Belle II France input to the IN2P3 national prospects 2020-2030

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The standard model (SM) of particle physics is very powerful to explain the phenomena observed at particle physics experiments and it has proven to be successful in many respects, including the predictions of the existences of then unknown particles such as the top quark, the W and Z bosons, or even the Higgs boson. Despite this success, the SM fails at providing an explanation for dark matter, and, more fundamentally, it entails a high number of free parameters which limits its predictive power (the couplings between quark flavours, for example, can not be estimated in the frame of the SM). These limitations of the SM justify the searches for phenomena beyond our current understanding of particle physics which would be a signature of new physics (NP).

In contrast to LHC experiments operating at the energy frontier, wherein new particles are sought via direct production that is limited by the accessible beam energy, Belle II will search for NP at the intensity frontier. With the unprecedented luminosity accessible at the upgraded SuperKEKB facility, Belle II will seek indirect evidence of NP by searching for signatures of new particles or processes through measurements of suppressed flavour physics reactions or deviations from SM predictions. Any observed discrepancies could then be interpreted in terms of NP models. This enables a probe for NP to energies above 10 TeV.

The Belle II experiment is a substantial upgrade of the Belle detector and operates at the SuperKEKB energy-asymmetric e^+e^- collider. The design luminosity of the machine is 8×10^{35} cm^{-2} s^{-1} and the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than its predecessor. Belle II collected its first collisions in 2019, and is expected to operate for the next decade. An upgrade of Belle II detector is now being discussed based in an increase of the luminosity which would allow to accumulate about 250 ab^{-1}.

IN2P3 joined Belle II in 2017 and was able to make significant contributions in the commissioning of the detector and studies of the machine induced background, as well as in the cooling and operation of particle identification detector (ARICH) and to the quality assurance monitor for the first data. We have been recently selected to upgrade the Belle II data acquisition (DAQ) system in order to improve the Belle II detector performance. The hardware installation at KEK will occur during the 2020 shutdown period with the installation and commissioning of boards for a couple of subsystems. The rest of the DAQ system will be installed and commissioned during the shutdown period of 2021. Belle II France with CCIN2P3 will also contribute significantly to the processing of raw data from 2021.

The French Belle II groups will play a major role in the exploitation of the large data sample, focusing its efforts on the search of New Physics in the electroweak penguin $b \to s$ processes ($b \to s\gamma$, $b \to sll$, $b \to s\nu\nu$) as well as proposing an ambitious physics program on τ physics.

RARE B DECAYS

Flavour-changing neutral-current transitions are expected to be sensitive to NP effects. These transitions are forbidden at tree level in the SM but are allowed only at suppressed loop level, and NP could arise from the exchange of a heavy particle in the electroweak penguin loop diagram.

$b \to s\gamma$

In the SM, the final state s quark that couples to a W boson is left-handed, causing the photon emitted in $b \to s\gamma$ transitions to be almost completely left-handed. Several theories beyond the SM predict a significant right-handed component for the photon polarization: in the minimal supersymmetric model (MSSM), left-right squark mixing causes a chirality flip along the gluino line in the electroweak penguin loop [1], while in some grand unification models right-handed neutrinos (and the associated right-handed quark coupling) are expected to enhance the right-handed photon component [2]. Various complementary approaches have been proposed for the determination of the polarization of the photon in $b \to s\gamma$ transitions.

Information on the photon polarization can be obtained from B decays to three hadrons and a photon [4]. This approach is enabled by the fact that the three final-state hadrons allow the construction of a parity-odd triple product that inverts its sign with a change in the photon chirality, and by the existence of interference between the amplitudes of the hadronic system. In $B \to K_{\rm res}\gamma$ decays, where $K_{\rm res}$ is a kaonic resonance decaying to a $K\pi\pi$ final state, the required interference in the $K\pi\pi$ system can arise from several sources. In the case of a single $K_{\rm res}$ state, the helicity amplitudes must contain at least two terms with a non-vanishing relative phase. This can occur between intermediate resonance amplitudes in the decay $K_{\rm res} \to K\pi\pi$, between S and D wave amplitudes in the decay, or between two intermediate $K^*\pi$ states with different charges, related by isospin symmetry (this last type of interference is possible only in decays containing a π^0 in the final state). Interference can also appear in the presence of different overlapping $K_{\rm res}$ states; in fact, the presence of numerous interfering resonances makes it very difficult to distinguish them, thus complicating the interpretation of the observed distributions.

