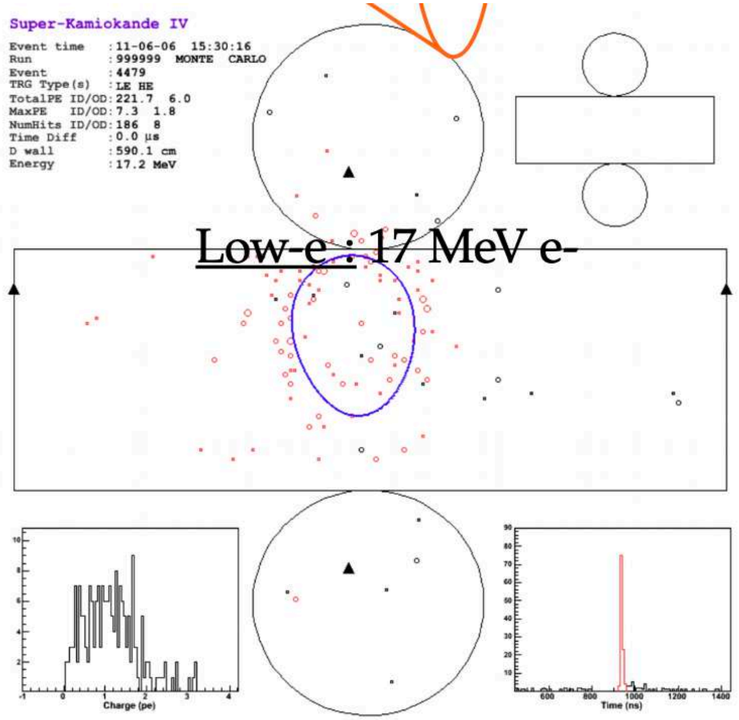


Supernovae

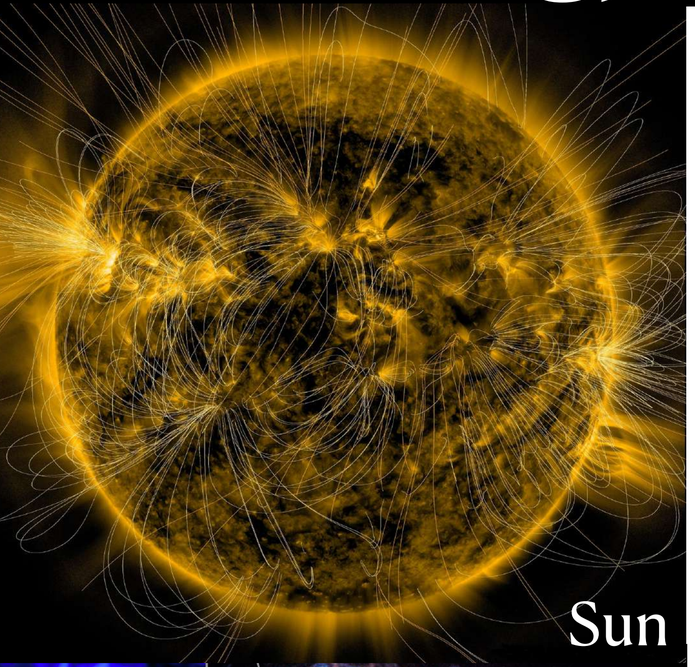
Very Sparse Information

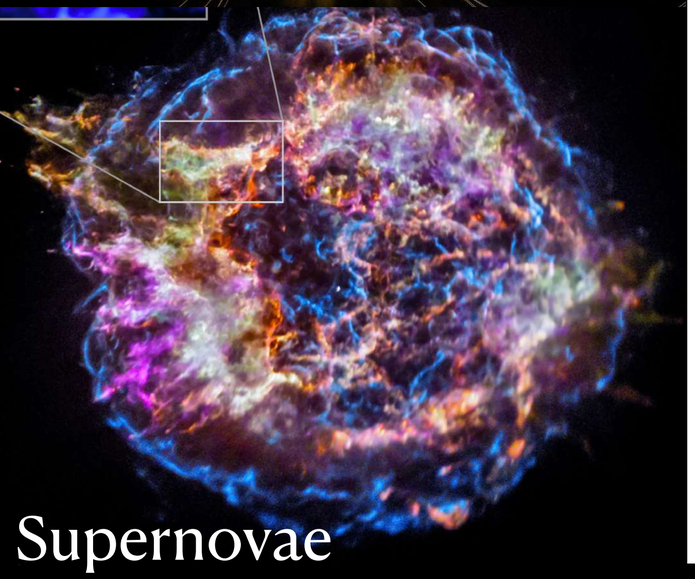
→ Selecting signal
vs Dark Rate hit PMTs

