High-Orders Fields in the LHC

PhD Thesis Presentation

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Plan

Outline

Introduction

Decapolar Studies

Dodecapolar Studies

Decatetrapolar Studies

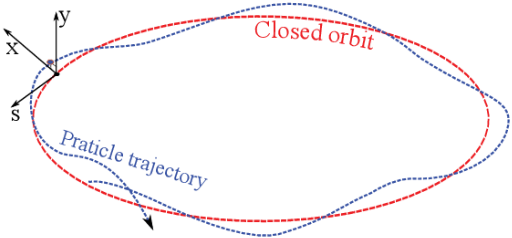
Conclusions

Outline

- Introduction
  - How particles are bent
  - What problems can arise
  - LHC-specific overview
- Thesis Work
  - Decapole Studies
  - Dodecapole Studies
  - Decatetrapole Studies
- Conclusion

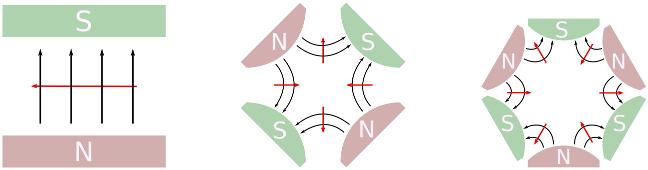
Plan

Going in Circles



- All particles oscillate around the ring
- The perfect particle follows the closed orbit
- The number of transverse oscillations per turn is the tune: Q_x and Q_y

Magnets and Optics

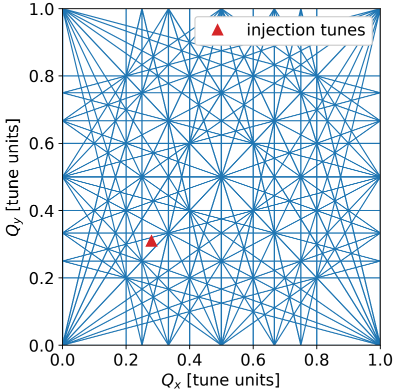


Dipole (b_1) Quadrupole (b_2) Sextupole (b_3)

- Linear elements
  - Dipoles bend the particles
  - Quadrupoles focus the beam
- Non-Linear elements
  - Sextupoles correct off-momentum focusing (chromaticity)
  - Octupoles (b_4) correct amplitude related tune change
  - Decapoles (b_5) correct some chromaticity and amplitude detuning

Optics: a set of magnet strengths and the related observables

Resonances



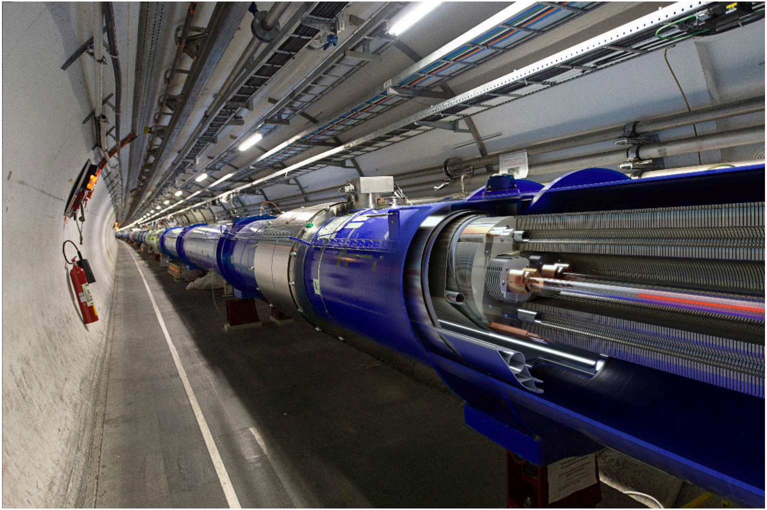
Resonances aren't a nice thing

- Unstable motion, losing particles
- First goal is to avoid them
- Second is to make them weaker

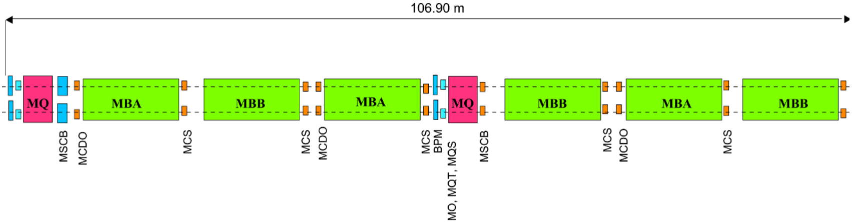
- Condition:

$$a \cdot Q_x + b \cdot Q_y = p \quad ; \quad a, b, c \in \mathbb{N}$$

The LHC



Arc Structure



- Cell: basic block that is repeated
- Total of 1232 dipoles in the machine
- Correctors from sextupoles to decapoles

- Magnetic errors of magnets are modeled
  - Strong errors from dipoles need to be corrected!

