Alignment Procedures for the PXD/SVD

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Introduction
- Alignment for Belle II
- Current Belle Alignment
- Alignment with $e^+e^- \rightarrow \mu^-\mu^+$

Track-based Alignment
- Used Program Package
- Internal Alignment
- Weak modes

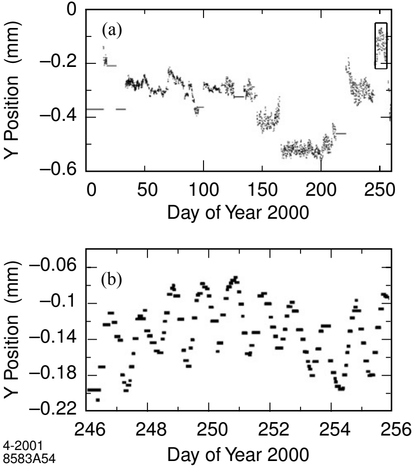
Conclusions

Alignment for Belle II

Belle II vertex detector

- PXD will be mounted directly on the beampipe
- SVD will be attached to the CDC
- mechanically independent subsystems
- experience from BABAR shows: Frequent and large relative movements possible

➡ frequent, time-dependent alignment needed



Global alignment of the BABAR SVT

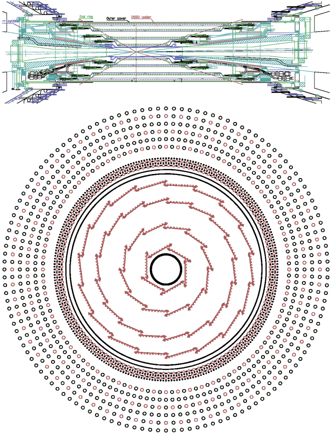
Current Belle Alignment

Alignment of the SVD2 using cosmic muons without magnetic field

1. internal alignment of all 246 Modules with respect to each other
2. global alignment of rigid SVD with respect to CDC
3. lorentz-shift correction using run cosmics

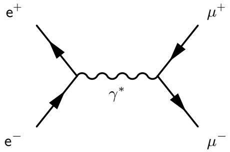
Limitations

- dedicated cosmic runs needed
- at most 2 distinct alignment runs a year
- statistics will not increase with luminosity of collider



Belle SVD2

Alignment with $e^+e^- \longrightarrow \mu^-\mu^+$



Goal

Implementation of a new alignment procedure for the Belle SVD2 using mainly muon pairs from e^+e^- annihilation as preparation for Belle II

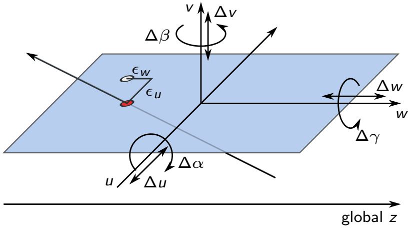
- high statistics
  $\sigma(e^+e^- \longrightarrow \mu^+\mu^-) \approx 0.77\,\mathrm{nb}$

$$\sim 15\,\mathrm{s}^{-1}\ @\ 2\times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\sim 600\,\mathrm{s}^{-1}\ @\ 8\times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- large transverse momentum
  $p_t \gtrsim 2\,\mathrm{GeV}$
- back to back in center of mass system
- not back to back in Lab system
  (asymmetric energies, crossing angle)

Track-based Alignment



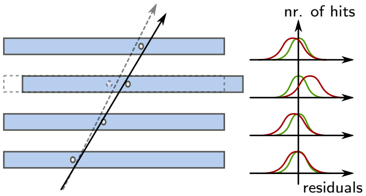
Residual ϵ: Distance hit $\Leftrightarrow$ track

ideal: residuals normal distributed
mean 0, width σ_r

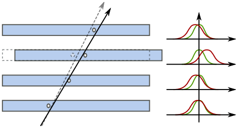
but: real wafer position not known
assembly precision $\sim 100\,\mu$m

Necessary to determine absolute position of every detector module

- wrong positions will distort/degrade residual distribution
- minimize residuals by adjusting module position
- at least 6 degrees of freedom per module (3 translation + 3 rotation)



