Very preliminary

Effects of the IR misalignments around the IP
+ Model independent analysis of the orbit through the IR
+ X-y coupling due to beam-beam focusing

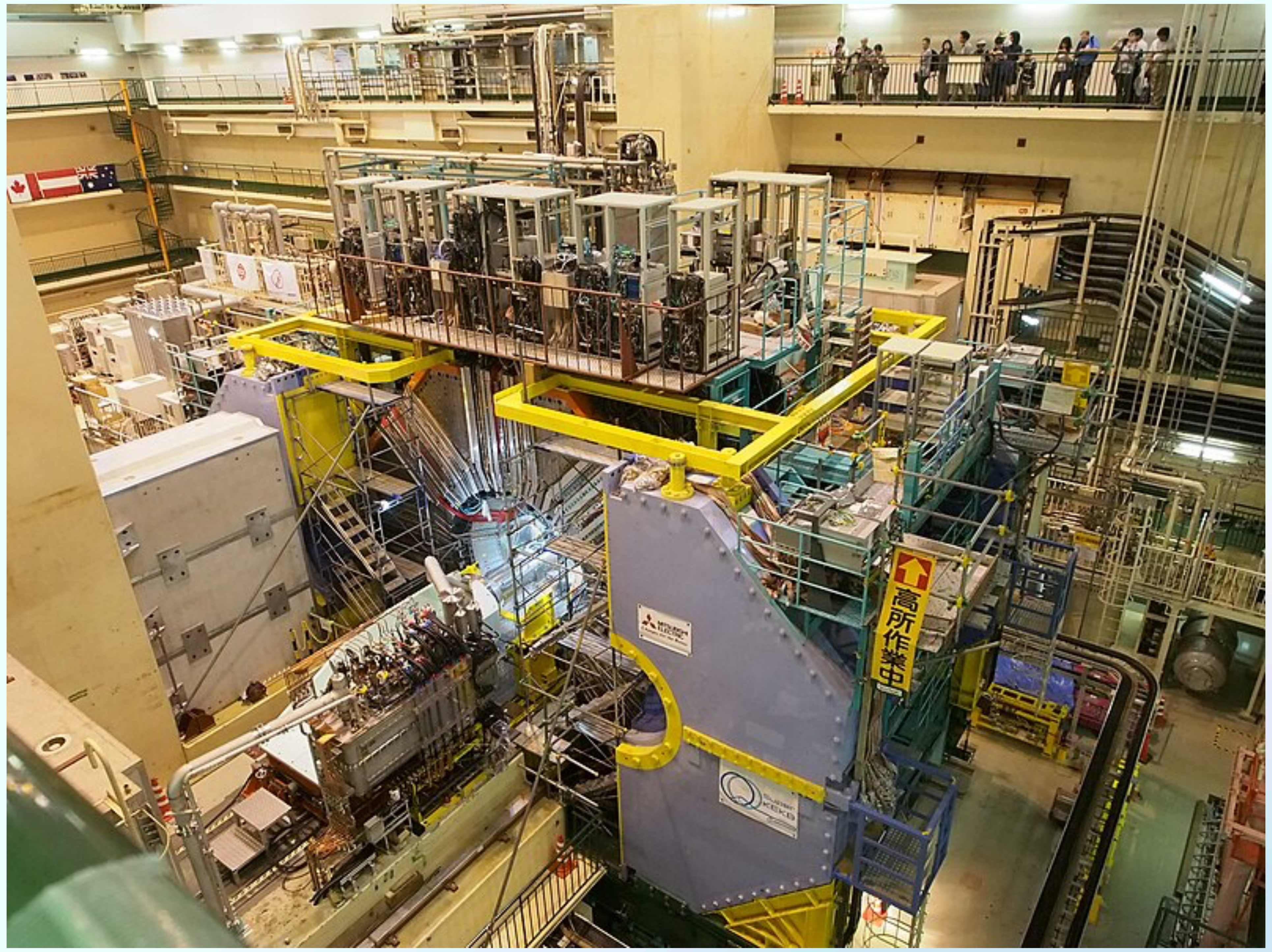
K. Oide (UNIGE/CERN/KEK), H. Koiso (KEK)
Jan. 15, 2025 @ 28th KEKB-ARC

We thank to M. Masuzawa, K. Matsuoka, G. Mitsuka, A. Morita, Y. Ohnishi, H. Sugimoto, R. Žlebčík, and all colleagues of SuperKEKB/Belle-II.
K. Oide thanks to S. Asai, H. Ego, T. Koseki, K. Shibata, M. Tobiyama for inviting to visit KEK/ACCL.

Work supported by the FCC Feasibility Study (FCC-GOV-CC-0004, EDMS 1390795 v.2.0), via M. Benedikt and F. Zimmermann.

Alignment of the detector (a speculation) — SuperKEKB

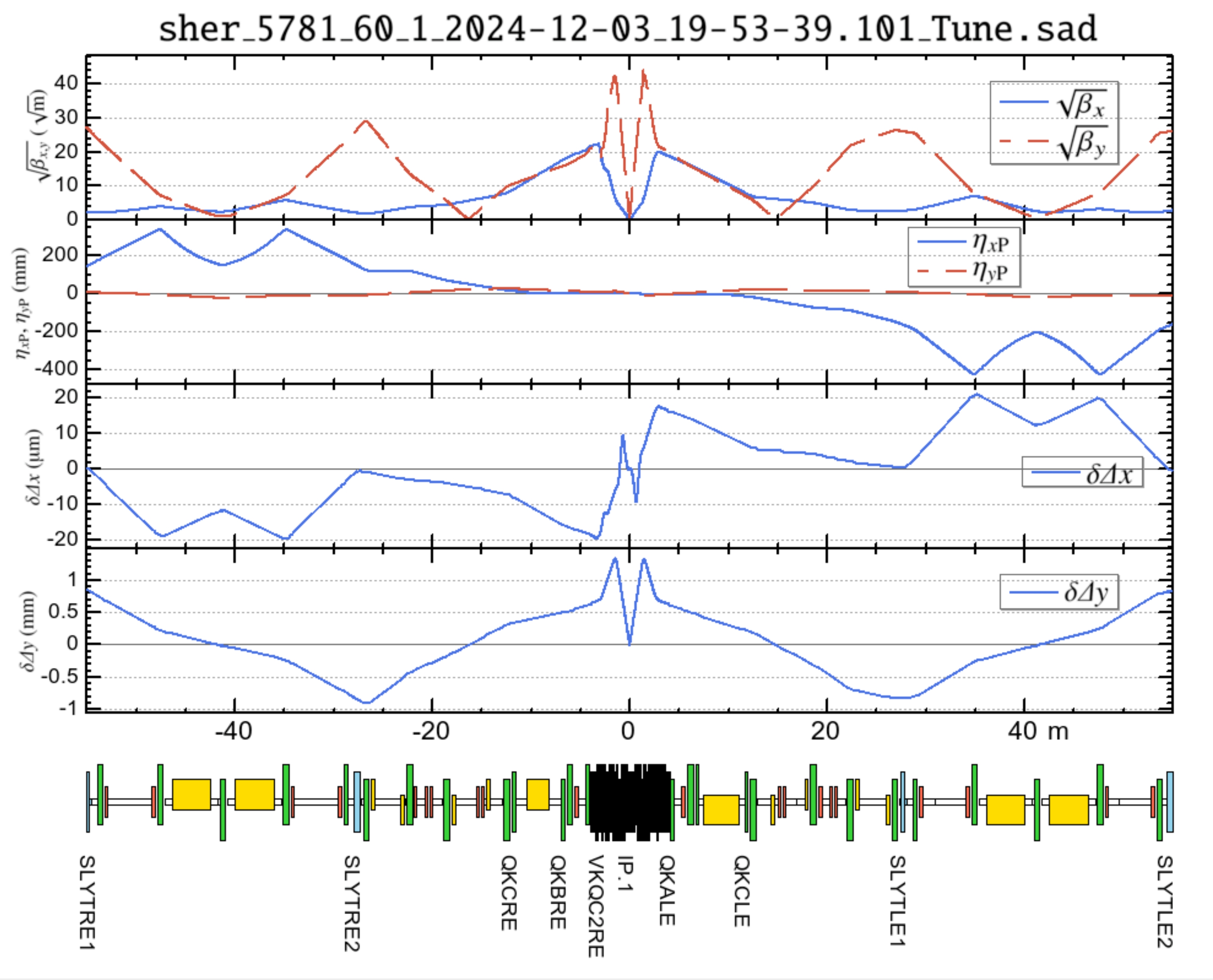
- All accelerator components of SuperKEKB have been well aligned with accuracy better than $\sigma \lesssim 100\,\mu\mathrm{m}$.
- However, the orbit around the interaction region looks strange:
  - Unexpected shining of the inner detector by SR was observed.
  - Strange steering of the orbit is required to ensure the collision and to avoid the SR shining.
- A speculation is that the alignment of the Belle-II detector might have large errors, in positions and angles, relative to nearby accelerator components.
  - It may explain the low beam-beam parameter (0.03) achieved so far.
- If it is true, re-alignment of accelerator components is necessary, by smoothly redefine the ring layout in this straight from the IP to the arc.
  - It is very difficult to move the detector itself (1400 tons) with a good accuracy.

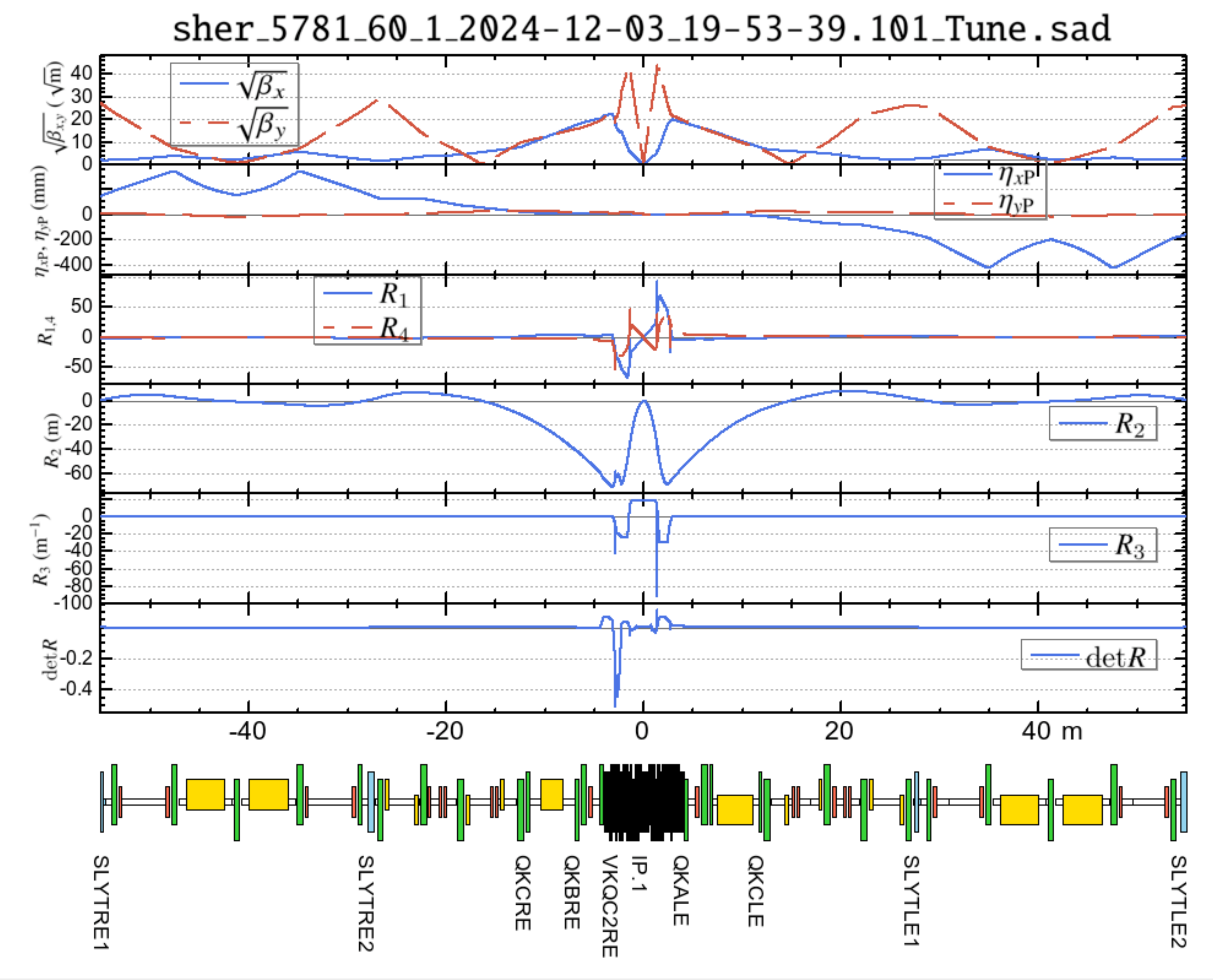


https://en.wikipedia.org/wiki/Belle_II_experiment

A preliminary estimation of the tilt effect (HER, vertical)

- Lattice: sher_5781_60_1_2024-12-03_19-53-39.101_Tune.sad, via H. Koiso.
- Put 1 mrad vertical tilt angle `CHI2` of the solenoids at the IP, `ESLE0/ESRE0`.
  - The entire solenoid/QCS block in IP±4 m is supposed to be tilted.
- Look at the orbit/coupling/emittance under the `GEOFIX` flag.
- The resulting vertical emittance: $\varepsilon_y = 71\,\mathrm{pm}$.



