Alignment for the first precision measurements at Belle II

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for the ***Belle II Collaboration***

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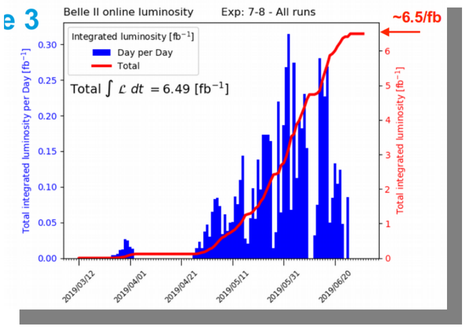
Belle II Experiment

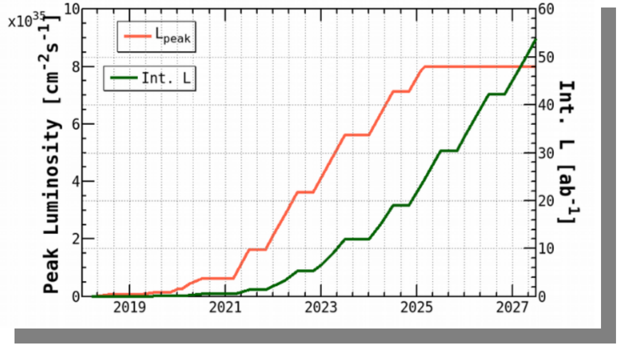
Precision Detector for Precision (B)-Physics requires precision alignment (and calibration)

Ability to discover **New Physics @ Precision Frontier** relies on reducing **measurement uncertainitities:**

Statistics → extreme luminosity **SuperKEKB**:
→ huge data sample



Now 1st data: spring 2019



Future...

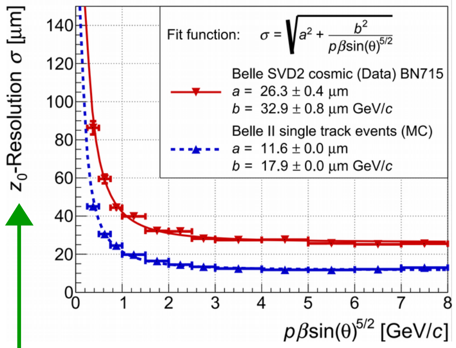
Systematics → better detector **Belle II:**
→ better software, algorithms, ...
and **alignment** & calibration !

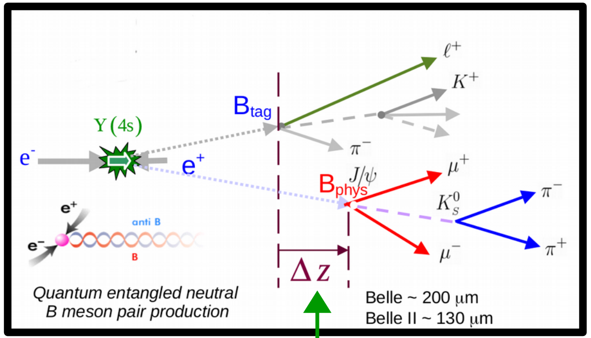
„We suspect there is an alignment/calibration issue"

Quote from random HEP experiment :-)

You can probably name it: Incorrect magnetic field, weak mode, time-dependence … Alignment is a complicated business and can take ~ years for large HEP experiment to resolve „all" „issues" and claim it is „perfect" (did that ever happen?)

B-Physics requires excellent **vertex resolution**, PID, momentum & energy resolution ...

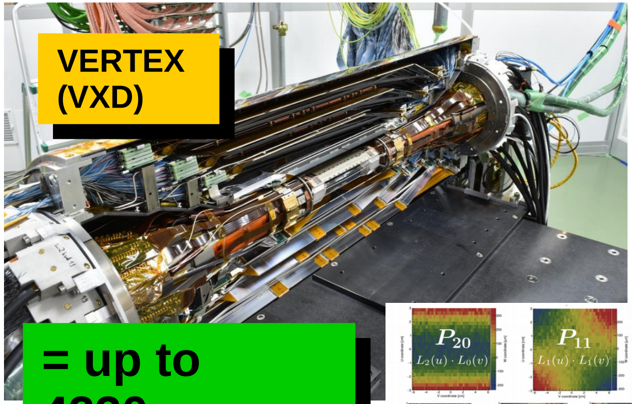




Belle II Detector and (some of) its alignment parameters...

