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

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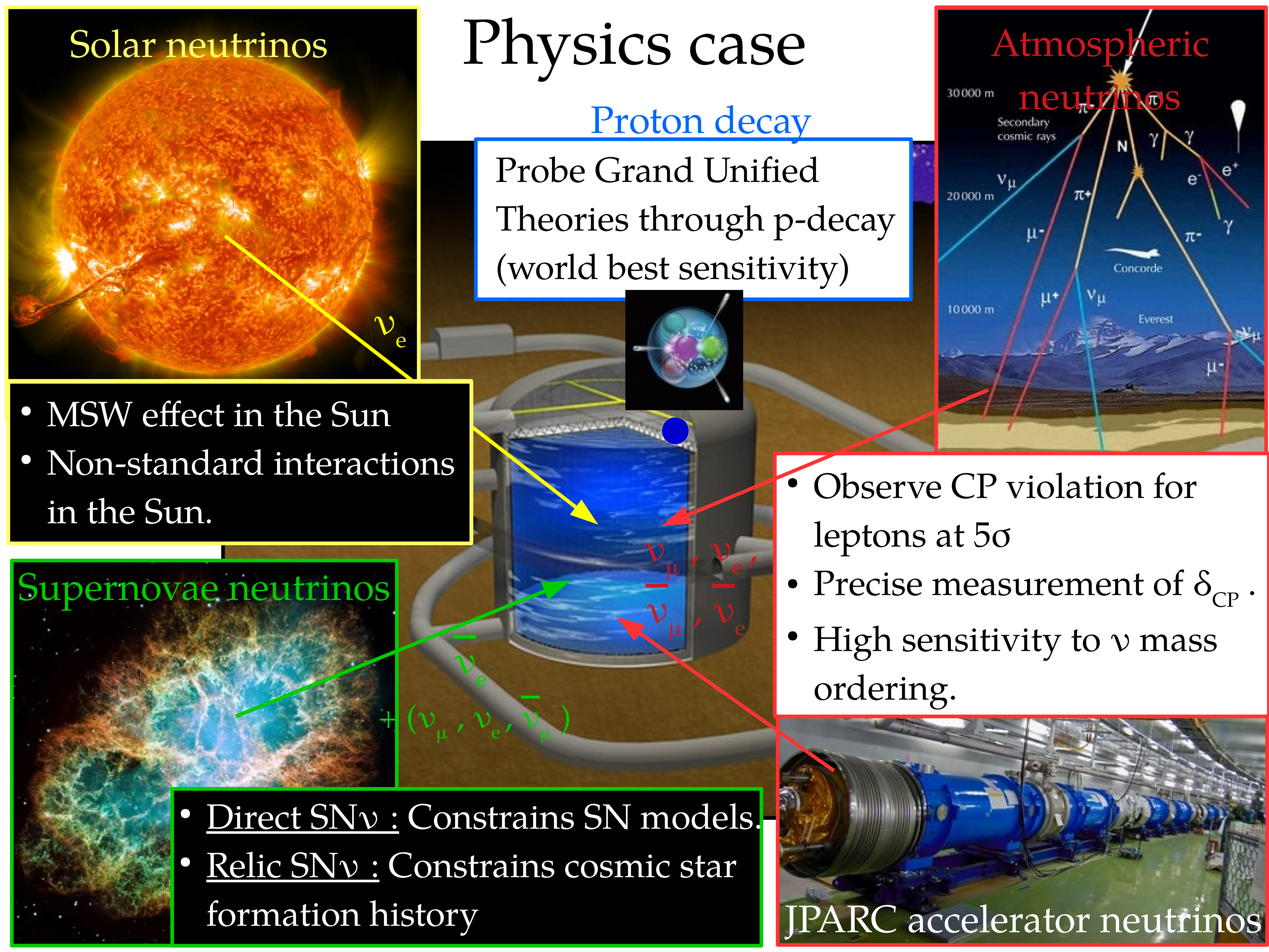
for the Nu 11 group

TYL-FJPPL meeting, Nantes, 2025/05/14

I. HK Physics & reconstruction overview



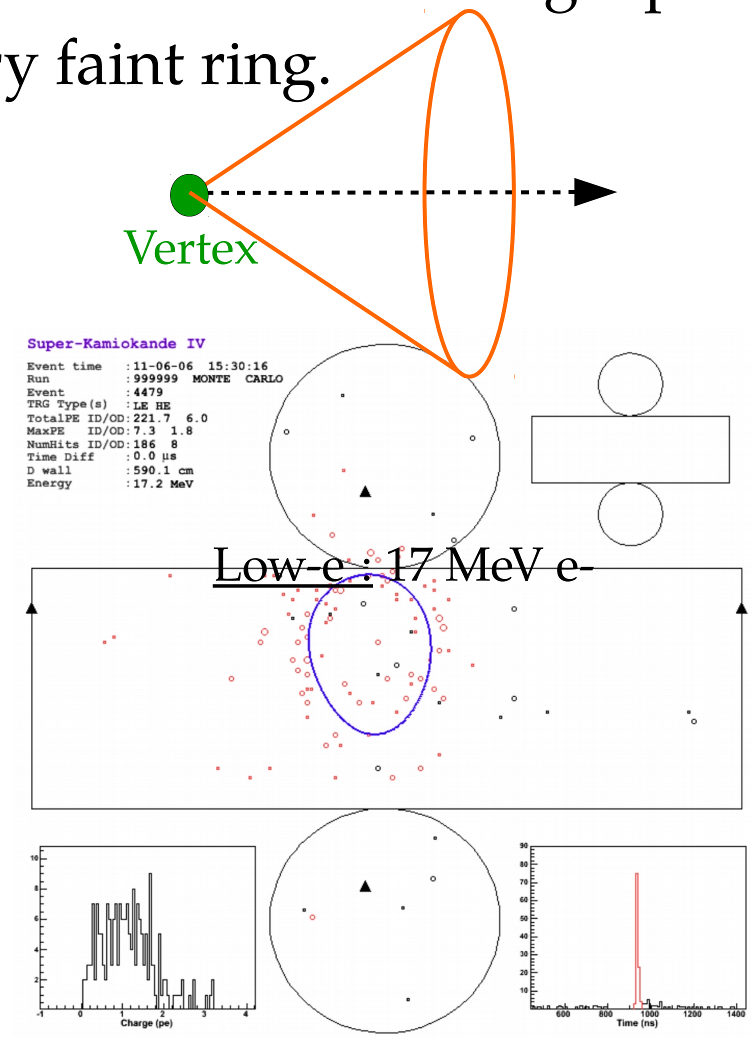
Physics case
Solar neutrinos
ν_e
• MSW effect in the Sun
• Non-standard interactions in the Sun.
Proton decay
Probe Grand Unified Theories through p-decay (world best sensitivity)
Atmospheric neutrinos
30 000 m
20 000 m
10 000 m
Secondary cosmic rays
Concorde
Everest
• Observe CP violation for leptons at 5σ
• Precise measurement of δ_{CP} .
• High sensitivity to ν mass ordering.
ν_μ, ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$
Supernovae neutrinos
$\bar{\nu}_e$
$+ (\nu_\mu, \nu_e, \bar{\nu}_\mu)$
• Direct SNν : Constrains SN models.
• Relic SNν : Constrains cosmic star formation history
JPARC accelerator neutrinos

Low and high energies

- Two very ≠ regimes & event topologies :

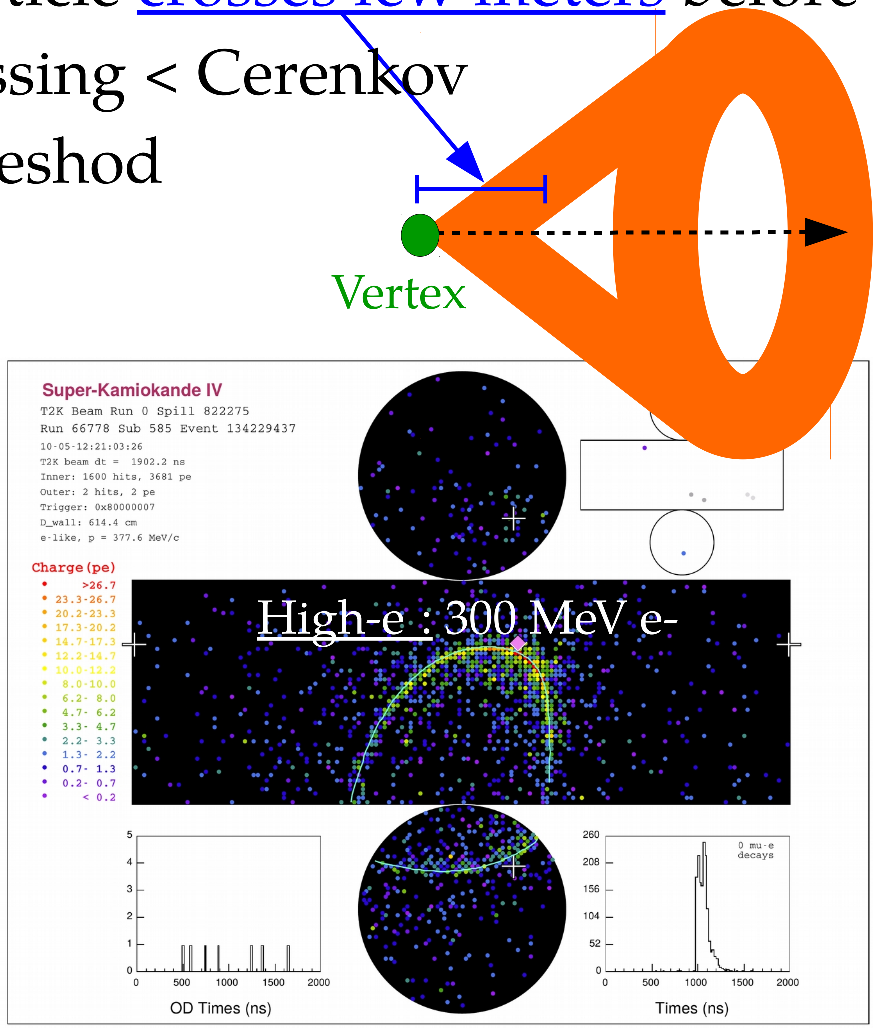
E < 50 MeV :

