Alignment & Calibration of Belle II Tracking Detectors

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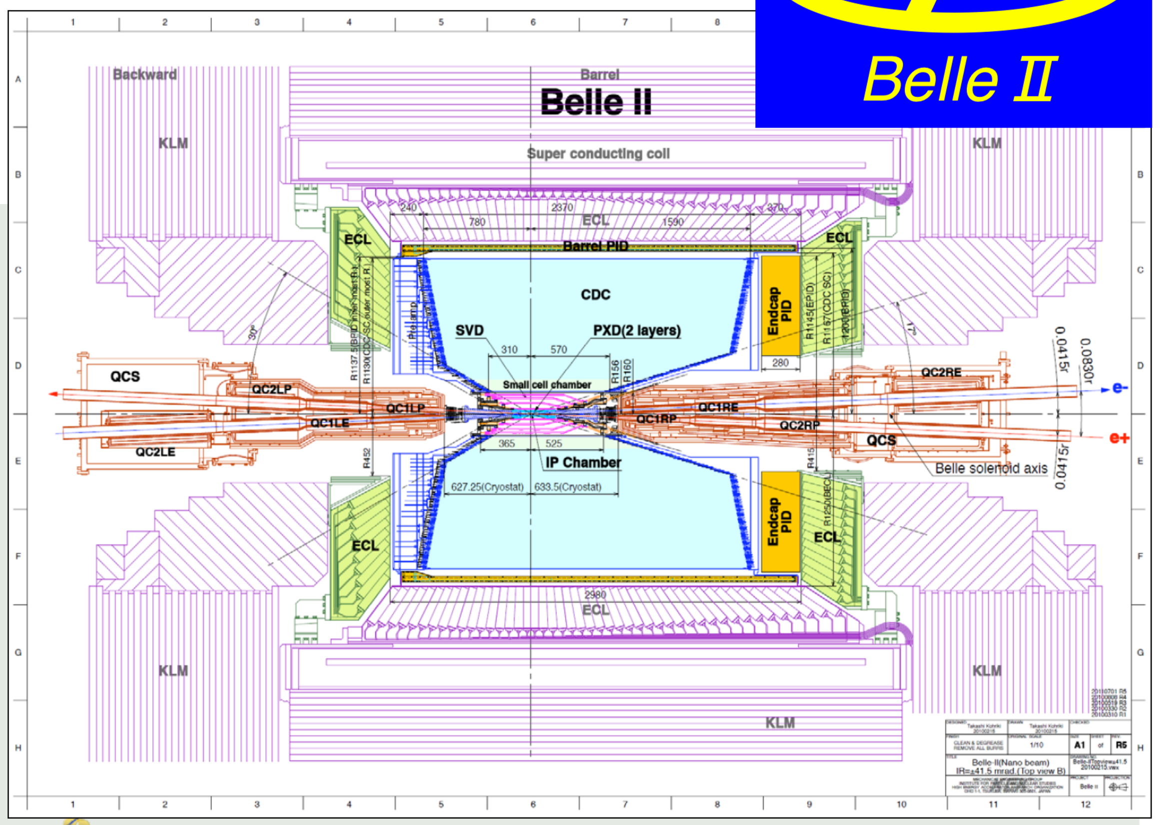


Belle II and its tracking detectors

The Belle II experiment will start taking data in 2018. With 40 times higher luminosity, it aims to acquire 50 ab^{-1} data sample of B-$\bar{B}$ events. In order to manage higher occupancy and background, a new silicon vertex detector (VXD) combined from pixel and strip sub-detectors, will be installed together with upgrade of the main tracking device, the drift chamber. The high target performance of the detector, in particular vertex and momentum resolution, motivated the development of fast and reliable alignment and calibration procedures.

We present track-based alignment and calibration of the vertex and tracking detector using a global approach of Millepede II combined with advanced track model, solving the mathematical problem in an efficient and precise way.

