Beam-based vs model corrections in LHC IRs

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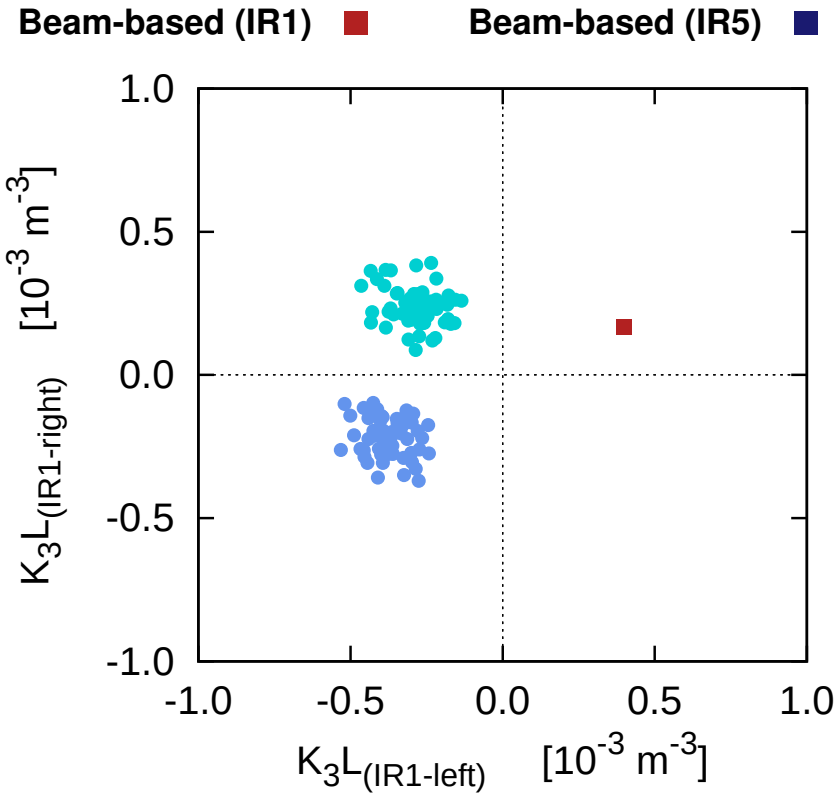
with many thanks to the whole OMC team

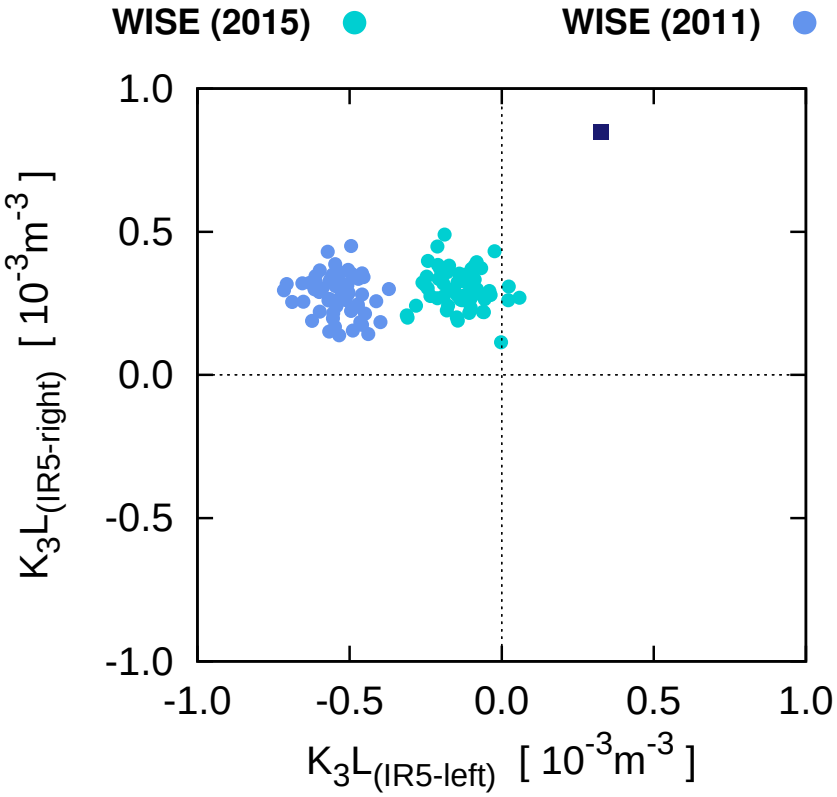
Beam-based vs model based corrections in LHC IRs

→ **which set of error tables to use?**

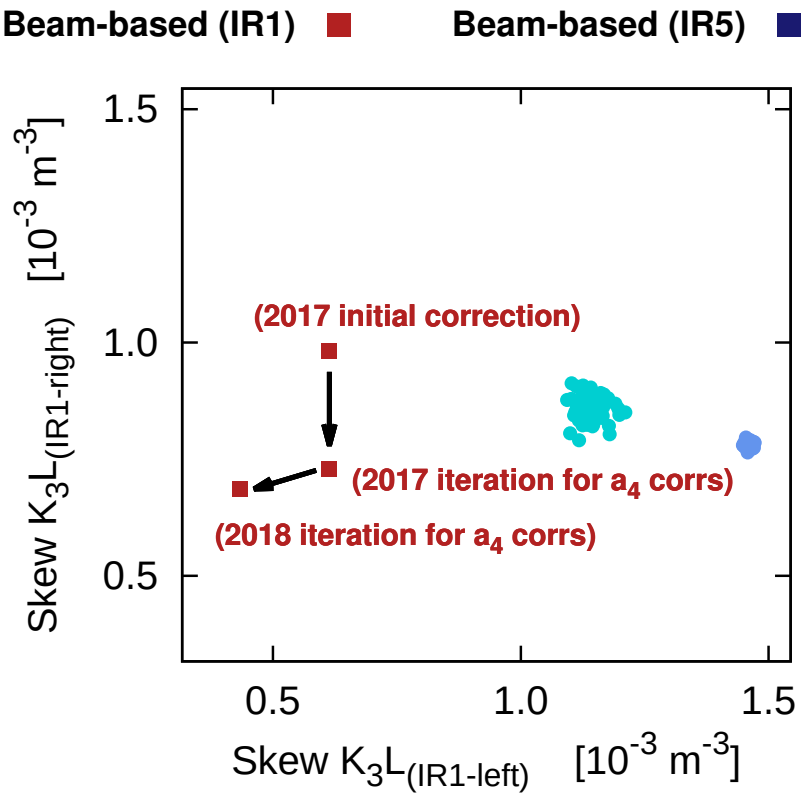
- **'Pre-LS1 WISE'**
  - → generated 2011
  - → sextupole/octupole/decapole errors unseeded in triplets
- **'Post-LS1 WISE'**
  - → generated 2015
  - → multiple bug fixes implemented in LS1 (more relevant for geometry?)
  - → error estimate dependent on magnet powering
  - → b_4 in MQXB & a_6 in MQXA unseeded in triplets
  - → Warm MBXW have several multipoles unassigned