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



E > 50 MeV :

- Particle crosses few meters before passing < Cerenkov threshod



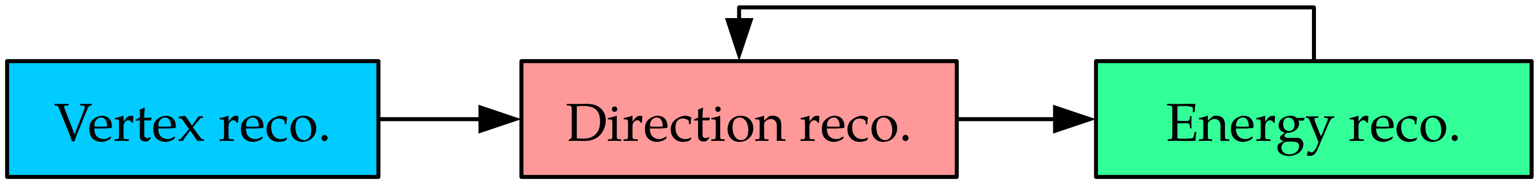
- Need/have 2 very ≠ reconstruction algorithms in the 2 regimes.

I. Low energy reconstruction improvements

Low energy reconstruction

T. Afif
N. Moreau

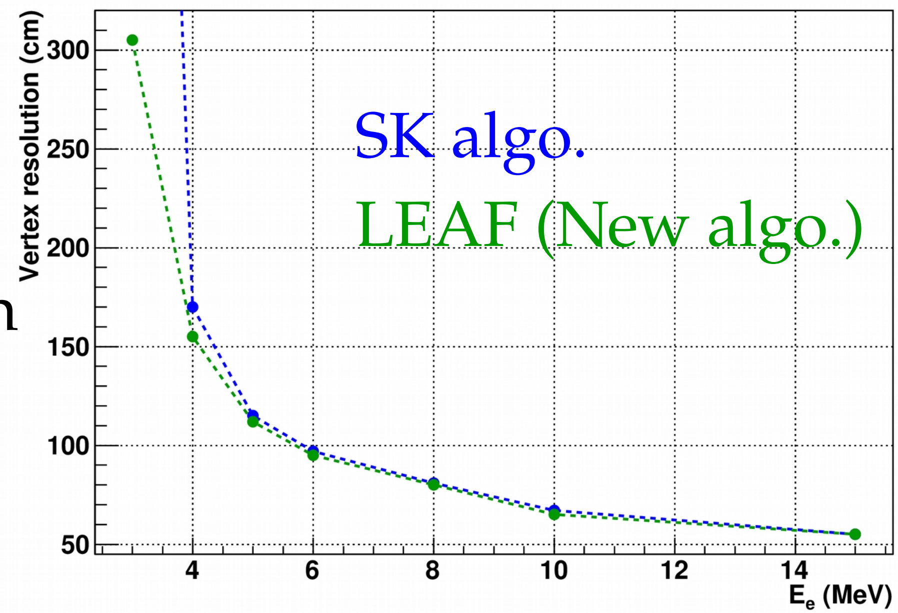
- <u>At low energy, the reconstruction is sequential :</u>

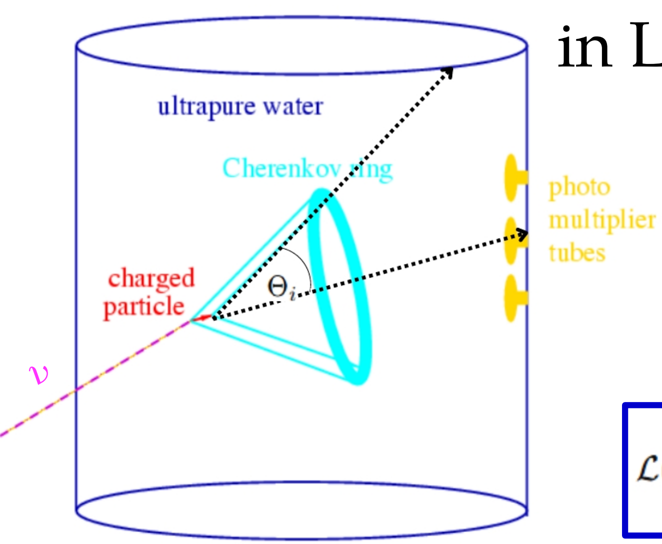


Key is the vertex finder !

- <u>Vertex :</u> SK algorithm updated by our group to modern C++ soft. (LEAF)
  → We had already shown sensible improvements at low energy.

- <u>In 2024, we tackled 2 limitations :</u>
  1. Implement particle direction & energy reconstruction → Crucial for ν oscillation in L/E.





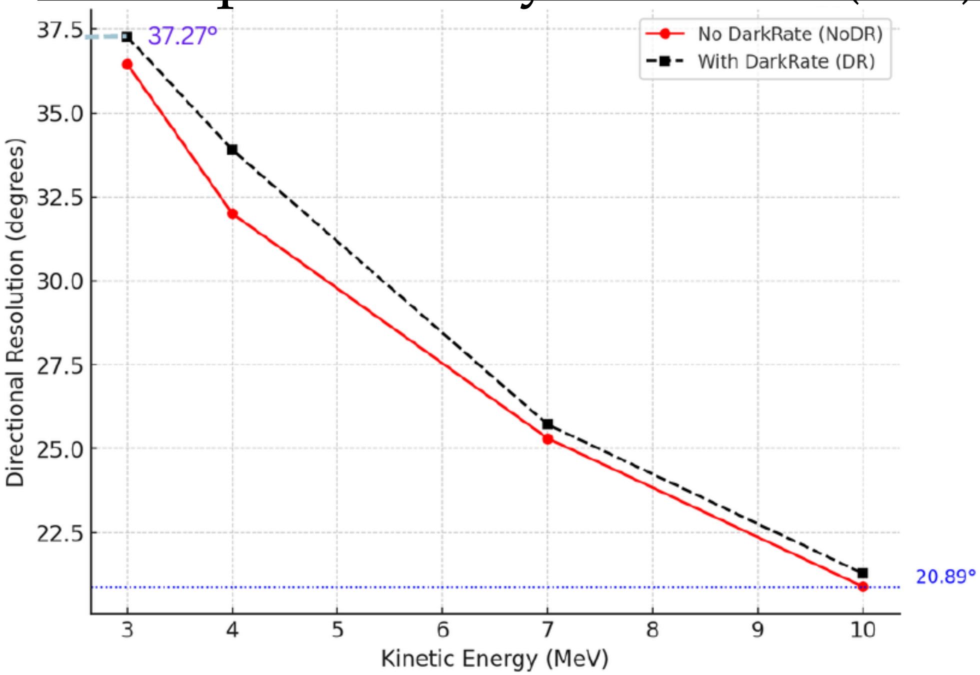
Use Cherenkov profile with PMT angular correction

$$\mathcal{L}(\vec{d}) = \sum_{i=1}^{N_{20}} \left(\ln f(\cos\Theta_i, E) \times \frac{\cos\theta_i \cdot \sin\theta_i}{F(\theta_i)} \right)$$

