



# Suppress beam background using ML in BESIII trigger

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At BESIII, the trigger efficiency consistently exceeds 99%.<sup>[1]</sup>

	GTL	Condition	Bhabha		Dimuon		2-prong	4-prong
			Barrel	Endcap	Barrel	Endcap		
E	0	NClus.GE.1	100.00	100.00 <sup>+0.00</sup> <sub>-0.41</sub>	99.93±0.01	94.74 <sup>+4.35</sup> <sub>-11.09</sub>	99.64±0.01	99.97
	1	NClus.GE.2	98.69±0.03	98.20 <sup>+0.62</sup> <sub>-0.87</sub>	95.14±0.08	84.21 <sup>+5.47</sup> <sub>-13.01</sub>	98.01 <sup>+0.03</sup> <sub>-0.02</sub>	99.63 <sup>+0.01</sup> <sub>-0.02</sub>
	7	BEtot_H	100.00	0.17±0.02	0.68±0.03	4.81 <sup>+2.00</sup> <sub>-1.12</sub>	89.88±0.04	93.25 <sup>+0.03</sup> <sub>-0.04</sub>
M	9	Etot_L	100.00	100.00 <sup>+0.00</sup> <sub>-0.41</sub>	99.82±0.01	100.00 <sup>+0.00</sup> <sub>-9.24</sub>	99.63±0.01	99.99
C	10	Etot_M	100.00	100.00 <sup>+0.00</sup> <sub>-0.41</sub>	10.25±0.11	0.00 <sup>+0.00</sup> <sub>-0.00</sub>	97.01±0.03	99.44±0.02
	12	NBClus.GE.1	100.00	0.99±0.01	99.93±0.01	0.00 <sup>+0.00</sup> <sub>-0.00</sub>	99.34±0.01	99.90±0.01
	13	NEClus.GE.1	0.94±0.02	100.00 <sup>+0.00</sup> <sub>-0.41</sub>	1.68 <sup>+0.04</sup> <sub>-0.05</sub>	94.74 <sup>+4.35</sup> <sub>-11.09</sub>	36.93±0.06	41.85±0.07

Physical Events : Beam Background Events  $\approx$  **1:1** (In  $J/\psi$  peak)

Testing the Hadron Ratio for different Energy Point

(Use Trigger test data)

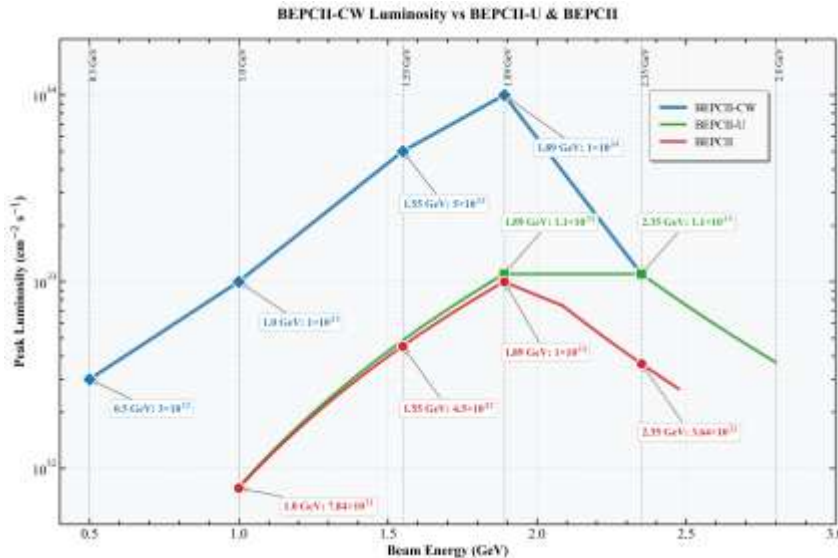
	Num of Event	Num of Hadron	Hadron Ratio
$J/\psi$ peak	8.74M	2.58M	29.47%
$\sqrt{s} = 4.680\text{GeV}$	12.75M	0.27M	2.1%

- 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  $J/\psi$  data[J]. Chinese Physics C, 2021, 45(2): 023002.



## BEPCII plan to update with crab waist scheme<sup>[2]</sup>



Luminosity increase by  $\times 10$   
below 1.89GeV



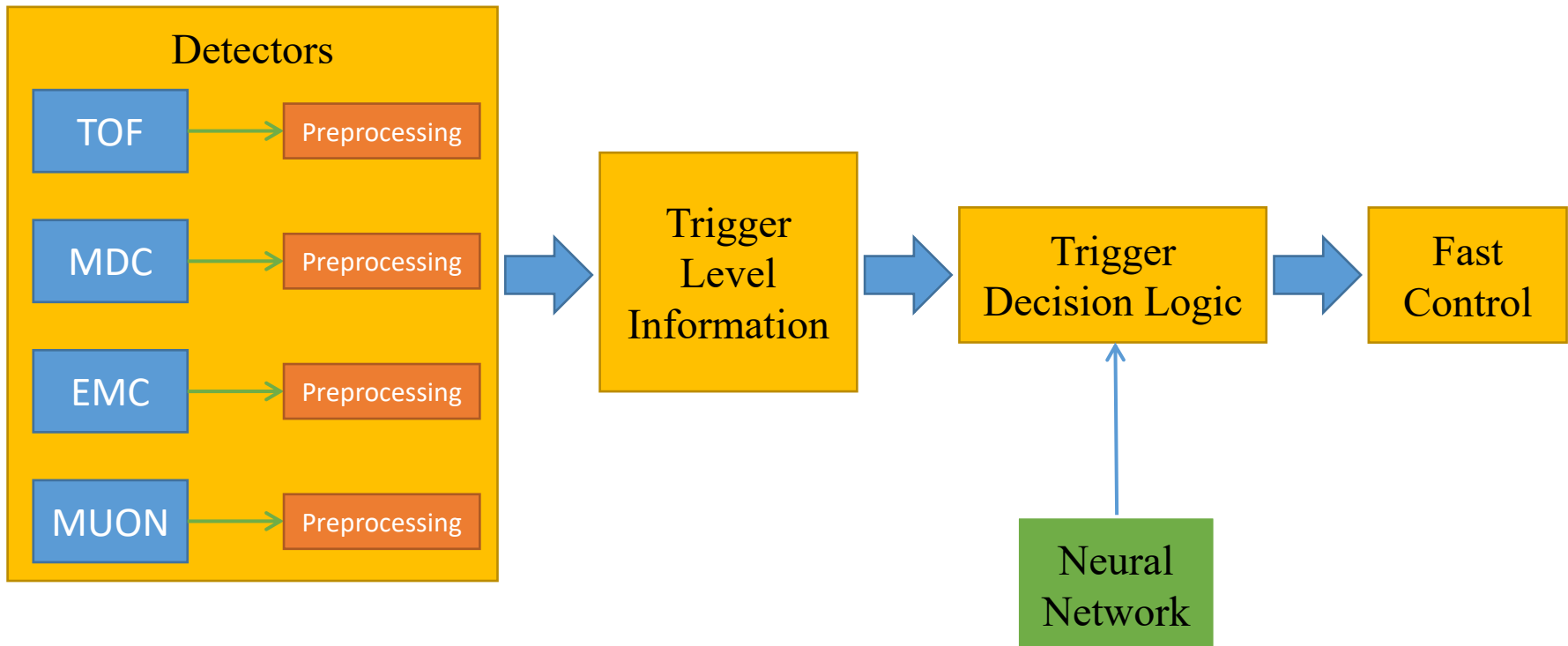
- DAQ need update
- **Trigger need update**
- ...

