VXD Alignment: Experiences from Phase 2 and Phase 3

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May 27, 2019

Outline

Alignment of vertex detector of the Belle II

Belle II commissioning run or **Phase 2** in Belle II jargon

VXD commissioning run or **VXD Phase 3 setup** on table in clean room

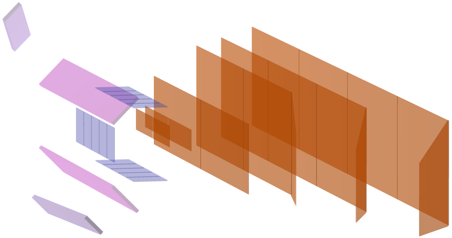
Phase 3 early runs

Validation of vertex detector alignment

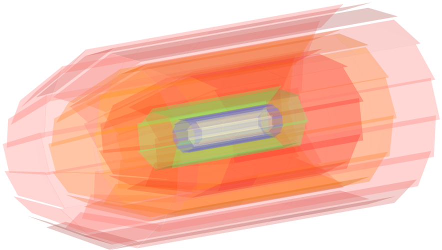
Summary

Vertex detector (pixel & strip detector)

Phase 2 setup



Phase 3 setup



	Radius [mm]	*Thickness* [μm]	R/ϕ *pitch* [μm]	*Z pitch* [μm]	*Sensors*
PXD Layer 1	14	75	50	55 - 60	2×8
PXD Layer 2	22	75	50	70 - 85	$2 \times 2^*$
SVD Layer 3	39	300 - 320	50	169	2×7
SVD Layer 4	80	300 - 320	50	240	3×10
SVD Layer 5	104	300 - 320	50	240	4×12
SVD Layer 6	135	300 - 320	50	240	5×16

Track based alignment procedure and Millepede II

- Sensors measure hit positions of charged particles passing their sensitive area.
- Tracking reconstruction software combine hits to creating track.
- Transformations between local sensor system and global (Belle II) system are used.
- Alignment parameters are used in transformation matrices and vectors.
- Procedure, which determine alignment parameters, is called **alignment procedure**.
- The procedure uses residual between measured and expected positions of hits.

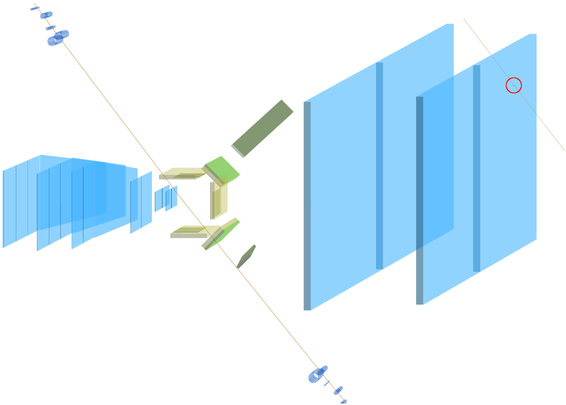
$$r_{ij}(\boldsymbol{\tau}_j, \boldsymbol{a}) = u_{ij}^{m} - u_{ij}^{p}(\boldsymbol{\tau}_j, \boldsymbol{a})$$

- For alignment purpose χ^2 function is defined as:

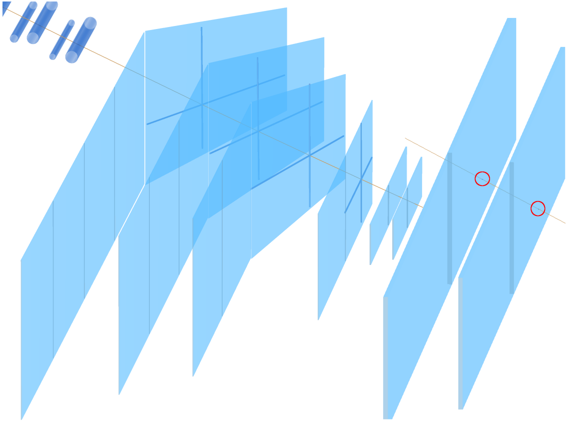
$$\chi^2(\boldsymbol{\tau}, \boldsymbol{a}) = \sum_{j}^{tracks} \sum_{i}^{hits} \left(\frac{r_{ij}(\boldsymbol{\tau}_j, \boldsymbol{a})}{\sigma_{ij}} \right)^2 \approx \sum_{j}^{tracks} \sum_{i}^{hits} \frac{1}{\sigma_{ij}^2} (r_{ij}(\boldsymbol{\tau}_j^0, \boldsymbol{a}^0) + \frac{\partial r_{ij}}{\partial \boldsymbol{a}} \delta \boldsymbol{a} + \frac{\partial r_{ij}}{\partial \boldsymbol{\tau}_j} \delta \boldsymbol{\tau}_j)^2$$

