Detector Alignment at Belle II

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Belle II Collaboration

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Bonn

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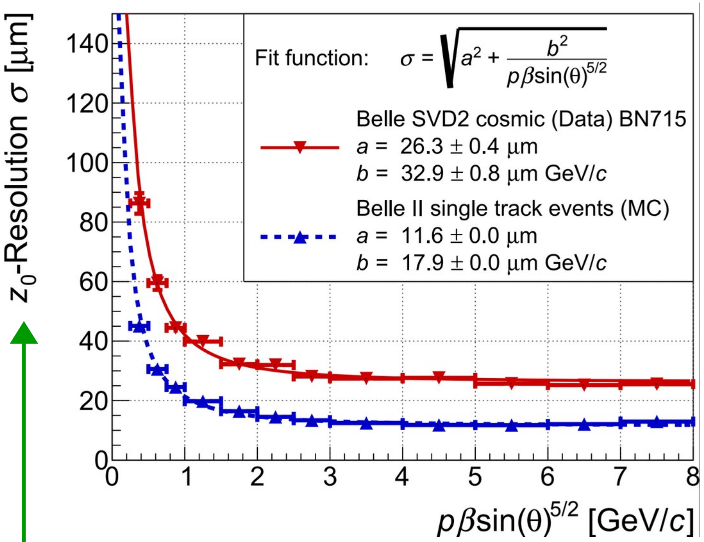
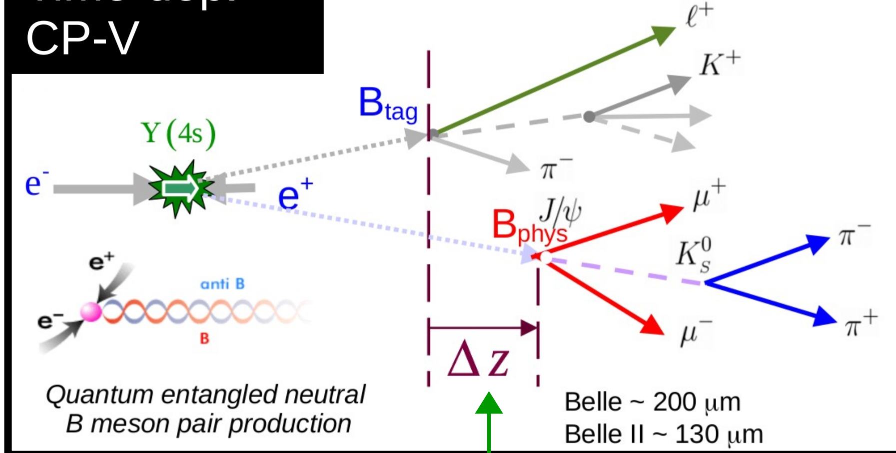
Precision @ Belle II

Just two examples...



Time-dep. CP-V



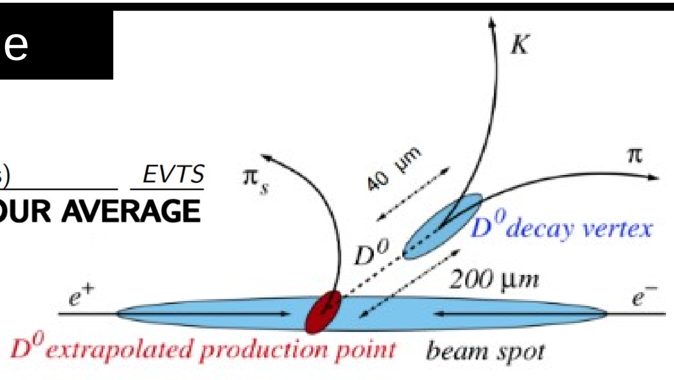
Alignment precision at level of micrometers needed

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

D^0 lifetime

PDG:

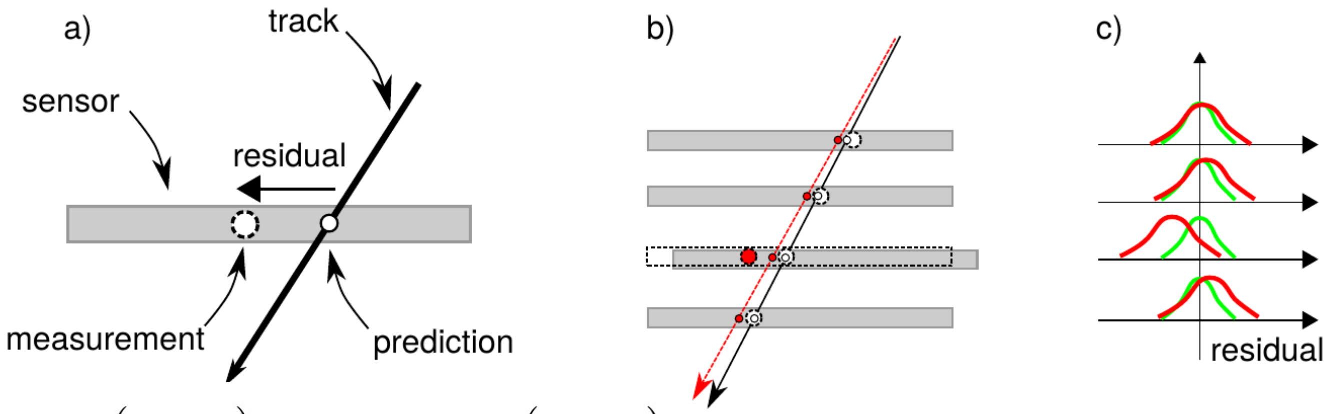
VALUE (10^{-15} s)	EVTS
410.1± 1.5 OUR AVERAGE	



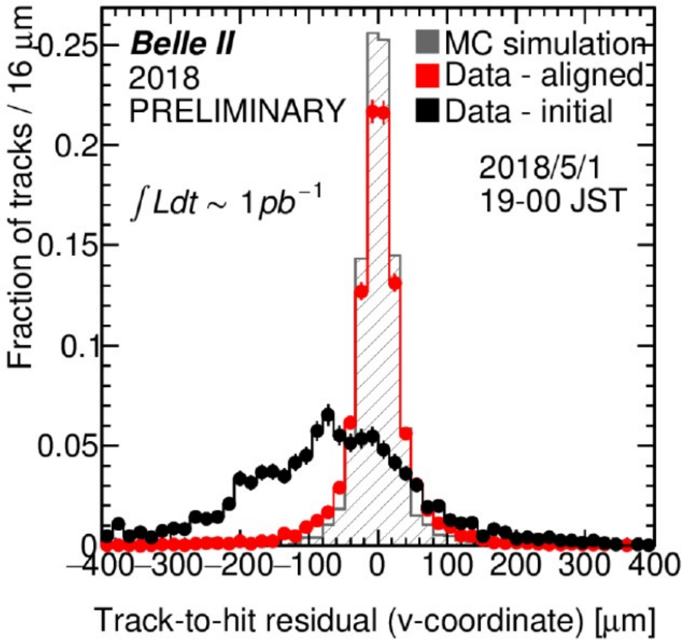
Track-based alignment

Detection elements not in assumed positions/orientations/…

→ biased measurements & sub-optimal **residuals**

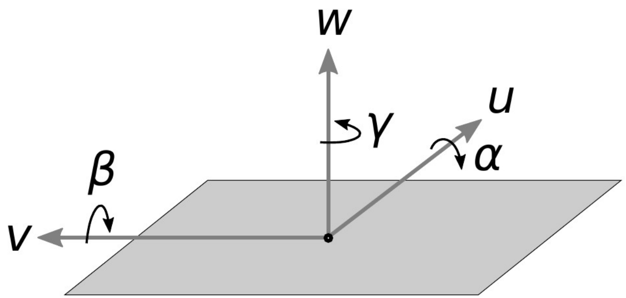


$$r_{ij}(\boldsymbol{a}, \boldsymbol{q}_j) = m_{ij} - p_{ij}(\boldsymbol{a}, \boldsymbol{q}_j)$$



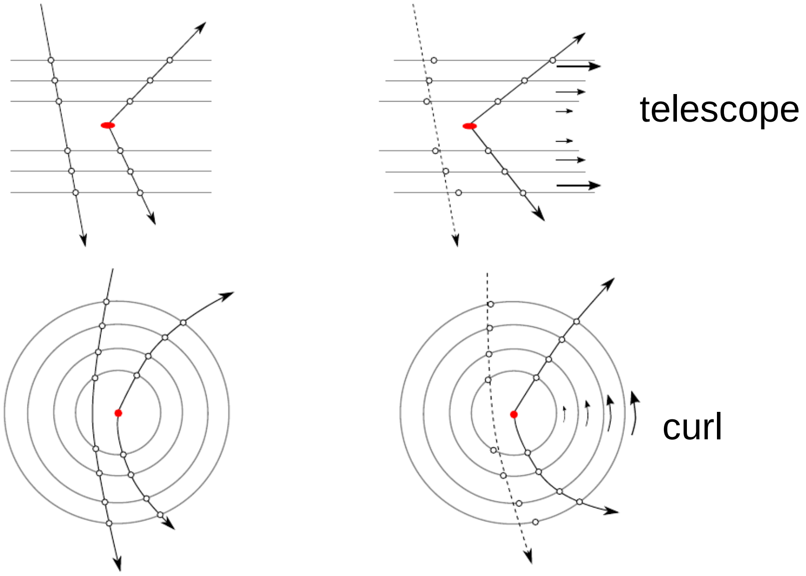
Estimate the geometry directly from the trajectories
→ minimize many millions of residuals!

$$\chi^2(\boldsymbol{a}, \boldsymbol{q}) = \boldsymbol{r}^\intercal(\boldsymbol{a}, \boldsymbol{q})\boldsymbol{V}^{-1}\boldsymbol{r}(\boldsymbol{a}, \boldsymbol{q}) \quad \to \text{min}$$

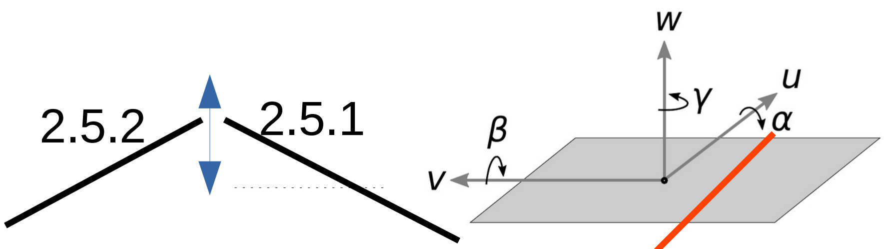


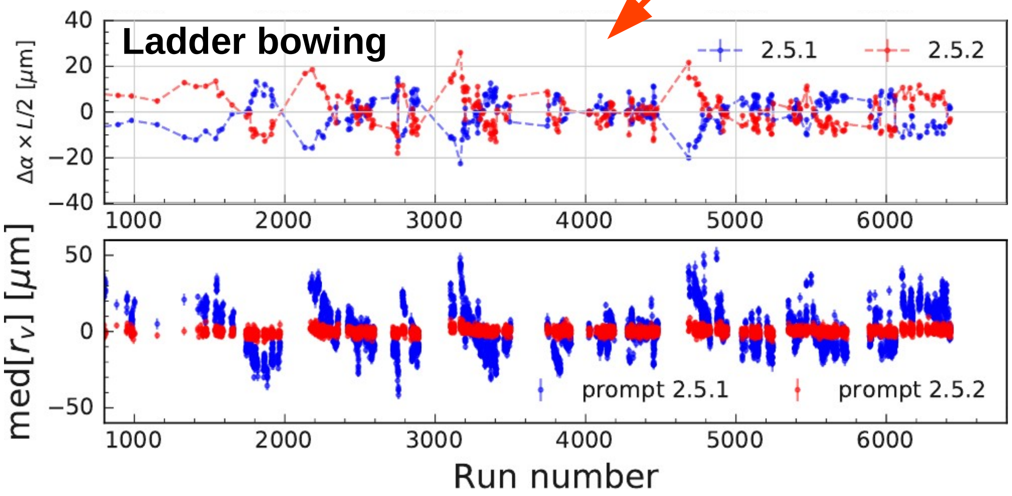
Alignment Challenges

- Weak Modes
  - (some) data not sensitive to (some) deformations



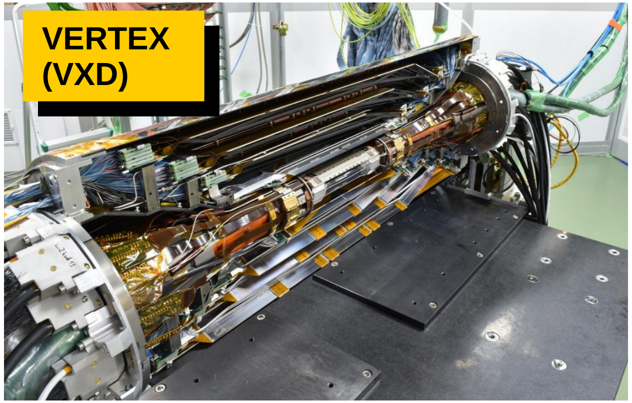
- Time-dependence
  - Detector not stable, many effects at play



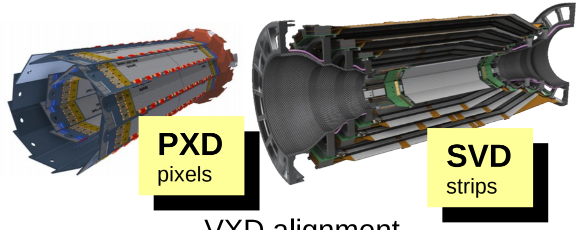


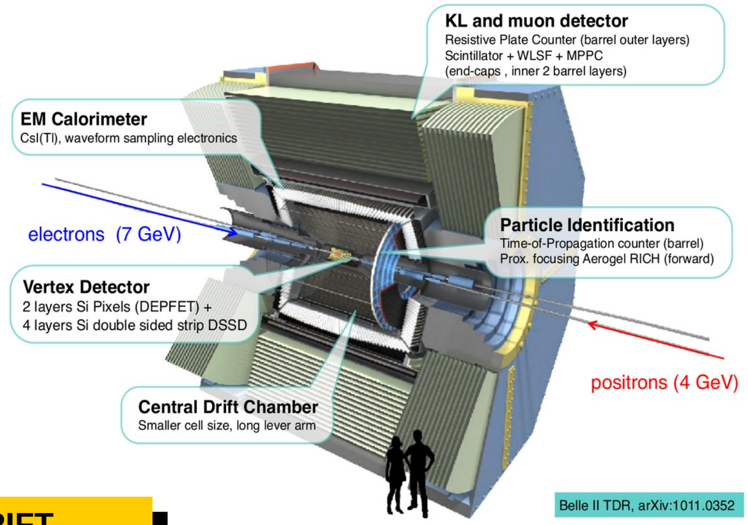
- Detector&reco model issues
  - e.g. imperfect magnetic field description

Belle II Alignment „Constants“



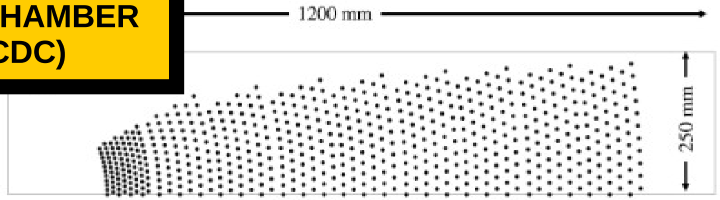
212 sensors
x **18** parameters

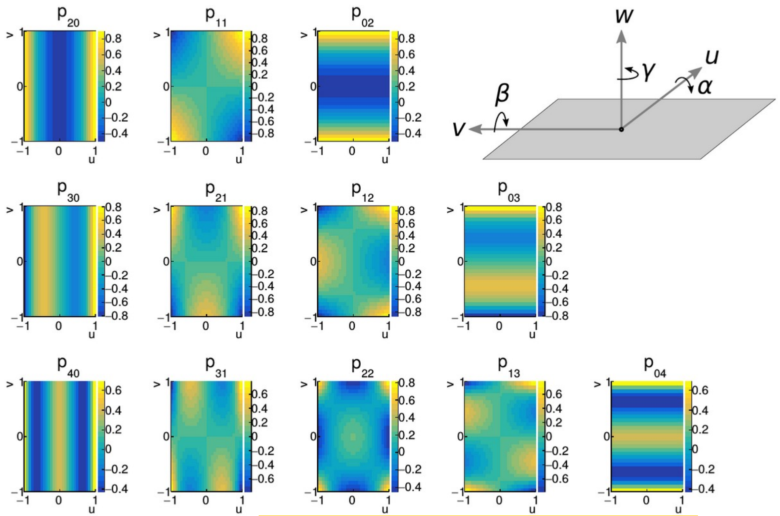


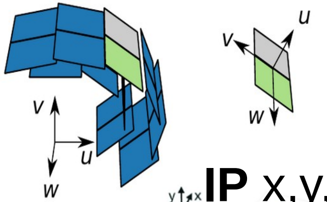


VXD alignment
hierarchy: half-shells →
ladders → sensors

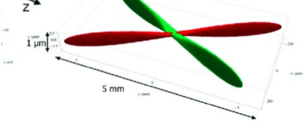
DRIFT CHAMBER (CDC)



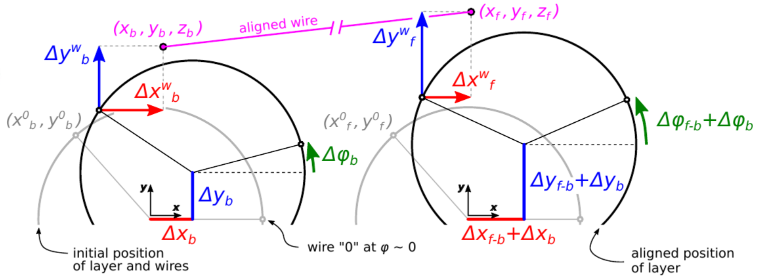




IP x,y,z



56 layers x 6 parameters
14,336 wires x 4 parameters

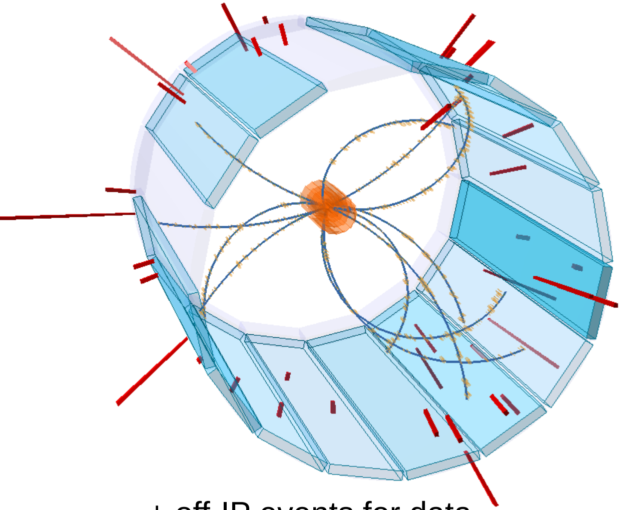


More than 60,000 parameters to be determined

* with help of J. Kandra

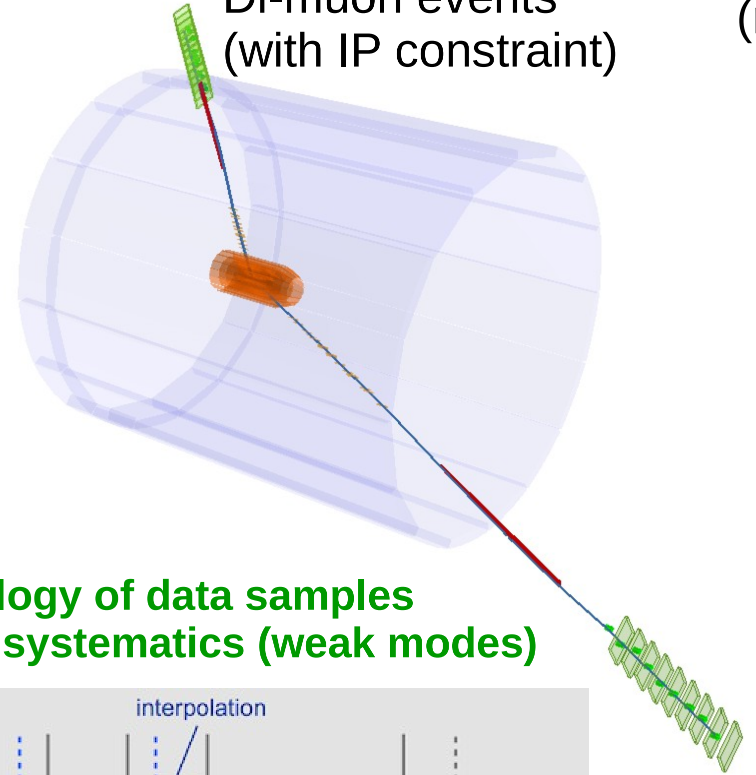
Data Samples for alignment

Hadronic events

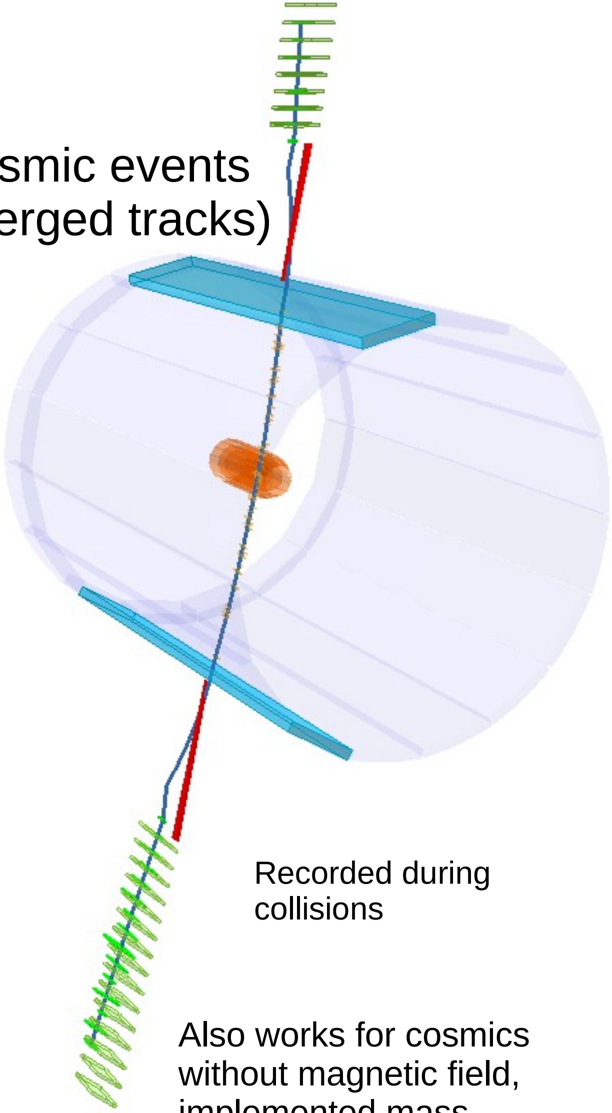


+ off-IP events for data

Di-muon events
(with IP constraint)



Cosmic events
(merged tracks)

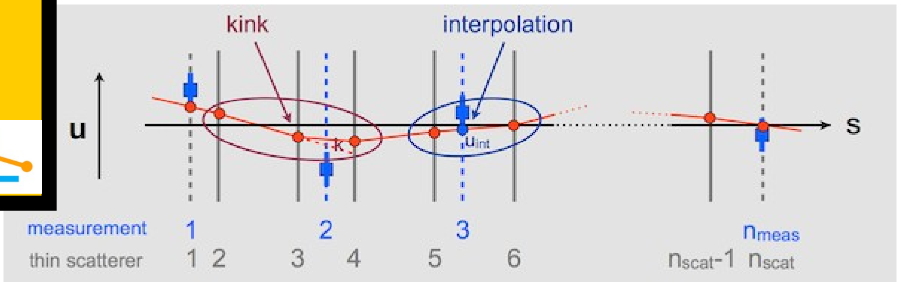


Recorded during collisions

Also works for cosmics without magnetic field, implemented mass-constrained decays ...

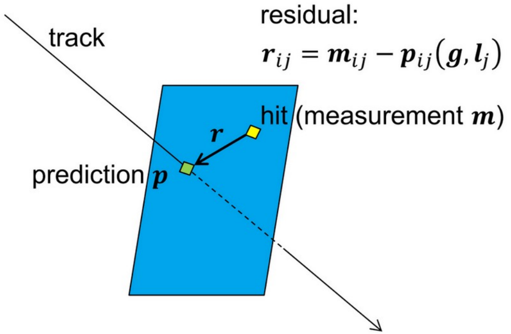
Rich topology of data samples to reduce systematics (weak modes)

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



Belle II = low mom. particles relative to CMS

Alignment Algorithm: Millepede II

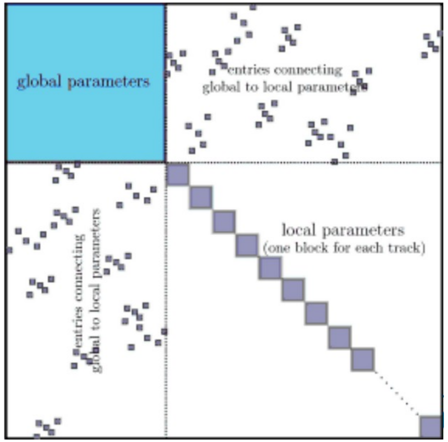


Minimize over all parameters:

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

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

Millepede II



~ 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

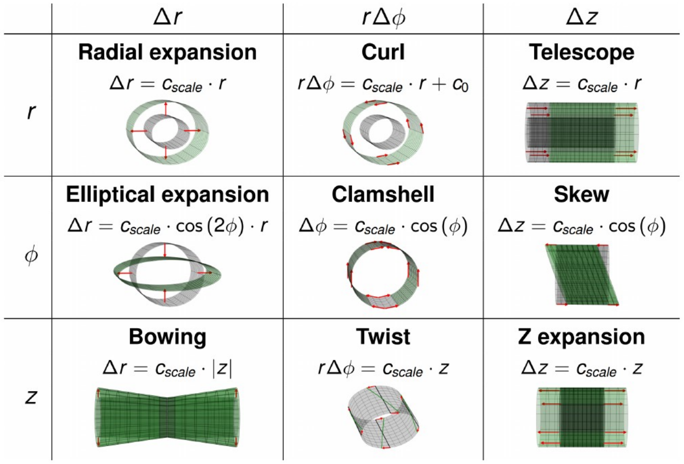
Time in minutes. Table from C. Kleinwort

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

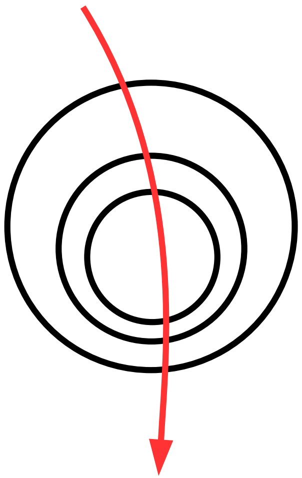
https://www.terascale.de/wiki/millepede_ii/
https://helmholtz.software/software/millepede-ii

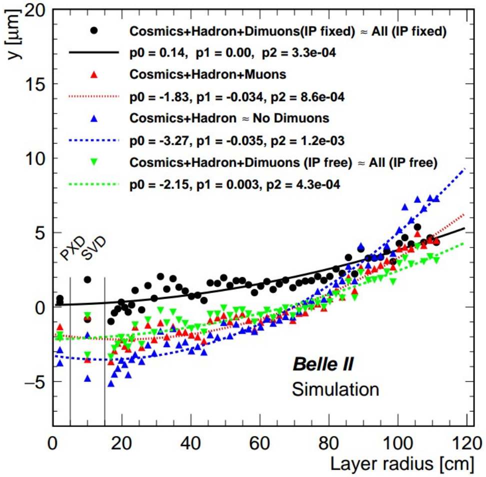
*Using 10 cores @ Xeon(R) CPU E5-2640 v3 @ 2.60GHz. 20GB of memory required.