2025 : *LEAF* (*BONSAI* from Super-K)
Light emitted from a single point



Low Energy | DSNB



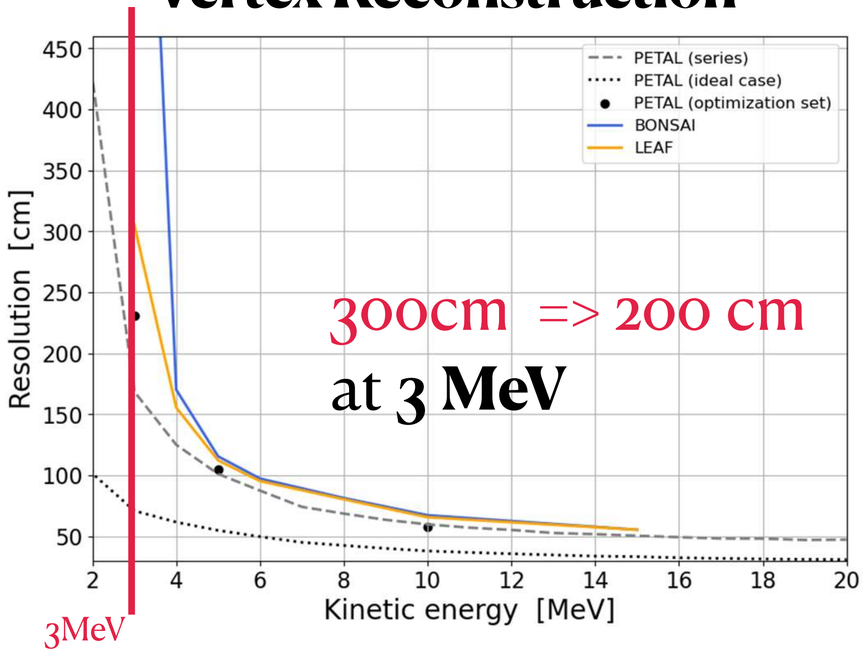


Very Sparse Information

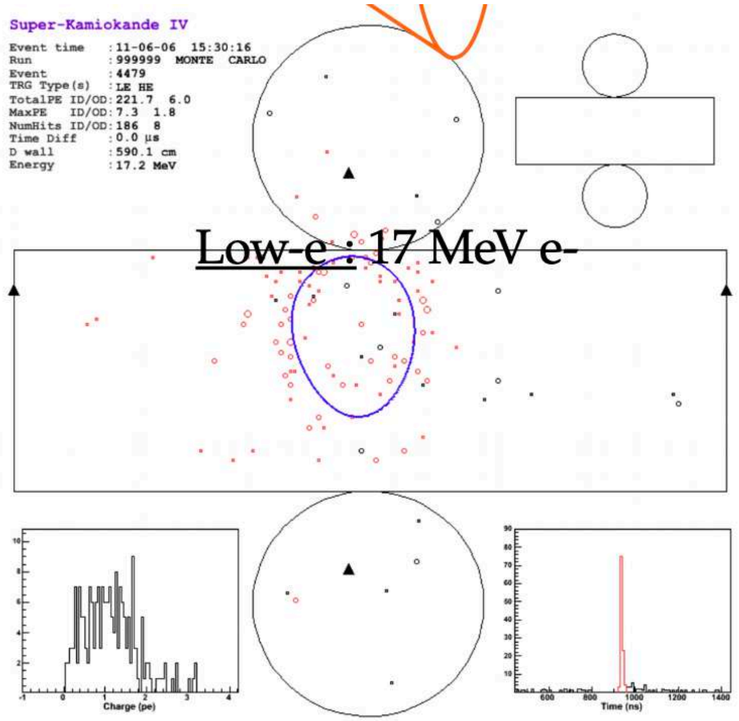
Selecting signal
vs Dark Rate hit PMTs

2025 : *LEAF* (*BONSAI* from Super-K)
Light emitted from a single point

Vertex Reconstruction



300cm => 200 cm
at 3 MeV



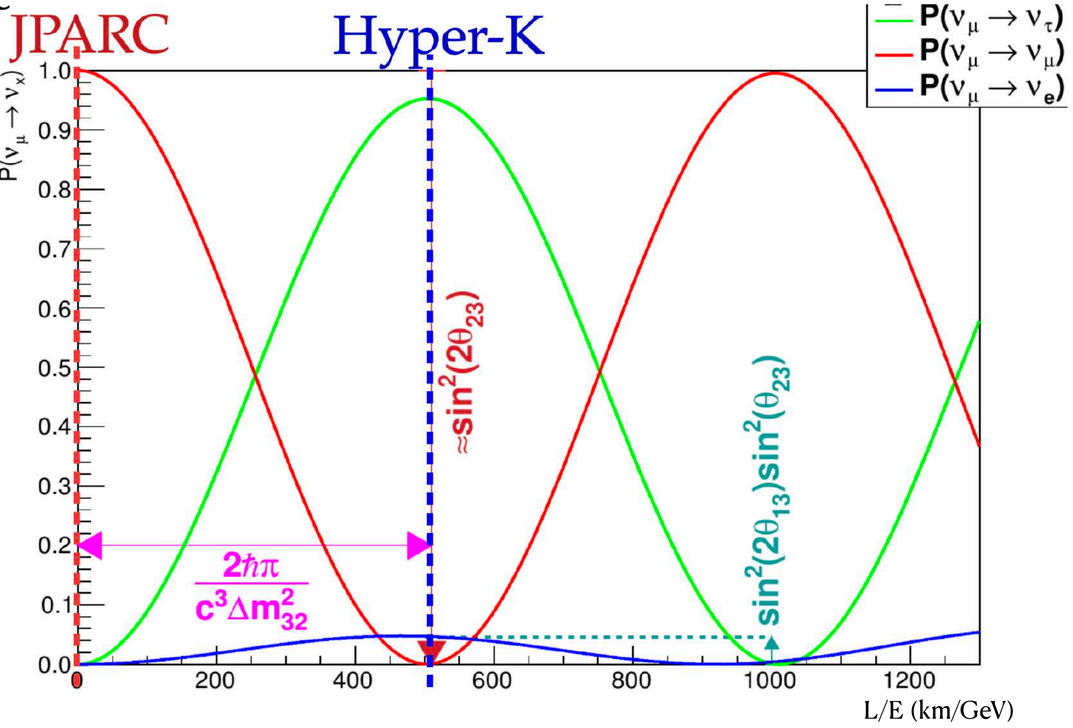
This year : ***PETAL***
a DNN-based approach

