The Silicon Vertex Detector of the Belle II Experiment

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on behalf of the Belle II SVD Collaboration

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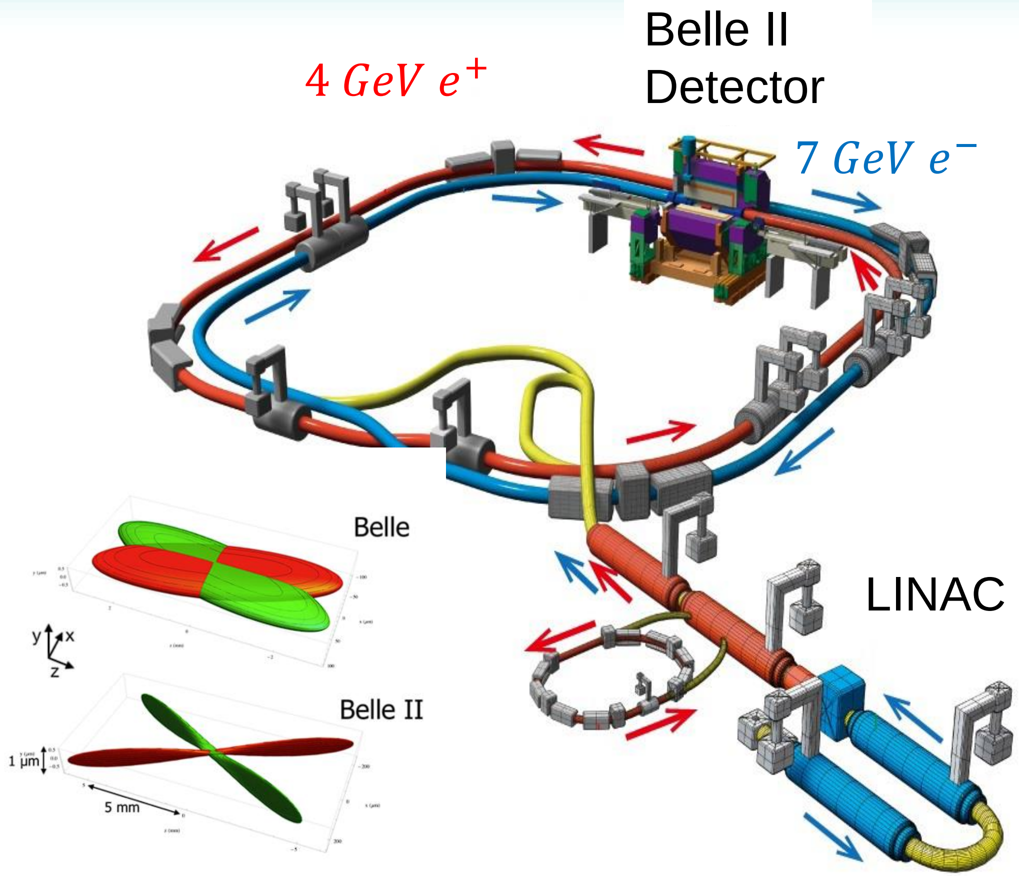
Outline

- SuperKEKB and Belle II
- Silicon Vertex Detector (SVD)
- Operation & Performance
- Beam backgrounds & Radiation effects
- Summary

SuperKEKB and Belle II

- SuperKEKB collider (KEK, Japan)
  - Asymmetric energy ($4\ GeV\ e^+$ & $7\ GeV\ e^-$)
  - CM energy: 10.58 GeV for $\Upsilon(4S)$ resonance
  - Nano beam scheme to achieve high luminosity
  - Target luminosity: $6 \times 10^{35}\ cm^{-2}s^{-1}$
  - Target Integrated L: $50\ ab^{-1}$
- B factory at luminosity frontier <-> LHC
  - Search for new physics with B, charm, and τ rare decays
- So far ~ $424/fb^{-1}$ are collected since March 2019
  - $\sim 4.7 \times 10^{34} cm^{-2}s^{-1}$, the new world record luminosity more than twice of KEKB



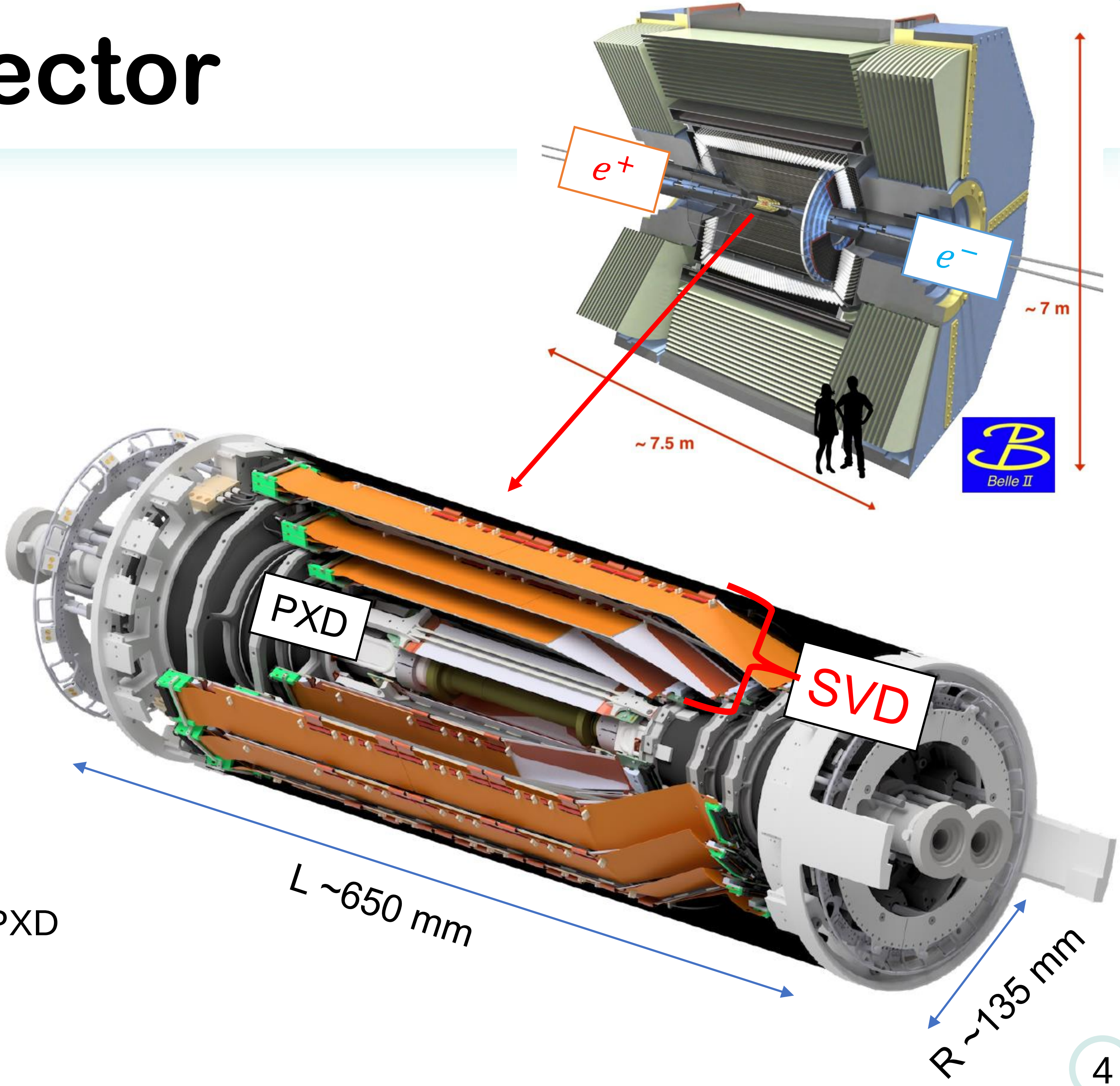
- SuperKEKB

Belle II vertex detector

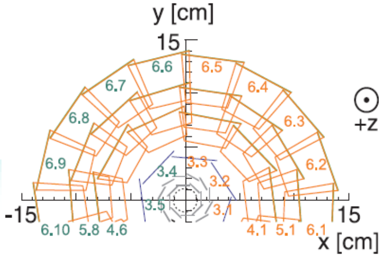
- Vertex detector (VXD)
  - 2 layers pixel detector (PXD)
    - DEPFET pixel sensor
  - 4 layers silicon vertex detector (SVD)
    - Double-sided Silicon Strip Detector

- Main features of Belle II SVD
  - Extrapolate tracks to PXD
  - Standalone tracking for low p_T tracks
  - Precise vertexing of K_S
  - Particle identification via dE/dx

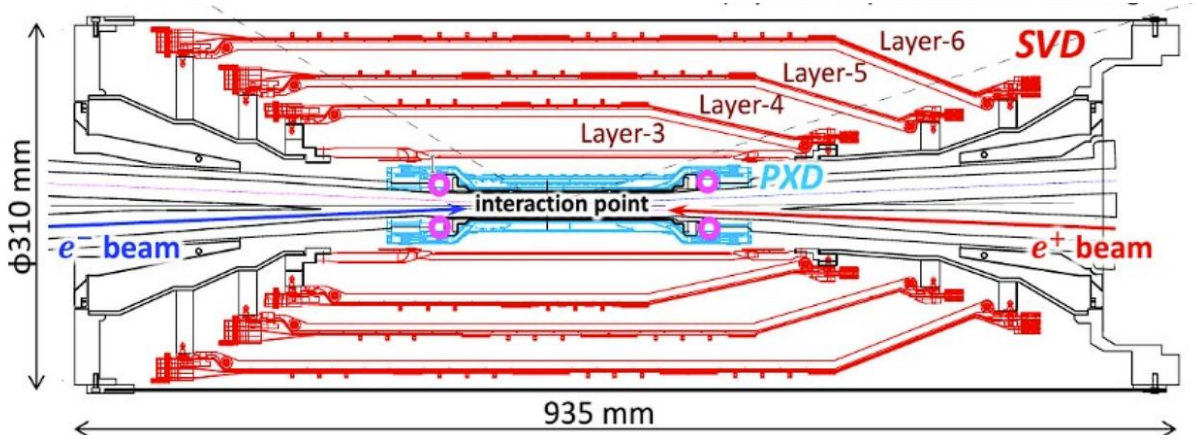
- SVD+PXD operation requirements
  - High background environment, with hit rates of 20 and 3 MHz/cm^2 for PXD (R = 14 mm) and SVD L3 (R = 40mm)
  - Radiation hardness: 2 and 0.2 Mrad/yr for PXD and SVD L3



Silicon Vertex Detector (SVD)



Physics acceptance: θ = 17-150°



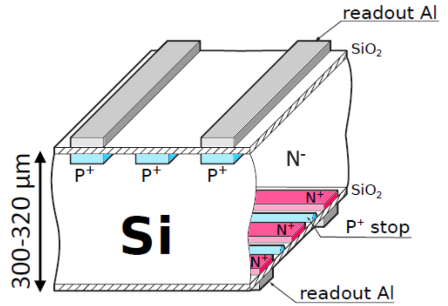
Diamond radiation sensors

- Each detector layer is organized in mechanically and electrically independent subsets called ladders
- Low material budget: 0.7%X_0 per layer
  - Total silicon area $1.2\ m^2$
- Diamond sensors for radiation monitor and beam abort

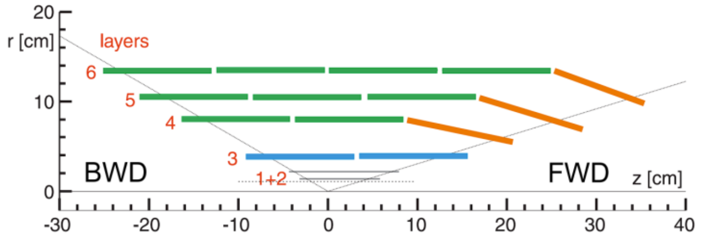
Layer	Ladders	Sensors /ladder	Radius (mm)
L3	7	2	39
L4	10	3	80
L5	12	4	104
L6	16	5	135
Total	45	172	

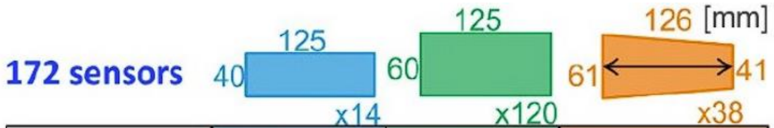
SVD sensors and front-end ASICs

- Double-sided Silicon Strip Detector (DSSD)
  - AC coupled strips
  - Depletion Voltage: 20-60 V
  - Operation Voltage: 100 V



- 3 different DSSD shapes

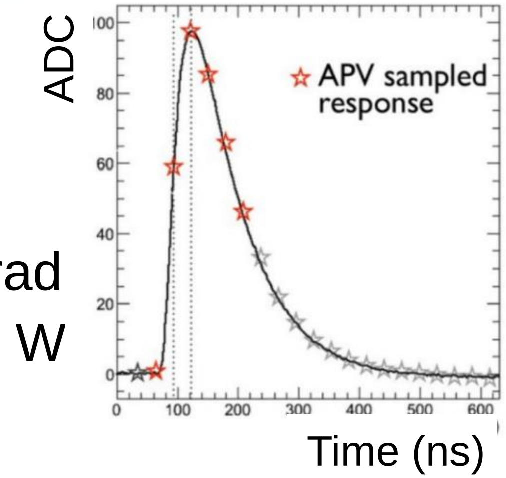




	Small	Large	Trapezoidal
# of p-strips*	768	768	768
p-strip pitch*	50 µm	75 µm	50-75 µm
# of n-strips*	768	512	512
n-strip pitch*	160 µm	240 µm	240 µm
thickness	320 µm	320 µm	300 µm
manufacturer	HPK		Micron

