Quantum Computing and Machine Learning Workshop 2025

Study of CNN Algorithms for PID System in STCF

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Outline

I. Background

II. PID System

III. CNN Algorithms

IV. π/K Identification Performance

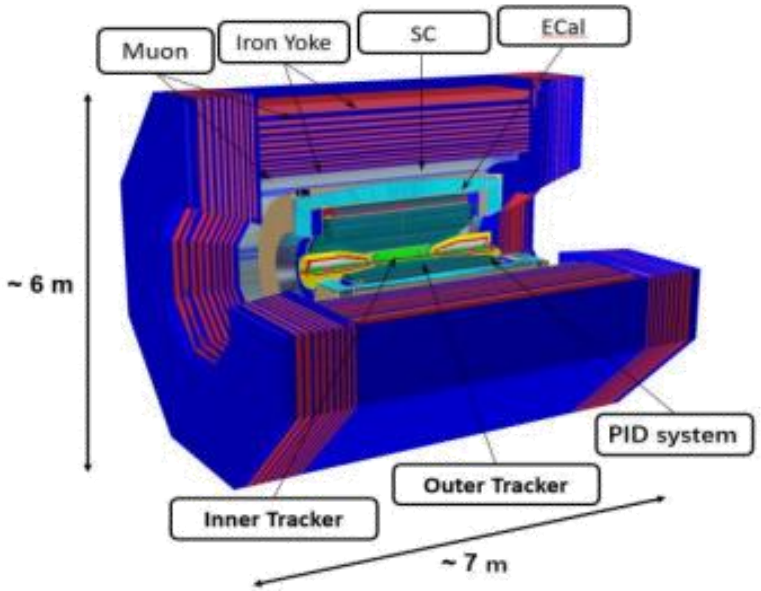
V. Summary

1 Super Tau-Charm Facility

Super Tau-Charm Facility（STCF）is a new generation of positron-electron colliders proposed in China

- Center-of-Mass Energy 2-7 GeV
- Peak luminosity 0.5×10^{35} $cm^{-2}s^{-1}$
- higher-luminosity upgrades and beam polarization in the future
- charm quarks and τ leptons
- Non-perturbative strong interactions and hadronic structure
- Search for new physics

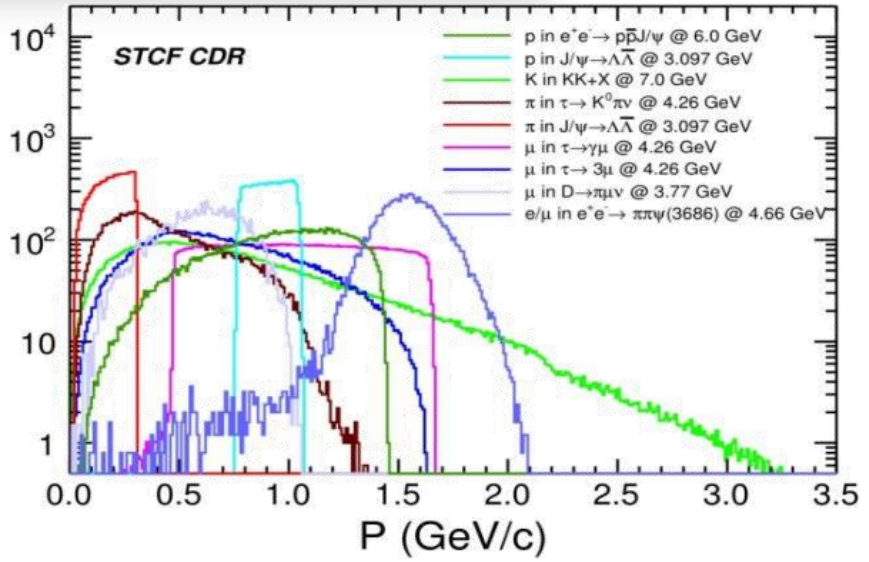
Tracking system(ITK 和 MDC)，Particle identification system(PID)，Electromagnetic calorimeter(ECAL)，Superconducting solenoid（SCS），Muon detector (MUD)



1 PID Requirements

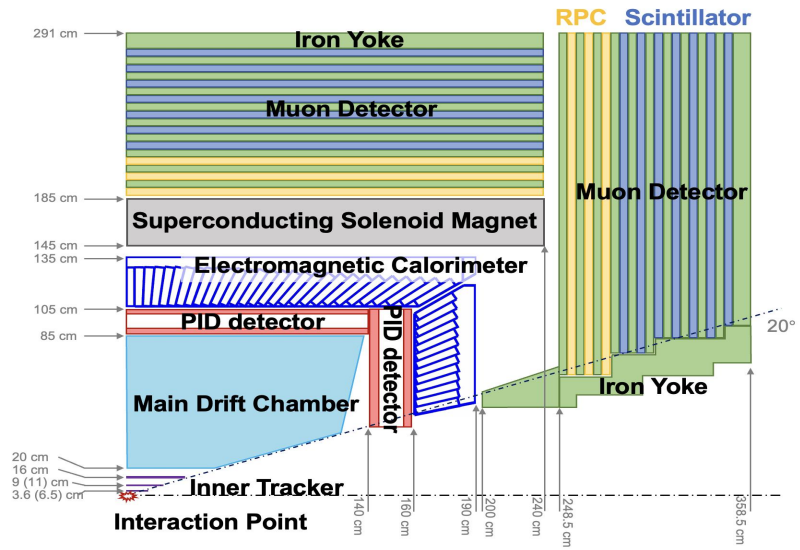
Particle identification（PID）is an important tool for conducting physics research in collider experiments.

- p < 2 GeV/c, π /K misidentification rate < 2%, identification efficiency > 97%
- p > 0.7GeV/c, μ identification efficiency > 95%;
- 0.5GeV/c < p < 0.7GeV/c, μ identification efficiency > 70%
- Good neutral particle identification capability



The **PID system** uses two Cherenkov detector technologies:

- Endcap：a time-of-flight detector based on the detection of the internal total-reflected Cherenkov light（DTOF）
- Barrel：a Ringing Imaging Cherenkov detector（RICH）/（BTOF）



1 Machine learning-based PID Technology

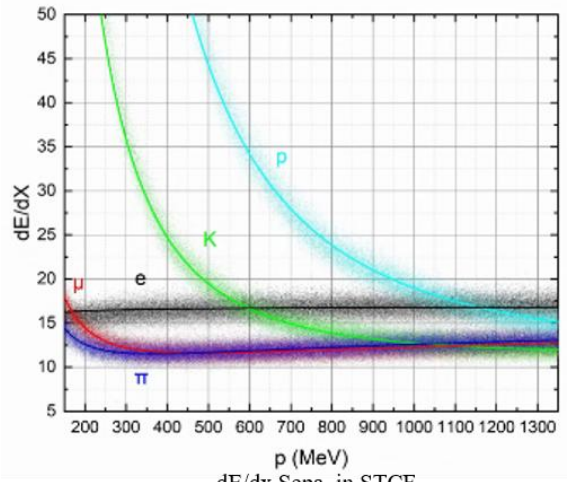
Relying solely on information from a single sub detector makes it challenging to accurately distinguish particles

