Identify neutral hadrons using ECL at Belle II experiment

Y.-T. Chen, J.-H. Su, M.-Z. Wang, J.-G. Shiu (NTU)

- Belle II Detector
- Partical Identification
- ECL Standalone $K_L^0/\overline{n}$ Identification
- Application in Physics Analyses
- Summary

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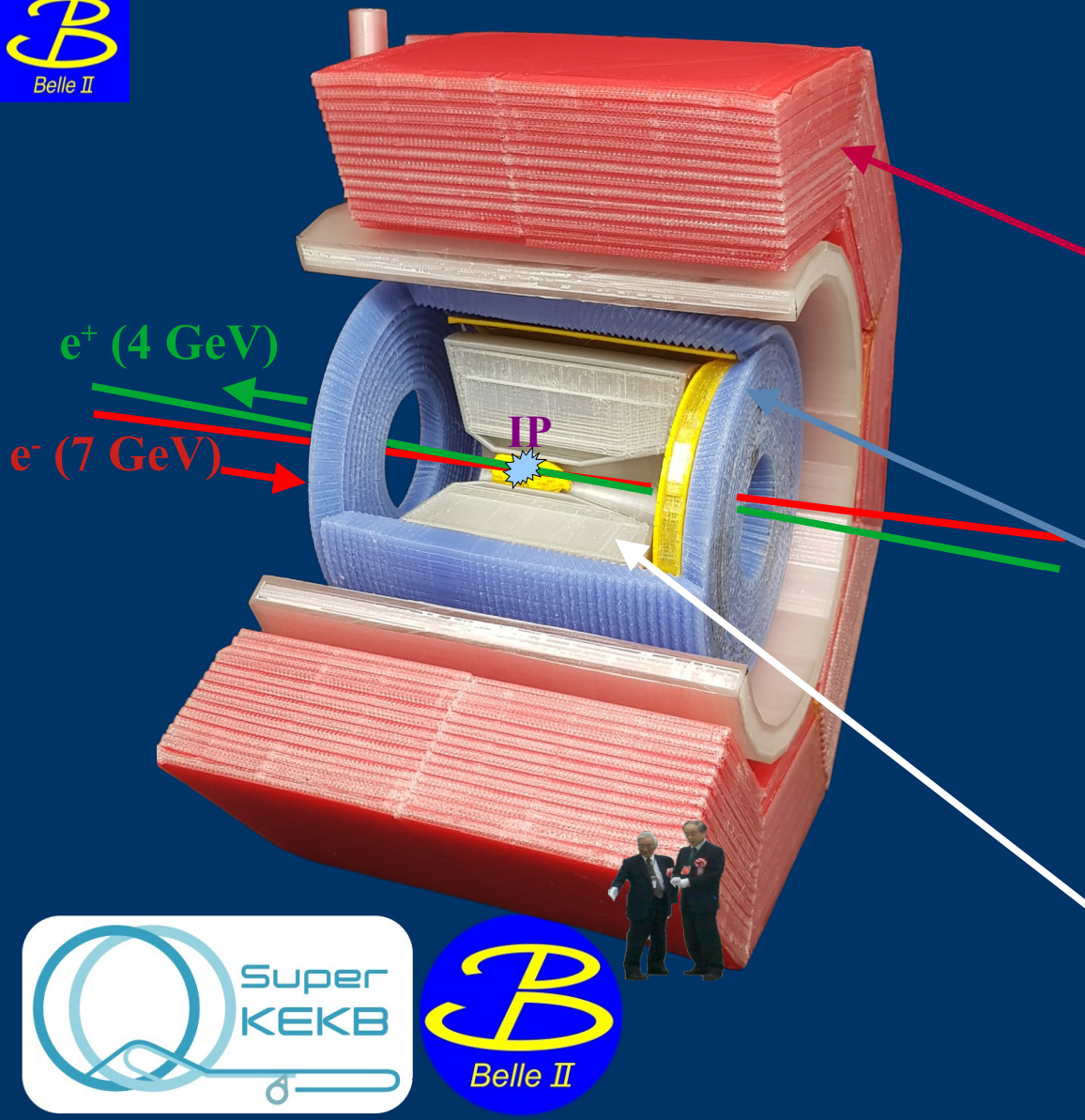
Belle II Detector

(without EKLM)

2019~ , target 6×10^{35} $cm^{-2}s^{-1}$ and 50 ab^{-1}

up to 2024, 5.1×10^{34} $cm^{-2}s^{-1}$ and 575 fb^{-1}



KLM(for μ, K_L^0 PID): 25° ~ 155°

baseline reference

ECL(for e, γ): 12.4° ~ 155°

8736 Cs(Tl) crystals

16.1 X_0

0.68 λ_0

angular resolution ~ O(1) mrad

new readout with waveform sampling

→ offline pulse shape discrimination (PSD)

CDC: 17° ~ 150°

charged track veto

Long long ago, there was a study ...

