

# Belle II Track Reconstruction and Results from first Collisions

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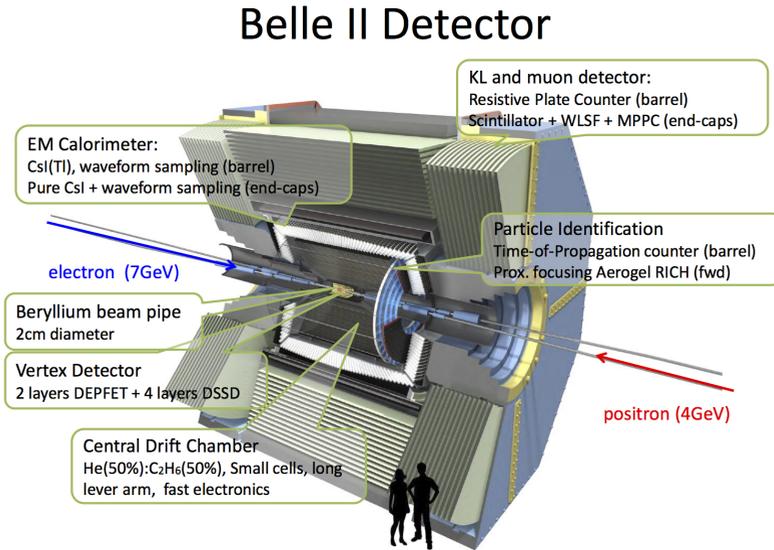
**Abstract.** In April 2018,  $e^+e^-$  collisions of the SuperKEKB B-Factory have been recorded by the Belle II detector in Tsukuba (Japan) for the first time. The new accelerator and detector represent a major upgrade from the previous Belle experiment and will achieve a 40 times higher instantaneous luminosity. Special considerations and challenges arise for track reconstruction at Belle II due to multiple factors. This high luminosity configuration of the collider increases the beam-induced background by many factors compared to Belle and a new track reconstruction software has been developed from scratch to achieve an excellent physics performance in this busy environment. Even though on average only eleven signal tracks are present in one event, all of them need to be reconstructed down to a transverse momentum of 50 MeV and no fake tracks should be present in the event. Many analyses at Belle II rely on the advantage that the initial state in B-factories is well known and a clean event reconstruction is possible if no tracks are left after assigning all tracks to particle hypotheses. This contribution will introduce the concepts and algorithms of the Belle II tracking software. Special emphasis will be put on the mitigation techniques developed to perform track reconstruction in high-occupancy events. First results from the data-taking with the Belle II detector will be presented.

## 1 Introduction

The Belle II experiment is operated at the asymmetric electron-positron collider SuperKEKB and recorded its first hadronic collision event at the end of April 2018. It is the successor of the Belle experiment, which ran from 1998 to 2010, and uses the same operating principle as the former KEKB collider to confirm the violation of  $CP$  symmetry in the  $B$  meson system. As a so-called B-factory, SuperKEKB operates on the  $\Upsilon(4S)$  resonance, which allows it to produce and record data from a large number of  $B$  mesons. With the upgrade, the instantaneous luminosity will be increased by a factor of 40 to  $8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$ . Ultimately, Belle II is expected to record 50 times more collisions than Belle and to significantly increase the sensitivity of various searches and measurements [1]. Both the detector [2] and the software [3] used to process the data have been upgraded to take advantage of technological developments and to be able to handle the greatly increased data rate.

The Belle II detector design, illustrated in figure 1, continues to use many proven hardware options of Belle but is significantly upgraded in other areas. The innermost silicon-based tracking system VXD is a new development and consists of two layers of pixel sensors (PXD) and four layers of strip sensors (SVD), which are arranged in ladders around the interaction point. Following this is the central drift chamber (CDC) which uses the technologies proven

in Belle and was sufficiently upgraded to support higher-occupancy environments. Next are the Time-of-Propagation (TOP) system in the barrel region and the Aerogel Ring Imaging Cherenkov counter (ARICH) system in the endcap area which provide particle identification. These inner parts of the detector are located inside of a 1.5 T strong magnetic field. Finally, the electromagnetic calorimeter and the K-Long and Muon Detector (KLM) complete the instrumentation of Belle II.

