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

- 7 GeV e^-, 4 GeV e^+, $\sqrt{s} = 10.58$ GeV for $\Upsilon(4S)$
- Target integrated luminosity 50 ab^{-1}
- Target instantaneous luminosity 6×10^{35} cm^{-2} s^{-1}

Belle II

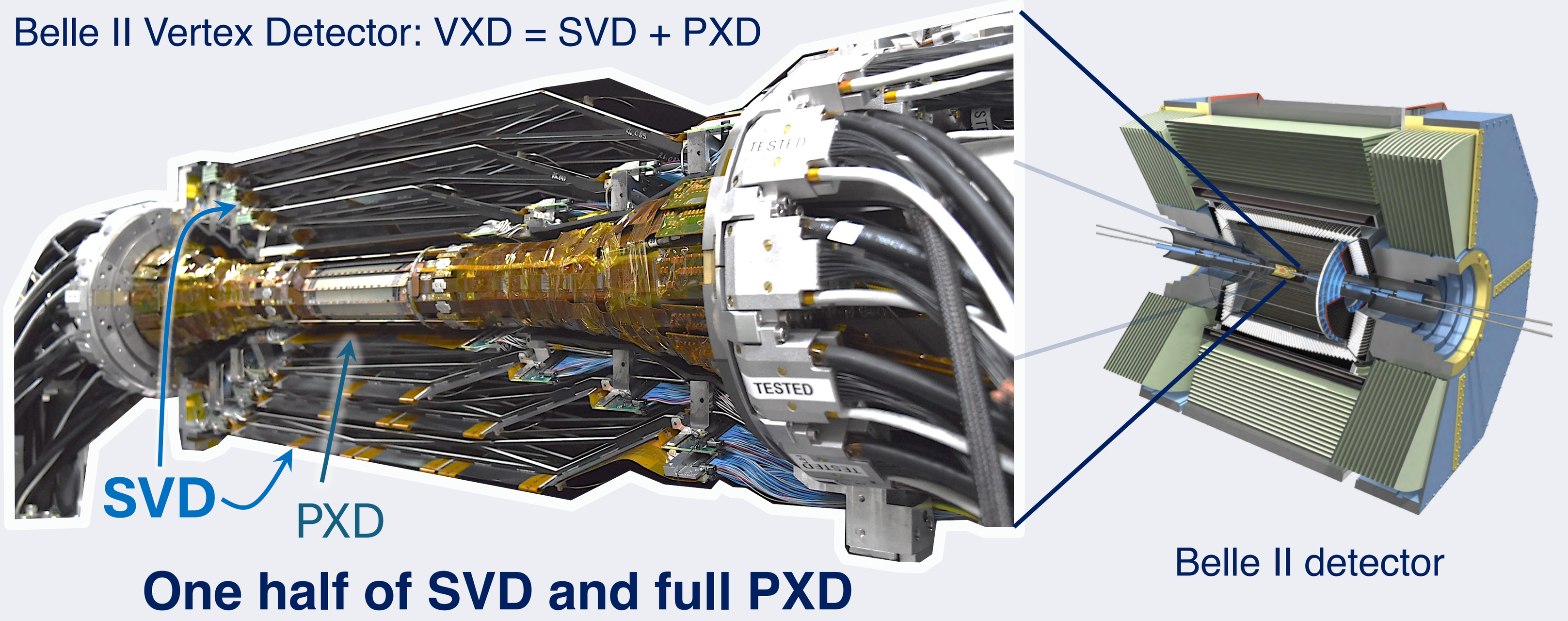
- Measures phenomena from the beam collision provided by SuperKEKB
- searches for new physics beyond the standard model at the luminosity frontier

Belle II Silicon Vertex Detector (SVD)

Thickness: ~320 um

- 4 layers of the Double-Sided Silicon Detector, strip pitch (um): 50/75 (P side, $r\phi \equiv u$), 160/240 (N side, $z \equiv v$)
- Constitute VXD with 2 layers of DEPFET pixel detector (PXD); inner PXD 2 layer + outer 4 SVD layer
- Readout ASIC: APV25, shaping time 50 ns
- Cooling: two-phase CO_2 flow
- Provides precise hit information to reconstruct track, reconstruct vertex, particle identification with dE/dx

