

Status of the Belle II experiment and ML applications to the particle physics experiments

2022/3/24

M. Iwasaki

Osaka-City U., Osaka-City U. NITEP,
Osaka U., RCNP, Osaka U., IDS



Contents

1. Belle II experiment

1-1 Introduction

1-2 Operation status + recent results on CKM

2. Application of ML to the Collider Exp.s

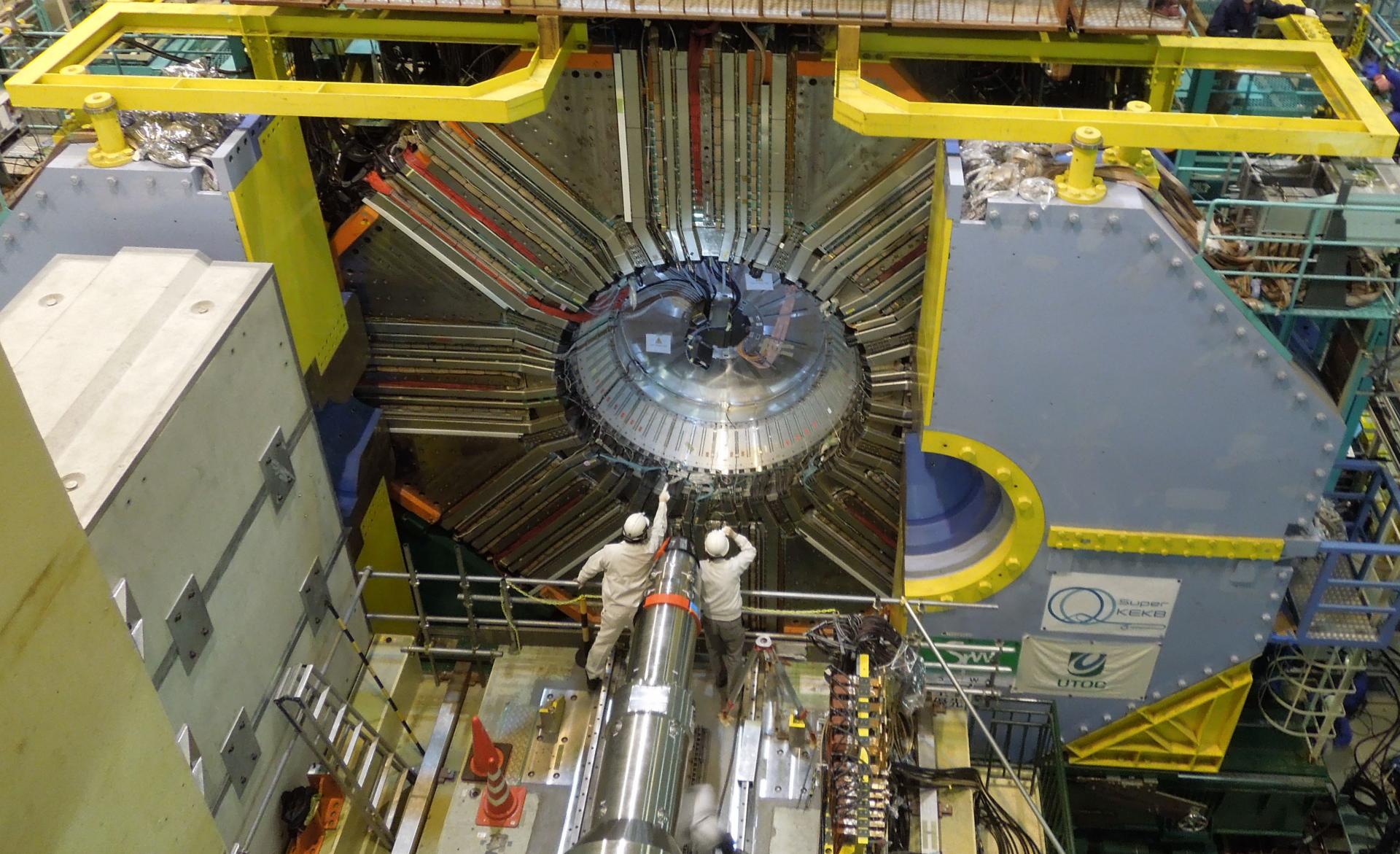
2-1 Accelerator tuning using ML

2-2 DNN with low-level data

2-3 Data reduction based on the sparse sampling

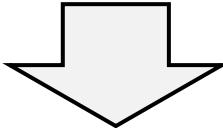
Skip if time is short

1. *Belle II experiment*



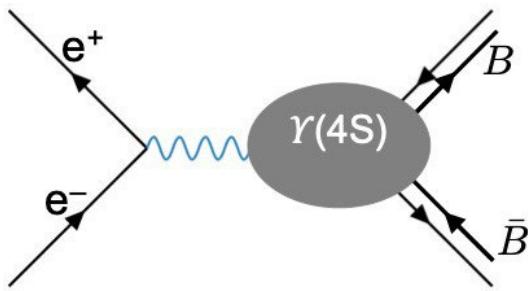
1-1: Introduction

The SuperKEKB / Belle II experiment

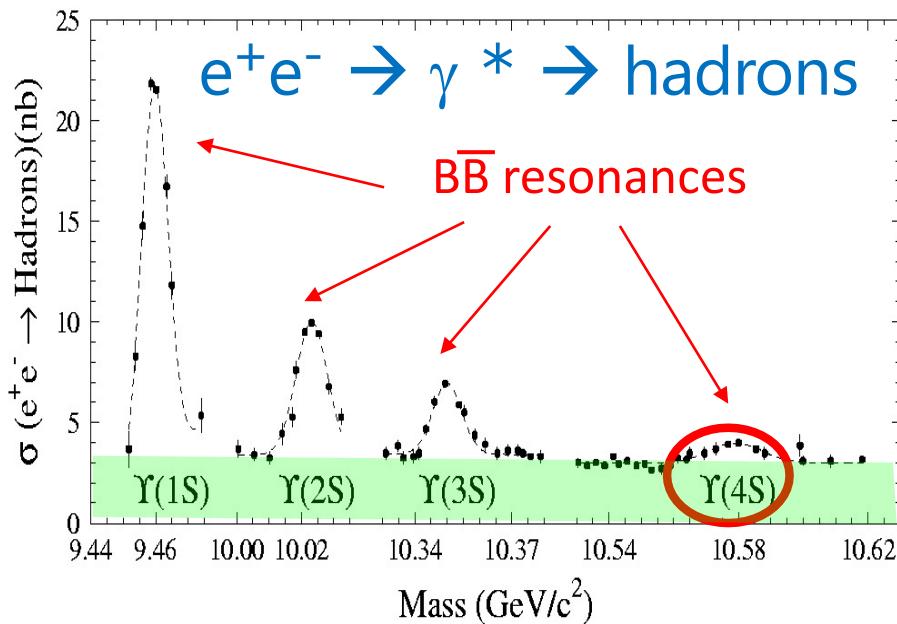


Upgrade of the KEKB / Belle
B-factory experiment in Japan

Produces huge amount of $B\bar{B}$ mesons pairs on the $\Upsilon(4S)$ resonance

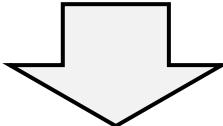


$$\sqrt{s} = 10.58 \text{ GeV}$$



1-1: Introduction

The SuperKEKB / Belle II experiment



Upgrade of the KEKB / Belle
B-factory experiment in Japan

Produces huge amount of $B\bar{B}$ mesons pairs on the $\Upsilon(4s)$ resonance

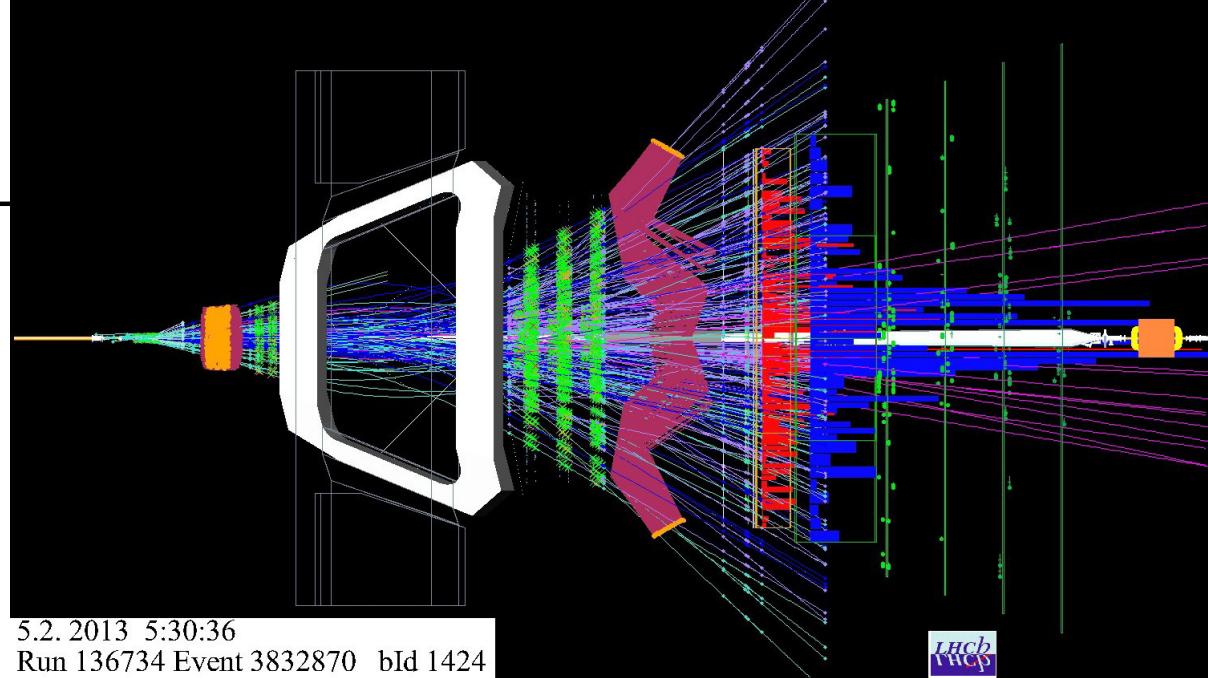
“Luminosity frontier experiment”

*Low energy experiment indirectly probing
high energy using high statistics data*

Production of B Mesons

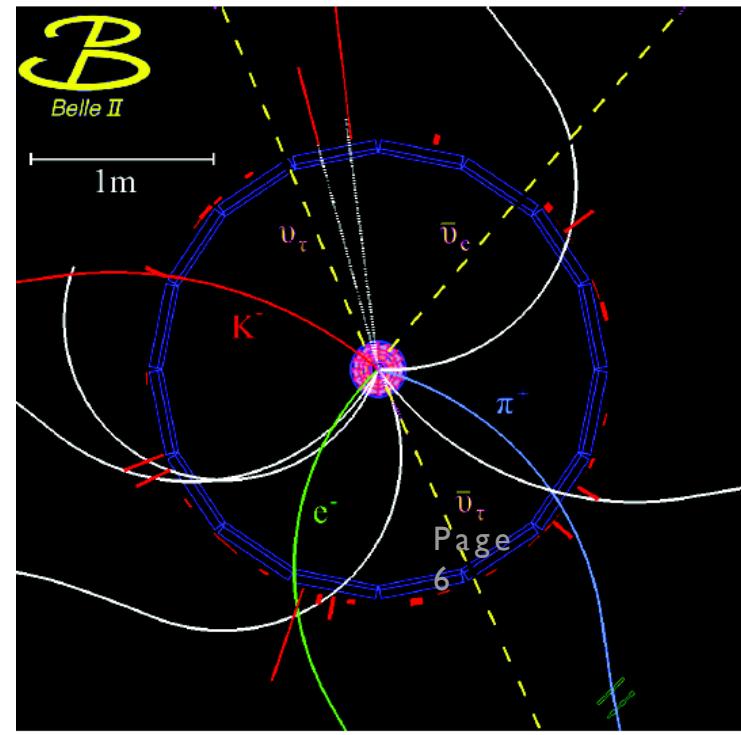
Hadron collider:

- Production of b hadrons in strong interaction
- Vertexing



B factory:

- $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$
- Known properties of events and B mesons
- Unique opportunities

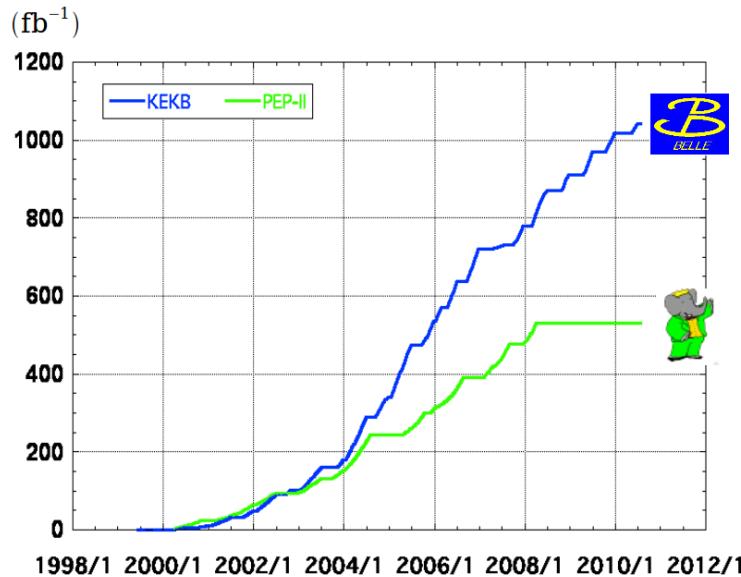


(Past)B-factory in KEK Japan

In 1999 – 2010, KEKB/Belle accumulated
~800 million BB pairs, and

observe the CP violation in the B meson sector

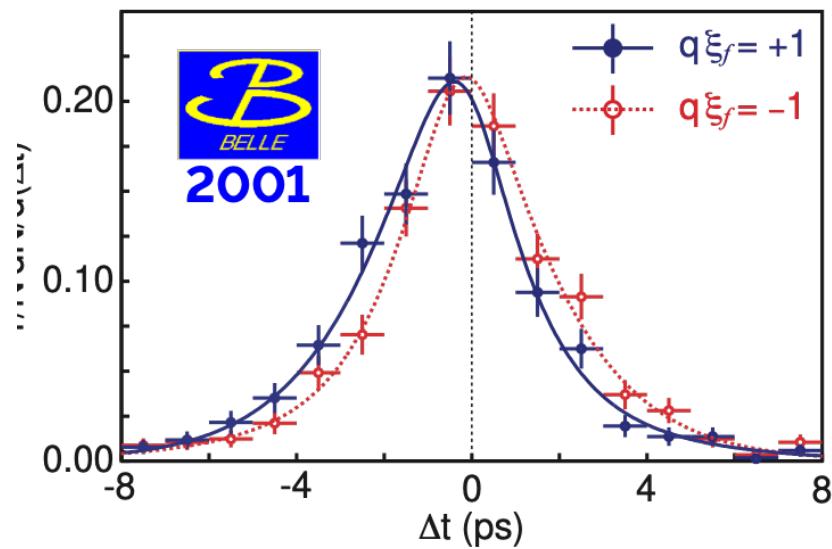
Integrated luminosity of B factories



$> 1 \text{ ab}^{-1}$
On resonance:
 $\Upsilon(5S): 121 \text{ fb}^{-1}$
 $\Upsilon(4S): 711 \text{ fb}^{-1}$
 $\Upsilon(3S): 3 \text{ fb}^{-1}$
 $\Upsilon(2S): 25 \text{ fb}^{-1}$
 $\Upsilon(1S): 6 \text{ fb}^{-1}$

