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The Belle II experiment and SuperKEKB upgrade

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Abstract: The Belle II/SuperKEKB experiment is an e^+e^- collider running at the Υ(4S) resonance energy to produce B meson pairs. As an upgrade of the Belle/KEKB experiment, it will start physics data taking from 2018 and with ~40 times luminosity. Its goal is to accumulate 50 ab^{-1} of e^+e^- collision data. Now the upgrade of the sub-detector systems is on-going in KEK. The physics program has a wide range of areas, including searches for direct CP violation (CPV), lepton flavour violation and dark matter. The current upgrade status of Belle II and SuperKEKB is reviewed and some physics opportunities at this facility are introduced.

Key words: Belle II; SuperKEKB; e^+e^- collider; New Physics

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Belle II 实验和超级 KEKB 升级

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摘要:Belle II/超级 KEKB 实验是一个在 Υ(4S)共振态能量点运行产生 B 介子对的正负电子对撞机. 作为 Belle/KEKB 实验的升级,它将从 2018 年开始以大约 40 倍的亮度取数,目标是收集 50 ab^{-1}的正负电子对撞数据. 现在子探测器系统的升级正在 KEK 进行. 物理项目涉及范围很宽,包括寻找直接 CP 破坏、轻子味破缺、暗物质. 本文回顾当前 Belle II 和超级 KEKB 升级状况并介绍该设施带来的物理机遇.

关键词:Belle II;超级 KEKB;正负电子对撞机;新物理

0 Introduction

The so-called B factory is an e^+e^- collider running at the Υ(4S) resonance energy to produce B meson pairs. The major B factories are Belle running at KEKB in Japan and BaBar running at PEP-II in US. The total data set collected by these two facilities is ~1.5 ab^{-1} of e^+e^- collision data. With that data sample, they've reached physics achievements in areas like the CKM angle measurement, $|V_{cb}|$ and $|V_{ub}|$ measurement, semileptonic and leptonic B decays, rare B decays, τ physics, D^0 mixing and CPV, B physics at the Υ(5S), two-photon physics and new resonances[1].

To search for the New Physics (NP), which

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is physics beyond the Standard Model (SM), the Belle/KEKB experiment will be upgraded to Belle II/SuperKEKB[2]. The upgraded detector is planning to take ~50 ab^{-1} of $e^{+}e^{-}$ collision data. The SuperKEKB asymmetric electron-positron collider can provide a clean environment for producing B meson pairs via $\Upsilon(4S)$ resonance decay. Its designed luminosity is 8×10^{35} $cm^{-2}\cdot s^{-1}$, which is about 40 times larger than the KEKB collider. The 50 ab^{-1} overall integrated luminosity corresponds to 55 billion $B\bar{B}$ pairs, 47 billion $\tau^{+}\tau^{-}$ pairs, and 65 billion $c\bar{c}$ states.

In this article, we introduce the Belle II/SuperKEKB experiment, the current status and the future plan of the experiment, and the opportunities for New Physics.

1 SuperKEKB

Many sub-systems of the SuperKEKB accelerator need to be upgraded for achieving the 40 times luminosity compared with KEKB. The most important part is the beam size. By using the so-called nano-beam technology[3], the beam bunches are significantly squeezed to 60 nm thick at the collision point as shown in Fig. 1. The beam energies of positron and electron will be changed slightly, from 3.5 GeV/8 GeV to 4 GeV/7 GeV, to achieve a less boosted center-of-mass system.

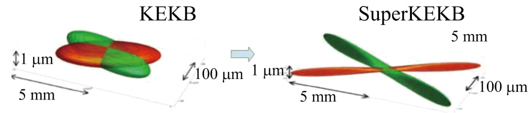


Fig. 1 The beam size comparison between KEKB (left) and SuperKEKB (right)

2 Belle II detector

As shown in Fig. 2, most sub-detectors of Belle will be upgraded for Belle II. This includes the newly designed vertex detection system (PXD and SVD), a drift chamber with longer arms and smaller cells, a completely new PID system which consists of TOP detector in the central region and ARICH detector in the forward end, the electromagnetic calorimeter (ECL) with upgraded crystals and electronics, and upgraded $K_L-\mu$ detection system (KLM). More details will be introduced in the following sections.

