Operational experience and performance of the Belle II Silicon Vertex Detector after the first SuperKEKB Long Shutdown

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Belle II Silicon Vertex Detector

SuperKEKB [1] and Belle II [2] [1] Y. Ohnishi *et al.*, *PTEP* 2013, 03A011 (2013). [2] T. Abe *et al.*, *arXiv*:1011.0352.

- SuperKEKB collides 7 GeV e^- with 4 GeV e^+ at $\sqrt{s} = 10.58$ GeV
- Target instantaneous luminosity 6×10^{35} cm^{-2} s^{-1} to collect 50 ab^{-1} data sample
- Belle II records collision data for precision measurements and searches for beyond-the-standard-model physics

Belle II Silicon Vertex Detector (SVD) [3] [3] K. Adamczyk *et al.*, *JINST* **17** P11042 (2022)

- The SVD consists of 4 layers of double-sided silicon-strip detectors (DSSDs), which are outside 2 layers of pixel detectors (PXD)
- The DSSDs are 300~320 um thick and have readout strip pitch 50/75 um (P side), 160/240 um (N side)
- Readout with APV25 ASIC that has a 50 ns shaping time
- Provides precise hit information for tracking and vertexing, as well as $\mathrm{d}E/\mathrm{d}x$ information for particle identification

Belle II Vertex Detector: VXD = SVD + PXD

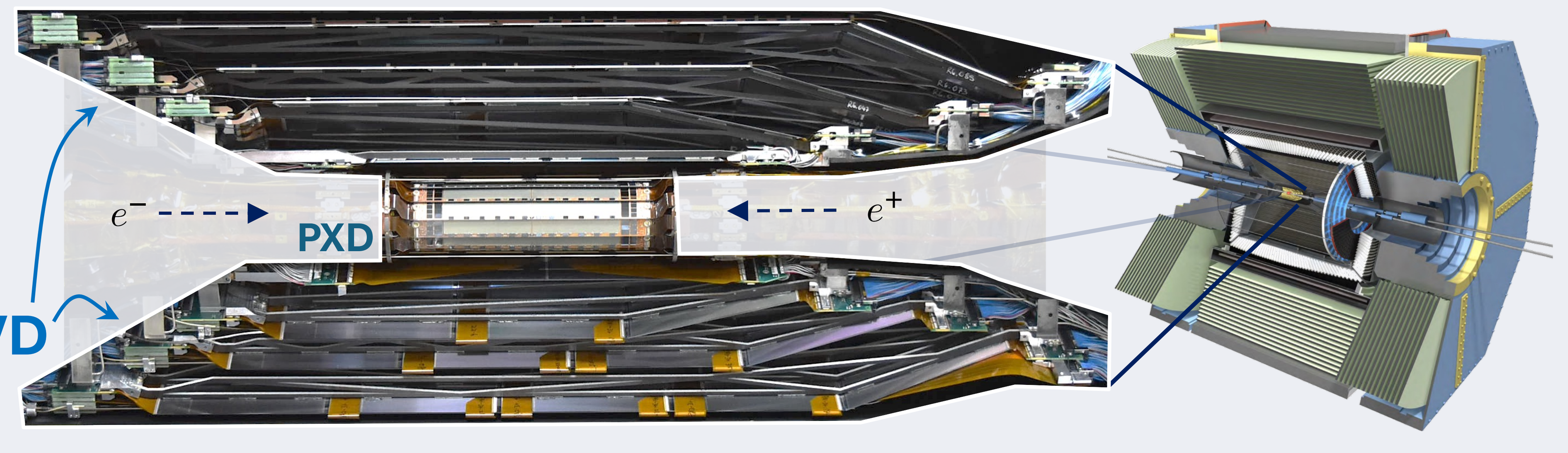


Photo of the full PXD + half SVD — Belle II detector

Timeline and operations

2022 June — **2024** January — We are Here! Just beginning

Run 1

- Recorded integrated luminosity $\mathcal{L}: 426\ \mathrm{fb}^{-1}$
- Achieved instantaneous luminosity $\mathcal{L}: 4.7 \times 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- Smooth and stable operation without major issue
- Excellent SVD performance
  - ✓ Good SNR (13-30)
  - ✓ Large hit efficiency ($\gtrsim$ 99%)
  - ✓ Masked strips < 1%