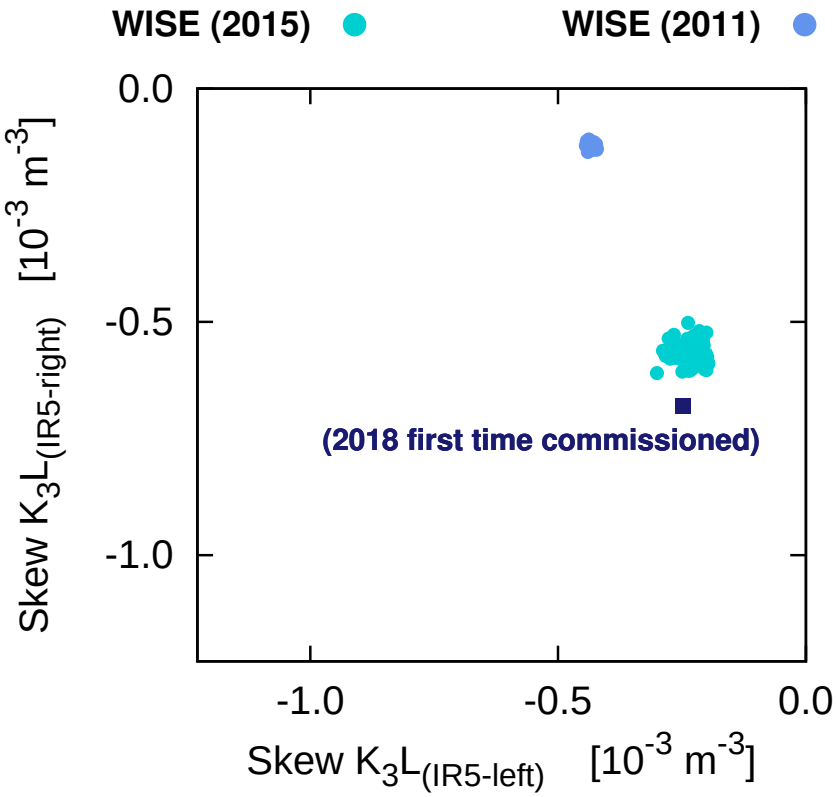
Normal sextupole corrections





Skew sextupole corrections

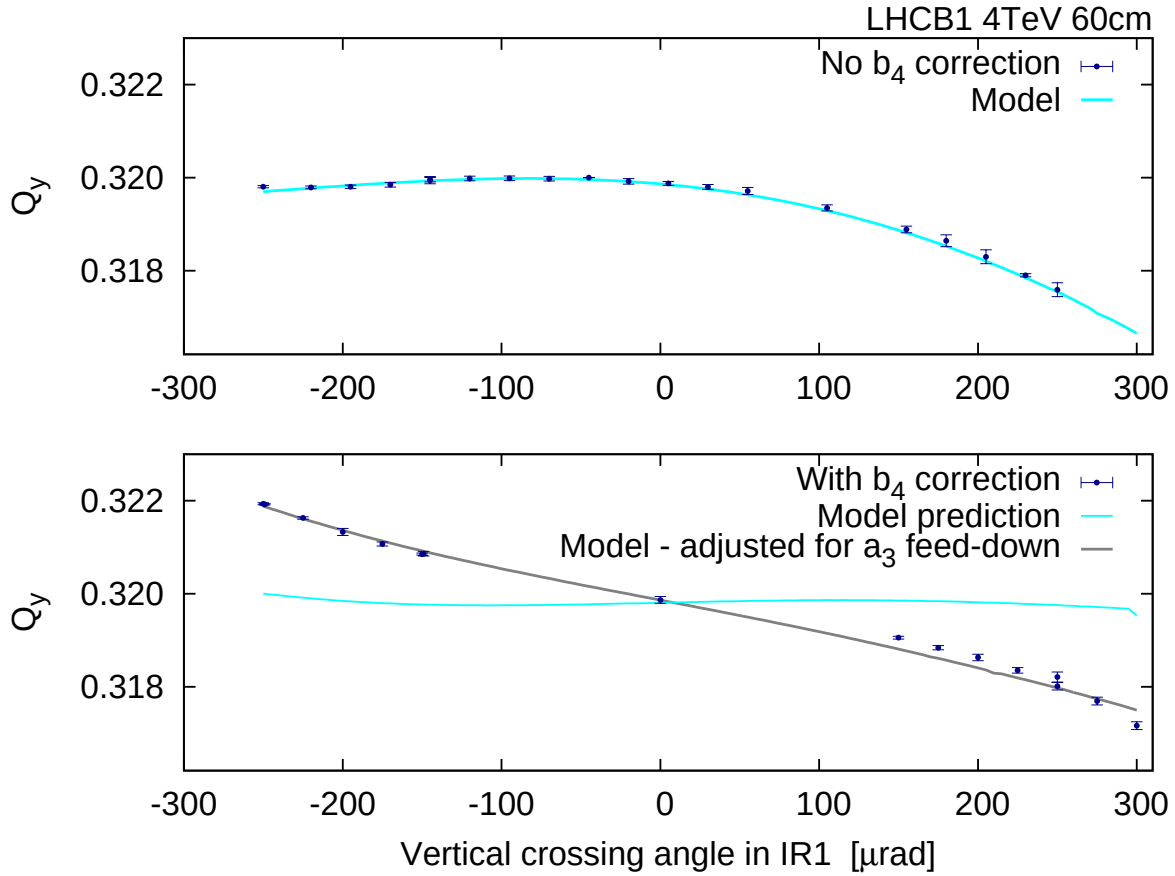




Discrepancies

- **Discrepancies with magnetic-model well beyond seeds**
- **No clearly significant benefit to 2011 vs 2015 error tables**

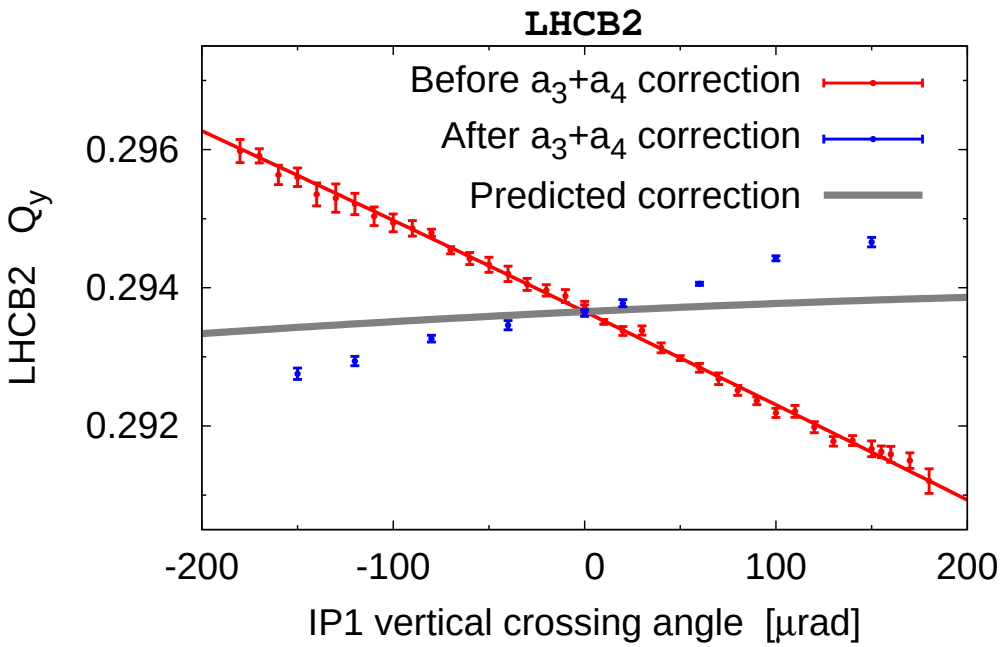
Impact of normal/skew octupole corr on required sextupole corr's



- **Beam offset in MCOX spoils a3 correction**
- **Estimate ∼1mm offset**
- **Transparent to 2017/18 commissioning**
  (b4 applied first)

Similar issue with skew octupole corrections in 2017/18

→ a3 corrections in IR1 had to be iterated multiple times



- **1mm H-offset of MCOSX R1**
- **We do care about corrector alignment**

- **Not currently attempting to include geometric errors**
  → egeoc tables don't show a comparable offset (0.2mm)
- **Not surprising that sextupole corrections don't agree: offset effects are comparable order-of-magnitude to discrepancies**

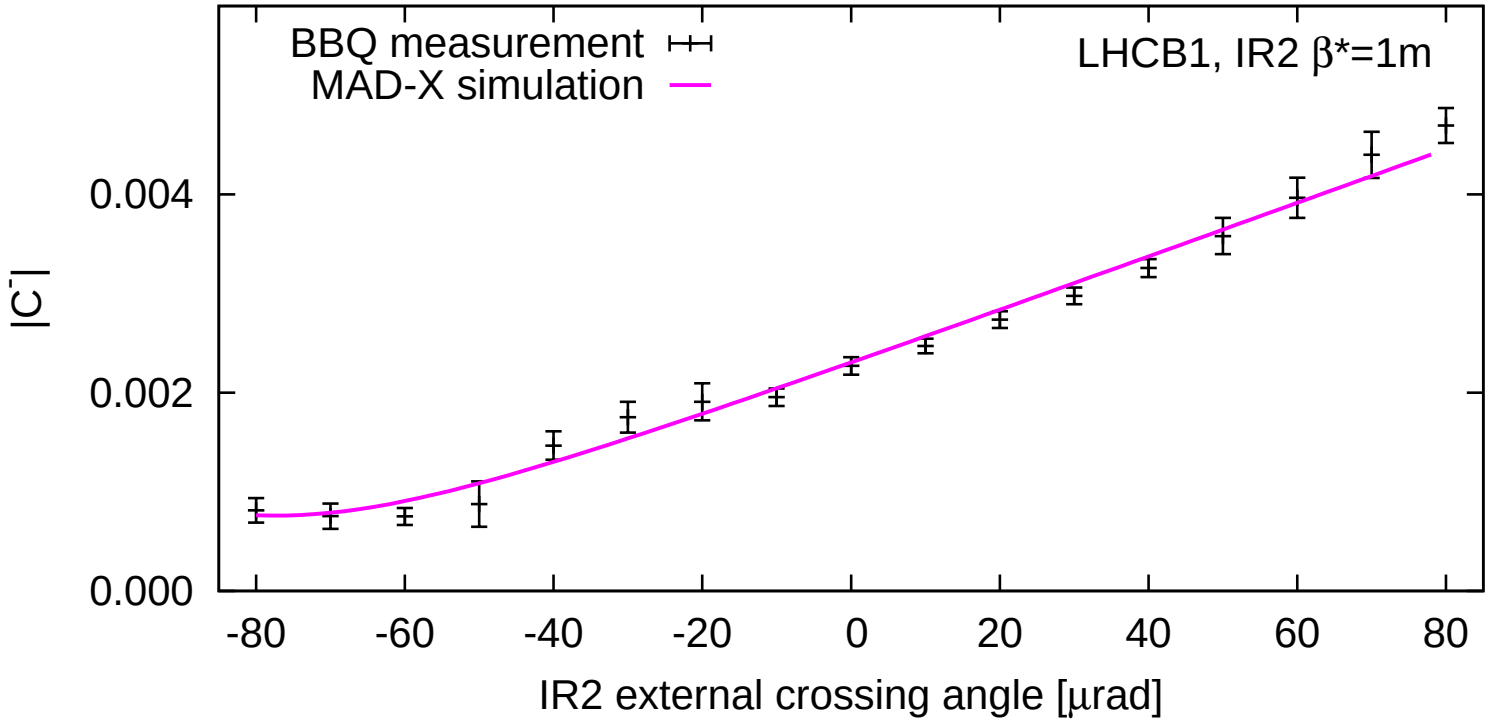
Corrector alignment tolerance from DA is $\pm$ 1mm

