Suppress beam background using ML in BESIII trigger

H. L. Zhang[1], K. Li[2], J. H. Yin[1], B .P .Chen[2], G .F. Xu[2]

Nankai University[1]
IHEP[2]

Outline

Motivation

At BESIII, the trigger efficiency consistently exceeds 99%.[1]

			Bhabha		Dimuon		2-prong	4-prong
	GTL	Condition	Barrel	Endcap	Barrel	Endcap		
	0	NClus.GE.1	100.00	$100.00^{+0.00}_{-0.41}$	99.93±0.01	$94.74^{+4.35}_{-11.09}$	99.64±0.01	99.97
	1	NClus.GE.2	98.69±0.03	$98.20^{+0.62}_{-0.87}$	95.14±0.08	$84.21^{+8.47}_{-13.01}$	$98.01^{+0.03}_{-0.02}$	$99.63^{+0.01}_{-0.02}$
E	7	BEtot_H	100.00	0.17±0.02	0.68±0.03	$4.81^{+2.06}_{-3.12}$	89.88±0.04	$93.25^{+0.03}_{-0.04}$
M	9	Etot_L	100.00	$100.00^{+0.00}_{-0.41}$	99.82±0.01	$100.00^{+0.00}_{-9.24}$	99.63±0.01	99.99
C	10	Etot_M	100.00	$100.00^{+0.00}_{-0.41}$	10.25±0.11	$0.00^{+0.09}_{-0.00}$	97.01±0.03	99.44±0.02
	12	NBClus.GE.1	100.00	0.99±0.01	99.93±0.01	$0.00^{+0.09}_{-0.00}$	99.34±0.01	99.90±0.01
	13	NEClus.GE.1	0.94±0.02	$100.00^{+0.00}_{-0.41}$	$1.68^{+0.04}_{-0.05}$	$94.74^{+4.35}_{-11.09}$	36.93±0.06	41.85±0.07

Physical Events : Beam Background Events ≈ **1:1** **(In J/psi peak)**

Testing the Hadron Ratio for different Energy Point

(Use Trigger test data)

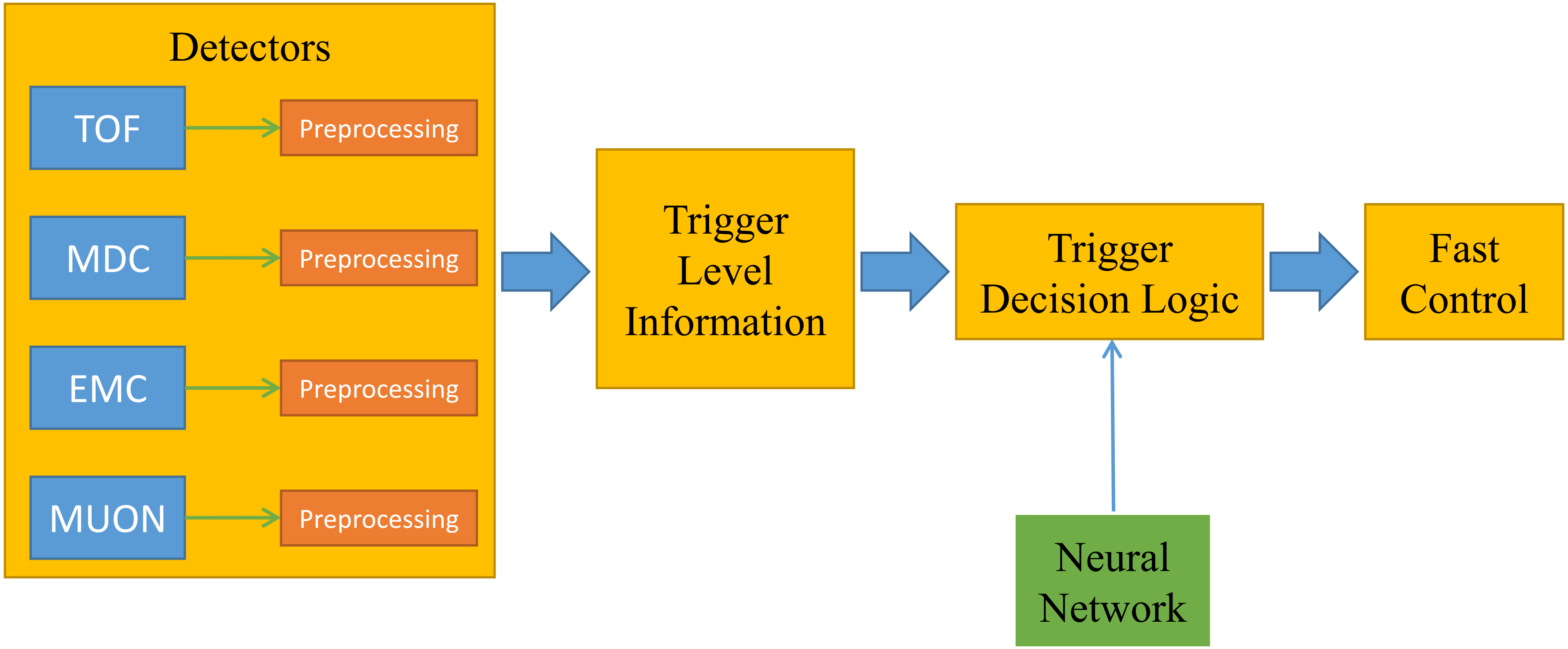
	Num of Event	Num of Hadron	Hadron Ratio
J/ψ peak	8.74M	2.58M	29.47%
$\sqrt{s} = 4.680\text{GeV}$	12.75M	0.27M	2.1%

- We hope to use NN to reduce the Beam Background trigger rate while maintaining a high trigger rate for Physical Events.

[1]Ablikim M, Achasov M N, Adlarson P, et al. Study of BESIII trigger efficiencies with the 2018 J/ψ data[J]. Chinese Physics C, 2021, 45(2): 023002.

