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Physics impact and status of the R&D for the Belle II Vertex Detector Upgrade

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Belle II is an experiment operating at the intensity frontier, with a vast physics program aimed at improving our knowledge of many fundamental quantities and at searching for signals of physics beyond the standard model. Data taking started in 2019 and the performance of the detector matched the expectations, allowing the experiment to have much better sensitivity than its predecessors BaBar and Belle. However, the accelerator background conditions proved to be dramatically more challenging than anticipated, at the level that some of the Belle II components will see a strong degradation of their performance once the accelerator will reach the design luminosity. The sensitivity of the experiment will be seriously affected. In this contribution we will review the status of data taking, our projections for the evolution of the machine-related backgrounds, and our plans for an extensive detector upgrade, to be carried out around the year 2032. We will focus in particular on the VTX, the proposed new silicon vertex tracker.

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*Speaker

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1. Introduction and data taking history

The Belle II experiment is installed at the asymmetric-energy e^+e^- SuperKEKB collider [1], which operates at a center-of-mass energy corresponding (or close) to 10.58 GeV. Its physics program is vast [2] and covers measurements related to the determination of the parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix of quark mixing, the study of rare decays of the B and D mesons and of the τ lepton, the determination of the properties of exotic hadrons, the searches for Dark Sector mediators, and in general all precision measurements that can be done at these energies to test the validity of the standard model.

Belle II takes advantage of the successful experience of BaBar and Belle, which together have collected an integrated luminosity of $\sim$1.5 ab^{-1} operating at the same energies. The detector is described in detail in [3] and consists of seven subdetectors and a superconducting solenoid, arranged cylindrically around the e^+e^- interaction region, with the axis of the solenoid roughly corresponding to the direction of the colliding beams. From the innermost to the outermost, the subdetectors are: the pixel vertex detector (PXD), silicon vertex detector (SVD), central drift chamber (CDC), time-of-propagation detector (TOP) and aerogel ring-imaging Cherenkov detector (ARICH), electromagnetic calorimeter (ECL), and K_L^0 and muon detector (KLM). All subdetectors with the exception of the KLM (which occupies the gaps in the return yoke of the magnetic field) are within the volume of the superconducting solenoid, which produces a 1.5 T magnetic field. The tracking of charged particles is performed by the combination of PXD (which consists of two layers of silicon pixel sensors), SVD (four layers of double-sided silicon strips), and CDC (a helium-ethane detector gas with drift cells organized in 56 layers).

The goal of Belle II is to accumulate 50 ab^{-1}, operating at a peak instantaneous luminosity of 6×10^{35} cm^{-2} s^{-1}. The first physics data taking campaign, denoted Run 1, took place in the period 2019-2022, during which an integrated luminosity of 424 fb^{-1} was recorded, inclusive of 19 fb^{-1} of data taken around the energy of 10.75 GeV for spectroscopy studies, and 42 fb^{-1} collected at 10.52 GeV for the study of the continuum (i.e. non $b\bar{b}$) background. In 2022-2023 (the so-called Long Shutdown 1), data taking was interrupted to allow for maintenance and upgrade work on the accelerator and on the detector, most notably with the replacement of the first, incomplete (the second layer covered only 20% of the azimuthal angle) PXD subdetector with the full PXD2. Data taking resumed with the Run 2 in 2024; at the moment of writing, additional 150 fb^{-1} have been accumulated, with the accelerator reaching a peak luminosity of 5.1×10^{34} cm^{-2} s^{-1} (about 10% higher than what was achieved in Run 1).

2. Expected backgrounds

The slower than anticipated progress with the luminosity was also associated to much higher accelerator-related backgrounds. While some of the problems (damage to collimators, sudden beam losses, ...) have a transitory nature and are expected to be resolved in the near future, it became increasingly clear that the safety factors that were considered for the backgrounds during the design phase of several Belle II subdetectors will be insufficient when we will reach the target instantaneous luminosity, with severe consequences on the physics sensitivity of the experiment.

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The accelerator experts believe that with the current machine configuration, it will be possible to reach an instantaneous luminosity of 2.8×10^{35} cm^{-2} s^{-1}. In these (*pre-LS2*) conditions, we expect that the detectors that are most sensitive to beam backgrounds will still retain a safety margin (ratio of maximum tolerable over expected background) of about 3.

