Belle II detector alignment with Millepede II

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*for the **Belle II Collaboration***

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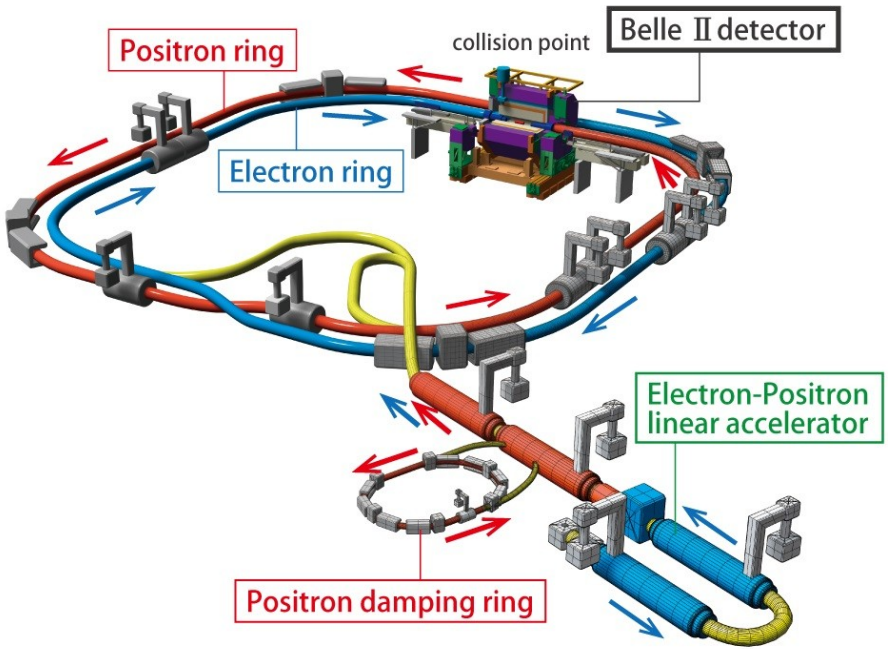
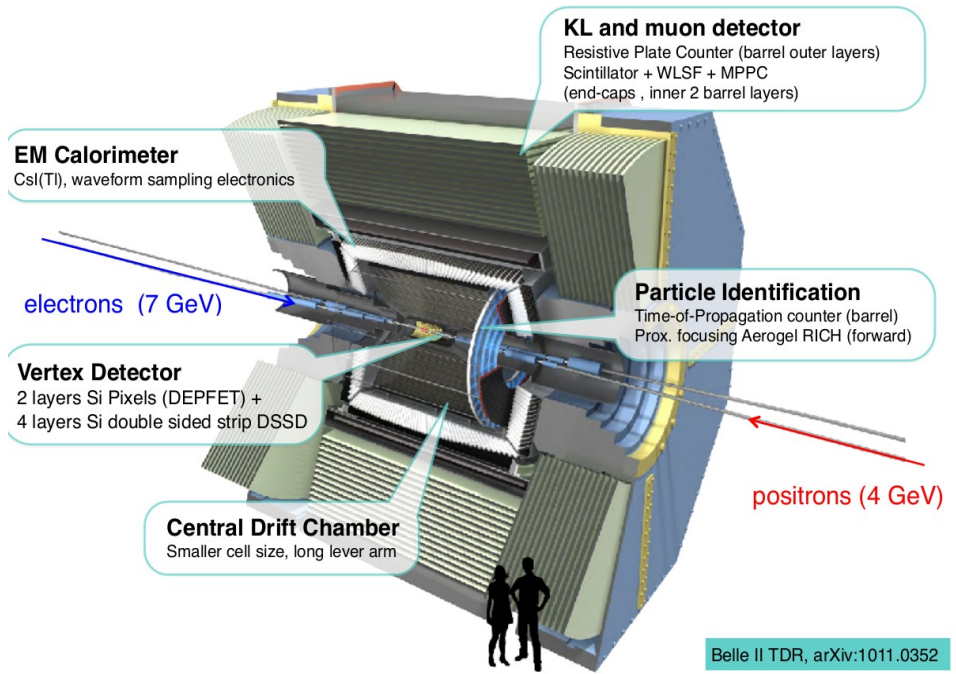
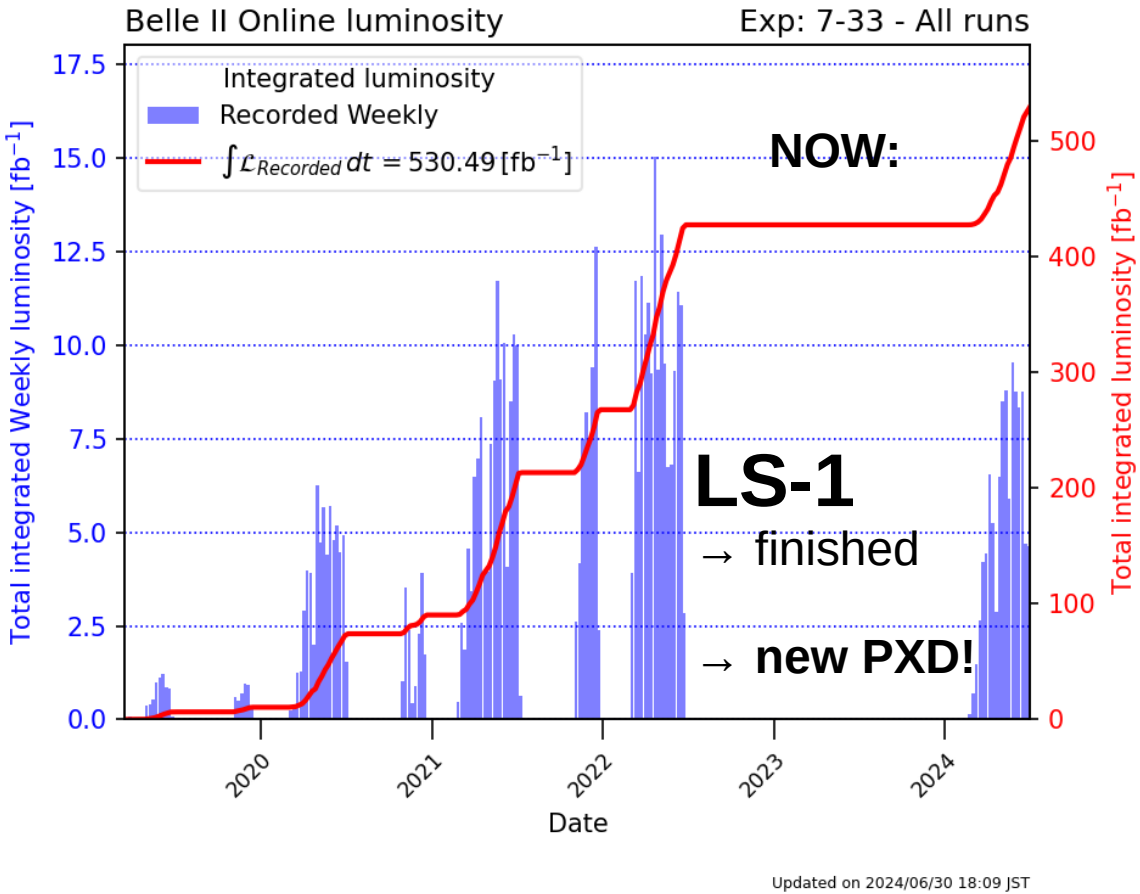
SuperKEKB & Belle II

- Upgrade of KEKB & Belle, taking physics data since 2019
- Worlds‘ highest luminosity electron-positron collider (KEK, Tsukuba, Japan) at Upsilon(4S) resonance → B physics, D physics, tau physics …





