Belle II

SVD

東京大学
THE UNIVERSITY OF TOKYO

The Silicon Vertex Detector of the Belle II Experiment

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2023.09.04

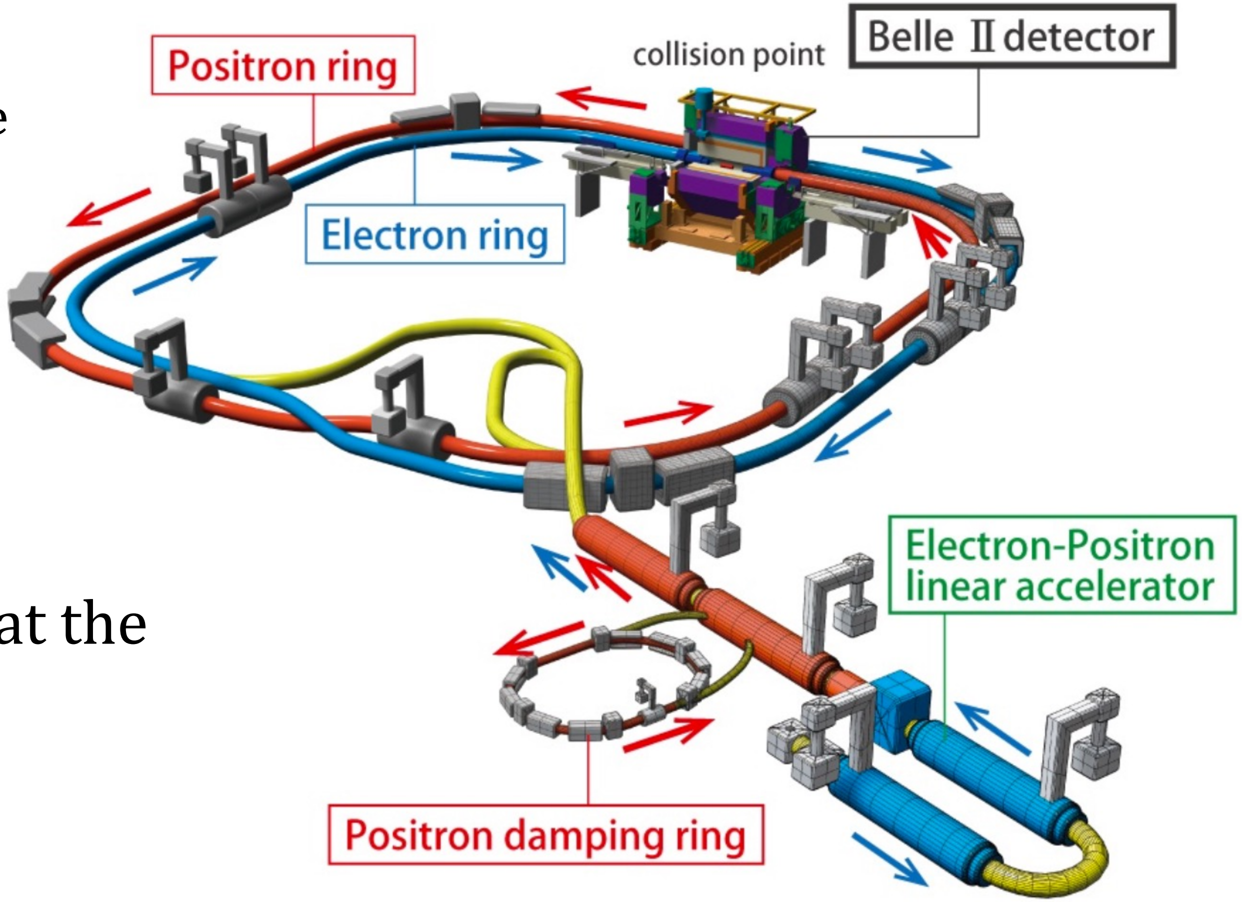
SuperKEKB and Belle II Experiment

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

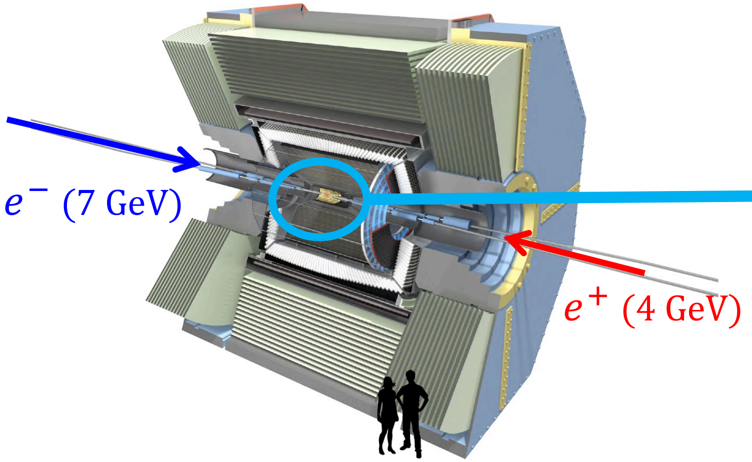
	$\int \mathcal{L}\, dt$	$\mathcal{L}$
Target	50 ab^{-1}	6×10^{35} $cm^{-2}\,s^{-1}$
Achieved	424 fb^{-1}	4.7×10^{34} $cm^{-2}\,s^{-1}$

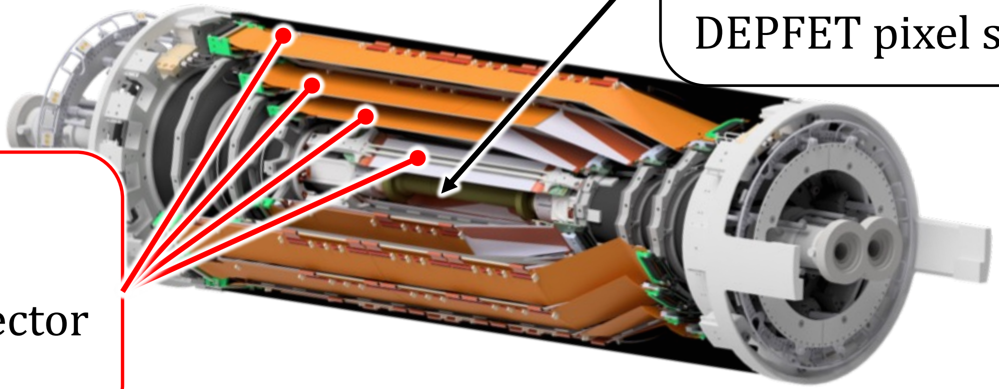
New world record!

- 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)

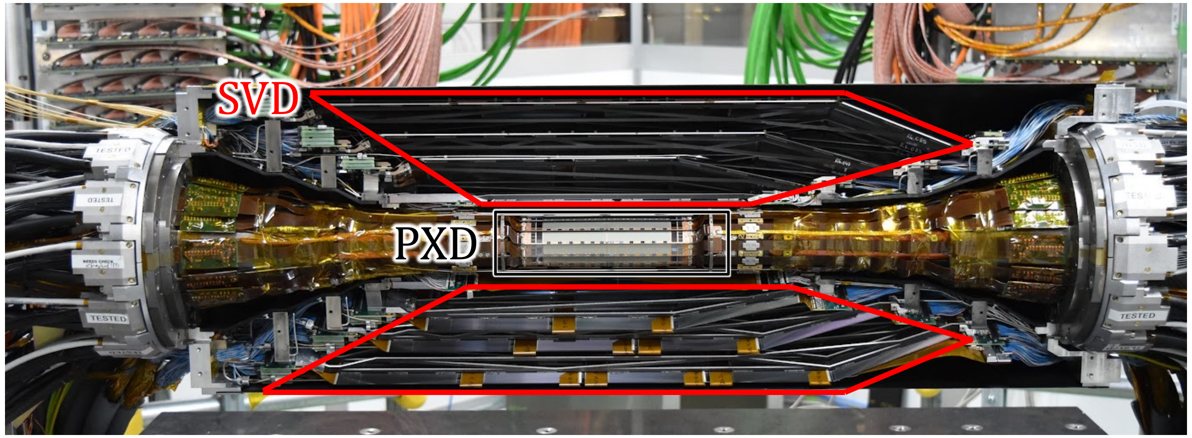




PXD
Layer 1,2
Silicon Pixel Detector
DEPFET pixel sensor

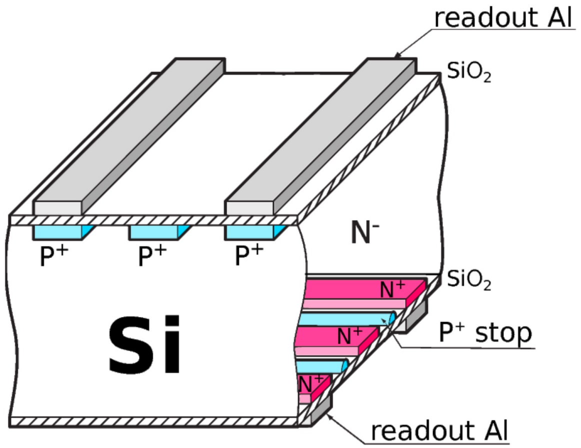
SVD
Layer 3,4,5,6
Silicon Strip Detector
DSSD sensor

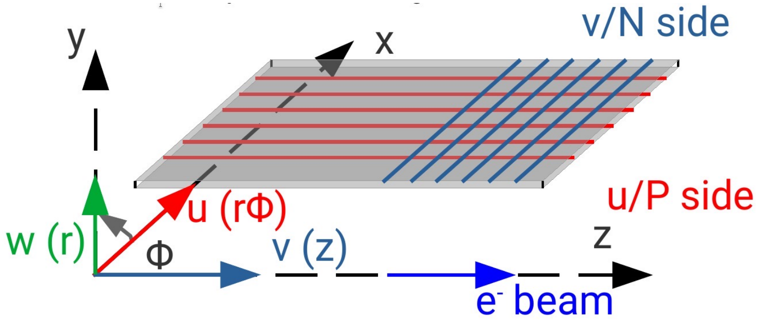
- Main features of Belle II SVD
  - Participation in vertex detection
  - Standalone tracking for low momentum tracks
  - Particle identification with dE/dx
- Operate at high background environment, for SVD innermost layer:
  - Hit rate ~ 5 $\mathrm{MHz/cm^2}$
  - Ionization dose ~ 0.35 Mrad/yr



SVD sensors and front-end ASIC

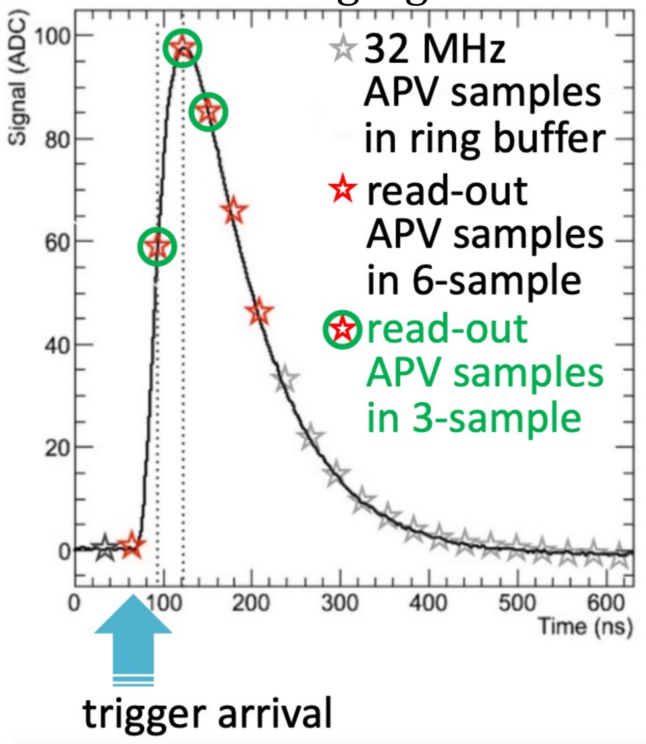
- Double-sided Silicon Strip Detector (DSSD)
  - Provide 2-D spatial information
  - Depletion voltage: 20~60 V
  - Operation voltage: 100 V





