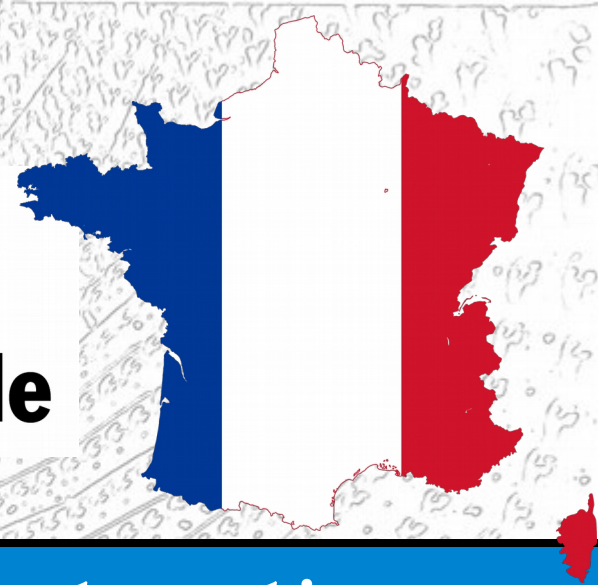




Hyper-Kamiokande



Nu 11 : Upgrade of the reconstruction algorithms from Super-K towards Hyper-K

Masaki Ishitsuka (Tokyo University of Science) &

Benjamin Quilain (Laboratoire Leprince-Ringuet, CNRS/Ecole polytechnique)

the Nu 11 group



International Laboratory for Astrophysics, Neutrino and Cosmology Experiments

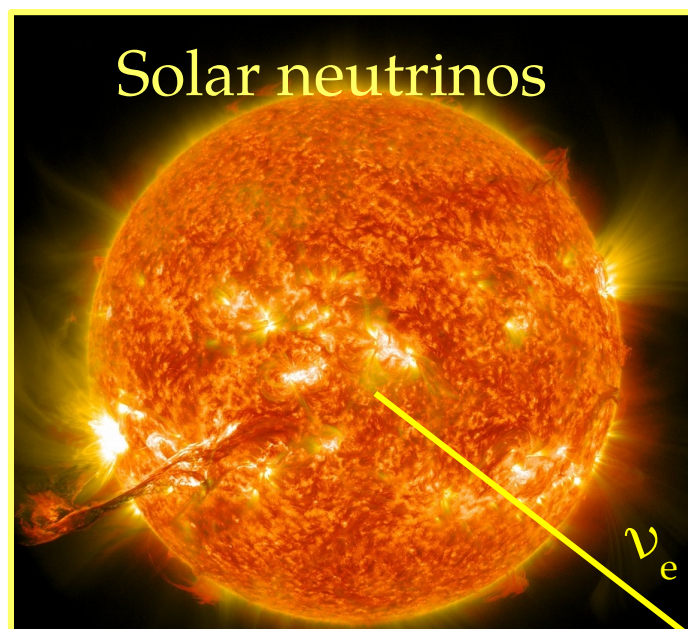


TYL-FJPPL meeting, KISTI, Daejeon, 2024/05/23



I. HK Physics & reconstruction overview

Solar neutrinos

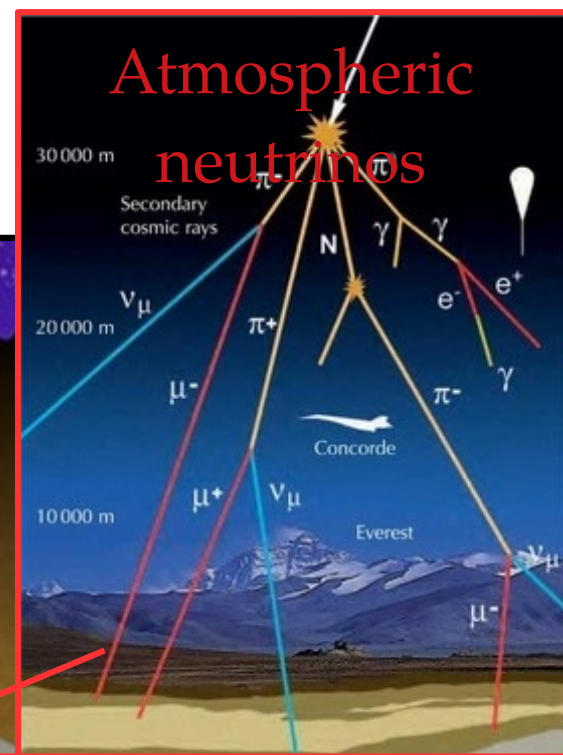


- MSW effect in the Sun
- Non-standard interactions in the Sun.

Physics case

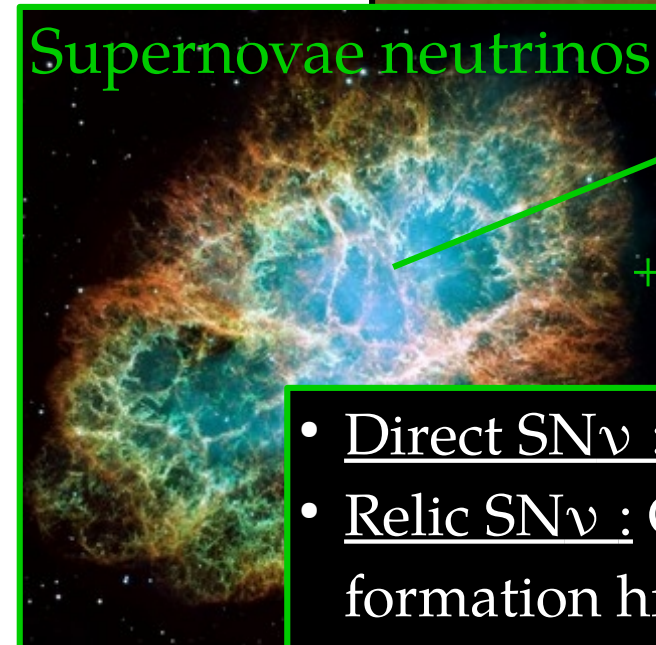
Proton decay

Probe Grand Unified Theories through p-decay (world best sensitivity)

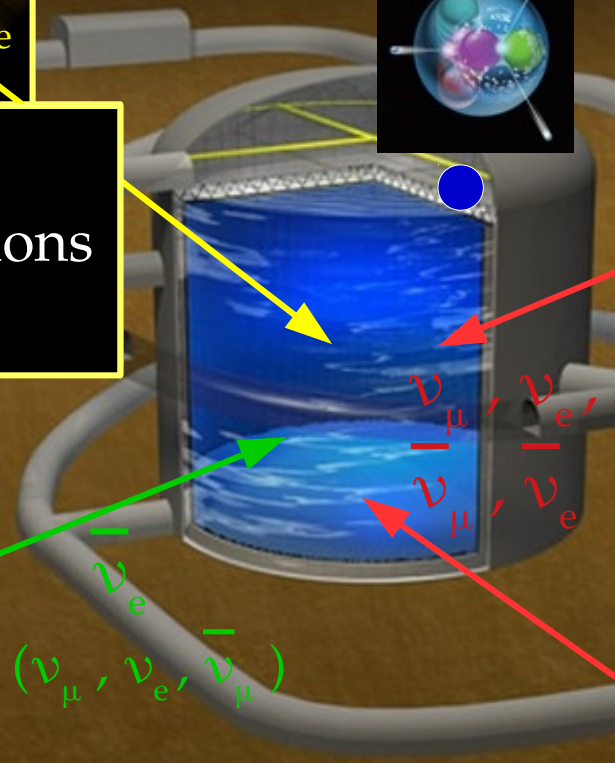


- Observe CP violation for leptons at 5σ
- Precise measurement of δ_{CP}
- High sensitivity to ν mass ordering.

Supernovae neutrinos



- Direct $SN\nu$: Constrains SN models.
- Relic $SN\nu$: Constrains cosmic star formation history



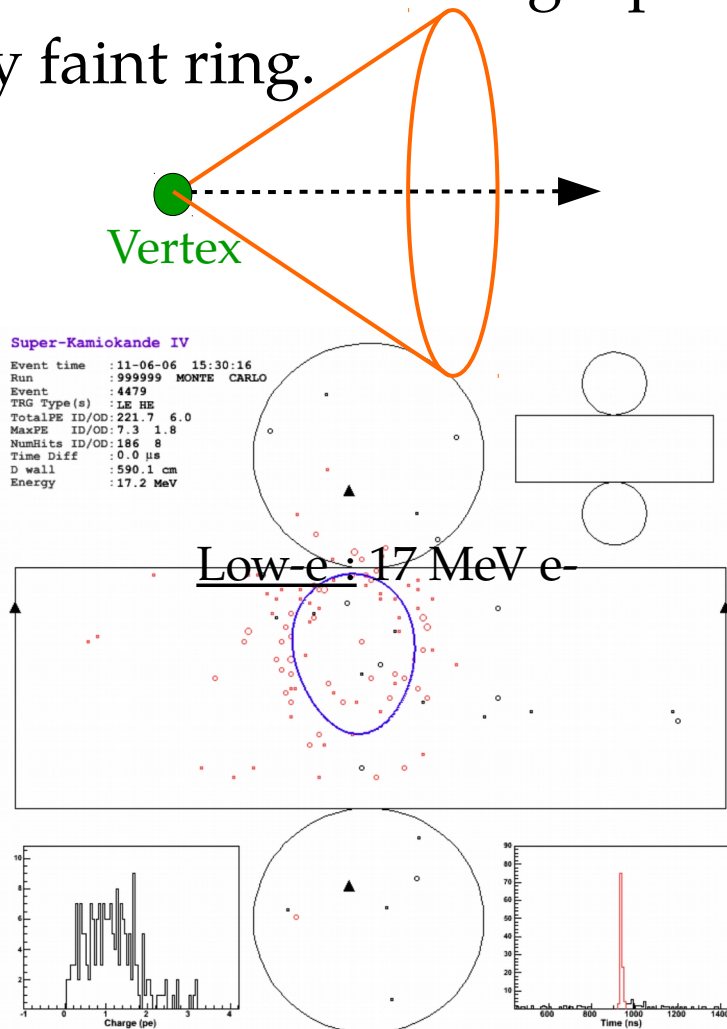
JPARC accelerator neutrinos

Low and high energies

- Two very \neq regimes & event topologies :

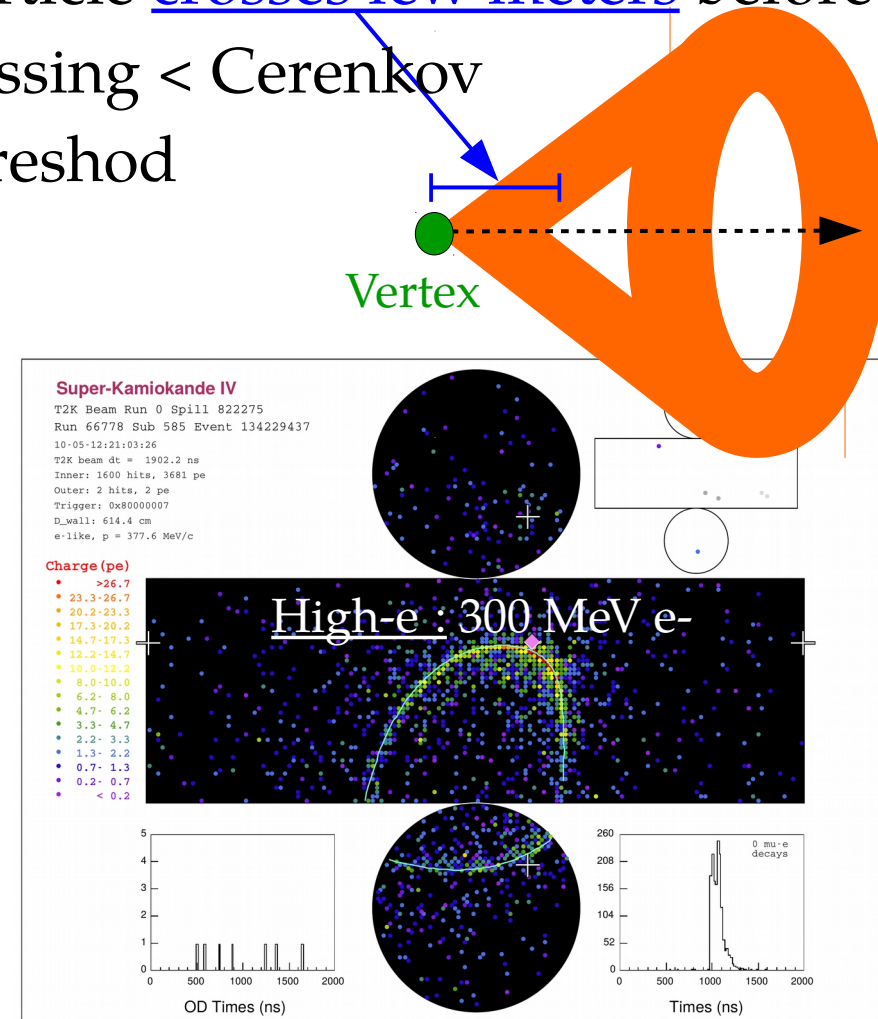
$E < 50$ MeV :

- Light emitted from single point.
- Very faint ring.



