B-factory Programme Advisory Committee
Full report for
Focused Review Meeting

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1 Short summary

Due to the ongoing COVID restrictions, this B-factory Programme Advisory Committee (BPAC) meeting took place again remotely. It was focused on the status of the SuperKEKB and Belle II operation, with the following questions asked by the director of the Institute of Particle and Nuclear Studies:

- Is the balance between luminosity improvement and stable data production adequate?
- Are Belle II and SuperKEKB fully protected against the beam induced damages?
- Is offline data processing after data taking smooth enough for timely physics publication?
- Is data quality adequate for physics analysis?
- Does current analysis programme cover the all important topics? Are any important subjects missing?

In this summary section, the committee addresses those questions, as well as the plan to collect data at above $\Upsilon(4S)$ resonance energies, to setup an international task force for increasing the SuperKEKB luminosities and human resources issue of the neural network based track trigger of Belle II.

The goal for the past running period in 2021 was to enhance the luminosity of SuperKEKB by increasing the number of stored bunches and the bunch charges with relaxed collimator settings. A high background rate of up to 3 MHz per photon detector of the barrel particle identification system (TOP) was anticipated, but considered to be acceptable in view of the long shutdown planned in summer 2022, when the photon detectors affected by ageing will be replaced by more robust ones. As a result, the integrated luminosity was more than doubled compared to that collected by the end of 2020. In this regard, the committee considers that this approach has been viable. On the other hand, there were a number of problems, such as poor injection quality and frequent beam blow-up, limiting seriously the luminosity and stability of the machine operation. There is still no in-depth understanding for the causes of those problems. Effort should be continued to improve the performance of the injection, which is the main bottleneck for increasing the beam current and one of the key elements for reducing the background. The detector performance should be carefully monitored to promptly detect any sign of degradation. An indication of gain loss in the central drift chamber reported during this meeting is worrisome.

Continuous effort has been made to avoid catastrophic beam losses causing damages to the machine and detector. The committee considers the measures being taken, i.e. introduction of more beam monitors and background detectors, and reducing the time needed for beam abort, to be very appropriate. Nevertheless, several catastrophic beam losses happened and damages to the machine collimator and Belle II pixel vertex detector occurred. The cause of those losses has not yet been clearly identified. Given this situation, the committee urges to further improve the beam monitoring and background detection and encourages to continue investigating ways to reduce the time needed for beam aborts.

The overall scheme for the Belle II data processing is adequately developed and no intrinsic bottleneck has been observed. The collaboration is encouraged to continue stress testing the system to iron out remaining shortfalls, mainly in the automation. In this context, the availability of personnel for detector calibration, in particular detector experts, remains a concern. Fully functional run-dependent simulation is another important issue for the analysis of high statistics data. The collaboration should pay close attention not to accumulate unprocessed data.

Understanding of the detector performance for charged and neutral particles has been continuously improving and it is not a limiting factor for the physics analysis with the current data statistics. To be prepared for analysis with the targeted amount of data before the start of the long shutdown in summer 2022, however, more work is needed to achieve a better understanding of the detector performance to keep systematic uncertainties under control. Not only the differences between the simulation and real data should be addressed, but also effort should be made to optimise the performance for a variety of physics analyses. The particle identification capability is particularly crucial and given the complexity of the TOP, the committee recommends that more people get involved in thorough studies to understand the detector characteristics.

The overall progress in physics analysis is very good. The collaboration managed to produce several interesting results in areas where the Belle II detector can make unique contributions with limited statistics, notably in the search for dark sector particles. Flavour anomalies observed by the LHCb experiment are the current focal point of the community. Many of the relevant studies require data statistics that will not be available for some time. However, the superior capability for detecting photons and the clean event production process of e^+e^- annihilations should allow Belle II to detect B meson decay final states that are difficult for the LHCb experiment to access. The committee encourages the collaboration to continue their analysis of rare tau decays, which provide a unique advantage of the Belle II experiment over other experiments. BPAC also suggests extending Belle II analyses of charmed hadron lifetimes to Ω_c and Ξ_c to examine recent LHCb results. The committee strongly encourages the collaboration to continue exploiting the unique properties of the Belle II data.

The idea to collect some data above the $\Upsilon(4S)$ energies had already been presented during the March BPAC annual meeting and was seen positively by the committee and more details were given during this meeting. The committee agrees with the collaboration's assessment that the appropriate time for the operation at higher energy would be in December during Run 2021c. Given the unique physics opportunity provided by this data set, the committee reiterates its strong support.

In the past, the committee has suggested that accelerator experts from laboratories in different countries could be invited to participate in the SuperKEKB machine development to increase the luminosity. It is encouraging to learn that the SuperKEKB and Belle II teams are now making effort to realise this and the committee is looking forward to learn about the progress during the next meeting.

