The Silicon Vertex Detector of the Belle II Experiment

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on behalf of the Belle II SVD collaboration

September 25, 2023

Outline

Silicon Vertex Detector in Belle II experiment

- Belle II experiment at luminosity frontier in search for new physics beyond standard model
- **SuperKEKB** collider: Asymmetric e^+e^- collisions at $\Upsilon(4S)$ resonance at 10.58 GeV
- **Vertex Detector (VXD)** sits nearest to the interaction point with total 6 Layers
  - Inner 2 layers of **Pixel Detector (PXD)**: DEPFET pixel sensor
  - 4 layers of **Silicon Vertex Detector (SVD)**: Double-sided strip
  - Requirements: excellent vertex resolution and operation in a high-background environment

Target

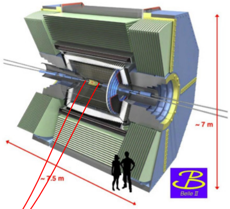
$\int \mathcal{L}dt = 50\text{ab}^{-1}$

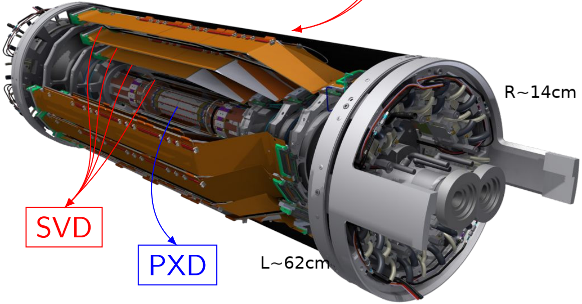
$\mathcal{L} = 6 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$

Achieved

$\int \mathcal{L}dt = 424\text{fb}^{-1}$

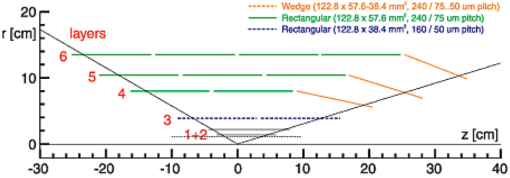
$\mathcal{L} = 4.7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$

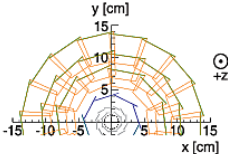




Main SVD features

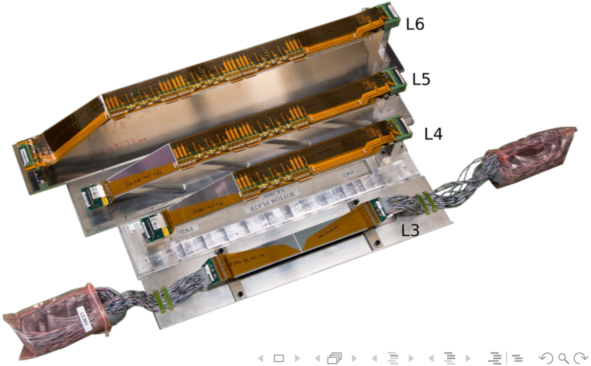
- Standalone tracking for low momentum tracks and precise vertexing of K_s
- Extrapolate tracks to PXD
- Provide particle identification using dE/dx.





SVD sensors are organised in electrically and structurally independent **ladders**

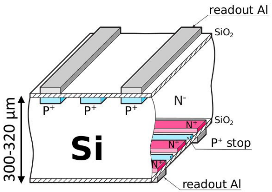
Layer	Ladder	Sensors per Ladder	Radius (mm)
3	7	2	39
4	10	3	80
5	12	4	104
6	16	5	135

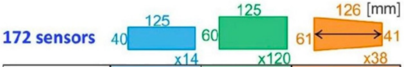


- Forward sensors are slanted to maximise acceptance with smaller incidence angle
- Low material budget of 0.7% X_0 per layer