- In the future, the detector trigger system need a full update
- **This study is intended as a pre-study for the upgrade.**

[2] Feasibility study of future BEPCII upgrade with crab waist scheme. Dou Wang, Physics and Software Workshop in Spring 2026.



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



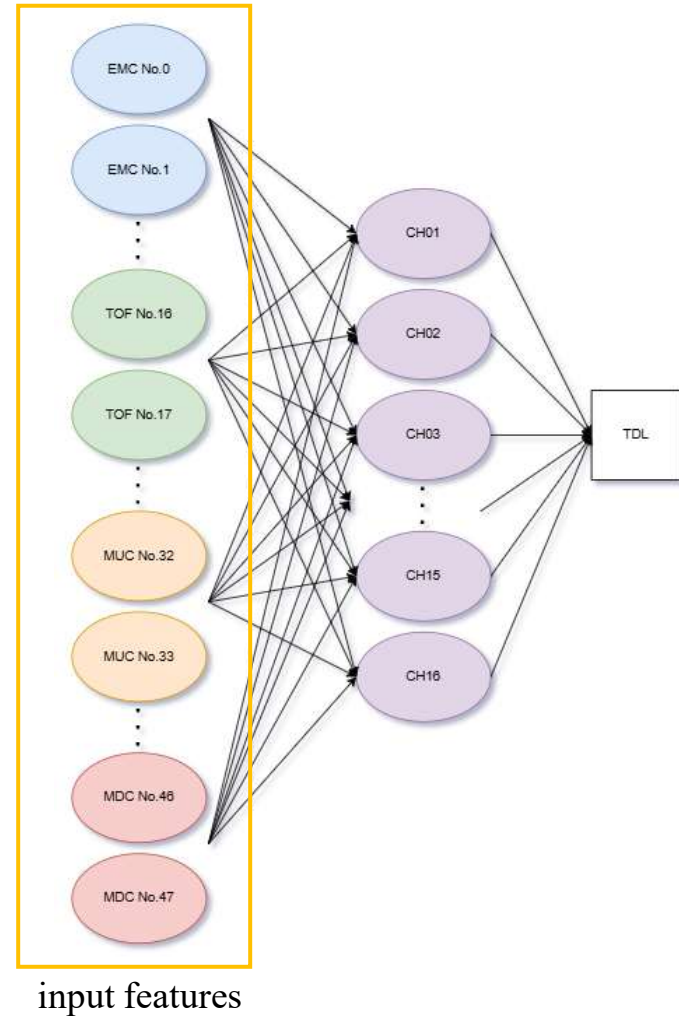


## BESIII Trigger system:

- 48 Conditions
- 16 Channels

Electromagnetic calorimeter (EMC)		
0	NClus.GE.1	Number of Clusters $\geq 1$
1	NClus.GE.2	Number of Clusters $\geq 2$
.....		
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 $\geq 2$
.....		

Use these trigger conditions as input features!





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)

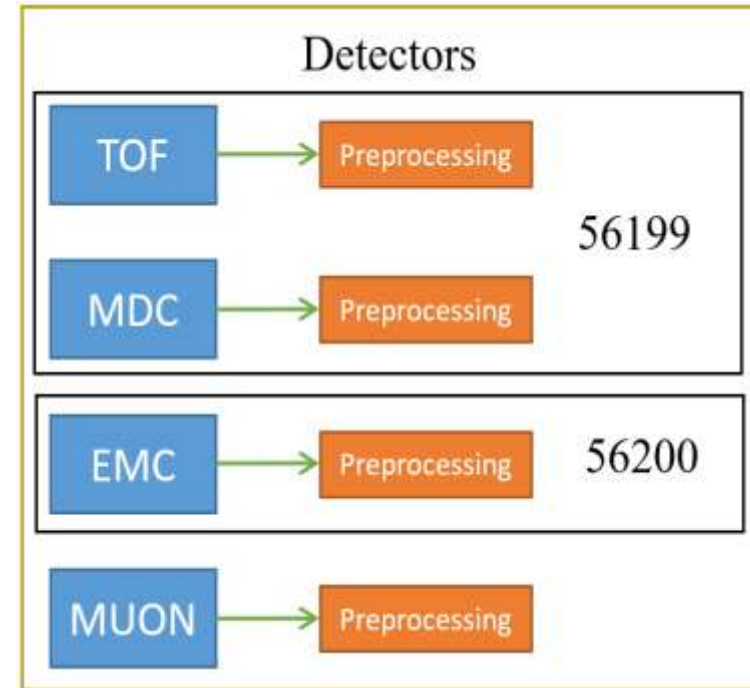
(will called MDC&TOF only and EMC only)

Use boss version: 7.0.3

Beam Background: Hadron

56199  $\approx$  2:1

56200  $\approx$  2:3



4.680GeV Data:

Run Number	Events Num	Trigger
90858-90869	3.14M	MDC & TOF(CH03)
90870-90876	9.28M	EMC(CH12)

Use boss version: 7.2.0

Random Trg Data:

- J/psi peak
- 3.686GeV
- 3.686GeV
- 4.740GeV

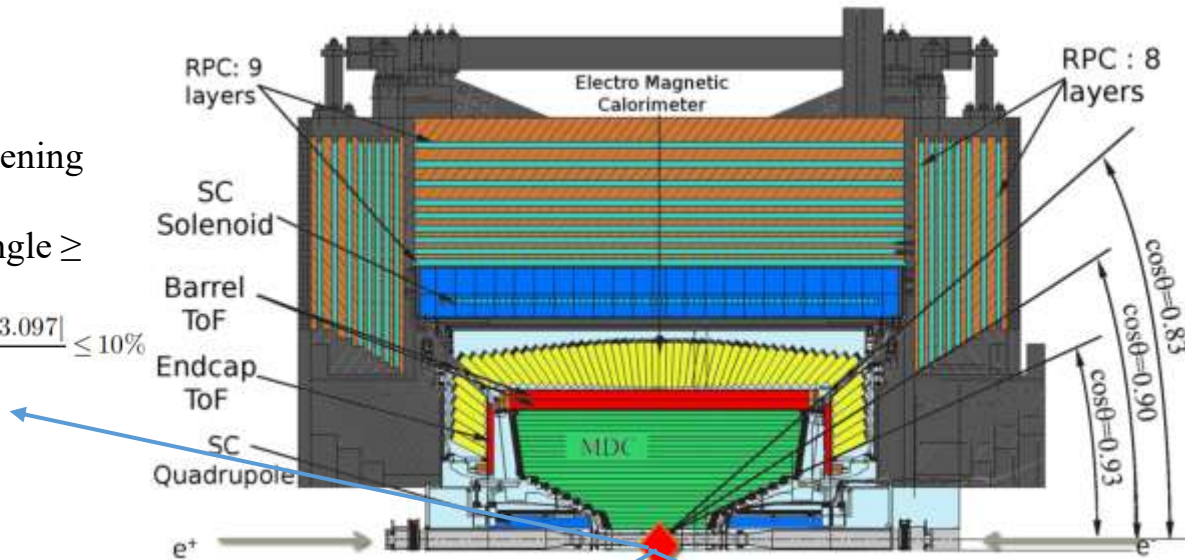
The traditional method focused on : **Hadron**, **Bhabha**, **Dimuon**  
The data other than these three categories are tag as **Beam Background**

