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Belle II status and plans

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The search for physics beyond the Standard Model using indirect probes in the flavour sector is considered to be a very promising approach. Precision measurements of B, charm and τ decays complement direct searches at the highest energies and provide crucial, new information. This is the motivation for the upgrade of the KEK B factory into a Super B factory, which aims at collecting 50 ab^{-1} of e^+e^- collision data at the $\Upsilon(4S)$ resonance. In this article, we briefly review the physics case of this facility and report the present status of the upgrade.

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1. Introduction

The B factory at the Japanese national laboratory for particle physics KEK in Tsukuba is currently being upgraded to become a Super B factory. Starting in the Japanese fiscal year 2014, SuperKEKB will collide bunches of electrons and positrons at the center-of-mass energy of the $\Upsilon(4S)$ resonance with an instantaneous luminosity of 8×10^{35} cm^{-2}s^{-1}. This corresponds to an fifty-fold increase with respect to the previous machine. With data being delivered at this rate, the Belle II experiment can accumulate about 50 ab^{-1} by the year 2022. This corresponds to about 55 billion $\Upsilon(4S) \to B\bar{B}$ and about 47 billion $e^+e^- \to \tau^+\tau^-$ events.

This huge dataset will allow investigating extensions to the Standard Model (SM) through precision measurements in the B, charm and τ sectors. A special feature of Belle II – compared to hadron colliders – is the clean, low background environment, which allows to perform inclusive measurements and detect final states with multiple missing particles. In the following we briefly comment of the Belle II physics case and review the current status of the SuperKEKB collider and the Belle II detector.

2. Belle II physics

Belle II aims at probing a wide range of extensions to the SM through precision measurements in the B, charm and τ sectors. Four main research avenues will lead to this goal:

- The study of flavor changing neutral current (FCNC) transitions, *e.g.*, $b \to s$ penguin transitions and the mixing of neutral meson states, allows to search for new physics in loops,
- Improved measurements of the sides ($|V_{ub}|$) and angles (ϕ_2 and ϕ_3) of the unitarity triangle will consist a precision test of the Cabibbo-Kobayashi-Maskawa mechanism [1] and thus allow searching for new CP-violating phases, typically present in extensions to the SM,
- Semileptonic and leptonic B decays with τ leptons are extremely sensitive to New Physics scenarios with an extended Higgs sector. These final states typically have two or three missing neutrinos and can only be studied at lepton colliders,
- Last but not least, Belle II allows to search for lepton flavor violation (LFV) in τ and B decays. Large LFV is introduced by the SUSY breaking mechanism or by models with right-handed neutrino couplings.

This research program has a strong complementarity with high-p_T searches performed at the Large Hadron Collider (LHC): Indirect probes can explore regions of the parameter space which are not covered at the LHC, or provide additional information on new phenomena possibly discovered at the highest energies. This shall be illustrated with two examples:

Search for the charged Higgs boson with $B \to \tau\nu$

The Higgs sector of various extensions of the SM is richer and might contain charged Higgs bosons as well. In generic Type II Two Higgs Doublet Models (which also include the MSSM),

