Alignment studies at Belle II Vertex detector

XXVI Cracow EPIPHANY Conference
(on LHC Physics: Standard Model and Beyond)

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on behalf of the Belle II collaboration

Cracow, Poland, January 7 - 10, 2020

Outline

Belle II and vertex detector

Alignment

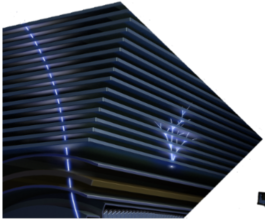
Alignment results

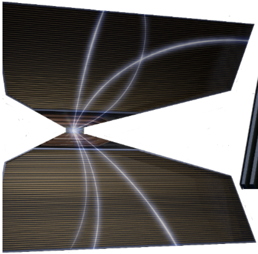
Validation vertex detector alignment

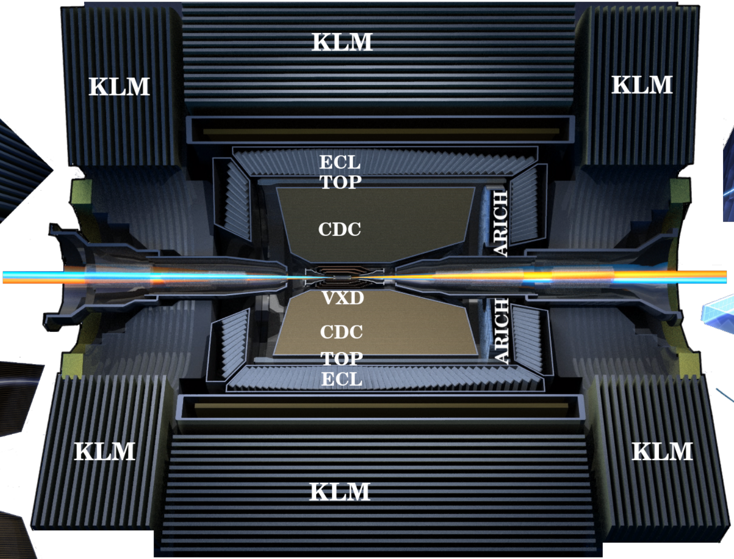
Monitoring of systematic displacement

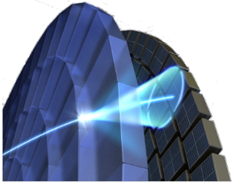
Summary

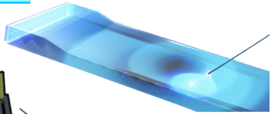
BELLE II DETECTOR

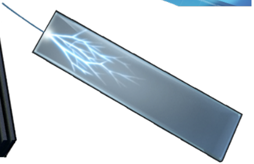






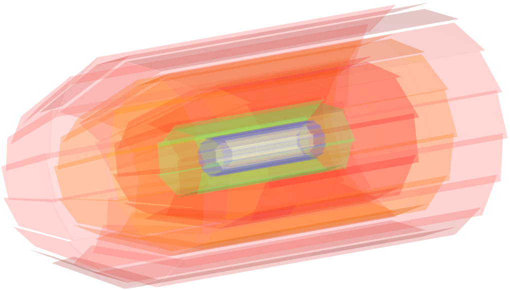






More at Wednesday's talk about "Belle II status and Prospect" by Zdenek Dolezal

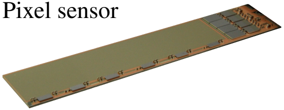
VERTEX DETECTOR (PIXEL & STRIP DETECTOR)



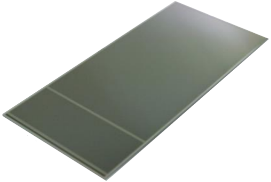
	Radius [mm]	*Thickness* [μm]	R/ϕ *pitch* [μm]	*Z pitch* [μm]	*Sensors*
PXD Layer 1	14	75	50	55 - 60	2×8
PXD Layer 2	22	75	50	70 - 85	$2 \times 2^*$
SVD Layer 3	39	300	50	160	2×7
SVD Layer 4	80	300 - 320	75	240	3×10
SVD Layer 5	104	300 - 320	75	240	4×12
SVD Layer 6	135	300 - 320	75	240	5×16

*PXD Layer 2 is not complete, but full pixel detector will be used after replacement in 2021.

