Improving Particle Identification in the Belle II TOP detector through Machine Learning

Cecilia Antonioli
University and INFN of Padova

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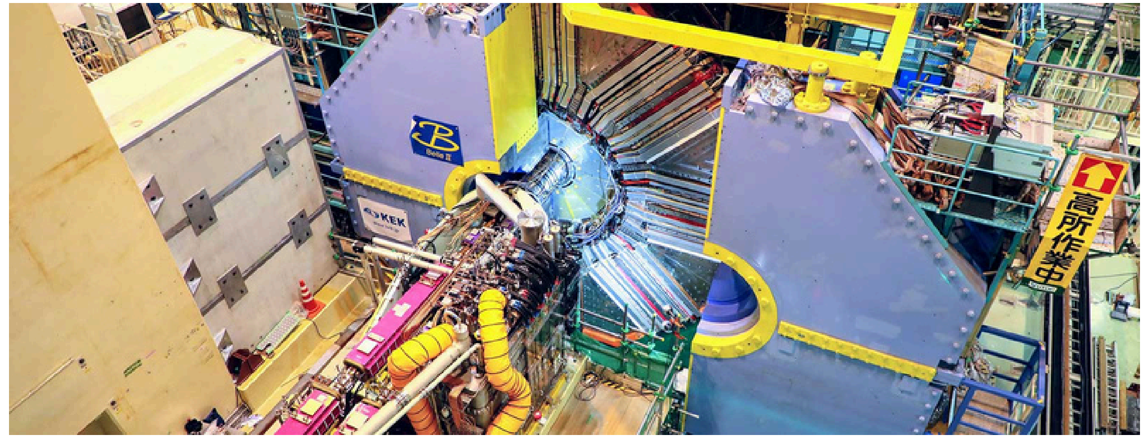
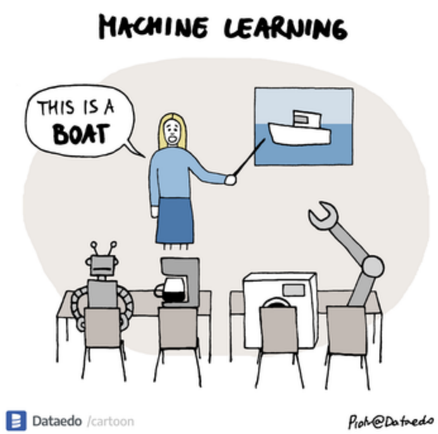
Outline

- Introduction
- Belle II experiment
- TOP counter
- TOP working principle
- TOP PID Likelihood
- TOP PID with Machine Learning





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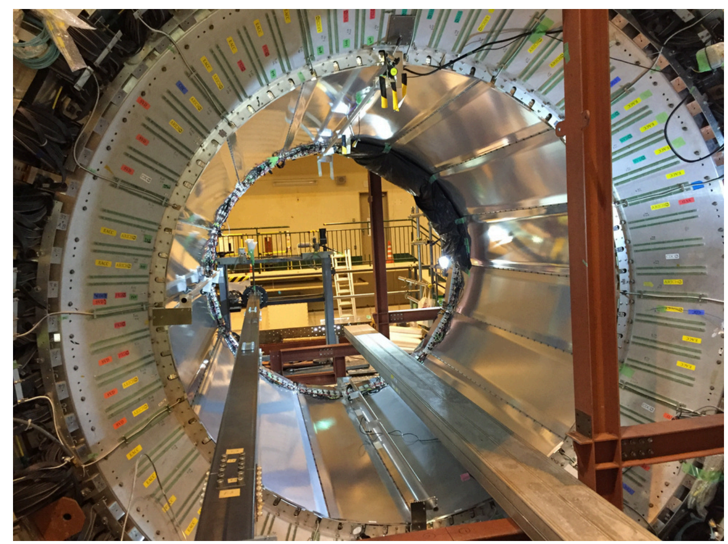


