The Silicon Vertex Detector of the Belle II Experiment

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Outline

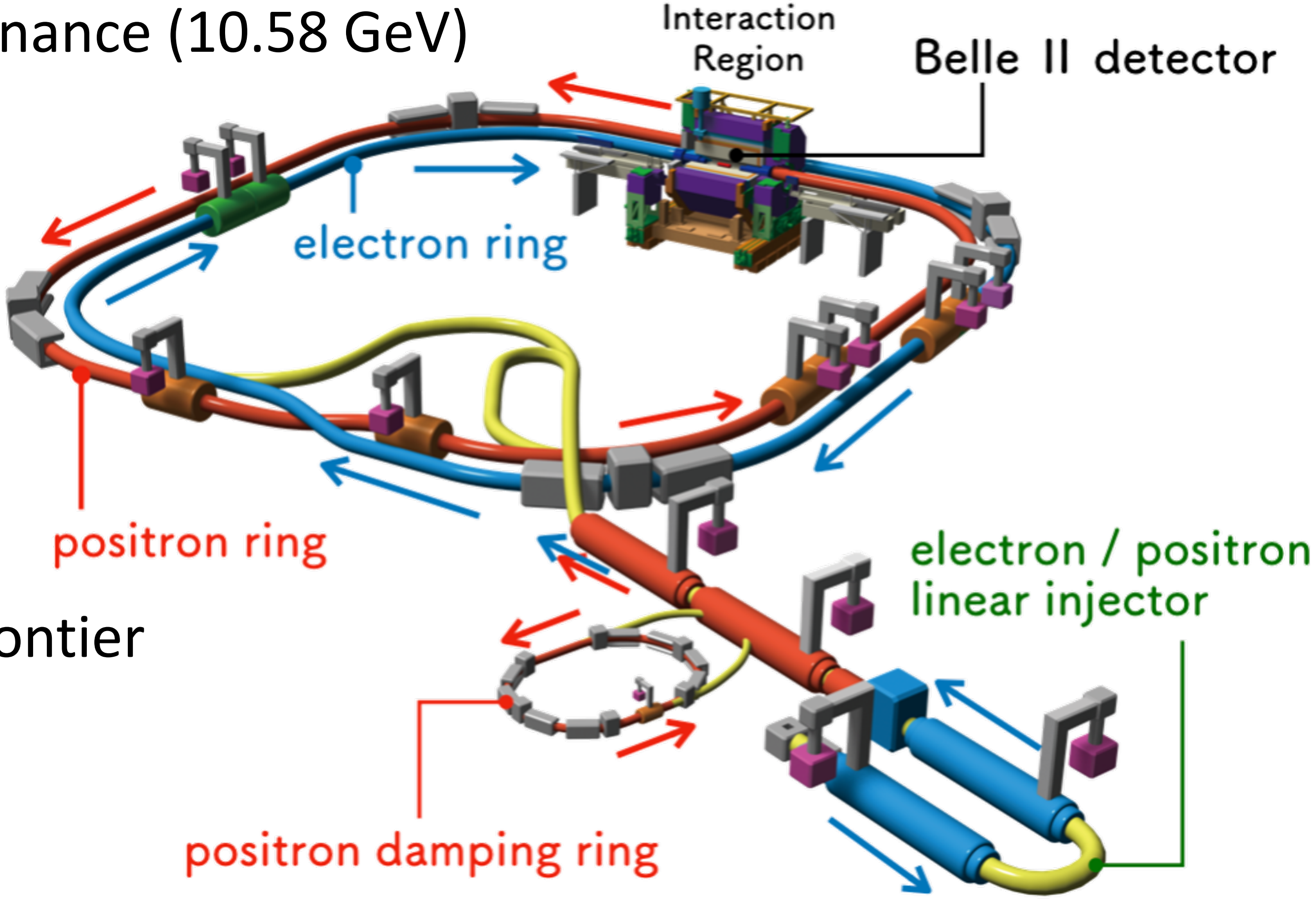
- Introduction
- Operation & Performance
- Beam background & Radiation effect
- Conclusions

Introduction

Belle II/SuperKEKB

◆SuperKEKB: dedicated accelerator for Belle II

- Asymmetric e^+e^- collisions at Υ(4S) resonance (10.58 GeV)
- Target integrated luminosity: 50 ab^{-1}
- Target instantaneous luminosity: $\sim 6 \times 10^{35}\ cm^{-2}s^{-1}$
- Current record: $3.1 \times 10^{34}\ cm^{-2}s^{-1}$



◆Belle II

- New physics search at the luminosity frontier
- Accumulated 213 fb^{-1} data
- Essentials for physics programs:
  - Precise determination of decay vertices
  - Low momentum tracking
  - Good particle identification

Belle II Vertex Detector

Requirements

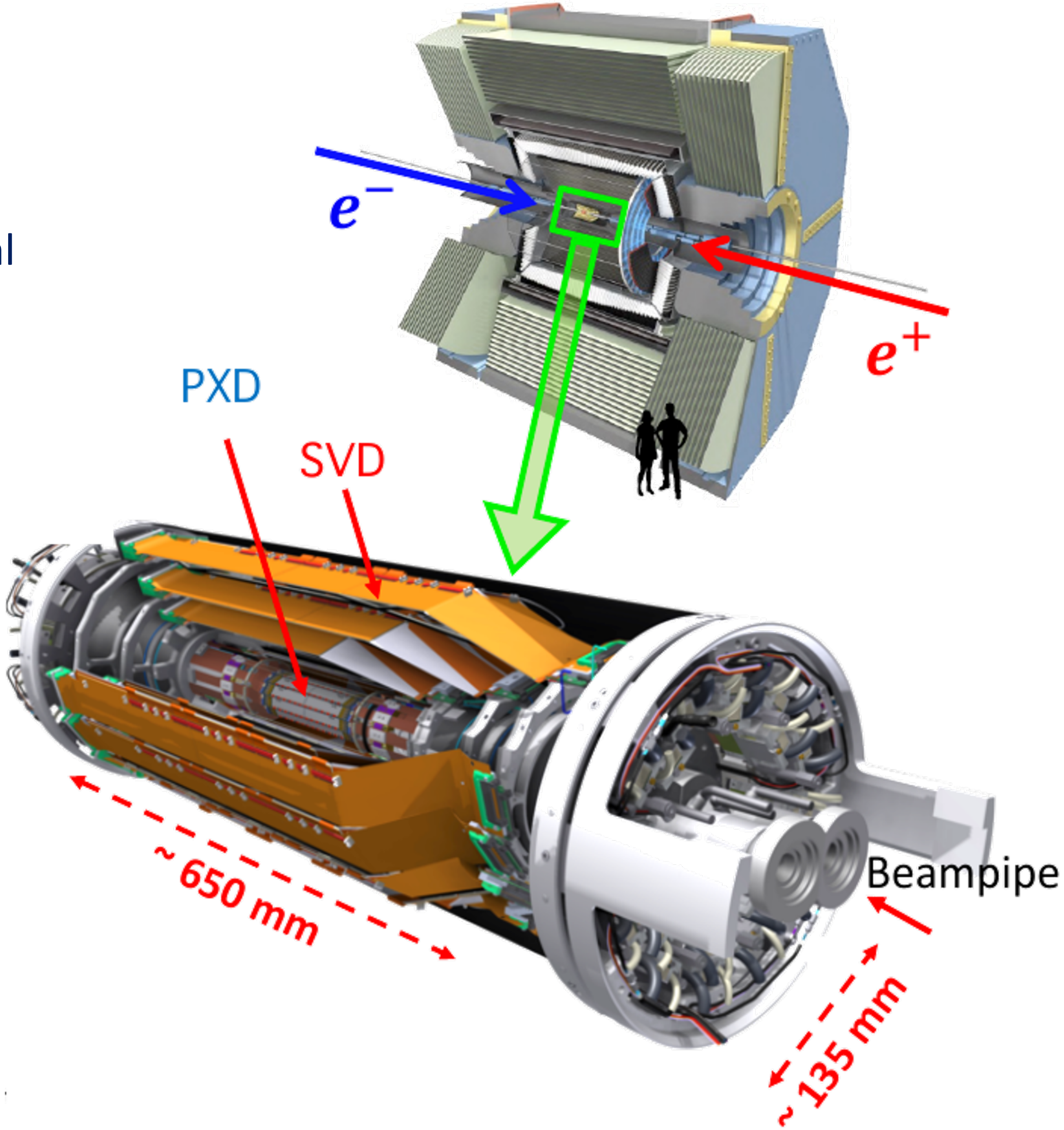
- Better vertex resolution with respect to Belle to compensate reduced Lorentz boost
  - improved point resolution/reduced inner radius/lower material
- Operate in high background environment
  - Hit rates: 20-3 MHz/cm^2 @R=14-40mm
- Radiation hard
  - 2-0.2 Mrad/yr @ R = 14-40 mm

