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Two Stage Gamma-Neutron Source Classification in Water Cherenkov Detectors: Energy Threshold Screening and Machine Learning Pulse Analysis

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Water Cherenkov detectors (WCDs) offer a robust and economical solution for real time radiation monitoring by detecting Cherenkov light from charged particles moving faster than light in water. This work presents a novel two stage classification framework for gamma-neutron discrimination: an initial physics based energy threshold filters unambiguous low energy gamma sources, followed by a machine learning ensemble that resolves ambiguities at higher energies. The detector response was characterized using ^{60}Co (1.17/1.33 MeV), ^{137}Cs (0.66 MeV), and a shielded ^{241}AmBe source, with lead, paraffin, and cadmium shielding employed to isolate neutron and gamma interactions. Energy calibration established a linear ADU to MeV conversion enabling identification of a neutron detection threshold at 2.62 ± 0.77 MeV via 3σ significance analysis. Stage one categorizes sources as pure gamma (below threshold) or neutron emitting (at threshold). For ambiguous cases above threshold, a machine learning pipeline utilizing pulse shape analysis was developed. A soft voting ensemble (Bagging, CatBoost, and MLP) achieved 0.816 accuracy and 0.921 AUC. This hybrid scheme combines physics based filtering with ML refinement, offering an interpretable and scalable solution for nuclear security, nonproliferation monitoring, and fundamental radiation research. Future work will explore deep learning architectures for waveform analysis and advanced statistical models for low energy spectra.

Detector System & Response

Detector Specifications

Component	Description
Active Medium	Pure water: Cherenkov radiator + neutron moderator
Active Volume	1.0 m^3 (d: 94 cm × h: 147 cm)
Photodetection	XP1802 9" PMT, 1230 V, 300–650 nm
Signal Acquisition	Red Pitaya FPGA, 125 MS/s, LAGO DAQ and LAGO board

Radiation Interactions

Gamma Radiation: Compton, photoelectric, pair production → secondary electrons → Cherenkov photons

Charged Particles: Direct Cherenkov or via bremsstrahlung

Neutrons: Moderated by water + captured by ^{1}H → 2.22 MeV prompt gammas

Radioactive Sources & Shielding Configurations

Source Characteristics

Source	Emission	Shielding / Purpose
^{60}Co	γ: 1.17, 1.33 MeV	Unshielded calibration
^{137}Cs	γ: 0.66 MeV	Unshielded calibration
^{241}AmBe	n: $(0-11$ MeV$)$ + γ: 4.44 MeV	Pb (10 cm): isolate neutrons
		BP + Cd: select 4.44 MeVγ
		Pb + Paraffin: produce 2.22 MeVγ