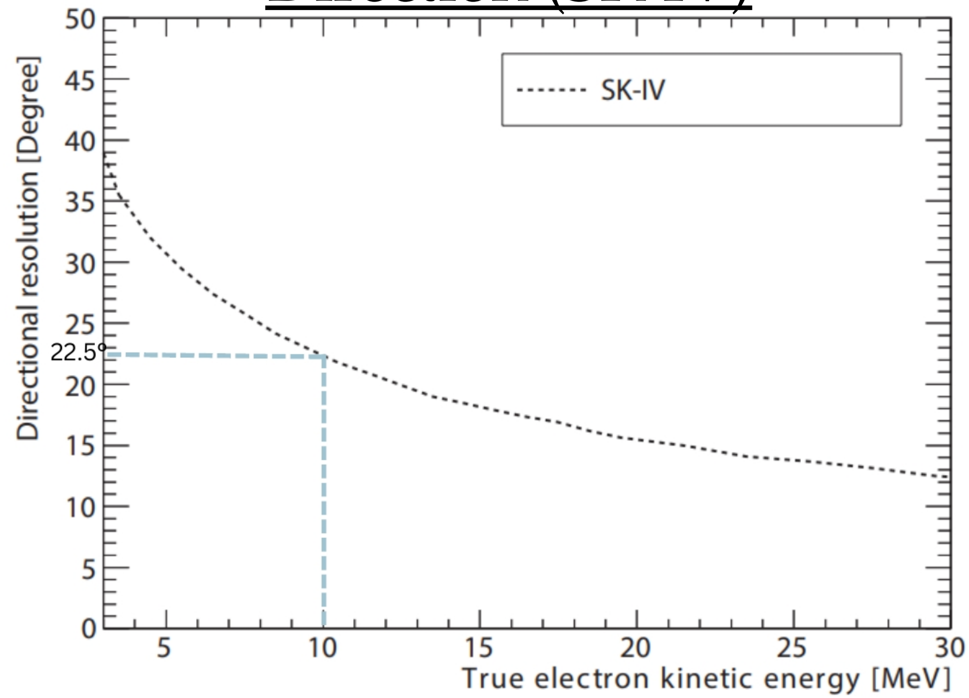
Improving low energy reconstruction

T. Afif
N. Moreau

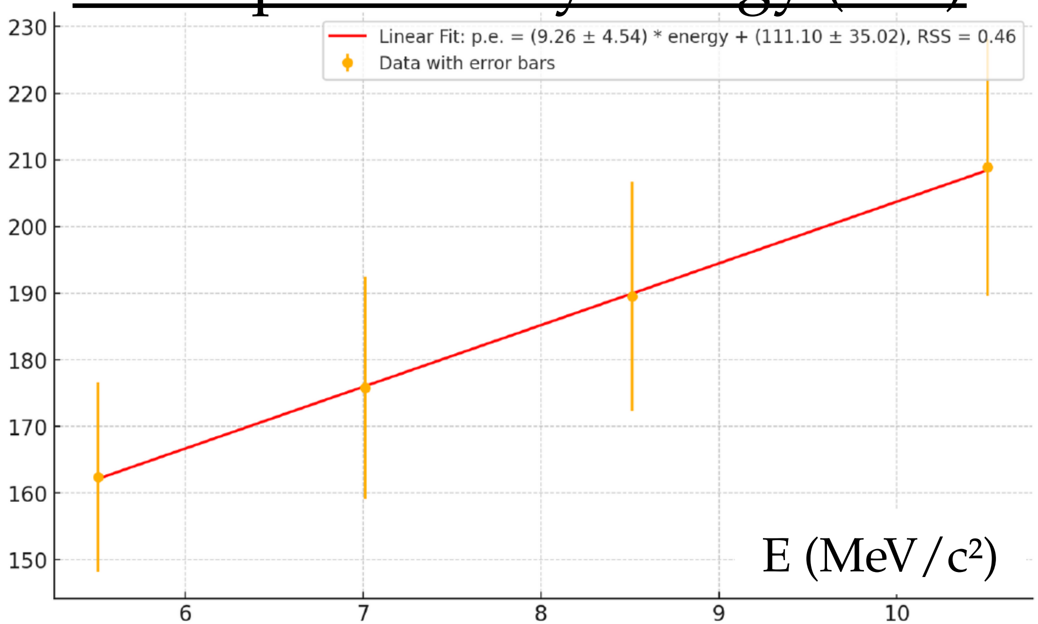
LEAF preliminary direction (HK)



Direction (SK-IV)



LEAF preliminary Energy (HK)



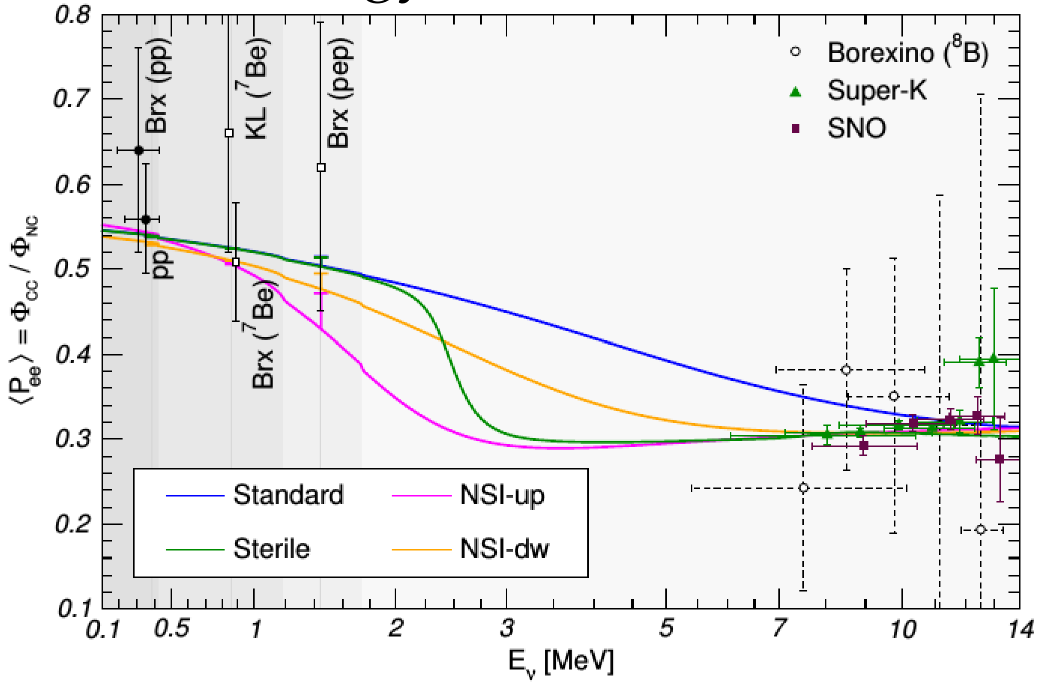
- Implemented direction reco. in LEAF using SK method : @10 MeV : 21.3° (HK LEAF) vs 22.5° (SK)

- Energy reconstruction on-going:

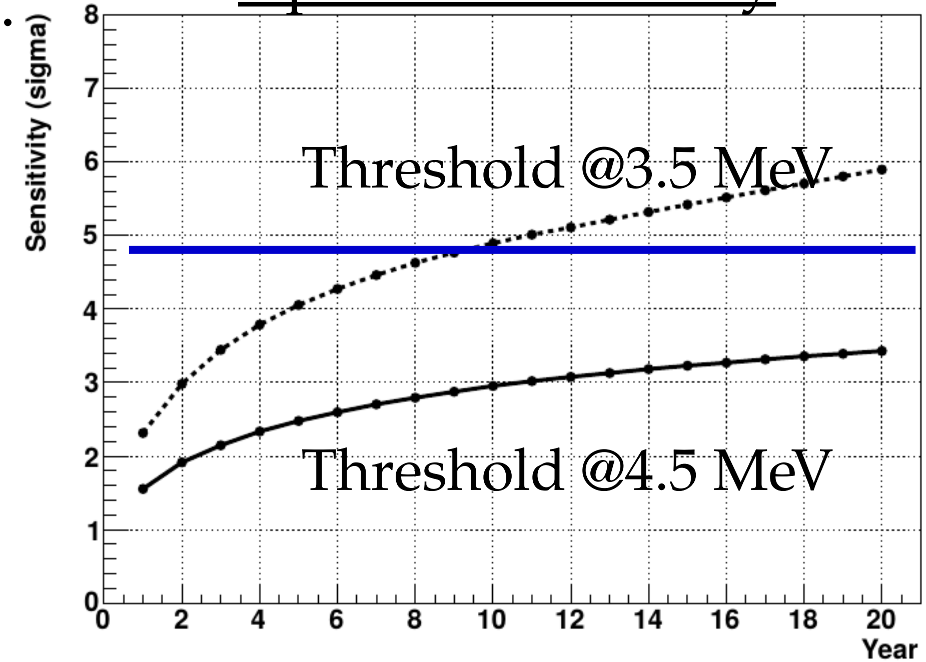
→ Resolution @10 MeV (preliminary) is 1.8 MeV → To be improved.

Improving low energy reconstruction

2. ↓ HK energy threshold : now 3-4 MeV.



Up-turn sensitivity

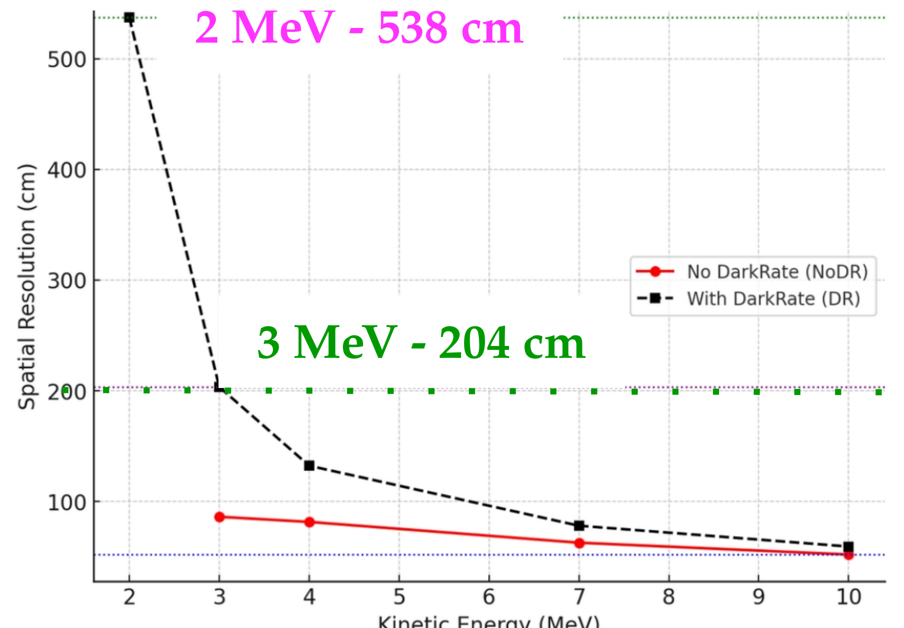


- Dominant impact of PMT dark rate.
- We fine-tuned LEAF ~ 3 MeV.

→ Improved vertex resolution @3 MeV from 3m → 2m.

→ Work-in progress to reach 2 MeV.

→ Work so far carried by French team,



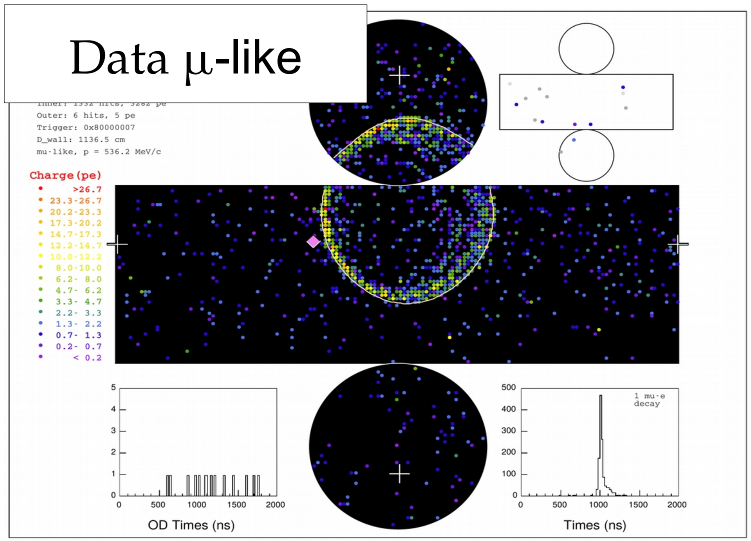
but Y. Ashida (Tohoku) & A. Santos (IPMU) are joining this autumn !

