
Belle II

SVD

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# The Silicon Vertex Detector of the Belle II Experiment

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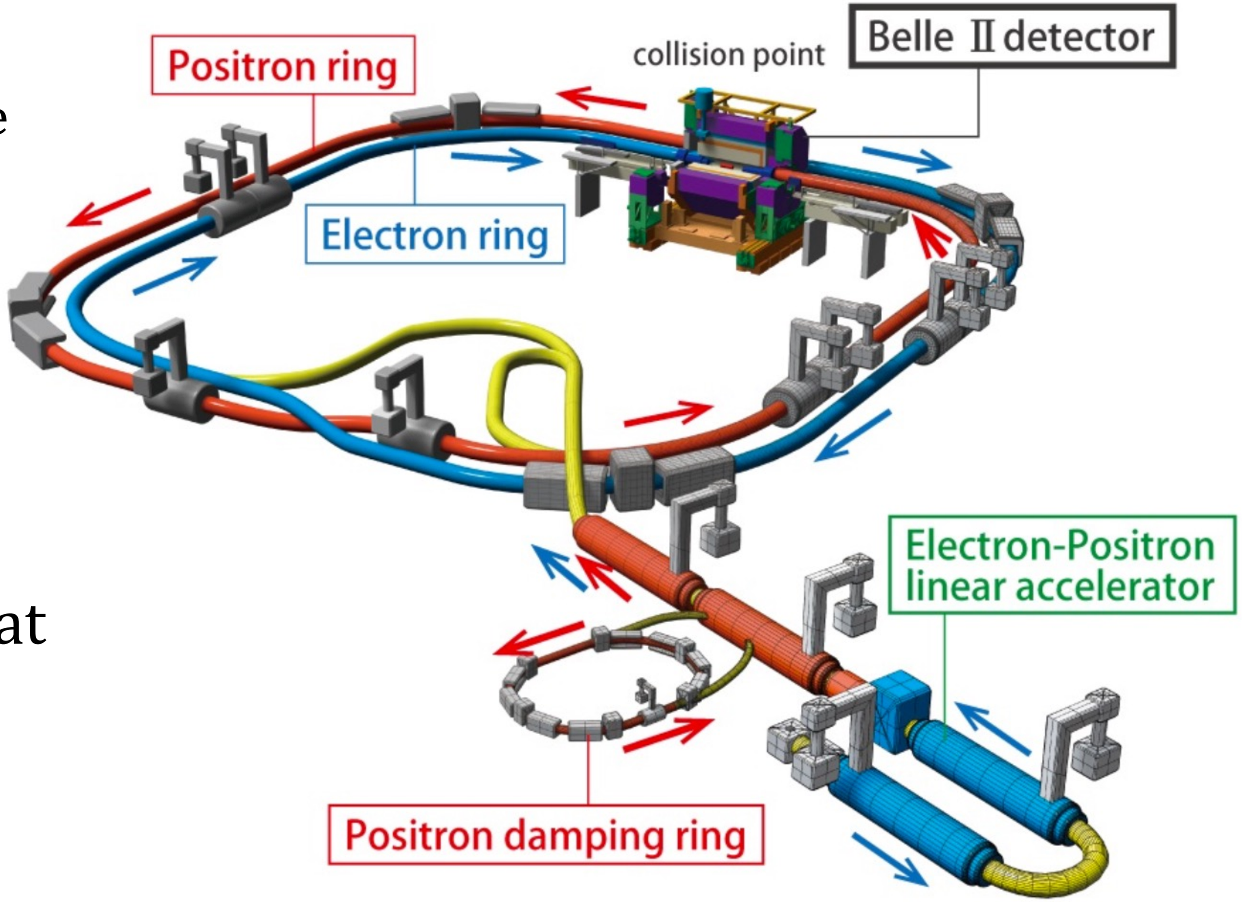
# SuperKEKB and Belle II Experiment

- SuperKEKB
  - Asymmetric $e^+e^-$ collision at $\Upsilon(4S)$ resonance

| | $\int \mathcal{L}\, dt$ | $\mathcal{L}$ |
|---|---|---|
| Target | 50 $ab^{-1}$ | $6\times10^{35}$ $cm^{-2}\, s^{-1}$ |
| Achieved | 424 $fb^{-1}$ | $4.7\times10^{34}$ $cm^{-2}\, s^{-1}$ |

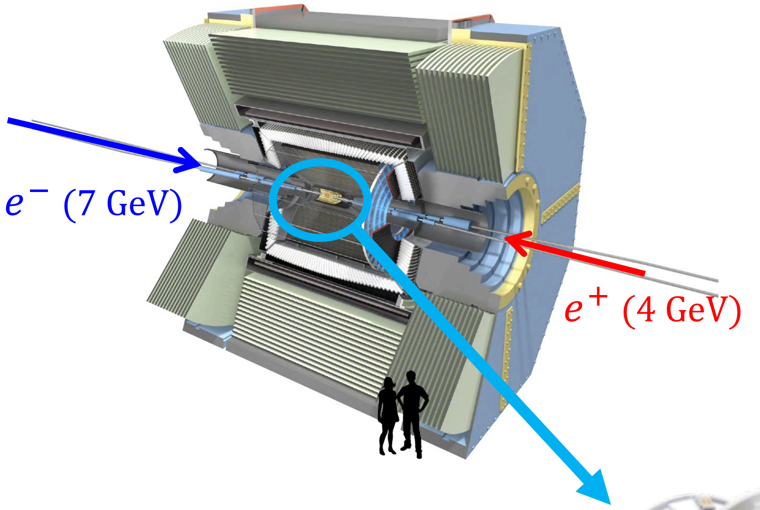
New world record!

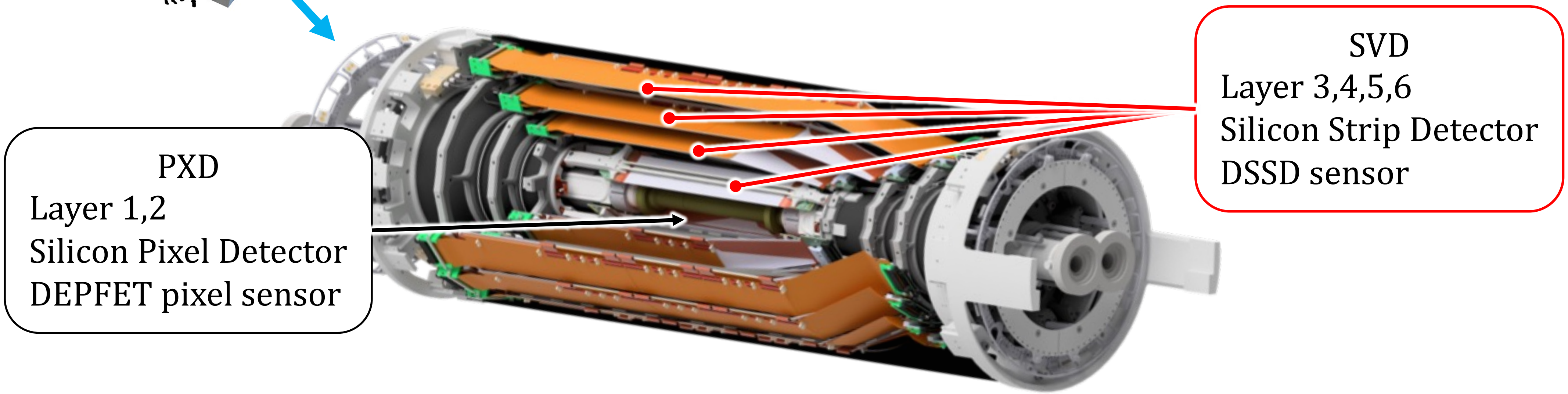
- Belle II experiment: New physics search at the luminosity frontier
- Good vertex reconstruction required for:
  - Precise physics measurement
  - Beam-induced background rejection



# Belle II vertex detector (VXD)

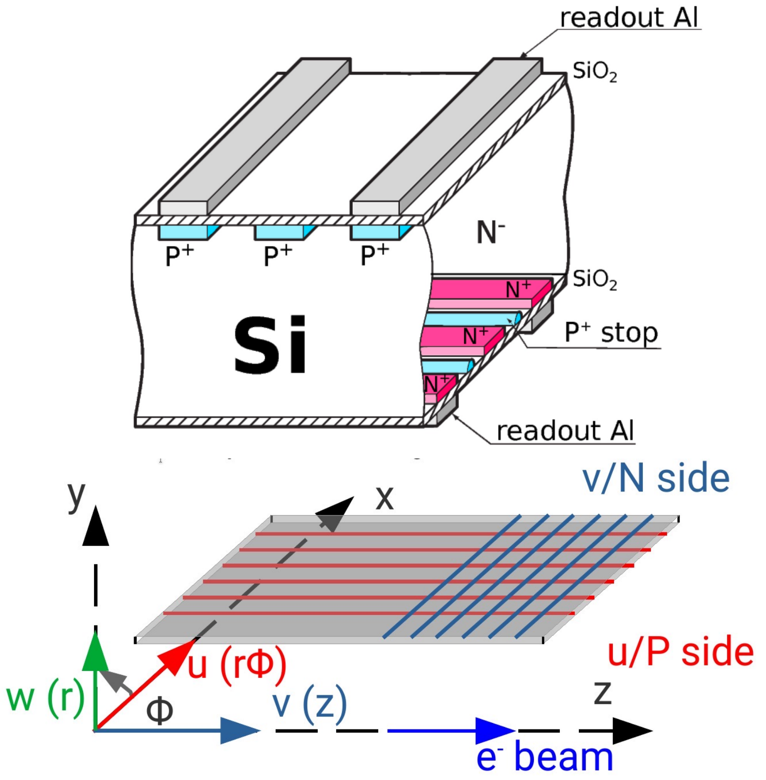
- Main features of Belle II SVD
  - Participation in vertex detection
  - Standalone tracking for low momentum tracks
  - Particle identification with $dE/dx$



