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Measurement of the cluster position resolution of the Belle II Silicon Vertex Detector

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41 **Abstract**

42 The Silicon Vertex Detector (SVD), with its four double-sided silicon strip sensor
43 layers, is one of the two vertex sub-detectors of Belle II operating at SuperKEKB
44 collider (KEK, Japan). Since 2019 and the start of the data taking, the SVD
45 has demonstrated a reliable and highly efficient operation, even running in an
46 environment with harsh beam backgrounds that are induced by the world's
47 highest instantaneous luminosity.

48 In order to provide the best quality track reconstruction with an efficient
49 pattern recognition and track fit, and to correctly propagate the uncertainty on
50 the hit's position to the track parameters, it is crucial to precisely estimate the
51 resolution of the cluster position measurement. Several methods for estimating
52 the position resolution directly from the data will be discussed.

53 *Keywords:* Belle II, Vertex detector, Cluster position resolution

54 **Introduction**

55 The Belle II experiment [1] operates at the high-energy physics intensity fron-
56 tier and searches for physics beyond the Standard Model [2] in rare b , charm and
57 tau decays. Belle II is collecting data since March 2019 at the e^+e^- asymmetric
58 energy collider SuperKEKB [3] at Tsukuba, in Japan, mainly at the centre of
59 mass energy of the $\Upsilon(4S)$ resonance, 10.58 GeV. By achieving a design instan-
60 taneous luminosity of $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, it will collect a final data set of 50 ab^{-1} .
61 Relevant features of the Belle II detector to attain its main physics goals are the
62 precise and efficient track reconstruction capabilities, including for those with
63 low momentum, decay vertex determination and identification of different kinds
64 of charged particles. The vertex detector plays a crucial role in fulfilling each
65 of these requirements. It is composed of two layers of DEPFET pixel sensors
66 (PXD), with the innermost layer at 1.4 cm from the interaction point, and 4
67 layers of double-sided silicon strip sensors (SVD).

68 **1. The Belle II silicon strip detector**

69 The Silicon Vertex Detector SVD [4] is composed of 172 double-sided silicon
70 strip detectors (DSSD) distributed in four layers of 7, 10, 12 and 16 ladders
71 with 2, 3, 4 and 5 sensors each, for a total material budget of 0.7% of the
72 radiation length per layer on average. Along the sensors, strips are arranged
73 in perpendicular directions on opposite sides and the signal is collected by the
74 APV25 chips which provide an analog readout: the u/P side measures the $r\phi$ -
75 direction and the v/N side provides information on the z -coordinate along the
76 beam line.

	Small	Large	Trap.
No. u/P readout strips	768	768	768
No. v/N readout strips	768	512	512
Readout pitch u/P strips (μm)	50	75	50-75
Readout pitch v/N strips (μm)	160	240	240
Sensor thickness (μm)	320	320	300
Active Length (mm)	122.90	122.90	122.76
Active Width (mm)	38.55	57.72	57.59-38.42

Table 1: Geometrical details of the SVD DSSD sensors. All sensors have one intermediate floating strip between two readout strips.

77 Layer 3 is equipped with “small” rectangular sensors, Layer 4-5-6 are build
78 with “large” rectangular sensors and a “trapezoidal” one. The geometrical
79 details of the different sensors are shown in Tab. 1.

80 The SVD plays a crucial role in reconstructing the decay vertex and low-
81 momentum particles, providing stand-alone tracking capabilities and contribut-
82 ing to charged particle identification through the ionisation energy-loss informa-

tion. Moreover, it contributes to extrapolating the tracks towards the PXD and defining the region of interests to reduce the PXD data size. An excellent cluster position resolution is mandatory for SVD reconstruction, and it is a crucial input for tracking to improve the quality of reconstructed tracks and vertices, moreover its knowledge is necessary to correctly propagate the uncertainty on the track extrapolation.

2. Cluster position resolution analysis strategy

The tracks traversing the SVD sensors activate adjacent strips that are gathered into clusters. To each reconstructed cluster we assign (Fig. 1):

- the cluster position $m = \frac{\sum_i X_i S_i}{\sum_i S_i}$ obtained as the center of gravity of all strips position X_i of the given cluster weighted by the charge collected on each strip S_i ;
- an *unbiased* track position intercept t from the track finding [5] and its error σ_t , where the track reconstruction is performed excluding the cluster considered for the resolution measurement;
- the true position x , only in simulation.

The cluster position resolution is extracted from the residuals $R = m - t$ of the cluster position with respect to the unbiased track intercept position and the effect of the track extrapolation error is subtracted.

We consider three distinct approaches in this paper:

- **Event by Event** (EBE): consists in removing event-by-event the error on track extrapolation σ_t from the residual R in quadrature.

$$\sigma_{cl}^{EBE} = \sqrt{\langle R^2 - \sigma_t^2 \rangle_{trunc}}. \quad (1)$$

Here, *trunc* refers to the truncation of $R^2 - \sigma_t^2$ optimized on the simulation to match the true resolution, defined as the width of the distribution of $m - x$. The truncation is needed to eliminate the long non-Gaussian tail of the $R^2 - \sigma_t^2$ distribution.