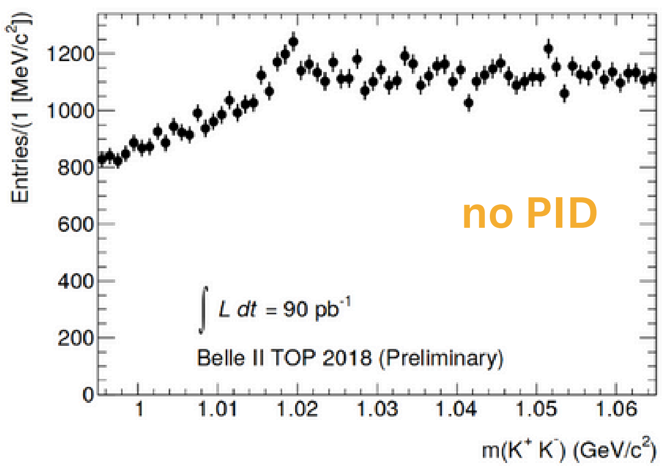
Introduction

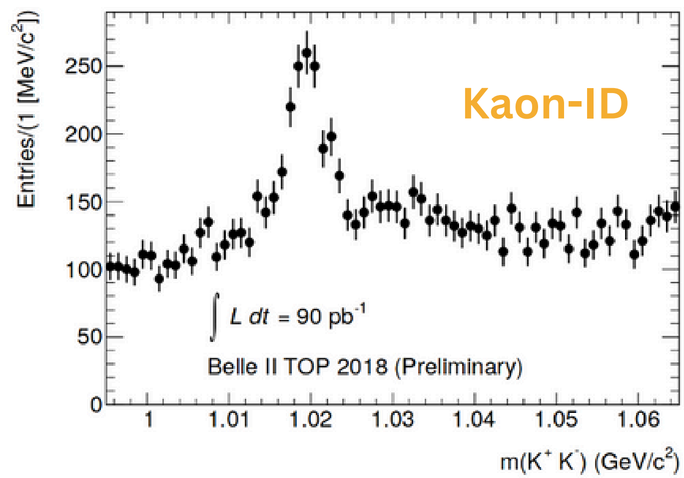
Reliable particle identification (PID) is essential for a flavor physics experiment

At *B*-factories, PID is required for

- the tagging of the *B*-meson flavor
- precision measurements of rare *B*/*D* decays
- ...

An example of PID effect on *Φ → K+ K-* reconstruction





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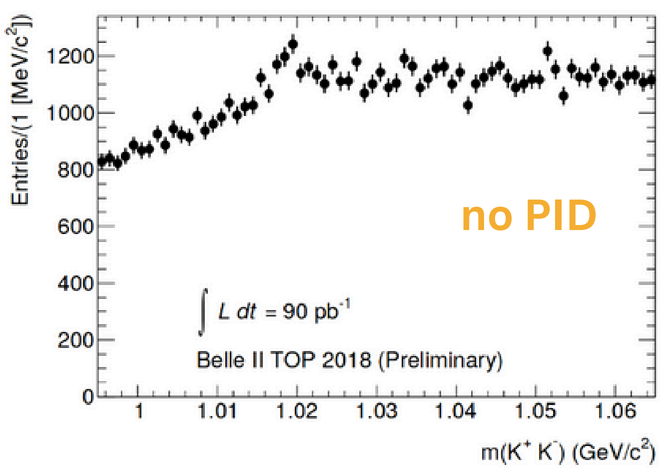
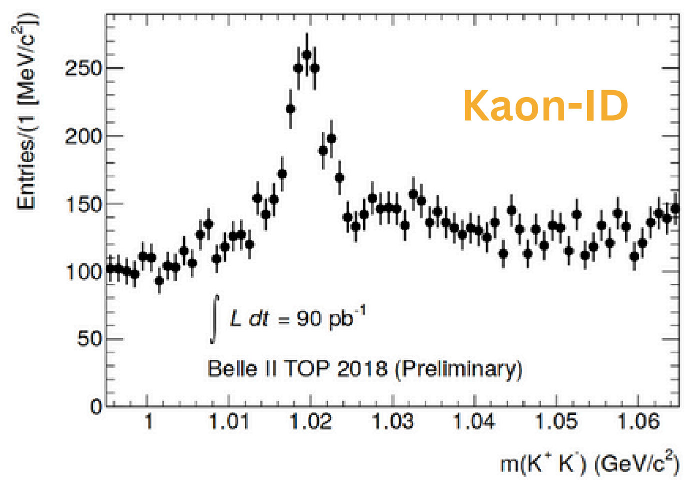
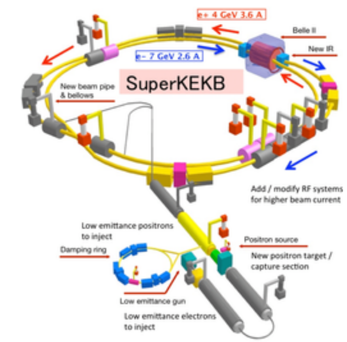