Pb: Lead, BP: Borated Paraffin, Cd: Cadmium

Shielding Configurations for neutron–gamma separation

(a) Sources (b) Pb

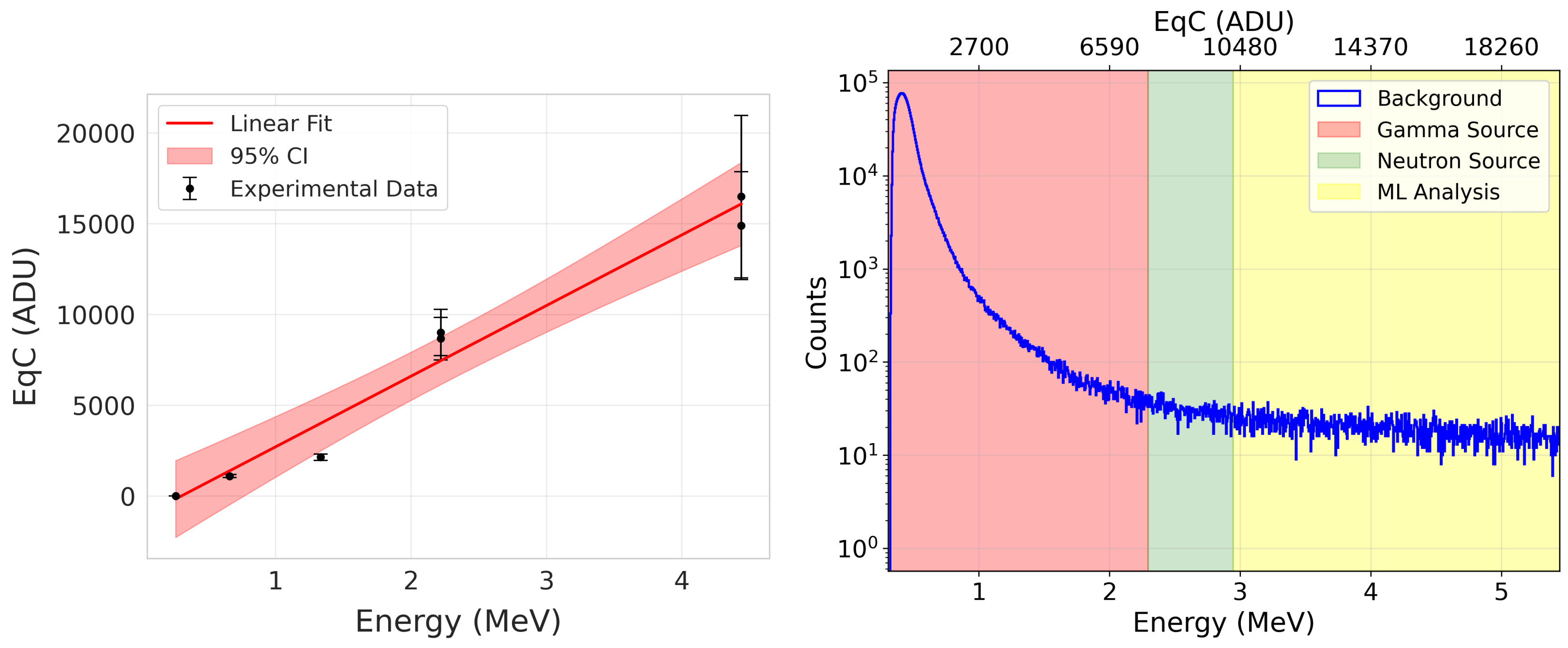
(c) BP + Cd (d) Pb + Paraffin

Stage 1: Physics based Cut

The **cutoff point** marks the maximum energy where a source signal becomes statistically indistinguishable from background (3σ criterion). This point, determined through rigorous uncertainty analysis (statistical bootstrapping, systematic variations, and bin discretization), defines the fully contained energy deposition in the detector. A strong linear correlation ($R^2 = 0.966$) was found:

$$\mathrm{EqC_{ADU}} = (3.89 \pm 0.84) \times 10^3 \cdot \mathrm{E_{MeV}} - (1.19 \pm 2.29) \times 10^3$$

This calibration enables spectral transformation from equivalent charge (ADU, ADC units) to energy (MeV), crucial for identifying a neutron detection threshold at 2.62 ± 0.77 MeV and classifying radiation sources.