Pixel sensor



Strip trapezoidal sensor



Strip rectangular sensor

TRACK BASED ALIGNMENT PROCEDURE AND MILLEPEDE II

- Sensors measure hit positions of charged particles passing their sensitive area.
- Tracking reconstruction software combine hits to a 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.

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

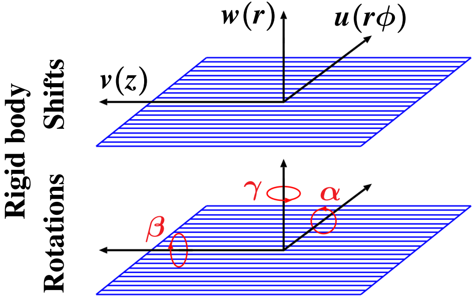
  $\boldsymbol{\tau}_j$ is vector of track parameters and $\boldsymbol{a}$ is vector of alignment parameters
- For alignment purpose χ^2 function is defined as:

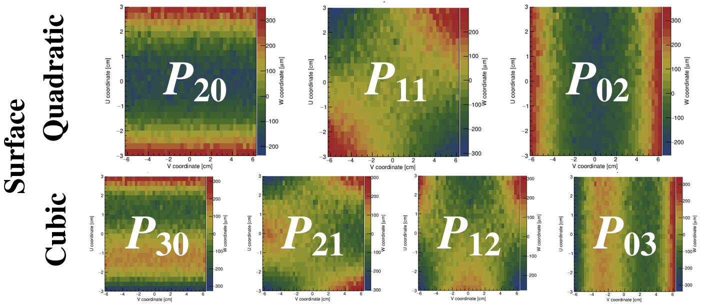
$$\chi^2(\boldsymbol{\tau}, \boldsymbol{a}) = \sum_j^{tracks} \sum_i^{hits} \left(\frac{r_{ij}(\boldsymbol{\tau}_j, \boldsymbol{a})}{\sigma_{ij}} \right)^2 \approx \sum_j^{tracks} \sum_i^{hits} \frac{1}{\sigma_{ij}^2} (r_{ij}(\boldsymbol{\tau}_j^0, \boldsymbol{a}^0) + \frac{\partial r_{ij}}{\partial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

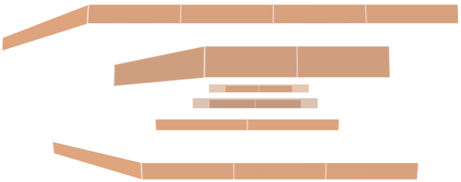
- **Millepede II** is based on global linear χ^2 minimization. [1]
- Constrains can be applied/included in the algorithm.

[1] V. Blobel, C. Kleinwort: *A new method for the high-precision alignment of track detectors, arXiv:hep-ex/0208021*

Vertex detector alignment parameters





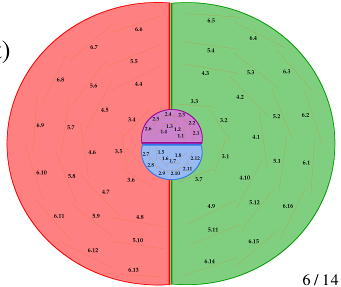


- It can be used per sensor:
  - 6 rigid body parameters (top left)
  - 7 surface parameters (top right)

$\sim 212 \cdot 13 = 2756$ parameters

- Per ladder (bottom left) and per halfshell (bottom right) it can be used 6 rigid parameters.

