Optics and non-linear beam dynamics at 4 and 6.5 TeV

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Contents I - 2012 experience

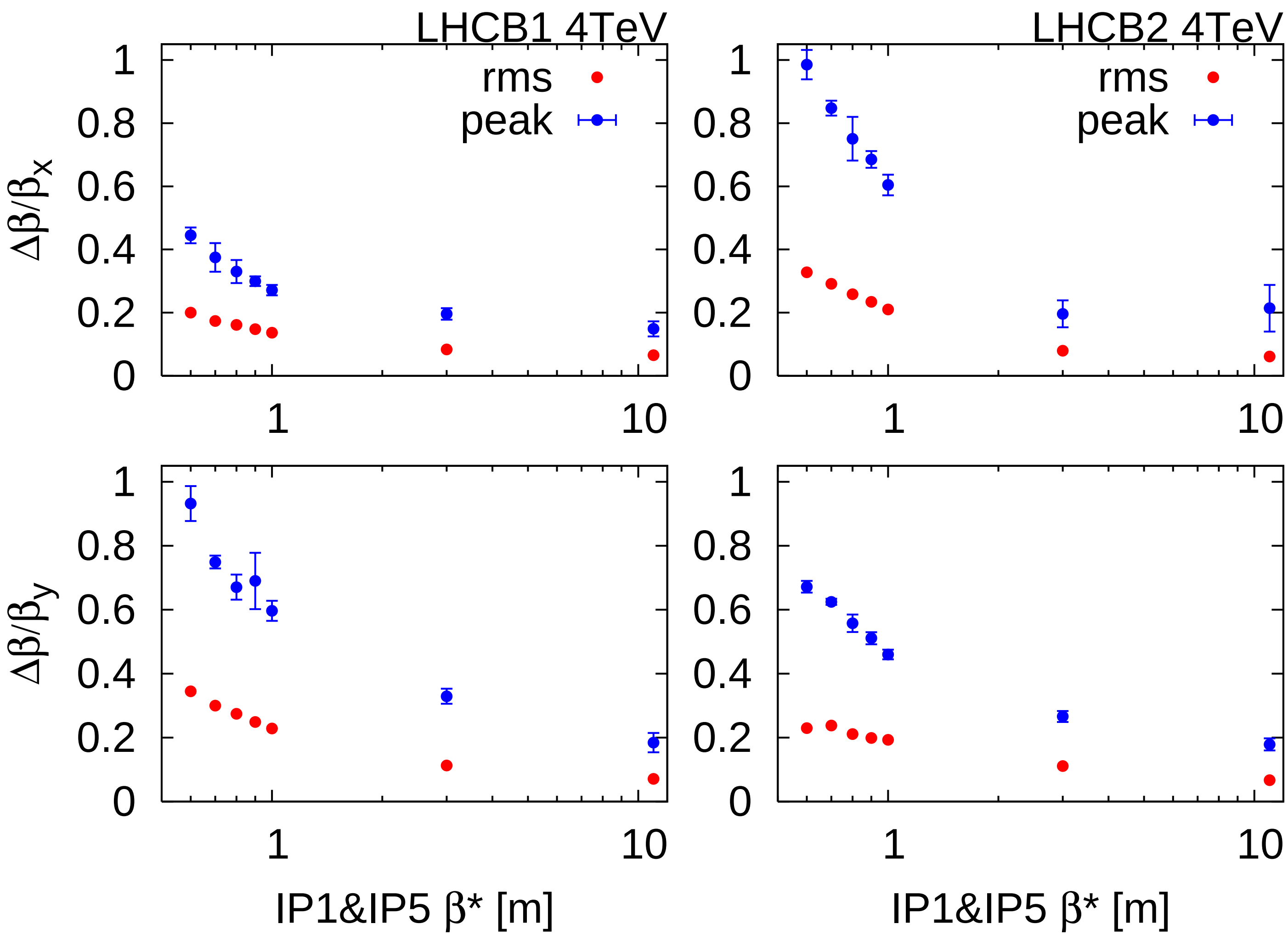
- ⋆ Record low β-beating
- ⋆ Automatic coupling correction
- ⋆ MQY 1% calibration errors
- ⋆ DA measurement at injection
- ⋆ Chromatic coupling correction
- ⋆ IR non-linear correction
- ⋆ Measurement of amplitude detuning

Contents II - Post LS1 era

- ⋆ Injection β^*
- ⋆ Collision tunes @ injection
- ⋆ Ramp & Squeeze and Collide & Squeeze
- ⋆ ATS? Flat optics?
- ⋆ Octupole reach at 6.5 TeV
- ⋆ DA at 0.4 m (Nominal optics)

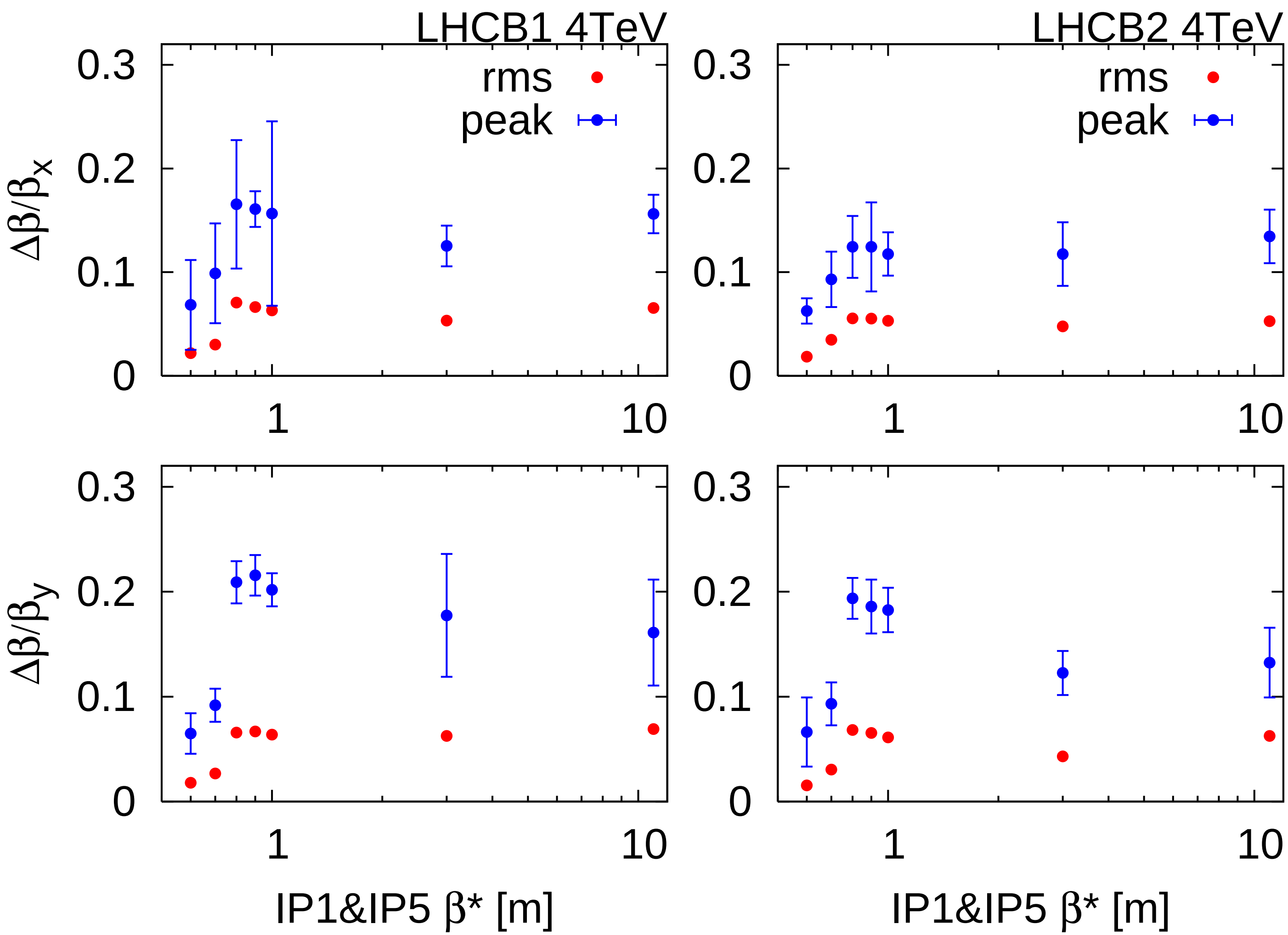
OMC team
2011

Record low β-beating - Strategy



Measuring virgin machine (100% β-beating!) to compute best local corrections (also for coupling)

Record low β-beating - Correction



Local and global corrections yield about 7% β-beating at 0.6 m!

LHC optics makes history

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Record low β beating in the LHC

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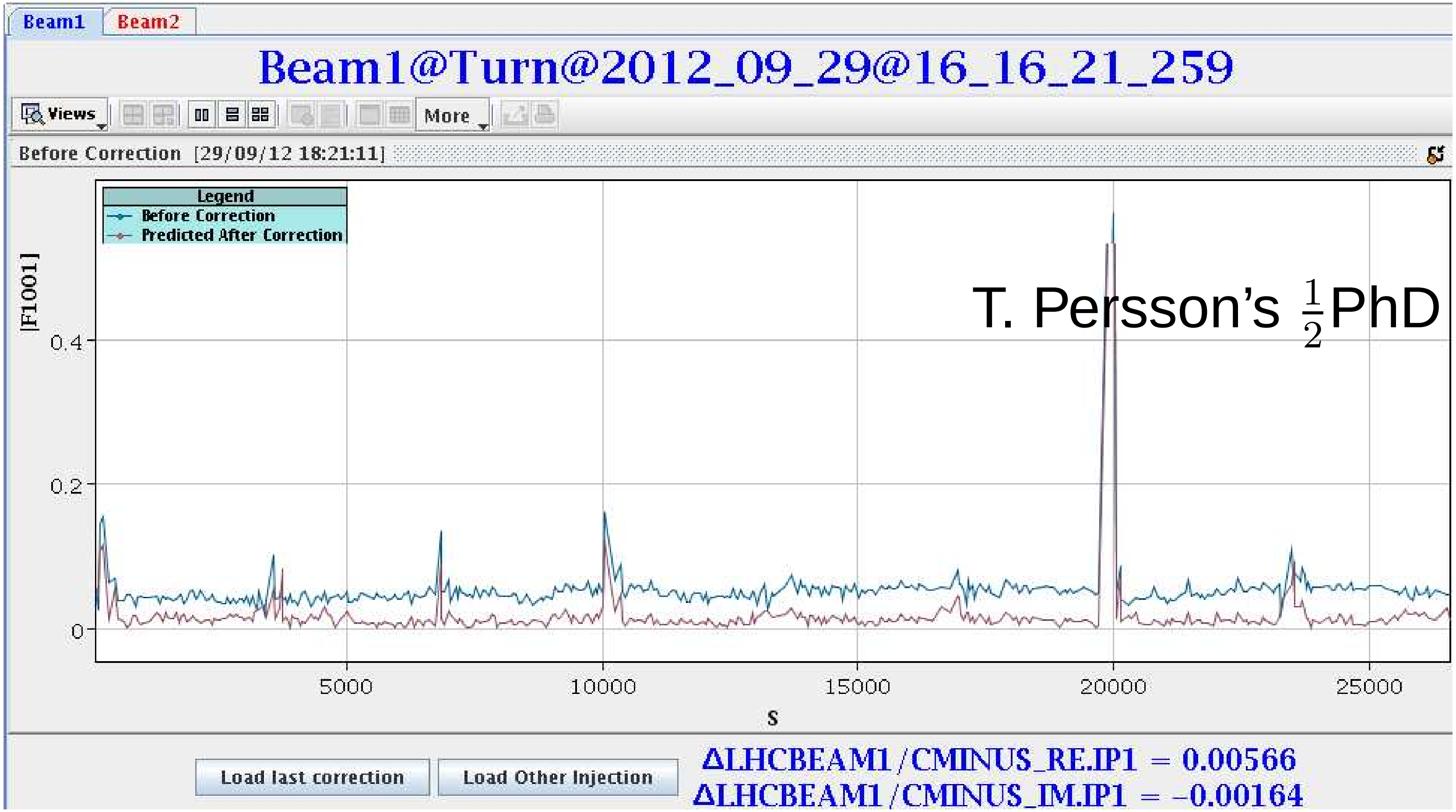
Lepton Collider	Circumference [km]	Peak $\Delta\beta/\beta$ [%]	Hadron Collider	Circumference [km]	Peak $\Delta\beta/\beta$ [%]
PEP II	2.2	30	HERA-p	6.3	20
LEP	27	20	Tevatron	6.3	20
KEKB	3	20	RHIC	3.8	20
CESR	0.8	7	LHC	27	7

Coupling correction improvements in 2012

Better global knobs for beam 2, very stable local corrections and an automatic tool based on inj. oscillations:



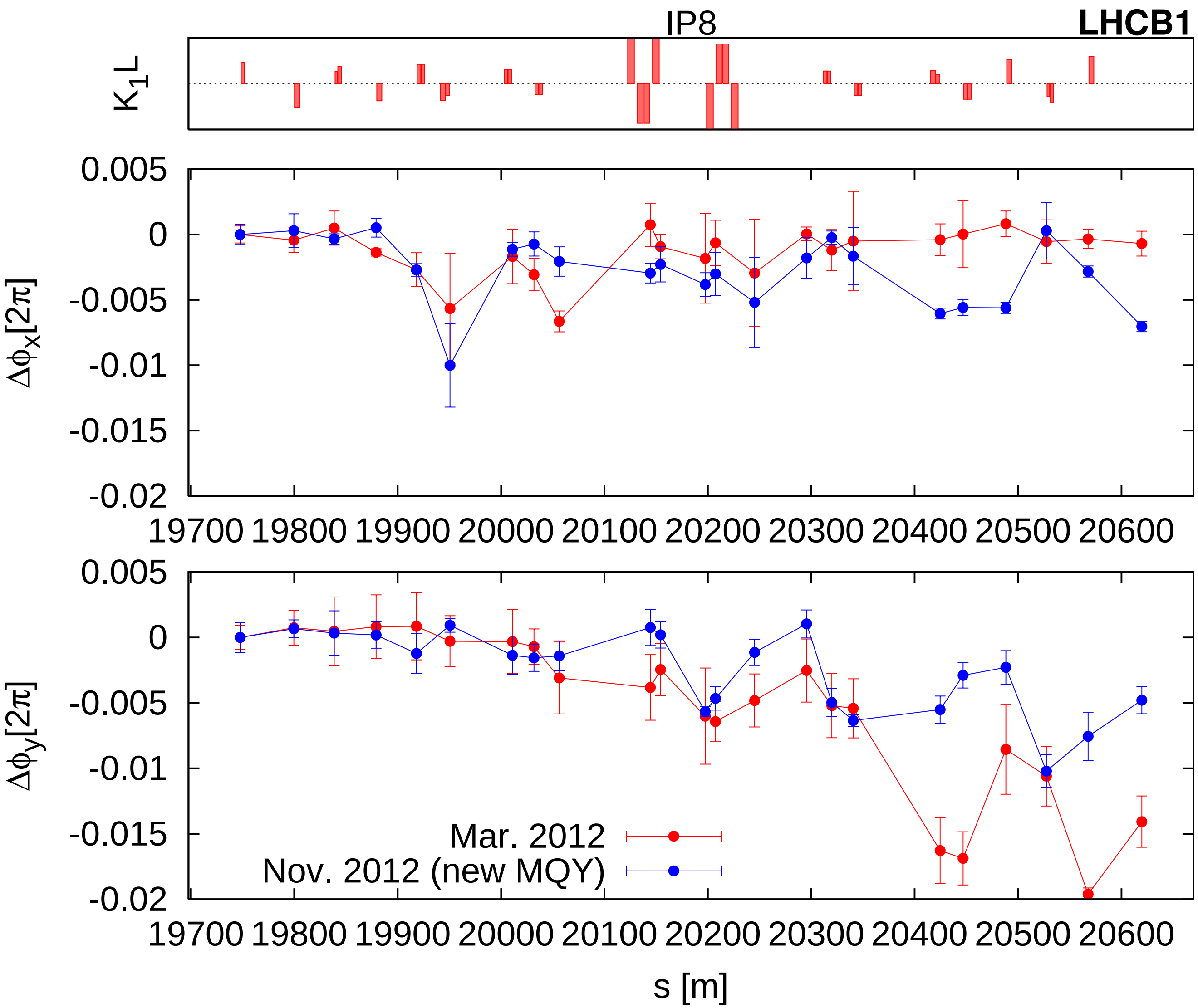
It seems that coupling problems disappeared in 2012

MQY - Beam based Vs new calibrations

Element	Beam based corrs [%]	Per's new cal [%]
RQ4.L5B2	1.01	1.53
RQ4.L5B1	0	0.32
RQ5.L6B1	0.60	0.72
RQ5.L6B2	0.70	0.73
RQ4.L8B1	1.00	1.22
RQ4.L8B2	0	1.19
RQ4.R8B1	0	0
RQ4.R8B2	2.40	0
RQ5.R8B2	0.80	0.95
RQ5.R8B1	2.70	0.99

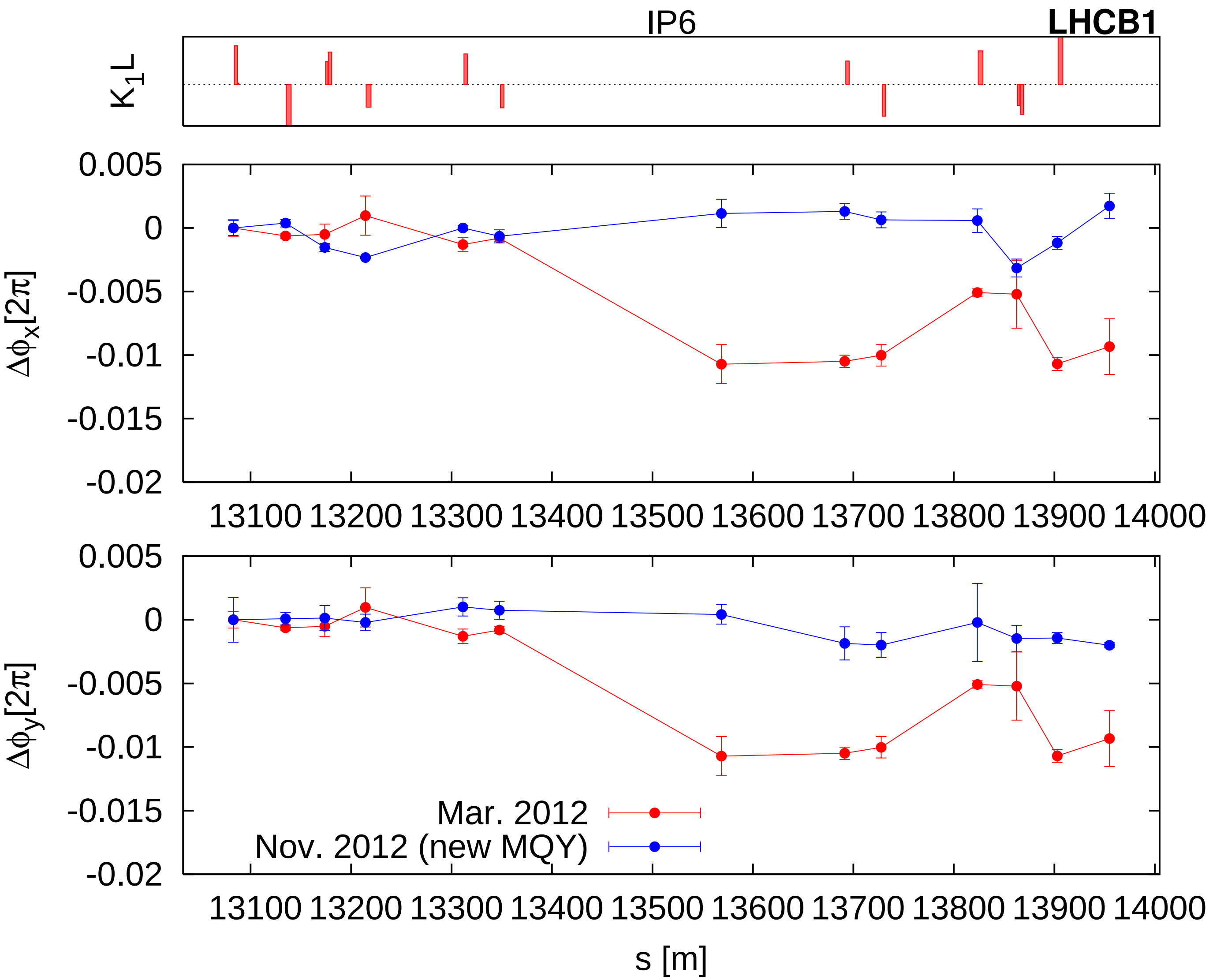
IR5 & IR6 errors found with beam. IR8 always difficult $\longrightarrow$ Needed experiment.

MQY Experiment - IR8



Excellent!

MQY Experiment - IR6



Excellent!

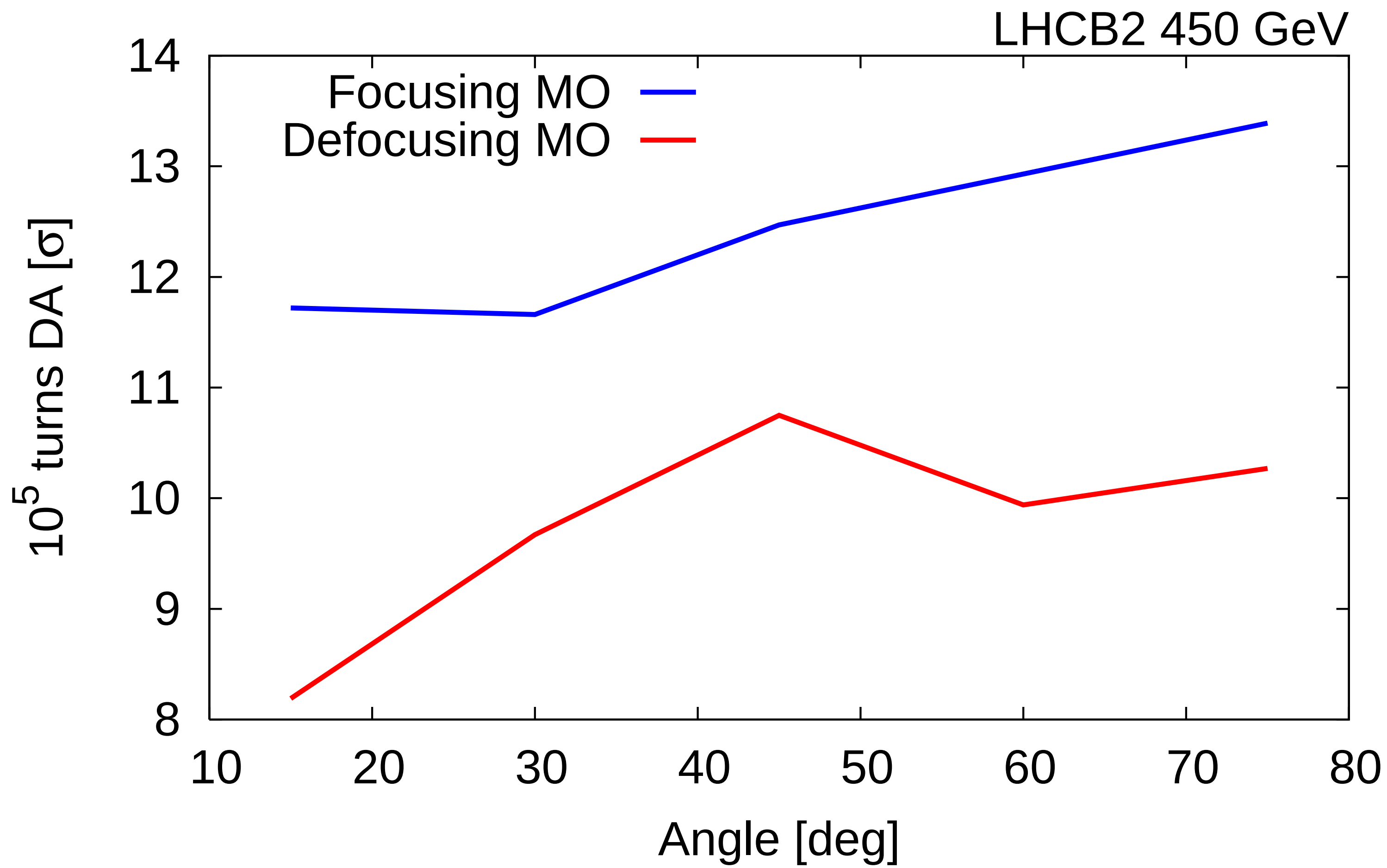
Good bye 1% errors!