Motivation

- more statistics than previous result (Belle II 363 fb^{-1} V.S. CLEO 9.1 fb^{-1})
- $\overline{n}$ direct detection from EM calorimeter
- validation of CLEO result and color-suppression
- potential of first measurement

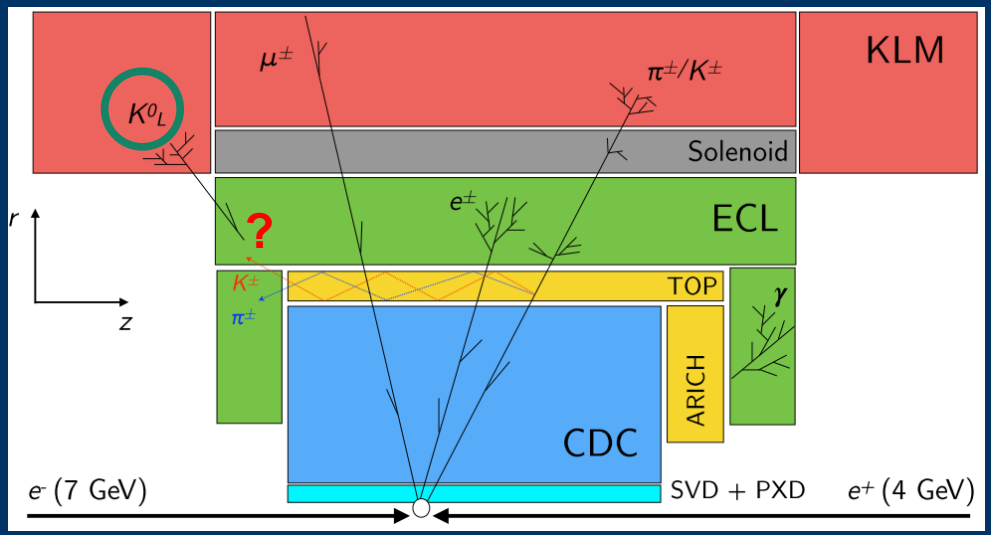
from PDG 2024	color-favored		color-suppressed	
$B^0 \to DN\overline{N}$	$B^0 \to D^- p\overline{n}$	$B^0 \to D^{*-} p\overline{n}$	$B^0 \to \overline{D}^0 p\overline{p}$	$B^0 \to \overline{D}^{*0} p\overline{p}$
	$(?? \pm ?) \times 10^{-4}$	$(14 \pm 4) \times 10^{-4}$	$(1.04 \pm 0.07) \times 10^{-4}$	$(0.99 \pm 0.11) \times 10^{-4}$
$B^0 \to D\pi$	$B^0 \to D^- \pi^+$	$B^0 \to D^{*-} \pi^+$	$B^0 \to \overline{D}^0 \pi^0$	$B^0 \to \overline{D}^{*0} \pi^0$
	$(25.1 \pm 0.8) \times 10^{-4}$	$(26.6 \pm 0.7) \times 10^{-4}$	$(2.67 \pm 0.09) \times 10^{-4}$	$(2.2 \pm 0.6) \times 10^{-4}$

Particle Identification

- Particle identification (PID) is the procedure/algorithm using the detector measured information to recognize a particle's identity → likelihood.
  - It is one of the essential part to reconstruct a physics event from detected signals.

- In Belle II Analysis Software Framework (BASF2), PID is implemented for
  - standard charged: e, μ, $\pi^{\pm}$, $K^{\pm}$, p/d,
  - standard neutral: K_L^0 (KLM), γ

- How about …
  - feasibility to use ECL to do K_L^0 PID?
  - $n/\bar{n}$? (left behind since Belle).