Thesis Work

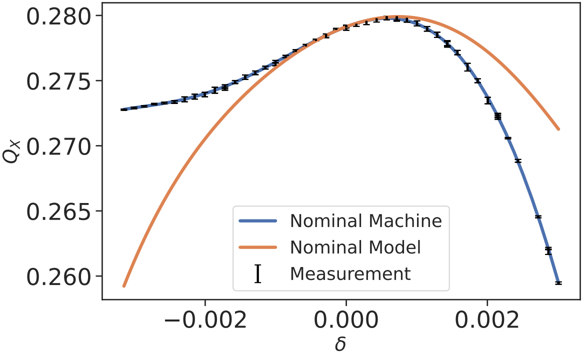
High order fields might become problematic once we reach higher performances with the next upgrade of the accelerator: HL-LHC.

- Magnetic error model of decapolar fields isn't accurate
  - Finding the discrepency
  - Correcting decapolar fields in operation
- Finding ways to measure higher orders and their impact
  - Dodecapoles and decatetrapoles

Understanding high order fields helps inform design and optimisation of other accelerators!

Plan

Magnetic Model Discrepancy



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

Possible sources

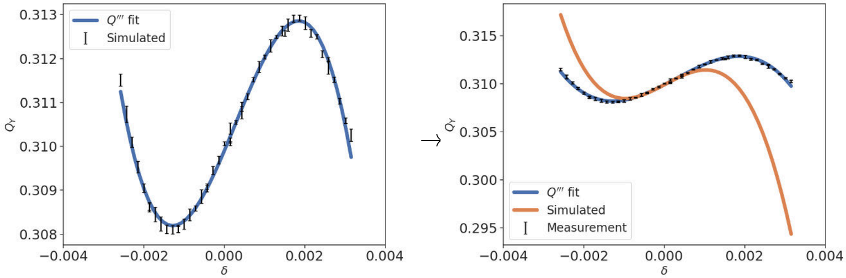
Is it coming from the measurement technique itself or errors?

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

- Correctors response
- Magnetic model

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

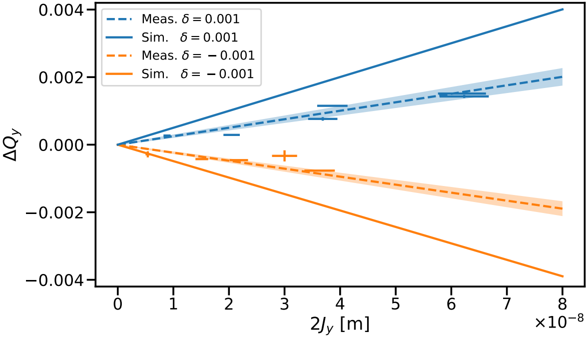
Checking the Correctors



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

$\rightarrow$ I to K, crosstalk and coupling ruled out
$\rightarrow$ 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 expression than Q'''
- Factor ≈ 2 compared to simulations again
- First time ever measured in the LHC

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

Decay in Main Dipoles

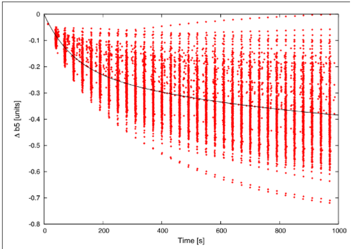


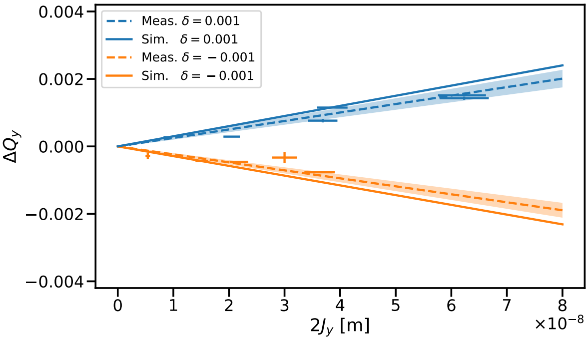
Figure 31: Decay of integrated b_5 at injection (430 apertures) and the decay fit (black line).