$E > 50$ MeV :

- Particle crosses few meters before passing $<$ Cerenkov threshold



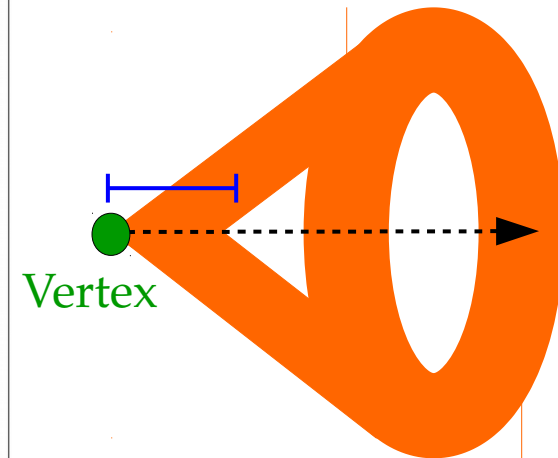
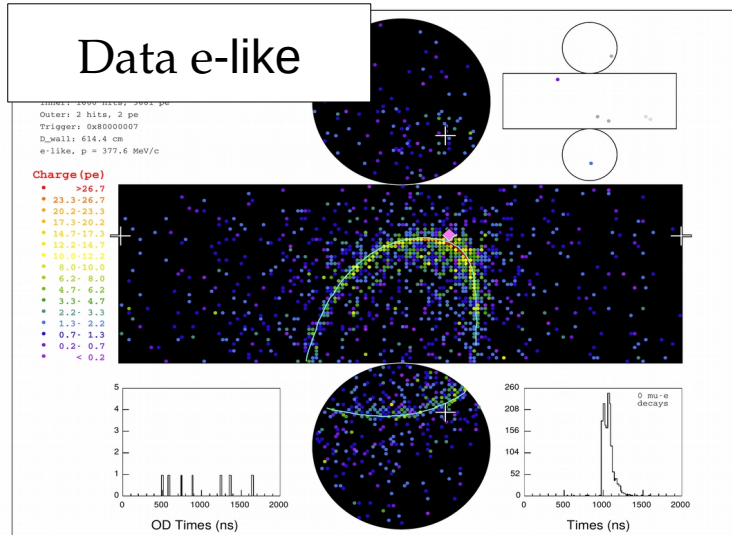
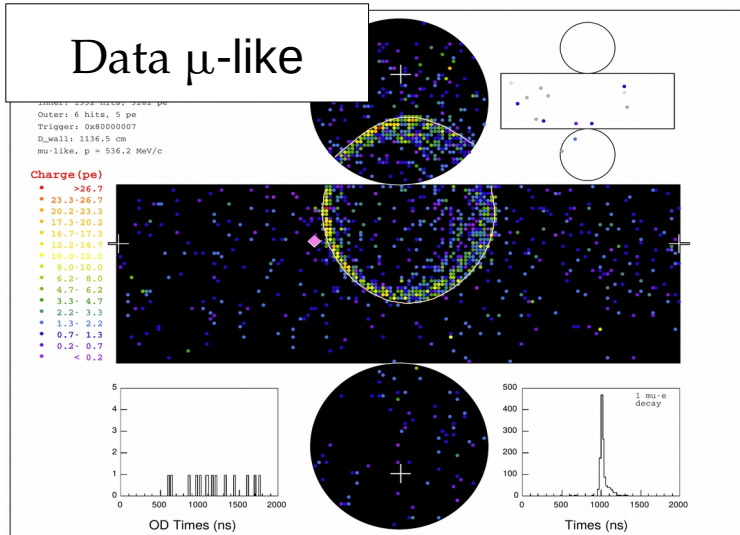
- Need/have 2 very \neq reconstruction algorithms in the 2 regimes.



II. Upgrade the fiTQun algorithm

fiTQun high-energy algorithm

- Simultaneous fit of 7 parameters using all PMTs charge&time:
 $\{X\}_i = (\text{vertex position, vertex time, momentum, direction, particle type})$



Likelihood-based fitter :

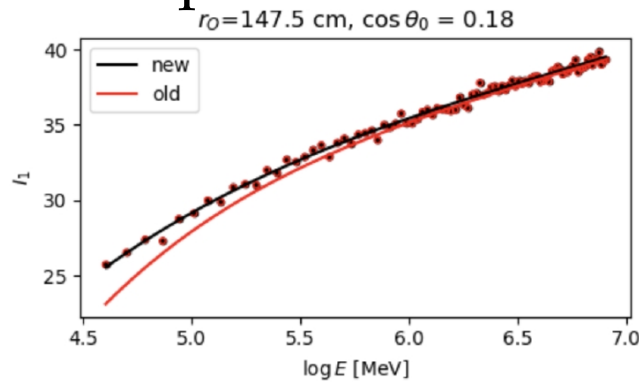
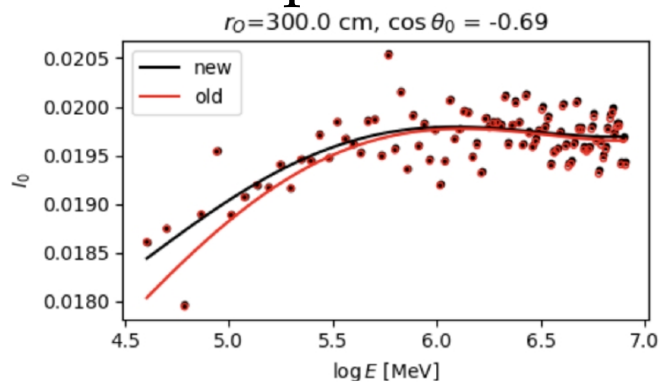
$$L(\mathbf{x}) = \prod_j^{\text{unhit}} \underbrace{P_j(\text{unhit}|\mu_j)}_{\text{PMT unhit probability}} \prod_i^{\text{hit}} \underbrace{\{1 - P_i(\text{unhit}|\mu_i)\}}_{\text{PMT hit probability}} \underbrace{f_q(q_i|\mu_i)}_{\text{PMT charge pdf}} \underbrace{f_t(t_i|\mathbf{x})}_{\text{PMT timing pdf}}$$

- fiTQun has supported SK physics for 15 years-old
 → Performant & robust !

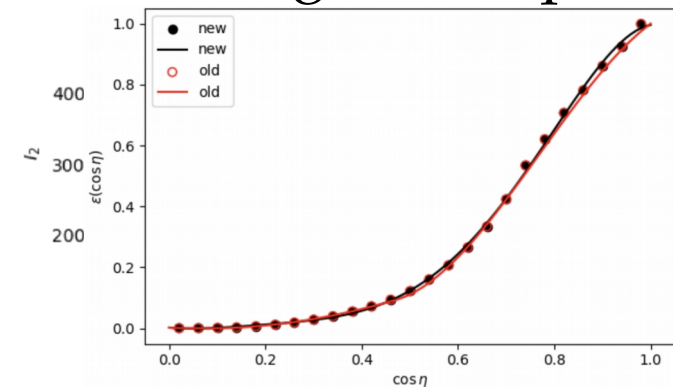
Upgrade & modernize fiTQun towards HK

- But is slow : 90s per electron @500 MeV → Too slow for very high statistical era of HK when reaching 1% syst/stat. ⇒ Optimize it.
→ 2023 : Modernized the code to allow time optimisation in 2024.

- G. Diaz has re-written part of the code : Perl → Python
→ Show potential room for improvements



PMT angular response



- Now fine-tuning fiTQun for HK & preparing the very first HK
« specific » production (Not scaled from SK)

→ Our group has a central role (M. Ishitsuka & S. Bolognesi as physics convener, B. Quilain, R. Matsumoto & G. Diaz are preparing fiTQun₇)

Testing fiTQun on data : SK atmospheric ν

- Improve fiTQun robustness : make it work with every SK periods

Phase	Dates	Livetime (Days)	Photo-coverage (%)	Neutron tagging
SK I	1996–2001	1489.2	40	–
SK II	2002–2005	798.6	19	–
SK III	2006–2008	518.1	40	–
SK IV	2008–2018	3244.4	40	H
SK V	2019–2020	461.0	40	H
SK Gd	2020–Present	–	40	H+Gd

43 % of the statistics for atmospheric ν cannot be analysed !

- Used the very old (APfit) algorithm from SK.

→ Mass-ordering measurement $> 2\sigma$: $\Delta\chi^2 = 5.7$

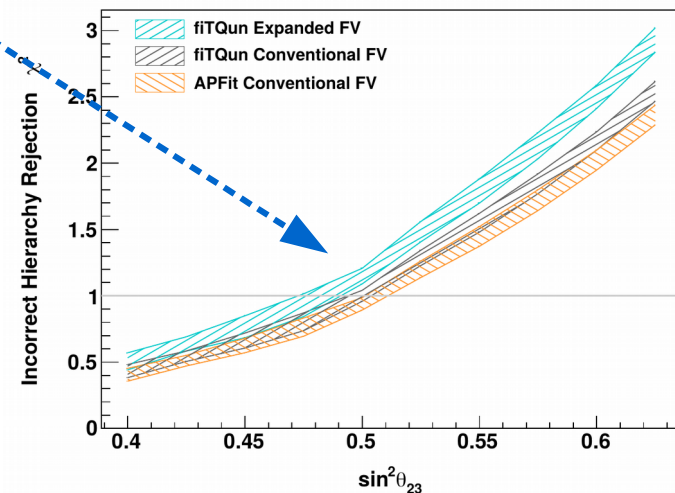
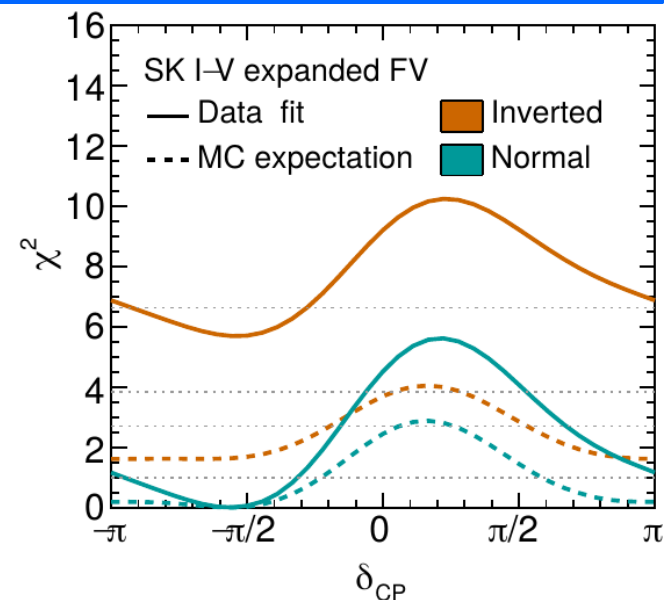
→ Less performant in FV-size & PID

→ C. Quach now try to include fiTQun w/SK-I,II&III (w/ R. Wendell - Kyoto U.)

