The Silicon Vertex Detector of the Belle II Experiment

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Outline

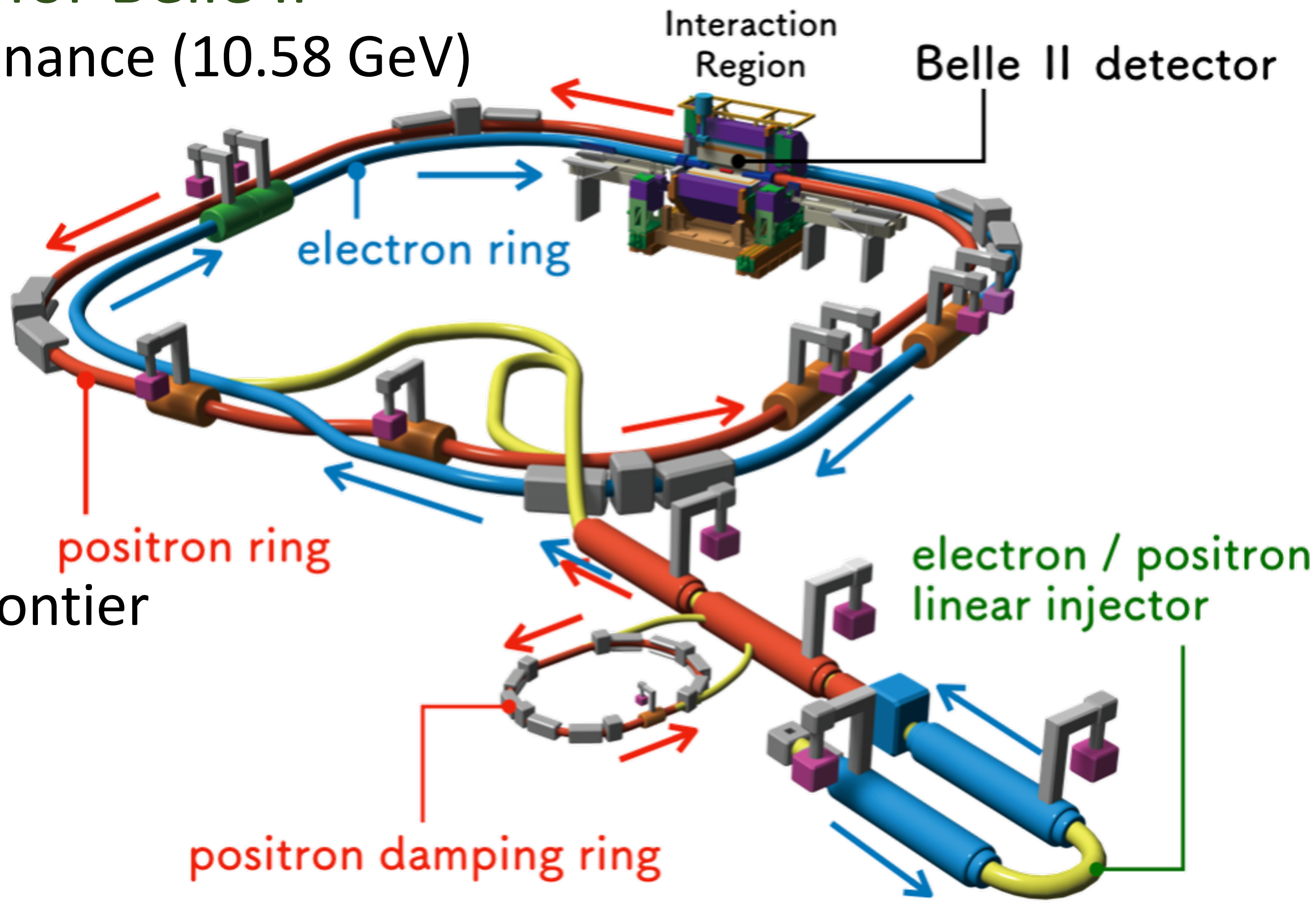
- Introduction
- Operation & Performance
- Beam background & Radiation effect
- Conclusions

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: $3.1 \times 10^{34}\ cm^{-2}s^{-1}$

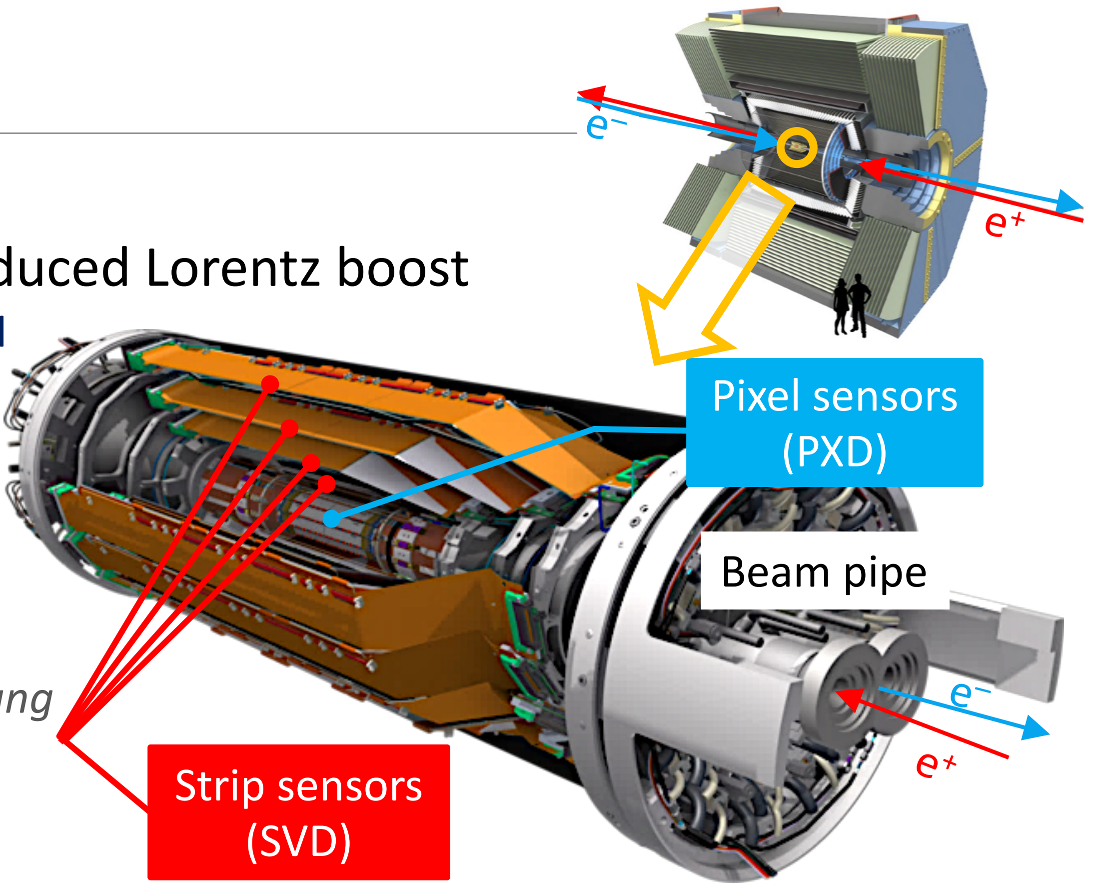


Belle II

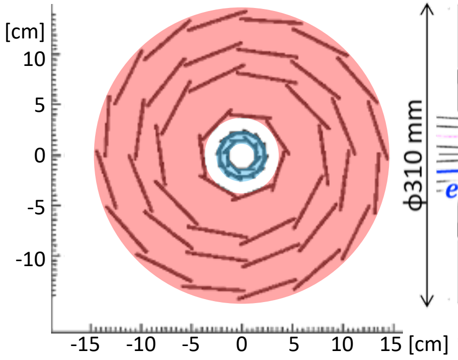
- New physics search at the luminosity frontier
- Accumulated 213 fb^{-1} data
- Essentials for physics programs:
  - Precise determination of decay vertices
  - Low momentum tracking
  - Good particle identification

