LHC Effective Model for Optics Corrections

PhD Thesis Presentation

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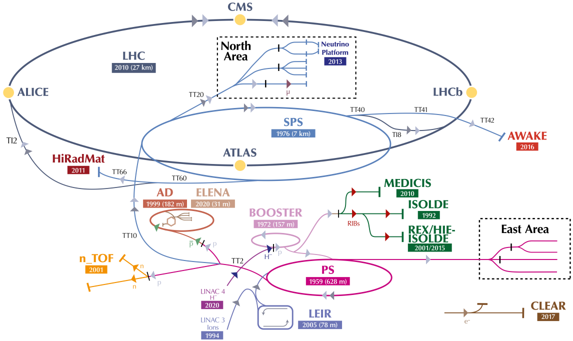
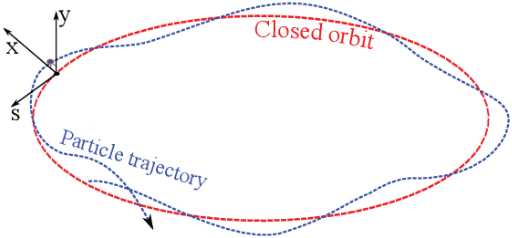
Introduction



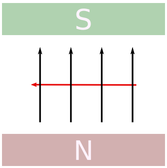
- Accelerators are needed to probe high energy physics
- The LHC is the most advanced accelerator today
    - Challenging to push further the parameters
    - Optimizations require new methods

Particle Trajectory

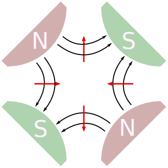


- All particles oscillate around the ring
- Number of transverse oscillations per turn is the tune: Q_x and Q_y
  - Fractional part is important! In the LHC around 0.28 and 0.31
- Trajectory is created by magnetics fields and can be disturbed

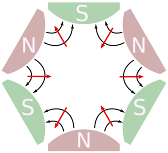
Magnets and Optics



Dipole



Quadrupole

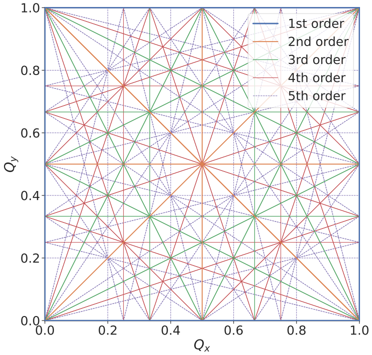


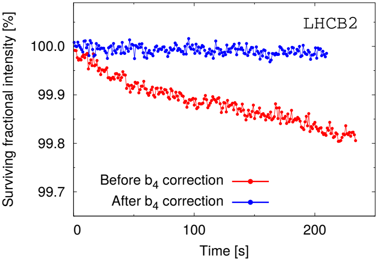
Sextupole

- Linear elements
  - Dipoles bend the particles
  - Quadrupoles focus the beam and set the tune
- Non-Linear elements
  - Sextupoles correct particles with a momentum-offset (δ, chromaticity)
  - Octupoles correct tune change with large amplitudes (amp. detuning)
  - Decapoles correct higher-orders chromaticity and amplitude detuning