## Bhabha:

EMC Cluster Opening angle  $> 166^\circ$

MDC opening angle  $\geq 175^\circ$

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



## Dimuon:

MDC Opening angle  $> 178^\circ$

$(E/c, P_x, P_y, P_z)$  Limit the scope

$P < 2 \text{ GeV}/c, E < 0.7 \text{ GeV}$

## Hadron:

Two or more good Tracks

MDC Opening Angle  $< 170^\circ$



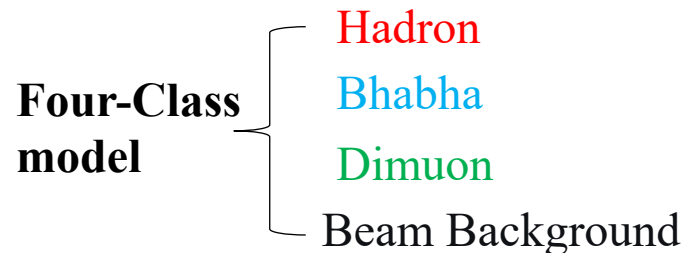
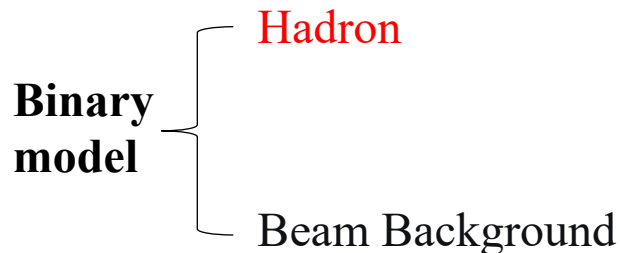
## No research on the Beam Background Trigger Rate

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

.....

### Our Scheme:

- 1、Reproduce the traditional method and calculate the trigger rate of Beam Background
- 2、Train a **Binary classification model** and a **Four-Class classification model** to compare its results with traditional methods.
- 3、Use **High-Energy point** data and **Random Trg** data for testing





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**

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

Matched well!

.....

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



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.



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

## Supervised Learning

### Inputs

- 48 Trigger Conditions

### Hidden

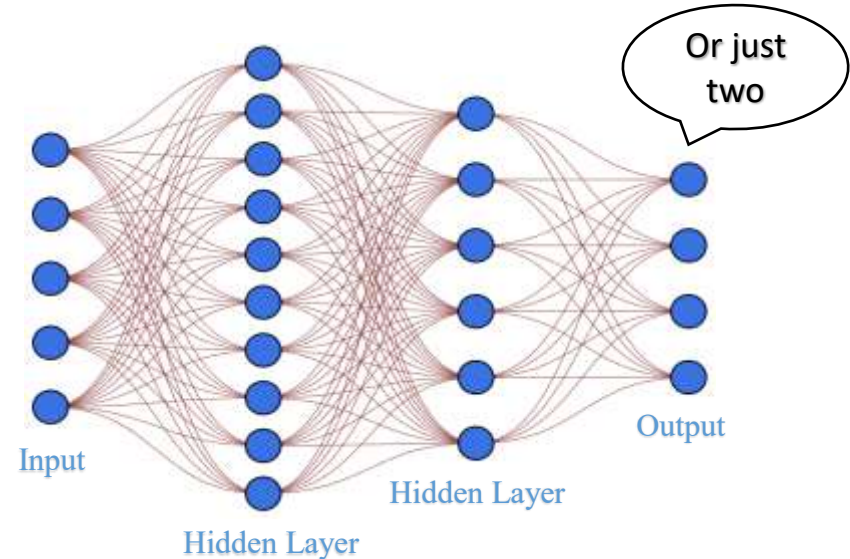
- 64 Nodes per Layer
- Two hidden layers
- Dynamic Learning Rate Adjustment

### Outputs

- Prediction results of binary classification or four-class classification

### Threshold

- Which let the TPR matches the traditional method





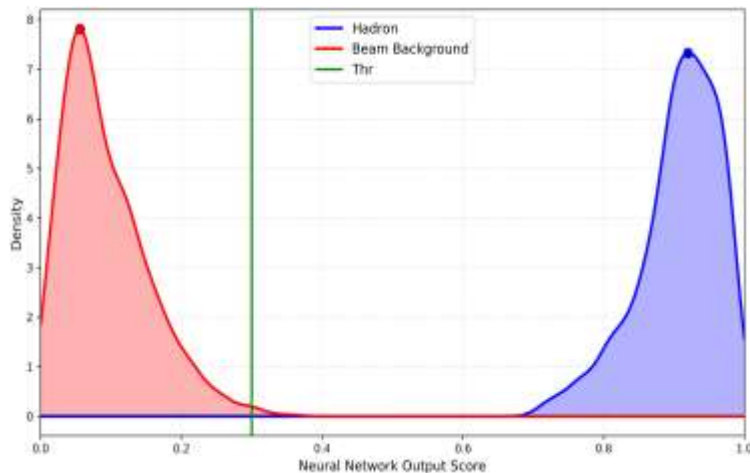
Model Prediction  
Score:  $P_i$



If  $P_{Hadron} > \mathbf{Thr}$   
Predicted as **Hadron**

(Binary model  
stopped, Remaining  
events predicted as  
Beam Background)

Score Distribution



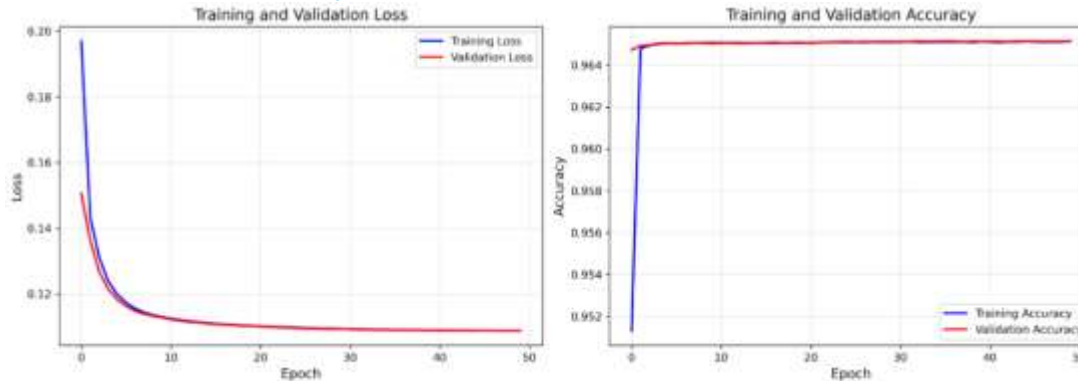
If  $P_X$  is Higher  
Predicted as **X**

