Development of a hardware trigger using machine learning in the Belle II experiment

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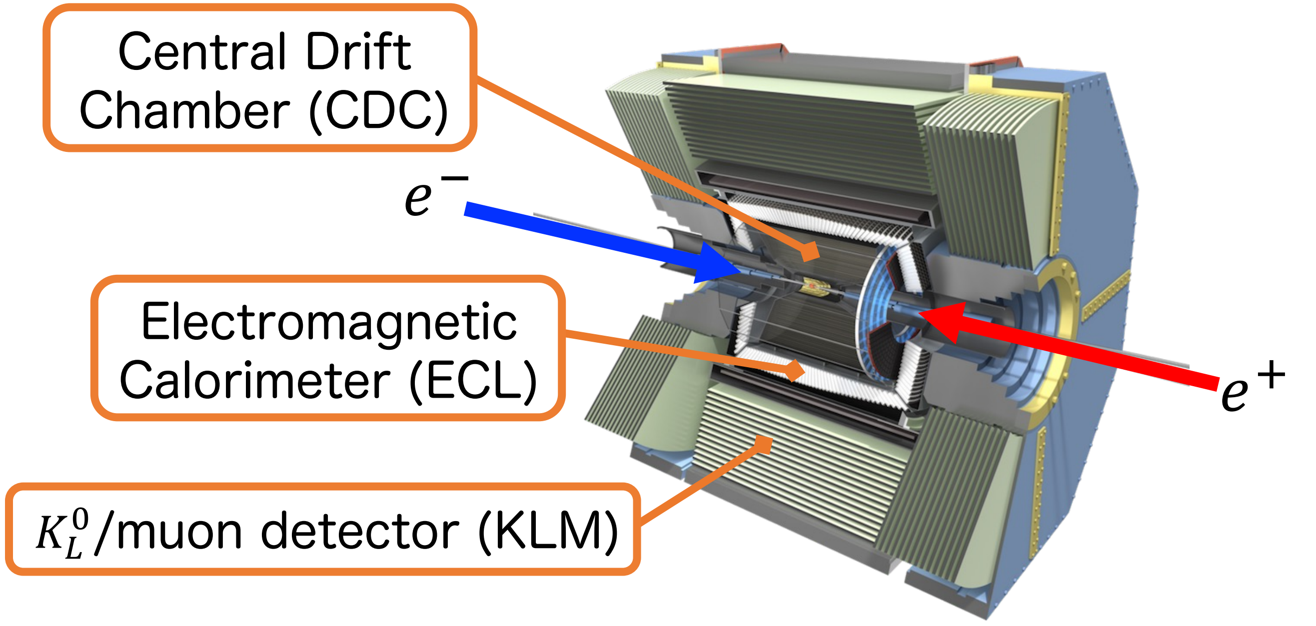
Belle II experiment

- High luminosity B factory experiment
- Collide 7GeV e^- and 4GeV e^+ using the SuperKEKB accelerator
- Measure a huge amount of elementary particle reactions and search for new physics

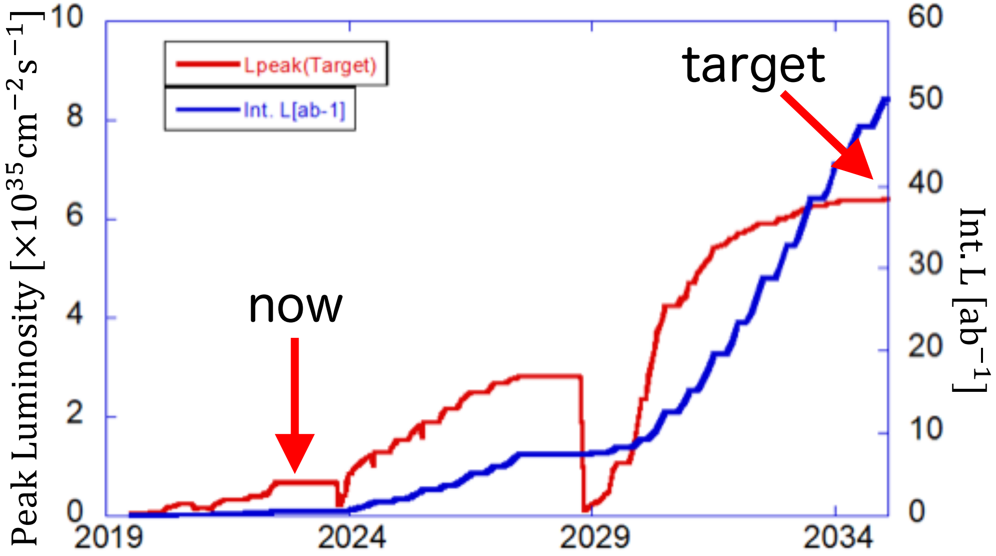


- Instantaneous luminosity

Current value $= 4.7\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

10 times more

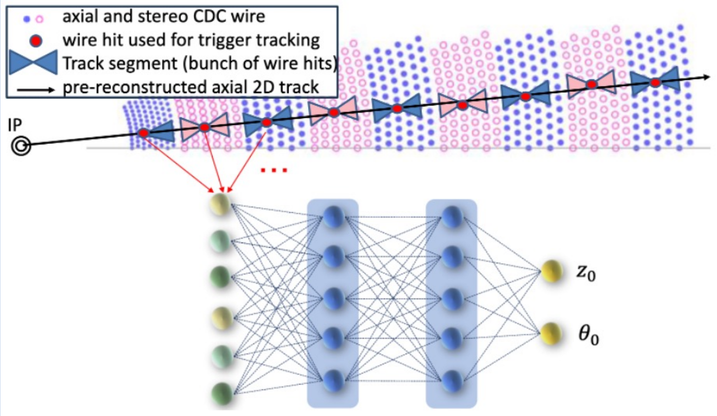
Target value $= 6.0\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



