The Silicon Vertex Detector of the Belle II Experiment

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For the Belle II SVD Collaboration

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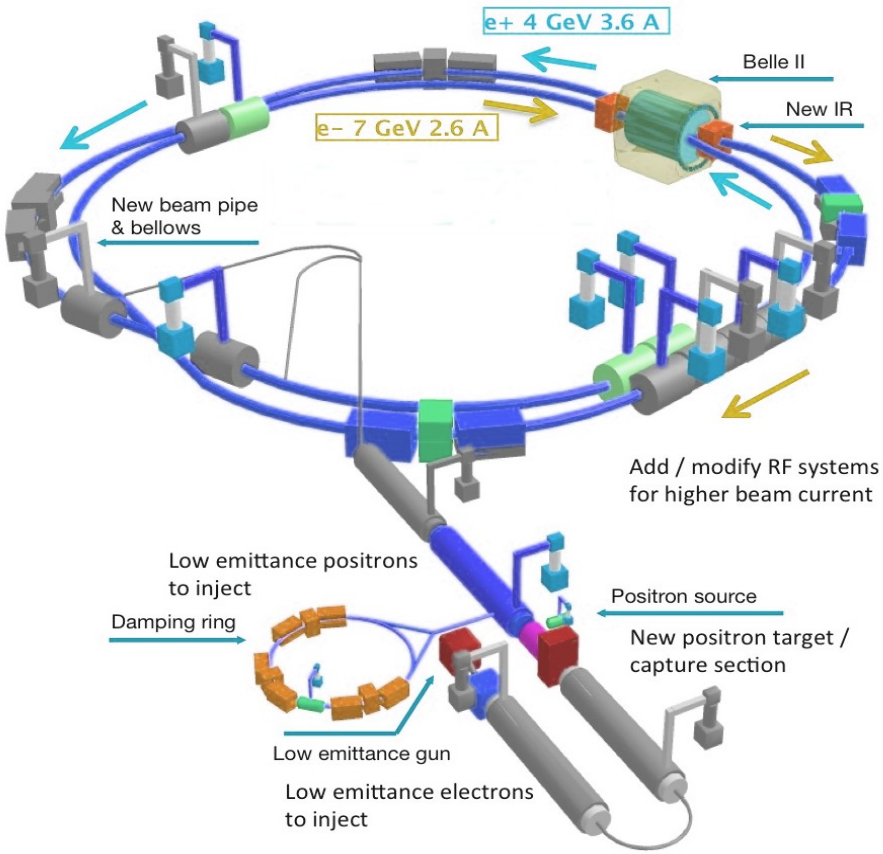
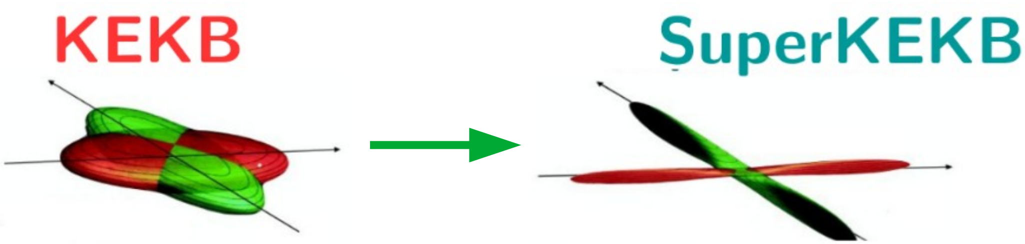
Outline

- **SuperKEKB, Belle II and the Silicon Vertex Detector**
- **Operation and Performance**
- **Beam Background**
- **Radiation Damage Effects**
- **Summary**

SuperKEKB

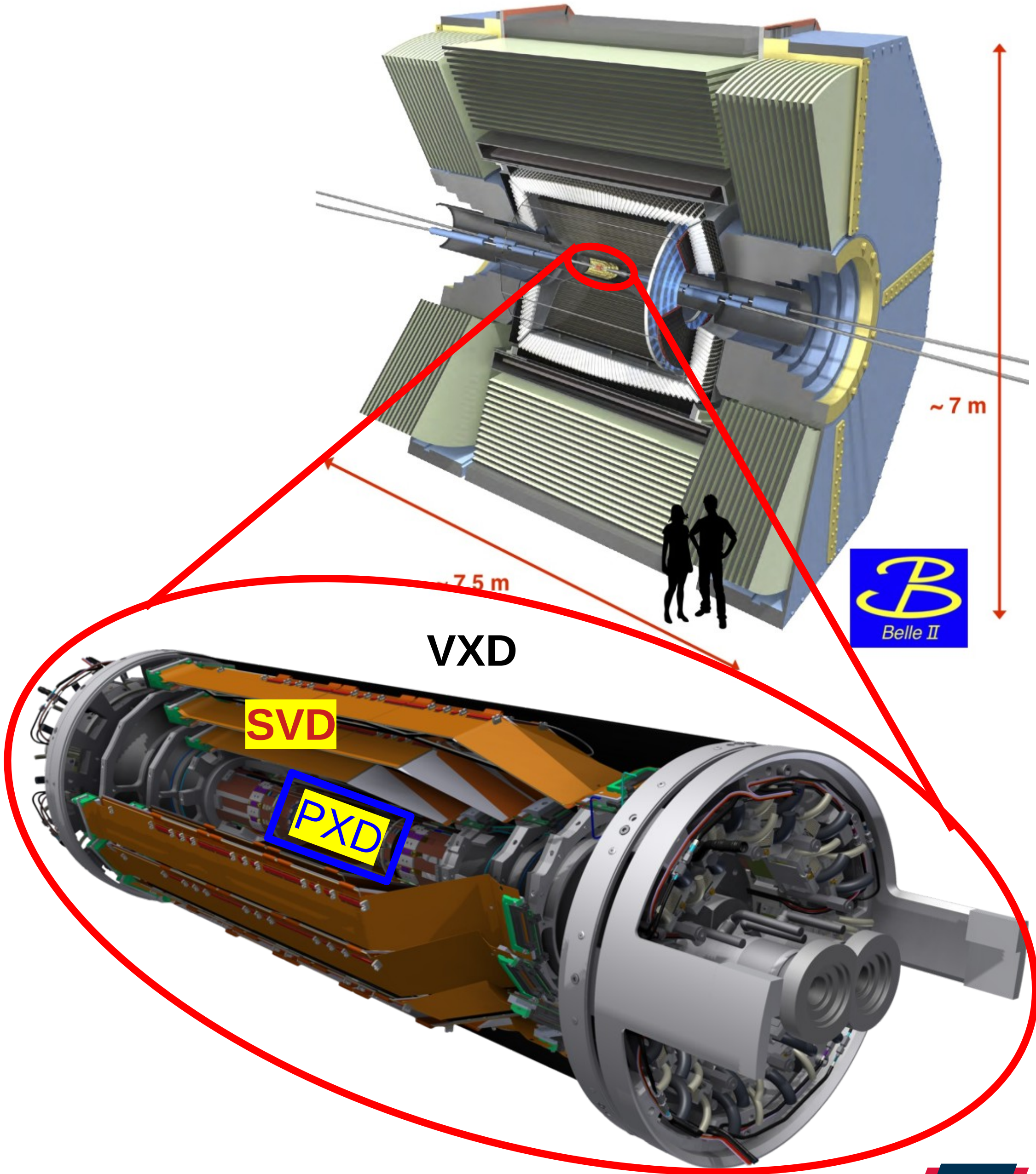


- **Belle II is hosted at the SuperKEKB accelerator**
  - Asymmetric energy e^+e^- (4 & 7 GeV) collider in Tsukuba, Japan
  - Nominal CMS energy 10.58 GeV = M(Υ(4S)), Υ(5S) and Υ(6S) also producible
- **Full event reconstruction, decays with neutral/soft particles**
- **Goal for SuperKEKB:**
  50x integrated Belle luminosity → 50/ab
  - nano-beam-scheme : ~6 x 10^{35} cm^{-2} s^{-1}
  - 30x KEKB instantaneous luminosity
- **So far ~420/fb are collected since March 2019**
  - 4.7 x 10^{34} cm^{-2} s^{-1} instantaneous luminosity in June 2022



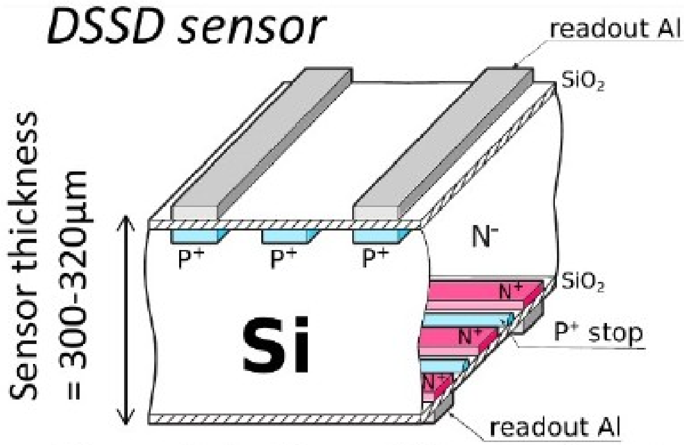
Belle II

- **Vertex Detector – VXD**
  - Composed of PXD (2 layers) and SVD (4 layers)
- **Pixeldetector – PXD**
  - DEPFET pixel sensor, layers 1 & 2
  - Innermost layer 14 mm from interaction point
- **Silicon Vertex Detector – SVD**
  - Double-sided silicon strip sensors (DSSD), layers 3,4,5,6
  - Innermost layer at 40 mm
- **SVD requirements from precision physics program:**
  - Good vertex resolution
    - Improved point resolution, reduced inner radius, low material budget
  - Extrapolate tracks to PXD
    - Used to define Region of Interest (ROI) for data reduction
    - ROI calculated by CPU farm (HLT)
  - Stand-alone tracking for low p_T tracks
  - PID with dE/dx
  - Precise K_S vertexing

