High-Orders Fields in the LHC

Measurement and Modelling

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Thanks to the **O**ptics **M**easurements and **C**orrections Team at CERN

Plan

Outline

Decapolar Studies

Dodecapolar Studies

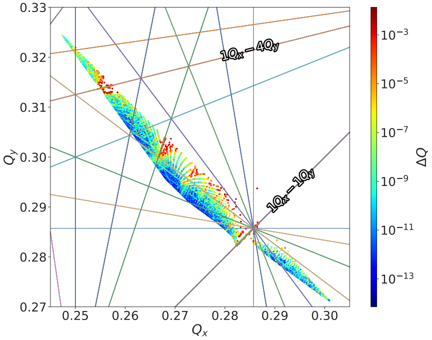
Decatetrapoles

Conclusions

Acknowledgements

Outline

Beam-based studies of Non-Linear Errors in the LHC



- Focus on magnetic model
- Trying corrections
- Characterizing error sources

- Previous studies:
  - Sextupoles
  - Octupoles
- Challenging to go higher
  - Decapoles
  - Dodecapoles
  - Decatetrapoles

→ Important for future accelerators like HL-LHC and FCC

Plan

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Decapolar Studies
- Magnetic Model Discrepancy
- Possible sources
- Checking the Correctors
- Chromatic Amplitude Detuning
- Decay in Main Dipoles
- Implementation of Decay
- Resonances

Dodecapolar Studies

Decatetrapoles

Conclusions

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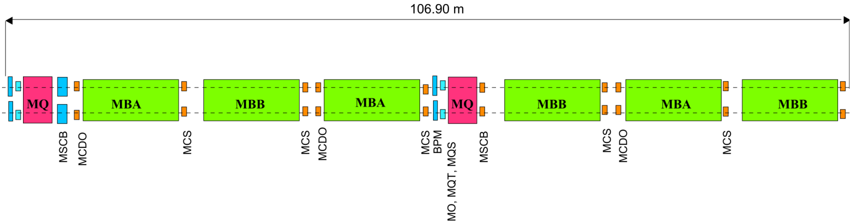
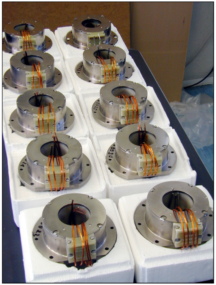
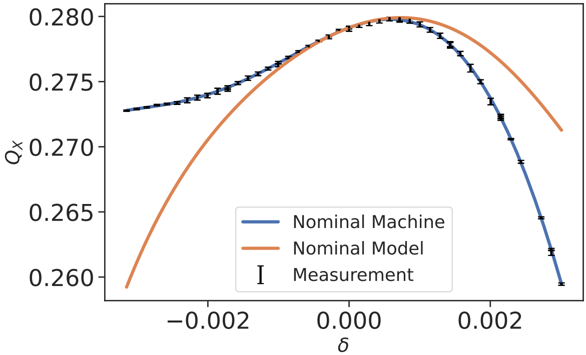
Decapolar Studies





- Large b_5 at injection in main dipoles
- Current corrections based on magnetic measurements
- *MCD* Correctors every 2^{nd} dipole

Magnetic Model Discrepancy



- Corrections of Q''' based on magnetic measurements
- Discrepancies between model and measurements
  - Off by factor 2, but why?

Possible sources

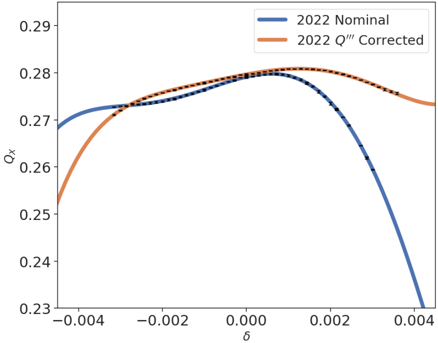
Is it coming from the measurement technique itself or errors?

$$Q(\delta) = Q_0 + Q'\delta + \frac{1}{2!}Q''\delta^2 + \underbrace{\frac{1}{3!}Q''\delta^3}_{\text{this guy}} + \cdots$$

- Magnetic model
- Correctors response
- Higher-order Dispersion
- Momentum compaction factor
- Coupling