Optics: a set of magnet strengths and the related observables

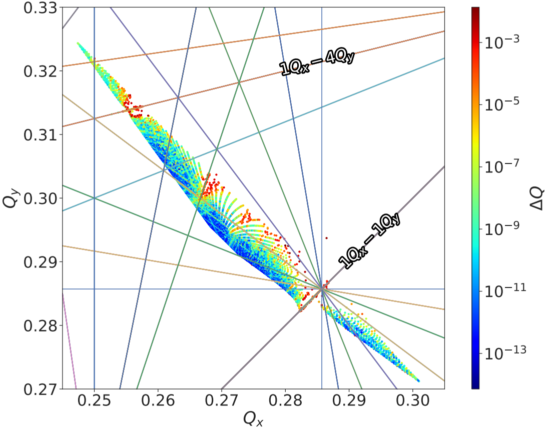
Resonances





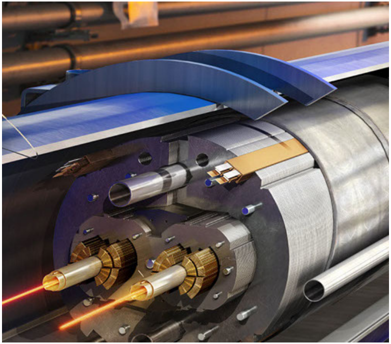
- Resonances lead to unstable motion and increasing amplitudes
  - Goal is to avoid, or at least minimize them
- Dynamic Aperture: amplitude particles can reach before being lost
  - Can be measured with lifetime studies

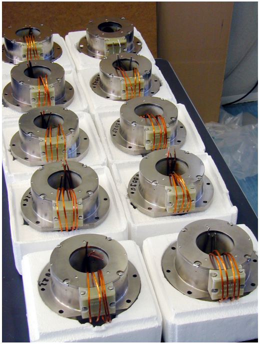
Resonance Driving Terms



- RDT f_{jklm}: Coefficient linked to a resonance strength
- Example of f_{1004}, from decapolar fields
  - Excites resonance $1Q_x - 4Q_y$

Field Errors





- Coils were measured during LHC's construction
  - A magnetic model for errors is then used for simulations
  - Time dependent decay was also measured
- Efforts were done in the past to measure various orders
  - Good understanding of linear and some non-linear errors
  - High-orders only via indirect observables

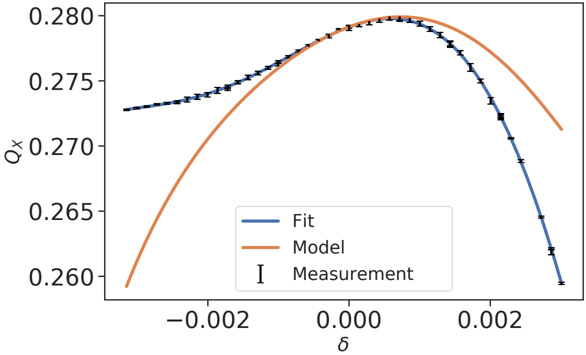
Thesis Work

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 seems incomplete
  - Understanding discrepency between simulations and measurements
  - Correcting decapolar fields in operation

- Finding ways to measure higher orders and their impact
  - Dodecapoles and decatetrapoles

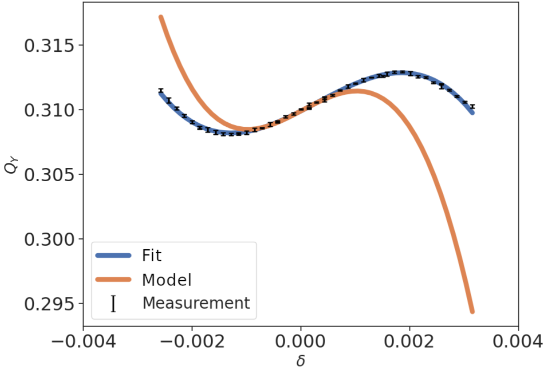
Magnetic Model Discrepancy



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

- Corrections of Q''' based on magnetic measurements
  - Model and measurements off by factor 2, but why?
- Possibles sources:
  - Correctors response
  - Magnetic model