Machine learning: excellent performance in PID by extracting useful features in high-dimensional spaces

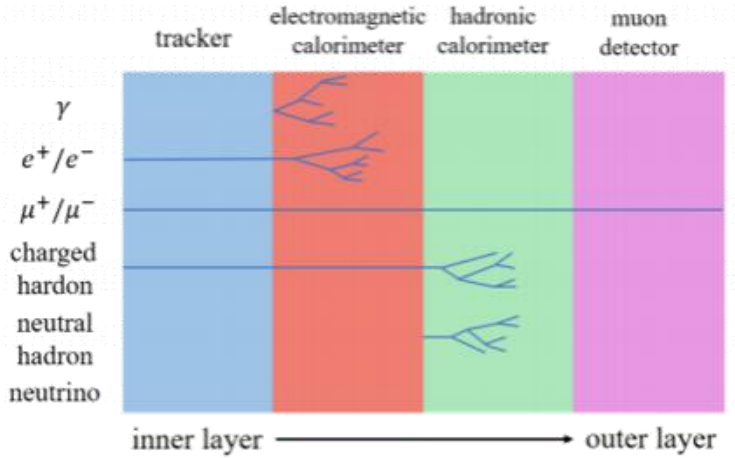
- Combining information from multiple sub detectors
- Fully use the raw detector response

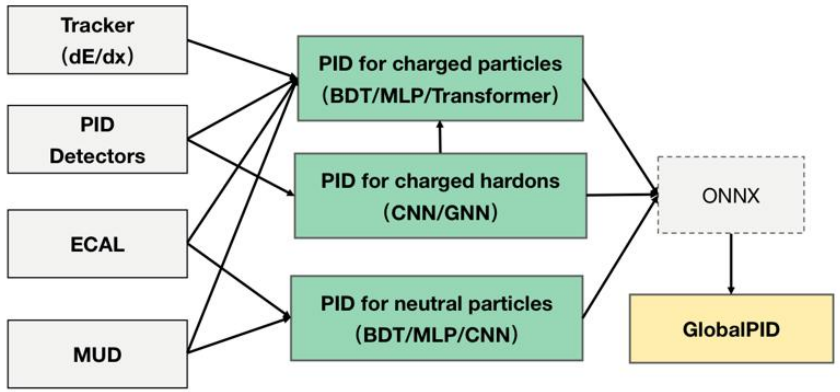
Customized ML-based PID algorithms, deployable in OSCAR via ONNX.

This work develops a CNN for π/K identification using raw detector responses and track-level features to meet STCF PID requirements.



dE/dx Sepa. in STCF

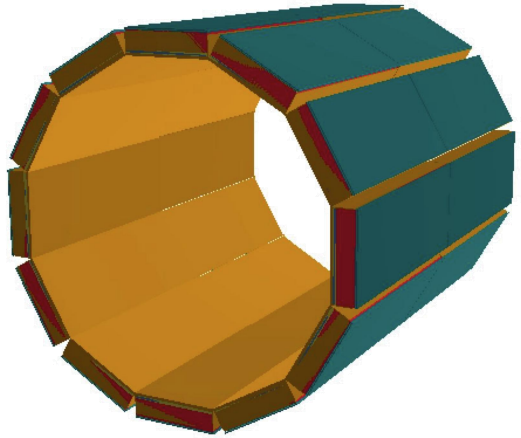


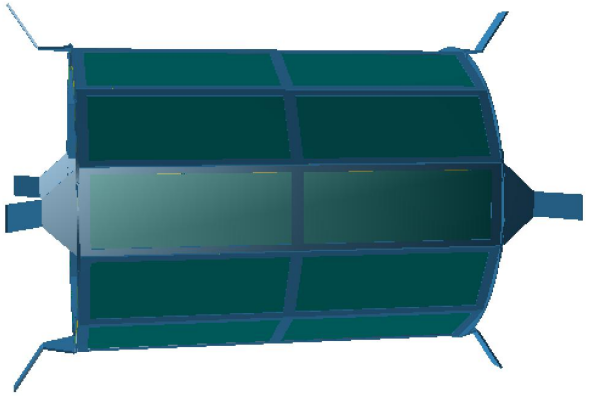


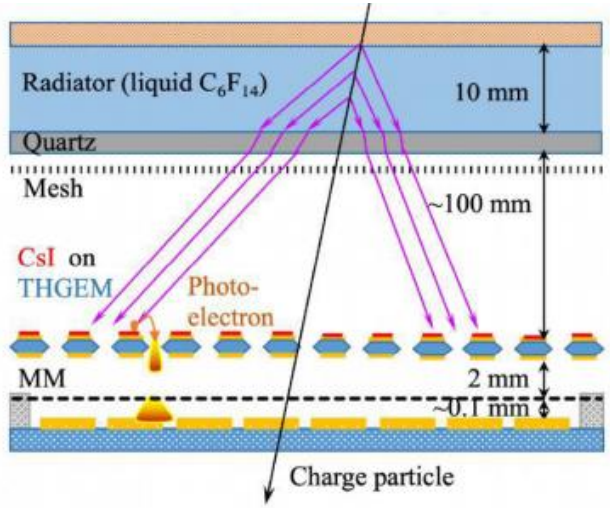
2 PID System —— RICH

The barrel PID detector of the STCF is a Ring Imaging Cherenkov(RICH) Detector.

- Composed of 12 identical modules, covering a polar angle range from 36° to 144°
- Radiator: C_6F_{14} and the quartz
- The particle and Cherenkov photons propagate forward to the CsI photocathode, and are finally imaged on PMT