*readout strips – one floating strip on both sides

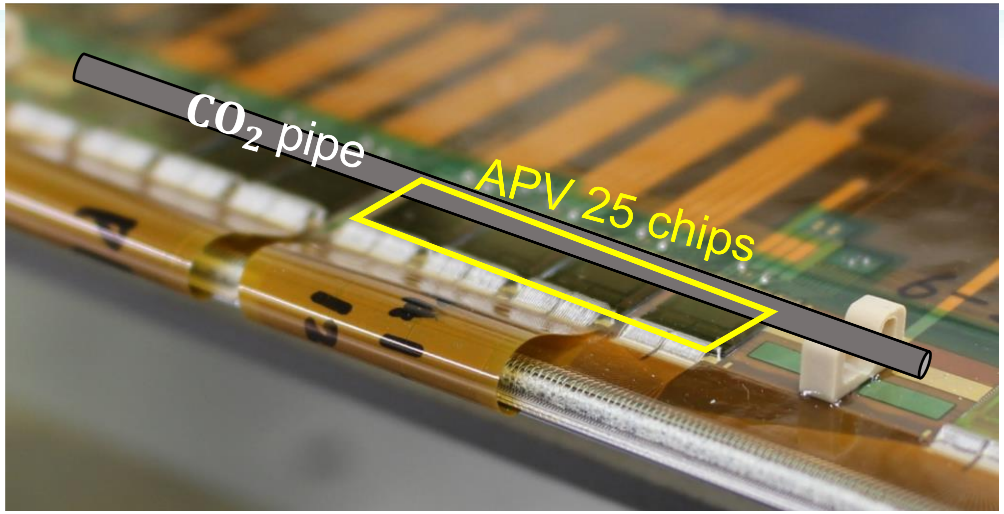
- APV25 front-end chip
  - Shaping time of 50 ns
  - 128 channels
  - Radiation hard: >100 Mrad
  - Power consumption: 0.4 W /chip (700 W in total)

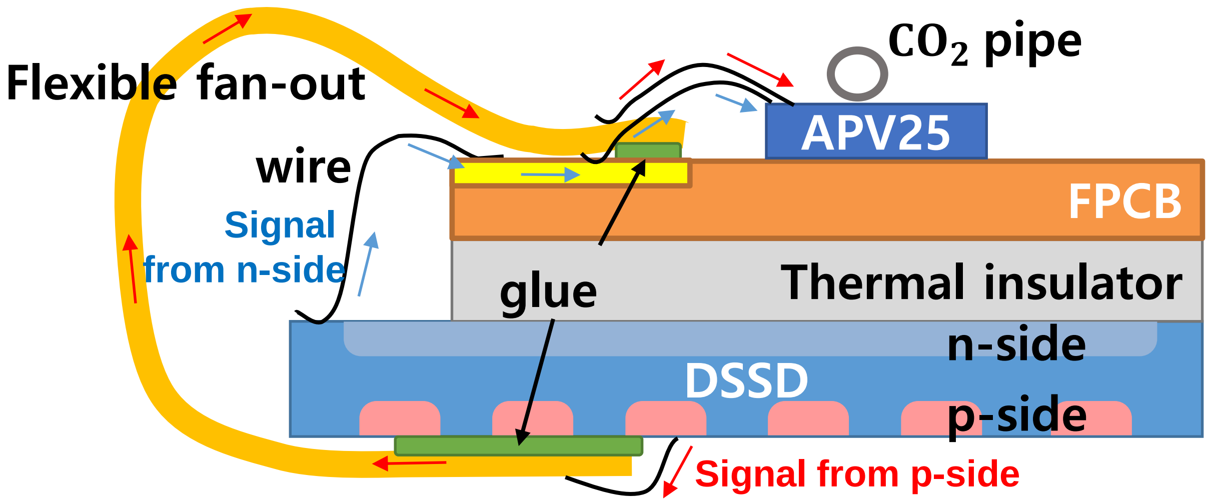


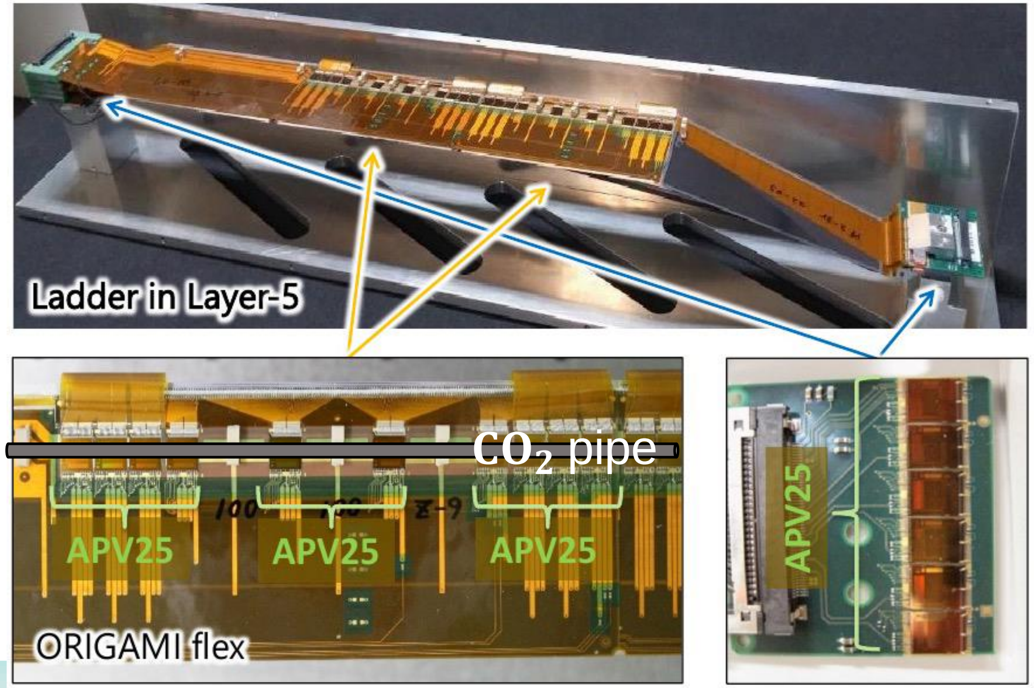
- Operated in multi-peak mods @ 32 Mhz
  - corresponding to 1/16 of the SuperKEKB RF clock
  - 6 subsequent samples recorded, 3/6-mixed acquisition mode also prepared to reduce the dead time, data size and occupancy at high luminosity

Origami chip-on-sensor concept

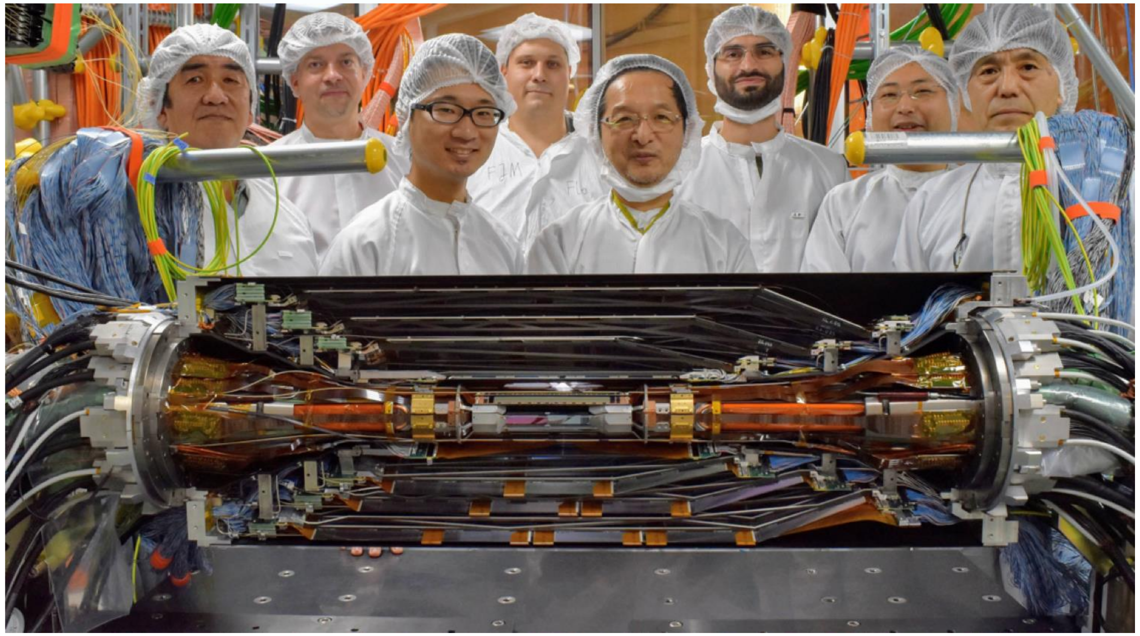
- Readout chips directly on each middle sensor:
  - Shorter signal propagation length → smaller capacitance and noise
- Cool only one side with two-phase CO_2 (-20℃) cooling







Construction, assembly, installation



- 2008 Sep: first Origami chip-on senor concept
- 2010 Oct: Belle II Technical design report
- 2018 Feb/Jul: 1st/2nd SVD half-shell assembled
- 2018 Nov: installed in Belle II
- 2019 Mar: first beam collision with complete detector

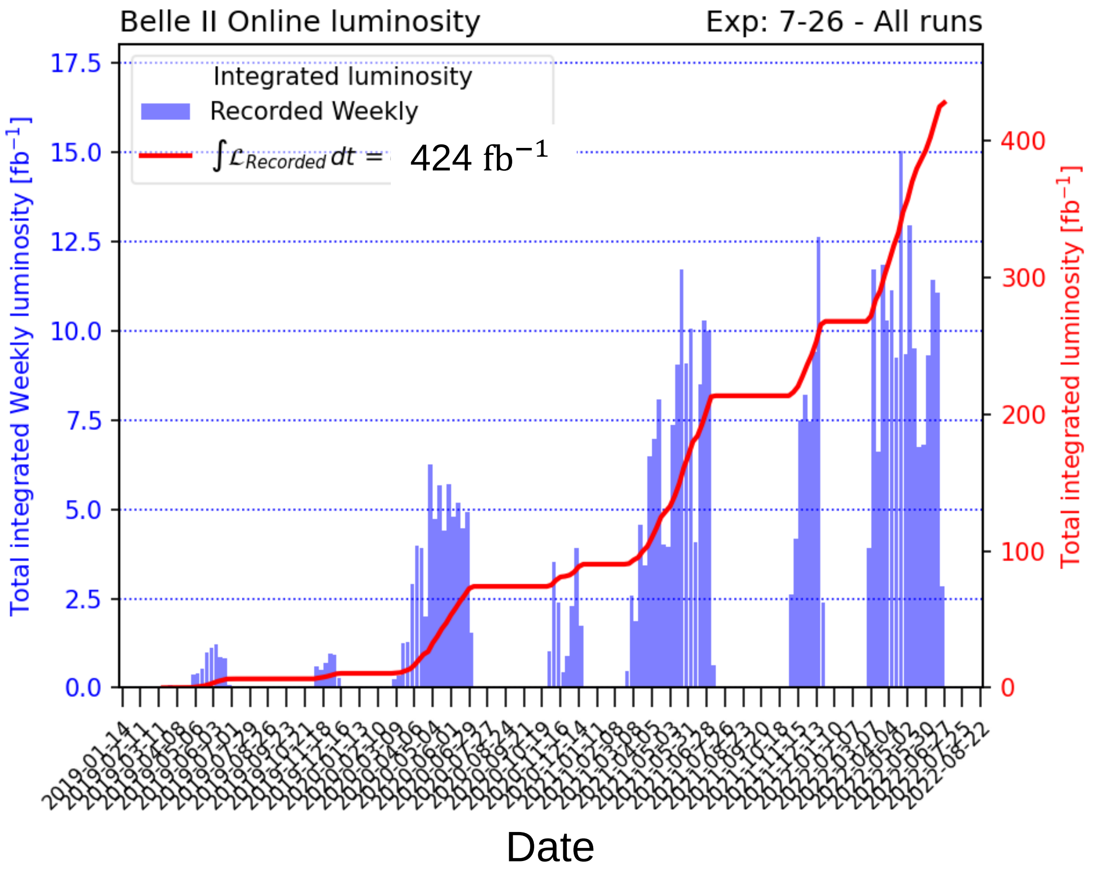
SVD operation & performance

SVD operation

- Reliable and smooth operation with no major issues since installation
  - A small number of defective channels (<1%)
  - **Stable** temperature and calibration constants evolution consistent with expectations

