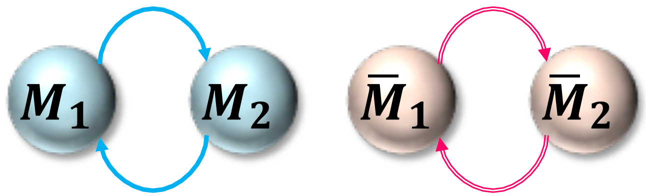
Excitement at the first collision (2018-04-26 00:38)

The Belle II experiment has been kicked off.

Takeo Higuchi (Kavli IPMU)

Before Belle (-1979)

1960 | 1969



***CP* violation:** difference between the interactions among the matter particles and those among the anti-matter particles

1964 **First discovery of *CP*-violating events** in the neutral *K*-meson system by J. Cronin *et al*.

1970 | 1979

1973 **Kobayashi-Maskawa theory**

- The *CP* violation was allowed when the number of the **quark generations would be ≥ 3**.
- The *CP*-symmetry with the 3rd-generation quarks involved would be highly violated.

KM Theory

Quark coupling constants

$V_{q_u q_d}$ for quark interactions ($q_d \leftrightarrow q_u$)
$V^*_{q_u q_d}$ for anti-quark interactions ($\bar{q}_d \leftrightarrow \bar{q}_u$)

***CP* violation** (quark/anti-quark difference) $\Leftrightarrow$ $V_{q_u q_d} \neq V^*_{q_u q_d}$

$\Leftrightarrow$ $V_{q_u q_d}$ is a complex number

$\Leftrightarrow$ $\arg(V_{q_u q_d}) \neq 0$

Number of the quark generations: 2 → 3

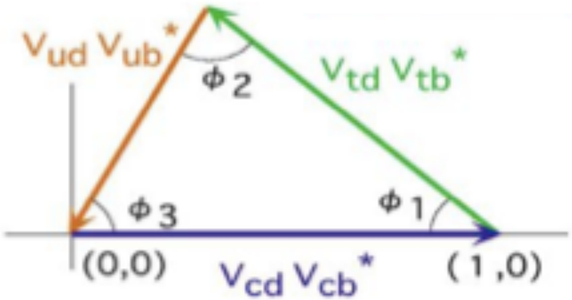
$$V_{n=2} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \xrightarrow{\text{Extend}} V_{n=3} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The V_{td} and V_{ub} can be complex numbers.

Unitarity triangle

$$V_{n=3} V^{\dagger}_{n=3} = I \quad \rightarrow$$

$$V_{ud} V_{ub}{}^* + V_{cd} V^*_{cb} + V_{td} V^*_{tb} = 0$$



$\arg(V_{td}) \sim \phi_1$

$\arg(V_{ub}) \sim \phi_3$

$\phi_1 \neq 0, \phi_3 \neq 0$ **... KM ansatz**

Before Belle (1970-1990)

1970 | 1979

1974 Independent discoveries of the heavier 2^{nd}-generation quark c.

1977 Discovery of the lighter **3^{rd}-generation quark** b.

1980 | 1989

1980 Discussion by A. I. Sanda *et al.* on the **experimental feasibility of the ϕ_1 measurement** in the B-meson system.

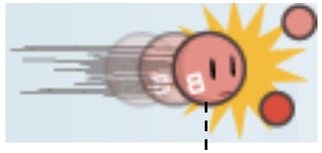
1983 Independent measurements of the **B-meson lifetime** by MAC and Mark II → long enough for the ϕ_1 measurement.

1987 Observation of **large B^0-$\overline{B}^0$ mixing** by ARGUS → large enough for the ϕ_1 measurement.

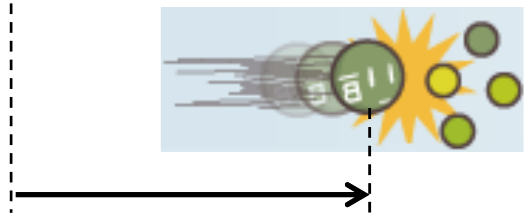
KM Phenomenology

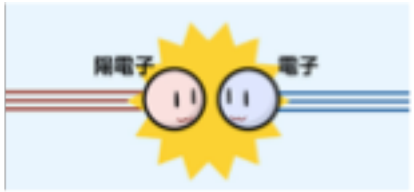
Manifestation of the ϕ_1

Decay at $t = t_1$



Decay at $t = t_2$



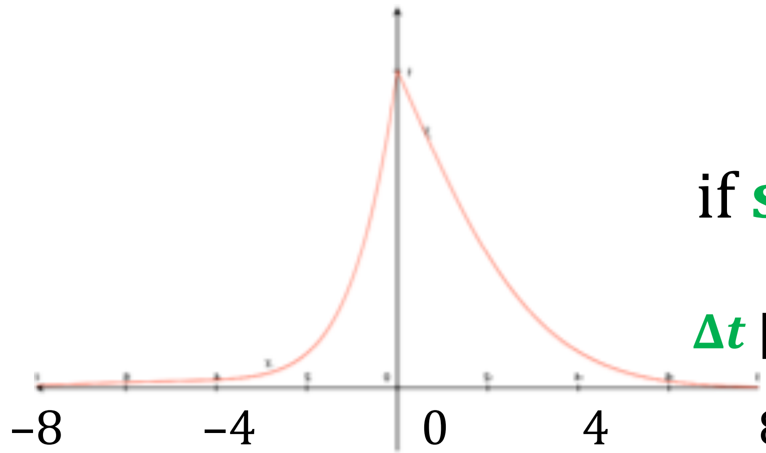


e^+-e^- collision

$B/\bar{B}$ pair creation at $t = 0$

$\Delta t \equiv t_2 - t_1$

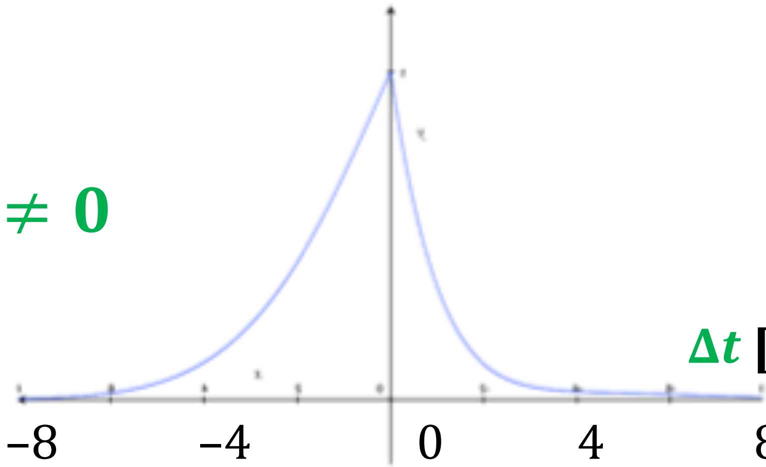
$$P(\Delta t)_{B_1=B^0} \propto e^{-\frac{|\Delta t|}{\tau_B}}[1 + \mathbf{\sin 2\phi_1} \sin \chi \Delta t]$$



$$\neq$$

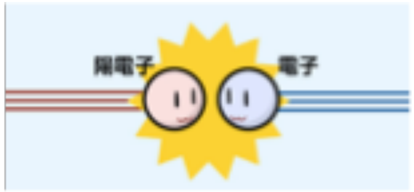
if $\sin 2\phi_1 \neq 0$

$$P(\Delta t)_{B_1=\bar{B}^0} \propto e^{-\frac{|\Delta t|}{\tau_B}}[1 - \mathbf{\sin 2\phi_1} \sin \chi \Delta t]$$



KM Phenomenology

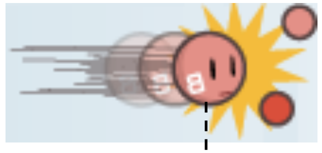
Manifestation of the ϕ_1



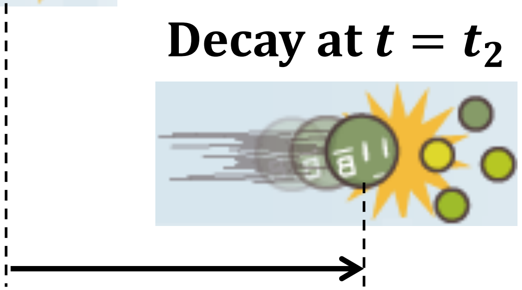
e^+-e^- collision

$B/\bar{B}$ pair creation at $t = 0$

Decay at $t = t_1$



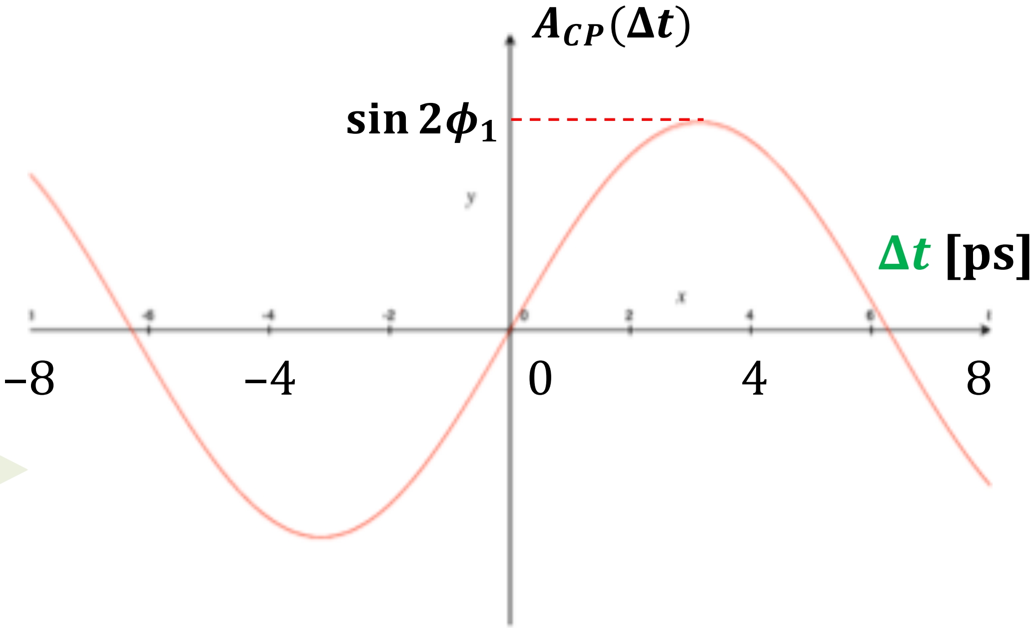
Decay at $t = t_2$



$\Delta t \equiv t_2 - t_1$

$$A_{CP}(\Delta t) \equiv \frac{P(\Delta t)_{B_1=B^0} - P(\Delta t)_{B_1=\bar{B}^0}}{P(\Delta t)_{B_1=B^0} + P(\Delta t)_{B_1=\bar{B}^0}}$$

$$= \mathbf{\sin 2\phi_1} \sin \chi \Delta t$$



Before Belle (1980-1999)

1980 | 1989

1987 First discussion on the KM-test experiment within wise men.

1988

KEK Internal 88-1
May 1988
H

PROPOSAL FOR
STUDY OF B PHYSICS
BY
A DETECTOR WITH PARTICLE IDENTIFICATION
AND HIGH RESOLUTION CALORIMETRY
AT TRISTAN ACCUMULATION RING

National Laboratory for High Energy Physics(KEK)

H. Aihara
University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113

Nara Women's University, Nara-shi, Nara-ken 630

A.I. Sanda
Rockefeller University, 1230 York Avenue, New York, New York
10021-6399, U.S.A.

Kyoto University of Education, Kyoto-shi, Kyoto-fu 612

NATIONAL LABORATORY FOR
HIGH ENERGY PHYSICS

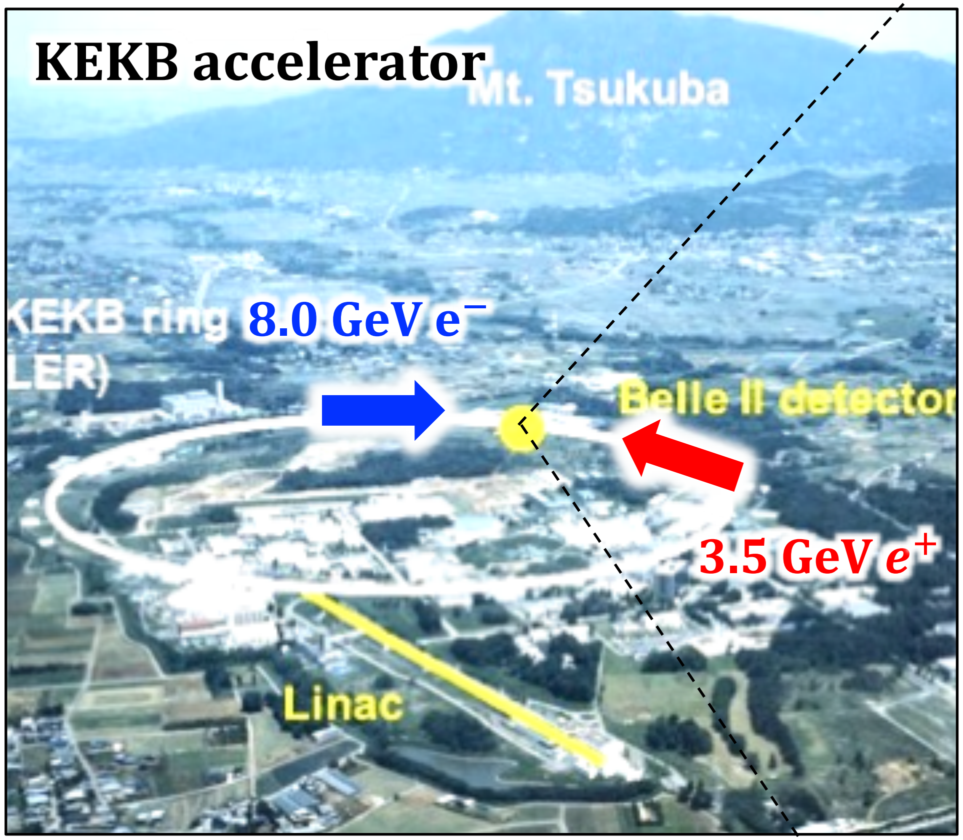
A. I. Sanda, H. Aihara, ..., "**Proposal for study of B physics by a detector with particle identification and high resolution calorimetry at TRISTAN accumulation ring**," KEK Internal 88-1 (1988)

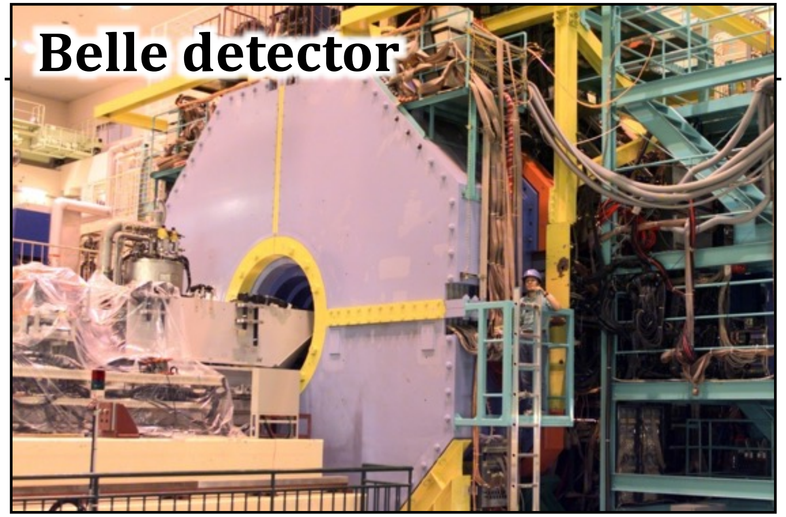
1990 | 1999

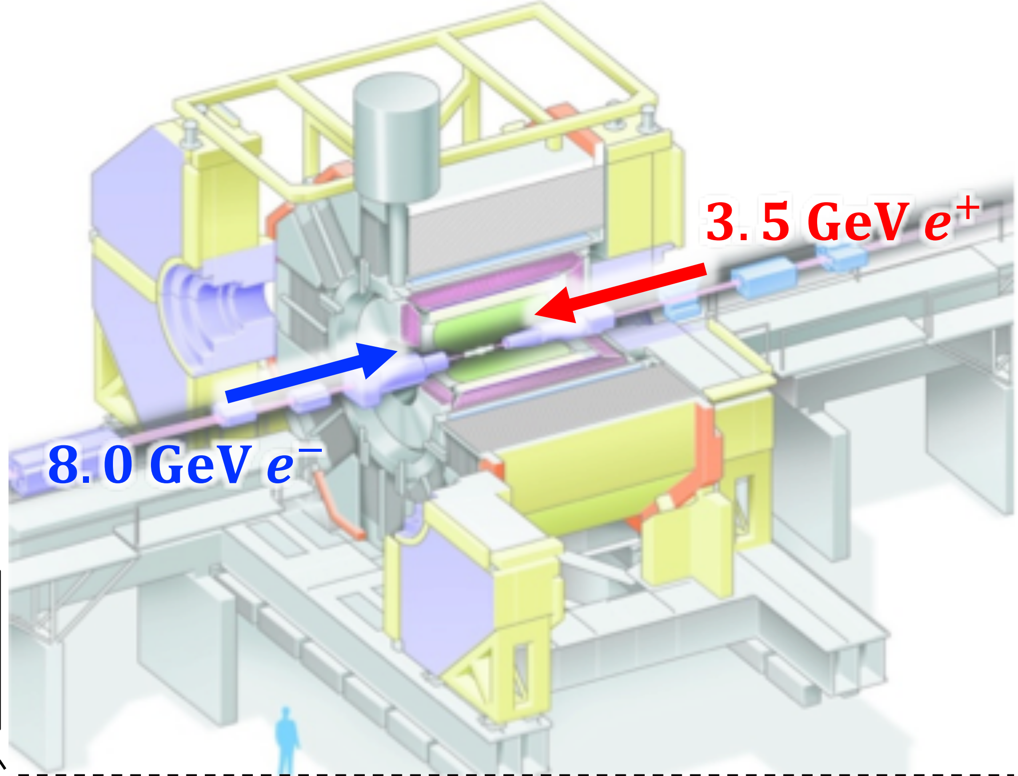
1994 Approval of the Belle experiment by the government.

1997 MSc student. Member of the Belle collaboration.

Belle ~~II~~ Experiment





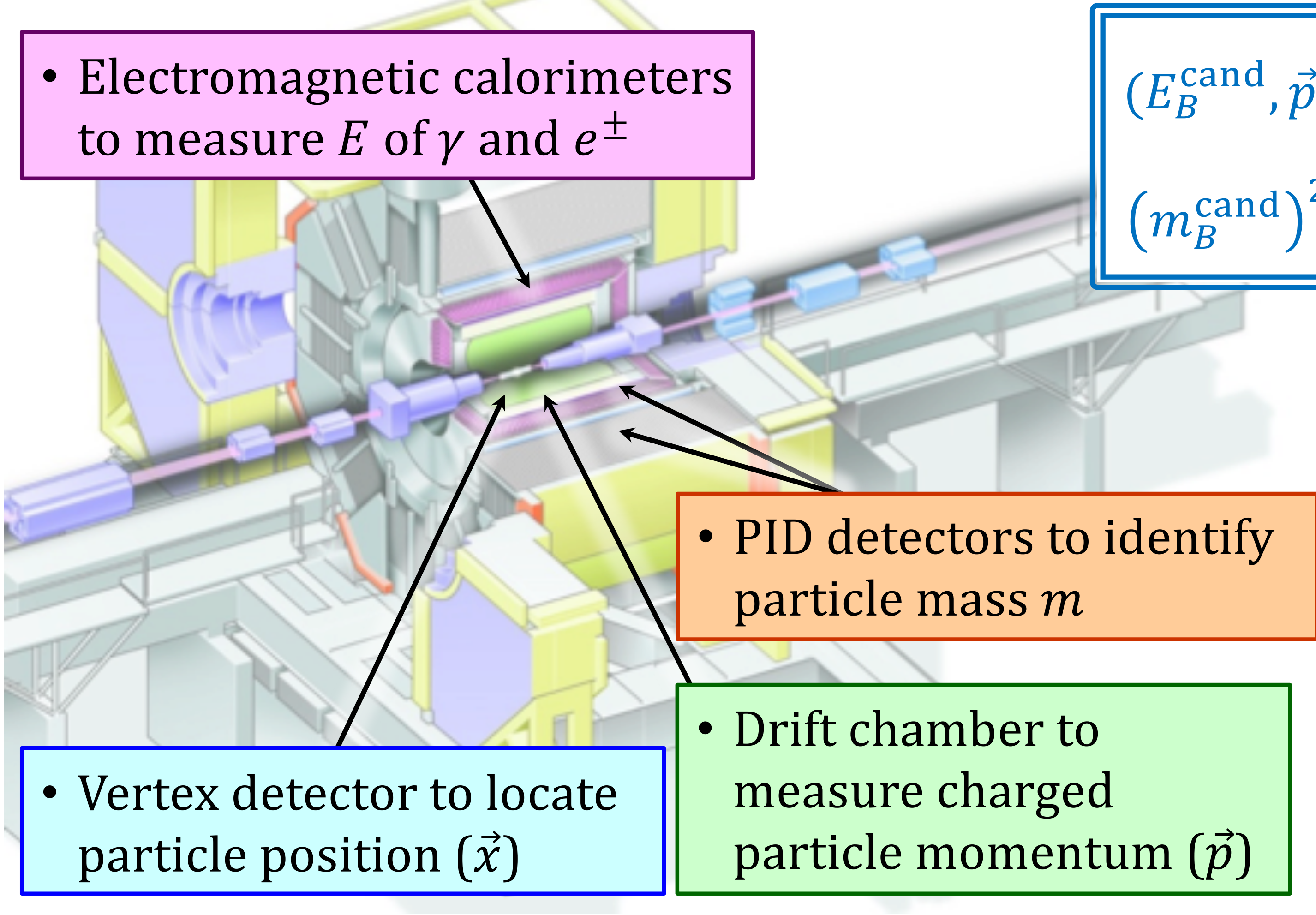


- KEKB produced *B* mesons.
- Belle measured *B*-decay particles.

Belle Detector

- Both $B^0, \bar{B}^0$ are not stable particles $\Rightarrow$ $B^0, \bar{B}^0$ decay to a number of particles.
- The Belle detector measured $(\boldsymbol{E}, \vec{\boldsymbol{p}})$ and $\vec{\boldsymbol{x}}$ of each daughter particle.