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



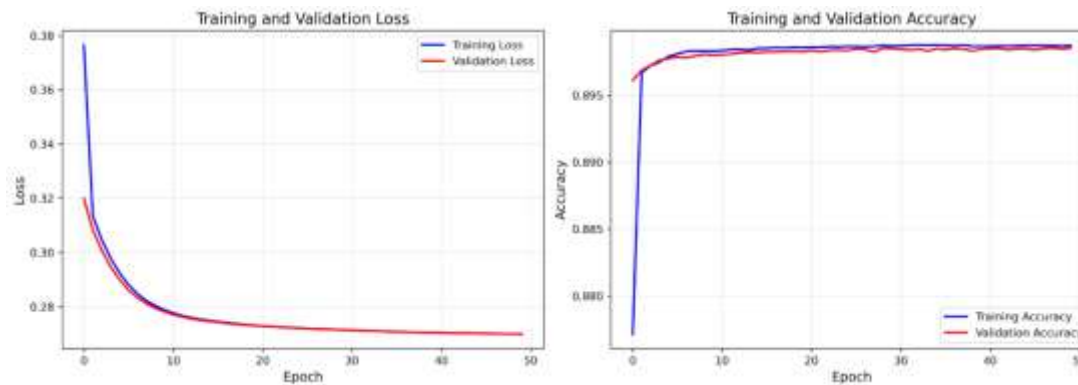
Parameter and metric situations of the training and validation sets

## MDC&TOF only



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

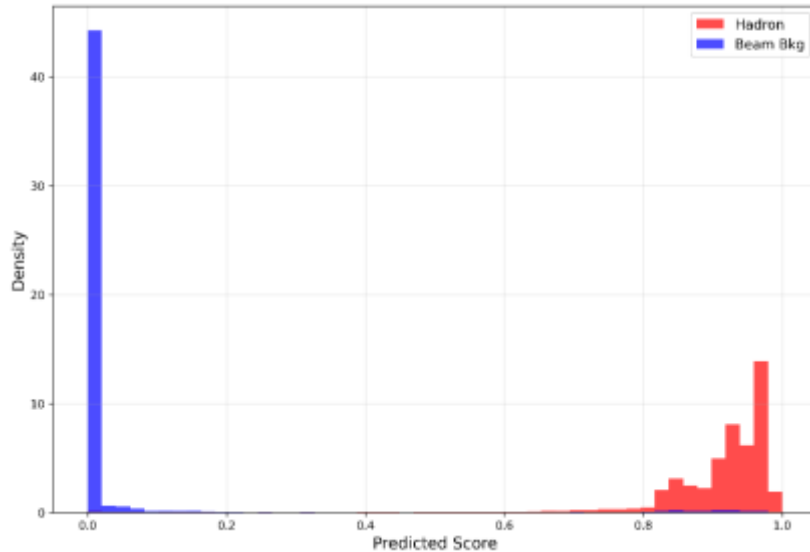
## EMC only



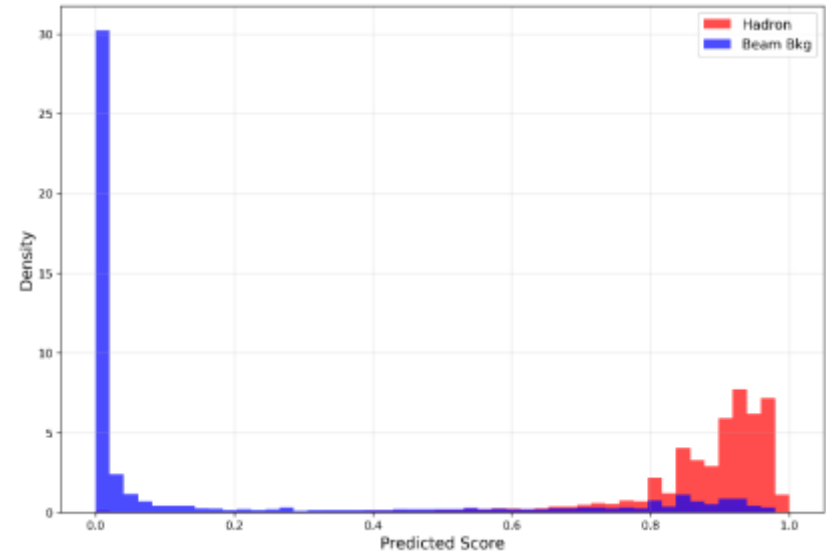


## Predicted Score Distribution

MDC&TOF only



EMC only



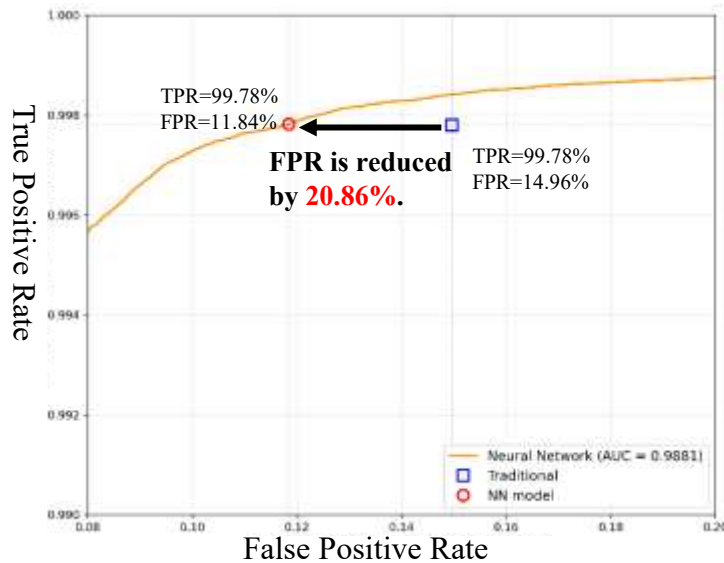
- The two types of events are well separated by the model.
- Need an extremely low threshold to meet the high TPR requirement



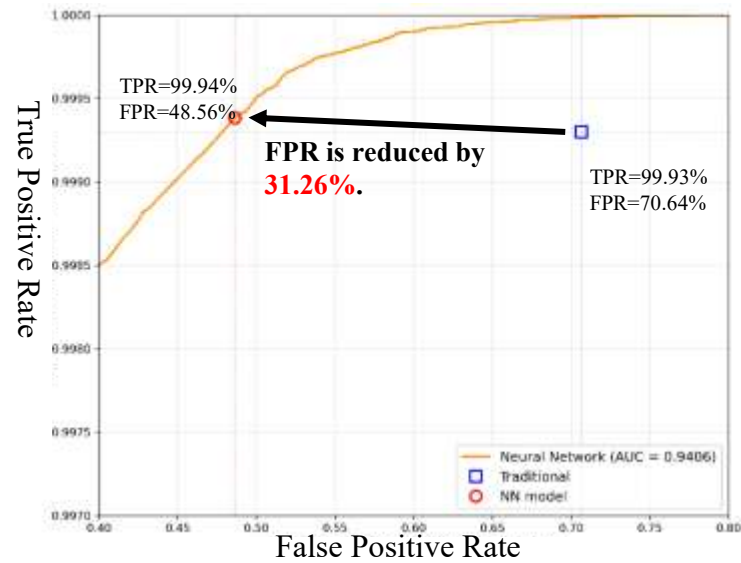
## Beam Background Trigger Rate:

