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

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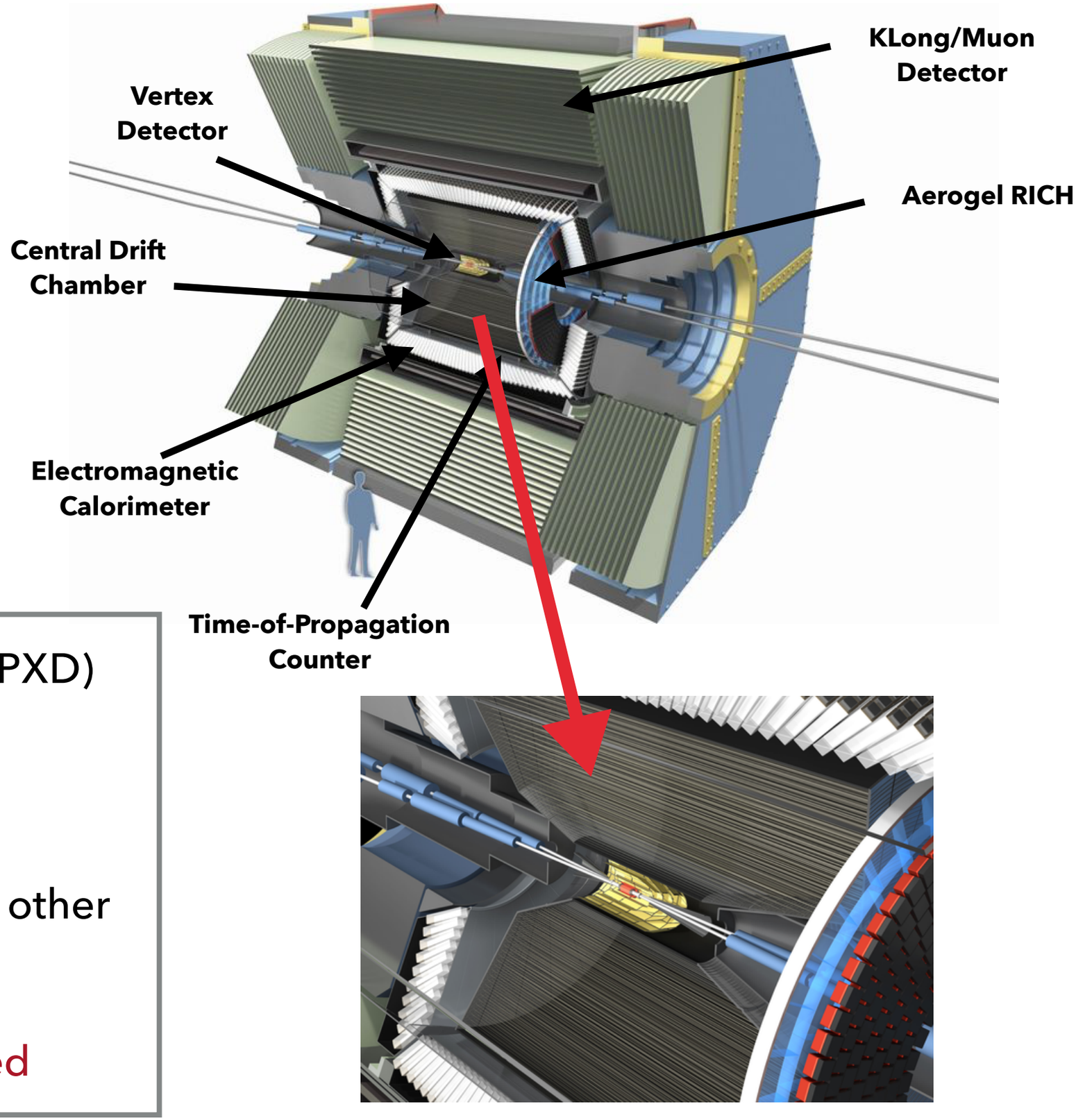
The Belle II Experiment