SVD sensors & front-end

- Double-sided Silicon Strip Detectors (DSSD): provides 2D spatial information: u/P-side $\rightarrow r\phi$, v/N-side $\rightarrow z$
- 172 sensors with 224k readout strips covering $1.2\,\text{m}^2$
- Readout chip on top of sensor: origami concept
- 3 different types of DSSD shapes



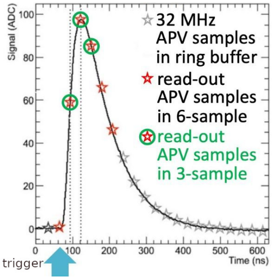


	Small	Large	Trapezoidal
# of p-strips*	768	768	768
p-strip pitch*	50 µm	75 µm	50-75 µm
# of n-strips*	768	512	512
n-strip pitch*	160 µm	240 µm	240 µm
thickness	320 µm	320 µm	300 µm
manufacturer	HPK		Micron

*readout strips – one floating strip on both sides

Front-end ASIC APV25

- Radiation hard: >100 Mrad
- Fast pulse shaping time of 50 ns
- Power consumption: 0.4 W/chip
- 128 channels per chip
- Multi-peak mode at 32 MHz
  - Records 6 samples
  - 3/6-mixed acquisition also ready for high luminosity runs

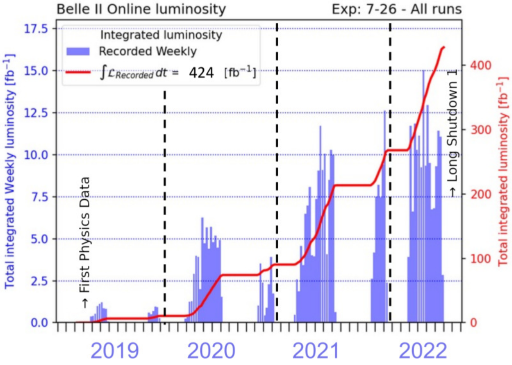


Outline

SVD operation status

Timeline

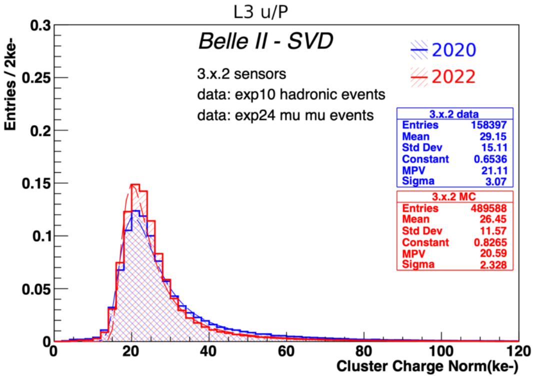
- **March 2019:** First Physic Data with VXD
- **July 2022:** Long-Shutdown (LS1) activity
  - Accelerator and detector maintenance & improvements
  - **VXD upgrade** with new PXD + current SVD
- **December 2023:** Resume beam operation

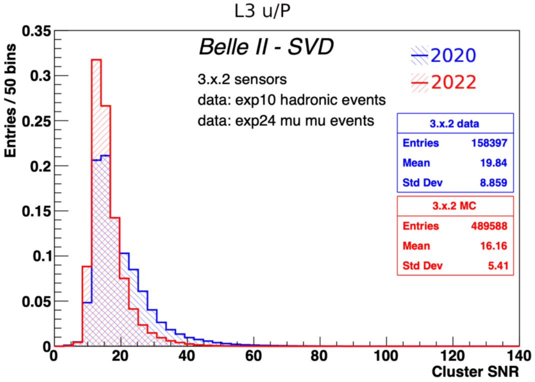


Smooth and stable operation without major issues

- Masked strips are less than 1%
- Stable environment and calibration constants' evolution consistent with expectation
- Excellent detector performance $\Longrightarrow$ Good signal-to-noise ratio (SNR), precise position resolution and large hit efficiency (>99%)
- Background effects are well under control