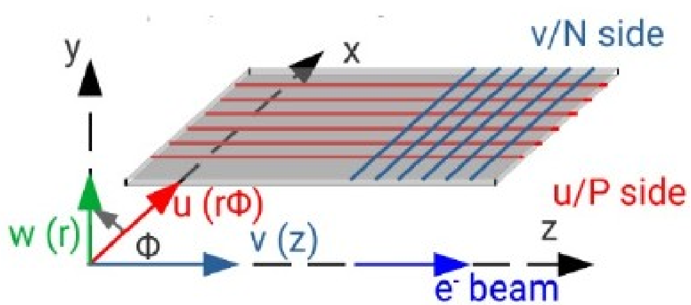


Silicon Vertex Detector (SVD) - I

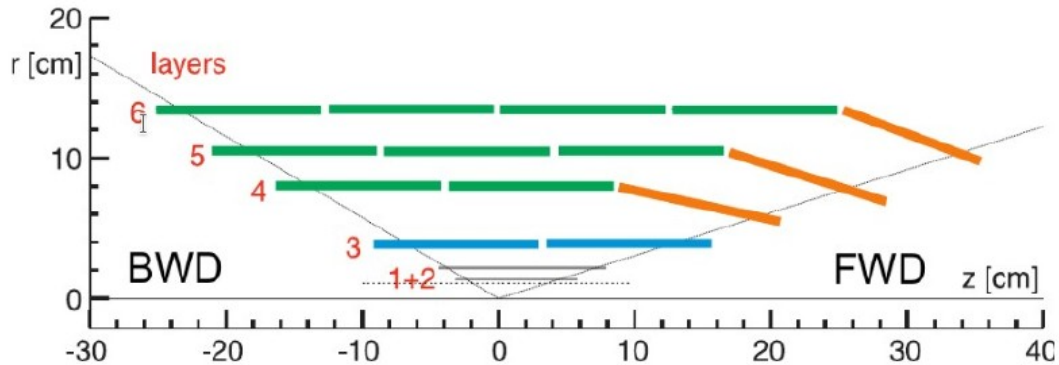
- **SVD concept: DSSDs**
  - 2D positioning information
  - Strips are AC-coupled to n-type substrate
  - Fully depleted at 20-60 V, operated at 100 V

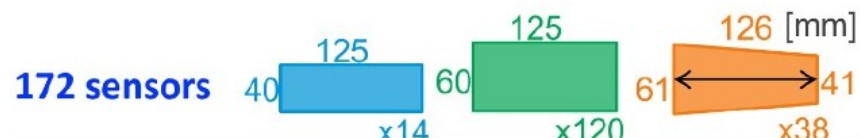


AC-coupled strips on N-type substrate
Full depletion voltage: 20-60V
Operation voltage: 100V



- **SVD layout**
  - 3 different DSSD shapes
  - 172 sensors, 224k readout strips
    1.2 m^2 total sensor area





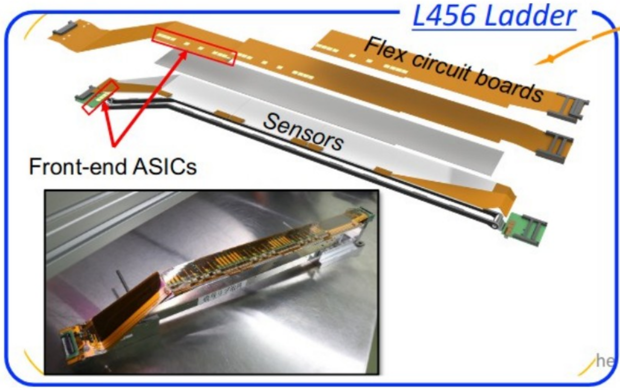
	Small	Large	Trapezoidal
# of p-strips*	768	768	768
p-strip pitch*	50 µm	75 µm	50-75 µm
# of n-strips*	768	512	512
n-strip pitch*	160 µm	240 µm	240 µm
thickness	320 µm	320 µm	300 µm
manufacturer	HPK		Micron

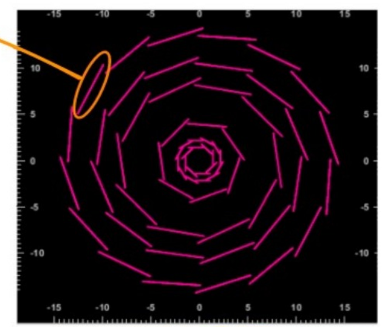
*readout strips – one floating strip on both sides

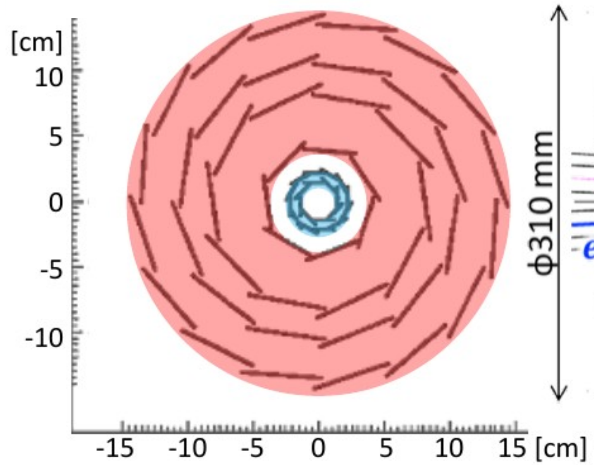
Silicon Vertex Detector (SVD) - II

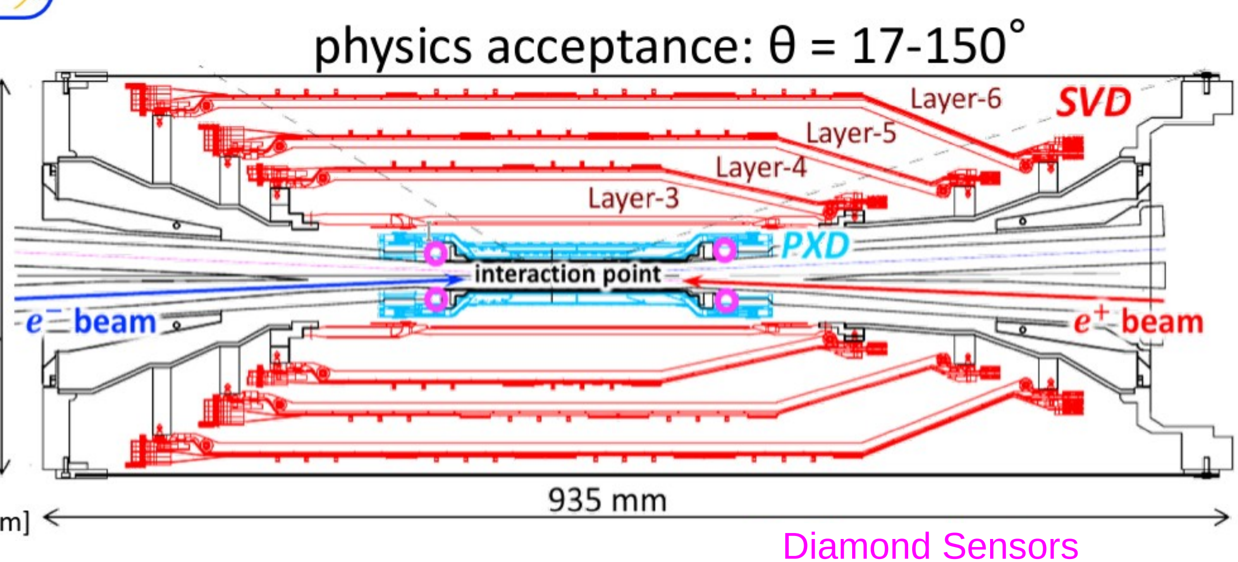
- **Low material budget: 0.7% X_0 per layer**
- **Signal connected to front-end ASICs by flex circuits**
  - Layer 3 chips outside the active area
  - chip-on-sensor for layer 4, 5 and 6

- **Diamond sensors for radiation monitor and beam abort**
  - Operation in high background environment, hit rates of 3 MHz/cm^2 at R = 40 mm
  - Radiation hardness at nominal luminosity: 0.2 Mrad/yr at R = 40 mm