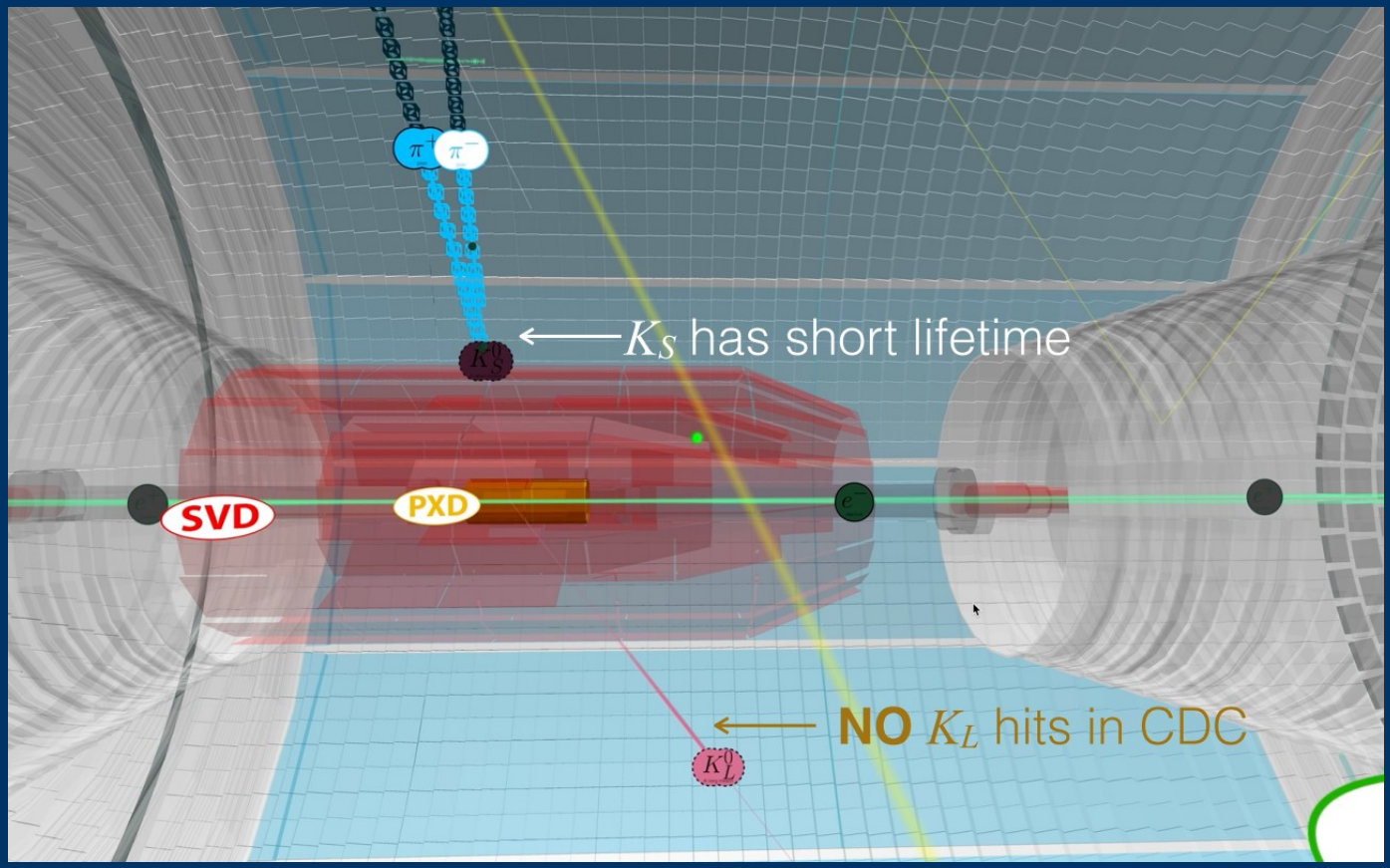


For K_L^0

Q1: Does K_L^0 leave enough signal inside ECL?
→ It is a hadron, so … .

Q2: If yes, could we distinguish it from others?
→ Could discriminative AI help?

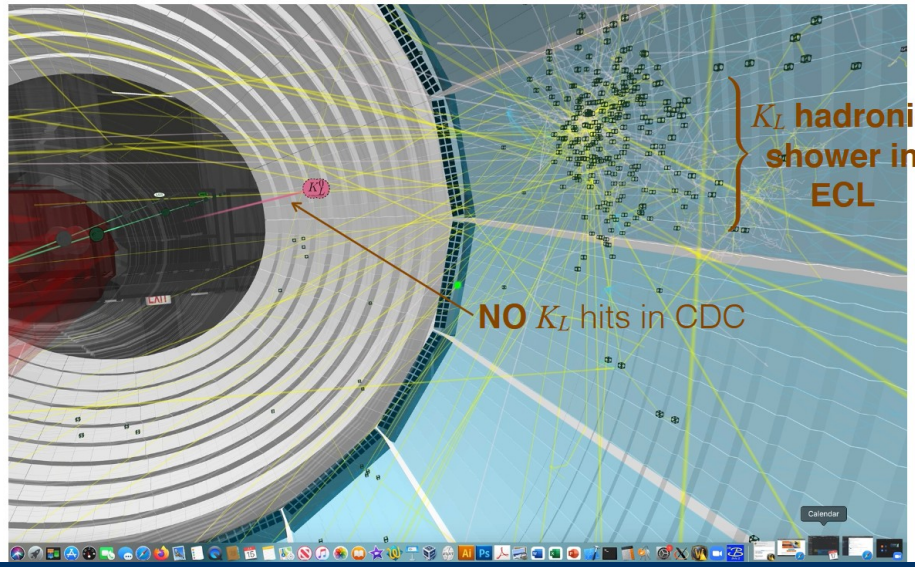
$K_L{}^0$Simulation leaves no hit in PXD, SVD, and CDC