Pixel Detector (PXD)

- DEPFET pixel sensors: layer-1-2
- Innermost layer 1.4 cm from interaction point

Silicon Vertex Detector (SVD)

- Double-sided Si strip sensors: layer-3-4-5-6
- Low material budget: 0.7% X_0 per layer



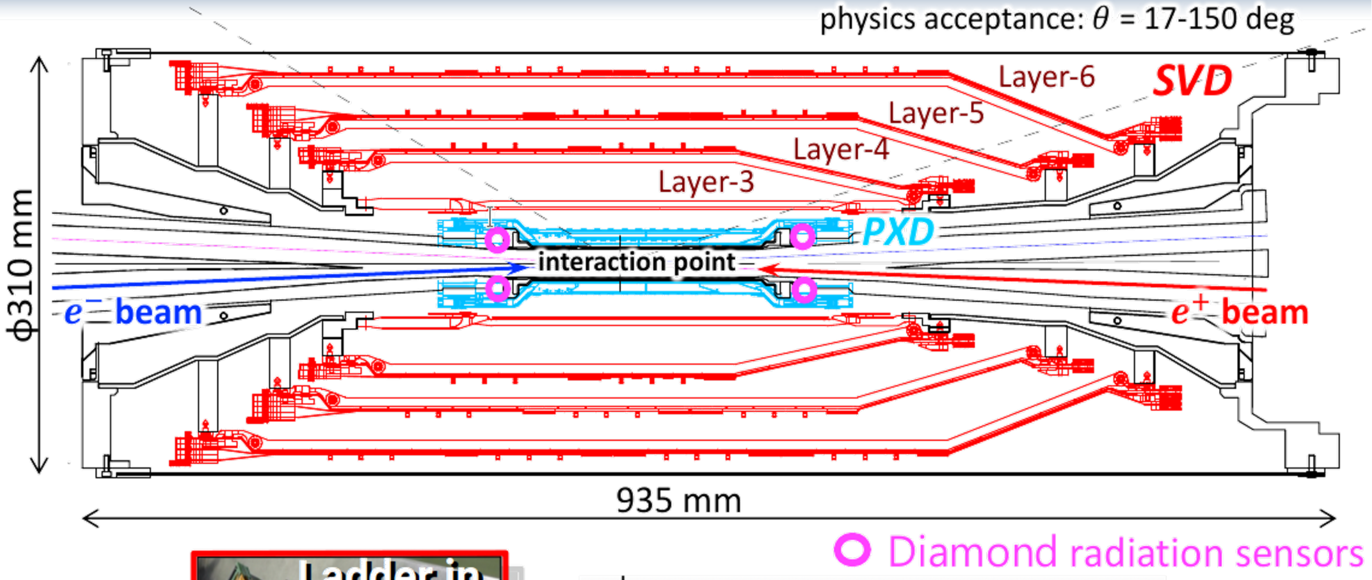
The Silicon Vertex Detector (SVD)

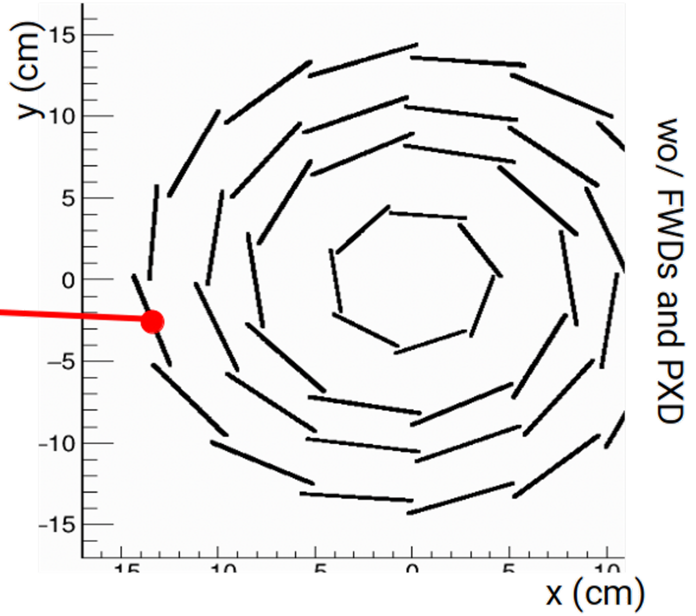
SVD Roles

- Extrapolate tracks to PXD
  - essential for reconstruction of decay vertices
  - PXD region of interest for data reduction
- Stand-alone tracking for low p_T tracks
- Precise vertexing of K_S
- PID with dE/dx

Diamond sensors

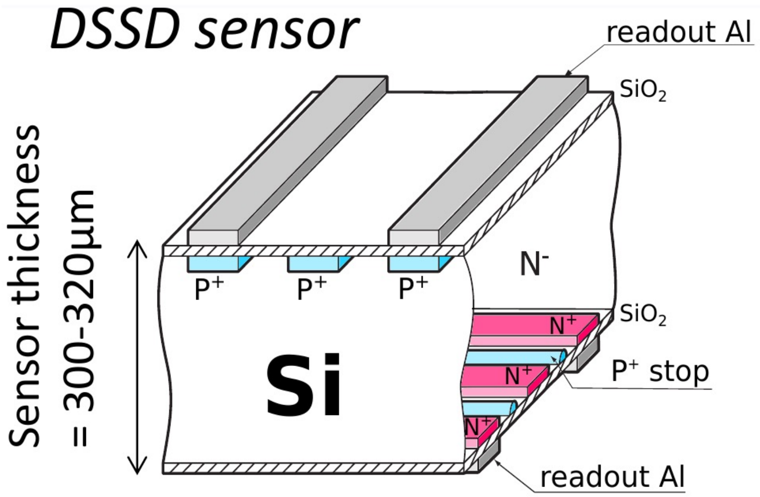
- placed on the beam pipe
- for radiation monitor and beam abort



