Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Machine Learning Algorithms for Multi-Messenger Astroparticle Physics

Spoke 2 Annual Meeting – 20 Dec. 2023

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Outline

- Introduction
- Super-Kamiokande overview
- State of the art of reconstruction in Super-Kamiokande
- Proton decay and scientific motivation for reconstruction with Machine Learning algorithms
- Hyper-Kamiokande and perspectives
- Conclusions and plans

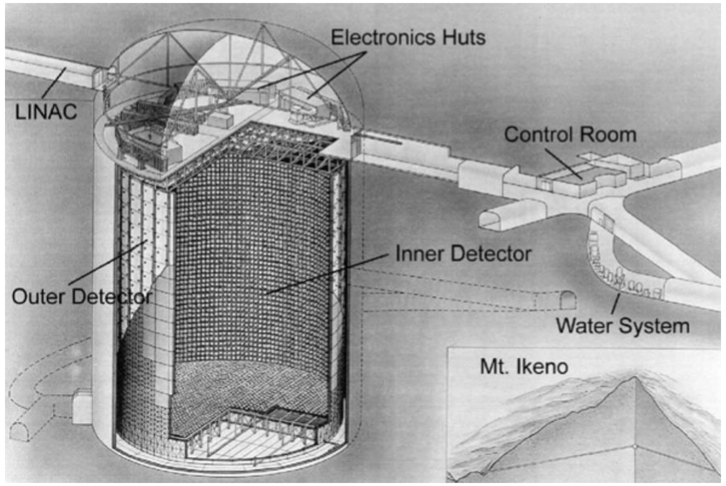
Introduction

- Machine Learning algorithms bring a new opportunity of investigation and analysis of phenomena in Multi-Messenger Astroparticle Physics
- Possible applications in both event reconstruction and simulation
- Let's focus on reconstruction in water Cherenkov detectors

Super-Kamiokande (SK), Kamioka mine, Japan

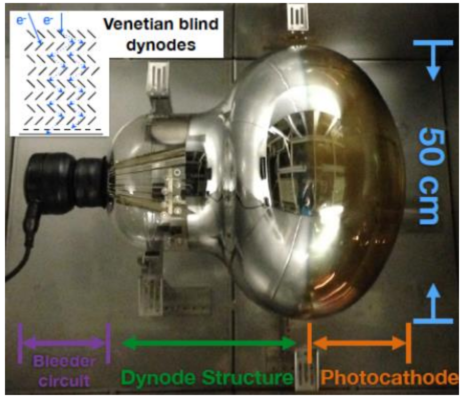
39 m x 40 m cylindric tank filled with 50 kton of ultrapure water, of which 22.5 kton inside Fiducial Volume, divided into two optically insulated sections:

- **Inner Detector (ID):** 11k 50 cm Photomultiplier Tubes (PMTs) (40% coverage) facing inwards.
- **Outer Detector (OD):** 2k 20cm PMTs facing outwards



Some research topics in SK:

- **Proton decay**
- Neutrino oscillations (2015 Nobel Prize)
- Neutrino astrophysics



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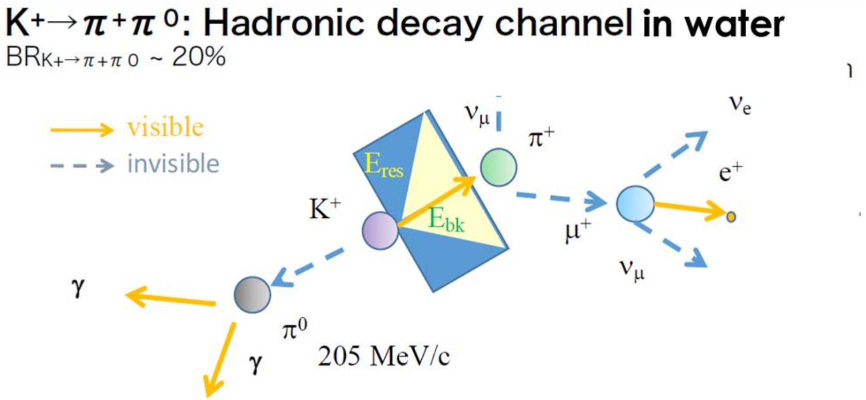
Proton decay p-> ν K^{+} as a case study in SK