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

### MDC&TOF only ROC Curve



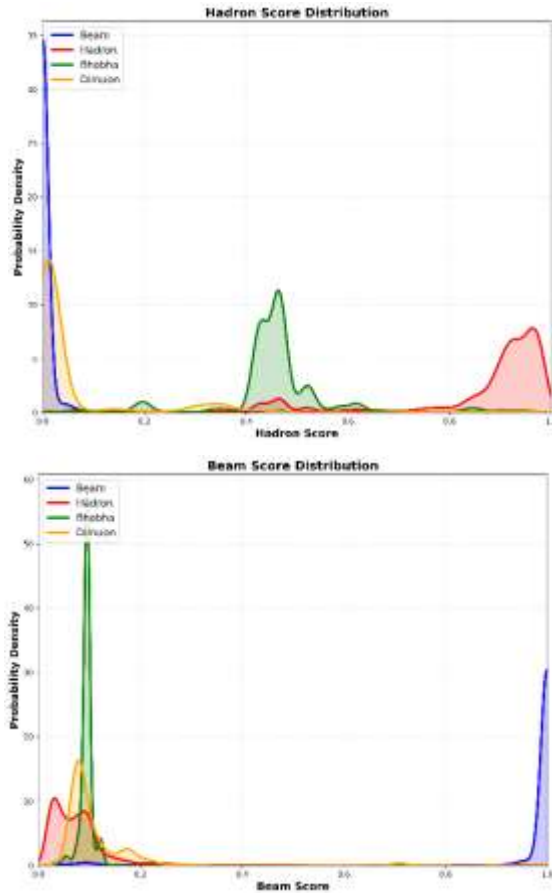
### EMC only ROC Curve



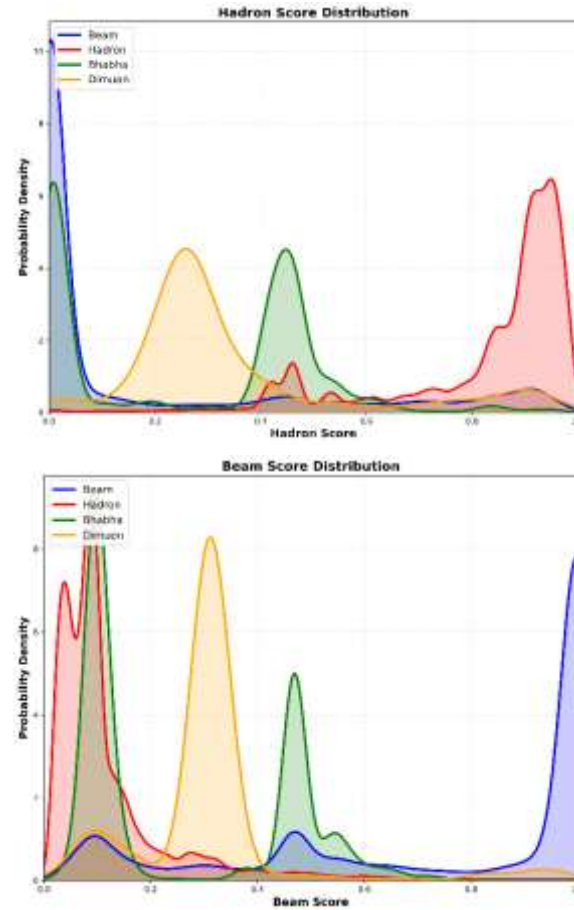
	MDC&TOF only		EMC only	
	TPR(%)	FPR(%)	TPR(%)	FPR(%)
BESIII Work	99.78	14.96±0.02	99.93	70.64 ± 0.03
NN Model	-	11.76±0.02	99.94	48.56 ± 0.04



## MDC&TOF only



## EMC only

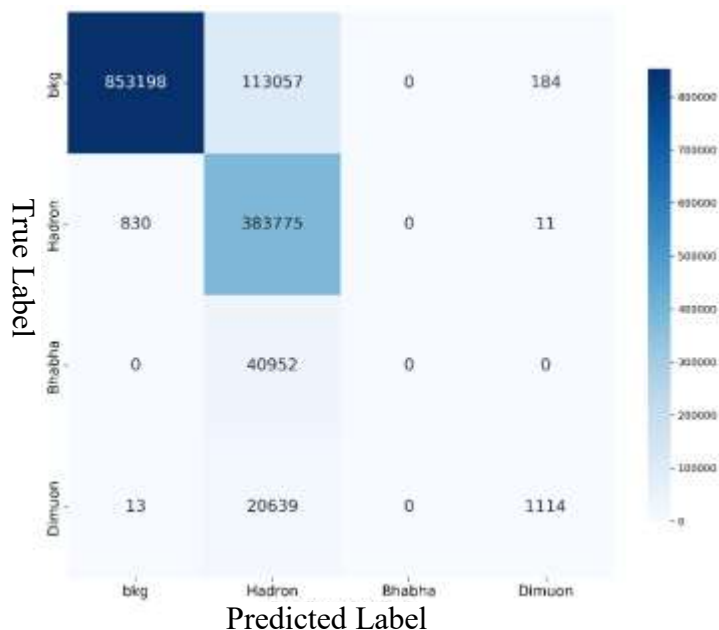


- Both distributions, Hadron and Beam Background are relatively easy to distinguish

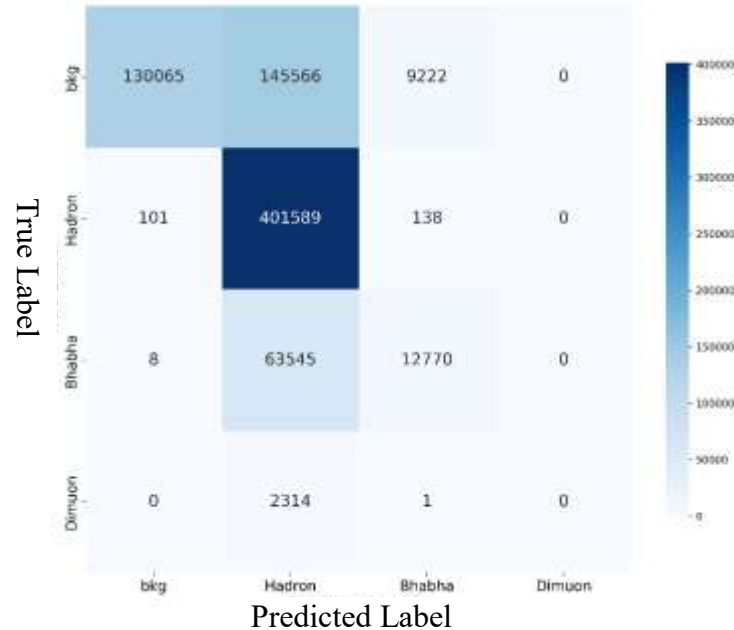
# Four-class Classification



## 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

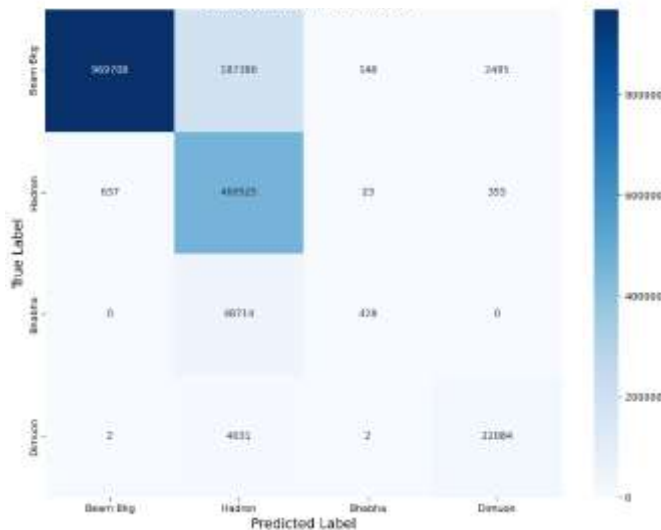
- For **MDC&TOF only**, FPR is reduced by **21.79%**
- For **EMC only**, FPR is reduced by **26.40%**
- The main focus is on Beam Bkg and Hadron

Slight TPR drop  
Significant Bkg drop!

