Belle II detector alignment with Millepede II

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*for the **Belle II Collaboration***

Scientific Computing Seminar

Friday Dec 6, 2024, 2:00 PM → 3:00 PM Europe/Berlin

SR 2

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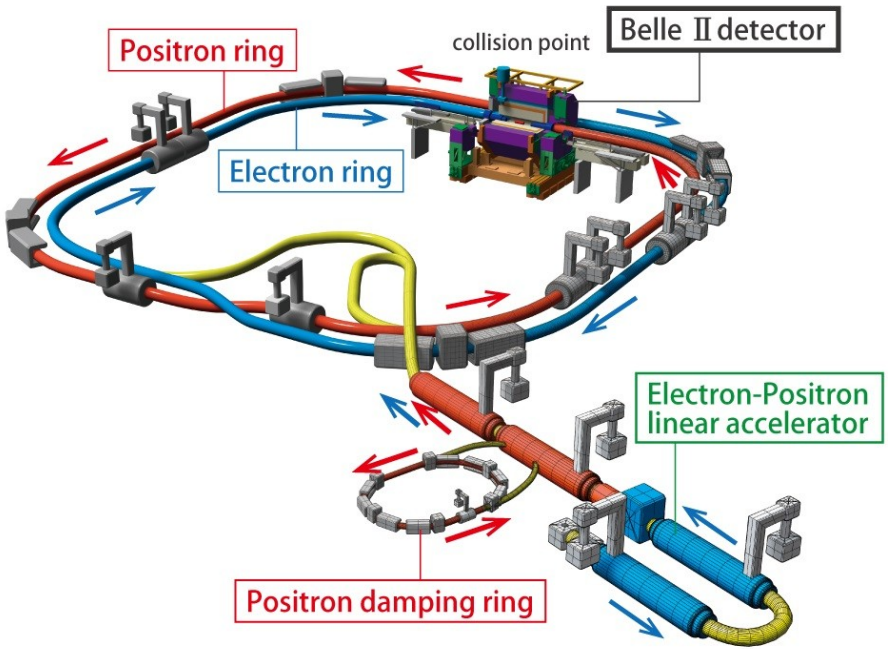
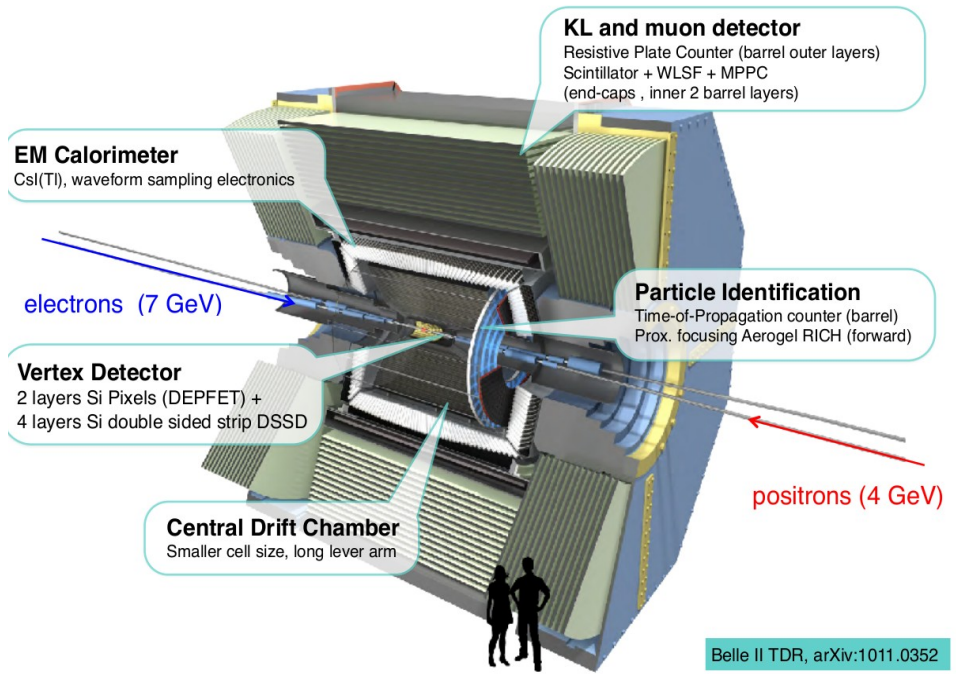
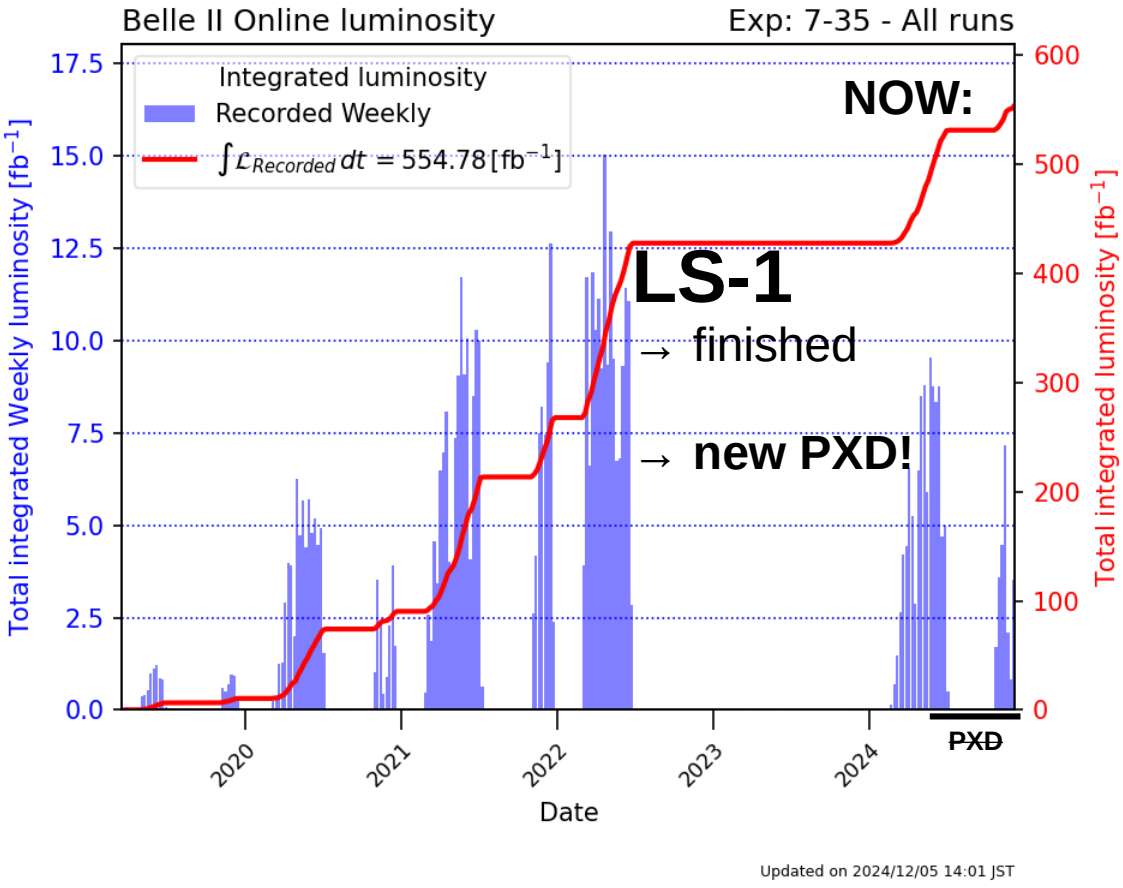
SuperKEKB & Belle II

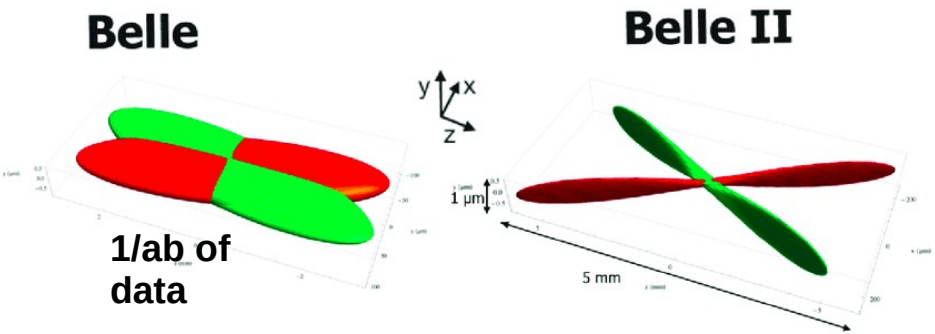
- Upgrade of KEKB & Belle, taking physics data since 2019
- Worlds‘ highest luminosity electron-positron collider (KEK, Tsukuba, Japan) at Upsilon(4S) resonance → B physics, D physics, tau physics …

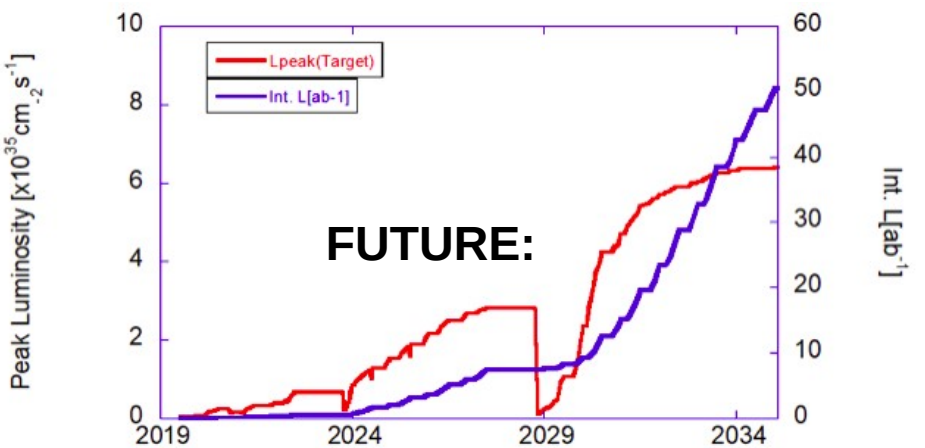




Past, Present, and Future



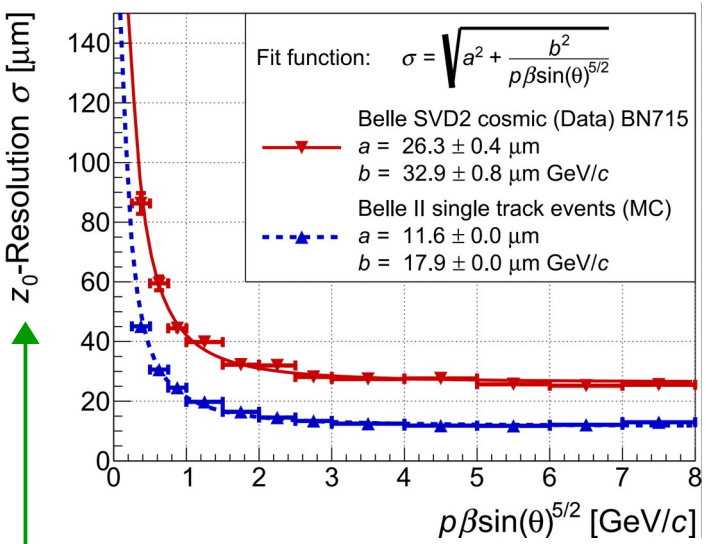


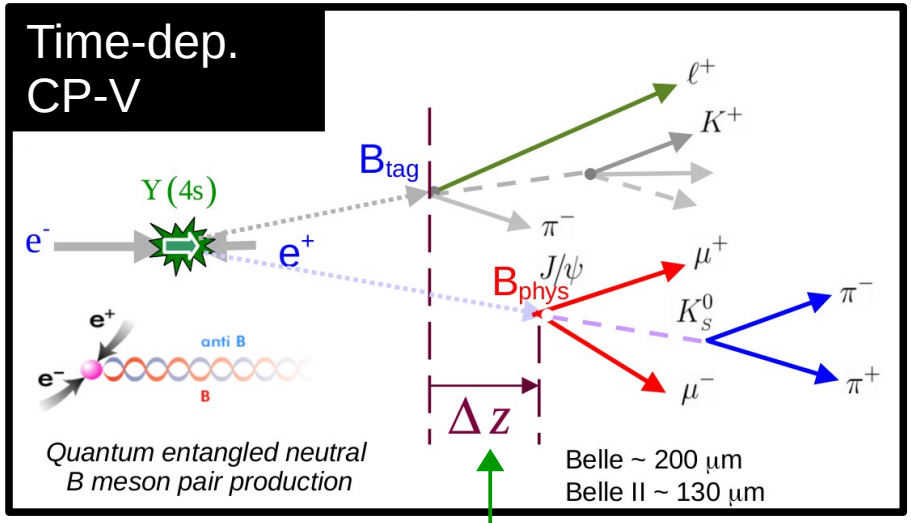


Systematic errors will start to dominate measurement precisions for many analyses

Precision @ Belle II

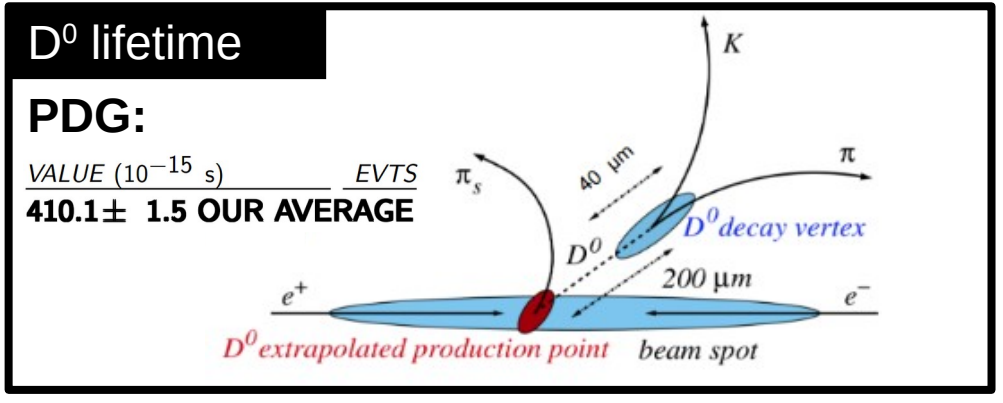
Just two examples...





Alignment precision at level of micrometers needed

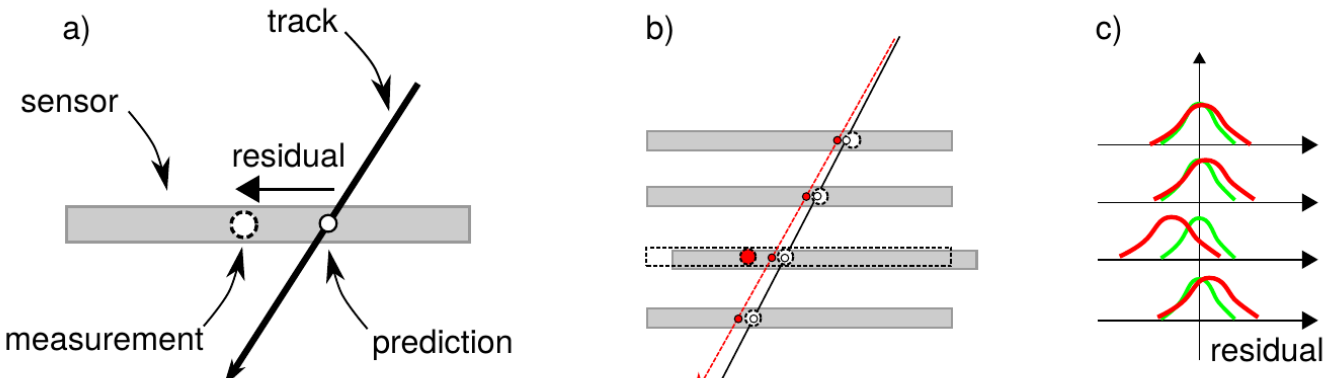
→ **Advanced track-based (time-dependent) alignment**

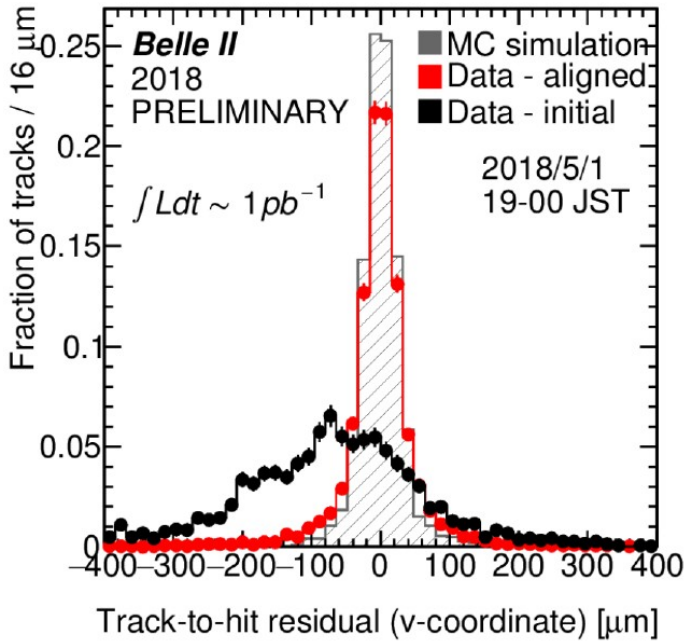


Track-based alignment

Detection elements not in assumed positions/orientations/…

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

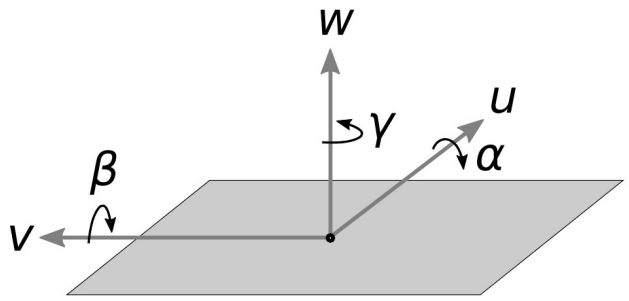




$$r_{ij}(\boldsymbol{a}, \boldsymbol{q}_j) = m_{ij} - p_{ij}(\boldsymbol{a}, \boldsymbol{q}_j)$$

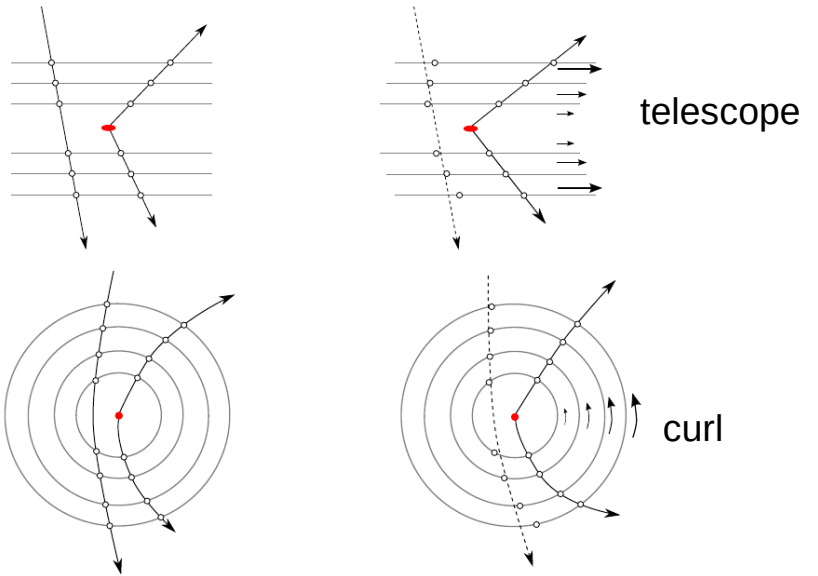
Estimate the geometry directly from the trajectories
→ minimize many millions of residuals!