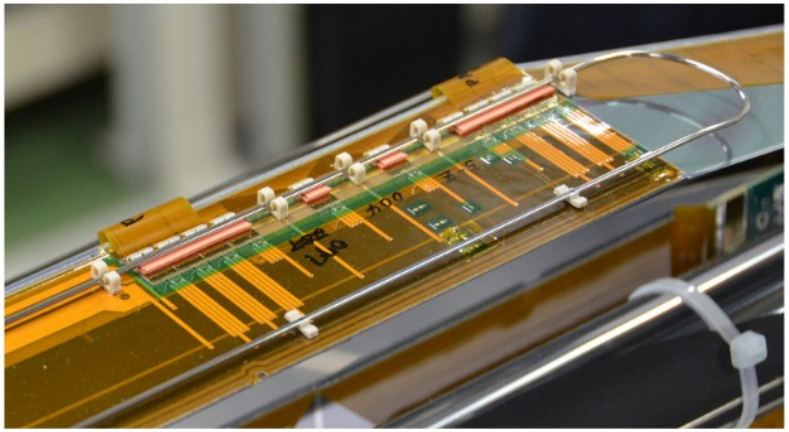


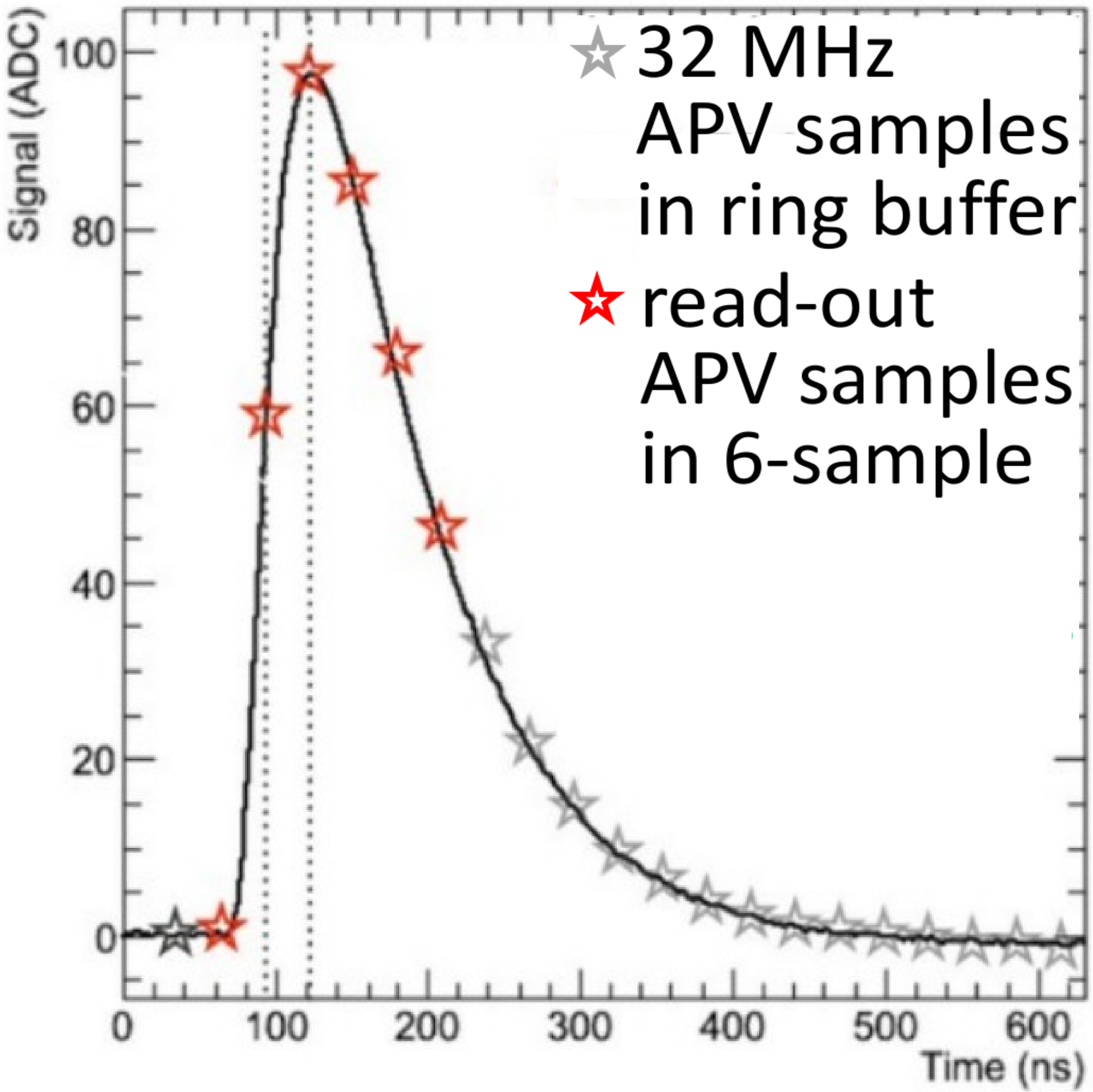




SVD front-end ASICS – APV25

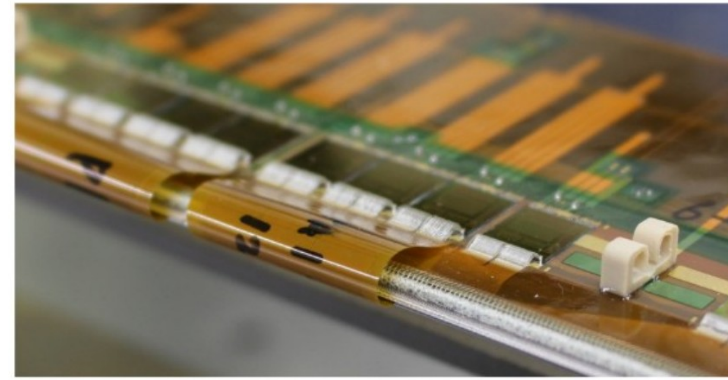
- **Originally developed for CMS silicon tracker**
  - Fast: 50 ns shaping times
  - Radiation hard: > 100 Mrad
  - Power consumption: 0.4 W/chip (700 W in total)
  - 128 channel inputs per chip
- **Operated in “multi-peak” mode @ ~32 MHz clock**
  - Bunch-crossing frequency ~8*32 MHz, clock not synchronous with them as in CMS
  - 6 subsequent samples read-out

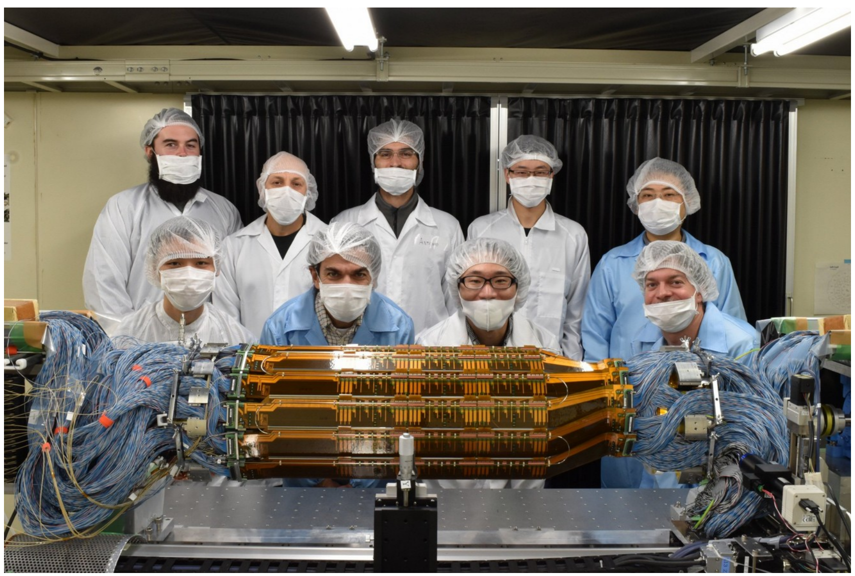


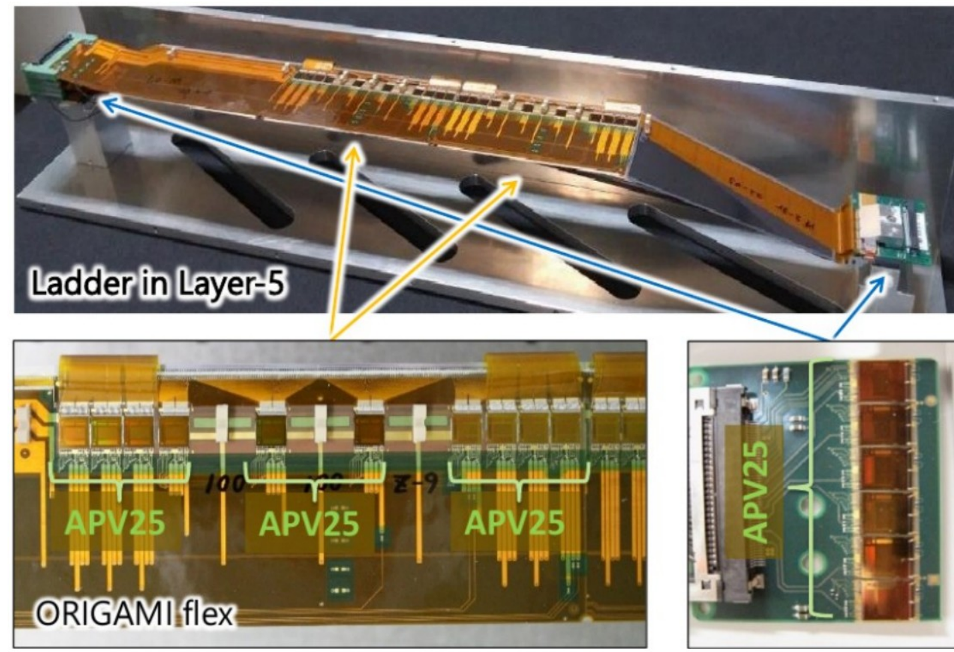


Origami chip on sensor concept

- **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 two-phase CO_2 (-20° C) cooling**



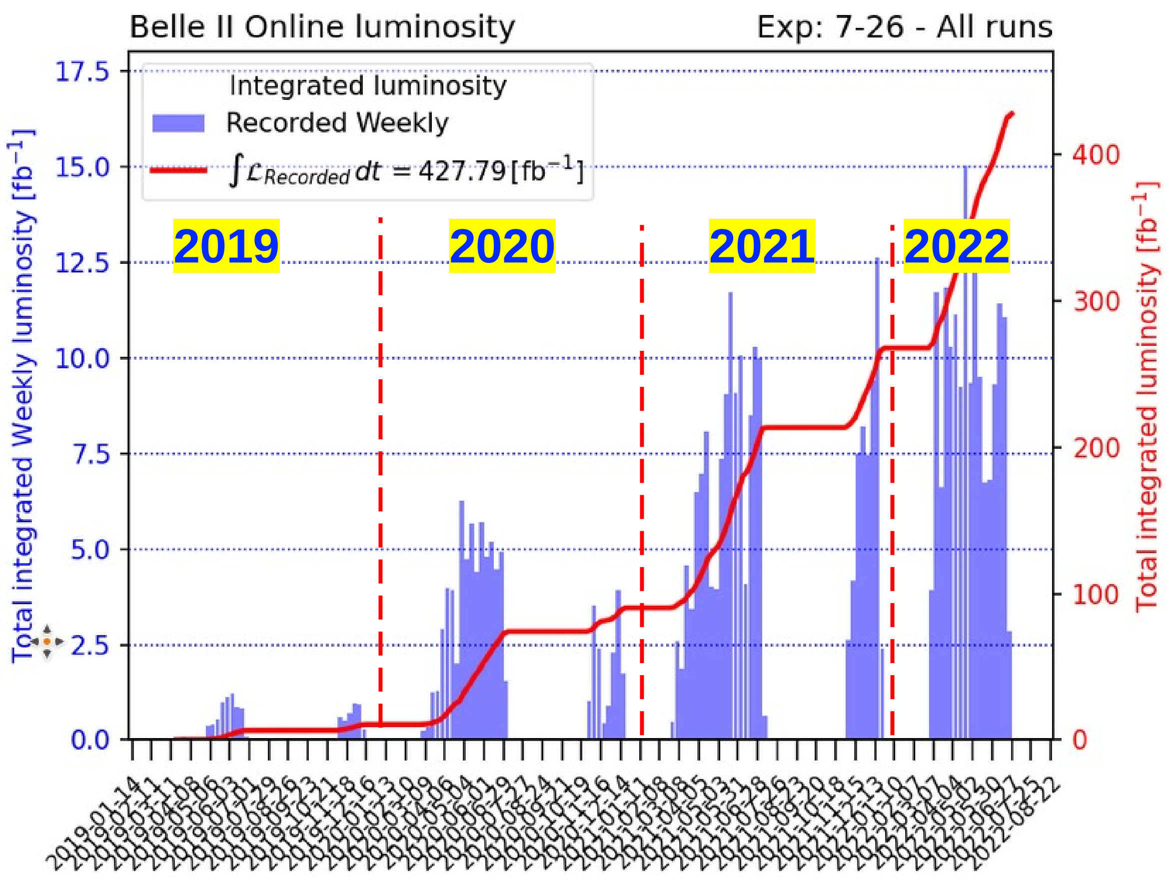




2008/Sep	2010/Oct	2018/Feb-Jul	2018/Nov	2019/Mar
First Origami chip-on-sensor concept	Belle II Technical design report	1st/2nd SVD half-shelf assembled	SVD installed in Belle II	First Collision with complete detector