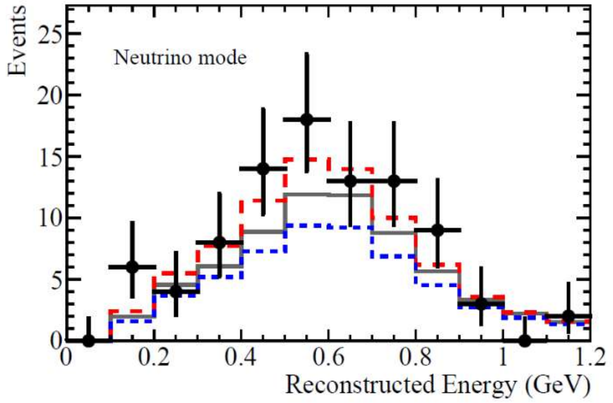
=> Already outperforming likelihood methods

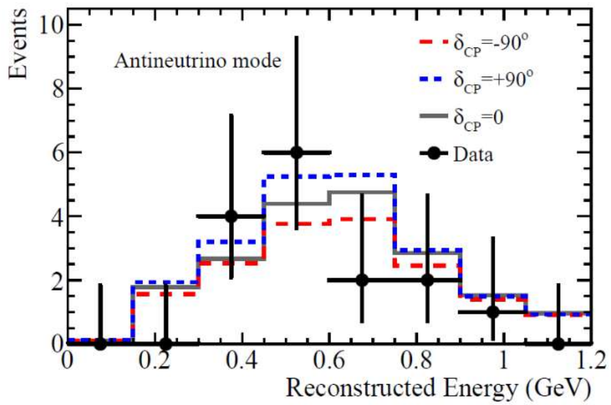
High E | Single Ring Samples - Particle Identification

Main channel for CP violation :