→ Vertex Detector plays an important role

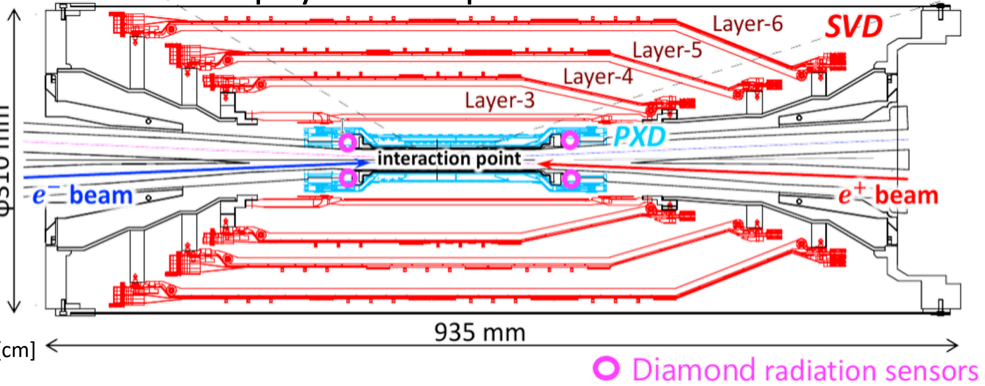
Belle II Vertex Detector



- Requirements
  - Better vertex resolution than Belle to compensate reduced Lorentz boost
    - improved point resolution, reduced inner radius and lower material
  - Operate in high background environment
    - expected hit rate: 3 MHz/cm^2 @ SVD layer-3
  - Radiation hard
    - expected 0.2 Mrad/yr. @ SVD layer-3
- Layers-1-2: Pixel Detector (PXD) → *talk by Boqun Wang*
  - DEPFET pixel sensors
  - Innermost layer 1.4 cm from interaction point
- Layers-3-6: Silicon Vertex Detector
- Diamond sensors
  - For radiation monitor and beam abort

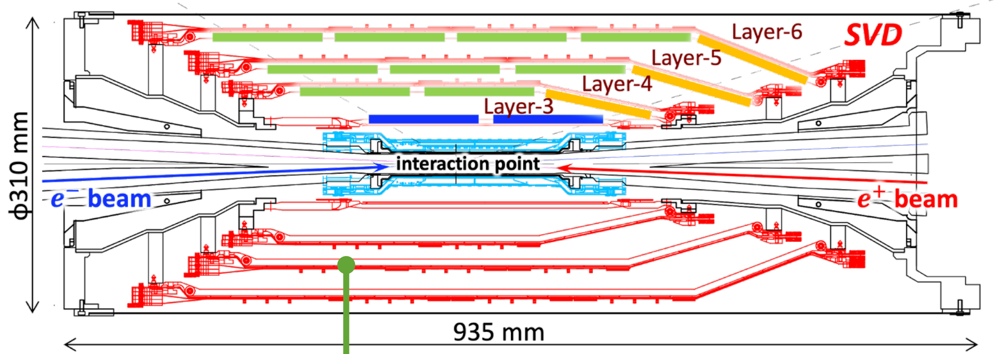


physics acceptance: θ = 17-150°

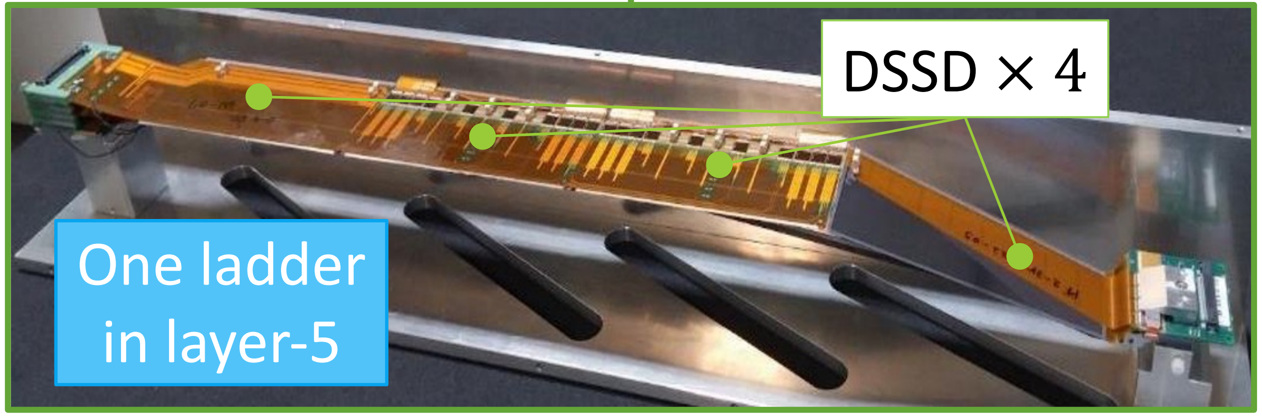


Belle II Silicon Vertex Detector (SVD)

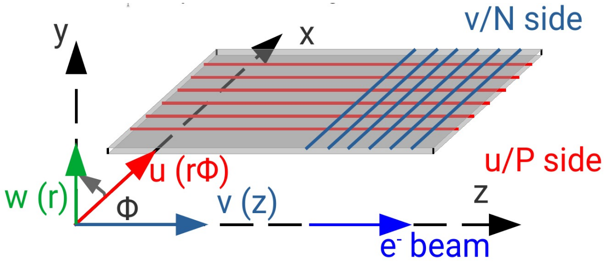
- **Layer-3-6: Silicon Vertex Detector (SVD)**
  - Double-sided Si strip detectors (DSSDs)
  - Low material budget: 0.7% X_0 per layer

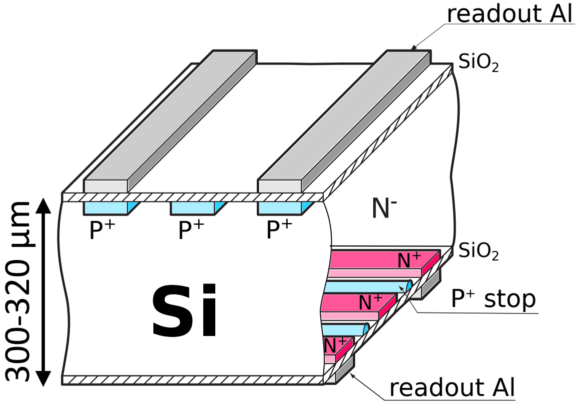


- **SVD Roles**
  - Extrapolate tracks to PXD
    - essential for reconstruction of decay vertices
    - PXD region of interest for data reduction
  - Stand-alone tracking for low p_T tracks
  - Precise vertexing of K_S
  - PID with dE/dx



- **DSSDs**
  - Provide 2-D spatial information
  - Strips are AC-coupled to n-type substrate
  - Fully depleted at 20-60 V, operated at 100 V
  - Total: 172 sensors = 1.2 m^2 sensor area = 224k readout strips





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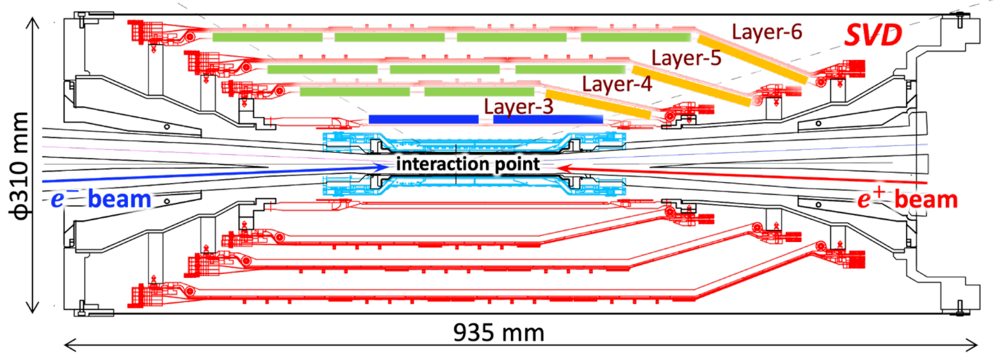

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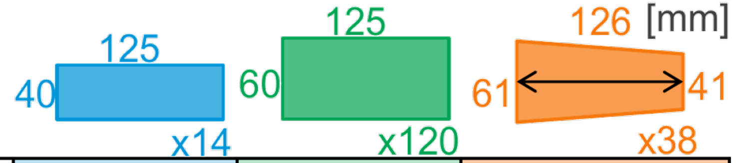
172 sensors