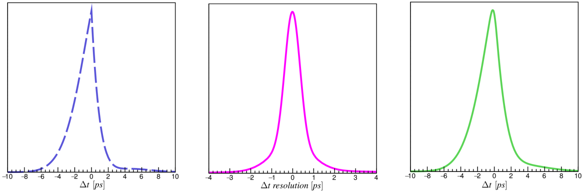
$\sim (65 + 4) \cdot 6 = 414$ parameters



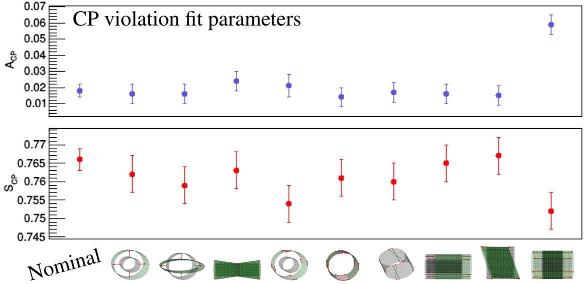
IMPORTANCE OF DETECTOR ALIGNMENT

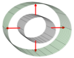
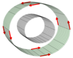
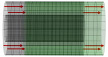
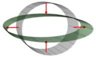
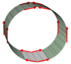
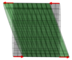
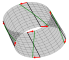
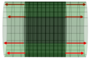
- Alignment is important for time dependent CP Violation analysis

Physical distribution $\otimes$ Detector resolution = Measured distribution



- Sensor displacements deform detector resolution distribution.



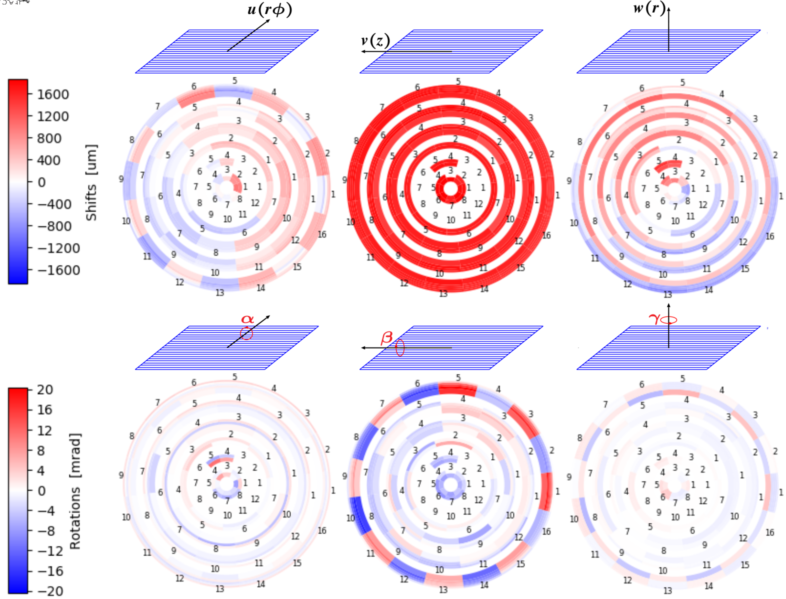
	Δr	$r\Delta\phi$	Δz
r	**Radial expansion** $\Delta r = c_{scale} \cdot r$ 	**Curl** $r\Delta\phi = c_{scale} \cdot r + c_0$ 	**Telescope** $\Delta z = c_{scale} \cdot r$ 
ϕ	**Elliptical expansion** $\Delta r = c_{scale} \cdot \cos(2\phi) \cdot r$ 	**Clamshell** $\Delta\phi = c_{scale} \cdot \cos(\phi)$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

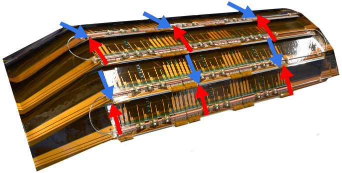
χ^2 invariant modes of minimization algorithm

TIME DEPENDENT ANALYSIS REQUIRES:

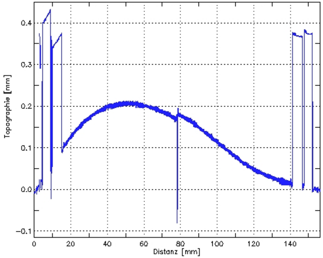
1) Precisely determined alignment and calibration constants.
2) Validated alignment constants and uncertainties.
3) Monitoring of systematic displacement of vertex detector