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



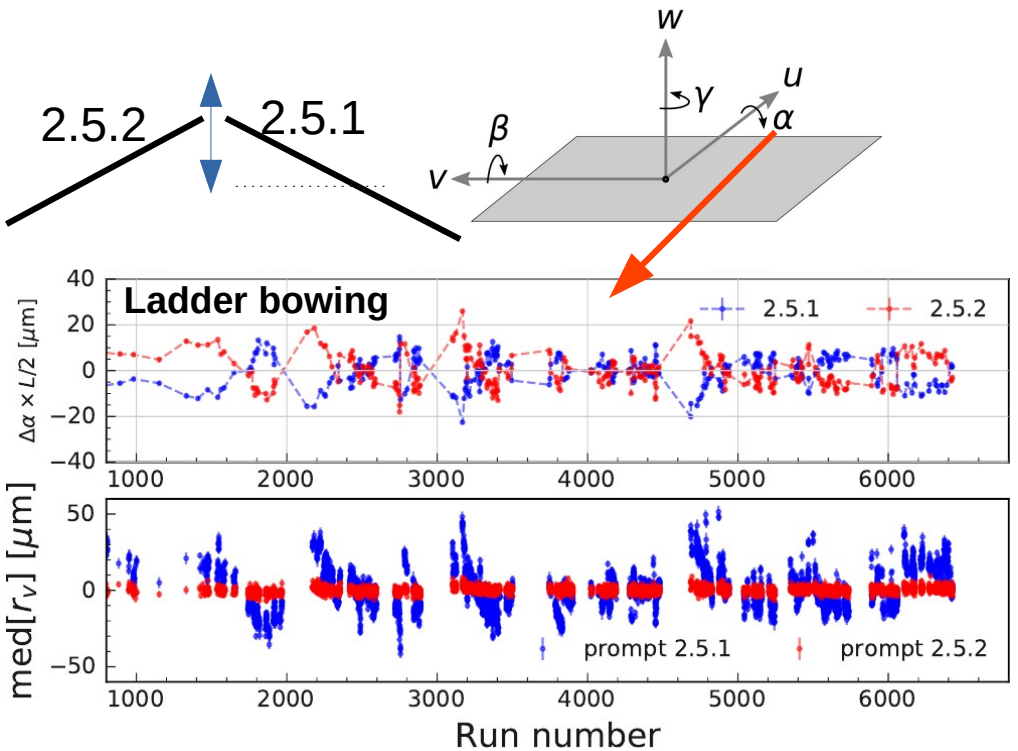
Alignment Challenges

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

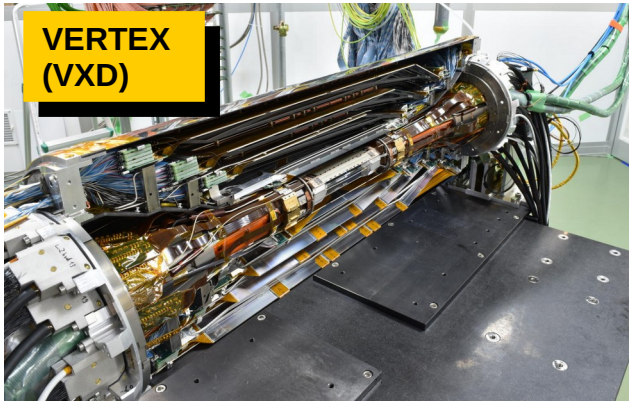


- Detector&reco model issues
  - e.g. imperfect magnetic field description

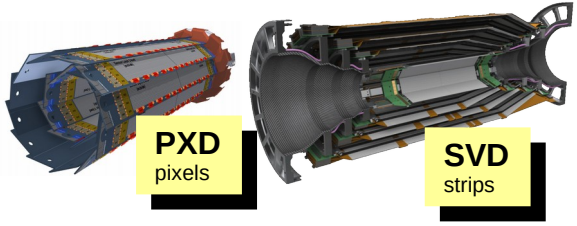
- Time-dependence
  - Detector not stable, many effects at play

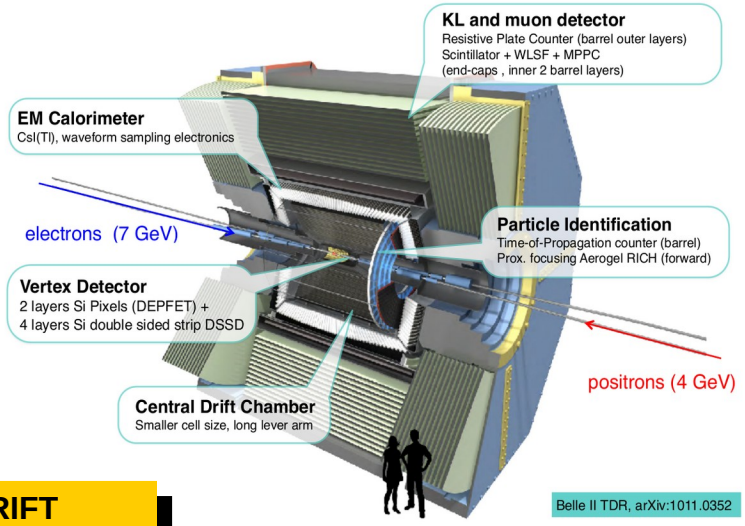


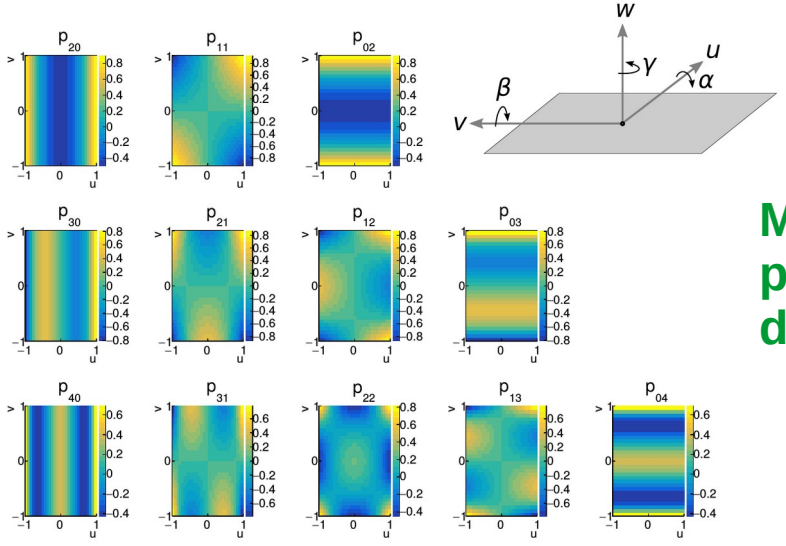
Belle II Alignment Parameters: Local Alignment



212 sensors
x **18** parameters

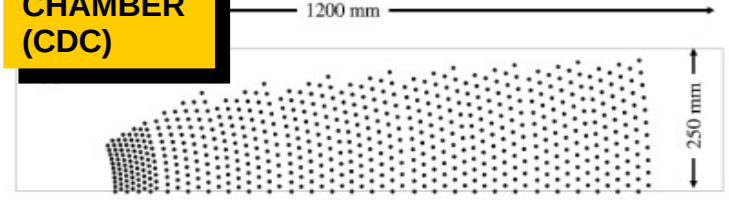




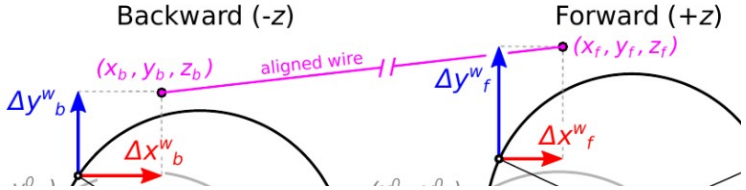


More than 60,000 parameters to be determined

DRIFT CHAMBER (CDC)



14,336 wires x 4 parameters

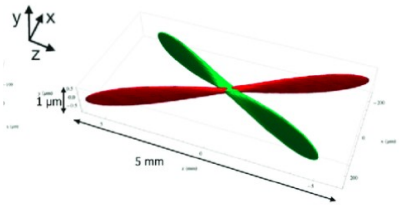


Belle II Alignment Parameters: Global Alignment

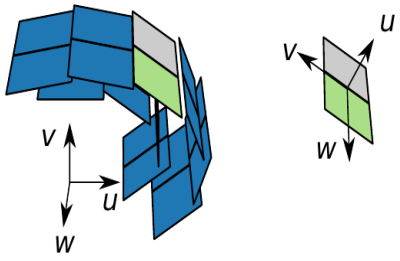
Relative positions of sub-detectors and larger structures*

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

IP position

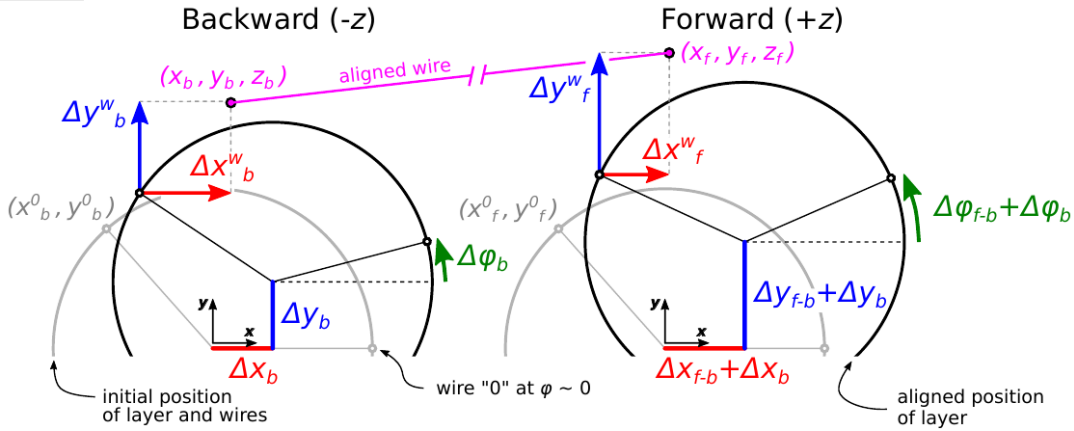


VXD half-shells and ladders



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

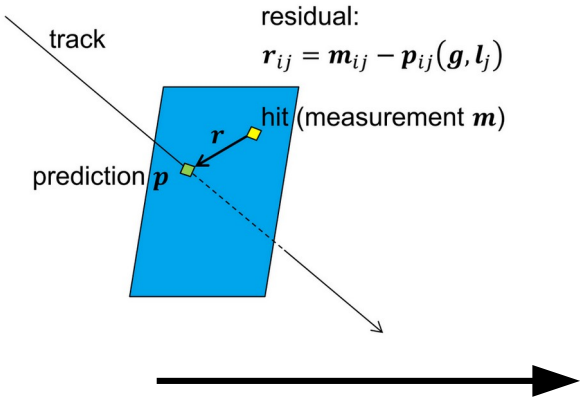
CDC layers



Alignment of all degrees of freedom should be done simultaneously

*Redundant DoFs removed by linear equality constraints

Alignment Algorithm: Millepede II

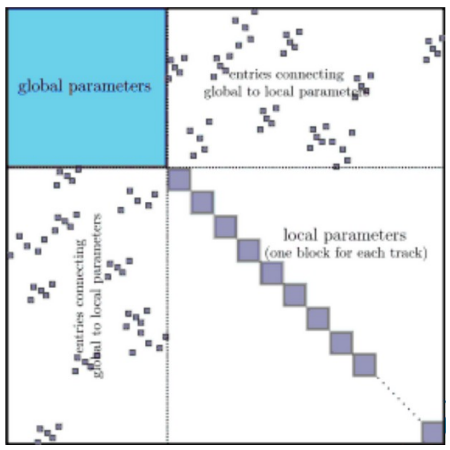


Minimize over all parameters:

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

$\boldsymbol{g}$ ... 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

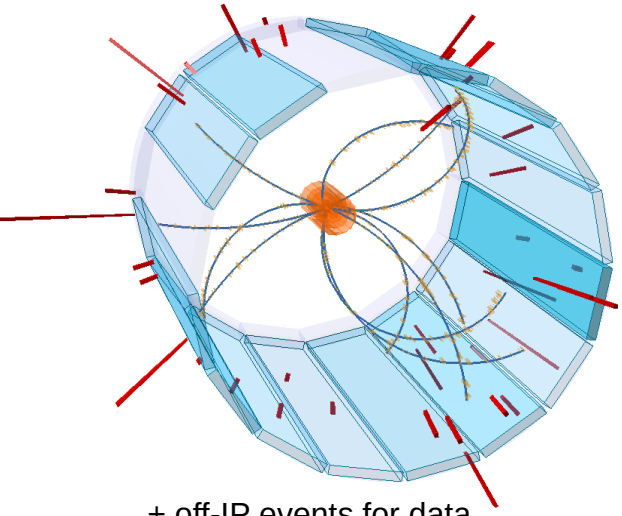
With recent speed-ups, an exact solution for 60k parameters can be obtained in about 30 min*!

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.

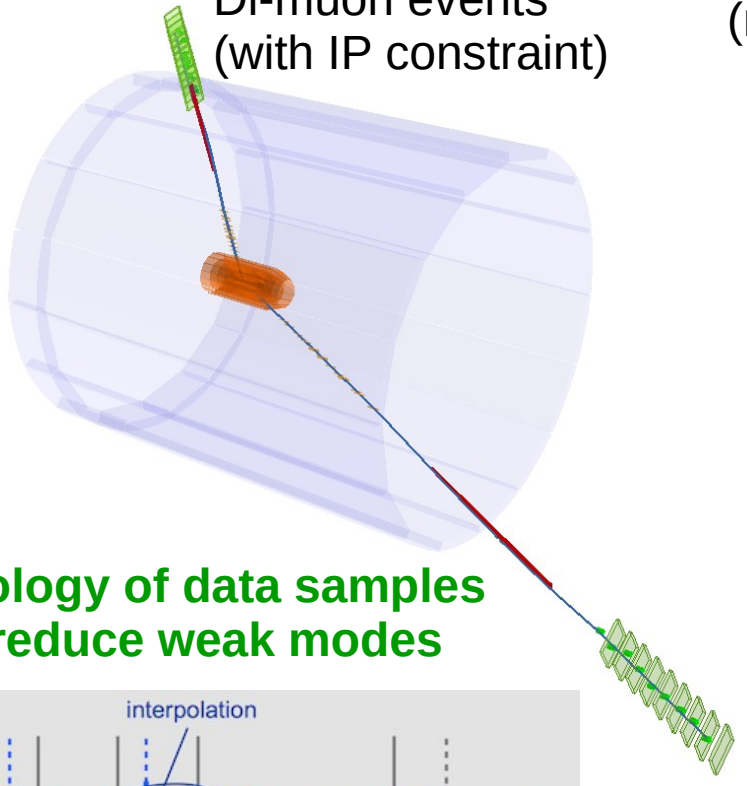
Data Samples for alignment

Hadronic events

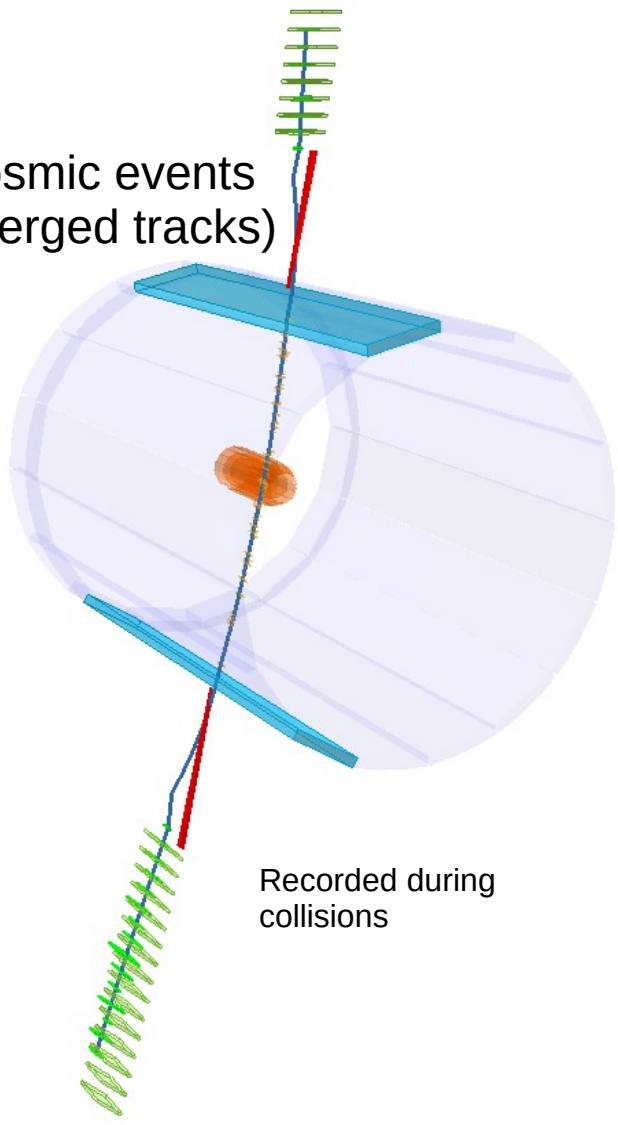


+ off-IP events for data

Di-muon events
(with IP constraint)



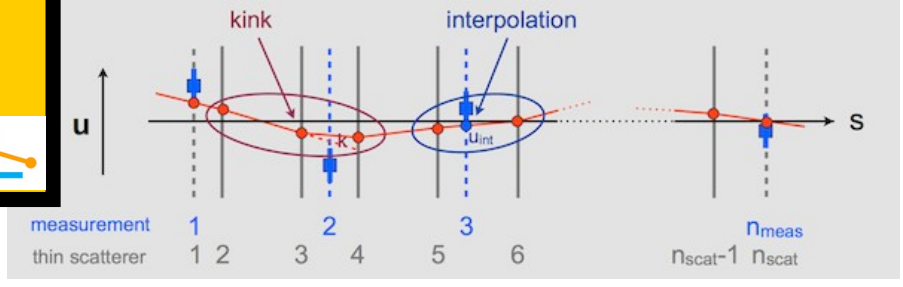
Cosmic events
(merged tracks)



