The Silicon Vertex Detector of the Belle II Experiment

Abdul Basith K

(For the Belle II SVD Collaboration)

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

SVD

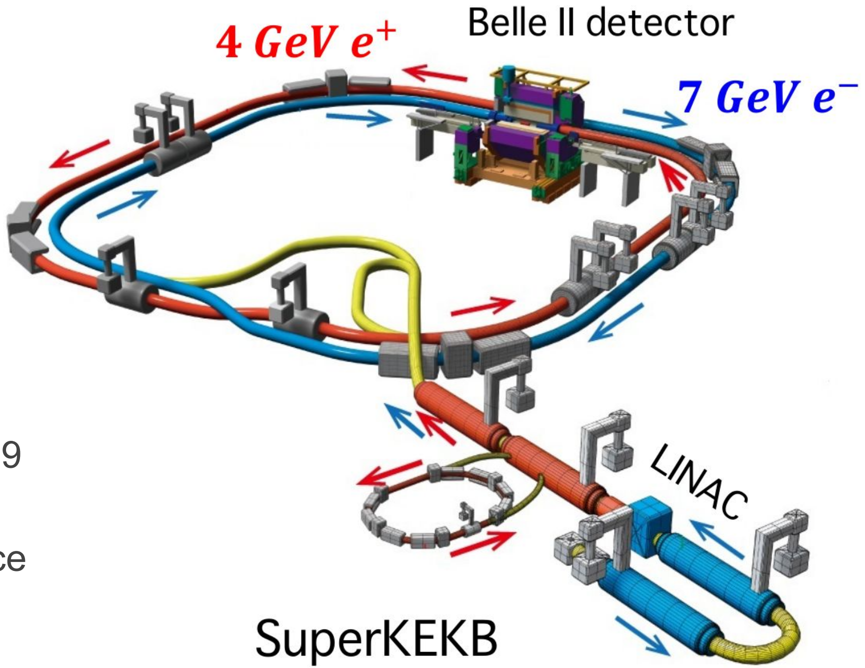
Belle II

Outline

- SuperKEKB and Belle II
- Belle II Silicon Vertex Detector
- Operation & performance
- Beam background, radiation effects & future perspective
- Long Shutdown 1 (LS1) activities with new VXD installation
- Summary and conclusions

SuperKEKB and Belle II

- SuperKEKB: dedicated accelerator for Belle II
  - e^+e^- collisions at Υ(4S) resonance (10.58 GeV)
  - Target integrated luminosity: 50 ab^{-1}
  - Target instantaneous luminosity: ~6×10^{35} cm^{-2} s^{-1}
  - World record peak luminosity: 4.7×10^{34} cm^{-2} s^{-1}



- Belle II detector
  - New physics search at the luminosity frontier
  - **So far 424 fb^{-1}** data accumulated since March 2019
  - Clean environment; well defined initial state
  - Excellent vertexing and flavour tagging performance
  - Efficient neutral reconstruction capability

Belle II Vertex Detector (VXD)

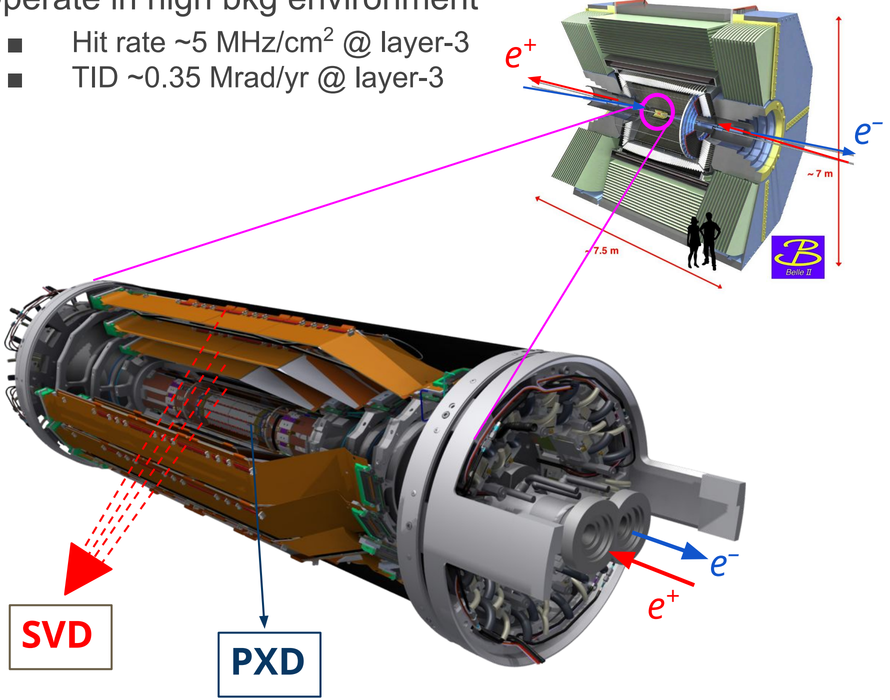
- Layers 1,2: Pixel Detector (PXD)
  - DEPFET pixel sensors
  - Innermost layer 1.4 cm radially from interaction point

  (See Laci Andricek's talk on PXD)

- Layers 3-6: **Silicon Vertex Detector** (**SVD**)
  - Double sided silicon strip detectors

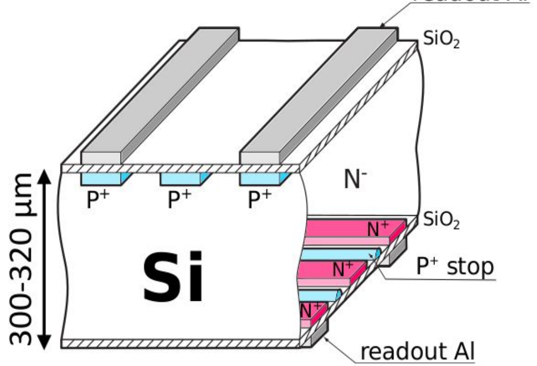
- Main features of SVD
  - Standalone tracking for low momentum tracks
  - Extrapolate tracks to PXD
  - Precise vertexing of K_S
  - Particle identification using dE/dx

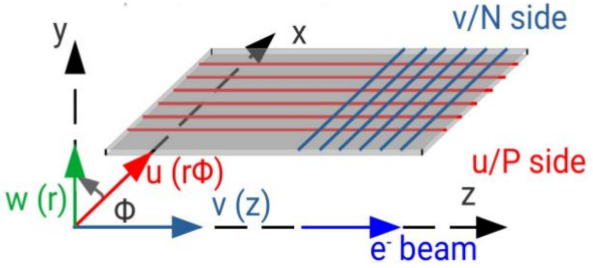
- VXD Requirements:
  - Better vertex resolution than Belle
  - Operate in high bkg environment
    - Hit rate ~5 MHz/cm^2 @ layer-3
    - TID ~0.35 Mrad/yr @ layer-3



