Belle & Belle II
시간 의존 **CP** 비대칭 정밀 측정과 실리콘 검출기 연구

강국현 (경북대학교)

2026.06.13 2026년도 KSHEP 봄 학술대회

Outline

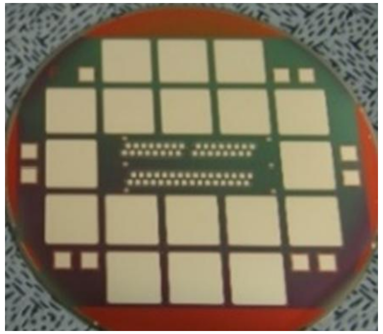
- Introduction
- Belle & Belle II experiment & Time-dependent CP violation (TDCPV)
- Silicon Vertex Detector (SVD) & Future Vertex Detector (VTX)

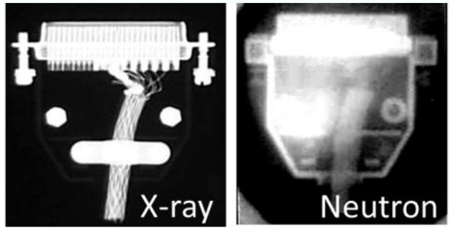
Jeju University

- 연구실 첫 발표 (2010.07)
  - 제주대학교 계절학기
  - 스킨스쿠버 & 승마

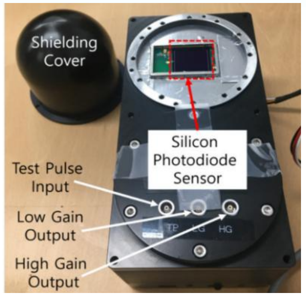
- 연구실 간택

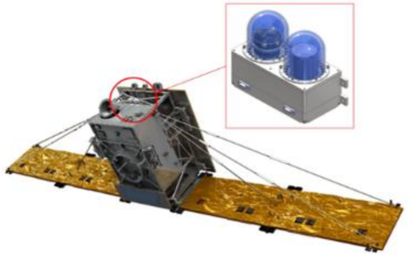
Kookhyun Kang





- Neutron imaging[1]





PostDoc

Professor

TDCPV in $B^0 \rightarrow K_S^0 K_S^0 K_S^0$

Search for $B^0 \rightarrow K_S^0 K_S^0 \gamma$

2012 2014 2016 2018 2020 2022 2024 2026

?

SVD module R&D

SVD mass production

SVD operation

SVD deputy leader

SVD re-installation

PIN diode Radiation damage study

Photo PIN Diode for ISS-CREAM

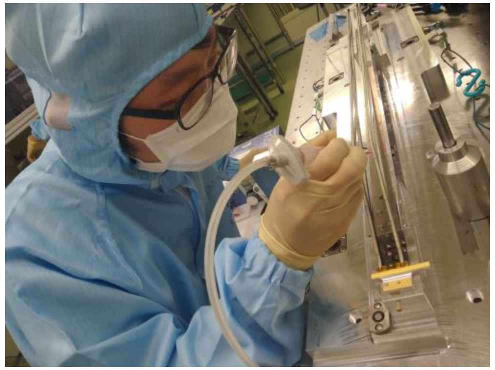
Neutron detector

SSD for RAON

PD for x-ray Cargo system

DOI measurement using PSSD

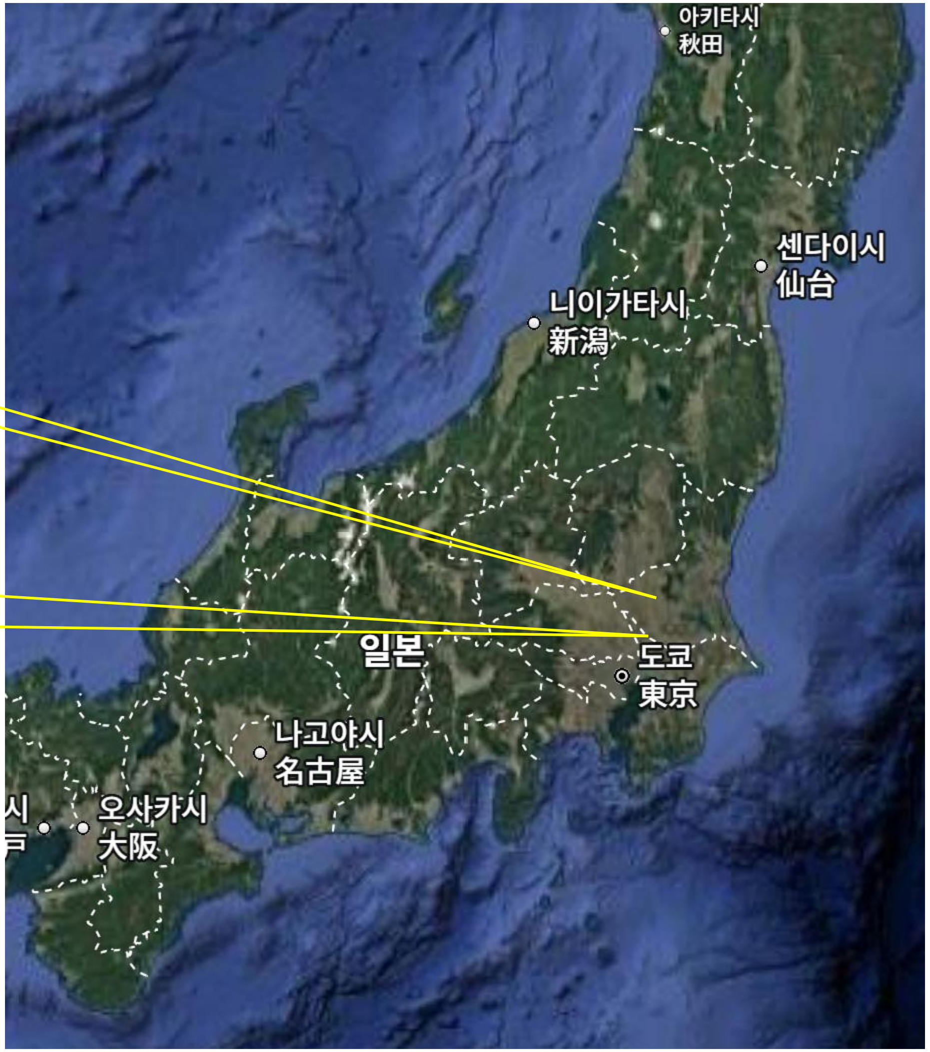
pixelated silicon sensor with JFET



Kookhyun Kang

Belle & Belle II experiments in Japan

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

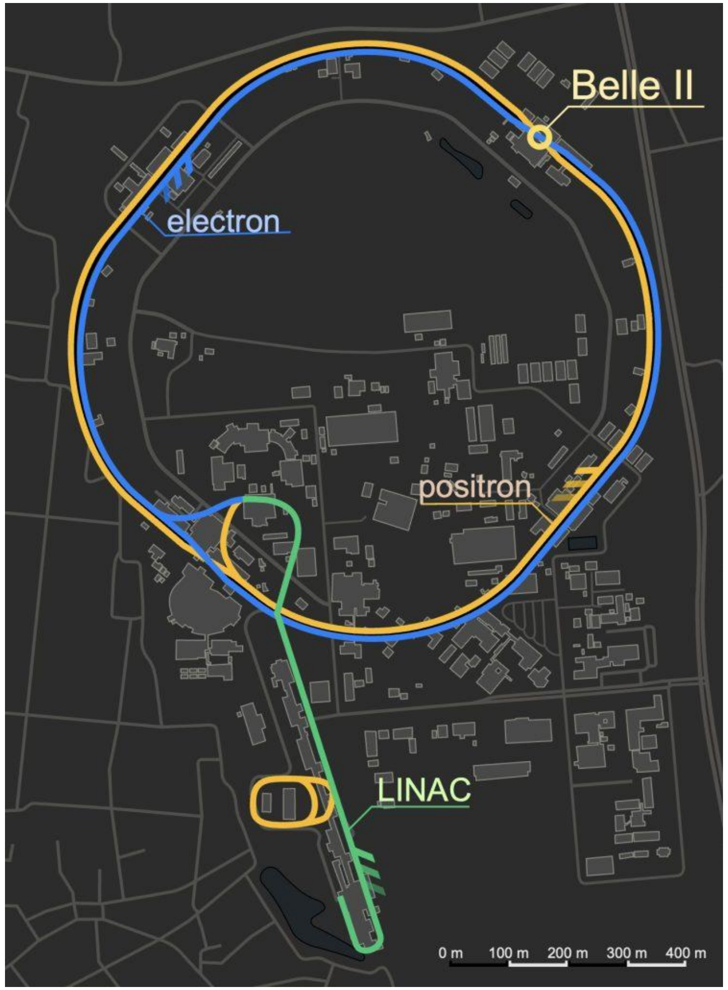


Super KEKB collider

- $4\ GeV\ e^{+}$ & $7\ GeV\ e^{-}$
  - **CM energy**: 10.58 GeV for $\Upsilon(4S)$
  - **Asymmetric energy**
  - **Lepton collider**

- **Luminosity Frontier**
  - Target luminosity: $6 \times 10^{35}\ cm^{-2}s^{-1}$
  - Target Integrated L: $50\ ab^{-1}$

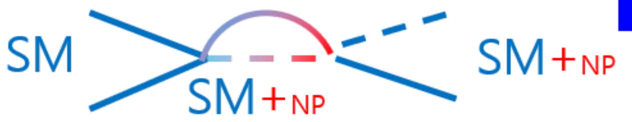
- Search for new physics with B, charm, and τ rare decays
  - **Time dependent CP violation (TDCPV) using rare decay**



둘레:3km
vs LHC: 27 km

Luminosity Frontier

- Discover NP contributions through precision measurements of SM observables



Indirect search = Luminosity frontier

Direct search = Energy frontier (at LHC)

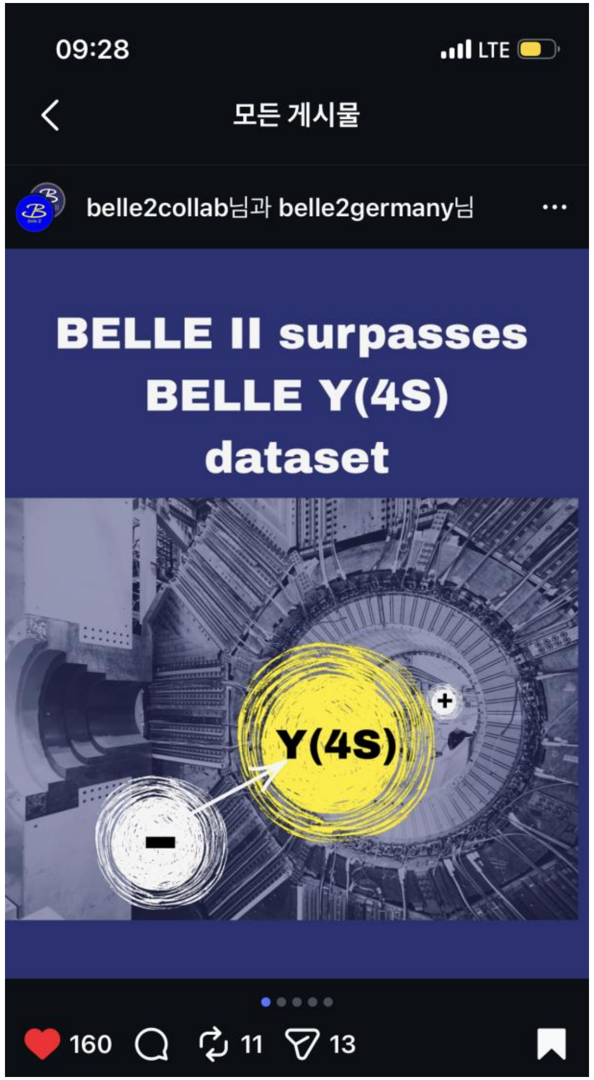
- How to find NP though indirect searches?