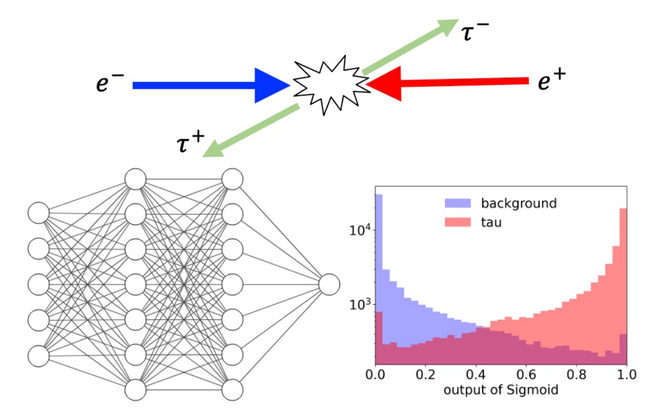
Machine Learning in Belle II trigger

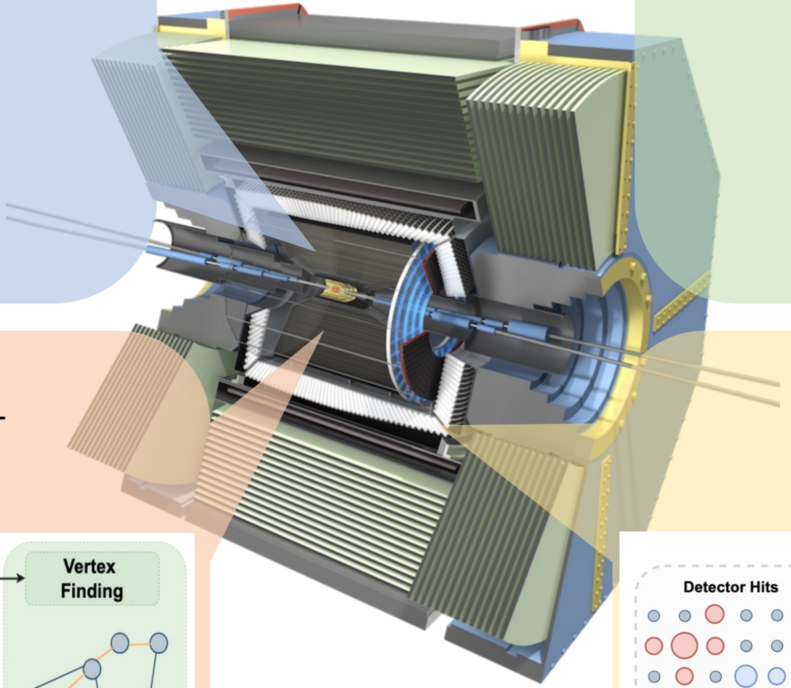
↓ This talk

Neural network for 3D tracking (CDC)

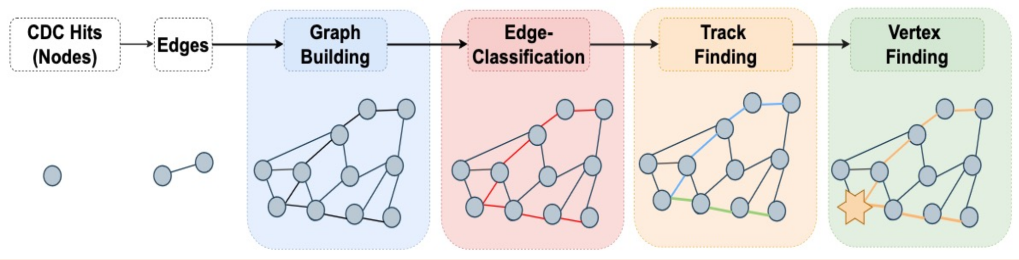


Neural network for low-multi physics Trigger

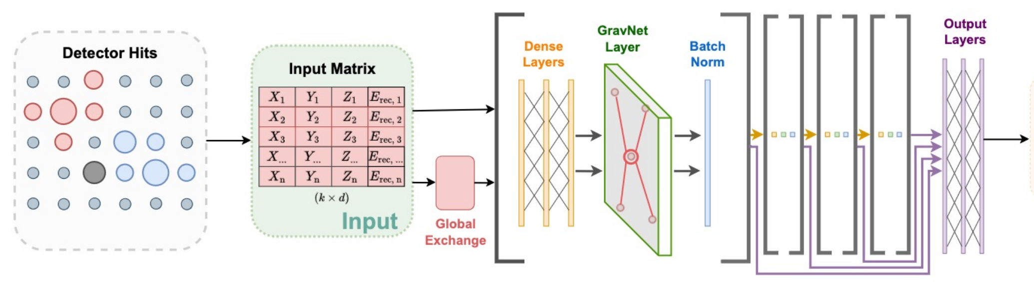




Graph neural network for tracking (CDC)