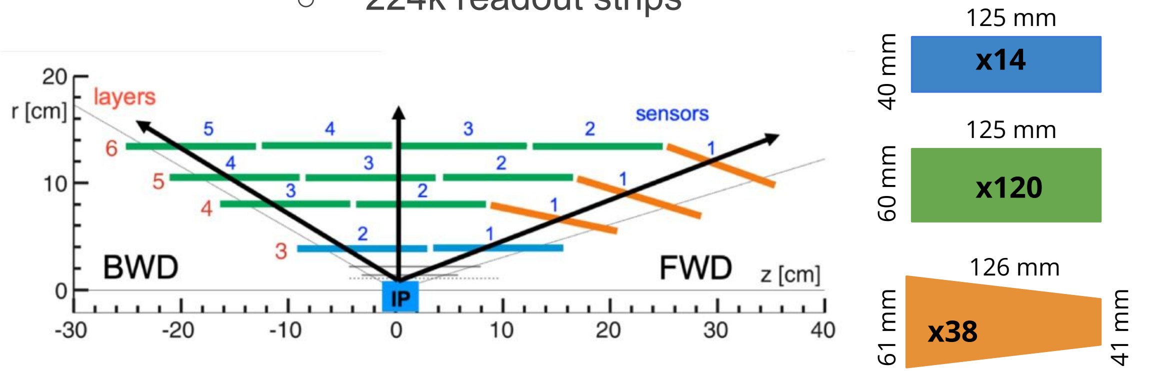
DSSD sensors

- Double-sided Si strip detectors
- Provide 2-D spatial information
- Depletion voltage 20-60 V, Operation voltage 100 V





- 3 different DSSD shapes
  - 172 sensors with 1.2 m^2 sensor area
  - 224k readout strips

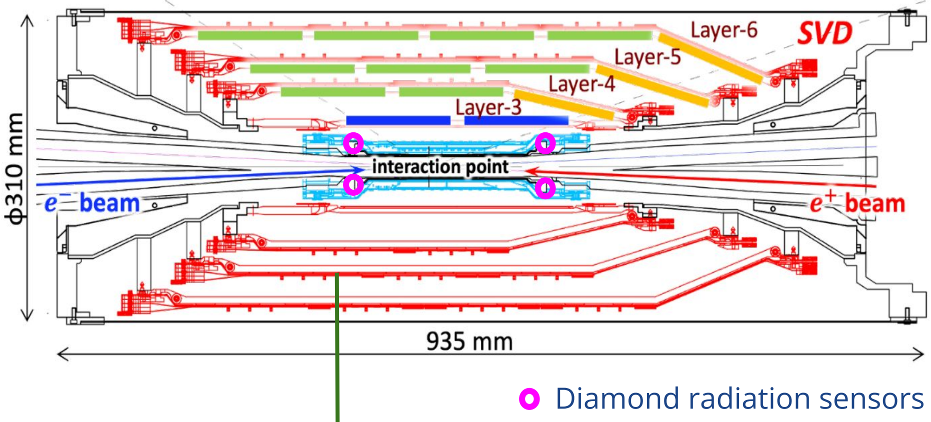


Type	Number of readout strips		Readout pitch (µm)		Thickness (µm)	Manufacture
	P side	N side	P side	N side		
Small	768	768	50	160	320	HPK
Large	768	512	75	240	320	
Trapezoidal	768	512	50-75	240	300	Micron

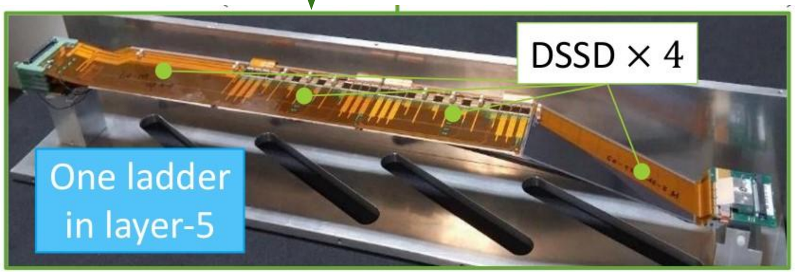
All sensors have one intermediate floating strip between two readout strips

SVD layout

- 4 layer structure
- Each layer is organized in mechanically and electrically independent subsets called **ladders**
- Low material budget: 0.7% X_0 per layer
- Diamond sensors for radiation monitor and beam abort



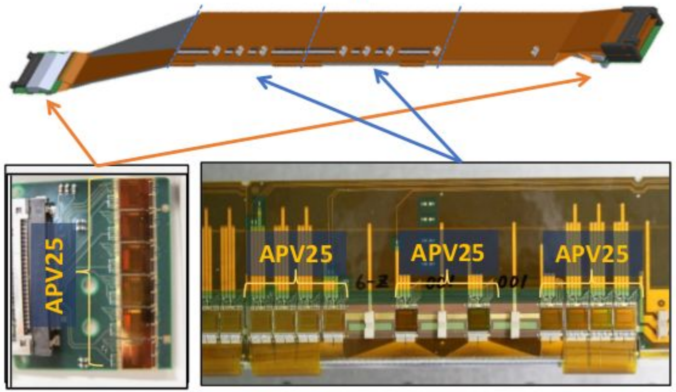
Layer	Ladders	Sensors /ladder	Radius (mm)
L3	7	2	39
L4	10	3	80
L5	12	4	104
L6	16	5	135
Total	45	172	



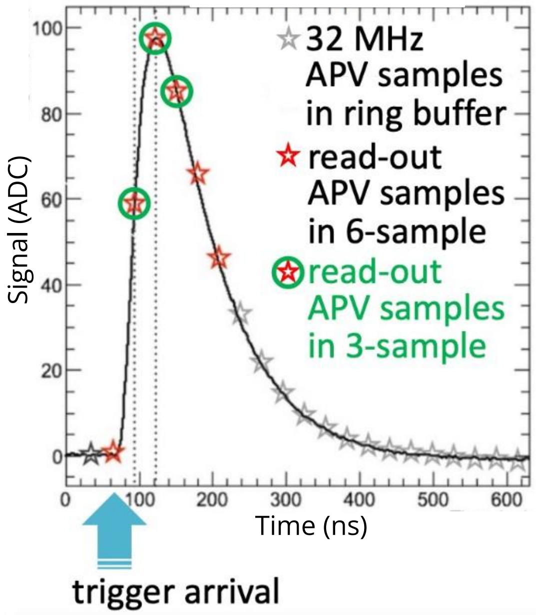
Front-end ASIC: APV25

- Originally developed for CMS silicon tracker
- Fast: 50 ns shaping times
- Radiation hard: > 100 Mrad
- Power consumption: 0.4 W/chip (700 W in total)
- 128 channels per chip, analog pipeline
- Operated in multi-peak mode @ 32 MHz:
    - 6 subsequent samples recorded

APV25 chips in ladder



Analog signal



3/6-mixed acquisition mode is also prepared for high luminosity runs:

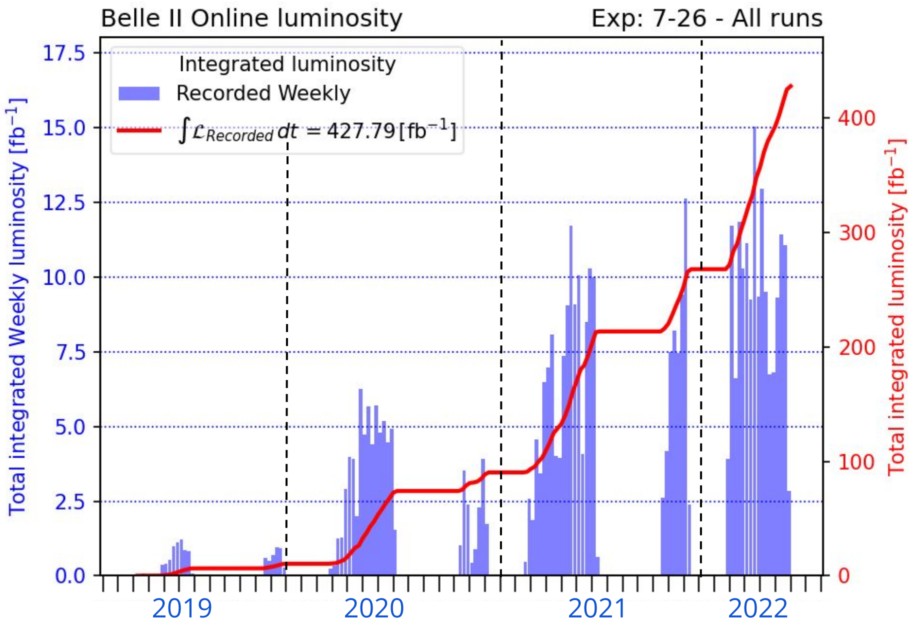
- To reduce background occupancy, dead-time and data-size
- Switching sampling number according to the timing precision of trigger
- The mode is implemented and tested in the real setup