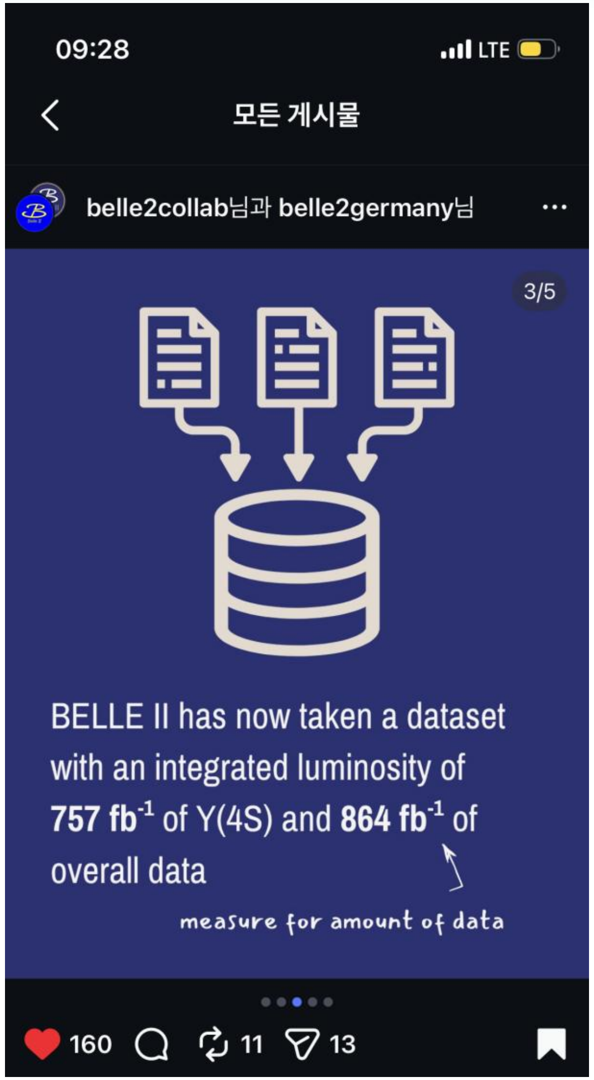
Precise predictions from theory Rare or forbidden processes	= ?	Precise measurements from experiments

Large statistics

Motivation of the Belle II experiment

Belle II data > Belle data! (2026.06.05)

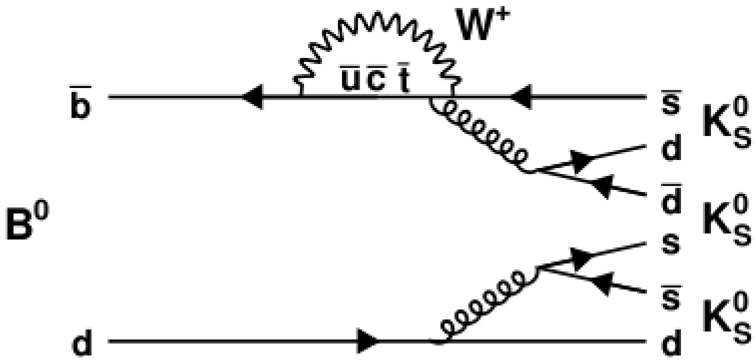


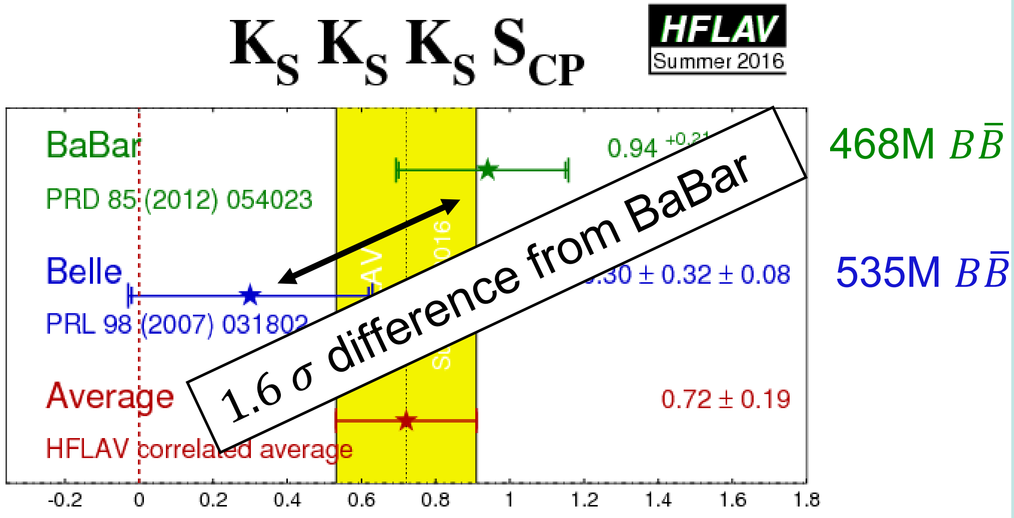


Belle II data > Belle data! (2026.06.05)

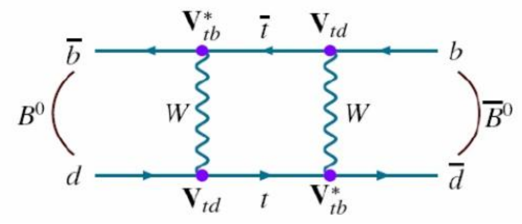
TDCPV in $B^0 \to K_S^0 K_S^0 K_S^0$ - Motivation

NP

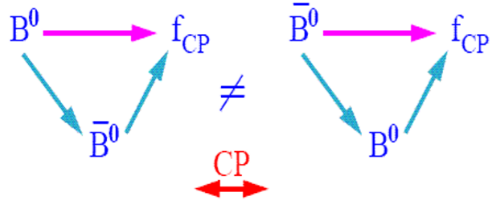




- Loop diagram
- Time-dependent CP violation
  - S: Represents how the behavior (decay amplitude) of matter (B^0) and antimatter ($\bar{B}^0$) differs over time
  - $S = -\sin 2\phi_1^{eff}$, called CKM unitarity angle
  - Large deviation from S ($\sin 2\phi_1$) in a tree diagram could be evidence of NP



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



-Mixing induced CP violation (S)

TDCPV in $B^0 \to K_S^0 K_S^0 K_S^0$ - Motivation

S = mixing-induced CP violation
A = direct CP violation

- Time-dependent CP asymmetry

$$\mathcal{A}_{CP} = \frac{P\left(\bar{B}^0(\Delta t) \to f_{CP}\right) - P\left(B^0(\Delta t) \to f_{CP}\right)}{P\left(\bar{B}^0(\Delta t) \to f_{CP}\right) + P\left(B^0(\Delta t) \to f_{CP}\right)} = S sin(\Delta m \Delta t) + A cos(\Delta m \Delta t)$$

here the time dependent decay rate (P) is given by

$$P = \frac{e^{-\frac{|\Delta t|}{\tau_{B^0}}}}{4\tau_{B^0}} \times (1 + q[S sin(\Delta m_d \Delta t) + A\cos(\Delta m_d \Delta t))$$

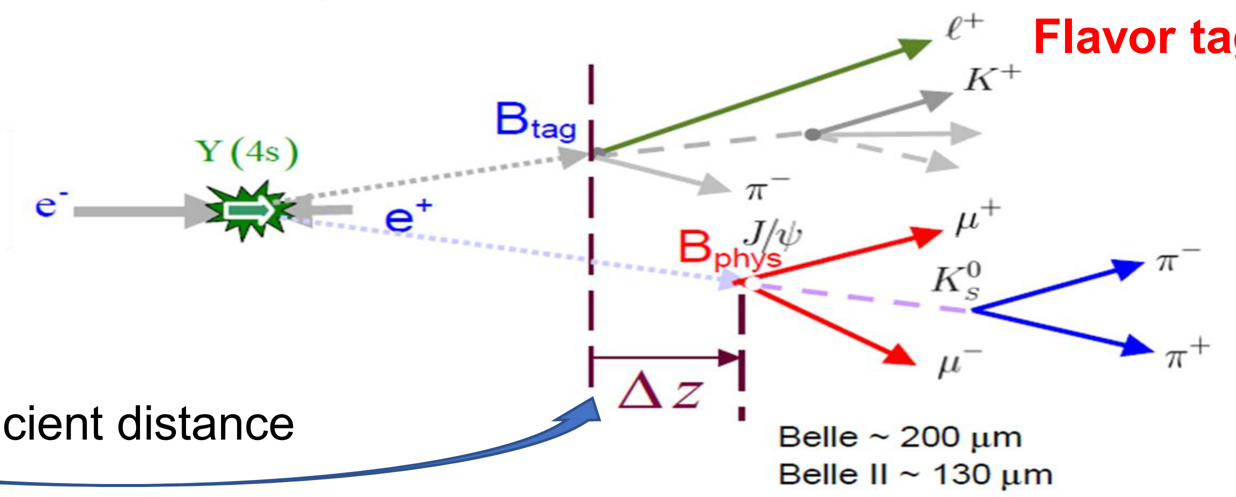
q = flavor information of tag side
Δm_d = mass difference between
Δt = distance between B-meson pairs

Flavor tagging

Asymmetric energy

Lorentz boost = 0.425

Sufficient distance

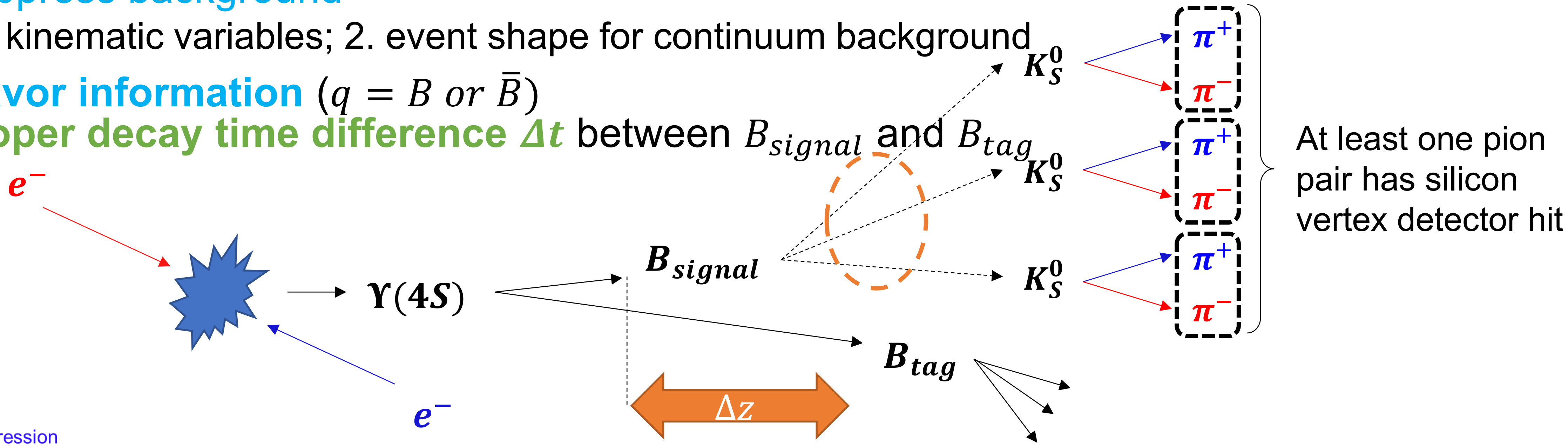


$\Delta t = \Delta z/\beta\gamma c,\ \Delta z \approx 200\ \mu m$
$\beta\gamma$= boost factor 0.425

TDCPV in $B^0 \to K_S^0 K_S^0 K_S^0$ - Analysis Procedure

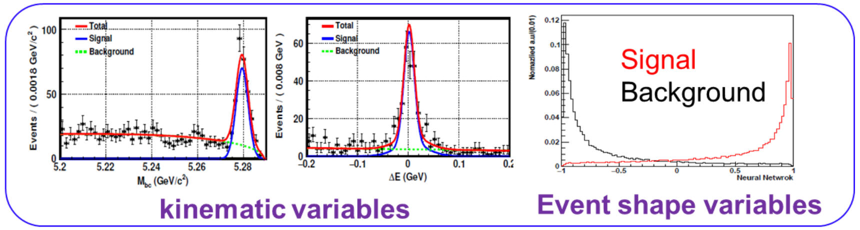
Key features
Clean environment (lepton collider)
Center of mass energy at $\Upsilon(4S)$
Asymmetric-energy

- 1. Reconstruct B_{signal} $(B^0 \to K_S^0 K_S^0 K_S^0)$ candidate and B_{tag} (generic B decay)
- 2. Suppress background
  - 1. kinematic variables; 2. event shape for continuum background
- 3. **Flavor information** $(q = B \; or \; \bar{B})$
  Proper decay time difference Δt between B_{signal} and B_{tag}