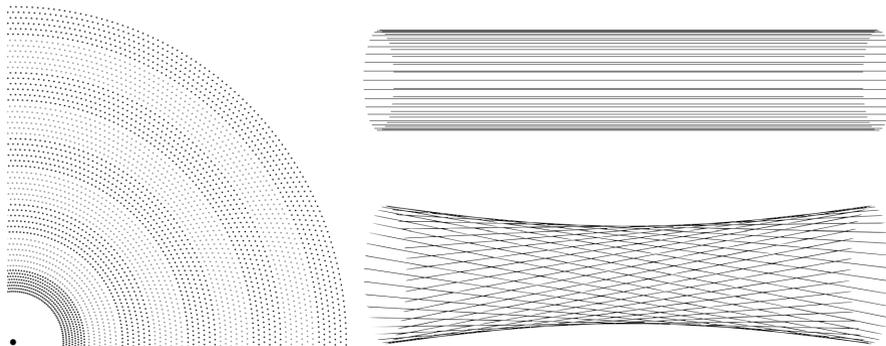


**Figure 1.** Illustration of the Belle II detector.

## 2 Belle II Tracking Detectors

The Belle II innermost silicon-based tracking system is a completely novel development and combines double-sided strip sensors on four outer layers and DEPFET pixel sensors for the inner two layers. This novel tracking system is able to improve the longitudinal impact parameter resolution  $\sigma_z$ , compared to Belle, by a factor of two in the momentum region larger than 300 MeV and achieves an absolute resolution of 15  $\mu\text{m}$  for charged particles with an energy larger than 1 GeV.

The inner volume of the CDC contains 14,336 sense wires, defining drift cells with a size of about 2 cm. The sense wires are arranged in layers, where 6 or 8 adjacent layers are combined in a so-called superlayer, as seen in figure 2. The outer eight superlayers consist of six layers with 160 to 384 wires. The innermost superlayer has eight layers with 160 wires in smaller (half-size) drift cells to cope with the increasing background towards smaller radii. The superlayers alternate between axial ("A") orientation, aligned with the solenoidal magnetic field (z-axis), and stereo ("U", "V") orientation. Stereo wires are skewed by an angle between 45.4 and 74 mrad in positive or negative direction. The direction changes sign between U and V layers, with a total superlayer configuration of AUAVAUAVA. By combining the information of axial and stereo wires, it is possible to reconstruct a full 3D track.



**Figure 2.** Left: Quadrant of a slice of the  $r$ - $\phi$  projection of the drift chamber. The innermost superlayer contains eight layers, the following ones each six. Right: Visualization of stereo wires relative to axial wires. The skew is exaggerated.

### 3 Tracking Environment and Challenges

The most prominent event topologies used in B-factories analysis are  $\Upsilon(4S) \rightarrow BB$  decays. On average, these events contain 11 charged tracks from the  $B$  decays. Additional topologies used in physics analyses are low-multiplicity events like  $\Upsilon(4S) \rightarrow \tau\tau$  or  $\Upsilon(4S) \rightarrow \mu\mu$  decays, which result in just one or two charged particles in the detectors acceptance region.

A major challenge for track reconstruction at Belle II is the machine induced-background which has increased approximately ten times compared to Belle. This results in large parts of the hits recorded in the PXD, SVD and CDC detectors to originate from background radiation sources and not from the primary interaction. For the SVD, this signal-to-background hit ratio is 1:6, while for the CDC it is 1:2.

One major advantage of B-factories over proton colliders, like the LHC, is that the kinematics of the initial B-pair state is well known. This allows to perform analyses which rely on missing energy techniques or involve neutral particles like  $\pi^0$ . To leverage this advantage for physics analyses, as many particle as possible need to be properly reconstructed to get the best missing energy resolution achievable. Collision particles, which have not been reconstructed, or so-called fake particles which were not present in the collision but are artifacts from a sub-optimal reconstruction procedure degrade the missing momentum resolution. For the tracking system, this means that all charged particles, even down to very low momenta, need to be reconstructed and a very low fake rate needs to be achieved.

Belle II's approach to achieve these goals is to employ specific tracking algorithms which are tailored for the specific sub-detectors and using selection criteria in each step of the processing to limit the number of wrong track combinations as early as possible.

### 4 Tracking Architecture

The Belle II Experiment developed the `basf2` framework which is based on C++ and allows to implement reconstruction algorithms as modules which are loosely coupled and transfer data only via a common exchange container, named `DataStore`. This allows to split the reconstruction task as a chain of independent and interchangeable modules. The `RecoTrack` class is used as a common exchange format between algorithms to transfer track candidates from sub-detectors and their respective hits. The final output of the track reconstruction is the

Track class, which contains the tracks with the hits from all sub-detectors and provides the fitted track parameters to the analysis user.