Operation Experience

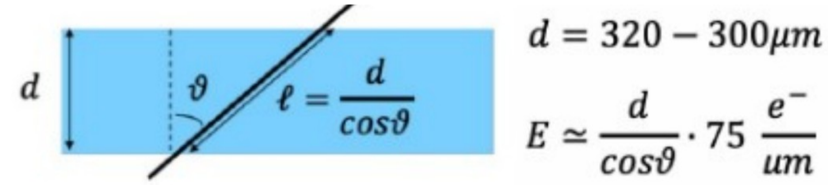
- **Reliable and smooth operation with no major issues since installation**
  - Total fraction of masked strips < 1%
  - One APV25 chip (out of 1748) disabled in spring 2019, fixed by cable reconnection in summer 2019
  - Temperature and calibration constants are evolving gradually
- **Excellent detector performance**
  - Average sensor hit efficiency > 99% and stable with time
  - Updated simulation better agrees with data
  - Reasonable cluster charge distribution

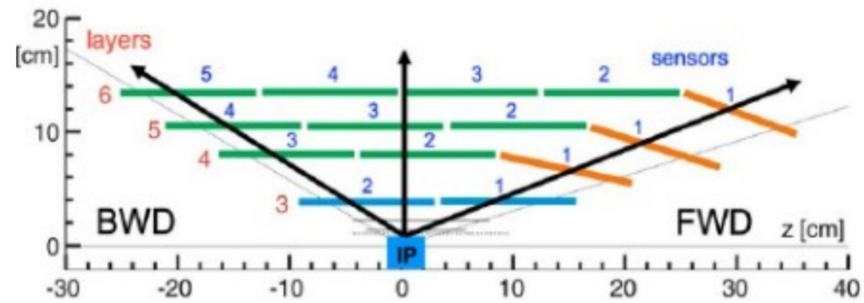


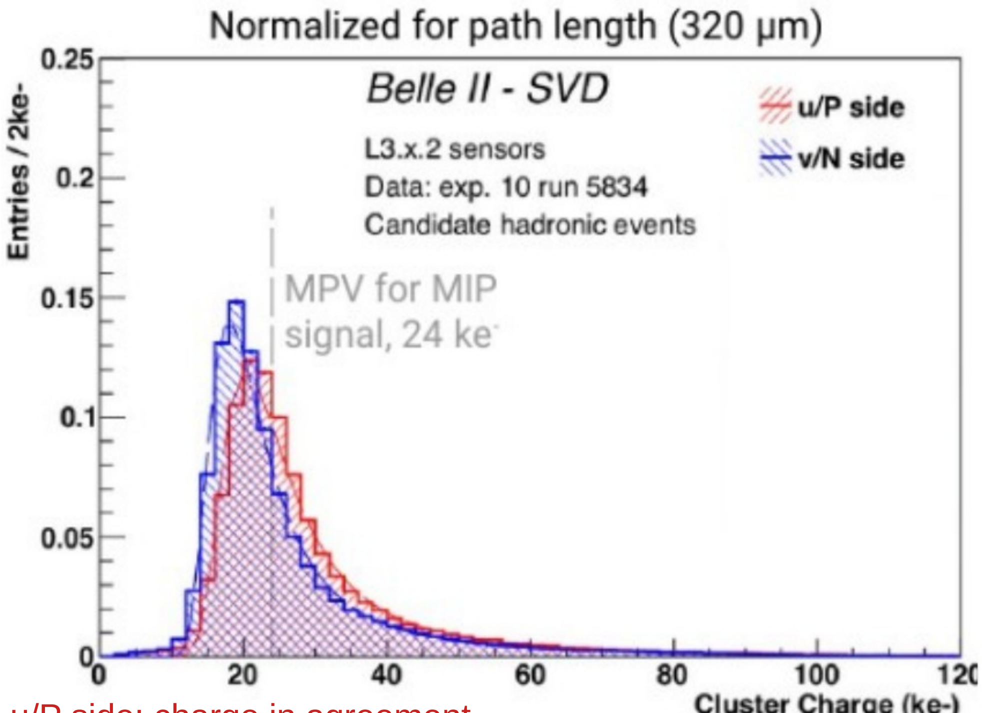
→ *Continuous data taking during anti-COVID measures, thanks to an excellent shifter/operator/coordinator team (local and remote)*

Signal charge and signal to noise ratio

- **Signal charge depends on the incident angle and varies with sensor position [Backward (BWD), Forward (FWD)]**
- **Normalized for the track path length in silicon (E*d/l) similar in all sensors and consistent with expectations**
- **Very good cluster Signal to Noise Ratio (SNR) in all 172 sensors (most probable value: 13-30)**

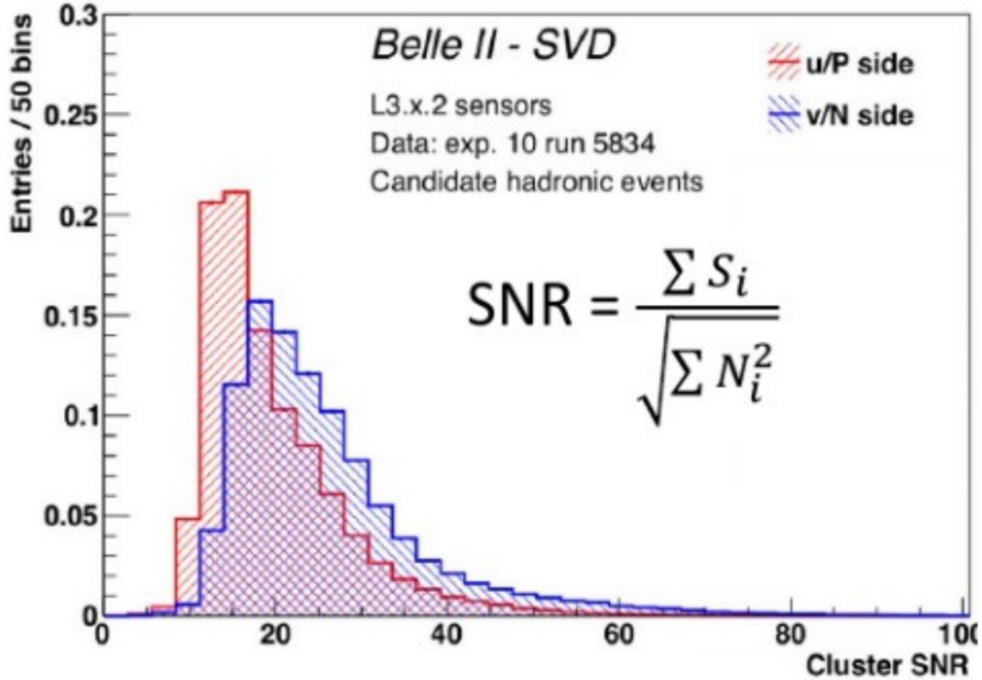






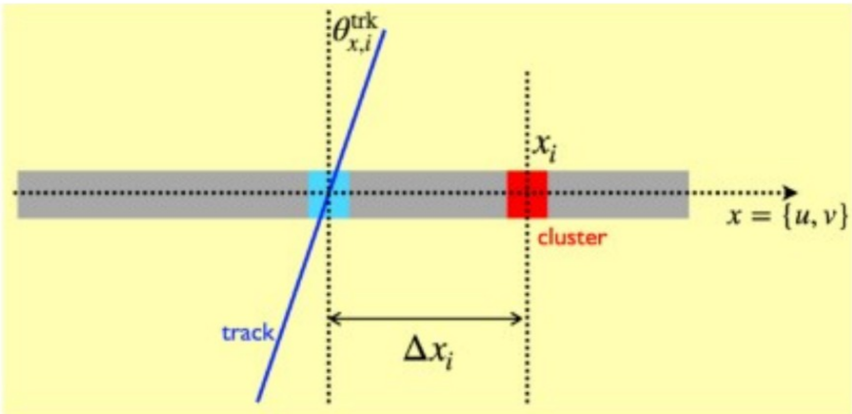
u/P side: charge in agreement with expectation from MIP taking into account 15% uncertainty in APV25 gain calibration

v/N side: 10%-30% signal loss due to large pitch and presence of floating strips



u/P side: larger noise due to longer strip length (larger inter-strip capacitance)