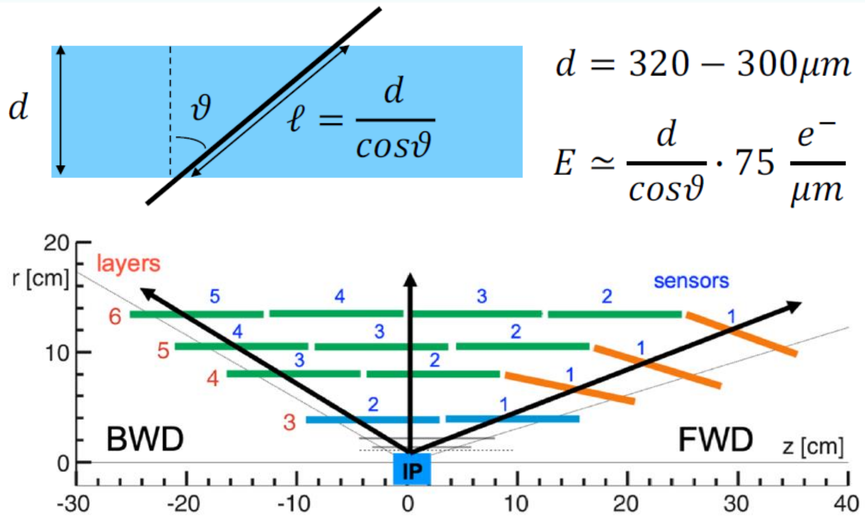
- Continuously taking data during COVID pandemic
  - excellent shifter/operator/coordinator (local and remote) system

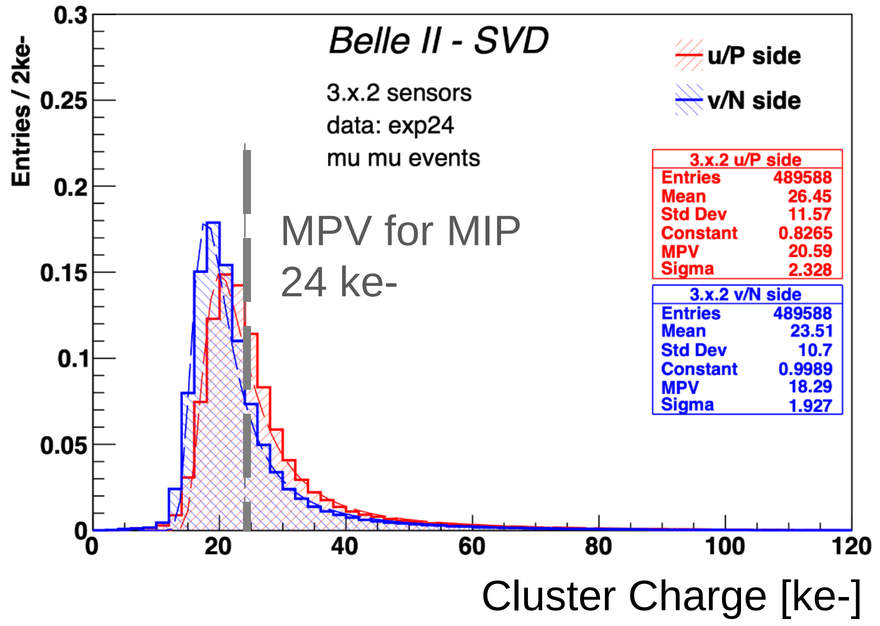
- **Excellent detector performance**
  - a large hit efficiency (>99%)
  - a good signal-to-noise ratio (SNR)

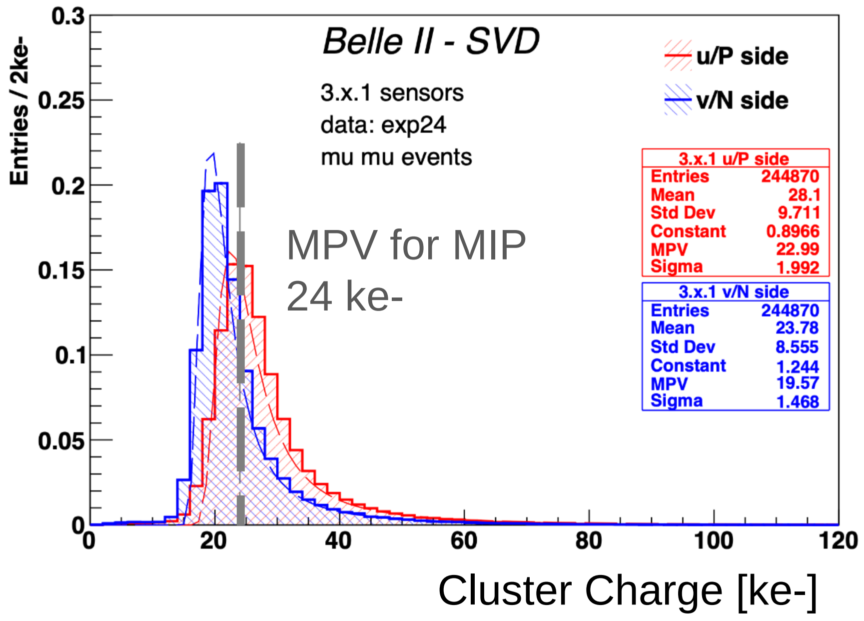


Cluster charge

- Signal charge depends on the incident angle
- Normalized for the track path length in silicon ($E \cdot d/\ell$), cluster charges are similar in all sensors and matches the expectations from MIP data taking
  - u/P side: MPV 21 ke-





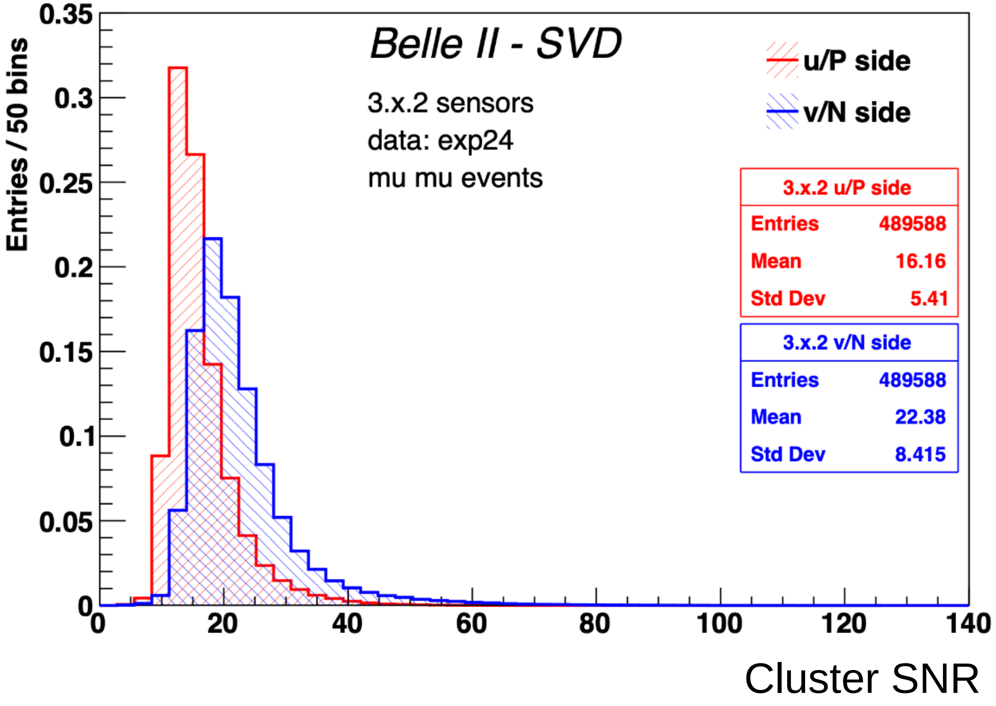


u/P: charge in agreement with expectation from MIP taking into account 15% uncertainty in APV25 gain calibration

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

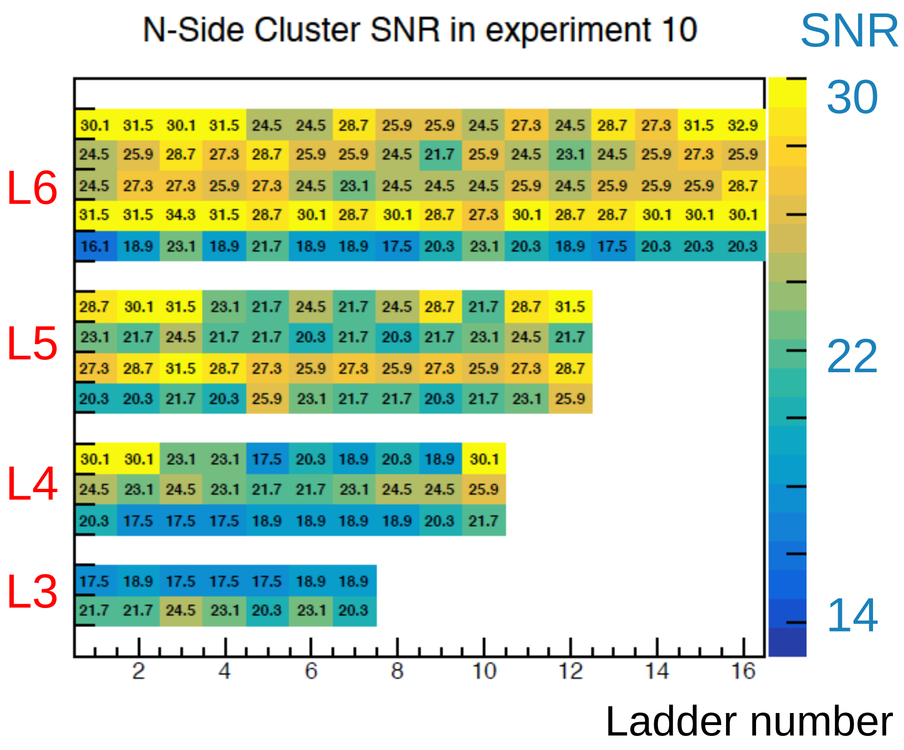
Cluster Signal to Noise Ratio

- $SNR_{cl} = \frac{\Sigma_{strip} S_i}{\sqrt{\Sigma_{strip} N_i^2}}$
- Very good cluster Signal to Noise Ratio (SNR) in all 172 sensors
  - MPV: 13 - 30 depending on sensor position and side

