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Belle II experiment status and measurement perspectives

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Summary. — The Belle II experiment is a multi-purpose flavour physics facility designed to collect electron-positron collision data at the unprecedented instantaneous luminosity of $0.8 \times 10^{-36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The former collider KEKB and the Belle detector are undergoing important upgrades in order to achieve the high-luminosity collision scheme and to sustain the enhanced level of backgrounds. The unique capabilities of this new machine will allow to study a wide range Standard Model (SM) processes with an unequalled precision and to perform beyond SM searches up to now inaccessible.

1. – Introduction

In the past years, the Belle and BaBar experiments, operating at the electron-positron colliders KEKB (Tsukuba, Japan) and PEP-II (Stanford, US), respectively, have offered important insights into the flavour sector of particle physics. The achievements of the two collaborations, which collected together an integrated luminosity of about $1.5\,\mathrm{ab}^{-1}$, culminated in the nobel prize for physics awarded in 2008 to Kobayashi and Maskawa for their theory of CP violation [1].

In order to answer some of the still opened questions in the flavour physics sector and to unveil the nature of the tensions occurring in the current observations, a larger amount of data is needed. For this purpose the KEKB collider and the Belle detector are being upgraded to reach an instantaneous luminosity of $0.8 \times 10^{-36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and to cope with the expected overwhelming level of backgrounds.

2. – SuperKEKB and Belle II

In the SuperKEKB collider, beams of electrons and positrons with energy of 7 GeV and 4 GeV, respectively, will mainly collide at a centre-of-mass energy of 10.58 GeV corresponding to the peak of the $\Upsilon(4S)$ resonance (data taking at other $\Upsilon(nS)$ resonances is also scheduled). At the design luminosity, the machine will produce 10^{10} B pairs per year, becoming therefore the most prolific B-factory ever built.

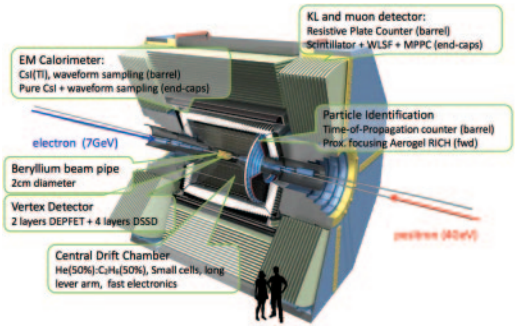

Fig. 1. – Belle II detector.

The gain of a factor of 40 in luminosity foreseen by the SuperKEKB collider with respect to its predecessor KEKB, is obtained by means of higher beam currents ($\sim 2\times$) and strong beams squeezing near the interaction point ($\sim 20\times$). To achieve this big improvement and at the same time keep under control the beam instabilities, the machine has faced several upgrades involving the radio frequency cavities, the dipole and quadrupole magnets, the beam pipe, and the interaction point (IR) optics (nano-beam scheme [2]).

As for the collider, the Belle detector is going through major upgrades (fig. 1) which can be summarized as the following, going from the inside out:

- new vertex detector (VXD) composed of pixel detectors and double-sided silicon detectors. The reduction of the beam pipe size (2 cm of diameter) allows to place the detector closer to the interaction point;
- central tracking device (Central Drift Chamber, CDC) with smaller drift cells and extending to a larger radius;
- new particle identification (PID) detectors, the Time of Propagation (TOP) and the Aerogel Ring Imaging Cherenkov (ARICH);
- new electronics, of the wave-form-sampling type, for the electromagnetic calorimeter (ECL); as an upgrade option, the replacement of the endcap scintillator crystals (CsI(Tl)) with a radiation tolerant version (pure CsI) is considered as well;
- replacement of RPCs of the muon and K_L detectors (KLM) in the endcap with scintillators instrumented with silicon photomultipliers.

The mechanical structure and the superconducting solenoid providing a magnetic field of 1.5 T are left unchanged. These features lead to several improvements of the detector performances, from the vertex resolution and efficiency of K_S and slow pions reconstruction (VXD, CDC), to the pion/kaon separation (PID) and machine background rejection (ECL).

In 2015 the upgrade of the KEKB collider was completed and on the 26th of February 2016 the first beams have circulated and have been successfully stored in the rings. In 2016 all the sub-detectors have been assembled (phase 1), except for the VXD, and in 2017 will undergo a global cosmic rays run. In 2018, for the first time the Belle II detector will take collision data (phase 2) and at the beginning of 2019 the full physics program will start with the inclusion of the VXD detector (phase 3). The plan of the experiment is to run at least until 2024 collecting $\sim 50\,\mathrm{ab}^{-1}$ of data.