The committee was very impressed by the demonstrated performance of the neural network track trigger. It is already an important component of the Belle II trigger and will play an even more significant role when the level of background increases with higher luminosities. The committee thinks that it is essential to maintain the expertise and human resources in order to ensure the further development and maintenance of the system. The committee would also like to see a global strategy for the trigger development for the coming years.

Further details are given in the following sections. Lastly, the committee would like to congratulate the Belle II collaboration and the accelerator team for their impressive achievement. Steady support for the experiment by KEK is also very much appreciated.

2 Physics

2.1 Status

The overall progress and plan for physics analyses is very good. The collaboration managed to produce several interesting results in the areas where the Belle II detector can make unique contributions with limited statistics.

Several new analyses were completed during the winter and submitted to the arXiv. This includes measurements of B meson branching fractions and CP violating asymmetries. Most of the analyses used ~ 63/fb collected in 2019/2020. Belle II rediscovered the $B \to \eta' K$ decay and the measured branching ratio is consistent with the world average.

The $B \to J/\psi K_L^0$ decay mode was also rediscovered. These two decays will be used in the future for the study of time-dependent CP violation and the extraction of the CKM angle ϕ_1. Branching fractions for the $B \to D^{(*)}K$ and $B \to D^{(*)}\pi$ decays were found to be consistent with previous measurements. These are very important decay modes for the future determination of the CKM angle ϕ_3. CP-violating charge asymmetries in the $B \to K\pi,\ B \to \pi\pi$ decays were also measured and agree with previous determinations. Belle II set also a new bound on the $B^+ \to K^+\nu\bar{\nu}$ branching fraction. Thanks to an inclusive new tagging method, the sensitivity of the measurement is similar to the one obtained by the Belle analysis but with ~ 10 times less data.

Several analyses are close to completion: (1) the measurement of the D^0 and D^+ lifetime that demonstrates the vertex reconstruction capabilities of Belle II; (2) the first Belle + Belle II combined analysis for the extraction of the CKM angle ϕ_3. The preliminary analysis with Belle data only reduced the uncertainty on the ϕ_3 angle from $\sim 15°$ to $\sim 11°$. One expects an improvement of an additional one degree by adding Belle II data; (3) The search for Dark Higgsstrahlung using only 2019 data. The collaboration is targeting several analyses for the EPS conference. This includes studies of $B \to K\pi\pi\gamma$, $R(J/\psi)$, and $B \to \rho\ell\nu$ using the Full Event Interpretation method.

The collaboration is also working on a paper on the Belle II flavour tagger and on a new track trigger that will be particularly useful to investigate dark sector models producing signatures with displaced vertices (this is the case of e.g. inelastic Dark Matter models). This is a unique opportunity for Belle II.

More in the future, Belle II plans several measurements of τ properties and, in particular, of the τ lifetime and test of lepton flavour universality in τ decays by measuring the ratio of the branching fractions, $\tau \to \mu\nu\nu/\tau \to e\nu\nu$. The lifetime measurement is expected to be competitive with the corresponding Belle analysis with 200 to 300 fb^{-1} of data. Toward the end of 2021, for a period of roughly two weeks, the collaboration plans to collect as much data as possible above the $\Upsilon(4S)$, at around 10.75 GeV, with the aim of clarifying the nature of the unexpected peak structure observed in the past.

2.2 Concern

- In addition to the threat of damaging the detector due to the catastrophic beam losses, the future physics results can be compromised by systematics without further improvement in understanding of the detector performance.

2.3 Recommendations

- In addition to measurements of D-mesons and Λ_c baryons lifetimes that demonstrated the excellent vertex reconstruction capability of the Belle II detector, strong effort for measuring the charm baryon lifetimes, including those of the Ω_c and Ξ_c, is highly recommended.

- Measurements of $B^0 - \bar{B}^0$ mixing amplitudes and the CKM parameters $\sin 2\phi_1$ with already available 200 fb^{-1} of data is recommended as a consistency check of new analysis techniques.

- Present focal point of the flavour community is the clarification of various anomalies observed in the B meson decays. Analyses of electroweak anomalies $R_{D^{(*)}}$ and $R_{K^{(*)}}$ require large datasets that are not yet available at Belle II. However, studies of other relevant observables, such as ratios of inclusive decay rates $\Gamma(B \to X_c \tau \nu_\tau)/\Gamma(B \to X_c \ell \nu_\ell)$, which make use of Belle II clean event environment, should be explored by the collaboration. The committee commends the analysis of $B \to K\nu\bar{\nu}$ decay rate and recommends extending the studies to include final states with K^* .

- Tau decays including rare ones into beyond the Standard Model states could also provide a unique chance for the Belle II experiment. Studies of charmed baryons are also interesting. In general, BPAC strongly encourages the collaboration to fully exploit the superior capability for detecting photons and B decays which are difficult for LHCb to access.