Graph neural network for clustering (ECL)



Tau particle decay

- Belle II experiment is also Tau factory and Tau is very important for physical analysis
- Focus on the $e^-e^+ \to \tau^-\tau^+$ event

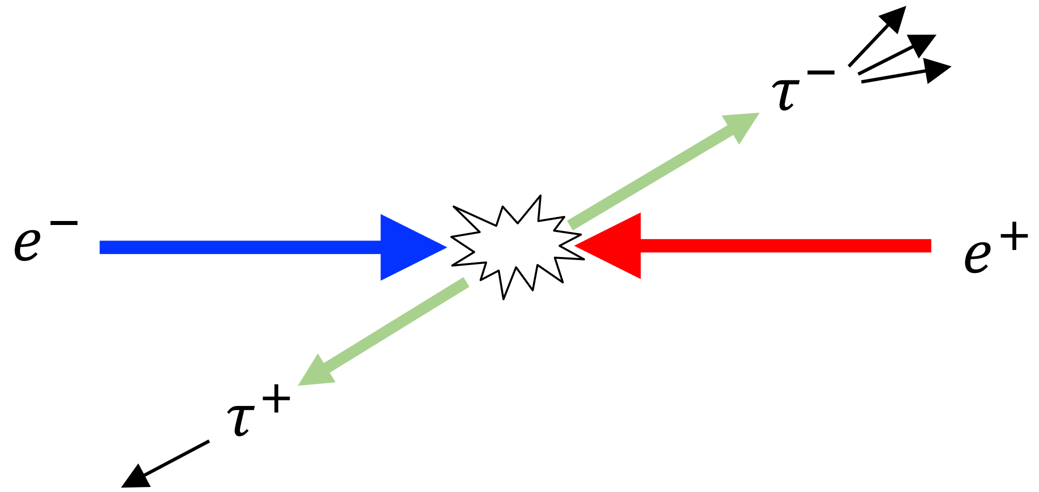
<u>1 charged particle</u>

$\tau^- \to e^-\bar{\nu}_e\nu_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$

$\tau^- \to \pi^-\nu_\tau$, $\tau^- \to \pi^-\pi^0\nu_\tau$ etc

<u>3 charged particles</u>

$\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$, $\tau^- \to \pi^+\pi^-\pi^-\pi^0\nu_\tau$ etc



→ The total number of charged particles must be an even number.

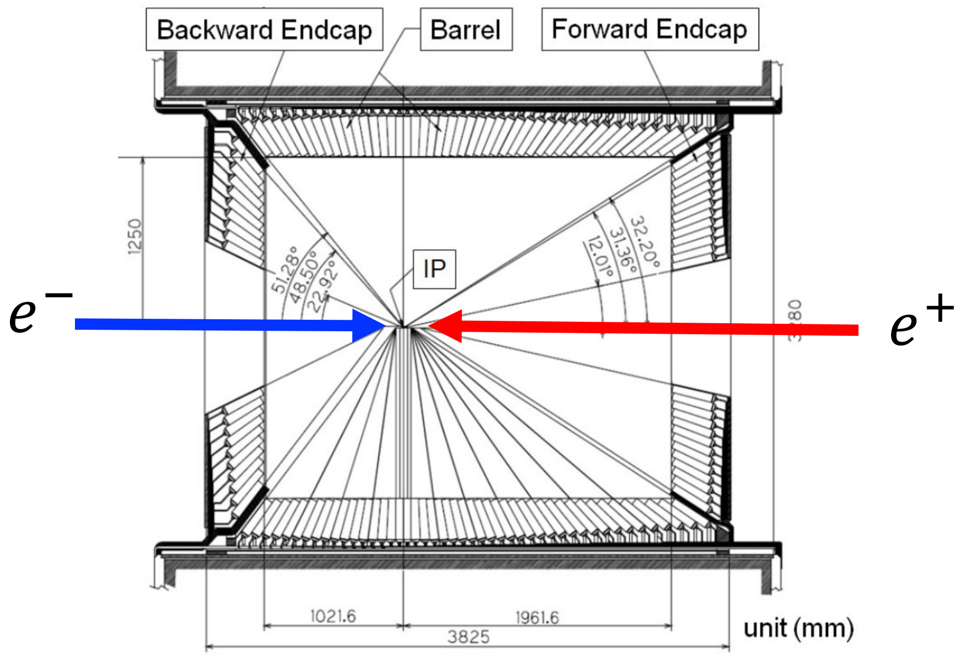
2 charged particles : 72%   4 charged particles : 25%

fewer tracks

- Electromagnetic calorimeter (ECL) is mainly used to select tau decay events.