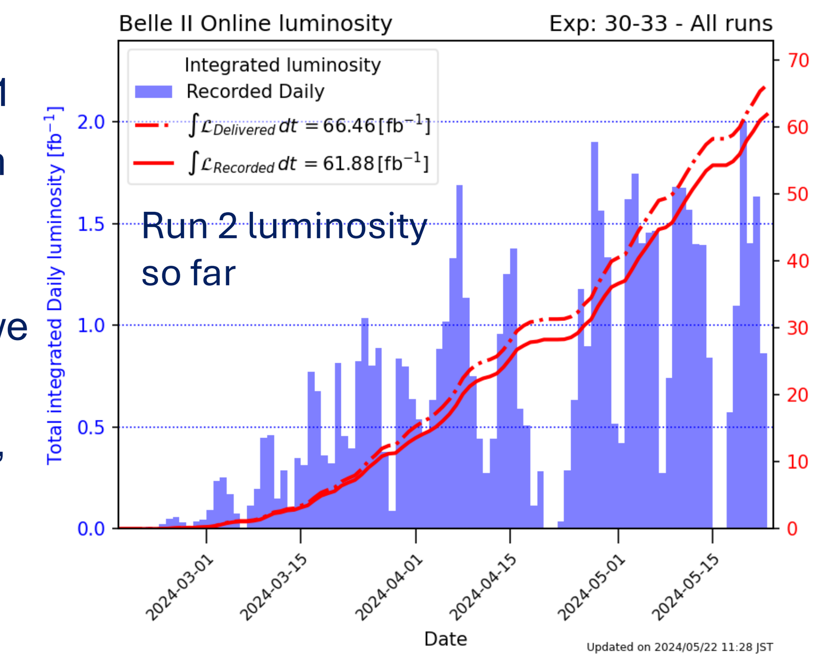
Long Shutdown 1

- VXD reinstallation with new PXD modules with the same SVD
- SVD was split into its two halves to allow the new PXD installation
- Several SVD tests were performed at each step of the VXD reinstallation to check its condition and spot problems
- Lowered cooling temperature to accommodate a higher PXD power consumption
- Checked the VXD alignment and performance using cosmic ray after reinstallation → confirmed good performance

Run 2

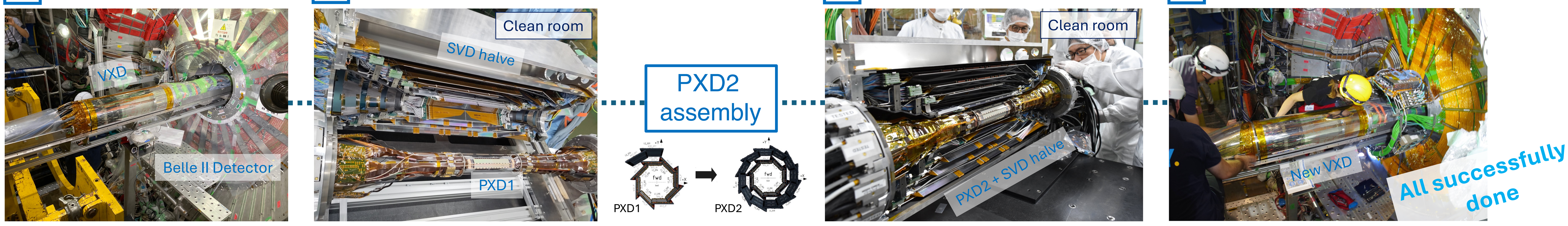
- Smooth and stable operation
- Physics performance is as good as Run 1
- SuperKEKB is trying to increase its beam current and optimize beam condition to achieve higher instantaneous luminosity
- Higher background dose is anticipated, we monitor the SVD status continuously
  - ■ Checking noise, calibration constant, and leakage current