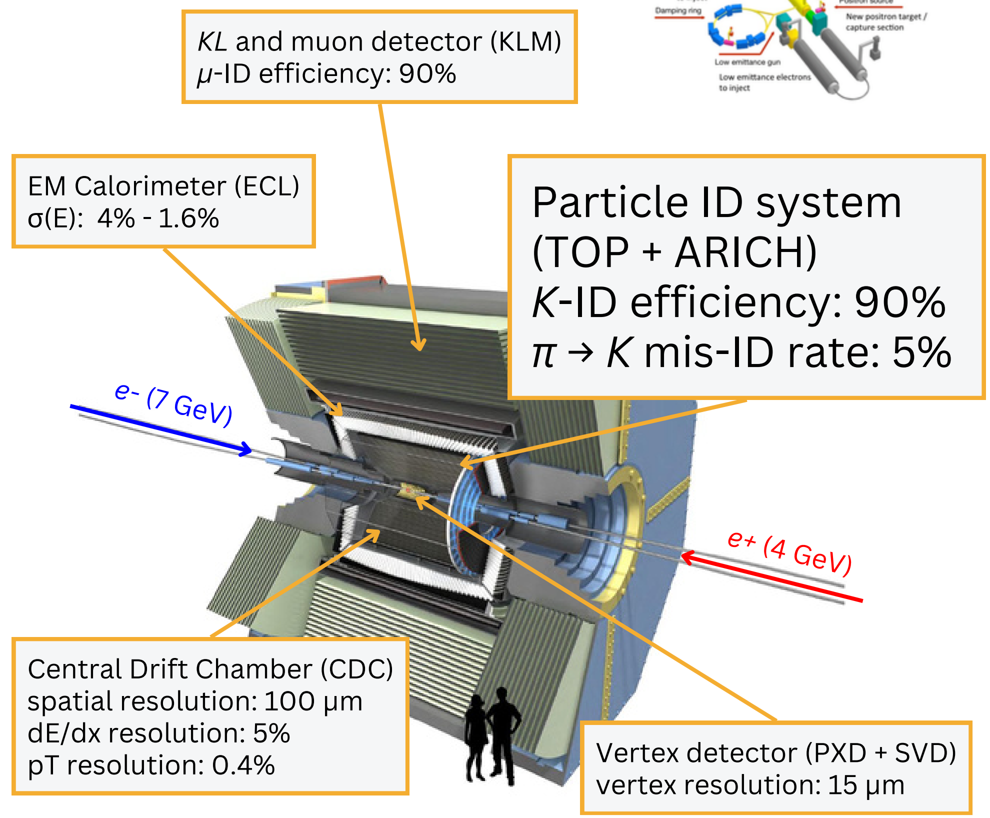
Belle PID performance

- *K*-ID efficiency: 90%
- $\pi \to K$ mis-ID rate: 10%

Belle II experiment at SuperKEKB



- Belle II is a luminosity frontier experiment to search for Physics Beyond the Standard Model
- It is located at SuperKEKB, the asymmetric *e+e-* collider at KEK in Tsukuba, Japan
- Collisions are (mostly) at the *Y(4S)* resonance, $\sqrt{s}$ = 10.58 GeV
- Peak luminosity record (Dec. 2024) $L = 5.1 \times 10^{34}$ cm^{-2} s^{-1}
- Accumulated 575 fb^{-1}

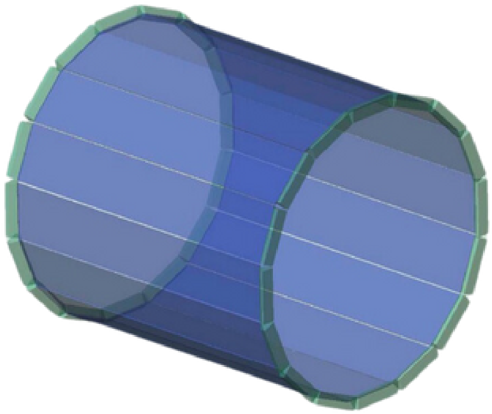


PID at Belle II

- Two dedicated PID devices:
  - **TOP in the barrel**
  - ARICH in the forward endcap
- All Belle II sub-detectors (except PXD) contribute to PID
- Six types of "stable" charged particles: *e*, *μ*, *π*, *K*, *p*, *d*

TOP counter

TOP stands for **Time-Of-Propagation**



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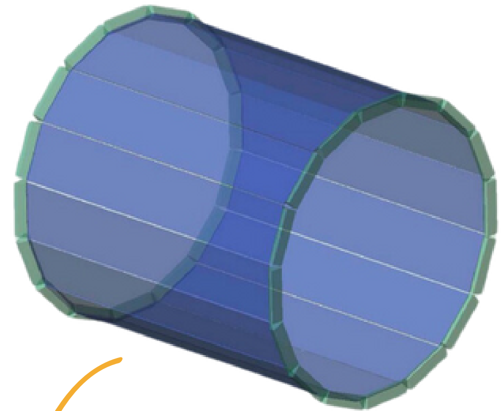