→ A step towards 3σ constraints on MO.

- Nice progresses showing it seems possible

→ Hopefully a highlight in next year report !



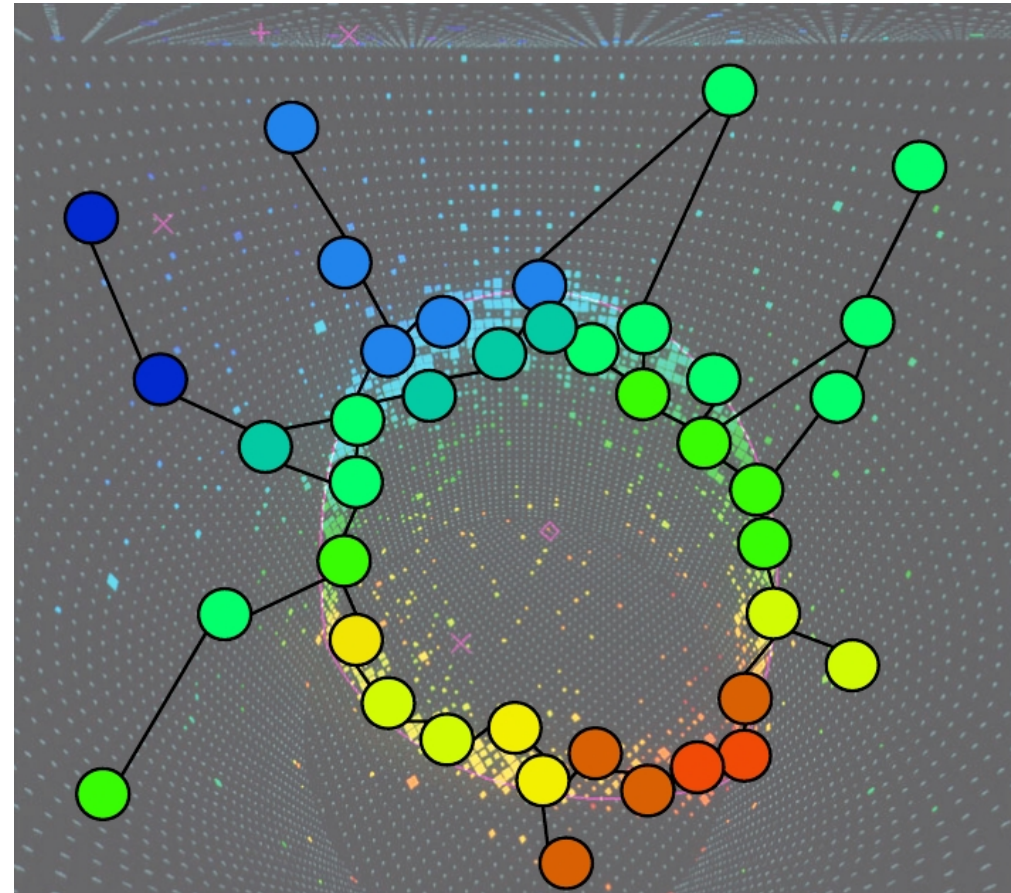
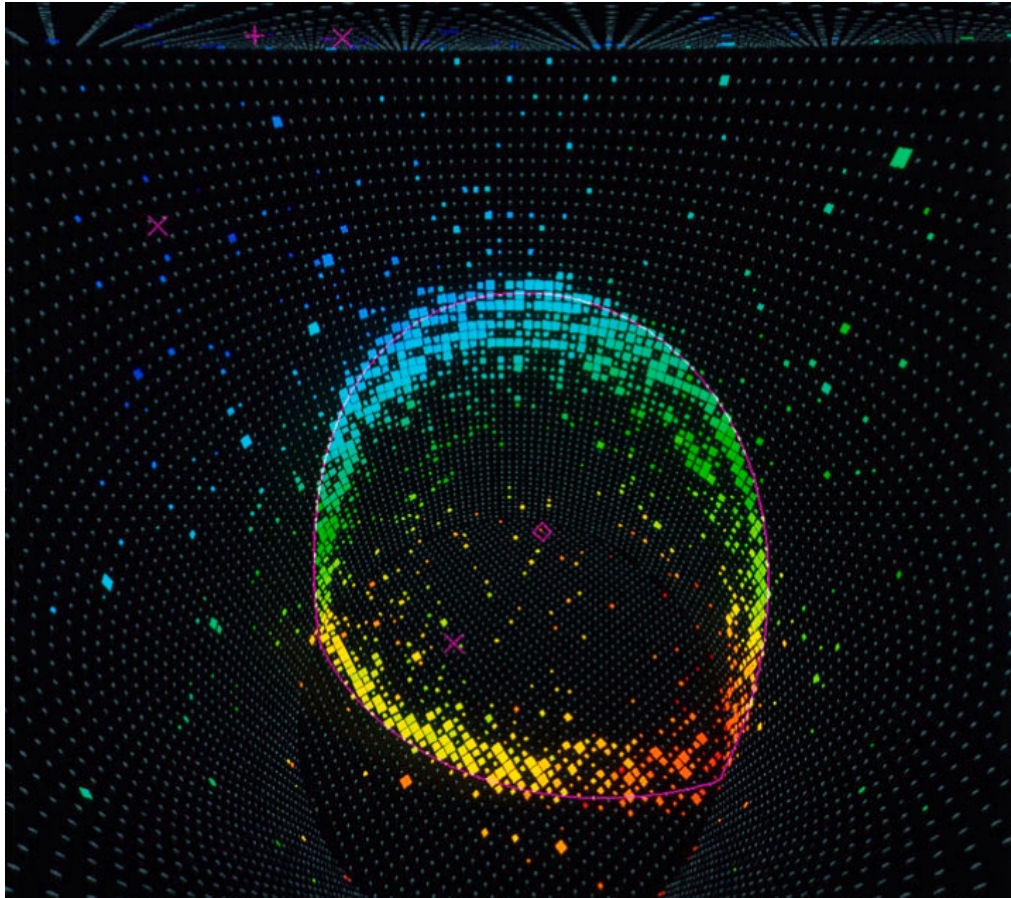


III. A new Machine learning reconstruction

A new ML-based reconstruction : GRANT

- GRANT : Graph-Neural Network (GNN) algorithm

→ Each hit PMT = a node of the GNN.

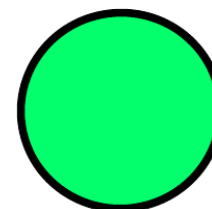
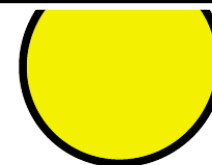
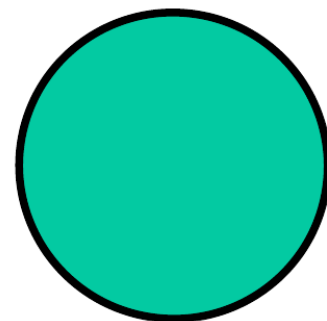
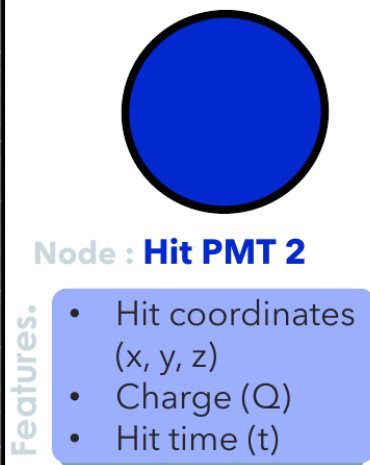
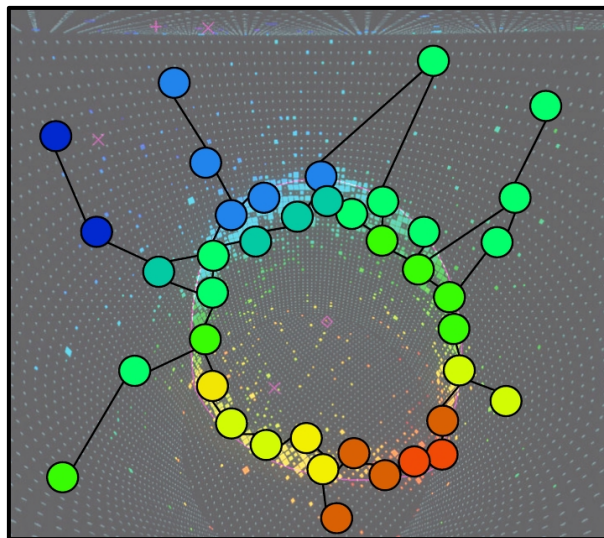


- Why a GNN :

- Easy to adapt to non-Euclidean geometry (here, a cylinder + time) ⇒ Impressive results on e.g. IceCube experiment.

Basic principles of GRANT

- Use the PMT informations (position, hit charge, hit time) to construct a Graph i.e. a connected array of PMTs → To e.g. reconstruct a ring.

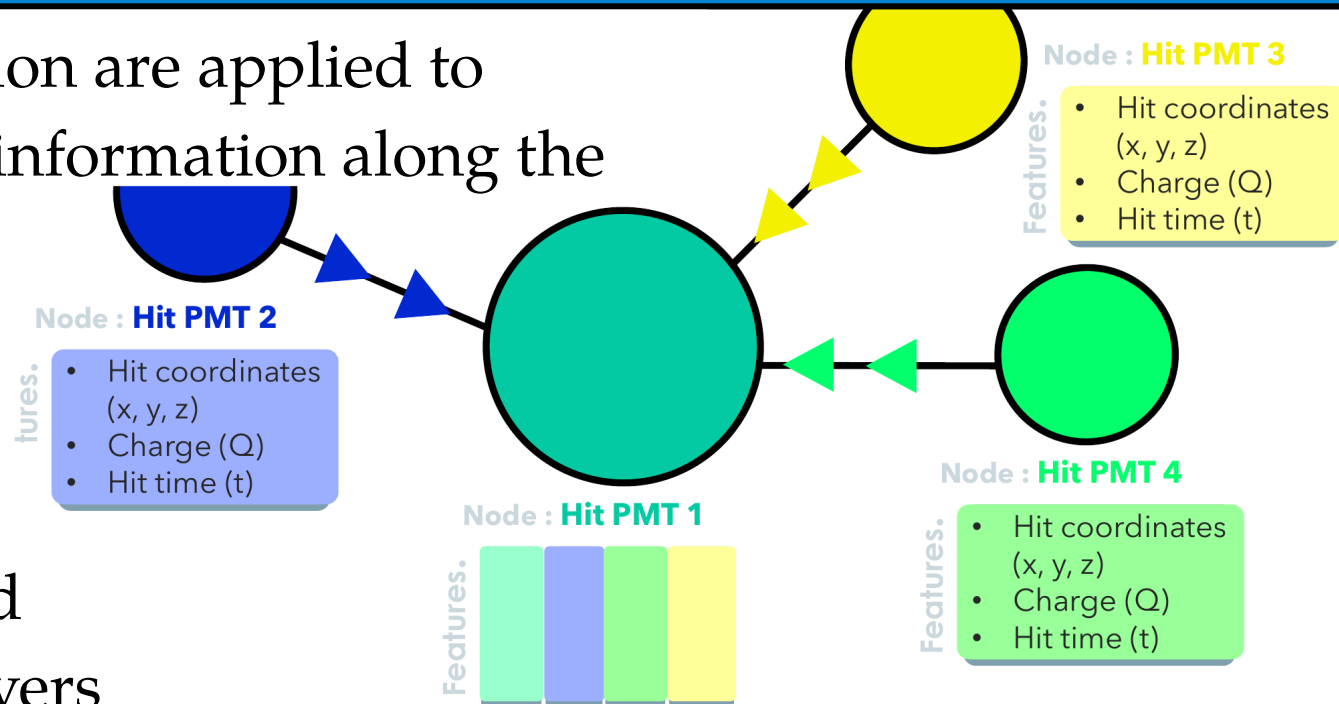


- How to connect the nodes/PMTs ?
 - Based on their spatial proximity ?
→ Clear image of a ring.
 - Based on their « charge deposit » proximity ?
 - Based on their hit time proximity ?
→ Great to reconstruct vertex through triangulation.
 - All at once ?