- **Millepede II** is based on global linear χ^2 minimization.
- Constrains can be applied/included in the algorithm.
- The algorithm can determine rigid body, surface parameters or Lorentz angle corrections.

Software reconstruction of charged tracks in vertex detector



Cosmic track in PXD sensor during Phase 2

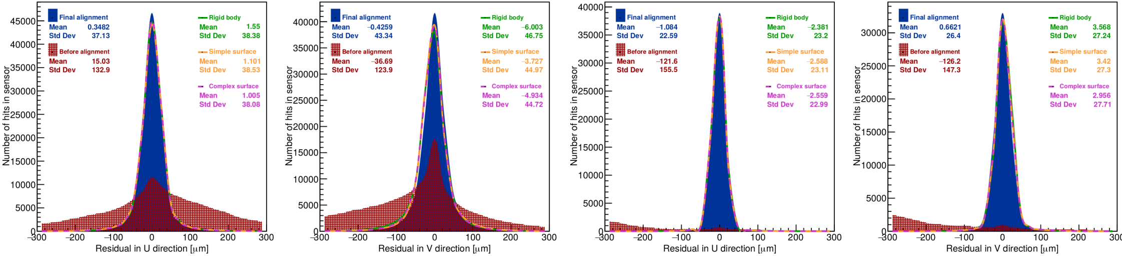


Track coming from collisions during Phase 2

Phase 2 results: Precision

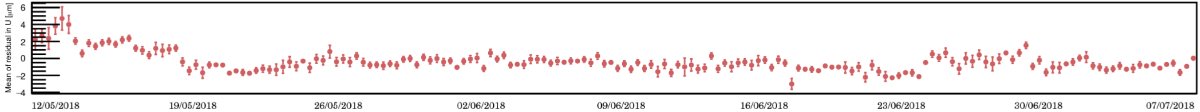
Pixel sensor - 1.1.2

Pixel sensor - 2.1.2

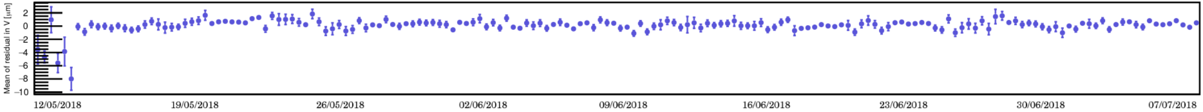


- PXD sensors provide precise measurement with standard deviation smaller than 40 $\mu\mathrm{m}$
- Standard deviations of other sensors were from 20 to 40 $\mu\mathrm{m}$
- It was not observed surface deformations of PXD sensors, but SVD sensors were deformed.

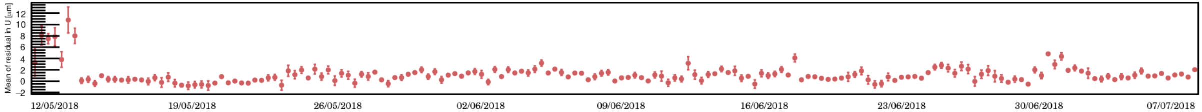
Phase 2 results: Stability



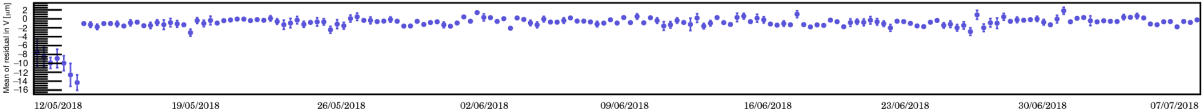
Means of U residual as function of date, when data was collected, for sensor pixel - 1.1.2