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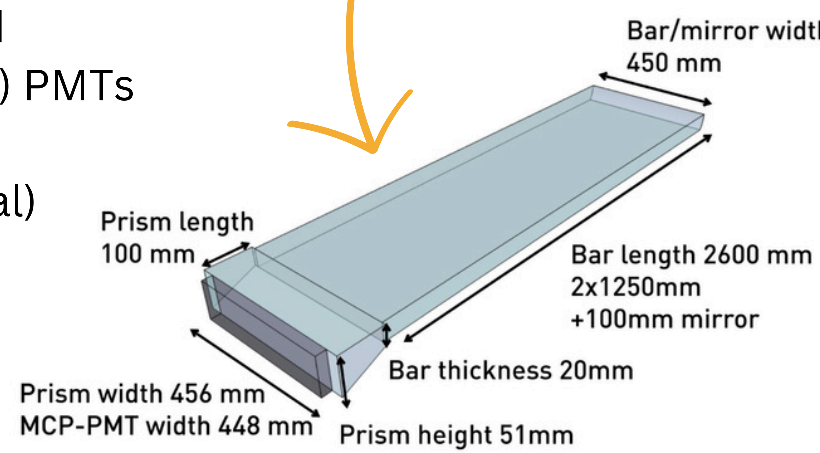
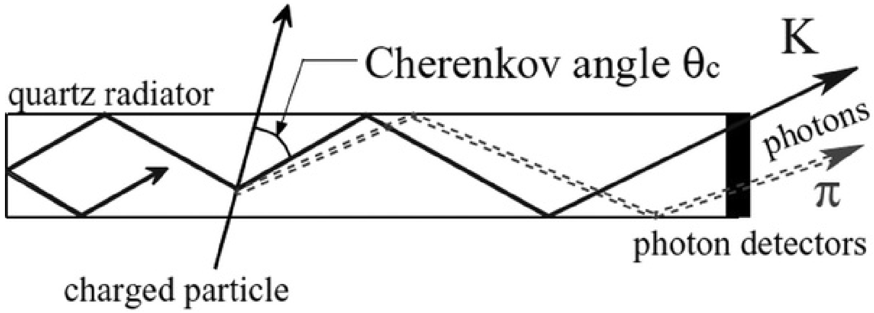
Each module consists of

- 2 quartz (n = 1.47) bars glued together
- a focusing mirror at one end
- a small expansion prism at the other end
- an array of 32 Micro Channel Plate (MCP) PMTs
  - arranged in 2 rows
  - 4 × 4 channels each (512 pixels in total)
  - transit time spread < 50 ps



TOP working principle

TOP is a ring-imaging Cherenkov device



Dependence on particle mass and momentum

$$\cos\theta_C = \frac{1}{n\beta}$$

- Photons propagate within the quartz bar by internal reflection
- The 2D information of a Cherenkov ring-image is given by the **arrival time** and the **hit position** of the Cherenkov photons at the photon detector plane

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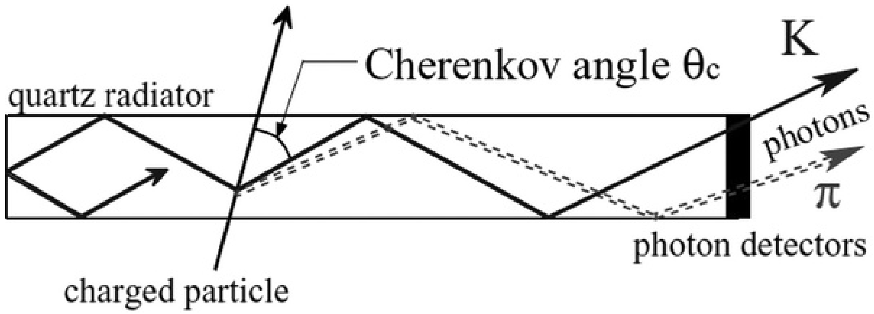