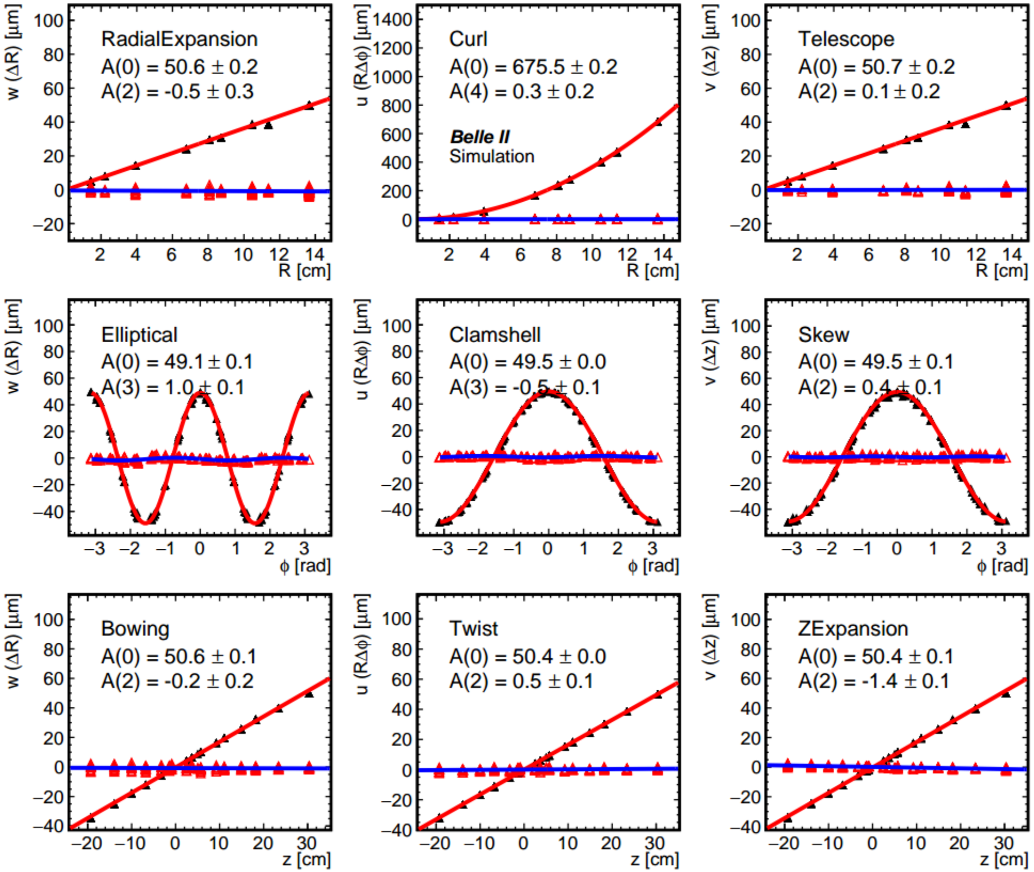
Weak Modes in Prompt Alignment (without wires and IPdimuons)



MC tests of **VXD** weak mode misalignments



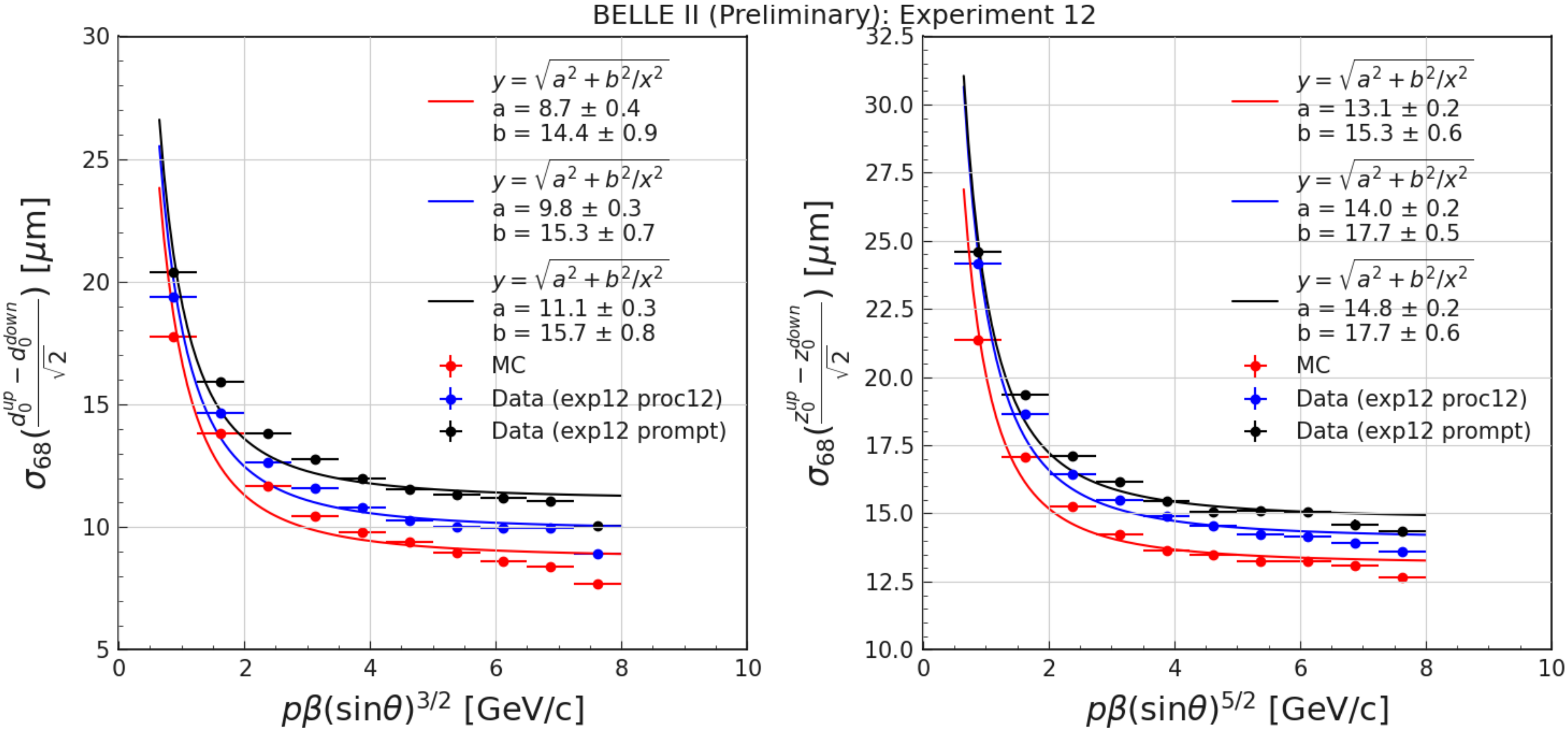




Weak modes in prompt alignment are well constrained

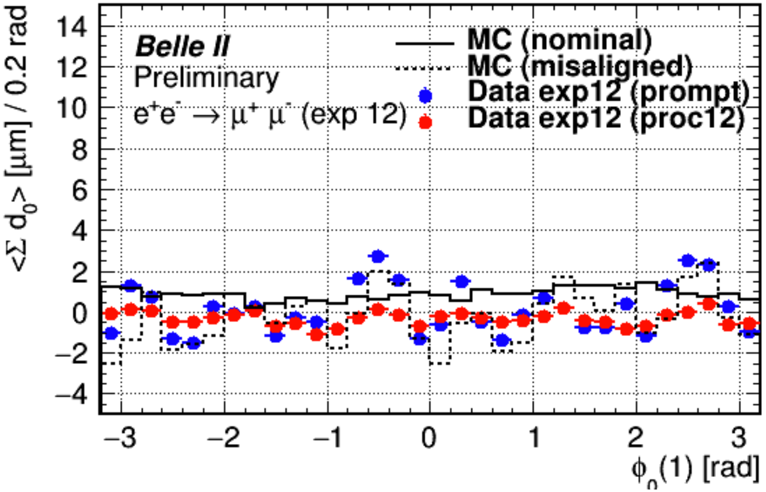
Impact Parameter Resolutions

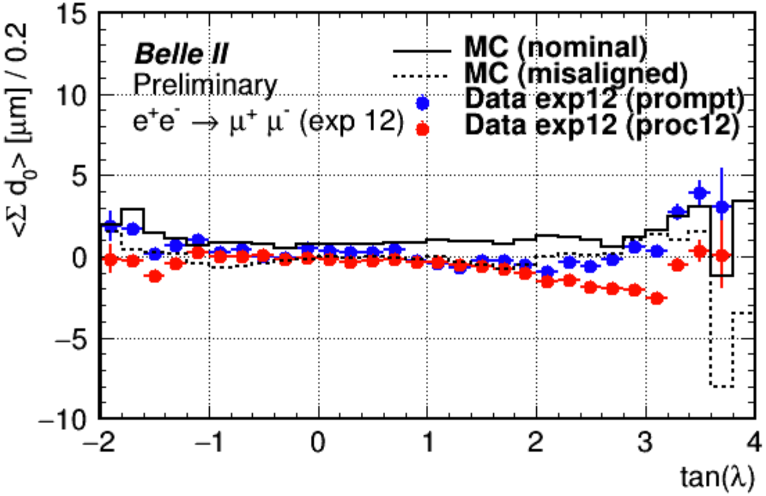
selection="abs(Z01)>0.3&& abs(Z02)>0.3"



Reprocessing-like alignment deployed already at prompt calibration stage since 2021 → no waiting for reprocessing for publication-level alignment quality!

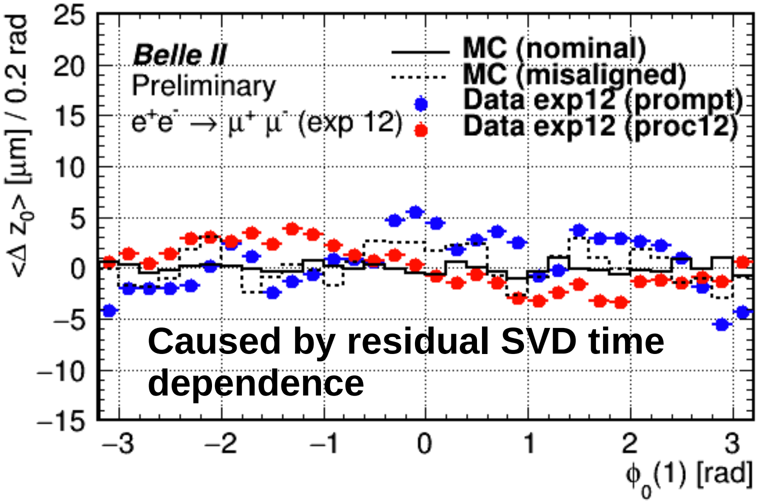
Vertexing systematics for dimuons



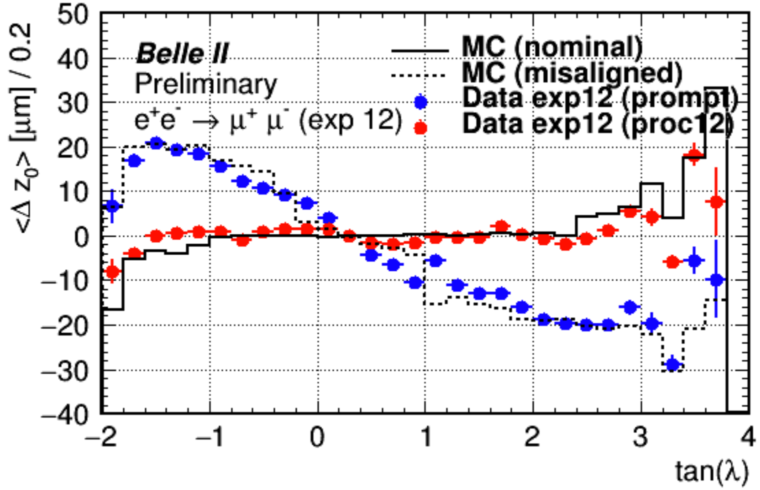


Note that our ideal MC has a bias in d_0 :-)

No significant remaining systematics



Caused by residual SVD time dependence

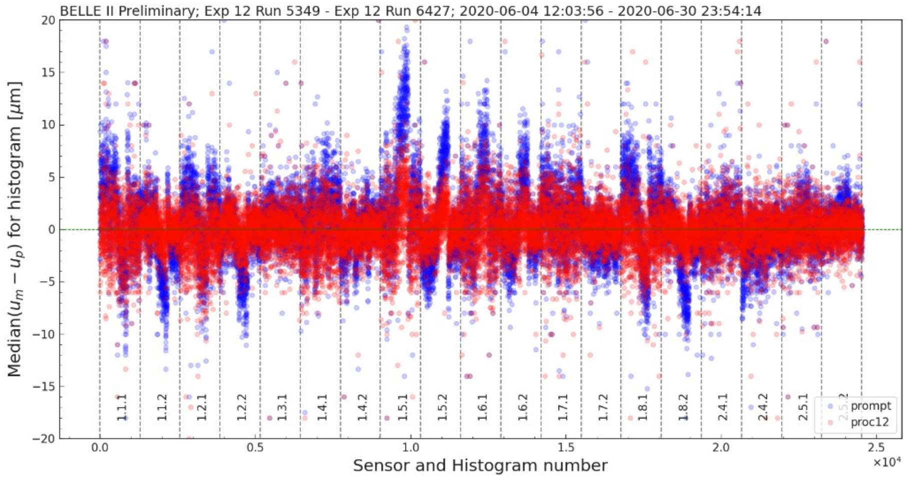


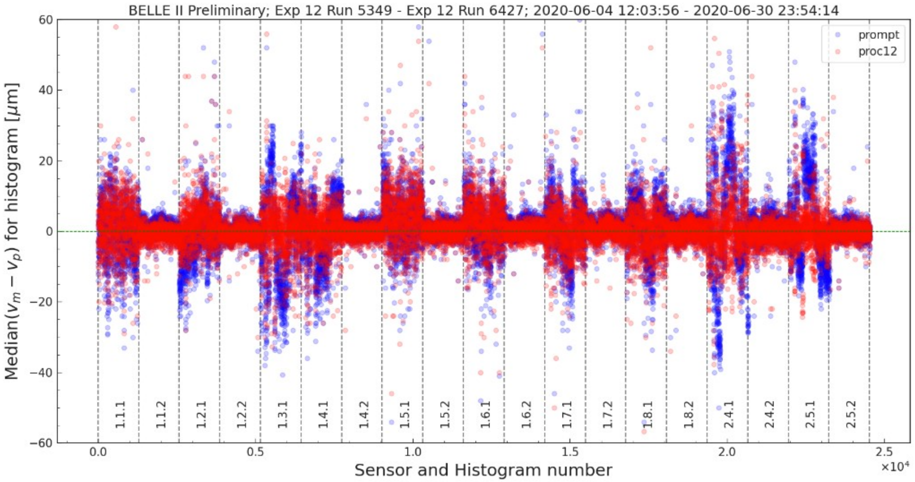
Radical improvement for z_0 bias vs tan(lambda).

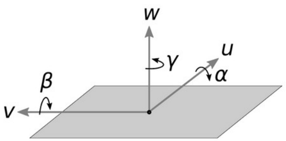
Systematics can be well reproduced on MC

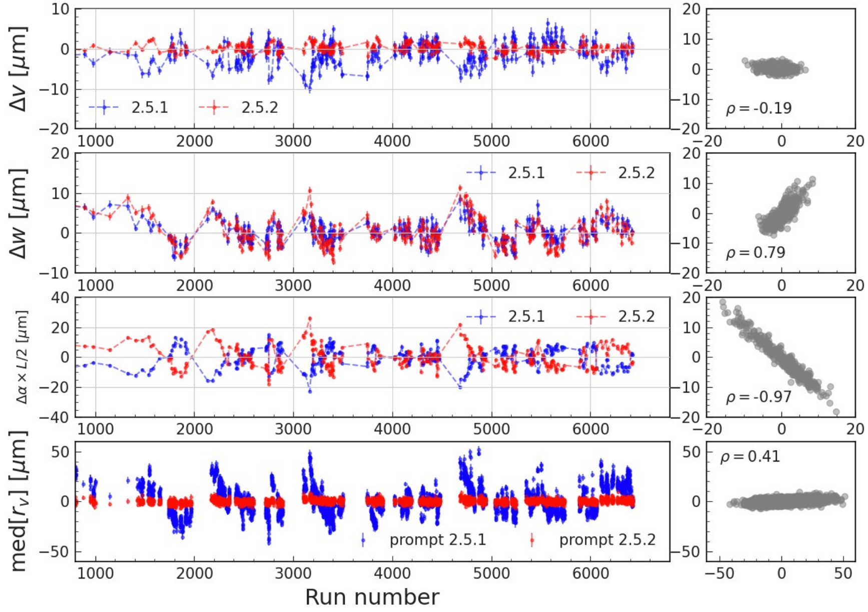
More systematic checks in cosmics validation – see backup

PXD Alignment evolution example





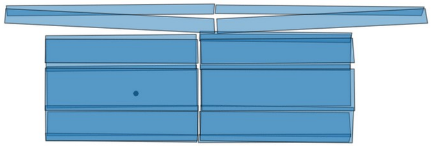




Belle II PXD

Experiment 12 Run 3496 - 3745

alignment corrections × 100

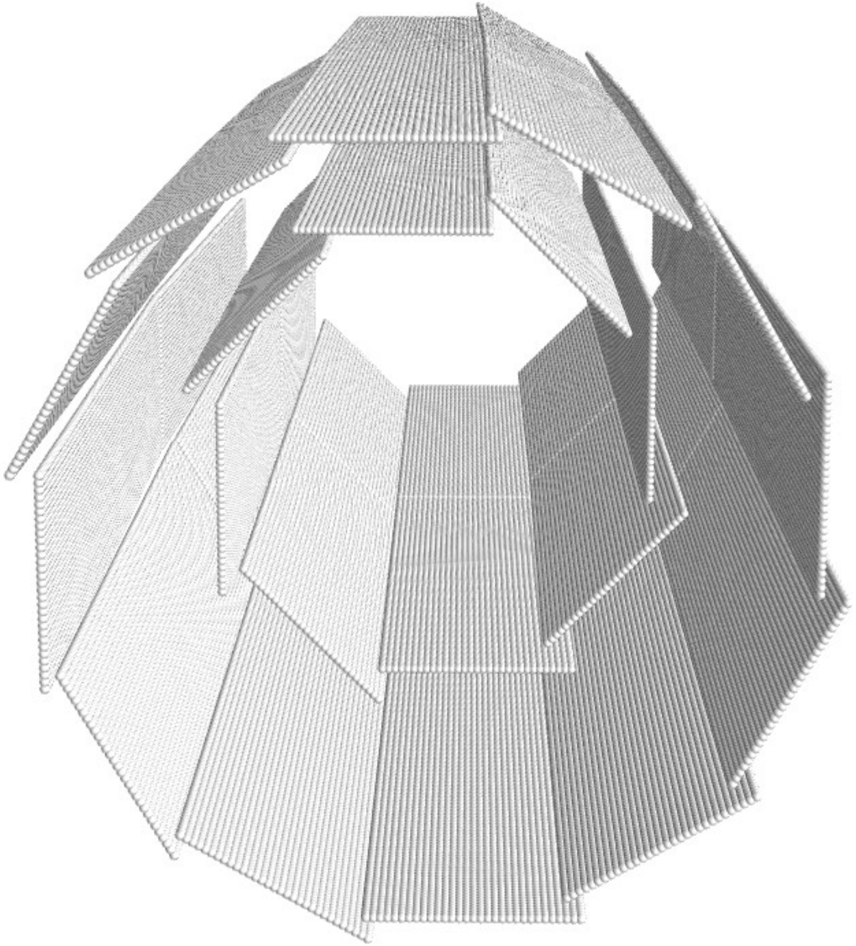


Animated gif:

*Differences to first exp12 alignment shown in animation

https://www.dropbox.com/scl/fi/v6pe79t07vr974jxa6ct9/pxd_exp12.gif?rlkey=18w7r00j3qglnpyu4vsmr7yrj&st=6eb6je68&dl=0

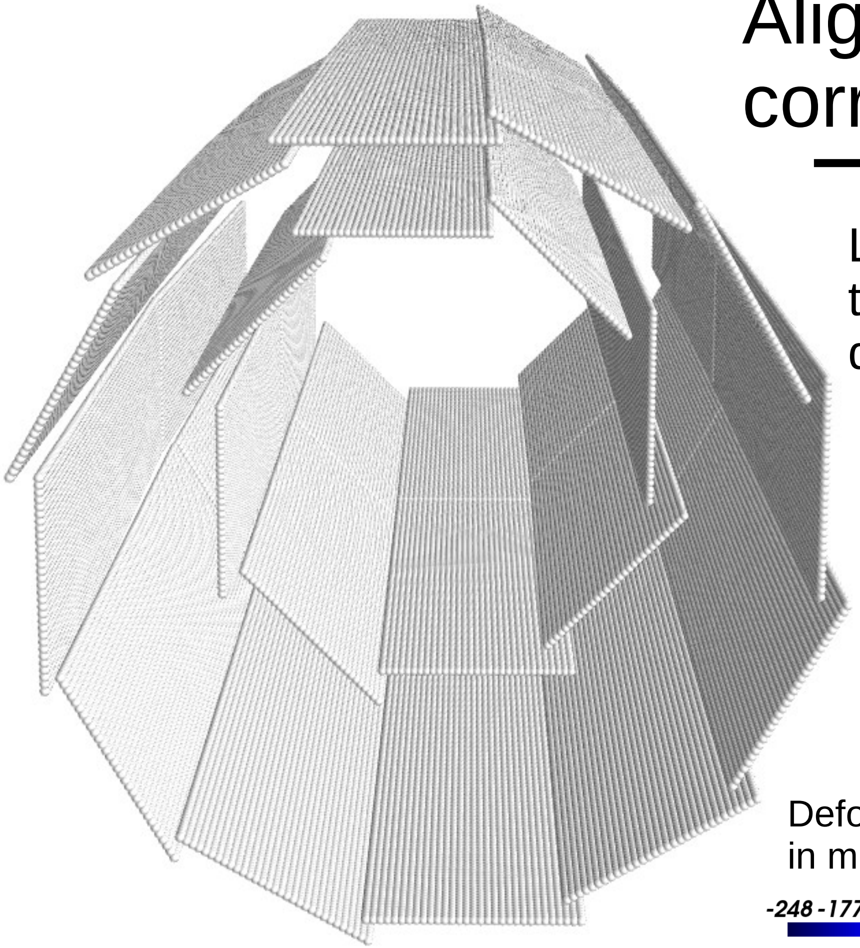
New PXD & Alignment



Real shape of the PXD2 (sensitive areas)

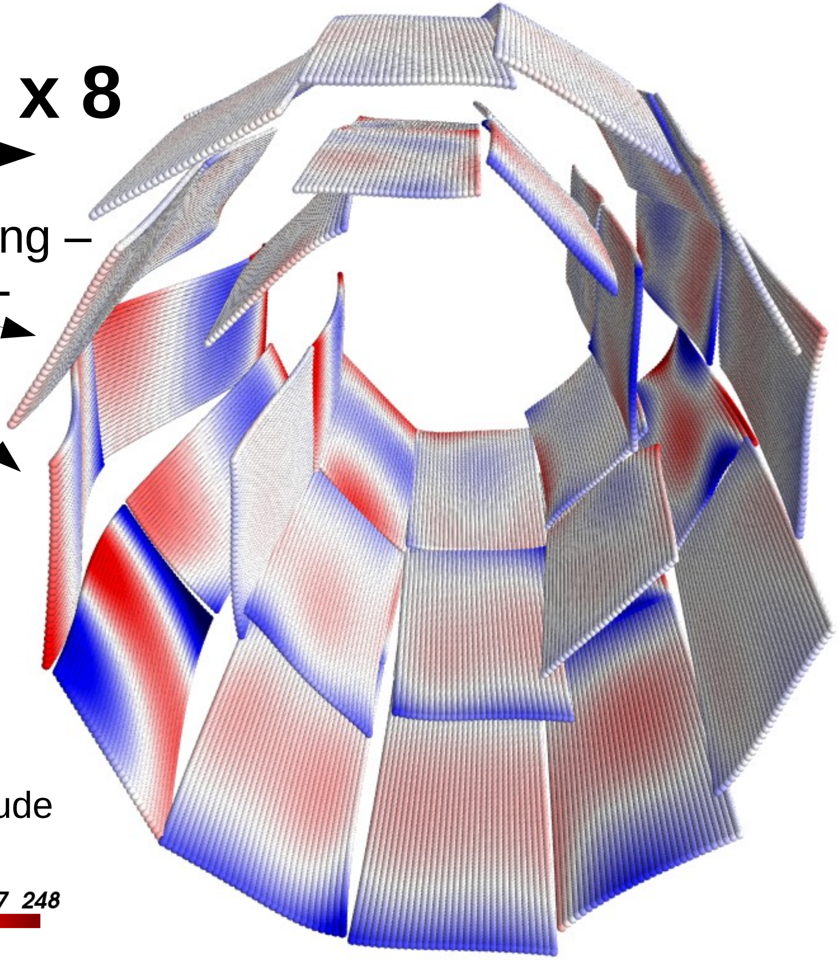
as determined by the alignment
during commissioning (B=0T cosmics)

New PXD & Alignment x 8

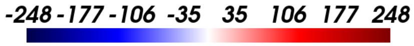


Alignment corrections **x 8**

Ladder bowing – temperature-dependent

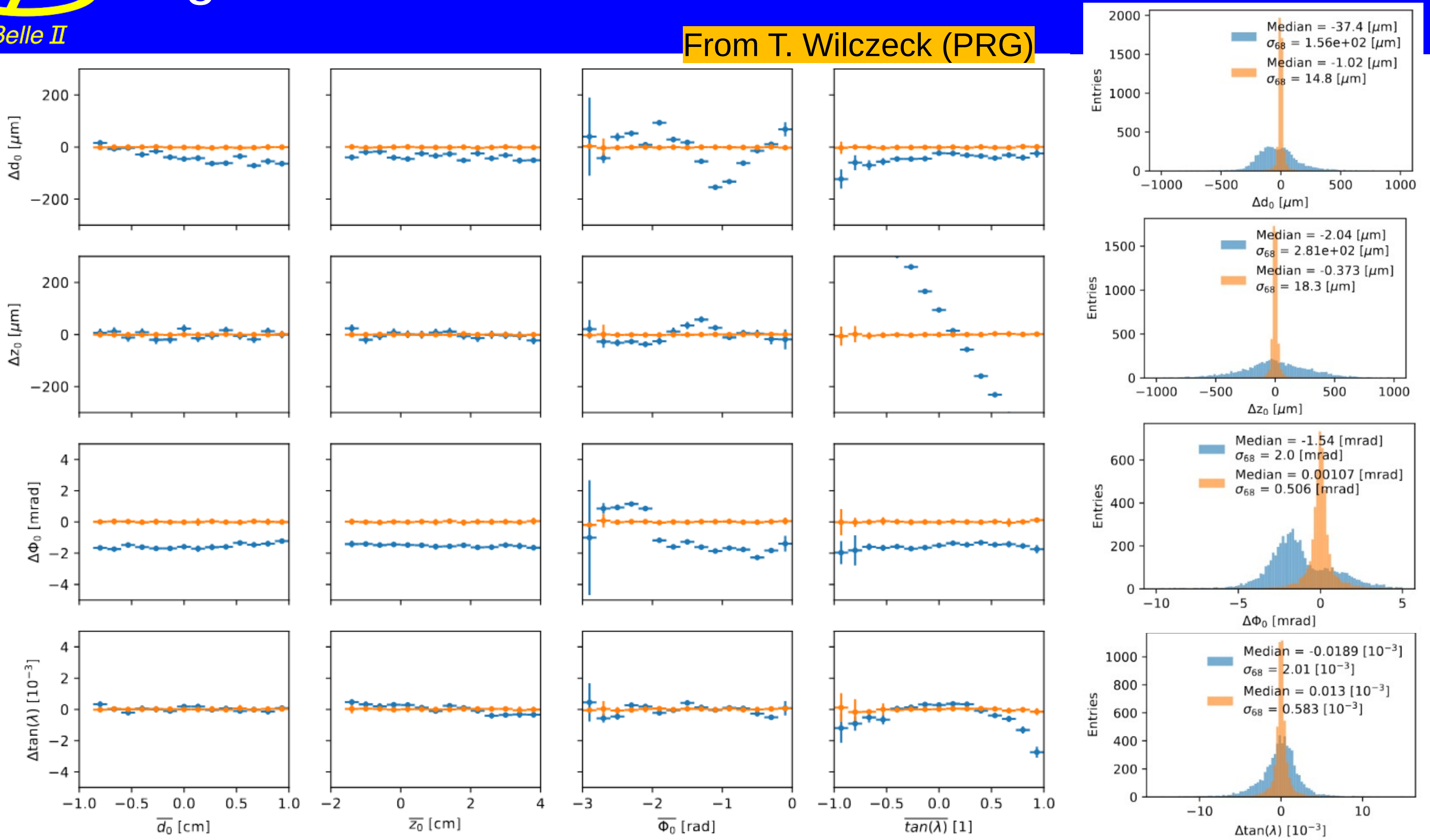


Deformation amplitude in micrometers

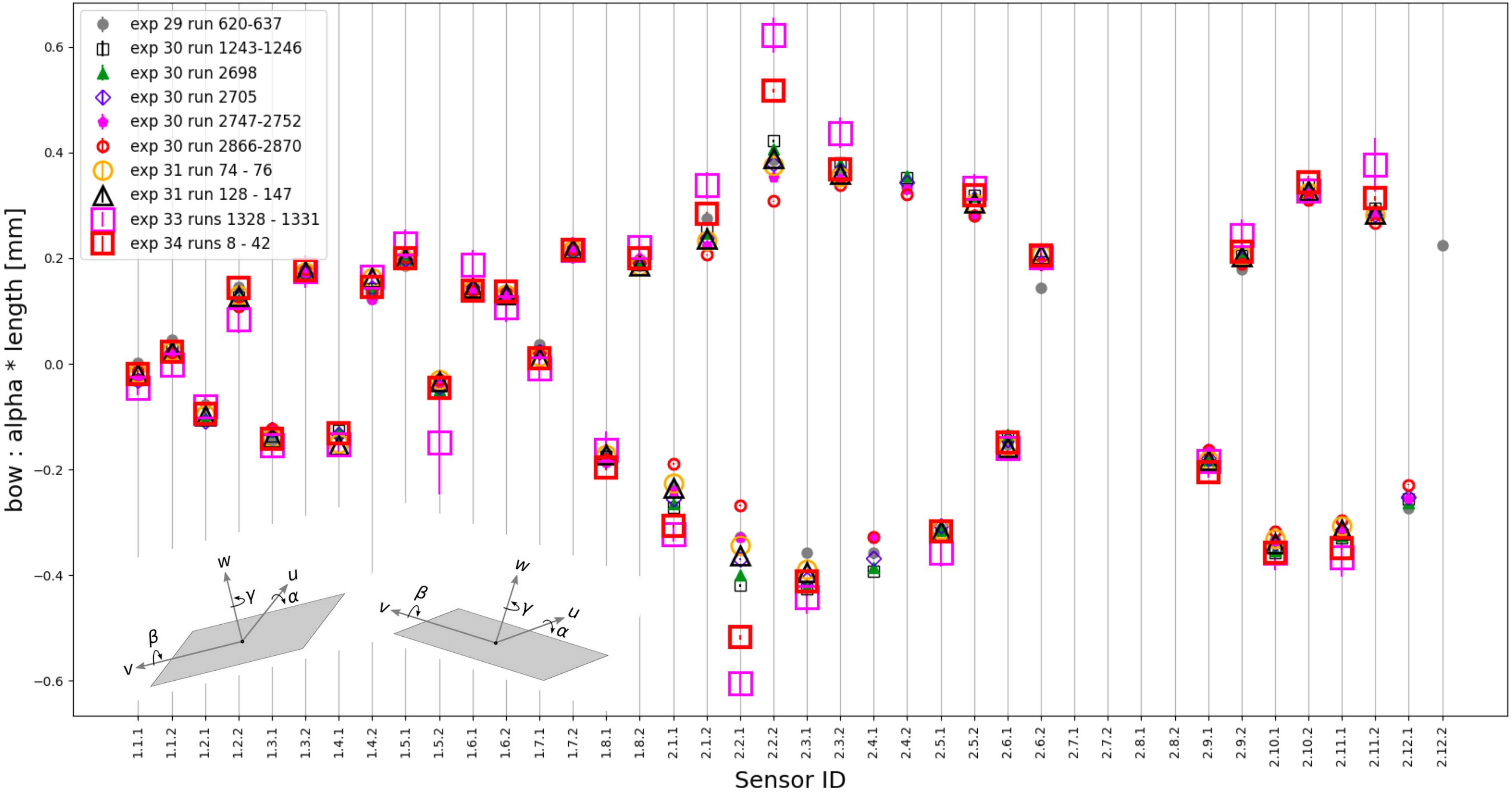


Alignment & Performance with cosmics & B=0T

From T. Wilczeck (PRG)