Belle II Vertex Detector: VXD = SVD + PXD



One half of SVD and full PXD

Belle II detector

Timeline and operations

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

Run 1

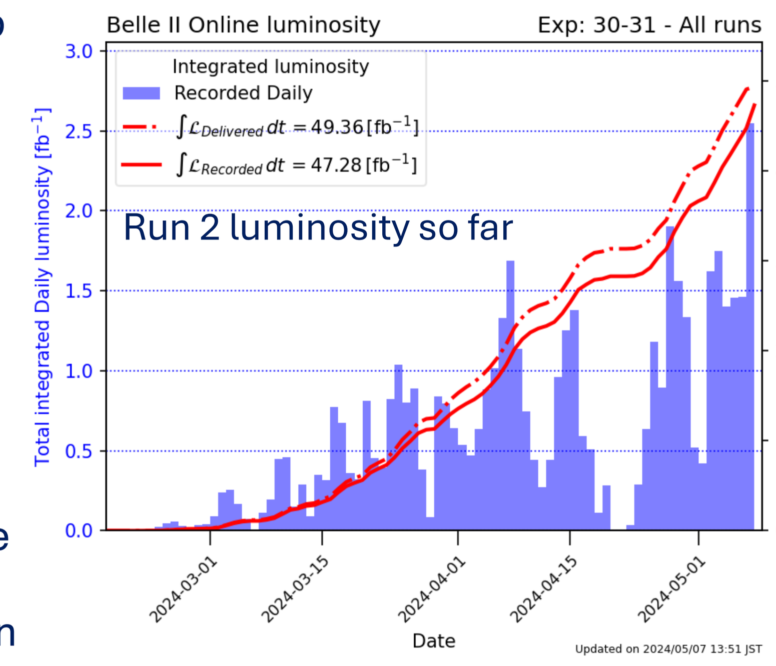
- Recorded integrated luminosity $\mathcal{L}: 424\ \mathrm{fb}^{-1}$
- Recorded instantaneous luminosity $\mathcal{L}: 4.3 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- Smooth and stable operation without major issue
- excellent physics performance
  - ✓ Good SNR (13-30)
  - ✓ Large hit efficiency ($\gtrsim$ 99%)
  - ✓ Masked strips < 1%

Long Shutdown 1

- VXD reinstallation for installing new PXD modules with the same SVD
- SVD was split into its two halves to allow access for the new PXD installation
  - Intense hardware activities > 5 months
- Several SVD tests were performed at each step to check the SVD condition and spot problems
- Optimized the cooling condition (lowered cooling temperature) with higher PXD power consumption
- Using cosmic-ray to check the VXD alignment and performance after VXD installation → good agreement with expectation

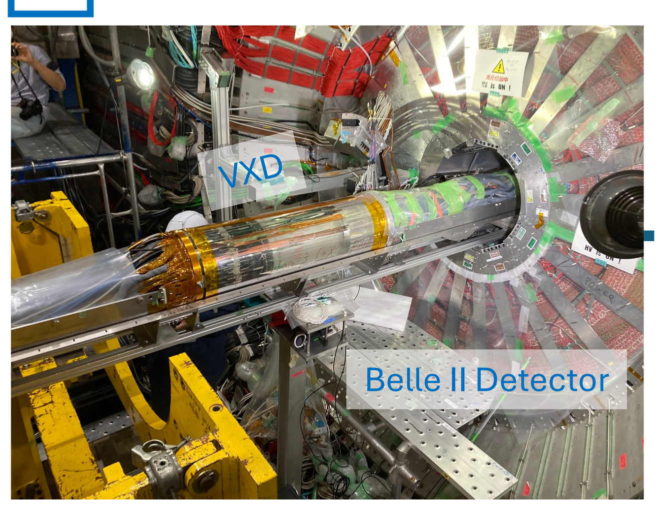
Run 2

- Using cosmic-ray data taking campaign to check the detector readiness before starting SuperKEKB beam operation
- Smooth and stable operation
- Physics performance is as good as pre-LS1
- SuperKEKB is trying to increase its beam current and optimize beam condition to achieve higher instantaneous luminosity
- higher background dose is anticipated, we are conducting SVD sanity checks on a weekly basis while monitoring the situation

