Lessons learned from LHC optics control in view of HL-LHC

On behalf of the OMC team:

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Anticipate HL-LHC will strongly push optics parameters influencing the commissioning strategy

- β^*, levelling, flat-optics, ATS factors , crossing angles, aggressive optics reduction in first years

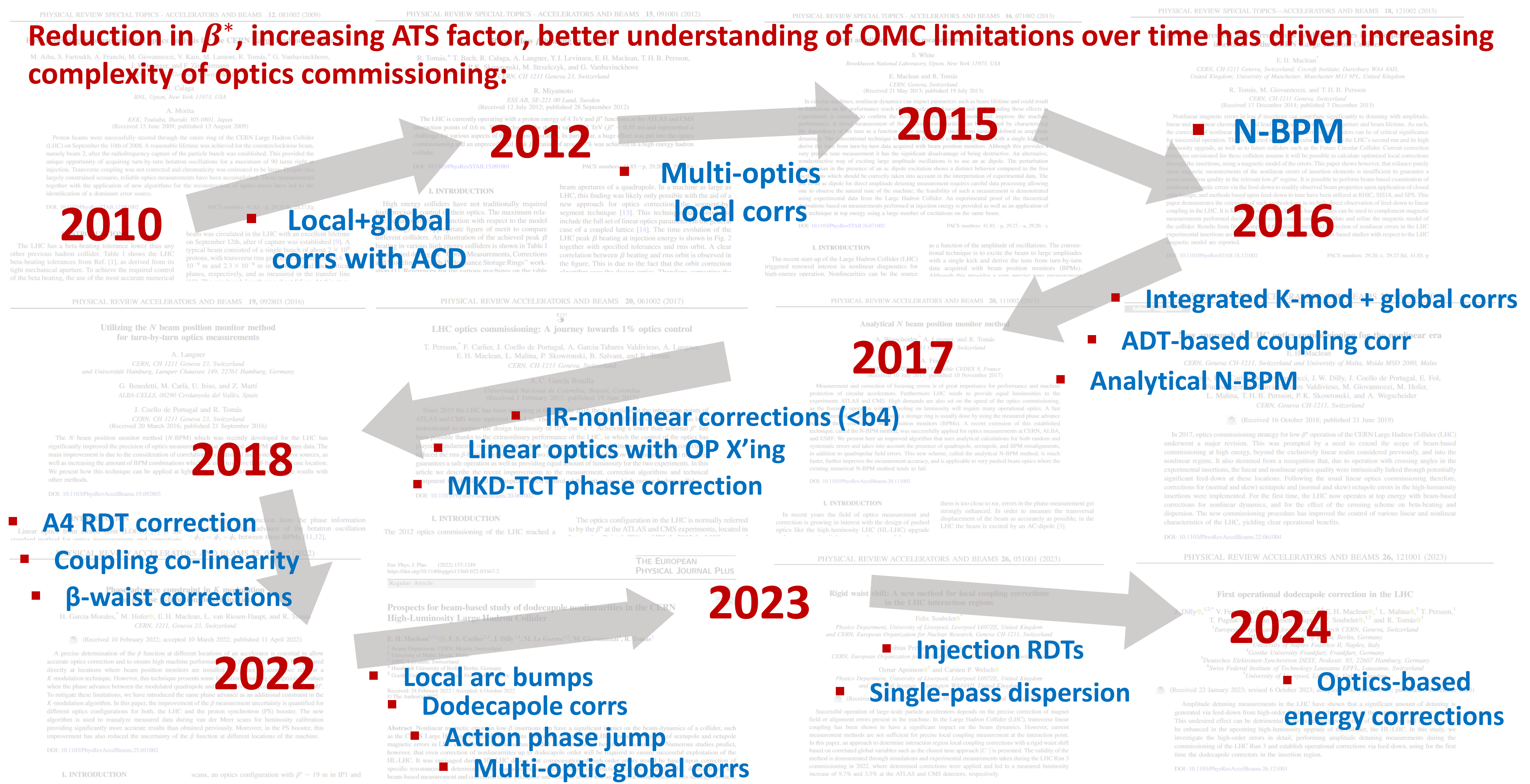
Run3 LHC commissioning also placed similar (if less extreme) demands

- Commissioning straight away to low β^*, β^* levelling, higher ATS factors, multiple commissioning of new optics

Aim of this talk is to look at Run3 experience and particular challenges/developments relevant to HL

- Local/global correction experience
- RDT compensation
- Local arc errors
- Energy errors
- Dispersion
- Collimator hierarchy and beam-beam optics measurements
- High-order errors
- Commissioning time

Reduction in β^*, increasing ATS factor, better understanding of OMC limitations over time has driven increasing complexity of optics commissioning:



2010

- Local+global corrs with ACD

2012

- Multi-optics local corrs

2015

- N-BPM

2016

- Integrated K-mod + global corrs
- ADT-based coupling corr
- Analytical N-BPM

2017

- IR-nonlinear corrections (<b4)
- Linear optics with OP X'ing
- MKD-TCT phase correction

2018

- A4 RDT correction
- Coupling co-linearity
- β-waist corrections

2022

- Local arc bumps
- Dodecapole corrs
- Action phase jump
- Multi-optic global corrs

2023

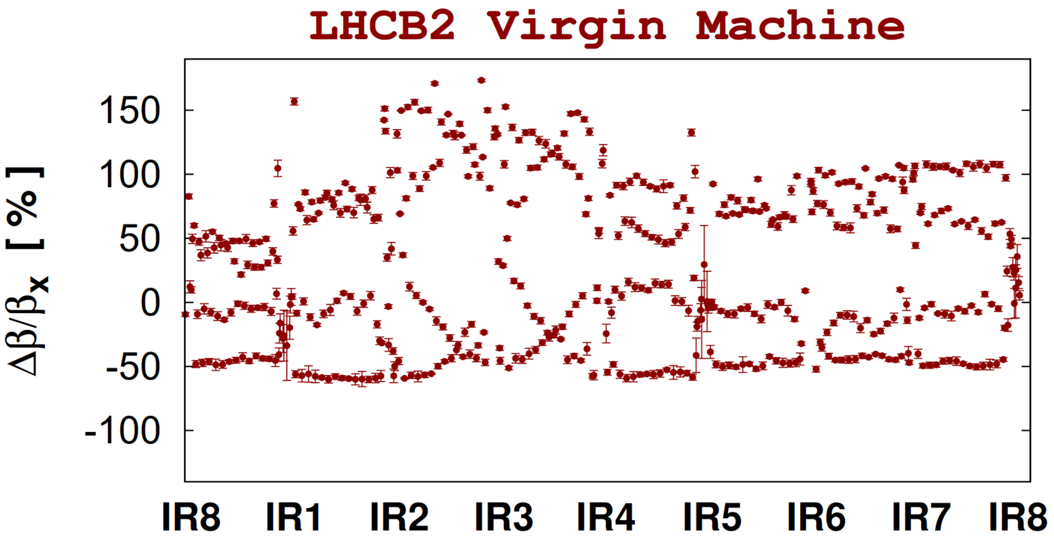
- Injection RDTs
- Single-pass dispersion

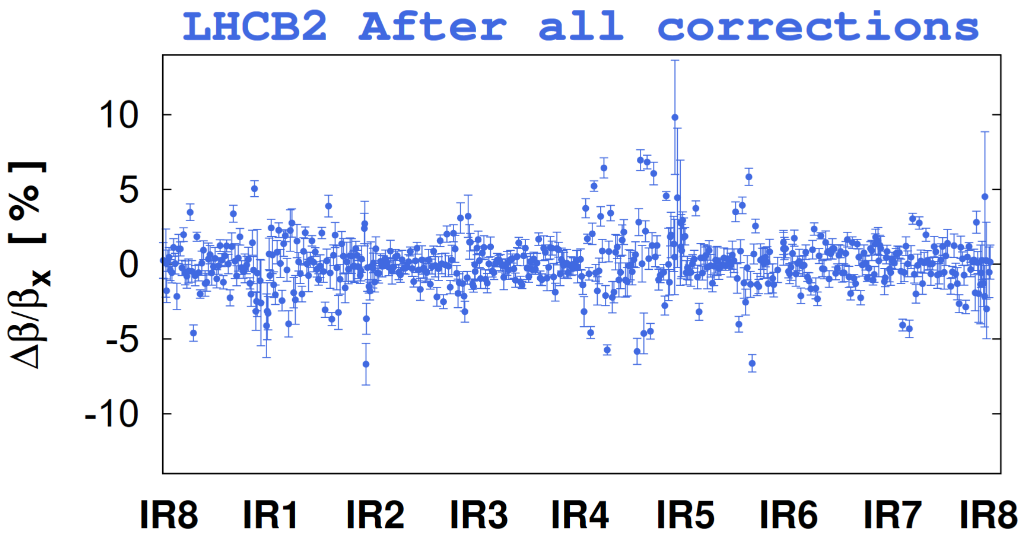
2024

- Optics-based energy corrections

Successfully commissioned optics straight-away to 30cm in first year of Run3

- In 2022 achieved target β-beat quality, and luminosity imbalance from optics within 1%.
- Key demonstration can commission directly to very pushed optics (same β^* expected in first years of HL-LHC)





- Significant time reduction for local corrections

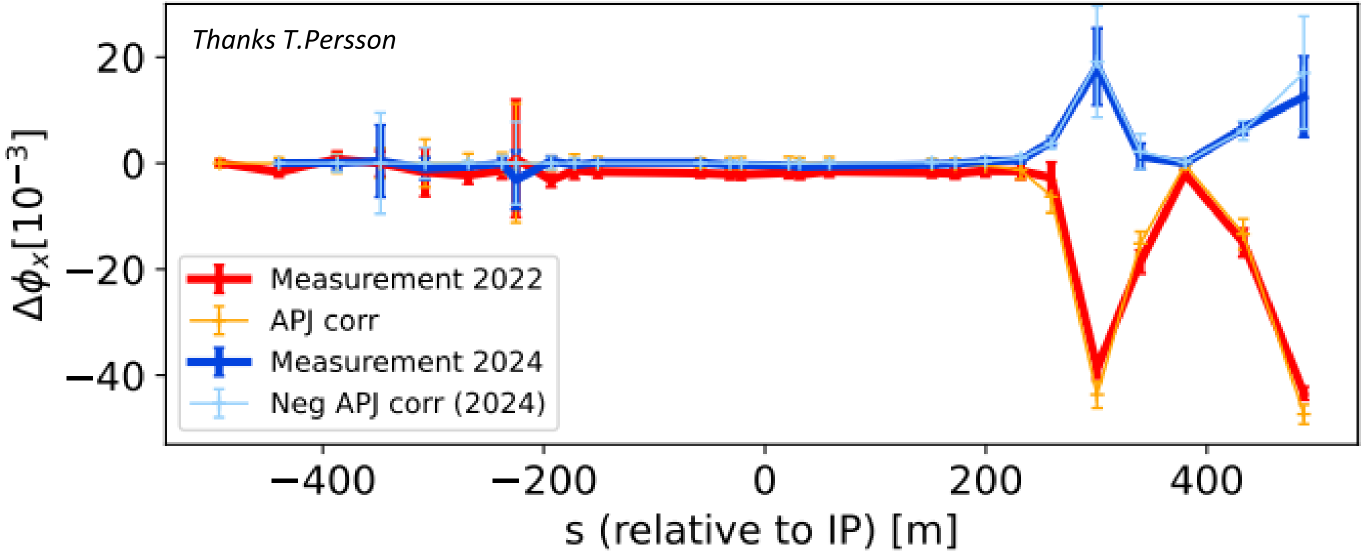
→ In 2015 took ≈ 5 shifts / 2 weeks to reach point where local IR corrections were incorporated

→ achieved online in Run3 !

