Identification of Beam Particles Using Detectors based on Cerenkov effect and Machine Learning in the COMPASS Experiment at CERN

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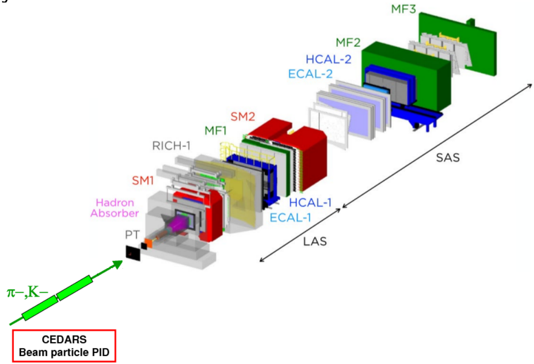
COMPASS

- COMPASS = Common Muon Proton Apparatus for Structure and Spectroscopy
- Experiment with fixed target on the SPS accelerator
- Study of hadron structure and spectroscopy using high intensity muon and hadron beams

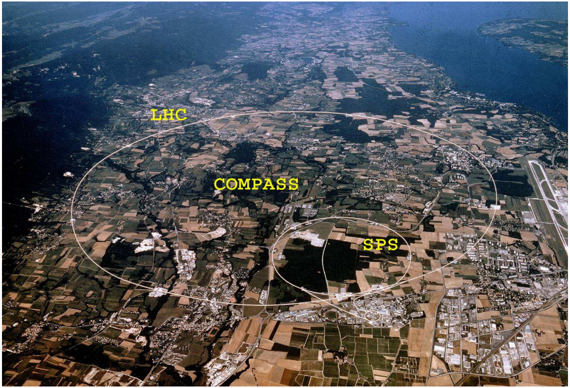


COMPASS spectrometer (Drell-Yan setup) [3].

COMPASS

- Since 2012 (COMPASS II phase), the main focus is on the Deeply Virtual Compton scattering, Hard Exclusive Meson Production, Semi-inclusive Deeply Inelastic Scattering, polarized Drell-Yan processes and Primakoff reactions

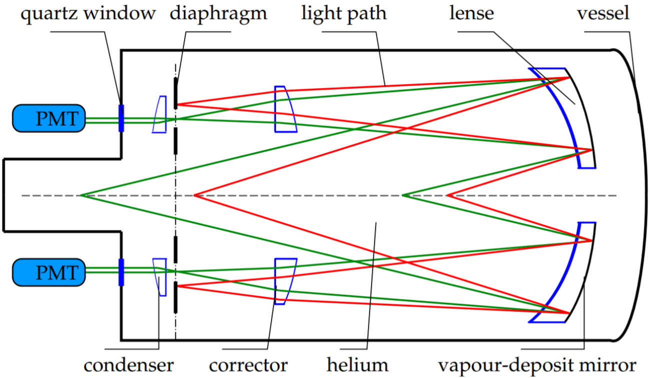
- In 2023 COMPASS should be replaced by AMBER = Apparatus for Meson and Baryon Experimental Research



COMPASS air view [4].

CEDAR detectors

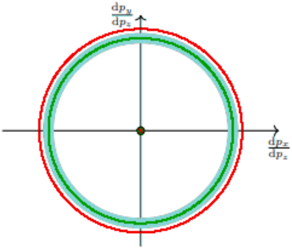
- CErenkov Differential counters with Achromatic Ring focus
- Use Cherenkov radiation for particle identification (π^-, K^-, $\bar{p}$)
- Cherenkov photons are detected by 8 photomultipliers
- 2 alike detectors positioned upstream the target



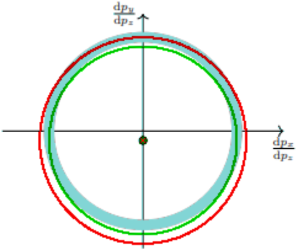
CEDAR schematic [4].

CEDAR detectors

- Designed as majority counter, where for highly parallel beam 6-8 PMT should fire to positively identify a particle
- **Not all beam particles traverse the CEDAR detectors parallel to their optical axis**
- A likelihood ansatz was developed to account for this issue
- Response of each PMT parameterized individually as a function of radiation angle

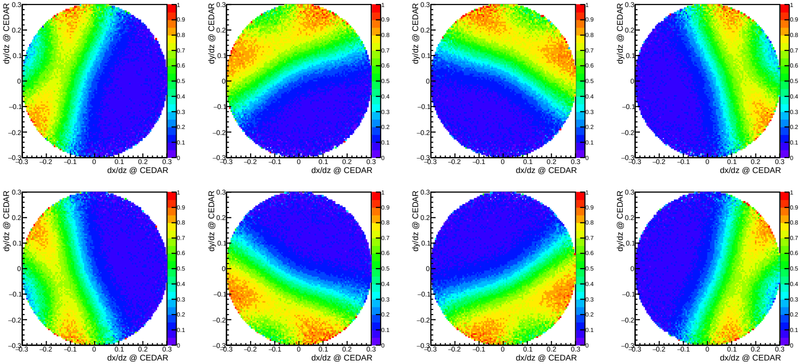


Beam parallel to optical axis [2]



