LHC Optics in 2011

LARP CM16 (May 17th, 2011)

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On behalf of LHC Optics Team aka "Beta-beaters":
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Many thanks to M. Aiba (PSI) and ABP, OP, BI

Highlights

- For 2011 run, β^* changed from (3.5,3.5,3.5,3.5) m to (1.5,10,1.5,3) m at IPs (1,2,5,8). This is due to
  - IP1 and IP5: further squeeze allowed after reviewing of aperture at tertiary collimators.
  - IP2 and IP8: luminosities could exceed design values.
- During the recommissioning, optics measurements/corrections with **AC dipoles** performed:
  - Peak β-beating is reduced to ~10% at collision with local + global corrections. β-beating up to flattop is verified to be good enough.
  - Coupling corrected at collision and later at injection and ramp for B2 during one MD.
  - Good machine stability verified.
  - K-modulation performed to β^*.
- Improved diagnosis tools: GUI, codes, new analytics formula to measure coupling with AC dipoles.
- Supported MDs: collision tunes from injection, 90 m β^*, ATS.

LHC optics correction goal

- Optics tolerances (LHC Design Repor):

Table 4.10: *Operational optics tolerances.*

Parameter	tune	coupling	chromaticity	orbit (global)	orbit (local)	β-beat	dispersion spurious / normalized
Limit	$\pm 3 \times 10^{-3}$	$\|c_-\| \ll 3^{-3}$	± 2.0	4 mm	0.1 σ	20 %	27 %

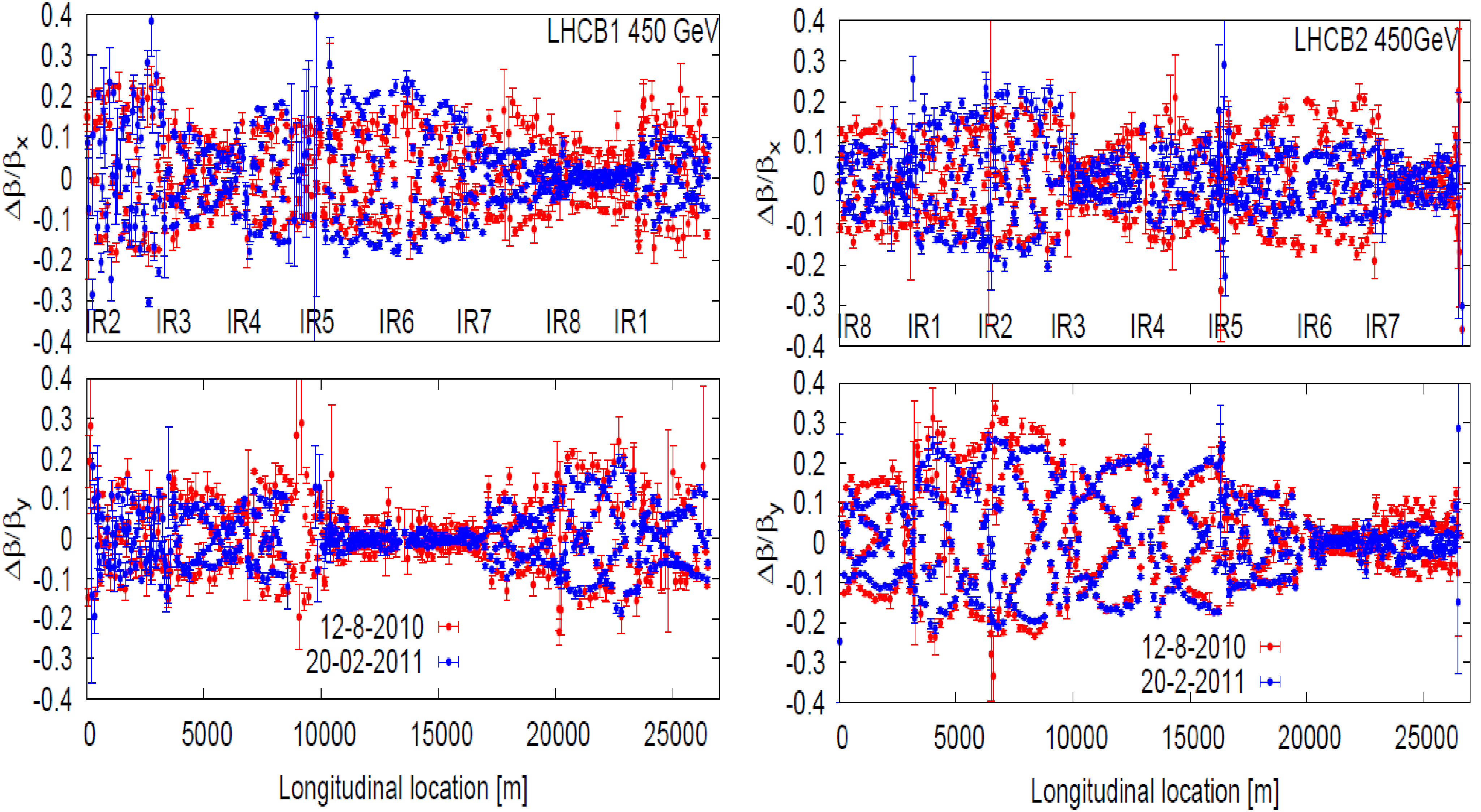
- β-beating tolerance including off momentum effects (LHC Project Roport 501):