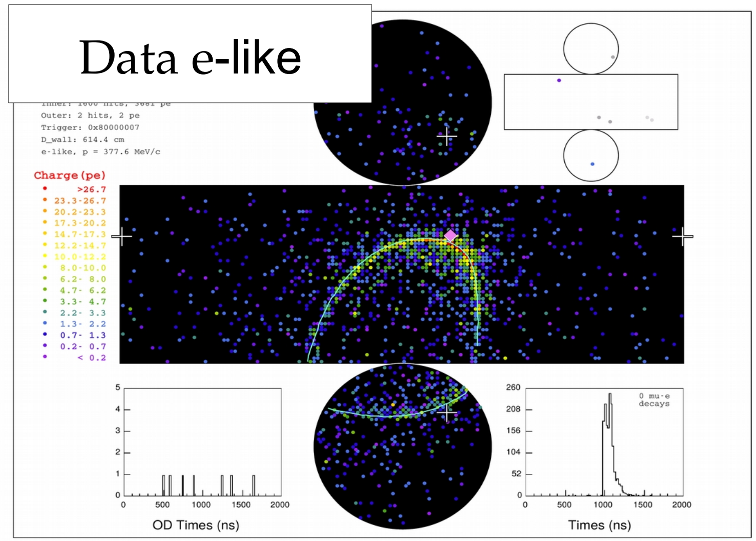
II. High energy reco. - historical algorithm

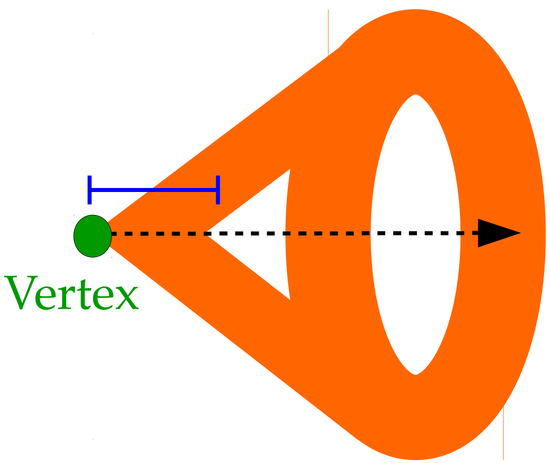
FiTQun high-energy algorithm

- Simulatenous fit of **7 parameters** using all PMTs charge&time:

  $\{X\}_i$ = (vertex position, vertex time, momentum, direction, particle type)







Likelihood-based fitter :

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

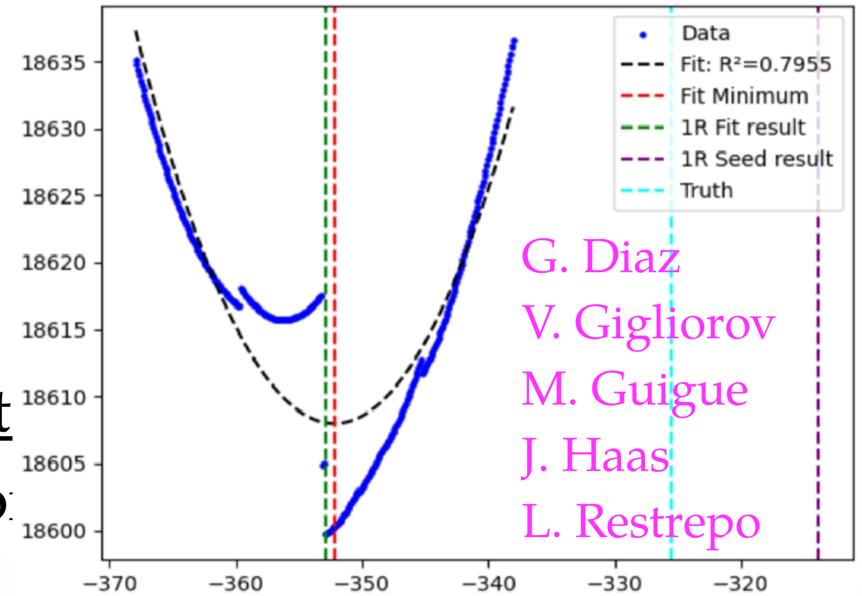
$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_{i}^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_i)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

- fiTQun has supported SK physics for 15 years-old

  → Performant & robust !

Upgrade & modernize fiTQun towards HK

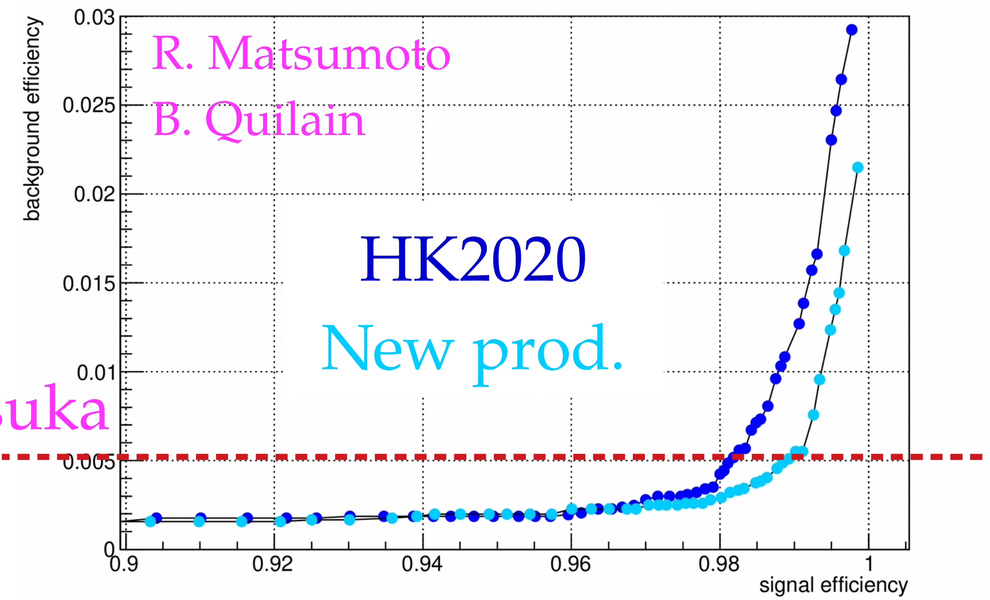
- But is slow : 90s per electron @500 MeV → Too slow for very high statistical era of HK when reaching 1% syst/stat. ⇒ Optimize it.



- Smoothen likelihood to replace SIMPLEX by MIGRAD (much faster)

- Have tuned fiTQun for HK for the very 1st HK « specific » production (Not scaled fro

	HK 2020	HK 2024
vertex res (cm)	28 cm	24 cm
dir. res (°)	2.7°	2.7°
mom. res (MeV/c)	8.2 %	3.9 %

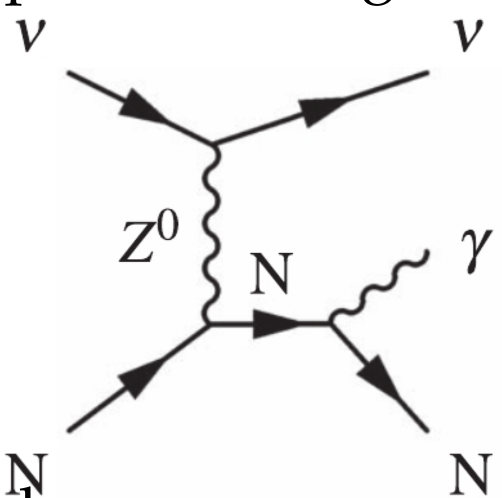


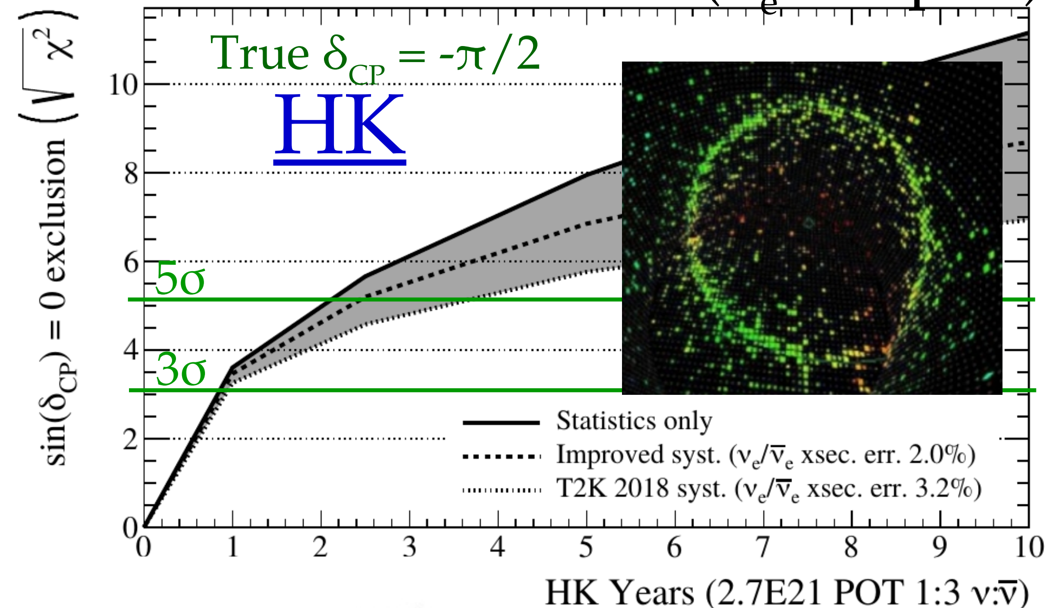
→ Our group has central role : M.Ishitsuka & S. Bolognesi as physics convener, B. Quilain, R. Matsumoto as reco leaders.