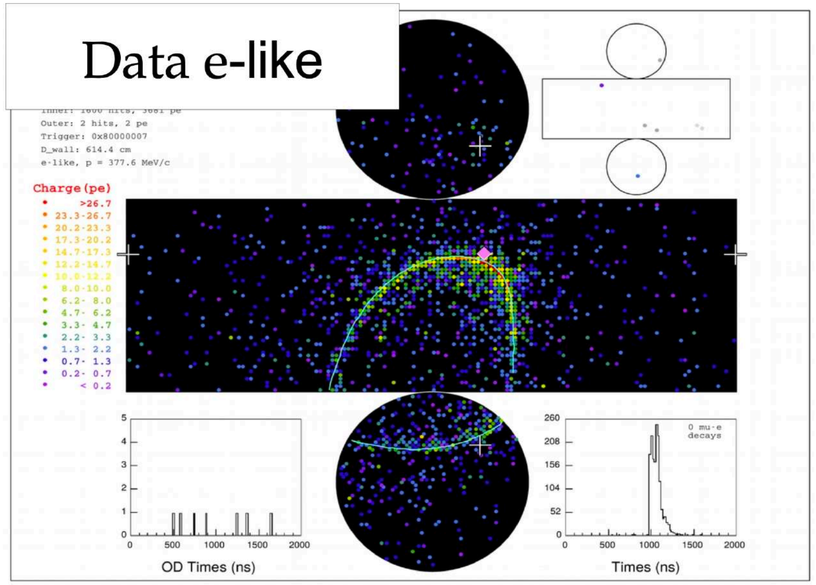
$\nu_\mu \rightarrow \nu_e$ oscillation

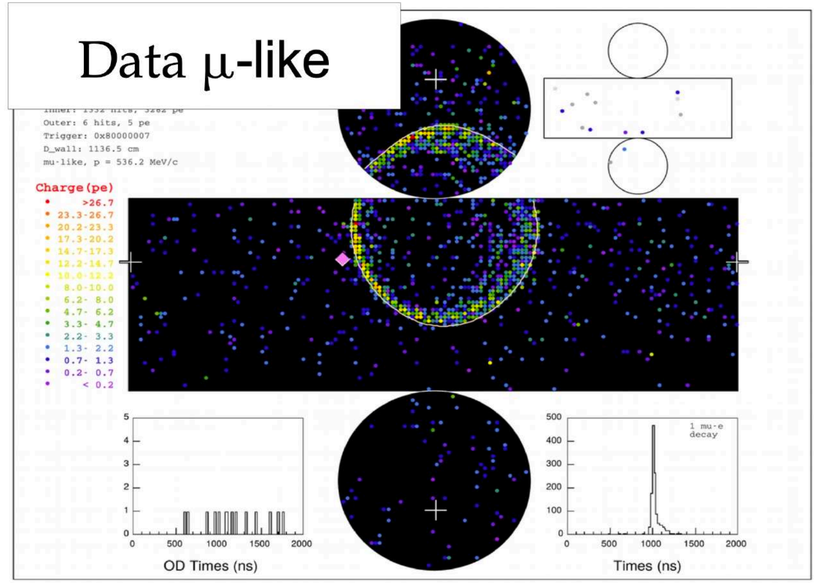






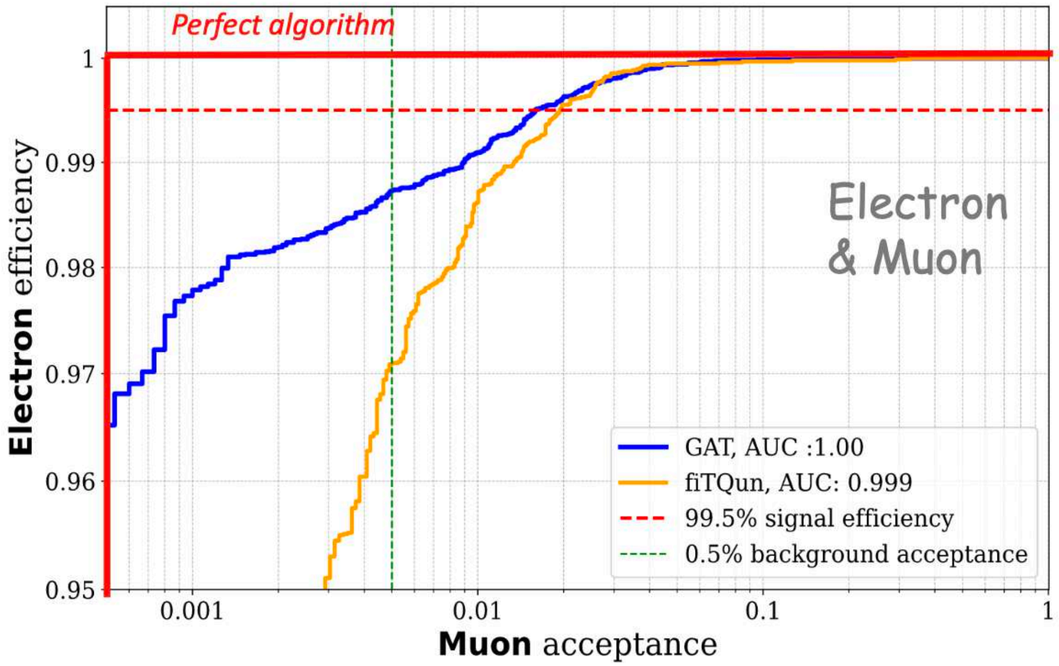
T2K experiment



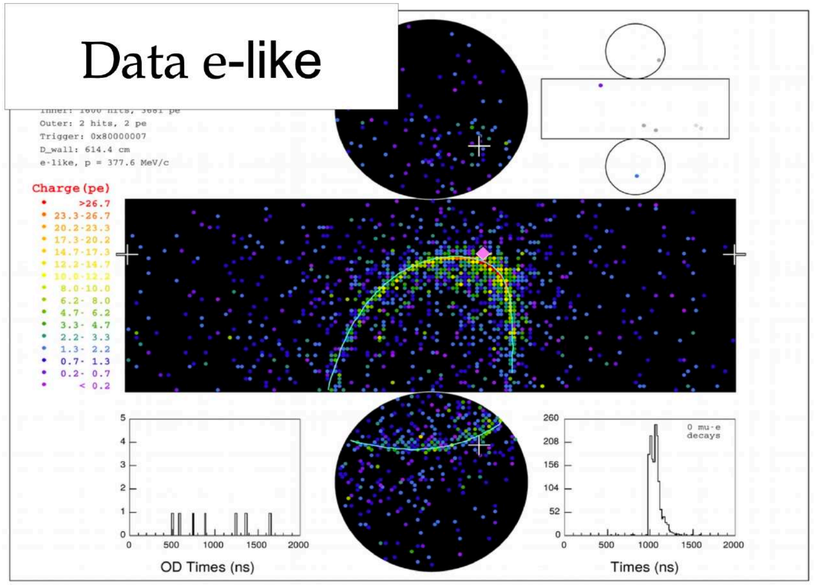


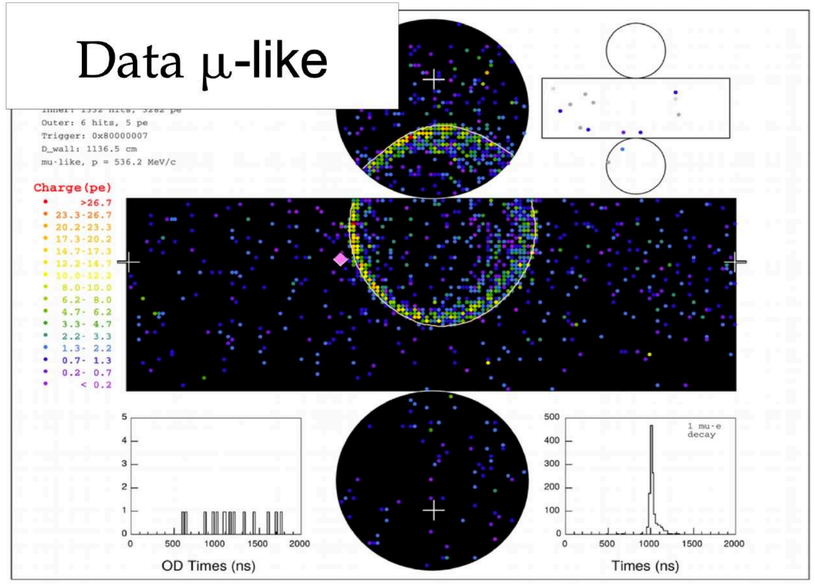
High E | Single Ring Samples - Particle Identification

Efficiency : Rec. Positive **And** True Positive / Total true **positive**
Acceptance : Rec. Positive **But** True Negative / Total true **negative**