Electromagnetic calorimeter (ECL)

- Combination of Thallium doped Cesium Iodide scintillator and photodiode

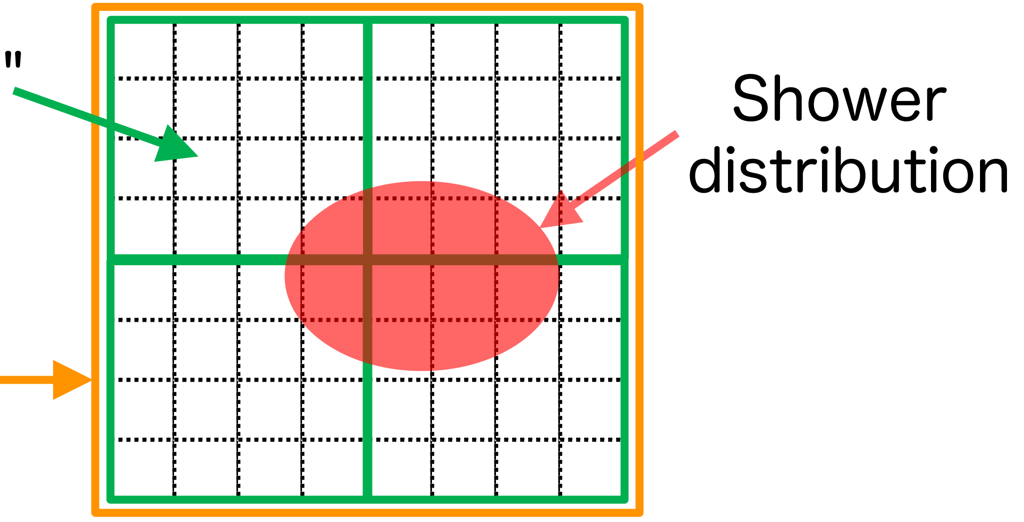


<u>Measurable Information</u>

- Energy loss of particles
- Position where the particle passed

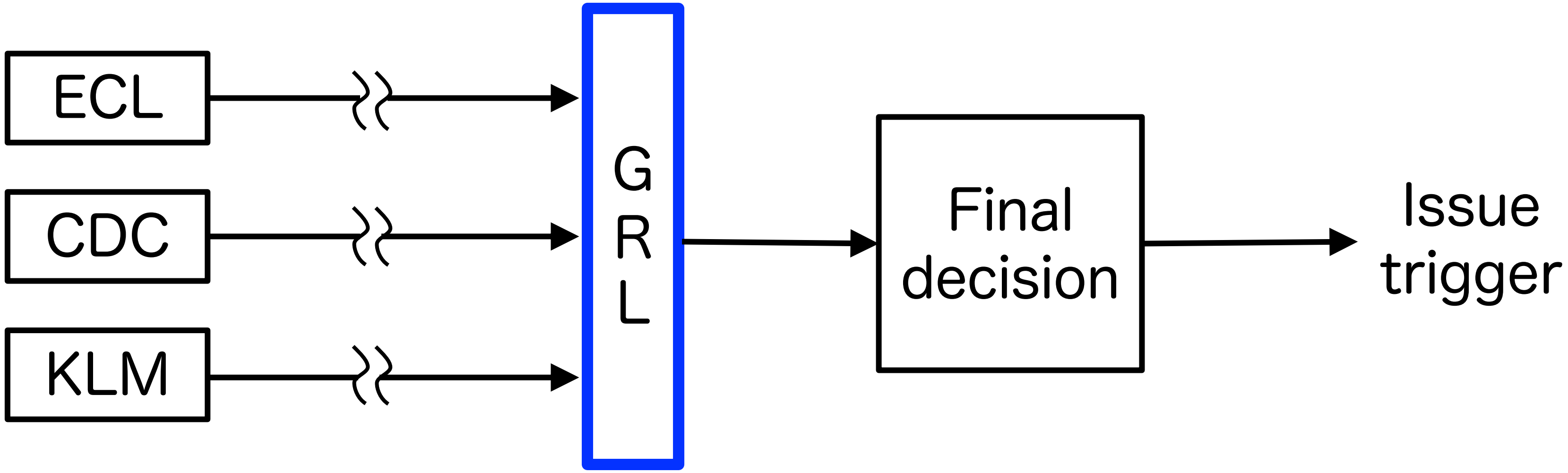
- 4x4=16 crystals are combined as a "trigger cell" for hardware trigger purpose

- The entire trigger cells triggered by a single particle is called a "cluster"



Hardware trigger system

- Select events to reduce DAQ readout rate and data volume
- Total latency must be below 4.4 μs → Online data processing using FPGA



GRL (Global Reconstruction Logic)

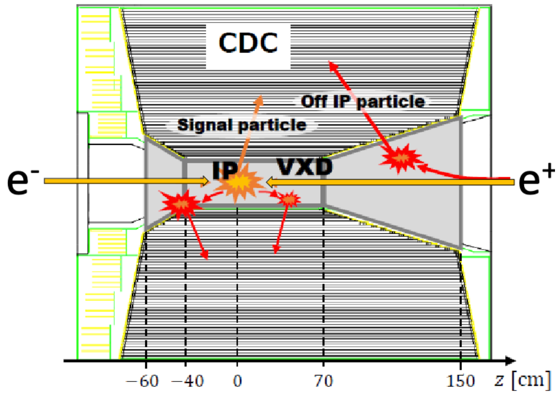
- Combine information from each detector to identify particles, etc.
- Limitation
  - Trigger rate of ECL < 15kHz
  - Latency < 500 ns

Motivation and purpose of this research

■ Tau generate fewer daughter particles than B mesons and are difficult to trigger.