Off resonance./scan:
 $\sim 100 \text{ fb}^{-1}$

$\sim 550 \text{ fb}^{-1}$
On resonance:
 $\Upsilon(4S): 433 \text{ fb}^{-1}$
 $\Upsilon(3S): 30 \text{ fb}^{-1}$
 $\Upsilon(2S): 14 \text{ fb}^{-1}$
Off resonance:
 $\sim 54 \text{ fb}^{-1}$



→Confirm the prediction of the Kobayashi-Maskawa theory

SuperKEKB project

The observed CP violation is too small to explain the number of surviving matter particles in the current universe

→ It is important to search for the new laws of physics
(= hidden laws of physics in the early universe)

*KEKB has been upgraded to SuperKEKB
for more precise experiment to probe the early universe*

Design luminosity of the SuperKEKB accelerator

x30 of the KEKB's world record

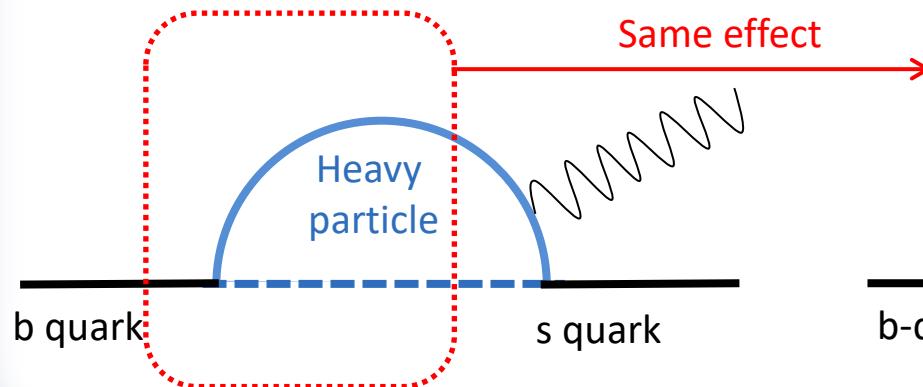
to accumulate high statistics of 50ab^{-1} data

→ *Probe > O(TeV) energy scale*

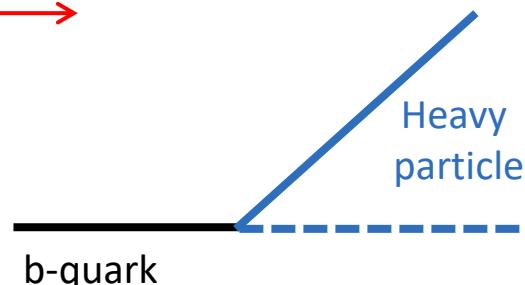
SuperKEKB/Belle II Experiment

Low energy experiment indirectly probing the higher energy based on the high statistics data

SuperKEKB (Luminosity Frontier)



Energy Frontier Experiment

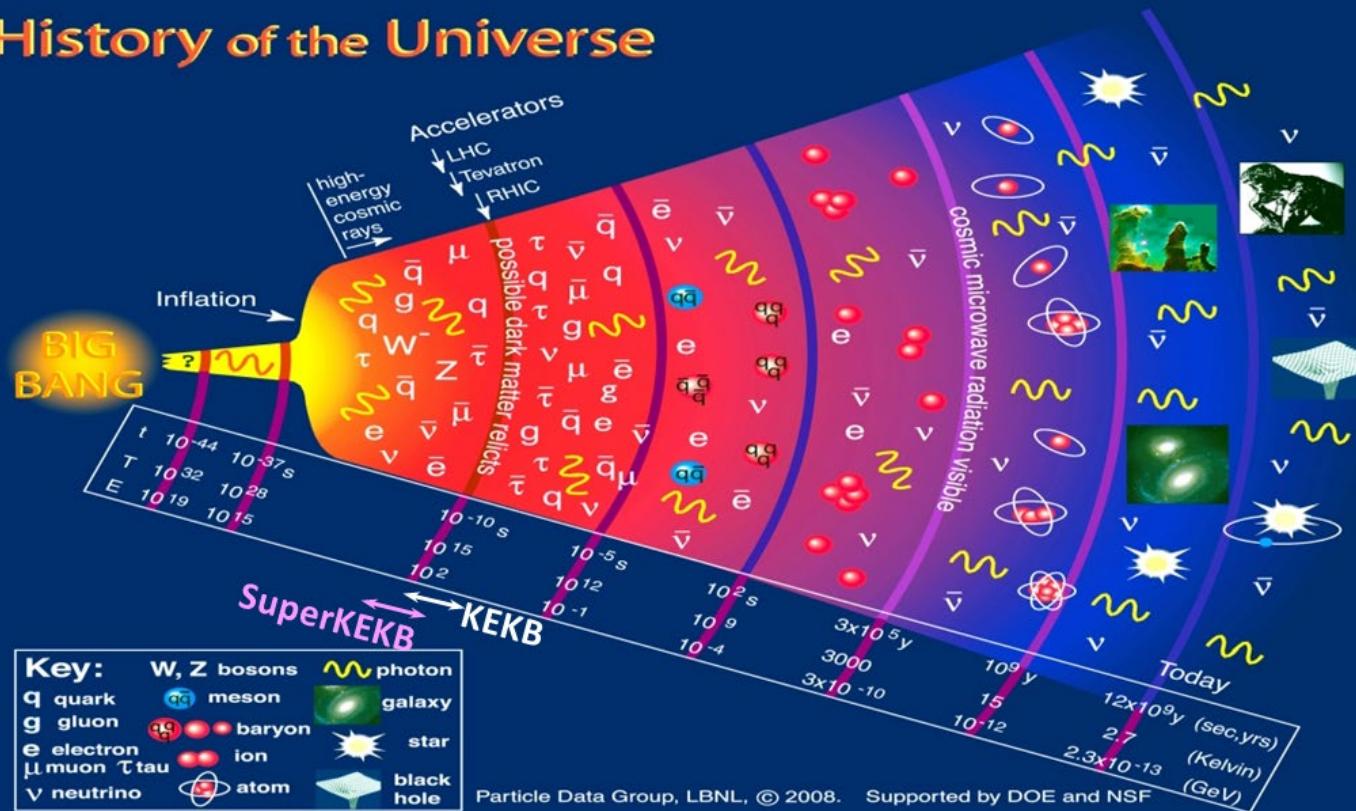


Key of SuperKEKB → “High statistics data”

SuperKEKB/Belle II Experiment

Low energy experiment indirectly probing the higher energy based on the high statistics data

History of the Universe



Key of SuperKEKB → “High statistics data”

Strategies for increasing Luminosity

Three Key factors for a factor of ~30 gain

Beam-beam parameter

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

Annotations for the Beam-beam parameter equation:

- Lorentz factor
- Beam current
- Classical electron radius
- Beam size ratio@IP
1 ~ 2 % (flat beam)
- Vertical beta function @ IP
- Lumi. reduction factor
(crossing angle)&
Tune shift reduction factor
(hour glass effect)
0.8 ~ 1
(short bunch)

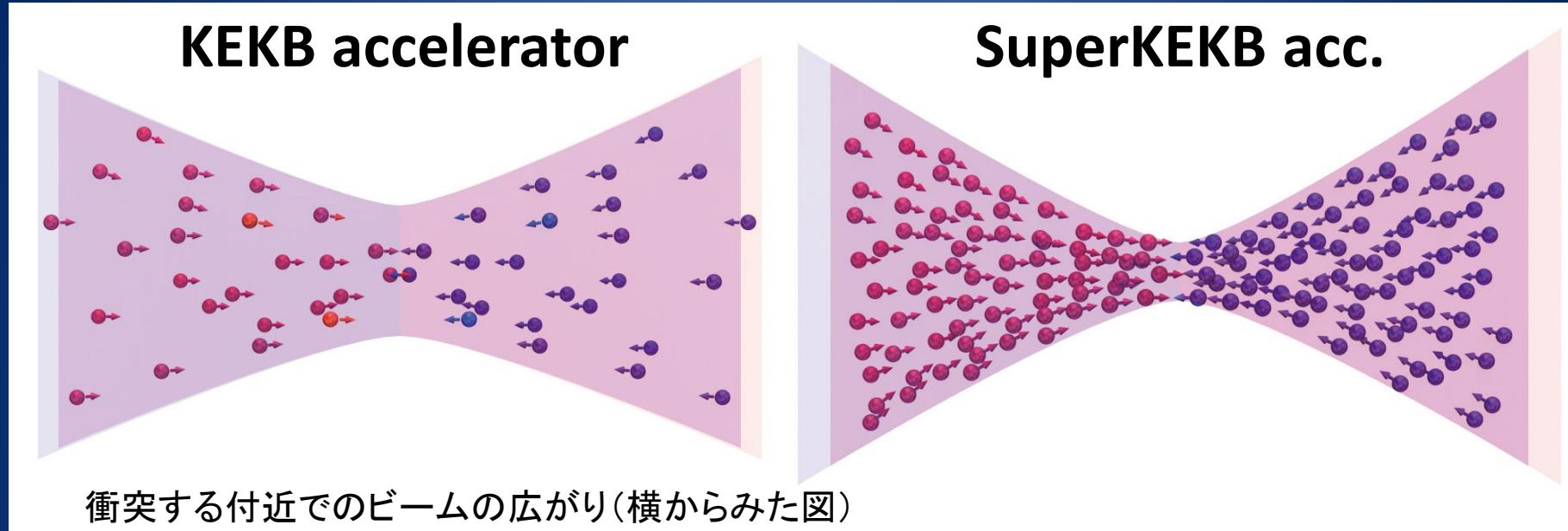
- (1) Smaller β_y^***
- (2) Increase beam currents**
- (3) Increase ξ_y**

“Nano-Beam” scheme

First proposed by P.Raimondi for SuperB

Collision with very small spot-size beams

Strategies for increasing Luminosity



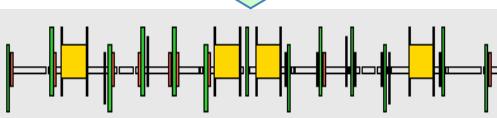
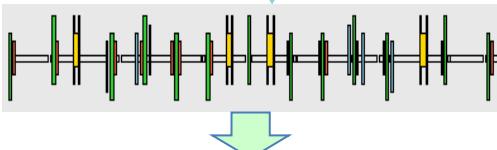
1/20 Beam size x 1.5 beam current
→ 30 times higher Luminosity

To get the higher luminosity,
KEKB was upgraded to SuperKEKB

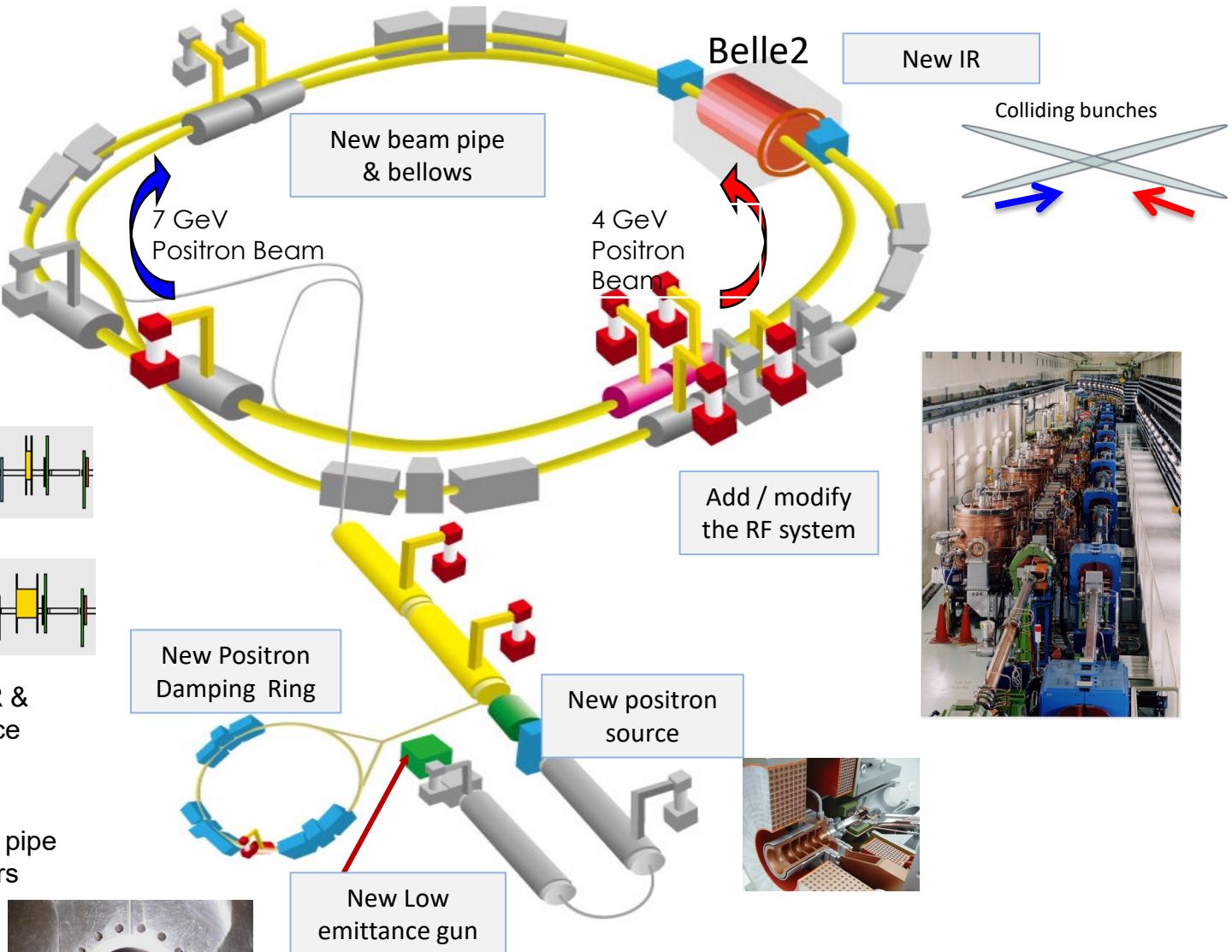
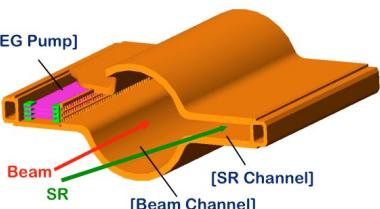
KEKB to SuperKEKB How to upgrade