- Computed from magnetic meas.
- Sextupolar decay implemented in operation
- Decapolar component constant in models
- Decapolar decay *not* implemented
- Quite large and fast at injection

$\rightarrow \bar{b_5}$ from 1.1 to 0.6 in main dipoles

$\rightarrow$ Decay is important to consider

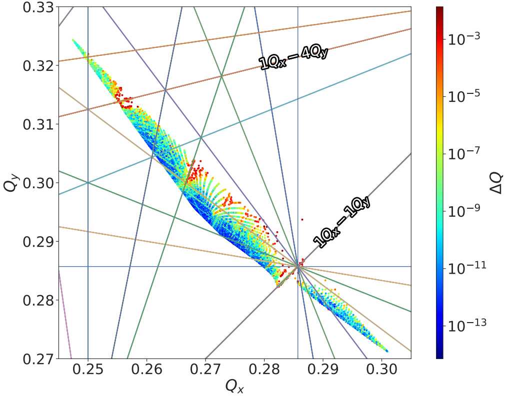
Implementation of Decay



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

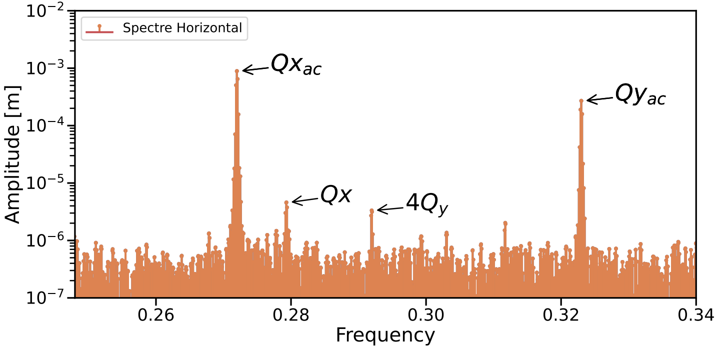
$\rightarrow b_5$ discrepancy comes from our error model

Resonance Driving Terms



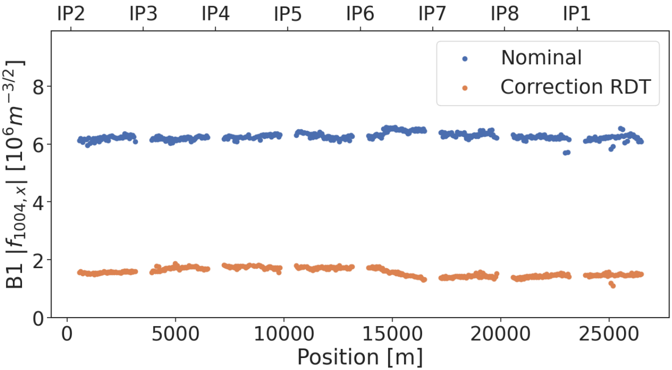
- Coefficient linked to a resonance amplitude
  - Resonances : $(j-k)Q_x + (l-m)Q_y = p \quad ; \quad p \in \mathbb{N}$
  - With $j+k+l+m=n$, order of field
- Example of f_{1004}
  - Excites resonance $1Q_x - 4Q_y$

Turn-by-Turn Spectrum



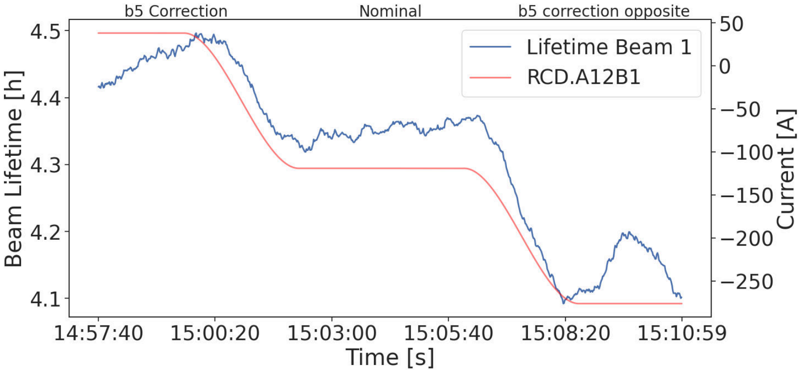
- Several lines are clearly visible
  - AC-Dipoles tunes, due to transverse excitation
  - Example of decapolar resonance at $4Q_y$
- Resonance Driving Terms are linked to line amplitude

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

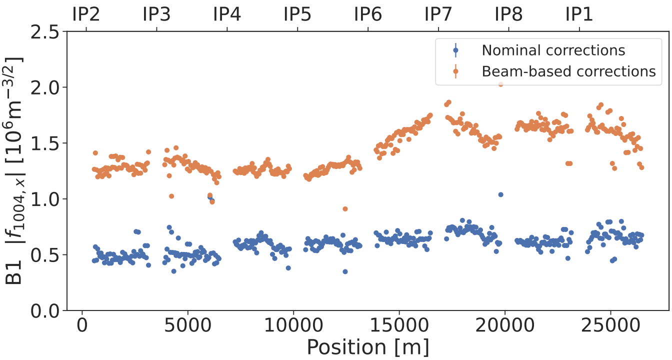
Lifetime Impact of Corrections



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

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

Other Sources for RDT?



