Belle II (PXD) Alignment

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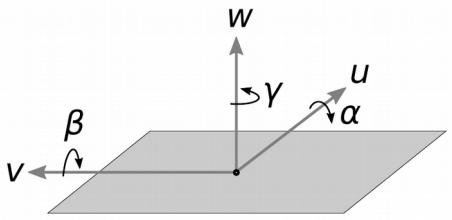
Overview

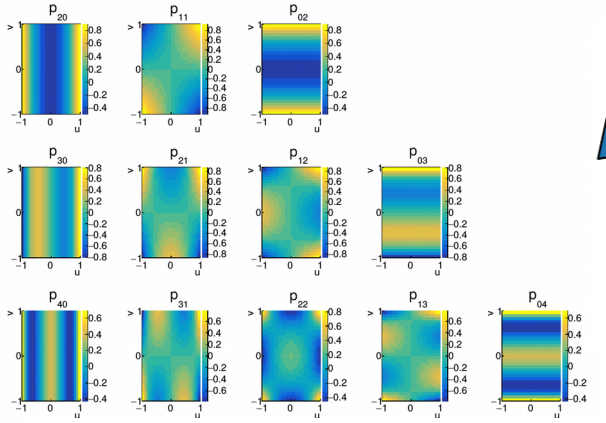
- Introduction
- PXD from alignment point of view in Spring 2020 and 2021 reprocessing (proc12)
- New automated combined PXD+SVD+CDC alignment
- Recent PXD performance with the new alignment
- Summary

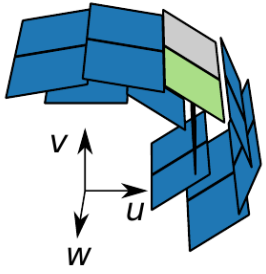
Introduction

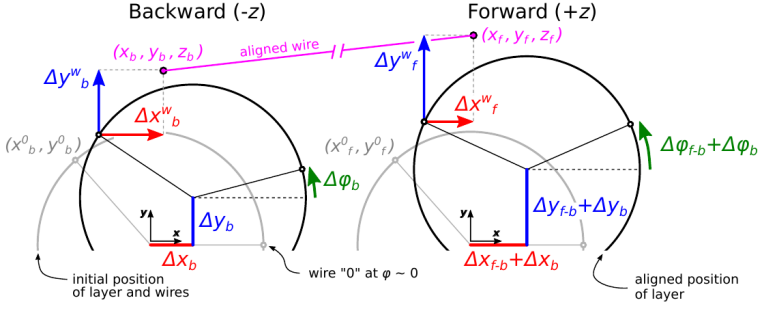
* KLM is also using Millepede II but not simultaneously with tracking detectors, only afterwards (currently)

- Alignment method: Millepede II
  - Subdetectors: PXD, SVD, CDC *
  - Full exact solution of the alignment problem
  - All subdetectors always aligned together
    - All correlations automatically resolved
  - Up to 60k parameters including CDC wires
  - Sensor deformations up to quartic
- Major update since 2021c
  - Validated by 2021 reprocessing (proc12) of Spring 2020 data
  - Advanced alignment with run-dependence deployed as regular prompt calibration



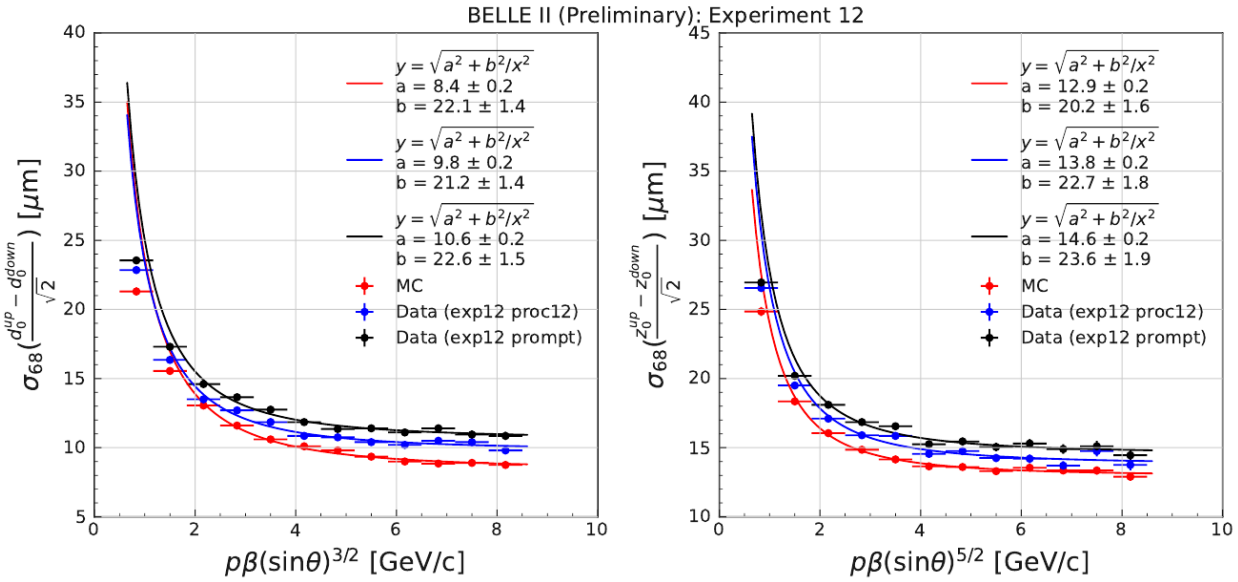






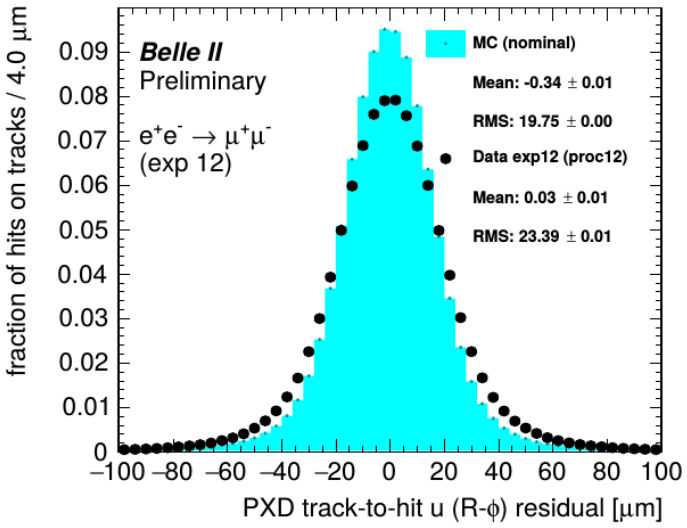
PXD in 2021 reprocessing alignment

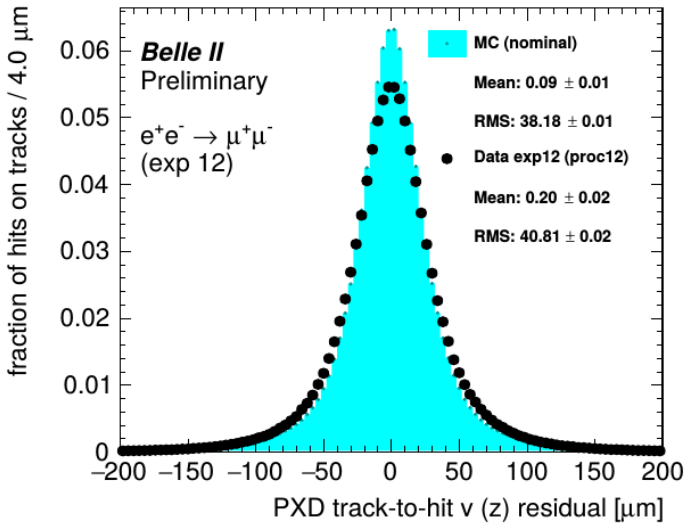
- Data from Spring 2020 used for extensive validations
  - Experiment 12: 03/04 – 06/30 2020
- Evaluated performance of reprocessing alignment
  - Full realignment with CDC wires + run-dep alignment
- Studies of (residual) time-dependence



