The Belle II Experiment

– Quest for New Physics –

Particle Physics: Searching for the fundamental law of the universe

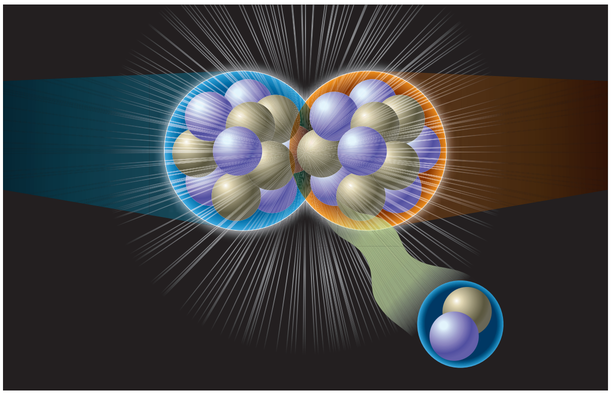
From the time of ancient Greek philosophers, people have continued to question the origin of the matter that forms the world. The Earth where we live and the matter that makes up the universe have diversity, which seems infinite. However, all matter is composed of "elementary particles". Particle physics, which examines the ultimate constituents of matter has progressed greatly in the 20th century; the exploration has lead to the discoveries of the atom, the nucleus, quarks and other fundamental particles. The laws that rule the microscopic world of elementary particles are important for understanding the early high energy stages of the birth of the universe.

Antiparticles disappeared from the Universe

It is known that "antiparticle" counterparts exist for all elementary particles. Antiparticles have almost the same properties as particles except that the electric charge is opposite for antiparticles. When a particle and an antiparticle meet they annihilate and turn into energy. Antimatter composed of antiparticles has not been discovered in the universe.

When the high energy state, which existed immediately after the creation of the universe, is artificially created using an accelerator, particle-antiparticle pairs are inevitably produced. In other words, immediately after the creation of the universe equal numbers of particles and antiparticles produced from the high energy state of the Big Bang existed.

The antiparticles paired up with particles and annihilated. For an unknown reason, only particles survived in the universe. Why did the anti-particles disappear? This is one of the mysteries that the Belle II experiment attempts to solve.

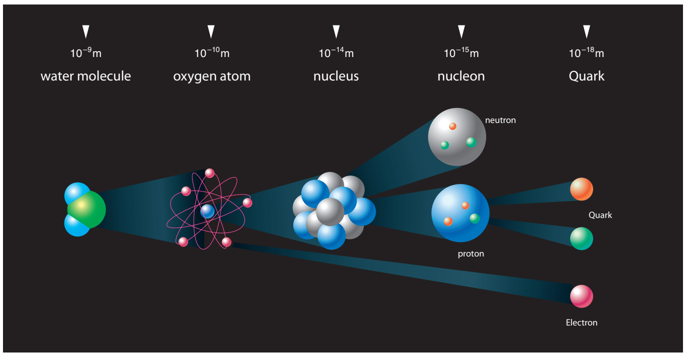


When particles and antiparticles meet, they annihilate.

Beyond "the Standard Model" of Particle Physics

The matter that surrounds us is made up of atoms. The atoms are made up of a nucleus and electrons, and the nucleus is composed of protons and neutrons. Furthermore, the protons and the neutrons have been found to be composite particles consisting of quarks.

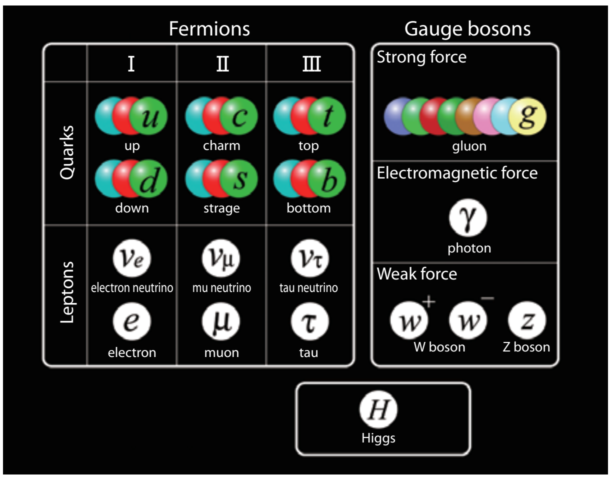
In the current theory of elementary particles, the quarks which form protons and neutrons, and the leptons, which are from the same family as the electrons and the neutrinos, are thought to be the elementary particles which make up matter. There are six types of quarks and leptons that can be arranged in three generations. There are also the elementary particles that transfer "weak force", "electromagnetic force" and "strong force", and the Higgs boson that gives masses to particles. The behavior of the elementary particles is described by the theory known as "the Standard Model".



All matter is made of elementary particles.

Experiments' results have been very well explained by the Standard Model, which was theoretically established in the 1970s. However, we know that mysteries that cannot be solved by the Standard model still remain.

For example, the Standard Model cannot explain the disappearance of antiparticles from the universe. It cannot explain the nature of either the dark matter or dark energy, which are considered to be the major constituent of the universe. To answer these questions, we need to explore new laws of physics beyond the Standard Model.