Track-based Alignment



$$\chi^2(\mathbf{a}, \boldsymbol{\tau}) = \epsilon(\mathbf{a}, \boldsymbol{\tau})^T V^{-1} \epsilon(\mathbf{a}, \boldsymbol{\tau})$$

$$\chi^2(\mathbf{a}, \boldsymbol{\tau}) = \sum_{i \in tracks} \sum_{j \in hits} \left(\frac{track(\mathbf{a}, \boldsymbol{\tau}_i) - hit_j}{\sigma_j} \right)^2$$

Solution for linearized χ^2

$$\underbrace{\left(\mathbf{J}^T \mathbf{V}^{-1} \mathbf{J}\right)}_{\mathbf{C}} \begin{pmatrix} \Delta \mathbf{a} \\ \delta \boldsymbol{\tau} \end{pmatrix} = \underbrace{\left(\mathbf{J}^T \mathbf{V}^{-1} \epsilon(\mathbf{a}_0, \boldsymbol{\tau}_0)\right)}_{\mathbf{b}}$$

local alignment:

- neglect correlations between modules
- keep track parameters fixed
- χ^2-function per pro module
- small matrices (typical 6×6)

global alignment (Millepede):

- one global χ^2-function
- all correlations taken into account
- “large” set of equations (1476×1476 for Belle, similar for Belle II)

Used Program Package

Alignment

Solve set of linear equations with large number of parameters

$$\mathbf{C}\begin{pmatrix}\Delta\mathbf{a}\\ \delta\boldsymbol{\tau}\end{pmatrix} = \mathbf{b} \qquad \begin{array}{rl}\text{alignment corrections} & \Delta\mathbf{a}\\ \text{track corrections} & \delta\boldsymbol{\tau}\end{array}$$

- $\mathbf{C} = \mathbf{J}^T\mathbf{V}^{-1}\mathbf{J}$ very large, $\sim$ millions of rows.
- simultaneous minimization of residuals with respect to alignment and track parameters
- not interested in corrections for tracks

Millepede/Millepede II

- program package to solve special χ^2-problems
- used for the alignment by H1, HERA-B, CDF, LHCb and CMS
- optimized for up to $\mathcal{O}(50000)$ parameters
- reduction of matrix size using Schur complement

Matrix reduction

Any set of linear equations with invertible submatrix $\mathbf{C}_{22}$

$$\left(\begin{array}{c|c} \mathbf{C}_{11} & \mathbf{C}_{21}^T \\ \hline \mathbf{C}_{21} & \mathbf{C}_{22} \end{array}\right) \begin{pmatrix} \Delta\mathbf{a} \\ \delta\boldsymbol{\tau} \end{pmatrix} = \begin{pmatrix} \mathbf{b} \\ \boldsymbol{\beta} \end{pmatrix}$$

can be solved using the Schur complement $\mathbf{S} = \mathbf{C}_{11} - \mathbf{C}_{21}^T \mathbf{C}_{22}^{-1} \mathbf{C}_{21}$

$$\begin{pmatrix} \Delta\mathbf{a} \\ \delta\boldsymbol{\tau} \end{pmatrix} = - \left(\begin{array}{c|c} \mathbf{S}^{-1} & -\mathbf{S}^{-1}\mathbf{C}_{21}^T\mathbf{C}_{22}^{-1} \\ \hline -\mathbf{C}_{22}^{-1}\mathbf{C}_{21}\mathbf{S}^{-1} & \mathbf{C}_{22}^{-1} - \mathbf{C}_{22}^{-1}\mathbf{C}_{21}\mathbf{C}_{21}^T\mathbf{S}^{-1}\mathbf{C}_{22}^{-1} \end{array}\right) \begin{pmatrix} \mathbf{b} \\ \boldsymbol{\beta} \end{pmatrix} \qquad (1)$$

$$\mathbf{C} = \left(\begin{array}{c|cccc} \sum \mathbf{C}_i & \mathbf{G}_1 & \mathbf{G}_2 & \cdots & \mathbf{G}_n \\ \hline \mathbf{G}_1^T & \boldsymbol{\Gamma}_1 & 0 & \cdots & 0 \\ \mathbf{G}_2^T & 0 & \boldsymbol{\Gamma}_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{G}_3^T & 0 & 0 & \cdots & \boldsymbol{\Gamma}_n \end{array}\right)$$