- It is important to maintain a broad program of searches for dark sector particles for both short and long terms. The analysis of 700 fb^{-1} data could already give world leading limits on many dark sector models, including visible and invisible dark photons and Z', axion-like-particles, and Dark Higgsstrahlung.

- Spectroscopy studies for regular and exotic resonances are encouraged.

- BPAC strongly supports the collaboration plan to collect data above the $\Upsilon(4S)$ for a two-week period toward the end of 2021. The effort to elucidate whether the 10.75 GeV peak is of a conventional nature or exotic (e.g. a tetraquark) is of great scientific promise and should be fostered. Belle II is the only experiment worldwide that can access this goal.

- The committee encourages the continuation of the interactions between the Belle and Belle II scientists with the goal to perform combined measurements.

3 Machine and background

3.1 Status

The background study group of Belle II and the accelerator team together have collected an impressive amount of information regarding the various background sources of SuperKEKB. They have obtained information about beam-gas backgrounds and backgrounds related to Touschek scattering. These are the two main steady-state non-luminosity related backgrounds for the detector. Based on current measurements, these backgrounds are at acceptable levels and are not limiting the beam currents at present. Increased limits on the background rates of the sub-systems, notably for TOP, have allowed for a more relaxed collimator setting configuration, which improved the injection quality and beam lifetime. In addition, a major effort has gone into improving the GEANT4 model for the detector and the accelerator from the injection beam lines up to the interaction point. The background rates obtained from the simulation are now in a good agreement with the measurements for most of the Belle II sub-systems, except KLM and ARICH for which the simulations will require further refinements. This detailed modelling has also led to a better understanding of the observed neutron background levels around and inside the detector. The local background sources are now being more carefully shielded and the simulation study can now be used to optimise further shielding efforts. Efforts are ongoing to further improve the description of the detector geometry in order to obtain more precise information from the local neutron sources. The two teams have also greatly improved the simulation of the collimators around each ring. The background team has developed sophisticated algorithms for obtaining optimal collimator setting configurations that have been verified with machine data. This understanding has been used to obtain hints about the location of the start of the catastrophic beam losses that generate presently the most problematic backgrounds for the detector. These events develop very fast (in a few turns) making it very difficult to abort the stored beam in time to prevent damage to the detector and to machine equipment such as collimators. Some of these events also quench the final focus doublets. Attempts are now being made to localise the source (or sources) of these catastrophic beam losses. Beam loss detection has benefited from the introduction of the CLAWS detector that is 4.4 μs faster, on average, in issuing a beam abort than the diamond sensors. Work is ongoing to further improve the CLAWS detector response time. Placing more fast diagnostic devices, such as the CLAWS detector, around both entire rings is considered with the intention of localising the start of these large beam losses.

3.2 Concerns

- Injection efficiency is still an issue related to the collimator settings which are needed to protect the detector and final focus elements.
- Catastrophic beam losses remain a primary concern.
- Background levels are still high in the detector.

3.3 Recommendations

- The committee recommends moving forward as quickly as possible in placing more fast diagnostic detectors around each ring. These elements should improve localising the start of the catastrophic beam loss events. They also may further improve the abort time.
- The committee suggests more studies of SuperKEKB operation with further relaxing background limits. While this would increase the radiation damage of some of the detector sub-systems, a plan could be developed to replace them during the coming long shutdown.
- The committee agrees with the background study team to further improve the detector simulation. This will help producing a better agreement of the background

rates between the simulation and measurements, and in identifying and locating the background sources in and around the detector. This effort is strongly encouraged.

- The committee also encourages further studies of collimator settings with the aim of improving injection quality and beam lifetime. This will also reduce the risk of damage to both the detector and to the accelerator. These studies could include the option of adding more adjustable and also fixed collimators that are much less expensive and use less space. These studies need to be closely associated with thresholds for transverse mode coupling instabilities.

4 Data taking and detector operation

4.1 Status

In 2021, a high priority has been placed on enhancing the integrated luminosity (with higher instantaneous luminosity and longer run time) so that it could surpass the BaBar integrated luminosity of 424 fb^{-1} at $\Upsilon(4S)$. To achieve this goal, the limit for the L1 trigger has been raised to 14 kHz, and the limit on TOP PMT hit rate for the single beam and injection backgrounds to 3 MHz during the data taking.

After restoring the beam currents and the luminosity to the level achieved in 2020 runs, the beam currents were raised by increasing the number of bunches from 978 to 1565. However, the beam currents were found to be constrained by poor injections rather than the new limit set for the TOP PMT hit rate. In addition, frequent beam loss decreased the effective run time. The total integrated luminosity increased by 123 fb^{-1} and reached 214 fb^{-1}. Even higher instant luminosity will be required to achieve the initial integrated luminosity goal for 2021.