2.1 VXD

The vertex detector (VXD) consists of two parts: PXD in the inner part[4] and SVD in the outer part[5]. PXD consists of two layers of DEPFET (DEPleted p-channel Field Effect Transistor) and SVD consists of four layers of DSSD (Double Sided Strip Detectors), as shown in

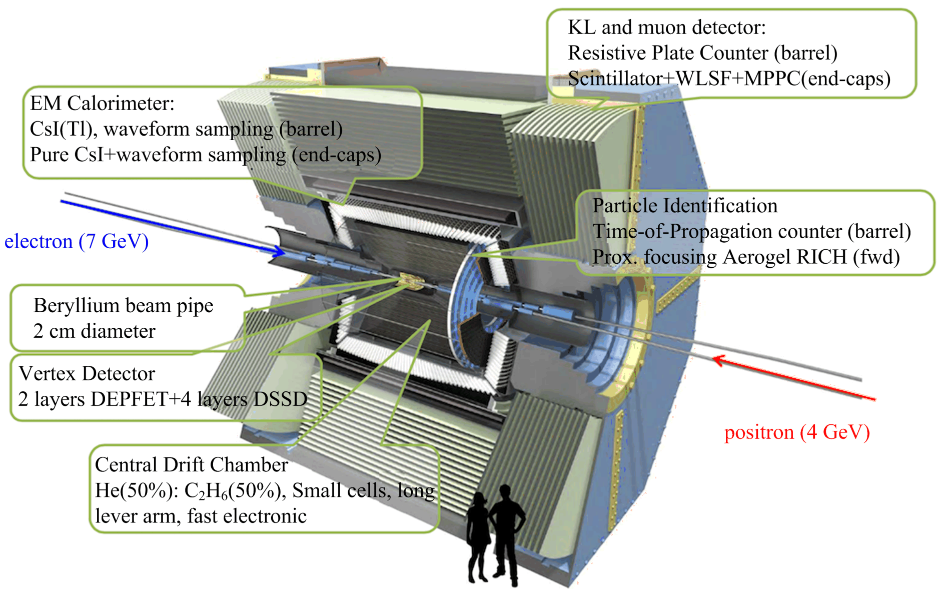


Fig. 2 Overview of the Belle II detector and its sub-detectors

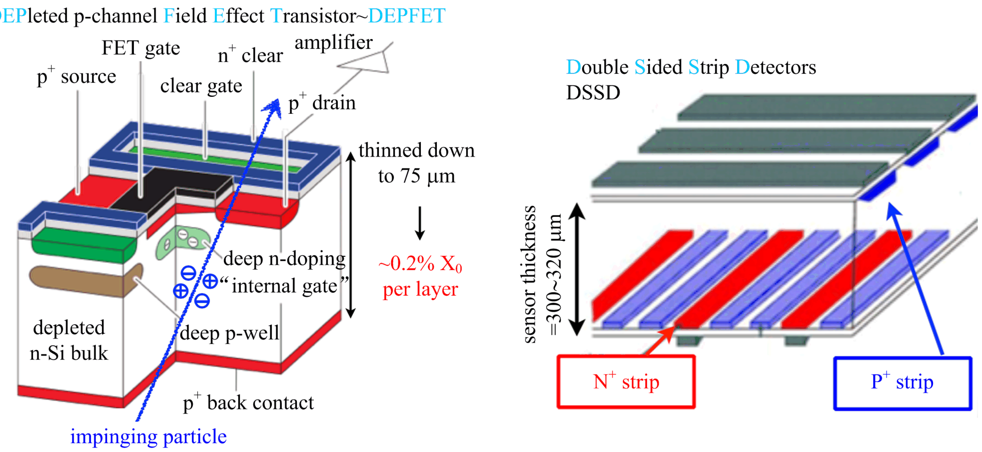


Fig. 3　The structure of the DEPFET (left) and DSSD (right)

Fig. 3. These two sub-detectors combined should have a good vertex resolution for charged tracks. Now the system integration is on-going, and a beam test for VXD has just finished in the spring of 2016.