- 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

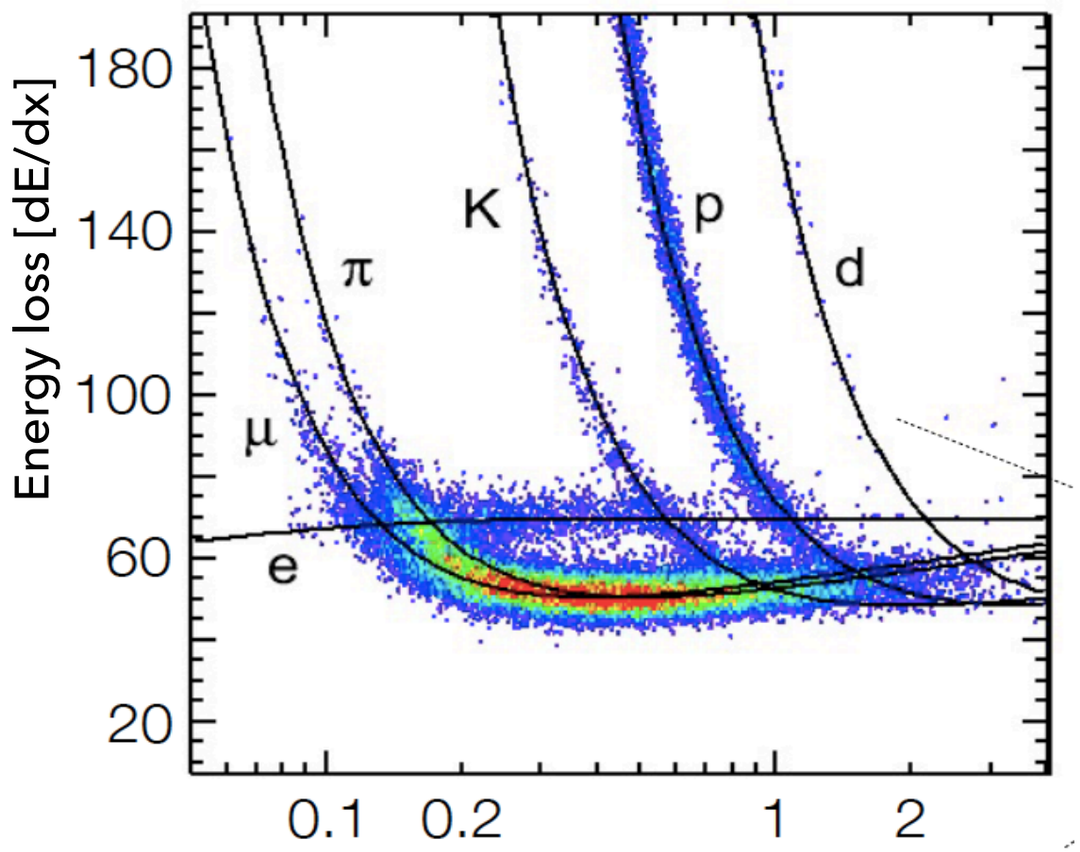
➡ Online data reduction is required

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:

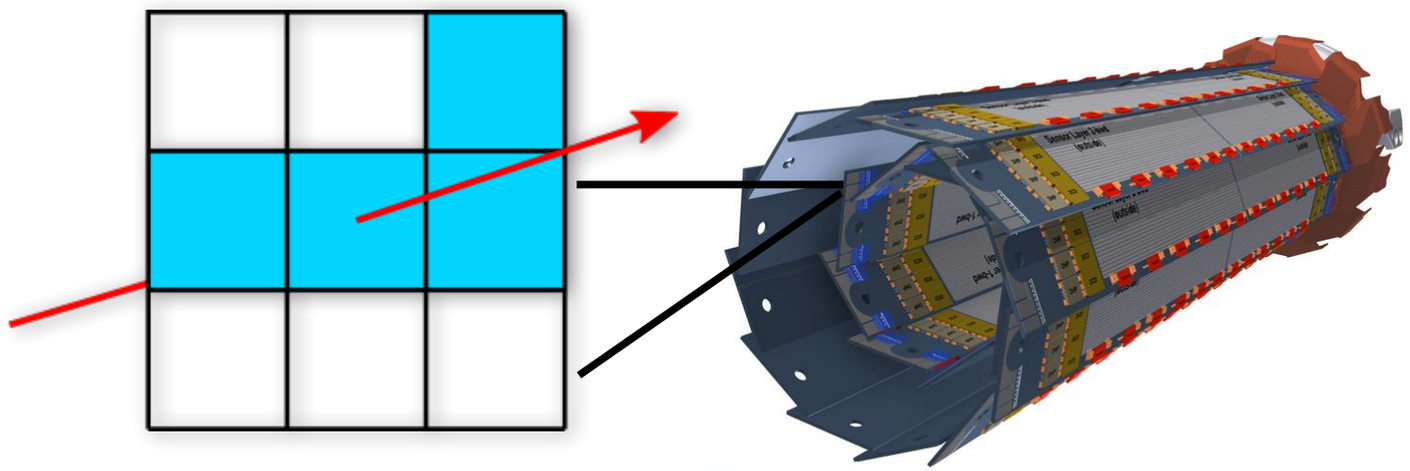
- Filter out signal particles against beam background with PXD data only