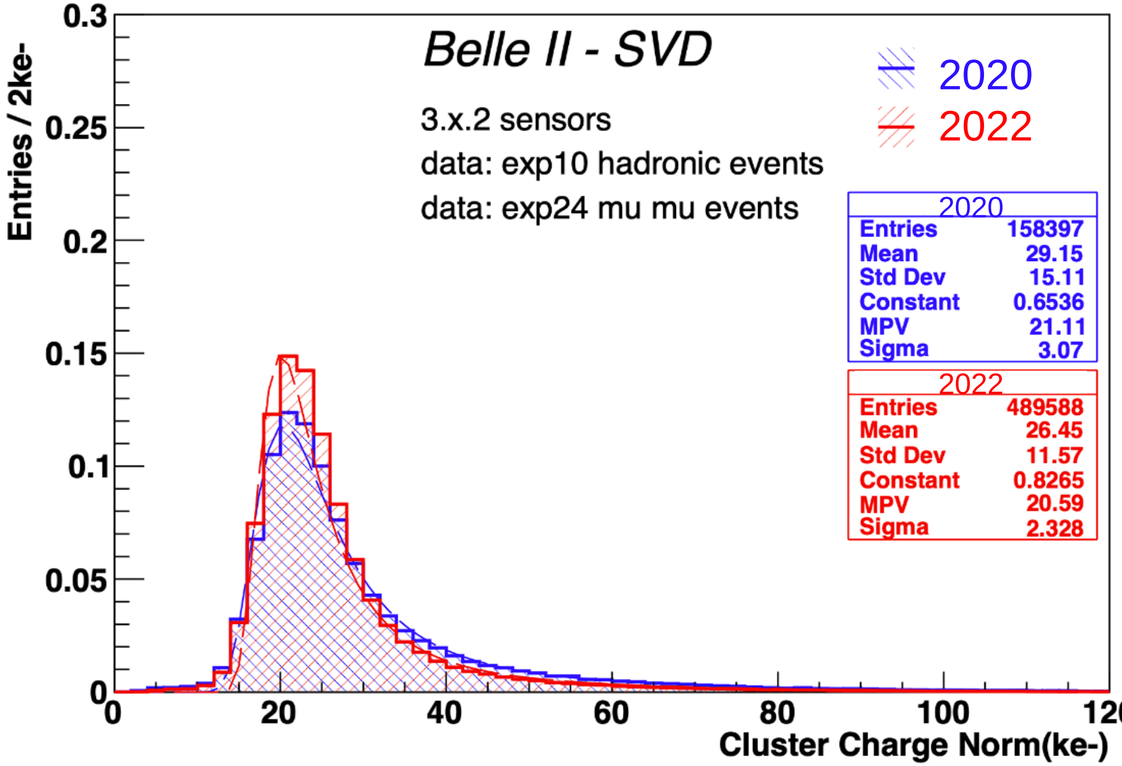


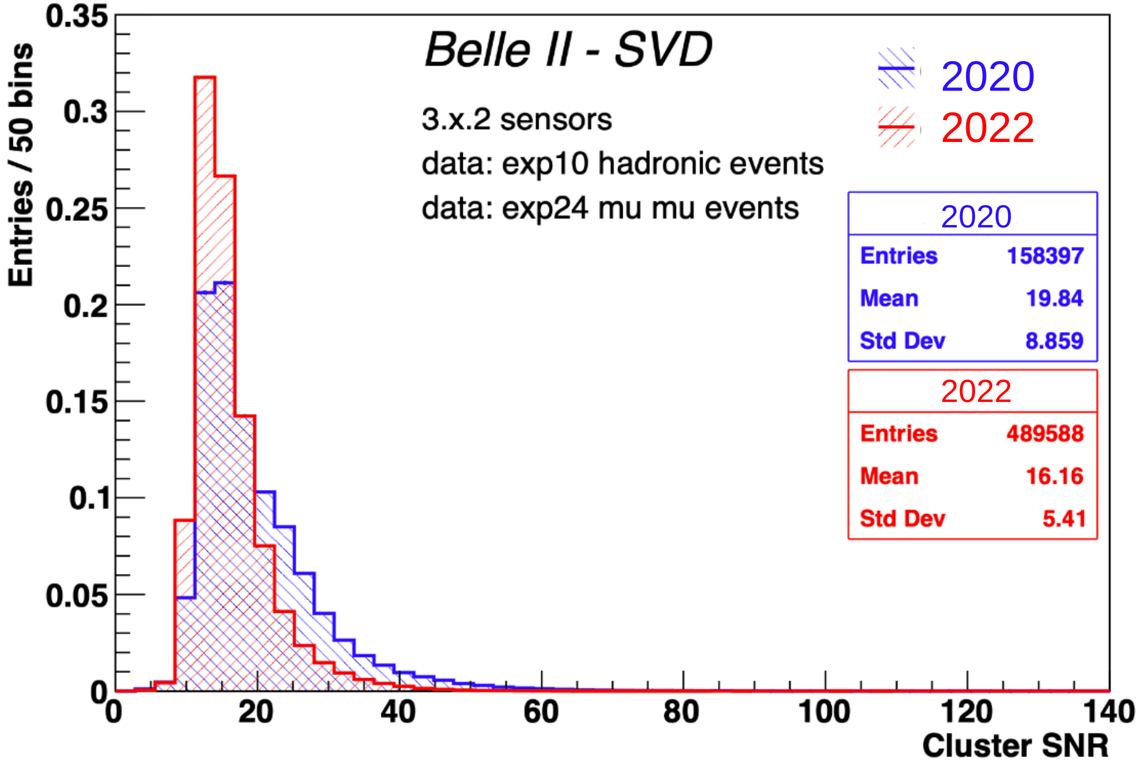
Before irradiation

Sensor position/type	$(u/P)side$ $Noise(e-)$	$(v/N)side$ $Noise(e-)$
Layer 3 (small)	930	630
Layer 4/5/6 Origami (large)	958	510
Layer 4/5/6 BWD (large)	790	680
Layer 4/5/6 FWD (wedge)	740	640



Cluster Charge & SNR (2020 vs 2022)



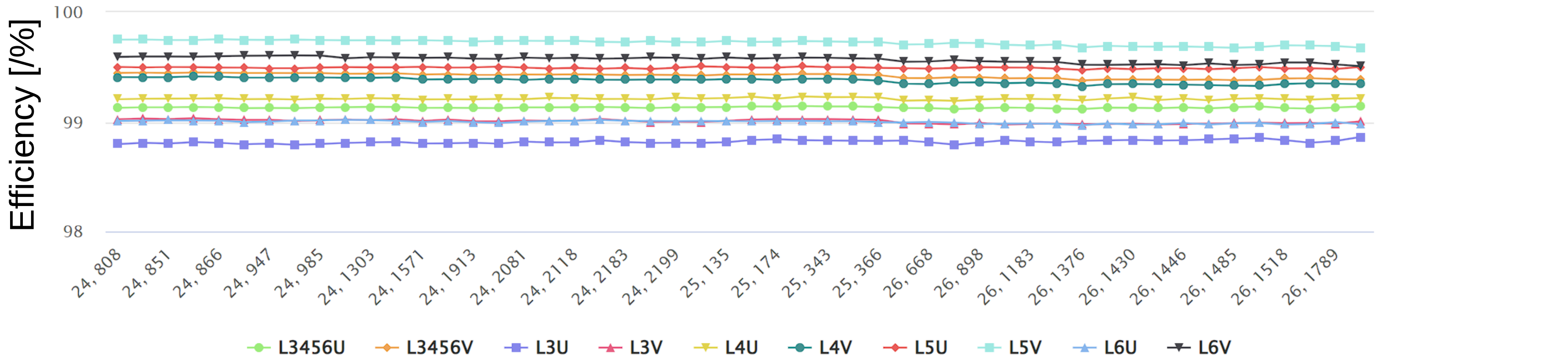


2020 vs 2022 comparison **shows good stability!**

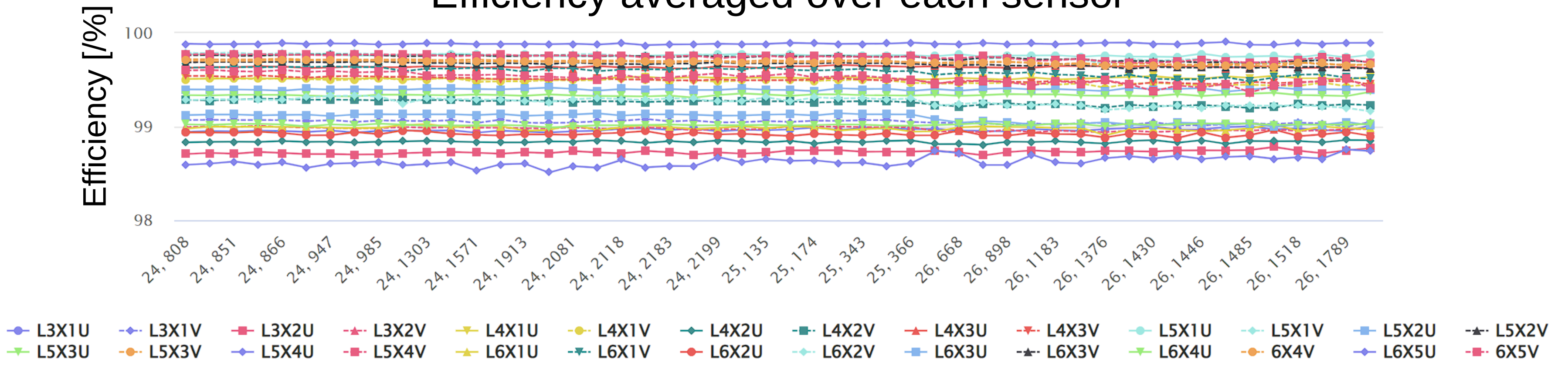
- Similar cluster charge normalized to the track length
- There are some small changes visible in SNR due to increased noise from radiation damage (@ 20-30% in layer 3)

Average hit efficiency

Average Efficiency per layer



Efficiency averaged over each sensor



2022 February

2022 June

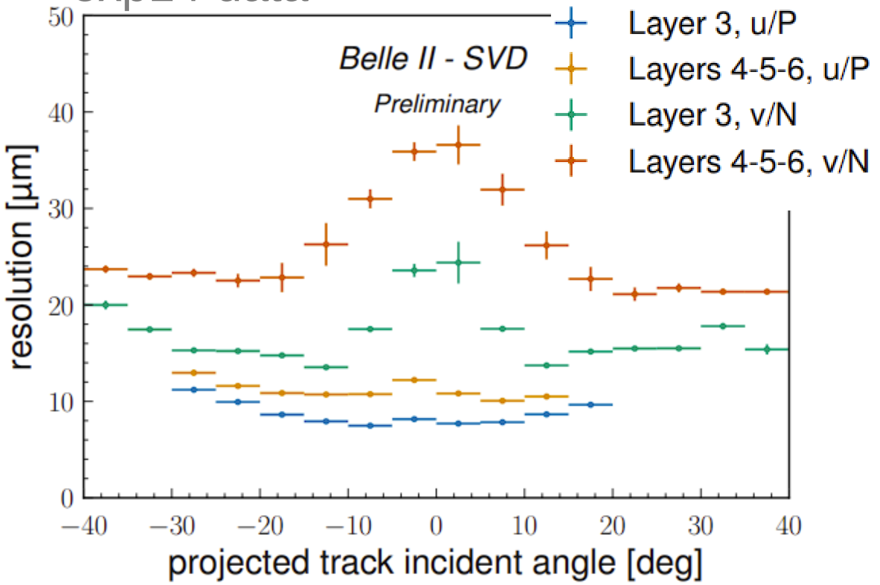
Hit efficiency very high and very stable in time

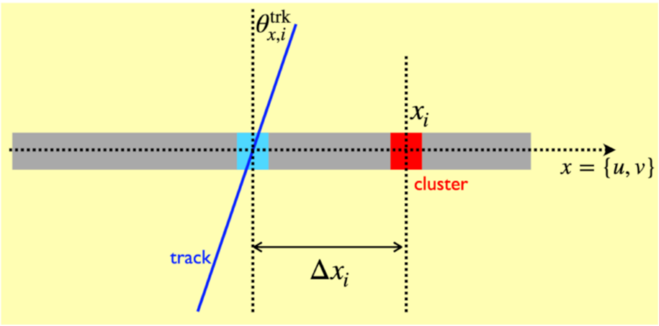
→ 99% for most of the sensors

Cluster position resolution - 1

- 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-→μ+μ- events
- Good resolution, generally in agreement with pitch expectations

exp14 data

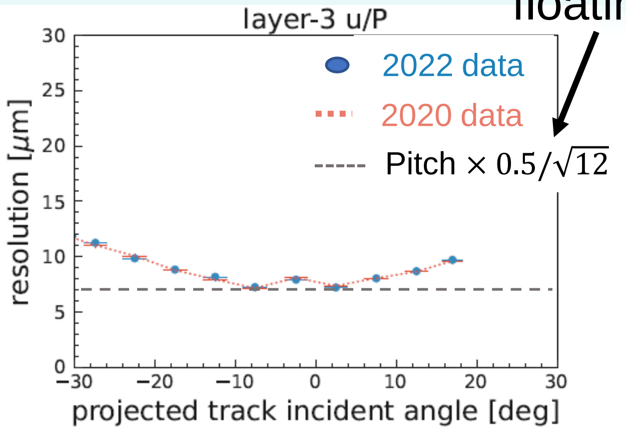


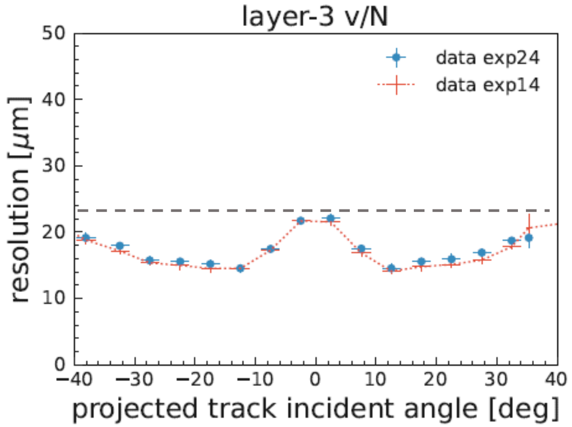


$$\sigma_x = \sqrt{\left\langle (\Delta x_i)^2 - \left(\sigma^{trk}_{x,i}\right)^2 \right\rangle}$$