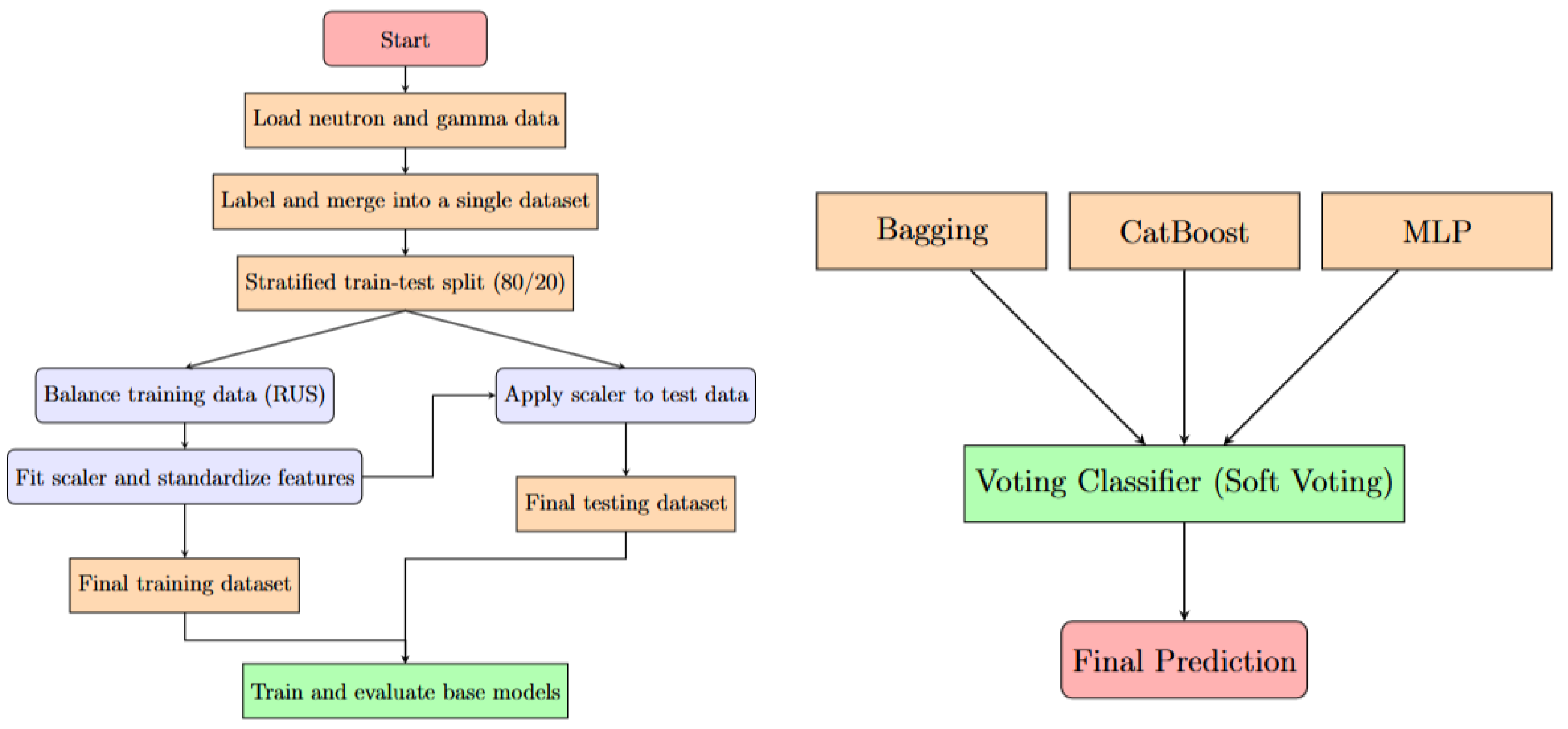


Left: Energy calibration curve with best-fit line and 95% CI band. Right: Converted energy spectrum showing the neutron detection threshold (green band) separating gamma-dominated (red) and ambiguous (yellow) regimes.

Stage 2: Machine Learning Classification

Data Preparation

- Unified dataset of labeled neutron-gamma pulses.
- **Preprocessing pipeline** (see left diagram): Stratified 80/20 split → `RUS` balancing → `StandardScaler` normalization.
- **Input features:** 32 temporal ADC values per pulse, capturing full shape.



