Neural Network KLM trigger

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Motivation

- More sophisticated trigger over current one
- Improved exclusion of Cosmic Muon Background
- Improved Muon and Hadron identification

Data and Clustering

Data

- Use HLT calibrated data from experiment 30 run 3508 for training and run 3505 for testing for muon and hadron data
- Use experiment 30 run 3461 for training and run 3460 for testing for cosmic
- Added stipulation that Muon events require at least MuonID reconstruction ≥ 0.9 and Hadron events require a KLID reconstruction ≥ 0.3

Clustering

- Simple clustering algorithm
- If a single sector has 7 or more hits cluster all hits in that a sector

Neural Network based KLM TRG

General Framework

- Deep neural network using trigger level info
- Output Identifier of particle type (Muon, Hadron, Cosmic)
- Output is a 3 length softmax likelihood function
- L(Muon), L(Hadron), L(Cosmic)
- Separate NNs for EKLM and BKLM

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Neural Network overview

Software

- Developed in Tensorflow and using a Keras based Deep Neural Network

Input Features

- First Layer
- Total Number of Unique Layers
- Simple average: $0.5 * (max(strips) + min(strips))$
- Simple average of ϕ and z strips in First Layer of cluster
- Simple average of ϕ and z strips in Last Layer of cluster
- Simple average of ϕ and z strips in First Layer outside the cluster

Output Features

- 3 length softmax output of likelihood of particle type
- $(L_{Muon}, L_{Hadron}, L_{Cosmic})$

Neural Network Development: MC vs Raw

- Original model worked off MC data, generated version v08-01-00
- Muons and Hadron were ParticleGun simulations and CRYInput used for Cosmic
- When tested on raw data, model performed very poorly if trained on MC
- Main issue of concern was the clustering algorithm is rather simple, and affected by background
- CRYInput wasn't able to produce cosmic similar to those in the raw data

Neural Network Development: Positional Information

- Model was supposed to output positional information of ϕ, θ and dz of cluster
- dz and ϕ predictions had very large uncertainties even when trained on MC
- Switch to training on raw data made predicting positional info much more resource intensive so is removed

Neural Network Development: Input Features

- Model used Sector and Section info for positional info, useless with purely classification based model
- Simple average replaced difference of ϕ and z as it performed better for raw data
- Total number of hits of cluster had very good separation for MC data, but due to simple clustering, no improvement on results for raw data

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Configuration of Neural Network overview

- Total trainable parameters of 1667
- 65% sparsity pruned

Layer	Nodes	Activation
Trivial Input	9 (non-trainable)	N/A
1st Hidden	64	tanh
2nd Hidden	16	tanh
ID output	3	softmax

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Training of Models

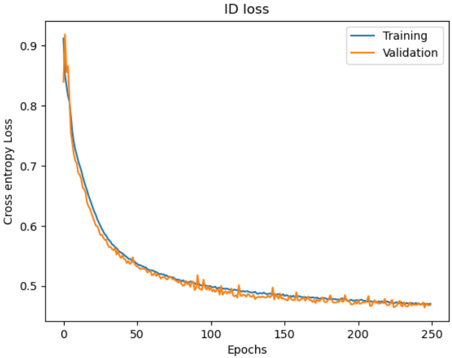
Event distribution

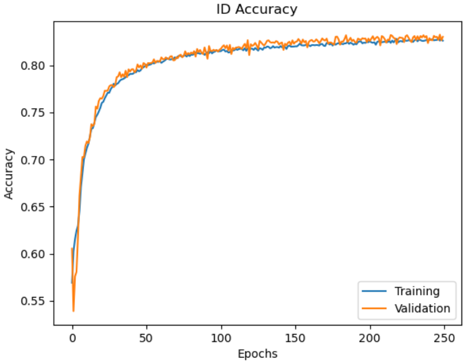
- Required at least one Primary Sectors (minimum 7 hits)
- 8000 Muon events, 8000 Hadron events, 8000 Cosmic events
- 80% events used for training
- 20% events for validation
- 4000 Muon, Hadron and Cosmic events respectively for testing (different run)

Hyper-parameters

- Learning rate: 0.001
- Batch size: 64
- Epochs: 250
- Loss: Cross Entropy

Particle ID likelihoods Model Training Results





hls4ml Model Synthesis/Performance

hls4ml

- Program to convert Keras based model in python, to work in Verilog/Vivado and on FPGAs used in trigger
- FPGA part used: XCVU080-FFVB2104-2-E (UT4)
- More details on backup slides