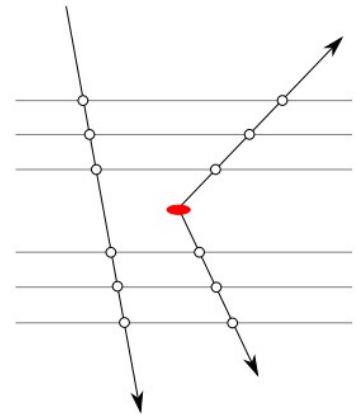
Recorded during collisions

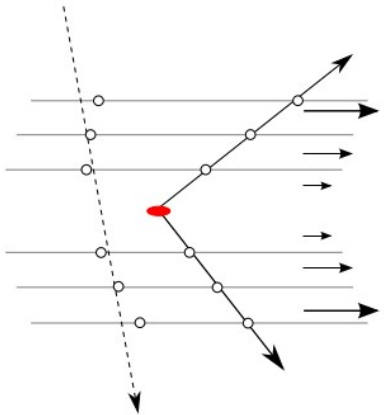
Rich topology of data samples helps to reduce weak modes

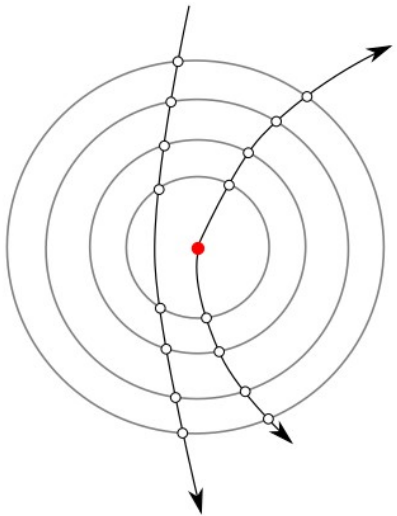
General Broken Lines (GBL)
Track model with proper description of multiple scattering

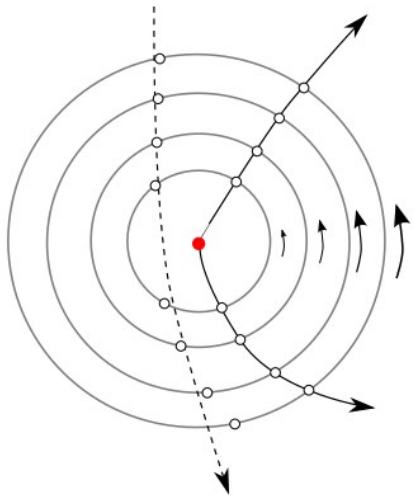


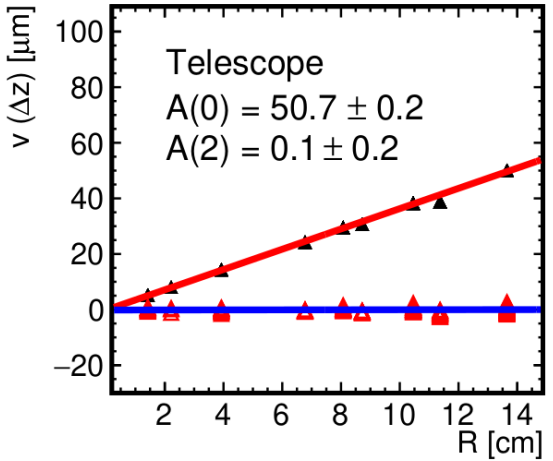
Reducing weak modes with rich track topology

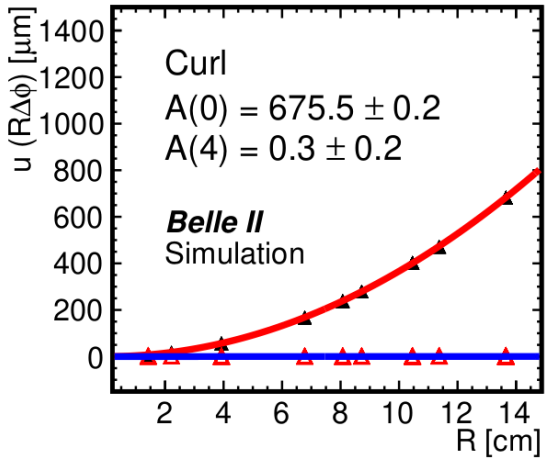












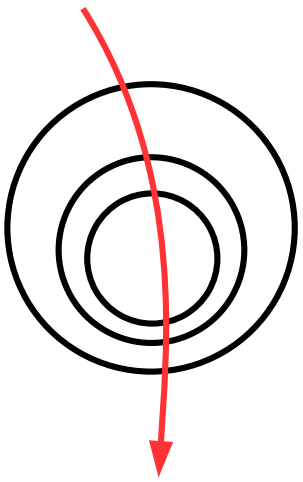
VXD deformation before alignment...

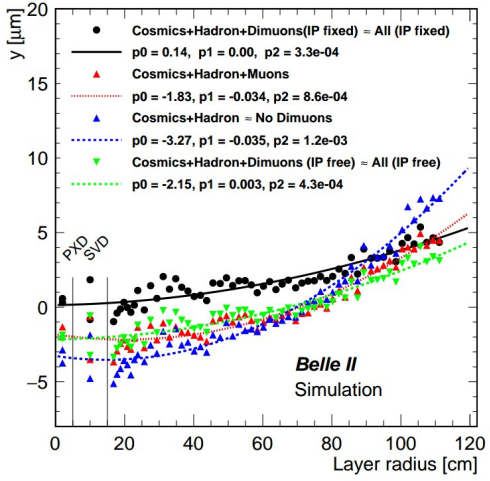
...and after

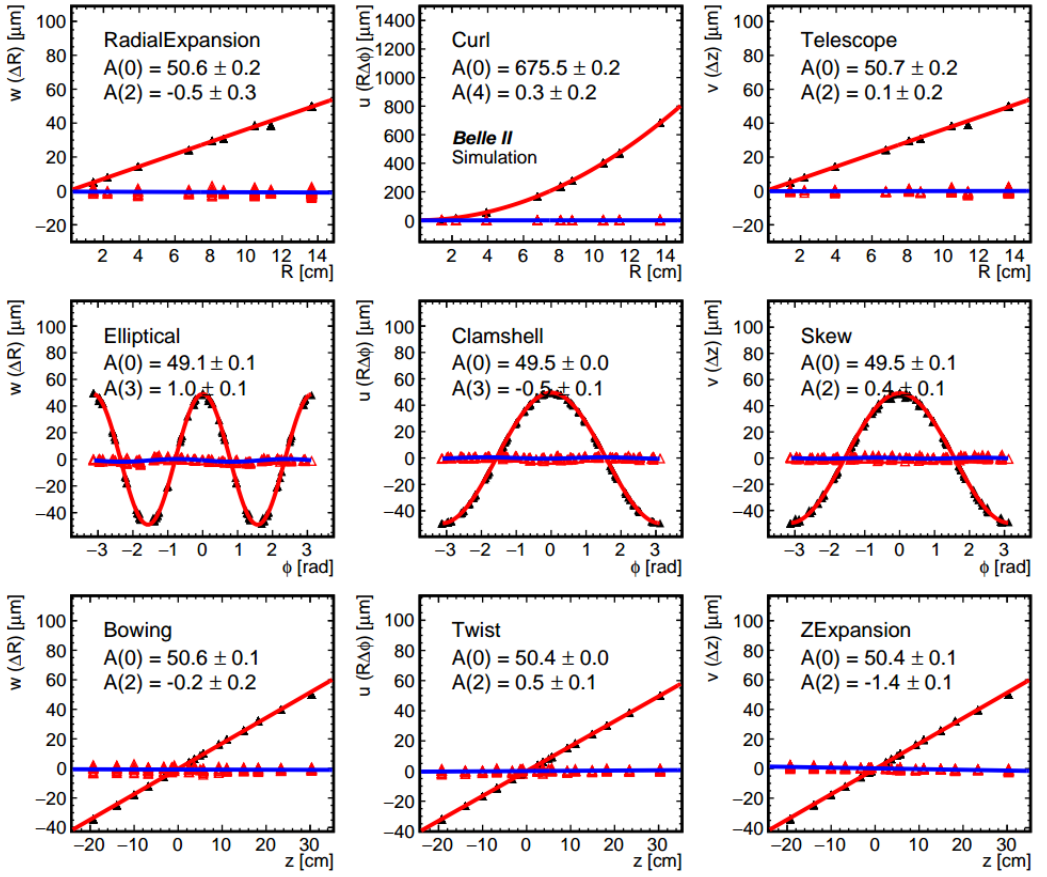
Weak Modes in Prompt Alignment (without wires and IPdimuons)

	Δr	$r\Delta\phi$	Δz
r	**Radial expansion** $\Delta r = c_{scale} \cdot r$	**Curl** $r\Delta\phi = c_{scale} \cdot r + c_0$	**Telescope** $\Delta z = c_{scale} \cdot r$
ϕ	**Elliptical expansion** $\Delta r = c_{scale} \cdot \cos(2\phi) \cdot r$	**Clamshell** $\Delta\phi = c_{scale} \cdot \cos(\phi)$	**Skew** $\Delta z = c_{scale} \cdot \cos(\phi)$
z	**Bowing** $\Delta r = c_{scale} \cdot \lvert z \rvert$	**Twist** $r\Delta\phi = c_{scale} \cdot z$	**Z expansion** $\Delta z = c_{scale} \cdot z$

MC tests of **VXD** weak mode misalignments







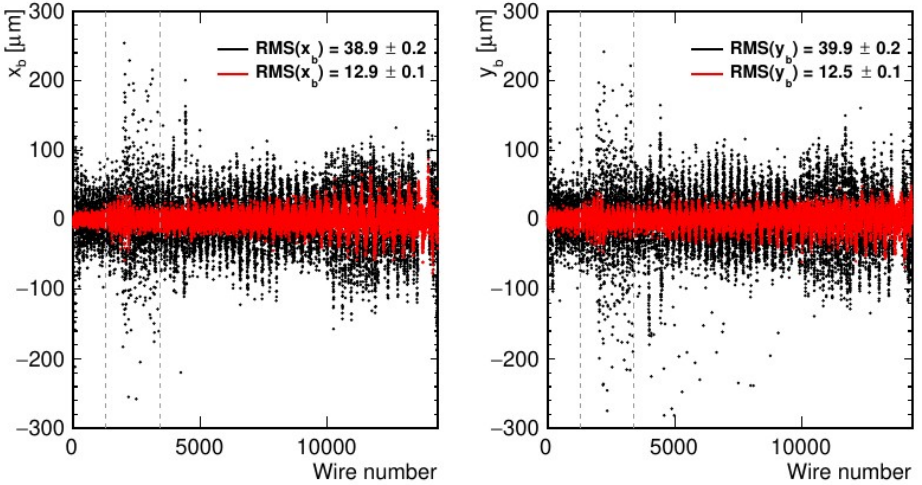
Weak modes in prompt alignment are well constrained

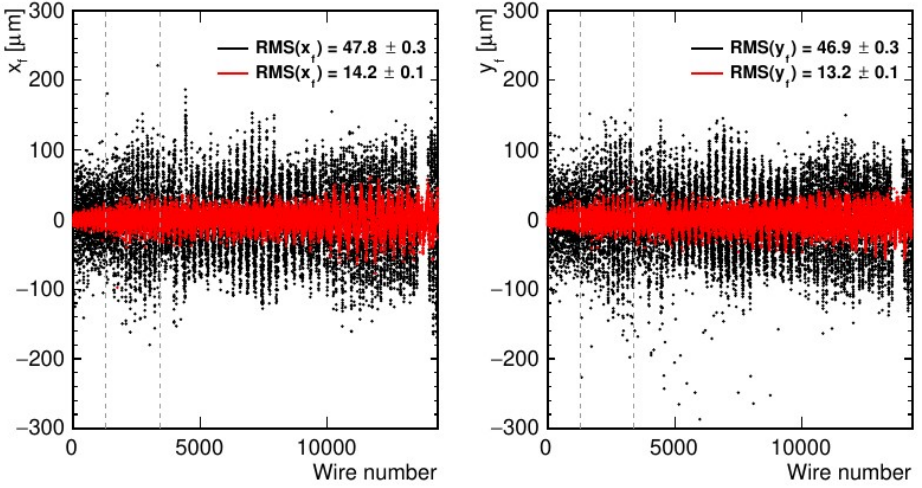
Full scale MC tests with misaligned wires

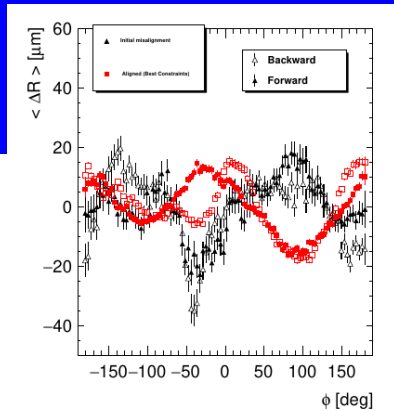
Black: initial realistic misalignment

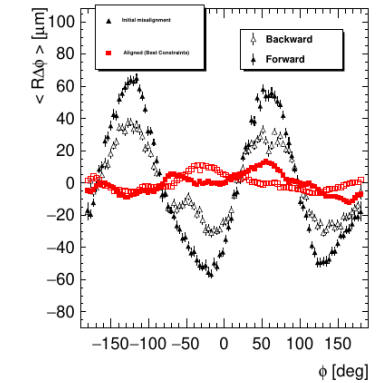
Red: remaining residual misalignment

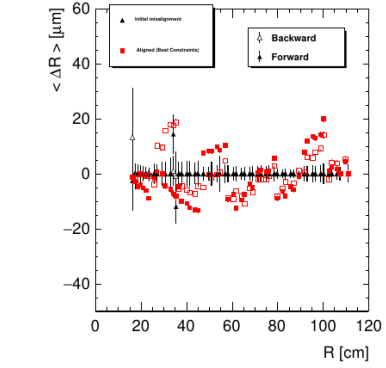
Can recover from a realistic wire misalignment to negligible residual misalignment in a single iteration!



