Beam-based studies of nonlinear optics at the LHC

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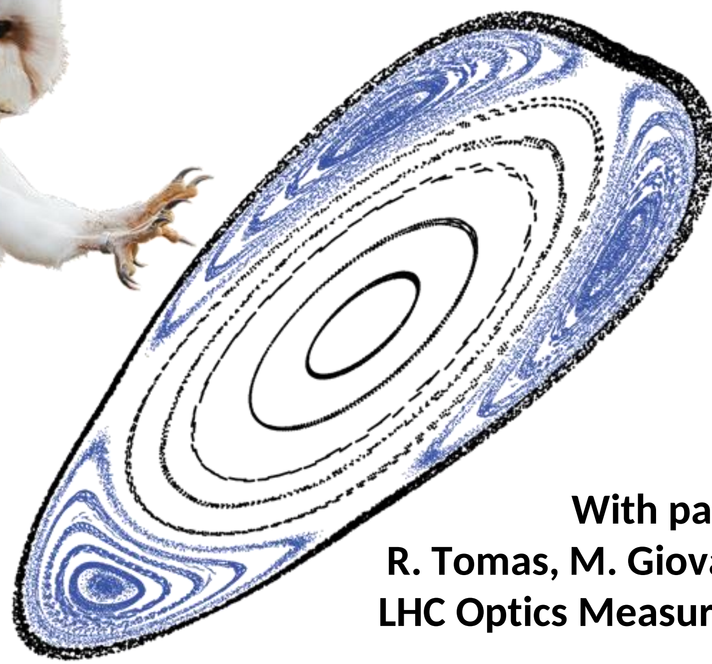
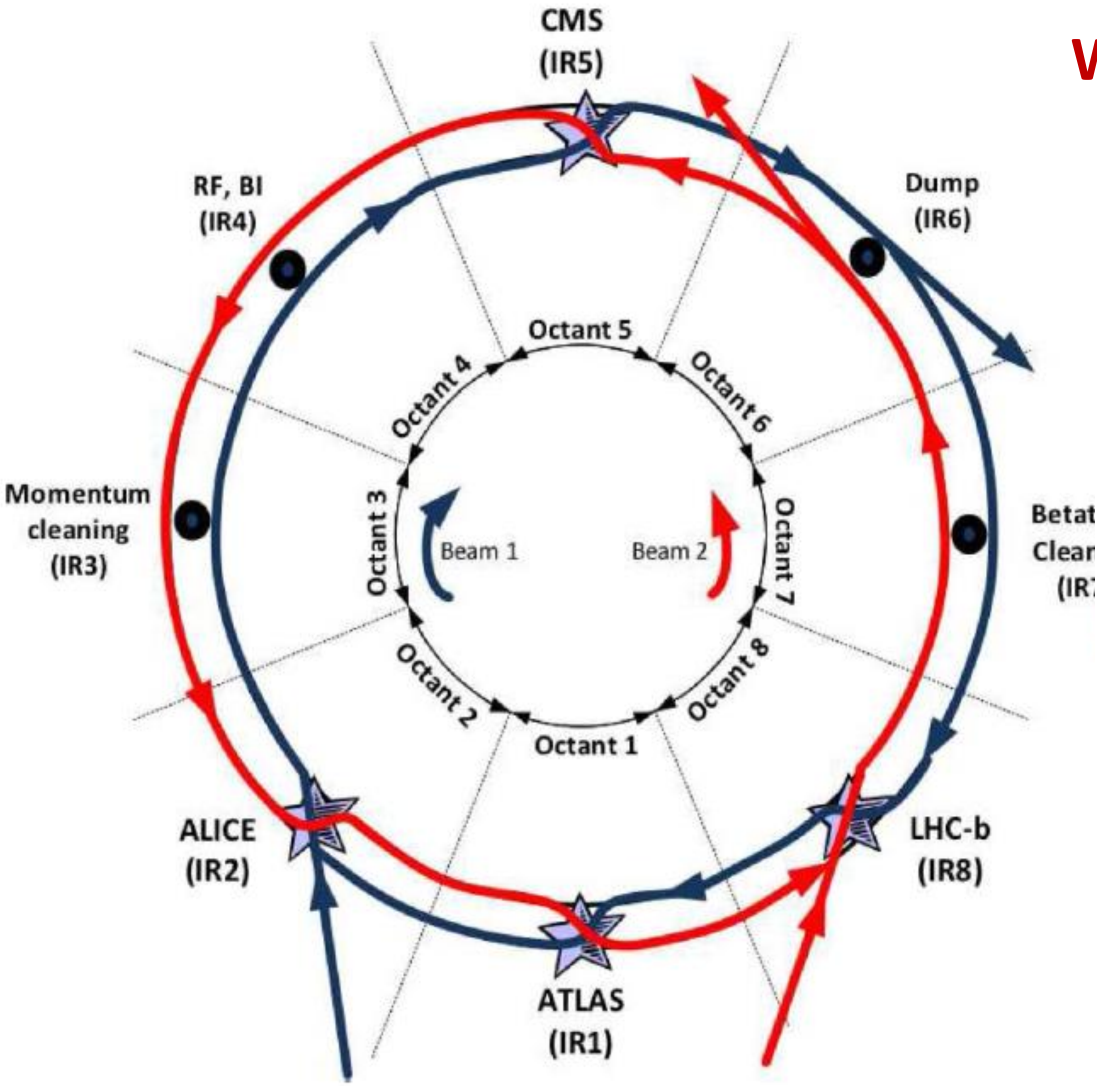


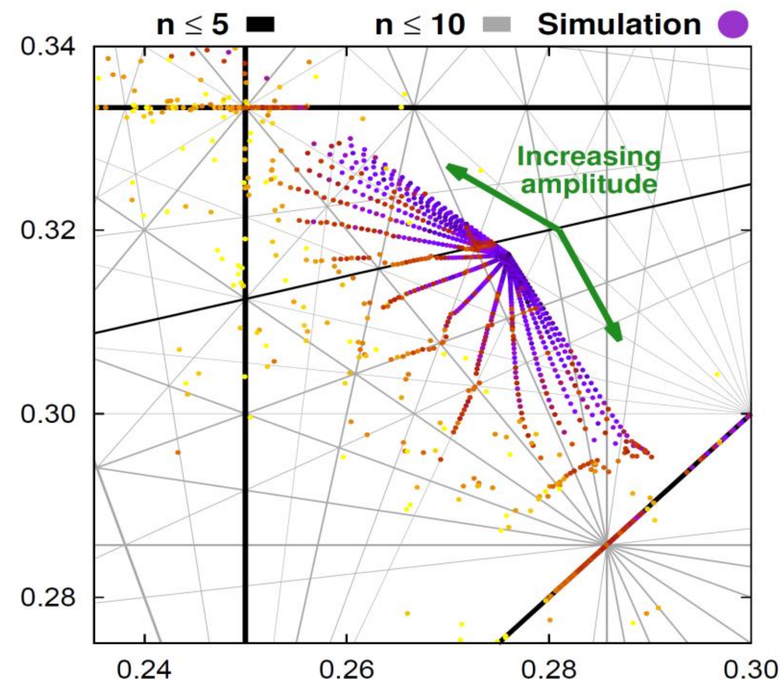
**With particular thanks to
R. Tomas, M. Giovannozzi, T. Persson, and the
LHC Optics Measurement and Correction Team**

The Large Hadron Collider (LHC)



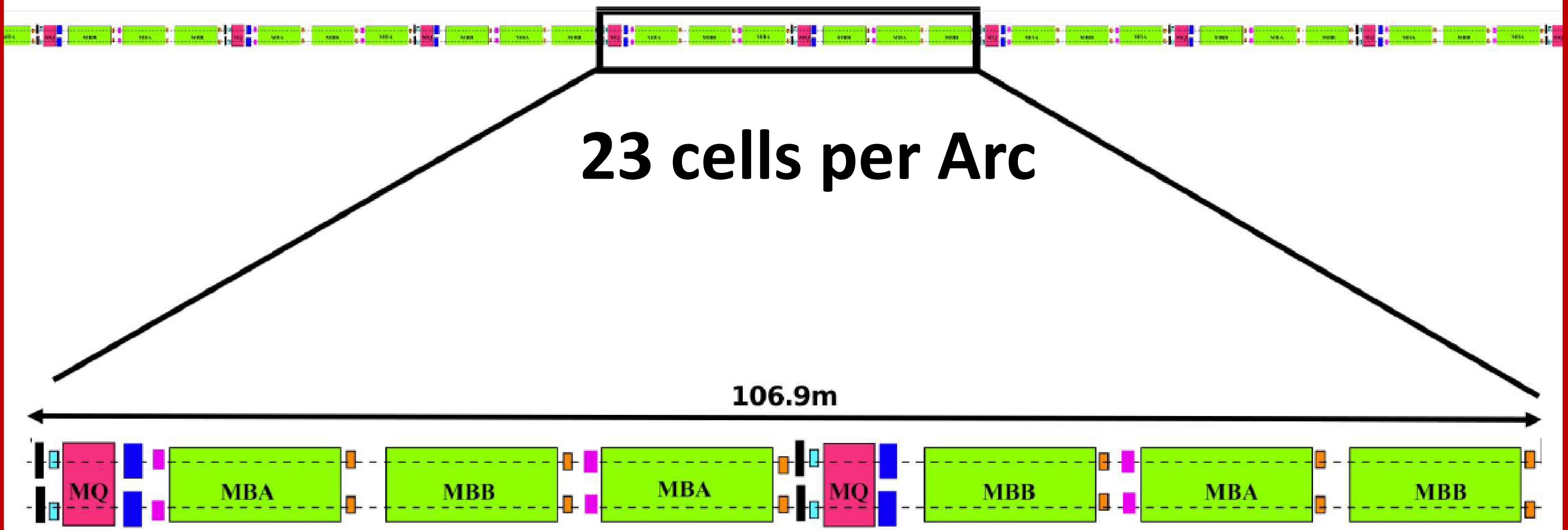
WP for injection: ≈ (0.280,0.310)
≈ (0.275,0.295)

WP at 6.5TeV ≈ (0.31,0.32)



- 8 straight insertion regions (IRs) & 8 bending Arcs *'A12 → A81'*

Nonlinear optics at injection dominated by errors in main arc dipoles and main arc quads



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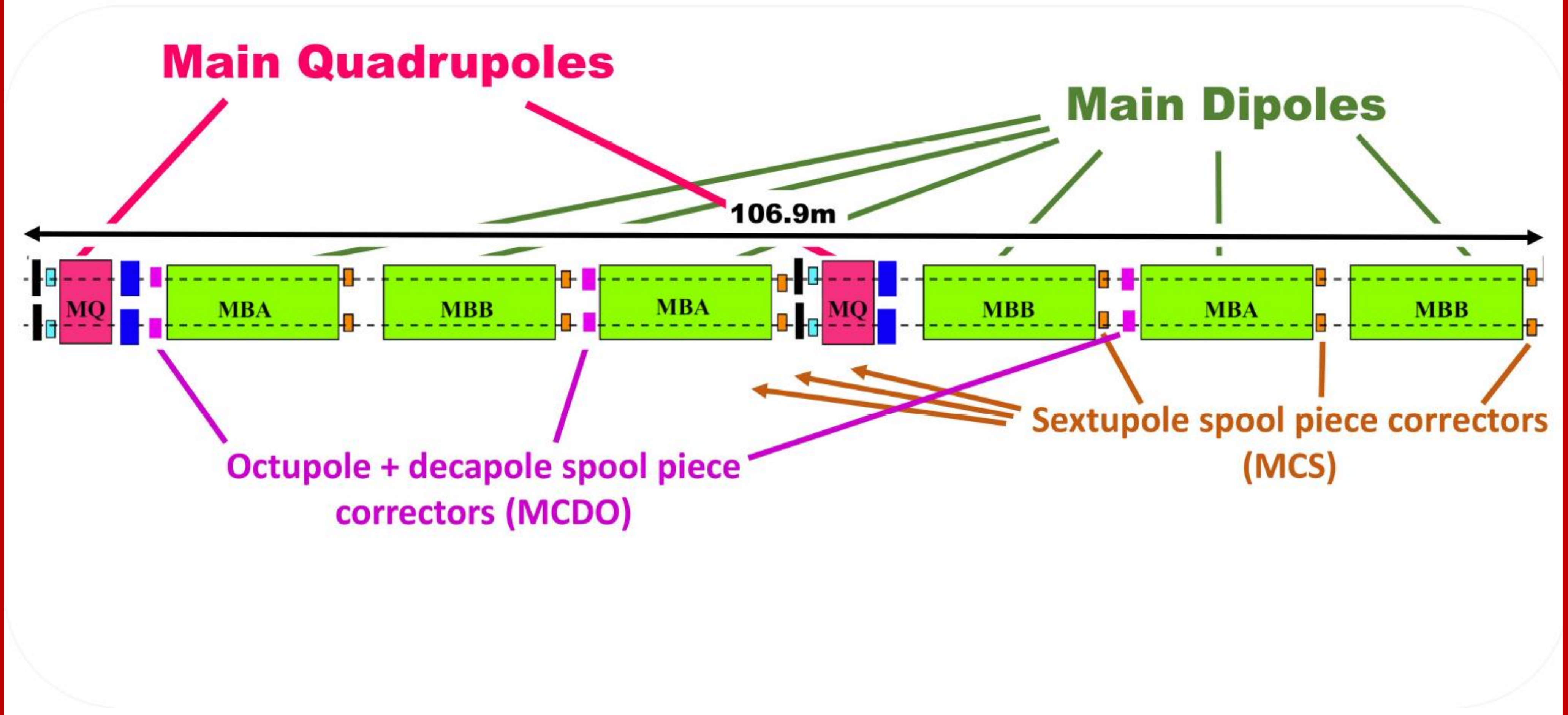
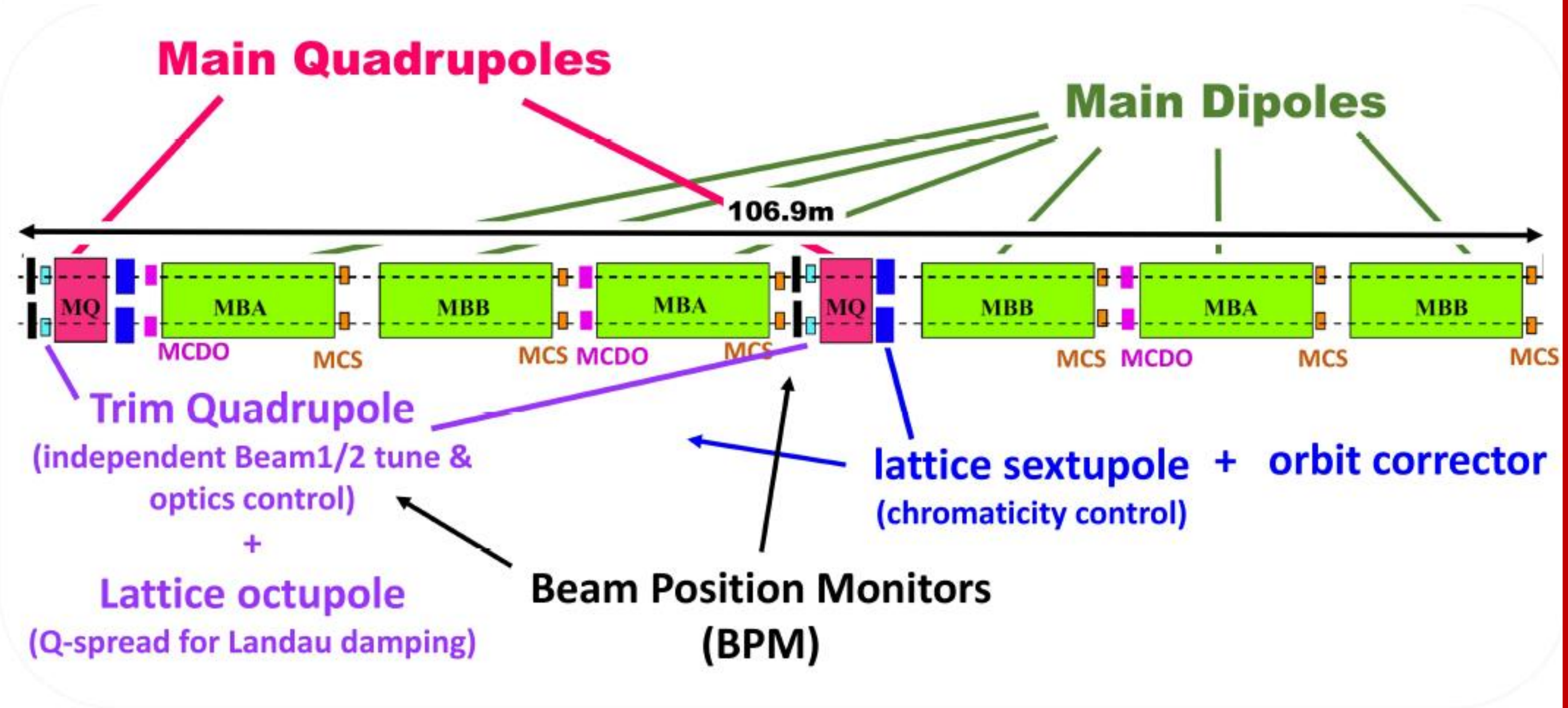
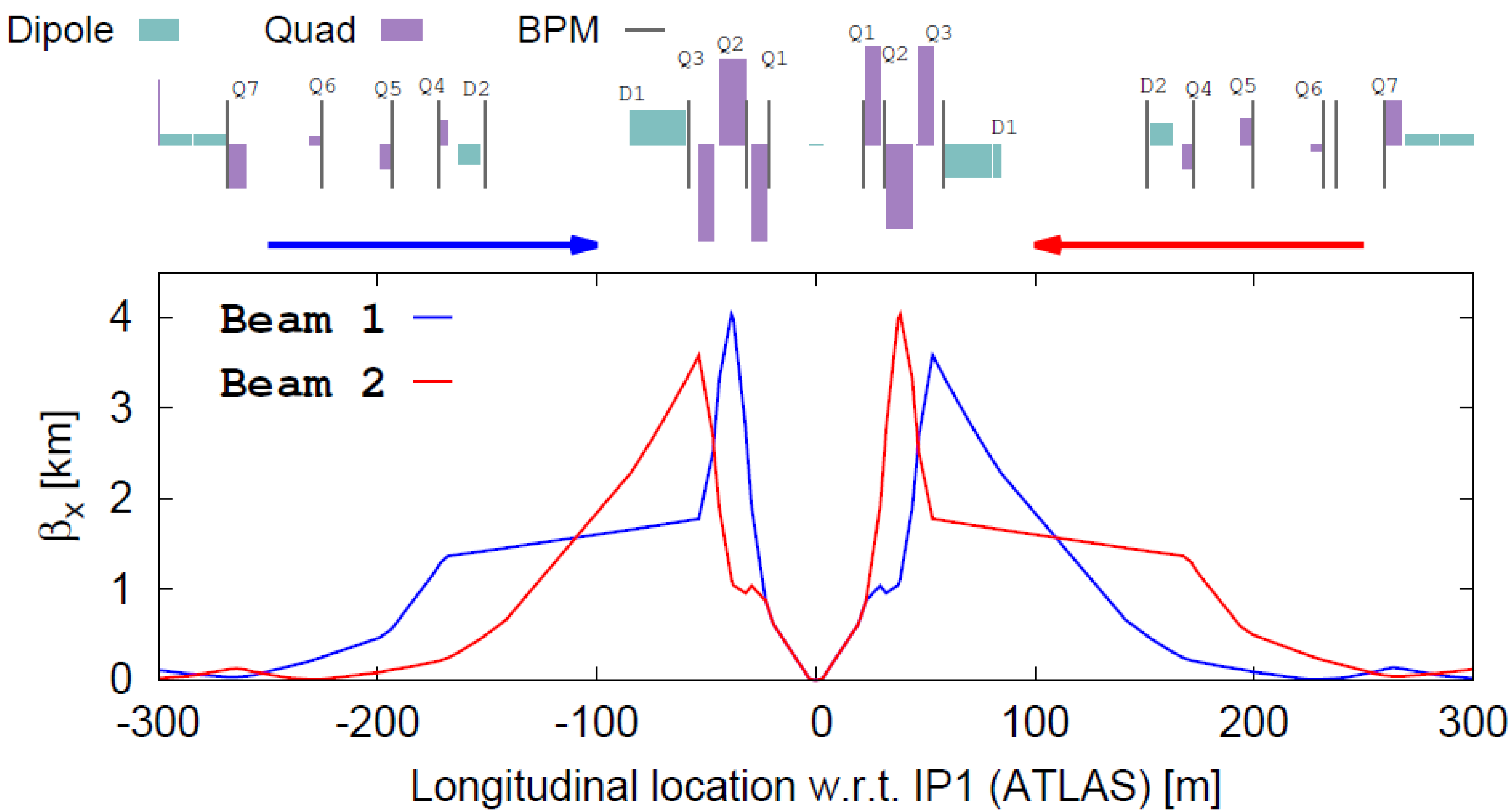


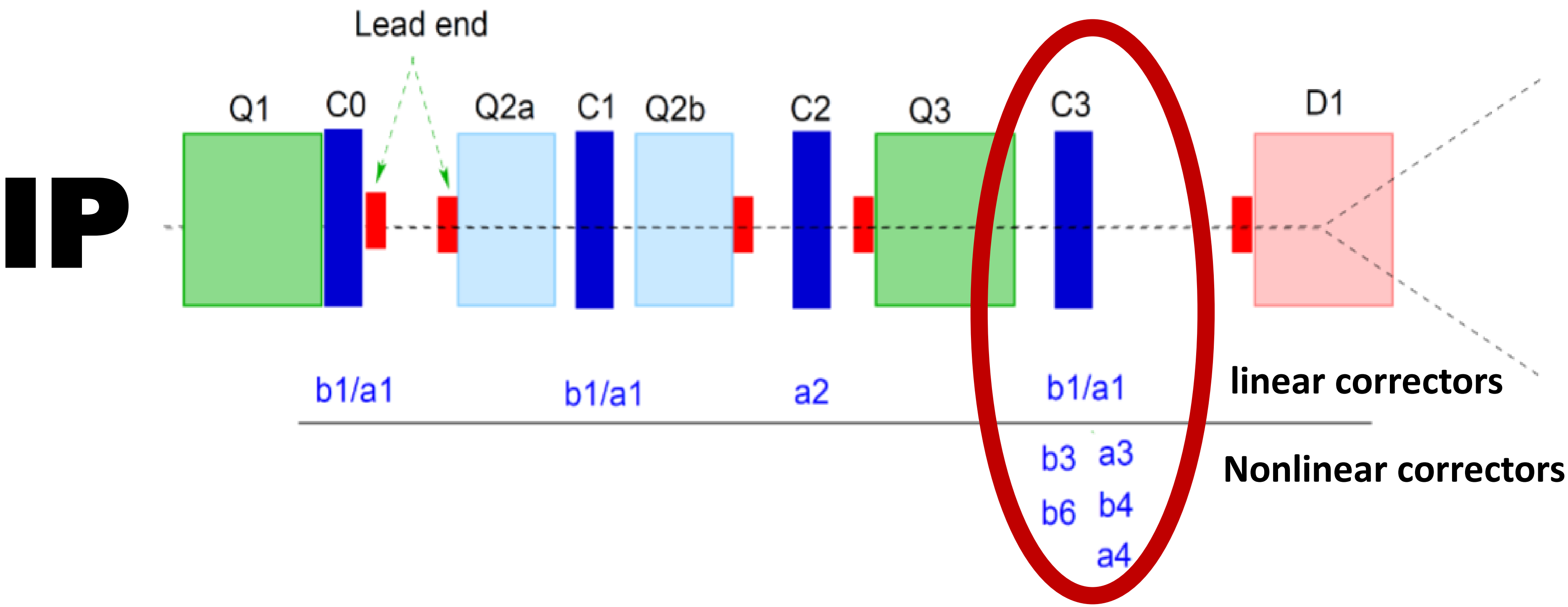
Nonlinear optics at injection dominated by errors in main arc dipoles and main arc quads





Largest sources of nonlinear optics errors at end-of-squeeze are in the triplets and separation dipoles

Dedicated nonlinear correctors left and right of the experimental IRs

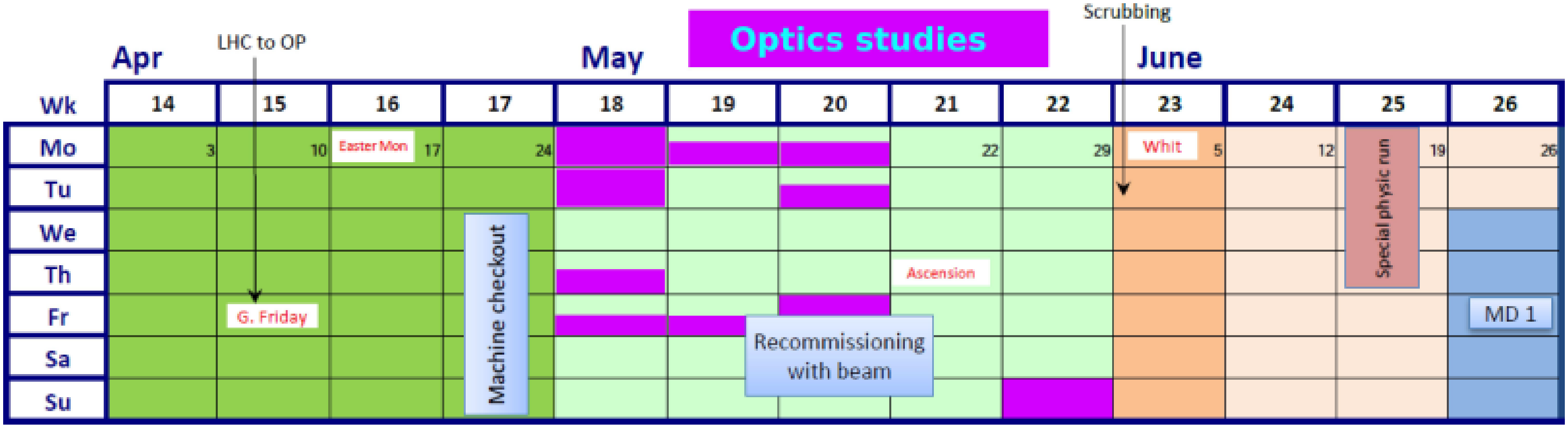


LHC Optics Measurement & Correction (OMC) team, 2017

2 main category of beam-based optics activity:

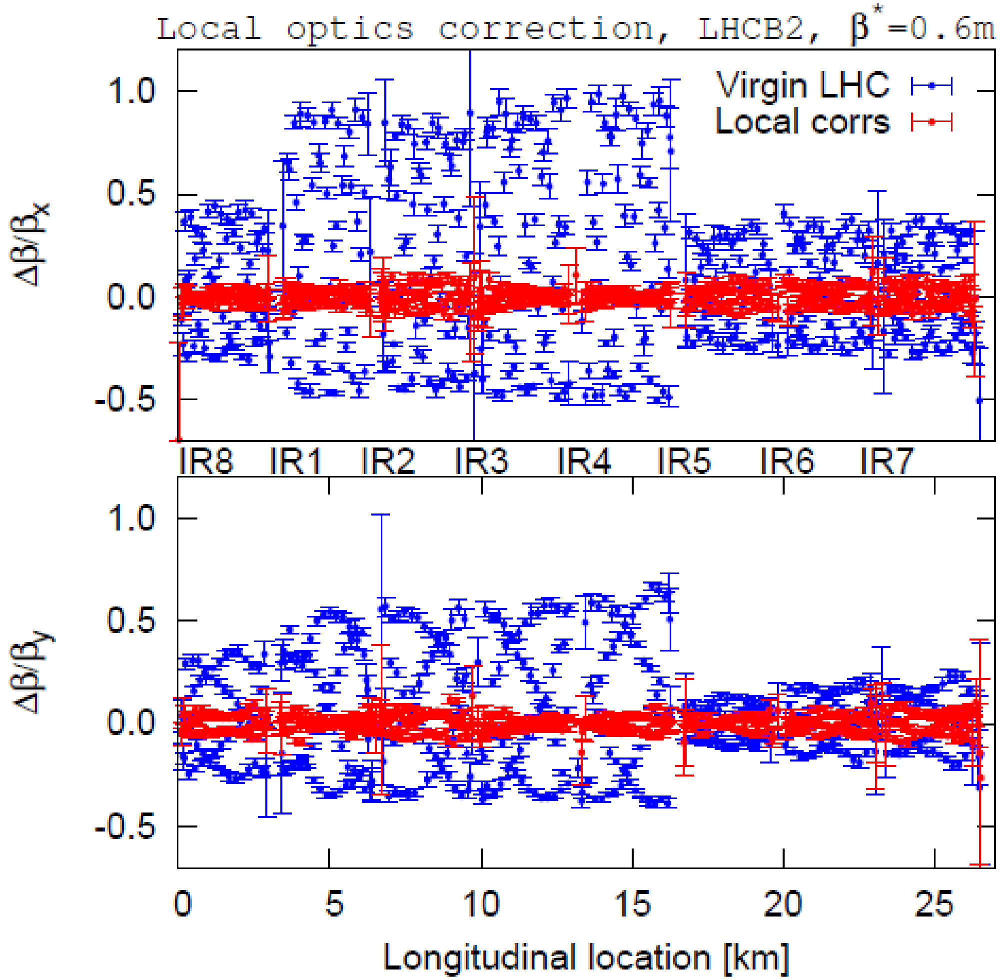
➢ Commissioning

(1month at start of year + extra for special optics)

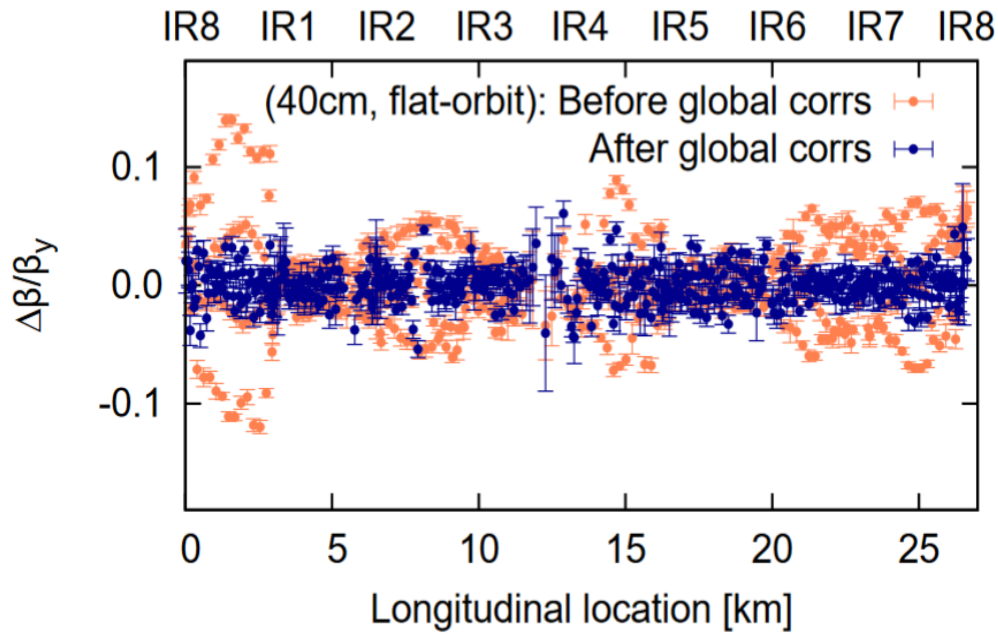


➢ Machine Development `MD'

(4-5 blocks per year, 1week / block)

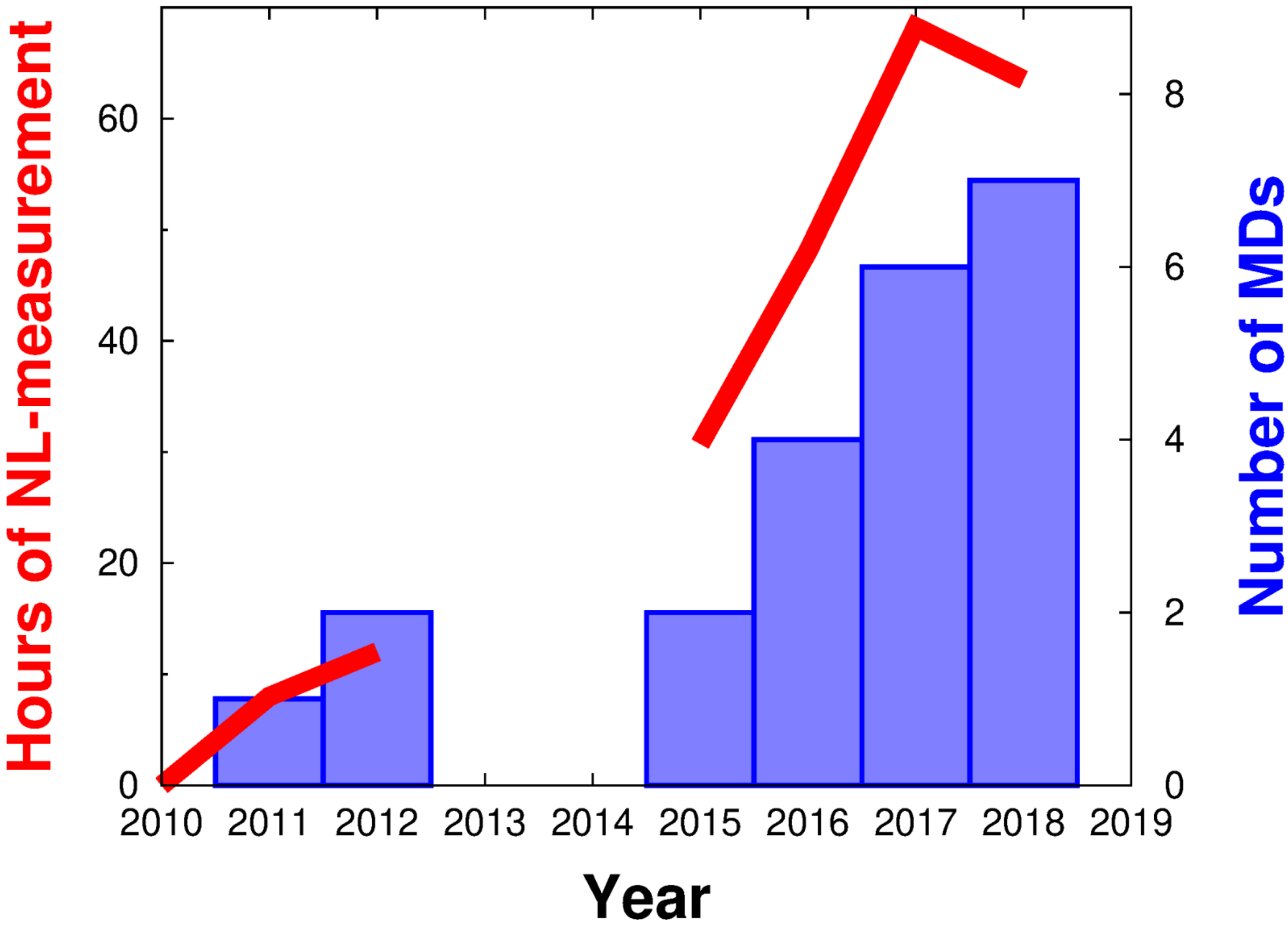


Linear optics is well controlled at LHC



Nonlinear optics is becoming more and more important

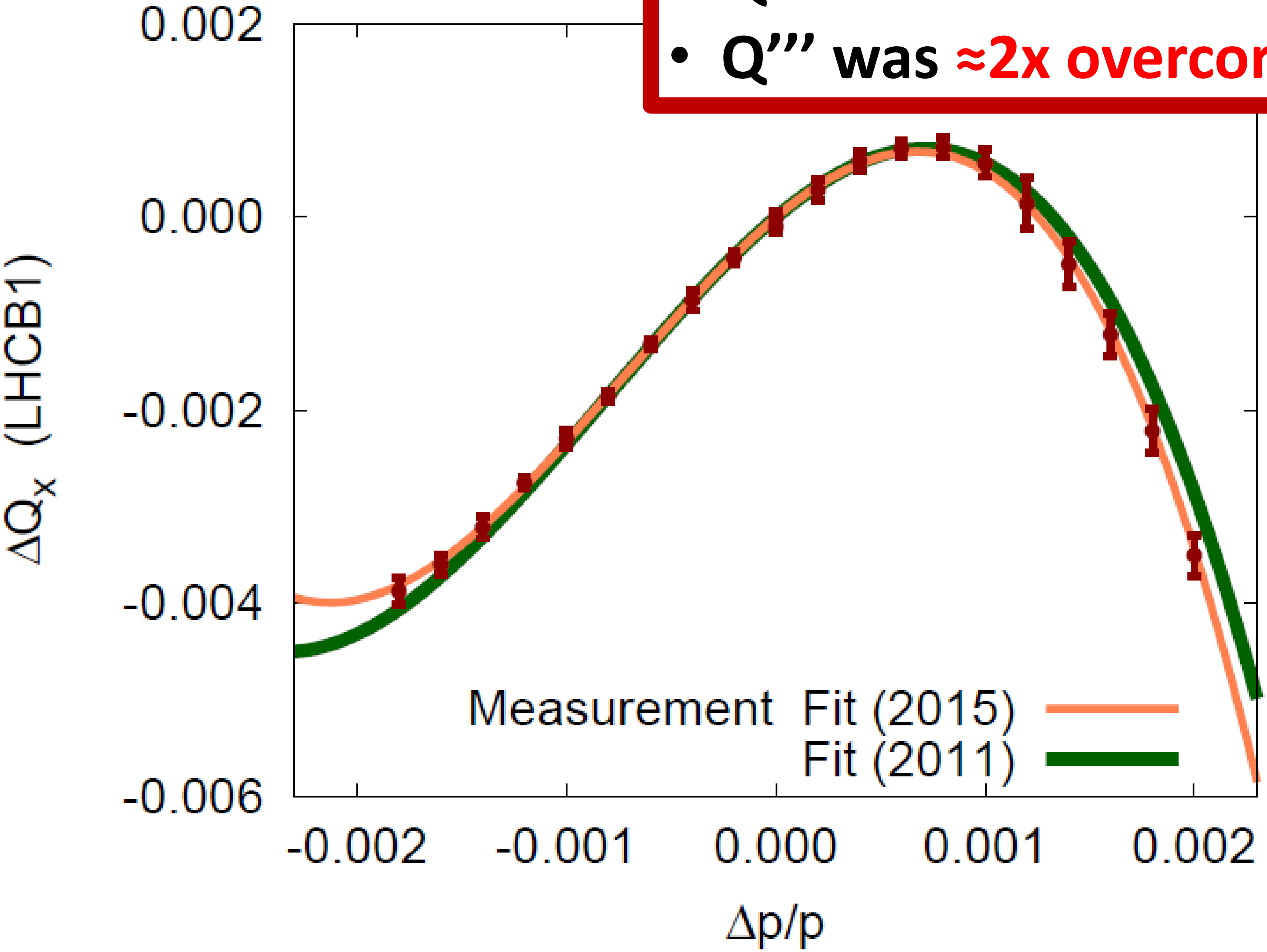
- **Since 2017 spend comparable amount of time in commissioning on nonlinear as linear**
- **Significantly more time spent on nonlinear optics MDs**

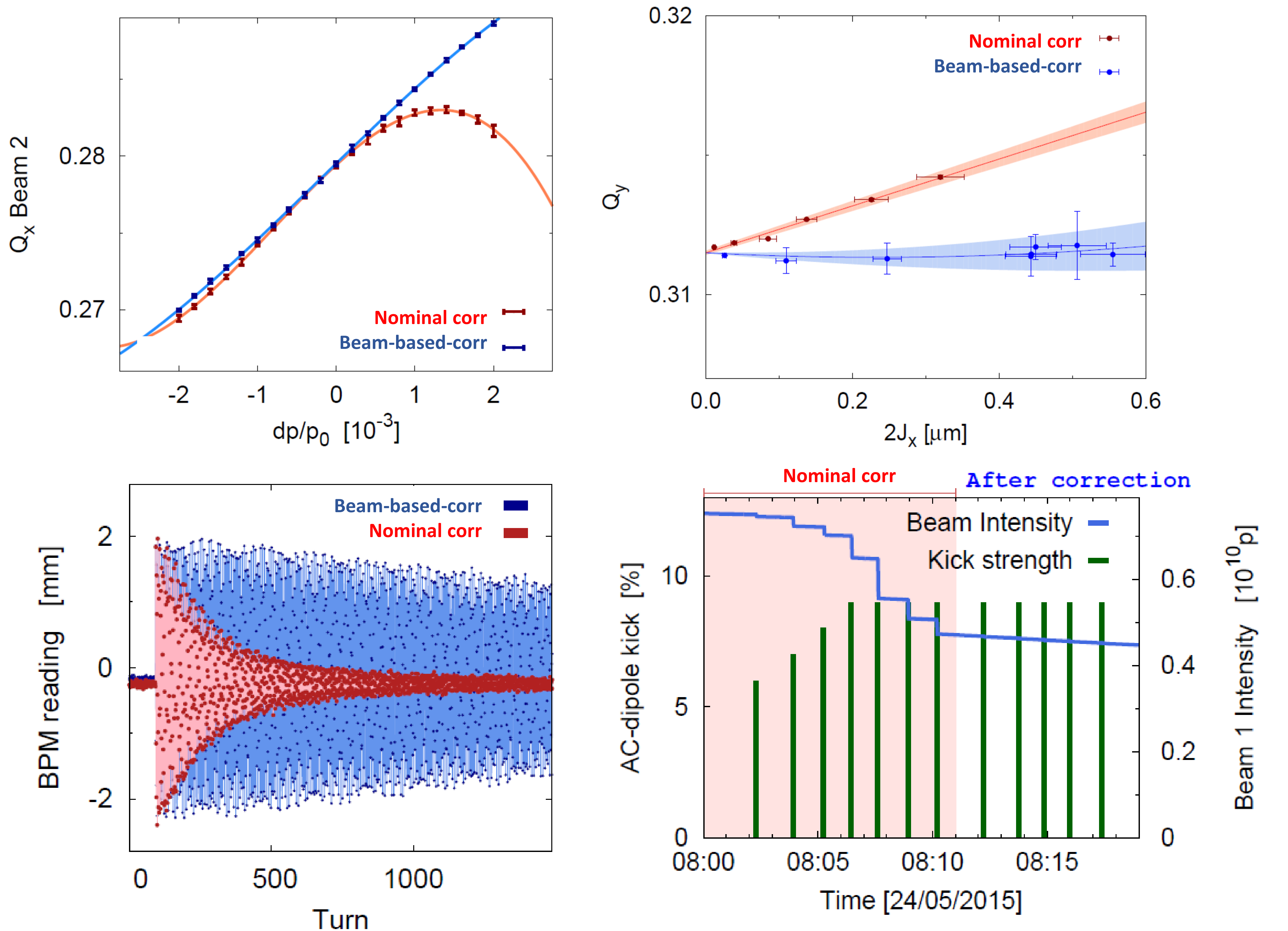


What have we been getting up to in the control room?

