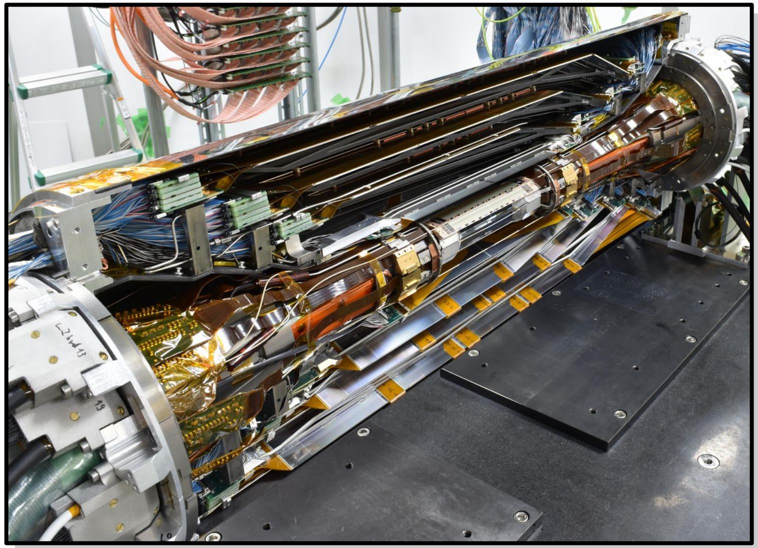
New Results from the Silicon Vertex Detector of the Belle II Experiment

EPS – HEP Online Conference 2021, July 26



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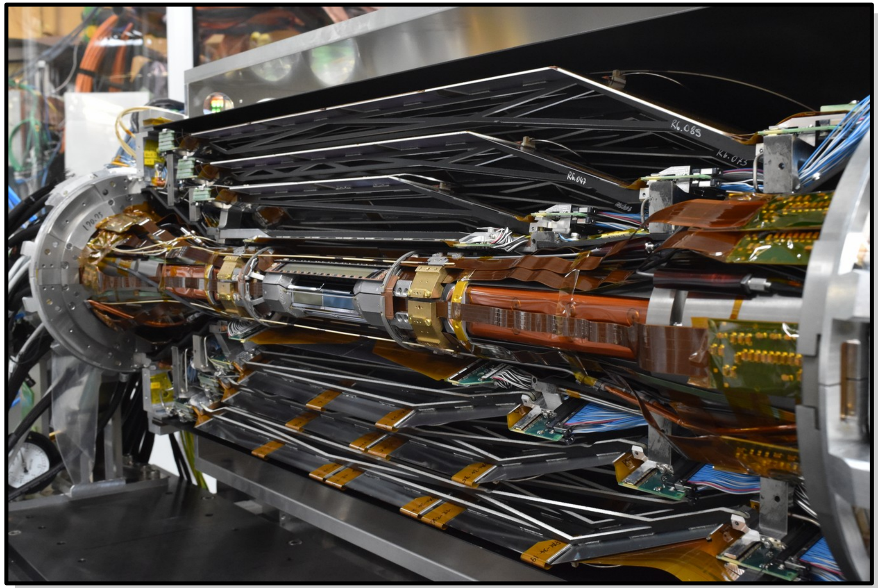
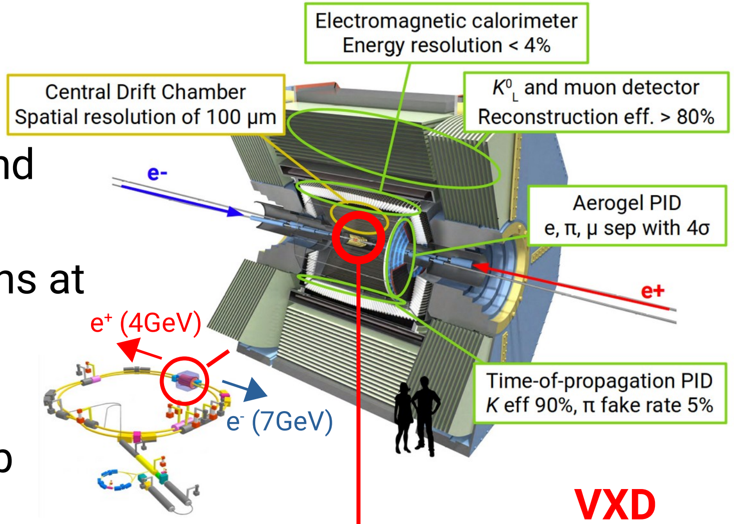
Outline

- Introduction to the Silicon Vertex Detector (SVD) in the Belle II Experiment
- SVD description
- Overview of the operational experience, SVD performance and new results
- Summary and Conclusions



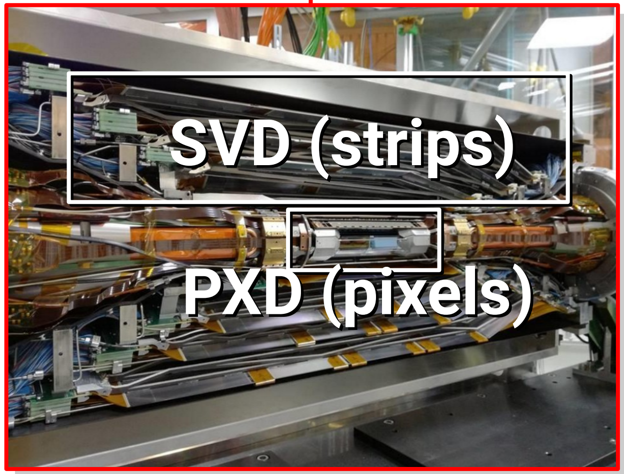
The Belle II Experiment

- Luminosity-frontier experiment, exploring new physics beyond the Standard Model
- Installed at the SuperKEKB collider: **asymmetric** e^+e^- collisions at $\sqrt{s}$ = 10.58 GeV with target luminosity of L ~6.5 · 10^{35} $cm^{-2}s^{-1}$
- Target Integrated Luminosity: 50/ab
- Operation with full detector started in 2019 up to now 210/fb have been collected



For more details about the Belle II experiment, please refer to **C. Niebuhr plenary talk** on Friday!

- **Vertex Detector (VXD)**
  - → Pixel Detector (PXD): 2-layers of DEPFET pixel sensors, innermost layer at 1.4 cm from the IP
  - → Silicon Vertex Detector (SVD): 4-layers of Double-Sided Silicon Strip Detector



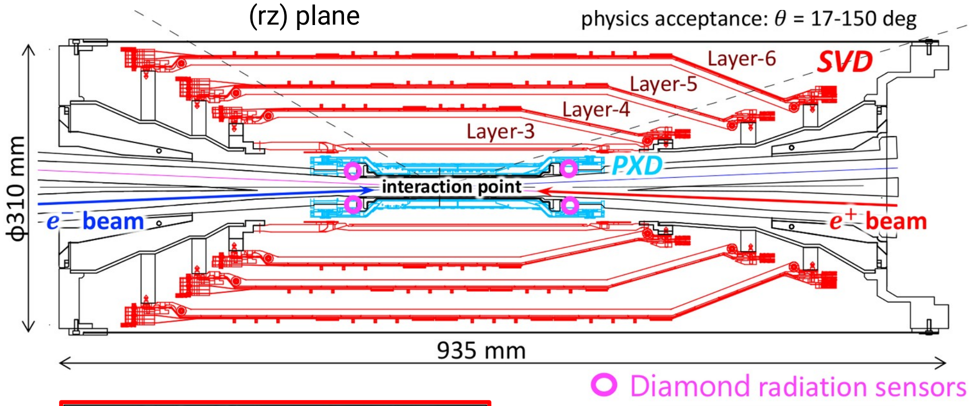
Silicon Vertex Detector (SVD)

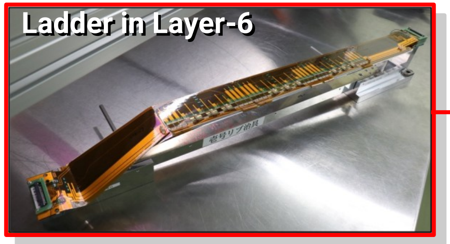
- **SVD layout**

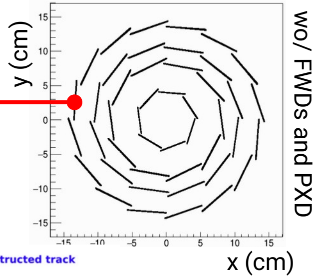
Layer	Ladder/Layer	Sensor/Ladder	Slant angle
3	7	2	0^o
4	10	3	11.9^o
5	12	4	17.2^o
6	16	5	21.1^o