What is left:

- ⋆ Triplet (et al) errors in the 1‰level
- ⋆ Triplet longitudinal misalignments
- ⋆ Dipole b_2 errors & MQT correction

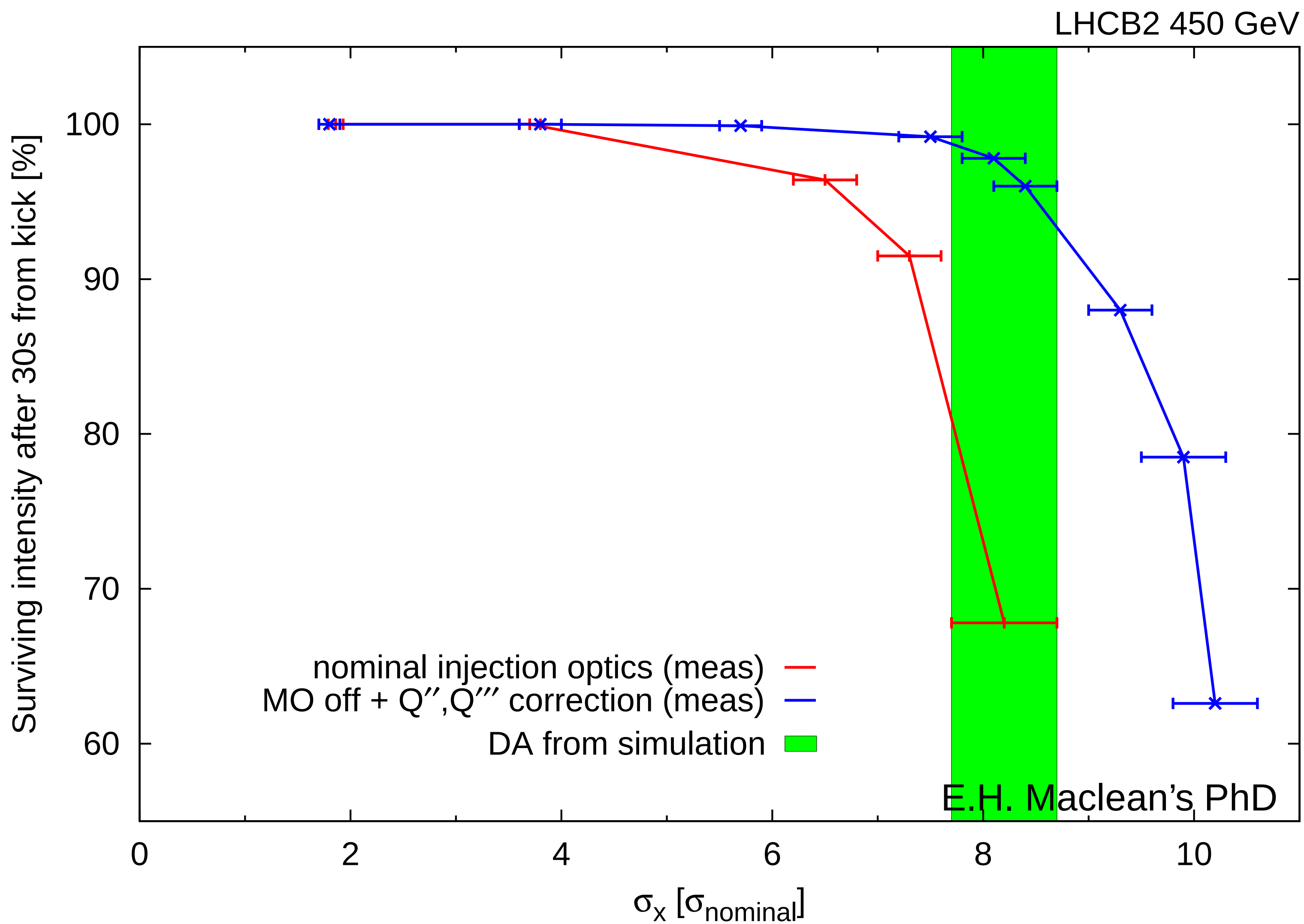
If properly addressed β-beating$\approx$3% at reach!

DA at Injection - Two MO polarities



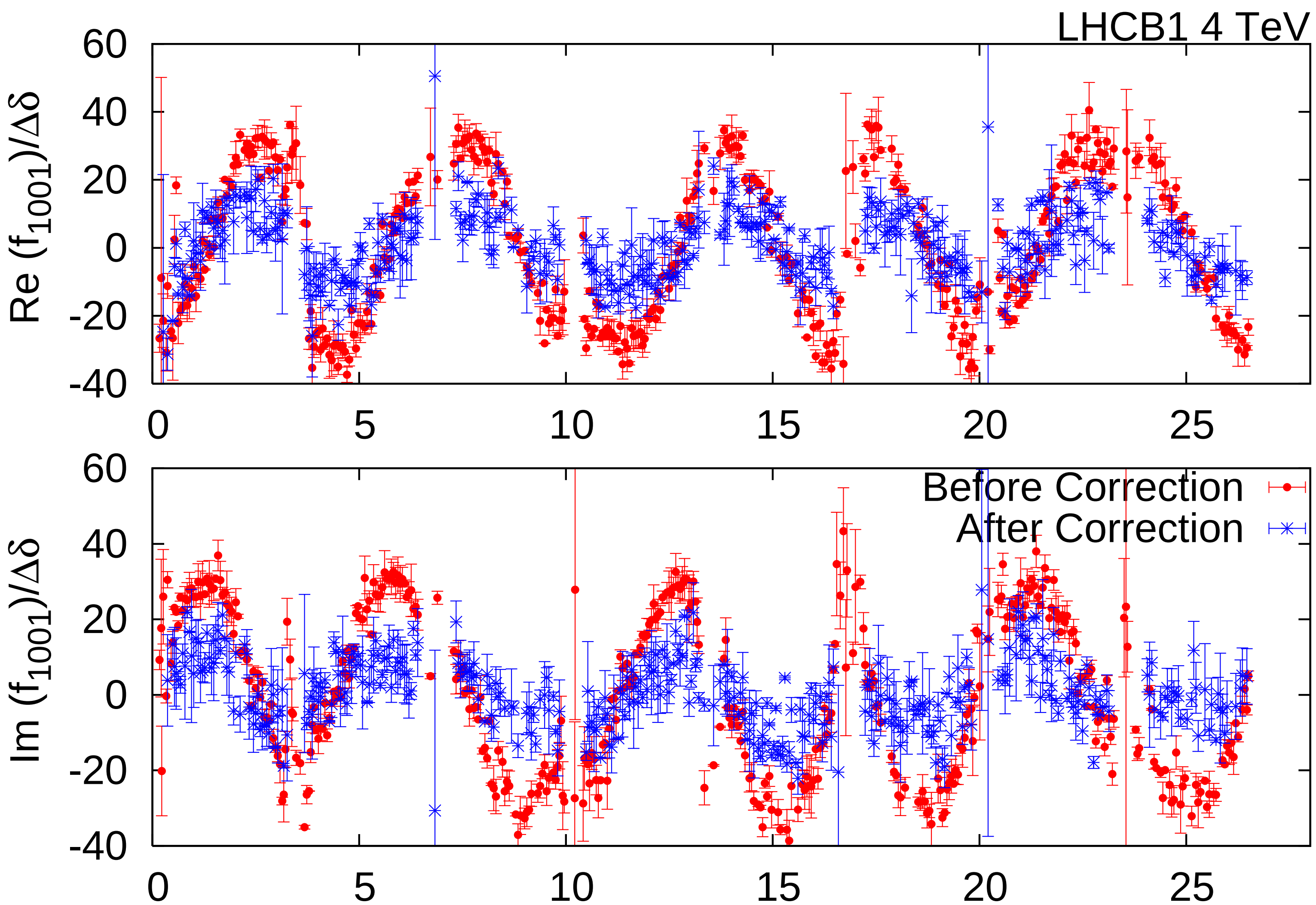
MOs affect DA at injection $\longrightarrow$ Minimize their str.

DA at Injection - Experimental benchmark



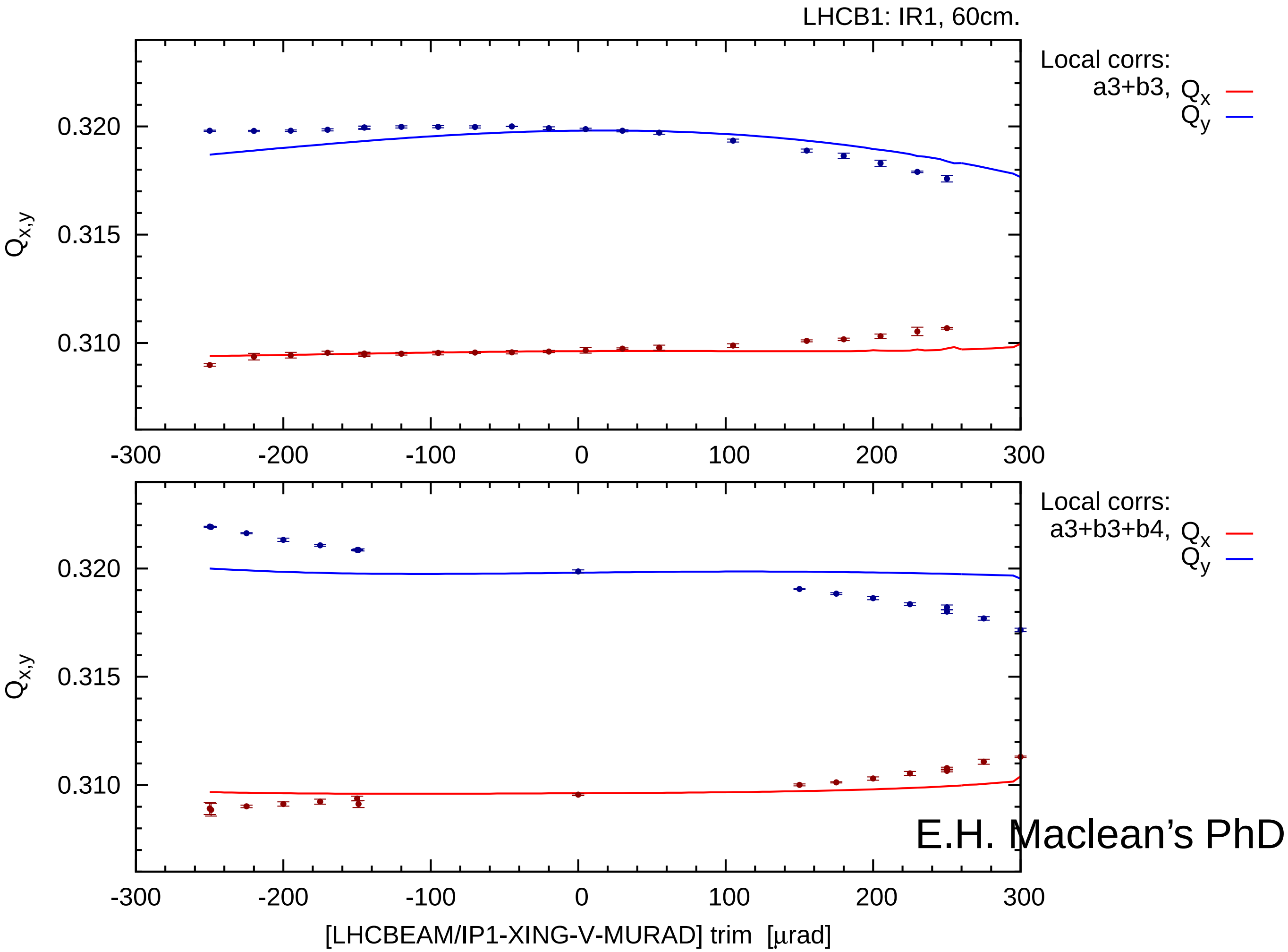
Excellent agreement → Reliable model and simulations.

Chromatic coupling correction at β^{*}=0.6 m



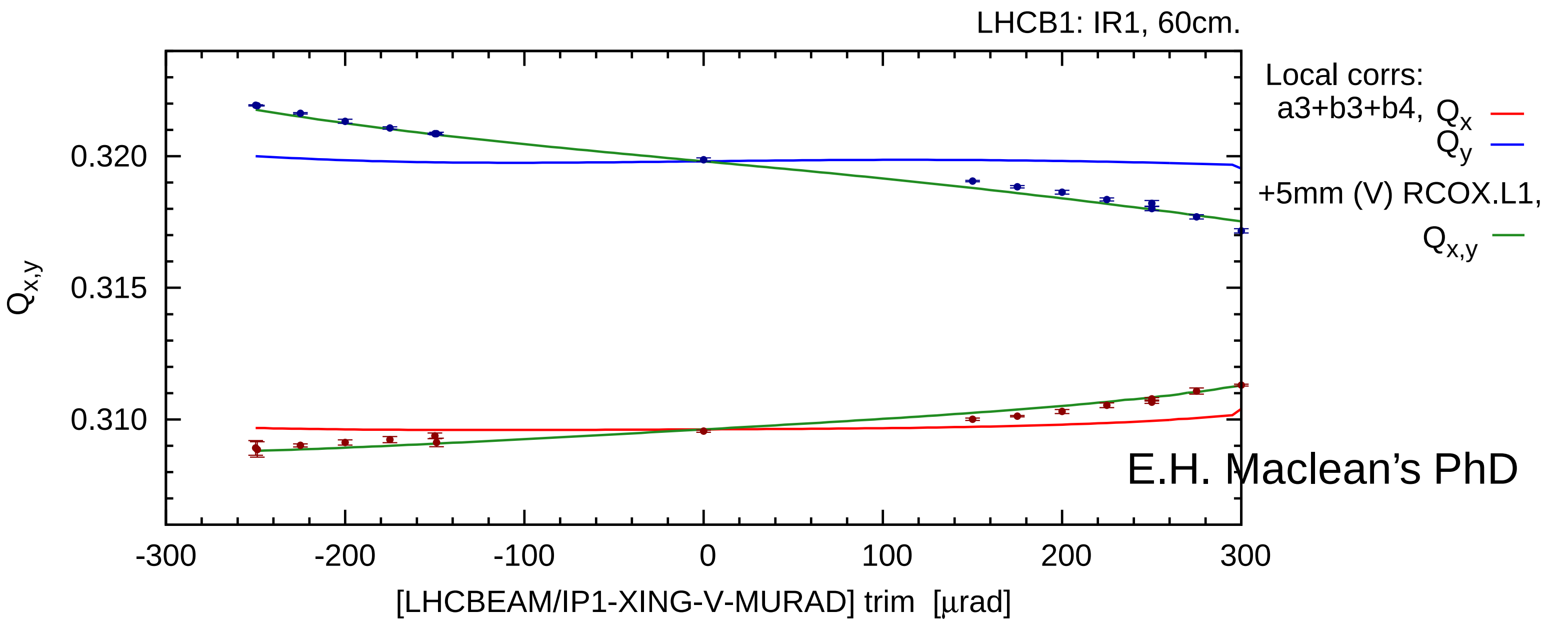
First chromatic coupling correction in the LHC