Improving fiTQun: e/γ separation

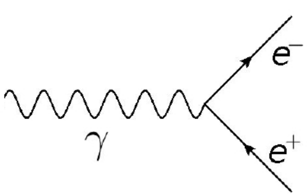
A. Choquet

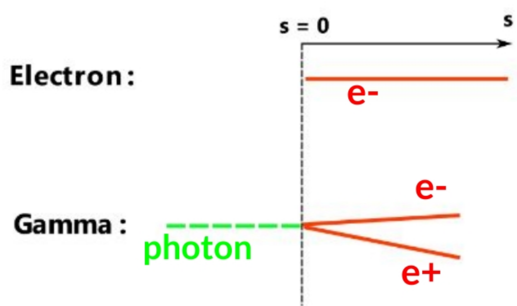
- Motivation : Important background for CP violation search (ν_e samples)

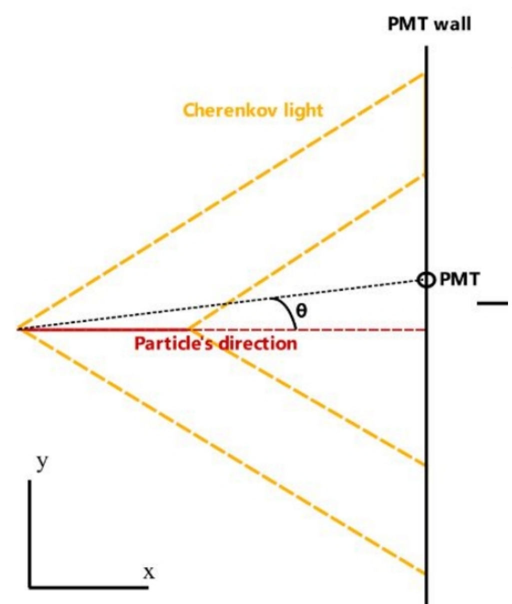




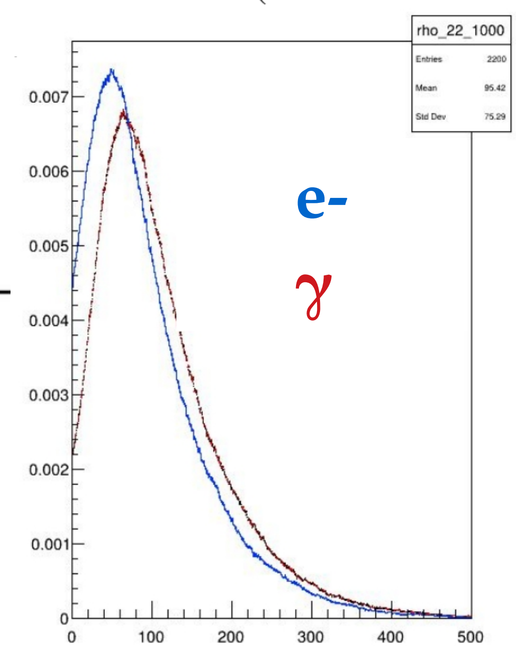
- Arthur tries to use ring external photon (late arrival time) to identify γ.







Cone of light generated by Cherenkov radiation



Distance along the particle directory (s)

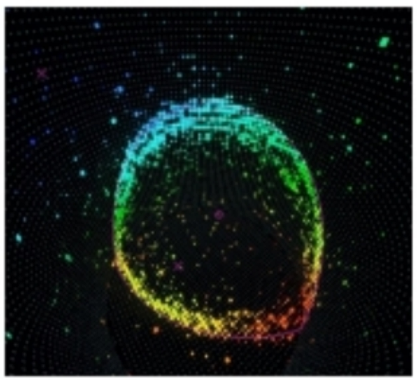
- Work in-progress → Results this summer.

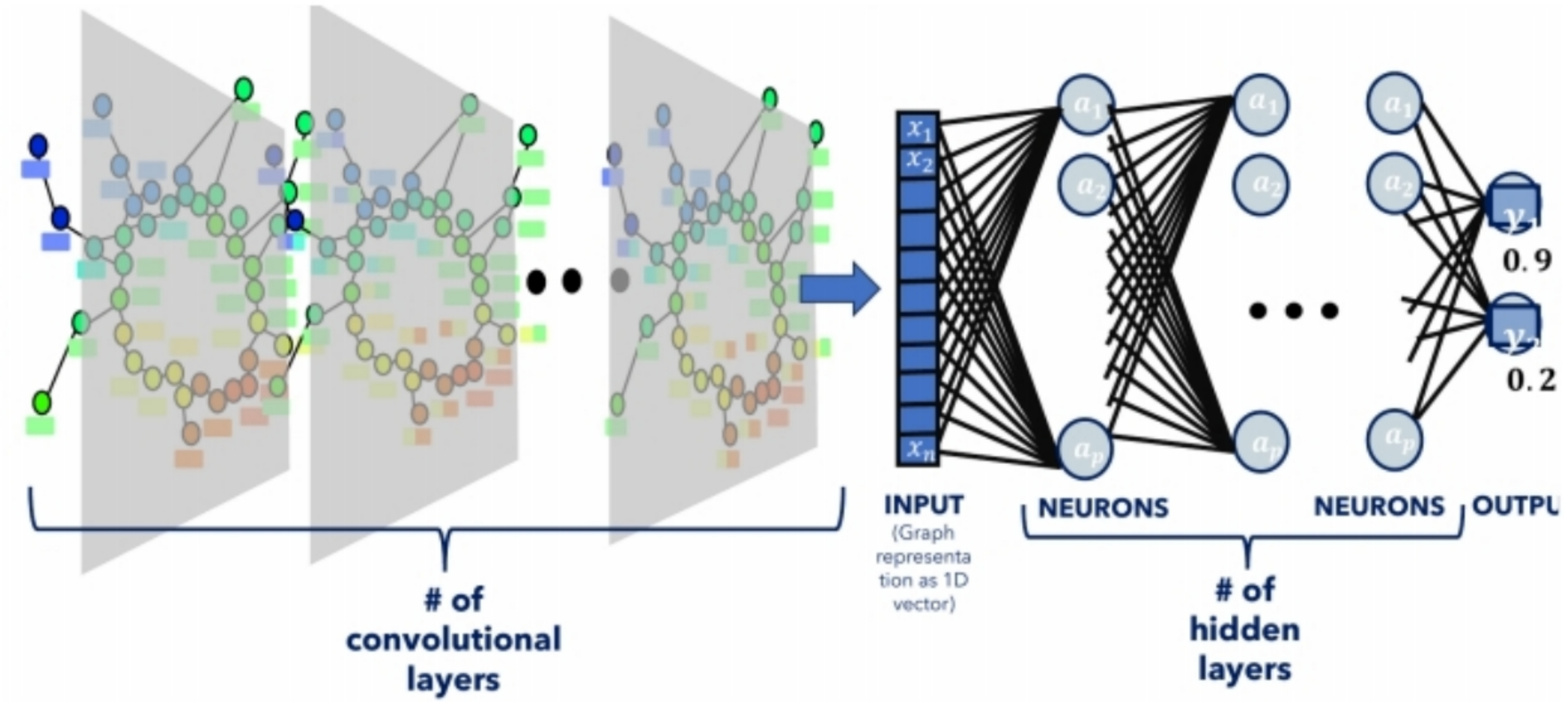
III. High energy reco. with Machine learning

A ML-based reconstruction : GRANT

C. Quach
E. Le Blevec

- GRANT : Graph-Neural Network (GNN) algorithm
  → Each hit PMT = a node of the GNN





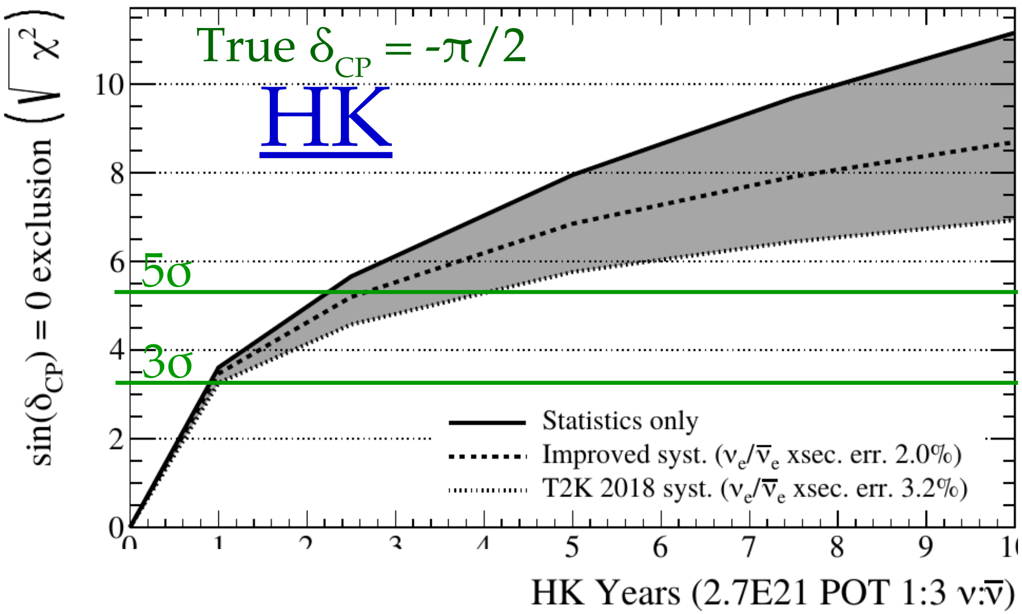
- This GNN was developed from 2022 by **our group** (for low-energy)
  → Adapted to high energy from 2023.
  → Last year, we have shown the result of 4 first classifications :