In 2024 triplet polarity of IR1 was reversed

It was possible to extrapolate local IR1 corrections from previous year to the new triplet polarity

→ **Began 2024 commissioning with initial guess corrections for IR1 simply inverting 2022/23 knobs**



Success of this approach reflects good understanding of local errors in IR

→ **Knowledge that has been developed over many years, over commissioning of many different optics**

HL-LHC commissioning will be performed with new triplets, new errors

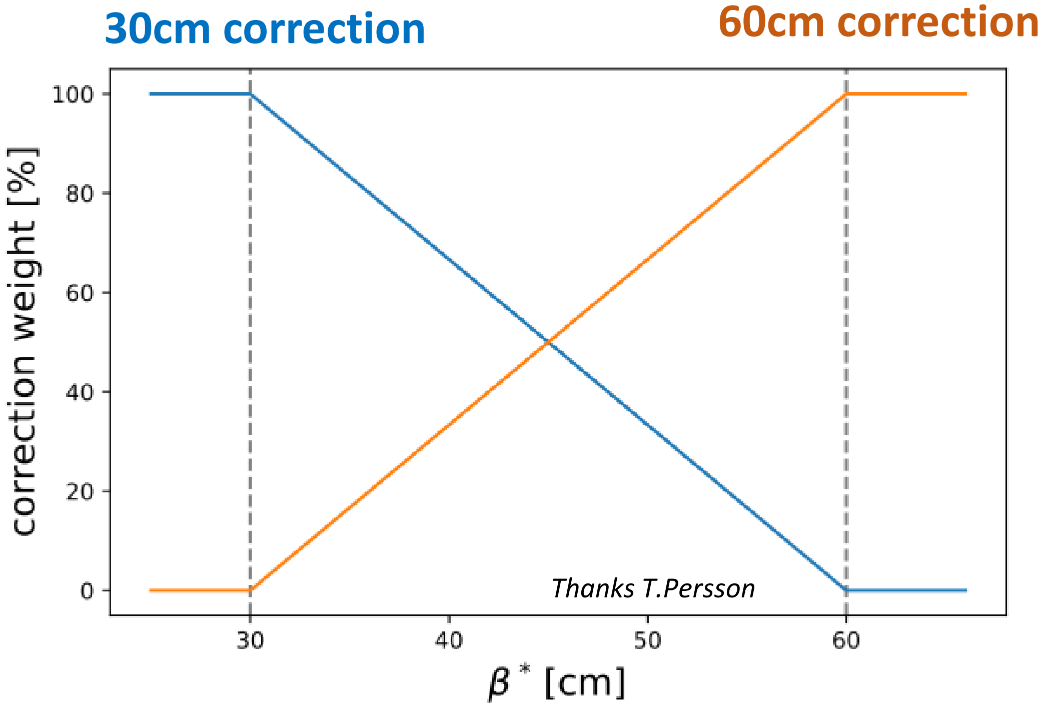
- **In Run3 have been developing and testing multiple complementary methods to help correctly identify local IR errors Segment-by-segment, Action-Phase-Jump, ML-based error reconstruction: aim is that consistency between different methods can help identify best possible local errors and corrections**

After correction of strong local errors, generally perform global correction to optimize final β-beat and β^*

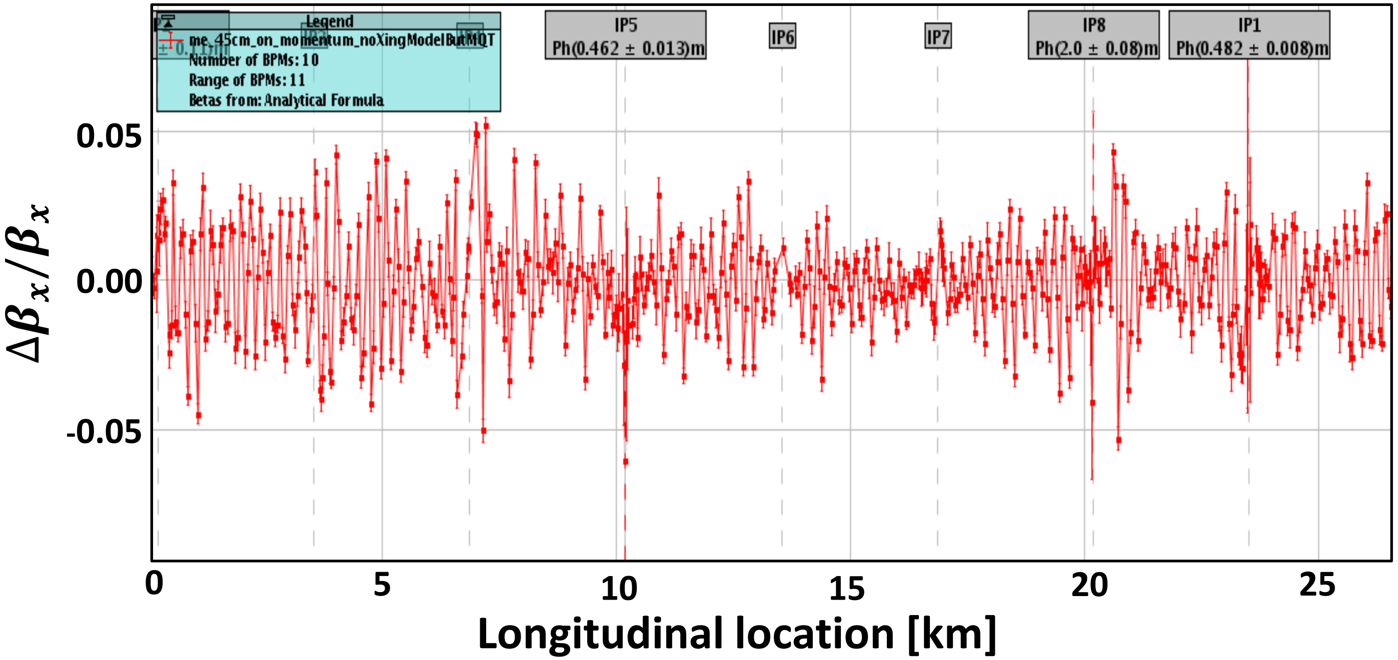
→ In Run 2 performed single global optimization for final β-beat and β^* at end-of-squeeze.

Switch to luminosity levelling required tight optics control throughout the squeeze

- Not practical to measure/correct at every match point or levelling-step (recent HL-LHC optics MD had >20 matched points!)
- Strategy adopted is to correct at a few β^* and trim in/out global corrections during squeeze steps, validating at intermediate points
- Works well so far in LHC – being studied in HL-LHC MDs with higher ATS factors



β-beat at 45cm

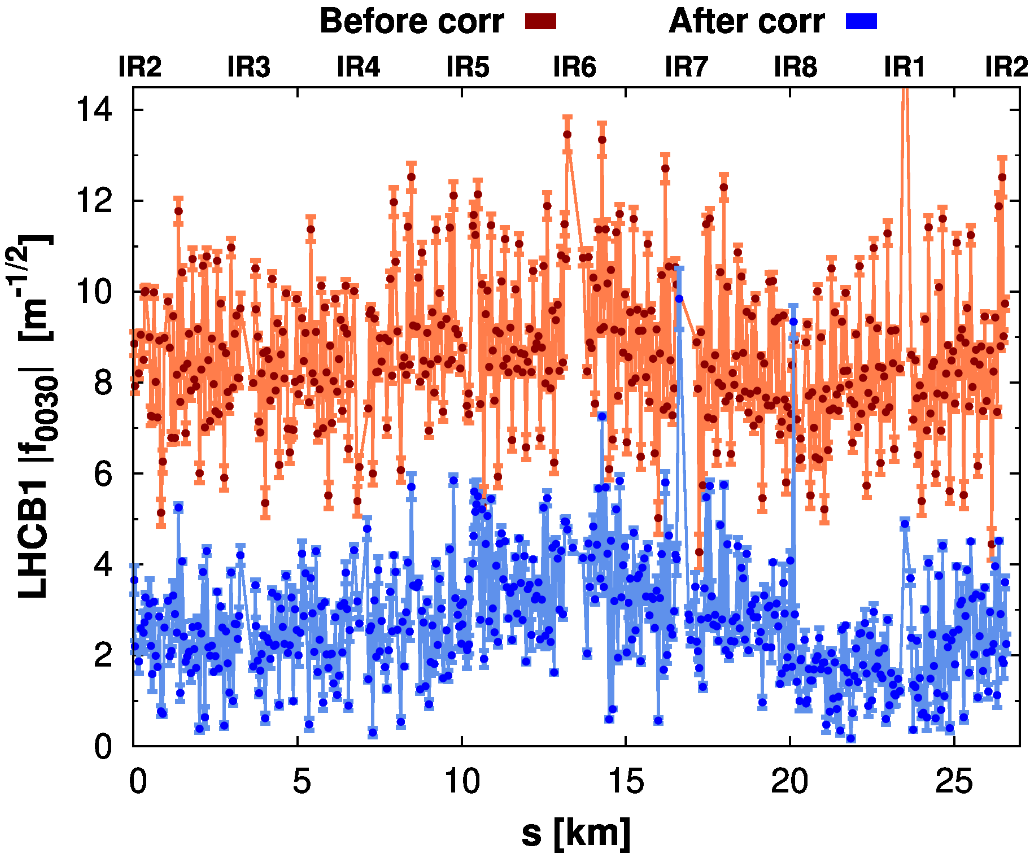


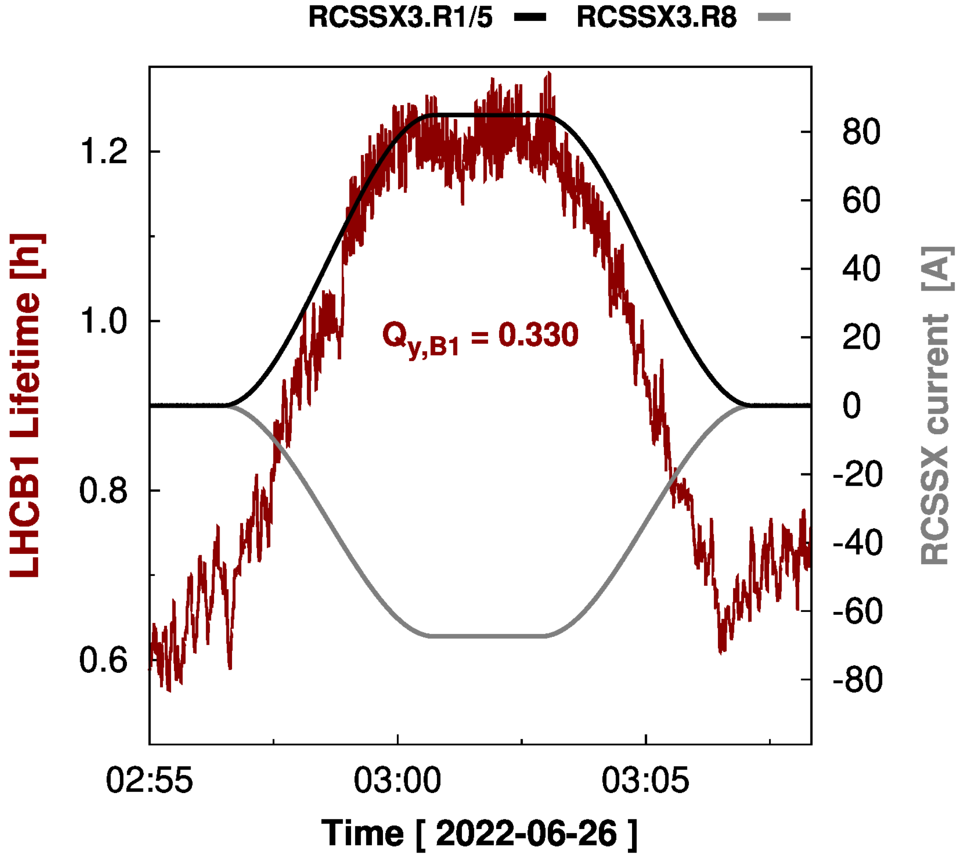
Significant progress towards making direct RDT corrections for nonlinear optics corrections routine in LHC

→ effort which has been ongoing since first studies of sextupole resonances back in 2010!