To reach 6.0×10^{35} cm^{-2} s^{-1}, the interaction region should undergo a major redesign, which is currently under study. We cannot therefore make any precise predictions on the expected backgrounds (with the exceptions of those that are directly related to the luminosity), so we are considering the following scenarios:

1. *optimistic*, in which the contributions of the single beam backgrounds (that include the Toushek and beam gas components) are scaled by a factor **2** with respect to the pre-LS2 conditions;
2. *intermediate*, where the scale factor is **5**;
3. *pessimistic*, where the scale factor is **10**.

Figure 1 shows the expected rates for each subdetector in these three scenarios. It is apparent that, already in the intermediate conditions, there will be no safety factor for the SVD, CDC, and TOP, with obvious negative repercussions on the data quality.

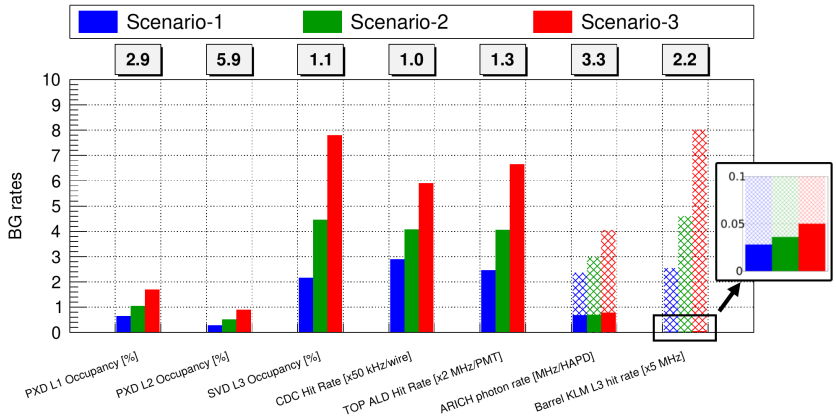

Figure 1: Expected rates for the Belle II subdetectors at the target luminosity of 6.0×10^{35} cm^{-2} s^{-1} for the three scenarios that we are considering: optimistic (blue bars), intermediate (green), and pessimistic (red). The hatched bars represent the contributions from neutron backgrounds. The numbers in the boxes above each subdetector's set of colored bars represent the safety factors for the individual subdetectors when assuming the intermediate scenario.

3. Upgrade plans

Our assumptions on the expected backgrounds and the upgrade plans that we are going to summarize in this section are covered in detail in [4]. It is currently foreseen that Belle II will have a two-years long shutdown (*Long Shutdown 2*) around the year 2032, for which we are considering the following interventions:

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- on the accelerator, several aging components and accelerating cavities will be replaced or upgraded. Also, a re-design of the interaction region, which is necessary to reach the target luminosity, is currently under study;
- the PXD and SVD are going to be replaced with the VTX, a silicon monolithic pixel detector;
- the replacement of the CDC is under consideration. It is possible that the chamber will be replaced with a combination of a silicon detector (at inner radii) and a gas chamber (at the outer ones);
- most of the photosensors of the TOP will be replaced, either with new Micro-Channel Plate photomultiplier-tubes or with silicon photomultipliers (SiPM);
- new, faster electronics for the readout of the ECL crystals will be installed, and the replacement of the currently installed photodiodes with SiPM is under study;
- the resistive-plate chambers of the KLM will either be operated in avalanche mode or replaced with scintillators that will allow a measurement of the time of flight to be achieved;
- new trigger strategies, heavily based on machine learning, will be deployed in order to cope with the higher backgrounds and preserve the sensitivity of the experiment, particularly to the low multiplicity final states.

In the last part of this contribution, we will concentrate on the VTX, the proposed upgrade for the silicon vertex trackers.

4. VTX: the new silicon vertex detector

Maintaining high tracking efficiency and resolution in the expected high background conditions requires to increase the space-time granularity of the detector. We find that the monolithic active pixel sensor CMOS technology provides all the requirements that we list in Table 1. The candidate sensor is the Optimised BElle II monolithic pIXel sensor (OBELIX), designed starting from the TJ-Monopix2 sensor [5], developed for the ATLAS upgrade. The OBELIX chip, whose physical and logical layout is displayed in Fig. 2, adopts the same TJ-Monopix2 matrix with a new digital periphery developed for the application in Belle II.