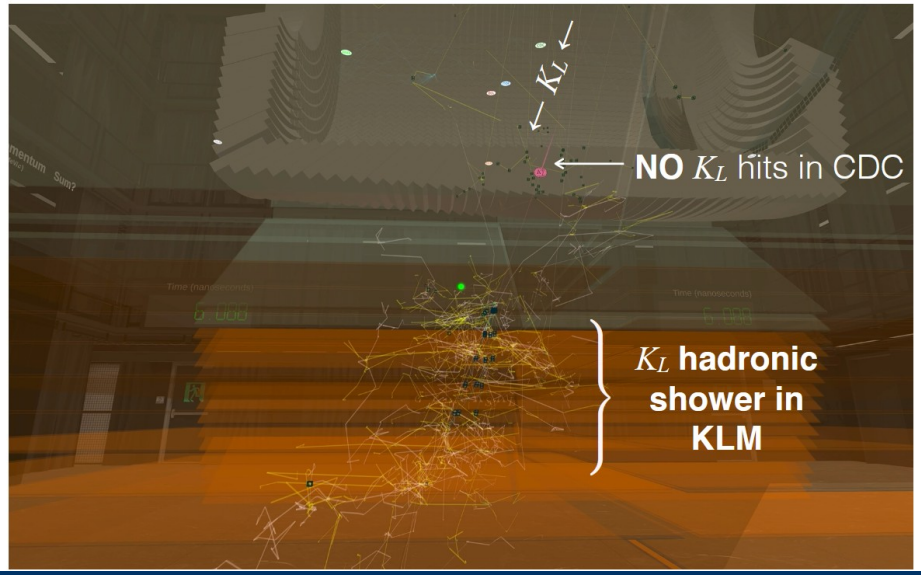
→ how about ECL and KLM?

Simulation based on our best knowledge: acceptance at KLM standalone ~ 50%

K-longs suffer strong interaction with ECL nuclei ⇒ hadronic shower
without a matching CDC track



… or K-longs suffer strong interaction with KLM iron nuclei ⇒ hadronic shower
without a matching CDC track



Does K_L^0 leave enough signal inside ECL?

Ans. to Q1: Probably YES!!

ECL Standalone $K_L^0/\overline{n}$ Identification

Using fastBDT for the classifier training

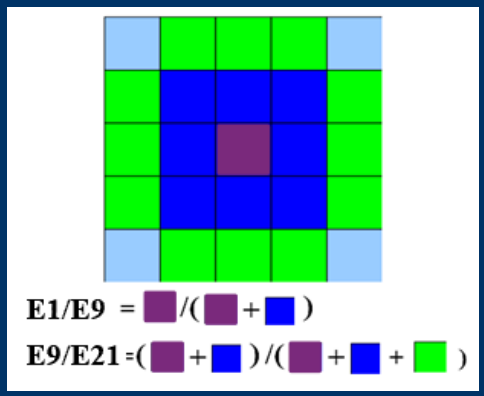
- MC studies using signal and background samples.
- The truth matching for neutral clusters in Belle II software does not work 100%. We use only ones with truth matching for training.
- We leave n behind at this moment.

K_L^0 Classifier Training (MC study)

K_L^0 PID (Jheng-Hao Su)

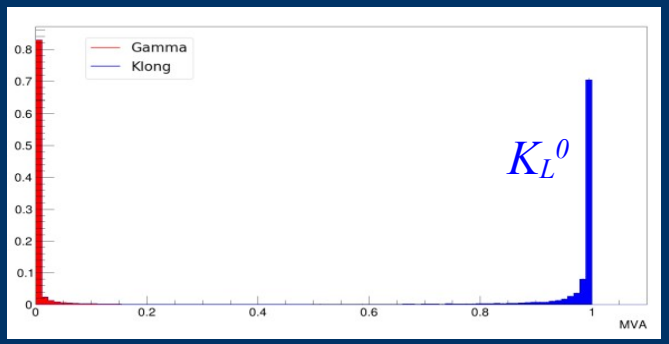
K_L^0 100 fb^{-1} **(candy)**
other neutrals 10 fb^{-1} **(stone)**

