Alignment and Calibration of the Belle II Detector

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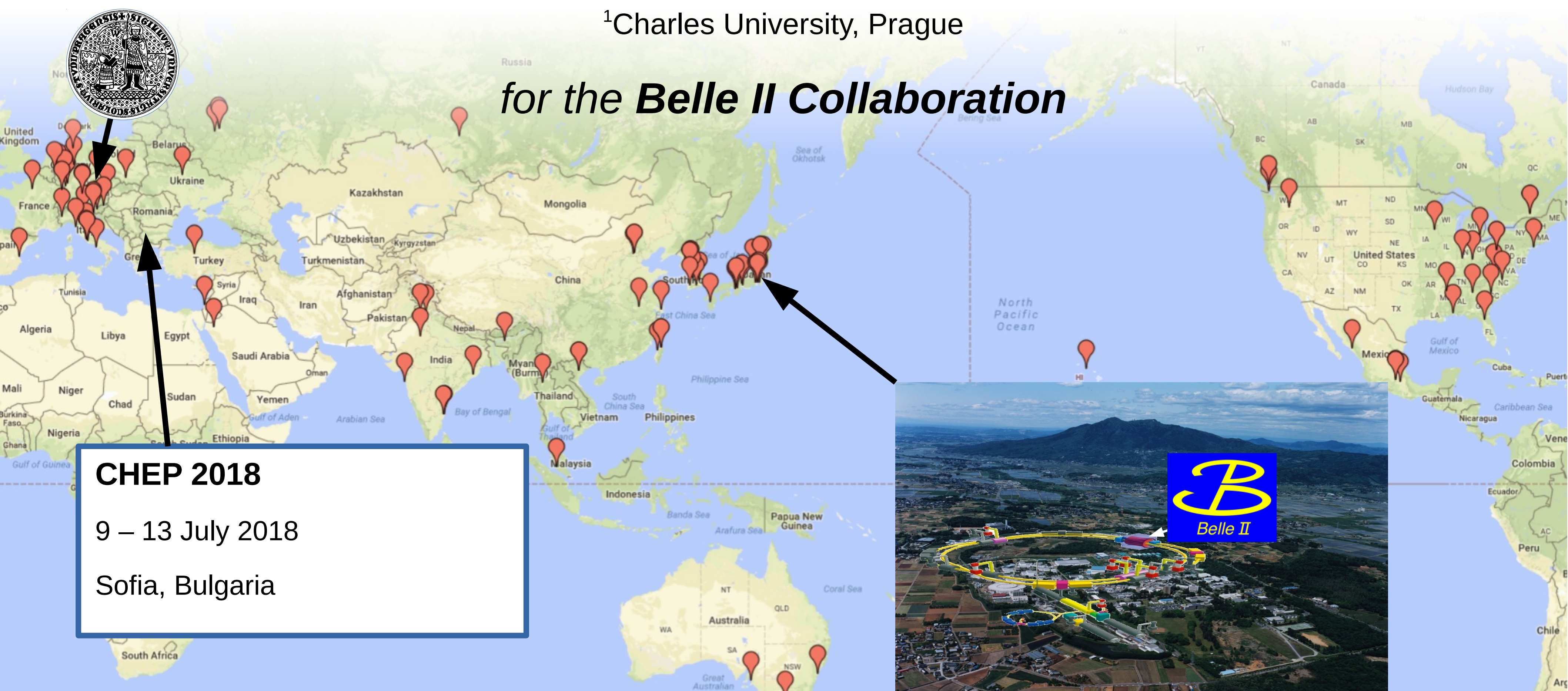
for the ***Belle II Collaboration***



CHEP 2018

9 – 13 July 2018

Sofia, Bulgaria

Super-B-Factory: The Precision Frontier

- Discover New Physics by **precision measurements** (could differ from SM predictions due to new virtual particles in loops – access beyond reach of energy frontier)

  → reduce statistical and systematic uncertainities (experiment & theory)

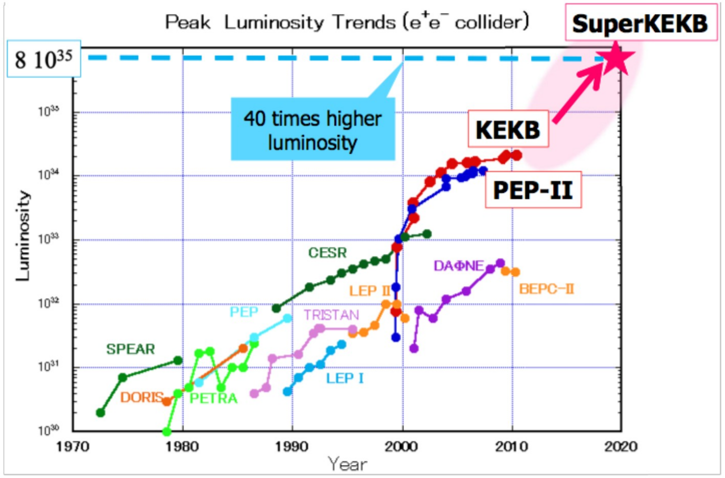
NP 2008: Kobayashi & Maskawa: Decisive confirmation of CKM picture

- B-Factories (until 2010): KEKB & PEP II

  Asymetric e+/e- collider @ $E_{CM} = m_{\Upsilon(4S)}$

  → study CPV, decays of B, D, tau …

$\mathscr{L}_{peak}=2\cdot10^{34} \rightarrow 8\cdot10^{35}/cm^2s$



- New generation: Super-B-Factory

  Increase statistics 50 times (50ab-1)

  → upgraded collider: **SuperKEKB**

  Reduce systematics

  → upgraded detector: **Belle II**

  → novel tools and methods for reconstruction, …, **calibration** and **alignment**, ...