➔ Low material budget: 0.7%X_0 per layer

➔ Diamond sensors for radiation monitor and beam abort

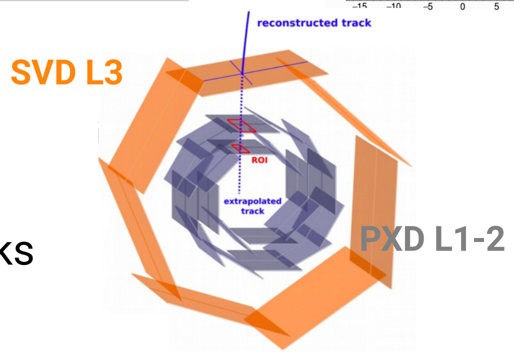






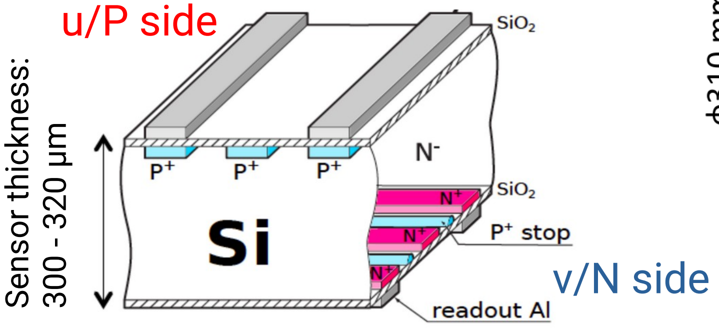
- **SVD roles:**
  ➔ Extrapolate tracks to PXD (Region-Of-Interest, ROI)
    - PXD data reduction to cope with storage and bandwidth limits

  ➔ Standalone tracking and PID using SVD *dE/dx* for low p_T tracks

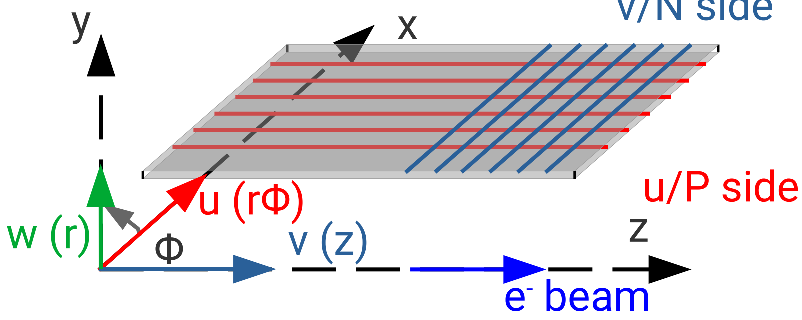


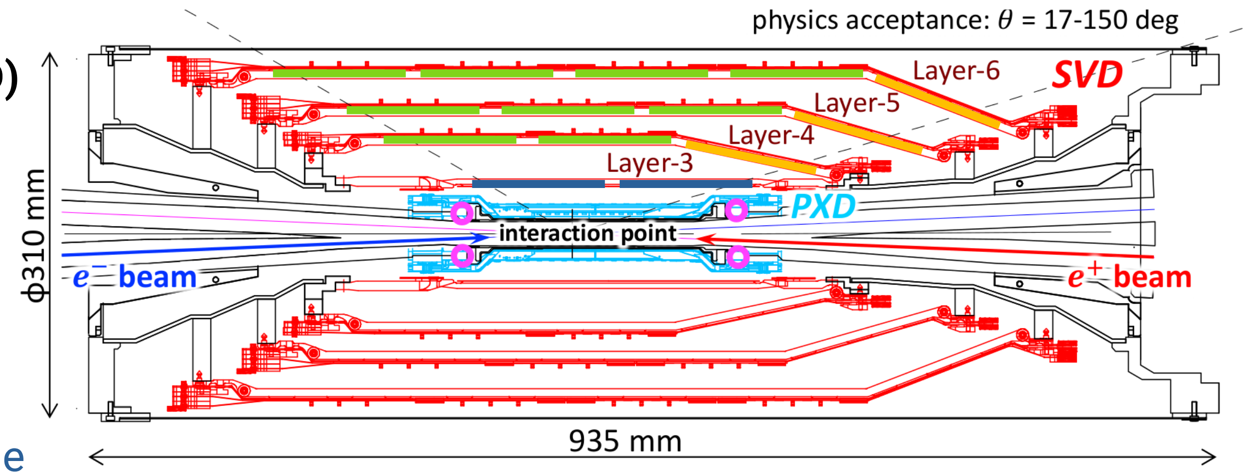
SVD Strip Silicon Sensors

- **Double-Sided Strip Detector (DSSD)**
  ➔ Provide 2D spatial information



AC-coupled strips on N-type substrate:
Full depletion voltage: 20-60V
Operation voltage: 100V



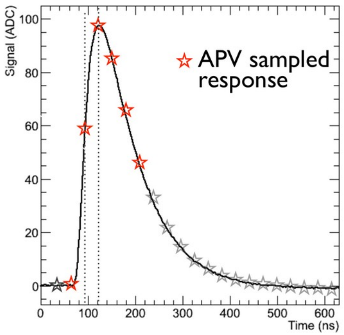


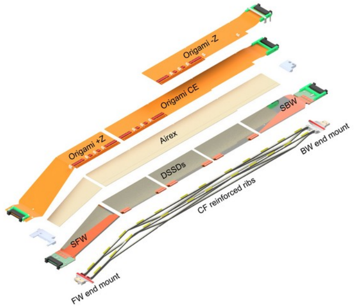
	Small sensors	Large sensors	Trapezoidal sensors
Readout strips P-side	768	768	768
Readout strips N-side	768	512	512
Readout pitch P-side	50 μm	75 μm	50 – 75 μm
Readout pitch N-side	160 μm	240 μm	240 μm
Sensor active area (mm^2)	122.90×38.55	122.90×57.72	$122.76 \times (38.42 - 57.59)$
Sensor thickness	320 μm	320 μm	300 μm
Manufacturer	Hamamatsu	Hamamatsu	Micron

- **Total:** 172 sensors, 1.2 m^2 sensor area, 224k readout strips (1 intermediate floating strip between 2 readout strips)

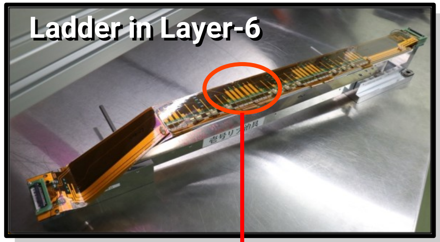
Front-end and Chip-On-Sensor

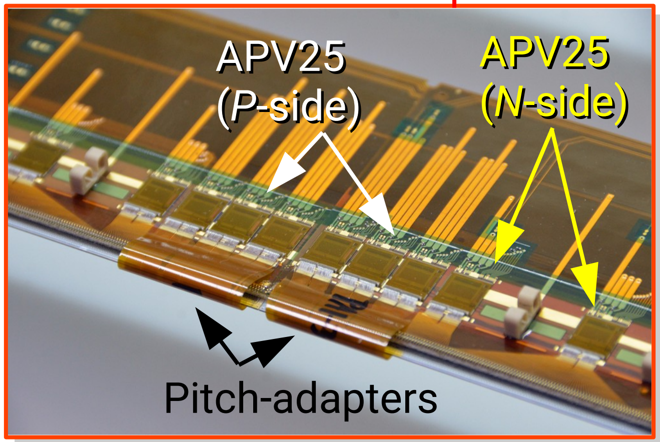
- **Front-end ASIC readout system: APV25 chip**
  - ➔ Fast: 50 ns shaping time
  - ➔ Radiation hardness (> 100 Mrad)
  - ➔ 128 channel inputs per chip
  - ➔ Operated in multi-peak mode at 32 MHz
    - collisions every 4 ns and clock not synchronous with them as in CMS
    - 6 samples recorded, 3/6 samples in future to reduce data size



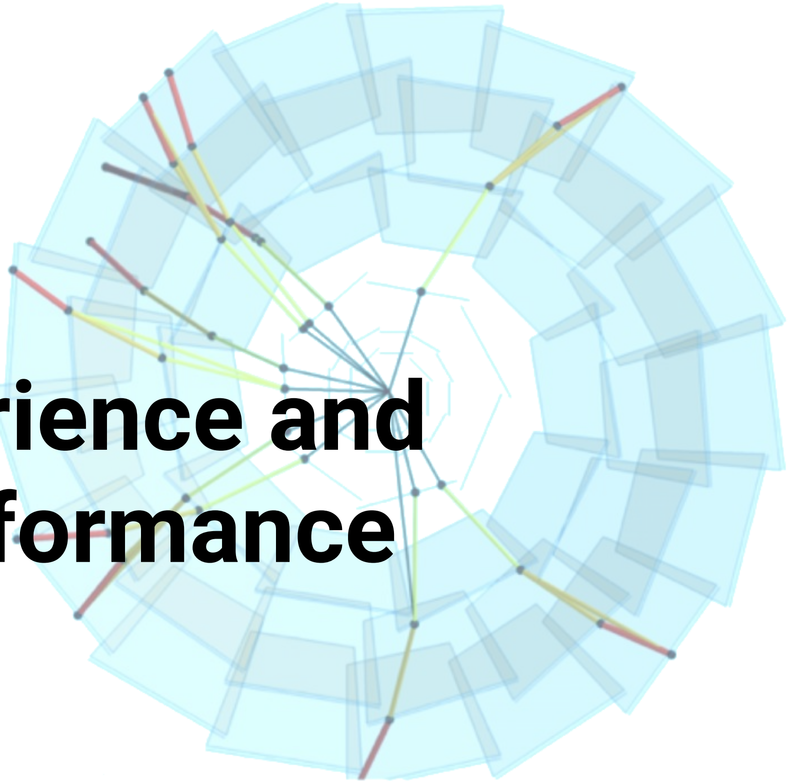


- **Origami Chip-On-Sensor concept**
  - ➔ Chips on each sensor to minimize length of the strip connected
    - smaller capacitance and noise
  - ➔ Chips on the same side of the sensor using wrapped flex to readout both strip sides (pitch adapters)
    - cooling only on one sensor side, with thin stainless steel pipes (bi-phase -20 °C CO_2)
  - ➔ Chips thinned to 100 µm to reduce material budget