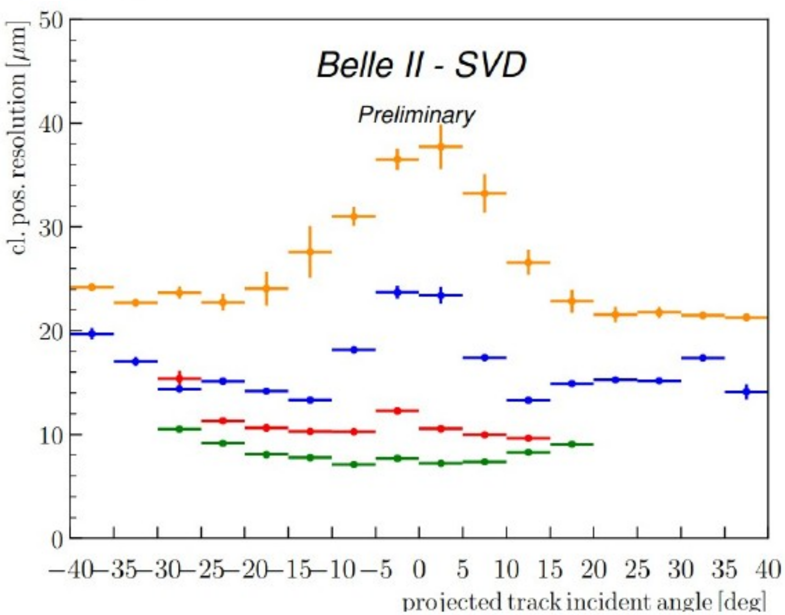
Cluster position resolution

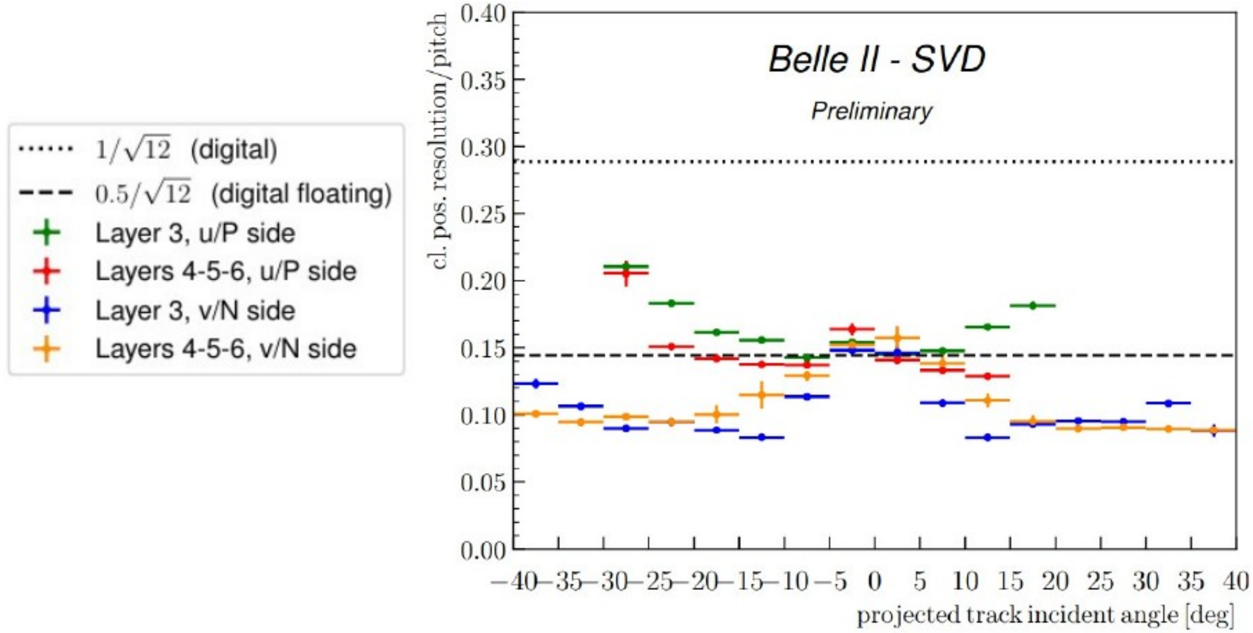


$$\sigma_x = \sqrt{\left\langle (\Delta x_i)^2 - \left(\sigma^{trk}_{x,i}\right)^2 \right\rangle}$$

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

- **Excellent resolution on the position is crucial for good quality reconstructed tracks and vertices**
- **Resolution estimated from residual of the cluster position w.r.t unbiased track extrapolation using $e^+e^- \rightarrow \mu^+\mu^-$ events**
- **Effect of track extrapolation error is subtracted**
- **Good resolution, generally in agreement with pitch expectations**
  - Black dashed and dotted line in lower right plot





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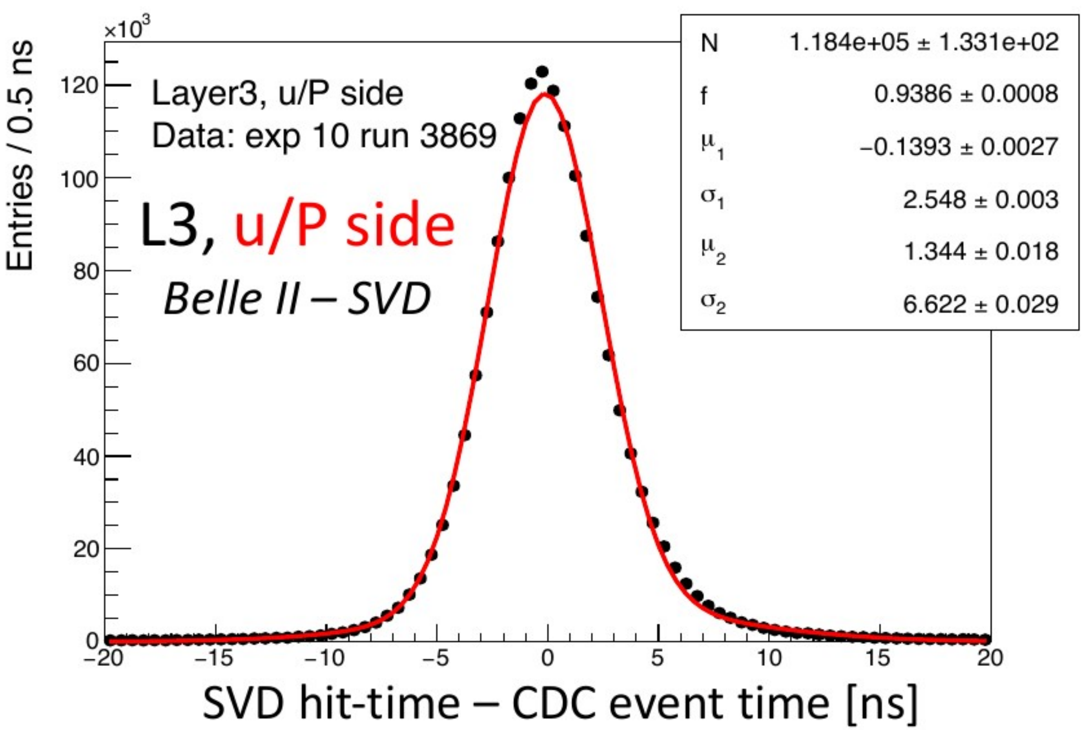
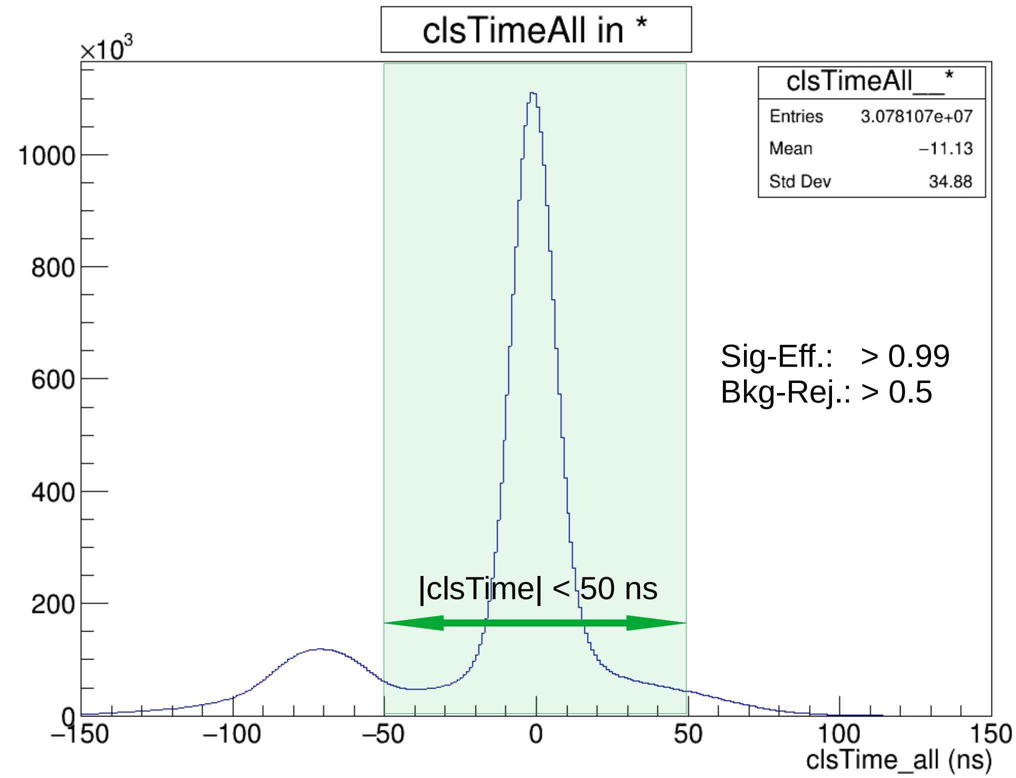
Hit-time resolution

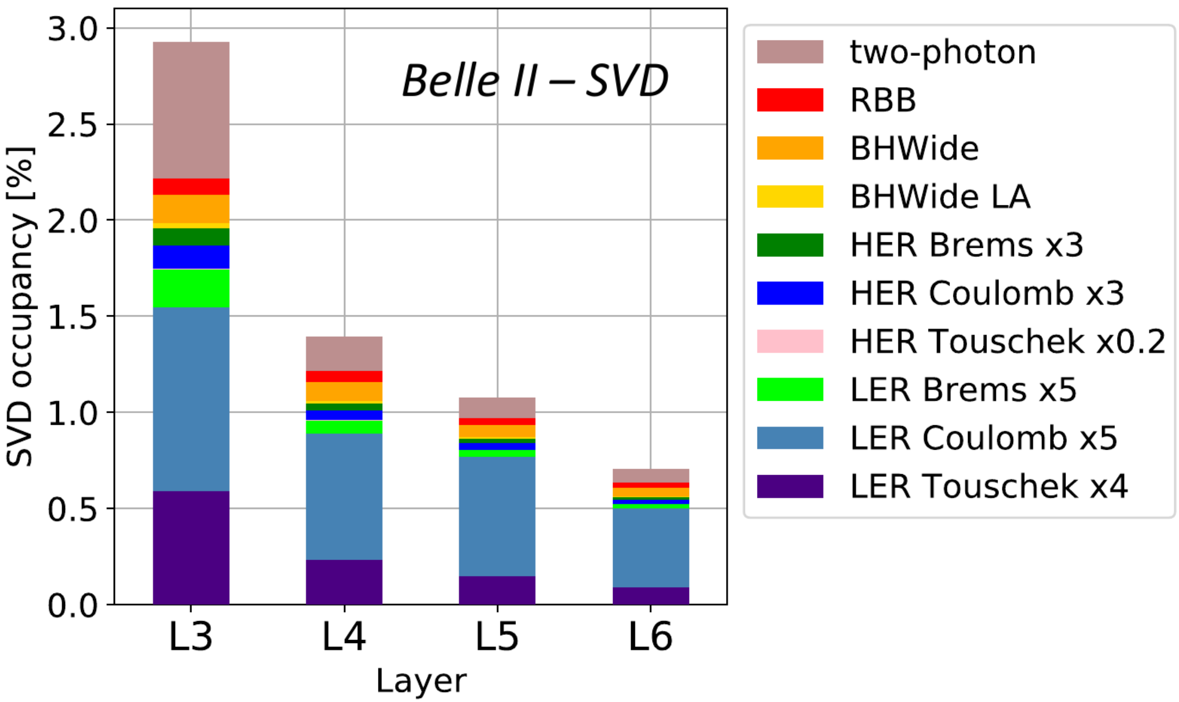
- **Excellent hit time resolution (< 3 ns) w.r.t. event time provided by Central Drift Chamber (event t_0)**
- **Able to efficiently reject off-time background hits**
  - Will be used for higher luminosity and background levels
  - A tighter selection can be achieved by removing the trigger jitter contribution (hit time – t_0)
- **Improvement in High Level Trigger performance by using SVD hit time to compute the event t0:**
  → same resolution and 2000 times faster computation time w.r.t. the CDC event t0.