$\rightarrow$ Need to do some more measurements to find out

Checking the Correctors

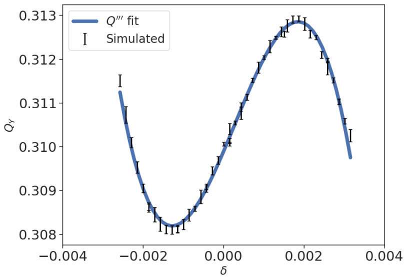


Plane	$\Delta Q''' [10^6]$ Meas.	Sim.
B1		
X	2.3 ± 0.1	2.5
Y	-1.5 ± 0.1	-1.4

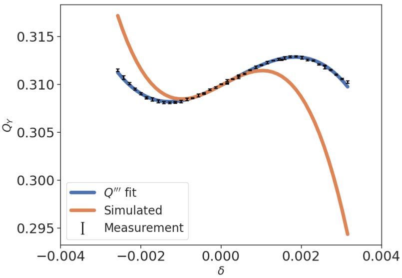
- Beam-based corrections applied on correctors
- Shift in Q''' almost identical for meas. and sim.

$\rightarrow$ Correct shift is always observed

Checking the Correctors



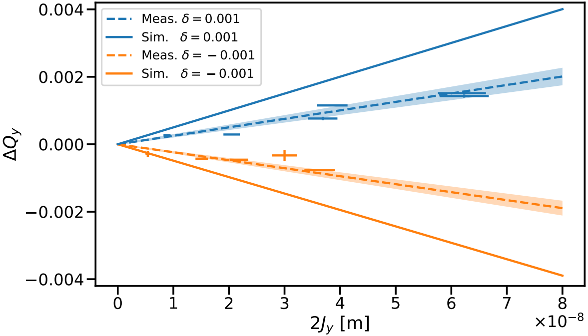
→



- Octupolar and decapolar correctors turned off
- Model and measurements for Q''' are still factor ≈ 2 off
- Discrepancy still there despite various corrector configurations

→ I to K, crosstalk and coupling ruled out
→ Correctors do not cause the discrepancy

Chromatic Amplitude Detuning



$$\Delta Q(J_x, J_y, \delta) = \frac{\partial^2 Q}{\partial J_x \partial \delta} J_x \delta + \frac{\partial^2 Q}{\partial J_y \partial \delta} J_y \delta + \frac{1}{3!} \frac{\partial^3 Q}{\partial \delta^3} \delta^3$$

- Different dependence on dispersion than Q'''
- Factor ≈ 2 compared to simulations again
- First time ever measured in the LHC

$\rightarrow$ Points to an error in our b_5 model, in the arcs

Decay in Main Dipoles

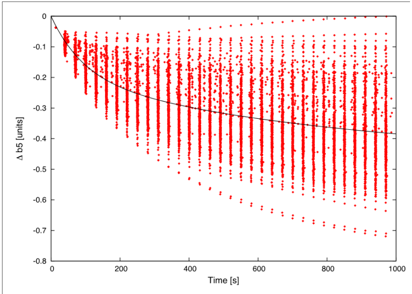


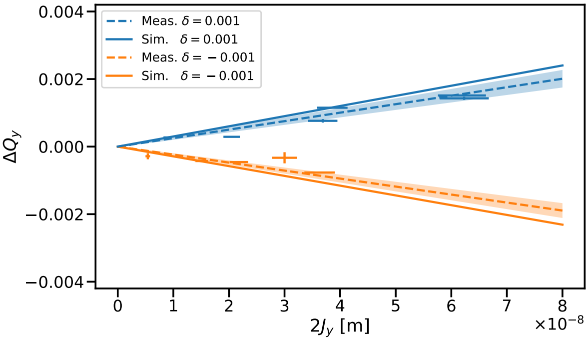
Figure 31: Decay of integrated b_5 at injection (430 apertures) and the decay fit (black line).

- b_3 decay implemented in operation
- Computed from magnetic meas.