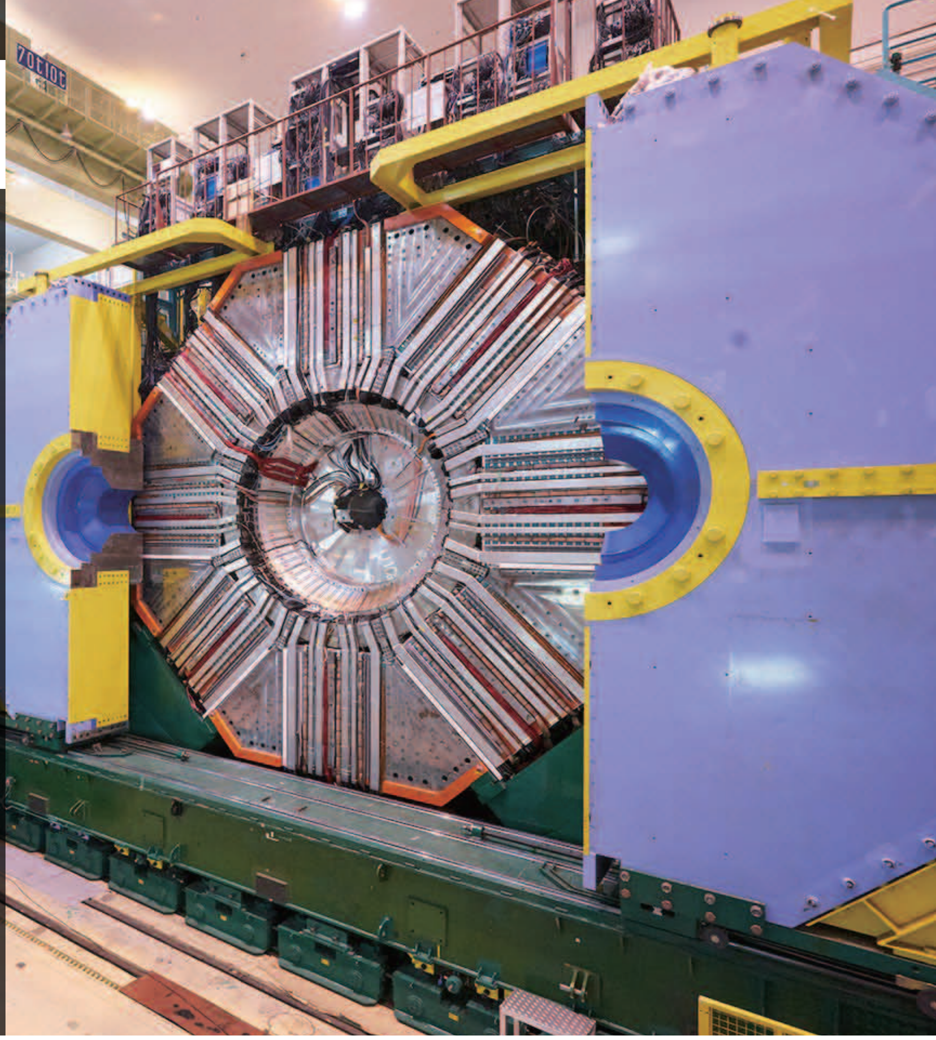
Particles of the Standard Model

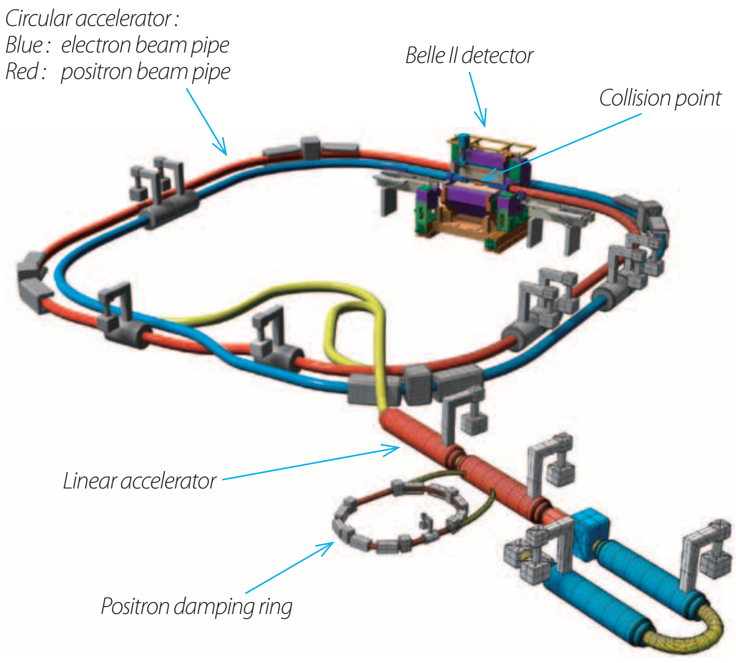
Belle II Experiment and SuperKEKB accelerator

The Belle II experiment, which is an international particle physics collaboration at KEK in Tsukuba, Japan, focuses on the investigation of particles called B mesons, which are produced in collisions of accelerator particle beams. The B meson is about 5.6 times heavier than the proton and decays into various other particles in about 1.5 picoseconds (1 picosecond is one trillionth of a second). The Belle II detector, which examines the B meson decays, has been significantly upgraded from the Belle experiment, which completed operation in 2010, and uses state-of-the-art technology.

The Belle II experiment investigates particle-antiparticle symmetry breaking and extremely rare phenomena, which are thought to have occurred in the early universe, by collecting 50 times more data than in the previous Belle experiment. Analyzing the huge Belle II dataset may reveal unknown particles and the nature of the forces that govern them. This allows us to discover new laws of physics and unveil the mystery behind the disappearance of antimatter from the universe.

Introduction to the Belle II experiment :
https://www.youtube.com/watch?v=vnrQcF-jmpM



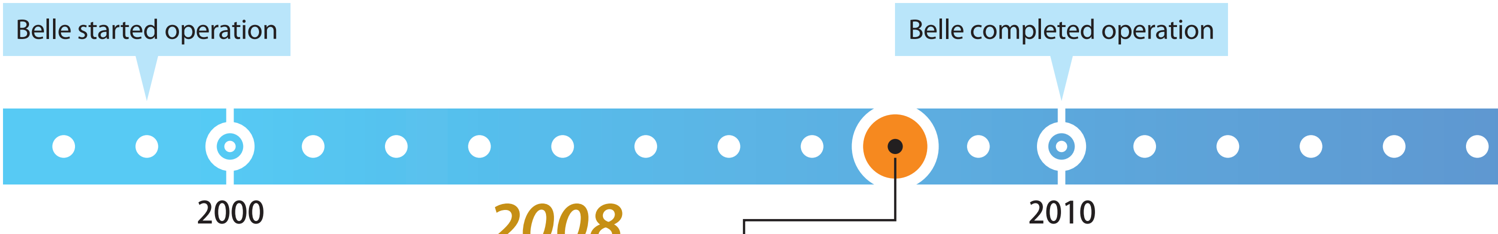


SuperKEKB Accelerator

SuperKEKB is a collider accelerator with a circumference of 3 km. Electrons and positrons are accelerated to energies of 7 billion and 4 billion electron volts, respectively, in a linear accelerator and then are injected into two circular storage rings and circulated in opposite directions. When the electrons and positrons accelerated close to the speed of light are brought into collision in the center of the Belle II detector, a large number of various particle reactions, which are thought to have taken place in the early universe, are generated. The accelerator energy is set to produce a large number of B meson/anti B meson pairs in the collisions of the two beams. Hence the accelerator facility is called a Super B Factory (a factory producing a large number of B mesons).

The KEKB accelerator, the accelerator that preceded SuperKEKB, achieved the world record for "luminosity", which is a figure of merit for accelerator performance related to the number of particle reactions that are produced. In the SuperKEKB accelerator, a luminosity 40 times greater than in the KEKB accelerator is achieved by introducing start of the art technology, such as nanobeams, which makes it possible for the accelerated electrons and positrons to be focused to 20 µm (0.02 mm) in width and 100 nm (0.0001 mm) in height, and provide the Belle II detector with an integrated luminosity 50 times larger than KEKB.