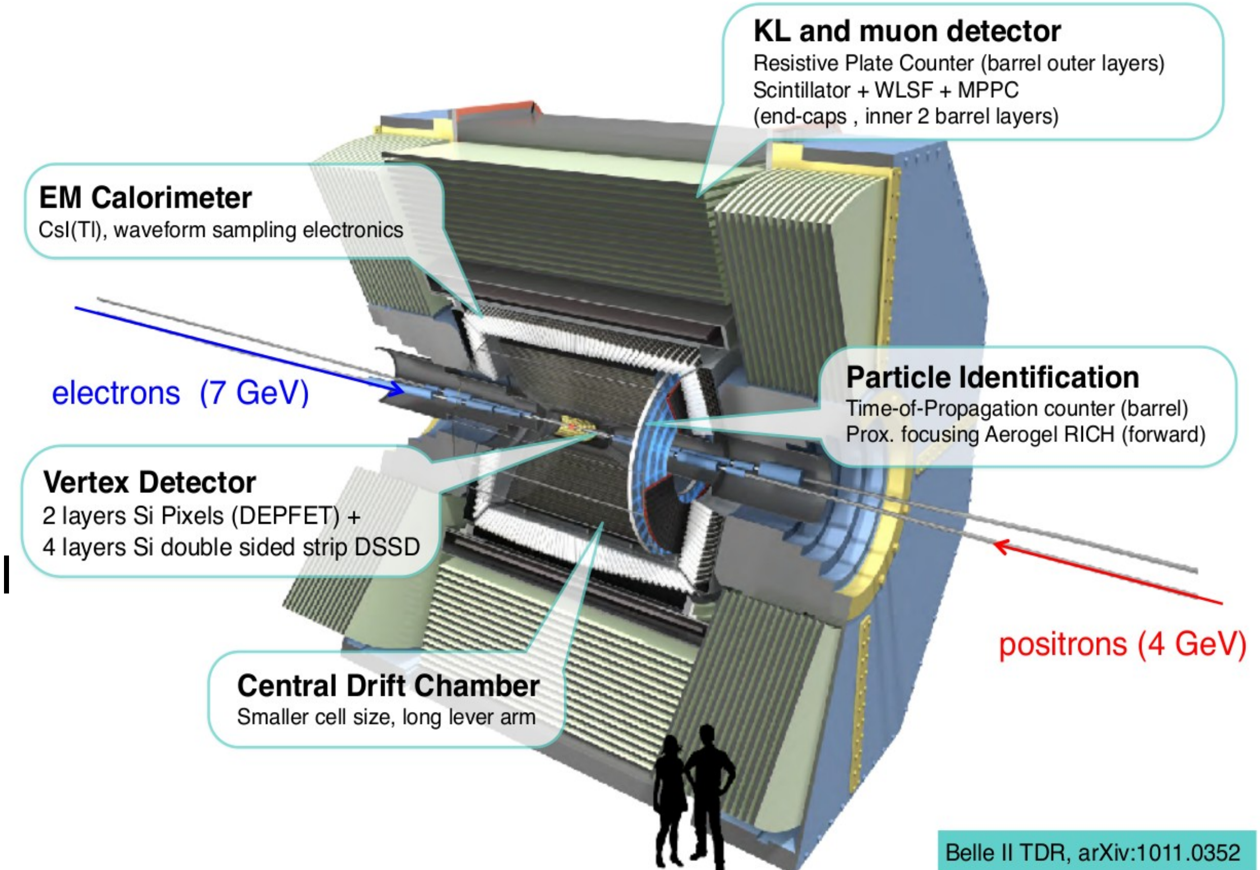
→ Thomas Kuhr [285]: plenary Wed 9:30

Belle II Experiment

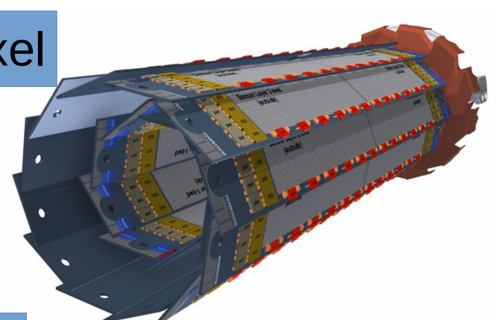
- Many upgrades to improve performance / ensure radiation hardness / handle higher data rate …
- New vertex detector (VXD)