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

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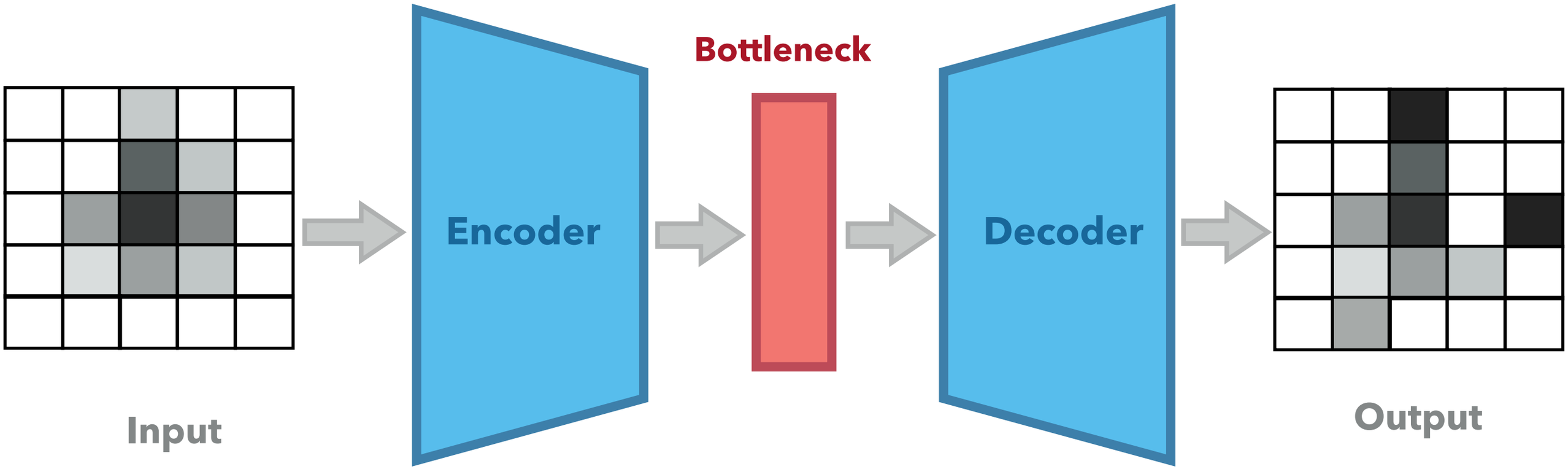
before training