BESIII Trigger

BESIII Trigger System: Deployed in 2009
Very stable during operation
Extremely high hadron trigger rate



BESIII Trigger

BESIII Trigger system:

- 48 Conditions
- 16 Channels

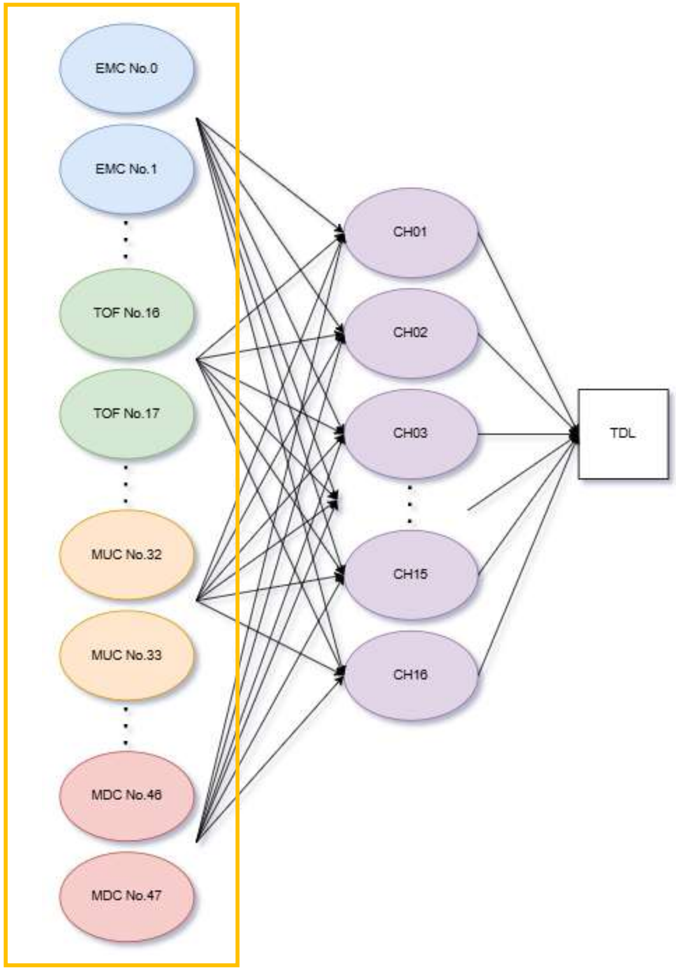
Electromagnetic calorimeter (EMC)		
0	NClus.GE.1	Number of Clusters ≥ 1
1	NClus.GE.2	Number of Clusters ≥ 2

……

Time of flight system (ToF)		
16	ETOF_BB	Endcap TOF Back to Back
17	BTOF_BB	Barrel TOF Back to Back
18	NETOF.GE.2	Number of Endcap TOF hits ≥ 2

……

Use these trigger conditions as input features!



input features

Datasets

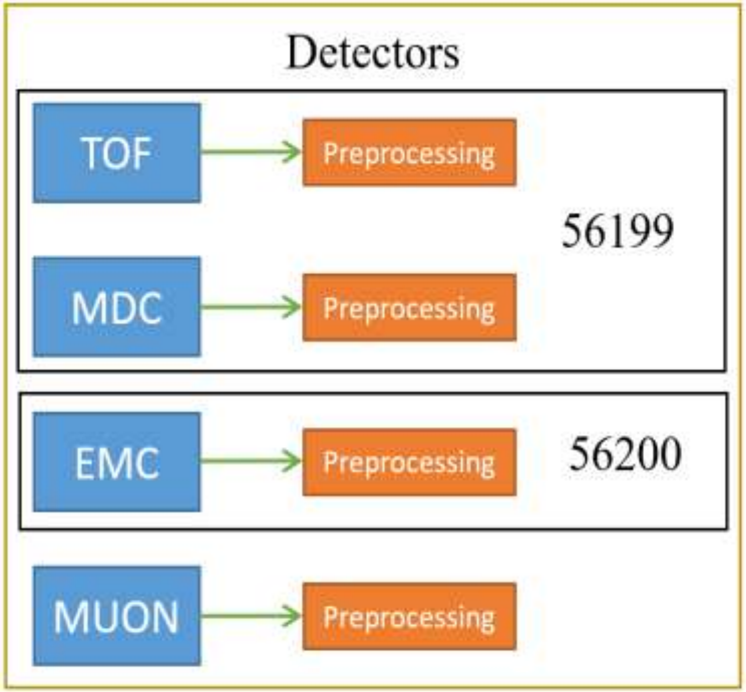
Use two dedicated runs
Run Number: 56199 and 56200
Energy Point: J/psi peak

Run Number	Events Num	Trigger
56199	5.66M	MDC & TOF(CH03)
56200	3.06M	EMC(CH12)

(will called MDC&TOF only and EMC only)

Use boss version: 7.0.3

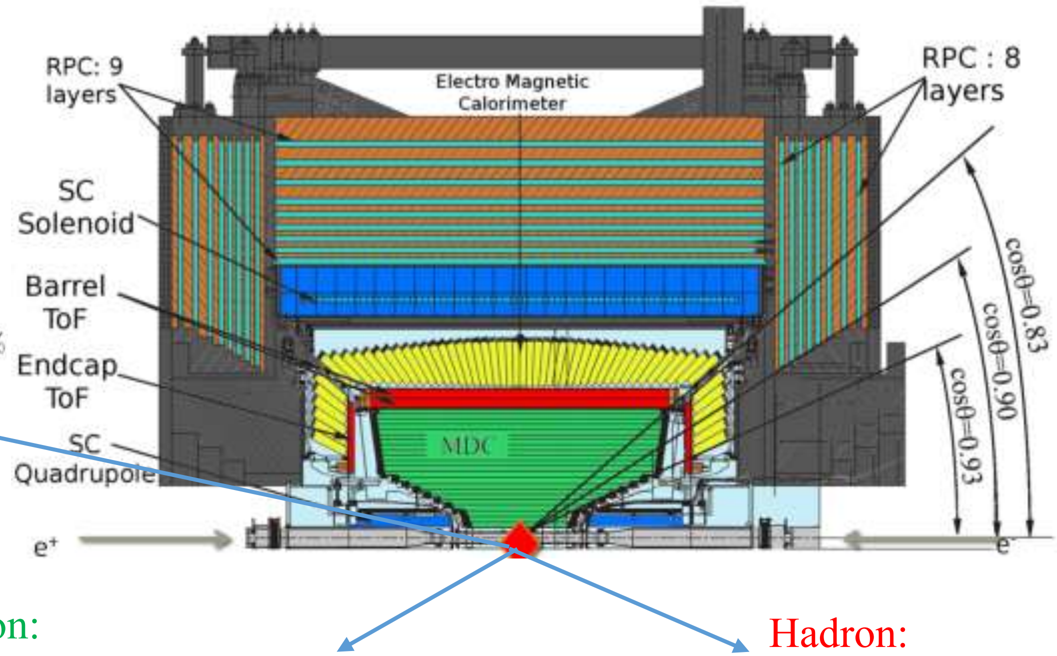
Beam Background:Hadron
56199 ≈ 2:1
56200 ≈ 2:3