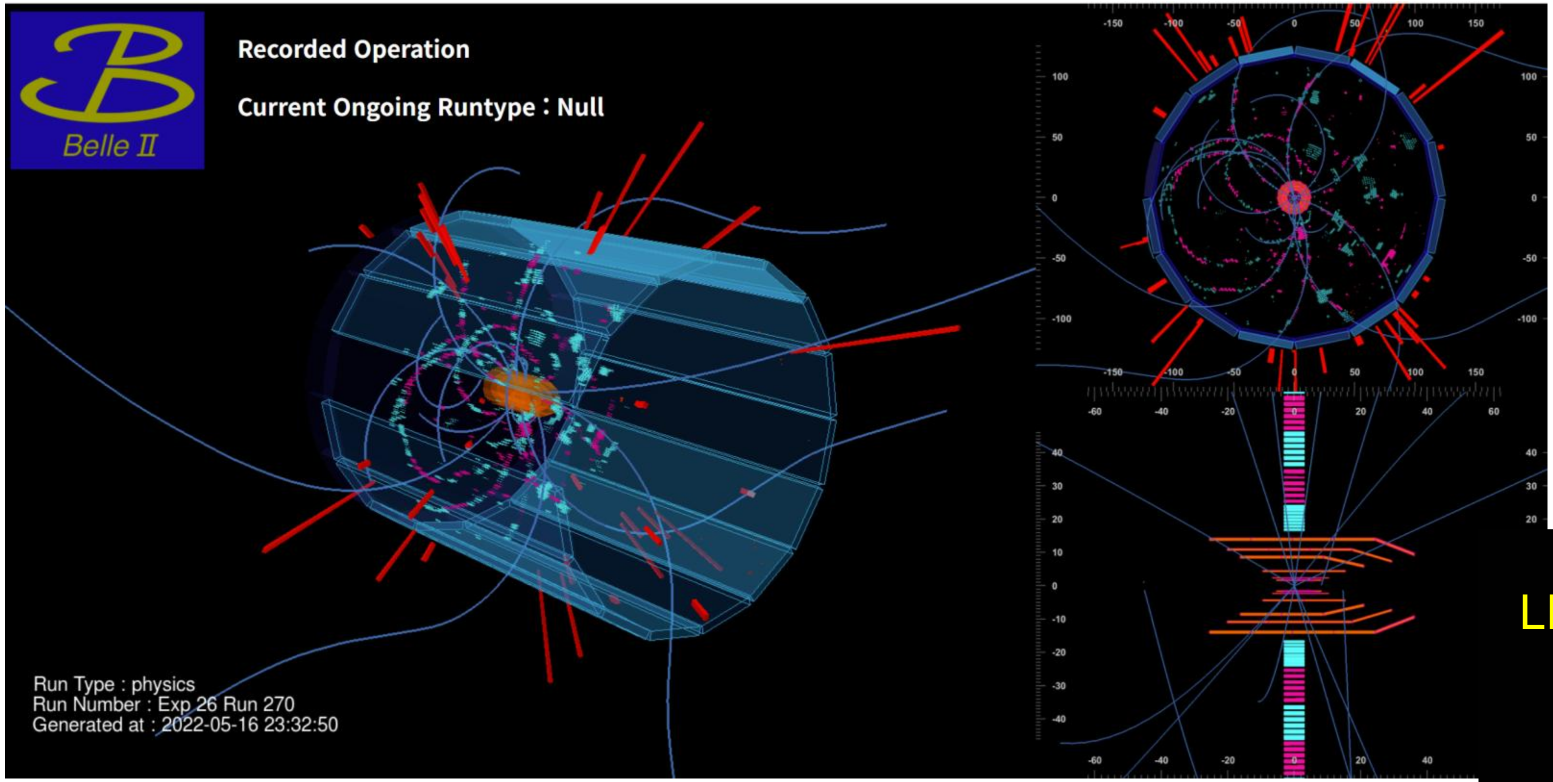


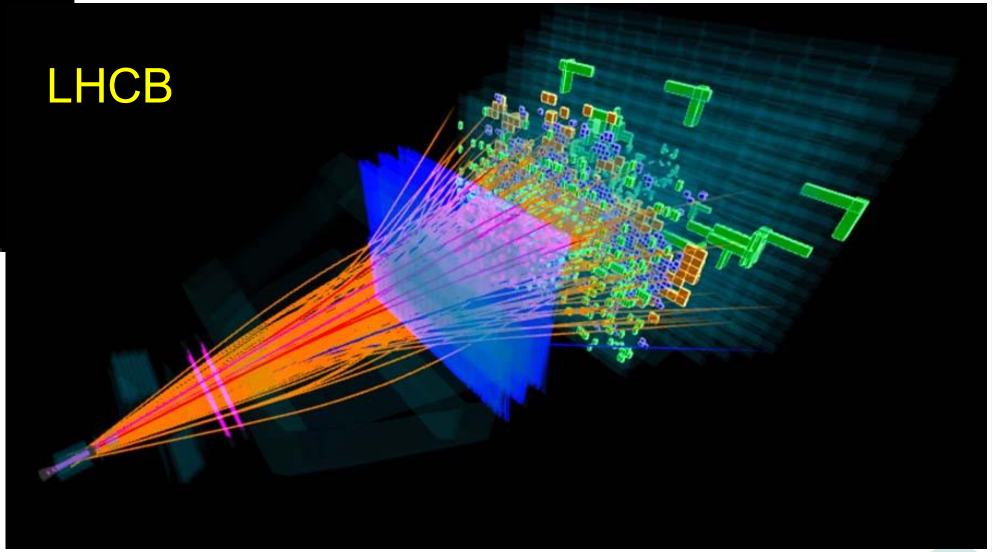
$\Delta z \approx 200\ \mu m,\ \Delta t\ (\sim ps) = \Delta z/\beta\gamma c$
$\beta\gamma$= Lorentz boost (0.425)

For background suppression

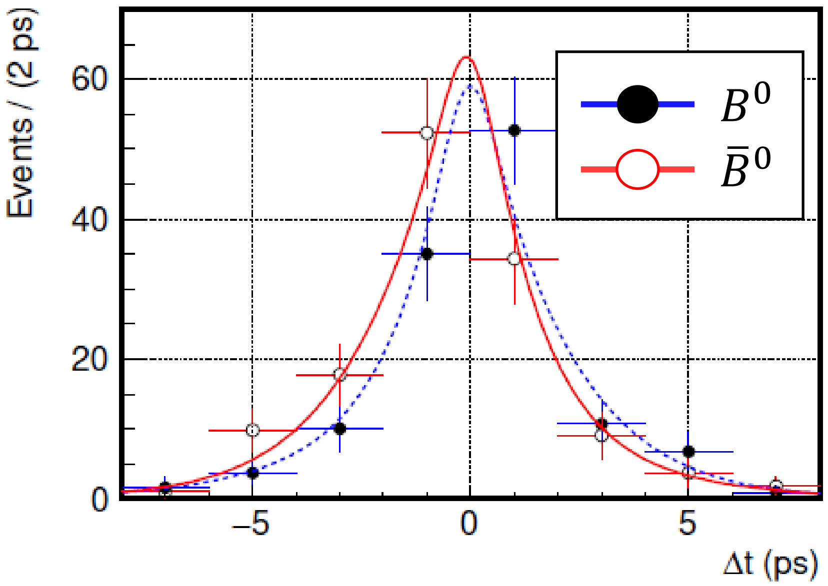


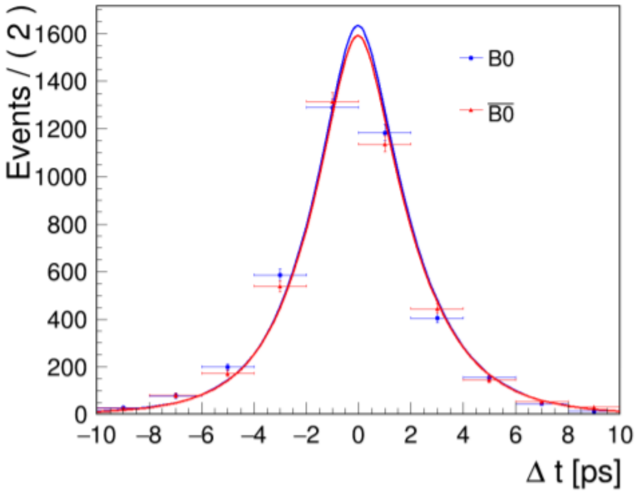
Example of event display for $\Upsilon(4S) \to B\bar{B}$





TDCPV results in $B^0 \to K_S^0 K_S^0 K_S^0$





Without TCPV

$S_{K_S K_S K_S}(B^0 \to K_S K_S K_S)$

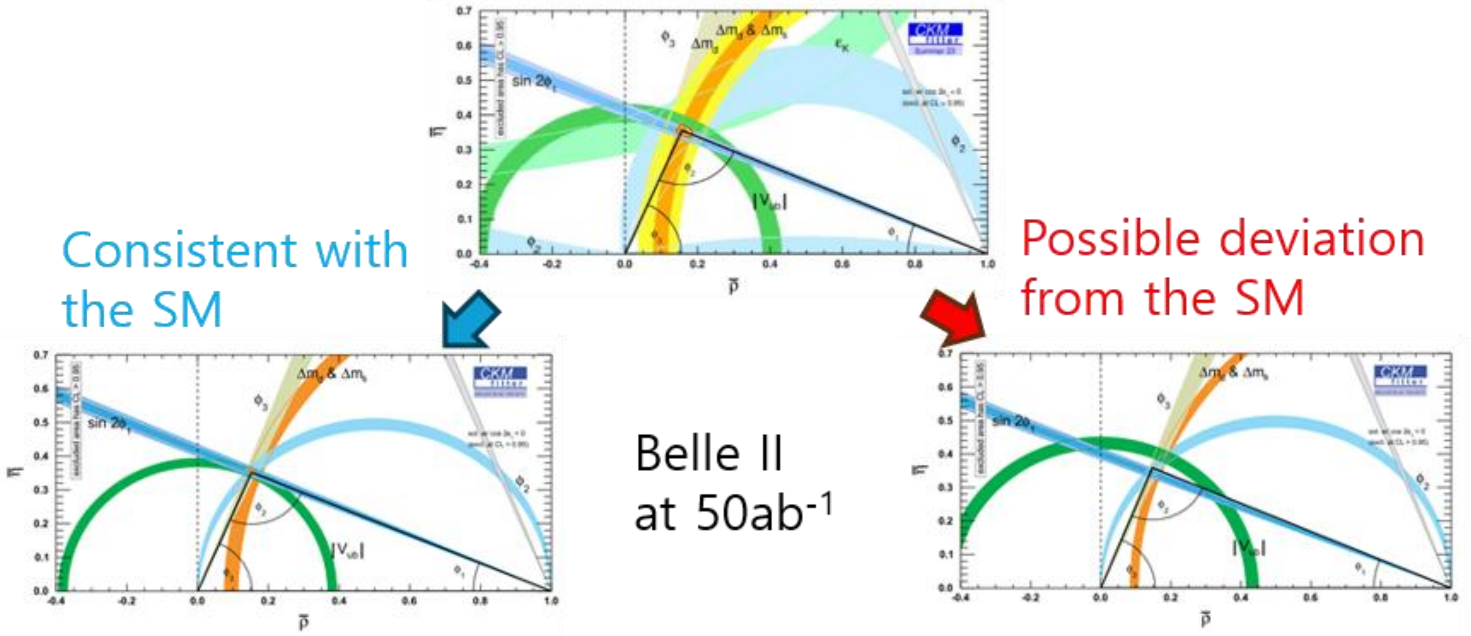
VALUE	DOCUMENT ID		TECN	COMMENT
−0.82±0.17 OUR AVERAGE				
−0.71±0.23±0.05	KANG	21	BELL	$e^+e^- \to \Upsilon(4S)$
$-0.94^{+0.24}_{-0.21}\pm0.06$	LEES	12I	BABR	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.71±0.24±0.04	AUBERT	07AT	BABR	Repl. by LEES 12I
0.30±0.32±0.08	CHEN	07	BELL	Repl. by KANG 21

- Measurement results
  - Obtained number of signal events: 258 ± 17
  - $S\ (-\sin 2\phi_1^{eff}) = -0.71 \pm 0.23\ (stat) \pm 0.05\ (syst)$
  - $C = \ 0.12 \pm 0.16\ (\mathrm{stat}) \pm 0.05\ (\mathrm{syst})$
    - Direct CP violation: $P(B^0 \to K_S^0 K_S^0 K_S^0) \neq P(\bar{B}^0 \to K_S^0 K_S^0 K_S^0)$

"World Best Sensitivity"

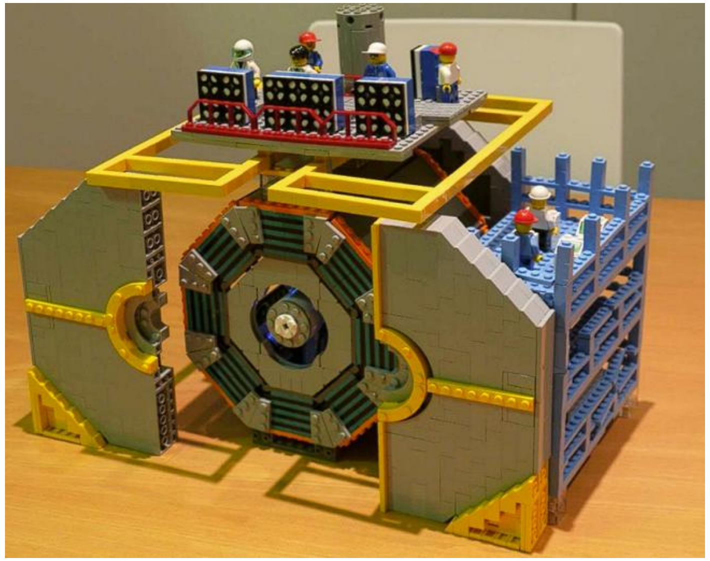
TDCPV future

CKM Unitarity Triangle: present status and Belle II reach

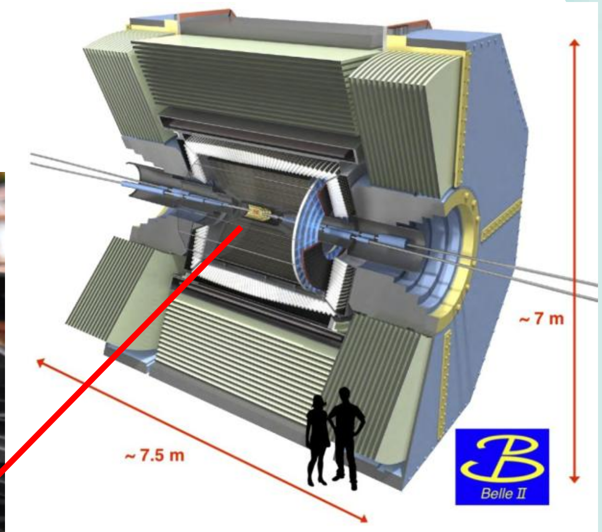


- C. Marinas (Belle II Collaboration), “The Belle II Experiment at SuperKEKB -- Input to the European Particle Physics Strategy”, arXiv.2503.24155.
- Precise TDCPV measurements require precise vertex reconstruction, which in turn demands an excellent silicon vertex detector.