IR1 non-linear correction - Beam 1



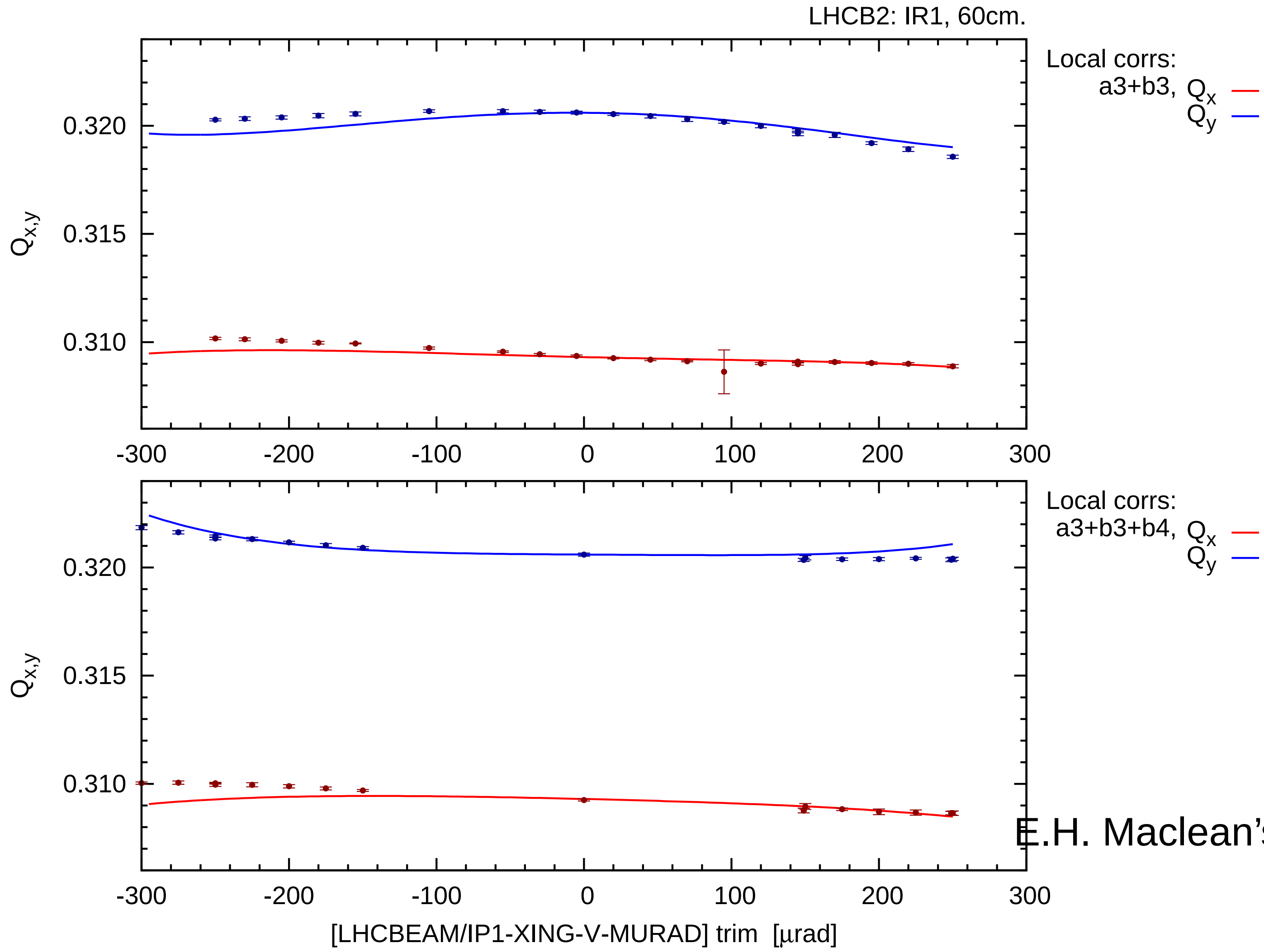
a3 and b3 corrections OK. Large discrepancy when applying the b4 correction.

5 mm misalignment in RCOX.L1?



A vertical misalignment of ≈5mm in RCOX.L1 explains the observation. This should be carefully taken into account in future IR corrections.

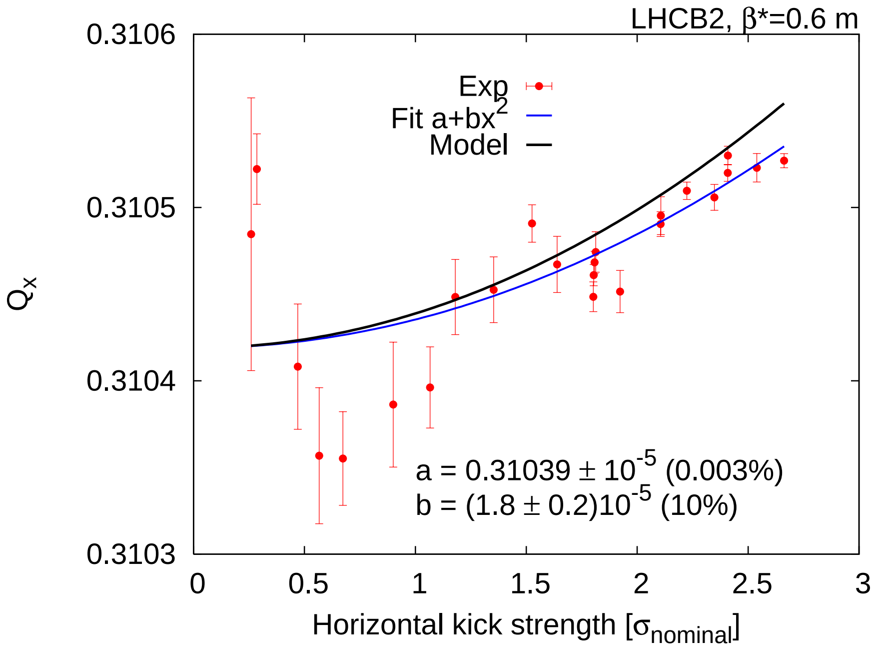
IR1 non-linear correction - Beam 2

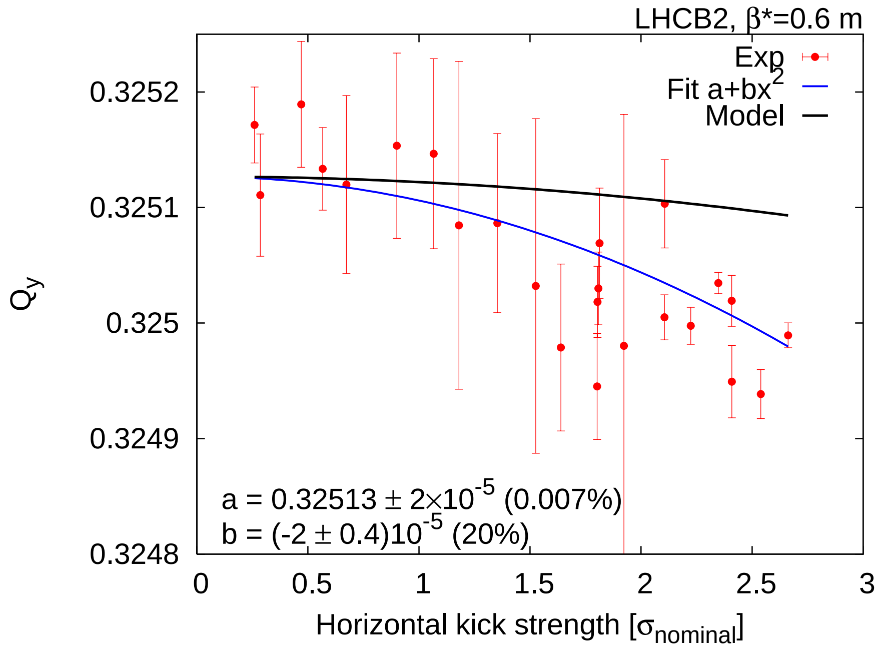


E.H. Maclean's PhD

Good corrections for beam 2.

Amplitude detuning - Beam 2H

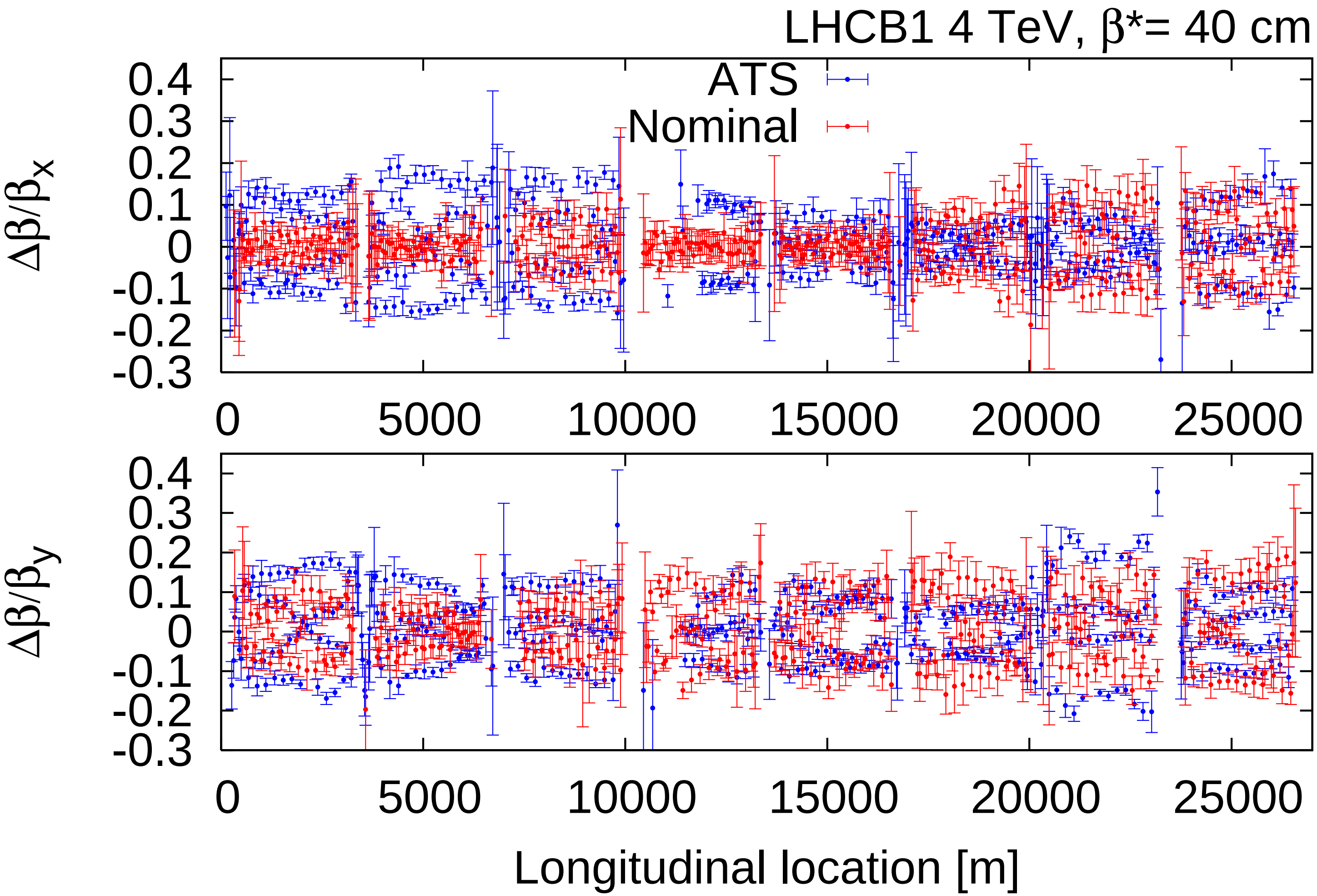




First measurement of amplitude detuning with AC dipoles! IR1 and IR5 corrections are in. AC dipole effect on model is under investigation.