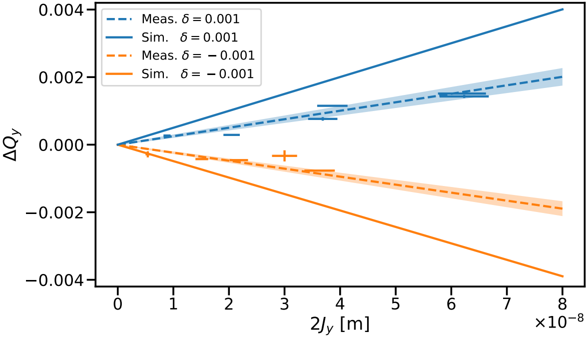
Checking the Correctors



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

$\rightarrow$ Correctors do not cause the discrepancy

Chromatic Amplitude Detuning

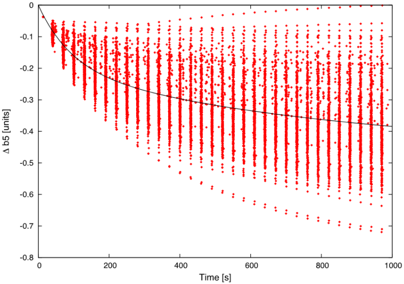


$$\Delta Q(J_x, J_y, \delta) = \frac{\partial^2 Q}{\partial J_x \partial \delta} J_x \delta + \frac{\partial^2 Q}{\partial J_y \partial \delta} J_y \delta + \frac{1}{3!} \frac{\partial^3 Q}{\partial \delta^3} \delta^3$$

- 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



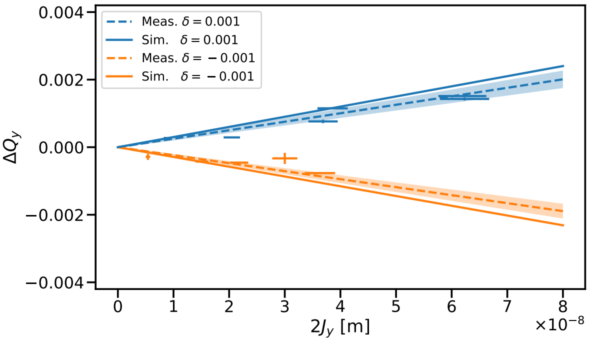
Change of decapolar component in dipoles over time, from Field Model documentation[1]

- Decapolar decay in the dipoles was neglected 15 years ago
- Subsequently not integrated in magnetic model
- Is actually quite large!

→ Average decapolar component halved in main dipoles!
Decay is important and needs to be considered

[1]https://lhc-div-mms.web.cern.ch/tests/MAG/Fidel/

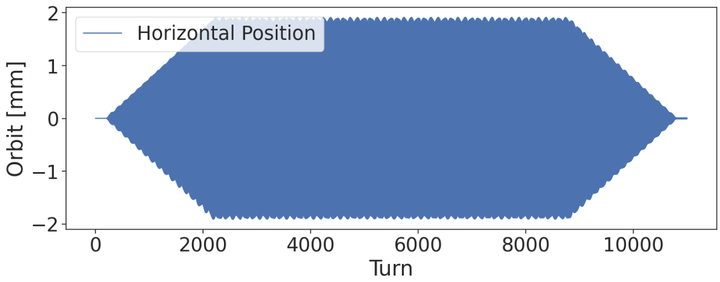
Implementation of Decay



- Average decapolar decay substracted in simulations
- Most of the difference is now explained
  - Both for Q''' and Chromatic Ampdet.

$\rightarrow$ Discrepancy comes from our error model

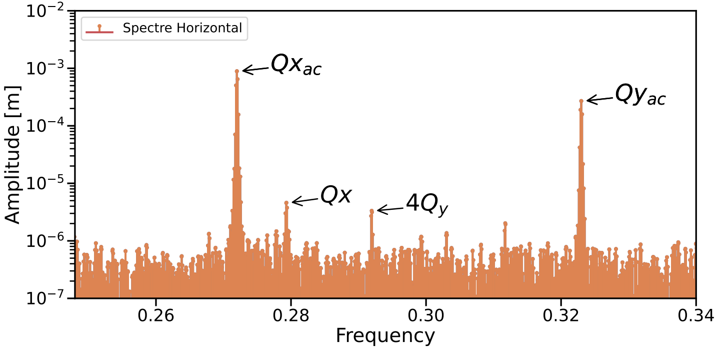
Measuring RDTs



- The beam is excited by an AC-Dipole
  - Creates large coherent oscillations
- Quantities like RDTs require high amplitudes
  - Can be challenging to attain due to forced dynamic aperture