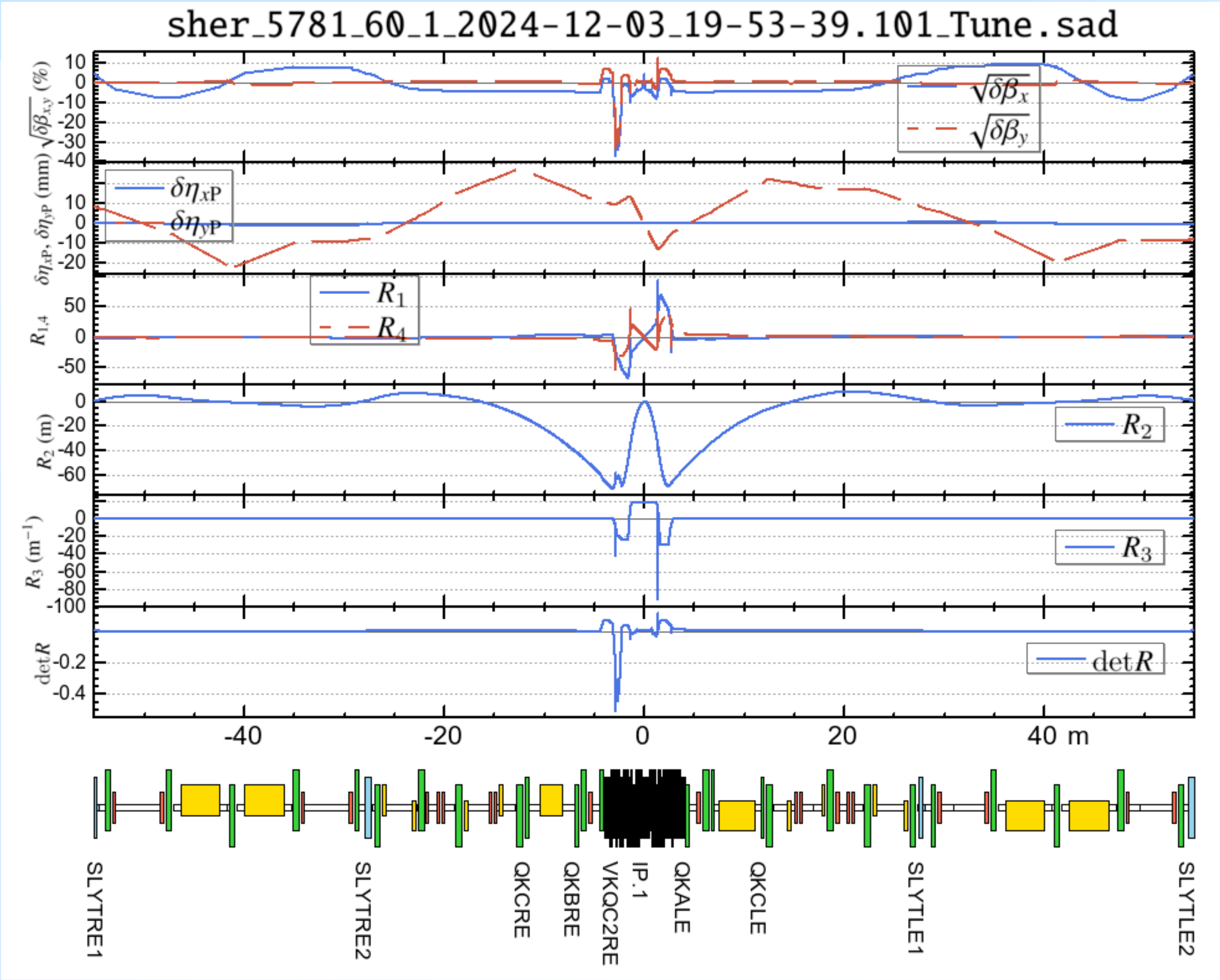


Try some coupling/dispersion correction

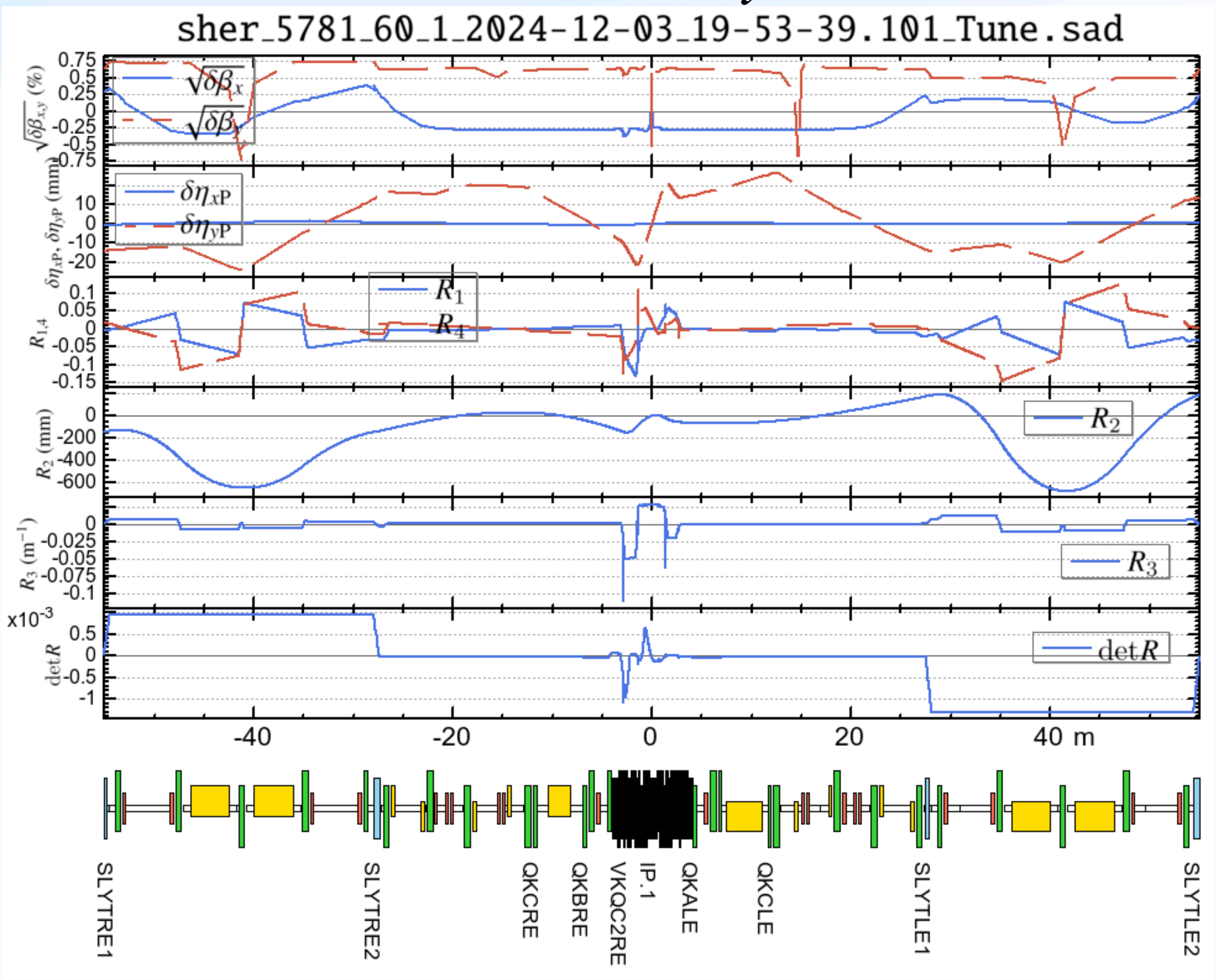
- Try some coupling/dispersion corrections using QK* K1, SLY*|VKQC* SK1.
- The orbit is not corrected at all.

!Variable	Keyword	Now	!	Previous	Saved	Minimum	Maximum	Couple	Coefficient
SLYTRE1	SK1	-1.63353985E-4	!	-1.62762E-4	.000000000	-1.00000E99	1.000000E99		1.00000000
SLYTRE2	SK1	-6.84843895E-4	!	-6.84278E-4	.000000000	-1.00000E99	1.000000E99		1.00000000
QKCRE	K1	-6.4663255E-10	!	-6.5028E-10	.000000000	-1.00000E10	1.000000E10	<--	1.00000000
QKBRE	K1	-2.32351782E-4	!	-2.32352E-4	-2.32353E-4	-1.00000E10	1.000000E10	<--	1.00000000
QKARE	K1	.001147496558	!	.001147497	.001147497	-1.00000E10	1.000000E10	<--	1.00000000
VKQC2RE	SK1	.004770963045	!	.004771467	.004765530	-1.00000E99	1.000000E99		1.00000000
VKQC1RE	SK1	.001532240551	!	.001532530	.001543115	-1.00000E99	1.000000E99		1.00000000
VKQC1LE	SK1	-.002661361969	!	-.002660525	-.002674089	-1.00000E99	1.000000E99		1.00000000
VKQC2LE	SK1	6.753939169E-4	!	6.768604E-4	6.806217E-4	-1.00000E99	1.000000E99		1.00000000
QKALE	K1	-1.27943824E-4	!	-1.27944E-4	-1.27944E-4	-1.00000E10	1.000000E10	<--	1.00000000
QKBLE	K1	1.311801576E-4	!	1.311801E-4	1.311814E-4	-1.00000E10	1.000000E10	<--	1.00000000
QKCLE	K1	-1.52610352E-9	!	-1.53276E-9	.000000000	-1.00000E10	1.000000E10	<--	1.00000000
SLYTLE1	SK1	2.895570950E-4	!	2.896855E-4	.000000000	-1.00000E99	1.000000E99		1.00000000
SLYTLE2	SK1	7.461324696E-4	!	7.462682E-4	.000000000	-1.00000E99	1.000000E99		1.00000000