CDC Central Drift Chamber

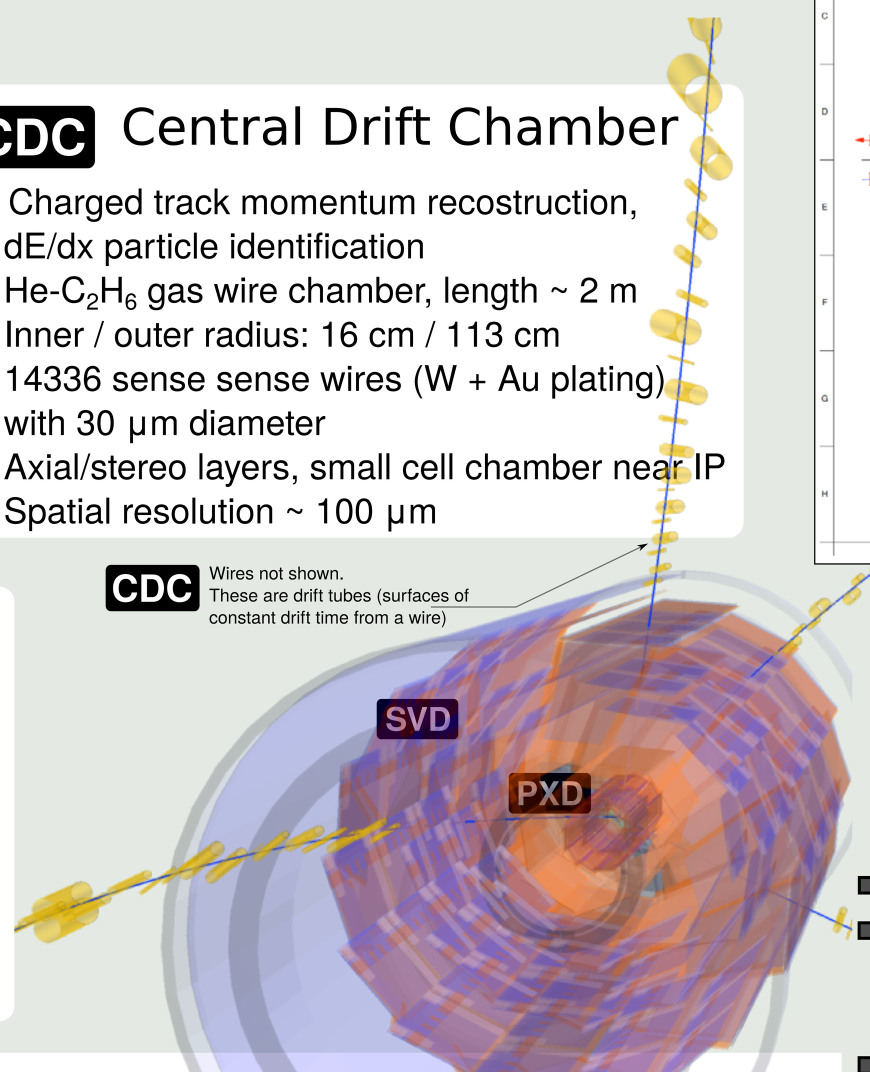
- Charged track momentum recostruction, dE/dx particle identification
- He-C_2H_6 gas wire chamber, length ~ 2 m
- Inner / outer radius: 16 cm / 113 cm
- 14336 sense sense wires (W + Au plating) with 30 µm diameter
- Axial/stereo layers, small cell chamber near IP
- Spatial resolution ~ 100 µm

PXD Pixel Detector

- 8M pixels for precise vertex reconstruction
- 2 layers of DEPFET (DEPfeted Field Effect Transistor) silicon sensors
- 1st layer: 14 mm from interaction point with 8 sensors (50 µm x 55–60 µm pixels)
- 2nd layer: 50 µm x 70–85 µm, 12 sensors
- All sensors' active areas thinned to 75 µm