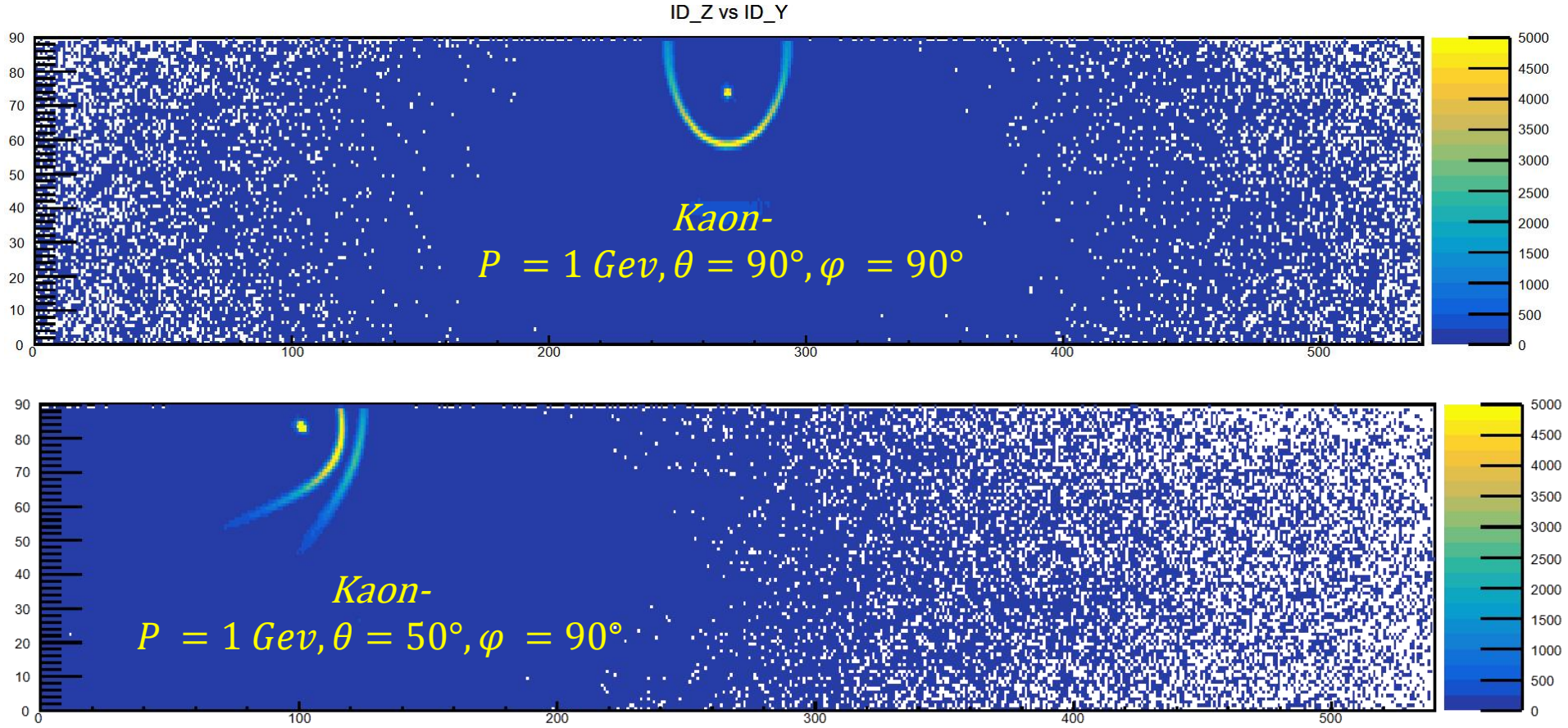






2 PID System——RICH

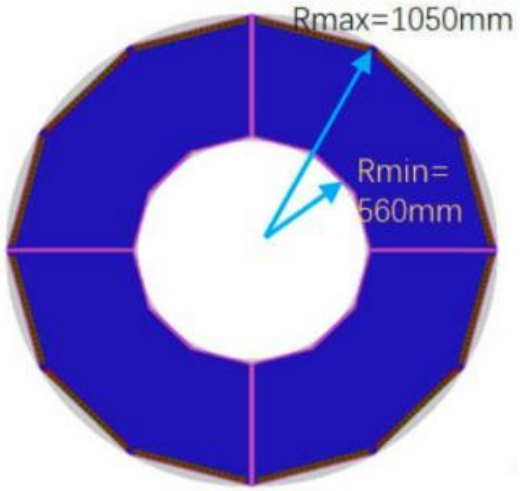
- The 2.7 × 0.45 m² anode plane is segmented into readout channels with a pixel size of 5 × 5 mm²
- A 90 × 540 2D image is constructed based on the PMT channels that receive Cherenkov photons
- Cherenkov rings exhibit shapes such as quasi-elliptical、quasi-hyperbolic patterns

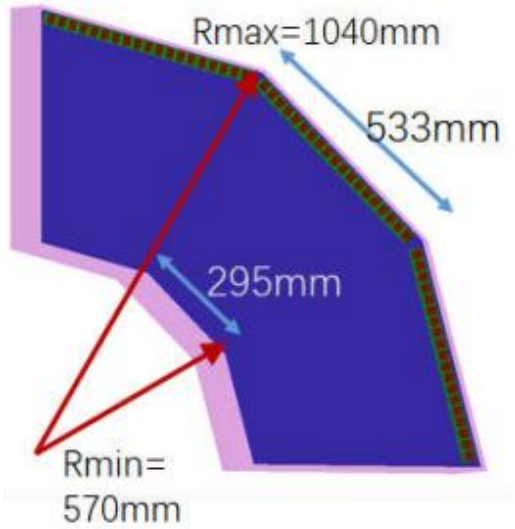


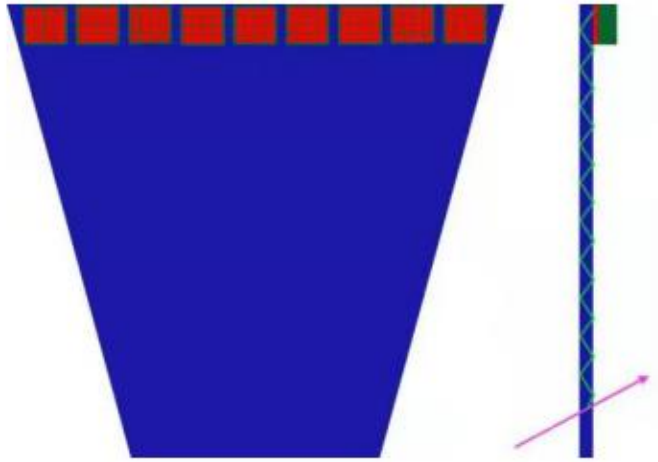
2 PID System——DTOF

As the endcap PID detector of the STCF, the DTOF employs a technology based on the detection of internally total-reflected Cherenkov light

- DTOF consists of two identical discs, containing multiple sectors
- covering in polar angles of ~20-36°
- synthetic fused silica serves as the Cherenkov radiator to generate photons
- an array of MCP-PMTs are optically coupled to the radiator along the outer side to detect the Cherenkov photons