Selection

The traditional method focused on : **Hadron**, **Bhabha**, **Dimuon**
The data other than these three categories are tag as **Beam Background**

Bhabha:
EMC Cluster Opening angle > 166°
MDC opening angle ≥ 175°
$\frac{|E_{emc}(e^+)+E_{emc}(e^-)-3.097|}{3.097} \leq 10\%$



Dimuon:
MDC Opening angle > 178°
(E/c, P_x, P_y, P_z) Limit the scope
P < 2 GeV/c, E < 0.7 GeV

Hadron:
Two or more good Tracks
MDC Opening Angle < 170°

Scheme

No research on the Beam Background Trigger Rate

Channel	Bhabha		Dimuon		2-prong	4-prong
	Barrel	Endcap	Barrel	Endcap		
CH01	0.65 ± 0.02	$99.10^{+0.43}_{-0.70}$	0.63 ± 0.03	$99.04^{+0.96}_{-11.09}$	15.88 ± 0.04	$31.30^{+0.03}_{-0.05}$
CH02	$99.60\pm\ 0.02$	0.03 ± 0.01	$99.76^{+0.06}_{-0.08}$	$1.18^{+0.85}_{-0.78}$	84.88 ± 0.06	98.97 ± 0.02

……

Our Scheme:

- 1、Reproduce the traditional method and calculate the trigger rate of Beam Background
- 2、Train a **binary classification model** to verify the feasibility of the solution.
- 3、Train a **four-class classification model** to compare its results with traditional methods.

Binary model
- Hadron
- Beam Background

Four-class model
- Hadron
- Bhabha
- Dimuon
- Beam Background

Traditional Method

Calculated the signal efficiency for Hadron event

$$\varepsilon_i = \frac{\text{Number of Events passing Condition i}}{\text{Number of Events}}$$

1、EMC only to calculate **MDC and TOF Conditions**
2、MDC&TOF only to calculate **EMC Conditions**

	BESIII Work		Reproduction	
GTL	2-prong(%)	4-prong(%)	2-prong(%)	4-prong(%)
0	99.64 ± 0.01	99.97	99.03 ± 0.01	99.94
1	$98.01^{+0.03}_{-0.02}$	$99.63^{+0.01}_{-0.02}$	97.03 ± 0.02	99.50 ± 0.01

Matched well!

……

Use the same method, we can calculate the traditional trigger rate of the Beam Background!

Traditional Method

Calculate the trigger rate using the traditional method

MDC&TOF only

Channel	Hadron TPR(%)	Hadron FPR(%)
CH01	28.09	1.05
CH02	99.45	16.95
CH04	53.21	10.65
CH05	99.62	15.98
CH06	99.48	16.95
CH09	88.38	7.17
CH12	98.14	8.43
Total	99.78	14.96

EMC only

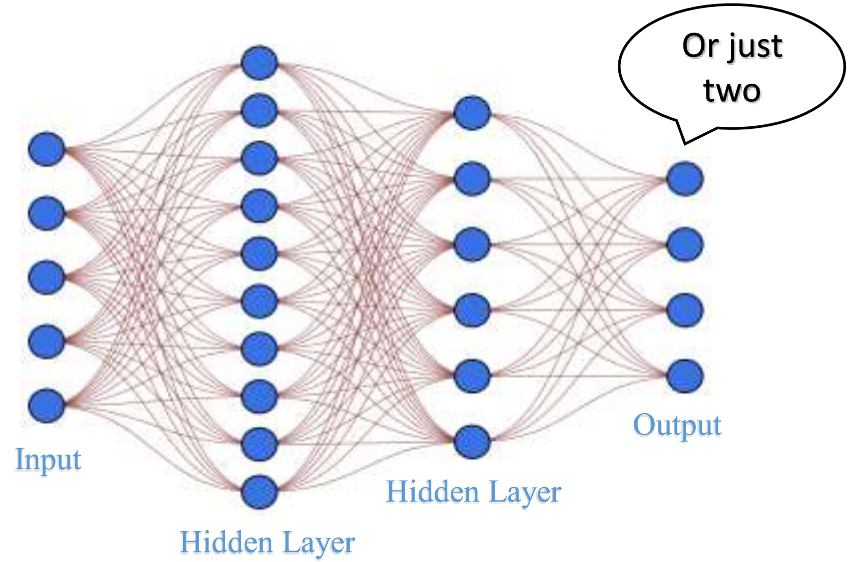
Channel	Hadron TPR(%)	Hadron FPR(%)
CH01	29.23	20.63
CH02	93.59	22.23
CH04	54.74	9.50
CH05	99.68	45.48
CH06	97.28	29.32
CH09	90.49	40.60
Total	99.93	70.64

TPR: True Positive Rate, the proportion of triggered **Hadron**
FPR: False Positive Rate, the proportion of triggered **Beam Background**

These two results will serve as the traditional method results for comparison with the NN model results.

Model Structure

Our model is a feed-forward dense neural network with two hidden layers. (For FPGA!)