PXD2 ladder bowing amplitude in different 2024 periods



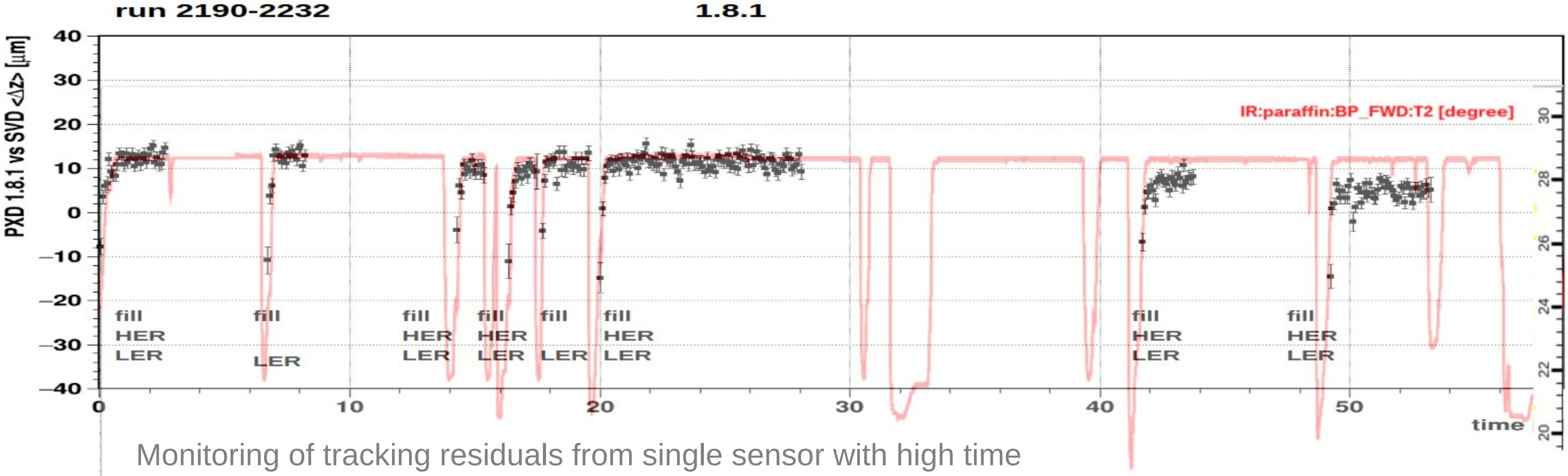
Max bowing for operated ladders between 300–650 um.

Depends on beam currents (and which sensors are turned on)

Two ladders with largest bowing turned off in beam operations :-(

PXD2 & New Alignment Challenges

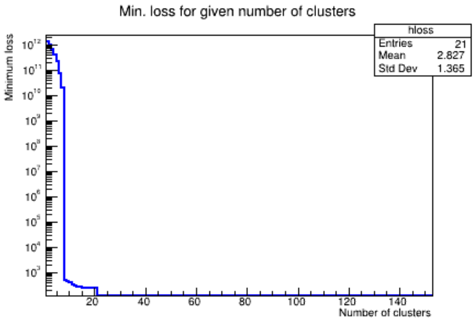
- Observed (also) very fast bowing-like deformations correlated to beampipe temperature ← depends on beam currents

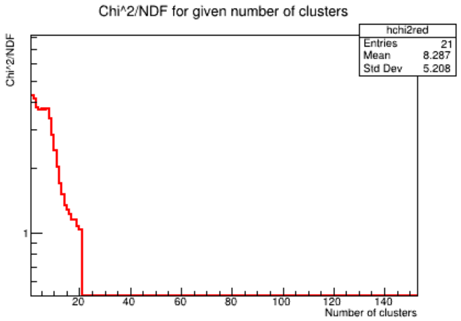


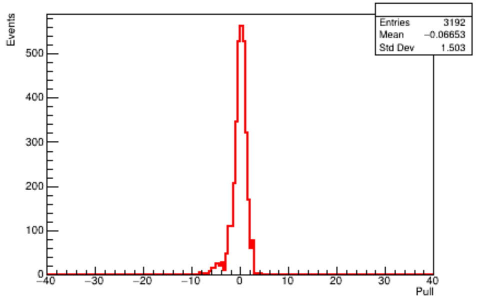
Monitoring of tracking residuals from single sensor with high time resolution using „all raw data“

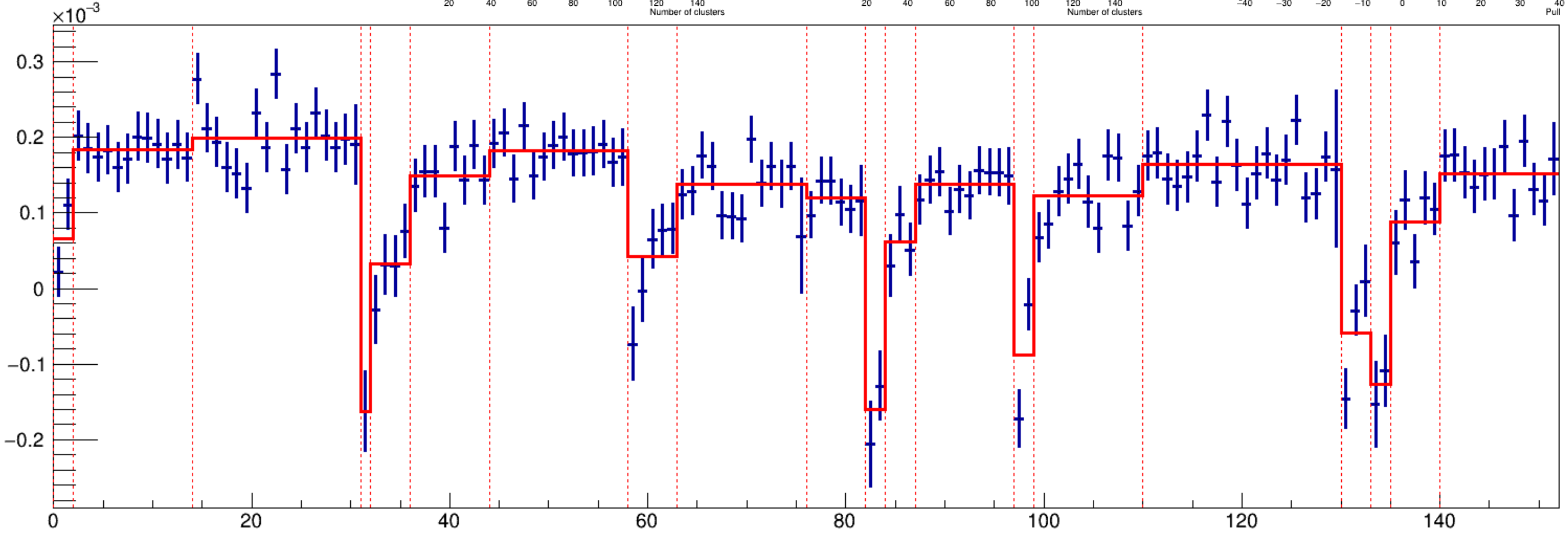
Automatic IoVs from clustering with loss function?

Dynamic programming exact solution with arbitrary loss function (e.g. minimum amount of data, constraints...)









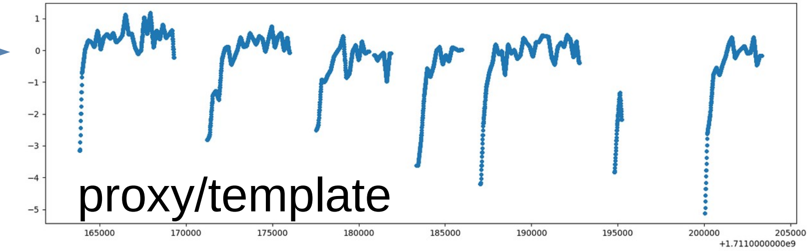
Would need much more data and parameters (for IoVs) for alignment ...

Alignment with Time-Dependent Template(s) ?

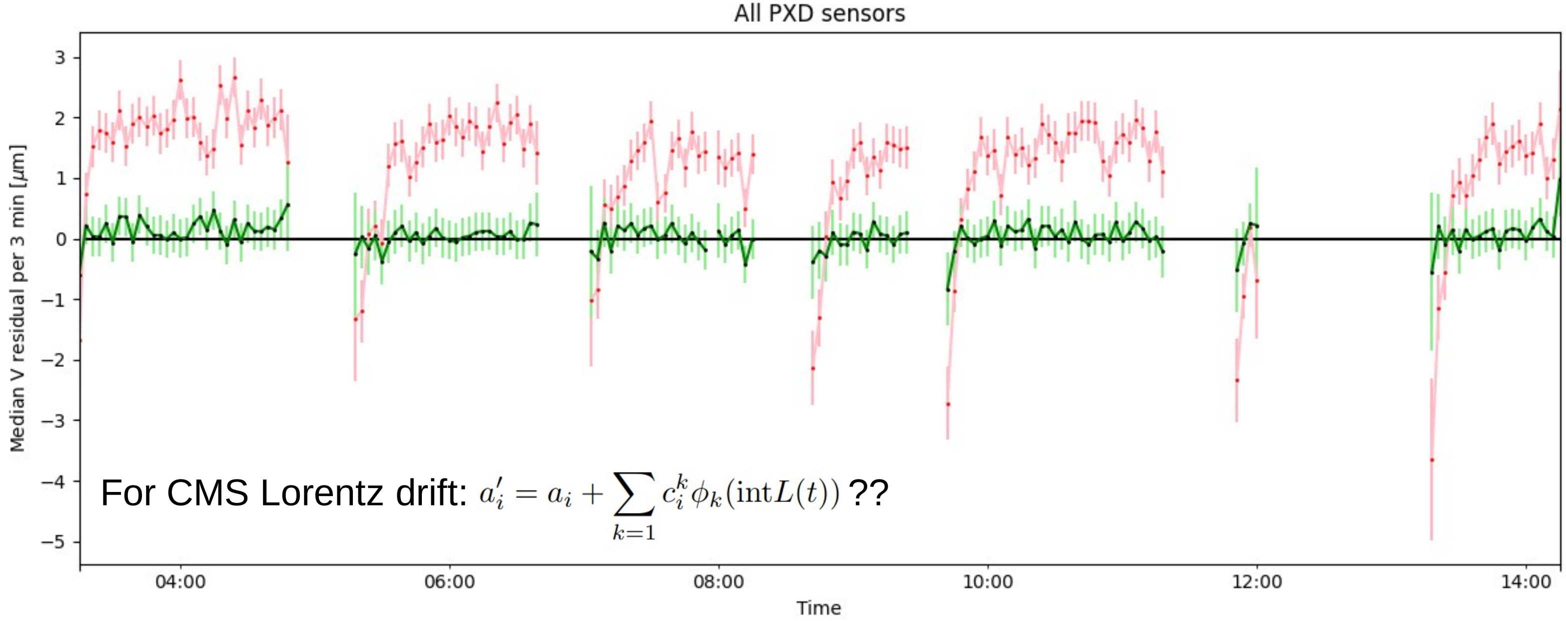
$$(a_0, a_1, ...a_n, a_{n+1}, ...a_N) \rightarrow (a_0, a_1, ...a_n, a_{n+1}, ...a_N, \boxed{c_0, c_1, ...c_n})$$

Deformation coefficients determined by Millepede II

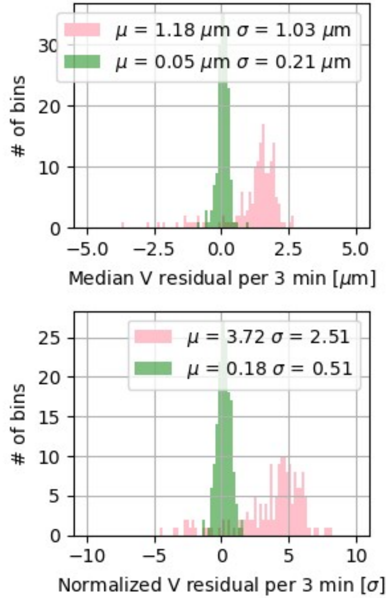
$$a'_i = a_i + \boxed{c_i}\phi(t)$$



Time-dependence in template, coefficients to time-dependent proxy determined simultaneously with standard alignment → only double the number of time-dep. parameters (in the simplest case)

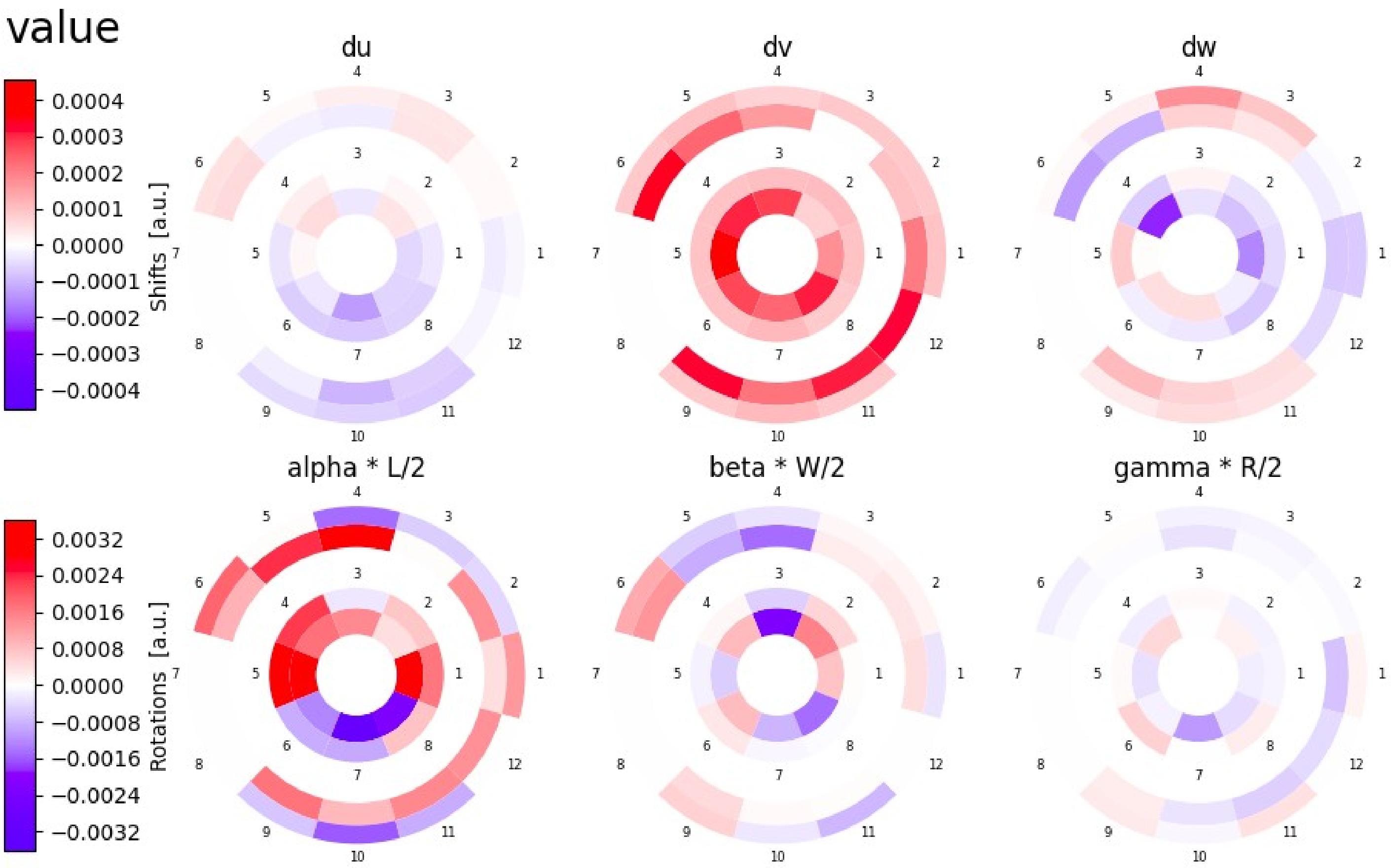


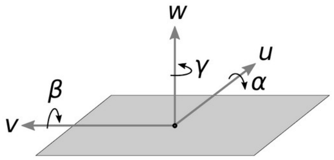
For CMS Lorentz drift: $a'_i = a_i + \sum_{k=1} c_i^k \phi_k(\mathrm{int}L(t))$??



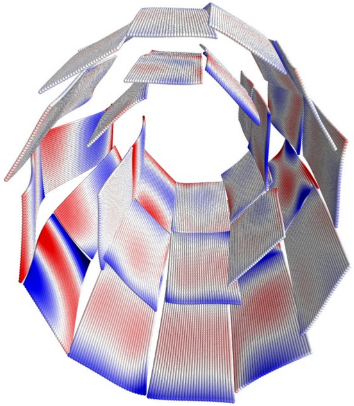
Or, if you „know“ deformation coefficients, determine instead single amplitude in many IoVs...

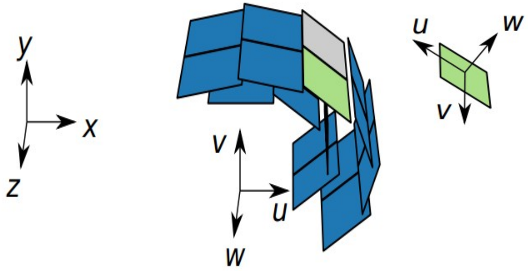
PXD deformation coefficients (rigid body)





„nominal“
deformation (x8):





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)
- Alignment performance pretty good in MC simulations and data validations
  - Some remaining discrepancies related residual time dependence and to imperfect magnetic field description or other detector modelling defficiencies
  - Data-driven conservative misalignment scenario available for systematics estimation in physics analyses

    + one more data-driven (from day-to-day alignment differences) + 2 MC-based (residual misalignments)
- New challenges with new PXD
  - Need much „faster“ alignment if the beam conditions keep changing frequently
  - 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!

Belle II

BACKUP

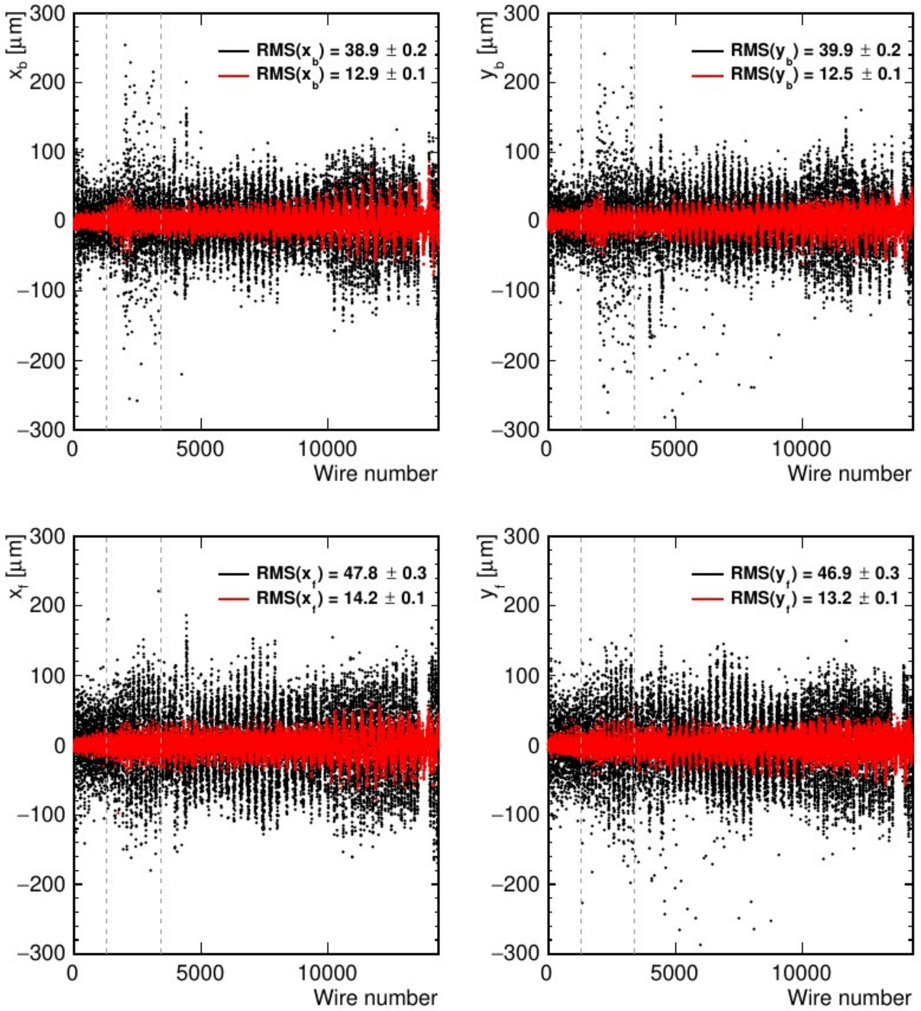
Full scale MC tests with misaligned wires

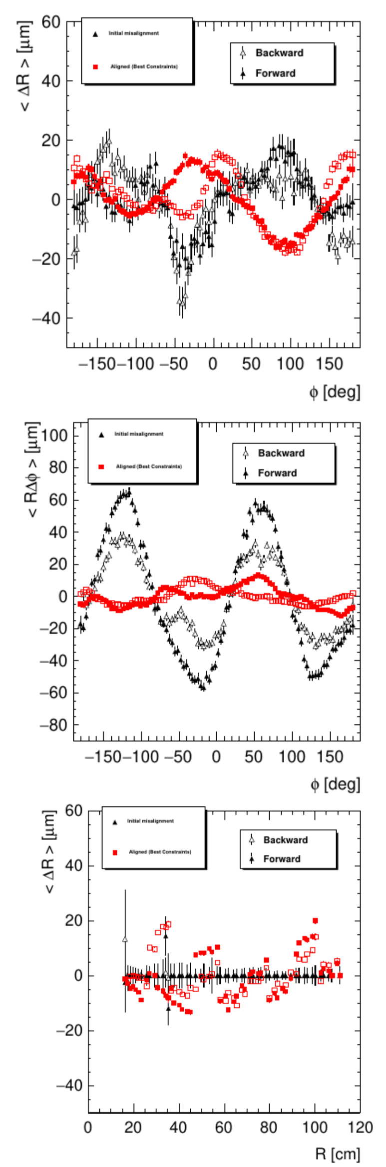
Black: initial realistic misalignment

Red: remaining residual misalignment

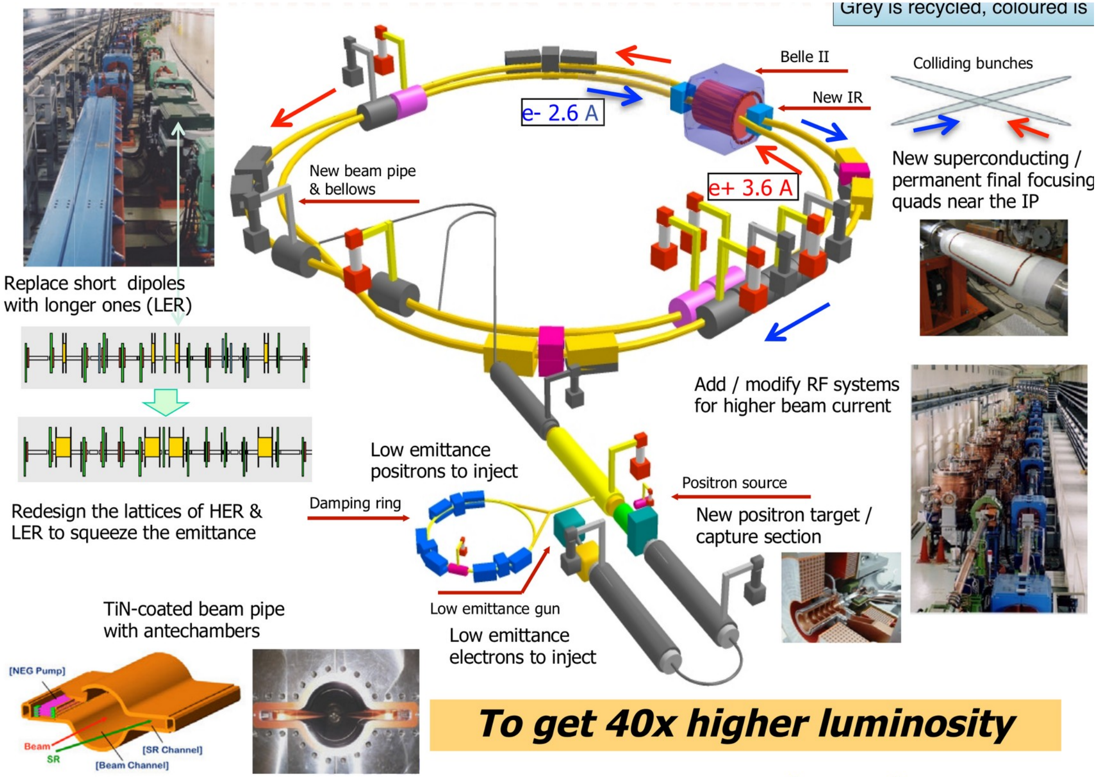
Can recover from a realistic wire misalignment to negligible residual misalignment in a single iteration!