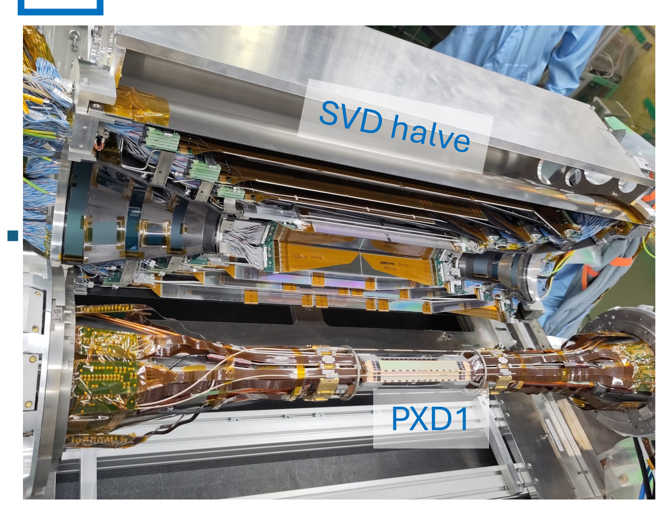


VXD reinstallation

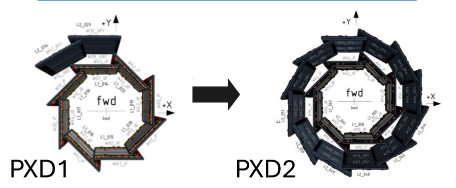
1 VXD extraction



2 SVD detachment from PXD1



PXD2 reconstruction

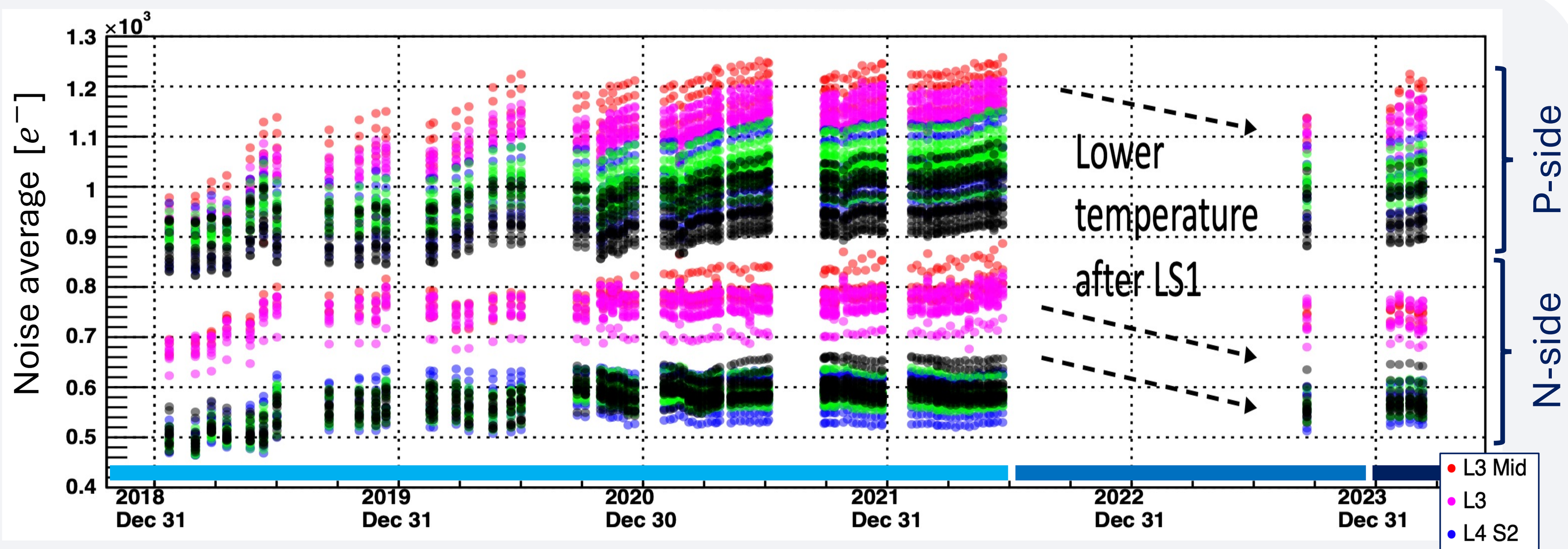


3 SVD attachment to PXD2

4 New VXD installation

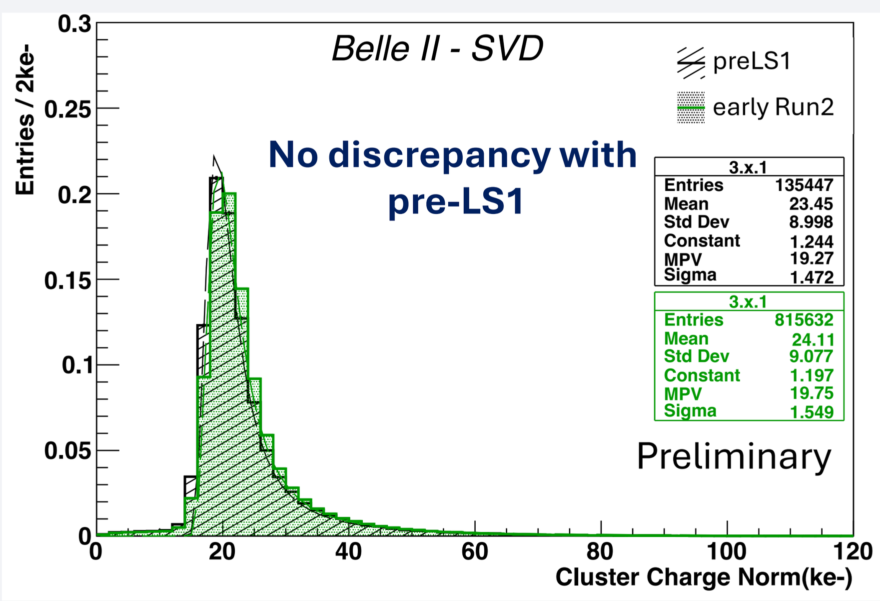
All successfully done

SVD performance after LS1

