

Slow pion identification at the **Belle II PXD with machine** learning J. Bilk, S. Käs, S. Lange, E. Prencipe, T. Schellhaas

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Introduction

Belle II Detector

- B-meson factory at Tsukuba, Japan
- e+e⁻ collisions at 10.58 GeV
- our group is focused on the data acquisition of the pixel detector
- the pixel detector (PXD) consists of two layers of DEPFET silicon pixels
- they have a radius of 14mm and 22mm and are made up of 8 and 12 modules respectively
- each module has 256 × 768 pixels (in total 8 mil. pixels)

Belle II Detector

KL and muon detector: Resistive Plate Counter (barrel) Scintillator + WLSF + MPPC (end-caps)

EM Calorimeter: CsI(TI), waveform sampling (barrel) Pure CsI + waveform sampling (end-caps)

> Particle Identification Time-of-Propagation counter (barrel) Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe 2cm diameter

electron (7GeV)

Vertex Detector 2 layers DEPFET + 4 layers DSSD

> Central Drift Chamber He(50%):C₂H₆(50%), Small cells, long lever arm, fast electronics

positron (4GeV)



Slow Pions

- signal:
 - semi-leptonic decays of B mesons to charged D* mesons, which are sensitive to new physics
 - charged D^{*} mesons decay to slow pions by D^{*+(-)} → D⁰ pi⁺⁽⁻⁾
 - due to the low momentum often do not reach drift chamber, and therefore do not generate a reconstructed track

idea: identify slow pions based on cluster properties in the PXD

- background:
 - electrons from beam background and QED processes such as e⁺e⁻ → e⁺e⁻e⁺e⁻

$B^{0} \rightarrow D^{*-}(2010)l^{+}\nu_{l}$ $\hookrightarrow \bar{D}^{0}\pi_{slow}^{-}$

 $\bar{B}^0 \to D^{*+}(2010)l^-\bar{\nu}_l$ $\hookrightarrow D^0\pi^+_{slow}$

Slow Pions

- due to the low momentum often do not reach drift chamber
 - no reconstructed track on trigger system
 - no region-of-interest generated on trigger system
 - PXD data are deleted on ONSEN system, before reaching data storage
- long term project: ML decision online on FPGA (cluster rescue)



D0 mass & D*- mass



- significant difference found!

David Münchow, Gießen

A Look at the Events

PXD Cluster Examples

Front view for slowpions



Side view for slowpions



Event: slowpions



Front view for slowpions



Side view for slowpions



Event: slowpions





Event: slowelectrons Front view for slowelectrons Side view for slowelectrons

Front view for slowelectrons



Side view for slowelectrons

Event: slowelectrons





Slow Pions vs Electrons Feature Importance



Features

- 160

120

0

Slow Pions vs Electrons Correlation Matrices

clsCharge -	1.00	0.66	0.87	0.75	0.76	-0.00	-0.00	0.01	0.00	0.11	
seedCharge -	0.66	1.00	0.26	0.21	0.23	-0.01	-0.01	0.00	0.00	0.05	
clsSize -	0.87	0.26	1.00	0.89	0.84	-0.00	-0.01	0.01	0.00	0.10	- 0.8
uSize -	0.75	0.21	0.89	1.00	0.56	0.01	-0.01	-0.00	0.00	0.01	
vSize -	0.76	0.23	0.84	0.56	1.00	-0.01	-0.03	0.01	0.00	0.16	- 0.6
uPosition -	-0.00	-0.01	-0.00	0.01	-0.01	1.00	-0.00	-0.00	-0.01	0.01	- 0.4
vPosition -	-0.00	-0.01	-0.01	-0.01	-0.03	-0.00	1.00	-0.00	0.00	0.36	
xPosition -	0.01	0.00	0.01	-0.00	0.01	-0.00	-0.00	1.00	-0.00	0.01	- 0.2
yPosition -	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	-0.00	1.00	0.00	- 0.0
zPosition -	0.11	0.05	0.10	0.01	0.16	0.01	0.36	0.01	0.00	1.00	0.0
	clsCharge -	seedCharge -	clsSize -	uSize -	vSize -	uPosition -	vPosition -	xPosition -	yPosition -	zPosition -	