Means of V residual as function of date, when data was collected, for sensor pixel - 1.1.2

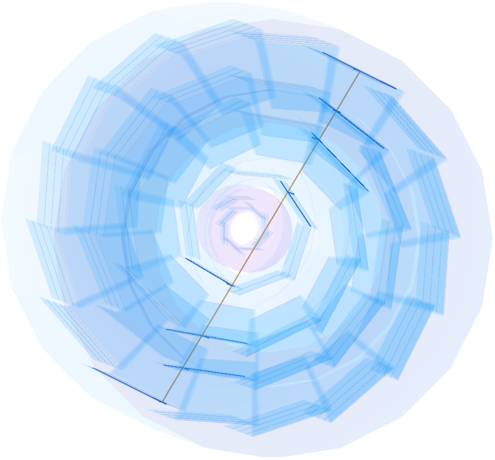


Means of U residual as function of date, when data was collected, for sensor pixel 2.1.2.

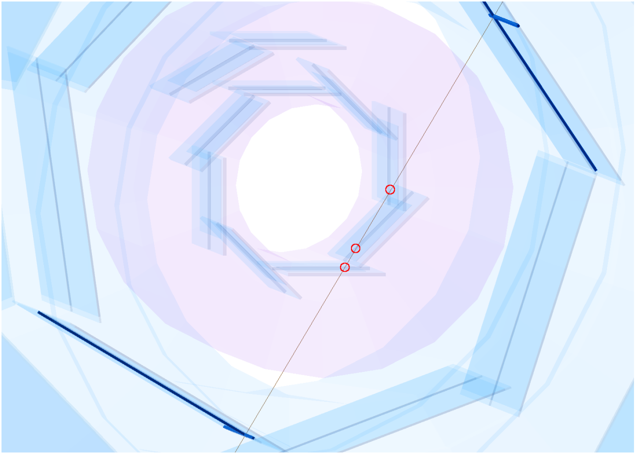


Means of V residual as function of date, when data was collected, for sensor pixel 2.1.2.

Software reconstruction of cosmic track in vertex detector

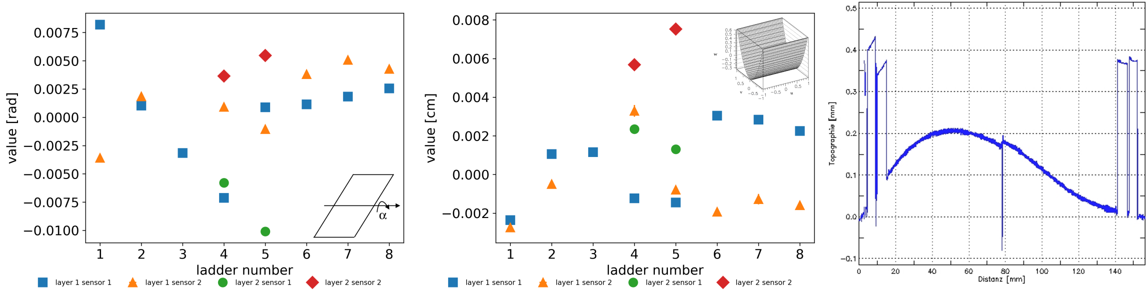


Cosmic muon passing vertex detector



In zoomed picture PXD hits are on cosmic track

VXD Commissioning results: Layer 2

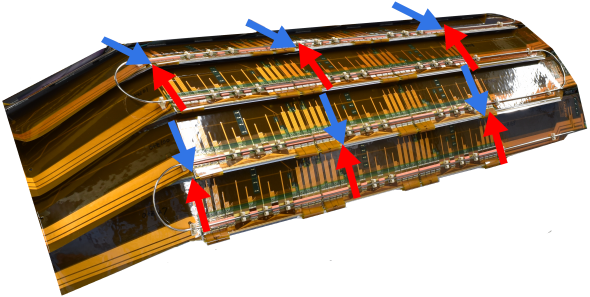


Result for rotation around shorter axis (left), surface deformation as function of longer edge (center) and survey measurement before installation (right)