Total Latency	Cycles	BRAM	DSP	FF	LUT
115 ns	16	1%	45%	$< 1\%$	5%

Result	Keras Model	hls4ml Model
Accuracy	83.0%	81.9%

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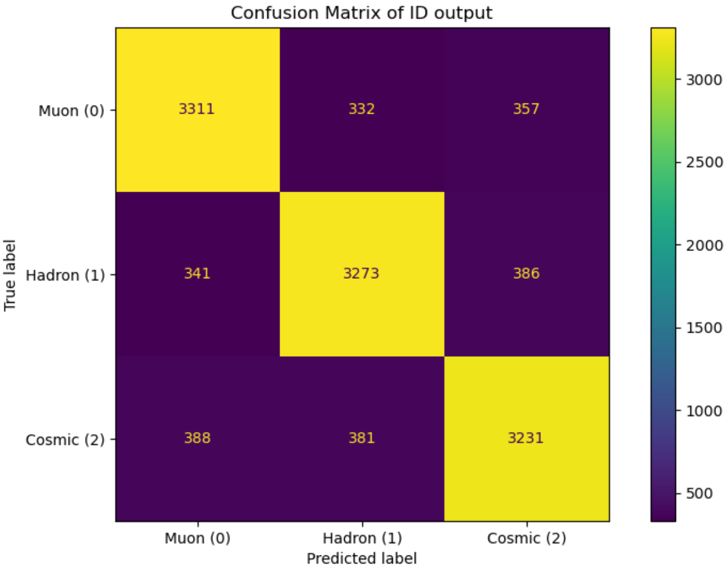
Confusion Matrix for hls4ml model



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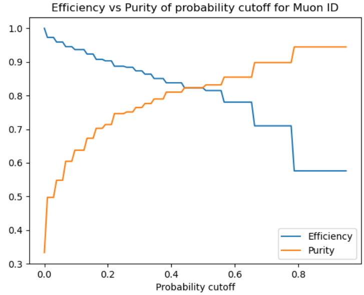
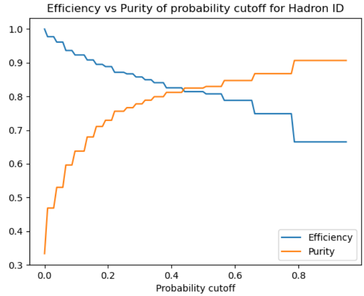
Model Output into trigger conditions

- Need to use these likelihoods to use generate actual trigger conditions
- Cut along likelihood to determine if this event is worth keeping
- Independent cuts along Muon and Hadron likelihood didn't show very good results
- Keeping 90 – 95% efficiency results in purities between 60 – 70%





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Binary likelihoods: Idea

- Main concern is cosmic misidentification
- Muons being identified as hadrons and vice versa aren't as bad
- Make cuts along binary likelihoods using model output
- e.g. Muon: $\frac{L_{Muon}}{L_{Muon}+L_{Cosmic}}$
- Looks at the models correlation between likelihood predictions
- Direct calculation of trigger rate and cosmic misidentification

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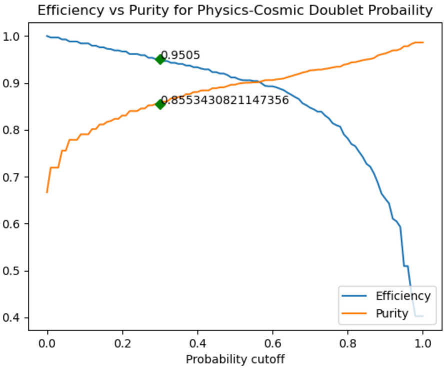
Binary likelihoods: Use

- Event has 2 triggers: Muon: 0 or 1 Hadron: 0 or 1
- 2 stage trigger
- Cut along entire physics (non-cosmic) likelihood: $\frac{L_{Muon}+L_{Hadron}}{L_{Muon}+L_{Hadron}+L_{Cosmic}}$
- If passed, then cut along Muon-Cosmic and Hadron-Cosmic likelihoods, if pass then muon and/or hadron trigger
- Additionally: If model predict 1 likelihood for physics event, skips cuts and is passed
- If they events do not make initial cut or don't trigger a muon or hadron, they are labelled as cosmics

Results of Binary likelihood: Muon EvP



- Trigger cares about High efficiency: +90-95%
- Highlighted cut at 0.3
- 95.1% of Physics events are kept, and of the kept events 85.5% are Physics events
- Trigger rate needs real numbers: 7604 correctly identified as Physics events, 1284 Cosmics identified as Muons

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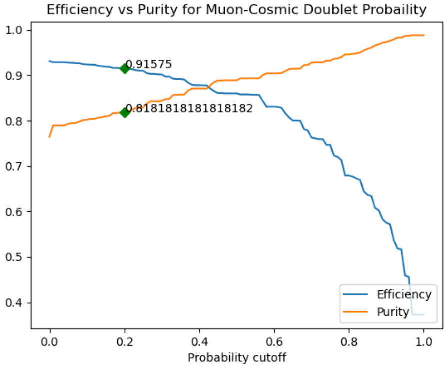
Results of Binary likelihood: Muon EvP