Before correction: $\varepsilon_y = 71\,\mathrm{pm}$

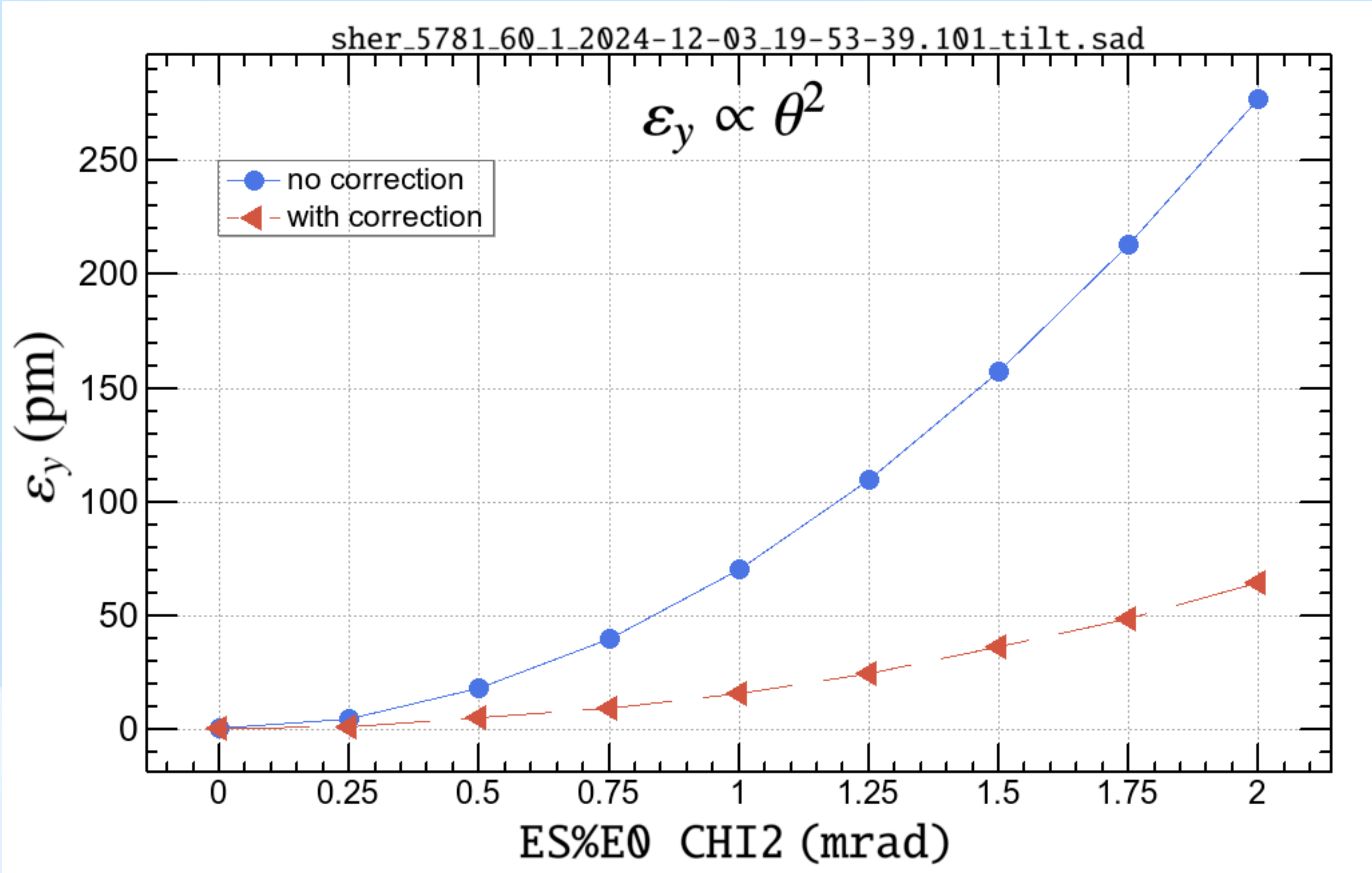


After correction: $\varepsilon_y = 16\,\mathrm{pm}$

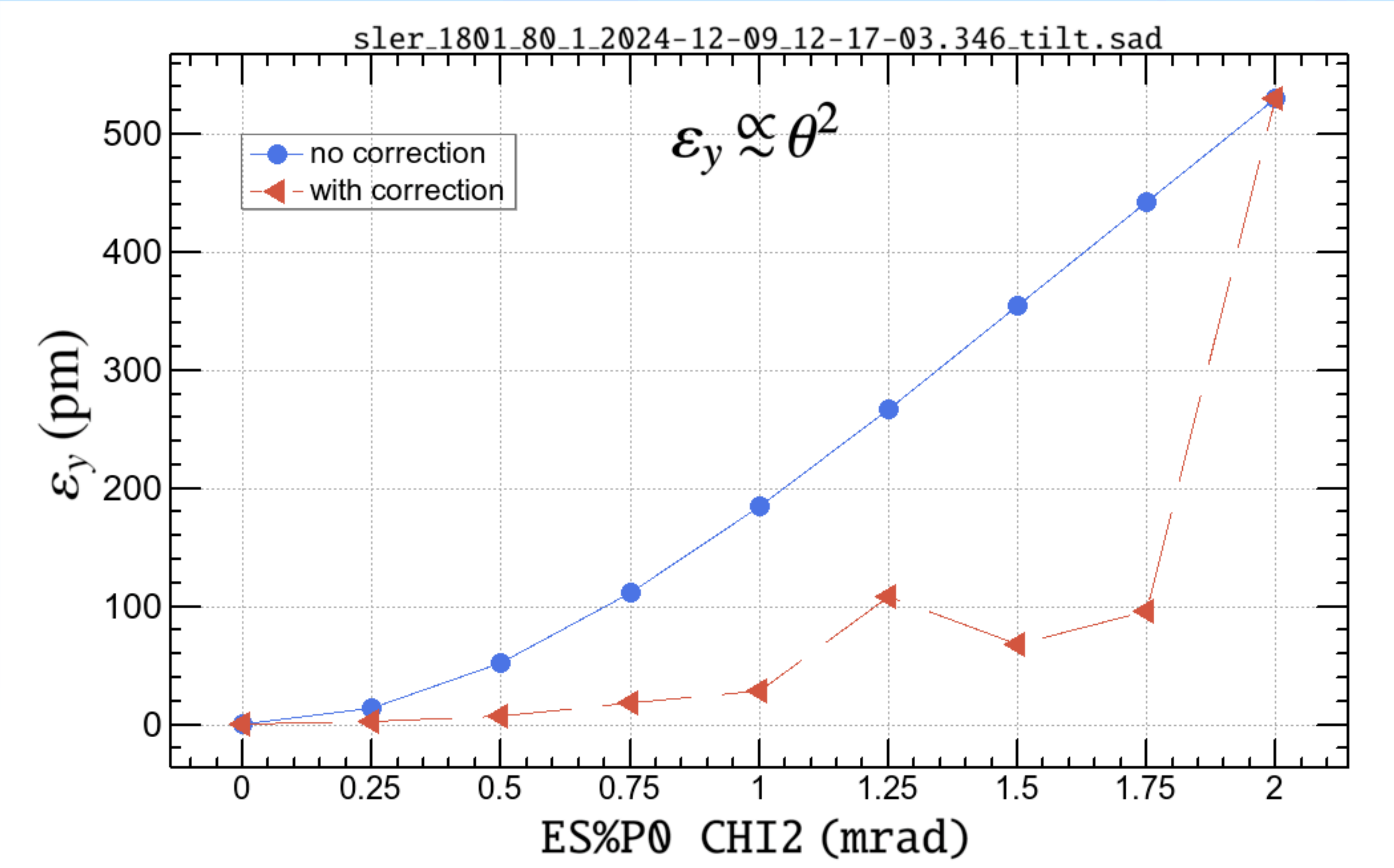


Error angle dependence (HER/LER)

HER



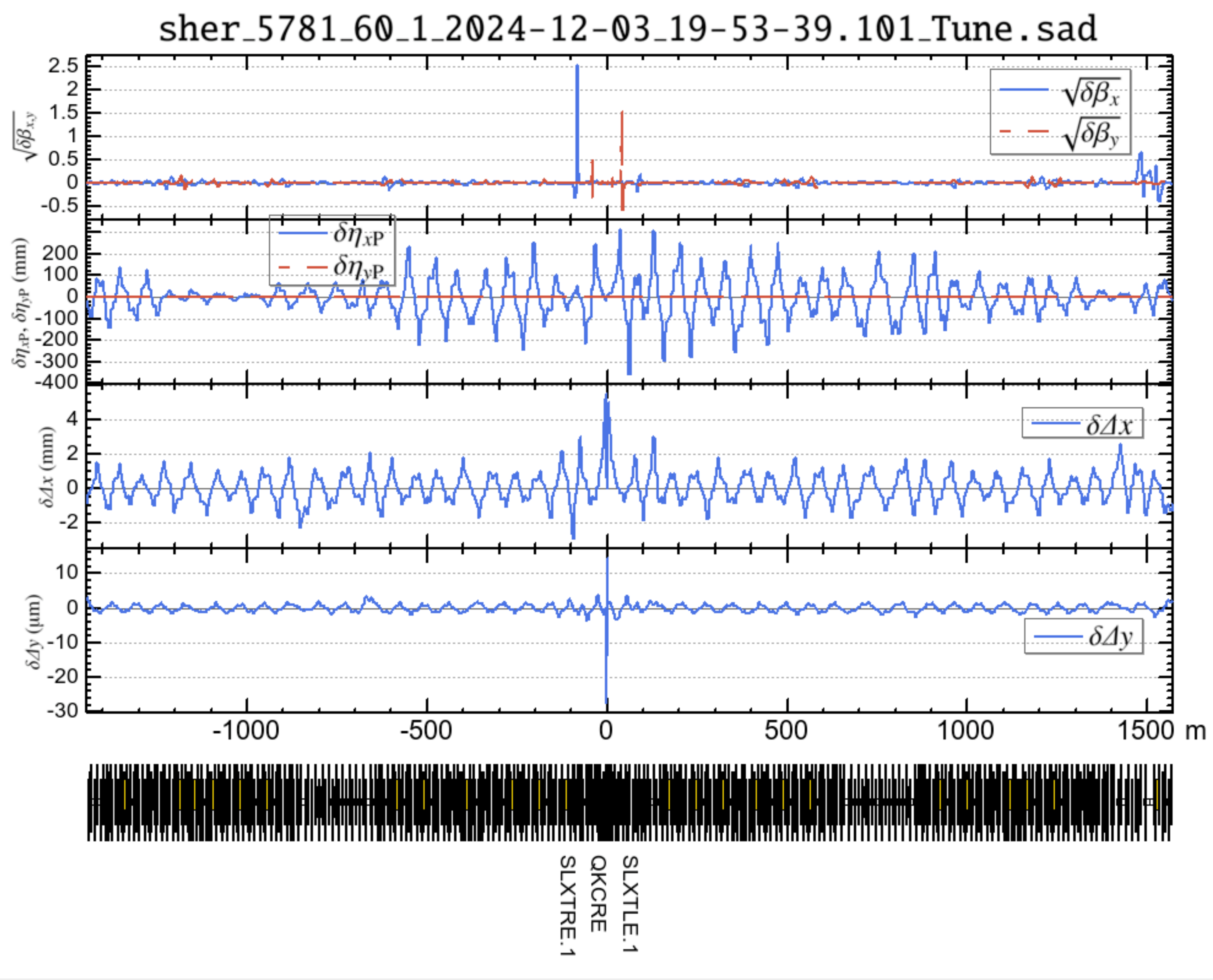
LER

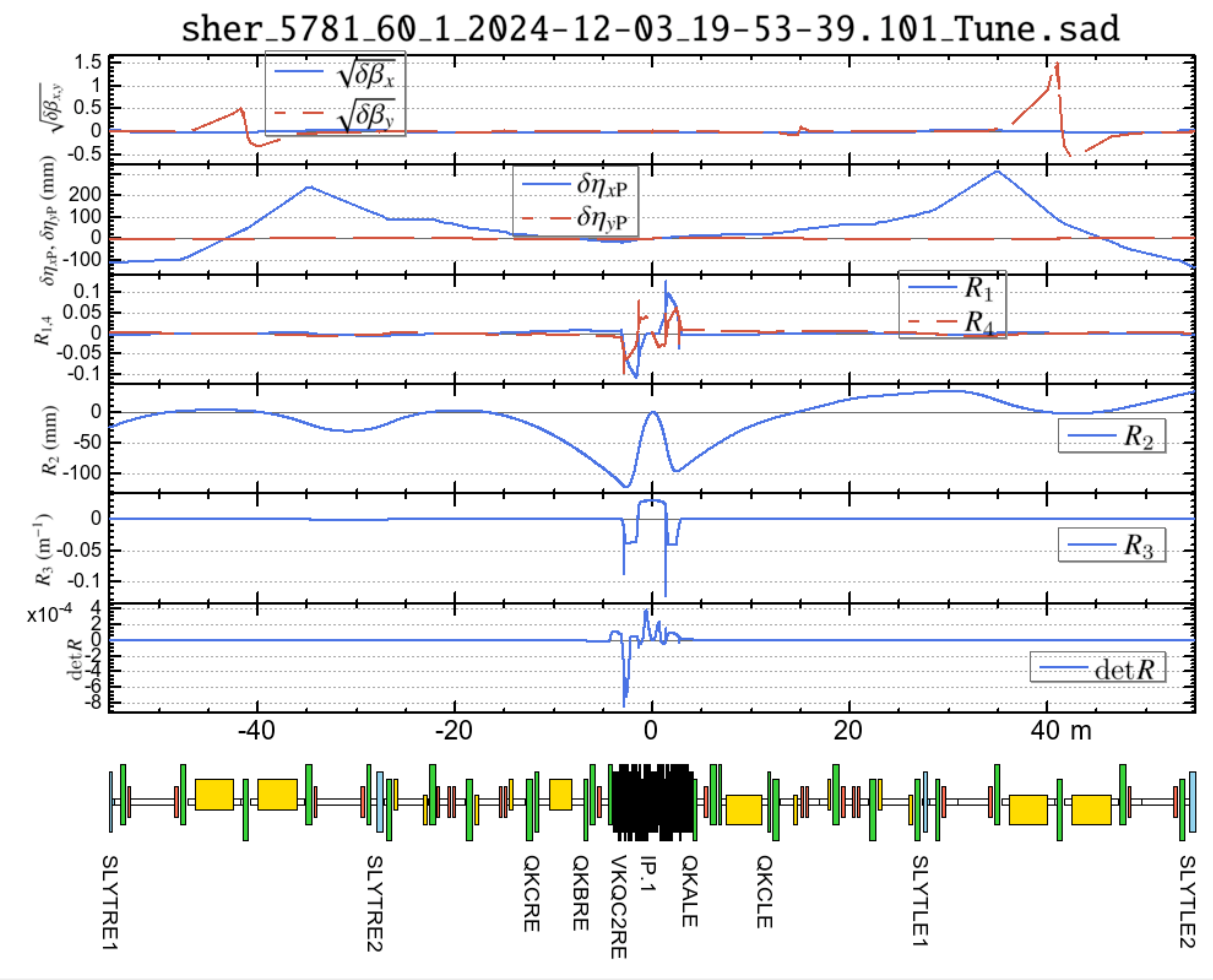


- The vertical emittances before/after correction seem roughly proportional to $\mathtt{CHI2}^2$.
  - The result for the LER after correction looks more irregular than the HER.
- If we allow $\varepsilon_y \lesssim 20$ pm after correction for both rings, the tolerance should be $\mathtt{CHI2} \lesssim 0.7$ mrad.

Horizontal tilt effect (HER)

- Add 1 mrad horizontal tilt angle `CHI1` of the solenoids at the IP, `ESLE0/ESRE0`.
  - The entire solenoid/QCS block in IP±4 m is supposed to be tilted.
- Look at the orbit/coupling/emittance under the `GEOFIX` flag.
- The resulting vertical emittance: $\varepsilon_y = 64\,\mathrm{pm}$.
- Horizontal orbit/dispersion leak over the ring, larger than the vertical tilt.