- 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

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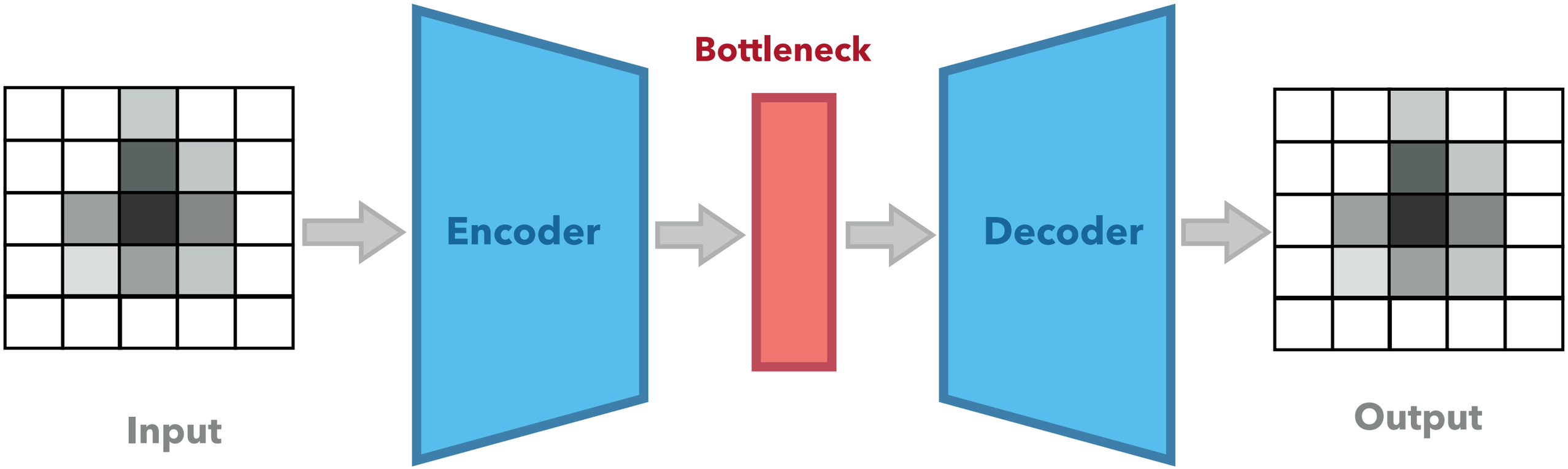
after training



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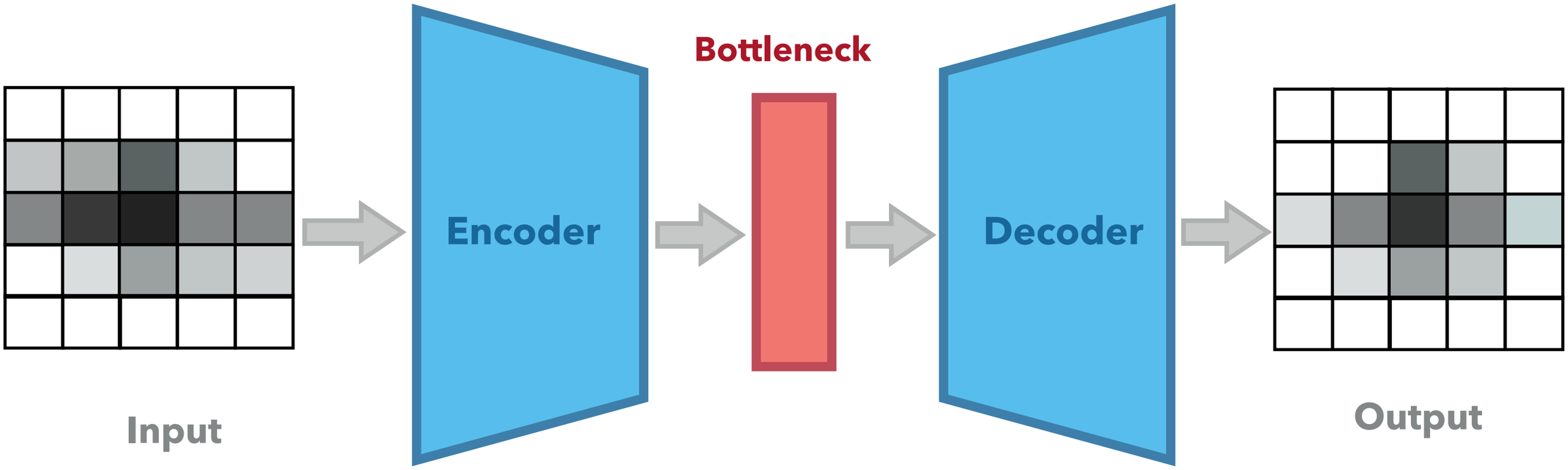
Auto-encoders - evaluation