Supervised Learning

Inputs

- 48 Trigger Conditions

Hidden

- 64 Nodes per Layer
- Two hidden layers
- Dynamic Learning Rate Adjustment

Outputs

- Prediction results of binary classification or four-class classification

Threshold

- Which let the TPR matches the traditional method

Classification Score

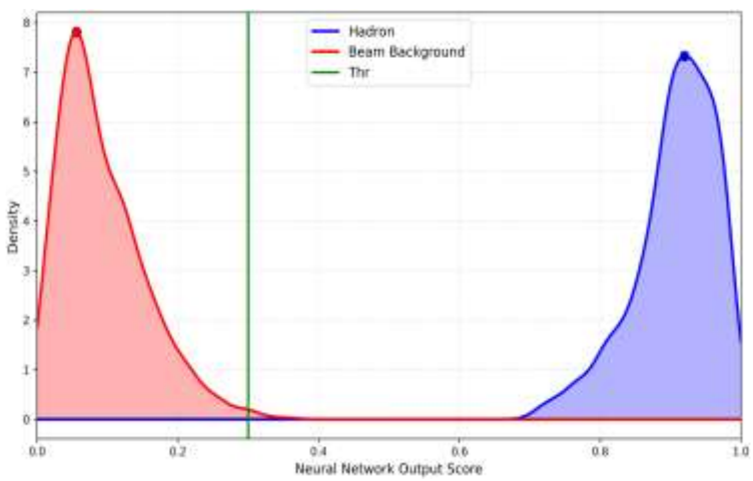
Model Prediction
Score: P_i

If $P_{Hadron} > \boldsymbol{Thr}$
Predicted as Hadron

(**Bianry model** stopped, Remaining events predicted as Beam Background)

If P_X is Higher
Predicted as **X**

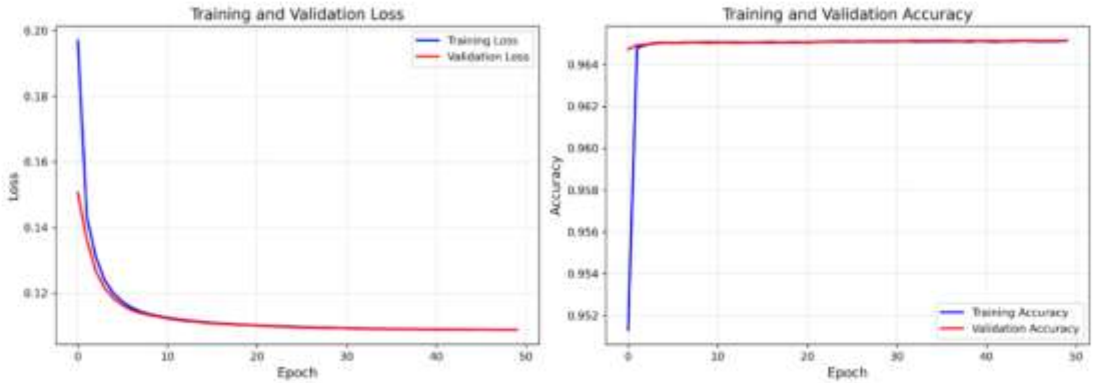
Score Distribution



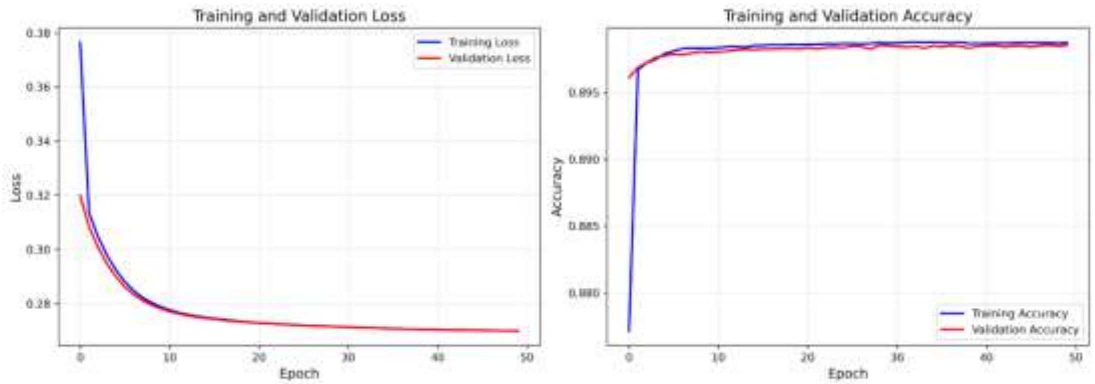
Thr is the threshold that allows the hadron TPR to reach 99.78% or 99.93%.