	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

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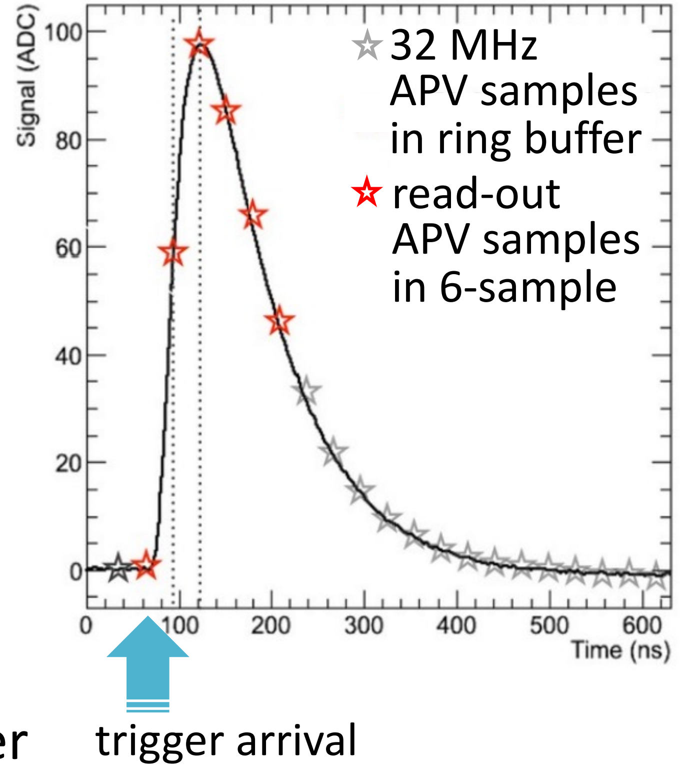
Front-end ASIC: APV25

- 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 read-out



3/6-mixed acquisition mode prepared for higher luminosity

- To reduce background occupancy, trigger dead-time and data-size
  - Half time-window, half FIFO usage and half data-size for each hit in 3-sample
- Switching sampling number according to the timing precision of trigger
- The functionality already implemented in the real setup and confirmed to work
  - few hours of physics data-taking was smooth
- Performance study needed before moving to 3/6-mixed mode
  - Hit efficiency is the first step → slide 16
  - To be checked: position resolution, dE/dx, hit-time

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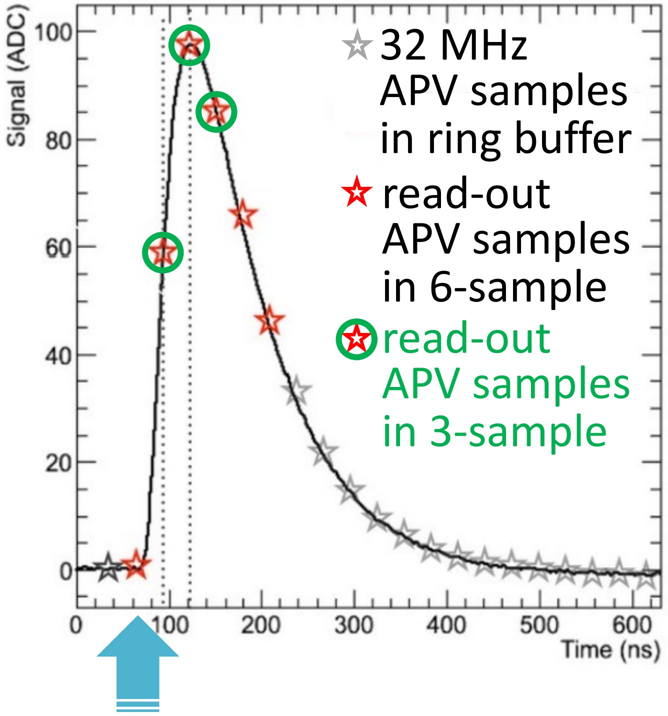

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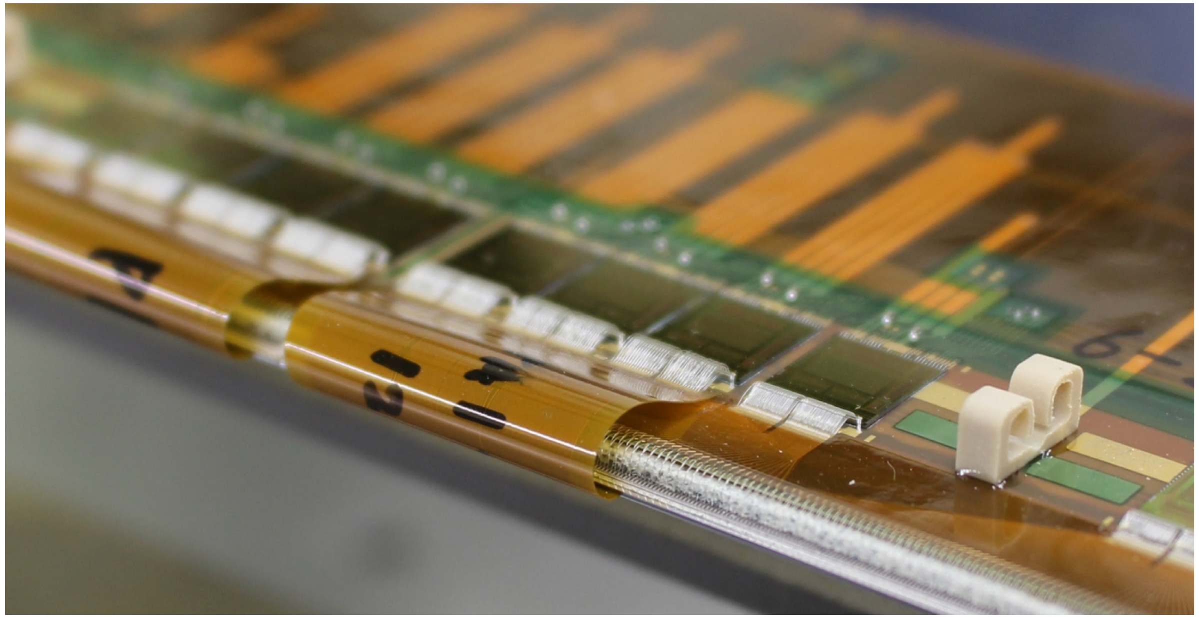
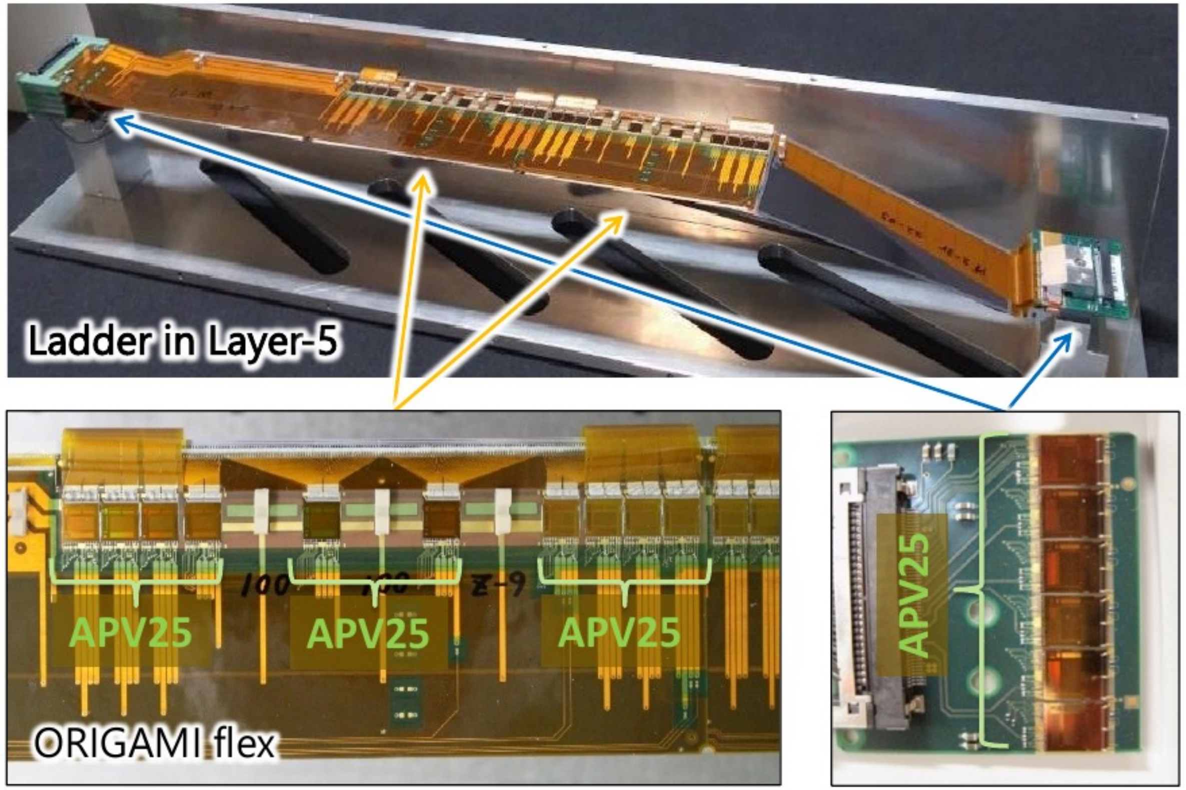
Origami chip on sensor concept

