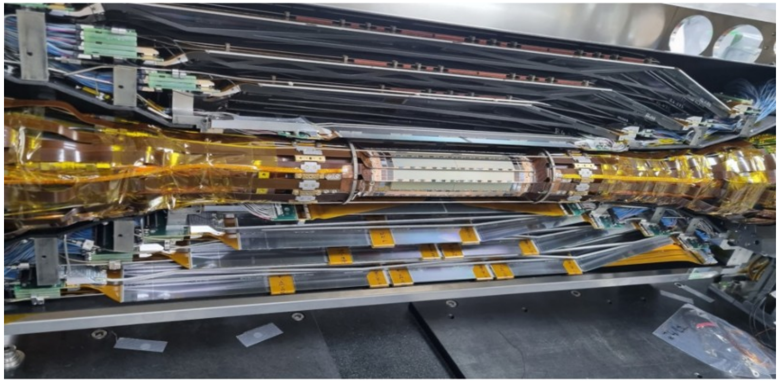
The 32nd International Workshop on Vertex Detectors

Sestri Levante (GE, IT), 16-20 October 2023

The Silicon Vertex Detector of the Belle II Experiment



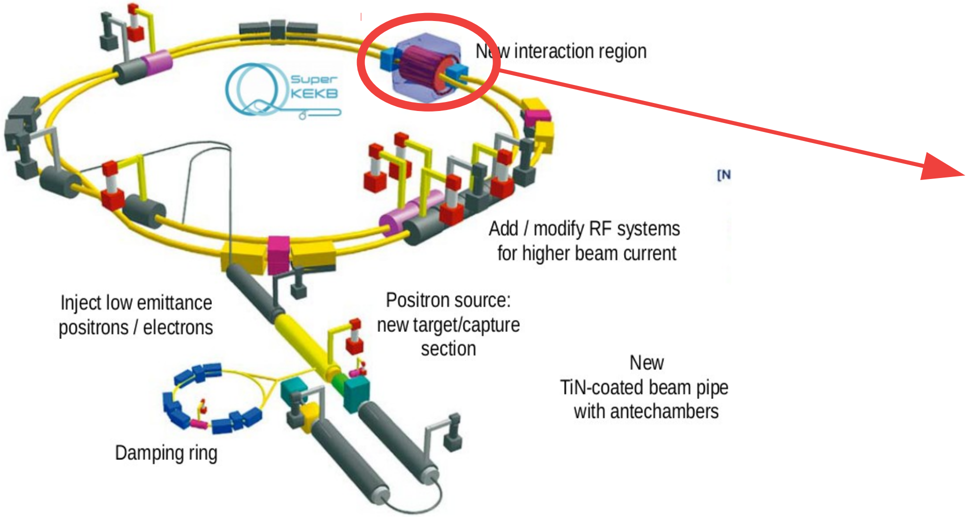
Jarek Wiechczyński
(for the Belle II SVD Collaboration)

Outline

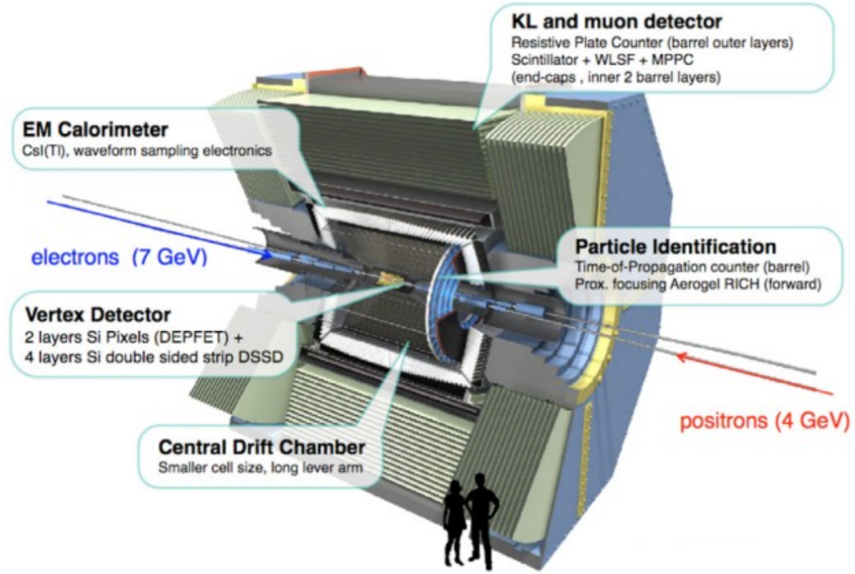
- Belle II experiment & vertex detector
- Silicon Vertex Detector (SVD) overview
- SVD operation status and performance
- High luminosity perspective & software developments
- Long shutdown 1 activities
- Summary

SuperKEKB accelerator and Belle II detector

SuperKEKB



Belle II



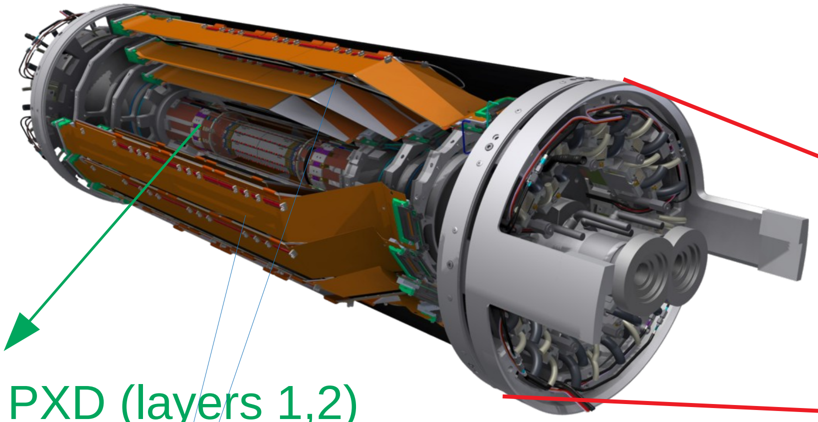
- Asymmetric e^+e^- collider operating at $\Upsilon(4S)$ resonance energy in the CM frame
  → clean source of B mesons from $\Upsilon(4S) \rightarrow B\bar{B}$ process
- instantaneous luminosity achieved: 4.7×10^{34} cm^{-2}s^{-1} **(world record!)**

  Goal: **6 x 10^{35} cm^{-2}s^{-1}**

- Excellent vertexing and good hermeticity
- Integrated luminosity achieved so far: 424 fb^{-1}