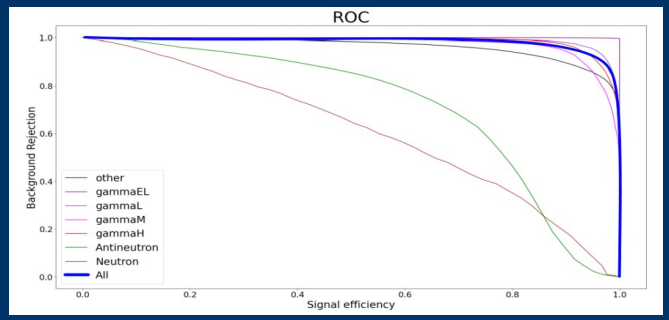
neutral cluster
w/ truth matching*



training variables

clusterPSDMVA
clusterE
clusterLAT
clusterE9E21
clusterE1E9
clusterZernikeMVA
clusterZernikeMoment40
clusterZernikeMoment51
.....





Ans. to Q2: YES?!

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training results: training/test samples consistent

Calibration (K_L^0)

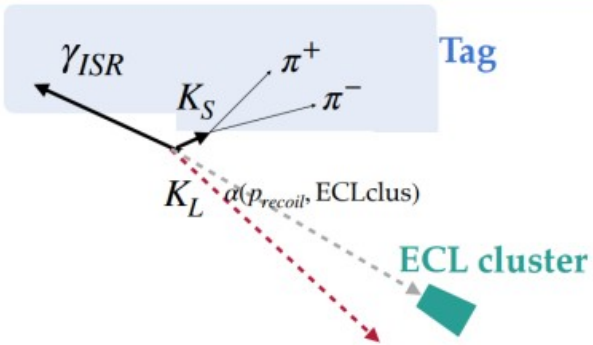
- Calibration with $e^+e^- \to \phi(\to K_L^0 K_S^0)\gamma$ (standard missing momentum method)

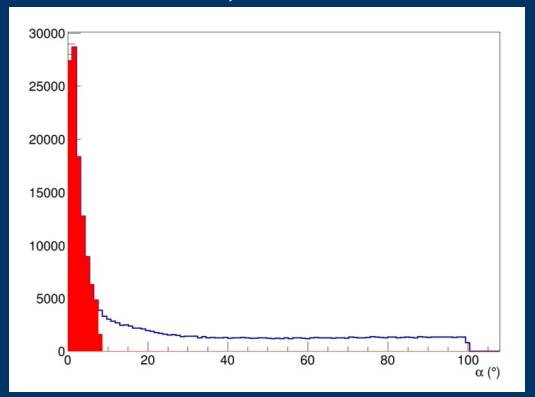
K_S^0: 0.49 < M < 0.504 GeV/c^2

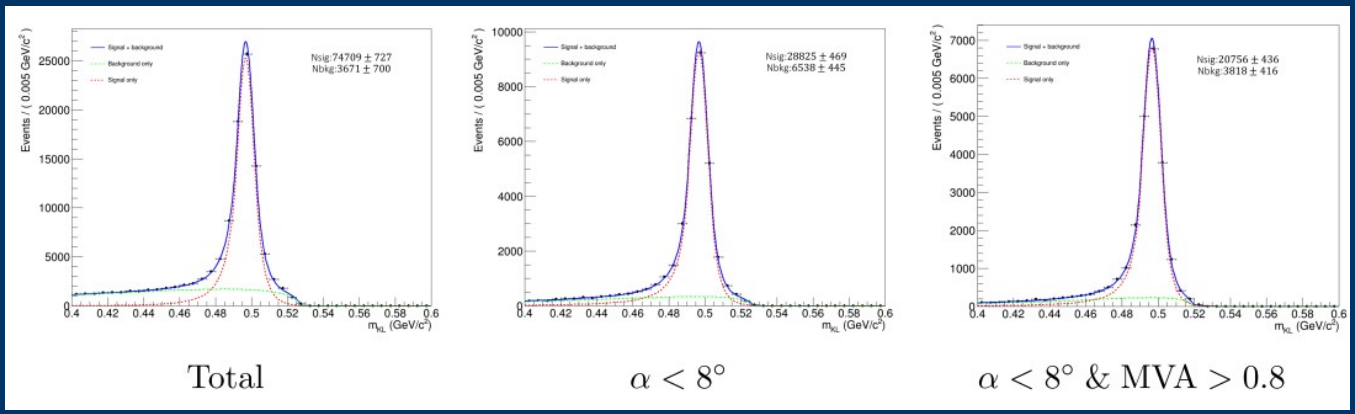
$-0.85 < \cos\theta_{K_S^0} < 0.95$

γ: 4.5 < E_γ^* < 5.4 GeV

K_L^0: $\alpha < 8^\circ$







The K_L^0 mass distribution in data.