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

Digital floating

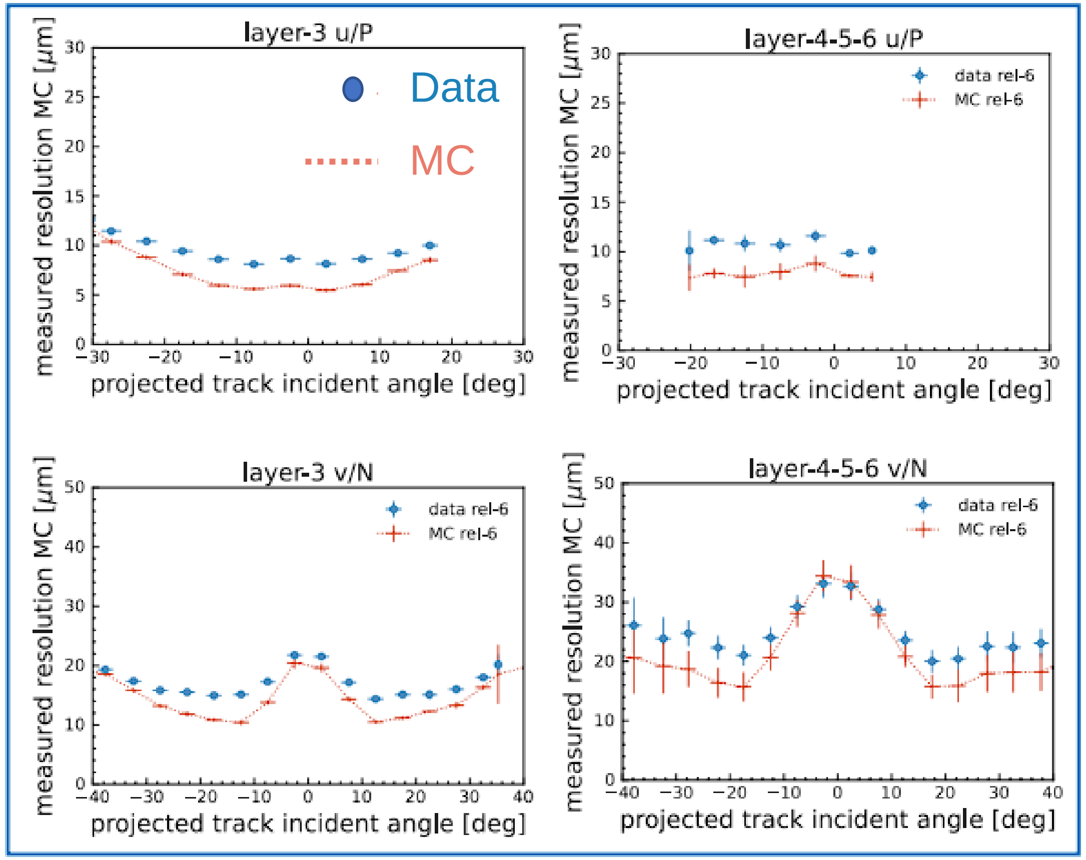




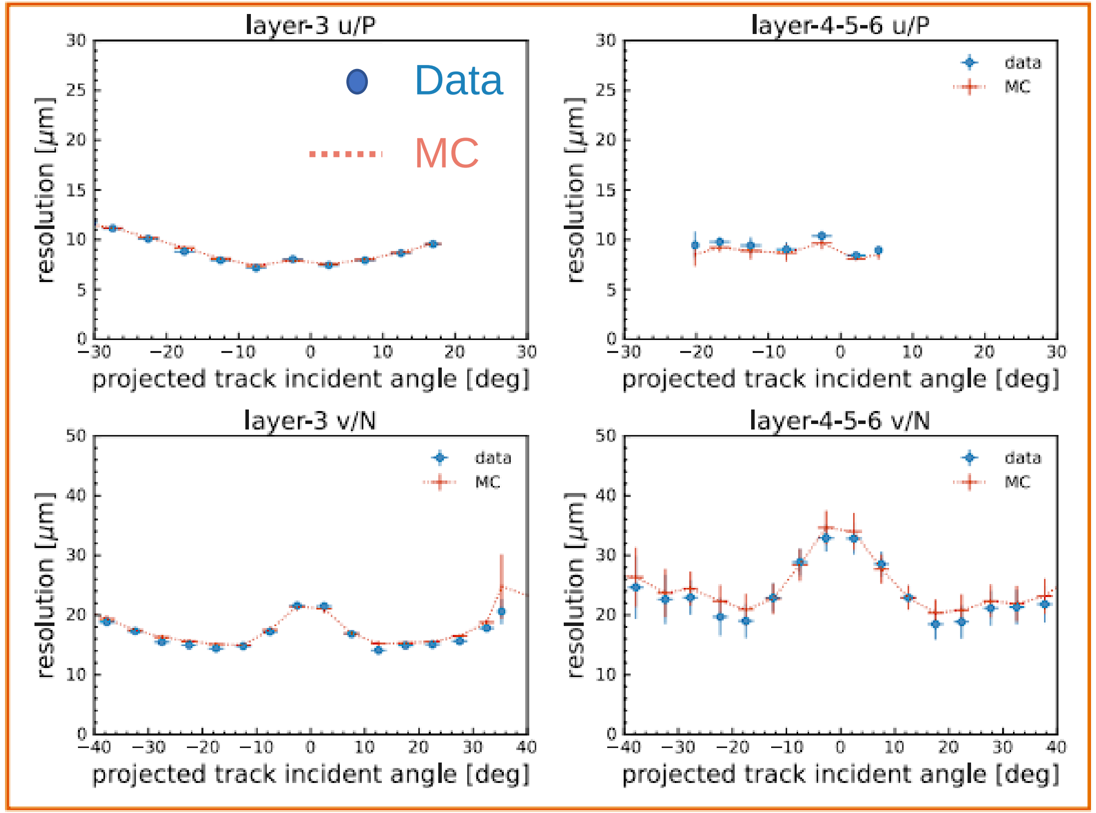
- Good stability of the cluster position resolution on data, comparing the results on 2020 vs 2022

Cluster position resolution - 2

Before smearing



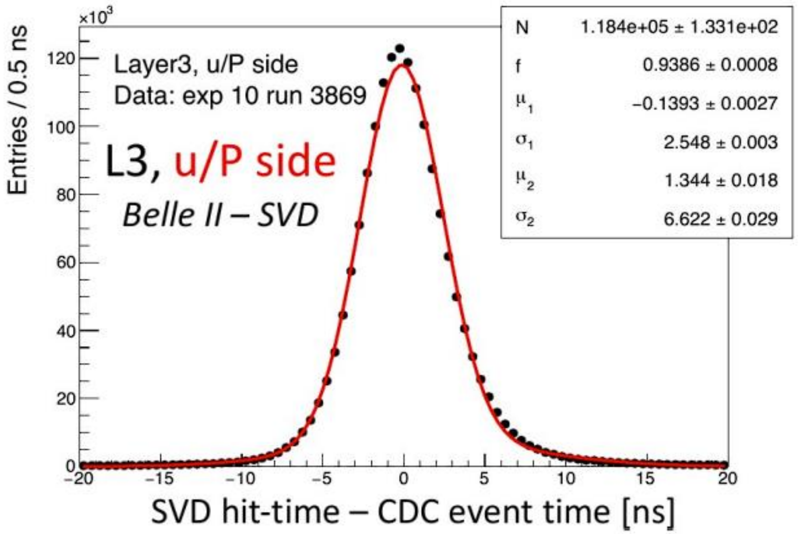
After smearing

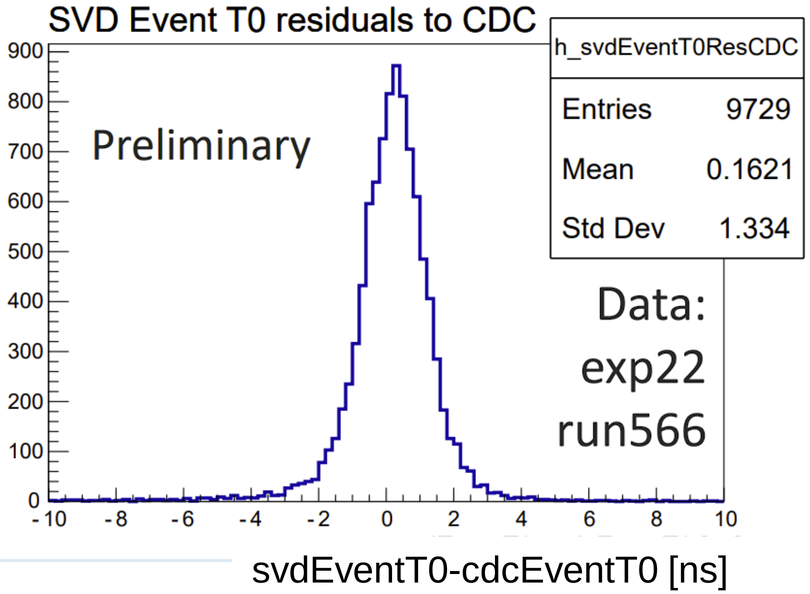


- Introduce angle dependent smearing to solve too optimistic MC!

Hit-time resolution

- Excellent hit time resolution (<3ns) w.r.t. event time of the collision (event T0) provided by Central Drift Chamber
  - Able to efficiently reject off-time background hits
- Reconstruction of the eventT0 with SVD, that is now the default in Belle II reconstruction, instead of use of the CDC event T0
  - Same resolution and 2000 times faster computation time w.r.t. the CDC event T0
  - Allowing to speed up the High Level Trigger (HLT) reconstruction and therefore cope with the higher trigger rate expected at higher luminosity

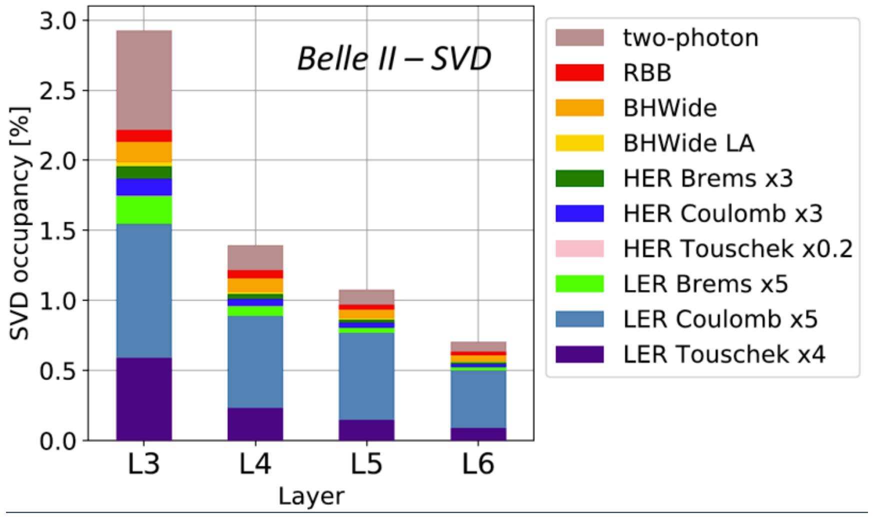




Beam backgrounds & Radiation effects

Beam background and hit occupancy limit

- Beam background increases SVD hit occupancy → degrades tracking performances
  - At present average hit occupancy in layer 3 is around 0.5% and well under control
- Current occupancy limit in layer 3 is ~3%
  - hit time cut could increase this number to 6%, due to improved background rejection with hit time
  - Studies with SVD standalone tracking ongoing to validate the performance (benchmark finding efficiency > 90% and fake rate < 20%)
  - Extrapolation at designed luminosity $L = 8 \times 10^{35}\ cm^{-2}\ s^{-1}$, we expect an average occupancy of about 3% in layer 3 (estimated scaling MC with data/MC ratio), but predictions are still affected by large uncertainties. **



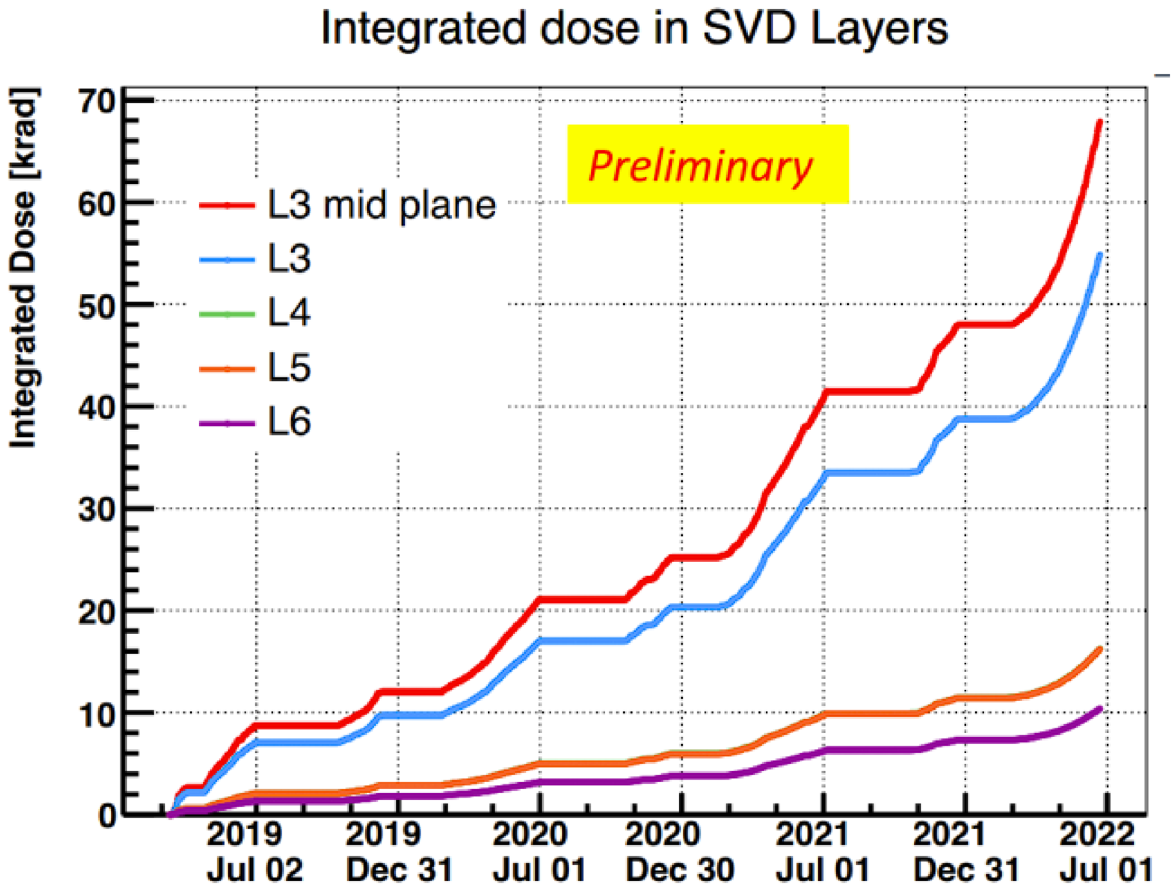
** Large uncertainties on long term background extrapolation, computed assuming optimal collimator settings, and even larger unknown from possible machine design evolution to reach the target luminosity. **