  Goal: **50 ab^{-1}**

Vertex Detector (VXD) of Belle II

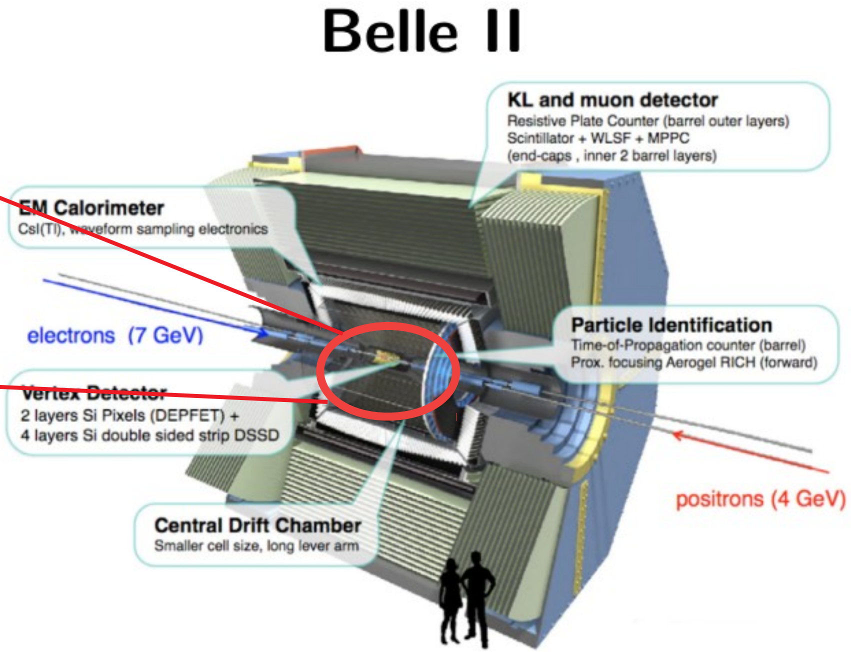


- PXD (layers 1,2)

  Innermost part consists of DEPFET pixel sensors
  → Precise determination of decay vertices

- SVD – 4 layer structure (layers 3-6)

➔ Extrapolation of the tracks to PXD
➔ Low momentum tracking
➔ Help with particle identification using dE/dx



- Excellent vertexing and good hermeticity
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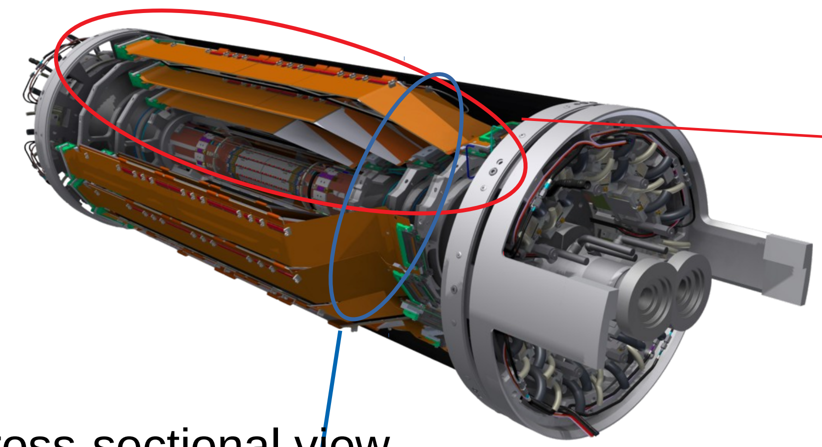
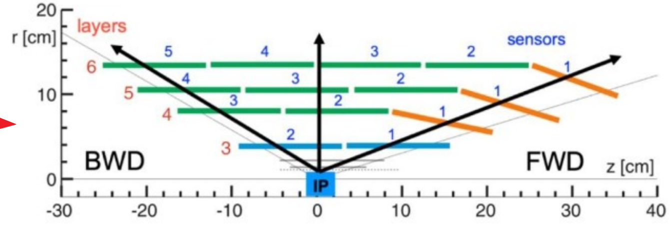
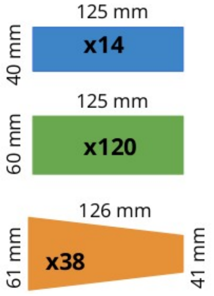
SVD structure



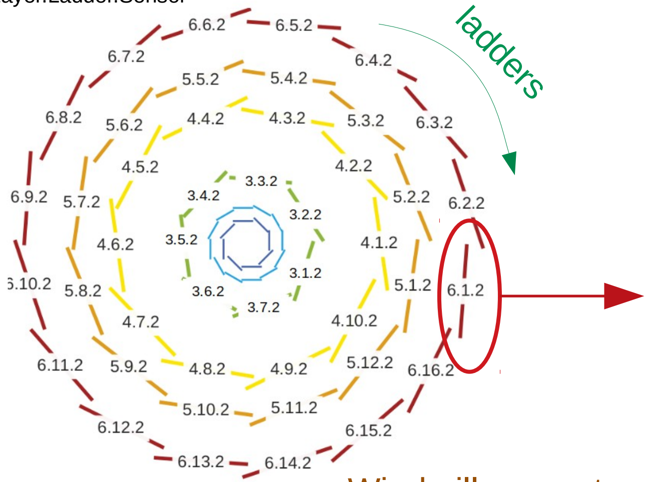
3 different DSSD shapes





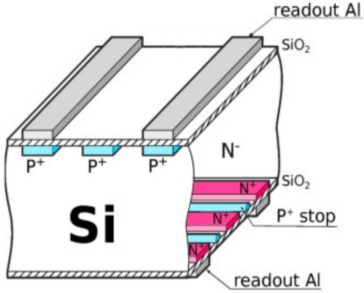
Type	Number of readout strips		Readout pitch (μm)		Thickness (μm)	Manufacture
	P side	N side	P side	N side		
Small	768	768	50	160	320	HPK
Large	768	512	75	240	320	HPK
Trapezoidal	768	512	50-75	240	300	Micron