2.2　CDC

As the main tracking device for charged tracks, the CDC in Belle II is larger than that in Belle and it has a smaller cell size, as shown in Fig. 4. This should improve the momentum and dE/dx resolution. The stringing for the CDC was finished in January of 2014 with 51456 wires and now it is being commissioned with cosmic rays.

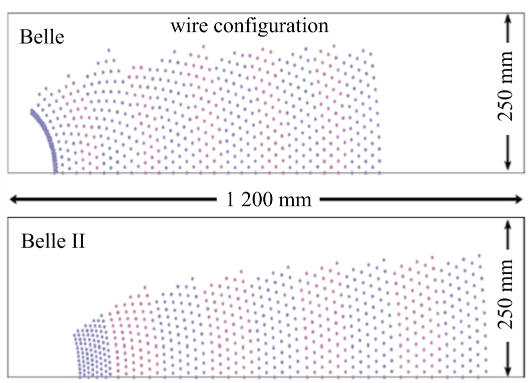


Fig. 4　The comparison of CDC wire configurations between Belle (top) and Belle II (bottom)

2.3　TOP

The imaging Time of Propagation sub-detector (TOP or iTOP) will be used for particle identification in the barrel region of Belle II[6]. There are 16 TOP modules, and each one consists of two quartz bars, one mirror, one prism, and an array of photo-detectors to collect Cerenkov photons generated by charged tracks going through the radiator, as shown in Fig. 5. To distinguish between kaons and pions, the photo-detectors have excellent position and timing resolution. This is achieved by using multi-channel-plate photomultiplier tubes (MCP-PMTs) and new waveform sampling electronics.

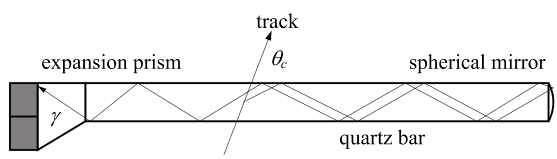


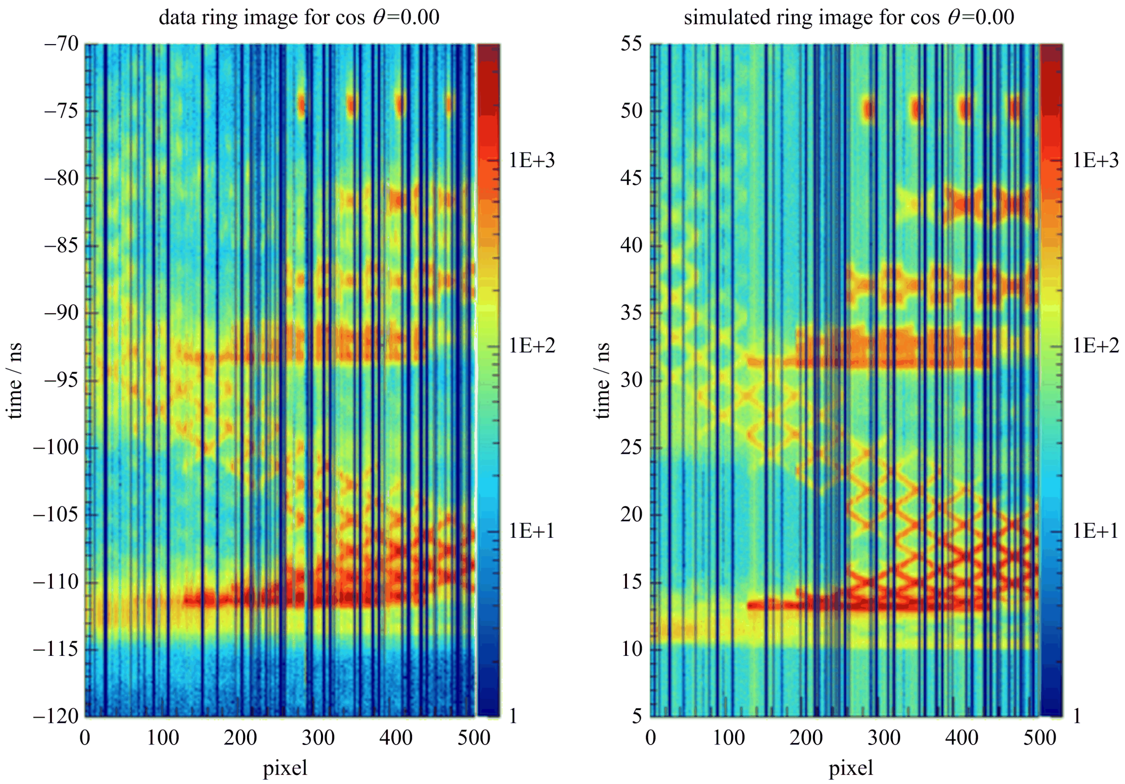
Fig. 5　The structure of the TOP detector