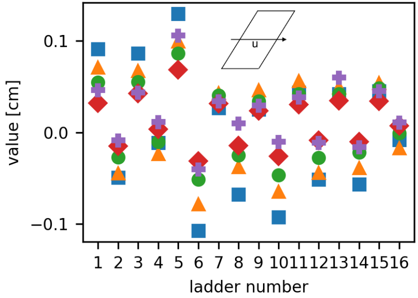
- Backward sensors - 2.*.2 are affected a large surface deformation as function of longer edge.
- Sensors in second layer are high rotated around shorter axis with opposite sign for sensors in ladders.
- Ladders in second layer have **bowed** structure.
- The structure corresponds with results observed during survey measurements before installation.

VXD Commissioning results: Zebra effect in sixth layer

Schematic view

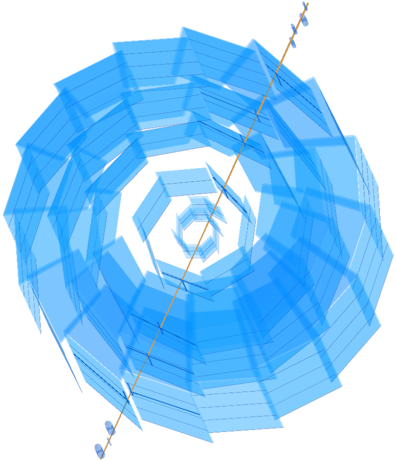


U coordinate in sixth layer

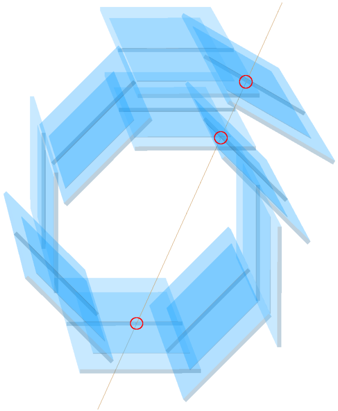


- During installation of cooling pipes was observed displacement of SVD sensors in sixth layer. The scale of displacement is about 1 mm.
- Alignment procedure observed similar structure. The large effect was observed in U coordinate of sensors. Small effect can be seen in β angle and surface parameters.
- Design of cooling pipes cases this issue according discussion with experts.