- Top part of Eq. 1 are the desired alignment corrections
- Only $\mathbf{C}_{22}$ has to be inverted, inexpensive since block diagonal
- No approximation, all correlations still included

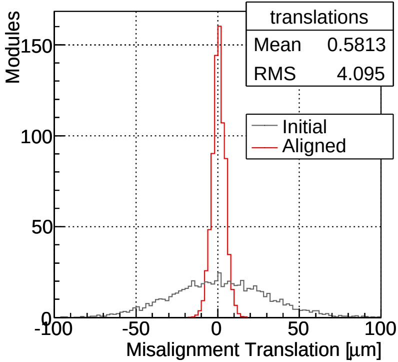
Final set of equations

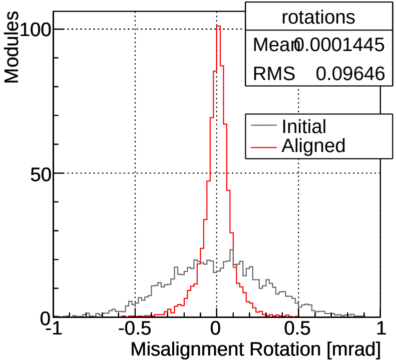
$$\left(\sum \mathbf{C}_i - \sum \mathbf{G}_i \boldsymbol{\Gamma}_i^{-1} \mathbf{G}_i^T\right) \Delta\mathbf{a} = \left(\sum \mathbf{b}_i - \sum \mathbf{G}_i (\boldsymbol{\Gamma}_i^{-1} \boldsymbol{\beta}_i)\right)$$

Internal Alignment

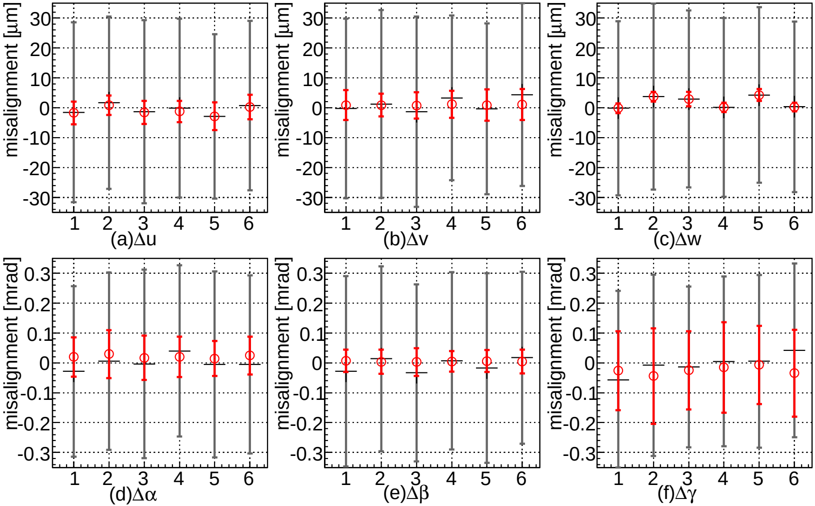
Current Status

- internal alignment of all the 246 SVD modules
- no alignment with respect to the CDC yet
- single tracks from muon 10^6 pair events
- initial misalignment of 30 μm (0.3 mrad) for translations (rotations) of all modules.



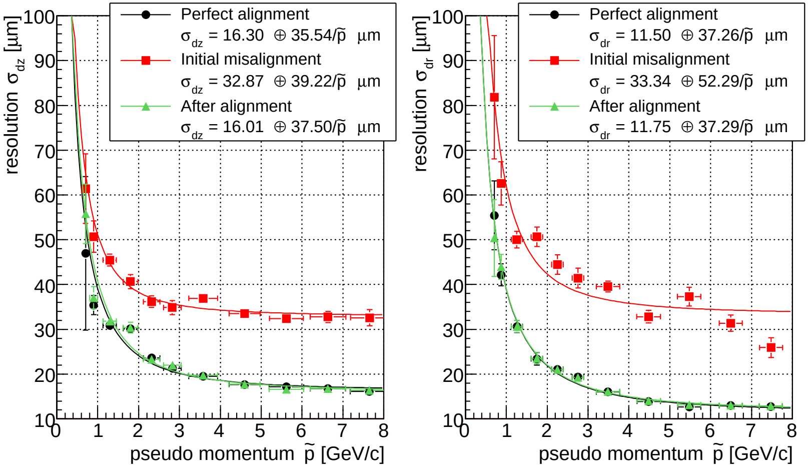


Remaining misalignment per parameter



Remaining misalignment for all 6 degrees of freedom and 6 independent misalignment scenarios