Alignment results: Rigid body parameters



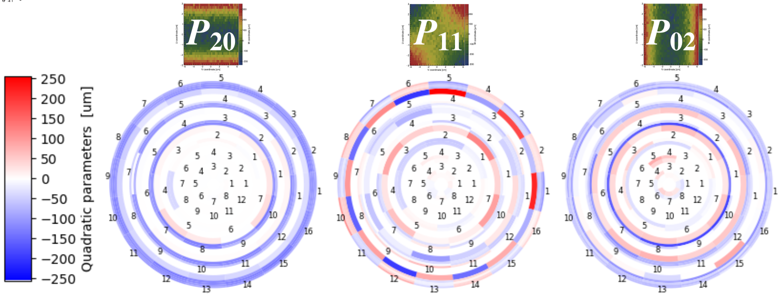


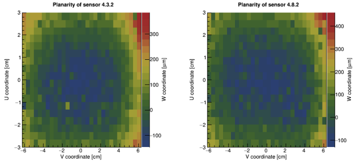
Zebra effect for 6^{th} layer is seen in u and β parameters



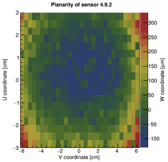
Shape of ladders in 2^{nd} layer is seen w, α, P_{02} and P_{03}

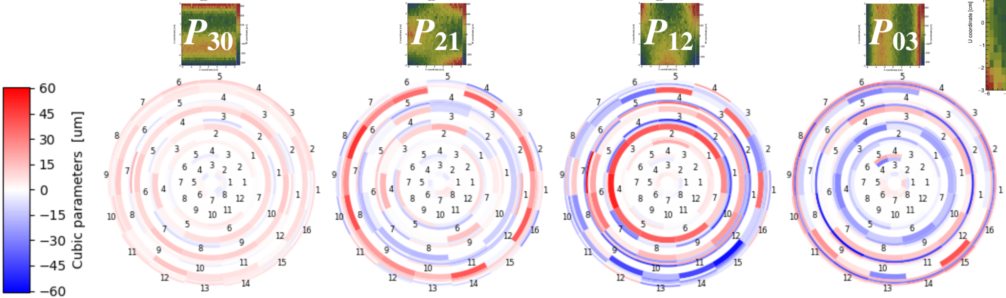
ALIGNMENT RESULTS: SURFACE PARAMETERS



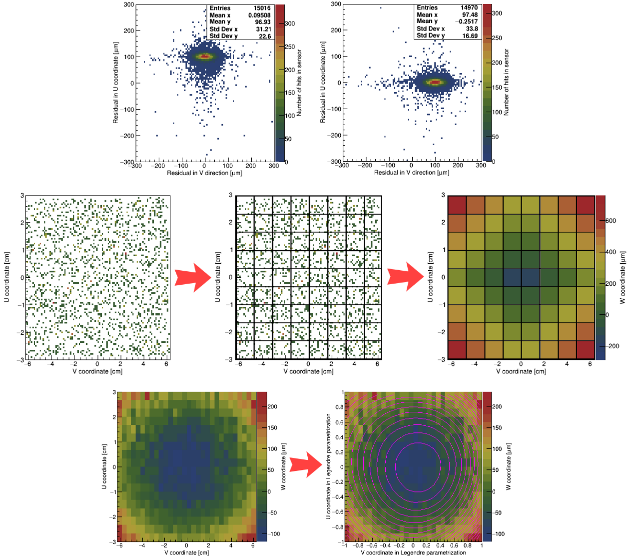


Sensor surface deformation in data parametrized by P_{20} and P_{02}





Validation of alignment parameters



Track-to-hit residuals

- Standard method for alignment validation
- Means of distributions as *u* and *v* parameters