Correlation Matrix

clsCharge -	1.00	0.67	0.62	0.43	0.43	0.02	-0.11	-0.04	-0.00	0.09		- 1 0
seedCharge -	0.67	1.00	0.10	0.06	0.05	0.04	-0.04	-0.04	-0.00	-0.11		1.0
clsSize -	0.62	0.10	1.00	0.62	0.81	0.01	-0.21	-0.03	-0.00	0.37		- 0.8
uSize -	0.43	0.06	0.62	1.00	0.11	-0.04	-0.03	-0.01	-0.00	0.01		- 0.6
vSize -	0.43	0.05	0.81	0.11	1.00	0.02	-0.27	-0.03	-0.00	0.49		- 0.4
uPosition -	0.02	0.04	0.01	-0.04	0.02	1.00	-0.01	0.00	0.00	0.01		0.0
vPosition -	-0.11	-0.04	-0.21	-0.03	-0.27	-0.01	1.00	0.00	-0.00	-0.07		- 0.2
xPosition -	-0.04	-0.04	-0.03	-0.01	-0.03	0.00	0.00	1.00	0.00	-0.01		- 0.0
yPosition -	-0.00	-0.00	-0.00	-0.00	-0.00	0.00	-0.00	0.00	1.00	-0.00		0.2
zPosition -	0.09	-0.11	0.37	0.01	0.49	0.01	-0.07	-0.01	-0.00	1.00		
	clsCharge -	seedCharge -	clsSize -	uSize -	vSize -	uPosition -	vPosition -	xPosition -	yPosition -	zPosition -		

Correlation Matrix

Slow Pions vs Electrons Seed Charge Histogram



Multi Pixel Clusters



Cluster Size impact on ROI selection Cluster Size



Results

The Confusion Matrix Binary Case

- we have two classes
- TP, TN, FN and FP can be read directly from the matrix



Predicted Class



Evaluating Performance Machine Learning Algorithm

• Sensitivity

Number of events correctly identified by the NN as a signal (TP), divided by all real signal events (TP + FN) is also called "efficiency" in particle physics

Precision

Number of events correctly identified by the NN as a signal (TP), divided by all events identified by the NN as a signal (TP + FP) is also called "purity" in particle physics

• Specificity or Selectivity

Number of events correctly identified by the NN as background (TN), divided by all real background events (TN + FP) is called "background rejection" in particle physics



CNN

- Master thesis Johannes Bilk Precision (Efficiency) 82 %
- Sensitivity (Purity) 81%
- excluding 1-pixel cluster reduces precision by 3%
- multiclass vs. binary (one NN vs. many NN, all particle species) reduces precision by factor 2





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CNN

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Decision Trees

- Master thesis Stephanie Käs Precision (Efficiency)
- see table next page Sensitivity (Purity)
- Small Decision Tree with only 3 layers reaches 81% accuracy
- 1. cluster charge (97.6 % information content)
 - (reminder: no cluster reco, total charge is just the 9x9 ADC sum)
- 2. ADC value of pixel 41
 - (center of matrix, 1.1% information content)
- 3. z coordinate (1.3% information content).







Decision Trees

Тур	max. Tiefe	Präzision [%]	Sensitivität [%]	Genauigkeit [%]
	2	82	80	81
	3	82	80	81
Ctol Trop	5	82	80	81
Sta. Tree	10	80	84	81
	15	78	82	79
	20	77	80	78
AdaBoost	_	82	80	81
	2	77	68	74
	3	80	65	74
Developer	10	81	80	81
RandomForest	15	82	80	81
	50	80	79	80
	100	80	78	79
	2	80	83	81
	3	80	84	81
VCDaaat	10	80	84	82
AGBOOST	15	80	83	81
	50	79	82	80
	100	79	82	80



Support Vector Machine

- Bachelor thesis Timo Schellhaas Precision (Efficiency) 82.7 %
- Sensitivity (Purity) 68.5 %
- can be improved ?
- dimension n+1 is generated with radial basis functions
 - maybe wrong function for our problem



Source: Simple Tutorial on SVM and Parameter Tuning in Python and R | HackerEarth Blog

Summary

- PXD essential for slow pion tracking
- slow pion classification with machine learning was tested:
 - CNN, Decision trees, SVM (shown today)
 - MLP, SOM, Auto-encoder, Hopfield Network and GNN (not shown today)
 - Efficiency > 80 % and Purity > 80 % with almost all methods
- Flat decision tree with only 3 layers maybe best candidate algorithm for FPGA implementation



Thank You for Listening

Back Up