Coincident Detection of Neutrinos and Charm Hadrons

with SND@LHC and ATLAS

Machine Learning for Signal–Background Classification

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E FÍSICA EXPERIMENTAL DE PARTÍCULAS

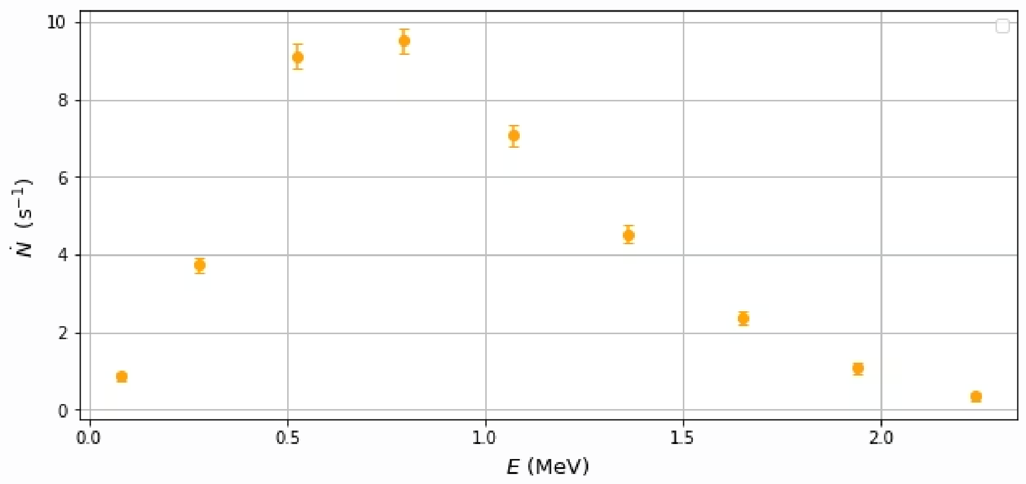
The neutrino

The existence of the neutrino can be inferred from

simple experiments

- Beta decays provide a continuous spectrum in energy → three bodies after the decay
- Also, angular momentum conservation in beta decays suggests the existence of a spin ½ particle

The neutrino was postulated in 1930 by W. Pauli



Energy spectrum of the beta decays of sample of 90-Sr

Neutrino detection

- **1950s: First detection of neutrinos**
- 1987: First detection of supernova neutrinos
- 2008: LHC starts operating
- 2022: SND@LHC starts operating
- **2023: First detection of neutrinos with the SND@LHC**

SND@LHC detector (Copyright © CERN)

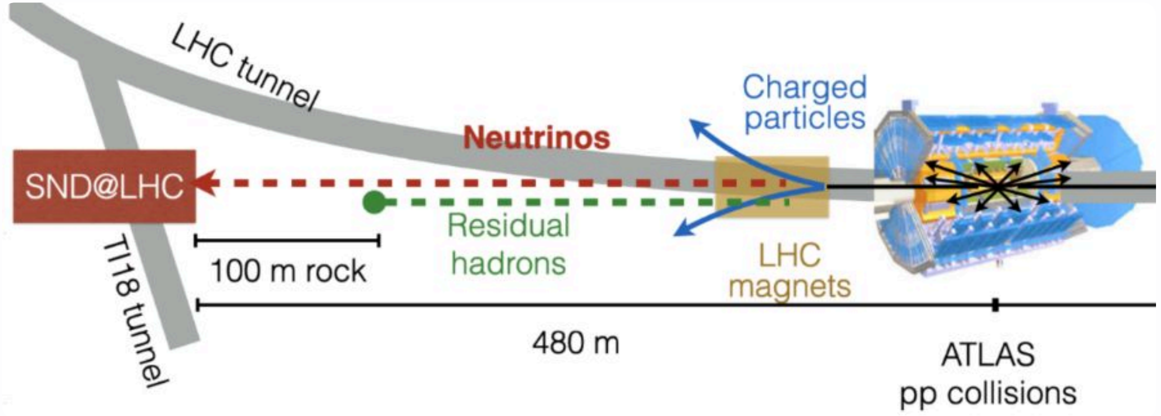
Coincident detection of neutrinos at SND@LHC and ATLAS

ATLAS

- Proton–proton collisions
- Production of many particles, including charm hadrons
- Neutrinos are produced in particle decays

SND@LHC

- Located ~480 m from ATLAS
- Designed to detect neutrinos
- Neutrinos can travel through the rock and LHC infrastructure up to the detector