Parameter and metric situations of the training and validation sets

MDC&TOF only



EMC only

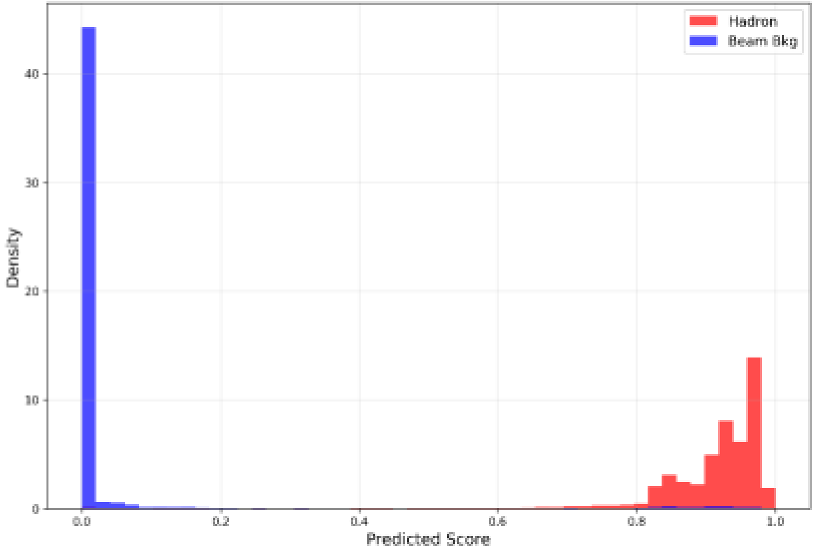


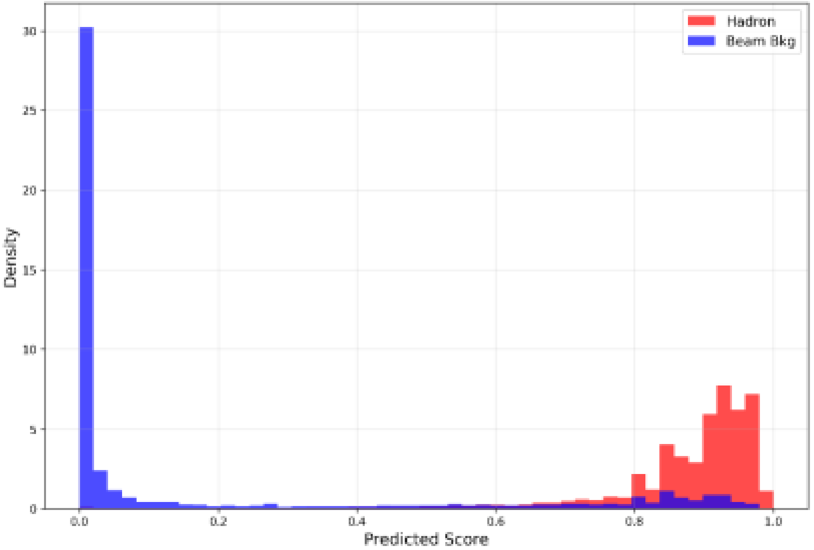
- Loss decreases with training
- Accuracy increases with training
- The training and validation sets are well-aligned.

Binary Classification

Predicted Score Distribution

MDC&TOF only | **EMC only**



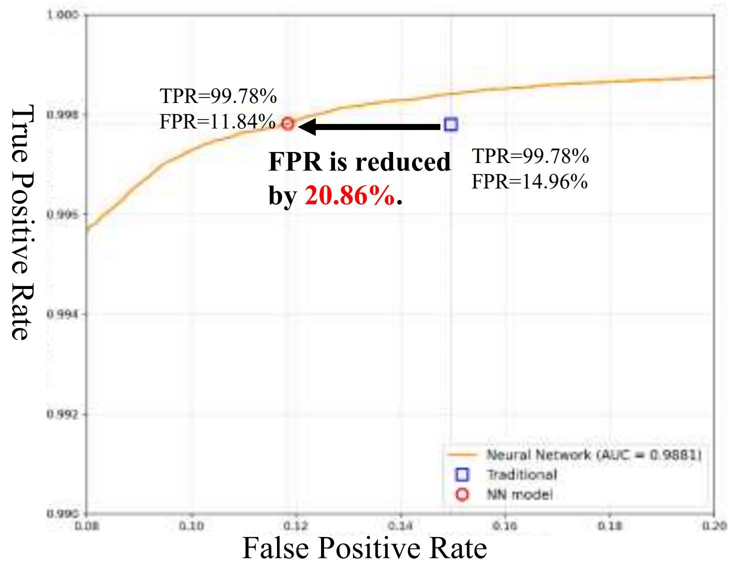


- The two types of events are well separated by the model.
- Need an extremely low threshold to meet the high TPR requirement

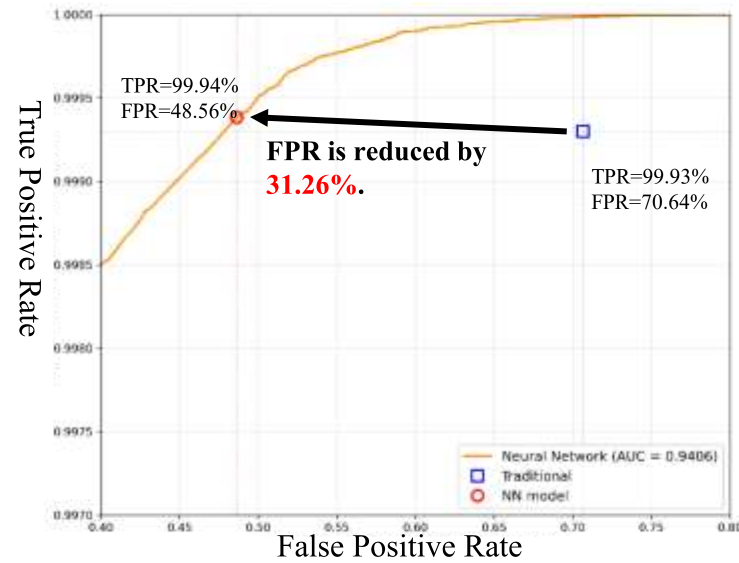
Beam Background Trigger Rate:

$$\frac{[N_{Beam\ Background} \&\&(TPR > Thr)]}{N_{Beam\ Background}}$$

MDC&TOF only ROC Curve



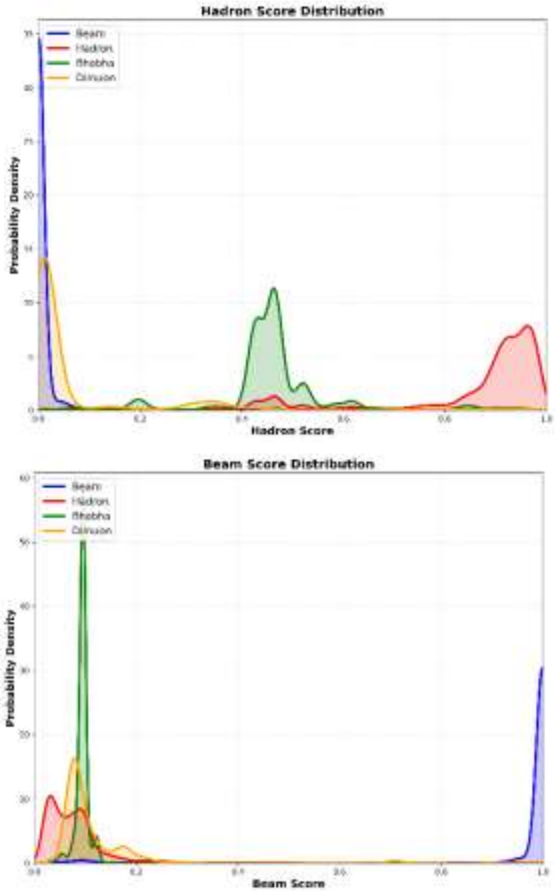
EMC only ROC Curve



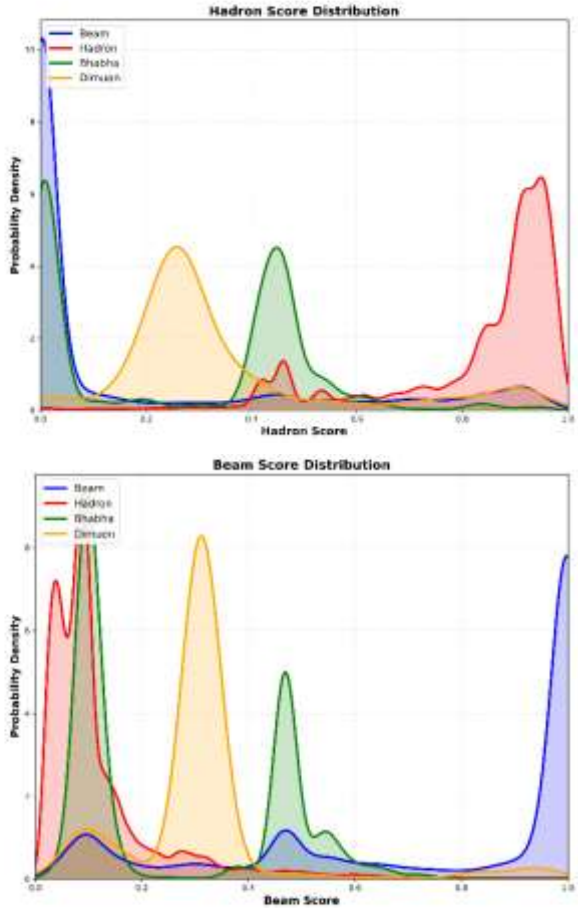
	MDC&TOF only		EMC only	
	TPR(%)	FPR(%)	TPR(%)	FPR(%)
BESIII Work	99.78	14.96±0.02	99.93	70.64 ± 0.03
NN Model	-	11.76±0.02	99.94	48.56 ± 0.04

Four-class Classification

MDC&TOF only



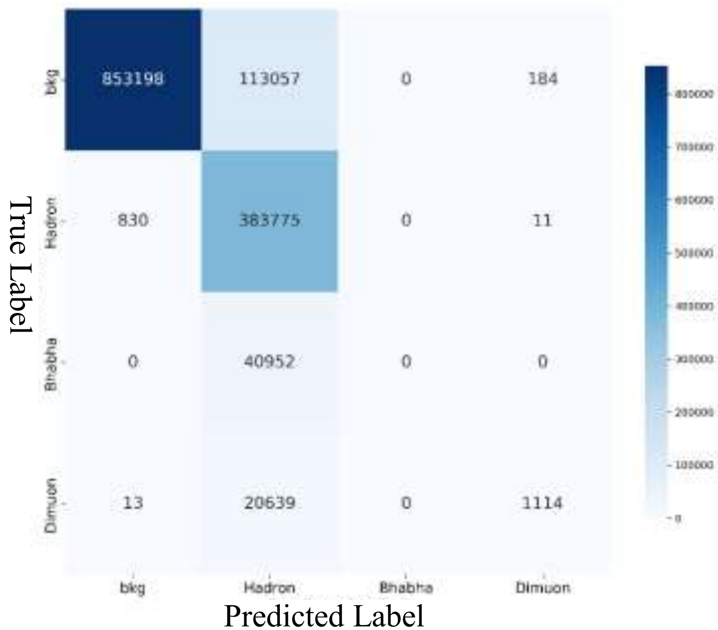
EMC only



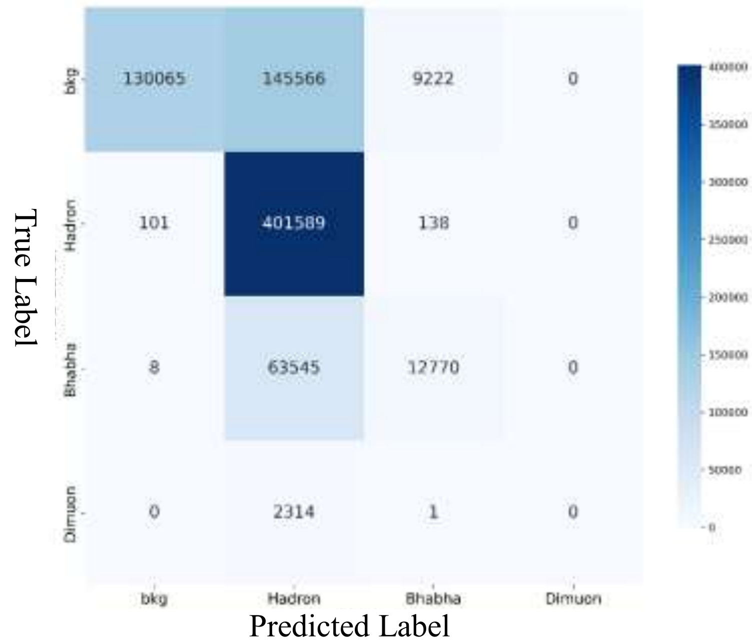
- Both distributions, Hadron and Beam Background are relatively easy to distinguish

Four-class Classification

MDC&TOF only



EMC only



	MDC&TOF only		EMC only	
	TPR(%)	FPR(%)	TPR(%)	FPR%)
BESIII Work	99.78	14.96±0.02	99.93	70.64 ± 0.03
NN Model	-	11.70±0.02	-	51.99 ± 0.04

- For MDC&TOF only, FPR is reduced by **21.79%**
- For EMC only, FPR is reduced by **26.40%**
- The main focus is on Beam Bkg and Hadron

Slight TPR drop
Significant Bkg drop!

