A Convolutional Neural Network Algorithm for 2.5 MeV Neutron Discrimination in $LaCl_3$ Scintillators

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$LaCl_3$ scintillators: neutron spectroscopy

Main reaction of interest for neutron spectroscopy: $^{35}Cl(n,p)^{35}S$ → Q-value = 0.6 MeV

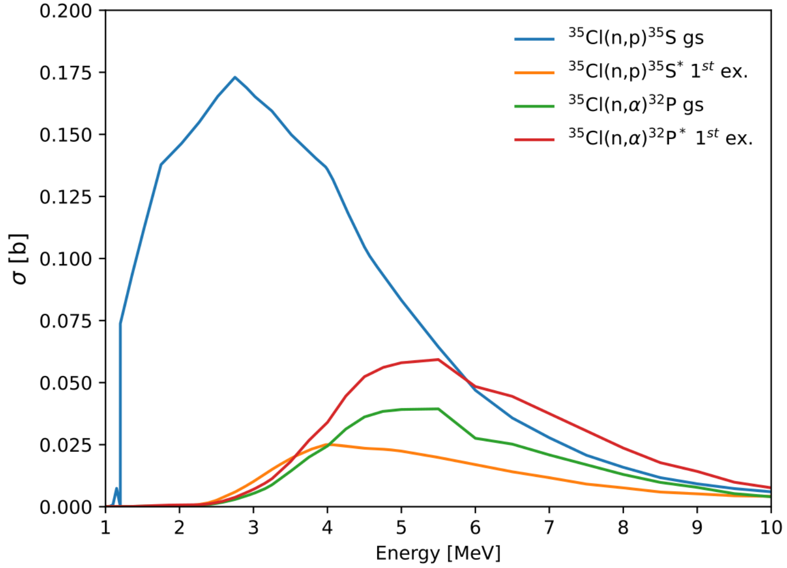
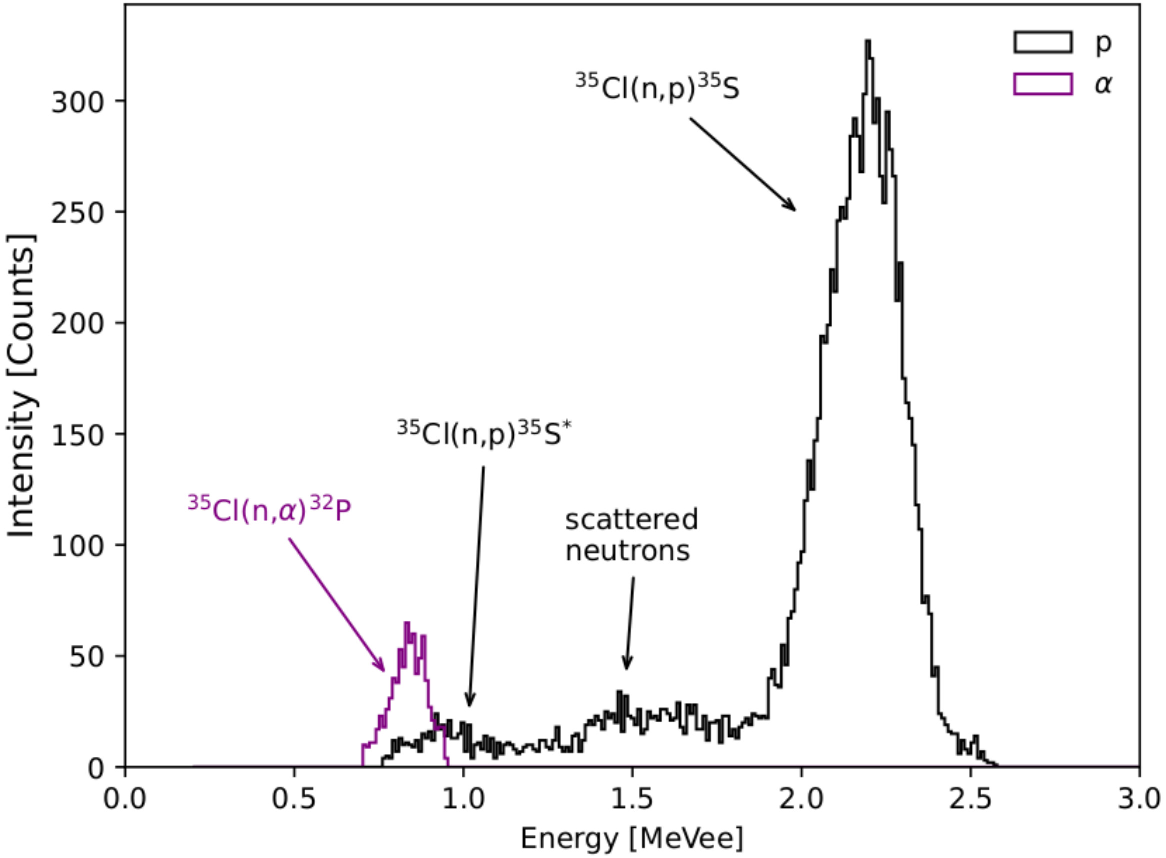


Figure 1. Cross sections of the different reaction channels from ENDF/B-VIII.0 library [10].