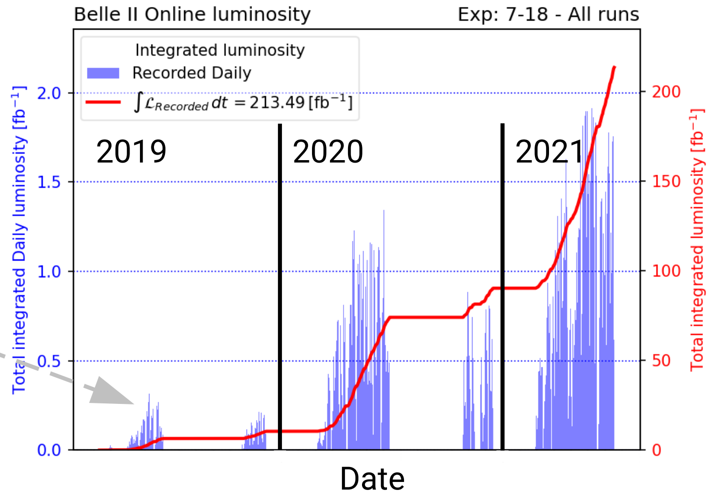


SVD Operational Experience and Particle Detection Performance

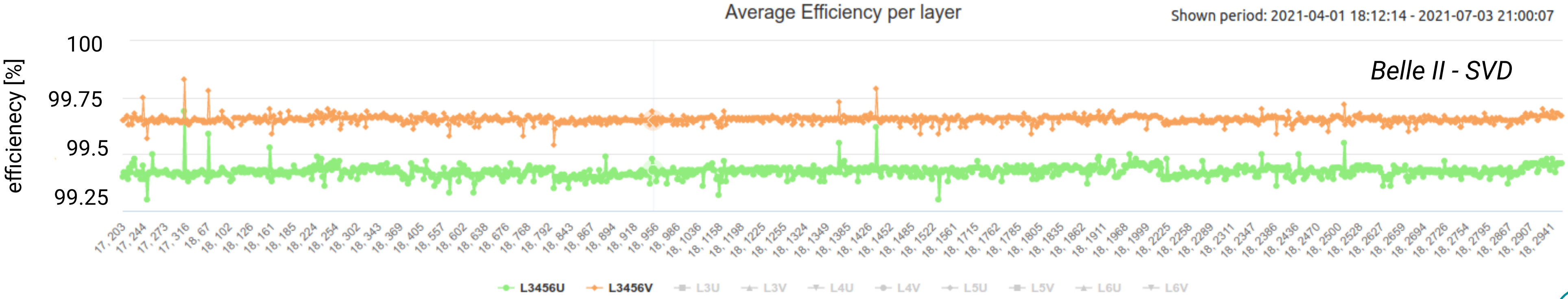


Operational Experience

- **SVD was installed in 2018, and has been operated since 2019**
- **Reliable and smooth operation, without major problems**
  - ➔ Total fraction of masked strips < 1%
  - ➔ One APV25 chip (out of 1748) disabled in spring 2019, that was fixed by cable reconnection in summer 2019



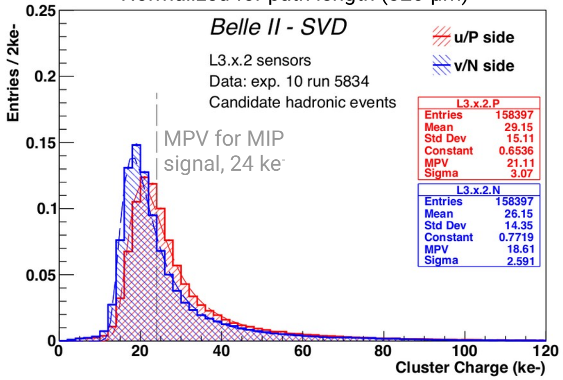
- **Performance of the detector are excellent**
  - ➔ Average sensor hit efficiency for the four SVD layers is > 99% and stable with time

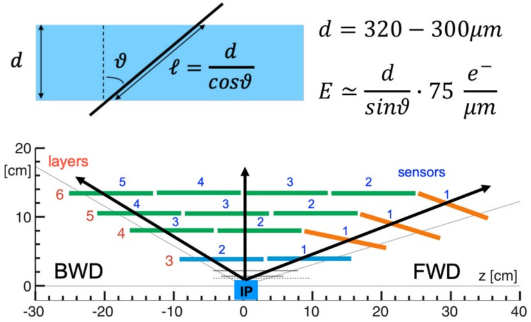


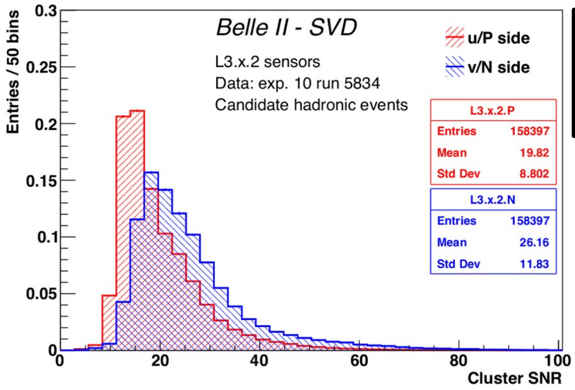
Signal Charge and Signal-to-Noise Ratio

- **Signal charge released in SVD and normalized for the path length is similar in all sensors and matches the expectations**
  - ➔ u/P side: charge is on average 21 ke⁻ in agreement with 24 ke⁻ expected for MIP (taking into account for ~15% uncertainty in APV25 gain calibration)
  - ➔ Signal loss of about 10% - 30% on the v/N: due to the large pitch combined with the presence of a floating strip
- **All 172 sensors have very good SNR with MPV between 13 and 30**
  - ➔ Larger noise in u/P due to longer strip length (larger interstrip capacitance): SNR in v/N side > SNR in u/P side

Normalized for path length (320 μm)





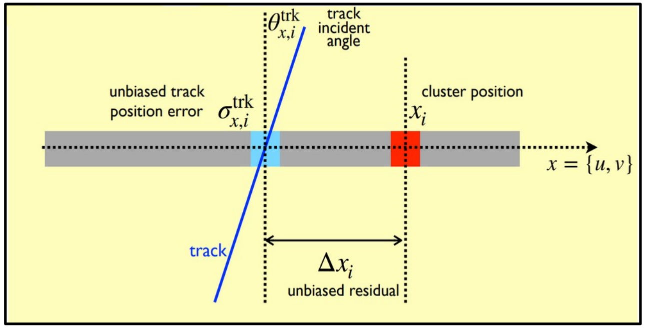


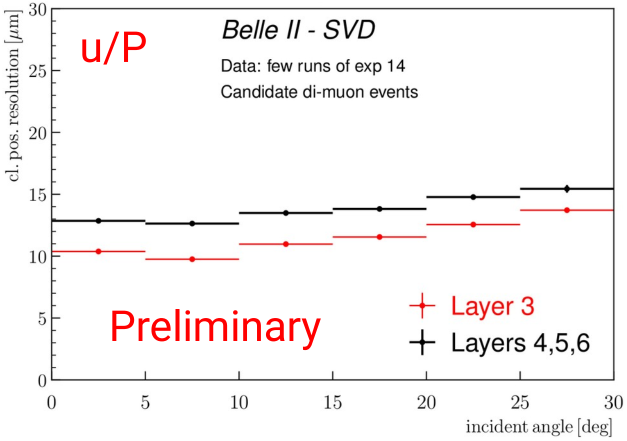
$$SNR_{cls} = \frac{\sum_{strips} S_i}{\sqrt{\sum_{strips} N_i^2}}$$