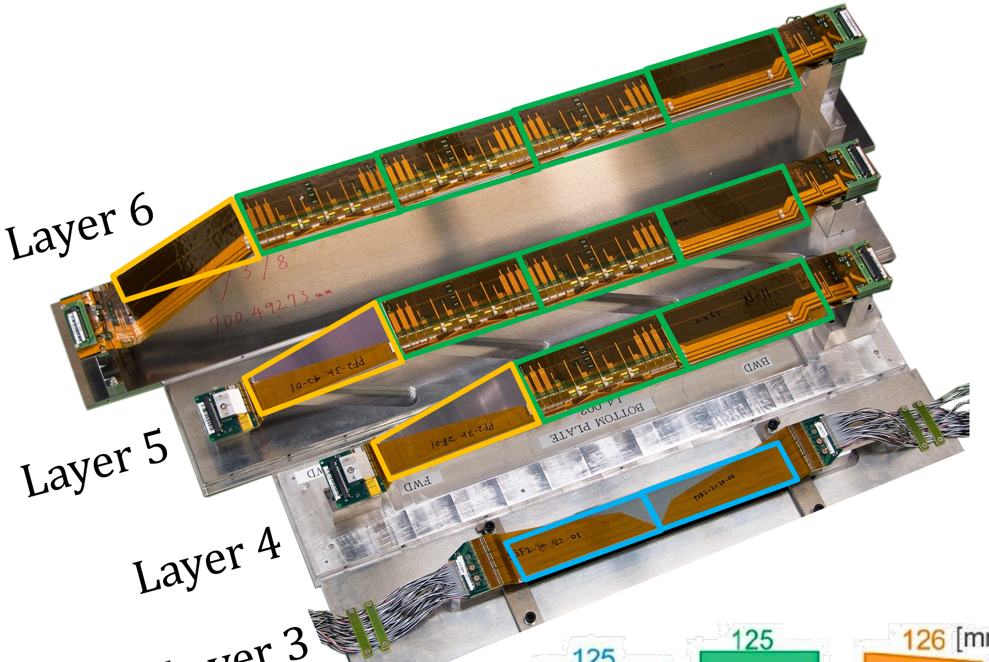
- APV25 front-end ASIC operate @ 32 MHz
  - 128 channels per chip
  - 50ns shaping time
  - Radiation hardness > 100 Mrad
  - Power consumption: 0.4 W/chip

Analog signal

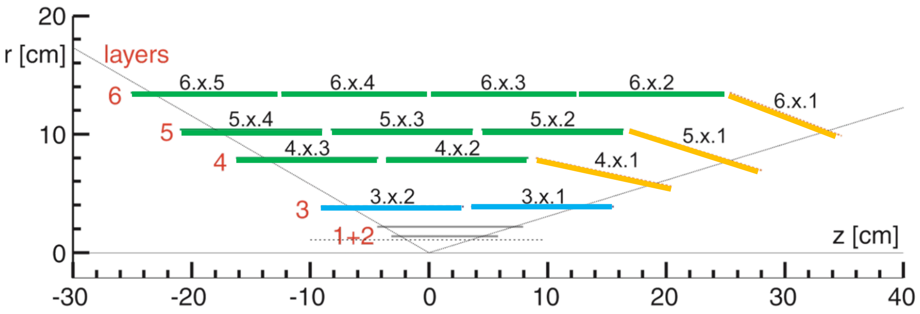


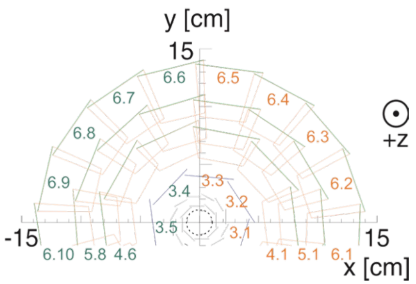
- 6 subsequent samples readout
- 3/6 mixed acquisition mode prepared for high luminosity runs

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





172 sensors

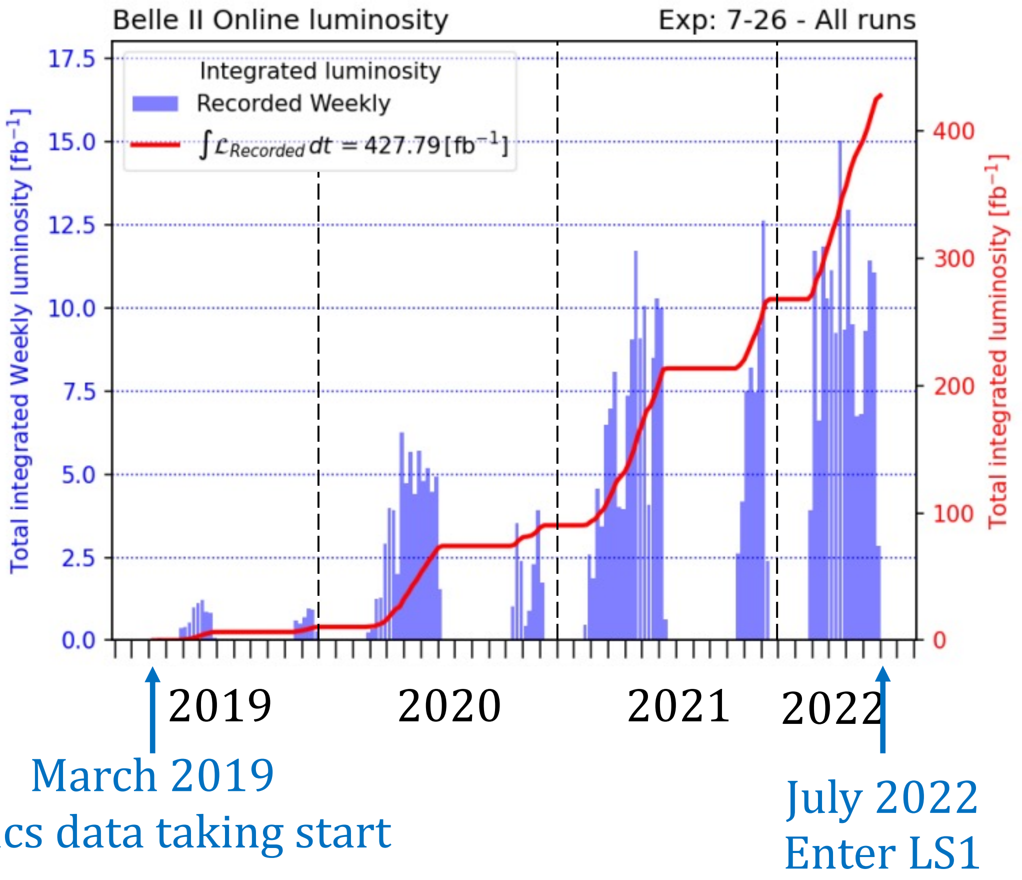
	Small	Large	Trapezoidal
# of p-strips*	768	768	768
p-strip pitch*	50 µm	75 µm	50-75 µm
# of n-strips*	768	512	512
n-strip pitch*	160 µm	240 µm	240 µm
thickness	320 µm	320 µm	300 µm
manufacturer	HPK		Micron

*readout strips – one floating strip on both sides

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

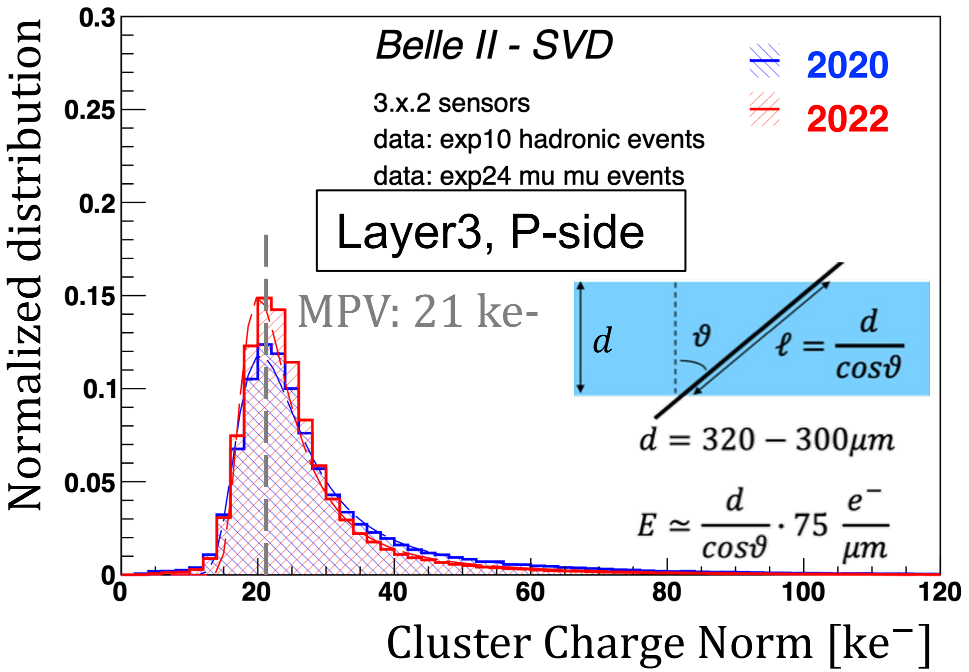
SVD operation

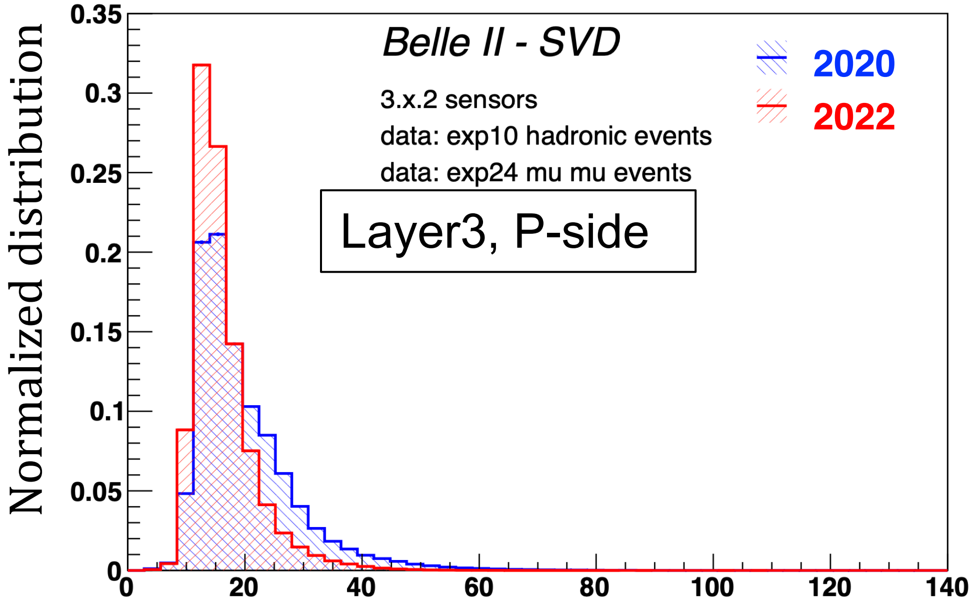
- Smooth and reliable operation without major issue
  - So far total masked strips < 1%
  - Stable environment and calibration constants evolution consistent with expectation
- Excellent detector performance!
  - Good signal-to-noise ratio (SNR), precise position resolution and large hit efficiency (>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