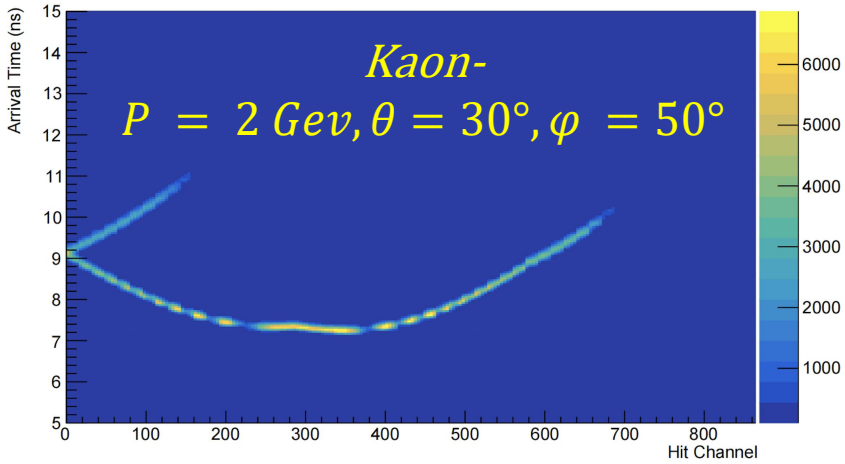


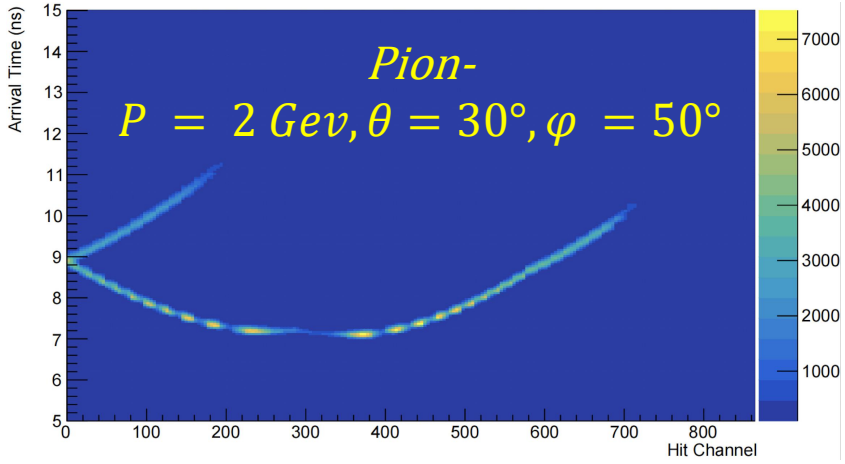




2 PID System——DTOF

Using the original response from the detector, construct a two-dimensional pixel map:





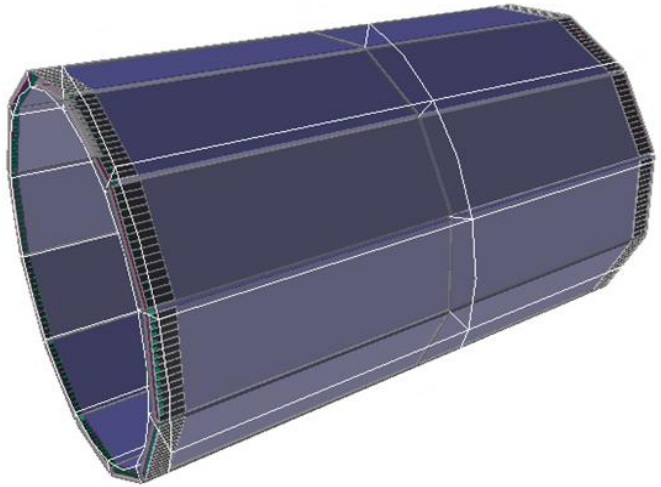
- X-label: Hit channels of Cherenkov photons received by the PMT
- Y-label: Arrival time of Cherenkov photons received by the PMT
- Value: Number of photons in the bin

- $0 \leq 4*\text{Channel\_x} + \text{Channel\_y} \leq 768$
- $5 \leq$ Time ≤ 20 ns (Time resolution： 50 ps)
- Bin number: Channel * Time = 192 * 300

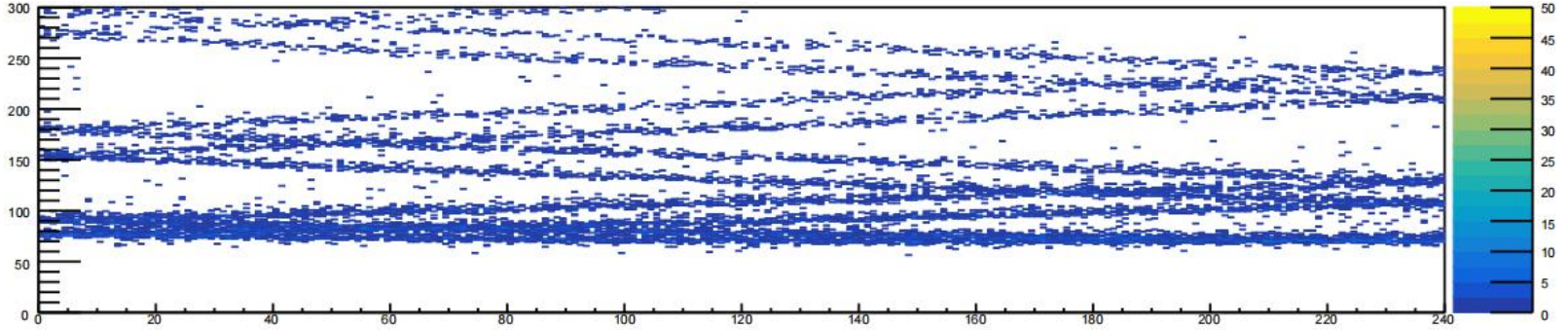
2 PID System——BTOF

BTOF as an alternative barrel design, adopts a principle similar to the endcap DTOF.

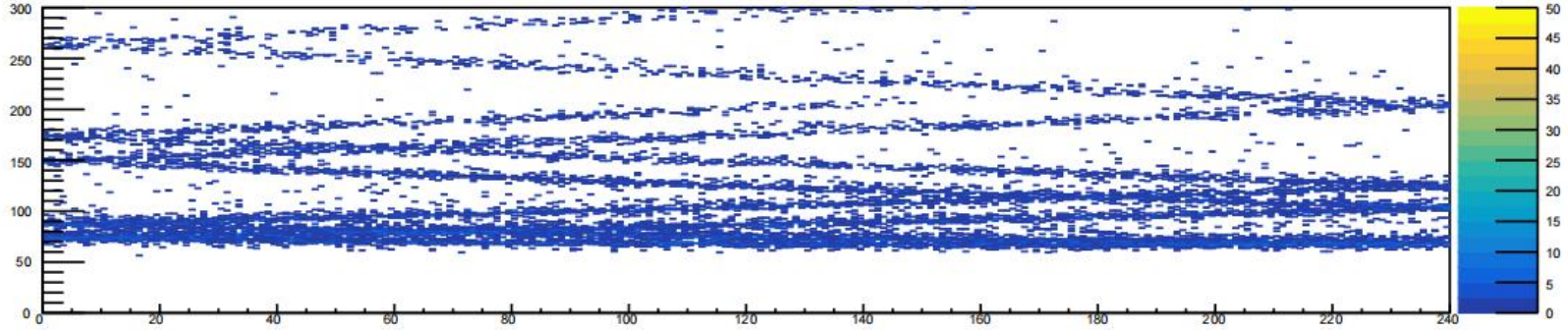
- 12 modules， Covering a polar angle range from 36° to 144°
- On the outer side of the quartz, 15 MCP-PMTs (each with 1 × 16 pixels) are arranged
- 5ns < Time < 20ns (Time resolution 50 ps)
- Bin number: Channel * Time = 240*300