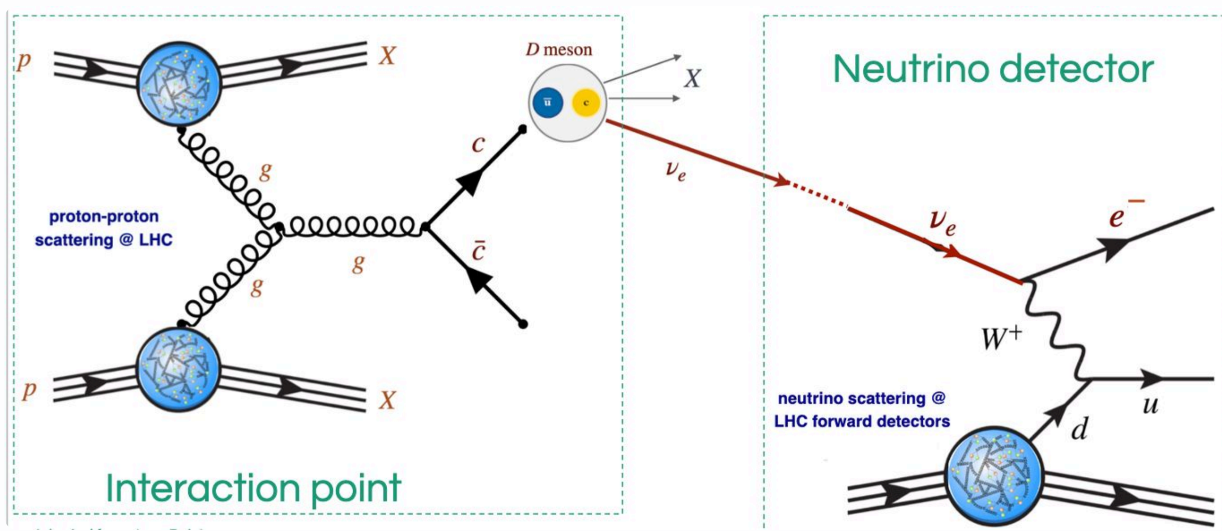


Objectives

Make a coincident detection of

A charm-producing event at ATLAS	A neutrino interaction at SND@LHC

...produced by the same proton–proton collision.



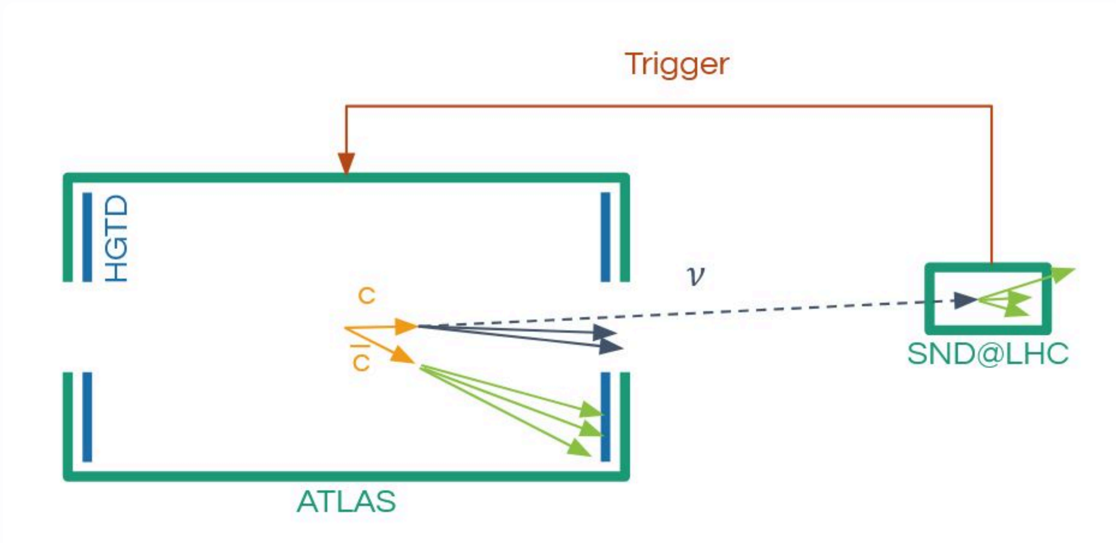
Objectives

Many collisions take place at ATLAS but not all information can be stored. To make the coincident detection it is necessary to

learn how to discriminate between

- events at ATLAS in which a neutrino is produced and can be detected at SND@LHC (**signal events**)
- events at ATLAS where no neutrino is formed or no neutrino can be detected at SND@LHC (**background events**)