In the detector operations, challenges in maintaining a sufficient number of people for taking the shift still remain due to COVID-19 travel restrictions, although efforts have been made to increase remote shifts. It was noted that the two remote shifters do most of the shift tasks whereas one local shifter takes care of the run control and high voltage operation. The data taking efficiencies have been close to 90% since 2020 and slightly improved in 2021 by more automation, better documentation and improved skills of the shifters. A non-negligible cause of run stops is due to Single Event Upsets (SEUs) of the TOP and CDC electronics caused by the neutron background. In the short term, it is planned to make the recovery easier for the shifter. The CDC electronics will be upgraded in 2026. In addition, neutron backgrounds will be reduced by adding neutron shielding.

Since the collimator tuning plays a critical role in keeping the beam background, beam instabilities and beam lifetime under control, the Belle II collaboration has formed a collimator group, to improve the organisation and visibility of the collimator tuning task. The collimator management is increasingly important since relaxed collimation is now preferred to avoid a reduced physical aperture and to increase the beam lifetime, while tighter collimation would be preferred to avoid beam aborts due to bad injections. The collimator positions heavily depend on the quality of the beam injections.

4.2 Concern

- The committee is concerned that the detector operation is managed by a small number of shifters.

4.3 Recommendations

- The committee encourages to reduce the load for taking remote shifts through further automatising the detector operation and improving documentation so that more shifters will sign up.
- The committee recommends the collaboration to increase support for the collimator group.

5 Selected hardware issues

5.1 Pixel and Monitoring Detectors

5.1.1 Status

As noted already in the machine and background section, increasing the beam currents has been a challenge and has come with associated risks for the Belle II detector operation. Unfortunately, the pixel detector has been affected by a large beam loss on May 10 that has caused some damage. In this particular event, the beam abort was issued by the VXD diamonds and about ten PXD gates stopped functioning and one switcher chip was damaged. Unstable operation was observed for several days after the event. Full operation of the PXD in gated mode is still being implemented. Fabrication of the new beam pipe for the new pixel detector is on schedule. No update was given on the production status of the new pixel detector.

The CLAWS sensors, made of scintillator and SiPMs, mounted on the QCSL and QCSR, have been utilised for the beam aborts since May 26. The system can issue the abort 4.4 μs faster on average than the diamond sensors. Adding new beam loss sensors is being investigated for better beam monitoring.

5.1.2 Concern

- Damage to the pixel detector is worrisome.

5.1.3 Recommendations

- Re-evaluate the thresholds for beam aborts to minimise damage to the pixel detector and optimise the overall feedback system in preparation for the run with the new pixel detector after the long shutdown in 2022.
- Continue investigating the cause of the catastrophic beam losses by improving the beam monitoring and background detection, and explore further possibilities to reduce time needed for beam aborts.

5.2 Particle identification and photon detectors

5.2.1 TOP:

The TOP worked well during the 2021ab run, with 94.4% of channels operating in June 2021, having lost about 1% of the channels since the beginning of the run. It has now been about five years since the TOP installation and a maintenance access will be needed. A power cable has failed and eight boardstacks will need to be replaced during the 2022 shutdown. Sufficient spare boards are now available at KEK. The high hit rate PMTs with increasing current draws, and frequent hit rate spikes, etc. continue to be observed. They are being closely monitored as they occur in all three PMT types and may impact the PMT longevity. The DAQ firmware has generally been well-behaved, but several problems, including lockups of the SCROD processing system, have impacted operations. The DAQ upgrade is ready for the 2021c run. Injection veto masking is being looked at closely, as the TOP readout gives a few percent dead time when the injection background is high. This could become a significant issue for higher trigger rates.

The monitoring of the relative efficiency for the photon detectors has been so far based on $\mu^+\mu^-$ data. Most PMTs have stable efficiencies, while about 5% of them have shown a decrease. This needs further investigation. An alternative monitoring method using a laser pulsing system is being developed. Final preparations are underway for the maintenance activities during the long shutdown in 2022. A total of 224 PMTs will be replaced along with failed boardstacks, cables and other components. Tools are being designed and tested in a mockup at Nagoya University, and personnel is being trained. Procedures have been established and documented. The schedule that has been developed seems reasonable, but will be challenging to implement and entails some risk.

5.2.2 ARICH

The ARICH operation was reasonably stable during the 2021ab data taking. There was no major downtime longer than 30 minutes during run 2021b. A new recovery script has been provided to shifters to correct most of the ARICH DAQ errors. A GUI is being worked on. An ongoing concern is the stability of the high voltage and bias voltages of the HAPD photon detectors. About 5% of the HAPDs are disabled due to high and bias voltage problems and another 1% are off due to a low voltage cable problem. These issues have increased by 2.5% (relative) during the run and there is some instability in the currents, which is a concern. No repairs are planned inside the detector during the upcoming long shutdown in 2022, as there are no plans to detach the ARICH from the ECL. The low voltage cable will be repaired and that should reactivate the five disabled HAPDs. For the second long shutdown currently envisaged in ~ 2026, the repair or replacements of some modules. In addition, potential improvement in the aerogel radiators is being considered and studies are ongoing.