Kaon- $P = 2\,Gev, \theta = 66°, \varphi = 50°$



Pion- $P = 2\,Gev, \theta = 66°, \varphi = 50°$

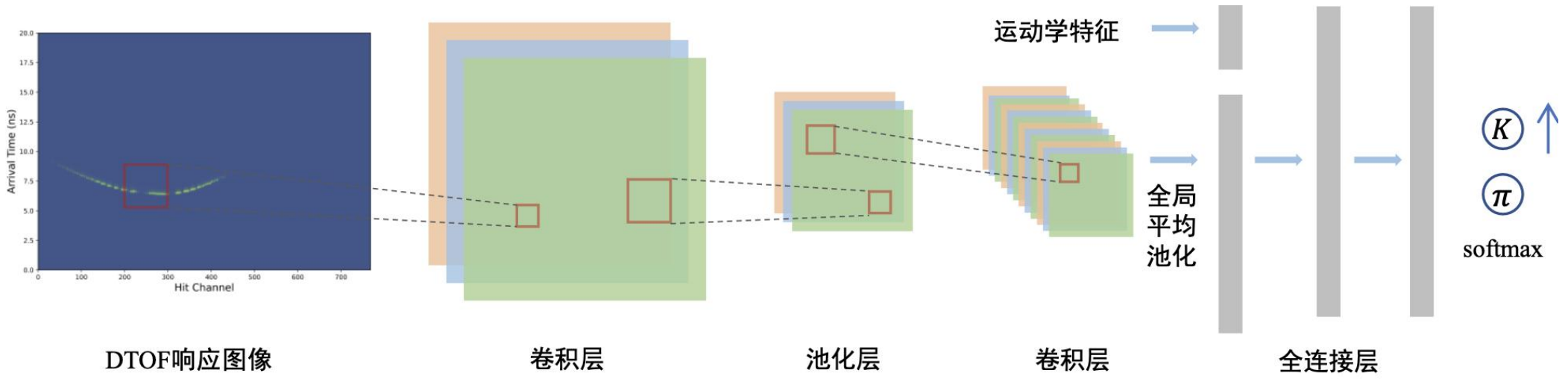


3 Data Sample

OSCAR (2.6.2) simulates the digitized MC samples for Pion/Kaon

- $p \in$ 0.3-2.4 GeV/c
- barrel（RICH and BTOF polar angel range from 36°~90°）
- endcap（DTOF polar angle from 20°~36°）

- Select single-module, single-track events
- Input：2D images + 3D hit position & momentum (from Tracking system)



3 CNN Model: EfficientNetV2

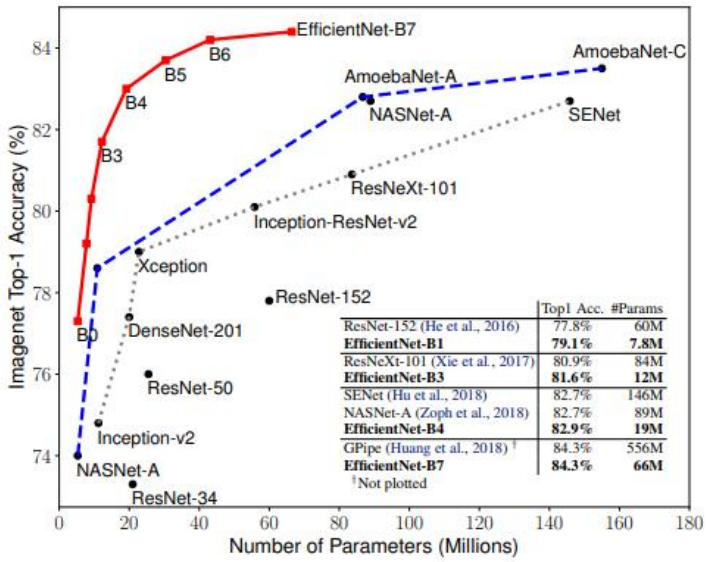
Google EfficientNet

Version1: Use a composite coefficient to uniformly scale the depth, width, and input image of the network
Version2: More lightweight, it reduces the number of parameters, thereby accelerating computation speed

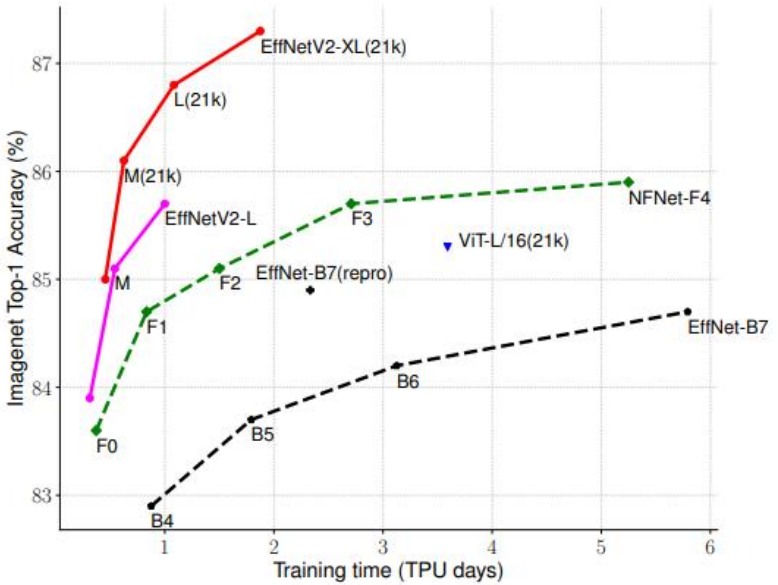
EfficientNetV2-S (customized for DTOF)

阶段	操作类型	步长	输出通道	层数
图像主干路径：DTOF 输入图像（尺寸 300 × 192）				
1	3 × 3 卷积	2	24	1
2	Fused-MBConv1_3 × 3	1	24	2
3	Fused-MBConv4_3 × 3	2	48	4
4	Fused-MBConv4_3 × 3	2	64	4
5	MBConv4_3 × 3	2	128	6
6	MBConv6_3 × 3	1	160	9
7	MBConv6_3 × 3	2	256	15
8	1 × 1 卷积 + GAP	-	1280	1
辅助路径：粒子运动学输入向量（5 维）				
8	全连接映射	-	32	1
多模态融合与分类头				
9	拼接 + 全连接层	-	256	1
10	π / K 概率输出	-	2	1