## 5 CDC Track Finding

The first stage of the CDC pattern recognition is to filter out clusters of hits which were most likely produced by background effects. A charged particle creates around 70 hits in the CDC which all have neighbouring hits. In contrast, hits induced by background radiation are isolated or in smaller clusters. This feature is exploited by using a boosted decision tree (BDT) to classify each input hit in a signal or background category and not process hits in the background category further. This procedure is very fast as the runtime scales almost linearly with the amount of input hits, contrary to the downstream pattern recognition steps, and the performance-optimized FastBDT [4] library is used. The benefits include a greatly reduced combinatorial complexity for later track finding stages, which results in a faster runtime and lower fake rate.

One of the employed pattern recognition methods is the global track finder, based on the Legendre transformation [5] of hits in the CDC. Belle II's solenoid provides a longitudinal magnetic field inside of the CDC volume. Charged particles experience the Lorentz force while propagating through the CDC volume and follow helical trajectories. In the Legendre-space, each hit results in a sine curve and all hits originating from one particle intersect at the same location, if energy loss is neglected and the particles are assumed to originate from the interaction point. This simplifies the track-finding to the search for the point where most sine curves intersect. A fast iterative quad tree algorithm [6] is used to search for areas of high curve densities where parameters are shared by one track. The quad search is limited to a certain depth to account for a spread of the intersection points due to energy loss. All points contained within one quad tree cell are then assigned to a track candidate.

As the legendre method assumes that tracks originate from the center of the detector, a second tracking finding method is implemented to search for displaced or very short tracks. This step is called the local finder and builds segments from individual hits in each super layer. For this, a search graph of hits in one CDC super-layer is created and a cellular automaton method searches for connected entries (hits).

In the final step, the track candidates found by the global and local methods are combined to prevent clones and an additional quality criteria are applied on the combined tracks.

## 6 VXD Track-Finding

The VXD track-finding has to be performed with the output from two different detectors with distinct challenges. The SVD relies on the combination of the double-sided strip measurements to so-called space points to have three dimensional hit information for the pattern recognition stage. As it is not known a priori which strip clusters need to be combined with which other cluster on one sensor element, the combinatoric complexity increases with more hits on one sensor and many so-called *ghost hits* are created. In order to achieve excellent tracking efficiency, the novel concept of SectorMaps has been implemented in the Belle II track-finding software. SectorMaps are directed acyclic graphs and model the search space where to look for hits originating from the same particle. Each sensor element is split into multiple sectors and the search relations of these sectors are trained with truth information from simulated events. In addition, the SectorMap does also store various filter criteria which found two-hit or three-hit combinations must fulfil in order to be considered for the track search. For example, a filter can use the computed transverse momentum of a three-hit combination. The cut values of these filters are also automatically trained using simulated events.

A cellular automaton approach is now used to explore the possible combinations of hits provided by the SectorMap to form track candidates. The quality of these track candidates is evaluated with a fast fitting method and candidates of inferior quality are rejected.

Due to the large 20  $\mu$ s read-out window of the DEFPET system and the closeness to the beam, the PXD contains many more background hits than the other detectors and therefore has a very high occupancy. Therefore, the PXD hits are not used in the initial pattern recognition for the VXD system. It proved much more efficient to use the combined SVD and CDC tracks, extrapolate them into the inner two pixel layers and assign compatible PXD hits to the track. This method has the benefit of having a very precise knowledge of the trajectory parameters, which limits the potential PXD hits to pick.

For the PXD hit assignment procedure, a combinatorial kalman filter (CKF) is employed which implements an extrapolation and vectorized kalman update procedure and accounts for magnetic field and energy loss. After compatible hits on the second PXD layer have been found, the track state is updated with these hits to improve the precision when picking hits from PXD layer one.

## 7 Track Combining and Fitting

Combining tracks in the SVD and CDC detectors uses a similar CKF method as for the PXD hit assignment. The final tracks are then fitted with the deterministic annealing filter (DAF) of the GENFIT [7] track fitting package to extract the final trajectory parameters.