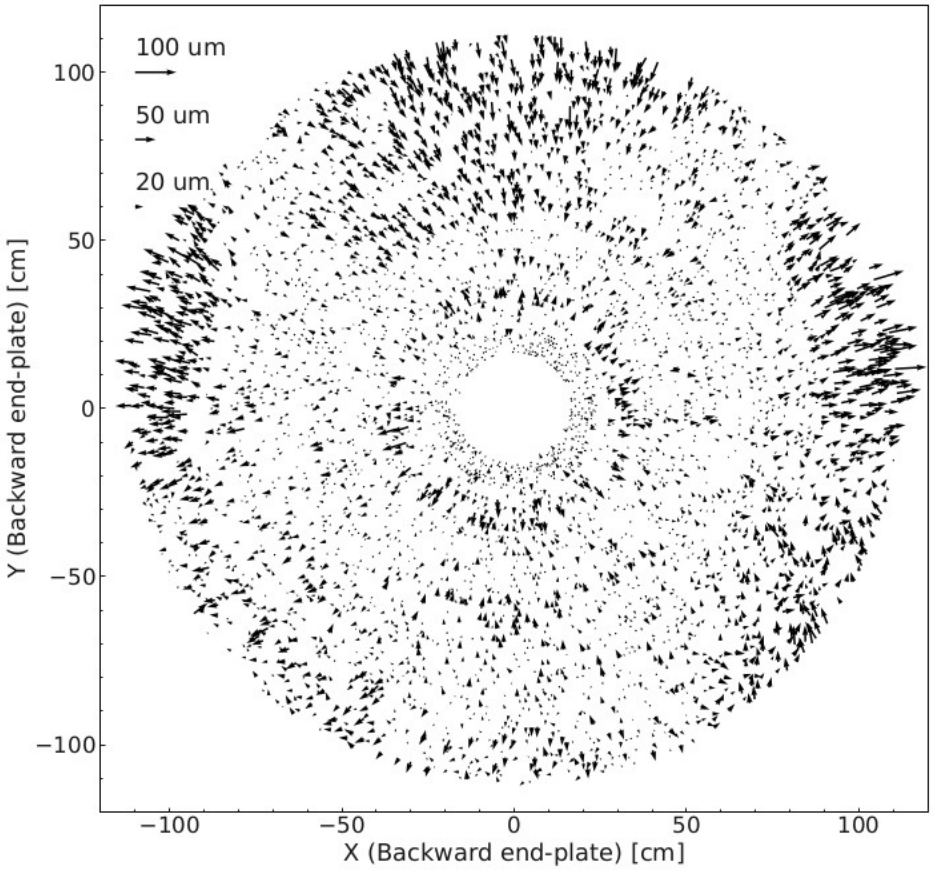


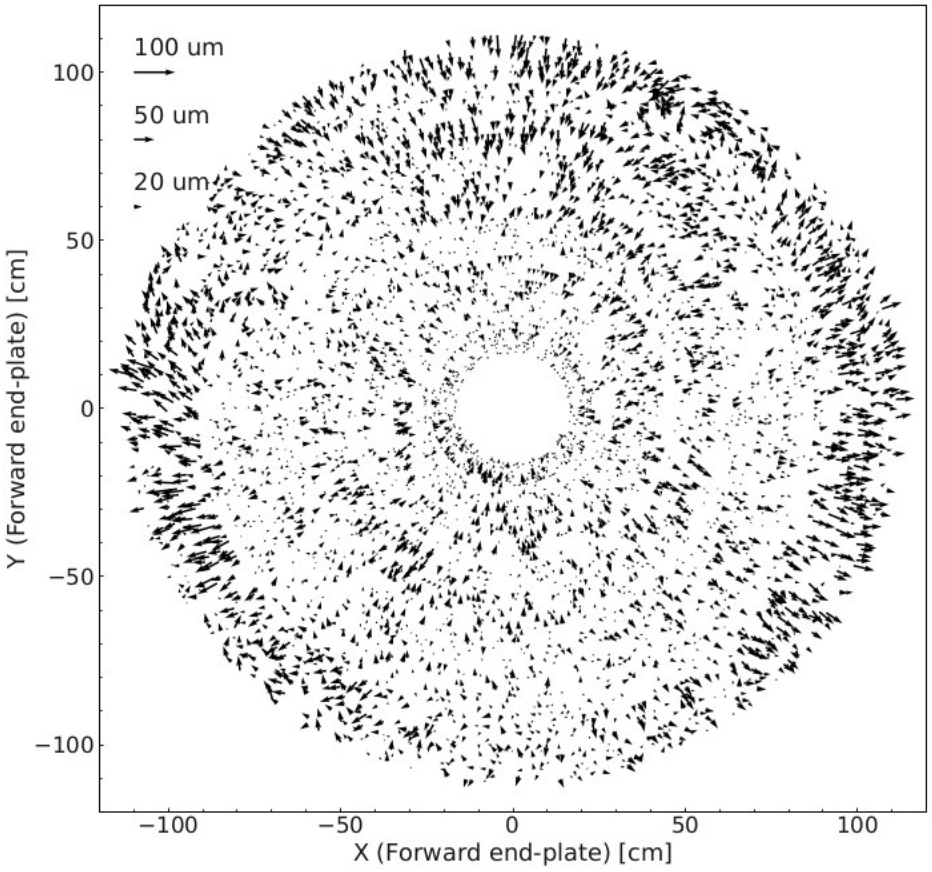






Residual wire misalignment in MC





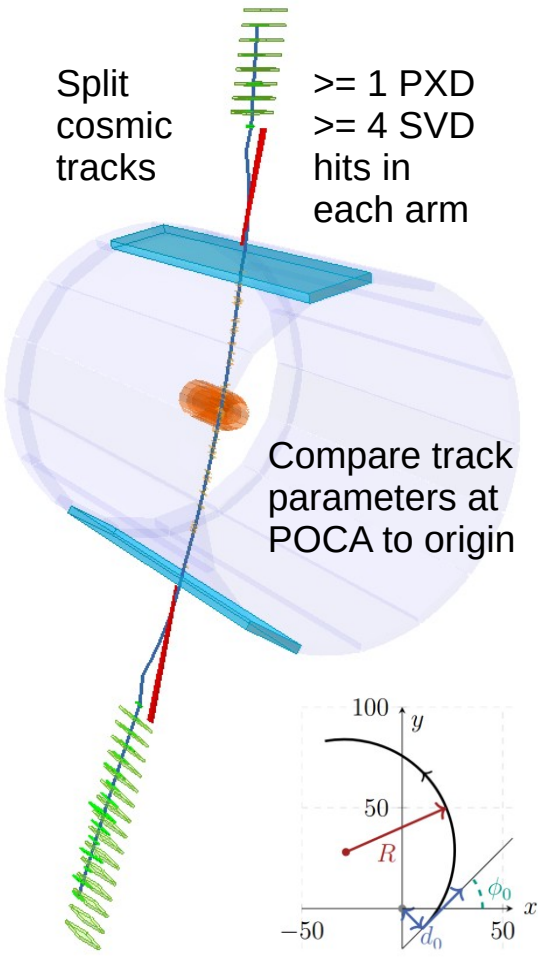
Only 20% randomly selected wires shown

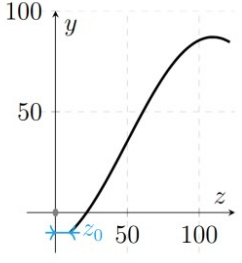
Cosmic Validation with PXD+SVD+CDC

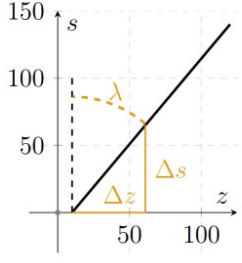
Split cosmic tracks

>= 1 PXD
>= 4 SVD hits in each arm

Compare track parameters at POCA to origin



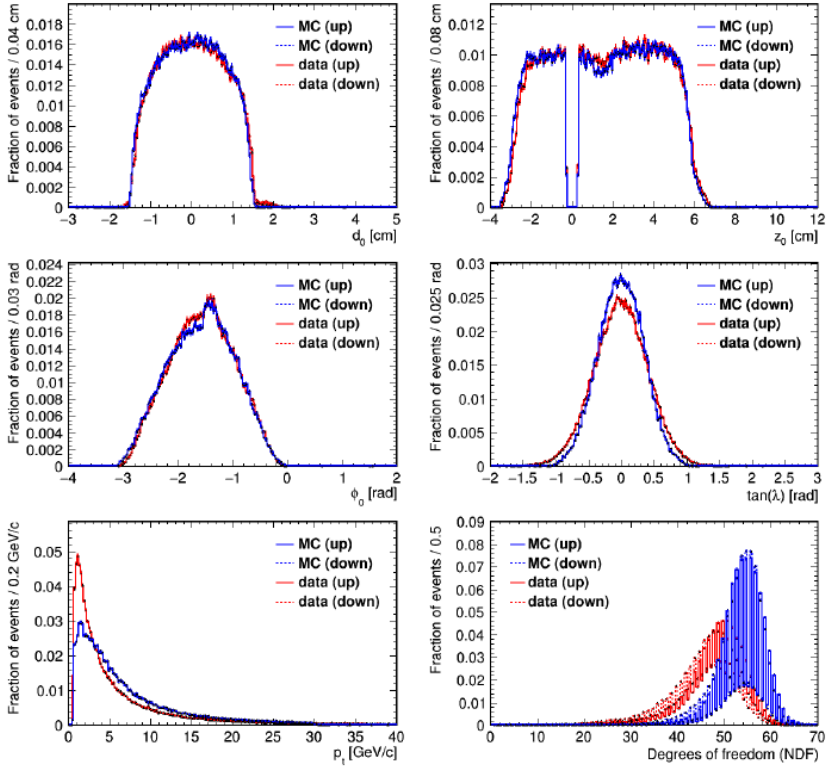




MC with bkg. overlay for exp12

All data from exp12

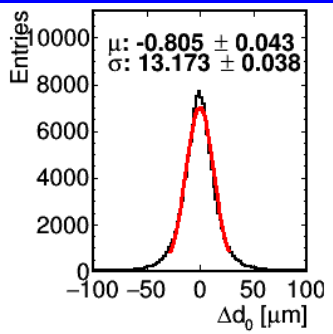
Both about 130k full tracks

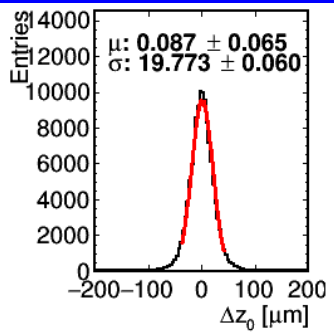


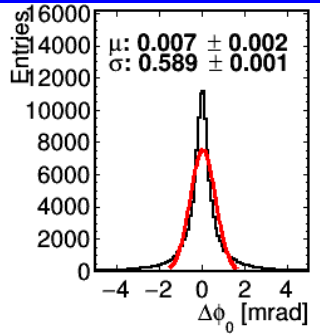
Distributions for transverse momentum and number of CDC hits are slightly different

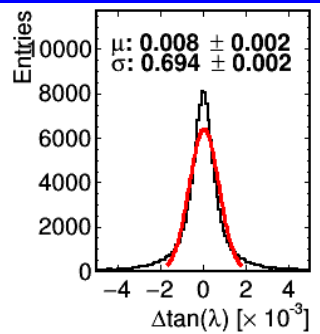
Helix Parameter Resolutions

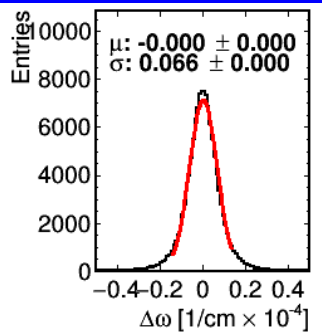
```
selection="abs(Z01)>0.5 &&
abs(Z02)>0.5 && Pt1>0.6 &&Pt2>0.6"
```



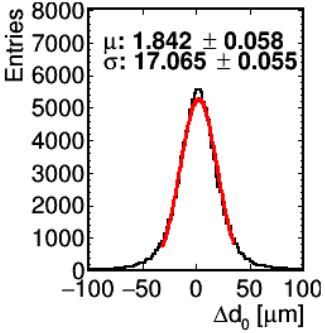


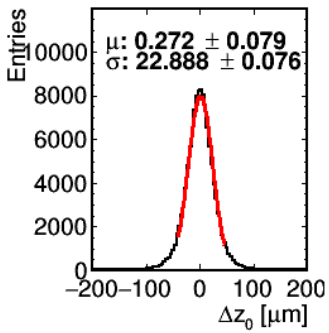


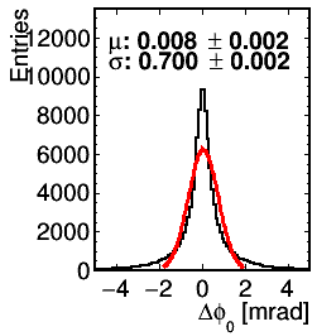


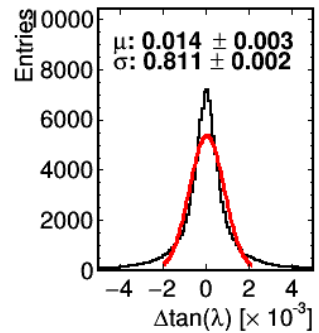


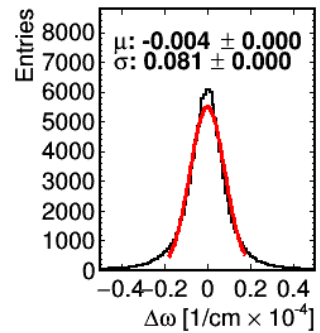
MC



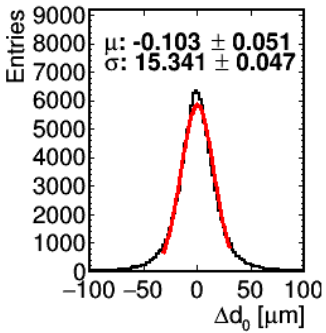


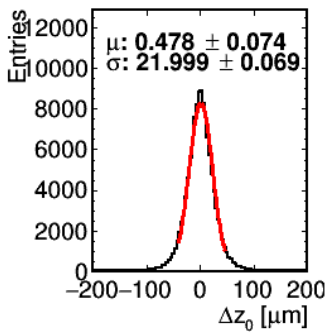


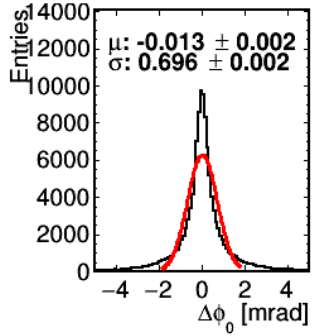


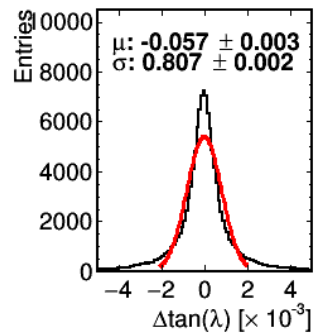


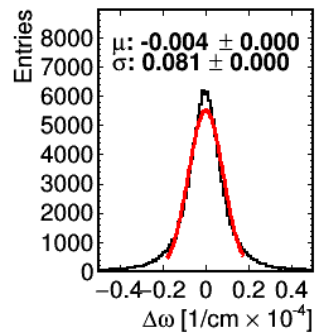
Prompt exp12







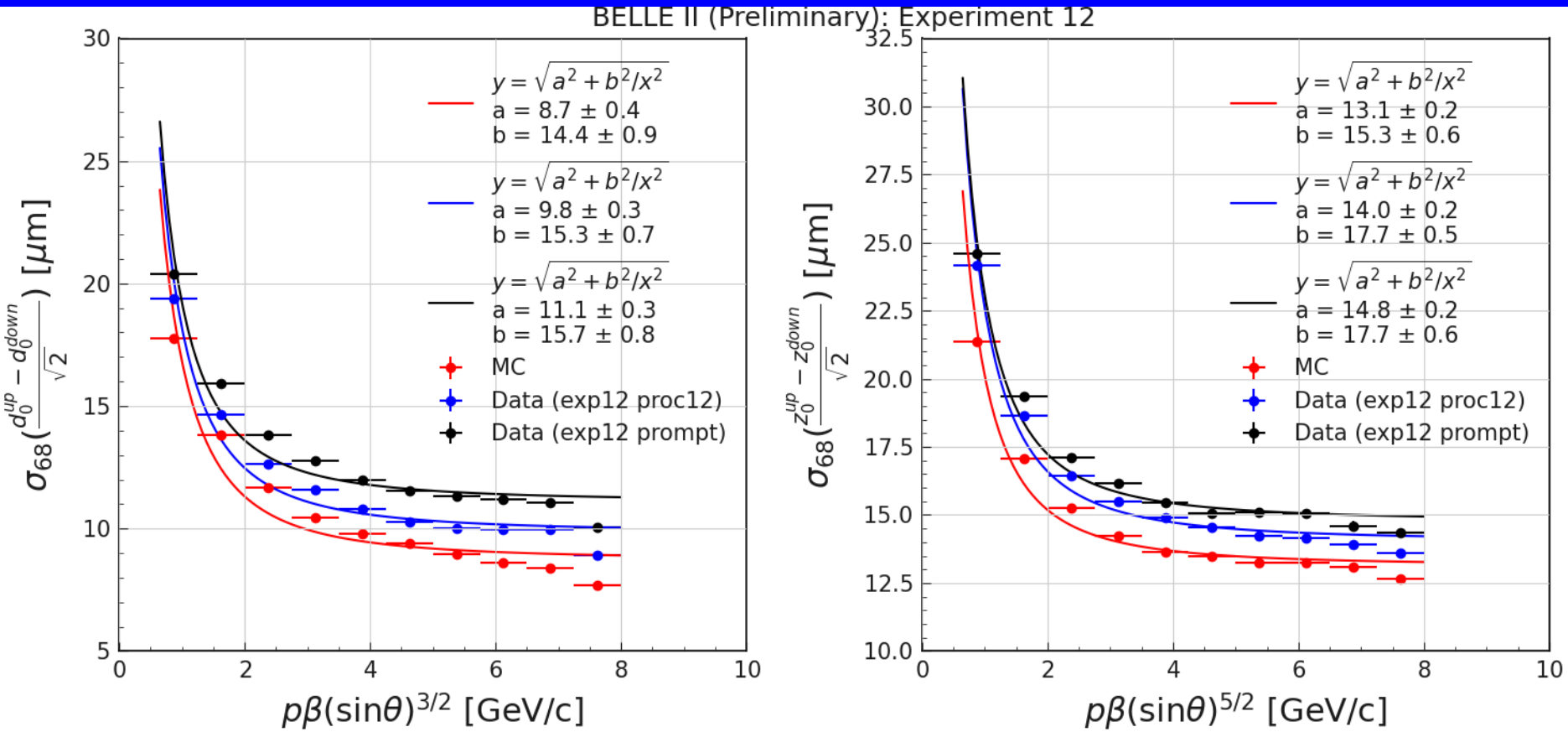




Proc12 exp12

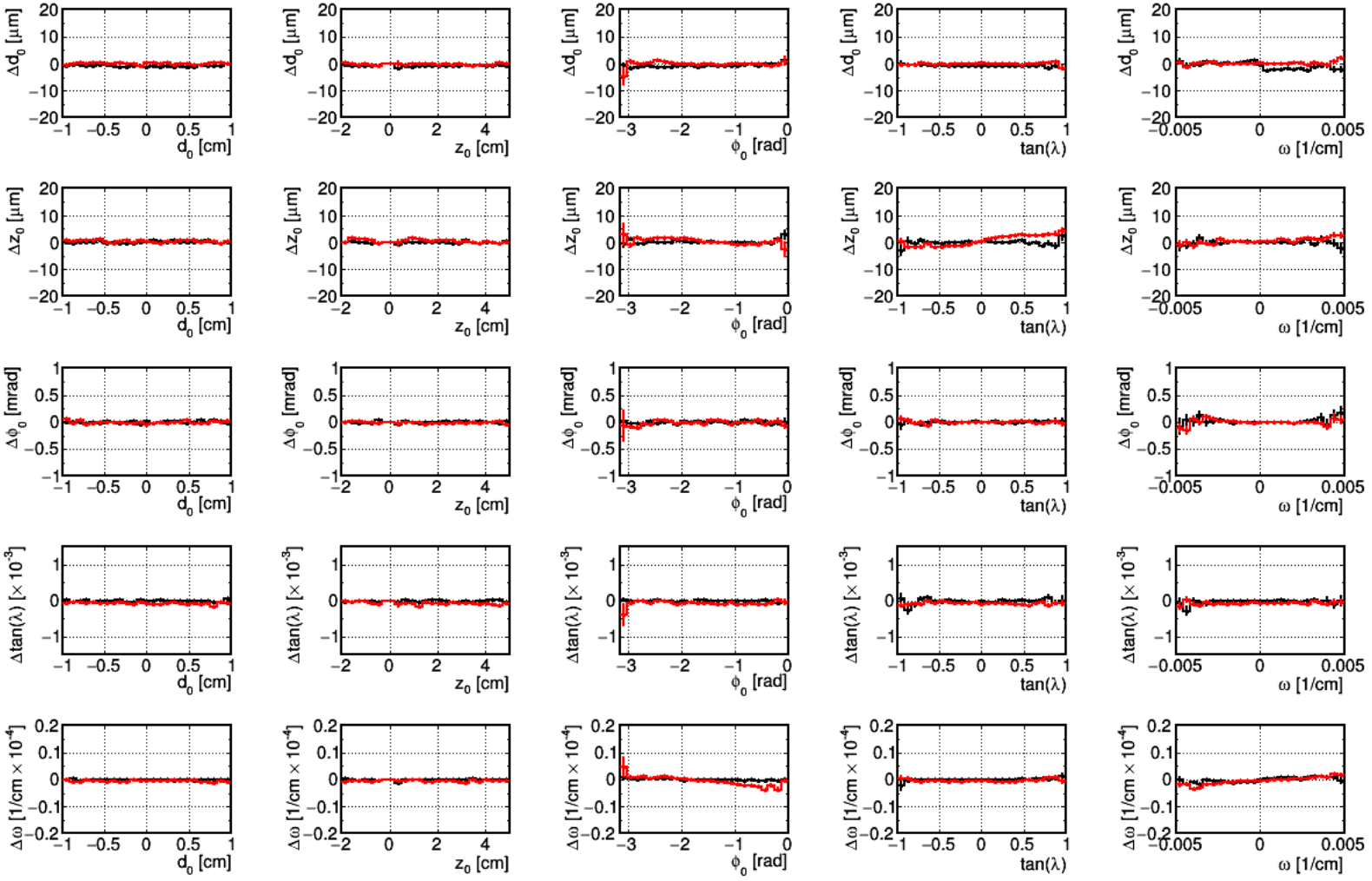
Impact Parameter Resolutions

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



Less than 15%/10% difference in d_0/z_0 remains. Remaining Data/MC difference mainly due to too optimistic SVD resolution in (old) MC and residual time-dependencies.