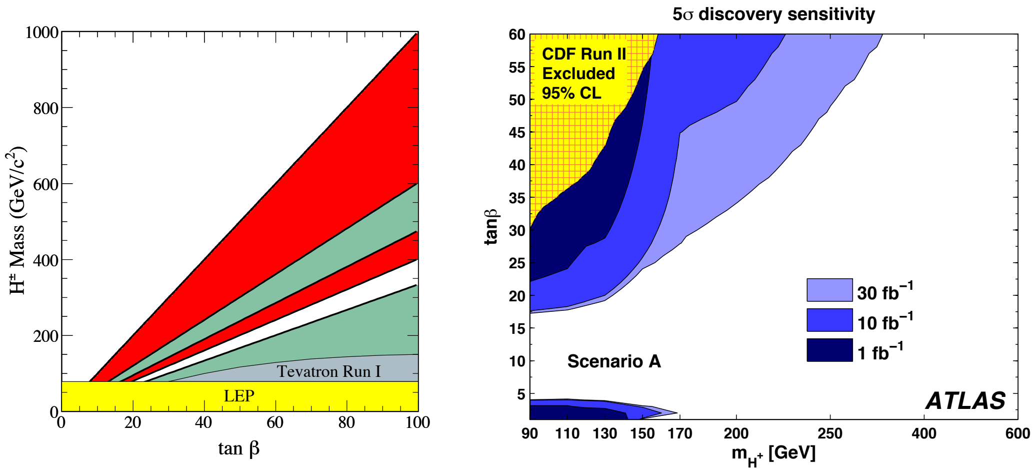

Figure 1: Left: The red area shows the 5σ discovery reach for the charged Higgs boson using the decay mode $B \to \tau\nu$ and 50 ab^{-1} of $\Upsilon(4S)$ data (from Ref. [4]); Right: The charged Higgs boson 5σ discovery sensitivity of ATLAS for 14 TeV running (from Ref. [5]).

the charged Higgs boson H^+ behaves like the intermediate vector boson W^+ and can thus alter the rate of $B \to \tau\nu$ with respect to the SM [2],

$$\Gamma(B^+ \to \tau^+\nu) = \Gamma_{\rm SM}(B^+ \to \tau^+\nu)\left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2 ,$$

where $\Gamma_{\rm SM}$ denotes the SM partial decay width, and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs fields, which is a free parameter of the model. The $B \to \tau\nu$ decay width can thus be suppressed or enhanced compared to the SM value.

Experimentally, the measurement of $B \to \tau\nu$ is challenging due to multiple neutrinos in the final state and can be done only at lepton colliders: To reduce backgrounds to a manageable level, one B meson in the $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ event is fully reconstructed in a hadronic decay mode and the properties of the remaining particle(s) are compared to those expected for signal and background. The most powerful variable for separating signal and background is the residual measured energy ($E_{\rm ECL}$) observed in the detector after all particles associated with either the signal- and tag-side B meson are removed. For signal, $E_{\rm ECL}$ should thus be consistent with zero. The excess of $24.1^{+7.6}_{-6.6}$ events found by Belle [3] corresponds to a branching fraction of $(1.79^{+0.56}_{-0.49}(stat)^{+0.46}_{-0.51}(syst)) \times 10^{-4}$. Extrapolating this result to 50 ab^{-1}, we obtain the 5σ discovery area at Belle II shown in red in Fig. 1 (left). For every value of $\tan\beta$, the charged Higgs mass reach exceeds the upper limit from direct searches by about a factor two, Fig. 1 (right).

Search for lepton flavor violation in τ-decays

Lepton flavor conservation in the SM is associated with neutrinos being massless. The discovery of finite neutrino masses thus implies violation of lepton flavor conservation. However, charged lepton flavor violating (LFV) processes are suppressed by the factor $(\Delta/m_W)^4$, where Δ is the neutrino mass difference and m_W the W-boson mass (≈ 80.4 GeV). The resulting branching fractions, $\mathcal{O}(10^{-53})$ to $\mathcal{O}(10^{-49})$, are beyond experimental reach.

Ratio	LHT	MSSM scenario 1	MSSM scenario 2
$\mathscr{B}(\tau \to 3e)/\mathscr{B}(\tau \to e\gamma)$	$0.4-2.3$	$\approx 1\times 10^{-2}$	$\approx 1\times 10^{-2}$
$\mathscr{B}(\tau \to 3\mu)/\mathscr{B}(\tau \to \mu\gamma)$	$0.4-2.3$	$\approx 2\times 10^{-3}$	$0.06-0.1$
$\mathscr{B}(\tau \to e\mu\mu)/\mathscr{B}(\tau \to \mu\gamma)$	$0.3-1.6$	$\approx 2\times 10^{-3}$	$0.02-0.04$
$\mathscr{B}(\tau \to \mu ee)/\mathscr{B}(\tau \to \mu\gamma)$	$0.3-1.6$	$\approx 1\times 10^{-2}$	$\approx 1\times 10^{-2}$
$\mathscr{B}(\tau \to 3e)/\mathscr{B}(\tau \to e\mu\mu)$	$1.3-1.7$	≈ 5	$0.3-0.5$
$\mathscr{B}(\tau \to 3\mu)/\mathscr{B}(\tau \to \mu ee)$	$1.2-1.6$	≈ 0.2	$5-10$