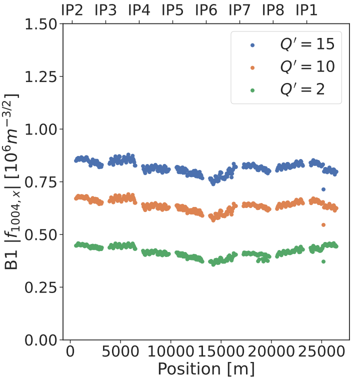
- Weird behaviour of the RDT
  - Amplitude seemed to vary every year, even with same Q'''
  - Additional corrections of Q'' increased it

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

Sextupolar and Octupolar Contributions

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

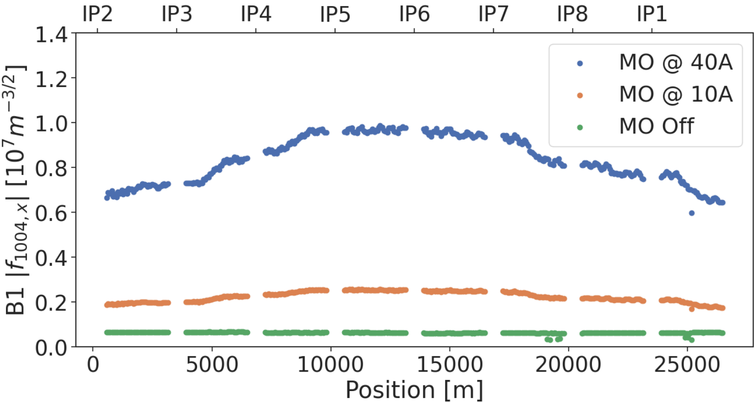
$$
\begin{aligned}
h =& h_1 + h_2 && \Rightarrow \text{1}^{\text{st}} \text{ order} \\
&+ \frac{1}{2}[h_1, h_2] && \Rightarrow \text{2}^{\text{nd}} \text{ order} \\
&+ \frac{1}{12}[h_1, [h_1, h_2]] && \\
&- \frac{1}{12}[h_2, [h_1, h_2]] && \Rightarrow \text{3}^{\text{rd}} \text{ order} \\
&+ \cdots .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



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

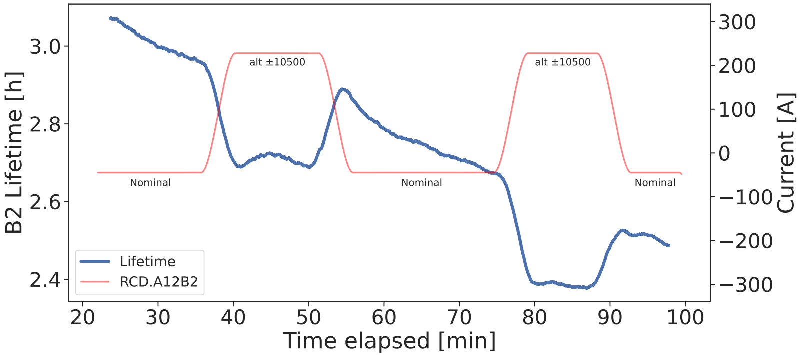
$\rightarrow$ Feed-up from sextupoles and octupoles contribute to b_5 RDTs