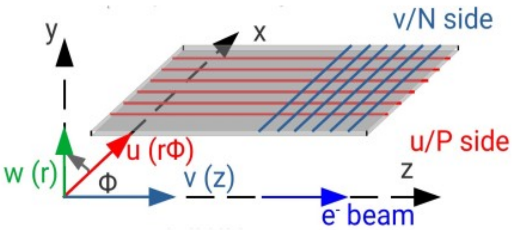
Cross-sectional view



Windmill geometry

DSSD sensors - Double-sided Silicon Strip Detectors

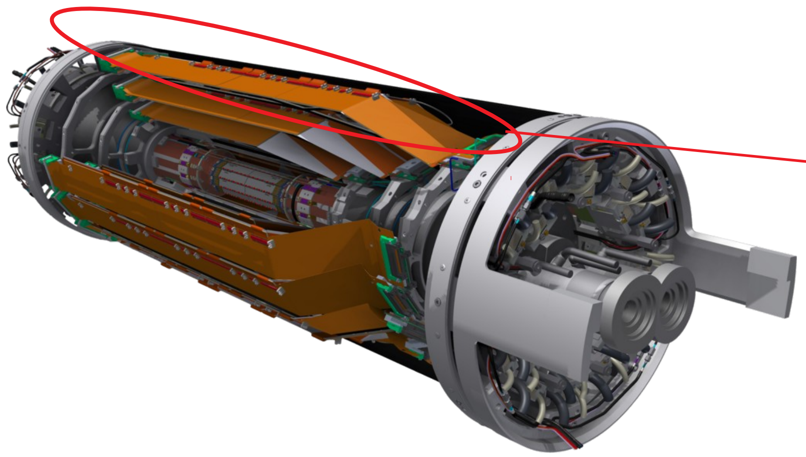


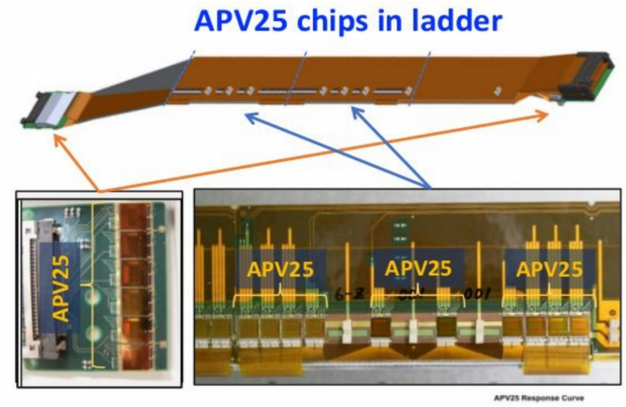


- Provide 2-D spatial information
- Depletion voltage 20-60 V
- Operation voltage 100 V

- ○ 172 sensors with 1.2 m^2 sensor area
- ○ 224k readout strips

Front-end electronics

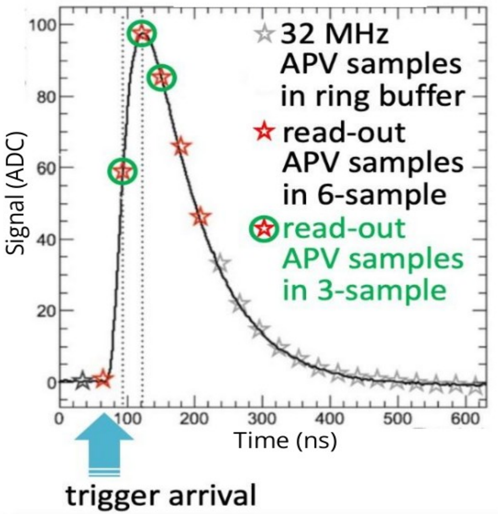




Central DSSD sensors connected to front-end APV25 ASICs via flex circuits

→ „origami scheme”

Analog signal



By default:

- 6 subsequent samples readout

Alternative for high luminosity runs:

- 3/6 mixed acquisition mode
  - → allows to reduce data size due to enhanced background occupancy
  - → 3 or 6 sample mode depends on the timing precision of the trigger for particular event

Frontend ASIC APV25:

- 128 channels per chip
- 50 ns shaping time
- Radiation hardness > 100 Mrad
- Power consumption: 0.4 W/chip
- Multi-peak mode at 32 MHz

SVD operation & status

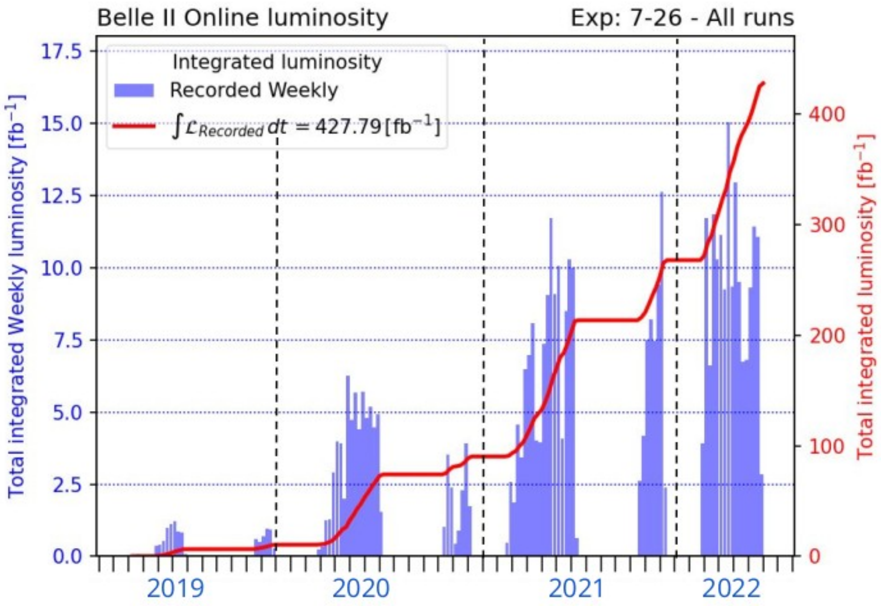
Timeline

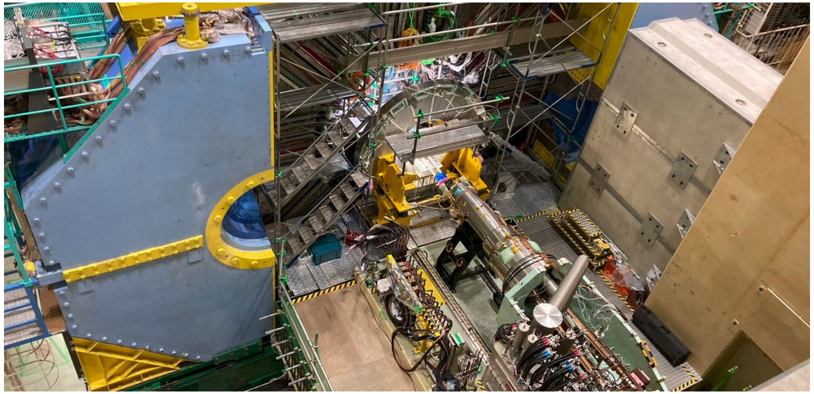
March 2019: Start of data taking…

- Very smooth performance of the SVD without major problems
- Total number of masked strips < 1%
- Stable environment, calibration constants evolution consistent with expectation
- Radiation damage effects are well under control
- Excellent detector performance:
  → efficiency, signal-to-noise ratio (next slides)