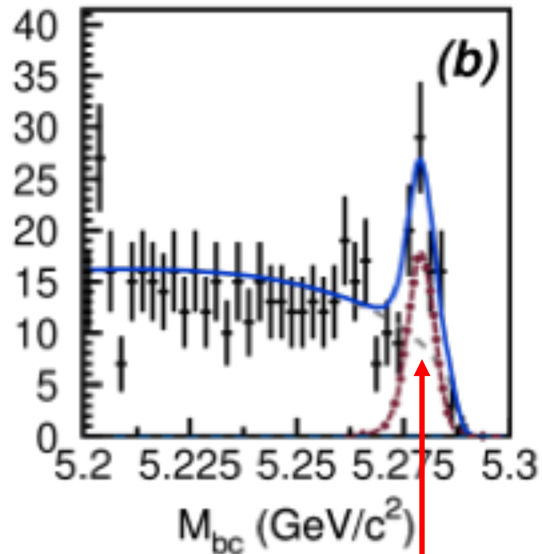
$$\Lsh\ \boldsymbol{E}^2 = \boldsymbol{m}^2 + |\vec{\boldsymbol{p}}|^2$$



- Electromagnetic calorimeters to measure E of γ and $e^{\pm}$
- PID detectors to identify particle mass m
- Vertex detector to locate particle position $(\vec{x})$
- Drift chamber to measure charged particle momentum $(\vec{p})$

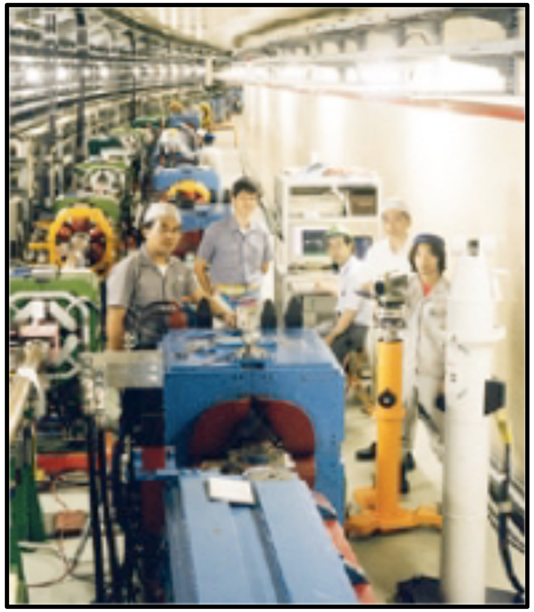
$$\left(E_B^{\text{cand}}, \vec{p}_B^{\text{cand}}\right) = \sum_i^{\text{dau}} \left(E_i, \vec{p_i}\right)$$

$$\left(m_B^{\text{cand}}\right)^2 = \left(E_B^{\text{cand}}\right)^2 - \left(\vec{p}_B^{\text{cand}}\right)^2$$

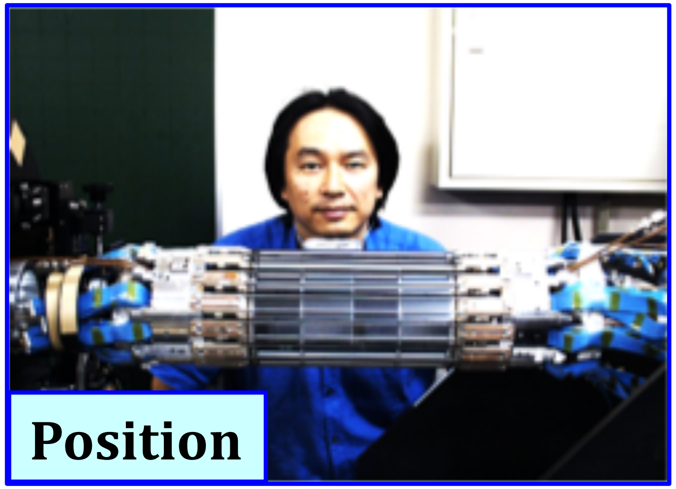


Resonance at m_B

Belle Construction



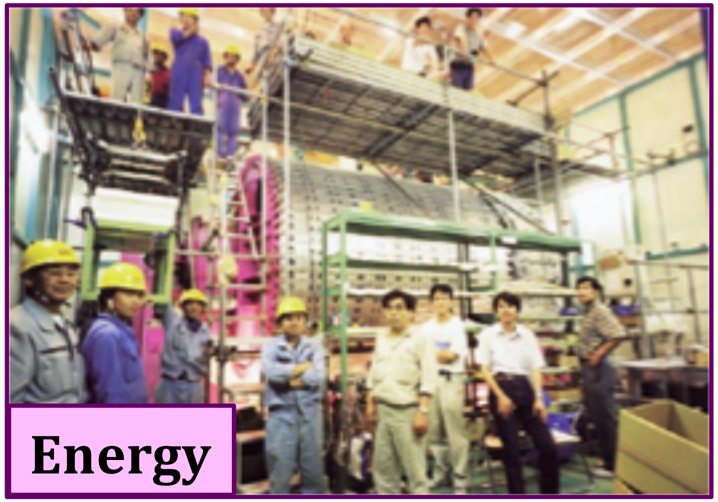
Renovation of the TRISTAN ring for the KEKB accelerator



Silicon vertex detector

Central drift chamber

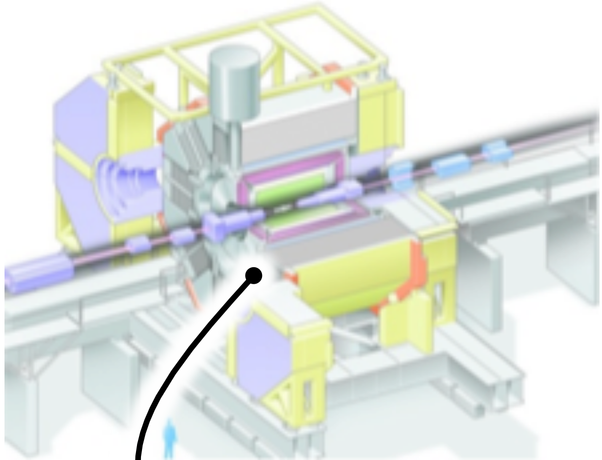
Aerogel Cherenkov counters



Electromagnetic calorimeters

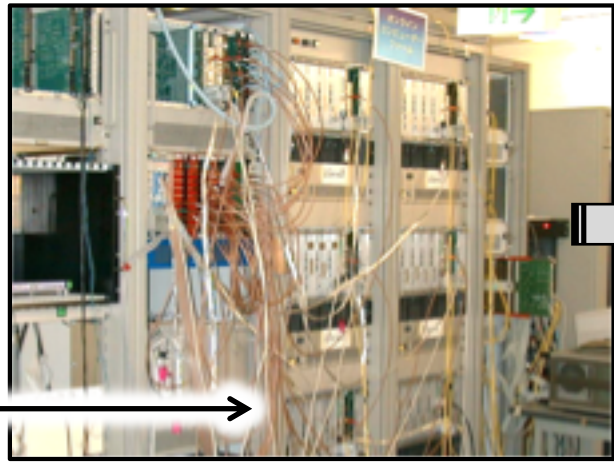
Belle Data Acquisition System

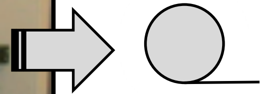
… because DAQ systems are rarely talked about.



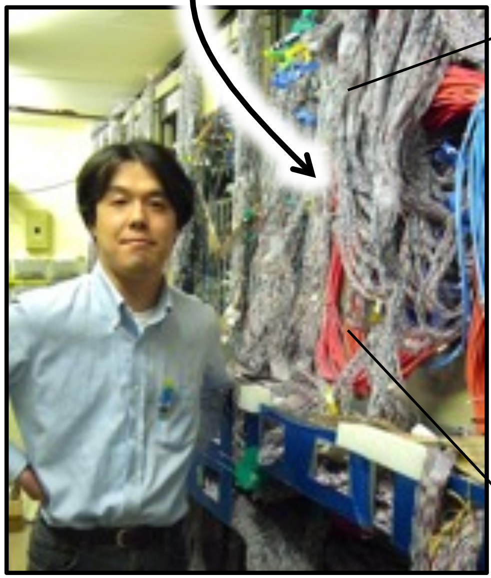
Event builder

Don't dance in front of the rack ☹

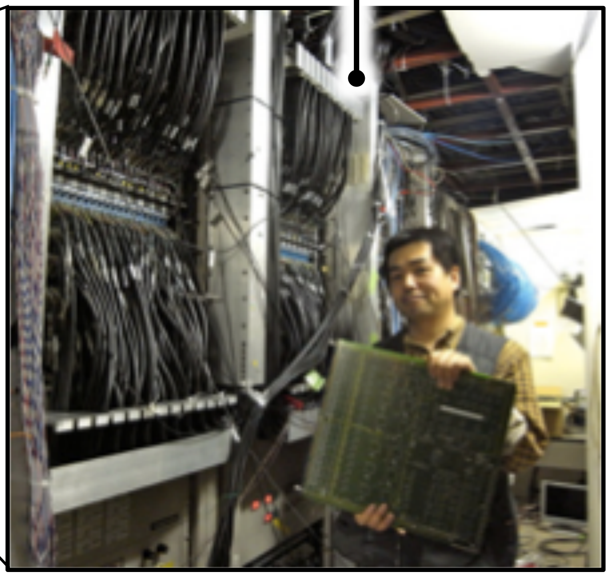




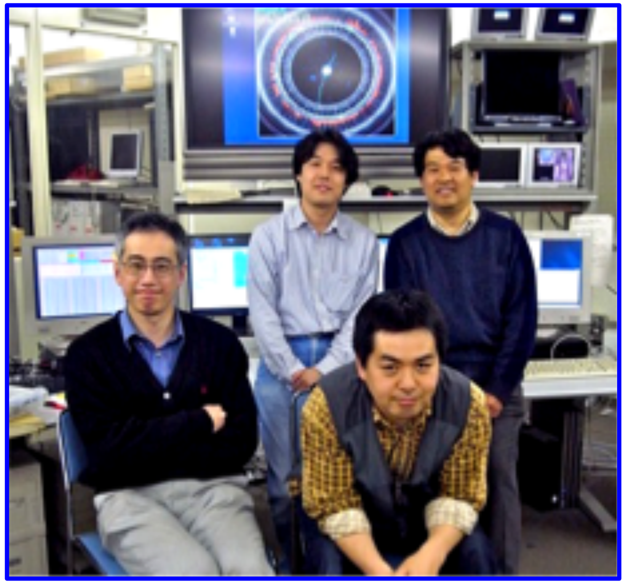
Tape



Analog signals over tons of cables



Q-to-T and time-to-digital converters

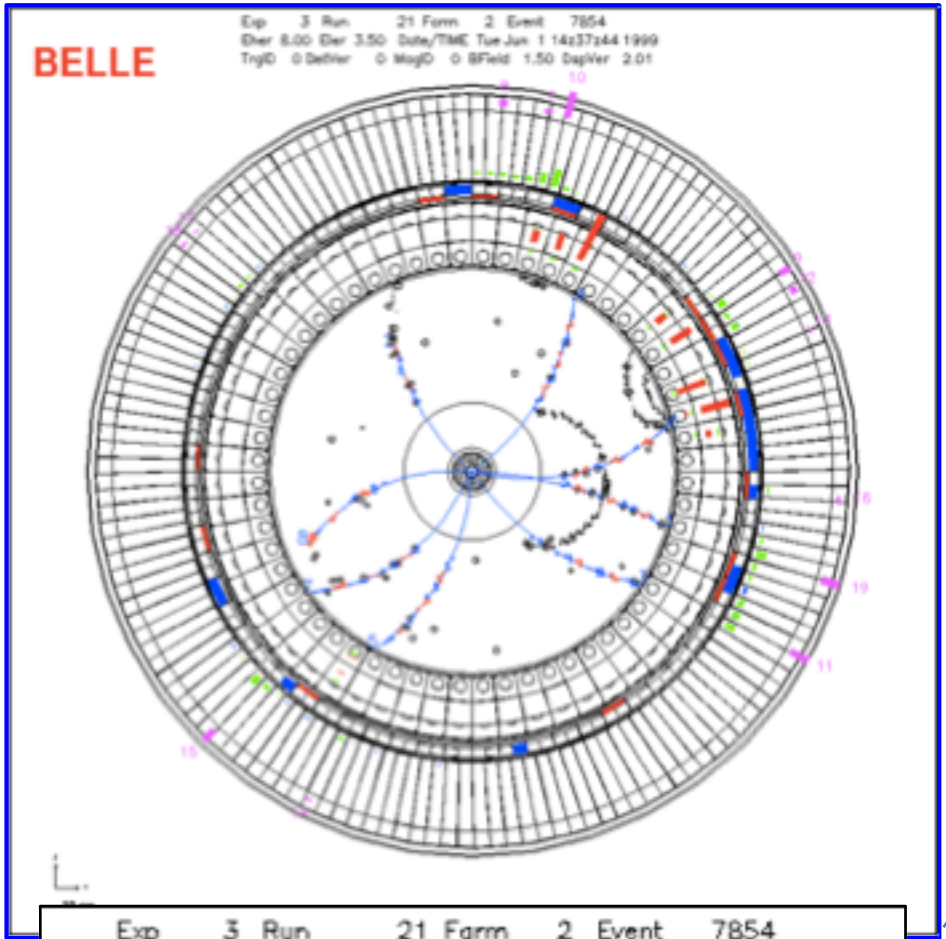


DAQ crews (only four…)

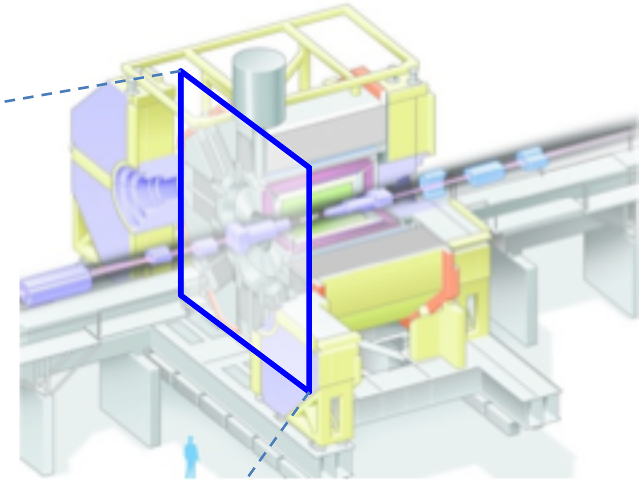
TH was youngest among the four
⇒ took 24/7 on-call shift.

Belle Kick Off (1999/06/01)

Early event display



Exp 3 Run 21 Farm 2 Event 7854
Eher 8.00 Eler 3.50 Date/TIME Tue Jun 1 14z37z44 1999
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 2.01



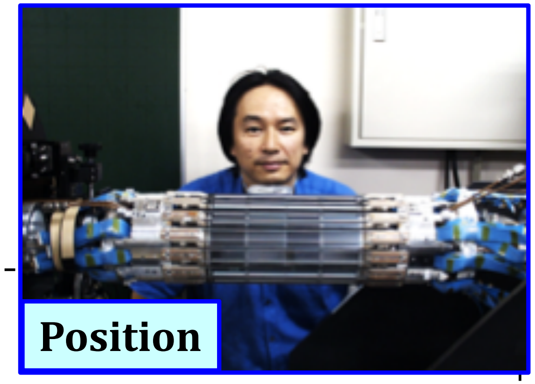
Conclusions

- KEK-B is working!
- The whole Belle detector is working!
- The Belle reconstruction and analysis software are working!
- If we can just keep air out of the beam pipe, we have an exciting few years ahead.

6/19/99 Beauty 99, Bled, Slovenia, June 21, 1999 16

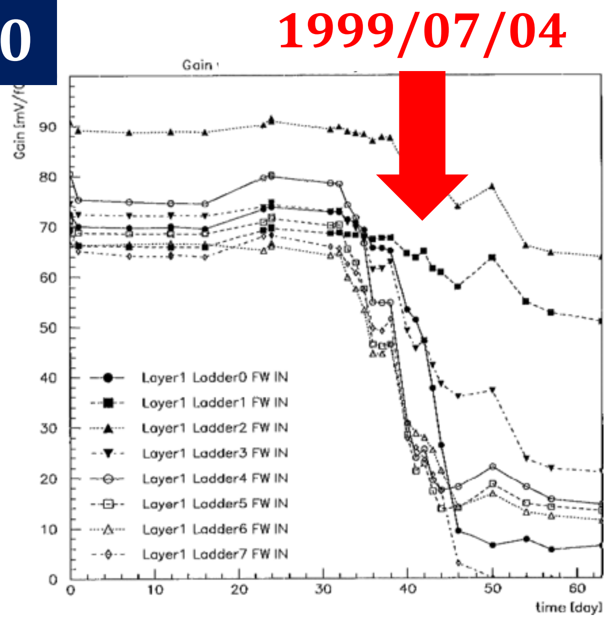
Presented in BEAUTY99 on **1999/06/19** 😊

Disasters on the Belle SVD



Silicon vertex detector

SVD 1.0



Significant gain drop in the SVD readout chips was observed just 35 days after the proudful start of the experiment

→ **the SVD had got no use** 😰

The readout chips were damaged by a synchrotron radiation.

SVD 1.1

SVD1.1 was assembled by mid. Aug. from spare SVD modules (called ladders) plus additionally produced ones 😌

On 08/24, during the SVD1.1 commissioning, **six ladders were found electrically damaged** 😱

The cause could not be pinned down. Static charge? Thunder?

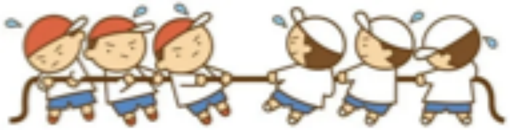
SVD 1.2

SVD1.2 was assembled by 09/02 and installed to the experiment on 09/10.

Hectic summer...

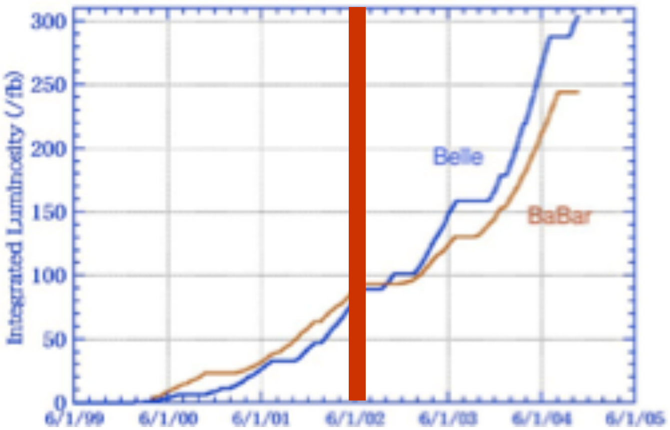
Measurement of $\sin 2\phi_1$

Belle



BaBar Another KM-test experiment carried out in Stanford, US.

Amount of the collected data



BaBar had collected larger amount of data than Belle (before 2002/06).

2001/02/09 (~10×10^6 $B\bar{B}$ pairs)

$$\sin 2\phi_1 = +0.58^{+0.32}_{-0.34}{}^{+0.09}_{-0.10}$$

Not significant results to claim $\phi_1 \neq 0$

2001/02/12 (23×10^6 $B\bar{B}$ pairs)

$$\sin 2\phi_1 = +0.34 \pm 0.20 \pm 0.05$$

Not significant results to claim $\phi_1 \neq 0$

2001/07/18 (~29×10^6 $B\bar{B}$ pairs)

$$\sin 2\phi_1 = +0.99 \pm 0.14 \pm 0.06$$

Confirmation of $\phi_1 \neq 0$!

2001/07/05 (32×10^6 $B\bar{B}$ pairs)

$$\sin 2\phi_1 = +0.59 \pm 0.14 \pm 0.05$$

Not significant results to claim $\phi_1 \neq 0$

Saved by lucky statistical fluctuation 😉

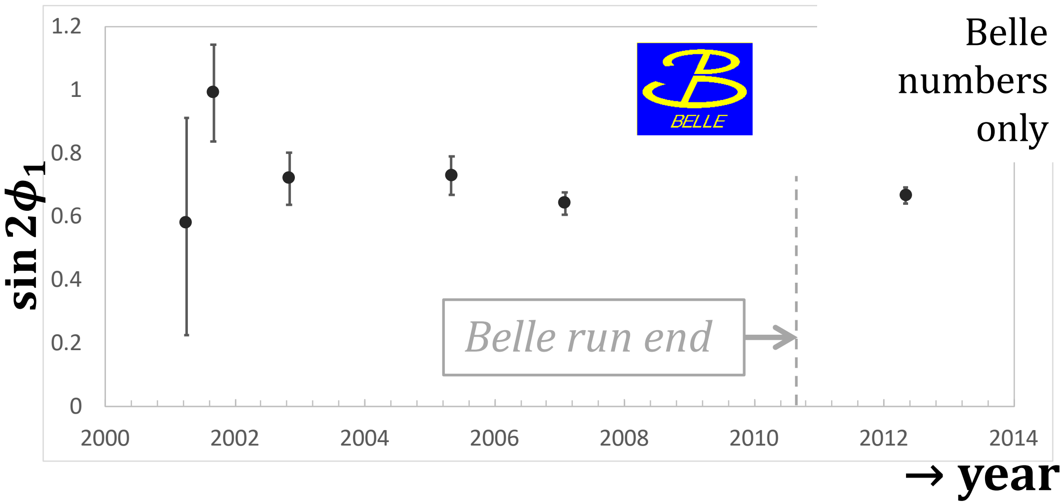
TH's Ph.D. thesis

Measurement of $\sin 2\phi_1$

Nobel Prize in 2008

The results from Belle and BaBar provided the experimental foundation for Kobayashi and Maskawa's 2008 Nobel Prize in Physics.

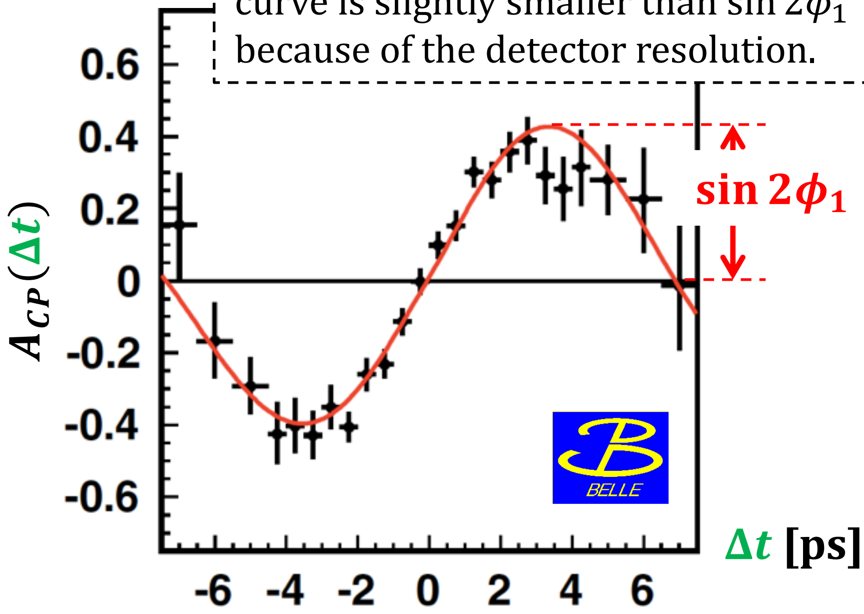
Updates of the $\sin 2\phi_1$



$$(\sin 2\phi_1)_{\mathrm{WA}} = +0.699 \pm 0.017$$

$$\phi_1 = (22.2 \pm 0.7)^\circ \quad \text{(HFLAV 2018)}$$

The apparent amplitude of the sine curve is slightly smaller than $\sin 2\phi_1$ because of the detector resolution.



The asymmetry is clearly visible.

Search for a New Physics

After the KM test ...

After the KM test, the main objectives of Belle shifted to **search for a new physics beyond the Standard Model** (of particle physics).

New physics beyond the Standard Model

- Why only the matter remains in the Universe while the antimatter had vanished?
- What is dark matter?
- Why the formulations for quarks and leptons are so similar?

Theoretical prediction: new physis $\sim O(1)$ TeV ?

$(\sin 2\phi_1)^{\text{other}} - (\sin 2\phi_1)^{\text{KM-test}} \neq 0$?

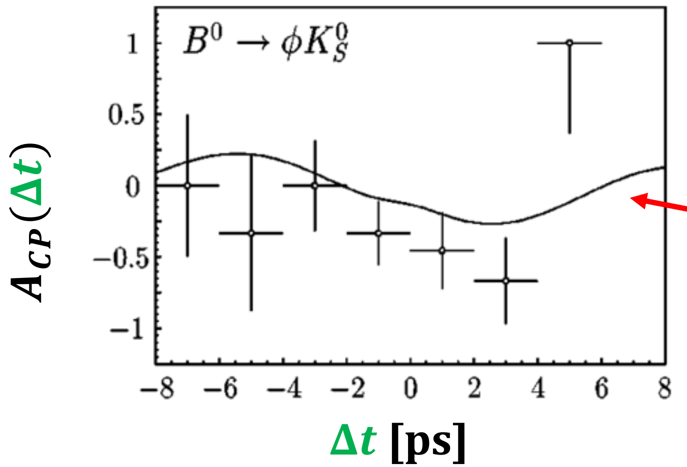
- Measured and collected $\sin 2\phi_1$-equivalent values in as many other B-meson decays as possible than the one for the KM test, and compared the measurement with the $\sin 2\phi_1$.

$(\sin 2\phi_1)^{\text{other}} - (\sin 2\phi_1)^{\text{KM-test}} \neq 0 \;\Rightarrow\;$ Discovery of the new physics

Search for a New Physics

Hint of the new physics in 2002/12 ...