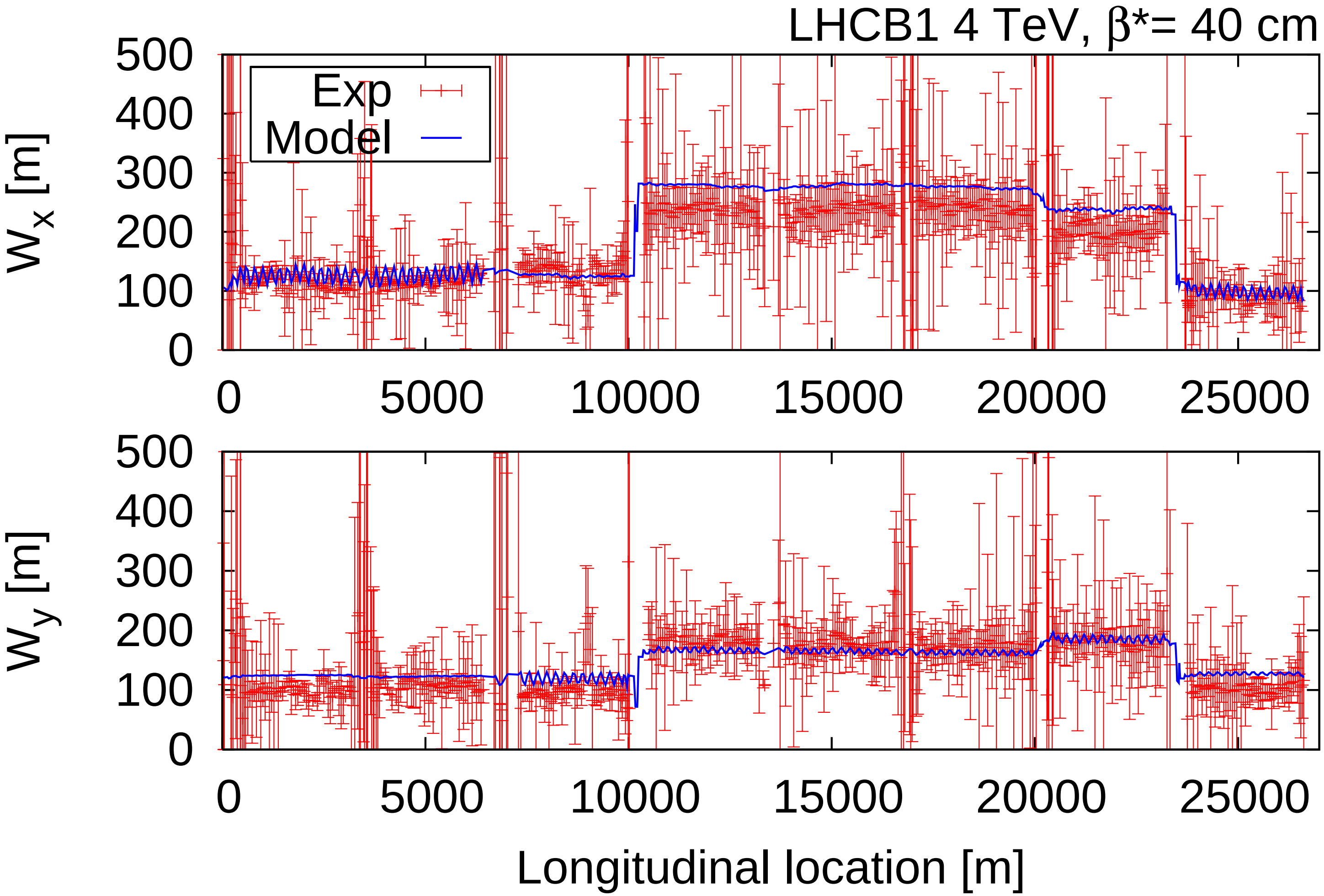
MDs facing post LS1 era

β-beating at $\beta^* = $40 cm



Two realizations of β^*=40 cm with local corrections with similar β-beating.

Chromatic β at $\beta^* = 40$ cm (Nominal)



Chromatic β is as predicted by the model.

POST LS1 ERA

Optics commissioning

	Shifts	
	2012	2015
Injection	1	1
Ramp or	0	0
Ramp&Squeeze		2
Squeeze or	3	3
β^* leveling		7
Total	4	4-10

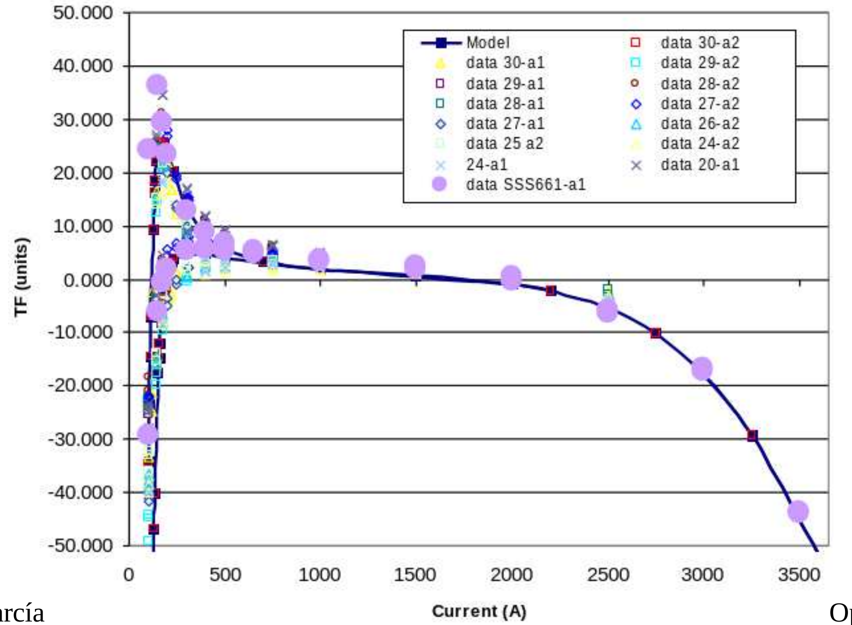
Triplet non-linear and chromatic coupling corrections will need extra shifts.

Lower β^* at injection in IR1 & IR5?

- ⋆ Avoid ramping up & down some magnets $\rightarrow$ No change of hysteresis branch, better calibration
- ⋆ Less complexity $\rightarrow$ Faster commissioning
- ⋆ Saving time if Ramp & Squeeze does not work or boosting it.
- ⋆ Limits to the β^* are low magnet strengths and aperture.

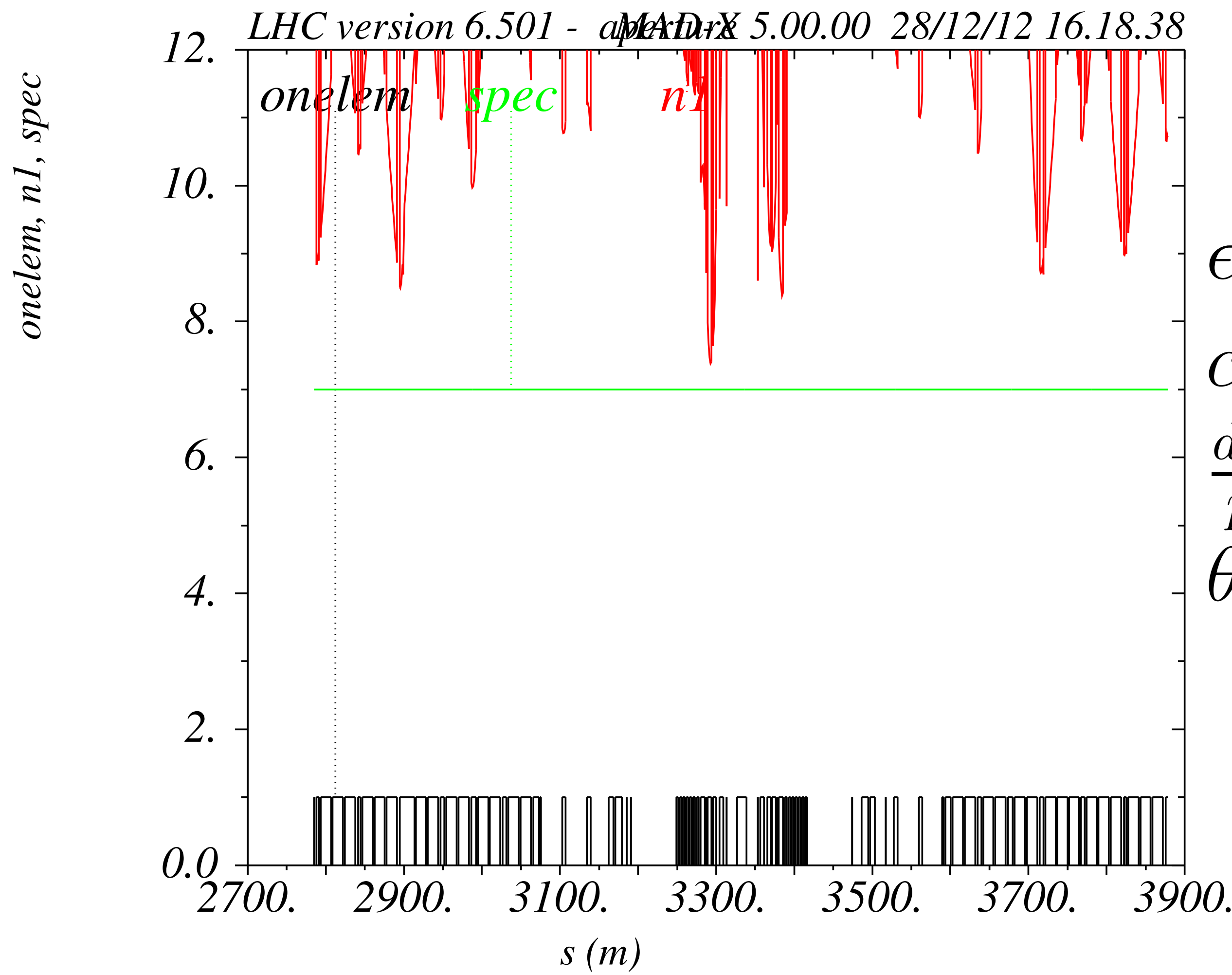
Lowest β^* from magnets - P. Hagen

- ⋆ Only MQY cause marginal operation ($I<120$ A) at β^*=5 m
- ⋆ However, looking at measurement data we believe the $I_{\rm min}$ in the FiDeL model can be lowered to 110-115 A
- ⋆ β^*=5 m OK: Q4.L1B2=119A, Q4.L1B1=116A, Q4.R1B2=119A, ...



Courtesy of W. Venturini

Injection β^* = 7 m in IR1&IR5?



$\epsilon_{x,y} = 3\mu$m

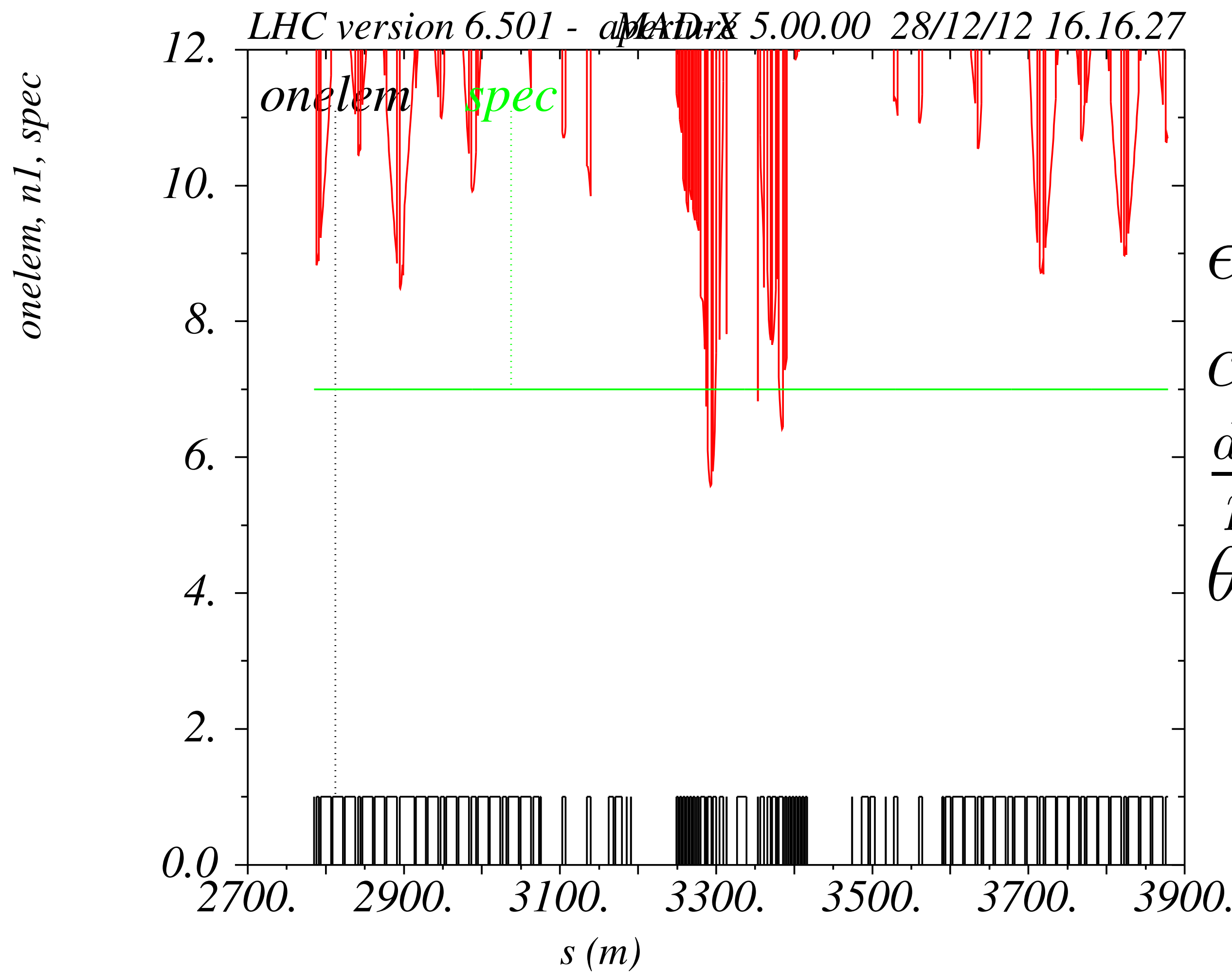
$c.o. = 3$mm

$\frac{dp}{p} = 0.5‰$

$\theta = 190\mu$m

Maybe OK β^*=7 m.

Injection β^* = 5 m in IR1&IR5?



