From 2D to 3D tracking trigger

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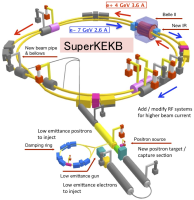
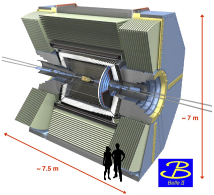
Introduction

- The Belle II detector is an e^+e^- collider situated in Tsukuba, Japan, designed to study the properties of B mesons.
- Due to its high luminosity, beam backgrounds become an egregious problem — the DAQ has a limit of processing data. We need to select out most of the backgrounds before they enter the DAQ.





Introduction

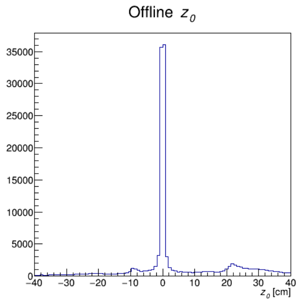
Imagine you want to choose all the most expensive tuna sushi while selecting out all the cheap cucumber rolls in a high speed Sushi train...

Introduction

The 3D tracker

- It determines the **z-vertex (z_0)** and **polar angle (θ)** of the tracks using **geometric transformations** and **linear regressions,** utilizing the information from the CDC (central drift chamber).

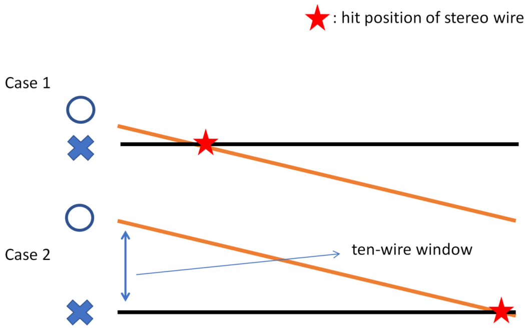
- One important characteristic of beam backgrounds — they are usually not originated from the interaction point (IP). A 3D tracking module is designed to exploit this fact to skim off beam backgrounds.



Principles

The z position finder (also known as the 3D finder)

- Some wires of the CDC are tilted on purpose (we call them stereo wires). For each stereo wire, there will be a z position. By comparing the difference between the hit position with tilting (actual hit position) and that without tilting, we can measure the z position.
- The Belle II CDC has four stereo layers, so the 3D tracker has four ten-wire windows.



Principles

Linear regression fitting

- Linear regression fitting is applied to obtain z_0 and θ using s (arc length of the track in 2D) and z information, where σ_i is the error of the z position:

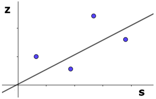
$$\chi 2 = \sum_{i=0}^{4} \frac{[z_i - (\cot\theta \times s_i + z_0)]^2}{\sigma_i^2}.$$

- The cotθ and the z_0 that minimize the χ^2 can be found analytically as below:

$$\cot\theta = \frac{\sum_{i=0}^{4}(\frac{1}{\sigma_i^2})\sum_{i=0}^{4}(\frac{s_i z_i}{\sigma_i^2}) - \sum_{i=0}^{4}(\frac{s_i}{\sigma_i^2})\sum_{i=0}^{4}(\frac{z_i}{\sigma_i^2})}{\sum_{i=0}^{4}(\frac{1}{\sigma_i^2})\sum_{i=0}^{4}(\frac{s_i^2}{\sigma_i^2}) - \sum_{i=0}^{4}(\frac{s_i}{\sigma_i^2})\sum_{i=0}^{4}(\frac{s_i}{\sigma_i^2})}$$

$$z_0 = \frac{-\sum_{i=0}^{4}(\frac{s_i}{\sigma_i^2})\sum_{i=0}^{4}(\frac{s_i z_i}{\sigma_i^2}) + \sum_{i=0}^{4}(\frac{s_i^2}{\sigma_i^2})\sum_{i=0}^{4}(\frac{z_i}{\sigma_i^2})}{\sum_{i=0}^{4}(\frac{1}{\sigma_i^2})\sum_{i=0}^{4}(\frac{s_i^2}{\sigma_i^2}) - \sum_{i=0}^{4}(\frac{s_i}{\sigma_i^2})\sum_{i=0}^{4}(\frac{s_i}{\sigma_i^2})}.$$