~78×10^6 $B\bar{B}$ pairs



$(\sin 2\phi_1)^{\text{KM-test}} = +0.734 \pm 0.054$ (as of 2002/12)

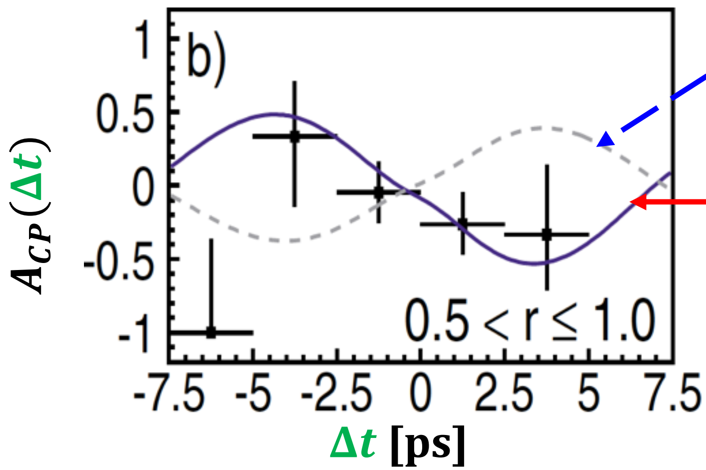
The NP-search results published in 2002/12:
$(\sin 2\phi_1)^{\text{other}} = -0.83 \pm 0.72$
(other = B-meson decay to ϕK^0)

2.1σ deviation ⇒ indication of the NP

Data size doubled

Observation of the new physics in 2003/08 ...

~140×10^6 $B\bar{B}$ pairs



$(\sin 2\phi_1)^{\text{KM-test}} = +0.731 \pm 0.056$ (as of 2003/08)

The NP-search results published in 2003/08:
$(\sin 2\phi_1)^{\text{other}} = -0.99 \pm 0.50$
(other = B-meson decay to ϕK^0)

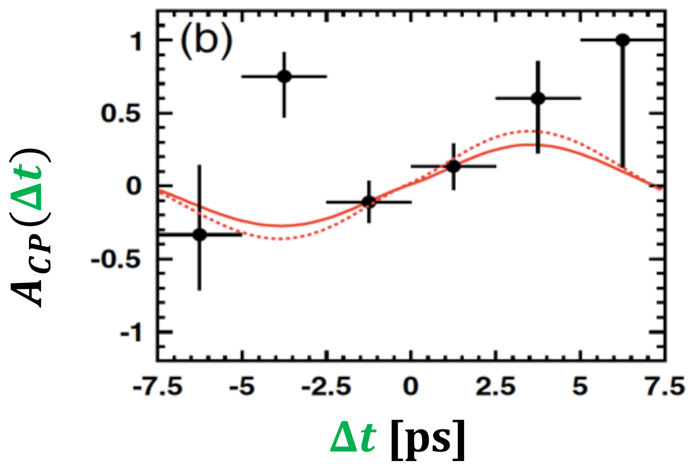
3.5σ deviation ⇒ observation of the NP

TH contributed to these analyses.

Search for a New Physics

Disappearance of the new physics in 2010/07 ...

$657\times10^6\ B\bar{B}$ **pairs**



$(\sin 2\phi_1)^{\mathrm{KM-test}} = +0.699 \pm 0.017$ (as of 2018)

The NP-search results published in 2010/07:

$(\sin 2\phi_1)^{\mathrm{other}} = +0.90^{+0.09}_{-0.19}$

(other = B-meson decay to ϕK^0)

The two numbers became consistent to each other...

This was the topic of my wife's Ph.D. thesis...

Lessons

- We were very unlucky.
- **We needed/need more data** to surely claim the discovery of a new physics.

Belle Shutdown for Upgrade

Belle shutdown: 2010/06/30

The KEK DG (A. Suzuki) shutdown the KEKB accelerator on 2010/06/30.

KEKB records

Peak luminosity (event delivery rate)

$$\boldsymbol{L_{\mathrm{peak}} = 2.1\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

(world record at the time)

Integrated luminosity (recorded events)

$$\boldsymbol{\int L dt = 1.05\ \mathrm{ab}^{-1}}$$

(world record)

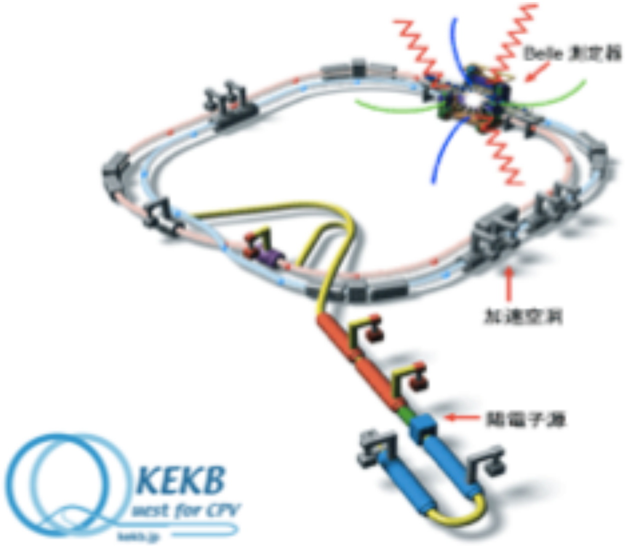
Belle achievements

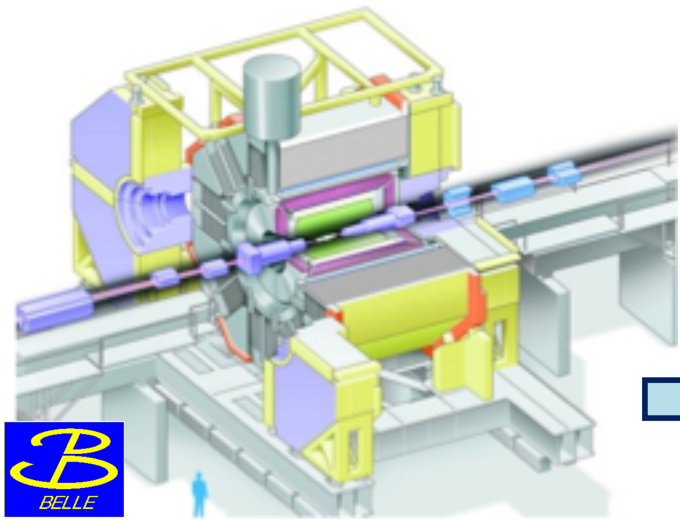
Publication of 500+ physics papers

- Verification of the KM theory
- Observation of $B \to K^{*}\ell\ell$
- Measurement of the CPV in $b \to sq\bar{q}$
- Discovery of exotic hadrons
- Evidence of the direct CPV in $B \to K\pi$
- Observation of $b \to d\gamma$
- Evidence for $B \to \tau\nu$
- Evidence for D^0-$\bar{D}^0$ mixing
- Excess in $B \to D^{*}\tau\nu$ …

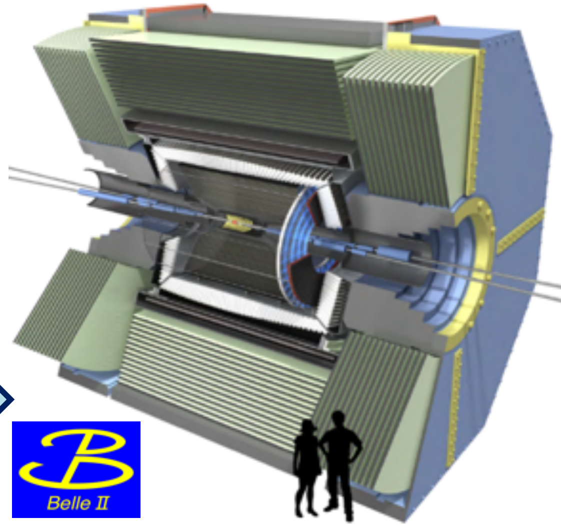
Belle to Belle II

KEKB/Belle





SuperKEKB/Belle II



Design luminosity

$\times 40$ KEKB
$= 80 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-2}$

Data size to collect

$\times 50$ Belle $= 50\ \mathrm{ab}^{-1}$

Challenges in the detector

- Faster particle-hit response
- More radiation hardness
- Improvement in the detector performance

Name of Belle/Belle II

$$B = el + le$$

The ***B*** mesons are generated from the collision of the **el**ectrons and positrons (snortce**le**).

The *b* quarks are usually called **<u>bottom quarks</u>** but sometimes called **<u>beauty quarks</u>**.

'Beauty' is Belle in French.

✓ **Belle** ✗ **Bell**

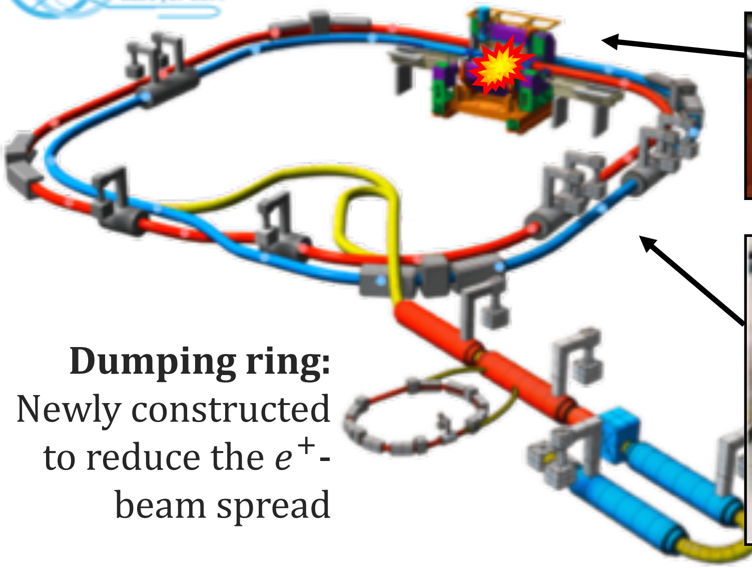
e + ɘ =

SuperKEKB Accelerator

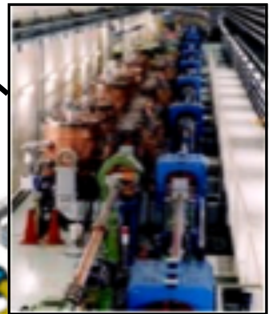
$$\underset{\text{events } [\mathrm{s}^{-1}]}{Y} = \underset{\text{cross-section } [\mathrm{cm}^2]}{\sigma} \times \underset{\text{Luminosity } [\mathrm{cm}^{-2}\mathrm{s}^{-1}]}{L}$$

$$L \propto \frac{\text{Beam current}}{\text{Beam size}}$$

One bunch contains 50B e^+/e^-.



Focusing magnets: Newly installed to reduce the beam size.

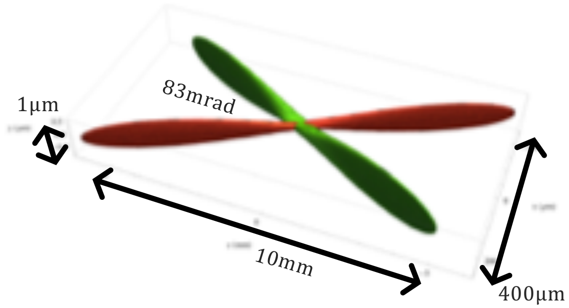


RF system: newly installed to increase the beam currents

e^-: 1.19A → 2.6A
e^+: 1.64A → 3.6A

Dumping ring: Newly constructed to reduce the e^+-beam spread

Nano-beam scheme



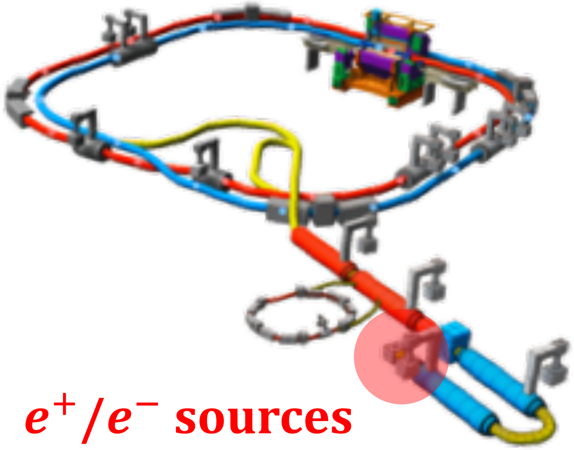
Increases the luminosity by minimizing the beam size in the e^+-e^- interaction region with the focusing magnets.

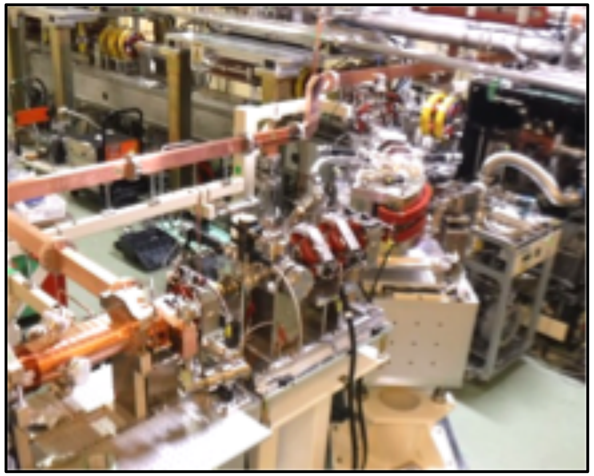
Beam current → **×2**, beam size → **× 1/20**

$$L_{\mathrm{KEKB}}^{\mathrm{peak}} = 2.1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow L_{\mathrm{SKEKB}}^{\mathrm{design}} = 80 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

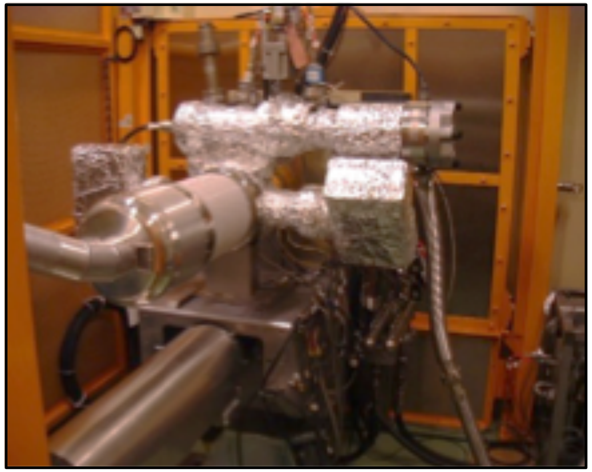
SuperKEKB Rare Footages

The beam electrons are generated as thermal electrons; the beam positrons are generated from the e^+/e^- pair creation by colliding the generated electrons to a tungsten target.

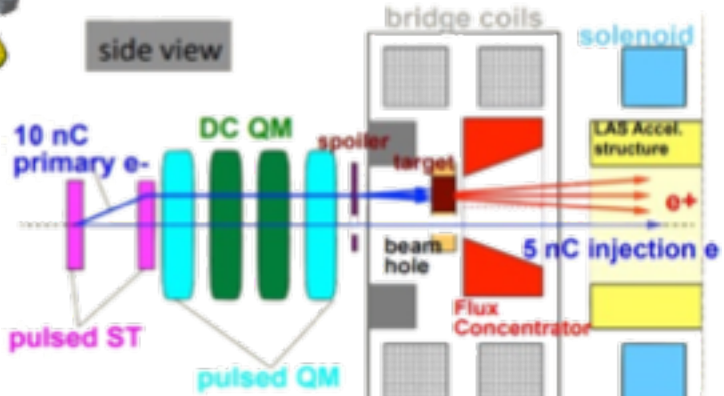


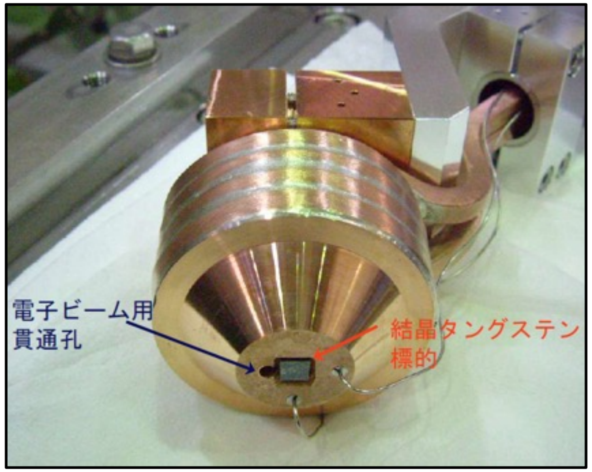


e^- source for the e^- beam



e^- source for the e^+ beam

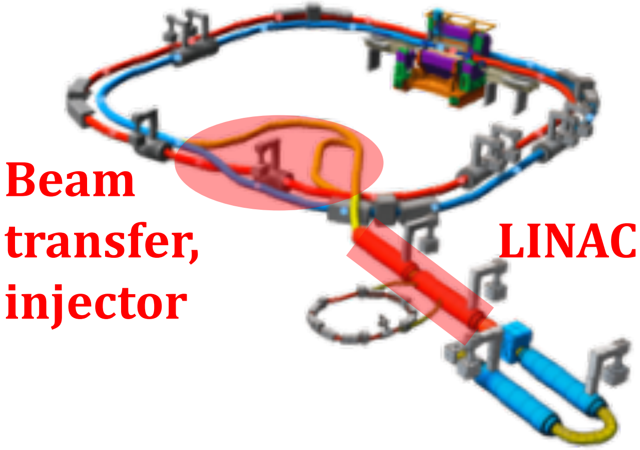


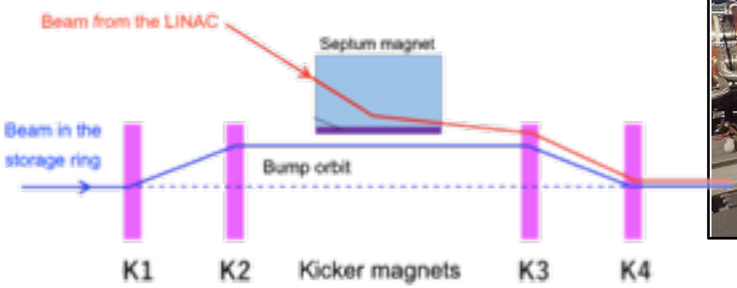


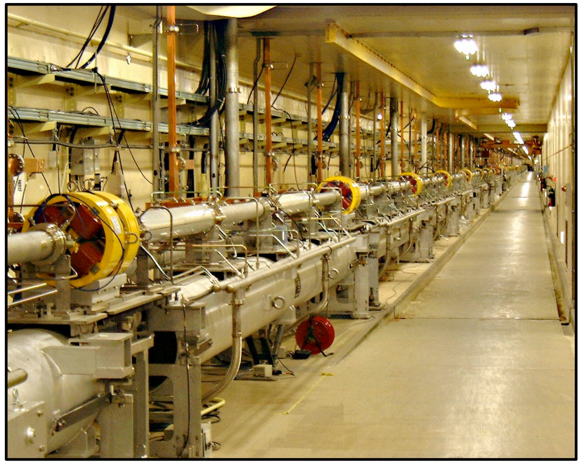
Tungsten target

SuperKEKB Rare Footages

The generated electrons and positrons are accelerated with the LINAC and injected to the main rings through the beam transport.

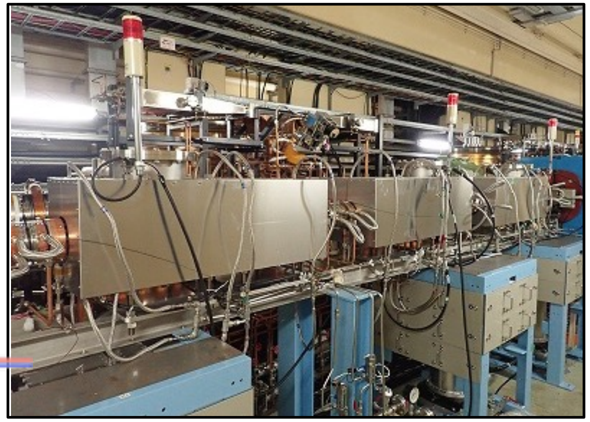




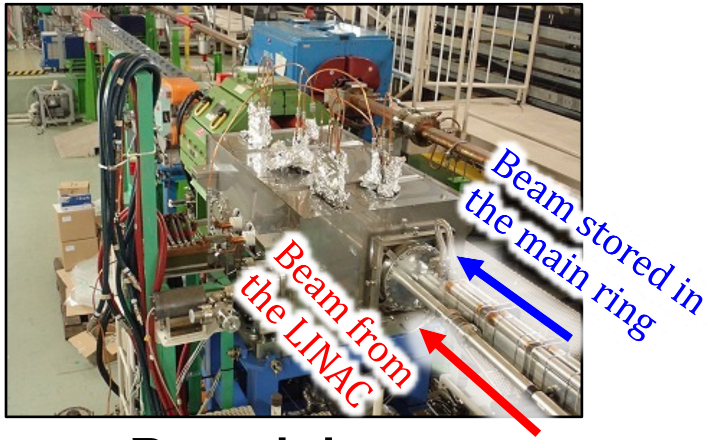


LINAC

Beam transport from the LINAC to the main ring



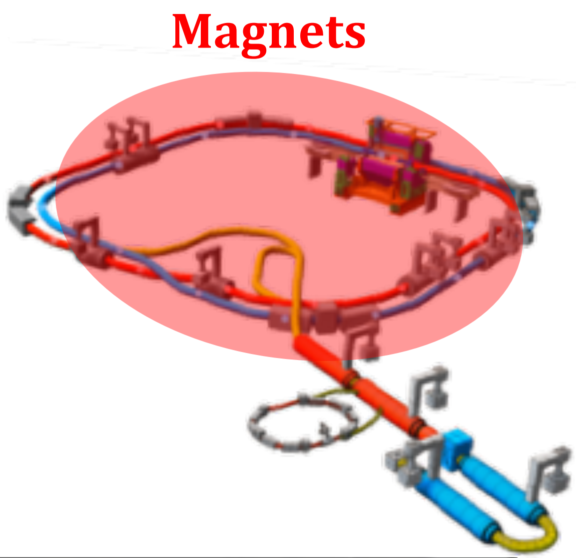
Kicker magnets



Beam injector

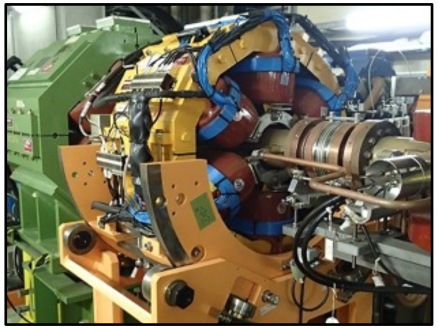
SuperKEKB Rare Footages

Magnets are used to bend the e^+/e^- beam direction and to control the beam bunch size and beam monochromaticity. ~2600 magnet units are installed in the SuperKEKB tunnel.



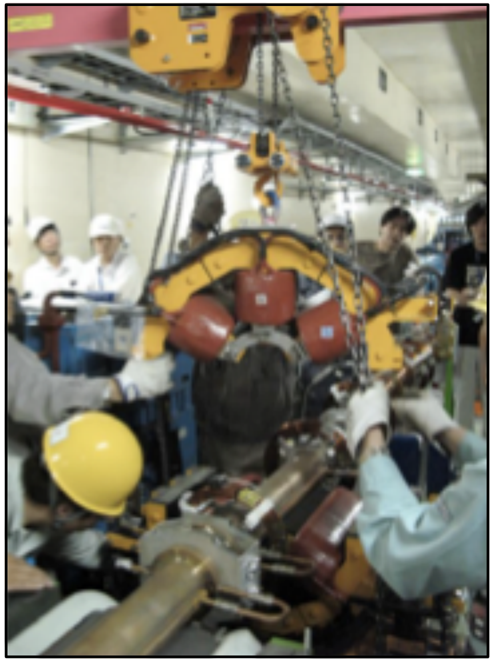
Bending magnet

Focusing magnet



Sextuple magnet

Removing a sextuple magnet →

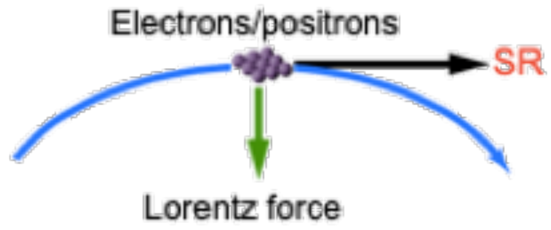


Magnet stockyard

↑ Installing a bending magnet.