Prototype TOP modules have been tested during the beam test at SPring-8 at LEPS in 2013, and good agreement between data and MC simulation has been obtained[7], with timing requirement $\sim O(100\ \text{ps})$, as shown in Fig. 6.

As of May 2016, all TOP modules have been assembled, tested and installed to the Belle II detector. The commissioning of all modules is underway.

2.4　ARICH

Aerogel Ring Imaging Cerenkov (ARICH) detector will be used for particle identification in the forward end-cap. Two layers of aerogel with different indices of refraction will be used to improve the resolution of the detector[8]. For



Each pixel represents one read-out channel

Fig. 6 The TOP beam test data (left) and simulated MC sample (right)

readout, 420 Hybrid Avalanche Photo Detectors (HAPD), each with 144 channels, will be used, as shown in Fig. 7.

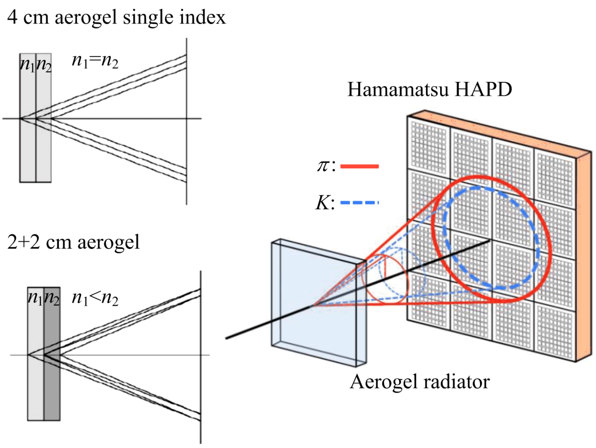


Fig. 7 The focusing mechanism (left) and the structure (right) of ARICH

2.5 ECL

For the upgrade of the ECL detector, the crystals in barrel side will be re-used and the crystals in the end-cap will be refurbished. New electronics, such as bias filter and waveform sampling will be used for the upgraded detector[9]. Now the cosmic ray test is underway. The expected performance for ECL is shown in Fig. 8[10].

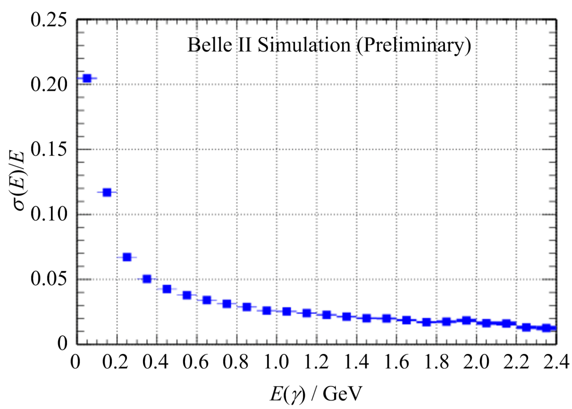


Fig. 8 The expected performance of the ECL detector[10]

2.6 KLM

The endcaps and the inner layers of the barrel resistive plate chambers (RPCs) of KLM has been replaced with scintillators due to increased backgrounds expected in Belle II, as shown in Fig. 9. The barrel KLM was the first sub-detector to be installed in Belle II.