First use of decomposition solution method in Millepede





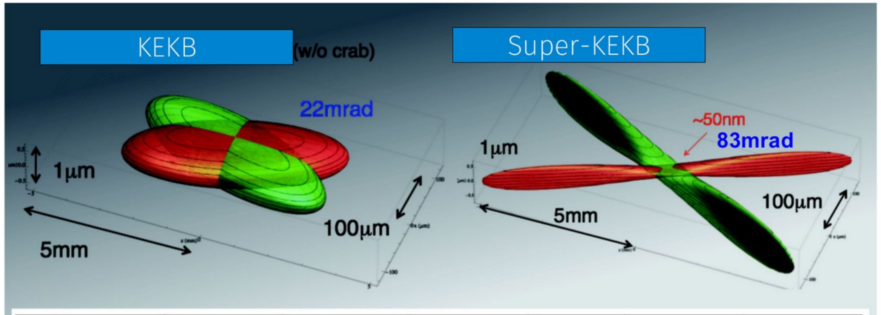
KEKB → SuperKEKB



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



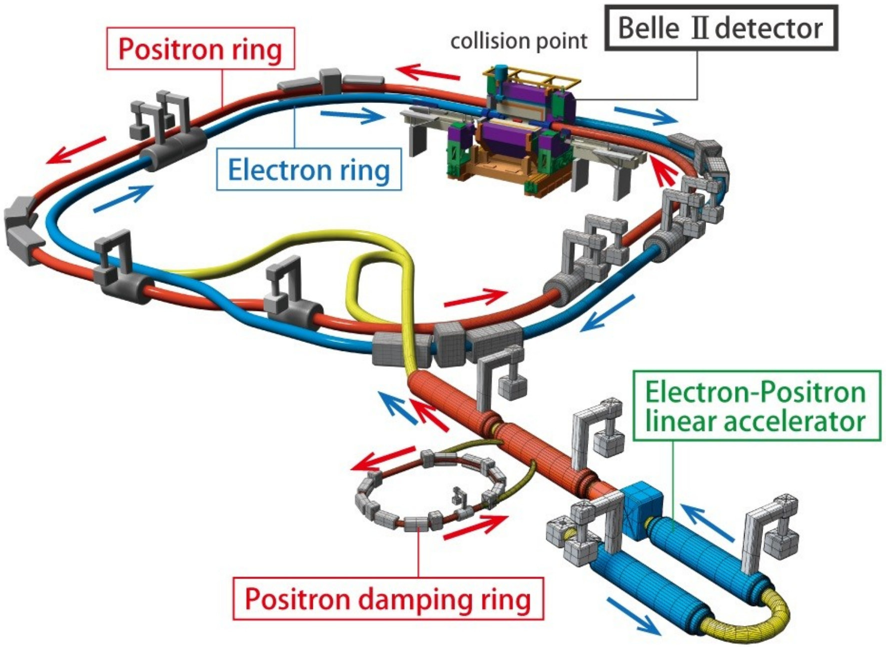
	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

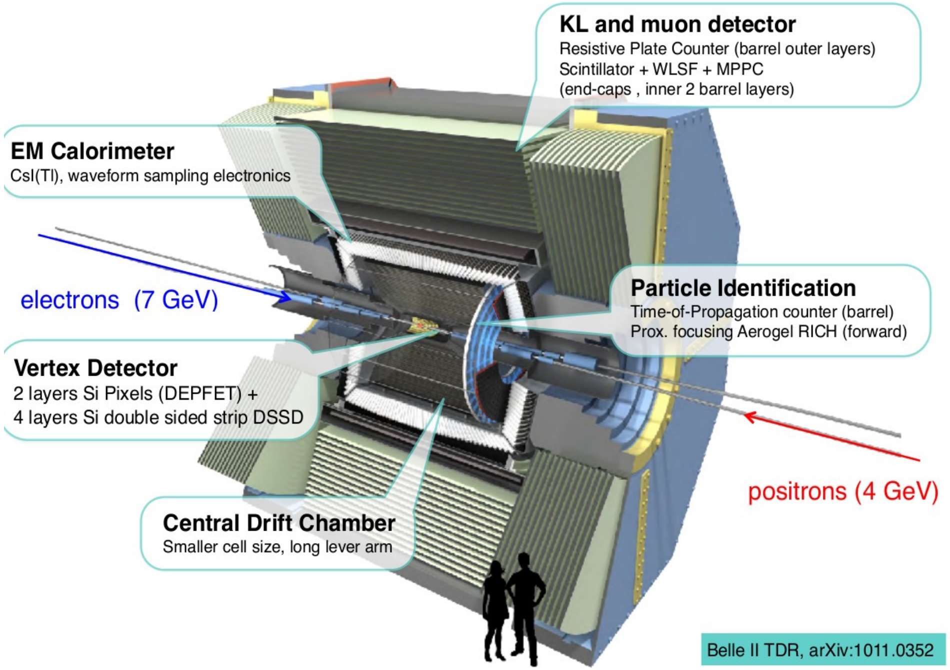
factor 20

factor 2-3

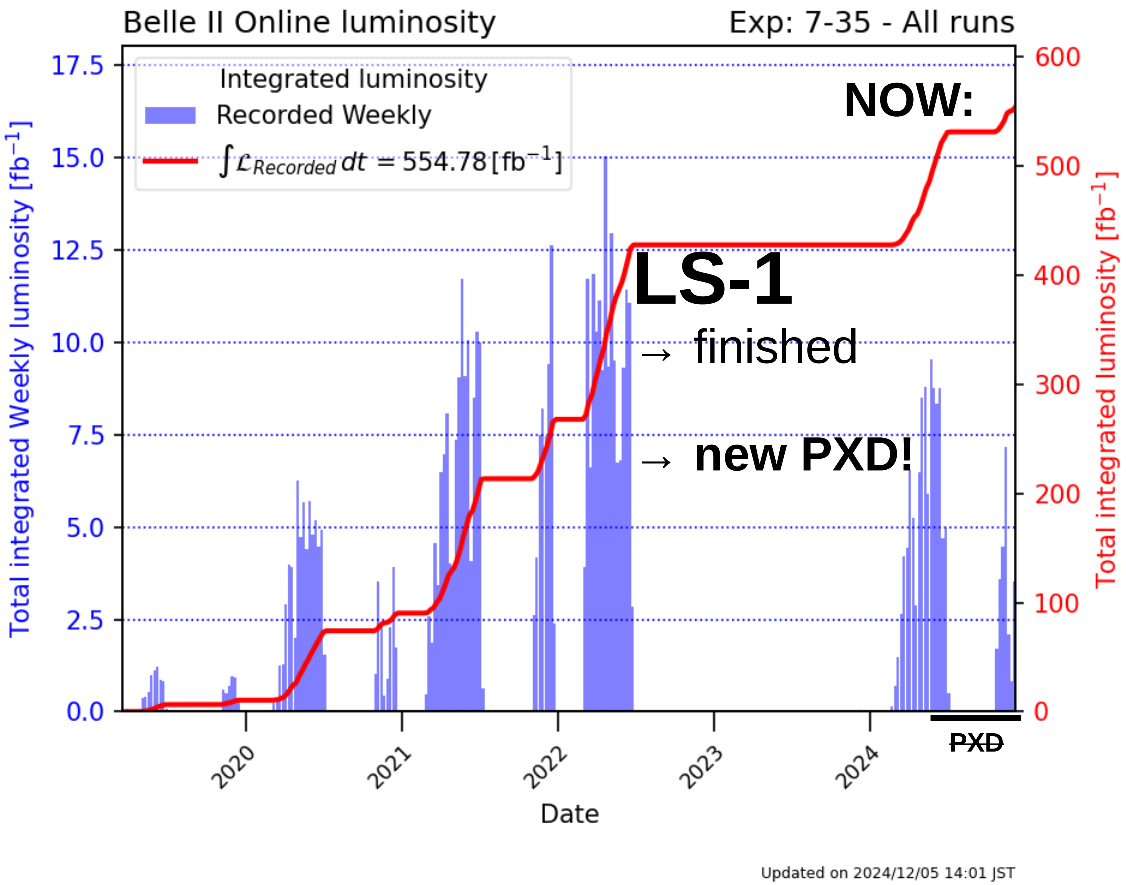
SuperKEKB & Belle II

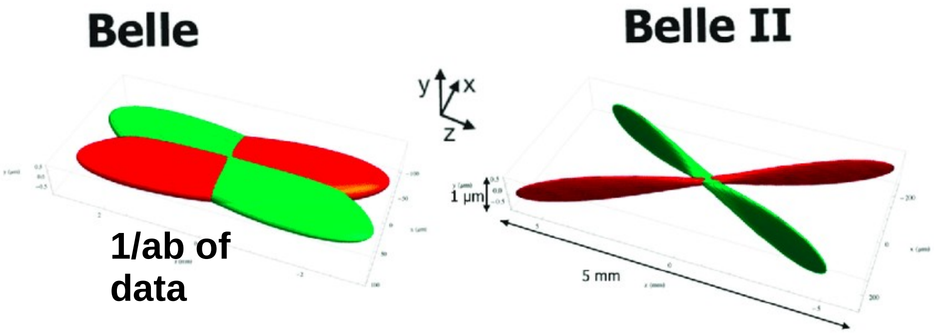
- Upgrade of KEKB & Belle, taking physics data since 2019
- Worlds‘ highest luminosity electron-positron collider (KEK, Tsukuba, Japan) at Upsilon(4S) resonance → B physics, D physics, tau physics …

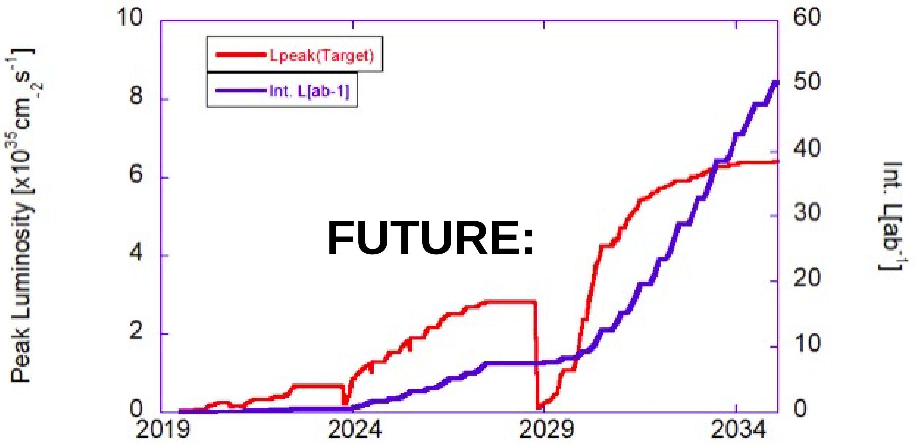




Past, Present, and Future



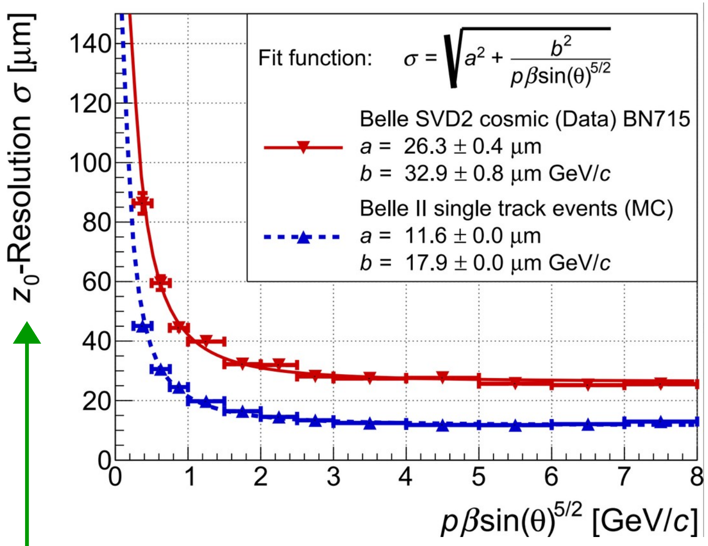




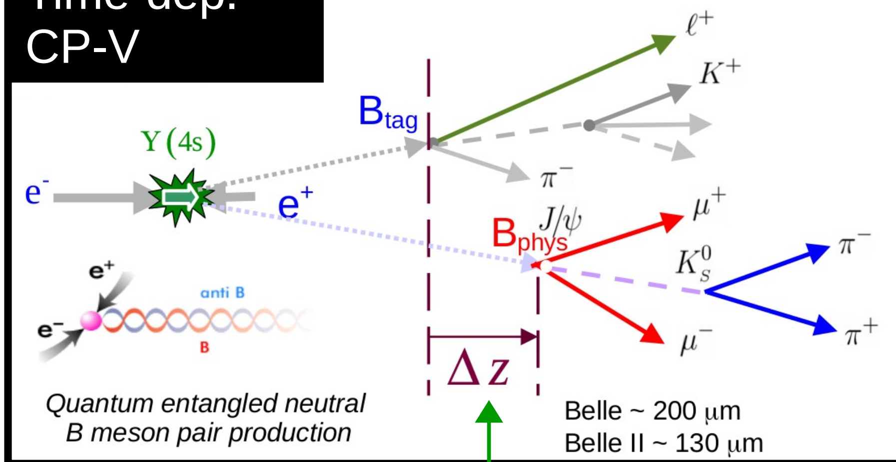
Systematic errors will start to dominate measurement precisions for many analyses

Precision @ Belle II: low-momentum compared to CMS

Just two examples...



Time-dep. CP-V



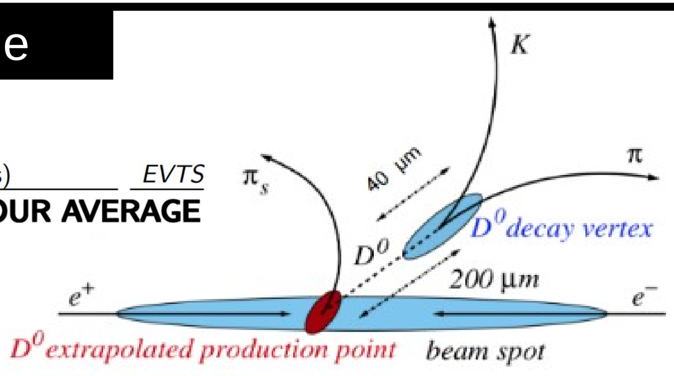
Alignment precision at level of micrometers needed

Advanced track-based (time-dependent) alignment

D^0 lifetime

PDG:

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

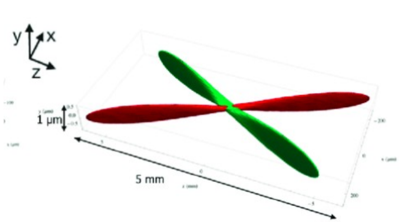


Belle II Alignment Parameters: 2/2

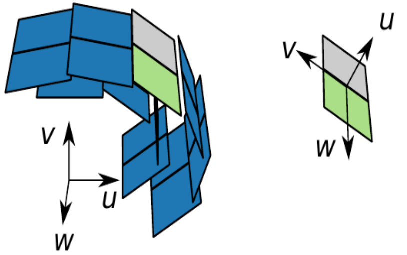
Relative positions of sub-detectors and larger structures*

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

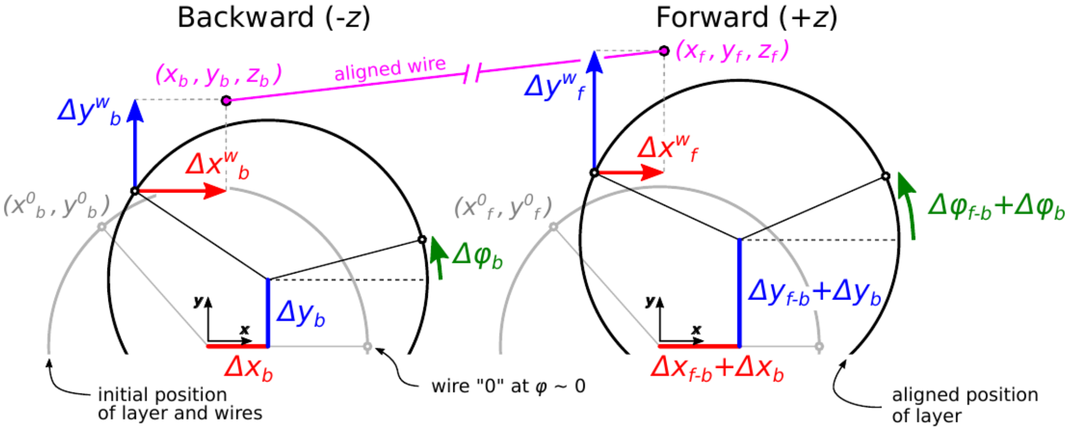
IP position



VXD half-shells and ladders



CDC layers



sub-detector	alignable elements	alignment parameters	$\sum$ 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

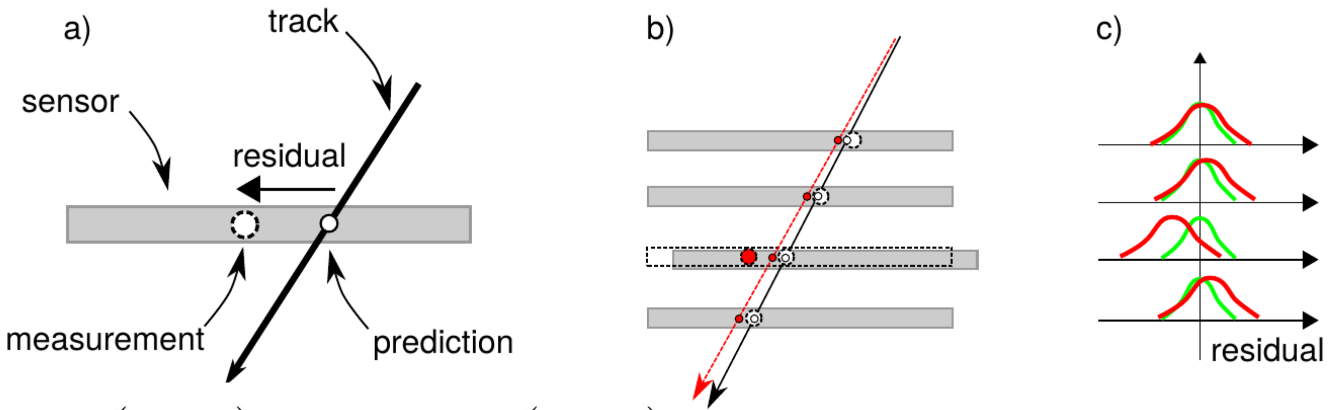
Alignment of all degrees of freedom should be done simultaneously → Millepede II !!!

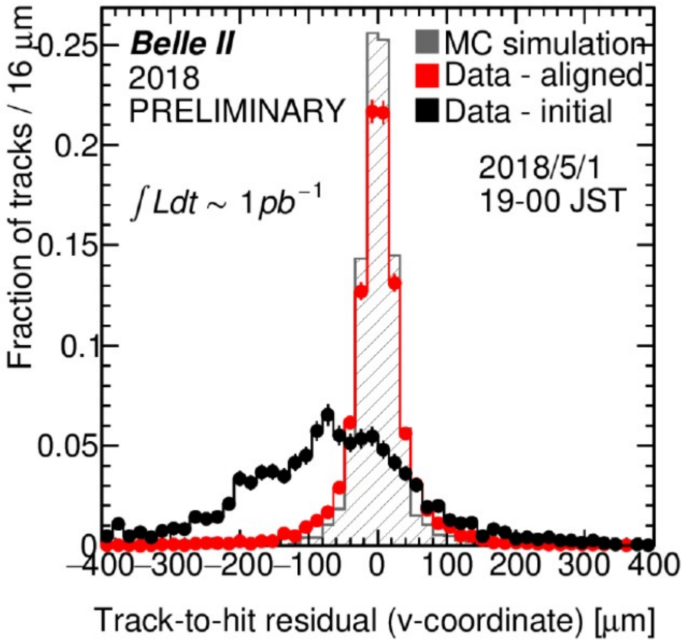
*Redundant DoFs removed by linear equality constraints

Track-based alignment

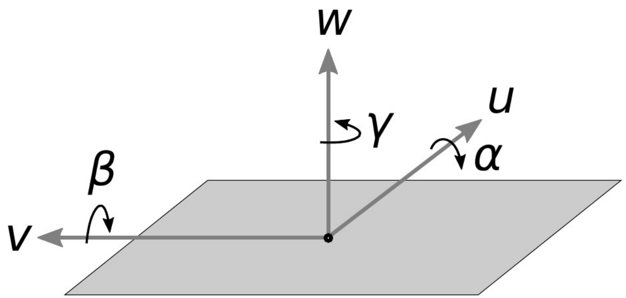
Detection elements not in assumed positions/orientations/…

→ biased measurements & sub-optimal **residuals**





$$r_{ij}(\boldsymbol{a}, \boldsymbol{q}_j) = m_{ij} - p_{ij}(\boldsymbol{a}, \boldsymbol{q}_j)$$

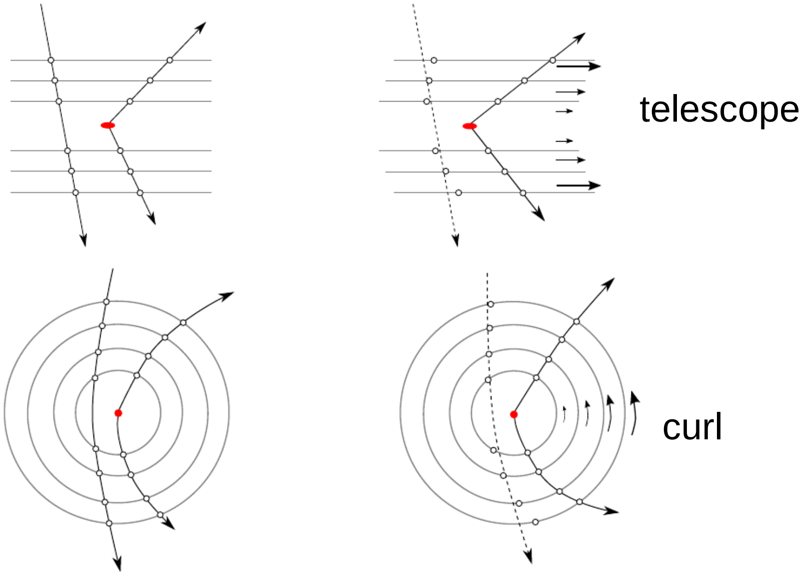


Estimate the geometry directly from the trajectories
→ minimize many millions of residuals!

$$\chi^2(\boldsymbol{a}, \boldsymbol{q}) = \boldsymbol{r}^\mathsf{T}(\boldsymbol{a}, \boldsymbol{q})\boldsymbol{V}^{-1}\boldsymbol{r}(\boldsymbol{a}, \boldsymbol{q}) \quad \to \text{min}$$

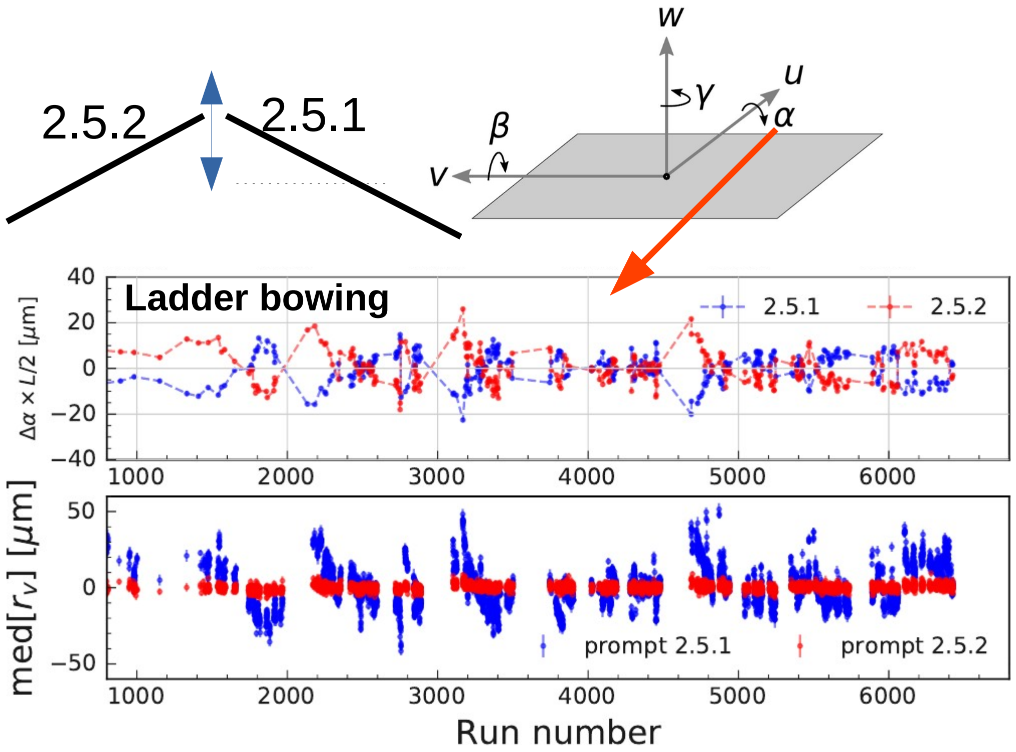
Alignment Challenges

- Weak Modes
  - (some) data not sensitive to (some) deformations

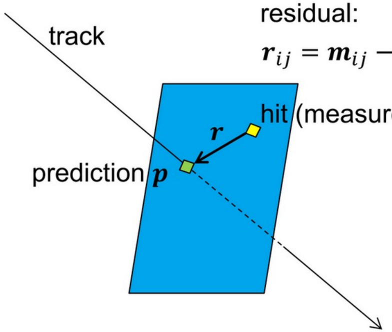


- Detector&reco model issues
  - e.g. imperfect magnetic field description

- Time-dependence
  - Detector not stable, many effects at play



Alignment Algorithm: Millepede II



residual:
$\boldsymbol{r}_{ij} = \boldsymbol{m}_{ij} - \boldsymbol{p}_{ij}(\boldsymbol{g}, \boldsymbol{l}_j)$

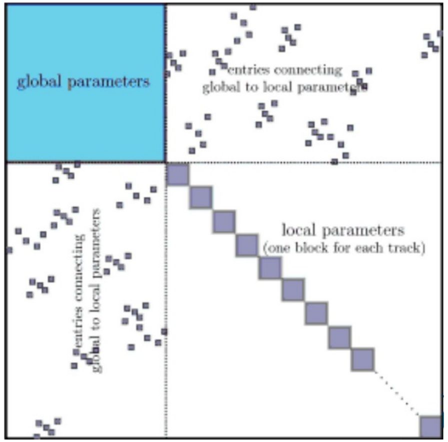
hit (measurement $\boldsymbol{m}$)

Minimize over all parameters:

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

$\boldsymbol{g}$ ... alignment parameters (global)
$\boldsymbol{l}_j$ ... track parameters (local)

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

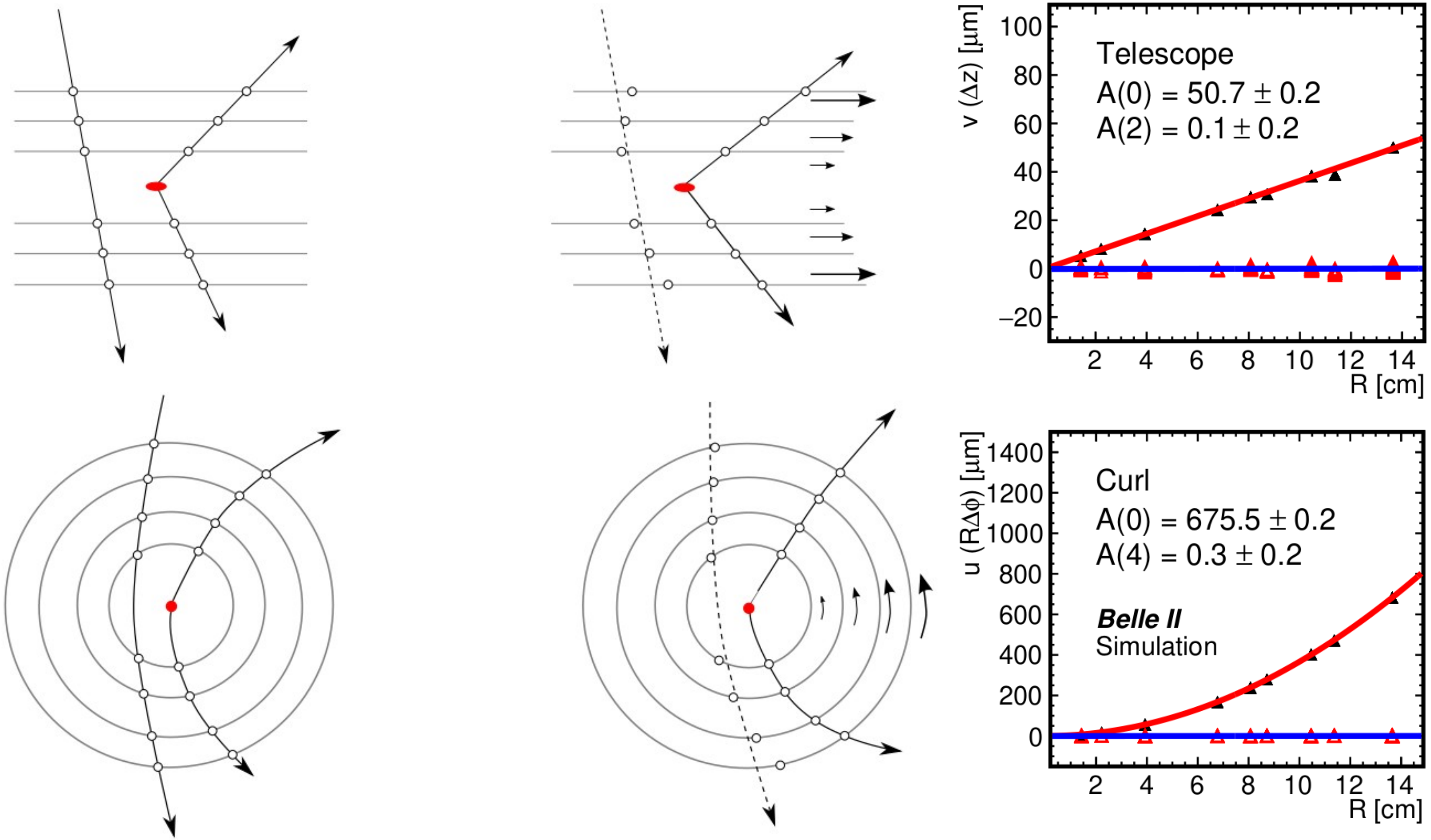
Time in minutes. Table from C. Kleinwort