SVD Strip Vertex Detector

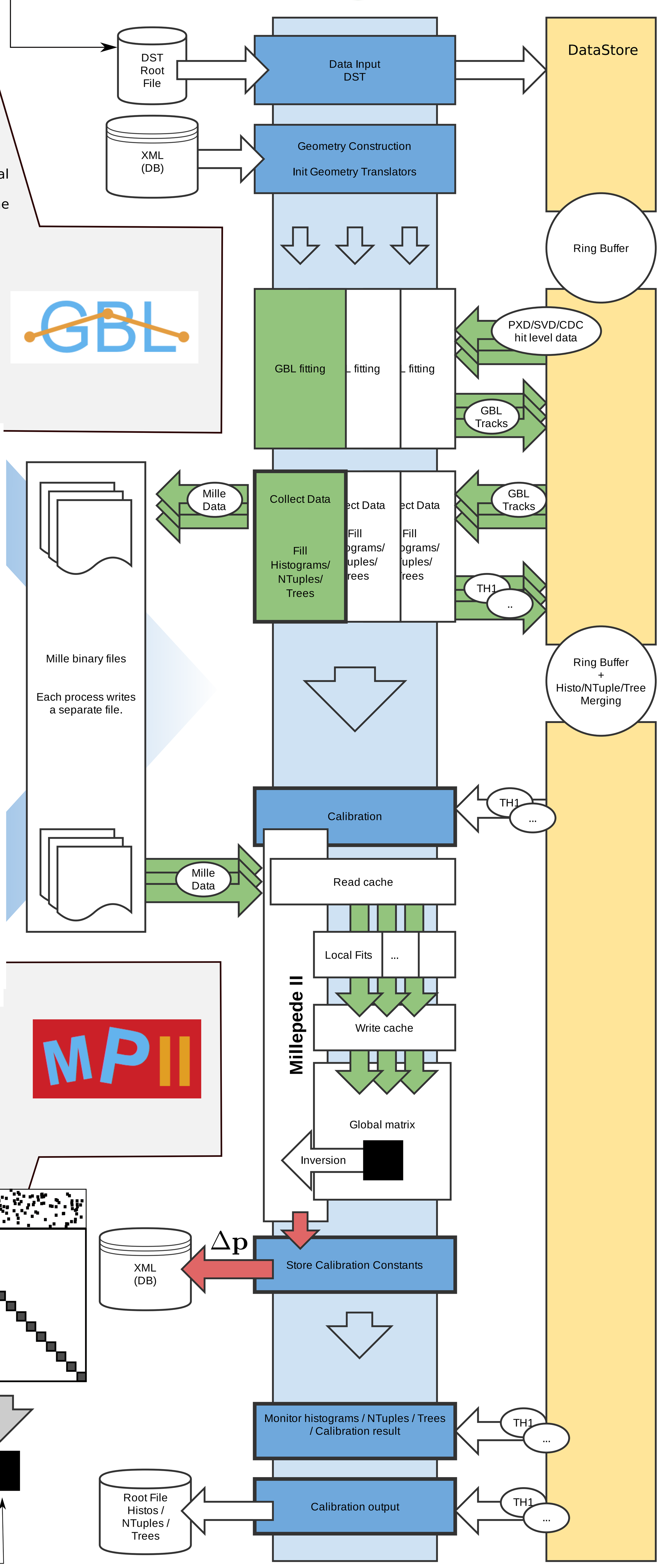
- Vertex reconstruction + extrapolation to PXD for data reduction + e.g. K_S decays outside PXD
- 4 layers of double-sided silicon strip sensors
- 187 sensors (~300 µm thickness) with fast readout
- 1st layer at R=38mm (pitch z/R-φ: 50 / 160 µm)
- Layers 2/3/4 at R=80/115/140 mm (75 / 240 µm) with slanted forward trapezoidial sensors



Software Framework

for simulation, reconstruction, calibration and analysis

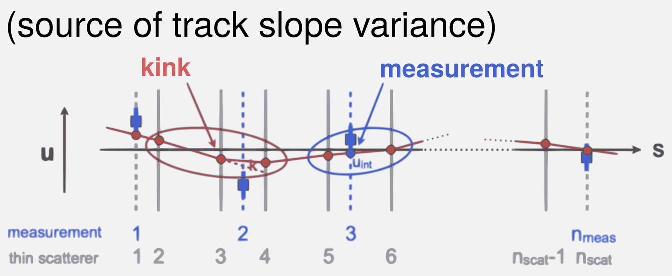
- **B**elle **2** **A**nalysis and **S**imulation **F**ramework (basf2)
- Modern HEP framework written in C++11 and using Python for user control (but you can do almost everything with Python:-) including software modules
- Covers all software tasks: data aquisition/simulation, online/offline reconstruction, calibration, physics analysis ...
- Modular design, I/O and object interchange and lifetime managed via DataStore able to stream ROOTified objects
- Full scale Geant4 and detector simulation
- Development of **basf2 Calibration Framework** in progress
- Uses mature basf2 features: modules, logging, histograming ...
- Seamless parallelization of event processing and data collection