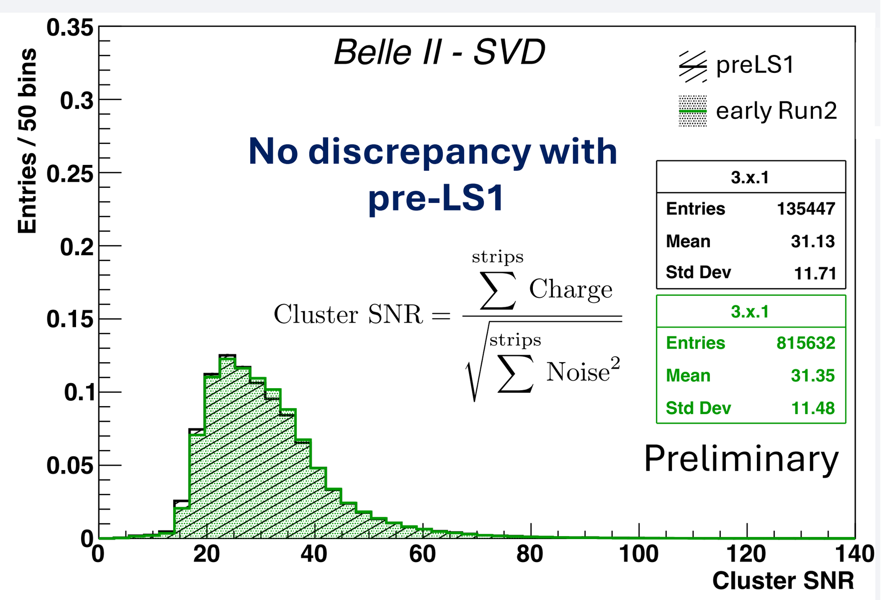


- Noise increased 10 ~ 30% during Run 1 due to radiation damage on the sensor
  - Measured radiation dose of Run 1 in Layer 3 is < 70 krad
- Reduction in noise by up to 10% during LS1 due to lower operating temperature and annealing effect on the sensor
- Noise has resumed its escalation from the beginning of Run 2