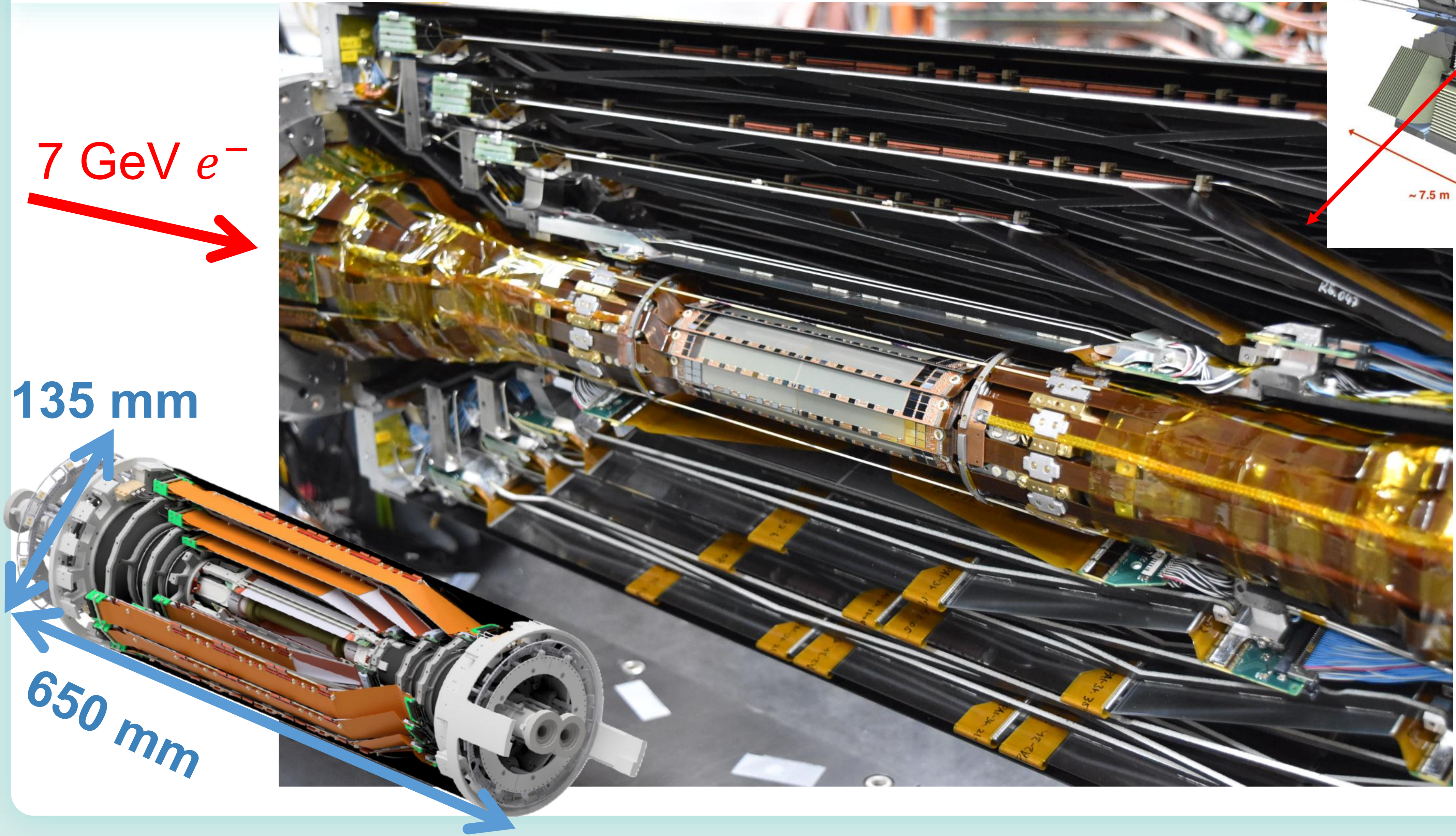
Silicon Vertex Detector



Silicon Vertex Detector (SVD)

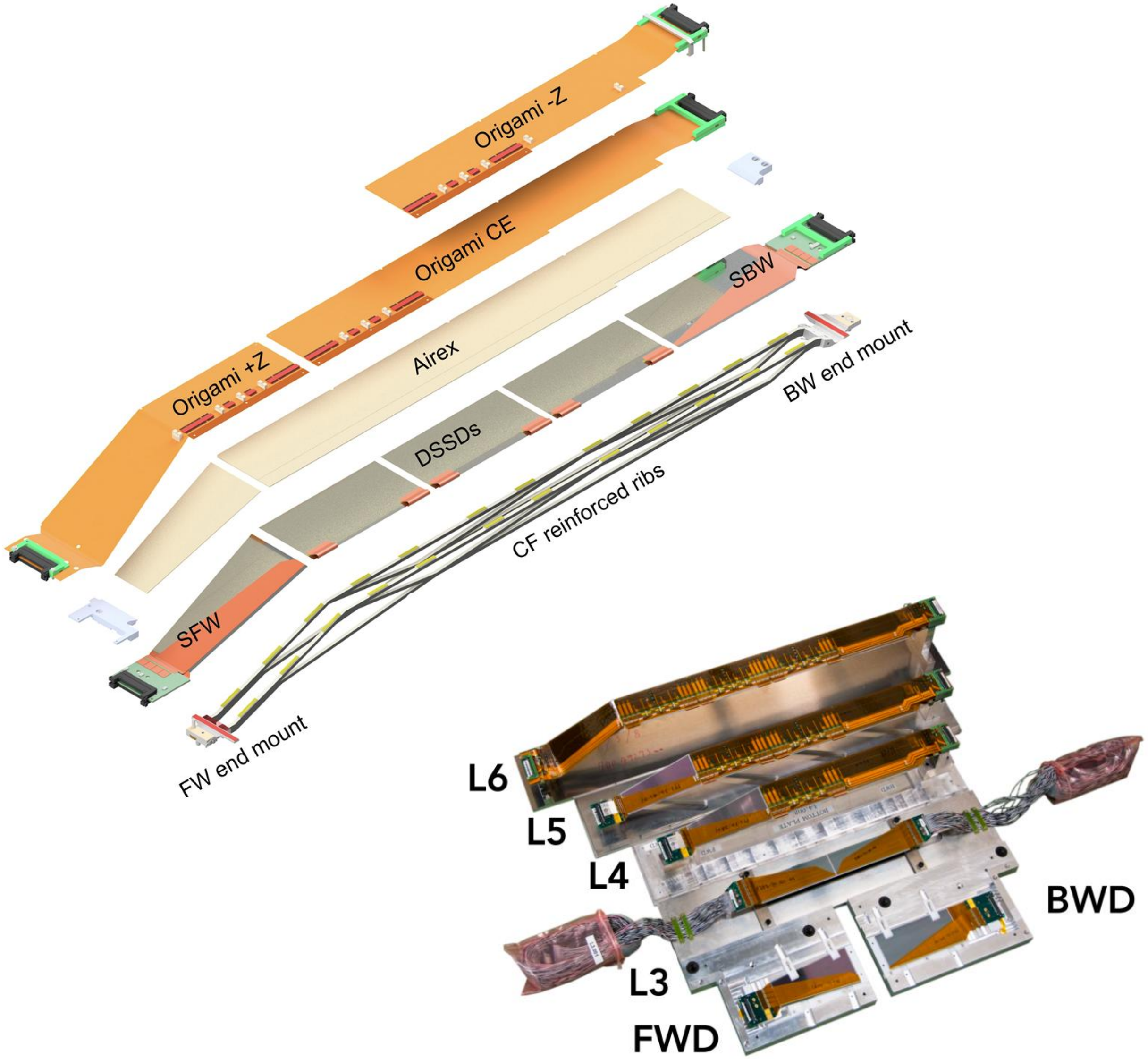


7 GeV e^-

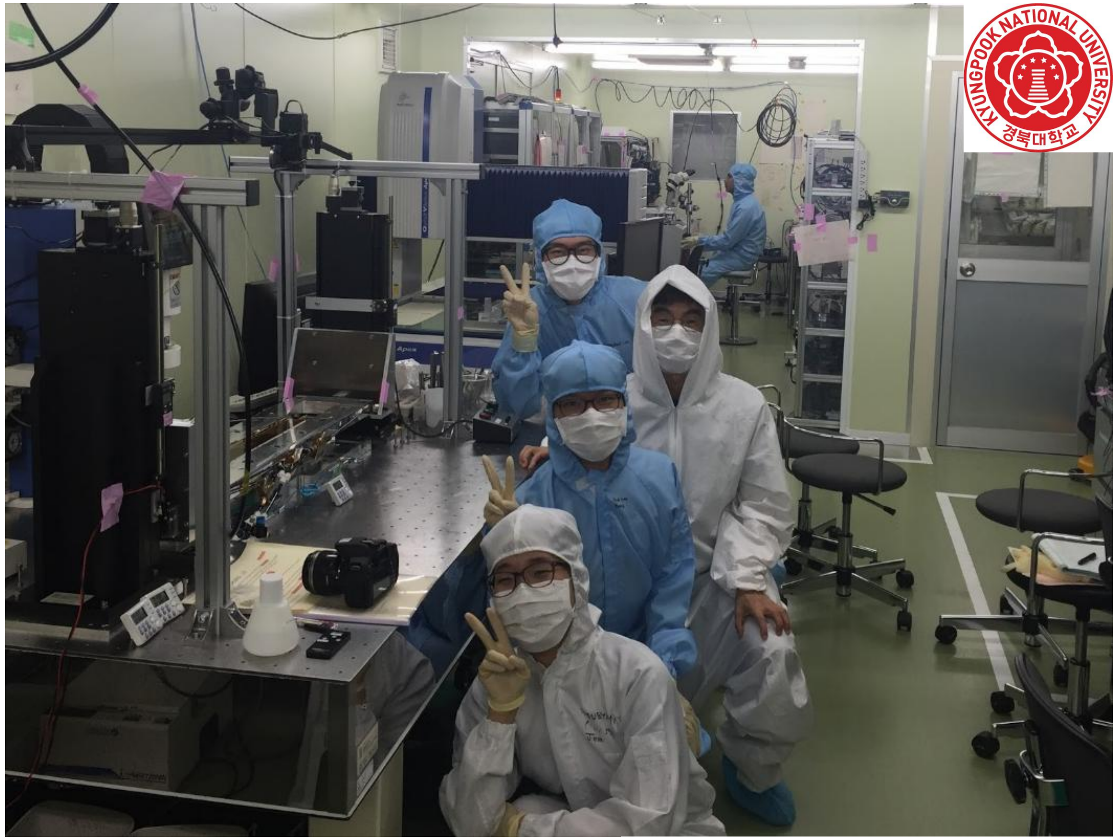


8 GeV e^+

Ladder



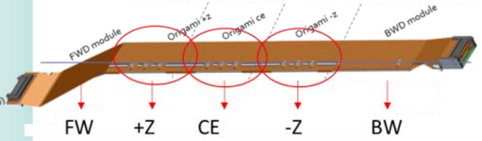
Origami -Z
Origami CE
Airex
SBW
BW end mount
Origami +Z
DSSDs
CF reinforced ribs
SFW
FW end mount
L6
L5
L4
L3
FWD
BWD



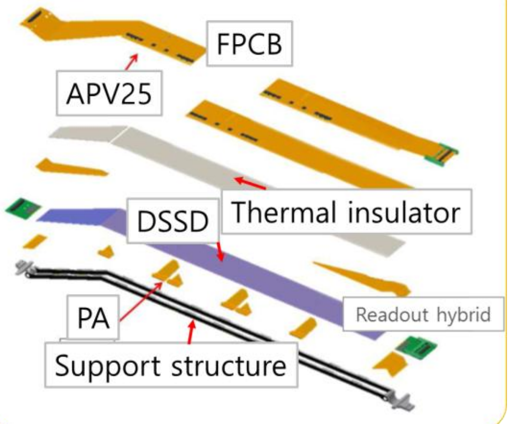
SVD – construction

FRAGILE
HANDLE WITH CARE

Components of the L6 ladder



- 5 DSSD modules on L6
- Components
  - Hybrid board (2)
  - FPCB (3)
  - Flexible pitch adapter (PA)
  - DSSD (5)
  - Support structure (2)
  - etc.