Last Year : **Same performances** as fiTQun
Now : **Outperforms**





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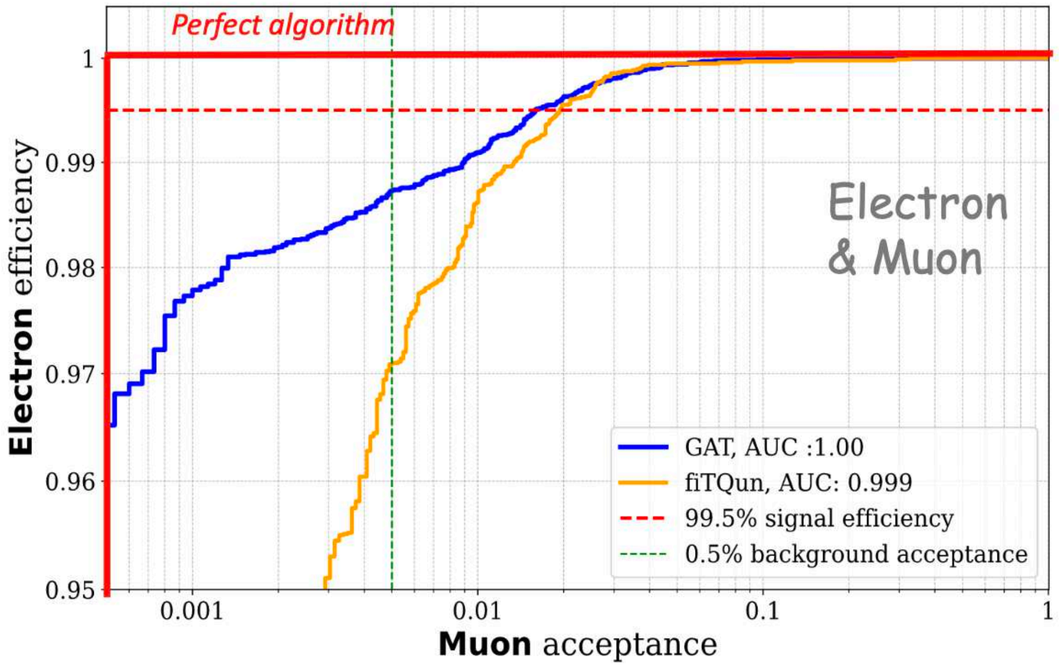

Reducing mis-id rates ...

High E | Single Ring Samples - Particle Identification

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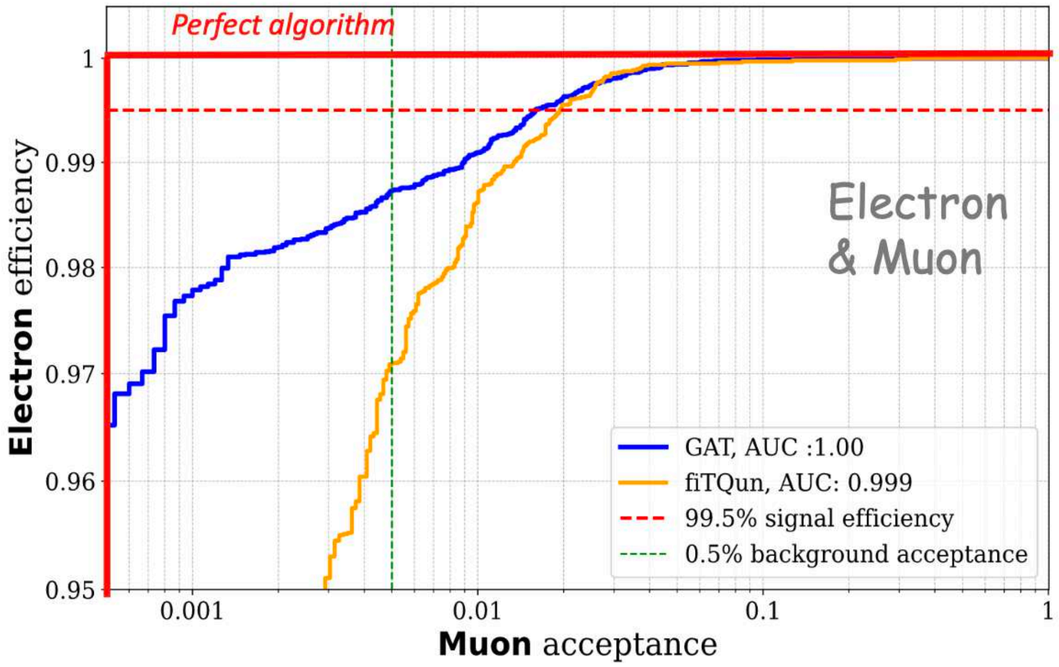
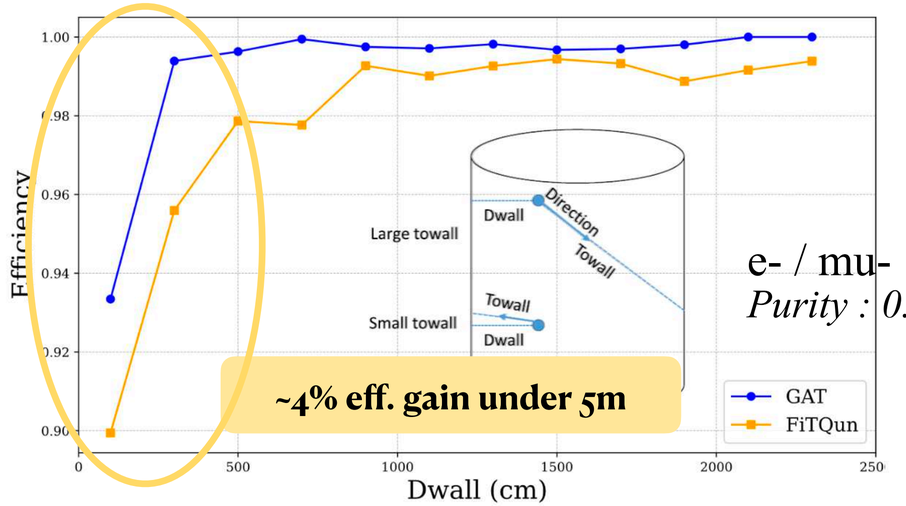


Reducing mis-id rates ...