Belle II

*NOTE: Electromagnetic calorimeter and PID have their independent alignment procedures not covered in this talk (but they consider to join :-)

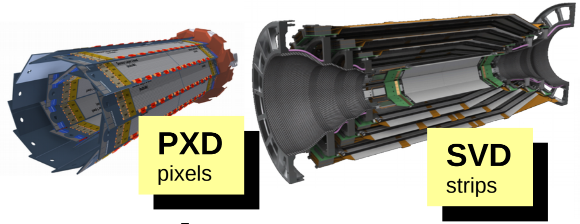


VERTEX (VXD)

= up to 4230 parameters

6 rigid body per half-shell, ladder, sensor. 3 + 4 (+ 5) deformation parameters per sensor

20 + 192 = **212** sensors

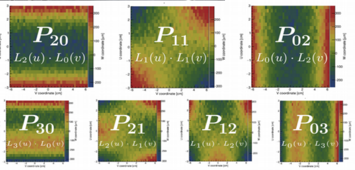


PXD pixels

SVD strips

+ 4 half-shells

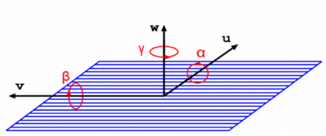
+ 20 + 45 = 60 ladders

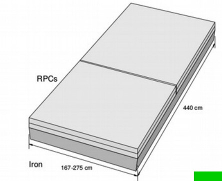


+ Sensor deformations

Parametrised as 2D Legendre polynomials up to 4th order

Alignment parameters for rigid body
3 shifts + 3 rotations



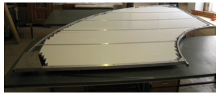


X 8 sectors
X 15 layers

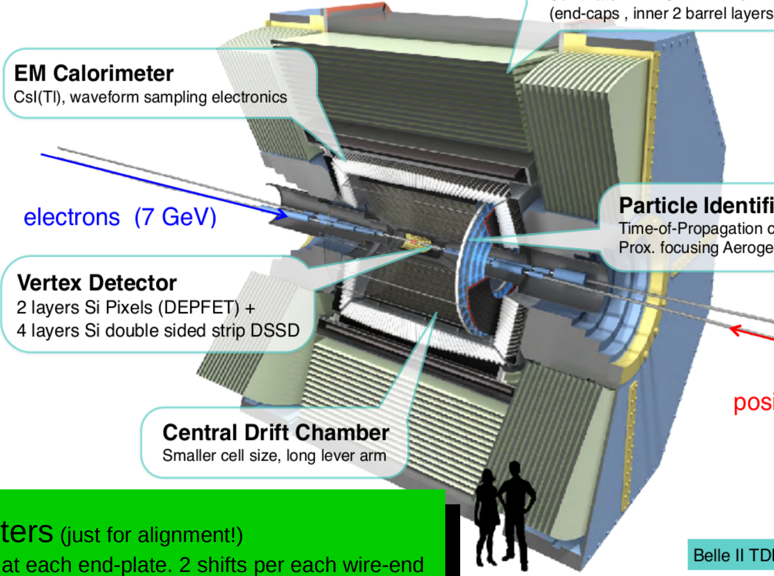
Muon & KL (KLM)

= 1032 parameters

2 shifts + rotation per module



X 12 + 14 layers
X 4 sectors

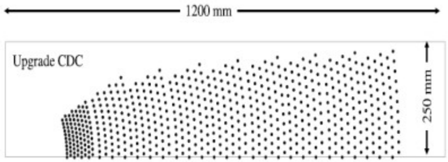


Belle II TDR, arXiv:1011.0352

IP = 3 parameters

x, y, z position of primary interaction region

DRIFT CHAMBER (CDC)



56 layers
+ 14336 wires

Implemented also some CDC calibrations not covered in this talk (Time-walks & T0's already tested sucesfully on data)

= 57680 parameters (just for alignment!)
2 shifts and rotation per layers at each end-plate. 2 shifts per each wire-end

Up to 62 945* alignment parameters

All numbers for MC (in reality some sensors not installed, wires inactive etc.)

Alignment in Belle II Software
Integration with software and calibration frameworks

Calibration and alignment of the detector is crucial to reach designed **physics performance**

Millions of **calibration constants** needed for detector operation and data reconstruction / analysis → many need to be produced from the data

Alignment fully integrated in our **basf2** software and workflow for constants production with **CAF**

We largerly profit from using our common software tools

basf2

Belle II analysis software framework

C++ modules for event processing, Python steering, GEANT4 simulation...