- The correction factor is calculated in different cosθ and P at different K_L^0 cut. Overall correction is $\epsilon_{data}/\epsilon_{MC} \sim (82.0 \pm 3.6)\%$

$\bar{n}$ Classifier Training (MC study)

$\bar{n}$ PID (Yun-Tan Chen)

$\bar{n}$ 100 fb^{-1} **(candy)**
other neutrals 1 fb^{-1} **(stone)**

→ neutral cluster w/ truth matching*

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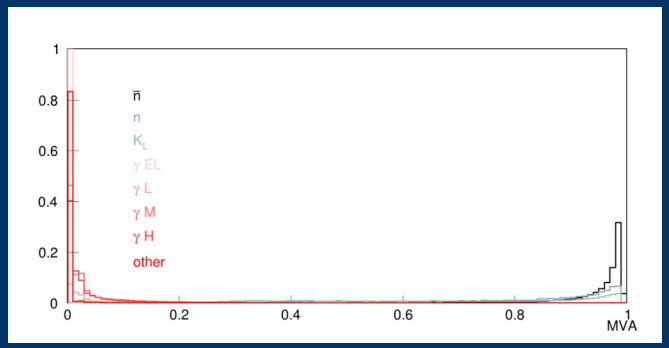
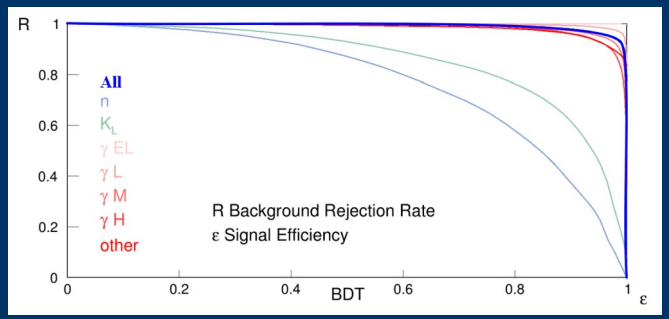
* NOTE
The truth matching for neutral clusters in Belle II software does not work 100%.

The results demonstrate only the classification performance.

The exact signal efficiency should be checked in physics analysis case by case.





training results: training/test samples consistent

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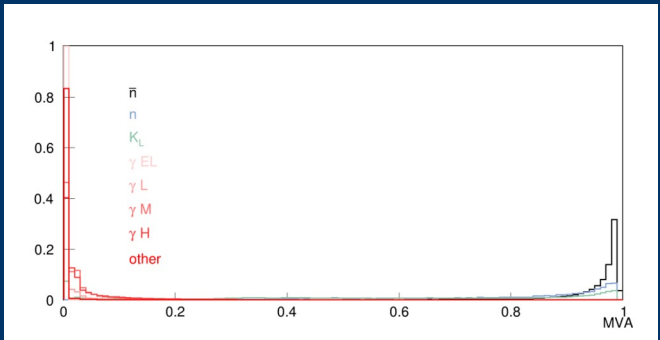

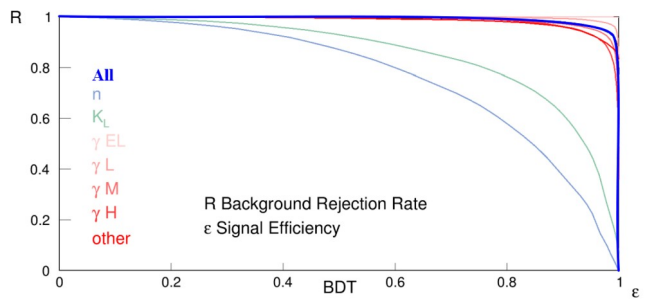

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A similar study has been done for Belle data by Yuan-Ru Lin. Belle Note BN1592