Track Fitting with General Broken Lines (GBL)

General Broken Lines

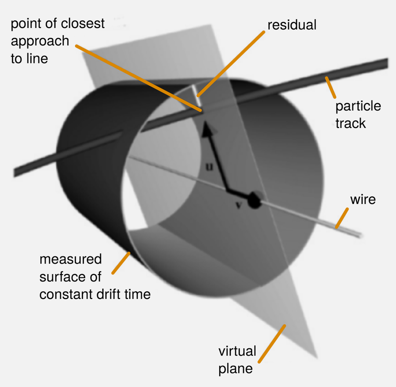
- Track model with proper description of **multiple scattering** (MS)
- Trajectory constructed from points with a **measurement** and/or a **thin scatterer** (source of track slope variance)



- Fit parameters also include kink angles at scatterers, common curvature correction, drift time corrections (CDC)
- Global linearized χ^2 fit by minimization of residuals and kinks yields full covariance matrix of the track (incl. correl. from MS)

GENFIT

- Generic track fitting toolkit
- Runge-Kutta track extrapolation
- Arbitrary measurement dimension
- Local measurement system constructed at virtual planes (detector planes in VXD)



- Integrated in Belle 2 Software Framework
- Interface to GBL and Millepede calibration

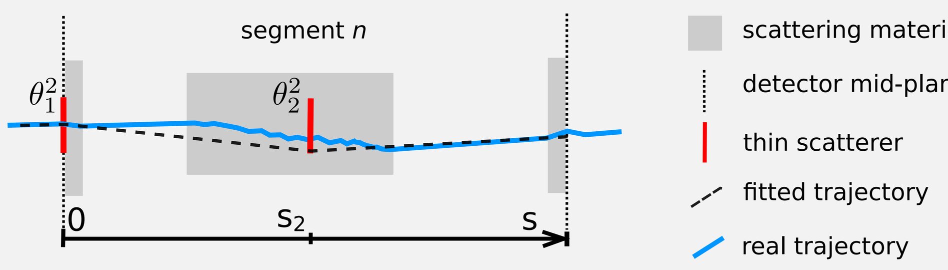
Material Treatment

- GBL trajectory constructed from track candidate
- Reference seed extrapolated to integrate material distribution and calculate moments of x/X_0

$$\bar{s} = \int \frac{s\,ds}{X_0(s)} \Big/ \int \frac{ds}{X_0(s)}, \qquad \Delta s^2 = \int \frac{(s-\bar{s})^2\,ds}{X_0(s)} \Big/ \int \frac{ds}{X_0(s)}$$

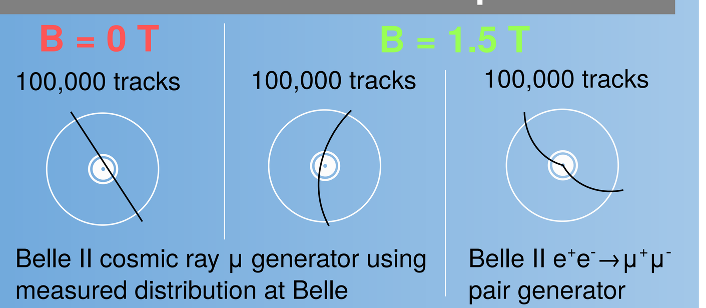
- Material between each two detector planes (in VXD) translated to two equivalent thin scatterers (1st at plane, 2nd at s_2) with MS angle variance θ_1^2 and θ_2^2

$$\theta_1^2 = \frac{\theta^2 \Delta s^2}{\Delta s^2 + \bar{s}^2} \qquad \theta_2^2 = \frac{\theta^2 \bar{s}^2}{\Delta s^2 + \bar{s}^2} \qquad s_2 = \frac{\Delta s^2 + \bar{s}^2}{\bar{s}}$$