Projection of sensor surface

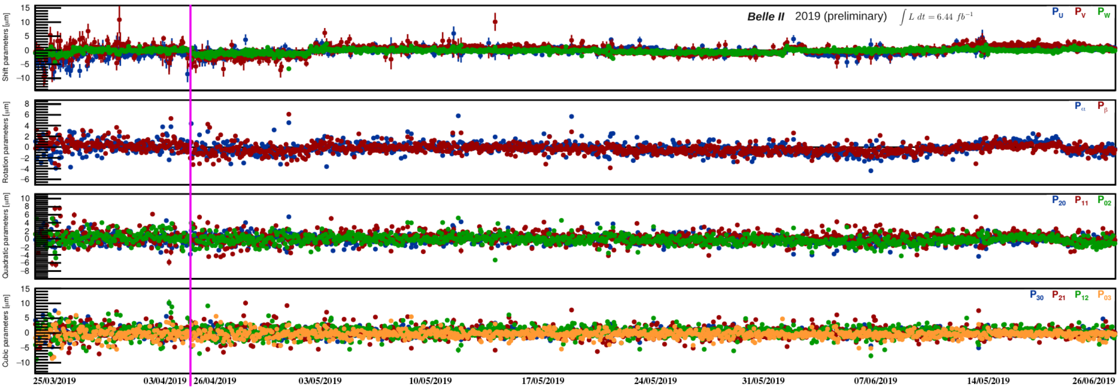
- Dividing sensor surface to n $\times$ m matrix
- W-residual as $r_W = \frac{r_U}{\tan \alpha_U} = \frac{r_V}{\tan \alpha_V}$
- Weighted by $(\tan \alpha_{U,V})^2$ during averaging
- Averaging all measurements in cell

Fitting sensor surface

- From local sensor system to Legendre
- Fitting other alignment parameters
- Parameter γ can not be fitted

VALIDATION OF ALIGNMENT PARAMETERS: SENSOR 4.3.2

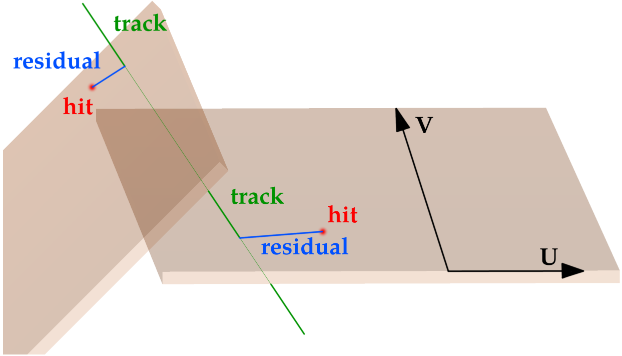
- All alignment parameters (without γ) are validated.
- Parameters of each vertex detector sensor are studied as function of time (per run).



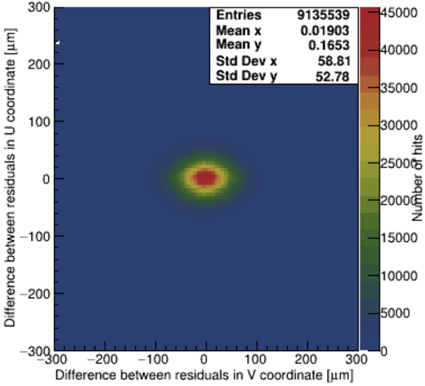
The validation plot presented stability of alignment parameters during data taking in spring 2019. In beginning of April fire accident break is happen. The parameters are fluctuate in range $\pm$ 10 μm. Other sensors look very similar, otherwise alignment procedure is processed.

Monitoring systematic displacement: Overlaps

- A track passing two neighbour ladders in one layer can be used for studying systematic displacement.