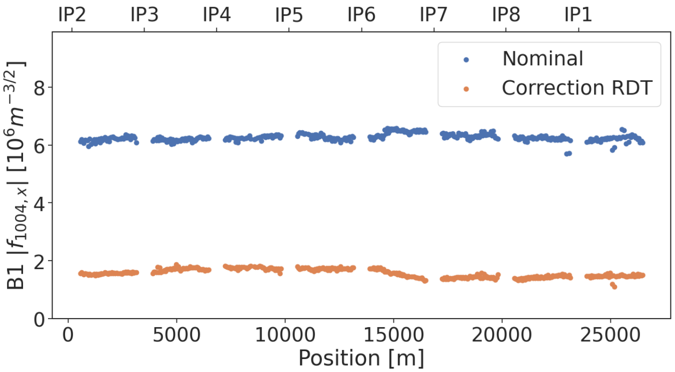
→ Thanks to prior advancements, it is now possible to measure decapolar RDTs!

Frequency Spectrum



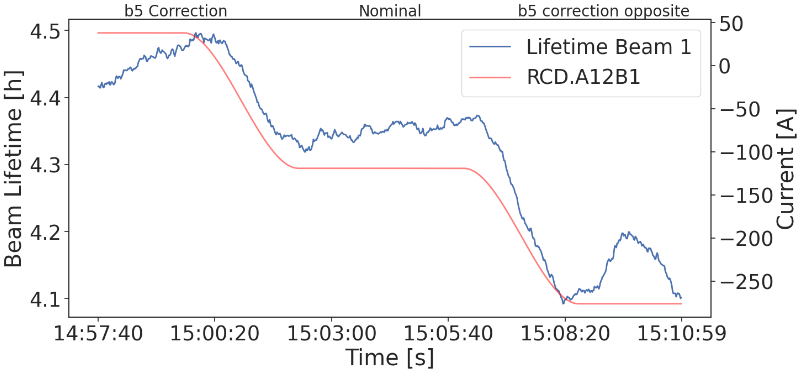
- Several lines are clearly visible
  - AC-Dipole tunes
  - Example of decapolar resonance at $4Q_y$
- Resonance Driving Terms are linked to the line amplitude
  - Normalized to the main line and then fitted over several measurements

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

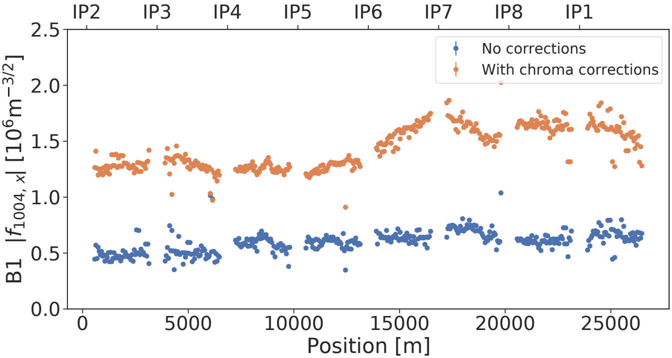
Lifetime Impact of Corrections



- Clear improvement of lifetime with decapolar 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 configuration
  - Additional octupolar corrections of Q'' increased it