Replace short dipoles with longer ones (LER)

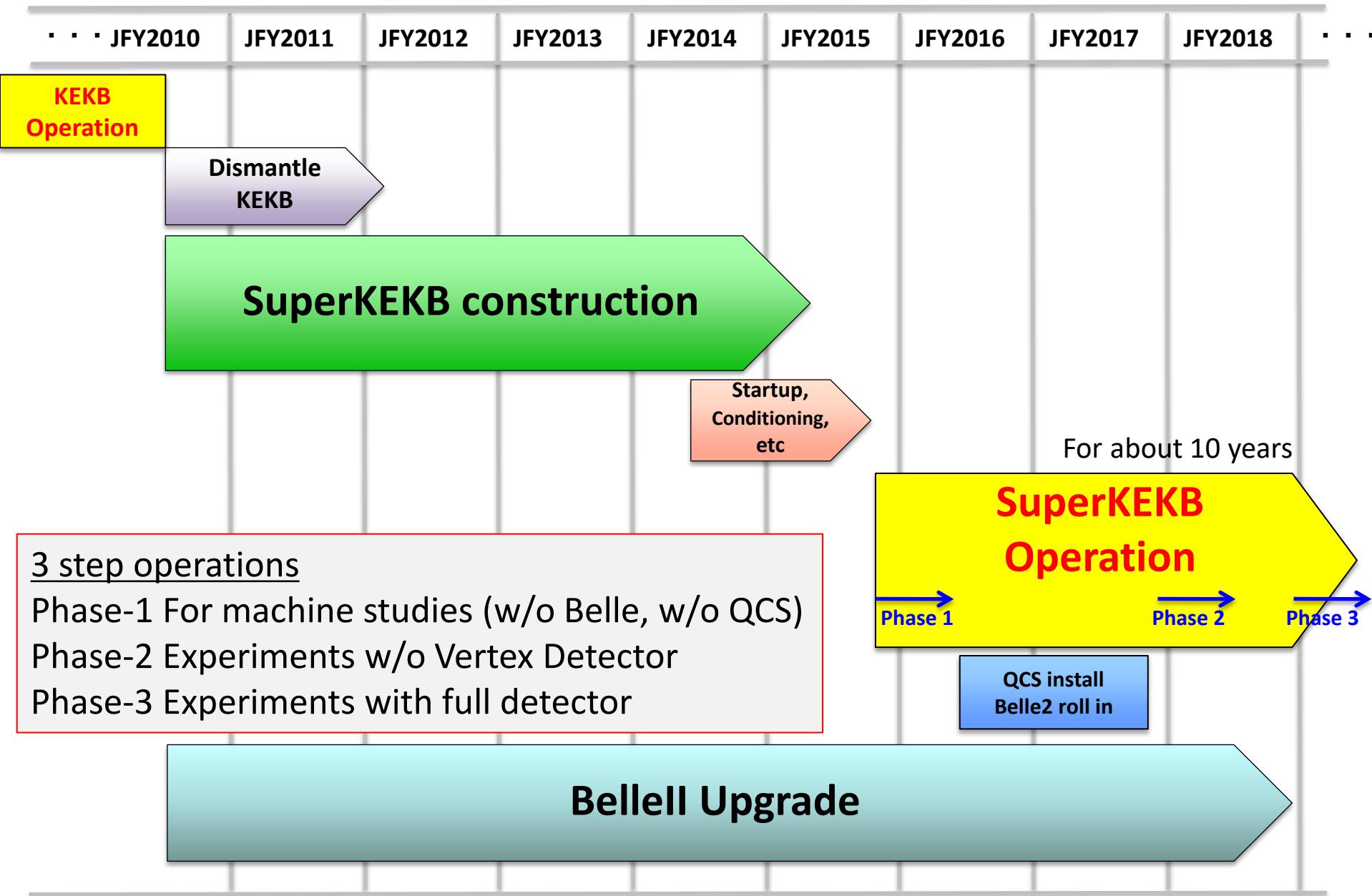


Redesign the lattices of HER & LER to squeeze the emittance

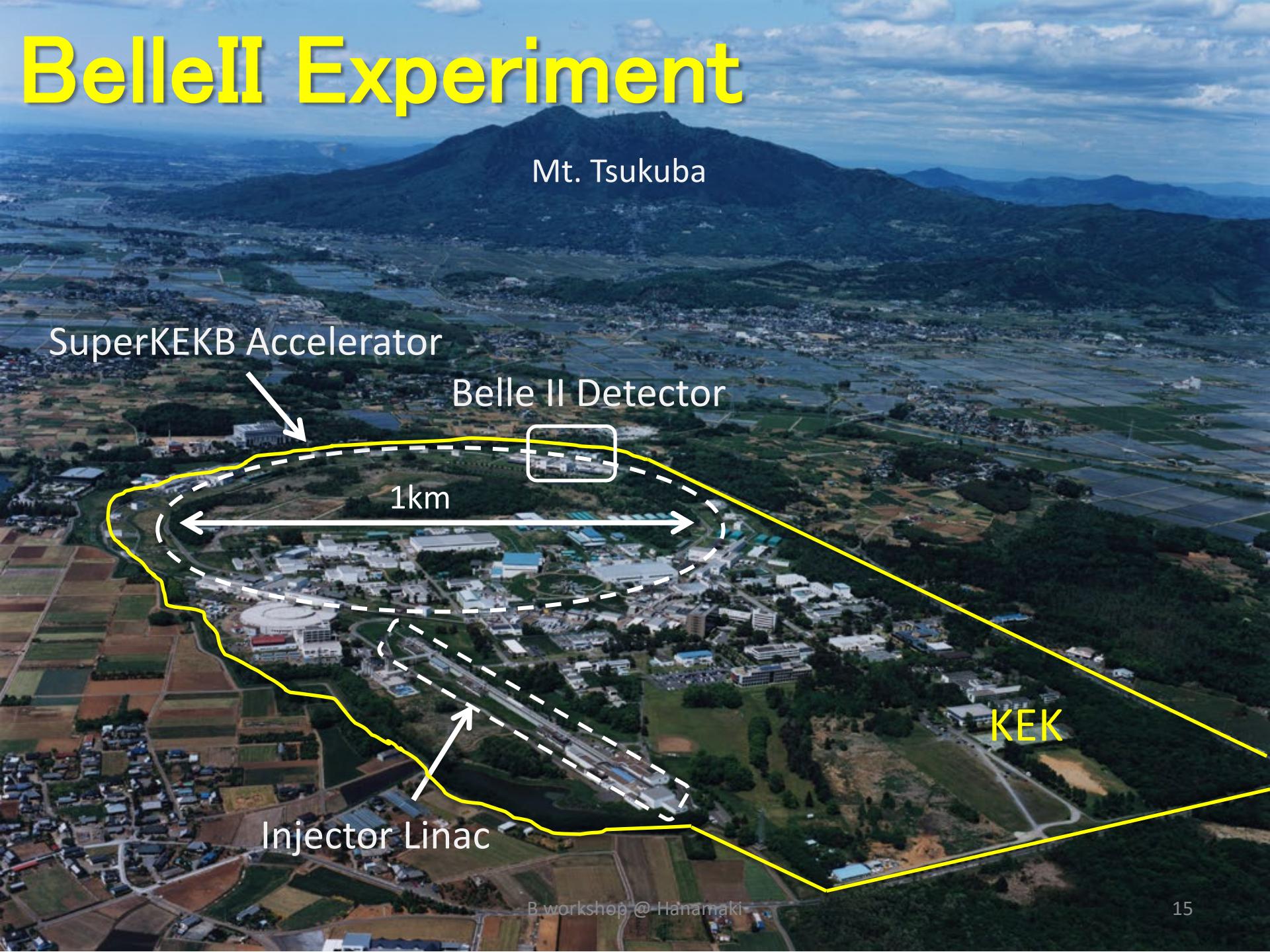


To get x30 higher luminosity

Belle I to Belle II

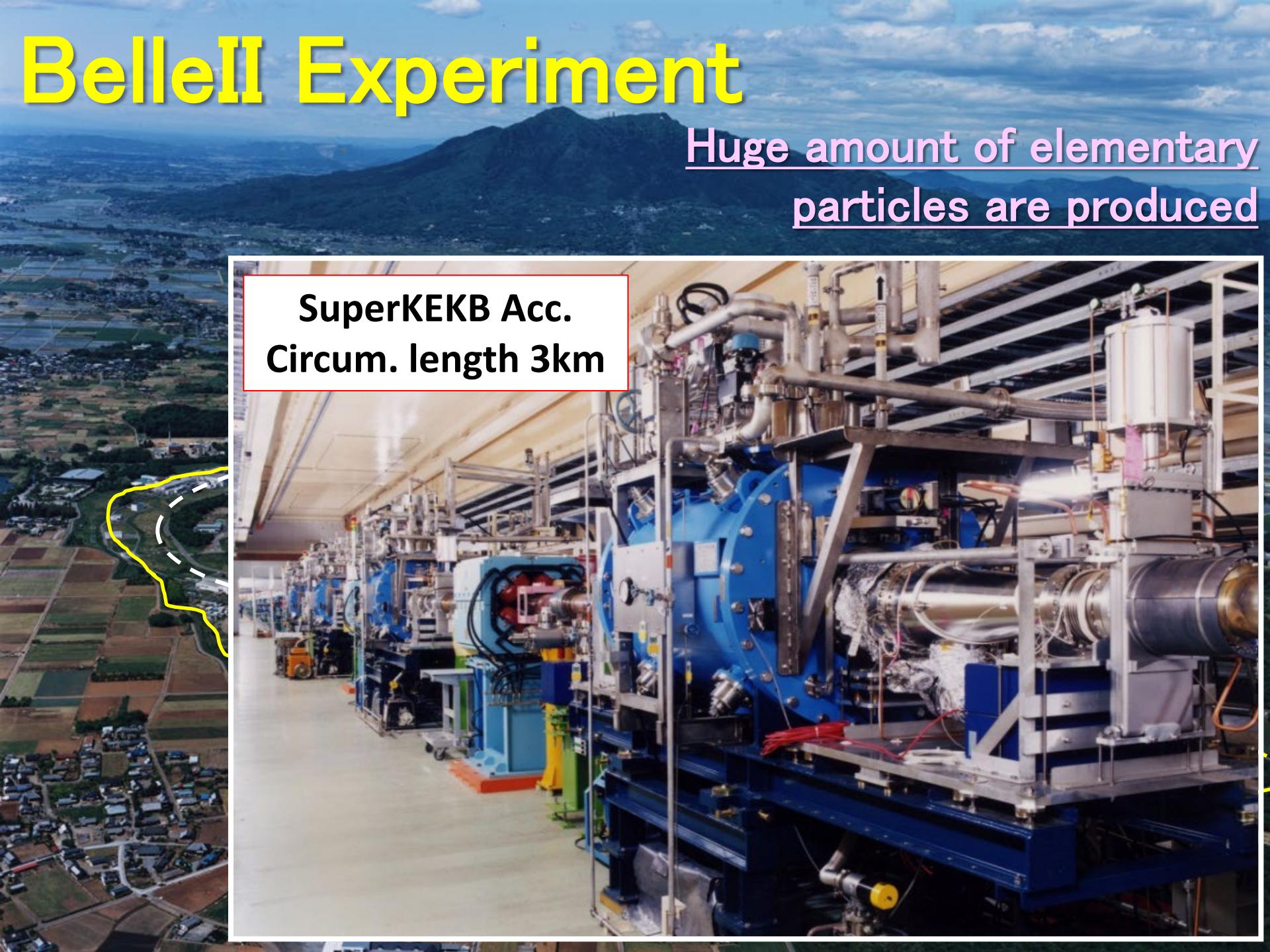


BelleII Experiment



BelleII Experiment

Huge amount of elementary
particles are produced



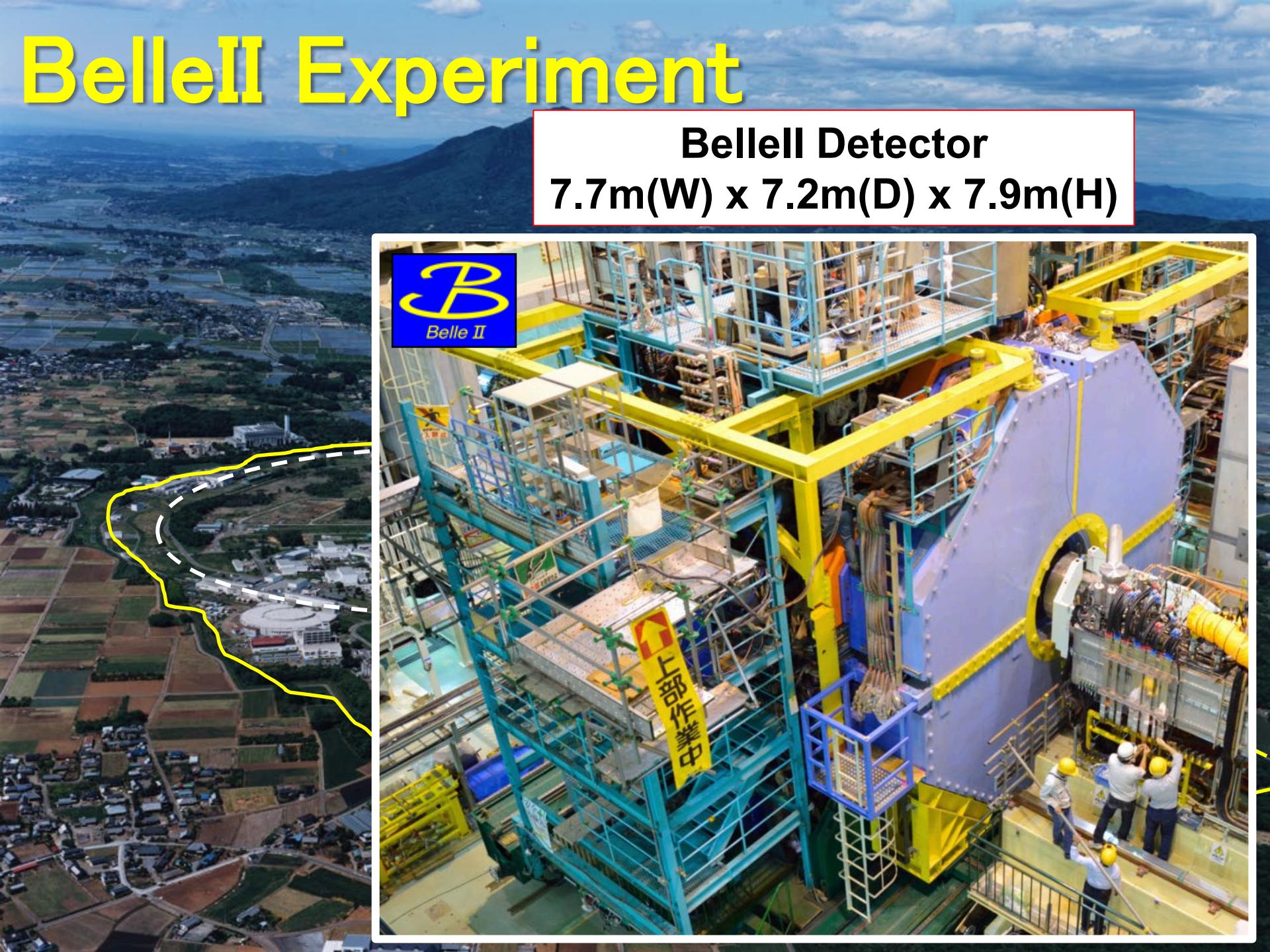
SuperKEKB Acc.
Circum. length 3km



BelleII Experiment

BelleII Detector

7.7m(W) x 7.2m(D) x 7.9m(H)



Belle II Detector

7.7m(W) x 7.2m(D) x 7.9m(H)

EM Calorimeter

CsI(Tl), waveform sampling

Electron beam
(7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector

2 layers DEPFET + 4 layers DSSD

Central Drift Chamber

He(50%):C₂H₆(50%), **small cells**,
long lever arm, **fast electronics**

Trigger
Up to 30kHz

K_L and muon detector

Resistive Plate Counter (barrel outer layers)
Scint. + WLSF + MPPC (end-caps , inner 2 barrel)

Particle Identification

Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

Positron beam
(4GeV)

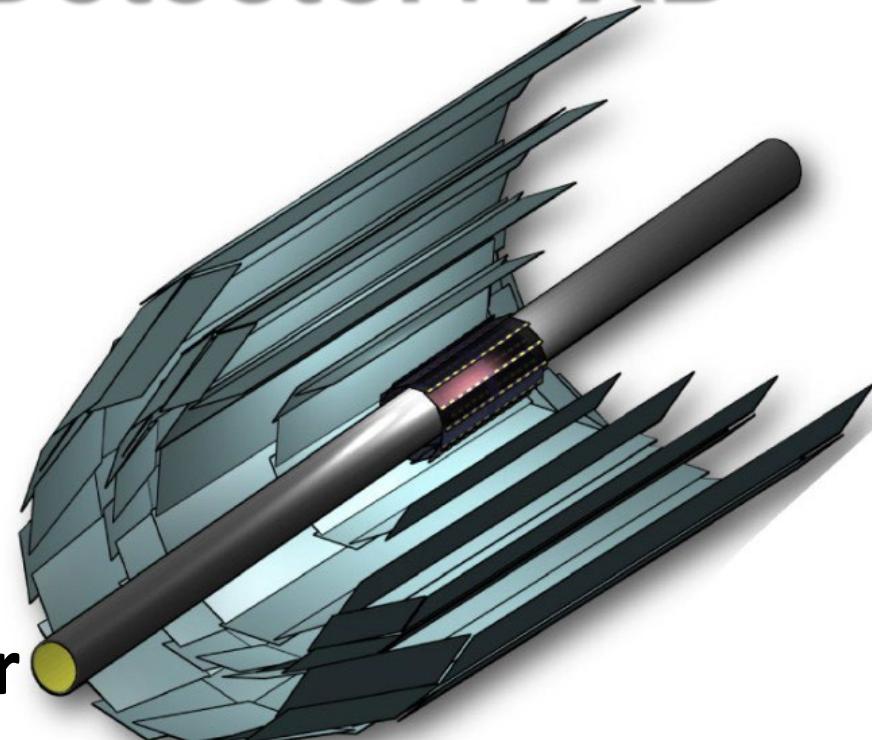
Belle II Vertex Detector: VXD

$$\text{VXD} = \text{PXD} + \text{SVD}$$

PXD : PiXel Dector

DEPFET(DEPleted p-channel FET)

2 Layers ($r = \underline{14}$, 22mm)



SVD : Silicon Vertex Detector

DSSD (Double Sided Silicon Strip)

4 Layers ($r = 38, 80, 115, \underline{140}$ mm)

Belle II VXD covers $r = 14\text{mm} - 140\text{mm}$ area

BelleI : SVD only (4 layers DSSD $r=20 - 88$ mm)

$20 \rightarrow 14\text{mm}$ x2 better impact parameter resolution $(14/20)^2$ 19

Belle II Vertex Detector: VXD



Installed in 2018.

PXD

1st layer and
2 ladders of 2nd layer

SVD

4 layers

*News: In 2022-23, do a long shutdown
(LS1) and replace with a 2-layer PXD.*

Geography of the International Belle II collaboration

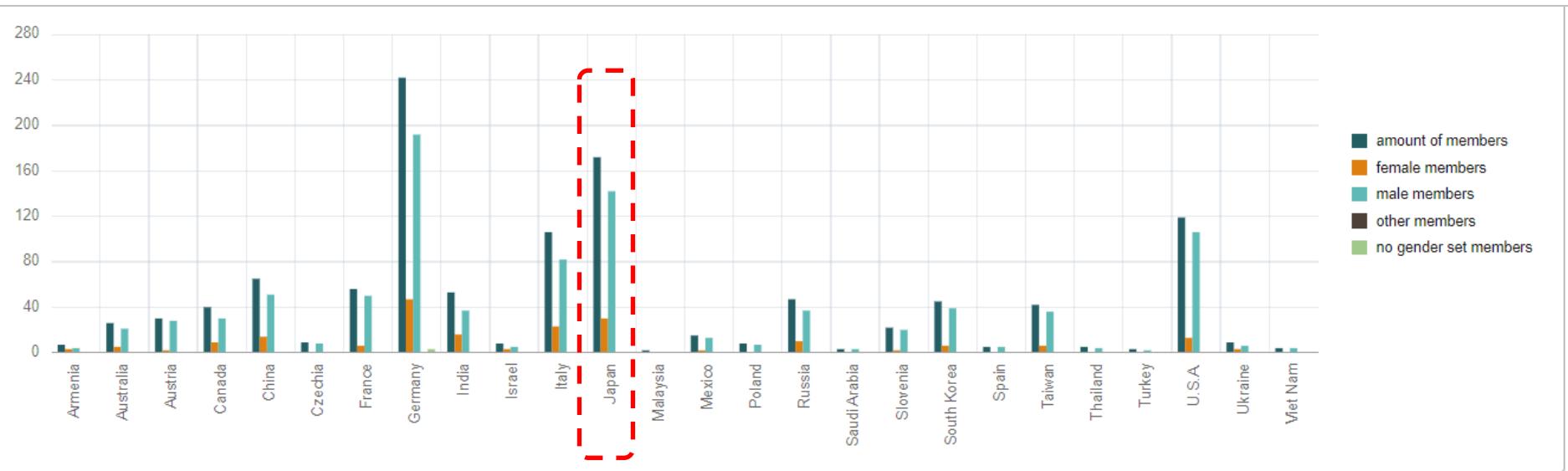


Belle II now has grown to
~1100 researchers
from 26 countries
(121 institutes)