In conclusion, the maximum tolerable β-beating induced by the machine imperfections is reduced to

$$\begin{cases} \left(\frac{\Delta\beta_x}{\beta_x}\right)_{\mathrm{peak}} < 14\% \ / \ 15\% & \text{for the injection / collision optics} \\ \left(\frac{\Delta\beta_y}{\beta_y}\right)_{\mathrm{peak}} < 16\% \ / \ 19\% & \text{for the injection / collision optics.} \end{cases}$$

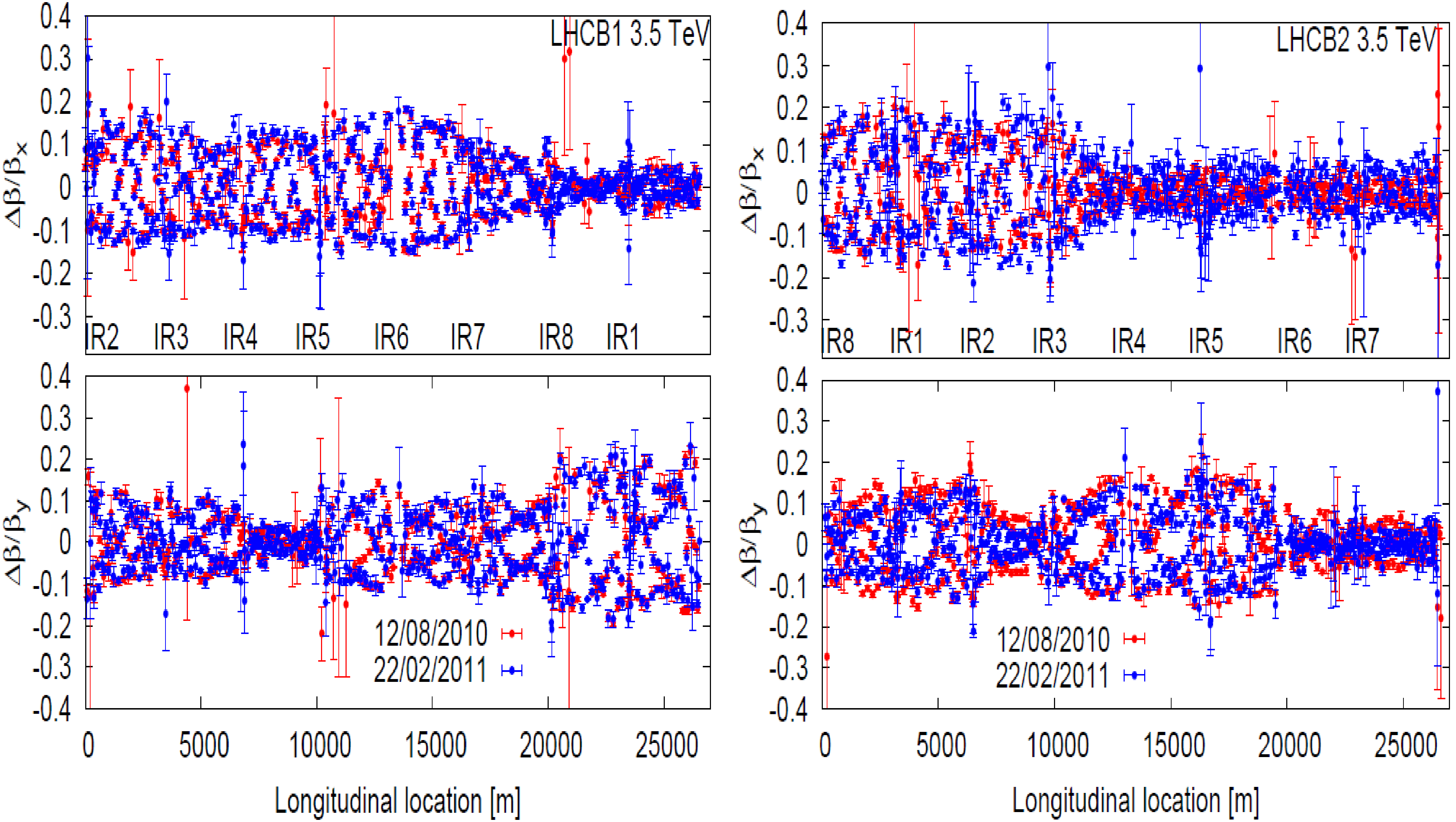
- Despite the smaller emittance (and better orbit ?), we use these numbers as our goal.