Same magnetic field, geometry, track fitting, vertexing … as standard reconstruction

GENFIT2

For generic track reconstruction

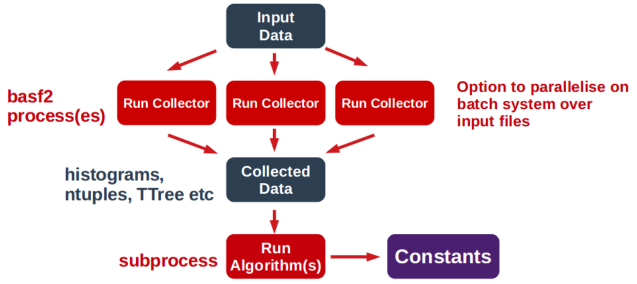
Different fitters, any measurement type, inhomogeneous magnetic field, energy loss & material effects

CAF

Calibration and alignment framework

Managment of multiple calibrations: dependencies, iterations, data aggregation, job submission, databases …

„Developers (physicists) can concentrate on the algorithms“

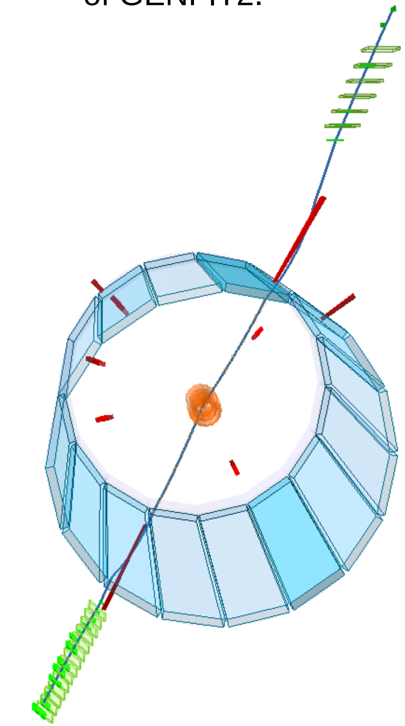


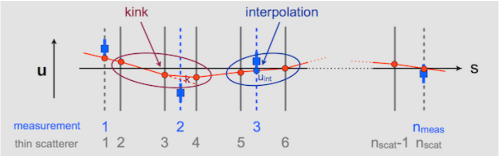
C++ collectors and algorithms for heavy lifting.
Python for workflow management.
Airflow for orchestration of constant production

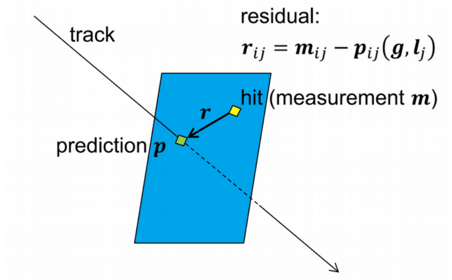
Millepede II & General Broken Lines for Belle II (global) alignment & calibration

General Broken Lines (GBL)

Global $\chi 2$ track refit with advanced treatment of multiple scattering using material extrapolation of GENFIT2.







Single charged tracks, cosmics (magnet ON/OFF), vertex and/or mass constrained (2-body) decays can be used as alignment input

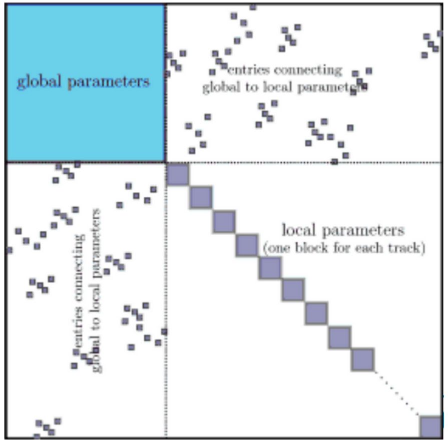
Millepede II

Global linearized $\chi 2$ minimization for very large number of parameters

Minimize χ^2 w.r.t alignment parameters

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

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



~ 100's of millions of local (track) parameters for typical alignment

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

All **correlations kept** in the solution!

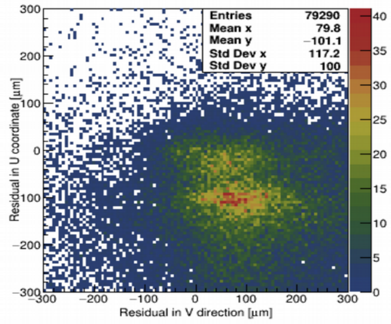
Matrix for global par.
→
Diagonalization, Inversion, GMRES...