First task (circa. 2011-12) was characterization of residual nonlinearities at injection (nominal corrections applied)

- Q'' was 10x worse than expected
- Q''' was ≈2x overcorrected





Q_x Beam 2
0.28
0.27
Nominal corr
Beam-based-corr
-2
-1
0
1
2
dp/p0 [10^-3]
0.32
Q_y
0.31
Nominal corr
Beam-based-corr
0.0
0.2
0.4
0.6
2J_x [μm]
BPM reading [mm]
Beam-based-corr
Nominal corr
2
0
-2
0
500
1000
Turn
Nominal corr
After correction
Beam Intensity
Kick strength
AC-dipole kick [%]
10
5
0
0.6
0.4
0.2
0
Beam 1 Intensity [10^10 p]
08:00
08:05
08:10
08:15
Time [24/05/2015]

Decapole correction observed to generate very large ΔQ''

- Consistent with systematic 0.25mm offset of all decapole spools

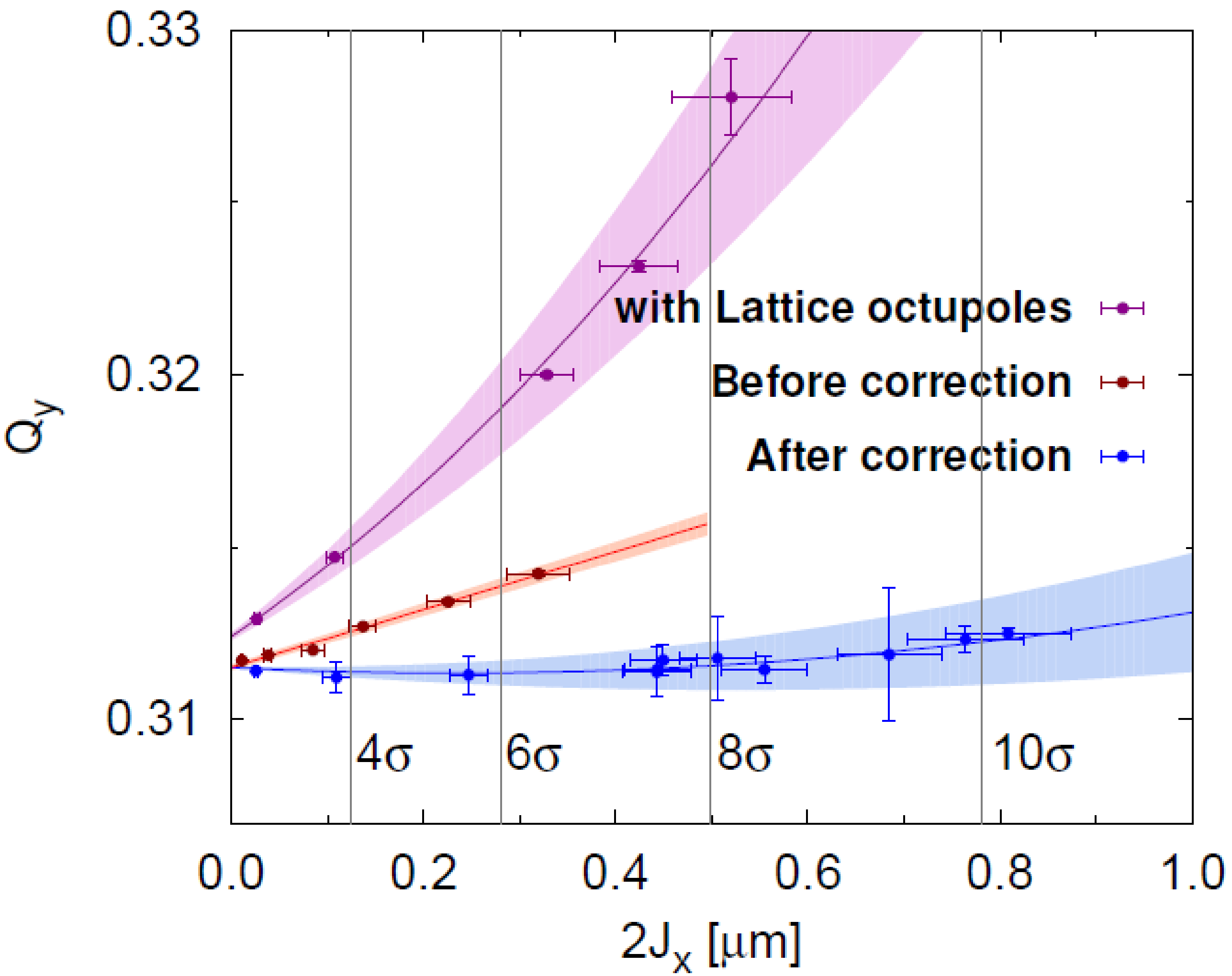
Nominal `correction' had substantially increased the octupole errors

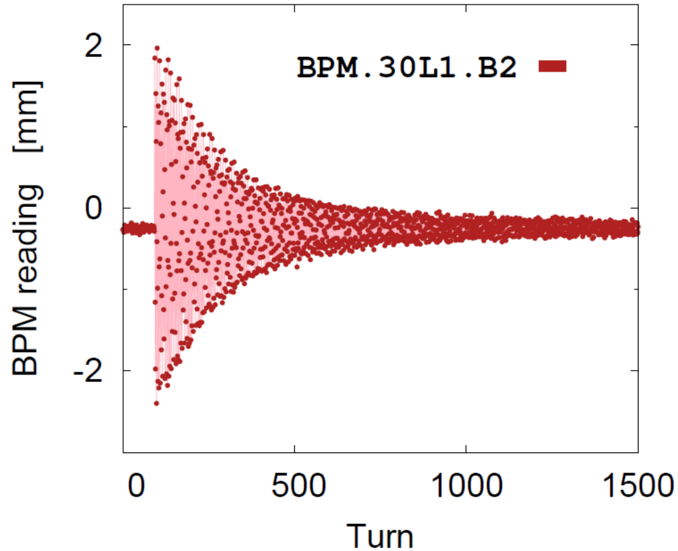
Beam-based nonlinear chromaticity correction incorporated into operation since 2015

In Lumi-Production have strong octupoles for Landau damping

- **Once knowledge from NL-chroma studies included model detuning agrees to ≈10%**

Measurement of nonlinear observables in the Large Hadron Collider using kicked beams, PRAB 17, 081002





One BIG caveat:

transverse coupling

In Lumi-Production have strong octupoles for Landau damping

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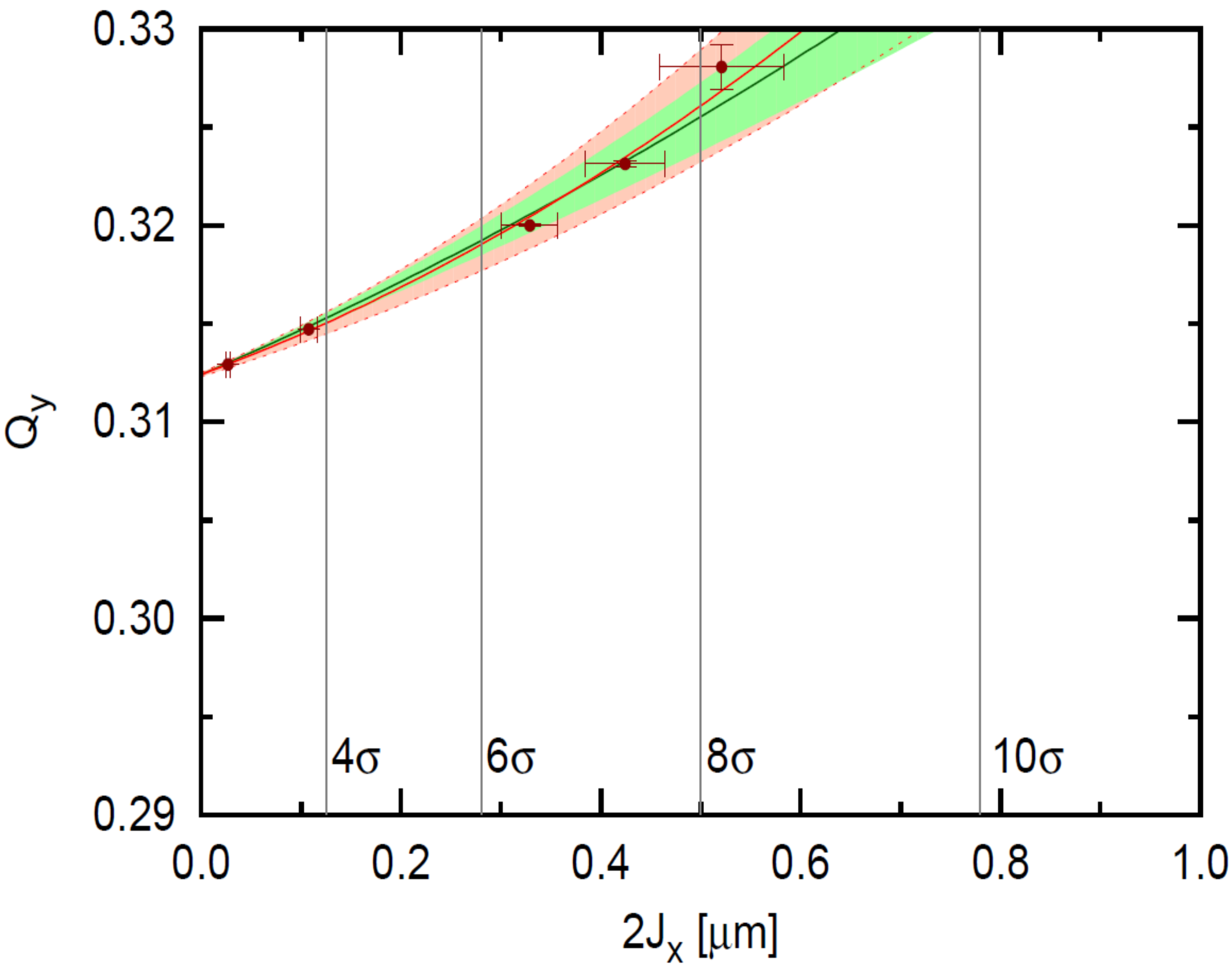
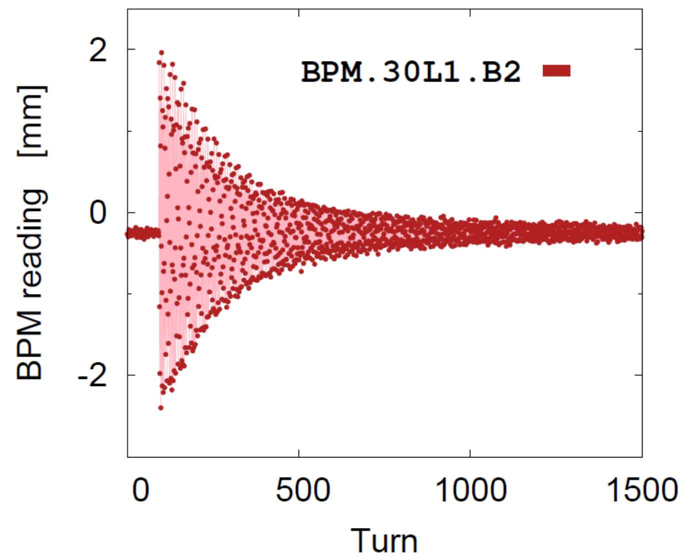
Measurement of nonlinear observables in the Large Hadron Collider using kicked beams, PRAB 17, 081002

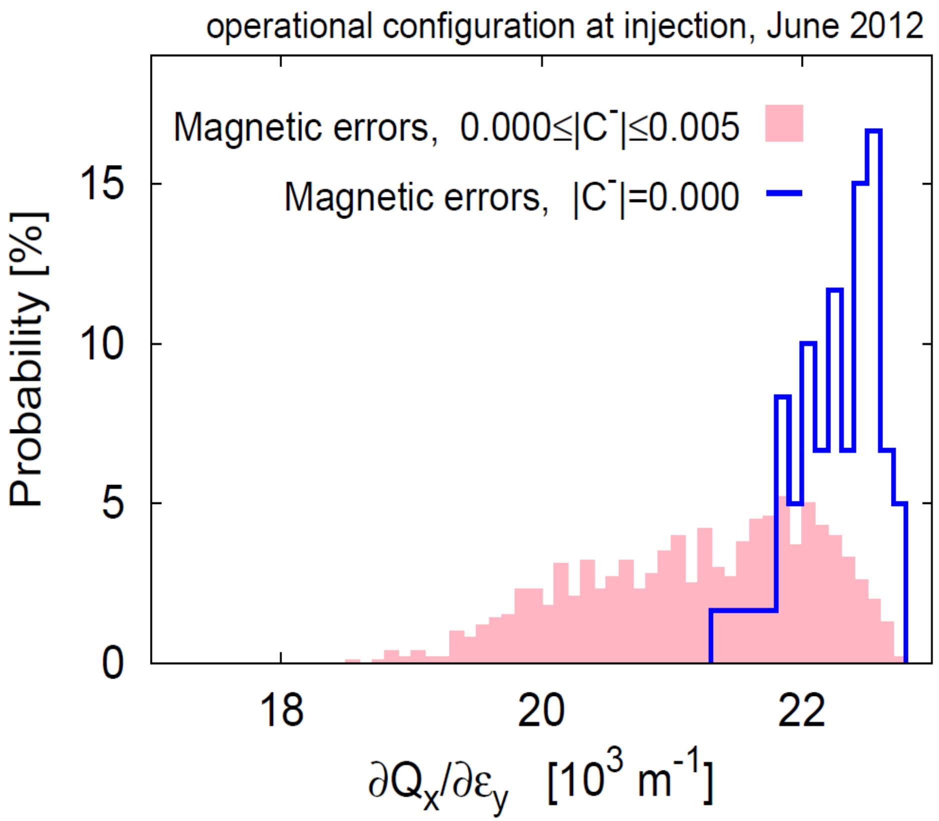


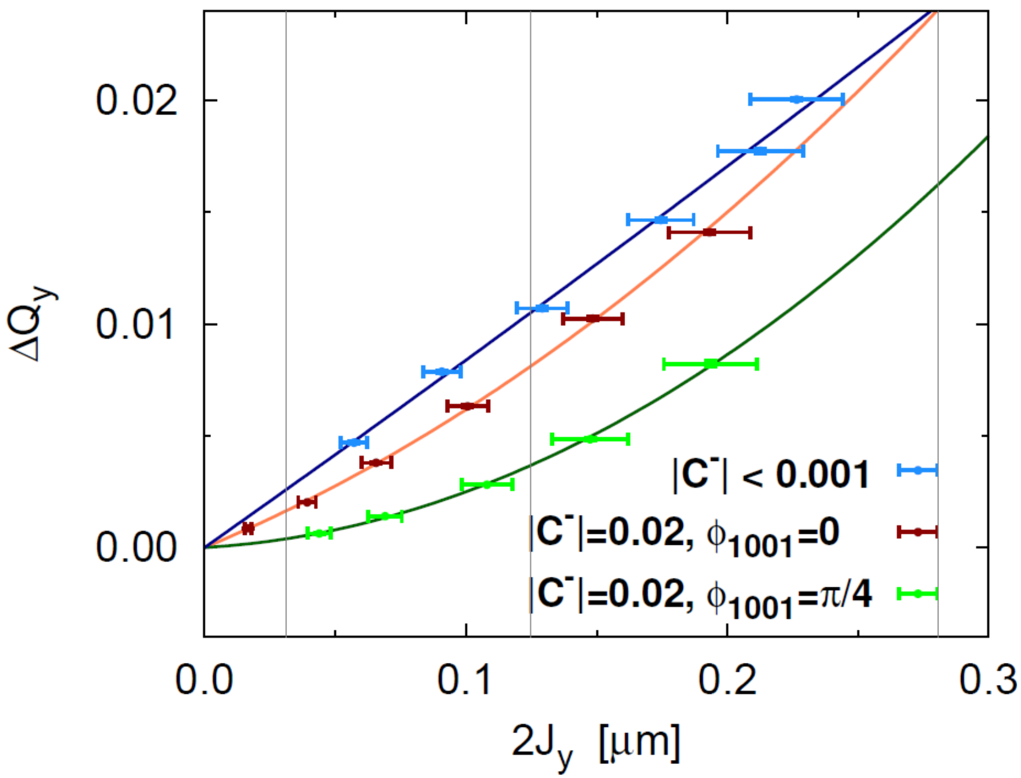


One BIG caveat:

transverse coupling

Linear coupling causes large changes to amplitude detuning in simulation & measurement





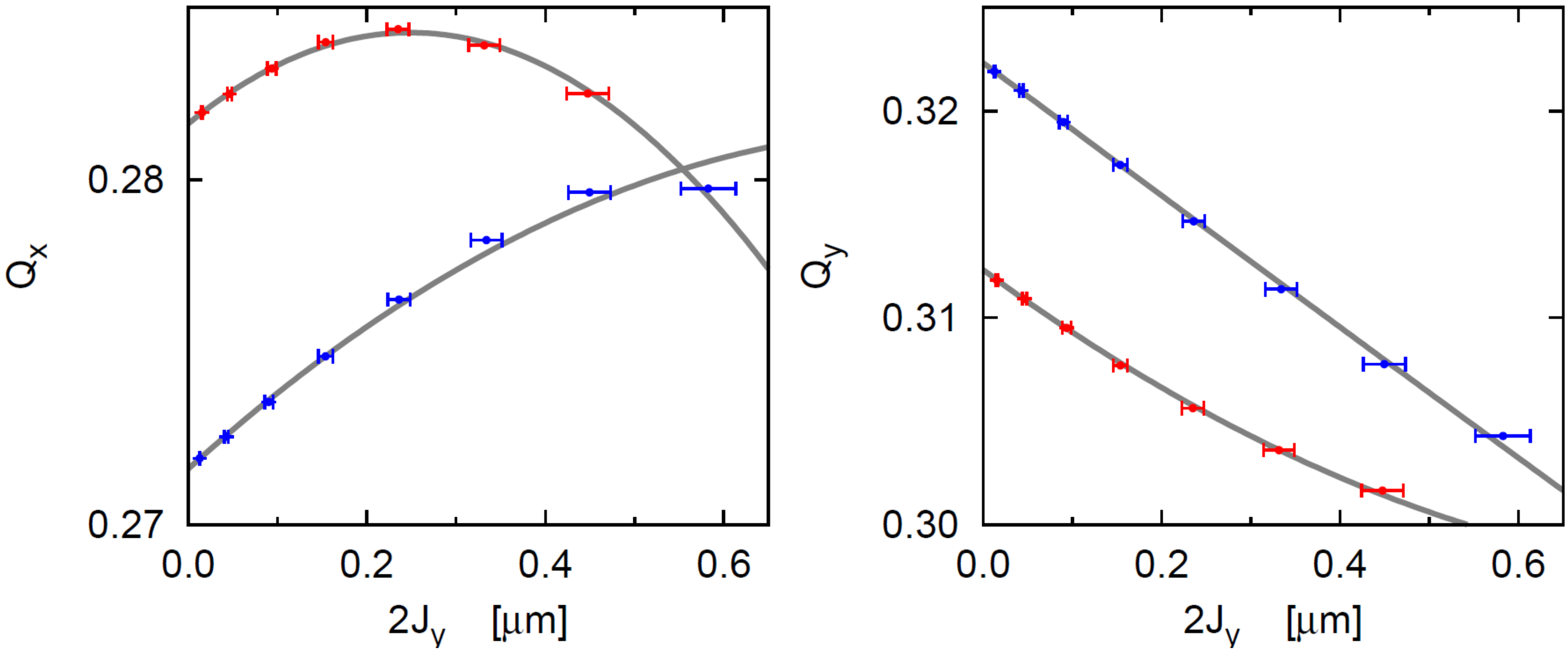
Linear coupling is the single largest source of uncertainty and variability in the nonlinear optics of the LHC:

- **By extension also critical for Landau damping in LHC**

Observe highly nonlinear pattern of detuning when approaching the $(Q_x - Q_y)$ resonance (measurement & simulation)

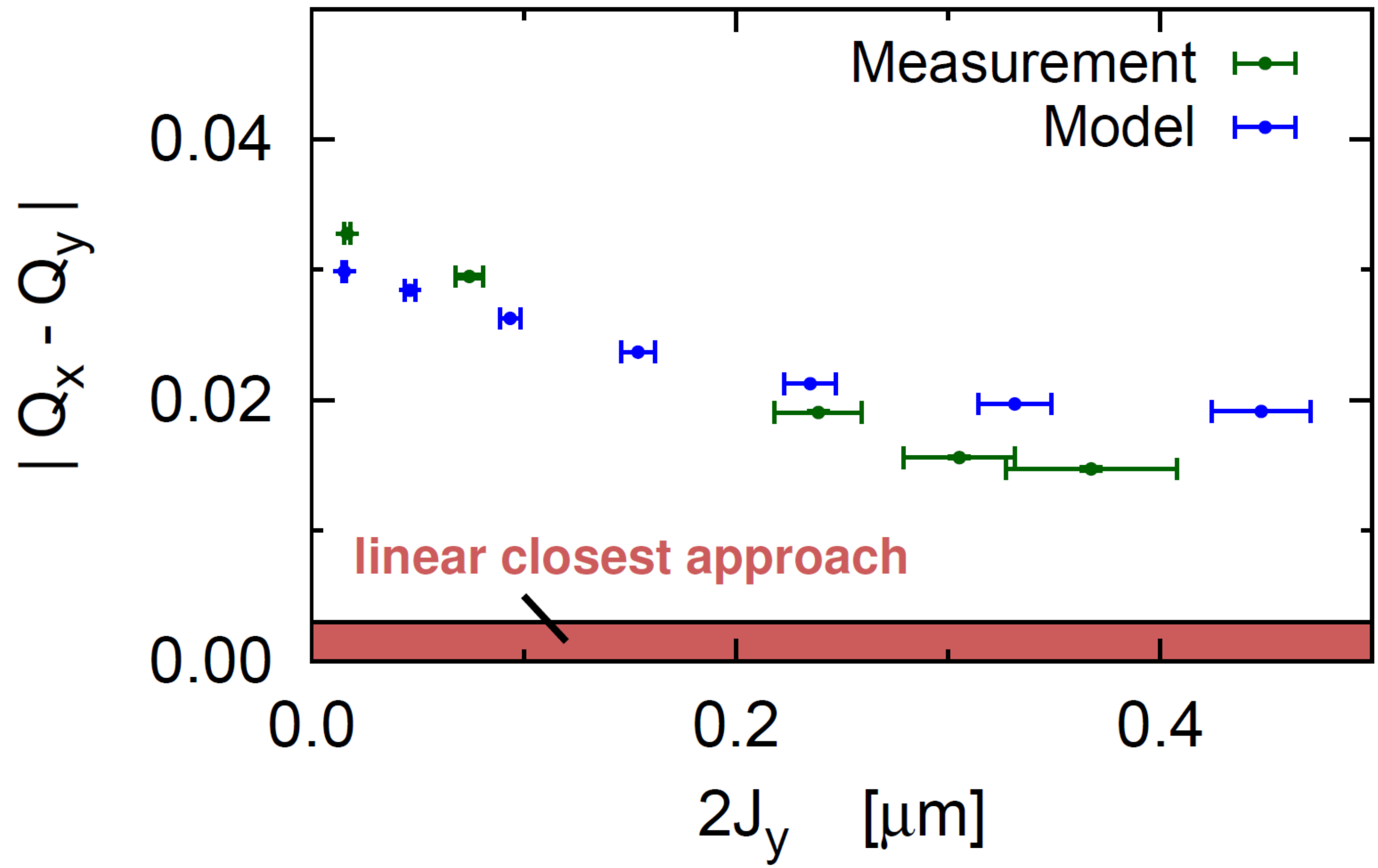
- **Extremely sensitive to unperturbed working point**

Simulated detuning approaching the $(Q_x - Q_y)$ resonance



Usually we consider change of $Q_{x,y}$ with $J_{x,y}$:

- **Instead consider change of tune separation vs action**
- **Observe saturation of the tune separation far in excess of linear ΔQ_{min}**



Tried to interpret via an Amplitude Dependent Closest Tune Approach

Measurement of nonlinear observables in the Large Hadron Collider using kicked beams, PRAB 17, 081002

2 sources identified in simulation & tested with beam:

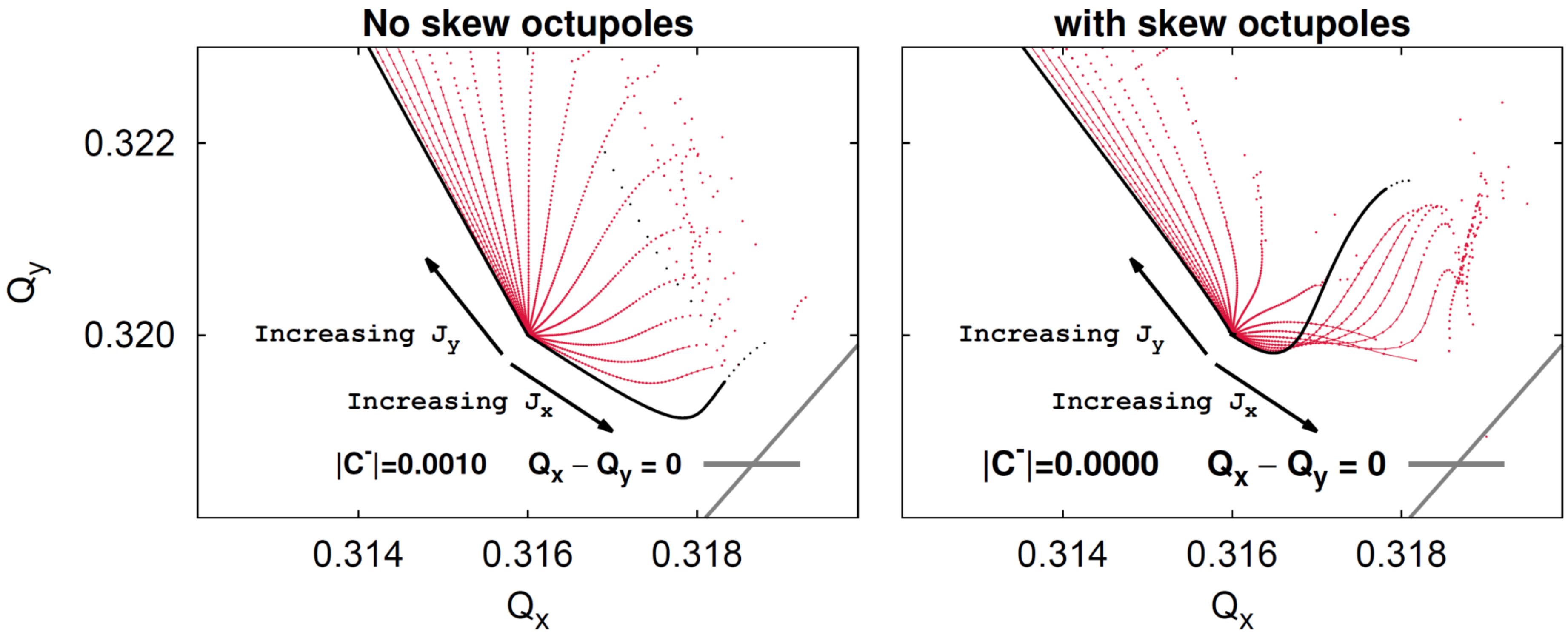
- **Linear coupling + normal octupole**

  Nonlinear coupling studies in the LHC, TUPTY04, IPAC'15

- **Skew octupole + normal octupole**

  Amplitude dependent closest tune approach generated by normal and skew octupoles IPAC'17 WEPIK091

  CERN-ACC-NOTE-2018-0027

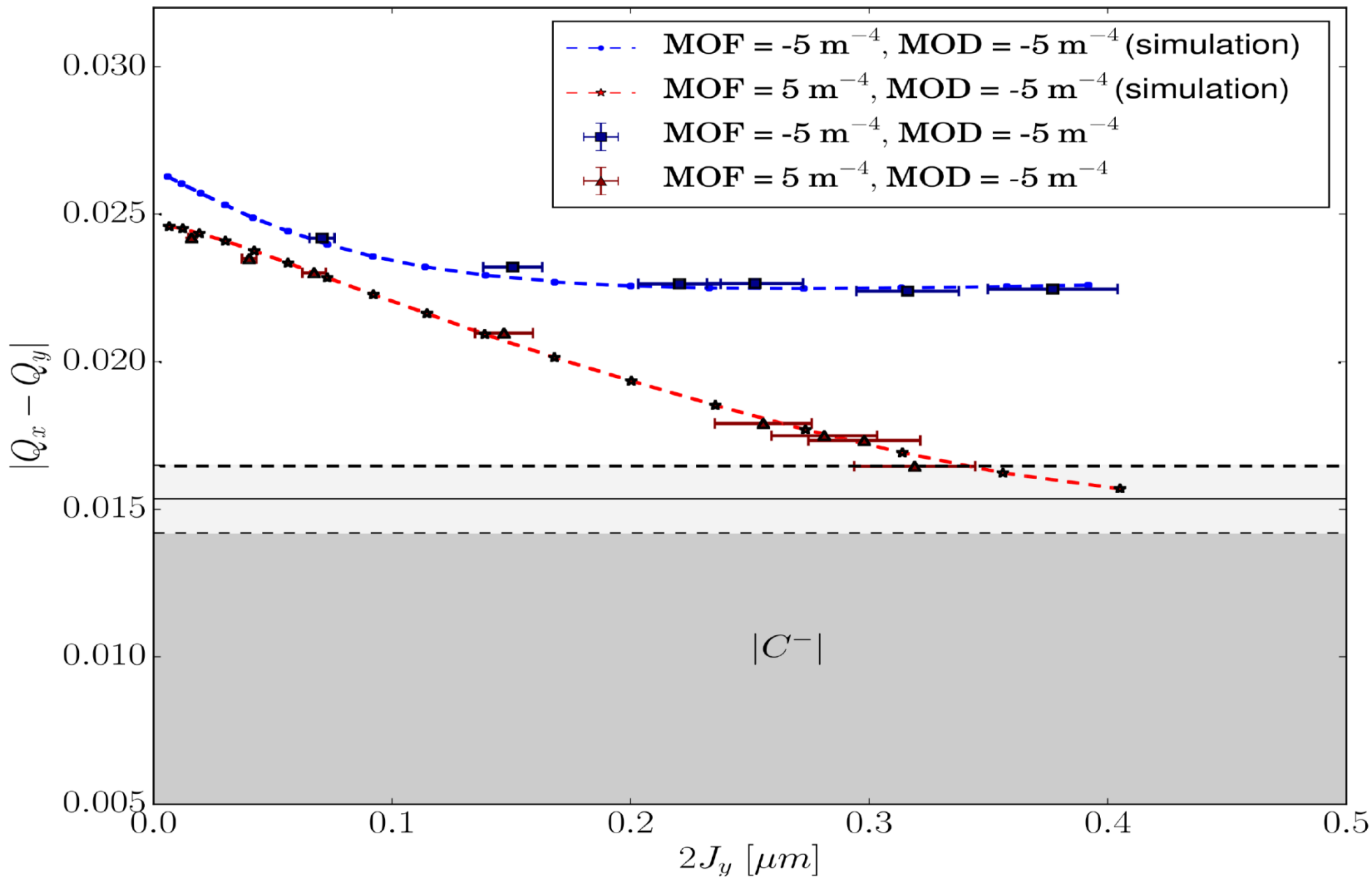


Footprint distortion from uncompensated skew-octupoles a potential issue for Landau damping in HL-LHC

Some first attempts at theoretical predictions & validation:

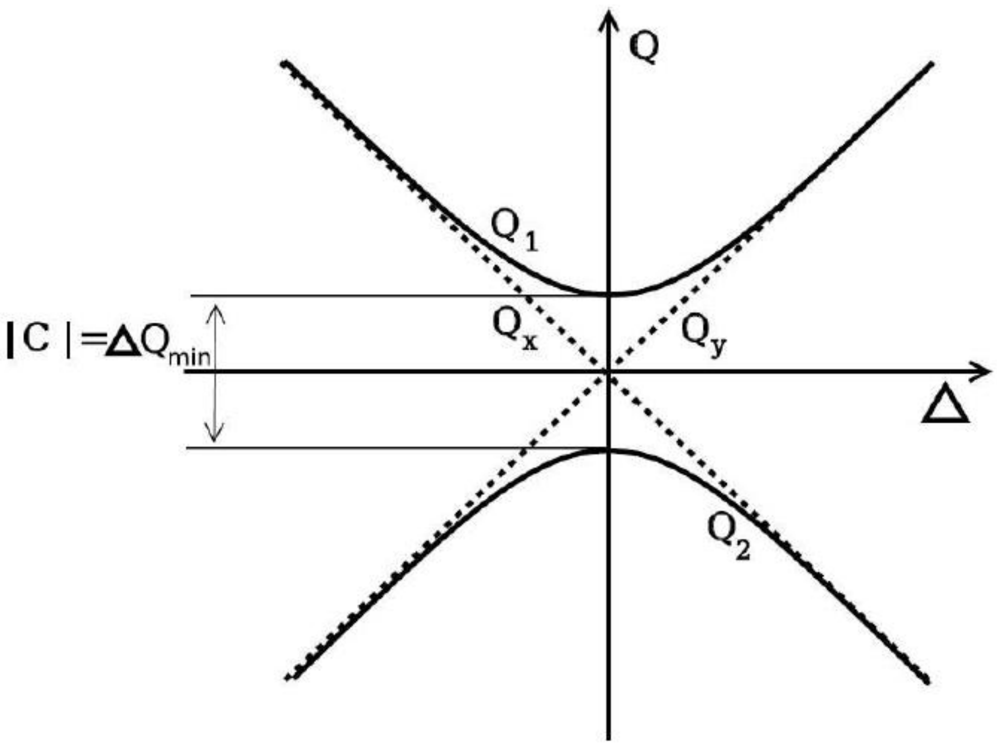
R.Tomas, T.Persson, E.Maclean, Amplitude dependent closest tune approach, PRAB 19, 071003

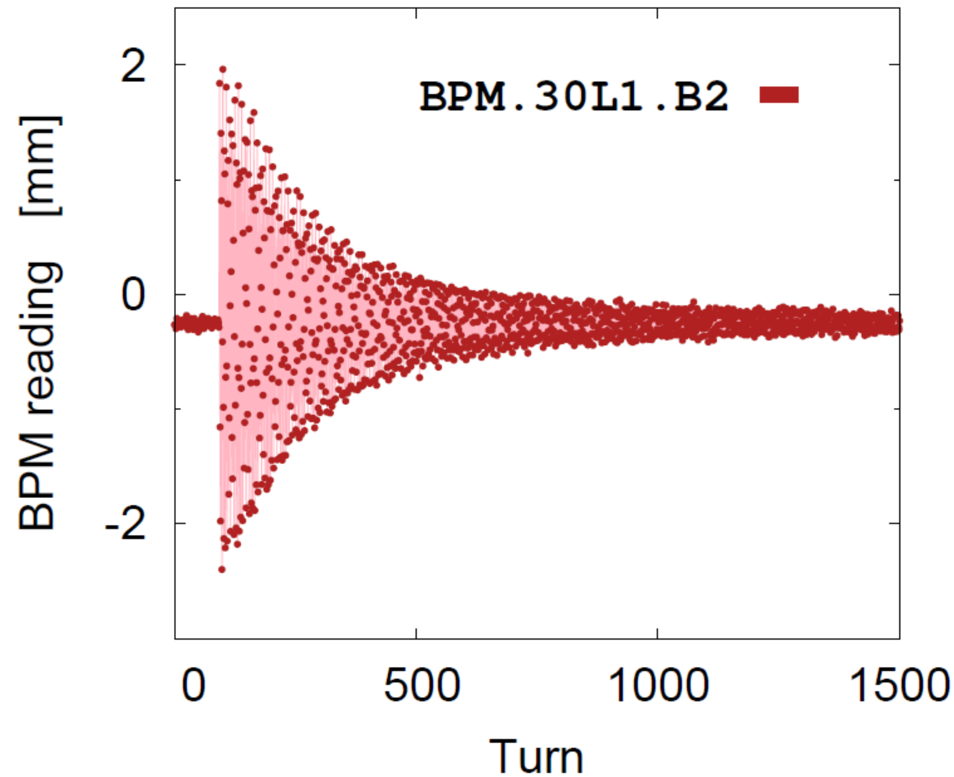
$$\Delta Q_{min} \approx 2\sqrt{\kappa^2 + h_{1111}\kappa\sqrt{J_x J_y} - \frac{h_{1111}^2}{32}(J_y - J_x)^2}$$



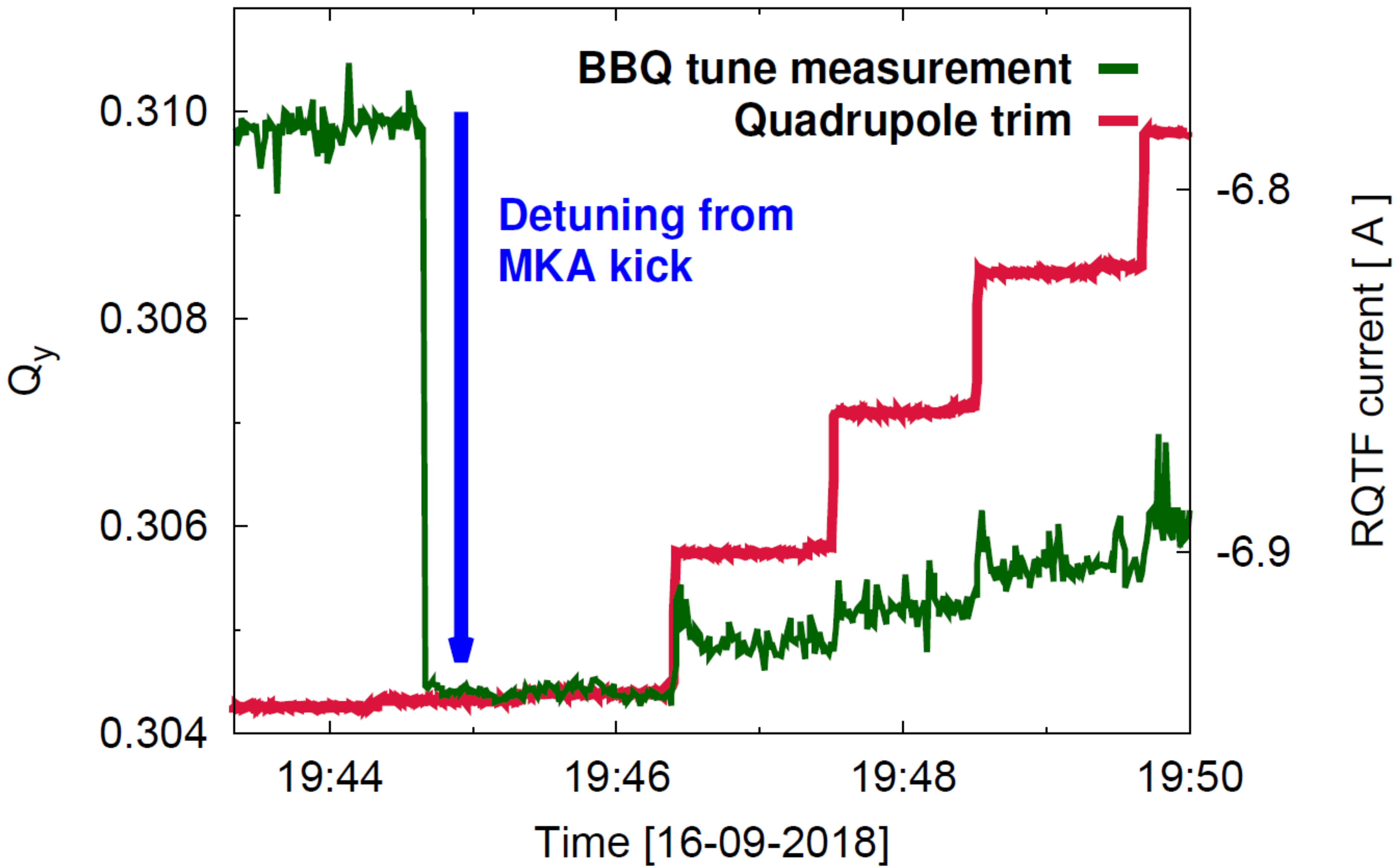
Suppression of amplitude dependent closest tune approach and its behavior under forced oscillations, PRAB 22, 051001
T.Persson, R.Tomas, E.Maclean

Classical linear coupling measurement measures ΔQ_{min} by using quad trim to try and force tunes to the $Q_x - Q_y$ resonance