Injection β-beating: 2010 vs. 2011



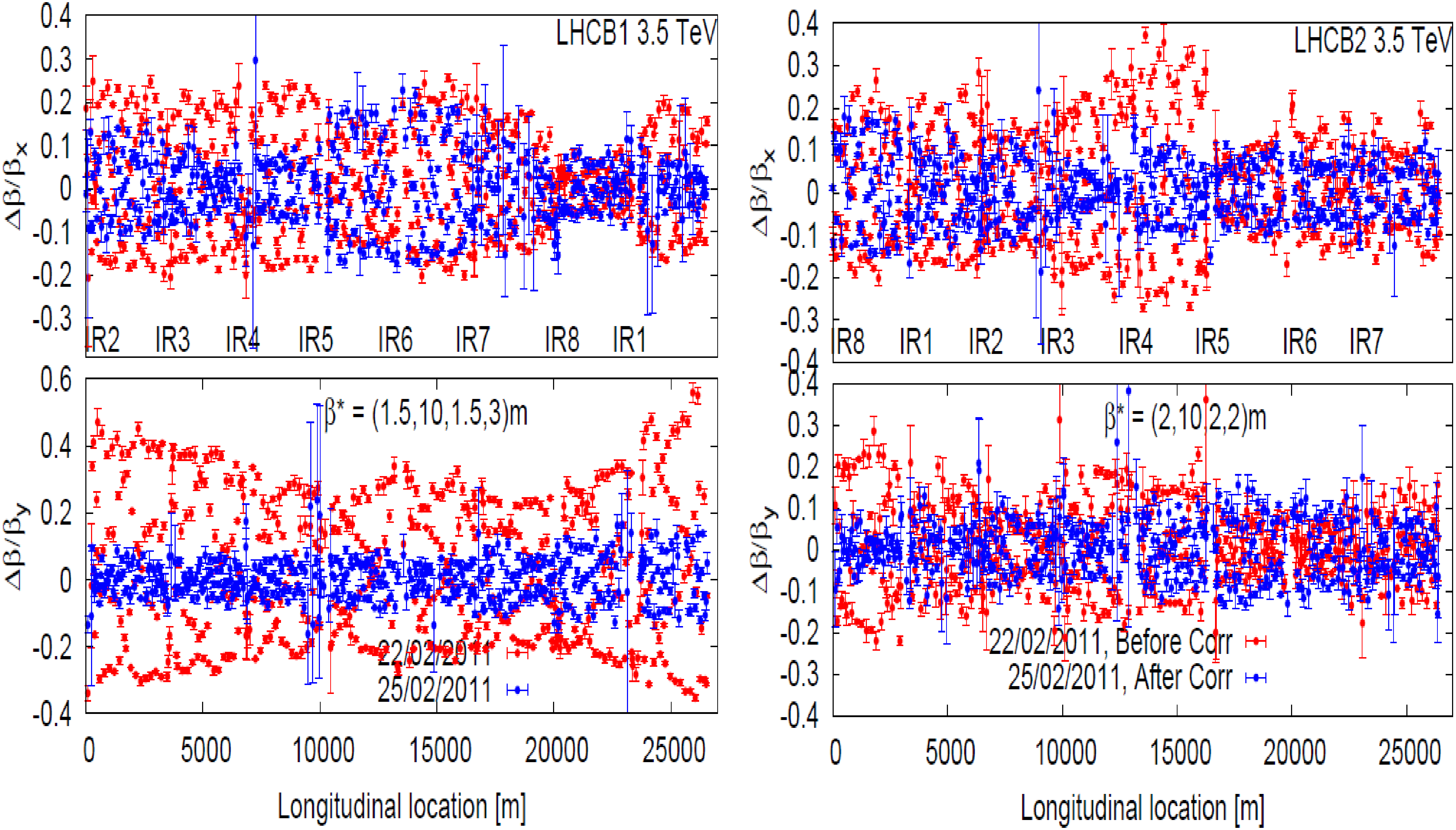
- Same corrections as 2010: MQXB2.L2/8 (0.51%), MQXB2.R2/8 (0.64%)
- ~10% difference after ~7 months.