SVD operation & performance

Operational experience

Smooth and reliable operation since the start of data taking

- Efficient shifter/operator/coordinator (local and remote) system
- So far total fraction of masked strips is less than **1%**
- One APV25 chip disabled in spring 2019 (out of 1748) and fixed by cable reconnection in summer 2019

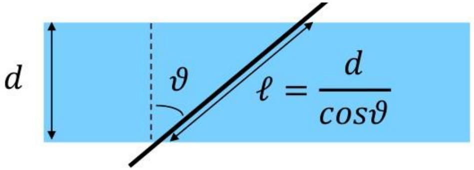


Excellent detector performance!

- Cluster charge distribution matches the expectation & very good signal to noise ratio (SNR) → next slide
- Stable hit efficiency: **>99%** in most of the sensors

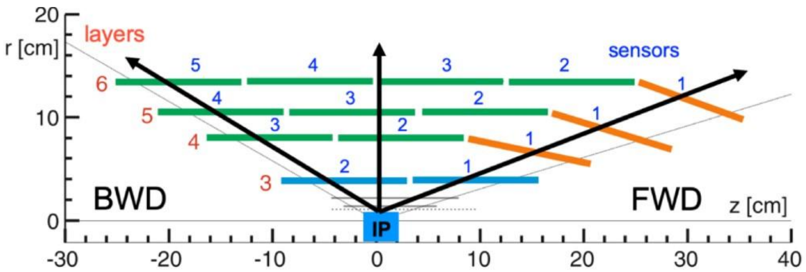
- **Mar 2019:** First collision data
- **July 2022:** LS1 for maintenance & improvement of machine and detector: **installation of the VXD with a new PXD2 completed with two layers + current SVD**
- Planning for SuperKEKB to resume in **Dec 2023**

Cluster charge & SNR

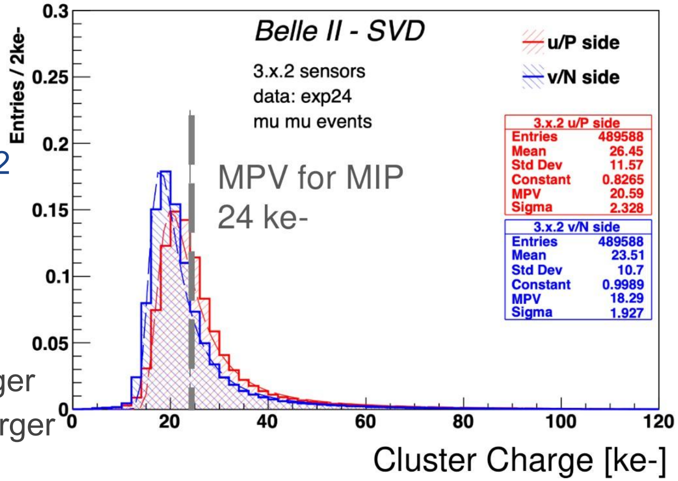


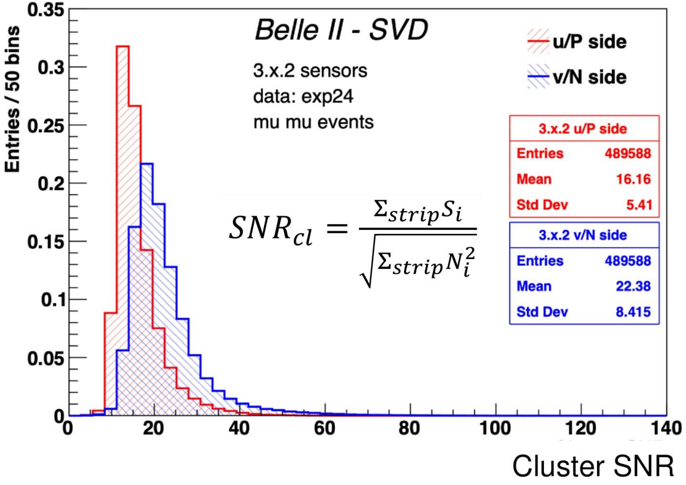
$d = 320 - 300\mu m$

$E \simeq \frac{d}{\cos\vartheta} \cdot 75\ \frac{e^-}{\mu m}$



- Signal charge depends on the incident angle
- Cluster charges are similar in all sensors and matches the expectations from MIP data taking
- **u/P side**: agrees with expectation considering the uncertainty in calibration
- **v/N side**: 10-30% signal loss due to large pitch and floating strip





$$SNR_{cl} = \frac{\Sigma_{strip} S_i}{\sqrt{\Sigma_{strip} N_i^2}}$$

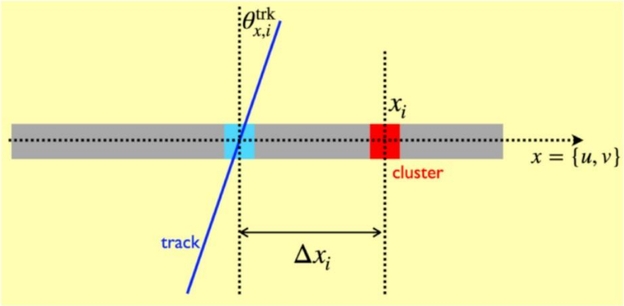
- Very good cluster SNR in all 172 sensors

  → **MPV: 13 - 30** depending on sensor position and side

- **u/P side:** Noise is generally larger due to longer strip length and larger inter-strip capacitance

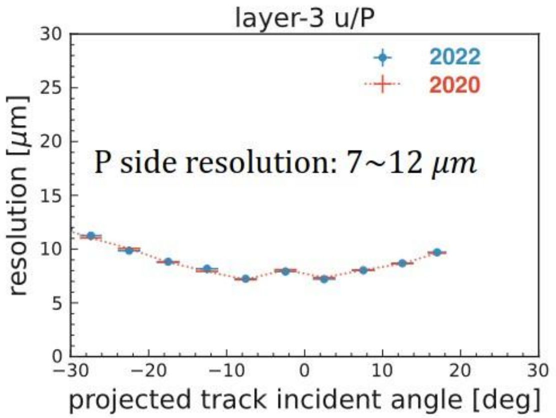
Position resolution

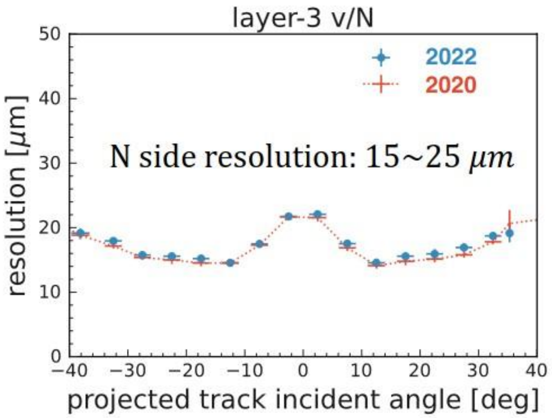
- Using the residual of the cluster position with respect to the intercept of the track extrapolation
  - Measured on di-muon sample ($e^+e^- \rightarrow \mu^+\mu^-$)
  - Effect of track extrapolation error is subtracted
- Good resolution achieved; generally in agreement with pitch expectations
- Good stability during operation



$$\sigma_x = \sqrt{\left\langle (\Delta x_i)^2 - \left(\sigma_{x,i}^{\text{trk}}\right)^2 \right\rangle}$$