cf. Belle
~400 collaborators
13 countries, 57 institutes

Youth and potential: There are ~330 graduate students in Belle II

Japanese Participation



2nd largest group in Belle II

172 members from 16 institutes

Chiba, Hiroshima, IPMU, KEK, Kitasato, Nagoya, Nara-WU, Niigata, NPC,
Okinawa, Osaka-City, Toho, Tohoku, Tokyo-Met., U. Tokyo, Yamagata

Japanese Contribution

TOP (Nagoya, KEK)



ECL (Nara W.)



Computing (KEK+ Universities)



A photograph showing three people in white lab coats and blue hairnets standing behind a metal frame structure. The person on the left is wearing a white mask, the person in the middle is wearing a white mask, and the person on the right is wearing a white mask.

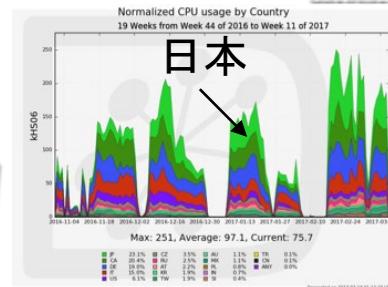
A group of approximately ten people, including men and women of diverse ages, are posed for a group photo. They are all wearing white hard hats and light blue safety vests over dark shirts. The setting is a large industrial facility, specifically a particle accelerator, characterized by a massive, complex circular structure made of steel and glass. The accelerator's interior is visible in the background, showing various components and equipment. The group is arranged in two rows: some people are standing in the back row, while others are kneeling or sitting in the front row. The overall atmosphere is professional and suggests a team of scientists or engineers.

CDC (Osaka-City, NPC, KEK)

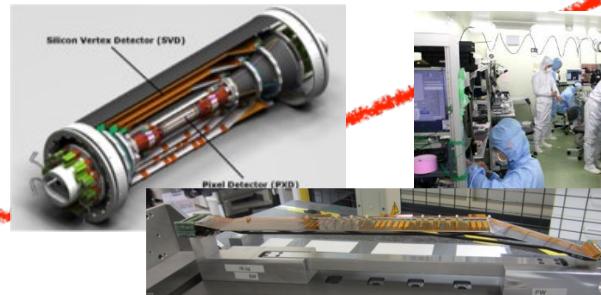


A photograph showing two researchers in a laboratory. One researcher is in the foreground, wearing a white lab coat and glasses, looking down at a circular sample held by forceps. The other researcher is partially visible behind them. They are working in a dark room with a bright light focused on the sample.

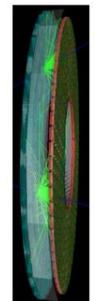
A-RICH (Tookyo, M., Niigata, Chiba, Toho, KEK)



Trigger + DAQ (KEK)



SVD (U.Tokyo, IPMU, Tohoku, KEK)