From Belle to Belle II



2008

The Novel prize in physics

Dr. Makoto Kobayashi and Dr. Toshihide Maskawa

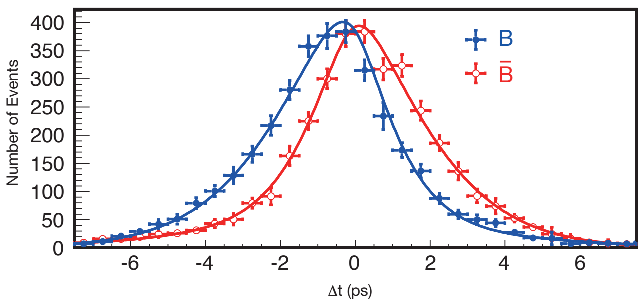
Achievement of the Belle Experiment

The Belle experiment, which preceded the Belle II, operated from 1999 to 2010 and accumulated approximately eight hundred million B meson and anti B meson pairs. One of its most important achievements was the validation of the CP violation hypothesis that was the basis for the 2008 Nobel Prize in Physics for Dr. Makoto Kobayashi and Dr. Toshihide Maskawa.

CP means that the laws of physics remain unchanged when particle and antiparticle are exchanged and mirror-imaged. In 1964, a measurement at an accelerator in the United States showed that this symmetry is violated in K meson decay. However, the underlying mechanism for CP violation remained a mystery for a long time.

The Kobayashi-Maskawa theory, which explains how the CP violation arises, predicted that a large CP violation would occur in the decays of B mesons, particles containing bottom quarks that belong to the third generation. The Belle experiment was constructed in order to verify this theory.

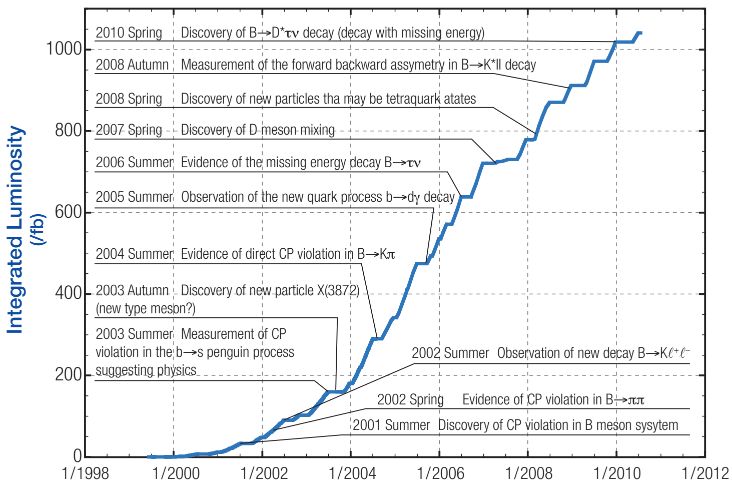
In 2001, the Belle experiment and the BABAR experiment, which ran at the same time in the U.S., finally observed large CP violation in the B meson sector and confirmed the prediction of the Kobayashi-Maskawa theory.



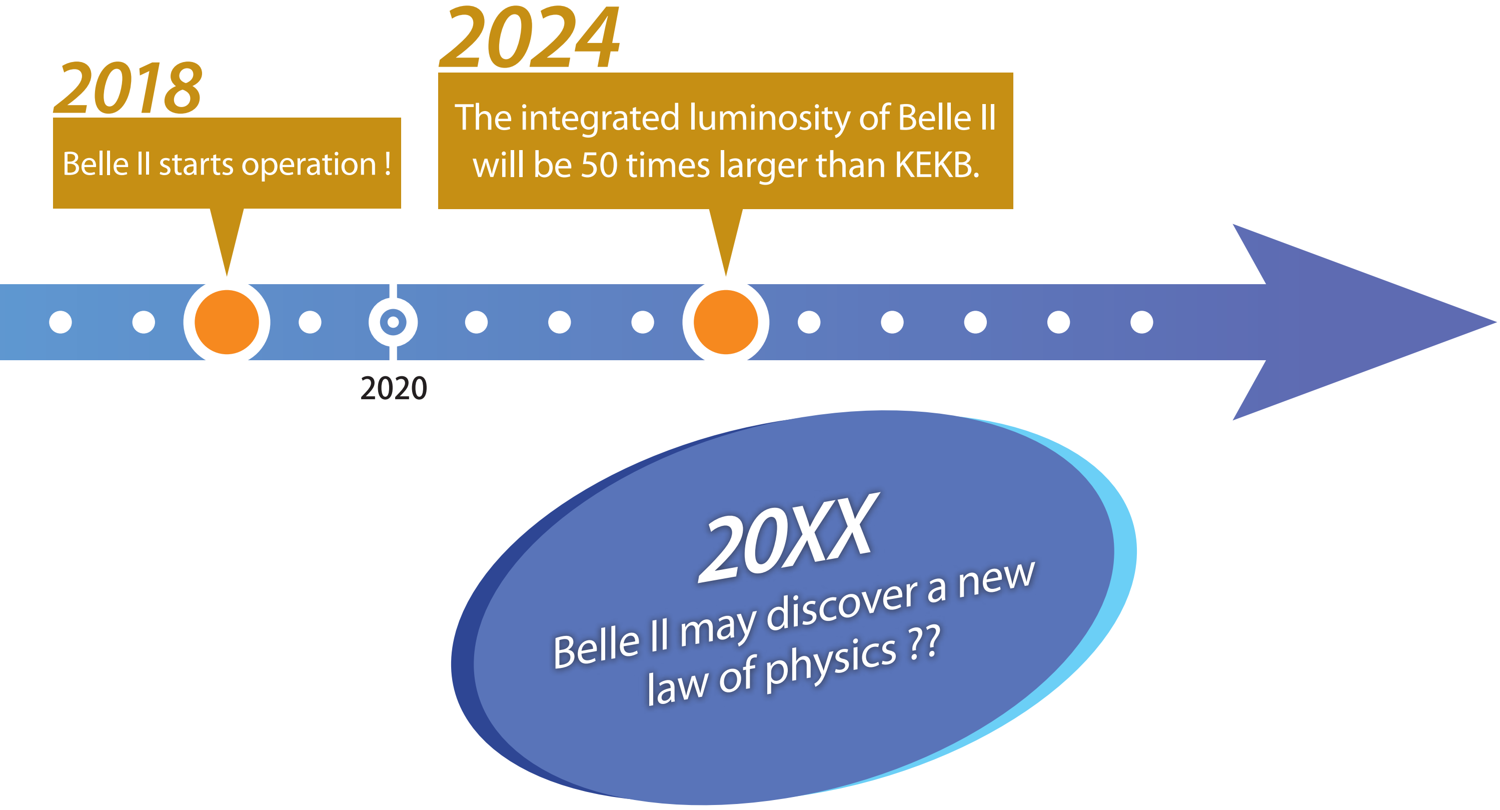
Assymmetry observed in the decay time distributions of B and anti-B mesons demonstrates the existence of large CP violation

Pursuing a Solution to the Remaining Mystery

Various measurements were carried out by the Belle Experiment and almost all of them can be explained by the Kobayashi-Maskawa theory. On the other hand, we have come to the understanding that CP violation in the Kobayashi-Maskawa theory is too small to explain the number of surviving matter particles in the universe. The Belle experiment also found indications that suggest imperfections in the Standard Model of particle physics. In order to confirm these, a very large amount of additional data well in excess that accumulated by the Belle Experiment is required.