SuperKEKB Rare Footages

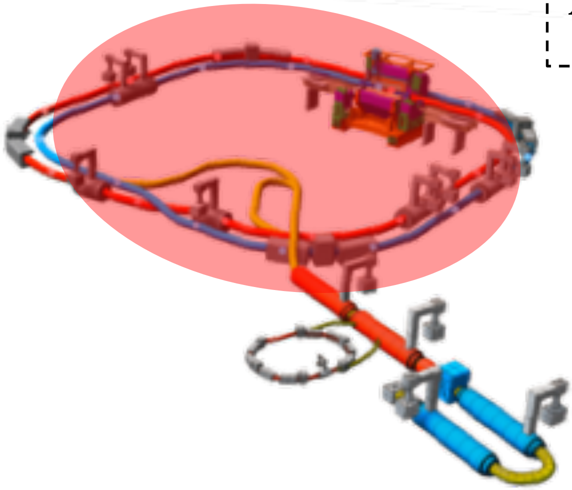
Cavities, beam pipes



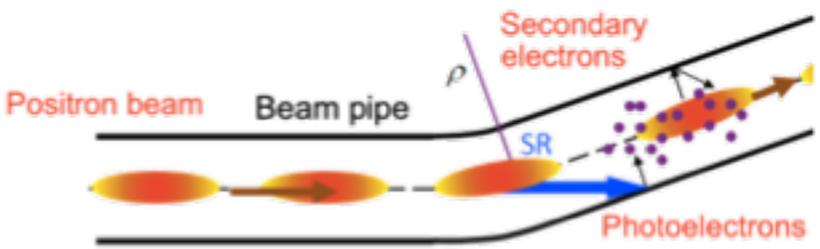
The beam loses the energy because of the SR. The cavities compensate the energy loss.

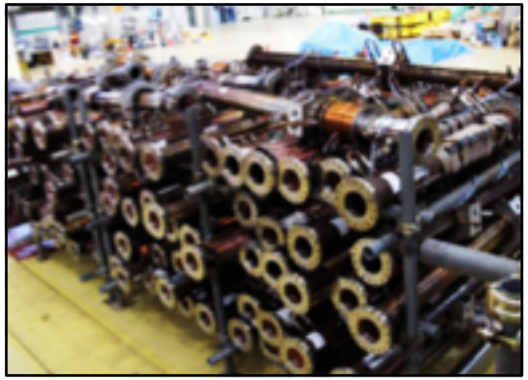
ARES cavities

SC cavities

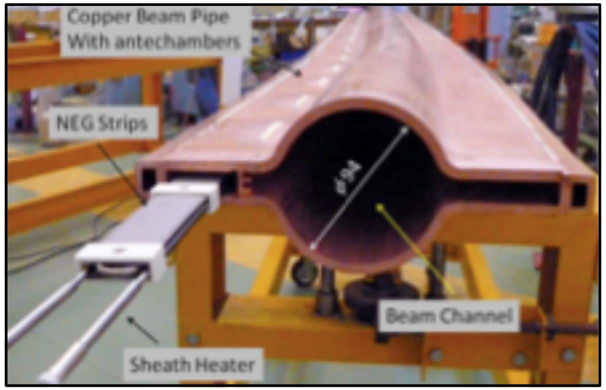


The SR generates the photoelectrons when it hits to the beam-pipe wall. The PEs mess up the positron bunch. The secondary electrons generated by the PEs do the same.





Removed KEKB beampipes

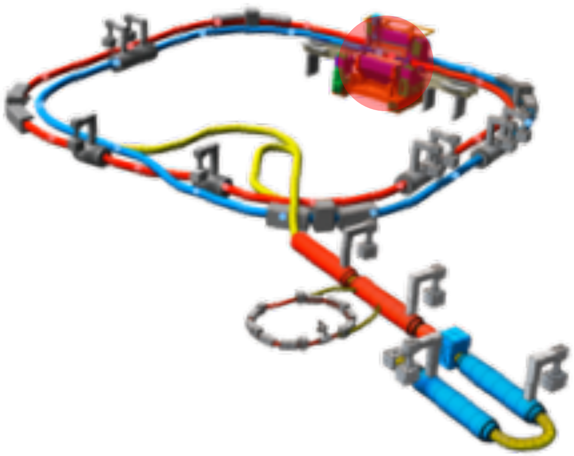


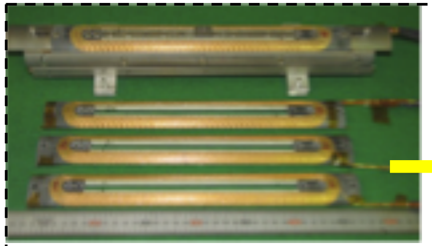
TiN coated beam pipe with antechambers

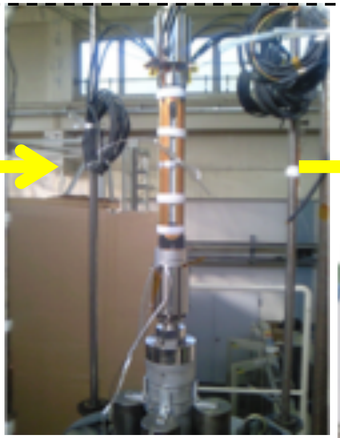
SuperKEKB Rare Footages

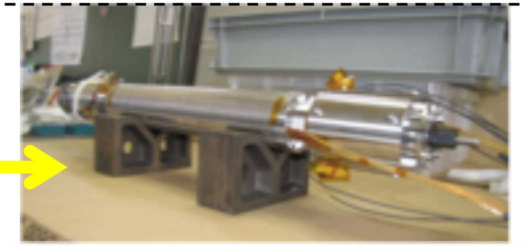
The nano-beam scheme is realized by a state-of-the-art QCS system comprised of 55 SC magnets and cryostat.

Nano-beam scheme

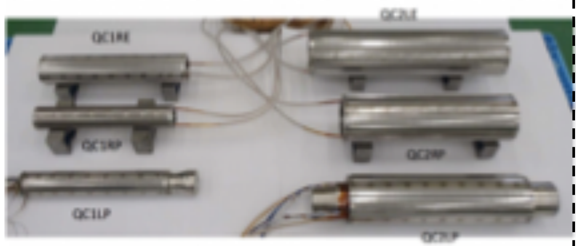


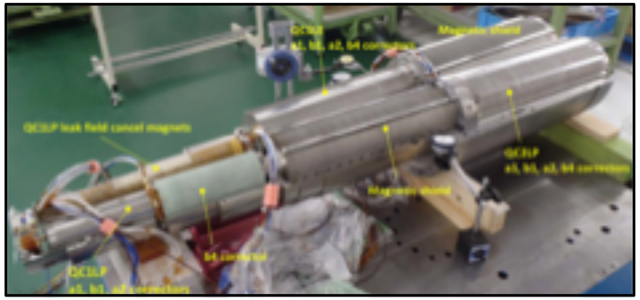




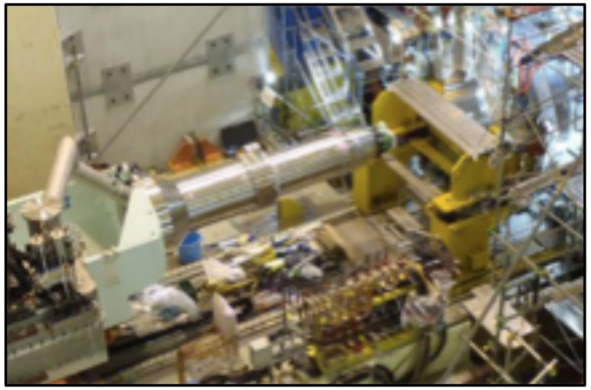


Assembly of solenoid units

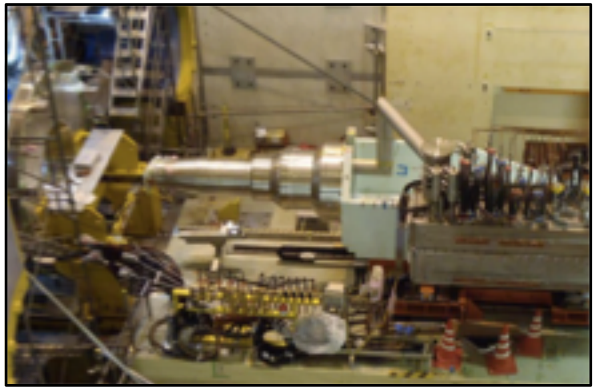




Assembly of the solenoid unit

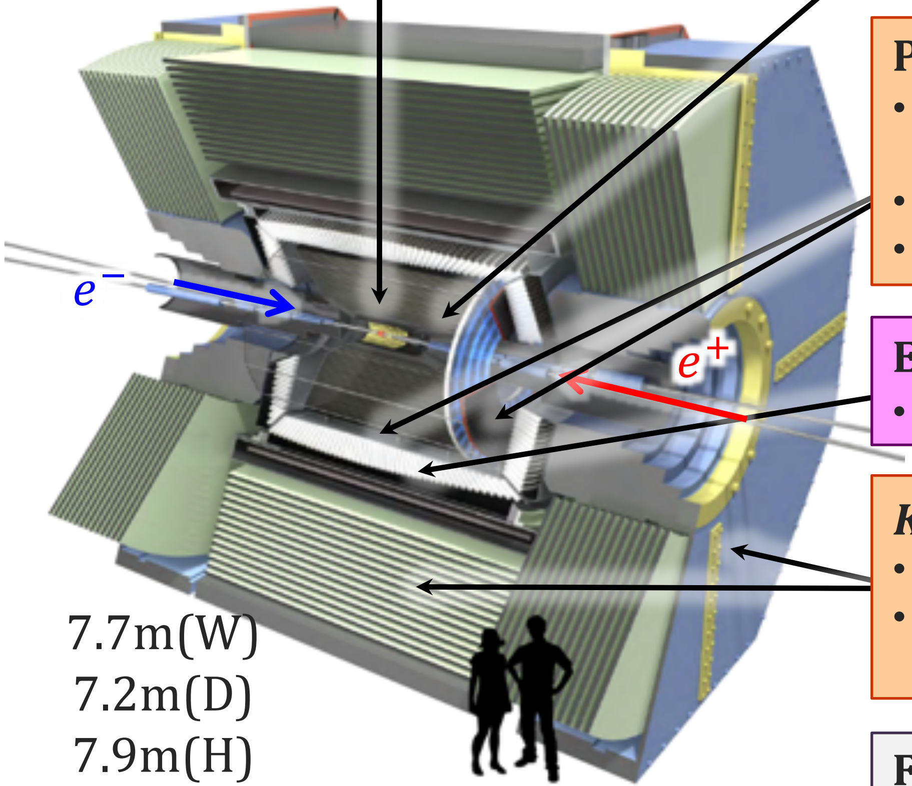


QCSR (e^+ upstream)



QCSL (e^- upstream)

Belle II Detector



Vertex detectors
- Inner 2 layers: Pixel detectors
- Outre 4 layers: Strip detectors

Drift chamber (p, PID)
- Longer lever arm than Belle
- Smaller cell size than Belle

PID detectors (K/π ID)
- Barrel: Time-Of-Propagation counters
- Endcap: Aerogel RICH
- Wrong PID … half of Belle

EM calorimeter (E_e, E_γ)
- CsI(Tl) + wave-form sampler

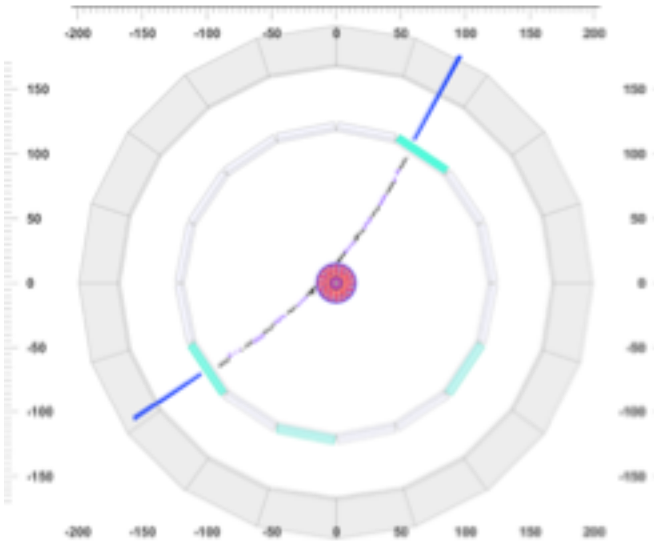
$K_L^0\mu$ detector
- Outer barrel: RPC (streamer)
- Endcap, inner barrel: Sci. + WL shifter

Fast and broadband DAQ

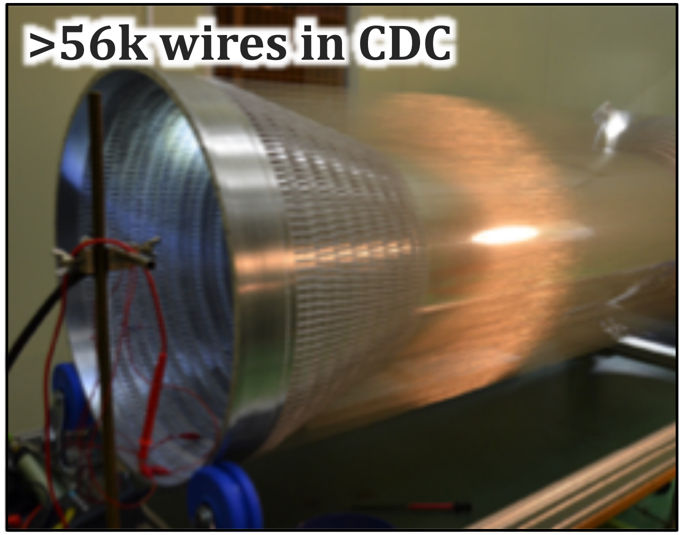
>1000 collaborators

Challenges in the detector upgrade
- Capability of larger event rate 500 Hz → 30 kHz
- Tolerance to harsher radiation (×10-20 beam BG)
- Performance improvements

Central Drift Chamber




Wire stringing

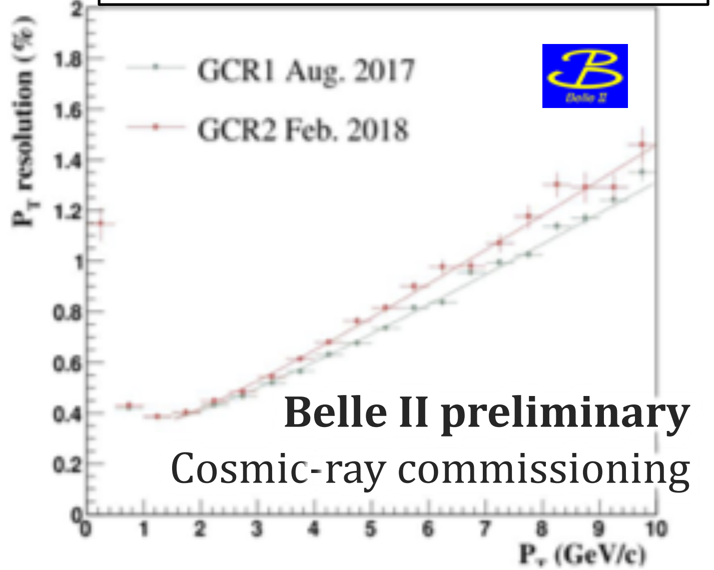

>56k wires in CDC

Theory: $\boldsymbol{p_{\mathrm{T}}}[\mathrm{GeV}/c] = 0.3 \times B[T] \times R\ [\mathrm{m}]$

p_{T} resolution was found $\sim 0.3\%$ for $p_{\mathrm{T}} = 2\mathrm{GeV}/c$

Transportation to Belle II

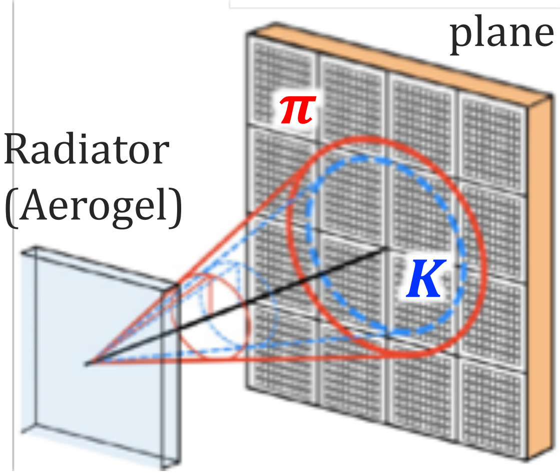

Installation



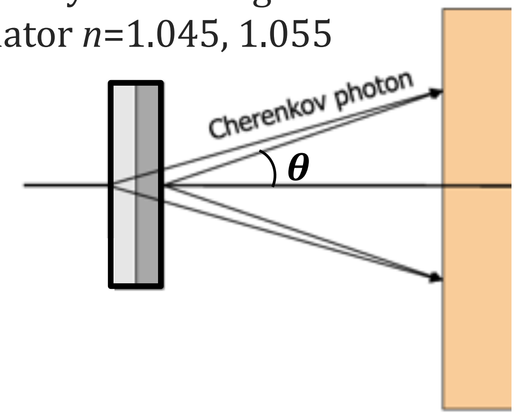
Aerogel RICH Counters

Photodetection plane

Radiator (Aerogel)

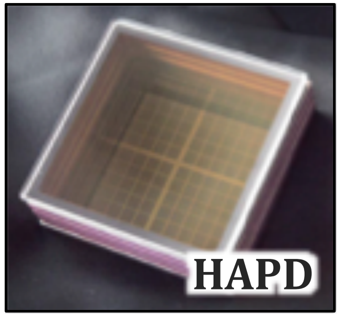


Multi-layer focusing radiator n=1.045, 1.055

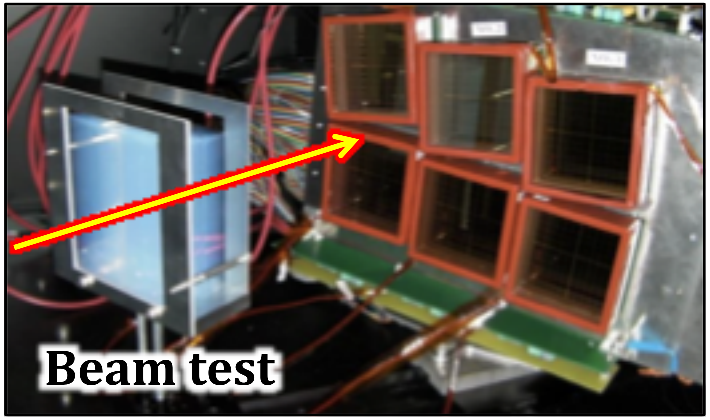


Theory: $\cos\theta = \frac{1}{n}\sqrt{1 + \left(\frac{m}{p}\right)^2}$

Aerogel

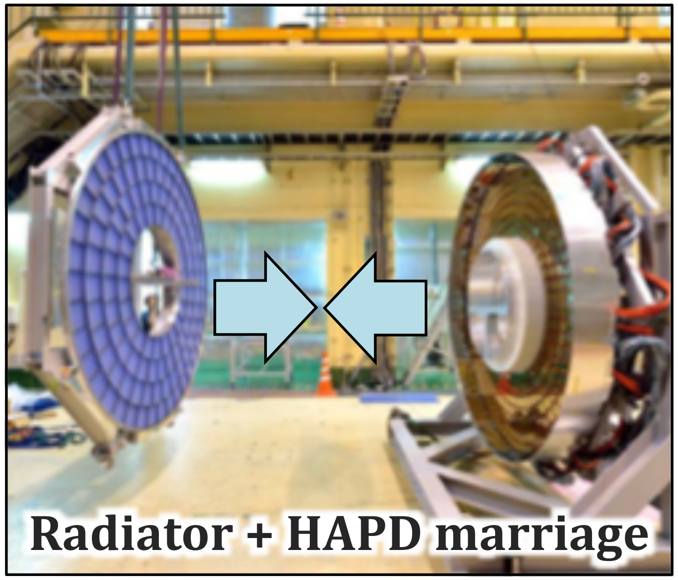


HAPD

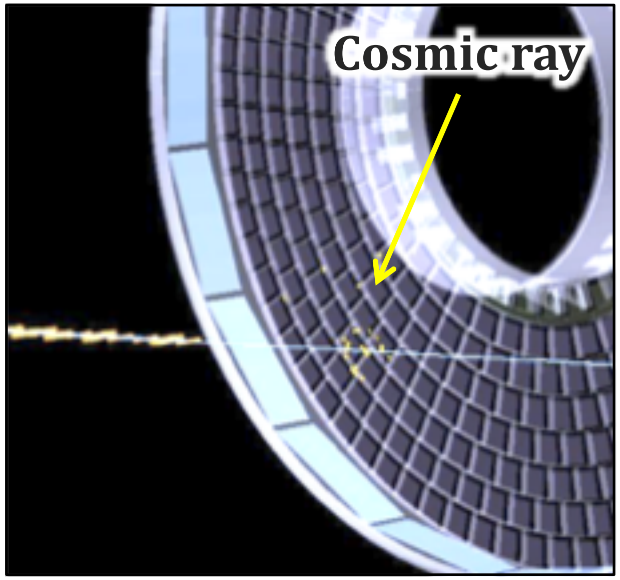


Beam test

Attaching the HAPDs

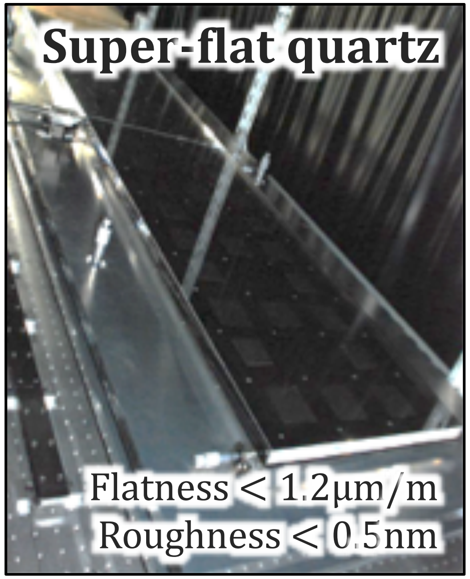


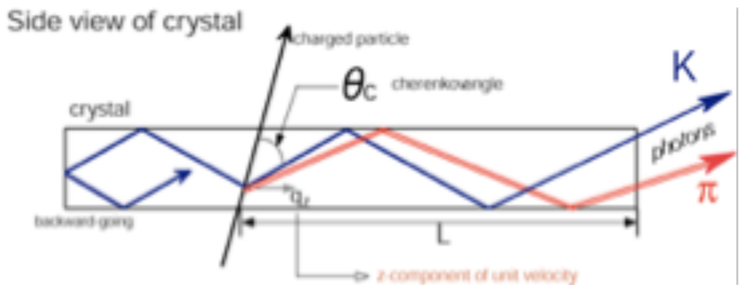
Radiator + HAPD marriage



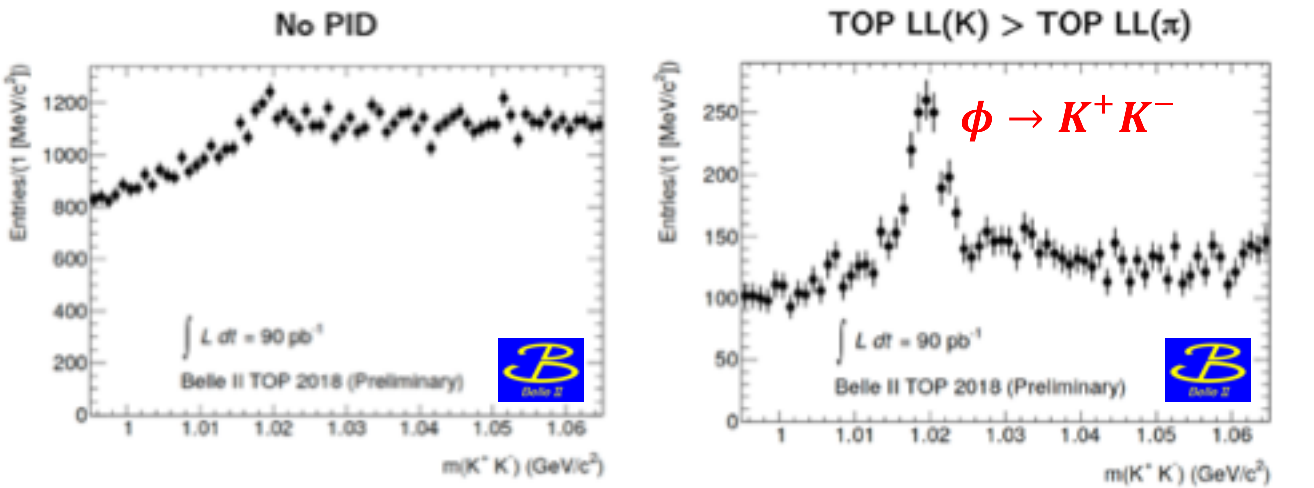
Cosmic ray

Time-of-Propagation Counters





K/π separation by measuring the difference in TOF and end-point of Cherenkov-light propagations in a quartz.