Past, Present, and Future

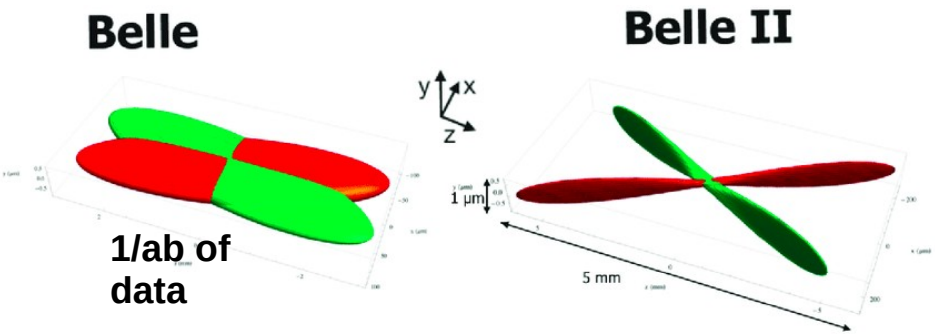


NOW:

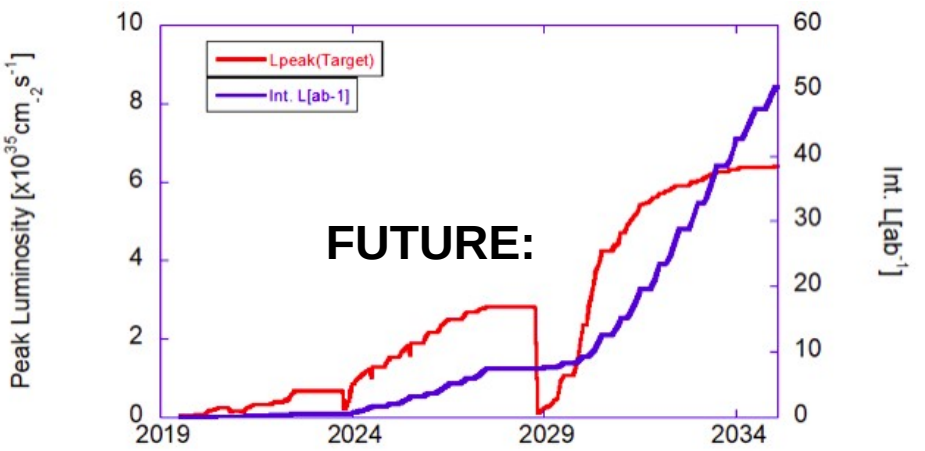
LS-1

→ finished

→ **new PXD!**



1/ab of data

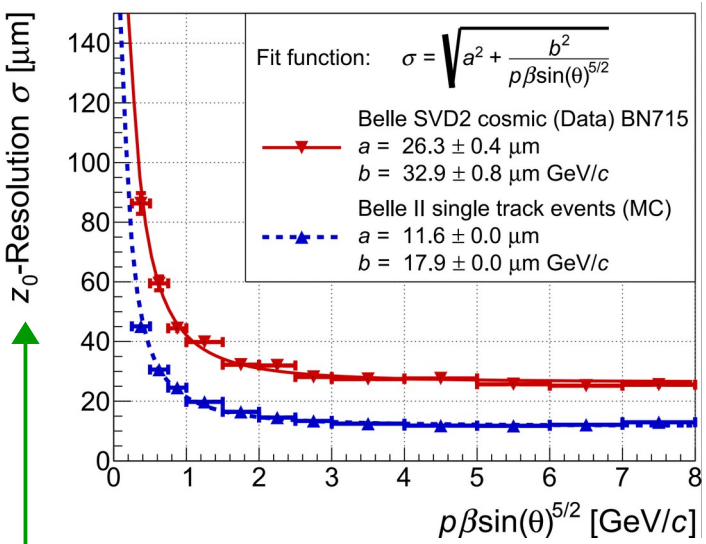


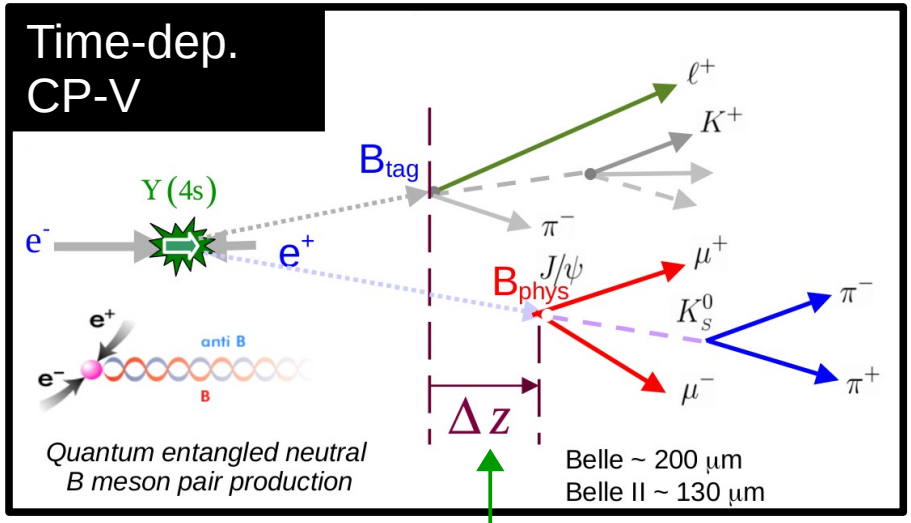
FUTURE:

Systematic errors will start to dominate measurement precisions for many analyses

Precision @ Belle II

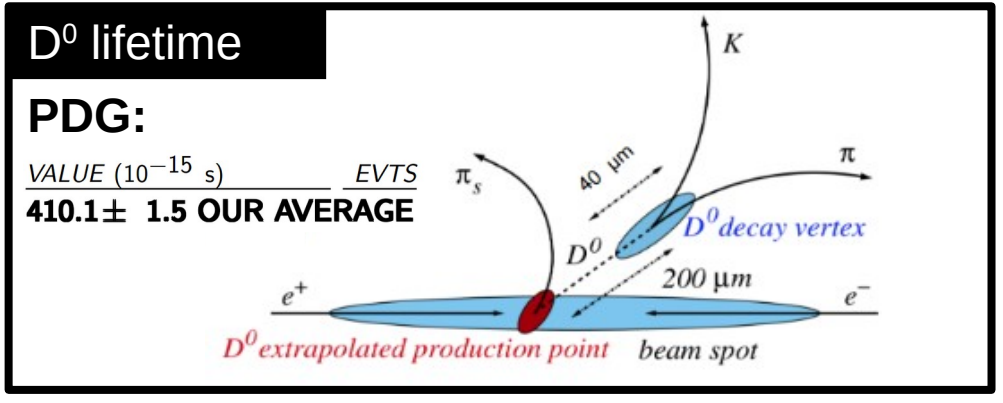
Just two examples...