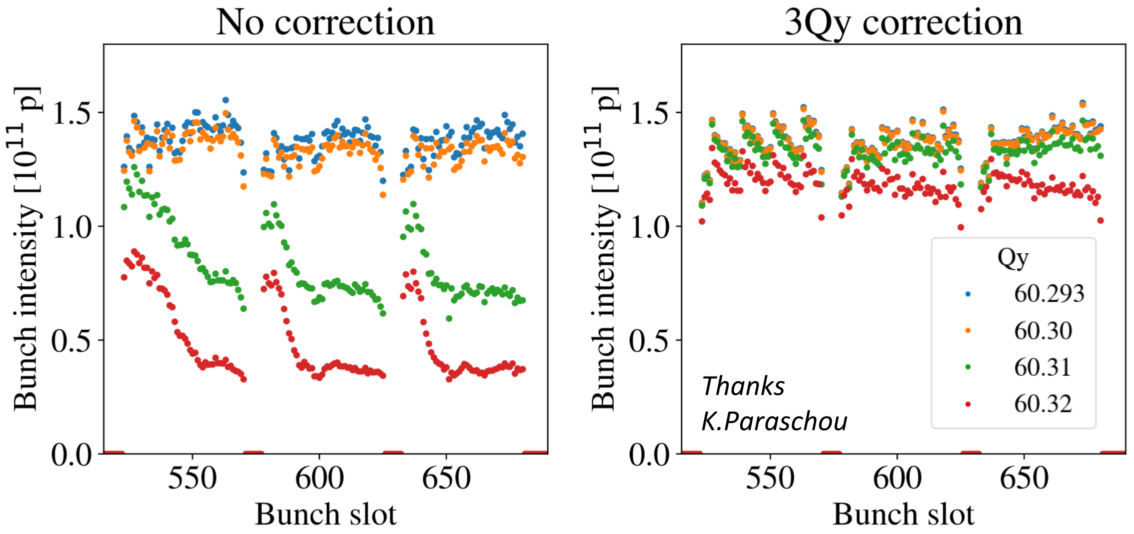
Particular focus during Run3 has been optimization of resonances at injection

- In many cases corrections never intended in baseline LHC strategy e.g. 3QY → demonstrates good flexibility of the corrector packages

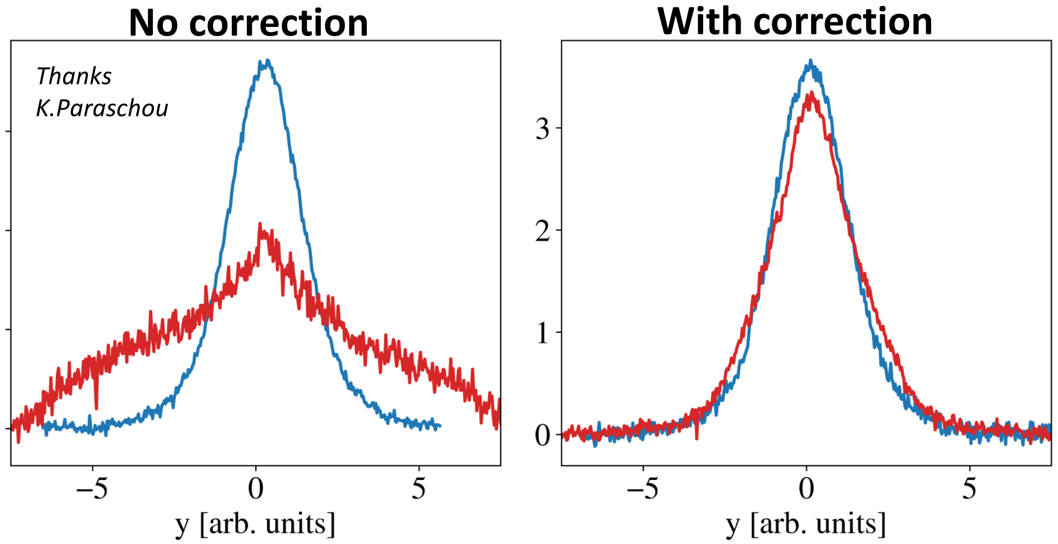




Normal/skew sextupole resonance corrections aim to improve good WP region → particularly relevant for reversed MO polarity



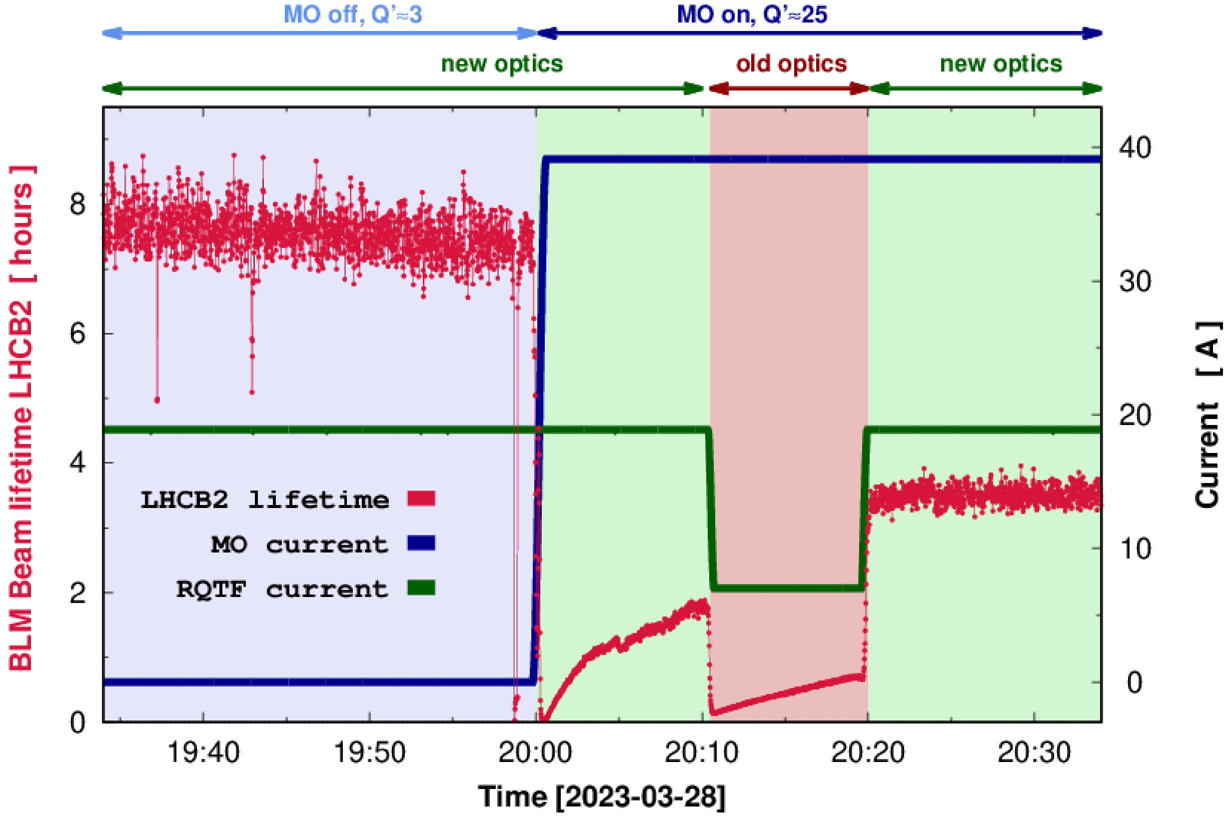
Thanks K.Paraschou



Thanks K.Paraschou

New optics design at injection used to help suppress resonances driven by Landau octupoles

→ **being incorporated directly into HL-LHC optics design**

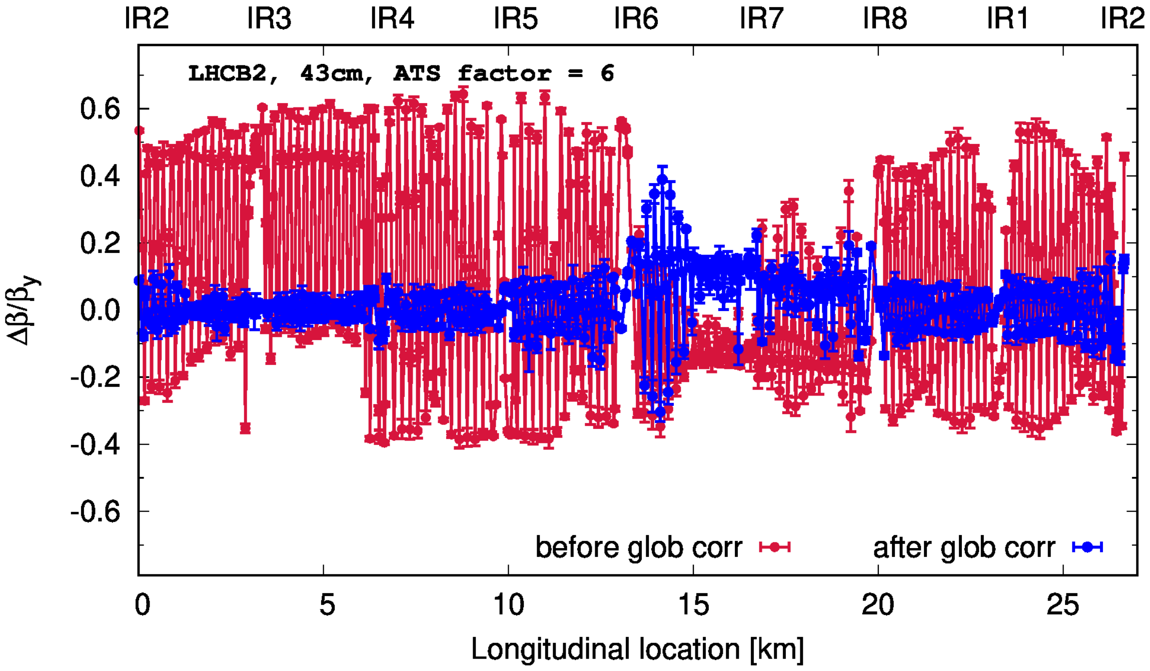


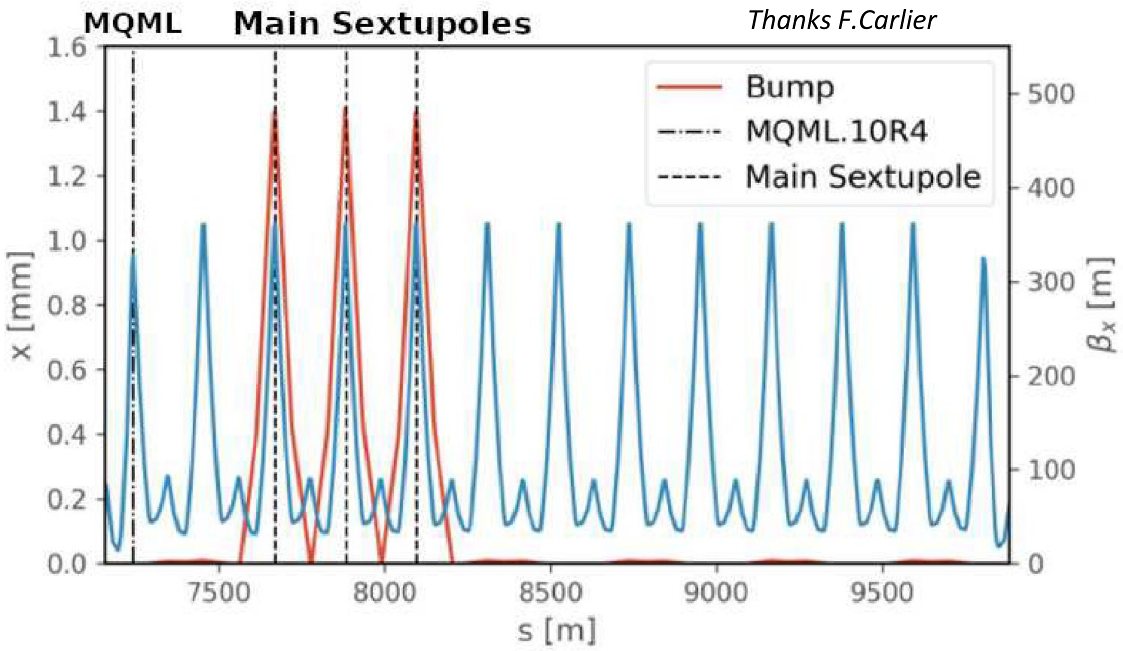
Lots of good news!

