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

Belle II SVD paper, JINST, 17, 2022

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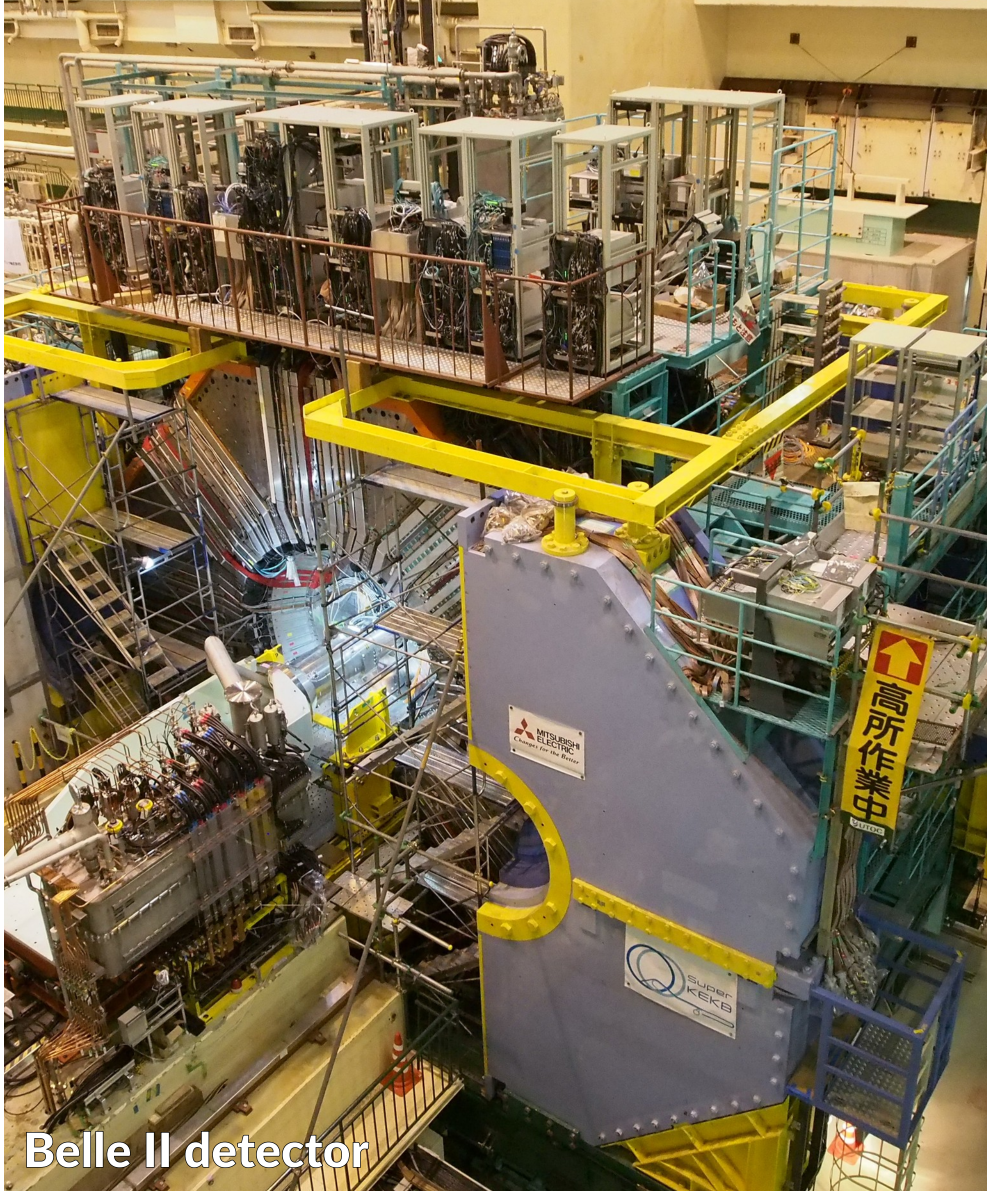
Outline

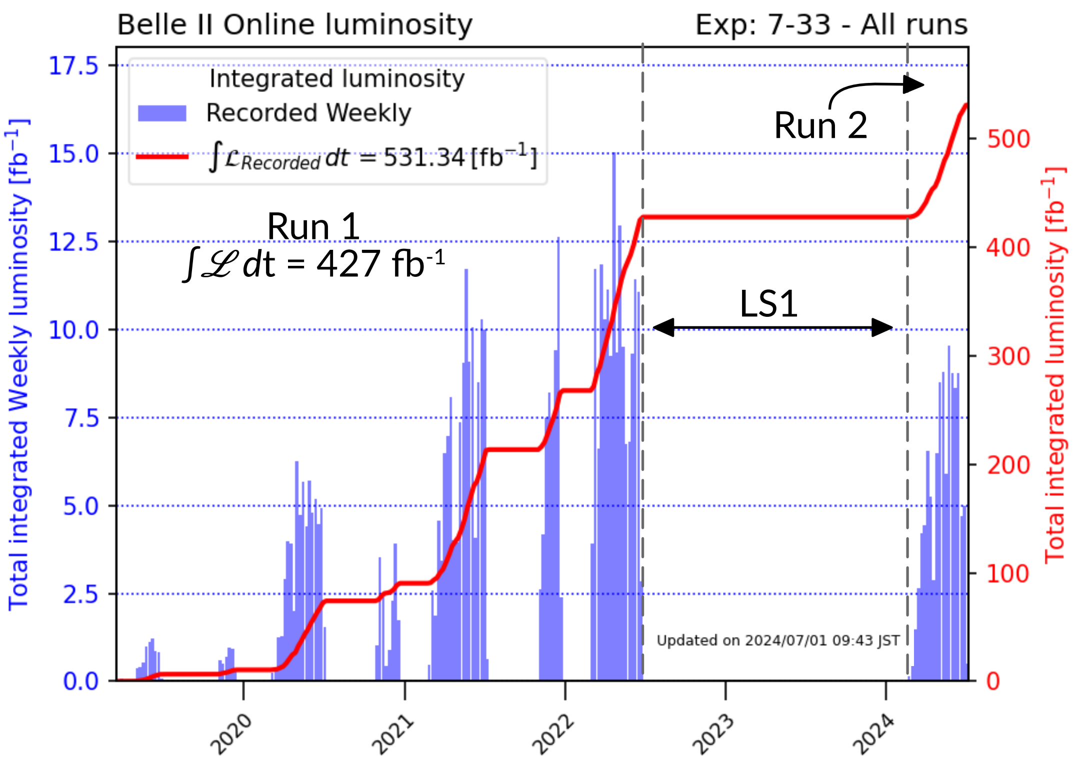
- The Belle II experiment and the Silicon Vertex Detector (**SVD**)
- **SVD** operations and performance
  - → From Run 1 to Run 2, through the long-shutdown (LS1)
- **SVD** towards the high luminosity
- Summary and conclusions

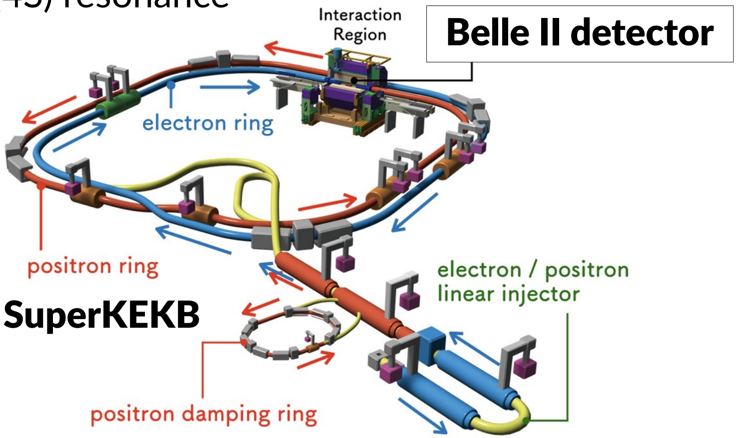


The Belle II experiment at SuperKEKB

[1] K. Nakamura on "The Belle II Upgrade Program" (at 8:48)