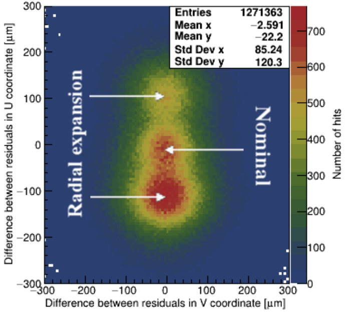
$$r_{1,2}^{u,v} = \frac{m_{1,2}^{u,v} - p_{1,2}^{u,v}}{\sigma_{1,2}^{u,v}}, \quad d^{u,v} = r_2^{u,v} - r_1^{u,v}$$



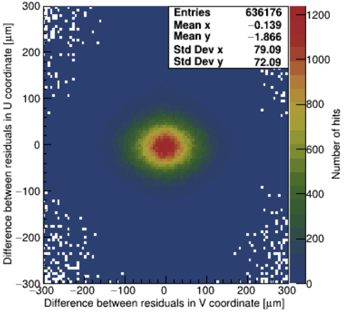
Monte Carlo results

- Standard residuals in overlapping area are determined.
- Difference between them are calculated.
- Differences for both directions are filled.

February 2019

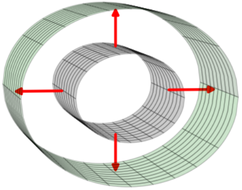


April 2019



First checks in February 2019 showed discrepancy between Monte Carlo and data results.

Detailed studies introduced a radial expansion of barrel strip sensors about 100 μm.

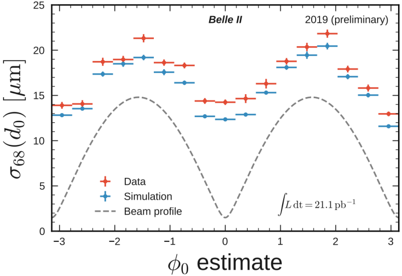


The source of discrepancy was in wrongly used pitch of rectangular strip sensors.

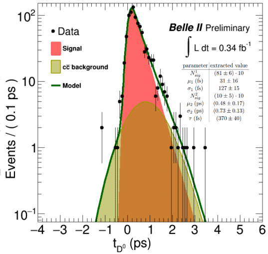
After fixing observed discrepancy data results were close to Monte Carlo. However small observed differences can be solved by improvements in reconstruction software.

SUMMARY

- Sophisticated alignment procedure was applied.
- Twelve from thirteen parameters per sensor are validated in each run using cosmic or collision data.
- Alignment results are precise and stable.
- Possible systematic displacement of vertex detector is monitored using tracks passing overlapping area of layers.
- The studies help to understand vertex detector and check reconstruction software.
- Presented studies show our way to monitor quality of data taken by the Belle II vertex detector.
- Some experiences is published:
  - Parametrization and validation in arXiv:1910.06289
  - Monitoring systematics displacement in arXiv:1906.08940



Measurement of beam spot



Measurement of D^0's lifetime

talk

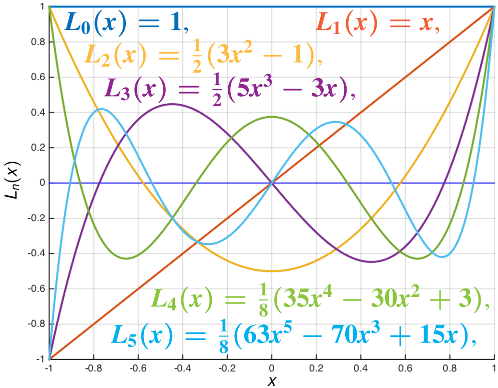
8/1 **Zdenek Dolezal**: Belle II status and Prospects

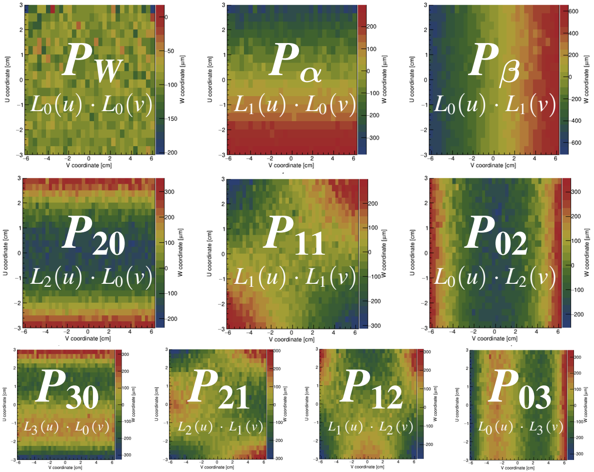
9/1 **Riccardo Manfredi**: Diamond detector for radiation monitoring and beam abort at Belle II