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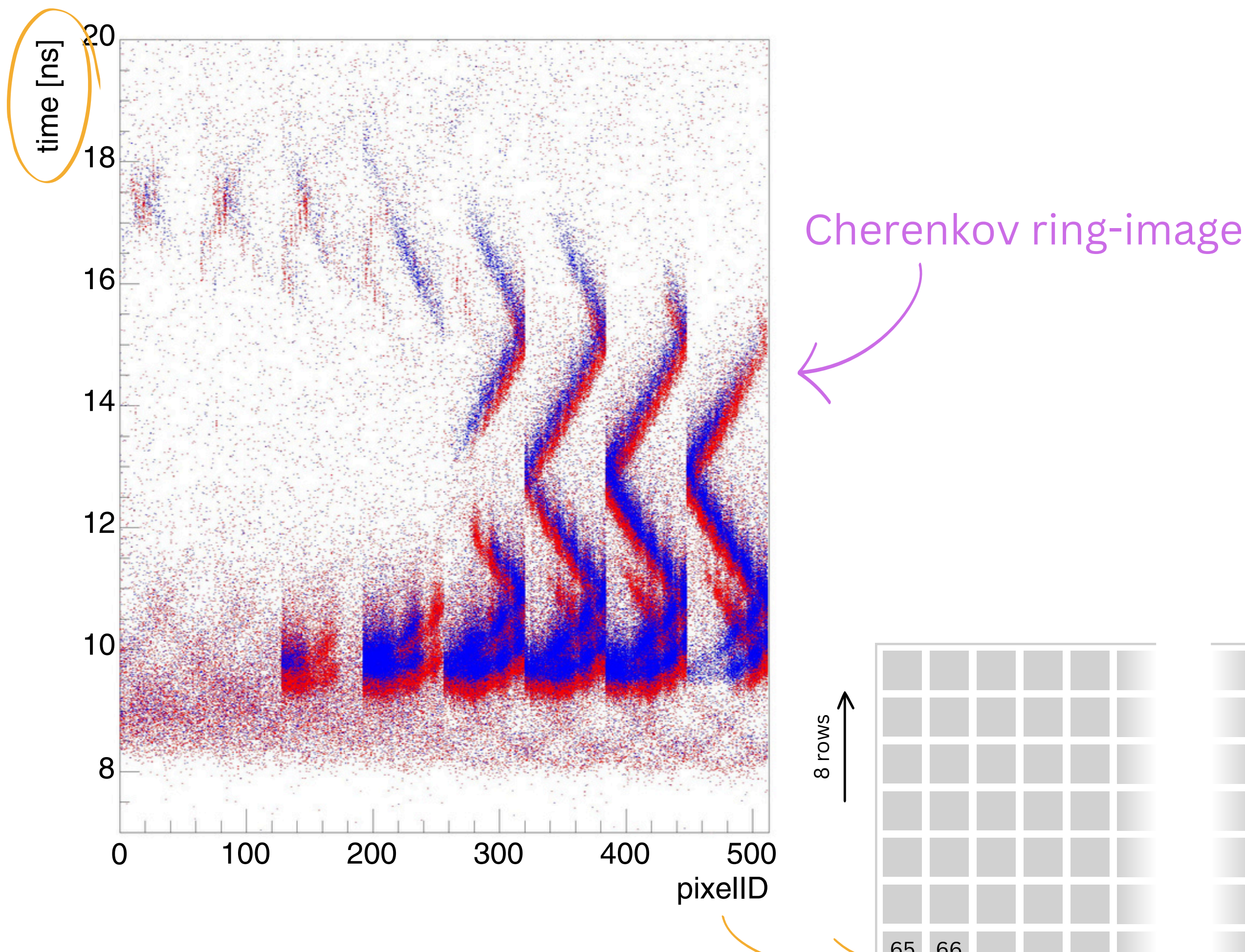
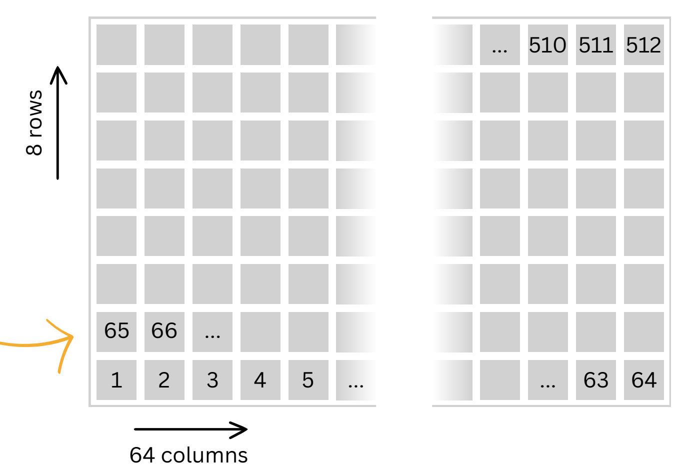
K* and *π (with same momentum, impact position and impact angle on the bar) emit Cherenkov photons at **different θc** → different path length → **different time of propagation and hit position on the photon detector plane**

- Time resolution < 100 ps for good PID performance

Photon pattern

Example of measured pattern for thousands of photons, for simulated **pions** and **kaons** with p = 2.0 GeV/c, θ = 90 deg, φ = 41.5 deg





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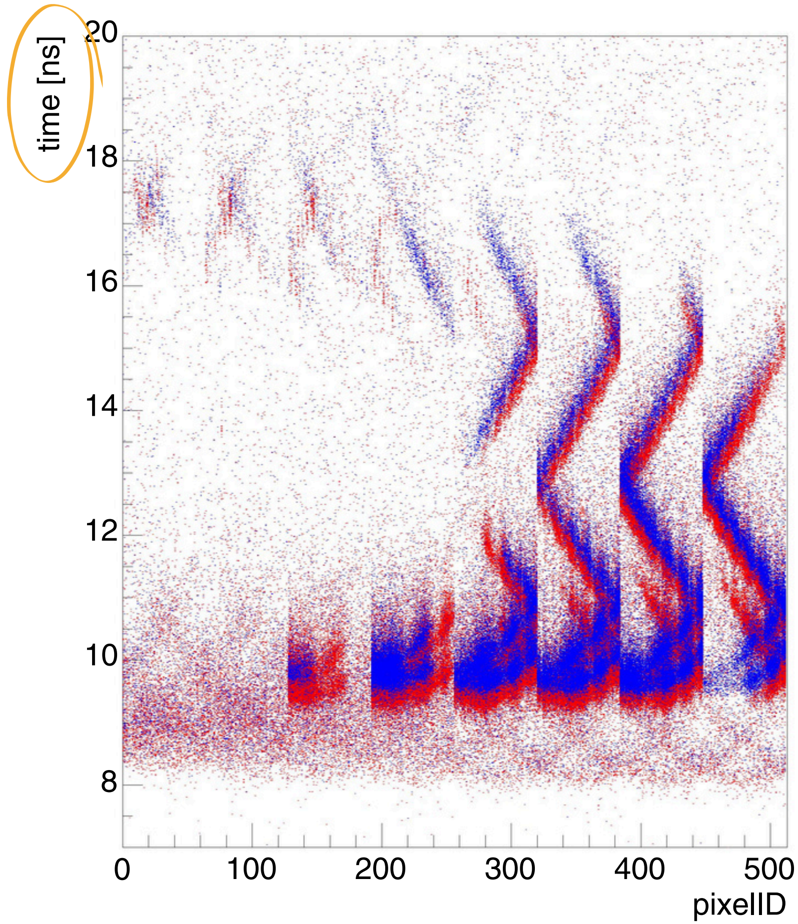
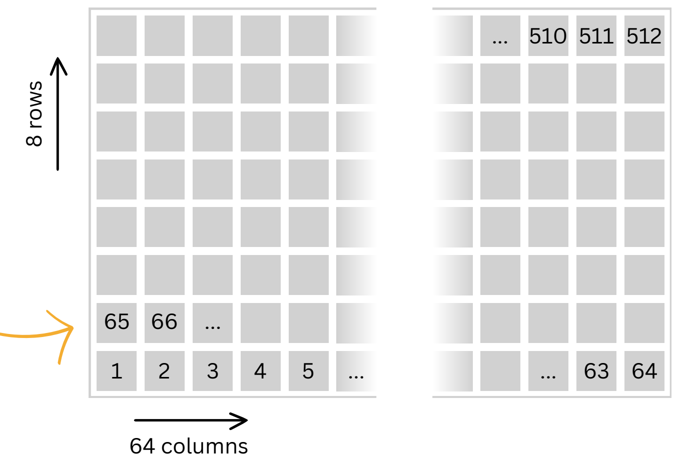