Table 1: Branching fractions of LFV τ-decays in the little Higgs model with T-parity (LHT) and in two minimal supersymmetric model (MSSM) scenarios ($m_{\mathrm{SUSY}} \approx 100$ GeV and $m_{\mathrm{SUSY}} \approx 1$ TeV) (from Ref. [4]).

The situation is quite different if there are new particles, which have masses of the order of the weak scale and couple to leptons. In fact, many extensions to the SM, such as supersymmetry, little Higgs and extra-dimension models predict enhanced LFV decays. For LFV τ-decays, branching fractions can be as high as the range experimentally accessible at Belle II, $\mathscr{O}(10^{-9})$ to $\mathscr{O}(10^{-7})$. In SUSY models, LFV τ-decays can receive significant contributions from diagrams containing SUSY particles in loops via slepton mixing. In this case, the largest LFV modes are radiative τ-decays such as $\tau \to \mu\gamma$ and $\tau \to e\gamma$. The radiative LFV decay rate is proportional to m_{SUSY}^{-4} (where m_{SUSY} is a typical SUSY particle mass) and becomes small when masses are larger than 1 TeV. In this case the modes mediated by the Higgs boson exchange, such as decays to three leptons (*e.g.*, $\tau \to 3e$, $\tau \to 3\mu$) become relatively important.

At Belle II, upper limits at the level of 10^{-9} are expected in the absence of signal, *e.g.*, $\mathscr{B}(\tau \to \mu\gamma) < 10\times 10^{-9}$ and $\mathscr{B}(\tau \to 3\mu) < 3\times 10^{-9}$ (at 90% C.L.) [4]. The expected pattern of τ LFV depends strongly on the kind of underlying New Physics (Table 1). If new phenomena are found at the LHC, the observation and non-observation of specific τ LFV modes will provide crucial insights into the nature of the beyond-SM physics. The full range of τ LFV modes can be covered only at a Super B factory.

3. Accelerator

SuperKEKB is built by upgrading the existing KEKB machine, which is an asymmetric energy collider consisting of an 8 GeV electron (HER) and a 3.5 GeV positron ring (LER) located on the KEK Tsukuba campus [6]. KEKB has achieved an instantaneous luminosity of 2.1×10^{34} cm^{-2}s^{-1} in 2009. To go beyond the KEKB performance, there are basically two strategies which can be discussed by considering the expression for the instantaneous luminosity,

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_{y,e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right) .$$

Here, $\gamma_{e\pm}$ is a relativistic factor, r_e is the classical electron radius, σ_x^* and σ_y^* are the horizontal and vertical beam sizes at the interaction point (IP), $I_{e\pm}$ are the stored currents, $\xi_{y,e\pm}$ is the beam-beam parameter, β_y^* is the vertical β-function at the IP, and R_L/R_{ξ_y} is a reduction factor reflecting the finite crossing angle of the beams.

	KEKB		SuperKEKB	
Parameter	LER	HER	LER	HER
Beam energy E_{beam} (GeV)	3.5	8	4	7
Half crossing angle ϕ (mrad)	11		41.5	
Horizontal emittance ε_x (nm)	18	24	3.2	5.0
Emittance ratio κ (%)	0.88	0.66	0.27	0.25
Beta functions at IP β_x^*/β_y^* (mm)	1200/5.9		32/0.27	25/0.31
Beam currents I_{beam} (A)	1.64	1.19	3.60	2.60
Beam-beam parameter ξ_y	0.129	0.090	0.0886	0.0830
Luminosity L (cm$^{-2}s^{-1}$)	2.1×10^{34}		8×10^{35}	

Table 2: Machine parameters of the present KEKB collider and of SuperKEKB (from Ref. [7]).