- **Belle II** Luminosity-frontier experiment that searches for physics beyond the Standard Model
- **SuperKEKB** Asymmetric e^+e^- collisions mainly at 10.58 GeV, i.e. at the Y(4S) resonance





- **Long-shutdown (LS1)** Several accelerator and detector maintenance and improvements

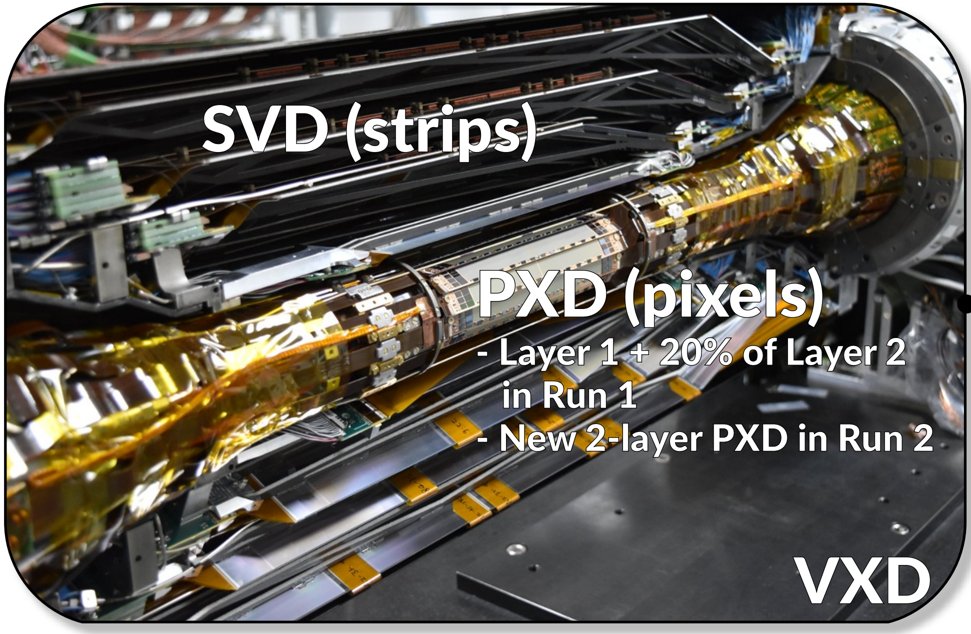
Target	Achieved
$\int \mathcal{L}\, dt = 50\ \mathrm{ab}^{-1}$	$\int \mathcal{L}\, dt > 530\ \mathrm{fb}^{-1}$
$\mathcal{L}_{peak} = 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$\mathcal{L}_{peak} = 4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

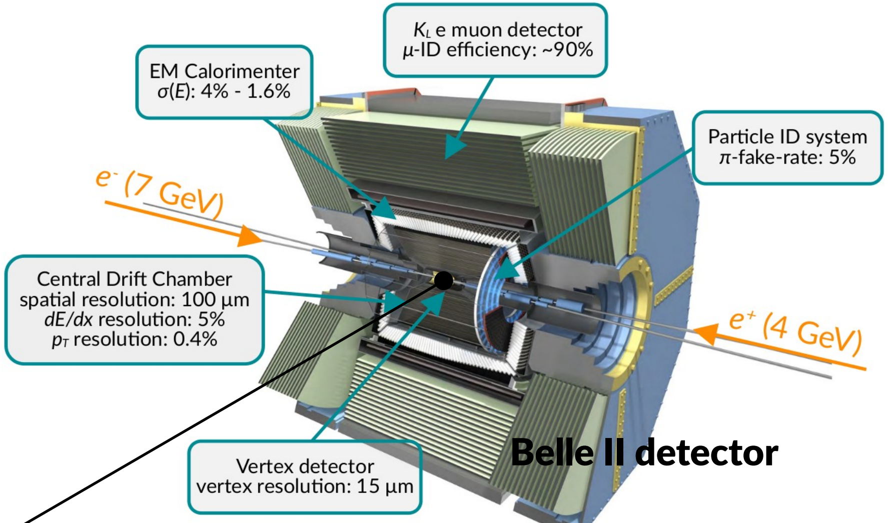
Belle II Physics Book, PTEP 2019 12 (2019)

The Belle II VerteX Detector (VXD)

VXD Nearest detector to the interaction point

- Inner 2 layers of PiXel Detector (**PXD**): DEPFET pixel sensors
- 4 layers of Silicon Vertex Detector (**SVD**): Double-sided strip sensors





K. Nakamura on "The Belle II Upgrade Program" (at 8:48)

VXD requirements:

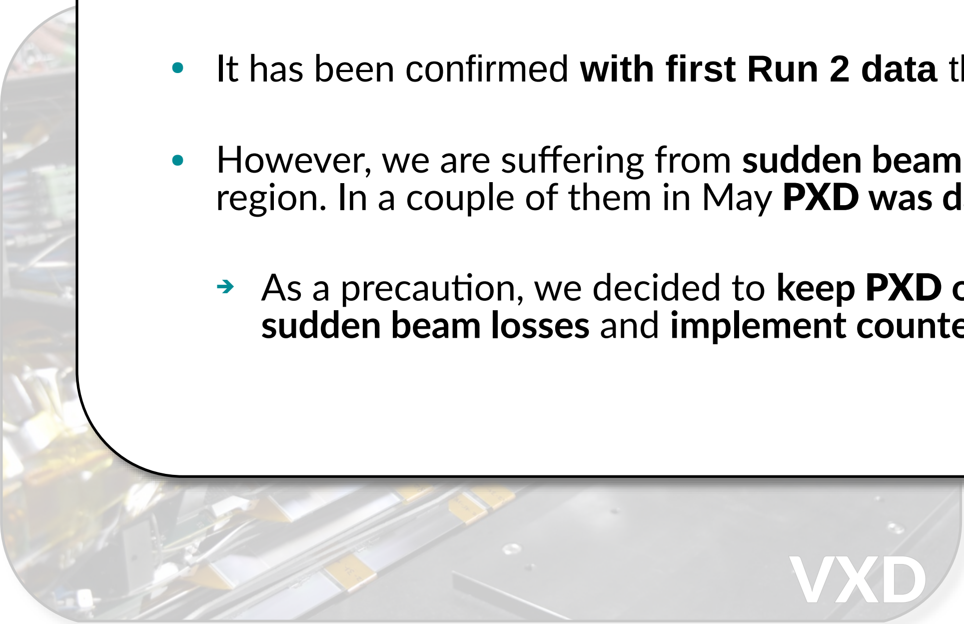
- Excellent vertex resolution ~15 μm
- Low-material budget ~3.8% X_0
- Radiation hardness to operate in high-background condition

The Belle II VerteX Detector (VXD)

VXD Nearest detector to the interaction point

- Inner 2 layers of PiXel Detector (**PXD**): DEPFET pixel sensors
- 4 l
  se

- This talk will cover only **SVD**
- It has been confirmed **with first Run 2 data** that the **new PXD works well**
- However, we are suffering from **sudden beam loss events**, with **large doses** at the interaction region. In a couple of them in May **PXD was damaged** (**2% dead channels**)
  - → As a precaution, we decided to **keep PXD off** while **we are investigating the sources of sudden beam losses** and **implement countermeasures** to **stabilize the beam operation**