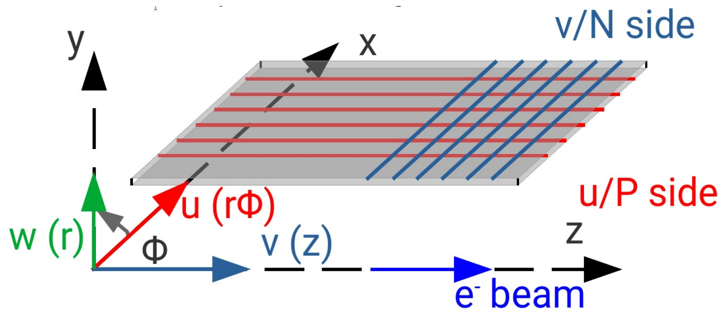


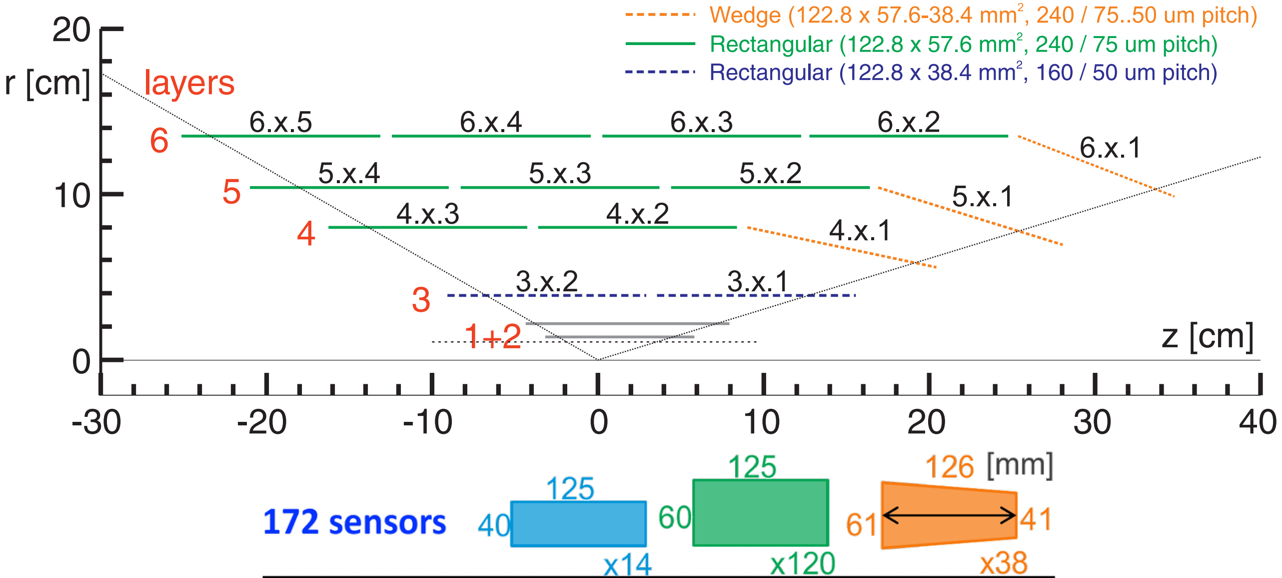
SVD: Double-sided Silicon Strip Detector

- Provide 2-D spatial information



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





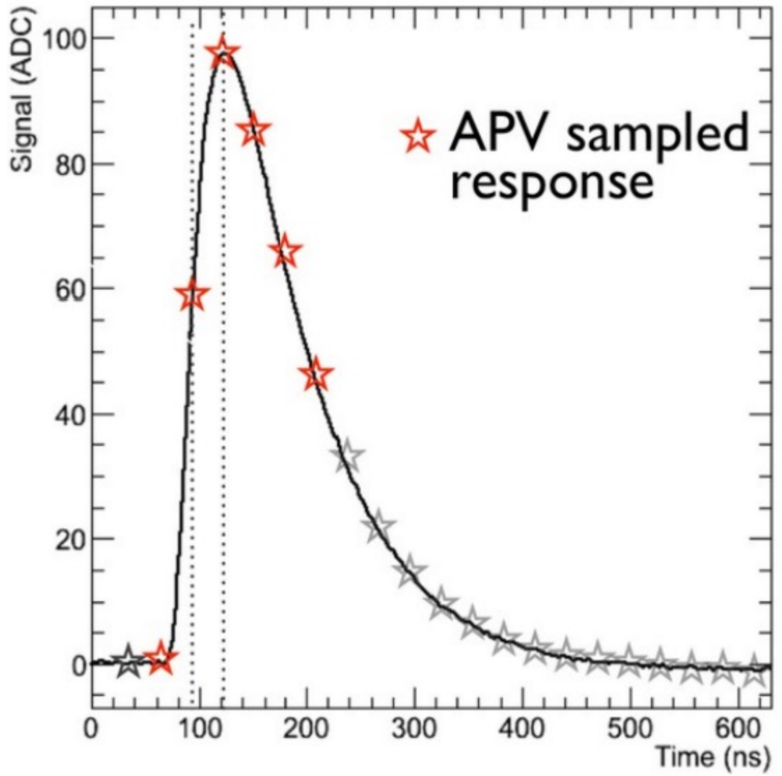
	Small	Large	Trapezoidal
# of p-strips*	768	768	768
p-strip pitch*	50 μm	75 μm	50-75 μm
# of n-strips*	768	512	512
n-strip pitch*	160 μm	240 μm	240 μm
thickness	320 μm	320 μm	300 μm
manufacturer	HPK		Micron

*readout strips – one floating strip on both sides

- Total: 172 sensors, 1.2 m² sensor area and 224k readout strips

Front-end ASIC: APV25

- Originally developed for CMS silicon tracker
- Fast: 50 ns shaping times
- Radiation hard: > 100 Mrad
- Power consumption: 0.4 W/chip (700 W in total)
- 128 channel inputs per chip
- Operated in “multi-peak” mode @ ~32 MHz
  - Bunch-crossing frequency ~8*32 MHz, clock not synchronous with them as in CMS
  - 6 subsequent samples recorded (3-sample also possible)
- 3/6-mixed acquisition mode prepared for higher luminosity
  - To reduce the dead time/data size/background hit occupancy
  - Switching sampling number according to the timing precision of trigger
  - The functionality already tested in the real setup and confirmed to work



3-sample DAQ mode: only 3 subsequent samples recorded

- half time-window → less background occupancy
- halve APV25 FIFO usage → reduce dead-rate
- → data-size reduced to less than a half

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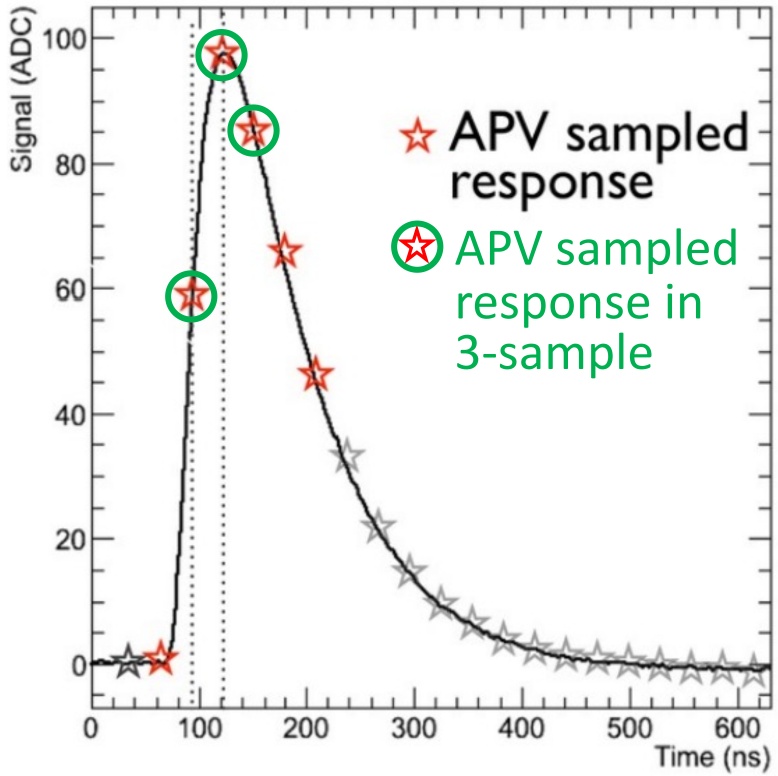