Use hls4ml to building! (FPGA: xcvu9p-flga2104-3-e)

(Just use MDC&TOF only data to test)

```
+ Timing:
    * Summary:
    +--------+---------+----------+------------+
    |  Clock |  Target | Estimated| Uncertainty|
    +--------+---------+----------+------------+
    |ap_clk  | 5.00 ns | 4.325 ns |    0.62 ns |
    +--------+---------+----------+------------+

+ Latency:
    * Summary:
    +---------+---------+-----------+-----------+-----+-----+----------+
    |  Latency (cycles) |  Latency (absolute)   |  Interval | Pipeline |
    |   min   |   max   |    min    |    max    | min | max |   Type   |
    +---------+---------+-----------+-----------+-----+-----+----------+
    |       10|       10| 50.000 ns | 50.000 ns |    1|    1| function |
    +---------+---------+-----------+-----------+-----+-----+----------+

* Summary:
+---------------------+---------+-------+---------+---------+-----+
|         Name        | BRAM_18K| DSP48E|    FF   |   LUT   | URAM|
+---------------------+---------+-------+---------+---------+-----+
|DSP                  |        -|      -|        -|        -|    -|
|Expression           |        -|      -|        0|        6|    -|
|FIFO                 |        -|      -|        -|        -|    -|
|Instance             |        3|   3059|     5922|   121460|    -|
|Memory               |        -|      -|        -|        -|    -|
|Multiplexer          |        -|      -|        -|       36|    -|
|Register             |        -|      -|     3099|        -|    -|
+---------------------+---------+-------+---------+---------+-----+
|Total                |        3|   3059|     9021|   121502|    0|
+---------------------+---------+-------+---------+---------+-----+
|Available SLR        |     1440|   2280|   788160|   394080|  320|
+---------------------+---------+-------+---------+---------+-----+
|Utilization SLR (%)  |       ~0|    134|        1|       30|    0|
+---------------------+---------+-------+---------+---------+-----+
|Available            |     4320|   6840|  2364480|  1182240|  960|
+---------------------+---------+-------+---------+---------+-----+
|Utilization (%)      |       ~0|     44|       ~0|       10|    0|
+---------------------+---------+-------+---------+---------+-----+
```

hls4ml

We hope:

Latency < 500 ns ☑

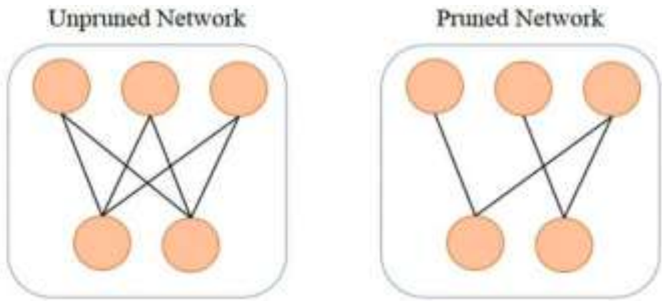
Utilization < 50%

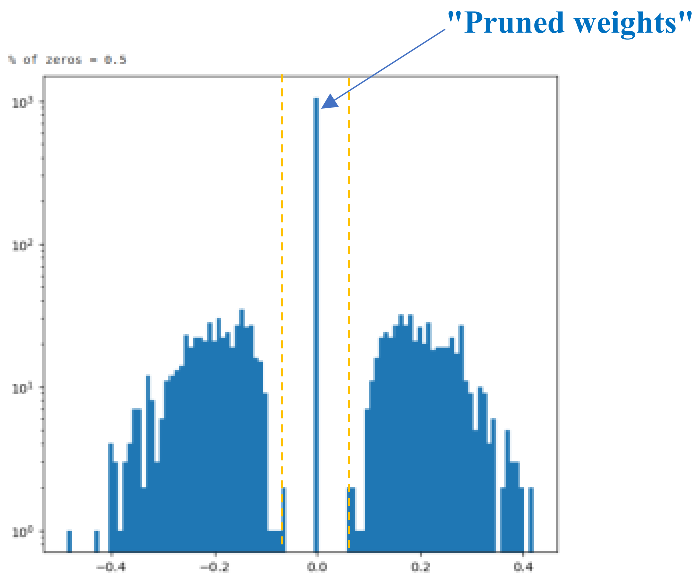
- The FPGA used for testing is superior to the FPGA currently used in BESIII.

Need to optimize!

HLS4ML

1、Pruned



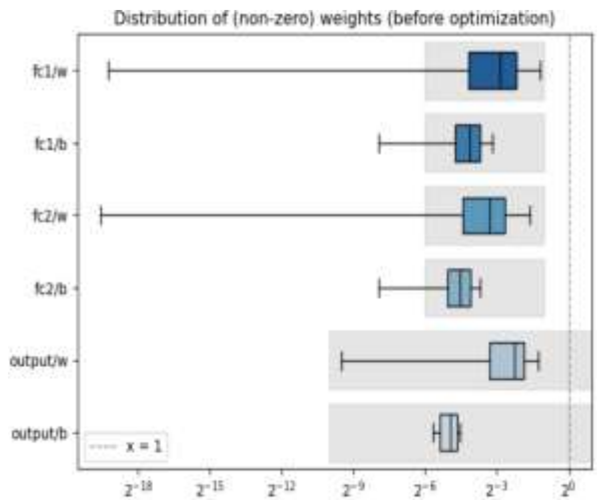


- Remove the links with lower weights.