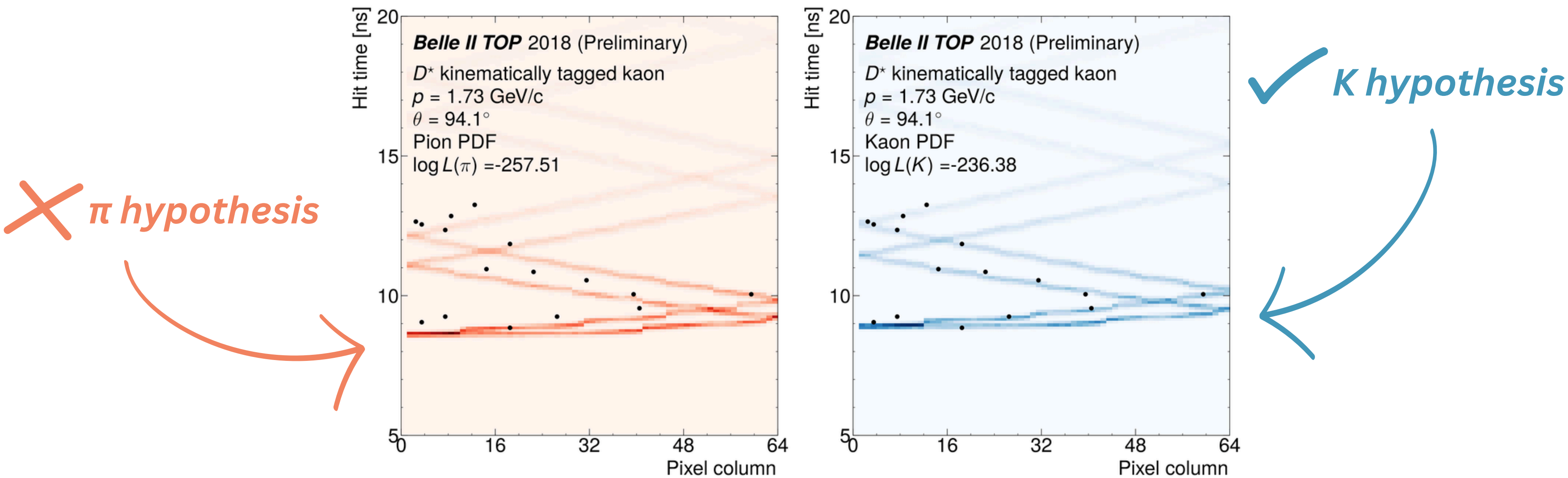
Cherenkov ring-image



Note: 20-40 photons are typically detected per event!