Correlation of helix parameter biases: MC vs proc12



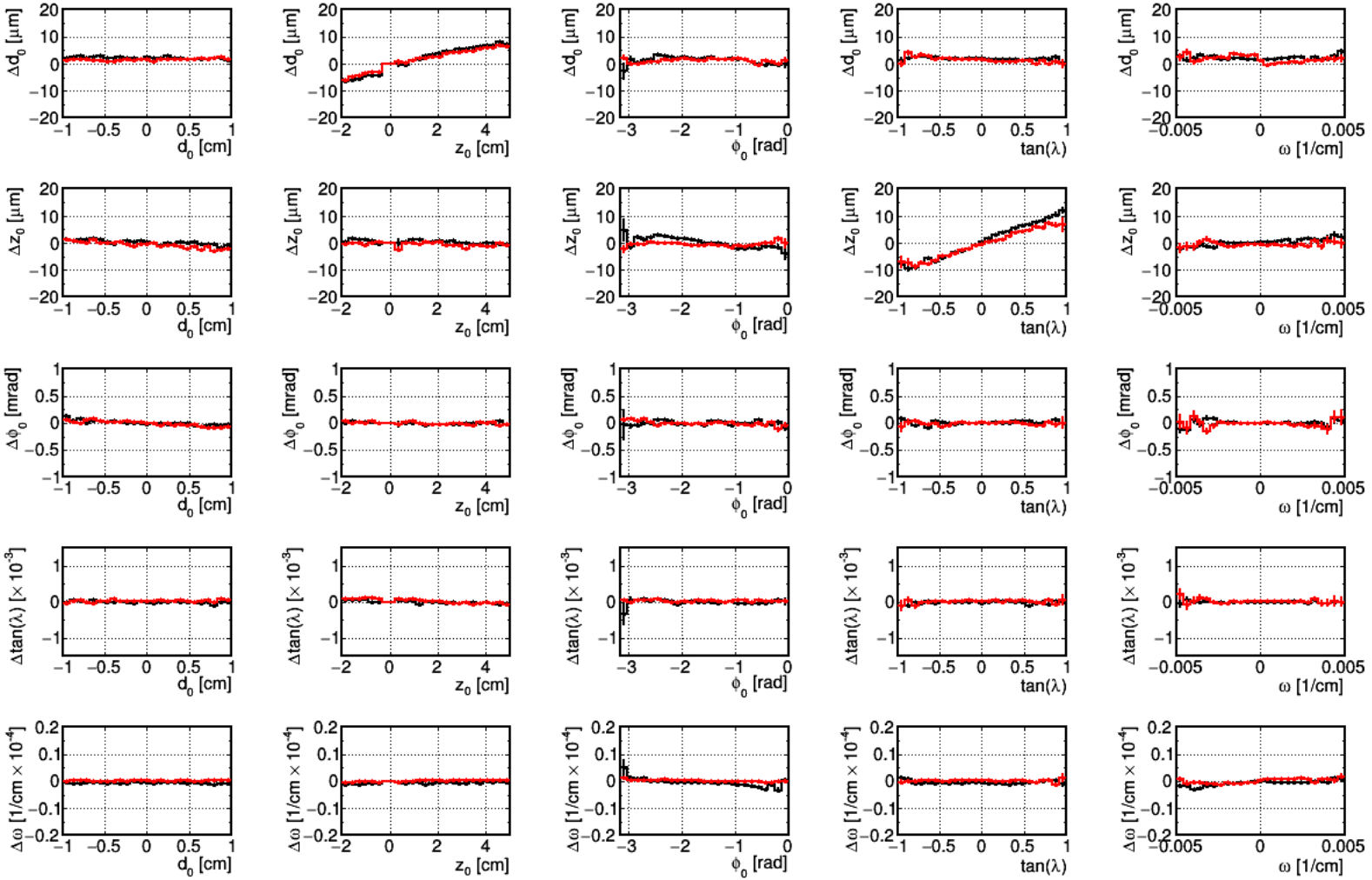
MC

Proc12 exp12

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

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



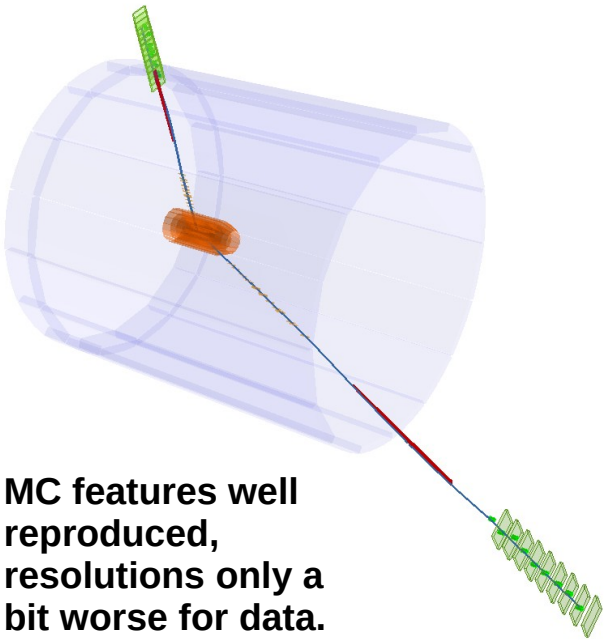
Bias and correlation reproduced

Main correlation well reproduced

Prompt exp12

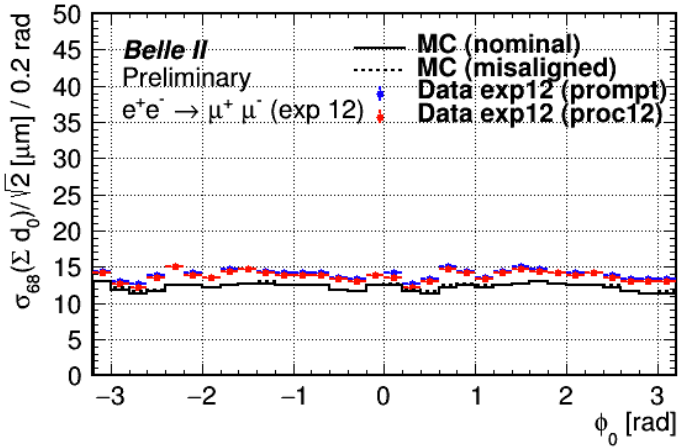
MC With Misal.

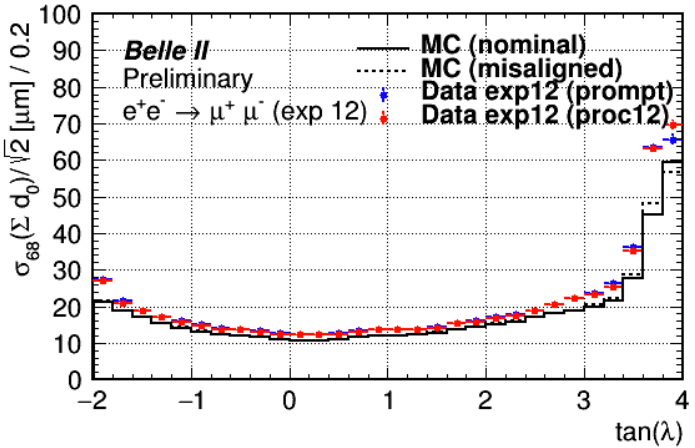
Validation with Dimuons: Angular dep. of vertex resolutions

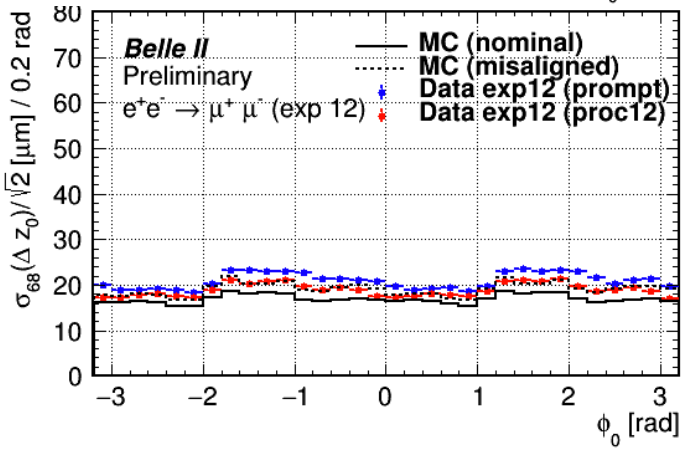


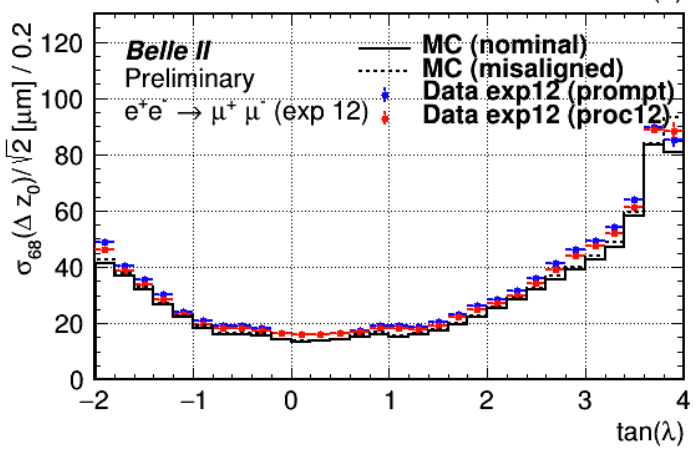
MC features well reproduced, resolutions only a bit worse for data.

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



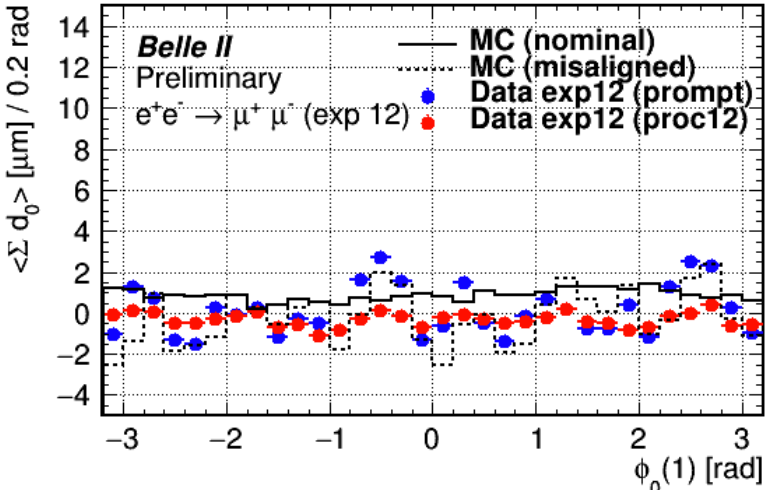


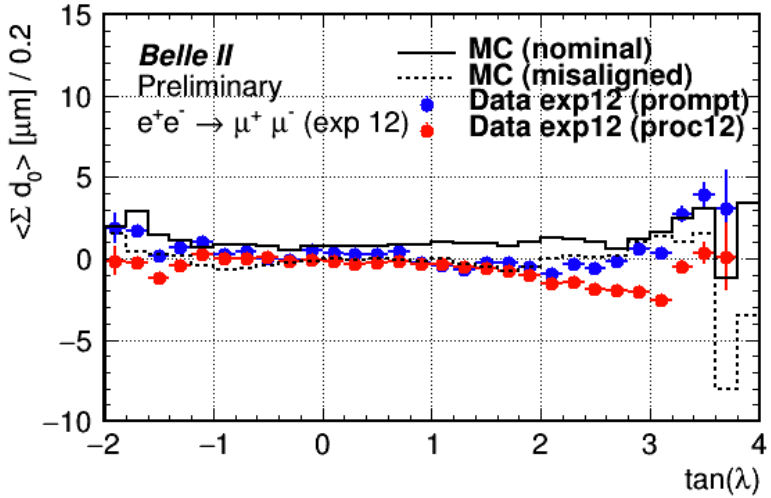




Angles for positive-charge muon candidate

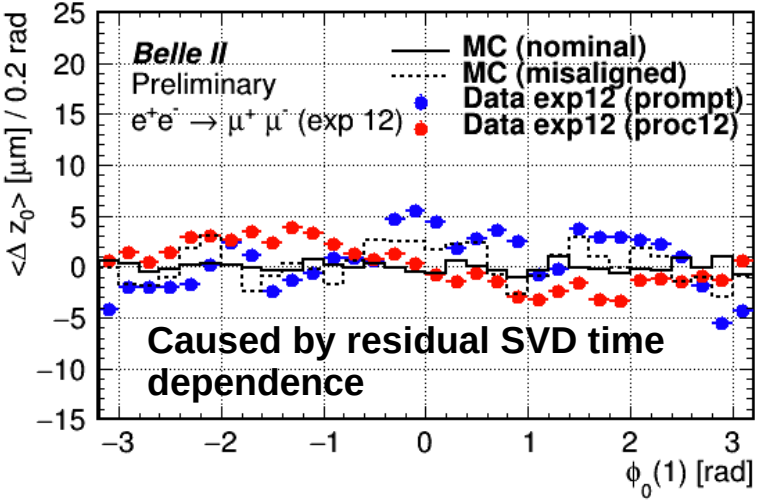
Vertexing systematics for dimuons

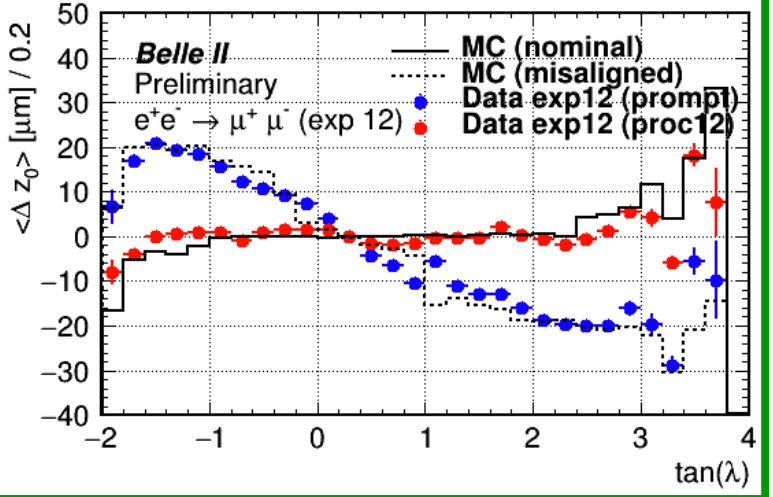




Note that our ideal MC has a bias in d_0 :-)

No significant remaining systematics in proc12

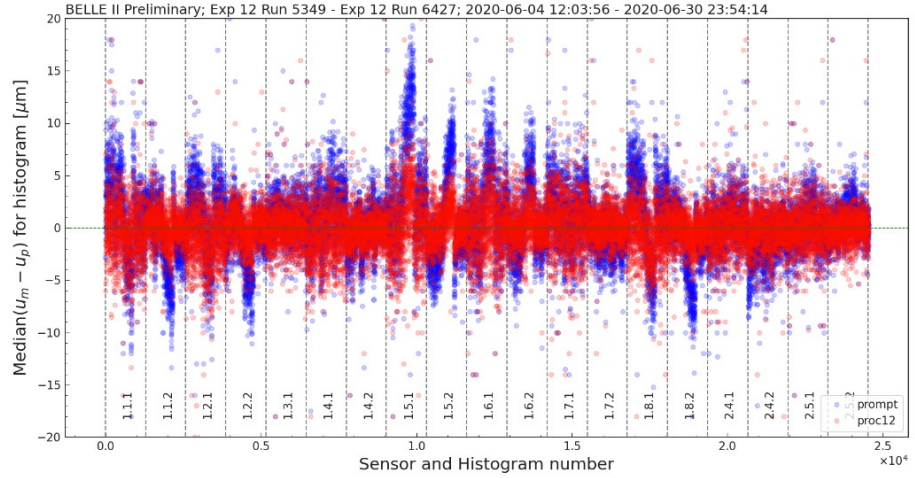


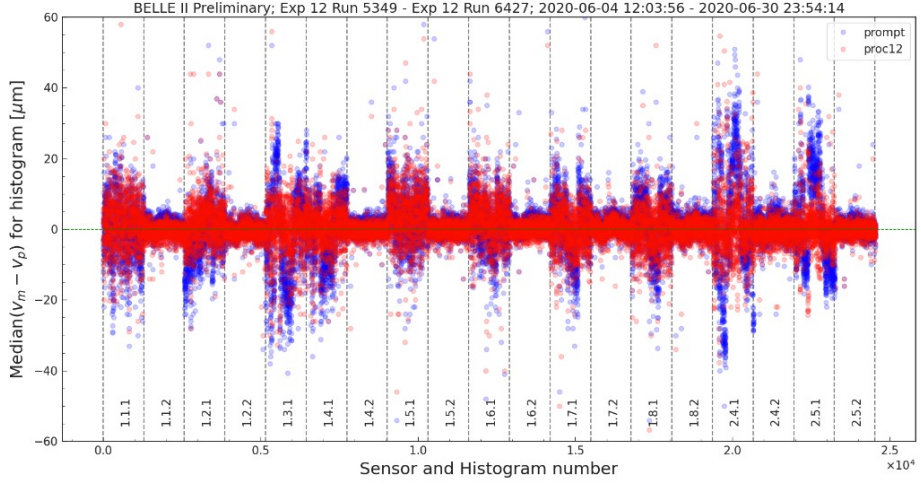


Radical improvement for z_0 bias vs tan(lambda).

