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Operation of the Neural z-Vertex Track Trigger for Belle II in 2021 - a Hardware Perspective

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Abstract. To reduce the background the z-Vertex Track Trigger estimates the collision origin in the Belle II experiment using neural networks. The main part is a pre-trained multilayer perceptron. The task of this perceptron is to estimate the z-vertex of the collision to suppress background from outside the interaction point. For this, a low latency real-time FPGA implementation is needed. We present an overview of the architecture and the FPGA implementation of the neuronal network and the preprocessing. We also show the handling of missing input data through preprocessing with specially trained neuronal networks implemented in hardware. For this, we will show the results of the z-vertex estimation and the latency for the implementation in the Belle II trigger system. Major update for the preprocessing stage utilizing a 3D Hough transformation processing step is ongoing.

1. Introduction

The Belle II experiment at the asymmetric-energy electron positron collider SuperKEKB in Tsukuba, Japan, aims for high precision measurements of CP violation in the B-meson system and searches for new physics beyond the Standard Model in rare decays of B-mesons and τ leptons. Recently, SuperKEKB has reached a luminosity record of 3.8×10^{34} cm^{-2}s^{-1}, but is also facing large backgrounds from beam interactions with accelerator components (beam pipe, focusing quadrupoles, etc.) away from the collision area the so-called interaction point. To ensure that mainly physics-relevant data are stored, a two-stage trigger system has been developed for Belle II. At the first trigger level (L1) the Central Drift Chamber (CDC), the electromagnetic calorimeter (ECL) and the muon detector (KLM), provide deadtime-free, pipelined trigger decisions, followed by the high level software trigger (HLT), executed on a compute farm. The track triggers are derived from the CDC, which has 56 layers and is segmented into five axial superlayers (SL), parallel to the beam (z)-direction, and four so-called stereo SL, interspersed between the axial super layers. Each of the SL contains six adjacent wire layers. The stereo layers enable the measurement of tracks in three spatial dimensions. Initially, only the axial wire layers were used for the trigger, yielding 2D tracks transverse to the beam directions. This trigger requires at least two tracks and has no possibility to filter out events which come from outside of the interaction point (IP) and is therefore very sensitive to the dominating background.

Here, a new track trigger, based on neural networks, uniquely provides the z component of the tracks, thus enabling the trigger to reject most of the background from outside of the

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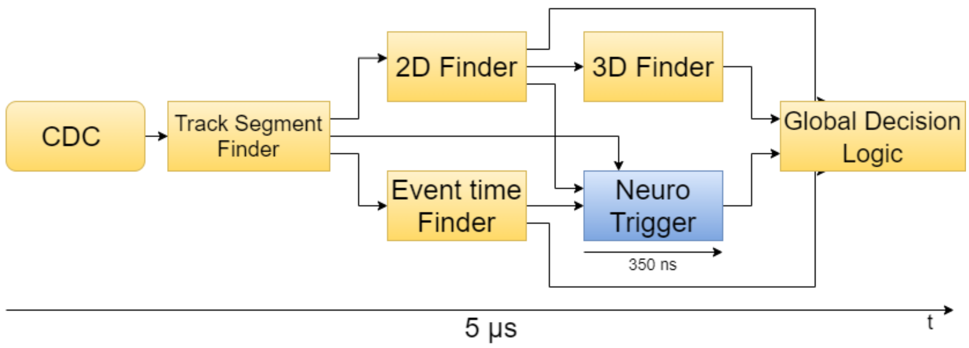

Figure 1. Schematic of the CDC L1 Trigger chain. The Neuro Trigger denotes the z-vertex track finder, based on neural networks.

IP. The neural z-vertex track trigger is presented here, mainly concentrating on the hardware aspects, giving some details on its performance, and discussing some developments for the near future [4, 6].