## 8 Results from first Collision Data

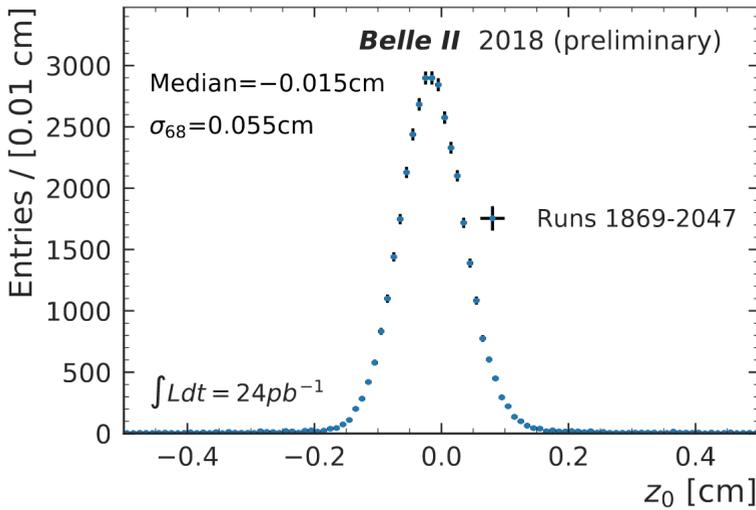
The Belle II Phase 2 run started in February 2018 with the complete outer detectors and a commissioning version of the VXD detector to study the machine background. In this configuration, the VXD was equipped with two PXD ladders and four SVD ladders. This instrumented a small slice in  $\varphi$  with all VXD 6 layers to be installed in Phase 3 in 2019. The CDC was fully instrumented. The first collided electron-positron beam and the detection of hadronic events was achieved in the early morning hours of the 26th of April 2018.

These first events were successfully processed in Belle II's high-level trigger farm (HLT), and online event displays with reconstructed tracks were displayed live in the control room.

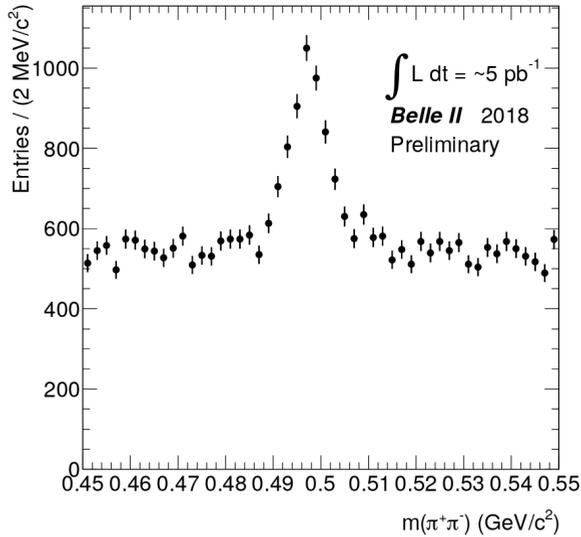
Fast feedback to the SuperKEKB-Accelerator group is important during the early commissioning phase of the accelerator to improve the machine's performance and background environment for Belle II. One novel feature to achieve the 40 times higher luminosity is the nano-beam scheme which allows for a very strong focusing at the beam interaction point up to 10  $\mu$ m (20 times smaller than KEKB).

One important benchmark parameter for this technique is the beam size at the interaction point. Figure 3 shows the longitudinal size of the impact parameter is well below 2 mm, which confirms that the nano-beam scheme is working. It should be noted that this is not the design beam size, as the beam size was configured to be wider in this early running period.

Phase 2 ended in July 2018 and since then, multiple successful reprocessings of the recorded data have been performed. Rediscovery of known physics processes is now an important benchmark to establish the integrity of the Belle II detector and reconstruction. The tracking software has been a vital input to many of these studies. As an example, figure 4 shows the reconstructed  $K_S^0$  mass from the decay  $K_S^0 \rightarrow \pi^+ \pi^-$ , where the two charged pion tracks have been found and fitted by the software described in this paper.



**Figure 3.** Longitudinal component of the interaction vertex estimated using single tracks originating from the interaction vertex in early Belle II events [8].



**Figure 4.** This figure shows the invariant mass distribution of  $K_S^0 \rightarrow \pi^+\pi^-$  in  $5\text{pb}^{-1}$  of collision data. Events are required to contain at least three good tracks to reject beam induced background, Bhabha scattering, and other low multiplicity background sources [9].

## 9 Conclusion

The Belle II track reconstruction consists of multiple algorithms which are adapted to the requirements of each of the tracking detectors employed at Belle II. The information retrieved

by each detector is combined in order to provide a single list of particle tracks to the physics users. These tracks have been fitted with hits from potentially all three tracking sub-detectors: PXD, SVD and CDC.

The design and implementation of the track reconstruction proved highly successful with the first collision runs in Phase 2.

## References

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