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

https://www.terascale.de/wiki/millepede_ii/
https://helmholtz.software/software/millepede-ii

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

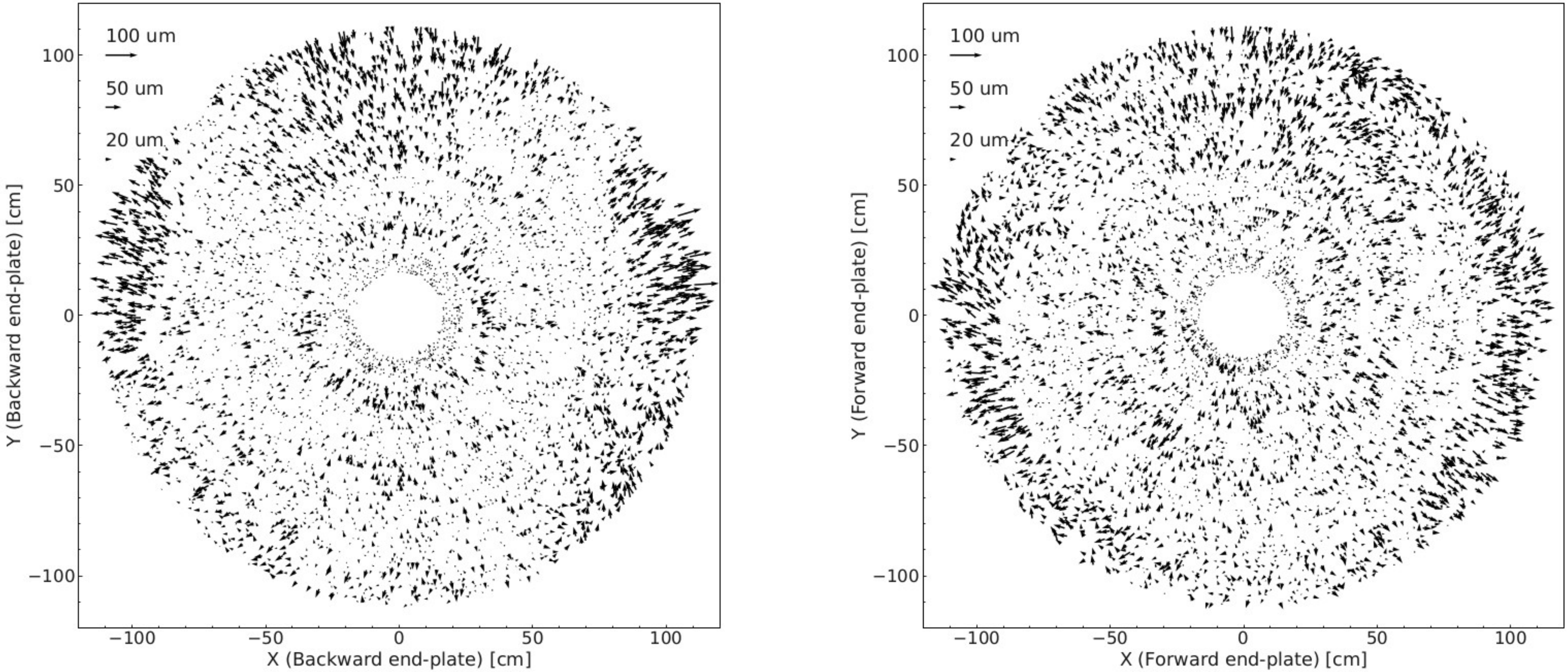
Reducing weak modes with rich track topology



VXD deformation before alignment...

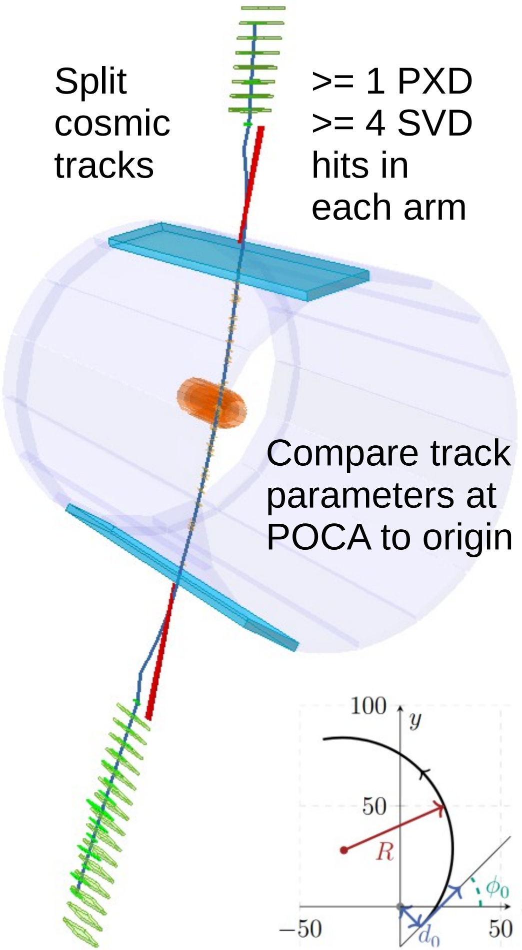
...and after

Residual wire misalignment in MC



Only 20% randomly selected wires shown

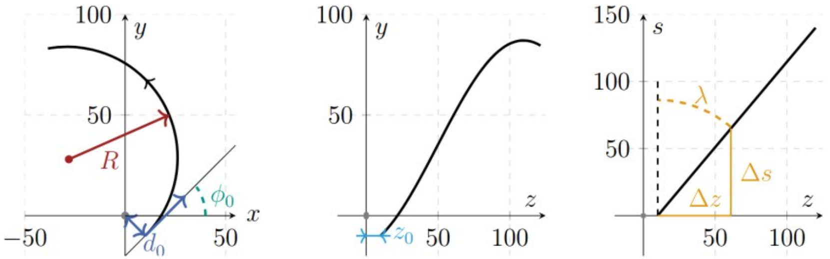
Cosmic Validation with PXD+SVD+CDC

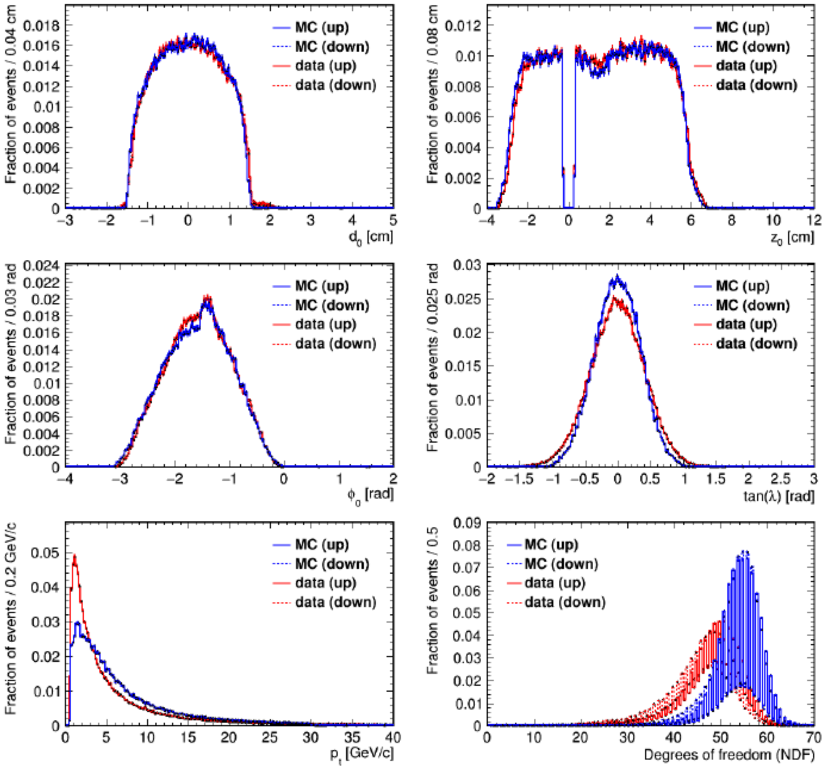


MC with bkg. overlay for exp12

All data from exp12

Both about 130k full tracks

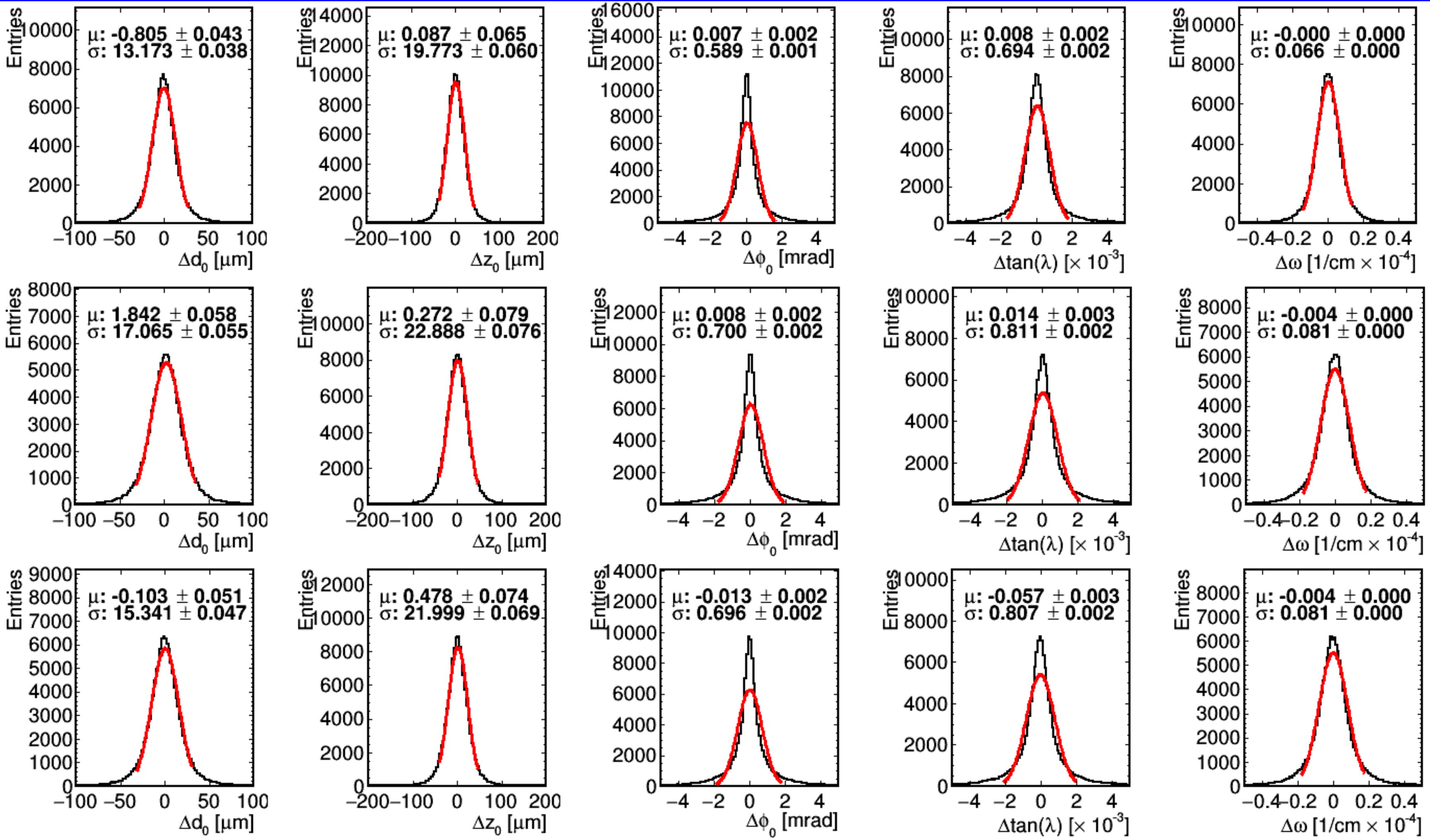




Distributions for transverse momentum and number of CDC hits are slightly different

Helix Parameter Resolutions

selection="abs(Z01)>0.5 && abs(Z02)>0.5 && Pt1>0.6 &&Pt2>0.6"

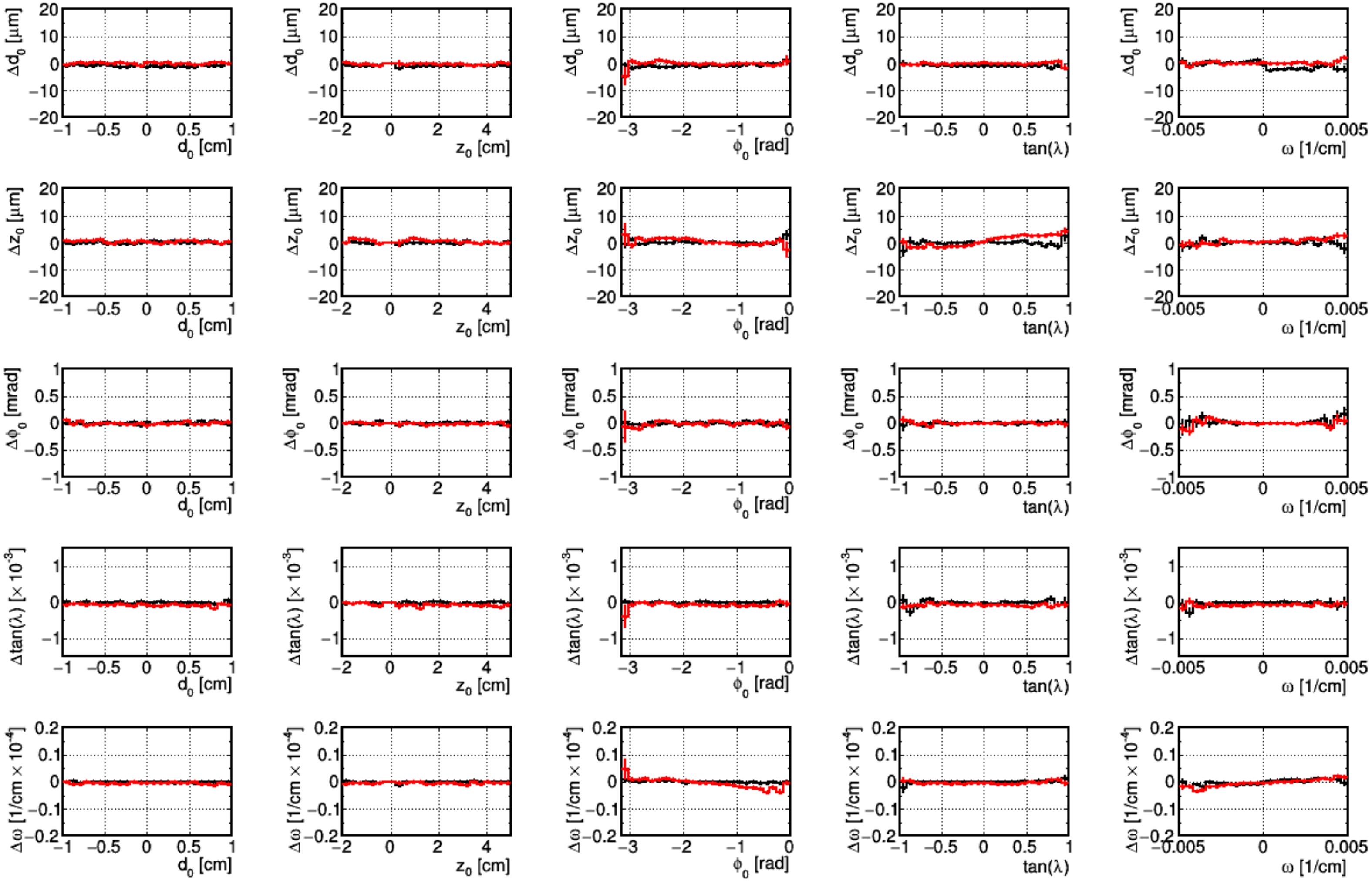


MC

Prompt exp12

Proc12 exp12

Correlation of helix parameter biases: MC vs proc12



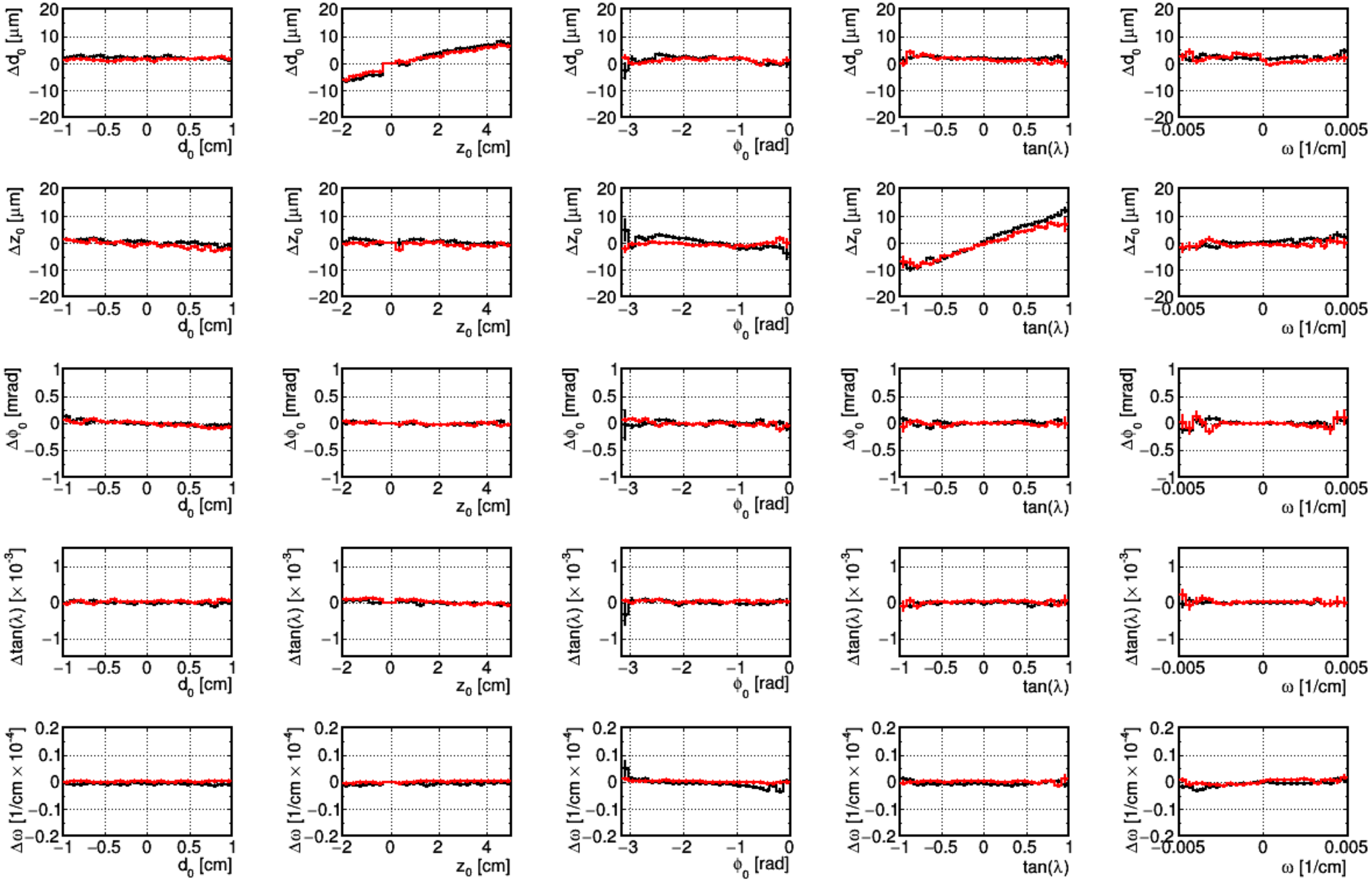
Slight slope in z_0 vs tan(lambda) remains, but reduced significantly from prompt (see next slide)

MC

Proc12 exp12

Correlation of helix parameter biases: Conservative misalignment

Old prompt alignment vs MC with misalignment = largest misalignment scenario (of 4) used for alignment systematics estimation by physics analyses



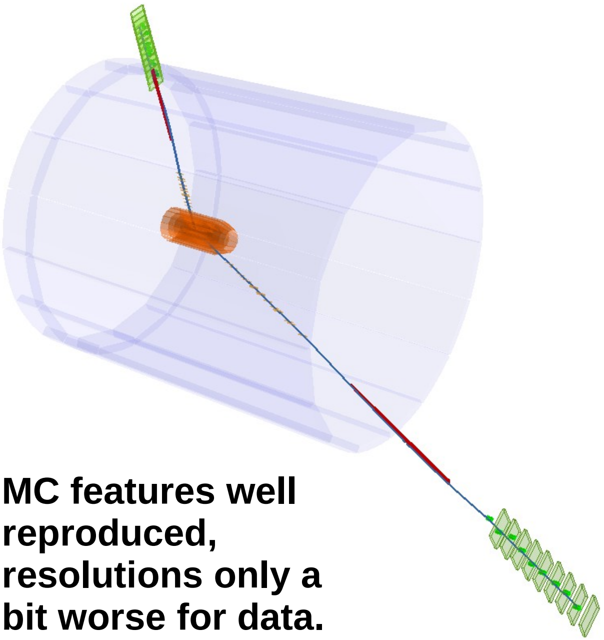
Bias and correlation reproduced

Main correlation well reproduced

Prompt exp12

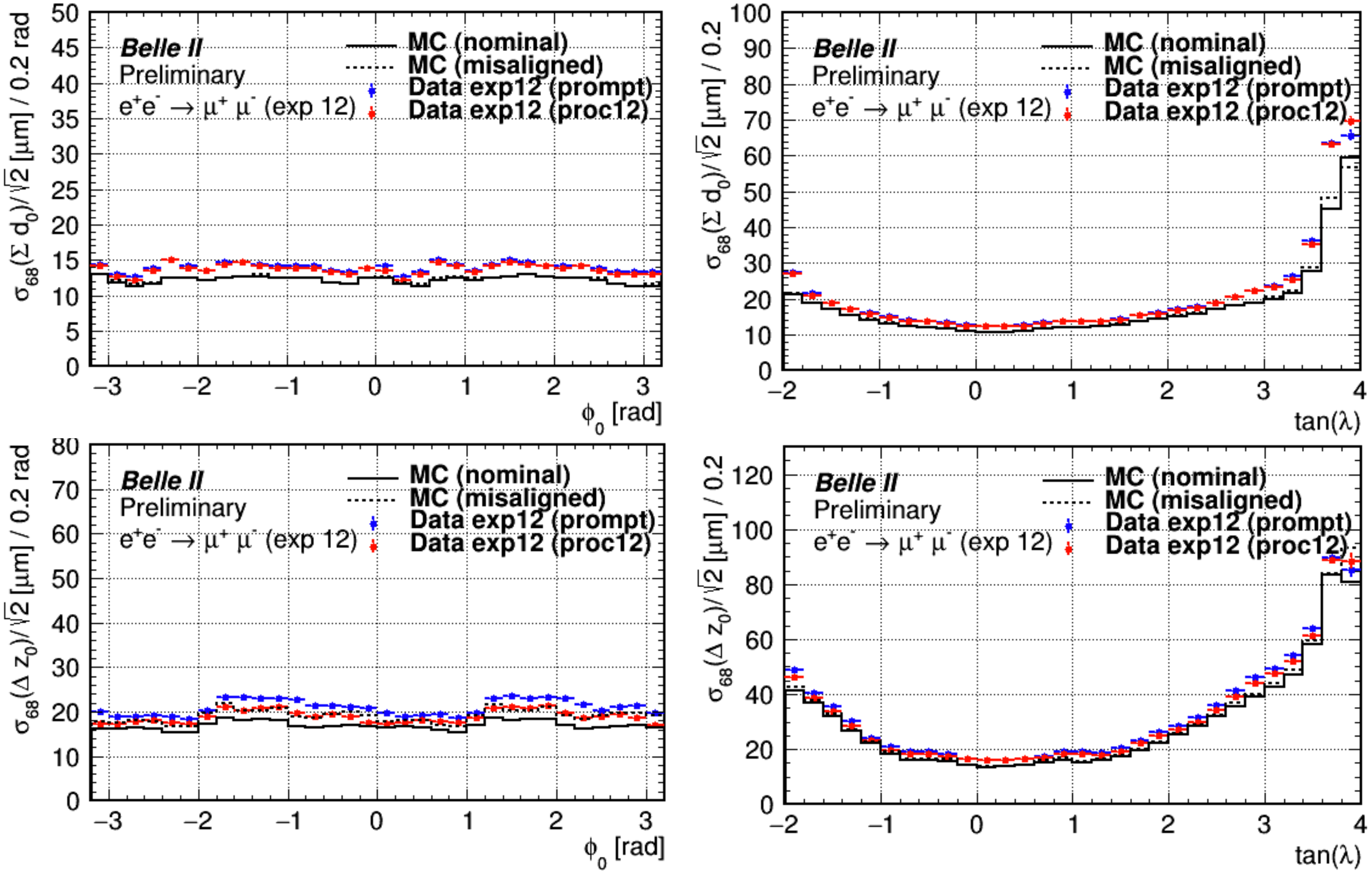
MC With Misal.

Validation with Dimuons: Angular dep. of vertex resolutions



MC features well reproduced, resolutions only a bit worse for data.