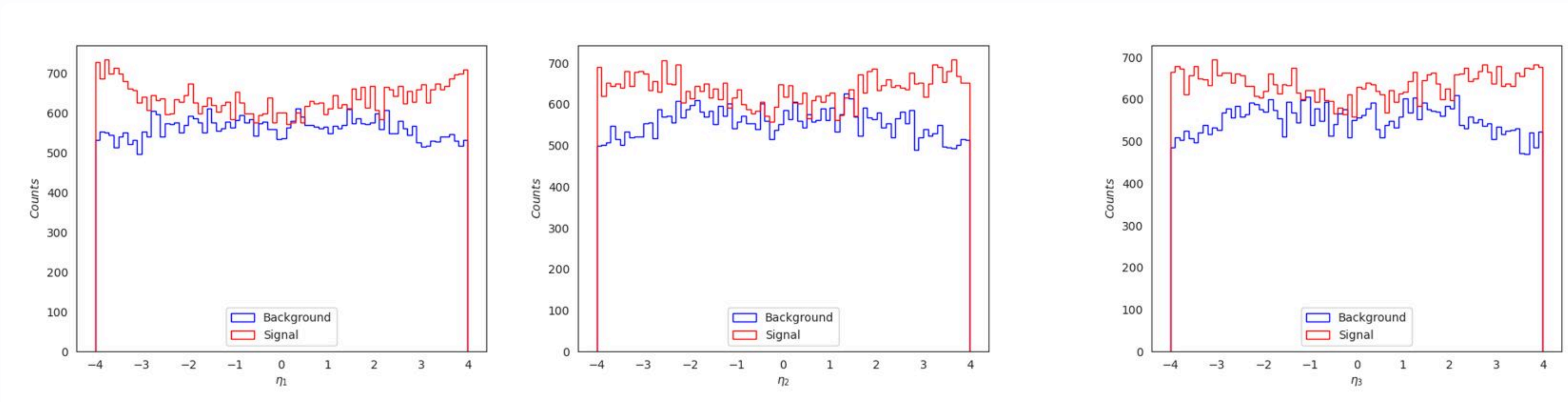
based on the ATLAS and SND@LHC detector measurements



Differentiating between signal and background

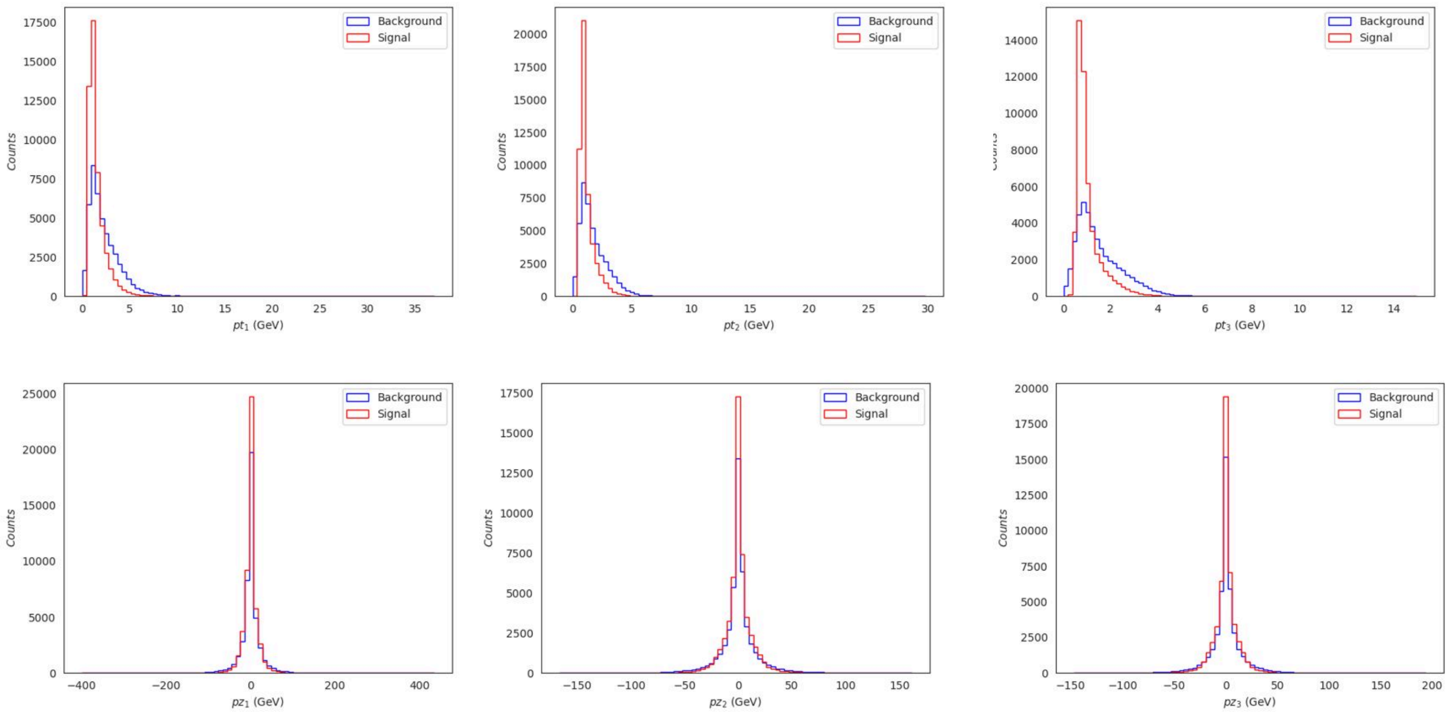
Database: Pythia8 event generator with the SoftQCD physics model for **Background**