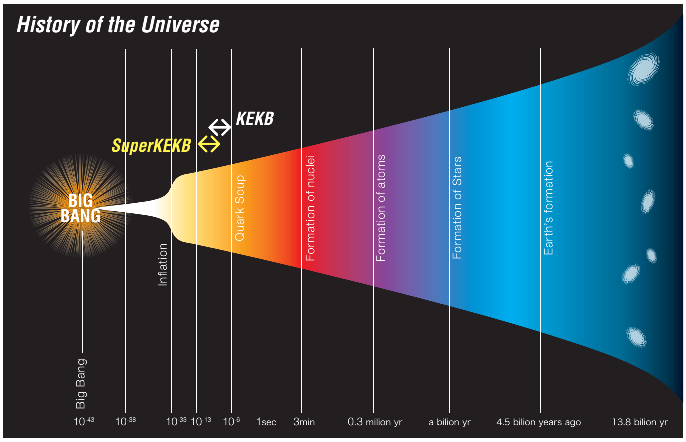


History of the major results and accumulated luminosity of the Belle experiment



Searching for Hidden Laws of Physics in the Early Universe

The Belle II experiment searches for unknown laws of physics that were important immediately after the Big Bang. In the high energy state of the early universe, it is believed that unknown laws of physics with CP violation that go beyond the Kobayashi-Maskawa theory were important. Such new physics may lead to new particles and physics phenomena such as supersymmetric particles and the existence of extra dimensions. New physics phenomena will be searched for using ultra-precise measurements with 50 times more data than in the Belle experiment.

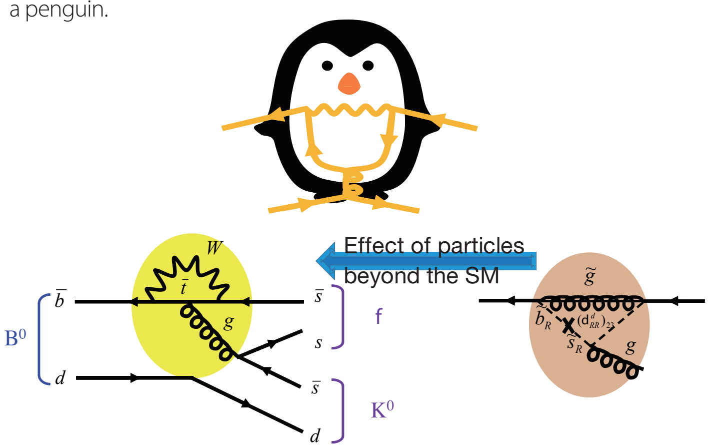


Instantaneous Ultra-High Energy State Appeared in B Meson Decay

One of the keys to finding new laws of physics is penguin decays. In these decays the bottom quark in the B mesons goes through an intermediate state, in which it is instantly turned into another particle. Using this characteristic, the effects of an unknown heavy particle can be investigated; the Heisenberg uncertainty principle of quantum mechanics allows a ultra-high energy state that may have existed in the early universe to develop in the intermediate state of a penguin decay.

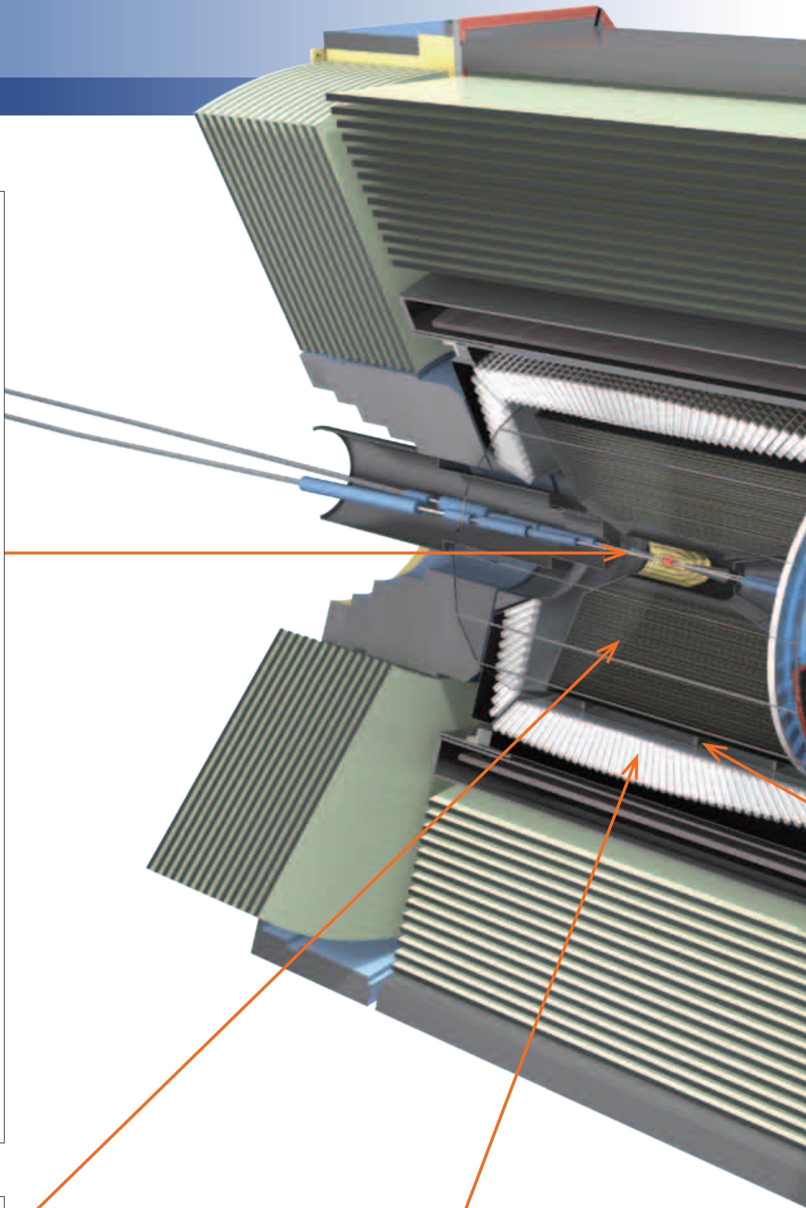
Penguin decays are rare, occurring once in several tens of thousands of B mesons. However the Belle experiment proved that such measurements are possible. Precise measurement of the properties of penguin decays are made possible by the large amount of data from the Belle II experiment and allow us to investigate the effect of unknown laws of physics.