The L1 CDC trigger consists of a set of distinct FPGA systems, operating in sequence and in parallel, as seen in fig. 1. At the end of the chain the Global Decision Logic (GDL) is located, in which all the trigger signals of the CDC subsystem come together, as well as those from the other subdetectors (not shown in fig. 1). For the complete L1 trigger chain, from the CDC frontend (denoted by "CDC" in the figure) to the GDL, the latency budget is only 5 μs. After receiving the analog signals from the total of 14,336 drift wires, the CDC frontend electronics sends the digitized and zero-suppressed signals to the Track Segment Finder (TSF) [1]. The TSF arranges the wire signals in each of the superlayers into certain geometrical patterns ("hour-glass" shapes), so-called Track Segments (TS). The signals from the central wires in these 2336 TS patterns are then fed into the 2D Finder and the Event Time Finder [7]. Based on the signals from the TSF, the 2D Finder uses Hough transforms to determine a 2-dimensional track, while the Event Time Finder is used to calculate the drift times in each of the central wires in the TS. From there, two different algorithms are implemented in FPGAs, namely the 3D Finder [3] and the z-Vertex Track Trigger. The 3D Finder tries to determine the origin of the collision in the z direction using a linearized least square algorithm, but is not yet operational. The z-Vertex Track Trigger estimates the z coordinate and the polar scattering angle θ of each track in the event. These results are then transmitted to the GDL which decides whether or not to start the full readout of the event and hands the data over to the second trigger stage, the High-Level-Trigger, executed in software.

2. The z-Vertex Track Trigger

The z-Vertex Track Trigger estimates the collision origin on the z-axis and the polar scattering angle θ for each track in the event. For this purpose, an existing track of the 2D Finder is taken and fed with additional data from the stereo track segments into a pre-processing step, followed by a fully connected single-hidden-layer neural network. The complete architecture is shown in fig. 2 and implemented on 4 Universal Trigger Board 3 (UT3) on a Virtex 6 FPGA (XC6VHX380T), one for each quadrant of the CDC.

The complete architecture is pipelined and needs only 288 ns for the calculation, including the preprocessing. This is within the acceptable latency range of 350 ns specified by the trigger system. The z-Vertex Track Trigger consists of 4 UT3 FPGAs working in parallel, each covering a quadrant of the CDC. This allows a maximum of 4 tracks to be estimated simultaneously. The input consists of a 2-dimensional track from the 2D Finder with the corresponding axial track

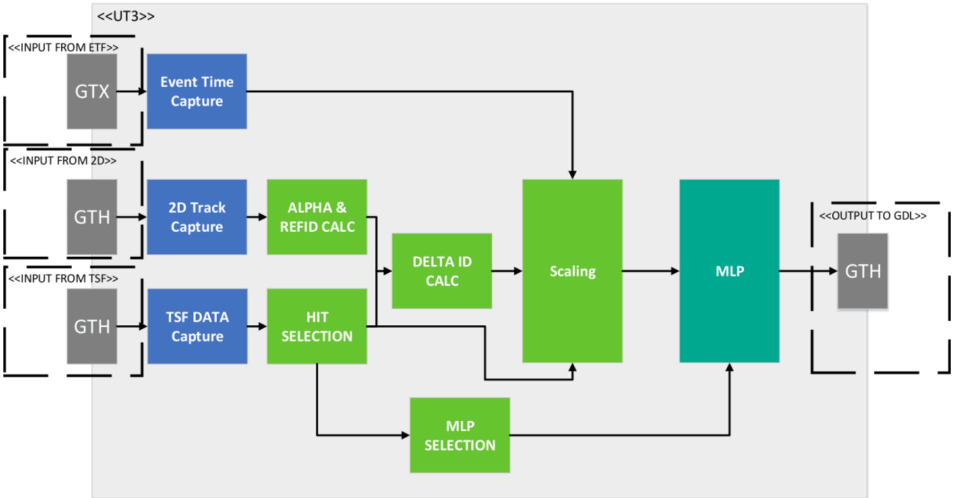

Figure 2. Hardware architecture for the z-Vertex Track Trigger [5]