2、Precision adjustment

Two hidden layers : (16, 6)
Output layer : (16, 6)

Two hidden layers : (6, 0)
Output layer : (16, 6)



After Optimize:

* Summary:

Name	BRAM_18K	DSP48E	FF	LUT	URAM
DSP	-	-	-	-	-
Expression	-	-	0	6	-
FIFO	-	-	-	-	-
Instance	3	3059	5922	121460	-
Memory	-	-	-	-	-
Multiplexer	-	-	-	36	-
Register	-	-	3099	-	-
Total	3	3059	9021	121502	0
Available SLR	1440	2280	788160	394080	320
Utilization SLR (%)	~0	134	1	30	0
Available	4320	6840	2364480	1182240	960
Utilization (%)	~0	44	~0	10	0

* Summary:

Name	BRAM_18K	DSP48E	FF	LUT	URAM
DSP	-	-	-	-	-
Expression	-	-	0	6	-
FIFO	-	-	-	-	-
Instance	3	13	18126	98896	-
Memory	-	-	-	-	-
Multiplexer	-	-	-	36	-
Register	-	-	3658	-	-
Total	3	13	21784	98938	0
Available SLR	2184	520	617600	308800	0
Utilization SLR (%)	~0	2	3	32	100
Available	6552	1560	1852800	926400	0
Utilization (%)	~0	~0	1	10	0

+ Timing:
  * Summary:

Clock	Target	Estimated	Uncertainty
ap_clk	5.00 ns	4.319 ns	0.62 ns

+ Latency:
  * Summary:

Latency (cycles) min	Latency (cycles) max	Latency (absolute) min	Latency (absolute) max	Interval min	Interval max	Pipeline Type
7	7	35.000 ns	35.000 ns	1	1	function

- Latency < 500 ns ☑
- Utilization < 50% ☑
- The model can easily meet the requirements for FPGA deployment.

Summary

- We have completed the training of both binary and four-class classification models in two Runs.
- Using the Neural Network, we have reduced the trigger rate of beam background while maintaining a high signal trigger efficiency.
-

	Binary Classification	Four-class Classification
MDC&TOF only	20.86%	21.79%
EMC only	31.26%	26.40%

- We conducted synthesis using hls4ml, and it basically meets the hardware resource requirements and latency requirements.
- Our work can also be simulated in other experiments, such as **Belle II, STCF and CEPC.**

Future Work

- Random Trigger Data : Use Channel 10

CH09	NClus.GE.1&& BEtot_H	For Neutral
CH10	-	Random
CH11	NBTOF.GE.2&& LTrk_BB	Not used

- Testing the trigger rate:

Not affected by the current trigger system

	Trigger Rate(%)
Hadron	91.56
Beam Bkg	0.18

- **Use these data to test the model performance**

- High-Energy Point like:4.160Gev

	Num of Event	Num of Hadron	Hadron Ratio
J/ψ peak	8.74M	2.58M	29.47%
$\sqrt{s} = 4.680\text{GeV}$	12.75M	0.27M	2.1%

More worthwhile to do!

- Data is get ready!
- Testing will be carried out soon!

Future Work

Software

Use pytorch to training FNN

PyTorch

☑

Hardware

Use Vivado or hls4ml

to translate into FPGA

Vivado HLS

hls4ml

☑

FPGA

Next to do:

- Use random trigger data to verify the model's level-1 trigger efficiency.
- Test the model's performance at High-Energy Points.
- Attempting offline hardware testing on the FPGA.
- **Implement new trigger logic in BESIII**

Thank you !

Hadronic Selection

Control Sample Selection:

$|\cos\theta| < 0.93$
$|dr| < 10$ cm
$|dz| < 1$ cm

Hadron Selection:

1、Charge Hadronic Event Selection:
Two or more good tracks are required in the MDC.
If exactly two tracks, the opening angle between them is required to be less than 170°.

Bhabha Selection：

1、Two EMC clusters are required to have an opening angle larger than 166°.

2、$\frac{|E_{emc}(e^+)+E_{emc}(e^-)-3.097|}{3.097} \leq 10\%$

3、MDC opening angle ≥ 175°.

Dimuon Selection:

1、MDC opening angle ≥ 178°.

2、For each track, P < 2 GeV/c, E < 0.7 GeV.

3、The four-momentun(E/c, P_x, P_y, P_z) is required to fall into (2.8 to 3.3, -0.1 to 0.1, -0.1 to 0.1, -0.2 to 0.2)

Beam Background

Events failing the selection criteria

Traditional Method

$$\varepsilon_i = \frac{\text{Number of Events passing Condition i}}{\text{Number of Events}}$$

	BESIII Work		My work	
GTL	2-prong(%)	4-prong(%)	2-prong(%)	4-prong(%)
0	99.64 ± 0.01	99.97	99.03 ± 0.01	99.94
1	$98.01^{+0.03}_{-0.02}$	$99.63^{+0.01}_{-0.02}$	97.03 ± 0.02	99.50 ± 0.01
7	89.88 ± 0.04	$93.25^{+0.03}_{-0.04}$	87.37 ± 0.05	90.51 ± 0.04
9	99.63 ± 0.01	99.99	98.77 ± 0.02	99.95
10	97.01 ± 0.03	99.44 ± 0.02	96.07 ± 0.03	99.21 ± 0.01
12	99.34 ± 0.01	99.90 ± 0.01	98.69 ± 0.02	99.83 ± 0.01
13	36.93 ± 0.06	41.85 ± 0.07	33.75 ± 0.07	41.90 ± 0.07
17	57.21 ± 0.06	83.21 ± 0.05	53.36 ± 0.07	81.07 ± 0.06
19	$74.69^{+0.05}_{-0.06}$	77.87 ± 0.06	77.22 ± 0.06	78.87 ± 0.06
20	$87.81^{+0.05}_{-0.06}$	99.04 ± 0.02	86.85 ± 0.05	98.86 ± 0.02
21	99.63 ± 0.01	99.96	99.12 ± 0.01	99.95
38	46.62 ± 0.06	$83.01^{+0.05}_{-0.06}$	47.69 ± 0.07	83.10 ± 0.05
42	37.34 ± 0.06	76.21 ± 0.06	36.08 ± 0.07	75.26 ± 0.06
44	93.67 ± 0.05	99.86 ± 0.02	93.00 ± 0.04	99.87 ± 0.01
45	99.67 ± 0.01	99.98	99.22 ± 0.01	99.98

(The relative uncertainties of the items with no uncertainties indicated are less than0.01%)