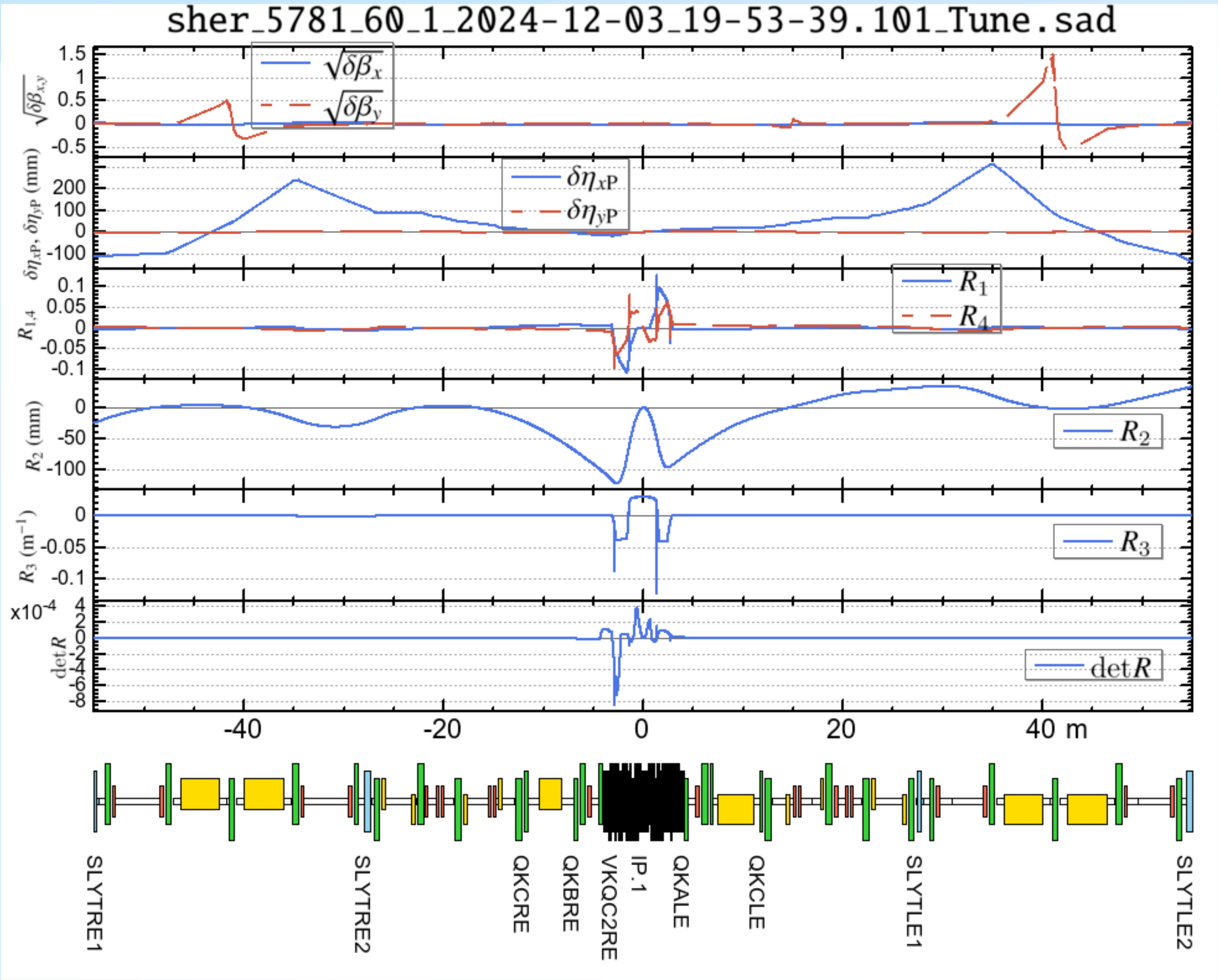
Coupling/dispersion corrections (HER, horizontal)

- Try some coupling/dispersion corrections using `QK* K1`, `SLY*|VKQC* SK1`.
- The orbit is not corrected at all.

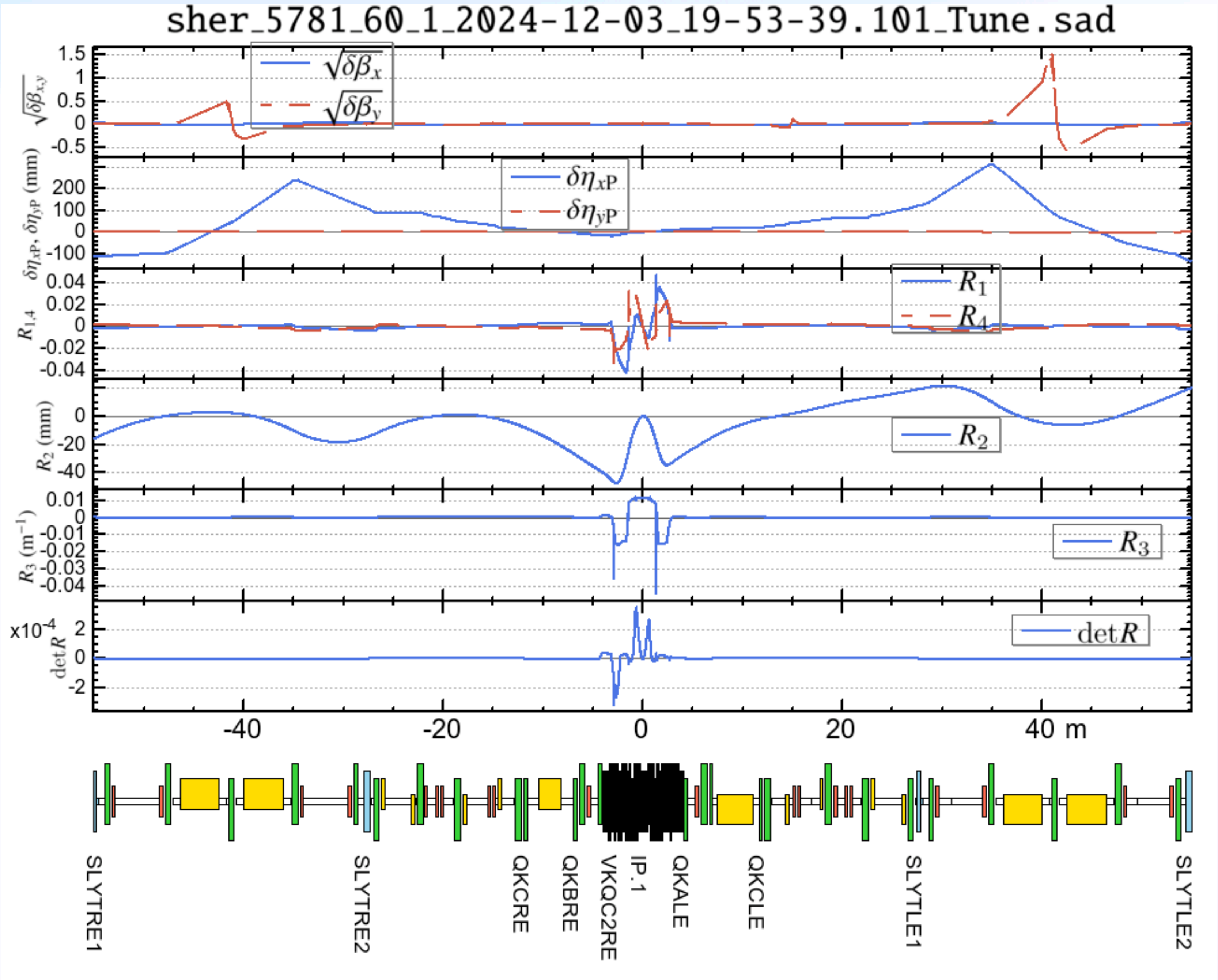
```
!Variable     Keyword    Now              !   Previous     Saved         Minimum        Maximum       Couple      Coefficient
 SLYTRE1      SK1       -3.94884385E-5 !  .000000000  .000000000  -1.00000E99   1.000000E99               1.00000000
 SLYTRE2      SK1       5.546172886E-5 !  .000000000  .000000000  -1.00000E99   1.000000E99               1.00000000
 QKCRE        K1        -3.97263105E-5 !  .000000000  .000000000  -1.00000E10   1.000000E10 <--           1.00000000
 QKBRE        K1        -2.36879392E-4 ! -2.32353E-4 -2.32353E-4  -1.00000E10   1.000000E10 <--           1.00000000
 QKARE        K1         .001147434874 !  .001147497  .001147497  -1.00000E10   1.000000E10 <--           1.00000000
 VKQC2RE      SK1        .004601723807 !  .004765530  .004765530  -1.00000E99   1.000000E99               1.00000000
 VKQC1RE      SK1        .001831170111 !  .001543115  .001543115  -1.00000E99   1.000000E99               1.00000000
 VKQC1LE      SK1       -.002016174143 ! -.002674089 -.002674089  -1.00000E99   1.000000E99               1.00000000
 VKQC2LE      SK1       2.969753588E-4 ! 6.806217E-4 6.806217E-4  -1.00000E99   1.000000E99               1.00000000
 QKALE        K1        -1.27782780E-4 ! -1.27944E-4 -1.27944E-4  -1.00000E10   1.000000E10 <--           1.00000000
 QKBLE        K1        1.075430233E-4 ! 1.311814E-4 1.311814E-4  -1.00000E10   1.000000E10 <--           1.00000000
 QKCLE        K1        -5.95195784E-5 !  .000000000  .000000000  -1.00000E10   1.000000E10 <--           1.00000000
 SLYTLE1      SK1       -1.16384529E-5 !  .000000000  .000000000  -1.00000E99   1.000000E99               1.00000000
 SLYTLE2      SK1       9.334351839E-6 !  .000000000  .000000000  -1.00000E99   1.000000E99               1.00000000
 SLYTLE2      SK1       7.461324696E-4 ! 7.462682E-4  .000000000  -1.00000E99   1.000000E99               1.00000000
```

Horizontal tilt seems more correctable than the vertical.

Before correction: $\varepsilon_y = 64\,\mathrm{pm}$



After correction: $\varepsilon_y = 0.6\,\mathrm{pm}$



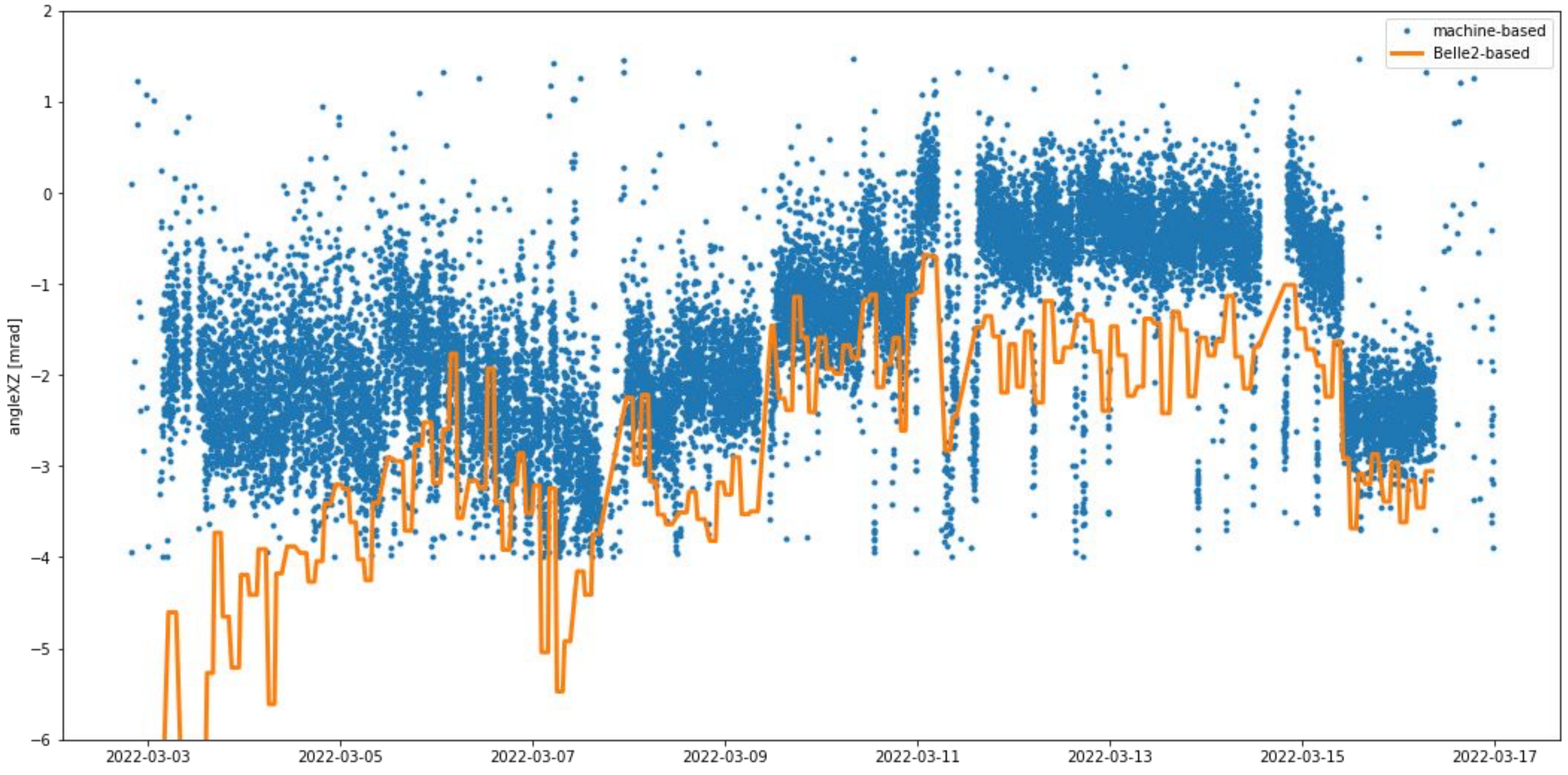
Tilt in beam spot at the IP observed by Belle II (R. Žlebčík)

https://kds.kek.jp/event/41965/contributions/212425/attachments/154759/196655/beamParameters.pdf (2022)