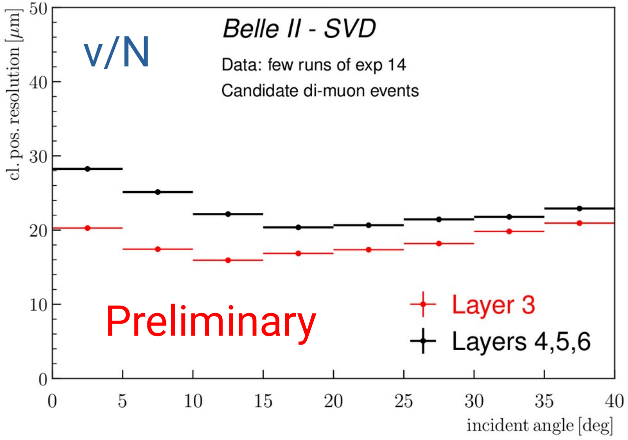
Cluster Position Resolution

- Preliminary cluster position resolution measured on data is 10 – 15 μm for the u/P side and 15 – 30 μm for the v/N side depending on the track incident angle and Layer
  - → Good results, but still room for improvement in particular in the u/P side
  - → Estimated from the residual of the cluster position with respect to the unbiased track extrapolation using $e^+e^- \rightarrow \mu^+\mu^-$ events. Effect of the track extrapolation error is subtracted
  - → We are still optimizing the measurement to improve the accuracy, and tuning the simulation to improve data-simulation agreement

$$\sigma_x = \sqrt{\frac{1}{N}\Sigma_i^N\left(\Delta x_i\right)^2 - \left(\sigma_{x,i}^{trk}\right)^2}$$

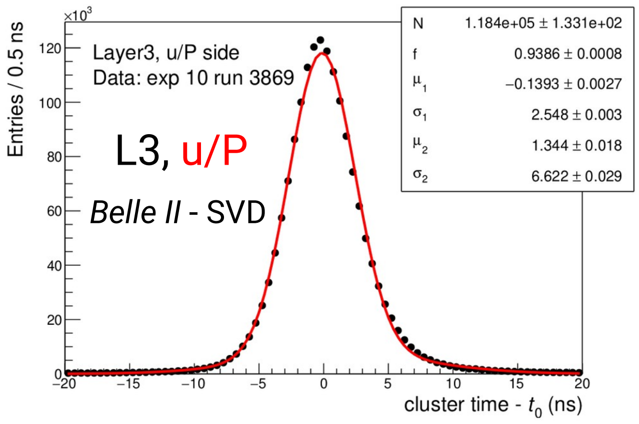


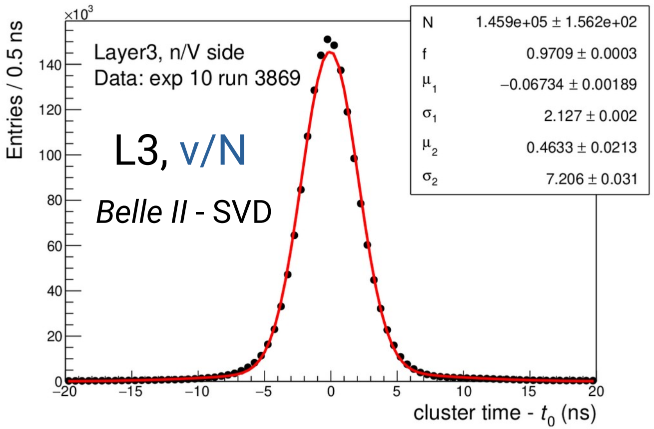


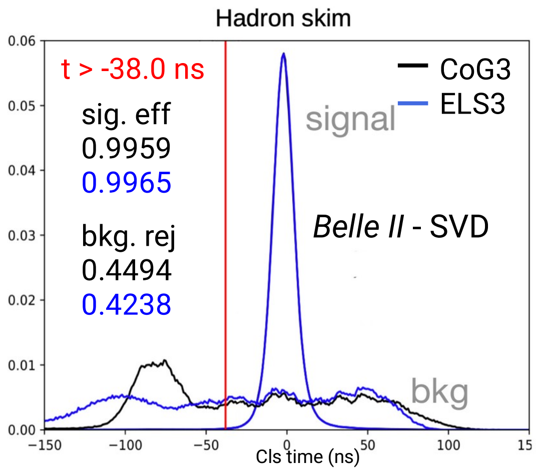


Hit Time

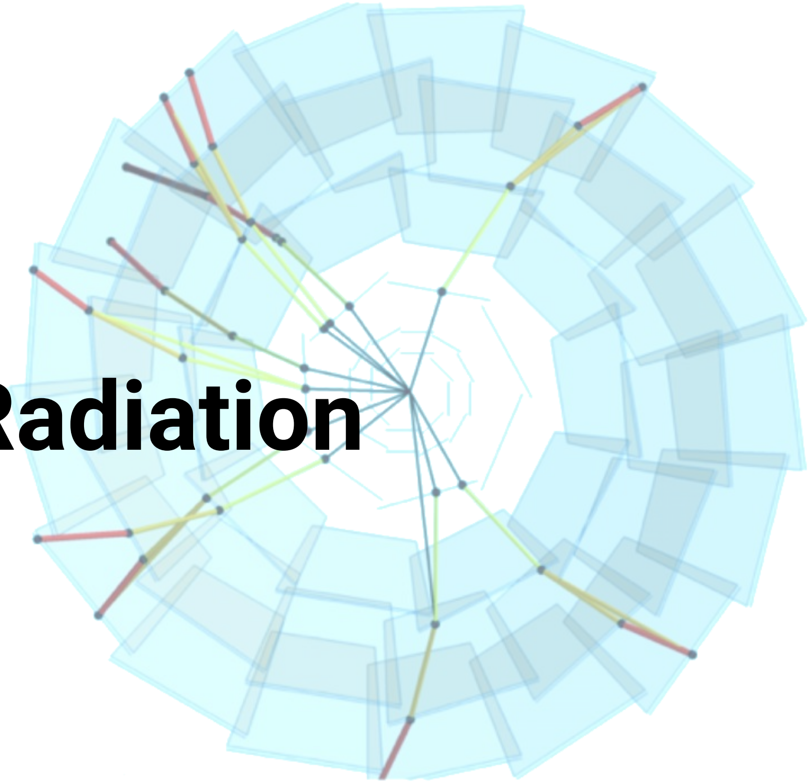
- Excellent hit time resolution: u/P side: ~2.9 ns, v/N side: ~2.4 ns, estimated from the residual of the SVD hit time with respect to the event time (t_0) provided by the CDC
- Currently we are running at low luminosity and background levels, however in future cluster time information will be crucial to reject off-time beam BG hits
  - → Results of the study performed on data for BG rejection show we can achieve 45% BG cluster rejection with 99.5% efficiency
  - → Additional studies on cut optimization for BG rejection ongoing







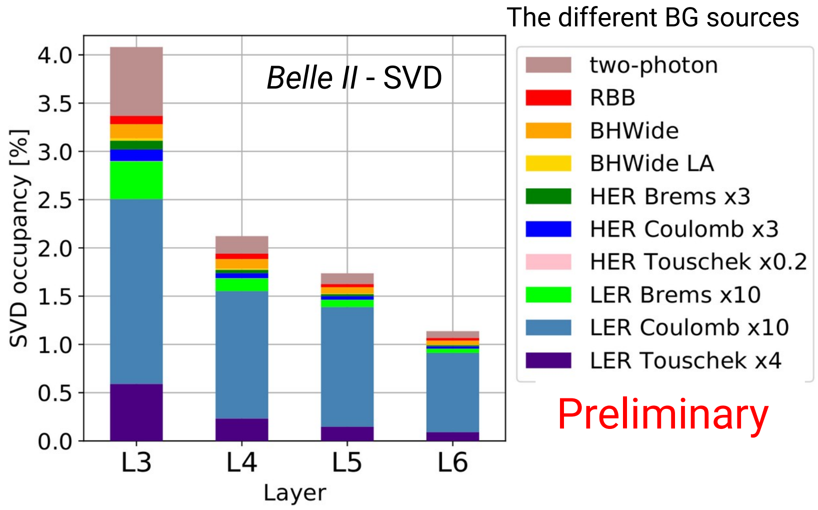
Beam Background & Radiation Effects On SVD



Beam Background

- **Projection of hit occupancy at $L = 8.0 \cdot 10^{35}\ cm^{-2}\ s^{-1}$ is about 4% in Layer-3**
  - ➔ Estimated by MC scaled with data/MC ratio from BG studies in 2020
  - ➔ Corresponding to dose of ~300 krad/smy, and a 1-MeV neutron fluence of ~$6.9 \cdot 10^{11}\ n_{eq}/cm^2/smy$

smy = 10^7 s



- **Beam Background and SVD Occupancy**
  - ➔ Beam BG irradiating SVD increases hit occupancy, and a large hit occupancy degrades SVD tracking performance: present limit is 3% in Layer-3
  - ➔ With future BG rejection based on hit-timing cut, this limit can be relaxed by a factor ~2
  - ➔ At present, averaged hit occupancy in Layer-3 is ~0.5%