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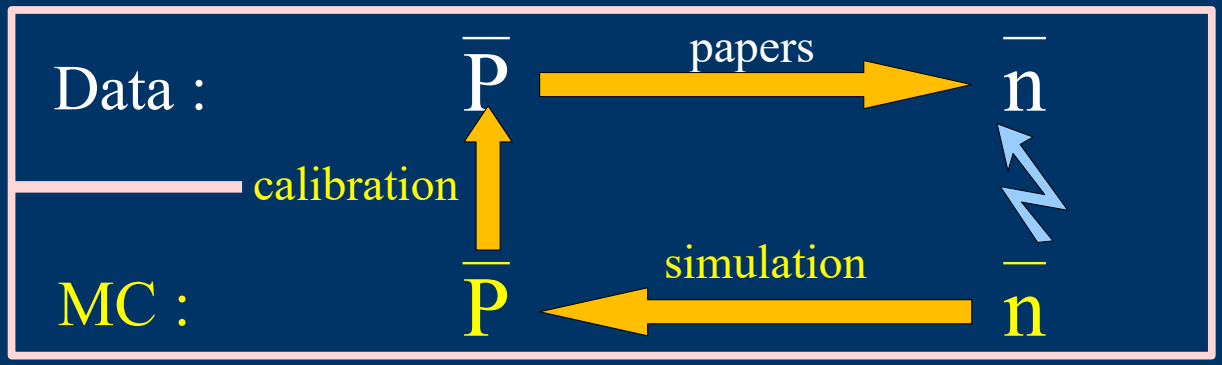
training results: training/test samples consistent

Calibration ($\bar{n}$)

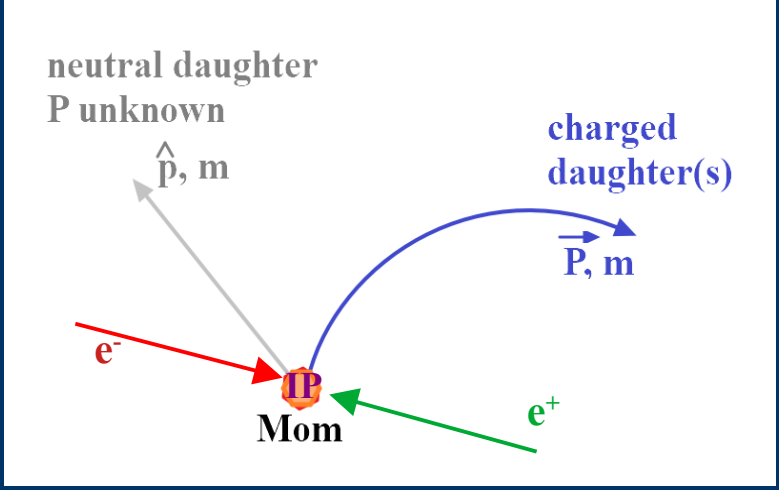
- Using $\bar{\Lambda} \to \bar{p}\,\pi^+$ for calibration
  - Use $\bar{p}$ to mimic $\bar{n}$, extrapolate $\bar{p}$ to ECL (treat charged cluster as a neutral one)
  - $\bar{p}$ and $\bar{n}$ have similar nuclear interaction cross section (P > 0.4 GeV/c)
  - p and $\bar{n}$ have same simulation package in GEANT (3/4)
  - Correction of $\bar{p}$ efficiency by $\bar{\Lambda} \to \bar{p}\,\pi^+$ between MC and real data
  - Relying on MC for additional correction between $\bar{p}$ and $\bar{n}$

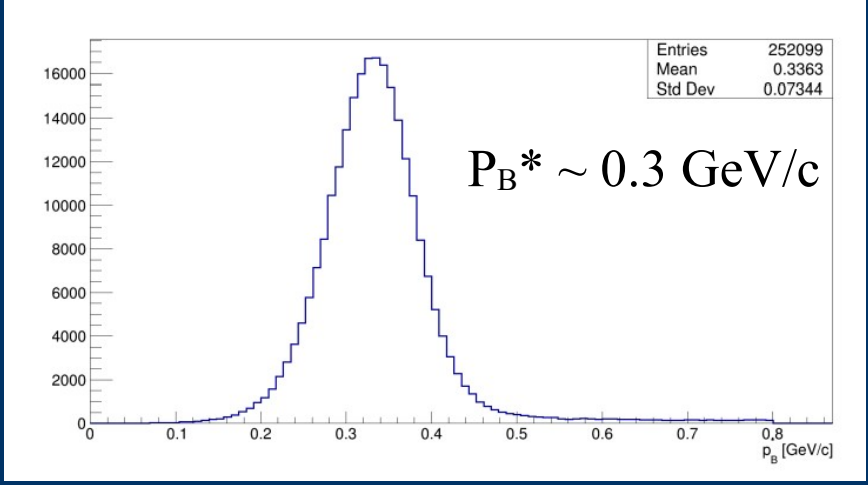


- Systematic uncertainty
  - Detection correction (related to ECL detector and reconstruction software).
  - Selection correction (related to $\bar{n}$ PID).
  - Methodology.
  - The correction factor is calculated in different cosθ and P at different K_L^0 cut. Overall correction is $\epsilon_{data}/\epsilon_{MC} \sim (84.0 \pm 3.0)\%$

Application in Physics Analysis

- Suitable for decays of
  mom(short lived) → one neutral daughter + charged daughter(s)
- ECL cluster center from the IP: the flying direction of the neutral daughter.
- Applying mom(mass) to constrain the neutral daughter's momentum magnitude.
  - This approach could apply not only to B decays.
- Check the signal peaking of ΔE^* or P_m^* (mom's P in c.m.).