BeamSpot xz-tilt (March 03 - March 16)

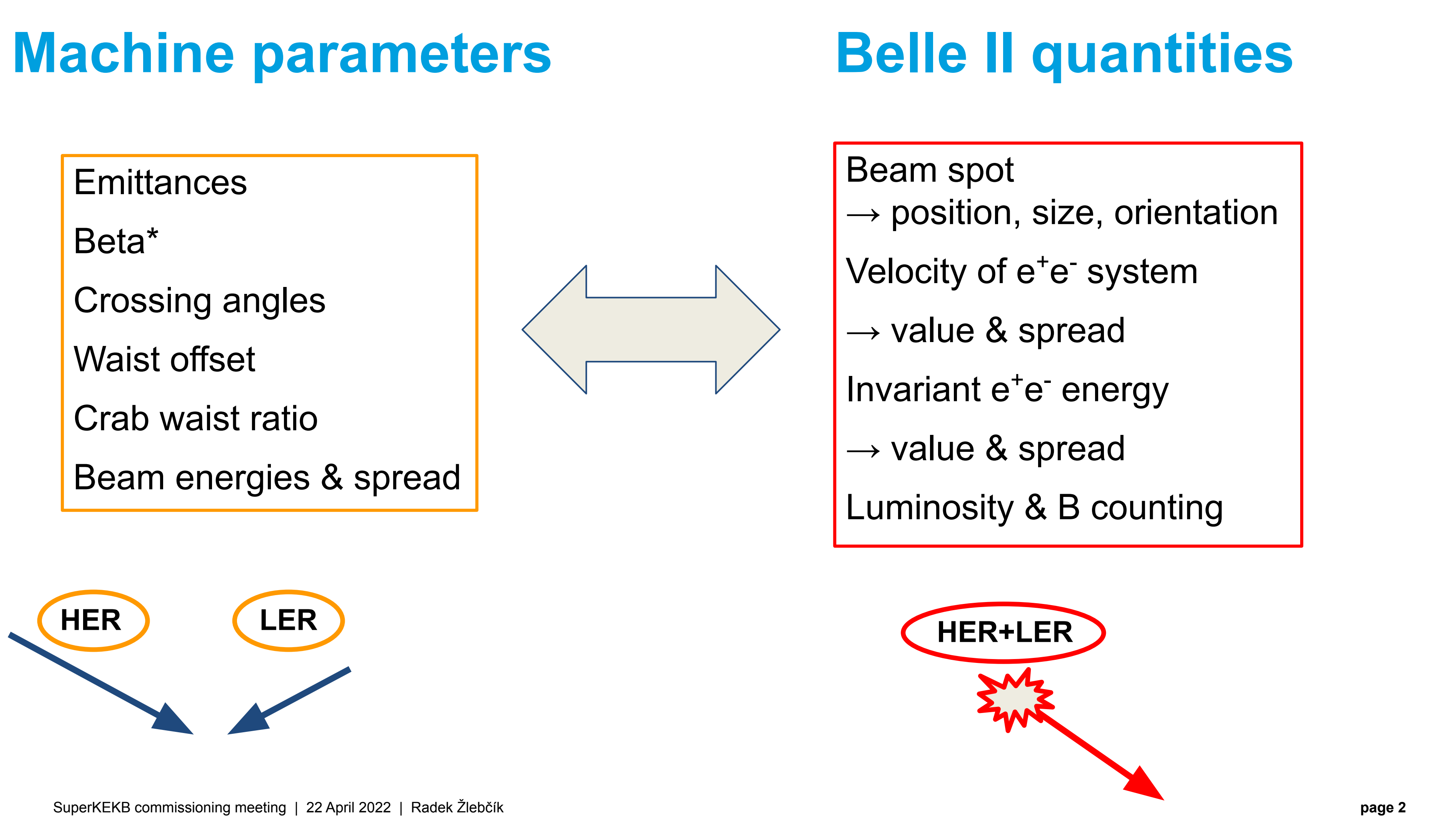
- There is a correlation but values not identical

$$\theta_{xz} = \theta_C \frac{\sigma_{Lx}^2 - \sigma_{Hx}^2}{\sigma_{Lx}^2 + \sigma_{Hx}^2}$$



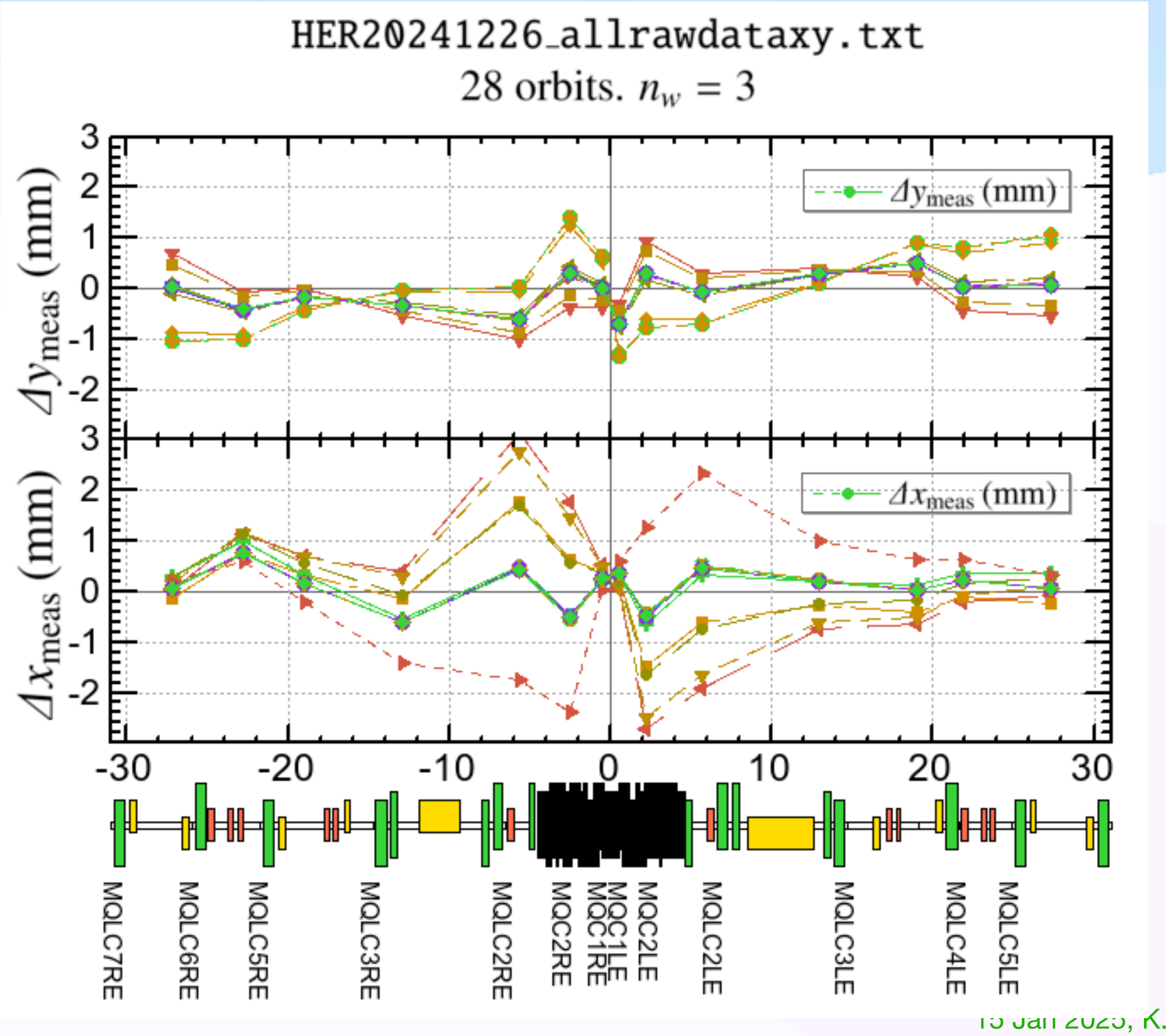
SuperKEKB commissioning meeting | 22 April 2022 | Radek Žlebčík

- A clear discrepancy has been observed in the beam x-z tilt angle at collision between accelerator-based and Belle II-based measurements, by 1-2 mrad.
- The Belle II result depend on the systematic errors in the beam sizes.



Model-independent analysis (MIA) for orbits through the IR

- Here let us discuss the behavior of the beam orbits through the interaction region (IR):
  - Look at the region between the nearest (YCCS/crab) sextupoles around the IP, about ±30 m.
  - The orbits measured by the BPMs attached to each quadrupole are the results at least of:
    - orbit from the outside of this region
    - magnets settings in this region
    - misalignments of each magnet in this region
    - offset and rotation of each BPM
- Then if we look at a set of orbits taken during the orbit-response matrix measurement for the β-correction, we can isolate the the external part from each orbit.
- Each set consists of 28 orbits; 6x2 kicked orbits, each of which is surrounded by two ‘base’ closed orbits.
- 4 sets/ring in the December run.



Singular value decomposition for the MIA

- Let us define the complex obit difference matrix

$$\mathrm{B} \equiv \{\Delta z_{ij}\} = \{\Delta x_{ij} + i\Delta y_{ij}\}, \quad (i = 1, N;\ j = 1, M)\ , \tag{1}$$

$$\Delta x_{ij} \equiv x_{ij} - \left(\frac{x_{ij}^0 + x_{ij}^1}{2}\right)\ , \tag{2}$$

$$\Delta y_{ij} \equiv y_{ij} - \left(\frac{y_{ij}^0 + y_{ij}^1}{2}\right)\ , \tag{3}$$

where x_{ij} and y_{ij} are the horizontal and vertical BPM readings of the i-th measurement at the j-th BPM of the kicked orbit. The superscripts 0 and 1 denote the base closed orbit measured right before and after the measurement of the kicked orbit.

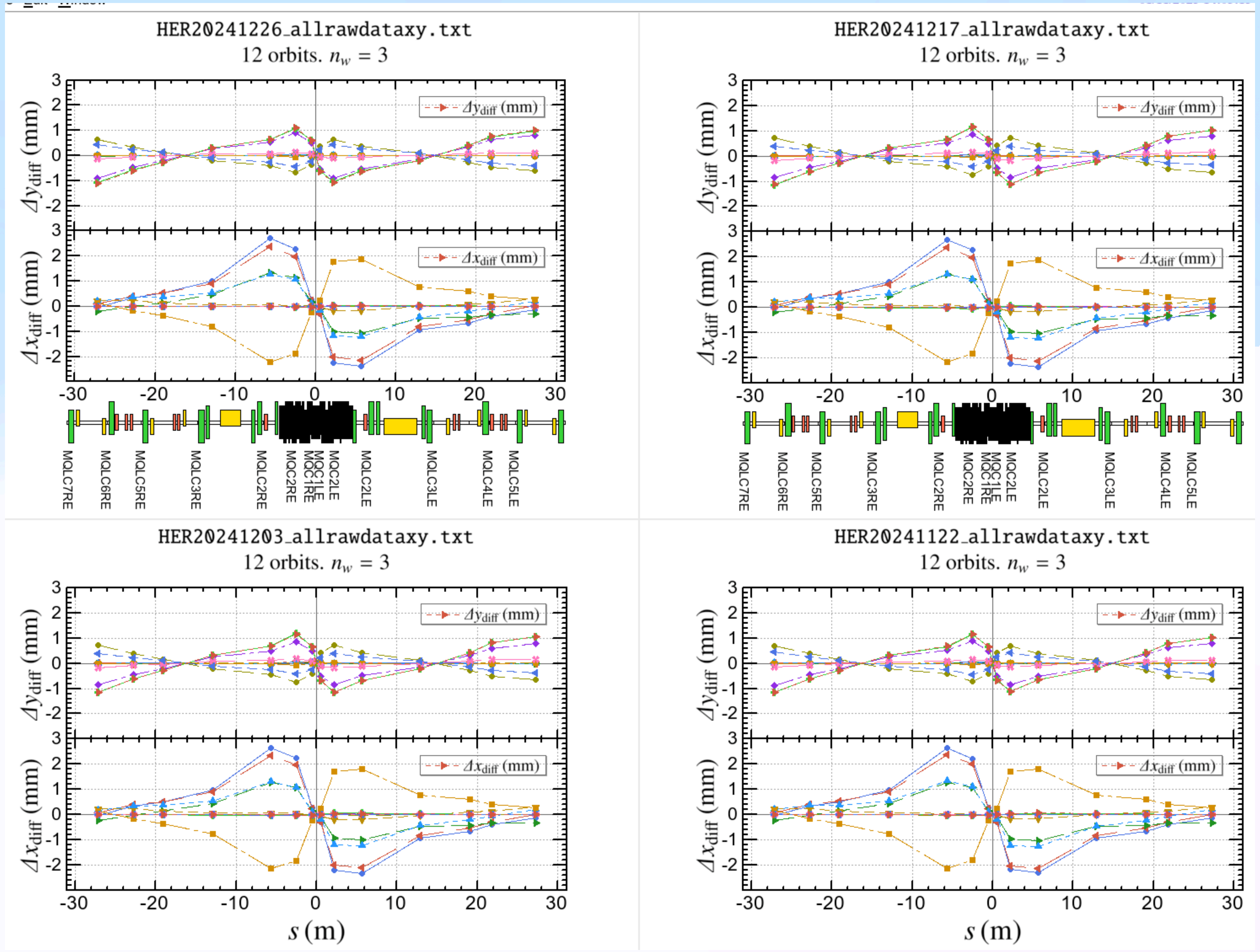
- The matrix B represents the characteristics of the linear orbit transportation in this region. Note that the matrix B does not depend on the BPM offsets and dipole kicks in this region.