POWHEG event generator for **Signal**, which simulated events generating a pair production of charm quarks resulting in a neutrino in the range of detection of the SND@LHC (η_ν > 6.5)

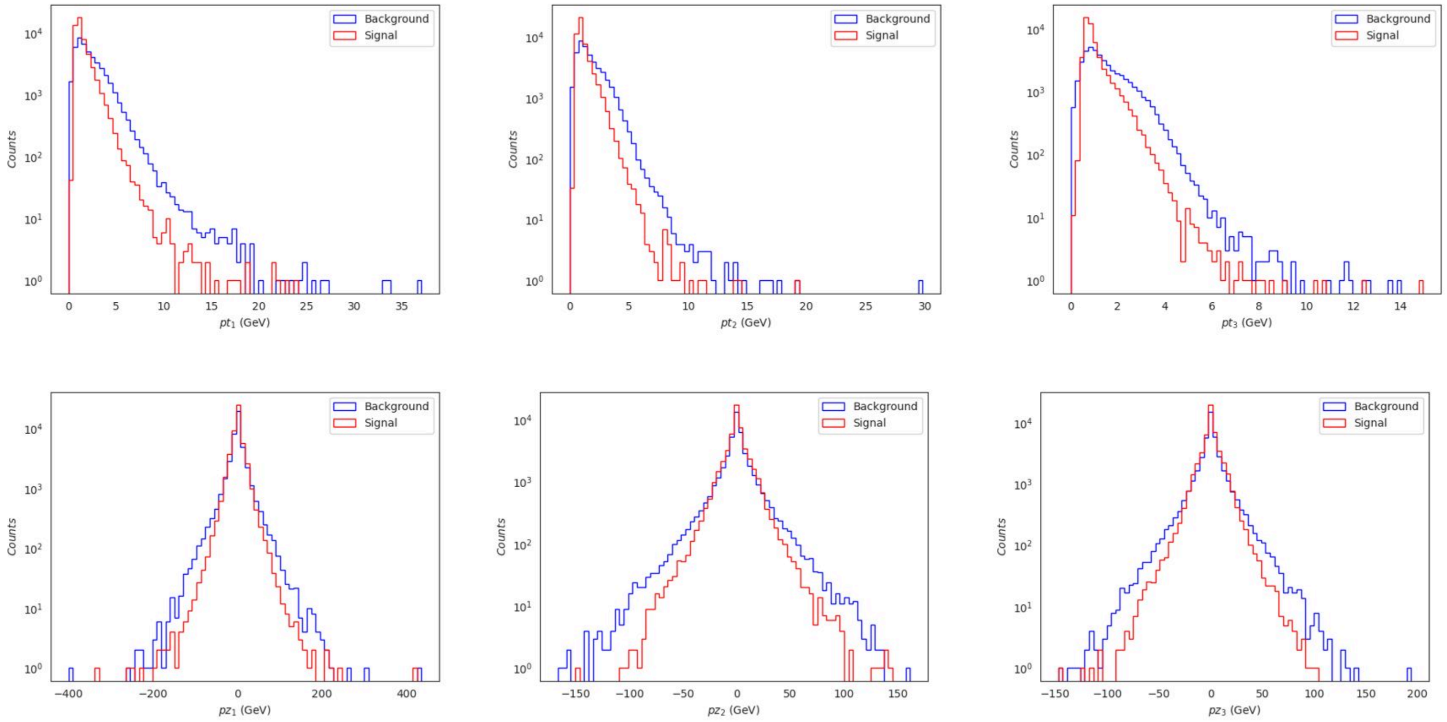


$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Differentiating between signal and background