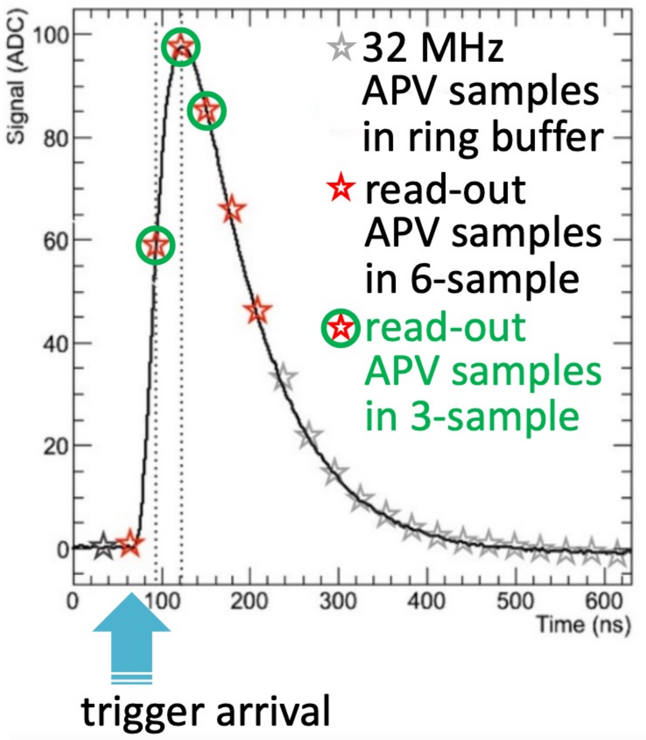



# SVD sensors and front-end ASIC

- Double-sided Silicon Strip Detector (DSSD)
  - Provide 2-D spatial information
  - Depletion voltage: 20~60 V
  - Operation voltage: 100 V

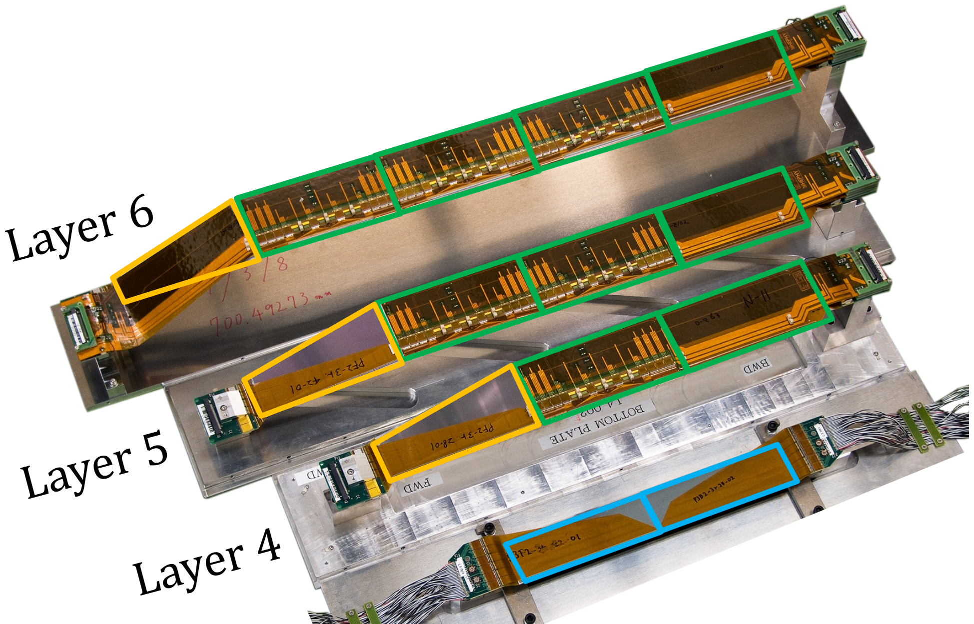



- APV25 front-end ASIC operate @ 32 MHz
  - 128 channels per chip
  - 50ns shaping time
  - Radiation hardness > 100 Mrad
  - Power consumption: 0.4 W/chip

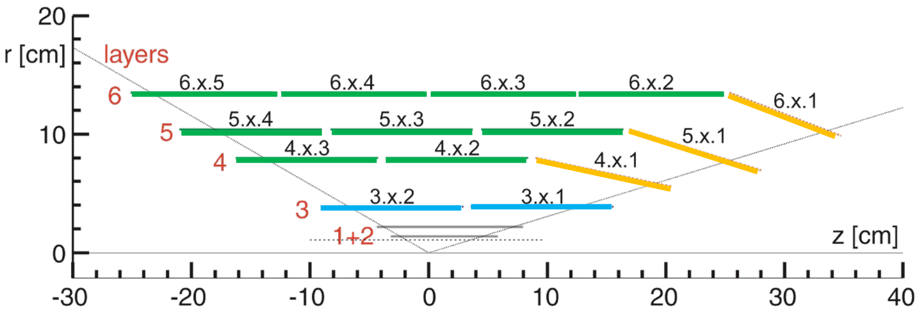


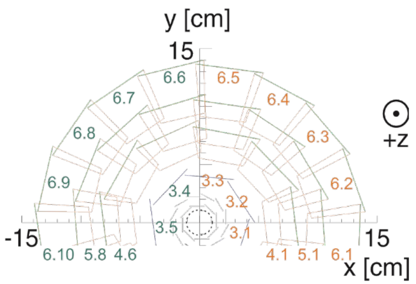

- 6 subsequent samples readout
- 3/6 mixed acquisition mode prepared for high luminosity runs

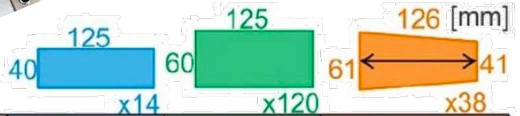
# SVD structure




- DSSD sensors and APV25 ASICs are grouped into ladders
- 172 sensors, 1.2 m$^2$ sensor area, 224k readout strips
- Low material budget: 0.7% $X_0$/layer



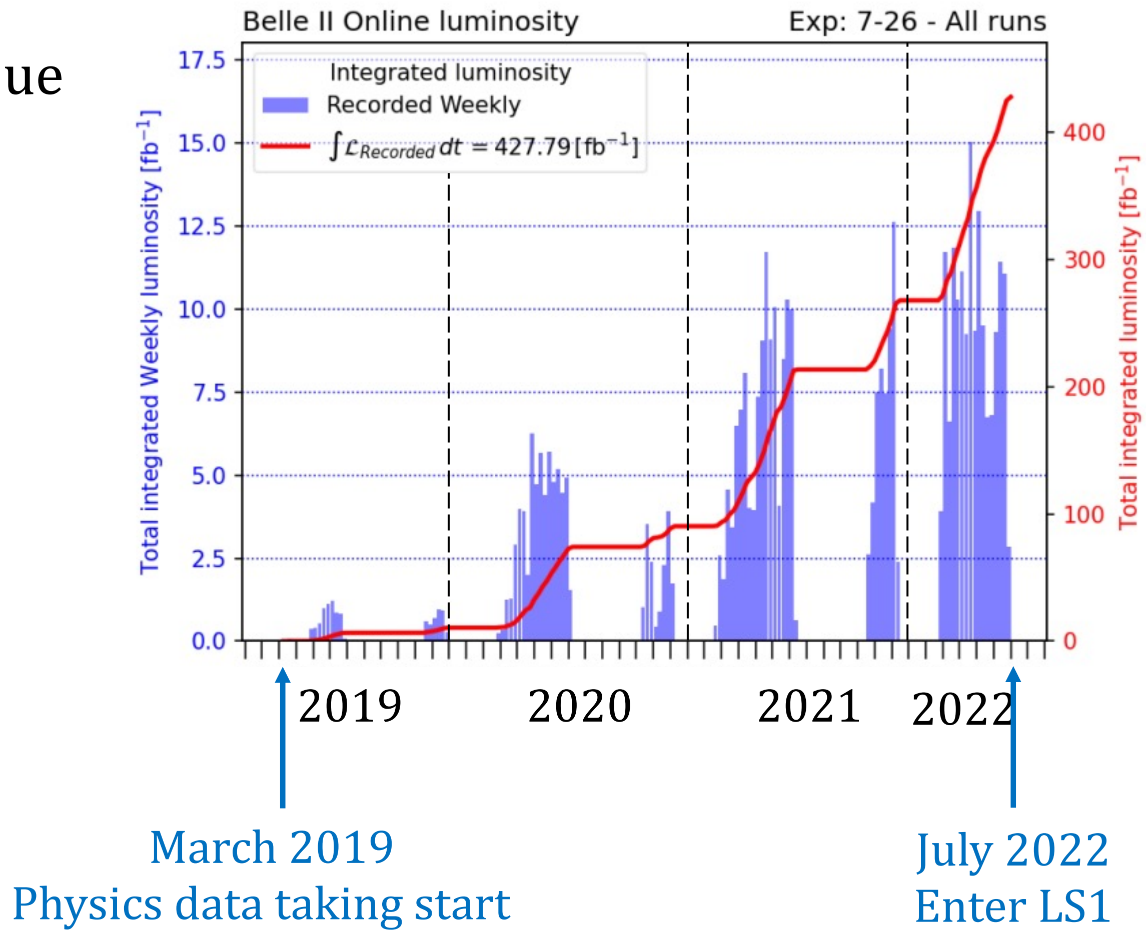

| | Small | Large | Trapezoidal |
|---|---|---|---|
| # of p-strips* | 768 | 768 | 768 |
| p-strip pitch* | 50 µm | 75 µm | 50-75 µm |
| # of n-strips* | 768 | 512 | 512 |
| n-strip pitch* | 160 µm | 240 µm | 240 µm |
| thickness | 320 µm | 320 µm | 300 µm |
| manufacturer | HPK | | Micron |

*readout strips – one floating strip on both sides

| Layer | Ladders | Sensors /ladder | Radius [mm] |
|---|---|---|---|
| L3 | 7 | 2 | 39 |
| L4 | 10 | 3 | 80 |
| L5 | 12 | 4 | 104 |
| L6 | 16 | 5 | 135 |