Errors for points as sigma_68/sqrt(N) shown but mostly not visible

Integrated residuals: data vs. MC

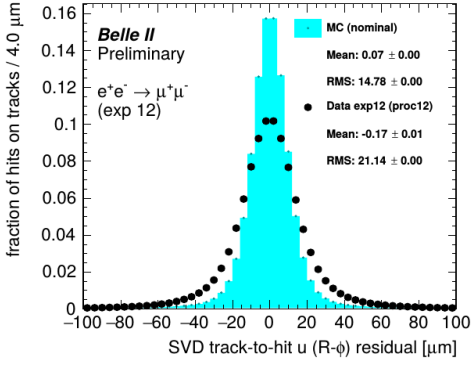


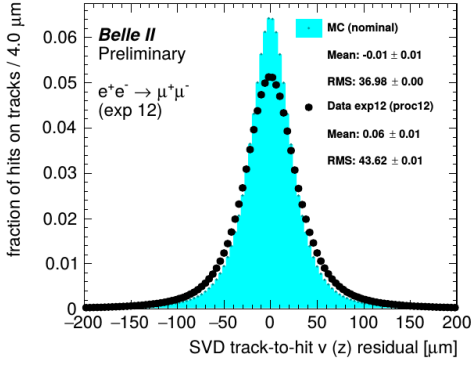


Integrated over all sensors and dimuon data of exp12
→ very large statistics – errors not shown

Alignment not reponsible for most of the data/MC difference

Mostly SVD effect:
Too optimistic SVD sensor resolution on MC





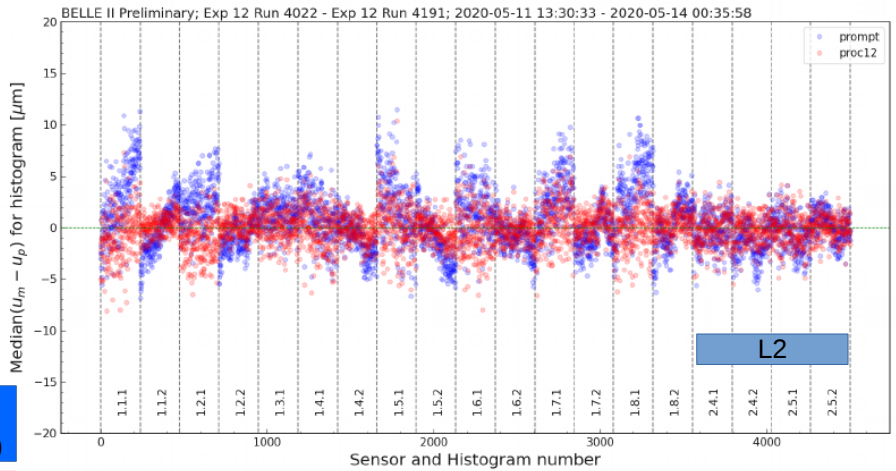
Evolution of median residuals per each PXD sensor

2.5 days

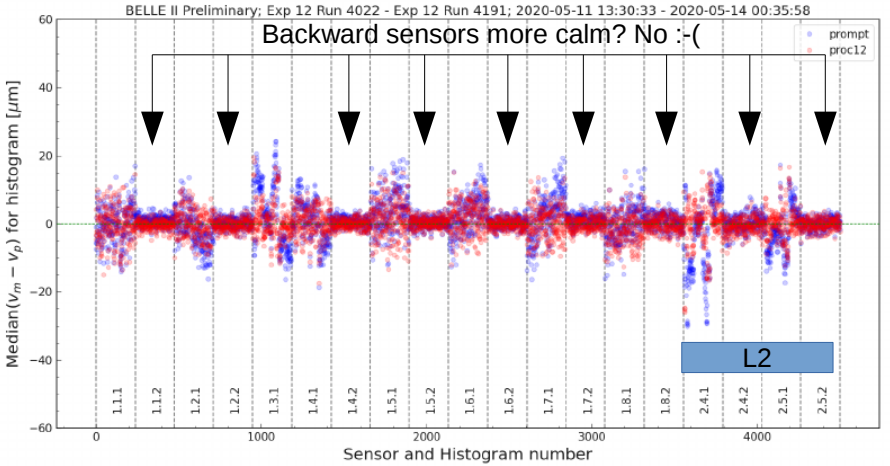
prompt
= no rundep

proc12
= rundep

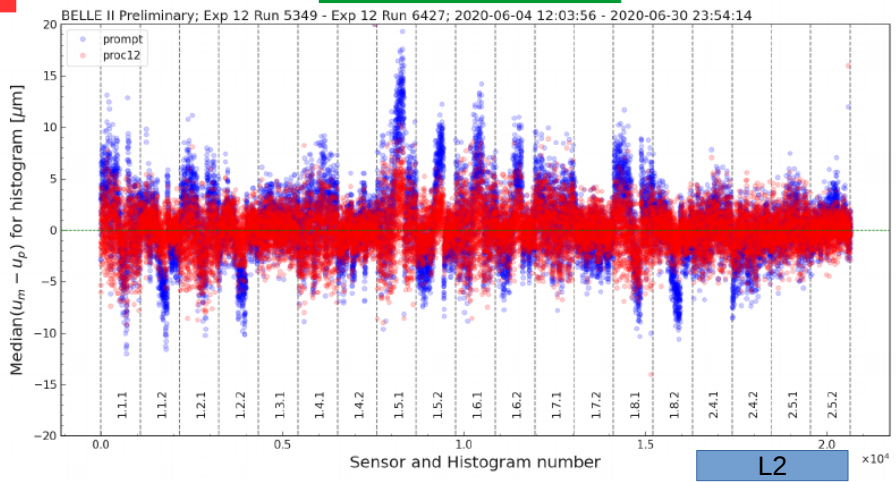
~25 days

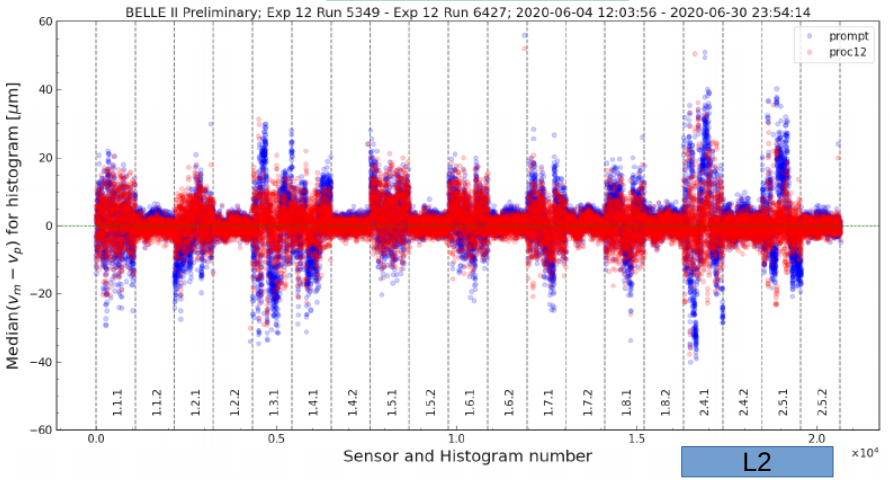


U (R-phi)