Only very few parameters in this expression can be significantly altered: To increase luminosity, one can increase the stored currents I_{e^+} and I_{e^-}, which corresponds the *high current* strategy. The main disadvantage of this solution is the need to substantially increase the power of the accelerating cavities, leading to high operation costs. High currents also imply high levels of background in the experiment from beam-beam and beam-gas scattering. The high energy loss due to synchrotron radiation causes machine damage and backgrounds in the detector. Mainly because of high operation costs, this option was dropped.

The second strategy is the *low emittance* scheme, originally proposed for the Italian SuperB project. This option has been adopted as the baseline for SuperKEKB [7]. It foresees a drastic squeezing of the IP beam size σ_y^* from 1.1 μm at KEKB to 0.08 μm at SuperKEKB. Due to this extremely small vertical beam size, this option is also referred to as nano-beam scheme. Low emittance means that the average spread of particle positions and momenta must be extremely small, to make particles actually collide in this small volume. A luminosity of 8×10^{35} cm^{-2}s^{-1} can be achieved with only a moderate increase in beam currents compared to KEKB. The full set of SuperKEKB machine parameters is given in Table 2.

On the hardware side, the upgrade from KEKB to SuperKEKB requires the replacement of the long TRISTAN dipoles with shorter ones, a new interaction region with new final focusing quadrupoles near the IP, and a redesign of the HER and LER lattices to squeeze the emittance. The beam pipes in both rings will be replaced to reduce electron cloud instabilities due photo electrons produced in the beam pipe. A major upgrade of the accelerating RF cavities is not necessary. The injector complex needs to be modified to obtain low emittance electrons and positrons. This includes a new positron damping ring, a new positron target and a new RF gun for electrons with reduced emittance.

The SuperKEKB upgrade project has now formally started with a ground-breaking ceremony held at KEK on November 18, 2011. On February 7, 2012 the first new LER dipole magnets were installed in the tunnel, the installation of the remaining magnets being foreseen in this year. Commissioning of SuperKEKB will start in the Japanese fiscal year 2014. The goal is to accumulate physics data equivalent to 50 ab^{-1} by the year 2022 (Fig. 2).