Software reconstruction of cosmic track in vertex detector

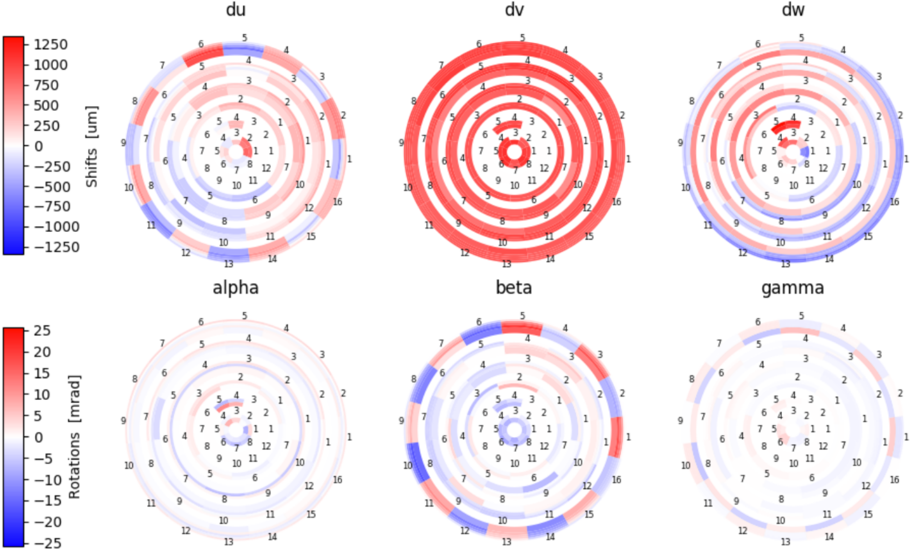


Cosmic muon passing Belle II detector

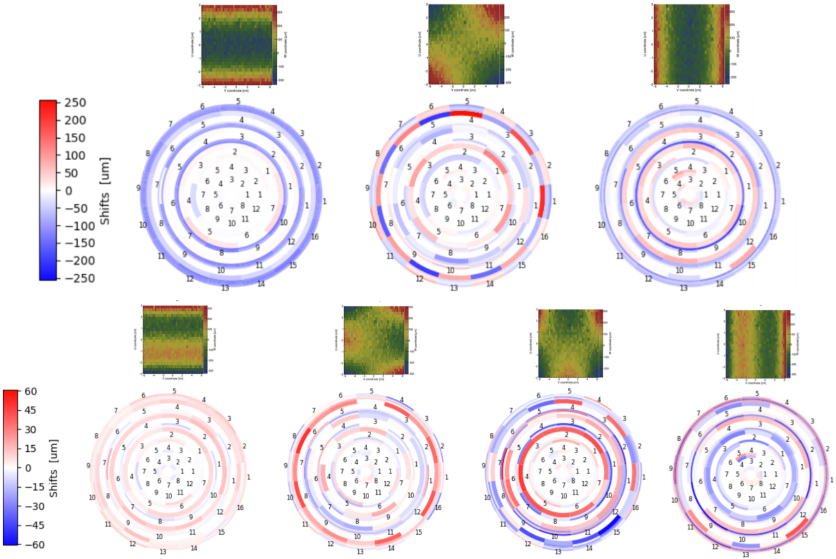


The track passing through PXD sensors

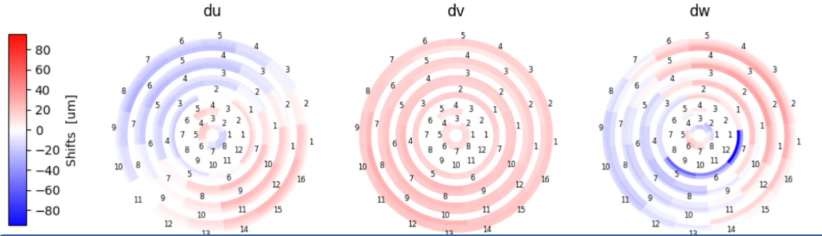
Phase 3 early result (exp 7): Rigid body parameters

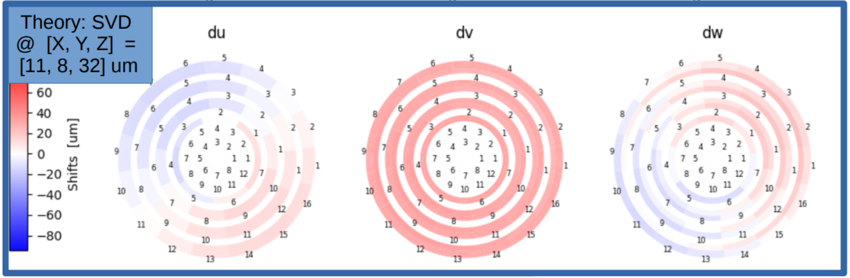


Phase 3 early result (exp 7): Surface parameters



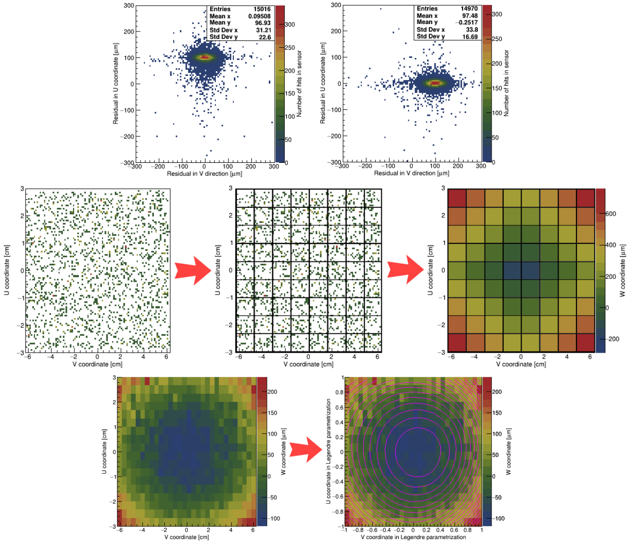
Phase 3 early result: Comparison between experiments 5 and 7





Vertex detector is moving as function of change status of QCS on scale of tents μm.