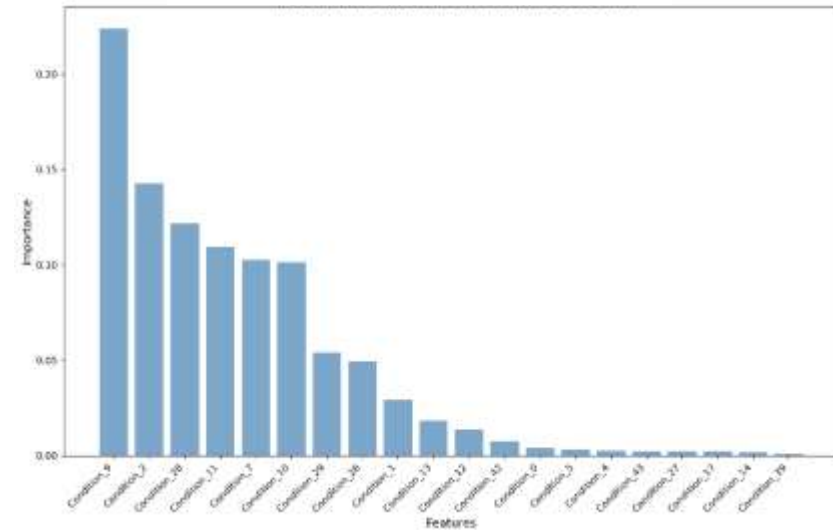
Using BDT to test:

- Performance lower bound
  - Generalization ability
- (Use MDC&TOF only data)

Confusion Matrix



Feature Importance



	NN model		BDT XGBoost	
	TPR(%)	FPR(%)	TPR(%)	FPR(%)
MDC&TOF only Model	99.78	11.70 ± 0.02	99.78	16.16 ± 0.03

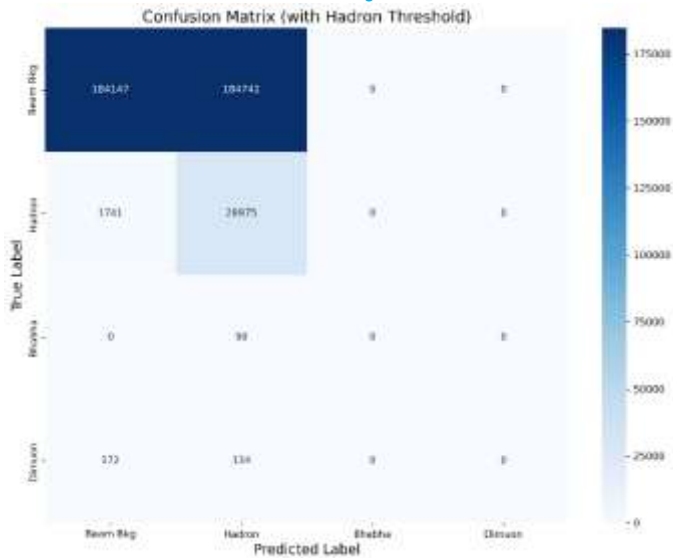
- NN achieve **27.6% lower FPR than BDT**.
- Low importance Feature can be removed to reduce model complexity.



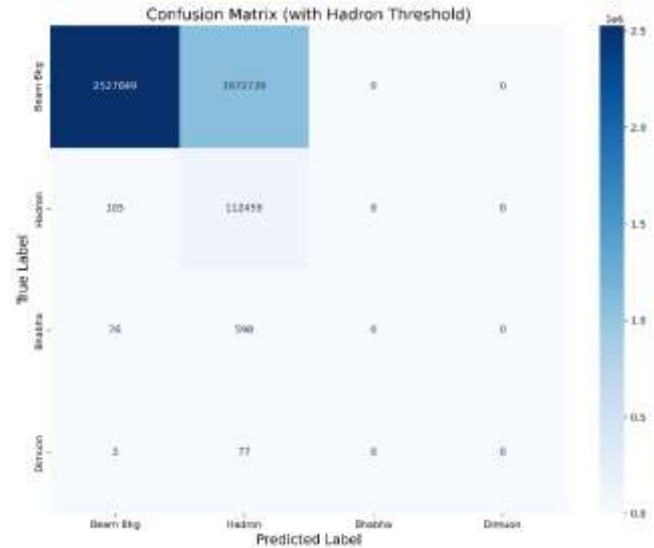
## Training Model on 4.680GeV

(Same model structure as J/psi)

### MDC&TOF only

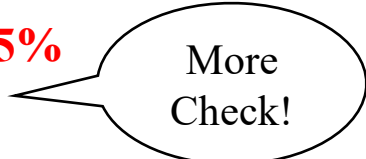


### EMC only



	MDC&TOF only		EMC only	
	TPR(%)	FPR(%)	TPR(%)	FPR(%)
Traditional Method	93.82	60.53	99.41	53.14
NN Model	94.38	51.30	99.88	27.81

- For **MDC&TOF only**, FPR is reduced by **15.25%**
- For **EMC only**, FPR is reduced by **47.67%!**