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

Sextupolar and Octupolar Higher-Order Contributions

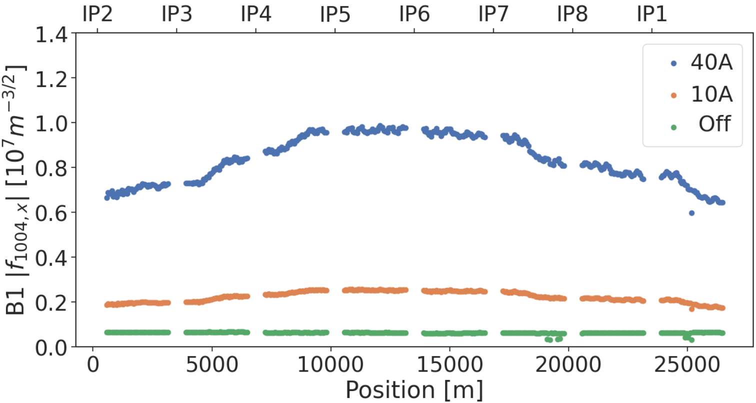
Via higher-orders of the transfer map, $e^{:h_1:}e^{:h_2:} = e^{:h:}$

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

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

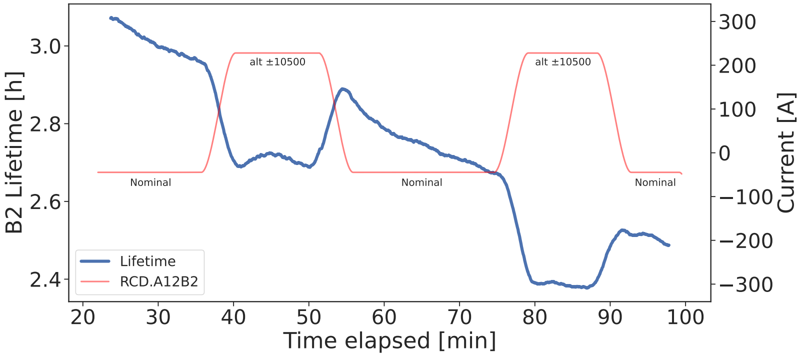
$\rightarrow$ Feed-up from sextupoles and octupoles contribute to decapolar RDTs
Actually never measured before in the LHC!

RDT from Landau Octupoles



- Strong octupoles are used to introduce coherent instabilities damping
- But they increase this RDT by one order of magnitude!

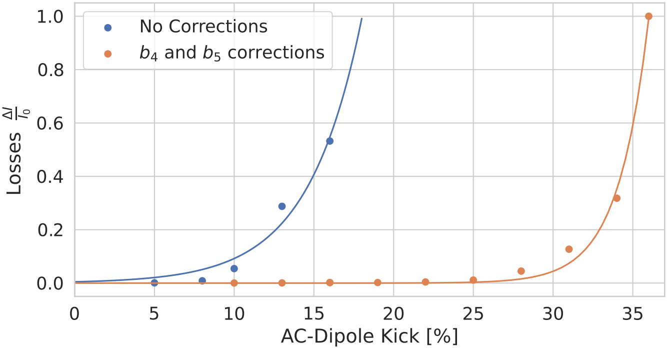
Landau Octupoles Impact on Lifetime



- Artificially increased RDT to match expected decapolar impact of sextupoles and octupoles
- Lifetime is negatively impacted by 10%

→ Considering higher-order effects is important

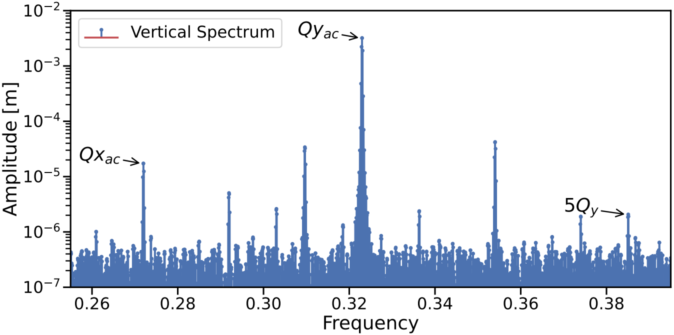
Forced Dynamic Aperture



- We now have a good understanding of interplay of fields
- Allows to implemented in operation the new corrections
  - Octupolar (b_4) and decapolar (b_5)
  - Forced Dynamic Aperture clearly improved