5.3 Concerns

- The TOP group will be challenged by the overlapping demands of operations and calibrations, ongoing preparations for the upcoming long shutdown, and the need to increase analysis efforts to better understand performance at the detector level.
- The performance of the detectors could be affected by the background rates and that has to be carefully studied.

5.4 Recommendations

- The TOP group is encouraged to add more personnel to help understand and improve detector performance, especially by carefully studying the performance in the relevant detector phase space (as discussed in the last report from the committee), comparing data with simulation, and improving reconstruction software.
- Detailed practice with mockups will be essential to making the replacement of the photodetectors a success in the upcoming long shutdown.

5.5 KLM

5.5.1 Status

The main effort to consolidate the KLM system during the summer of 2020 was a success, and the downtime caused by the KLM system has been reduced significantly since run 2020c. Stable performance has been maintained during 2021ab. The layer hit efficiency greater than 80% was achieved for the most of the layers in 2020c, and there seems to be room for further improve the performance of the remaining layers by adjusting the threshold or high voltage.

The collaboration is to be commended on the effort to understand the neutron backgrounds in the detector. Spectral and directional measurements of the neutron background have been carried out with the neutron Time Projection Chamber (TPC) detectors installed in the tunnel. A clear correlation between KLM endcap hits and modified collimation schemes was established, confirming the hypothesis that Touschek losses at the collimators induce neutron backgrounds. A 40% hit rate reduction was achieved in the KLM endcap through a modified collimation scheme. Also a reduced fast neutron flux in the tunnel was observed with the TPCs.

5.6 Concern

There is no particular concern.

5.6.1 Recommendations

- Continue the neutron studies for the shielding design.
- Continue the adjustment of the threshold and high voltage to improve hit efficiency.

5.7 Central Drift Chamber

5.7.1 Status

Gain degradation has been observed in the dE/dx calibration using data taken in autumn of 2020 and spring of 2021, compared to the run periods in 2019 and in spring of 2020. Systematic analysis of different datasets revealed a step-wise gain decrease, usually appearing after shutdown periods. There is no obvious correlation between gain changes and CDC operational currents or background conditions. In addition to the dE/dx gain, distributions of raw ADC signals have been also compared. Systematically lower median ADC values have been observed for spring 2021 with respect to autumn 2020 for all layers: the ratios varies in the range of 0.85-0.95 for the inner layers (L1-L9) and are nearly constant ($\sim$ 0.85) for the outer layers (L10 - L55). The gain of layer L54, where the high voltage was turned off for a significant fraction of the data taking period, behaves in the same way as the neighbouring layers. There is no ϕ-dependence (top/bottom asymmetry) observed in the dE/dx gain, indicating the absence of any significant temperature gradient across the chamber. The overall tendency is consistent between cosmic data and recent physics runs, where measured pressure, water content and temperature around the CDC endplates were stable, and no significant change in the electronics gain was confirmed with the test-pulse data. Based on these findings, the preliminary conclusion is that the gain degradation is unlikely to be related to the total accumulated charge, which amounts to $\sim$ 30 mC/cm/wire for the innermost CDC layers. In the medium term, gas analysis studies are foreseen to carefully check the ratio of helium and ethane in the mixture, and to measure the dependence of the gain on the gas flow. During the summer 2021 shutdown, the plan is to determine the gas gain from cosmic runs, with well-monitored conditions, as a function of decreasing water content, and to compare gain (median ADC) in the new data with the old cosmic runs taken in 2017-2018, before water was routinely added into the mixture;

5.7.2 Concerns

- The source of the dE/dx gain degradation is still not understood;
- Shortage of personnel in the CDC group (both for online operations and for development of mitigation strategies) remains critical and requires help from other groups in the collaboration;
- In the long term, there are justified concerns related to the use of hydrocarbons in the gas mixture in the high background environment. Progress in ageing studies has been slower than originally hoped for (also due to COVID-19).

5.7.3 Recommendations

- Every effort should be made to ensure that the level of personnel engaged in the CDC hardware and software studies is adequate to address CDC concerns and mitigation strategies for the long-term CDC operation.

- Background-related study of the CDC performance (tracking, triggering, PID), based on the extrapolated hit rates to higher luminosities, needs to be continued since the background situation is significantly more challenging than anticipated during the design stage.

6 Detector performance

6.1 Status

Data taking for runs 2021ab was impacted by concerted efforts to enhance the luminosity of SuperKEKB by increasing the number of stored bunches and the bunch charges. These measures were expected to result in higher beam generated backgrounds, while staying below levels that were considered potentially damaging for certain detector components, or that will lead to intolerable ageing, for instance, by keeping TOP PMT rates less than 3MHz.

