Machine Learning Particle Classifier for Water Cherenkov Detectors

Hyper-Kamiokande neutrino experiment

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Hyper-Kamiokande

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Neutrinos and their Detection

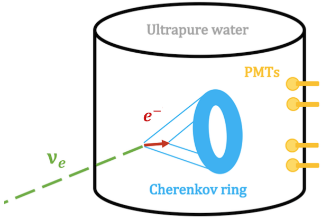

Figure 1: WCD scheme

- Subatomic elementary particles
- Mysterious but yet abundant
- Very elusive
- Key in the understanding of our Universe
- Indirect detection (Cherenkov effect)
- Binary classification: e^- vs. γ background

Hyper-Kamiokande and IWCD

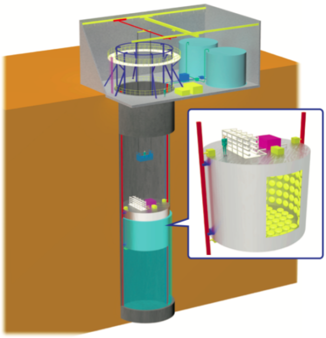

Figure 2: Schematic of the IWCD detector [1]

- Based in Japan
- Expected to be completed in 2027
- Software including ML algorithms
- IWCD at 0.7-2 km from source
- h=6m, r=4m
- 536 mPMT modules (19 PMTs each)
- PMT records charge and time
- Use time as a performance booster

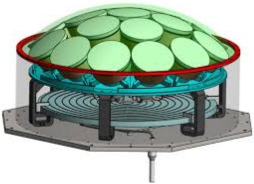

Figure 3: mPMT module design for HK [2]

Dataset

- Simulated data (using WCSim)
- Around 3M events
- Balanced dataset
- Uniform distributions

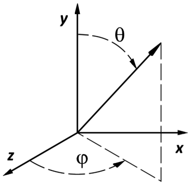

Figure 4: Coordinate system

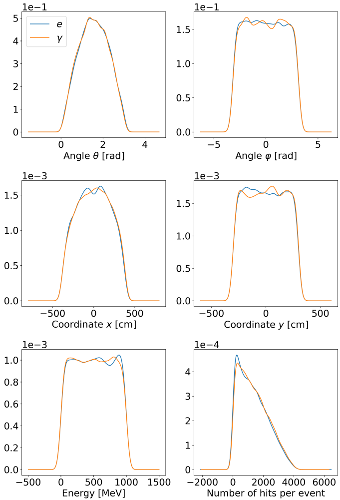

Figure 5: Event distributions (metadata)

From Data to Images

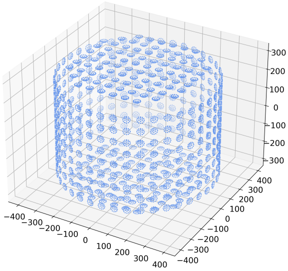

Figure 6: PMTs in 3D tank

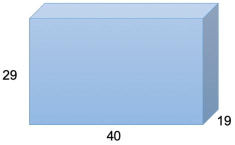

Figure 7: Original image size

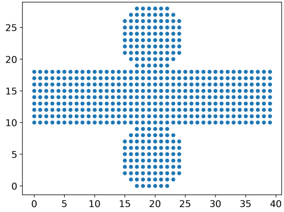

Figure 8: mPMTs in unwrapped tank

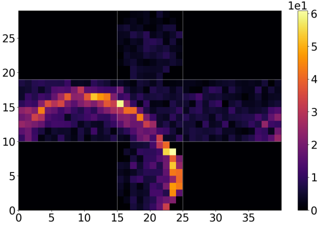

Figure 9: mPMT charge sum for an event

Time information

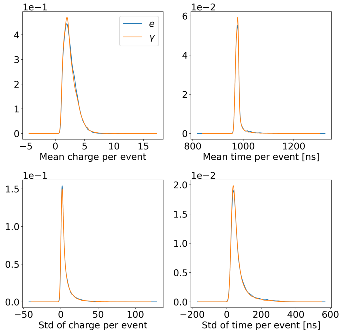

Figure 10: Event distributions

$$\tilde{q} = \frac{q}{1 + \frac{|t - \mu_t|}{\sigma_t}} \qquad (1)$$

Approaches:

- As channel (charge-like)
- Embeded in scaling factor (1)
- Order pixel features chronologically

Add-ons:

- Scaling: hit standardization
- mPMT aggragated representation (mean and standard deviation)