Highlights of the SVD performance

Cluster charge & SNR



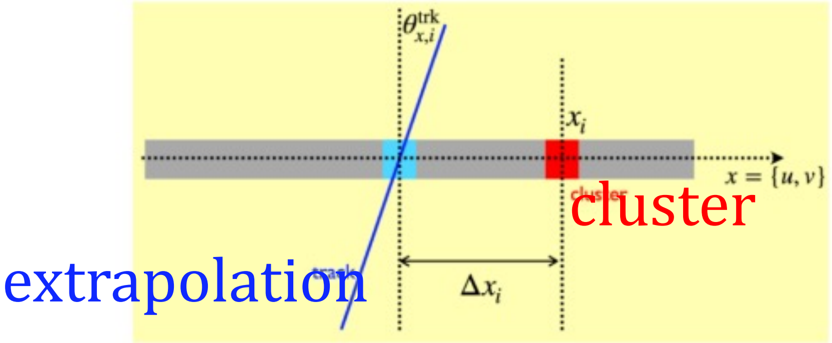


$$\text{ClusterSNR} = \frac{\sum^{\text{strips}} \text{Charge}}{\sqrt{\sum^{\text{strips}} \text{Noise}^2}}$$

- 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

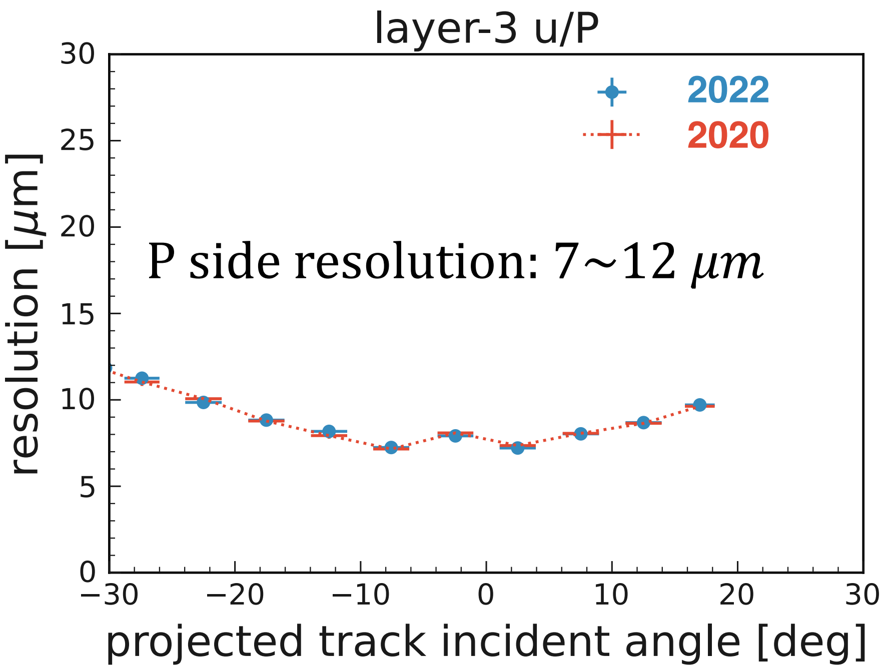
Position resolution

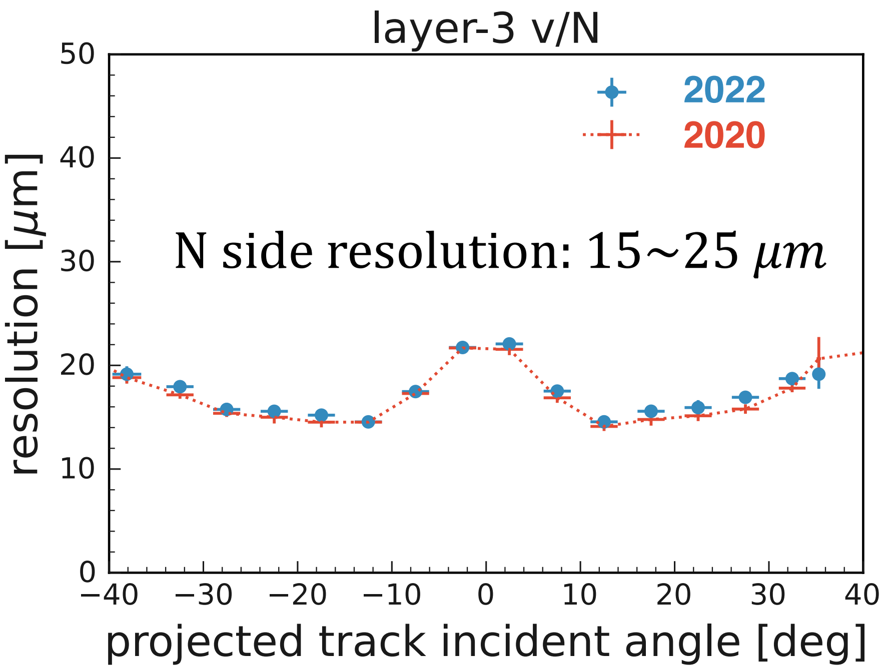
- Estimated from residual of cluster position with respect to unbiassed track extrapolation in $e^+e^- \to \mu^+\mu^-$ events
- Good resolution in agreement with expectations
- Good stability during operation



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

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

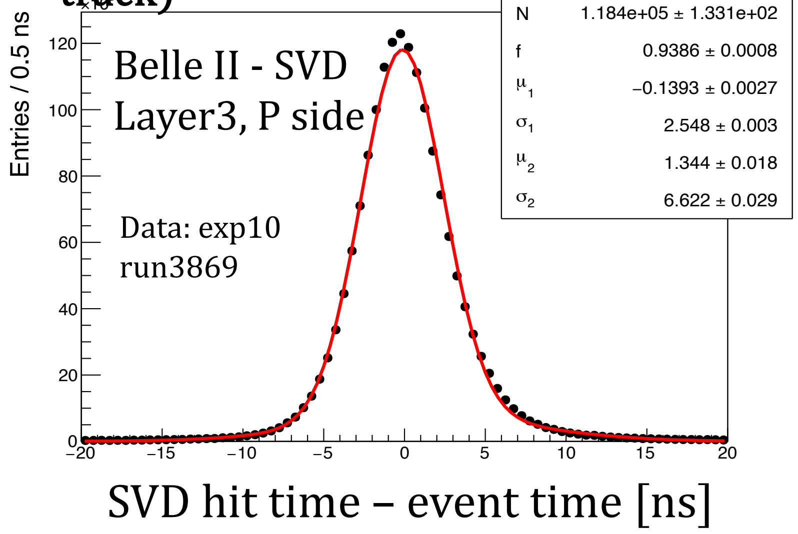


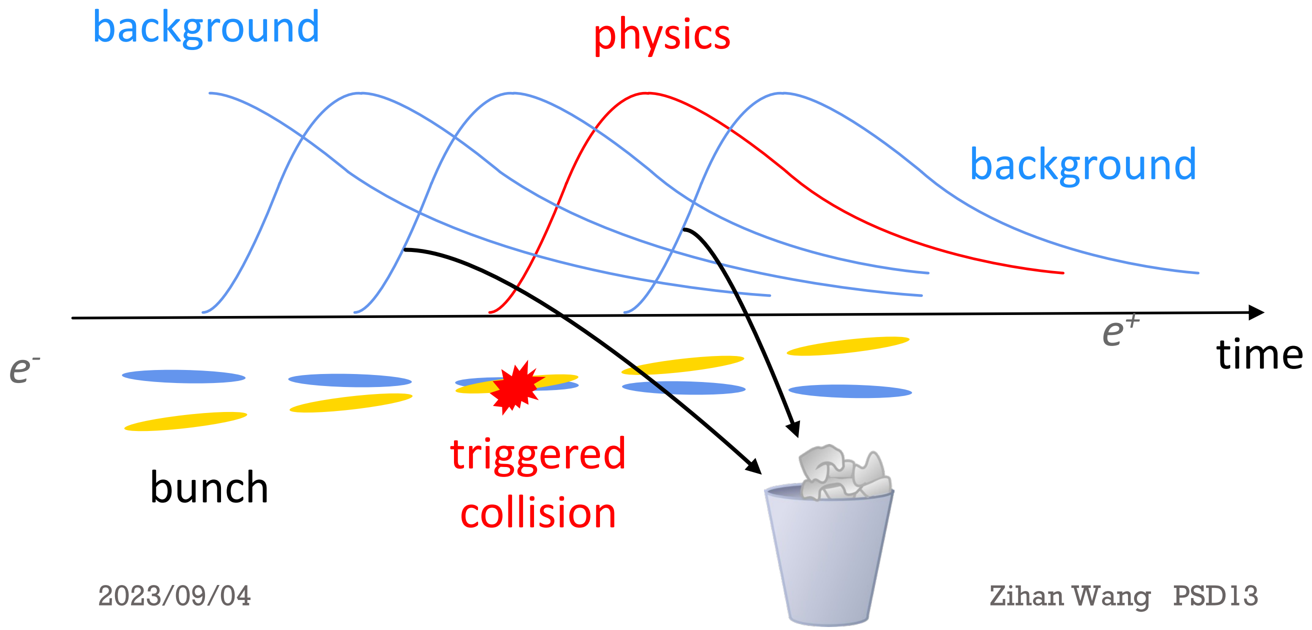


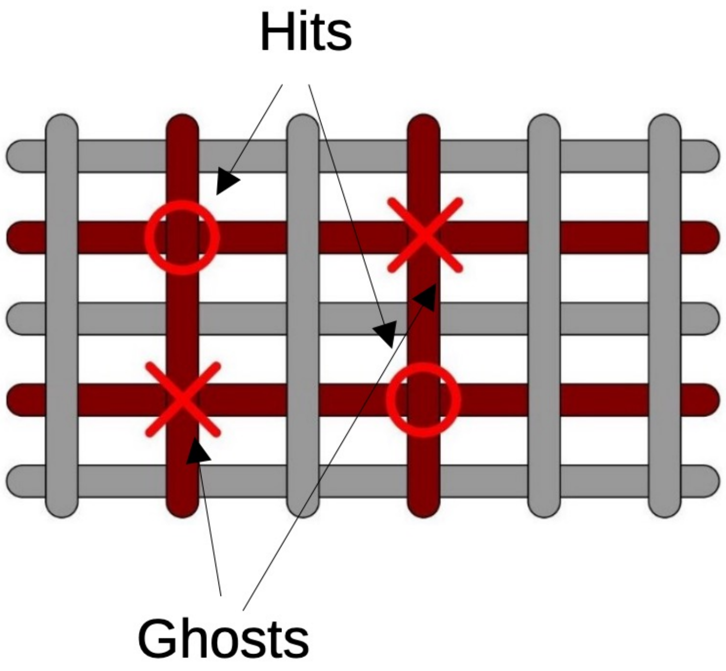
Hit time

- Excellent hit time resolution (< 3 ns) w.r.t event time
  - SuperKEKB bunch spacing: ~ 6 ns
  - SVD acquisition window ~ 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)