→ **but also some issues/challenges emerged for first time in Run3**

With increased ATS factors local errors in the arcs become a challenge for optics commissioning

- Traditional OMC used local corrections in IRs to reduce β-beat to ≈10%-20%, followed by global corrections
- HL-LHC optics MD tested up to $\mathrm{ATS\ factor} = 6$ → saw up to 60% β-beat even with IR-corrections applied
- Attempts to correct residual with basic global corrections (even multiple iterations) failed to achieve required β-beat





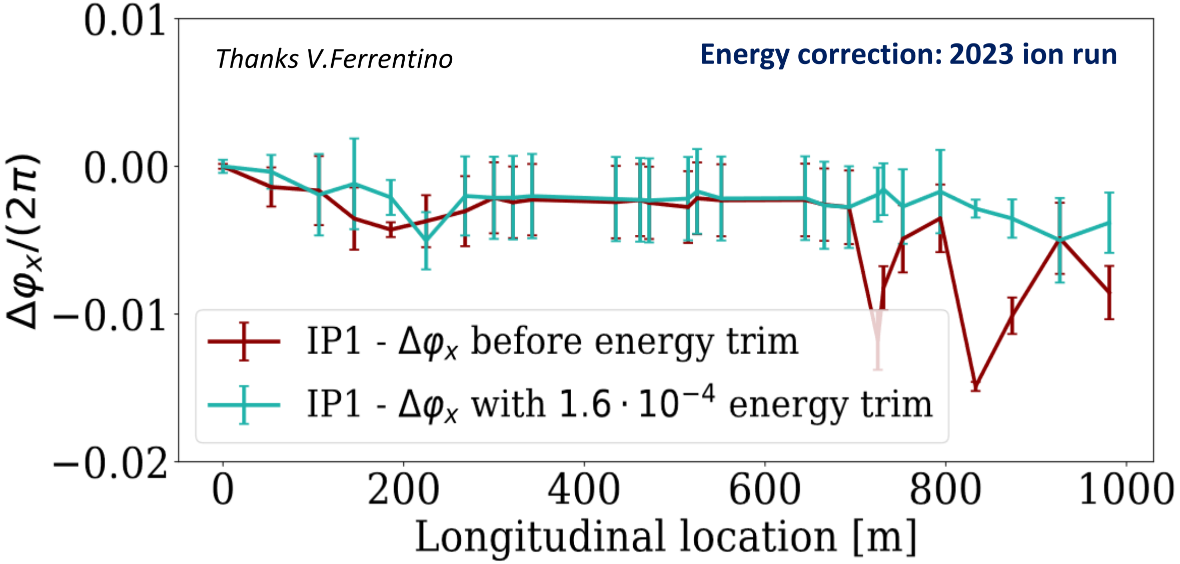
Thanks F.Carlier

- Solution is local corrections in arcs via feed-down from orbit bumps in MS → beneficial for LHCB1 during HL-LHC MDs at ATSF=3,6
- Still far from online corrections → LHCB1 corrections for high-ATS factor tests determined over ~1month between MDs

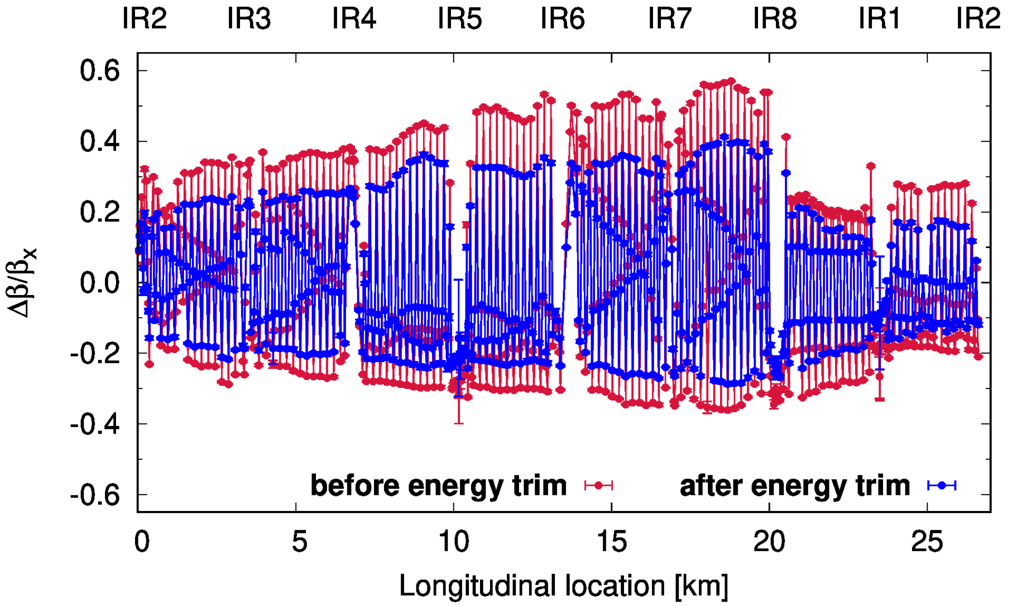
  → hope that corrections found in Run3 can help in Run4, but no experience of stability of local arc errors over LS (local IR errors known to vary)

At low-β^* optics becomes sensitive to slight changes in energy from orbit setup during commissioning

- **First noticed during 2022 commissioning, where influenced optics reproducibility**
- **During 2023 ION commissioning able to identify energy errors from local IR optics corrections**


Thanks V.Ferrentino

Energy correction: 2023 ion run


Energy correction: 2024 commissioning

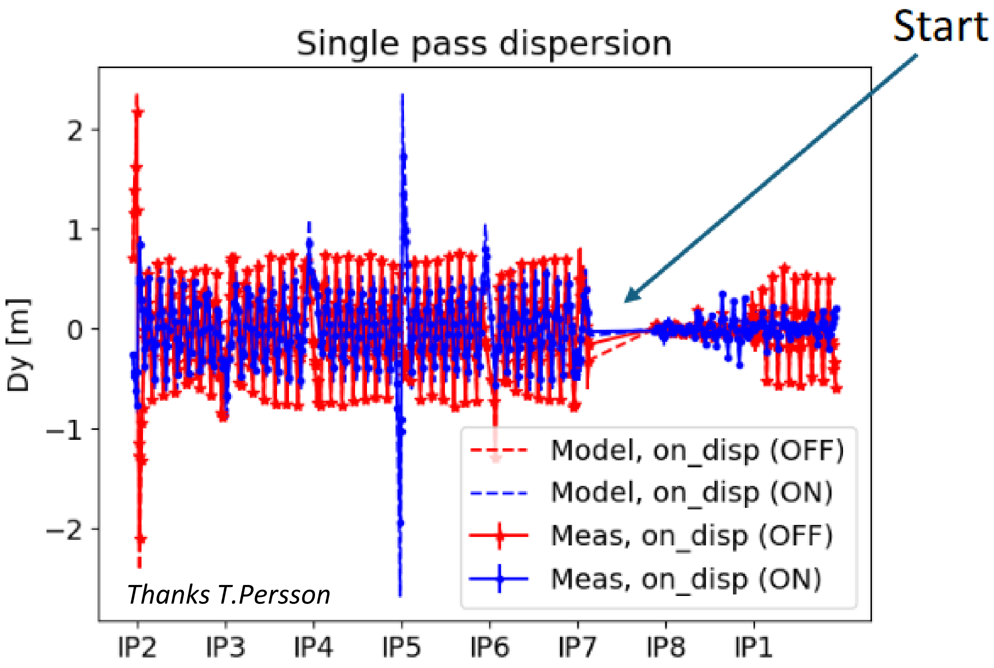
- **During 2024 commissioning had to perform 4 separate re-corrections of energy via optics tools following changes in orbit setup, causing beta-beat shifts in range 10-20%**
- **Corrections performed online, but still relatively time consuming**
- **Only become more challenging for HL-LHC: aim to develop automated checks/corrections to simplify commissioning**

Vertical dispersion never considered a priority for optics commissioning

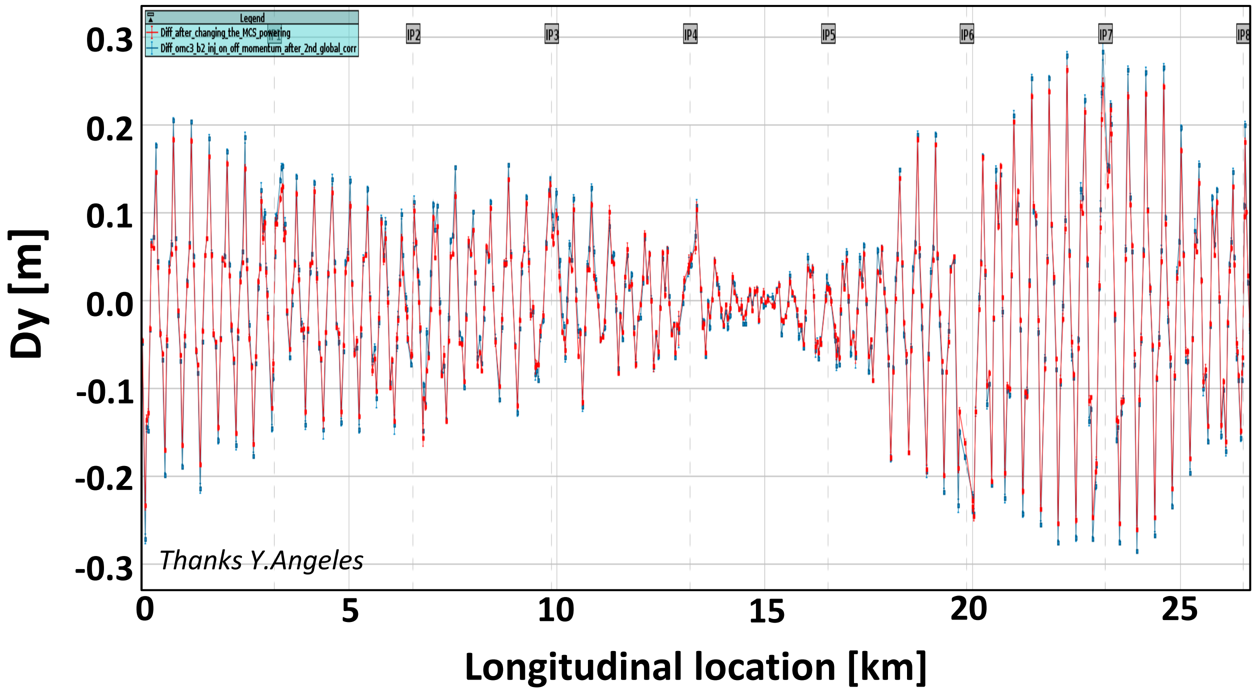
→ Several occasions now in Run3 where starts to cause or identify problems