$\sigma_{x,i}^{\text{trk}}$ = unbiased track position error

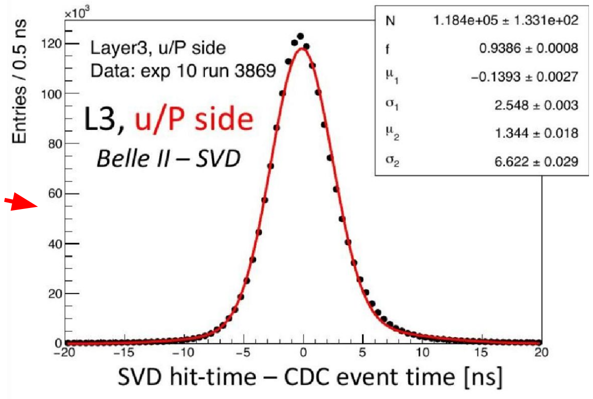


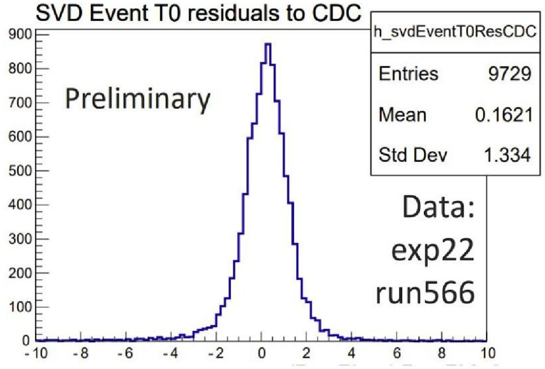


Hit time resolution

- **Excellent hit time resolution (< 3 ns)**
  - Measured w.r.t. event time of the collision provided by Central Drift Chamber (CDC)
- **Track time** computed combining hit time of clusters associated to the track:
  - relative to the time of the collision
- **Event time** computed combining hit time of clusters associated to all tracks of the event
  - Same resolution (~ 1 ns) and 2000 times faster computation time w.r.t. the one computed with CDC
  - Allowing to speed up the High Level Trigger reconstruction and therefore cope with the higher trigger rate expected at high luminosity

SVD hit time resolution (clusters on track)



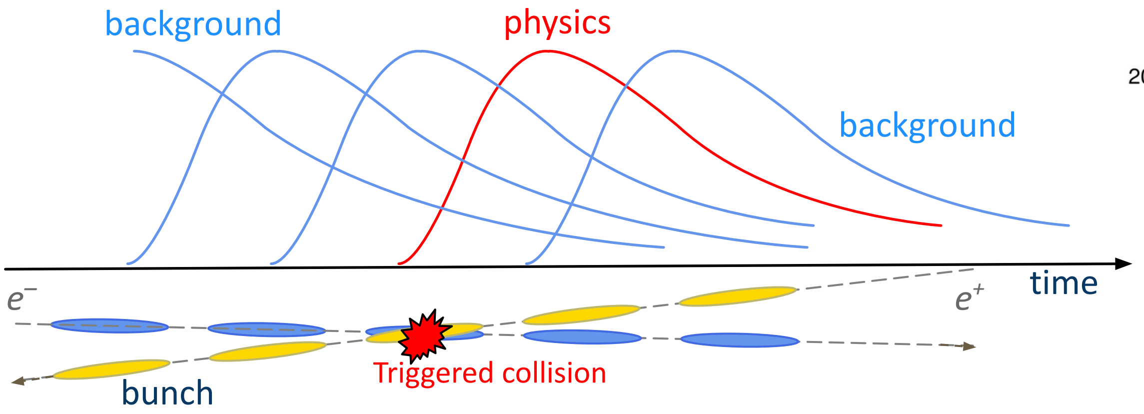


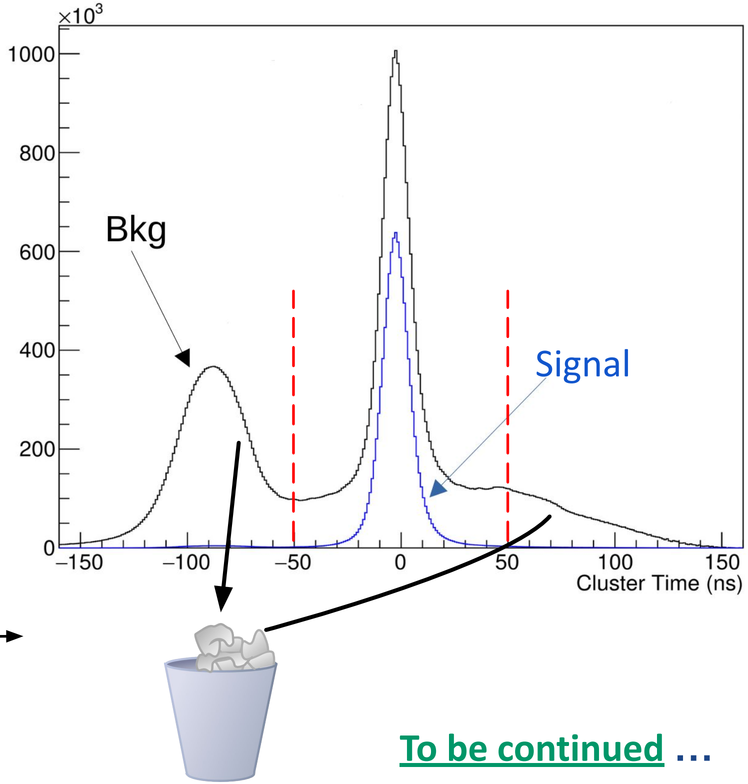
SVD event time – CDC event time [ns]

The power of hit time

- Physics signal hits come from triggered collision, while off-time beam background hits come from many other bunches
  - SuperKEKB has continuous bunch crossing (bunch spacing 6 ns)
  - SVD sees hits from machine beam induced background from several bunches near the triggered collision ($\mathcal{O}$(100 ns))
- A selection based on SVD hit-time allows to reject off-time beam background hits

SVD hit time distribution (data May 2022)





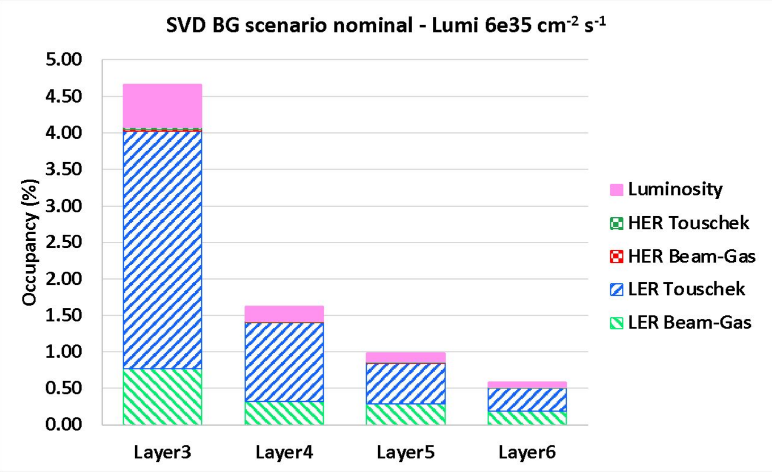
To be continued …

Beam background, radiation effects & future perspective

Beam Background effects

1. **Integrated radiation damage** → can deteriorate sensor performance increasing leakage current, strip noise & changing depletion voltage
   - Dose and sensor parameters constantly monitored to assess the effect over the experiment lifetime → good safety margin
2. **High instantaneous SVD hit occupancy** → can degrade tracking performance
   - Present average hit occupancy in layer 3 is less than 0.5% and well under control
   - Developments in SVD reconstruction SW to improve robustness against future higher occupancy