- Radiation hardness to operate in high-background condition

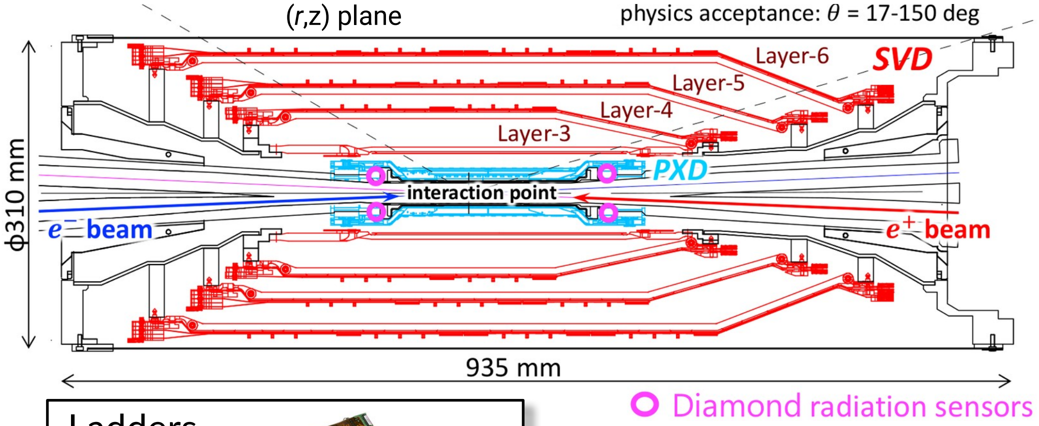
The Silicon VerteX Detector (SVD)

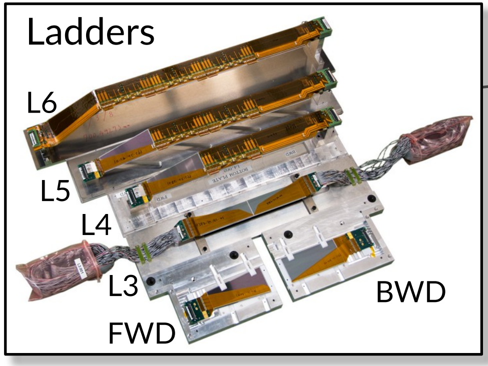
SVD structure

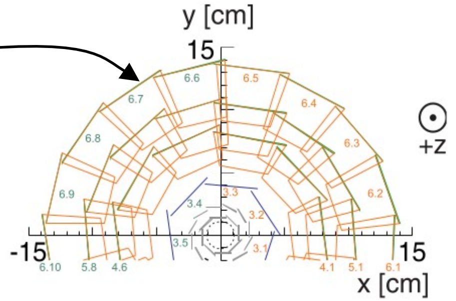
- **172 sensors** grouped into **ladders**
  - 1.2 m^2 of sensitive area, **224k readout strips**
- **Slanted forward sensors** to maximize acceptance with smaller incidence angle
- **Low material budget** ~0.7% X_0/Layer
- Diamond sensors for radiation monitor and beam abort

Main SVD functions

- Standalone **tracking** and **particle identification**, with *dE/dx*, **for low p_T tracks**
- **Extrapolate tracks to PXD**
  - **PXD** data reduction to cope with storage and bandwidth limits





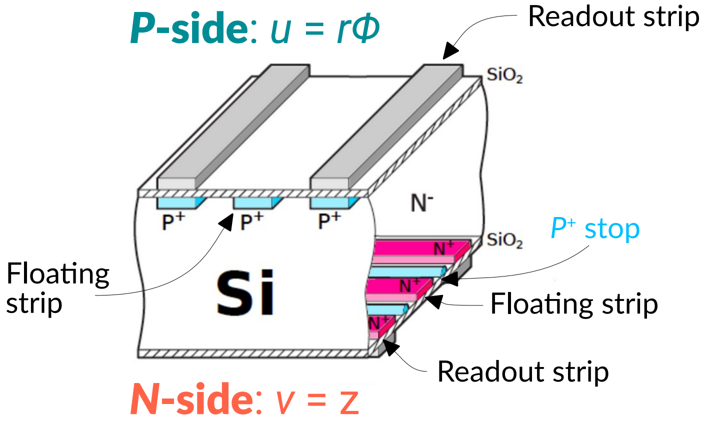


Layer	Ladders	Sensors/Ladd.	Radius	Slant angle
3	7	2	39 mm	0°
4	10	3	80 mm	11.9°
5	12	4	104 mm	17.2°
6	16	5	135 mm	21.1°

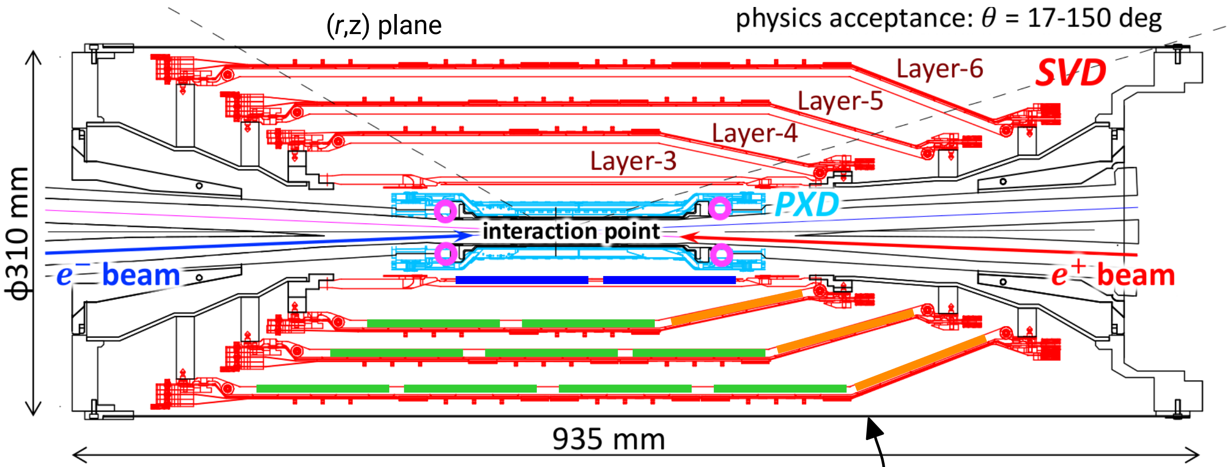
SVD DSSD sensors

Double-Sided Strip Detector (DSSD)

- Perpendicular strips
- Provide **2D spatial information**



- Depletion voltage: 20–60 V
- Operation voltage: 100 V



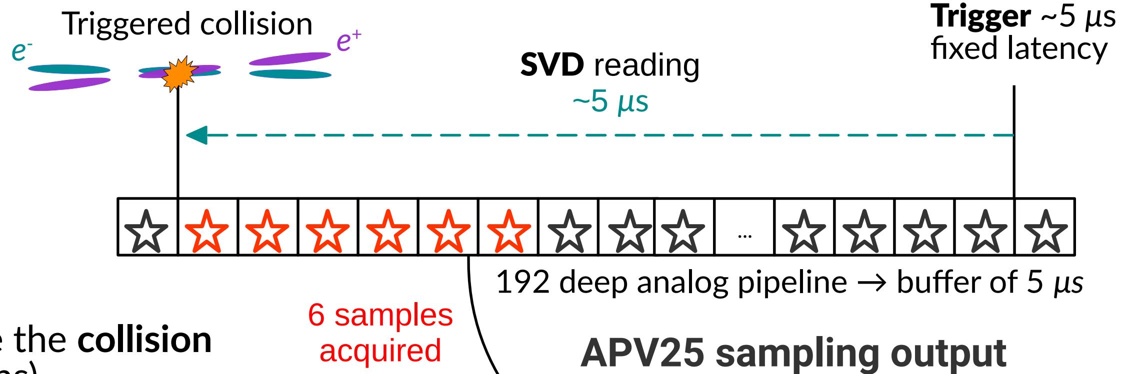
	Small sensors	Large sensors	Trapezoidal sensors
Readout strips *P*-side*	768	768	768
Readout strips *N*-side*	768	512	512
Readout pitch *P*-side*	50 μm	75 μm	50 – 75 μm
Readout pitch *N*-side*	160 μm	240 μm	240 μm
Sensor active area (mm^2)	122.90 x 38.55	122.90 x 57.72	122.76 x (38.42 – 57.59)
Sensor thickness	320 μm	320 μm	300 μm
Manufacturer	Hamamatsu	Hamamatsu	Micron