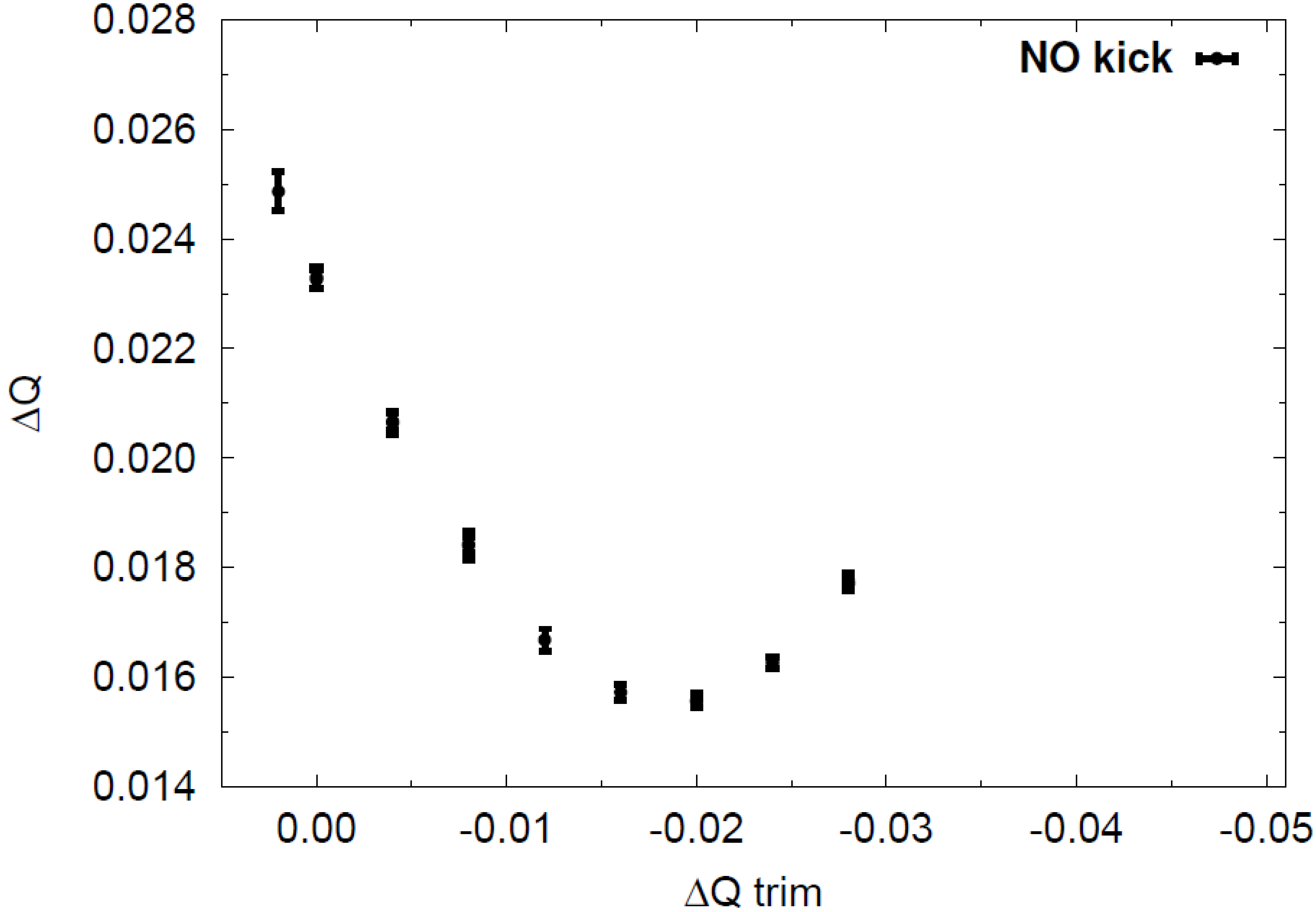




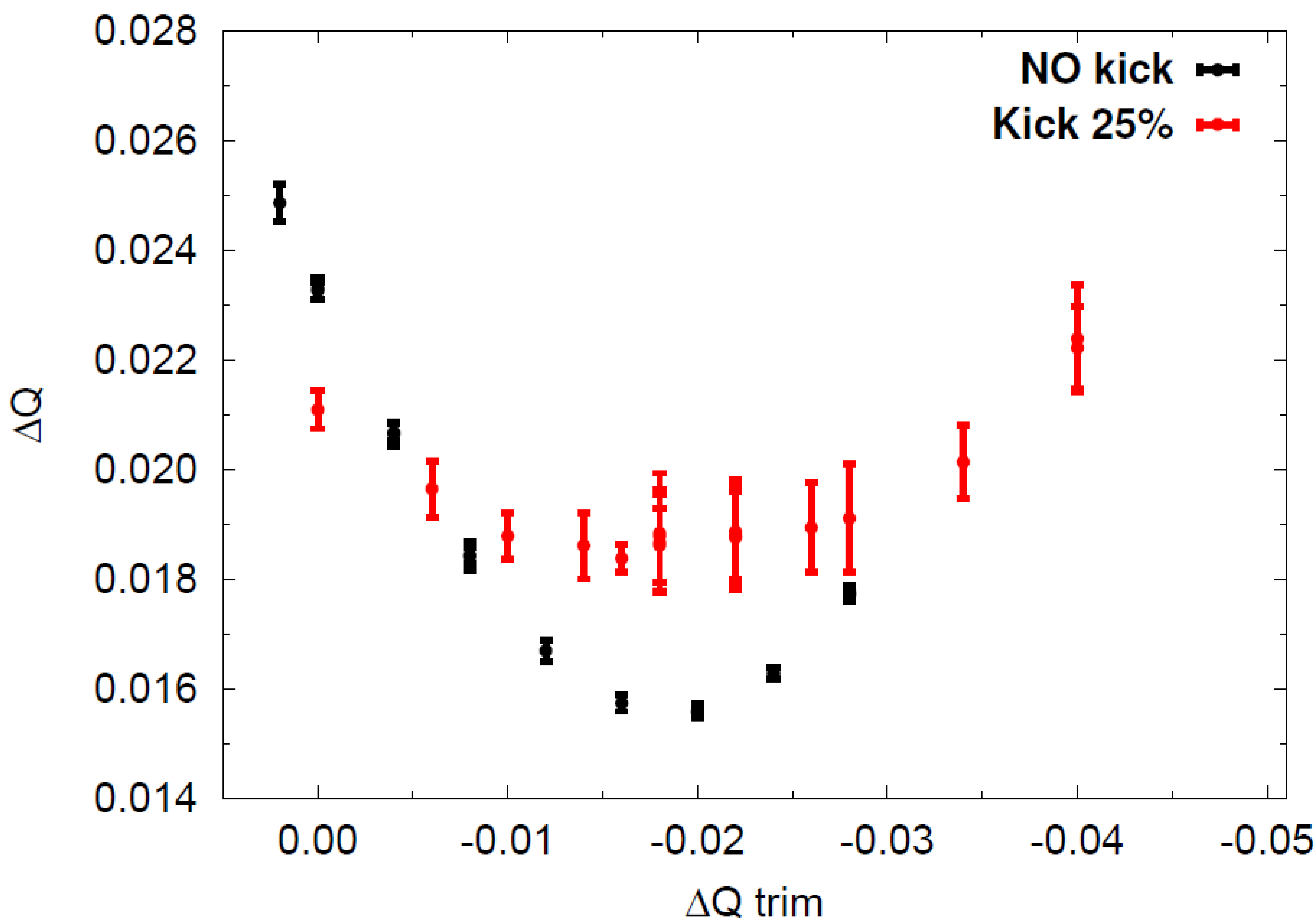
Try classical ΔQ_{min} measurement, but having first kicked beams with MKA (closest approach of a phase space doughnut)



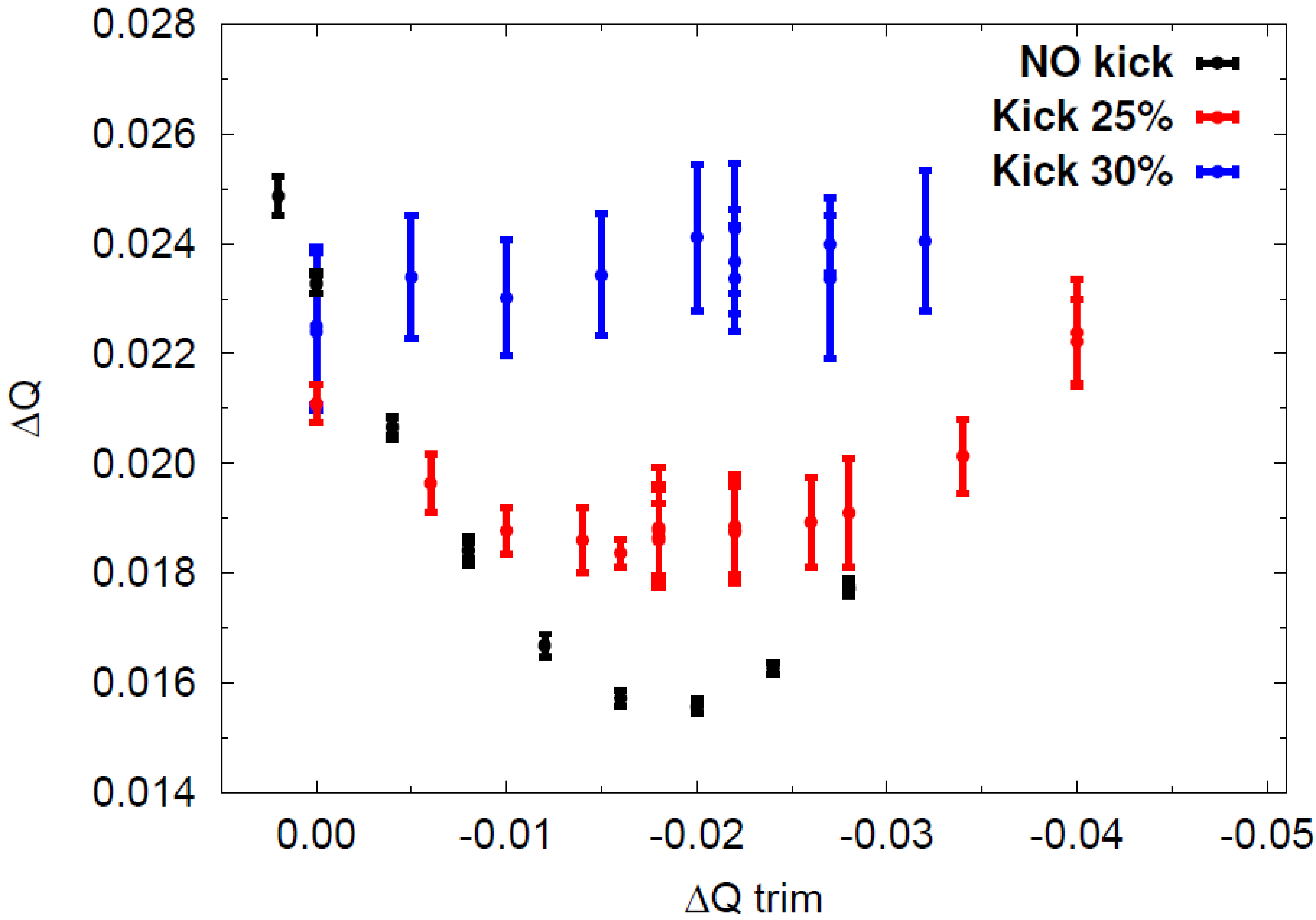
BBQ tune measurement
Quadrupole trim
Detuning from
MKA kick
0.310
0.308
0.306
0.304
Q_y
-6.8
-6.9
RQTF current [A]
19:44
19:46
19:48
19:50
Time [16-09-2018]



NO kick
ΔQ
0.028
0.026
0.024
0.022
0.020
0.018
0.016
0.014
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
ΔQ trim

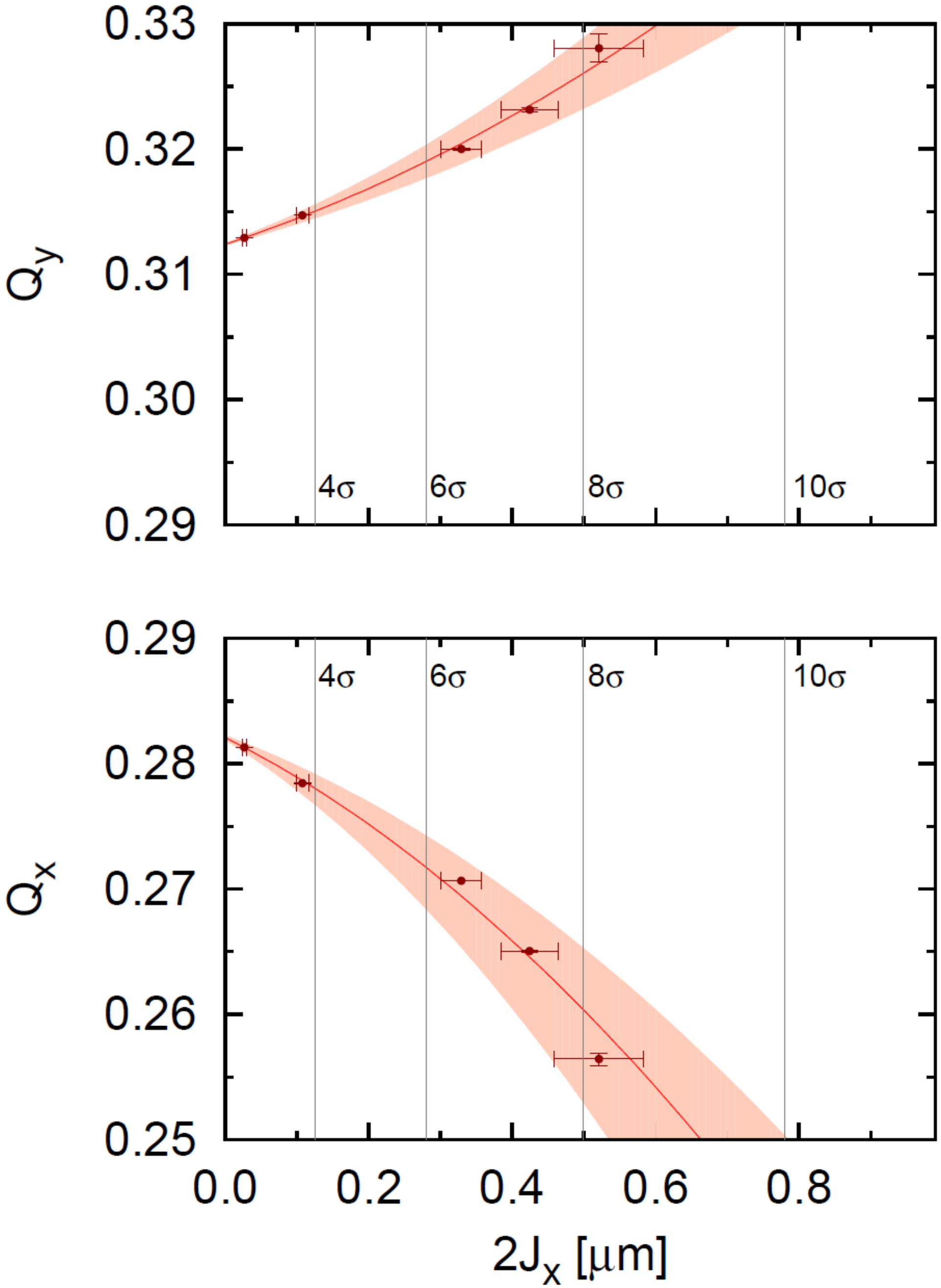


NO kick
Kick 25%
ΔQ
ΔQ trim
0.028
0.026
0.024
0.022
0.020
0.018
0.016
0.014
0.00
-0.01
-0.02
-0.03
-0.04
-0.05

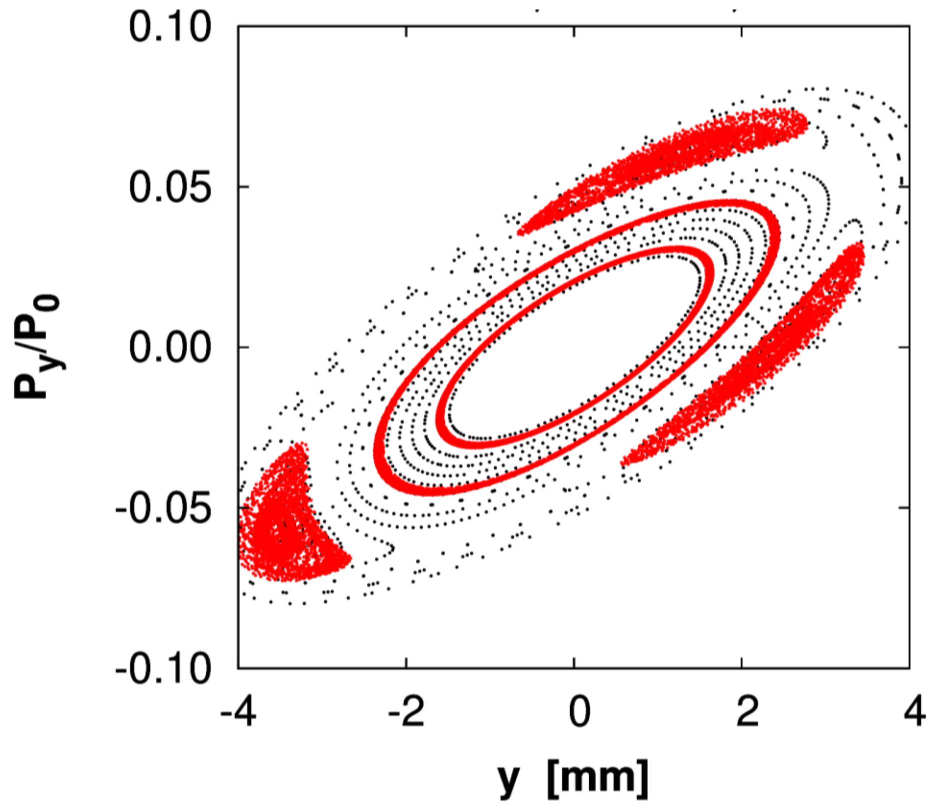


NO kick
Kick 25%
Kick 30%
0.028
0.026
0.024
0.022
0.020
0.018
0.016
0.014
ΔQ
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
ΔQ trim

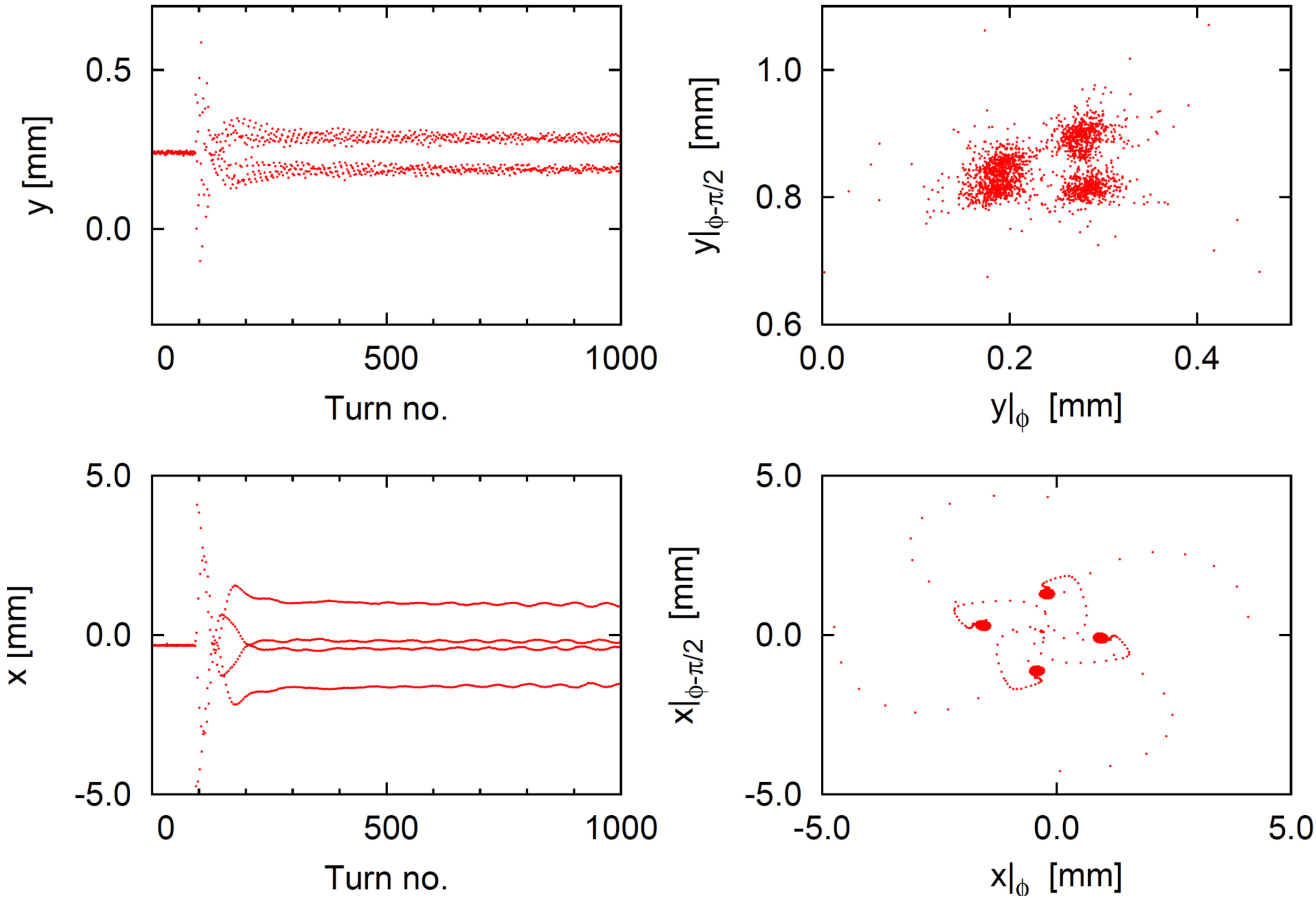
In Lumi-Production have strong octupoles for Landau damping



Can also detune towards $4Q_x$ & $3Q_y$

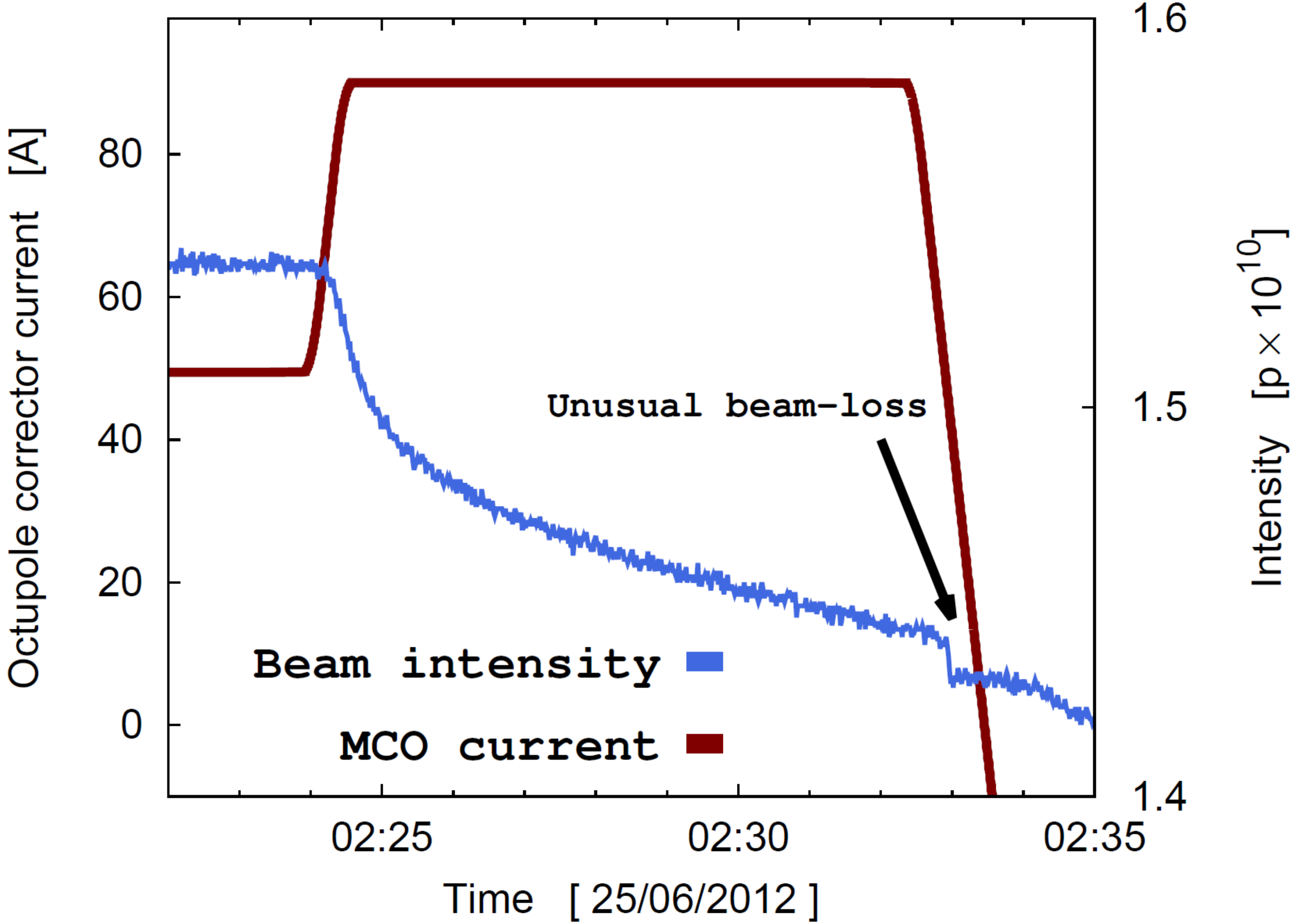


Measured turn-by-turn BPM data from a single kick

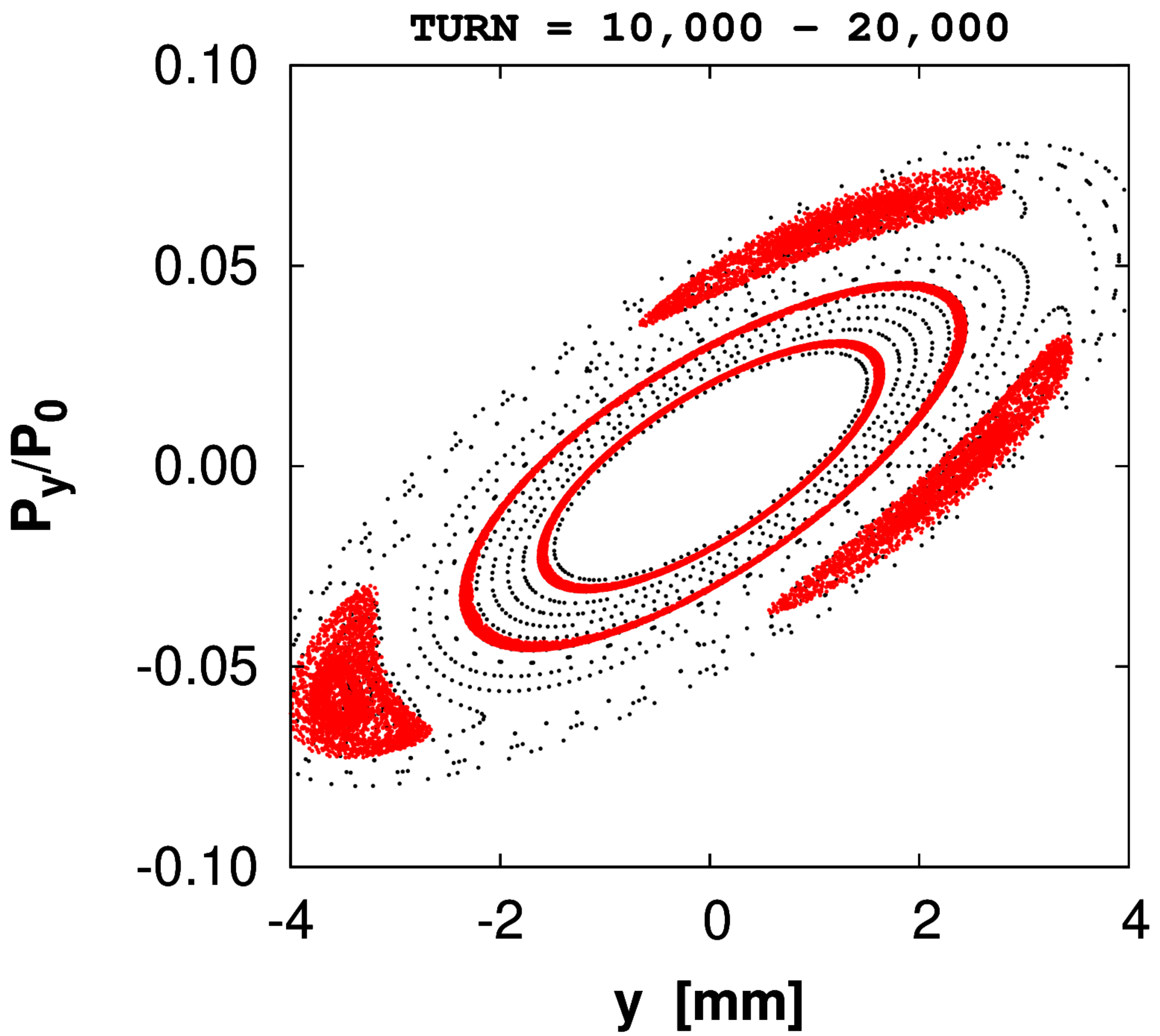


Some interesting consequences from low-order resonances

→ e.g. abrupt beam-losses during octupole trim



Particles trapped in islands are transported out to larger amplitudes during slow decrease of octupole strength, e.g. simulated octupole rampdown over 100,000 turns:



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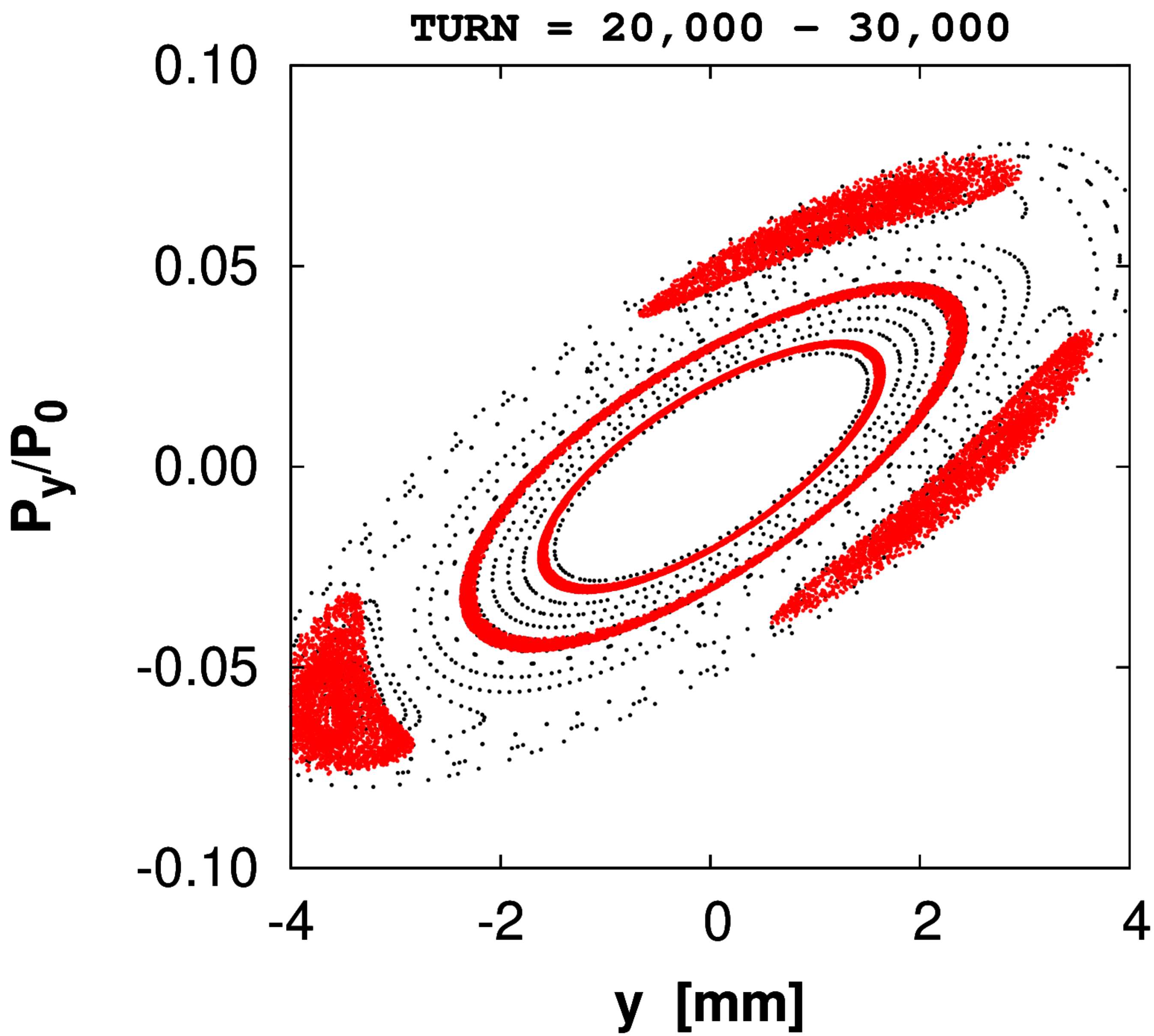

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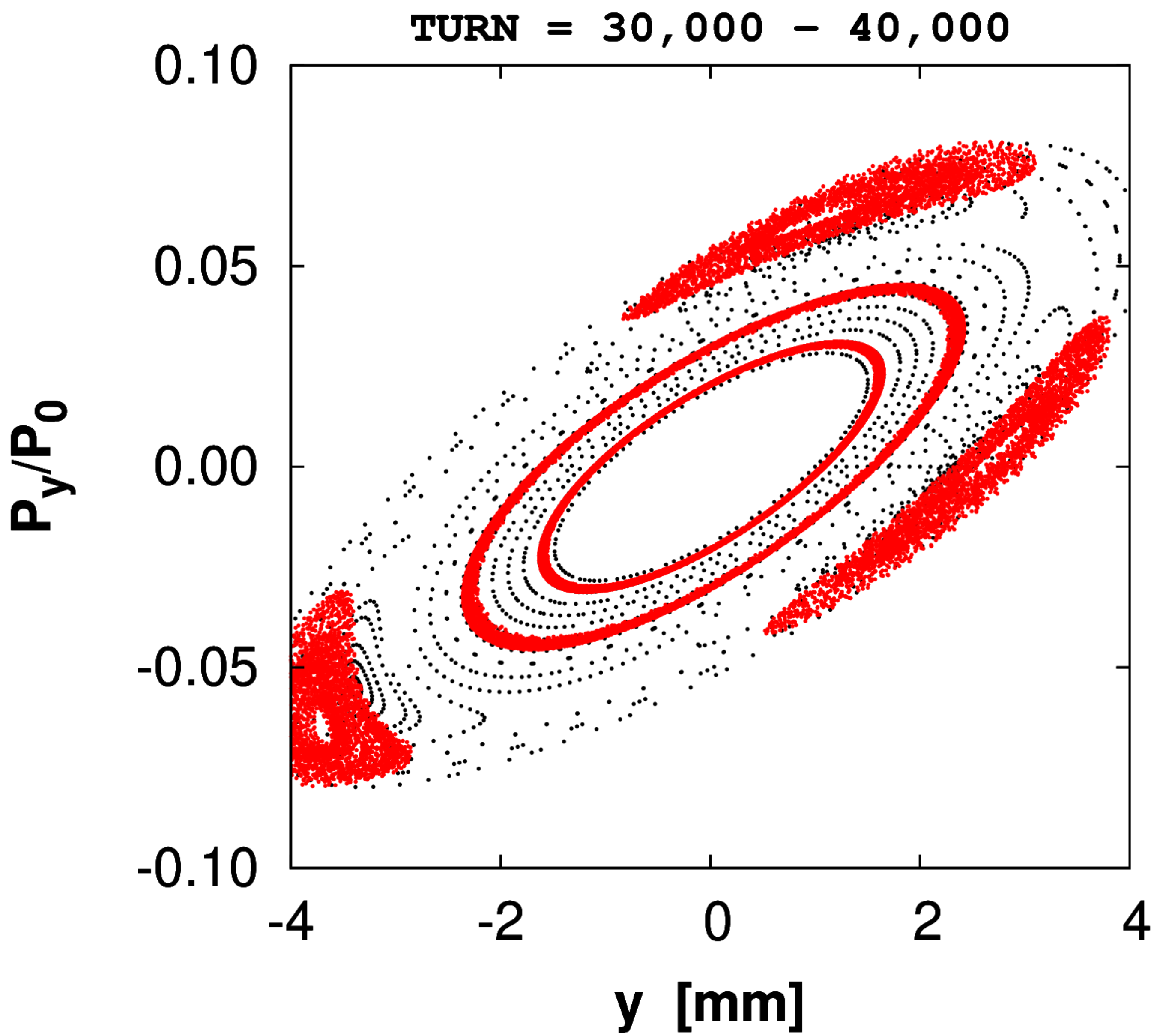

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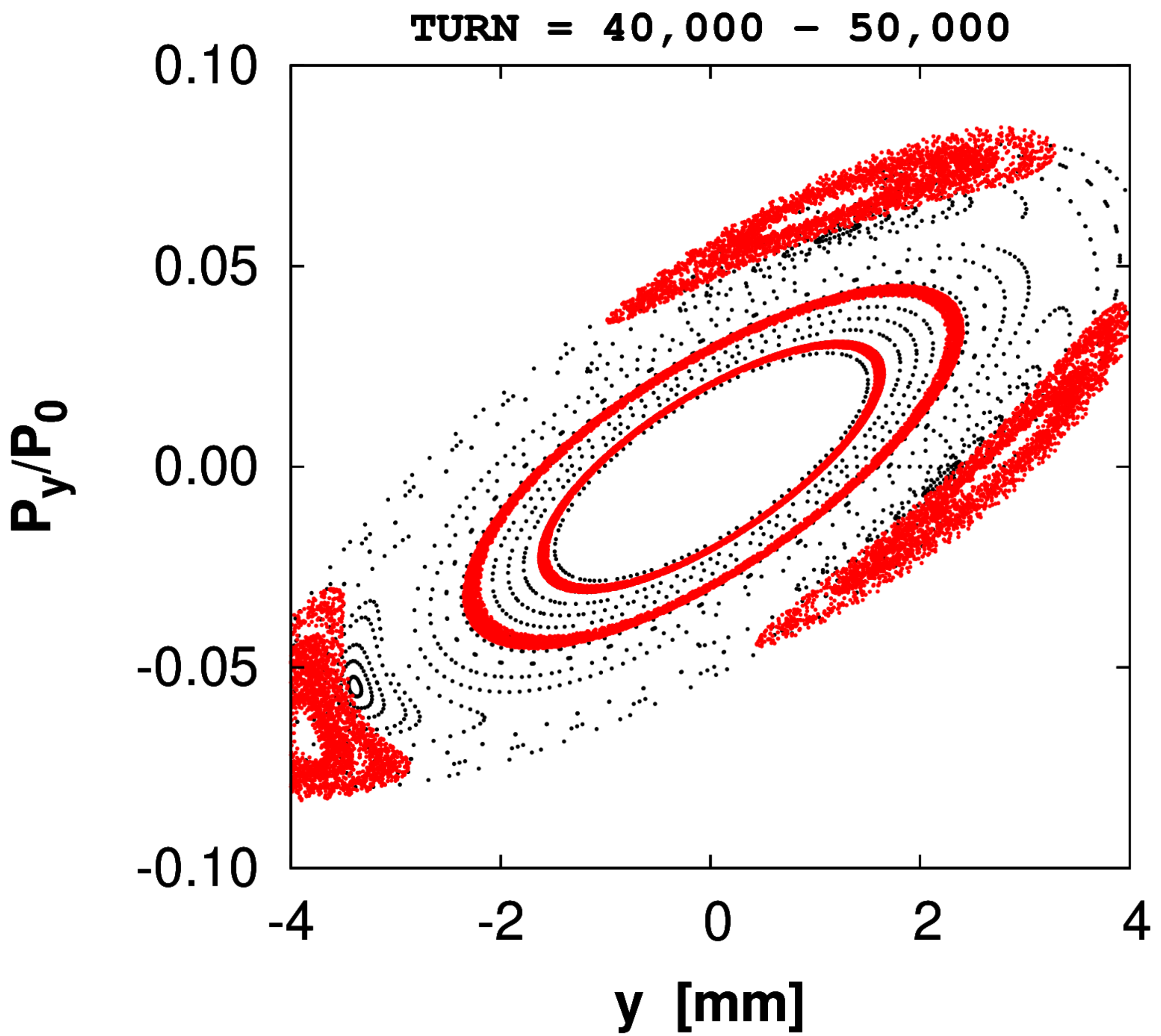