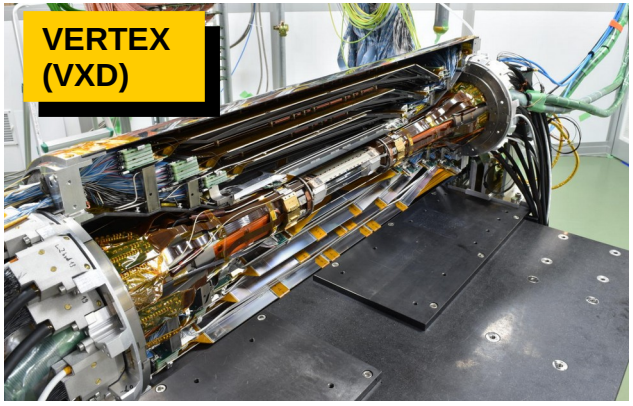


Alignment precision at level of micrometers needed

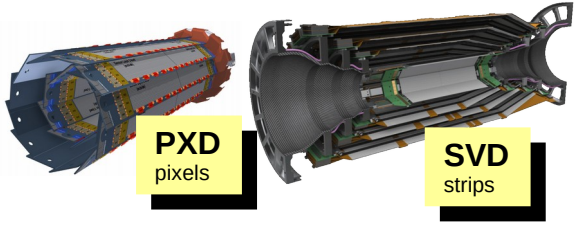
→ **Advanced track-based (time-dependent) alignment**

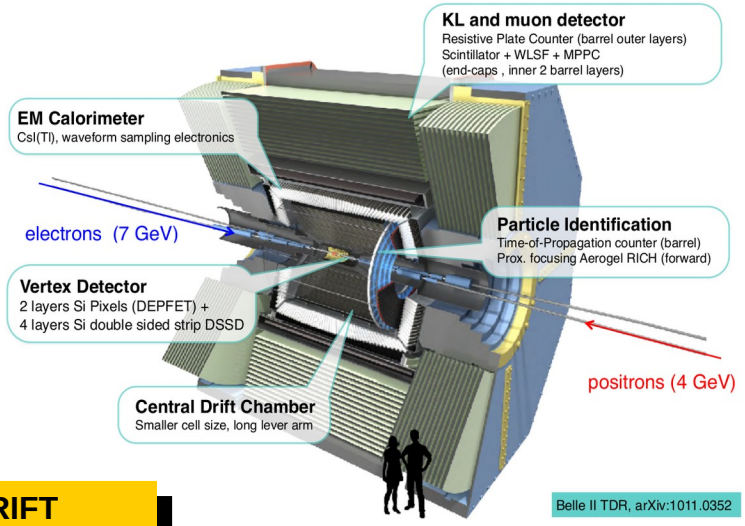


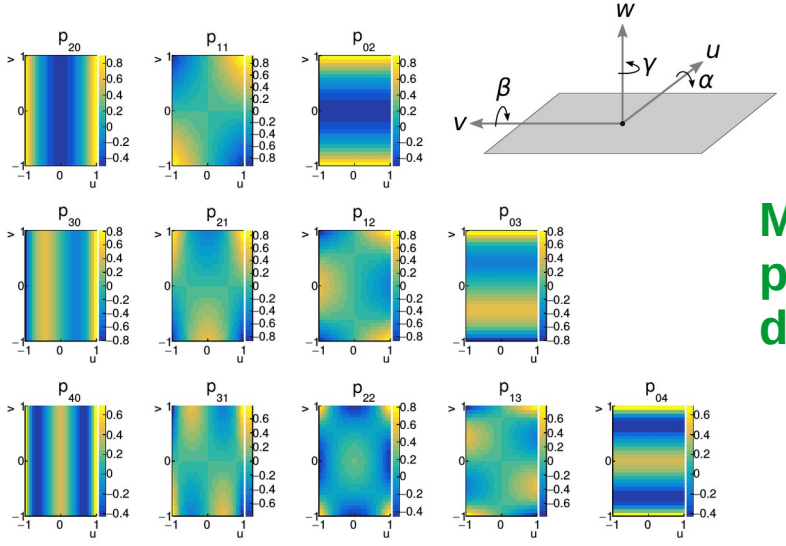
Belle II Alignment Parameters: Local Alignment



212 sensors
x **18** parameters

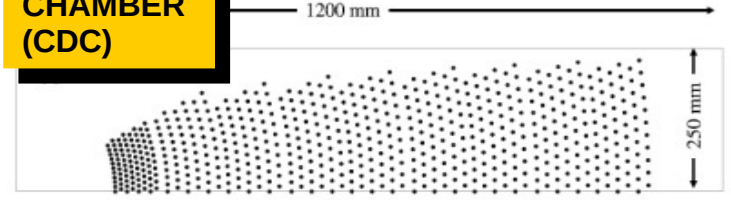




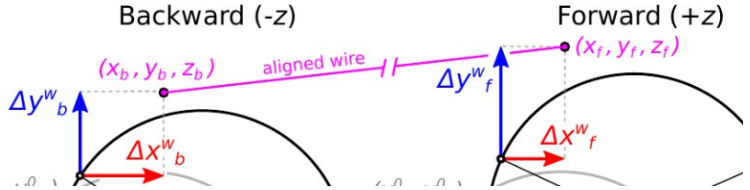


More than 60,000 parameters to be determined

DRIFT CHAMBER (CDC)



14,336 wires x 4 parameters

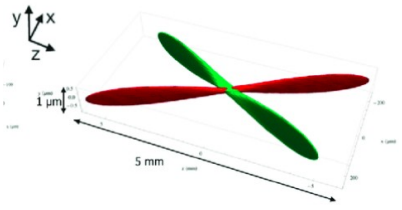


Belle II Alignment Parameters: Global Alignment

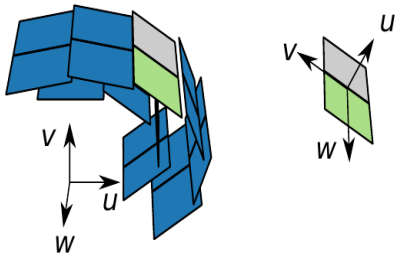
Relative positions of sub-detectors and larger structures*

Problem: Correlations with local alignment and correlations of different sub-detectors!

IP position

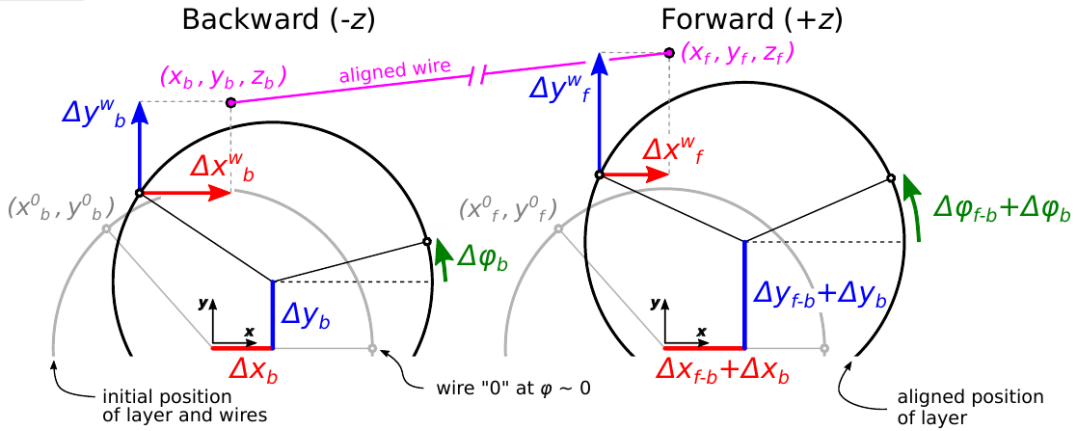


VXD half-shells and ladders



sub-detector	alignable elements	alignment parameters	∑ parameters
IP	primary vertex position	x, y, z	3
VXD (PXD + SVD)	20 (PXD) + 187 (SVD) sensors	$u, v, w, \alpha, \beta, \gamma$	120 + 1,122
		P_{20}, P_{11}, P_{02}	60 + 561
		$P_{30}, P_{21}, P_{12}, P_{03}$	80 + 748
	4 half-shells	$x, y, z, \alpha, \beta, \gamma$	24
CDC	56 layers	$x, y, \phi, dx, dy, d\phi$	336
	14,336 wires	x_B, y_B, x_F, y_F	57,344