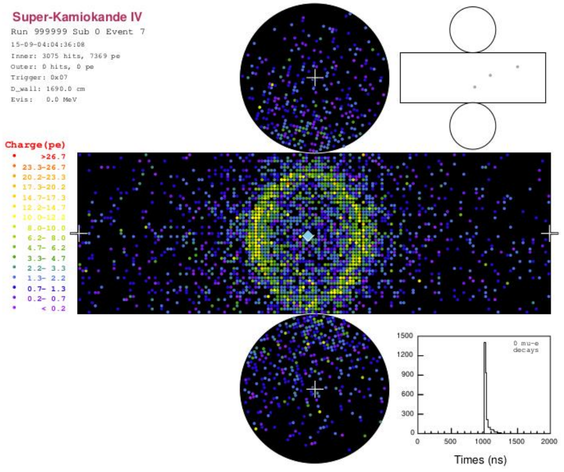
p -> ν K^{+}
Partial lifetime limit: 5.9 x 10^{33} yrs

Reference Study with APFit:
PHYSICAL REVIEW D90,072005 (2014)
«Search for proton decay via p→νK using 260 kiloton · year data of Super-Kamiokande»

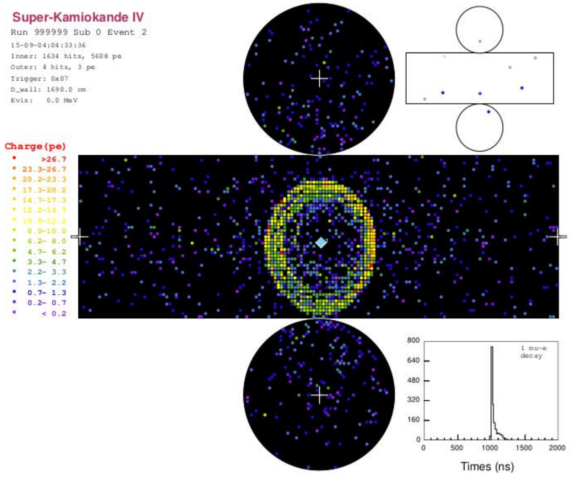


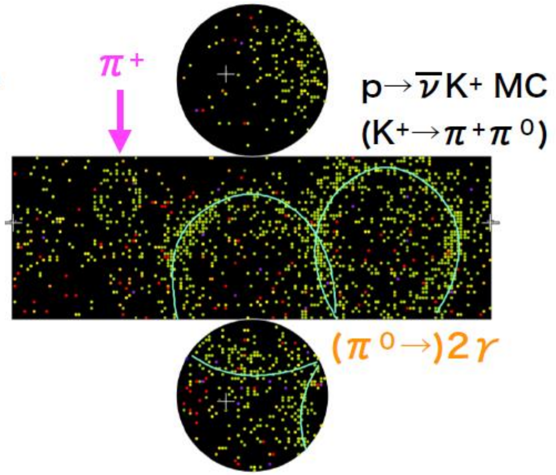
Upon trigger, for each hit PMT, charge produced and time of the hit are collected (event)

Showering (e-like)



Non showering (muon-like)





Atmospheric neutrino interaction events are background for this analysis

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State of the art of reconstruction in SK

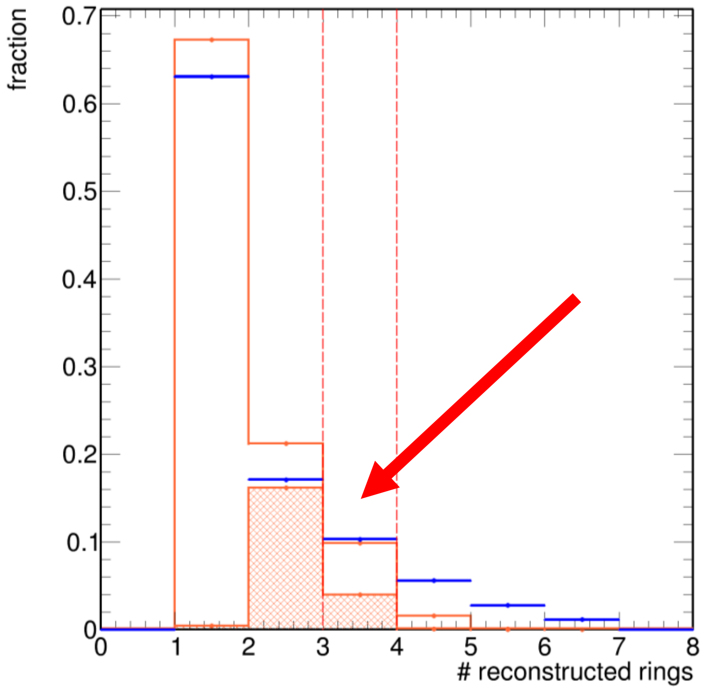
	APfit	fiTQun
Type of fit	Sequential (vertex, ring counting, PID, michel-e tagging)	Single log-likelihood function minimization $$L(\mathbf{x}) = \prod_j^{\text{unhit}} P_j(\text{unhit}\vert\mathbf{x}) \prod_i^{\text{hit}} [1 - P_i(\text{unhit}\vert\mathbf{x})]\, f_q(q_i\vert\mathbf{x}) f_t(t_i\vert\mathbf{x})$$
Used by	Super-Kamiokande	T2K, MiniBooNE, Super-Kamiokande, Hyper-Kamiokande
Max # rings	5	6
PID	$e^{\pm}$, $\mu^{\pm}$	$e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$
CPU time per SK event	< 1 min/event	~ 10 min/event