- b_5 component constant in models
- b_5 decay *not* implemented
- Quite large and fast at injection

$\rightarrow$ Decay is important to consider

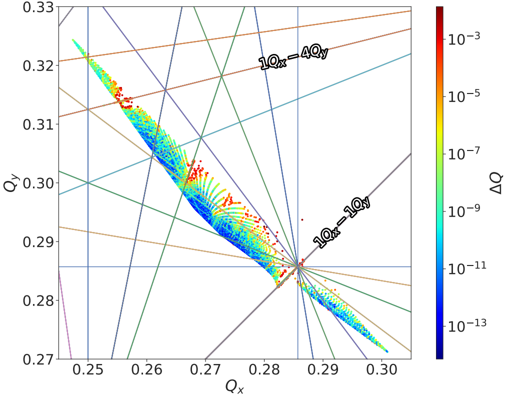
Implementation of Decay



- Average b_5 decay substracted in simulations
- Most of the discrepancy is now explained
  - For Q''' and Chromatic Ampdet.

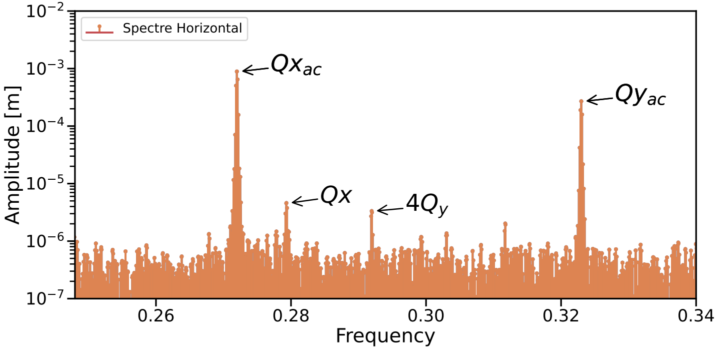
$\rightarrow$ b_5 discrepancy comes from our error model

Resonance Driving Terms



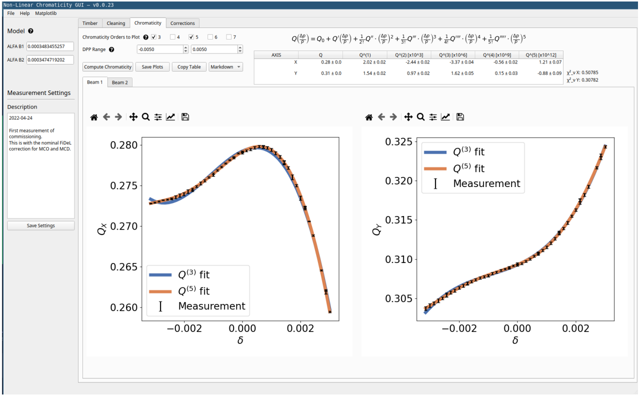
- Coefficient linked to a resonance amplitude
  - Resonances : $(j-k)Q_x + (l-m)Q_y = p \quad ; \quad p \in \mathbb{N}$
  - Multipole of order $n \rightarrow n = j+k+l+m$
- Example of f_{1004}
  - Excites resonance $1Q_x - 4Q_y$
  - Measured for the first time at injection

Turn-by-Turn Spectrum



- Several lines are clearly visible
  - AC-Dipoles tunes, due to transverse excitation
  - Example of decapolar resonance at $4Q_y$
- Resonance Driving Terms are linked to line amplitude
- New collimation setup allowed for higher kicks

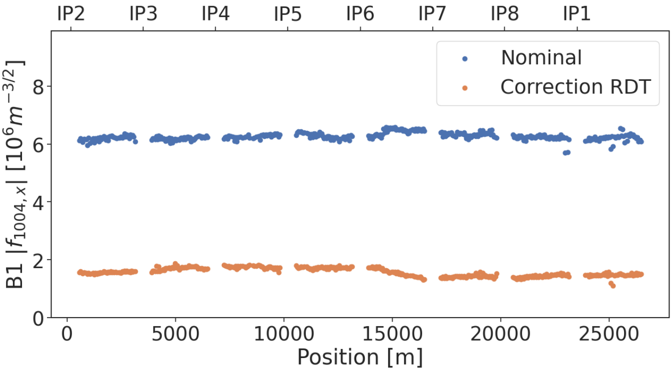
GUI for Online Measurements and Corrections



- Developped a new tool for chromaticity
  - Allows online analysis and corrections
- Also allows combined chromaticity and RDT correction for b_4/b_5