- Trigger cares about High efficiency: 90-95%
- Highlighted cut at 0.2
- 91.6% of Muon events are kept, and of the kept events 81.8% are Muons
- 3663 correctly identified Muons, 814 Cosmics identified as Muons
- Less important: 167 Hadrons identified as Muons

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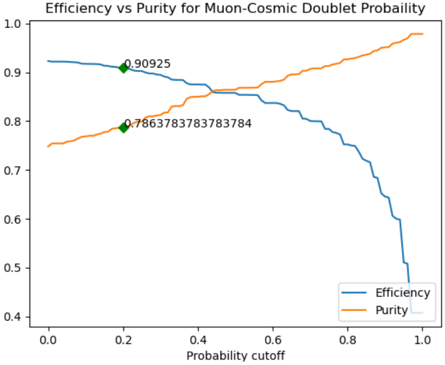
Results of Binary likelihood: Hadron EvP



- Trigger cares about High efficiency: 90-95%
- Highlighted cut at 0.2
- 90.9% of Hadron events are kept, and of the kept events 78.6% are Hadrons
- 3637 correctly identified Hadrons, 988 Cosmics identified as Hadrons
- Less important: 137 Muons identified as Hadrons

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Multiple conditions

- Will get events will multiple conditions of both Muon and Hadron
- 1130 Muon events and 565 Hadron events and 516 Cosmic events are labelled as both Hadron and Muon triggers
- Roughly half of misidentified cosmics are misidentified both for Muon and Hadron triggers

Events lost before model

- How many events am I losing with the prepossessing steps?
- Clustering algorithm is simple, and isn't main issue
- Main issue is requiring hits in both ϕ and Z axis in the First Layer of the cluster
- 2 ways to solve: improve clustering algorithm or create backups
- In future will use Richard's Straight Line Fitter so seems unnecessary to improve clustering algorithm (and make this problem irrelevant)
- Instead created a Backup First and Last Layer, i.e. Second and Second Last Layer of the cluster

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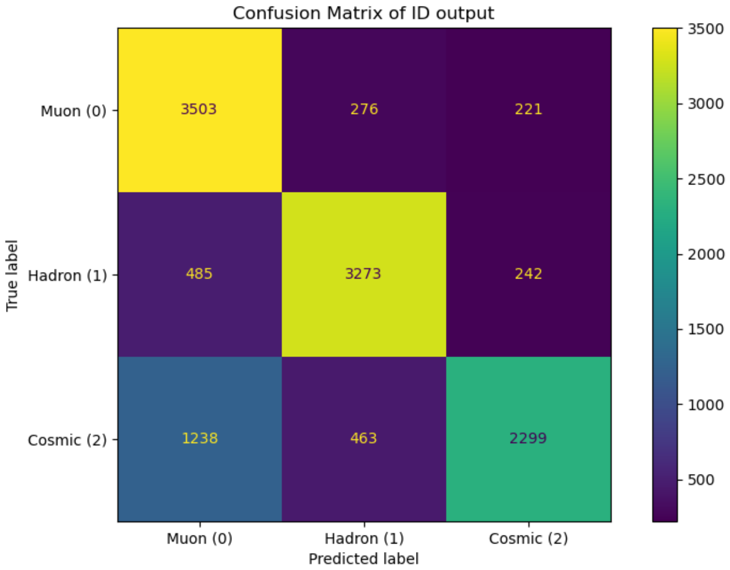
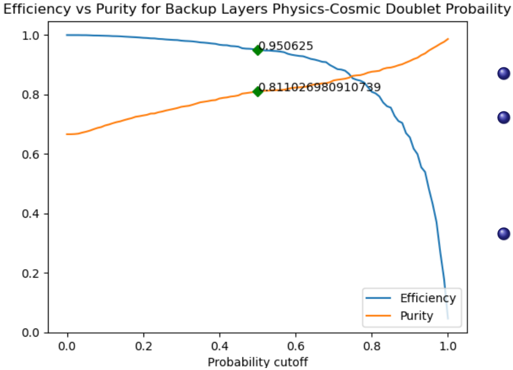
Backup layers

- Muon raw data has 20003 events, containing between 2+ Muons
- Number of particles reconstructed: 40249
- 75% of Muons interact with the barrel, so have $\approx$ 30000 potential clusters
- Current reprocessing only generates 16036 valid clusters
- By adding this backup First/Last Layers we have 21932 clusters
- However with these added events we see an issue of a drop in performance of the model, specifically is Muon-Cosmic separation