  → improved vertex resolution

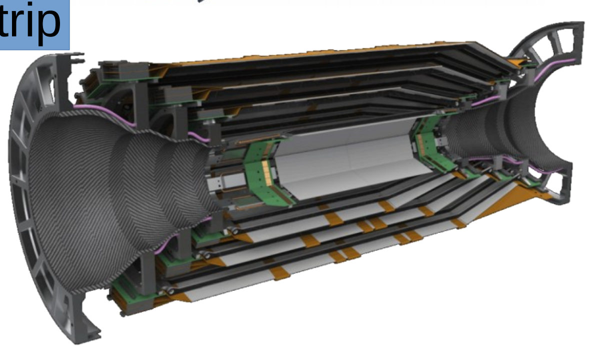
  → good **alignment** essential

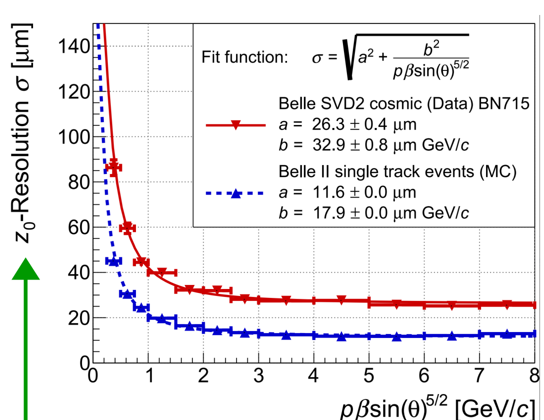


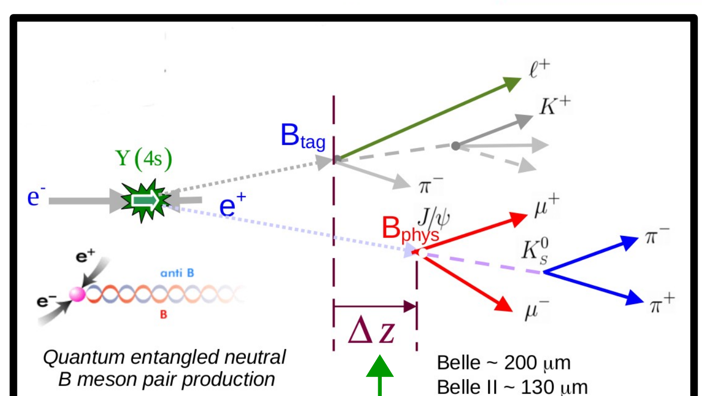
pixel



strip







Commisioning Phase 2

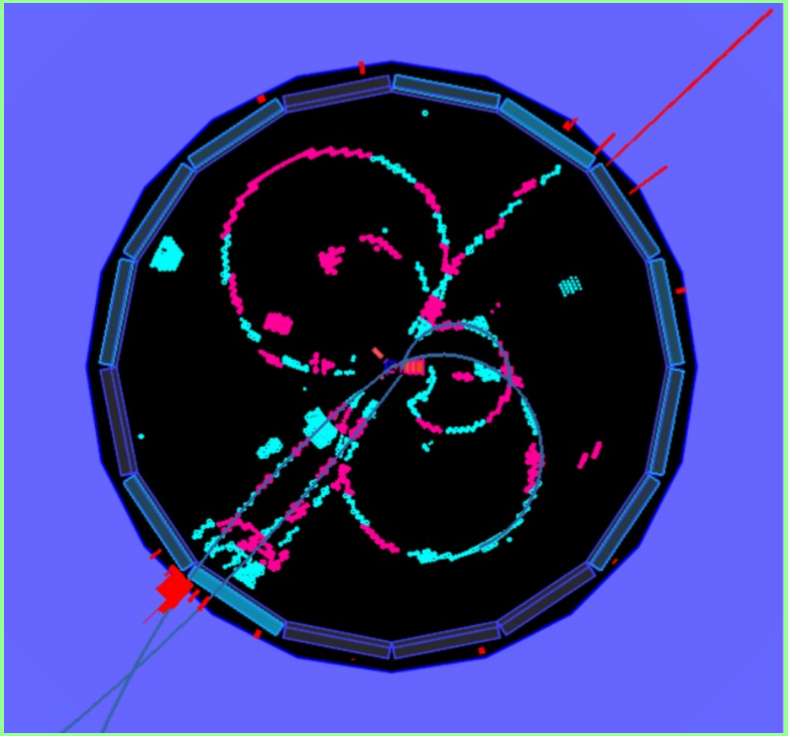
NOW RUNNING!

Phase 1 SuperKEKB commisioning (no collisions)

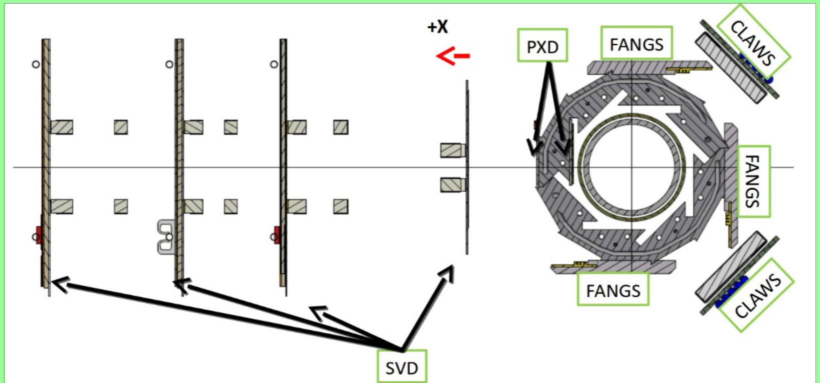
Phase 2 SuperKEKB & Belle II commisioning (no VXD)

- First collisions 26th April 2018
- Ends mid-July 2018 → VXD installation

First hadronic event in online event display:



- Limited to one section of full VXD (18 sensors)
- Dedicated radiation detectors
- Background commisioning – ensure safe enviroment for full VXD



Phase 2 VXD geometry & Beast radiation detectors

Phase 3 Physics run with full vertexing

- Starting 2019

Belle II Software & Calibration

- Calibration and alignment of the detector crucial to reach designed physics performance
- Millions of **calibration constants** needed for detector operation and data reconstruction / analysis → many of them need to be produced **from the data**

→ **Efforts to simplify calibrations' development, execution, automation ... by new software tools:**

Belle II Analysis and Simulation Framework (**basf2**)

→ Thomas Hauth: PyHEP

...

- Calibration & Alignment Framework (**CAF**)
  - Managment of multiple calibrations: dependencies, iterations, data aggregation, job submission, databases …

    → ***Developers (physicists) can concentrate on the algorithms***
- Automated calibration package **b2cal**