Assembly Procedure

Repeat

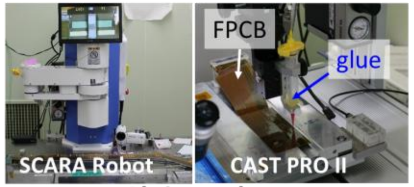
Sensor Alignment

- Jig with O(20 μm) tolerance
- Precision is measured by a CMM (Coordinate measuring machine).

CMM

Gluing

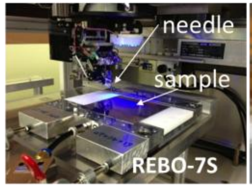
- Adhesive: epoxy (Araldite 2011)
- Glue is spread by gluing robots.



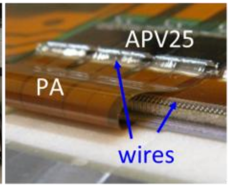
Gluing robots

Electrical connection*

- Wire-bonding
- Al (Si 1%) wire with Φ=25 μm

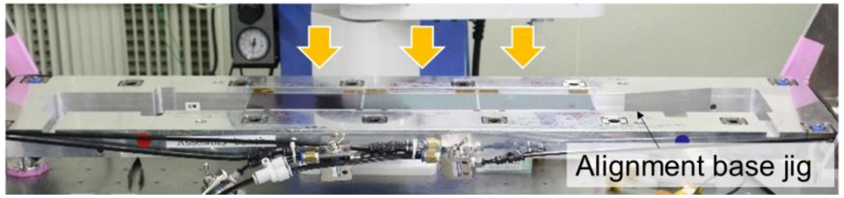


Wire-bonder

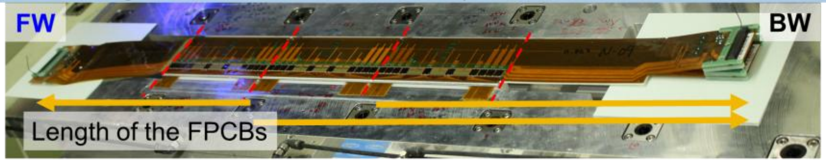


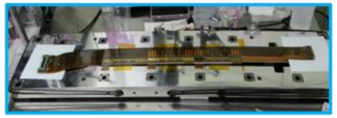
Bonded wires

Align the DSSDs on the alignment base jig.



Attach the thermal insulator and the Origami FPCBs, and then perform wire-bonding between the FPCBs and top side of the DSSDs.

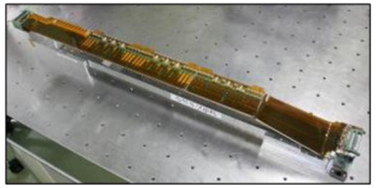




central sensors

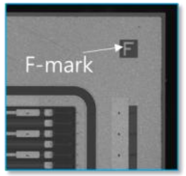
+

end sensors

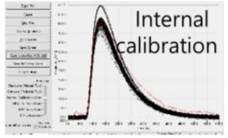


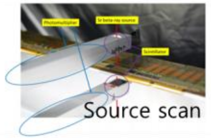
Complete ladder assembly

Ladder quality

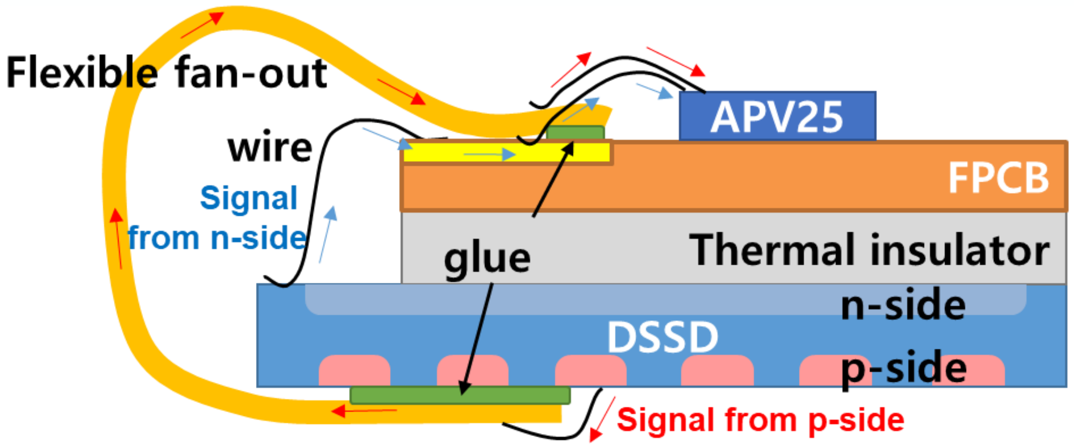


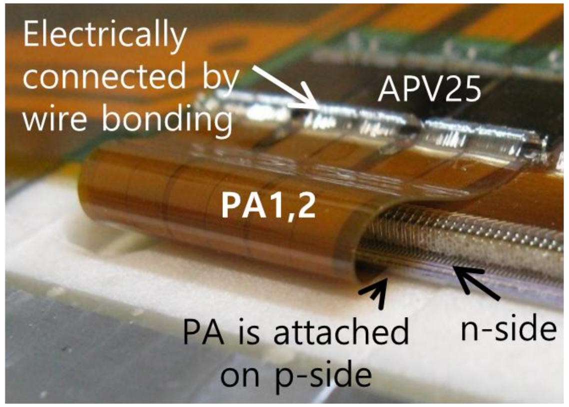
- **Mechanical** quality is verified by F-mark positions on the sensor using the CMM.

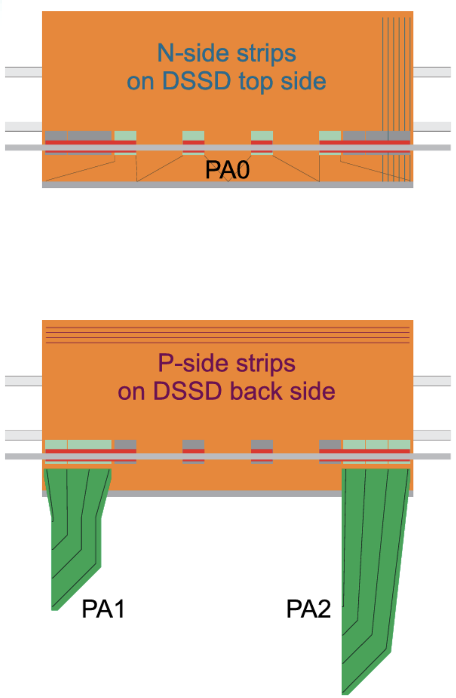




ORIGAMI

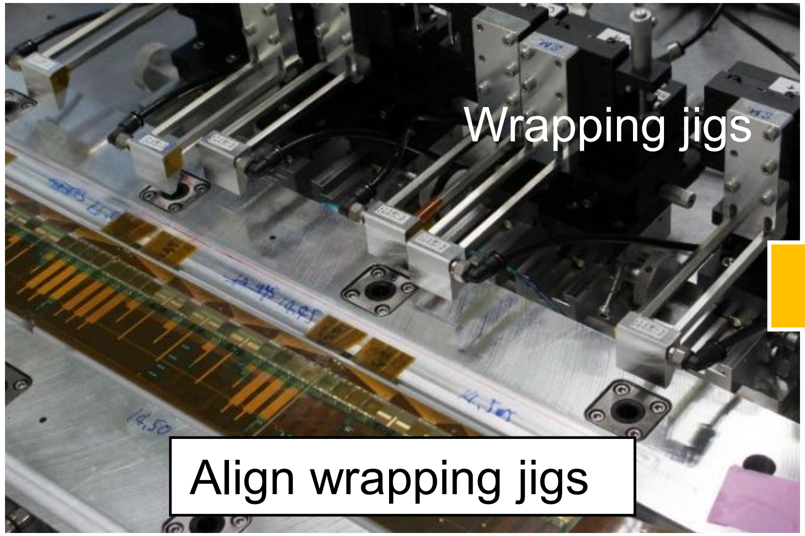


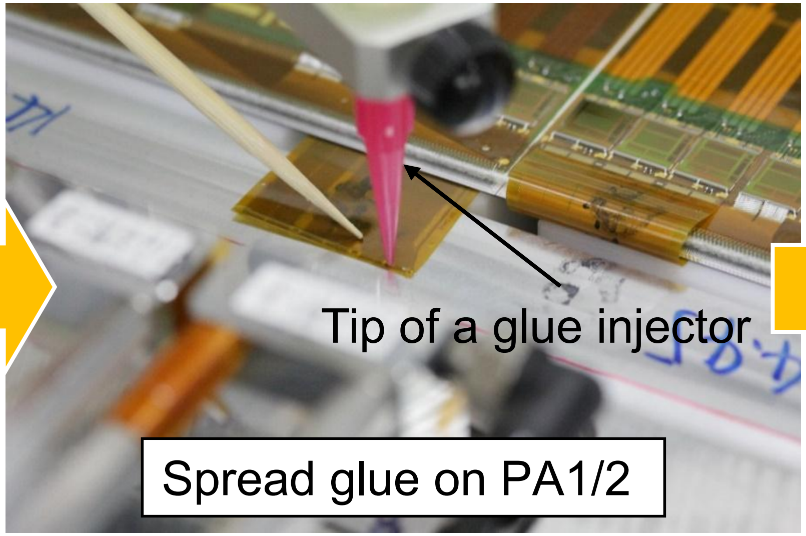


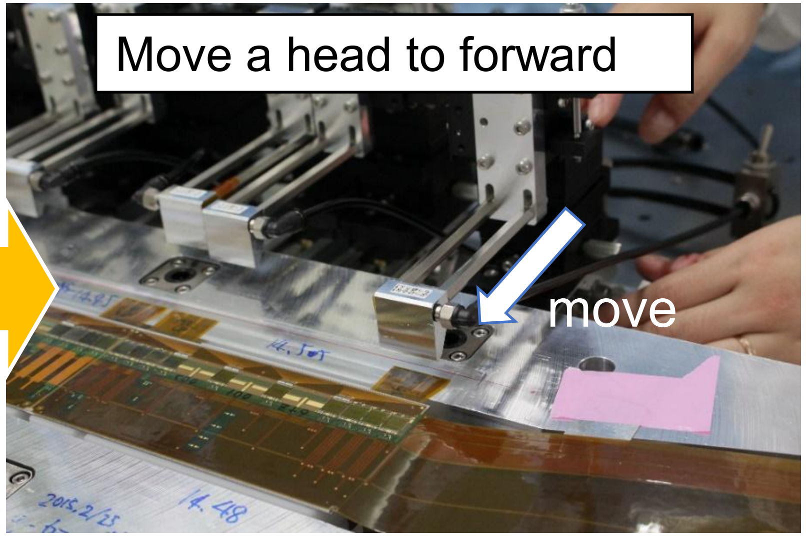


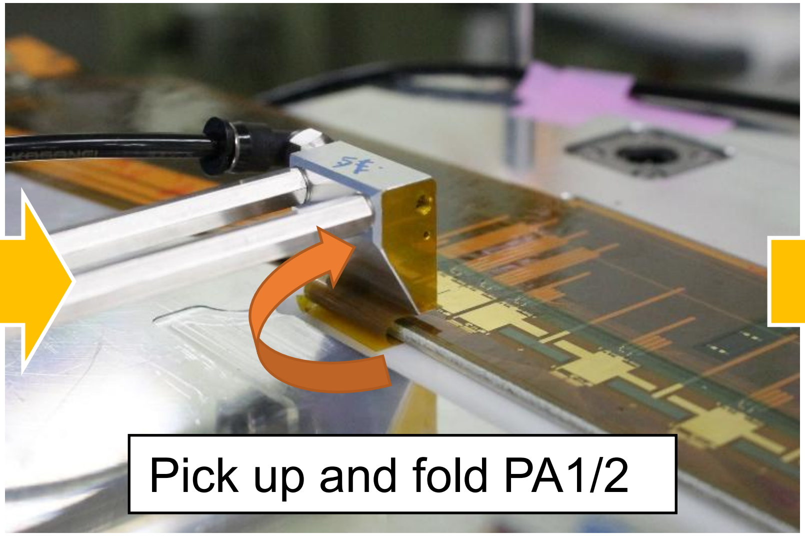
Low material budget: 0.7%X_0 per layer
Low noise due to the short sensor–APV25 connection length