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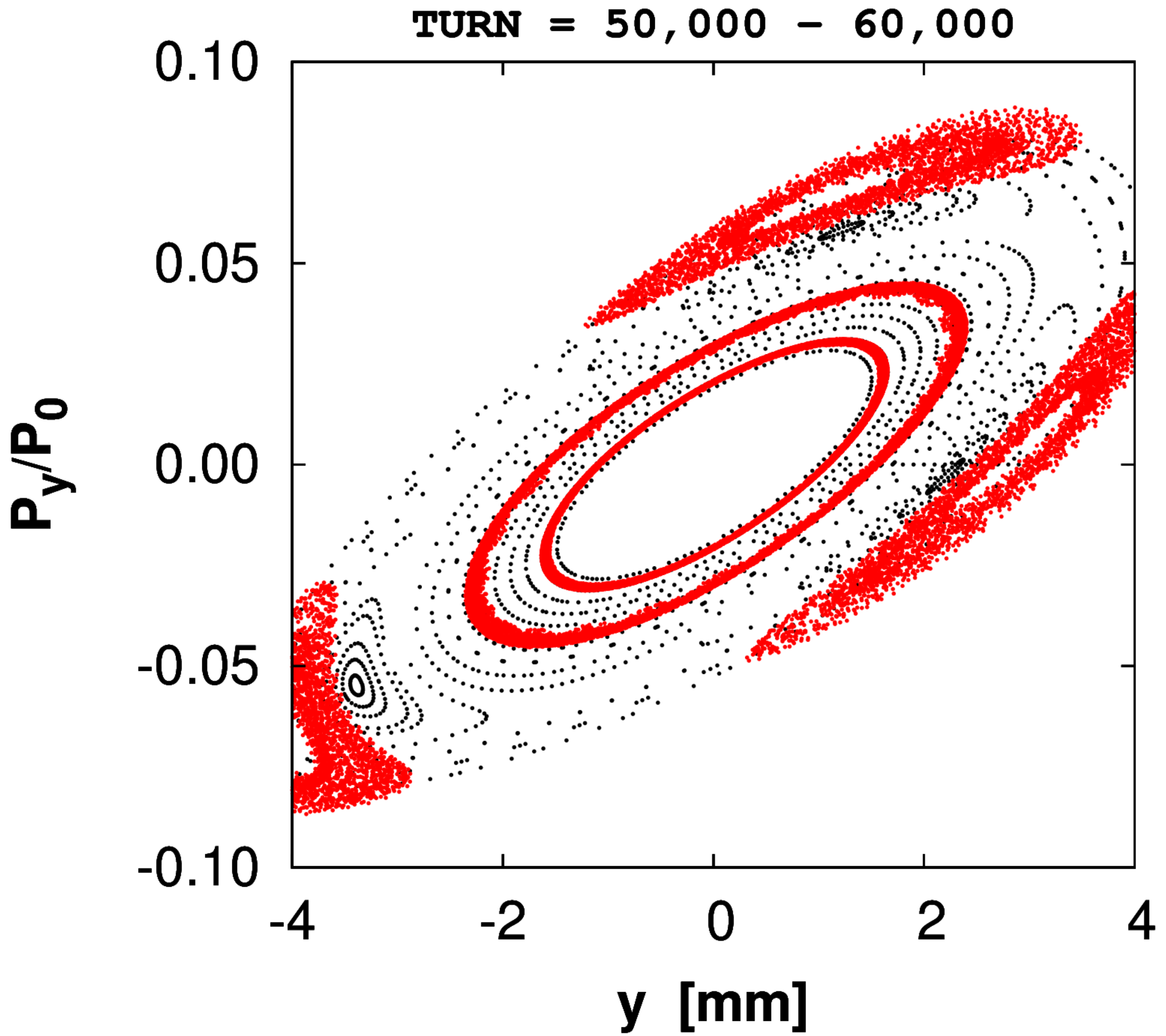

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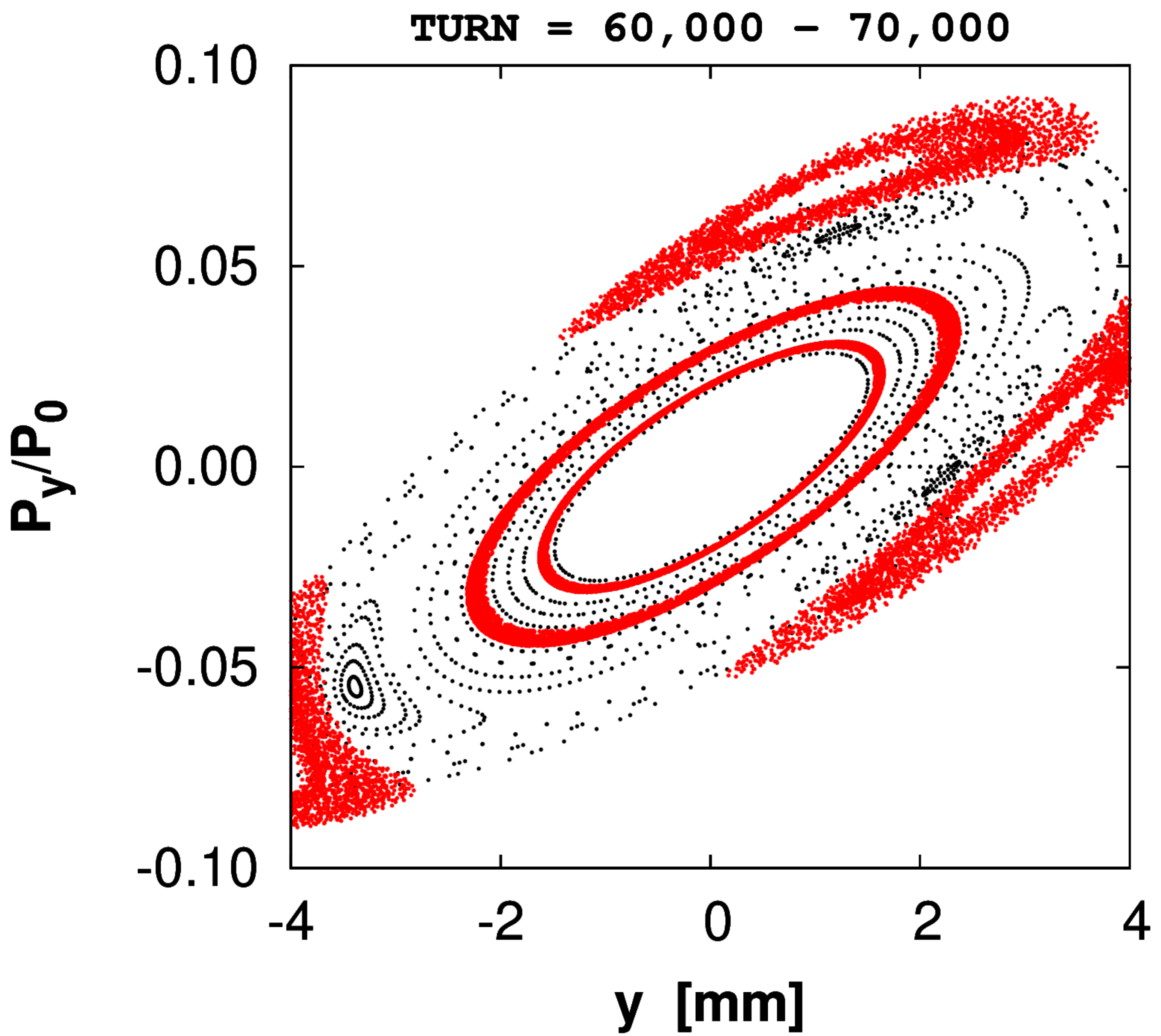

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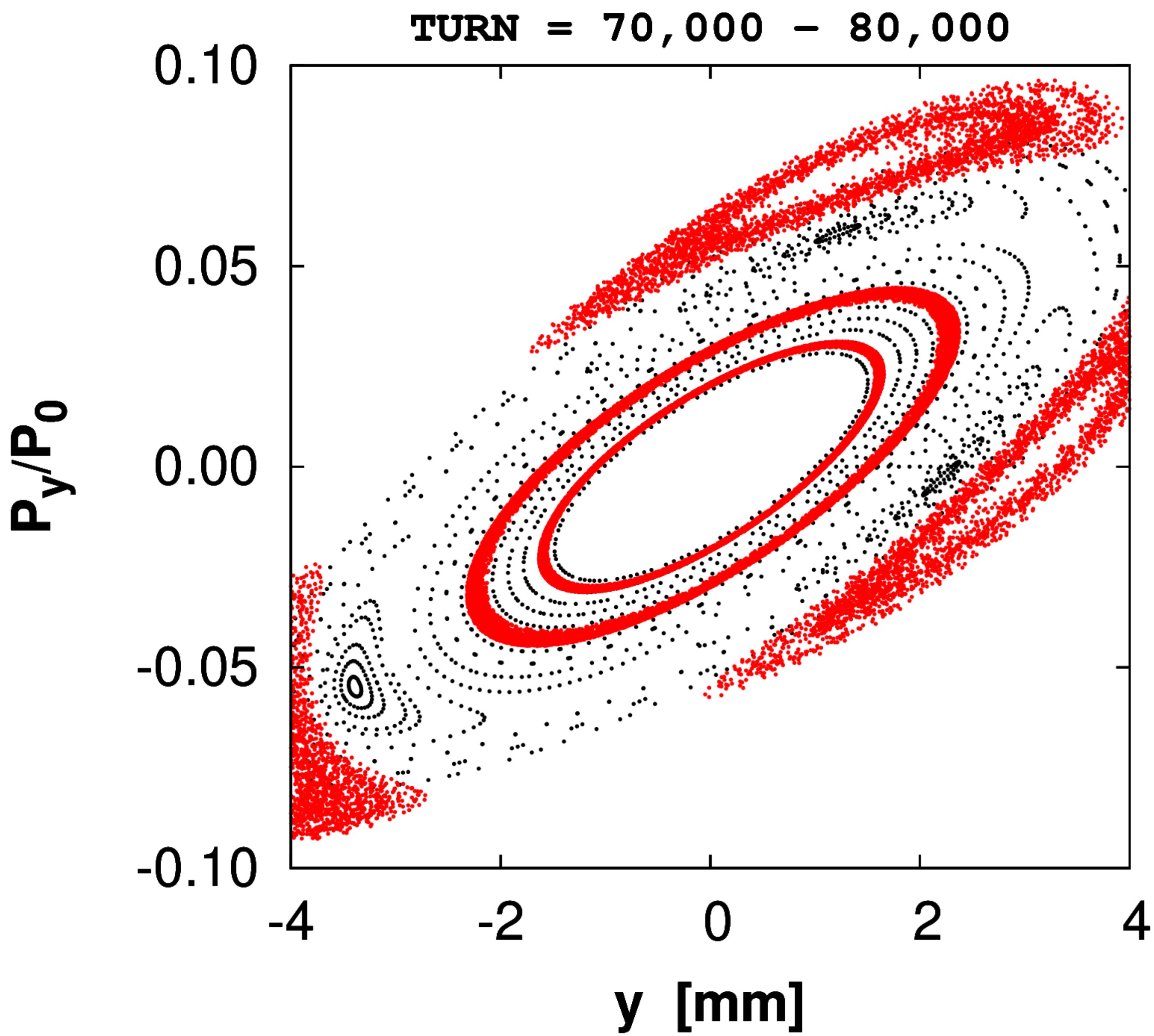
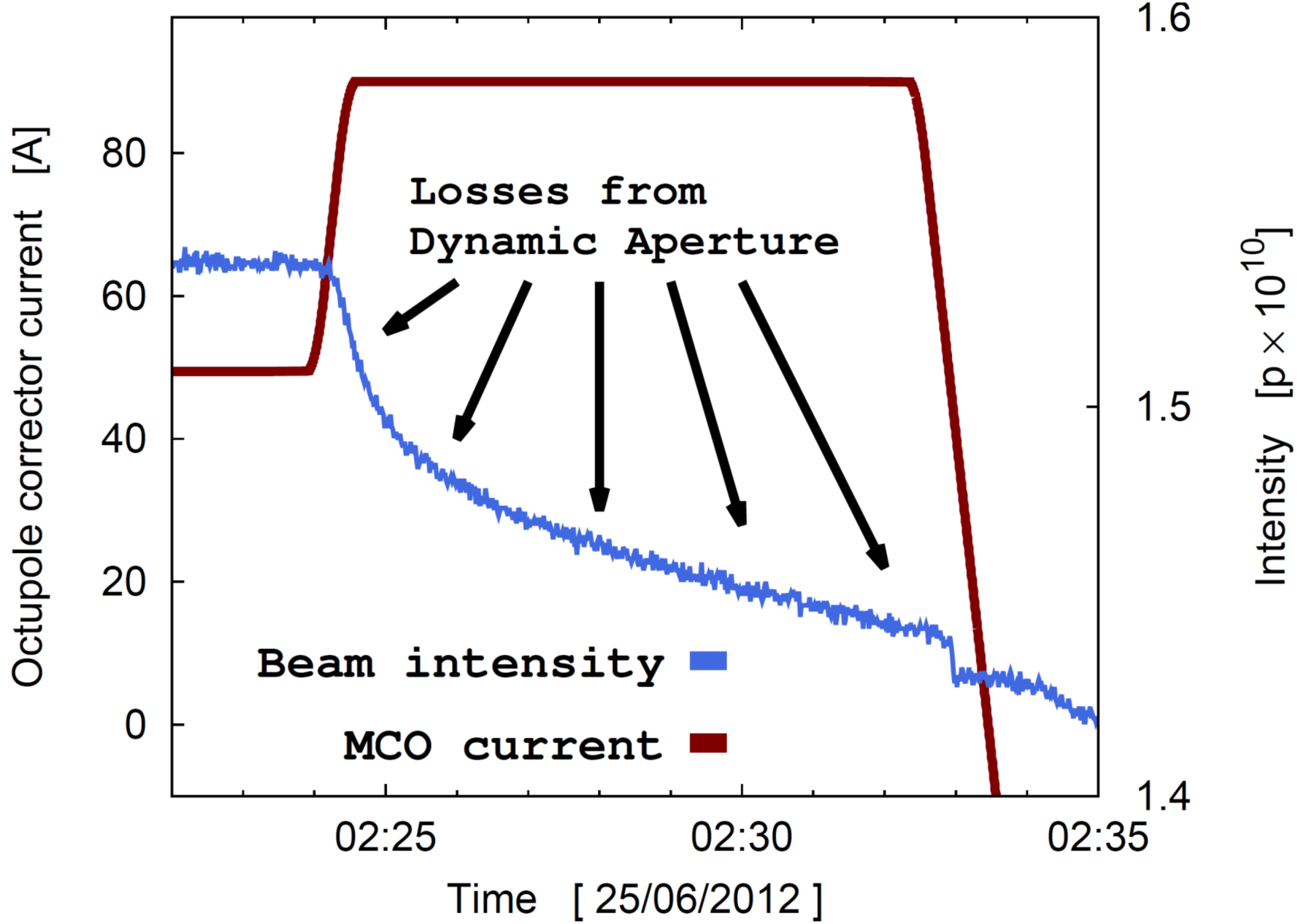


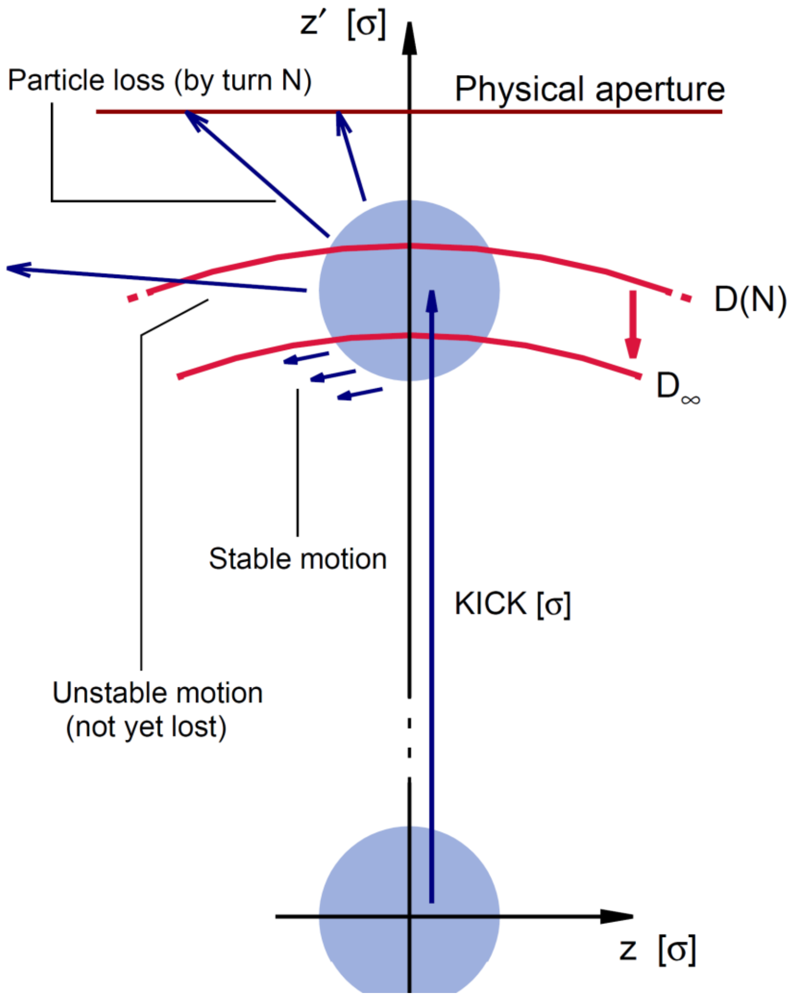
Multiple beam-based studies of dynamic aperture (DA)

- Amplitude below which particles survive for a given number of turns



Want to test how well the predicted dynamic aperture agrees with the real machine

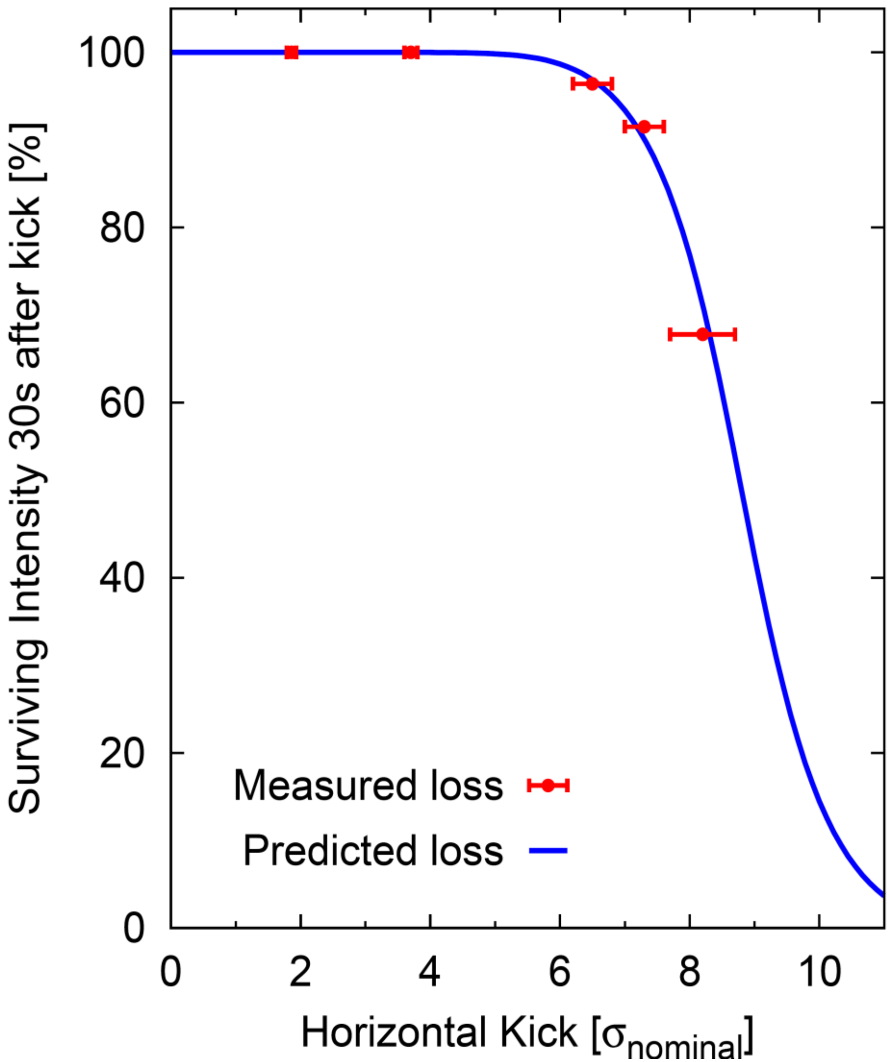
Traditional measurement via single kicks

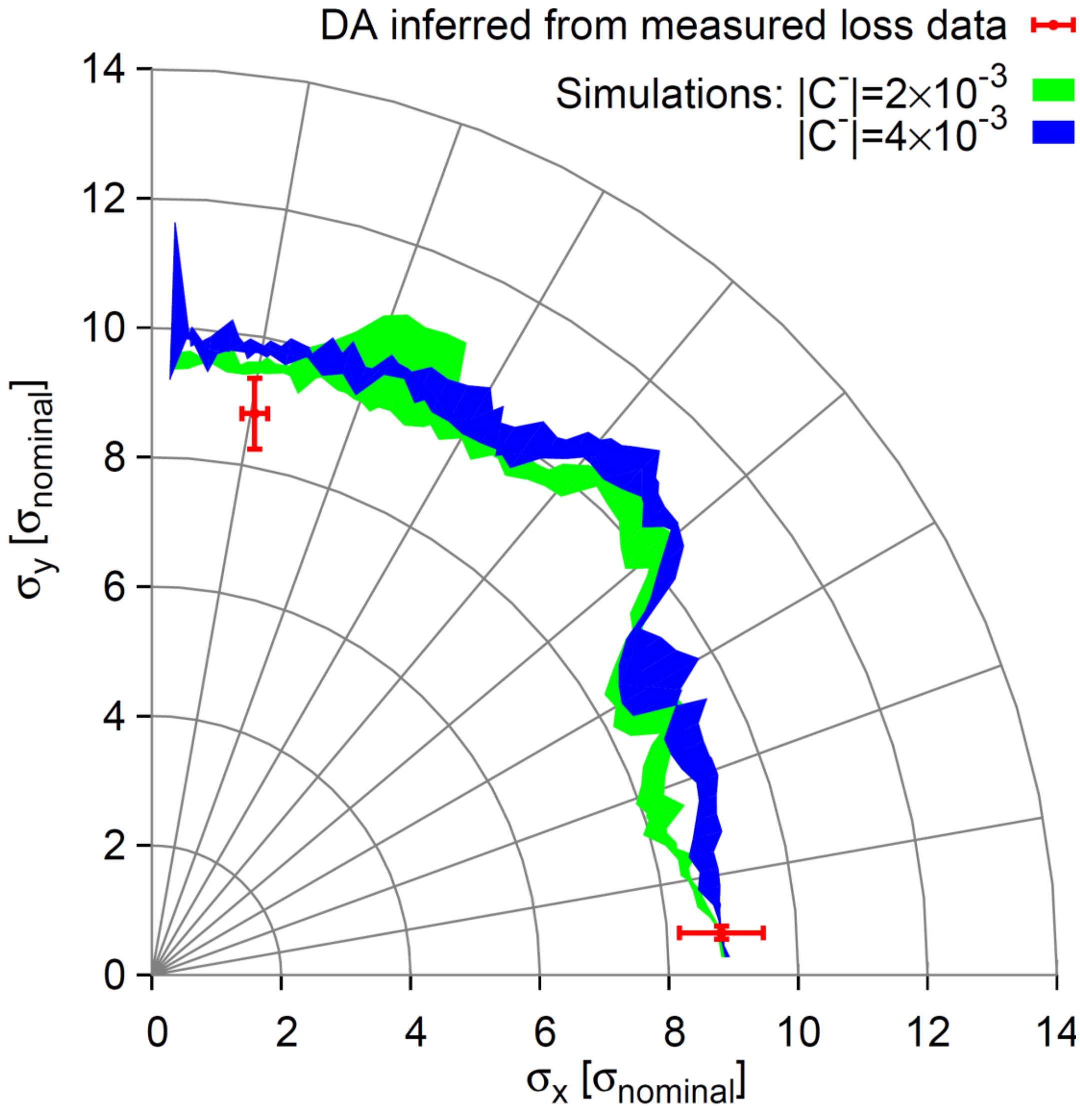


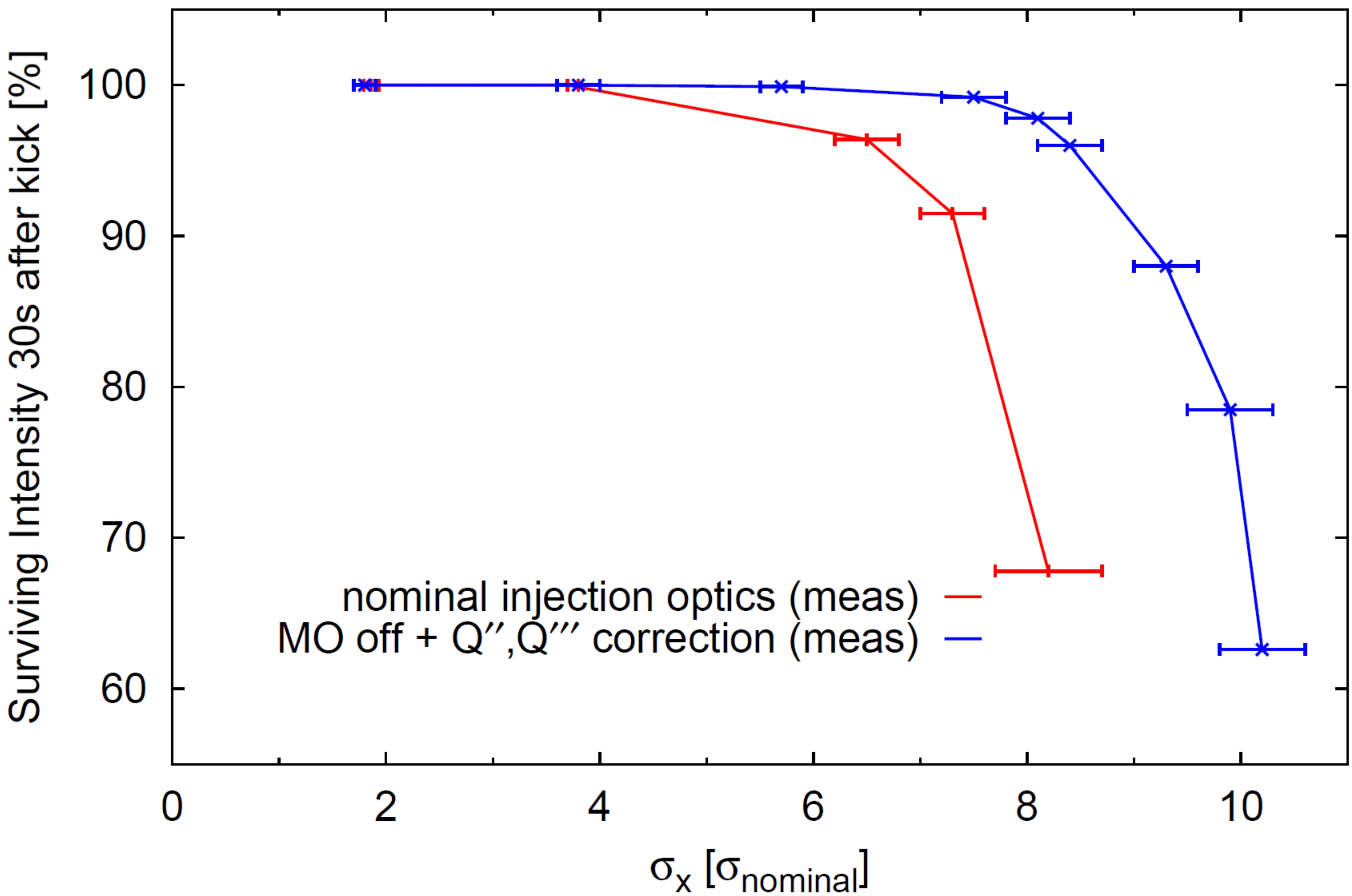
- LHC 'aperture kicker' dipole ramps up/down in $\sim 1/2$ turn
- Provide large amplitude displacement of pilot bunch ($\sim 10^{10} p$)
- Kick action determined from TbT BPM position data
- Beam-loss following kick determines distance between kick and DA(N)

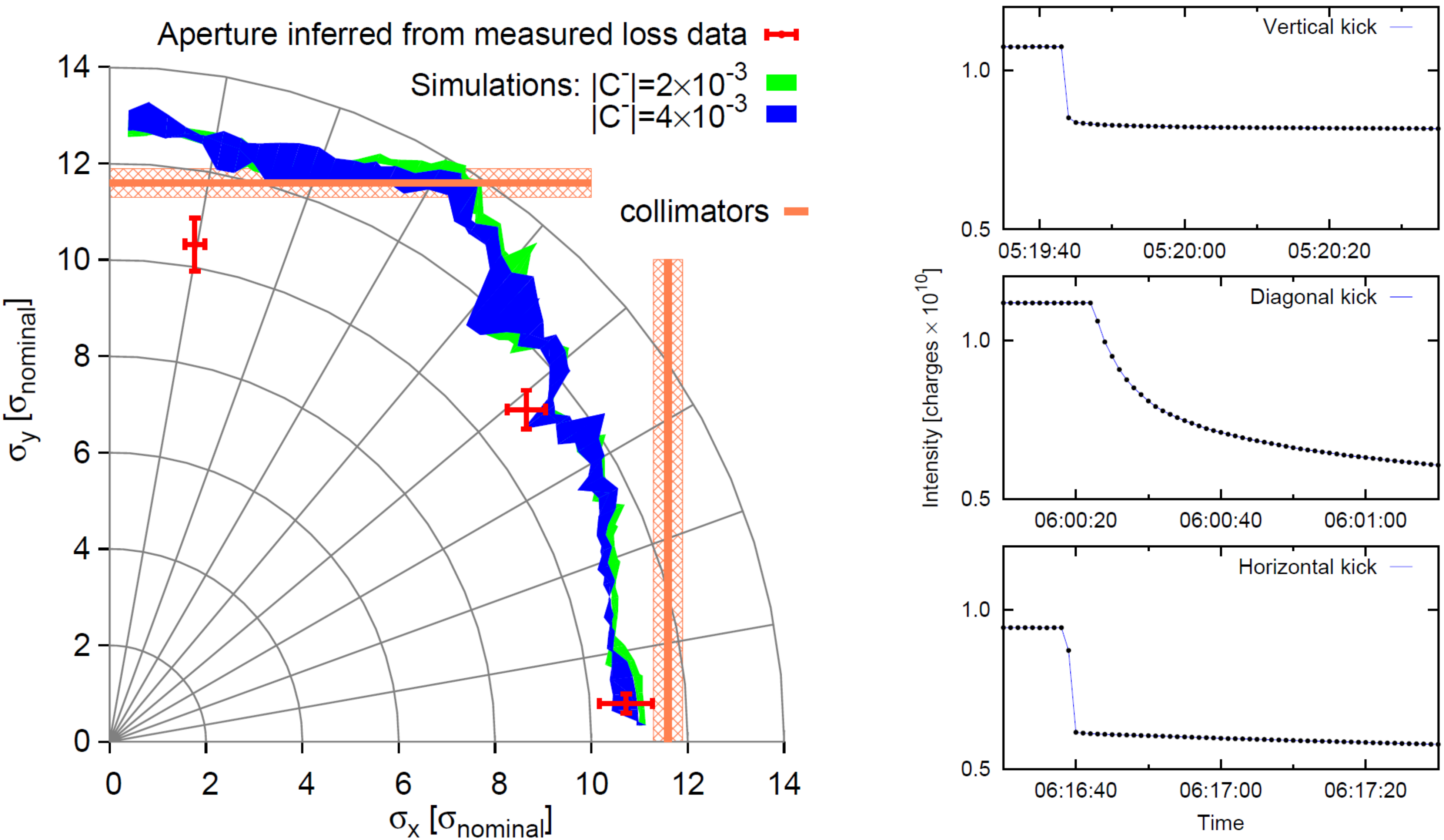
LHC 30s DA at nominal injection settings (2012)

Measurement of nonlinear observables in the Large Hadron Collider using kicked beams, PRAB 17, 081002





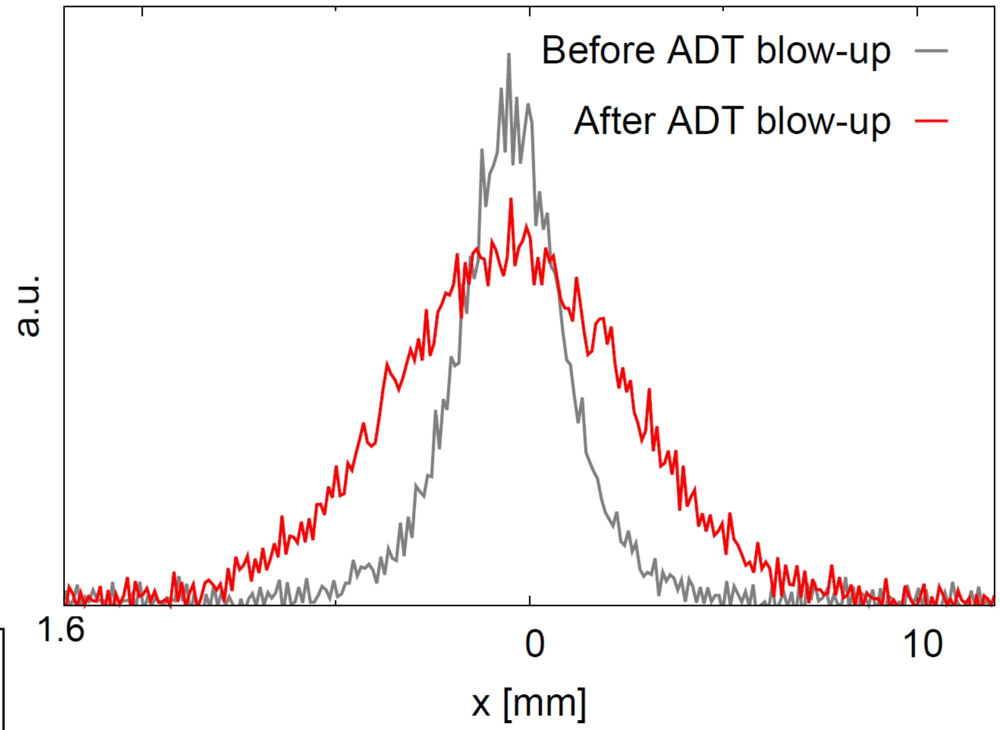

Surviving Intensity 30s after kick [%]
100
90
80
70
60
0
2
4
6
8
10
σ_x [$\sigma_{nominal}$]
nominal injection optics (meas)
MO off + Q′′,Q′′′ correction (meas)

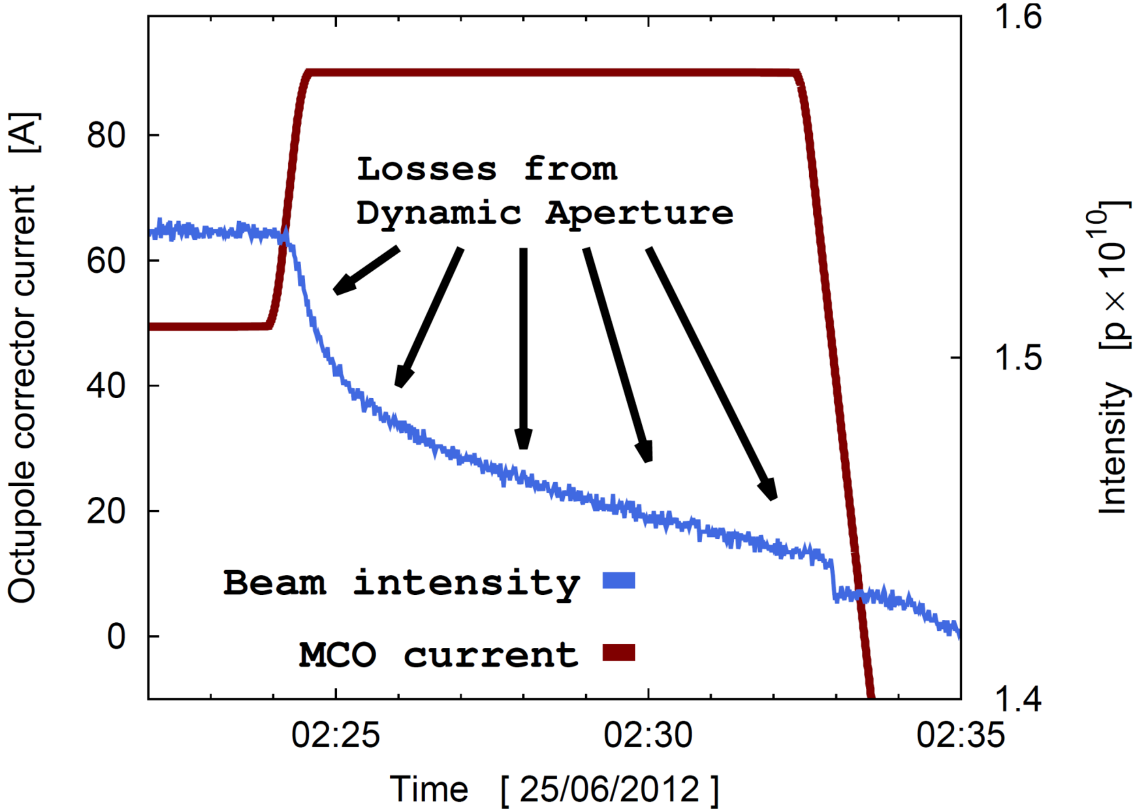


For single-kick based measurement see good agreement (≈10%) between simulated and measured dynamic aperture

Need alternative technique for DA measurement 6.5TeV

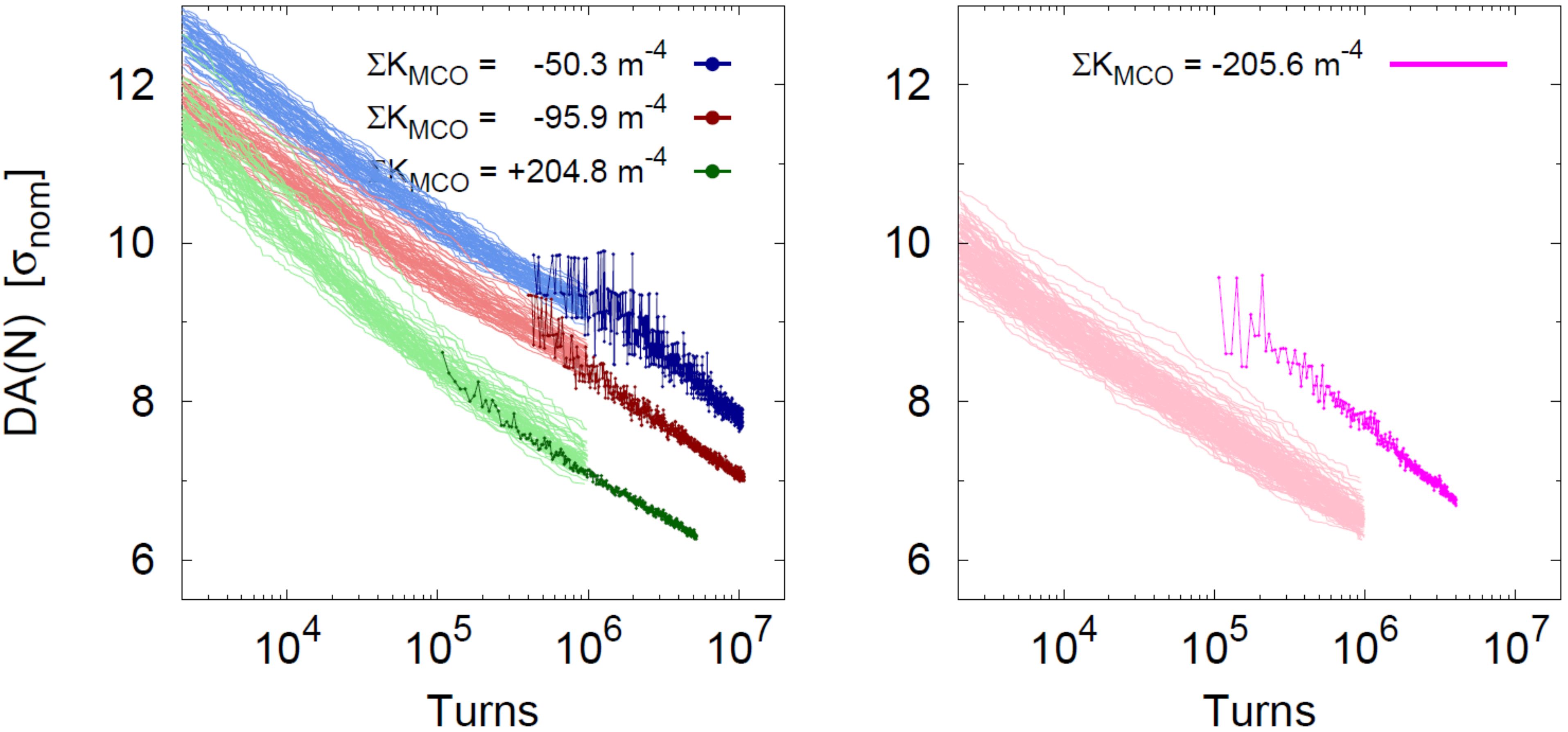
- Blow up bunches to large emittance with damper
- Slow heating limits quench risk





From losses & profile infer change of average DA vs time

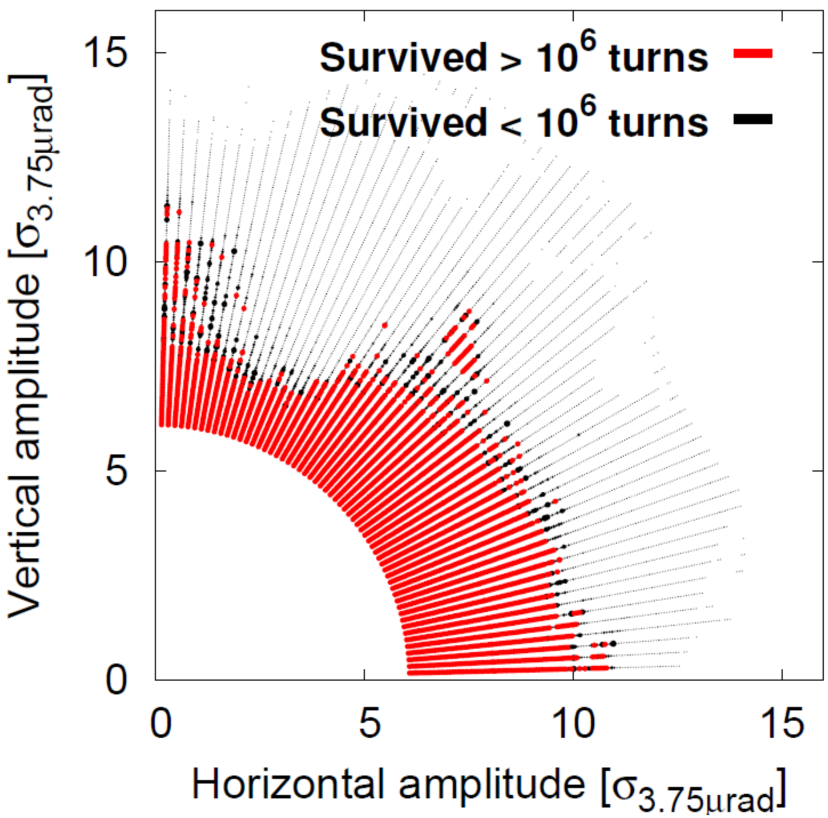
Compared average DA vs time for various configurations of octupole correctors in arcs