SVD cluster charge & SNR

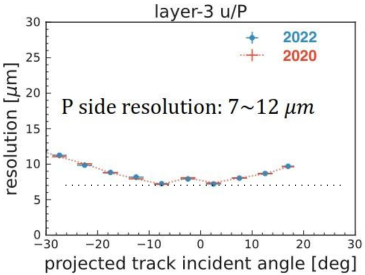


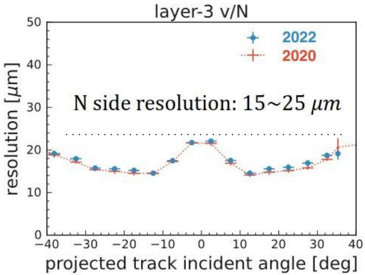


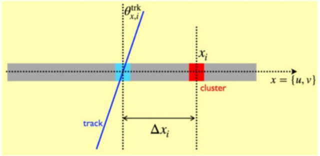
Good stability of cluster charge and SNR from 2020 & 2022

- Cluster charge normalised to track length similar in all sensors
- Small changes observed in SNR due to noise increase by radiation damage, as expected
    - MPV 13-30 depending on sensor position

SVD cluster position resolution







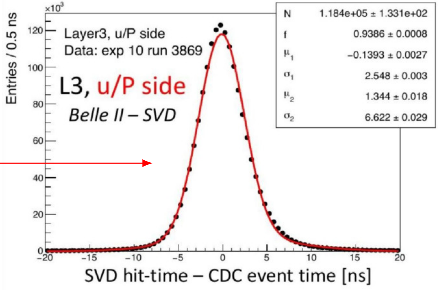
$$\sigma_x = \sqrt{\left\langle (\Delta x_i)^2 - \left(\sigma^{trk}_{x,i}\right)^2 \right\rangle}$$

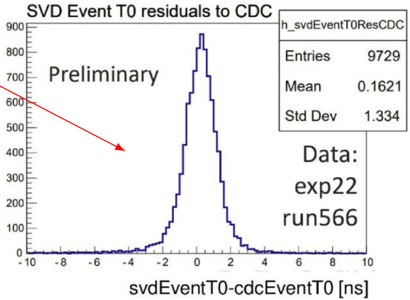
$\sigma^{trk}_{x,i}$ = unbiased track position error

- Position resolution is calculated from the cluster position with respect to the track extrapolation using $e^+e^- \to \mu^+\mu^-$ sample.
- Stable position resolution is observed during the operation.
- Good resolution, generally as expected with pitch expectations (dotted line)

SVD time resolution

- Excellent **cluster time** resolution of less than 3 ns
  - SuperKEKB bunch spacing: ∼6 ns
  - SVD acquisition window: ∼100 ns
- **Track time** is computed using all the hits on a tracks.
- **Event-time** in SVD is computed using all the clusters associated to selected tracks in an event.
  - The computation of event-time in SVD is ∼ 2000 times faster than the same from CDC
  - This feature speeds up the High Level Trigger (HLT) reconstruction helping it cope higher luminosity.



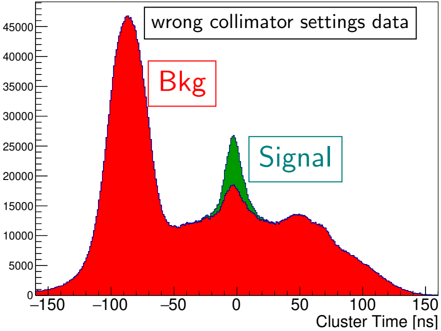


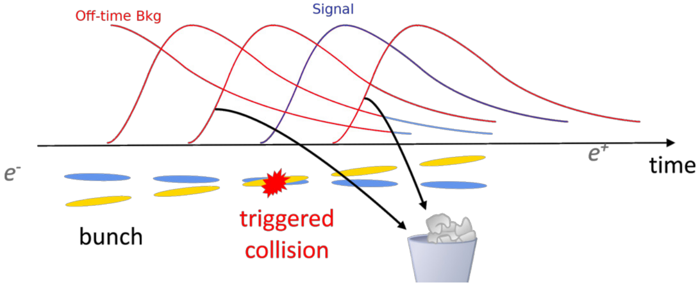
Outline

Reconstruction at high luminosity

- High luminosity comes with high beam backgrounds
- The accurate SVD time will be crucial in rejecting background and will allow to maintain the current excellent tracking performance
  - hit-time-based selection to remove off-time clusters
  - cluster time used to find suitable u/v pairs
  - tracking filters are trained with cluster time information