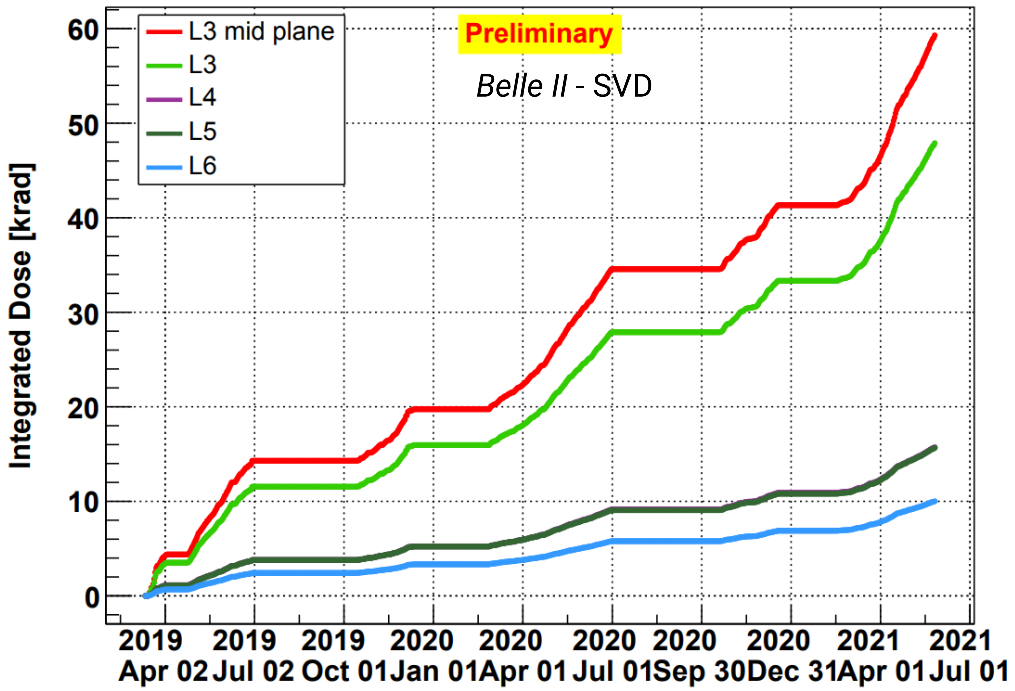
- **SVD robust against the radiation incidents**
  - ➔ A huge beam loss in June 2019 created 10 new pinholes (broken AC capacitors on the sensors) in the whole SVD (224k strips)
  - ➔ No new pinholes after that, though there have been similar beam losses several times

Integrated Dose

- **SVD dose estimated by dose on diamond sensors: 60 krad in Layer-3 mid plane (the most exposed to radiation)**

  → Dose estimate based on correlation between SVD occupancy and diamonds dose, with several assumption and large uncertainty (~50%)

  → 1-MeV equivalent neutron fluence: $\sim 1.4 \cdot 10^{11}\ n_{eq}/cm^2$ in first ~2.5 years (assuming the ratio dose/n_{eq} fluence from MC, $2.3 \cdot 10^{9}\ n_{eq}/cm^2/krad$)

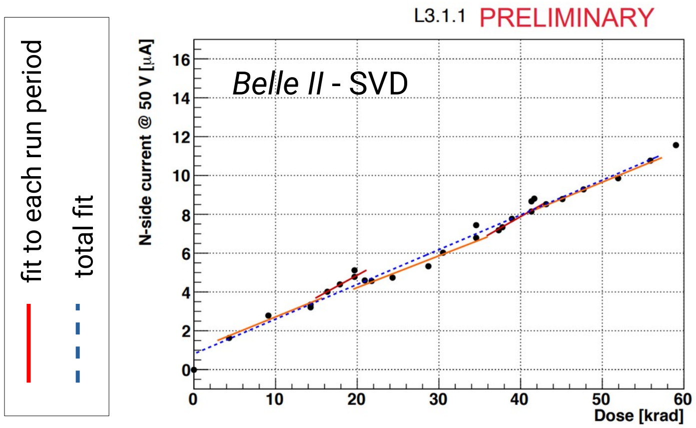


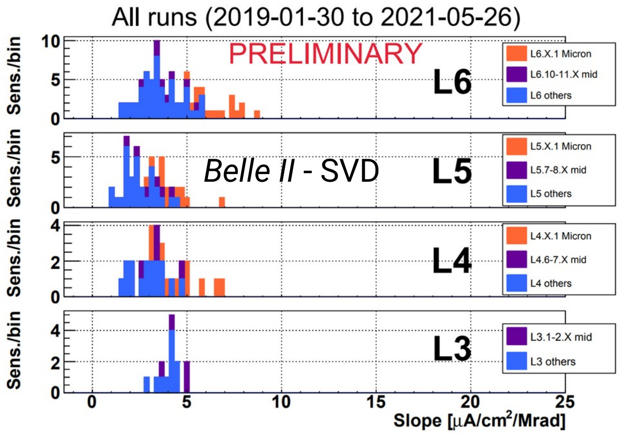
Radiation Effect On Leakeage Current

- **Sensor leakeage current increases linearly with dose, so with eq. neutron fluence proportional to that (as expected), consistent in all sensors and in reasonable agreement with expectation**
  - → Not affecting performance
  - → Slope: 2-5 μA/cm^2/Mrad with large variation due to temperature effects and dose spread among sensors in Layer
  - → Same order of magnitude as BaBar data: 1 μA/cm^2/Mrad at 20 °C

Nucl. Instrum. Meth. A 729 (2013) 615

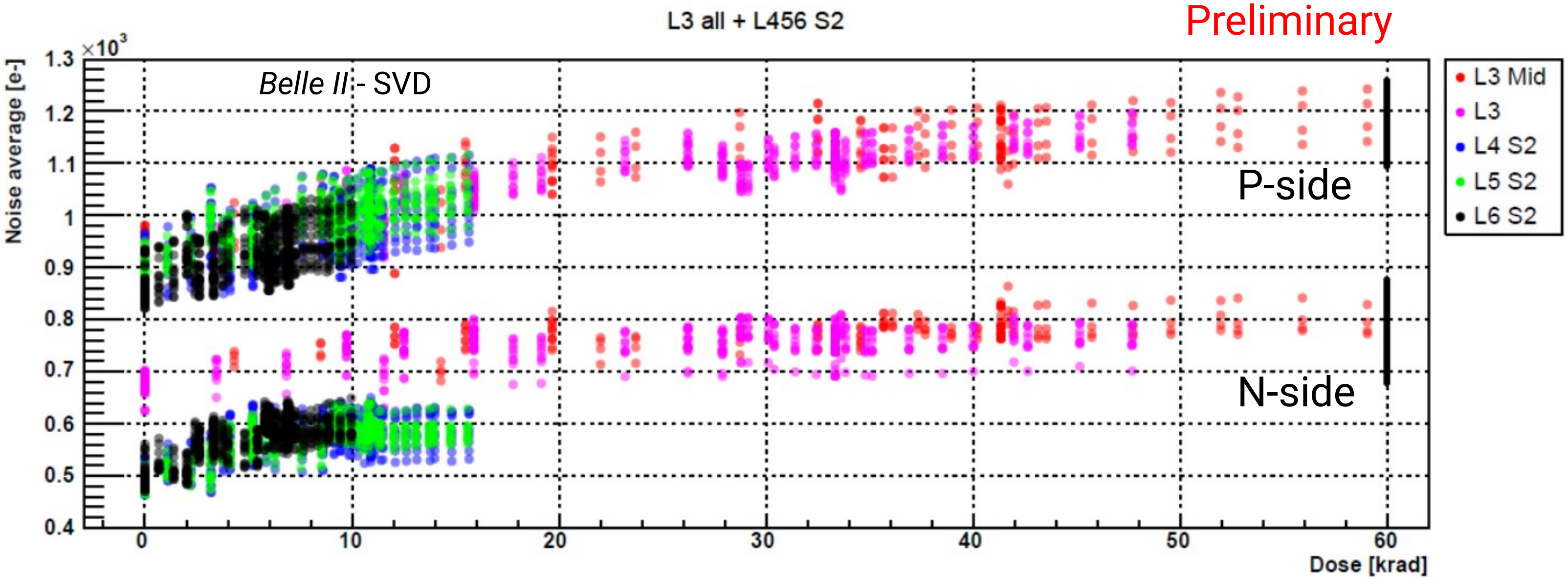
  - → Even after 10 Mrad, leakage current is not expected to significantly affect noise because of the short shaping time (50 ns) of APV25: noise dominated by sensor capacitance