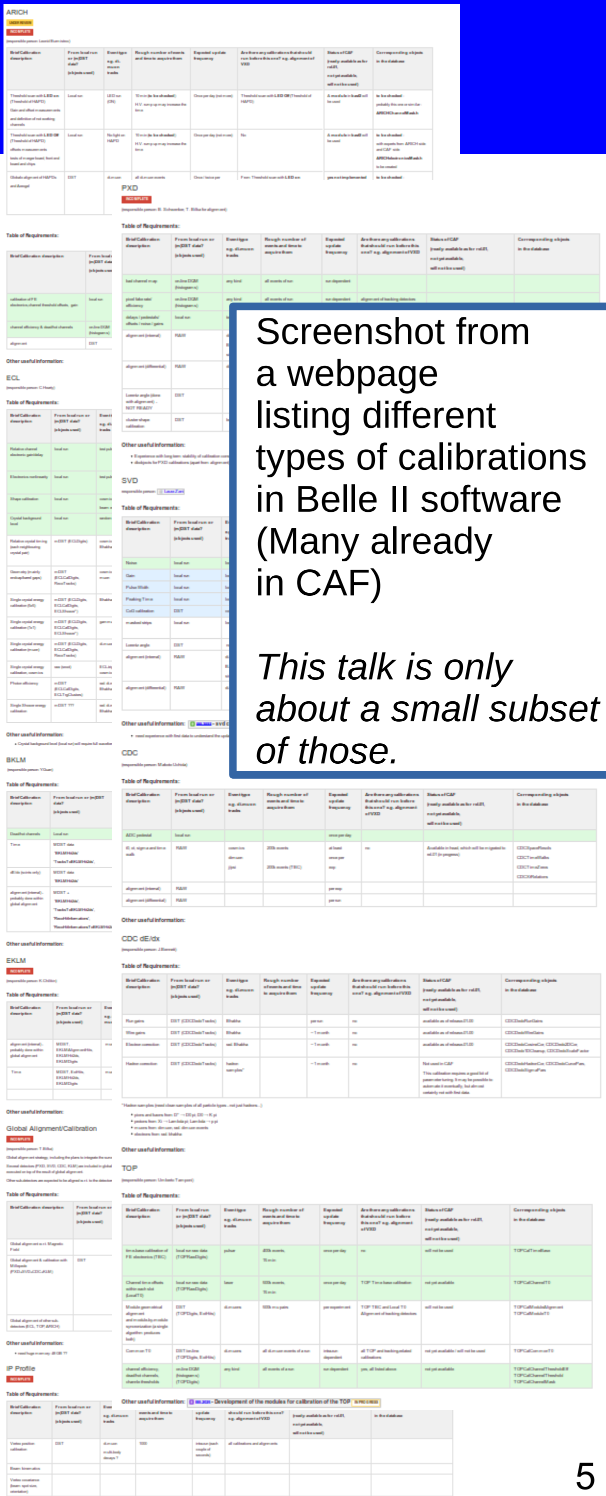
...

→ David Dosett [500]: poster

- Database
  - Time dependent „constants“ for data processing/reprocessing

...

→ Lynn Wood [285]: T4 Tue 11:15

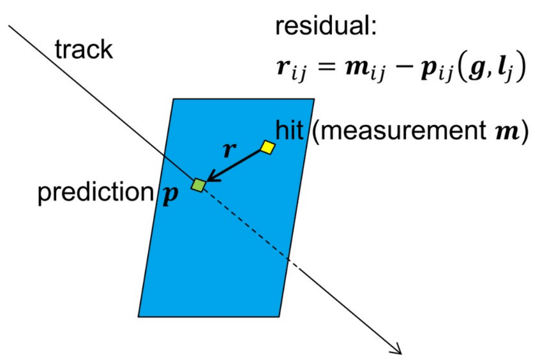


Screenshot from a webpage listing different types of calibrations in Belle II software (Many already in CAF)

This talk is only about a small subset of those.

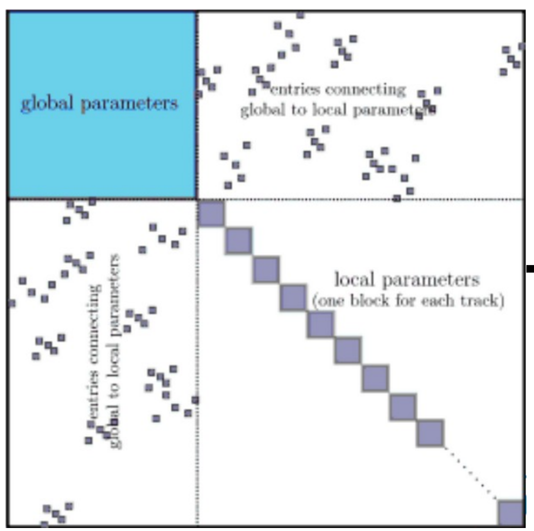
Track Based Alignment and Calibration with Millepede II

- Construction + e.g. laser survey ~ 100 um **X** intrinstic resolution 14 um (PXD)
- Better estimation of detectors' positions needed for precision measurements
  → track based alignment
- Track-to-hit **residuals** influenced by misalignment / miscalibration



→ **Minimize χ^2**

$$\chi^2(\boldsymbol{g}, \boldsymbol{l}) = \sum_{j}^{\text{tracks}} \sum_{i}^{\text{hits}} \boldsymbol{r}_{ij}^T(\boldsymbol{g}, \boldsymbol{l}_j)\, V_{ij}^{-1} \boldsymbol{r}_{ij}(\boldsymbol{g}, \boldsymbol{l}_j)$$



Block matrix algebra
- **no approximation** except linearization
  → iterations
- all **correlations kept** in the solution

Matrix for global par. → inversion

Millepede II

- Global linearized Chi2 minimization for very large number of parameters
  $\boldsymbol{g}$ ... alignment parameters (global)
  $\boldsymbol{l}_j$ ... track parameters (local)
- Used @ H1, CMS, Mu3e, COMPASS ...

*Scale of CMS tracker alignment with Millepede II (over 200k constants) ~ enough to align and calibrate „whole Belle II“ → will reduce possible weak modes (chi2 invariant distortions) in **global simultaneous fit** (cross-detector correlations kept) → try to include as many sub-detectors as possible*

Belle II

Integration in basf2

*under development or experimental

Millepede II using tracks in GBL representation as input – fully integrated in **CAF** and basf2.