Extensive tests on the TJ-Monopix2 sensor have been conducted to validate the performance relevant for the OBELIX design. Beam tests at the $3-5$ GeV electron beam at DESY before and after irradiation at 5×10^{14} n_{eq} cm^{-2} in the years 2023 and 2024 showed a small reduction (from 99.9% to 98.5-99%) of the detection efficiency, for a threshold of 250-300 e's, operating the sensor at relatively high temperature (45° C). A new campaign scheduled for 2025 will better characterize the performance as a function of the temperature and evaluate the cooling constraints for the innermost layers. The spacial resolution and sensitive depth are found to be consistent with the expectations.

Figure 3 shows the current nominal geometry for the VTX. As a baseline we are considering 5 layers of sensors arranged cylindrically (without slanting) at radii of 14.1, 22.1, 39.1, 89.5, and 140.0 mm. An alternative geometry has the third layer placed at 69 mm. The two inner layers will

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Table 1: Main requirements and specification for the VTX pixel sensors.

Radius	14-135 mm (same as current) θ acceptance will depend on the new IR design
Spatial resolution	$< 15\mu$m
Time-stamping	50-100 ns
Total material budget	$< 3.5\%\ X_0$
Trigger read-out	30 kHz, latency 10 μs
Average hit rate	up to 120 MHz cm^{-2}
Total Ionizing dose (inner)	100 kGy/year
NIEL fluence (inner)	5×10^{13} n$_{eq}$ cm^{-2}/year

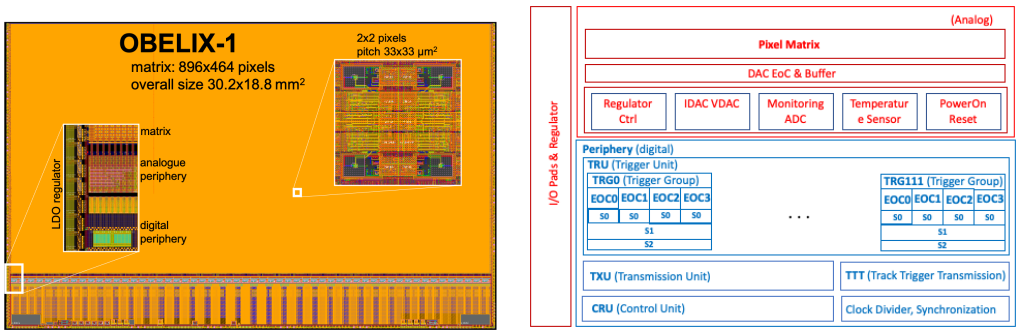

Figure 2: Physical (left figure) and logical (right) layout of the OBELIX sensor.

have a thickness of 0.2–0.3% X_0, depending on the selected cooling implementation. While air cooling alone may be insufficient, alternative options - such as thin cooling pipes along the ladder edges - are being evaluated, considering power consumption and chip temperature constraints after irradiation. The three outermost layers will have a thickness in the 0.3-0.8% X_0 range and will have single phase liquid cooling. The two innermost layers could feature an all-silicon ladder, integrating a block of four OBELIX chips from the same wafer, interconnected via a post-process redistribution layer (RDL). For the outer layers, a lightweight carbon fiber support structure is beeing developed. Further details on the current VTX design can be found in [6].

5. Performance

One of the major worries for the future is that the increase of the beam background levels will severely affect the tracking efficiency of the experiment, with serious consequences on its physics output. Figure 4 shows that the standalone tracking efficiency of the CDC (green markers) strongly depends on the background levels. The SVD+CDC combination (red markers) is very effective in recovering the efficiency, but a significant dependence remains. One of the main goals of the VTX is to fully recover the inefficiency produced by the highest beam backgrounds, as displayed by the black markers.

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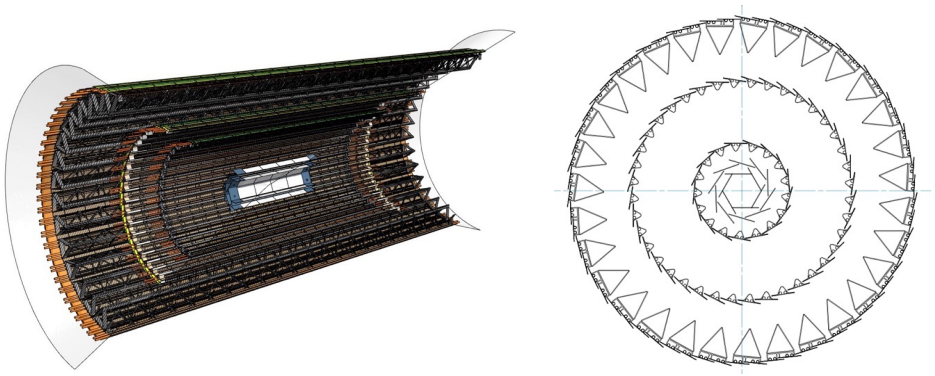

Figure 3: Cut 3D view (left figure) and end view (right) of the VTX in the nominal geometry.