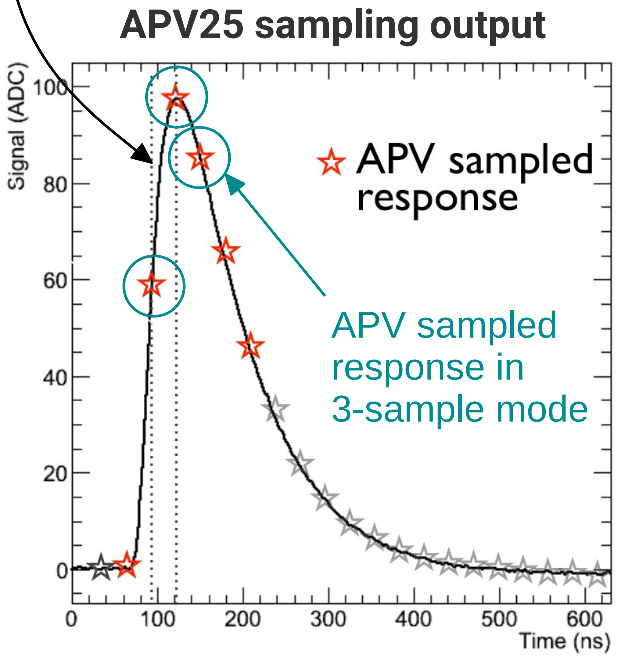
*One floating strip on both sides

Front-end ASIC and chip-on-sensor concept

Front-end ASIC – APV25 chip

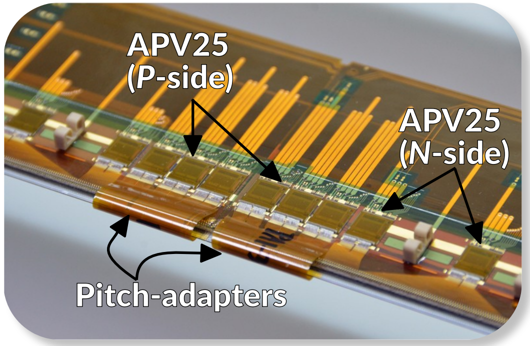
- **Radiation hardness** > 100 Mrad
- **Shaping time of 50 ns**
- 128 channel inputs
- Operated in **multi-peak mode at 32 MHz,** while the **collision frequency is 254 MHz** (quasi-continuos collisions)
  - We need to sample more than 1 to get the pulse shape and estimate the peak position
- **6 samples** recorded, **3/6 samples in future** to reduce data size



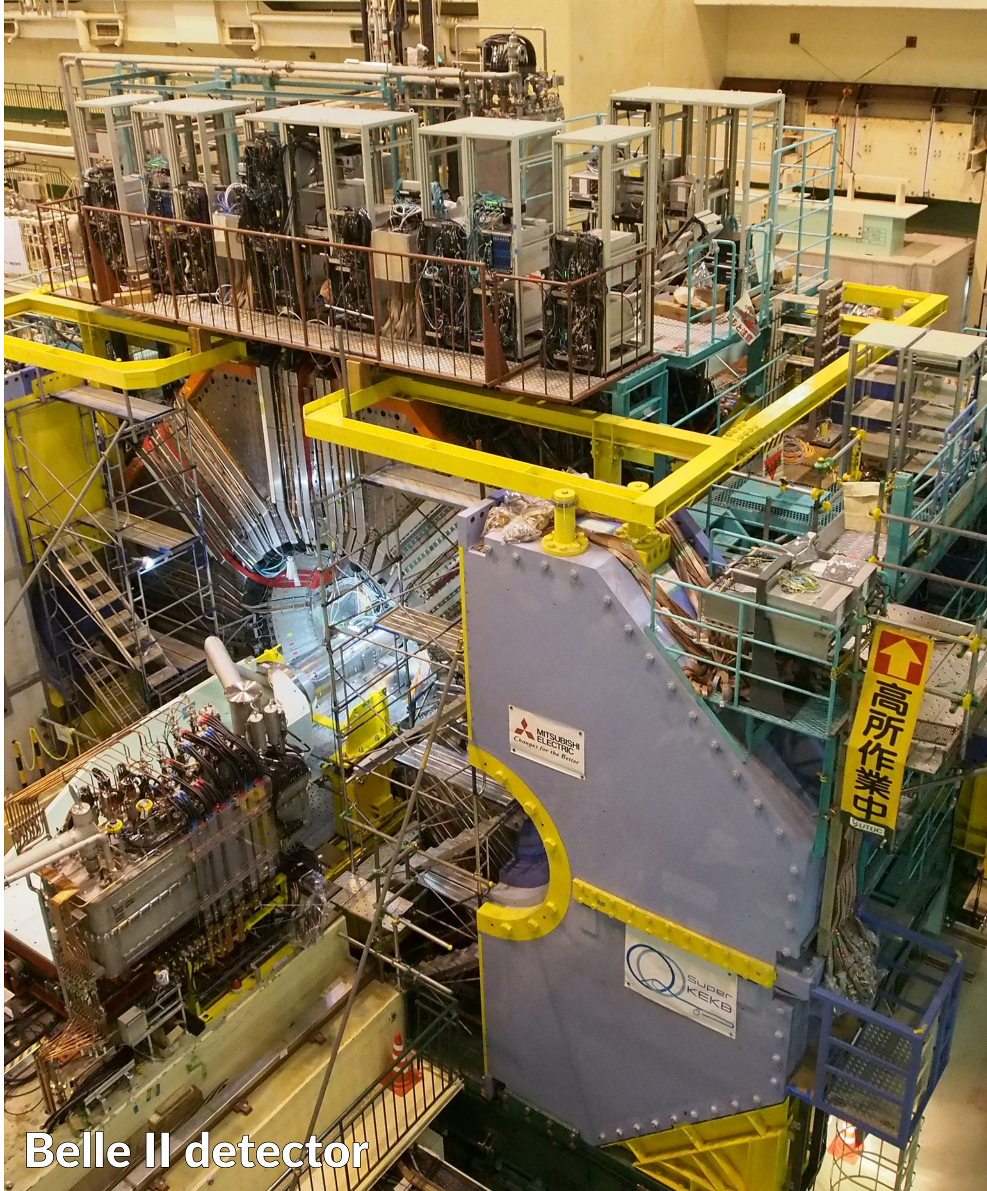


Chip-on-sensor concept (Origami)

- **Chips on each sensor** to minimize the signal path length
- **Chips on the same side of the sensor** using wrapped flex to readout sides
- Cooling only on one sensor side



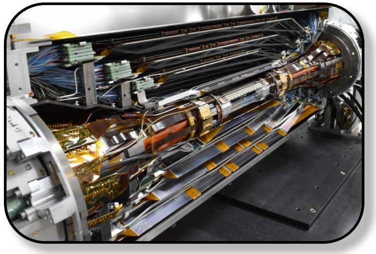
SVD operations and performance



Belle II detector

SVD Operational experience

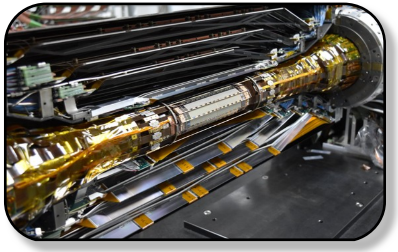
Run 1 First physics data with **VXD**



LS1

- Accelerator and detector maintenance and improvements
- **VXD** re-installation

Run 2 with **VXD** & full **PXD**



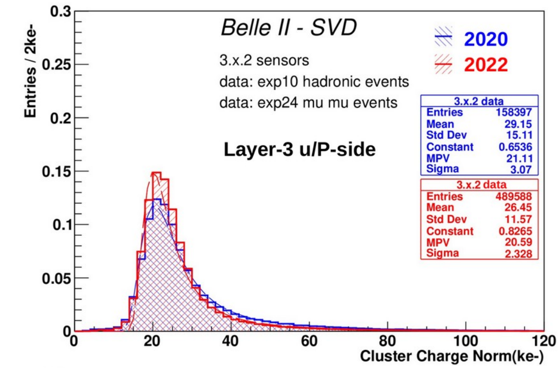
March 2019 → **June 2022** → **January 2024**