- 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

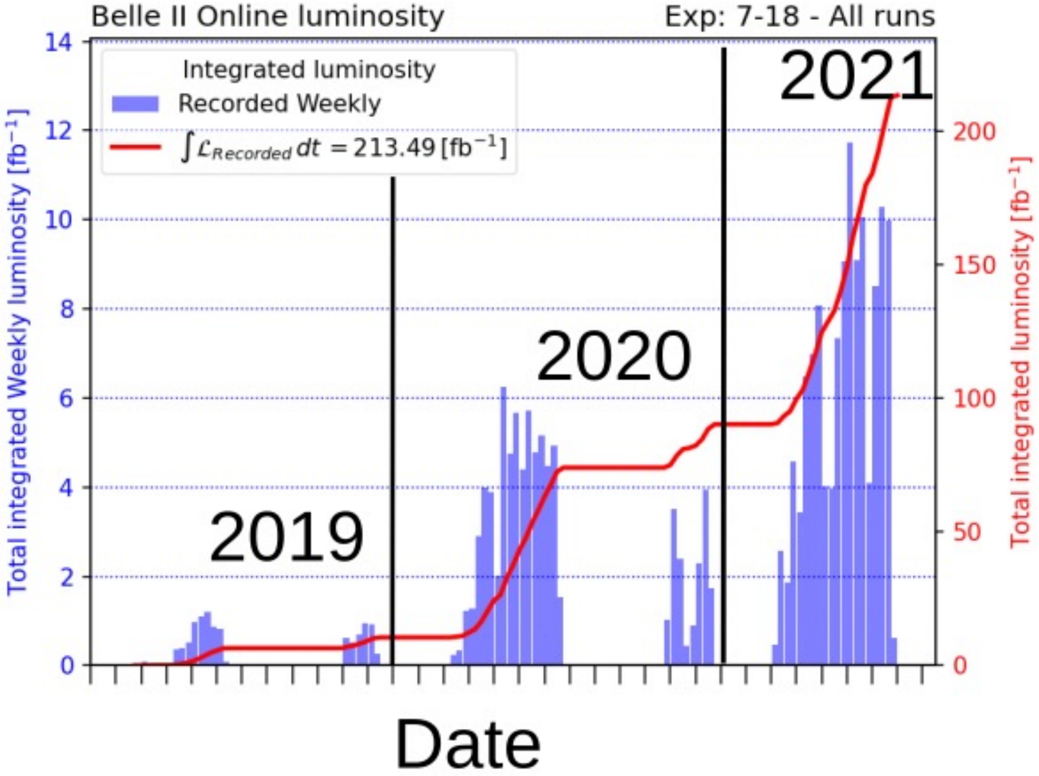




Operation & Performance

Operational experience

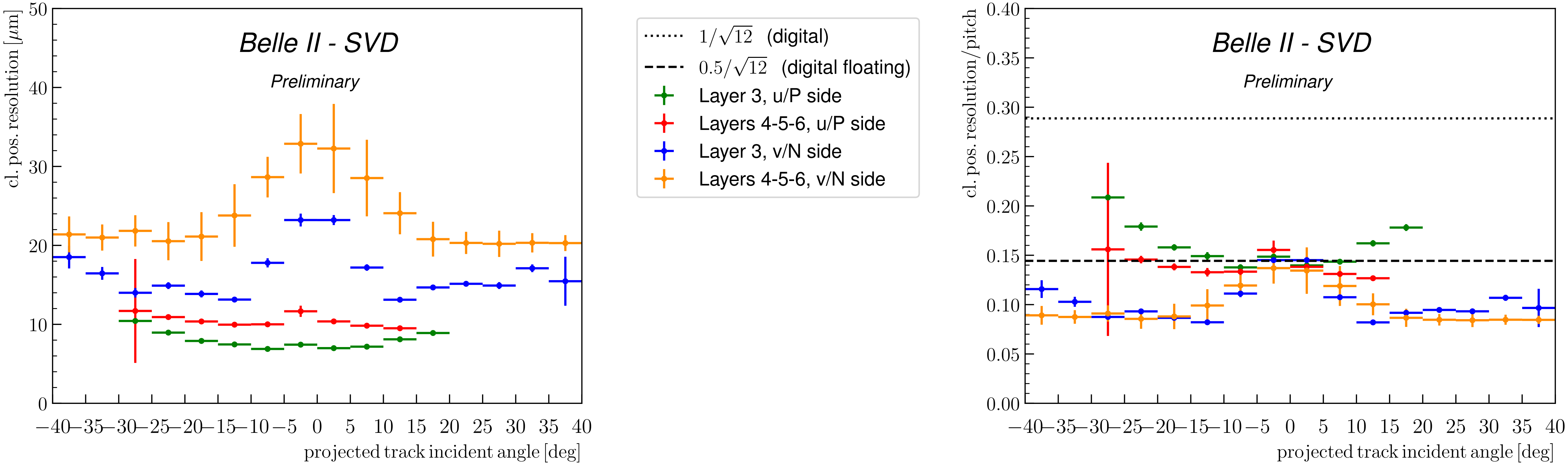
- SVD installed in 2018, operated since 2019
- Reliable and smooth operation without major problems
  - Total fraction of masked strips ~ 1%
  - One APV25 chip disabled in spring 2019 (out of 1748)
    → fixed by cable reconnection in summer 2019
- Excellent detector performance
  - already shown at Vertex 2020
  - Hit efficiency stably > 99% in most of the sensors
  - Reasonable cluster charge distribution
    - u/P side: agrees with MIP considering uncertainty in calibration
    - v/N side: 10-30% due to large pitch and floating strip
  - Very good SNR (most probable value: 13-30)
  - updated simulation better agrees with data
    → *YSF talk by Mateusz Kaleta*