→ Current trigger for tau particle decay is susceptible to <u>background events</u> (～1kHz)

Main component is beam background from beam pipe near the detector.



<u>Challenge</u>

When luminosity improves in the future, trigger rate will reach the limit of 15kHz

⇩ focus on machine learning

<u>Purpose of this research</u>

Make low rate and high purity hardware trigger

Develop a new tau decay event trigger using neural network and implement it in GRL

Neural network performance goal	
Trigger rate	less than 15kHz at Instantaneous luminosity $6.0\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Latency	below 500 ns
Resource	Fits inside GRL's FPGA

Convert neural network to hardware

■ hls4ml (high level synthesis for machine learning)

automatically converts Python machine learning models to FPGA firmware

Building and training models with Python → Convert to HLS project (C++) → Create IP core by HLS and Implement on FPGA

Keras

hls4ml

Vivado™ HLS

Easy to use with famous open source

- Can be converted in minutes to hours
- Quantization: Quantize weight and bias values
  Parallelization: Perform multiple calculations simultaneously within FPGA

→ Adjustable to suit resource and latency demands

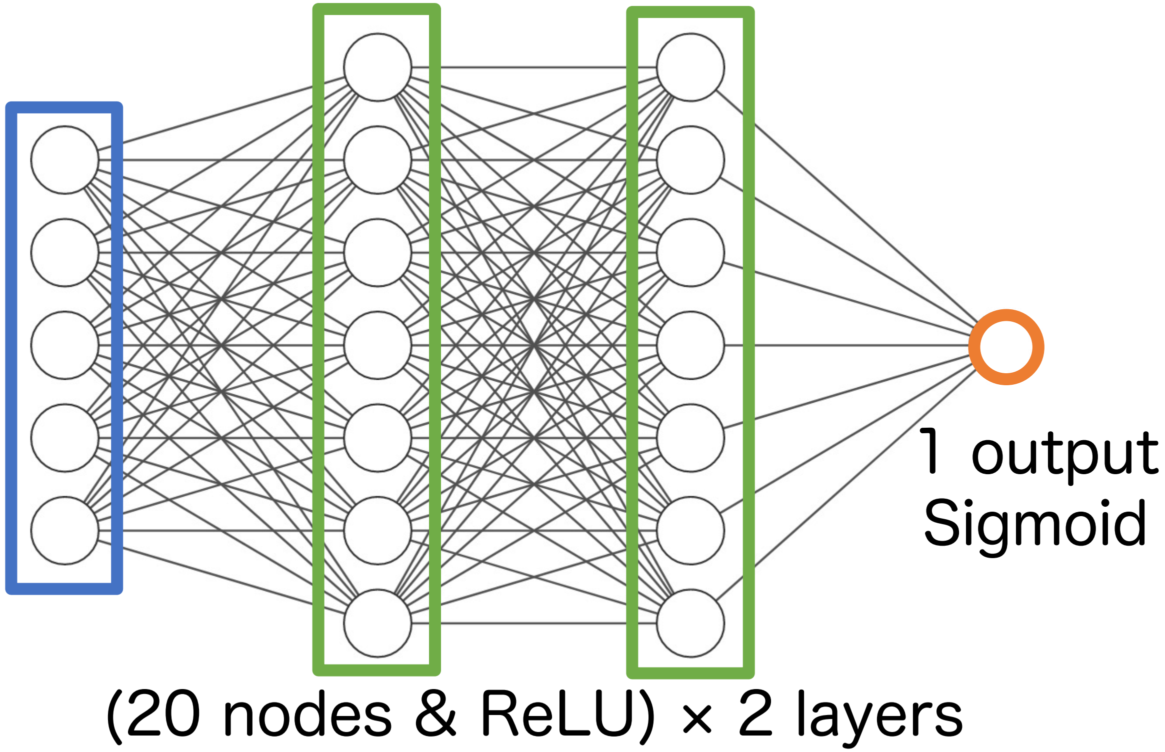
Neural network model and training data

Input only information from ECL

Input data	Num
Number of clusters	1
Energy of clusters	6
Polar angle of clusters	6
Azimuth angle of clusters	6

※Information of up to 6 clusters is sent from ECL.