Consistent IR-corrector misalignment at 1mm level will complicate HL-LHC commissioning

- **lower-order corrections depend on first establishing higher-orders**
- **Becomes complicated if higher-order corrections also depend on higher-order perturbations from lower-orders**

Sextupole errors in cold MBX (IR2)

- **2011: good agreement of feed-down to coupling in IR2**
  → completely dominated by b3 of cold D1



- **Attempts to correct in 2018 ION commissioning failed!**
  → compensated 1 beam only. Still to be understood

Skew octupole correction

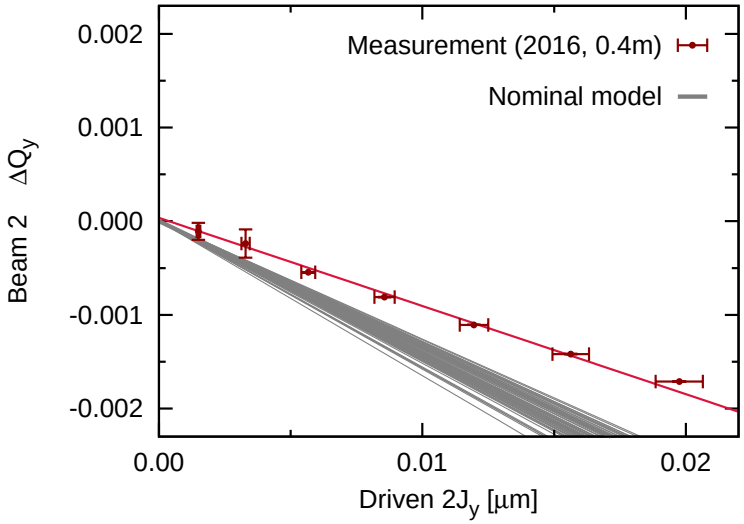
- **Limited value comparing beam- vs model-based correction for a_4**
  $\rightarrow$ **MCOSX L1 is broken**
- **2017: correct coupling feed-down in IR1 with single corrector**
- **2018: global RDT correction (f_{1210}) via 3 correctors in IR1+5**
- $\rightarrow$ Compare sum of L+R corrections

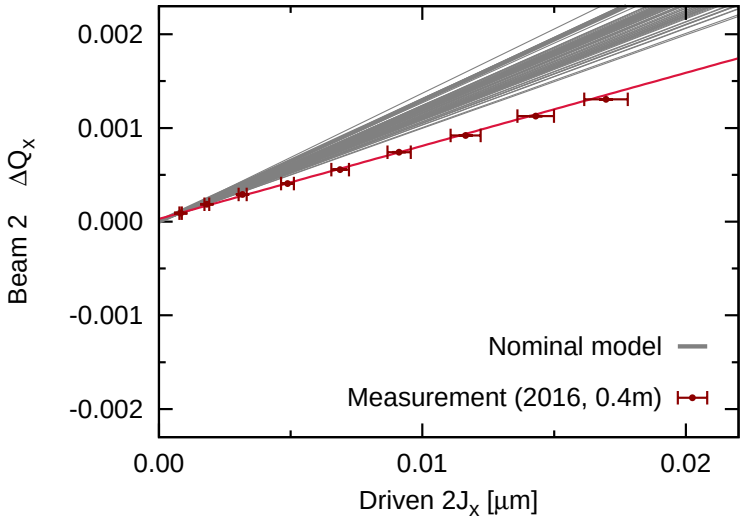
Corrector strength	Beam-based		model-based	
$[\mathrm{m}^{-4}]$	2017	2018	WISE (2015)	WISE (2011)
$\sum_{IR1} K_{4,skew}$	$+1.0$	$+0.50$	$+0.93 \pm 0.06$	$+0.86 \pm 0.01$
$\sum_{IR5} K_{4,skew}$	unused	-0.51	-0.52 ± 0.06	-0.63 ± 0.01

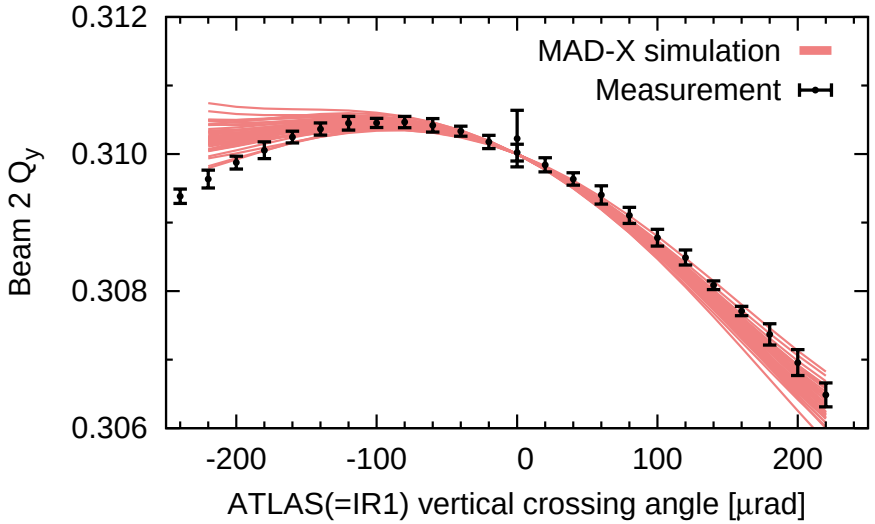
- **Sign and magnitude of beam-based corrections are comparable to model**