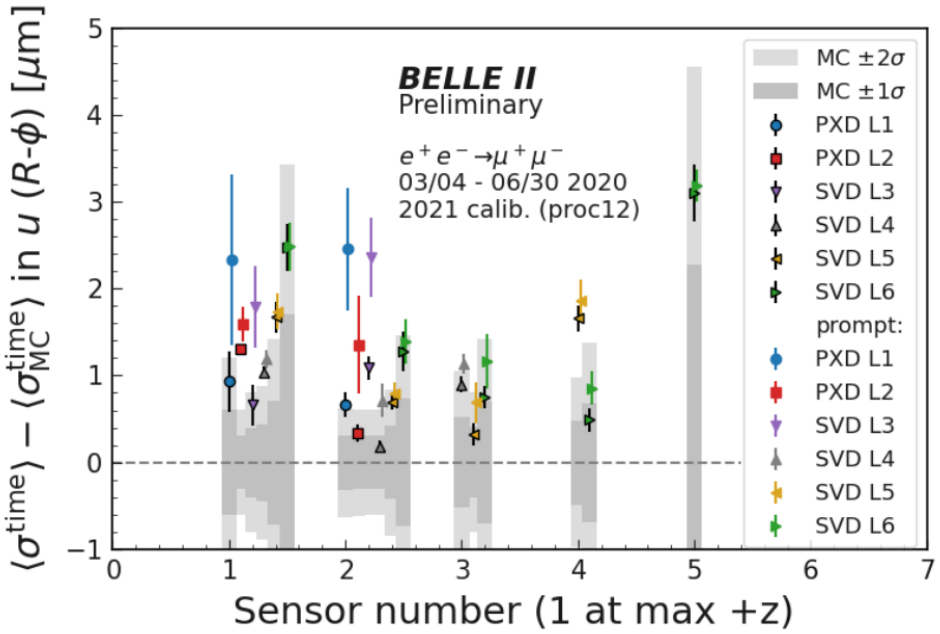
V (Z)

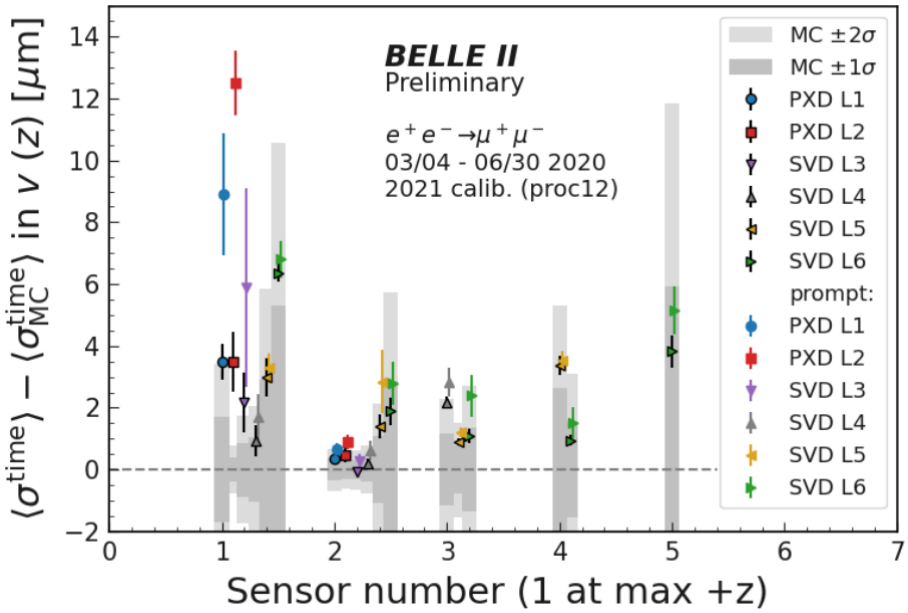




Estimated time-dependent instability from dimuons

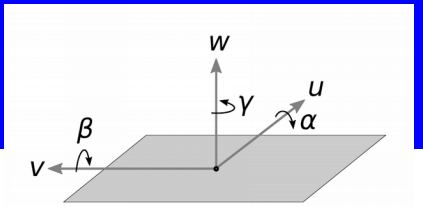
- PXD L2 shows very significant instability before reprocessing



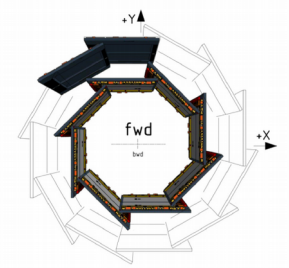


Forward sensors more affected due to large incidence angles of dimuon tracks
At backward sensors, the effect gets averaged for residuals
→ need alignment to decouple which degrees of freedom are responsible!