Differentiating between signal and background

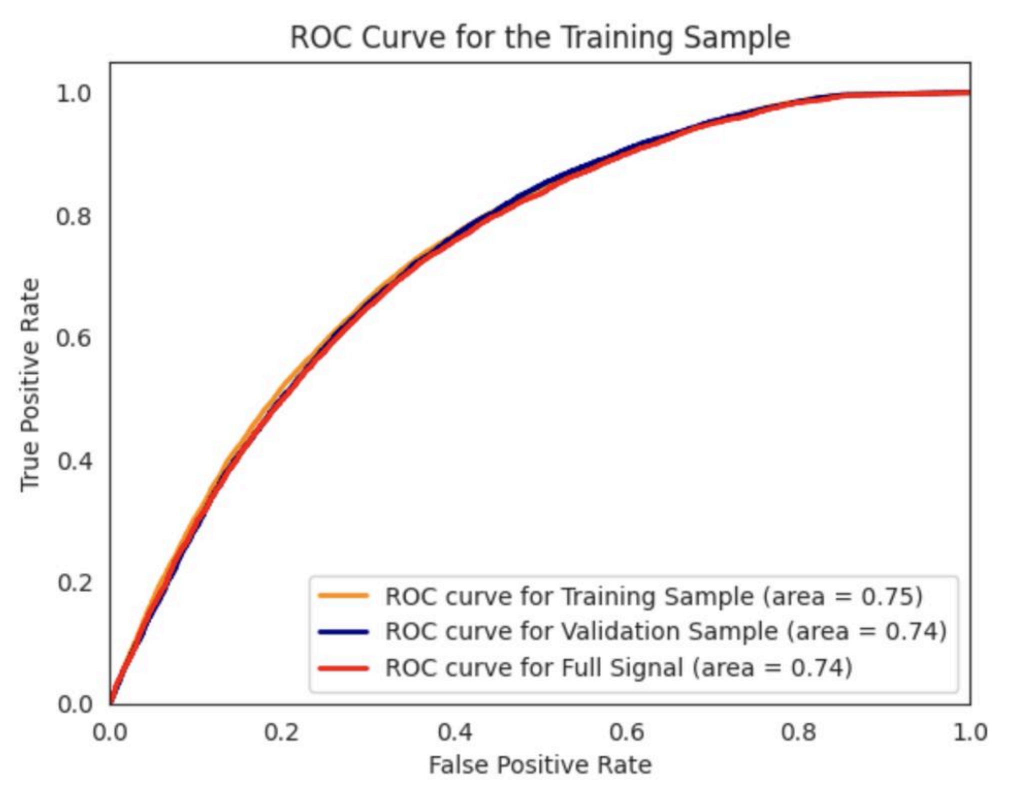


Previous work

- A Nerual Network was trained by João Goulão obtaining an AUC of 0.74 for Full Data in the discrimination of signal and background
- The neural network was trained on

$p_T,\ p_z,\ p$ of the three particles with the largest transversal momentum

$\eta_\nu,\ \phi_\nu, E_\nu,\ d\phi 2,\ d\phi 3,\ \nu_{\Delta\phi}$



Previous work ROC curve

Analysis and work done

· Neutral charges as well as other particles that cannot be detected at ATLAS were removed of the training

· Charge was added as a training feature in the neural network

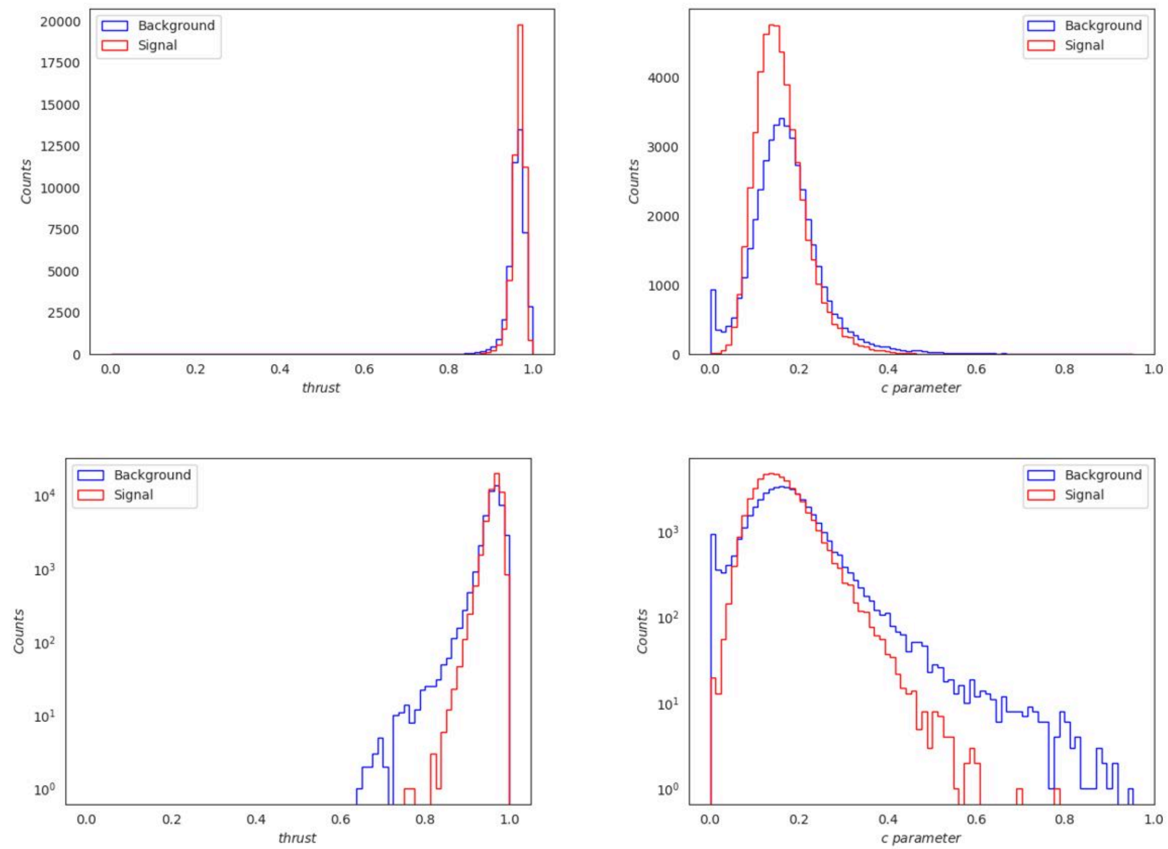
· Event-like variables were added as training features in the neural network