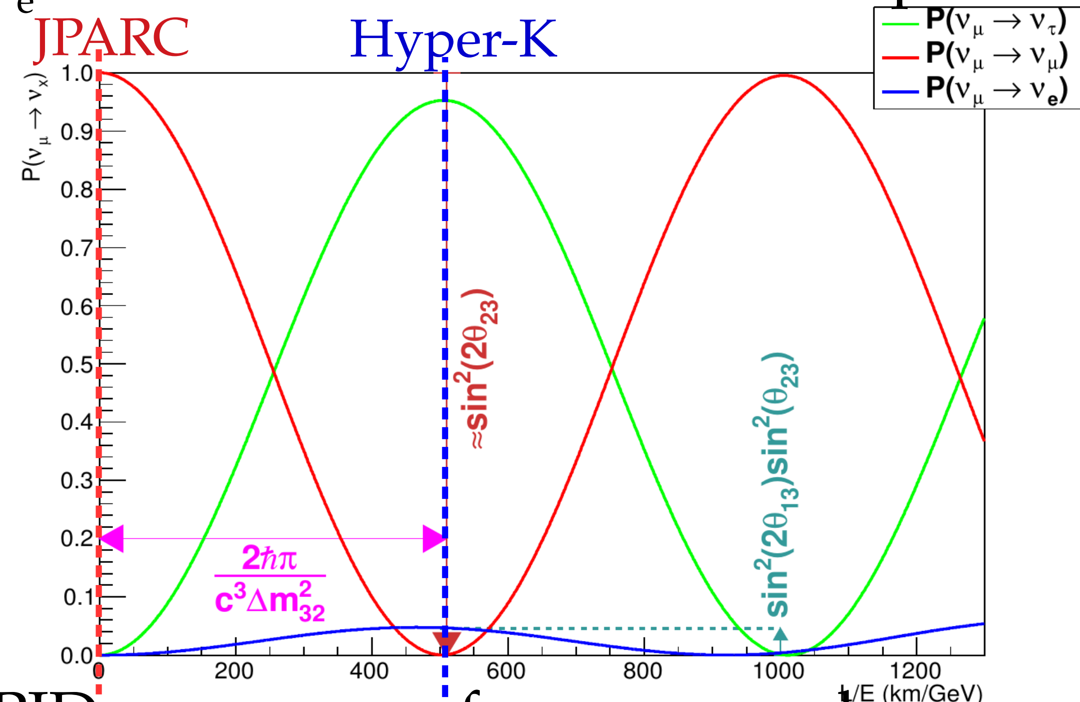
1. PID e/μ   2. PID e/π0   3. E-reconstruction   4. Vertex reconstruction

  → We had compared it to SK historical algorithm : fiTQun.

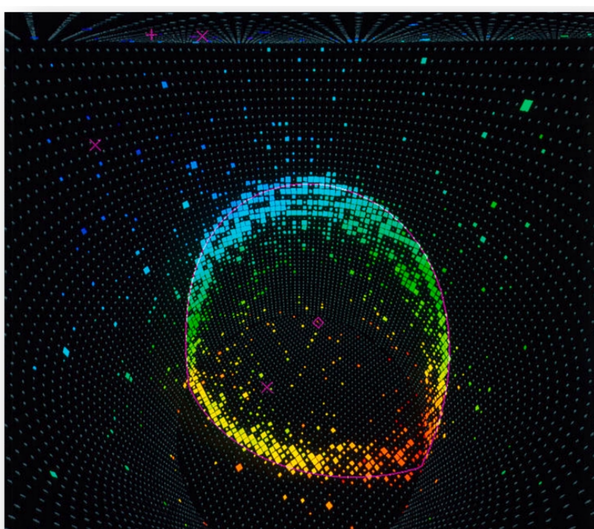
Focus of this year : high-energy physics

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

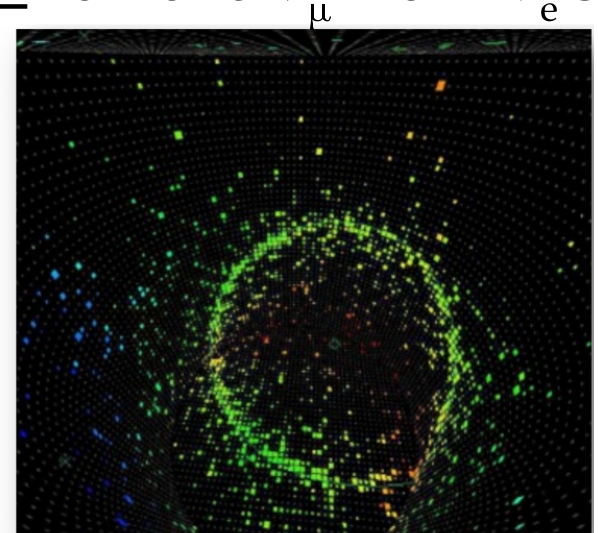




- e/μ is THE SK most fundamental PID : remove ν_μ from ν_e sample.



Sharp ring



Fuzzy ring

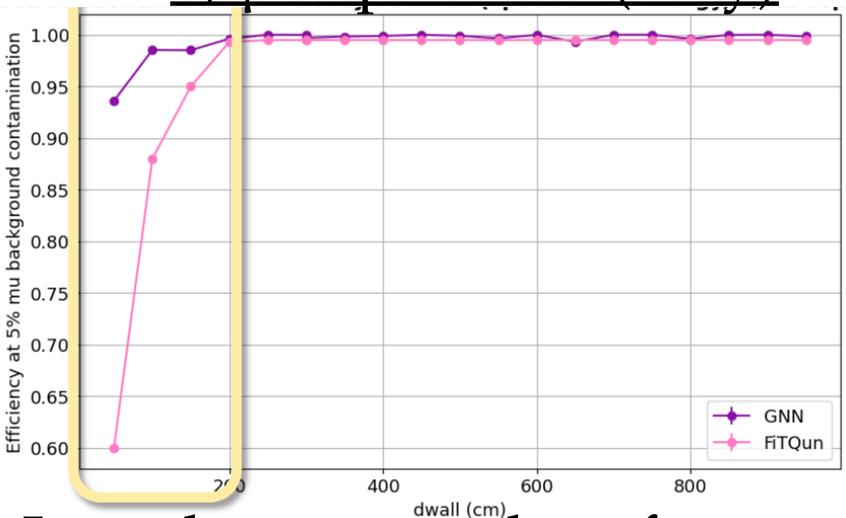
C. Quach
E. Le Blevec

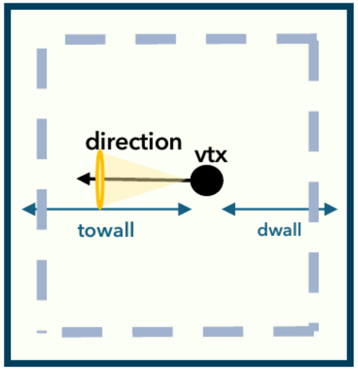
'05/2024

Basic classifier : e/μ separation

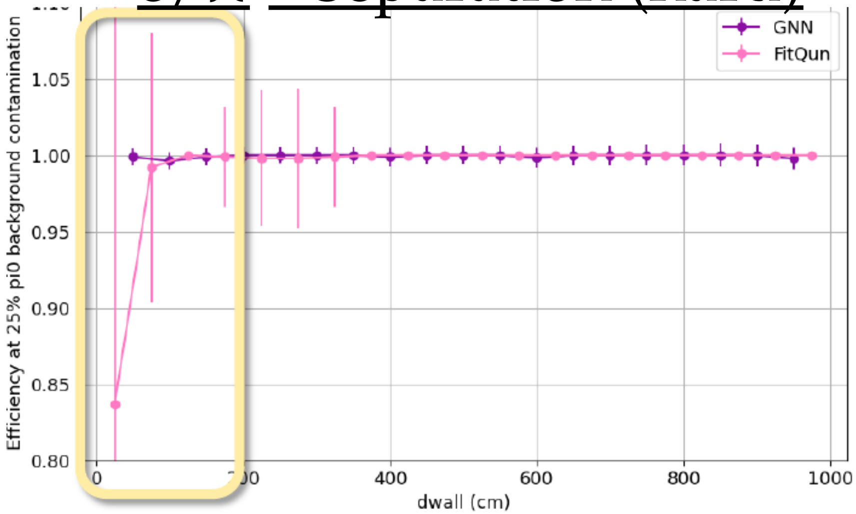
- GRANT : > 99 % e-efficiency for 5 % μ contamination → As fiTQun

e/μ separation (easy)

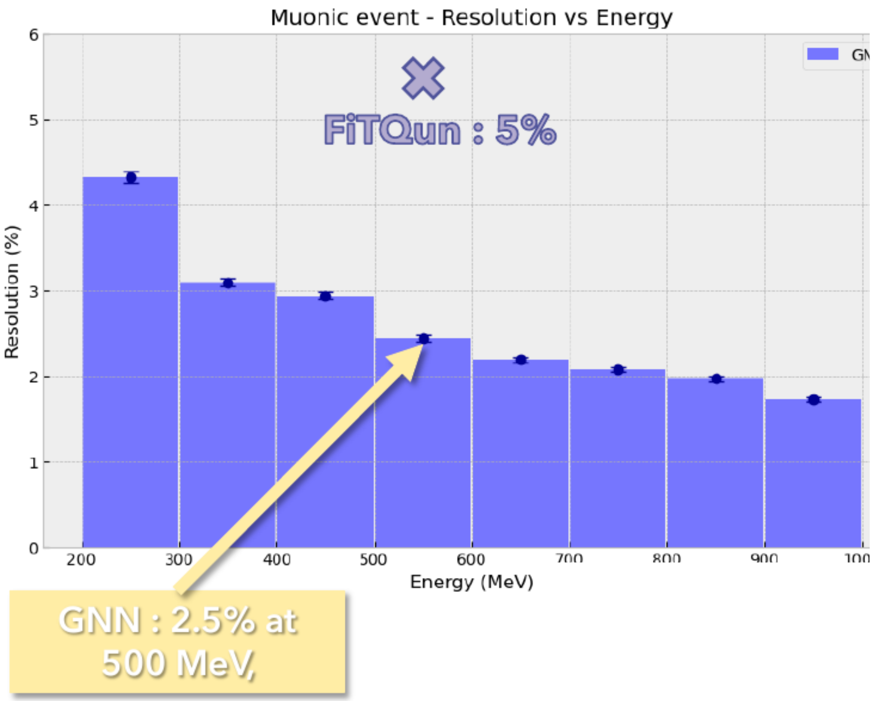




e/π^0 separation (hard)



- Largely improved performances out of FV → Enlarge FV & statistics !