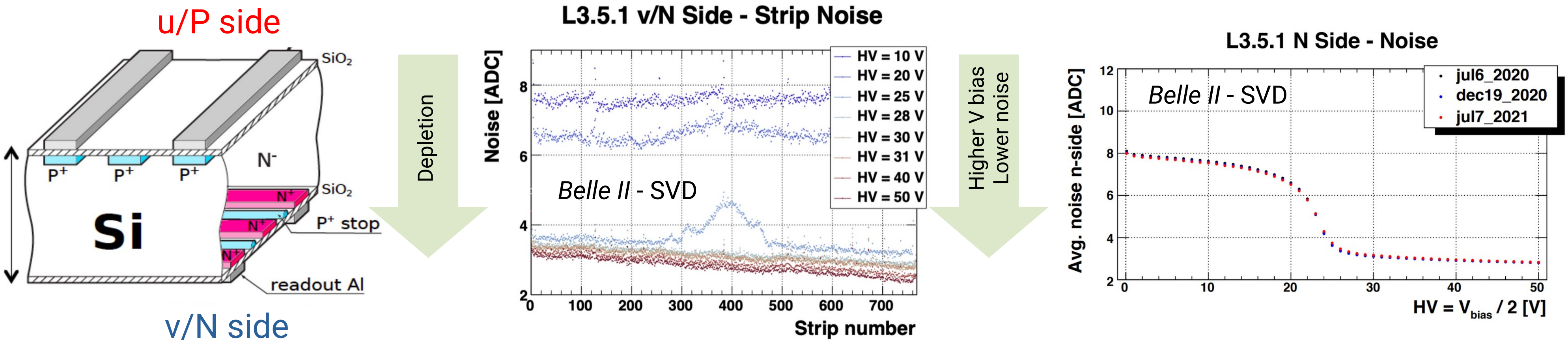
Radiation Effect On Strip Noise

- **Noise increase of 20 – 25% in Layer-3 → not affecting performance**
  - ➔ Likely due to radiation effects on sensor surface
  - ➔ Not linear as expected, due to increase in sensor interstrip capacitance for higher fixed oxide charge
  - ➔ Saturation seen on v/N side, and starting to be seen on u/P side as well



Radiation Effect On Depletion Voltage

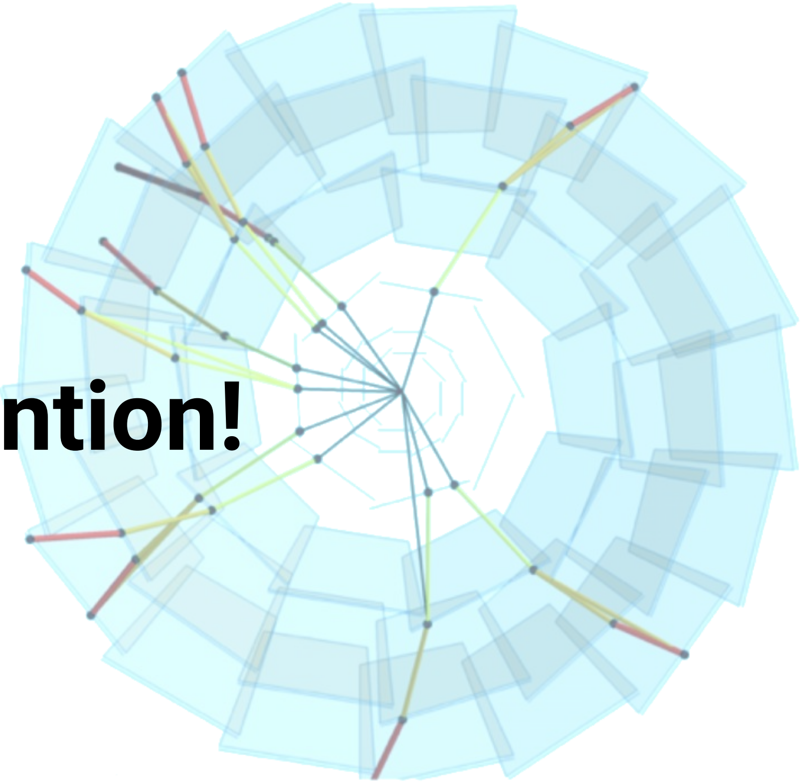
- **v/N-side strip noise drops to a minimum level at the full depletion**
  - ➔ Depletion develops from u/P side to v/N side, so v/N side strips become insulated only when the n-type bulk is fully depleted
  - ➔ Over-depletion bias still decrease noise slightly, because it reduces the electron accumulation layer present on the v/N side surface
- **Noise-HV scan to monitor the full depletion voltage**
  - ➔ No changes expected from July 2020 consistently with the low integrated neutron fluence expected



Summary and Conclusions

- **SVD has been taking data in Belle II since March 2019, with smooth and reliable operation since the beginning**
- **Some effects of radiation damage started to be seen, not affecting performance**
- **Excellent SVD performance confirmed on experimental data**
  - ➔ Some room for improvement in reconstruction and tuning of simulation
- **Hit time resolution: P-side ~2.9 ns, N-side ~2.4 ns**
  - ➔ Hit-timing selection to reject off-time background hits never used before
  - ➔ Currently we are running with low luminosity and background level, but it will be crucial with large luminosity and background
  - ➔ The limit on SVD occupancy of 3% to keep good tracking performance will be relaxed by a factor ~2 (studies still ongoing)
- **Ready to cope with increased beam background**
  - ➔ Hit-timing selection to reject off-time background hits
  - ➔ 3/6 mixed data acquisition mode of the APV25 to reduce data size

Thank you for the attention!



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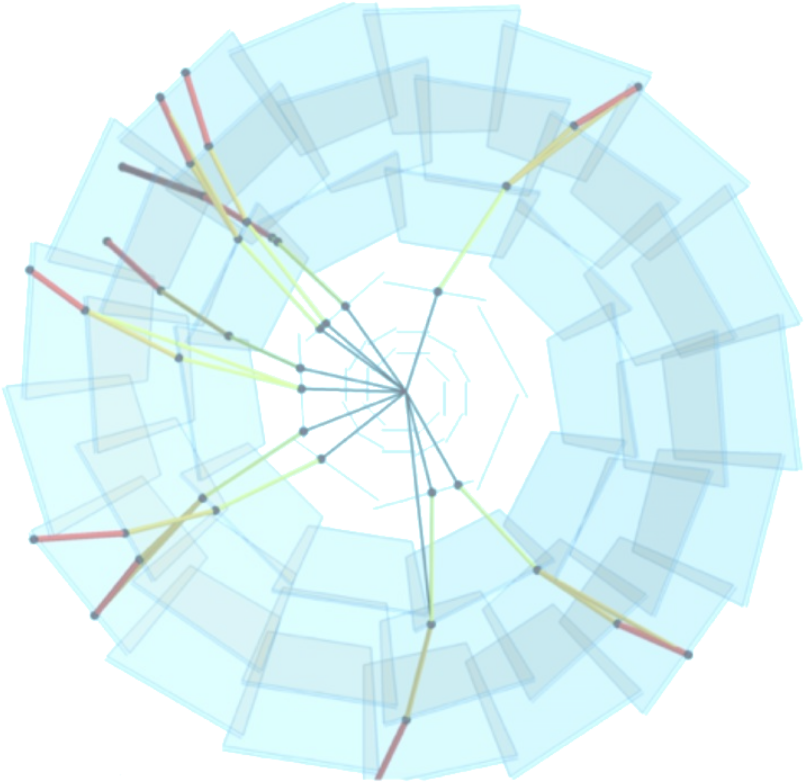
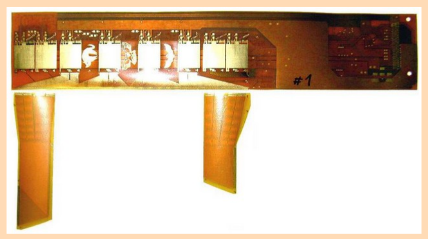
Backup Slides



Construction, assembly, installation

First Chip-on-Sensor concept



September 2008

October 2010

Belle II Technical Design Report (**TDR**)

KEK Report 2010-1
October 2010
H

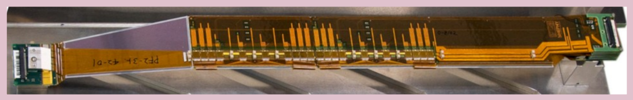
Belle II Technical Design Report

Belle II

Edited by: Z. Doležal and S. Uno

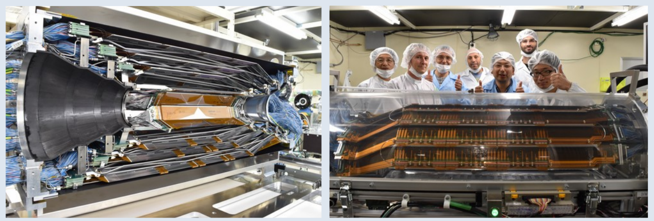
High Energy Accelerator Research Organization