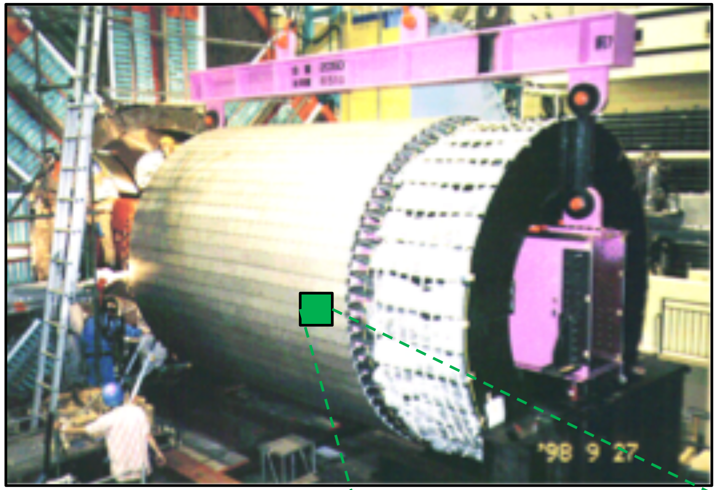


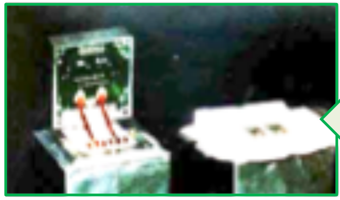
The $m_{K^+K^-}$ distributions without (left) and with (right) TOP PID applied. Combinatorial BG is properly reduced.

Other Outer Detectors

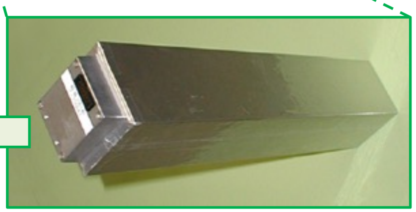
The EM calorimeters and $K_L\mu$ detector for Belle are reused in Belle II.

EM calorimeters (CsI(Tl))





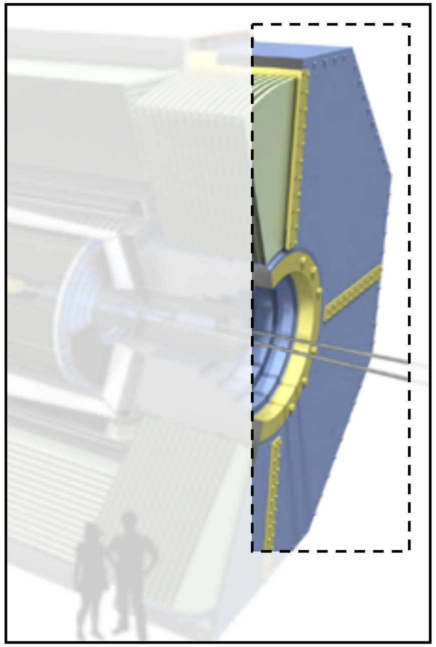
2 photodiodes



30cm long CsI(Tl) crystal ($16X_0$)

Waveform sampler

$K_L\mu$ detector



The RPCs (resistive-plate counters) of the endcap KLM were replaced with scintillators and optical fibers.

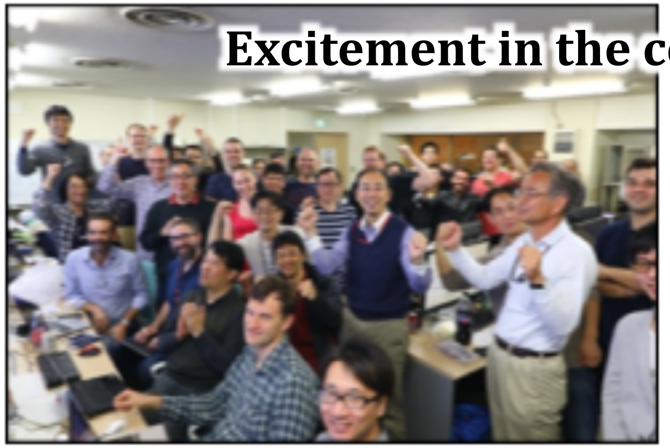
Belle II Roll-In

The Belle II detector with CDC, ARICH, TOP, ECL, and KLM installed was rolled-in to the SuperKEKB beam line on 2017/04/11.

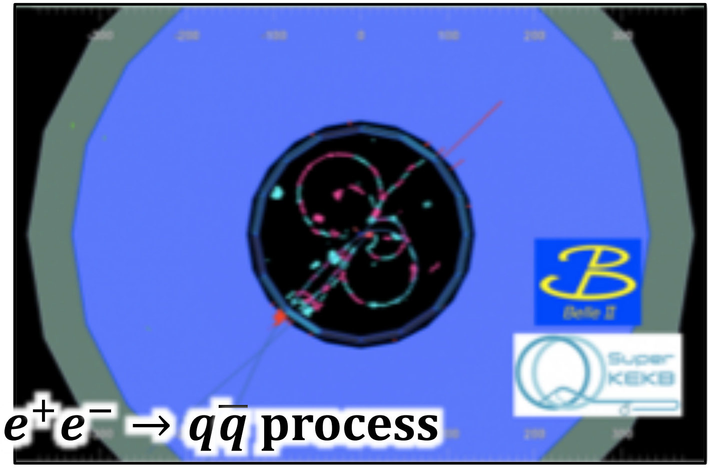
On 2018/04/26 ...

In KEK ...

Belle II had confirmed the first e^+-e^- collision at 0:38 AM.



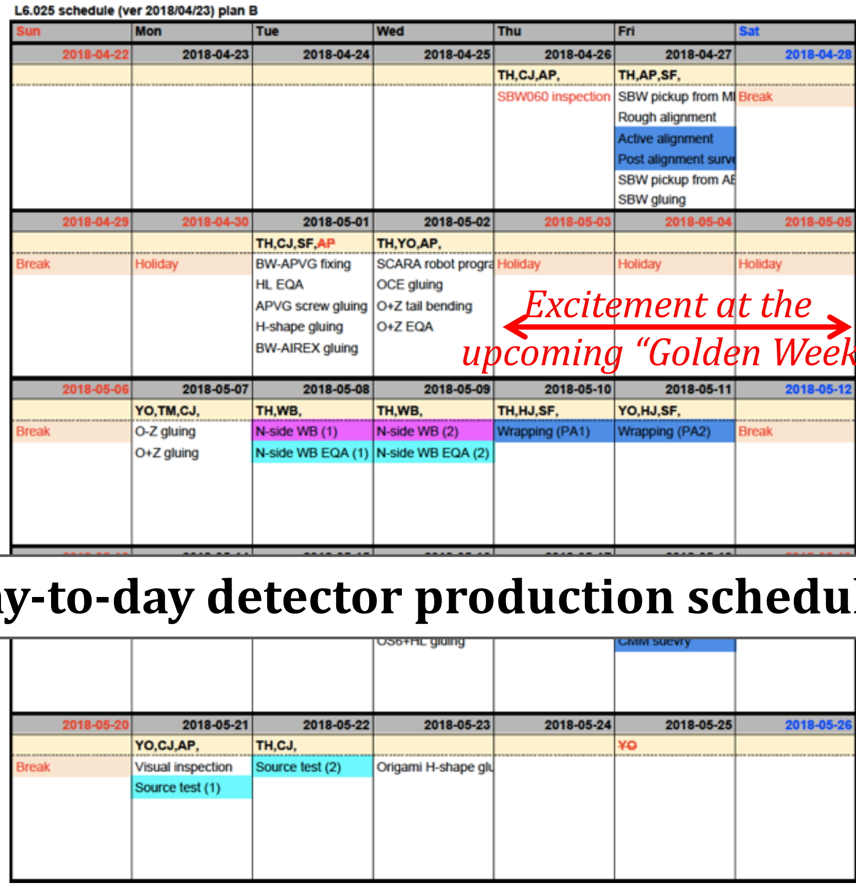
Excitement in the control room



Observed $e^+e^- \to q\bar{q}$ process

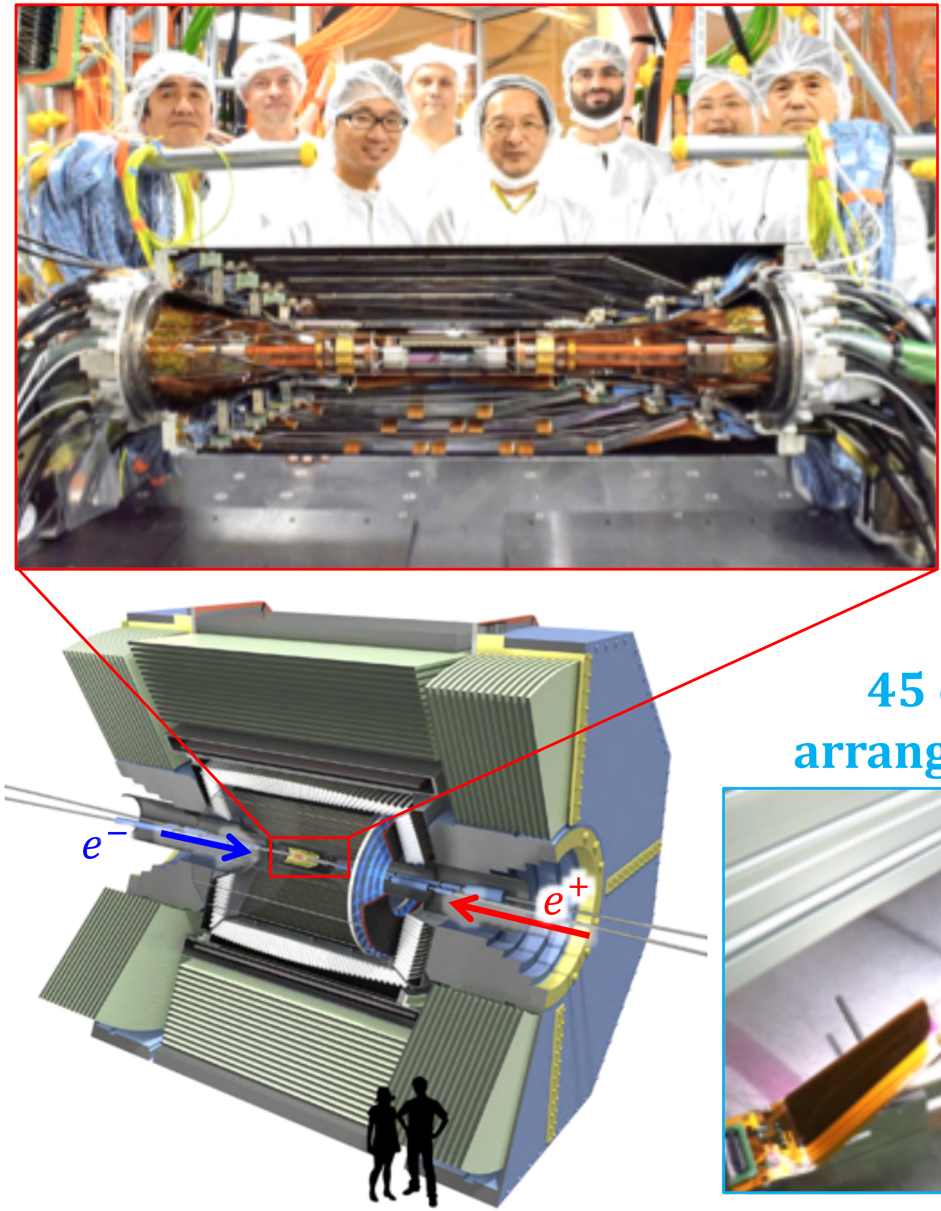
At IPMU ...

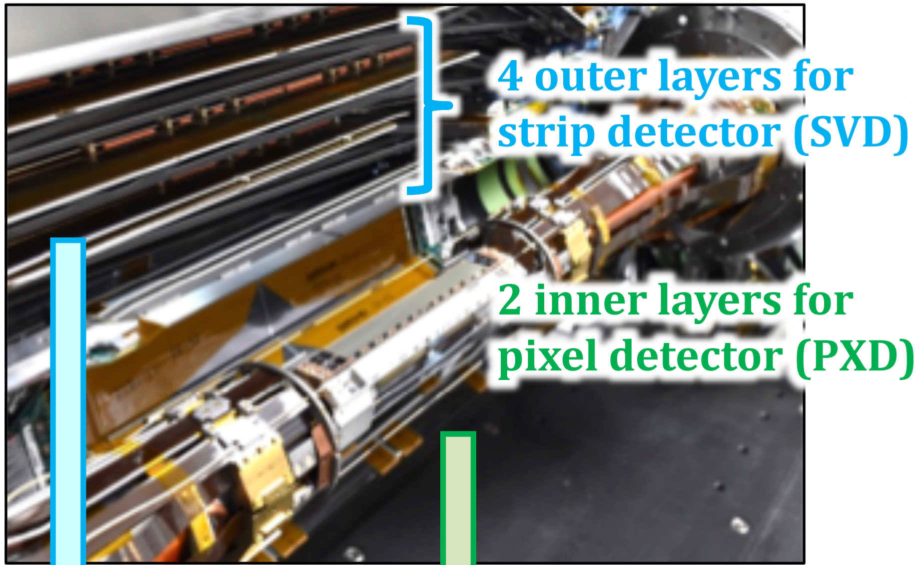
Production of inner-detector modules were still ongoing ...



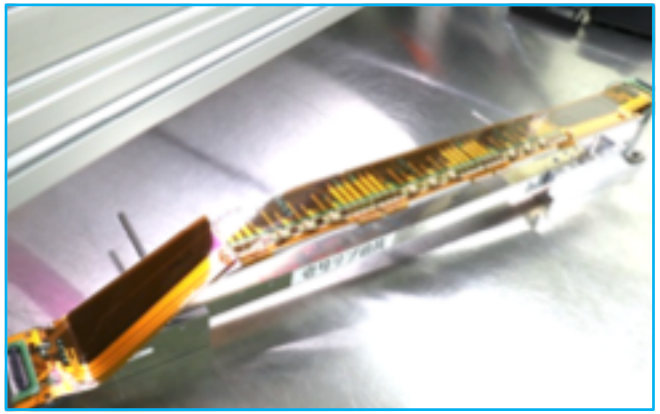
Day-to-day detector production schedule

Vertex Detectors





45 cylindrically arranged SVD ladders



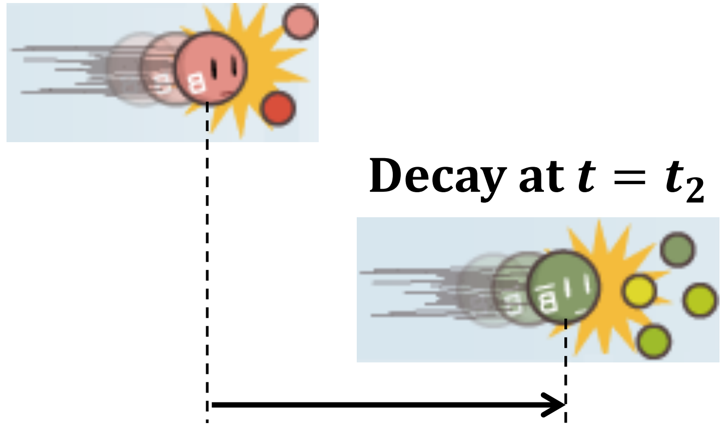
10 cylindrically arranged PXD ladders

Vertex Detectors

e^+-e^- collision

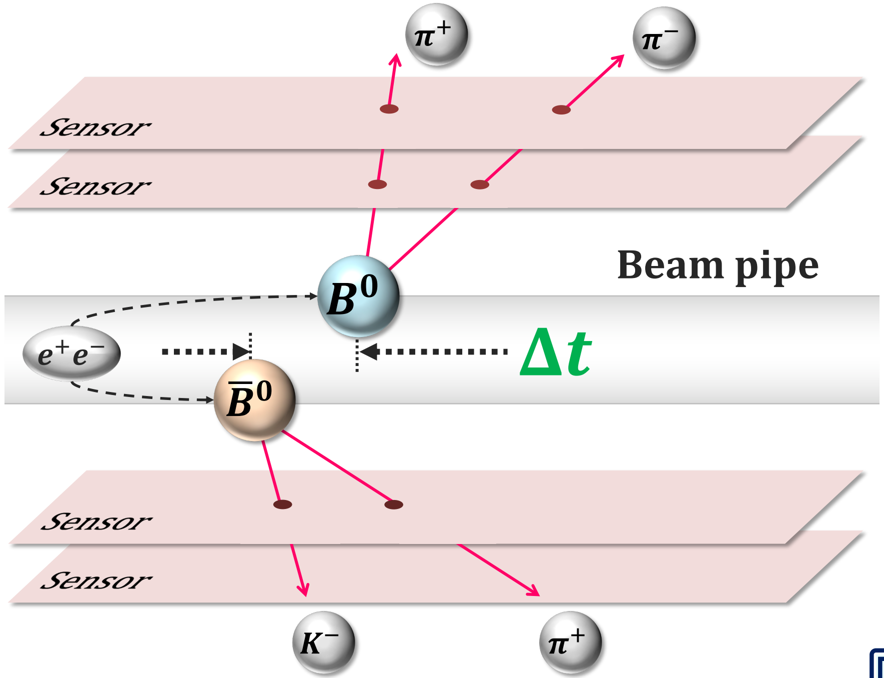
$B/\overline{B}$ pair creation at $t = 0$

Decay at $t = t_1$



Decay at $t = t_2$

$\Delta t \equiv t_2 - t_1$



Displacement of the two B-decay vertices: typically 130μm

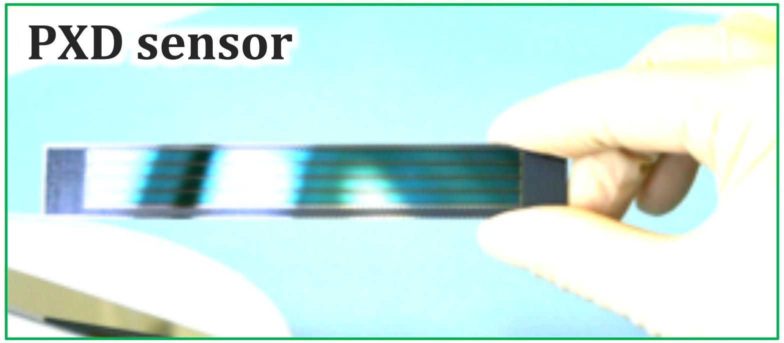
$$\Delta t \sim \frac{z_2 - z_1}{(\beta\gamma)_B c}$$

Velocity of the B meson determined from the beam energy: $(\beta\gamma)_B = 0.28$

$\Delta t \sim O(1)$ps → experimentally difficult to measure

The **vertex detectors are the essential devices** to access the new physics.

Pixel Detector (PXD)

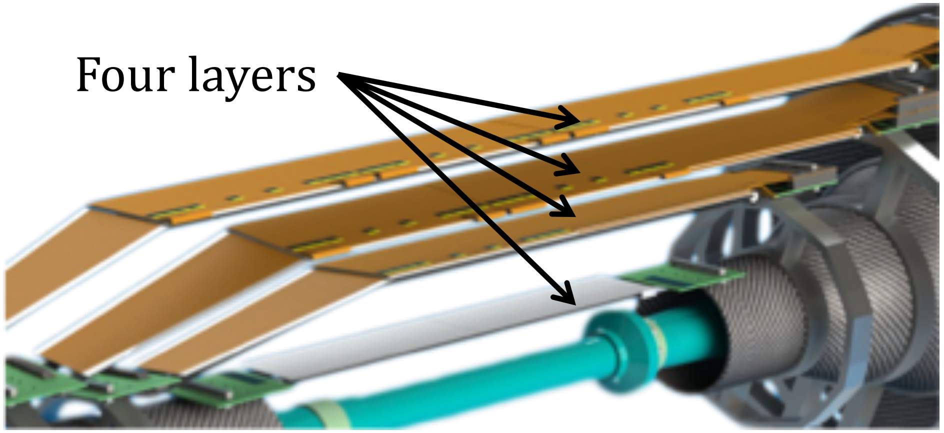

PXD sensor


PXD ladders

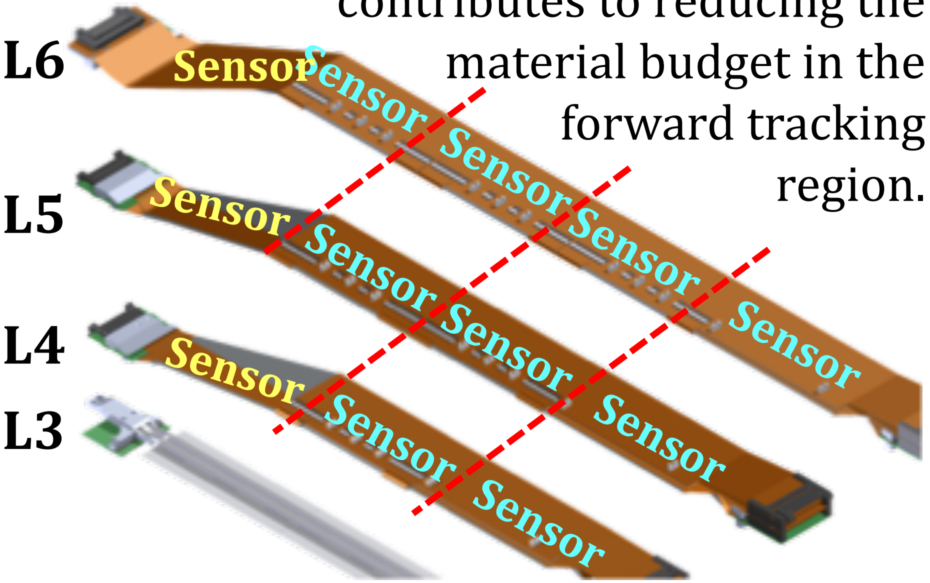

PXD cylinder assembled in Germany

Silicon Vertex Detector (SVD)

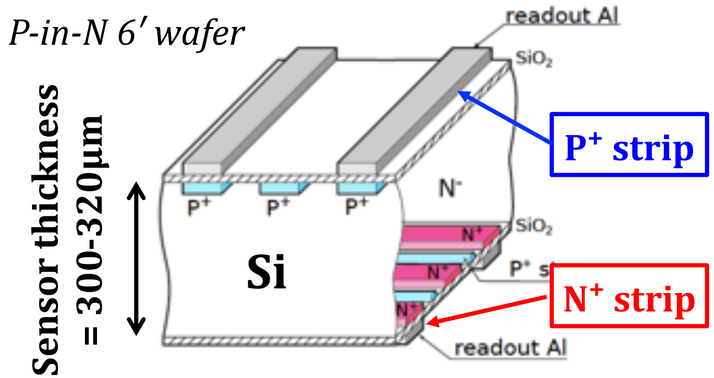
SVD structure

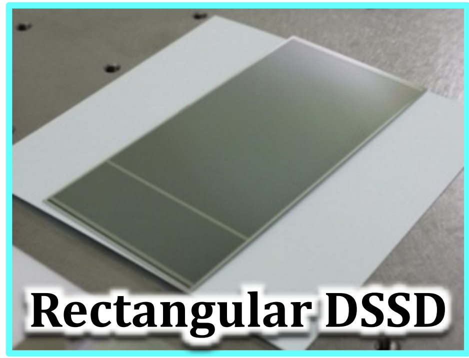


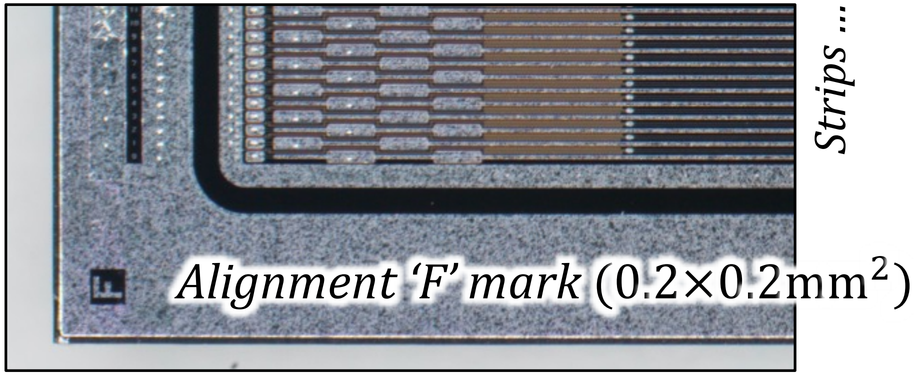
The characteristic lantern shape contributes to reducing the material budget in the forward tracking region.