Normal octupole correction

Beam-based correction via detuning & feed-down to $Q_{x,y}$

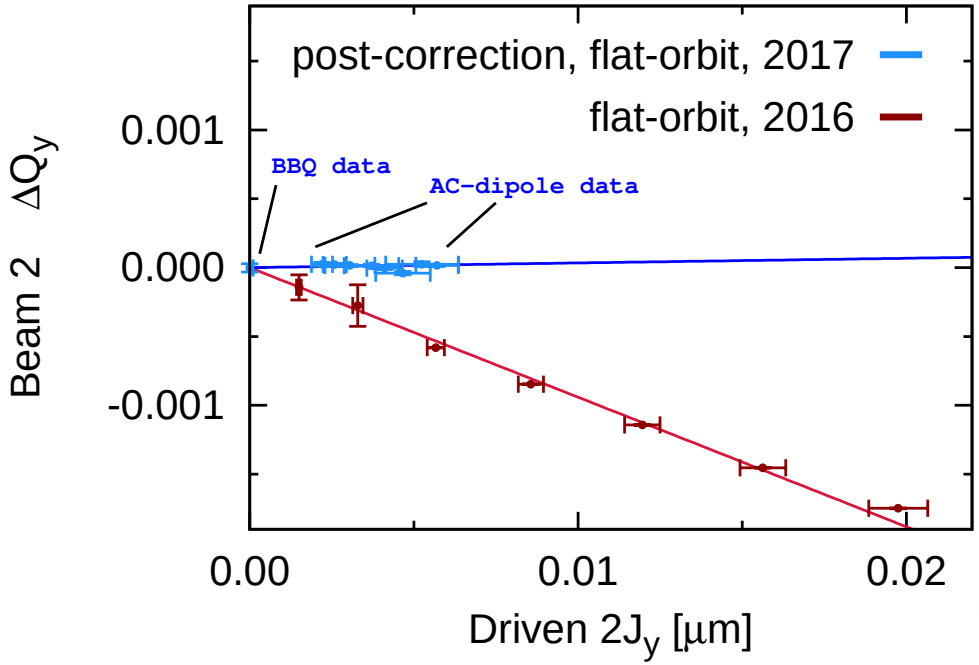






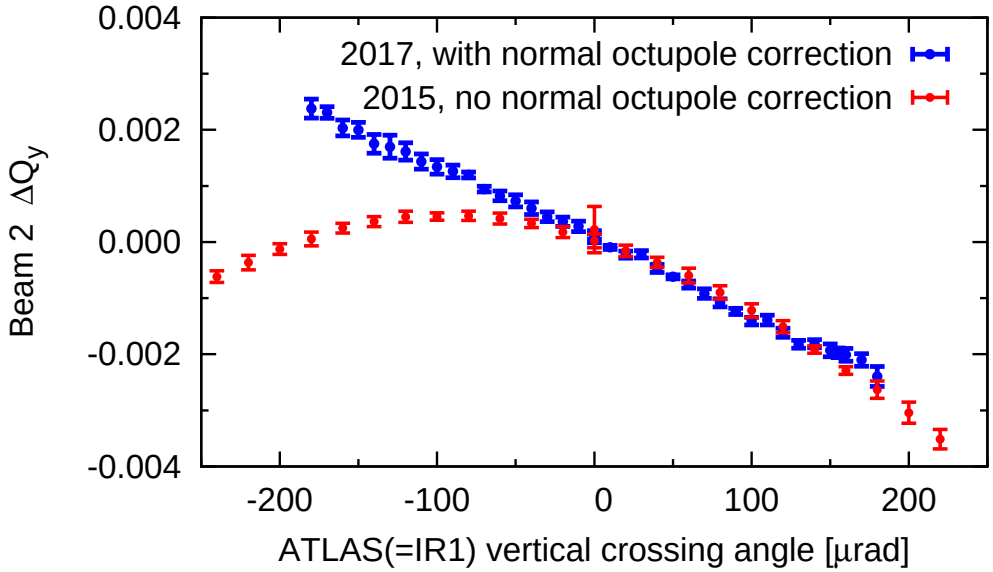
- **Model-based IR1 correction (feed-down agrees with model)**
- **Minimize residual detuning with IR5 correctors**

Extremely good detuning post-correction (flat-orbit)

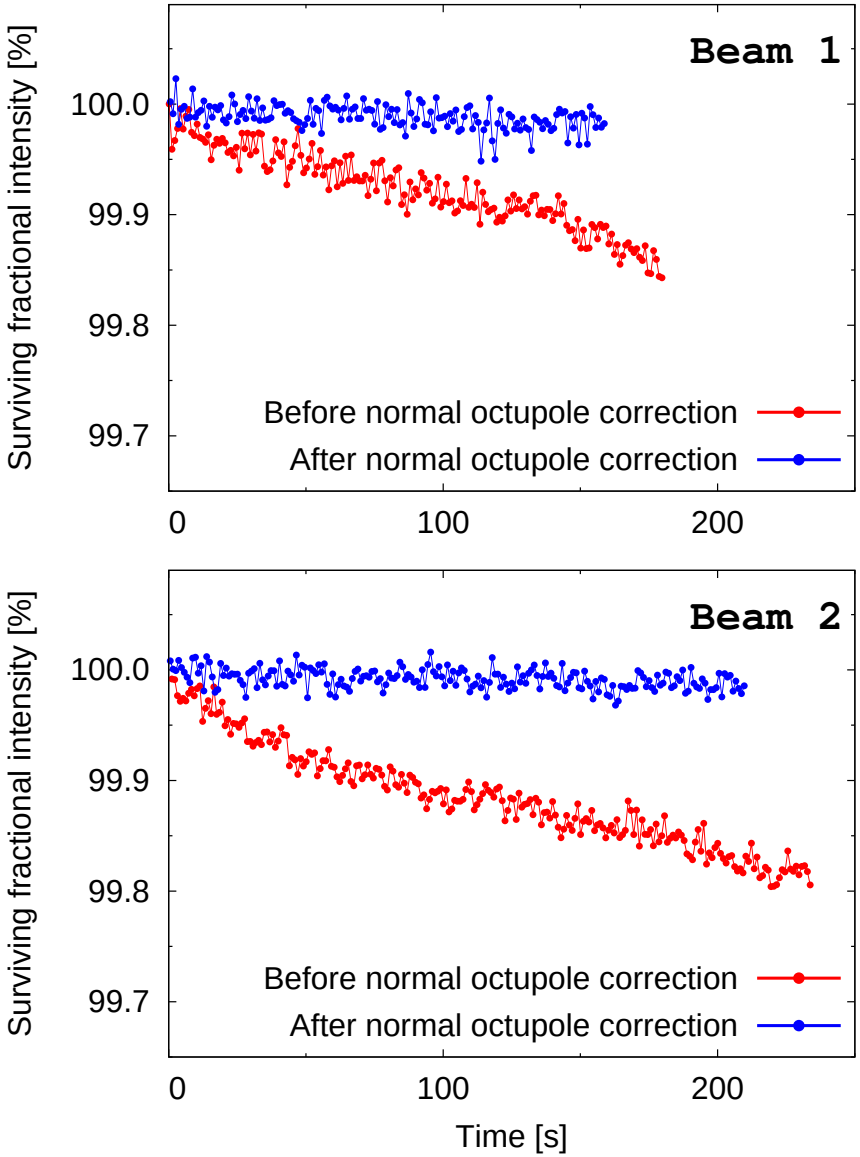


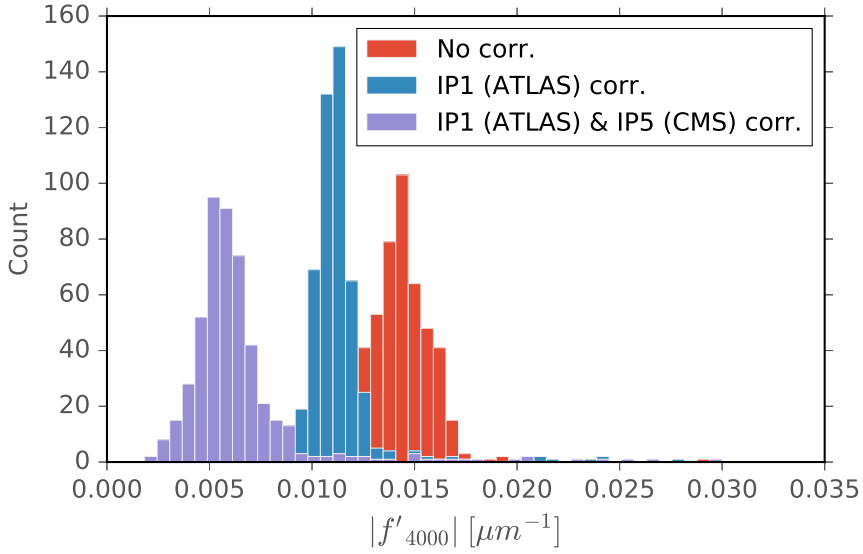
- re-validated in late-2017 & 2018-MD1
- Good global correction