segments and the possible stereo track segments from the Track Segment Finder. In addition, the time of the collision from the Event Time Finder is used to improve the spatial resolution. This data must be stored temporarily because of the different arrival times of the track segments, caused by the drifttime of maximally 500 ns. This is done in the capture units (TSF Data Capture, 2D Track Capture, Event Time Capture). The data is then pre-processed to select the appropriate stereo track segments based on the 2-dimensional track. Since it can happen that stereo track segments are missing due to latency constraints or inefficiencies in the CDC, speciall neural networks ("expert") are trained that can compensate for the omission of one of the four stereo track segments. These expert networks (expert 1-4) differ only in the weights and are loaded dynamically with the MLP selection that gets the track segment information from the hit selection. If all stereo track segments are present, expert 0 is selected. After the track segment selection, the input data for the neural network are prepared and an expert net is loaded. For each track segment in the track three variables are determined: the angle α describes the particle direction through the track segment and $\Delta\phi$ describes the deviation of the track to the track segment center for the stereo TS. Additionally, the drift time is calculated, subtracting the event time from the measured drifttime. This is done for each of the 9 super layers in parallel and results in 3*9=27 inputs for the neural network. The neural network consists of a classical feed-forward multilayer perceptron with 27 input neurons, 81 hidden layer neurons, and 2 output neurons (z and θ). Over the year 2020, the z-Vertex Track Trigger was integrated into the Belle II trigger system and tested extensively. The z-Vertex Track Trigger has been active since March 2021 and has been running stably ever since.

3. Vertex Resolution

The most important parameter for the z-vertex track trigger is the accuracy of the estimated z vertex along the beam axis. For this, Δz is used, which is the value estimated by the MLP minus the actual origin of the collision determined by the offline reconstruction. Figure 3 shows the resolution of the z-vertex track trigger for reconstructed tracks coming from the IP for all expert meshes. On the left are the Δz with a $\sigma = 4.51$ cm resolution as well as the vertex cut at $|z| < 15$ cm which roughly corresponds to a 3σ cut. The right plot shows the azimuth angle distribution over 360 degrees. The excess around zero degrees corresponds to the expectations from the transverse boost caused by the crossed electron and positron beams in the center of

Belle II.

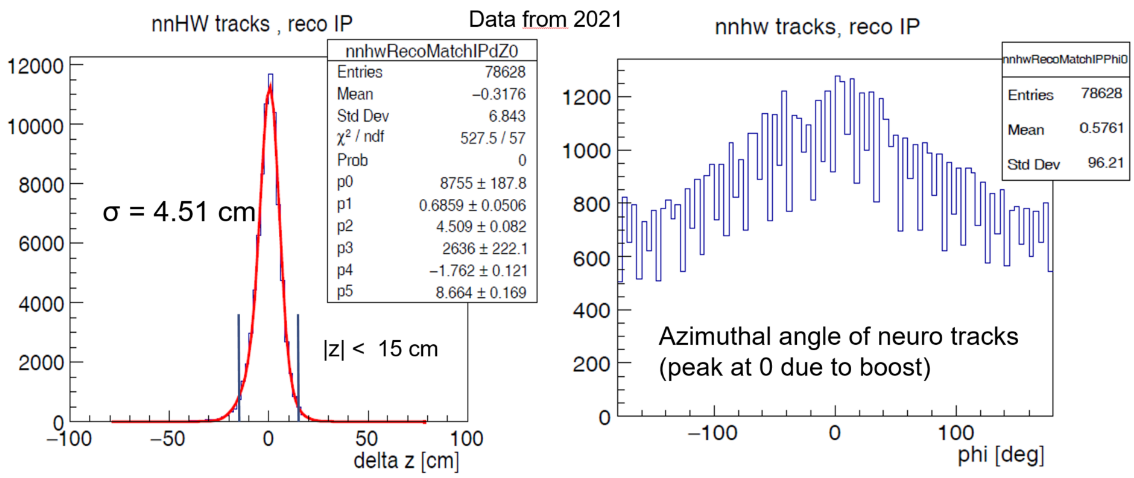

Figure 3. Resolution of the z-vertex from the neural estimates. On the right side the azimuthal distribution of the neural track is shown.

Figure 4 shows the different resolutions between expert net 0, where all stereo TS are present, and the expert nets 1-4 where one stereo layer is missing. In the right part, the azimuth angle distributions is shown. In the azimuthal distribution one observes a dip around 50°, caused by wire inefficiencies of the CDC. This inefficiency is compensated by the expert nets 1-4 (peak around 50°) which process the data with the missing stereo track segments. As expected, the z resolution is best at expert 0 with $\sigma = 3.8$ cm because all data are available here. For the expert networks 1-4, the resolution is still $\sigma = 5.9$ cm. Since expert net 0 is used most often and has the best resolution, the total resolution of all expert nets is $\sigma = 4.51$ cm (see fig. 3).