SVD2 Performance



(a) impact parameters z

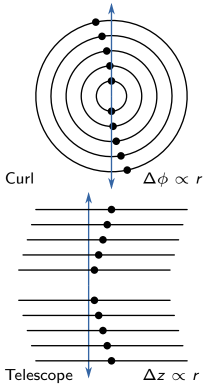
(b) impact parameters rϕ

Impact parameters obtained from cosmic muons

Weak modes

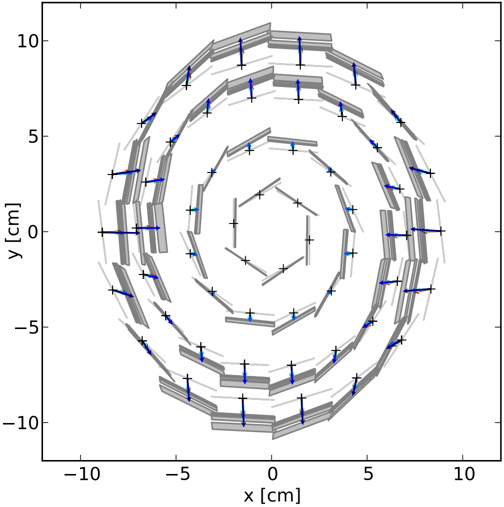
- depending on input: matrix **C** (almost) singular
- undefined (or weak) modes which do not change χ^2 but may introduce physics bias
- can be controlled by regularization (simultaneous minimization of residuals and the moduli of the alignment corrections)

	Δr	$\Delta \phi$	Δz
r	Radial Expansion (distance scale)	Curl (charge asymmetry)	Telescope (CM boost)
ϕ	Elliptical (vertex mass)	Clamshell (vertex displacement)	Skew (CM energy)
z	Bowing (CM energy)	Twist (CP violation)	Z expansion (distance scale)



Weak modes

- weak modes can be estimated from eigenvalue spectrum
- visualisation of current smallest eigenvalue
- would introduce significant bias depending on ϕ



Possible weak deformation in the current alignment procedure

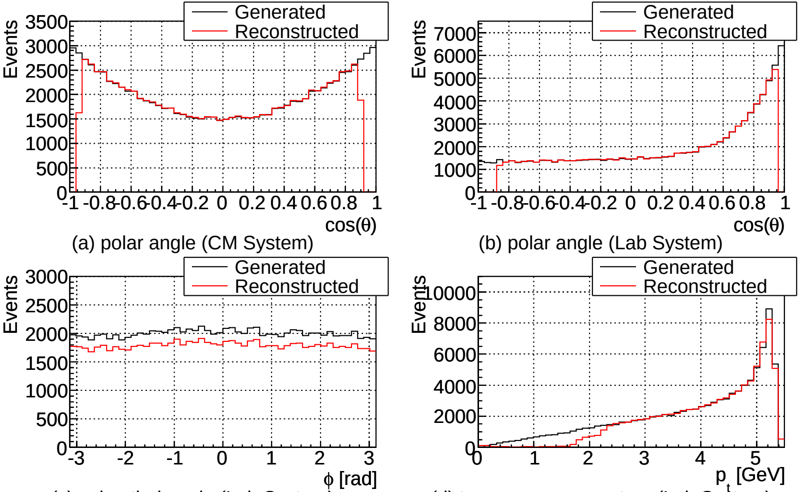
Conclusions

- internal alignment working
- negligible computing requirements ($\sim 3\,\text{h} + 2\,\text{min}$ for 10^6 events)
- complete weekly alignment seems possible
- global alignment much faster (only 6 degrees of freedom)

plans for the future

- external alignment with respect to the CDC
- simulation of larger misalignment
- further optimization of track sample selection
- pair-fit of muon pairs

Muon Pair Distributions



(a) polar angle (CM System)

(b) polar angle (Lab System)

(c) azimuthal angle (Lab System)

(d) transverse momentum (Lab System)