A precise measurement of the photon polarization parameter will come from an amplitude analysis of $B \to K\pi\pi\gamma$ decays, an analysis that combines information from the angular variables and the squared invariant-mass distributions which will only be possible with the large samples accumulated at LHCb and Belle II in the near future [5]. One advantage of Belle II will be the possibility to perform, with similar sensitivity, the analysis in two modes, $B \to K\pi\pi\gamma$ and $B \to K\pi\pi^0\gamma$. This will allow to check the consistency of the λ_γ obtained in both cases and verify that the result doesn't depend on the kaonic resonances considered.

Further information on right-handed photon could be obtained by measuring CP asymmetries in exclusive radiative decay modes such as $B \to f_{CP}\gamma$ decays, where f_{CP} is a particle or system of particles in a CP eigenstate [3]. This is typically the case for the time-dependent analyses of radiative b decays such as $B \to K^0_S\pi^0\gamma$. In the SM, the photon helicity is dominantly left-handed for $b \to s\gamma$, and right-handed for the conjugate process. As a consequence, $B \to K^0_S\pi^0\gamma$ behaves like an effective flavour eigenstate, and mixing-induced CP violation is expected to be small – a simple estimation gives: $S \sim -2(m_s/m_b)\sin(2\beta) \sim 3\%$ (assuming that the SM dipole operator is dominant, corrections to the above may allow values of S as large as 10% in the SM). Belle II offers the unique opportunity to perform time-dependent analysis where signal side vertex is performed with only K_S and consequently, with a 50 ab^{-1} data sample will obtain an uncertainty on S of 2%. Similarly, a measurement of the time-dependent CP asymmetry in the radiative-penguin decay $B \to K^0_S\pi\pi\gamma$ can be performed. A mixing-induced CP parameters of the process $B \to K^0_S\rho^0\gamma$ from the time-dependent analysis of $B \to K^0_S\pi\pi\gamma$ decays can be obtained by an explicit amplitude analysis of this mode or assuming isospin symmetry and the information from charged mode $B \to K\pi\pi\gamma$ to extract the corresponding dilution factor.

$b \to sl^+l^-$

The decays $B \to K^{(*)}l^+l^-(l = e, \mu)$, which are mediated by the $b \to sl^+l^-$ quark-level transition, constitute a flavour-changing neutral current process. Such processes are sensitive to particles predicted in a number of NP models. In recent years, intriguing hints for the violation of Lepton Flavour Universality (LFU) have been accumulated in semileptonic B decays, both in the neutral-current transitions $b \to sl^+l^-$ (i.e., R_K and R_{K^*}) and the charged-current transitions $b \to cl^-\nu_l$ (i.e., R_D, R_{D^*}). LHCb has reported deviations from the SM expectations in $b \to s\mu^+\mu^-$ processes as well as in the ratios R_K and R_{K^*}, which together point at NP affecting muons with a high significance. The first mission of the Belle II experiment will certainly be to confirm these deviations.

Assuming the current values, this will be achieved with a data sample of 20 ab^{-1} [6].

The decay $B \to K\tau^+\tau^-$ is the third family equivalent of $B \to Kl^+l^-$ and hence may provide additional sensitivity to NP due to third-generation couplings and the large mass of the τ lepton. Assuming a common NP explanation of $R_{D^{(*)}}$ and $R_{K^{(*)}}$, a very large enhancement of $b \to s\tau^+\tau^-$ processes, of around three orders of magnitude compared to the SM (1.2×10^{-7}), can be expected under fairly general assumptions [7]. The only available experimental result, from the BaBar experiment [8], is a 90% CL limit for the branching ratio of the $B^- \to K^-\tau^+\tau^-$ decay at 2.25×10^{-3}. This analysis uses hadronic B meson tagging techniques, where one of the two B mesons, referred to as the B_{tag}, is reconstructed exclusively via its decay into one of several hadronic decay modes. An analysis with Belle data sample is being performed which will not only use hadronic tag but also semi-leptonic tag, which recently has shown to provide the most stringent results [9]. This effort will be pursued with Belle II larger data sample to reach limit in 10^{-5} or better [6].