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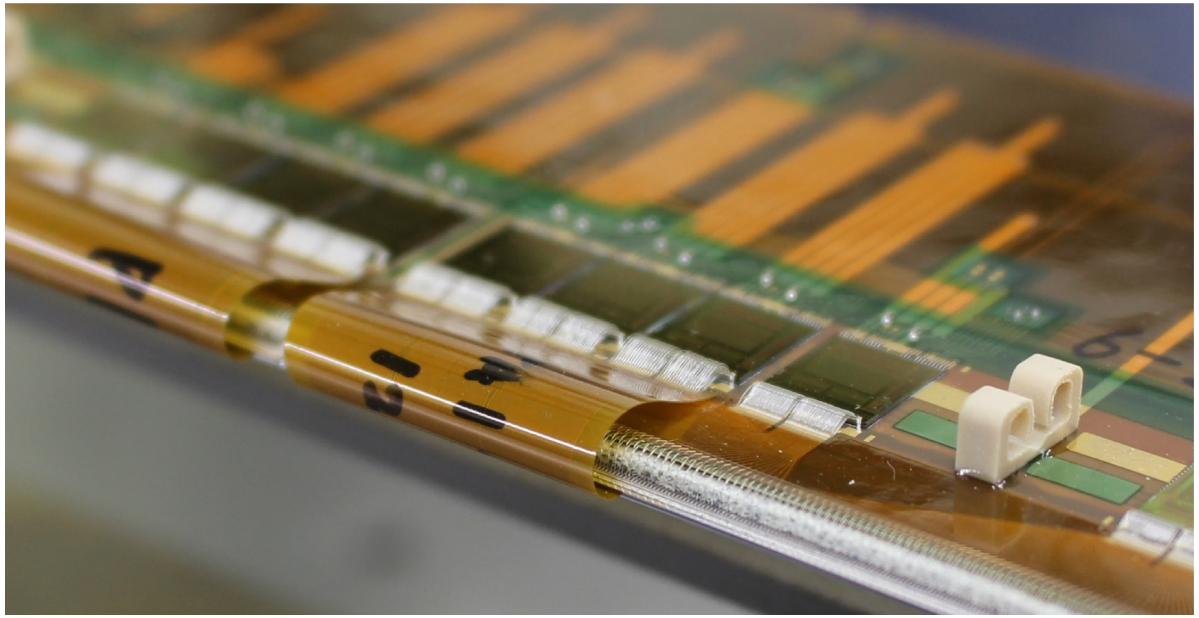
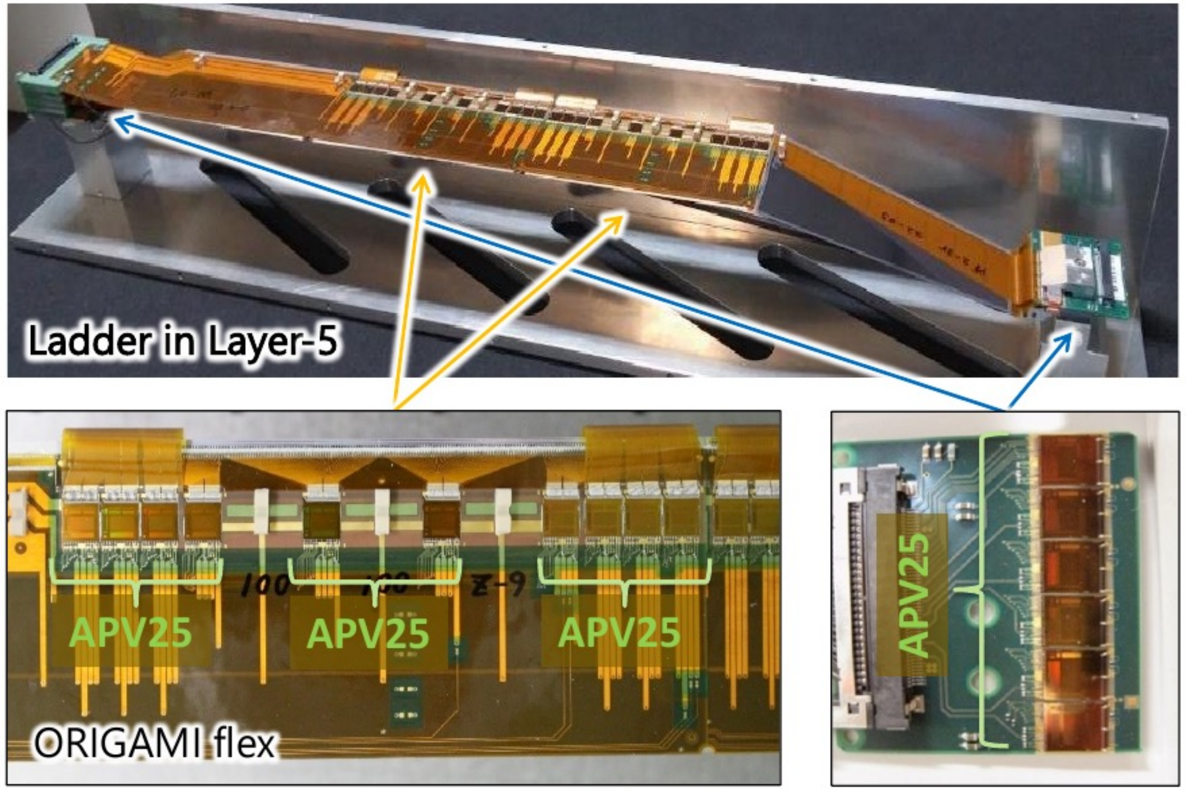
Origami chip on sensor concept

- Readout chips directly on each middle sensor
  - shorter signal propagation length (smaller capacitance and noise)
  - Thinned to 100 μm to reduce material budget
  - Wrapped flex to read both sides from the same side
  - Cool only one side with bi-phase –20 ℃ CO_2