V1 Accuracy

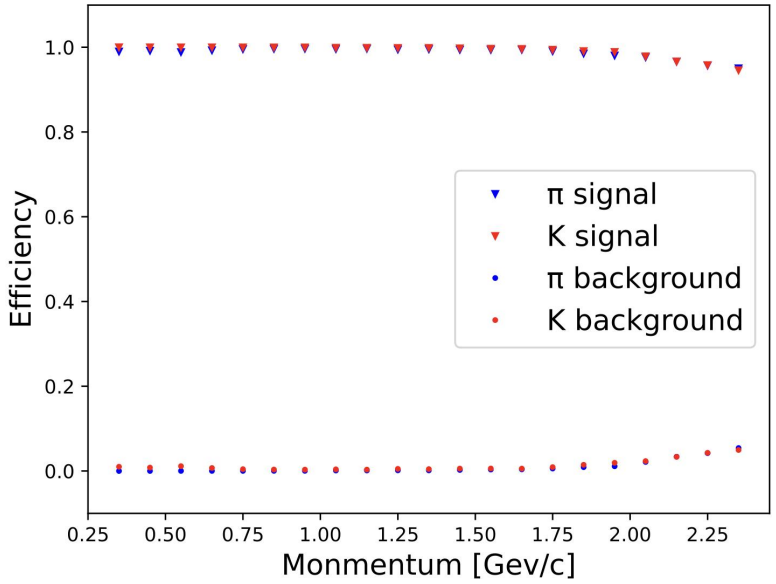


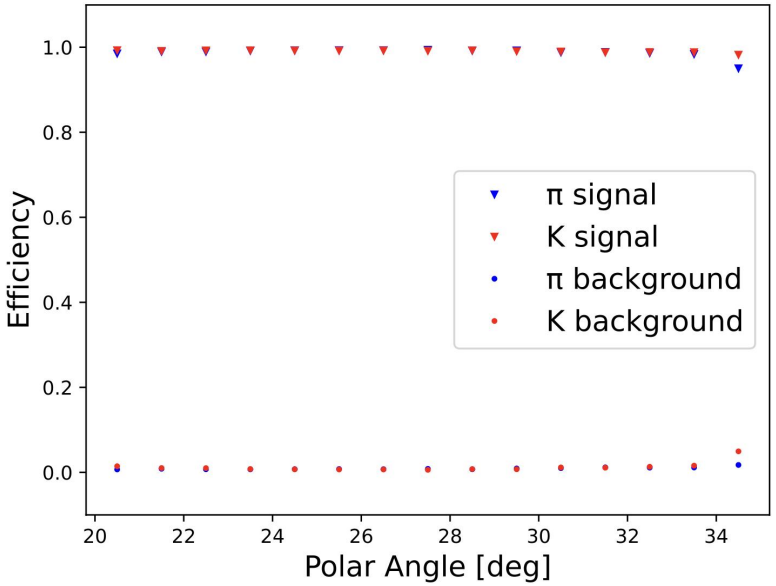
V2 Improvement



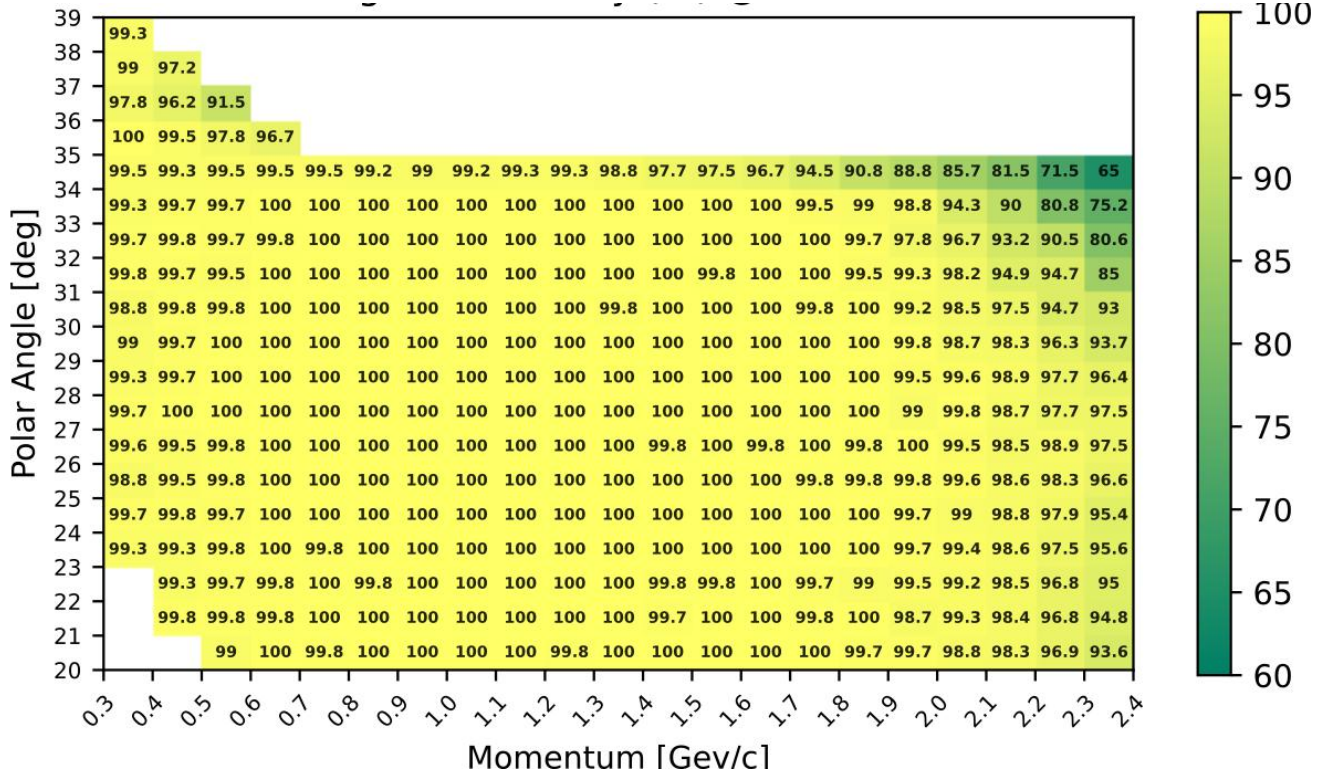
4 CNN π/k PID Performance——DTOF

The signal efficiency and background misidentification rate for pion/kaon across momentum and polar angle