# SVD operation

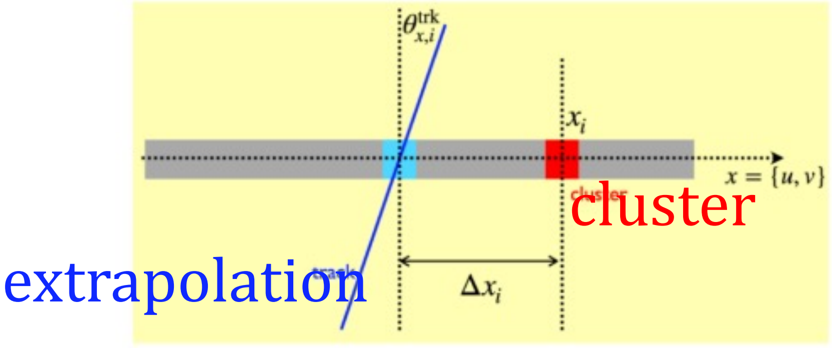
- Smooth and reliable operation without major issue
  - So far total masked strips < 1%
  - Stable environment and calibration constants evolution consistent with expectation
- Excellent detector performance!
  - Large hit efficiency (> 99%), precise position resolution and good signal-to-noise ratio (SNR)
- Background effects are well under control
- Enter Long Shutdown 1 (LS1) since July 2022
  - VXD upgrade with new PXD + current SVD
  - Planning to resume data taking from December 2023



# Highlights of the SVD performance

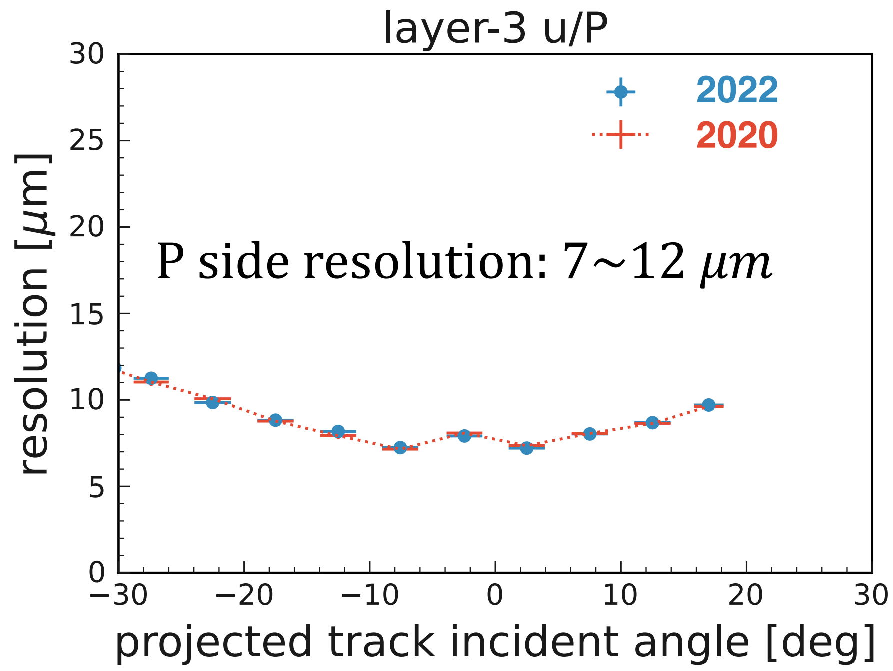
# Position resolution

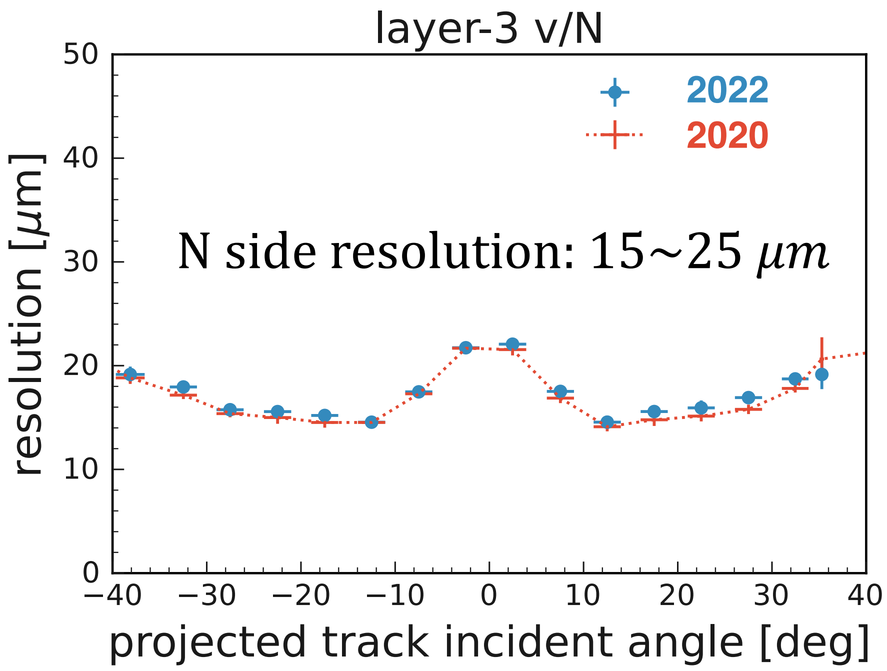
- Estimated from residual of cluster position with respect to unbiassed track extrapolation in $e^+e^- \to \mu^+\mu^-$ events
- Good resolution in agreement with expectations
- Good stability during operation



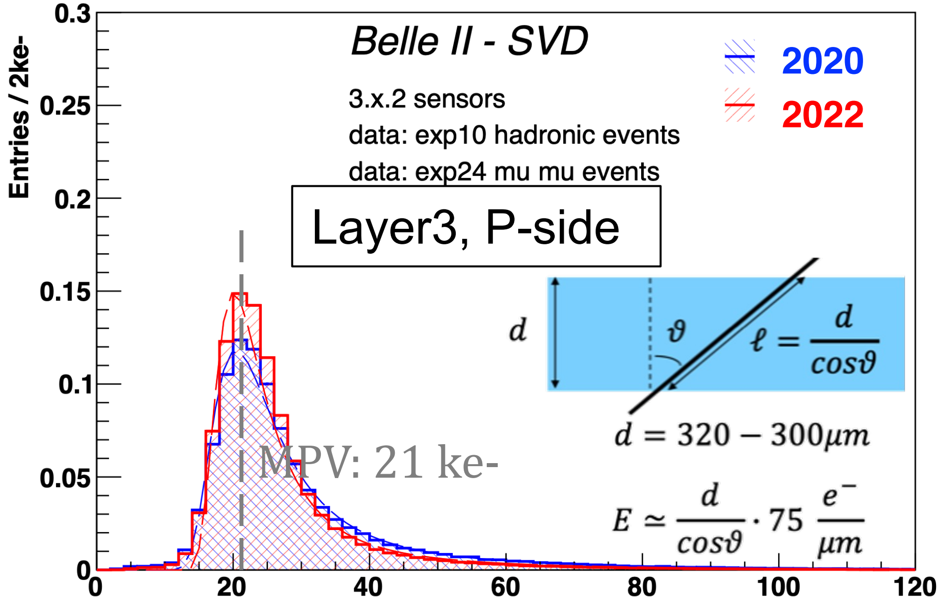

$$\sigma_x = \sqrt{\left\langle (\Delta x_i)^2 - \left(\sigma^{trk}_{x,i}\right)^2 \right\rangle}$$

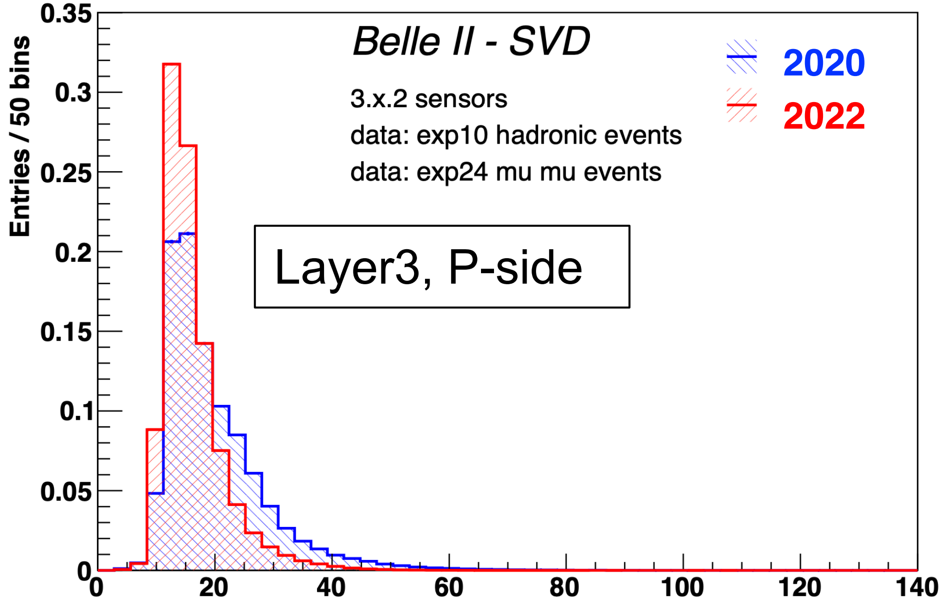
$\sigma^{trk}_{x,i}$ = unbiased track position error



# Cluster charge & SNR



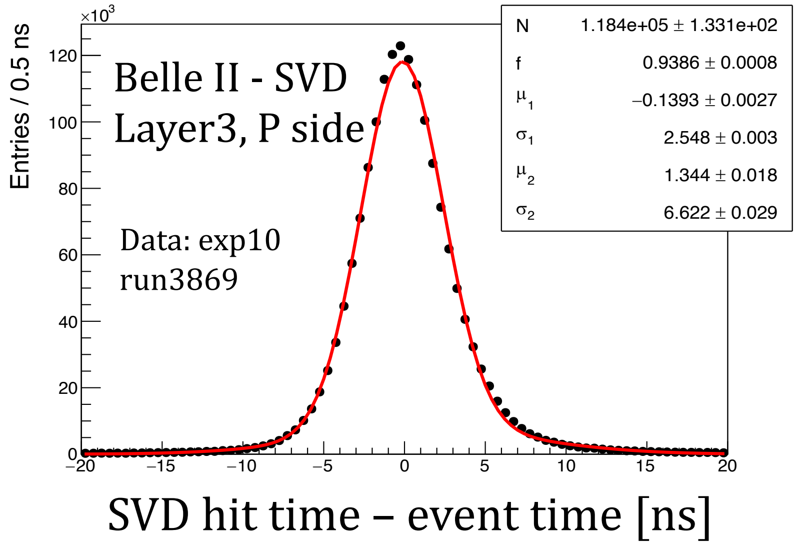

$$\text{ClusterSNR} = \frac{\sum^{\text{strips}} \text{Charge}}{\sqrt{\sum^{\text{strips}} \text{Noise}^2}}$$