$\epsilon_{x,y} = 3\mu$m

$c.o. = 3$mm

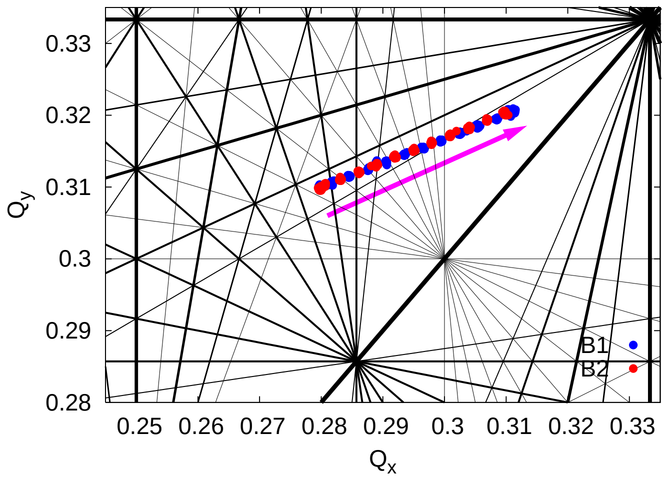
$\frac{dp}{p} = 0.5‰$

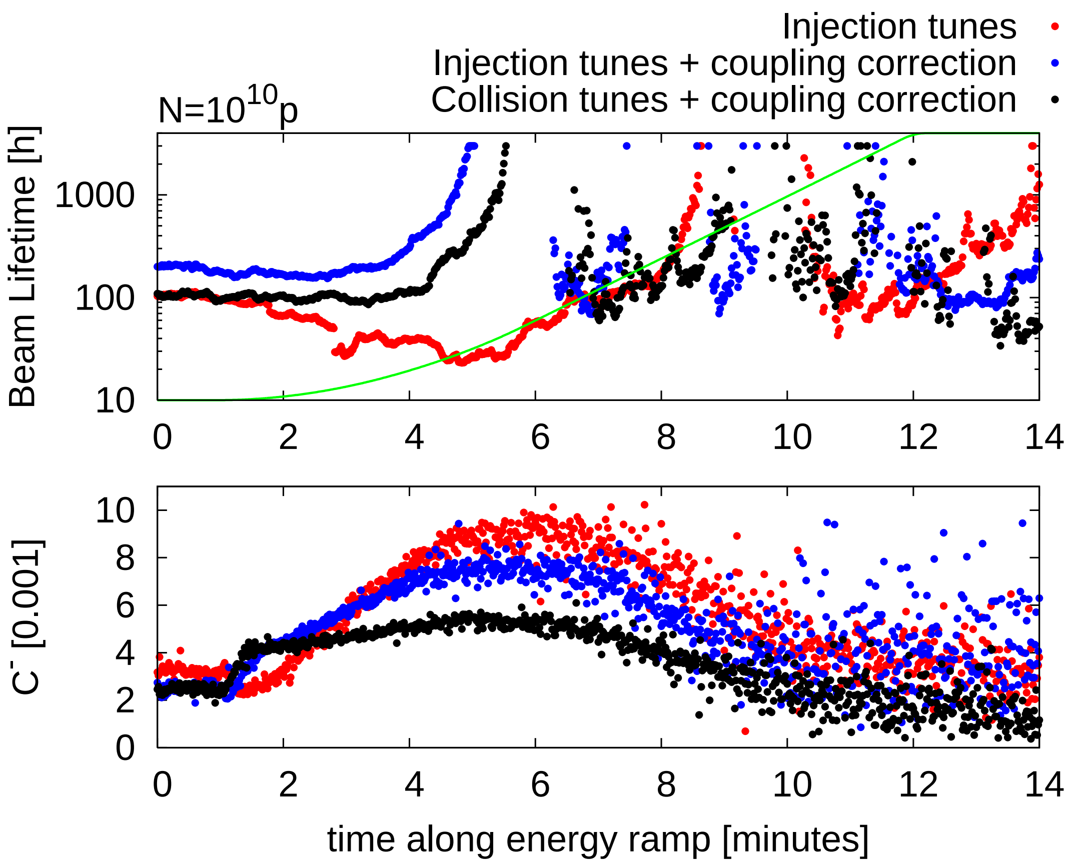
$\theta = 225\mu$m

Aperture not OK at $\beta^* \geq$5 m.

No tune jump - collision tunes @ injection

- ⋆ The tune jump is currently too violent for OFB
- ⋆ At lower β^* it would get more violent
- ⋆ Collision tunes @ injection and ramp (2011)





Ramp & Squeeze and Collide & Squeeze

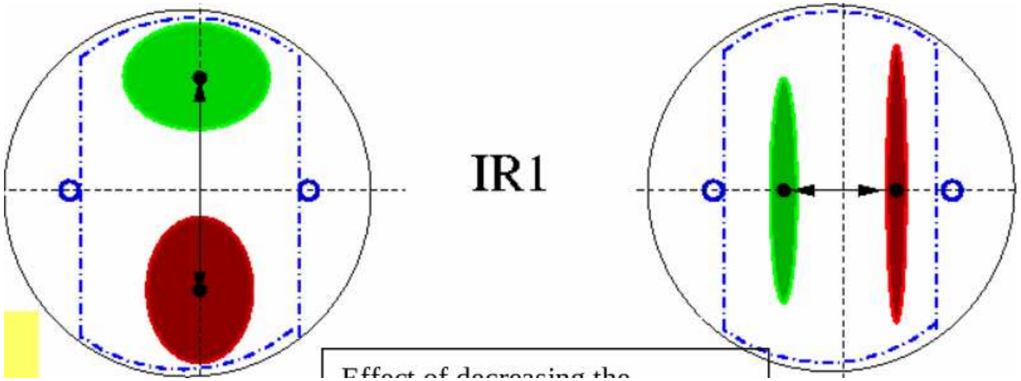
- ⋆ Too strong triplets in IR2 and IR8 might force ramp & squeeze at ≈6 TeV
- ⋆ avoidable **if** E ≤ 6.45 TeV or ...
- ⋆ **but** commissioning cost is not unaffordable.
- ⋆ Good optics corrections are needed for $\beta^* \leq 3$ m (natural β-beating≈35% @ 3m)
- ⋆ Improved tools are needed!

Improved tools after LS1

- ⋆ Moving from static to dynamic measurements
- ⋆ Already some experience during the ramp but at constant optics
- ⋆ B. Dehning requests a 3.5% resolution on β (currently $\approx$10% with single shot)
- ⋆ We requested to double the length of AC dipole flattop to improve single shot measurement (N. Magnin)
- ⋆ Need tools that give the optical status of the machine at any given time.

ATS? Flat optics?

- ATS can reach β^*=0.3 m in the pre-squeeze while for Nominal it is not clear
- ATS has some advantages:
  - Matching section apertures & strengths
  - Lower chromatic aberrations
  - Lower β^* at reach 'using the arcs'
- Stephane's flat scheme might allow for lower β^*:



- Final design should be decided based on global performances.

Lumi Vs β^* - 50ns H9 beams

β^*_x [m]	β^*_y [m]	θ μrad	Luminosity $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Δ [%]
0.5	0.5	201	1.90	
0.4	0.4	225	2.14	13
0.3	0.3	260	2.41	13
0.6	0.4	184	2.08	
0.6	0.3	184	2.40	15
0.6	0.2	184	2.94	23

Lumi Vs β^* - 25ns H9 beams

β_x^* [m]	β_y^* [m]	θ μrad	Luminosity $[10^{34}$cm^{-2}s$^{-1}]$	Δ [%]
0.5	0.5	282	1.60	
0.45	0.43	298	1.71	7
0.37	0.33	326	1.92	12
0.5	0.33	282	1.97	
0.5	0.23	282	2.36	20

Octupole reach at 6.5 TeV and β^{*}= 0.4 m

- Maximum **focusing** in MO, MCO & MCOX:

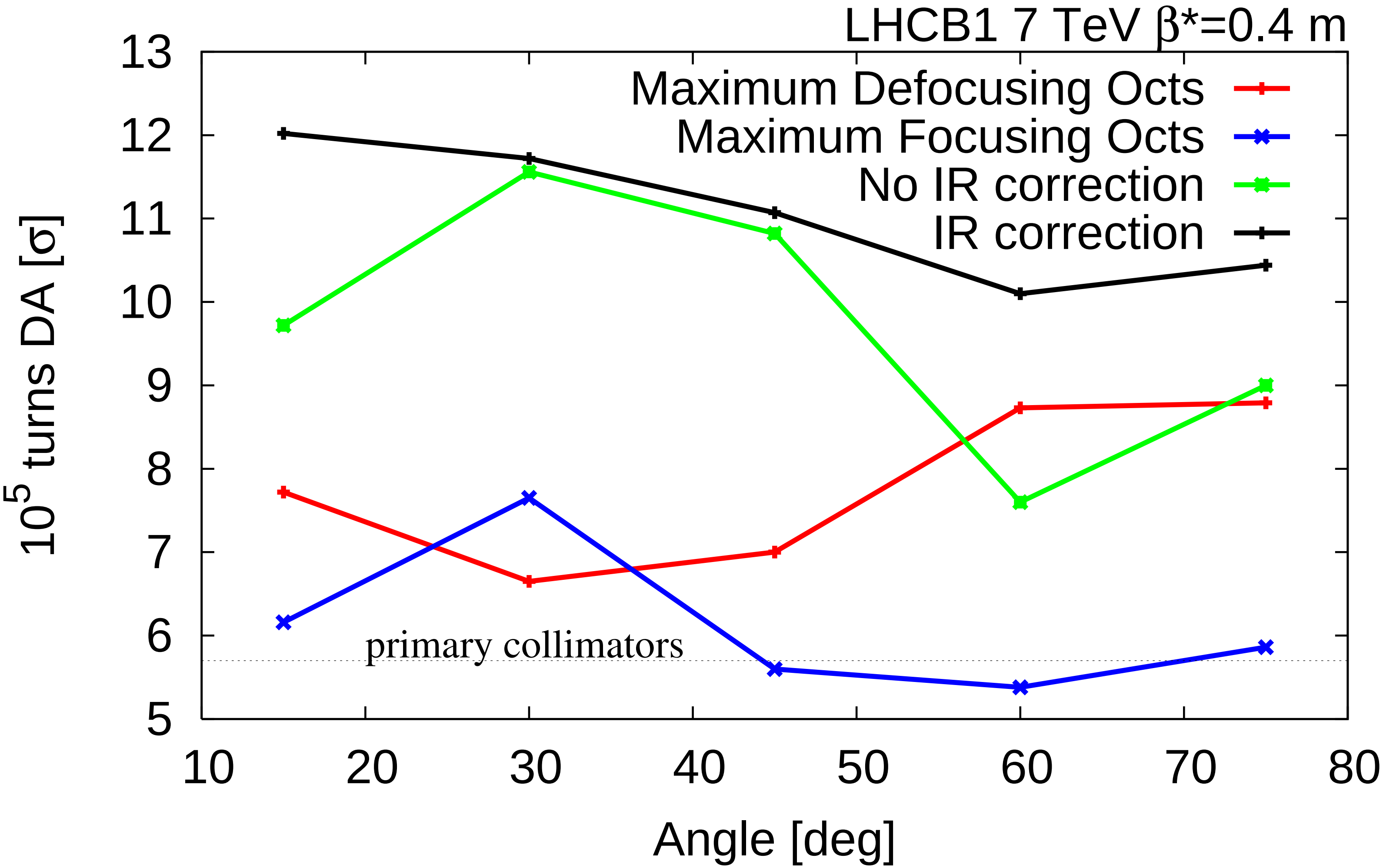
dQx/d2Jx =	1191	-1012	Amps (MO equiv.)
dQy/d2Jy =	619	-1319	Amps (MO equiv.)
dQx/d2Jy =	650	-2638	Amps (MO equiv.)

- Maximum **defocusing** in MO, MCO & MCOX:

dQx/d2Jx =	-586	1540	Amps (MO equiv.)
dQy/d2Jy =	-1086	1082	Amps (MO equiv.)
dQx/d2Jy =	-1482	1976	Amps (MO equiv.)

- $\pm$1200 Amps reached at least 50% of the terms, is this OK? DA?

DA at β^*=0.4 m, Nominal optics



IR non-linear correction recovers 4σ!

DA with strong octupoles is a serious concern.

Summary

- ⋆ LHC achieved record low β-beating for hadron colliders and many other first achievements in 2012:
  - DA measurement at injection
  - chromatic coupling correction
  - triplet non-linear correction
  - measurement of amp. detuning with AC dipoles
- ⋆ Linear and non-linear dynamics very well understood
- ⋆ β^* at injection $\geq$ 7 m
- ⋆ Let’s get rid of the tune jump
- ⋆ ramp&squeeze, squeeze&collide have a price
- ⋆ Dynamic measurements will need improved tools
- ⋆ Final β^* to be decided...
- ⋆ Triplet non-linear correctors are needed for DA and/or Landau damping (watch DA!).