Stable level, as expected



Cluster Charge Collection



Cluster Signal-to-Noise Ratio

- No degradation in the cluster charge collection level and cluster SNR from Run 1, both are the expected level. Hit efficiency also keeps high $\gtrsim$ 99%
- Masked additional few noisy strips that appeared after a large beam abort, but still total masked strips < 1%
- No change found in the full depletion voltage due to radiation damage so far

No degradation in physics performance

Radiation damage study

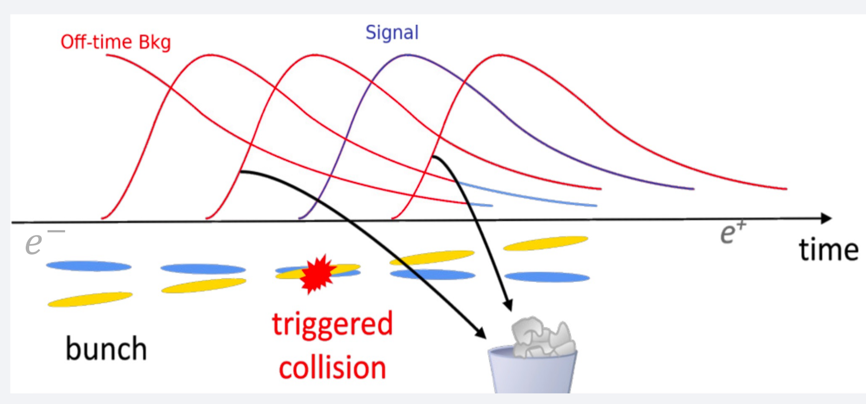
- Sensor Irradiation campaign: 90 MeV e^- beam at ELPH, Tohoku Univ, July 2022 up to 10 Mrad
  - ✓ Observed the full depletion voltage change with large dose s.t. > 0.4 Mrad
  - ✓ Type inversion occurs at 2 Mrad, equivariant neutron fluence fluence $6 \times 10^{12}\ n_{\mathrm{eq}}/\mathrm{cm}^2$
  - ✓ irradiated sensors confirmed to work with collecting charge well after type inversion
  - ✓ Linear correlation between dose and leakage current as NIEL hypothesis
  - ✓ the correlation is also confirmed in the operating sensors and the slope of dose vs leakage current is consistent

Estimated radiation dose: < 0.2 Mrad/year, 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 will degrade tracking performance such that an increase 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
  - Hit time measured with reference to the collision event time (T0) provided by the central drift chamber (CDC) now
  - SVD also has the same feature but offers a 2000 times faster computing speed to provide T0. It speeds up the High Level Trigger (HLT) reconstruction and helps it cope with HLT reconstruction in the high luminosity condition.

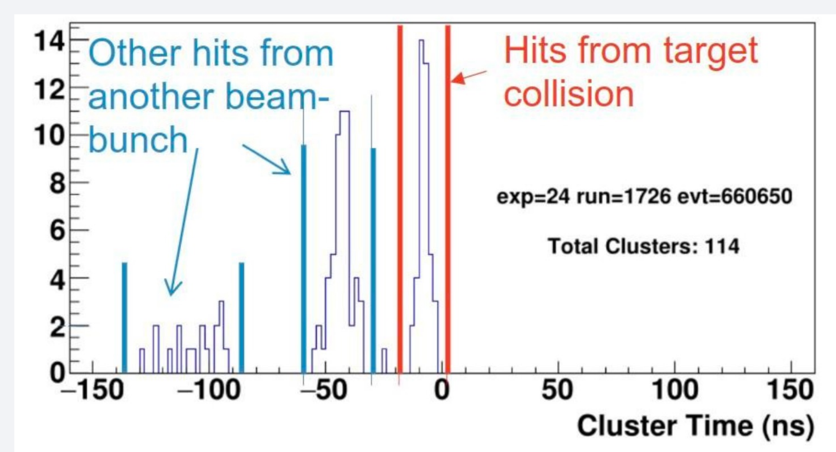
Hit-time selection



- With excellent hit time resolution (< 3 ns) remove off-time tracks
  - $|t_{u,v}| < 50$ ns
  - $|t_u - t_v| < 20$ ns