*It is called penguin decay because the diagram for the reaction resembles a penguin.



Feynman diagrams of the penguin decay for the standard model and a supersymmetry model

Belle II Detector



Measuring vertex points of particle decays

Vertex Detector (VXD)

The difference or asymmetry between the beam energies of the electrons and positrons in the SuperKEKB accelerators allows each produced B meson to travel about a hundred micrometers before it decays. The distance traveled enables a measurement of the decay time of the B meson.

The VXD (VerteX Detector) consists of two types of semiconductor sensors (PXD: Pixel type semiconductor detector, SVD: Silicon Vertex Detector equipped with strip sensors) for measuring the decay position of the B-meson. Position information for charged particles is obtained from electrical signals produced as they pass through a silicon sensor. After upgrading the Belle detector to Belle II, the inner diameter of the beam pipe was reduced from 3 cm to 2 cm, and the PXD (one pixel size is around 50 square microns) is mounted nearby the beam pipe. These changes help to improve the resolution on the vertex measurement. The SVD sensor area is also increased, from 88 mm radius to 135 mm in Belle II; this gives an improvement of 30% in the detection efficiency for Ks mesons decaying to pairs of π mesons.

Capturing the charged particle trajectory and measuring momentum

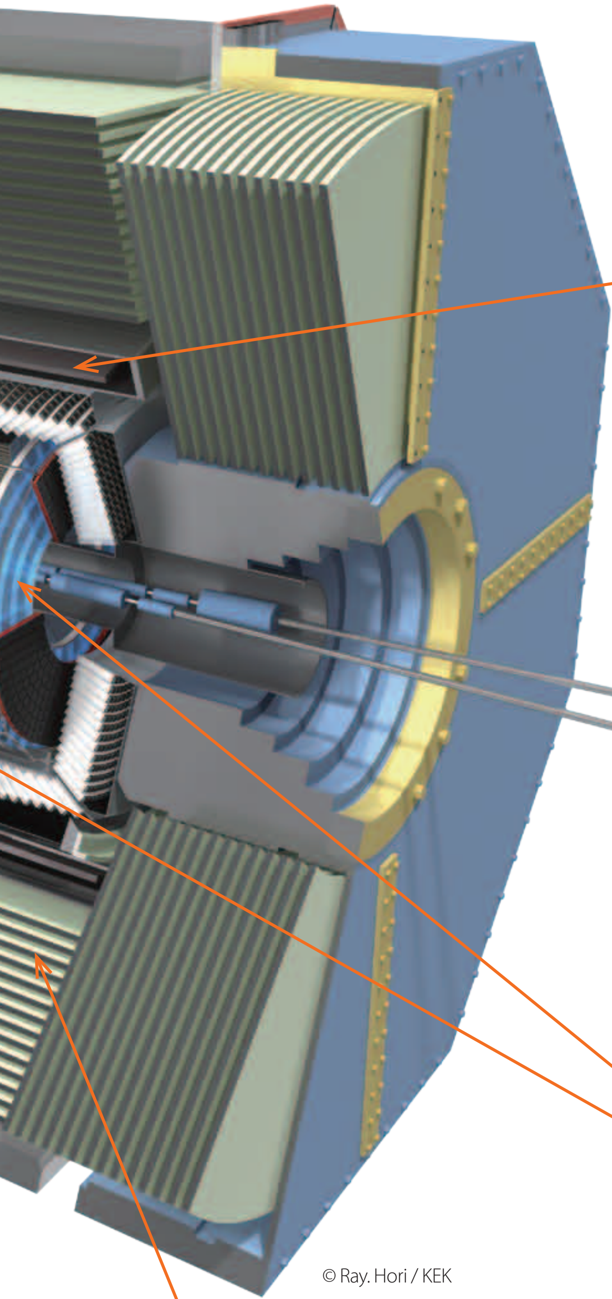
Central Drift Chamber (CDC)

The Central Drift Chamber of Belle II is a gaseous radiation detector, which is strung with many thin metal wires (56,576) inside a cylindrical volume with a 1.1 m radius. When a charged particle passes inside the gas of the chamber, an electric signal is detected in the nearest wire through an ionization process. The CDC can provide a precise momentum determination for each reconstructed track and information on particle identification using the signal size. The CDC is carefully designed to minimize the chamber material and avoid multiple scattering: by using unplated aluminum field wires and a helium based gas mixture.

Identifying electrons and measuring photons

Electromagnetic Calorimeter (ECL)

The ECL is a detector consists of Thallium doped Cesium Iodide crystals, which measures energies of photons and electrons produced in interactions. Particles, which make electromagnetic interactions such as electrons or photons, lose energy and emit light proportional to the energy when interacting inside the crystals. The energies of particles are measured by counting the amount of emitted light (photons) with photodiodes attached to the crystals. The flight direction of particles are estimated from the position of the interactions in the crystals. The ECL consists of 8736 crystals of dimensions 5.5x5.5x30 cm3 surrounding the interaction point. The Belle II ECL is one of the biggest total absorption type calorimeters with homogeneous crystals, and weighs about 43 tons in total.



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Bending tracks of charged particles

Superconducting Solenoid Magnet

The Belle II detector is equipped with a superconducting solenoid magnet just outside the ECL. It generates a magnetic field with a strength of 1.5 Tesla in the inside volume of the detector. A charged particle detected by CDC displays a spiral-shape trajectory, being bent by Lorentz force due to the magnetic field. We measure the momentum of the particle from the radius of curvature. The coil of the superconducting solenoid magnet is constructed from a special electric wire, which is made of a Titanium-Niobium alloy. The wire becomes superconducting after being cooled down to -268°C and then a huge electric current of as much as 4160 amperes can flow without resistance in its narrow 3 mm x 3 mm cross section.

Identification of kaons and pions

Time of Propagation(TOP) Counter, Aerogel RICH(ARICH) Counter

When a fast charged particle passes through a transparent medium (radiator), Cherenkov light is emitted at a certain angle (Cherenkov angle). The Cherenkov angle depends on velocity of an incident particle and, therefore, measurement of its velocity allows us to identify particle mass (=particle species) by combining information on the momentum provided from the CDC. Based on this technique, two new devices called TOP and ARICH perform precise particle identification, to distinguish pions and kaons (two types of charged particles).

TOP counter consists of 2.5 m long x 45 cm wide quartz plates 2 cm thick instrumented with micro-channel plate photomultipliers (MCP-PMTs). Cherenkov light generated by a charged particle travels inside the quartz plate and reaches the edge of the plate, where it is recorded by MCP-PMTs. Tiny difference of Cherenkov angles between a pion and a kaon, after bouncing at the internal faces in the quartz, results in differences in time of propagation of the Cherenkov light.