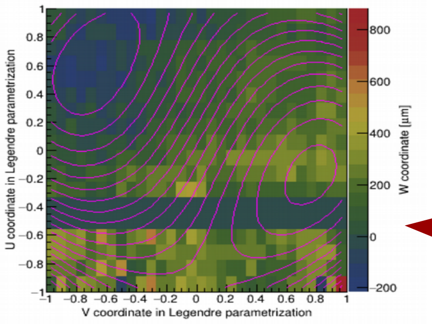
up to ~ 60k @ Belle II (now)

Ideally include as many sub-detectors and alignment & calibration constants as possible!

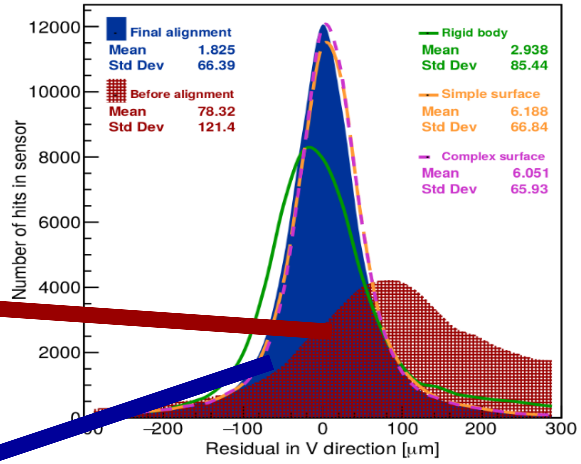
Performance with data
Track-to-hit residuals & sensor deformations

Initially large displacements (100‘s of um) and sensor deformations (up to ~0.5mm for some SVD sensors)



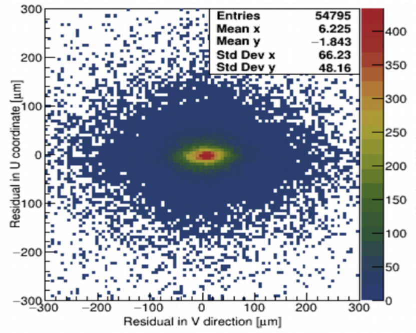


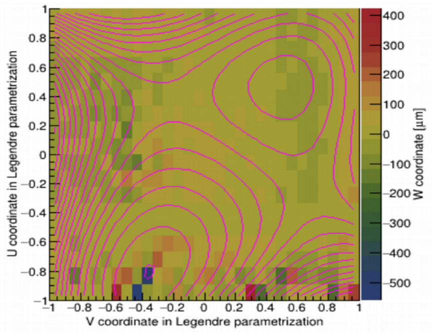
Sensor deformation have significant impact on track-to-hit residual distributions and resolutions



2D track-to-hit residuals in one SVD sensor (L4)

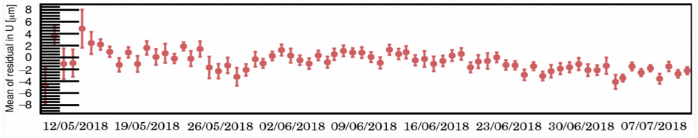
Sensor **deviation from flatness** derived from residuals dependence on angles of non-perpendicular tracks