Alignment validation procedure sensor by sensor



Standard track-to-hit residuals

- Standard method for validation alignment.
- Means of distributions as parameters.

Validation of sensor planarity

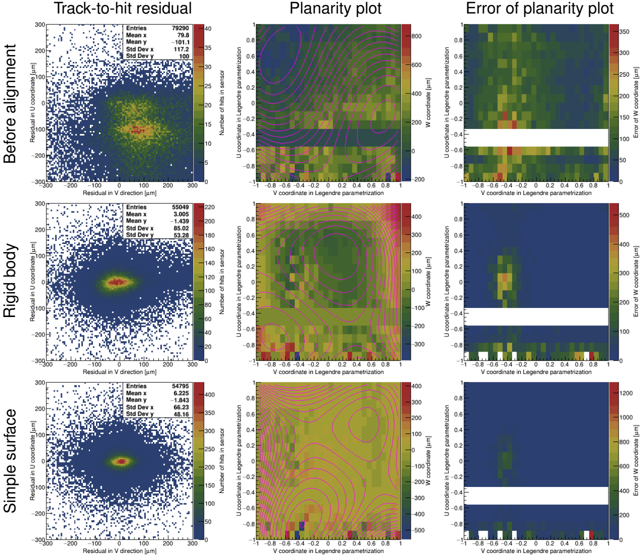
- Dividing sensor surface to n $\times$ m matrix
- W-residual as $r_W = \frac{r_U}{\tan \alpha_U} = \frac{r_V}{\tan \alpha_V}$
- Averaging all measurement in cell
- Weighed by $(\tan \alpha_{U,V})^2$ during averaging

Fitting planarity plot

- From local sensor system to Legendre
- Fitting by:

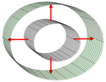
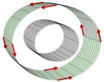
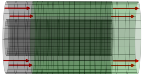
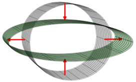
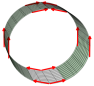
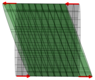
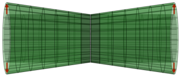
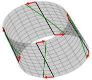
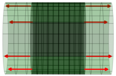
$$
\begin{aligned}
w(u,v) = {} & P_W \cdot L_0(u) \cdot L_0(v) + P_\alpha \cdot L_0(u) \cdot L_1(v) + P_\beta \cdot L_1(u) \cdot L_0(v) \\
& + P_{20} \cdot L_2(u) \cdot L_0(v) + P_{11} \cdot L_1(u) \cdot L_1(v) + P_{02} \cdot L_0(u) \cdot L_2(v) \\
& + P_{30} \cdot L_3(u) \cdot L_0(v) + P_{21} \cdot L_2(u) \cdot L_1(v) + P_{12} \cdot L_1(u) \cdot L_2(v) \\
& + P_{03} \cdot L_0(u) \cdot L_3(v)
\end{aligned}
$$

Validation alignment parameters (sensor 4.1.2 @ Phase 2)