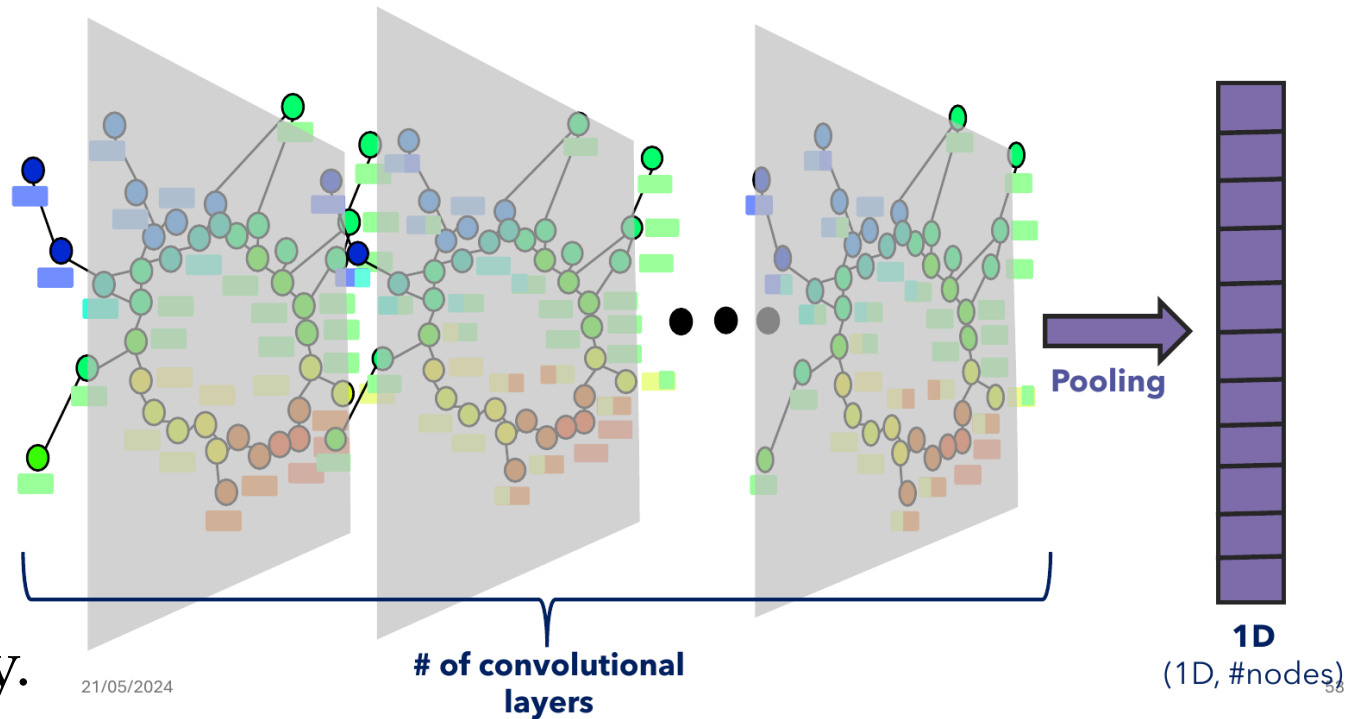
→ **Answers depends on the task we wish to accomplish.**

A new ML-based reconstruction : GRANT

- Aggregation + Convolution are applied to circulate/propagate the information along the nodes & « simplify it » using convolution.
→ 1 convolutional layer



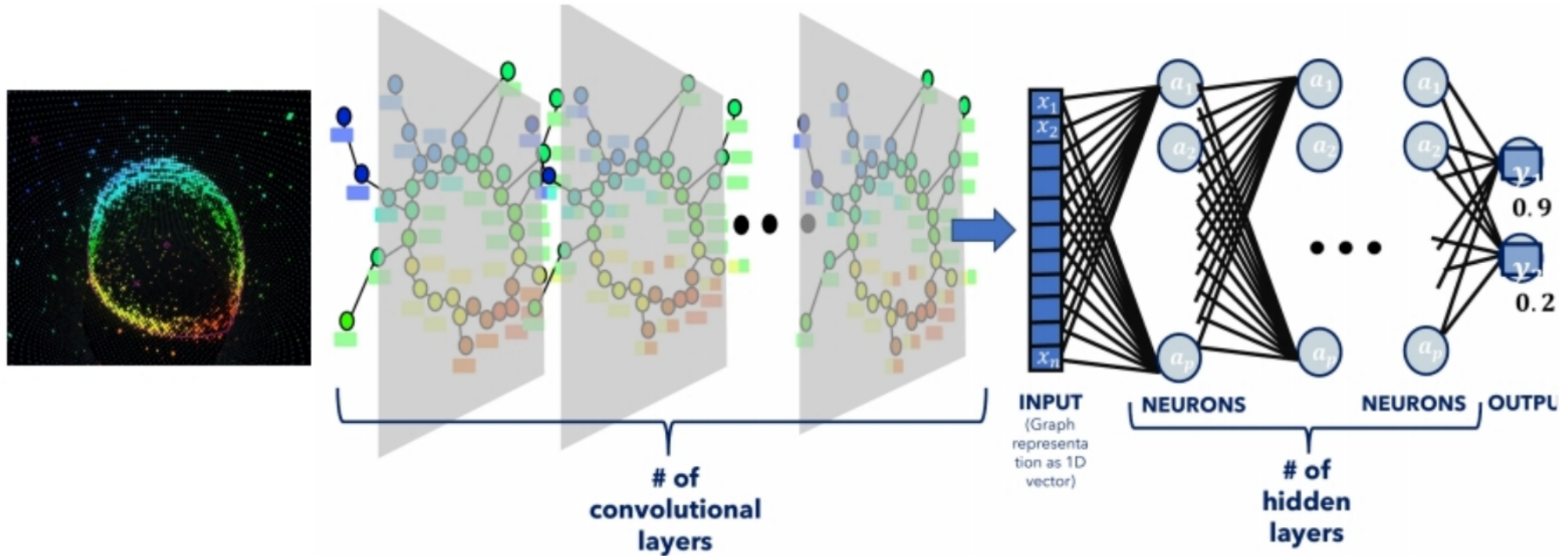
- The number of connected nodes, and number of layers should be optimized.
→ Problem dependent.
→ We optimized it through minimum gradient descent.



- Graph output is then aggregated in a 1D array.

A new ML-based reconstruction : GRANT

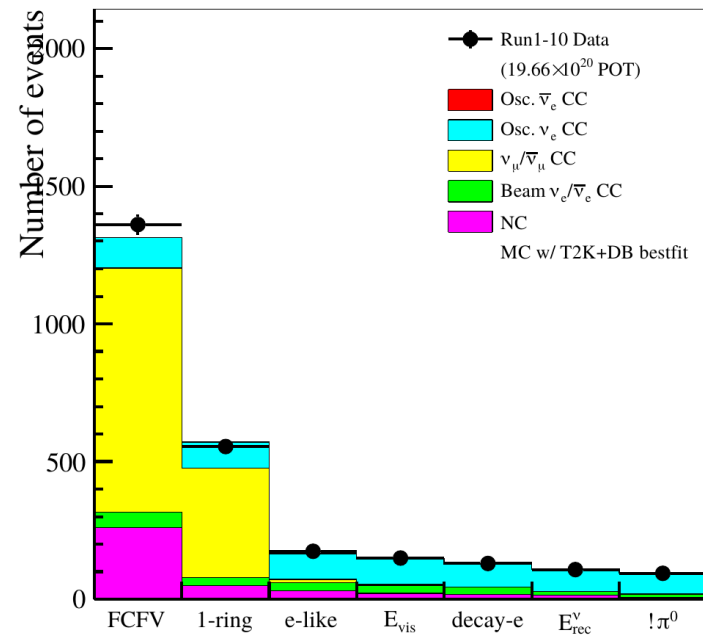
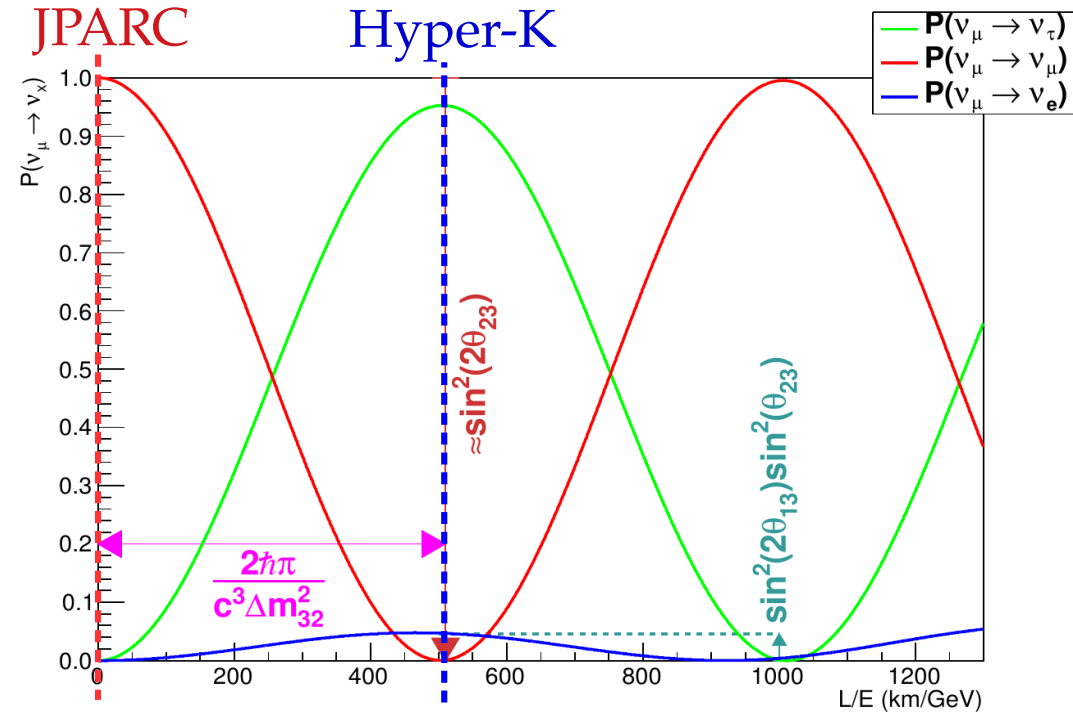
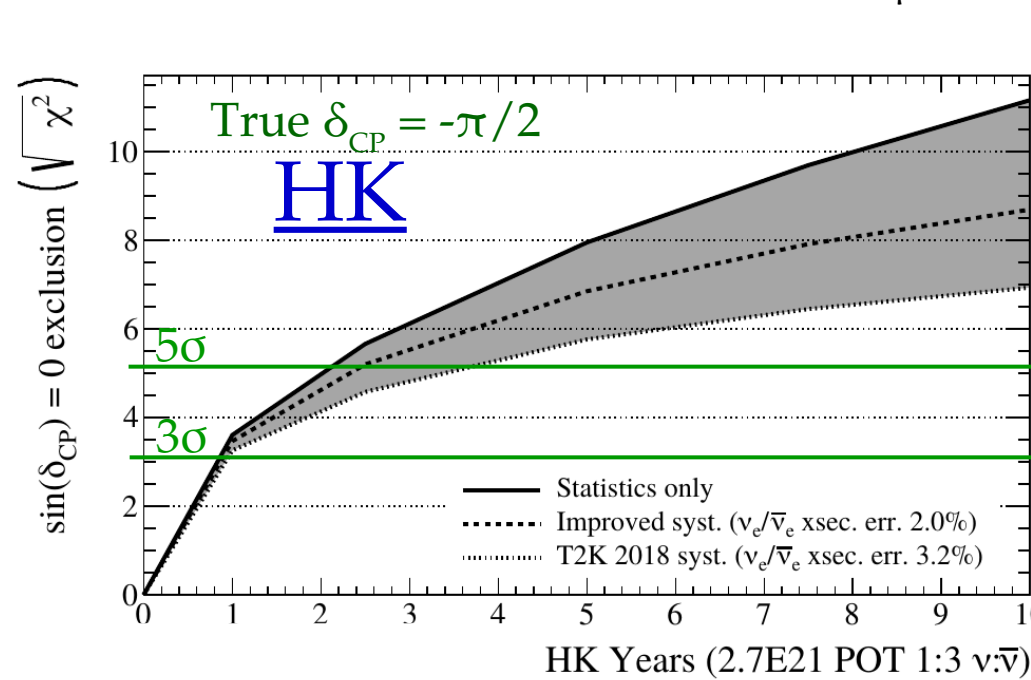
- A multi-layer perceptron basically does the final classification task
→ e vs μ , e vs π^0 , Energy regression etc.