- **Background extrapolation at nominal luminosity** of $L = 6 \times 10^{35}\ cm^{-2}\ s^{-1}$ estimated with detailed simulation of different sources (scaling MC with data/MC ratio).
  - Average occupancy of about 4.7 % in layer-3.
  - TID ~ 0.35 Mrad/yr , eq neutron fluence ~ $8 \times 10^{11}\ n_{eq}/cm^2/yr$
- **CAVEAT: Large uncertainty on long term background extrapolation** linked to future machine evolution and possible interaction region re-design, currently under study
  - Different BG scenarios (nominal, conservative) studied to assess SVD occupancy limits to preserve good tracking performance

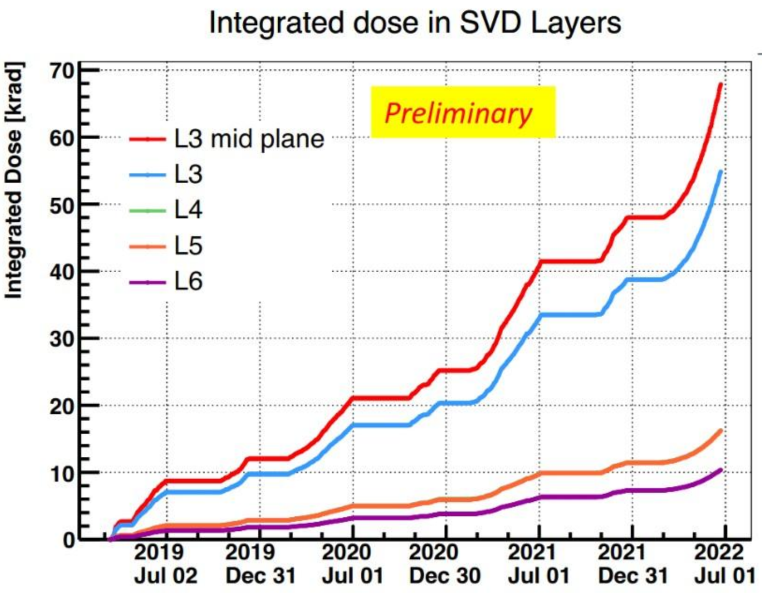


Integrated dose

- Diamond sensors used to monitor radiation dose
  - Correlation between SVD occupancy and diamond dose is used to estimate the SVD sensor dose

- Total SVD integrated dose on layer 3 mid plane **< 70 krad**
  - 1-MeV equivalent neutron fluence evaluated to be ~1.6 × 10^{11} n_{eq}/cm^2 in first 3 years
  - Assume n_{eq}/dose fluence ratio = 2.3 × 10^9 n_{eq}/cm^2 $/krad$ from simulation

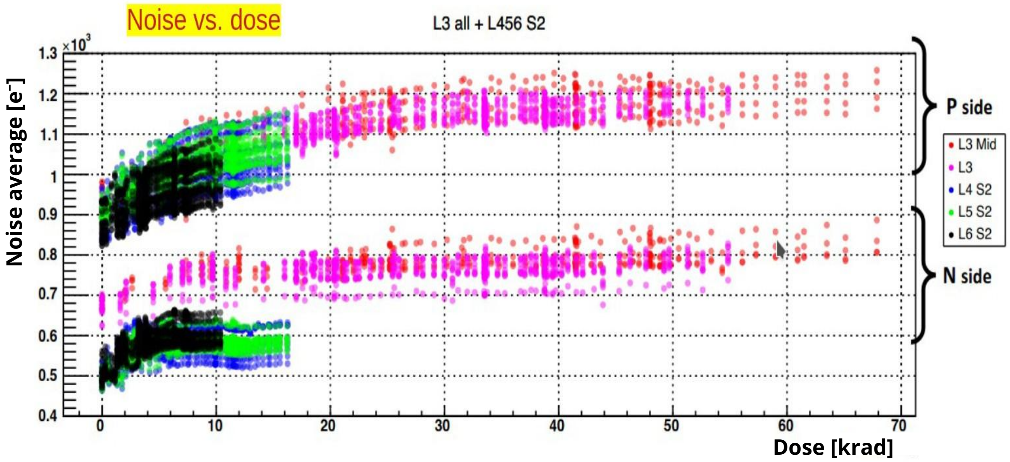
- First observable effects on sensor currents, noise and calibration constants, but **so far without degradation of the SVD performance**



Radiation effects (1)

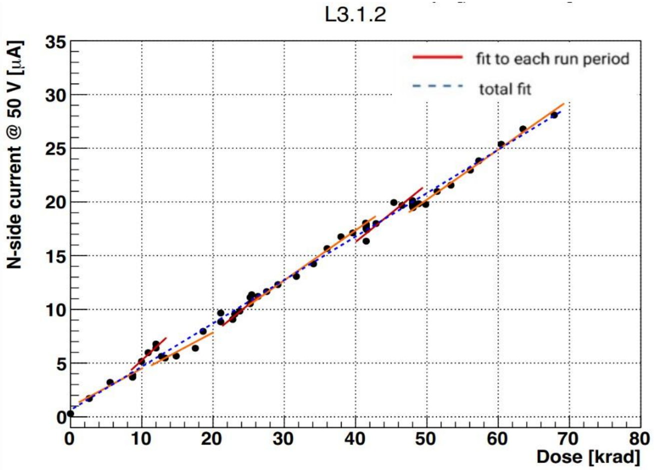
Strip noise

- Noise increase is < 20% (30%) for n(p) side, not affecting performance
- Non-linear increase due to fixed oxide charges in irradiated sensors → expected to saturate



Leakage current

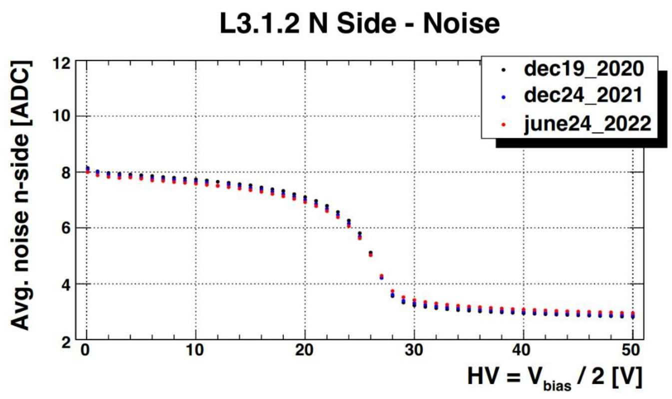
- Good linear correlation between leakage current and dose (equivalent neutron fluence) as expected from NIEL model
- Irradiation is not expected to degrade SVD performance, even up to 6 Mrad:
  - Contribution to noise negligible now due to short APV25 shaping time
  - After 6 Mrad SNR expected to be < 10 in Layer 3, due to the increased strip noise from leakage current contribution
- Good safety margin of about 2 on integrated radiation effects, considering background levels extrapolation at nominal luminosity: ~ 0.35 Mrad/yr & 8×10^{11} $n_{eq}/cm^2/yr$