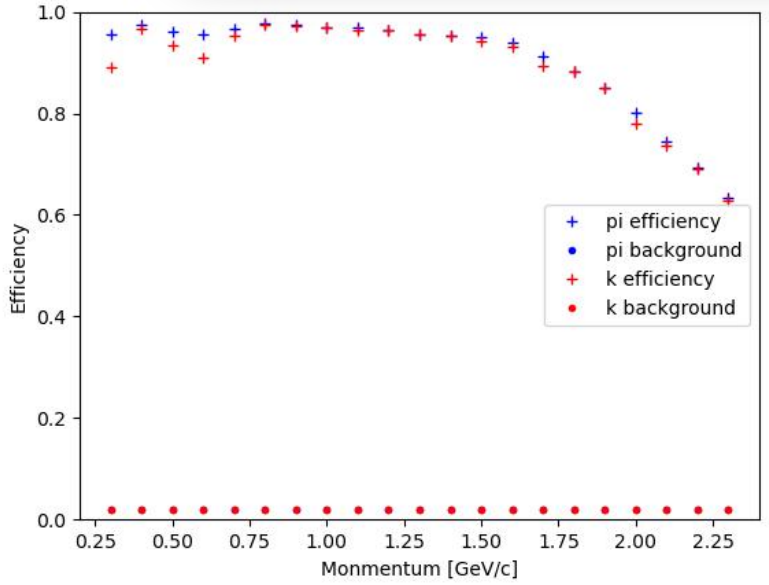


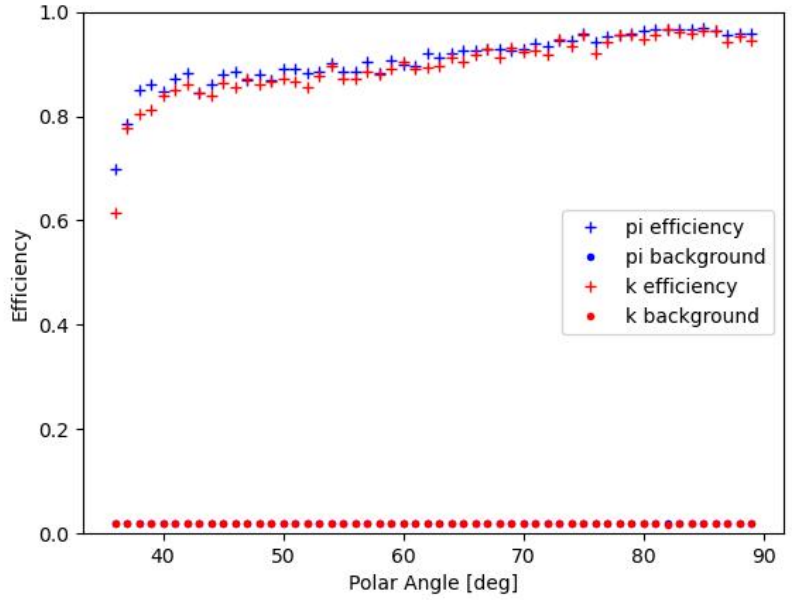
adjust thresholds on the predicted probabilities to control the misid rate of kaons < 2%:



- Meet the STCF requirements for π/K identification (p<2Gev/c, eff >97%)
- The performance in the high momentum and large angle shows a decline

4 CNN π/k PID Performance——RICH (preliminary)





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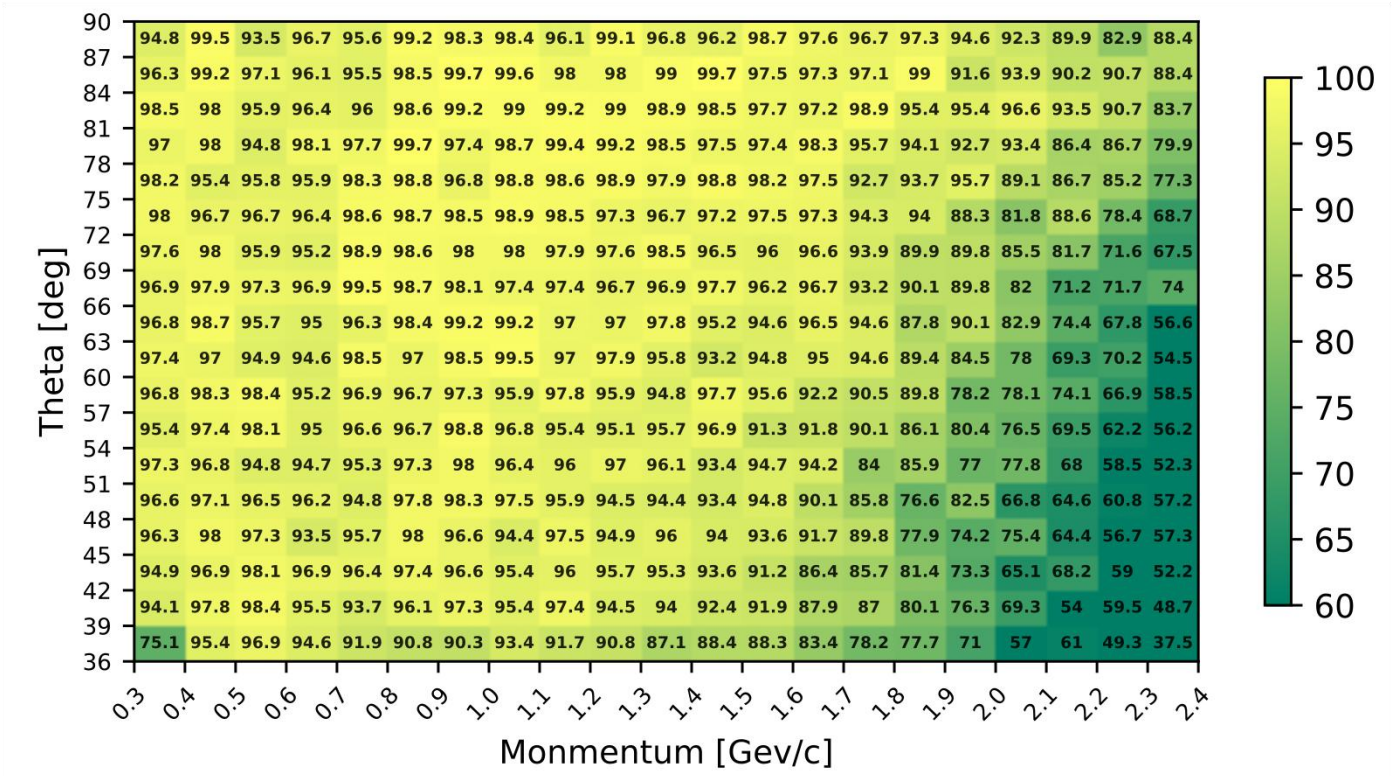
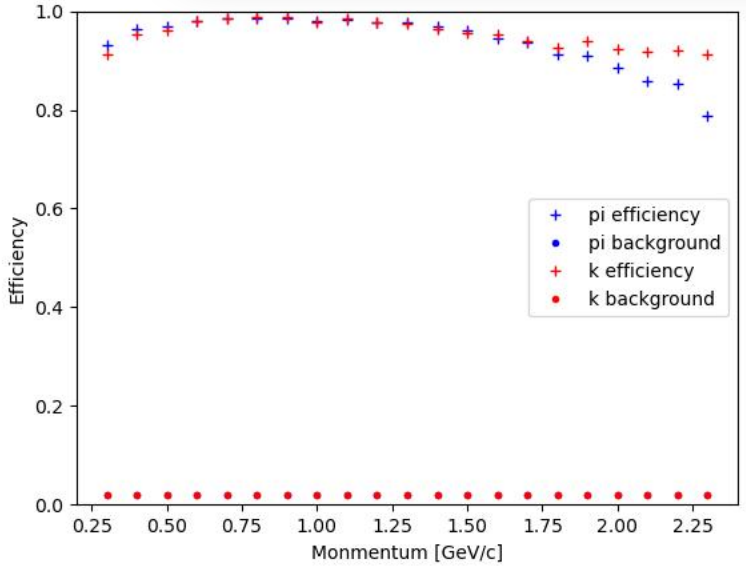
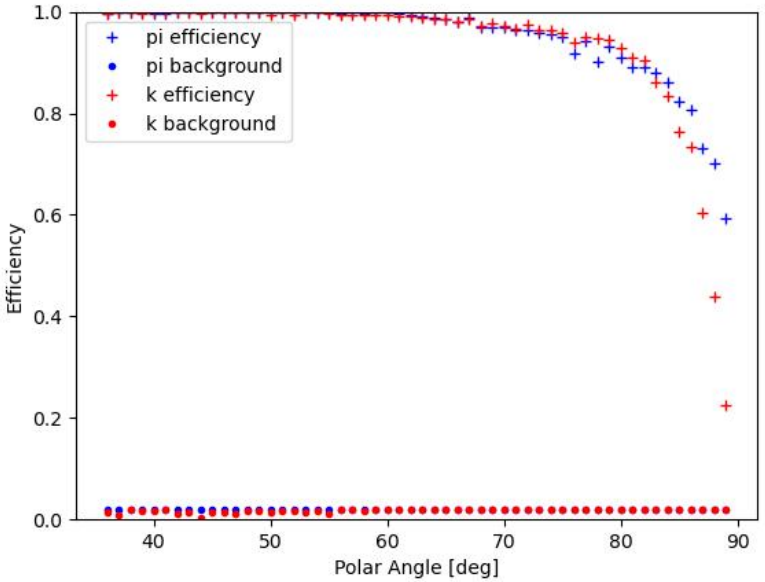