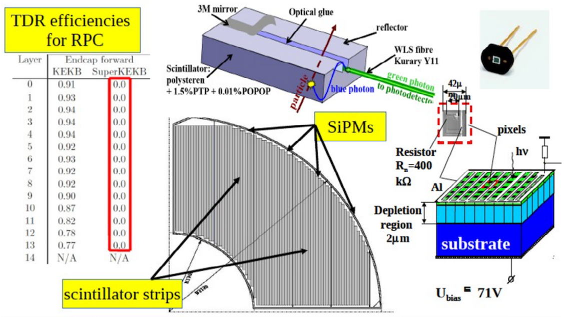
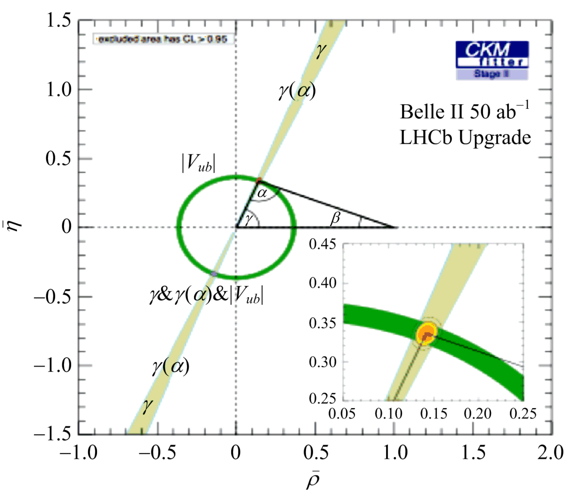


Fig. 9　The structure of the KLM detector

3　Physics opportunities

There should be many potential signals for new physics in Belle II, such as the flavor changing neutral currents, probing charged Higgs, new sources of CPV, lepton flavour violation decays, and searches for a dark photon. With the much larger data set compared with Belle and BaBar, Belle II will contribute to the search for new physics, together with the upgraded LHCb. For example, the CKM Unitarity Triangle should be significantly improved, as shown in Fig. 10[11].



This is a fit to the tree level measurements of the CKM UT angles.

Fig. 10　The predicted accuracy of CKM Unitarity Triangle with data taken by LHCb and Belle II, from Ref. [11]

3.1　Direct CPV in $D^0 \to \phi\gamma$, $\rho^0\gamma$

The direct CPV in radiative decays can be enhanced to exceed 1%[12] over standard model. The A_{CP} for $D^0 \to \phi\gamma$ could be up to 2%, and the A_{CP} for $D^0 \to \rho^0\ \gamma$ could be up to 10%. The decay for $D^0 \to \phi\gamma$ was first observed by Belle with 78 fb^{-1} of data, with the relative error on yield of about 25%[13]. For Belle II, with 50 ab^{-1} of data, the A_{CP} sensitivity will be reduced to 1%.

3.2　$D^0 \to \gamma\gamma$

The branching fraction of the decay $D^0 \to \gamma\gamma$ is predicted by SM as $\approx 10^{-8} \sim 10^{-11}$. Although the rate is low, New Physics (NP) processes can lead to significant enhancements[14].

This decay has been searched for by BaBar① and the upper limit with 470 fb^{-1} of data is 2.2×10^{-6} with 90% CL[16], as shown in Fig. 11.