SVD hit-time: all clusters



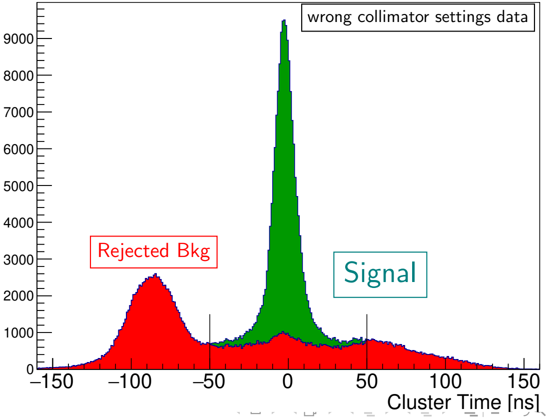


note: these data have been taken with wrong collimator settings and are affected by extremely high bkgs and only chosen to illustrate the impact of time selection

Background rejection with SVD hit-time selection

- Large contamination of off-time clusters in tracks if SVD time is not used in reconstruction
- The time-based hit selection and tracking filters reject the majority of the bkg while keeping above 99% of signal
  - $|t_{u,v}| < 50\,\mathrm{ns}$ & $|t_u - t_v| < 20\,\mathrm{ns}$
- Exploiting SVD time, the SVD Occupancy limit can be set at 4.7%.
  - There are still room for improvement

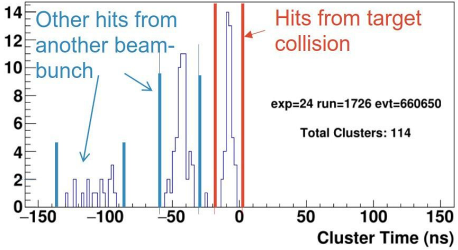
SVD hit-time: clusters-on-tracks

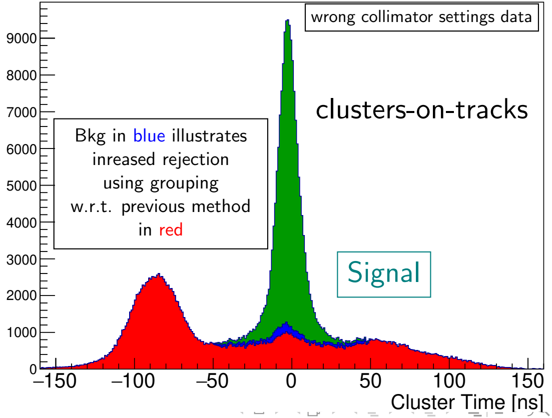


Background rejection with SVD cluster grouping

- Alternative method to the absolute cut on time to better exploit the hit time information
- Clusters are classified in groups on an event-by-event basis, based on time, and only the signal group is made available for tracking

  $\Longrightarrow$ Bkg rejection increased over the previous method reducing the rate of fake track due to bkg hits by 16%

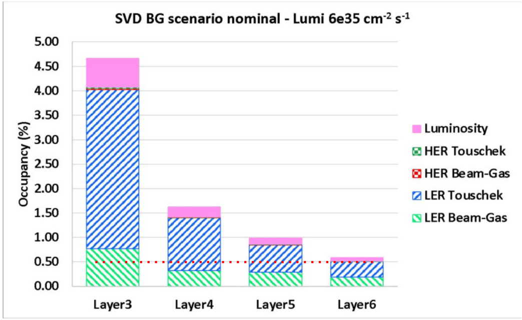




- Along with track-time selection, this method allows to set the SVD occupancy limit at 6%.