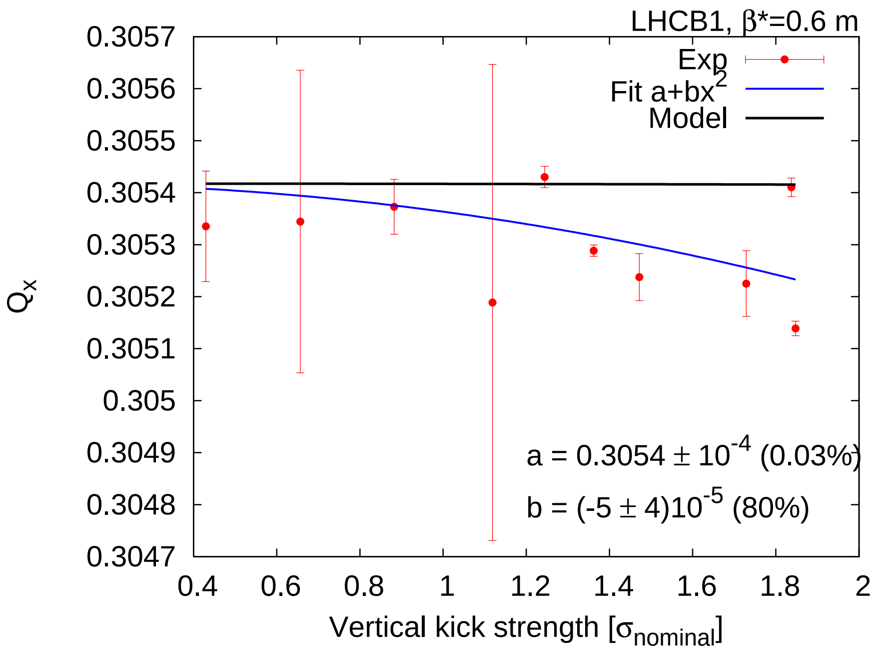
Extra Slides

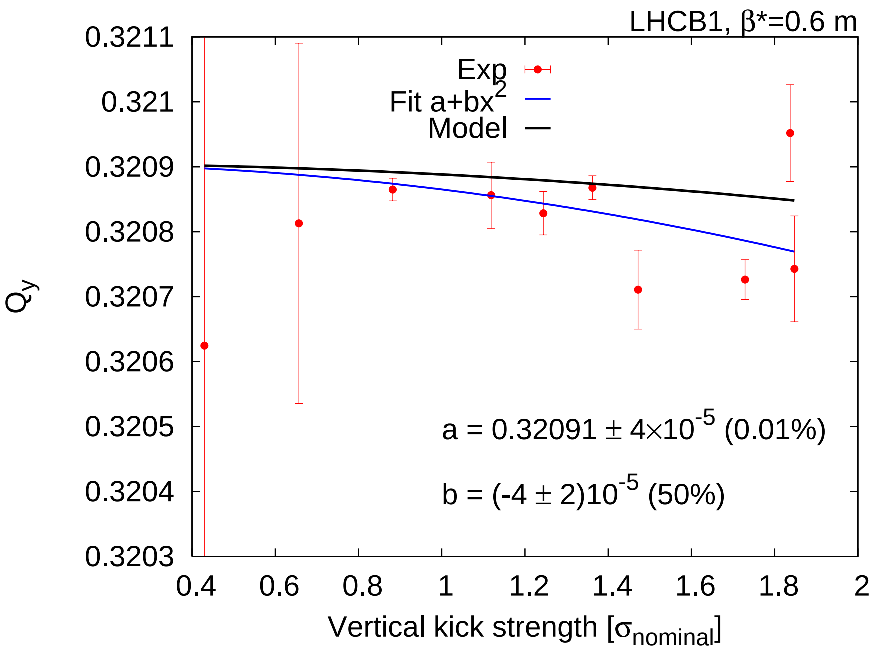
Chromatic coupling: Model Vs Exp

	Beam 1		Beam 2	
	Model	Exp	Model	Exp
KSS.a12	-0.0523	-0.0076	-0.0544	-0.0105
KSS.a23	-0.0335	0.0088	-0.0365	0.0101
KSS.a34	-0.0325	0.0028	-0.0313	0.0003
KSS.a45	-0.0313	-0.0049	-0.0239	-0.0069
KSS.a56	-0.0021	-0.0003	-0.0039	0.0024
KSS.a67	-0.0068	-0.0078	-0.0022	-0.0098
KSS.a78	-0.0356	-0.0058	-0.0335	-0.0070
KSS.a81	-0.0152	0.0000	-0.0182	0.0099

Experimental correction is weaker, good!

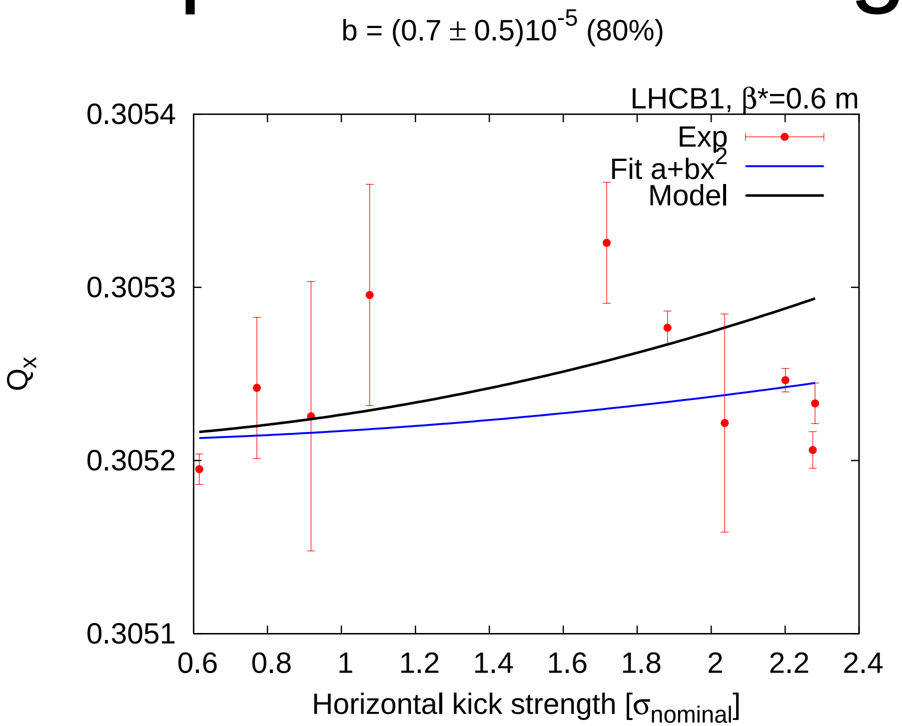
Amplitude detuning - Beam 1V

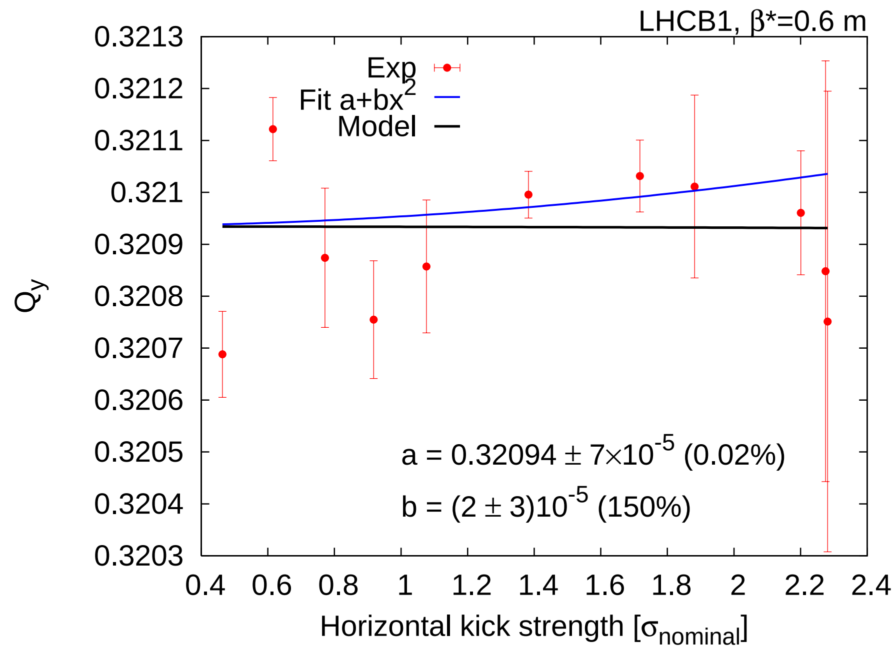




Lower excitation amplitude and poorer amplitude detuning measurement, yet consistent with model.

Amplitude detuning - Beam 1H

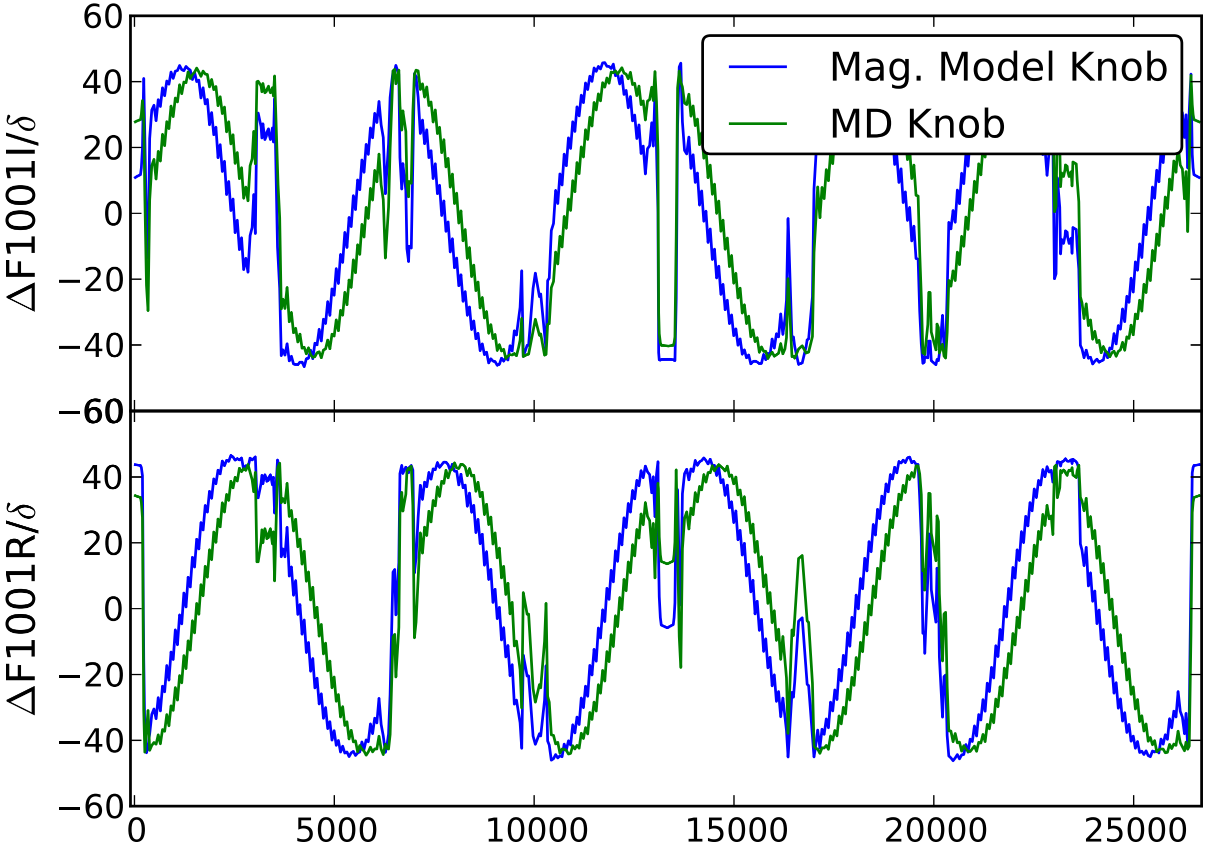




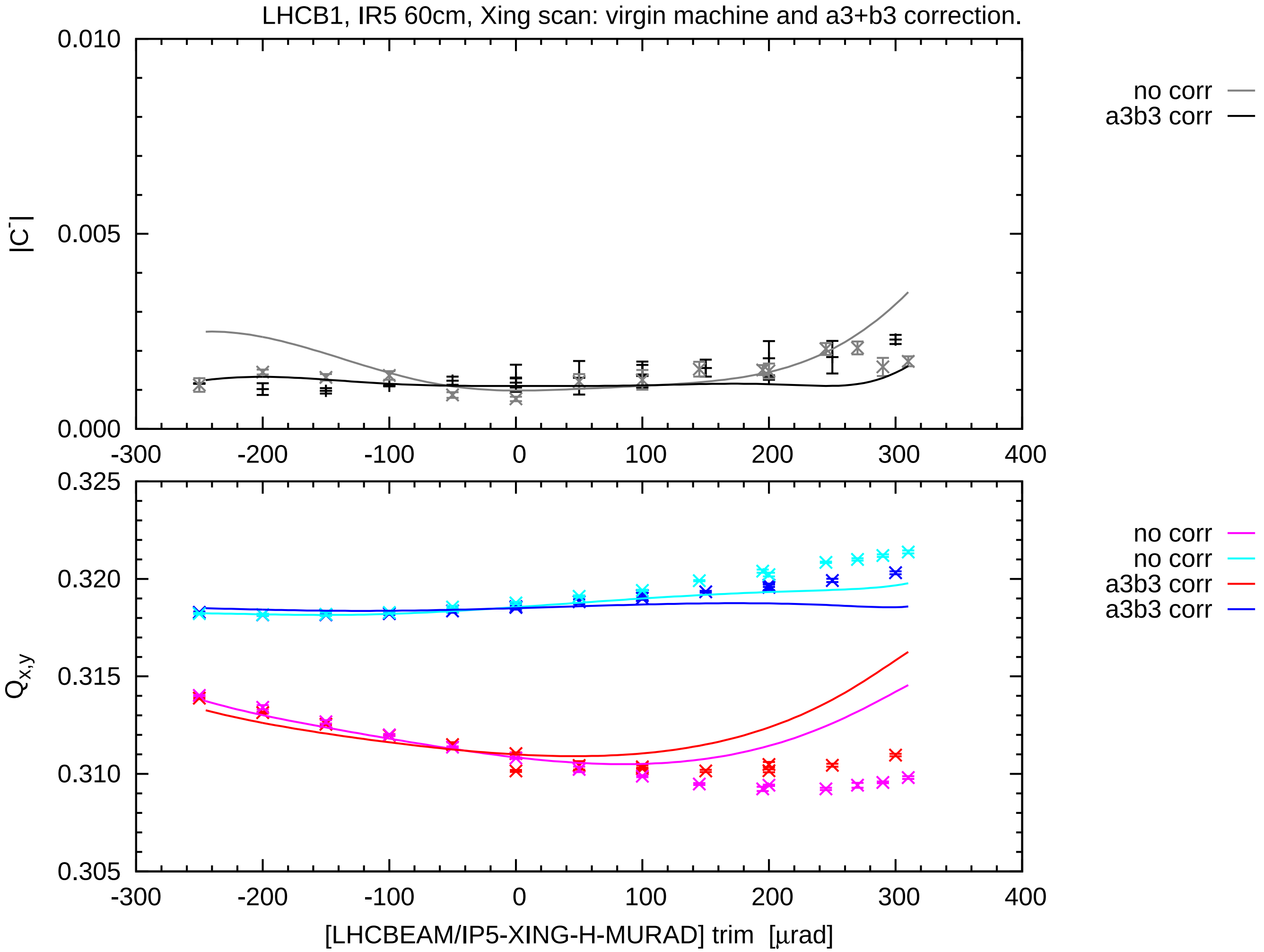
Beam 1 seems to have smaller amplitude detuning than Beam 2. Measurement still poor and consistent with model.