July 2022:
Long Shutdown 1 (LS1): **maintenance & improvement of the SuperKEKB and the detector**
→ VXD upgrade → new **PXD**, the same **SVD**

Plans for resuming the accelerator operation in **December 2023**

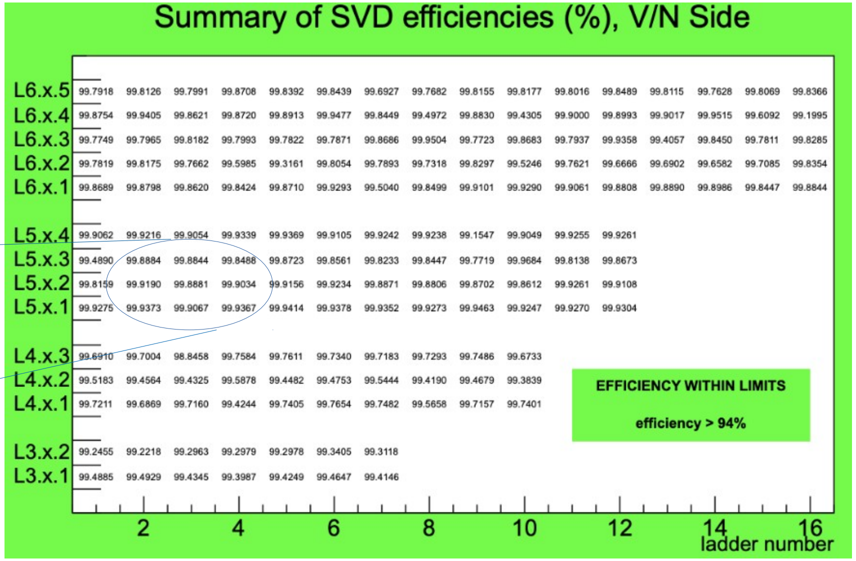




SVD efficiency

- Sensor efficiency is very high (>99%) for all the sensors

99.8884	99.8844	99.8488
99.9190	99.8881	99.9034
99.9373	99.9067	99.9367



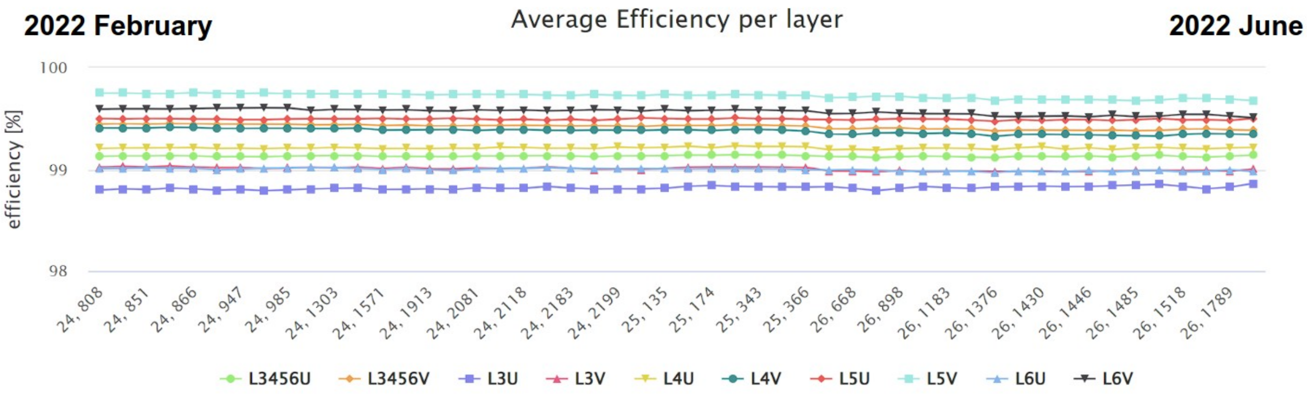
Summary of SVD efficiencies (%), V/N Side

Ladder number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
L6.x.5	99.7918	99.8126	99.7991	99.8708	99.8392	99.8439	99.6927	99.7682	99.8155	99.8177	99.8016	99.8489	99.8115	99.7628	99.8069	99.8366
L6.x.4	99.8754	99.9405	99.8621	99.8720	99.8913	99.9477	99.8449	99.4972	99.8830	99.4305	99.9000	99.8993	99.9017	99.9515	99.6092	99.1995
L6.x.3	99.7749	99.7965	99.8182	99.7993	99.7822	99.7871	99.8686	99.9504	99.7723	99.8683	99.7937	99.9358	99.4057	99.8450	99.7811	99.8285
L6.x.2	99.7819	99.8175	99.7662	99.5985	99.3161	99.8054	99.7893	99.7318	99.8297	99.5246	99.7621	99.6666	99.6902	99.6582	99.7085	99.8354
L6.x.1	99.8689	99.8798	99.8620	99.8424	99.8710	99.9293	99.5040	99.8499	99.9101	99.9290	99.9061	99.8808	99.8890	99.8986	99.8447	99.8844
L5.x.4	99.9062	99.9216	99.9054	99.9339	99.9369	99.9105	99.9242	99.9238	99.1547	99.9049	99.9255	99.9261				
L5.x.3	99.4890	99.8884	99.8844	99.8488	99.8723	99.8561	99.8233	99.8447	99.7719	99.9684	99.8138	99.8673				
L5.x.2	99.8159	99.9190	99.8881	99.9034	99.9156	99.9234	99.8871	99.8806	99.8702	99.8612	99.9261	99.9108				
L5.x.1	99.9275	99.9373	99.9067	99.9367	99.9414	99.9378	99.9352	99.9273	99.9463	99.9247	99.9270	99.9304				
L4.x.3	99.6910	99.7004	98.8458	99.7584	99.7611	99.7340	99.7183	99.7293	99.7486	99.6733						
L4.x.2	99.5183	99.4564	99.4325	99.5878	99.4482	99.4753	99.5444	99.4190	99.4679	99.3839						
L4.x.1	99.7211	99.6869	99.7160	99.4244	99.7405	99.7654	99.7482	99.5658	99.7157	99.7401						
L3.x.2	99.2455	99.2218	99.2963	99.2979	99.2978	99.3405	99.3118									
L3.x.1	99.4885	99.4929	99.4345	99.3987	99.4249	99.4647	99.4146									

EFFICIENCY WITHIN LIMITS

efficiency > 94%

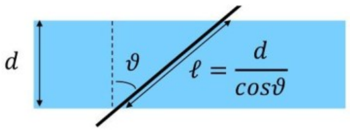
Data Quality Monitor plot



- Very stable over the whole period of data taking!