GBL

PHYSICS AT THE TERA SCALE Helmholtz Alliance

General Broken Lines (GBL)

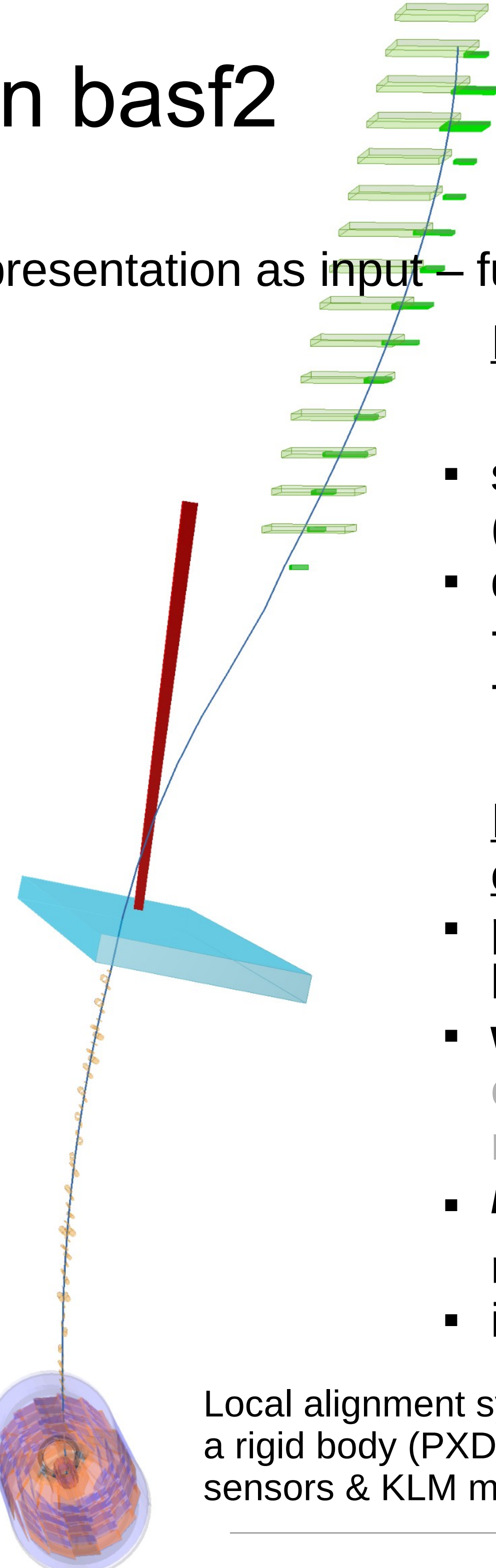
Global Chi2 track refit with advanced treatment of multiple scattering – fully compatible with Millepede II

GENFIT2

Generic toolkit for track reconstruction

→ Stefano Spataro [506]: T2 Tue 15:15

basf2



Simulated muon fitted by GBL in the Belle II event display

Input from standard reconstruction:

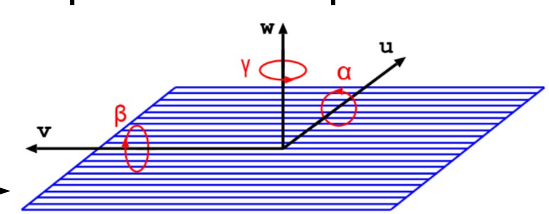
→ Thomas Hauth [463]: T2 Tue 15:00
[464]: T1 Wed 11:30

- single charged tracks, cosmics (with/without magnet)
- decays
  - ➔ vertex(+beam) constraint
  - ➔ +mass(+beam kinematics) constraint*

Integrated sub-detectors & constants:

- **pixel**, **strip**: rigid body sensors + hierarchy, deformations*, ...
- **wire chamber**: layer/wire alignment, calibrations: T0, time-walks, x-t relations, wire-sagging*, ...
- K_L & **muon** system: rigid body modules
- interaction point vertex position

Local alignment system for a rigid body (PXD, SVD sensors & KLM modules)



Calibrations & Performance with 1st data

Cosmics data

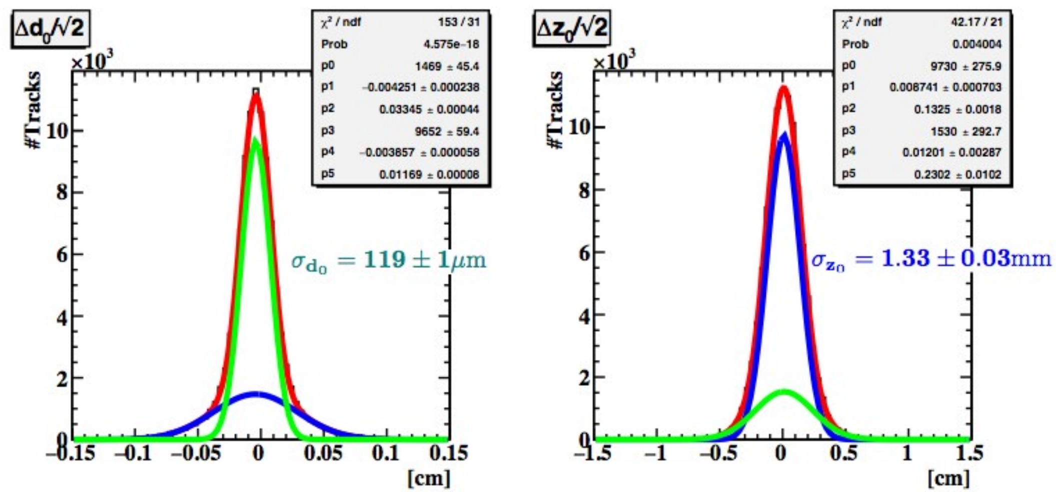
Drift chamber local alignment & calibration

(ported to CAF)

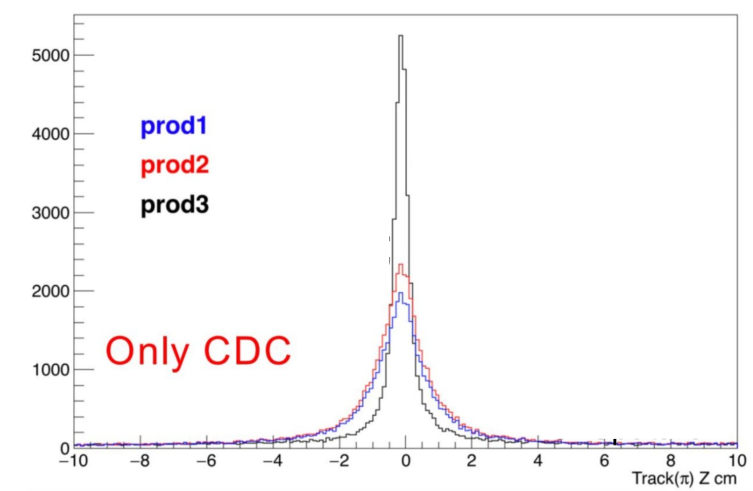
First collision data

Improvements in performance due to iteratively improving calibrations

Vertex resolution @ IP. CDC only on cosmics:

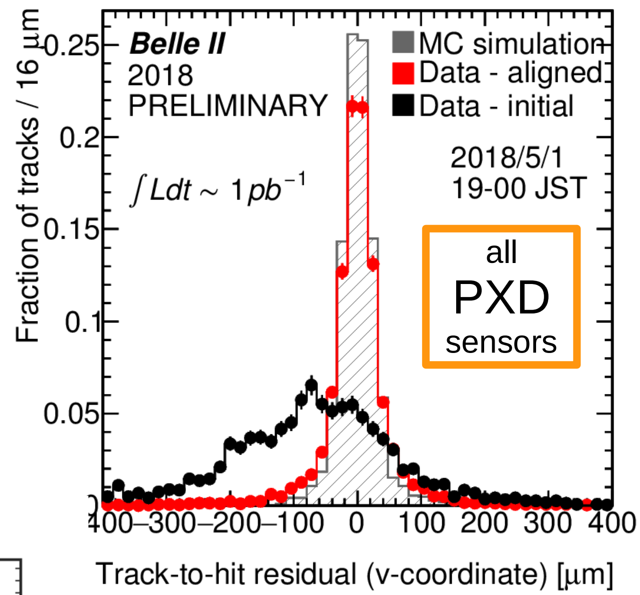


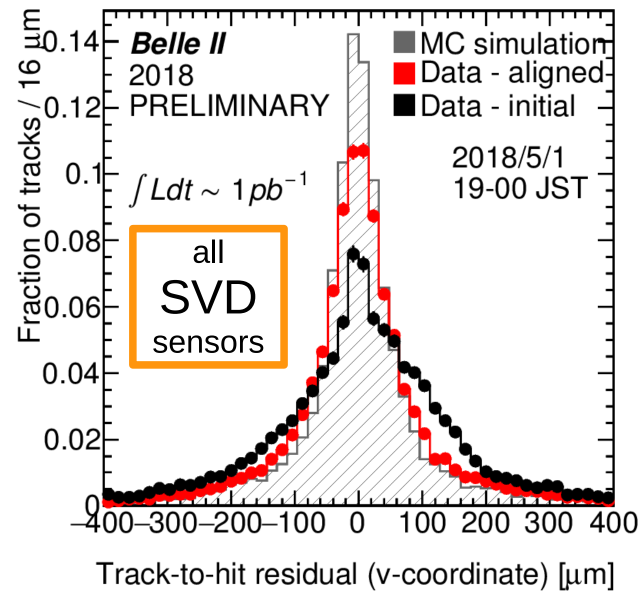
Origin of tracks in z-direction in central data re-processing showing improving z-resolution due to better drift chamber calibration and alignment:

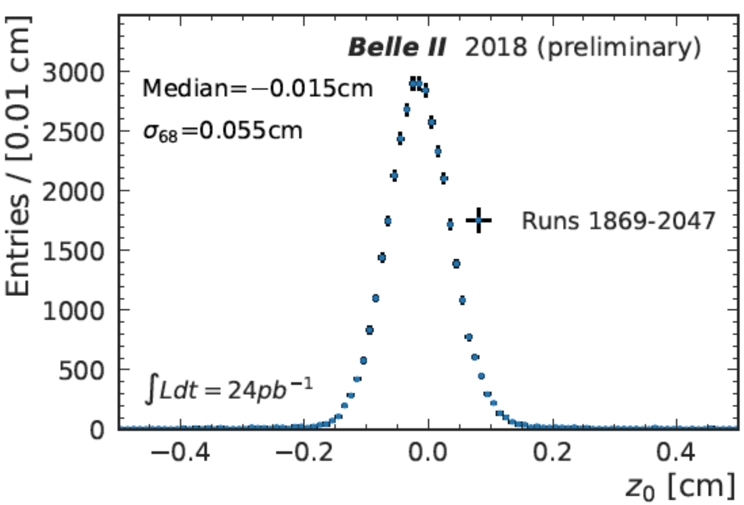


VXD Alignment with first collision data

VXD alignment sucessfuly performed using first data and validated with physics distributions







The interaction region profile in the longitudinal (z) direction, measured using the point of origin of charged particle tracks in the Belle II detector, showing the currently achieved interaction region longitudinal size of 0.55mm.

<u>VXD tracking residuals along global z-direction after **Millepede II** alignment with the first „physics“ run data</u> *(done the next morning)*

- Using all ~3k charged tracks with >= 4 hits in VXD
- Determined all **108 parameters** (18 x 6) at once
- GBL tracks continue to **drift chamber – fixed reference** (using local alignment & calibration from a cosmics run)
- Cosmic rays' VXD alignment used as starting point

Plans & Summary

Plans

- Continue in improving / validation of alignment & calibration on Phase 2 data ↔ time depence / stability of constants? → **online calibration** ...
- Remaining features should be finished and exercised with Phase 2 data to be ready for Phase 3 (physics @ record-breaking luminosity)

Summary

- Detector calibration and alignment essential for precision physics
- Many efforts on software side towards automation and tools development
- Global approach with Millepede for pixel, strip, drift chamber & muon system mostly implemented

- Successfully exercised alignment & calibration with cosmics and **first collision data**
- Even more exciting times coming! Stay tuned :-)

Thank you for your attention!