PoS(HQL 2012)023

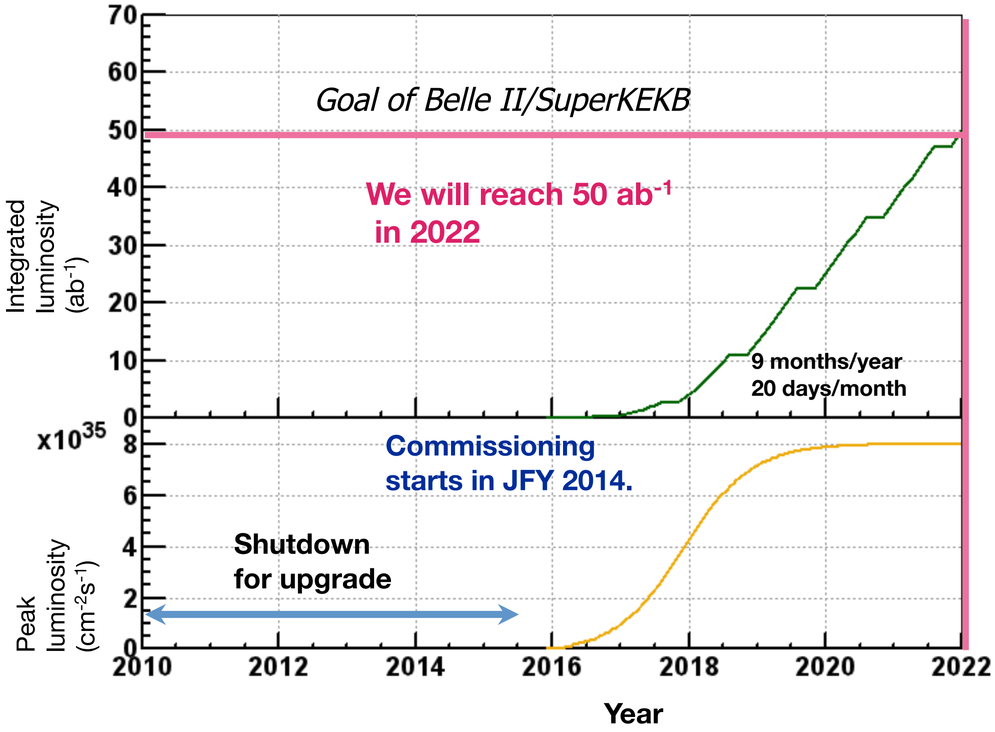

Figure 2: Luminosity prospects for SuperKEKB.

4. Detector

Also the Belle II apparatus will be constructed reusing many parts of the present Belle spectrometer [8]. The main challenges for the detector at SuperKEKB are:

- A ten to twenty-fold increase of backgrounds compared to KEKB, leading to higher radiation damage and higher rates of fakes hits in the tracking detectors and pile-up noise in the electromagnetic calorimeter,
- A ten-fold increase of the event rate compared to Belle, leading to increased requirements on the data acquisition system and the on- and offline computing infrastructure.

The design goal of Belle II is to maintain or even improve the data quality with respect to Belle in the high luminosity environment.

The baseline design of the Belle II detector is now documented in the Technical Design Report [7] and illustrated in Fig. 3. It foresees a replacement of the Belle 4-layer silicon vertex detector with a 2-layer DEPFET pixel device and a 4-layer silicon strip detector. DEPFET is a novel technology originally developed for vertex detection at the International Linear Collider (ILC), which has now reached a high level of maturity [9]. For Belle II, the use of very thin (75 μm) detectors with a pitch around 38×50 μm^2 is planned. The strip layers consist of double-sided silicon strip sensors (DSSD) read out by fast APV25 chips, originally designed for the CMS experiment at the LHC. The Belle II silicon detectors will cover the radii between 1.3 cm and 13.5 cm.