Cluster charge & Signal-to-Noise Ratio (SNR)

Collected charge depends on the incident angle of a track



$d = 320 - 300\mu m$

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

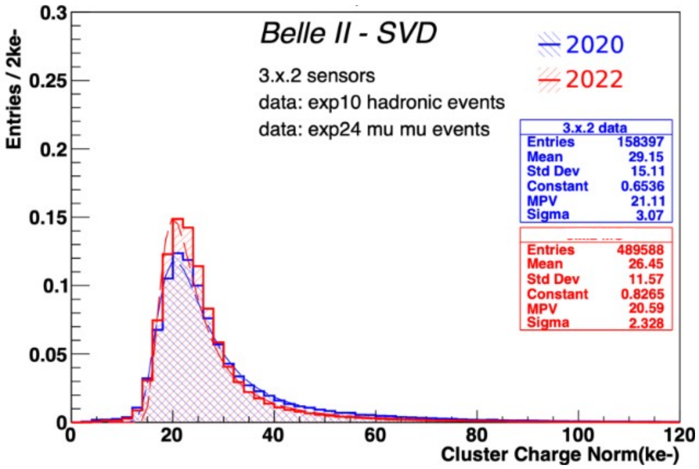
- Cluster charge similar in all sensors
  (if normalised to the track's length)
- 10-30% signal loss for v/N side due to larger pitch and floating strip

$$\text{ClusterSNR} = \frac{\sum^{\text{strips}} \text{Charge}}{\sqrt{\sum^{\text{strips}} \text{Noise}^2}}$$

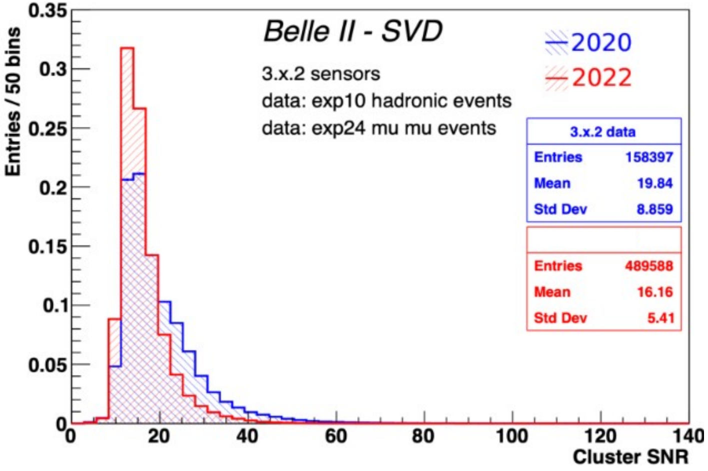
➡ Satisfying ratio in all 172 sensors!

- Larger noise for u/P side due to longer strip length and larger inter-strip capacitance
- Small changes in SNR due to radiation damage

L3 u/P



L3 u/P

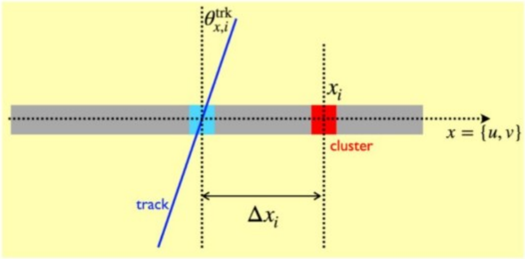


Good stability of both cluster charge and SNR during *2020 – 2022* data taking period

Position resolution

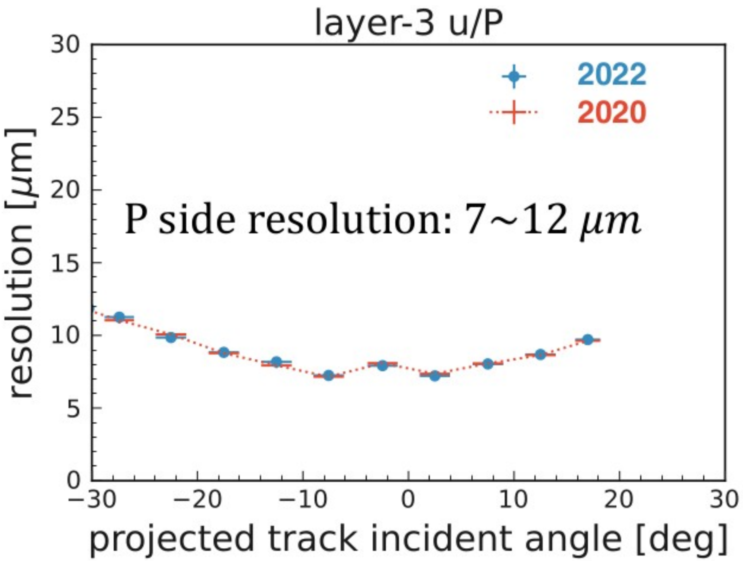
- Based on the residual of the cluster position with respect to the intercept of the unbiased track extrapolation
  → utilization of di-muon ($e^+ e^- \rightarrow \mu^+ \mu^-$) sample

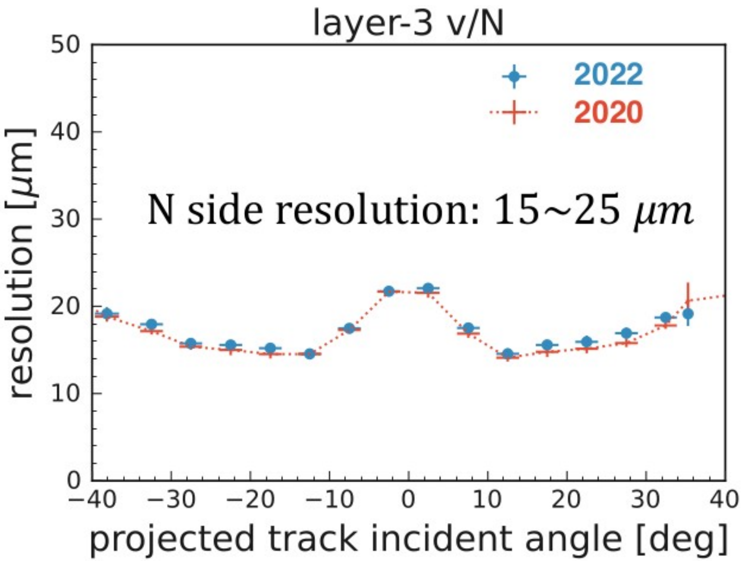
- Good and stable resolution during whole operation period (comparing data samples taken in 2020 and 2022)