BACKUP

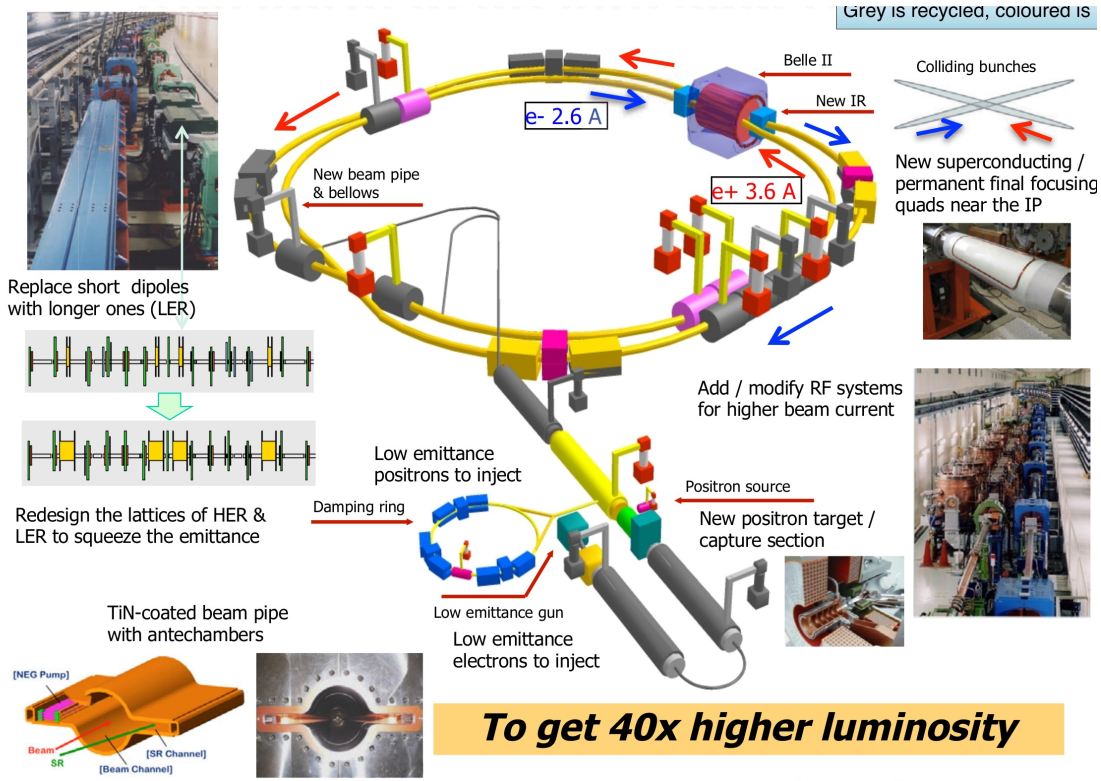
Online & Differential Alignment with Millepede II

- Existing setup in special simplified configuration feasible also for fast calibrations to be performed frequently or **online**
  - Coherent **movements of large structures** (pixel vs. strip vs. drift chamber …)
  - Position & kinematics of interaction region (overkill but enters as a constraint ← dedicated online calibration preffered to get initial values and precisions)
  - …
- Offline / Re-processing: Time dependent constants in global simultaneous fit
  - Low-level structures (individual sensors, wires …) more stable → only allow movements at higher levels and determine one alignment for lowest level = **differential alignment**

    → initial values from online alignment for higher levels

    → **more constants** to be determined (per each time/event/run interval)
  - Determine corrections to **all constants at once**
- Phase 2 should teach us much about possible time variantions
  - Software will adjust to real conditions (finally not just Monte Carlo for testing!)
- Phase 3 @ high luminosity → real online alignment possible (~ 6k muon pairs from e+e- collisions per second @ design luminosity!)

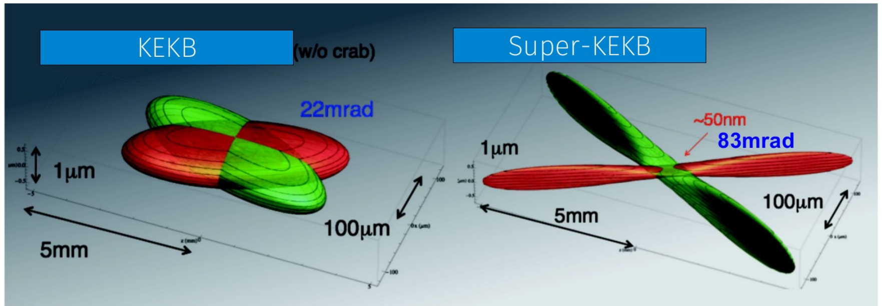
KEKB → SuperKEKB



beam current

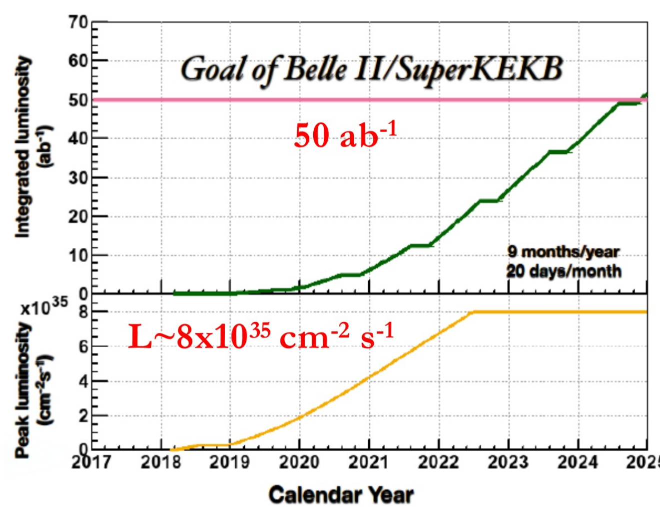
$$L = \frac{\gamma_{\pm}}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