19 inputs

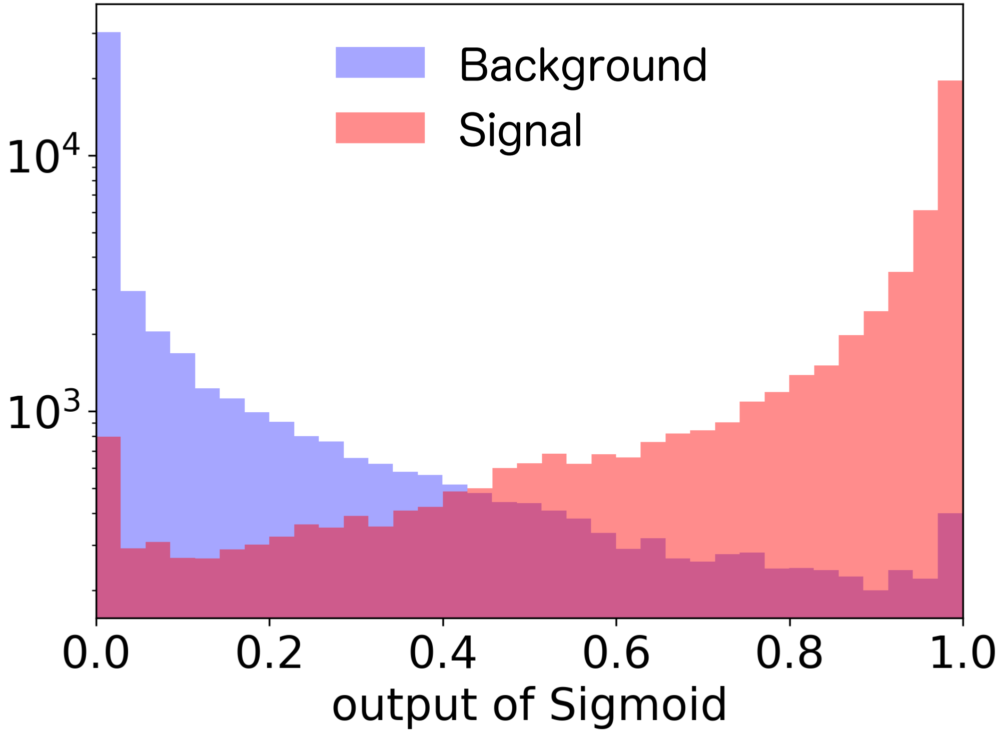


■ Dataset：Analyze experimental data and adding flags

Name	Detail	Flag	Training data	Test data
Signal	Tau decay like events, selected by initial offline event tagging	1	280k events	70k events
Background	All others triggered by the current hardware trigger	0	280k events	70k events

Neural network output

Output when inputting test data

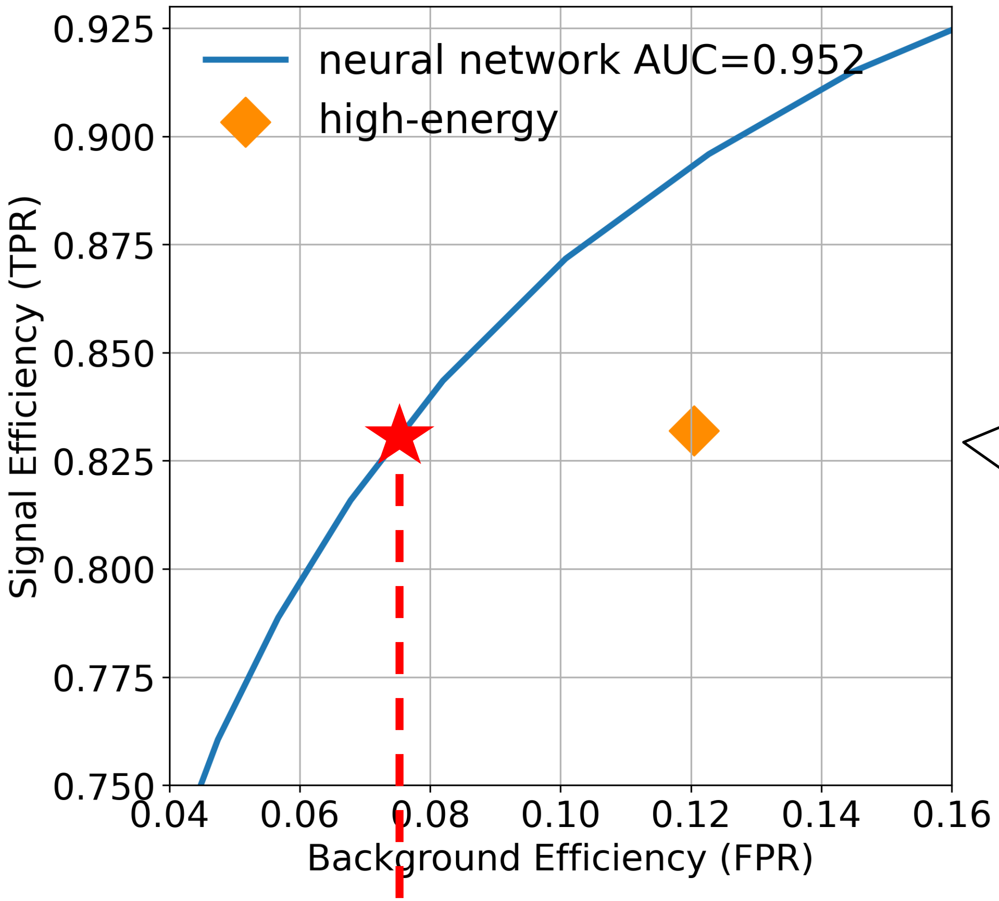


← During physics data taking, we set a threshold value on the output to decide whether to issue a trigger or not.