· Different approaches to data processing before the data was send to ML training were analysed

· Different parameters in the neural network training were analysed

· A different architecture was explored: The particle Flow Network (PFN)

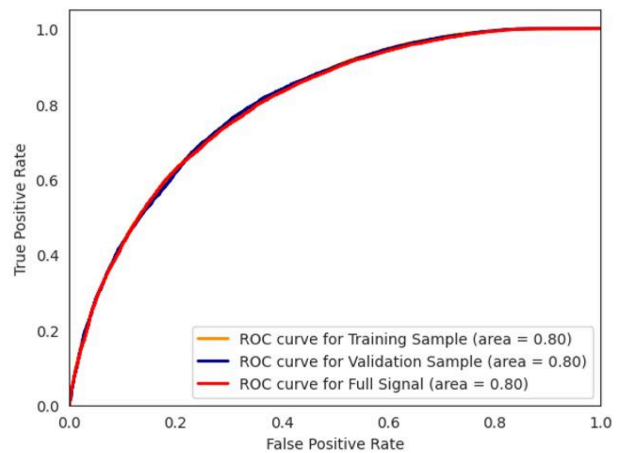
Event-like variables

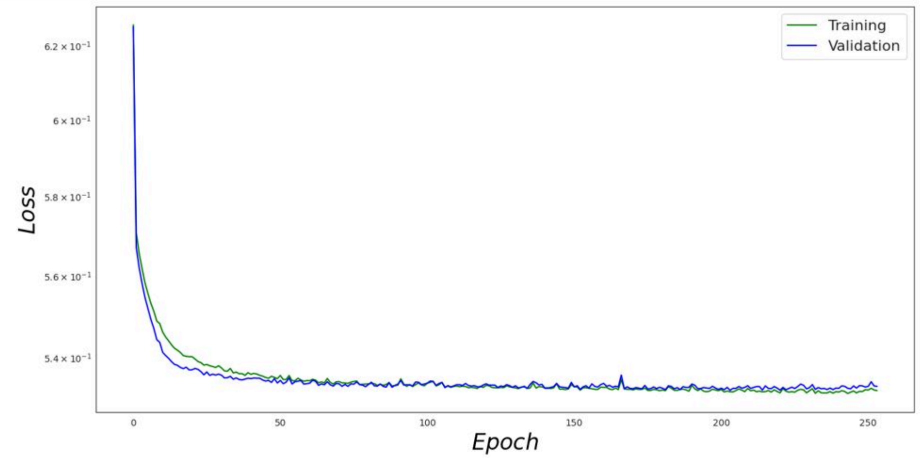


(logarithmic scale)

