Recovery of merged π^0's from ECL images of the Belle II detector using CNN

Naveen Kumar Baghel[1], Dr. Vishal Bhardwaj[2]

Department of Physical Sciences, IISER Mohali[1,2]

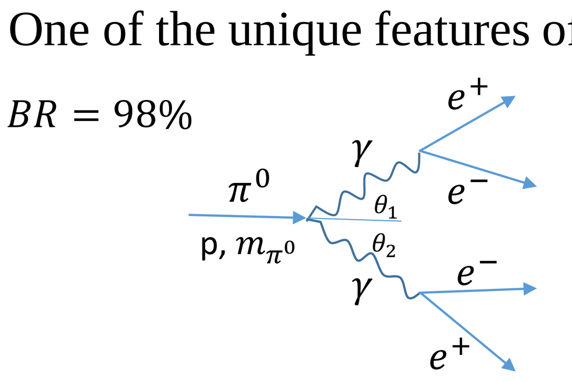
Physics Overview & Motivation

- Approximately one-third of the ***B***-decay products consist of π^0's or other neutral particles that generate photons across a broad energy spectrum ranging from 20 MeV to 4 GeV [1].
- Rare **B** decays are crucial for CP measurements, search for new physics beyond the Standard Model, and also for understanding the internal dynamics of the **B** mesons [2].
- The study of rare decays given in table involve π^0 and γ.

Rare Decays	$D^0 \to \gamma\gamma$	$D^0 \to \rho^0\gamma$	$D^0 \to \phi\gamma$
B.F	8.5×10^{-7}	10^{-5}	10^{-5}
Dominant Background	$D^0 \to K_S^0\pi^0$	$D^0 \to \pi^0\pi^0$	$D^0 \to \phi\pi^0$
B.F	1.24×10^{-2}	8.26×10^{-4}	1.17×10^{-3}

Ref R.L. Workman et al. (Particle Data group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

- One of the unique features of the π^0 meson is its decay mode.