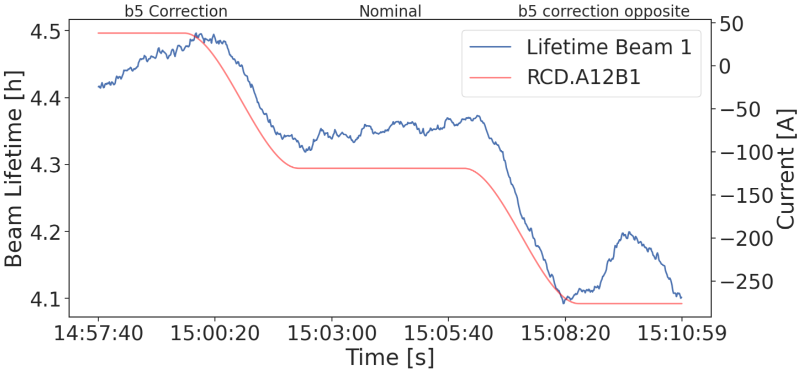
$\rightarrow$ Online measurements and corrections are fast and efficient

Measurement and Corrections



- Corrections based on a response matrix
  - Retrieves the current needed to replicate measurement
- Simultaneous corrections of f_{1004}, Q''' and chromatic amp.det.
- First correction of high-orders at injection

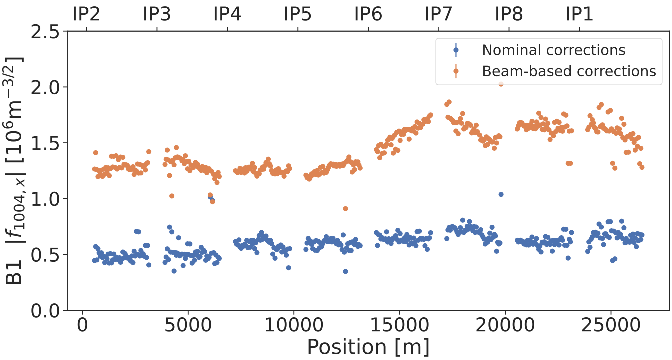
Lifetime Impact of Corrections



- Clear improvement of lifetime with correction
- And deterioration with opposite trim

$\rightarrow$ Gain of pilot lifetime at injection energy of $\approx 3\%$

Other Sources for RDT?



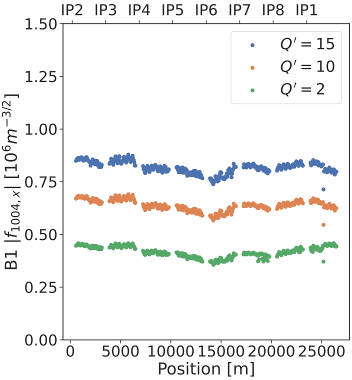
- Weird behaviour of the RDT
  - Amplitude seemed to vary every year, even with same Q'''
  - Additional corrections of Q'' increased it

$\rightarrow$ Corrections of Q''' not implemented in 2022

Sextupolar and Octupolar Contributions

Via higher-orders of the transfer map $e^{:h_1:}e^{:h_2:} = e^{:h:}$

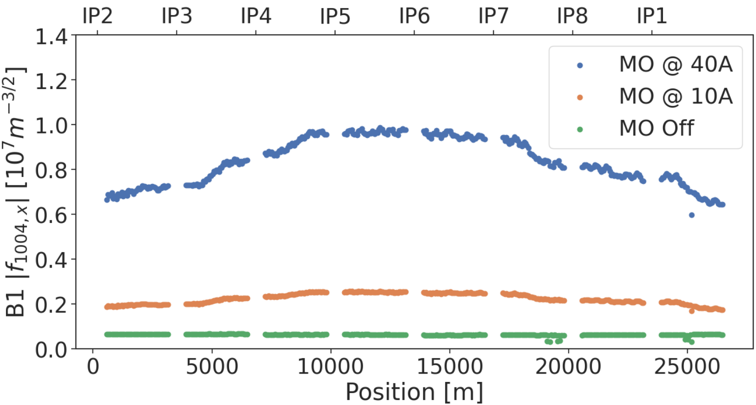
$$
\begin{aligned}
h = & h_1 + h_2 && \Rightarrow 1^{\text{st}} \text{ order} \\
& + \frac{1}{2}[h_1, h_2] && \Rightarrow 2^{\text{nd}} \text{ order} \\
& + \frac{1}{12}[h_1, [h_1, h_2]] && \\
& - \frac{1}{12}[h_2, [h_1, h_2]] && \Rightarrow 3^{\text{rd}} \text{ order} \\
& + \cdots .
\end{aligned}
$$