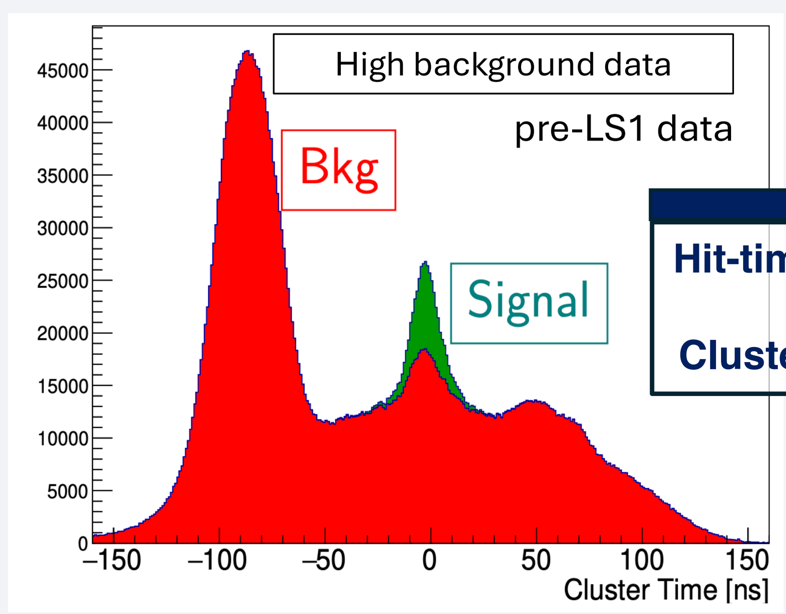
⇒ removed 50% off-time track with keeping signal efficiency > 99%

Cluster grouping



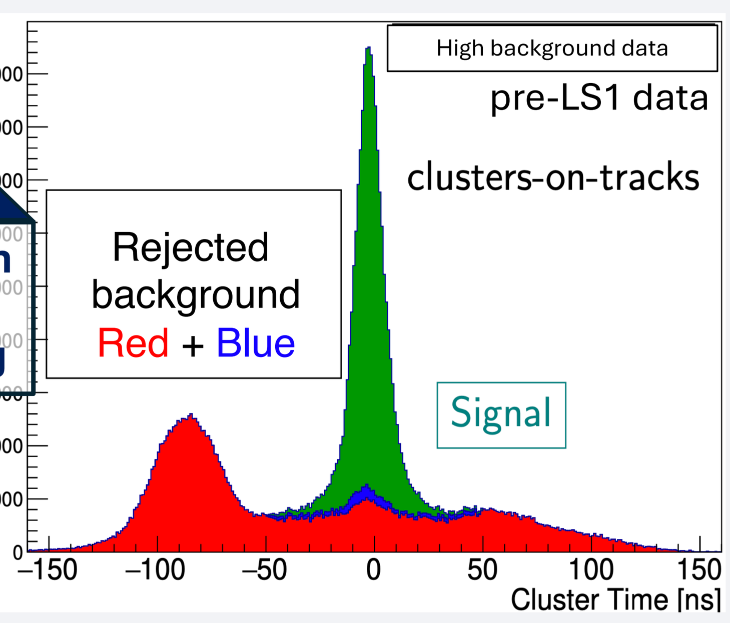
- Classified hit time on trigger event by event basis.
- Select a group close to 0 and prominent as a signal group to form tracks

⇒ reduce more fake track rate from Hit-time selection method



High background data without SVD time cut

Hit-time selection + Cluster grouping



The result after the cuts

- Hit-time selection can reject the red background region and the cluster grouping can reject the blue background region in the right figure above. These improvements lead to an increase in occupancy acceptance to about 6% for Layer 3.

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