Systematics can be well reproduced on MC

PXD Alignment evolution in exp12 reprocessing



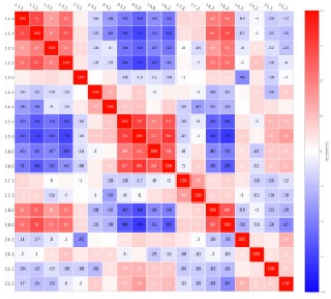


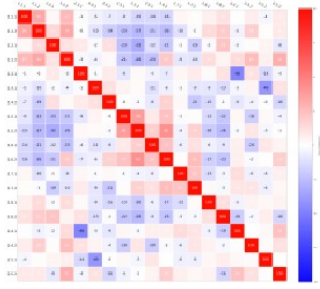
Even with this granularity (about 0.1/fb), alignment sometimes not fast enough to follow all movements

In U-direction, the remaining effects seem negligible

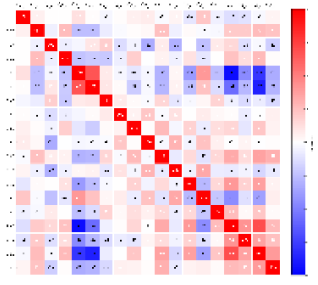
V-direction is worse and forward sensor more affected (due to track&detector topology)

Correlations of residuals

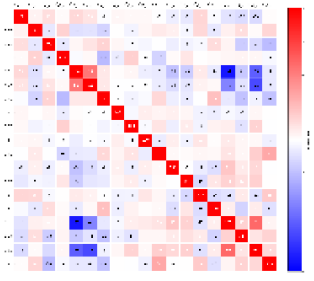




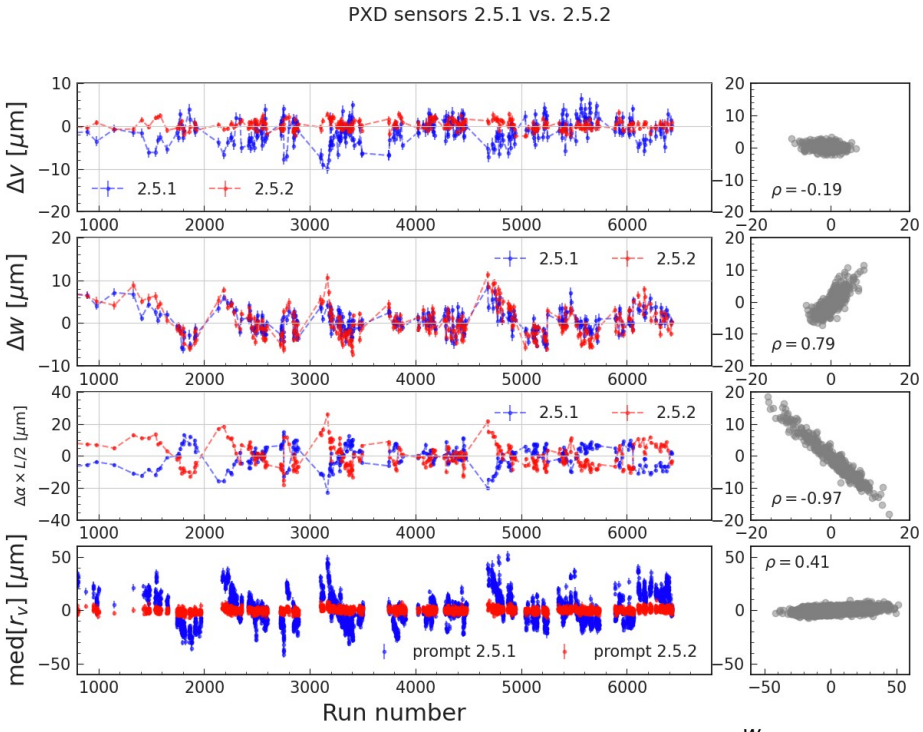
prompt

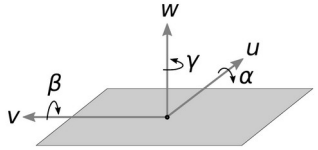


proc12



PXD Alignment evolution in exp12 reprocessing

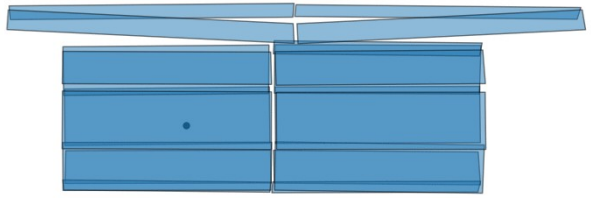




Belle II PXD

Experiment 12 Run 3496 - 3745

alignment corrections × 100

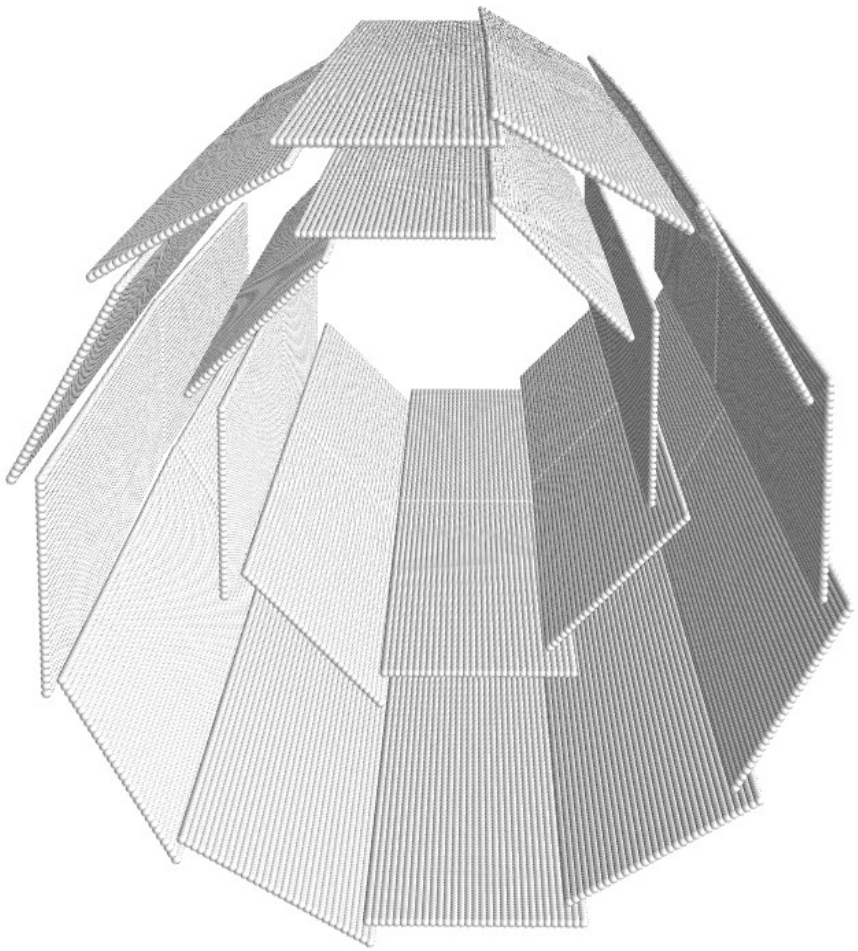


Animated gif:

*Differences to first exp12 alignment shown in animation

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

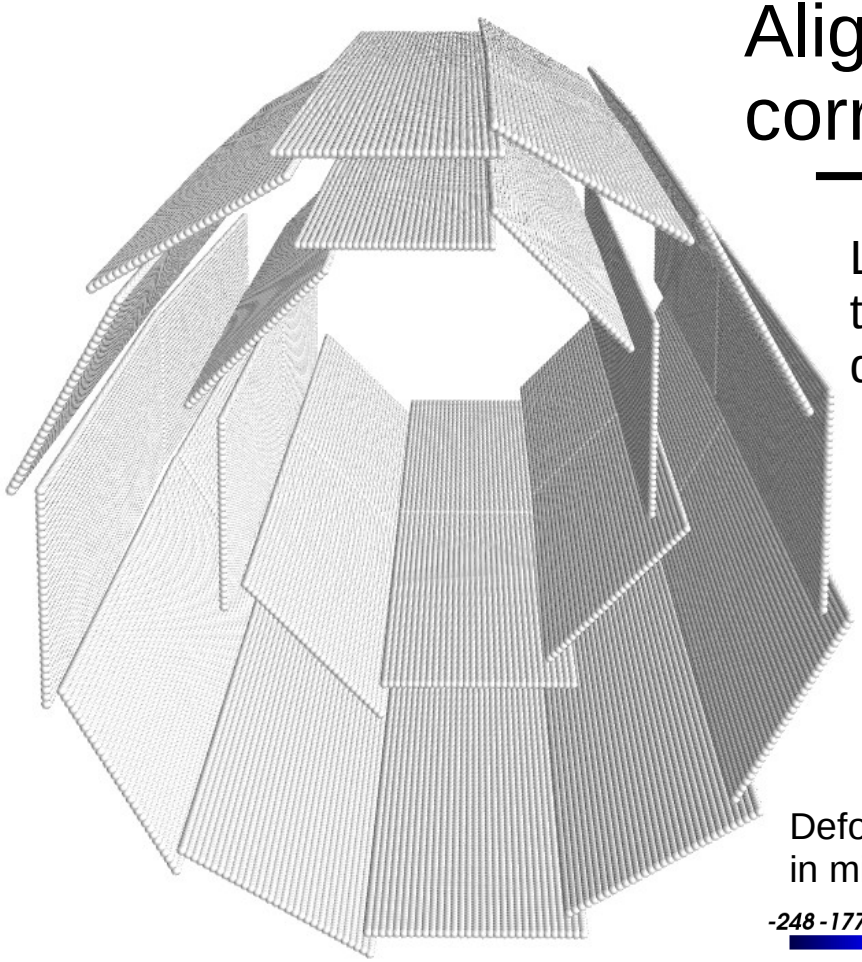
New PXD & Alignment



Real shape of the PXD2 (sensitive areas)

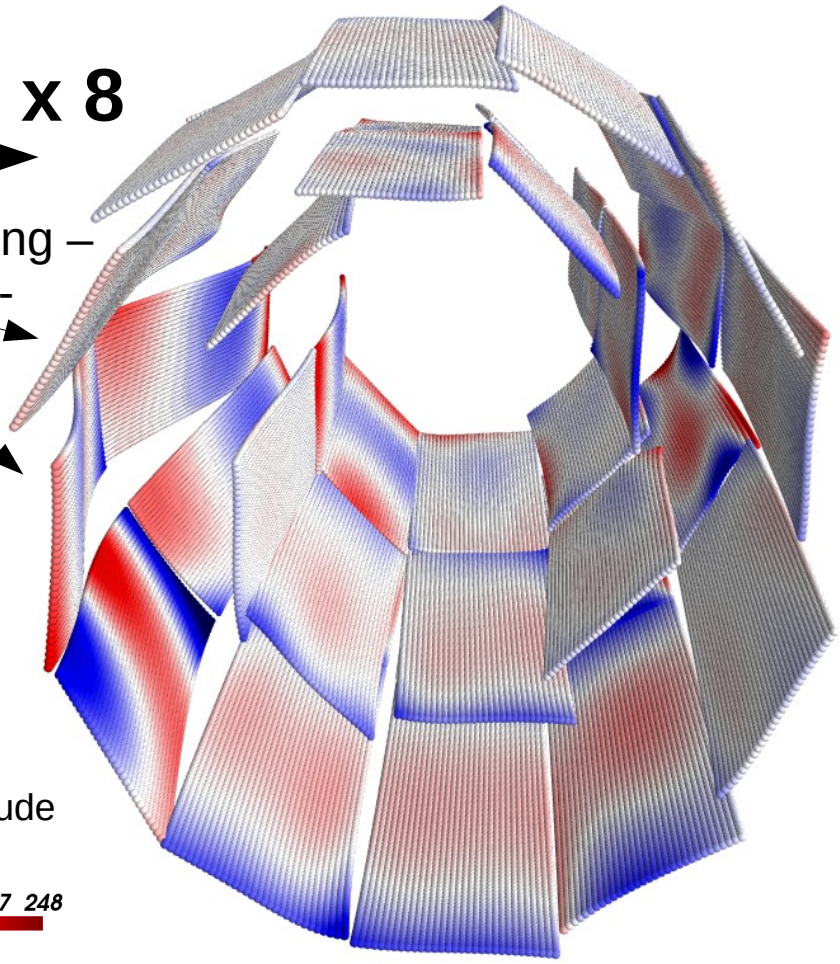
as determined by the alignment during commissioning (B=0T cosmics)

New PXD & Alignment x 8



Alignment corrections **x 8**

Ladder bowing – temperature-dependent

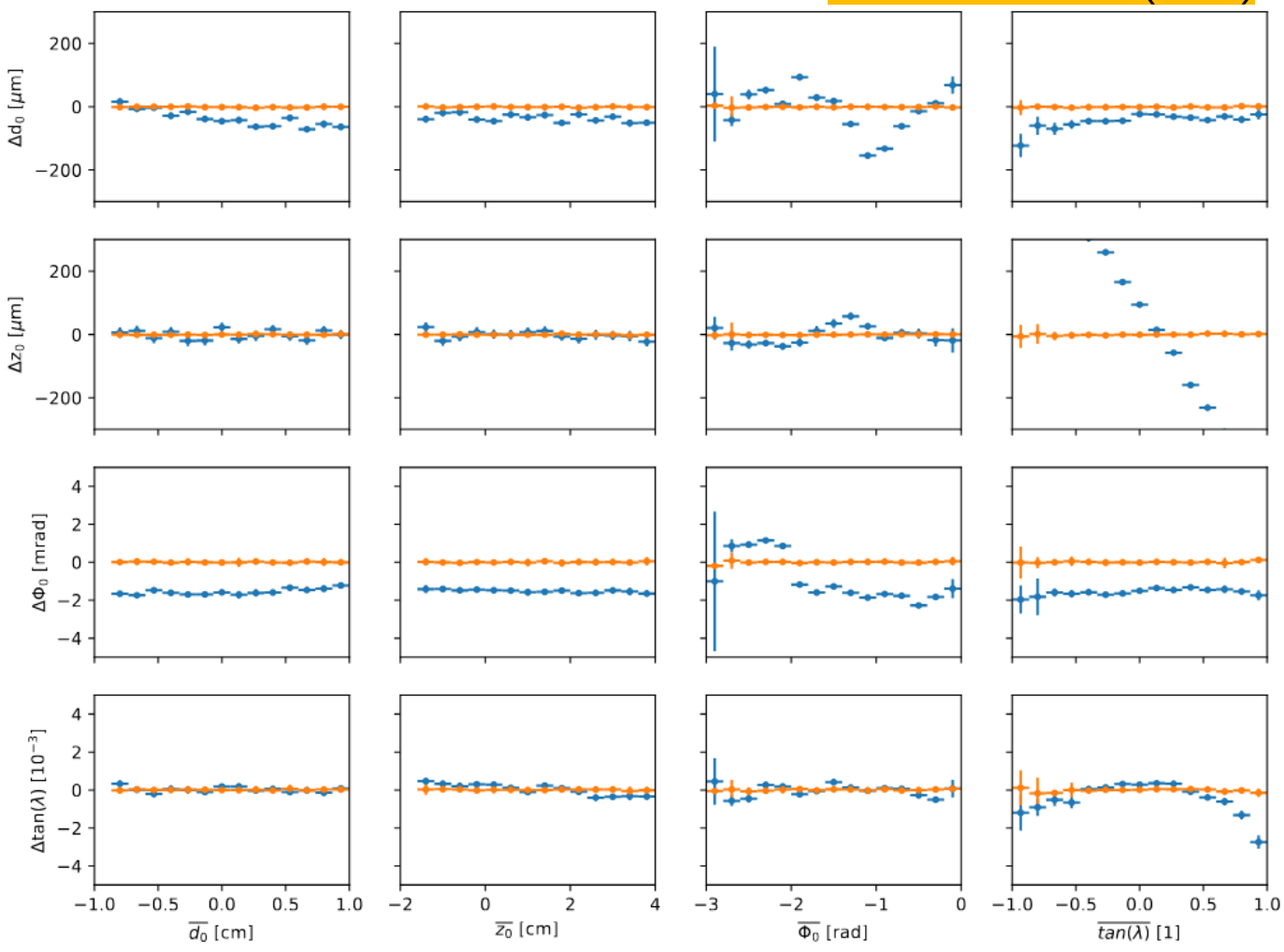


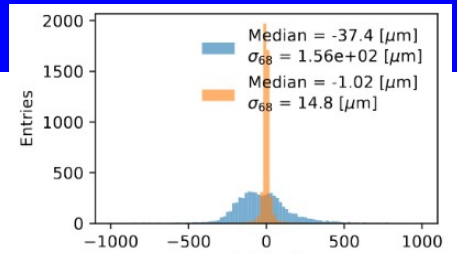
Deformation amplitude in micrometers

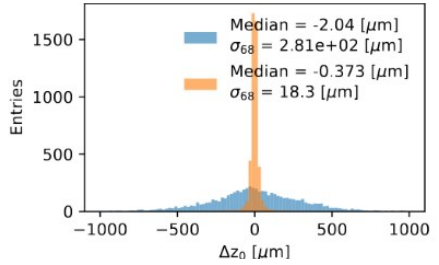
-248 -177 -106 -35 35 106 177 248

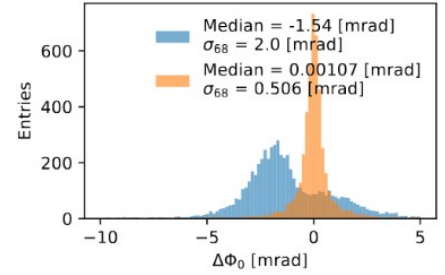
Alignment & Performance with cosmics & B=0T

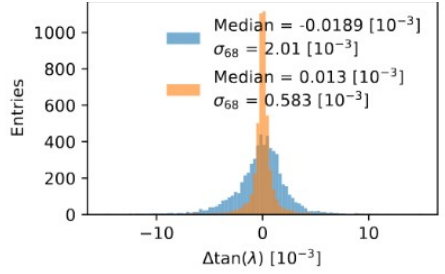
From T. Wilczeck (PRG)