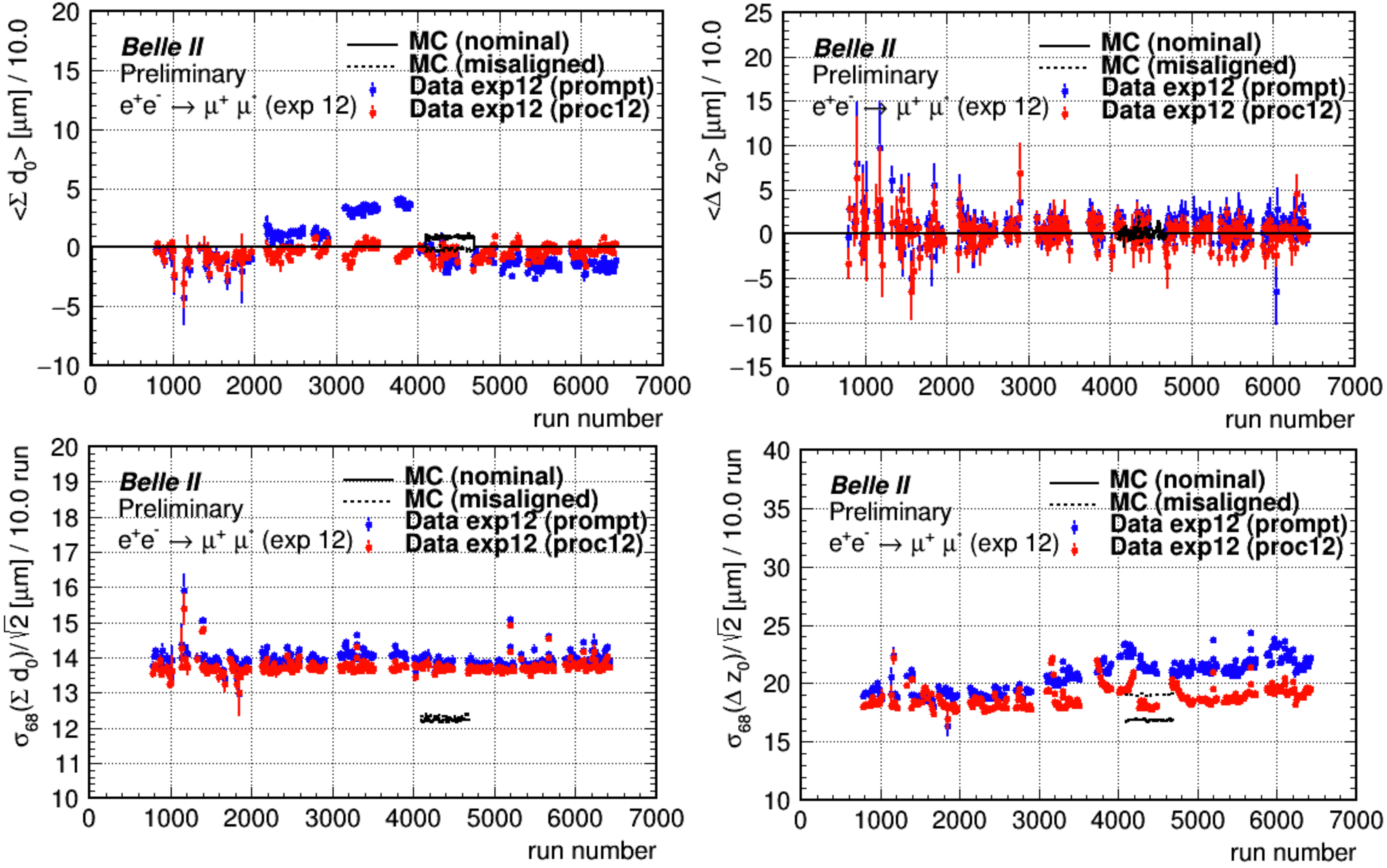
Offset in d_0 resolution related to (old) optimistic SVD simulation



Angles for positive-charge muon candidate

Run dependence of vertex parameter biases and resolutions with dimuons

MC withut background

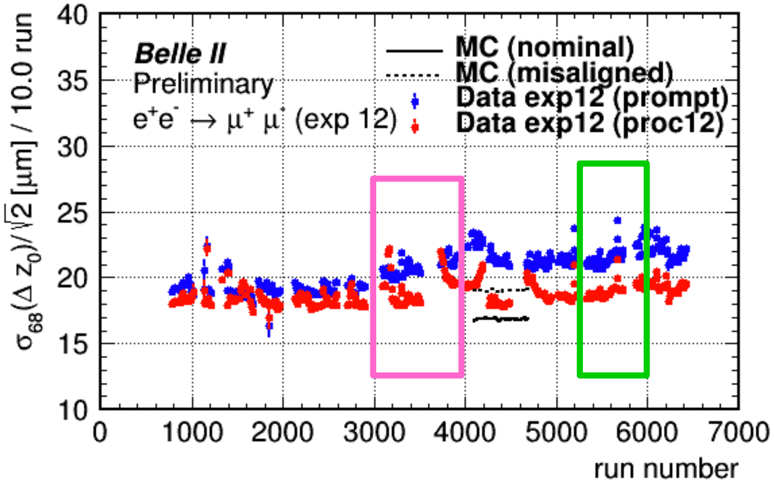


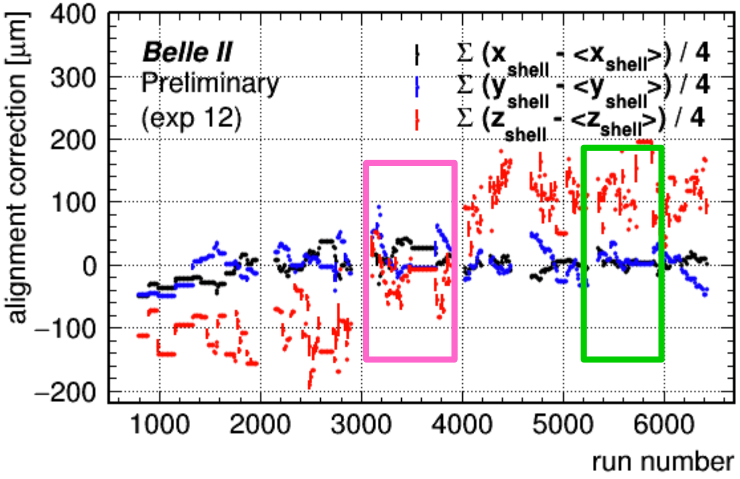
Significant improvement in d0 time-dependent biases. Not much can be seen in z0 (good average already at prompt)

Resolutions improved in proc12

Remaining time-dependence in z0 resolution **probably caused by residual SVD movements – long relaxation (days) after QCS on/off?**

Residual SVD time-dependence after major events



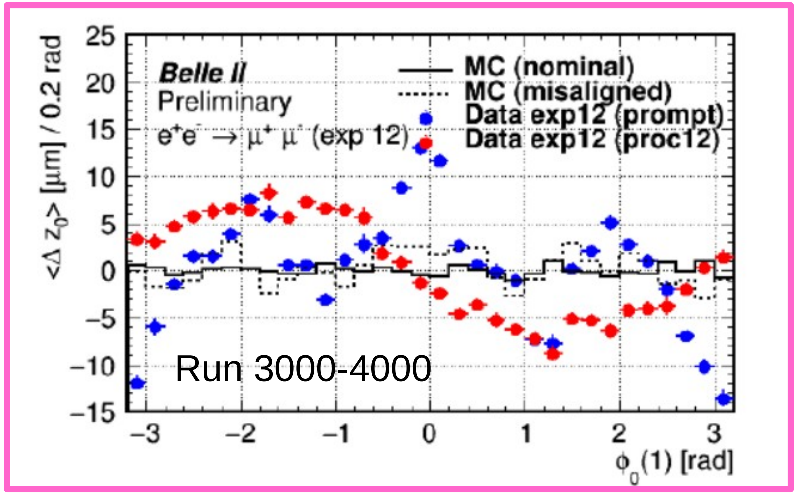


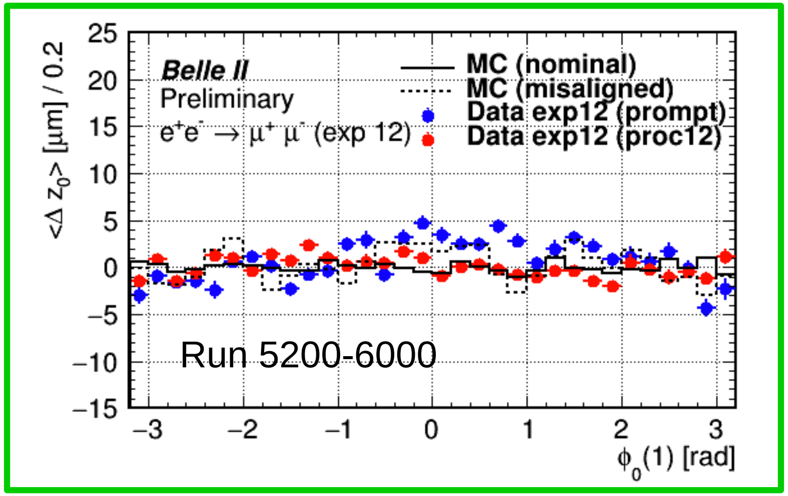
It seems the major remaining bias comes from a „typical“ deformation in **SVD**: Not corrected, because SVD sensors are aligned once per bucket (shells each run)

Big step upwards in CDC deformation – VXD follows, but something more happens for SVD.

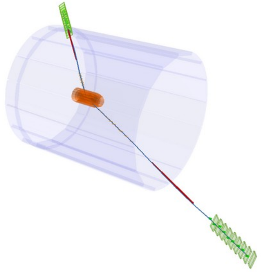
This is followed by continuous relaxation over several days… bad!!

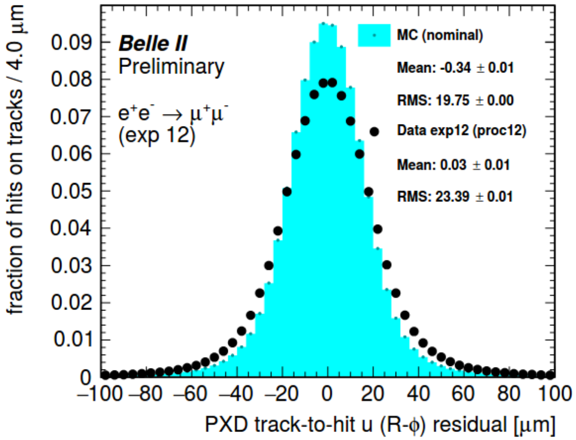
Looks a bit like ladders shifting in z (5-10um in L3, maybe 20um in L4+, but not consistently

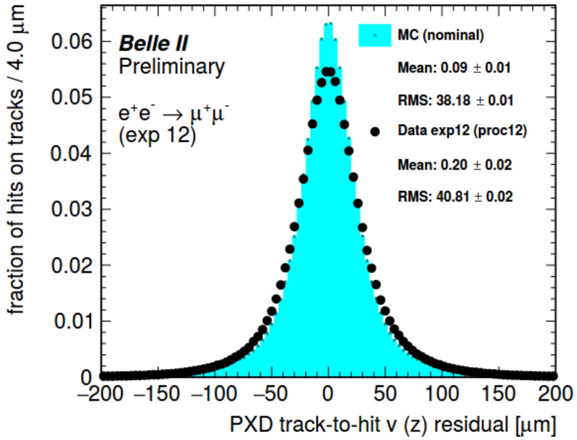


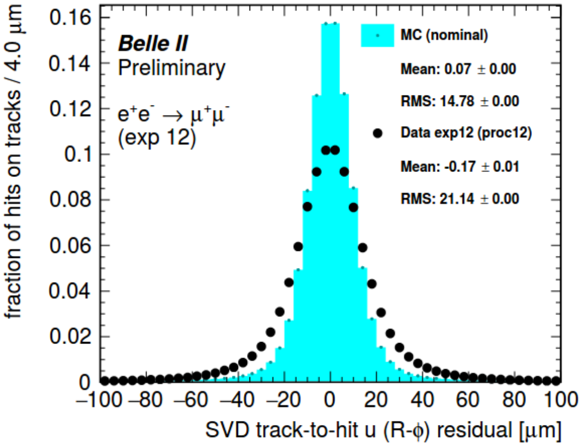


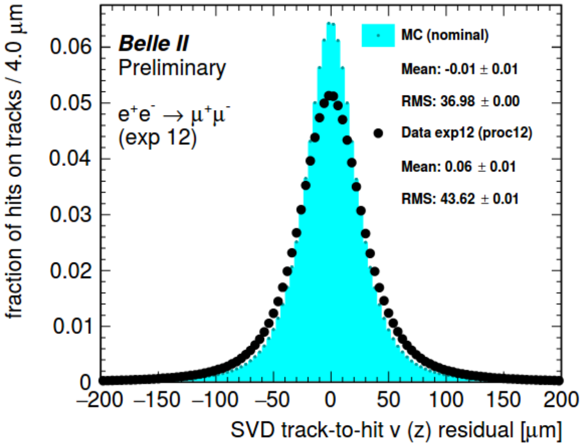
Alignment basics: residuals











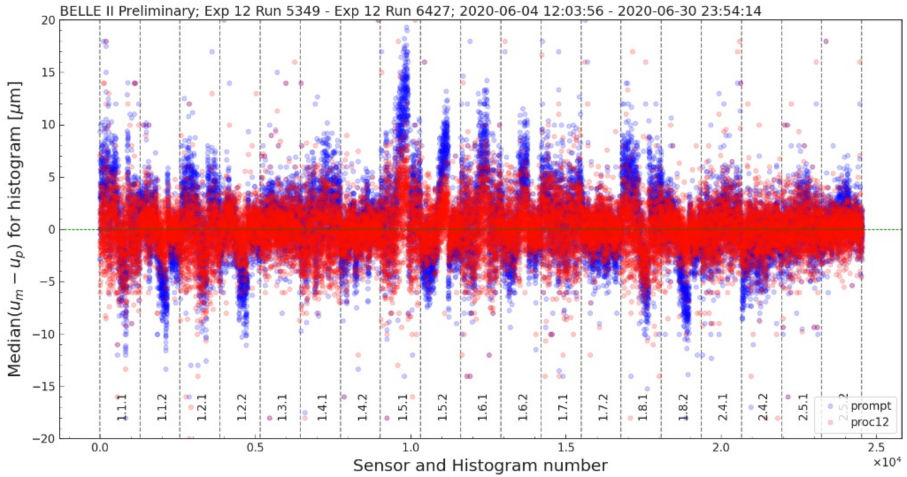
Integrated over all PXD/SVD sensors and mumu_tight skim files used for exp12 alignment validation

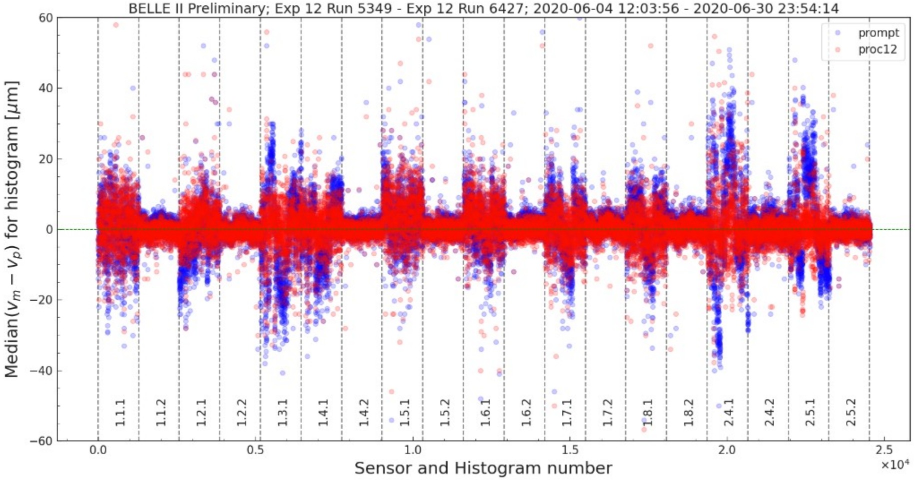
Much larger discrepancy for „u“ probably comes from SVD

Intrinsic SVD sensor resolutions too optimistic on older MC – new MC simulation will address this

Cannot be caused by any kind of misalignment (confirmed)

PXD Alignment evolution in exp12 reprocessing



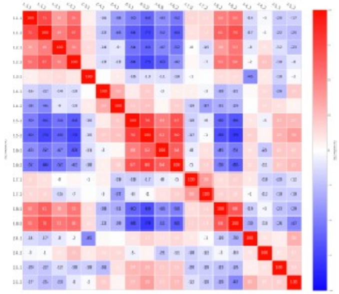


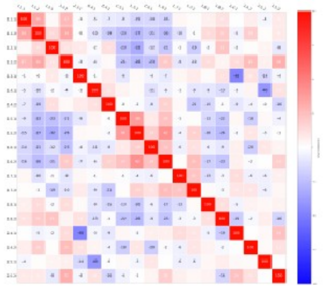
Even with this granularity (about 0.1/fb), alignment sometimes not fast enough to follow all movements

In U-direction, the remaining effects seem negligible

V-direction is worse and forward sensor more affected (due to track&detector topology)

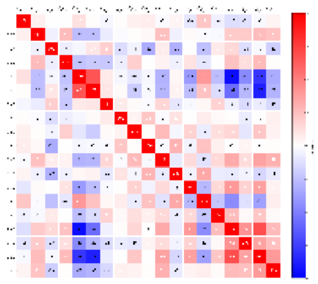
Correlations of residuals

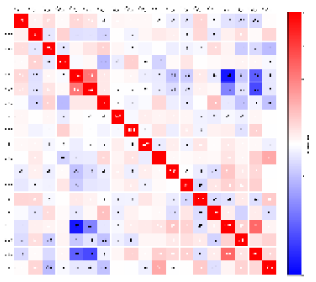




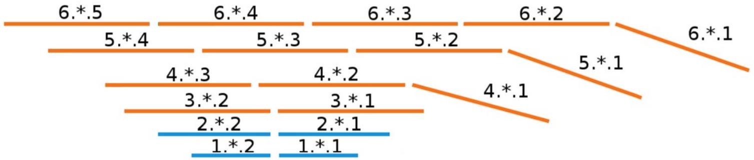
prompt

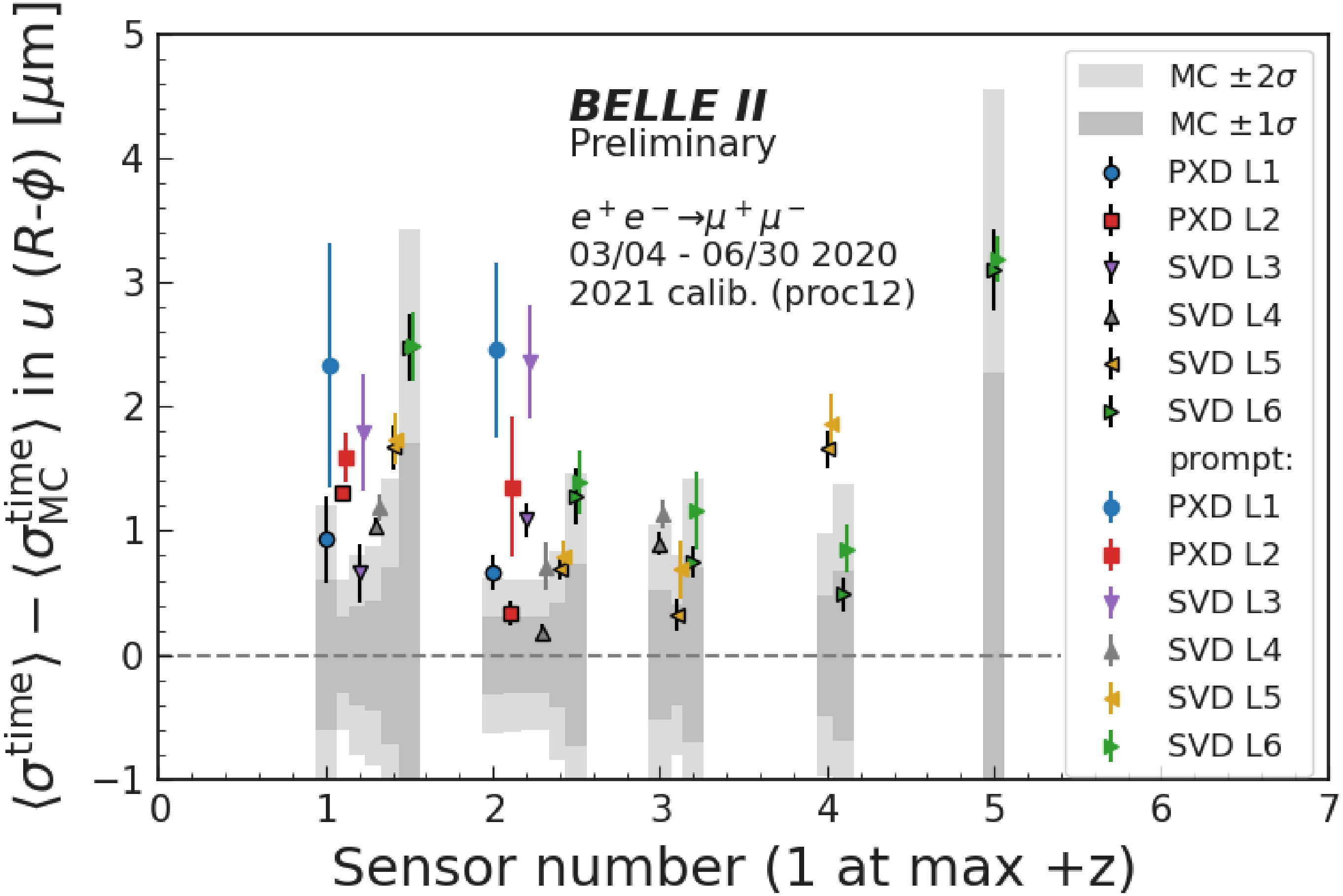
proc12



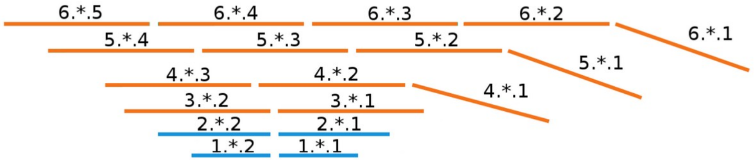


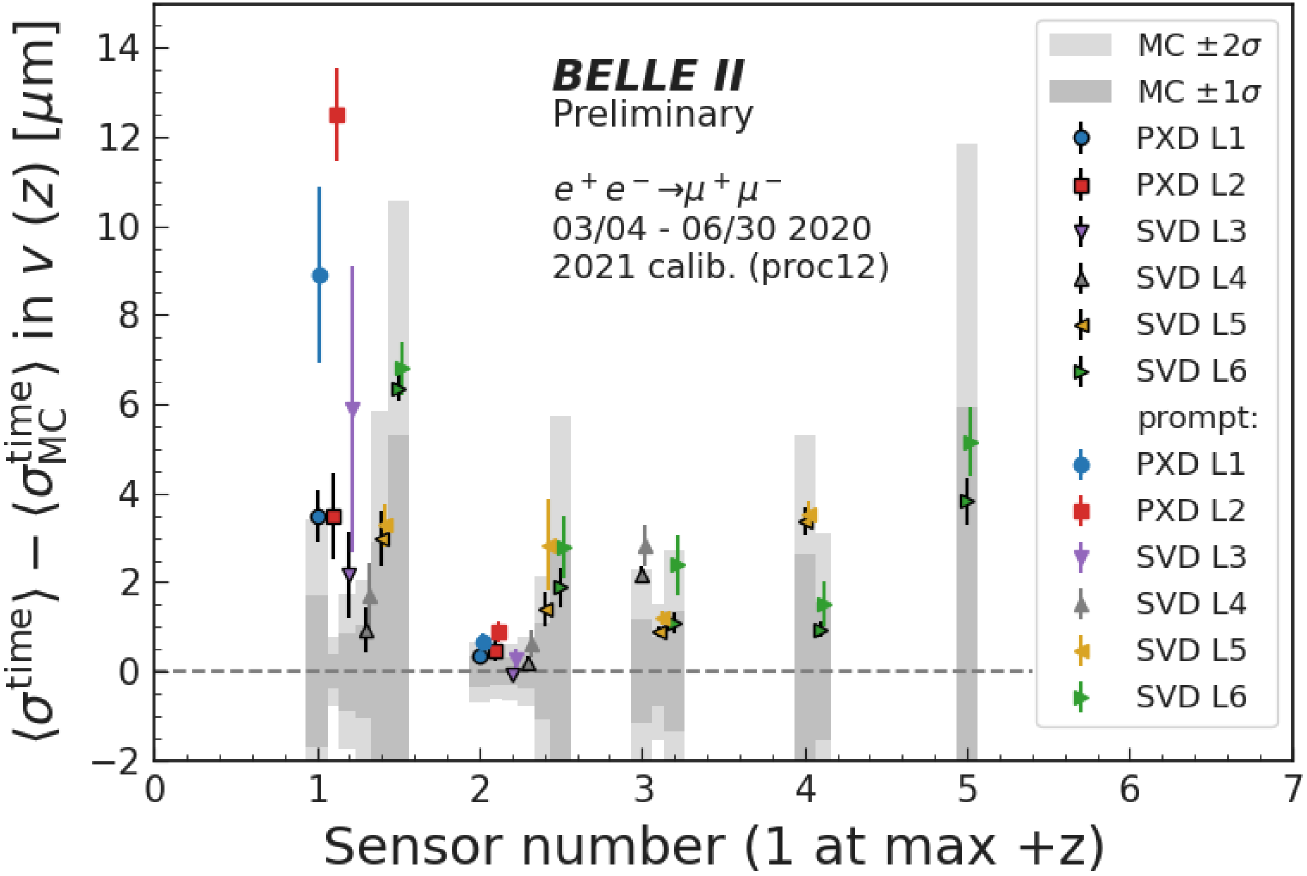
Instability in U



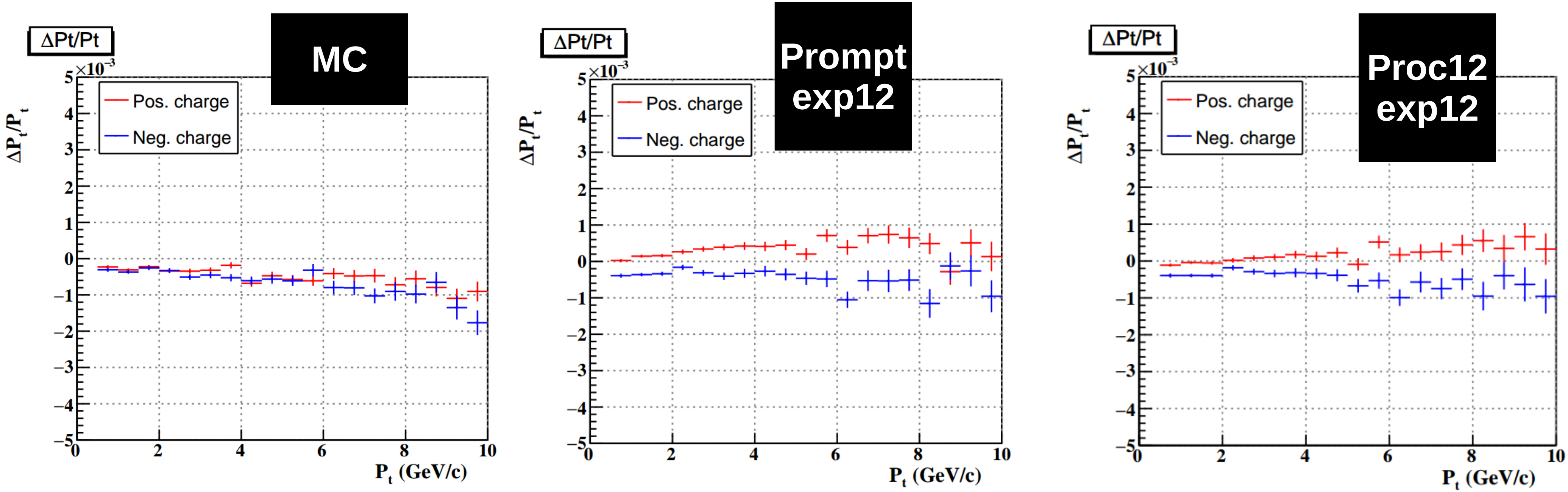


Instability in V





Charge-dependent momentum biases for cosmics



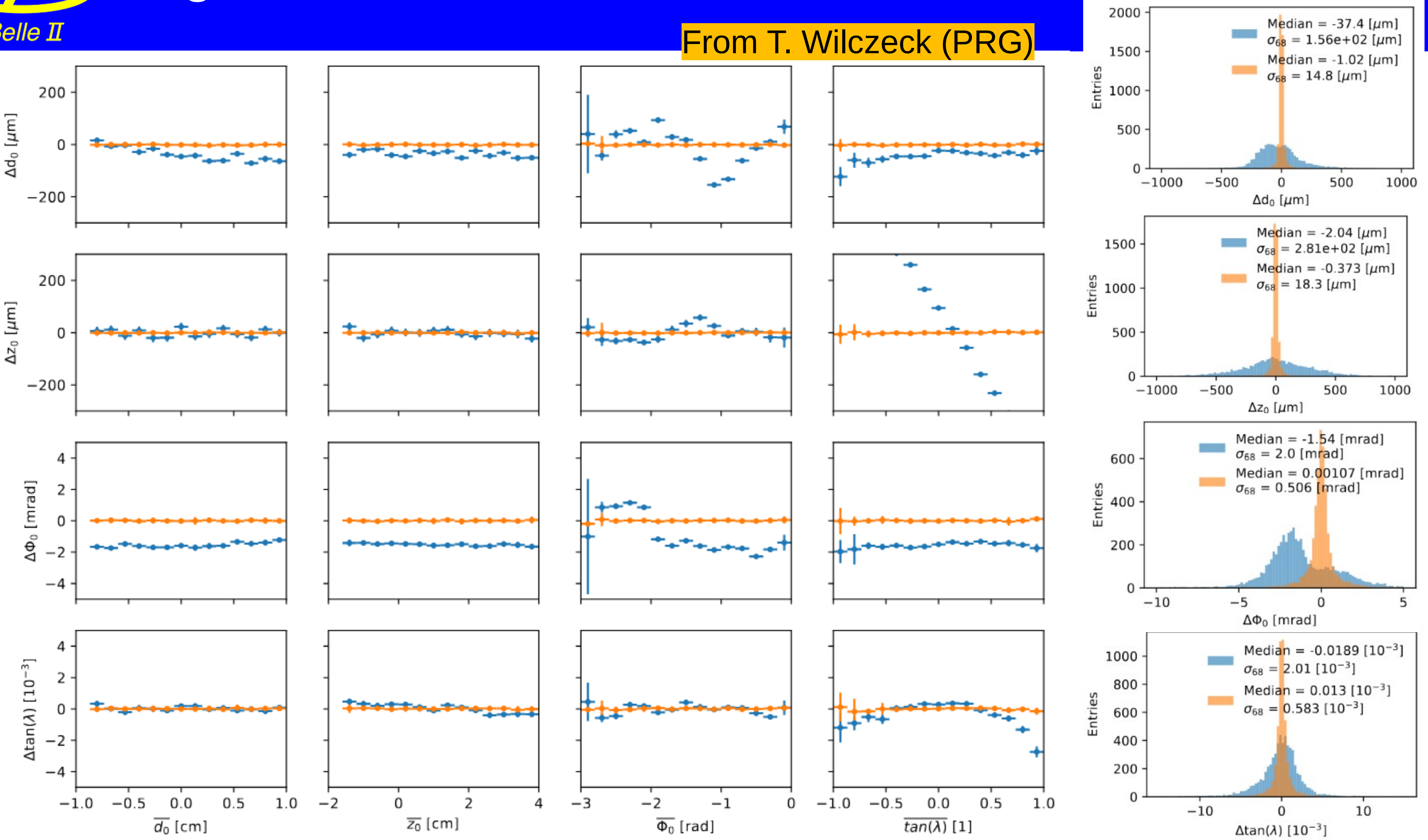
MC does have a larger bias, but not charge-dependent

It seems there is a residual twist caused by compensation of some inconsistencies (deformed CDC-endplates/ magnetic field description/?)