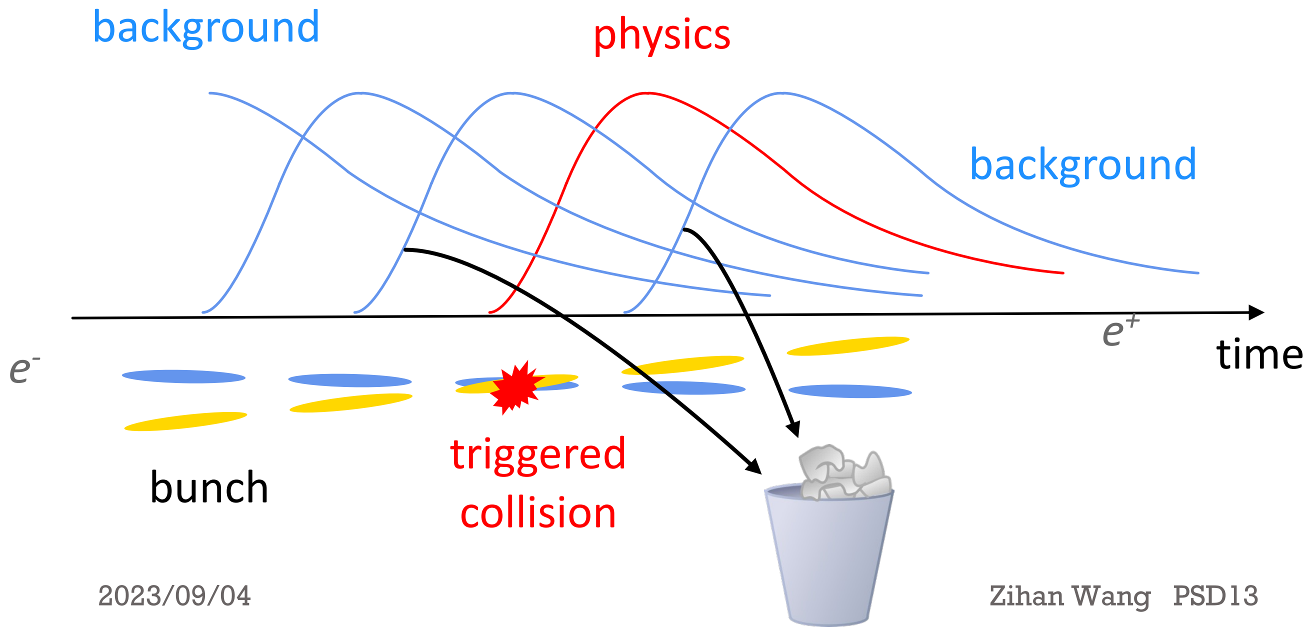
- Good stability of cluster charge and SNR from 2020 to 2022
  - Similar cluster charge, normalized to track length
  - Small SNR decrease due to increased noise from radiation damage
  - Still good SNR for all sensors, MPV ranging from 13~30 depending on sensor position and side

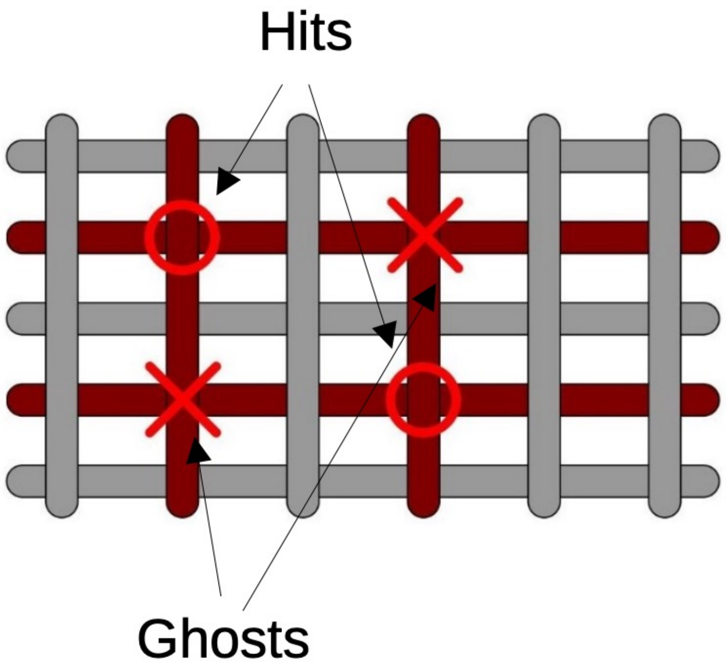
# Hit time

- Excellent hit time resolution (< 3 ns) w.r.t event time
  - SuperKEKB bunch spacing: ~ 6 ns
  - Background hit interval ~ 100 ns
- Hit time selection can
  - Reject off-time beam background hits
  - Reduce wrong combination of P and N side clusters

SVD hit time resolution (clusters on track)



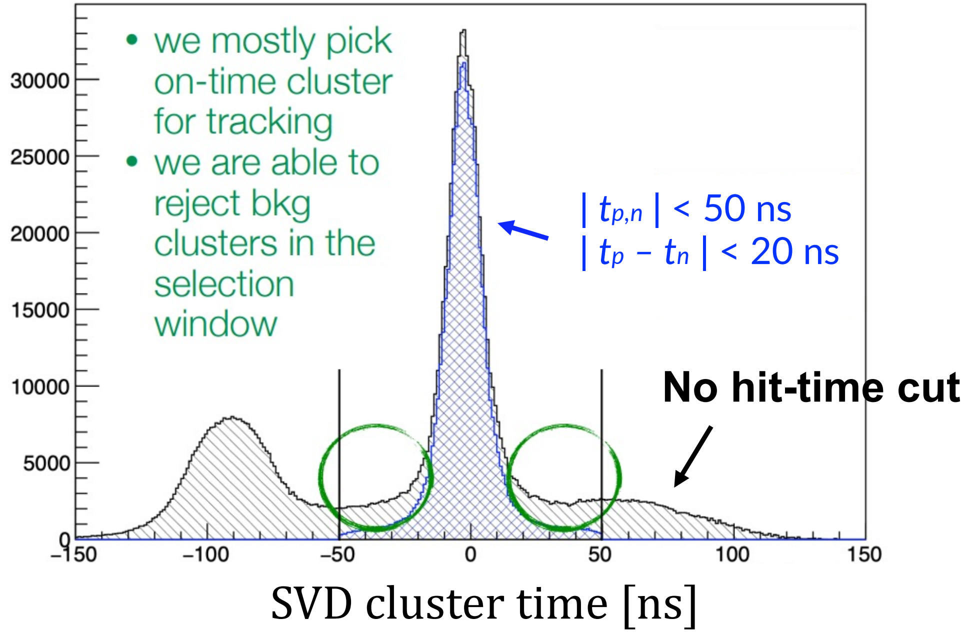



# Background rejection with hit time

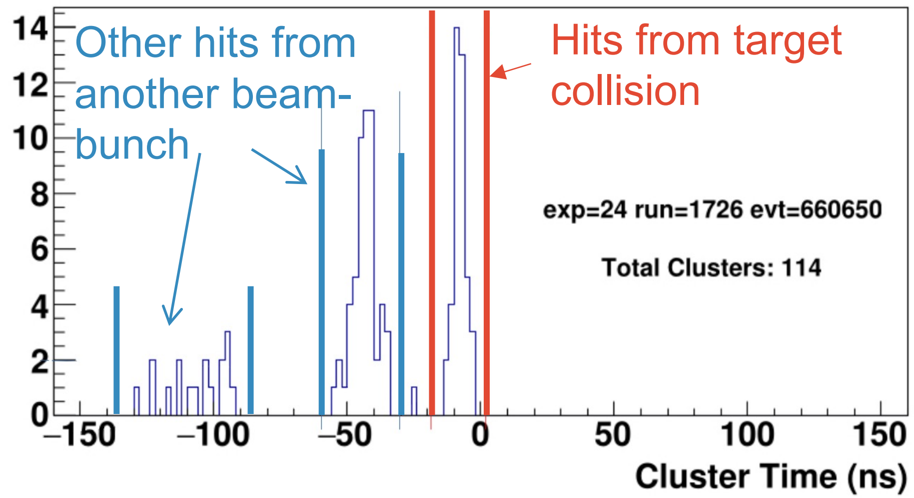
## Selection on the SVD hit-time

- Selection based on SVD hit-time and time difference between P and N side
- Reject 50% off-time background hits and keep 99% tracking efficiency
- Allow to set the hit occupancy limit at layer 3 to **4.7%** without tracking performance degradation