It is worth mentioning that, during phase 1, the commissioning detector Beast II (Beam Exorcism for A STable experiment) is already taking data near the IP, without collisions, to study in detail the machine backgrounds (as the Touschek scattering, beam-gas scattering, synchrotron radiation, and radiative Bhabha scattering).

3. – Physics program

The electron-positron colliders, and the Belle II experiment in particular, offer unique capabilities to study the flavour physics with respect to the hadron colliders. Running at the Υ(4S) resonance produces a very clean sample of B meson pairs, with a relatively low tracks multiplicity and detector occupancy. Furthermore the complete reconstruction of one of the two B mesons allows to infer the 4-momentum of the other B meson, crucial aspect in missing energy studies. In addition, large samples of τ leptons are also produced, allowing for searches of lepton flavour and lepton number violation in τ decays. Last but not least, the excellent performance of the ECL will provide also very high reconstruction efficiency of neutral final states.

The peculiar features of B-factories and the excellent performances of Belle II detector give access to a wide physics program. It includes the study of CP violation, the study of leptonic and semi-leptonic B decays to precisely measure angles and sides of the CKM unitarity triangle, rare B decays, charm physics, LFV in τ decays, hadron spectroscopy and dark sector searches.

In the following sections I will briefly address physics cases of three categories: the phase 2 physics, the early physics (pursuable in the first 1–2 years of data taking with full detector), and the rare processes which need the full Belle II dataset.

3˙1. *Hadron spectroscopy.* – The study of bottomonium and charmonium systems constitutes an important test of the QCD theory predictions based on quark models as the heavy quark symmetry [3]. In addition, recently discovered excited states as the Z_c^+ [4] and the Υ(4260) [5] do not seem to fit the conventional categorization to mesons and baryons, thus they are considered as candidates of exotic states, such as tetraquarks, glueballs and meson/baryon hybrids.

During the Belle II phase 2, the physics analyses will suffer from a reduced low momentum tracks reconstruction efficiency due to the absence of the VXD, but they will gain in a higher trigger efficiency which is possible for the low initial luminosity of collisions. Hadron spectroscopy will therefore be studied taking data at the peaks of Υ(nS) resonances, and performing energy scans around the Υ states. With just a pilot run collecting an integrated luminosity of $20\,\mathrm{fb}^{-1}$ at the Υ(6S) resonance, for example, we will have a 10 times larger dataset than Belle to investigate the nature of such exotic states.

3˙2. *Leptonic and semi-leptonic B decays.* – The purely leptonic B meson decays, B→ $l\nu$ provide a direct determination of the product of the B meson decay constant f_B and the magnitude of the CKM matrix element $|V_{ub}|$. Furthermore, interference with non-SM particles, as charged Higgs bosons in the s channel [6] or SUSY sfermions in s and t channels [7], would reflect in a modification of the measured branching ratio. The present Belle exclusion limits for the $tan\beta$ and M_H parameters space, where β is the

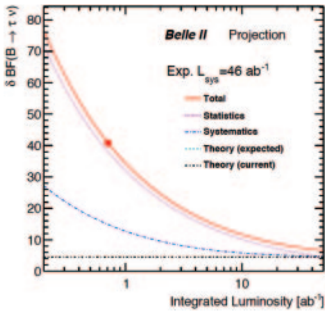

Fig. 2. – Expected statistical and systematic uncertainties on the branching ratio of B→ $\tau\nu$ with increasing Belle II integrated luminosity, compared to the theoretical uncertainty. L_{sys} denotes the luminosity at which the statistical precision matches the systematic uncertainty.

ratio of the vacuum expectation values of the two Higgs boson doublets and M_H is the mass of the bosons, will be largely improved with increasing integrated luminosity.

Due to the helicity suppression, the τ mode is much more abundant than the μ and e modes (by a factor 10^3 and 10^7, respectively), and indeed the B→ $\tau\nu$ decay is one of the golden modes that will be investigated with the first available ab^{-1} of Belle II data. The Belle collaboration found evidence of this channel in 2006 [8] studying four τ decay modes ($\mu\nu\nu$, $e\nu\nu$, $\pi\nu$ and $\rho\nu$) and reconstructing the other B-tag meson in hadronic modes. A key ingredient of the analysis is the E_{ECL} distribution, defined as the sum of energies of neutral clusters that are not associated with either the tagged B or the π^0 coming from the ρ decay. This variable is expected to peak at zero for the signal events, while it shows a broader distribution for the background processes. In fig. 2 the projection of the precision Belle II will achieve on the B→ $\tau\nu$ branching ratio is shown.