- $LaCl_3$ scintillators
  → inorganic crystals.
- 2.5 MeV neutron spectroscopy in NF.
- Compact alternative to TOFOR and MPR spectrometers
  → multi-lines-of-sight cameras possible
- Good alternative to CLYC scintillators: faster signal: ~100 ns vs > 1 μs → higher rate capability
- Energy resolution ~10% at 2.5 MeV
- Main application at the moment:
  - Fast ion studies



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Expected diffculties in using Lacl3 in nuclear fusion experiments

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$LaCl_3$ efficiency for gammas > efficiency for neutrons → high gamma counts

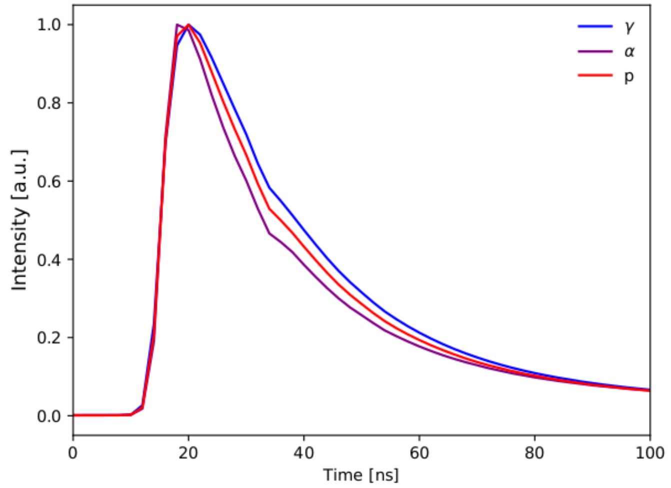
- Efficiency for 2.5 MeV neutrons through the $^{35}Cl(n,p)^{35}S$ reaction channel is **~ 1-3 %**

- Efficiency for Gamma rays:

~ 50% at 500 keV

~ 40% at 1 MeV

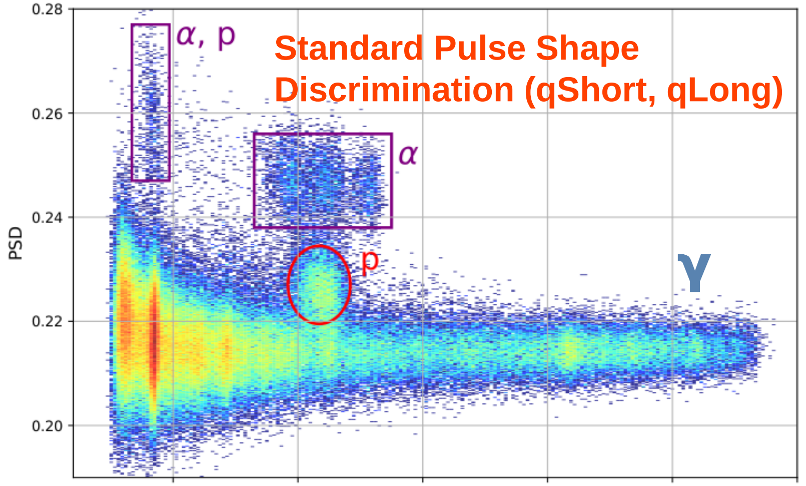
~ 30% at 10 MeV

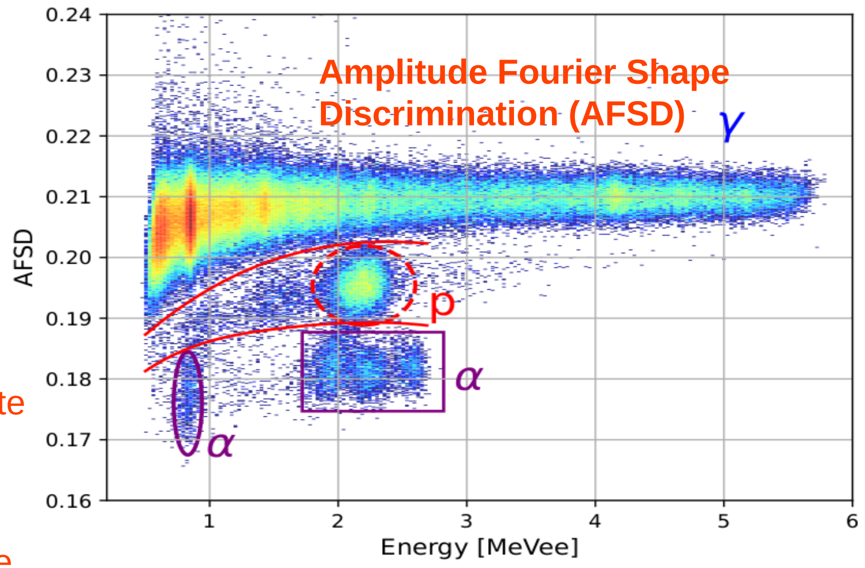


$$y[k] = \sum_{n=0}^{N-1} e^{-2\pi i \frac{k n}{N}} x[n] \rightarrow AFSD = \frac{\sum_{n=0}^{j} \|y[k_n]\|}{\sum_{n=0}^{i} \|y[k_n]\|}$$

Short gate

Long gate

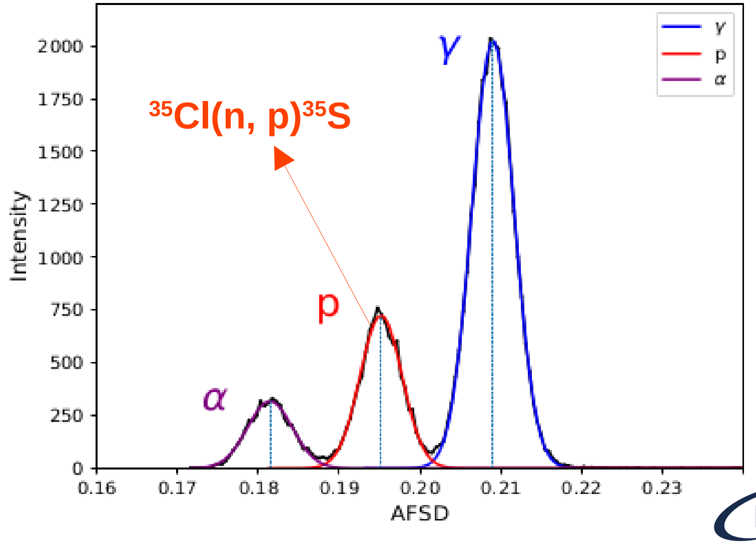




- AFSD: better discrimination compared to standard PSD.
- However, **optimal extraction regions might be different for different experiments and somewhat subjective.**
- → This could complicate FPGA implementation for real-time processing.

→ Possible solution: alternative algorithm with similar performance.

→ **Convolutional Neural Network**



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Single pulse NN discriminator:
training and validation measurements
at PTB (Physikalisch Technische Bundesanstalt, Germany)

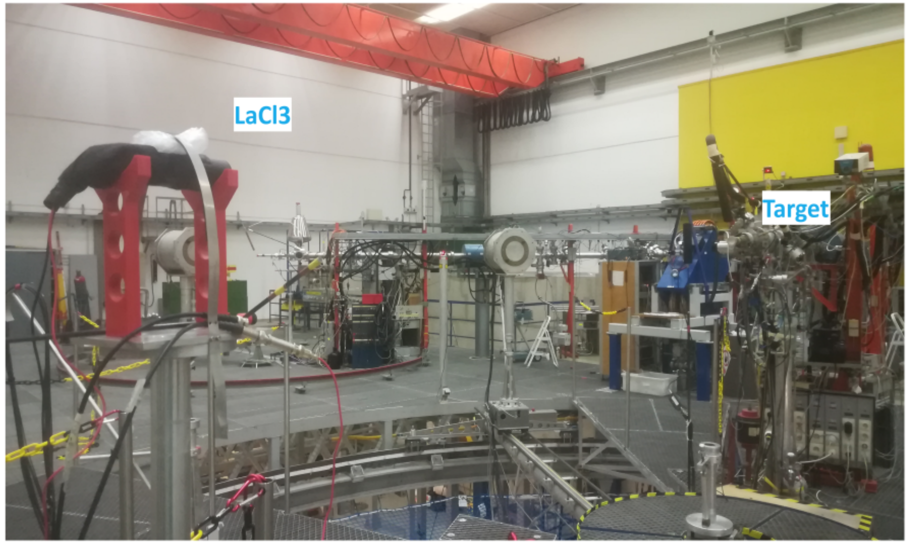
UNIVERSITAS STUDII PADUANI MCCXXII
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
INFN Istituto Nazionale di Fisica Nucleare
ISTP Consiglio Nazionale delle Ricerche

neutron dataset:

Measurements of neutrons with **9 different energies** from **~2 MeV to 5 MeV**

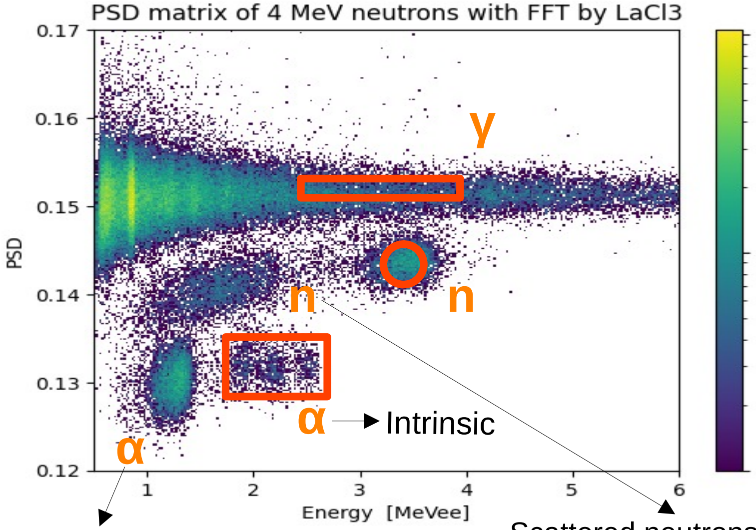
gamma and alpha dataset:

Gamma (= beta) **and alpha** particles:
intrinsic radioactivity of the $LaCl_3$ crystal
+ **gamma calibration sources** + **PTB data**



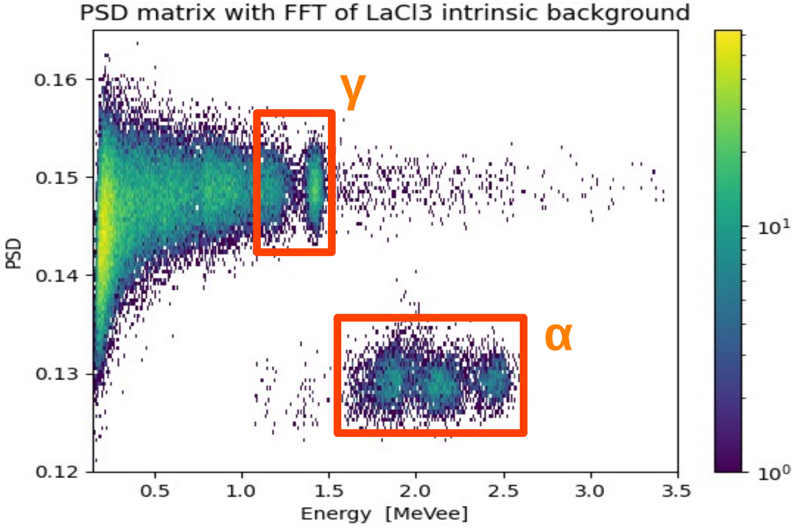
- **Low-scatter measurement hall of PTB**:
  - H and D beams, solid Ti(T) target or gas target made of D2 molecules.
  - Nuclear reactions: **p(T,n)^{3}He** or **D(D,n)^{3}He.**
- Changing detector angle wrt beam direction → selection of different neutron energies.
- Training with balanced classes: **Nalpha = Nneutrons = Ngammas = 208645.**
- **Supervised learning**: "true label" = **AFSD label.**
- AFSD regions carefully selected to have high confidence).

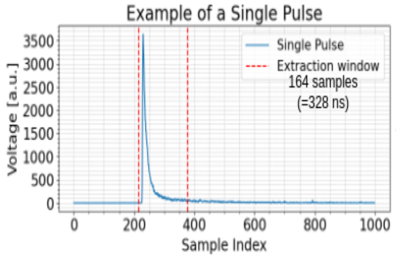
Example of AFSD sampling for training data (careful selection):

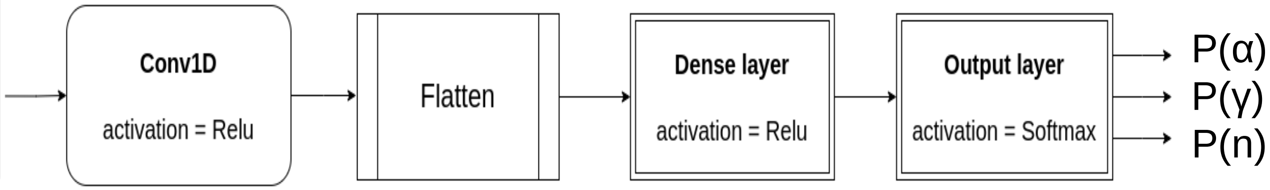


^{35}Cl(n,α)^{32}P

Scattered neutrons or
^{35}Cl(n, p)^{35}S* reactions (^{35}S excited states)