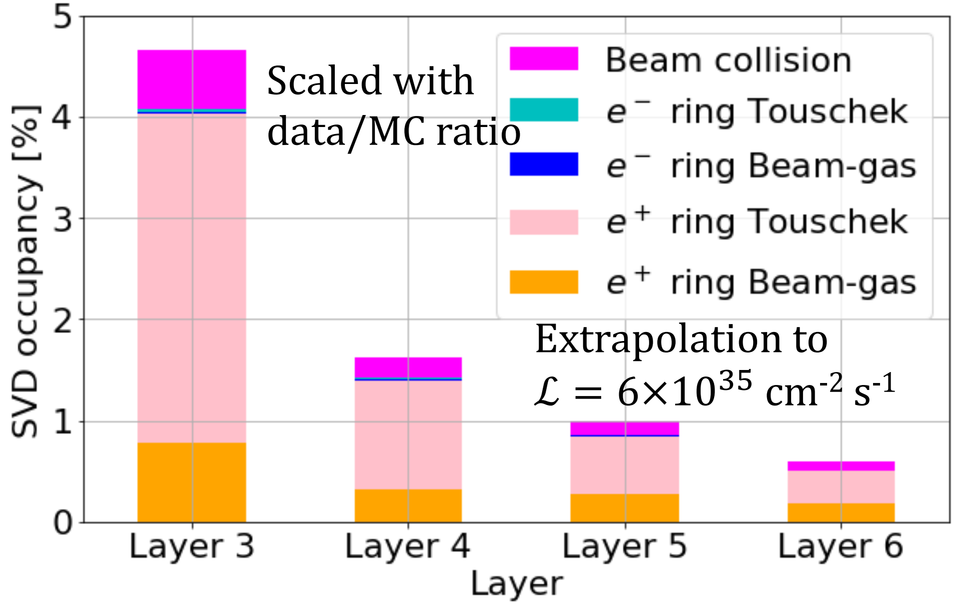

## Cluster grouping

- Group clusters coming from the same collision using hit-time event-by-event
- Use clusters from the same group for tracking
- With track time selection, further reduce the fake rate by 15%
- Increase the hit occupancy limit to **6%**



# Beam background effects on the SVD

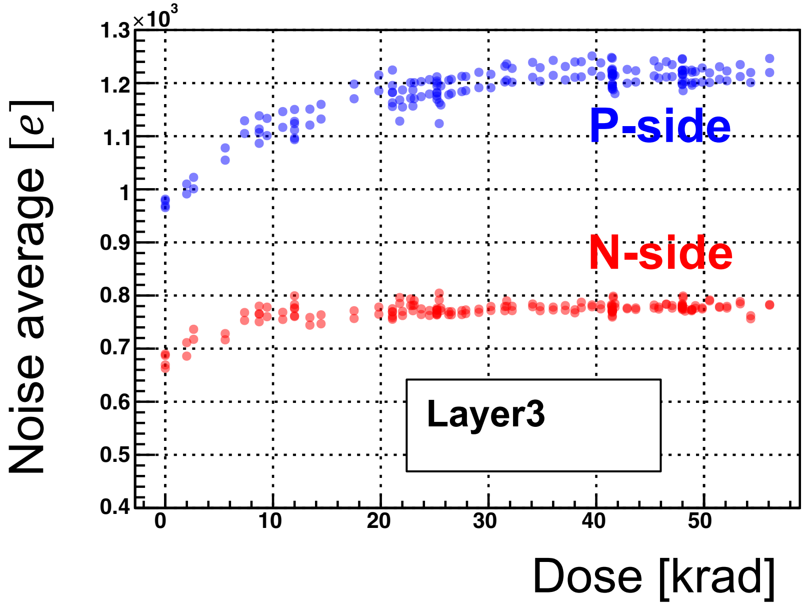
# Hit occupancy




- High occupancy could degrade tracking performance
- Current background level on layer 3 is less than 0.5% and well under control
- 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
- The small safety margin motivates vertex detector upgrade
  - See Jerome's talk for one of the upgrade options

# Radiation effects (1)

- Can deteriorate sensor performance increasing strip noise, leakage current & changing depletion voltage

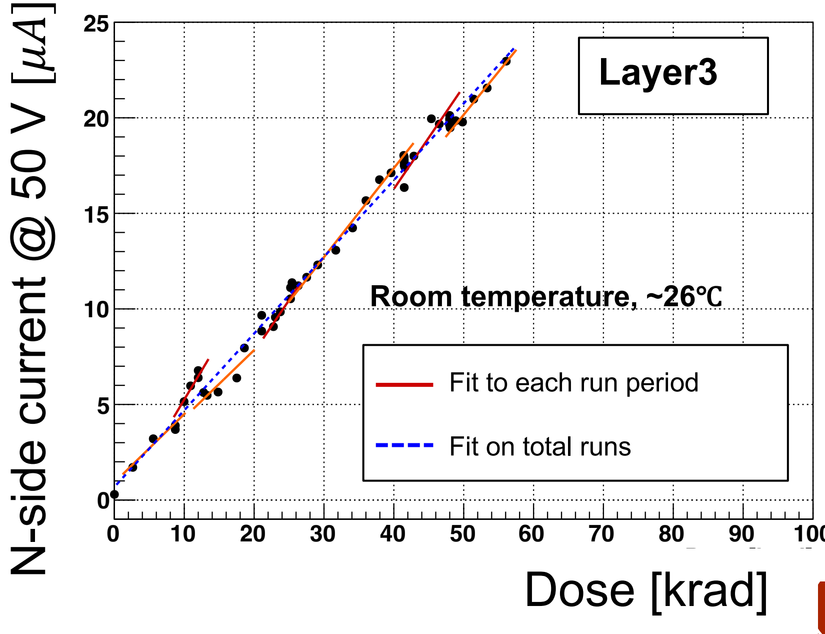



## Strip noise

- Noise increase < 20% (30%) for N(P) side
  - Due to fixed oxide charges that increase interstrip capacitance
  - Expect to saturate

## Leakage current

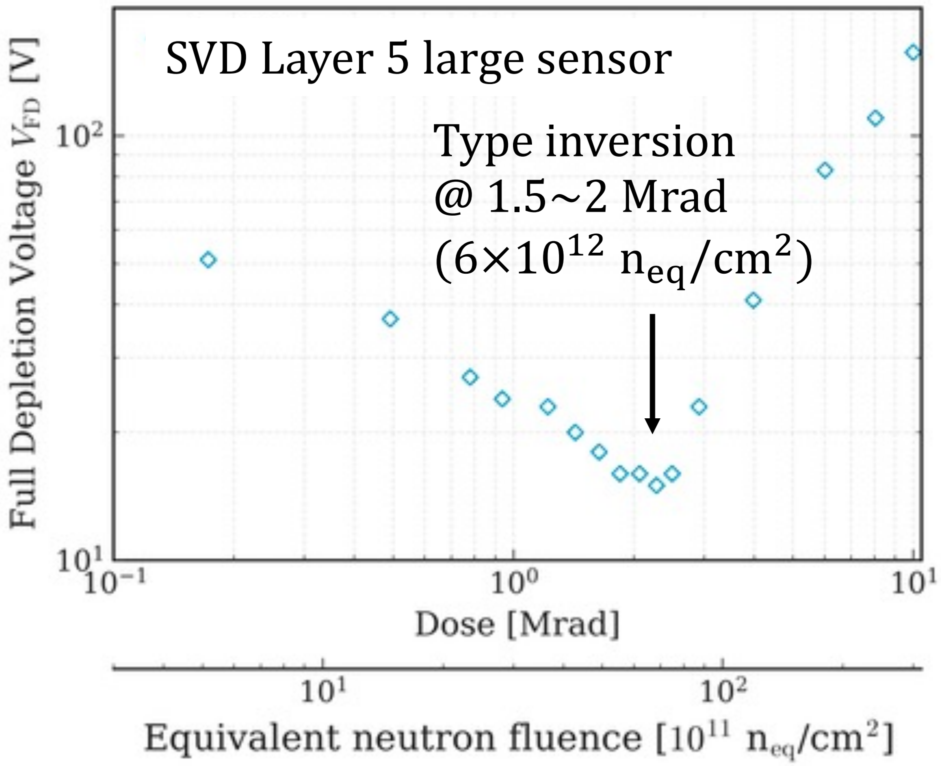
- Contribution to noise negligible now due to short APV25 shaping time
- Linear increase due to bulk damage by NIEL
- After 6 Mrad dose strip noise contribution from leakage current would reduce the Layer3 SNR < 10



# Radiation effects (2)

**Depletion voltage**

- Irradiation campaign up to 10 Mrad of a layer 5 sensor @ Tohoku Univ. in July 2022
  - 90 MeV $e^-$ beam
- Confirmed SVD sensors work well even after type inversion
- Good charge collection efficiency confirmed with Sr90 source measurement

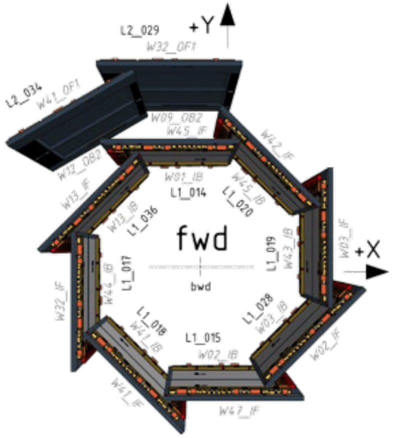


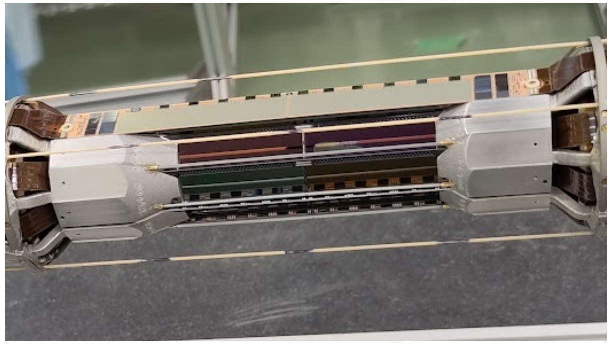

- Background extrapolation gives 0.35 Mrad/yr ($8\times10^{11}$ $n_{eq}/cm^2/yr$) of radiation dose (NIEL)
- SVD has good safety margin of 2 even after 10 years' operation at target luminosity, considering the 6 Mrad limit