About 31% of the operating time was dedicated to machine studies to increase the luminosity and control the backgrounds. For the remaining 67% of beam time the data taking efficiency was 89.5%, comparable to last year. A peak luminosity of $3.12 \times 10^{34}\text{cm}^{-2}\text{sec}^{-1}$ was reached and in total 120.36 fb^{-1} were recorded (8.8 fb^{-1} off resonance) this year, more than doubling the total data set of previous years. This is a remarkable achievement given the difficulties of the machine operation, specifically the much higher background conditions and severe beam losses due to injection problems, frequent beam blow-up of the Low Energy Ring for high High Energy Ring currents, and a large increase in Touschek scattering.

There is concern that in the future higher background rates will result in ageing effects in the TOP photon detectors and the PXD electronics. Up to now no measurable decrease in the quantum efficiency of the TOP PMTs has been observed during operation. And so far, there are no strong signs of loss in the performance of the TOP, however, offline monitoring revealed that about 5% of the PMTs indicated decreasing efficiency. Results of other more detailed studies of the most recent data recorded under higher beam backgrounds conditions have not yet been reported.

Charged particle identification is a very complex task relying on 6 different subdetectors (SVD, CDC, TOP, ARICH, EMC, and KLM) and their different response to particle type and momentum, and different geometric acceptance. Overall, the subdetectors were working quite well and methods are being developed to combine the information from the subdetectors using multivariate analyses, specifically likelihoods, Boosted Decision Trees (BDT) and Convolutional Neural Network (CNN). There is no strong sign yet of PID degradation with the higher PMT rates allowed in the 2021 runs, but modest degradation is not ruled out.

6.1.1 Charged Lepton ID

So far, the identification of electrons and the misidentification of charged hadrons has relied primarily on the ECL. But release-5 includes CDC dE/dx predictions based on data control samples. The introduction of an overall BDT (not yet including SVD and TOP information) with electron efficiencies of 90% resulted in a large reduction of the fake rates for pions and kaons ($< 0.5\%$). The plan is to include TOP information in the next data processing release. This should significantly improve the performance at lower momenta. For momenta > 0.6 GeV, the muon identification relies primarily on KLM information and at lower moments ECL and TOP information is expected to improve the muon-pion separation. Some promising results based on CNN trained ECL cells were presented and will be integrated into the standard processing by the end of 2021.

For J/ψ decays to charged lepton pairs, the electron and muon efficiencies in data and simulation agree very well. The calibrations of hadron fake rates are based on $K_S^0 \to \pi^+\pi^-$ decays and have improved due to more detailed CDC simulation, but there are indications that events with high track multiplicities show higher fake rates.

6.1.2 Charged Hadron ID

Charged hadron ID relies primarily on TOP in the barrel and ARICH in the end cap at higher momenta, with substantial contributions from CDC and SVD, especially at lower momenta. Unfortunately, there are only modest improvements in overall charged hadron ID performance since the March BPAC meeting. In particular, there are no major improvements in TOP performance, with substantial differences remaining between simulation and data. In release-5 the TOP performance improved for the hadrons, but the electrons were mismodeled leading to worse electron and charged pion separation. There is also little change in the overall ARICH performance, though the reconstruction was upgraded to include individual aerogel tile properties.

The TOP reconstruction software has been ported from Fortran to C++ and will be included in release-6. This should attract a larger group of experts to contribute to further developments of the code and thereby improve the TOP performance.

While there are some improvements to the recent data processing and simulations, several new puzzling features have appeared. Based on release-5, the CDC dE/dx results on kaons agree well for simulation and data, but the average kaon efficiency is lower by 10%, and the simulated kaon misidentification rate now exceeds the data. The drop in the kaon efficiency near $\cos\theta = 0$ persists and will require further study.

The most surprising observations are charge asymmetries of hadron ID efficiencies, which depend on the PID requirements. For CDC data, the asymmetries for kaons and pions are of opposite sign for data and simulations. For TOP data, the asymmetries for pions and kaons are smaller, have less dependence on the PID selection, and have the same sign in data and simulation. None of these effects are understood, and - though quite small - they will need attention.

6.1.3 Neutral Particle Detection

There have been several considerable improvements to the reconstruction of photons and the identification of neutral hadrons, pions, kaons, and neutrons, in the ECL. The neutral group worked closely with various physics groups, providing performance improvements and in some cases encouraging first applications at analysis level.