After alignment, the sensors are near to flat and residual distributions optimal

2018 PXD:

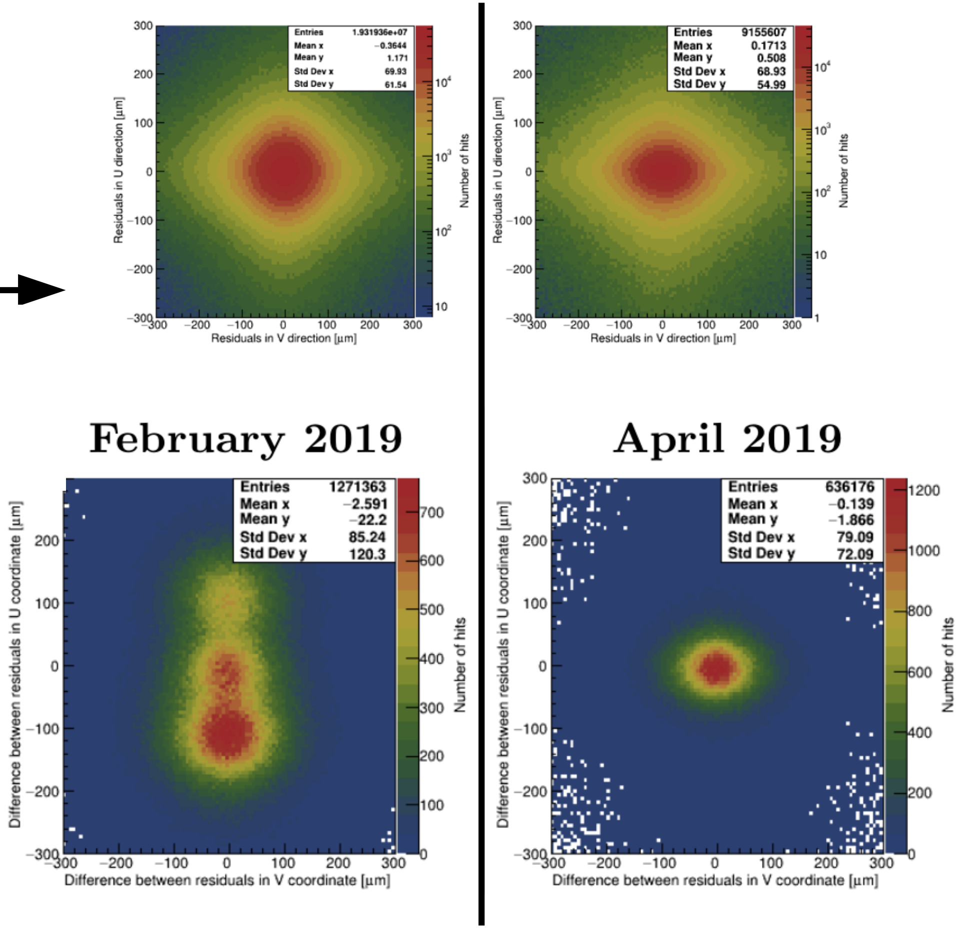


Monitoring stability using residuals after alignment (stable within < 10/20um for PXD/SVD)

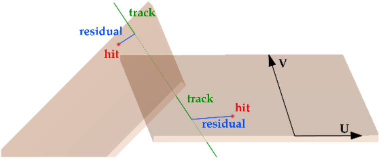
Validations with 2019 (cosmic) data
Overlap Track-to-hit residuals

Initialy aligned vertex and drift chamber with 2019 cosmics without magnetic field

Standard residuals did not show anything striking...



Overlap residual validation



Powerfull method to detect coherent detector misalignments

Standard residuals only weakly sensitive to **weak modes**, like radial expansion, twist etc. But needs lots of statistics

Found issue with wrong pitch size for SVD sensors in software → alignment compensated for it with radial-expansion-like deformation.

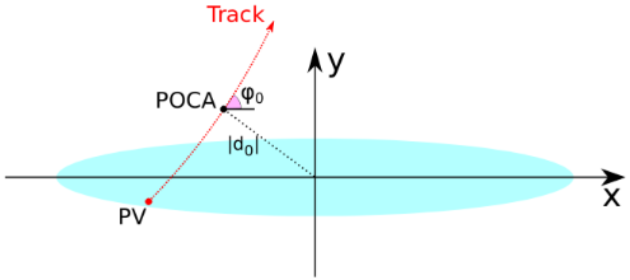
No indications of significant problems in overlap residuals afterwards.

Standard method

Compare two tracks with common vertex

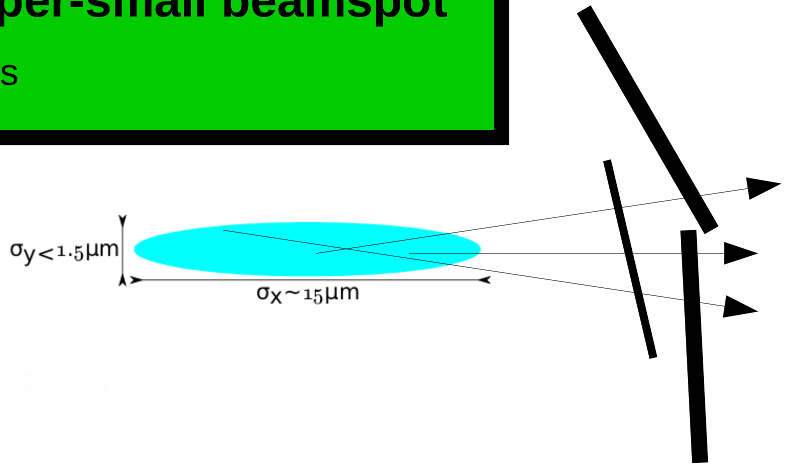
Difference of + and – track parameters at point of closest approach (POCA) to origin measure vertex resolution

Track parameters @ POCA:



Trick with super-small beamspot

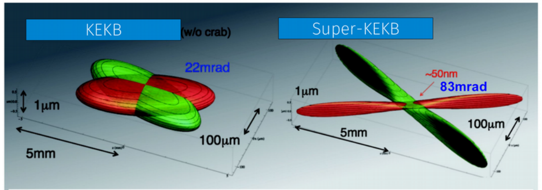
Using single tracks



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

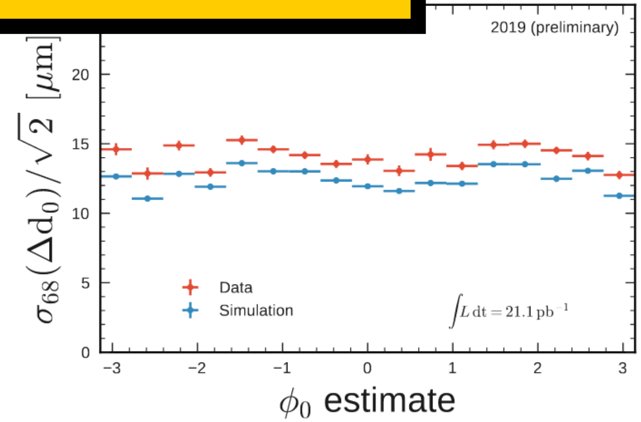
Our **vertical beamspot size** is so tiny, that for nearly **horizontal tracks**, the spread of d_0 *directly* measures vertex resolution

Going into vertical direction, beamspot size contribution increases

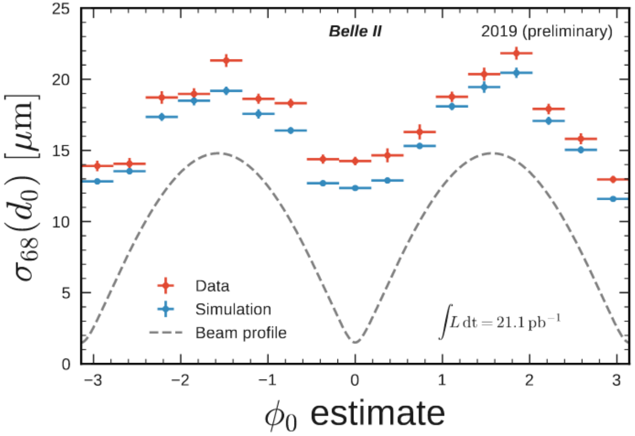
Performance with (collision) 2019 data
From vertex resolution to precision physics measurements

Standard method

$$\Delta d_0 \equiv d_0(t_-) + d_0(t_+).$$



$$\sigma_{68}(d_0) = \sqrt{\sigma_i^2 + (\sigma_x \cos\phi_0)^2 + (\sigma_y \sin\phi_0)^2}.$$



Trick with super-small beamspot

Impact parameter resolution in d0:

14.1 +/- 0.1 (stat) um

Both methods agree (also the slight discrepancy to MC simulation)

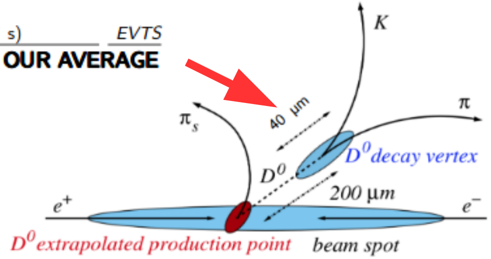
MC simulation probably too optimistic + sensor parameters not optimal + ...

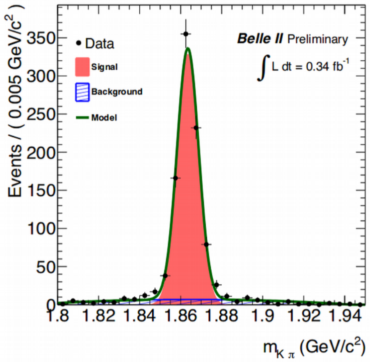
We can start doing precision physics...

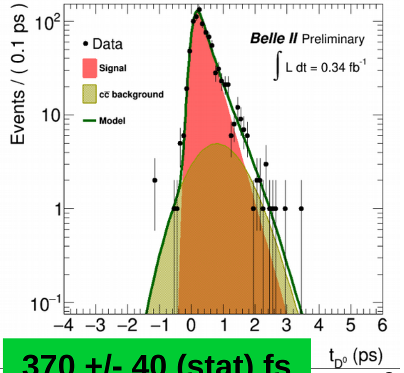
Example:
Measuring D^0 lifetime

PDG

VALUE (10^{-15} s)	*EVTS*
410.1± 1.5 OUR AVERAGE	







370 +/- 40 (stat) fs

Plans & Summary

Plans

- Tuning on data, learning from experience
  - Observed time dependence → differential alignment keeping sensors/wires fixed and allowing only larger structures‘ alignment to be time-dependent
- Running full procedure with all sub-detectors at once
  - Currently mostly simultaneous vertex + drift chamber alignment exercised
- Efforts towards full automation in **prompt calibration** on Airflow