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

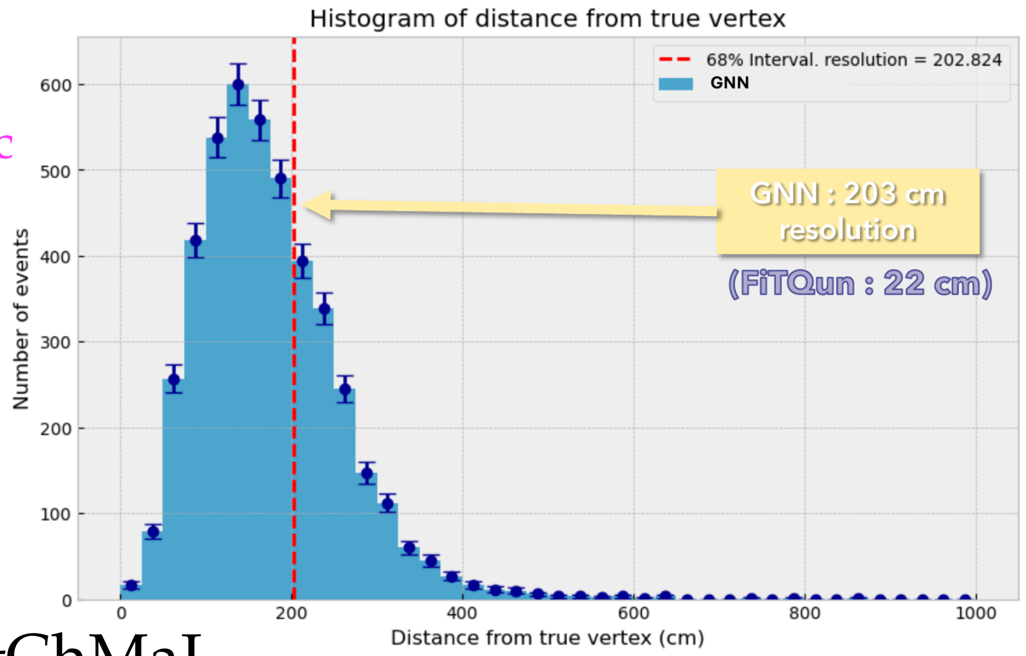
- And 3 order of magnitude gain in processing time !
→ But we still have some caveats to overcome towards ν data analysis.

Current caveats of ML-reconstruction

<u>Caveats :</u>

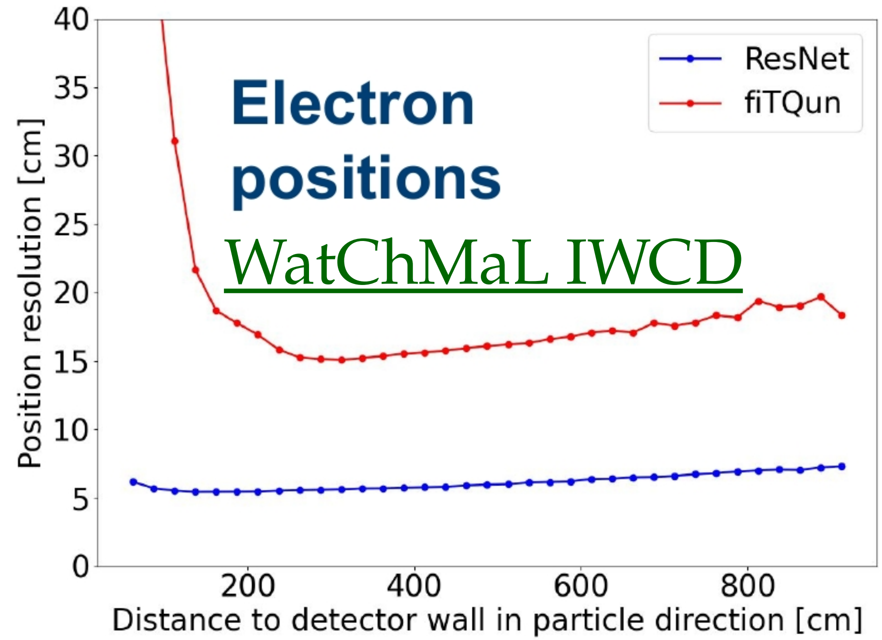
N. Prouse
P. De Perio
E. Le Blevec

- Vertex/multi-dimensional regression is limited (memory use)
- Multi-GPU use to largely reduce training speed.
- Only uses Graph Neural Networks.



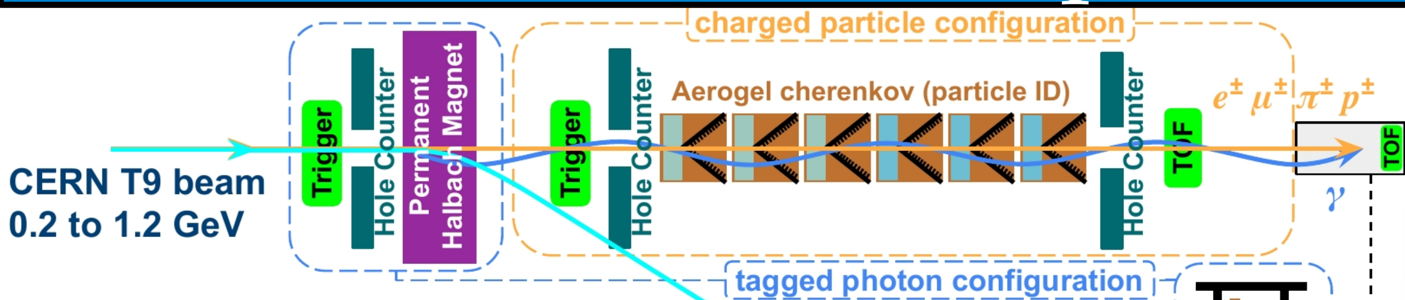
<u>In 2024 :</u> we merged GRANT and WatChMaL

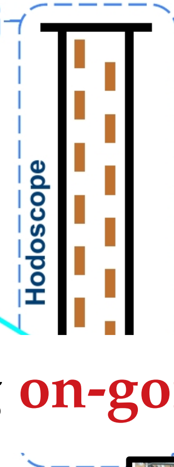
- <u>WatChMaL :</u> A ML algorithm dedicated to any Water Cherenkov, mostly uses CNN (ResNet50) & multi-GPU handling
  → Excellent vertex resolution…
- Mostly developed by SLAC&U. Tokyo (K. Terao, P. De Perio).
- Joint work between U. Tokyo & IN2P3



→ Finalized ! Now ripping the fruits of unified software for SK/HK.