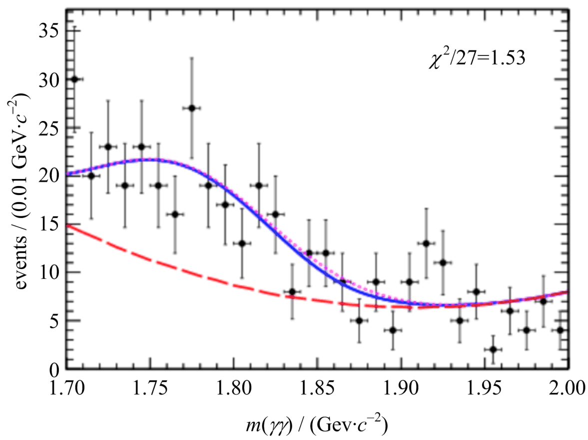


Fig. 11　The decay of $D^0 \to \gamma\gamma$ from BaBar[16]

With 50 ab^{-1} of data by Belle II, the upper limit could be improved to $\sim 2 \times 10^{-8}$, if it scales with luminosity L, or $\sim 2 \times 10^{-7}$, if it scales with $\sqrt{L}$.

3.3　τ Lepton Flavour Violation

The lepton flavour violation decays are highly suppressed by SM, with a branching fraction of $\sim 10^{-25}$. But they could be enhanced in certain New Physics scenarios, such as supersymmetry (SUSY)[17], little Higgs models[18] and extra dimensions[19].

Belle has searched for LFV[20-21], but no trace of NP has been found. As shown in Fig. 12, the red dots show the sensitivity for some LFV decays in Belle II[22]. The branching fraction of the decays

① Recently, Belle has presented an upper limit on this decay; see Ref. [15].

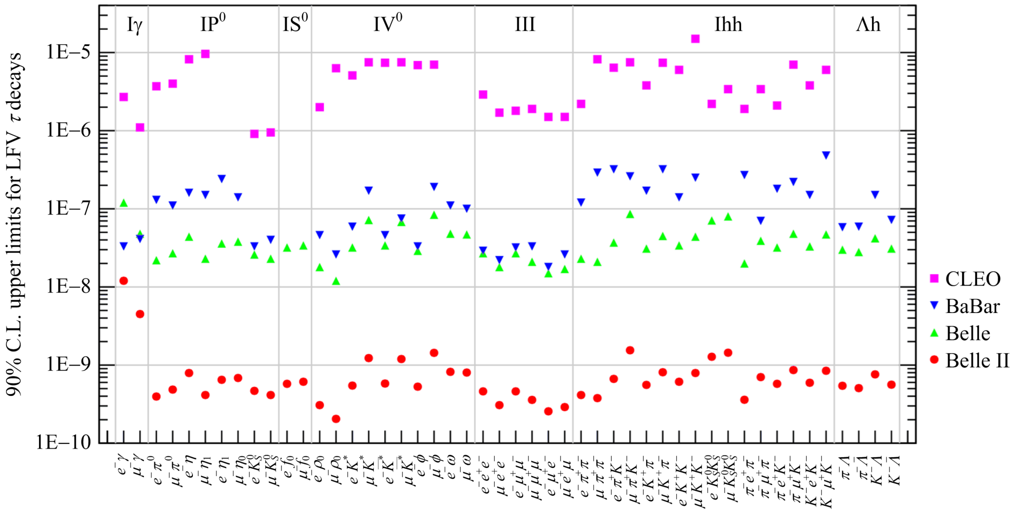


Fig. 12 The comparison of LFV upper limit by different experiments for different decay channels, from Ref. [22]

is within the capability of the Belle II experiment. Belle II will push many limits below 10^{-9}.

3.4 Dark sector

The dark photon A' is one candidate for dark matter that could be searched for at an accelerator. Its mass is predicted to be in the range of MeV to GeV[23]. The dark photon could be searched for in the reaction $e^{+}e^{-}\to\gamma_{ISR}A'$. There are two ways to detect a dark photon: probing leptonically decaying dark photons through mixing, or probing sub-GeV dark matter in invisible decays. In the latter case, the signature for the decay is a single energetic photon in the event, which requires the single photon trigger. The single photon trigger was not available in Belle but will be implemented in Belle II.