Cluster position resolution

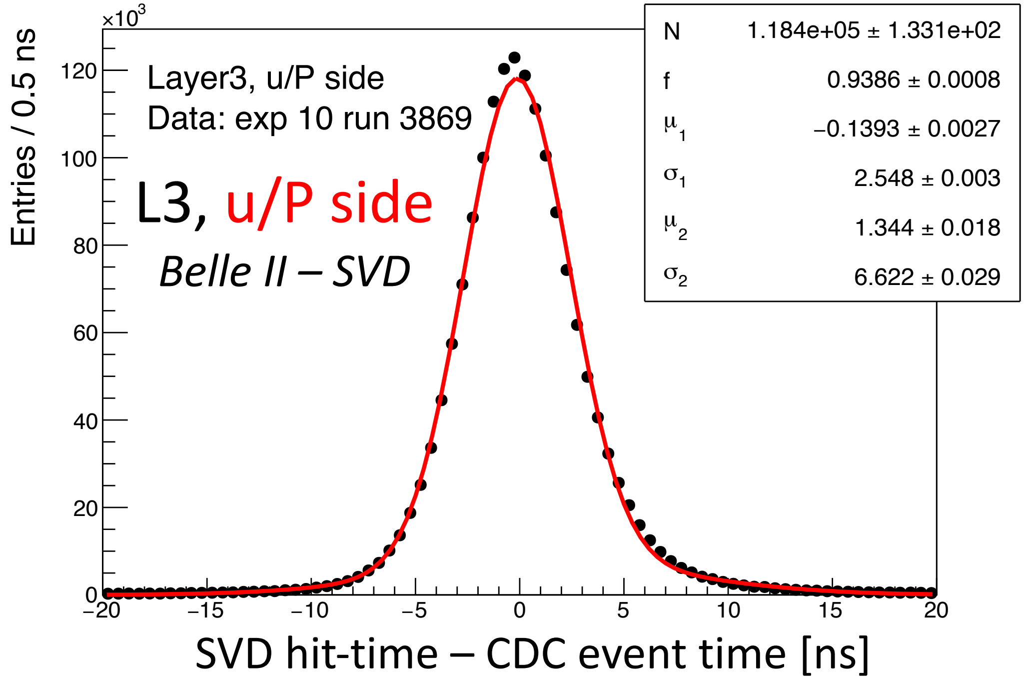
→ *YSF talk by Robin Leboucher*

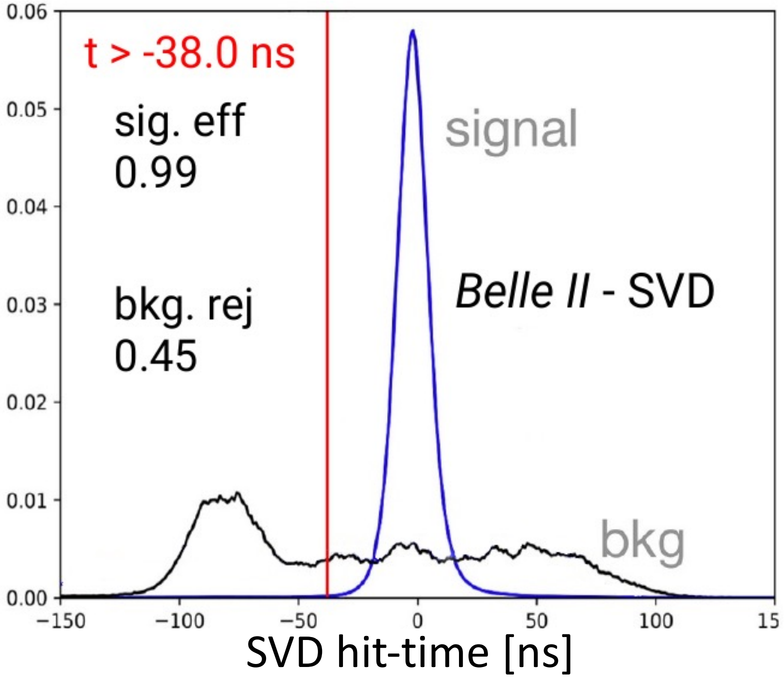
- Preliminary cluster position resolution measured on $e^+e^- \rightarrow \mu^+\mu^-$ data
  - Estimated from the residual of the cluster position with respect to the track (unbiased)
    - Effect of the track extrapolation error subtracted
  - Excellent position resolution in agreement with the expectations 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





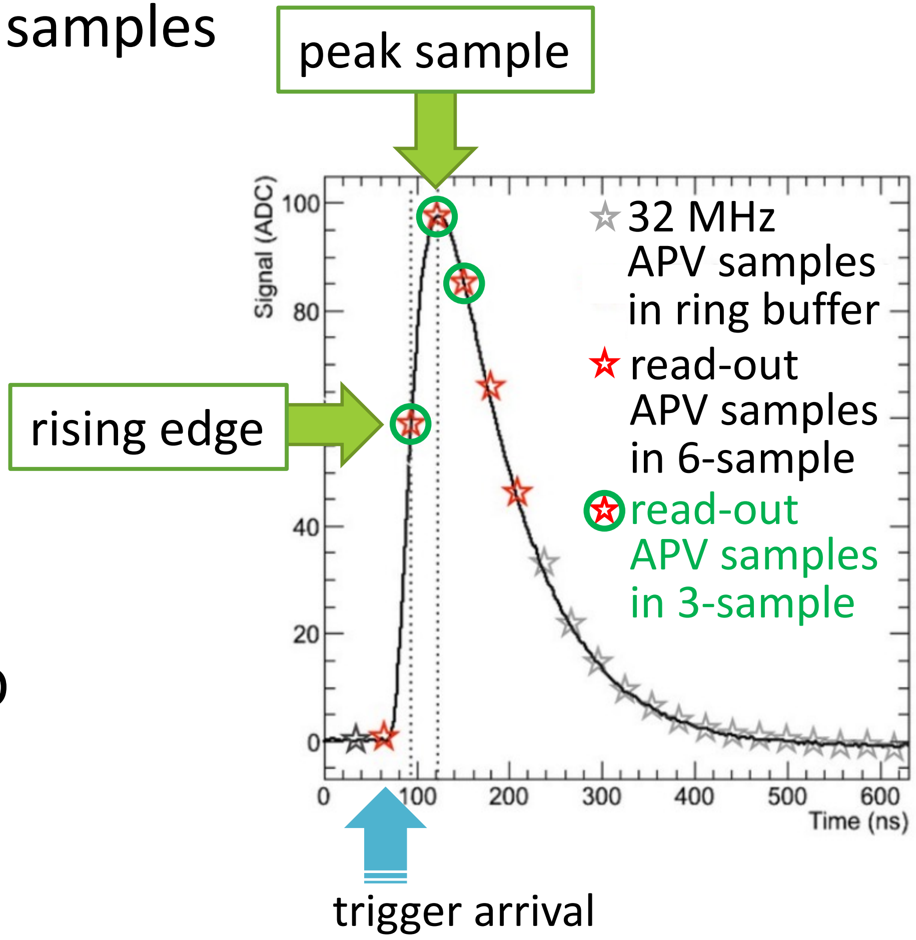
3-sample acquisition mode

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 timing is largely shifted
  - CDC event time is a good estimator

1st step: relative hit efficiency

- (hit efficiency in 3-sample)/(~ in 6-sample)
- Emulate 3-sample mode offline
- Efficiency based on track using CDC, SVD and PXD
- Relative efficiency > 99.9% for trigger timing shift within ±30 ns
  - almost a whole clock-cycle



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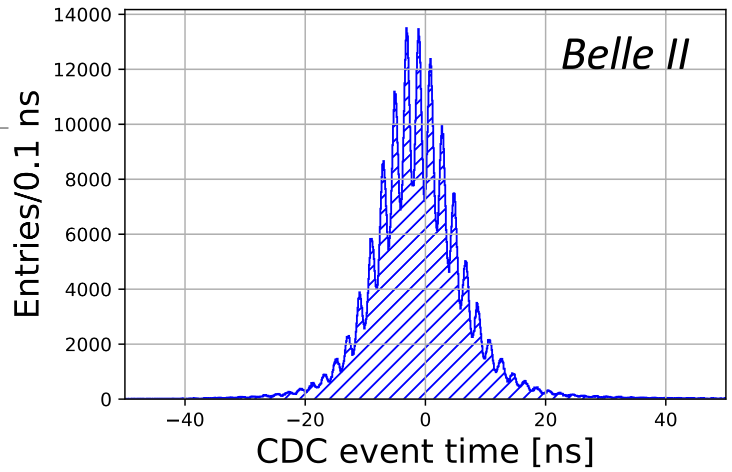
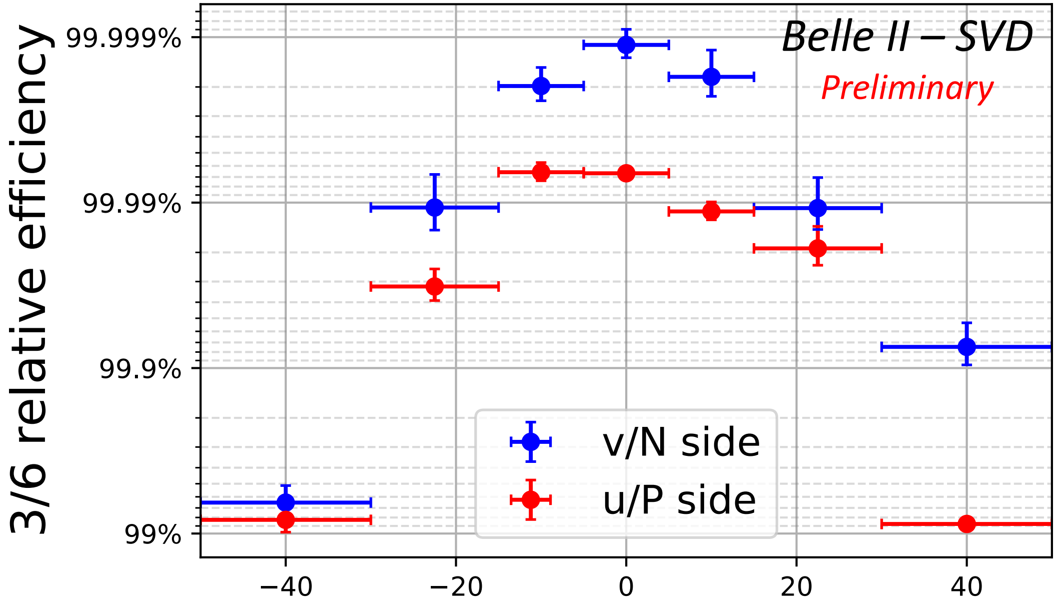