.. & increasing fiducial volume !

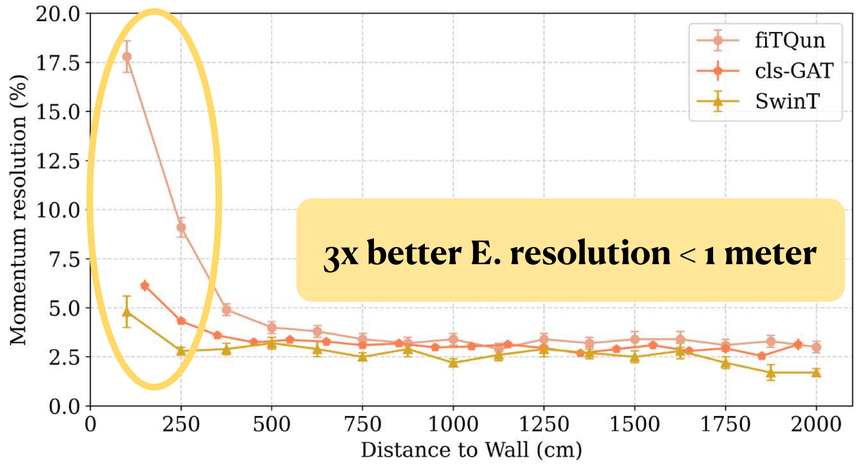
Particle Tagging



~4% eff. gain under 5m

e- / mu-
Purity : 0.5%

Mom. Reco



3x better E. resolution < 1 meter

High E | Single Ring Samples - Kinematics

Surpassing fiTQun on Particle ID

What about kinematics ?

Algorithm	Pos. res. (cm)	Dir. res. (°)	Mom. res. (%)
B. Quilain (2025)		***2025***	
fiTQun	28	2.6	3.8
GNN (*Base*)	200	-	4

High E | Single Ring Samples - Kinematics

Surpassing fiTQun on Particle ID

What about kinematics ?

Area that improved the most this year

Algorithm	Pos. res. (cm)	Dir. res. (°)	Mom. res. (%)
B. Quilain (2025)		***2025***	
fiTQun	28	2.6	3.8
GNN (*Base*)	200	-	4
		2026	
fiTQun	26.2	2.3	3.5
GNN (*Upgrade*)	28.0	-	3.5
ResNet-50	25.4	-	-
ResNet-152	22.1	1.9	2.5
ViT-based	12.7	1.2	2.3
CherRP	11.6	1.7	2.6

High E | Single Ring Samples - Kinematics

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WatChMaL
Water Cherenkov Machine Learning

Hyper-K
Super-K
WCTE

Shuoyu Chen
Andrew Atta
Nick Prouse
Felix Cormier
Kieren Joseph
John Nugent

IWCD ↔ Gilberto Rodriguez

CAVERNS
Cp Asymmetry discovery with an Enhanced Reconstruction algorithm for Neurinos in Super and Hyper Kamiokande

WCTE
Hyper-K

Lorenzo Périssé
Naomi Foster
Erwan Le Blévec
Mathias El Baz
Zhuojun Hu
Mathieu Ferey
Viet Nguyen

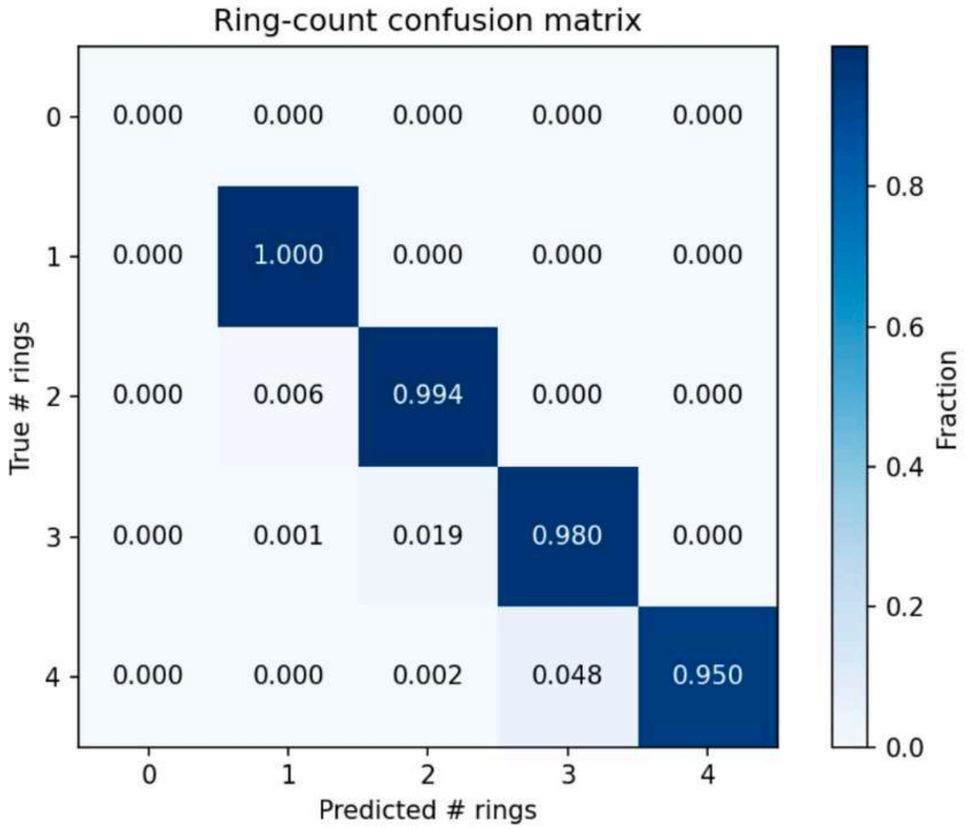
Neutron Tagging → *Energy* → *Multi-Rings*

Tokyo U. Kashiwanoha Campus :

Crucial meeting places at ILANCE & IPMU to coordinate these efforts & enhance ideas.