$b \to s\nu\nu$

$B \to K^{(*)}\nu\overline{\nu}$ decays have so far not been experimentally observed due to their branching fractions, at the level of 10^{-6} in the SM, and to experimental challenges as the signal consists only of a $K^{(*)}$ and missing energy. If the source of the observed flavour anomalies is new physics, then the $b \to s\nu\overline{\nu}$ transitions should also be affected and the $B \to K^{(*)}\nu\overline{\nu}$ branching fractions are expected to deviate significantly from their SM predictions. Since neutrinos do not couple to photons, the $b \to s\nu\overline{\nu}$ transition rates are theoretically cleaner to predict in the SM than $b \to sl^+l^-$ transition, due to the negligible long distance hadronic contributions, while the Z-mediated diagram is similar. Moreover, the neutrino flavour is not distinguished experimentally. Consequently, if new physics couples mostly to the third generation of leptons, and thus to tau-neutrinos, it could cause large enhancements of the $B \to K^{(*)}\nu\overline{\nu}$ branching ratios, without strongly impacting $b \to se^+e^-$ and $b \to s\mu^+\mu^-$ rates. These modes are also particularly sensitive to invisible particles, for example dark matter constituents, by considering these decays as $B \to K^{(*)}X$ where the new particle X decays into dark matter. The implementation of deep learning techniques in the current B meson tagging algorithm should allow the increase of the number of decay channels considered in the B_{tag} reconstruction and result in significant increase in the tagging efficiency. With such improvements, $B \to K^{(*)}\nu\overline{\nu}$ decays could be seen for the first time with about 10 ab^{-1}.

LFV B decays

Today, the investigation for lepton flavour violation (LFV) is particularly exciting thanks to the set of recent results using semi-leptonic B meson decays obtained by the BaBar, Belle and LHCb collaborations which appears to hint towards lepton-flavour non-universality, as in many models this effect comes along with LFV. The existing branching ratio limits for $b \to s\mu e$ modes are currently of order of $10^{-8} - 10^{-7}$ [10, 11] but only a single analysis [12] exists for the most interesting modes, $B \to K\tau l$ with ($l = e, \mu$). This result again is obtained with hadronic tag techniques, and, from the momenta of the reconstructed B, K, and l candidates, the τ four-momentum can be fully determined. The resulting τ candidate mass is the main discriminant against combinatorial background and 90% confidence level upper limits at the level of a few times 10^{-5} are obtained. Belle II can improve significantly these limits, not only thanks to the larger data sample available but also by attempting analyses with a semi-inclusive tag (forming a B_{tag} candidate around a fully reconstructed D or J/ψ) which are possible in this unique system where only one τ exists in the final state and no other τ or neutrino. Limits at 10^{-6} or even more stringent are possible. Similar strategy can be applied for LFV $B \to \tau l$ modes.

τ PHYSICS

Belle II has a broad τ physics program, in particular in searches for lepton flavour and lepton number violations (LFV and LNV), benefiting from the large cross section of the pairwise τ lepton production in e^+e^- collisions. The Belle II experiment is well suited to study τ physics, in fact since the decays of τ leptons involve neutrinos in the final state their study is very difficult at hadron colliders such as LHC. τ decays offer a whole range of possible studies, from understanding strong interactions, to precise tests of electroweak interactions, and potential discoveries of NP with LFV and lepton universality violation.

LFV τ decays

In the SM, LFV in the charged sector comes only from the neutrino oscillations, and flavour violating decays of charged leptons are hence dramatically suppressed as their probability of occurrence scales as $(m_\nu/m_W)^4 \sim 10^{-40}$ out of reach of current and future experiments. However, in numerous NP models such as supersymmetry or little Higgs, new couplings between leptons and particles with a mass of the order of the weak scale allow for a measurable amount of lepton-flavour violating processes with rates up to 10^{-8}, so within the reach of current experiments. The observation of LFV in the charged sector would constitute a clear signature of NP. Due to its high mass, the τ lepton, the heaviest of the three charged leptons in the SM, is expected to be very sensitive to the mechanism at the origin of fermionic masses and it provides a wide range of potential lepton-flavour violating decays to study, including modes with hadrons in the final state. In case LFV is observed, the correlations between the decay rates in the many decay channels available would be crucial to discriminate between the different NP scenarios at stake, because the various decay channels would be suppressed or enhanced differently according to the structure of these NP models. For these reasons, searches for LFV in τ decays generate a deep interest and a few experiments are being designed for this purpose (for example the TauLV project at CERN) or include them in their physics program like the Super Charm/Tau factory (Russia, China) or the FCC-ee at CERN.