# VXD reinstallation during Long Shutdown 1

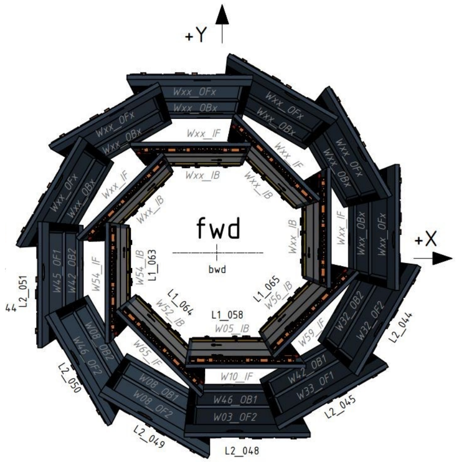
# VXD re-installation

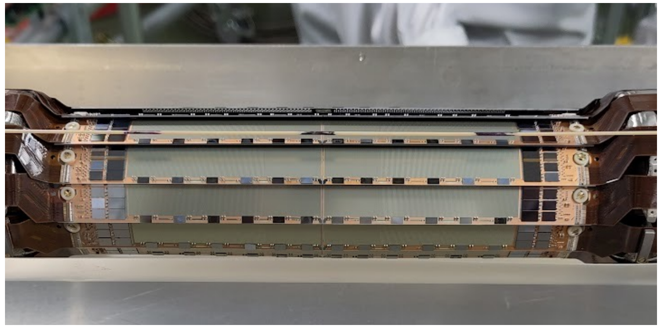
PXD1



PXD2



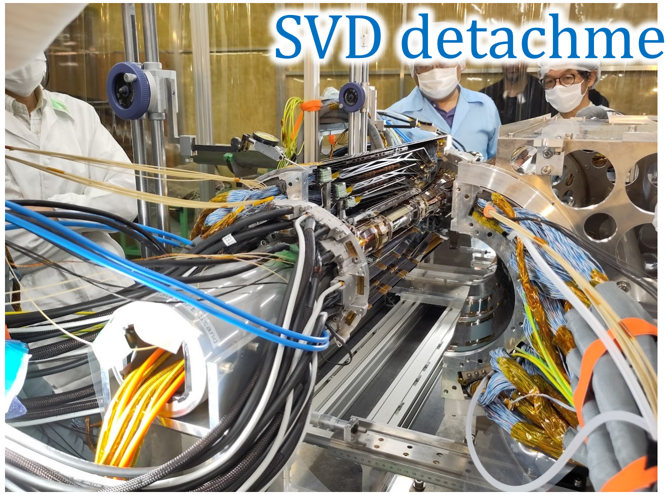



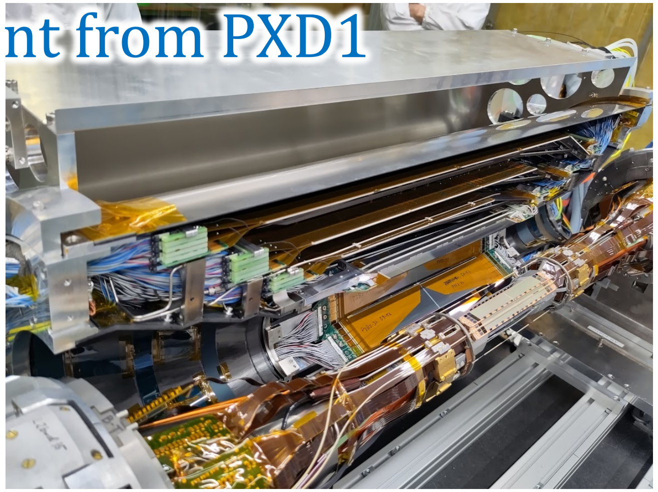
- Replace PXD1 with PXD2 whose 2nd layer is fully installed
- Intense hardware activities on the SVD for the VXD uninstallation and reinstallation

May 10 → May 16~17

VXD extraction

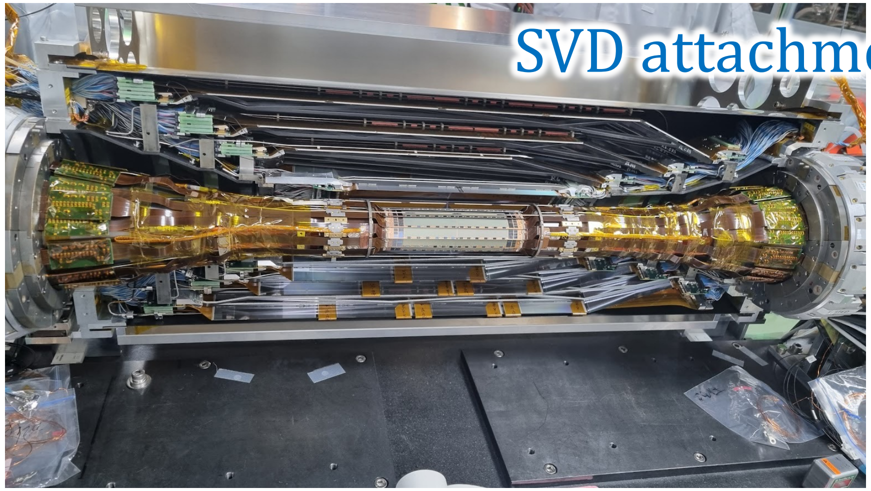
SVD detachment from PXD1





June 20~21 → July 28

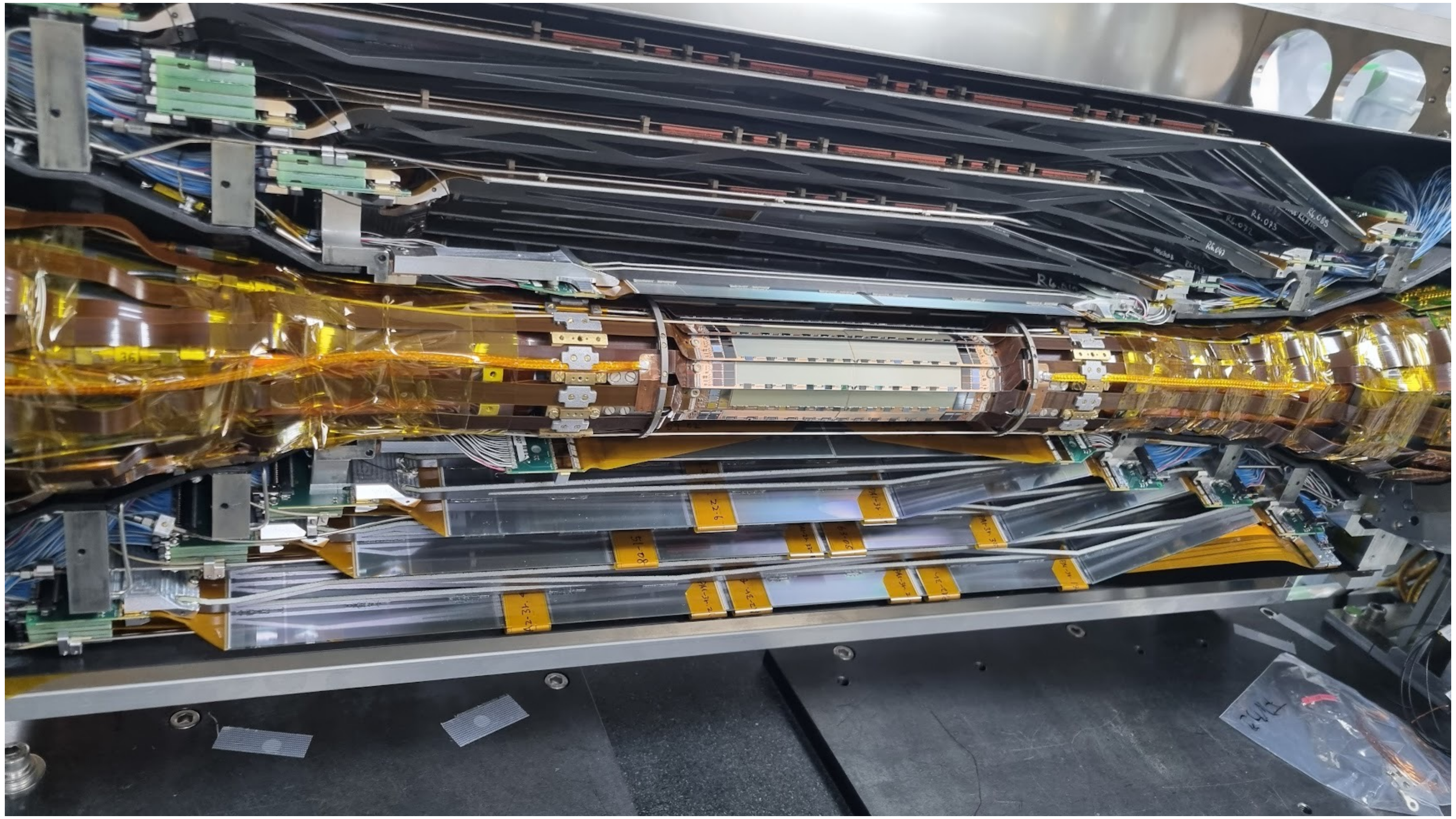
SVD attachment to PXD2



New VXD installed in Belle II

# VXD re-installation

- VXD now re-assembled in Belle II successfully
- No problems found in during new VXD commissioning in the clean room
- Functional tests & commissioning with cosmic in September



# Summary

- SVD has been taking data in Belle II since March 2019 with high quality
  - Excellent performance as expected
  - Effects on radiation damage observed, but no influence on performance yet

- Background extrapolation to target luminosity shows radiation dose is within safety margin, but hit occupancy could exceed our limit
  - VXD upgrade is under discussion