The semi-leptonic B meson decays are of particular interest for the potential sensitivity to the charged Higgs exchange (B $\rightarrow$ D$^{(*)}\tau\bar{\nu}$) and for precise measurements of $|V_{ub}|$ (B→ X$_u l\bar{\nu}$). In order to reduce the theory uncertainties affecting the first of the two processes mentioned above, the following ratio is usually taken into consideration: $R^{(*)} = BR(\mathrm{B} \rightarrow \mathrm{D}^{(*)}\tau\bar{\nu})/BR(\mathrm{B} \rightarrow \mathrm{D}^{(*)}l\bar{\nu})$. In fig. 3 (left) the current measurements of R and R^* are compared with the SM predictions. It is worth saying that, although the individual measurements do not show a significant disagreement with the SM, the com-

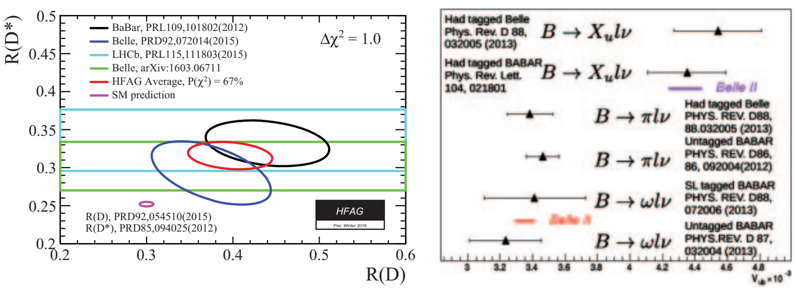

Fig. 3. – R *vs.* R^* measurements compared with the SM prediction (left) and $|V_{ub}|$ determinations with inclusive and exclusive semi-leptonic B-decays (right).

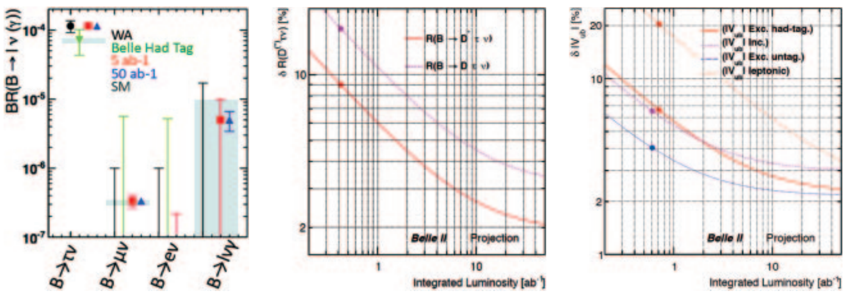

Fig. 4. – In the left plot the branching ratios of the purely leptonic and radiative leptonic B decays are shown comparing the world average (WA), the Belle measurements with hadronic tag, the Belle II projections at 5 and 50 ab^{-1}, and the SM prediction. In the middle plot the expected precision on R and R^* measurements with the increasing luminosity of the Belle II dataset is shown. In the right plot the uncertainty on the $|V_{ub}|$ measurement via exclusive and inclusive semi-leptonic and leptonic B decays is shown as function of the Belle II integrated luminosity.

bined measurement is about 4σ far from the prediction. In fig. 3 (right) the discrepancy between $|V_{ub}|$ determinations obtained through the study of inclusive and exclusive semi-leptonic B decays is shown, superimposed with the Belle II projections at 50 ab^{-1}.

In conclusion, with the precision expected at just few inverse ab of data collected (fig. 4) Belle II will be able to shed light on these puzzling questions in the flavour sector of particle physics [9].

3˙3. *Lepton flavour violation.* – The search for lepton-flavour–violating (LFV) processes in the charged-lepton sector represents a very powerful test of the SM. Being the heaviest lepton, the τ offers a wide range of possible LFV decays and it is the lepton with the highest couplings with beyond-SM particles. The branching ratios of the τ LFV decays are predicted to be of order of 10^{-25}, while different SUSY or extra-dimension models predict an increase of the branching ratio up to 10^{-7}–10^{-10} [10, 11].

The Belle II experiment will collect per year a number of $\tau^+\tau^-$ events which is 10 times the whole Belle dataset ($10^9 \tau^+\tau^-$ pairs) giving the possibility to improve the present limits on the branching ratios even by a factor of 100 (fig. 5).

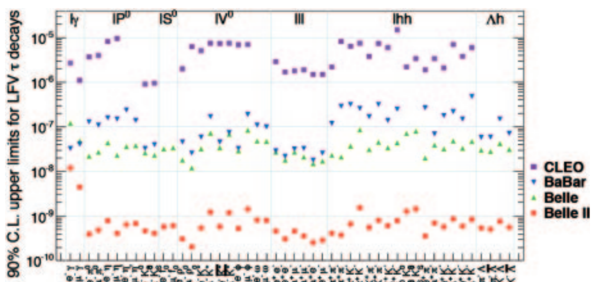

Fig. 5. – 90% CL upper limits on LFV τ decays. With different colors the dots represent the results obtained by CLEO, Babar, Belle, and the projection of Belle II limits.

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