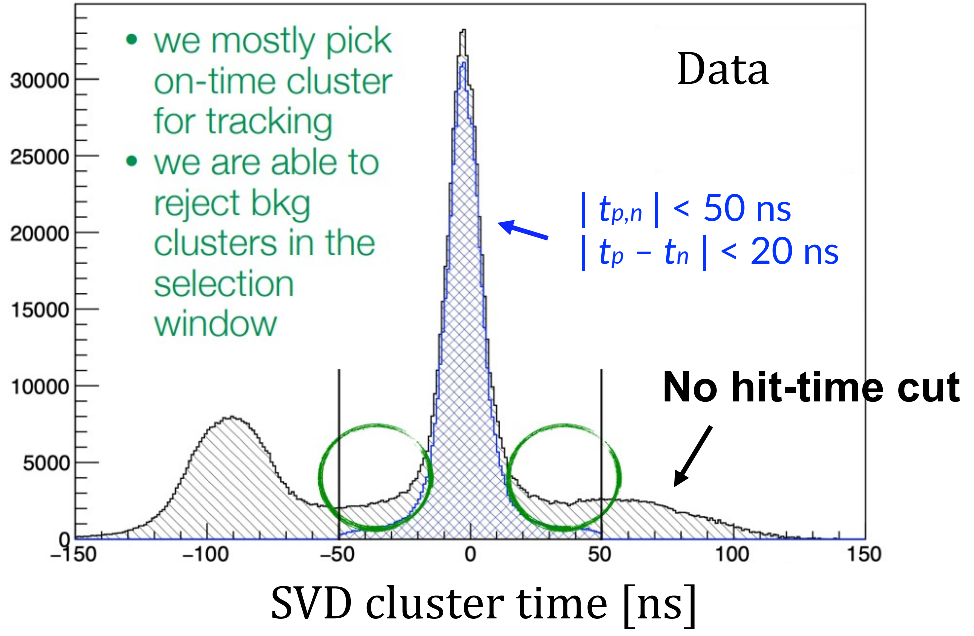






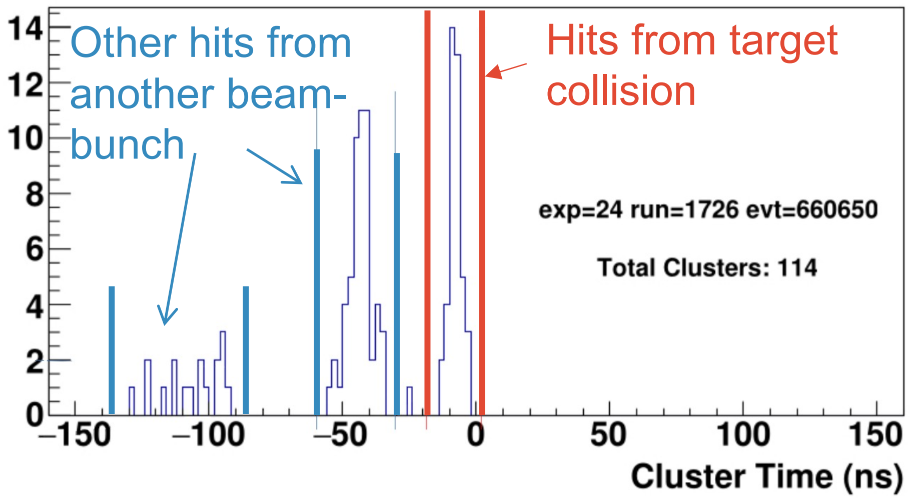
Background rejection with hit time

- Selection 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
  - Reduce the fake rate by 15%
- **Track time selection**
  - Further reduce the fake rate

⇒ Increase the hit occupancy limit to **6%**



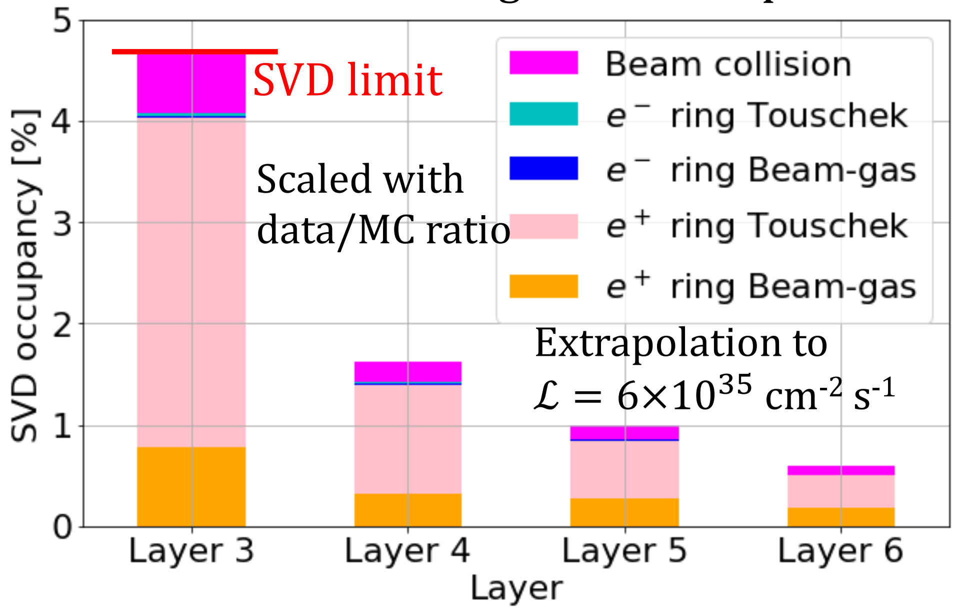
Beam background effects on the SVD

Hit occupancy

- High occupancy from beam background could degrade tracking performance
- Current background level on layer 3 is less than 0.5% and well under control

- Nominal 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
- Small safety margin and possible interaction region re-design motivates vertex detector upgrade
  - See Benjamin's talk for one of the upgrade options

Nominal beam background extrapolation



Radiation effects (1)

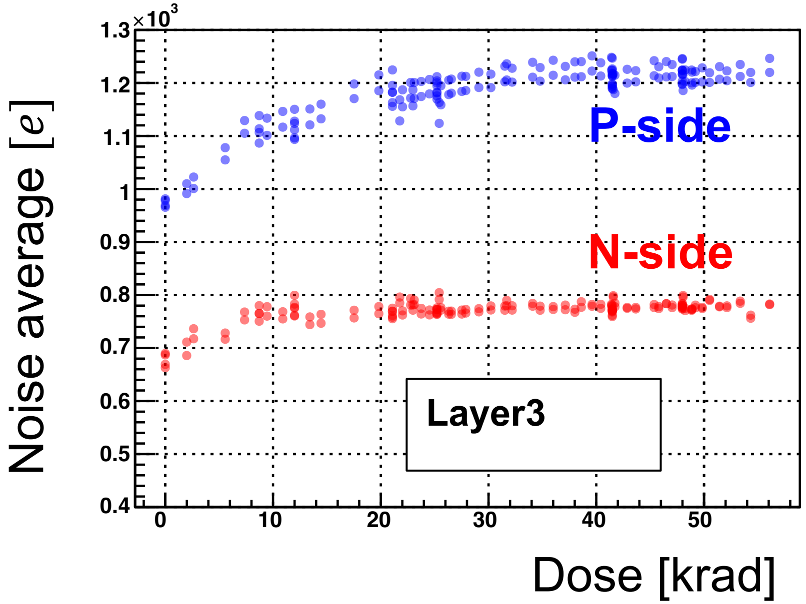
- Integrated radiation damage can deteriorate sensor performance increasing strip noise, leakage current & changing depletion voltage

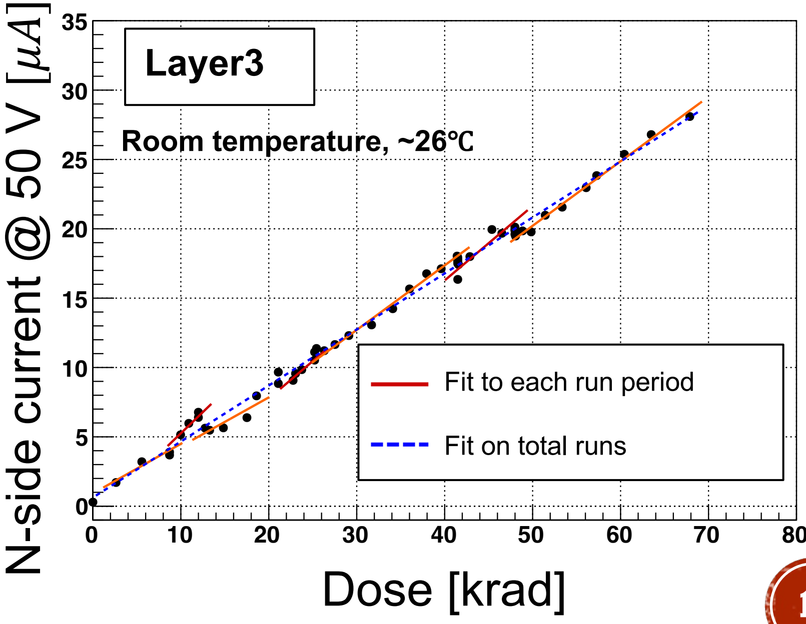
Strip noise

- 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 with equivalent neutron fluence (and dose) due to bulk damage by NIEL
- After 6 Mrad dose strip noise contribution from leakage current would reduce the Layer3 SNR < 10

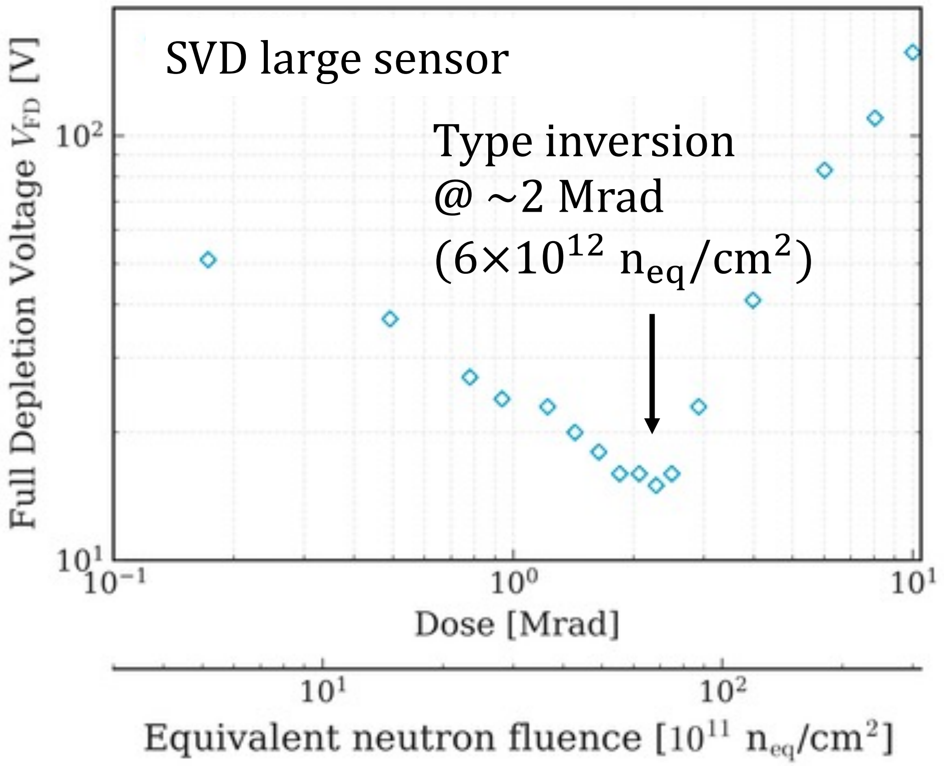




Radiation effects (2)