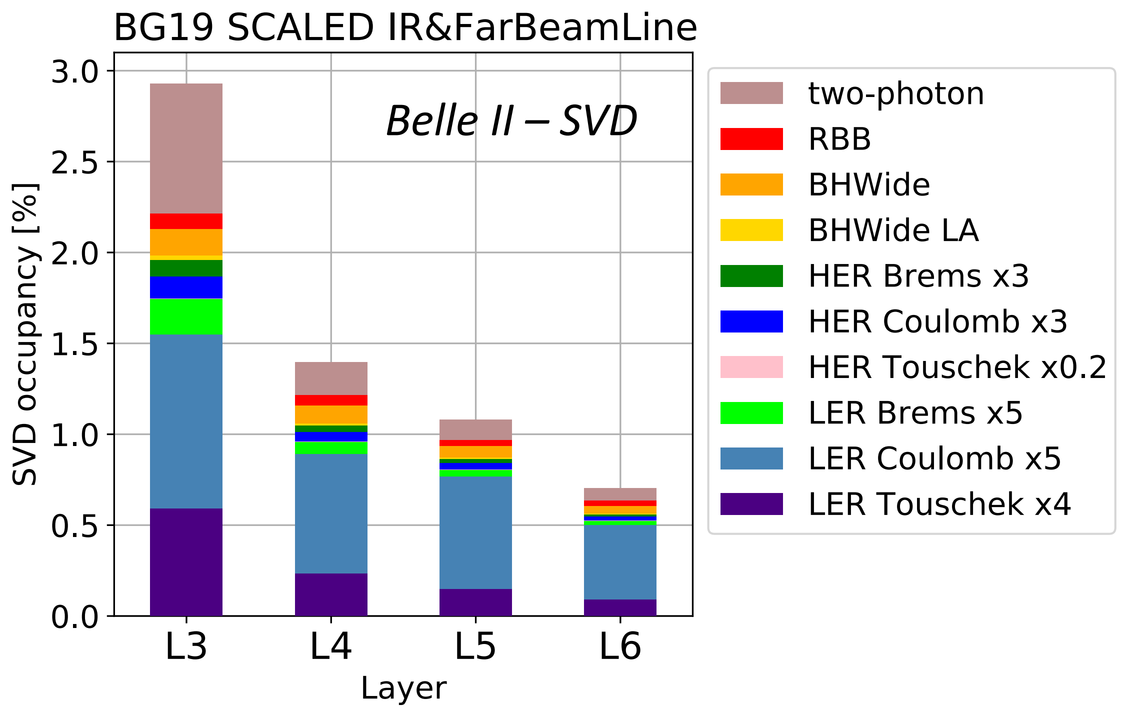
all sensors combined



Beam background & Radiation effect

Beam background and hit occupancy

- Beam background increases SVD hit occupancy which degrades tracking performance
  - Present occupancy limit in layer-3: ~ 3%
    - will be loosened to x~2 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
      - = 1-MeV neutron fluence of $\sim 5\times10^{11}$ n_{eq}/cm^2/smy
      - smy: Snowmass Year = 10^7 sec
    - Long term BG extrapolation affected by large uncertainties
      - optimization of collimator settings in MC
      - injection BG not included in data nor MC
    - → motivate VXD upgrade → *talk by Katsuro Nakamura*

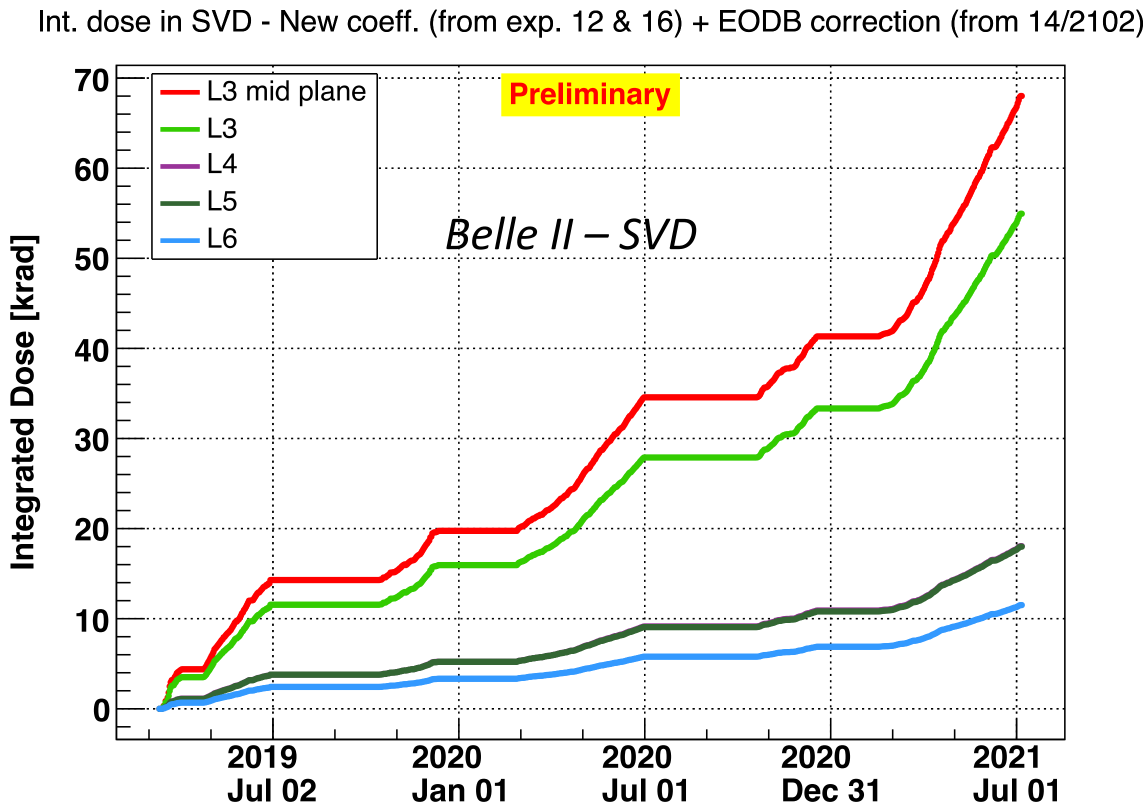


Integrated dose

- SVD dose estimated by dose on diamond sensors: 70 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%)

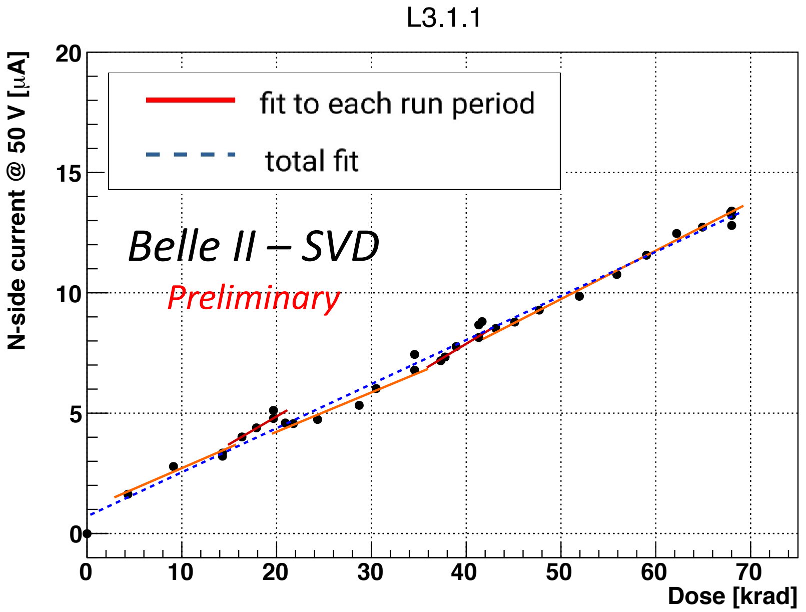
- 1-MeV equivalent neutron fluence: $\sim 1.6\times10^{11}$ n_{eq}/cm^2 in first 2.5 years
  - assuming dose/n_{eq} fluence ratio $= 2.3\times10^{9}$ n_{eq}/cm^2/krad from MC

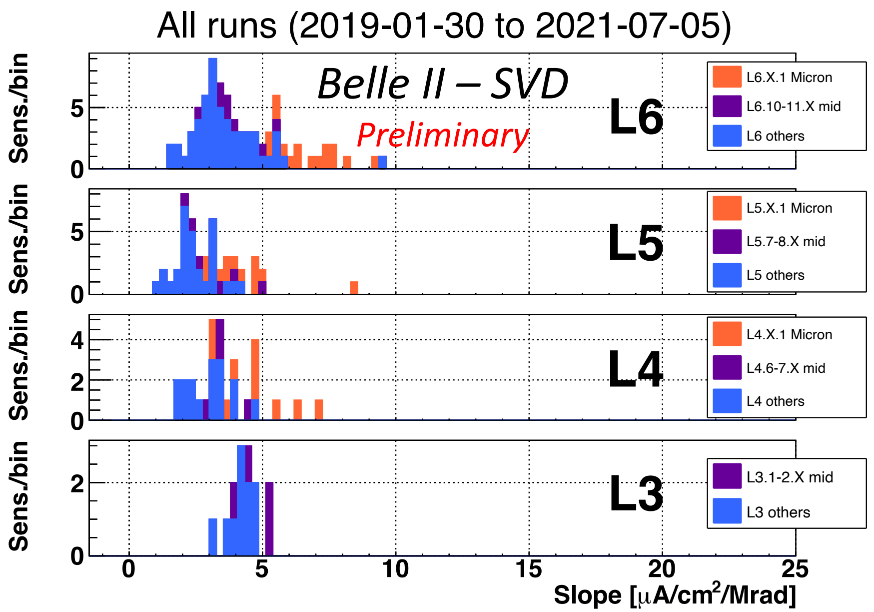
- analysis updated from last year
  - more suitable trigger used
    - physics trigger → Poisson trigger w/o injection veto
    - remove over estimation