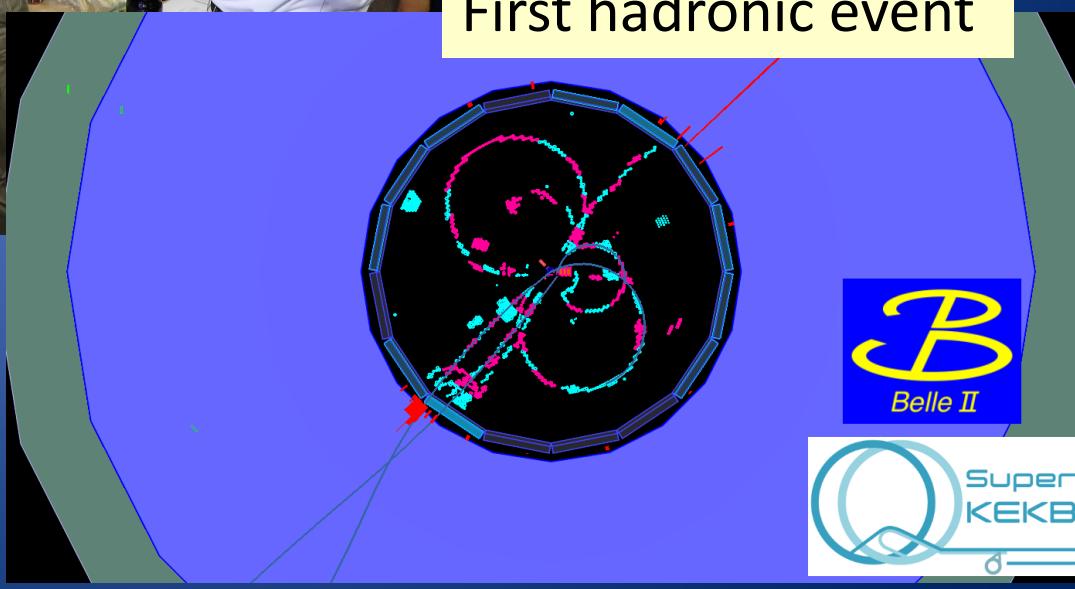
1-2: Operation Status + Recent Results



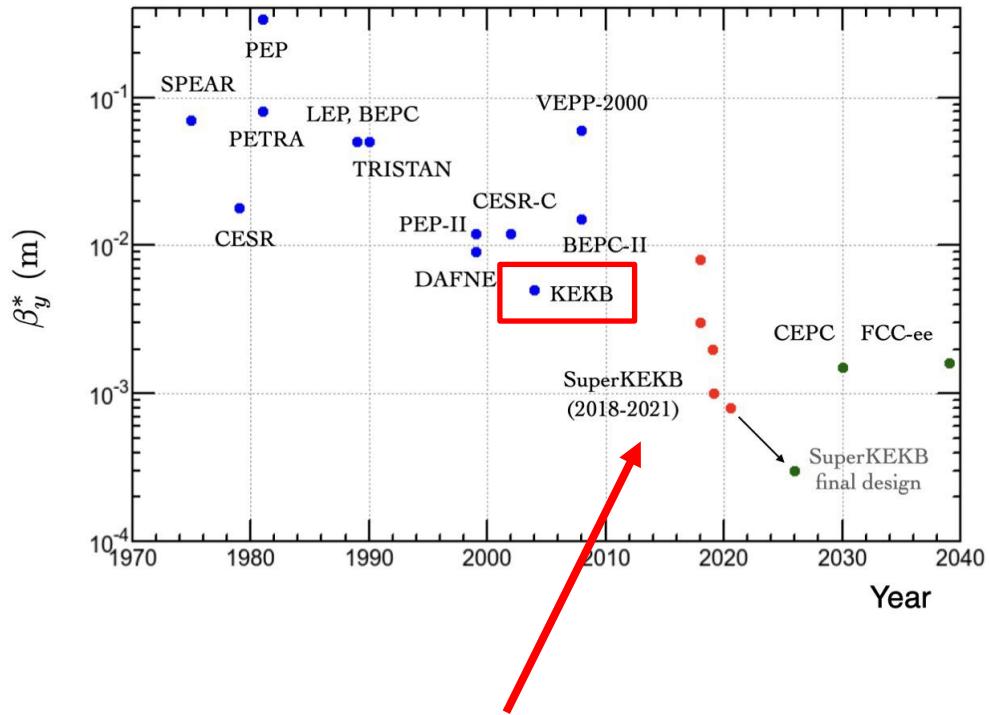
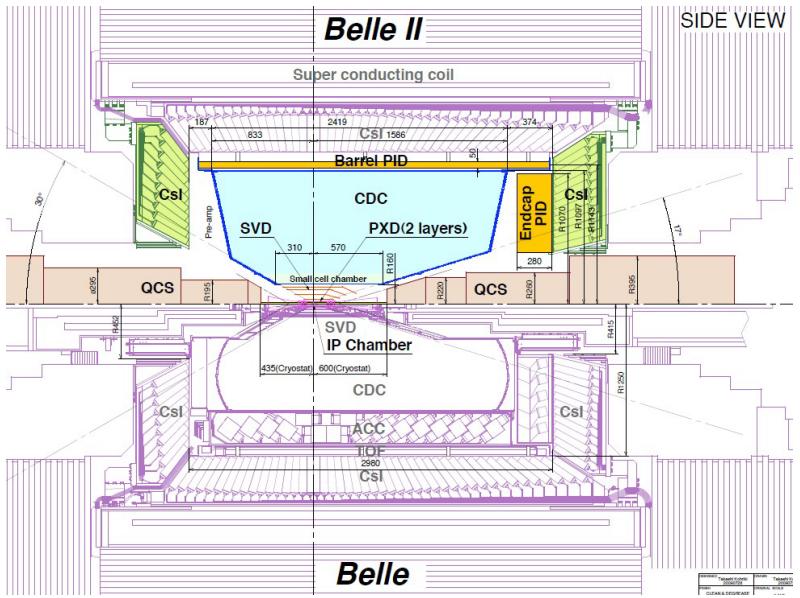
First collision
after 5.5 years
construction

First hadronic event

April. 26, 2018 0:38
Belle II control room

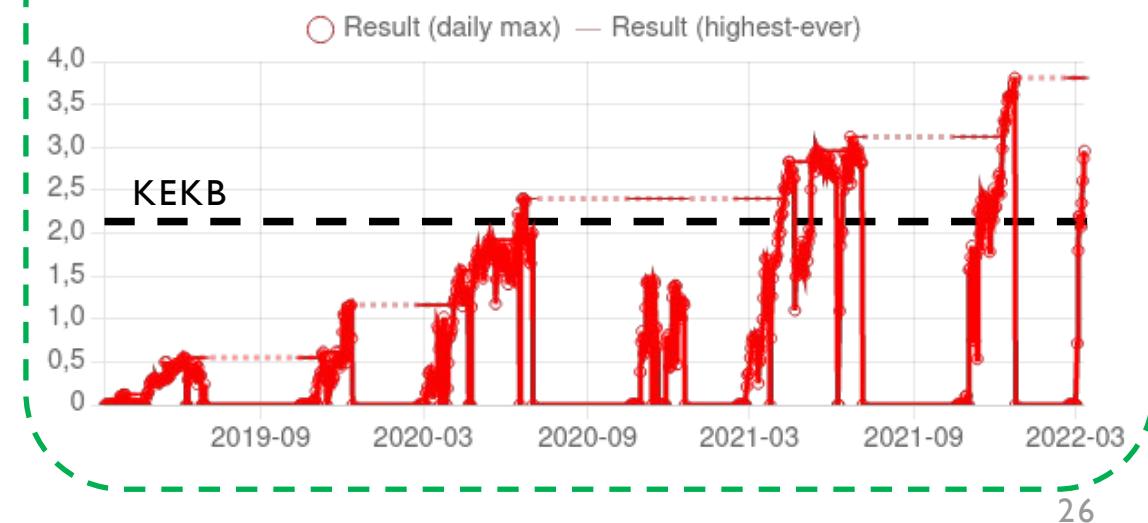
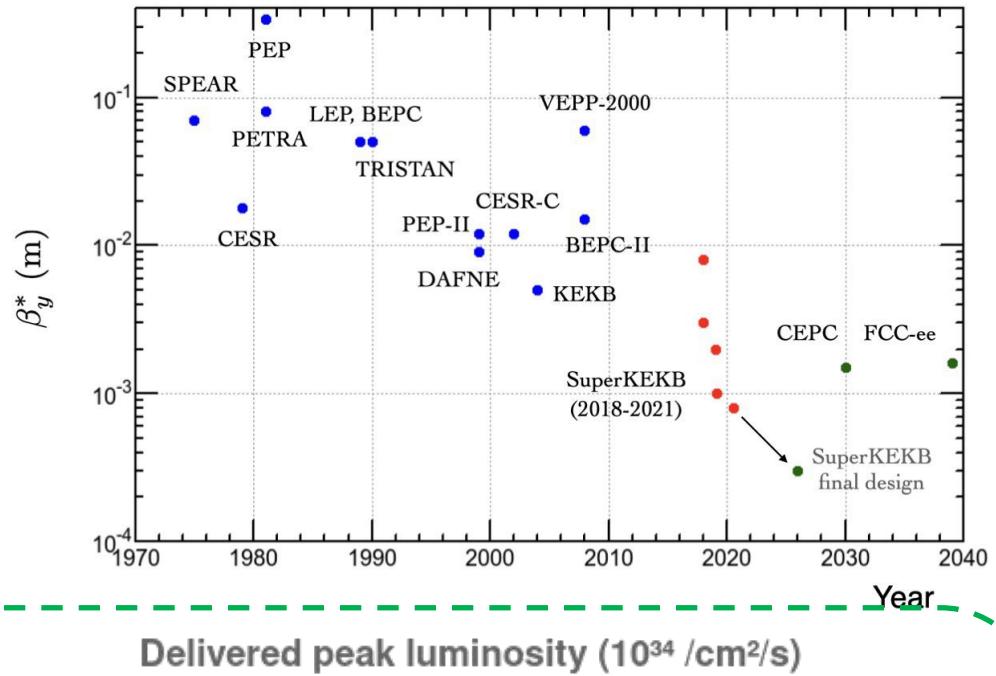
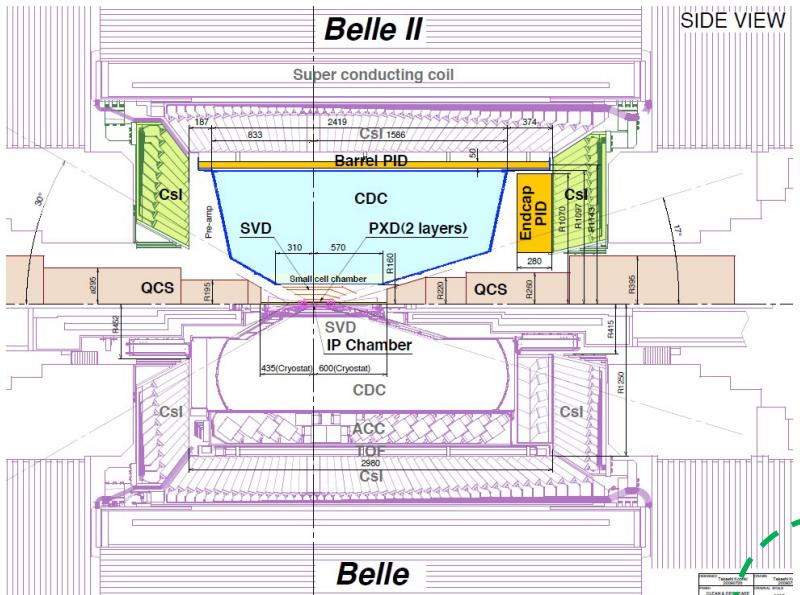