- Reduced quadratic part of tune variation
- Good local correction



also improved lifetime ($\beta^* = 0.14\,\mathrm{m}$) and 4Qx resonance strength



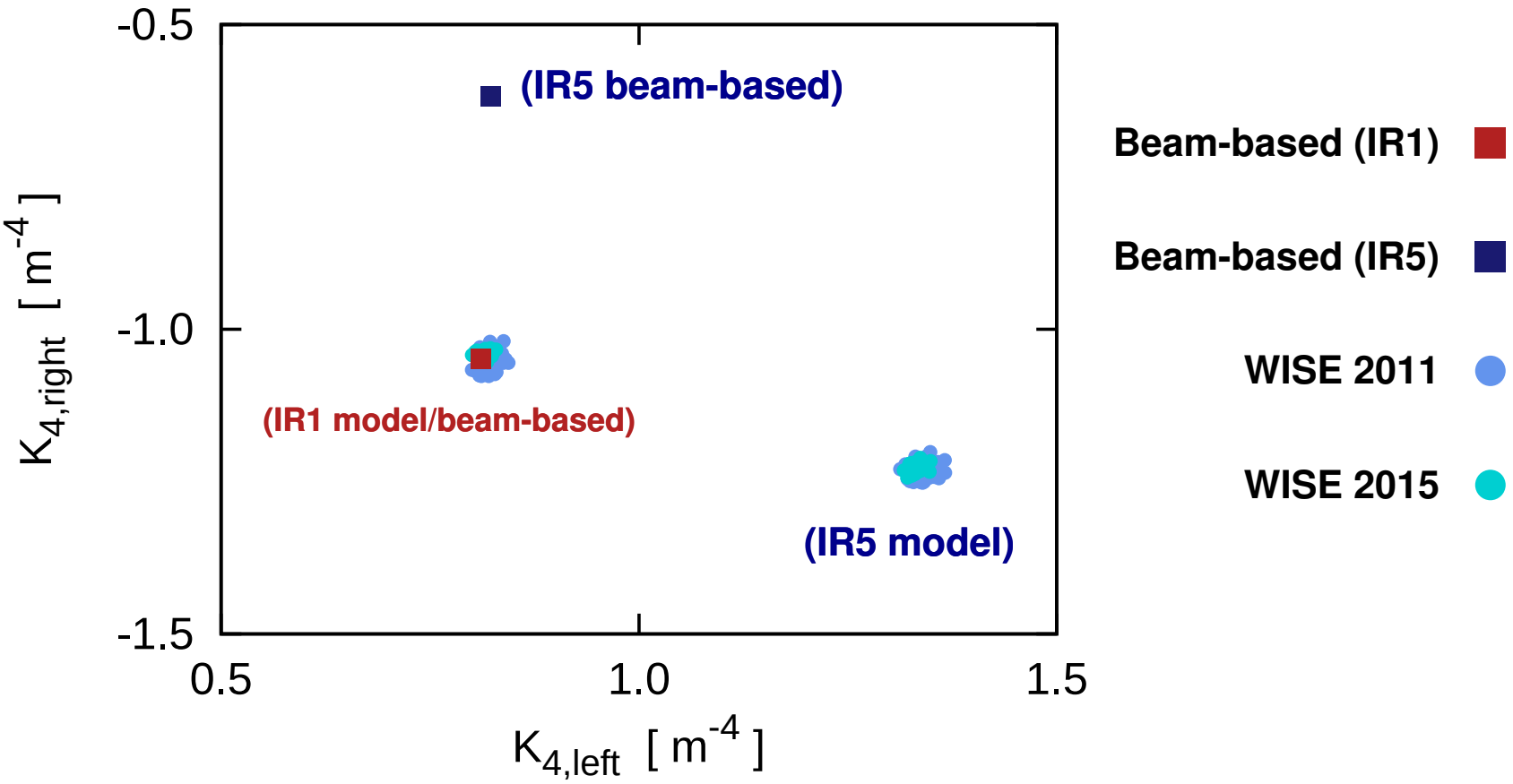


- **Lots of reasons to think b_4 is well corrected**

Significant discrepancy in a strong multipole component

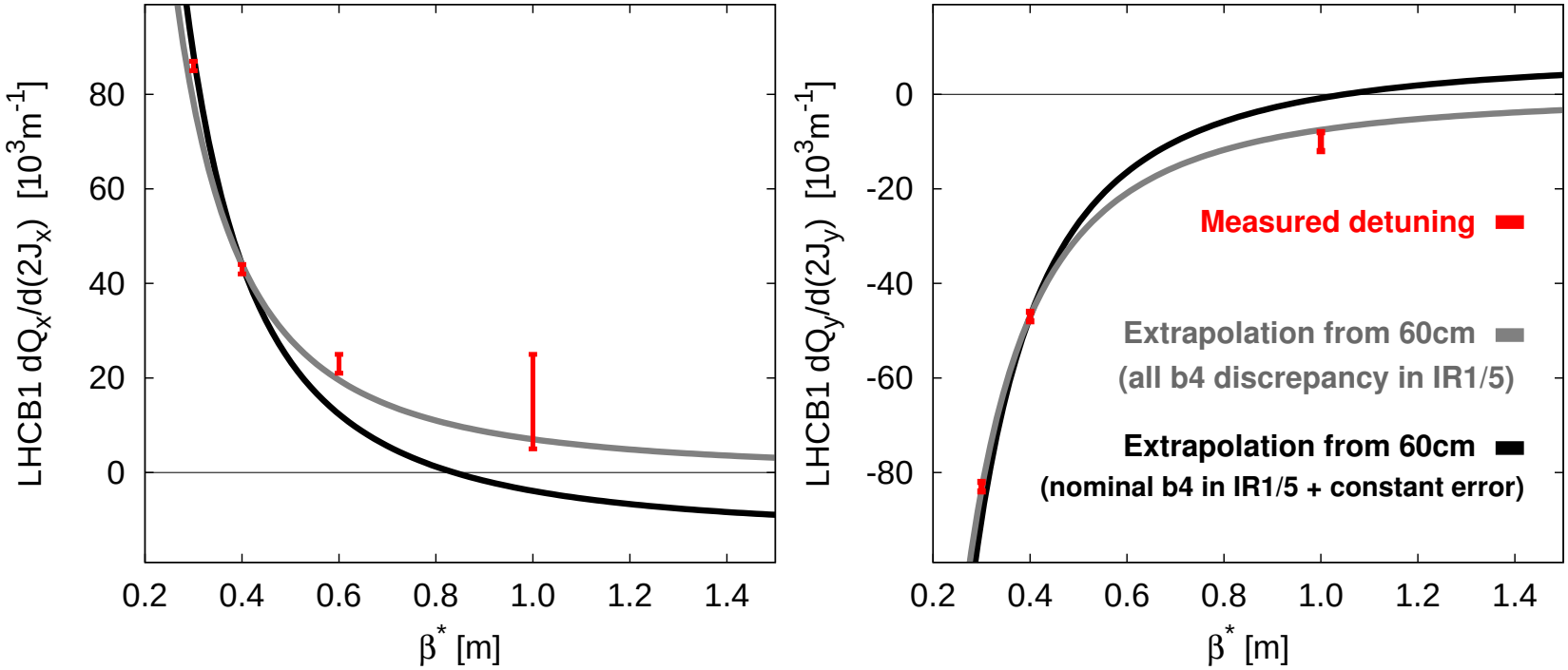
→ **expect larger correction in IR5 than IR1**

→ **actually find weaker correction in IR5**



Is the b_4 discrepancy believable?

Amplitude detuning constrains sum of IR1+IR5 correction
$\rightarrow$ see $\sim 30\%$ discrepancy in amplitude detuning
$\rightarrow$ additional source elsewhere in the ring?

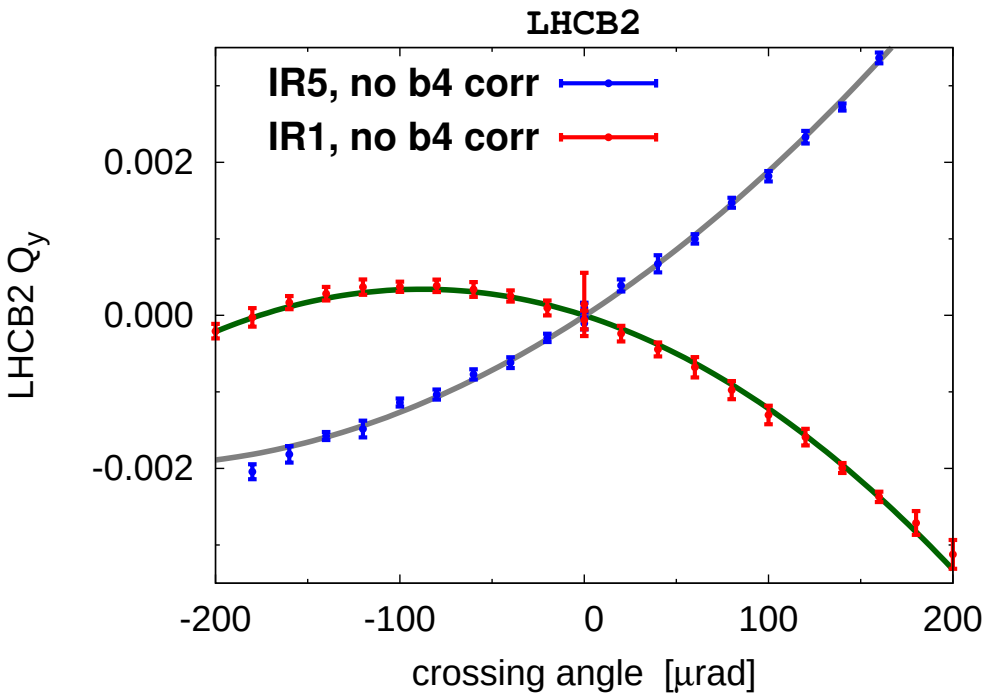


- **Detuning vs β^* consistent with IR1/5 discrepancy**
- **Correction for 2016 nominal optics still works well for ATS optics after sextupole correction**

Is the b_4 discrepancy believable?