High E | Multi Rings First Success

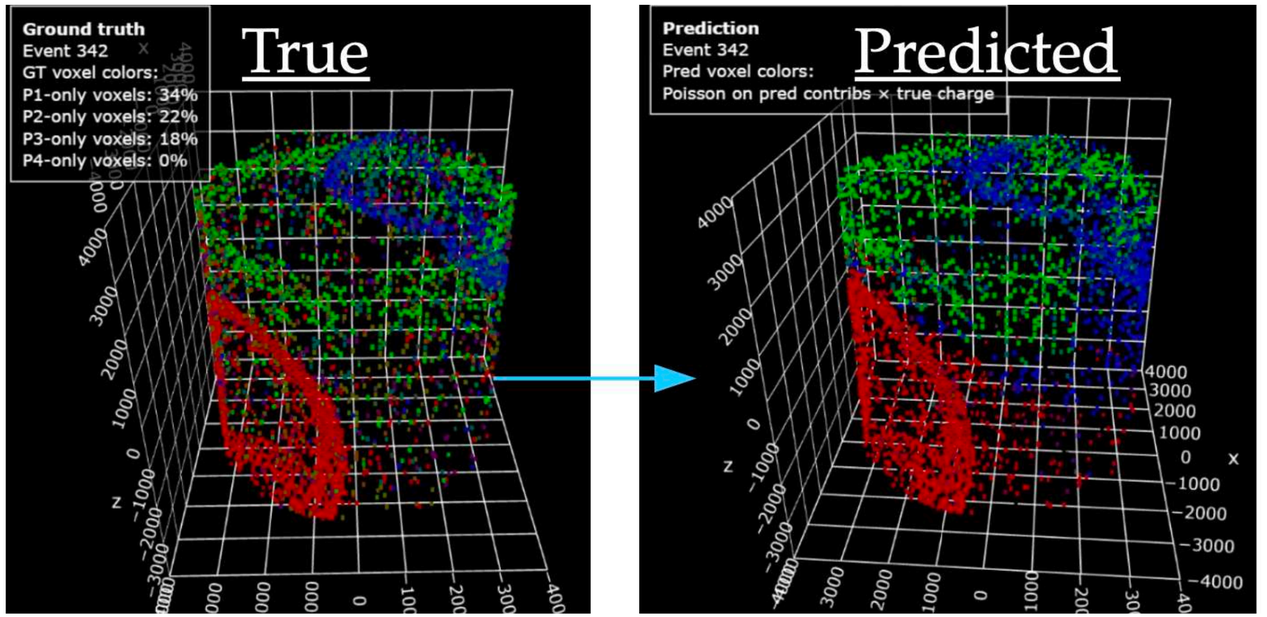
First algorithm to succeed in **Multi Ring Segmentation**



Leverage Sparse CNN 3D Features

+

Transformer Backbone



M. El Baz (visiting ILANCE for 6 months)

→ Opens rooms for **a lot of improvements**

Hybrid fitter, foundation models.. => ongoing efforts

Accelerating Reconstruction By Optimizing Softwares

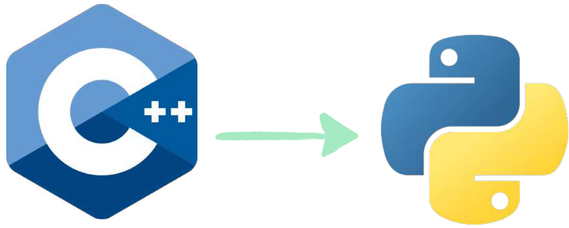
Improvements not only on physic performances

MC Tuning :
500years ~ 5M events

- **Single Ring** sample full reco. time

CPU time / event	1 ring e/μ PID	1 ring e/π⁰ PID	Energy & vertex reco.	Total
fiTQun	30s	50s	Simulatenous to PID	80s
CAVERNS	0.09s	0.07s	0.05s	0.11s

~ 2 order of magnitude faster



- Porting fiTQun c++ software on GPUs

	CPU (s)	GPU (s)	GPU/CPU
π+ 500 MeV	279s	2.4s	1/116
π0 500 MeV	483s	3.3s	1/145

Also ~2 order of magnitude gain

- Effort to write **fiTQun** on **python** & use extremely optimized xla libraries *(numba, jax..)*

Benchmarks to come soon

What Next ?