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 T. Tsuboyama and Z. Wang talks at today

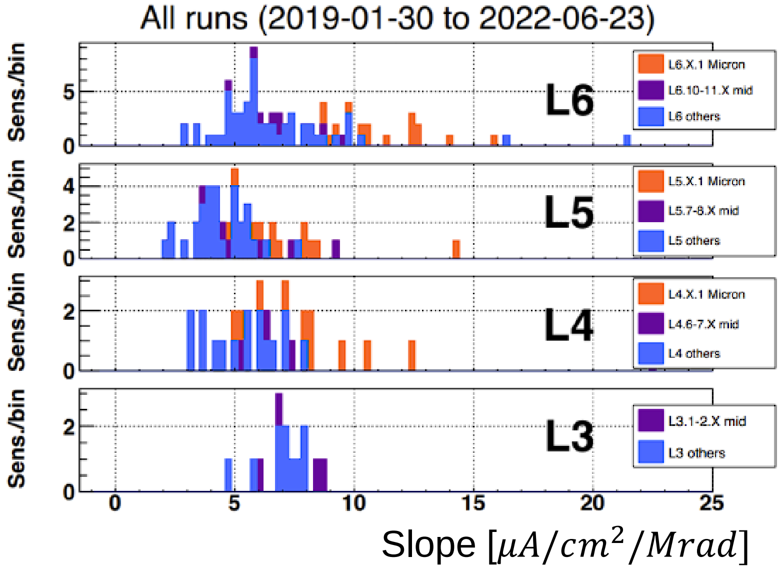
Integrated dose

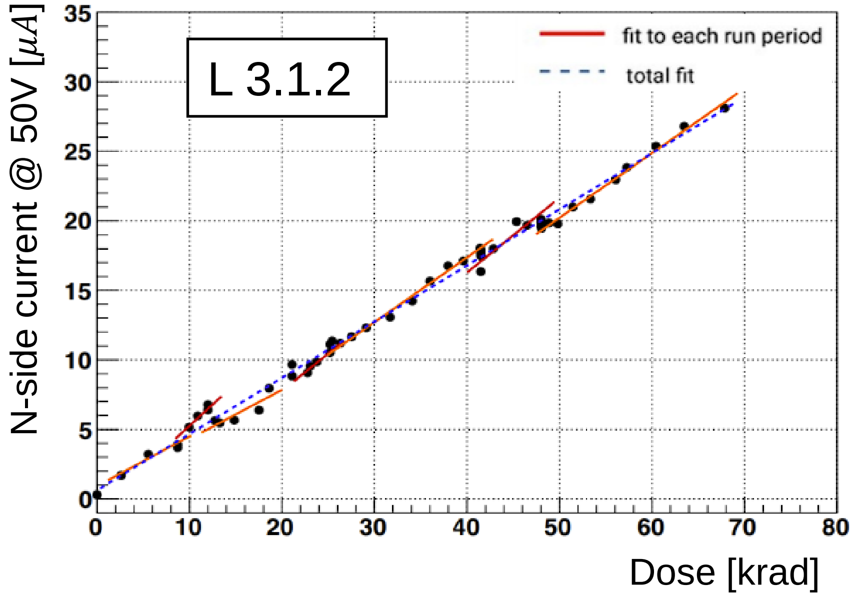
- Diamond sensors used to monitor radiation dose
  - Correlation between SVD occupancy and diamond dose is used to estimate the SVD sensor dose
- Total SVD integrated dose on layer 3 mid plane < 70 krad
  - 1-MeV equivalent neutron fluence evaluated to be $\sim 1.6 \times 10^{11}\ neq/cm^2$ in first 3 years
  - Assume neq/dose fluence ratio $= 2.3 \times 10^9\ neq/cm^2/krad$ from simulation
- First observable effects on sensor currents, noise and calibration constants, but so far without degradation of the SVD performance



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* ($1\ \mu A/cm^2/Mrad$ 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)
  - Slope is also compatible with the irradiation campaign in July 2022 using HPK and SVD sensor
- Irradiation is not expected to degrade SVD performance, even up to 6 Mrad
  - SNR expected to be < 10 in Layer 3
  - Leakage current will contribute to strip noise increase
  - Currently, noise increase dominated by sensor interstrip capacitance due to the short APV25 shaping time

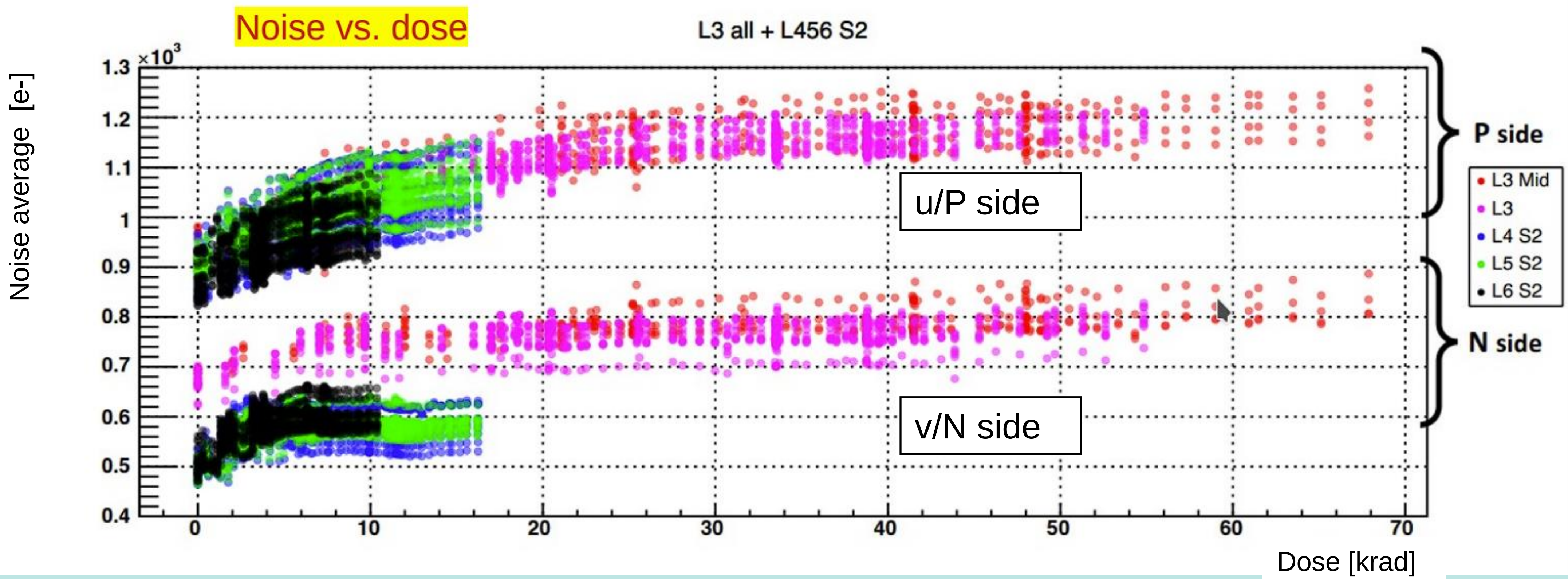




*[NIMA 729, 615-701, 2013]

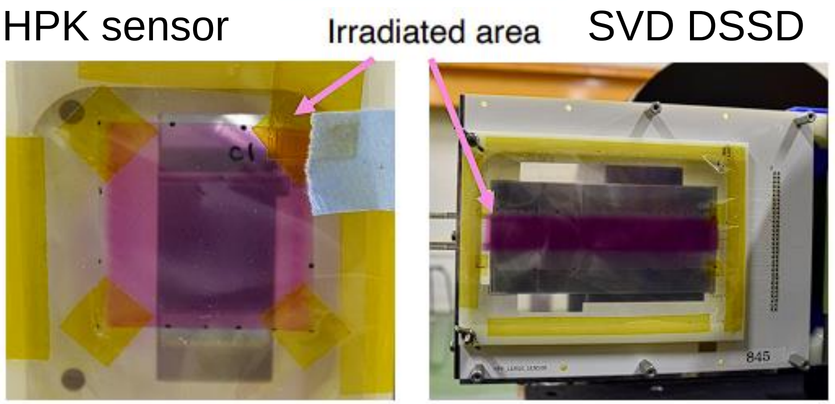
Radiation effect: strip noise

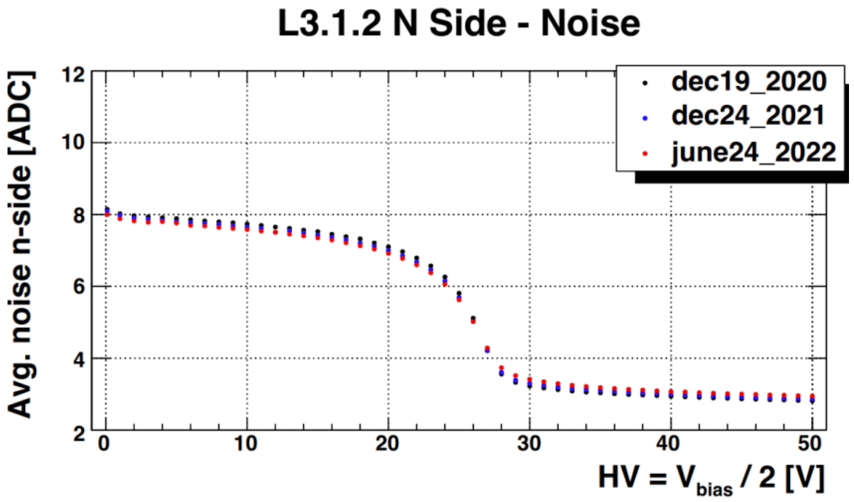
- Noise increase is < 20%(30%) for n(p) side, not affecting performance
- Induced by radiation effects on sensor surface: non-linear increase due to fixed oxide charges in irradiated sensors that increase inter-strip capacitance → expected to saturate
  - already saturated on n-side and layer 3 p-side, still rising on outer layer p-side

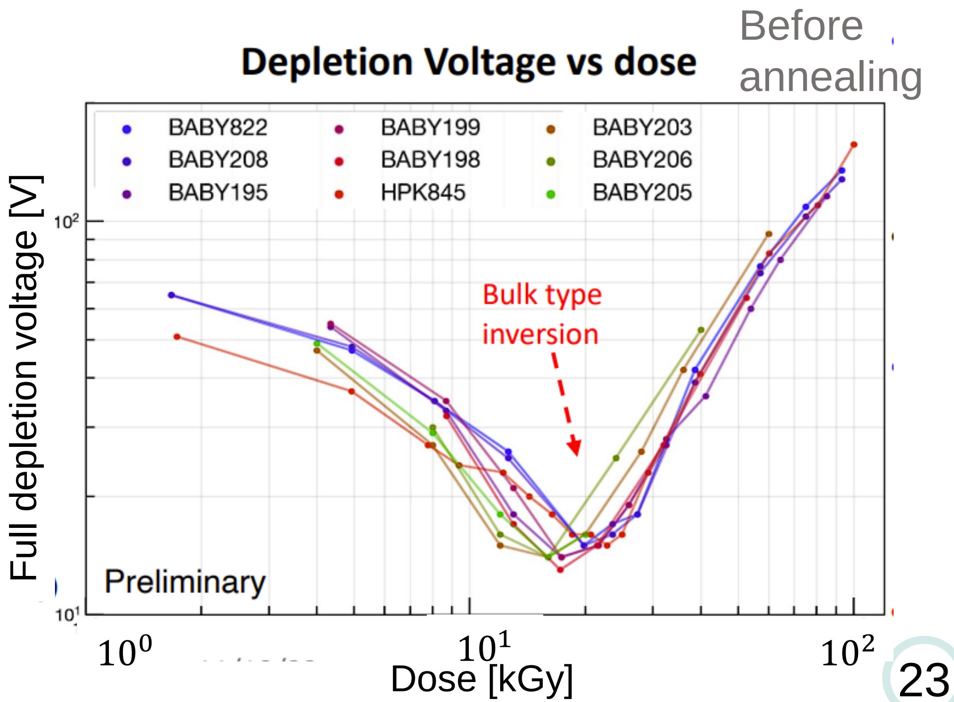


Radiation effect: depletion voltage

- Bulk damage can change effective doping and depletion voltage
  - Measure depletion voltage with scan (n-side strip noise Vs bias voltage)
  - No change in full depletion voltage observed with time so far, consistent with low integrated neutron fluence
- Irradiation campaign in July 2022
  - 90 MeV e- beam @ ELPH Sendai (Tohoku Univ.)
  - Type inversion confirmed between 1.5 – 2 Mrad
    → a equivalent neutron fluence $4.5 - 6 \times 10^{12}\ neq/cm^2$
  - Based experience on Babar sensor, SVD sensor will work well above type inversion → CCE measurement to confirm it