Made with GAMMA

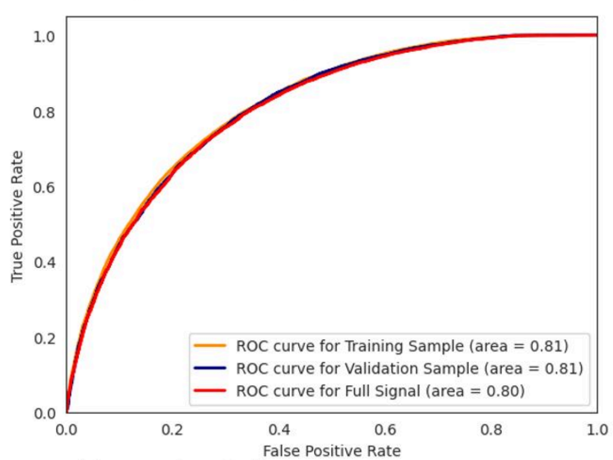
Results using event-like variables

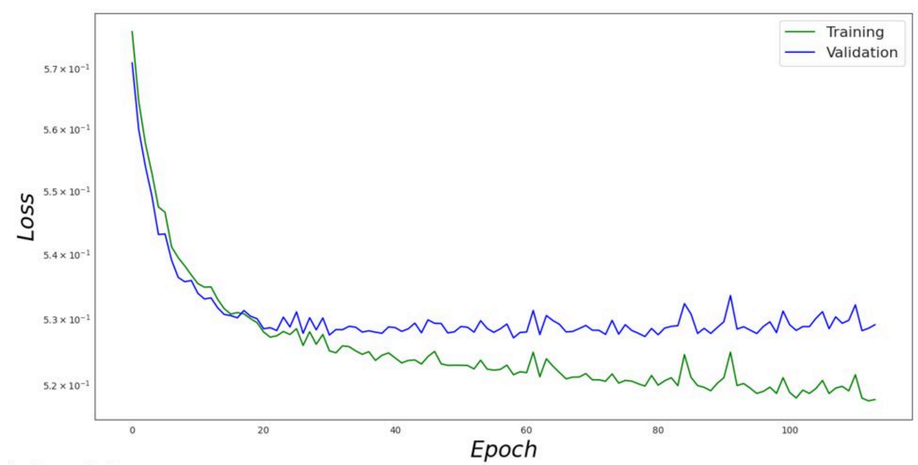




Depth: 2 layers

Width: 10 parameters





Depth: 3 layers

Width: 20 parameters

Same physics problem, two machine-learning approaches

Previous neural network

The neural network was trained on:

- Particle-level information only of the three particles with the largest tranversal momenutm

+

- Event-level variables → Not all information about the detailed particle structure is fed into the training

Particle Flow Network

Individual particles

→ Uses information from the individual particles

→ Keeps more details about the event structure

→ Can capture particle-level patterns that may be lost in global variables

> **Question**: Does using more detailed information about the particles help us identify the signal?

What goes into the PFN?

For each particle we use 6 features:

Transverse momentum p_T

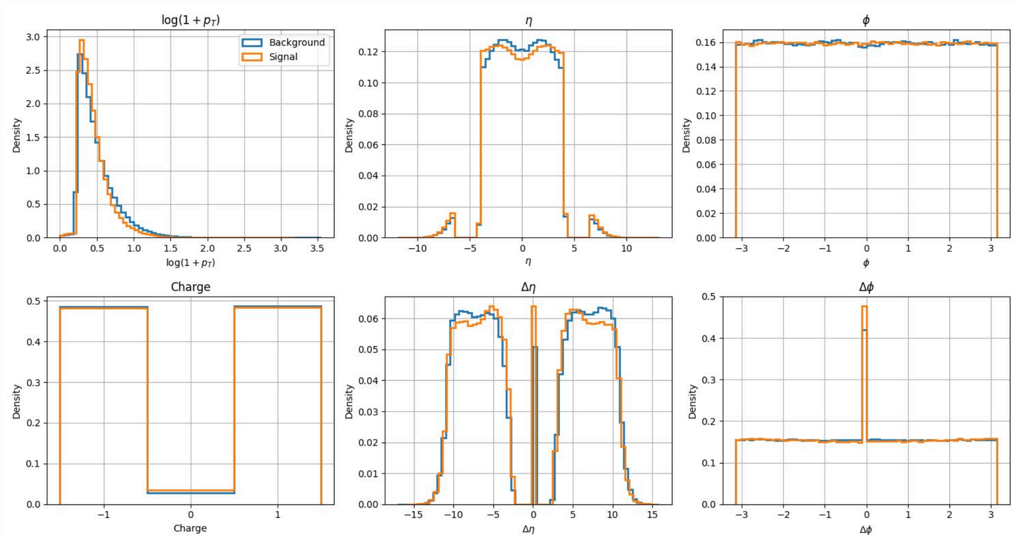
Pseudorapidity η

Electric charge q

Pseudorapidity difference to the neutrino $\Delta\eta$

Azimuthal difference to the neutrino $\Delta\phi$

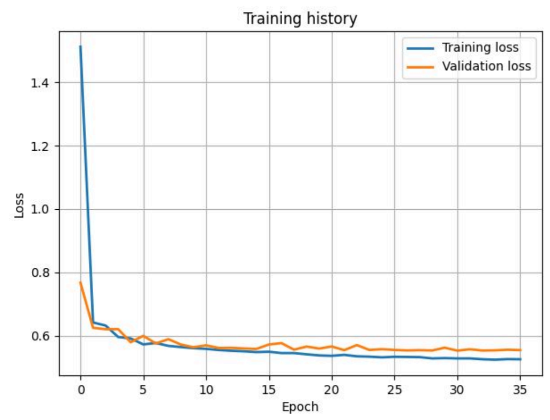
Event representation: Up to 200 particles per event.



Does the PFN learn?

Training performance

- The loss decreases during the first epochs and then stabilizes.
- Training and validation accuracy remain relatively close.
- Training accuracy reaches about 0.74.
- Validation accuracy reaches about 0.72.