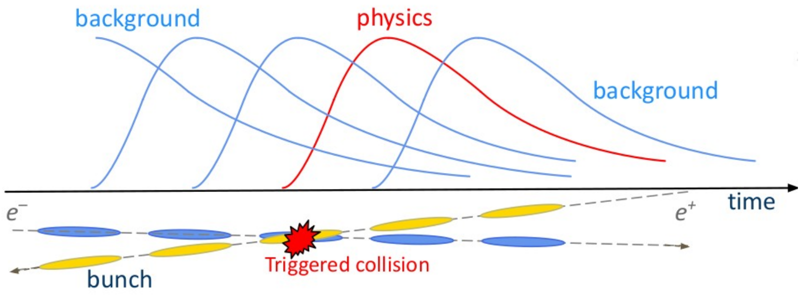
$$\sigma_x = \sqrt{\left\langle (\Delta x_i)^2 - \left(\sigma^{trk}_{x,i}\right)^2 \right\rangle}$$

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



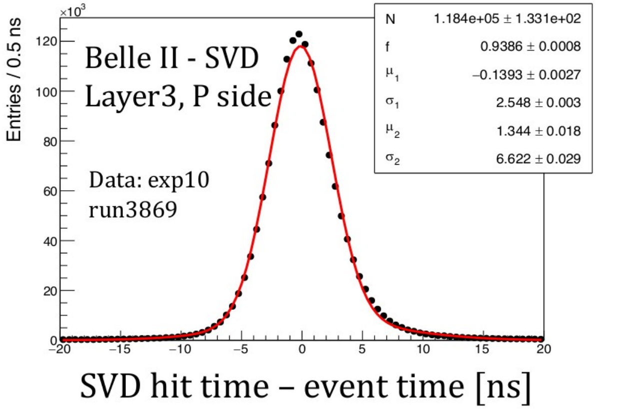


Hit time resolution



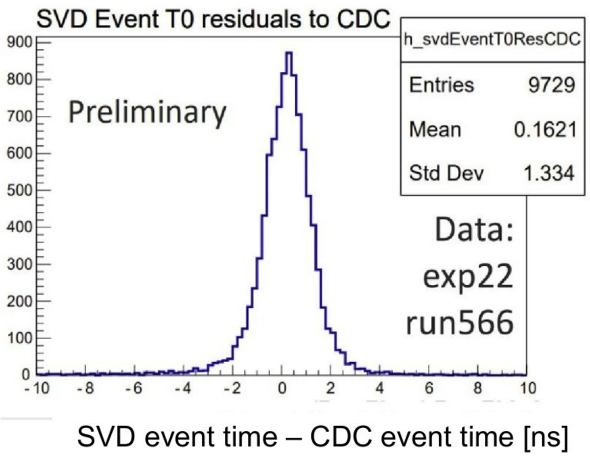
Hit time resolution: measured w.r.t. **event time** of the collision, provided by Central Drift Chamber (CDC)
→ excelent result of < 3 ns

SVD hit time resolution (clusters on track)



Track time: computed using all the hits on a track

Event-time: computed using all the clusters associated to selected tracks in the event



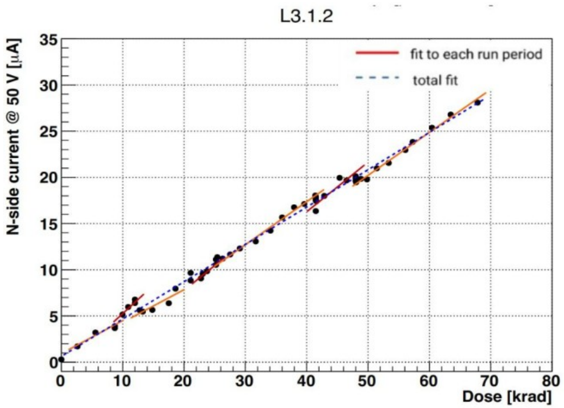
Similar resolution (~ 1 ns) but 2000 times faster computation time w.r.t. the one computed with CDC!!!

This feature speeds-up the High Level Trigger (HLT) reconstruction
→ important in the higher luminosity

Radiation effects

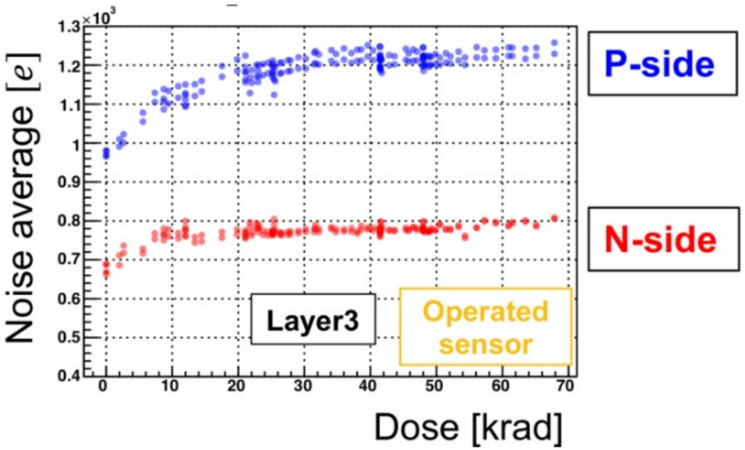
- Dose on SVD is constantly monitored using **diamond sensors** and hit occupancy
- Integrated radiation damage can deteriorate sensor performance:

increasing leakage current



- Linear dependence on the dose (equivalent neutron fluence)
- Negligible contribution to the noise due to short APV25 shaping time & still small current
- Deterioration in SNR (<10) after **6 Mrad** → leakage current increases strip noise
- Behaviour consistent with other experiments (BaBar) with similar detector/conditions

increasing strip noise



- Noise increase <20% (30%) for N (P) side
- Dominated by the inter-strip capacitance
- Expected to be saturated