- 2023 ION run suffered from large ALICE background
- Mitigated by increasing IP1 on_disp knob to modify vertical dispersion at collimators
- New procedures to determine single pass dispersion from conventional optics measurements being studied

- Studies of vertical dispersion throughout Run3 consistently show very large D_y error
- Seems to indicate very large skew quad error around **BPM.26R5.B2** to **BPM.30R5.B2**: e.g. large MQ tilt

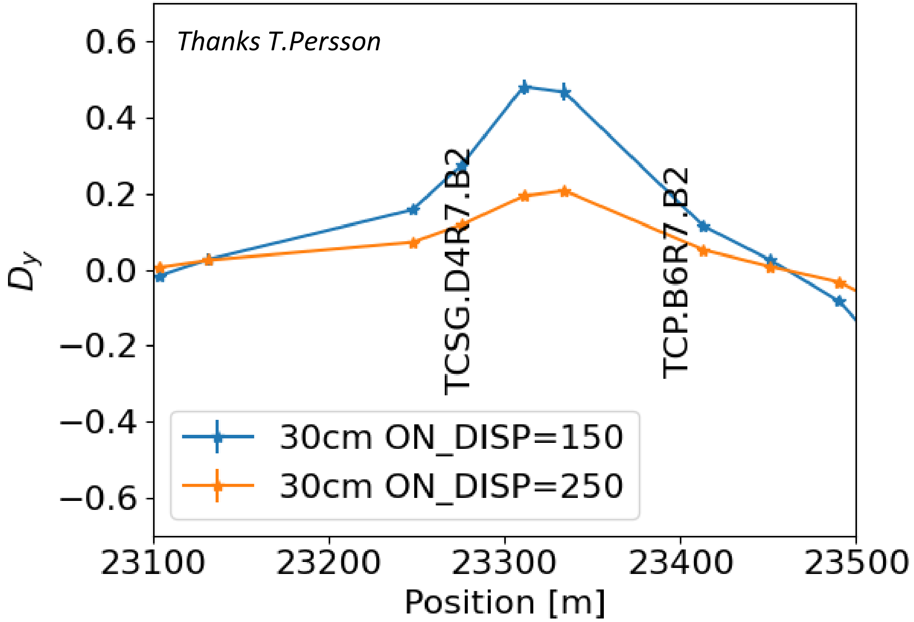


Thanks T.Persson



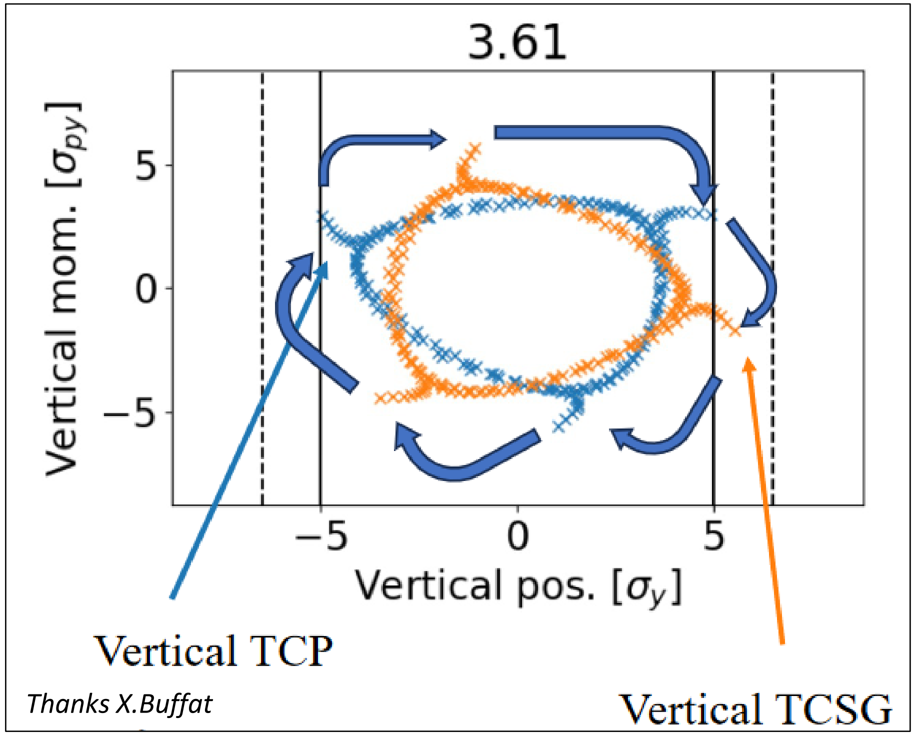
Thanks Y.Angeles

During 2024 intensity ramp up breakage of collimator hierarchy of LHCB2 was seen



Once again problem could be partially mitigated via increase of IP1 on_disp knob to modify vertical dispersion at collimators → **≈0.4σ increase in margin via Dy change**

- **Need to pay more attention to vertical dispersion during optics commissioning**

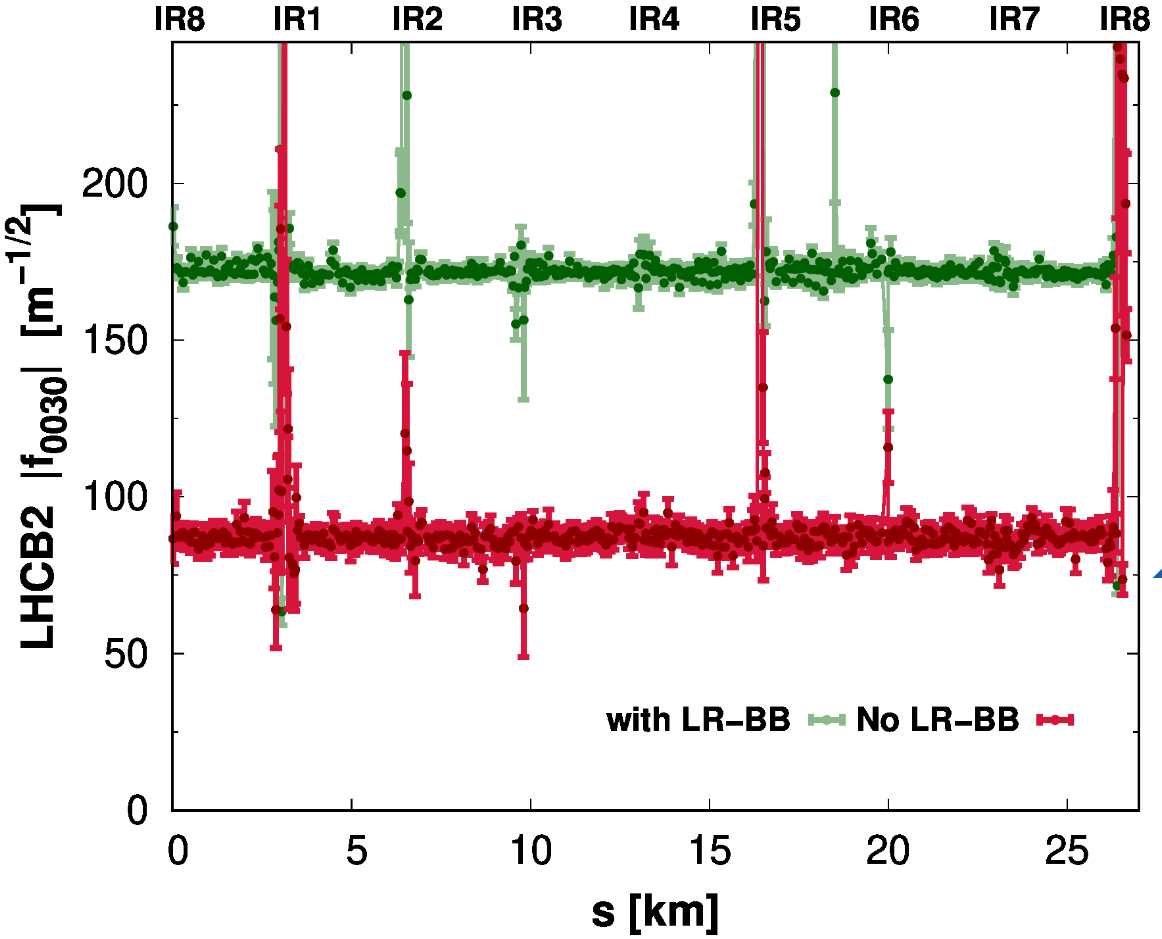


Thanks X.Buffat

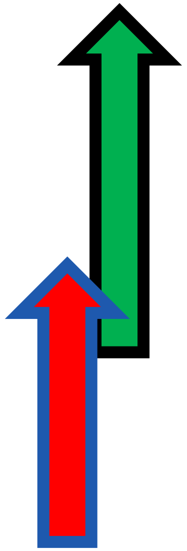
Extra sources required to explain hierarchy breakage, as didn't appear for single-beam → X.Buffat + K.Paraschou proposed 3Qy resonance

- **Off momentum particles can approach the 3Qy resonance: deterioration of change of 3Qy from beam-beam due to switch to RP optics could distort phase space differently at TCP/TCSG contributing to breakage**
- **Reduction in Q' to stop off-momentum particles hitting 3Qy gave ≈0.2σ margin**
- **Applying partial a3 correction for lattice errors gave ≈0.2σ margin**
- **Report on mitigation gains:** **D.Mirarchi, LBOC 4/06/24** https://indico.cern.ch/event/1420698/

During 2024 intensity ramp up breakage of collimator hierarchy of LHCB2 was seen → Appears that 3Qy resonance can also contribute to the breakage



Large contributions to measured 3Qy resonance strength from both lattice and LR-beam-beam



Lattice contribution is significantly worse than in previous years

→ **1/3 comes from a3 errors directly (now mitigated)**

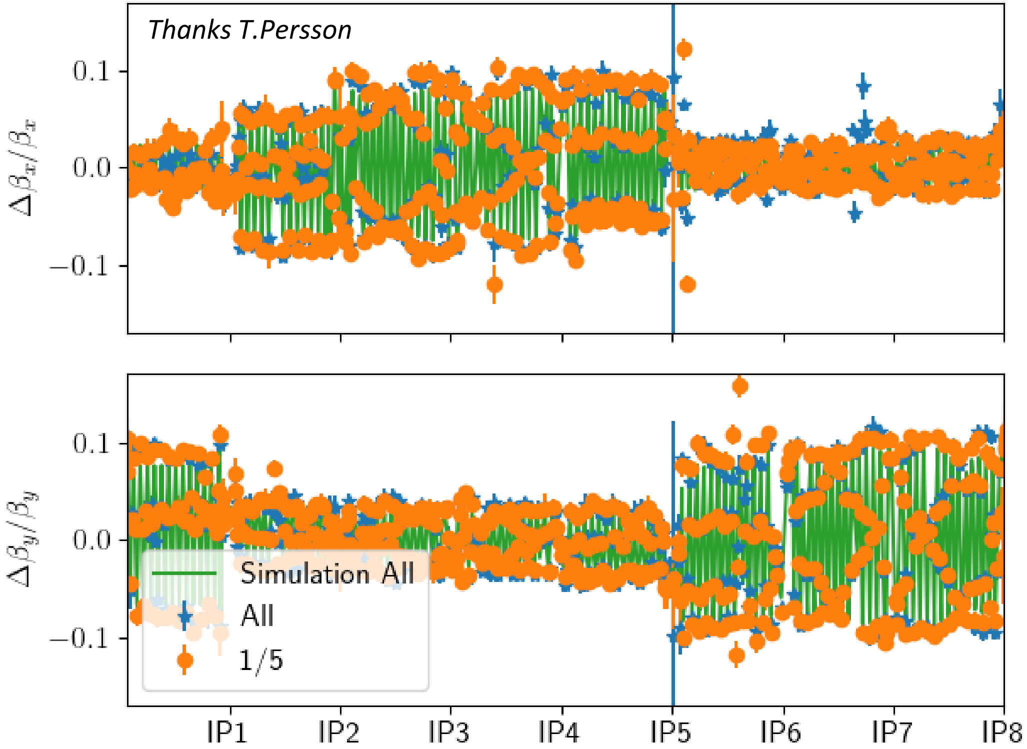
→ **2/3 comes from skew octupole feed-down (didn't manage to find a4 correction in 2024)**