Beam background and hit occupancy limit

- **Beam background increases SVD hit occupancy → tracking performance suffers**
- **Current occupancy limit in layer 3 is ~3%**
  → hit time cut could increase this number to 5%, due to improved background rejection
  - Studies with SVD standalone tracking ongoing to validate the performance (benchmark finding efficiency > 90% and fake rate < 20%)
  - Average hit occupancy in layer 3 is around 0.5% and well under control at current luminosity
  - At a benchmark luminosity of L = 8 x 10^{35} cm^{-2} s^{-1} , we expect an average occupancy of about 3% in layer-3 (estimated scaling MC with data/MC ratio)**



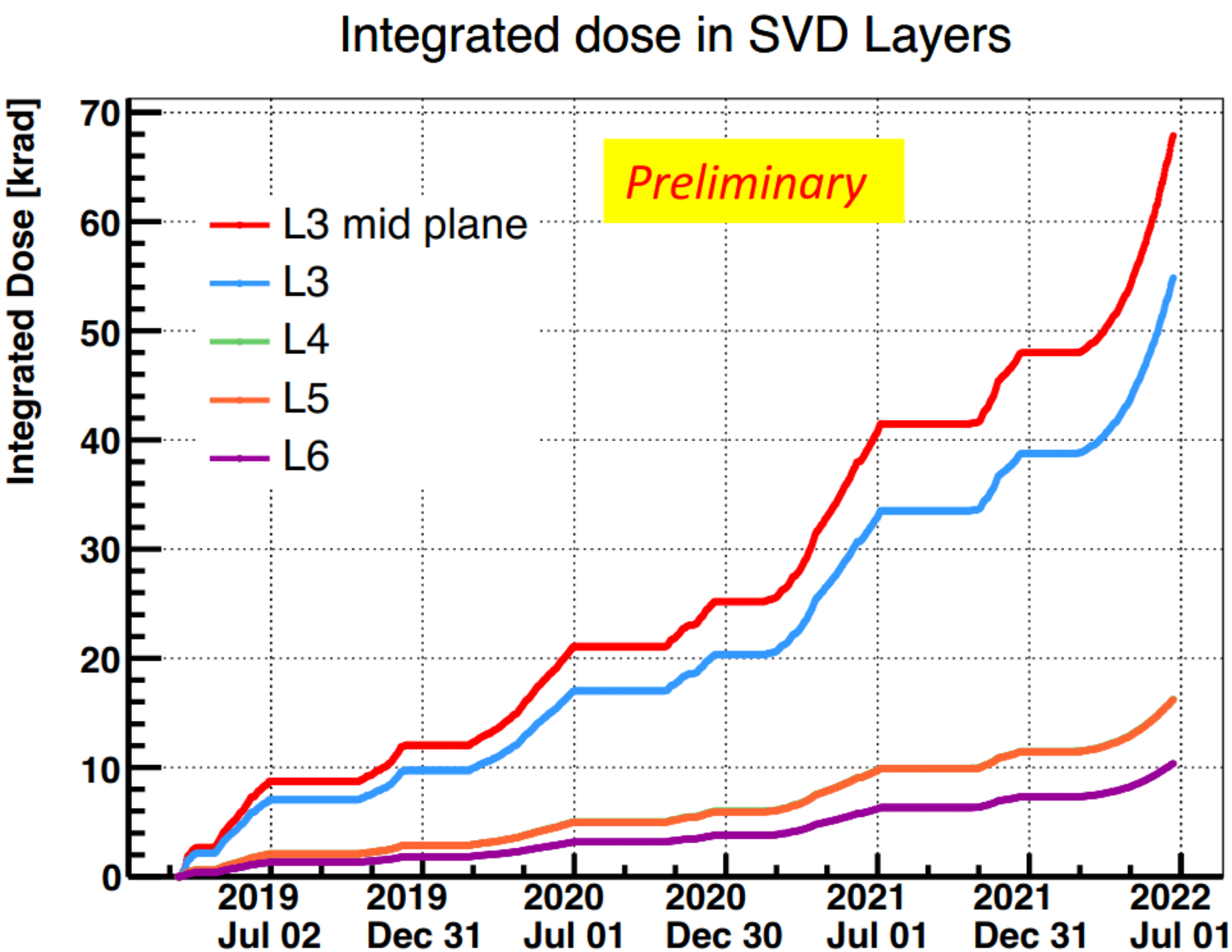
** Large uncertainties on long term background extrapolation, computed assuming optimal collimator settings and without injection background **

Small safety factor and large uncertainties on expected beam background motivate the vertex detector upgrade
→ improve tolerance to hit rates and radiation; technology assessment ongoing

More in the upgrade talk by Peter Krizan

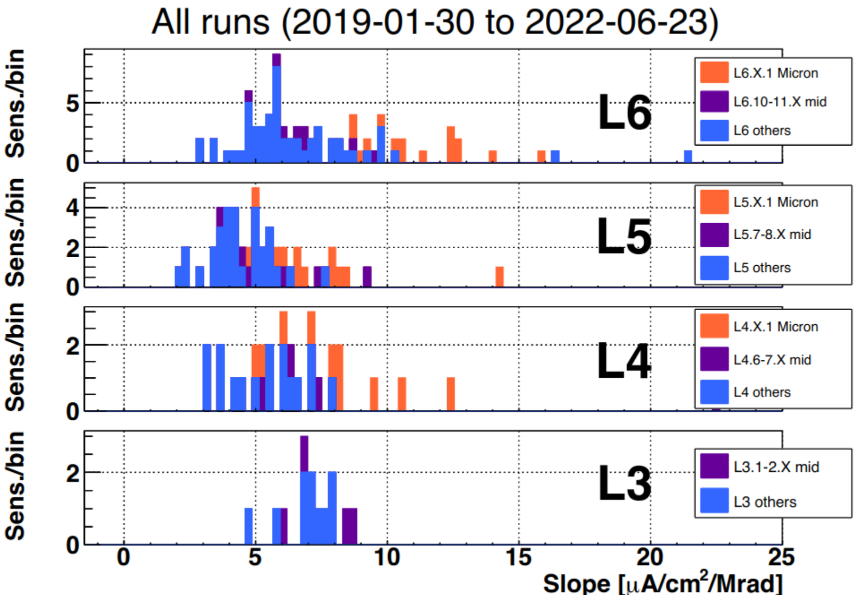
Integrated dose

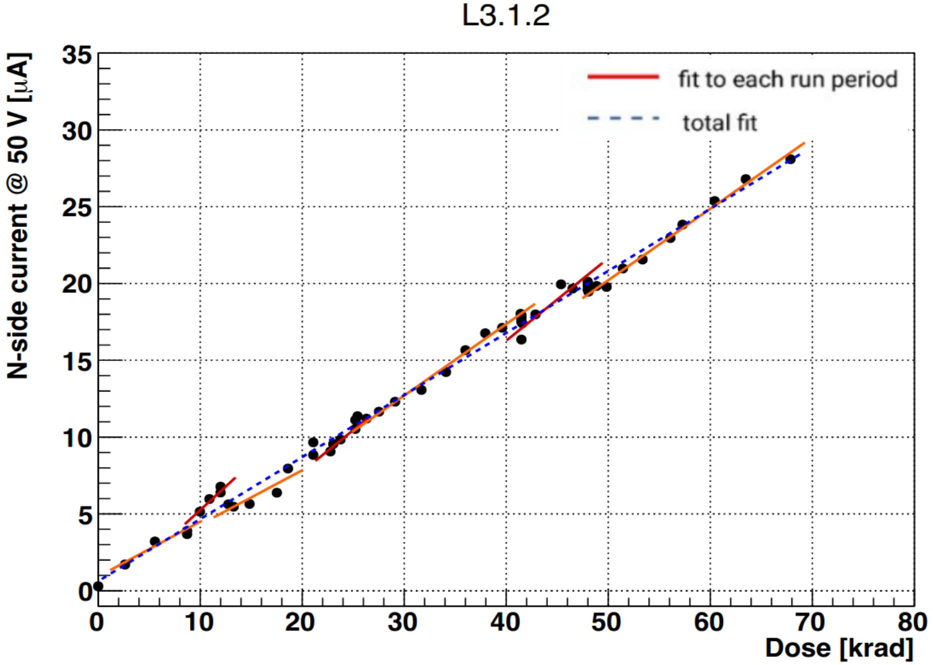
- **Estimated by using the good correlation measured on data among SVD occupancy and diamond dose**



- **SVD dose in the last 2022 period ~ 20 krad in most exposed layer 3 mid plane sensors**
  - Total SVD integrated dose on layer 3 mid plane < 70 krad
  - 1-MeV equivalent neutron fluence evaluated to be ~1.6×10^{11} neq/cm^2 in first 3 years (assume neq/dose fluence ratio = 2.3×10^9 neq/cm^2/krad from simulation)