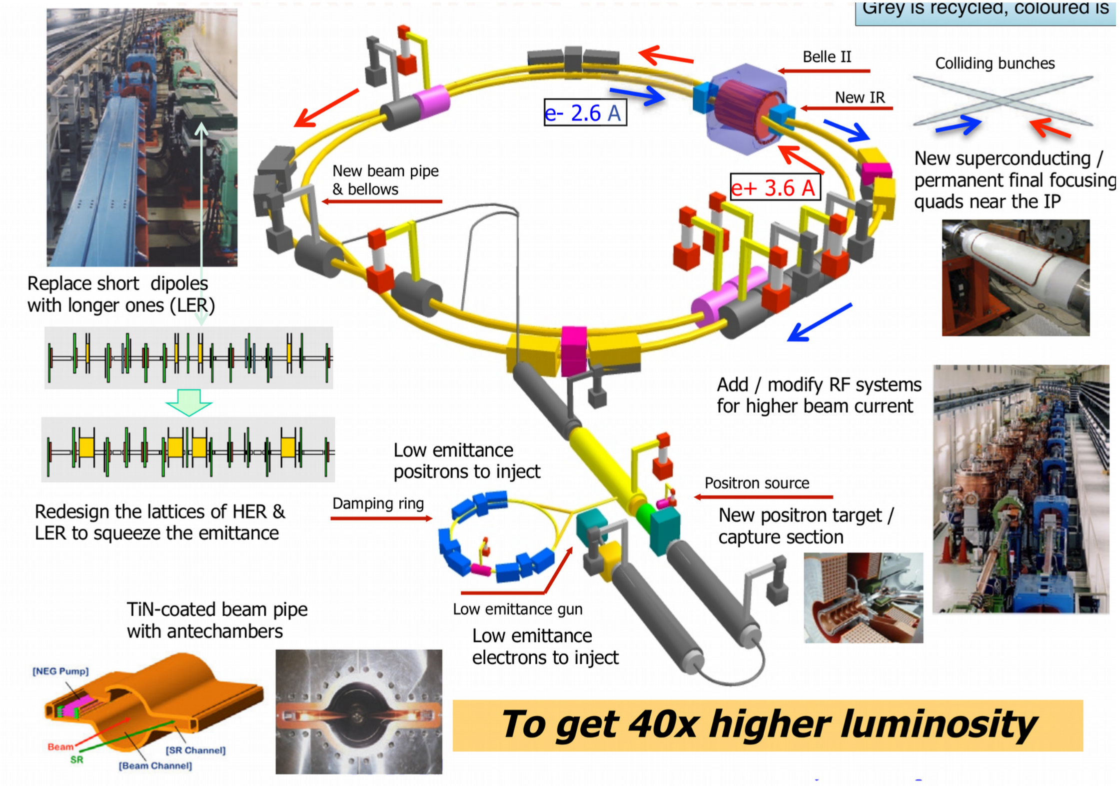
Summary

- **Detector calibration and alignment essential for precision physics!**
- Developed global approach with **Millepede II** for pixel, strip, drift chamber & muon system integrated with common tools and workflows
- Successfully exercised and validated alignment & calibration with cosmics and **first collision data**
- Even more exciting times coming with higher luminosity! Stay tuned :-)

Thank you for your attention!