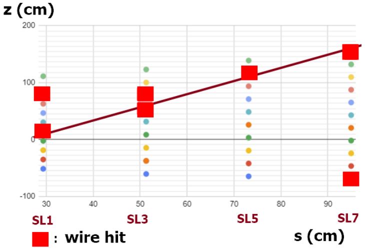
- All the calculation implemented in the FPGA board. The total latency of the 3D tracker is ~400 ns.



Principles

If there are multiple wire hits in a ten-wire windows, which one should be used?

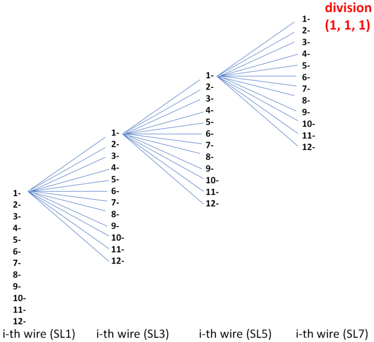
- Middle algorithm: choose the middle one (because they are closest to the IP).
- LUT (lookup table) algorithm: loop all the configurations of wire hits to find the one with the smallest χ^2 — all the possible χ^2 are precalculated and stored in a LUT for loop up. A psedo wire hit at the IP ($s = 0$, $z = 0$, $\sigma = 1$) is introduced to facilitate the fitting.



Principles

Divide and conquer method for the LUT algorithm

- There are $12 \times 12 \times 12 \times 12$ wires (including some pseudo wires) in the LUT algorithm. They are divided into smaller groups stage by stage (four stages) until there are only twelve wires in each group.
- Implement a four-round competition, then we will find which configuration of wire hits has the smallest χ^2.

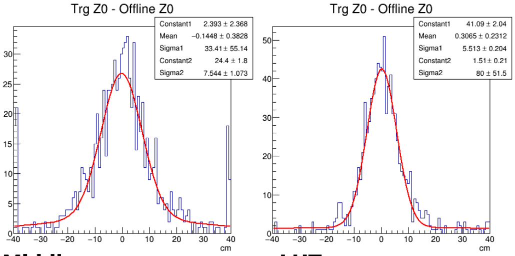


Results

The 2020 Belle II data shows that with $|z_0| < 35$ cm applied:

- The 3D tracker using Middle algorithm
  - Reject ~38% of the background events (relative to using 2D information only) — **this matches the results of another tracking module in our collaboration.**
  - keep ~97% of the signal events.
- The 3D tracker using LUT algorithm (test version; $9 \times 9 \times 9 \times 10$ window size)
  - Reject ~87% of the background events (relative to using 2D information only).
  - keep ~70% of the signal events.
  - Obtain greatly improved z_0 resolution

The 3D tracker using LUT algorithm (test version) shows greatly improved z_0 resolution and background rejection power, but the efficiency is lower — this is in our estimate because the test version only caught "very good" tracks (those tracks having valid wire hits in every stereo layer). The complete version (full window size) did not catch the beam run in 2020, but it is ready to launch.



Summaries

- We have designed a 3D tracker for the Belle II detector. It determines the z-vertex and the polar angle of the tracks using geometric transformations and linear regressions so as to reject the egregious beam backgrounds in the experiment.
- The 3D tracker using Middle algorithm can reject 38% of the background events (relative to using 2D information only) remaining 97% of the signal events when a $|z_0| < 35$ cm cut is applied.
- The 3D tracker using LUT algorithm (test version) shows greatly improved z_0 resolution and background rejection power, but the efficiency is lower. The complete version is ready to launch. We expect the efficiency can be saved and resolution will remain the same high.