- Then let us take the *singular value decomposition* (SVD) of the matrix B:

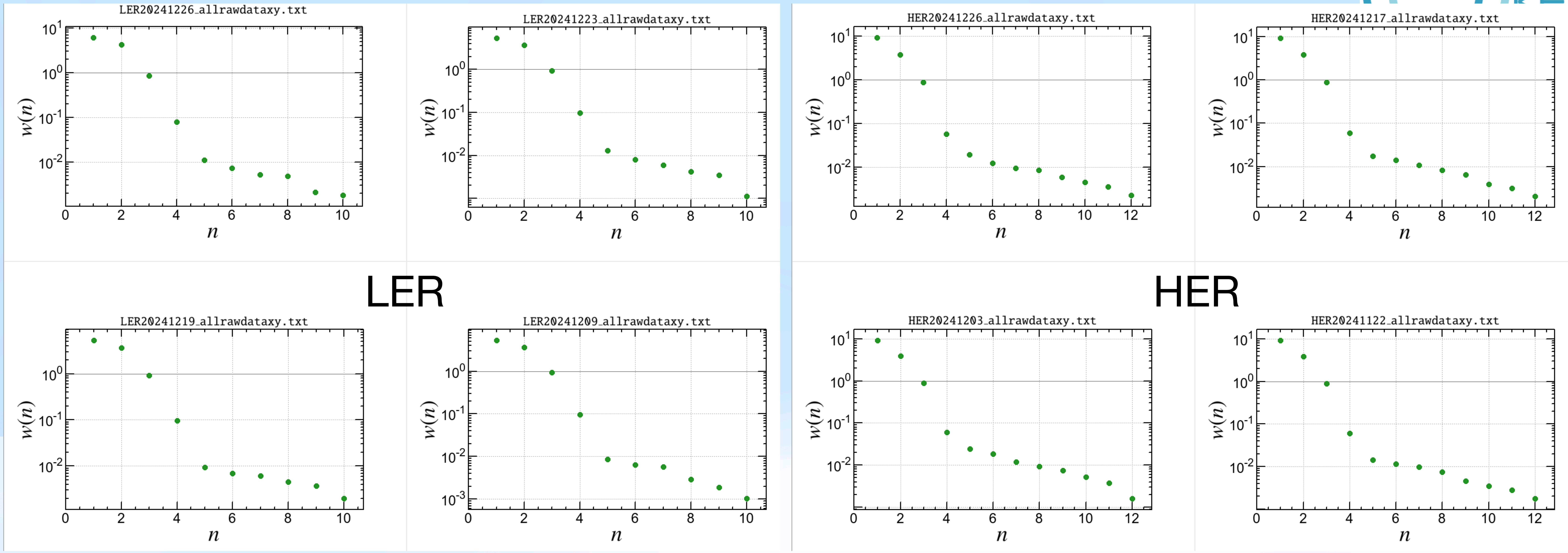
$$B = \mathrm{U}^{*T}\mathrm{diag}(\boldsymbol{w})\mathrm{V} \tag{4}$$

$$= \sum_k w_k \boldsymbol{u}_k^* \boldsymbol{v}_k^T\ , \tag{5}$$

where U and V are $N \times N$ and $M \times M$ normal matrices respectively, and $\boldsymbol{w}$ is a real vector of length M.



The spectra of singular values



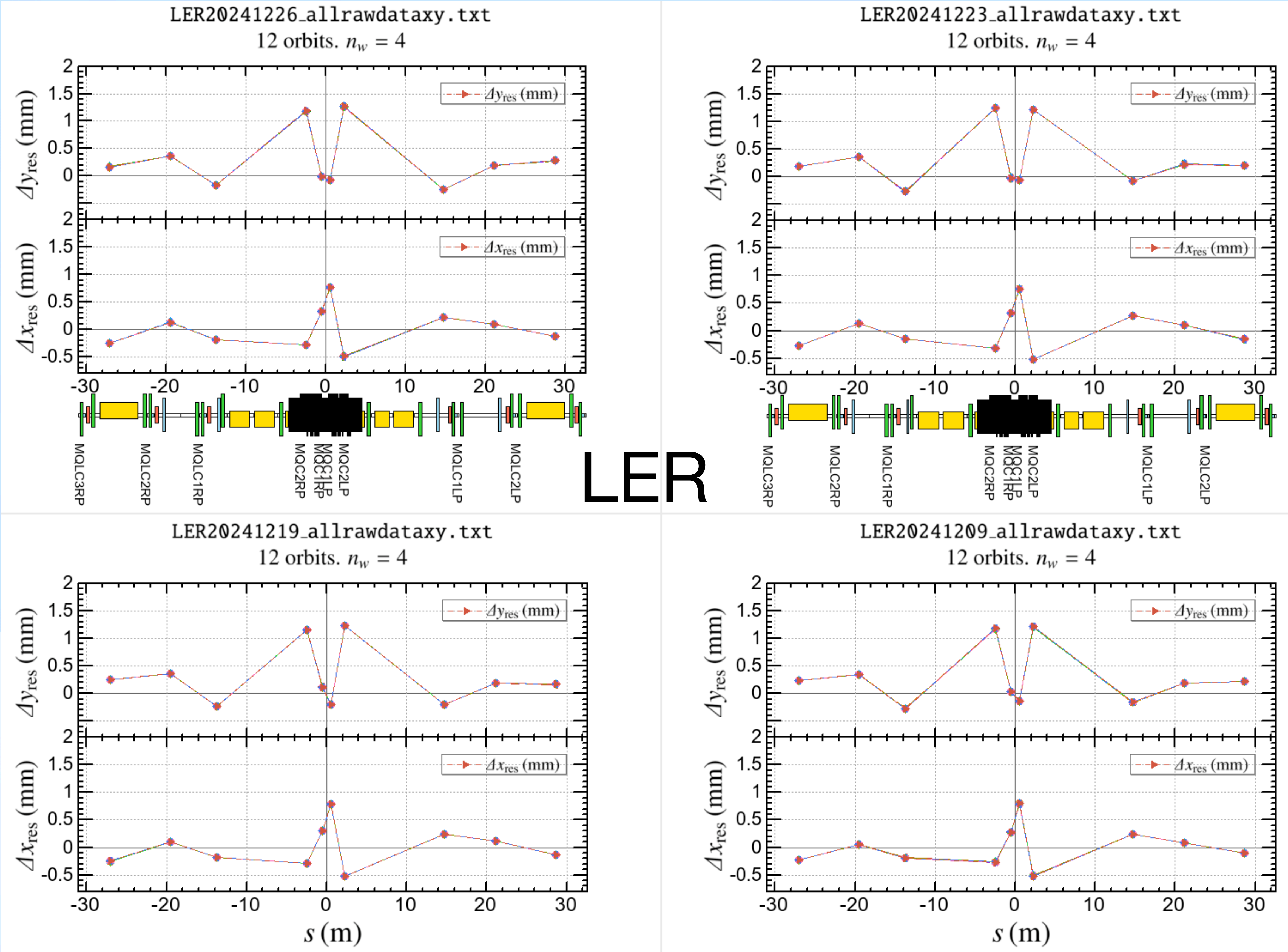
- The spectra of the singular values show that the first 4 (LER) or 3 (HER) have significance for all samples (why?).
- Thus we will use the matrices U′ and V′ truncated up to $n_w = 4$ or 3 columns below:

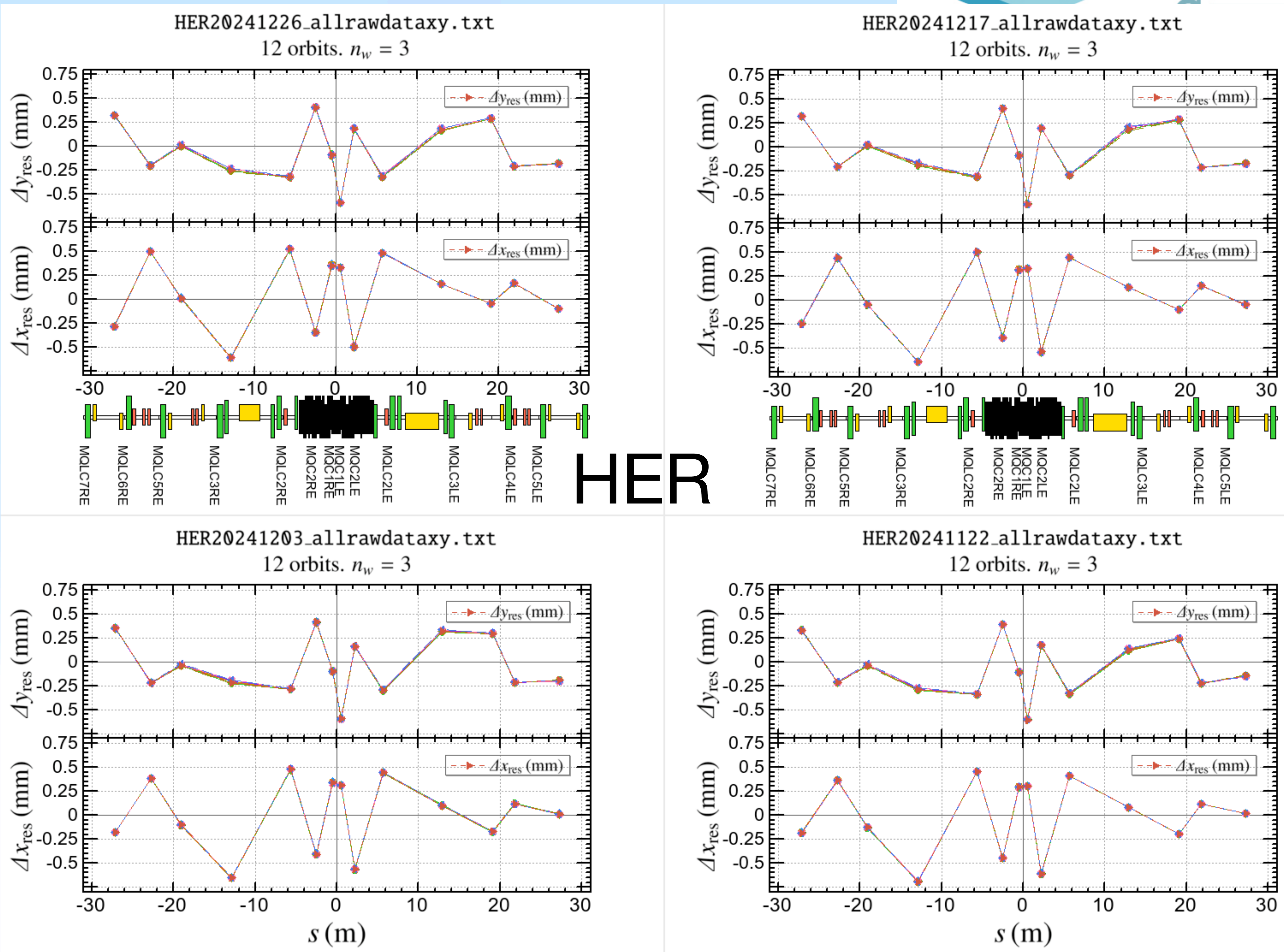
$$B \approx B' = \mathrm{U}'^{*T} \mathrm{diag}(\boldsymbol{w}')\mathrm{V}' \tag{6}$$

$$= \sum_{k=1,n_w} w_k \boldsymbol{u}_k^* \boldsymbol{v}_k^T \ , \tag{7}$$

The “intrinsic residual” components of the BPM data

Intrinsic Residual





- We can remove the components caused by the external source by subtracting the projections over V':

$$\mathrm{B}_{\mathrm{meas}} \equiv (x_{ij} + i y_{ij}) \tag{8}$$

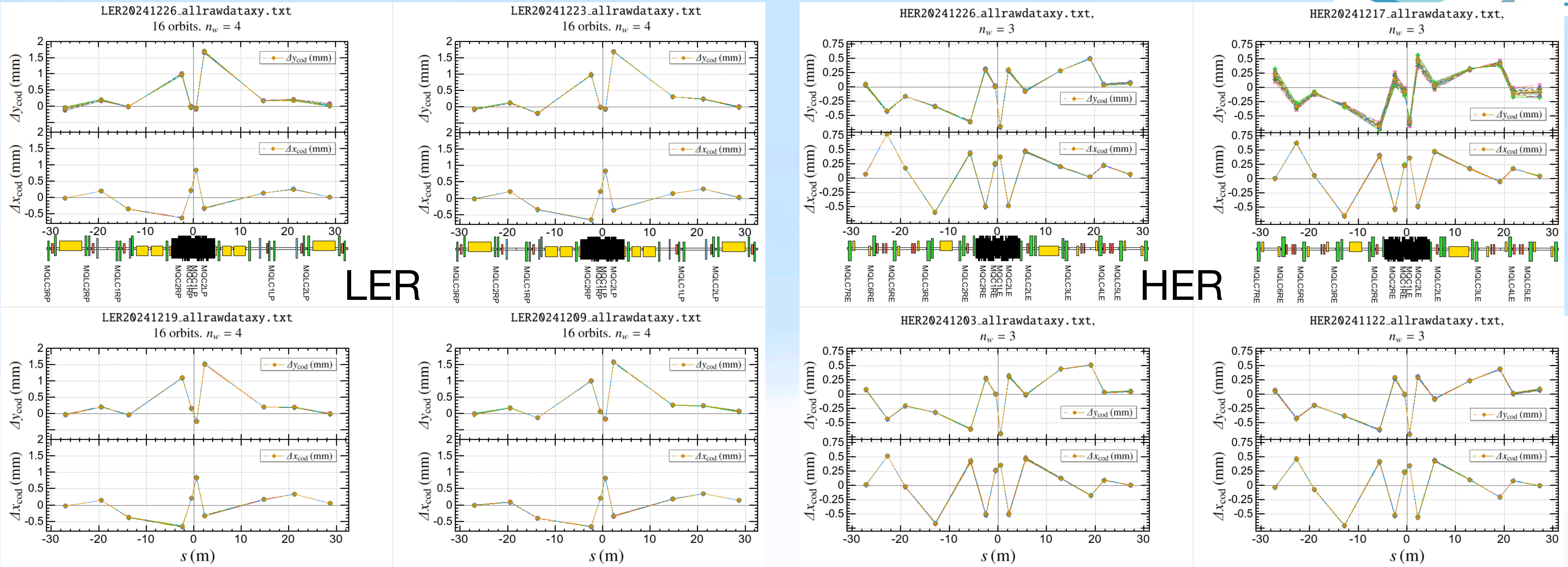
$$\mathrm{B}_{\mathrm{res}} = \mathrm{B}_{\mathrm{meas}} - \mathrm{B}_{\mathrm{meas}} \mathrm{V}'^{*T} \mathrm{V}' \tag{9}$$

- The resulting residual $\mathrm{B}_{\mathrm{res}}$ seems fairly identical to all orbits over samples, as shown above.