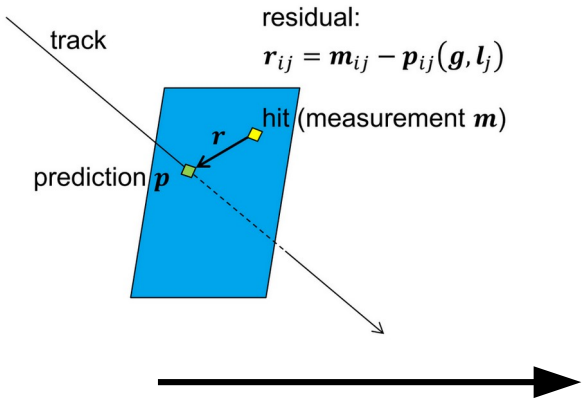
CDC layers



Alignment of all degrees of freedom should be done simultaneously

*Redundant DoFs removed by linear equality constraints

Alignment Algorithm: Millepede II



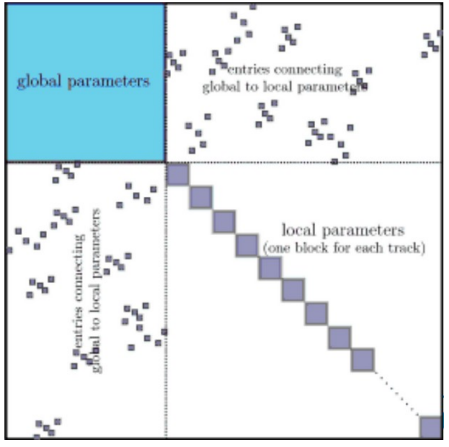
Minimize over all parameters:

$$\chi^2(g, l) = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} r_{ij}^T(g, l_j)\, V_{ij}^{-1} r_{ij}(g, l_j)$$

g ... alignment parameters (global)
l_j ... track parameters (local)

Millepede II

https://www.terascale.de/wiki/millepede_ii/



~ 100's of millions of track parameters for typical alignment

Block matrix algebra
→ **no approximation** except linearization (→ iterations)

All **correlations kept** in the solution!

up to ~ 60k @ Belle II

Matrix for global par.
→
Diagonalization, Inversion, MINRES, Decomposition ...

New: LAPACK for solution

Method	Factorisation	Calc. inverse	Q^tAQ, $QA^{-1}Q^t$	Total time
Decomposition	331	-	no A^{-1} 9.7	361
Inversion	-	852	20.0	898
MKL, packed	6.3	1338	18.4	1377
MKL, unpacked	4.2	19.8	2.1	40
OpenBlas, unpack.	4.8	10.0	15.9	45

Time in minutes. Table from C. Kleinwort

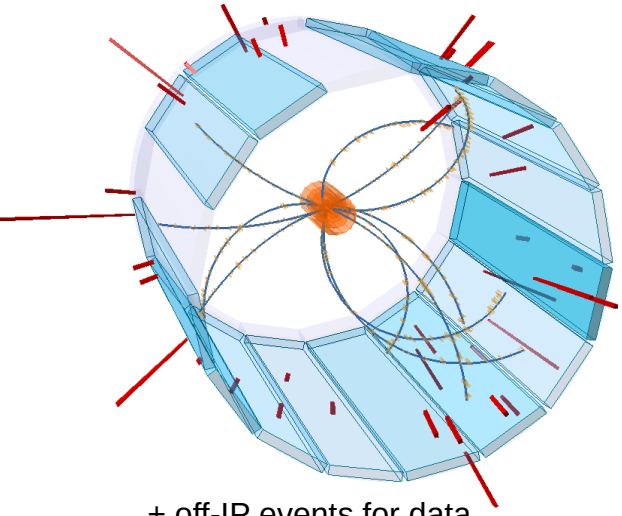
With recent speed-ups, an exact solution for 60k parameters can be obtained in about 30 min*!

*Using 10 cores @ Xeon(R) CPU E5-2640 v3 @ 2.60GHz. 20GB of memory required.

Challenge for most alignment problems are **weak modes** – linear combinations of parameters which leave Chi² (almost) unchanged → could bias track parameters and physics

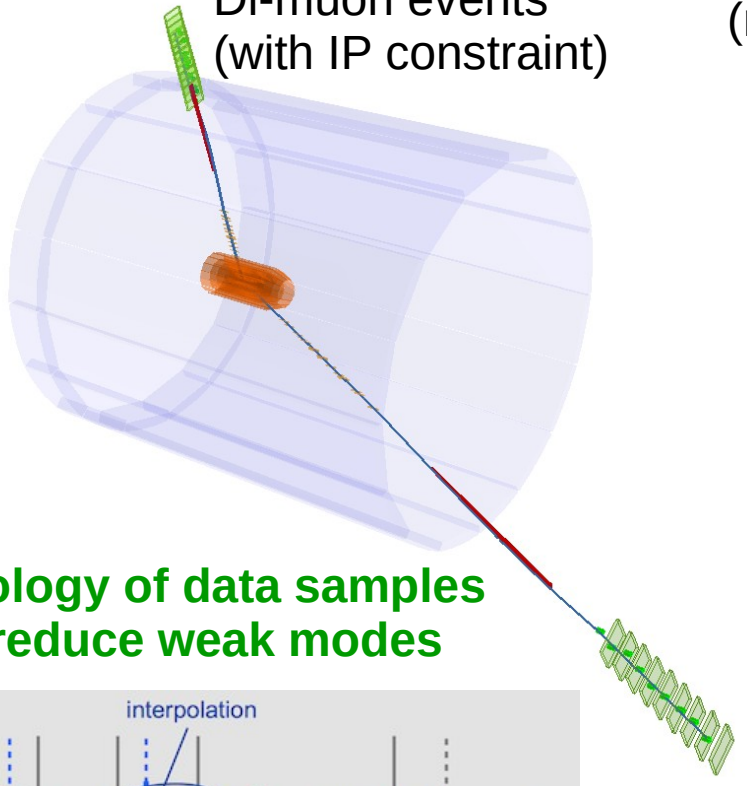
Data Samples for alignment

Hadronic events

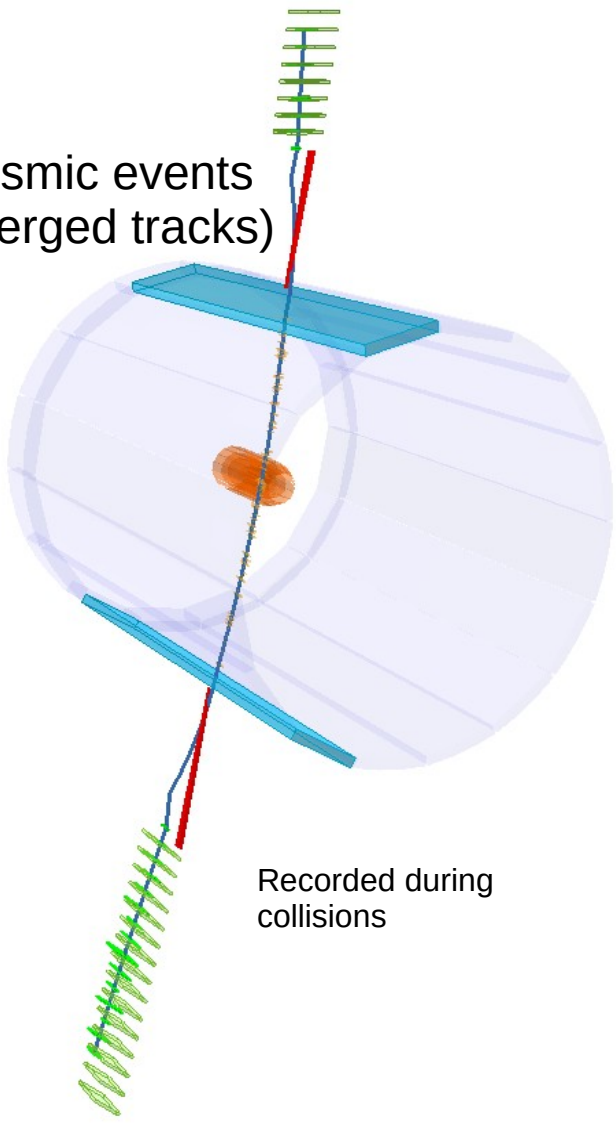


+ off-IP events for data

Di-muon events
(with IP constraint)