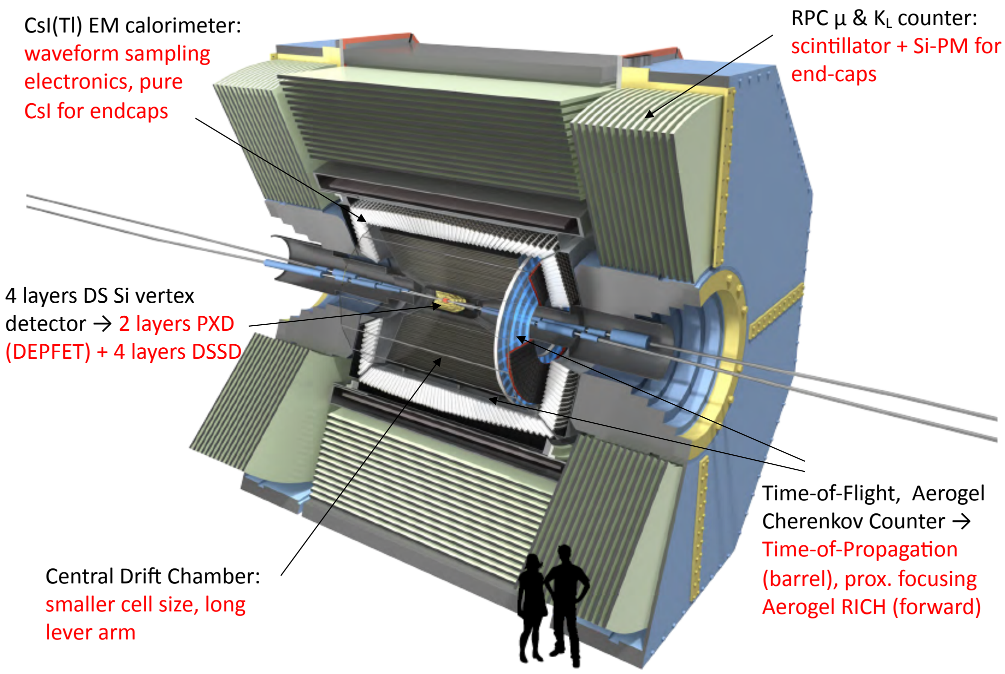

Figure 3: The Belle II detector upgrade.

Also the Belle drift chamber will be replaced. The Belle II chamber has a larger inner radius and smaller cells near the beam pipe to cope with higher backgrounds. The recover the momentum and dE/dX resolutions of Belle, also the outer radius is extended. Particle identification in the barrel region will be provided by a Time-of-Propagation (TOP) counter. The TOP consists of a quartz radiator readout by MCP-PMTs in the backward region. Cherenkov photons generated in the radiator are internally reflected and propagate to the PMTs. There, arriving photons are detected in two spatial dimensions and the time of propagation is measured. This three-dimensional information provides improved K/π separation compared to Belle. Another improvement is the new forward endcap particle identification system, consisting of a proximity focusing Cherenkov ring imaging counter with inhomogeneous aerogel radiators (ARICH).

The electromagnetic calorimeter has to cope with higher backgrounds. It is planned to replace the crystals in the endcap regions with pure CsI. For the entire device, new electronics with waveform sampling will be installed. Some resistive plate chambers of the present Belle muon system in the flux return of the magnet (KLM) will be replaced by scintillators for better background tolerance. In the endcaps the RPCs will be replaced with scintillator strips.

5. Summary

The investigation of physics beyond the Standard Model using indirect probes in the flavor sector complements searches at high energies and provides crucial, new information. This is the physics case of the KEK Super B factory, consisting of the SuperKEKB machine and the Belle II detector, constructed by upgrading the present B factory. The aim of the new facility is to collect a $\Upsilon(4S)$ data set equivalent to 50 ab^{-1} by the year 2022. This corresponds to about 55 billion $\Upsilon(4S) \to B\bar{B}$ and about 47 billion $e^+e^- \to \tau^+\tau^-$ events.

The upgrade strategy chosen for the machine is the low emittance option, in which the high luminosities are achieved by drastically squeezing the beam size at the interaction point. Also the detector undergoes a major upgrade with the replacement of many sub-systems. The Belle II detector will have improved rate tolerance and better hermeticity compared to Belle. The upgrade project was formally started in November 2011. Both the machine and the detector are on schedule for a start of commissioning in the Japanese fiscal year 2014.

References

[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[2] W. -S. Hou, Phys. Rev. D **48**, 2342 (1993).

[3] K. Ikado *et al.* [Belle Collaboration], Phys. Rev. Lett. **97**, 251802 (2006) [hep-ex/0604018].

[4] T. Aushev, W. Bartel, A. Bondar, J. Brodzicka, T. E. Browder, P. Chang, Y. Chao and K. F. Chen *et al.*, arXiv:1002.5012 [hep-ex].

[5] G. Aad *et al.* [ATLAS Collaboration], arXiv:0901.0512 [hep-ex].

[6] S. Kurokawa, Nucl. Instrum. Meth. A **499** (2003) 1.

[7] T. Abe *et al.*, arXiv:1011.0352 [physics.ins-det].

[8] A. Abashian *et al.* [Belle Collaboration], Nucl. Instrum. Meth. A **479**, 117 (2002).

[9] J. J. Velthuis *et al.*, Nucl. Instrum. Meth. A **579**, 685 (2007).

PoS(HQL 2012)023