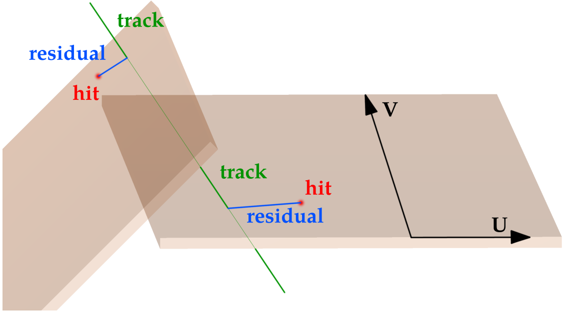
$[\mu m]$	*Before alignment*	*Rigid body*	*Simple surface*
P_U	-94.59 ± 0.56	-0.45 ± 0.24	-1.77 ± 0.22
P_V	78.31 ± 0.55	2.92 ± 0.37	6.18 ± 0.29
P_W	119.93 ± 0.52	12.46 ± 0.25	1.43 ± 0.16
P_α	87.56 ± 0.98	4.74 ± 0.60	-0.49 ± 0.24
P_β	-94.81 ± 0.86	-1.88 ± 0.53	-0.07 ± 0.27
P_{02}	4.97 ± 1.12	96.00 ± 0.78	-8.59 ± 0.32
P_{11}	69.98 ± 1.53	37.26 ± 0.90	5.04 ± 0.46
P_{20}	-12.64 ± 1.03	60.28 ± 0.60	4.12 ± 0.35
P_{03}	-46.88 ± 1.00	51.79 ± 0.93	8.72 ± 0.39
P_{12}	9.53 ± 1.74	59.64 ± 1.37	7.09 ± 0.55
P_{21}	-118.53 ± 1.65	-10.12 ± 1.30	-12.86 ± 0.63
P_{30}	12.12 ± 1.07	66.93 ± 0.81	7.49 ± 0.41
σ_{plot}	**77.82**	**19.54**	**17.88**

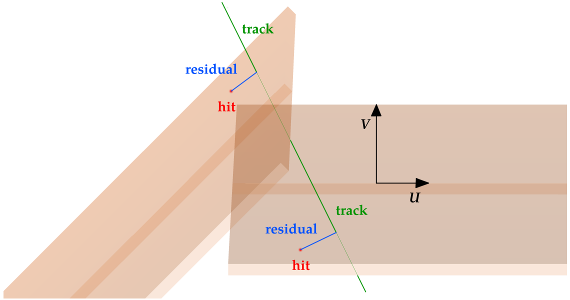
Possible cases of vertex detector geometries

	Δr	$r\Delta\phi$	Δz
r	**Radial expansion** $\Delta r = c_{scale} \cdot r$ 	**Curl** $r\Delta\phi = c_{scale} \cdot r + c_0$ 	**Telescope** $\Delta z = c_{scale} \cdot r$ 
ϕ	**Elliptical expansion** $\Delta r = c_{scale} \cdot \cos(2\phi) \cdot r$ 	**Clamshell** $\Delta\phi = c_{scale} \cdot \cos(\phi)$ 	**Skew** $\Delta z = c_{scale} \cdot \cos(\phi)$ 
z	**Bowing** $\Delta r = c_{scale} \cdot \lvert z \rvert$ 	**Twist** $r\Delta\phi = c_{scale} \cdot z$ 	**Z expansion** $\Delta z = c_{scale} \cdot z$ 

Validation of vertex detector geometry: overlaps

We observe overlap in track, if track is composed by two hits in same layer, but their ladder numbers are different. Then we can observe:





Overlaps with same sensor number

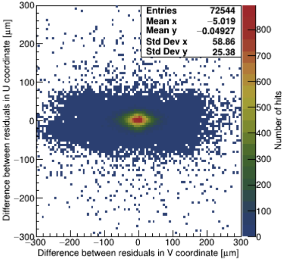
Overlaps with different sensor number

How to plot geometry of vertex detector using overlaps?

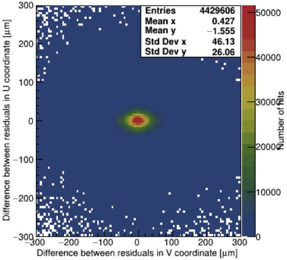
- Each overlap produce pair of residuals for each direction of measurement.
- We are looking for difference between pairs of residuals in both directions.

$$d^{u,v} = r_2^{u,v} - r_1^{u,v}, \quad r_{1,2}^{u,v} = \frac{m_{1,2}^{u,v} - p_{1,2}^{u,v}}{\sigma_{1,2}^{u,v}}$$

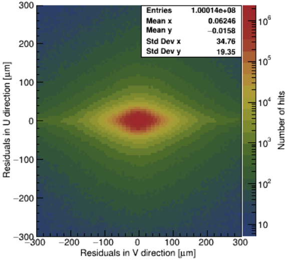
- Each difference depends on direction of measurement is filled to 2D histogram.
- For each category of overlaps we create separated histogram.
- For hits outside of overlapped area we plots standard 2D track-to-hit residual histogram.