→ **2/3 of lattice 3Qy still uncorrected: need new correction strategy for a4 in 2025 & HL → plan to correct directly on 3Qy feed-down in future**

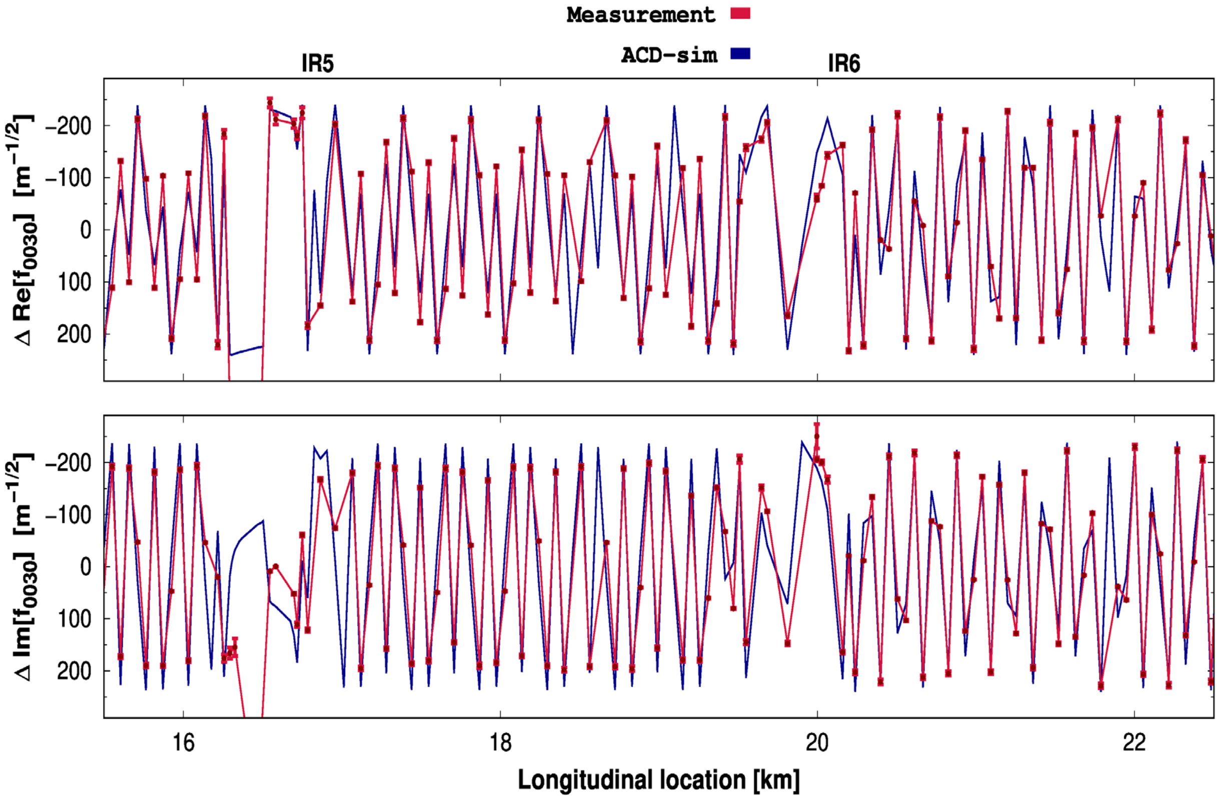
Following observations of hierarchy issue new measurement procedure used to examine optics from long-range beam-beam

- perform usual optics measurements with AC-Dipole on low-intensity pilot in collision with nominal trains
- required new dedicated measurement setup for collimators, BPMs, interlocks, developed by T.Persson

Allows direct benchmarking of linear and nonlinear optics perturbations driven by beam-beam



T.Persson, Long Range Beam-Beam investigation using Weak-Strong beams in the LHC
https://indico.cern.ch/event/1344947/contributions/6077565/

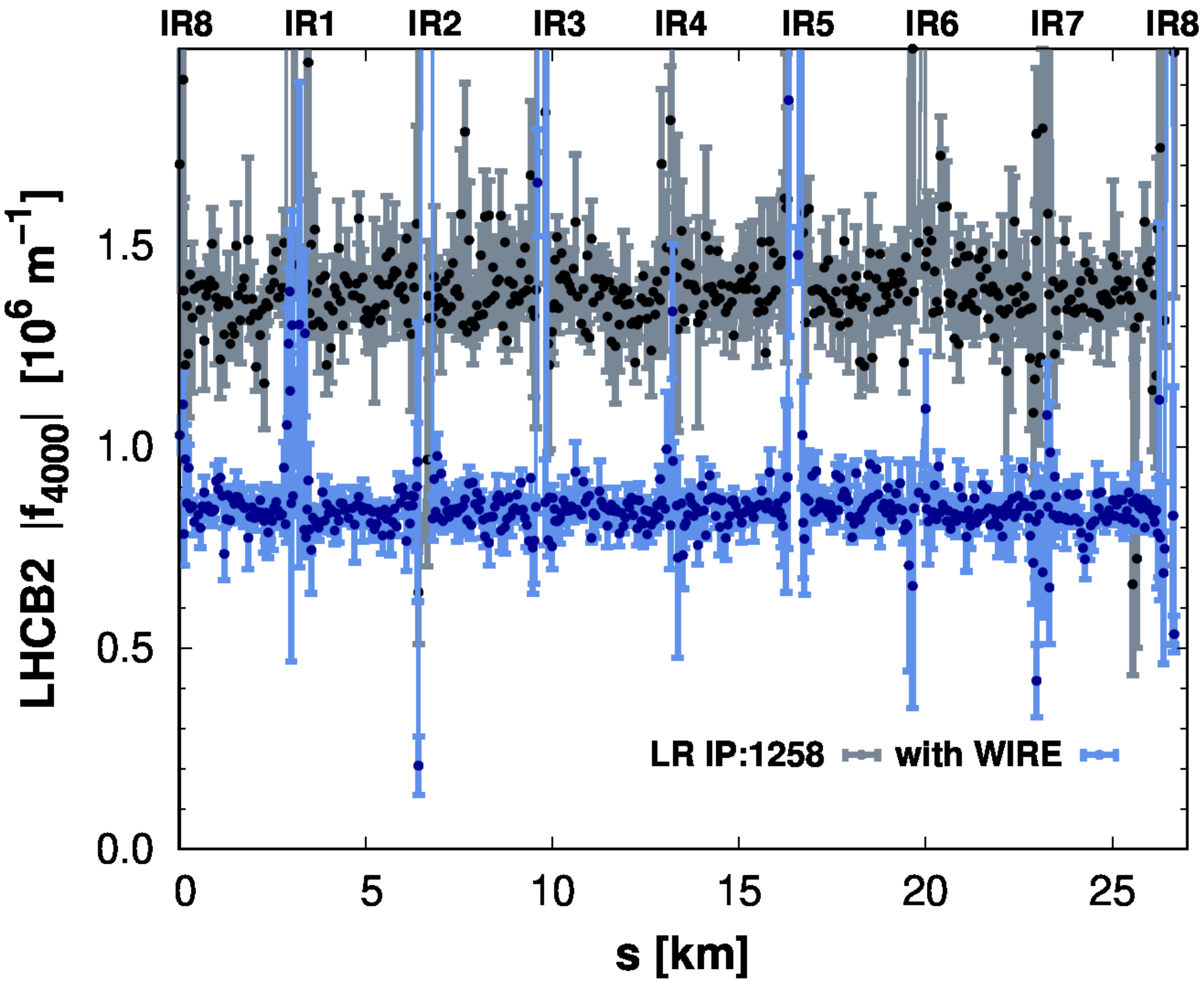


E.H.Maclean, Compensation of beam-beam driven RDTs in the LHC IRs
https://indico.cern.ch/event/1344947/contributions/6077566/

Correcting long-range beam-beam

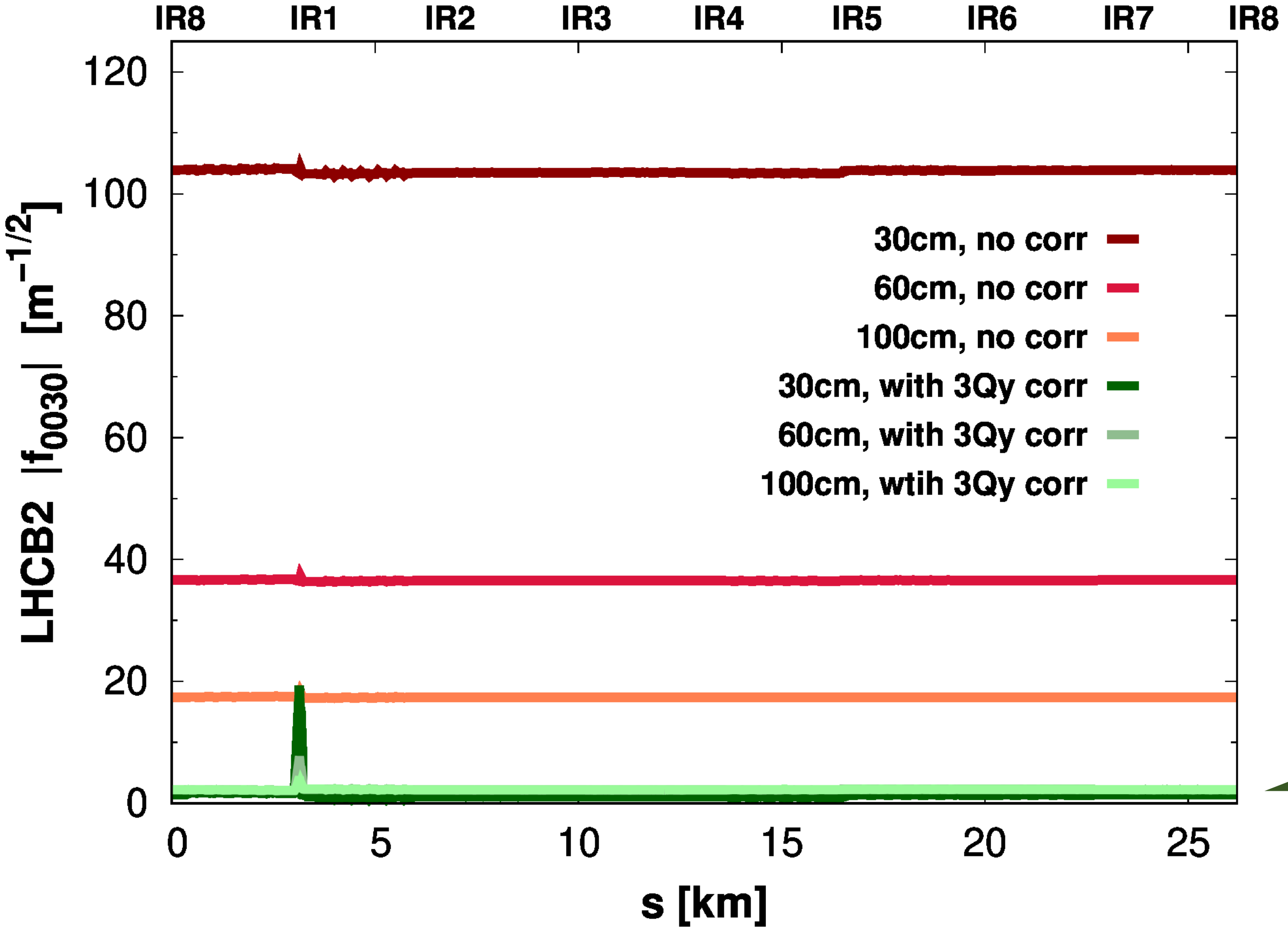
With well benchmarked models and ability to measure directly long-range beam-beam driven resonances can directly examine correction methods