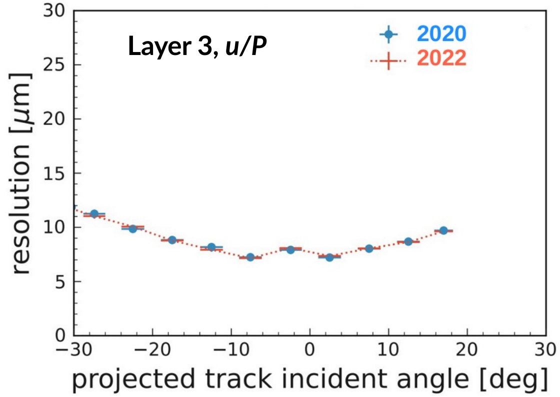
- **Reliable and smooth operation**, without major problems
- **Stable environment** and **calibration constants evolution consistent with expectation**
- **Excellent performance of the detector**
  - → Total fraction of **masked strips < 1%**
  - → Average sensor **hit efficiency** for the four **SVD** layers is **> 99% and stable** over time
- **Background effects well under control**

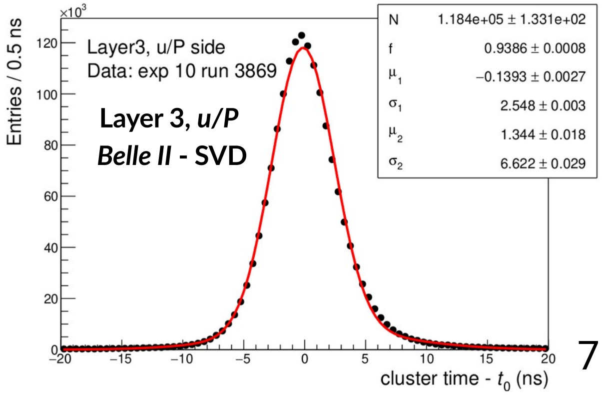
- **Reliable and smooth operation**
- **Physics performance as good as Run 1**
- **SuperKEKB** is working to **achieve higher** instataneous **luminosity**
  - → Increase the beam currents and optimize beam conditions
- **Background level similar to Run 1, but higher occupancy observed** due to different trigger configurations
  - → We monitor **SVD** status continuously
  - → **Occupancy still well below our limit**

Highlights of performance in Run 1

- **Stable cluster charge** matching the expectations (taking into account the ~15% uncertainty in APV25 gain calibration)
  - 24 ke^- expected for Minimum-Ionizing Particle (**MIP**) passing through a ~320 μm thick silicon sensor
- **Stable signal-to-noise ratio** (**SNR**)
  - All 172 senors have **SNR within 13–30**, depending on sensor position and side
  - **Small changes** observed **due to noise increase by radiation dose**
- **Stable position resolution within 10–25 μm** observed, as expected from strip pitches
  - Estimated from cluster position with respect to the track extrapolation on the sensors using $e^+e^- \rightarrow \mu^+\mu^-$ events
- **Excellent hit time resolution of < 3 ns**, measured with respect to the time of the collision provided by the Central Drift Chamber







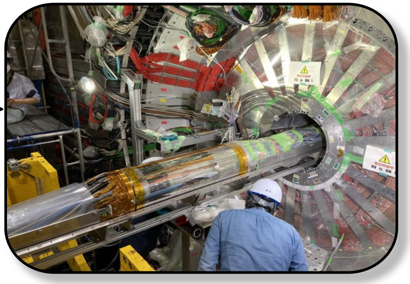
VXD re-installation - LS1

- **Upgrade VXD** with a complete **PXD** (same **SVD**)
- **Intense hardware activities** on **SVD** for the **VXD** de-installation/re-installation
  - More than 5 months with many delicate steps
- Several **SVD test campaigns** performed **after each step** during LS1
  - **Crucial to promptly spot problems** and **sanity check performance** at each step
- **Optimize the cooling conditions** with complete **PXD**