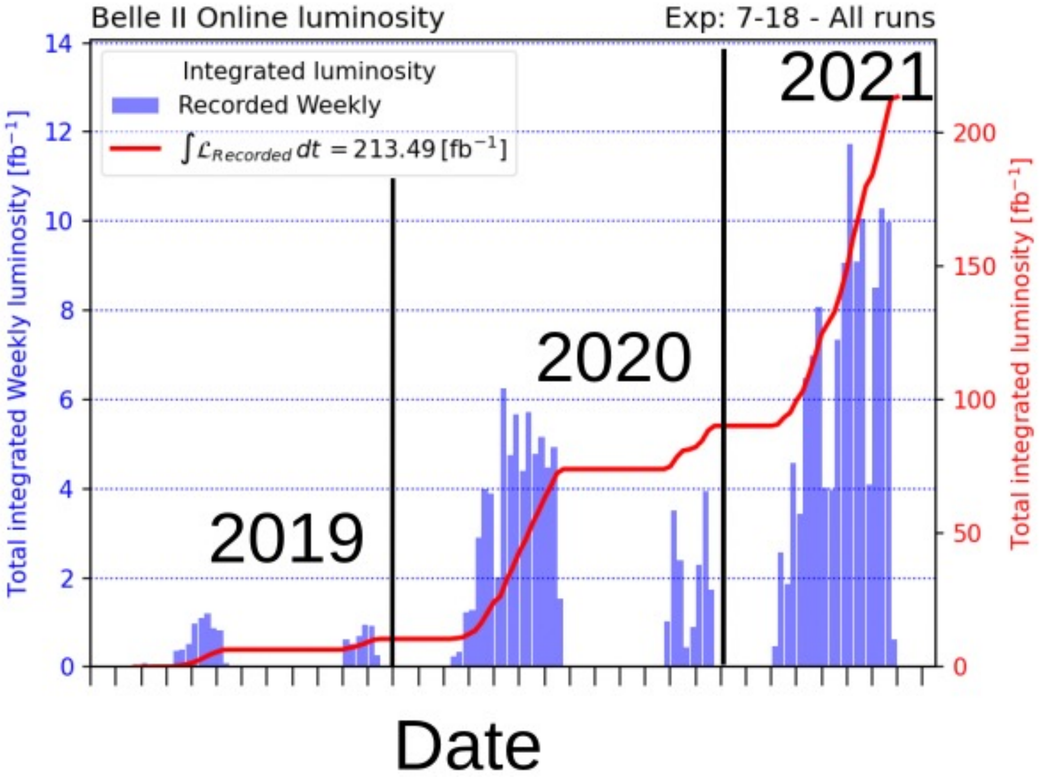




Operation & Performance

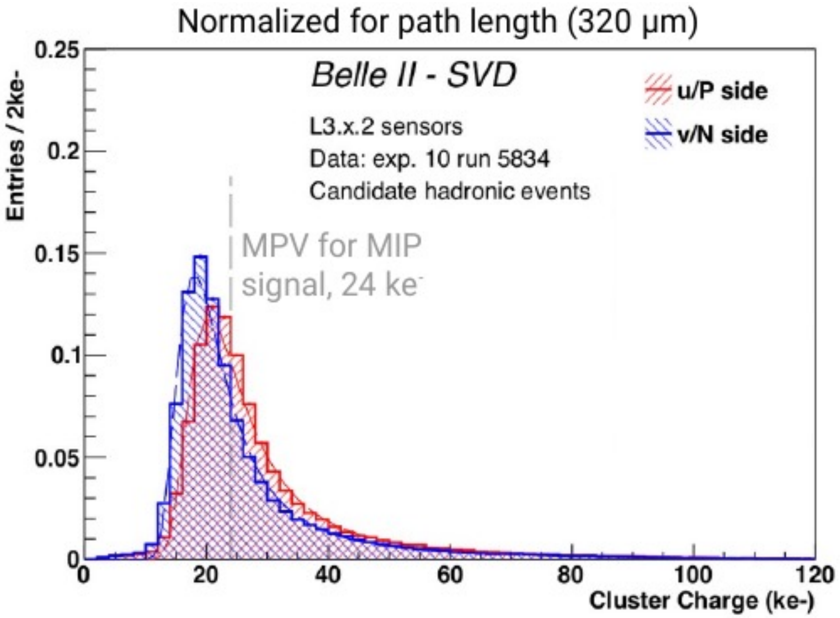
Operational experience

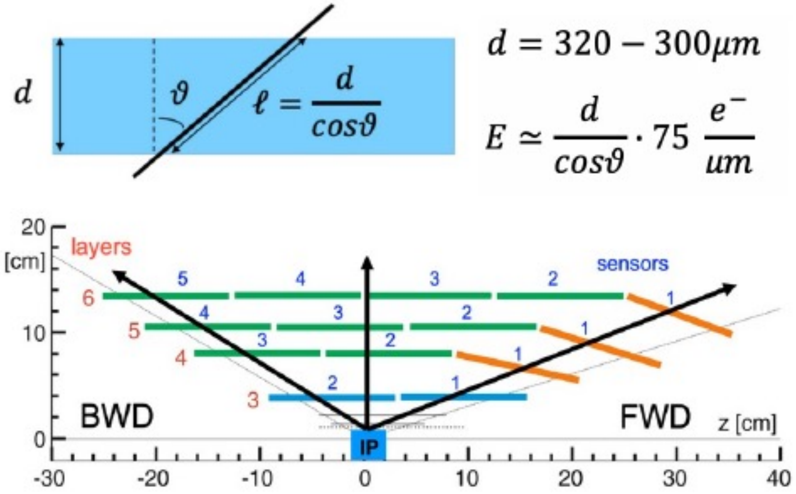
- SVD installed in 2018, operated since 2019
- Reliable and smooth operation without major problems
  - Total fraction of masked strips ~ 1%
  - One APV25 chip disabled in spring 2019 (out of 1748)
    → fixed by cable reconnection in summer 2019
- Excellent detector performance
  - hit efficiency stably > 99% in most of the sensors

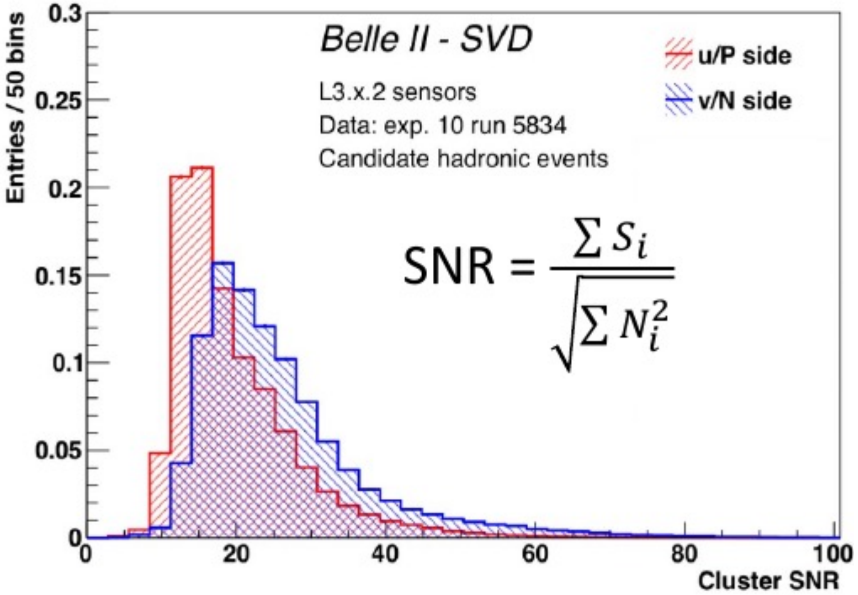


Signal charge and signal-to-noise ratio

- Signal charge: normalized for the track path length in silicon
  - u/P side: agree with MIP considering ~ 15% uncertainty in APV25 gain calibration
  - v/N side: 10-30% signal loss due to large pitch and presence of floating strip
    - similar in all sensors
- SNR: very good in all sensors (most probable value: 13-30)
  - u/P side: larger noise due to longer strip length (larger inter-strip capacitance)