SuperKEKB Status



*We squeeze the beam
smaller than KEKB*

SuperKEKB Status



Data Taking Status

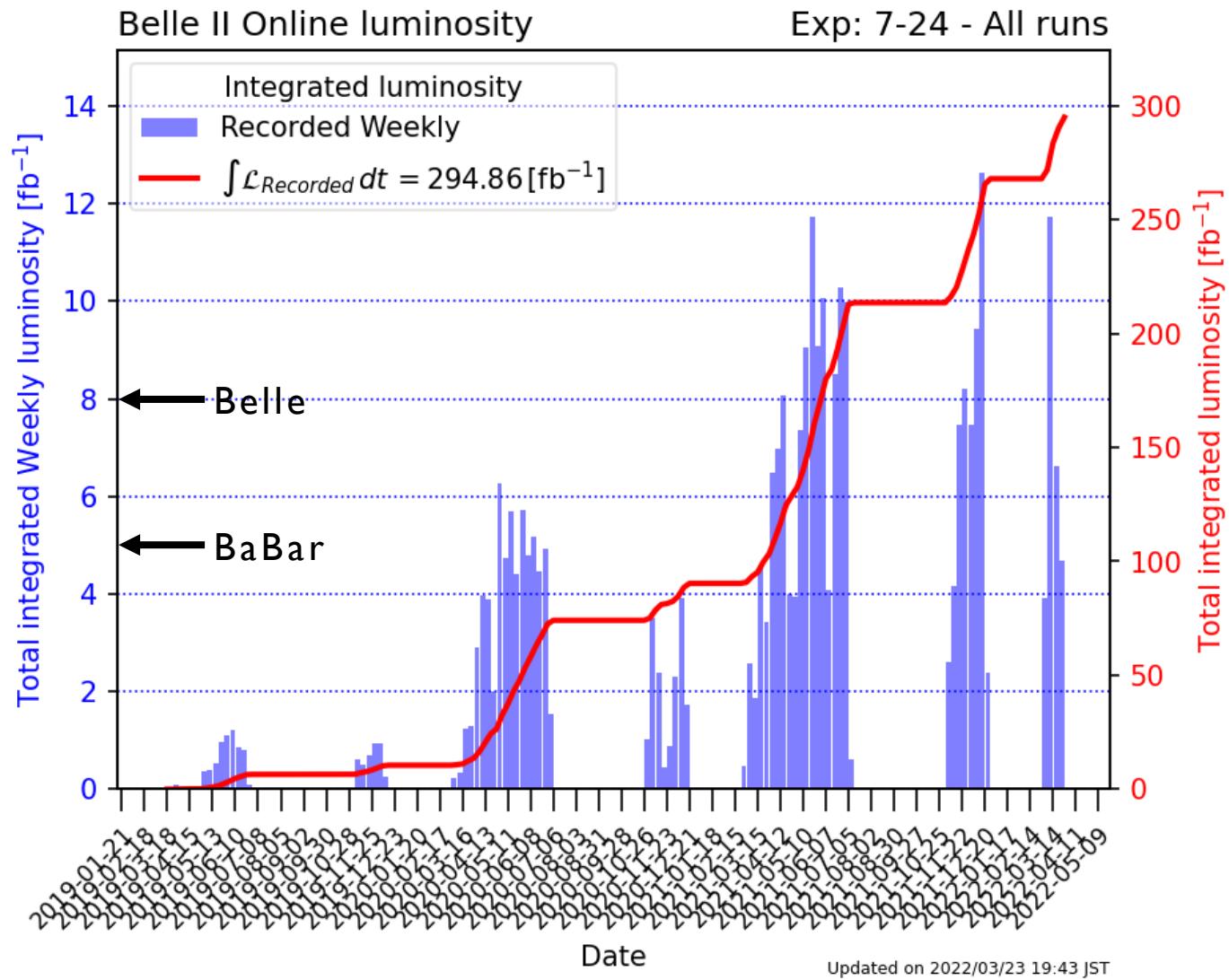
*Commissioning
run in 2018*



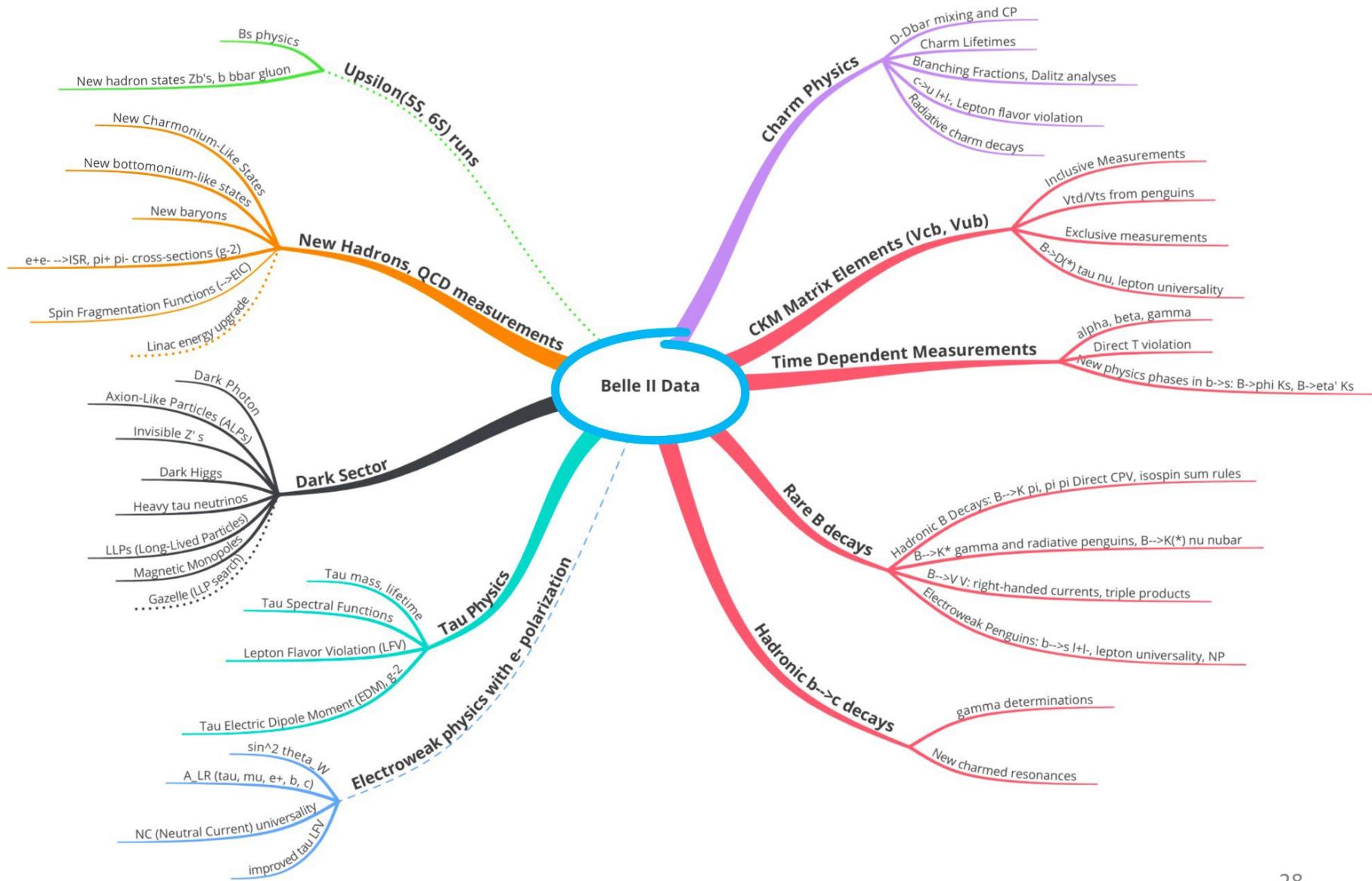
*Physics run
Started 2019*

**Collected
0.3 ab⁻¹ so far**

BaBar : 0.5 ab⁻¹
Belle : 1.0 ab⁻¹



Belle II Physics

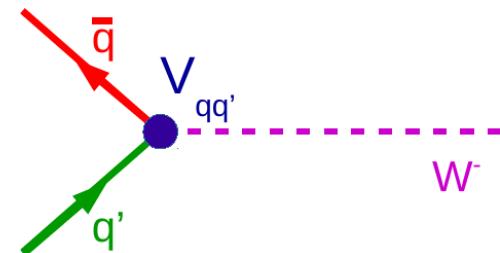


CKM Parameters

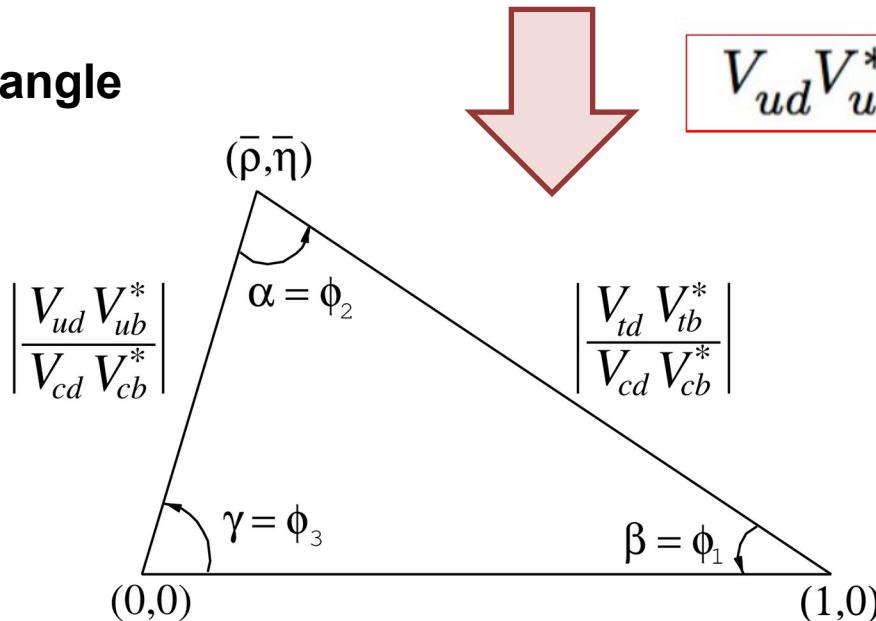
Cabibbo-Kobayashi-Maskawa (CKM) matrix

- Three generation of quarks.
- Each element ($V_{qq'}$) describes mixing of quarks via weak interaction in Standard Model (SM).

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



Unitarity triangle



$$\beta = \phi_1 = \arg \left(- \frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right)$$

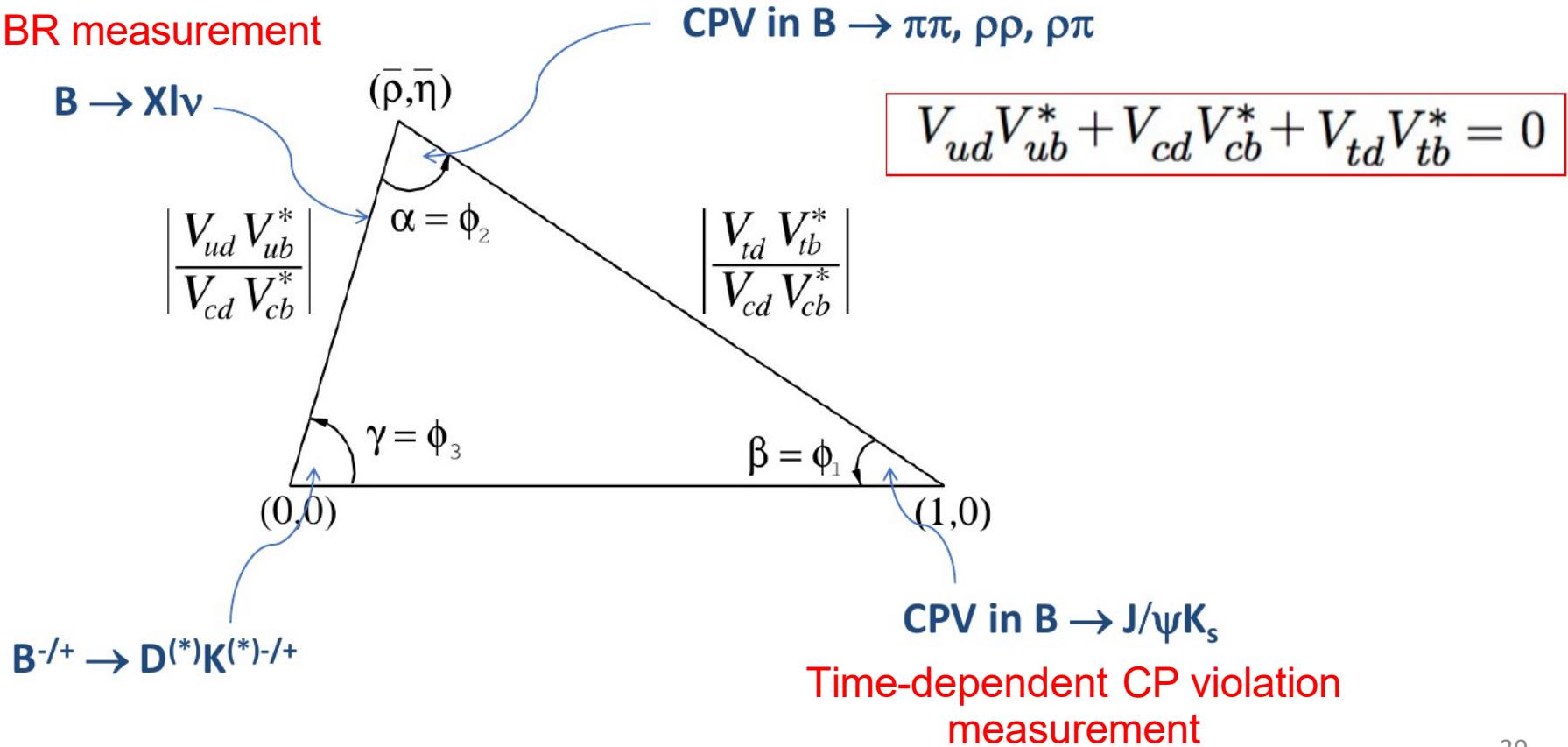
$$\alpha = \phi_2 = \arg \left(- \frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right)$$

$$\gamma = \phi_3 = \arg \left(- \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)$$

CKM Parameters

- In SM, CP violation arises via a non-zero phase of the CKM matrix.
- Precise measurement on UT angles and sides is a good test on SM.

BR measurement



Time Dependent CP Violation

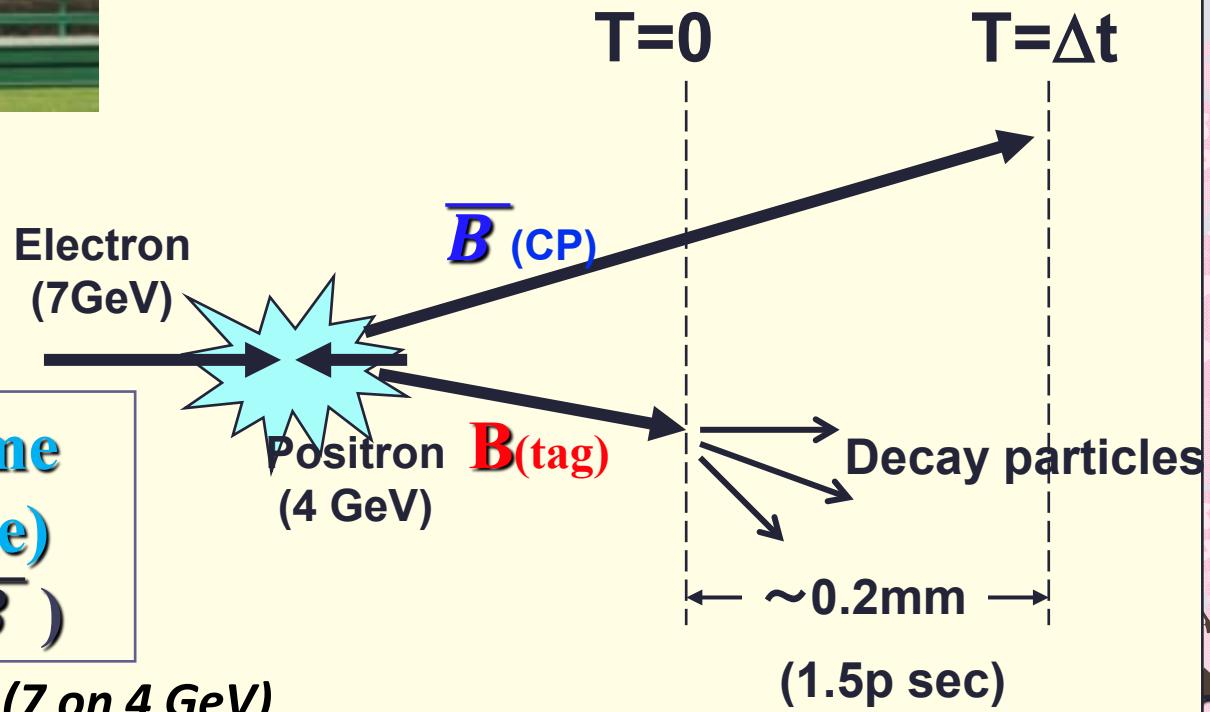
Time Dependent CP Violation



Measure Decay time
(\rightarrow distance)
and flavor (B or \bar{B})

Asymmetric beam energies (7 on 4 GeV)