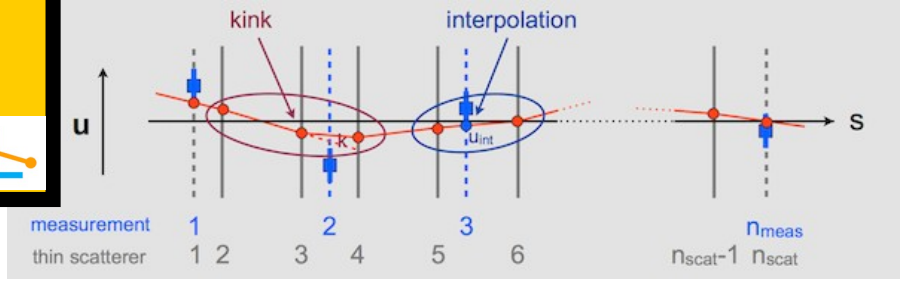
Cosmic events
(merged tracks)



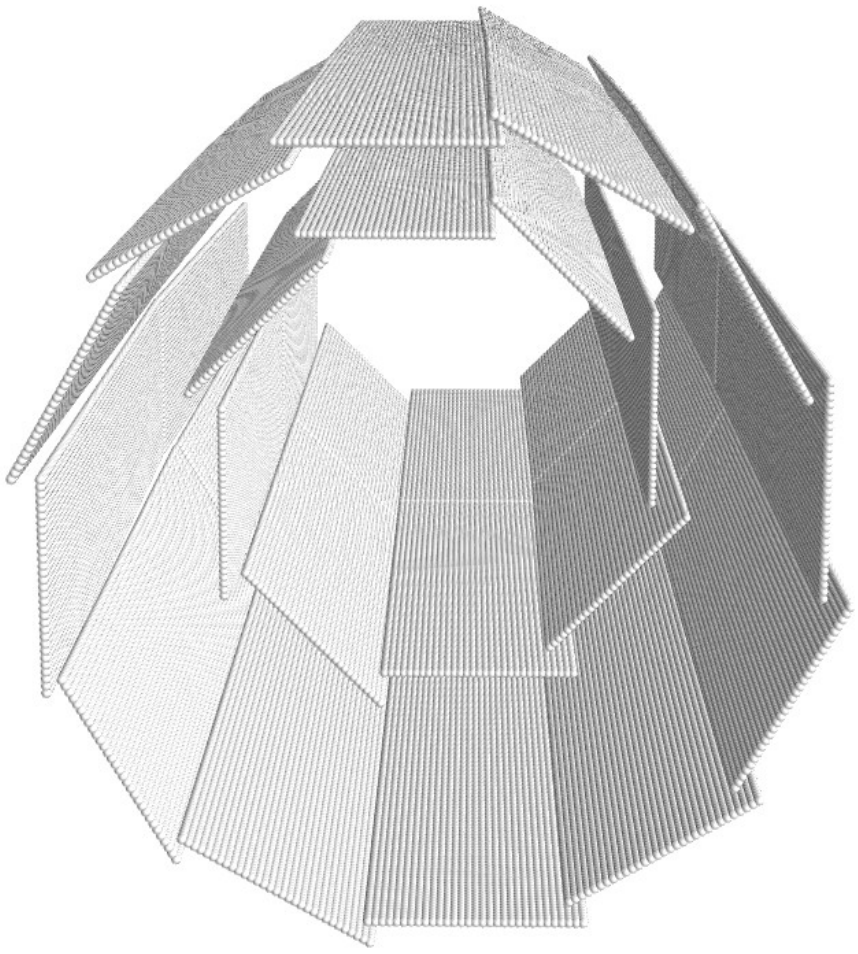
Recorded during collisions

Rich topology of data samples helps to reduce weak modes

General Broken Lines (GBL)
Track model with proper description of multiple scattering



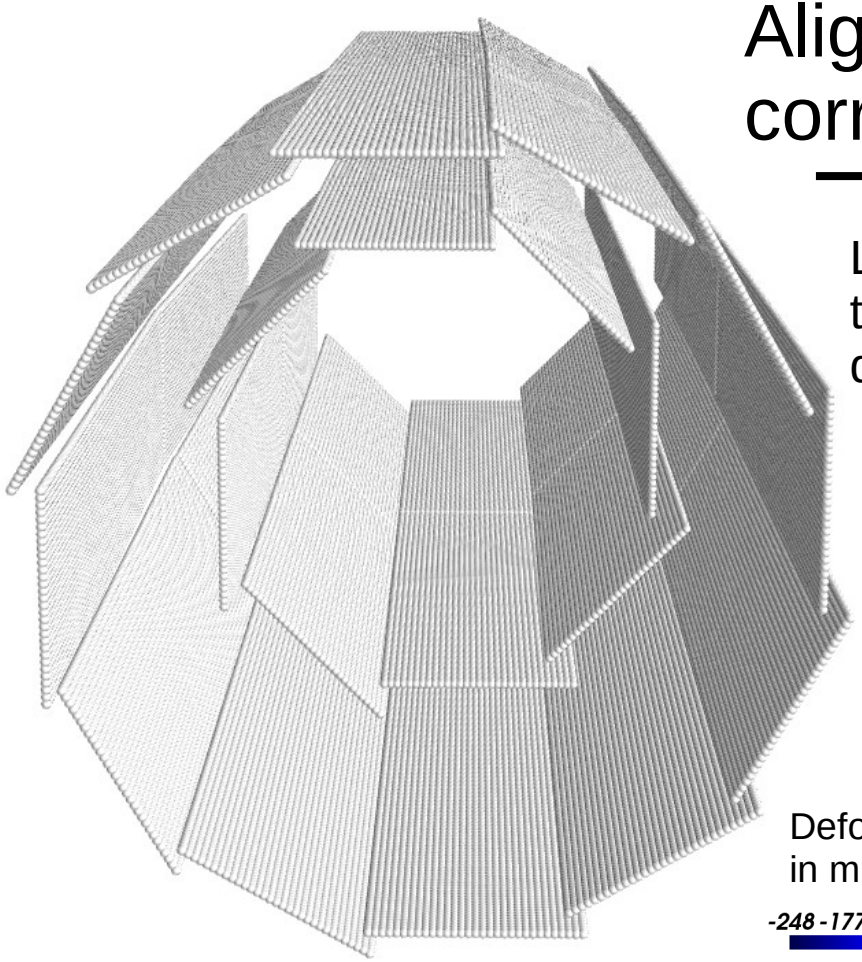
New PXD & New Alignment Challenge



Real shape of the PXD (sensitive areas)