ECL cluster leakage corrections, as a function of photon energy and angles, are now part of the bucket calibration. The observed small photon energy bias was addressed by energy and angle dependent sub-percent corrections applied at the analysis level. These corrections resulted in improved agreement between the data and simulation reported by the physics groups. The remaining bias will be addressed in MC-14. Photon efficiency studies as a function of energy and angles are being extended to cover the endcaps and to assess systematic uncertainties. To decrease out-of-time backgrounds a loose restriction on the cluster timing was introduced. The time resolution depends on the photon energy and beam background conditions, and the choice of this restriction will become more important at higher levels of beam backgrounds. Recent studies by the ECL group have resulted in an improvement of the timing resolution by a factor of two and further timing error calibrations are being planned.

Detailed studies of the photon energy resolution above 1 GeV have been presented, based on radiative muon pair production. They indicate larger uncertainties in data than in simulations, while the simulations show consistency between generated and reconstructed photon energies. Recent studies of π^0 efficiencies have indicated a momentum dependence below 1 GeV.

In Belle analyses, the variable E_{extra}, the sum of the energies of ECL clusters which are not associated with the reconstructed event, is frequently used as the primary variable to separate signal events from backgrounds. In the future, the operation at higher luminosity will result in increased energy deposits in the ECL by photons and neutrons from beam backgrounds. In addition, there will be large ECL clusters from hadronic showers or ionising particles that are split into several clusters of which only one is matched to the track. Likewise, neutrons and K_L^0 deposit energy in the ECL and may contribute to E_{extra}. Studies are underway to identify these background contributions.

6.2 Concerns

- Several of the subdetectors currently are not included in the PID analyses due a variety of problems that limit the quality of the data and are not fully understood.
- In the future, large increases in beam background will very likely result in radiation damage to some detector components. This and increased background hits in various subdetectors will impact the event reconstruction. Significant variations in performance as a function of track momenta and angles are likely to increase systematic uncertainties, given the large number of different decay modes contributing to signal and backgrounds for many analyses.

6.3 Recommendations

- The detector performance studies for particle identification should be scrutinised at all levels to arrive at a detailed understanding of the raw detector data and their calibrations, as well as the complex multivariate analyses combining information from different subdetectors.

- The CDC and SVD with dE/dx information are essential for low momentum charged particles, and thus need to be integrated in the overall particle identification as soon as practical. Calibrations based on data need to be developed to best combine the information from different subdetectors, including the ECL-endcaps and ARICH.

- The detector performance should be carefully monitored online to promptly detect signs of degradation. During the 2021 summer shutdown, the impact of various backgrounds on the detector and accelerator components should be assessed to understand rate limits. Additional shielding should be installed as well as online monitors to promptly detect any sign of degradation. This system should be tested for run 2021c and be ready for runs 2022ab.

- The committee would appreciate detailed off-line studies to clarify the PID performance, both overall and at the subdetector level as a function of geometry, momentum, and background rates. Paired plots of efficiency for signal particles and misidentification versus momentum and angles would be easier to interpret than the efficiency versus fake rates previously shown.

- The subdetector groups are encouraged to increase the personnel effort to better understand and improve the detector performance, by carefully studying the performance of the subdetectors in the relevant phase space, comparing with simulations, and improving the software. It is hoped that the new C++ version of the TOP software will attract younger scientists to engage in studies to enhance the detailed understanding and performance of TOP and also the other detector systems for charged and neutral particles.

7 Trigger and online

7.1 Status

The overall data-taking efficiency of the DAQ has reached 89.5%, which is a very respectable achievement although is still a little below the self-stated goal of the collaboration. The remaining reasons for run-stops include SEU-induced run-stop/starts.

The neural network level-1 track trigger (NNT) is providing z-information for tracks based on 2D track- and z-information of the CDC. The Single Track Trigger (STT) is successfully used for the data taking, and the level-1 trigger rate is significantly reduced while the efficiency is maintained as high. Projects for improving and augmenting the functionality of the level-1 trigger are well under way for the 2021c run, as well as for the 2022 runs.

The high-level trigger is now at about three quarters of its design capacity. It serves to reduce the recording rate, find Regions of Interest to reduce the amount of PXD data and identify events for calibration and monitoring purposes.

7.2 Concerns

- Although the SEUs at the current level are more of a nuisance than a serious concern, the problem will probably be aggravated at higher luminosities. A firmware solution for the TOP is planned for the coming long shutdown, but the front-end replacement of CDC is only foreseen for 2026.
- Even at lower luminosities, there is already a significant number of fake tracks reconstructed by the NNT. This problem is believed to come from the limited amount of input information from CDC axial and stereo track segments used in the current implementation.
- The NNT is powerful but also complex requiring hardware, firmware and software experts. The availability of all this personnel is unclear in the medium to long term.
- Despite hardware additions, the HLT has been having some difficulties to keep up with the level-1 output rate, although headroom has been created by introducing the prescaling of the level-1 Bhabha trigger.