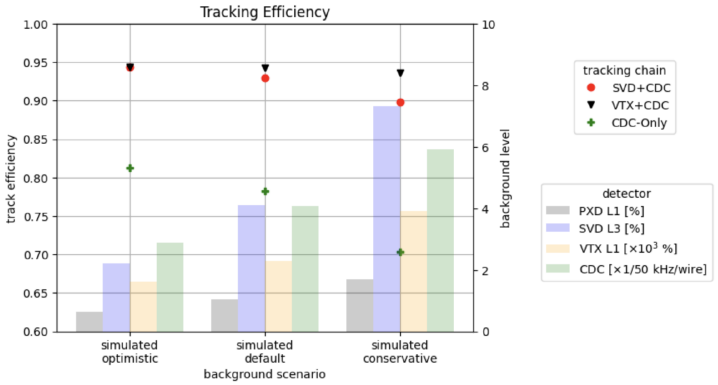

Figure 4: Occupancies (colored bars) of the current and planned tracking devices and corresponding tracking efficiencies (colored markers) for the SVD+CDC, VTX+CDC and CDC-only detector configuration in the three background scenarios. It is possible to see that the VTX can almost completely compensate the loss of efficiency of the CDC-only case (which the current SVD can only partially mitigate).

One of the areas in which we expect a major improvement is on the tracking efficiency and momentum and vertexing resolution of low-momentum tracks, such as the *soft pions* that originate from the $D^{*-} \to \overline{D}^0 \pi^-_{\text{soft}}$ decays and that very often do not enter the CDC volume. Figure 5 shows the comparison of the tracking efficiency for such particles between the current Belle II detector (for the intermediate background scenario) and the new VTX (for all background conditions). It is apparent that the new detector would afford an average increase of the efficiency by almost a factor 2 (and much higher at very low momenta). Moreover, the performance appears to be insensitive of the background conditions. This is of enormous consequence for the Belle II physics program, because measurements on many of the "golden channels" are performed on the recoil of fully reconstructed hadronic or semileptonic decays, in which D^* mesons appear very frequently. The expected improvement on low momentum tracking efficiency could thus translate into a $40-50\%$ increase on the effective luminosity at disposal for those measurements.

Another important part of the Belle II physics program concerns time-dependent analyses of the decays of B and D mesons, often in view of detecting CP-violating effects. The sensitivity

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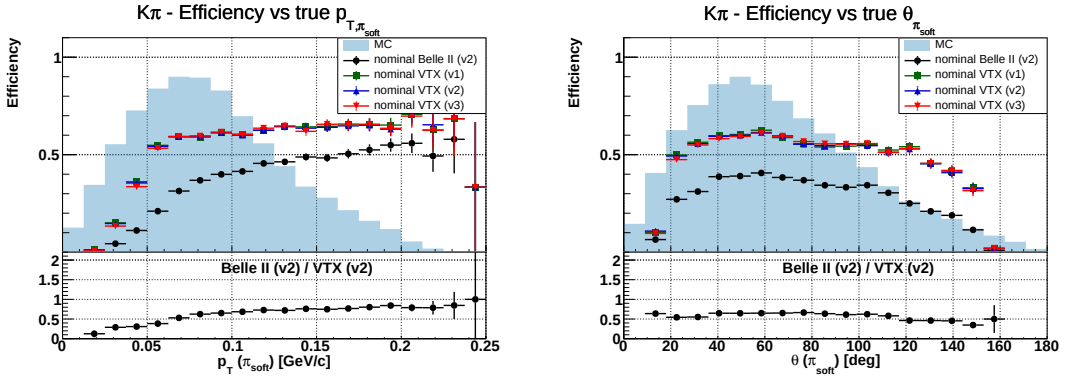