vertical beta function at IP

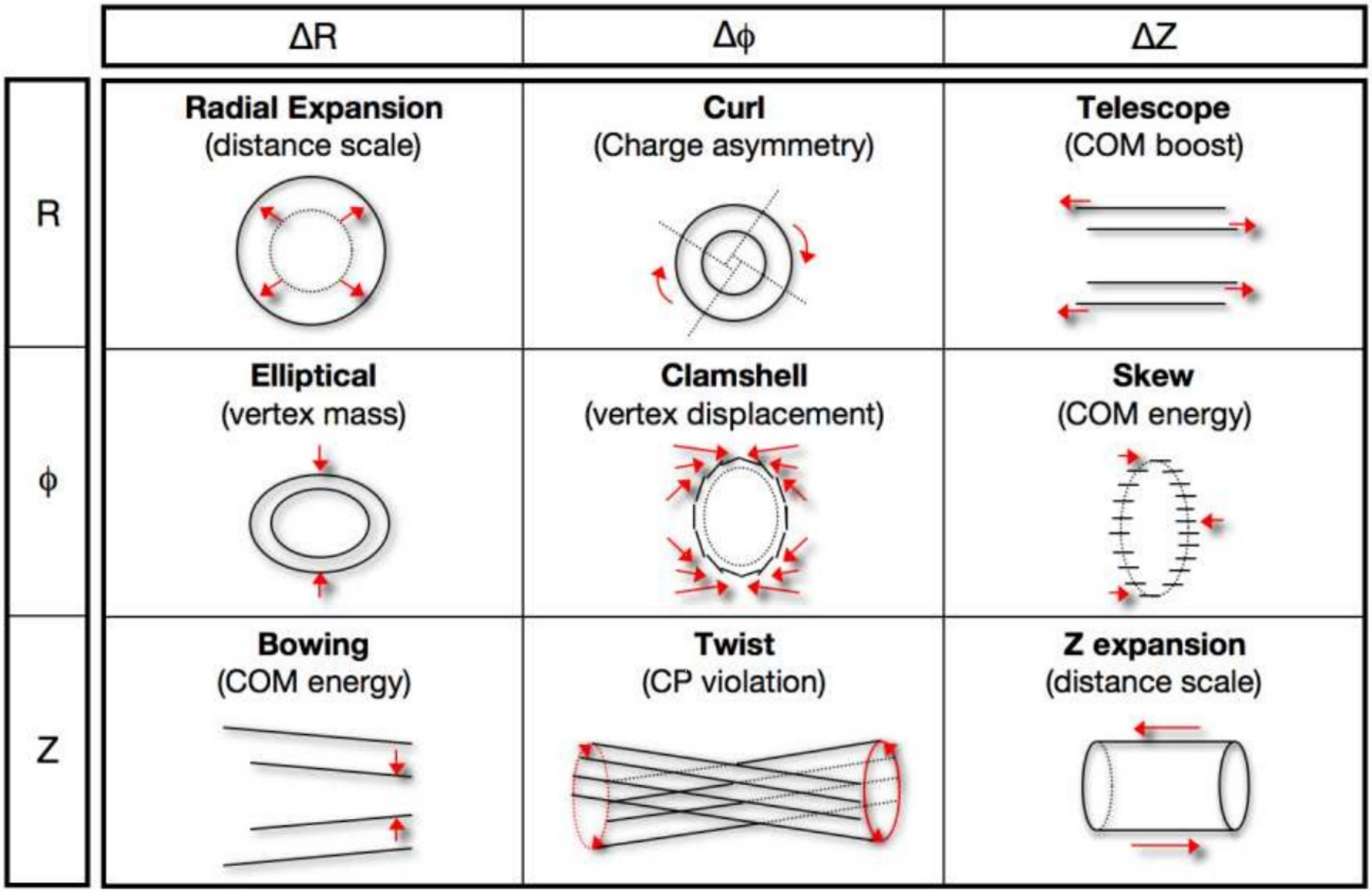


	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20 factor 2-3



Typical Weak Modes in Alignment for Detectors with B-Field & Cylindrical Symmetry



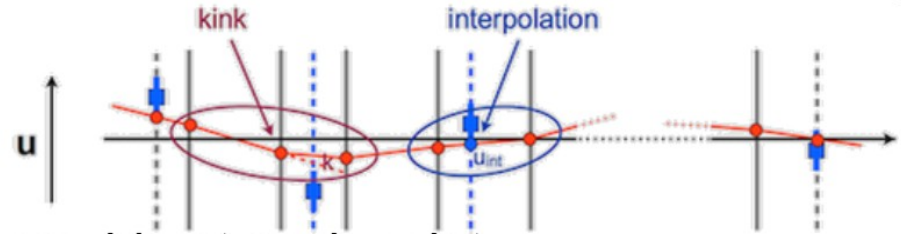
→ For tracks from IP, such distortions leave Chi2 unchanged, but change parameters of the tracks → bias in track parameters: weak modes are the biggest **challenge** in track based alignment

→ Several ways to reduce them: many track **topologies** (cosmics with/without magnetic field, tracks not from IP, vertex/mass constrained decays ...), detector **construction**: overlaps, survey or external **measurements** ...

General Broken Lines

GBL

- Track model with proper describtion of multiple scattering
- Track constructed from measurement and scattering points



- User has to provide at each point:
  - Residuals, measurement errors, projections from track coords.→ measurement coords.
  - Jacobians of propagation between adjacent points
  - Scattering errors at scatterers; derivatives of residuals w.r.t. align. params (for MP2)
- Track described by change of curvature and kinks at scattering points

$$\boldsymbol{x} = (\Delta q/p, \boldsymbol{u}_1, \ldots, \boldsymbol{u}_{\#\ \text{of scatterers}})$$

- Track fit by minimization of:

$$\chi^2(\boldsymbol{x}) = \sum_{i=1}^{n_{\#\ \text{meas}}} (\boldsymbol{H}_{m,i}\boldsymbol{x} - \boldsymbol{m}_i)^T \boldsymbol{V}_{m,i}^{-1} (\boldsymbol{H}_{m,i}\boldsymbol{x} - \boldsymbol{m}_i) + \sum_{i=2}^{n_{\#\ \text{scat}}} (\boldsymbol{H}_{k,i}\boldsymbol{x})^T \boldsymbol{V}_{k,i}^{-1} (\boldsymbol{H}_{k,i}\boldsymbol{x})$$

from measurements

from kinks

- Interface to MP2

→ Integrated into GENFIT2 package
→ Profits from generic treatment of many different measurement types
→ Advanced treatment of material for multiple scattering estimation (thick scatterers)