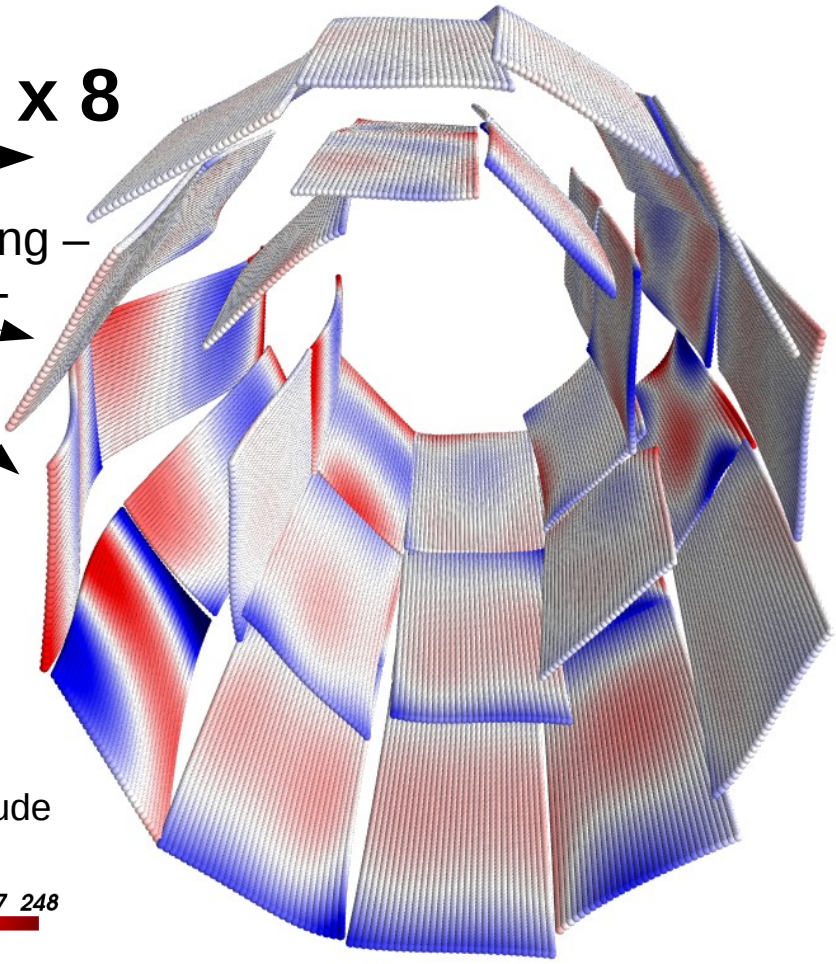
as determined by the alignment

New PXD & New Alignment Challenge



Alignment corrections **x 8**

Ladder bowing – temperature-dependent

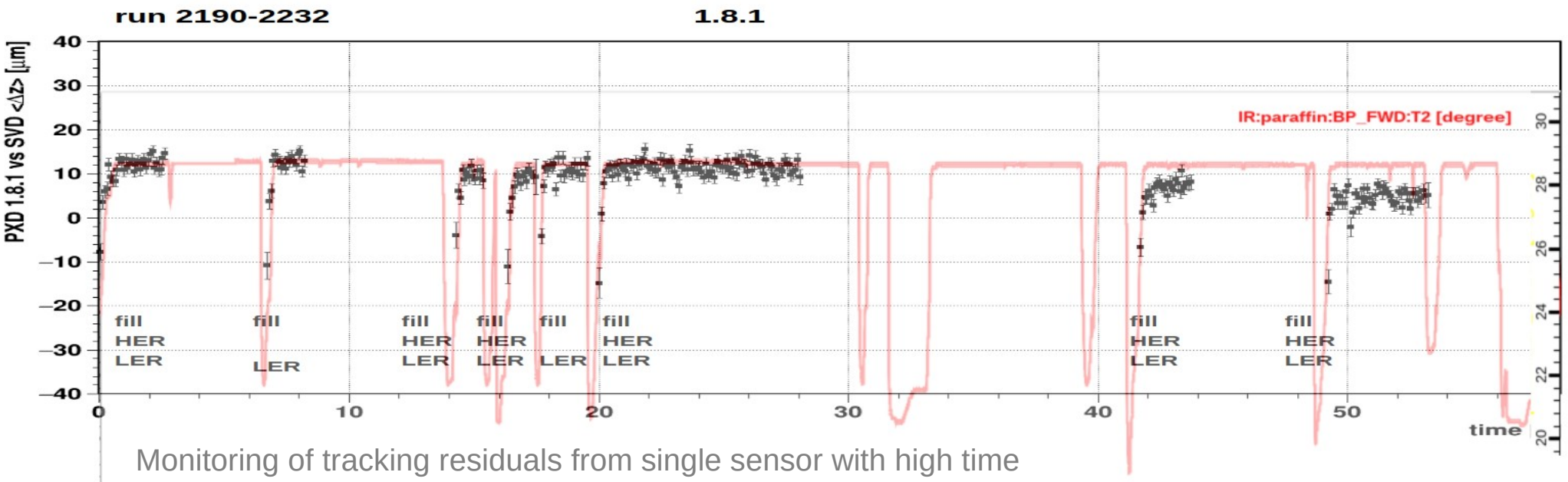


Deformation amplitude in micrometers

-248 -177 -106 -35 35 106 177 248

New PXD & New Alignment Challenge

- Observed (also) very fast bowing-like deformations correlated to beampipe temperature ← depends on beam currents
- Would need much more data for alignment



Monitoring of tracking residuals from single sensor with high time resolution using „all raw data“

Conclusion & Outlook

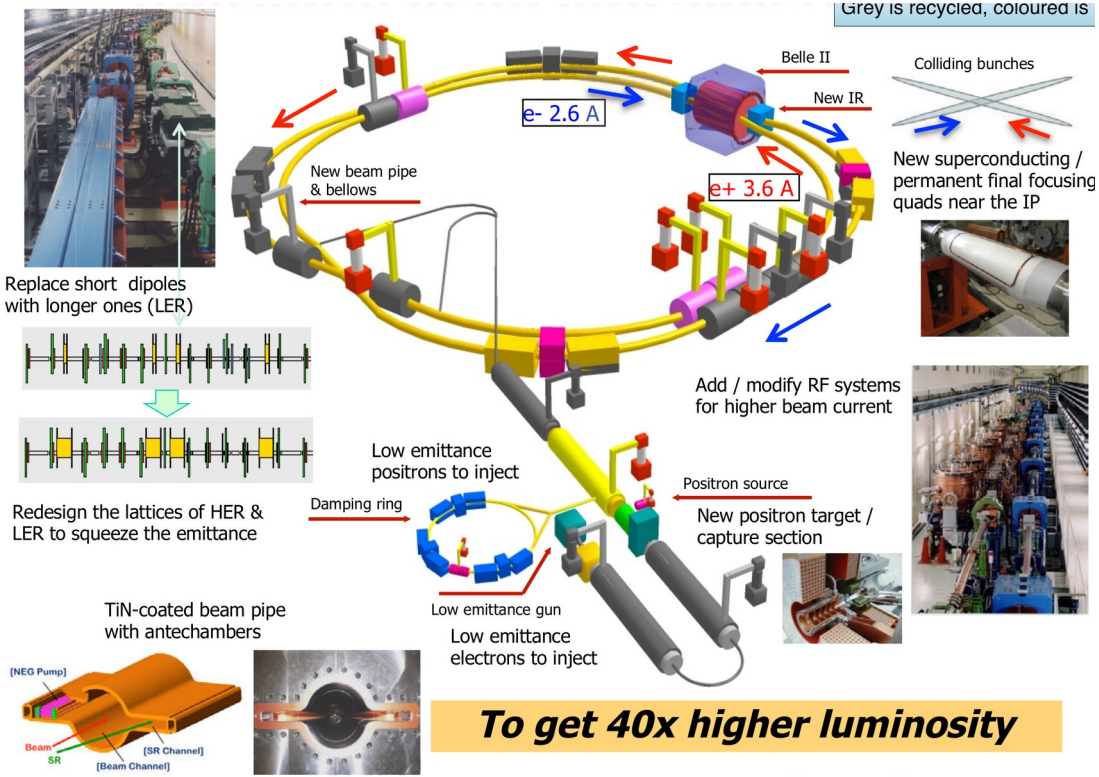
- Precise alignment required for precision physics
- Belle II alignment determines about 60k parameters for pixel and strip detectors and the drift chamber promptly after data-taking
  - CDC layers and PXD&SVD hafl-shells and individual PXD sensors are aligned about every 50k di-muon events (+some cosmics) → once in several hours (depending on lumi)
- New challenges with new PXD
  - Need much „faster“ alignment
  - But not all data available at the calibration site
  - Alignment already takes ¼ to ½ a day (multiple passes over data needed)
  - Possible solutions
    - Much more data for alignment → expensive
      - Alignment on GRID? (Need high-performance high-memory machine processing data after each collection step)
    - „Parametrize“ deformations with less degrees of freedom → maybe not feasible (work in progress)
    - Ignore (flag bad quality vertex data …)

    …

Thank you for your attention!