4. The "STT": a Minimum Bias Single Track Trigger

With the help of the estimated z position of the z-Vertex Track Trigger and the momentum determined by the curvature radius of the 2D track and the polar angle θ from the networks, a minimum bias single track trigger (STT) was realized. The STT has the conditions that at least one track is found in the range $|z| < 15$ cm around the interaction point (IP) (all other track triggers require at least 2 tracks). Furthermore the track is required to have more than 0.7 GeV (this is the minimum bias condition) to filter out the overwhelming rate of QED events coming from the IP. Figure 5 shows the distribution of the momentum p of reconstructed tracks against the z-coordinate. One clearly sees a large concentration of tracks with momenta less than 1 GeV. The momentum cut for the STT is shown as the horizontal dashed line.

The STT has been in operation since March 2021 and has been very stable in efficiency and trigger rate since then. Trigger analyses have shown that the efficiency of the STT is well above 95% for tracks above 0.7 GeV. This makes the STT the most efficient track trigger in the Belle II L1 trigger. In addition to its high efficiency, the STT also finds tracks that were previously suppressed by the 2-track L1 trigger and thus lost to physics analysis. Up to 12% of the tracks triggered by the STT can only be found by the STT.

5. Future Updates 3D Hough

The z-Vertex Track Trigger with the SST is the most efficient track trigger in the Belle II Trigger System, but there are still possibilities to improve this efficiency. Currently, the z-Vertex Track

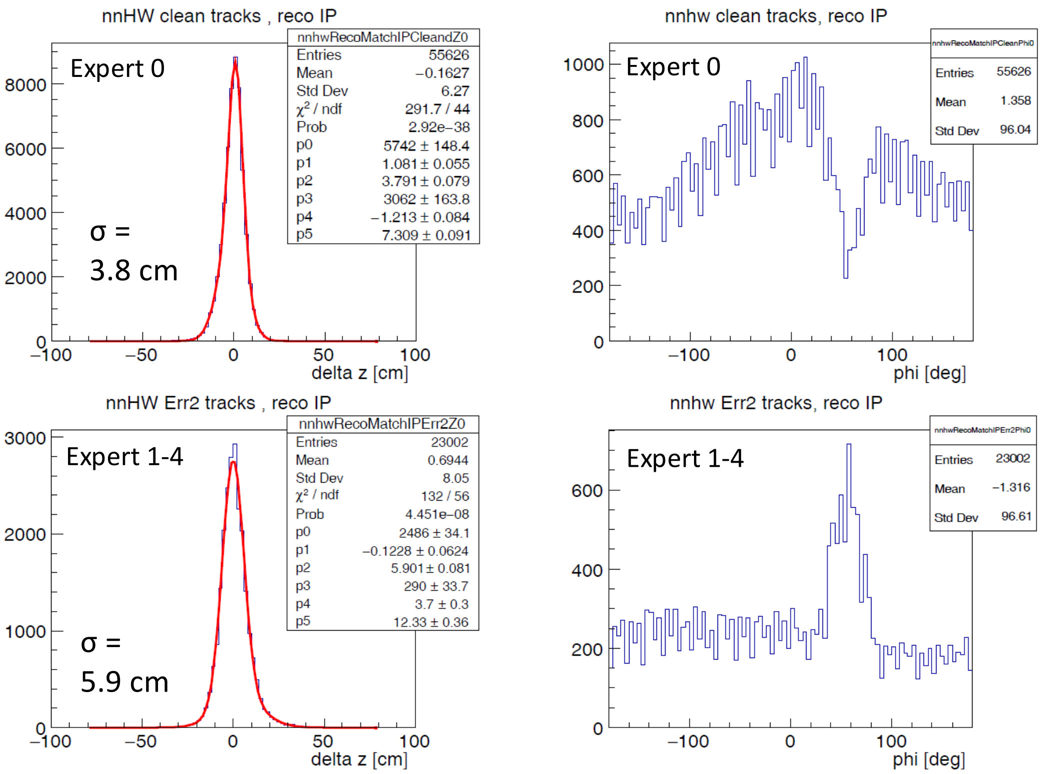

Figure 4. Resolution of the z-vertex for expert net 0 (top row) and expert net 1-4 (bottom row), see text.