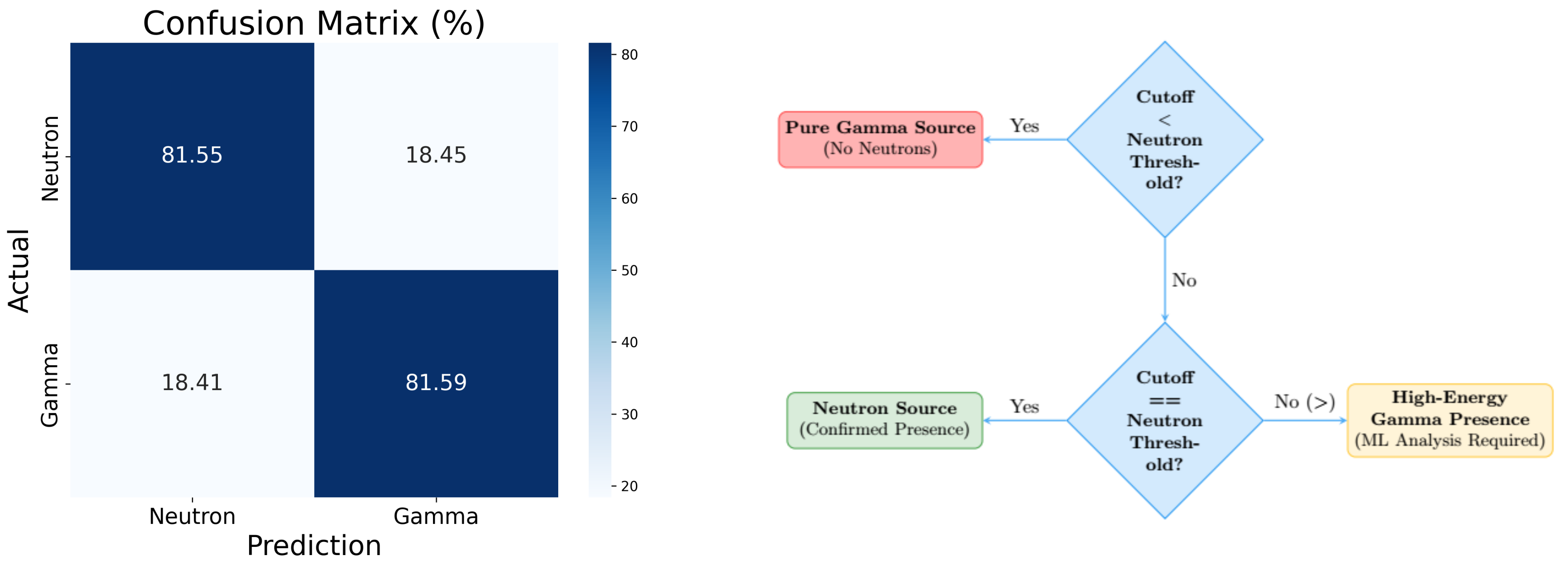
Left: The left branch processes the training set by applying class balancing and feature scaling, while the right branch ensures consistency in test set transformations. Both branches merge in the final stage, where classification models are trained and evaluated. Right: Soft voting ensemble architecture combining Bagging, CatBoost, and MLP classifiers.

Model Selection

- **Bagging**, **CatBoost**, and **MLP** classifiers, from over 25 candidates.
- Combined in a weighted soft voting ensemble, averaging probabilistic outputs (see right diagram above).
- Each model fine-tuned with `RandomizedSearchCV` (100 iterations, 5-fold CV).
- Optimal decision threshold: 0.52, balancing sensitivity and specificity.

Performance

- Accuracy: 0.816; AUC: 0.921 (95% CI: 0.919–0.922).



Left: Test set confusion matrix after threshold optimization. Right: Final classification workflow (traffic light) with decision nodes (blue) routing to gamma (red), neutron (green), or ambiguous (yellow), resolved by ML refinement.

Conclusions

- Developed a two stage approach for neutron-gamma source discrimination in a Water Cherenkov Detector (WCD).
- Established a linear ADU to MeV calibration ($R^2 = 0.966$) enabling energy based source discrimination.
- A machine learning classifier achieved high accuracy (0.816) and AUC (0.921) for pulse level neutron-gamma classification.
- Hybrid approach maximizes throughput: physics cut handles obvious cases, ML refines ambiguous pulses.
- This approach enhances WCDs as powerful tools for nuclear security and radiation research.