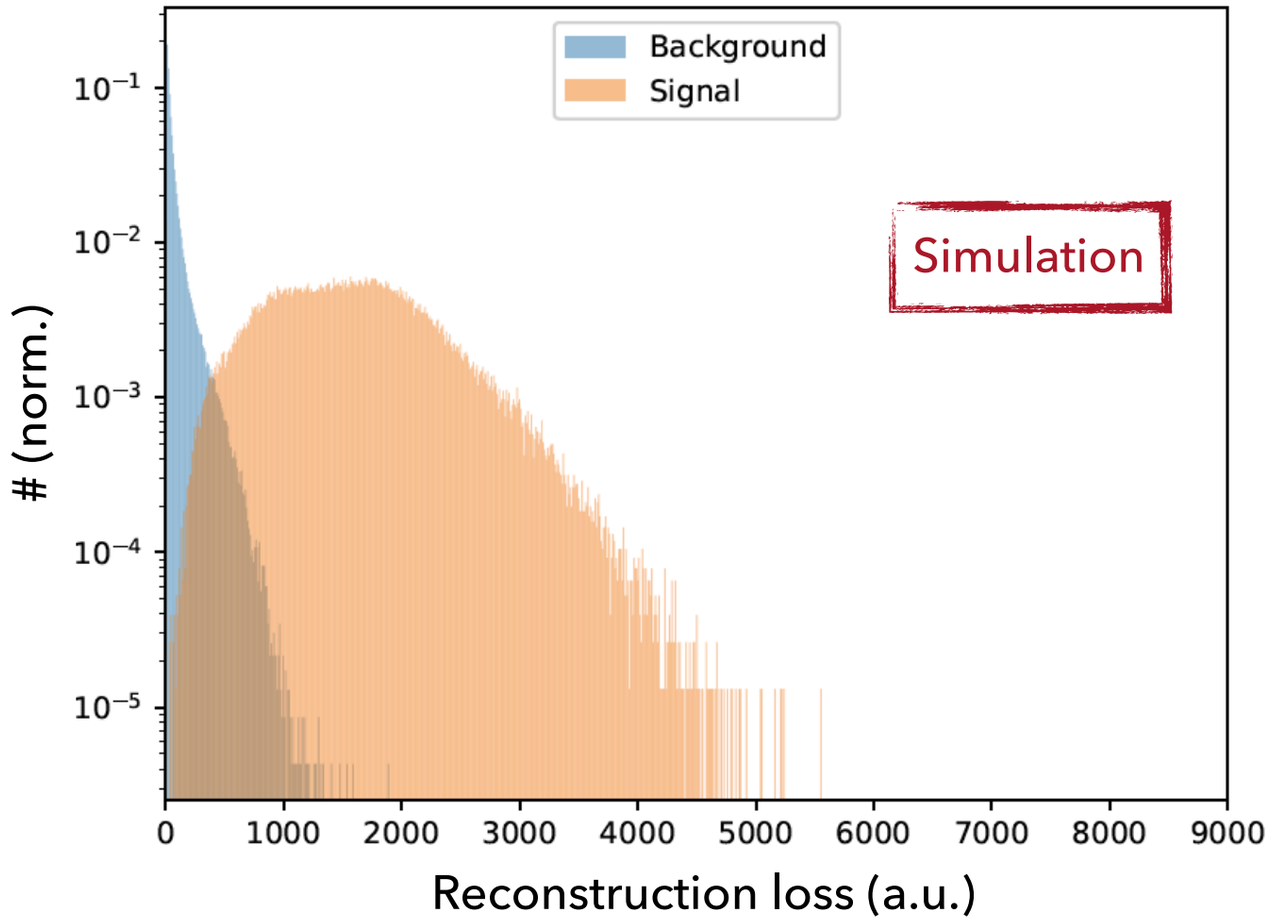
- In the evaluation step, the network will be able to reconstruct beam background matrices but fail if presented with signal matrices (= anomaly)