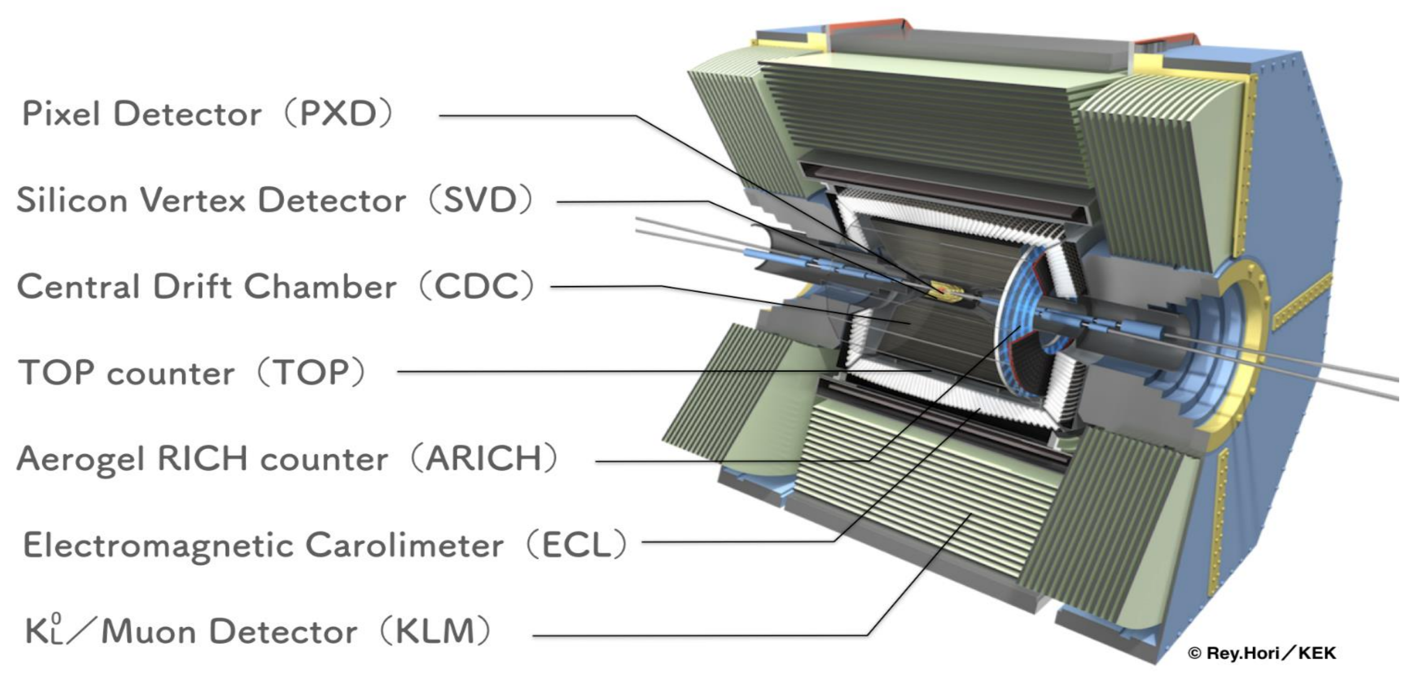


$$\cos\theta = \frac{p_{\pi^0}}{\sqrt{m_{\pi^0} + p_{\pi^0}^2}}$$

Where $\theta = \theta_1 + \theta_2$

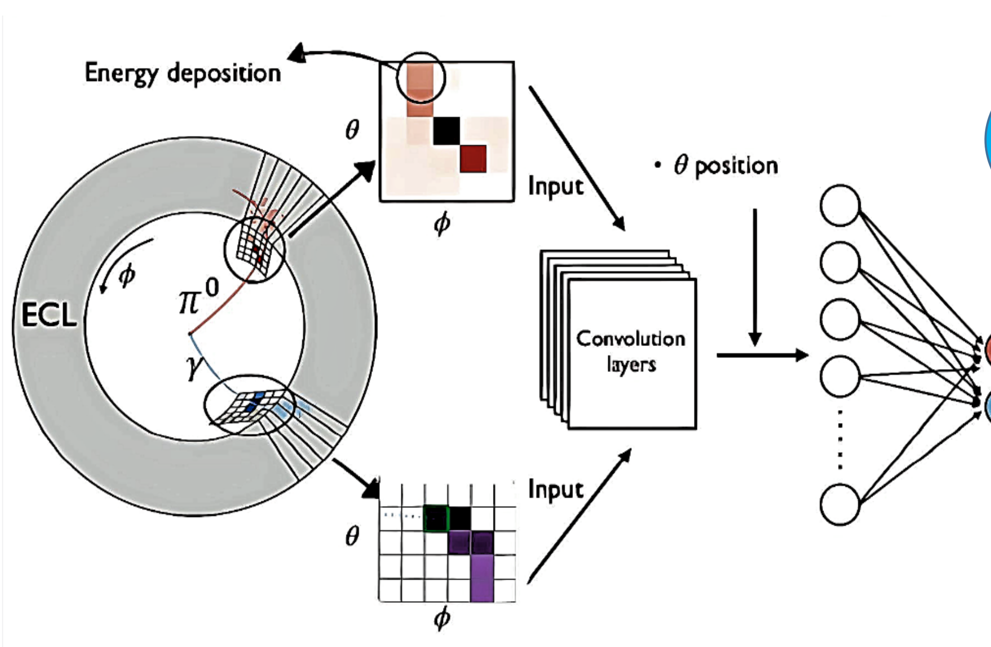
- From the relation between angular separation and momentum of the pion (π^0), the decay angle almost approaches less than 7° for the high momentum range i.e, above 2.5 GeV/c in Belle II.
- So at high momentum range, both the gammas of the π^0 appears to be merged, and therefore shower of π^0 look like a shower of one gamma to a detector, and this is the domain of our problem for the thesis.
- In conclusion, to conduct various B physics analyses for the Belle II experiment, it is crucial to distinguish neutral hadrons such as π^0's that imitate γ.