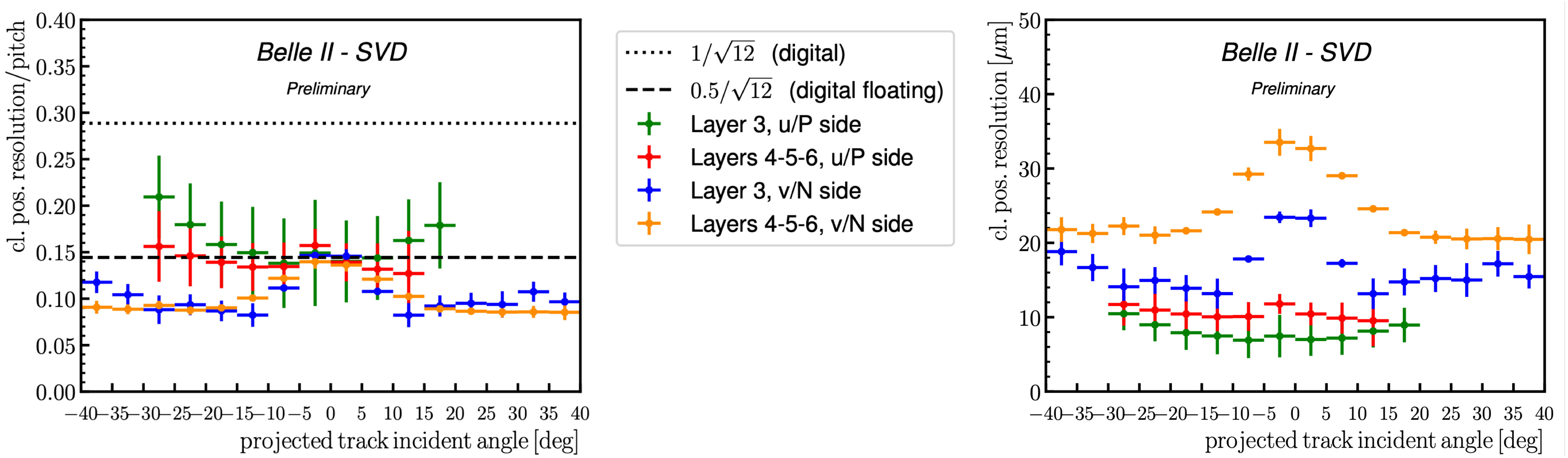






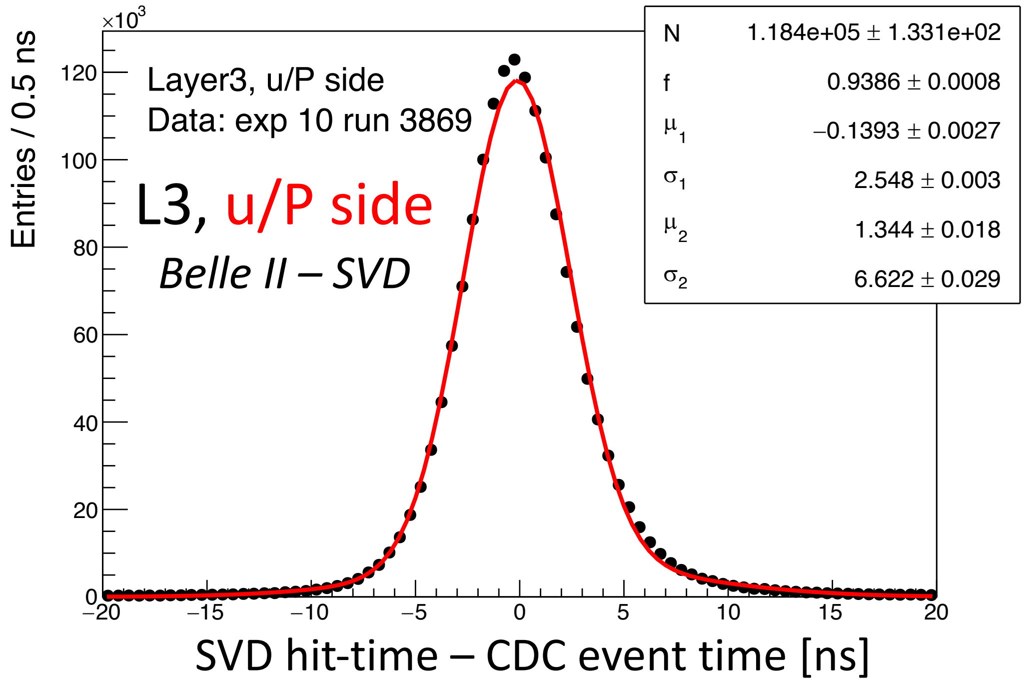
Cluster position resolution

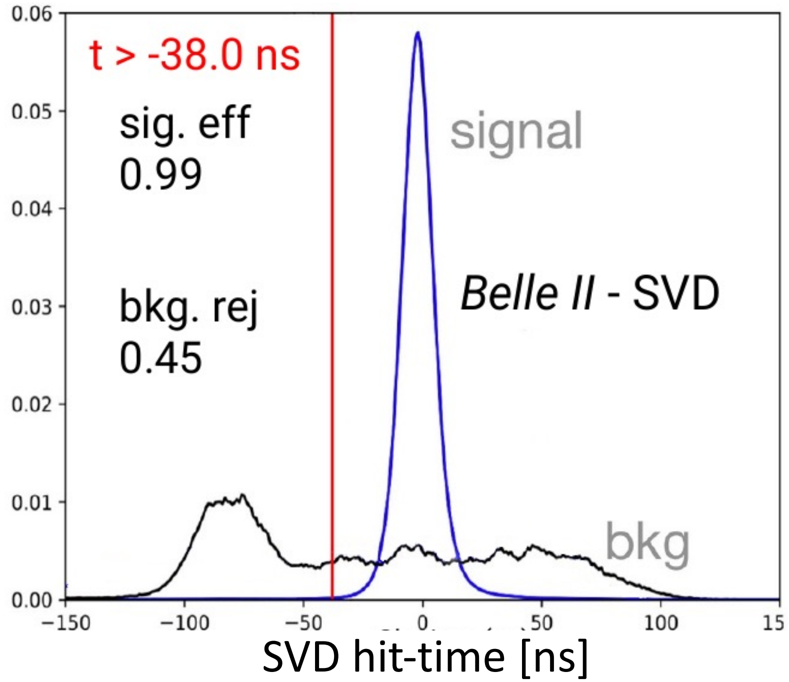
- Preliminary cluster position resolution measured on $e^+e^- \rightarrow \mu^+\mu^-$ data
  - Estimated from the residual of the cluster position with respect to the track (unbiased)
    - Effect of the track extrapolation error subtracted
  - Excellent position resolution in agreement with the expectations from the pitch
  - Still room for improvement for the u/P side (work ongoing)



Hit-time resolution

- Excellent hit-time resolution with respect to event time
  - event time estimated by central drift chamber (CDC) outside of SVD
  - (~ 2.9 ns u/P, ~ 2.4 ns v/N)
- Possible to efficiently reject off-time background hits
  - Will be used for higher luminosity and background levels

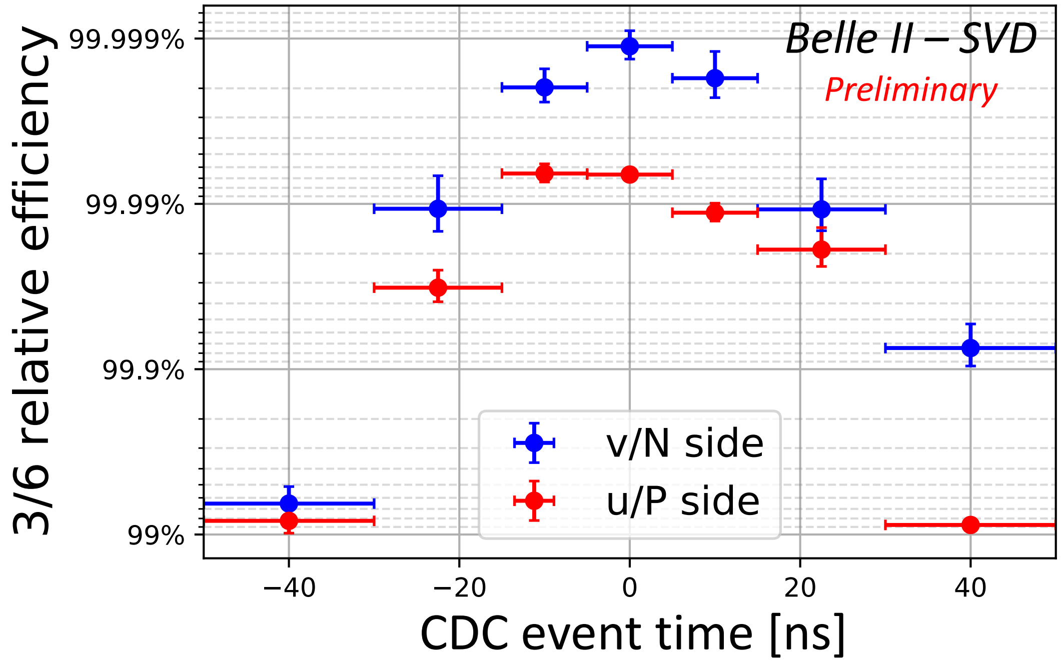




3-sample acquisition mode

- performance
  - ideal 3 samples provide enough information as 6 samples
    - amplitude – peak ADC sample
    - hit-time – rising edge of the waveform
  - degrades if the trigger jitter is large
- 1st step: efficiency (compared to 6-sample)
  - emulate 3-sample mode offline using trigger timing information
  - efficiency based on track using CDC, SVD and PXD
  - > 99.9% for trigger jitter less than 30 ns
    - almost a whole clock-cycle