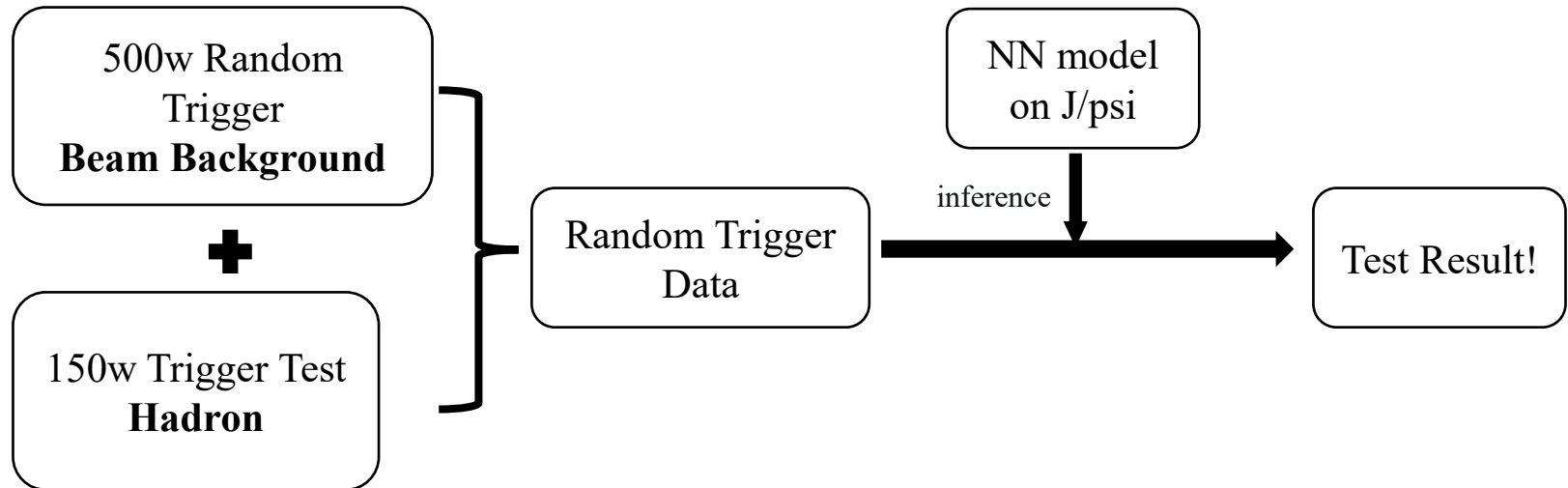




- Random Trigger Data : Use Channel 10

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

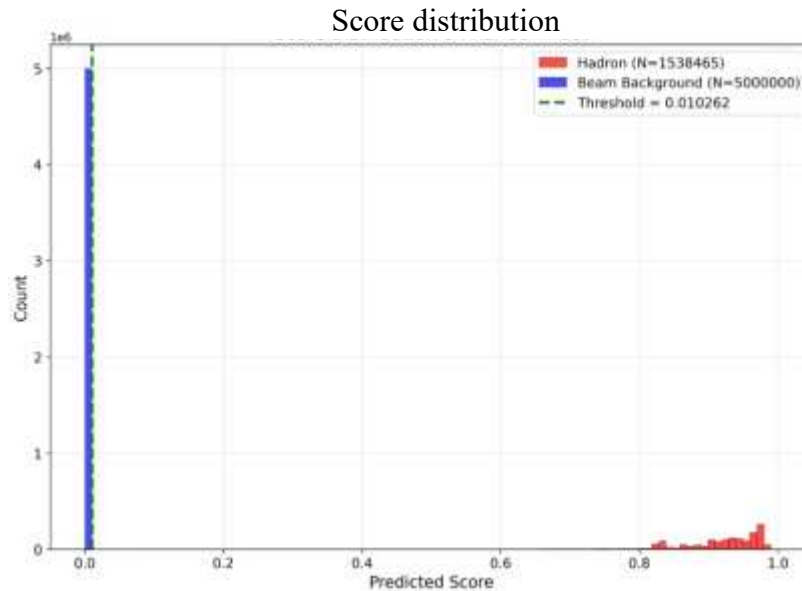
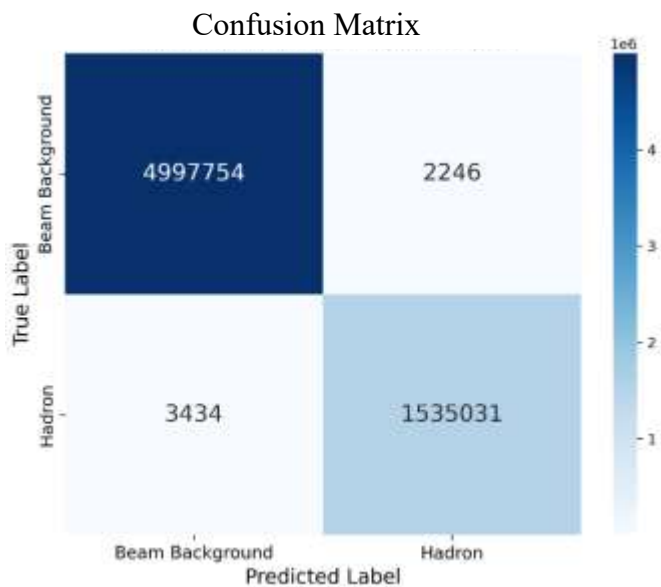
Study the model's background rejection capability:



- Test using **MDC&TOF only** data and model
- **Generalization** is evaluated by testing on backgrounds at different energy points.



- J/psi Beam Background + J/psi Hadron:

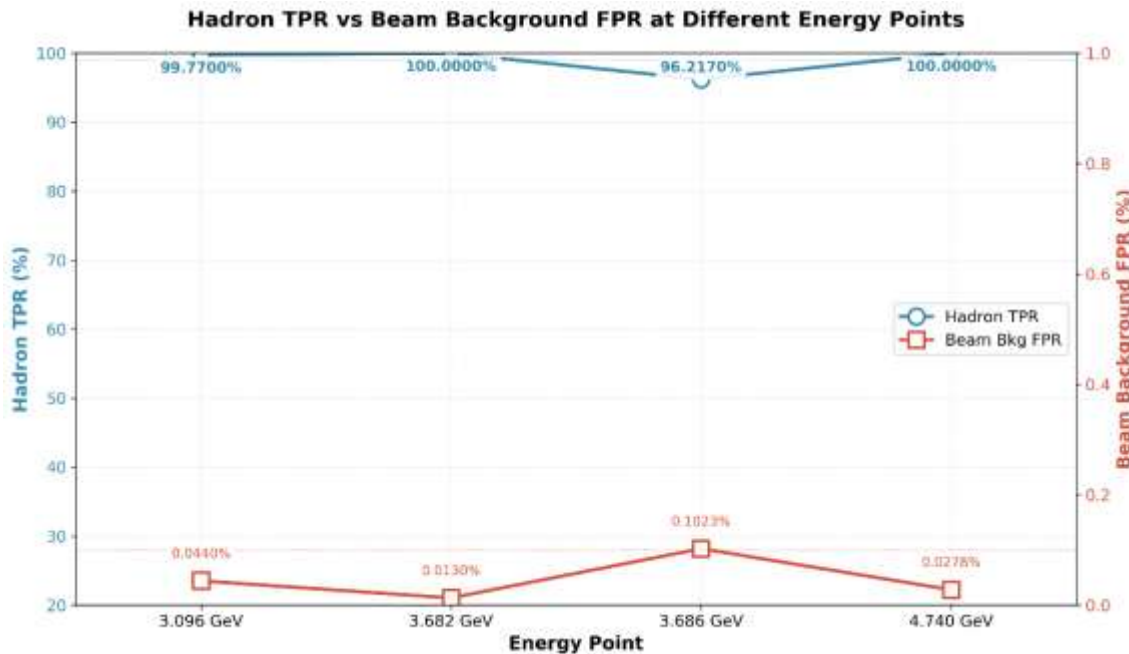


	FPR(%)
Traditional Method	0.11
NN model	0.044

- The neural network outperforms traditional methods in background suppression



- 3682\3686\4740 Beam Background + J/psi Hadron:



- 500w events as background for each energy point

- The model demonstrates reasonable generalization across different energy points

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 |
  +-----+-----+-----+-----+-----+