Nominal background prediction : SVD hit occupancy

- Present average hit occupancy is 0.5% at L3
  - well under control.
- Nominal extrapolation to target luminosity shows small safety margin w.r.t. 4.7% limit.
  - With large uncertainty due to future machine evolution and possible interaction region re-design, conservative extrapolation (8.7%) even exceeds 6% limit
- Small safety margin and possible interaction region redesign motivates vertex detector upgrade (S. Bettarini in next talk ...)



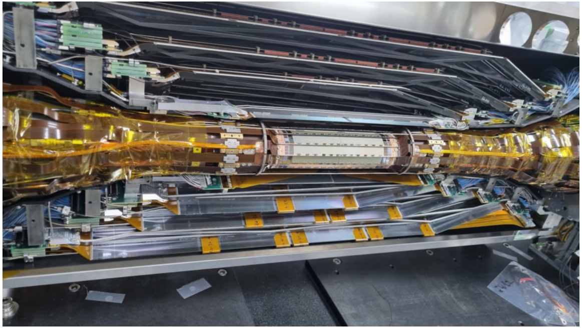
Outline

VXD re-installation in LS1

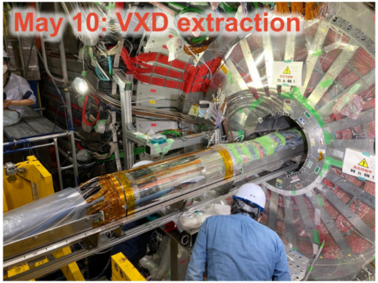
Intense hardware activities on the SVD for the VXD de-installation/re-installation

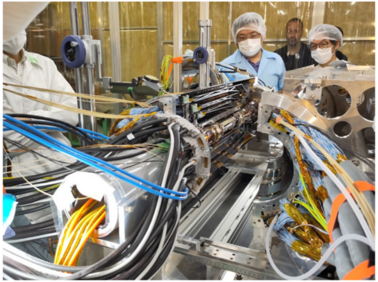
May 10	VXD extraction	Belle II
May 17	SVD detachment	activity
June 1	SVD commissioning	in
June 28	New VXD assembly	clean
July 14	New VXD commissioning	room
July 28	New VXD installation	Belle II
ongoing	Functional tests & commissioning with cosmic-ray	

No major issue on SVD during LS1 activity

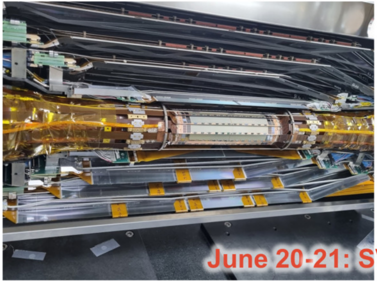


- Upgraded VXD is re-installed during LS1
  - New complete PXD + current SVD


May 10: VXD extraction




May 16-17: SVD detachment


June 20-21: SVD attachment


July 28: VXD re-installation

Summary

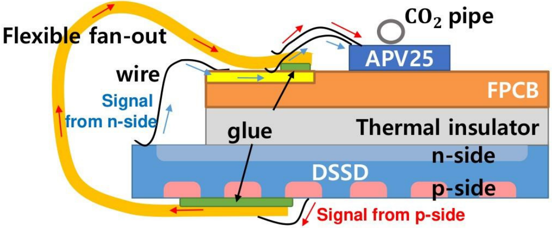
- SVD is performing stably and excellently as expected
  - The design, construction, operation and performance of the Belle II silicon vertex detector is published in the *SVD Technical Paper* (JINST 17 P11042 2022)
- During LS1, VXD is now re-installed at Belle II with new PXD2 and current SVD
  - commissioning with cosmic-ray is ongoing
- Improving SVD software against future high luminosity
  - The accurate SVD time will be crucial in rejecting background and will allow to maintain the current excellent tracking performance
- Background extrapolation to target luminosity shows hit occupancy could exceed our limit, while radiation dose is within safety margin:
  VXD upgrade is under discussion $\Longrightarrow$ more robust against high background and matching possible new interaction region now under evaluation