Features of fiTQun:

- overall reconstruction performance is better than APFit's
- It makes the reconstruction of charged kaon kinematics possible (charged pion PID)

We choose fiTQun as a reference for our development.

Results of analysis with fiTQun



SK ATM-ν MC (background)
SK PDK MC
True $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \gamma\gamma$ (hatching) (signal)

	Exposure (kton*yr)	#BG	BG sys. Err. (%)	Eff. (%)	Eff. Sys. Err. (%)	# candidates	Lifetime Limit (yrs)
This analysis	200	0.03 ± 0.02	50.9	2.9 ± 0.02	26.1	0	> 6.7 x 10^{32}
(2017	177	0.14	31.6	9.4 ± 0.1	8.7	0	> 2.4 x 10^{33})

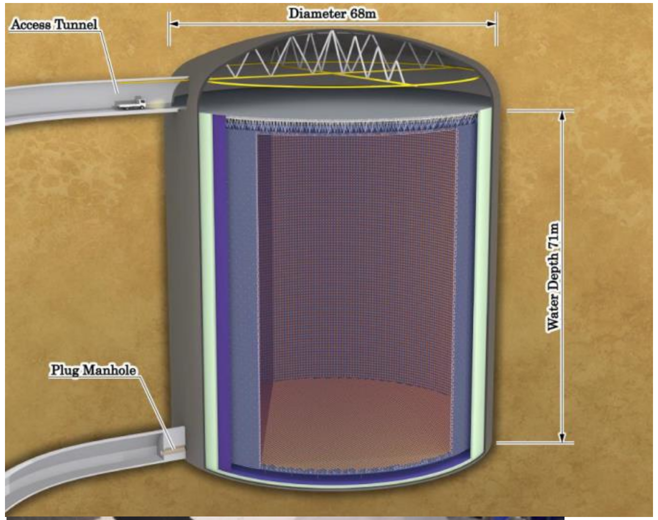
Low-background analysis in this proton decay channel with fiTQun is possible.

We aim to increase signal selection efficiency by improving ring detection.

Machine Learning algorithms are suitable candidates for this goal, especially Convolutional Neural Networks, Residual Networks, Graph Neural Networks performance given the image-like nature of events.

Results and plot from N.F. Calabria PhD Thesis, ‘Search for proton decay in Super-Kamiokande and perspectives in the Hyper-Kamiokande experiments’, 2023, Università degli Studi di Napoli.

Hyper-Kamiokande (HK) (Hida mine, Japan) and perspectives



HK is under construction: operation will begin in 2027!

- **Cylindrical tank: (68 m x 71 m)**
- **Fiducial volume: 0.19 Mton (~ 8 SK FV)**
- **20k 50 cm PMTs in the ID**
- **~ 1k composite photosensors (multi-PMT)**

fiTQun takes 1 order of magnitude CPU time more per multi-ring HK event with respect to SK

Two possible candidate approaches:

- **Port fiTQun code to run on GPUs**
- **Introduce Machine Learning algorithms for reconstruction, shifting the computational effort to training**

Conclusions and plans

- We want to study the performance of some promising Machine Learning algorithms applied to detection of Cherenkov rings and reconstruction of events in Water Cherenkov detectors

- We are developing a preliminary Monte-Carlo study in SK on single ring events.

- We are interested in both reconstruction performance and, especially for HK, computational cost as driving factors.

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THANK YOU!