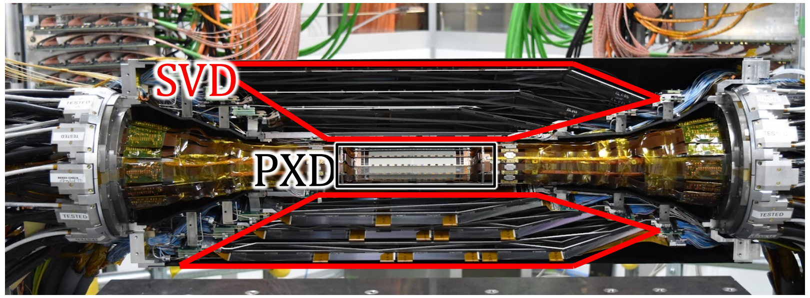
Bulk damage & depletion voltage

- No depletion voltage change observed in operating sensors
- Irradiation campaign of SVD sensors with 90 MeV *e*- beam @ ELPH, Tohoku Univ. July 2022, up to 10 Mrad (3×10^{13} n_{eq}/cm^2)
  - Confirmed SVD sensors work well even after type inversion
  - Good charge collection efficiency confirmed with Sr90 source measurement
  - Leakage current increase consistent with operating sensors



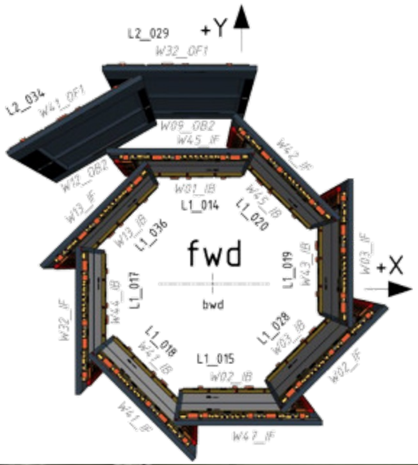
- Background extrapolation predicts radiation levels of 0.35 Mrad/yr (8×10^{11} $n_{eq}/cm^2/yr$)
- SVD has good safety margin of 2 even after 10 years' operation at target luminosity, considering the 6 Mrad limit

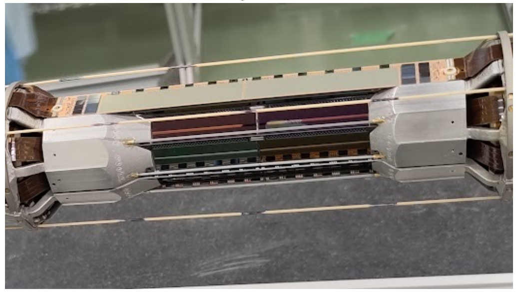
VXD reinstallation during Long Shutdown 1



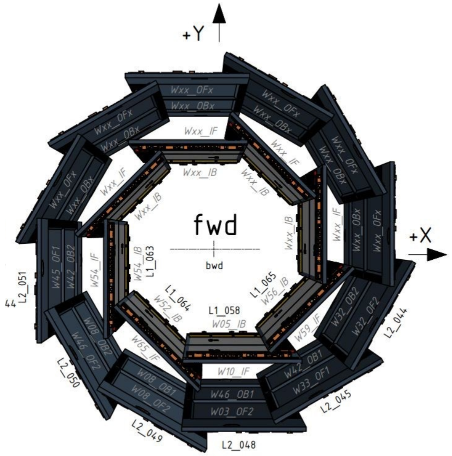
VXD re-installation

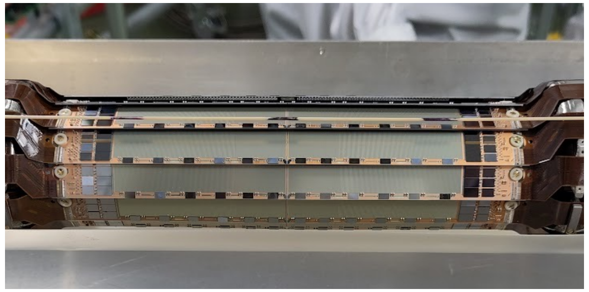
PXD1





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

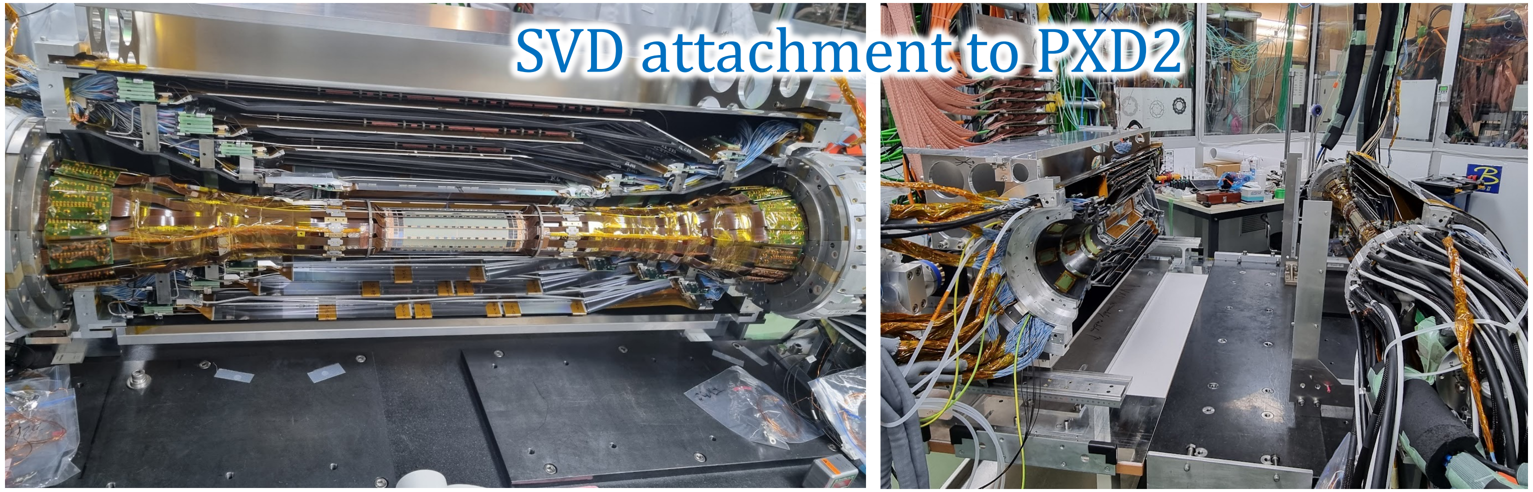
May 16~17


VXD extraction


SVD detachment from PXD1

June 20~21

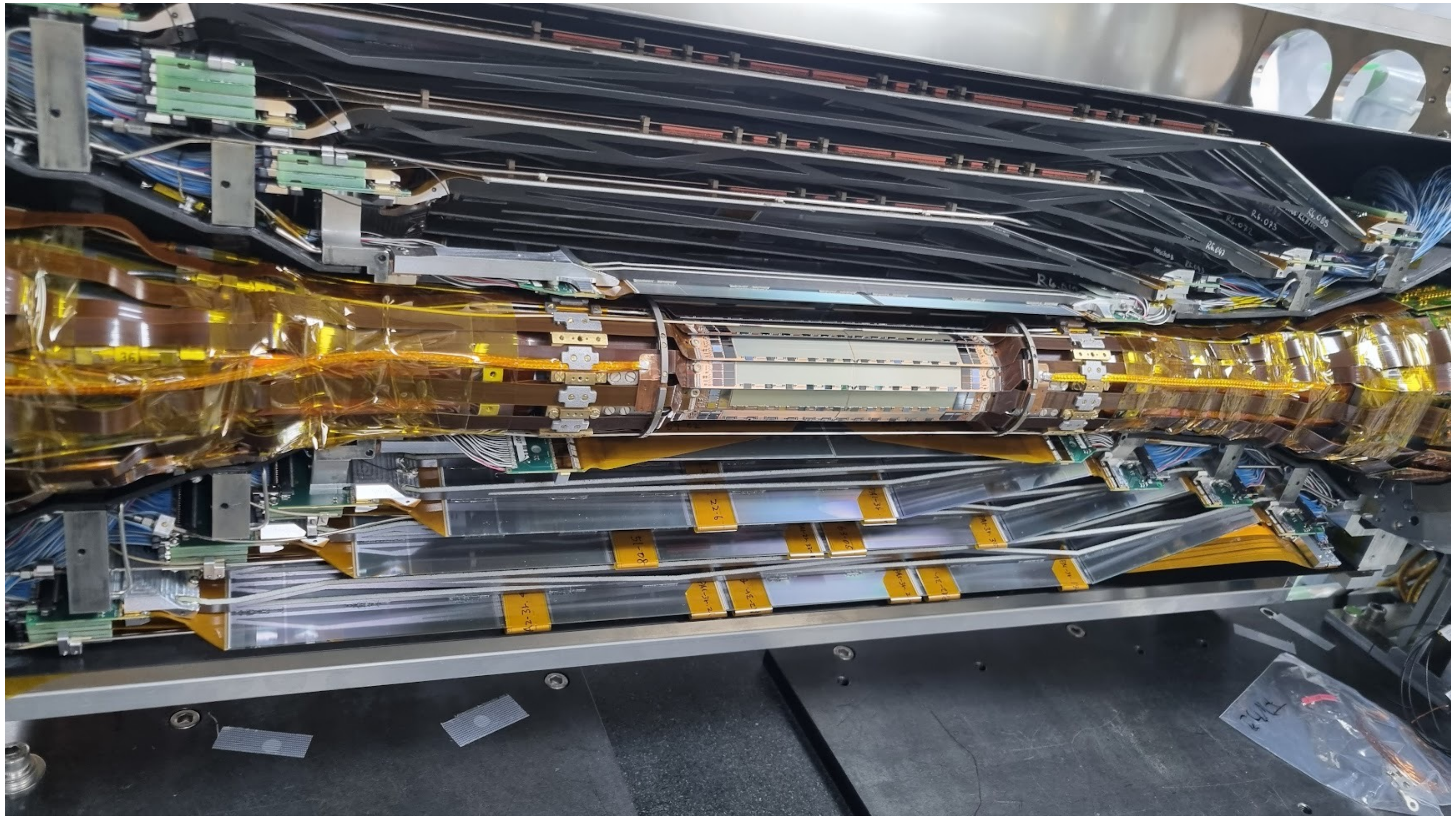
July 28


SVD attachment to PXD2

New VXD installed in Belle II

VXD re-installation

- VXD now re-installed 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 ⇒ more robust against high background and matching possible new interaction region