The other device, the ARICH, uses silica aerogel, the lightest solid material in the world, as the Cherenkov radiator. The Cherenkov photons are measured with newly developed position -sensitive sensor "hybrid avalanche photo-detector (HAPD)", placed 20 cm downstream from a radiator. An array of HAPDs provides efficient detection of Cherenkov photons together with accurate position information for each photon. Using these measurements, the Cherenkov angle is reconstructed to identify a charged particle. Both the TOP and ARICH enable us to detect a pion with 97% efficiency while reducing the kaon misidentification probability to a low level.

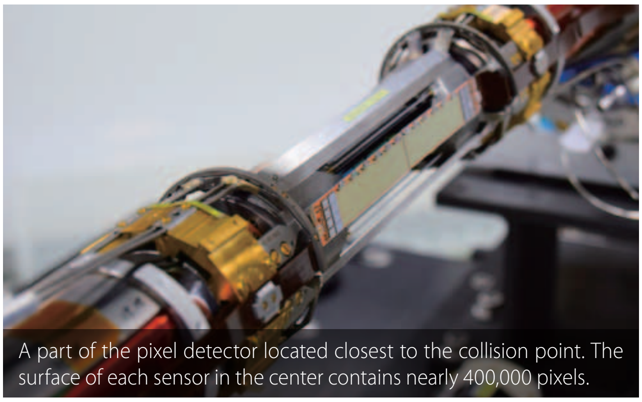
Identification of muons and detection of neutral K_L^0 mesons

K_L^0 and Muon Detector (KLM)

This detector is used to detect muons, which penetrate easily through most materials, and K_L^0 mesons, which are electrically neutral and cannot be detected until they interact with matter. The detectors are placed in the gaps of the iron Belle II structure. For the barrel part, we use a detector, with a gas mixture composed of argon and other gases that fills the region between two glass plates. For the endcap part and the inner two layers of the barrel with high background fluxes, scintillator strips and silicon photomultipliers are used.

Sub-detectors for the Belle II experiment

VXD (Vertex Detector)

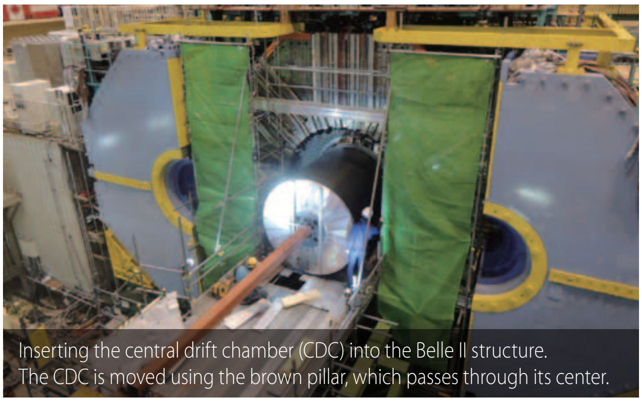


A part of the pixel detector located closest to the collision point. The surface of each sensor in the center contains nearly 400,000 pixels.

Assembly of silicon vertex detector (SVD).

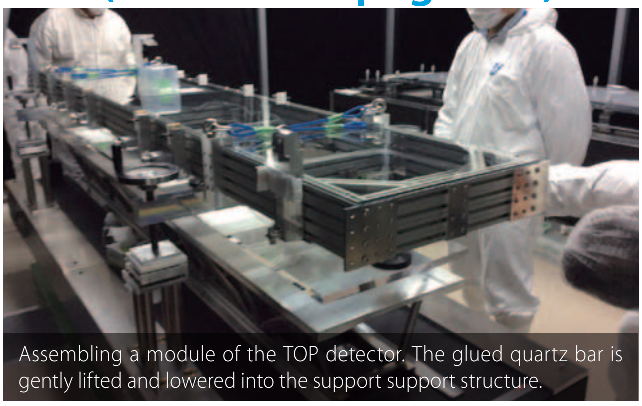
CDC (Central Drift Chamber)

Installing one of the about 57,000 wires in the chamber.

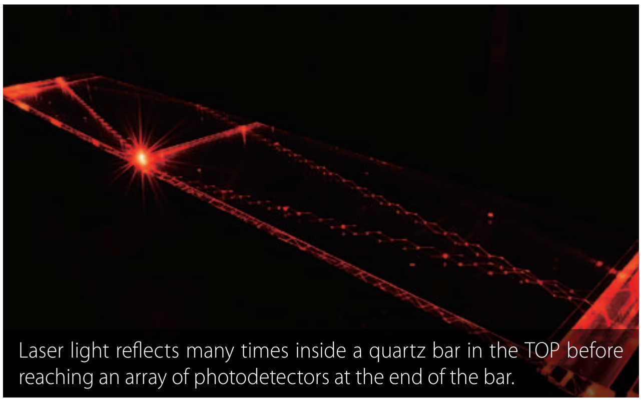


Inserting the central drift chamber (CDC) into the Belle II structure.
The CDC is moved using the brown pillar, which passes through its center.

TOP (Time of Propagation) counter

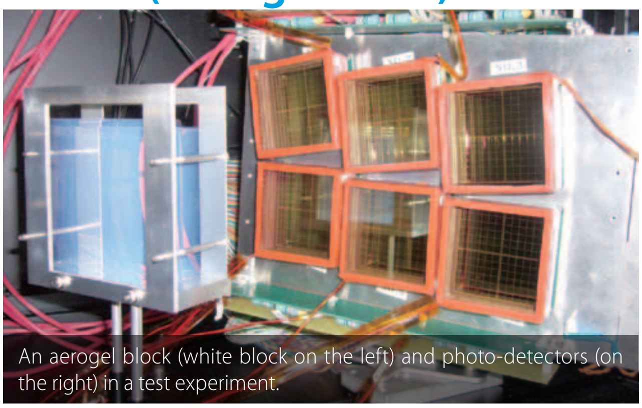


Assembling a module of the TOP detector. The glued quartz bar is gently lifted and lowered into the support support structure.

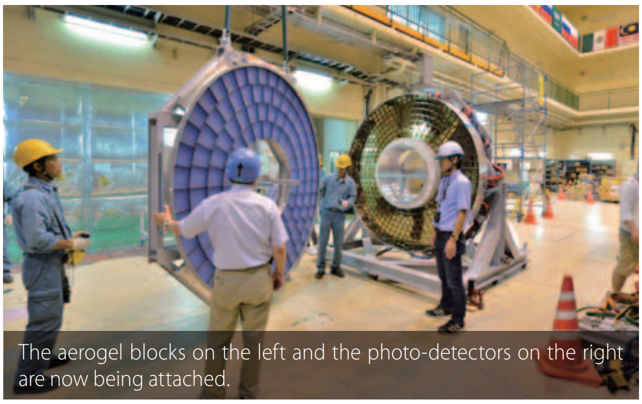


Laser light reflects many times inside a quartz bar in the TOP before reaching an array of photodetectors at the end of the bar.