Radiation effect on leakage current

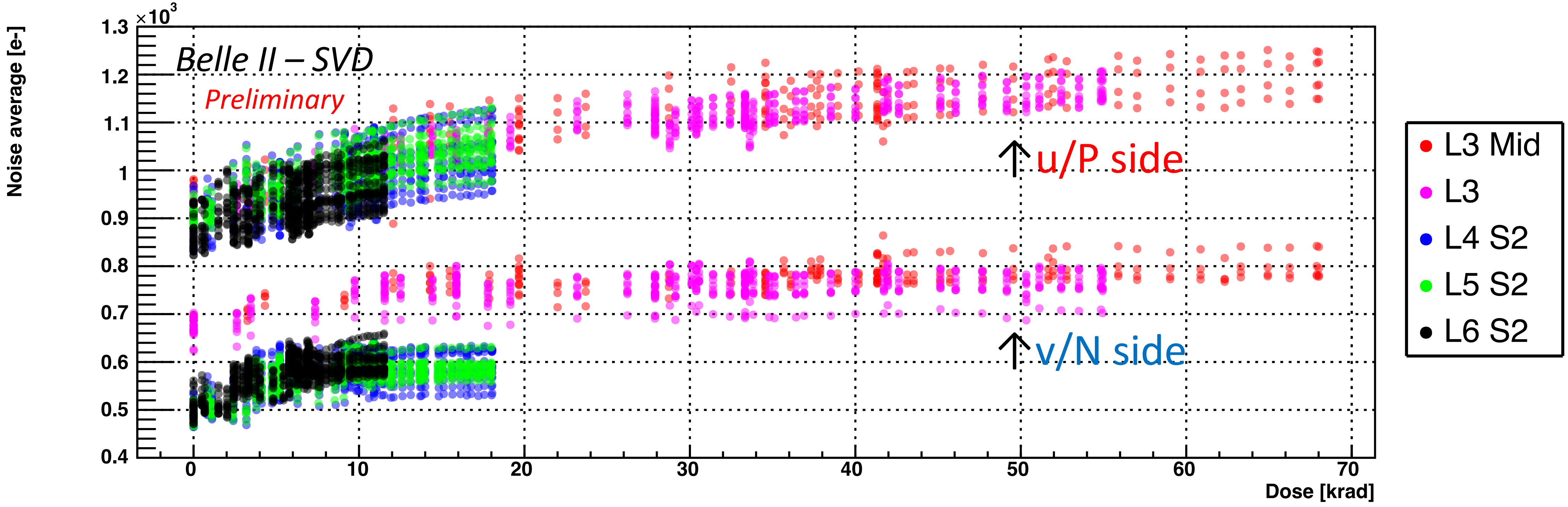
- Good linear correlation between leakage current and estimated dose
  - Slope: 2-5 μA/cm²/Mrad with large variations due to temperature effects and dose spread among sensors in layer (average dose in layer used in estimate)
  - Same order of magnitude as BaBar measurement (1 μA/cm²/Mrad @ 20 ℃)
    - [NIMA 729, 615-701, 2013]
  - Strip noise from leakage current is suppressed by short shaping time (50 ns) in APV25
    - comparable to the strip-capacitive noise only after 10 Mrad irradiation → not problematic for 10 years (2 Mrad)





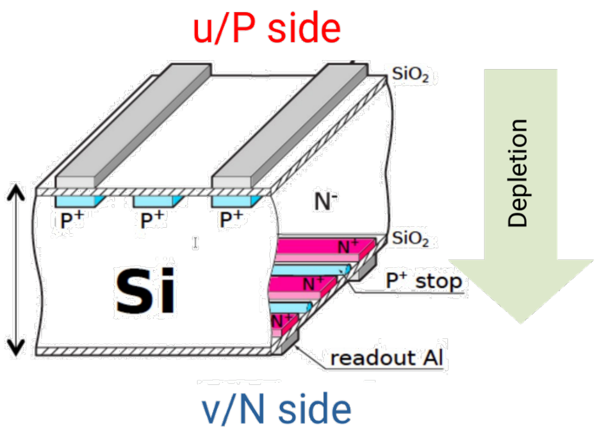
Radiation effect on strip noise

- 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

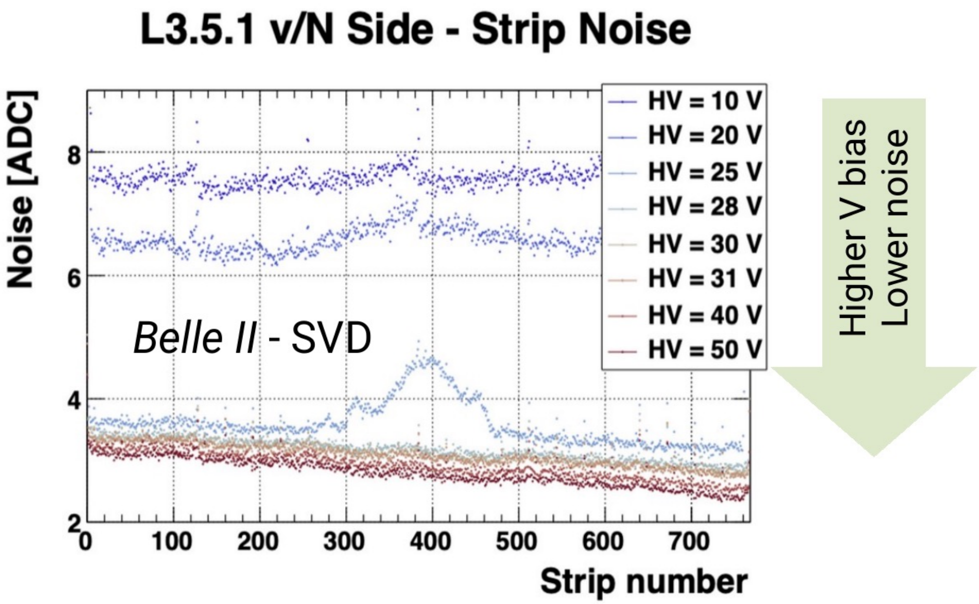


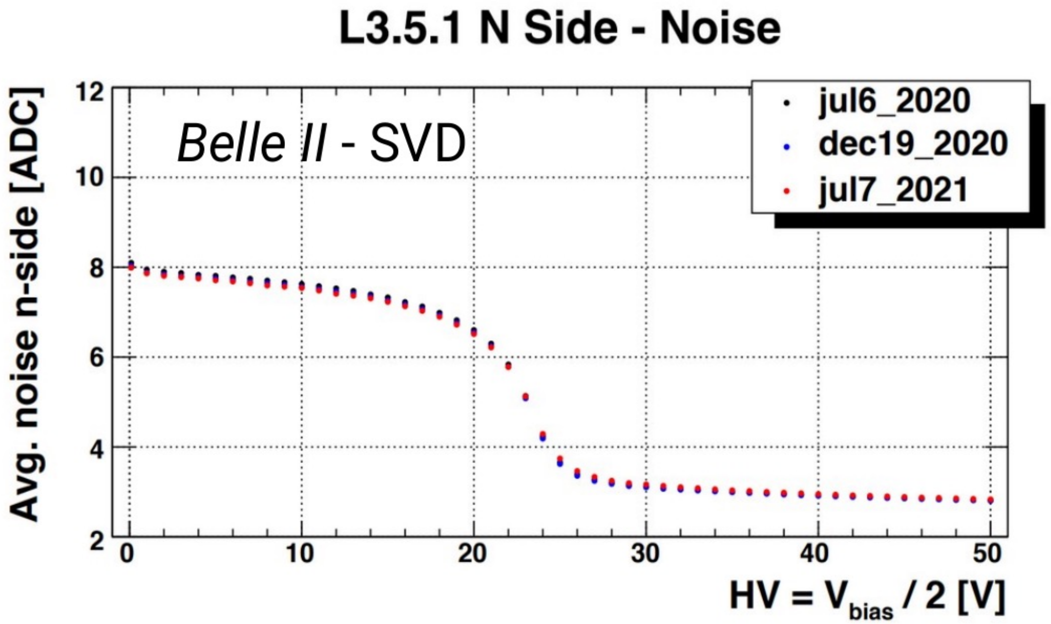
Radiation effect on depletion voltage

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



- No change in full depletion voltage observed with time
  - Consistent with low integrated neutron fluence ($\sim 1.6 \times 10^{11}$ 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
- Observed 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

Thank you!