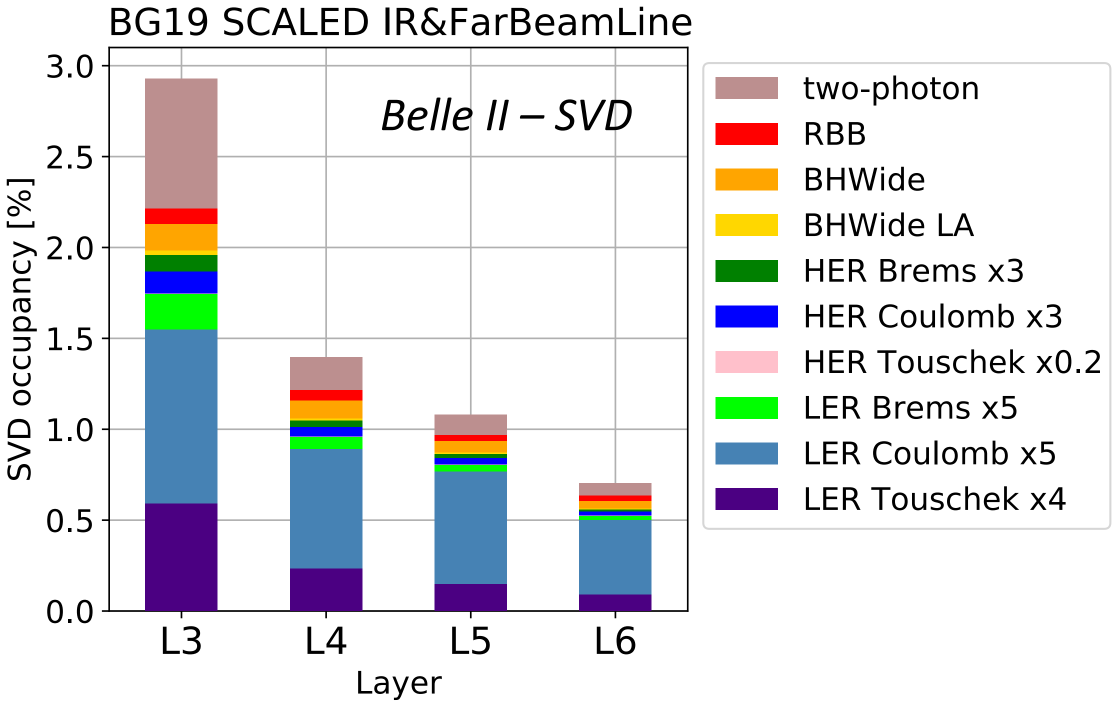
all sensors combined



Beam background & Radiation effect

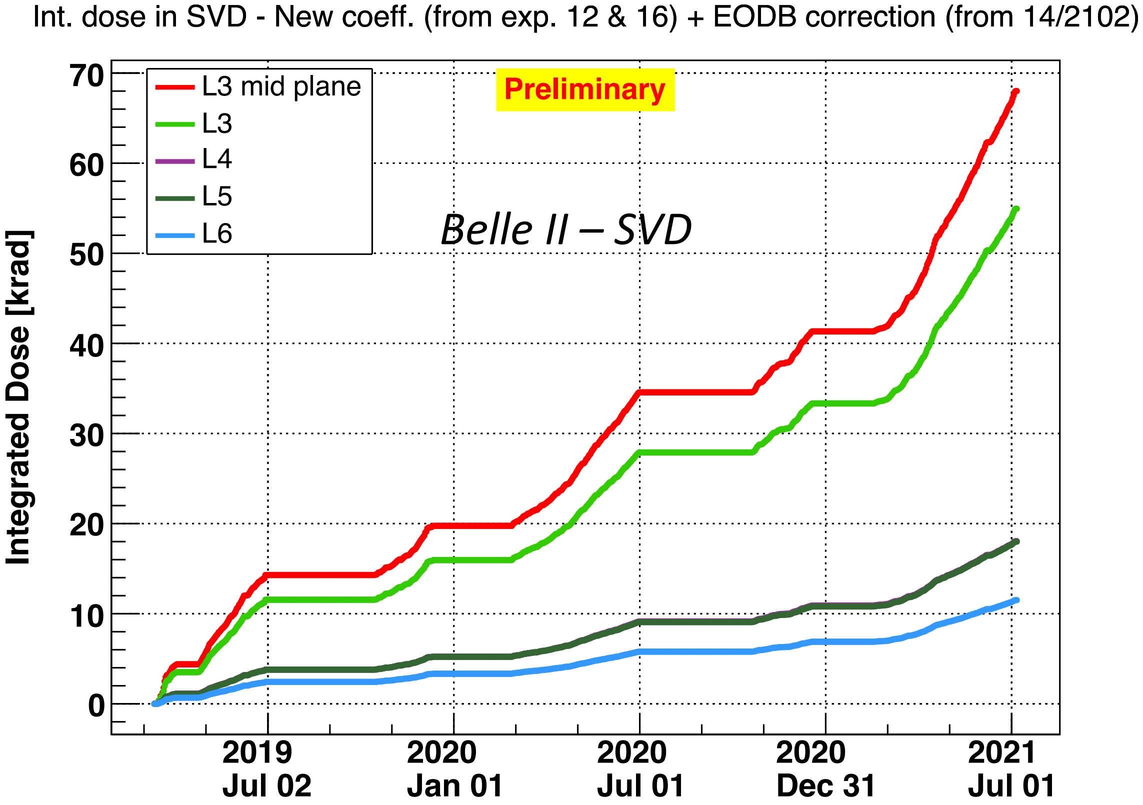
Beam background

- Beam background increases SVD hit occupancy which degrades tracking performance
  - Present occupancy limit in layer-3: ~ 3%
    - up to x~2 will be allowed using hit-time to reject background
  - With current luminosity, average hit occupancy in layer-3 is well under control (< 0.5%)
  - Projection of hit occupancy at $L = 8\times10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ is about 3% in layer-3
    - estimated by scaling MC with data/MC ratio
    - correspond to dose of ~ 0.2 Mrad/smy (smy = 10^7 s)
      - = 1-MeV neutron fluence of $\sim 5\times10^{11}$ $\mathrm{n_{eq}/cm^2/smy}$
    - Long term BG extrapolation affected by large uncertainties
      - collimation
      - injection BG (still not included)



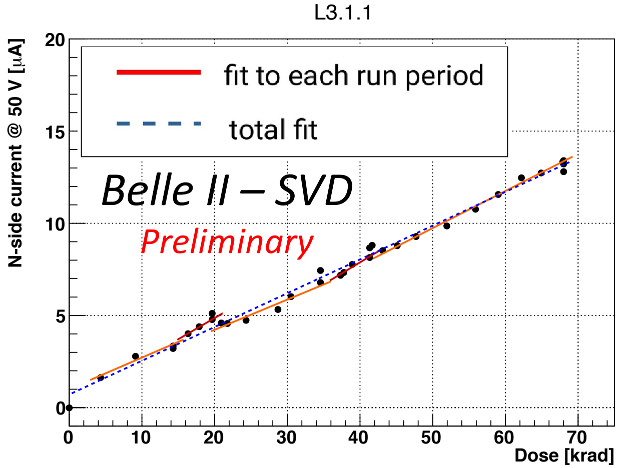
Integrated dose

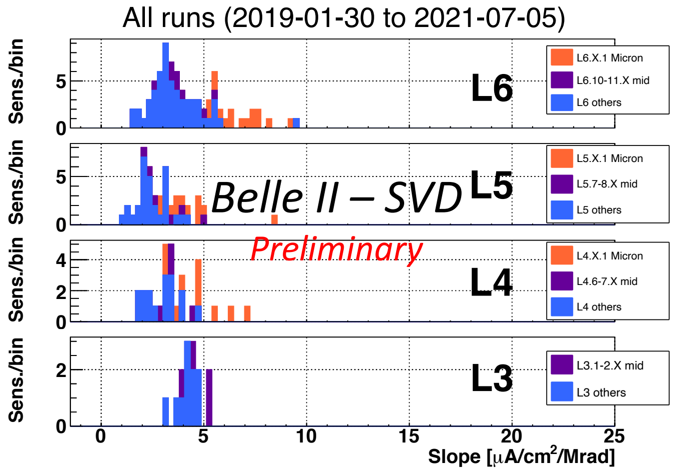
- SVD dose estimated by dose on diamond sensors: 60 krad in layer-3 mid plane (the most exposed to radiation)
  - Dose estimate based on correlation between SVD occupancy and diamonds dose
  - Several assumptions and large uncertainty (~ 50%)
- 1-MeV equivalent neutron fluence: $\sim 1.6\times10^{11}$ n_{eq}/cm^2 in first 2.5 years
  - assuming dose/neq fluence ratio $= 2.3\times10^{9}$ $n_{eq}/cm^2/krad$ from MC)