- Each plot contains 12 orbits, almost overlapping.
- In some cases, some fluctuations are still visible, showing the level of the measurement noise and other fluctuations.

The “intrinsic residual” is not the closed orbit

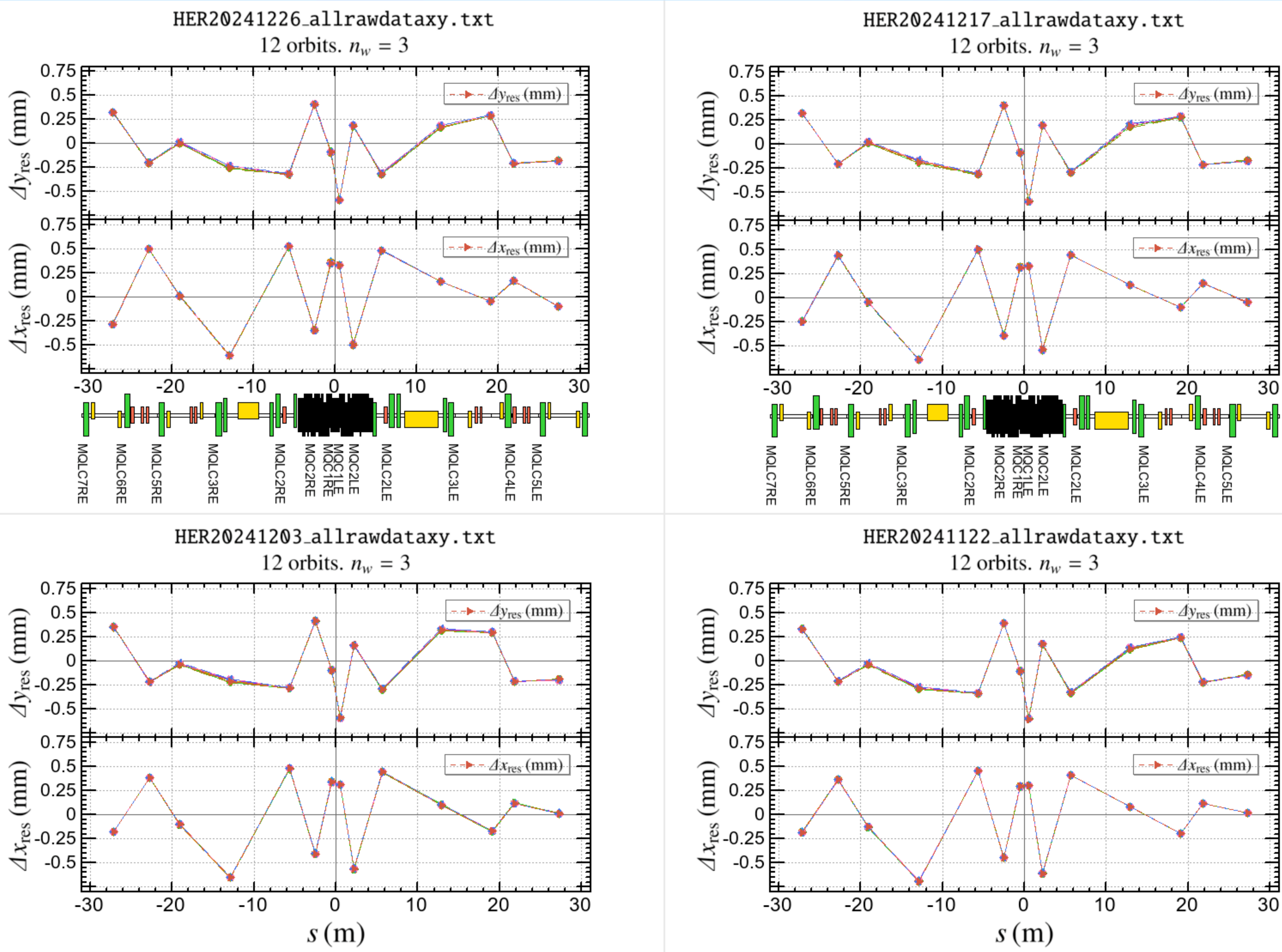
Closed Orbit



- The “intrinsic residual” (previous page) has some similarity with the base closed orbit (this page), but *they are still different*.
- This is because the closed orbit also has some external components.

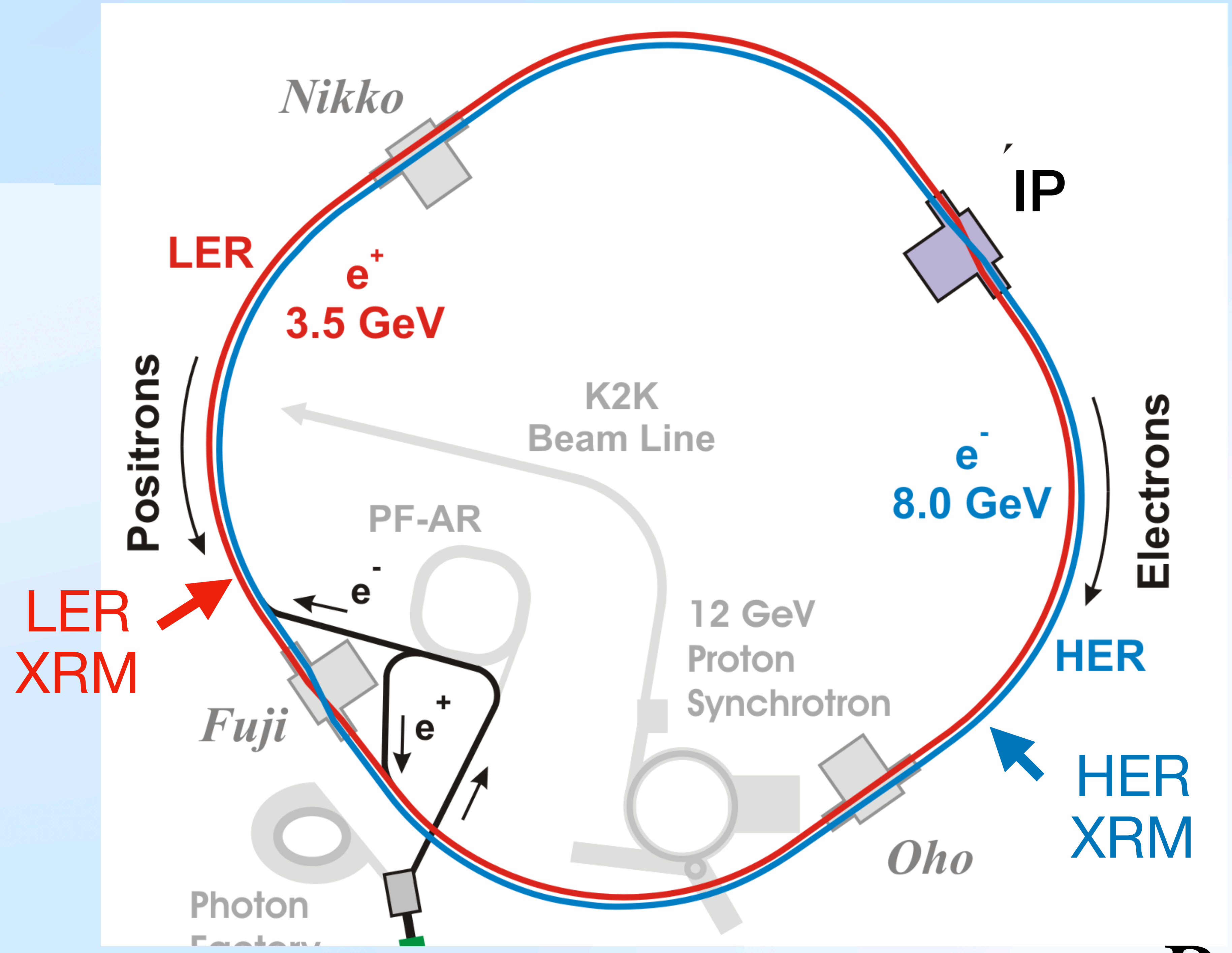
What does "intrinsic residual" imply?

- The "intrinsic residual" is a combination of machine errors within ±30 m around the IP. as the resuts of
  - BPM offsets
  - dipole kicks
  - quadrupole offsets
  - …
- The magnitude of the intrinsic residual (0.5/1.5 mm in the HER/LER) is larger than
  - BPM measurement noise
  - errors in the BPM offsets determined by Quad-BPM method.
- Thus the *easiest* guess is that these numbers just represent the misalignments of quadrupoles.
  - The vertical "angle" at the IP reaches 0.66 mrad in the HER.

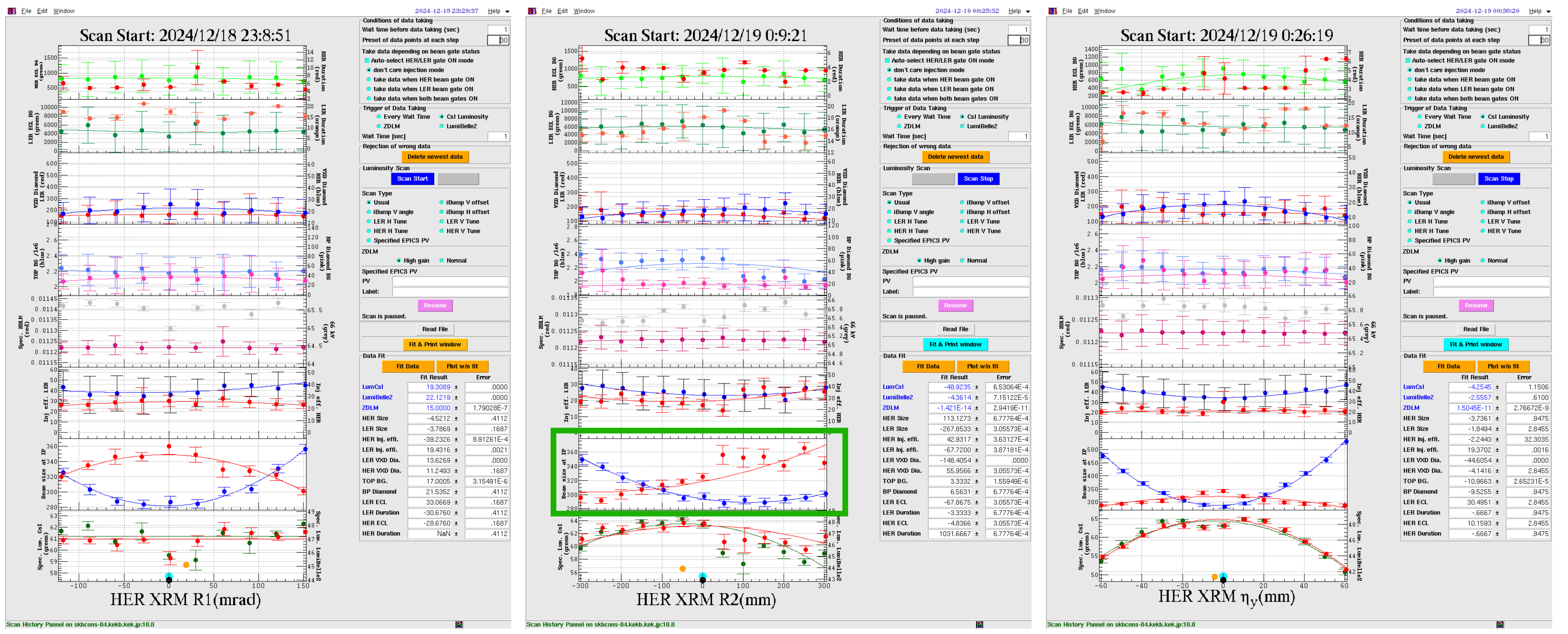


X-y coupling due to beam-beam focusing

- A x-y coupling & vertical dispersion control knobs at the XRM are produced & examined for both rings (H. Koiso, G. Mitsuka, A. Morita, H. Sugimoto & K. Oide).
  - Three knobs for R_1, R_2, η_y at XRM, without affecting outside the knob region.
  - Using skew-quadrupole windings on the arc sextupoles around the XRM.
- Without collision, either at low (50 mA) or high (1100/880 mA) current, the XRM size sits at the minimum of each knob.
- With collision, the HER R2 knob showed a significant shift of the minimum (below, middle).
- Thus a relative tilt between two beams at the IP is suspected, causing "*dynamic coupling*".