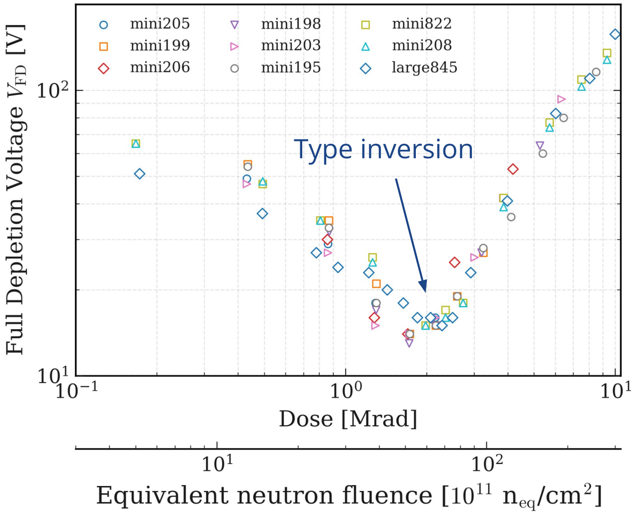


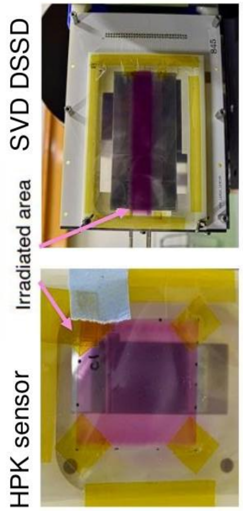
Radiation effects (2)

Depletion voltage

- Bulk damage can change effective doping and depletion voltage
  - Measure depletion voltage with scan (n-side strip noise vs bias voltage)
  - **No change in full depletion voltage observed with time so far**, consistent with low integrated neutron fluence







- **Irradiation campaign in July 2022**
  - 90 MeV e⁻ beam @ ELPH Sendai (Tohoku Univ.)
  - Type inversion confirmed ~2 Mrad → a equivalent neutron fluence ~6 × $10^{12}\ n_{eq}/cm^2$
  - Expect SVD sensor to work well also above type inversion:
    - Experience on BaBar sensor [NIMA 729, 615-701, 2013]
    - New measurements with Sr90 source on type inverted SVD ladder

SVD hit-time selections

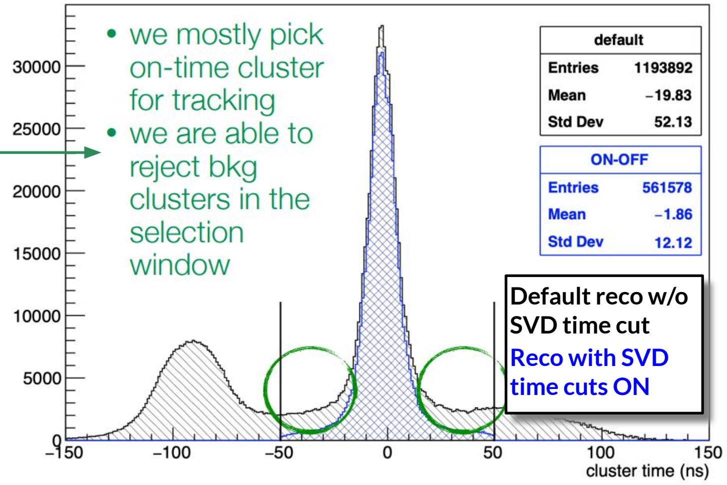
→ Fake rate: tracks reconstructed with hits from beam-induced background or originating from wrong combinations of hits

- **Challenge for the near future**
  - Improving SVD software robustness against high-background data expected with increasing luminosity
  - In high-background conditions, the fake rate will increase, degrading the SVD tracking performance

$|t_{u,v}| < 50$ ns
$|t_u - t_v| < 20$ ns

- Excellent SVD hit-time performance (resolution < 3 ns) allows to exploit SVD hit-time to efficiently remove off-time background
  - Efficient to remove 50% off-time hit background, keeping signal efficiency above 99%
  - Background rejection based on SVD hit-time selections already tested but not yet deployed on real data reconstruction

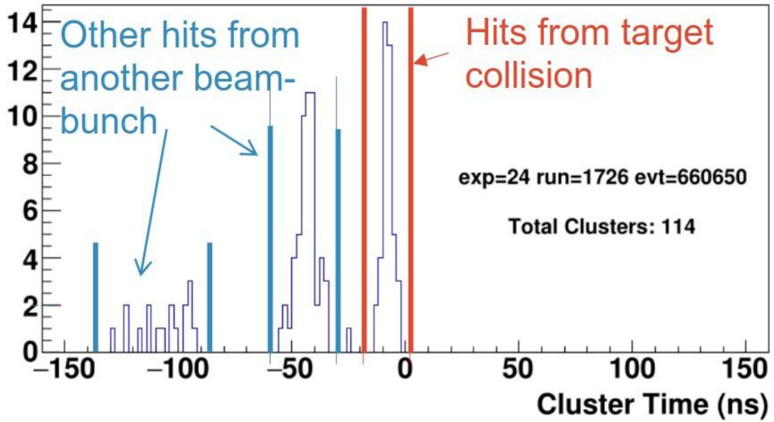
SVD hit time distribution (data May 2022)



- **SVD hit-time selections allow to set the SVD occupancy limit at 4.7% in nominal background scenario** (in the conservative scenario, SVD occupancy ~7.2% → we start to see some SVD tracking degradation)

Throw the heart over the obstacle

- Further decrease of fake rate will come from SVD cluster-time grouping and selection based on track time
- **Cluster Grouping**
  - Exploit SVD hit-time to implement a event-by-event classification of groups of hits (clusters)
  - **Selection based on Grouping further reduces the fake rate by 15% on high-background data**
- **Selection on track-time to remove off-time tracks**
  - Further reduce the fake rate by a factor 1.5 on high-background data



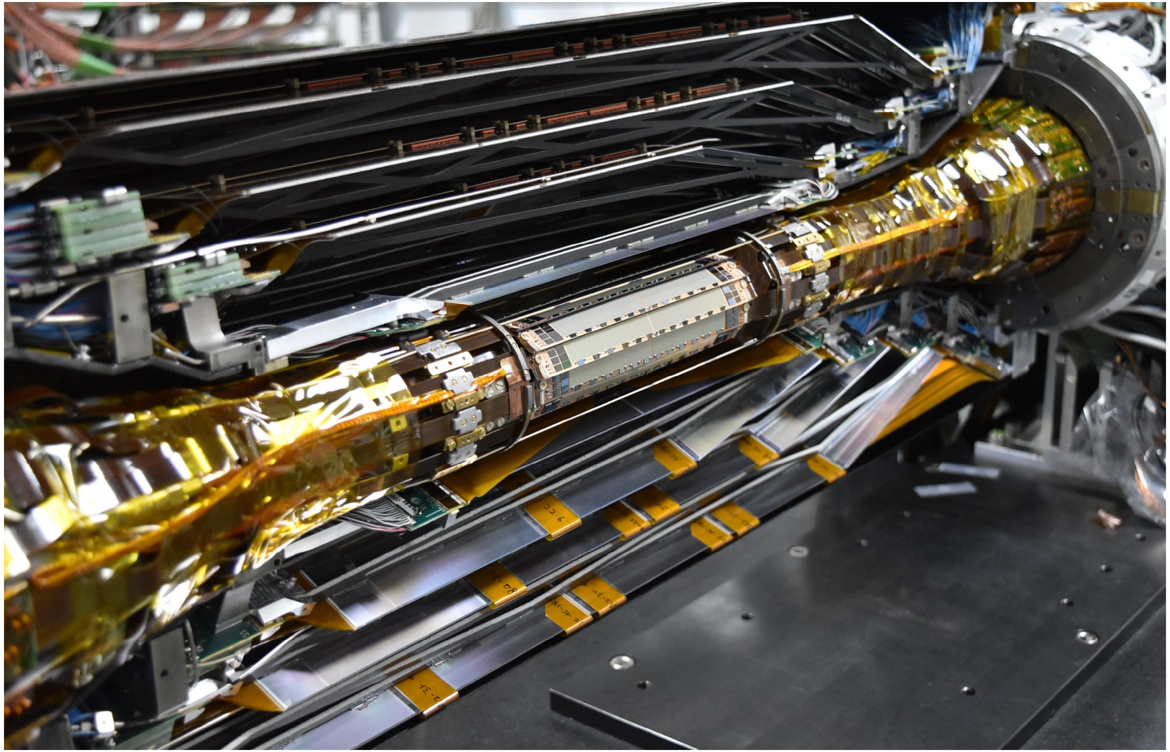
- **New features allow to further increase SVD occupancy limit from 4.7% to ~6%**
- **Possible re-design of the interaction region & small safety factor, due to large uncertainty on expected background, motivate the vertex detector upgrade now under study** to improve tolerance to hit rates & radiation → technology assessment ongoing