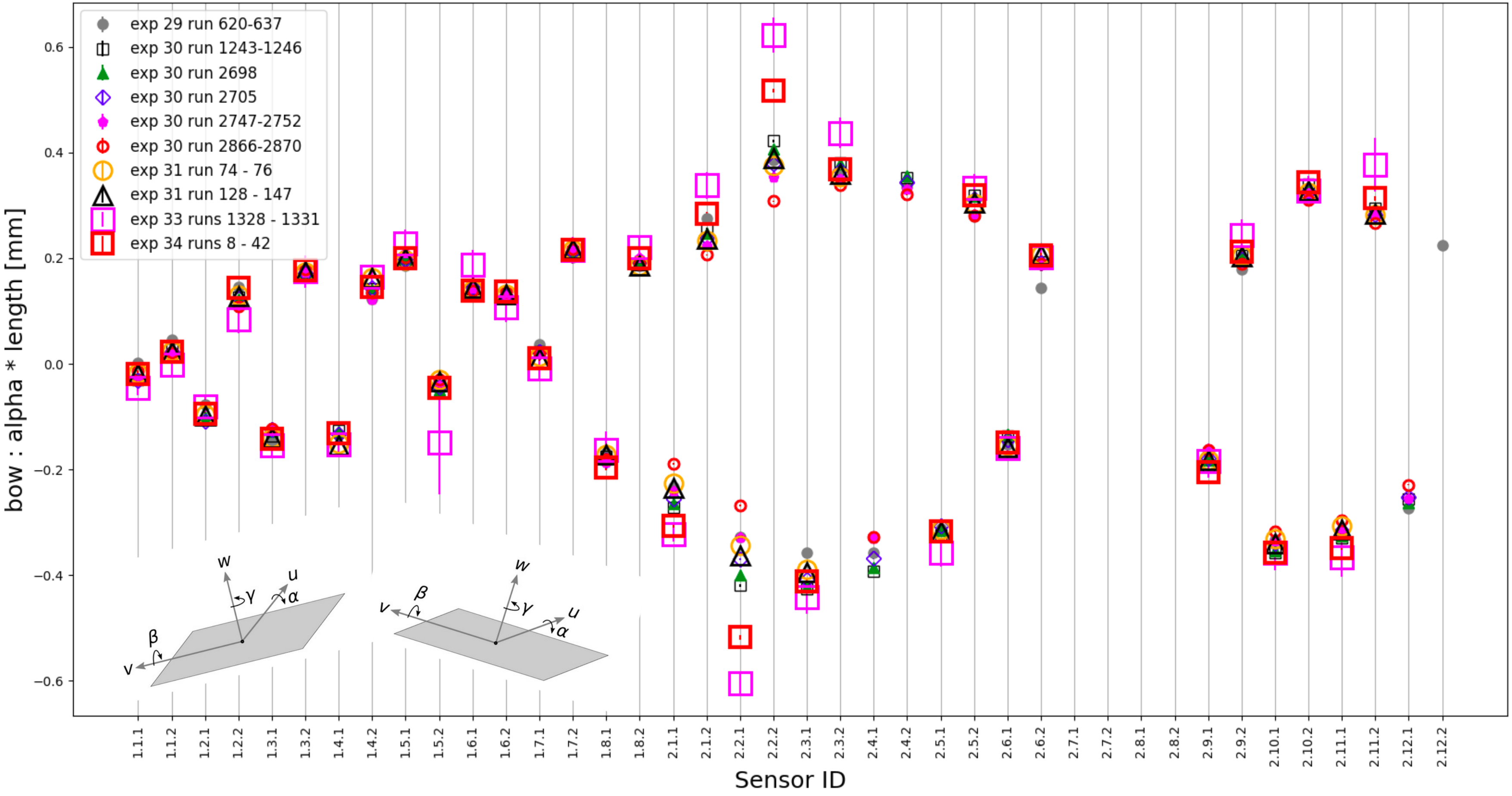
General small ($<10^{-3}$) problems with momentum biases (also vs. phi) might be related to compensation of problems beyond alignment (magnetic field / deformed CDC endplates / ...). Difficult to fix at alignment level (need better detector model). Solution: cos(theta) but also phi- and charge-dependent (sagitta) momentum corrections at analysis level.

Alignment & Performance with cosmics & B=0T

From T. Wilczeck (PRG)



PXD2 ladder bowing amplitude in different 2024 periods



Max bowing for operated ladders between 300–650 um.

Depends on beam currents (and which sensors are turned on)

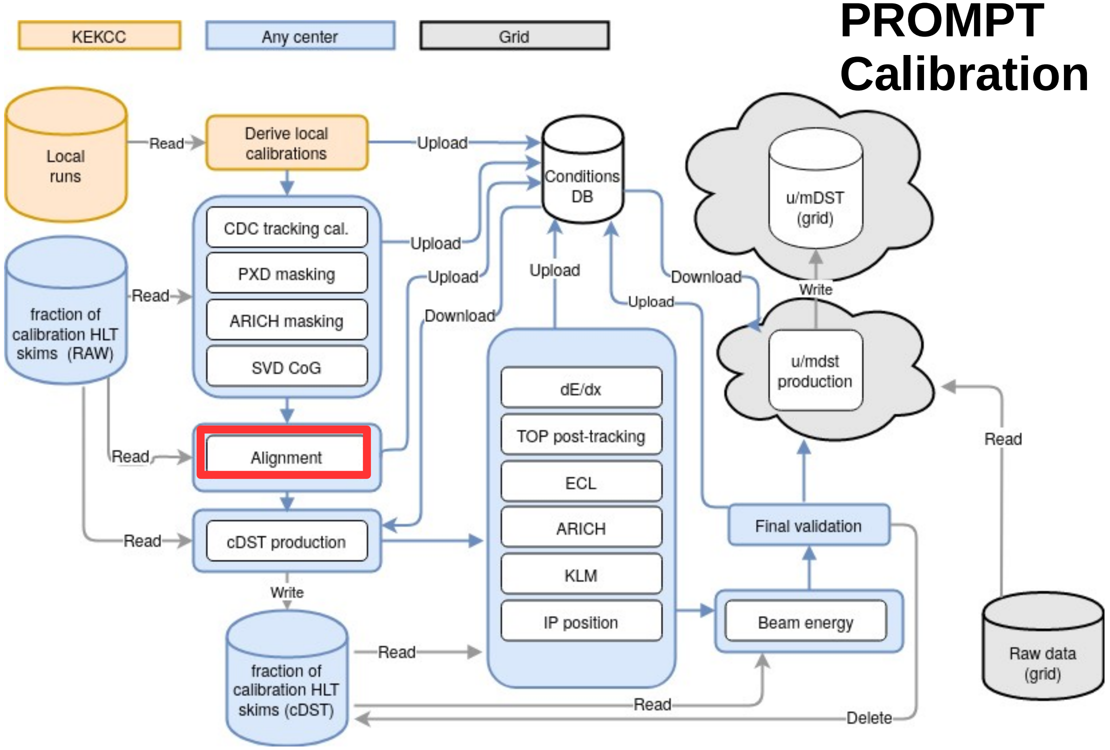
Two ladders with largest bowing turned off in beam operations :-(

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)

PROMPT Calibration



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

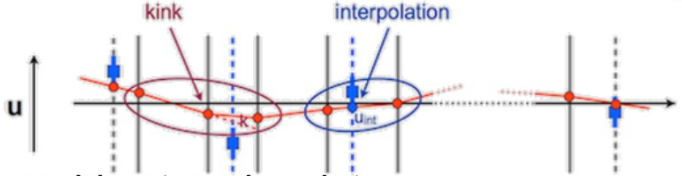
Belle II

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

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

- 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

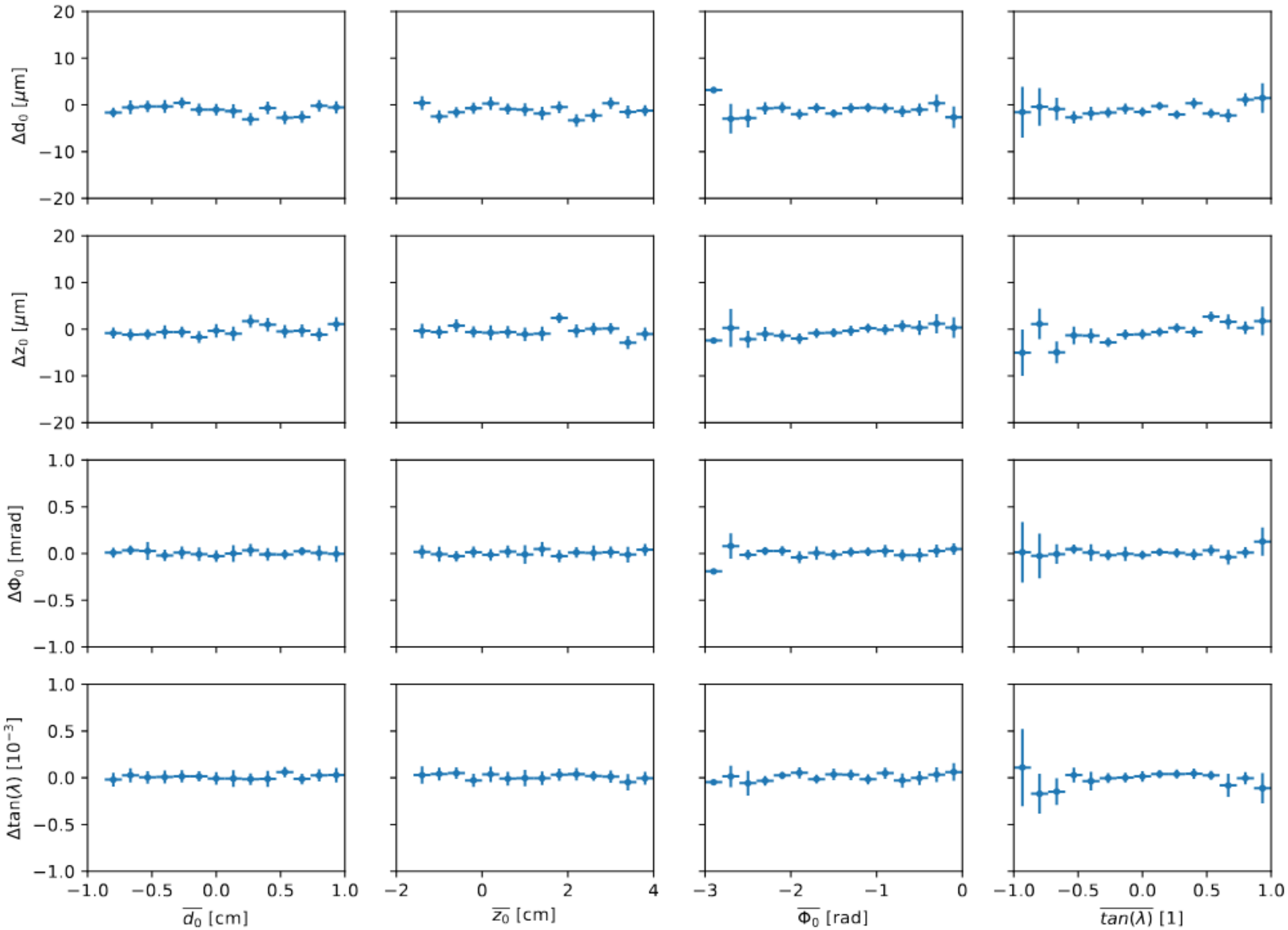
from kinks

- Interface to MP2

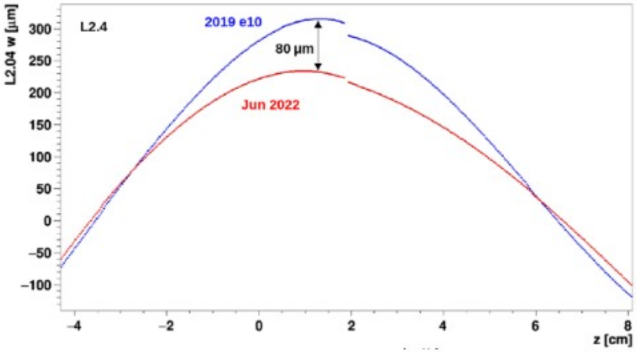
→ Integrated into GENFIT2 package
→ Profits from generic treatment of many different measurement types
→ Advanced treatment of material for multiple scattering estimation (thick scatterers)

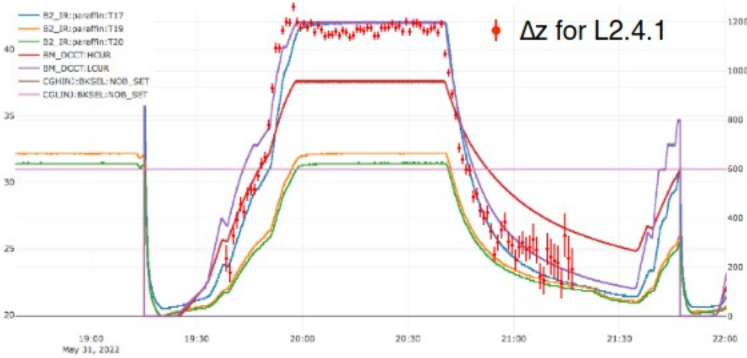
Performance with cosmics & B=0T (PXD2)

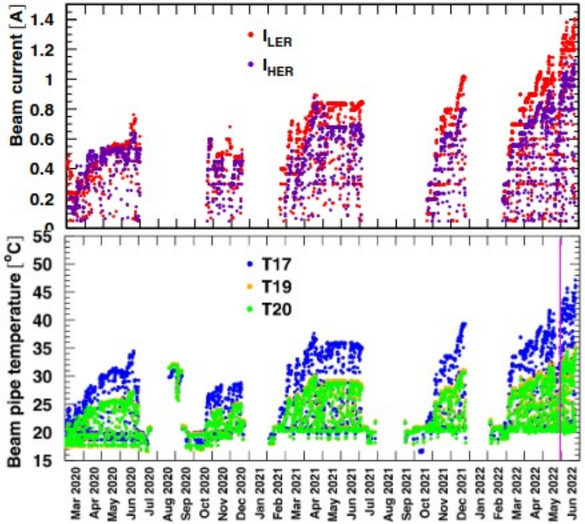
From T. Wilczeck (PRG)

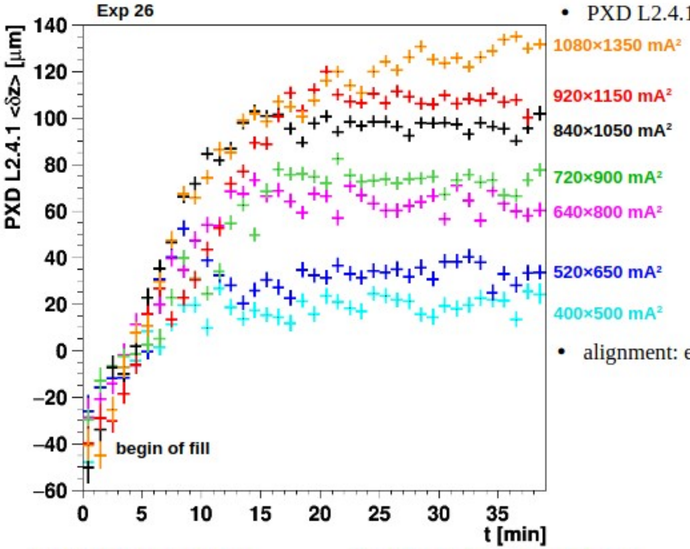


Reminder: Ladder Bowing in PXD1 L2 due to Beam Pipe Heating

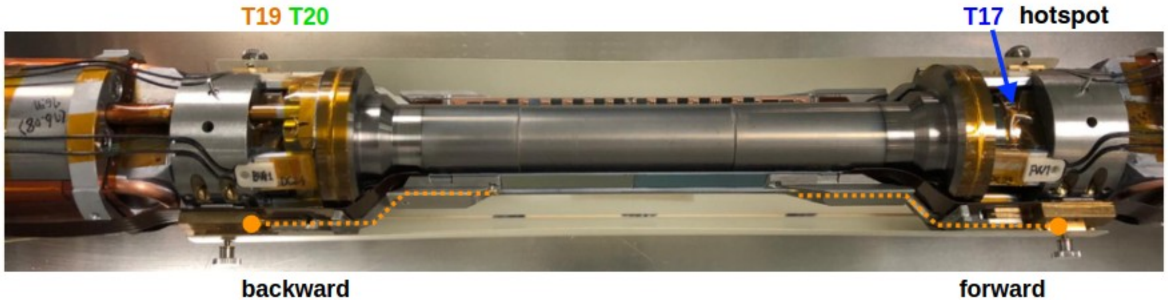








- PXD L2.4.1 vs SVD tracks: -δz
- alignment: e26 at 160×200 mA²



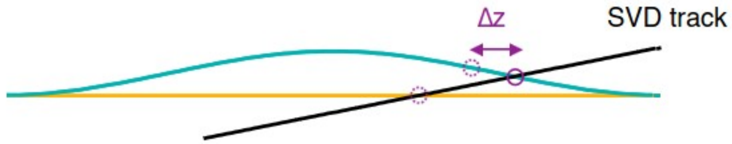
at run start: ≈constant

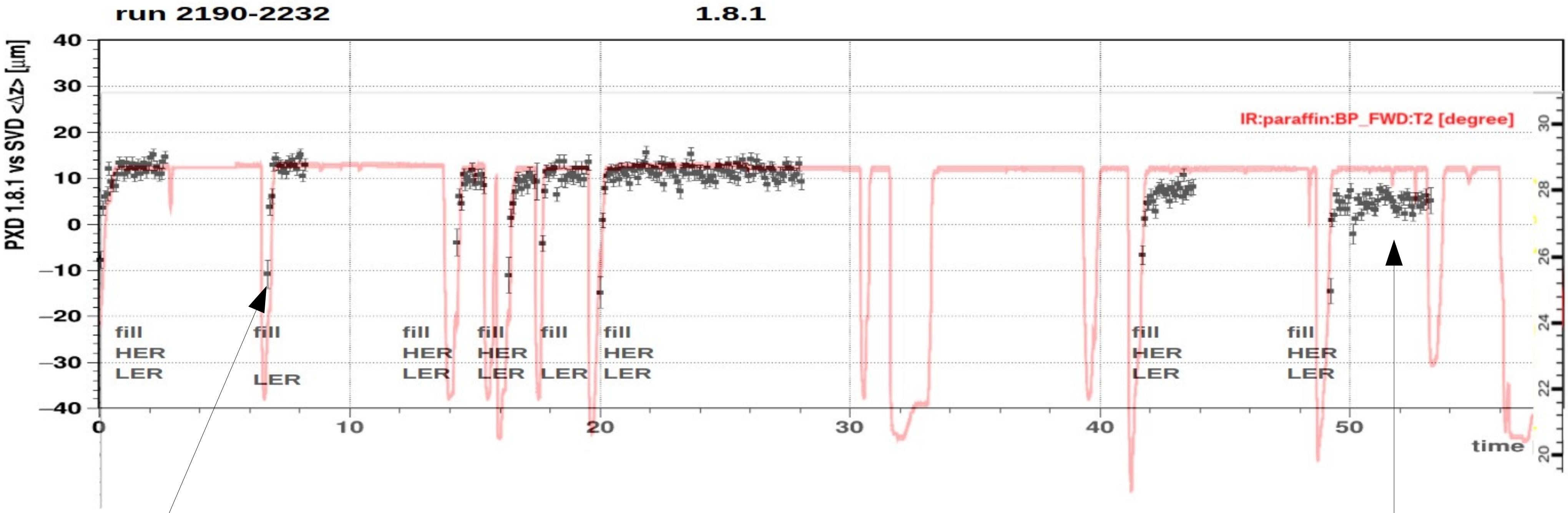
lumi state: depends on beams

Improved beam pipe cooling implemented in LS1

carsten.niebuhr@desy.de

L1 Ladder Bowing in March 2024





SVD tracks extrapolated to PXD → residual

Temperature itself probably not an ideal measure … level does not recover, some delay of onset possible

Question / Hypothesis

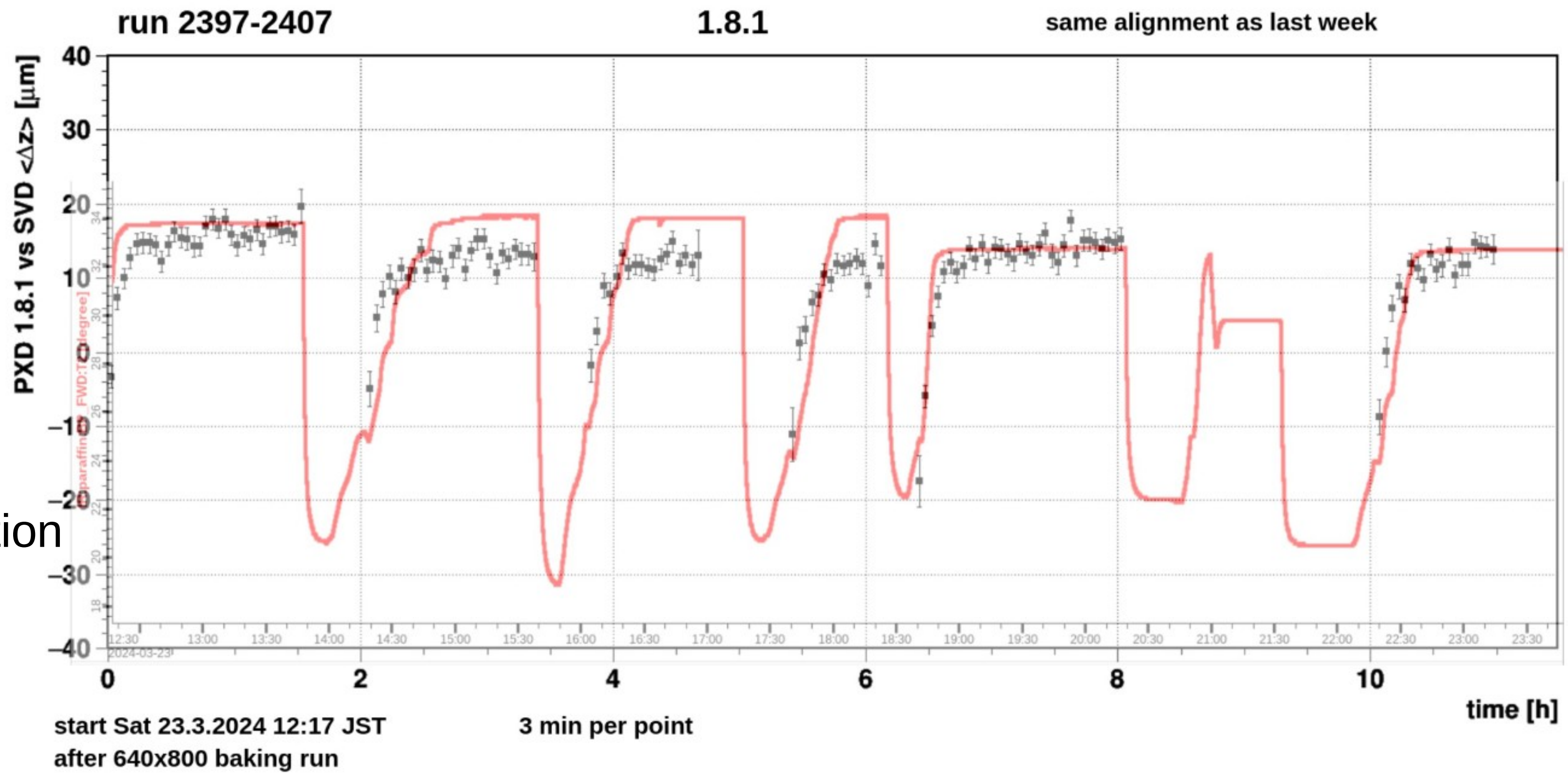
Can the deformation be described (in first approximation) by a single time-dependent parameter?

- All non-linearity in the time-dependence + each sensor parameter can have different (but constant) correlation to the temperature
  - Effects have to be reproducible (same temp → same deformation), relative behavior of sensors have to be constant (sliding starts at the same time)
- … at least in the first approximation

Assume such a parameter exists and we can extract it from the data. Can we correct for these effects now?

All charged tracks from IP: SVD to PXD extrapolation

L1 residual trend and beam pipe temperature

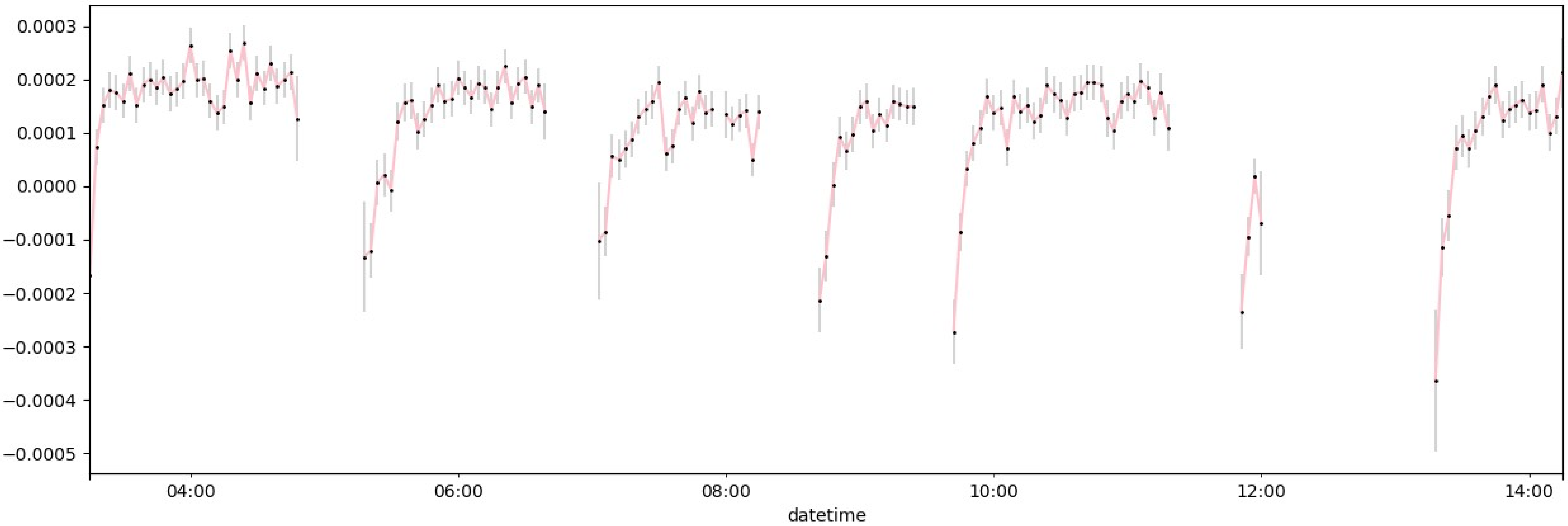


High-resolution data-driven proxies are „expensive“

correlation not perfect (time lag): other influencers?