BACKUP

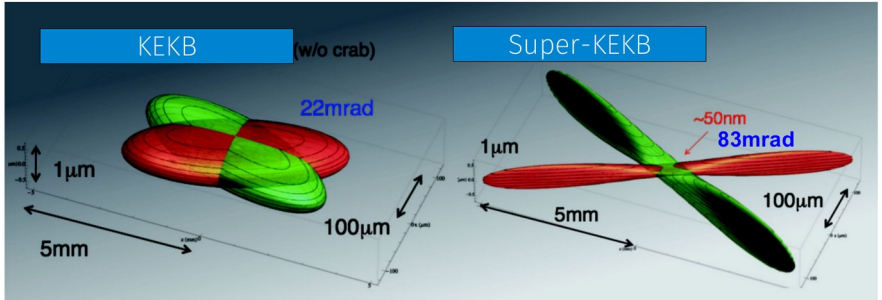
KEKB → SuperKEKB



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

beam current

vertical beta function at IP



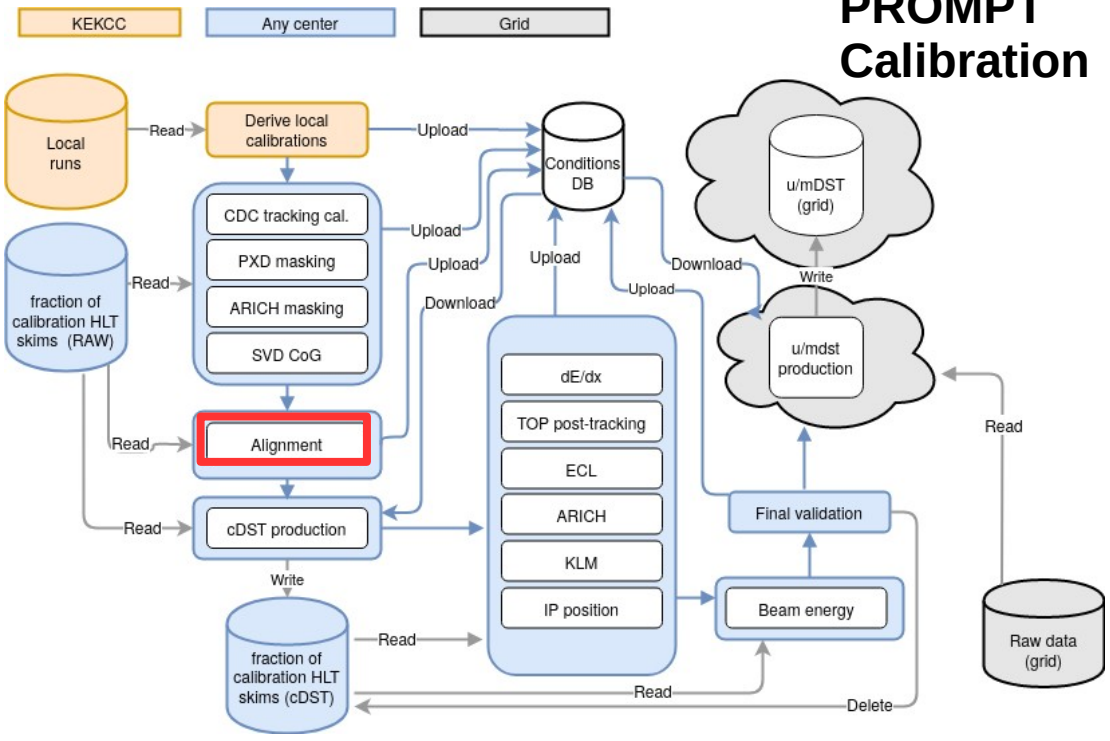
	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

factor 20

factor 2-3

Belle II Calibration and Data Production

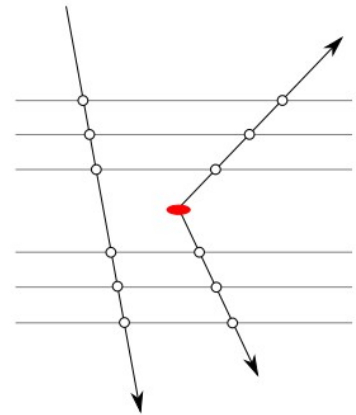
- Physics data calibrated in **prompt** calibration loop every **bucket**
  - Done at BNL
  - About a month after data
- Recalibration
  - KEKCC or NAF
  - After a year or two, all data when needed
  - Fix issues, improve...

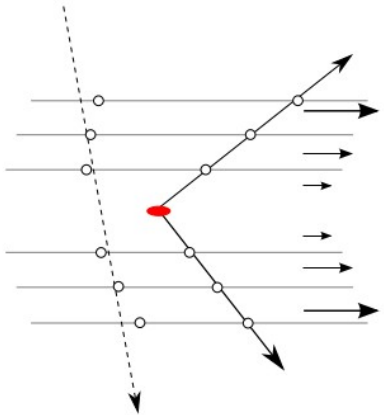


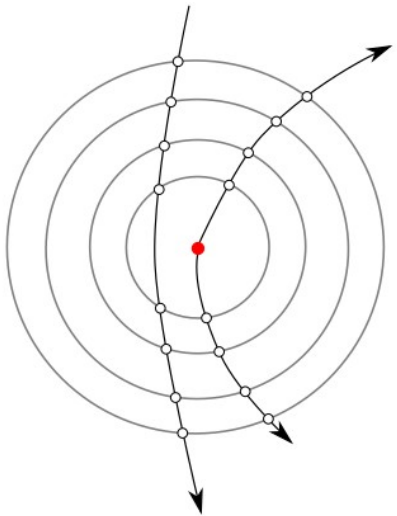
Bucket = several weeks of data-taking (scaled to about 10/fb)

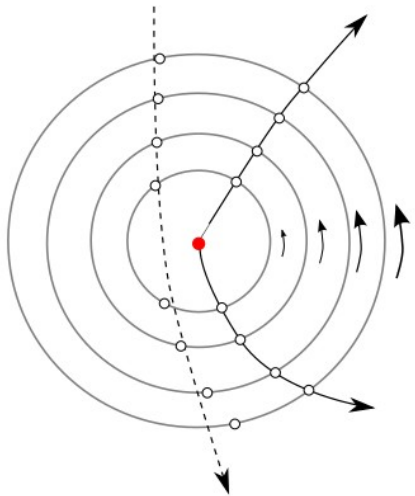
Alignment: aim to provide the best possible performance for physics already in prompt calibration

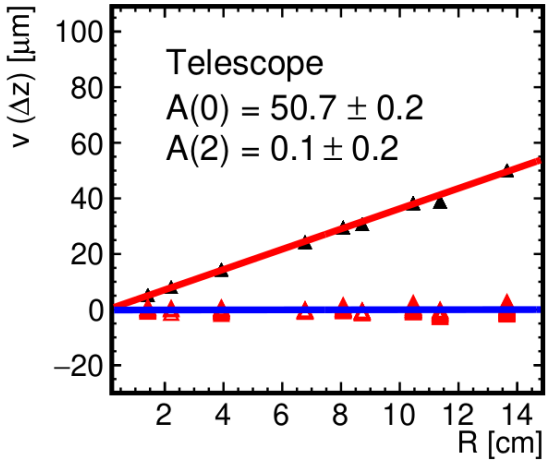
Reducing weak modes with rich track topology