Single pulse NN discriminator:
test phase

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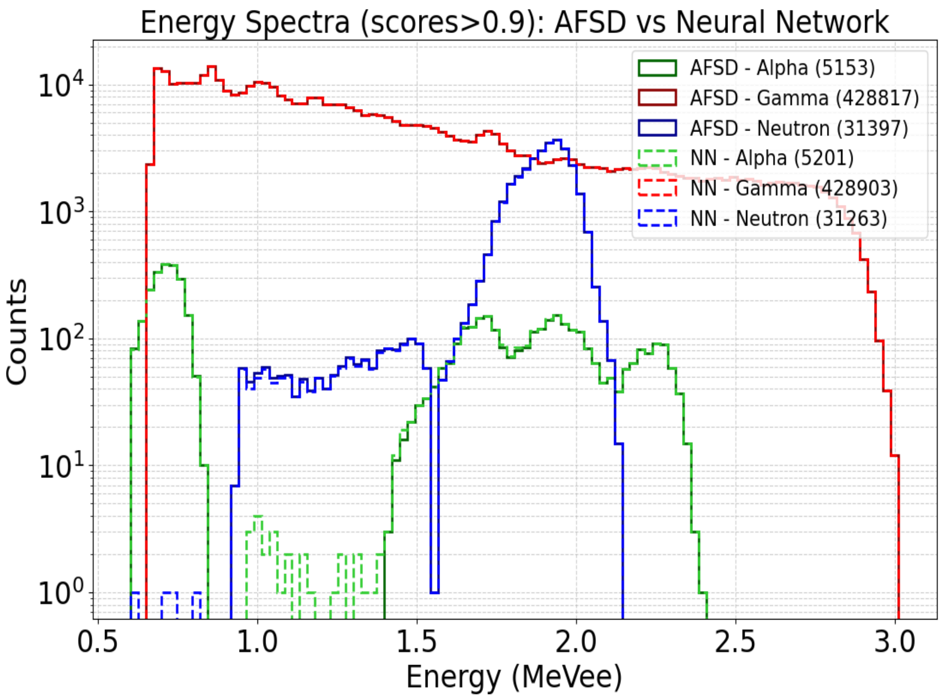
D-D neutron measurements (2.5 MeV) at NILE, UK:

- **Neutron Irradiation Laboratory for Electronics (NILE)** at the Rutherford Appleton Laboratory (RAL, in UK).
- Compact **Deuterium-Deuterium neutron generator** (2.5 MeV).
- **Significant amount of gamma background, thermal and scattered neutrons.**
- Radiation field **significantly more complex** than PTB.

  → test PSD performances in more realistic environment, **similar to fusion experiments.**

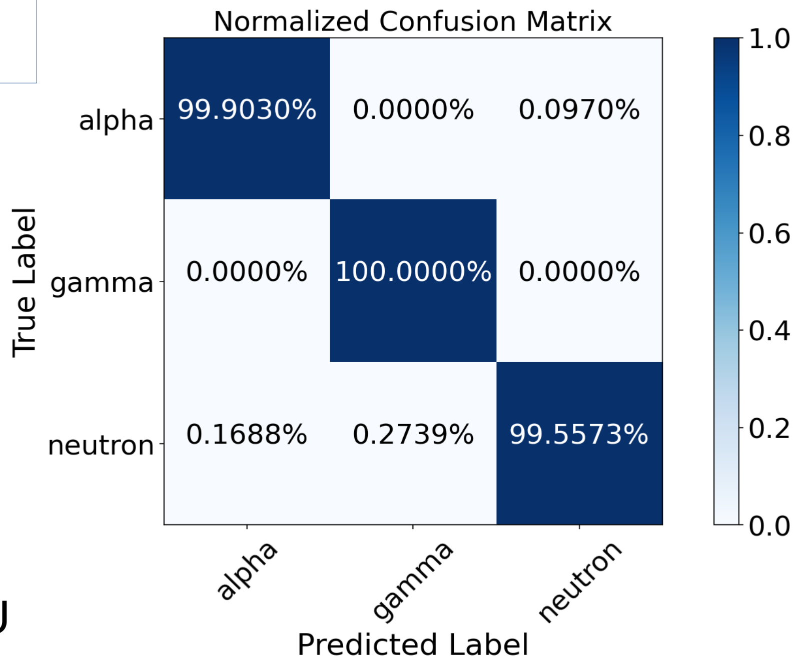


- - Prediction score > 90%.
  → discarded pulses = 0.74 % of the total number of pulses (all classes).
- Percentage of discarded neutrons = 9.16 % of only neutron pulses.

rationale: better to reject pulses than to pollute measurements

classification report

	precision	recall	f1-score	support
alpha	0.9898	0.9990	0.9944	5153
gamma	0.9998	1.0000	0.9999	428817
neutron	0.9998	0.9956	0.9977	31397
accuracy			0.9997	465367
macro avg	0.9965	0.9982	0.9973	465367
weighted avg	0.9997	0.9997	0.9997	465367



NOTE: with "neutron" we mean a neutron that creates p and ^{35}S in the crystal.