→ IR5 b4 correction calculated purely based on detuning

→ compare quadratic part of IR1 vs IR5 tune feed-down pre-correction



- **Consistently find quadratic part of Q-feed-down in IR5 < IR1**
- **e.g. quadratic fit to LHCB2 Q_y:**

$$\frac{\partial^2 Q_y}{\partial \theta^2}\Big|_{\mathrm{IR5}} = \quad 3.1 \times 10^{-8}$$

$$\frac{\partial^2 Q_y}{\partial \theta^2}\Big|_{\mathrm{IR1}} = -4.5 \times 10^{-8}$$

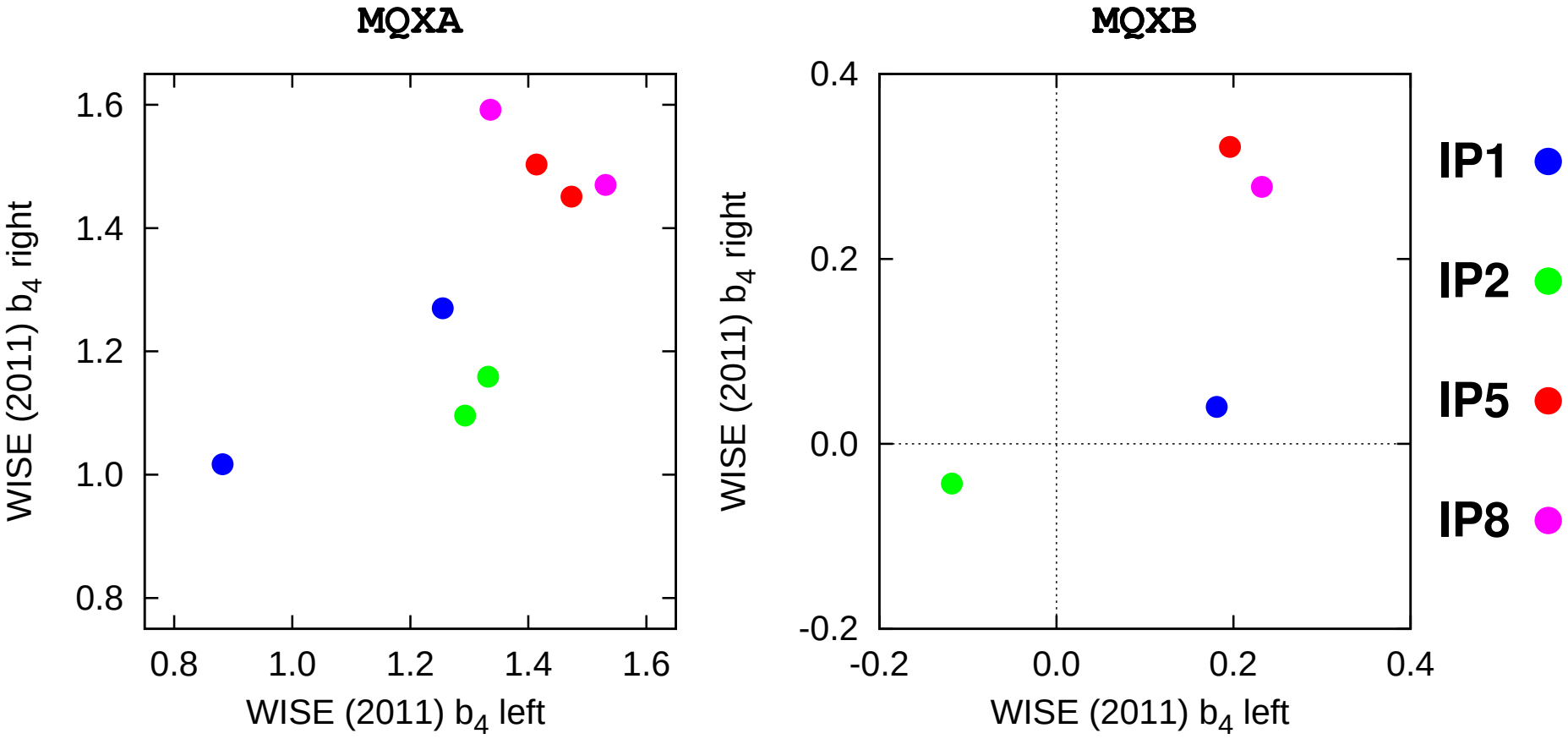
Measurements of feed-down to tune are not consistent with larger b4 errors in IR5 than in IR1 → this is consistent with beam-based corr'

Caveat: comparing measurements over multiple different years

Explanations? Error in magnetic model of b_4?

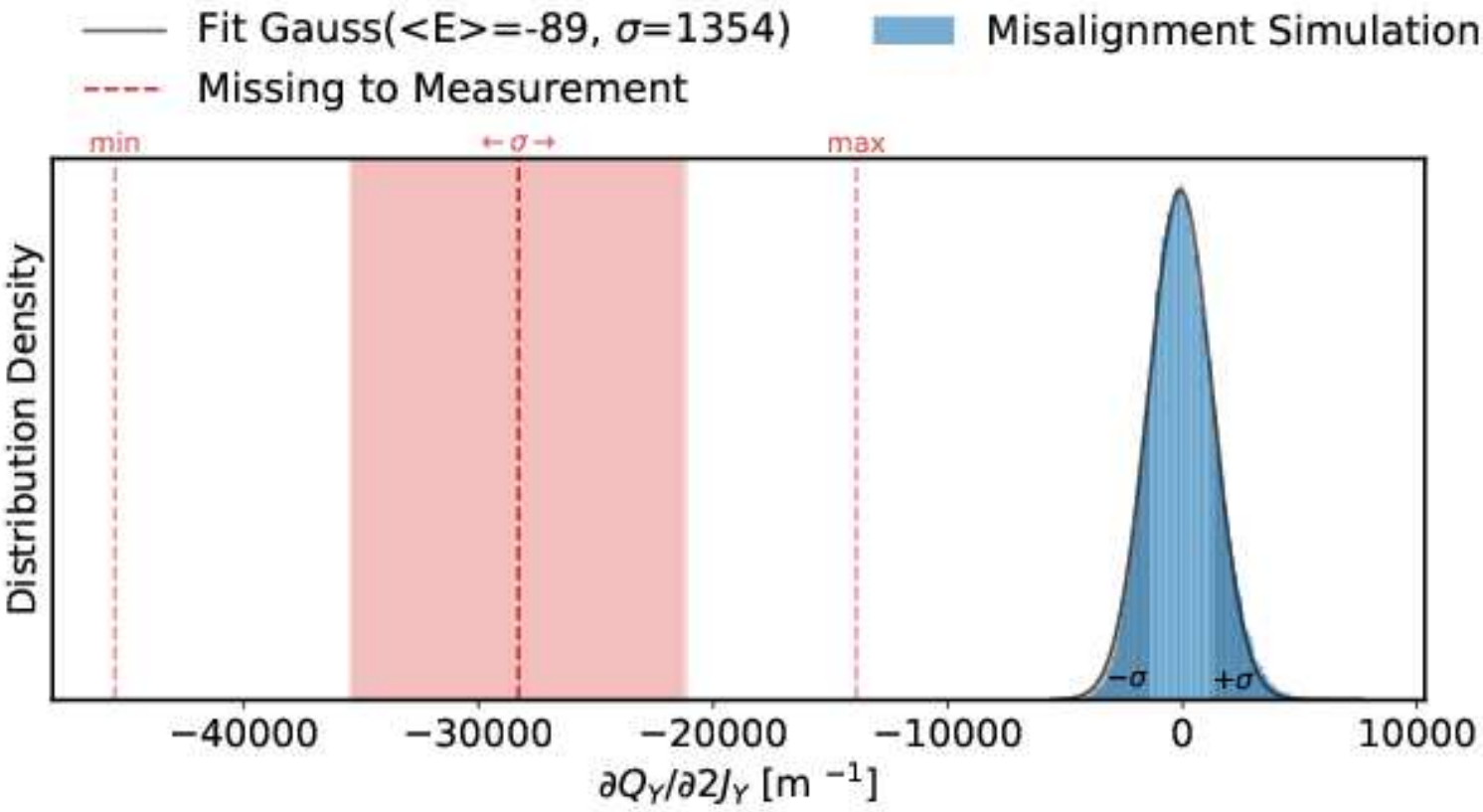
According to WISE tables, the triplet b_4 in IR5/8 appears systematically worse than IP1/2