Median V residual over all PXD sensors

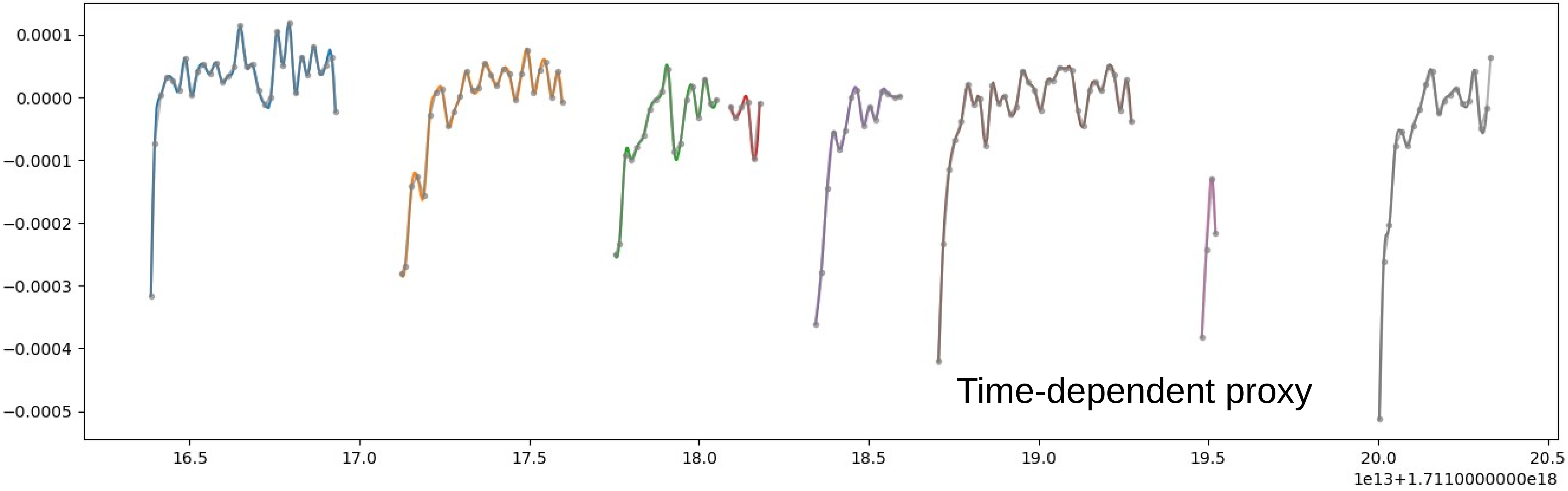
- Only di-muons, SVD to PXD extrapolation



Naive proxy – much better possible by „pre-solving“ alignment by absorbing residuals in u,v shifts for each sensor individually (higher-order residual proxies?)

Fit with splines for up-sampling

- Subtract average and fit with splines for upsampling



VXD deformation amplitude every 10 seconds

- Uploaded into database (IntraRunDependencies)
  - Our condition database has no notion of time – need to fabricate it ex-post and parameterize by event numbers (due to variations in luminosity)

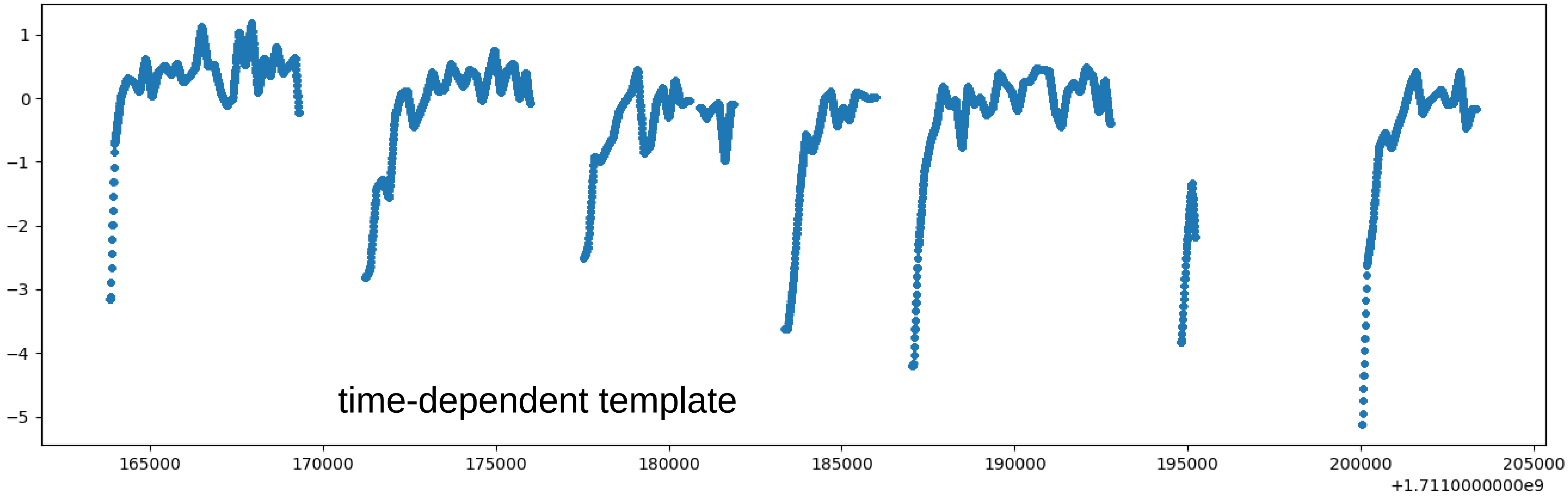
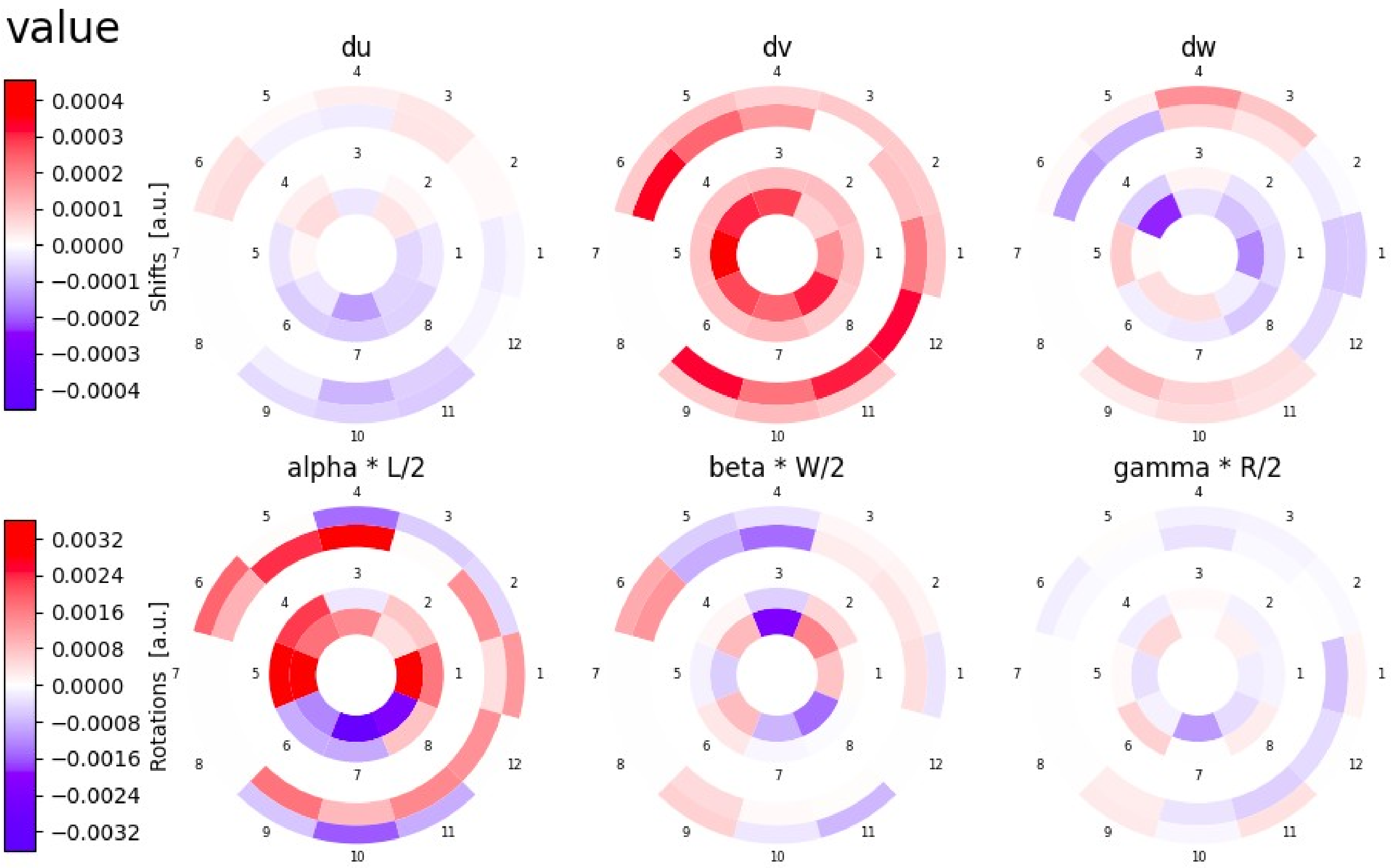


Figure from test of payload reading...

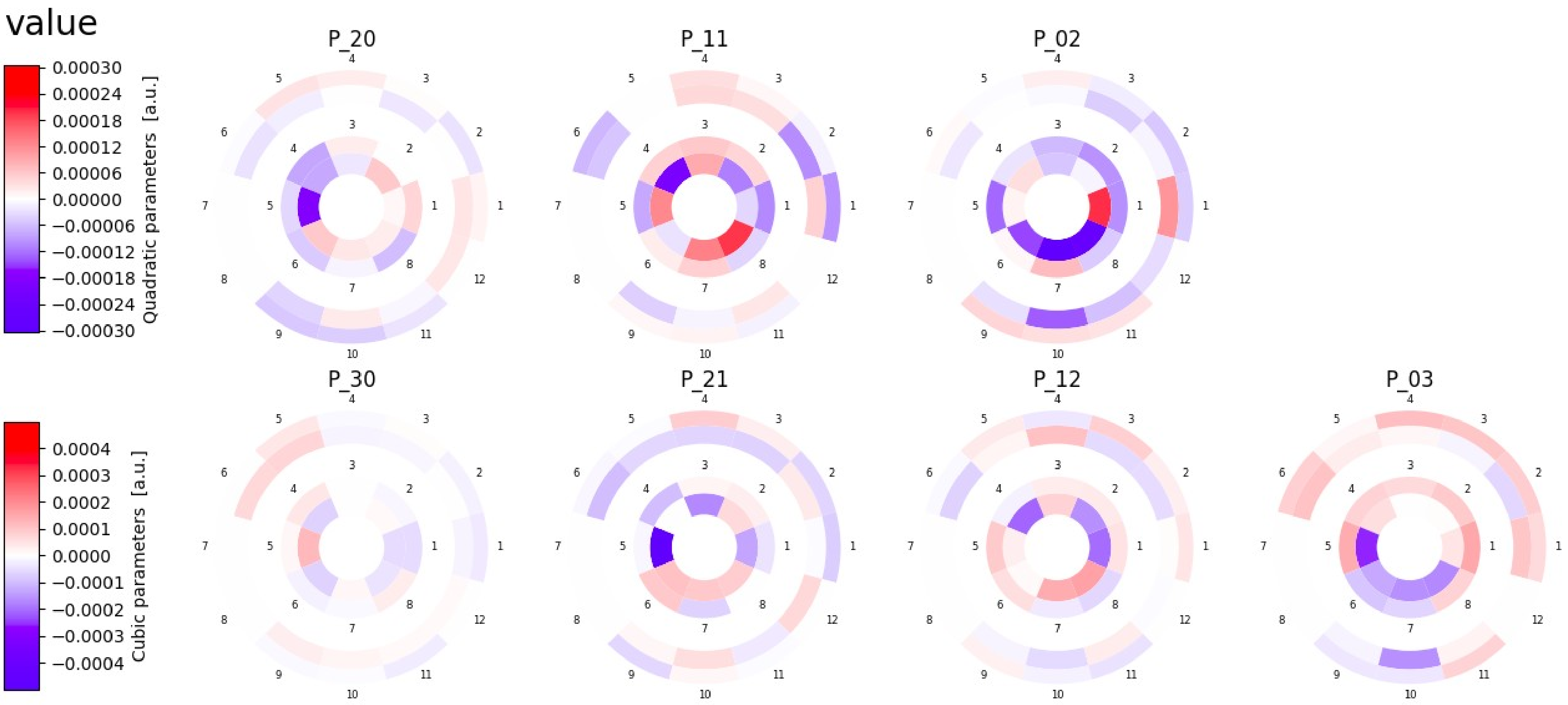
Alignment with deformation parameters extraction

- Define for each PXD sensor alignment parameter a new alignment parameter
  - Same derivative as original, but multiplied by the (time-dependent) bowing amplitude (taken from GT)
  - 40 (-5) x (6 + 3 + 4) = 520 (455) new parameters, constant over alignment period
- Determine complete VXD+CDC alignment + parameters of the deformation with Millepede II
  - Adjust the average and can absorb part of time-dependence which is coherent among sensors and proportional to the input bowing amplitude

PXD deformation coefficients (rigid body)



PXD deformation coefficients (surface)



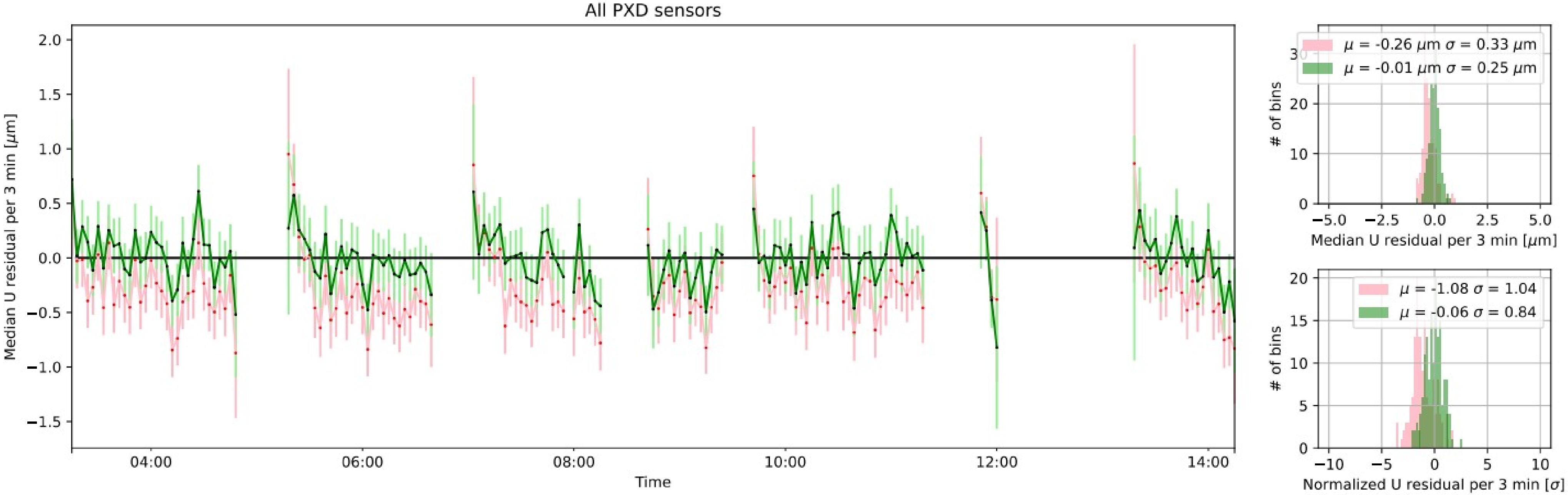
Cross-checks

- Compare residuals versus time before and after
- U / V
- All sensors vs. individual sensors

V residuals

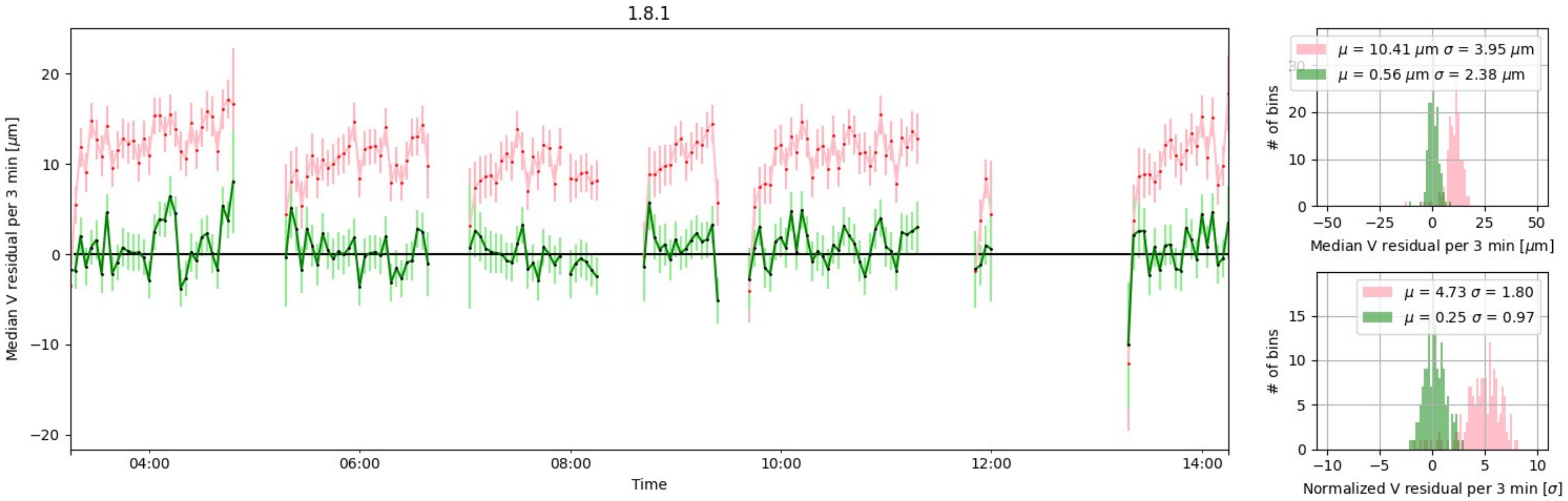
All PXD sensors
Median V residual per 3 min [μm]
Time
04:00
06:00
08:00
10:00
12:00
14:00
μ = 1.18 μm σ = 1.03 μm
μ = 0.05 μm σ = 0.21 μm
# of bins
Median V residual per 3 min [μm]
μ = 3.72 σ = 2.51
μ = 0.18 σ = 0.51
# of bins
Normalized V residual per 3 min [σ]

U residuals

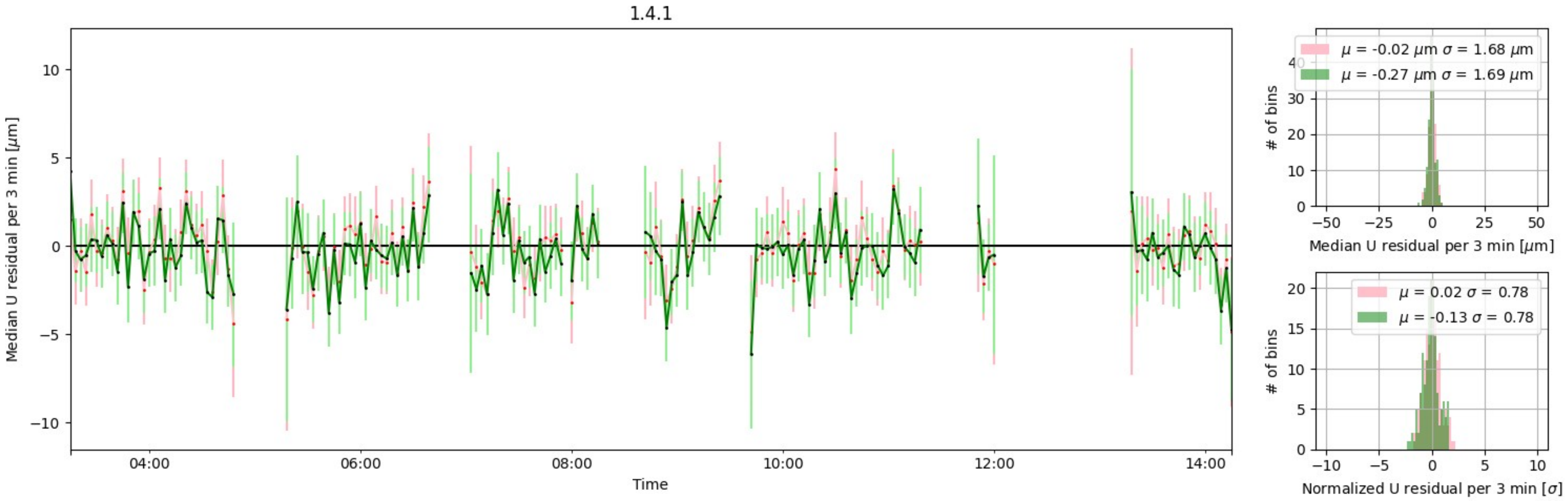


All PXD sensors
Median U residual per 3 min [μm]
Time
04:00
06:00
08:00
10:00
12:00
14:00
μ = -0.26 μm σ = 0.33 μm
μ = -0.01 μm σ = 0.25 μm
# of bins
Median U residual per 3 min [μm]
μ = -1.08 σ = 1.04
μ = -0.06 σ = 0.84
# of bins
Normalized U residual per 3 min [σ]

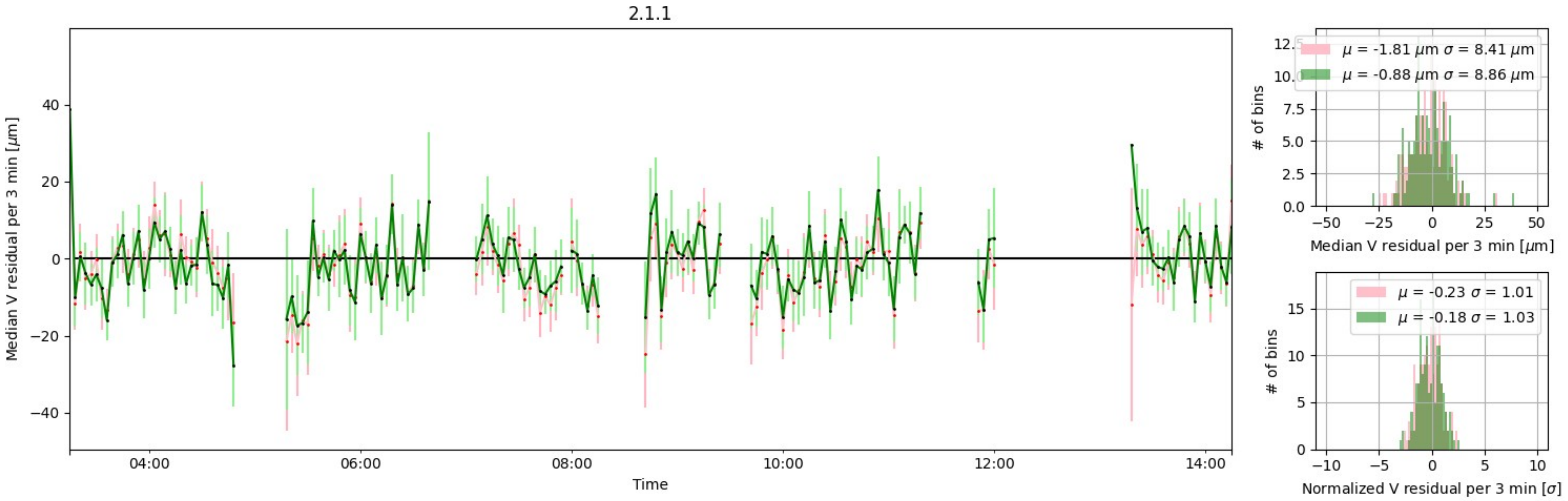
1.8.1 V residuals



1.4.1 V residuals



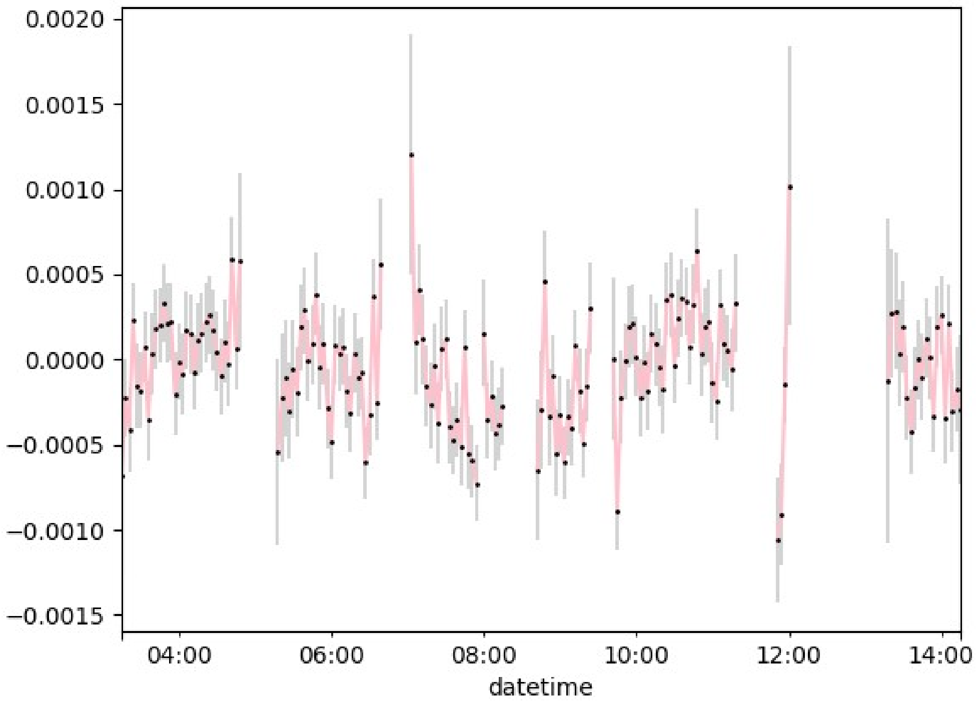
Example for L2 sensor



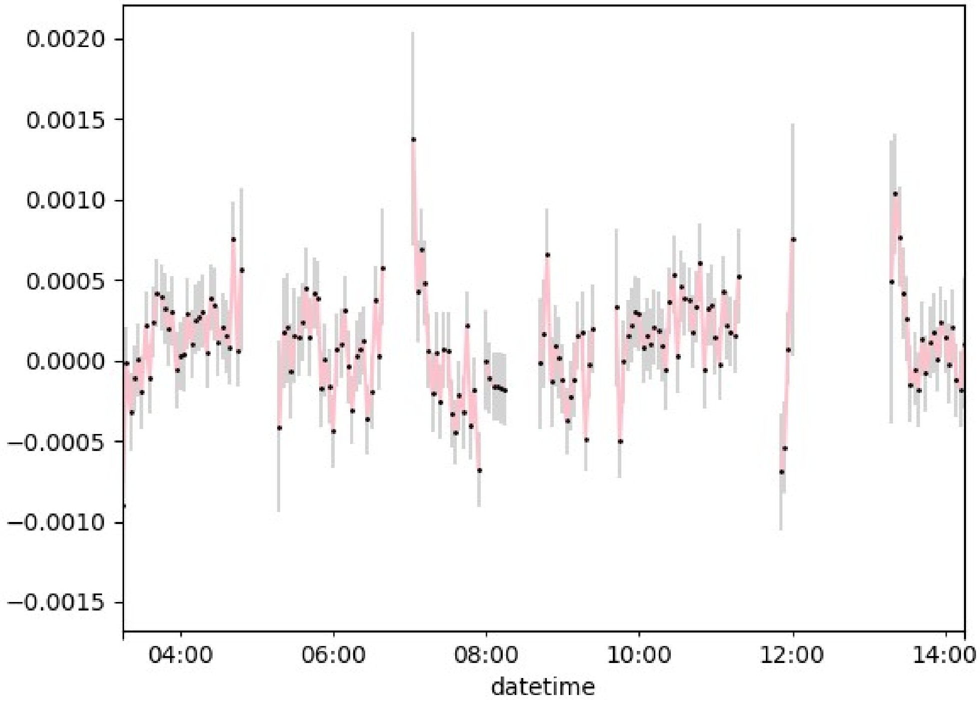
For L2 sensors, pulls usually not reduced

All L2 V residuals

- Probably should add indepedent proxy and coefficients for layer 2



before



after

Many open questions and work

- Really „safe“ method?
  - Proxy does not match? → „zero“ coefficients… still global minimum, should not get worse (really?)
- How much can we describe real detectors like this?
  - How many parameters can we reduce? Could describe slow evolution of high granularity structures at fine level? Needs already some knowledge of time dependence (L1+L2+... or separately? ...)
- Templates from residual validation vs. template basis
  - Physics-informed: continuous versus step movements
- Interaction with existing IoV methods, pixel detector recalibration (CMS), iterations, integration into existing workflows…
- Derivation of proxies
  - Machine learning? Learn from high-frequency proxies → better proxies for lower statistical resolution
- So far only „proof-of-concept“ on 10 hours of Belle II data
  - Possibly years of work (also for students)