ARICH (Aerogel RICH) counter

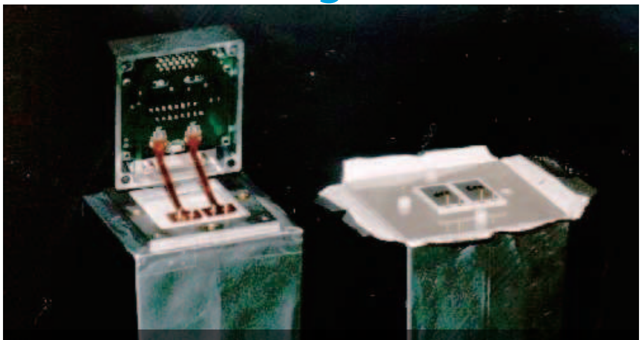


An aerogel block (white block on the left) and photo-detectors (on the right) in a test experiment.



The aerogel blocks on the left and the photo-detectors on the right are now being attached.

ECL (Electromagnetic Calorimeter)



8736 CsI(Tl) crystals readout by photodiodes are placed in a cylindrical array around the collision point.

Lifting the endcap electromagnetic calorimeter before attaching it to the BelleII detector.

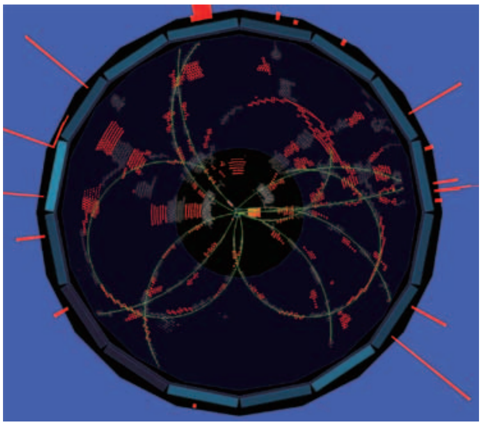
KLM (K_L^0 and Muon Detector)

Part of the KLM detector. Bar-shaped plastic scintillators that emit light in response to the passage of charged particles are combined to form a single plate.

The installation of the KLM detector is shown. Yellow plate with scintillator is being inserted into the light blue structure.

First collisions at Belle II

Electron-positron collisions in the SuperKEKB accelerator were first observed by the Belle II detector on April 26, 2018. This was an important milestone for the Belle II experiment, which enabled us to start collecting physics data.



Event display of the Belle II detector showing the decays of particles produced in an electron-positron collision.

Researchers in the Belle II control room celebrating the observation of the first collision events.

Data processing using the latest information technology

A large number of reactions are observed by the Belle II detector. It is very important to select and record those data, and to build and maintain the environment to perform the data analysis.

Trigger

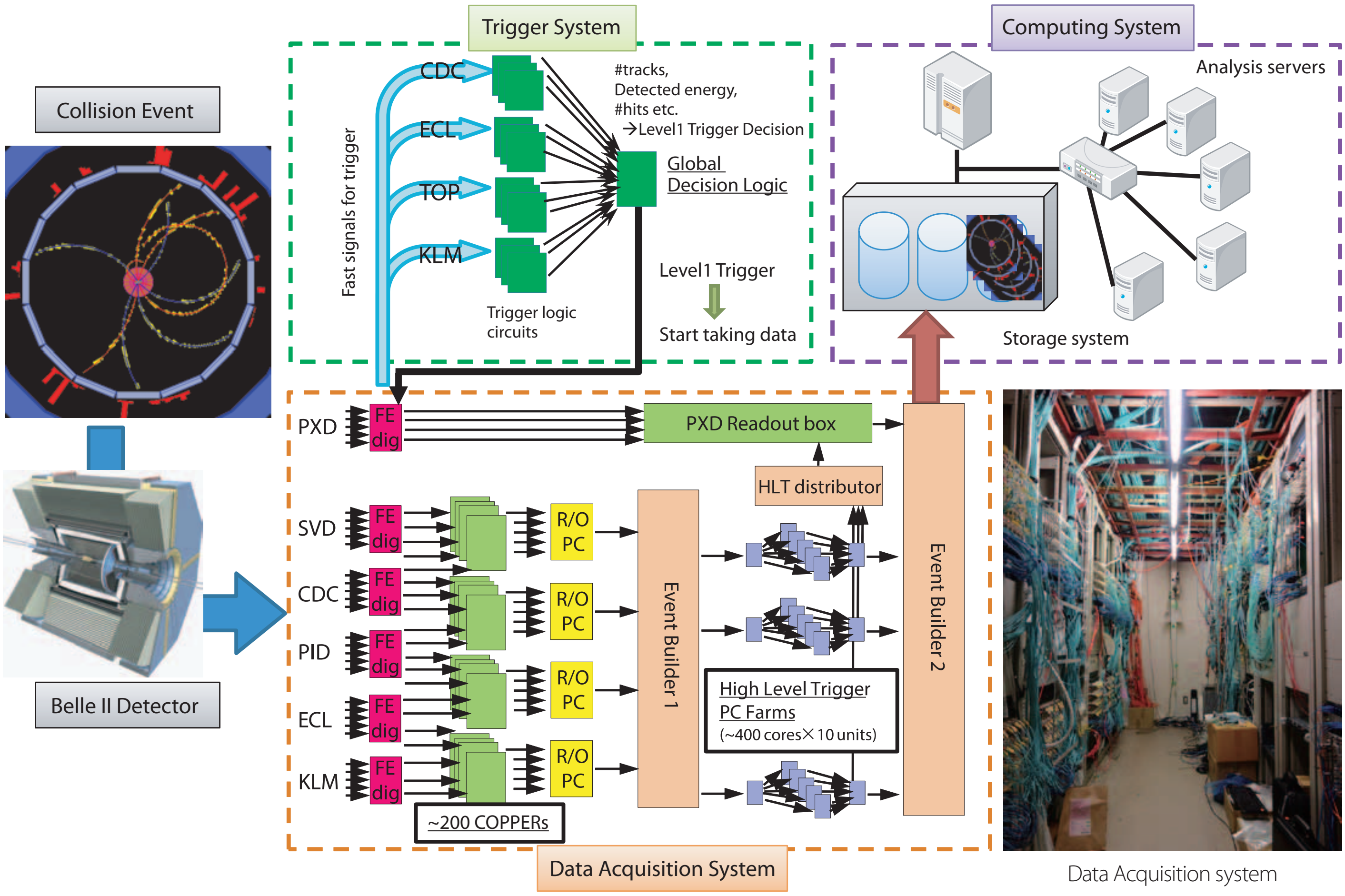
The trigger is a system to select interesting events in realtime. The trigger system is necessary to select B -anti B events because there are many background events, which are generated by beam-gas interactions, for example. The trigger system is always reading special data sent from the detectors and send a trigger signal to the DAQ within 4.5 microseconds when an interesting event occurs.