The Belle II Detector



- Belle II is located at the asymmetric SuperKEKB e^+e^- collider in Tsukuba, Japan.
- It collects data mostly at $\gamma(4S)$ resonance.
- The Electromagnetic Calorimeter (ECL) is critical to identify neutral particles by providing optimal resolution in reconstructing energy depositions.
- The ECL consists of total 8736 Cs(TI) crystals in three regions namely Forward Endcap, Barrel, and Backward Endcap with θ coverage of 12.1° to 31.36°, 32.2° to 128.7°, and 131.5° to 155.03° respectively [1].

Methodology



ML Model Used: Convolution Neural Network (CNN)

- Our approach involves direct identification of a π^0 shower that resembles a γ shower without any use of reconstruction information.
- Raw energy information from crystals and the position of the highest energy crystal (seed crystal) were used.
- This energy data was taken as pixel intensities to create an image structure per shower per event.
- A machine learning model, specifically a CNN, was then deployed using this image structure.

Data Generation & Analysis

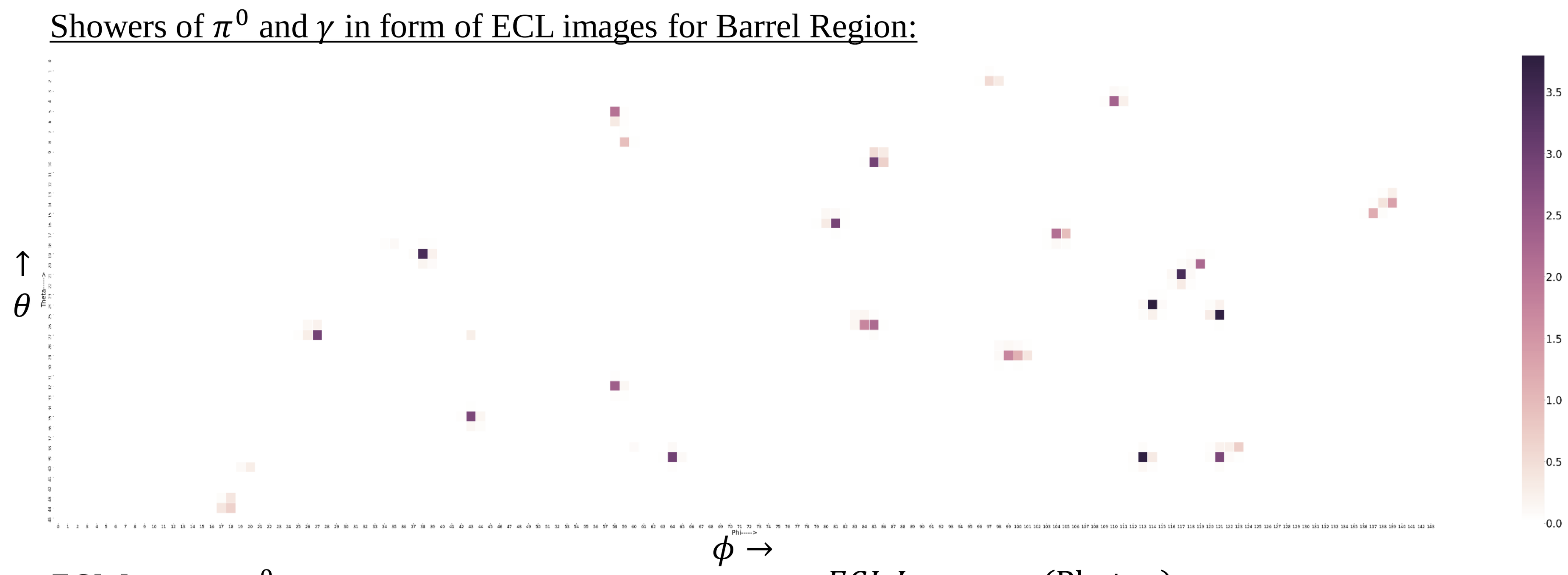
- Belle II Analysis Software Framework (basf2) is used in all aspects of the data-processing chain at Belle II.
- The framework is divided into packages, each covering different aspects of data processing and these packages contain libraries, modules and data-objects.