Bowing in L2

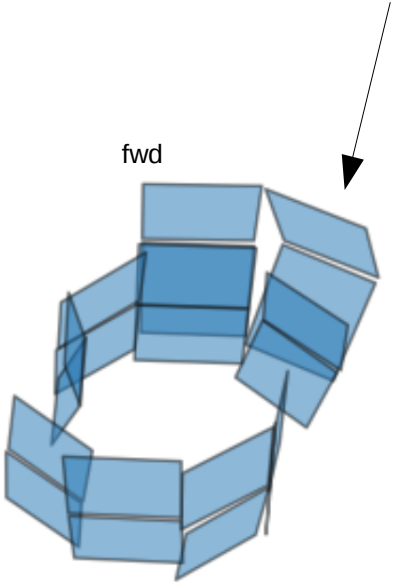


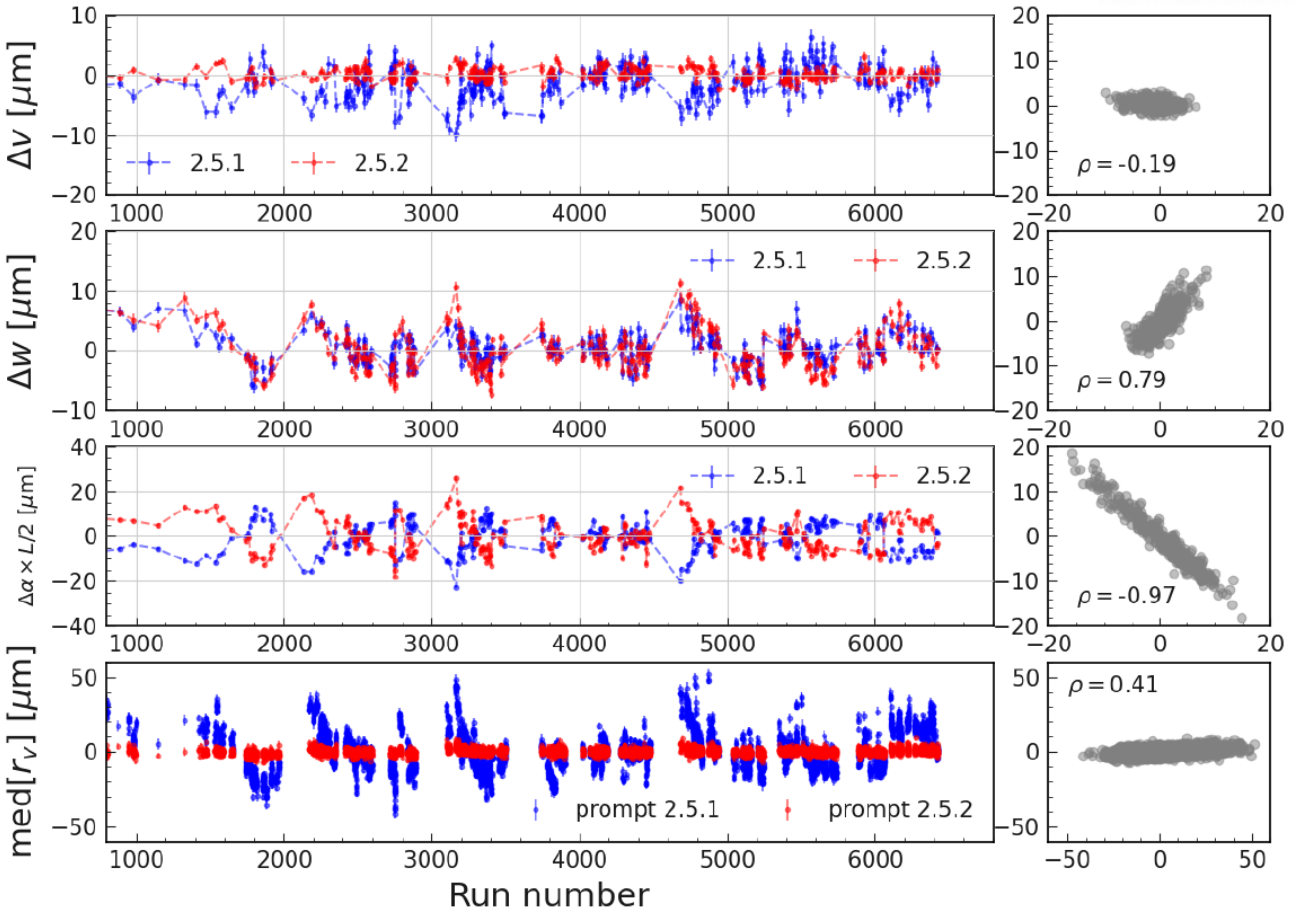
PXD sensors 2.5.1 vs. 2.5.2



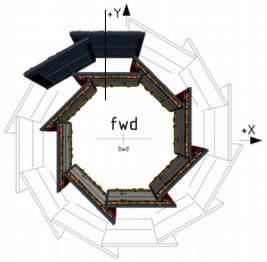
Exaggerated view of total PXD misalignment

The time-dep values are relative to time-indep, the total angle never reverses!