Tests on WCTE experiment @CERN

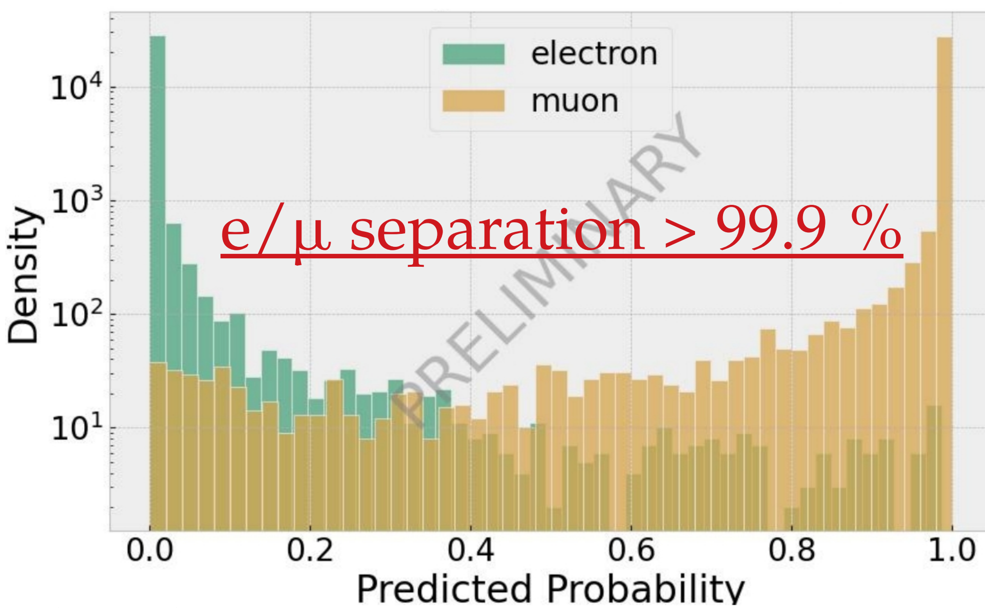


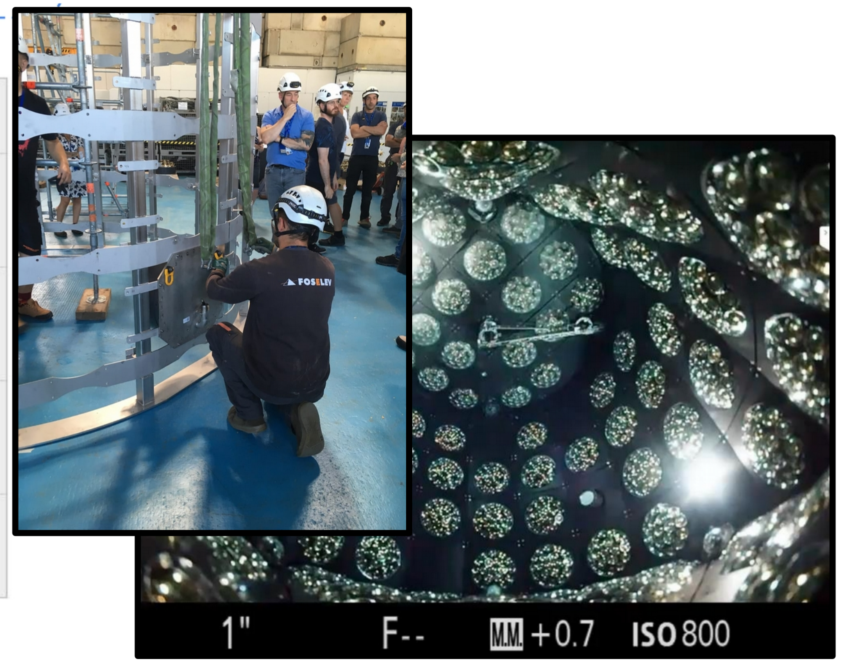


Unique opportunity to study tagged $e^\pm$, $\mu^\pm$, $\pi^\pm$, $p^\pm$ and γ beam of known momentum, position, direction

~50 ton WC detector with ~100 mPMT modules

- Huge contribution to installation from our team (P. De Perio et al.) → Data taking **on-going**
- Our algorithms are ready & well-trained on MC





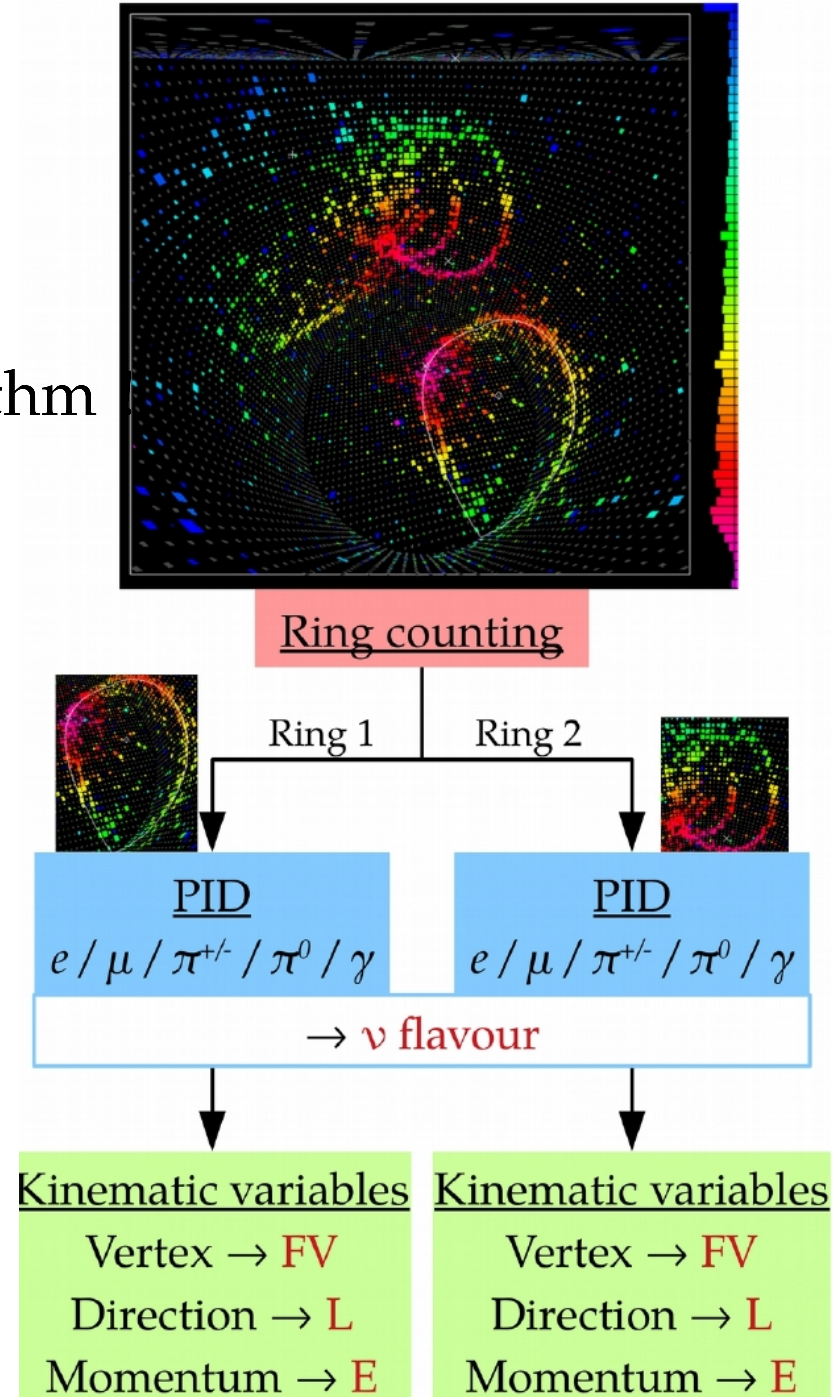
- Good quality data are coming now → Test on data this summer !

Prospects for 2025 from our team

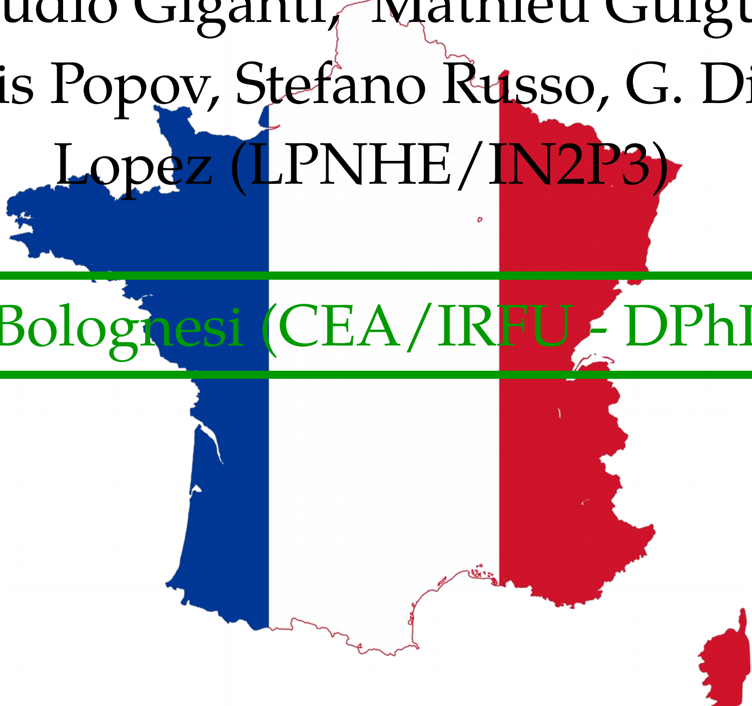
- <u>For GRANT-WatChMaL :</u>
  - Goal : have a complete reconstruction algorithm for SK/HK
    → Need a multi-ring identification
    → Will use our successful merged algorithm
  - Test on WCTE & SK data
    → We aim to show this next year !

- <u>For fiTQun :</u>
  - Have a full HK production chain ready this year to prepare HK in 2028.
  - Continue speed improvement.

- <u>For low energy :</u>
  - Goal to reduce the reco. threshold down to 2 MeV.



Our project members



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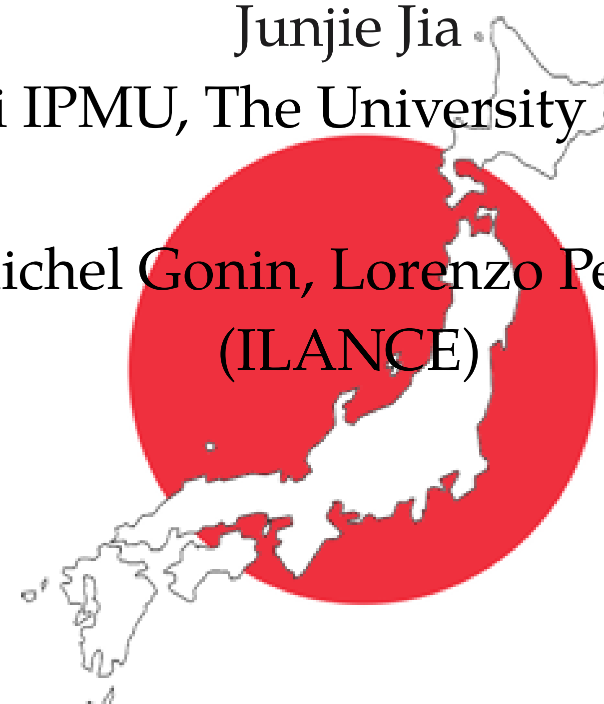
Jacques Dumarchez, Marco Zito, Claudio Giganti, Mathieu Guigue, Boris Popov, Stefano Russo, G. Diaz Lopez (LPNHE/IN2P3)

S. Bolognesi (CEA/IRFU - DPhP)



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