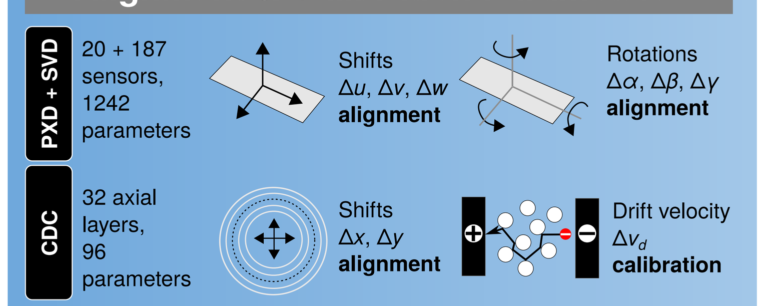


Test of simultaneous calibration and alignment of Belle II silicon vertex detector and central drift chamber

Simulated Track Sample



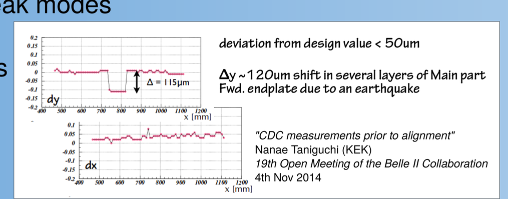
Alignment & Calibration Parameters



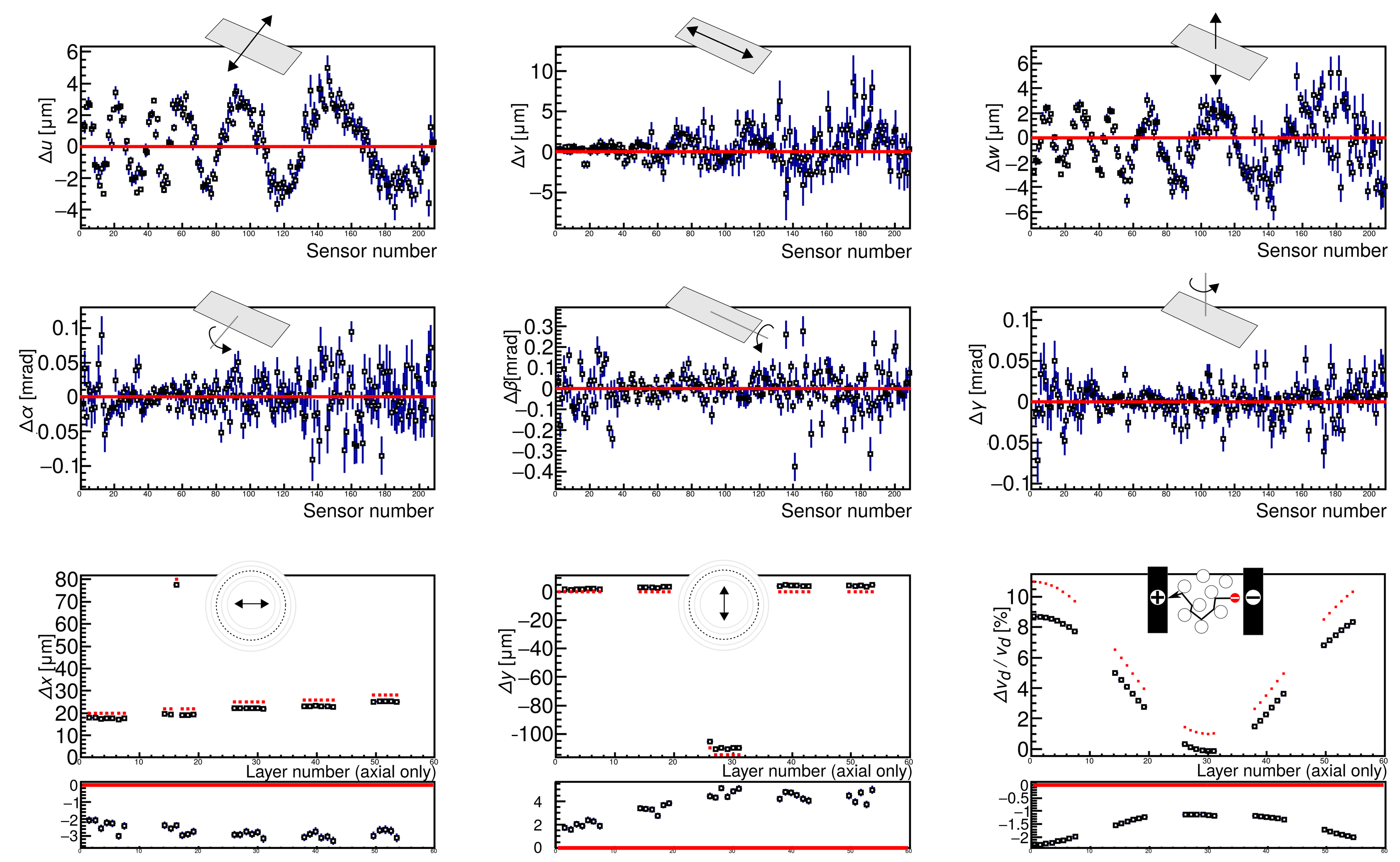
1338 global parameters - 10 fixed for reference = 1328 free