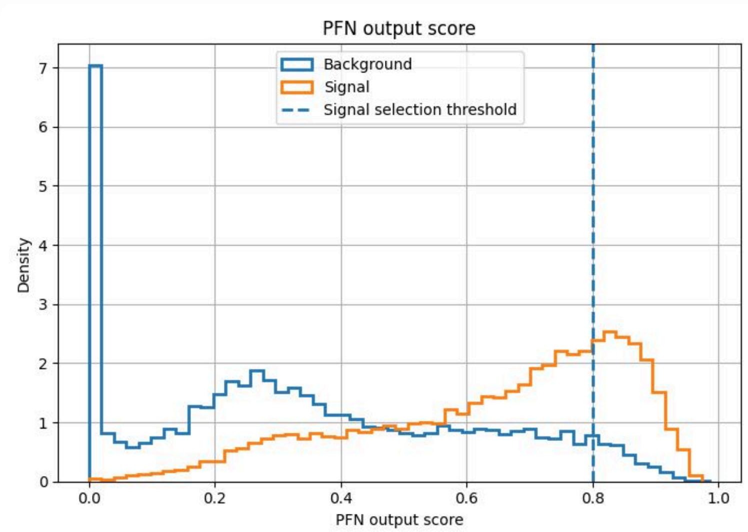


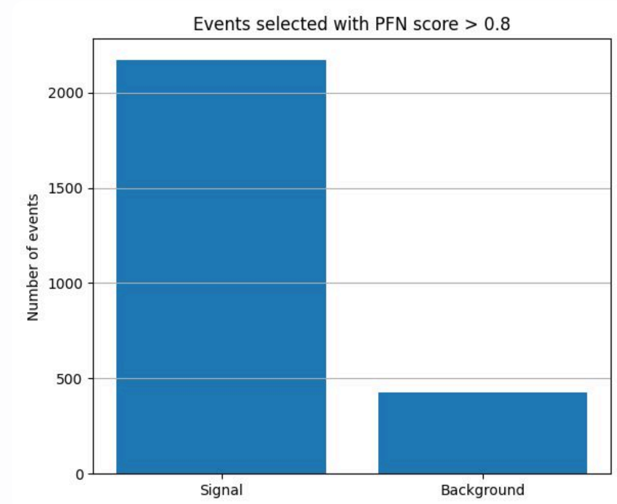
From a score to a signal selection

PFN output score

Each event receives a score between 0 and 1:

- Low score → more background-like
- High score → more signal-like





We chose a selection threshold:

PFN score > 0.8

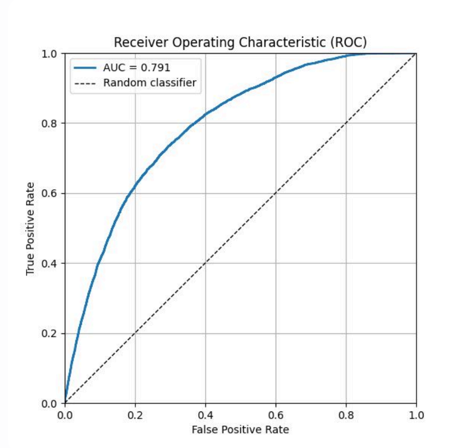
After applying this selection:

- **2173 signal events**
- **429 background events**

How well does it work?

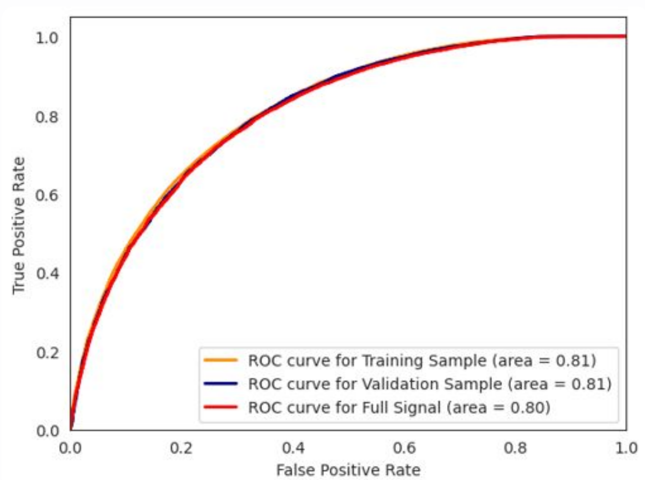
Comparing the two approaches

Model	Test AUC
PFN	**0.79**
Previous NN	**0.81**



Both models provide useful signal–background discrimination.

The previous neural network performs slightly better in this specific implementation.



Both models provide useful signal–background discrimination.

The previous neural network performs slightly better in this specific implementation.

Conclusion

From ATLAS events to neutrino–charm coincidences

Physics

The goal is to connect two parts of the same collision:

- ATLAS: the proton–proton collision and its produced particles
- Charm hadron decay: production of a neutrino
- SND@LHC: detection of the neutrino

Conclusion

From ATLAS events to neutrino–charm coincidences

Machine learning

The PFN shows that particle-level information contains useful signal–background discrimination.

With a cut of PFN score > 0.8, we selected:

- 2173 signal events
- 429 background events

Performance (Test AUC):

- AUC (PFN) = 0.79
- AUC (Previous NN) = 0.81

Final message

- ML can help identify ATLAS events compatible with the neutrino–charm signal.
- The PFN works, but more detailed particle-level information did not yet improve the classification.
- Further optimisation is needed to determine its full potential.