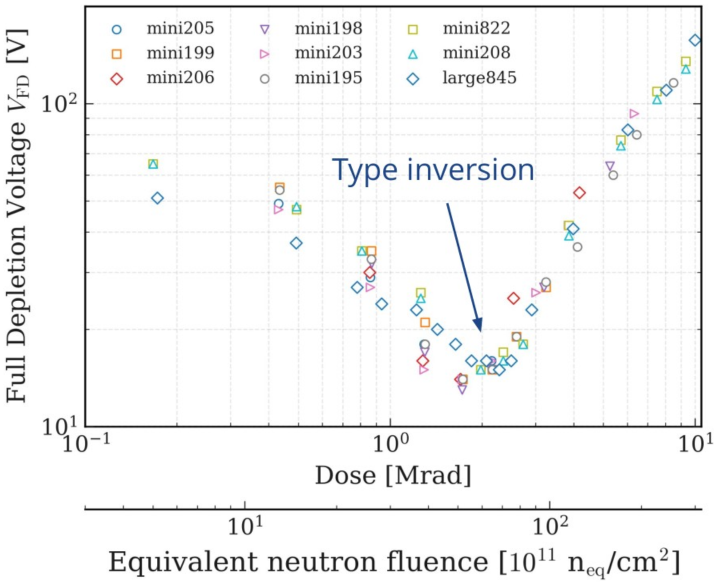
Radiation effects:
effect on depletion voltage

- Large radiation damage can cause a change in V_{FD}
- **Irradiation campaign** of SVD sensors with 90 MeV electron beam (ELPH, Tohoku University, July 2022)

  → Checking effects of high radiation on the sensors - up to 10 Mrad
  (eqivalent neutron fluence: 3×10^{13} n_{eq}/cm^2)

  → **Type inversion** confirmed at ~ 2 Mrad
  (eqivalent neutron fluence ~ 6×10^{12} n_{eq}/cm^2)

  → SVD sensors still expected to work well after **type inversion**



- No change of depletion voltage observed so far
- We estimate radiation levels of 0.35 Mrad/yr (8 x 10^{11} n_{eq}/cm^2 /yr) extrapolating background to the nominal luminosity

→ Wide safety margin for SVD even after 10 years of operation at target luminosity!

Beam Background & SVD Hit Occupancy

SVD occupancy increases with beam background
→ may lead to the deterioration of tracking performance

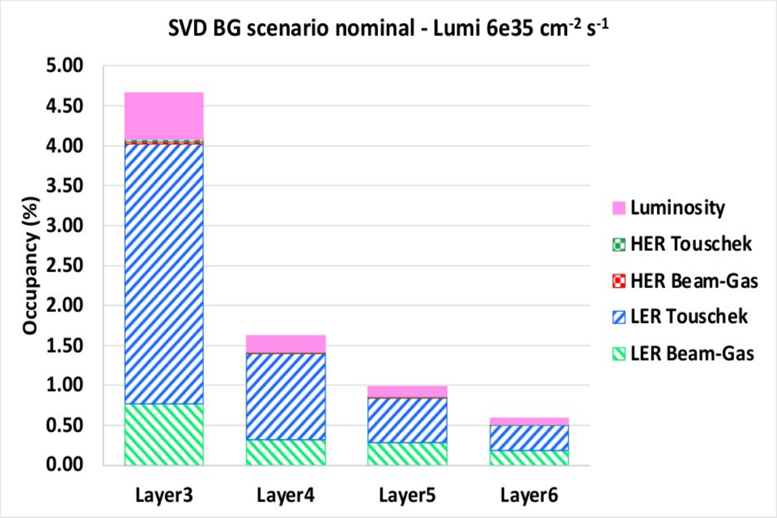
So far, average hit occupancy is ~0.5% for Layer 3 and well under control!

Background extrapolation at nominal luminosity of $L = 6 \times 10^{35}\ cm^{-2}\ s^{-1}$ based on detailed simulation including various sources of background (applying data/MC scale factors)

→ expected L3 occupancy very close to the limit of 4.7% (that ensures good tracking performance)

However: large uncertainty due to future machine evolution with possible interaction region re-design

→ conservative scenario increases L3 occupancy prediction up to 8.7%



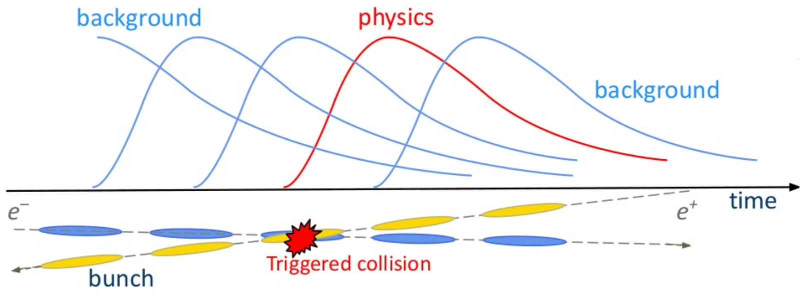
This motivates us to:

- constant ***development in SVD reconstruction software*** to account for future higher occupancy
- ***vertex detector upgrade*** as our safety factor might still be small & matching possible new interaction region

SVD hit-time selections

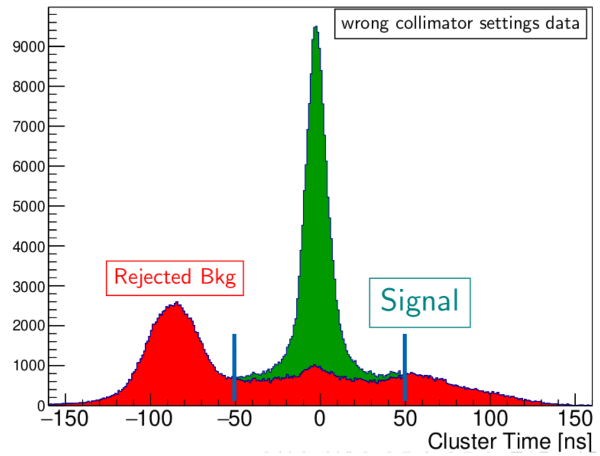
Signal hits come from triggered collision

- SVD acquisition window (~100 ns) is wide with respect to the SuperKEKB bunch spacing (~6 ns).



Selection based on SVD hit-time rejects off-time **background hits -** beam-induced background, background from the other bunches

SVD hit-time : clusters-on-tracks



Hit-time-based selection to remove off-time clusters:

→ time difference between ***u*** and ***v*** cluster: $|t_u - t_v| < 20$ ns

→ cut on absolute cluster time value: $|t_{u,v}| < 50$ ns

- This rejects the majority of the background, keeping above 99% of signal!