⇒ No severe damage observed so far

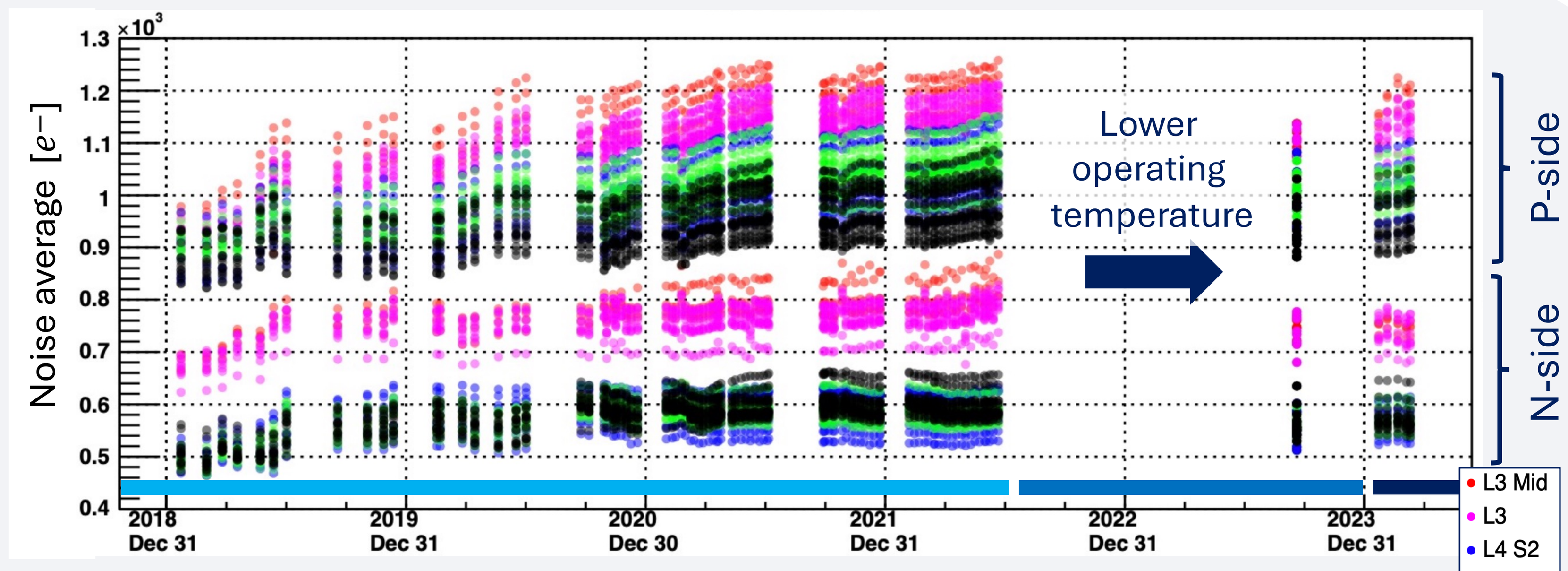


VXD reinstallation

1 VXD extraction — 2 SVD detachment from PXD1 — PXD2 assembly — 3 SVD attachment to PXD2 — 4 New VXD installation

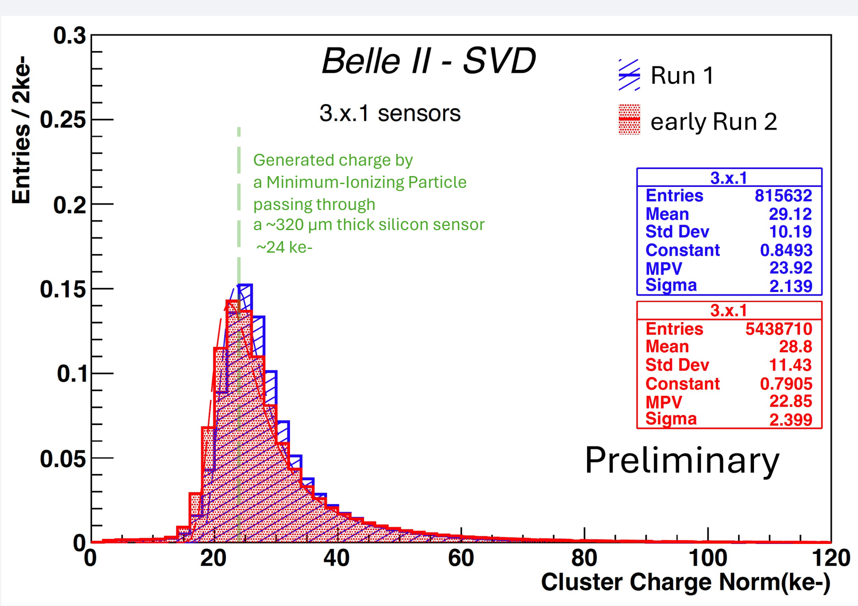


SVD performance after LS1

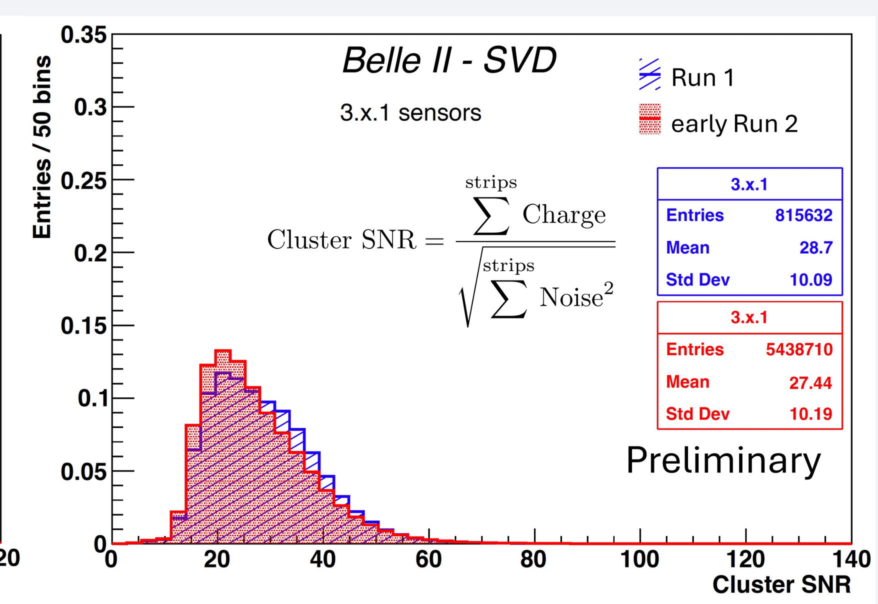


- Noise increased by 10 ~ 30% during Run 1 due to radiation damage on the sensors
  - ■ Measured radiation dose in Layer 3 is < 70 krad during Run 1
- Reduction in noise by up to 10% during LS1 due to lower operating temperature and annealing effect on the sensor
- Physics performance with Run 2 noise level is as good as Run1

Stable level, as expected



Cluster Charge Collection



Cluster Signal-to-Noise Ratio

- No significant changes in the cluster charge and cluster SNR from Run1. Small variation due to temperature effects still not corrected.
- ✓ Hit efficiency also keeps high $\gtrsim$ 99%
- ✓ Number of total masked strips ~ 1%
- ✓ No evidence of the radiation damage having impacted the full depletion voltage

Physics performance in Run2 as good as in Run1

Radiation damage study

- A 90 MeV e^- beam irradiated SVD sensors up to 10 Mrad at ELPH, Tohoku Univ.
  - ■ Estimated radiation dose is 0.2 Mrad/year on layer 3 with design luminosity
  - ✓ Type inversion occurs at 2 Mrad, equivalent neutron fluence fluence $6 \times 10^{12}\ n_{\mathrm{eq}}/\mathrm{cm}^2$
  - ✓ Linear correlation between dose and leakage current as NIEL hypothesis
    - ✓ The correlation is confirmed in the installed SVD sensors, and its slope is consistent with the irradiation study
  - ✓ **Type inverted Irradiated sensor confirmed to collect charge well after 10 Mrad irradiated**