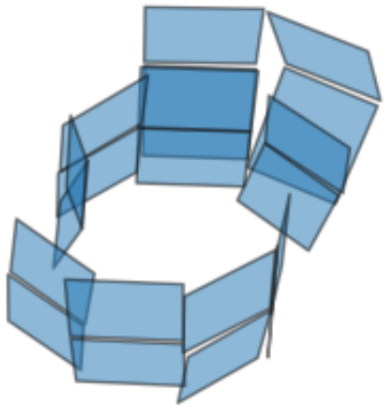




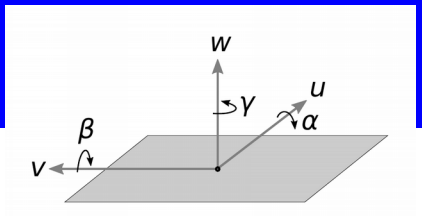
L1 versus L2: forward



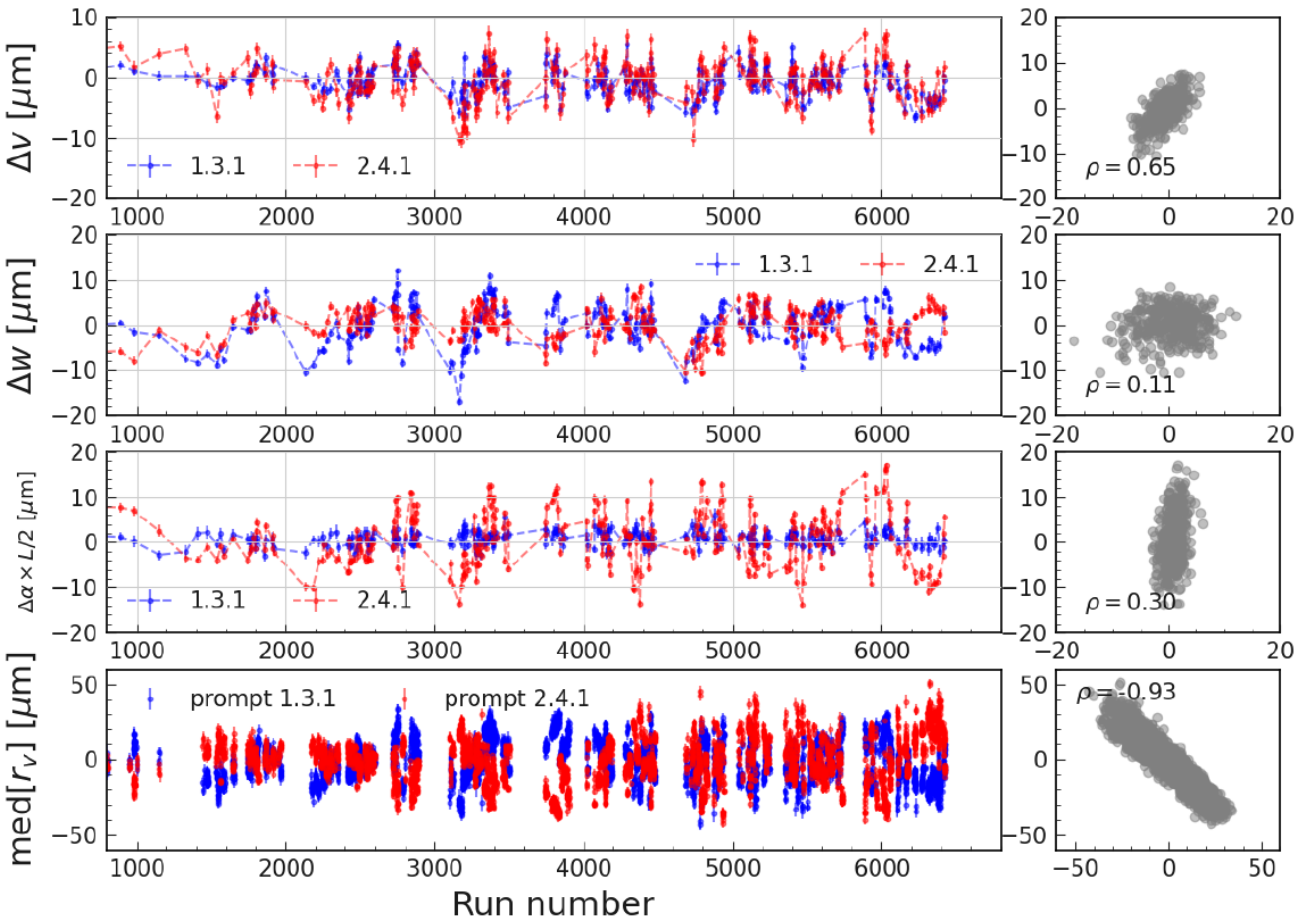
fwd



bwd

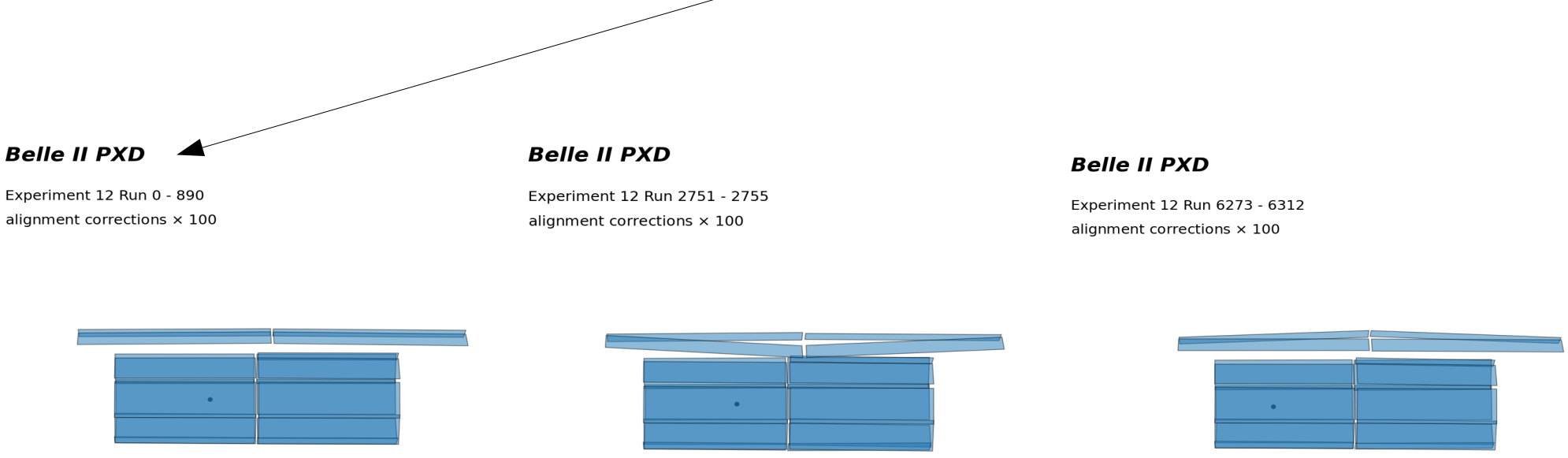


PXD sensors 1.3.1 vs. 2.4.1



Animation

- See
  https://www.dropbox.com/s/s1xs7qzyb9n5fvg/pxd_exp12.gif?dl=0
- Relative to first alignment in exp12



The new prompt alignment

N.B.: **Prompt** calibration

- Automated using Airflow, done in **buckets** (usually two weeks)
- BNL calibration center
- Many calibrations, not just alignment

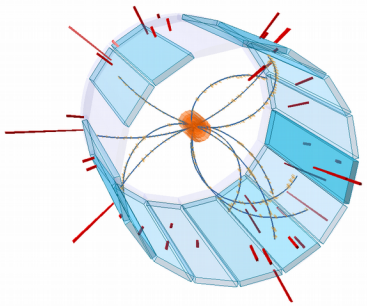
- Almost exact copy of the proc12 reprocessing configuration
- Deployed on Airflow since 2021c (Autumn), exp 20, bucket26
  - Now bucket32 running
  - Up to bucket31 shown in this talk

Full average alignment per bucket for all params

400k events

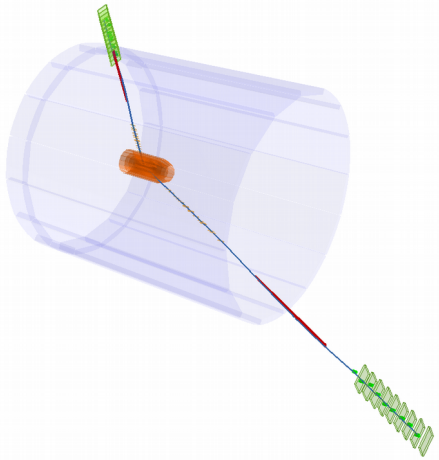
Hadronic events

+ off-IP events mixed 1:1



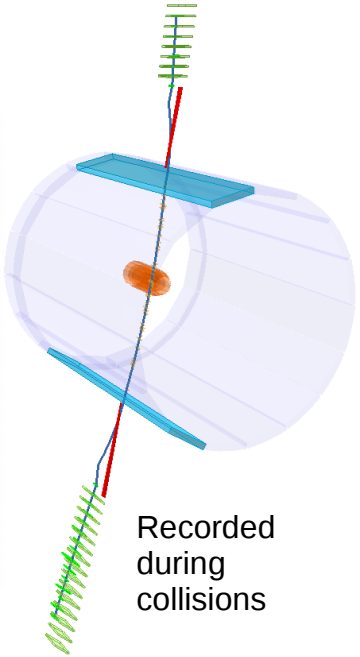
1.5M events

Di-muon events (with IP constraint)



0.7M events

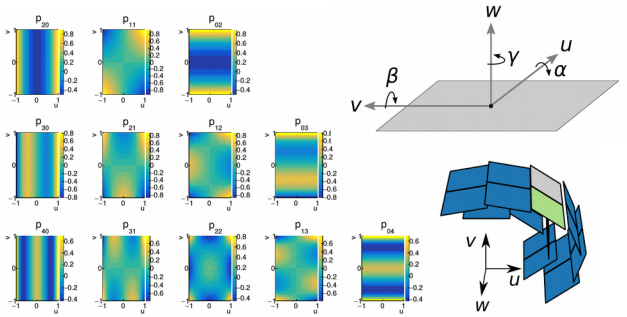
Cosmic events (merged tracks)



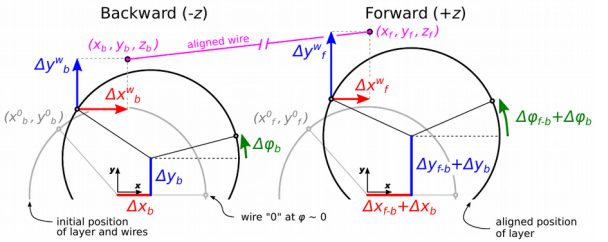
Recorded during collisions

MPII

Millepede II with decomposition (exact solution)



All sensors, deformations, half-shells



CDC layers and all wires

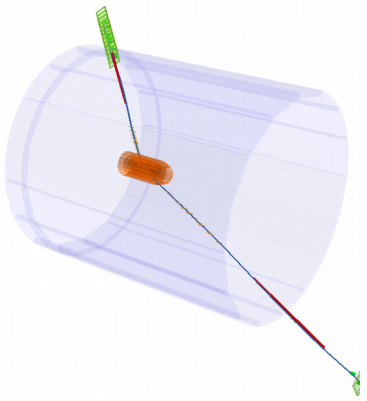
Best average value per bucket for more than 55k parameters

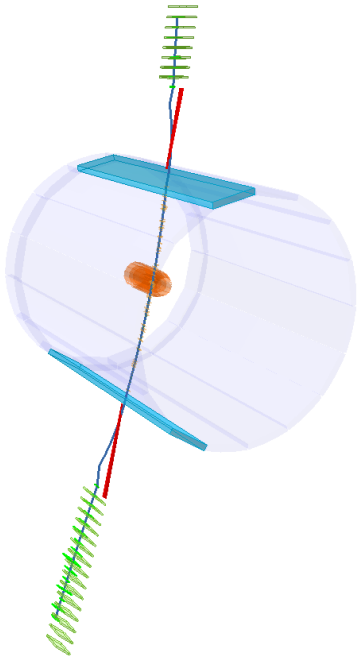
Run-dep alignment for each bucket on top

10M or all

2M

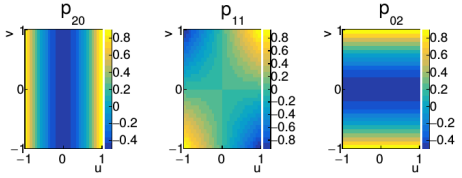
Di-muon events
(with floating IP constraint)