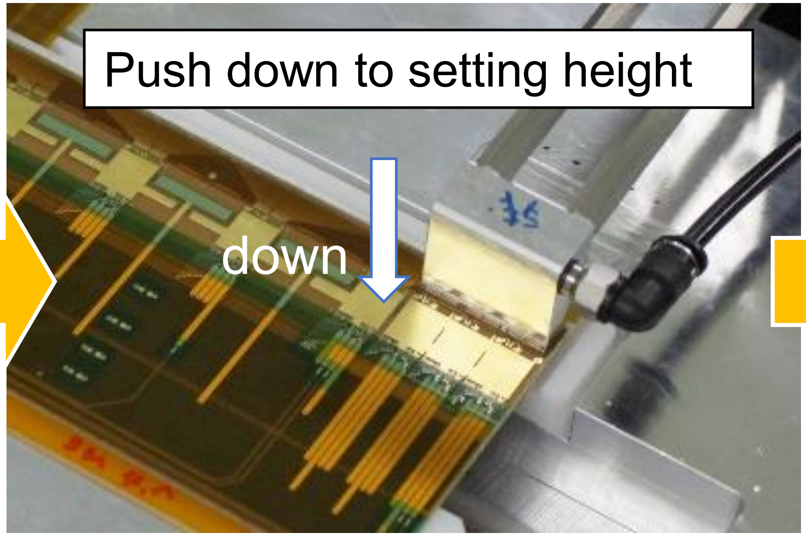
Gluing - Wrapping Procedure

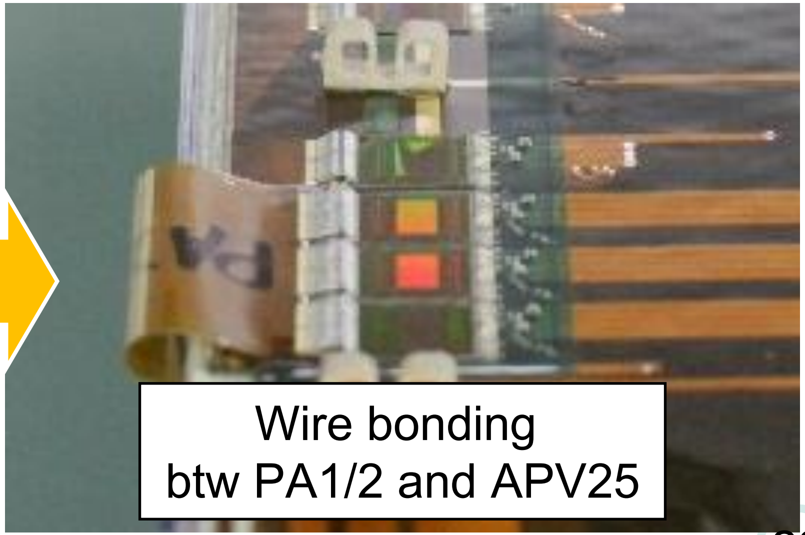




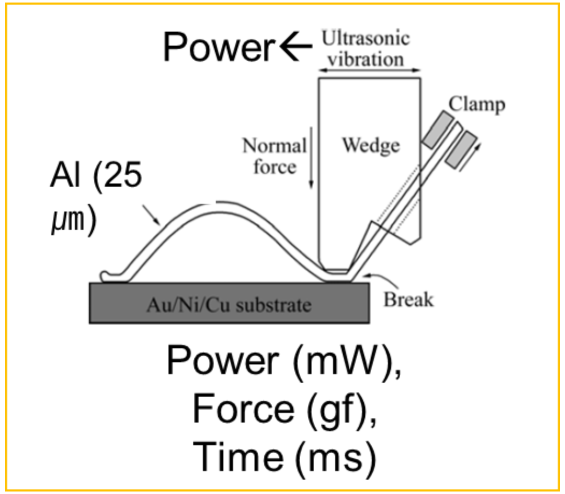


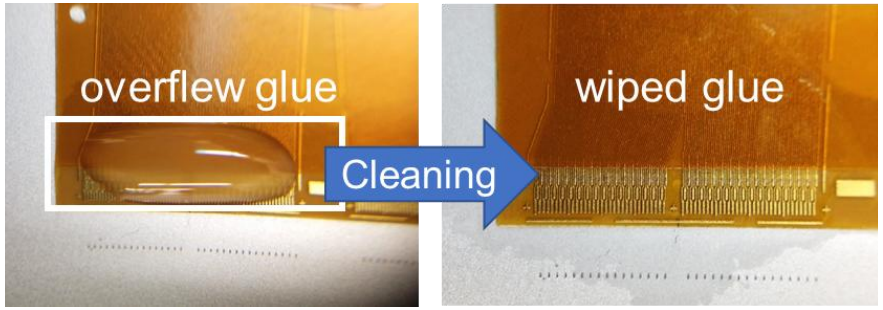




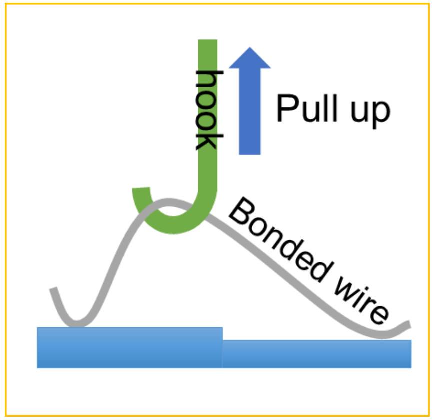


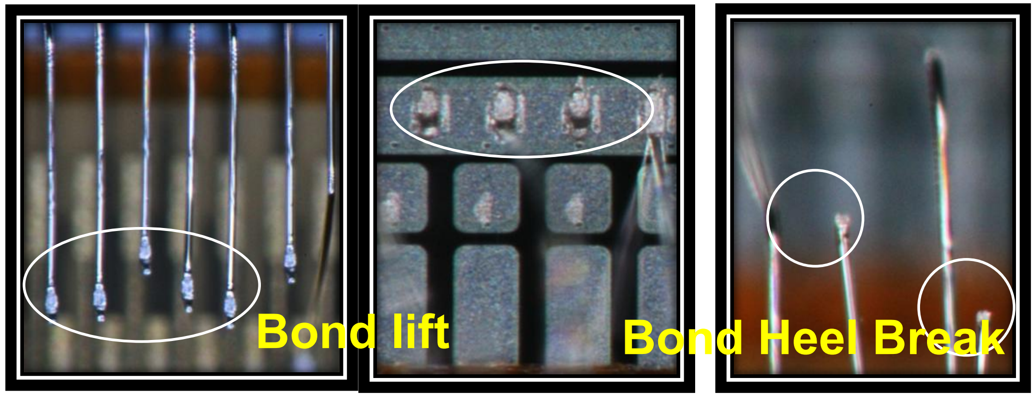
Wire bonding





Optimized bonding parameters and gluing quality led to a 99% bonding efficiency
- validated by pull-force measurements and bond pad inspections.





As a SVD deputy leader since Feb. 2023

- Management human resources

65 people from 16 institutions in 6 countries

Author	Task agreed	Start date	Expected end date (authorship qualification)	Description
Alice Gabrielli (now Ph.D. student, Trieste)	Mar 2021	Dec 2019	Oct 2020 (completed)	• In-depth characterization of di comparison with a reference s • Documentation of the results:
Mirco Dorigo (INFN staff researcher, Trieste)	Mar 2021	Jan 2020	Oct 2020 (completed)	• Supervision for all the analysis update of the Belle II radiation • Documentation of the results:
Sagar Hazra (Ph.D. student, TIFR)	Jun 2020	Jun 2020	Nov 2020 (completed)	• SVD operation and data moni • Leading role in SVD dE/dx cal conference. • Documentation of results: BEL
Rahul Tiwary (Ph. D. student, TIFR)	Jul 2020	Aug 2020	Feb 2021 (completed)	• Participation in the SVD opera • Develop the calibration of SVD • Documentation on results: BE

- Publication

Re-installation and performance of the
Belle II Silicon Vertex Detector

Belle II SVD paper, JINST, 17, 2022

42nd International Conference on High Energy Physics – ICHEP 2024

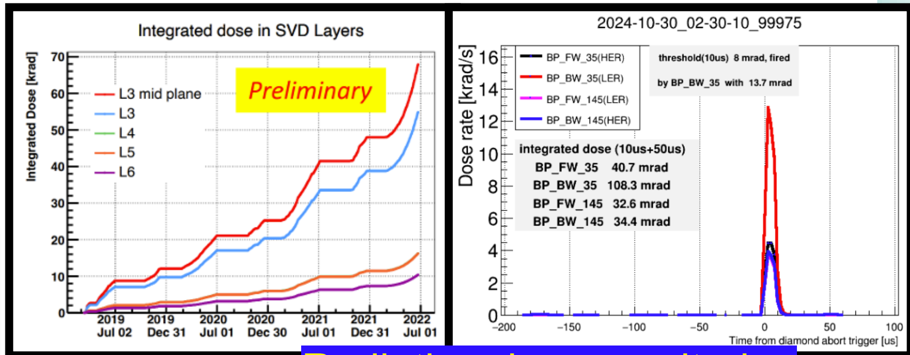
17-24 July, 2024, Prague – Czech Republic

Average 4 talks & 2 posters / year

The Silicon Vertex Detector of the Belle II Experiment

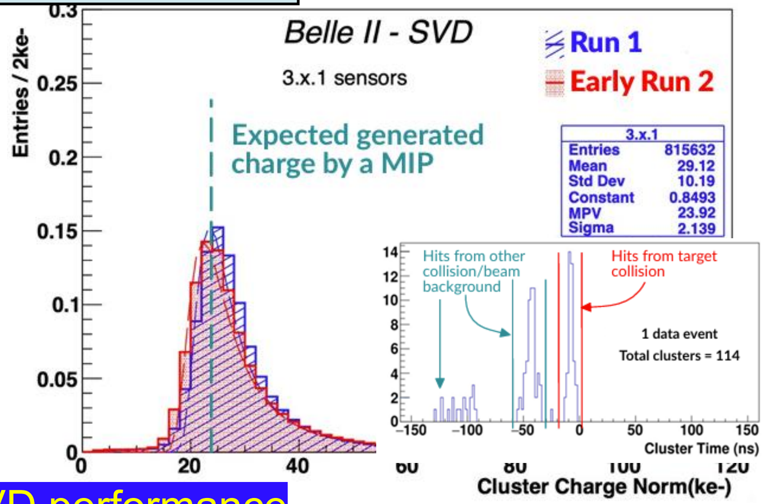
Kookhyun Kang - Kavli IPMU
on behalf of the Belle II SVD Collaboration
VERTEX 2022 Oct 24, 2022

- Radiation with diamond sensor



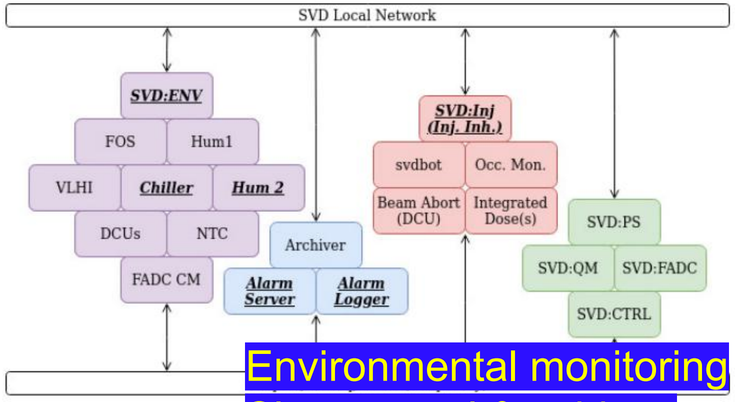
Radiation dose monitoring
& beam bort system

- Offline SW



SVD performance
& beam bkg. rejection

- Online SW



Environmental monitoring
Slow control & achieve

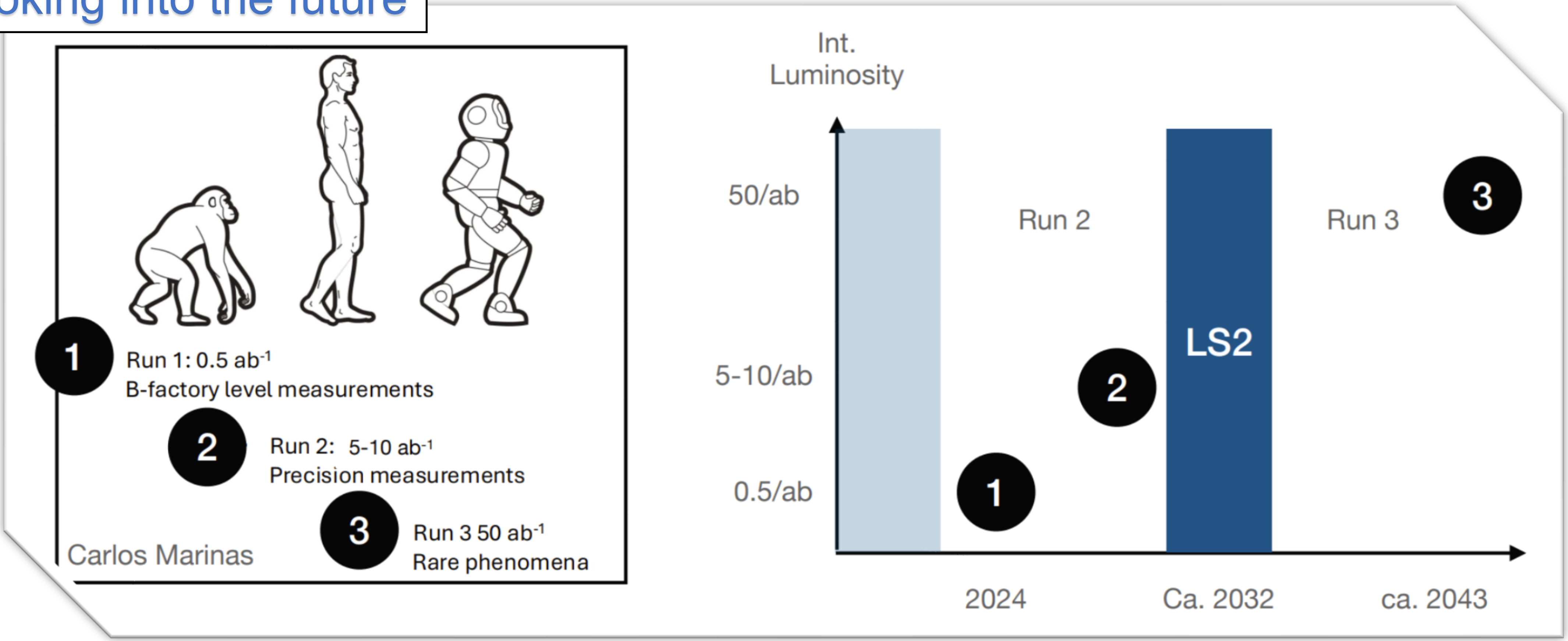
- SVD operation

First collisions of run 2 at the end of February 2024
'When we were young'