Radiation effect on leakage current

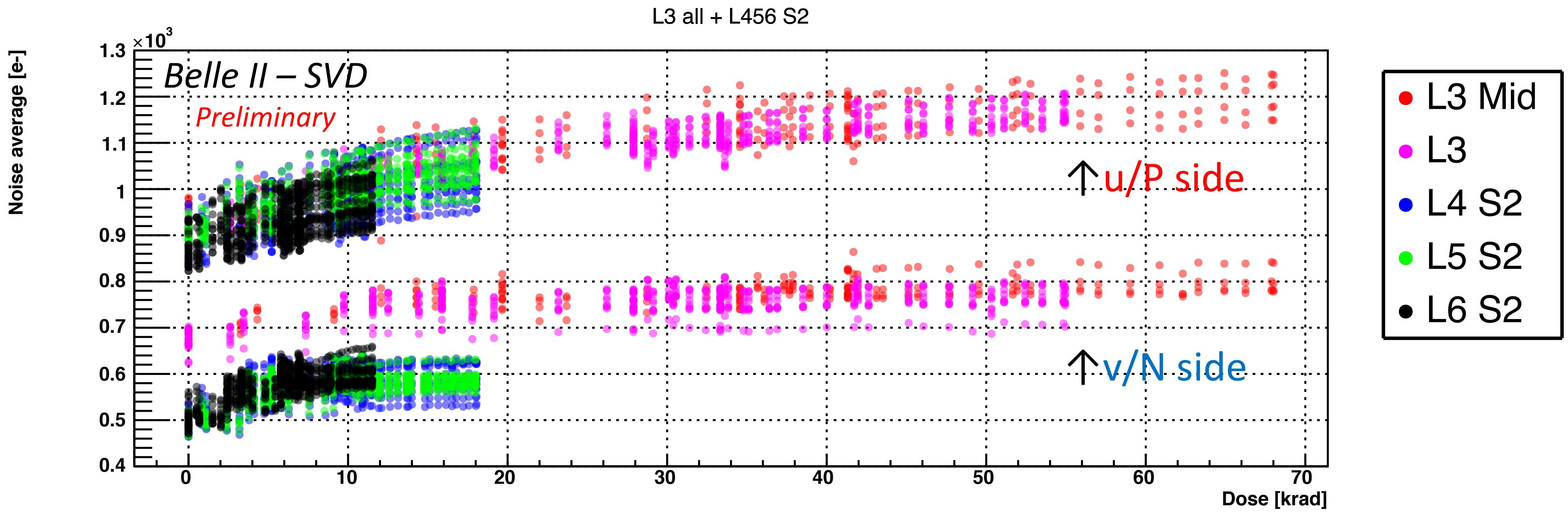
- Good linear correlation between leakage current and estimated dose
  - Slope: 2-5 µA/cm^2/Mrad with large variations due to temperature effects and dose spread among sensors in layer (average dose in layer used in estimate)
  - Same order of magnitude as BaBar measurement (1 µA/cm^2/Mrad @ 20 ℃) [NIMA 729, 615-701, 2013]
- Even after 10 Mrad irradiation, leakage current will not significantly affect strip noise
  - Noise dominated by sensor capacitance because of short shaping time (50ns) in APV25





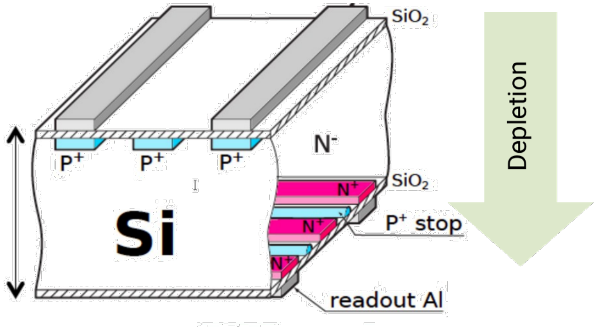
Radiation effect on strip noise

- Noise increase of 20-25% in layer-3
  - Not affecting performance
  - Likely due to radiation effects on sensor surface
    - Non-linear increase due to fixed oxide charges that increase inter-strip capacitance,
    - expected to saturate
  - Saturation seen on v/N side and starting to be seen on u/P

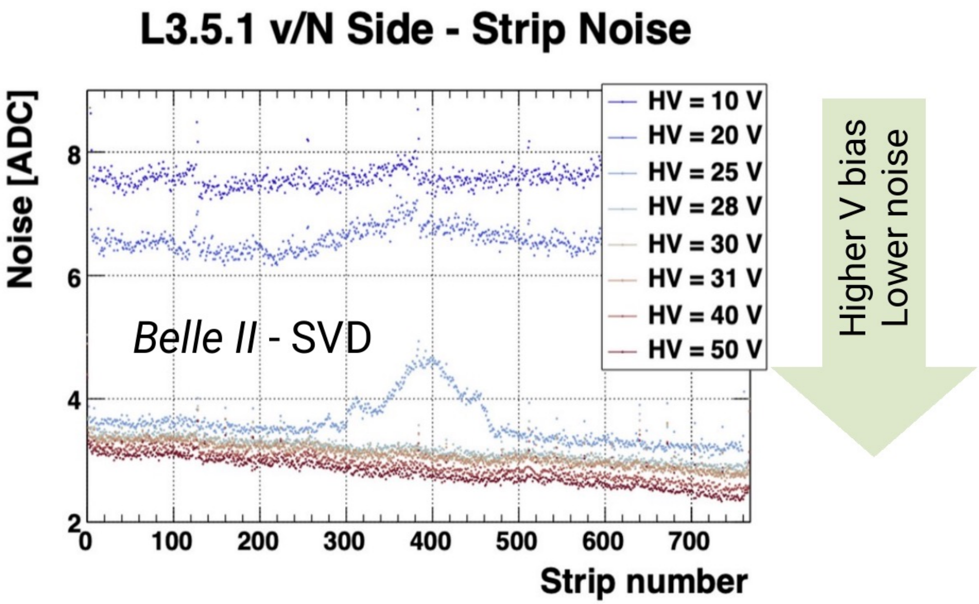


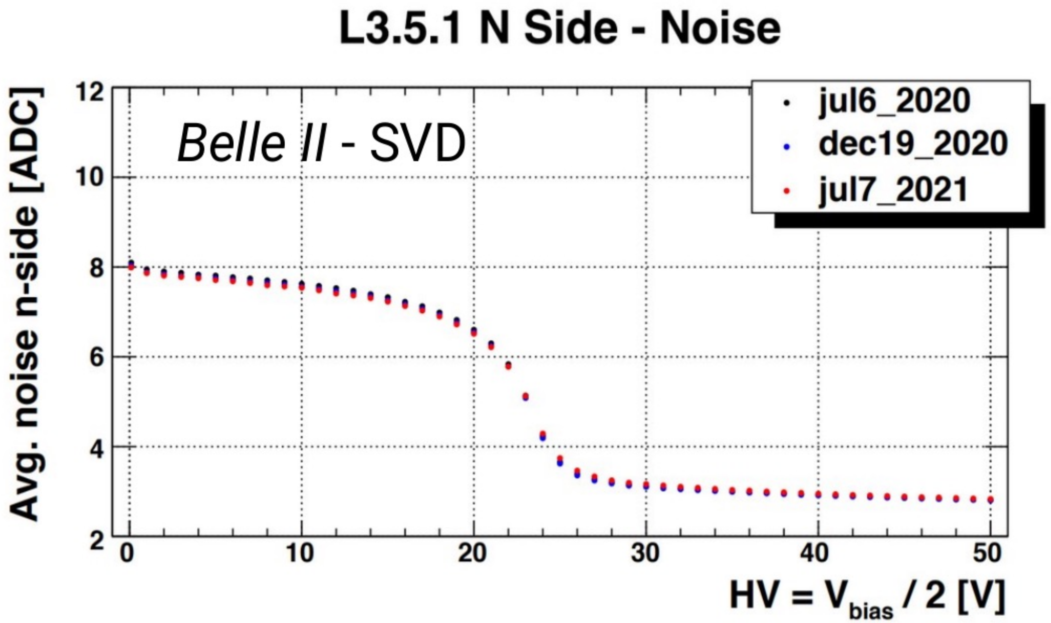
Radiation effect on depletion voltage

- Minimum of v/N side strip noise at full depletion
  - v/N side insulated only when the n-type bulk is fully depleted
  - Over-depletion bias still slightly decrease noise
    - reduce electron accumulation layer on n-side surface



- No change in full depletion voltage observed with time: consistent with low integrated neutron fluence ($\sim 1.6\times10^{11}$ n_{eq}/cm^2)





Conclusions

- SVD has been taking data in Belle II since March 2019 smoothly and reliably
- Excellent performance in agreement with expectations
  - Still some room for improvement in cluster position resolution
- Seen first effects of radiation damage at the expected level but not affecting performance
- Ready to cope with increased beam background
  - Reject off-time background using hit-time
  - 3/6-mixed acquisition mode to reduce dead time, data size and occupancy