2023

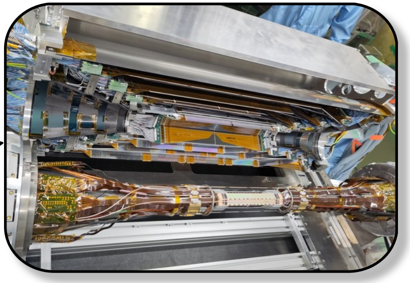
Belle II

May 10th — **VXD** extraction



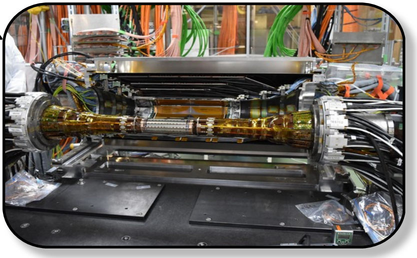
Clean room

May 17th — **SVD** detachment



June 1st — **SVD** commissioning

June 28th — New **VXD** assembly



July 14th — New **VXD** commissioing

Belle II

July 28th — New **VXD** installation

Sept. 22nd — Functional tests and commissioning with cosmic rays

Operation January 2024

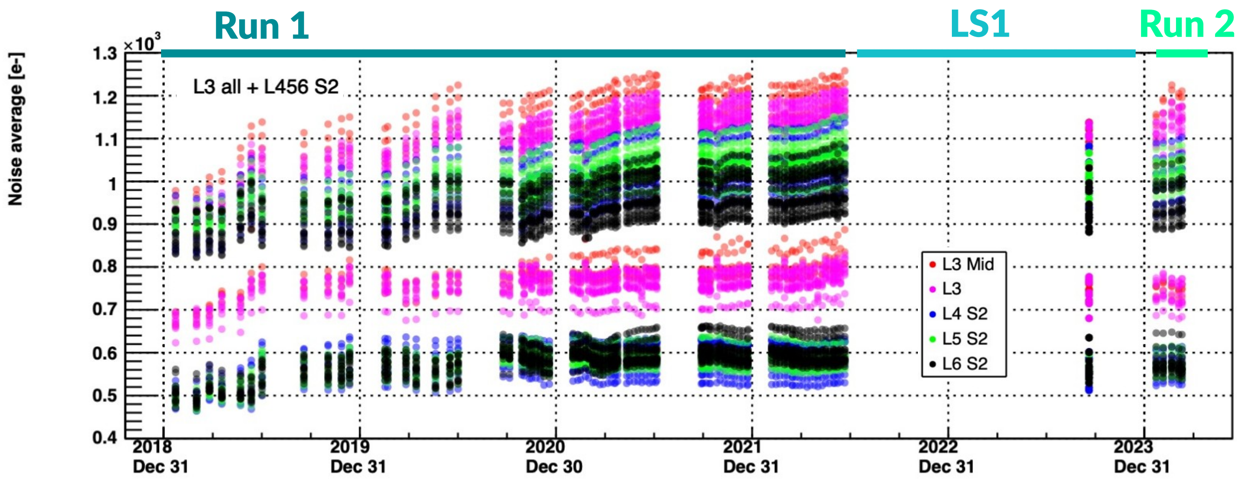
Highlights of performance in Run 2

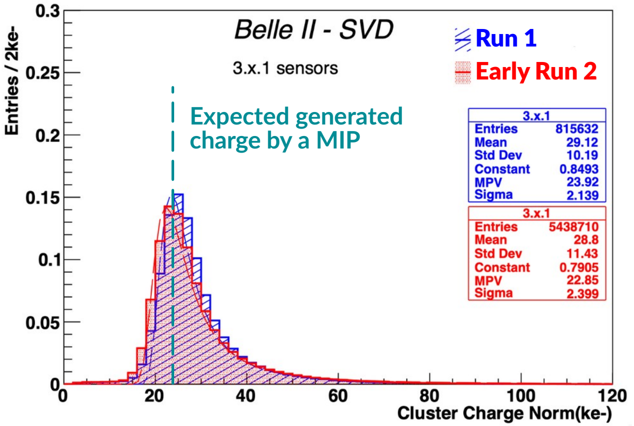
Evolution of noise

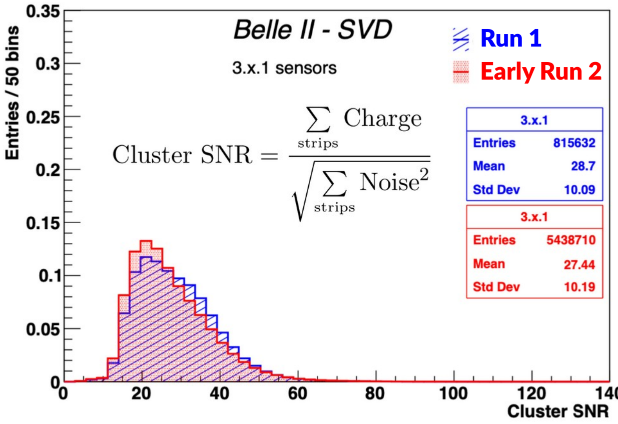
- Run 1: **increased by 10%–30%** due to radiation effect, as expected
  - ➔ Not affecting performance
- LS1: **reduced by up to 10%** due to lower operating temperature and annealing effect on the sensors
- Run 2: **increasing again**

Performance in Run 2 as good as in Run 1

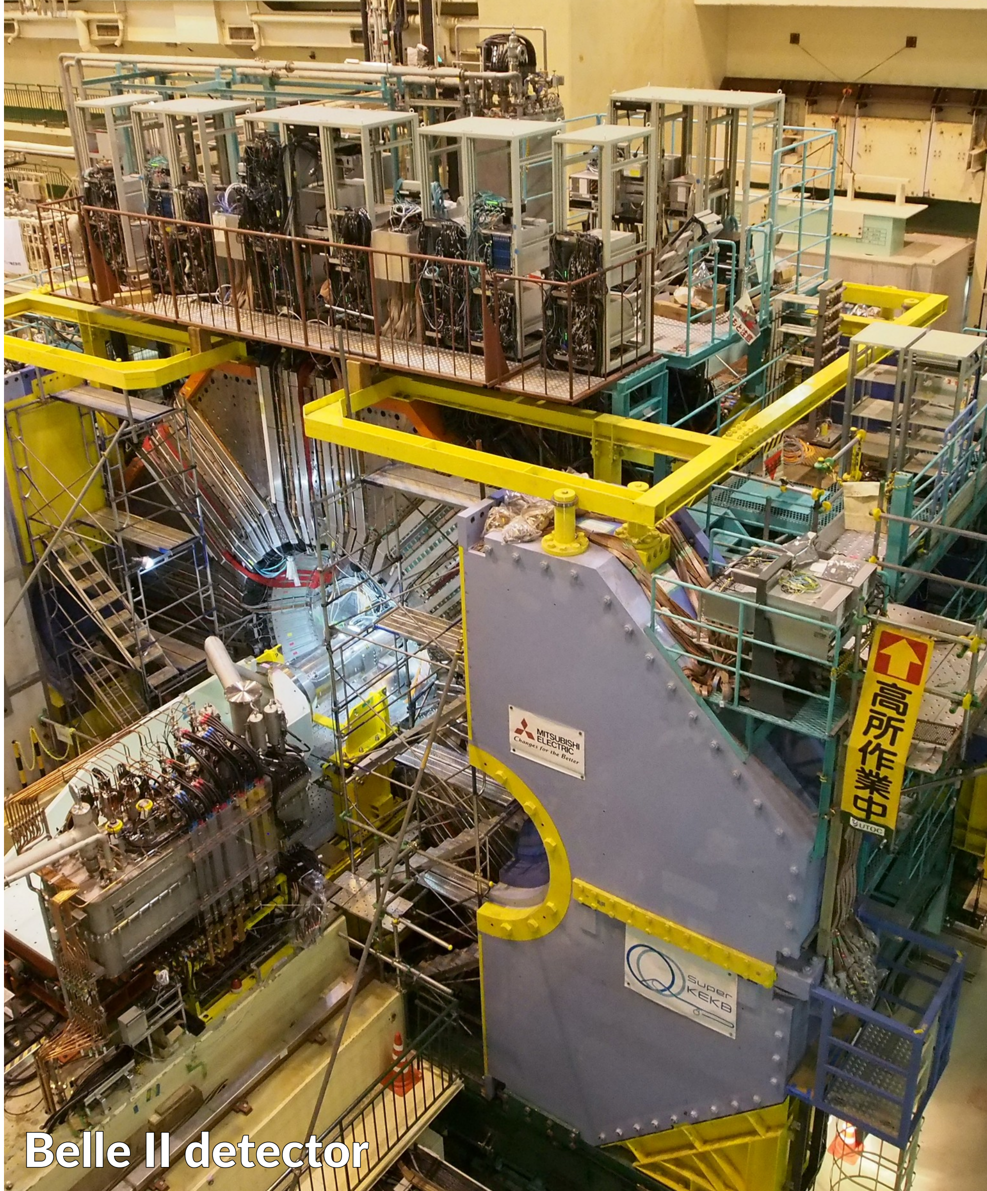
- **No** significant **changes in cluster charge** and **SNR**
- **Hit efficiency** keeps **> 99%**
- Number of total **masked strips ~1%**
- **No evidence of detrimental effect of the accumulated dose**





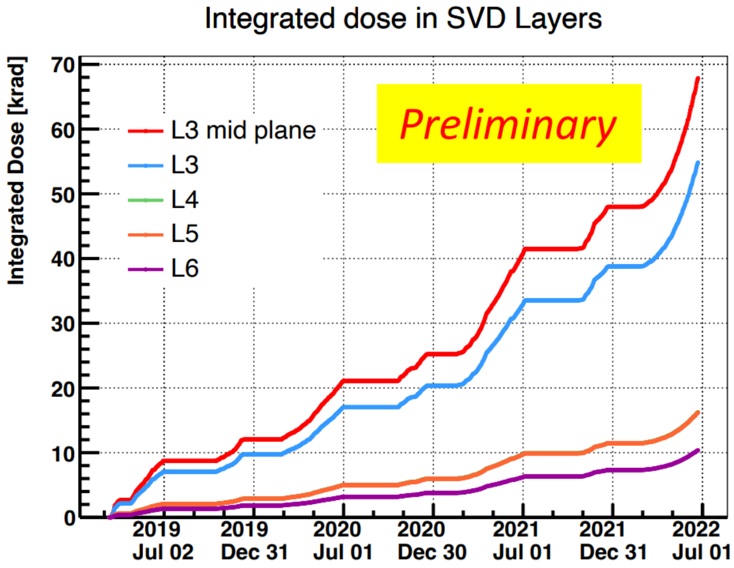


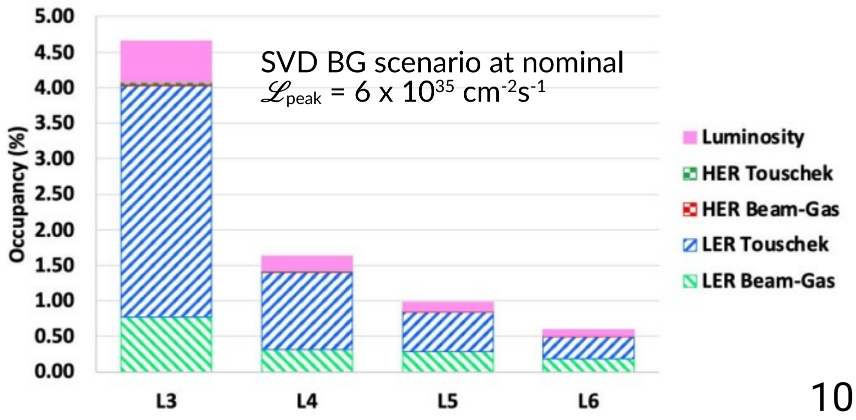
Towards the high luminosity



Beam background effects

- **Integrated radiation damage in Run 1**
  - **Deteriorate the sensor performance** increasing the **strip noise**, the **leakage current**, and changing the **depletion voltage**
  - Dose is constantly monitored using the **diamond detectors** and **hit occupancy**
  - Total **SVD integrated dose on Layer 3 is < 70 krad** (1.6 x 10^{11} $n_{eq}/cm^2/yr$) **in Run 1**
  - **Run 2: different temperature, calibration constants, etc...** need to be considered properly → **not included for now**
- Current **SVD hit occupancy is < 1%**
- Occupancy extrapolated **at target luminosity is 4.7% in Layer 3**
  - Large uncertainties due to machine development
- **High SVD** hit **occupancy** can **degrade tracking performance**
  - Developments in **SVD** software reconstruction