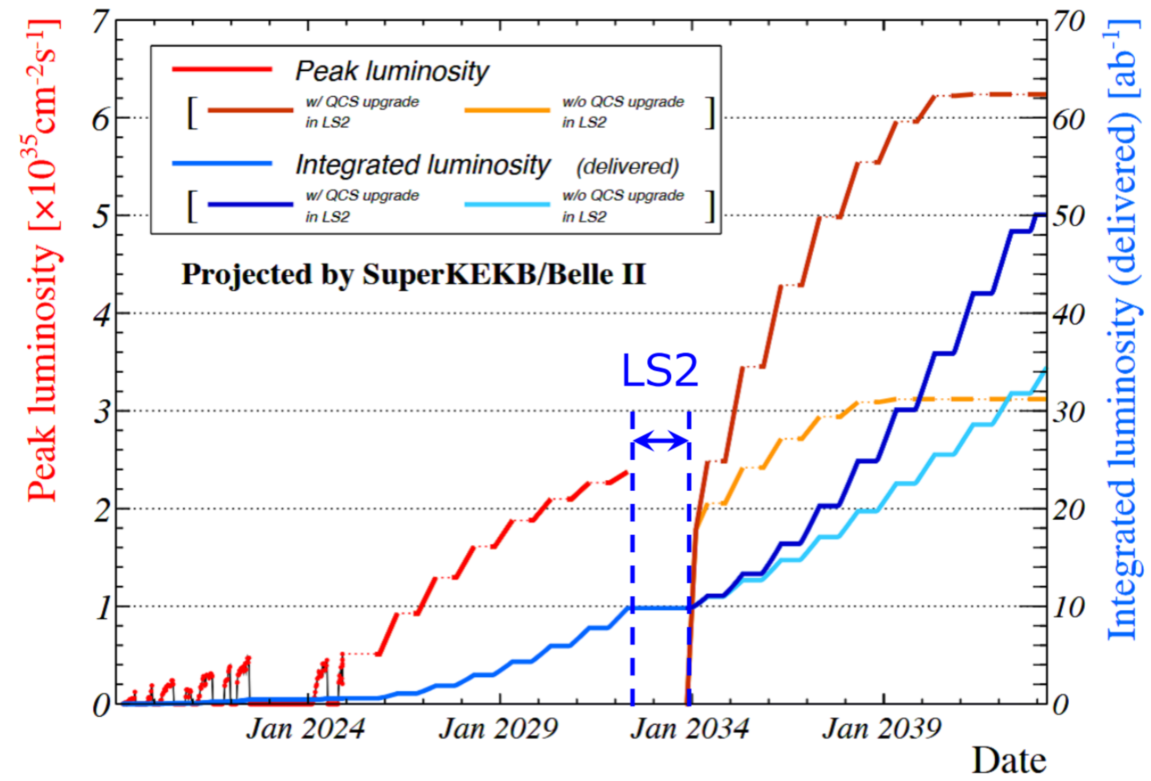
With three SVD
operation coordinators

Timeline for VTX upgrade

Looking into the future

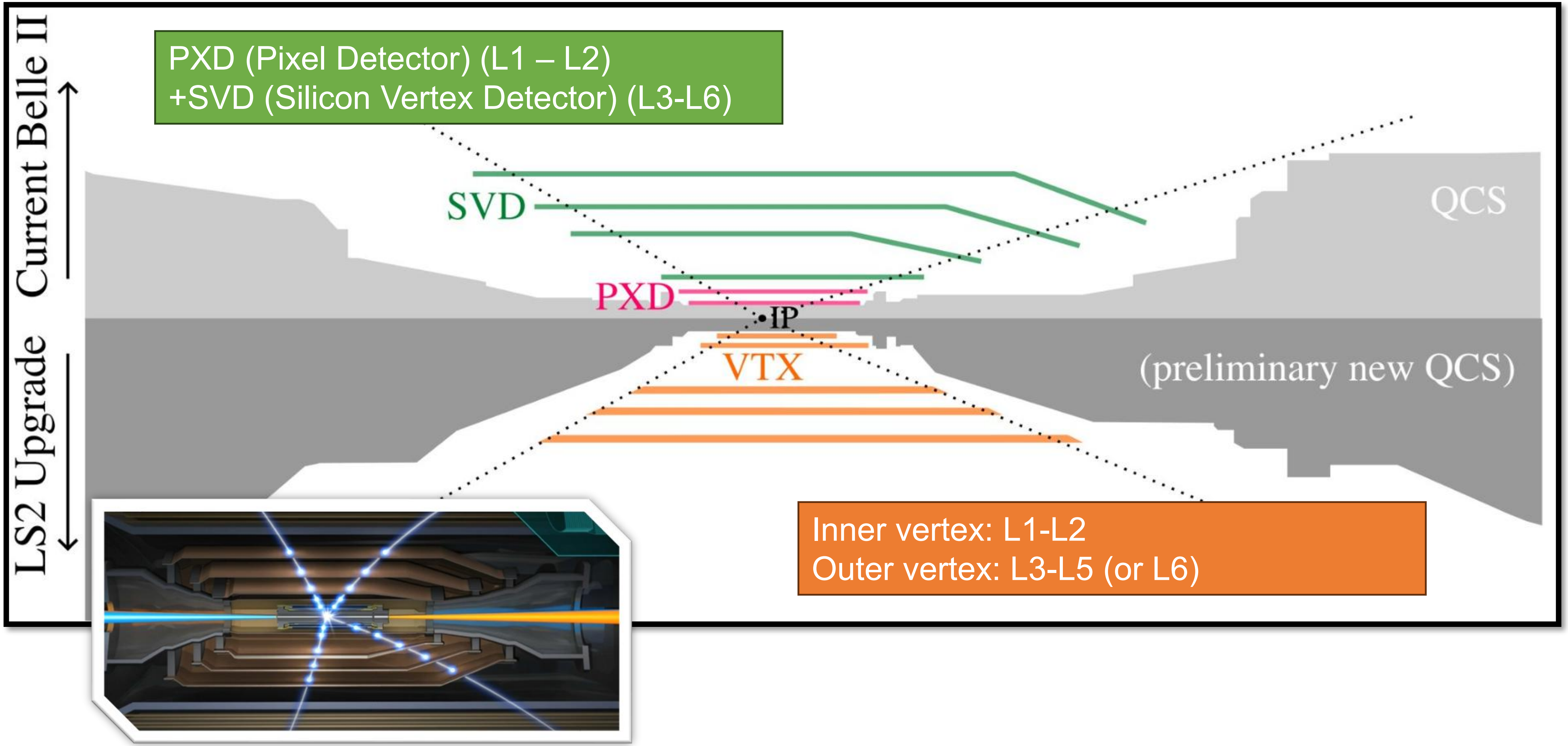


Super KEKB upgrade

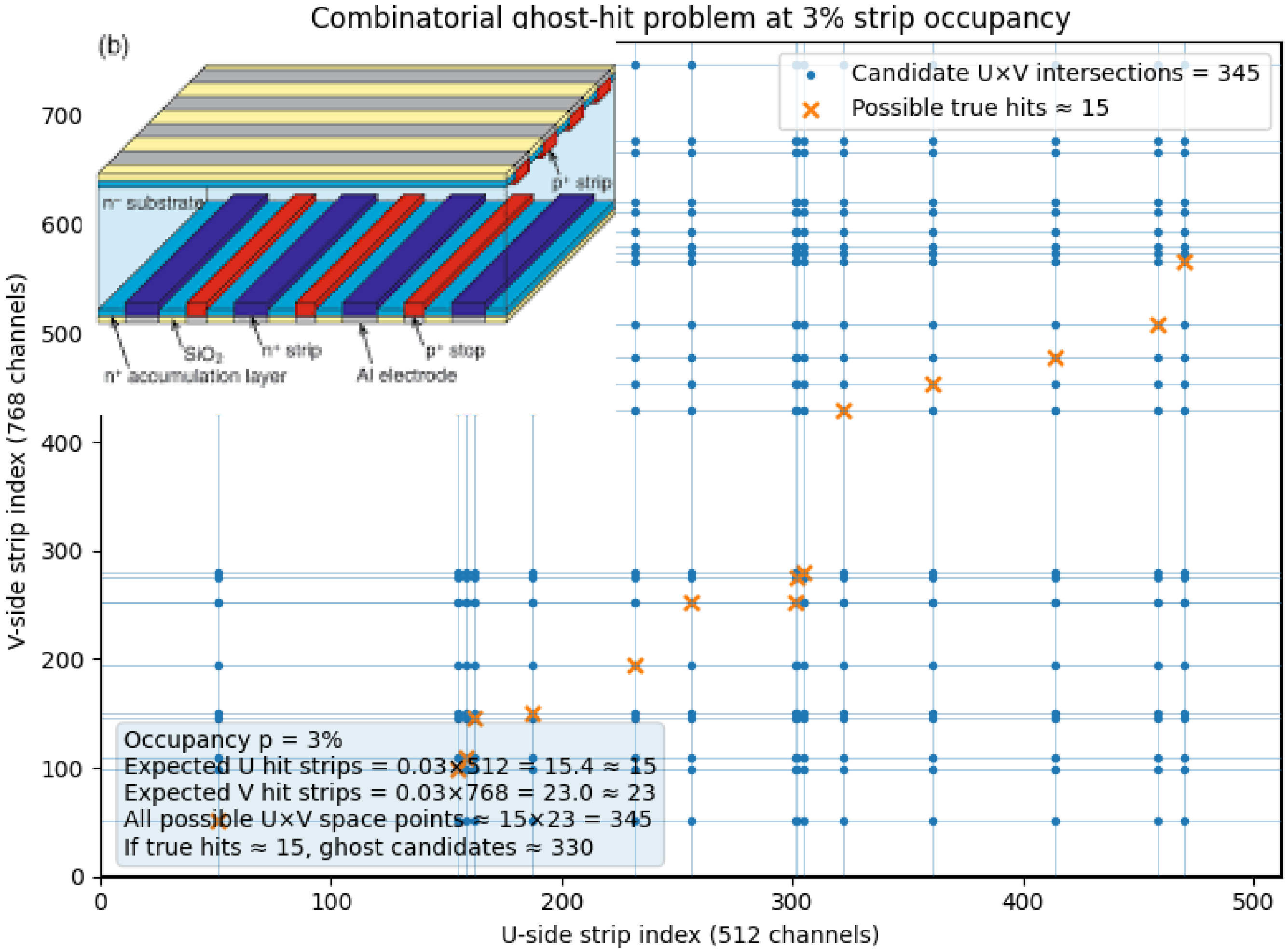


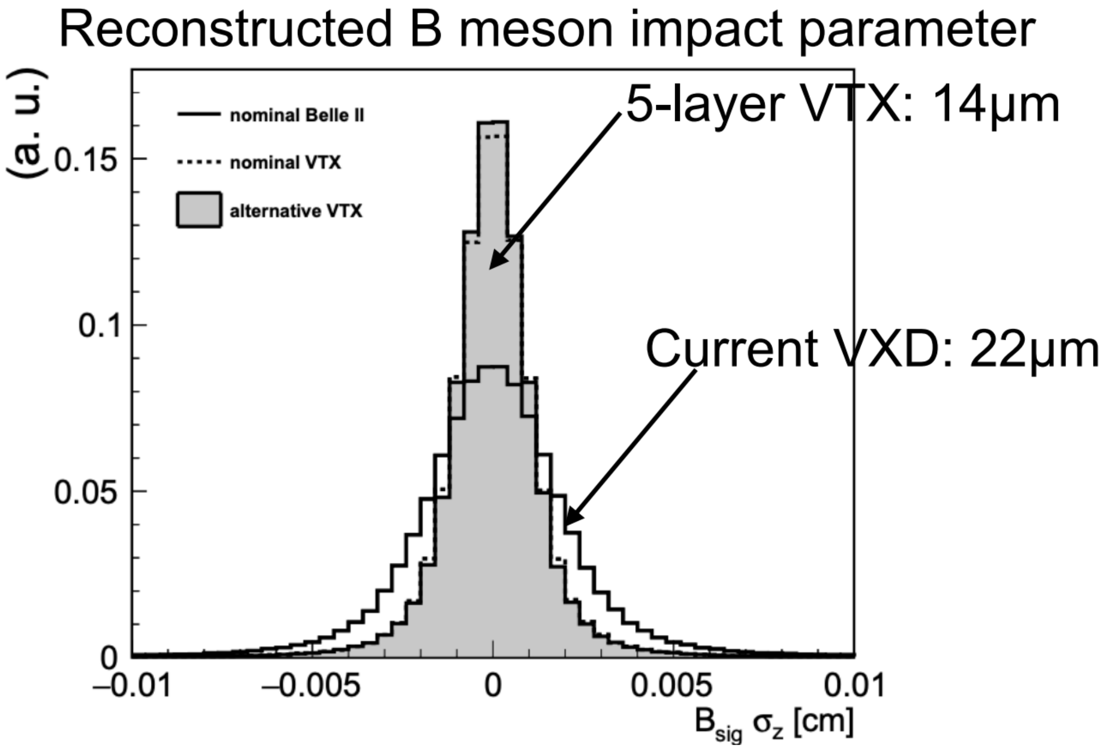
- To achieve higher luminosity at SuperKEKB, several accelerator systems must be upgraded, including the IR and QCS.
- As a consequence, the VTX must also be upgraded, both to match the new IR/QCS geometry and to operate reliably under the increased hit rate