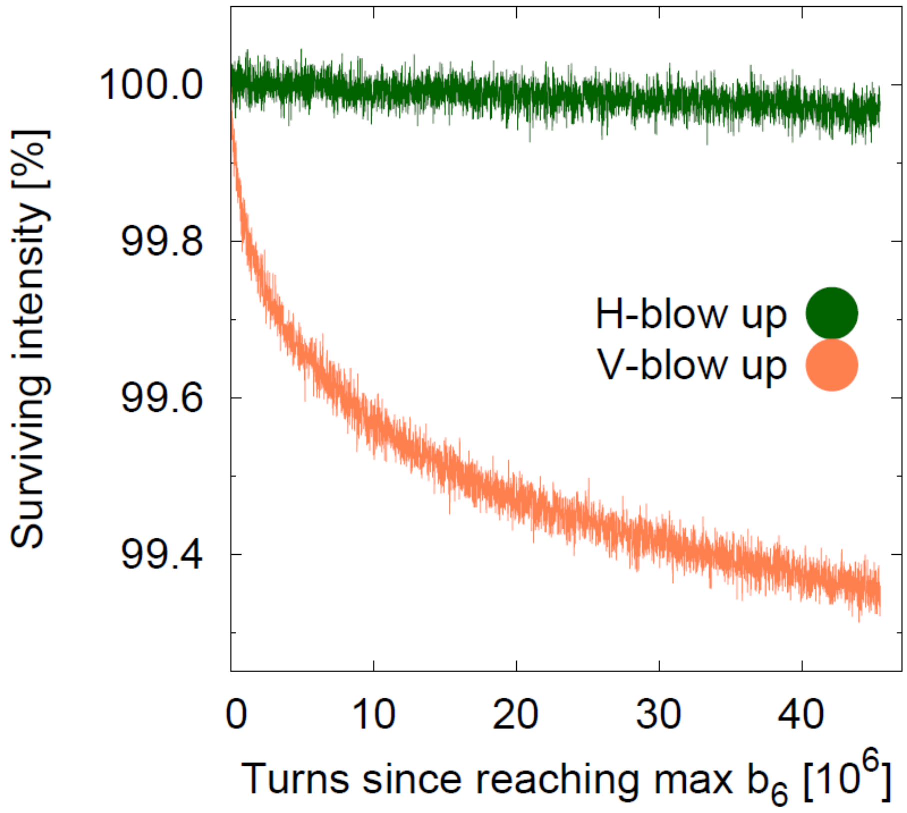


See comparable level of agreement as for single kicks

Probe shape of DA by blowing up in only H or V

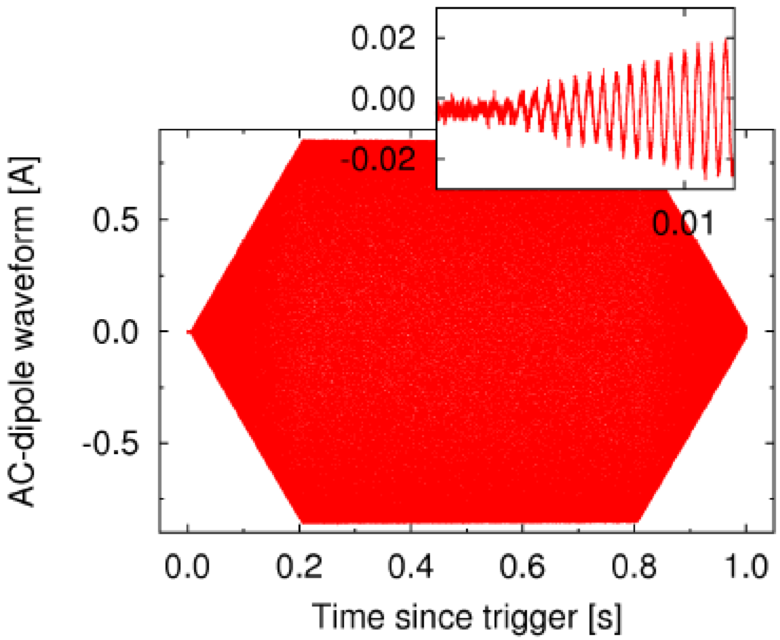
e.g. strong b6 source at (6.5TeV)

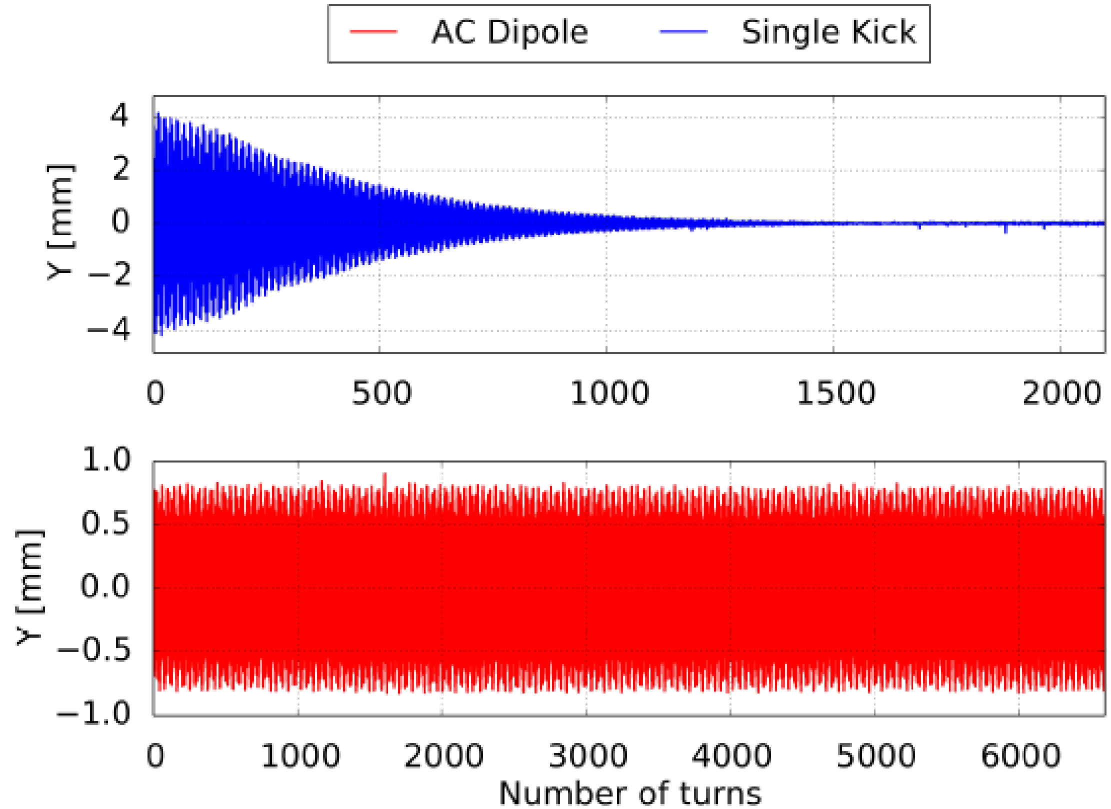




Need alternative method to measure amplitude detuning at 6.5TeV → excite with an AC-dipole!

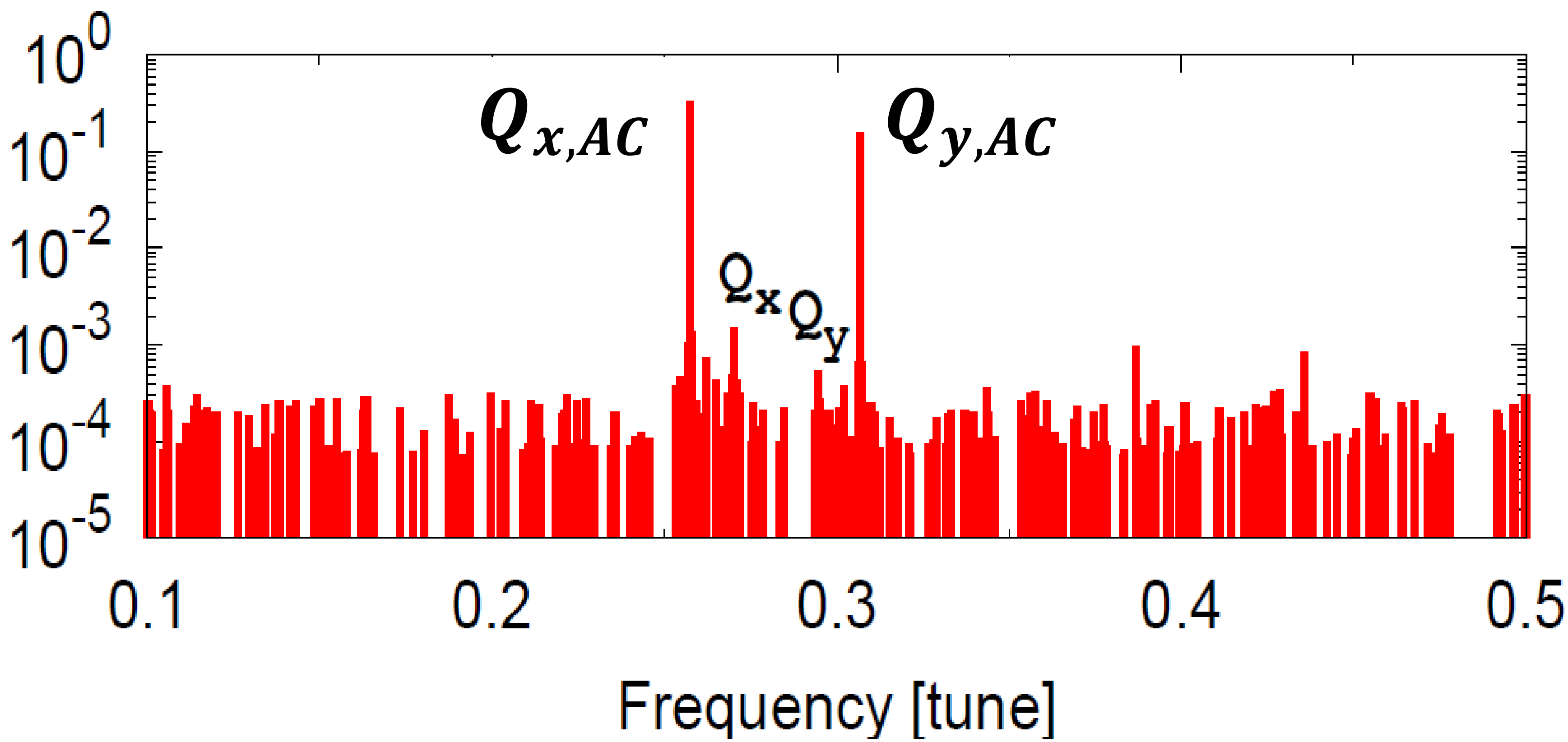
- **Repeated excitation of the same bunch without emittance blowup**
- **6000 turns of TbT data without decoherence**



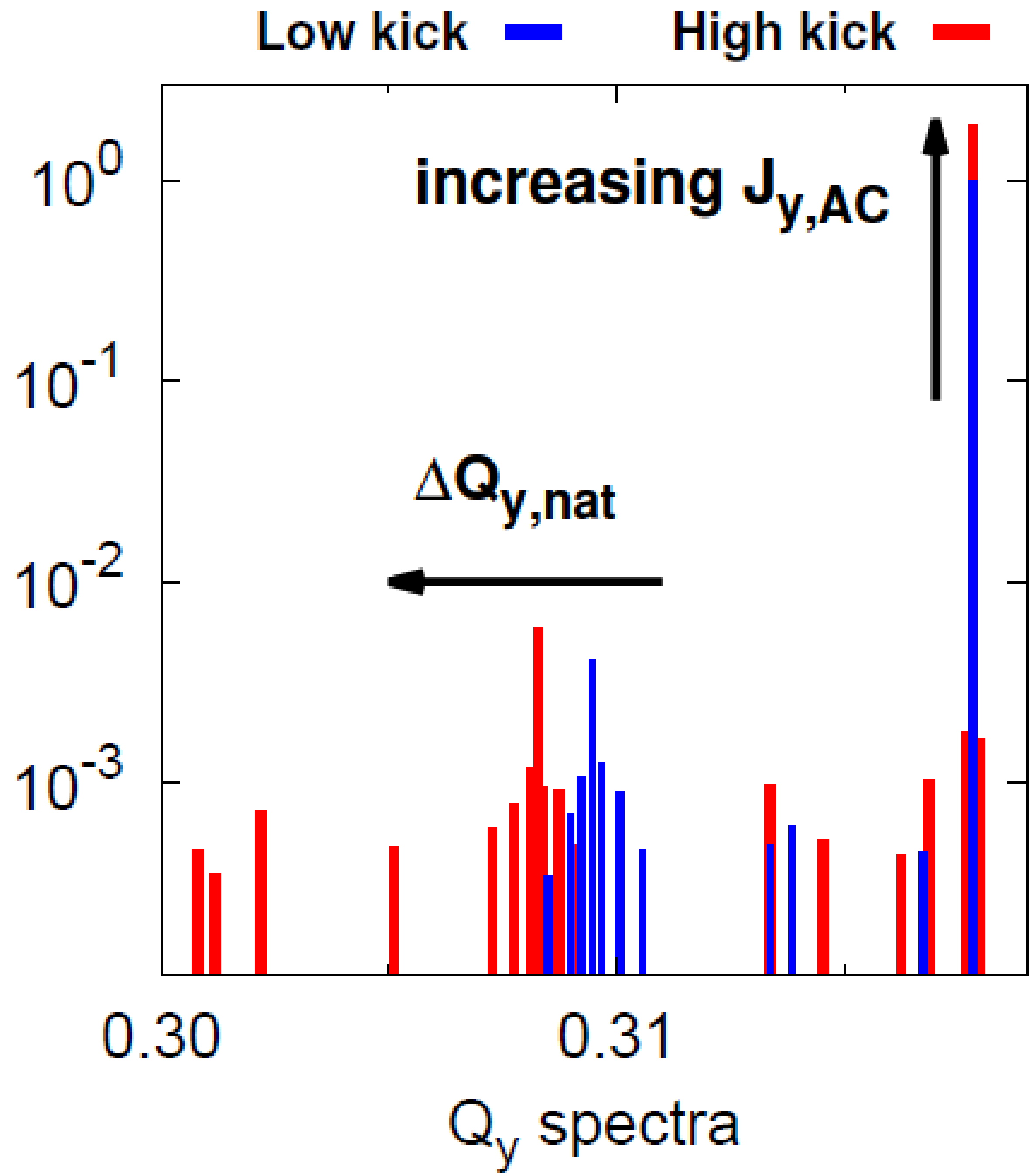


Need alternative method to measure amplitude detuning at 6.5TeV → excite with an AC-dipole!

- **Repeated excitation of the same bunch without emittance blowup**
- **6000 turns of TbT data without decoherence**

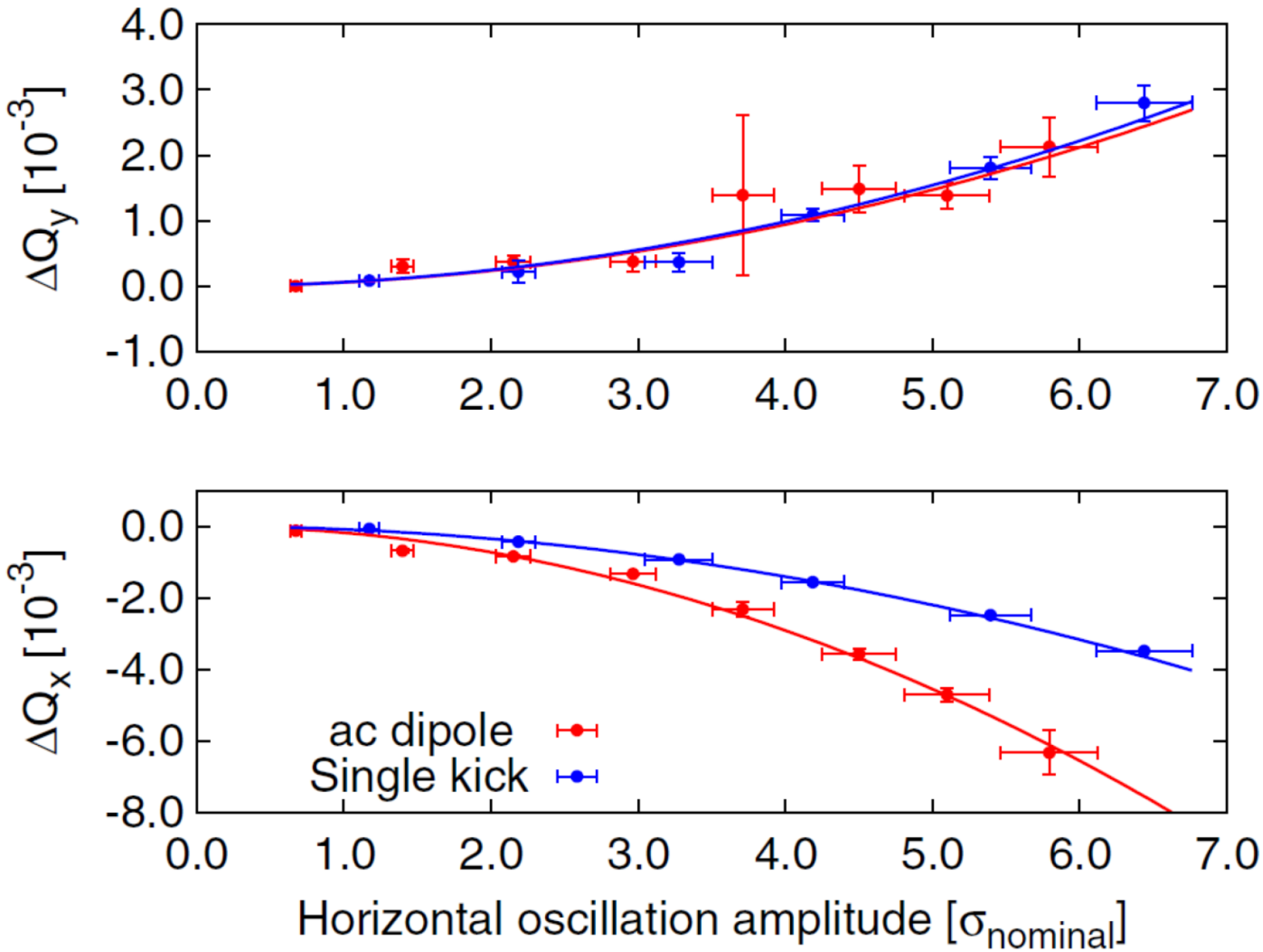


Measure change of natural tune with action of the driven oscillation



AC-dipole detuning related to that of free kicks, but not equal!

(e.g. linear detuning from b4 = factor 2 in direct detuning coefficients and factor 1 in cross-terms)

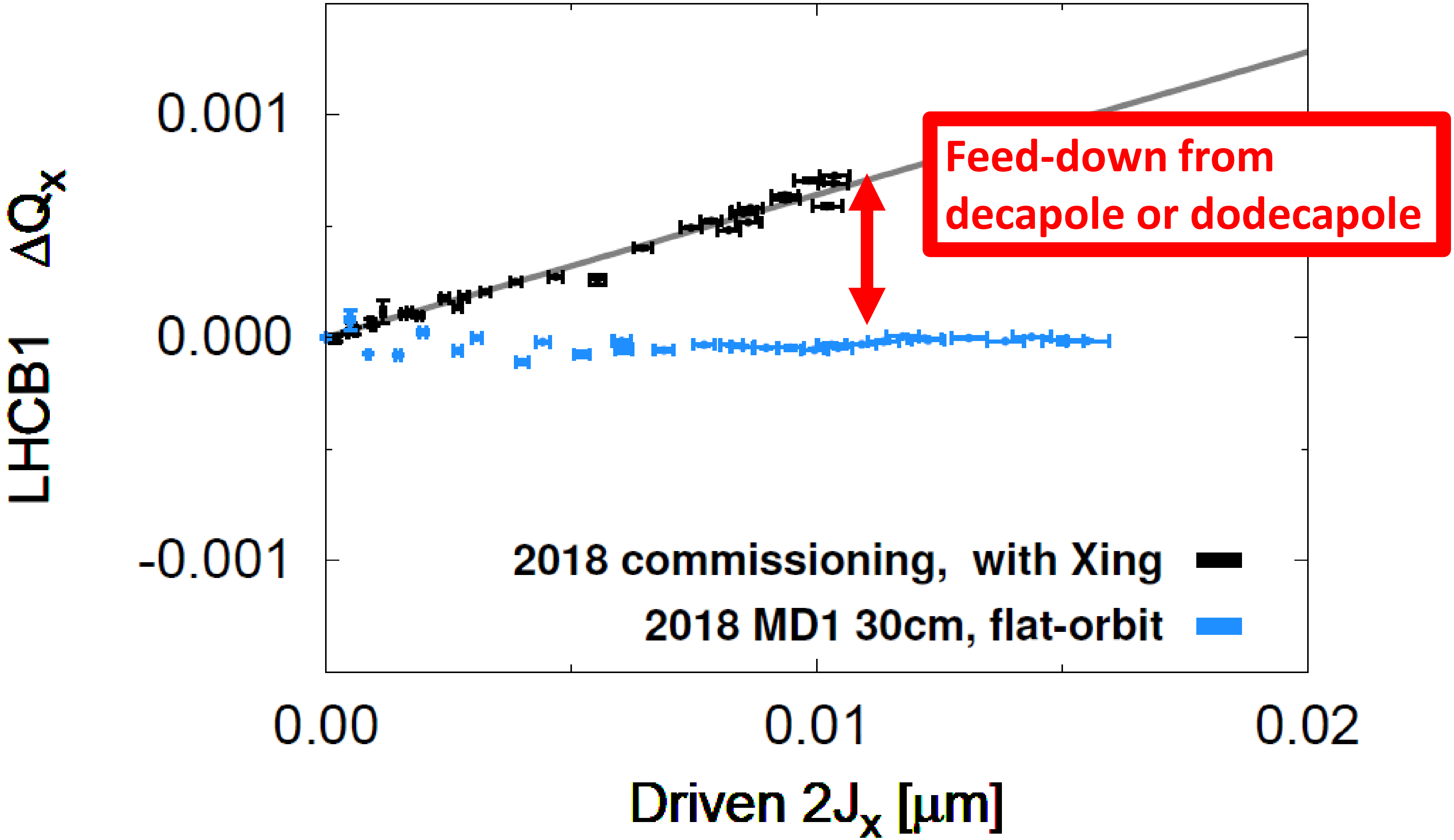


Phys.Rev.ST.AB,16,071002(2013)

Main use so far is to study footprint distortion during the β*- squeeze due to b4 errors in ATLAS/CMS IRs

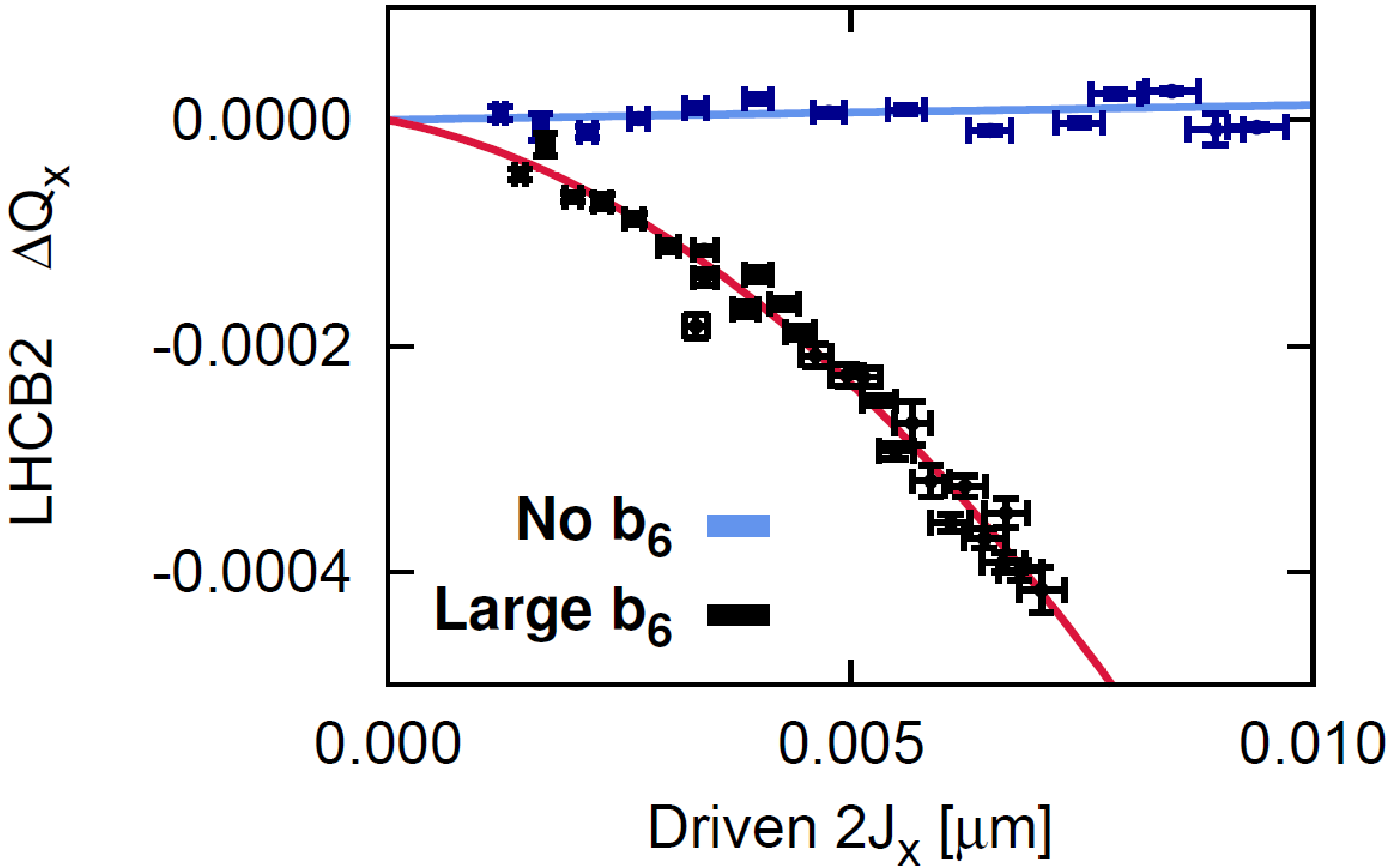
But can also study decapole & dodecapole errors via detuning

- via feed-down to first-order amplitude detuning

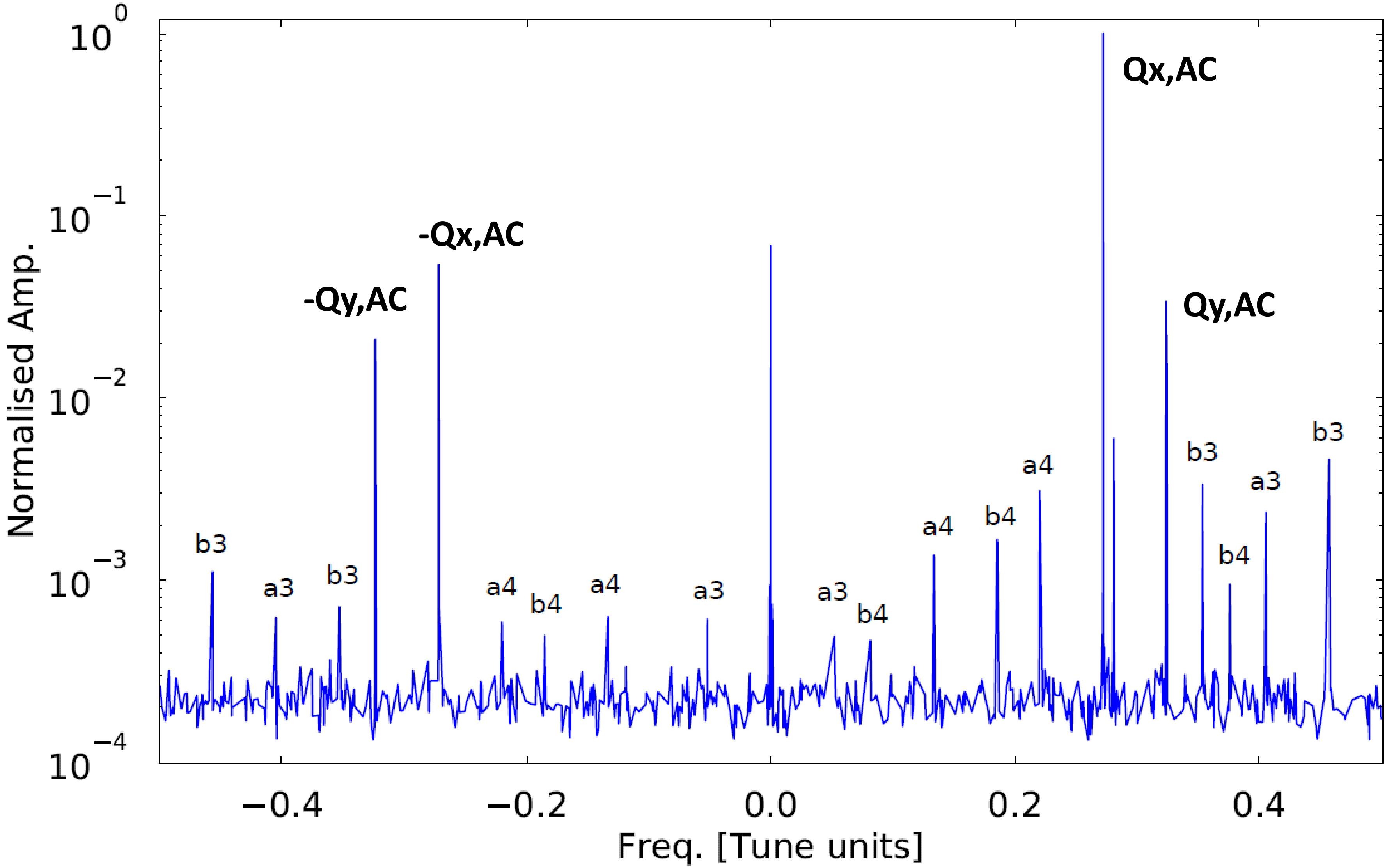


Study decapole & dodecapole sources

➢ via second-order amplitude detuning



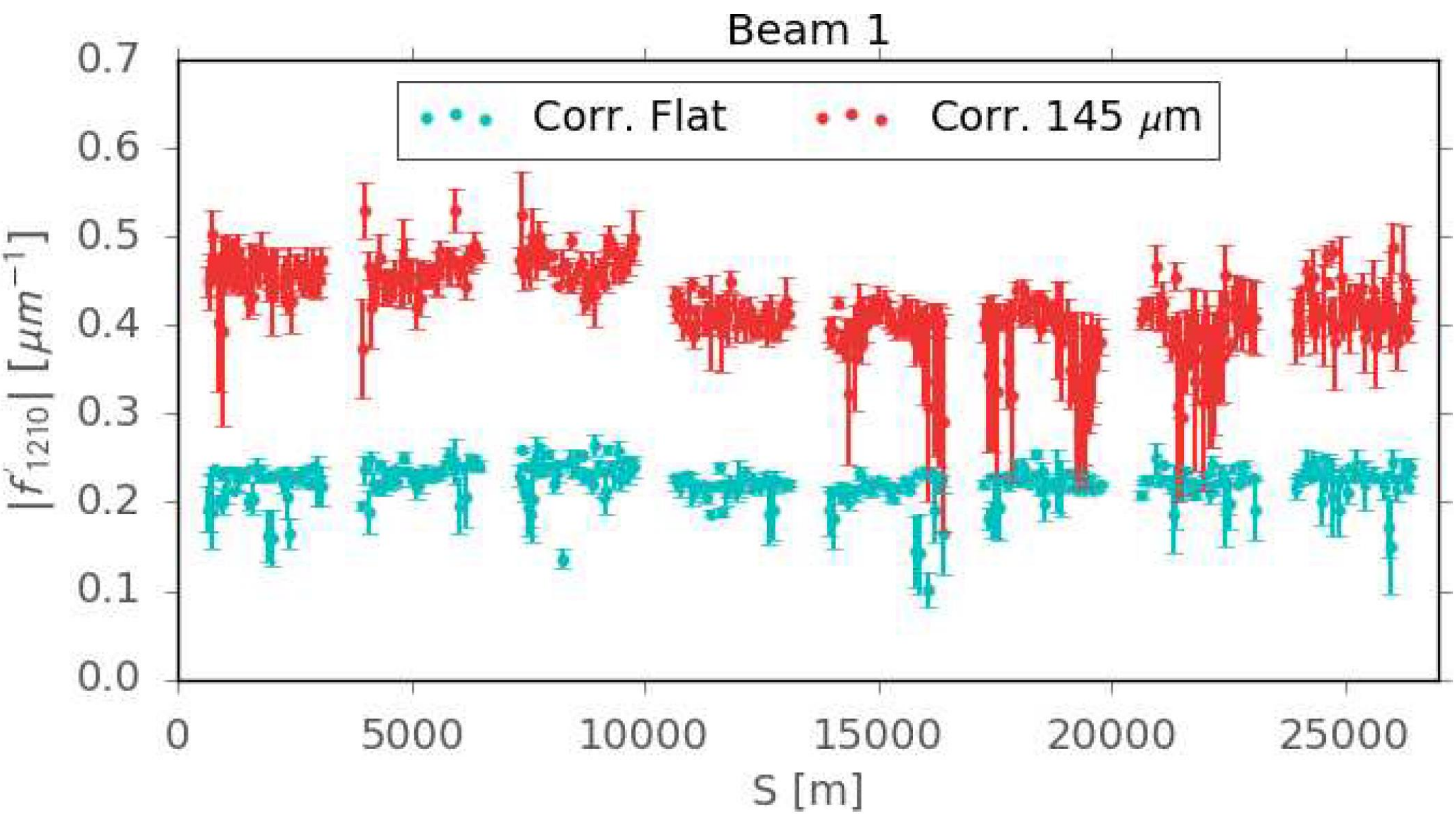
RDTs provide complementary observable for many multipoles



<u>Using RDTs of the driven motion</u> **not the same as RDTs of free motion**

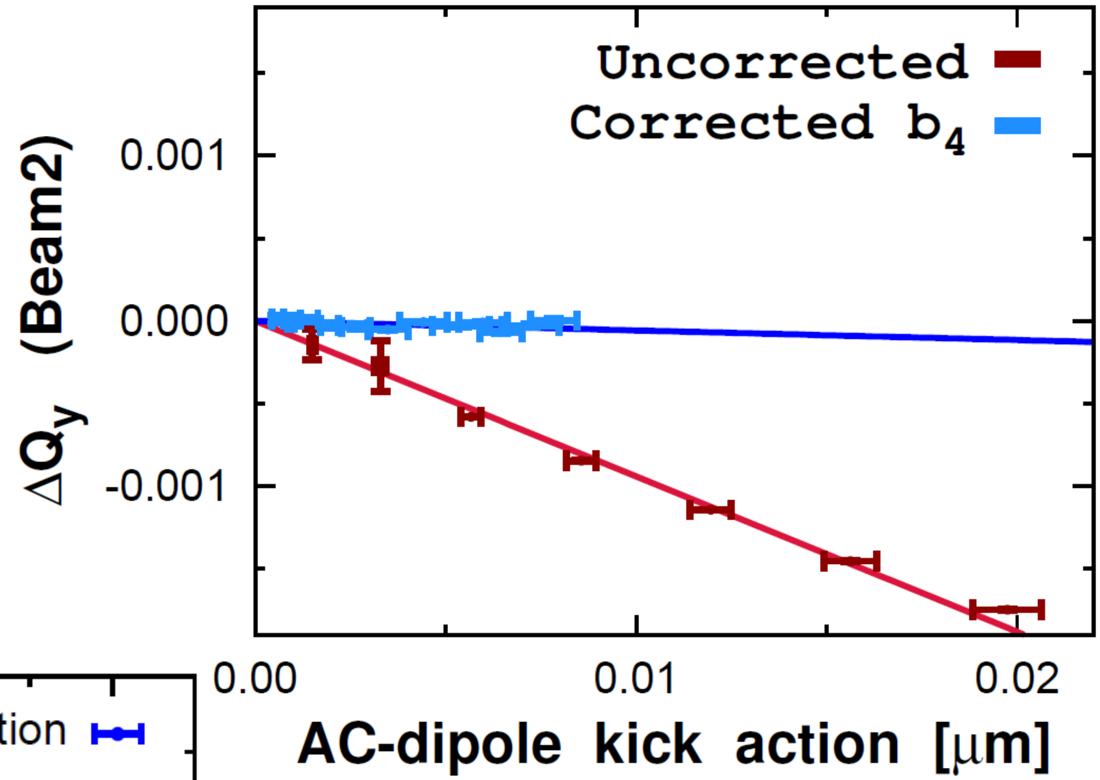
From F.Carlier (CERN) Ph.D thesis: feed-down to skew octupole RDT

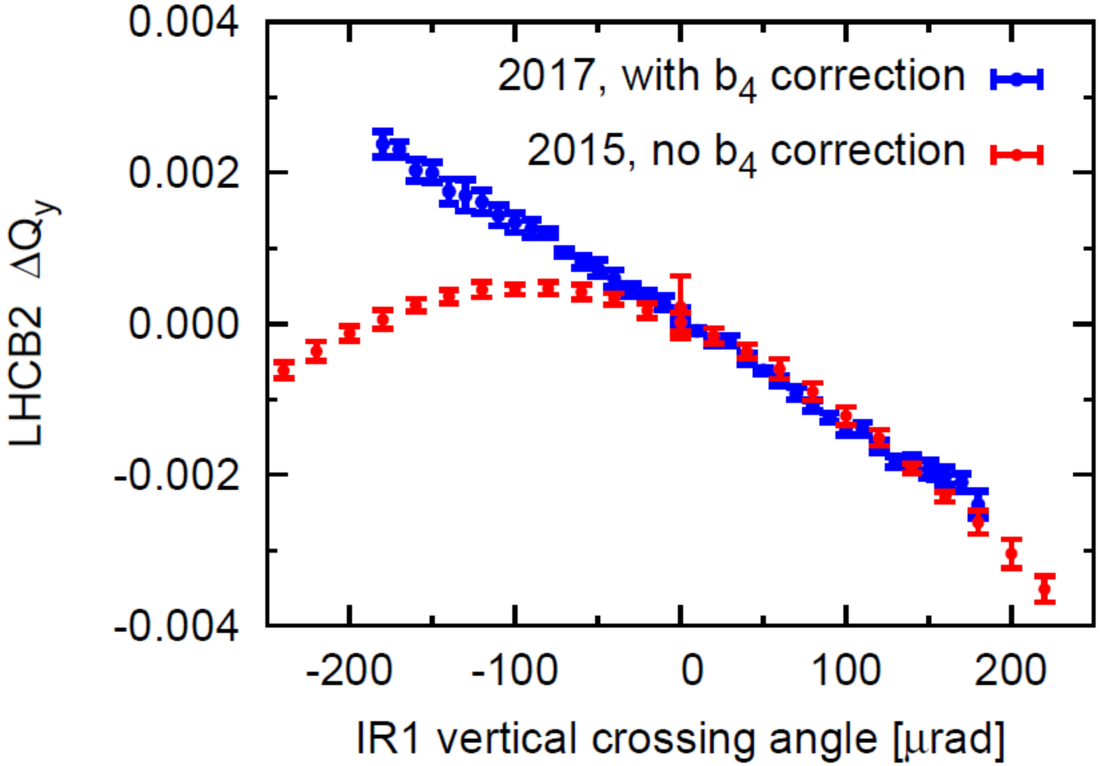
➡ **potential observable for high-order errors**

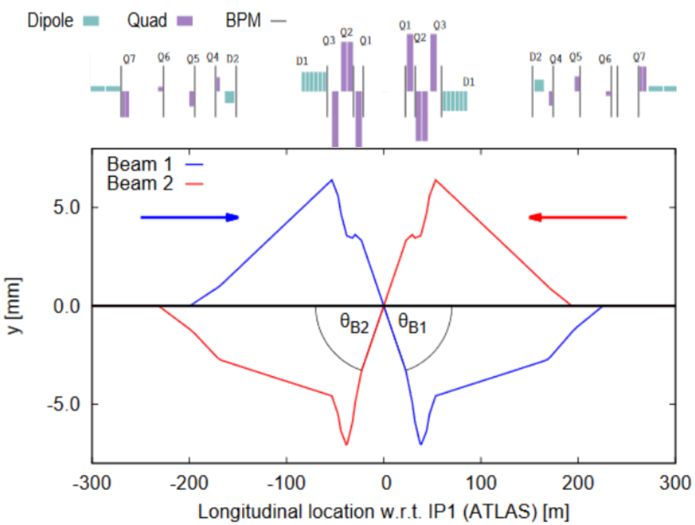


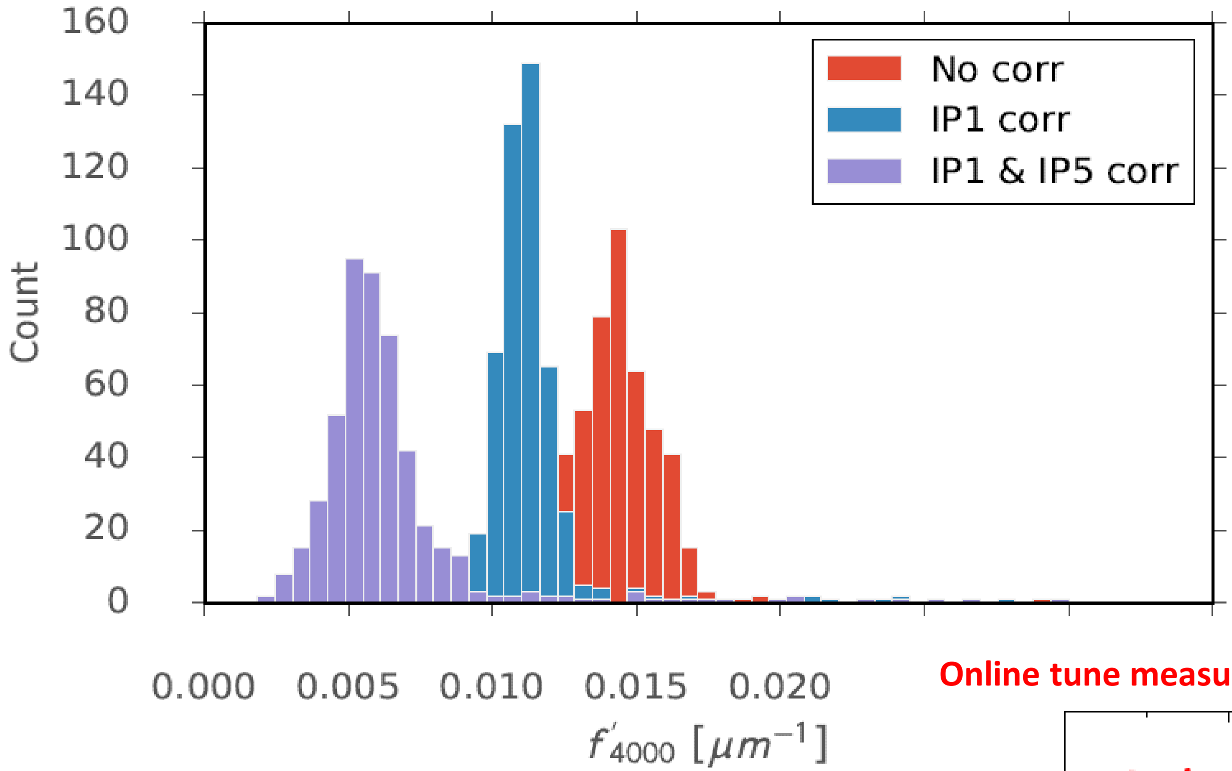
A new activity for the optics team since 2017: nonlinear optics commissioning at 6.5TeV