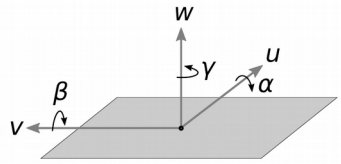




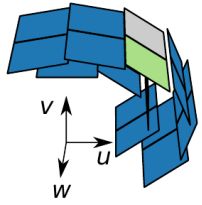
MPII

PXD sensors

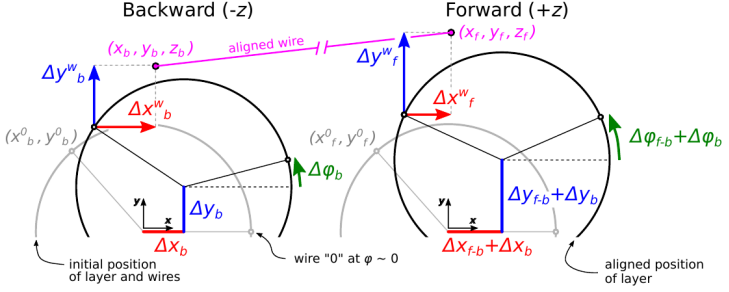




VXD half-shells



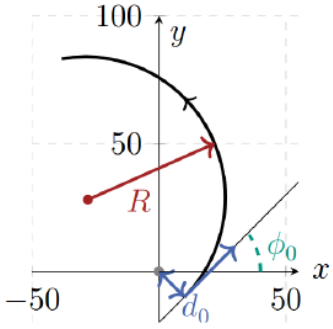
CDC layers

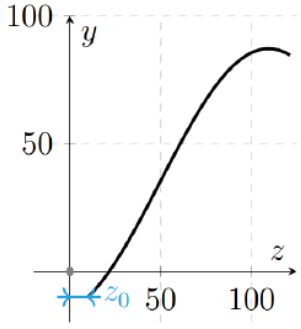


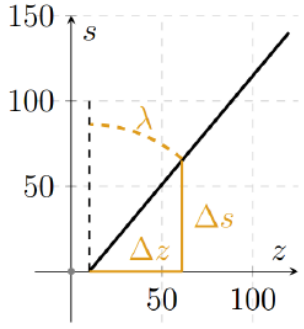
Every 80k events … O(10) of blocks per bucket

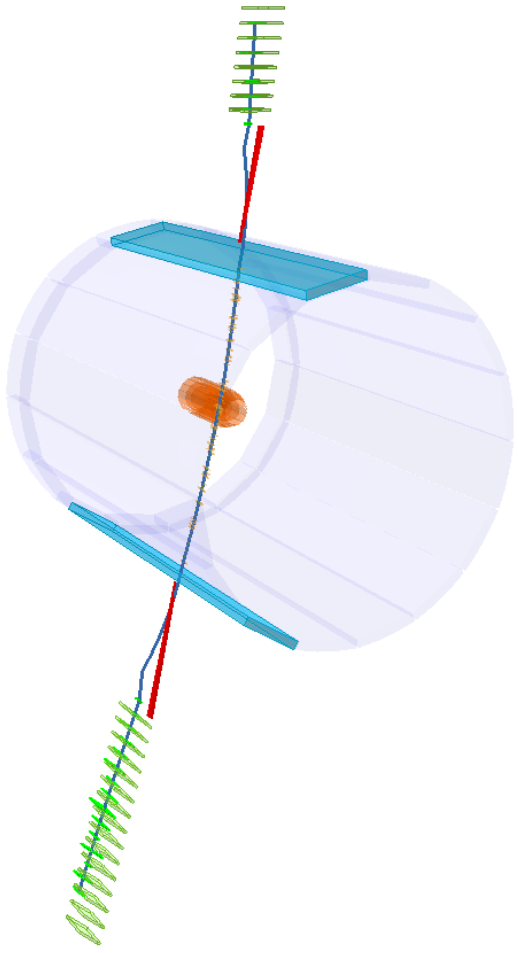
PXD performance with new alignment

- Standard performance evaluation method using cosmic rays
  - Cosmic skim recorded during collisions
  - Split muon track to two arms
  - Require at least 1 PXD hit and at least 4 VXD hits on each arm
  - Compare helix parameters at POCA for both both arms → resolution



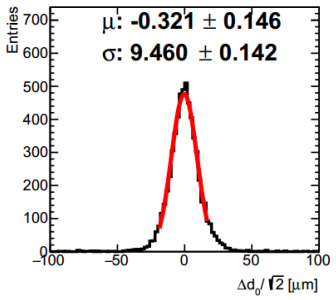


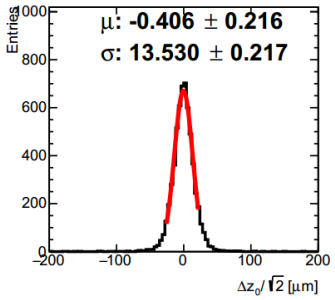


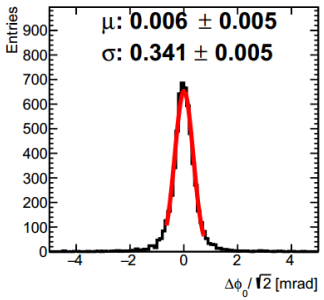


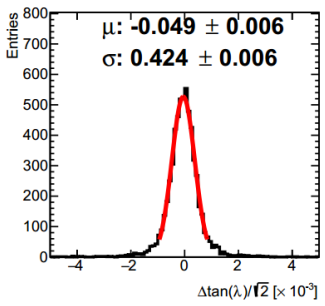
Helix parameter resolutions

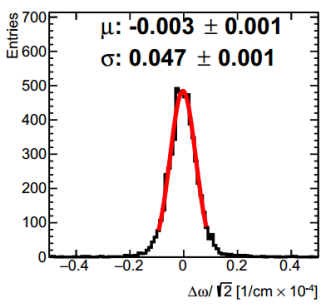
At 5 GeV/c reference momentum





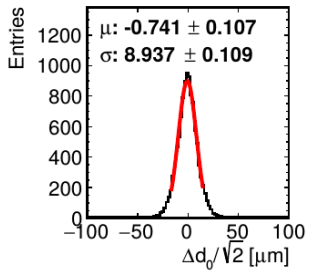


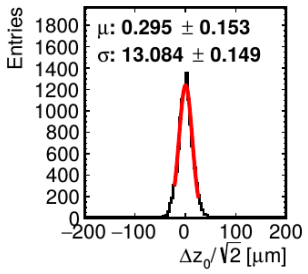


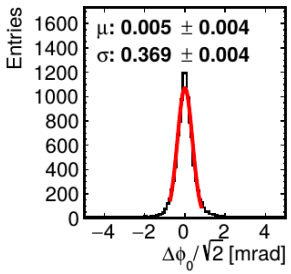


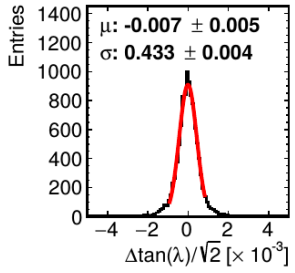
4.5 GeV/c < $p_t^{up/down}$ < 5.5 GeV/c

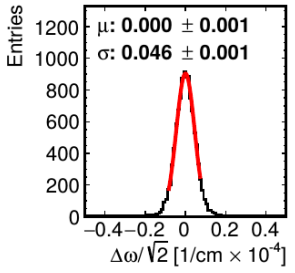
Buckets 26 – 31











4.5 GeV/c < $p_t^{up/down}$ < 5.5 GeV/c

MC

Data/MC correspondence very good for all helix parameters

Helix parameter biases and correlations

Buckets 26,27,28,29, 30,31

Exp 20 – 24 (r1460)