- 1^{st} order → decapoles
- 2^{nd} order → sextupoles and octupoles
- 3^{rd} order → sextupoles together

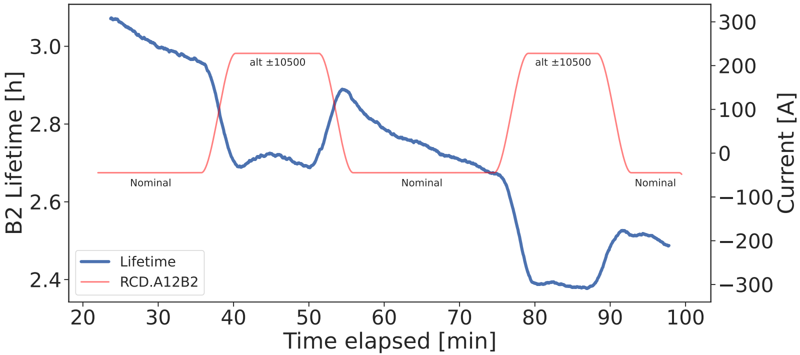
→ Feed-up from sextupoles and octupoles contribute to b_5 RDTs

RDT from Landau Octupoles



- Landau Octupoles quite strong at injection energy
  - RDT one order of magnitude stronger!

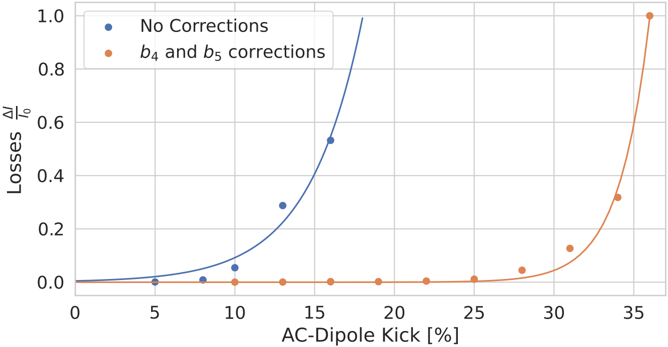
Landau Octupoles Impact on Lifetime



- Artificially increased RDT to match expected octupolar impact
  - Q''' staying constant
  - Lifetime got lowered by 10%

$\rightarrow$ Higher-order effects are important

Forced Dynamic Aperture



- Corrections now implemented in operation
- Forced Dynamic Aperture clearly improved

→ We can now kick higher with the AC-Dipole!

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Dodecapolar RDT f_{0060}

Decatetrapoles

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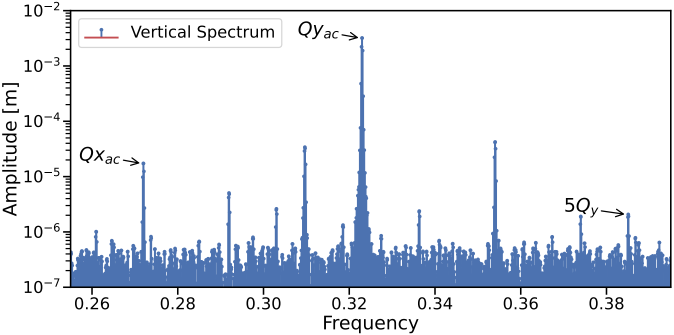
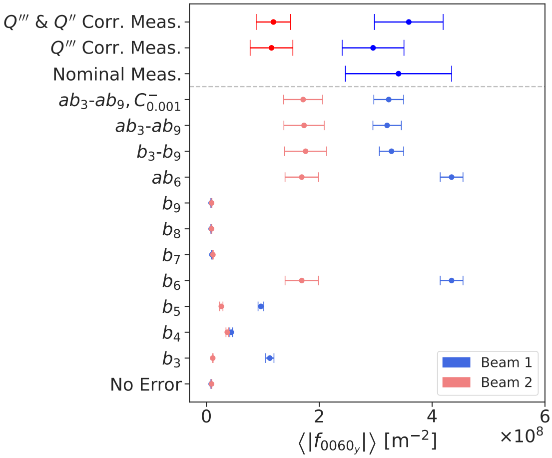
Dodecapolar RDT f_{0060}