Able to directly measure impact of the wire on the 4Qx resonance strength



Correcting long-range beam-beam

Using benchmarked simulations can find settings of IRNL corrector packages to suppress LRBB driven normal- and skew- sextupole resonances (3Qy,3Qx,Qx-2Qy) → application to OMC commissioning being studied



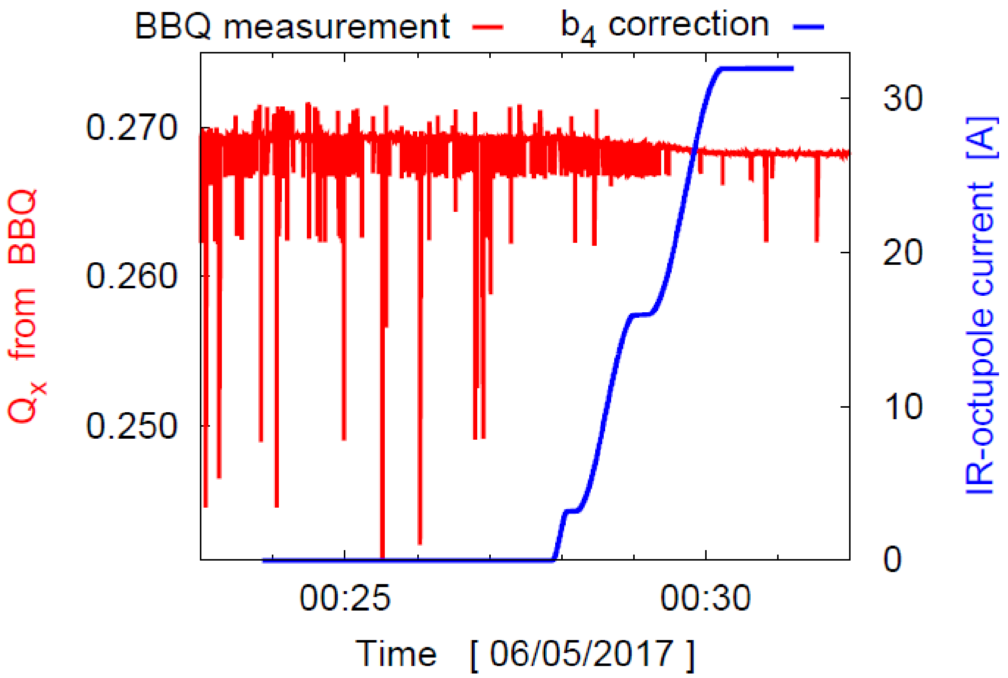
Without correction, 3Qy strength from LR-BB increases substantially through squeeze

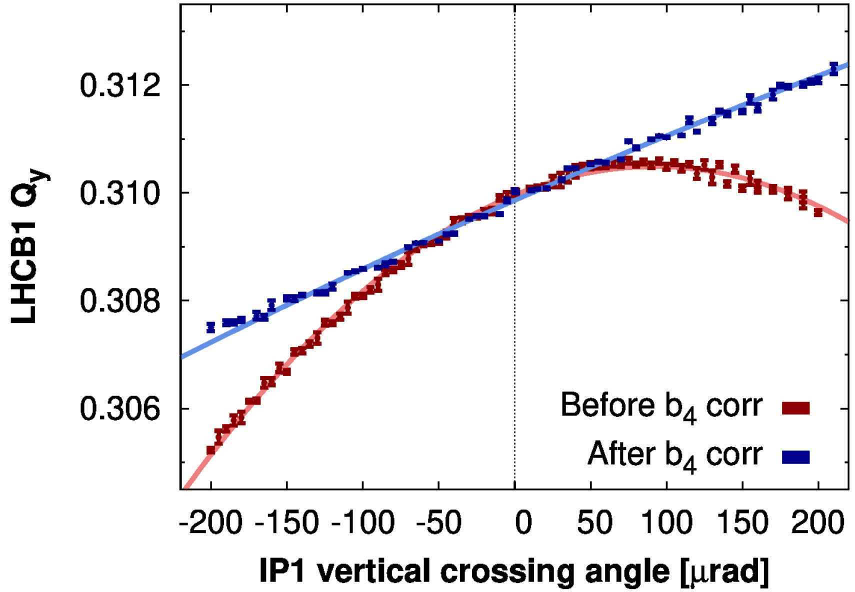
(simulation assumes constant beam-parameters)

Skew-sextupole correction keeps LRBB 3Qy corrected through squeeze

Detuning from octupole errors in IP1/5 causes significant problems for linear optics commissioning

- Rely on K-mod for linear optics and β^* correction → degraded by strong detuning
- Issue we have been aware of since late Run2, ran into again in 2024 as IR-b4 corrections had to be redone following polarity swap
- For 2024 ION cycle b4 corrections not initially included – no reliable K-mod data could be obtained, when attempted global corrections without K-mod data failed to achieve target β^*-beat





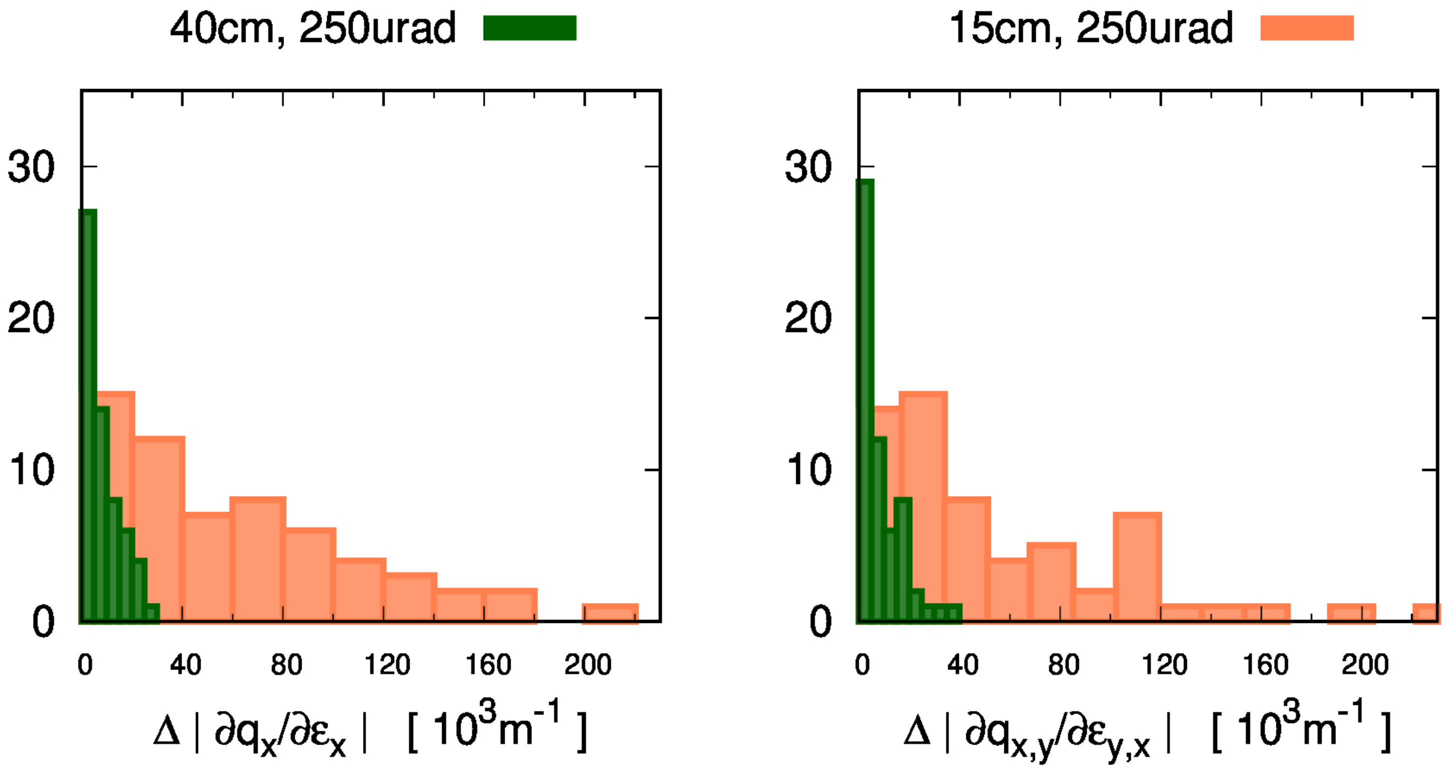
Normal octupole corrections essential for low-β linear optics commissioning: in practice well under control

→ online corrections achieved in 2024 via detuning+FD. Non-local corrections tested in case of MCOX breakage

High-order corrections in the low-β IRs

While b4 is well under control b6 could potentially cause similar issues in HL-LHC via feed-down with low-β^* and high crossing-angles

- **see clear problems for linear optics commissioning when detuning is around $40 \times 10^3 [\mathrm{m}^{-1}]$**
- **significantly higher tuning can degrade forced-DA to point where we struggle to excite with ACD to meaningful amplitude**
- **Target residual detuning for instabilities was estimated at $15 \times 10^3 [\mathrm{m}^{-1}]$ (old numbers)**