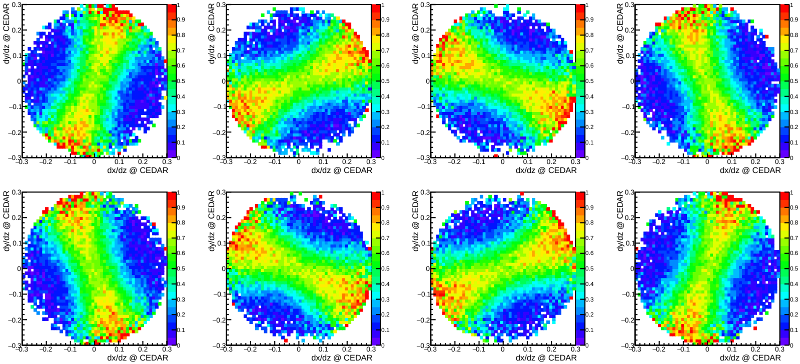
Beam with finite inclination [2]

CEDAR response for pions - MC



Amount of light collected by the 1st, 2nd, ..., 8th PMT as a function of dx and dy for pions.

CEDAR response for kaons - MC



Amount of light collected by the 1st, 2nd, ..., 8th PMT as a function of dx and dy for kaons.

Challenges with the 2018 data taking

- Beam composition: 97 % π^-, **2,5 %** K^- and < 1 % $\bar{p}$
- **Beam divergence up to 300 μrad** with only 10-15 % events within the designed range below 65 μrad

2008 data taking

- Low intensity beam $\longrightarrow$ no correlated events
- Very precise SI trackers $\longrightarrow$ precise knowledge of beam angle

2018 data taking

- 15 times higher beam intensity $\longrightarrow$ **correlated events**
- SI trackers replaced by FI detectors $\longrightarrow$ **lower angle measurement precision**

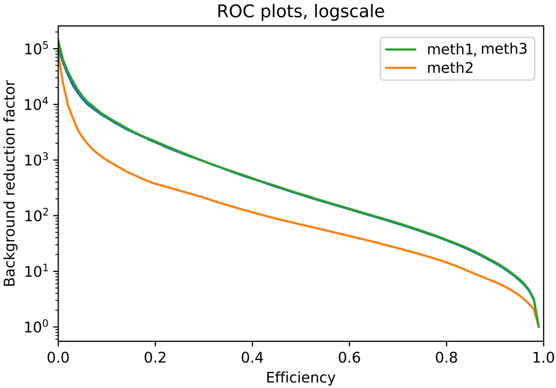
New Approach

- **The likelihood method cannot be used for the 2018 data taking and the AMBER experiment**
- New approach using artificial neural networks (NNs) was proposed
- 3 methods were evaluated:
  1. NN as a direct binary classifier - classify the particle type
  2. NN as a PMTs response predictor - predict the likelihood of a certain PMTs reponse assuming the particle type
  3. NN as a CEDAR response predictor - predict the likelihood of a specific PMTs pattern assuming the particle type

Methods comparison

- Method 2: less efficient, likely because it assumes no correlation between the PMTs

- Method 1 and 3 perform similarly, but method 1 is faster and easier to work with $\longrightarrow$ used for further analysis



ROC curves of the new methods.

Meta parameters optimization

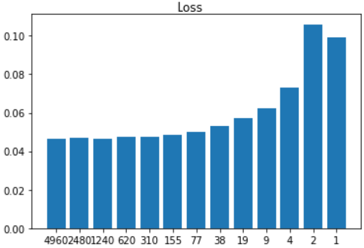
- Multi Layer Perceptron, Radial Basis Function and Random Vector Functional Network NNs were implemented and evaluated using k-fold cross validation $\longrightarrow$ MLP performed the best

- A differential evolution heuristic was used for optimization of the network's meta parameters (number of hidden layers, drop layers, activation functions, learning rate, etc.)

- Results imply the task is insensitive to network structure and its meta parameters, probably due to small input layer

Training dataset size

- Size of the dataset needed for successful training was determined
- Improvements obtained by enlarging the training dataset appear to be significant to around 300k events, i.e. $\approx$ 7.5k kaons



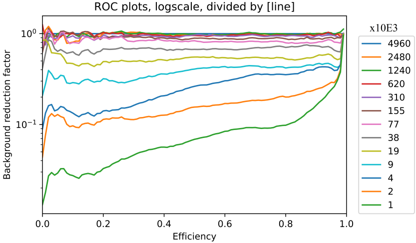


Figure: Values of loss functions and ROC curves of different dataset sizes (divided by curve of the largest dataset) used for training.

Inference in C++

- Using Frugally-deep library
- Model trained in Python with TensorFlow and Keras is exported to binary file
- Binary file is loaded in C++ program
- Inference can be performed with no dependency on Python Interpreter
- Model is integrated to PHAST - an open source C++ framework for physics analysis used at COMPASS

Classification quality

	predicted 0	predicted 1
actual 0	4 819 955	19 124
actual 1	60 667	60 666

Table: Confusion matrix for 50 % working point.