RDT from Landau Octupoles



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

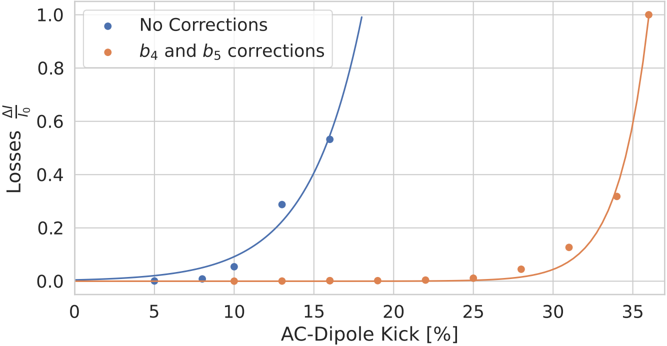
Landau Octupoles Impact on Lifetime



- 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

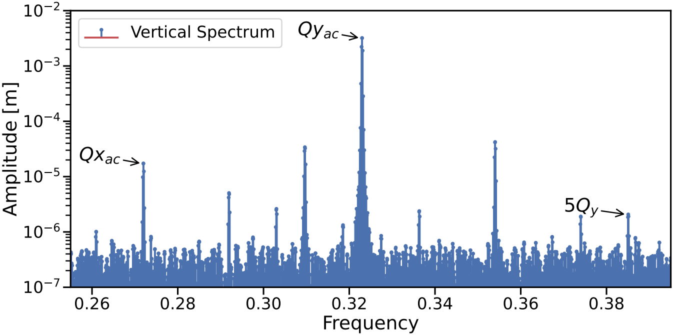


- Corrections now implemented in operation
- Forced Dynamic Aperture clearly improved

$\rightarrow$ We can now kick higher with the AC-Dipole!

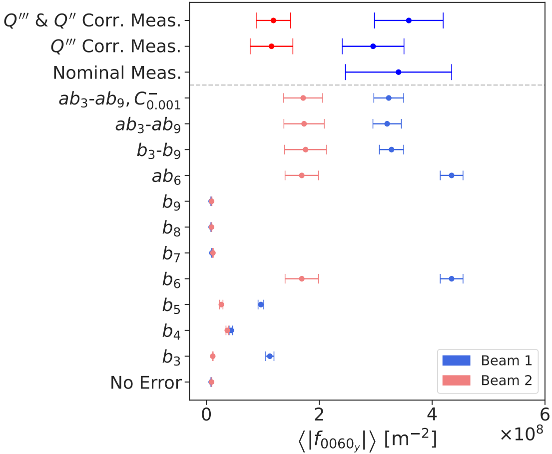
Plan

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}

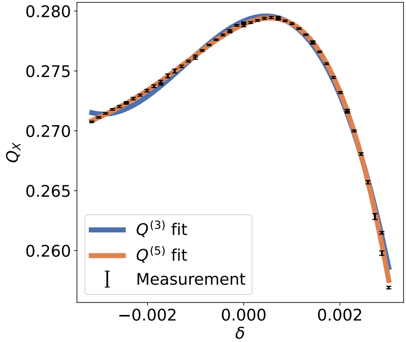


- b_6 dominates
- small impacts of b_3, b_4, b_5
- Beam1 $\times 2$ stronger

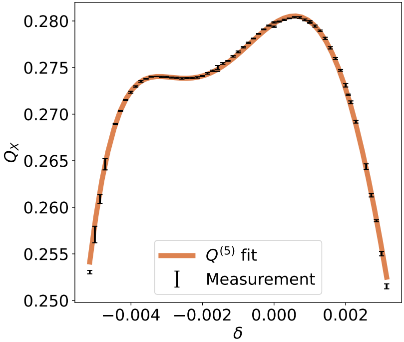
$\rightarrow$ Our model is accurate for this dodecapolar RDT

Plan

Chromaticity



$\rightarrow$

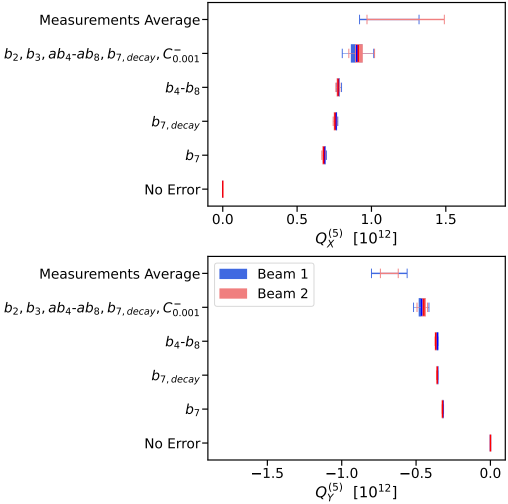


$$Q(\delta) = Q_0 + Q'\delta + \frac{1}{2!}Q''\delta^2 + \frac{1}{3!}Q''\delta^3 + \underbrace{\frac{1}{4!}Q^{(4)}\delta^4 + \frac{1}{5!}Q^{(5)}\delta^5}_{new!} + \cdots$$

- New collimation setup allowed us to increase momentum range
- Refined cleaning tune cleaning via new processing methods

$\rightarrow$ Clear effects of higher-order chromaticity

Chromaticity



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

→ Our model differs only by 20%

Plan

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 :)