VXD reinstallation during LS1

VXD reinstallation

- The second layer of PXD covers only one-sixth of the azimuthal angle
  - Upgrade VXD with new complete PXD + current SVD during LS1
  - Intense hardware activities on the SVD for the VXD de-installation/re-installation
  - Procedure for SVD detachment was well developed and reviewed in advance
  - SVD detachment & reattachment were done successfully
  - Sanity check with local runs shows no issues during the procedure

VXD now re-installed in Belle II → commissioning with cosmics in September



Summary & conclusions

- SVD has been taking data since March 2019 smoothly and reliably
- Excellent performance in agreement with expectations
- Observed first effects of radiation damage, not affecting performance
- Improving SVD software robustness against future high background
- During Long Shutdown we installed the new VXD, with the complete PXD2 and the current SVD
  - VXD re-commissioning with cosmic in Sep
  - On track to resume beam operation in Dec 2023
- SVD technical paper has been published in JINST :

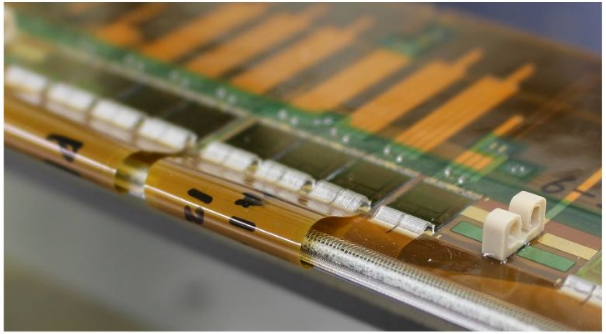
  The design, construction, operation and performance of the Belle II silicon vertex detector

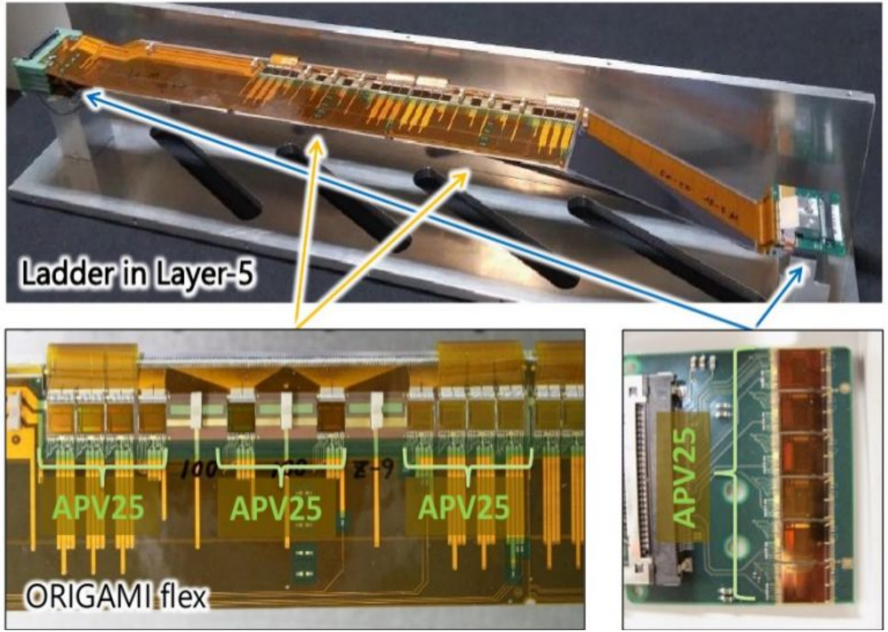
Thank you for your attention!

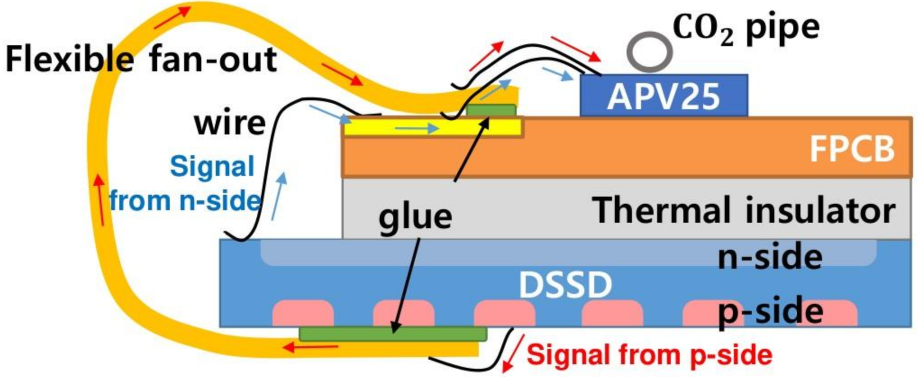
Additional slides

Origami chip on sensor concept

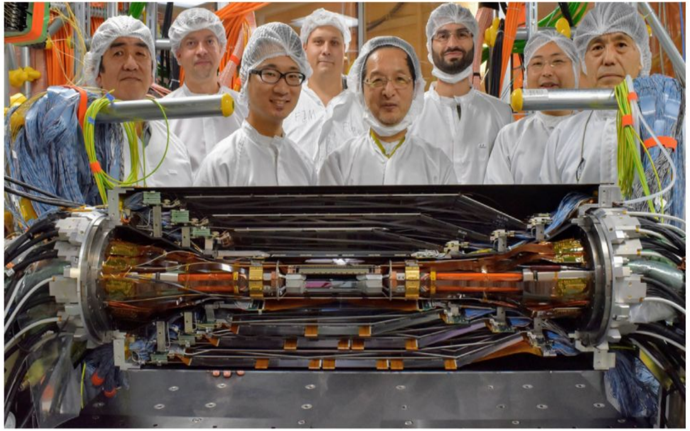
- Readout chips directly on each middle sensor:
  - APV chips thinned to 100 um to reduce material budget
  - Shorter signal propagation length → smaller capacitance and noise
- Wrapped flex to read both sides from the same side
- Cool only one side with bi-phase –20 °C CO_2