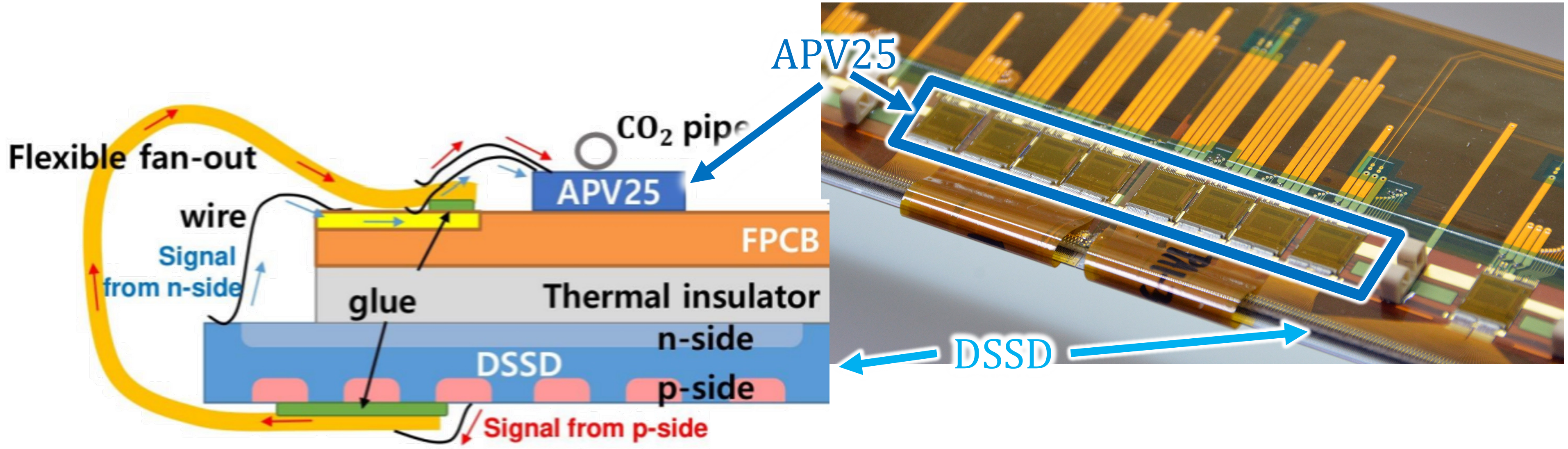
- During the Long Shutdown 1, new VXD with the complete PXD2 and the current SVD is re-assembled
  - Commissioning with cosmic in September
  - Plan to resume data taking in December

- SVD technical paper:
  - https://iopscience.iop.org/article/10.1088/1748-0221/17/11/P11042/pdf

# BACK UP

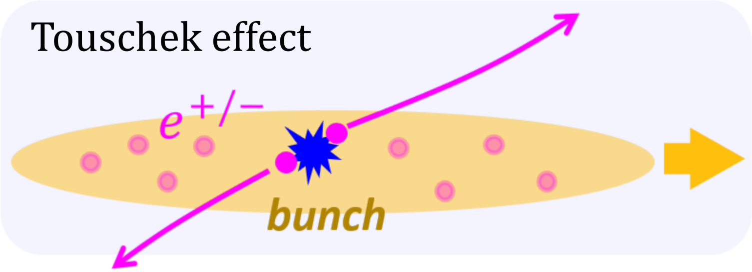
# Chip-on-sensor concept

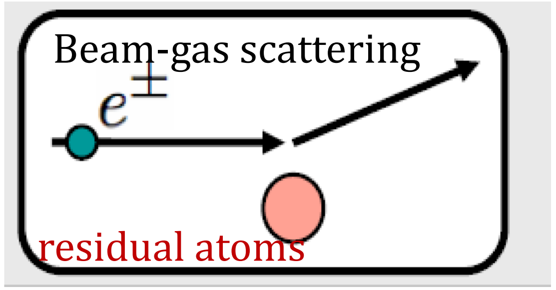
- Origami chip-on-sensor concept:
  - Shorter signal propagation length to reduce capacitance and noise
  - Two-phase $CO_2$ (-20 ℃ ) cooling



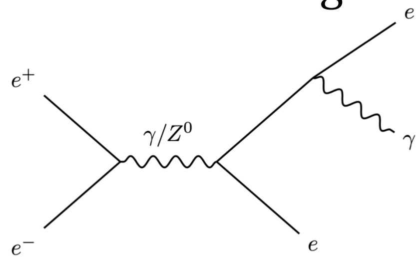
# Background sources

Single-beam induced background




Collision induced background

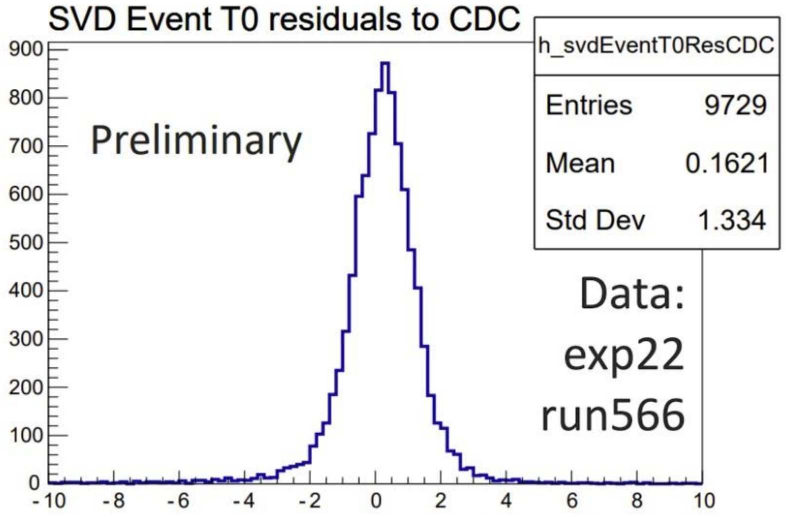



Radiative Bhabha

- Off-orbit particles hits beam pipe or detector materials and create showers
- **Radiation damage**
  - increasing leakage current, strip noise & changing depletion voltage
- **High instantaneous hit occupancy**
  - can degrade tracking performance

# SVD event time

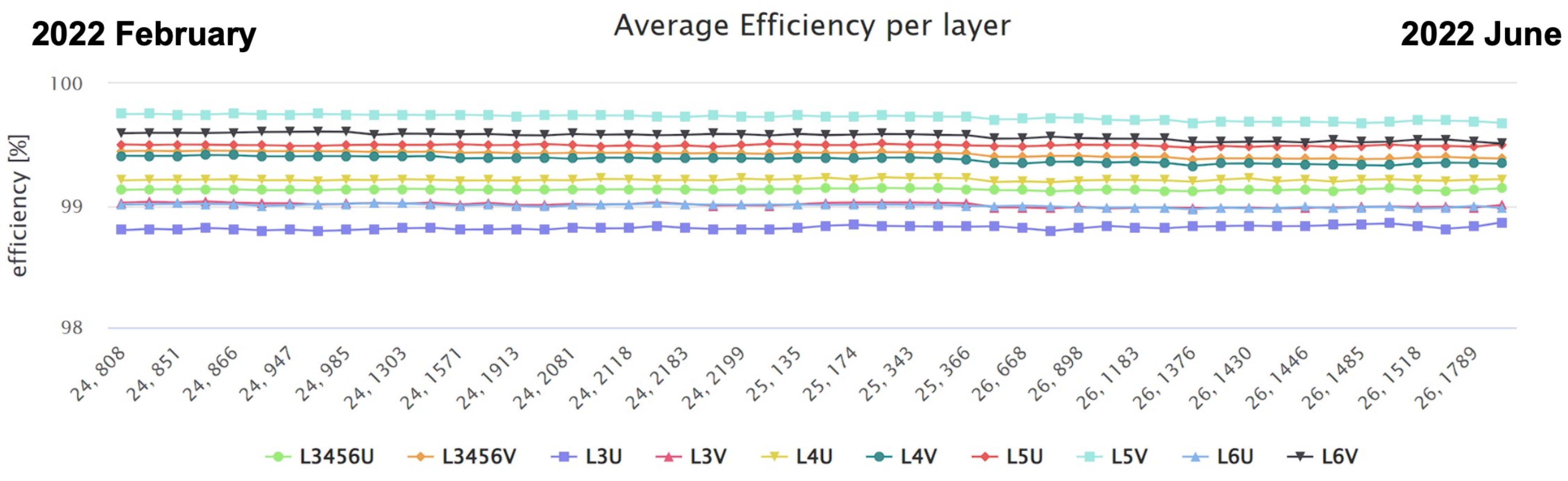
- SVD Event time computed from SVD clusters associated to tracks
  - Same resolution (~ 1 ns) but 2000 times faster computation w.r.t. the one computed with CDC
  - Allowing to speed up the online reconstruction and therefore cope with the higher luminosity operation




SVD event time – CDC event time [ns]