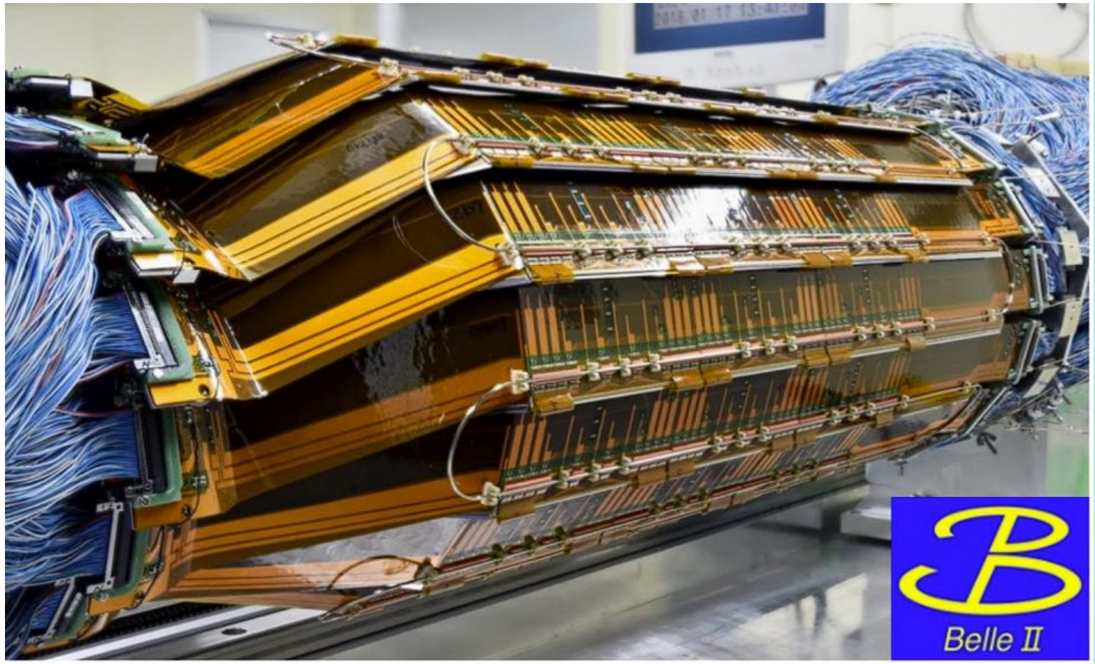


Summary

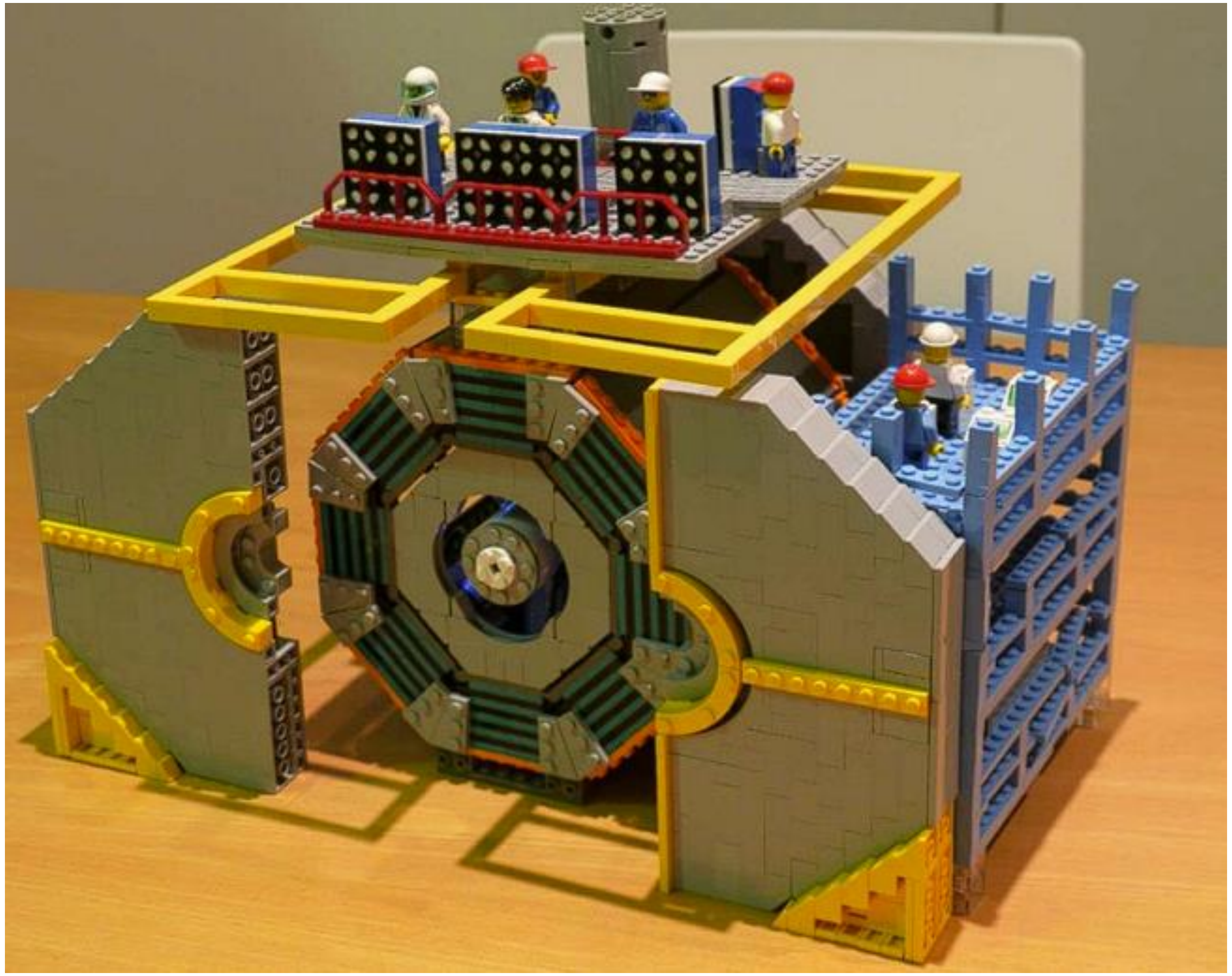
- SVD has been in operation providing high quality data since March 2019
  - SVD operated smoothly and reliably with an excellent performance w.r.t SNR, efficiency, position resolution, hit time resolution, and event T0 resolution
  - Observed first effects of radiation damage, not affecting performance

- Now we are in LS1
  - Preparing system to cope with higher background with excellent performance
  - SVD commissioning for VXD re-installation

- SVD technical paper has been accepted for publication by JINST
  - Available on arXiv: https://arxiv.org/abs/2201.09824

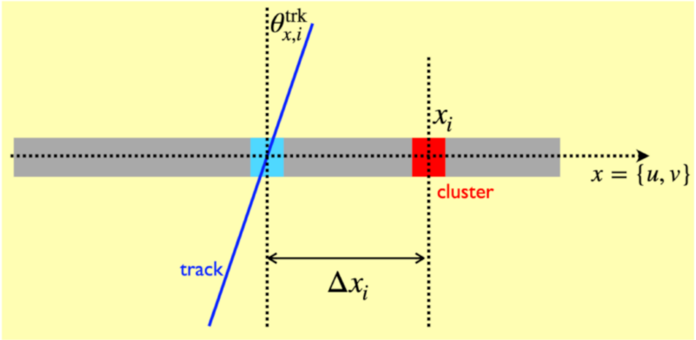


Back up



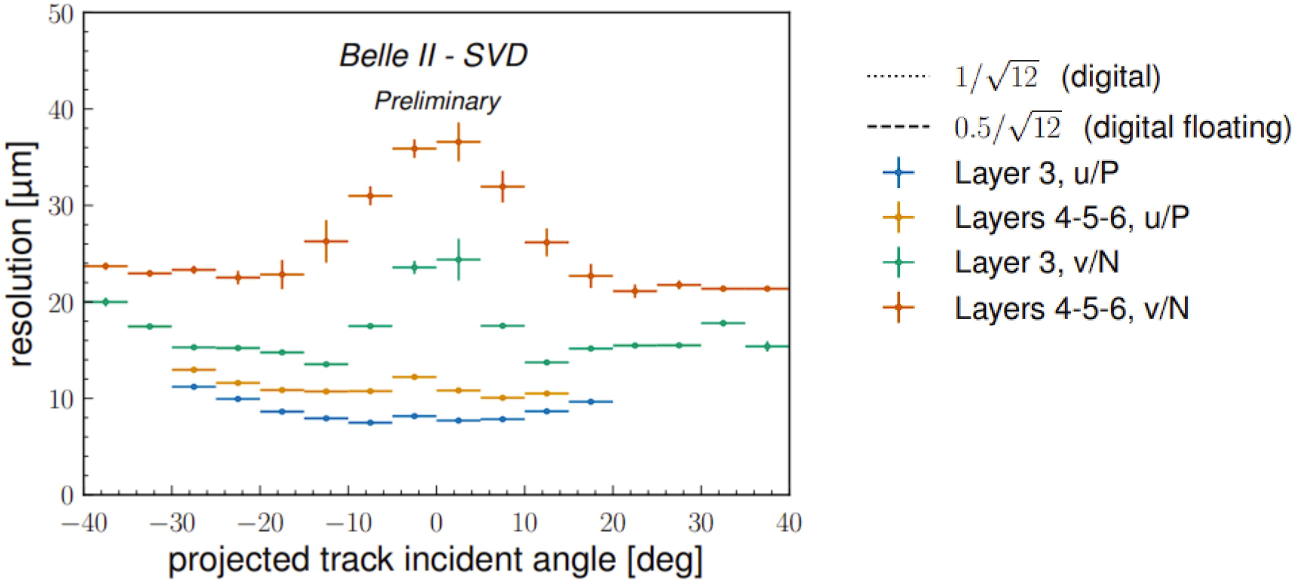
Cluster position resolution - 1

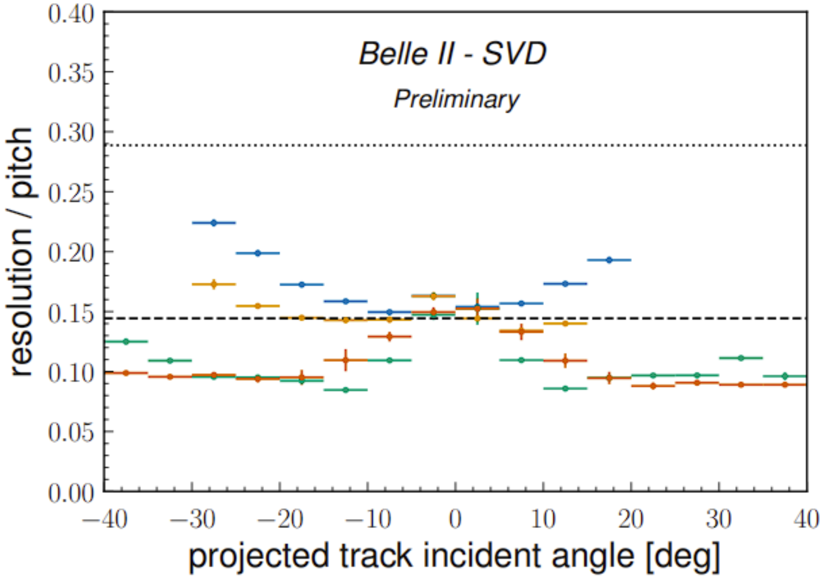
- Excellent resolution on the position is crucial for good quality reconstructed tracks and vertices
- Resolution estimated from residual of the cluster position w.r.t unbiased track extrapolation using e+e-→μ+μ- events
- Good resolution, generally in agreement with pitch expectations
- Introduce smearing to solve too optimistic MC (next slide)
  - $\sigma_{corr} = sign(\sigma^2_{data} - \sigma^2_{MC}) \cdot \sqrt{|\sigma^2_{data} - \sigma^2_{MC}|}$