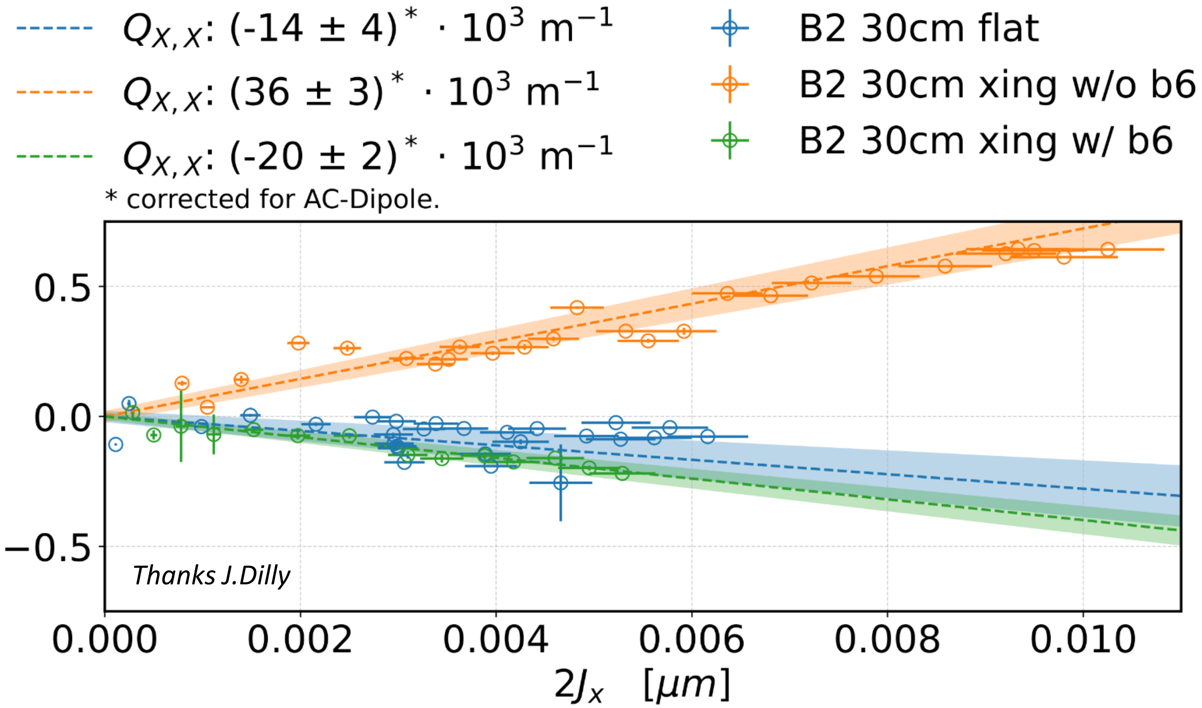


Even where b6 errors in triplets are in-spec, can potentially pose challenges for the optics commissioning at low β^* if uncorrected

Dodecapole corrections in IP1 and IP5 achieved for first time in 2022 by correcting feed-down to detuning with X'ing

- Still very far from an online correction – compensation in 2022 required multiple measurements over commissioning period, finally implemented via follow-up studies in MD several months later

- Following triplet polarity swap in 2024 attempted to find correction of b6 during 1-2 shifts in regular commissioning
  → in practice attempts were unsuccessful (since 2024 back to running without any dodecapole corrections)
  → b6 correction required very time-consuming detuning measurements at multiple Xing configurations
  → measurement quality suffered heavily from forced-DA limitation as lower orders still only partially compensated



Thanks J.Dilly

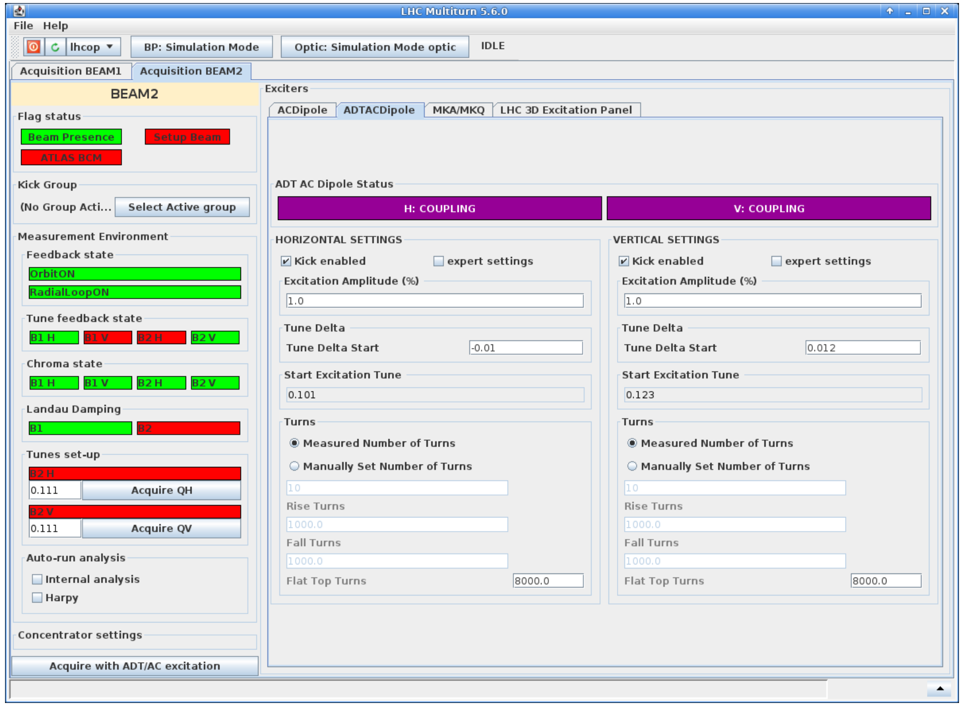
Multiple other challenges for high-order errors expected in HL-LHC

- **No practical experience of beam-based correction or validation of a5, b5, a6**

Commissioning time

Since trend towards increasing complexity seems likely to continue, significant effort being spent on improving OMC team tools/methods

→ nice example is switch to ADT-based coupling correction for routine monitoring without need for dedicated OMC measurements



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B2 H: 0.111

B2 V: 0.111

☐ Internal analysis
☐ Harpy

HORIZONTAL SETTINGS
☑ Kick enabled ☐ expert settings
Excitation Amplitude (%): 1.0
Tune Delta Start: -0.01
Start Excitation Tune: 0.101
Turns: ● Measured Number of Turns ○ Manually Set Number of Turns
10
Rise Turns: 1000.0
Fall Turns: 1000.0
Flat Top Turns: 8000.0

VERTICAL SETTINGS
☑ Kick enabled ☐ expert settings
Excitation Amplitude (%): 1.0
Tune Delta Start: 0.012
Start Excitation Tune: 0.123
Turns: ● Measured Number of Turns ○ Manually Set Number of Turns
10
Rise Turns: 1000.0
Fall Turns: 1000.0
Flat Top Turns: 8000.0

Thanks U.Karr

Various efforts to make use of AC-dipole measurements & OMC tools more accessible e.g. better model creation, automatic checks of measurement setup, OP sequences for optics measurements

In practice simplification/automation of measurement process is valuable first step, but only a few shifts per year where corrections are not required

→ work should continue towards improving efficiency of corrections

Beam-time requirements for commissioning are significantly constrained by limitations of the AC-dipole hardware

→ Need to take a certain number of kicks to perform an optics measurement – repetition frequency of AC-dipole kicks is limited

Conclusions

- LHC commissioning so far in good state throughout Run3
  → noting that push to smaller β^* and higher ATS-factors has driven increasing complexity of the commissioning process
  → need to continue improving efficiency of OMC tasks to accommodate future challenges of HL-LHC

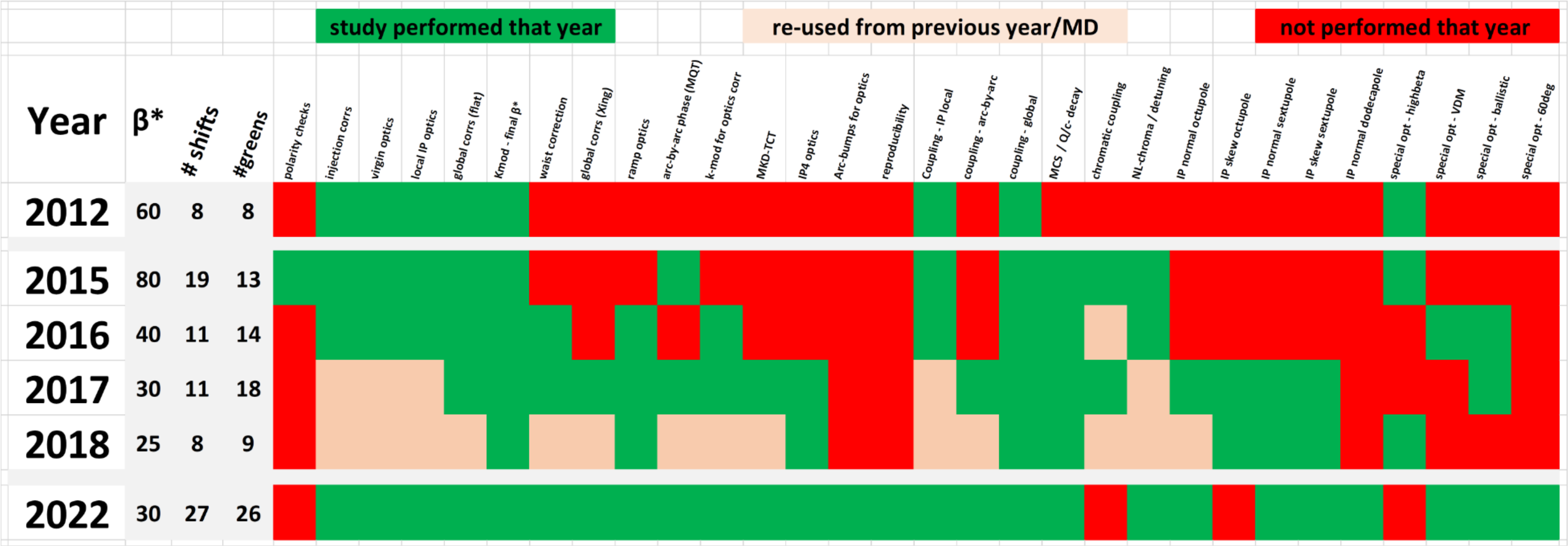
- A few clear challenges relevant to HL-LHC commissioning emerging during Run3
  → local arc errors become problematic at high-ATS factors: for now arc-bump compensation still far from being online correction
  → energy shifts during commissioning generate large beta-beat at low-β^*
  → high-order IR corrections still challenging & in some cases not online. Several multipoles with no experience of correction

- Learning that several aspects of the optics we have historically not worried about can potentially cause issues for operation
  → vertical dispersion → ALICE background, collimator heirarchy
  → IR skew sextupole and skew octupole → collimator heirarchy

- Very interesting application of OMC methods to study of long-range beam-beam
  → application to optics commissioning strategy being studied

Commissioning time

Significant increase in complexity of optics commissioning since Run1 – trend likely to continue in HL-LHC



🟩 study performed that year
🟧 re-used from previous year/MD
🟥 not performed that year

Year	β*	# shifts	#greens	polarity checks	injection corrs	virgin optics	local IP optics	global corrs (flat)	Kmod - final β*	waist correction	global corrs (Xing)	ramp optics	arc-by-arc phase (MQT)	k-mod for optics corr	MKD-TCT	IP4 optics	Arc-bumps for optics	reproducibility	Coupling - IP local	coupling - arc-by-arc	coupling - global	MCS / Q/c- decay	chromatic coupling	NL-chroma / detuning	IP normal octupole	IP skew octupole	IP normal sextupole	IP skew sextupole	IP normal dodecapole	special opt - highbeta	special opt - VDM	special opt - ballistic	special opt - 60deg
2012	60	8	8	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥
2015	80	19	13	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥
2016	40	11	14	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟥	🟥	🟥	🟥	🟩	🟥	🟩	🟩	🟧	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟥
2017	30	11	18	🟥	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟧	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟥
2018	25	8	9	🟥	🟧	🟧	🟧	🟧	🟩	🟧	🟧	🟩	🟧	🟧	🟧	🟩	🟥	🟥	🟧	🟧	🟩	🟩	🟧	🟧	🟧	🟩	🟩	🟩	🟥	🟩	🟥	🟥	🟥
2022	30	27	26	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟩

Biggest influence on commissioning time is optics stability from year-to-year

→ **Commissioning time scales relatively clearly with # of different activities / corrections to be performed**

→ **Trend continued in Run3 – 2023 had almost unchanged optics vs 2022: commissioned in 6 shifts**