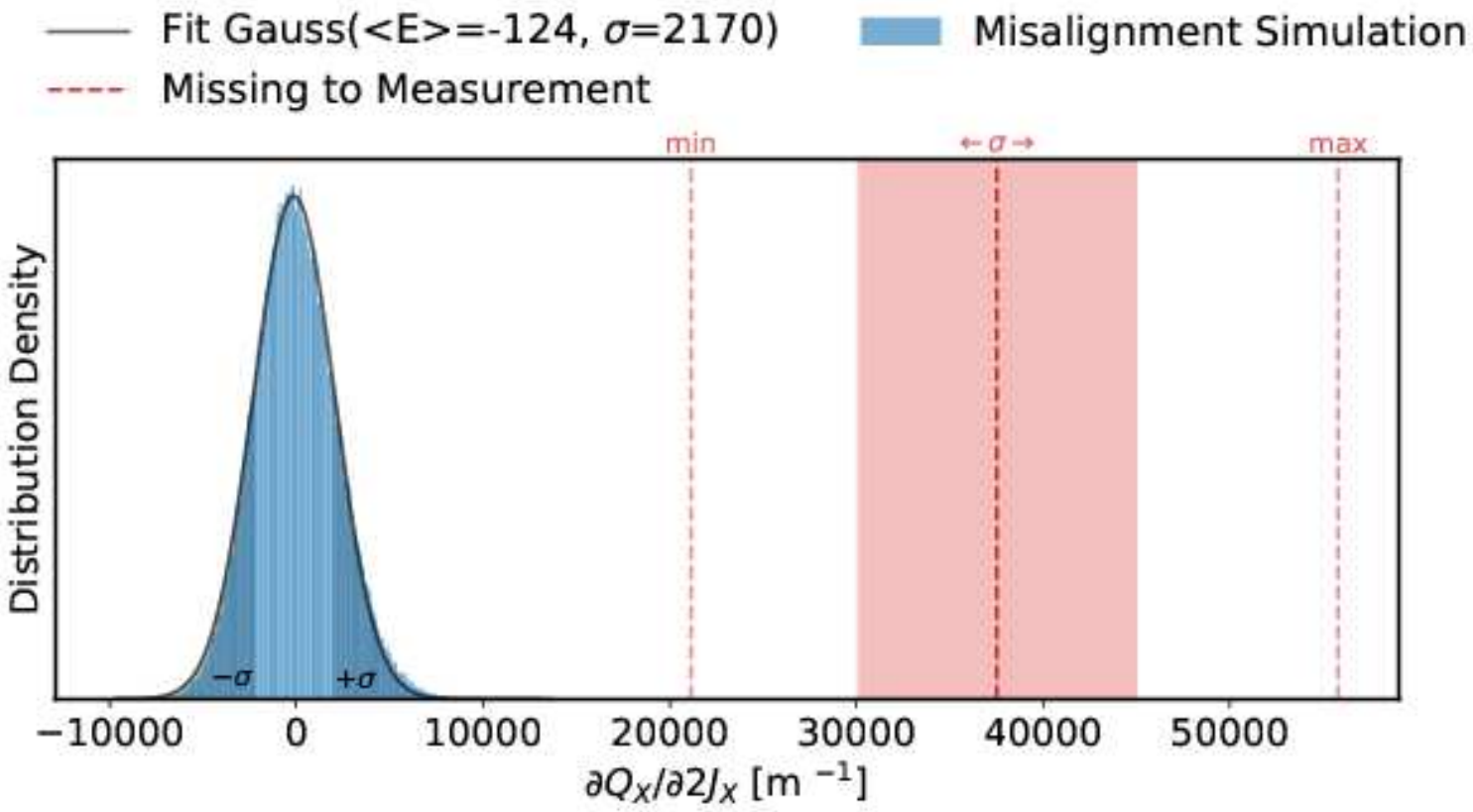
$\longrightarrow$ is this correct? $\longrightarrow$ if so, why?



Can IR alignment/offsets explain b4 discrepancy?

- **Apply random misalignments to triplets in IR5 with Gaussian distribution**
- $\sigma_{x,y} = 0.3mm$, **estimate from K-mod of typical offset of beam in Q1**

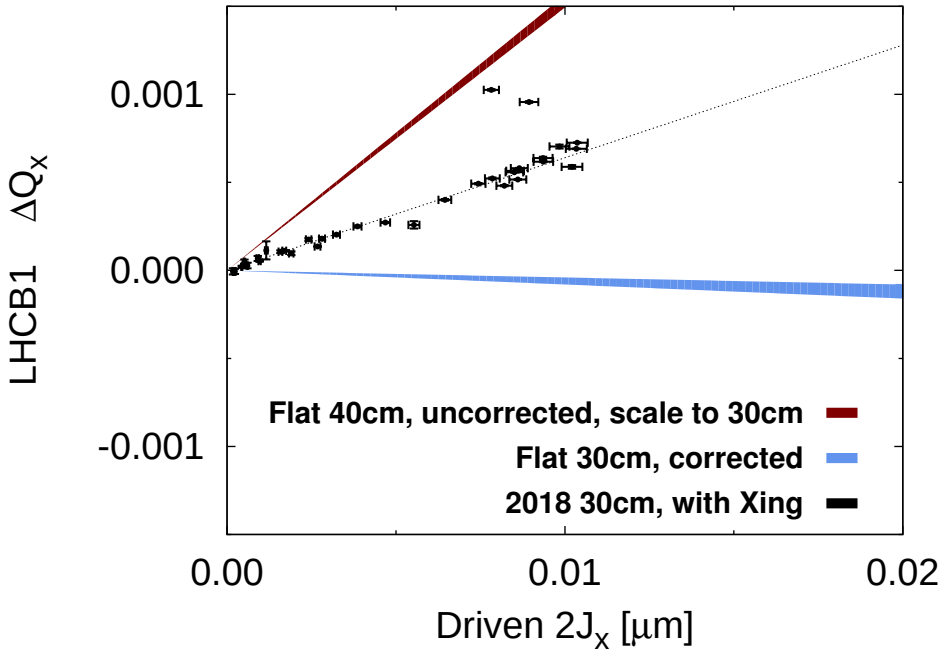


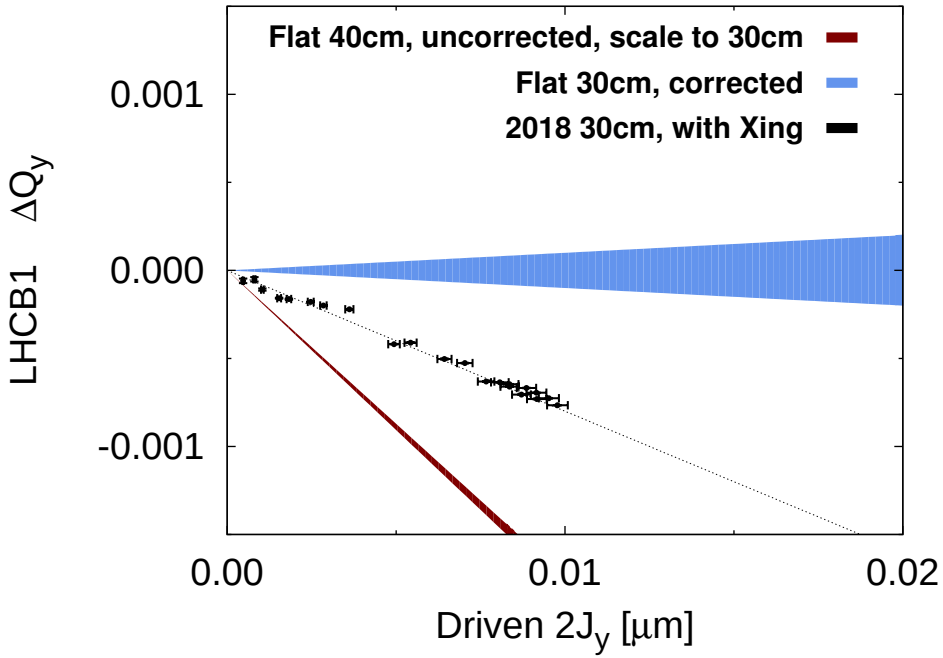


- **At 0.3mm level alignments explain** 10% **of missing b4.** Caveats:
  → only IR5
  → 0.3mm relevant to Q1,2. Q3 & MBX may be less controlled
- **Explanation via feed-down requires some extra non-conformity (orbit/alignment/higher-orders)**

Model vs measurement of higher-orders?