TOP PID Likelihood

We compare the **measured 2D distribution *x* - *t*** (*x* = pixel column) (black dots) of the photon hits with the **expected pattern analytically calculated** (colored lines) for *K* and *π* hypotheses → *K* and *π* TOP likelihoods



Note: the tracking system measures particle momentum, impact position and impact angle on the TOP bar

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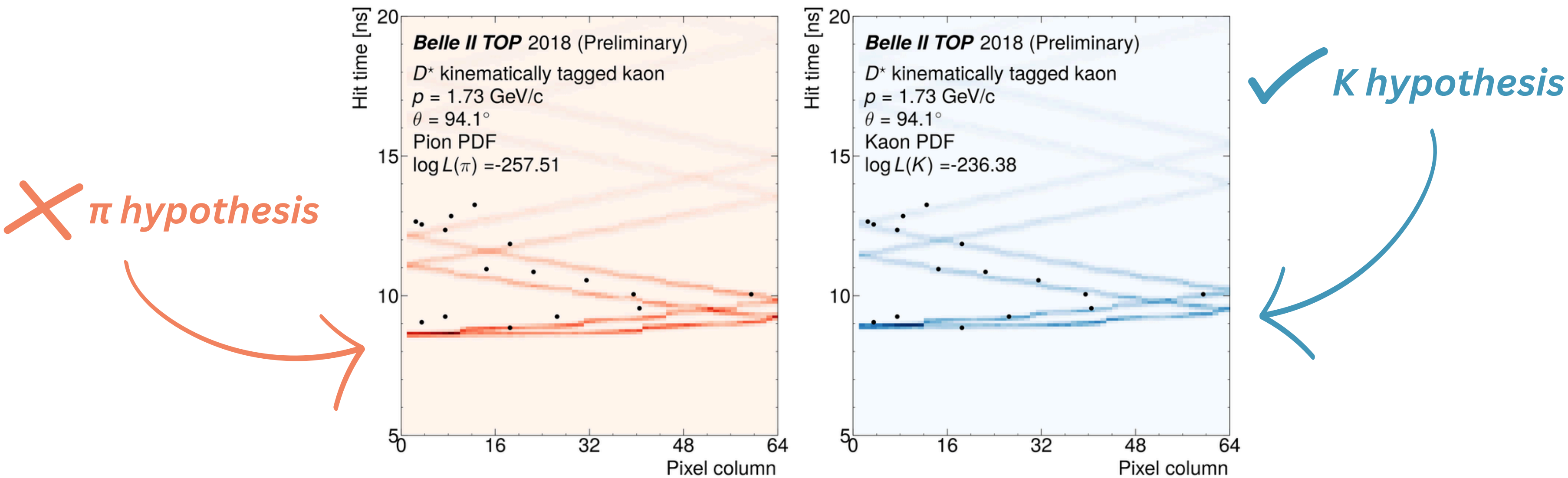

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The ratios of the TOP likelihoods are used to assign TOP PID probabilities

$$P_K = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi} \qquad P_\pi = 1 - P_K$$ (binary PID)

TOP only binary PID gives 85% of *K*-ID efficiency with 10% *π* → *K* mis-ID rate

TOP PID with Machine Learning (ML)

Why ML?

- The calculation of analytical TOP likelihoods requires a highly detailed simulation of all components of the TOP
- The simulation cannot perfectly reproduce the geometry of the TOP modules and the differences between them

→ With ML we can train using the data measured by the TOP (and the tracking system), so we do not need to simulate the TOP counter very precisely

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Training flow

Training on particle gun data → Training on generic MC data → Training on experimental data

Past results

→ Boosted Decision Tree (BDT) for K and π separation
  - Improved PID performance for particle gun events
  - Performance much decreased for generic MC events

(Very) Preliminary results with CNN

Proposal

→ Use a Convolutional Neural Network (CNN) for K and π separation
- CNNs are highly effective for pattern recognition

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Proposal

Use a Convolutional Neural Network (CNN) for *K* and *π* separation

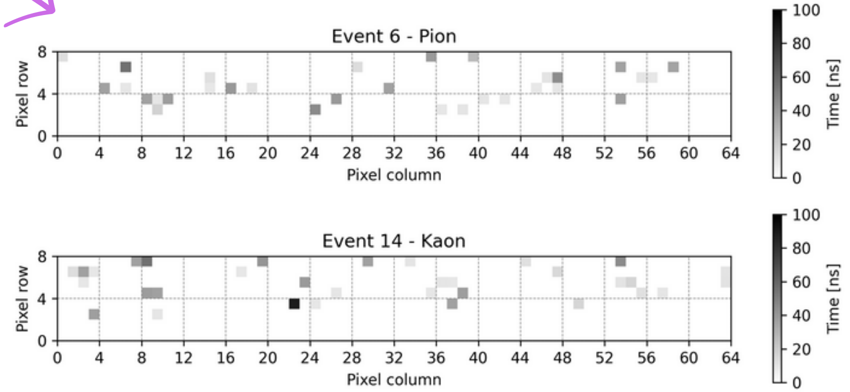
- CNNs are highly effective for pattern recognition

Simulated particle gun events

- ~200k particles (*K+* and *π+*) from the interaction point
- *p* = 2.0 GeV/c, *θ* = 90 deg, *φ* = 41.5 deg

CNN model

- Supervised learning
- Input:
  - images (8 x 64 x 1) (row x col x time)
- Network:
  - convolutional layers + dense layers
- Output:
  - binary classification: 1 for *π*, 0 for *K*
- Training sample (90%) + Testing sample (10%)
- Training for 1000 epochs