- First measurement made possible this Run
  - Thanks to new collimator sequence
  - b_4 and b_5 corrections improving forced DA
- Nice repeatability of measurements

Dodecapolar RDT f_{0060}



- b_6 dominates
- small impacts of b_3, b_4, b_5
- Beam1 $\times 2$ stronger

$\rightarrow$ Our model is accurate for this dodecapolar RDT

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- Chromaticity

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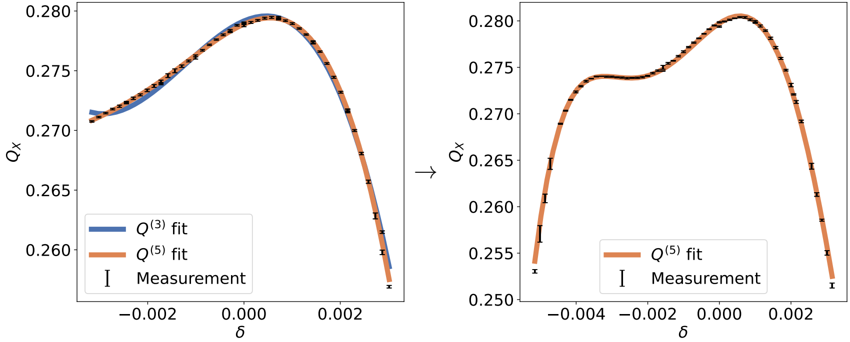
Chromaticity

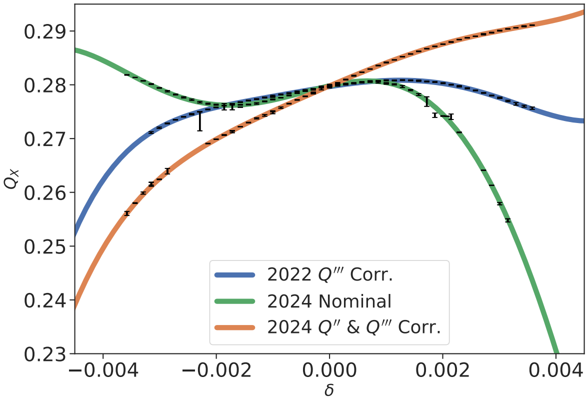


$$Q(\delta) = Q_0 + Q'\delta + \frac{1}{2!}Q''\delta^2 + \frac{1}{3!}Q''\delta^3 + \underbrace{\frac{1}{4!}Q^{(4)}\delta^4 + \frac{1}{5!}Q^{(5)}\delta^5}_{new!} + \cdots$$

- New collimation setup allowed us to increase momentum range
- Refined cleaning tune cleaning via GUI

→ Clear effects of higher-order chromaticity

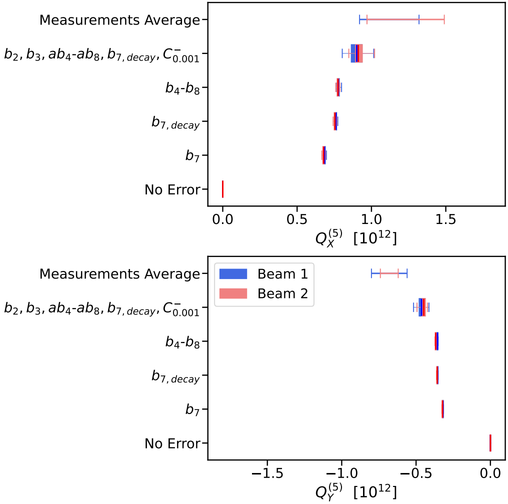
Chromaticity



Similar and repeatable measurements achieved

- Over 5 different corrector configurations
- With different optics and years appart

Chromaticity



- b_7 decay in main dipoles has small impact
- Some missing sources?

→ Our model differs only by 20%

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Conclusions

Progressed and achieved nice measurements of higher-order fields!

- Decapolar
  - Improved our understanding of decapolar fields and our model
  - Forced DA improved by novel corrections
  - First measurements and corrections of Chromatic Detuning and RDTs
- Dodecapolar
  - First measurement of f_{0060} and benchmark of model
- Decatetrapolar
  - Chromaticity measurements allow to probe up to Decatetrapole

$\rightarrow$ Good first characterization of high orders in the LHC :)

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