Sensitivity	0.5000
Specificity	0.9961
Accuracy	0.9839
Background reduction	253.04

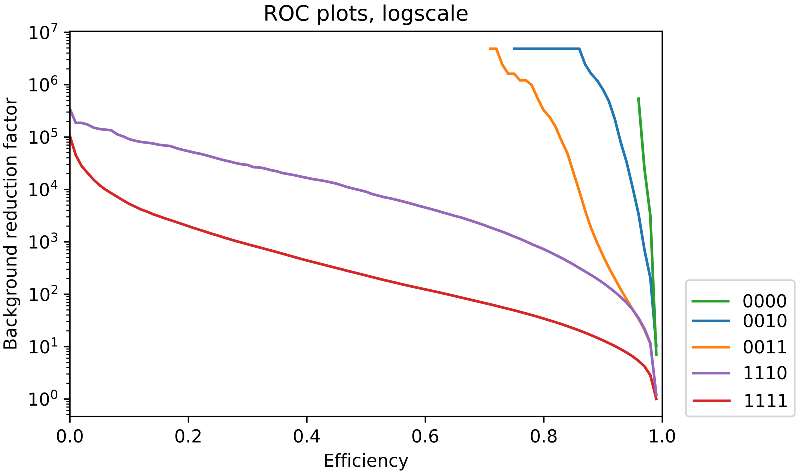
Table: Some statistics for 50 % working point.

An improvement is possible for the future AMBER Drell-Yan expriment $\longrightarrow$ identification of the effects aggravating separation is necessary

Possible improvements for AMBER

- In 2008, the background reduction factor at 90 % efficiency was $\approx$1000
- 4 issues needed to be taken into account in Monte Carlo simulations:
  1. MC-1xxx: additional undetected track (correlated noise)
  2. MC-x1xx: additional random noise
  3. MC-xx1x: PMTs inefficiency
  4. MC-xxx1: angle smearing
- Combinations of different effects were examined to identify the main factors complicating separation

Possible improvements for AMBER



The biggest improvements achievable by removing 1, 2, 3 and all problems.

Further achievable improvements for AMBER

- Each PMT consist of 4 pads responding individually
- The time of the hit of individual pads can be used to discard signal caused by an undetected track

- Replacing binary response of PMTs with number of active pads improves the separation almost as much as removing correlated noise

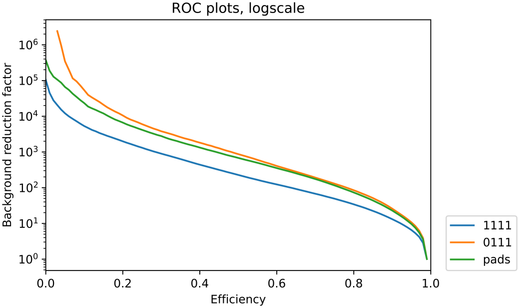


Figure: Using number of active pads.

How to improve

- To improve angle measurement precision $\longrightarrow$ replace FI detectors with radiation hard SI trackers
- To reduce correlated noise $\longrightarrow$ faster electronic (presently the signal length is 10ns, but can be reduced to 2ns)
- To reduce uncorrelated noise $\longrightarrow$ improve shielding
- To improve efficiency $\longrightarrow$ enlarge diaphragm opening to allow more photons to reach PMTs (in this moment would also increase correlated noise)

Summary

- 3 new methods and tools for their performance analysis were developed $\longrightarrow$ **method 1 seems to be the best**
- The model was optimized using genetic heuristic $\longrightarrow$ **the problem seems to be insensitive to NNs parameters**
- Issues aggravating separation were identified and improvement achievable by resolving them was quantified $\longrightarrow$ **more precise angle measurements offers the most significant improvement**
- Further possibilities for improvement were recognized and simulated $\longrightarrow$ **using pads, lowering PMTs hit times**
- The best model was integrated into physics analysis framework

References

[1] VOLDŘICH, František. *Identiffcation of Beam Particles Using CEDAR Detectors and Machine Learning in the COMPASS Experiment at CERN*. Prague, 2022. Diploma thesis. Czech Technical University. Supervisor: Martin Zemko, Consultant: Marcin Stolarski.

[2] "CEDAR PID using the Likelihood Approach for the Hadron-Beam", COMPASS Note 2017-1, https://wwwcompass.cern.ch/compass/notes/2017-1/2017-1.pdf

[3] TOWNSEND, April. *Probing transverse-spin-dependent nucleon structure in pion-induced dimuon production at COMPASS: APS April Meeting 2022* [online]. 10.4.2022 [cit. 2022-07]. Available at: https://wwwcompass.cern.ch/compass/publications/talks/t2022/APS_April_Meeting_2022_Presentation.pdf

[4] "The COMPASS setup for physics with hadron beams", COMPASS Coll., NIM A 779 (2015) 69. "The CEDAR counters for particle identification in the SPS secondary beams: a description and an operation manual", C. Bové et al., doi: 10.5170/CERN-1982-013, https://cds.cern.ch/record/142935.