BACKUP

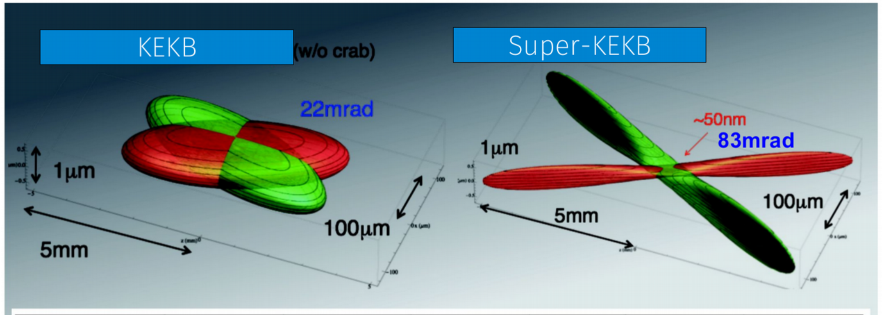
KEKB → SuperKEKB



beam current

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

vertical beta function at IP



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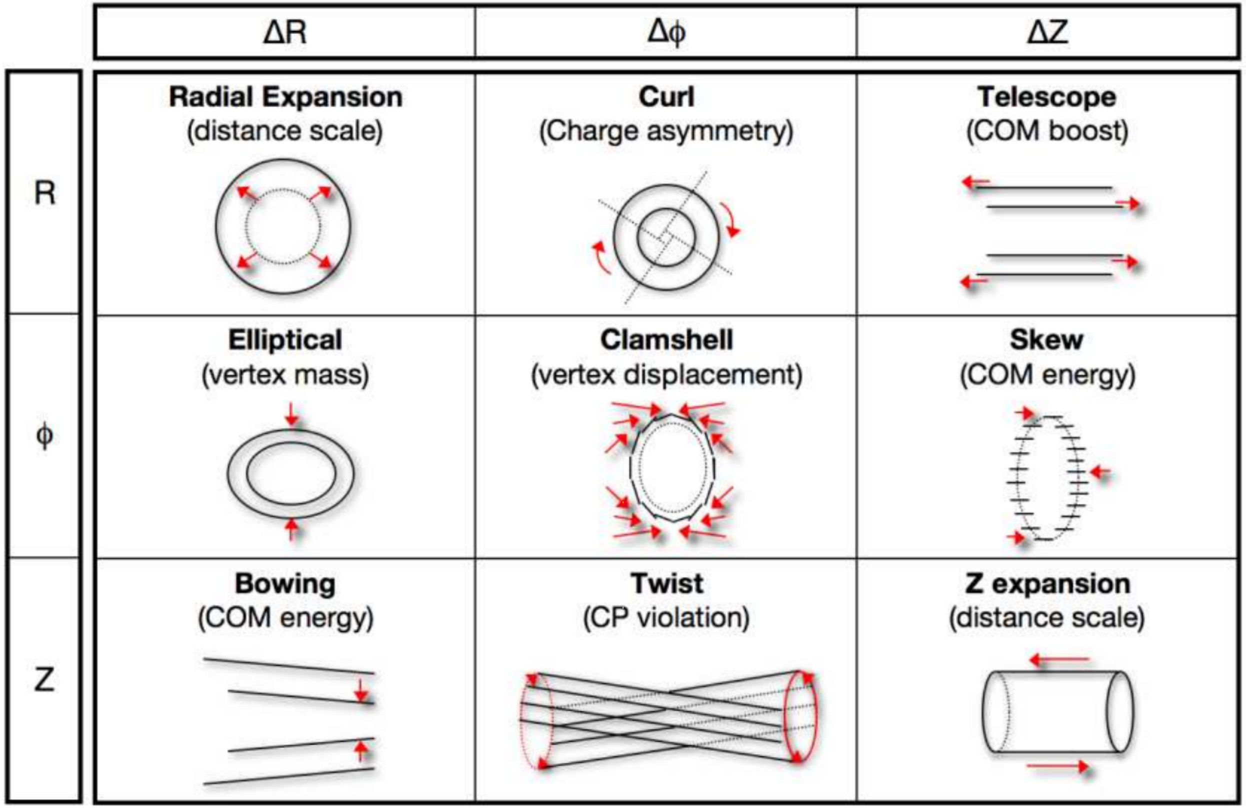
factor 20

factor 2-3

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

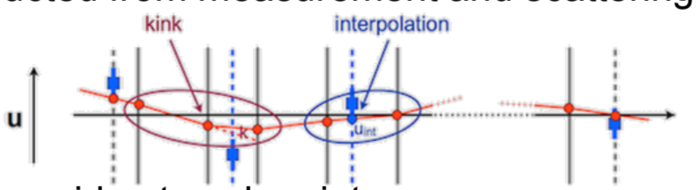


→ For tracks from IP, such distortions leave Chi2 unchanged, but change parameters of the tracks → bias in track parameters: weak modes are the biggest **challenge** in track based alignment

→ 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

- 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:

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

- 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)

Abstract

On March 25th 2019, the Belle II detector recorded the first collisions delivered by the SuperKEKB accelerator. This marked the beginning of the physics run with vertex detector.

The vertex detector was aligned initially with cosmic ray tracks without magnetic field simultaneously with the drift chamber. The alignment method is based on Millepede II and the General Broken Lines track model and includes also the muon system alignment and part of drift chamber calibrations. To control weak modes, we employ sensitive validation tools and
various track samples can be used as alignment input, from straight cosmic tracks to mass-constrained decays.

With increasing luminosity and experience, the alignment is approaching the target performance, crucial for the first physics analyses in the
era of Super-B-Factories. We will present the software framework for the detector calibration and alignment, the results from the first
physics run and the prospects in view of the experience with the first data.