Efficiency can be easily changed by moving the threshold
→ Much more flexible and adjustable than cut-based trigger logic

Performance evaluation

ROC curve



Expected to be about 9kHz (<15kHz) at luminosity $6\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

■ Main existing ECL trigger used for tau decay

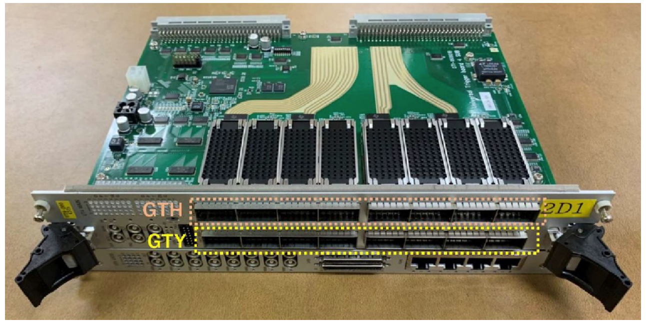
Name	Concept
high-energy	Total energy > 1 GeV while eliminating Bhabha scattering

- Vertical axis : Signal Efficiency
  = ratio of tau events that were correctly determined
- Horizontal axis : Background Efficiency
  = ratio of background events that were incorrectly determined to be tau events

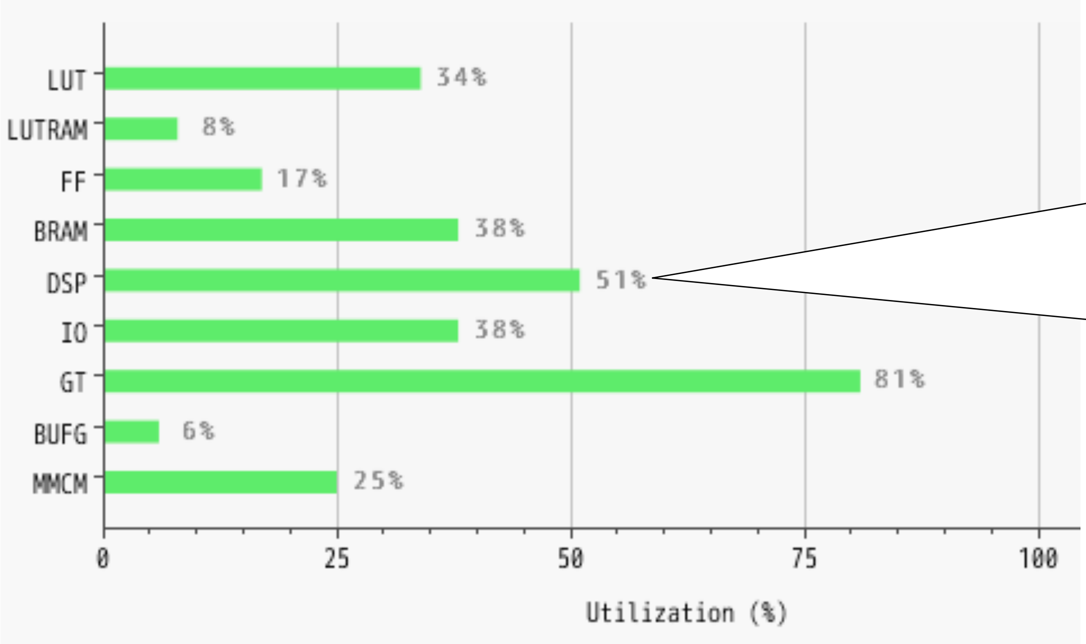
Neural network can reduce background by about 40% compared to 'high-energy'.

Implementation in GRL

■ GRL's FPGA ： Xilinx Virtex UltraScale XCVU080



FPGA resource usage



DSP= responsible for multiplication, addition and subtraction

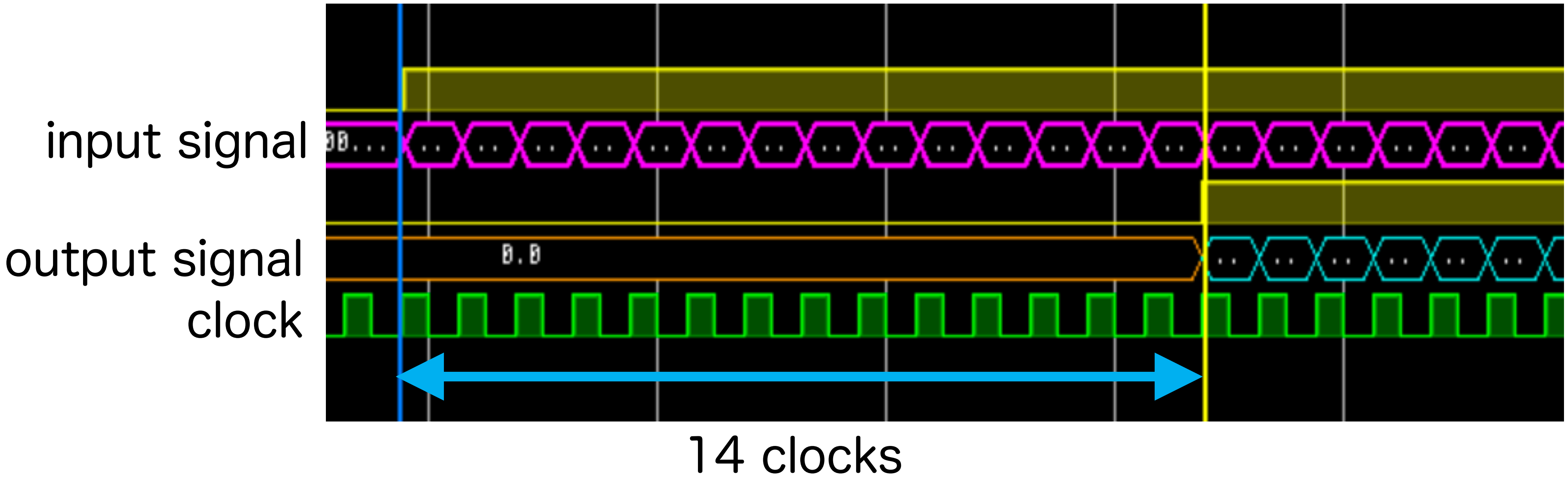
- Before adding neural net ：0%
- After adding neural net ：51%