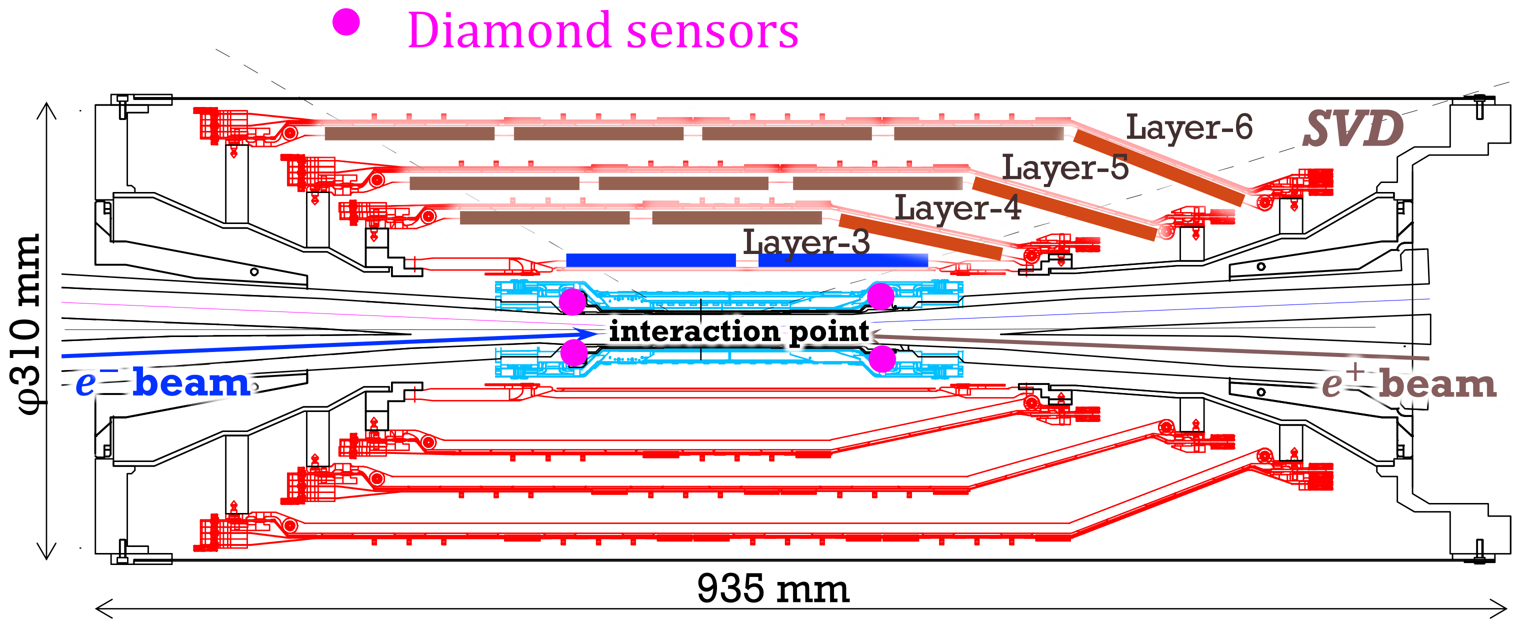
# Efficiency

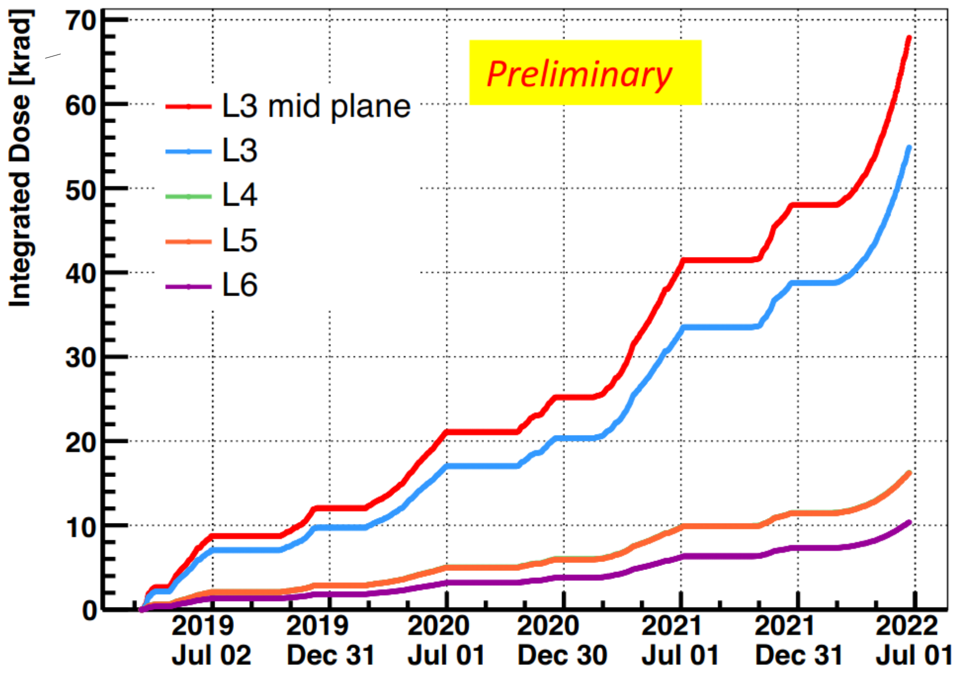
- Hit efficiency is very high and stable in time



# Radiation dose

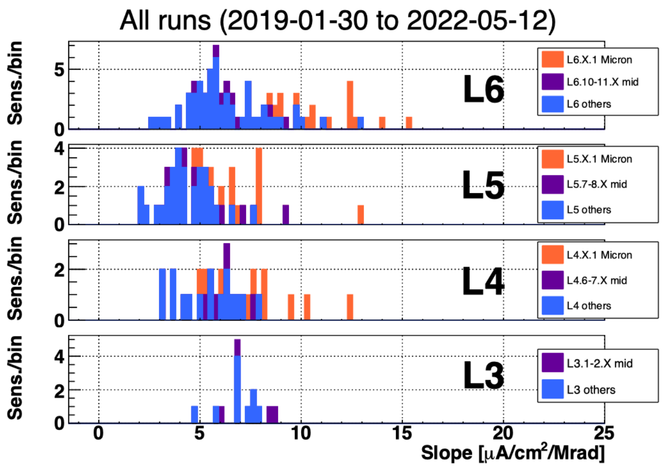
- Constantly monitored using diamond sensors

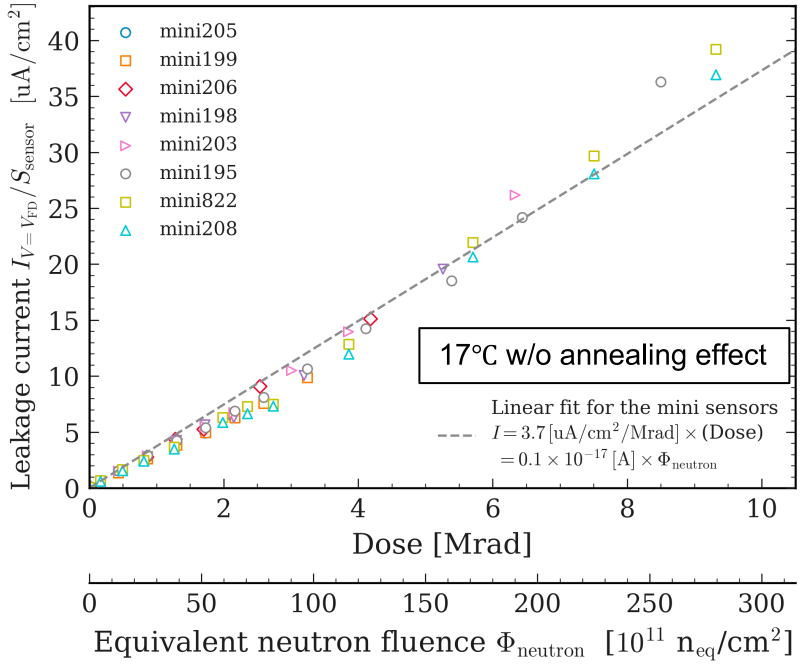


# Leakage current

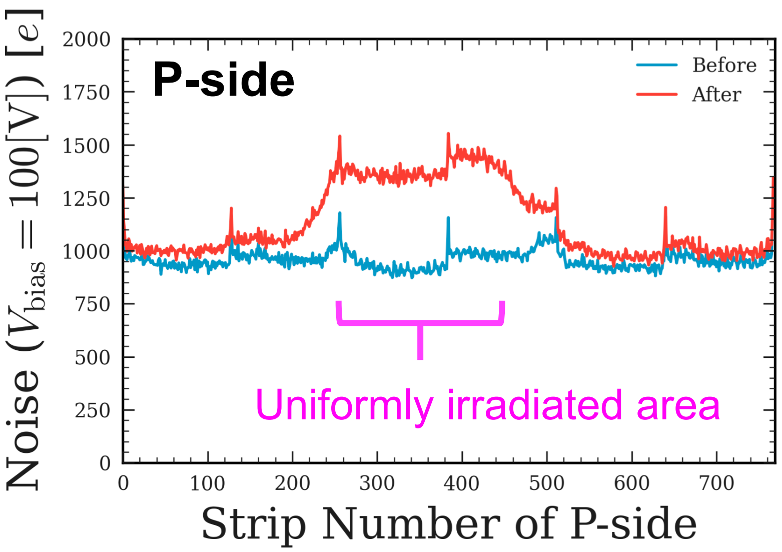
- Damage constant [μA/cm$^2$/Mrad] ranges from 4~8 for sensors operated at different temperature 10~26 °C
- Irradiation campaign gives 2.2 for sensors radiated at 24 °C after annealing
- Babar sensors operated at 27 °C has a damage constant of 2
  - NIMA 729, 615-701, 2013
- Good consistence for different measurement

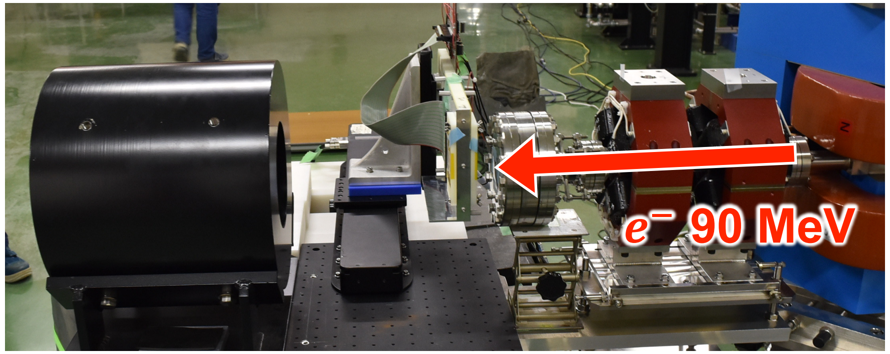


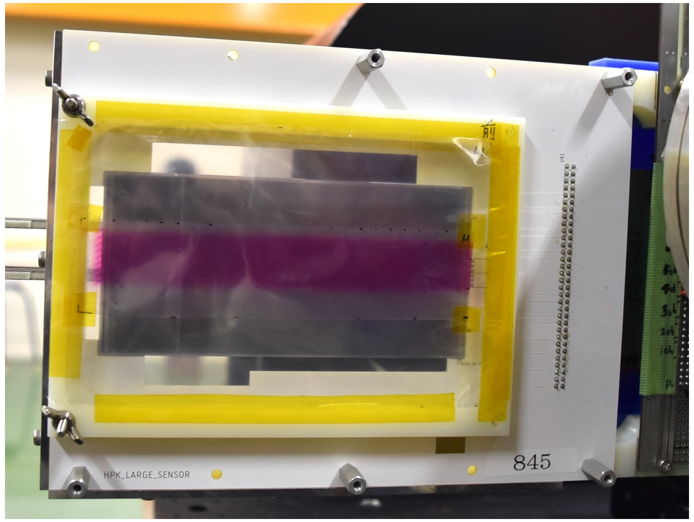
# Strip noise

- In the irradiation of 10 Mrad with annealing, **noise increase is ~40%**




Uniformly irradiated area



# Depletion voltage