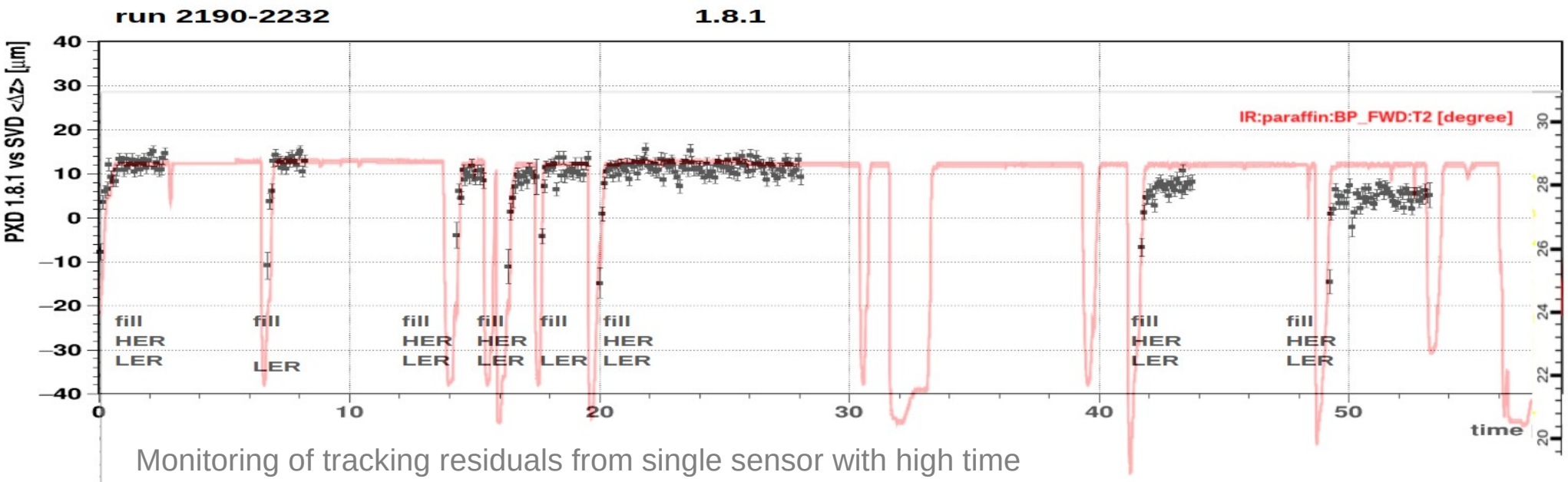






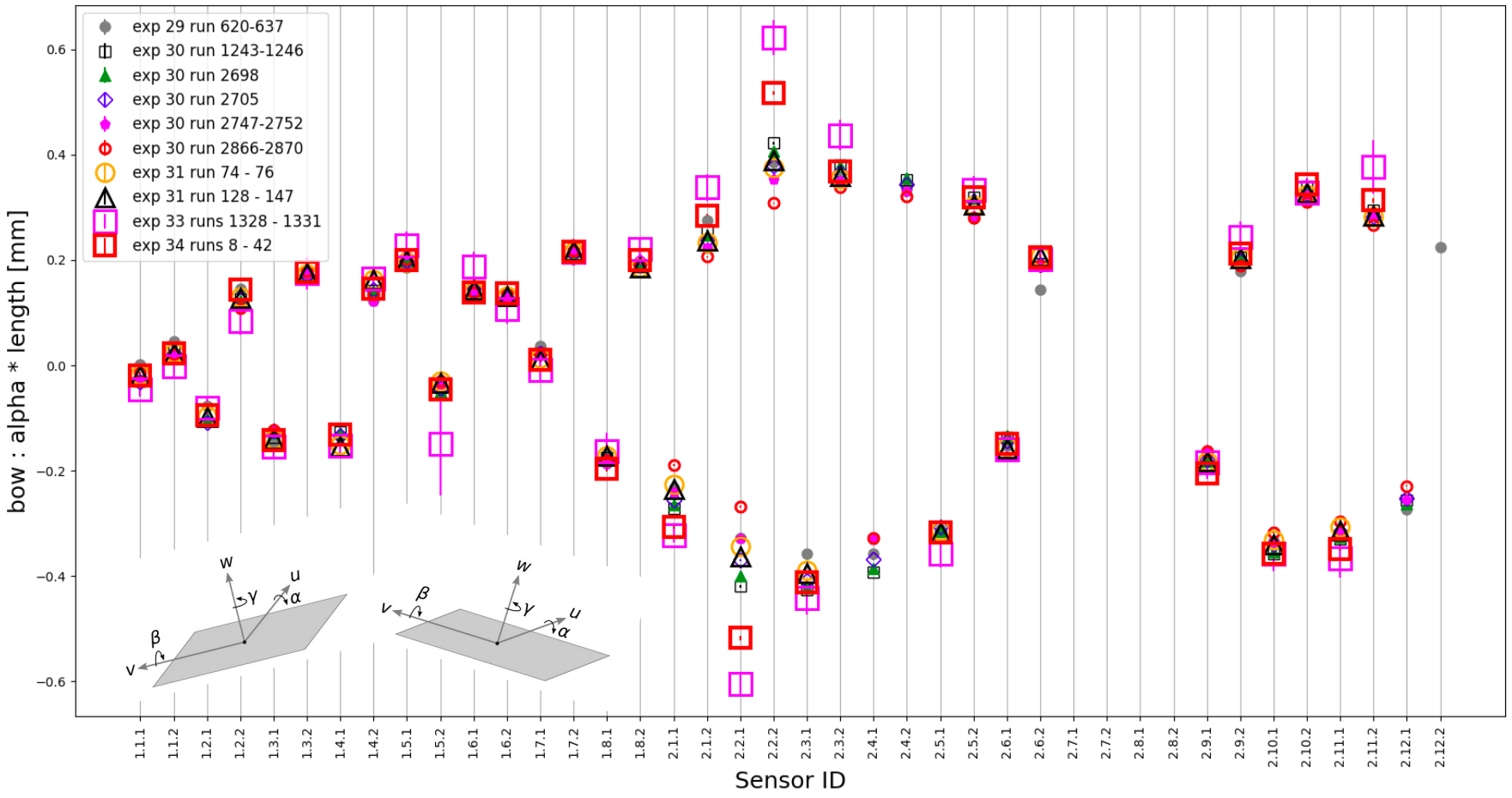
PXD2 & New Alignment Challenge

- 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“

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 :-(

Conclusion & Outlook

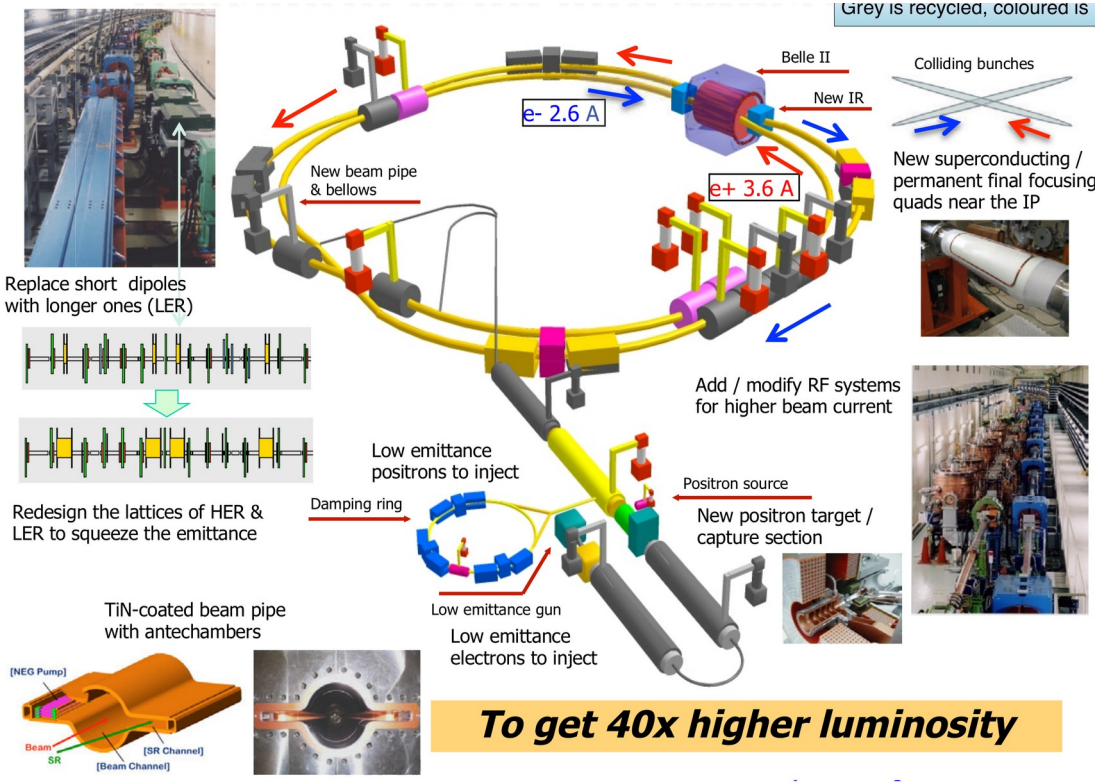
- Precise alignment required for precision physics
- Belle II alignment determines about 60k parameters for pixel and strip detectors and the drift chamber promptly after data-taking
  - CDC layers and PXD&SVD hafl-shells and individual PXD sensors are aligned about every 50k di-muon events (+some cosmics) → 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!

BACKUP

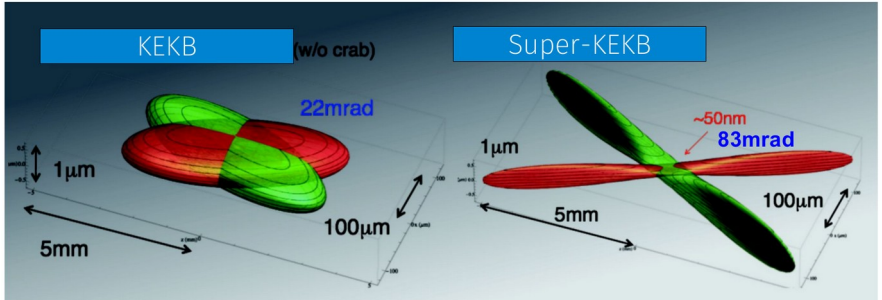
KEKB → SuperKEKB



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

beam current

vertical beta function at IP



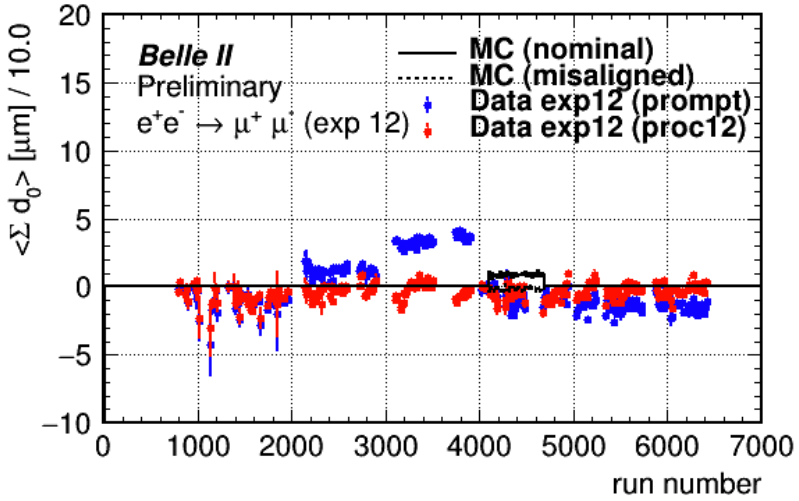
	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

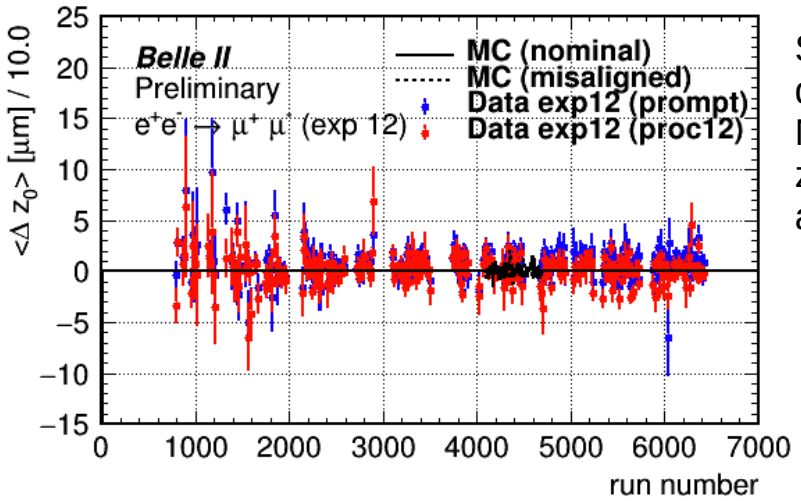
factor 20

factor 2-3

Run dependence of vertex parameter biases and resolutions with dimuons

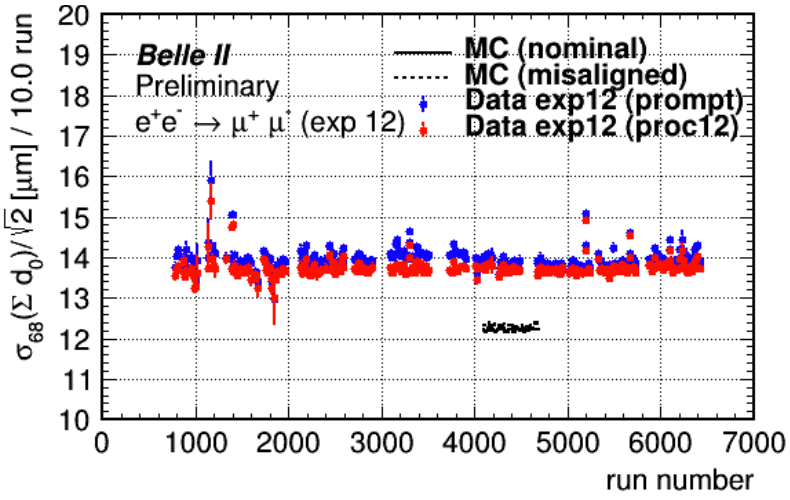
MC withut background

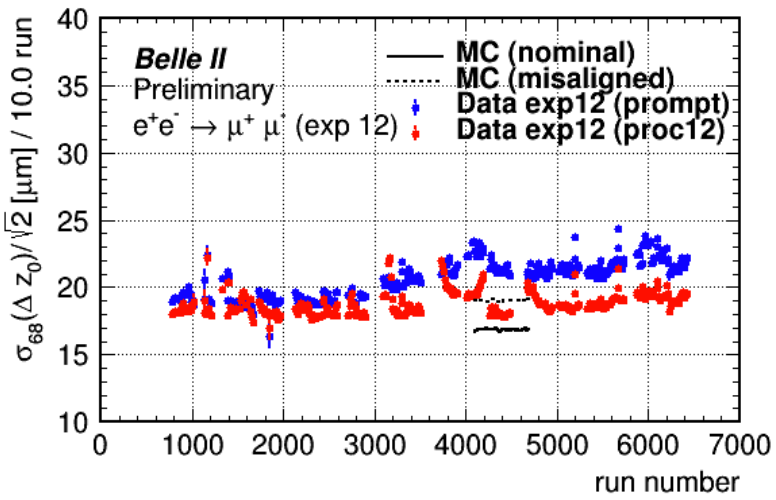




Significant improvement in d0 time-dependent biases. Not much can be seen in z0 (good average already at prompt)

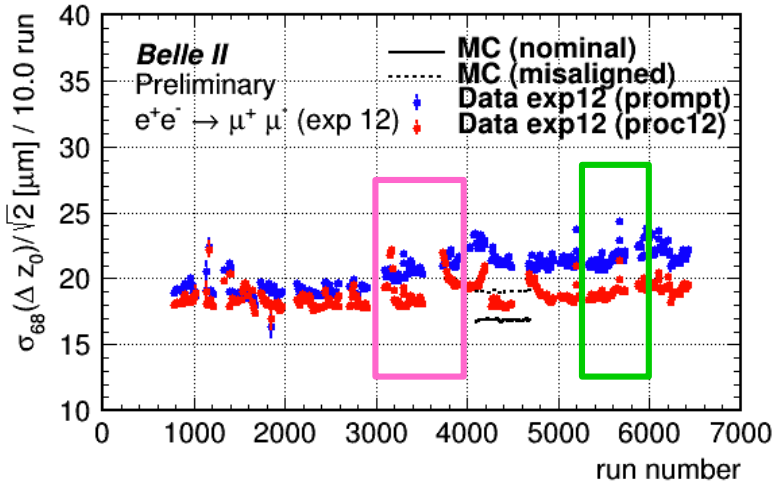
Resolutions improved in proc12

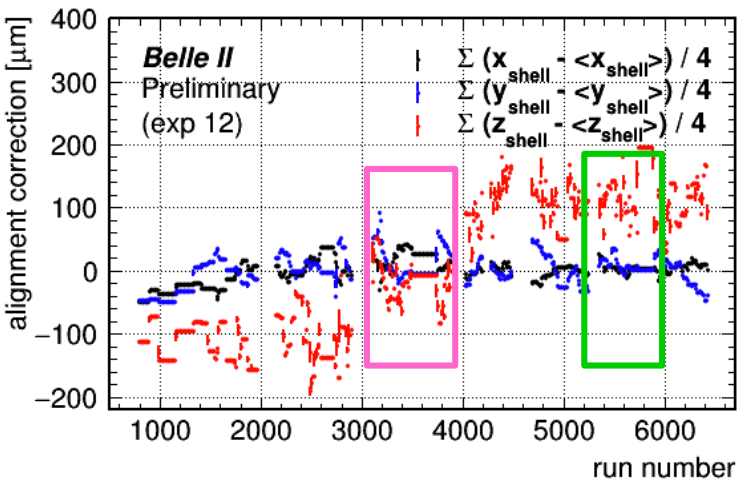




Remaining time-dependence in z0 resolution **probably caused by residual SVD movements – long relaxation (days) after QCS on/off?**

Residual SVD time-dependence after major events



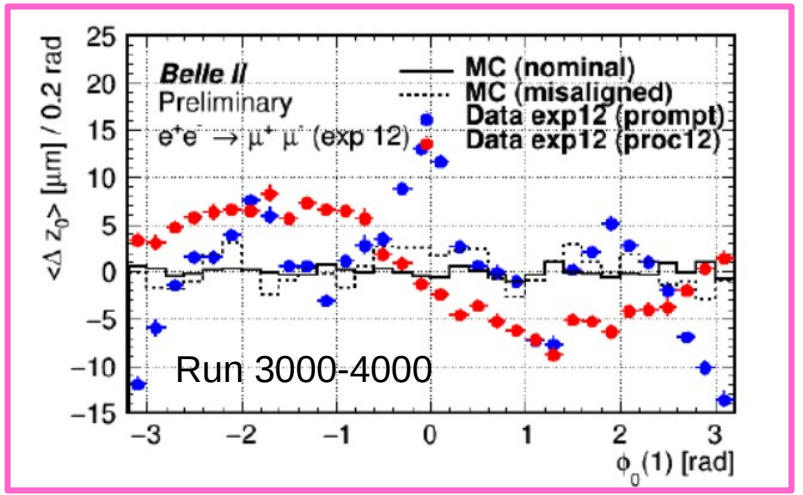


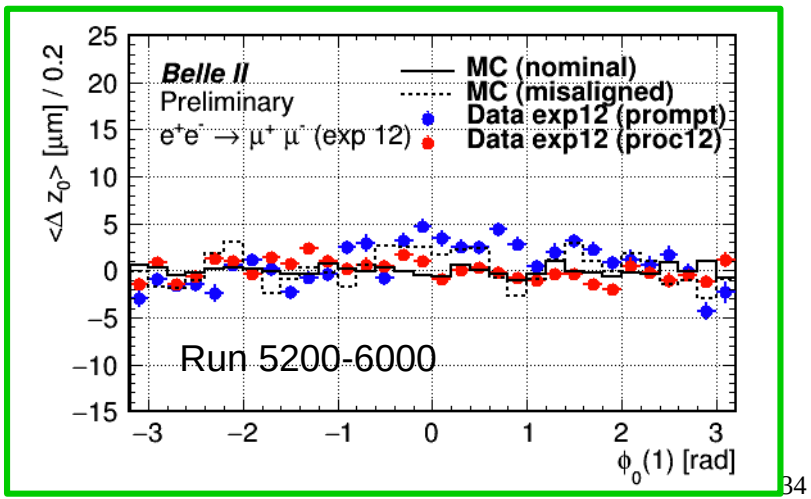
It seems the major remaining bias comes from a „typical“ deformation in **SVD**: Not corrected, because SVD sensors are aligned once per bucket (shells each run)

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

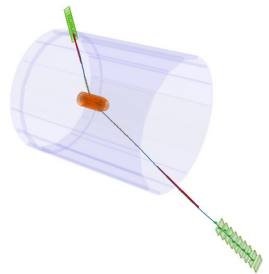
This is followed by continuous relaxation over several days… bad!!