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

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



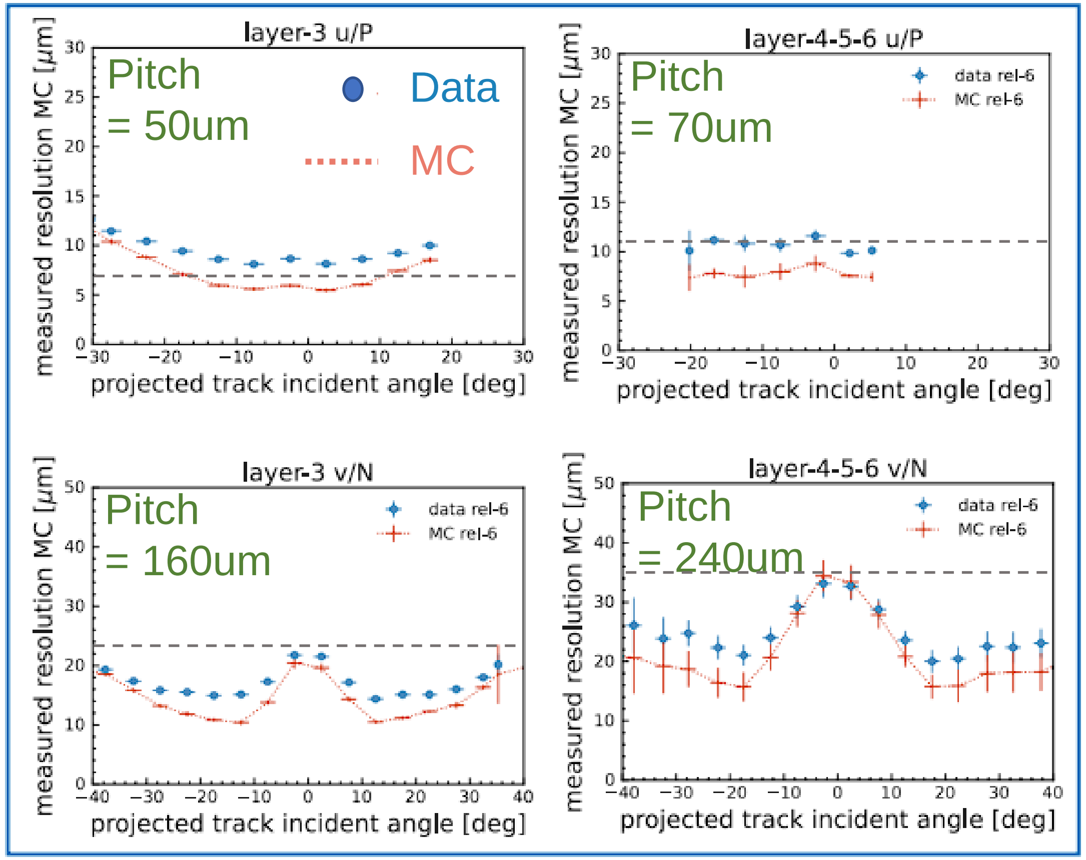


Cluster position resolution - 2

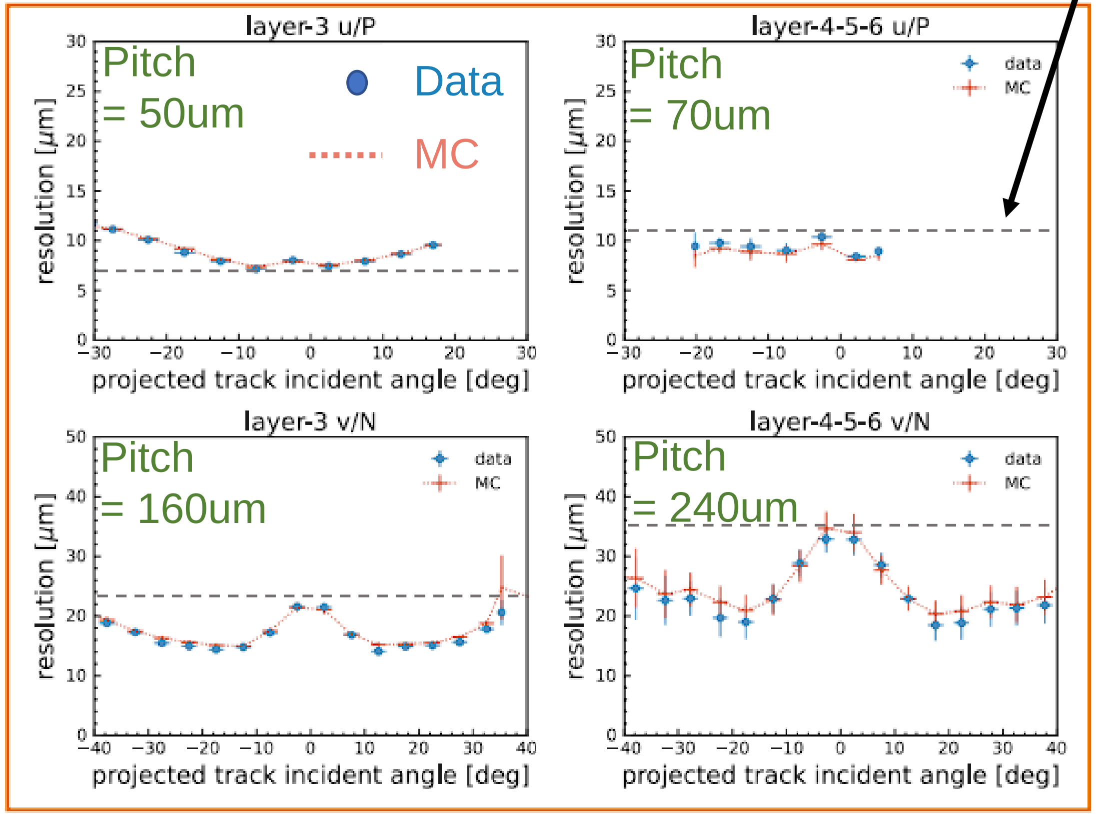
----- pitch × $\frac{0.5}{\sqrt{12}}$

digital floating

Before smearing



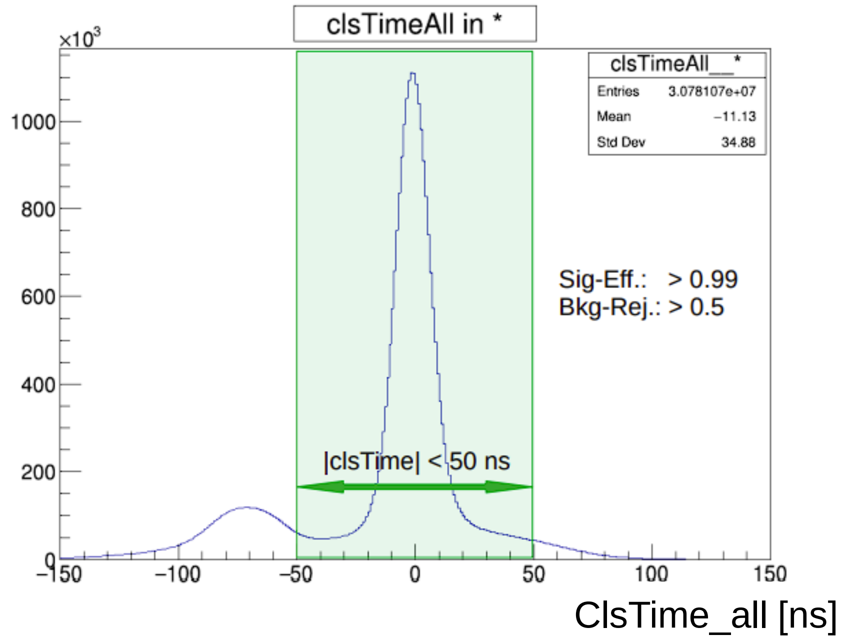
After smearing



- Introduce angle dependent smearing to solve too optimistic MC!

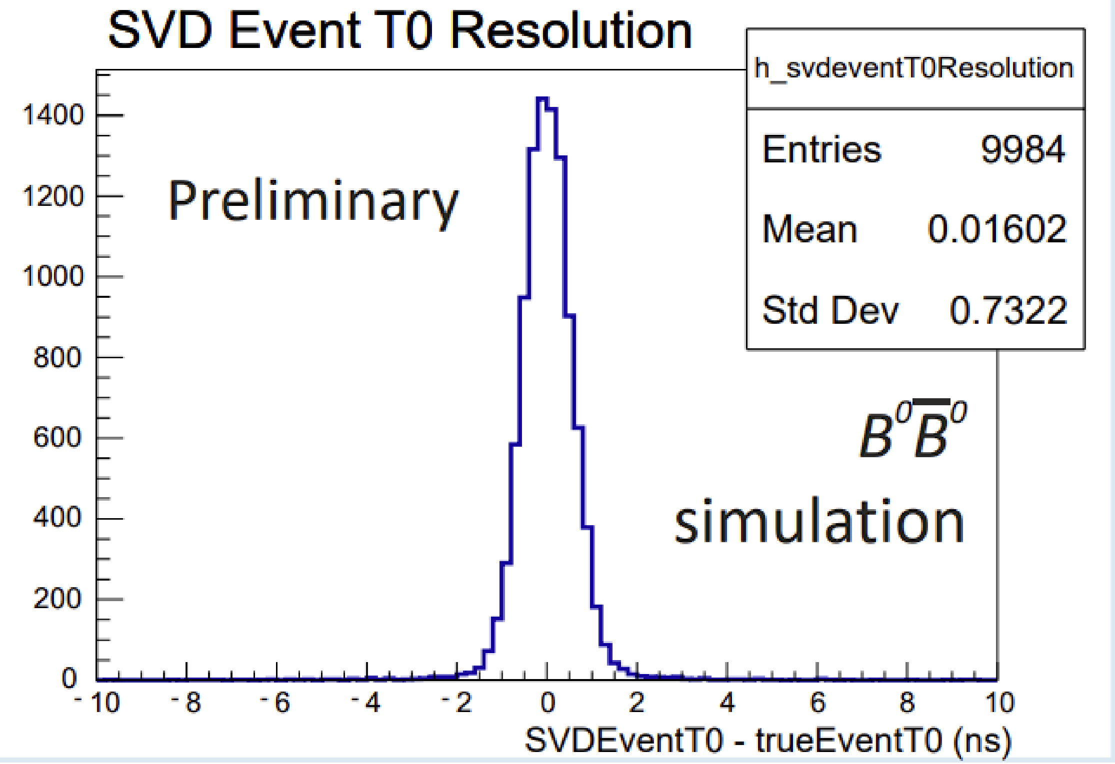
Hit-time resolution

- Back up plot

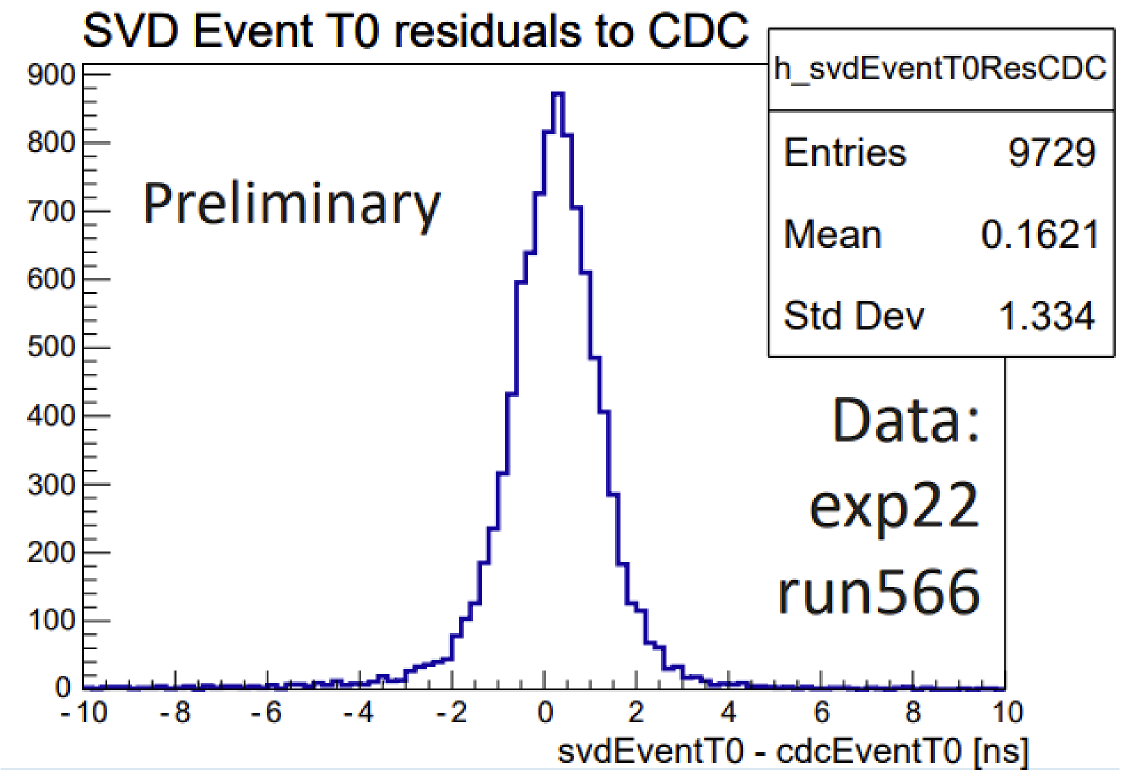


Hit-time resolution – event T0

- The event T0 is estimated for the first time with the SVD, as the average of the time of the clusters associated to selected good tracks:
  - $event\ T_0^{SVD} = \frac{1}{N_{cls}} \sum_{i=1}^{N_{cls}} t_i^{cls}$



Achievable SVD T0 resolution from MC simulation



SVD T0 residuals from data compared to CDC T0

SVD dose calculation

The method: SVD dose from BP diamond dose

- SVD dose calculation is based on correlation between SVD occupancy and BP diamond
  - https://confluence.desy.de/display/BI/SVD+dose+estimate+from+diamond+dose

1. Estimate SVD occupancy from diamond dose rate (C coefficients fitted from data)
   - **SVD occupancy = C1 * BW_325_diam +C2 * FW_325_diam + C**
   - BW_325_diam =BP_BW_325 more sensitive to LER , FW_325_diam =BP_FW_325 more sensitive to HER
2. Convert SVD occupancy to dose rate (f conversion factor measured on data)
   - SVD dose = f * SVD occupancy → **SVD dose = f * (C1 * BW_325_diam + C2 * FW_325_diam)**
     - +20% correction added to compensate for the EODB cut (very high occupancy events NOT saved)
3. Equation (2) holds also for integrated dose

- SVD integrated dose can be measured from diamonds that are always ON!

- Improved analysis from 2021 based on data from poisson trigger w/o injection veto
  - Details in Ludovico's talk @June '21 B2GM & master thesis
  - https://indico.belle2.org/event/4667/contributions/23183/attachments/11408/17412/svd_dose_b2gm_2021_06.pdf
  - https://docs.belle2.org/record/2759/

16/05/22 G. Rizzo - SVD dose revision 2