9/1 **Szymon Bacher**: Investigation of magnetic field inside Belle II spectrometer

9/1 **Borys Knysh**: $B \to K\pi\pi\gamma$ analysis in the Belle II Experiment

FROM LEGENDRE TO ALIGNMENT PARAMETRIZATION





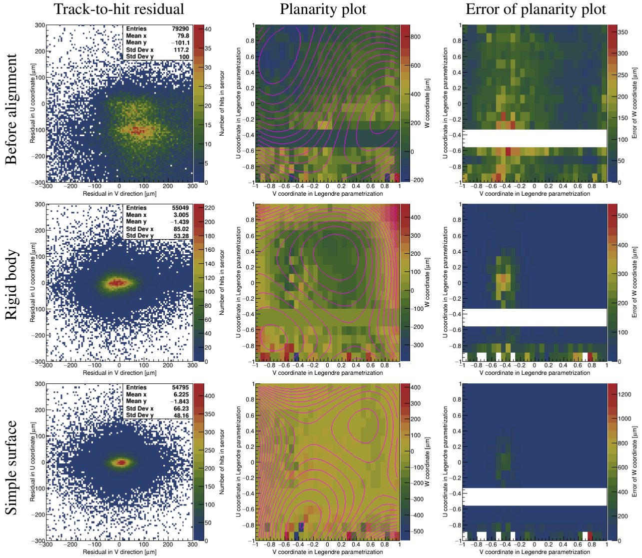
Legendre polynomials in one dimension

Orthogonality of Legendre polynomials:

$x \in [-1, +1] : \int_{-1}^{+1} L_i \cdot L_j \approx \delta_{ij} (= 0 \text{ for } i \neq j)$

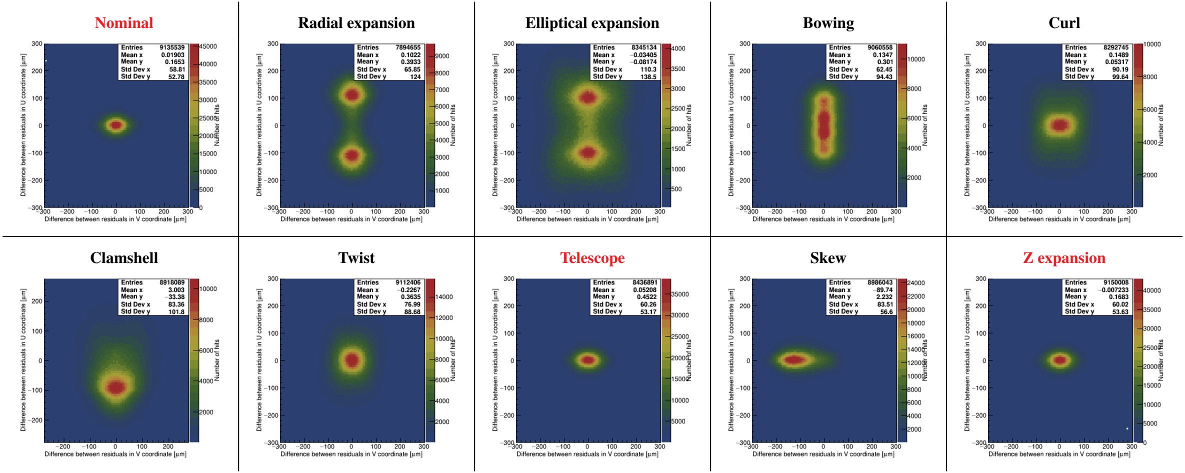
If sensor has a uniform illumination at least along one side, the contribution from different orders are independent.

Validation of alignment parameters: Sensor 4.1.2



[μm]	*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**

Overlaps with same sensor number: Cosmic @ MC



Many of χ^2 invariant modes are distinguishable from Nominal geometry and identified very clearly.

However **Telescope** and **Z expansion** are very difficult recognized from **Nominal** geometry.