With more than $10^9\tau^+\tau^-$ pairs recorded in total, the Belle and Babar experiments have lead the searches for LFV in τ decays. They have studied various LFV decays with one lepton and a photon in the final state (such as $\tau^- \to \mu^-\gamma$ or $\tau \to e^-\gamma$), one lepton and a hadron (such as $\tau^- \to \mu^-\eta$ or $\tau \to e^-\pi^0$, or three leptons (such as $\tau^- \to \mu^-\mu^+\mu^-$ or $\tau^- \to e^-\mu^+\mu^-$). The most stringent limits on these decays to date have been set by these two collaborations, and are of the order of $10^{-8} - 10^{-7}$. We expect that after 5 years of data taking and with the efforts on improving low momentum muon identification, Belle II will be able to reduce the upper limits on LFV and LNV τ decays by an order of magnitude.

Precision measurements

In the three-generation SM, the violation of CP is explained by the Kobayashi-Maskawa mechanism. It predicts the CP violation in the quark sector as well as an absence of CP violation in the lepton sector. Therefore, the study of CP violation in semi-hadronic τ decays offers a unique search of physics beyond the SM, namely a new source of CP violation beyond the Kobayashi-Maskawa mechanism. One interesting perspective is the CP violation measurement with an angular analysis of the three hadron final state. The most promising channel is $\tau \to K\pi\pi\nu$, where the CP violation search can be performed by using the three observables, $A^{CP}_{(i)}(i = 1, 2, 3)$ [13]. To maximize the sensitivity of this analysis, the $M(K\pi\pi)$, $M(K\pi)$ and $M(\pi\pi)$ distributions should all be measured and the $\tau \to \pi\pi\pi\nu$ channel can be used as a control sample to evaluate the detector bias by assuming the CP violation in $\tau \to \pi\pi\pi\nu$ is much smaller than that in $\tau \to K\pi\pi\nu$.

The current limit for the τ electric dipole moment (EDM) (d_τ) is several orders of magnitude less restrictive than that for the electron, muon, or neutron. The difficulty of the τ EDM measurement comes from its short lifetime. Therefore, the τ EDM can not be measured in an electrostatic field. At a e^+e^- collider, however, the τ EDM can be measured by using the correlation of decay product momenta in the process $e^+e^- \to \tau^+\tau^-$ [14]. It is also possible to improve the present experimental bound on the τ anomalous magnetic moment [15].

CONCLUSION

The Belle II experiment with a large dataset of 50 ab^{-1} will provide unique opportunities to contribute to the new physics quest, especially for modes with missing energy (with τ and/or neutrinos in the final state) as well as in the τ sector. Belle II collected its first collisions in 2019, and as soon as the designed luminosity is reached, we expect to accumulate 10 ab^{-1} of data every year. The French Belle II groups will play a major role in the exploitation of the large data sample, focusing its efforts on the search of New Physics in the electroweak penguin $b \to s$ processes ($b \to s\gamma$, $b \to sll$, $b \to s\nu\nu$) as well as proposing an ambitious physics program on τ physics based on the study of LFV decays and precision measurements in CPV and EDM. And, as described in this document, we have physics a program at every step of data accumulation.

There is also a growing activity in France dedicated to understand the limits for the current system and the requirements for shorter term and luminosity upgrade with the possibility of an upgrade of the vertex detector using CMOS sensors [16].

An upgrade of Belle II detector is now being discussed based in an increase of the luminosity which would allow to accumulate about 250 ab^{-1}, with the possibility of polarized beams, where Compton polarimetry will be a critical tool to reach the expected accelerator performance.

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