7.3 Recommendations

- The identified mitigation measures for the SEUs in the TOP and CDC front-ends should be pursued with vigour.
- The full 3D Hough transform using all CDC information for the level-1 trigger should be developed with high priority.
- The personnel for the NNT must be secured not only for the completion of the current implementation but also for the commissioning during and after the coming long shutdown, the long-term operation and further enhancement.
- Improvements of the HLT performance, which are safe from the physics point of view, should be continued as much as possible to have margin for unexpected increase in level-1 trigger rate. In the longer term, the trigger group could explore new triggers which could enhance the physics reach, such as displaced vertices.

8 Data processing

8.1 Status

The overall schema of the Belle II data flow was presented highlighting its distributed aspects. The three main computing centres are now carrying out well defined responsibilities: the first offline data hub for KEK, prompt processing of *buckets* for BNL and thorough calibration and validation of samples for physics publications for DESY. Production with mDST output format is performed at multiple Raw Data centres (RAWDCs). The

140 fb^{-1} of data available for the 2021 summer analyses was a sum of earlier samples reprocessed with the latest *proc12* official reprocessing and prompt 2021 processed data.

Data processing is becoming more and more automated and this has been reducing the time to make the data available. Prompt calibration is completed typically in seven days with two additional days to validate the quality. The calibration loop is fully automated, including the validation. Experts can override the automated results to avoid poor quality. Only some production related work is still carried out manually. BNL computing resources have been increased. Nevertheless, the thorough calibration is becoming a bottleneck for collection rates of more than 1 fb^{-1} per day. The size of the *buckets* will have to be determined with careful pre-scaling to cope with increased luminosity in order to avoid reprocessing of *hRAW* samples that would require re-staging of the full raw data. A prompt processing speed of $2-3$ fb^{-1} per day on the GRID is regularly achieved. Production at the RAWDCs has been proceeding very smoothly. This is very encouraging but it is still premature to have full confidence as the amount of data processed has been small.

Data processing speed is still too slow for the expected increase in luminosities to ensure fast availability of Belle II analysis samples with the latest features. Despite numerous tests and preparations, a delay of 21 days in the target date for the readiness of the data was reported. Various issues have hindered re-calibration in *proc12* engendering necessary adjustments. The committee did not identify principle issues. Most of the problems such as disk availability and adaptation of calibration scripts are usual startup issues, since the re-calibration has been performed in a fully distributed schema for the first time. Part of the delay was due to unexpected software issues when running over a large data sets. A major contribution to the delay is due to the limited availability of calibration experts from the subdetector groups that continues to be a concern. Additionally, the calibration procedure relied on a single *AirFlow* manager. The committee was informed that an additional person was being put in place to ensure sustainability.

Data processing is expected to be further streamlined. Building on the experience gained, calibration for *proc13*, with the new *release-06* software validated over the summer, will start promptly to finish well in time to provide the expected data set for summer 2022 analyses. The data set for Moriond 2022 presentations will still be mostly based on *proc12*.

Some improvements for analysis skimming were reported with the proposal to drop the run structure in the final uDST samples, where uDST is the output of analysis skims and analysis objects are added to mDST reconstructed objects. This reduces the heavy I/O overhead arising from downloading a large number of files when segmented with the runs. Tools are planned to be optimised for uDST, but use of mDST files will still be allowed for some special cases.

Production of run-independent Monte Carlo (MC) samples proceeds smoothly. At the same time, the production efficiency for run-dependent MC is hindered by the preparation of Global Tags and associated payloads. A delay of up to 42 days was reported for samples corresponding to one of the *buckets*. A smoothly running and fully functional run-dependent MC is essential for analysis of high statistics data with the necessary precision. Experience is being gained, and ways to improve have been identified by the

Belle II data processing and computing groups. In particular, the use of Rucio automated deletion of intermediate files is expected to improve the situation. Including the preparation and sign-off of payloads in the AirFlow calibration should also be beneficial. Establishing a beam condition manager to coordinate the preparation of all beam condition related payloads and machine background overlay files could further mitigate the problem. A new MC production strategy has been introduced with a clear classification of default MC samples (run-dependent and -independent mDST for analysis and cDST for calibration studies) and on-demand MC samples for specific investigations. At the same time, a revised nomenclature has been devised to ease the identification of MC samples for various processing and running conditions. To cope with the requests of skim production of signal MC samples, the data processing group proposes to create "skim liaisons" in each physics working group who should provide necessary information.

Significant developments were mentioned in order to improve and streamlines the *gbasf2/gb2* software tools providing the bridge between users and the data production and computing ecosystem in the distributed environment.

8.2 Concerns

- Not enough redundancy generating single point of failure in key positions, in particular for the calibration workflows
- Scalability of the computing model not fully tested.

8.3 Recommendations

- Continue automation of procedures and stress tests of the system to identify and solve remaining shortfalls
- In the long term, review various tools used for workflow management and explore compatibility of requirements among various tasks to consolidate.
- The collaboration should avoid accumulation of unprocessed data