Normal octupole correction in ATLAS & CMS IRs



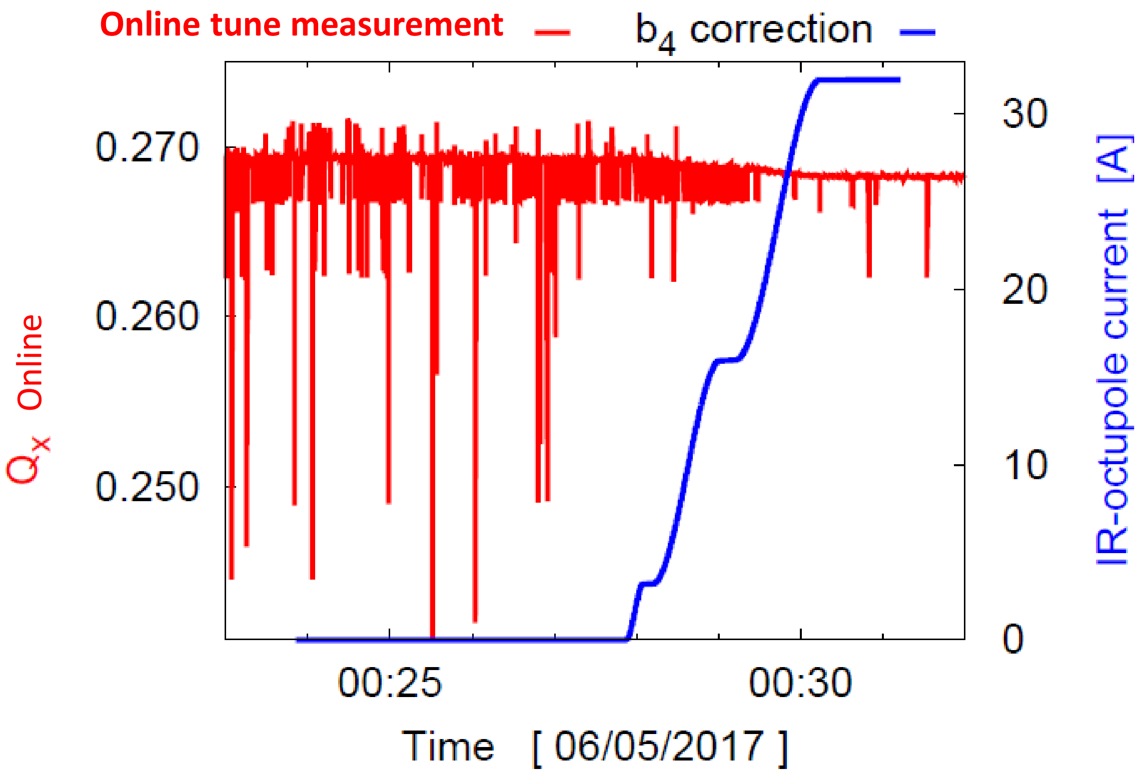




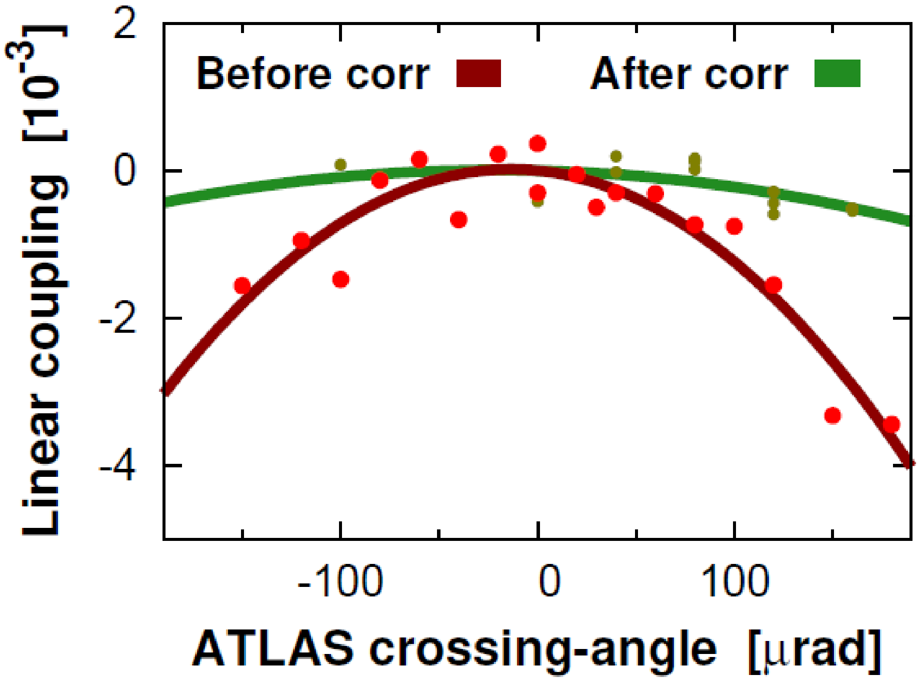


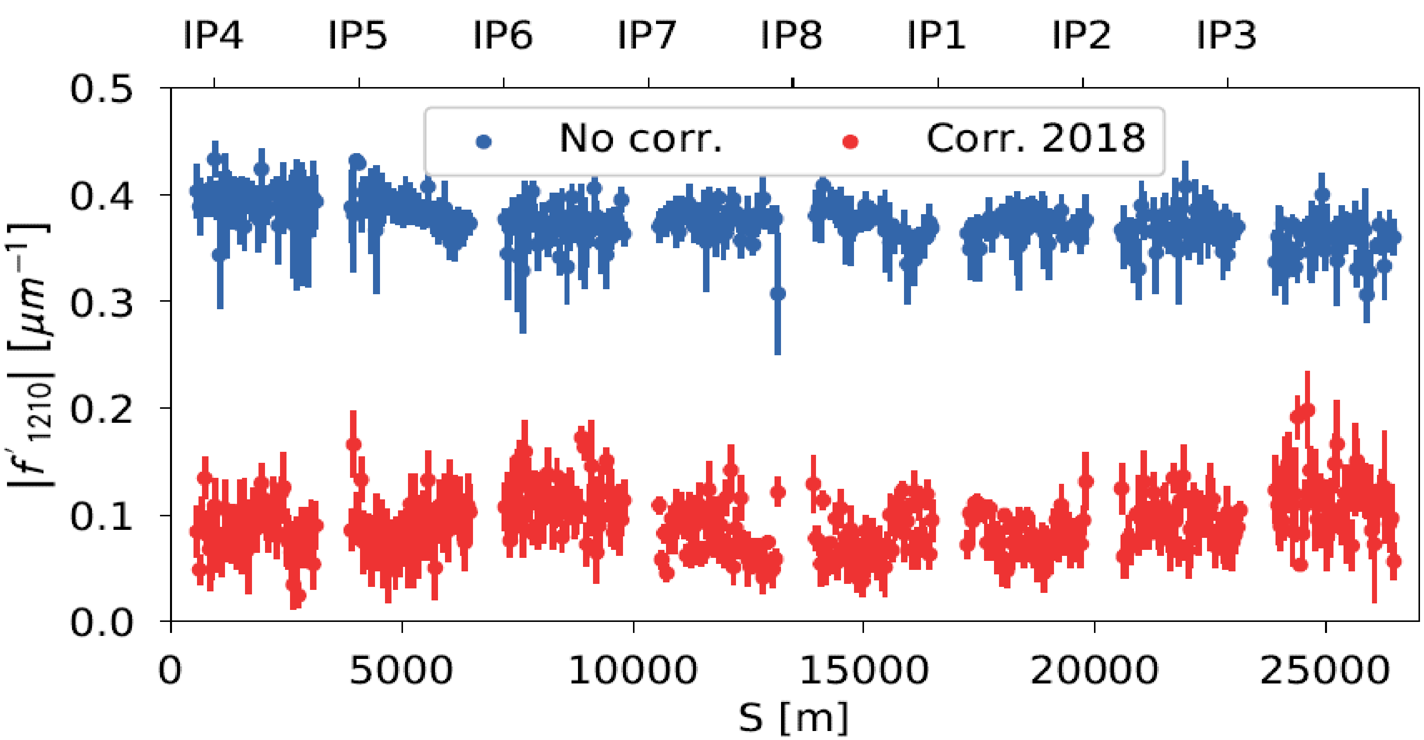
Reduced 4Qx strength

Improved performance of beam instrumentation

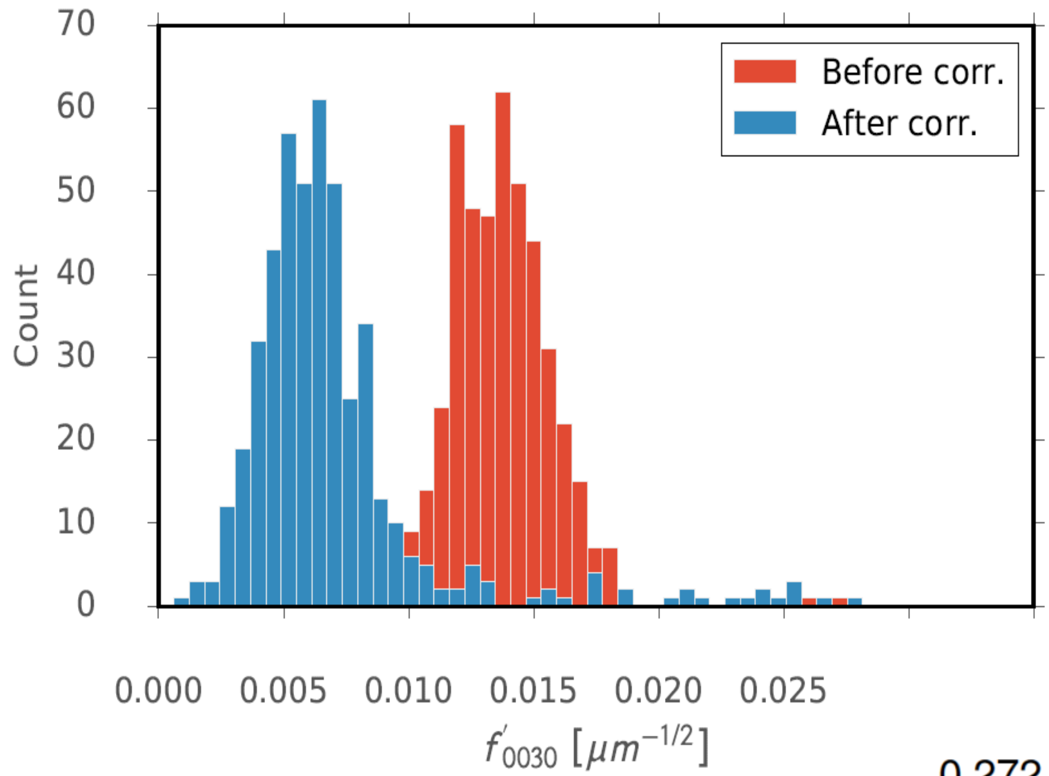


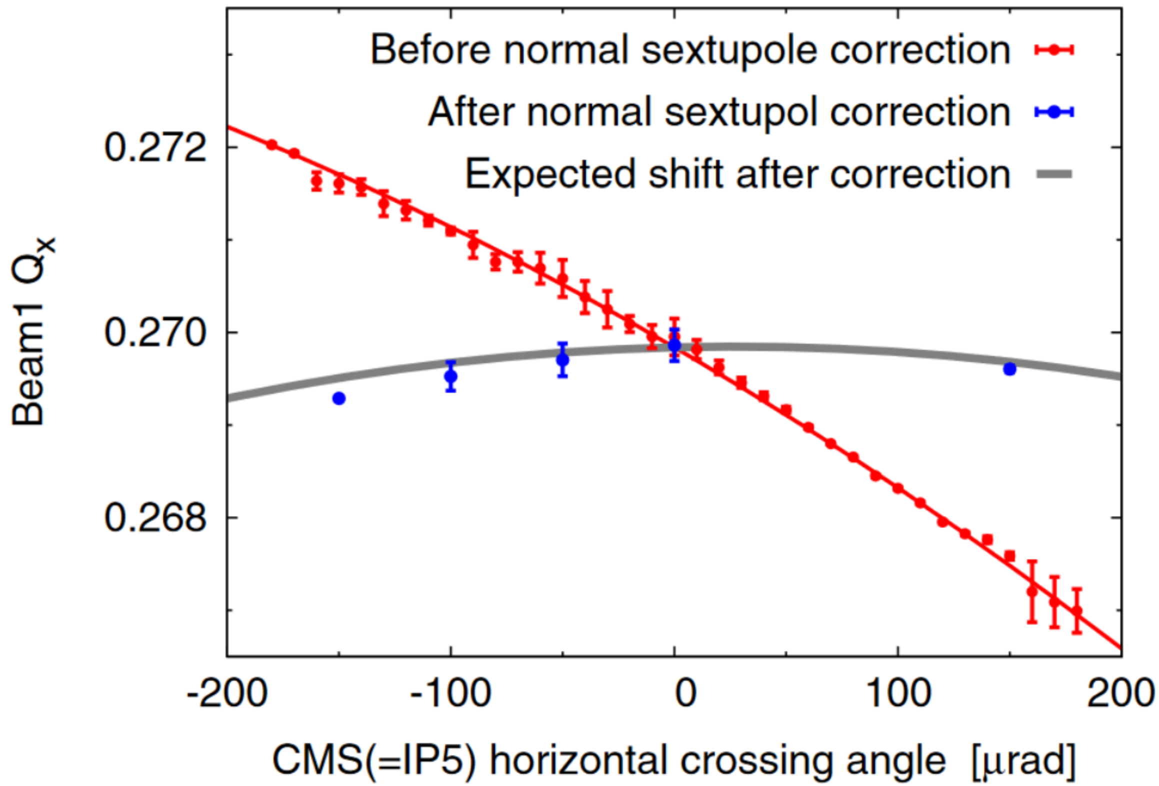
skew octupole correction in ATLAS & CMS IRs



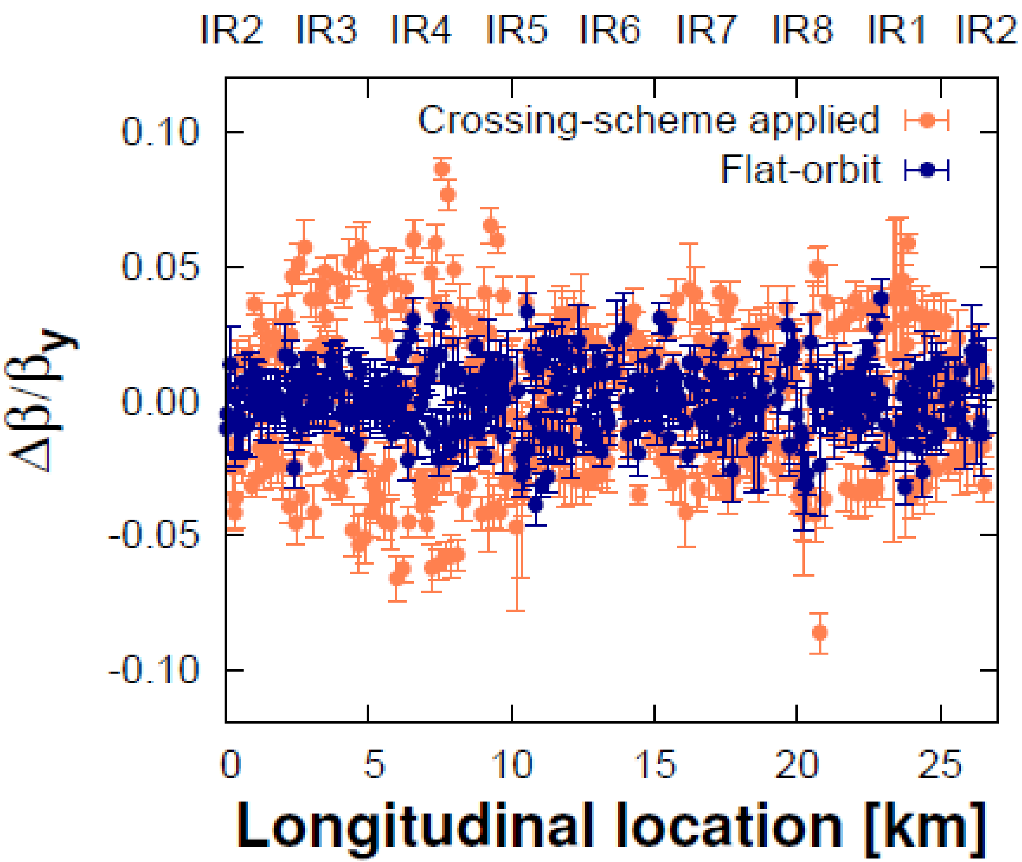


Normal & skew sextupole correction in ATLAS & CMS IRs





Several clear operational improvements due to inclusion of nonlinear optics commissioning: e.g. linear optics control



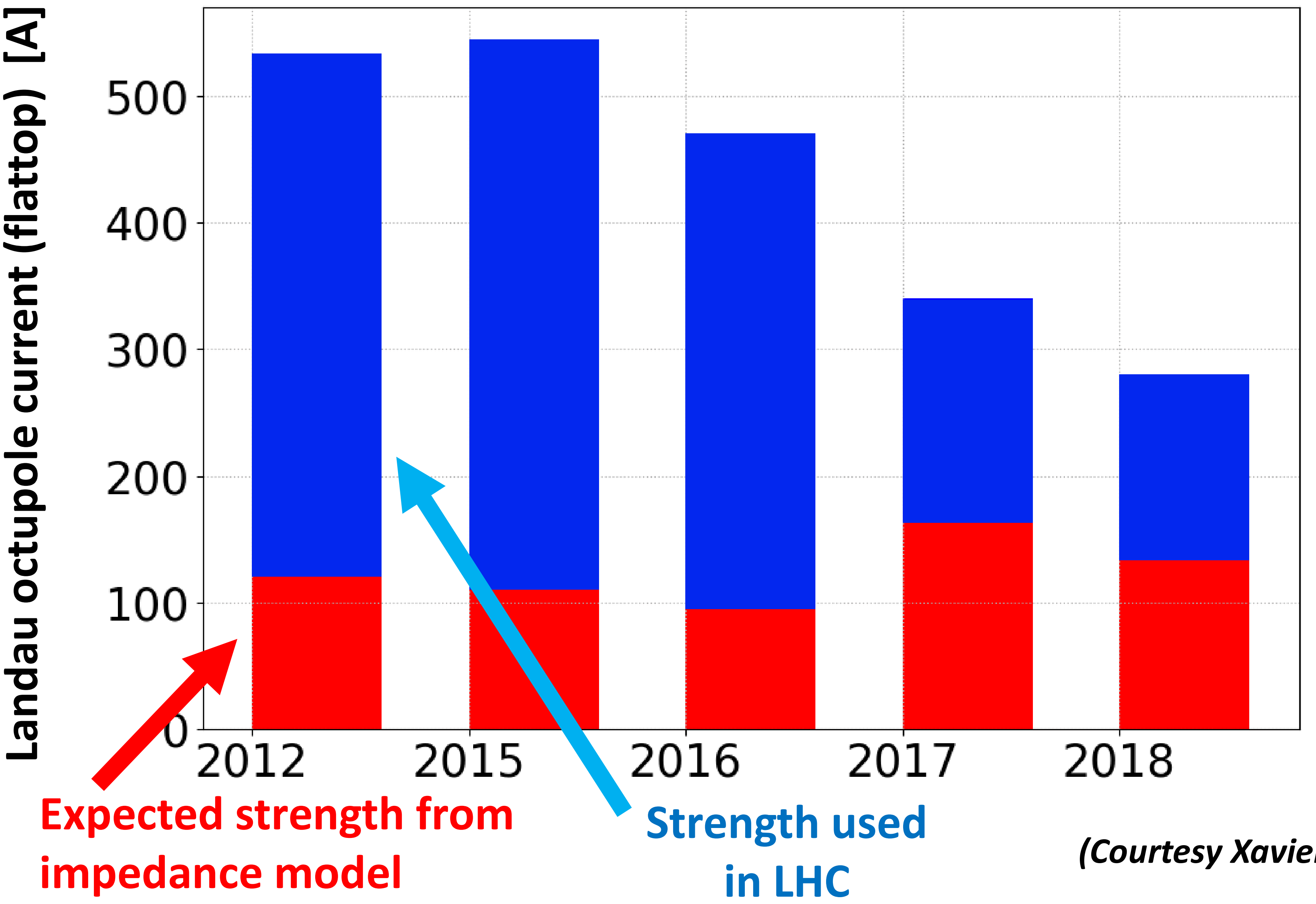
lumi-imbalance from optics without nonlinear corrs:

$$\frac{L_{\mathrm{CMS}}}{L_{\mathrm{ATLAS}}} = 0.974 \pm 0.004$$

lumi-imbalance from optics after correction:

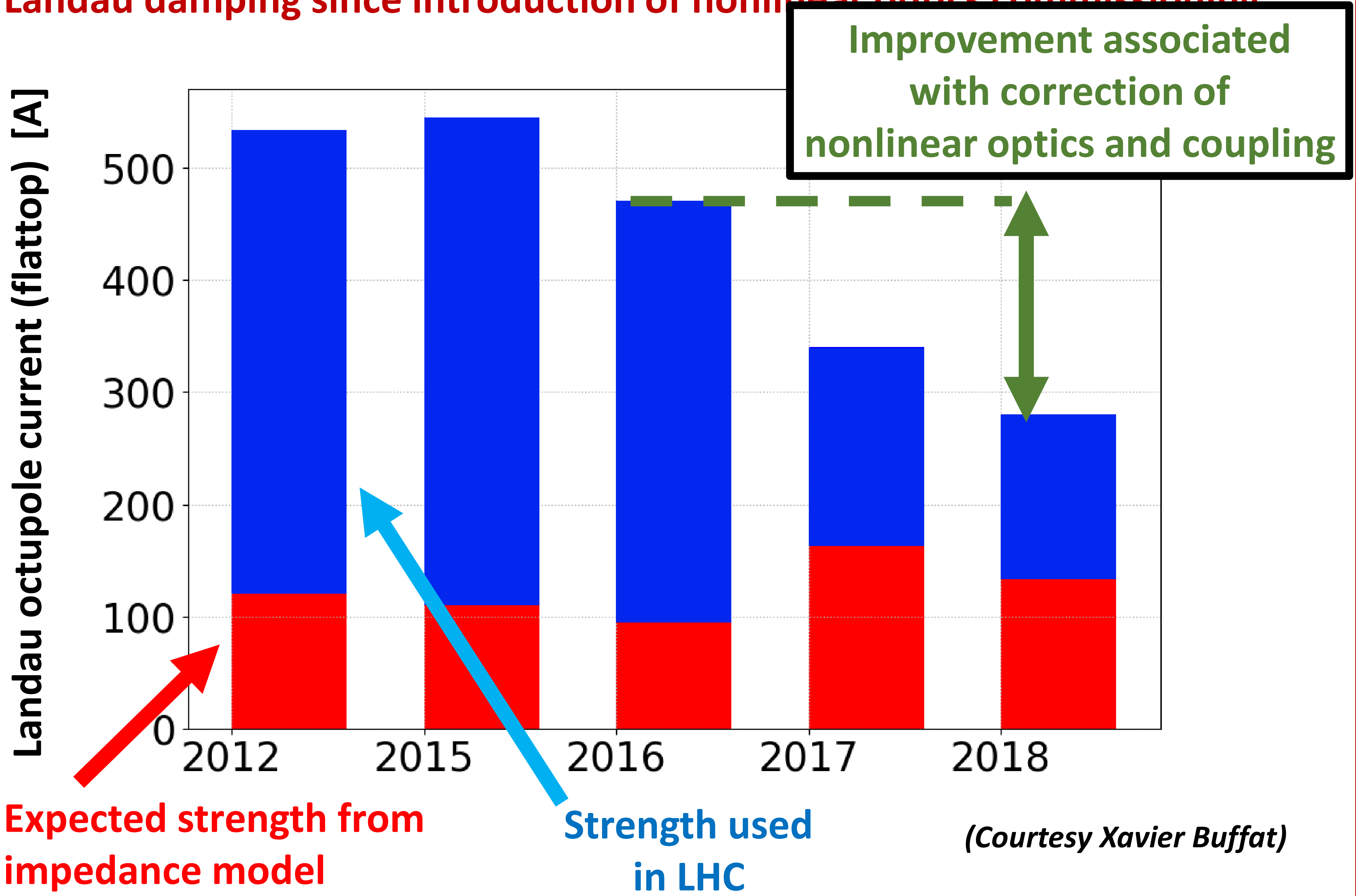
$$\frac{L_{\mathrm{CMS}}}{L_{\mathrm{ATLAS}}} = 1.003 \pm 0.004$$

Significant reduction in Landau octupole strength required to maintain Landau damping since introduction of nonlinear optics commissioning

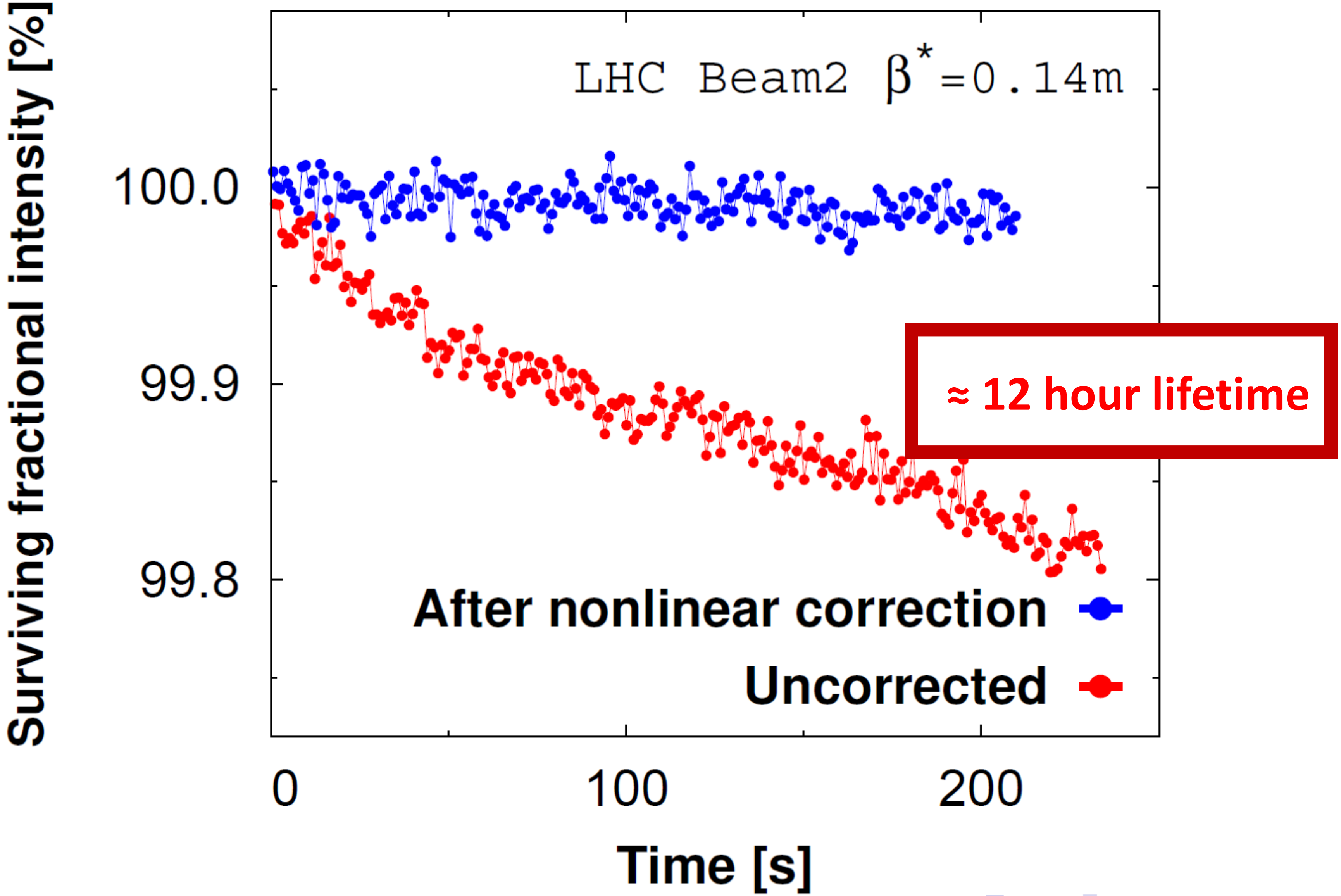


(Courtesy Xavier Buffat)

Significant reduction in Landau octupole strength required to maintain Landau damping since introduction of nonlinear optics commissioning



Observe pronounced effect from nonlinear optics commissioning on lifetime at low-β*




Is it worth all the night shifts?

More and more emphasis being placed on nonlinear optics at the LHC & in preparation for HL-LHC

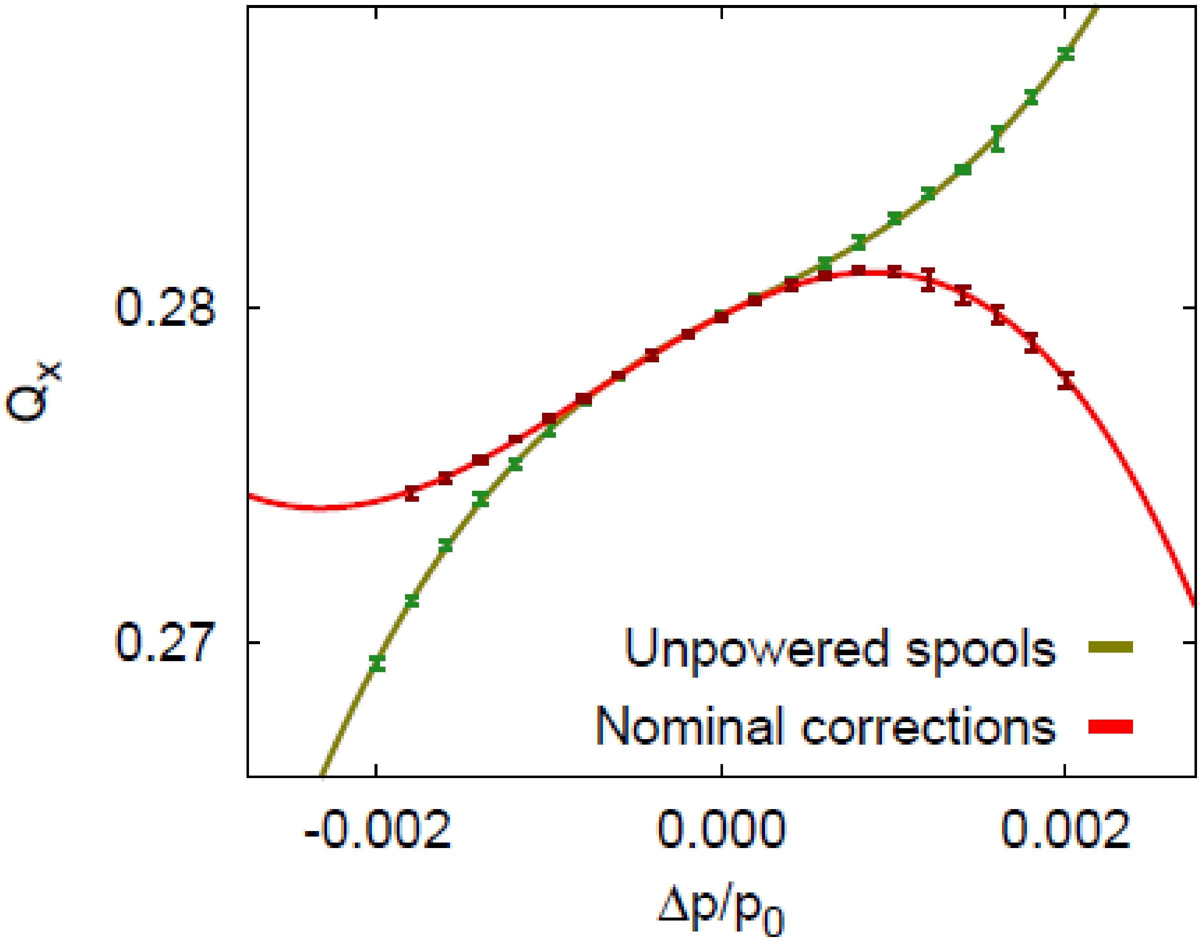
Reflected in the steady increase of time allocated for beam-based studies throughout Run1 and Run2

- Identify limitations in our understanding of the LHC model and LHC single particle dynamics
- Develop / refine measurement techniques for nonlinear optics at high energy where new tools are needed
- Use a wide variety of observables to correct the nonlinear optics of LHC & improve performance

Reserve

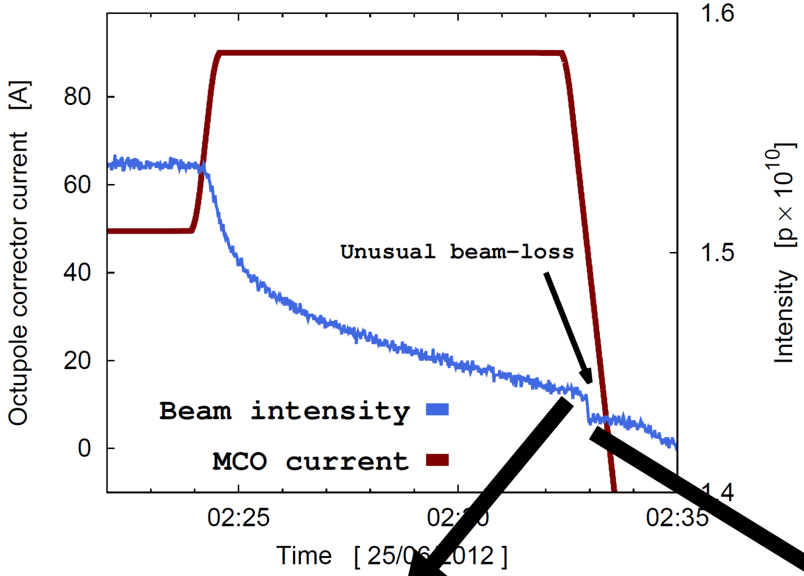
Decapole correction generates very large ΔQ’’

- **Consistent with systematic 0.25mm offset of all decapole spools**



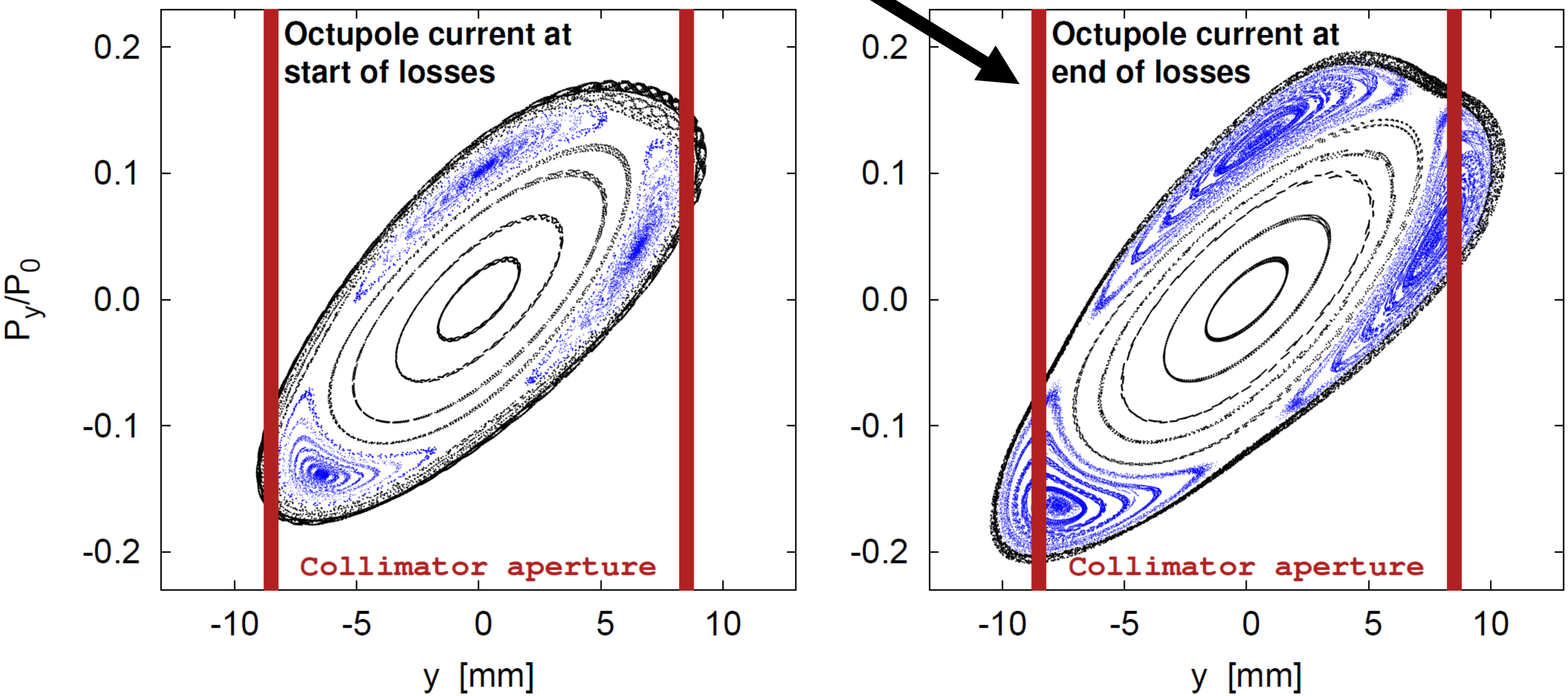
Nominal `correction’ <u>increased</u> octupole errors

Beam-based nonlinear chromaticity correction incorporated into operation since 2015