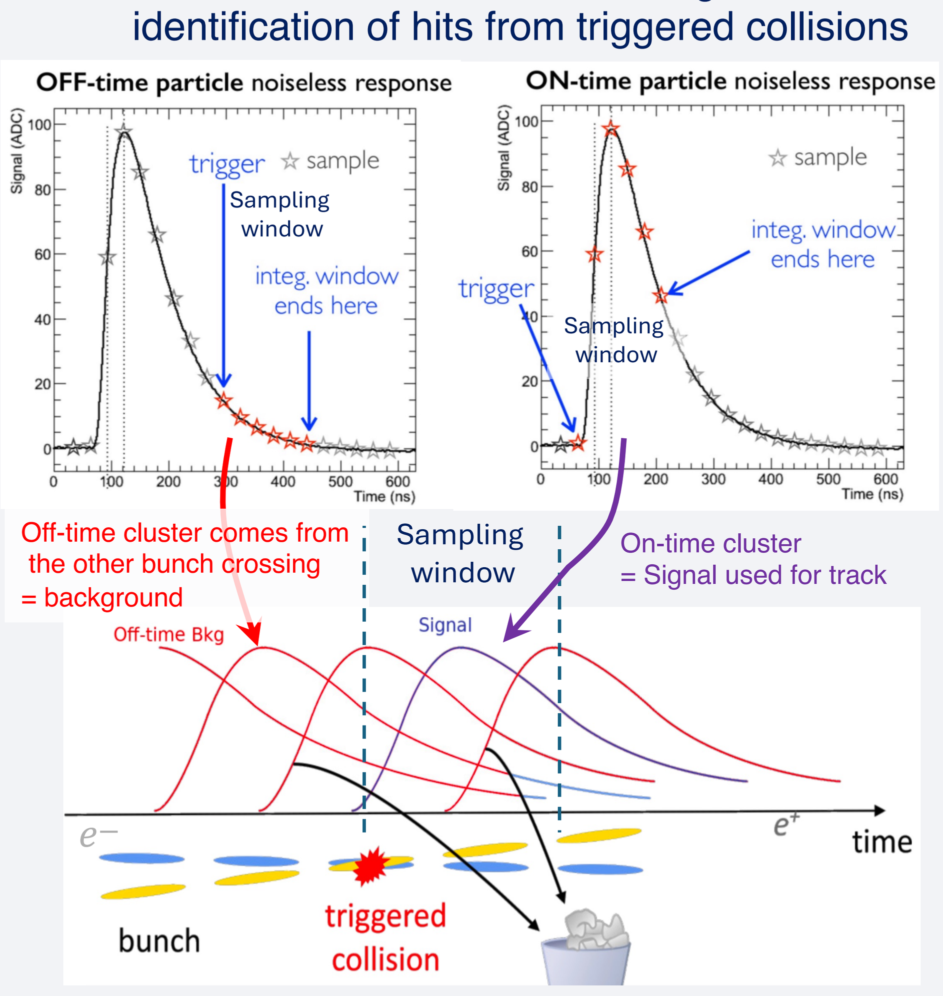
we have a good safety margin

Future background rejection

- Current hit occupancy is below 1%, but it is expected to rise as the background increases with higher beam luminosity in the future
- Higher occupancy degrades tracking performance by increasing the number of fake tracks
- We will implement hit-time selection and cluster-grouping methods, which are based on hit time to reject background and enhance occupancy acceptance,
  - ■ With excellent hit-time resolution (< 3 ns) to remove off-time tracks
  - ■ SVD has a feature that offers a 2000 times faster computing speed than a central drift chamber to provide collision time (T0). It speeds up the High-Level Trigger reconstruction and helps it cope with HLT reconstruction in the high luminosity condition