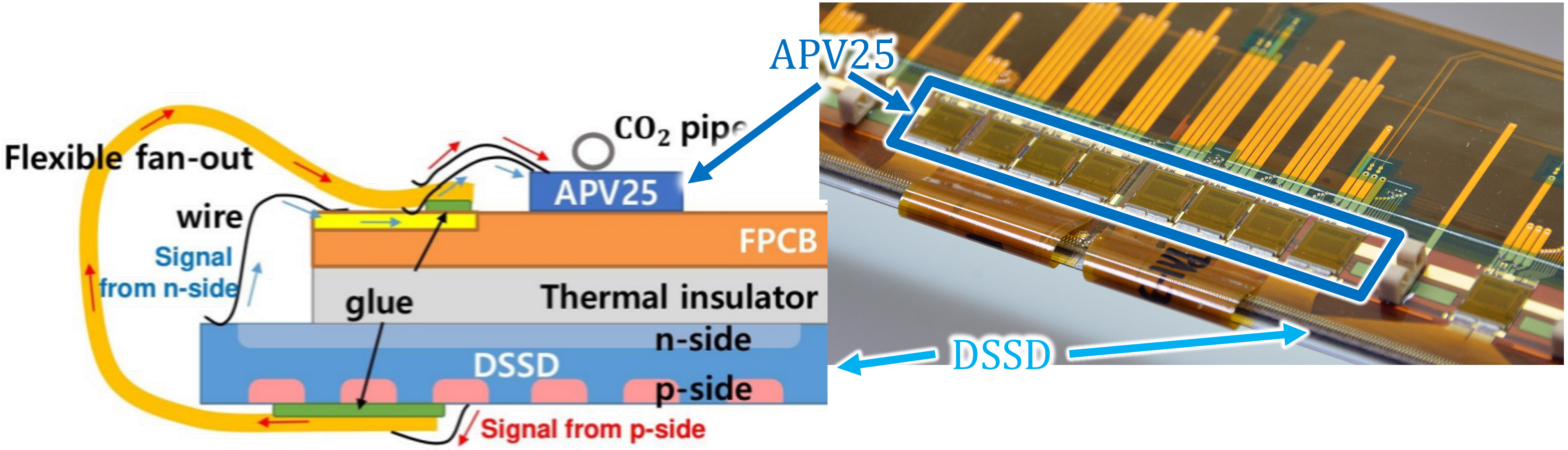
- During the Long Shutdown 1, new VXD with the complete PXD2 and the current SVD is re-installed
  - Commissioning with cosmic in September
  - Plan to resume beam operation in December

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

BACK UP

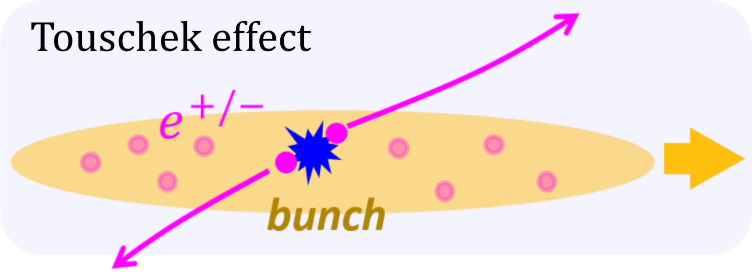
Chip-on-sensor concept

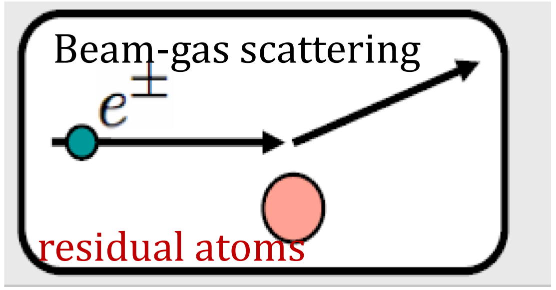
- Origami chip-on-sensor concept:
  - Shorter signal propagation length to reduce capacitance and noise
  - Two-phase CO_2 (-20 ℃) cooling



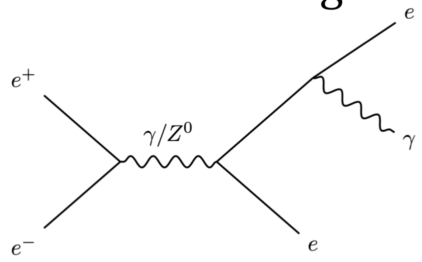
Background sources

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

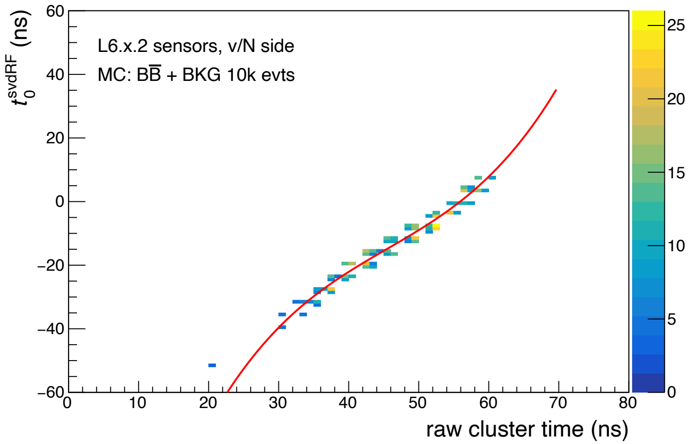
Strip info reconstruction

- Signal charge: highest sample among 6(3) samples in 6 (3) readout modes, converted to electrons based on calibration constants
- Signal time:

The raw **hit time** (t_{raw}) is determined as a weighted average of the sampling time (t_i) with the ADC count of the i-th sample A_i corrected by t_{peak} to remove differences in peaking times among the strips:

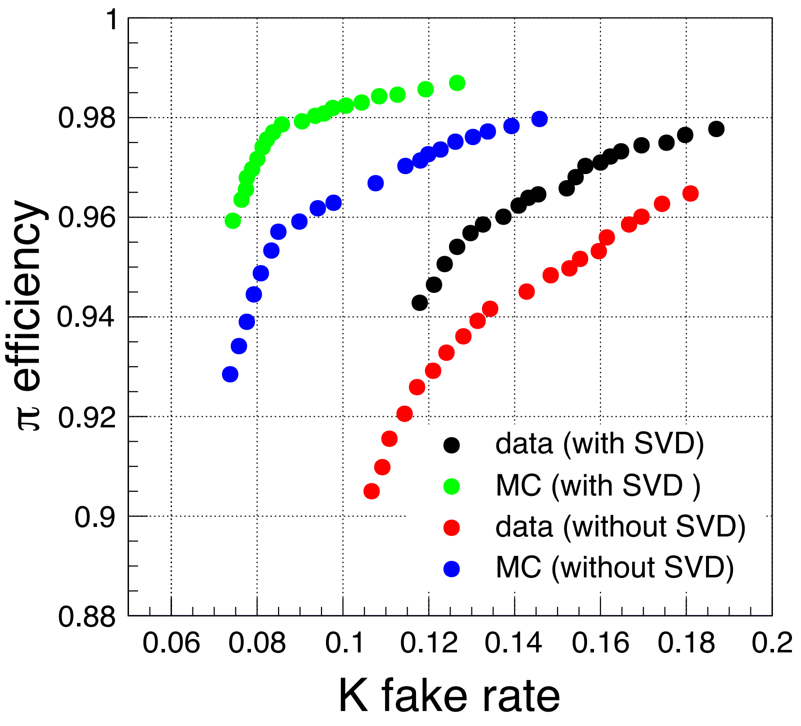
$$t_{\text{raw}} = \sum_{j=0}^{j=5} \frac{t_j \cdot A_j}{A_{\text{tot}}} - t_{\text{peak}}, \quad \text{with} \quad A_{\text{tot}} = \sum_{j=0}^{j=5} A_j \tag{8.1}$$

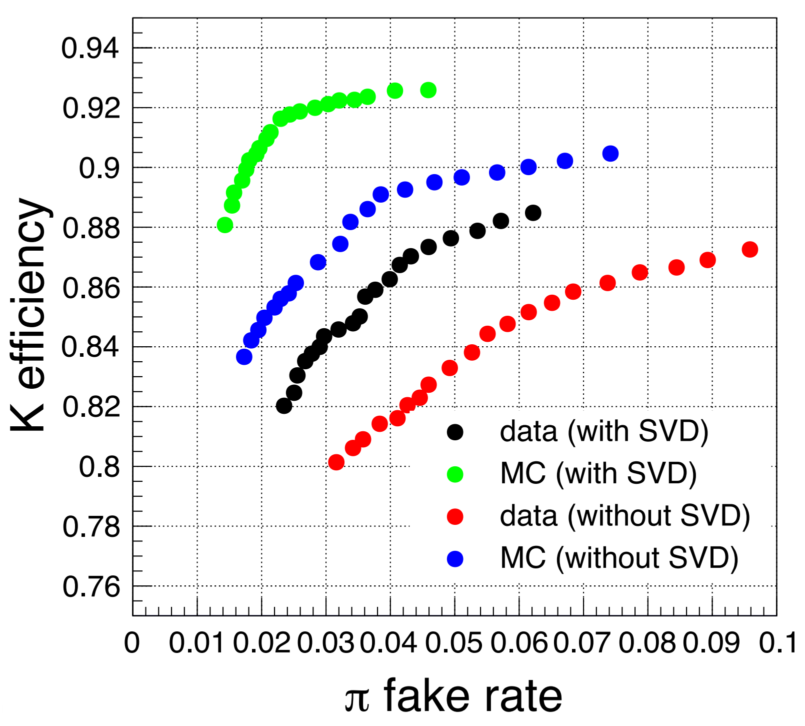
where $t_j = j \cdot 1/f_{\text{APV}}$ and $f_{\text{APV}} = 31.805$ MHz, and t_{peak} is determined for each strip from the local calibration and stored in the Conditions Database



Particle identification

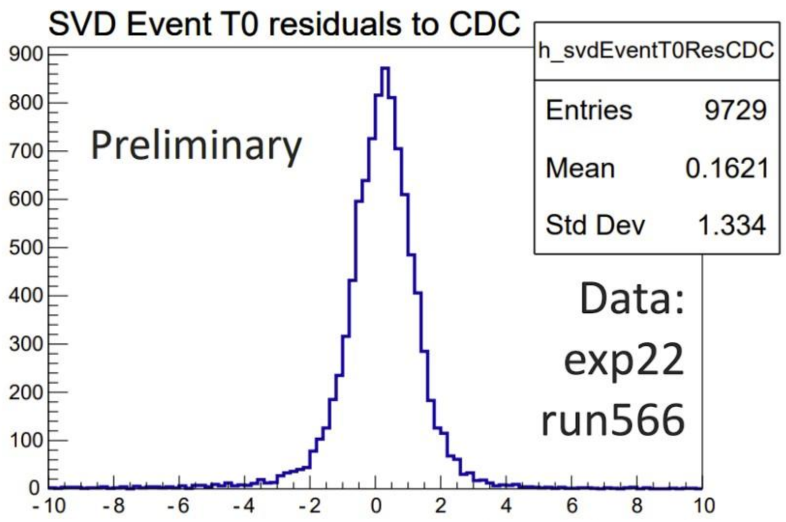
- Eg. $K - \pi$ separation using specific ionization (dE/dx)
- PDF derived from $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$ channel
- Under calibration and will be implemented into particle identification algorithm in the future