Chromatic coupling: Model Vs Exp

Beam 2

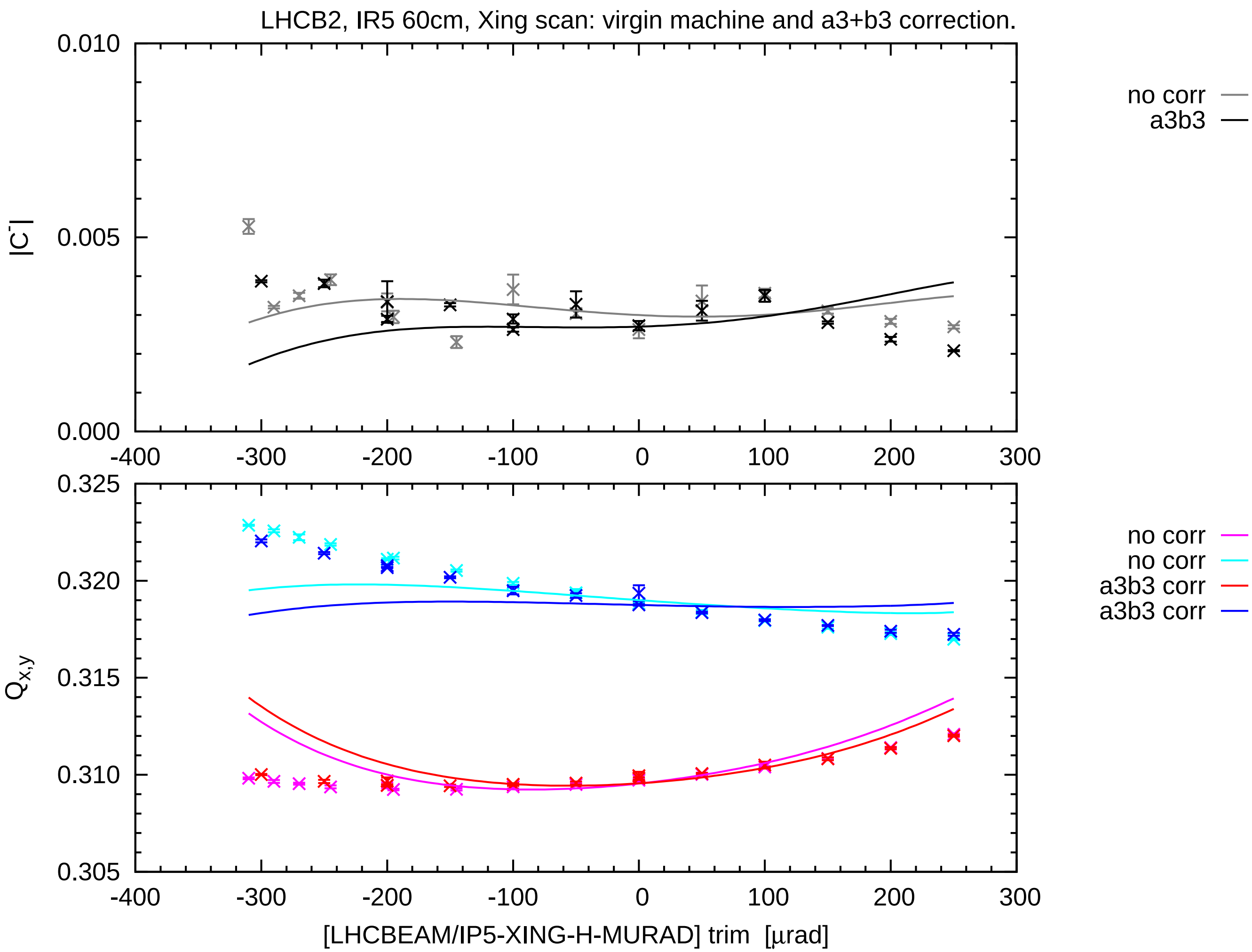


IR5 non-linear correction - Beam 1



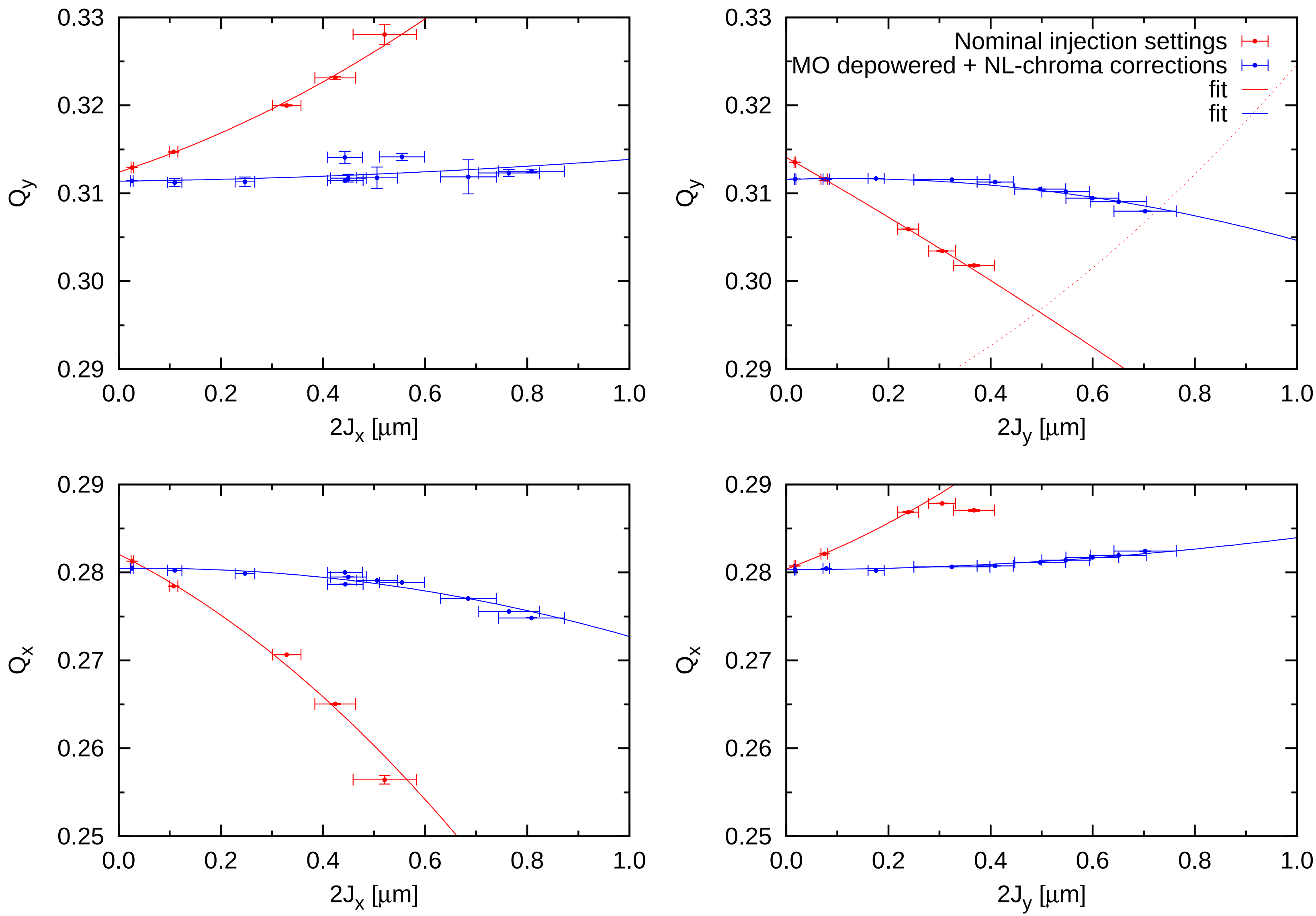
Significant deviations in IR5.

IR5 non-linear correction - Beam 2

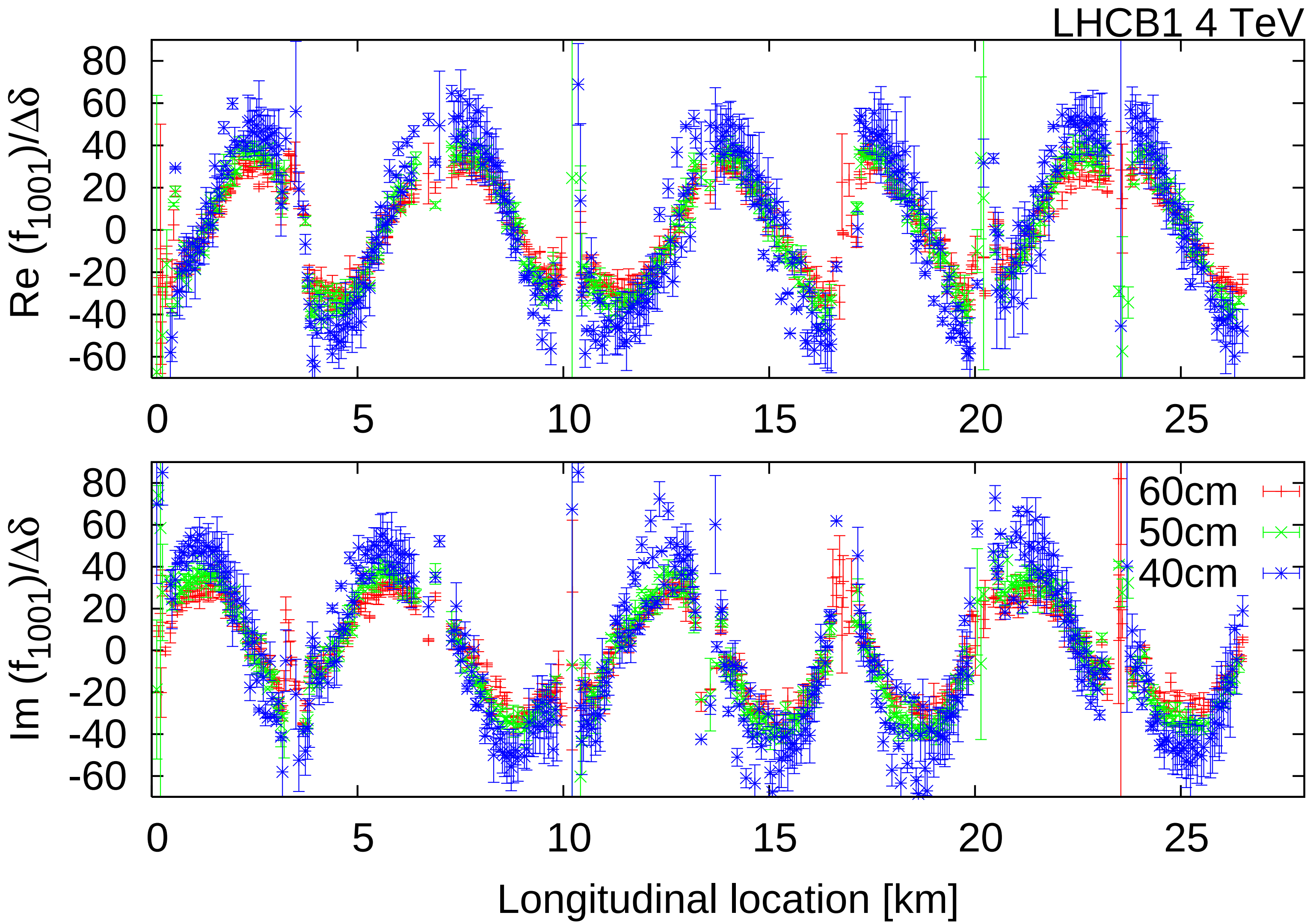


Also for beam 2 → need better corrections for IR5.

Amplitude detuning at injection, Beam 2



Chromatic coupling Vs β^*



At β^*=0.4 m a dp/p=0.001 gives $\Delta\Delta Q_{\min}$=0.0024.