Double-Sided Strip Detector





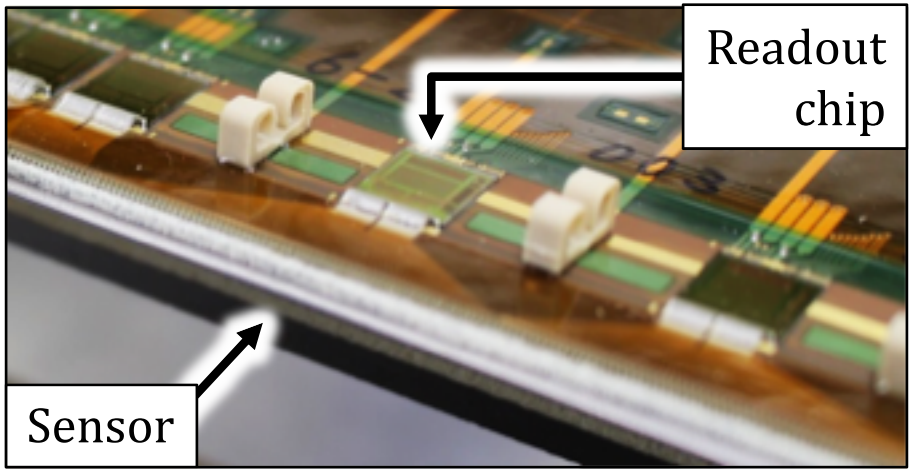


Novel Concepts in the SVD

Chip-on-sensor concept

In legacy ladder designs, strip signals were read out from the ladder ends → the long signal-path length introduced extra noise.

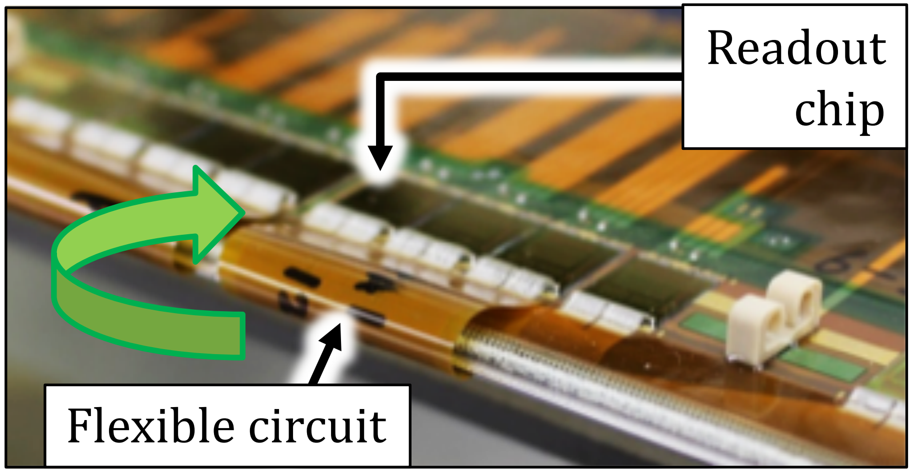
The readout chips of the SVD sensor strips are placed ON the sensor to minimize the path length.



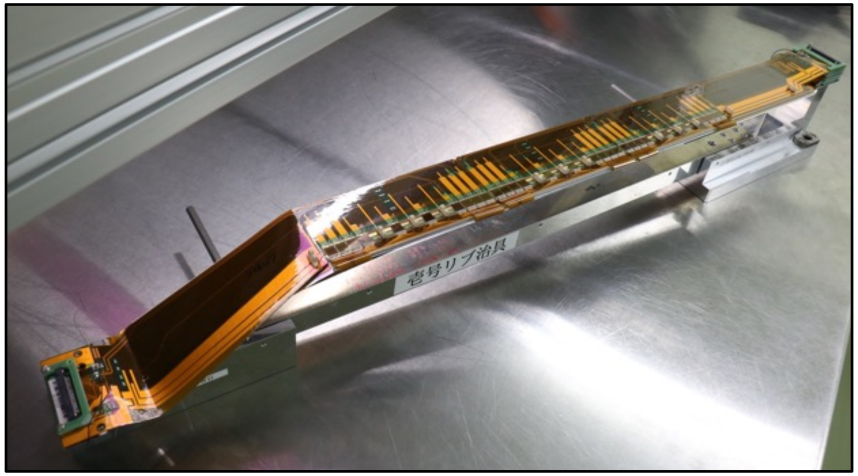
Origami concept

The strip signals on the sensor backside cannot be readout by the chips mounted on the sensor top side.

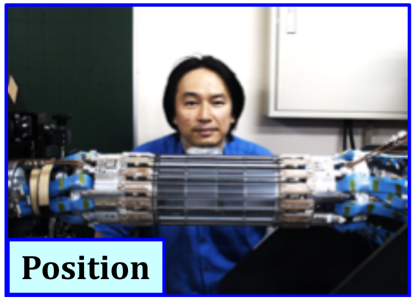
The backside strips are once connected to a flexible circuit and the signals are transmitted to the chips by folding the flexible circuit.



SVD Ladder Production

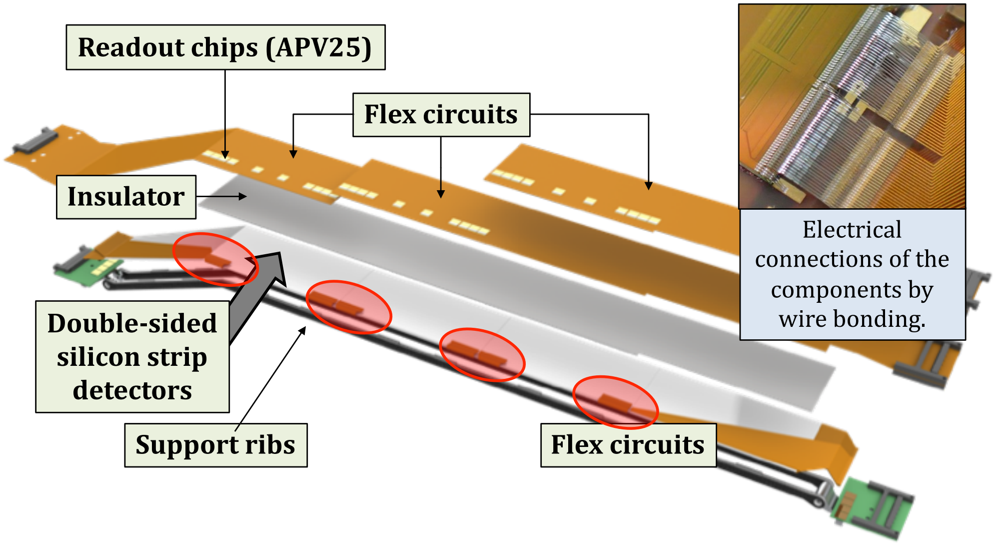


Belle-1 SVD ladder production



The production was outsourced to a company.

Belle II SVD ladder production



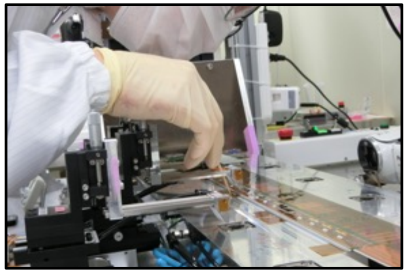
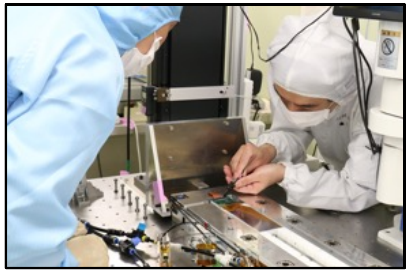
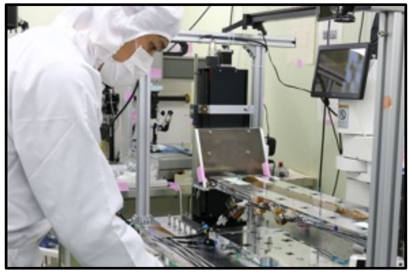
The ladder design became too novel to outsource the production. We had to produce the ladders by us.

INFN · The University of Melbourne · tifr tata institute of fundamental research · HEPHY · IPMU +

This was an unexperienced challenge for Japanese universities and institutes at least in high energy physics.

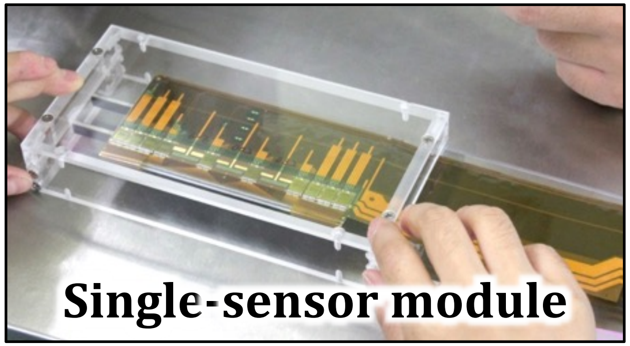
SVD Ladder R&D @ IPMU

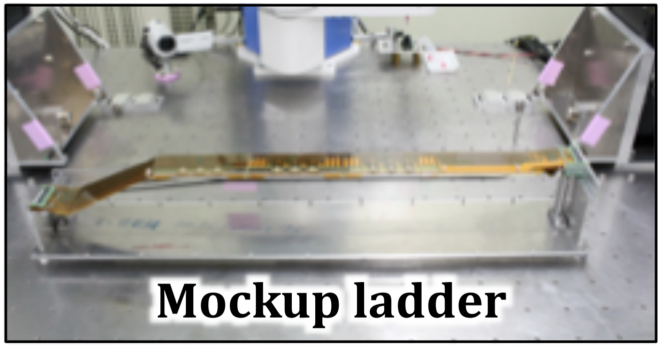
R&D on the “reproducible” ladder production procedure – 4 years

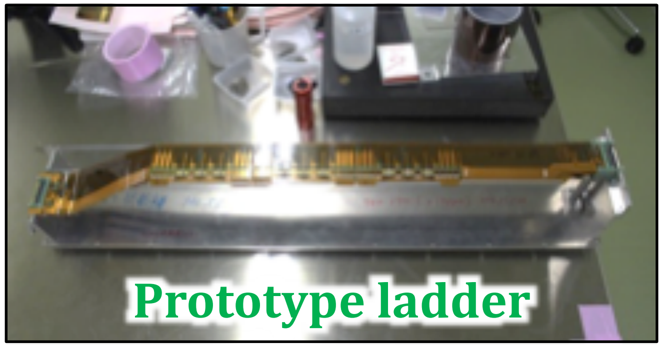






- *Precise sensor alignment*
- *Component gluing*
- *Wire bonding*
- *Mechanical quality assurance*
- *Electrical quality assurance …*

Several test productions


Single-sensor module


Mockup ladder


Prototype ladder

Good performance of the prototype ladder was confirmed in a beam test. ⇨ **Green light** for the production

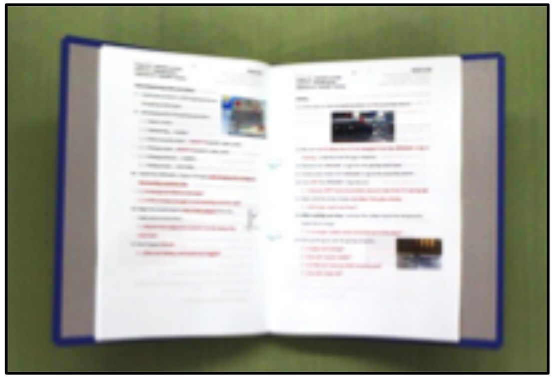
SVD Ladder Production @ IPMU

Ladder mass-production – 2 years

You could imagine repeating exactly the same production over 2 years was very difficult and painful for humans; however, we had to do that because we had no affordable parts or time to cure a failure by a new method.

Mantra

Never invent anything new in the cleanroom.



>100-page manual

New-operator's training course

Delivered 19 qualified ladders

- **Sensor distortion**
  $|\delta z| = 44 \pm 42\ \mu\mathrm{m}$ (req. <300 μm)
- **Wire bonding error rate**
  0.16% (req.<1%)

This was the first achievement for Japanese universities and institutes.

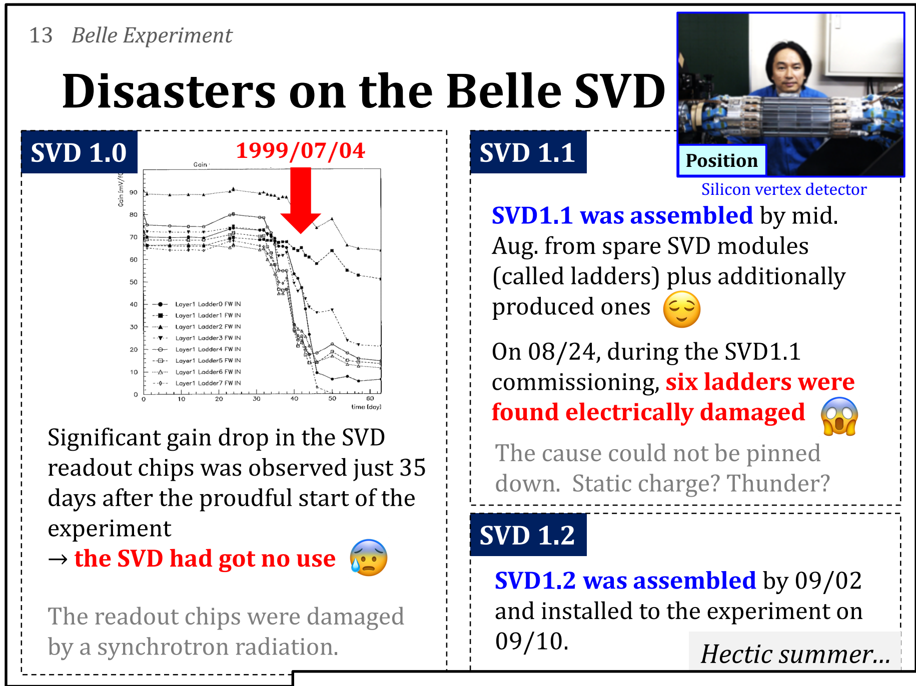
Now, some activities on semiconductor-detector production in Japanese universities and institutes can be seen.

Reduced-Scale Vertex Detector

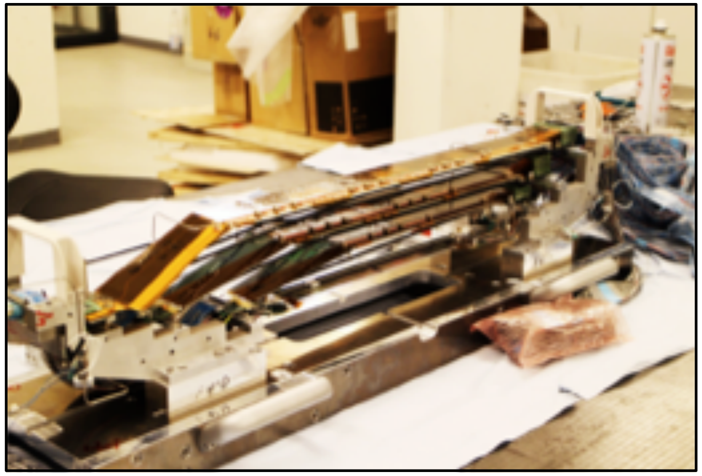
BEAST: reduced-scale VXD

A reduced-scale VXD (one prototype ladder per layer) was first installed **on the SuperKEKB beam line** to verify radiation safe environment for installing final VXD.

Radiation monitor, beam abort, and hard-wired interlock systems were also commissioned.



No disaster anymore

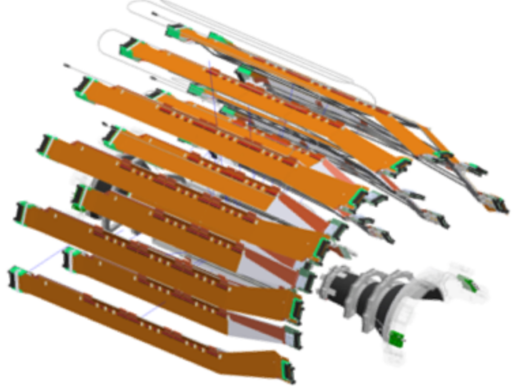


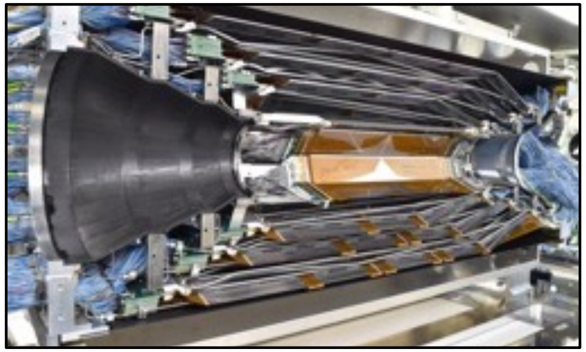
The dominant beam-background sources were found to be the Touschek process and residual gas in the beam pipe. The SR effect was negligible.

We confirmed the radiation environment was safe enough for the vertex detectors (at least for the operation in the first few years).

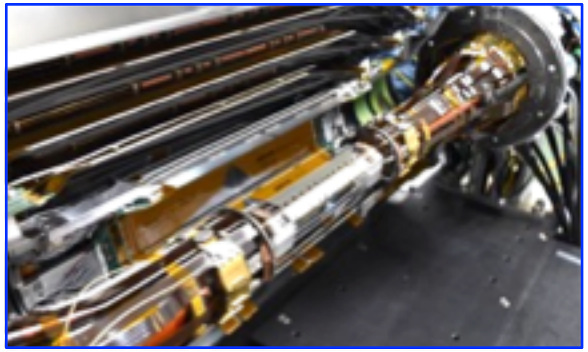
Vertex Detector Installation

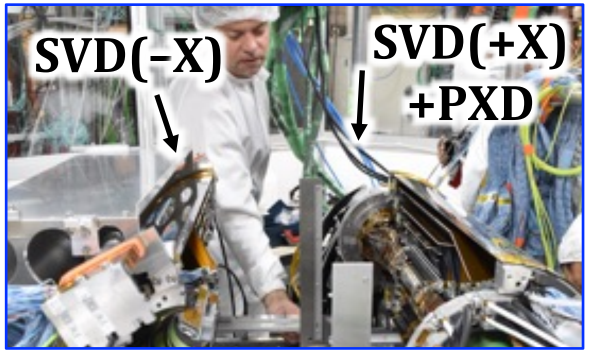
SVD construction

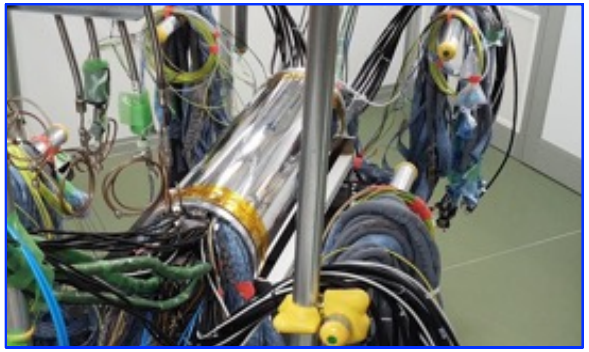




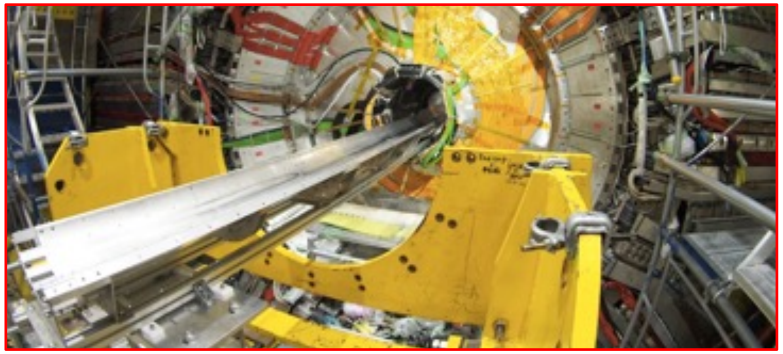
PXD+SVD = VXD marriage

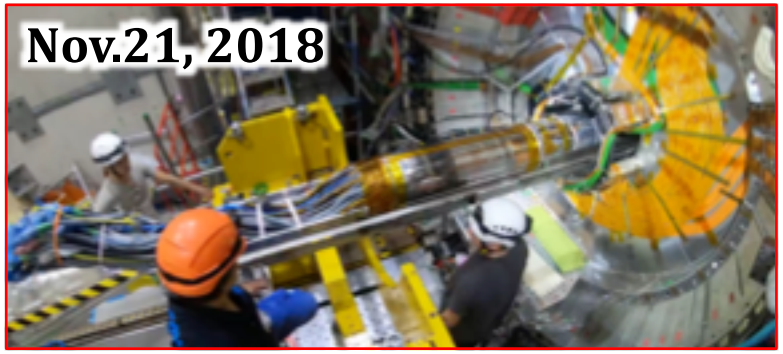






VXD installation



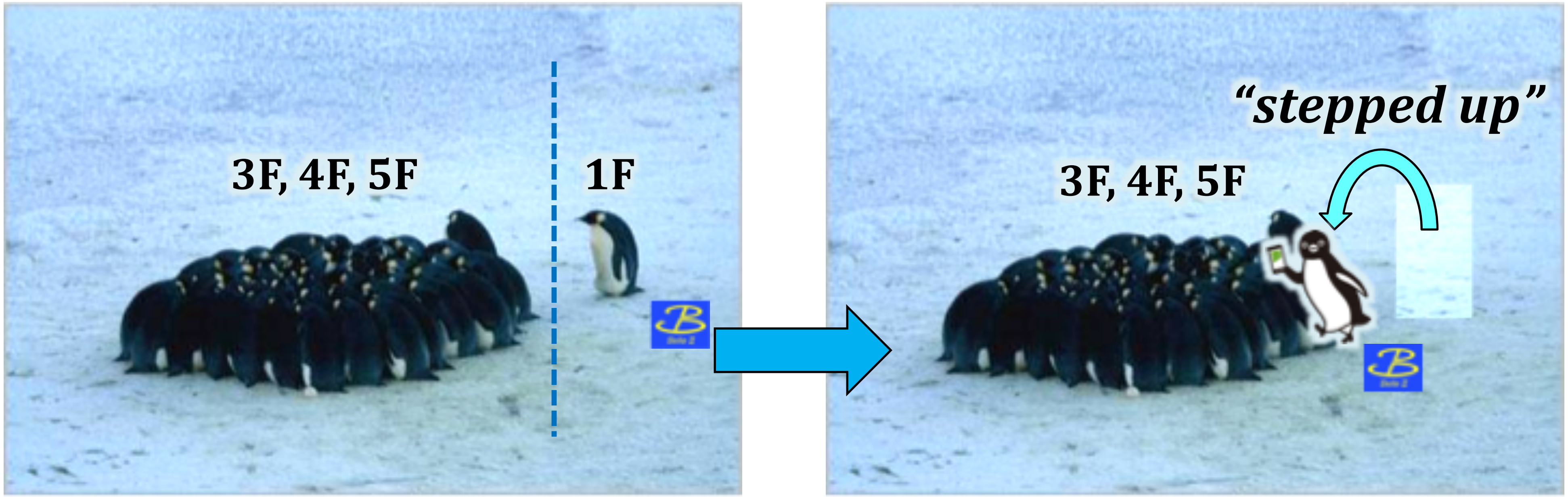


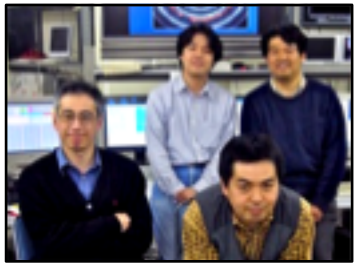
2012 - 2018

We were given the cleanroom on the ground floor of the building for the production of the Belle II vertex detector. We spent most of the six years there.

2019

The work in the cleanroom had been **over** in May 2018, and the vertex detectors had been installed to the experiment in November. We are now working *in our office*.



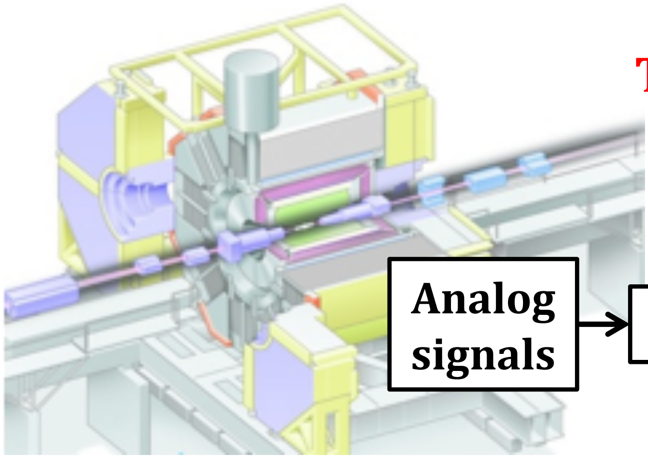


A Few Words on Belle II DAQ

... because DAQ systems are rarely talked about.