Future test: data from $LaCl_3$ at MAST-U

Additional developments (presented in the poster session)

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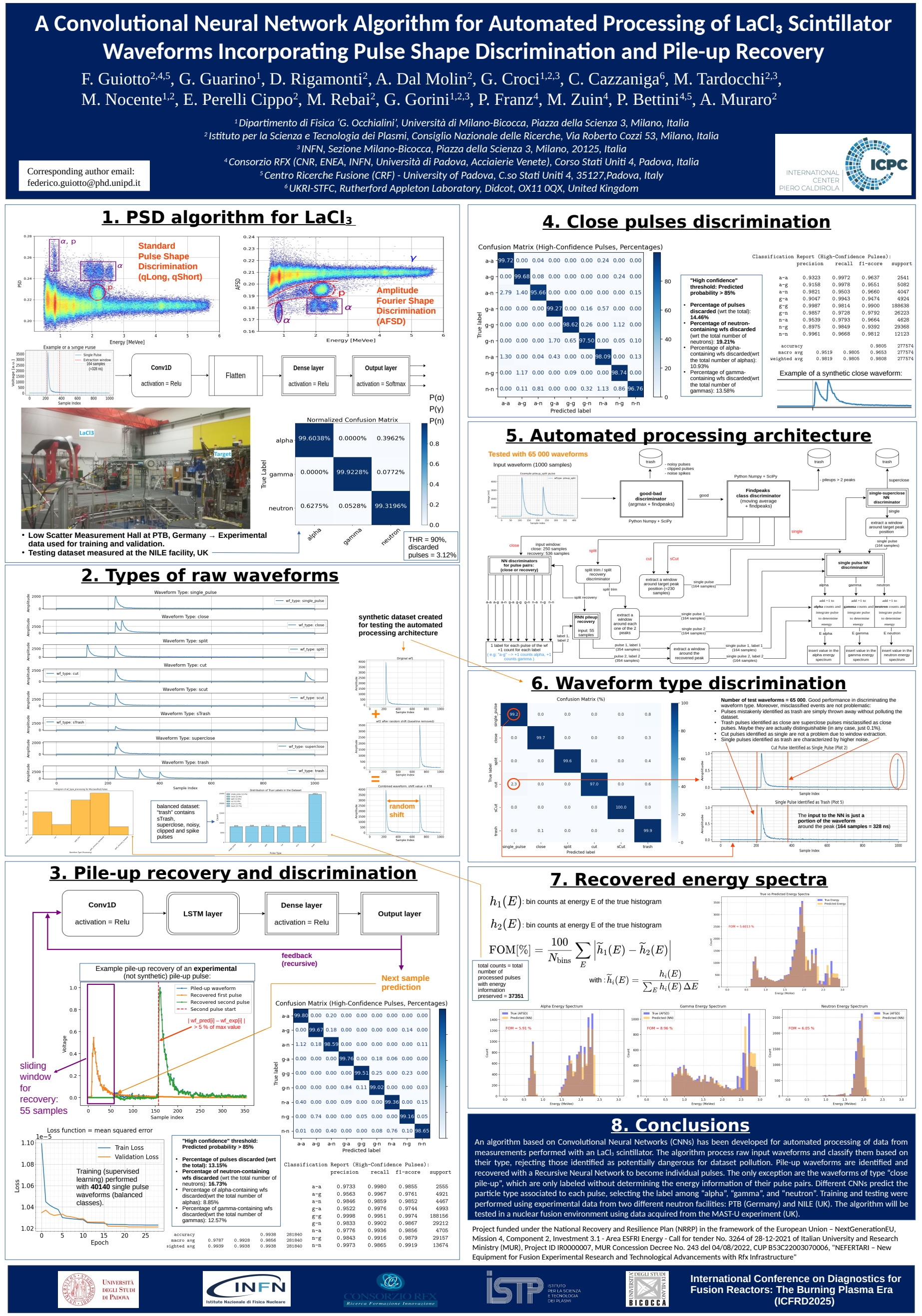
- **Algorithm upgraded**: composite architecture to **process data** from $LaCl_3$ neutron measurements **in an automated way.**
  → in view of **FPGA implementation** for real-time analysis: supervision by the operator is not feasible.
- The algorithm **processes raw waveforms** from the detector and **classify** them, **rejecting those identified as potentially dangerous for dataset pollution** (noisy, out of scale, degenerate pile-ups, etc).
- **Pile-up pulses are totally or partially restored**, depending on the waveform type.