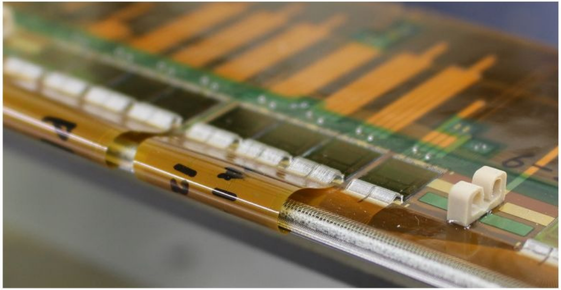
Thank You

Backup

Origami chip-on-sensor

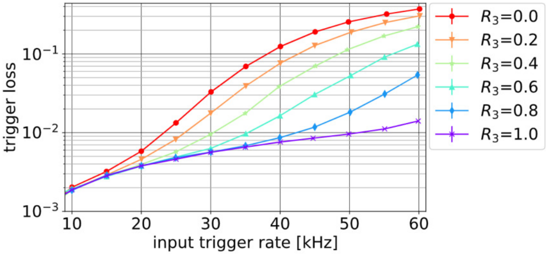
- Readout chip placed directly on top of Sensor
  - Wrapped flex to read signal from both side
  - Chips are thinned to 100μm to reduce material budget
  - Shorter signal propagation length;
    smaller capacitance and noise
- Single side cooling tube with CO_2





SVD 3/6-mixed DAQ mode

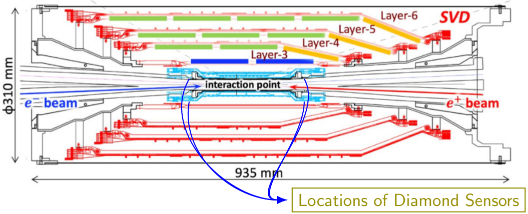
- SVD Data Acquisition consumes time which can attach a significant dead time at higher trigger rates
- Dead time can be reduced by acquiring less SVD samples per event
- Acquiring data with 3-mixed-6 samples is important to reduce the dead time which is useful at higher trigger rate
- 3-mixed-6 sample mode is prepared and tested in 2020c
- 3 or 6 samples are acquired in each event based on trigger jitters:
  Fine TRG (3-sample)
  Coarse TRG (6-sample)



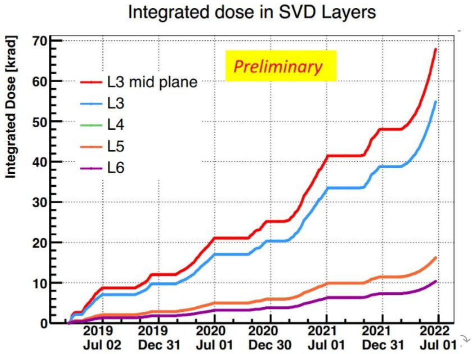
* 3% dead-time at 30 kHz with $R_3 = 0$
* 1% dead-time at 30 kHz with $R_3 = 0.4$

Integrated radiation dose on SVD

- Dose on SVD is constantly monitored using Diamond sensors and hit occupancy
  - Total integrated damage on L3, 70krad, $1.6 \times 10^{11} n_{\mathrm{eq}}/\mathrm{cm}^2$
  - No degradation of detector performance is observed

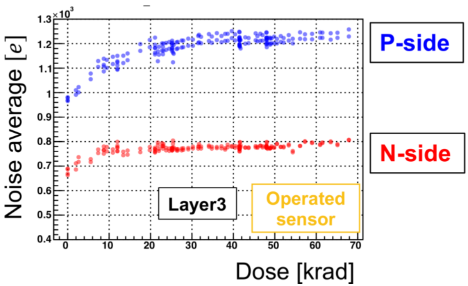


- Expected radiation damage at nominal luminosity, $\sim$0.35Mrad, $\sim 8 \times 10^{11} n_{\mathrm{eq}}/\mathrm{cm}^2$ per year
- Irradiation campaign on SVD sensors
  - with 90 MeV e^- beam at ELPH, Tohoku Univ. July 2022
  - Evaluated radiation tolerance of SVD sensors up-to 10Mrad, $3 \times 10^{13} n_{\mathrm{eq}}/\mathrm{cm}^2$
- SVD has a good safety margin for integrated radiation effects: expected to operate well at nominal luminosity for many years