Δ d0

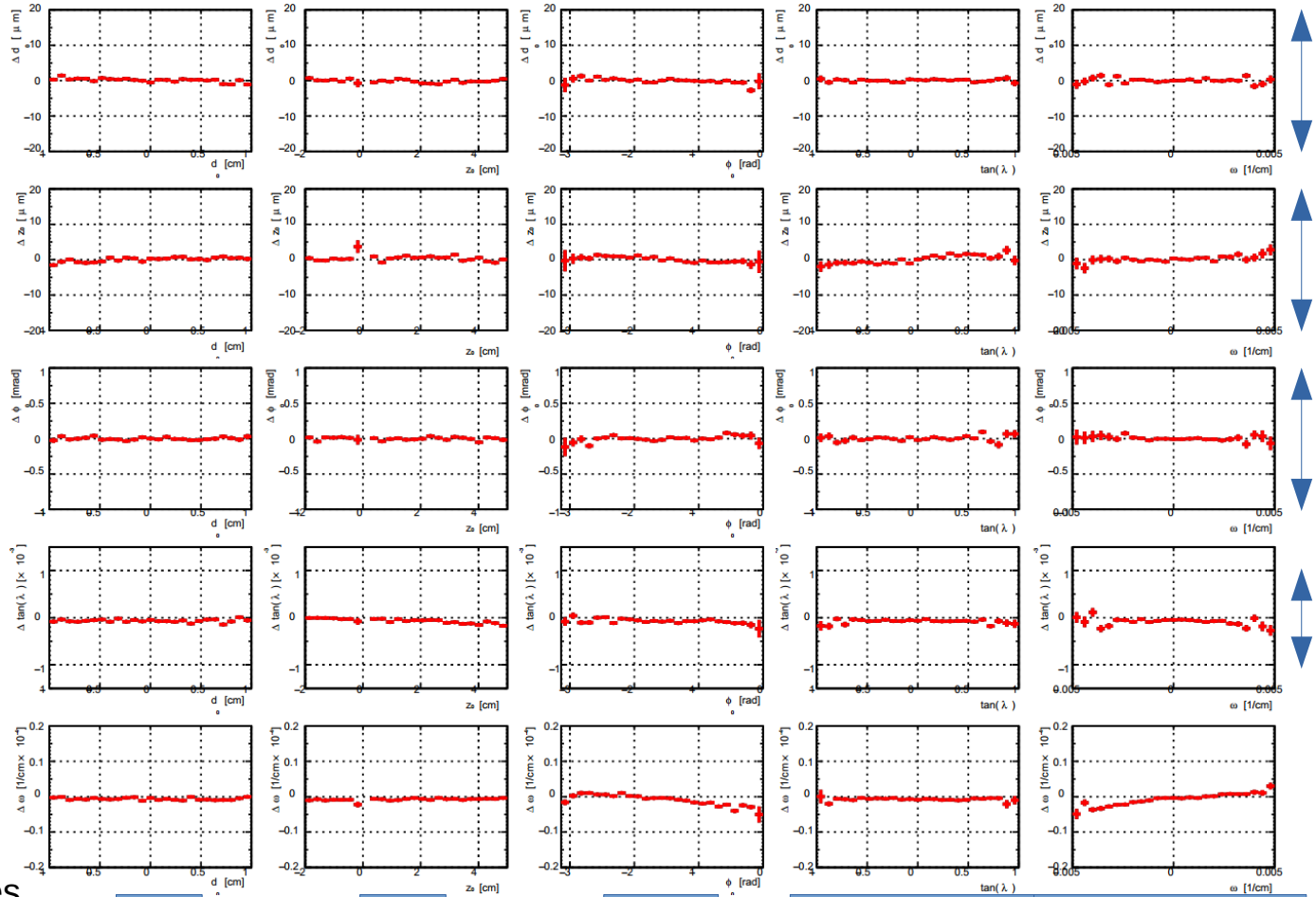
Δ z0

Δ phi0

Remaining biases negligible

Δ tan lambda

Δ omega = 1/R



20um

20um

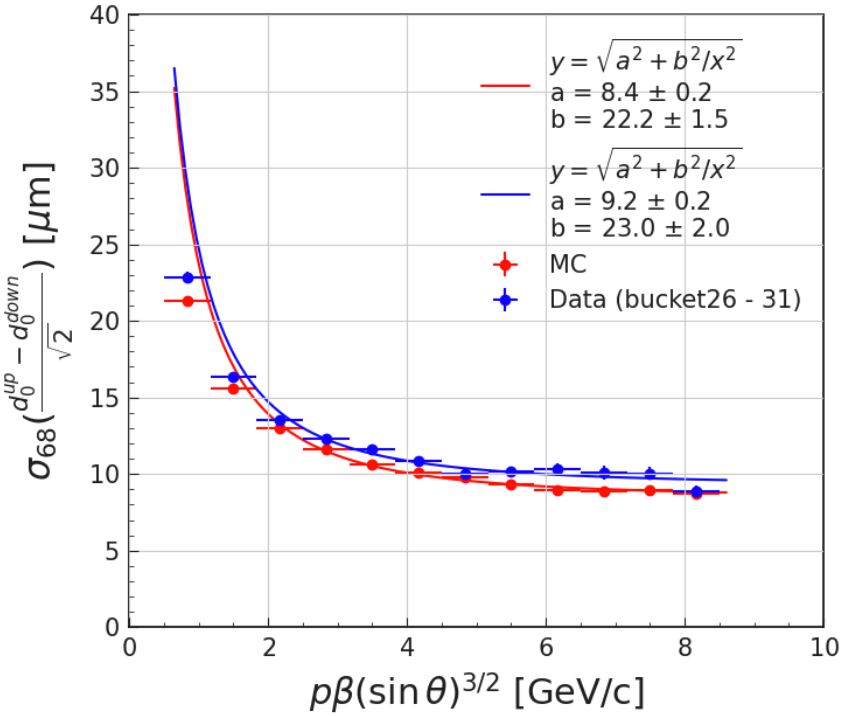
1mrad

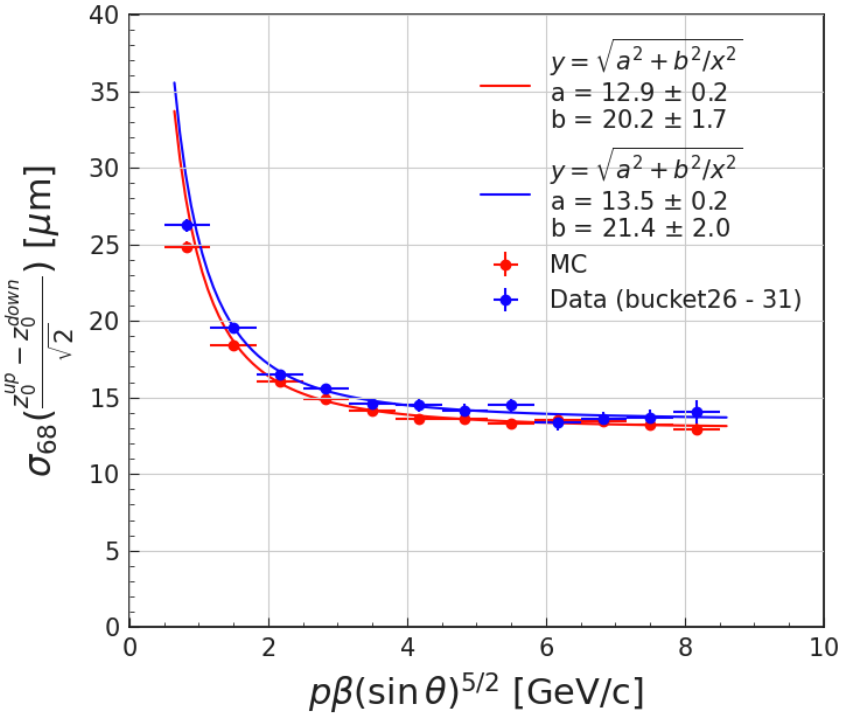
1mrad

d0 | z0 | phi0 | tan lambda | omega = 1/R

Worst issues for curvature biases in CDC – but still at < 10^{-3} level

Impact parameter resolutions vs pseudo-momentum





Difference to MC still dominated by too optimistic SVD resolution

Better than 10um/14um in d0/z0 !