The upper limits of dark photon measurement for different experiments are shown in Fig. 13[24]. Belle II has an advantage to search for dark photon A' with much higher integrated luminosity.

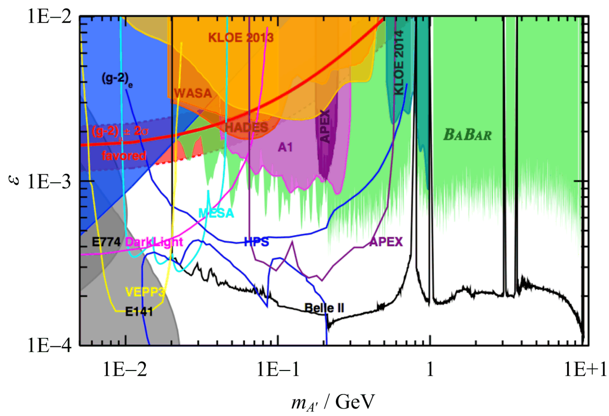


Fig. 13 The upper limit by different experiments in search of the dark photon, from Ref. [24]

4 Schedule

The SuperKEKB accelerator is now at the final stage of construction and the upgrade of the Belle II detector is on-going. As shown in Fig. 14, there are three phases in the commission and operation of Belle II. In Phase 1, which begins in early 2016, the commissioning of various components will start without rolling-in the detector. In Phase 2, which begins in the autumn of 2017, Belle II detector will be partly commissioned to take test physics data without the vertex detector. Finally, in Phase 3, which is expected to start at the end of 2018, the Belle II detector with full apparatus will take physics data.

The plan for instantaneous and integrated luminosity is shown in Fig. 15. According to this plan, the target integrated luminosity of 50 ab^{-1} will be achieved by 2024.

5 Conclusion

Belle and BaBar as B factories have made many contributions for flavour physics. As an upgrade, the Belle II/SuperKEKB experiment should play an important role in the search for New Physics. With

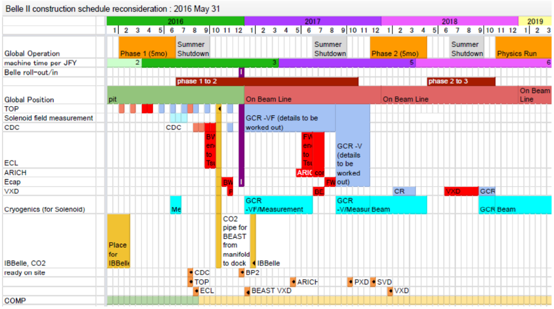


Fig. 14　The current Belle II commissioning schedule

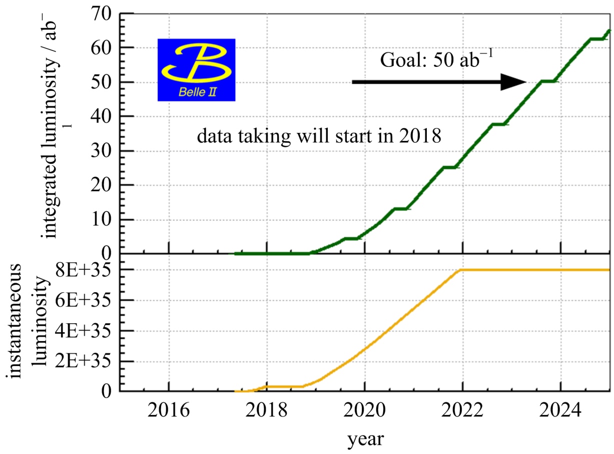


Fig. 15　The plan for Belle II data taking

the upgraded accelerator and detector, the experiment will have much higher luminosity and much better performance for detecting final state particles.

With the much larger data set collected with the upgraded detector, Belle II has a rich physics program, which makes it possible to study the channels with missing energy and neutral particles in the final states. Now the accelerator and detector are under construction, and the physics data taking will start at the end of 2018.

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