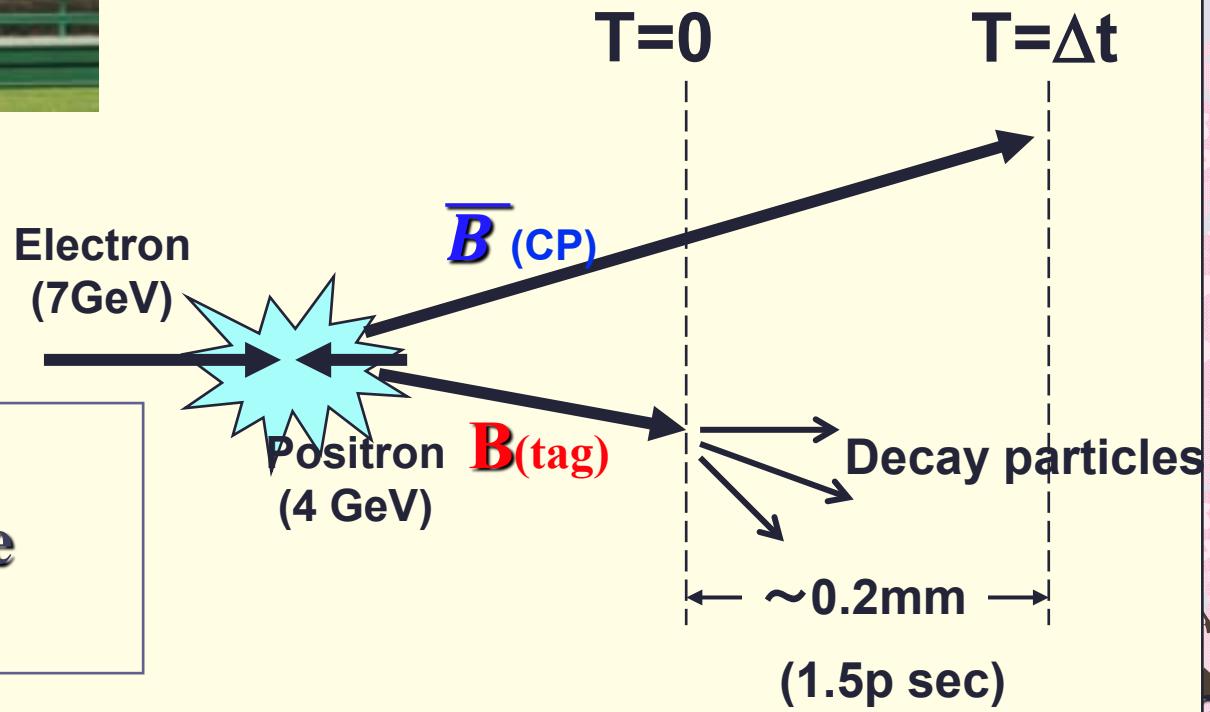
The decay distance increase ~ 7



Time Dependent CP Violation



Flip B and \bar{B}
and compare the
distributions



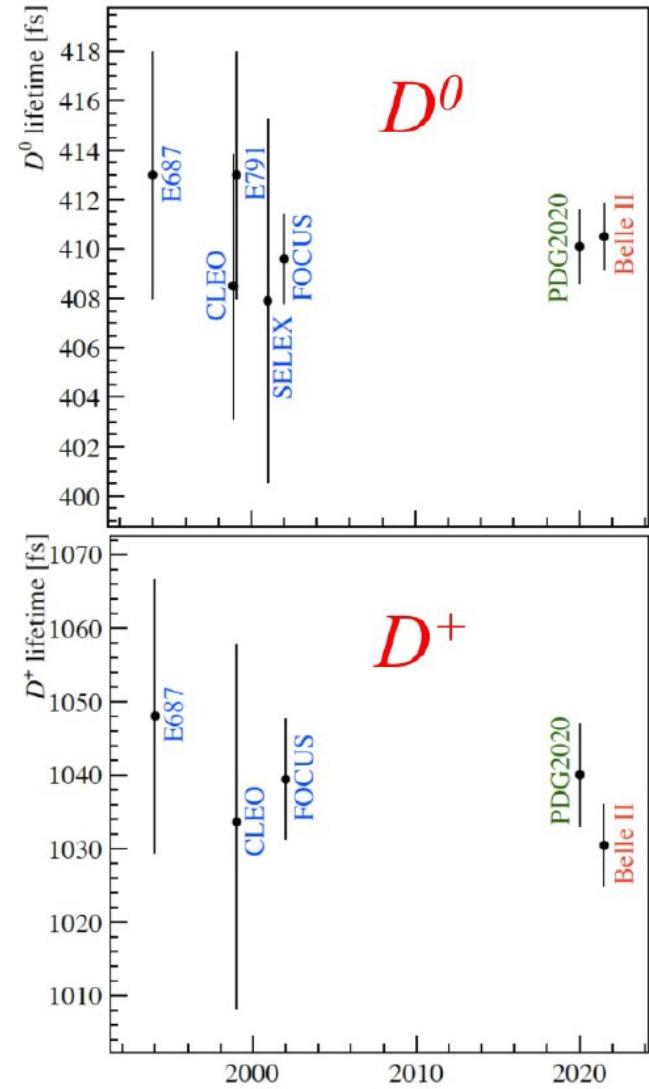
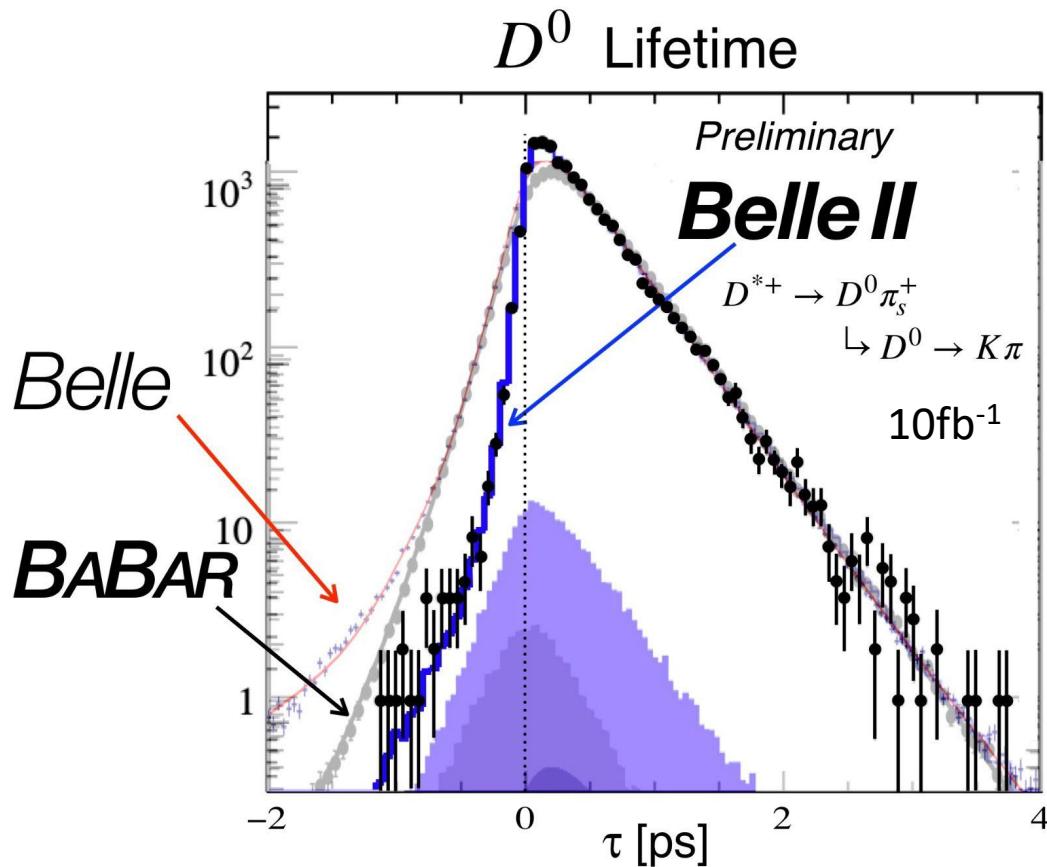
Measurement of the Time Dependent CP Violation

Key

Vertexing and Tagging performance

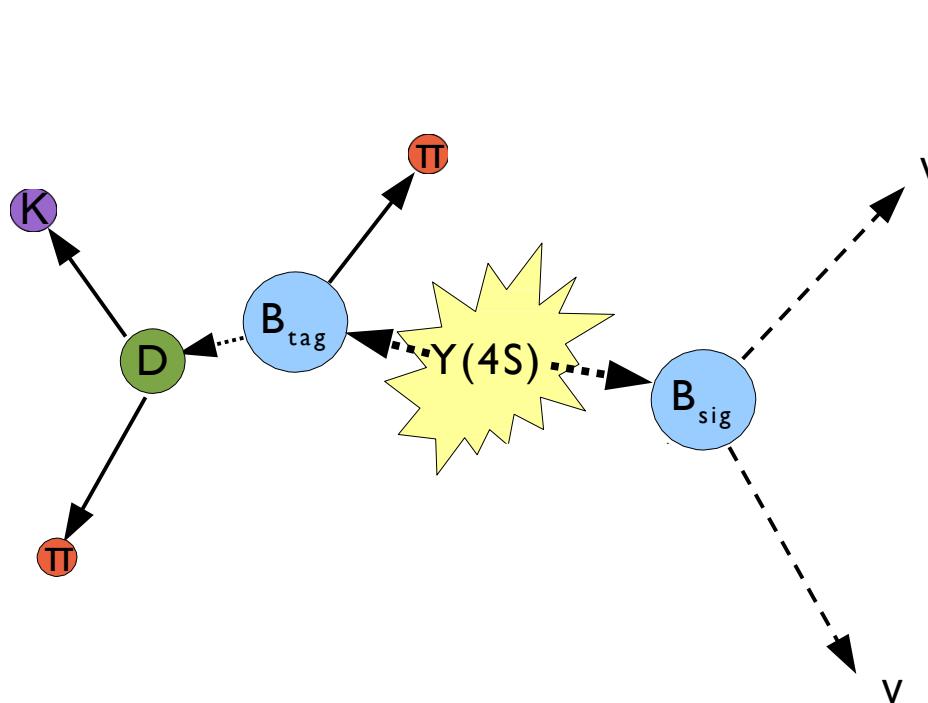
→ We'll show the D lifetime measurements and
Tagging performance first

D Lifetime measurements

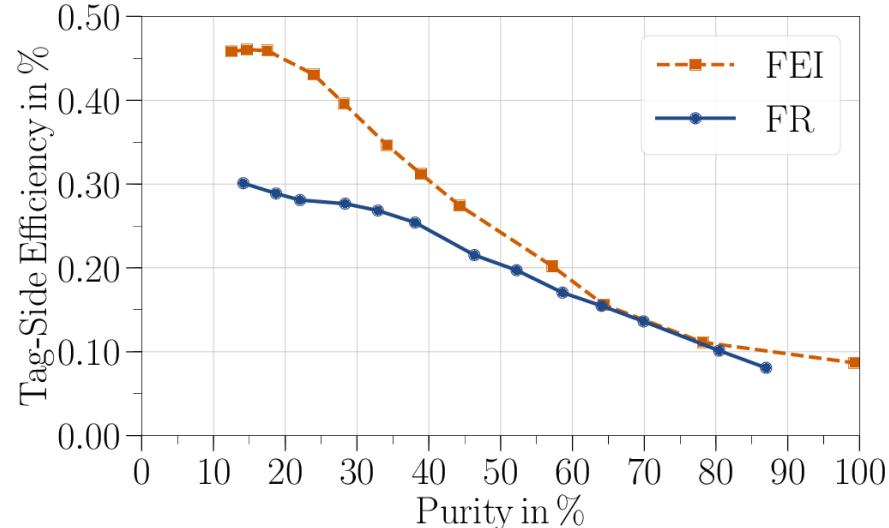


Results more precise than the World average
Proof of excellent vertexing performances

Reconstruction of Undetected Particles



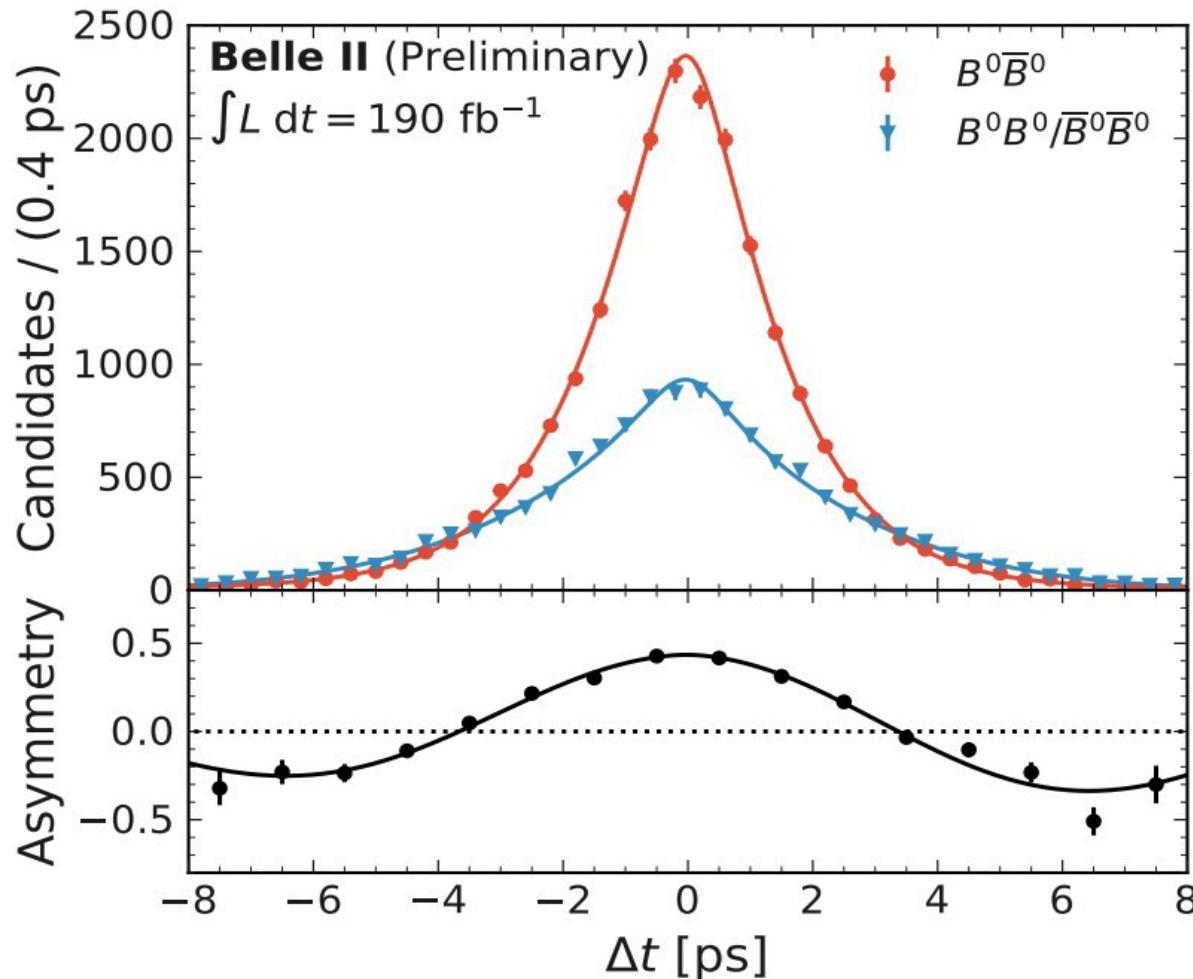
Comput. Softw. Big Sci. 3 (2019) 1, 6



Full reconstruction of B_{tag} decay in >5000 decay chains
with MVA tool.