Overlaps with different sensor number



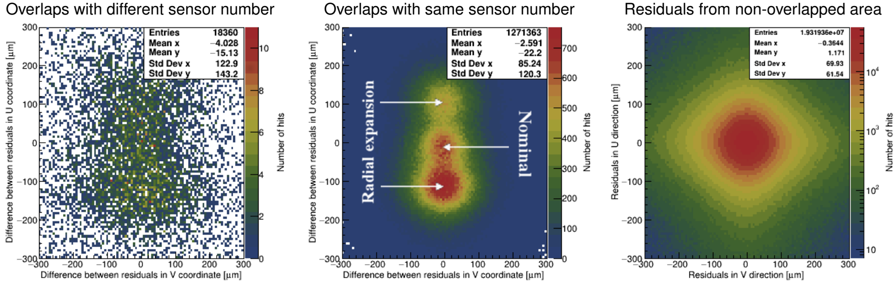
Overlaps with same sensor number



Residuals from non-overlapped area

Validation of vertex detector geometry using cosmics (5, 6 exp.)

We validated vertex detector geometry using cosmic data without magnetic field (exp. 5 and 6).

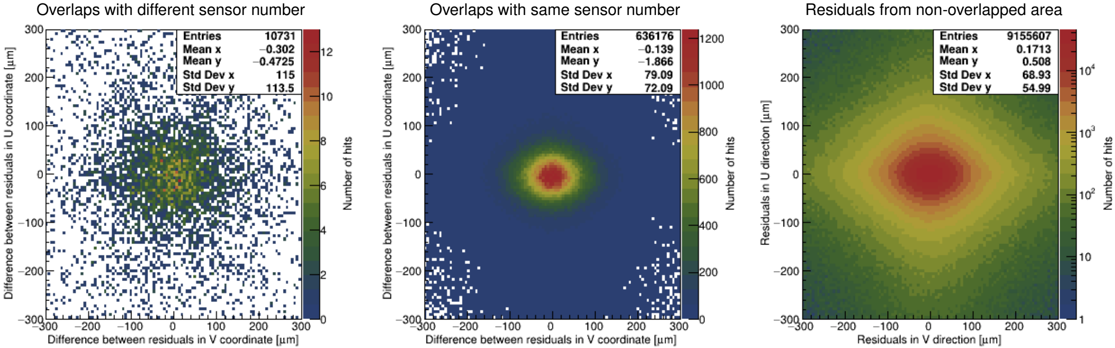


”Snowman” structure observed for residual difference distribution in overlaps with same sensor number can be explained as:

1) Top and bottom circles are coming from **radial expansion** of SVD rectangular sensors from layers 3, 4, 5 and 6. → wrong pitch of strip sensors in SVD software
2) Center circle is coming is from correct position of PXD sensors and SVD slanted sensors.

Validation of vertex detector geometry in cosmic data (7 exp.)

After fixing issue in SVD software we repeat validation procedure on cosmic data of experiment 7.



Result of tool used for searching weak modes of VXD detector.

VXD alignment is correct and no issues affect software reconstruction more.

Summary

- Pixel detectors provide very precise and stable measurement
- Observed issues for PXD (or SVD) sensors/ladders/layers correspond with expectations.
- Movement of vertex detector as function of change status QCS on scale of tents μm.
- Changes in alignment on scale of tents μm is not clearly understood.
- It is difficult to compare data taken with and without magnetic field.
- Because of several reasons: correct map of magnetic field, Lorentz angle correction, ...
- Repeat or start studies focused to improve alignment.
- Validation and monitoring procedures are very sensitive to small changes in alignment or software.