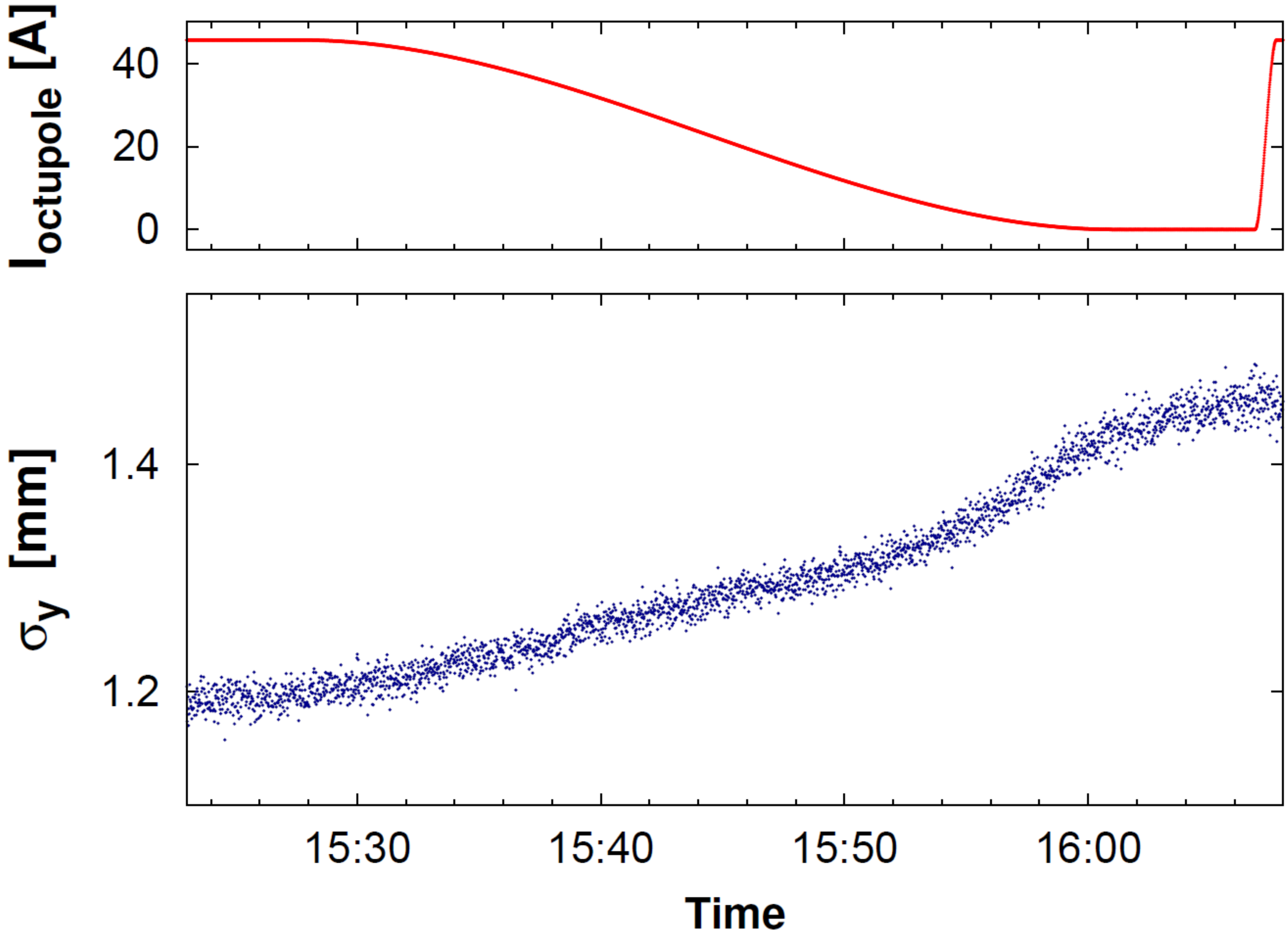


Beam-loss-monitors show losses occurred at the V-collimator

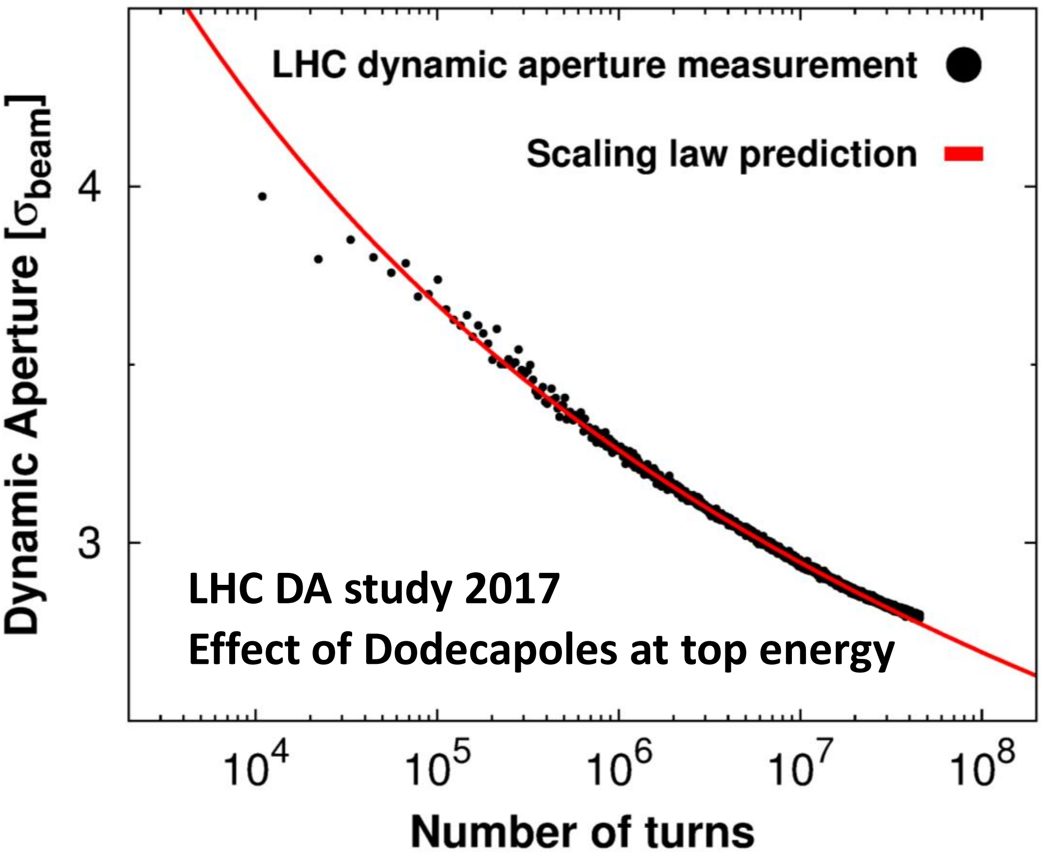
Observed losses explained by transport of particles in $3Q_y$



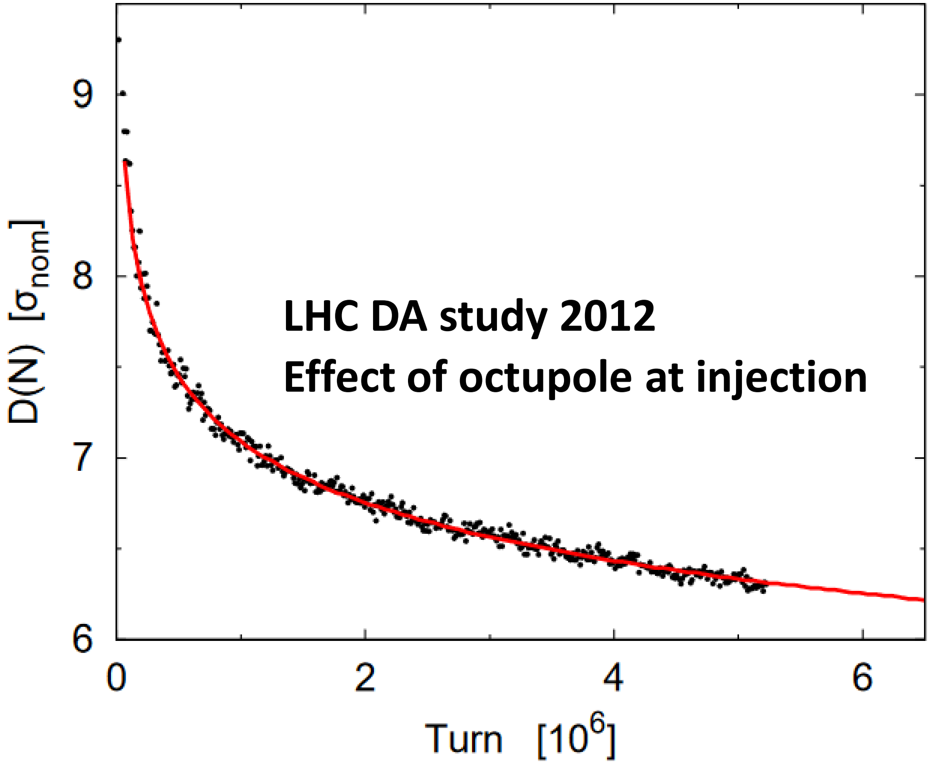
Being explored as potential mechanism for emittance growth in LHC ramp



Can perform measurements in the LHC to test whether scaling laws for dynamic aperture can allow extrapolation to long timescales relevant for LHC operation

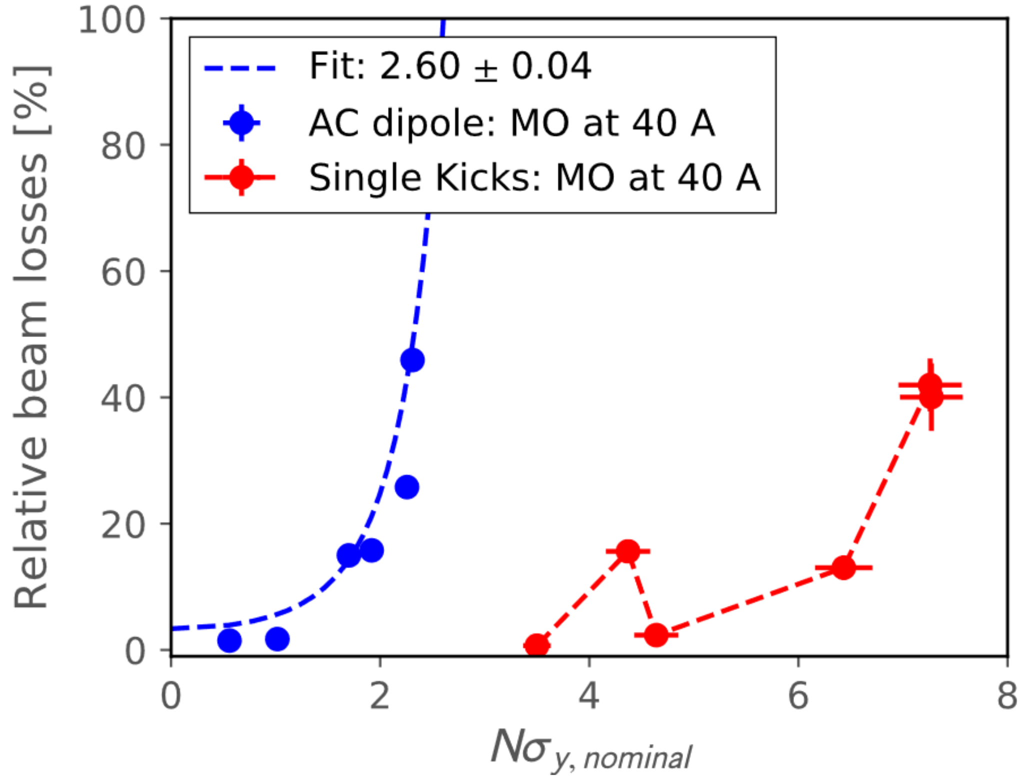


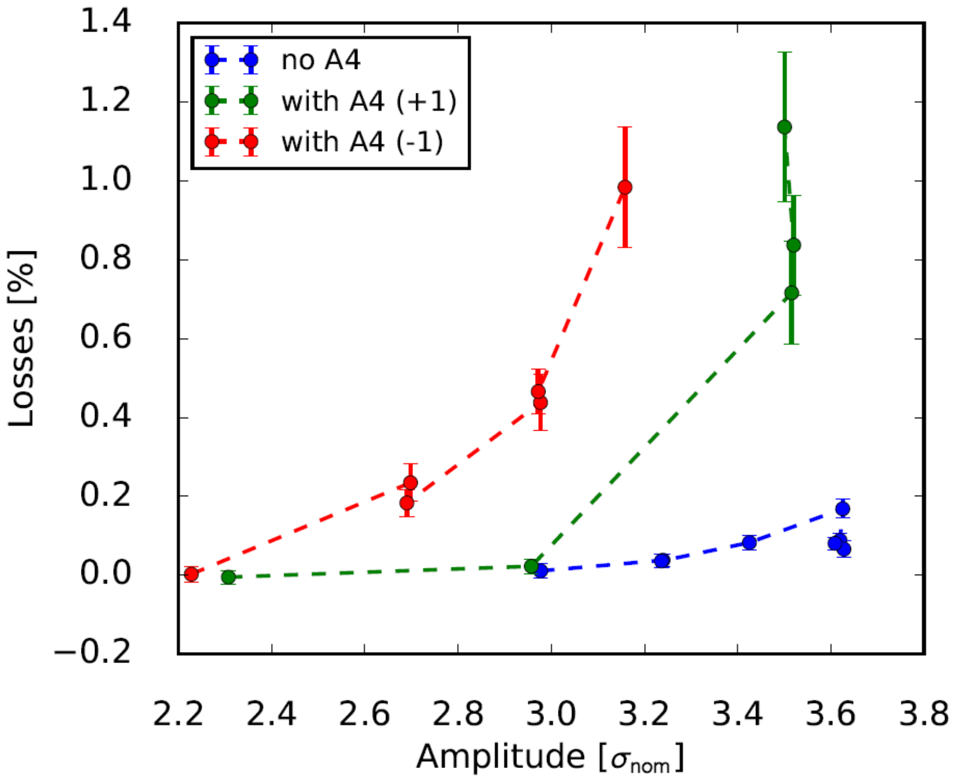
$$D(N) = D_\infty + \frac{b}{(\log N)^\kappa}$$



AC-dipole DA - Ph.D Thesis of Felix Calier (CERN)

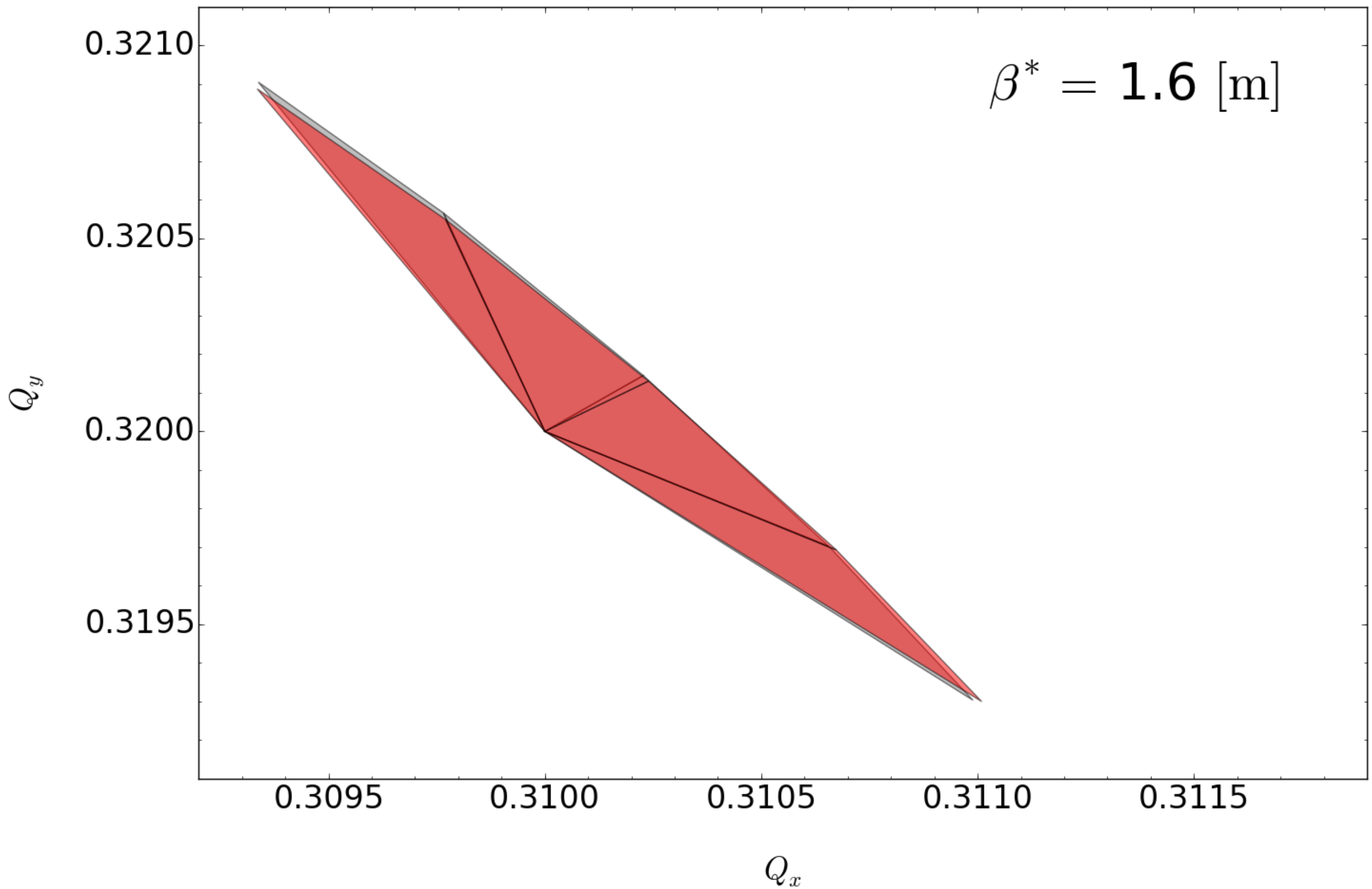
DA of driven oscillations can be significantly smaller than that of free oscillations





Provides a useful probe for testing nonlinear corrections at top energy

Main use so far is to study footprint distortion during the β*- squeeze due to b4 errors in ATLAS/CMS IRs



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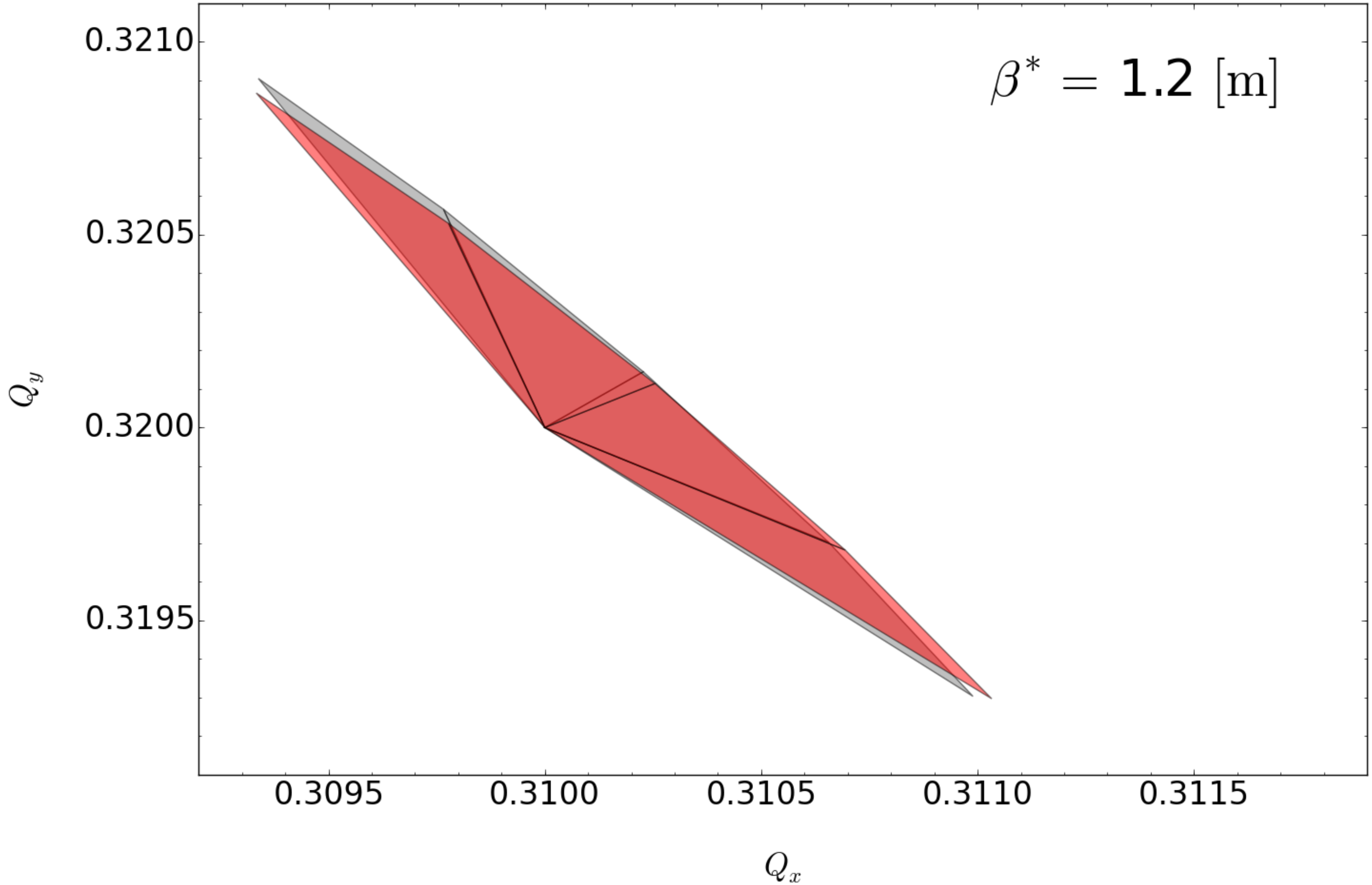

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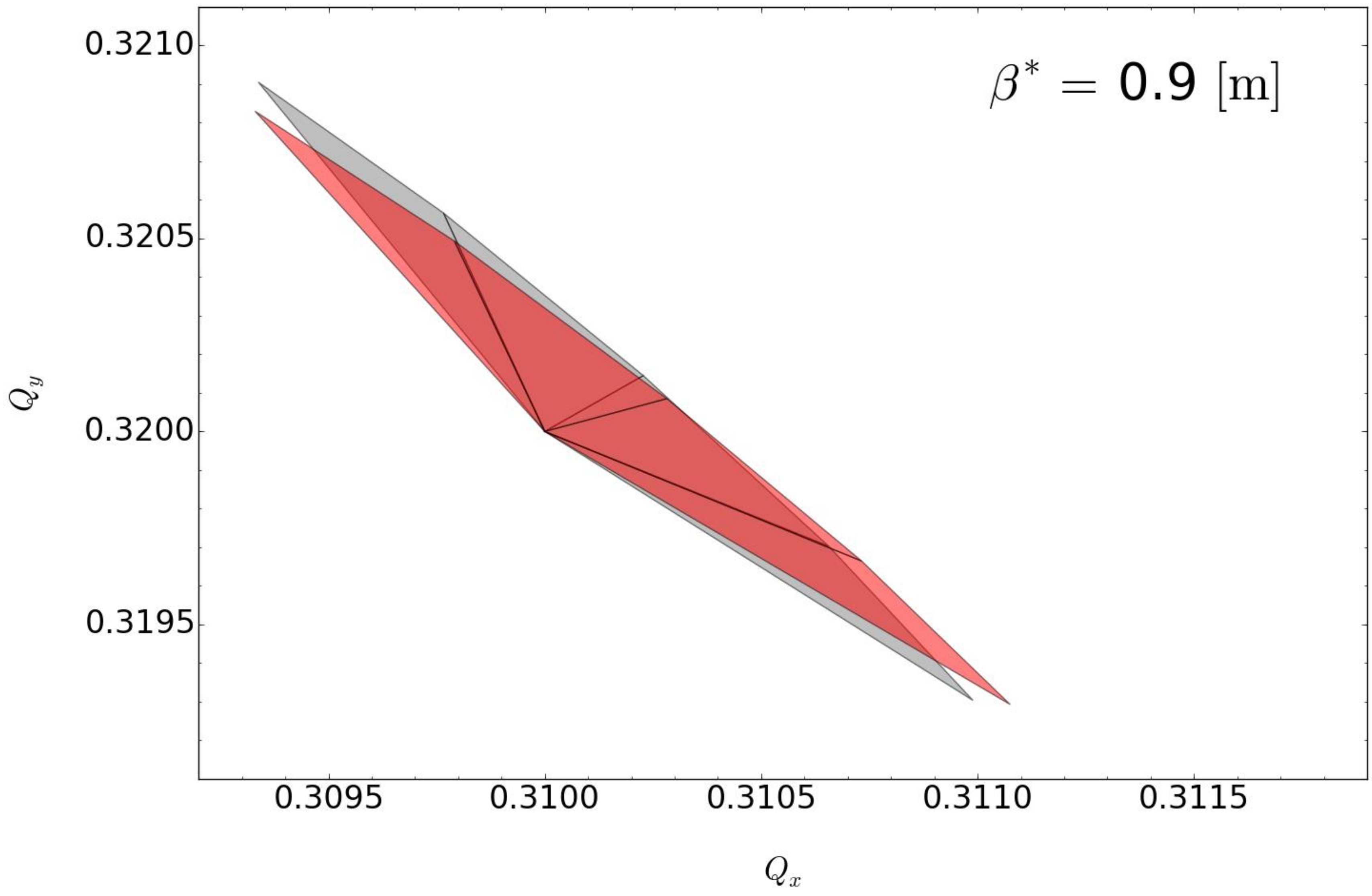

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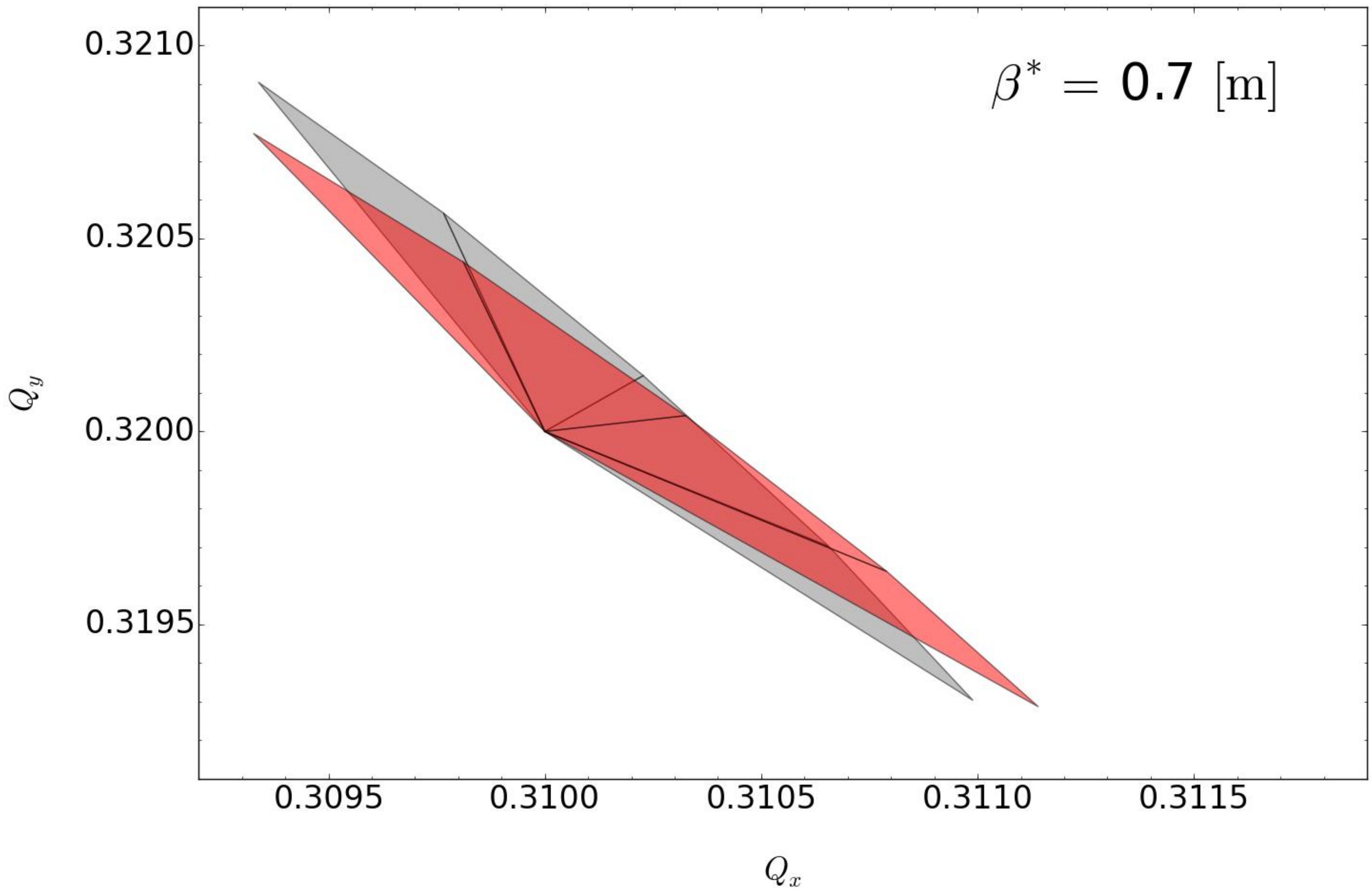

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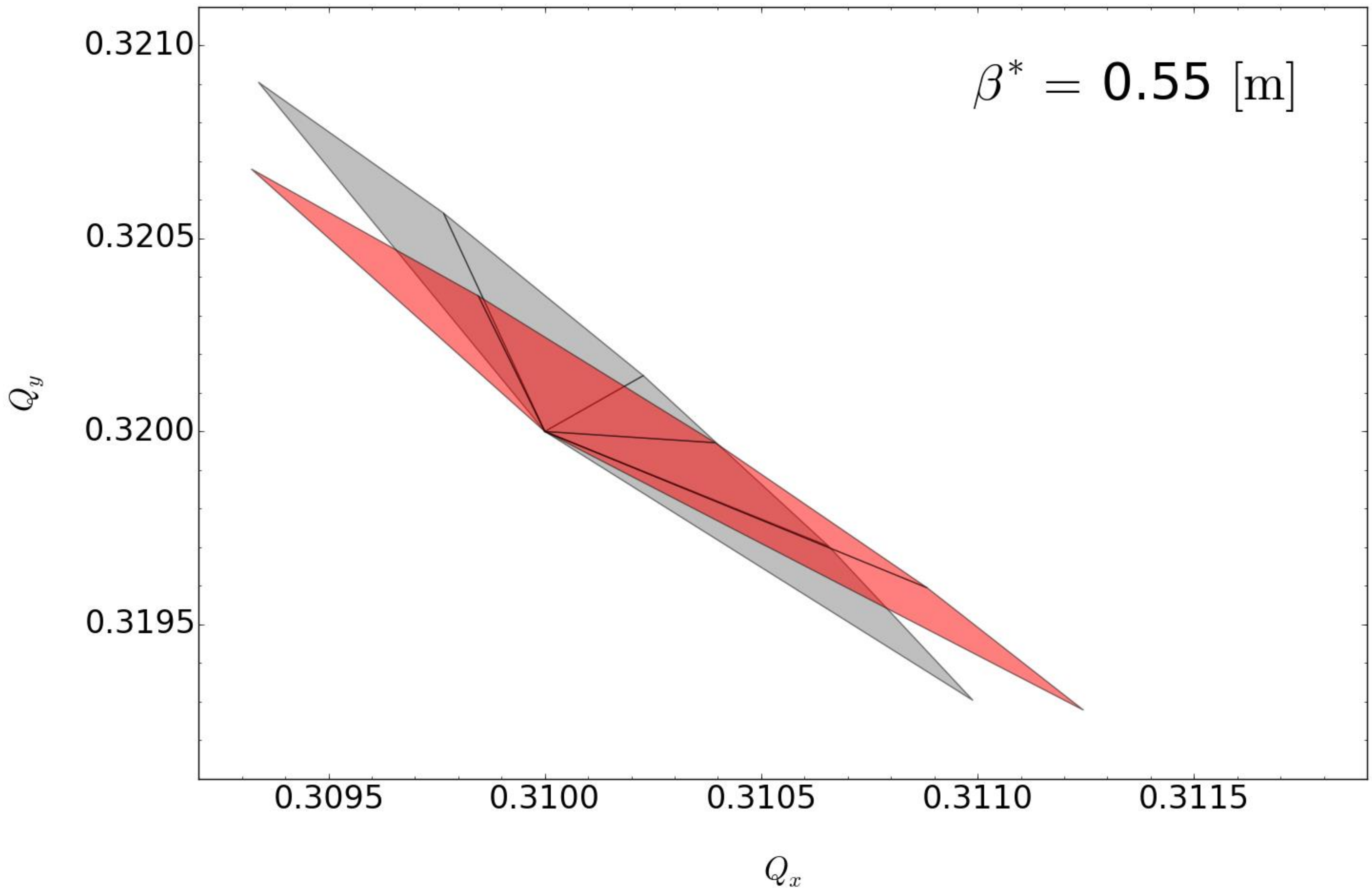

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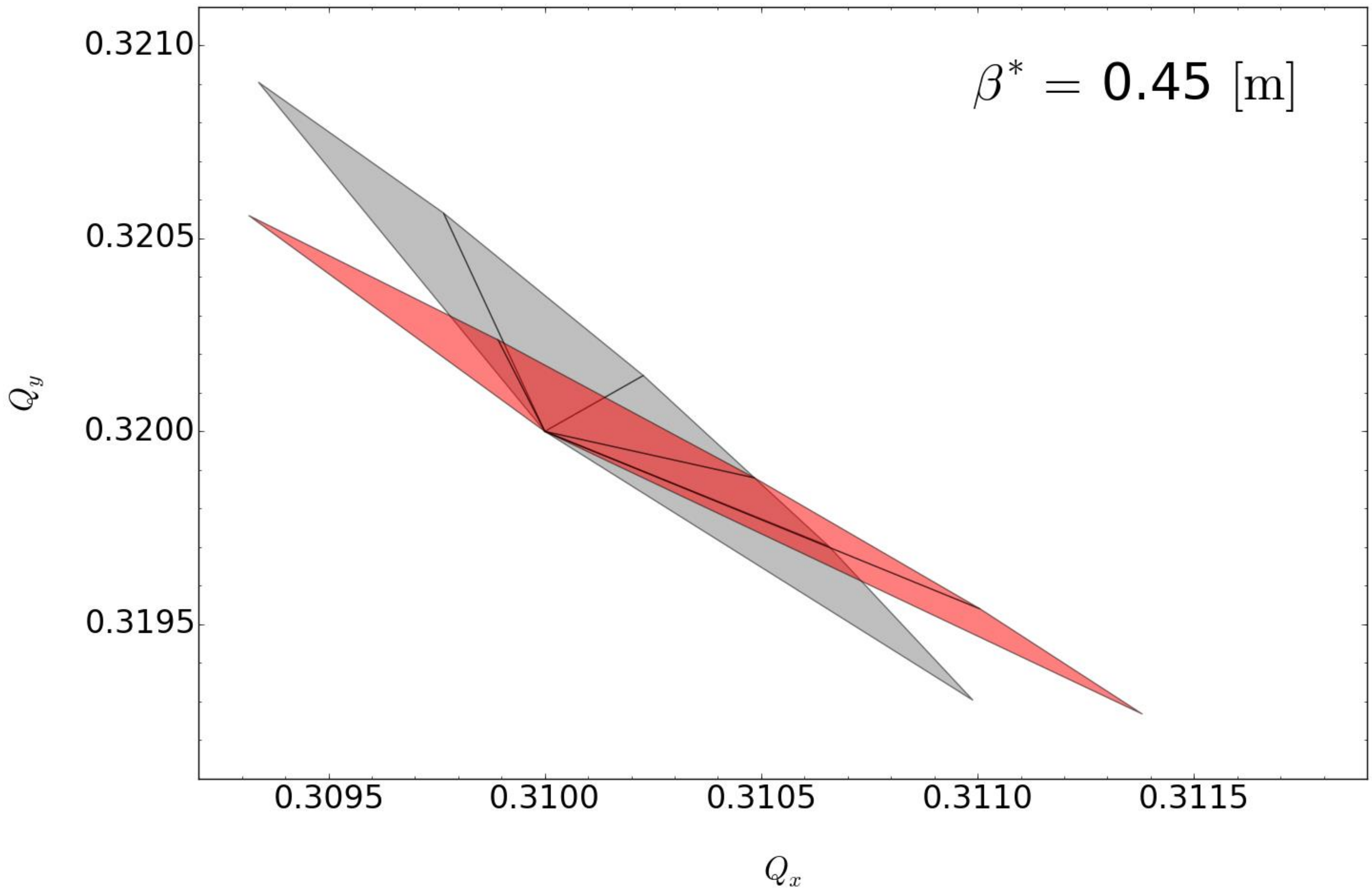

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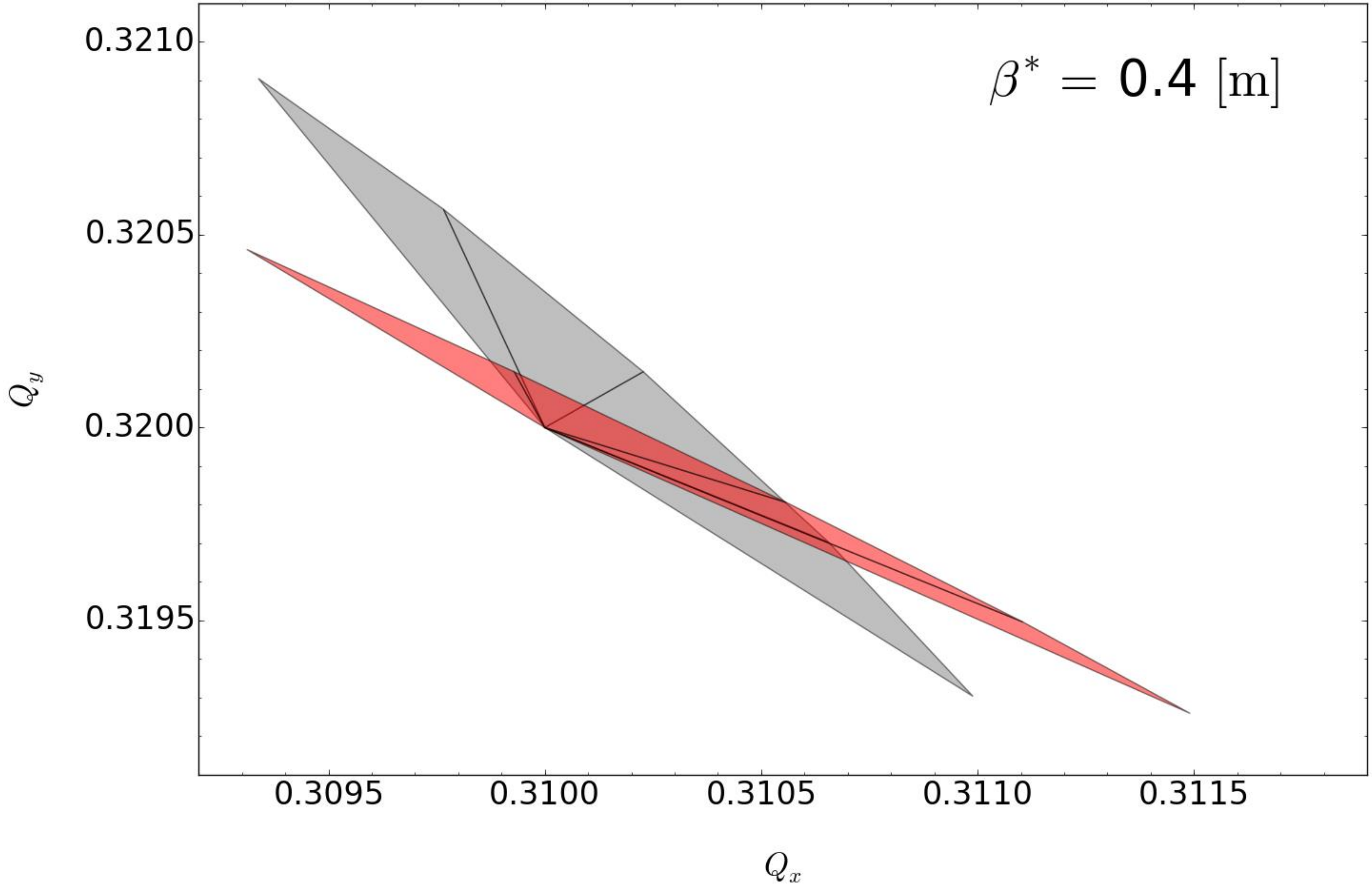

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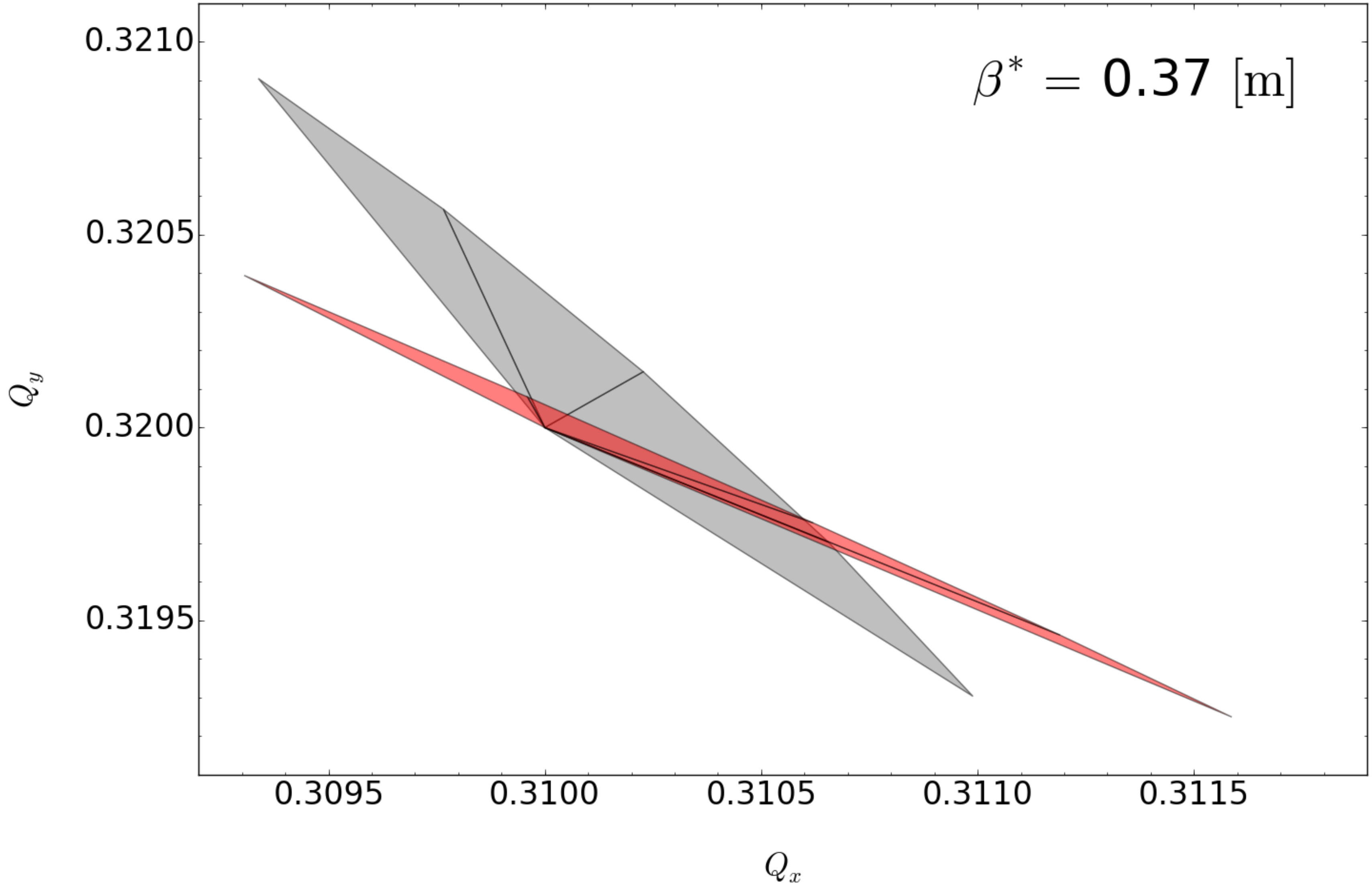