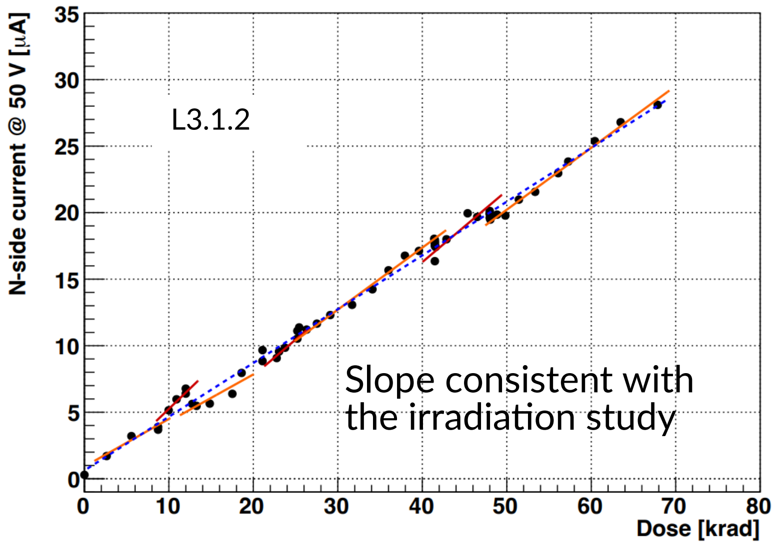




Radiation damages in Run 1

NIEL non-ionizing energy loss

- **Noise** Increasing, but not affecting performance (see slide 10)
- **Leakage current** Linear correlation between dose and leakage current as NIEL hypothesis in the installed sensors
- **Depletion voltage** No change in full depletion voltage due to bulk damage observed so far
  - As expected with only ~70 krad in Layer 3
- **Estimated radiation levels of 0.35 Mrad/yr** (8×10^{11} $n_{eq}/cm^2/yr$) at **target luminosity** $\mathscr{L}_{peak} = 6 \times 10^{35}$ $cm^{-2}s^{-1}$

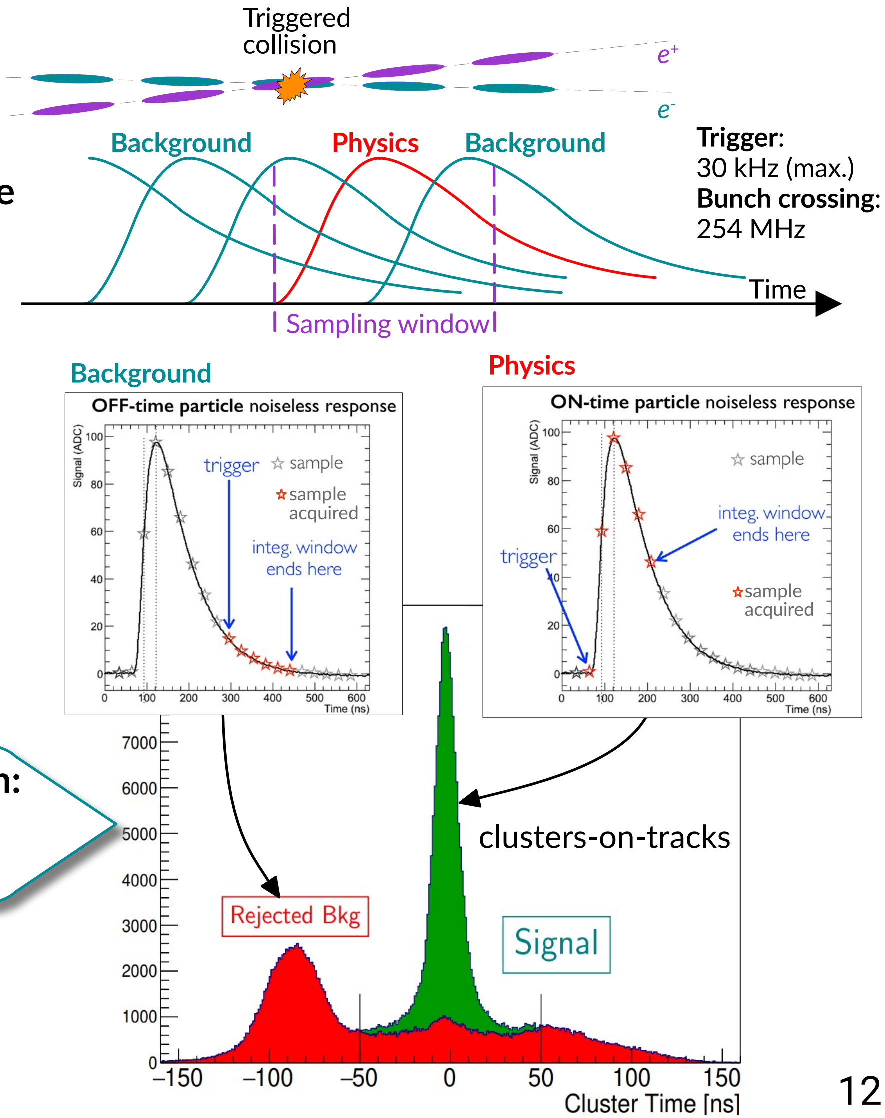


- **Irradiation campaign** in July 2022 with a 90 MeV e^- beam up to 10 Mrad (3×10^{13} $n_{eq}/cm^2/yr$)
  - **Type inversion** confirmed **at ~2 Mrad** (6×10^{12} $n_{eq}/cm^2/yr$)
  - Type inverted irradiated sensor **confirmed to collect charge well after 10 Mrad** irradiated
    - **Large safety margin** even after 10 years of operation at target luminosity

Background rejection

- **Crucial to** reduce occupancy and **keep high tracking performance in high background conditions**
- **Excellent hit time performace** (resolution < 3 ns) can be exploited to remove off-time tracks
  - **Hit-time selection**: remove 50% off-time hit background keeping > 99% of signal hits
  - Tested but not yet deployed in data reconstruction
- The hit time is determined from the APV sampled response in the sampling window
- **Background:**
  - **Peak < 50ns:** accumulation of off-time particles hitting the sensor before the beginning of the sampling window
  - **Uniform component:** single-beam background
- **SVD occupancy limit for Layer 3 can be set at 4.7%**

Hit-time selection:
$|t| < 50$ ns
$|t_U - t_V| < 20$ ns



Further background rejection

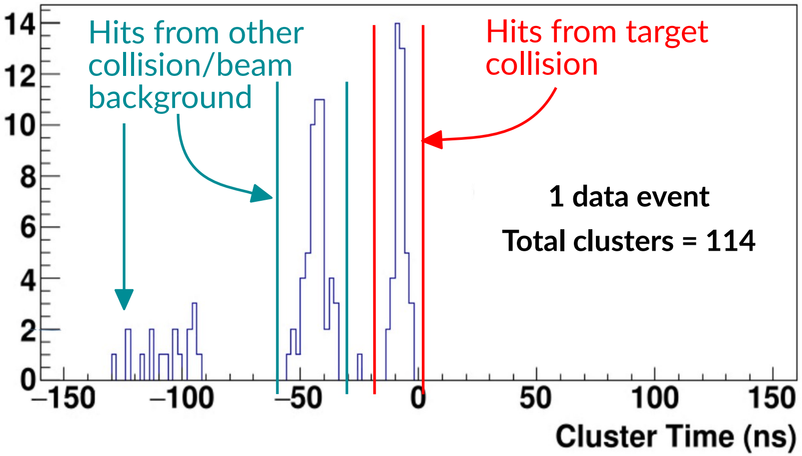
Cluster grouping Event-by-event classification of clusters into groups based on their time