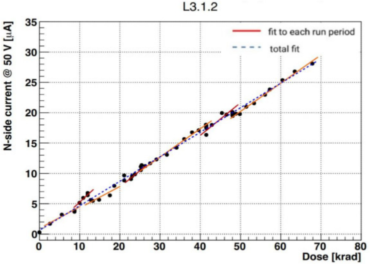


Radiation effects on SVD : strip noise and leakage current

- As expected, noise increases with increased radiation dose
  - increase <20% (30%) for N (P) side
  - dominated by the inter-strip capacitance
  - non-linear due to fixed oxide charges, expected to be saturated

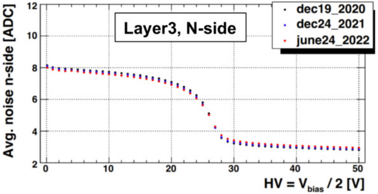


- Linear increases of leakage current with radiation dose as expected
  - proportional to the equivalent neutron fluence (expected from NIEL model)
  - Contribution to noise negligible now due to short APV25 shaping time
  - After 6 Mrad dose strip noise contribution from leakage current would reduce the Layer3 SNR <10

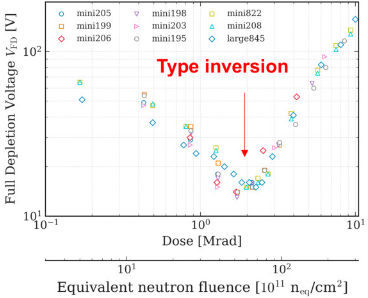


Radiation effects: full depletion voltage

- Bulk damage changes the effective doping and the full depletion voltage, V_{FD}.
- For operated SVD sensors, the V_{FD} is measured with N-side noise vs bias voltage.
  ⇒ No change in V_{FD} observed so far (<70 krad)



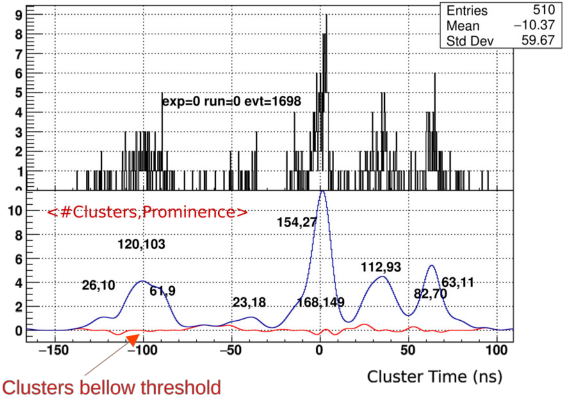
- In the irradiation campaign, the clear change in V_{FD} is confirmed with large radiation damage.
  - **Type inversion: 2 Mrad, 6×10^{12} n_{eq}/cm^2**
  - Based on experience on BaBar SVT sensor, SVD sensor will work well above type inversion
    ⇒ CCE measurement to confirm it.



*** EPS Slide of Sato-san**

SVD cluster grouping

- We start with an empty histogram of 0.5ns binwidth.
- The for each cluster in a event
  - We **add** a Normalized Gaussian to the histogram.
    - mean is the cluster time
    - width is the cluster time resolution
- Resolutions are already calculated and stored in the payloads along other parameters.
  - Resolutions are calculated for 3 types of sensors, 2 sides and for upto clusters size of 6.
  - Sensor types are
    - 0 : L3
    - 1 : L456, Sensor 1
    - 2 : L456, Others



Then we find all the peaks by fitting and removing Gaussian from the histogram.