- This GNN was developed from 2022 by **our group** (for low-energy)
→ Adapted to high energy from 2023.
→ From next slide, we will show the result of 4 first classifications :
1. PID e/μ 2. PID e/π^0 3. E-reconstruction 4. Vertex reconstruction
→ We will compare it to SK historical algorithm : fiTQun.

Focus of this year : high-energy physics

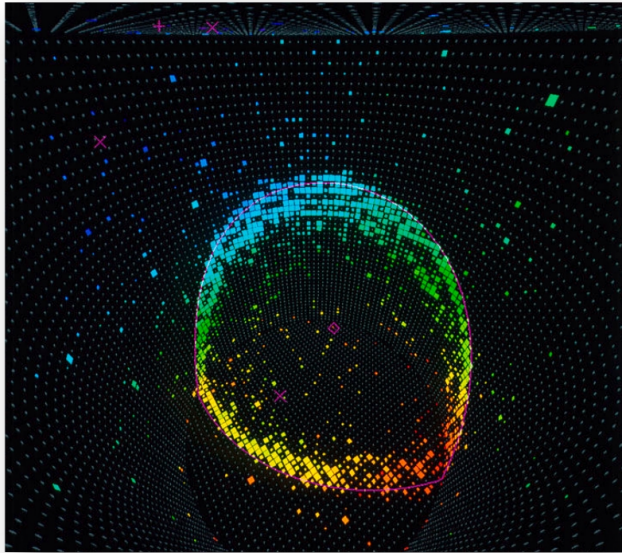
- Sensitivity to CP-violation : $\nu_\mu \rightarrow \nu_e$ oscillation \Rightarrow Clean e-like sample



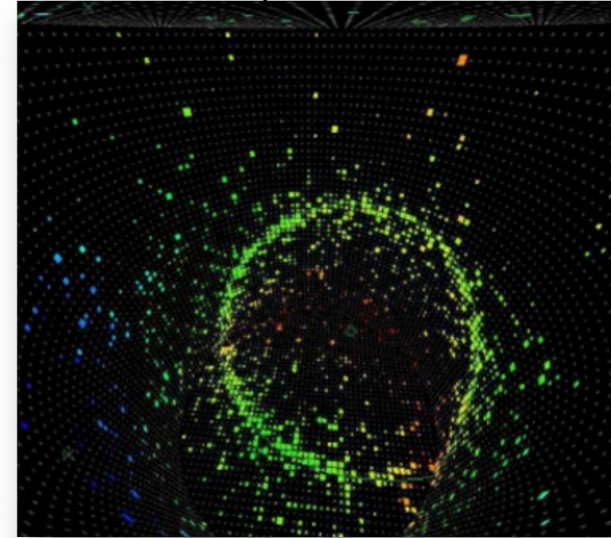
1. Vertex reco : Reconstructed in the FV
2. Ring counting : Number of rings = 1.
3. e/μ PID : the ring is electron-like.
4. E reco : Visible energy (E_{vis}) ≥ 100 MeV.
5. No decay electrons is detected.
6. $E_{\nu}^{rec} \leq 1250$ MeV.
7. e/π⁰ PID : rejection cut

Basic classifier : e/ μ separation

- e/ μ is THE SK most fundamental PID : remove ν_μ from ν_e sample.



Sharp ring

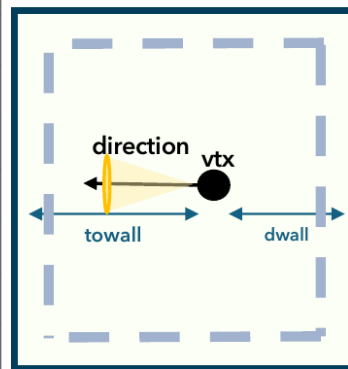
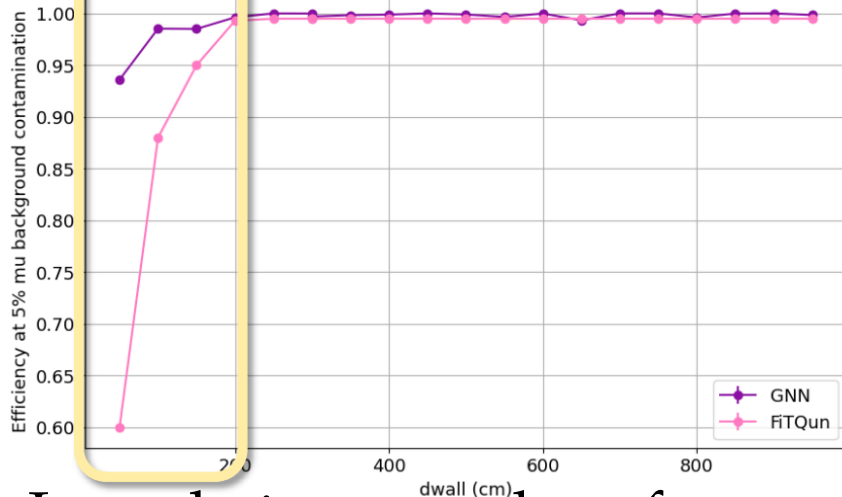


Fuzzy ring

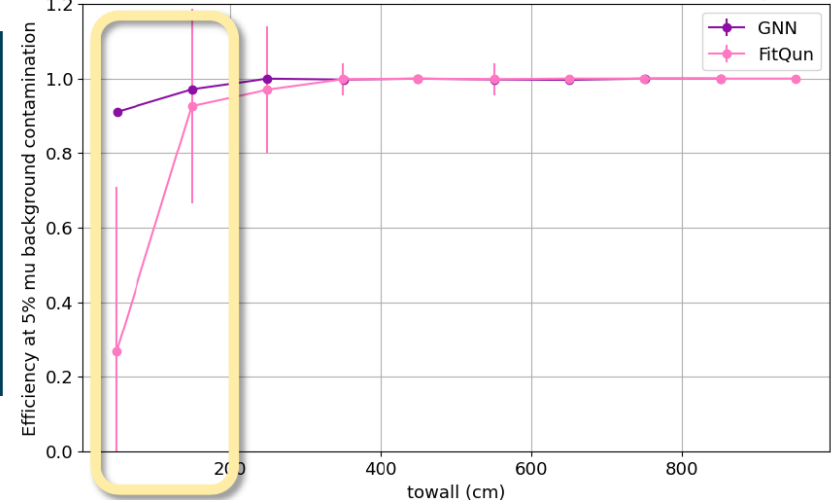
'05/2024

- GRANT : > 99 % e-efficiency for 5 % μ contamination \rightarrow As fitQun

Electron identification efficiency vs dwall (spectrum of energy, e/ μ separation)



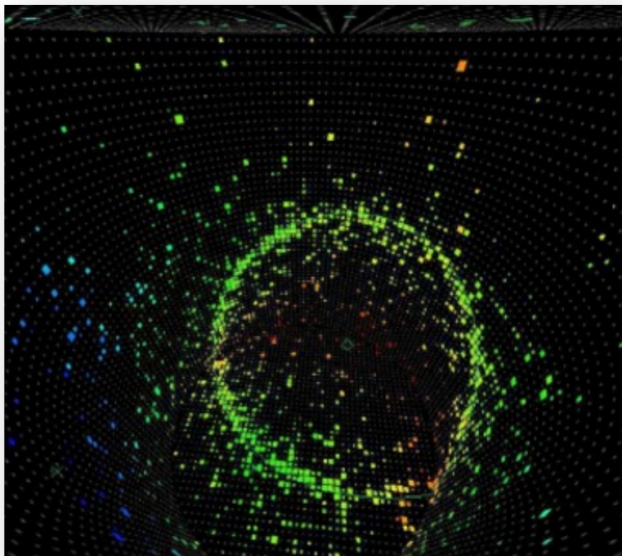
Electron identification efficiency vs towall (500 MeV, e/ μ separation)



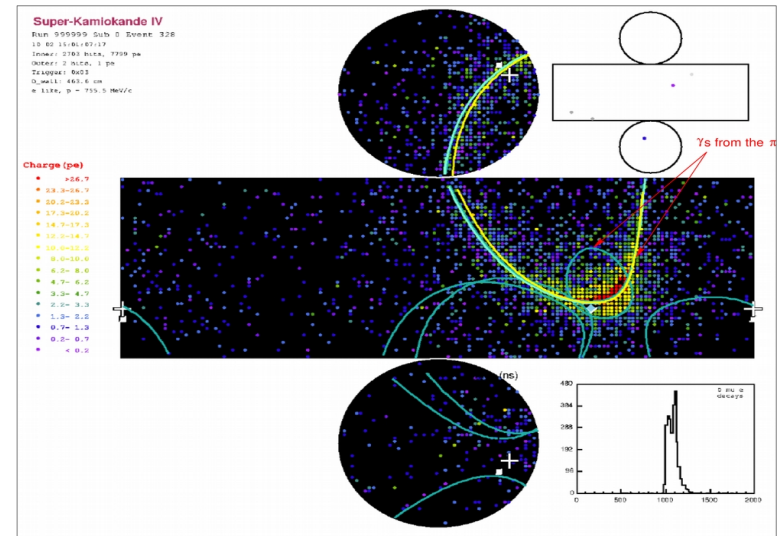
- Largely improved performances out of FV \rightarrow Enlarge FV & statistics !