- 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



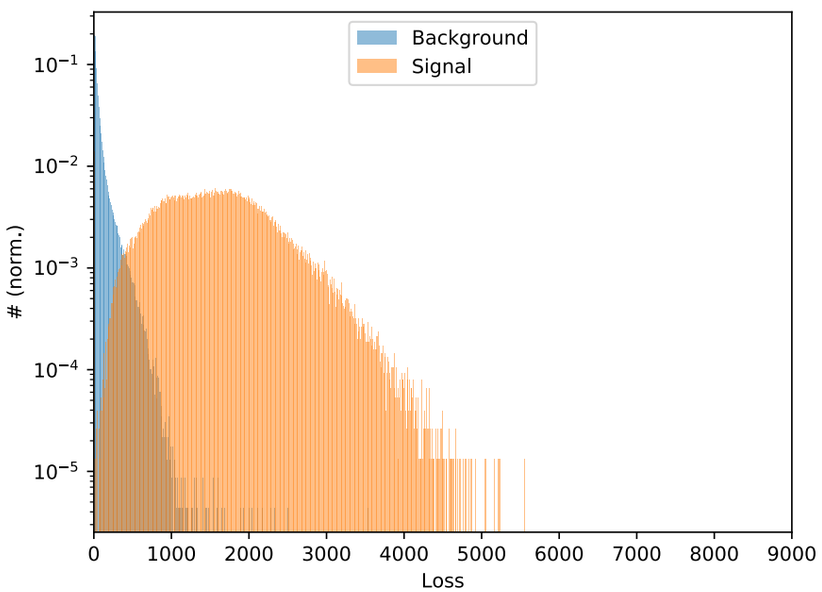
- Auto-encoders have a filtering functionality that needs to be combined with a subsequent in-depth analysis

Signal in Background data

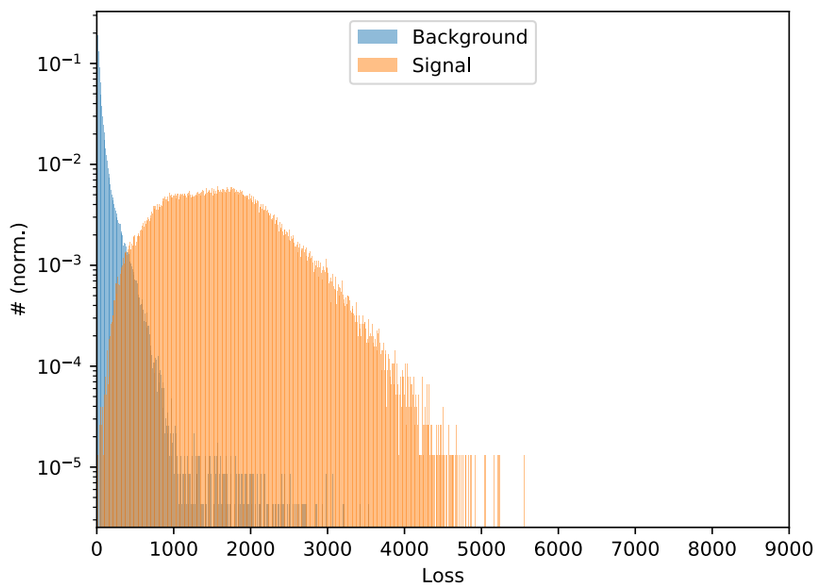
What happens if there is signal in the training data?

- 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

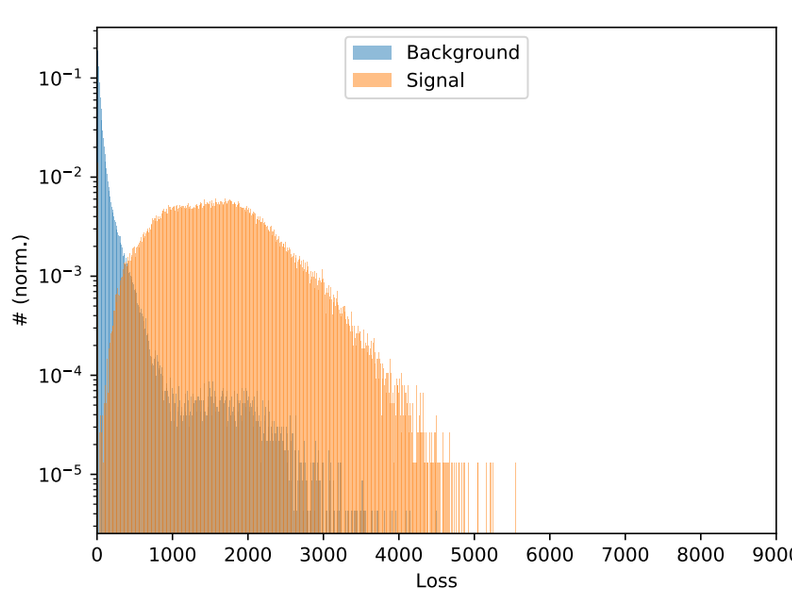
0.01% Signal



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)

  https://www.uni-giessen.de/fbz/fb07/fachgebiete/physik/institute/iipi/arbeitsgruppen/ag-lange/neuro/hopfield-networks-vertiefungsmodul-irina-heinz/view