Vertex Detector (VTX) - motivation



Vertex Detector (VTX) - motivation

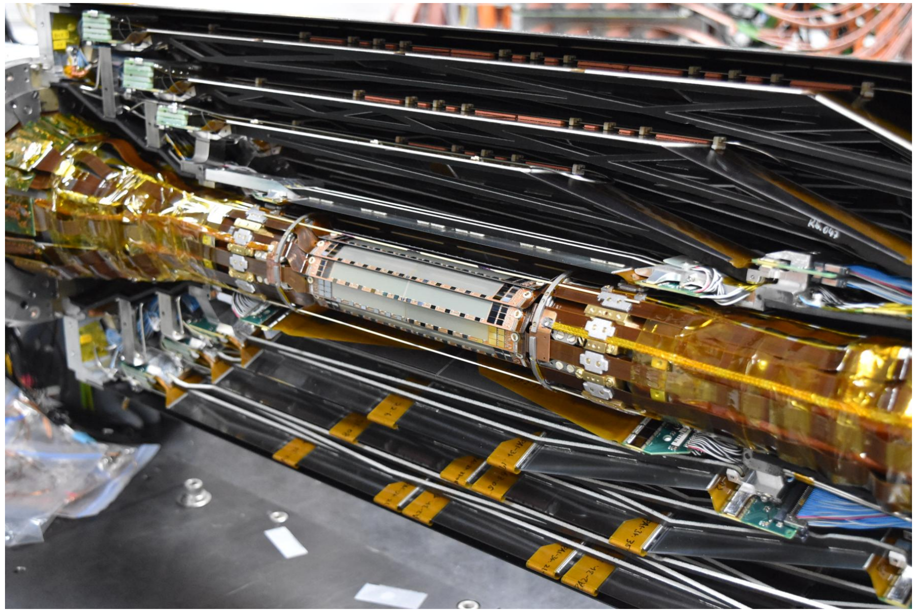




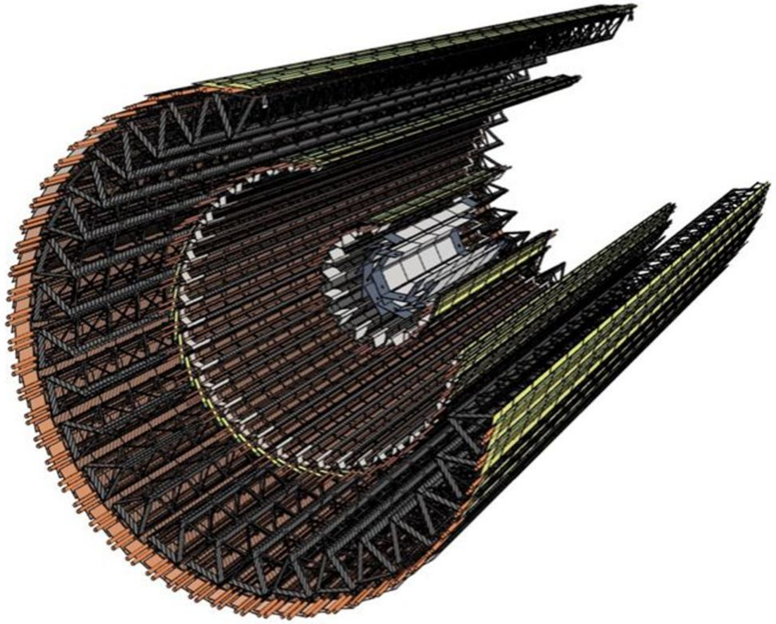
True hit: 15

Fake (ghost) hit= 330

Vertex Detector (VTX) - 1



PXD (Pixel Detector) (L1 – L2)
+SVD (Silicon Vertex Detector) (L3-L6)

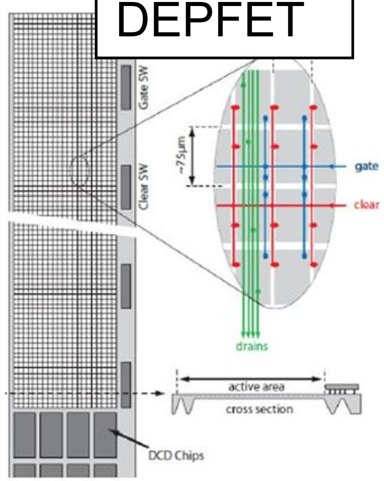


Inner vertex: L1-L2
Outer vertex: L3-L5 (or L6)

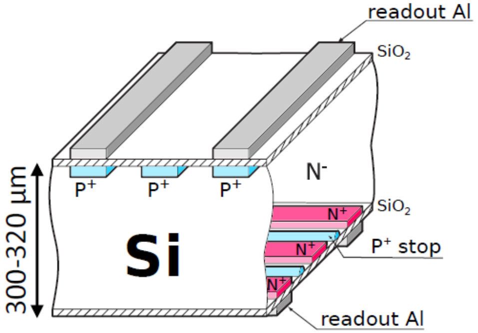
Material budget: 3.5% X/X0 → 3.0% X/X0
->sensor thickness 300 (SVD) -> 50 (VTX)
Radiation dose: 100 $MRad$

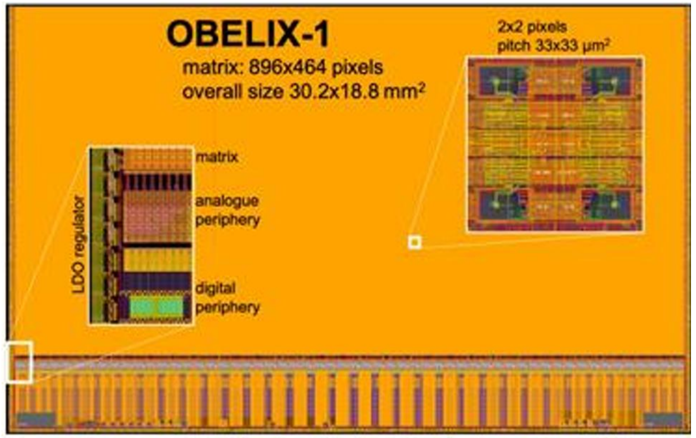
Vertex Detector (VTX) - 2

DEPFET



Double-sided
Strip Silicon Sensor

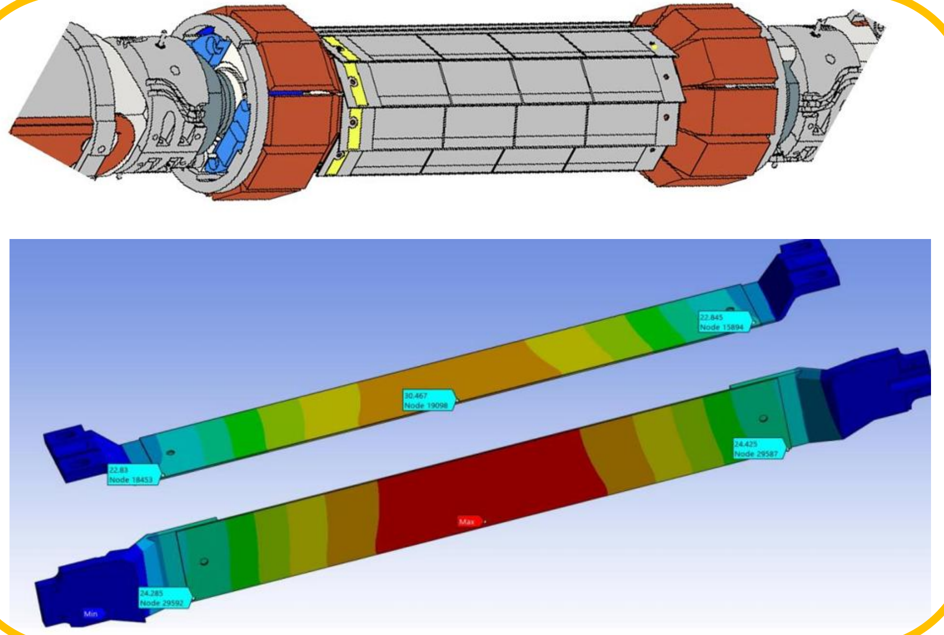




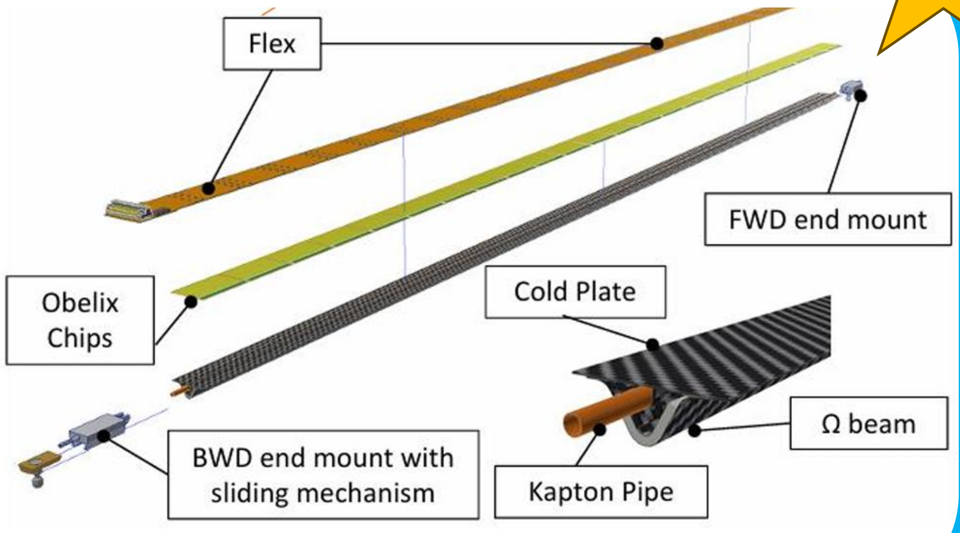
- Monolithic Active Pixel Sensor (MAPS) technology (sensor + readout)
  - OBELIX (Optimised BELle II monolithic pIXel) Sensor, based on TJ-Monopix2 prototype (developed for HL-LHC ATLAS)
- Based on beam test results of TJ-Monopix2, the OBELIX design is now being finalized.
  - First OBELIX → around the end of 2026

Hit rate: 120 $MHz\ /\ cm^2$ $\approx$ 4 x conservative bkg scenario
Trigger logic: $4\ \mu s\ \rightarrow 10\ \mu s$
Spatial resolution: $20\ \mu m\ \rightarrow 15\ \mu m$

Vertex Detector (VTX) - 3



Inner VTX



Outer VTX

- Inner VTX
  - Self-supported all-silicon modules
  - Cooling system is under development
    - with heat-conductance material (TPG)

✓ Outer VTX
  - Carbon-fiber structure with Airex foam as core material
  - Cold plate with liquid cooling

Summary

- Belle & Belle II experiment
  - Time-dependent CP violation
- Silicon Vertex Detector
  - Also silicon R&D in lab

- Future Plan
  - VTX upgrade for Belle II LS2
  - BIC silicon senso assemble for EIC
  - Silicon R&D and application

- Establish a Silicon Detector Group at KNU
  - Collaborate with colleagues at KNU and KSHEP

Belle II collobration

As of April 2026

- 1,200 members
  - 700 PhDs and PhD students
- 120 institutions from 28 countries/regions

• Chonnam National University, • Hanyang University, • KISTI, • Kyungpook National University, • Soongsil University, • Chung-Ang University, • Korea University, • Seoul National University, • Sungkyunkwan University, • Yonsei University