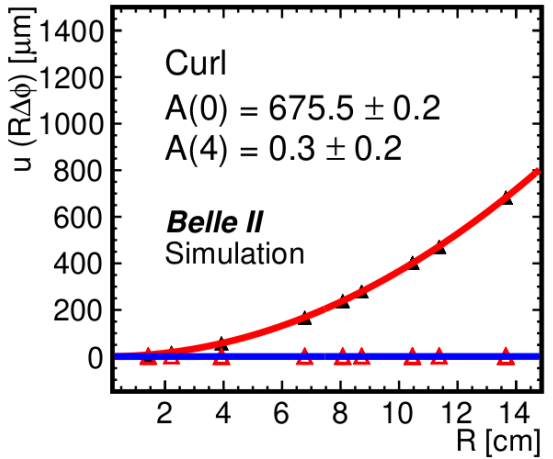








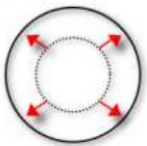
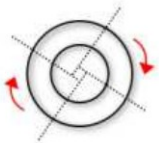
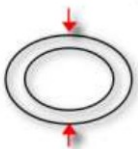
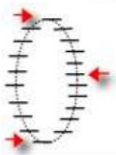
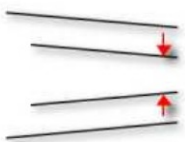
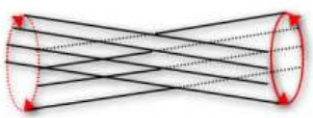
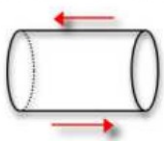




VXD deformation before alignment...

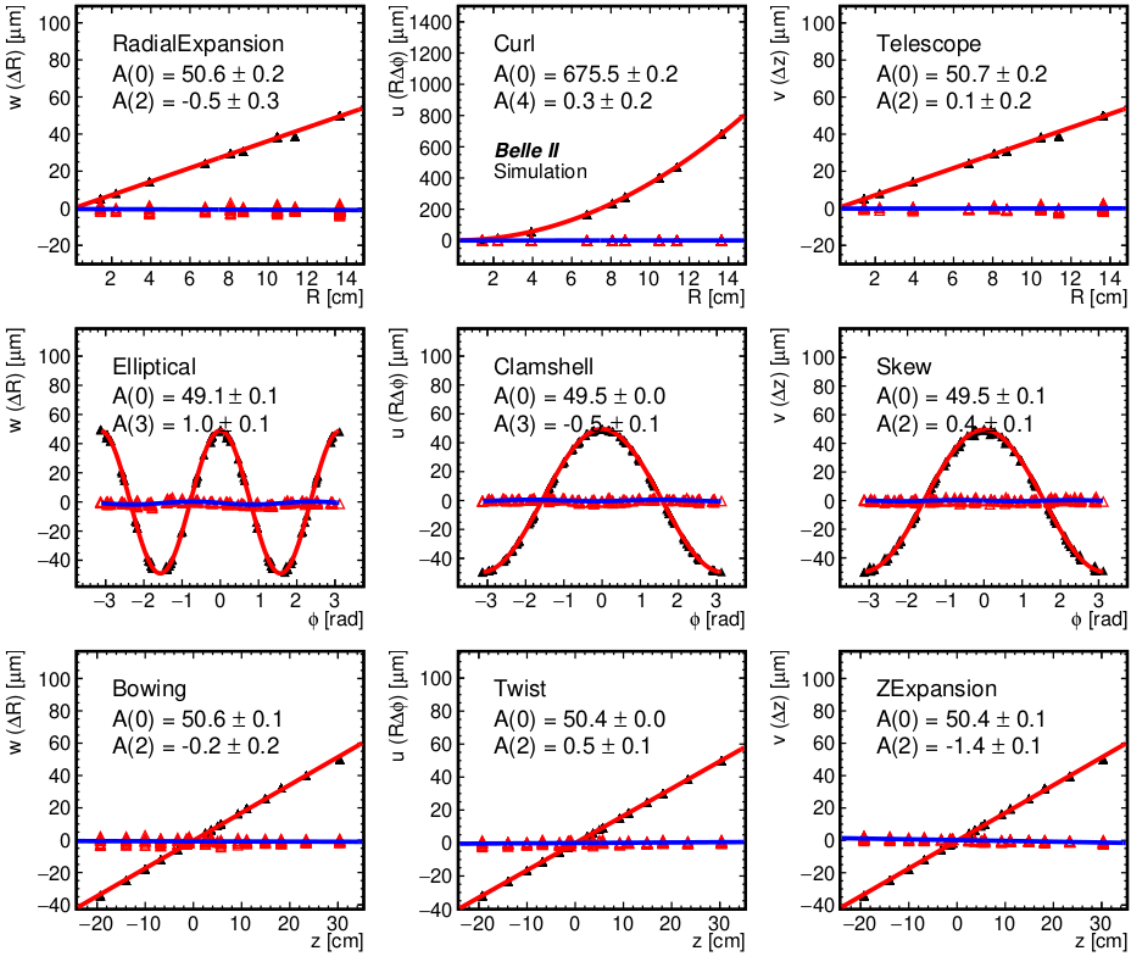
...and after

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

	ΔR	Δϕ	ΔZ
R	**Radial Expansion** (distance scale) 	**Curl** (Charge asymmetry) 	**Telescope** (COM boost) 
ϕ	**Elliptical** (vertex mass) 	**Clamshell** (vertex displacement) 	**Skew** (COM energy) 
Z	**Bowing** (COM energy) 	**Twist** (CP violation) 	**Z expansion** (distance scale) 

→ 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** ...

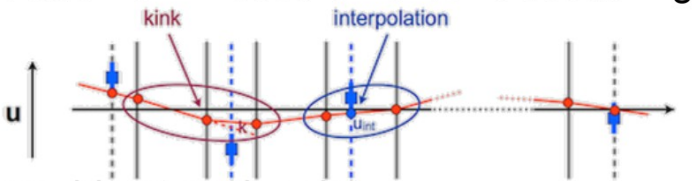

RadialExpansion
A(0) = 50.6 ± 0.2
A(2) = -0.5 ± 0.3
w (ΔR) [μm]
R [cm]
Curl
A(0) = 675.5 ± 0.2
A(4) = 0.3 ± 0.2
Belle II
Simulation
u (RΔφ) [μm]
R [cm]
Telescope
A(0) = 50.7 ± 0.2
A(2) = 0.1 ± 0.2
v (Δz) [μm]
R [cm]
Elliptical
A(0) = 49.1 ± 0.1
A(3) = 1.0 ± 0.1
w (ΔR) [μm]
ϕ [rad]
Clamshell
A(0) = 49.5 ± 0.0
A(3) = -0.5 ± 0.1
u (RΔφ) [μm]
ϕ [rad]
Skew
A(0) = 49.5 ± 0.1
A(2) = 0.4 ± 0.1
v (Δz) [μm]
ϕ [rad]
Bowing
A(0) = 50.6 ± 0.1
A(2) = -0.2 ± 0.2
w (ΔR) [μm]
z [cm]
Twist
A(0) = 50.4 ± 0.0
A(2) = 0.5 ± 0.1
u (RΔφ) [μm]
z [cm]
ZExpansion
A(0) = 50.4 ± 0.1
A(2) = -1.4 ± 0.1
v (Δz) [μm]
z [cm]

General Broken Lines

GBL

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

- 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)