→ More details in the poster presentation:

Poster number: 4



Conclusions

- A **Convolutional Neural Network** able to discriminate **alphas, gammas and neutrons** (reacting through the $^{35}Cl(n, p)^{35}S$ channel) has been developed as an alternative PSD method to the traditional one and the AFSD method.
- **Training** (supervised learning) was performed using **experimental data from intrinsic radiation, gamma calibration sources and neutrons** at different energies (2 – 5 MeV) **measured at the PTB facility** in Germany. The "true" labels were determined using the AFSD method (PSD based on Fourier Transforms).
- **A test** was performed using **2.5 MeV neutrons**, measured **at the NILE (UK) facility**, exploiting the D-D reaction. Good agreement was found in terms of accuracy, confusion matrix, classification report and energy spectra comparison.

- **Results** presented in this work should be considered **preliminary.**
  - New data will be used to train the NN, e.g. protons from INFN-Legnaro experiments.
  - The algorithm will be further tested with data from a nuclear fusion experiment: MAST-Upgrade (UK), where a $LaCl_3$ scintillator was recently installed (July 2025) for the detection of Deuterium-Deuterium neutrons.

Thank you for your attention.

Backup slides

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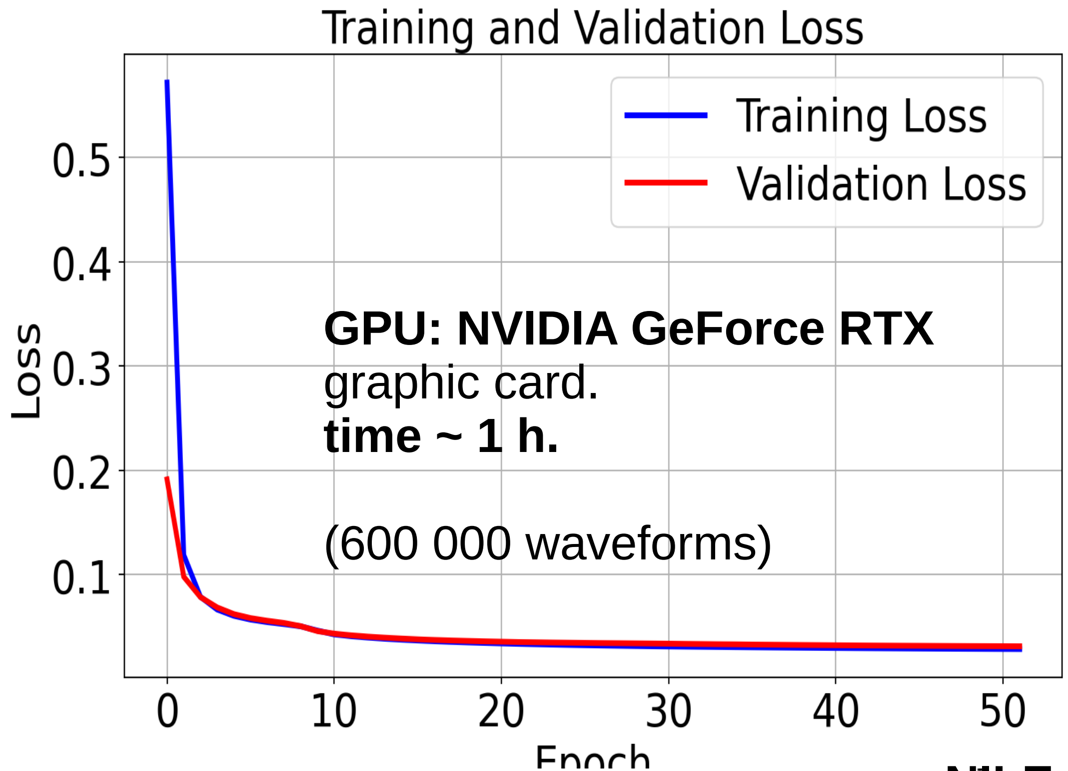
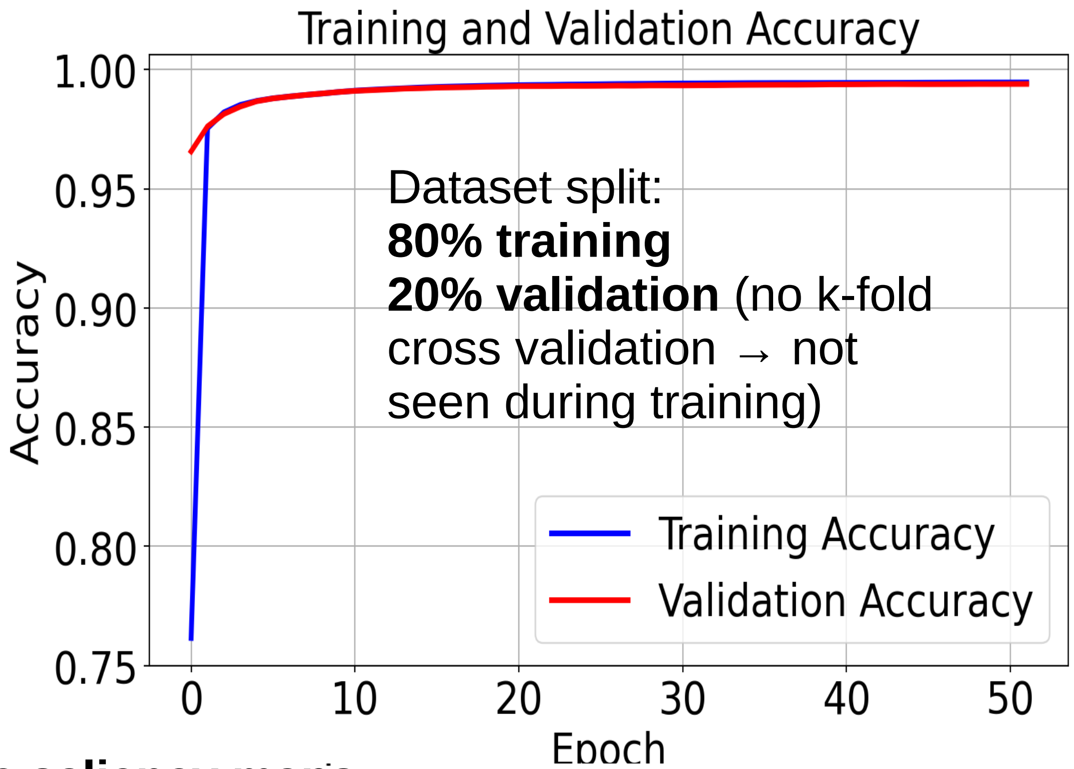
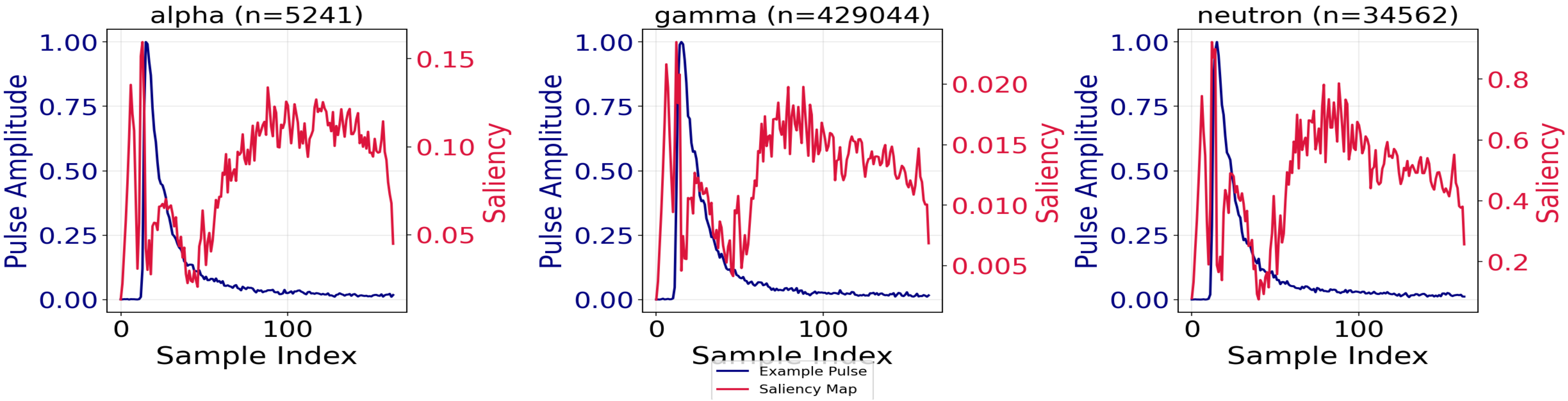




NILE average saliency maps:



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Test on 14.8 MeV neutrons measured at PTB

Model trained without gammas and alphas from PTB

- D beam, solid Ti(T) target: D(T,n)^{4}He reaction.
- AFSD vs Energy plot: **overlap among different classes**: choice of
- Optimal regions subjective to the operator → **problem for automatization.**
- **AFSD and convNN both applied to the dataset**: results are very close.

- **GEANT4 simulation: 14.8 MeV neutrons impinging on a**
- **Isolated LaCl3 crystal** → simulated neutron and experimental spectra comparison --> good agreement despite **simple model** simulation.