2026

What to Expect | 2026

- **Robustness studies of Single Ring NN**

  Sensitivity to MC parameters (water transparency, PMT efficiency..)
- **First test of Neural Networks on Super-K Data**
- **Per-Pipeline benchmarks for fiTQun**

  CPU/GPU/xla python
- **Low Energy Threshold**

  Lower it to 2MeV using NN
- **Enhance the Multi Ring Pipeline**

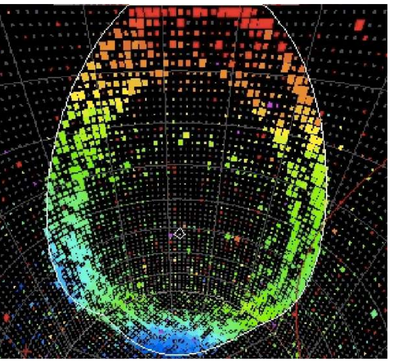
  Optimize the use of the lattent features
- **Paper publications**

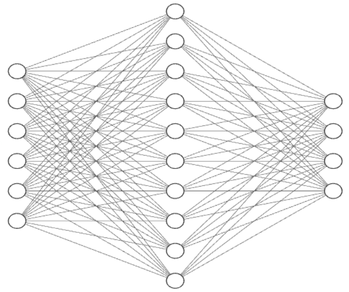
What to Expect | 2026 - NN-driven Reconstruction

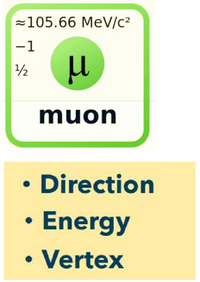
Reconstruction : Great improvements, and floor is not reached yet.

Step 1: Unifying models per E. Sector :

« one model for all variables »

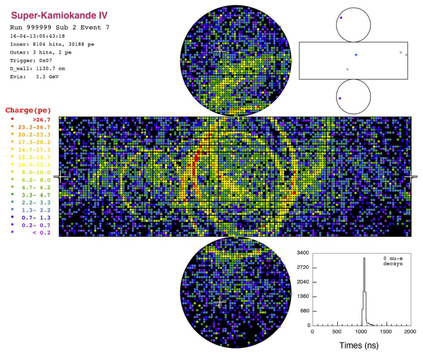


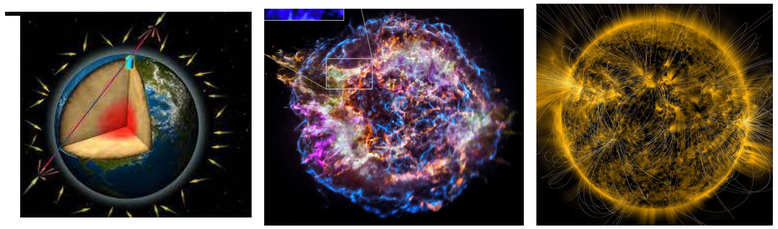




- Direction
- Energy
- Vertex

Step 2: Unifying models across E. Sectors ?





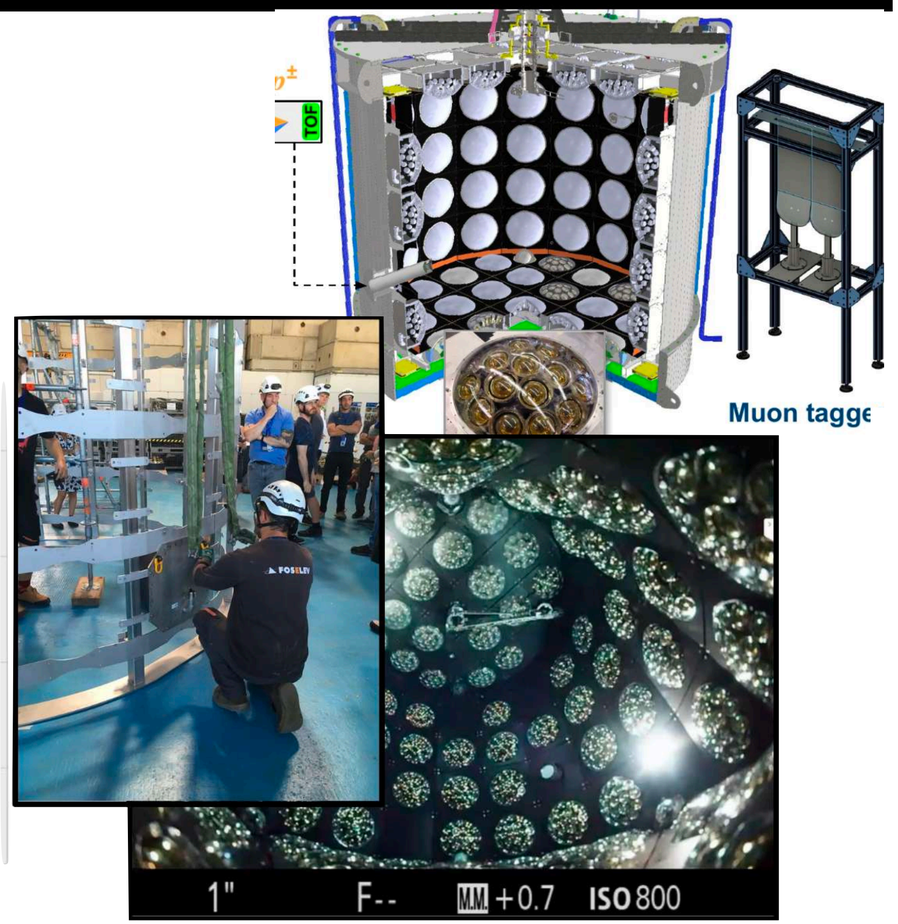
Multi Ring / Single Ring / Low E

Distinction only exists on our side.
It was more convenient to design per category likelihood methods, not true anymore for DNN

→ Requires to train models on **raw MC events**

Backup

WCTE : Status



- Data Taking **is finished**
- First result of NN-based reco on data to come soon !