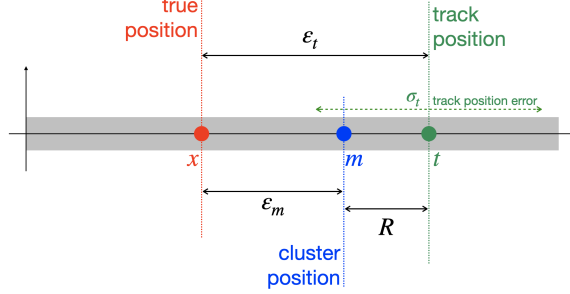


Figure 1: Schematic view of a sensor plane with the cluster position m , the *unbiased* track position t and the true position x only available in simulations, the measured residuals R .

- 110 • **Global:** differently from the EBE method, the so-called "global method"
 111 aims at removing the contribution of σ_t by subtracting in quadrature from
 112 the width of the residuals the width and central value of the track error.
 113 The resolution is finally extracted by:

$$114 \quad \sigma_{cl}^{GL} = \sqrt{\text{mad}^2(R) - \text{median}^2(\sigma_t) - \text{mad}^2(\sigma_t)}. \quad (2)$$

115 The median is used as estimator of the central value of σ_t distribution as
 116 is is robust against the outliers. For the same reason the widths of R and
 117 σ_t distribution are estimated with the *median absolute deviation*, which is
 118 defined, for variable y , as $\text{mad}(y) = 1.4826 \times \text{median}(|y - \text{median}(y)|)$.

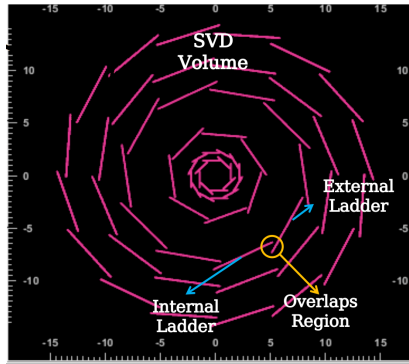


Figure 2: Schematic view of the SVD volume in the $r\phi$ direction.

- 119 • **Pair-method:** an alternative strategy [6] is implemented in Belle II

120 thanks to the SVD's windmill architecture, Fig. 2. The tracks are re-
 121 constructed, accepting only those with two hits in the same layer and
 122 on consecutive ladders and in the fiducial area. The residuals $m - t$
 123 determined on both overlapping ladders (internal and externals) are then
 124 subtracted to define the double residual ΔR . The double residuals are
 125 geometrically corrected to account for the non-parallel sensors on a same
 126 layer. Then ΔR is fitted with a Student's t-distribution T with the param-
 127 eters: the number of degrees of freedom ν ; the mean of the distribution μ ,
 128 and the variance σ^2 . The resolution $\sigma_{cl}^{\text{pair}}$ is finally defined as the width
 129 of T computed as the `sigma-68`¹:

$$130 \quad \sigma_{cl}^{\text{pair}} = \text{sigma-68}(T(X, \nu, \mu, \sigma)). \quad (3)$$

	L3	L4	L5	L6
Internal	20°;25°	5°;15°	5°;10°	0°;5°
External	-35°;-30°-30°;-20°-25°;-20°-25°;-15°			

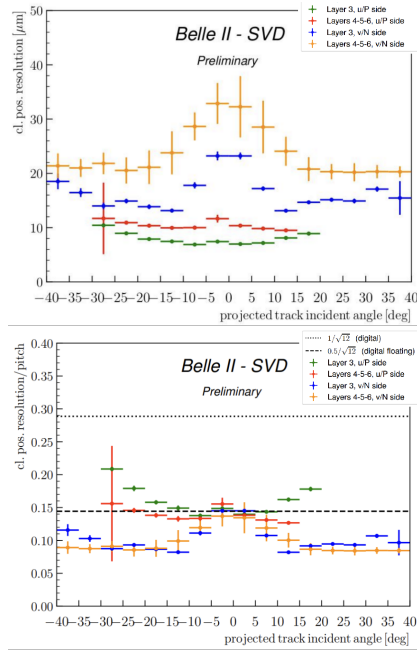
Table 2: Incident angle acceptance region for the u/P side in the pair-method.

131 The double residual has the advantage of being independent from the
 132 error on the extrapolated track intercept position, which is cancelled out
 133 in the double subtraction. The method decouples the contribution of the
 134 tracking precision from the actual cluster position resolution and is only
 135 marginally sensitive to the Coulomb scattering thanks to the small radial
 136 distance between the two overlapped sensors, however the incident angular
 137 range is limited following the u/P side as shown in Tab. 2.