TDC LeCroy 1877S

Belle-1 DAQ



up to
500 Hz

Too slow for Belle II

Analog signals → AMPs → Q-to-T converters → Event builder

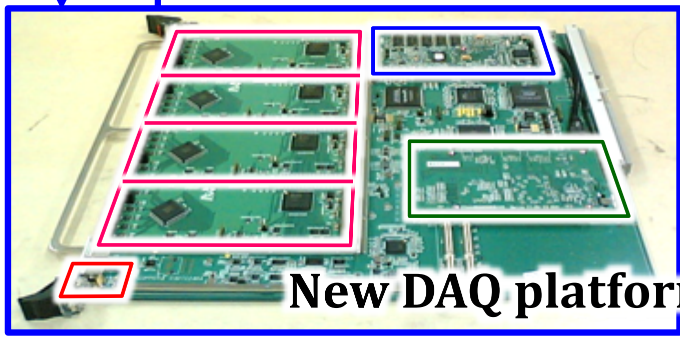
We designed and developed a new DAQ platform that can cope with the Belle II event rate and tested it in the Belle DAQ.

R&D for Belle II DAQ

Common motherboard

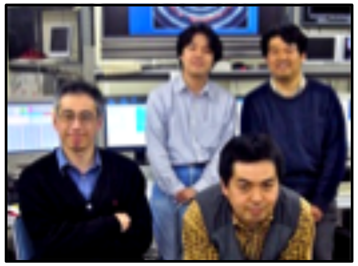
w/ the PCI bus, VME bus, add-on type TDC, homemade CPU

up to
30 kHz



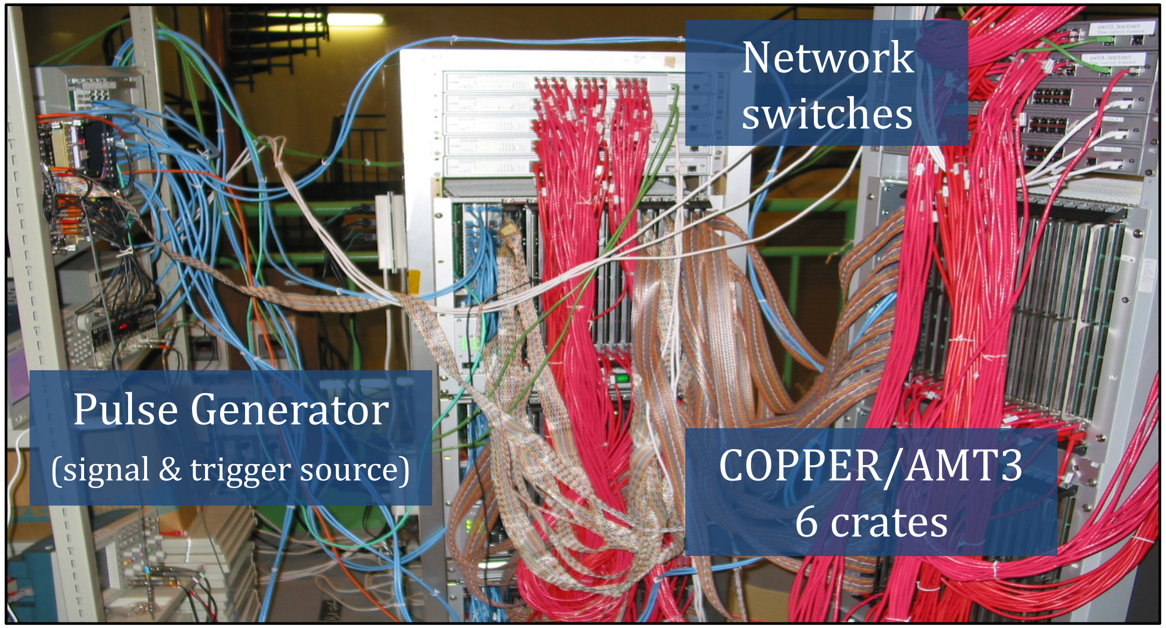
New DAQ platform

Event builder

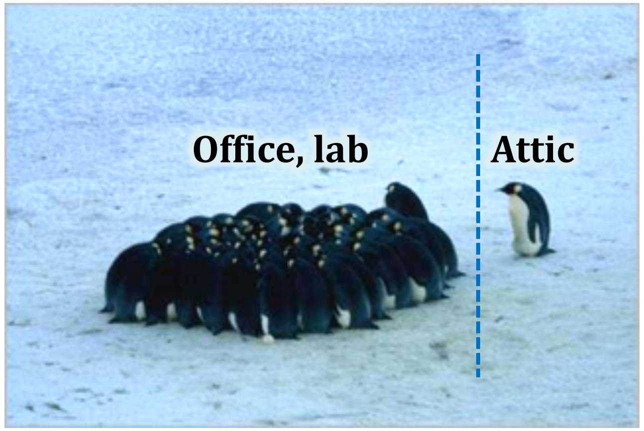


A Few Words on Belle II DAQ

... because DAQ systems are rarely talked about.



A full-scale test bench of the new DAQ system built in a small attic in KEK.

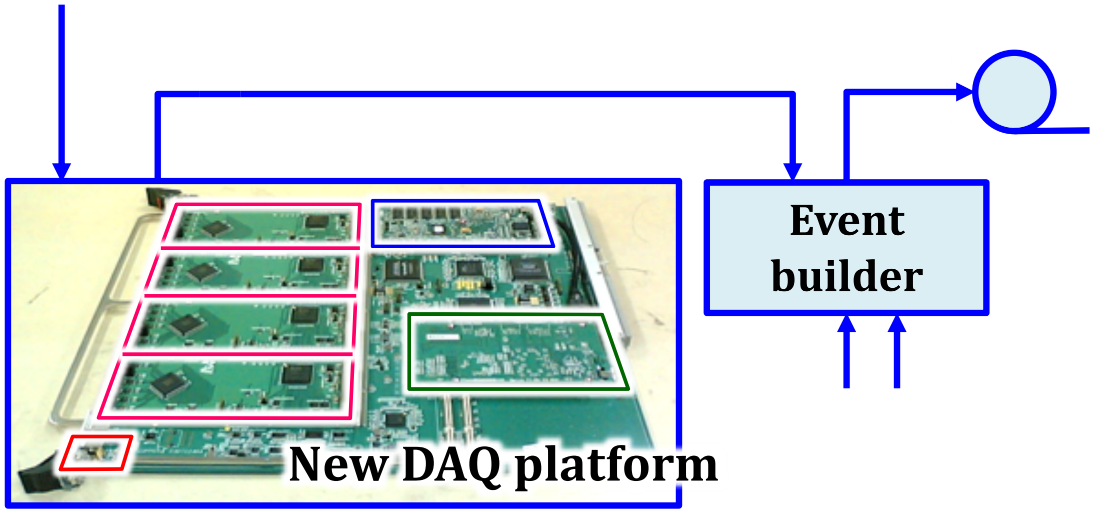


R&D for Belle II DAQ

Common motherboard

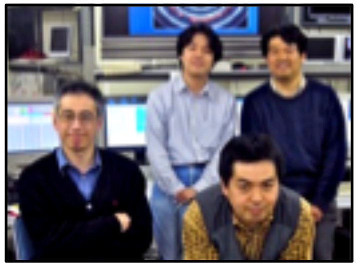
w/ the PCI bus, VME bus, add-on type TDC, homemade CPU

up to 30 kHz



A Few Words on Belle II DAQ

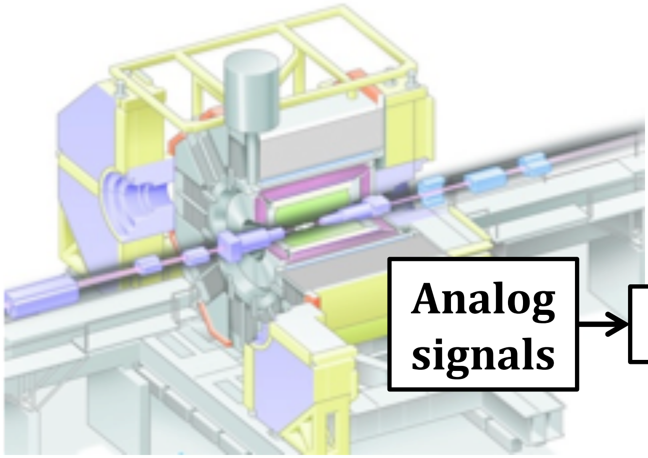
... because DAQ systems are rarely talked about.



Good performance and stability of the new DAQ system were demonstrated in Belle, **adopted as the Belle II DAQ standard.**

Performance study in Belle II (2019)

Belle-1 DAQ



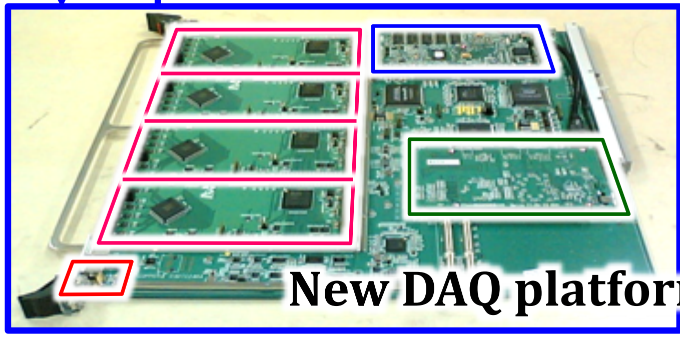
Analog signals → **AMPs** → **Q-to-T converters**

R&D for Belle II DAQ

Common motherboard

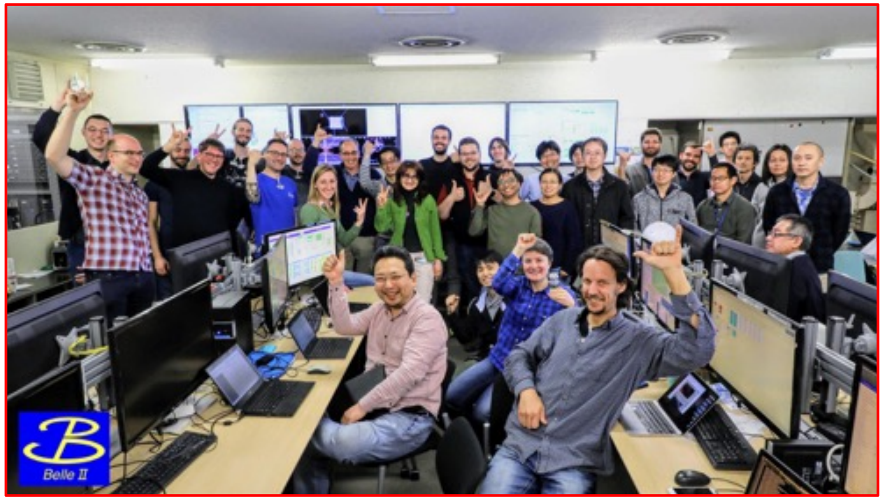
w/ the PCI bus, VME bus, add-on type TDC, homemade CPU

up to 30 kHz

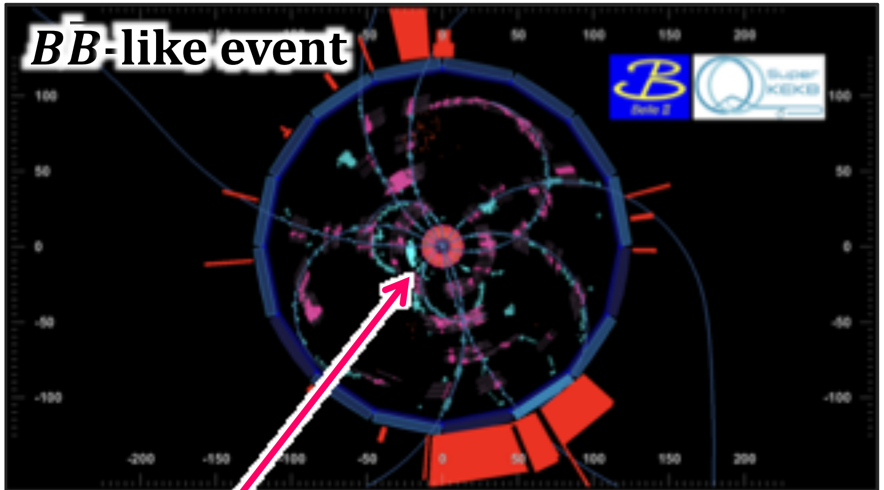


Event builder

Belle II Kick Off (2019/03/11)



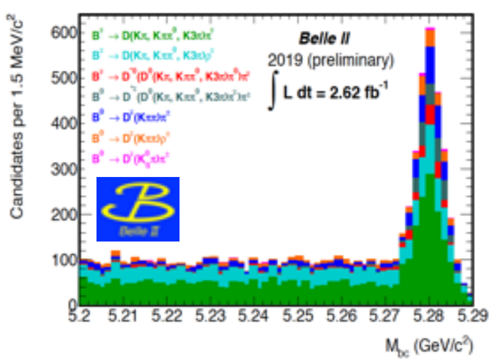
The full data taking had started on 2019/03/11.



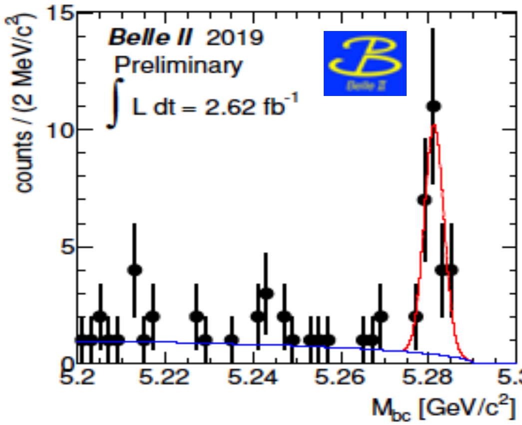
Vertex detectors

Rediscovery of the B meson

Rediscovery of $B^0, B^\pm$



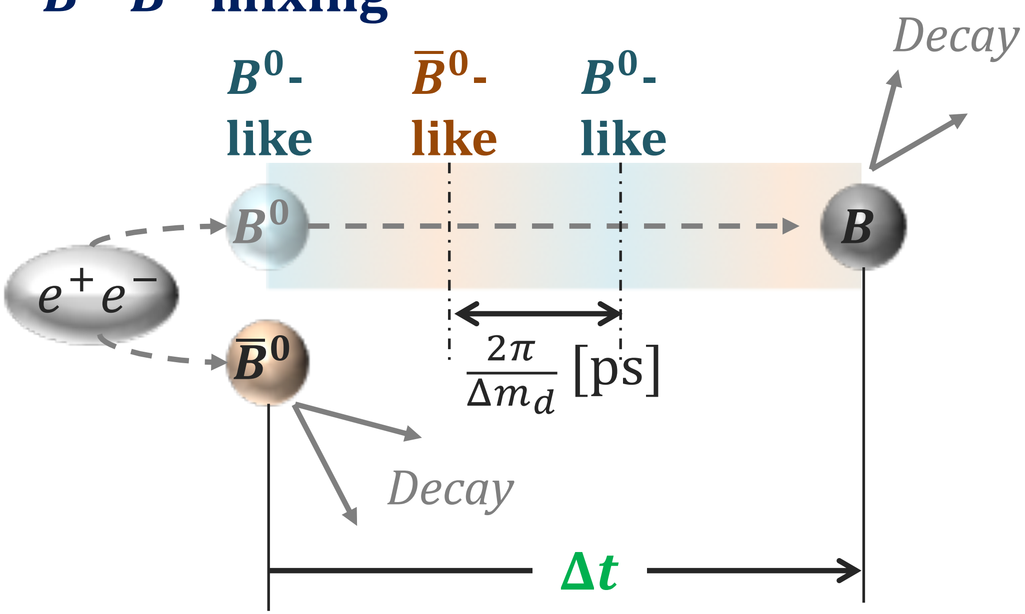
Rediscovery of $B^0 \to J/\psi K_S^0$



Early VXD Performance (2.66fb^{-1})

Rediscovery of the B^0-$\overline{B}^0$ mixing

B^0-$\overline{B}^0$ mixing

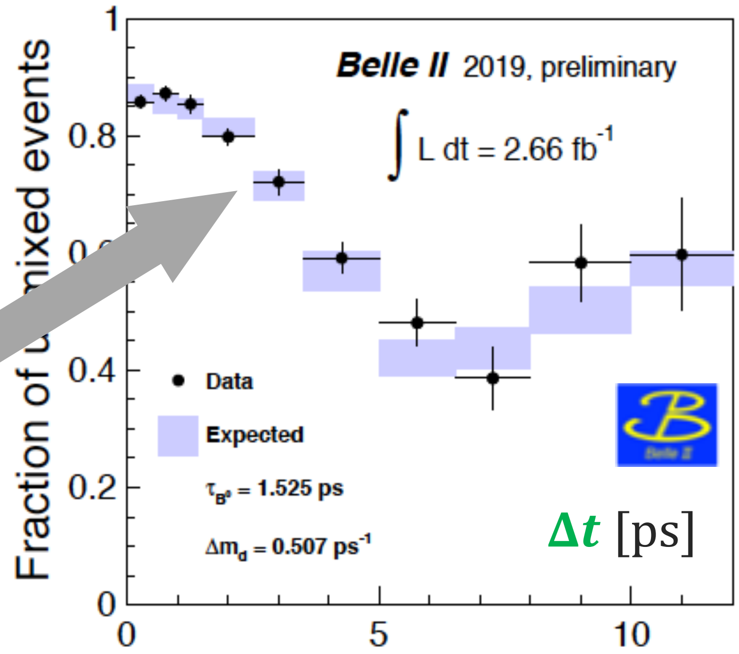


Probability of the B being B^0 or $\overline{B}^0$ oscillates along with the distance of the two B-decay vertices Δt.

$$P(\Delta t) \propto [1 - \cos(\Delta m_d \Delta t)]$$

Belle II has reconstructed event-by-event Δt with the SVD and other detectors and demonstrated the obtained $P(\Delta t)$ distribution was consistent with the expectation.

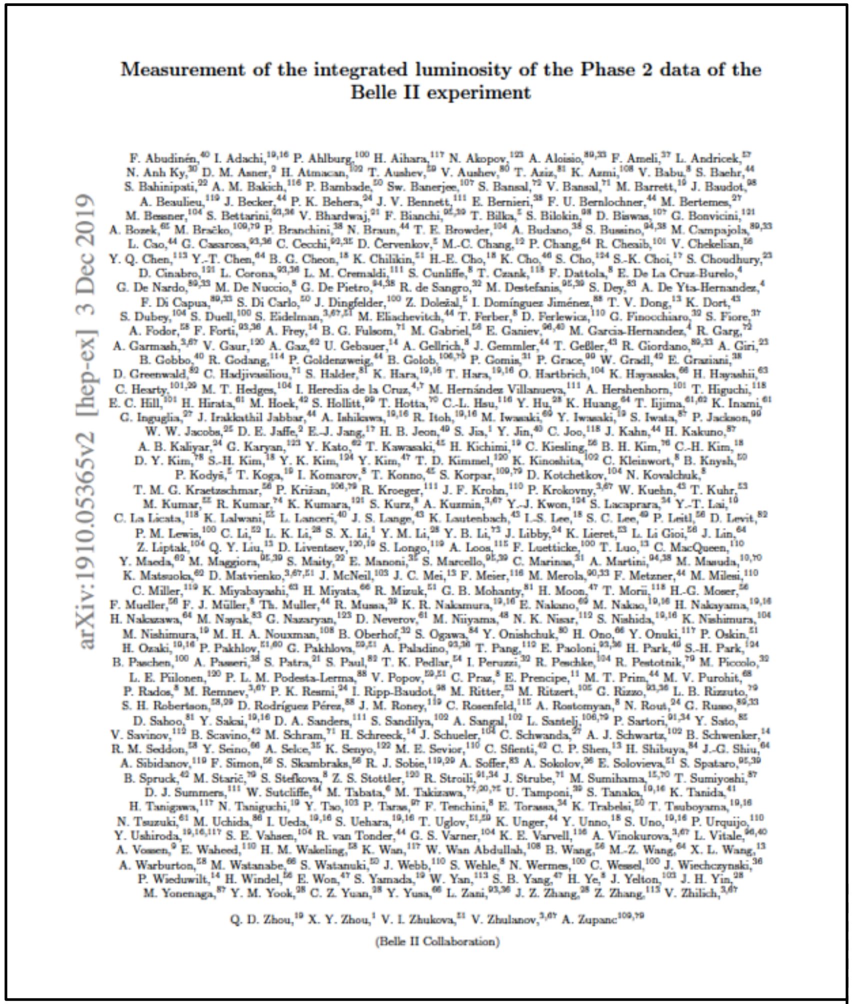
➡ **Demonstration of the good VXD capability of the new *CPV* search**



The First Physics Paper Accepted

F. Ameli *et al*. [Belle II Collaboration], "Measurement of the integrated luminosity of the Phase 2 data of the Belle II experiment," arXiv:1910.05365.

Accepted on 2019/12/03; to appear in Chin. Phys. C.