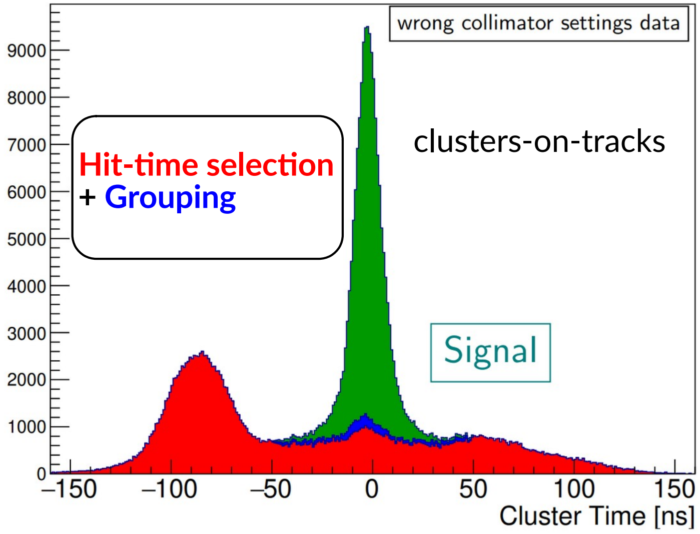
- **Further reduces tracking fake rate by up to 15%** on high-background data

Track-time selection Remove off-time track**, further reducing fake rate by a factor 1.5** on high-background data

Fake rate tracks reconstructed with hits from beam-induced background or originating from wrong combinations of hits

Track time Computed combining hit time of clusters associated to the track





- **Further increase SVD occupancy limit** for Layer 3 **from 4.7% to ~6%**
  - Large uncertainty due to future machine evolution and possible interaction region re-design, conservative extrapolation is 8.7%

Vertex Detector Upgrade (VTX, see talks [1] and [2] today at this same session**)**

[1] K. Nakamura on "The Belle II Upgrade Program" (at 8:48)
[2] A. Kumar on "Upgrade of the Belle II Vertex Detector with monolithic active pixel sensors" (at 15:57)

Summary & conclusions

Excellent performance and stability SVD has been taking data since March 2019 smoothly and reliably

- **Stable cluster charge**, **position resolution**, **SNR** in agreement with expectations, and **excellent hit-time resolution** (< 3 ns) and **hit efficiency** (> 99%)
- Some effects of **radiation damage** started to be seen, **not affecting performance**

LS1 New **VXD** with complete **PXD** installed

- **Intense hardware activities**
- The commissioning in Sept. 2023 **confirmed the good performance** of **SVD** as Run 1

Run 2 Started in January 2024

- **Confirmed the good performance** of **SVD** as Run 1

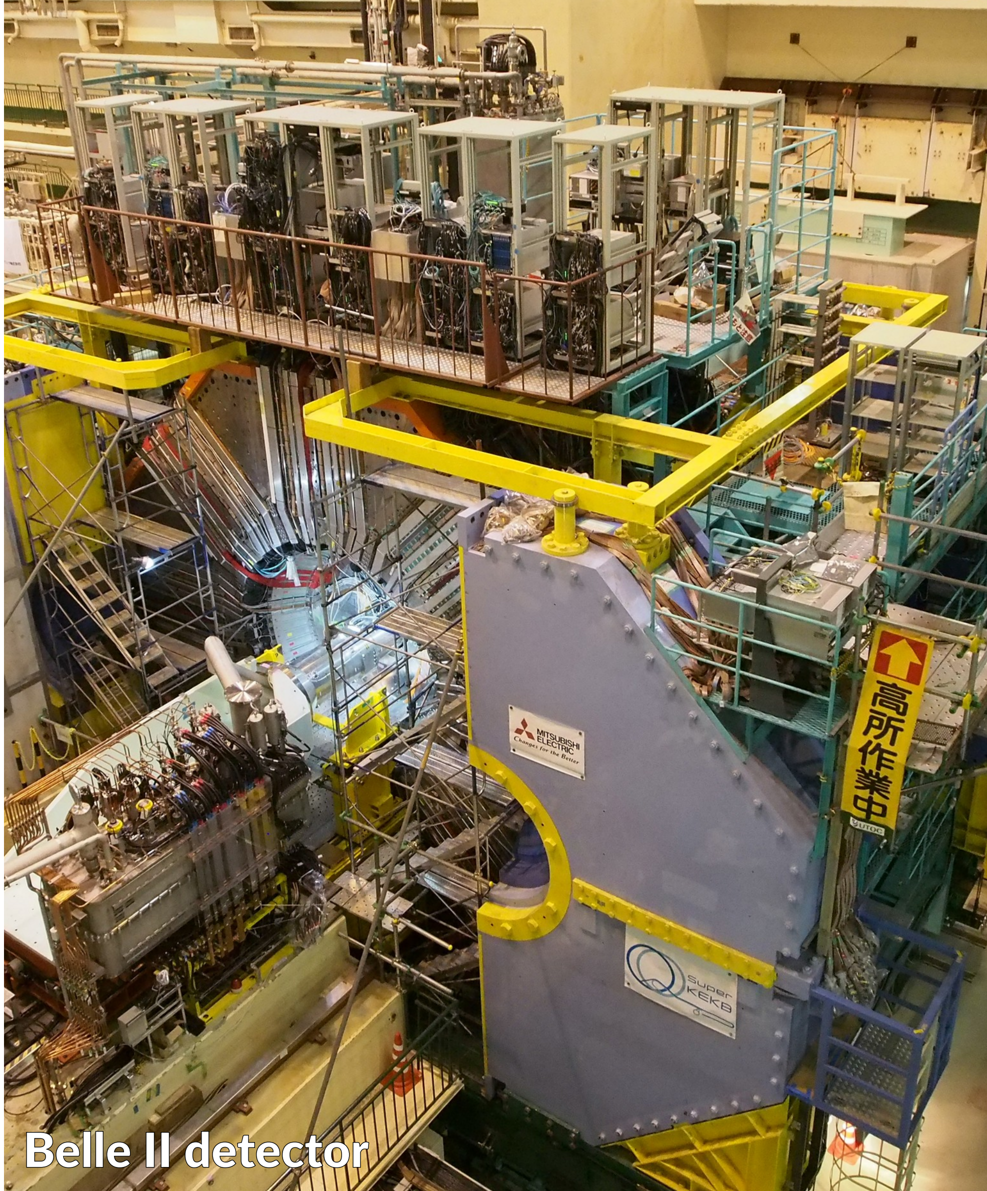
Towards higher luminosity Development of a robust **SVD** software to improve reconstruction with higher background

- **Excellent hit-time performance** are **crucial to reject off-time background** and keep high tracking perfomance

SVD technical paper JINST, 17, 2022

Belle II VXD (SVD half shell)

Backup slides



Belle II detector

SVD commissioning - LS1

Main goals

- Confirm all **SVD** sensors are **working as in Run 1**, and **detector performance**
- Check the **effect of temperature increase** due to complete **PXD** power consumption, and **optimize cooling condition** to **maintain/improve detector performance**

Functional tests and commissioning results

- **Very small variation in the calibration constants** (noise and gain) depending on temperature
- **Good performance as before reinstallation** from comparison of **cosmic run data** taken in June 2022 and September 2023, both without *B*-field