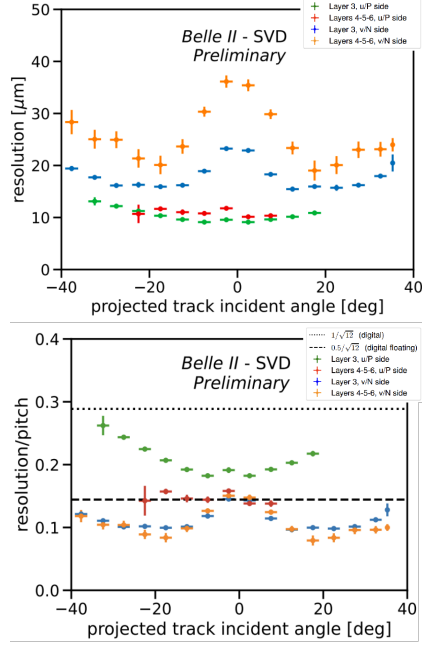
138 3. SVD resolutions measurement

139 The cluster position resolution is measured using $e^+e^- \rightarrow \mu^+\mu^-$ data, as a
 140 function of the track incident angle in bins from -40° to 40° with a 5° step.

¹`sigma-68` is half distance between 16th and 84th quantiles.



(a) Determined with the Event by Event method



(b) Determined with the Global method

Figure 3: Cluster position resolution (top) and resolution over strip pitch (bottom) for each sides and layers following the track incident angle.

141 Results are shown for the EBE method in Fig. 3a and for the global method
 142 in Fig. 3b. In both methods, the measured resolutions has the expected shape,
 143 showing a minimum at the incident angle for which the projection of the track
 144 along the direction perpendicular to the strips on the detector plane corresponds
 145 to two strip pitches. Given the various sensor pitches with one floating strip,
 146 the minimum is expected at 4° (7°) for the u/P side and at 14° (21°) on the
 147 v/N side, for layer 3 (4, 5 and 6).

148 In addition, the measured resolution for normal incident tracks is in fair
 149 agreement with digital resolution, that with a floating strip is equal to $pitch/(2\sqrt{12})$,
 150 with $11\ \mu\text{m}$ for u/P layer 4, 5 and 6; and 25 (35) for v/N layer 3 (4, 5 and 6) as
 151 shown in Fig. 3a and Fig. 3b. The digital resolution provides a reference value
 152 only under the assumption that a track activates only one strip. Tracks with

153 larger incident angle activate more strips and indeed our resolution is better
 154 than the digital one thanks to the analog readout. Layer 3 u/P side, the sen-
 155 sors with the smallest pitch, represents an exception: the measured resolution
 156 is slightly worse than the digital one for perpendicular tracks and it degrades
 157 with larger angles. This is effect is still under investigation.

158 Differently from EBE and Global methods, the pair method is sensitive to a
 159 limited incident angle range in u/P side by construction of the overlapping region
 160 in the $r\phi$ direction, therefore the resolutions measurement reported in Fig. 4 is
 161 averaged on the whole accessible angular range. The resolution measured with
 162 the pair method shown in Fig. 4 and detailed in Tab. 3 are higher than the
 163 measured resolution with the other methods, except for the v/N outermost
 164 layers. This behaviour is not fully understood, but will be the subject of future
 studies.

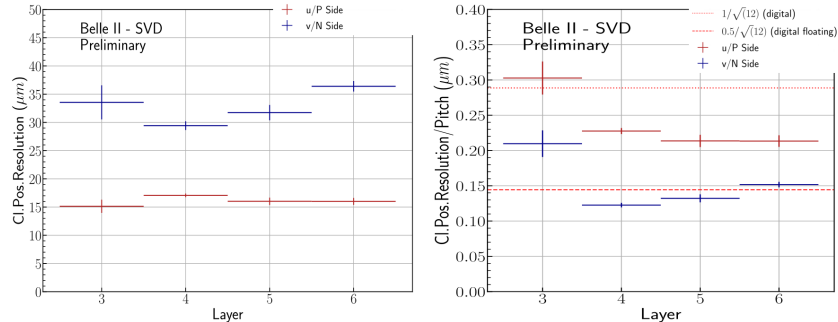


Figure 4: Cluster position resolution (top) and resolution over strip pitch (bottom) determined by the pair method for each sides and layers following the track incident angle.

165

166 Conclusions and Outlooks

167 Since the start of the data taking the SVD has demonstrated a reliable and
 168 highly efficient operation, with excellent performances confirmed by the mea-
 169 surement of the cluster position resolution, summarized Tab. 3. Some studies to
 170 investigate the small discrepancies observed on layer 3 u/P side and to further
 171 investigate larger deviation measured on pair overlaps method are planned.

	Digital	EBE	Global	Pair
Layer 3 u/P (μm)	7	7	9	15
Layer 456 u/P (μm)	11	10	11	16-17
Layer 3 v/N (μm)	23	24	23	33
Layer 456 v/N (μm)	35	32	35	29-36

Table 3: Summary of the digital and measured resolution taken at the normal incidence for the EBE and Global methods. For the Pair method the average on the whole accessible angular range is shown.

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