Refiner classifier : e/π^0 separation

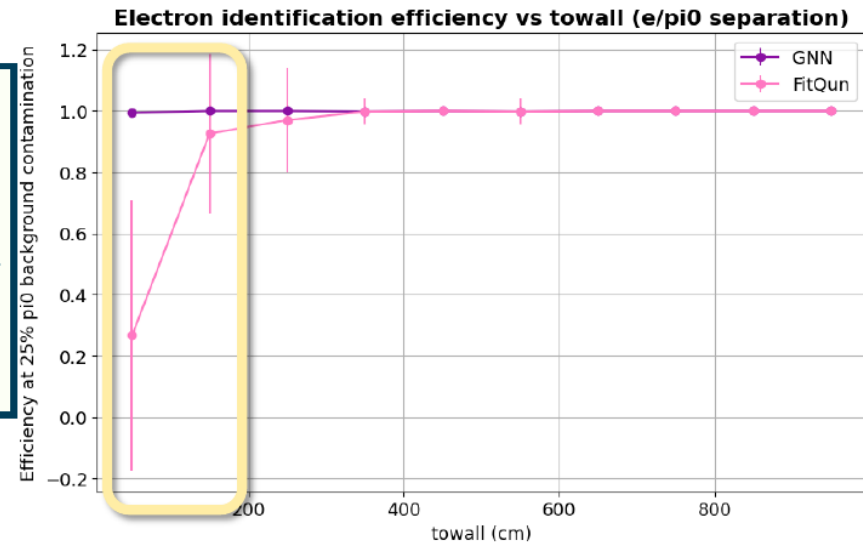
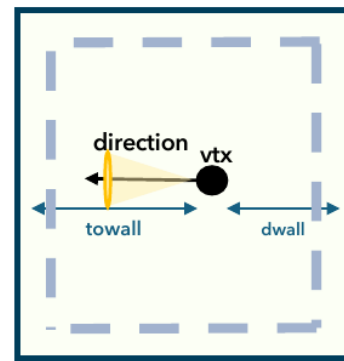
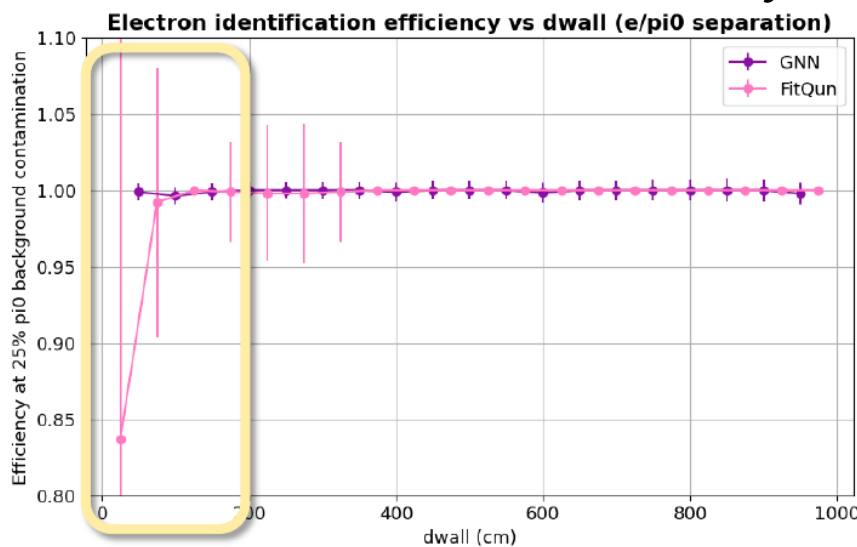
- e/π^0 PID is much more complex remove $NC\pi^0$ from ν_e sample.



Fuzzy ring



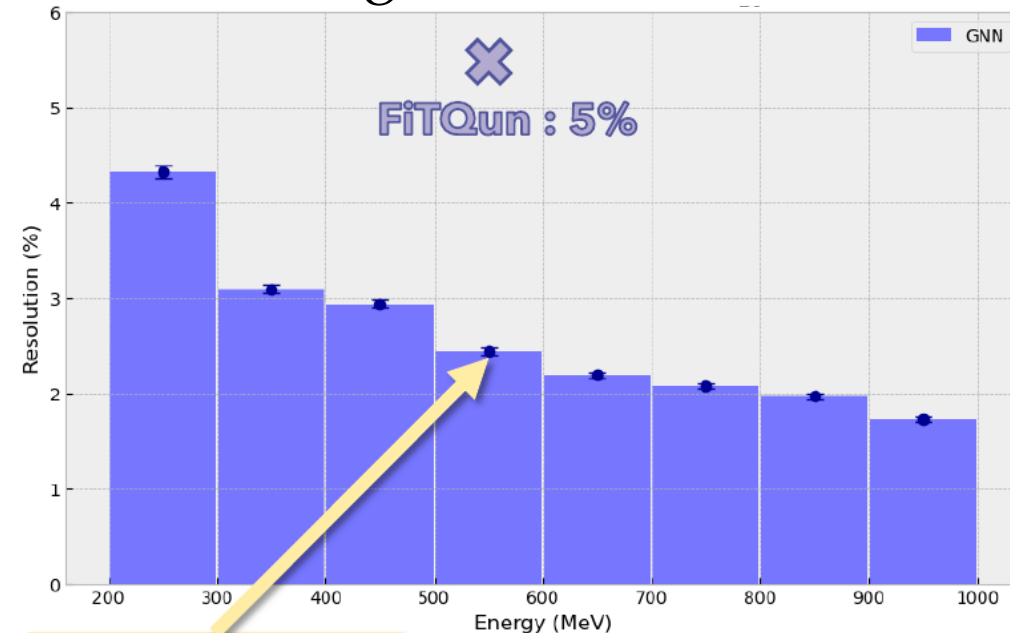
- GRANT : 98% e-efficiency @25% bkg contamination (fiTQun : 94%).



- GRANT surpasses fiTQun overall, especially close to wall \rightarrow enlarge FV.

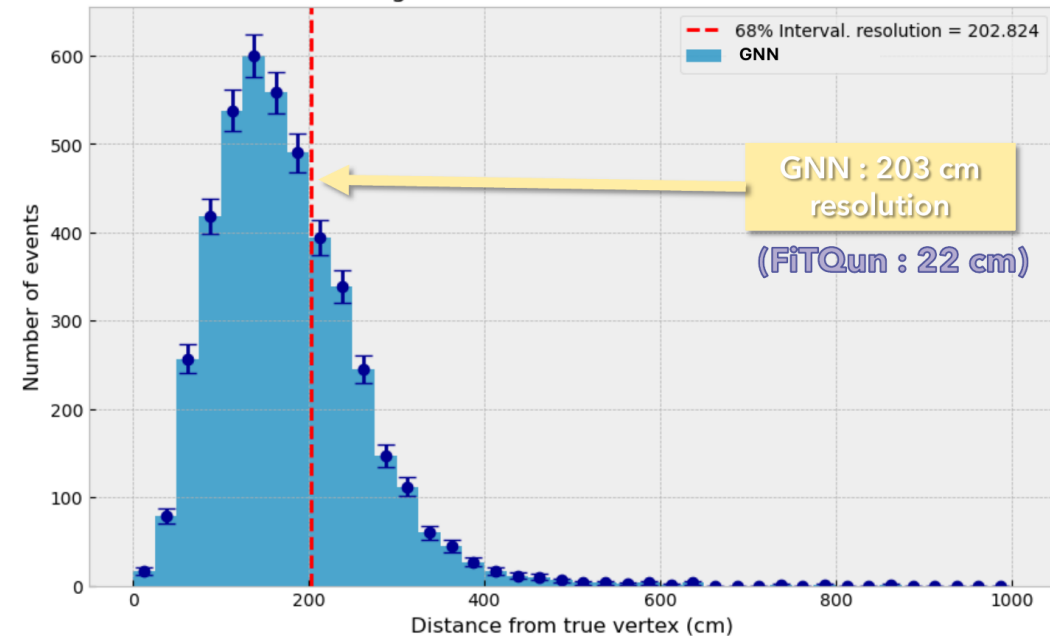
Continuous : Energy & vertex reconstruction

- After applying GRANT to binary classification → Test on continuous variable regression ⇒ Neutrino energy and interaction vertex.



GNN : 2.5% at 500 MeV,

21/05/2024



- GRANT E-resolution > fiTQun → But still a 1% E-bias to understand.

- Vertex resolution effort is **just starting**
 - Basically show we have no problem to fit a 3D continuous problem...
 - Now we are optimizing it !



Conclusions and next steps for 2024

Testing fiTQun on data : SK atmospheric ν

- Nu11 aims to upgrade the reconstruction algorithm for HK & SK
→ In 2023 : focused on most challenging high-energy sector.

- We developed a new GNN-based algorithm : GRANT

→ After 1 year : promising 1st result > fiTQun in e/μ , e/π^0 PID & E-resolution.
→ While being much faster !

- And upgrading the robust fiTQun from SK → HK :
→ Re-writing of the code to make its development easier.
→ Fine-tuning to HK (and not SK).

	GNN	FitQun
e/mu	99% electron efficiency at 5% muon bg acceptance, Dwall, towall analysis: After 2 m, efficiency above 99.4% !	99% electron efficiency at 5% muon bg acceptance,
e/gamma	58% efficiency at 50% bg acceptance... [Fixed energy]	None
e/pi0	98% electron efficiency at 25% pi0 bg acceptance. [Fixed energy] 78% electron efficiency at 25% pi0 bg acceptance [Spectrum of energy]	94% electron efficiency at 25% pi0 bg acceptance
Energy reconstruction for e & mu	<ul style="list-style-type: none"> • Electron : 5% resolution at 500 MeV, energy bias at ~4% • Muon : 7% resolution at 500 MeV, energy bias at ~7% 	<ul style="list-style-type: none"> • Electron : 7% resolution at 500 MeV • Muon : 6% resolution at 500 MeV
Vertex reconstruction for e & mu	<ul style="list-style-type: none"> • Electron : 91,7 cm longitudinal resolution, 153 cm transversal resolution, • Muon : 103 cm longitudinal resolution, 181 cm transversal resolution, 	