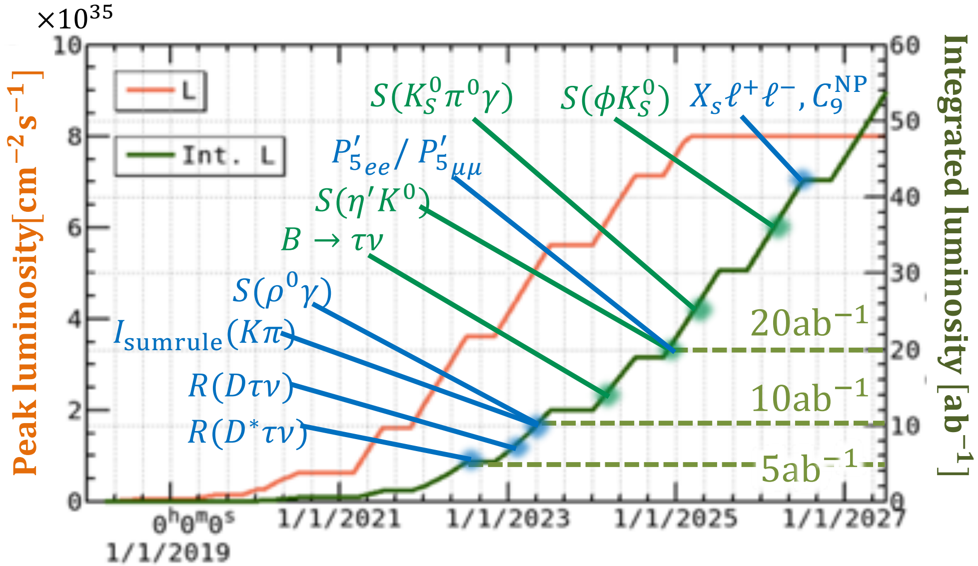



```
Reviewer(s)' Comments to Author:

Reviewer: 1
Comments to the Author
Thanks for taking my suggestions. I have no further comments.
Congratulations for the nice work, and (perhaps?) the first BelleII paper!
```

Future Prospect

Integrated luminosity upgrade



5σ (observation)

3σ (evidence)

$1\mathrm{ab}^{-1}$	Size of the Belle dataset
$5\mathrm{ab}^{-1}$	Middle of 2022
$10\mathrm{ab}^{-1}$	Middle of 2023
$20\mathrm{ab}^{-1}$	2024 – 2025
$50\mathrm{ab}^{-1}$	2026 – 2027

$50\ \mathrm{ab}^{-1}$ by 2027

Belle II upgrade

DAQ upgrade – decided	- 2021
Detector upgrade to accommodate with higher beam background than expected – under the design	In 4~6 years from now
Accelerator and detector upgrade aiming at $L = 400\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ – to be discussed	After the intermediate upgrade

New Physics Search at Belle II

Discovery of the new physics up to 10+ TeV

❶ Origin of the *CP* violation of the Universe ☜ **at IPMU**

Experimental searches for new *CP* violation in B/τ decays

❷ Nature of dark matter ☜ **at IPMU**

Experimental searches for dark-sector particles

❸ Structure of the interactions among the new particles

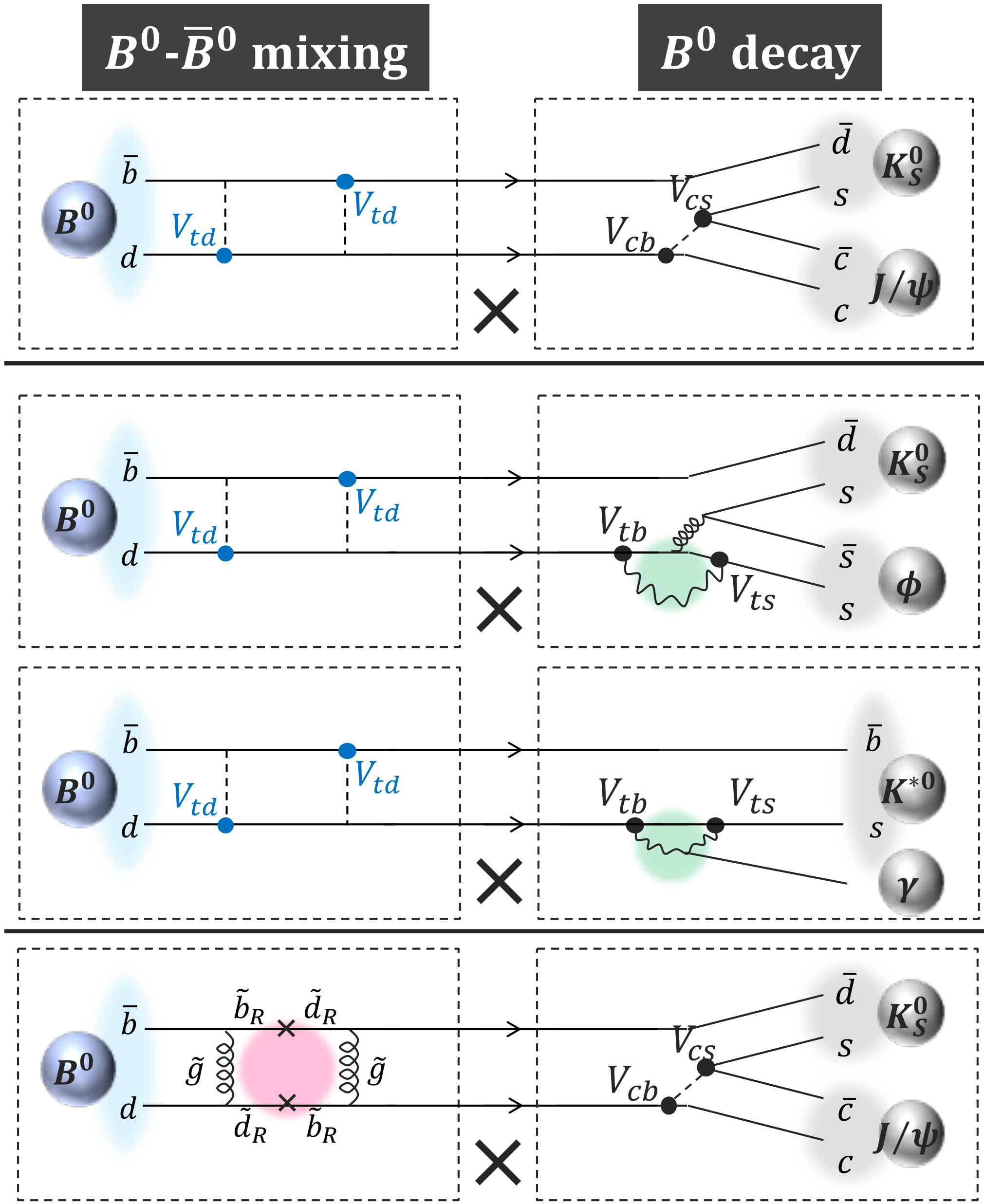
Experimental detections of new particles and interactions

Measure **as many observables as possible** and test the compatibility with the Standard Model predictions. $\underbrace{S_{\mathrm{obs}}}_{\text{Experimental observable(s)}} - \underbrace{S_{\mathrm{SM}}}_{\text{Standard Model prediction(s)}} \equiv \delta S \neq 0$?

500+ papers from Belle

1. $\delta S \neq 0 \Rightarrow$ discovery of the **new physics**
2. Develop the list of mode-by-mode $\delta S \rightarrow$ elucidate the model of the new physics

❶ Search for New CPV



$b \to c\bar{c}s$ ($B^0 \to J/\psi K^0$ …)

- Used to test the KM theory by measuring the arg$[(V_{td})^2]$

$b \to sq\bar{q}$ ($B^0 \to \phi K^0$ …)

$b \to s\gamma$ ($B^0 \to K^{*0}\gamma$ …)

- Will detect a new physics to appear in the B-decay loop by the quantum effect
- Was also studied in Belle

In addition to the **loop decay**, precise study on the **tree decay** is also important in Belle II.

$b \to c\bar{c}s$ ($B^0 \to J/\psi K^0$ …) [precision]

- Will detect a new physics to appear in the B^0-$\bar{B}^0$ mixing loop

❶ Search for New CPV

New physics in the B^0-$\bar{B}^0$ mixing

$|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$
$|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$

New CPV phase in p and q beyond the KM theory?

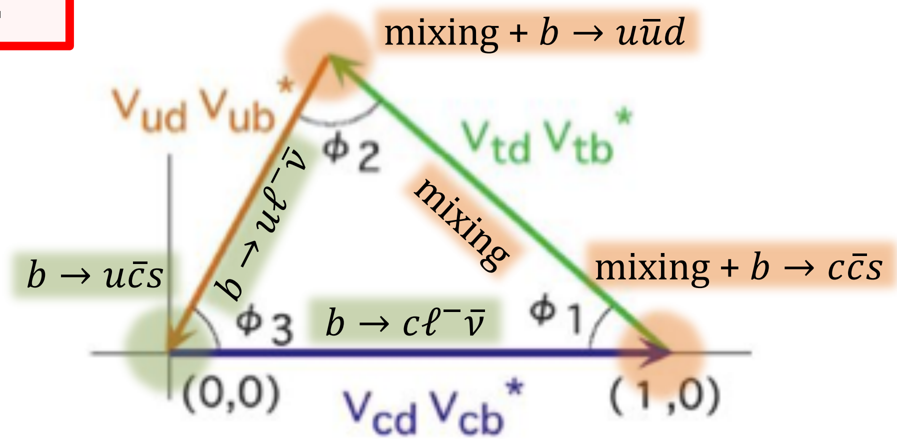
A new physics in the **10+ TeV region** can be explored by combining the precise studies on the B^0-$\bar{B}^0$ mixing.

Precise measurement of the B-meson CPV

➡ Precise measurement of the triangle

(the critical ambiguities are in the ϕ_3 and V_{ub})

Unitarity triangle



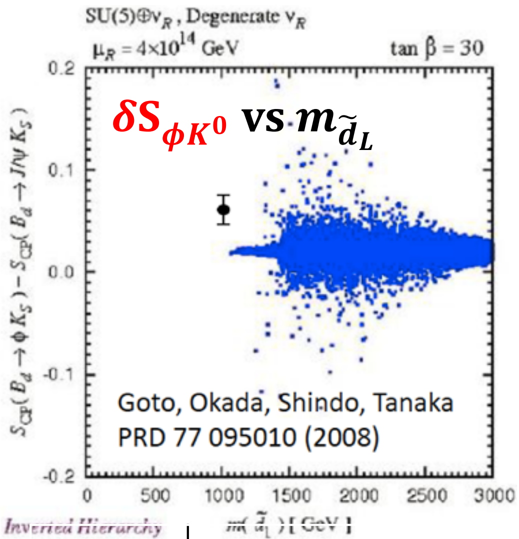
- Precise measurements of the **ϕ_1 in ($B^0 \to \psi(2S)K_S^0$)** and **ϕ_2 in ($B^0 \to \pi^+\pi^-$)** are ongoing at IPMU.
- We are working hard aiming at the publication of the first measurement in the next winter conference.

❶ Search for New CPV

New physics in the B^0 decay

$b \to sq\bar{q}$

$B^0 \to \phi K^0, \eta' K_S^0, 3K_S^0, \pi^0 K_S^0, \rho^0 K_S^0$ etc



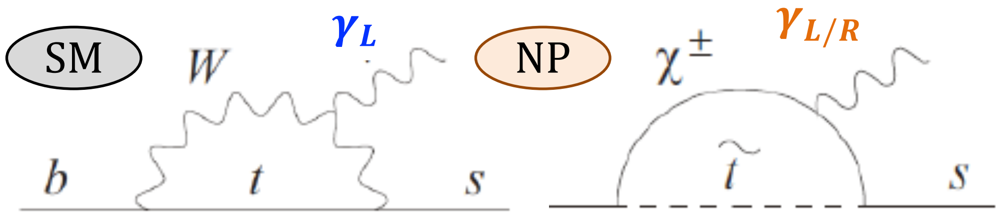
For example, the $\delta S_{\phi K^0}$ gives a constraint to the mass of a SUSY particle.

	Experiment	SM prediction
$\Delta S_{\phi K^0}$	$-0.06^{+0.11}_{-0.13}$	$[0.01, 0.05]$

	5ab^{-1}	50ab^{-1}
$\sigma(\Delta S)$	0.048	0.020

$b \to s\gamma$

$B^0 \to K_S^0 \pi^0 \gamma, \rho^0 \gamma$ etc



The effective CP-violating parameters in the $b \to s\gamma$ and $d\gamma$ decays are small because they are not the real CP eigenstate → the decays are sensitive to the right-handed NP.

	Experiment	SM prediction
$S_{K_S^0 \pi^0 \gamma}$	-0.16 ± 0.22	$(2.3 \pm 1.6)\%$

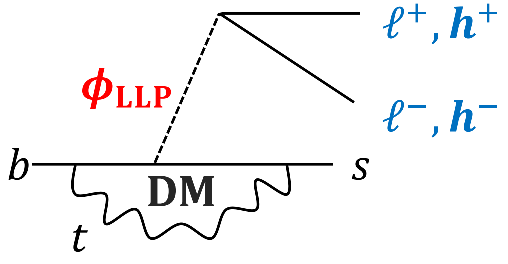
	5ab^{-1}	50ab^{-1}
$\sigma(\Delta S)$	0.10	0.031

E. Kou *et al.*, arXiv:1808.10567 (2018).

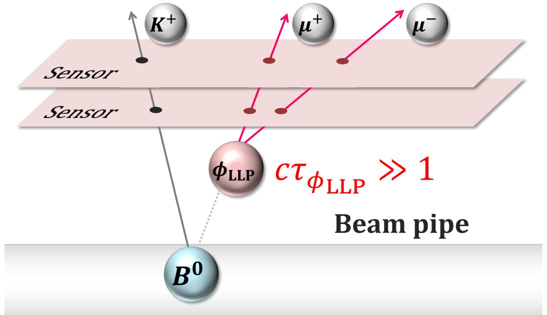
❷ Searches for Dark Matter

Search for ϕ_{LLP}

- The mediator ϕ_{LLP} mediates the interactions between **light DM** and the **SM particles**.
- Because the interaction $\phi_{\mathrm{LLP}} \Leftrightarrow$ **SM** is weak, the ϕ_{LLP} lifetime tends to be long.



$B \to \phi_{LLP}(\mu^+\mu^-, h^+h^-)K$

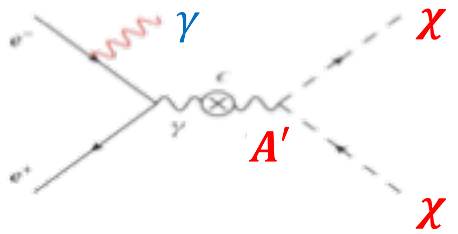


$R_{\mathrm{B2\ SVD}} = \mathbf{135mm}$
Good for the ϕ_{LLP} search

Sensitivity:

$0.2 < m_{\phi_{\mathrm{LLP}}} < 4.5\mathrm{GeV}/c^2$,
$0.01 < c\tau_{\phi_{\mathrm{LLP}}} < 1\mathrm{m}$

Direct search for light DM

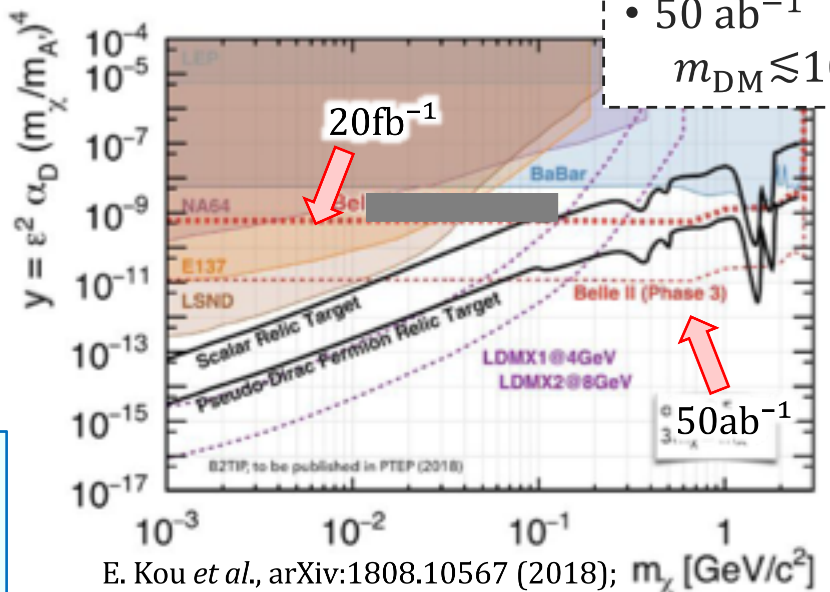


A' ... Dark photon
χ ... DM

$e^+e^- \to \gamma + $ **nothing**

Direct search for the $e^+e^- \to \gamma\chi\chi$ event became possible at Belle II thanks to new implementation of a single photon trigger.

- 20 fb^{-1}
  $m_{\mathrm{DM}} \lesssim 100\ \mathrm{MeV}/c^2$
- 50 ab^{-1}
  $m_{\mathrm{DM}} \lesssim 10\ \mathrm{MeV}/c^2$

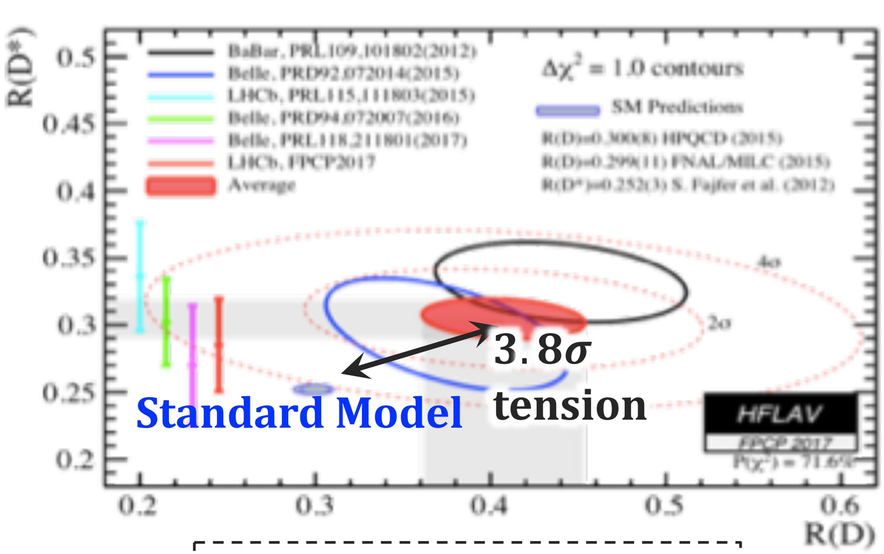


E. Kou *et al.*, arXiv:1808.10567 (2018);
E. Izaguirre *et al.*, PRL **115**, 251301 (2015).

Lepton Universality Violation

$b \to c\ell\nu$ LUV

$$R_{D^{(*)}} \equiv \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\mu\nu)}$$

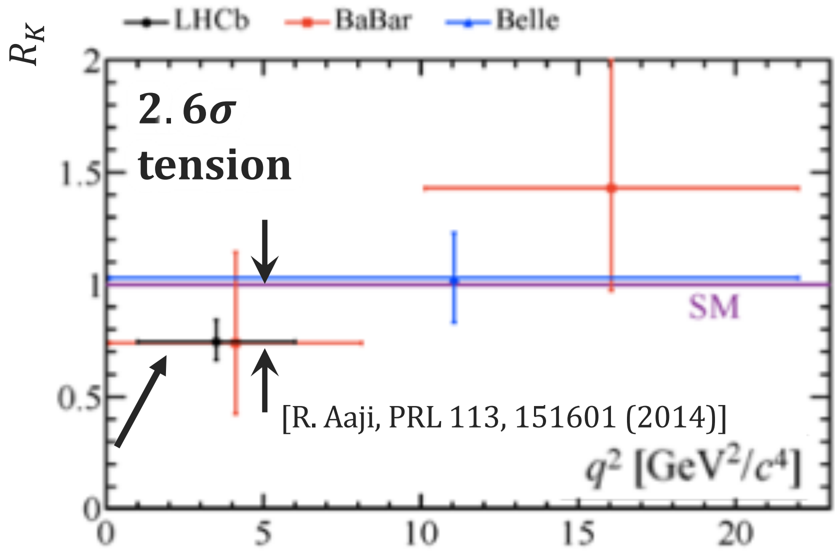


Sensitive to $H^{\pm}$ and LQ

- Conclude the new physics in $5\mathrm{ab}^{-1}$ data
- Determine the polarization P_τ in $50\mathrm{ab}^{-1}$ data
- Identify the new physics model from $R(D^{(*)})$ and P_τ

$b \to s\ell\ell$ LUV

$$R_{K^{(*)}} \equiv \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)}$$

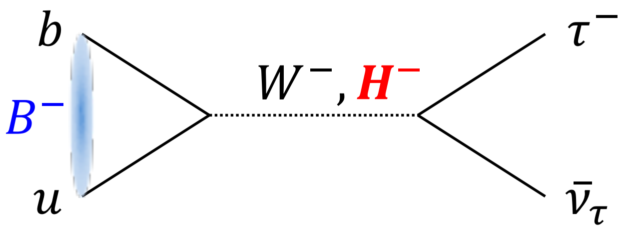


Sensitive to LQ and Z'

- Conclude the new physics in $10\mathrm{ab}^{-1}$ data and decide the next physics parameters to study on

Measurement of $\mathrm{Br}(B^+ \to \tau^+ \nu_\tau)$

$\mathrm{Br}(B^+ \to \tau^+ \nu_\tau)$



$$r_H = \frac{\mathrm{Br}(B \to \tau\nu_\tau)}{\mathrm{Br}(B \to \tau\nu_\tau)_{\mathrm{SM}}} = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

The mode is sensitive to the charged Higgs effect.

SM predictions

ℓ	$\mathrm{Br}_{\mathrm{SM}}$
τ	$(7.71 \pm 0.62)\times 10^{-5}$
μ	$(3.46 \pm 0.28)\times 10^{-7}$
e	$(0.811 \pm 0.065)\times 10^{-11}$

Measurements of the Br at Belle

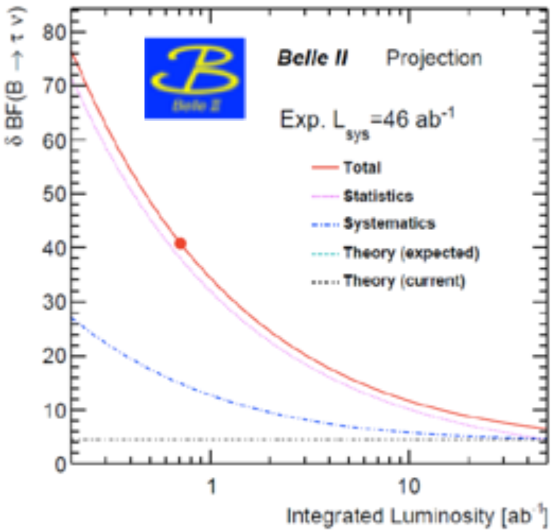
$$\mathrm{Br}(B^- \to \tau^- \bar{\nu}_\tau) = \left(0.72^{+0.27}_{-0.25} \pm 0.11\right)\times 10^{-4}$$

Phys. Rev. Lett. **110**, 131801 (2013)

$$\mathrm{Br}\left(B^- \to \mu^- \bar{\nu}_\mu\right) = (6.46 \pm 2.22 \pm 1.60)\times 10^{-7}$$

Phys. Rev. Lett. **112**, 031801 (2018)

Prospect on $\delta(\mathrm{Br})$ at Belle II



ℓ	$5\mathrm{ab}^{-1}$	$50\mathrm{ab}^{-1}$
τ	9%	4%
μ	20%	7%

Lepton Flavor Violation

	σ [nb]
$\Upsilon(4S)$	1.08
$\tau^+\tau^-$	0.91

B factory = τ factory

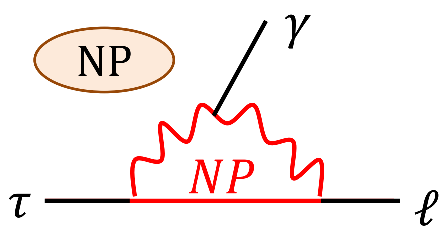
LFV decay in the SM

- The SM forbids the LFV decay to the level Br $< 10^{-40}$ even the neutrino mixing is taken into account.

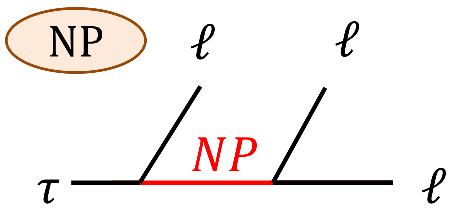
	Reference	$\tau \to \mu\gamma$
SM+ ν mixing	EPJ C8(1999)513	10^{-40}
SM + heavy Maj ν_R	PRD 66(2002)034008	10^{-9}
Non-universal Z'	PLB 547(2002)252	10^{-9}
SUSY SO(10)	PRD 68(2003)033012	10^{-8}
mSUGRA+seesaw	PRD 66(2002)115013	10^{-7}
SUSY Higgs	PLB 566(2003)217	10^{-10}

NP effect on the LFV decay

- The LFV decay can be enhanced to the level Br $\sim 10^{-9}$ in some NP scenarios.

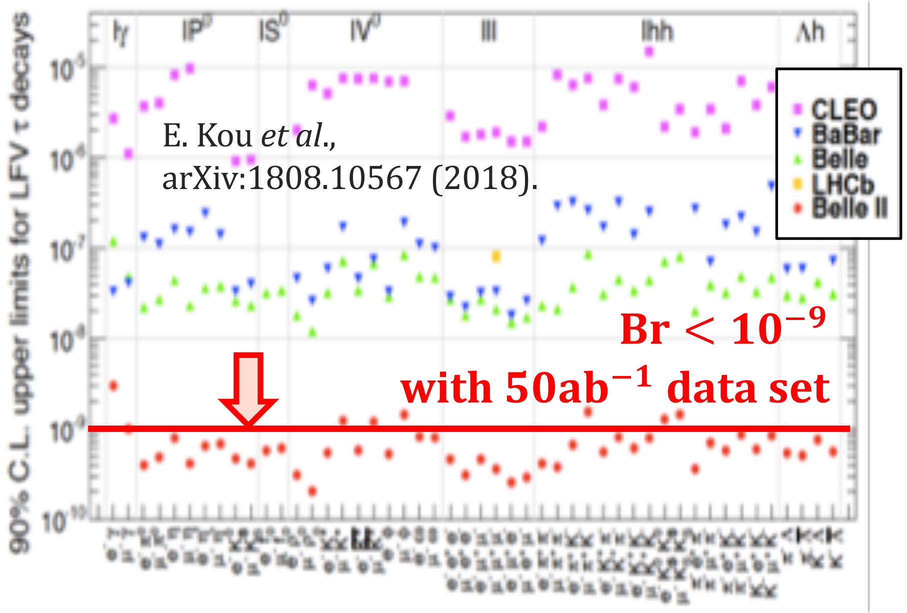


$\boldsymbol{\tau \to \ell\gamma}$



$\boldsymbol{\tau \to \ell\ell\ell}$

- The LFV τ decays with the Br level 10^{-9} can be detected with **50ab^{-1} Belle II data**.



τ-decay modes measurable at Belle II

Summary

- In quest of a new physics beyond the Standard Model, we had kicked off the Belle II experiment this March.

- We have confirmed nice performance of SuperKEKB and Belle II.

- We will bring up hot results from Belle II pretty soon.