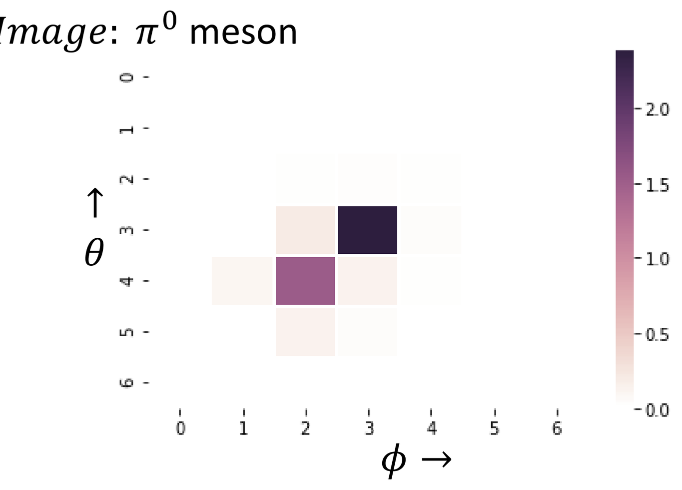
Event Generation → Simulation → Reconstruction → Output (mDST)

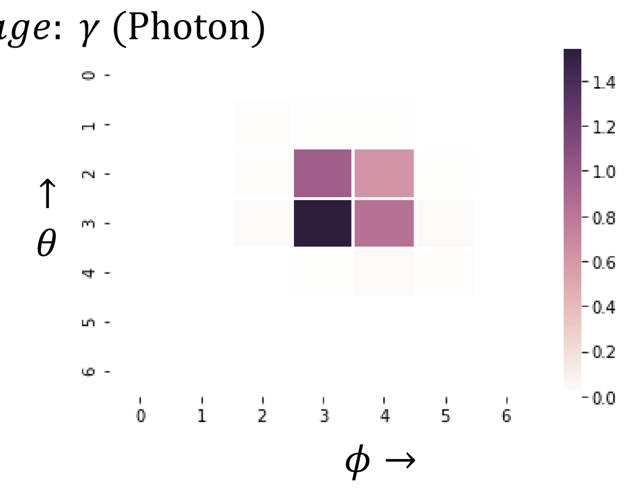
- Particle Gun Module
- Parameters Used: {'nTracks': 0, 'momentum': [2.5,4.0], 'phi': [-180,180], 'theta': [33,126]}

Note:- *Due to the geometry of ECL , This study work only focuses on the barrel region as endcaps are very irregular.*

Showers of π^0 and γ in form of ECL images for Barrel Region:







CNN Architecture & Implementation

- 10^4 single π^0 and γ candidates are generated with uniform distribution of transverse momentum between 2.5 GeV and 4.0 GeV from particle gun module.
- Around the Seed crystal of each shower per candidate per event, a window of 7*7 crystal with the measured deposited energy was selected to give input into CNNs.
- For training ~7.0×10^3 , ~1.5×10^3 for testing, and ~1.5×10^3 for validation, particle gun events of each candidates in the form 7*7 pixel images are used in the model.