Often used in fully connected layers

This neural network fits within GRL's available resources and implementation completed.

Implementation in GRL

Timing　　　Clock freq ＝127MHz



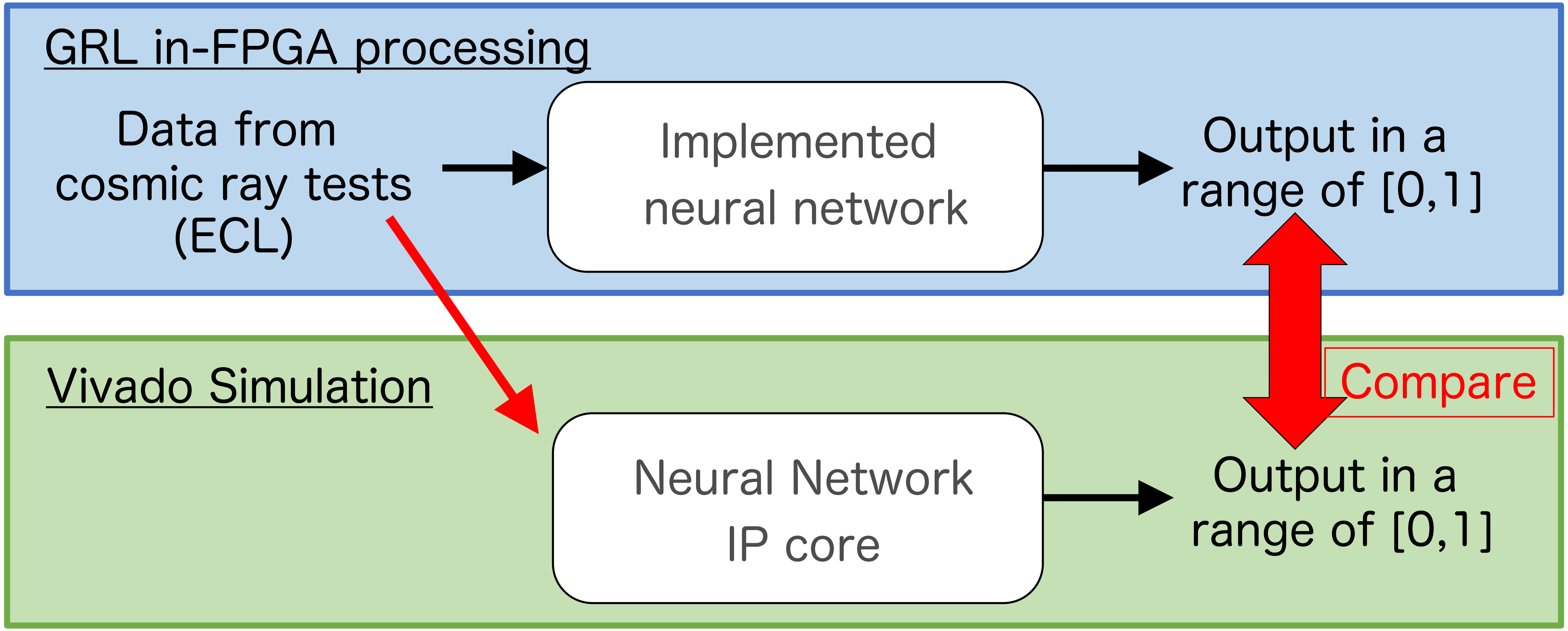
It takes 14 clocks from input to output ≈ 110 ns (< 500 ns)

Computation time of neural network is below the GRL latency limit

※ Accepts new input every clock and outputs every clock (pipeline processing)

Operation confirmation by cosmic ray test

- Actual measurements of cosmic rays with the Belle II detector and comparison of data with simulations



- We confirmed the implemented hardware functions as expected.

  → Plan to actually use it from the next physics run (from January 2024)

Summary

- In the Belle II experiment, we plan to significantly improve luminosity.
  Hardware triggers with low rate are required.

- We created a new trigger logic for tau particle decay with neural network.
  - It can reduce trigger rate compared to the existing one.

- Implementation has been completed in the Belle II hardware trigger system.
  - It cleared constraints of timing and resource.

- This trigger will be used from the next physics run (January 2024 ~).