HER XRM Tilt Knob scan during beam collision LER/HER 1100/880 mA



$$R_1 \approx -0.4 \times 10^{-3} \qquad R_2 \approx -113\,\mathrm{mm}$$

Dynamic coupling

- If there is an x-y coupling at the IP, the transfer matrix of the beam-beam focusing is represented as:

$$\mathrm{K} = \mathrm{R}^{-1}\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & -k_y & 1\end{pmatrix} R\ , \tag{9}$$

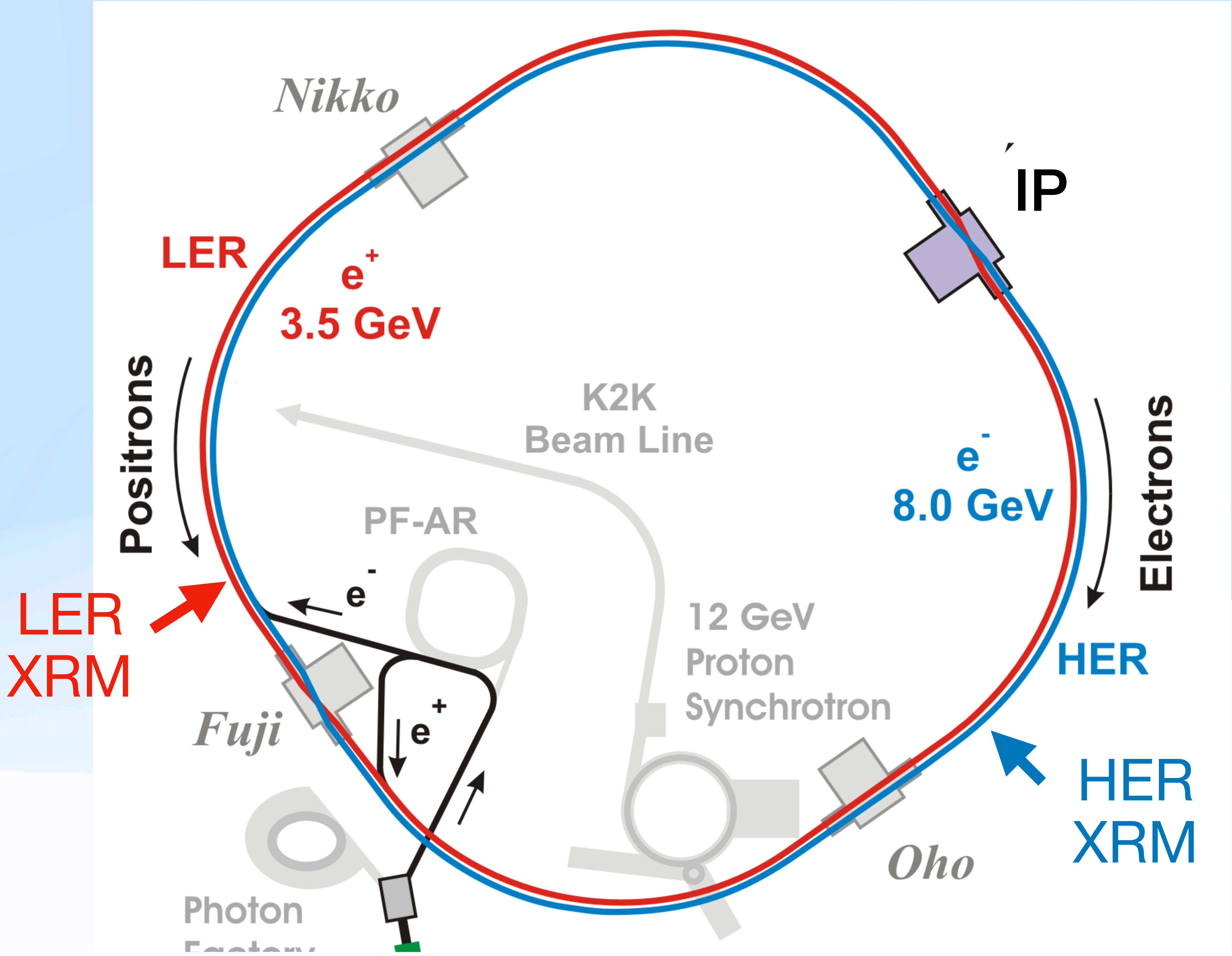
where $ky = 4\pi\xi_y/\beta_y^*$ and

$$R = \begin{pmatrix} a & 0 & -R_4^* & R2^* \\ 0 & a & R_3^* & -R_1^* \\ R_1^* & R_2^* & a & 0 \\ R_3^* & R_4^* & 0 & a \end{pmatrix}\ , \qquad a^2 + |R^*| = 1\ . \tag{10}$$

- We have neglected the horizontal beam-beam focusing, which is small due to the large crossing angle.

- Then the one-turn transfer matrix M from XRM to XRM is expressed as

$$\mathrm{M} = \mathrm{M}_{\mathrm{IP}\to\mathrm{XRM}}\mathrm{K}\mathrm{M}_{\mathrm{XRM}\to\mathrm{IP}} \tag{11}$$



Dynamic coupling (2)

- Then we can obtain the coupling parameters R_1 and R_2 at the XRM from M, after a lengthy calculation:

$$\begin{pmatrix} R_1 \\ R_2 \end{pmatrix}_{\mathrm{XRM}} = C \begin{pmatrix} \frac{\beta_x^*}{\beta_x}\left(e_x \sin\overline{\psi}_y + f_x \sin\psi_y\right) R_1^* + \left(g_x(\sin\overline{\psi}_y + \cos\mu_x \sin\psi_y) - h_x \sin\mu_x \sin\psi_y\right)\frac{R_2^*}{\beta_x} \\ \beta_x^*\left(\sin\overline{\psi}_x \sin\psi_y - \sin\psi_x \sin\overline{\psi}_y\right) R_1^* + \left(\cos\overline{\psi}_x \sin\psi_y + \cos\psi_x \sin\overline{\psi}_y\right) R_2^* \end{pmatrix} , \tag{12}$$

where

$$C \equiv \frac{k_y}{2\cos\mu_x - 2\cos\mu_y + \beta_y^* k_y \sin\mu_y} , \qquad \overline{\psi}_{x,y} \equiv \mu_{x,y} - \psi_{x,y} , \tag{13}$$

$$e_x \equiv \cos\psi_x - \alpha_x \sin\psi_x , \qquad f_x \equiv \cos\overline{\psi}_x + \alpha_x \sin\overline{\psi}_x , \tag{14}$$

$$g_x \equiv \alpha_x \cos\psi_x + \sin\psi_x , \qquad h_x \equiv \cos\psi_x - \alpha_x \sin\psi_x . \tag{15}$$

$\beta^*_{x,y}$	(80,1)	mm
$\beta_{x,y}$	(4.56,68.88)	m
$\alpha_{x,y}$	(-0.469,1.75)	
$\psi_{x,y}/2\pi$	(0.518,0.9996)	
$\mu_{x,y}/2\pi$	(0.529,0.620)	
ξ_y	0.015	

- If we plugin the parameters for the HER, we obtain:

$$R_{1,\mathrm{XRM}} = -3.69 \times R_1^* - 26.04/\mathrm{m} \times R_2^* \tag{16}$$

$$R_{2,\mathrm{XRM}} = 3.94\,\mathrm{m} \times R_1^* - 182.75 \times R_2^* \tag{17}$$

Dynamic coupling: guess the IP coupling (HER)

- Using Eqs. (16)(17), we can estimate the x-y coupling parameters at the IP from the measured values at the XRM:

$$(R_1^*, R_2^*) = (-3.78 \times 10^{-3}, 0.54\,\mathrm{mm})\ . \tag{18}$$

- On the other hand, the current settings of the IP knobs are

$$(R_1^*, R_2^*)_{\mathrm{knob}} = (12 \times 10^{-3}, 1.55\,\mathrm{mm})\ . \tag{19}$$

- Therefore the IP knobs are *correcting* the errors in the lattice as:

$$(R_1^*, R_2^*) = (R_1^*, R_2^*)_{\mathrm{error}} + (R_1^*, R_2^*)_{\mathrm{knob}}\ . \tag{20}$$

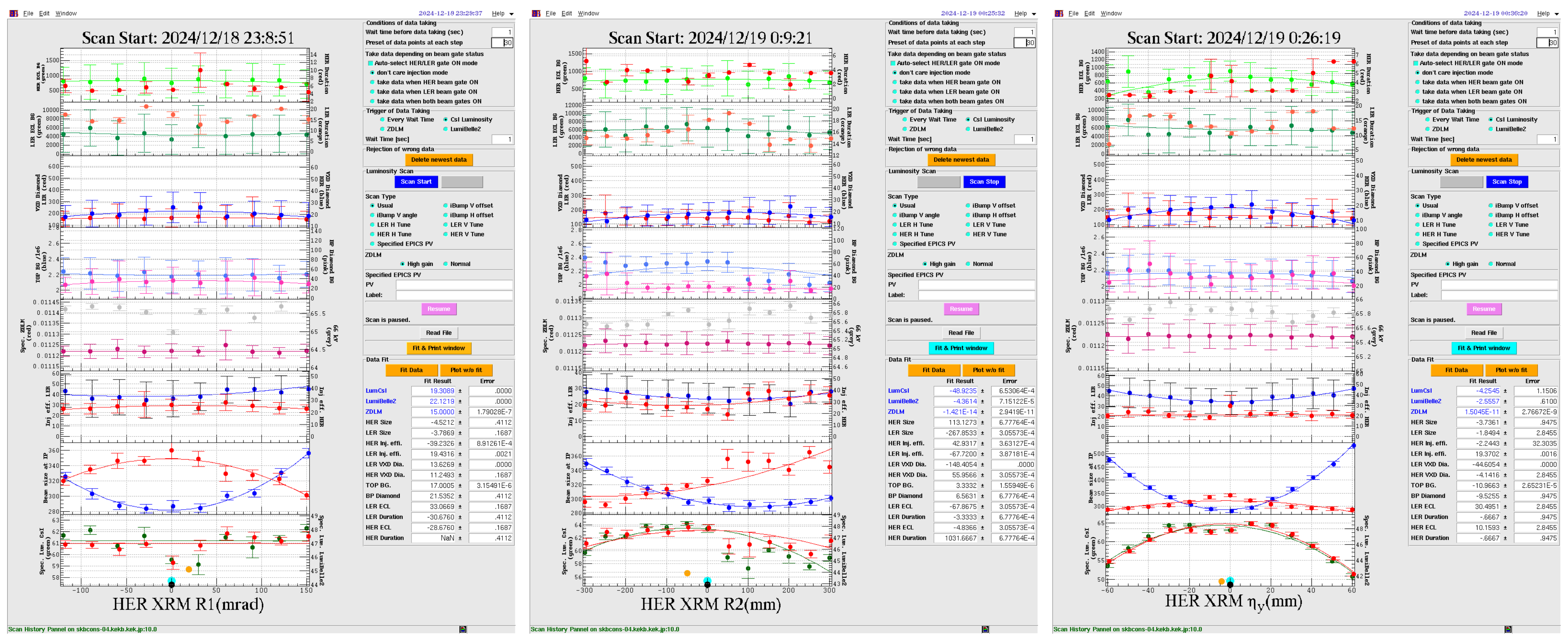
  So we can estimate the lattice error:

$$(R_1^*, R_2^*)_{\mathrm{error}} = (-15.78 \times 10^{-3}, -1.01\,\mathrm{mm})\ . \tag{21}$$

  By comparing Eqs. (19) and (21), we can say that the IP knobs corrects the errors in the right direction, but insufficient yet.

- The LER did not show significant shift in the measurement at the XRM.

HER XRM Tilt Knob scan during beam collision LER/HER 1100/880 mA



$$R_1 \approx -0.4 \times 10^{-3} \qquad R_2 \approx -113\,\mathrm{mm}$$

Tentative summary

- Effects by horizontal/vertical tilts of the detector solenoid are examined.
  - The entire solenoid/QCS block within IP±4 m is tilted by 1 mrad.
  - Increase of vertical emittance has been observed.
  - Correctable by IR skew quads within SLY region.
    - $\varepsilon_y = 0.6/16\,\mathrm{pm}$ (with hor./ver. tilts) achieved by the correction.
    - The horizontal tilt seems easier to correct than the vertical.
  - A dependence $\varepsilon_y \underset{\sim}{\propto} \theta^2$ is seen.
- Some discrepancy in the tilt of the beam spot has been observed at Belle II.
- A model-independent analysis (MIA) has been tried on the beam orbit measurements through the interaction region.
  - Significant deviation (“intrinsic residual”), which might represent the misalignments of quadrupoles, has been detected.
- The x-y coupling knob at the XRM tells the existence of “dynamic coupling”, caused by the beam-beam focusing and the residual coupling at the IP.