(Very) Preliminary results with CNN

Output:
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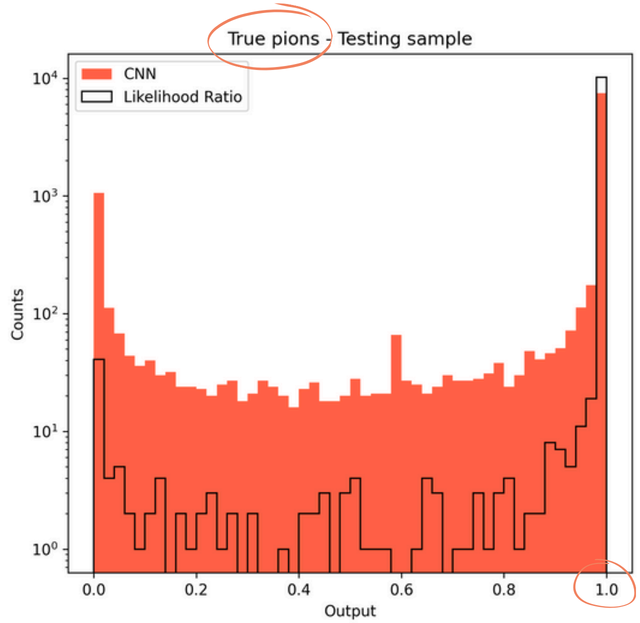
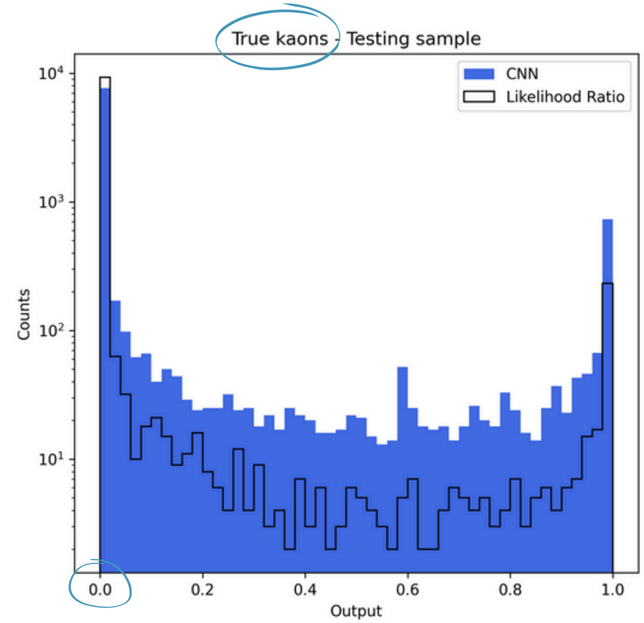
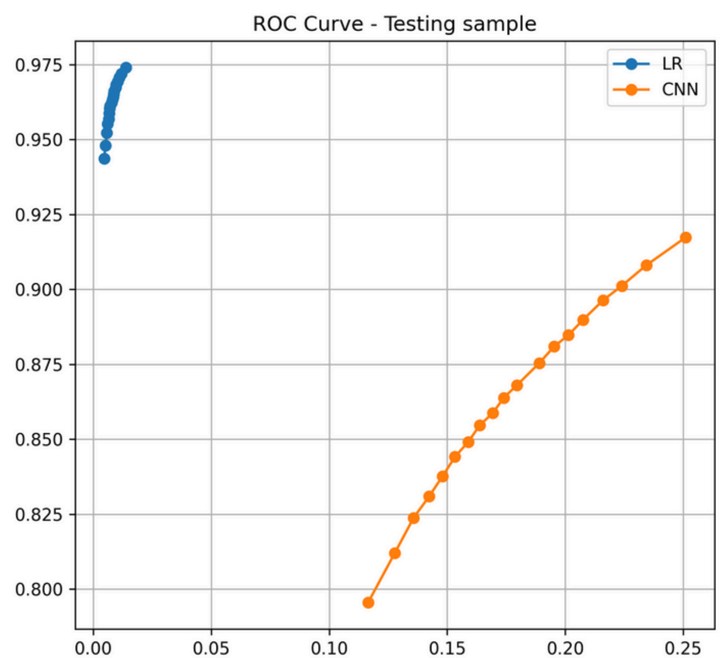
- 0 for K





K-ID efficiency



$\pi \to K$ mis-ID rate

The network is able to separate pions and kaons, but there is no improvement in PID performance (for now!)

Conclusion

- Belle II PID performance is better than Belle one
- TOP is a new concept Cherenkov detector type for PID that relies on precise timing of individual photons
- TOP only binary PID gives 85% of K-ID efficiency with 10% $\pi \rightarrow K$ mis-ID rate

Can we do better?

- We are exploring ML techniques for the TOP counter with the aim of improving PID performance
- Improved PID performance with BDT for particle gun events
- **Work in progress with CNN for particle gun events**
  - First tentative with images (row x col x time) as input
  - It is planned to use images (col x time) as input
- When we move to real data, we will have to take into account the dependence of PID performance on background conditions

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