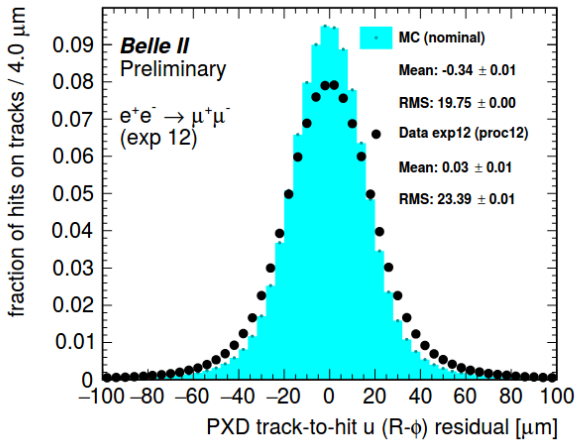
Looks a bit like ladders shifting in z (5-10um in L3, maybe 20um in L4+, but not consistently

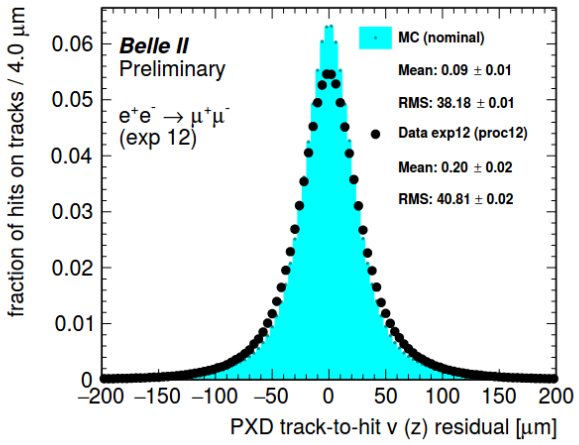


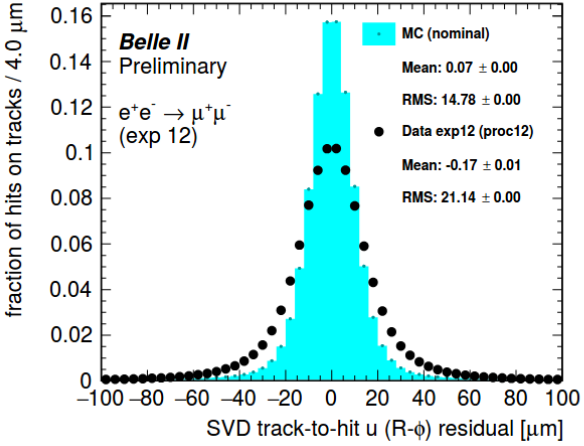


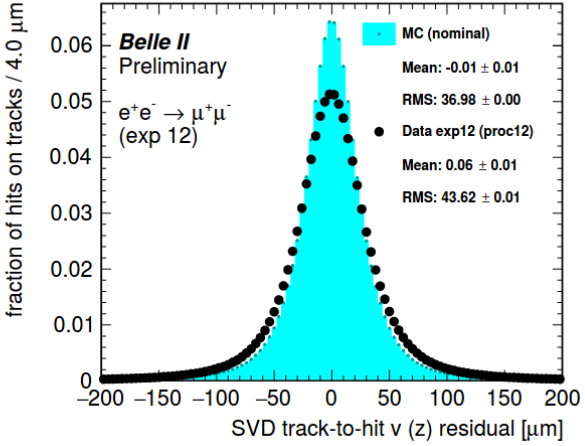
Alignment basics: residuals











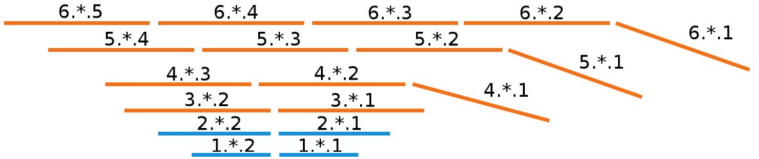
Integrated over all PXD/SVD sensors and mumu_tight skim files used for exp12 alignment validation

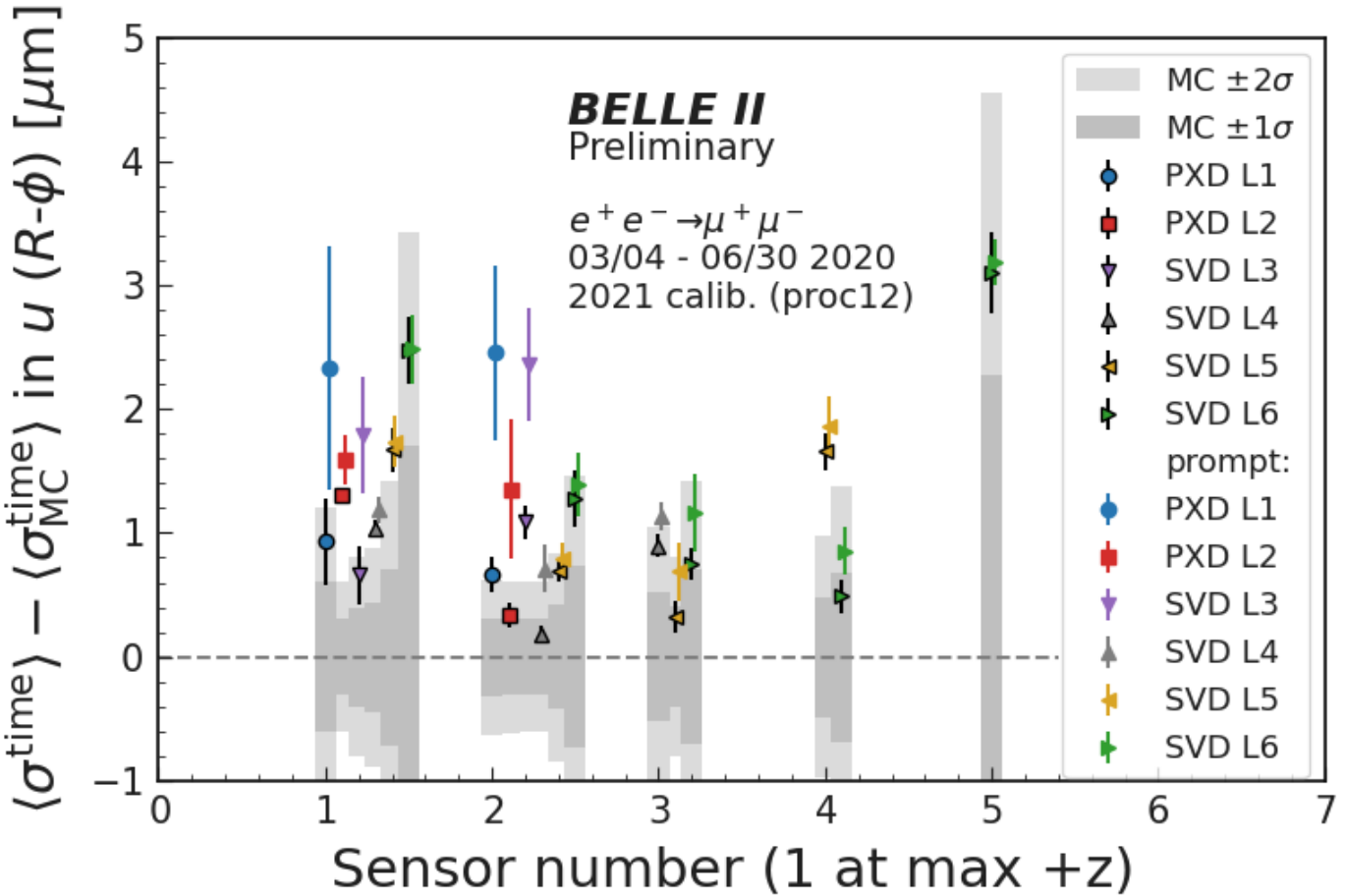
Much larger discrepancy for „u“ probably comes from SVD

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

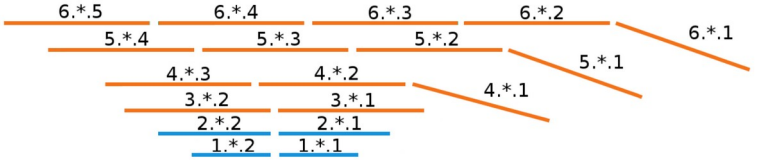
Cannot be caused by any kind of misalignment (confirmed)

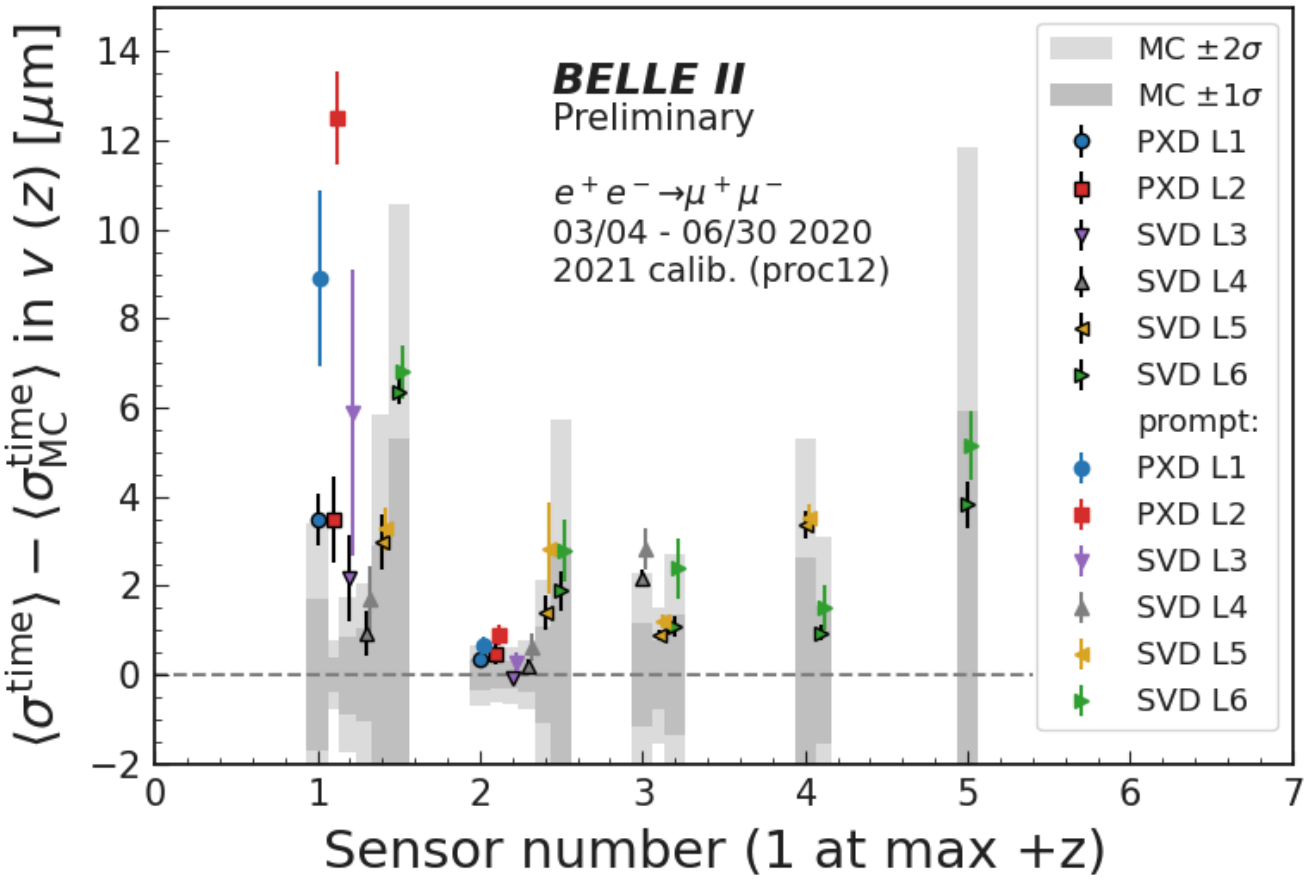
Instability in U



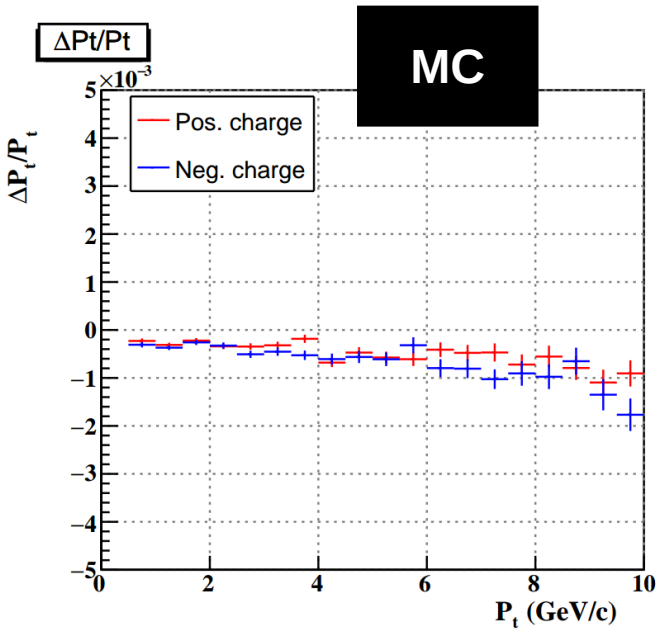


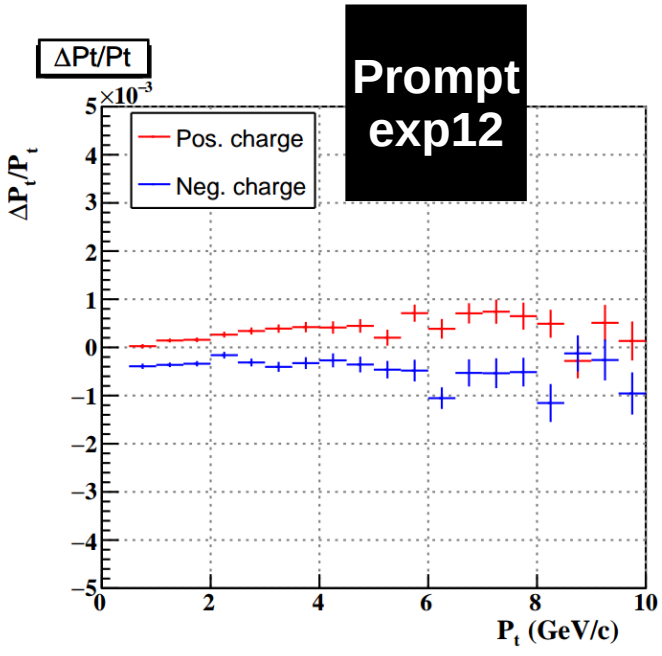
Instability in V

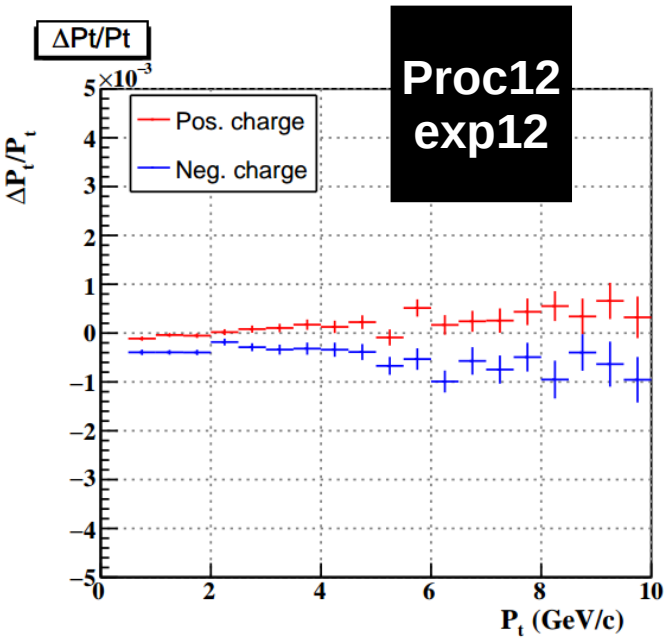




Charge-dependent momentum biases for cosmics







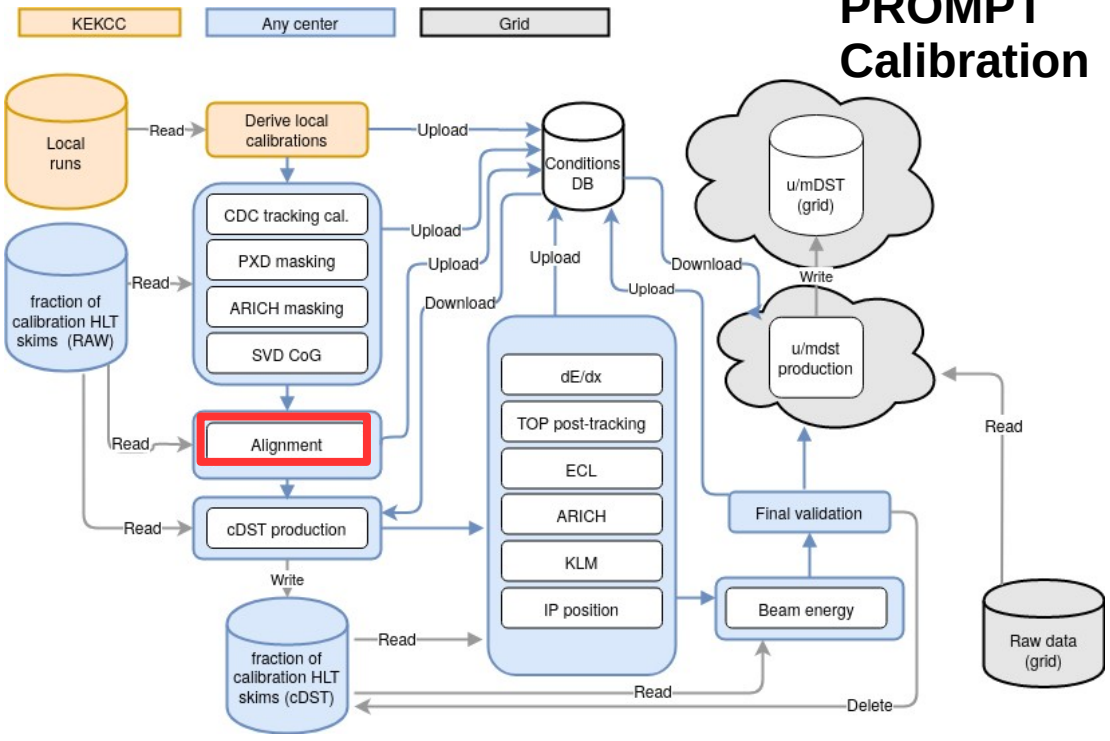
MC does have a larger bias, but not charge-dependent

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.

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)

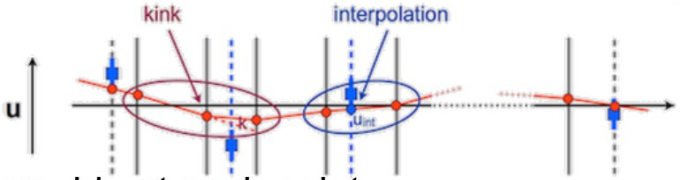
Alignment: aim to provide the best possible performance for physics already in prompt calibration

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)

Performance with cosmics & B=0T (PXD2)

From T. Wilczeck (PRG)