Trigger requires a found 2-dimensional track from the 2D Finder. It has been shown that a 3D Hough [2] preprocessing gives better results than the 2D finder, especially in the regions of shallow polar scattering angles and low transverse momentua. Prototype designs already exist which are also implemented in FPGA. These still have to be merged and tested in operation.

6. Summary

Since March 2021, the z-Vertex Track Trigger has been in active operation in the Belle II experiment. It estimates the origin of the collision along the beam axis using neural networks. At its core is a set of multilayer perceptron, which can be used to determine the origin on the beam axis with a resolution of $\sigma = 4.51$ cm. This allows realizing a 15 cm cut which suppresses background noise. With the origin information and the particle momentum, a minimum bias single track trigger has been realized. This allows to trigger on events to which the standard 2 track trigger was blind. The STT is the most efficient track trigger in the Belle II trigger system. To increase the efficiency in case of missing data from the stereo segments, so-called expert networks have been trained to retain efficiency.

The whole functionality is implemented on the FPGA hardware UT3 used in the experiment. The z-vertex track trigger architecture is fully multiplexed and meets the latency requirements with 288 ns for the complete preprocessing plus the MLP. For the future, an update of the data preprocessing to a 3D Hough process on the new FPGA platform UT4 is planned.

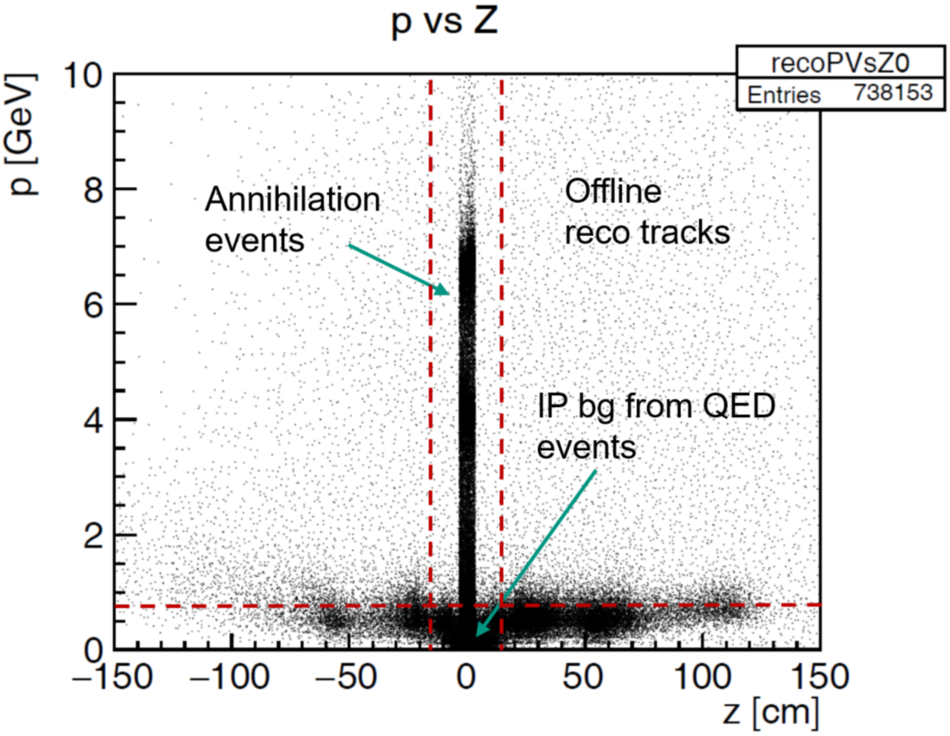

Figure 5. Distribution of the momentum p in GeV against the z impact in cm of fully reconstructed tracks. The required cut of $p < 0.7$ GeV for the STT is evident.

Acknowledgments
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