First completed Layer 5 ladder



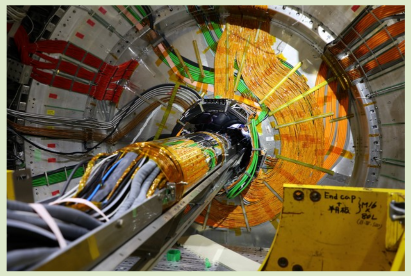
May 2015

February/July 2018



First/second "half shell" assembled

Installed in Belle II



November 2018

March 2019

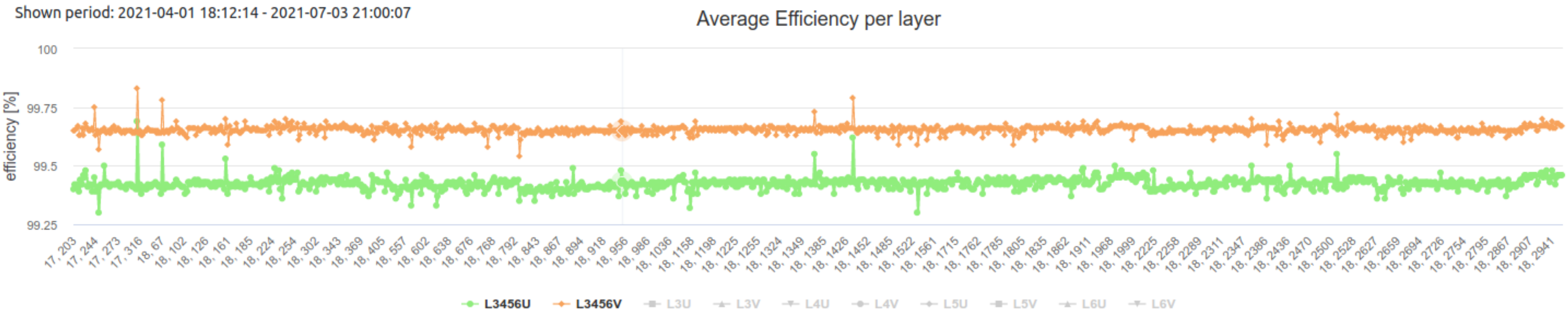
First collision data with full detector

Hit Efficiency

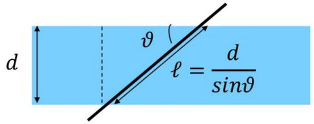
- **Performance of the detector is excellent**
  - ➔ Average sensor hit efficiency for the four SVD layers is > 99%
  - ➔ Very few sensors with 98 - 98.5% due to production defects
  - ➔ Stable with time

Average sensor hit efficiency

layer	$\varepsilon(u/P)(\%)$	$\varepsilon(v/N)(\%)$
3	99.83 ± 0.01	99.48 ± 0.03
4	99.69 ± 0.03	99.68 ± 0.03
5	99.66 ± 0.03	99.77 ± 0.04
6	99.31 ± 0.08	99.58 ± 0.06

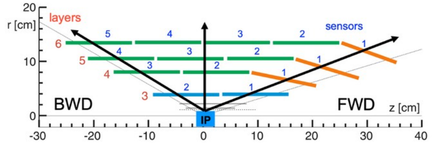


Signal Charge

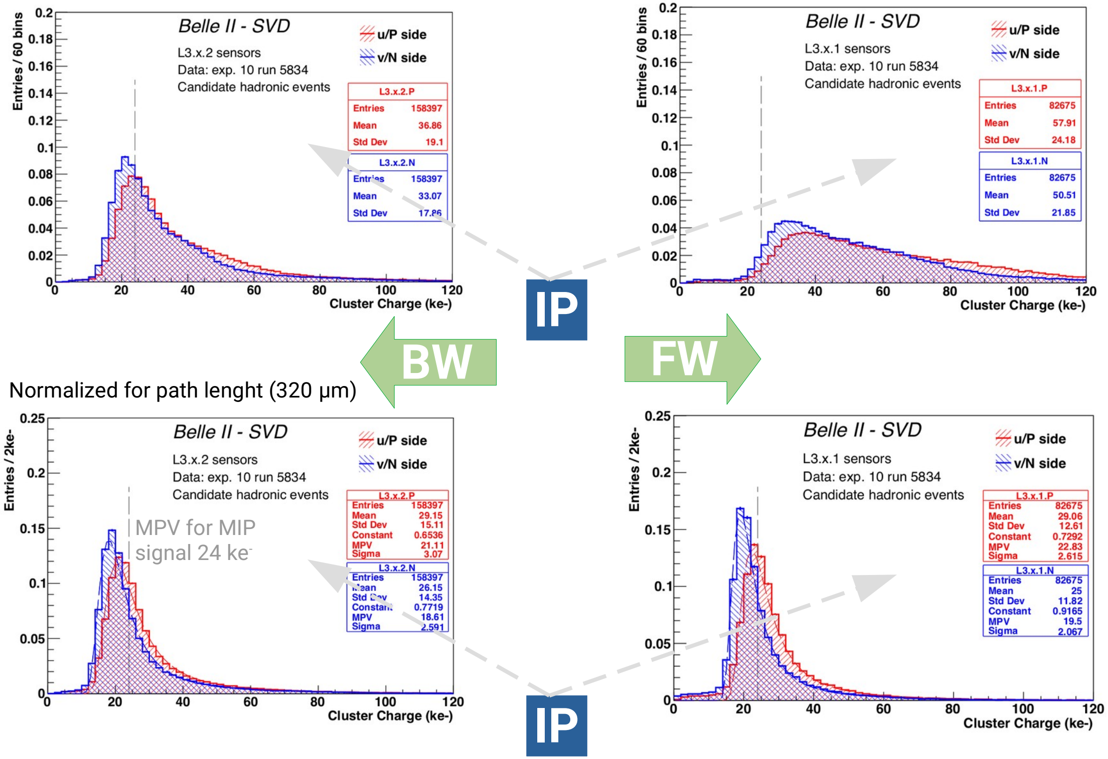


$d = 320 - 300\mu m$

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



- Signal charge released in the SVD depends on the track incident angle
  ➔ The charge is significantly larger for sensor in the FW and BW position



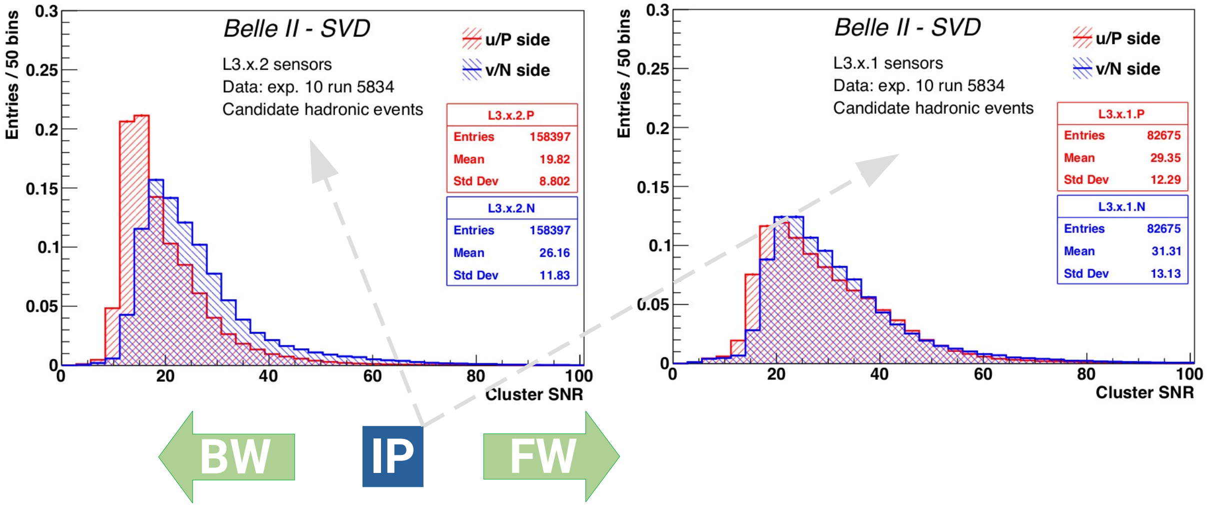
- Normalize for path length
  ➔ E · d/ℓ is similar in all sensors and matches the expectations
- Normalized cluster charge is on average 21 ke⁻ on the u/P side (with uncertainty of ~15% in APV25 gain calibration)
  ➔ In fair agreement with expected MPV for MIP signal of 24 ke⁻
- Signal loss of about 10% - 30% on the v/N: due to the large pitch combined with the presence of a floating strip

Signal-to-Noise Ratio (SNR)

- Larger noise in u/P due to longer strip length (larger interstrip capacitance)
- SNR depends on the charge and on the noise
  - ➔ Noise of u/P side > noise of v/N side
  - ➔ Signal depends on sensor position, due to the track incident angle

Equivalent Noise Charge (ENC)

Sensor position/type	u/P side ENC (e^-)	v/N side ENC (e^-)
Layer 3 (HPK small)	930	630
Layer 4/5/6 Origami (HPK large)	958	510
Layer 4/5/6 BWD (HPK large)	790	680
Layer 4/5/6 FWD (Micron wedge)	740	640