Data Acquisition System (DAQ)

The data acquisition system collects data from sub-detectors of Belle II. The DAQ system also performs preprocessing of data to record essential events effectively.

The data for each event are first readout by about 200 COPPER modules separated into small parts. The event builder system gathers data from COPPERs and reconstructs the event data. The high level trigger system consisting of hundreds of computers then analyzes the data and selects essential events for more detailed physics analysis.

The DAQ system can perform these processes and record data at 30kHz, reducing the input data of 30 Gbytes/sec to about 1 Gbyte/sec.

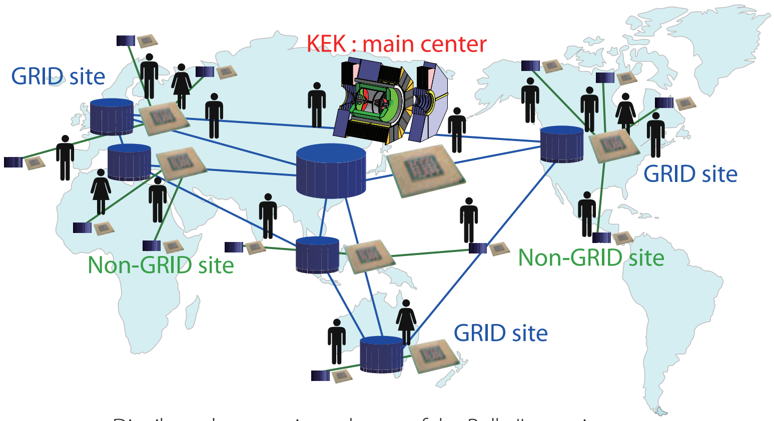


Data Acquisition system

Computing System

The Belle II experiment is expected to produce tens of peta-bytes (the equivalent of about 2 million DVDs) of real and simulated data per year at the peak of its operation. In order to process this large amount of data and provide physics results in a timely fashion, we adopt existing distributed computing technologies such as the "GRID" and "cloud", connecting the computing resources of collaborating institutes in the world via high speed networks.

Among them, the computing system in KEK plays a key role for the success of the Belle II experiment. Now, it has a roughly 10,000 cores of CPU, 13 PB of disk space and a 70 PB tape storage system and has started operation.



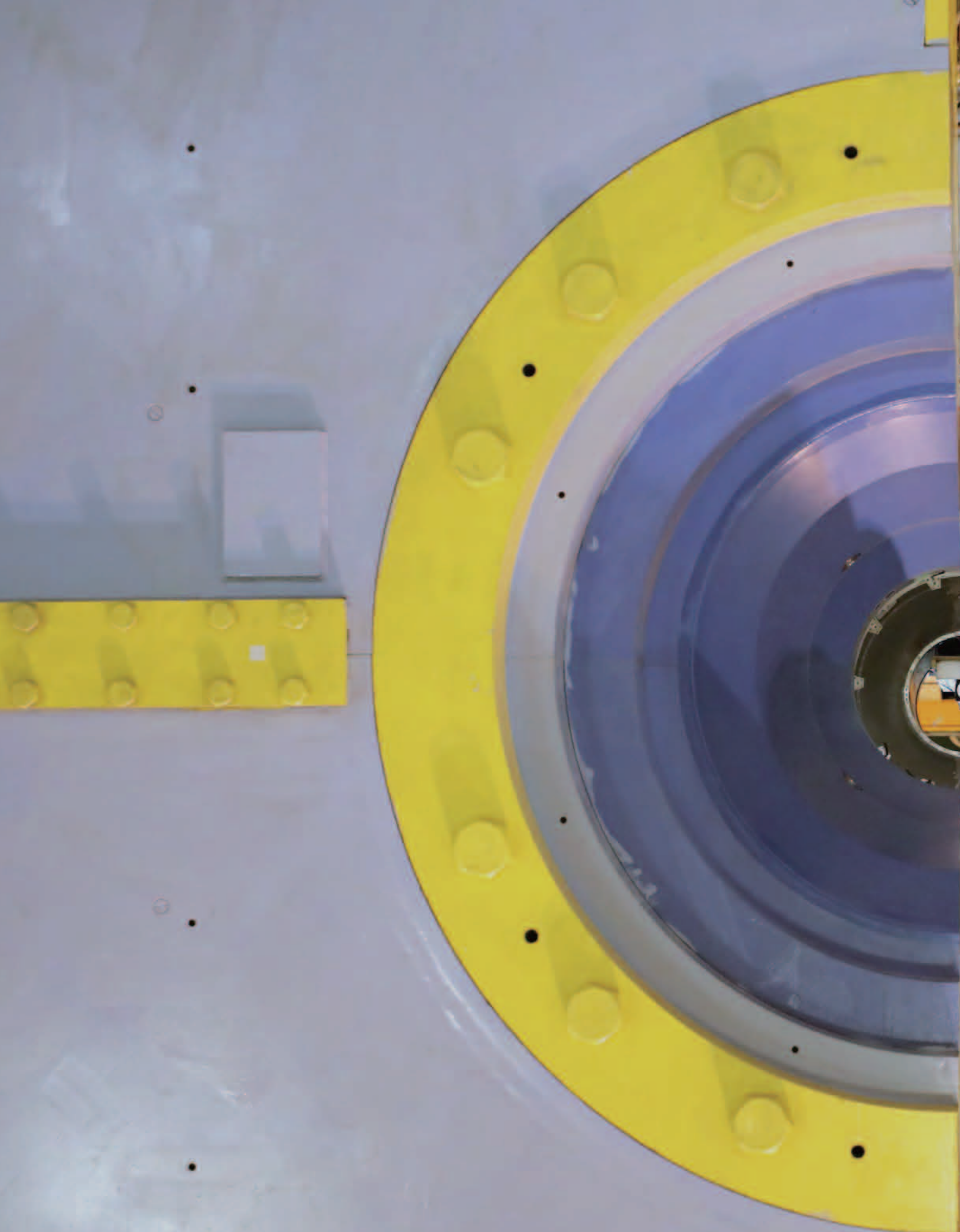
Distributed computing scheme of the Belle II experiments.

KEK central computing system

International Collaborative Experiment / Belle II Collaboration

The Belle II experiment is an international collaboration, which involves about 1000 scientists from 26 countries/regions and includes about 117 universities/research institutes as of November 2019.

Scientists gather three times a year for general collaboration meetings. A wide variety of video conferences are held by scientists from all over the world on a daily basis. The development of the Belle II sub-detectors, data collection and physics analysis are carried out within this international collaboration.



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