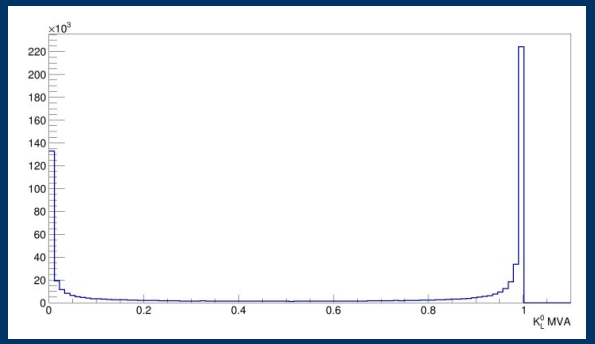


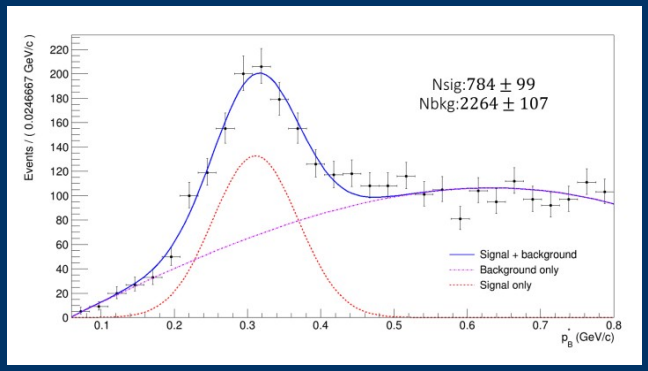


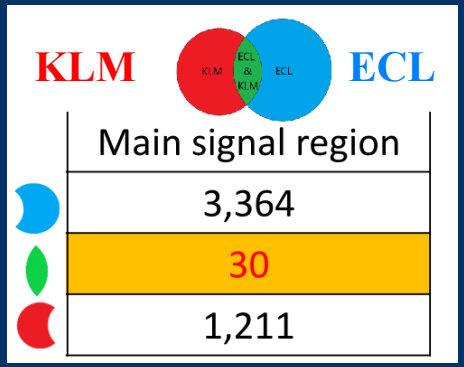
(For τ as the mom, $P_\tau^* \sim 5$ GeV/c)

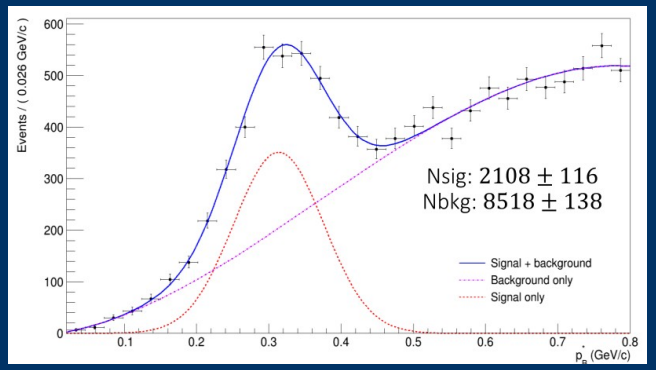
Application in Physics Analysis

- Check with $B^0 \to J/\psi(\to \mu^+\mu^-)K_L^0$ using LS1 data (362 fb^{-1} before 2024).
  - good muon
  - 3.06 GeV/c^2 < J/ψ mass < 3.12 GeV/c^2
  - K_L^0 by ECL standalone, MVA > 0.8
- Results in signal and branching fraction: $(8.85 \pm 0.62) \times 10^{-4}$
  (PDG: $(8.91 \pm 0.21) \times 10^{-4}$)
- Overlapping with K_L^0 (KLM alone) is very small.









* First publication: K.-N. Chu *et al. (Belle)*, "Study of $B^+ \to p\,\bar{n}\,\pi^0$", PRD 108 (2023) 112007

Summary

- Belle II experiment has started physics commissioning since 2019
- We have developed ECL standalone $K_L^0/\bar{n}$ PID using machine learning techniques at Belle II
  - K_L^0 PID almost double the total K_L^0 efficiency at Belle II
  - $\bar{n}$ PID offers a tool for physics analysis
- These tools can apply to tau physics, too, especially for BSM
- First paper using Belle data is published in 2023
- There are new studies on $K_L^0/\bar{n}(n)$ *ongoing* ....