SVD event time

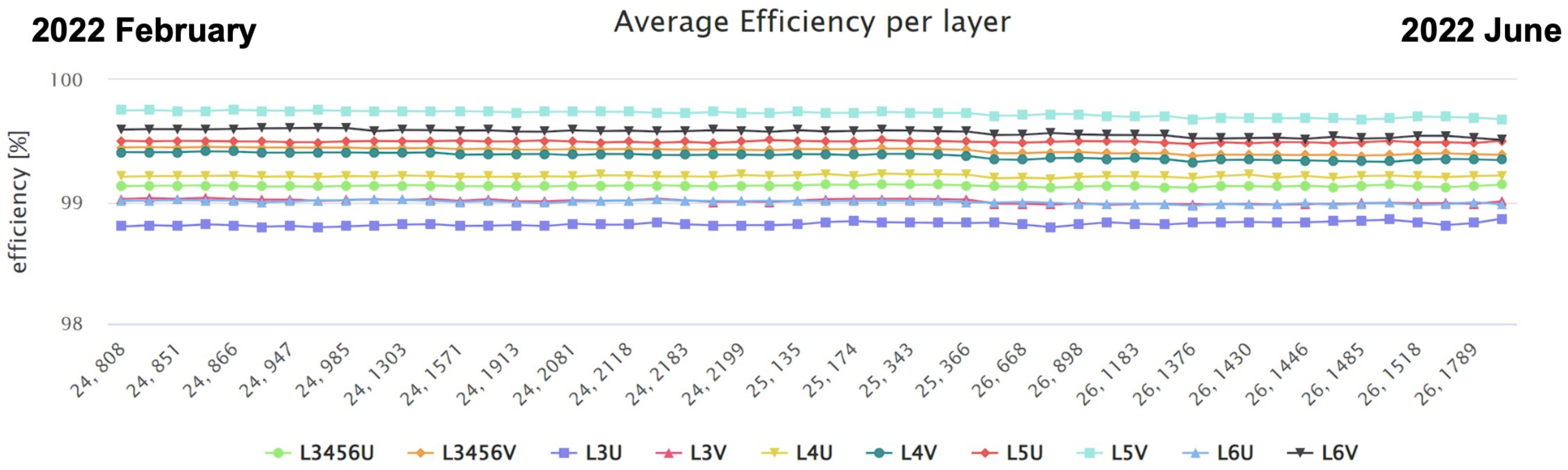
- SVD Event time computed from SVD clusters associated to tracks
  - Same resolution (~ 1 ns) but 2000 times faster computation w.r.t. the one computed with CDC
  - Allowing to speed up the online reconstruction and therefore cope with the higher luminosity operation



SVD event time – CDC event time [ns]

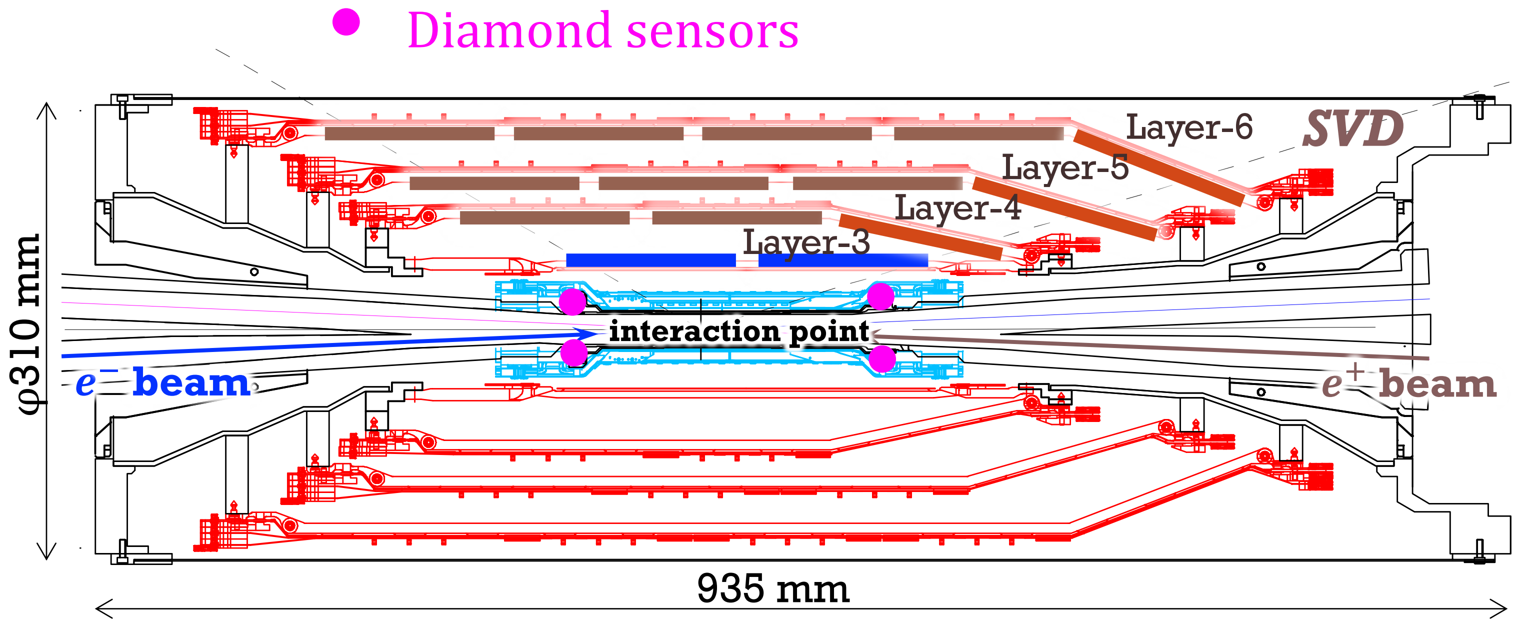
Efficiency

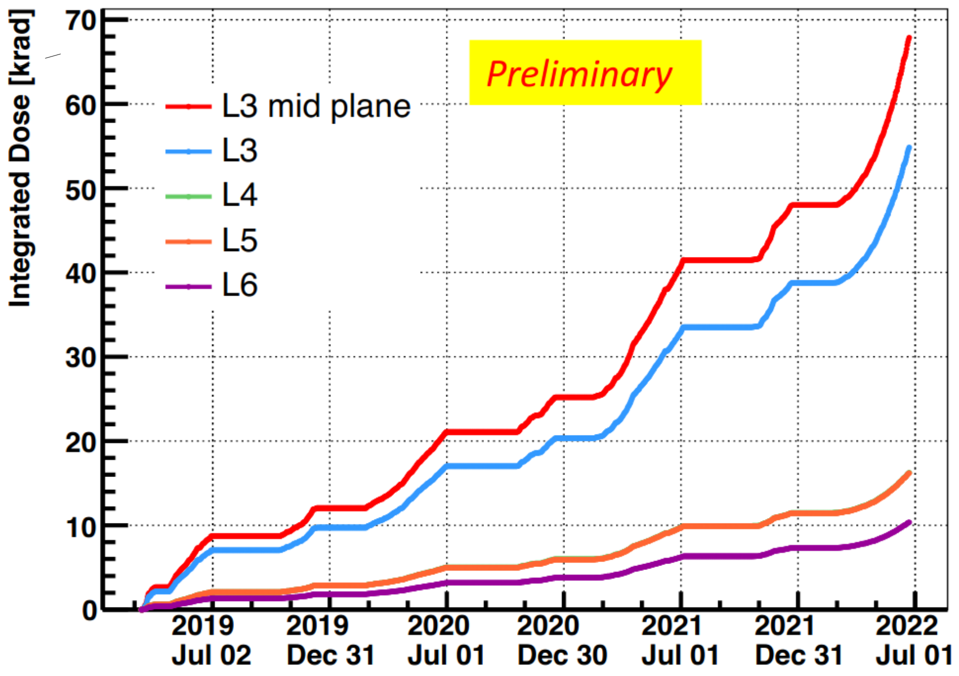
- Hit efficiency is very high and stable in time



Radiation dose

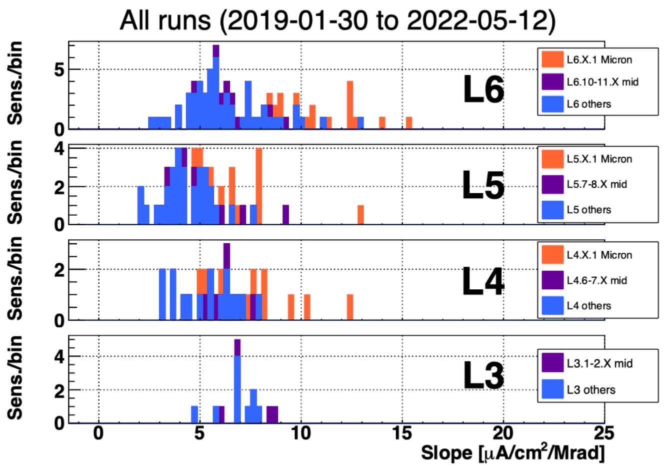
- Constantly monitored using diamond sensors

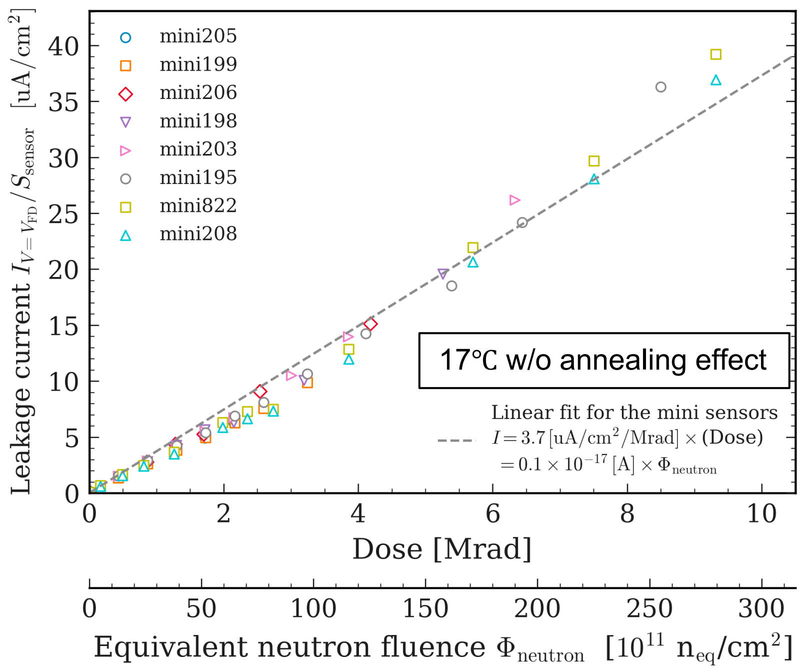




Leakage current

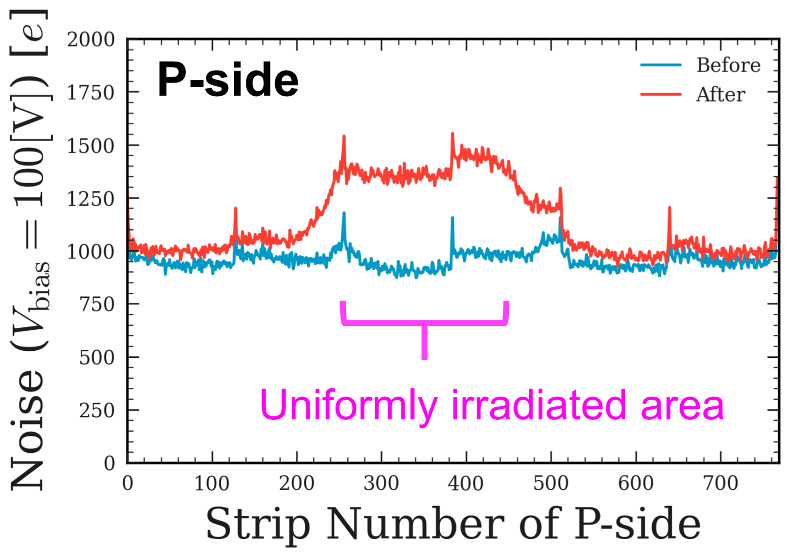
- Damage constant [μA/cm^2/Mrad] ranges from 4~8 for sensors operated at different temperature 10~26 °C
- Irradiation campaign gives 2.2 for sensors radiated at 24 °C after annealing
- Babar sensors operated at 27 °C has a damage constant of 2
  - NIMA 729, 615-701, 2013
- Good consistence for different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