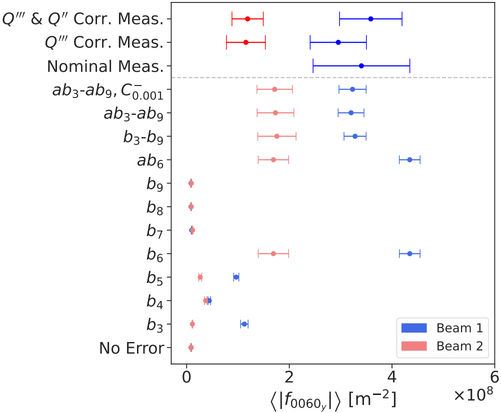
$\rightarrow$ We can now kick higher with the AC-Dipole!

Dodecapolar RDT f_{0060}



- First measurement made possible this Run
  - Thanks to octupolar (b_4) and decapolar (b_5) corrections improving DA
  - Never been possible before due to kick amplitudes
- Nice repeatability of measurements

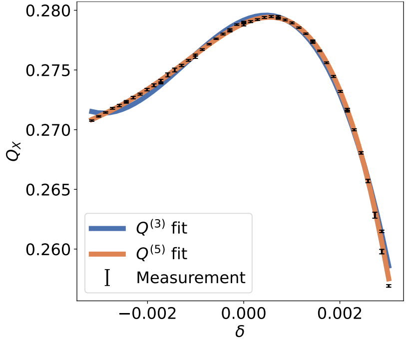
Dodecapolar RDT f_{0060}



- Dodecapoles (b_6) dominate
- Small impact of sextupoles through decapoles ($b_3 - b_5$)

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

Chromaticity



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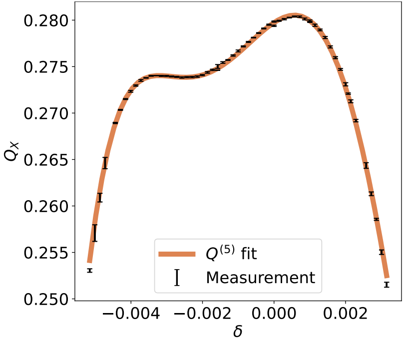
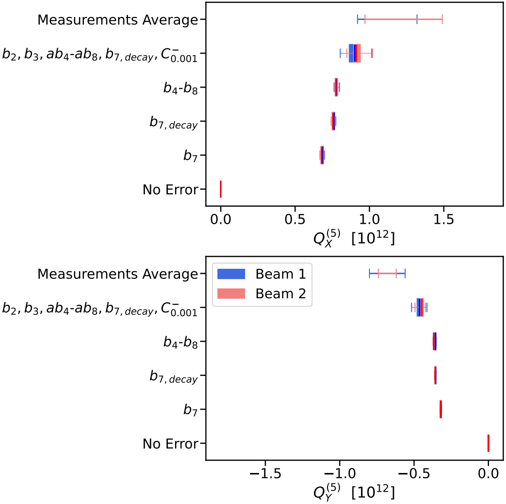


$$Q(\delta) = Q_0 + Q'\delta + \frac{1}{2!}Q''\delta^2 + \frac{1}{3!}Q'''\delta^3 + \underbrace{\frac{1}{4!}Q^{(4)}\delta^4 + \frac{1}{5!}Q^{(5)}\delta^5}_{\text{newly measured!}} + \cdots$$

- New measurement technique to increase scan range
- Refined tune cleaning via new processing methods

→ Clear effects of higher-order chromaticity

Chromaticity



- Decatetrapolar (b_7) decay has an impact
- Some missing sources yet to identify

→ Our model agrees relatively well!

Conclusions

Progressed and achieved first 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 :)

Conclusions

Thank you for your attention!