Radiation effect: leakage current





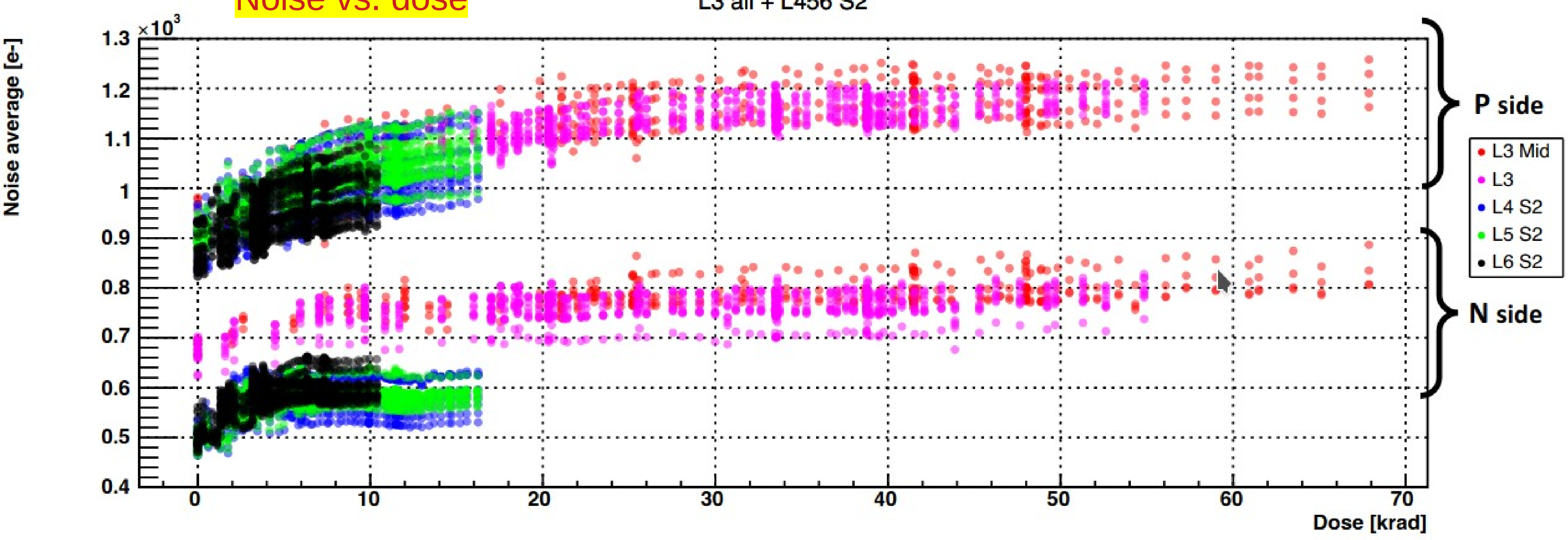
- **Good linear correlation between leakage current and estimated dose as expected from NIEL model $\Delta I = \alpha\, \varphi_{eq}\, V$ assuming a constant dose / φ_{eq} ratio**
- **Slope of the same order of magnitude as BaBar measurement* (1 µm/cm²/Mrad at 20° C)**
  - preliminary results show large variations due to temperature effects and dose spread among sensors in layer (average dose in layer used in estimate)
- **Irradiation is not expected to degrade SVD performance, even up to 6 Mrad:**
  - SNR expected to be still > 10
  - leakage current will contribute to strip noise increase
  - Currently, noise increase dominated by sensor interstrip capacitance due to the short APV25 shaping time

*[NIMA 729, 615-701, 2013]

Radiation effect: strip noise vs. dose

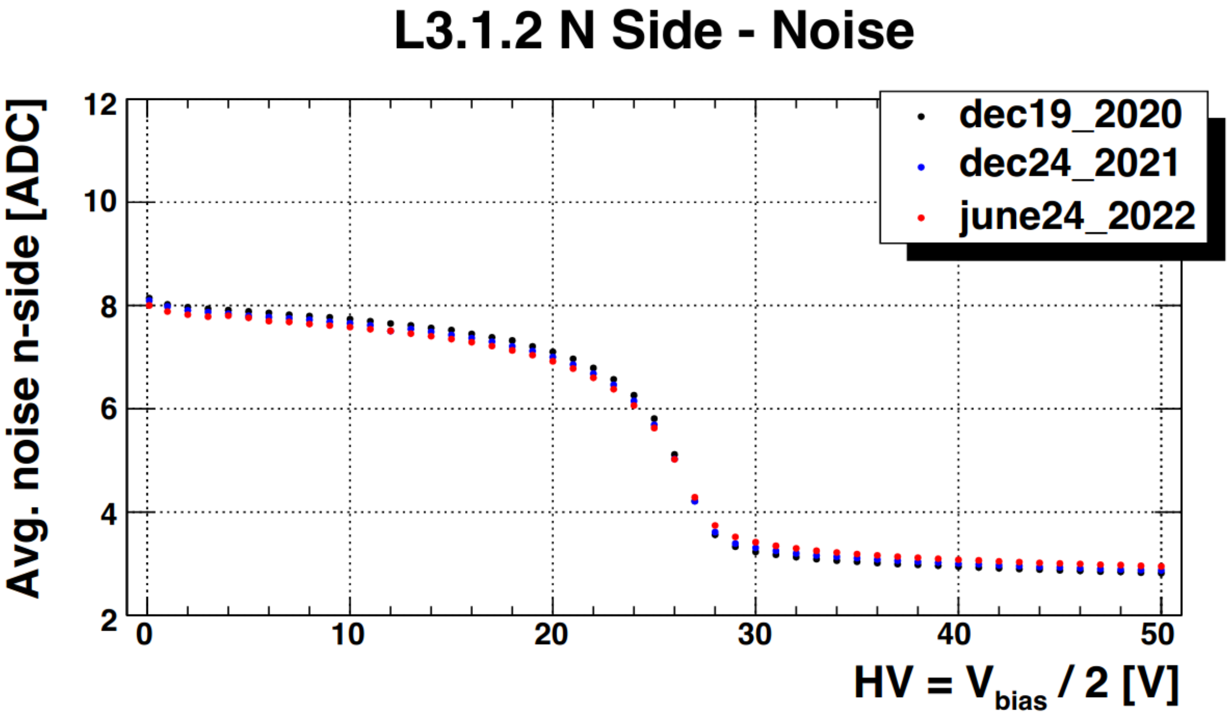
- **Noise increase is ~10-30% not affecting performance**
- **Induced by radiation effects on sensor surface: non-linear increase due to fixed oxide charges in irradiated sensors that increase inter-strip capacitance**
  - already saturated on n-side and layer 3 p-side, still rising on outer layer p-side
  - leakage current increase has no effect on strip noise due to short APV shaping time

Noise vs. dose

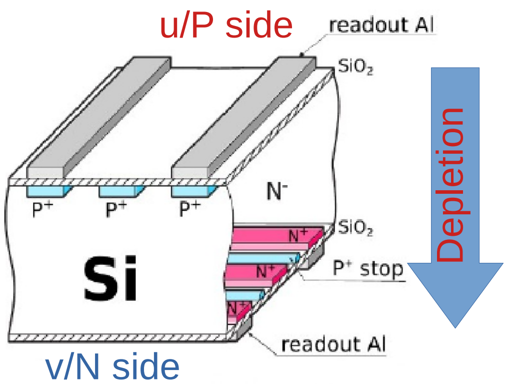


Radiation effect: bulk damage effect

- **Bulk damage can change effective doping and depletion voltage**
- **Measure depletion voltage with scan (n-side strip noise vs. bias voltage)**
  - n-side strips insulated only when the n-type bulk is fully depleted → minimum strip noise full depletion
  - Over-depletion bias still slightly decrease noise

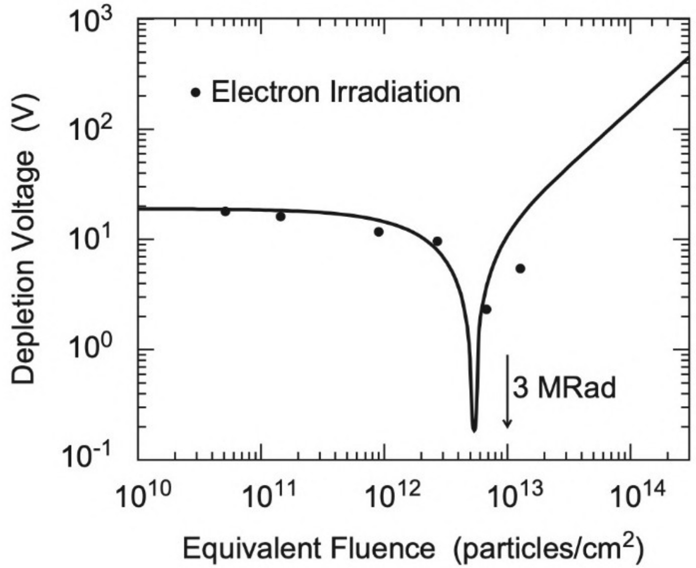


No change in full depletion voltage observed with time so far, consistent with low integrated neutron fluence(~1.6 x 10^{11} neq/cm^2)