Hit-time selection

- The hit time t is determined by the peak part of the signal sampling in the sampling window (6 samples).
- The peak position in the sampling window varies with the collision, enabling the identification of hits from triggered collisions



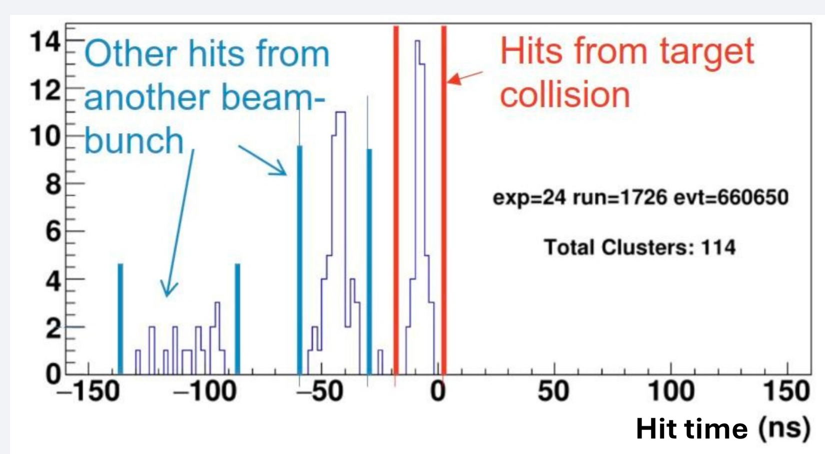
Apply simple selection on hit time

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

($u \equiv r\phi$, P side; $v \equiv z$, N side)

⇒ Removed 50% off-time track with keeping signal efficiency > 99%

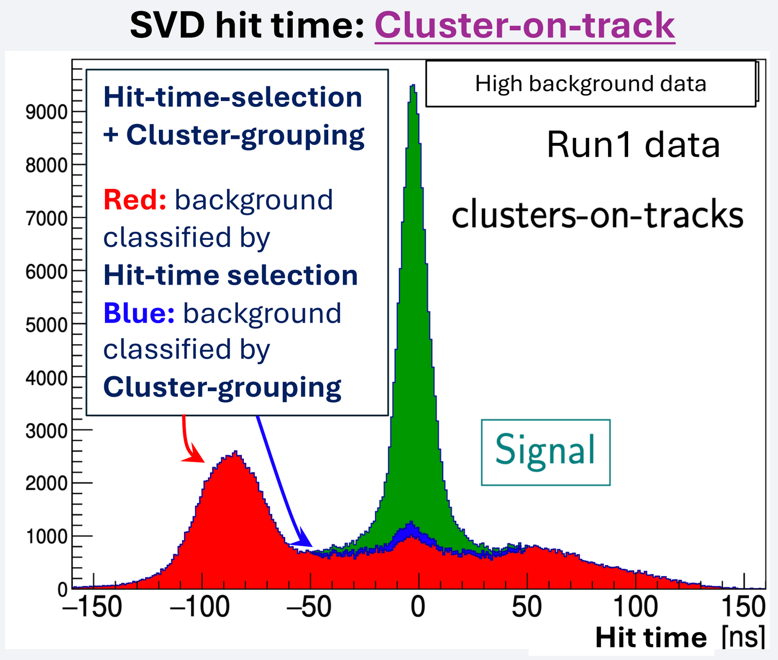
Cluster-grouping



- Classified hit time with respect to trigger on an event-by-event basis.
- Select a group close to 0 and prominent as a signal group to form tracks

⇒ Fake track rate can be reduced by 15%, outperforming the hit-time selection method.

SVD hit time: Cluster-on-track



Applied both methods to classified

- ✓ Hit-time-selection can reject the red background area and the cluster-grouping can reject additional fake signals (blue area) coming from the off-time cluster contamination
- ✓ **These improvements lead to an increase in acceptable occupancy for track reconstruction to about 6% in layer 3**

Ongoing study SNR at each sampling point of the APV25 differs between the background and the signal → Useful for 3-sample sampling to reject bkg and to reduce the SVD DAQ dead time

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