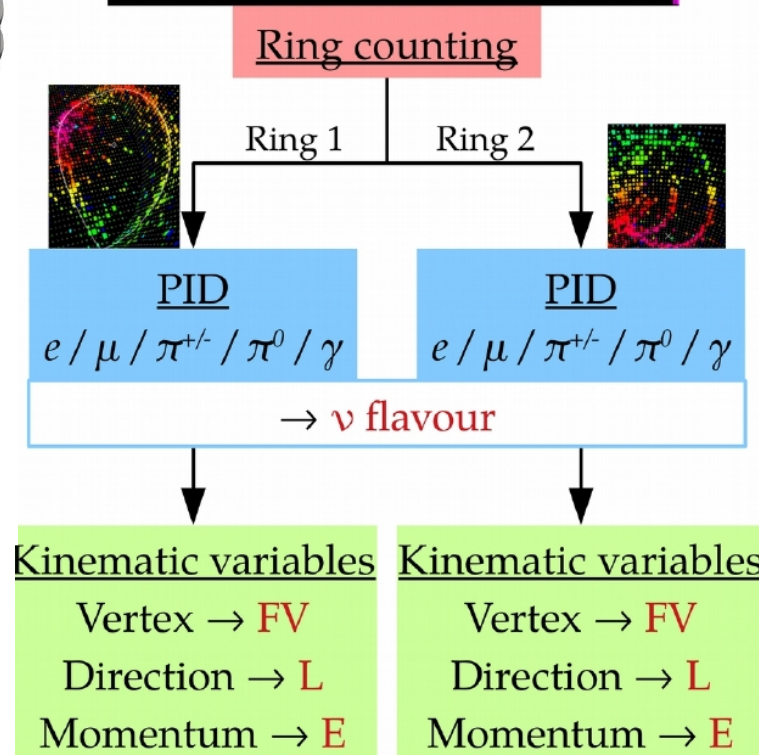
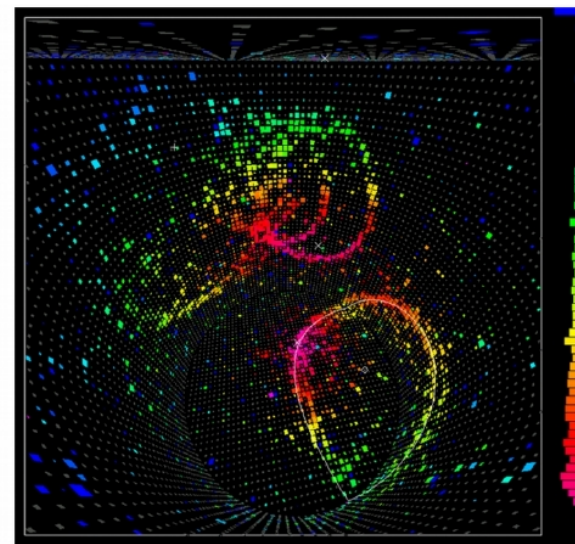
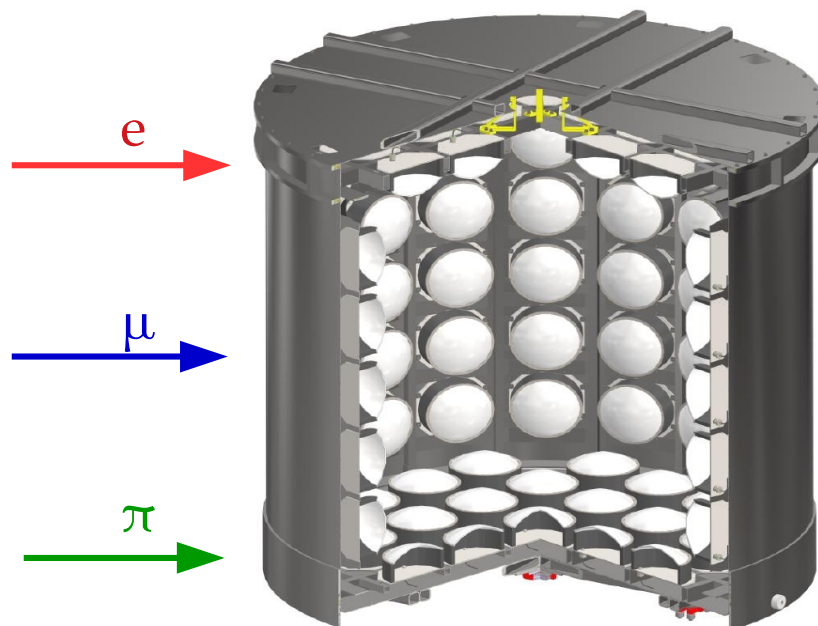
CPU time / event	1 ring e/μ PID	1 ring e/π^0 PID	Energy & vertex reco.	Total
fiTQun	30s	50s	Simultaneous to PID	80s
CAVERNS	0.09s	0.07s	0.05s	0.11s

→ Adapt&test w/ older SK periods to improve SK-atmospheric results.

Prospects for 2024

- For GRANT :

- Improve the vertex/direction reco.
- Create a ring-counting algorithm.
⇒ Final step to have an entire fitting algorithm
- Test it on Water Cherenkov Test Experiment data for 1st time to test its robustness.



- For fiTQun :

- Ride on the new software to improve its speed.
- Develop a e/γ fitter.
- Adapt it to SKI, II, III.

Our project members

Benjamin Quilain,

Margherita Buizza Avanzini, Olivier Drapier, Thomas Mueller, Pascal Paganini, A. Ershova, Antoine Beauchene, Andrew Santos, C. Quach, E. Le Blevec (LLR/IN2P3)

Jacques Dumarchez, Marco Zito, Claudio Giganti, Mathieu Guigue, Boris Popov, Stefano Russo, G. Diaz Lopez (LPNHE/IN2P3)

NEW

S. Bolognesi (CEA/IRFU - DPhP)

Masaki Ishitsuka

(Tokyo University of Science)

Masahiro Kuze, Shota Izumiyama, Kota Yoshida

(Tokyo Institute of Technology)

Patrick De Perio, César Jesus-Valls, Junjie Jia

(Kavli IPMU, The University of Tokyo)

Michel Gonin, Guillaume Pronost, Lorenzo Perisse (ILANCE)

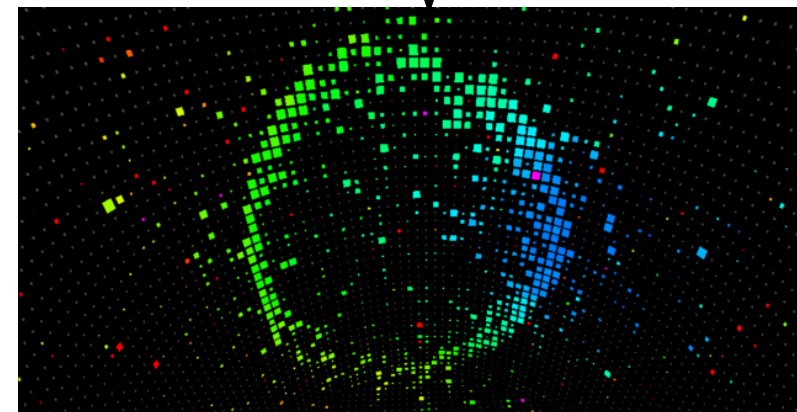
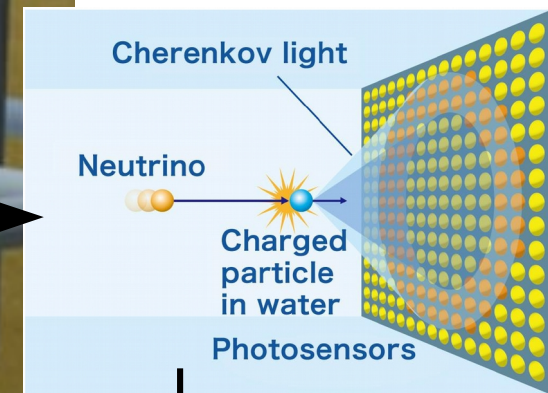
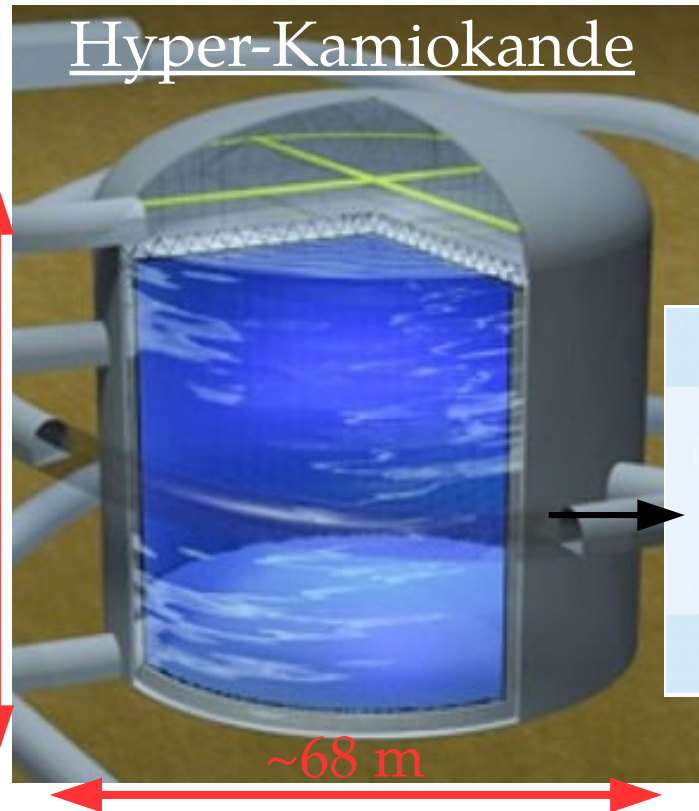
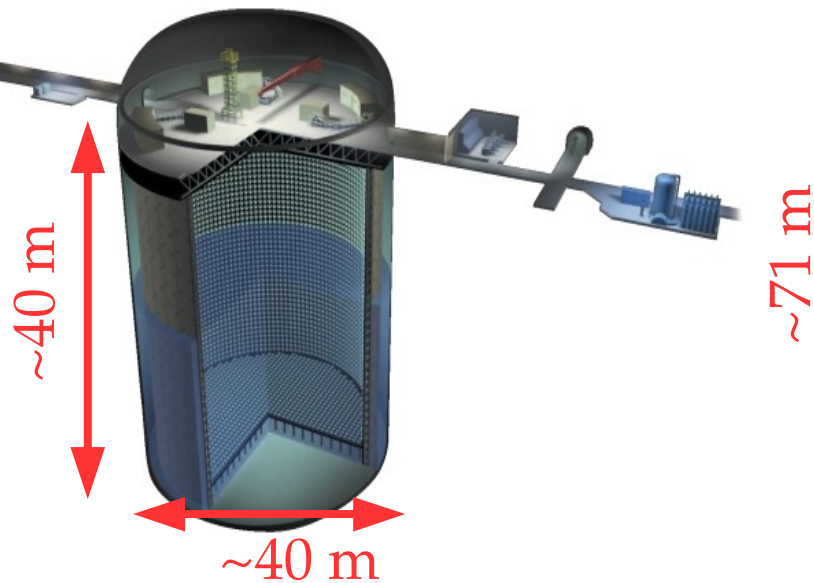


Additional slides

What is Hyper-K ?