BaBar SVT depletion voltage

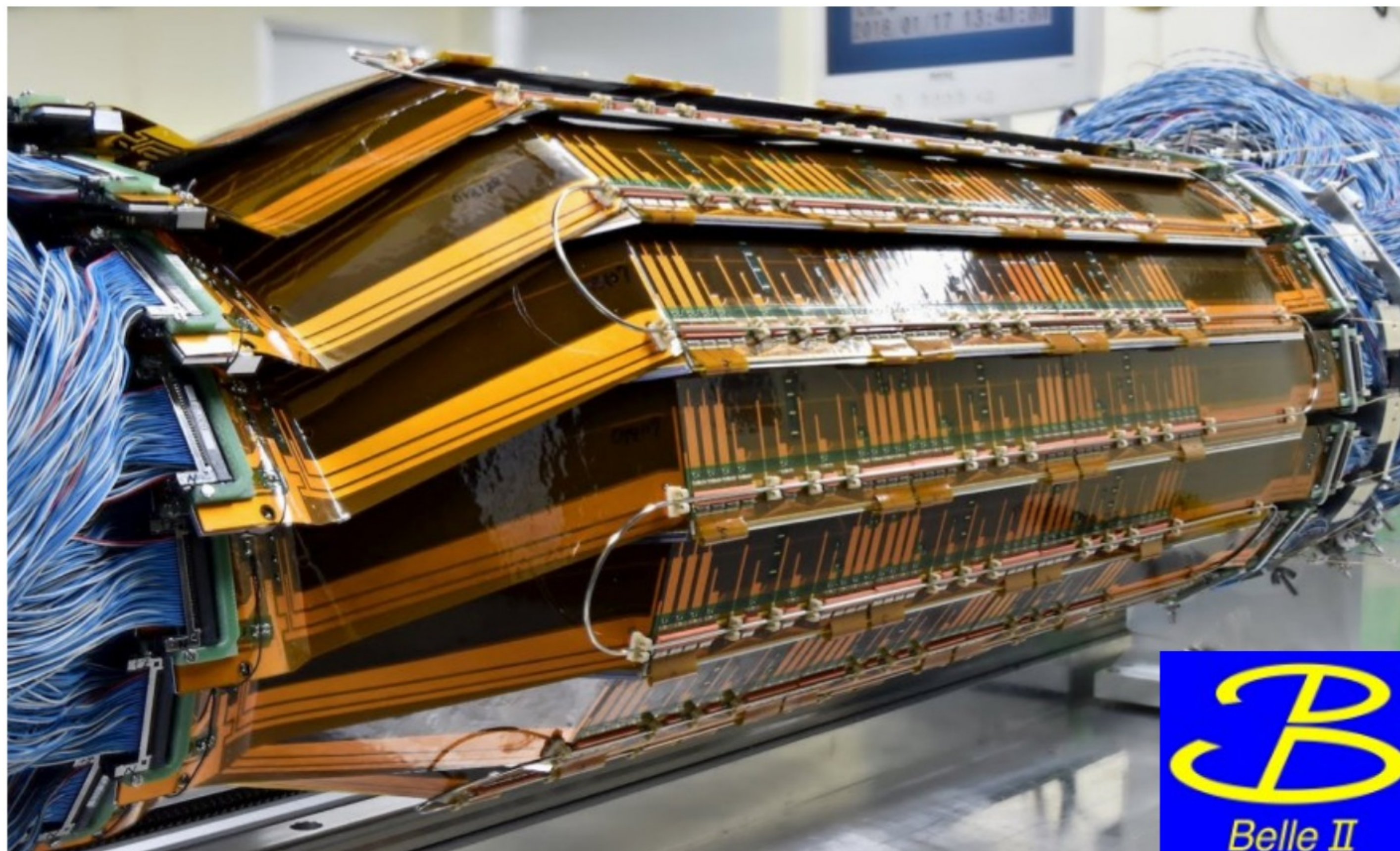
Nucl.Instrum.Meth.A 729 (2013) 615-701



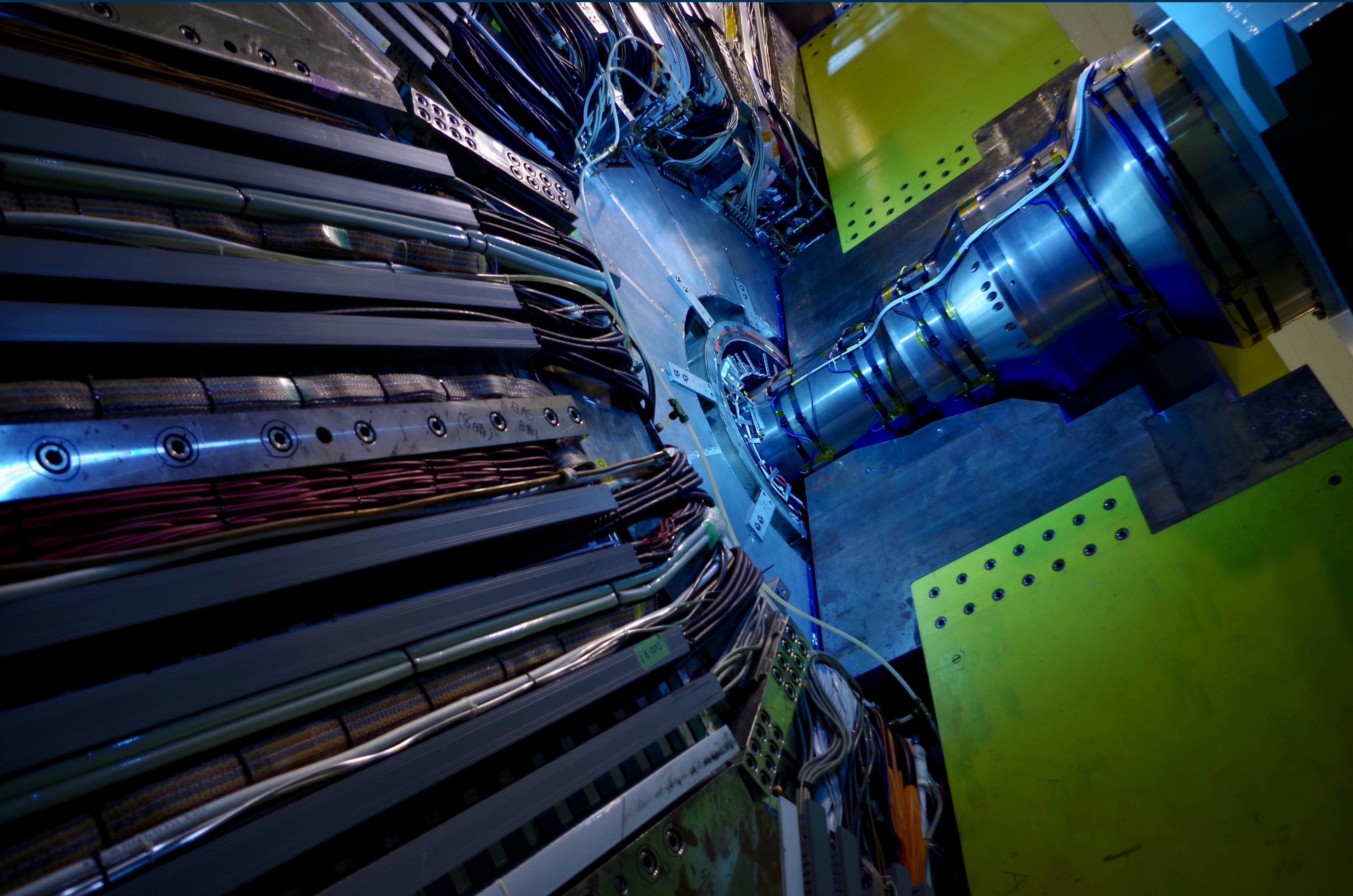
Summary

- **SVD has been taking data smoothly in Belle II since March 2019**
  - reliable operation and excellent stable performance!
- **Observed first effects of radiation damage, not affecting performance**
- **System prepared to cope with higher background by rejecting off-time background, exploiting the excellent SVD hit time resolution**

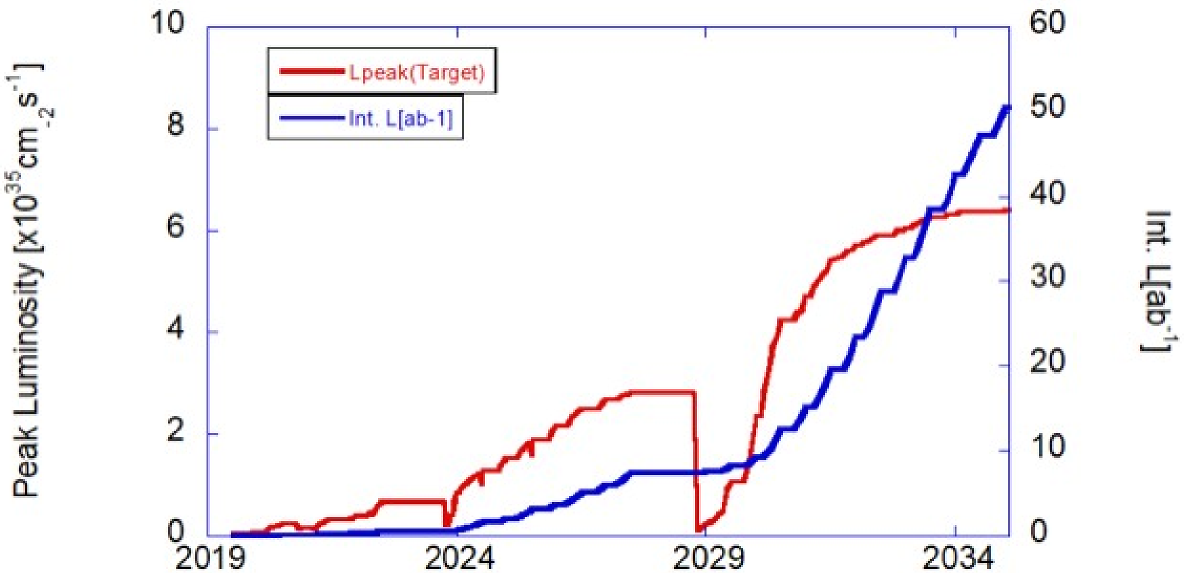
SVD technical paper accepted by JINST, available on arXiv: https://arxiv.org/abs/2201.09824

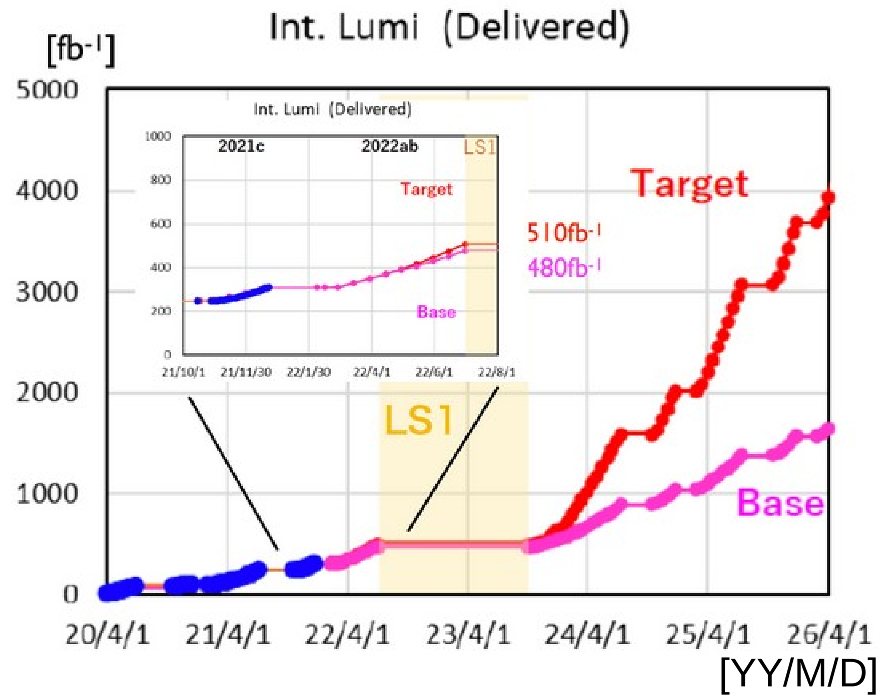


Thank You!



Luminosity projection of SuperKEKB





Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run.

- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027

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