- Voxel-Quantization - Detecting Clusters in Highdimensional Data (Specialization module Johannes Bilk, Johannes Budak)

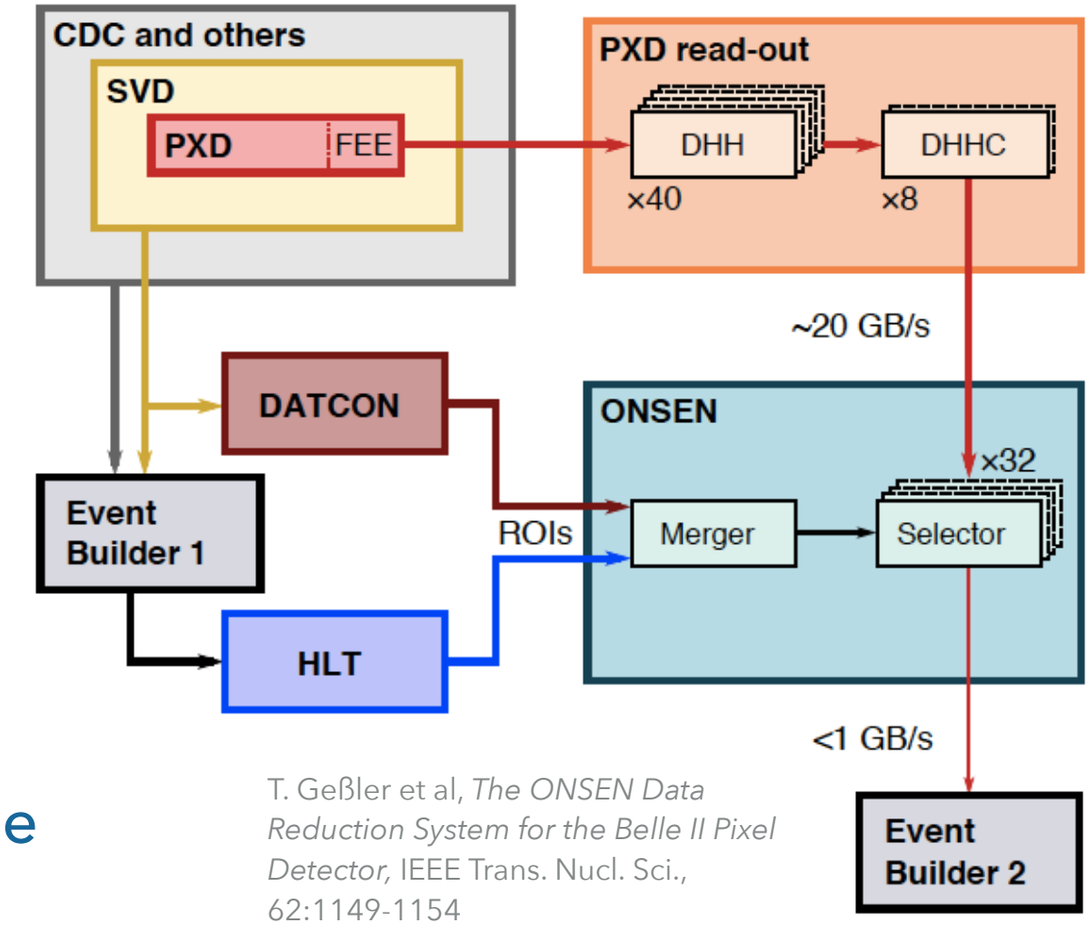
  https://www.uni-giessen.de/fbz/fb07/fachgebiete/physik/institute/iipi/arbeitsgruppen/ag-lange/neuro/bilk_budak/view

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



T. Geßler et al, *The ONSEN Data Reduction System for the Belle II Pixel Detector,* IEEE Trans. Nucl. Sci., 62:1149-1154

- Challenge: particles without a reconstructable track are not detected

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