Mis-Alignment & Mis-Calibration

- No mis-alignment for VXD sensors to check for stability and possible weak modes
- Misalignment of axial CDC layers in Δx, Δy similar to 2014 survey



- Mis-calibration of (linear) x-t relation by using layer - dependent Δv_d



Visible bias comming from simulations effects not yet taken into account in the reconstruction

Calibration with Millepede II

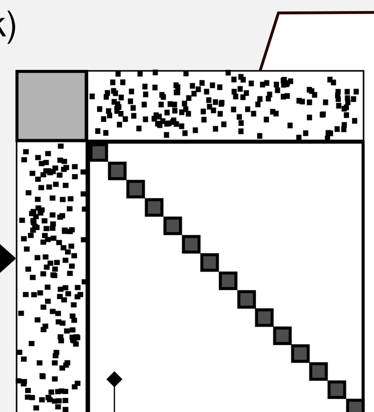
The Millepede method is designed to solve **linear least squares** problems with a simultaneous fit of all **global** (calibration) and **local** (track) parameters, irrespectively of the number of local parameters, keeping all correlations in the solution.

- Millepede II application is integrated into basf2
- Mis-calibration and mis-alignment influence track fit residuals
- Sum of normalized residuals (χ^2) of single measurements **linearized** around initial track and calibration parameters
- **Global (calibration) parameters** $\Delta\mathbf{p}$ to be determined

resolution | measurement | GBL prediction | How prediction depends on calibration params | How prediction depends on track params

Minimalize with respect to $\Delta\mathbf{p}$ and all $\Delta\mathbf{q}$

$$\chi^2(\Delta\mathbf{p}, \Delta\mathbf{q}) = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} \frac{1}{\sigma_{ij}^2} \left(m_{ij} - f_{ij}(\mathbf{p}_0, \mathbf{q}_{j0}) - \frac{\partial f_{ij}}{\partial \mathbf{p}} \Delta\mathbf{p} - \frac{\partial f_{ij}}{\partial \mathbf{q}_j} \Delta\mathbf{q}_j \right)^2$$



- **Local track parameters**, including scattering angles and drift time corrections
- All local and global parameters fitted simultaneously, resulting in a **huuuge matrix** equation to be solved
- Millepede utilizes the special structure of the matrix to reduce its dimension to the number of calibration parameters (no approximations)
- **Corrections to calibration parameters** retrieved by **inversion** (or using other methods for large matrices) of the reduced **global matrix**

Summary & Outlook

- The calibration infrastructure succesfuly tested
- First tests of simultaneous alignment & calibration of VXD&CDC promising, more detailed studies of systematics will follow
- Vertex & mass constrained decays, hierachical alignment
- More alignment parameters: wire-by-wire alignment of displacement, wire sag effect, CDC end-plates rotations/deformations, sensor deformations ...
- More calibration parameters: Lorentz angle in silicon sensors, realistic x-t relation

References

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[2] V. Blobel, C. Kleinwort, F. Meier, *Fast alignment of a complex tracking detector using advanced track models*, Computer Phys. Com., 182 (2011), 1760-1763
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[4] R.Itoh, *Implementation of parallel processing in the basf2 framework for Belle II*, J.Phys.: Conf. Ser. 396 (2012) 022026
[5] J. Rauch and T. Schlüter., *GENFIT - a Generic Track-Fitting Toolkit*, (2014) arXiv:1410.3698

Test Performance

- 8 x Intel® Core™ i7 950 @ 3.07GHz server
- Time to fit an average cosmic/IP track (on average 120 degrees of freedom): 20 ms (single core)
- Time to fit track sample and collect binary files: ~ 70 min (3 x 4 cores)
- Millepede running time: ~ 8 min