Much better data/MC correspondence than ever achieved at Belle with almost twice better resolution!
Physics impact of remaining residual misalignment small/negligible for vertexing

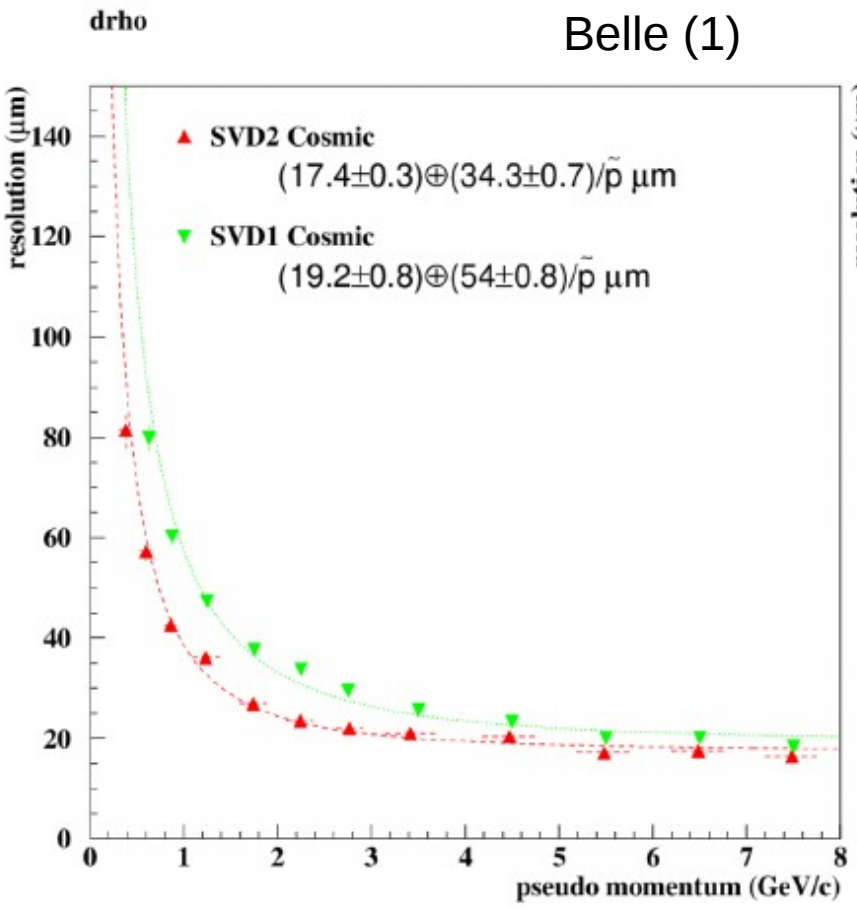
Summary

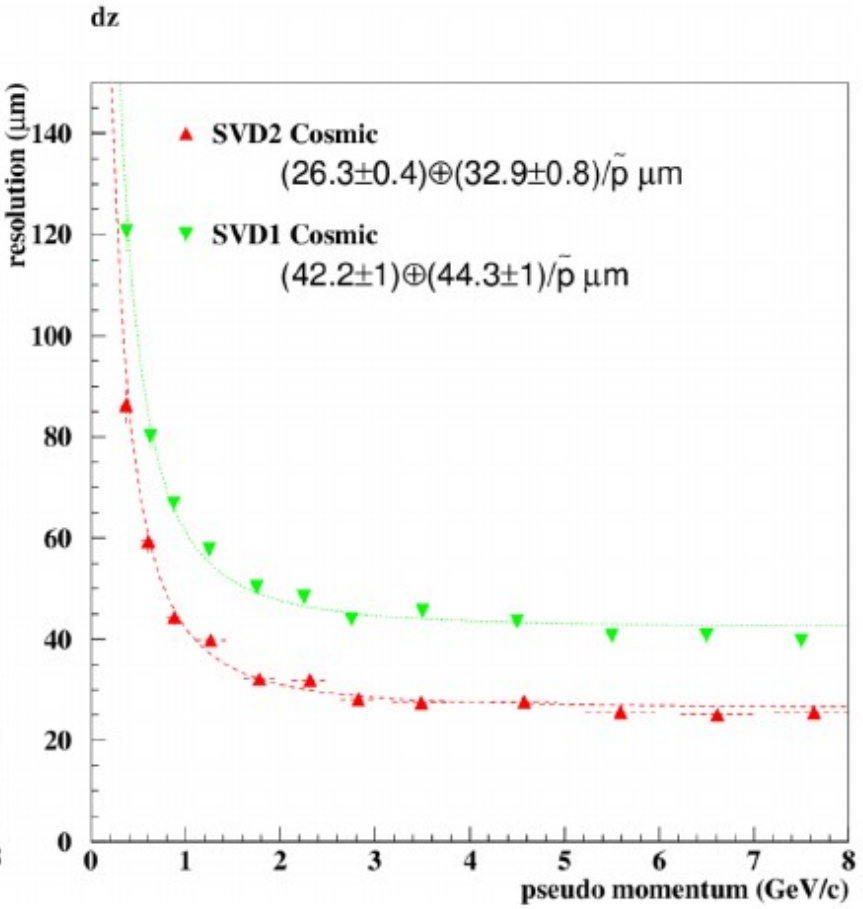
- We have a pretty advanced alignment procedure at Belle II
  - Belle II is probably first experiment to employ exact solution methods for 60k parameters regularly
    ...and align sensor-by-sensor run-by-run
- Alignment and PXD is ready for precision physics
  - Publication-level vertexing performance about a month after data-taking
  - PXD physics performance close to ideal MC with advanced alignment
- Some observed instabilities are a bit worrisome
  - This is more relevant for CDC deformations (VXD cables?), which however move also VXD
  - Layer 2 bowing should be probably understood – can significantly degrade performance for forward tracks
    - But maybe the complete L2 will be more stable?
- PXD half-shells do not close, most of overlaps lost
  - Overlaps also greatly reduced in SVD L3
  - Not a big problem for alignment (SVD L4+ overlaps fine), but something to consider during upcoming upgrade
- Plans
  - Correlate alignment results with detector and operation conditions/events
    - Hopes for collaborative effort
  - Improve time-dependence for SVD sensors
    - We can observe occasional continous SVD deformation after major events taking a couple of days to settle
    - Only minor improvement from physics point of view and a lot of work ...

Thank you for your attention!

BACKUP

Belle (1)


drho
resolution (μm)
SVD2 Cosmic
(17.4±0.3)⊕(34.3±0.7)/p̃ μm
SVD1 Cosmic
(19.2±0.8)⊕(54±0.8)/p̃ μm
pseudo momentum (GeV/c)


dz
resolution (μm)
SVD2 Cosmic
(26.3±0.4)⊕(32.9±0.8)/p̃ μm
SVD1 Cosmic
(42.2±1)⊕(44.3±1)/p̃ μm
pseudo momentum (GeV/c)

The moving z-reference in alignment payloads
The only known issue of the new alignment

Example for one PXD shell, but VXD moves as one piece, as well as any outer detector aligned w.r.t. CDC
Only z-coordinate was affected – no performance degradation expected
Workaround deployed since bucket32
Possible cause: iteration of inconsistencies in the geometric description of CDC