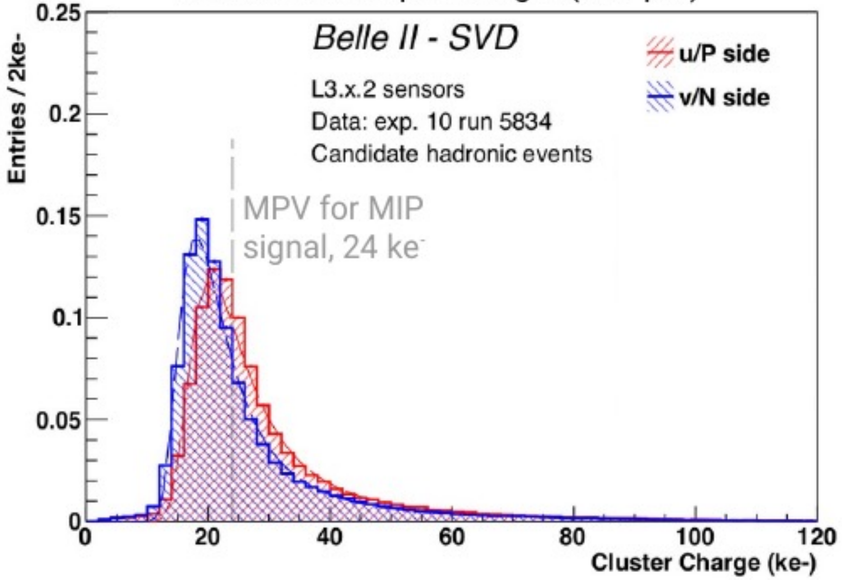
- YSF talks on Belle II SVD:
  - “Measurement of the cluster position resolution of the Belle II Silicon Vertex Detector” by Robin Leboucher
  - “Simulation of the Belle II Silicon Vertex Detector” by Mateusz Kaleta

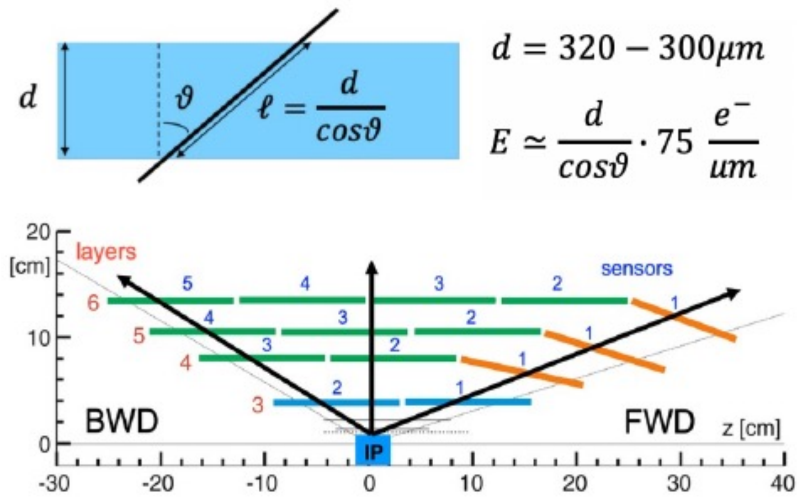
Backup

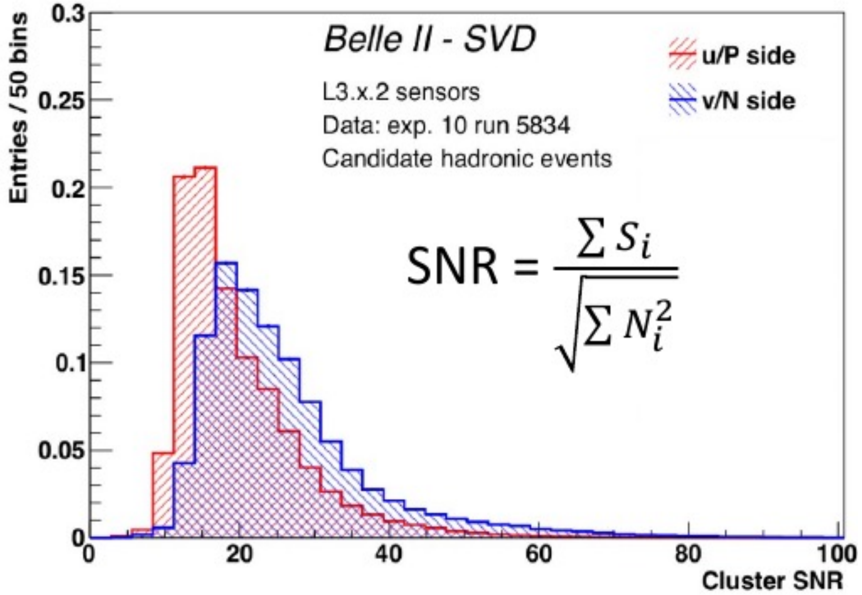
Signal charge and signal-to-noise ratio

- 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)

Normalized for path length (320 μm)







Hit-time estimation

- Neighboring strips over threshold are grouped into 'cluster'
- APV samples for strips $a_{\text{strip }0}, a_{\text{strip }2}, a_{\text{strip }2}$ are summed up:

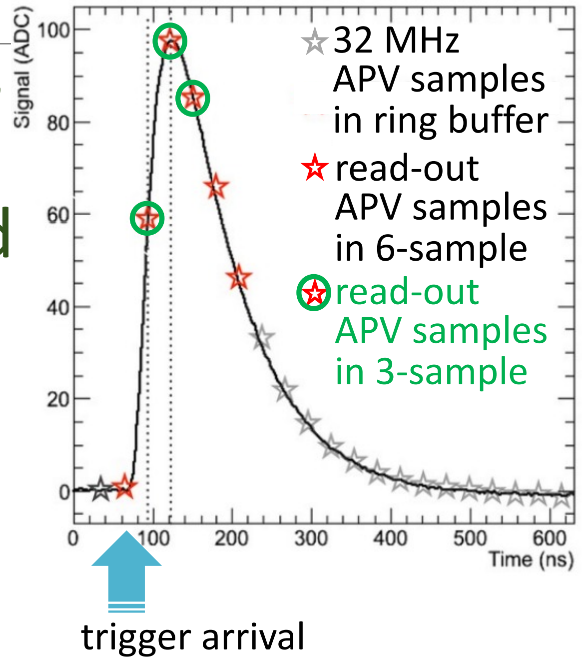
$$a_{\text{cluster }i} = \sum_{\text{strip}\in\text{cluster}} a_{\text{strip }i}$$

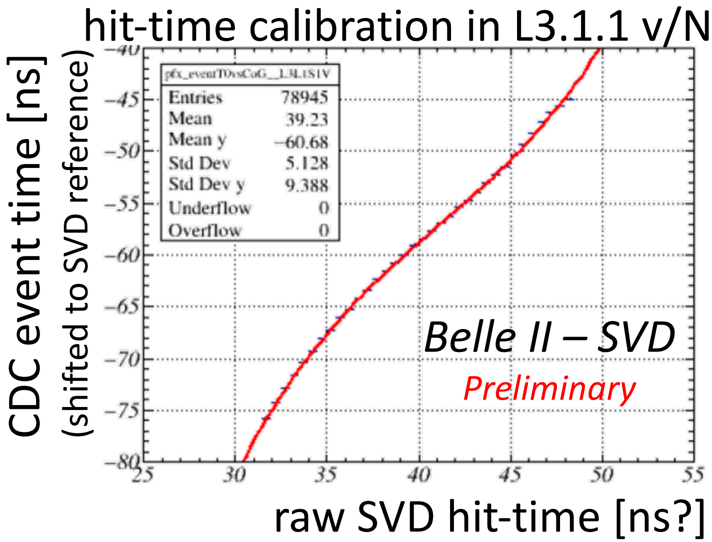
- "raw" hit-time is calculated as

$$\frac{\sum_i i\Delta t \cdot a_{\text{cluster }i}}{\sum_i a_{\text{cluster }i}},$$

where $\Delta t = 31$ ns (clock-cycle of APV25)

- this "raw" hit-time is calibrated to CDC event time
- to get SVD hit-time





3-sample acquisition mode

- efficiency
  - emulate 3-sample mode offline using trigger timing information
  - based on tracks using CDC, SVD and PXD hits
  - > 99.4% for trigger jitter less than 30 ns
- efficiency compared to 6-sample
  - 3-sample efficiency/6-sample efficiency
  - > 99.9% for trigger jitter less than 30 ns
    - almost a whole clock-cycle