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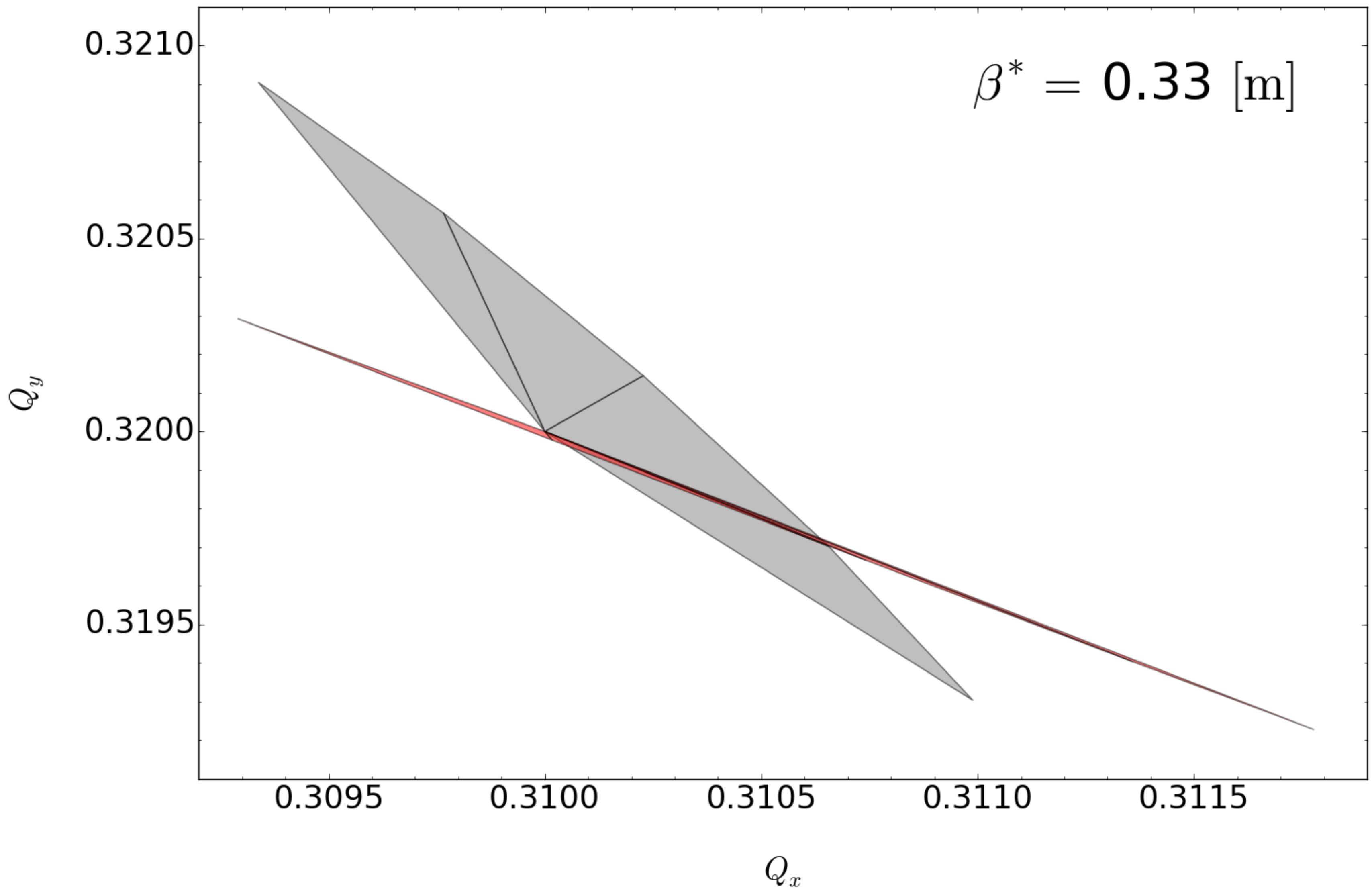

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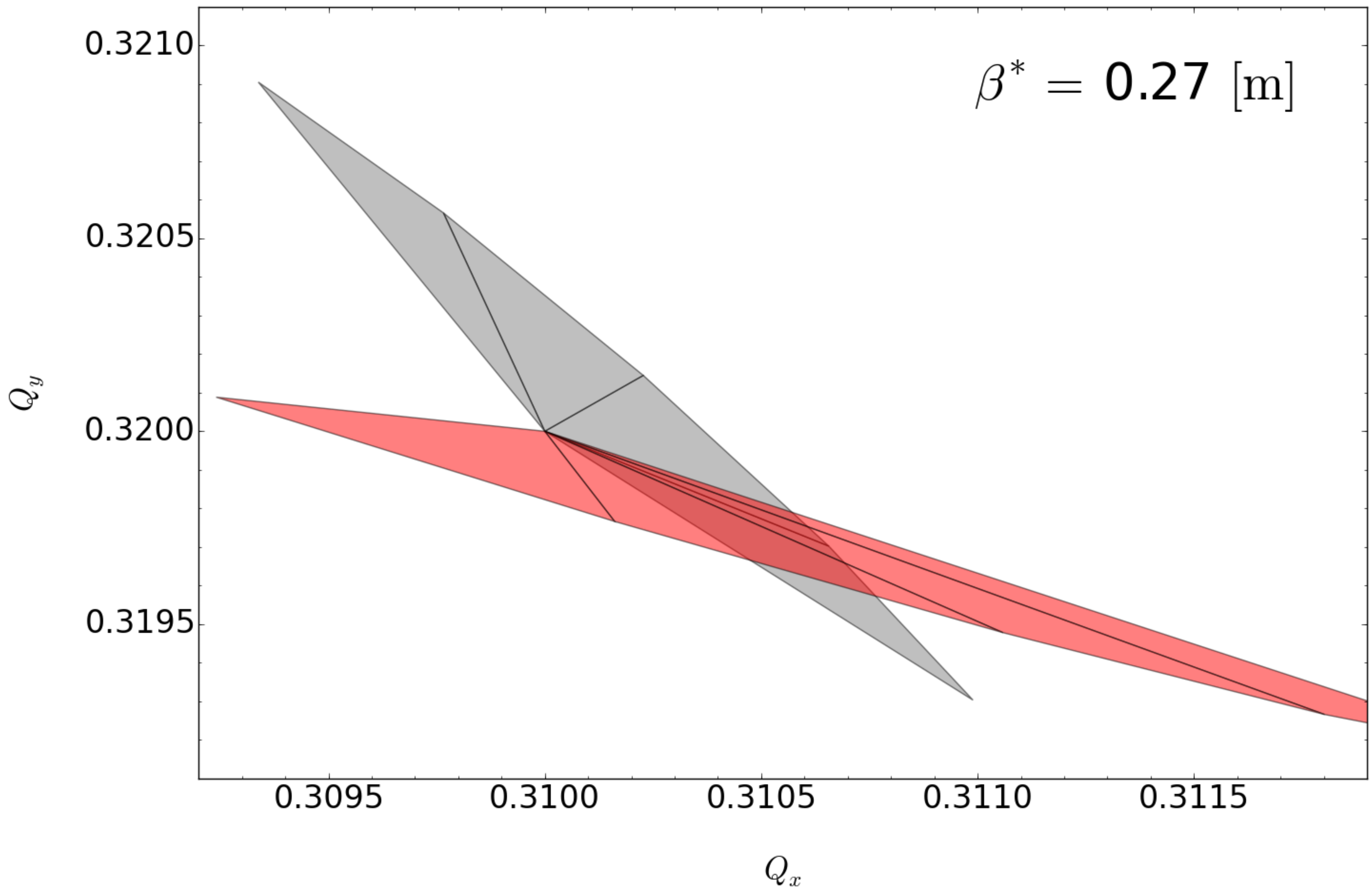
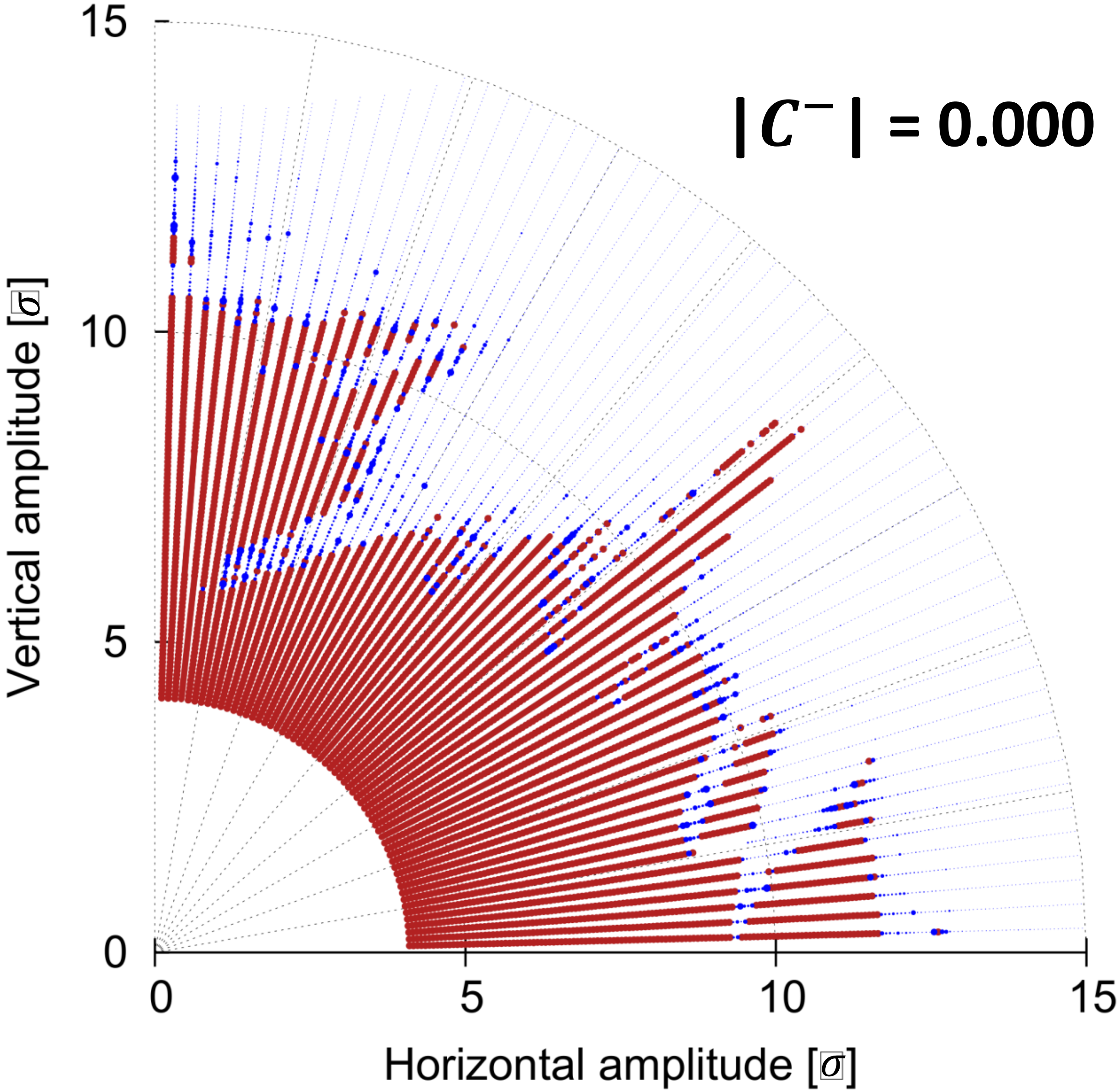
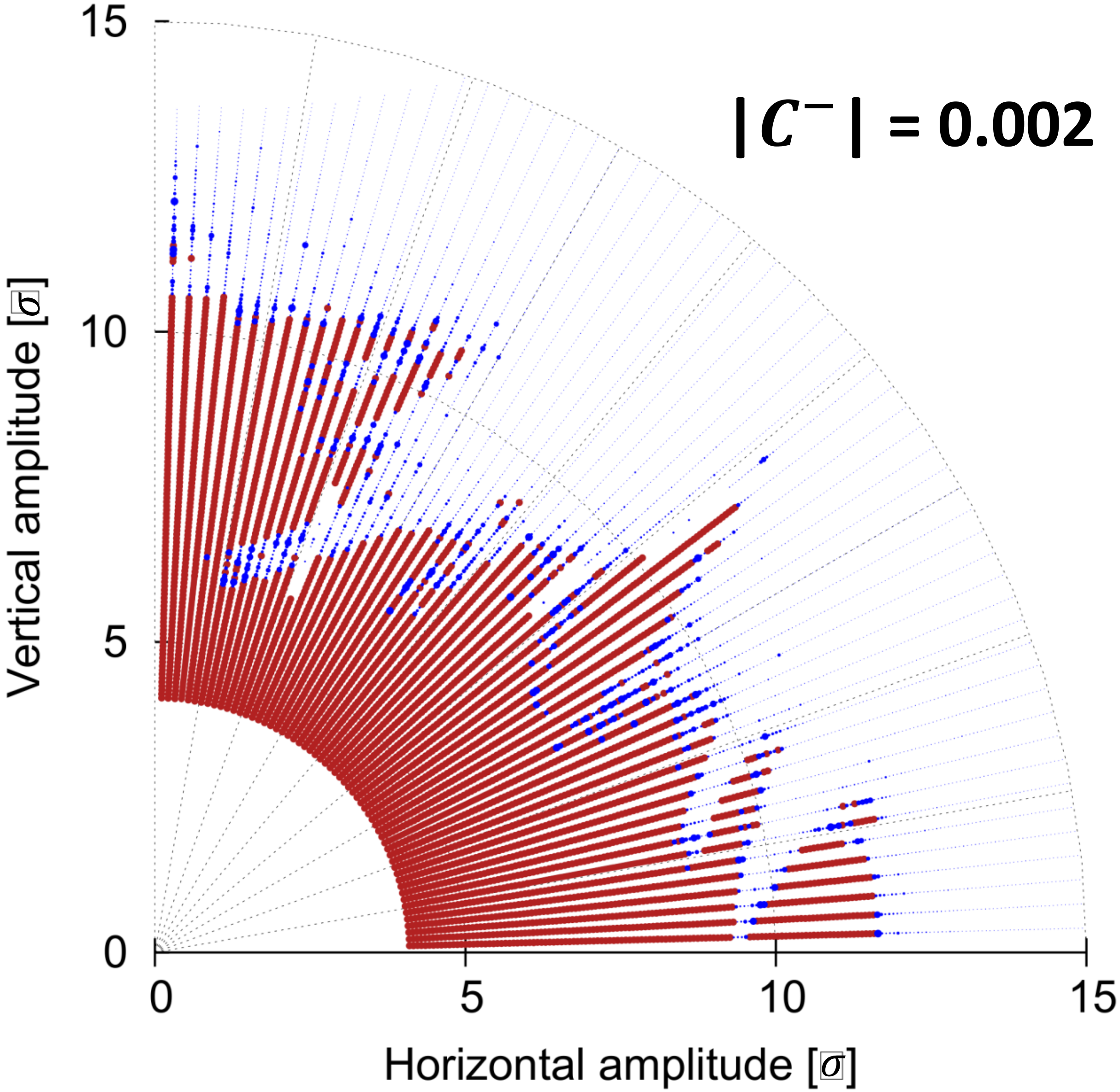


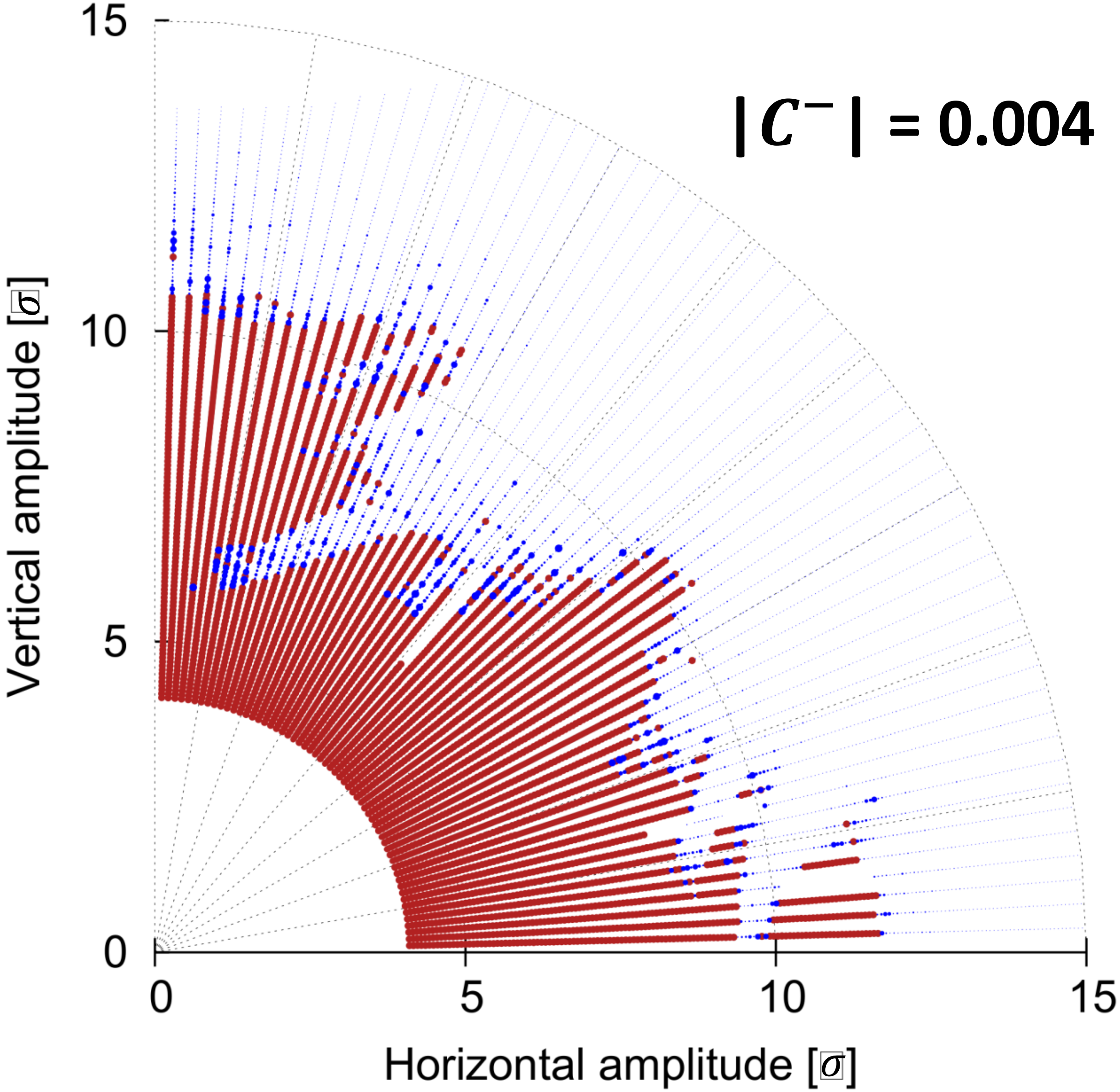
Linear coupling is major source of uncertainty in predicted DA



Linear coupling is major source of uncertainty in predicted DA



Linear coupling is major source of uncertainty in predicted DA



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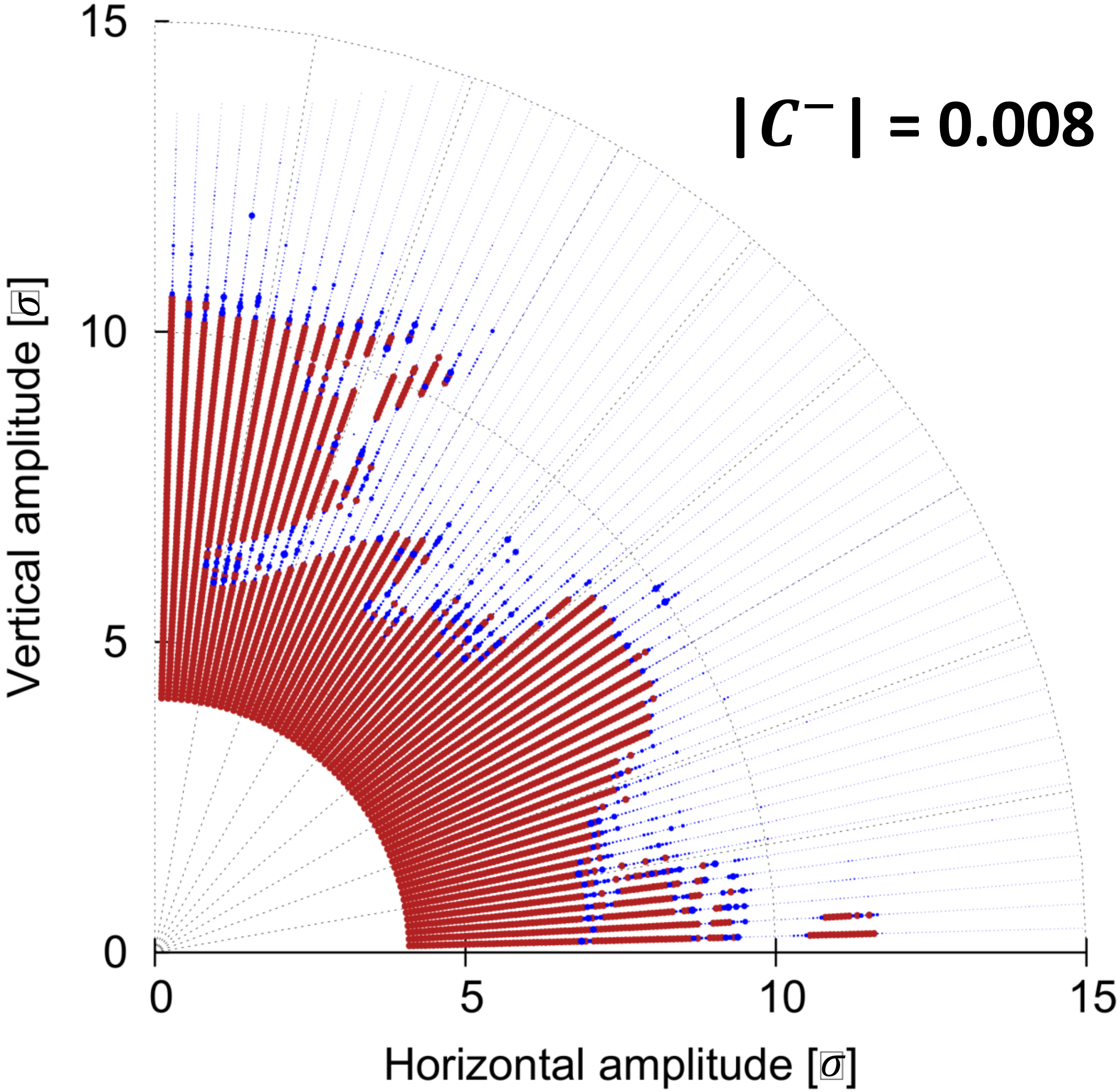

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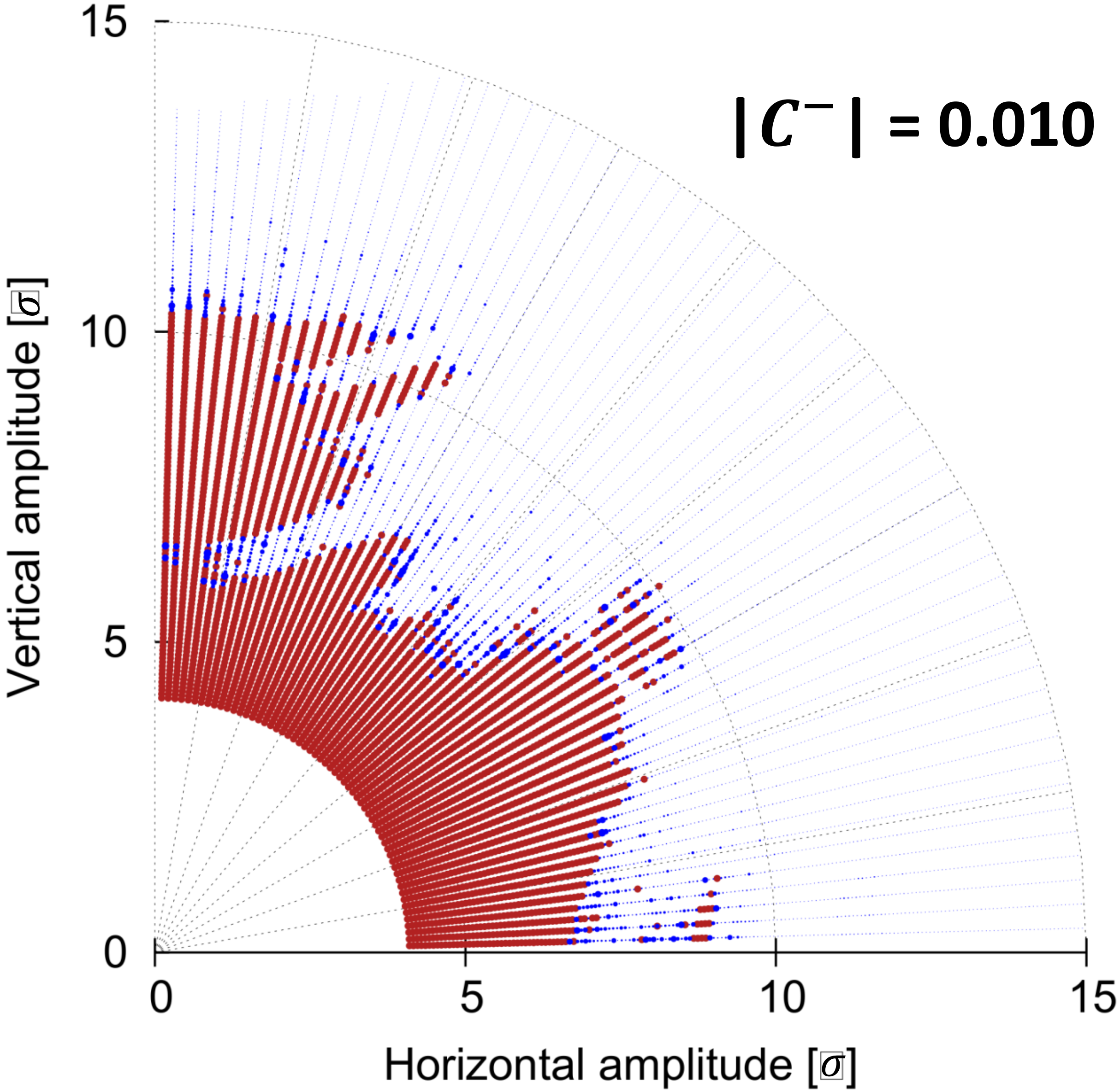
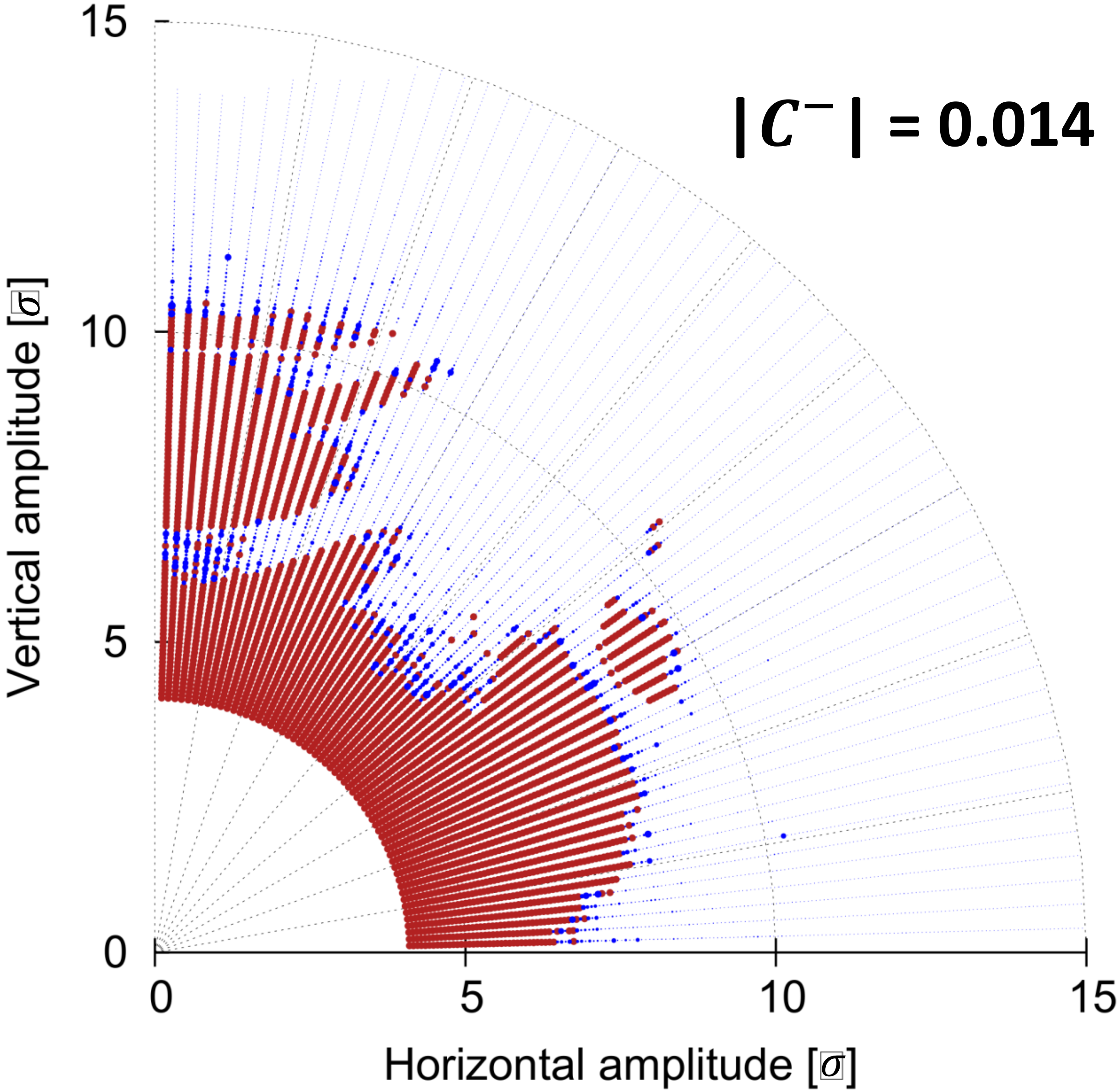
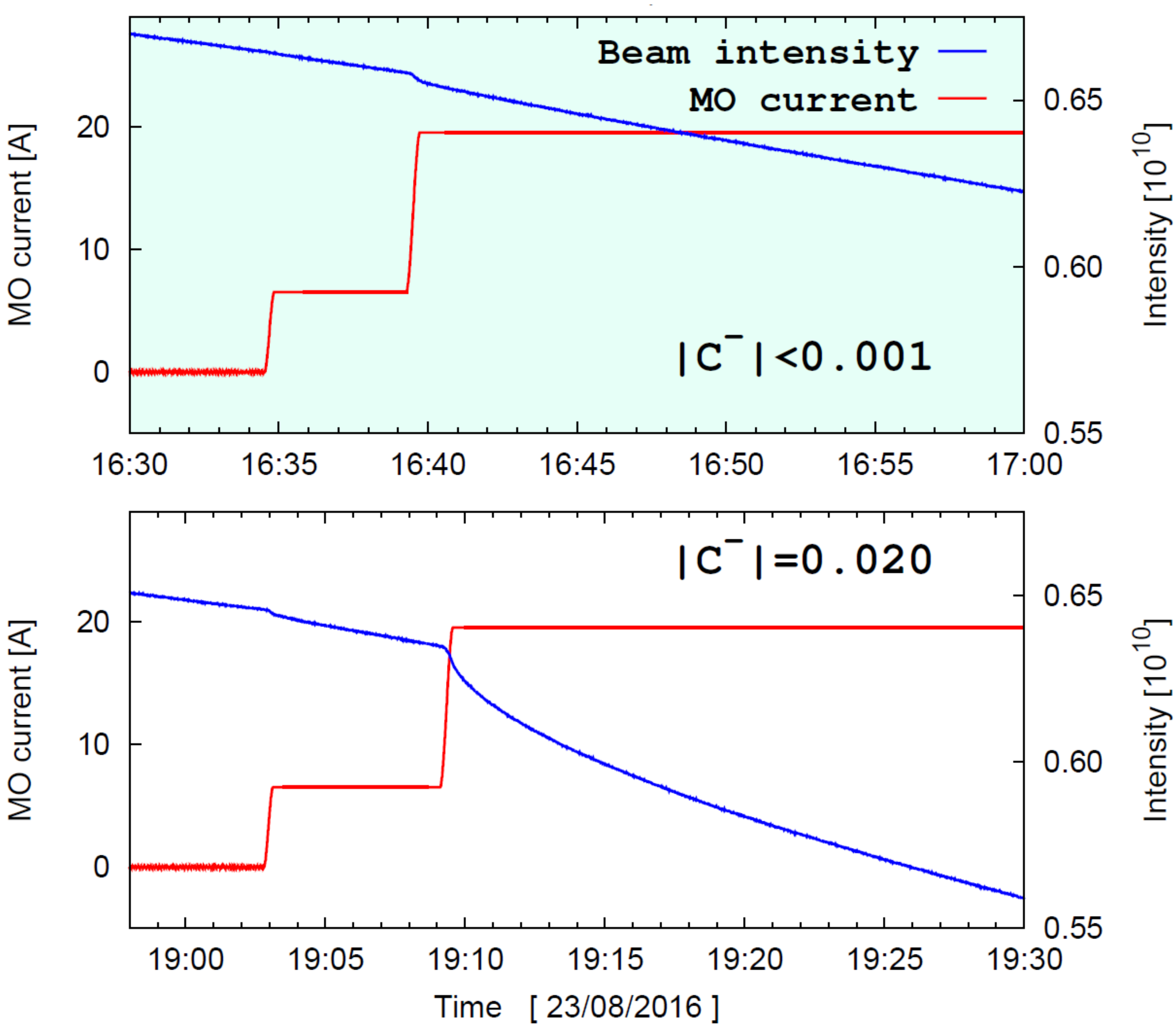


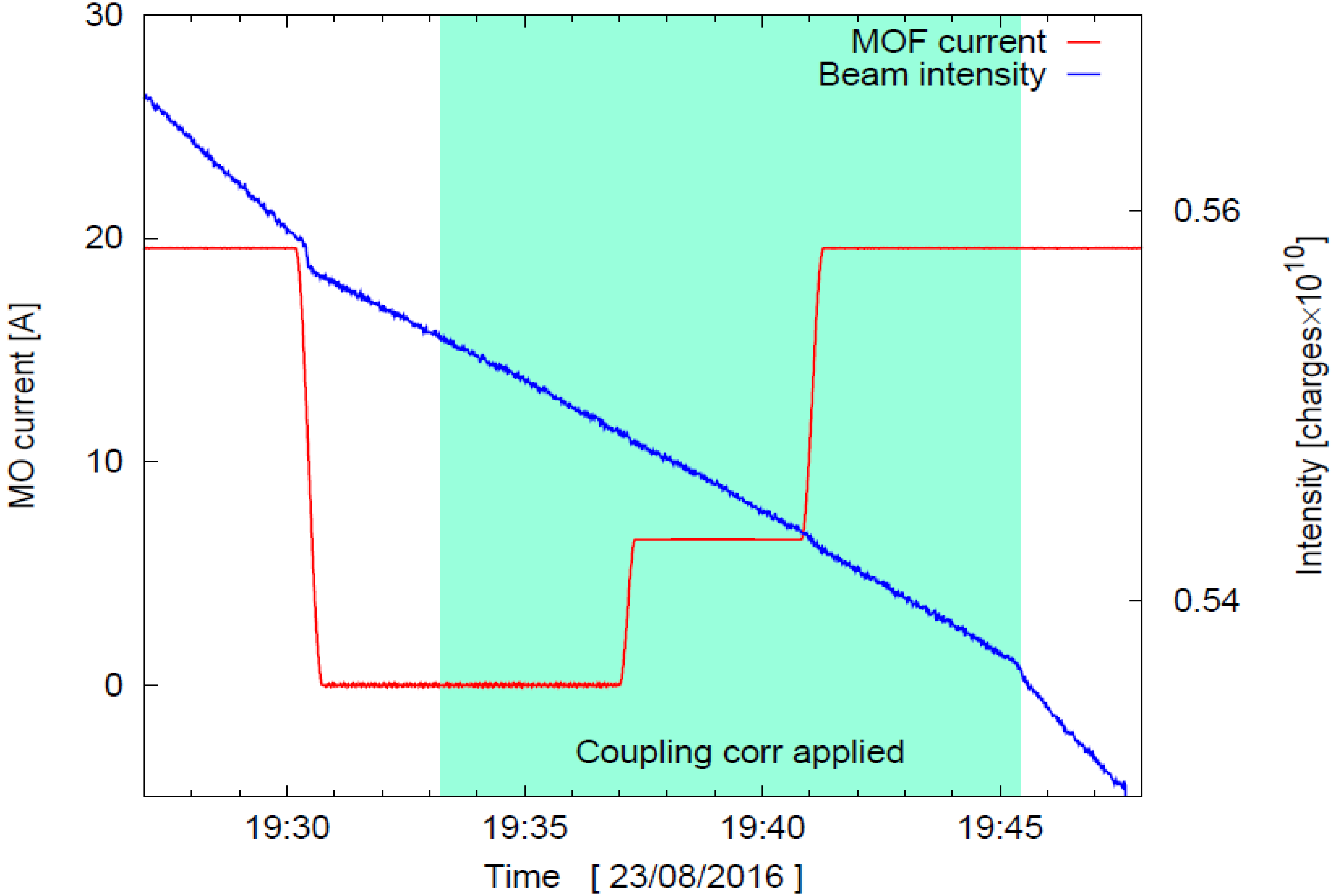
Linear coupling is major source of uncertainty in predicted DA



Linear coupling is major source of uncertainty in expected DA



Linear coupling is major source of uncertainty in predicted DA

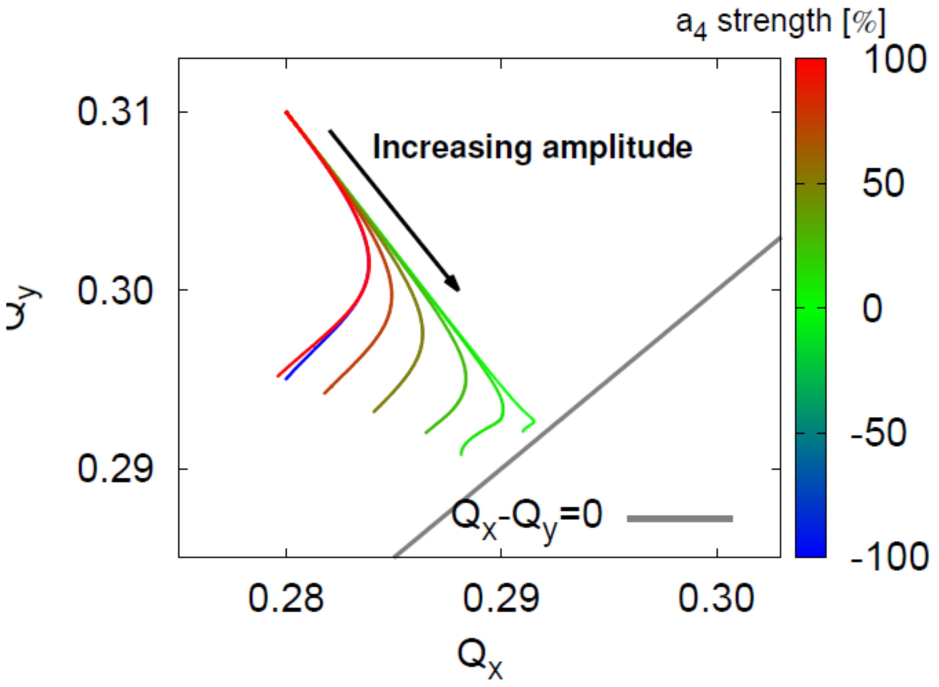


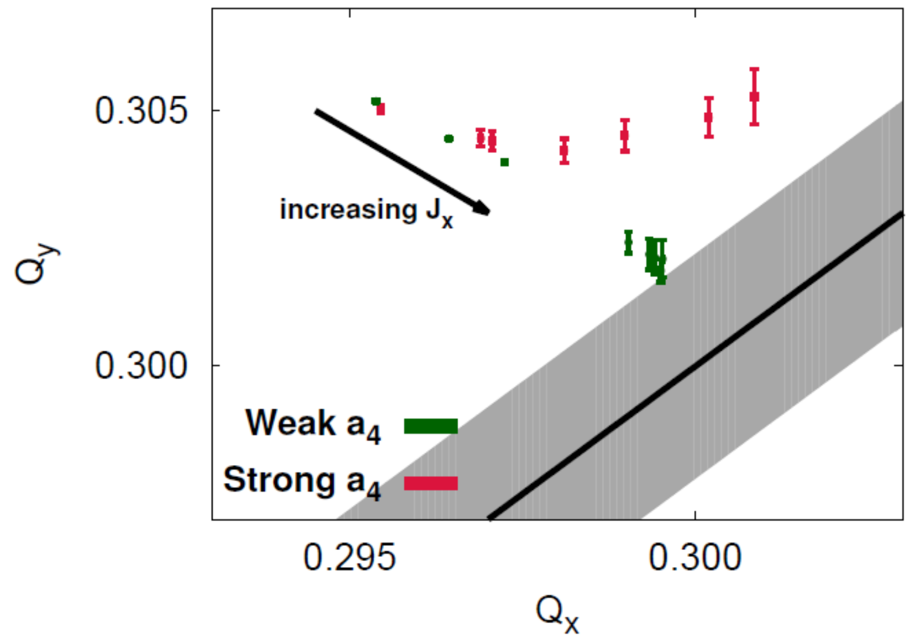
- ➢ **Impact of linear coupling on DA depends on octupoles**
- ➢ **Impact of Landau octupoles on DA depends on coupling**

$|C^-|$ & normal octupoles could still not fully explain 2012 observations

- Motivated further search in model for mechanisms generating ADECTA
- **Predict that a_4 alone did not generate ADECTA,**
  but $a_4 + b_4$ would generate ADECTA

Amplitude dependent closest tune approach generated by normal and skew octupoles
E.Maclean, T.Persson, R.Tomas, IPAC'17 WEPIK091





- **ADECTA from $a_4 + b_4$ demonstrated in dedicated MD in 2017**

E.Maclean,R.Tomas,T.Persson,F.Carlier, CERN-ACC-NOTE-2018-0027