CNN Parameters

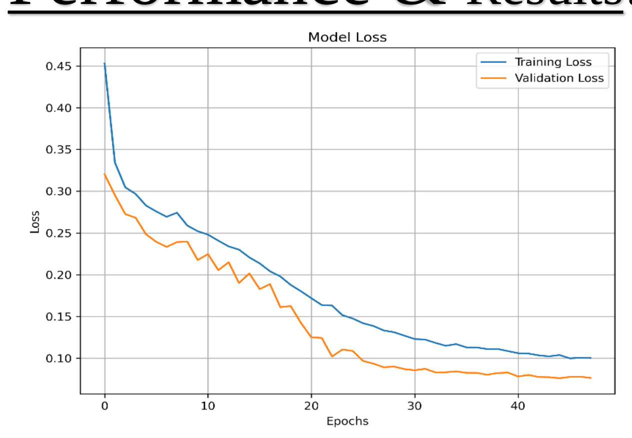
- Input shape: 7*7
- Kernel: (3,3), stride: (1,1), Padding: (1,1)
- No. of Fully Connected (FC) layers : 3
- Feature maps: 32 (size: 7*7), 32 (size: 5*5), 64 (size: 3*3)
- Dropout between FC1 and FC2 & FC2 and FC3 : 0.5 & 0.25
- Optimizer: Adam
- Learning rate: 0.001
- Loss: Binary Cross Entropy
- Batch Size: 32

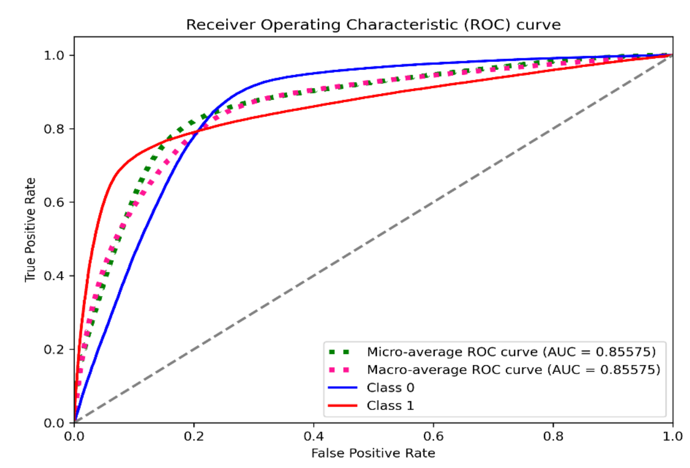
✓ The CNN flexibility and robustness were increased by submitting it to different π^0 and γ circumstances.

✓ The input contains numerous events of both the candidates when the hit is between the edges, corners, and center of the crystals.

Performance & Results:

Metric	Precision	Recall	F1-Score	Support
γ (Label: 0)	0.77	0.88	0.82	98220
π^0 (Label:1)	0.86	0.74	0.80	99958
Accuracy			0.81	198178
Macro Avg.	0.82	0.81	0.81	198178
Weighted Avg.	0.82	0.81	0.81	198178





- Using Monte Carlo samples the CNNs accomplished this task fairly well on a controlled and uncontrolled setup without beam background with an area under the curve (AUC) for the Precision-Recall curve of 0.86.
- The current results show us the scope of ML algorithms to improve the efficiency of π^0 particles with energy deposits in the ECL, which indicates that there is much more information in the 'raw' ECL images compared to currently used expert-engineered features.

Conclusion & Outlook

✓ It is showed that using patterns of energy depositions in the ECL, particle identification can be improved for high momenta π^0 *and* γ.

✓ Also, the CNN performance is superior since it does not rely on ECL cluster reconstruction.

✓ In order to check the model efficiency with the current methods already in basf2, based on reconstruction and likelihood approach , we plan to validate our trained neural network on MC embedded with noise similar to Belle II data. This study is still ongoing.

✓ This study can also be extended to endcaps region of the ECL by putting model into numerous circumstances of π^0 *and* γ (it is tedious but can be done), with some extra variables like shower shape momenta given to feed-forward neural network.

References

[1] Abe, Tetsuo, et al. "Belle II technical design report." *arXiv preprint arXiv:1011.0352* (2010).

[2] Kou, Emi, et al. "The Belle II physics book." *Progress of Theoretical and Experimental Physics* 2019.12 (2019)