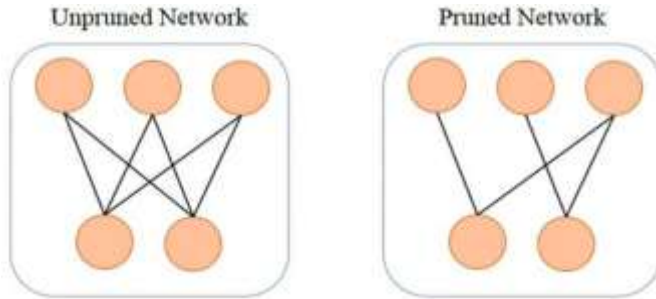
* Summary:
+-----+-----+-----+-----+-----+
| Name | BRAM_18K | DSP48E | FF | LUT | URAM |
+-----+-----+-----+-----+-----+
| DSP | - | - | - | - | - |
| Expression | - | - | 0 | 6 | - |
| FIFO | - | - | - | - | - |
| Instance | 3 | 3059 | 5922 | 121460 | - |
| Memory | - | - | - | - | - |
| Multiplexer | - | - | - | 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 |
+-----+-----+-----+-----+-----+
```

We hope:  
 Latency < 500 ns   
 Utilization < 50%

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

Need to optimize!

## 1、 Pruned



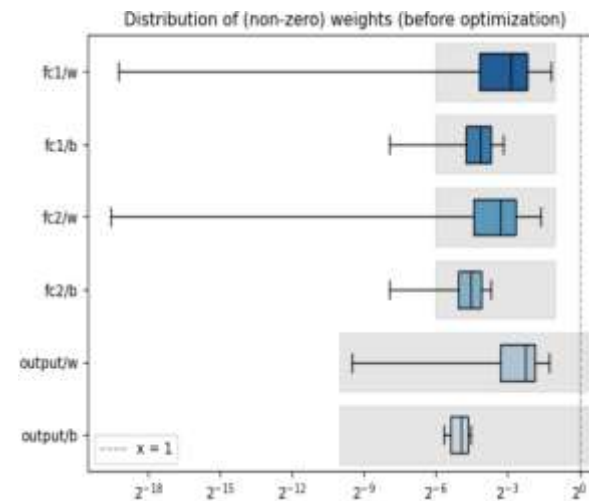
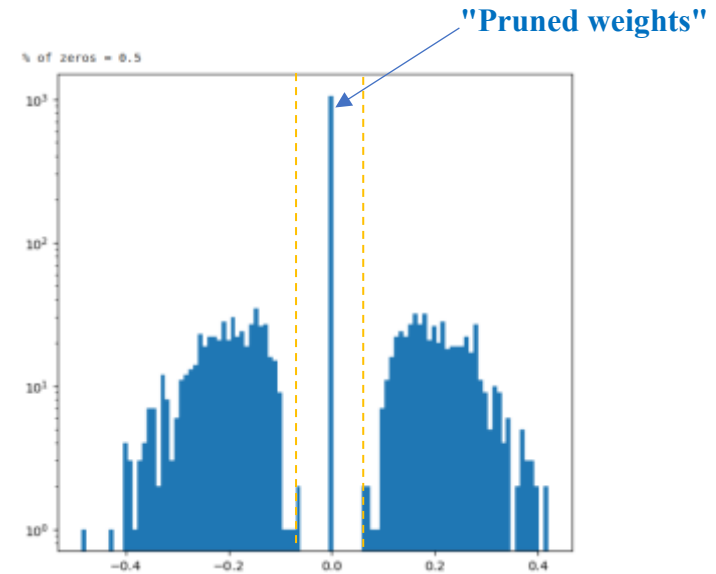
- Remove the links with lower weights.

## 2、 Precision adjustment

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



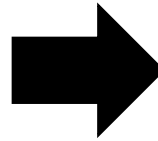
Two hidden layers : (6, 0)  
Output layer : (16, 6)



## 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

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

```
+ Timing:
```

```
* Summary:
```

Clock	Target	Estimated	Uncertainty
ap_clk	5.00 ns	4.319 ns	0.62 ns

```
+ Latency:
```

```
* Summary:
```

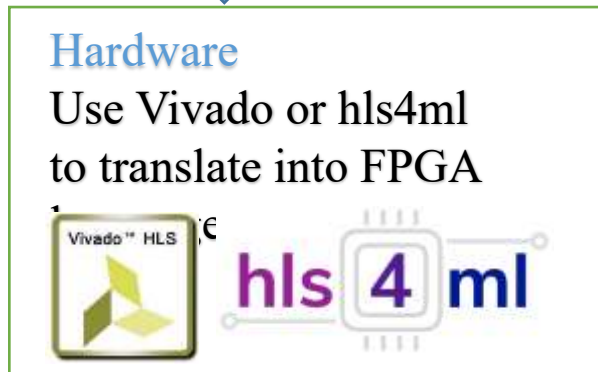
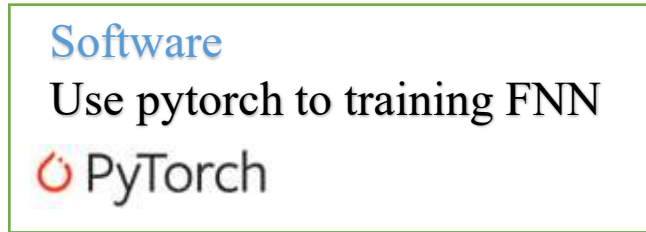
Latency (cycles)		Latency (absolute)		Interval		Pipeline
min	max	min	max	min	max	Type
7	7	35.000 ns	35.000 ns	1	1	function



- 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 evaluated the model performance at high energy points, and also tested its background rejection capability and generalization using random trigger data.
- 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**.



## Next to do:

- Optimization of the results for high-energy-point data.
- build the model using lower-level information(Such as the hit information from the MDC).
- Attempting offline hardware testing on the FPGA.
- **Implement new trigger logic in BESIII**



**Thank you !**



## Control Sample Selection:

$$|\cos\theta| < 0.93$$

$$|dr| < 10 \text{ cm}$$

$$|dz| < 1 \text{ cm}$$

## 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  $170^\circ$ .

## Bhabha Selection:

1、 Two EMC clusters are required to have an opening angle larger than  $166^\circ$ .

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

3、 MDC opening angle  $\geq 175^\circ$ .

## Dimuon Selection:

1、 MDC opening angle  $\geq 178^\circ$ .

2、 For each track,  $P < 2 \text{ GeV}/c$ ,  $E < 0.7 \text{ GeV}$ .

3、 The four-momentum ( $E/c, P_x, P_y, P_z$ ) 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



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

GTL	BESIII Work		My work	
	2-prong(%)	4-prong(%)	2-prong(%)	4-prong(%)
0	99.64 ± 0.01	99.97	99.03 ± 0.01	99.94
1	98.01 <sup>+0.03</sup> <sub>-0.02</sub>	99.63 <sup>+0.01</sup> <sub>-0.02</sub>	97.03 ± 0.02	99.50 ± 0.01
7	89.88 ± 0.04	93.25 <sup>+0.03</sup> <sub>-0.04</sub>	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 <sup>+0.05</sup> <sub>-0.06</sub>	77.87 ± 0.06	77.22 ± 0.06	78.87 ± 0.06
20	87.81 <sup>+0.05</sup> <sub>-0.06</sub>	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 <sup>+0.05</sup> <sub>-0.06</sub>	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 than 0.01%)



- Random Trigger Data : Use Channel 10

CH09	NClus.GE.1&& BEtot_ H	For Neutral
CH10	-	Random
CH11	NBTOF.GE.2&& LTrk_ BB	Not used

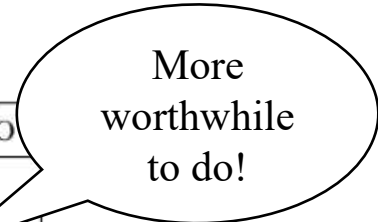
- Testing the trigger rate:  
Not affected by the current trigger system

	Trigger Rate(%)
Hadron	91.56
Beam Bkg	0.18

- Use these data to test the model performance

- High-Energy Point like:4.680Gev

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



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