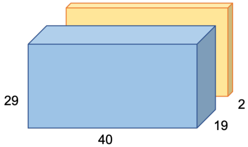

Figure 11: Hybrid representation

Monte Carlo Dropout

Uncertainty measures:

- Variance
- Margin of confidence
- Entropy
- Mutual information

Bhattacharyya distance to discriminate correct and incorrect prediction populations:

$$D_B(\mathrm{p},\mathrm{q}) = -\ln\left(\sum_i \sqrt{p_i q_i}\right)$$

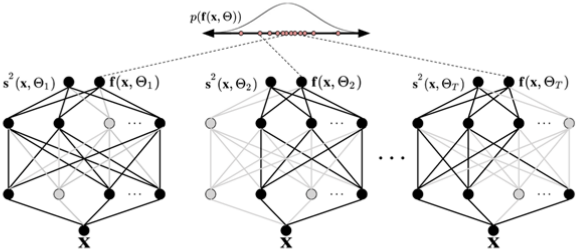

Figure 12: MCD concept [3]

Time information

Considered experiments:

- Charge and/or Time
- Hit standardization or None
- mPMT agg. or 19 features
- Time as scaling factor
- Chronological pixel ordering

Configuration:

- ResNet 18
- 20 epochs ($\sim$ 9 hours)
- Batch size: 512
- Adam with $lr = 1 \times 10^{-4}$
- Fixed seed
- 1 transformation

Model	Loss	Accuracy	F_1 score	AUC	σ_{AUC}
Q+Ts	0.6037	0.6713	0.6613	0.7332	0.0009
Qs+Ts	0.6042	0.6705	0.6601	0.7328	0.0014
Q+T	0.6106	0.6642	0.6481	0.7254	0.0013
Original	0.6272	0.6426	0.6201	0.7004	0.0010

Table 1: Average value of the loss function and performance metrics along with the standard deviation in the AUC.

Dropout

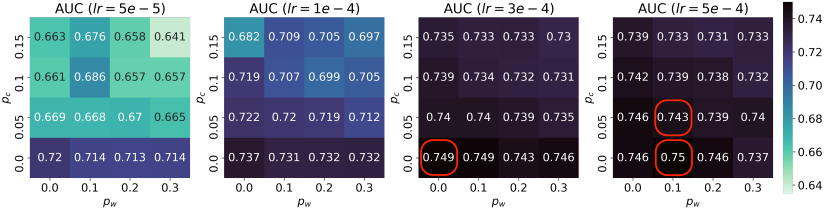

Figure 13: AUC values for different drop-neuron/channel dropout rates in training

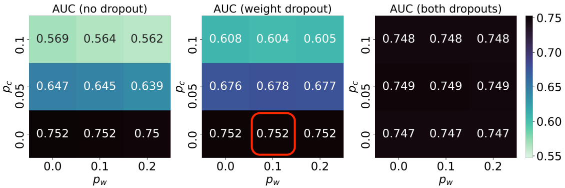

Figure 14: AUC values for different drop-neuron/channel dropout rates in validation

Uncertainty

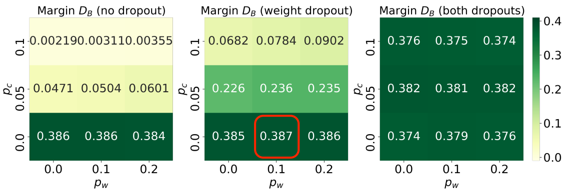

Figure 15: Bhattacharyya distance for different models and drop- neuron/channel dropout rates using the margin of confidence as uncertainty measure

$$M = \frac{1}{T}\sum_{t=1}^{T} |p_1^t - p_0^t|$$

$$D_B(\mathrm{p}, \mathrm{q}) = -\ln\left(\sum_i \sqrt{p_i q_i}\right)$$

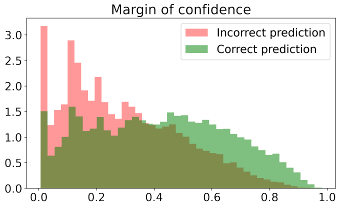

Figure 16: Histogram of correct and incorrect predictions for the margin of confidence and its discriminating power using the Bhattacharyya distance

Benchmarking

Model	Loss	Accuracy	F_1 score	AUC
Proposed	0.5856	0.6864	0.6795	0.7550
Original	0.6271	0.6427	0.6203	0.7007

Table 2: Loss function evaluated in the test set along with some performance metrics for the original configuration and the proposed model