Based on SVD time selection the SVD occupancy limit for Layer 3 can be set at 4.7%

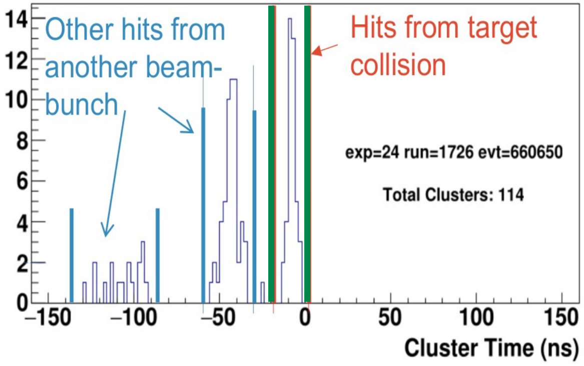
Further background rejection methods

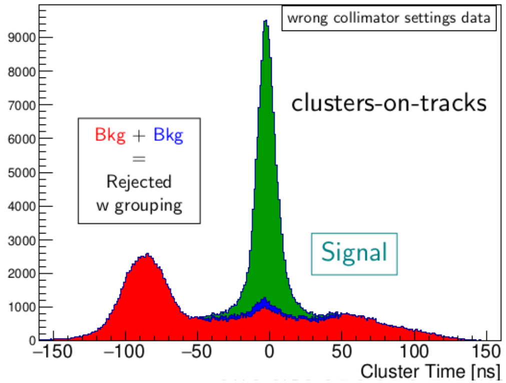
1) SVD Grouping

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

- Clusters belonging to tracks from the same collisions – collected in the same group!
- Other clusters are probably from the different collisions or beam background

→ reduces the ***fake rate*** by 16% for the *high-background* scenario





2) Selection on track-time to remove off-time tracks

→ further ***fake rate*** reduction by factor of 1.5 for the *high-background* scenario

These features (1 & 2) allow to increase SVD occupancy limit for L3 from 4.7% to ~6%

3) Possible re-design of the interaction region + small safety margin (due to large uncertainty on expected background)

→ motivation for the vertex detector upgrade

→ technology assessment ongoing

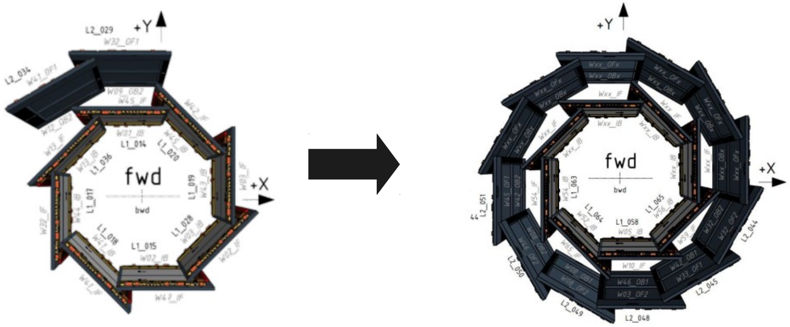
→ see Wednesday's talk ***„The DMAPS Upgrade of the Belle II Vertex Detector"*** *by Danwei Xu*

VXD re-installation during LS1

- Upgrade VXD with a **new PXD** (with the same SVD)

→ 2nd layer of PXD now covers the full azimuthal angle

(only 1/6 for the old PXD)

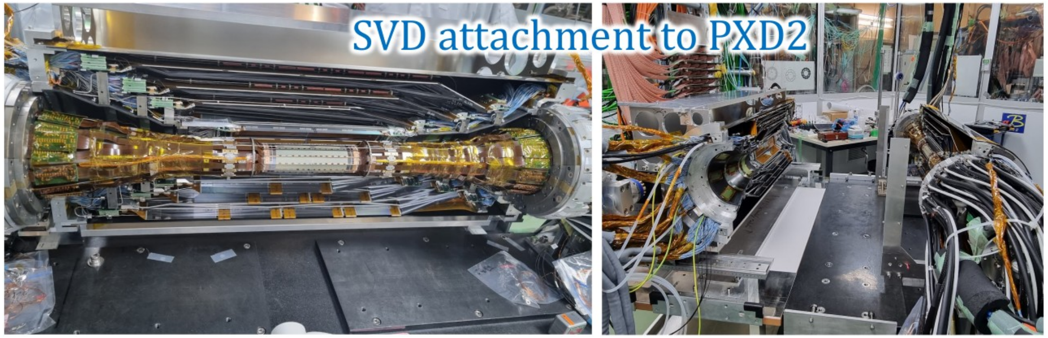


- Intense hardware activities on the SVD for the VXD uninstallation and reinstallation

10th May

16th-17th May

VXD Re-installation in LS1

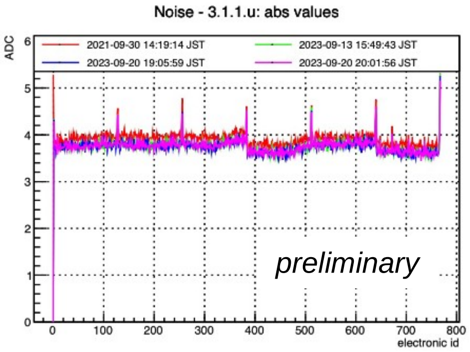


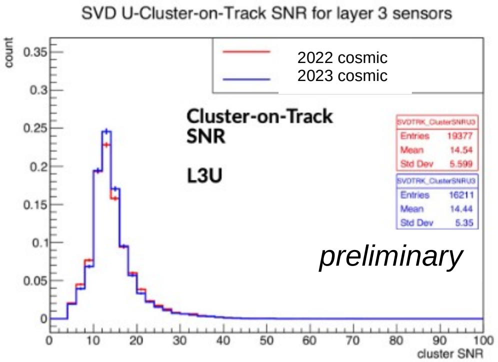
20-21 June

28 July

SVD detachment & reattachment successfully done!

- VXD commissioning (12 September - 1 October)
  - To confirm the PXD and SVD performance
  - To check impact of possible temperature increase on the sensor current (increased PXD power consumption)
  - **cosmic run** with no magnetic field (from 21 Sept.)





+ still excellent efficiency for all sensors!

Summary

SVD has successfully operated since March 2019

- Very smooth performance without major problems
- Good vertexing quality confirmed by the physics measurment (e.g. liftime analysis – $D^{0/+}$, D_s, B^0, Ω_c^0, Λ_c)

  https://confluence.desy.de/display/BI/Journal+Publications
- Some radiation damage effects observed – no impact on the performance so far

Performance expectation at the target luminosity

- Radiation dose is still within safety margin
- Extrapolated background level indicate that the occupancy in the SVD can exceed the current limit !
- Several SVD software improvements for a better performance in high background conditions
  → ***importance of the SVD hit time exploit***

- VXD upgrade under discussion ⇒ to be more robust against high background and matching possible new interaction region

VXD reinstallation at Belle II with complete PXD2 and current SVD during LS1

- Successfull commissioning with cosmic data
- **Plan to resume beam operation in December 2023**

SVD technical paper: *K. Adamczyk et al 2022 JINST 17 P11042*