Identification of exotic highly ionising particles at the Belle II pixel detector using unsupervised auto-encoders

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The Belle II Experiment

- The Belle II experiment is located at the asymmetrical electron-positron collider SuperKEKB in Japan
- Centre-of-mass energy 10.58 GeV and world-record luminosity

- 2-layer DEPFET pixel detector (PXD)
- Pixel sizes: 50 μm - 85 μm
- Data rate coming from PXD is drastically higher than rate of all other sub-detectors

⇒ Online data reduction is required
Anomalous particle signatures

- Detection of particles with low momentum, high charge deposition, uncommon trajectories is compromised by data reduction mechanism.

- Identification of these particles relying solely on PXD observables would help to mitigate this effect.

- Unique event signature of these particles facilitates identification in PXD.

Objective:

- Filter out signal particles against beam background with PXD data only.

Examples:

- Exotic new physics: magnetic monopoles
- Long-lived particles
- Relevant for various analyses: slow pions
Pixel detector observables

- Pixel detector observables used for this study:
  - Signal from 9x9 pixel matrix (optimized for our studies) around pixel with highest charge value
  - Global cluster position

- Why use machine learning techniques?
  - Information of multiple observables can be combined efficiently

- Why unsupervised?
  - No assumptions about signal or background required

- Why auto-encoders?
  - Can cope with large imbalance between signal and background

Part of the PXD readout system in the Giessen lab
Auto-encoders - Training process

before training

- Neural network learns to reconstruct pixel matrix that was created by beam background particles

- Difference between input and output matrix is used to adapt the weights during the training process
Auto-encoders - Training process

• Neural network learns to reconstruct pixel matrix that was created by beam background particles

• Difference between input and output matrix is used to adapt the weights during the training process
In the evaluation step, the network will be able to reconstruct beam background matrices but fail if presented with signal matrices (= anomaly).

The reconstruction loss is used to quantify the ability to reproduce a given pixel matrix.
Validation in simulation

• Simulation of beam background and (exotic) highly ionising particles (e.g. anti-deuterons, magnetic monopoles, …) as signal

• Signal is characterized by a high reconstruction loss

• Auto-encoders have a filtering functionality that needs to be combined with a subsequent in-depth analysis
What happens if there is signal in the training data?

- Training and evaluations were repeated with signal mixed into the training sample.
- Small amounts < 0.1% of signal are negligible, for a few percent of signal the training is compromised.
- Beam background is assumed to be orders of magnitude higher in the PXD suggesting that this effect is negligible for our studies.

0.01% Signal

0.1% Signal

1% Signal
Summary / Outlook

• **Data selection mechanism in PXD readout discards information that could be related to new physics**

• A PXD rescue system relying on PXD data only is developed

• **Auto-encoders as unsupervised machine learning technique are able to filter signal (= anomalous) PXD data against beam background**

• Studies about implementation of neural network on FPGAs for online application in progress

**Thank you very much!**
BACK-UP
**PROJECT OVERVIEW - FURTHER RESOURCES**

- **Mini-Workshop: Anomaly detection with Neural Networks, Giessen, 21.02.2020**
  
  https://indico.belle2.org/event/1658/

- **Search for Highly Ionizing Particles with the Pixel Detector in the Belle II Experiment (M.Sc. Thesis Katharina Dort)**
  
  https://docs.belle2.org/record/1382?ln=en

- **Self-Organizing Maps und Principal Components Analysis (B. Sc. Thesis Stephanie Käs)**
  
  https://docs.belle2.org/record/1600?ln=en

- **Hopfield Network for Cluster PID at the PXD (Specialization module Irina Heinz)**
  

- **Voxel-Quantization - Detecting Clusters in Highdimensional Data (Specialization module Johannes Bilk, Johannes Budak)**
  
  https://www.uni-giessen.de/fbz/fb07/fachgebiete/physik/institute/iipi/arbeitsgruppen/ag-lange/neuro/bilk_budak/view
PIXEL DETECTOR READ-OUT

- Data rate coming from PXD is drastically higher than rate of all other sub-detectors
  - Online data reduction is required
- ROIs (regions-of-interest) formed by HLT tracking and DATCON
- Challenge: particles without a reconstructable track are not detected

- Possible solution: a cluster rescue system to generate ROIs using other techniques