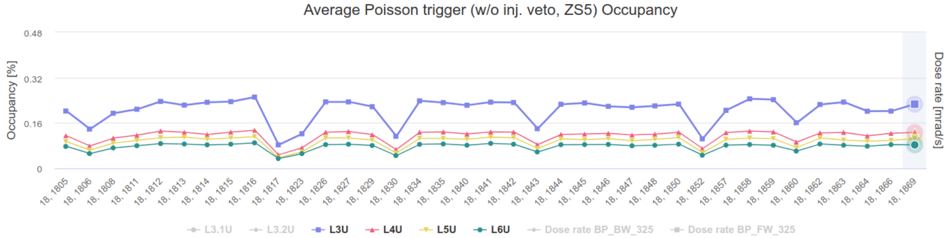


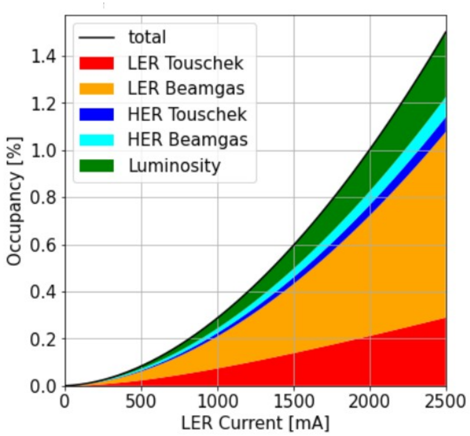
$$SNR_{cls} = \frac{\sum_{strips} S_i}{\sqrt{\sum_{strips} N_i^2}}$$

- SNR in v/N side > SNR in u/P side
- **All 172 sensors have very good SNR with MPV between 13 and 30**

SVD Occupancy

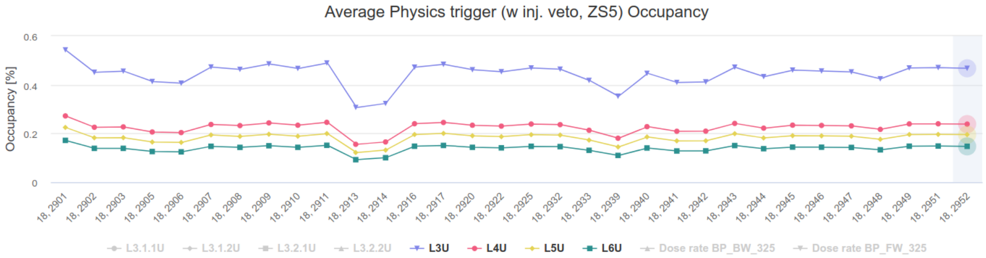
- **SVD measured occupancy in fair agreement with simulation**
  - ➔ Random trigger occupancy extrapolation 0.22%
    (LER current = 840 mA, nº bunches = 978, no injection BG included)
  - ➔ Measured poisson trigger occupancy (w/o injection veto) ~0.25%

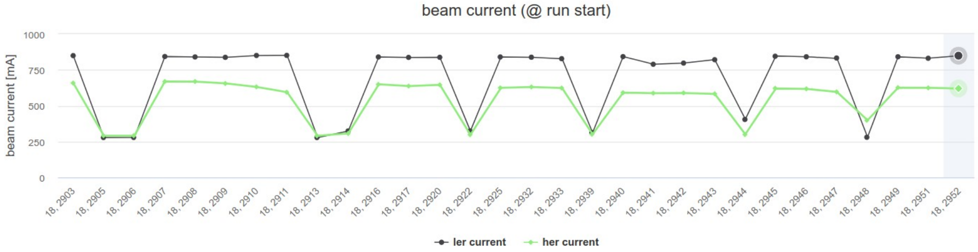




Extrapolation based on 2020 December Beam background study Random trigger occupancy, no injection bkg. included

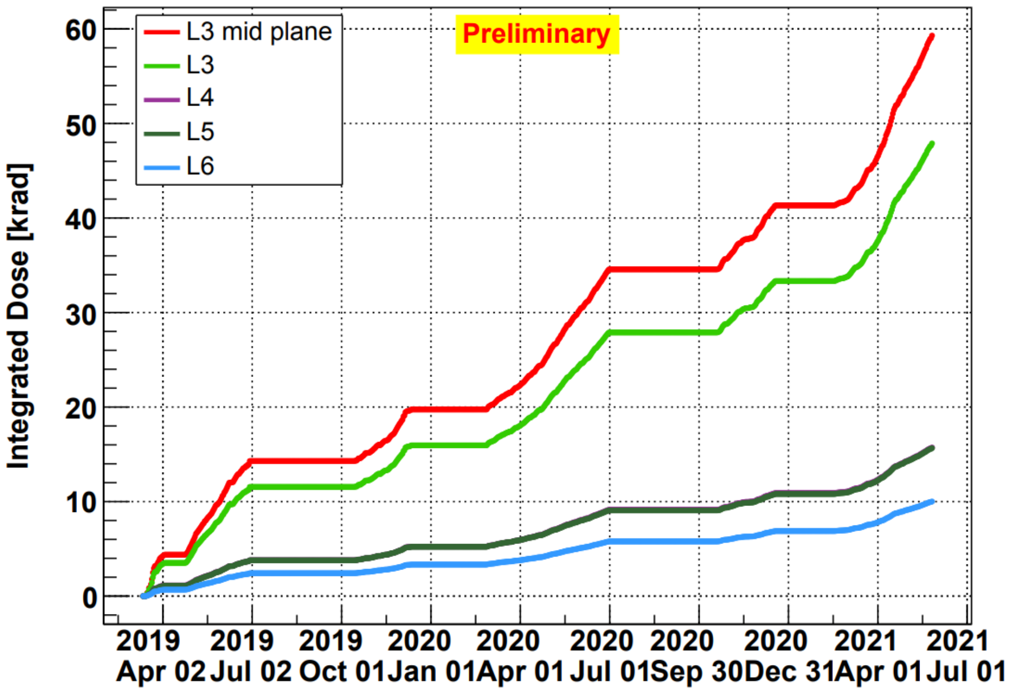
- **Beam BG level during operation under control at present**
  - ➔ Physics trigger occupancy higher than random trigger occupancy
  - ➔ Averaged hit occupancy in Layer-3 is ~0.5% (<< limit of 3%)





Integrated Dose

- **SVD dose estimated by dose on diamond sensors: 60 krad in Layer-3 mid plane (the most exposed to radiation)**
  - ➔ Dose estimate based on correlation between SVD occupancy and diamonds dose
  - ➔ Use of Poisson trigger data without injection veto (data available from 2021 runs)
  - ➔ Large uncertainty (~50%): Poisson trigger data not available for runs before December 2020
  - ➔ 1-MeV equivalent neutron fluence: $\sim 1.4 \cdot 10^{11}\ n_{eq}/cm^2$ in first ~2.5 years (assuming the ratio dose/n_{eq} fluence from MC, $2.3 \cdot 10^{9}\ n_{eq}/cm^2/krad$)



Hit Time Determination: CoG3 and ELS3

- **CoG3**
  - ➔ a_i is the ADC sample and Δt is the APV clock ~ 31 ns

$$T_{\mathrm{SVD;raw}} = \frac{\sum_{i=0}^{2} a_i \cdot i\Delta t}{\sum_{i=0}^{2} a_i}$$

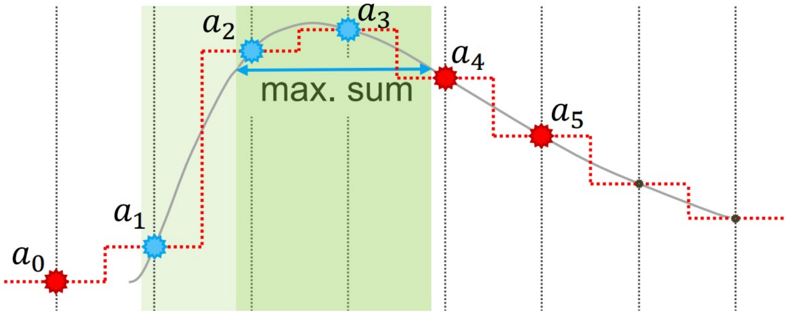
- **ELS3**
  - ➔ Approximate the signal waveform with CR-RC shaper response
  - ➔ Fit with least squares method, analitically solvable, to get $T_{\mathrm{SVD;raw}}$

$$a(t) = A\frac{t - T_{\mathrm{SVD;raw}}}{\tau}\exp\left(1 - \frac{t - T_{\mathrm{SVD;raw}}}{\tau}\right)$$

  - ➔ Shaping time constant τ = 55 ns

- Calibration of the raw SVD time performed exploiting the correlation with the event time t_0 provided by the CDC

Select the best 3 samples out of the 6



Read out directly only 3 sample