Figure 5: Reconstruction efficiency of $B^0 \to D^{*-}\ell^+\nu$ as a function of the transverse momentum of the π^-_{soft} from the $D^{*-} \to \overline{D}^0\pi^-_{\text{soft}}$ decay (left plot) and cosine of the polar angle of the π^-_{soft} track (right). We compare the performance of the nominal Belle II detector (black dots) with intermediate scenario background and the nominal VTX configuration in the three different background scenarios (colored markers). The shaded light blue histograms display the momentum and polar angle spectra of the π^-_{soft}. The bottom plots show the ratio between nominal Belle II and nominal VTX in the intermediate scenario background.

of those measurements depends on the ability of precisely determining the decay vertices of the particles under study. In Fig. 6 we show the comparison of the decay vertex resolution for B^0 mesons decaying to the $J/\psi K^0_S$ final state. We compare the performance of the current detector with that of the VTX in the nominal and alternative (with the third layer at 69 mm radius from the interaction region). We see a significant improvement in the resolution over the current detector and very small differences between the two geometries, as the vertexing resolution mainly depends on the innermost layers. Also in this area we do not see any significant dependence of the performance on the background levels.

An aspect in which the proposed VTX does not match the currently installed detector is the K^0_S reconstruction efficiency. This stems from the fact that, in order to reconstruct a track in the silicon vertex tracker, hits in at least three different layers must be detected. This means that any K^0_S flying past the third layer of the VTX will not be reconstructed. The current PXD+SVD detector, having a total of six layers, has a clear advantage over the VTX. The alternative VTX geometry, with the third layer moved farther away from the interaction region, reduces to $\sim 5\%$ the relative inefficiency compared to the current detector (for the nominal geometry the loss is $\sim 10\%$). Considering the improvements in the other areas, this is certainly acceptable, nevertheless we are also considering a 6-layer version of the VXT, which might be somewhat challenging from the point of view of mechanical integration.

6. Conclusions

Belle II started its physics campaign in 2019 and in its first years of activity it proved that the physics sensitivity is on par with the expectations and significantly better than that of Belle and BaBar. However, the progress of the accelerator was slower than anticipated and the background conditions much worse than the predictions, at a level that poses serious concerns about the ability

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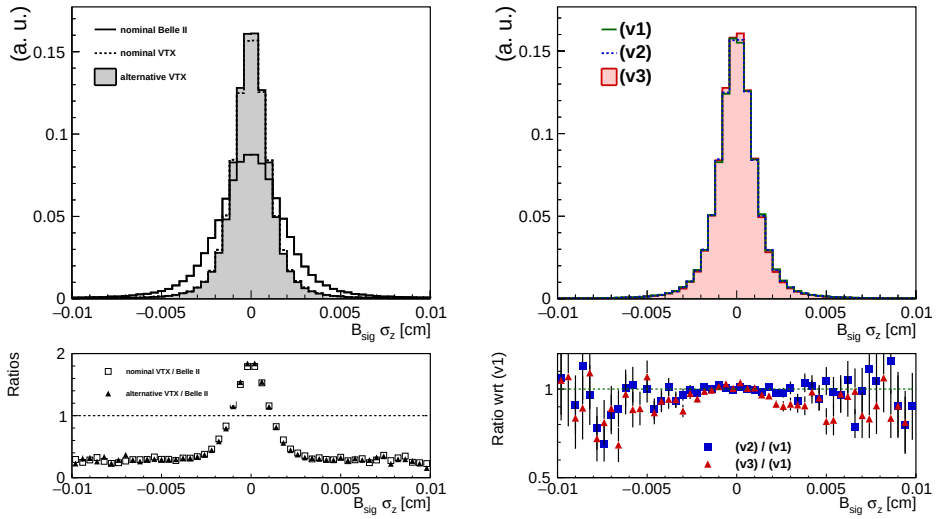

Figure 6: Left figure: comparison of the B decay vertex resolution along the z axis in $B^0 \to J/\psi K^0_S$ events for the nominal Belle II detector (solid line), nominal VTX geometry (dotted line) and alternative VTX geometry (filled grey histogram). The bottom plot shows the ratio between the VTX geometries (empty squares for the nominal and filled triangles for the alternative) and nominal Belle II. Right figure: B decay vertex resolution along the z axis for the nominal VTX geometry in the three background scenarios: optimistic (v1, green solid line), intermediate (v2, blue dotted line), and conservative (v3, red filled histogram). The bottom plot shows the ratio between the two higher background scenarios and the optimistic one.

of completing the physics program when the machine will reach the design luminosity. A major upgrade, to happen around the year 2032, is in preparation, with the goal of restoring and extending the physics sensitivity of Belle II so that the full physics program could be completed.

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