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Nils Braun

Combinatorial Kalman Filter and High Level Trigger Reconstruction for the Belle II Experiment

Doctoral Thesis accepted by
the Karlsruhe Institute of Technology,
Karlsruhe, Germany

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Supervisor's Foreword

We have entered an era in particle physics in which experimentation is led by computer programs and complex algorithms. Today's experiments have reached a complexity and intricacy such that no other way of analyzing the large streams of data—collected by instruments the size of houses and covering the area of soccer fields in some cases—can be imagined. It is fair to say that neither the discovery of the mechanism of charge-parity violation nor the confirmation of the existence of the Higgs boson, both feats that were rewarded with Nobel prizes, would have been possible without the use of state-of-the-art software and complex algorithms. And it is also reasonable to believe that such tools will play a crucial role in future discoveries. In this thesis, Dr. Nils Braun documents something one could consider the backbone of an experiment: During his Ph.D., he carried out work at Belle II and worked extensively on algorithms that reconstruct trajectories of charged particles traversing the detector. In addition, he made crucial contributions to the so-called online computing, which uses large computing farms to partially reconstruct collision events to decide which of them are of interest to physicists and should be stored to disk. At the time of writing, the Belle II experiment has just started to record electron and positron collisions produced by the SuperKEKB accelerator facility north of Tokyo in Japan. First preliminary physics results are expected this summer, and all of them will make use of the work carried out in this thesis.

Let me describe a typical collision at Belle II: Electrons and positrons are accelerated to nearly the speed of light and brought into colliding paths at the center of the Belle II detector. The detector has the size of a four-story building (with another building of similar size, shielded from the harsh radiation environment such collisions create, to read out the individual sub-detectors). During some collisions, a special type of quantum annihilation occurs, which produces two heavy Beauty quarks. These very unstable elementary particles decay after a very short lifetime of about 1.5 ps into a number of charged and neutral particles and these decay remnants allow us to study and understand the properties of our universe. Do new heavy fundamental particles exist? Is there a connection between the elusive Dark matter and everyday visible matter? In some sense, Belle II is a time machine that allows us to recreate conditions shortly after the Big Bang, when Beauty quarks were abundant and their properties had an impact on the future evolution of the universe. But let us return to Belle II: The decay remnants of both Beauty quarks travel through the detector, and in case of charged particles, three dedicated track reconstruction detectors reconstruct their trajectories. At the very center of the detector and closest to the collision point, a pixelated small sensor with over 7 million individual pixels is located. The volume outside is instrumented by double-sided strip-detectors and a sizable gaseous drift chamber. Both of the outer detectors possess a fast readout, and one crucial aspect of the data-taking scheme at Belle II is that the innermost pixel detector cannot be fully read out for each interesting collision. The information of the two outer detectors thus has to be used to extrapolate to a small region of interest on the pixel detector, which in turn can be read out. If this region of interest is wrong, the recorded information is lost, and with it much of the necessary precision needed to carry out physics measurements at the forefront of our field.

This is where Dr. Nils Braun and his thesis enter the scene: he took up this challenge in his outstanding Ph.D. work. He demonstrated that a combinatorial Kalman filter can be used to carry out such an extrapolation with the necessary precision. His Kalman filter implementation now plays a key role in the sequence of track reconstruction algorithms currently being employed by the Belle II collaboration. His thesis offers a very pedagogical introduction into the topic and offers an excellent starting point for, e.g., track reconstruction algorithms for future experiments. In addition to these crucial contributions, Dr. Braun also played a major part in optimizing the execution time of the online reconstruction code that stores or discards collision events selected by a fast hardware-based trigger. This decision is taken by partially reconstructing the collision event using a large computing farm called the high level trigger. The decision has to be executed within a narrow time window (dictated by the incoming stream of collision data and the limited processing power to select collision events for permanent storage). Dr. Braun's contributions here not only helped to keep the reconstruction time within the allocated limits but also contributed to a new error-proof parallelization implementation, which will stabilize the high level trigger operations in the future. All of this is also outlined in his thesis, providing interesting metrics and supplemental material to optimize such systems.

Thus in summary: This thesis is a must-read, it offers comprehensive and detailed documentation of the Belle II charged particle reconstruction algorithms, and it summarizes crucial parts of the online computing system.

Nils, it was a true privilege to work with you and I wish you the very best for your future! No matter what you will end up doing, you will be outstanding at it.

Sincerely

Karlsruhe, Germany
July 2019

Prof. Florian Bernlochner

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I always knew very well that there were many people out there I could rely on. I would like to express my sincere thanks to all of them, because without them this work would not have been possible.

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Track reconstruction and software development are above all teamwork, and our former Convener for Tracking, Dr. Martin Heck, was not only a good leader of the tracking group but has also brought our local working group in Karlsruhe forward with ever new ideas and improvements. His wealth of knowledge and experience was an enrichment for me. I want to thank him for the many years of collaboration and support. My sincere thanks go to Dr. Thomas Hauth. He was my supervisor for large parts of the thesis and my first help in case of problems. I would like to thank him for his competent help, his support despite the great geographical distance, the new ideas we had in the many discussions, and his very open and friendly nature. I could not have wished for a better supervisor.

Since my time as a master student, I have felt very comfortable in our working group and this is mainly due to my colleagues. I would like to highlight my (former) office colleagues Christian, Moritz, and Markus, with whom I was not only able to discuss common topics but also common problems and had a lot of fun. I would also like to thank everyone who proofread my work. My big thanks also go to the admin team of the institute, who managed to maintain a very smooth operation despite many external problems.

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