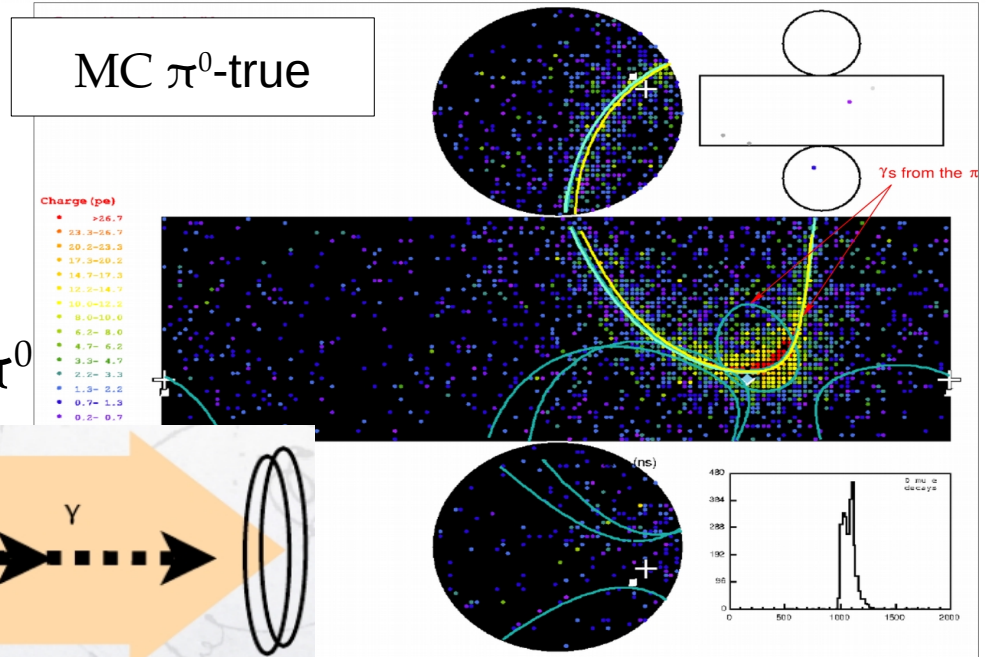
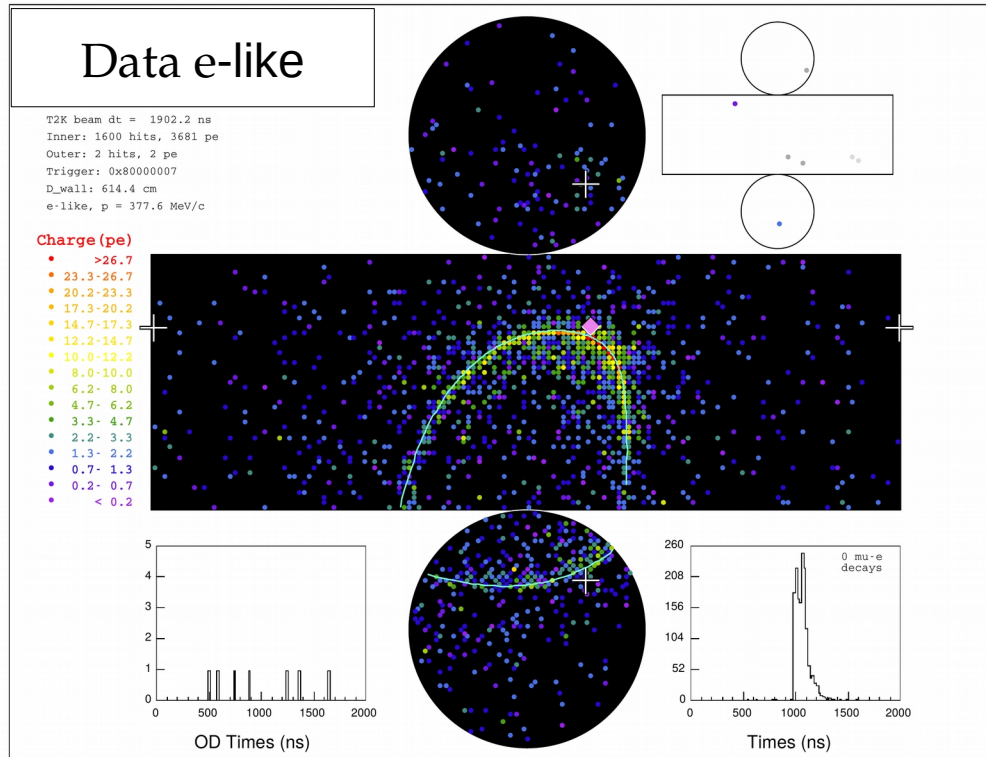
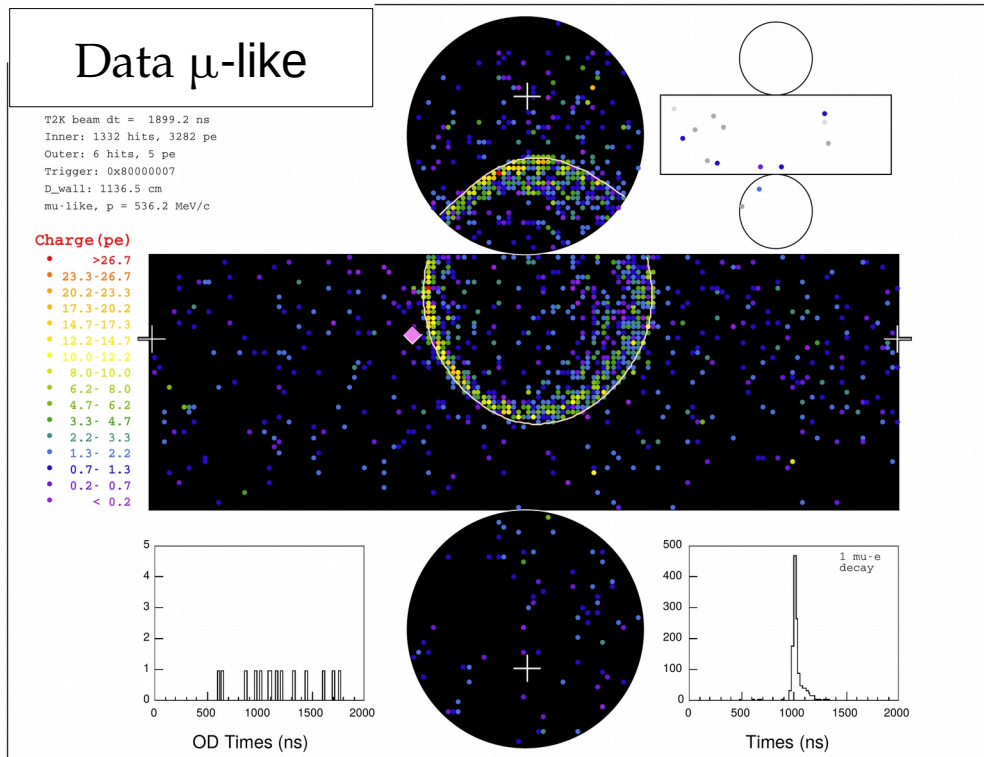
- Next generation of neutrino observatory in Japan → construction 2020-27
→ A 260 kton water Cherenkov detector → Fiducial Mass ~ 8 x SK.

Super-Kamiokande



	Super-K	Hyper-K
Site	Mozumi	Tochibora
Overburden	2780 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% (×2 efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	258 kton / 186 kton

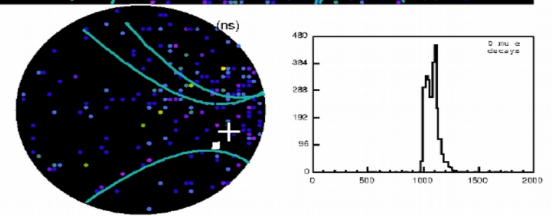
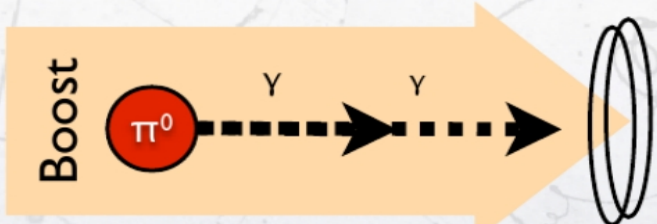
Focus of this year : high-energy physics



• We will show :

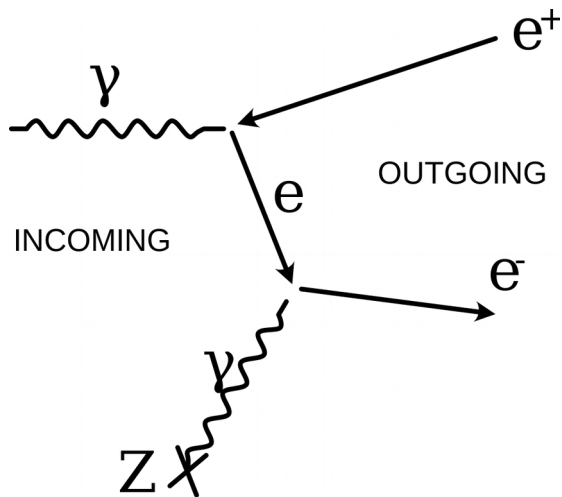
1. Vertex resolution.

2. Particle identification : e/μ & e/π^0

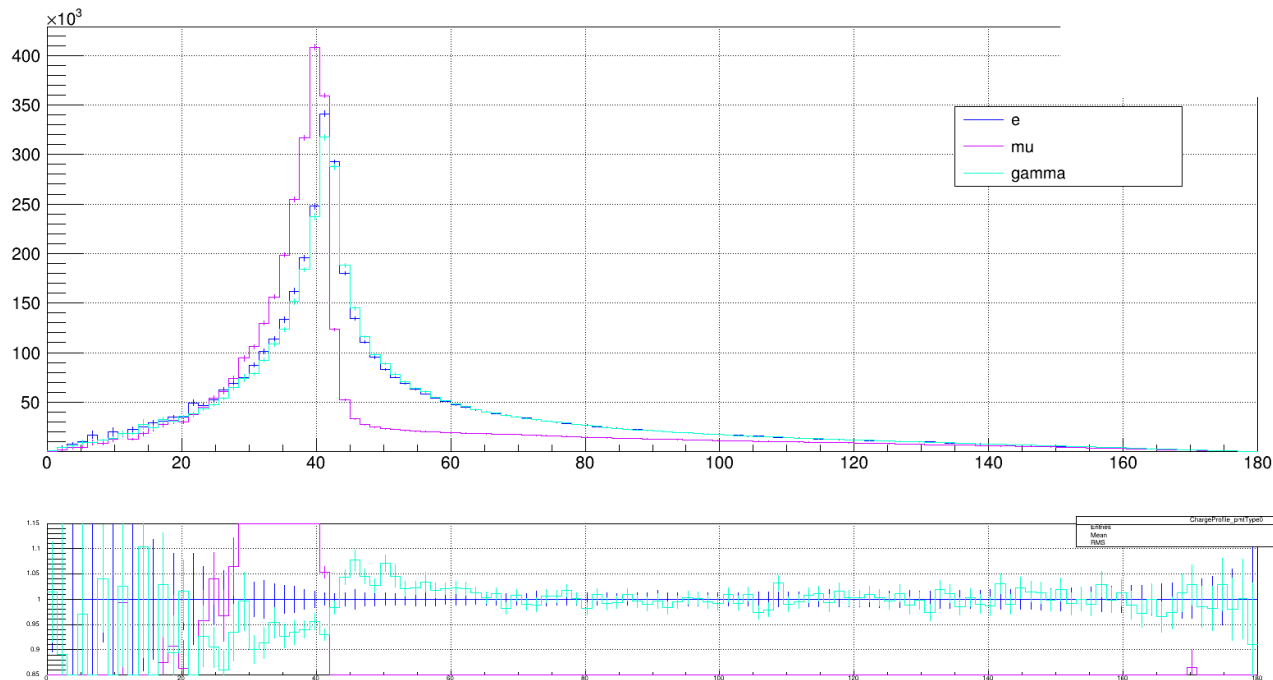


Limitations of current algorithm

- Dominant limitation is computing time : 90s / HK event @500 MeV
→ A major issue for any simulation aiming to study < 1 % systematics.
→ **Goal #2** : Significantly ↓ processing time before HK starts.
- Second limitation : Fine particle identification → e/γ separation
→ Not done in fiTQun. Both provides a « shower-like » fuzzy ring.



Superposition of 2 shower-like event



- **Goal #3** : Separate e/γ them using the outer-edges of the ring.

The fiTQun algorithm

PMT unhit probability

PMT hit probability PMT charge pdf

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

PMT timing pdf

- $X = (x, t, p, \theta, \varphi)$: Particle hypothesis \rightarrow 7 variables fit
- $\mu = \mu^{\text{dir}} + \mu^{\text{scat}}$: Poisson mean of predicted charge detected by each PMT, which is also a function of X

Normalization Integration along the particle track

$$\mu^{\text{dir}} = \underline{\Phi(p)} \int \underline{ds} \underline{g(p, s, \cos \theta)} \underline{\Omega(R)} \underline{T(R)} \underline{\epsilon(\eta)}$$

Cherenkov emission profile

PMT solid angle at $\eta=0$
 $\sim R^{-2}$

Light attenuation in water
 $\sim \exp(-R/L_{\text{attenuation}})$

PMT angular response