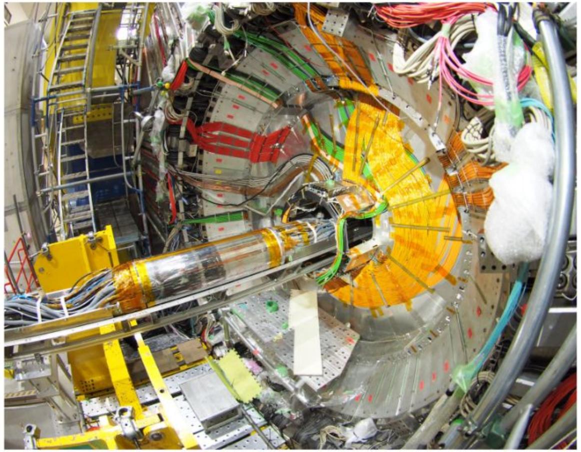




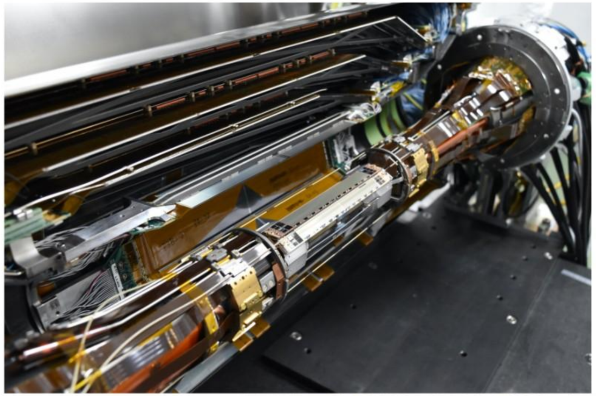


Construction, assembly and installation





- Sep 2008: First chip-on-sensor origami concept
- Oct 2010: Belle II Technical Design Report
- May 2015: First completed L5 ladder
- Feb/Jul 2018: First/second SVD half shell assembled
- Nov 2018: Installed in Belle II
- Mar 2019: First collision data with complete detector
- July 2022: LS1

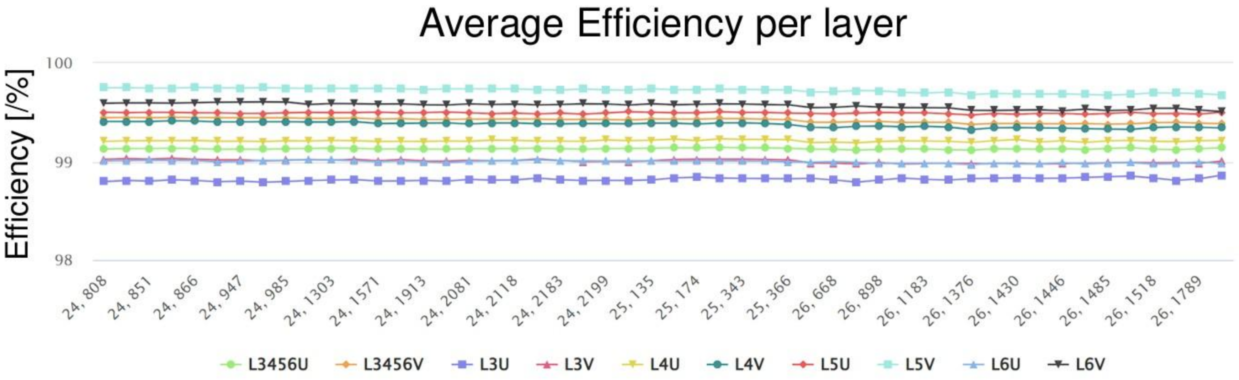


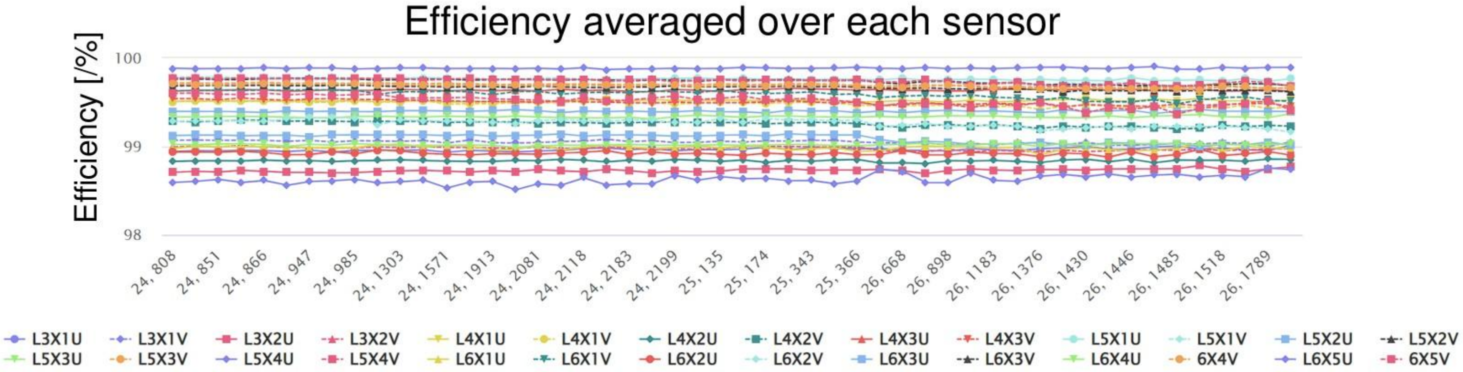
Hit efficiency

Shown for **Feb-June, 2022**

Very high and stable in time

> 99 % for most of the sensors





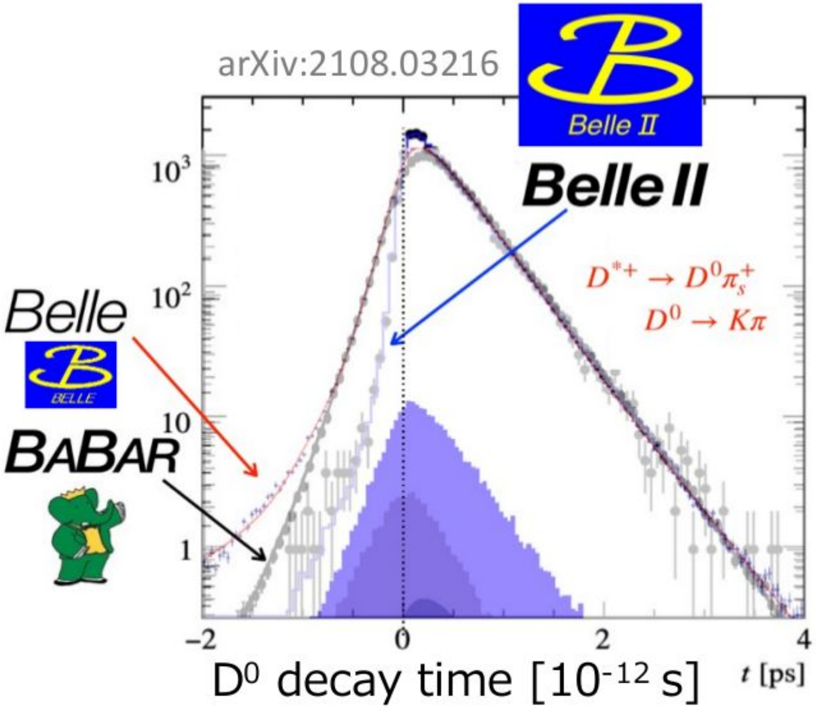
Vertex resolution

Excellent vertex resolution!

- 👉 Measured d0 resolution of 14.1 ± 0.1 µm

- D lifetime measurement
  - 👉 Vertex determination plays a key role in the lifetime measurement
  - 👉 Belle II time resolution is better than Belle/BaBar by factor about 2
  - 👉 World's most precise D lifetime measurements!

arXiv:2108.03216



$$\tau(D^0) = 410.5 \pm 1.1\,(\text{stat}) \pm 0.8\,(\text{syst})\ \text{fs}$$

$$\tau(D^+) = 1030.4 \pm 4.7\,(\text{stat}) \pm 3.1\,(\text{syst})\ \text{fs}$$