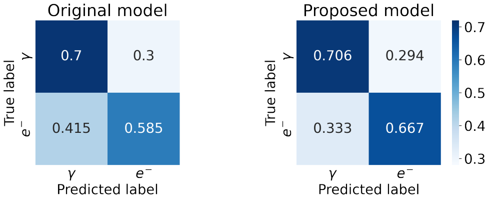

Figure 17: Row normalized confusion matrix for both original and proposed models

	Total	Electron	Gamma
Confidence (%)	38	39,1	37

Table 3: Mean confidence values of test set predictions

Bias Analysis

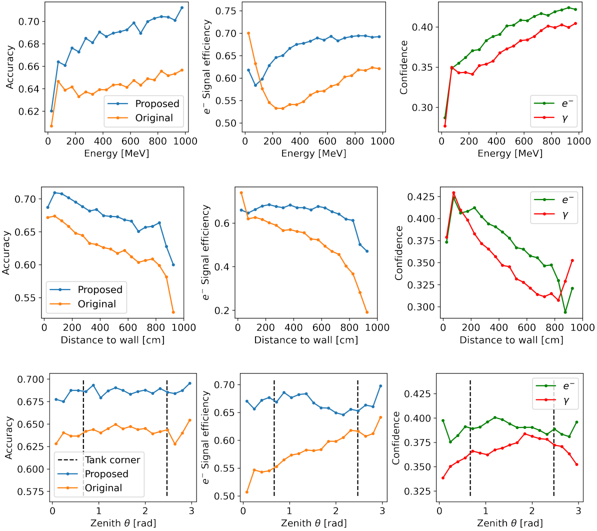

Figure 18: Proposed and original models compared in terms of performance for different features and confidence for both classes

Conclusions

- Time as a channel
- Hit standardization
- Hybrid representation: time mPMT aggregated
- Relative accuracy improvement of 7%
- Relative electron signal efficiency improvement of 16%
- Outputting margin of confidence in every prediction using MCD
- Enhanced and more stable behaviour towards different energy ranges, cone vertex positions and particle directions

Thank you!

[1] *T2K and beyond*. Accessed: 2022-05-30. 2021. URL: https://t2k-experiment.org/beyond-t2k/.

[2] Gianfranca De Rosa. "A multi-PMT photodetector system for the Hyper-Kamiokande experiment". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 958 (2020). Proceedings of the Vienna Conference on Instrumentation 2019, p. 163033. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2019.163033. URL: https://www.sciencedirect.com/science/article/pii/S0168900219313968.

[3] *Monte Carlo dropout*. https://docs.aws.amazon.com/prescriptive-guidance/latest/ml-quantifying-uncertainty/mc-dropout.html. Accessed: 2022-07-05.

Hyper-Kamiokande

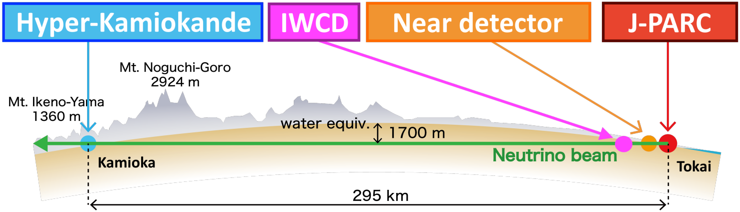

Figure 19: Map of the HK neutrino experiment with the main detector, the IWCD, the near detector and the source of neutrinos (J-Parc accelerator).

Event display

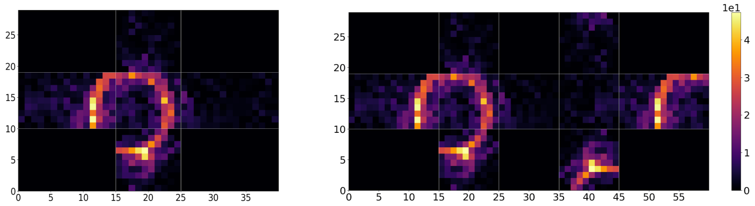

Figure 20: Sum of charge per mPMT for an electron event before and after padding

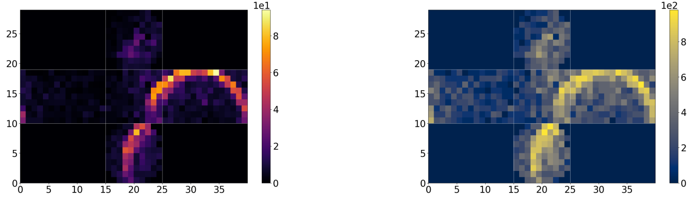

Figure 21: Sum of charge and average time detection per mPMT for a gamma event