→ see large change to detuning from crossing scheme

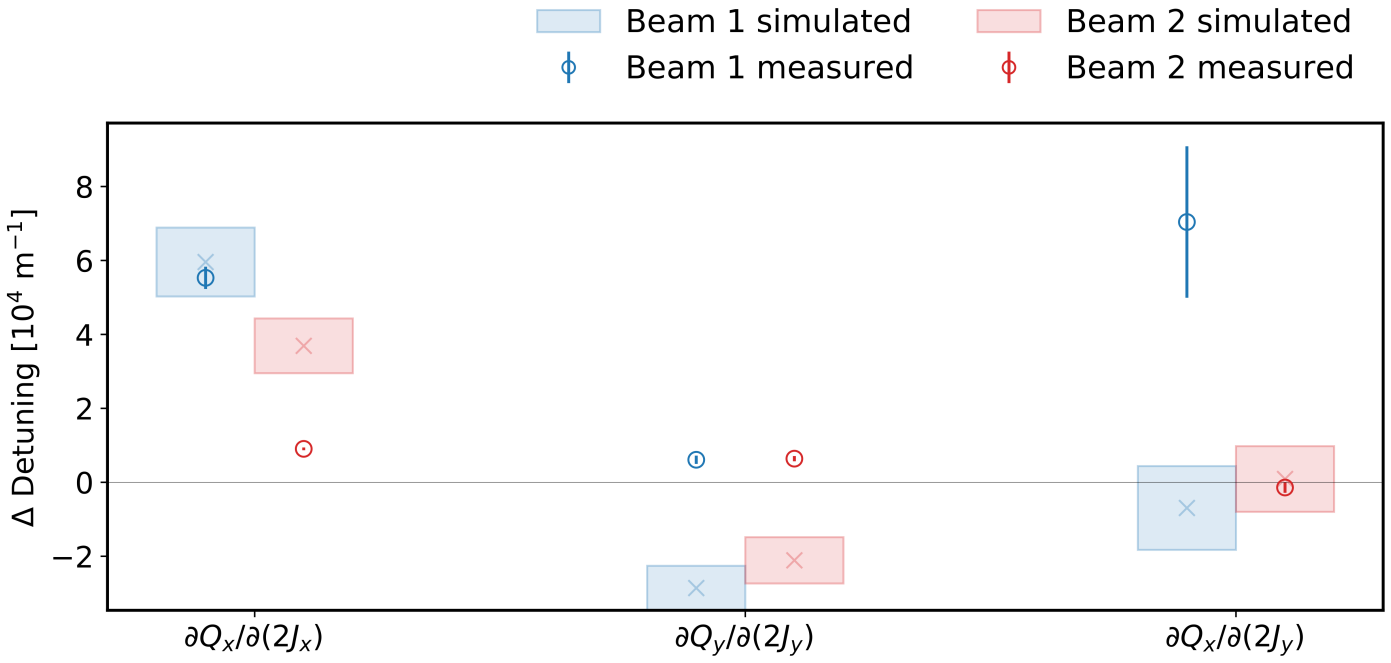




	LHCB1		LHCB2	
	Value	$\lvert I_{MO}\rvert$ correction	Value	$\lvert I_{MO}\rvert$ correction
$\partial Q_x/\partial 2J_x$	$+32$	$\Delta\lvert I_{MOF}\rvert = -108$	0	
$\partial Q_y/\partial 2J_x$	0		0	
$\partial Q_y/\partial 2J_y$	-40	$\Delta\lvert I_{MOD}\rvert = +142$	$+20$	$\Delta\lvert I_{MOD}\rvert = -70$

Comparable magnitude as detuning generated by b4 at flat-orbit

Compare measured feed-down from IR5 crossing angle to predictions of WISE tables



- **Observed feed-down comparable order-of-magnitude to model**
- **but doesn't precisely reproduce observations**
- **Everything contributes... IR1,IR5...a5,b5,b6...triplet,D1...**

Conclusions

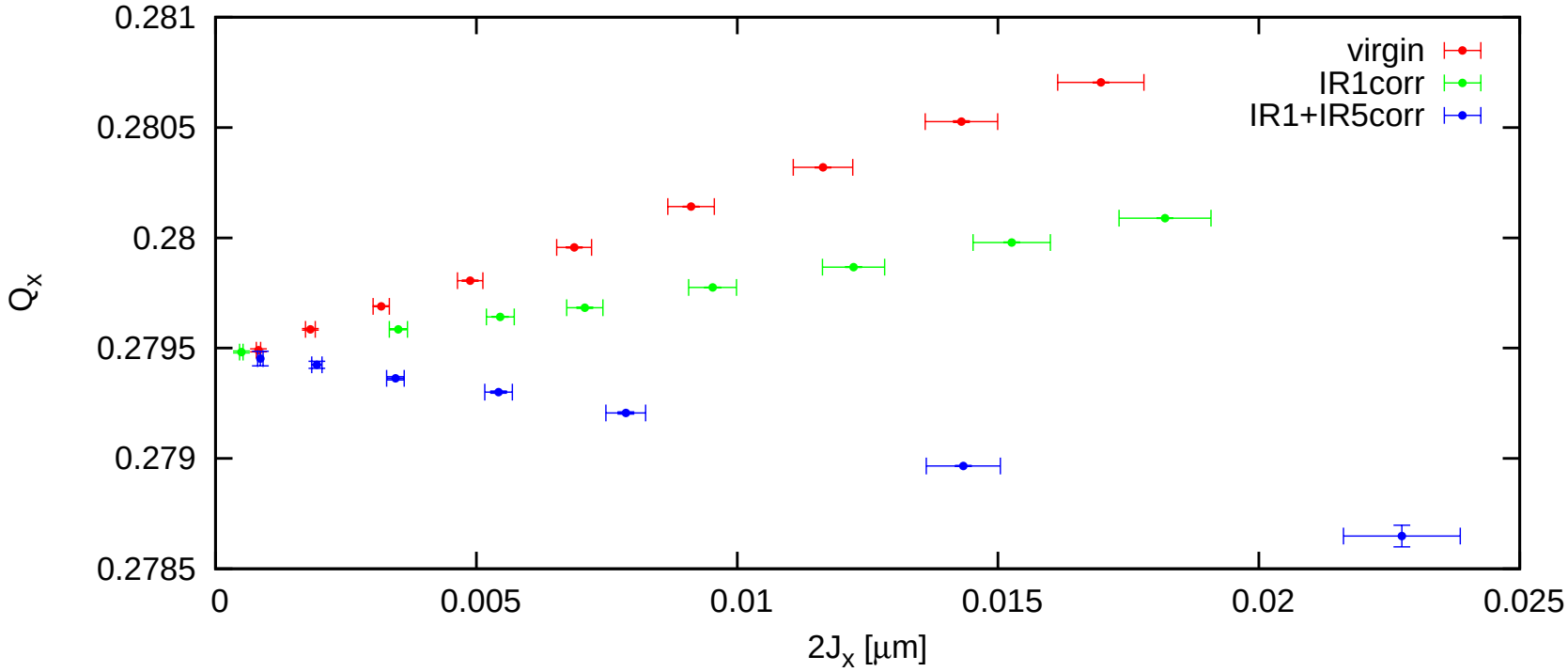
- Discrepancies with magnetic model for IR-sextupole correction
- Not surprising since observe comparable effects from alignment/orbit in higher-order correctors
- Global skew octupole corrections appear comparable to magnetic model
- Clear discrepancy in b4. Appears concentrated in IR5.
- No definitive explanation found.
- Decapole / dodecapole sources in model do not reproduce beam-based obs', but order of magnitude is comparable.

Reserve

Skew octupole correction

	Beam-based		model-based	
$[\mathrm{m}^{-4}]$	2017	2018	FiDeL	WISE
$K_{4,skew}$ L1 $[\mathrm{m}^{-4}]$	broken	broken	$+0.81 \pm 0.04$	$+0.78 \pm 0.007$
$K_{4,skew}$ R1 $[\mathrm{m}^{-4}]$	$+1.0$	$+0.50$	$+0.12 \pm 0.05$	$+0.08 \pm 0.006$
$K_{4,skew}$ L1 $[\mathrm{m}^{-4}]$	unused	-0.25	-0.03 ± 0.04	-0.08 ± 0.006
$K_{4,skew}$ R1 $[\mathrm{m}^{-4}]$	unused	-0.26	-0.49 ± 0.05	-0.55 ± 0.006

Nominal corrections overcompensated detuning in 2016 with 40cm nominal optics
→ no big effect from ATS



Correction calculated before IR-sextupole corrs worked well post-sextupole commissioning
→ No strong effect from IR-sextupoles