Confusion Matrix for Extra clusters

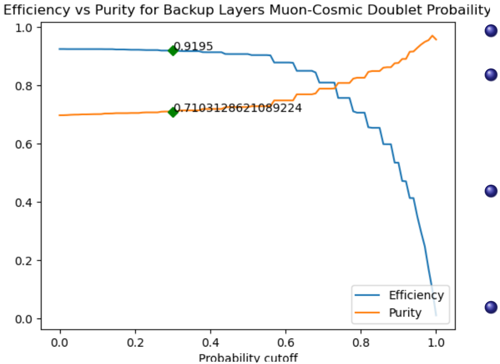


Results of Backup Layers Binary likelihood: Physics



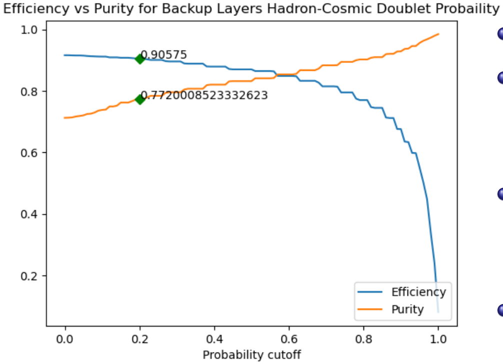
- Highlighted cut at 0.5
- 95.1% of Physics events are kept, and of the kept events 81.1% are Physics
- 7605 correctly identified Physics events, 2288 Cosmics identified as Physics

Results of Backup Layers Binary likelihood: Muon EvP



- Highlighted cut at 0.3
- 92.0% of Muon events are kept, and of the kept events 71.0% are Muons
- 3678 correctly identified Muons, 1500 Cosmics identified as Muons
- Less important: 105 Hadrons identified as Muons

Results of Binary likelihood: Hadron EvP



- Highlighted cut at 0.2
- 90.6% of Hadron events are kept, and of the kept events 77.2% are Hadrons
- 3623 correctly identified Hadrons, 1070 Cosmics identified as Hadrons
- Less important: 178 Muons identified as Hadrons

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Possible fix

- By reducing the sparsity reduction of the model was able to get better results, close to 81% accuracy during training
- However this sparsity reduction makes it resource usage too much
- Possible need some added input features/added complexity to overcome these new clusters

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Conclusion

- Current model without backup layers: 95.1% effiency and 85.5% purity for total physics events
- Muon: 91.6% efficiency 81.8% purity
- Hadron: 90.9% efficiency 78.6% purity
- Want to investigate extra cluster issue to reach similar results
- Double check tests of Vivado test bench
- Work on this projects for 1-2months going forward then move on to my physics work
- Right up code/possible Belle2Note and still consult on future of project beyond that

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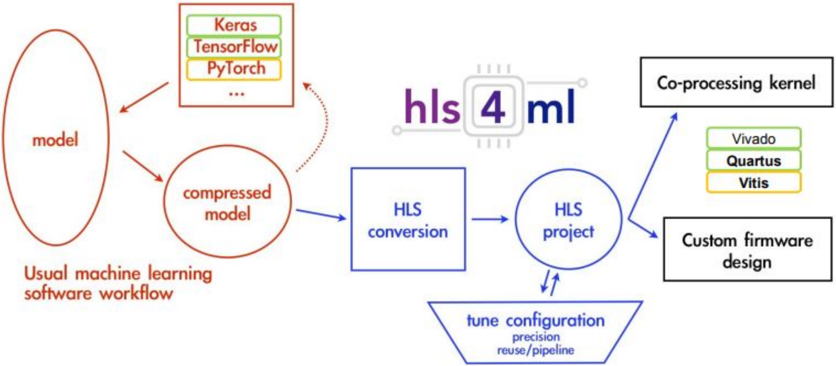
BACKUP SLIDES

hls4ml



FastML Team. hls4ml (Version v0.8.0) [Computer software]. https://doi.org/10.5281/zenodo.1201549

hls4ml details

hls4ml in this experiment?

- Reconstructed via RAM as this greatly reduced resource usage
- All internal layers use 16 total bits with 8 integer bits
- Output Layers use 7 total bits, with 2 integer bits
- FPGA part used: XCVU080-FFVB2104-2-E

Comparison and Synthesis of Model on FPGAs

Synthesis/Performance

- Latency and resource usage
- Bit restriction can hurt performance slightly
- hls4ml predict function vs keras predict function

Resource Definitions/Jargon

- LUT (Look Up Table): Basic logic of FGPA, generic functions that build the algorithm
- FF (Flip Flops): Build the pipeline of data with the clock pulse
- DSP (Digital Signal Processor): Performs arithmetic in the FPGA
- BRAM (Block RAM): Additional Memory usage