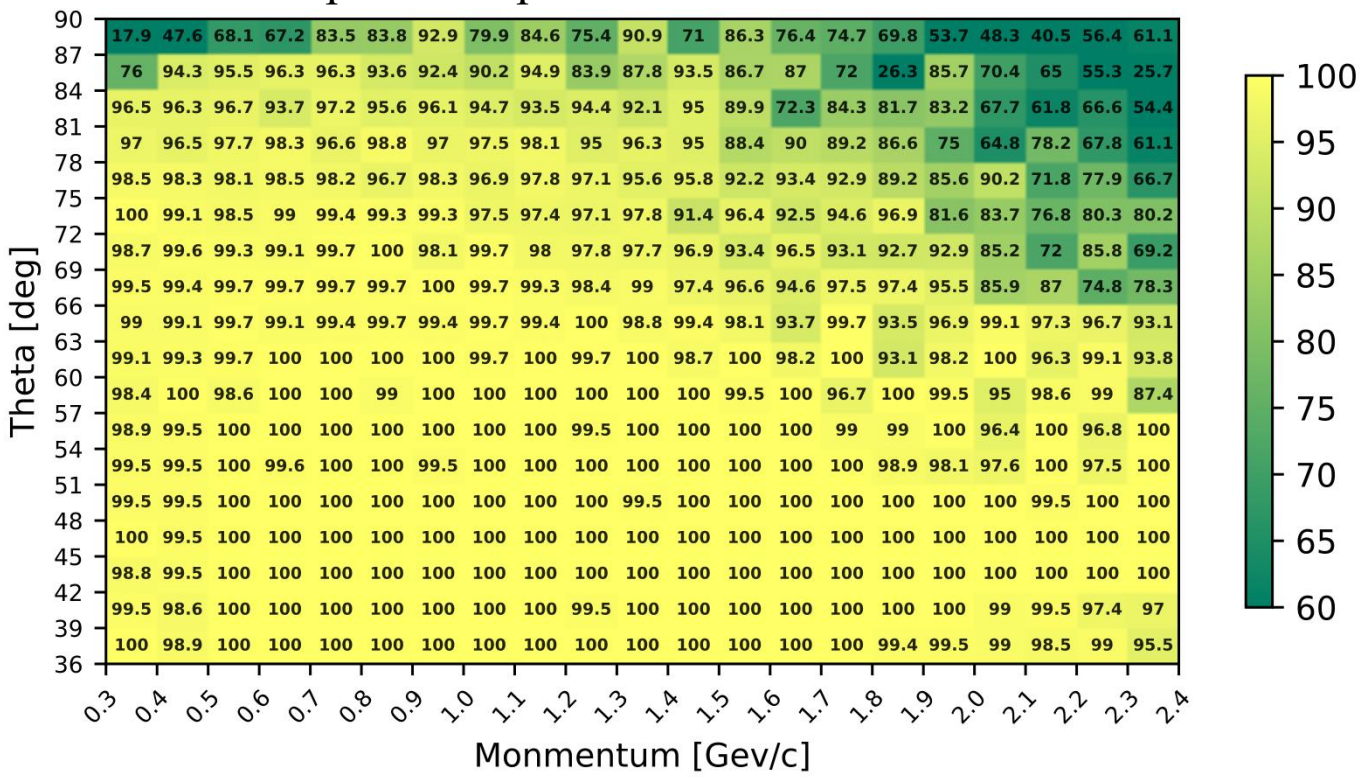
- CNN (DTOF-like): 90×540 2D image + track info (momentum, position)
- The performance in the high momentum and small angle shows a decline

4 CNN π/k PID Performance——BTOF (preliminary)





adjust thresholds on the predicted probabilities to control the misid rate of kaons < 2%:



- CNN (DTOF-like): 300×240 2D image + track info (momentum, position)
- The performance in the high momentum and large angle shows a decline

5 Summary

- A CNN model has been developed for the STCF PID system, using raw detector responses to construct structured pixel images, combined with track-level kinematic features for training.
- The current DTOF π/K identification performance meets STCF requirements, and the end-to-end CNN reconstruction algorithm can be extended to five-class classification.
- The CNN techniques used in DTOF have been applied to RICH and BTOF, with preliminary results obtained.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Thanks