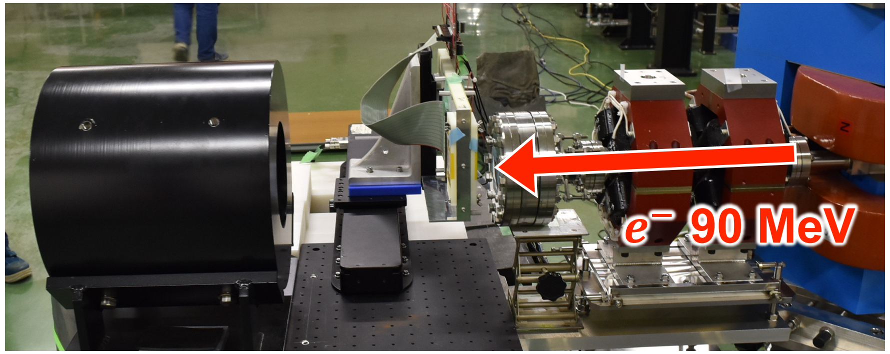




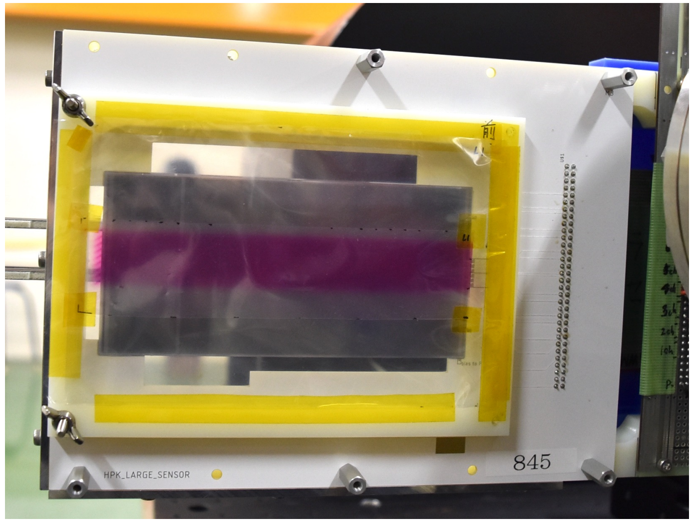
Strip noise

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

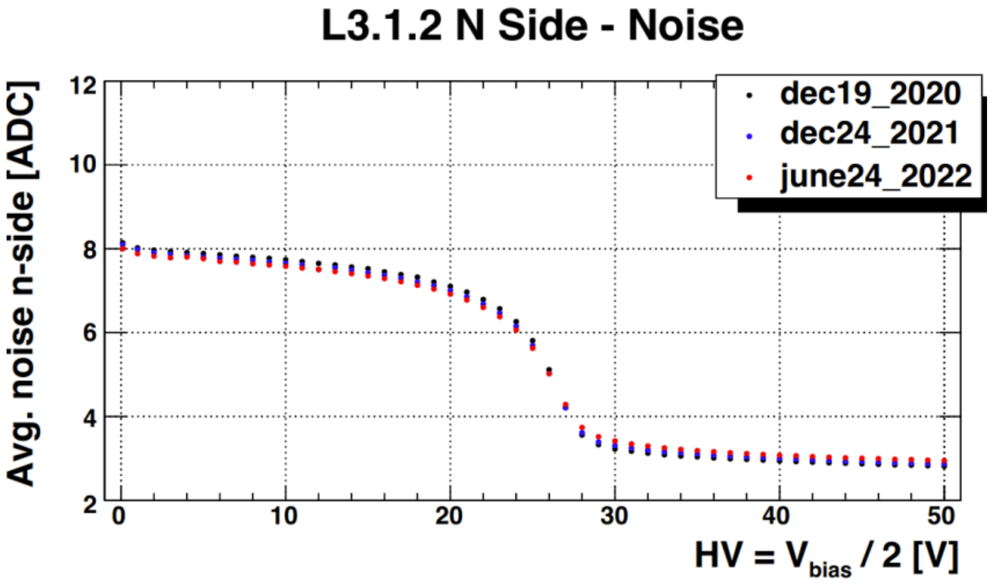


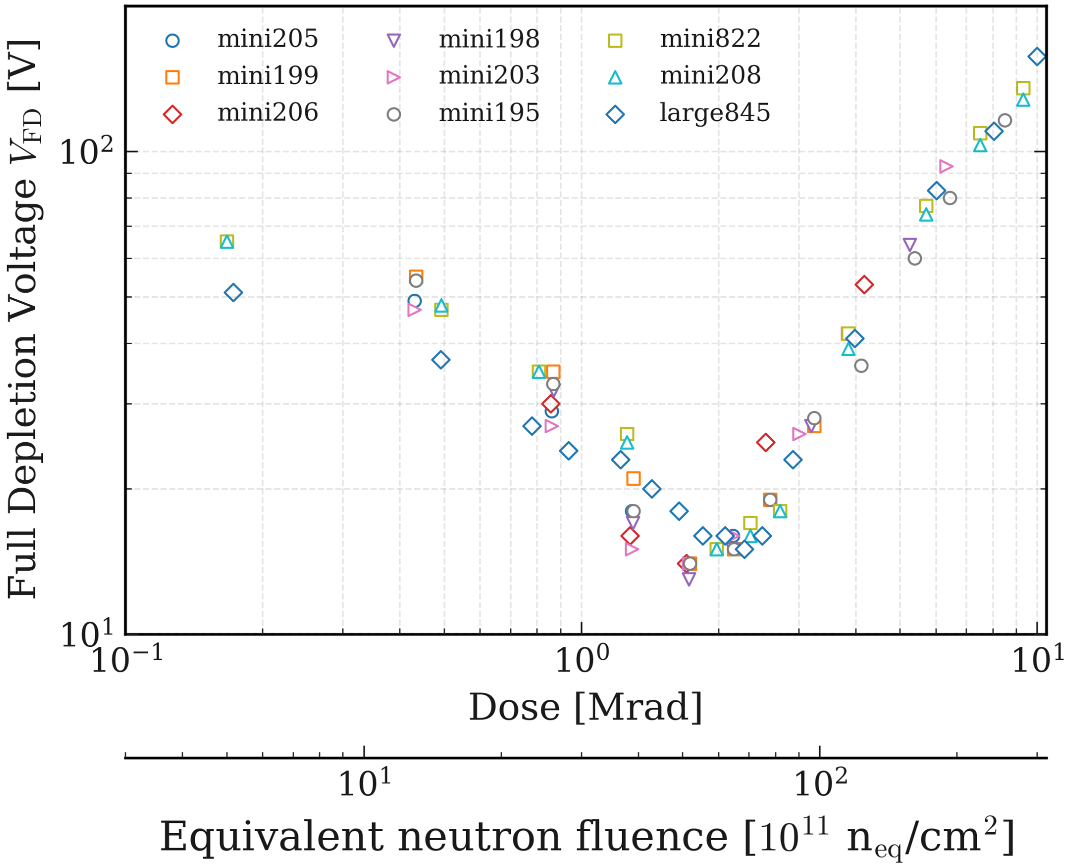


Uniformly irradiated area



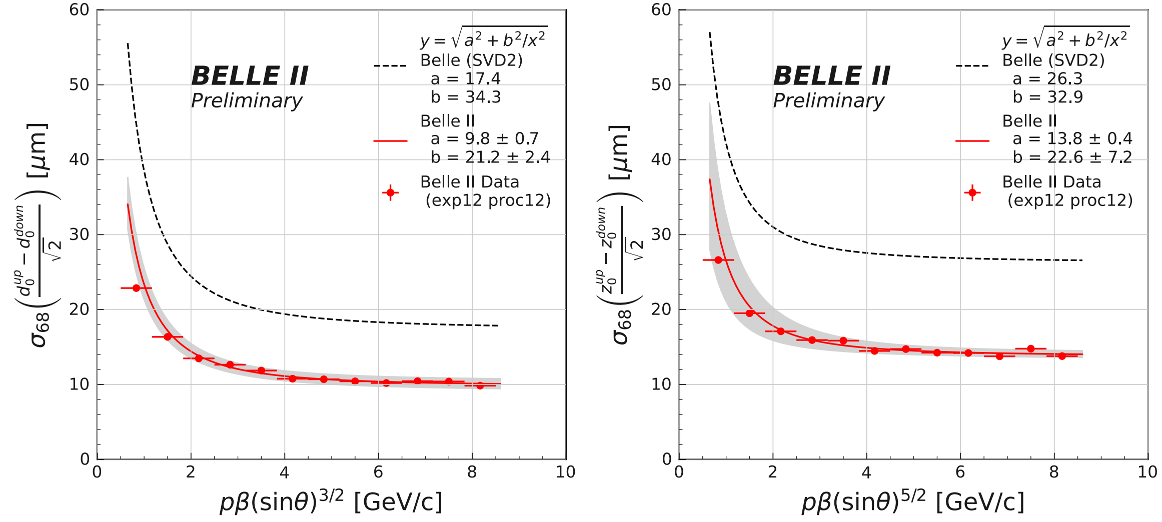
Depletion voltage





Vertex resolution

- Belle II vertex resolution is better than Belle by a factor of 2



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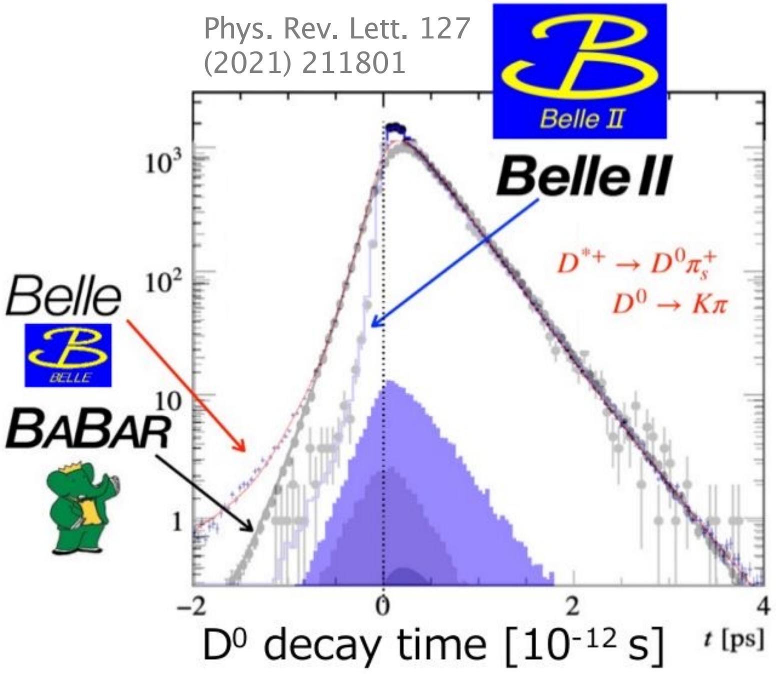

$$\tau(D^0) = 410.5 \pm 1.1\,(\text{stat}) \pm 0.8\,(\text{syst})\,\text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7\,(\text{stat}) \pm 3.1\,(\text{syst})\,\text{fs}$$