→ New Full Event Interpretation (FEI) package for Belle II
30-50% higher tagging efficiency with same purity,
than the Belle version (FR)

Time Dependent Mixing asymmetry (not CPV)

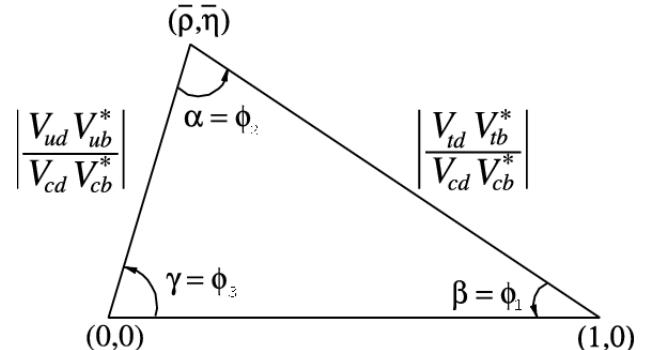
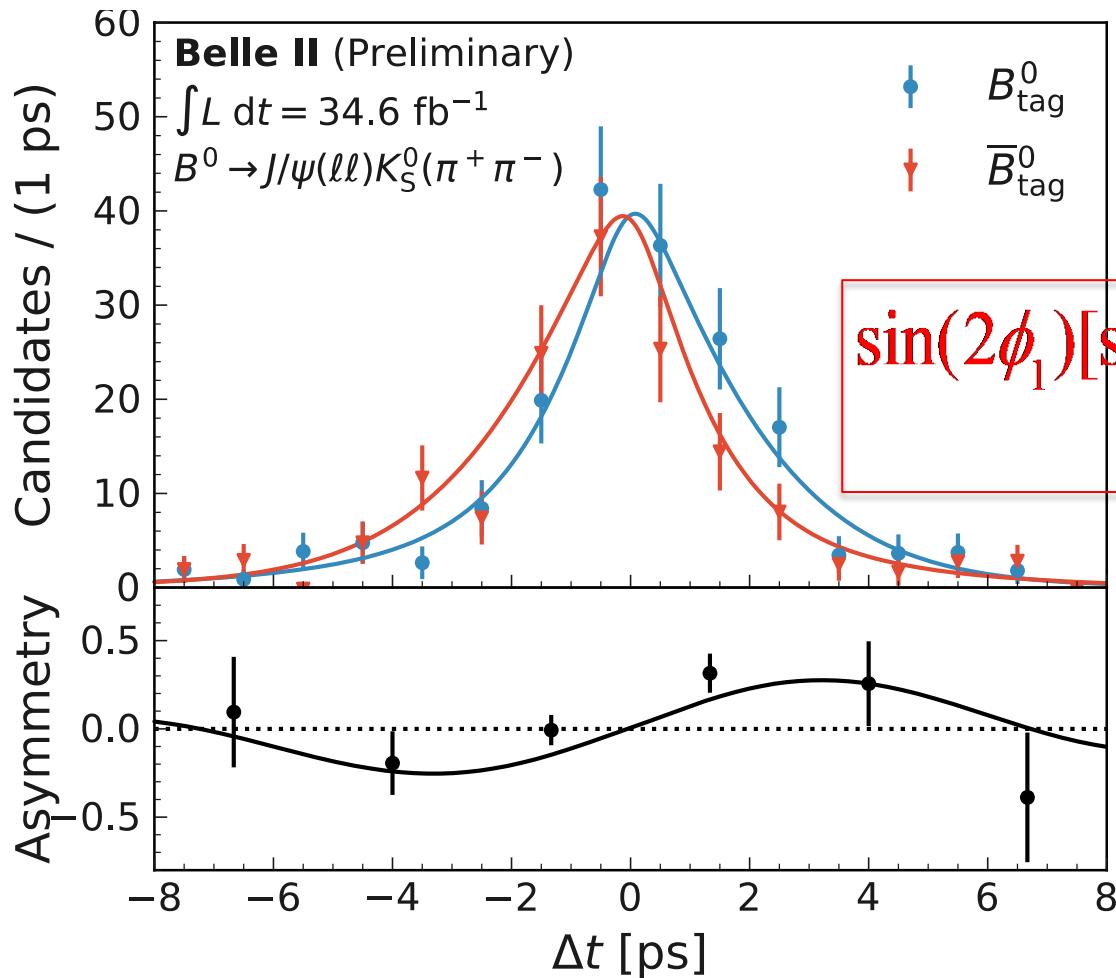


$$\Delta m_d = (0.516 \pm 0.008 \text{ (stat.)} \pm 0.005 \text{ (syst.)}) \text{ ps}^{-1}$$

World average: $0.5065 \pm 0.0019 \text{ ps}^{-1}$

Result compatible with world average

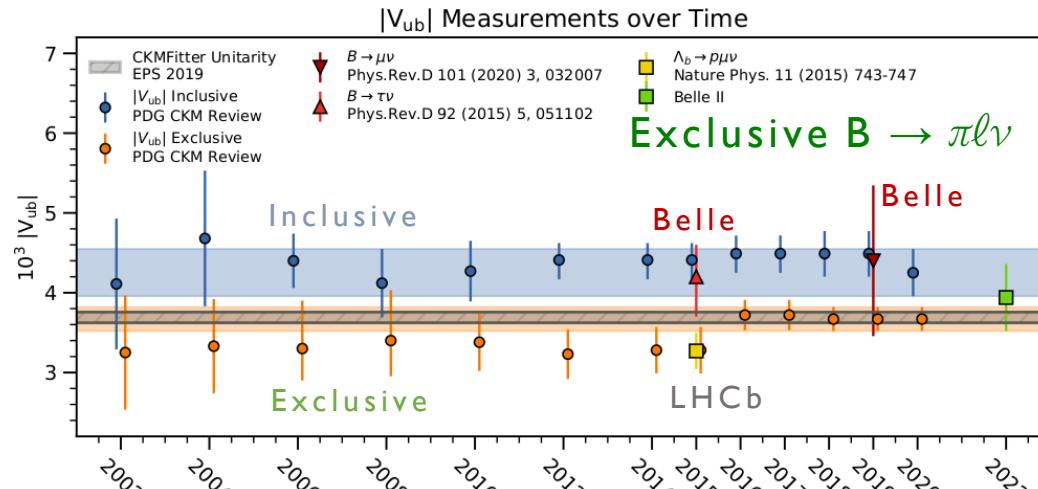
Hint of time-dependent CPV from Belle II (2.7σ significance)



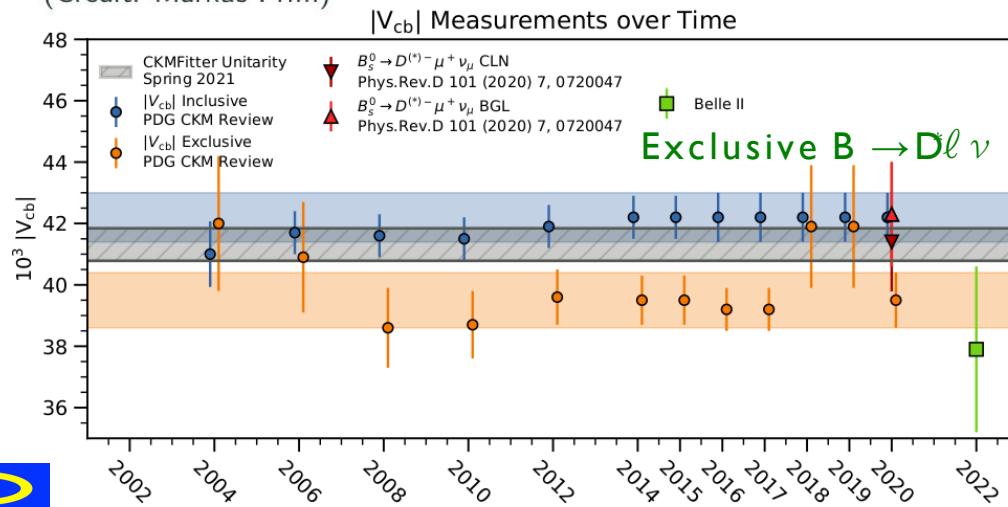
*Expect updates in summer
2022 (x6 more data)*

V_{ub} V_{cb}
Related analyses

Preliminary V_{xb} Measurements



(Credit: Markus Prim)



Further measurements

- **Exclusive $B \rightarrow \rho \ell \nu$**

arXiv:2111.00710

- **Inclusive $B \rightarrow X_u e \nu$**

arXiv:2103.02629

- **Exclusive $B^- \rightarrow D^- \ell \nu$**

arXiv:2110.02648

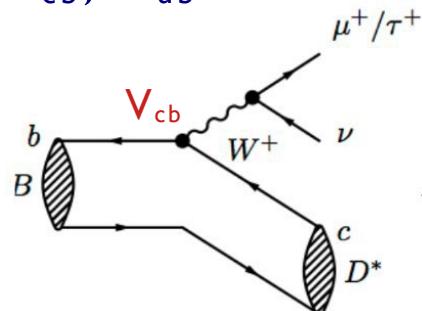
- **Inclusive $B \rightarrow X_c \ell \nu$**

arXiv:2111.09405

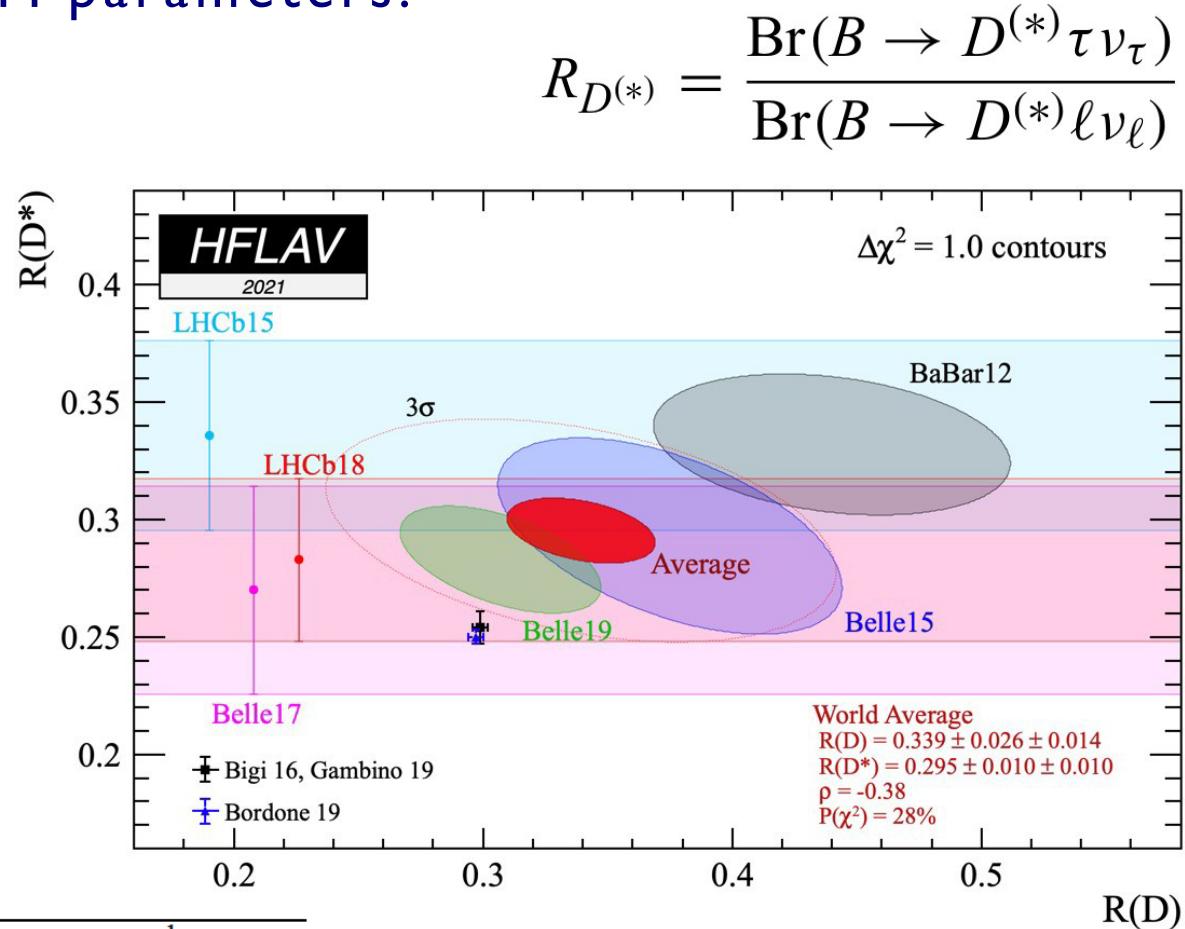
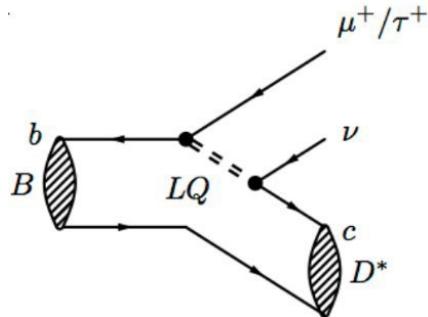
Semileptonic Decays

Measurement of SM parameters:

$$V_{cb}, V_{ub}$$



Search for NP:

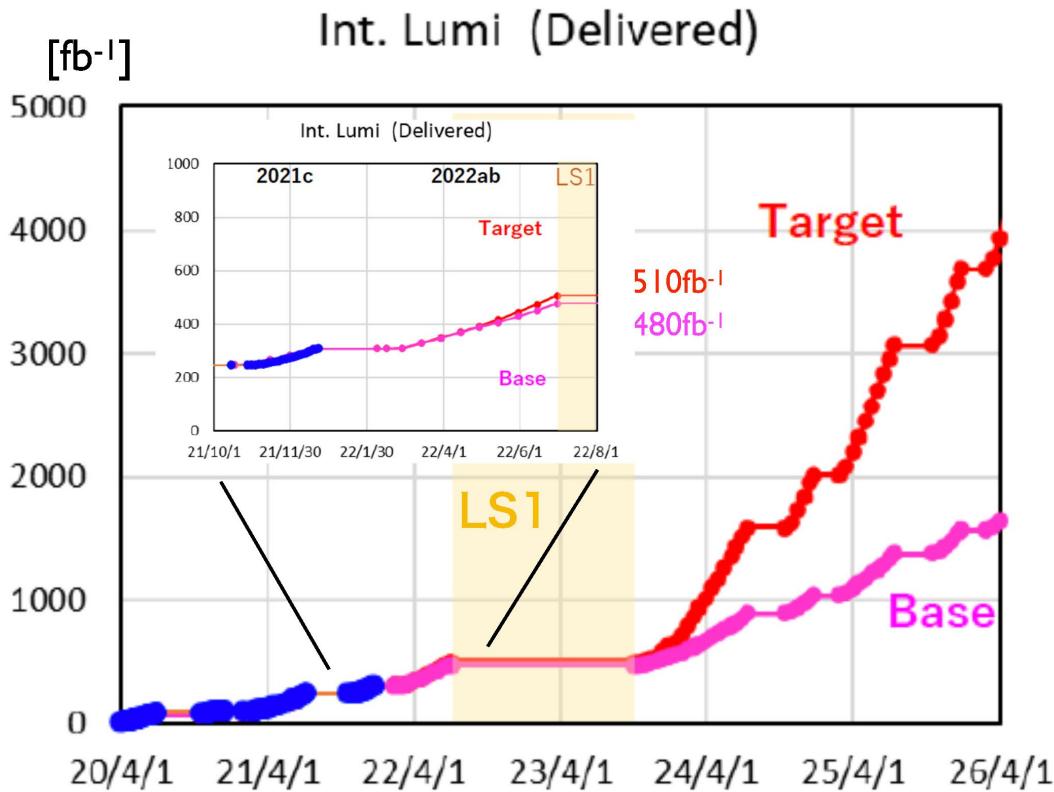


	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

Latest Belle measurement with semileptonic tags brings down to the WA discrepancy to $4 \rightarrow 3\sigma$

Prospects

Projection of Integrated Luminosity delivered by SuperKEKB



Long Shutdown
in 2022-2023 to install PXD2



[YY/M/D]