Flattop β-beating: 2010 vs. 2011



- Very small difference after ~7 months.
- No corrections.

Local β-beating corrections at collision



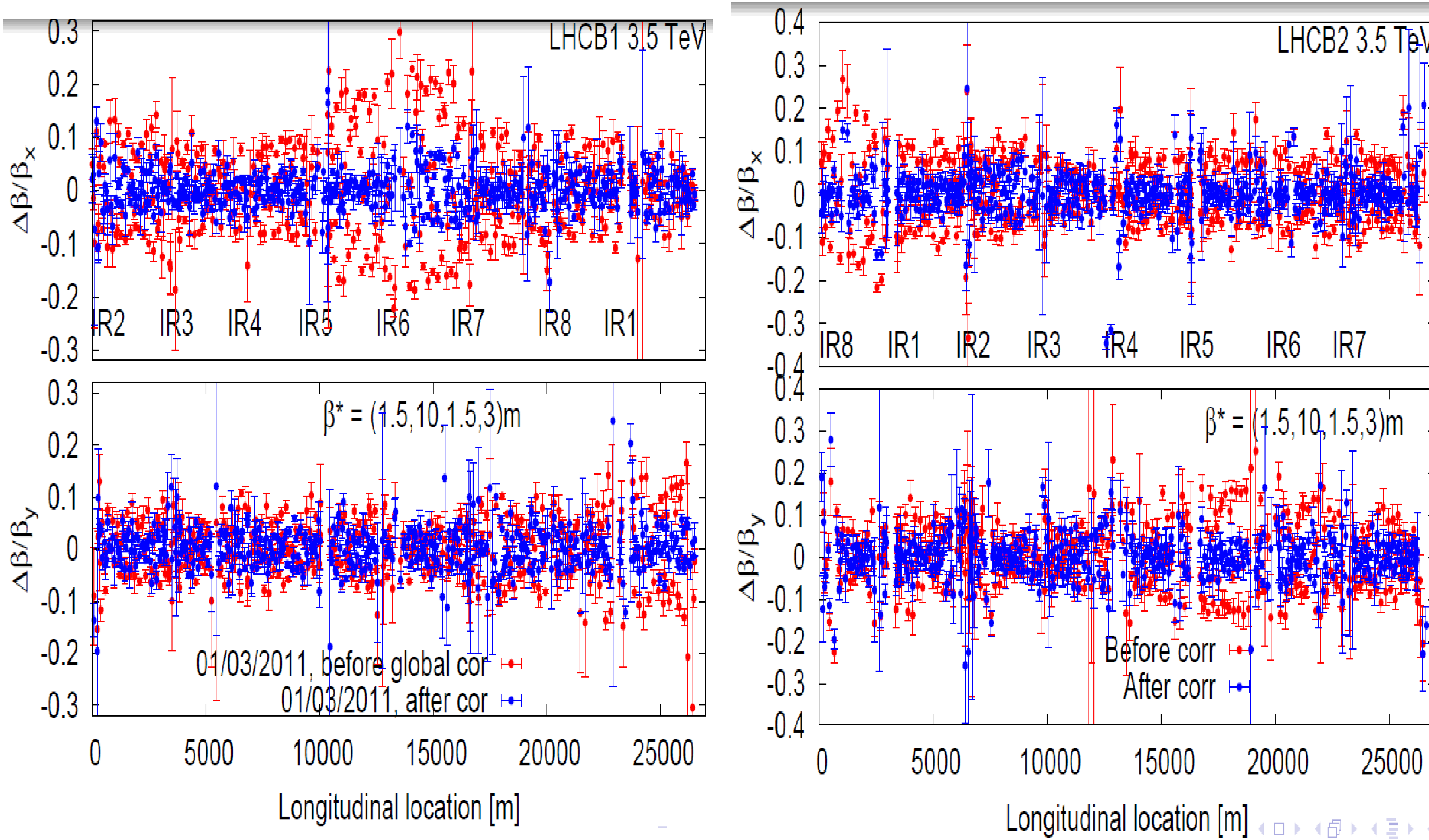
- Strategy: first correct local errors ALARA then apply global corrections.
- ~60% peak β-beating reduced to ~20%

List of local β-beating corrections

Corrector	ΔK	Relative change [%]
kq9.l1b1	3.8e-05	0.6 %
ktqx2.r1	-0.8e-5	0.09%
ktqx2.l5	1e-5	0.11 %
ktqx2.r5	1.3e-5	0.15 %
kq5.l6b2	-4.6e-05	0.7 %
ktqx2.l8	-2.3e-5	0.26 %
ktqx2.r8	-5.3e-6	0.06 %

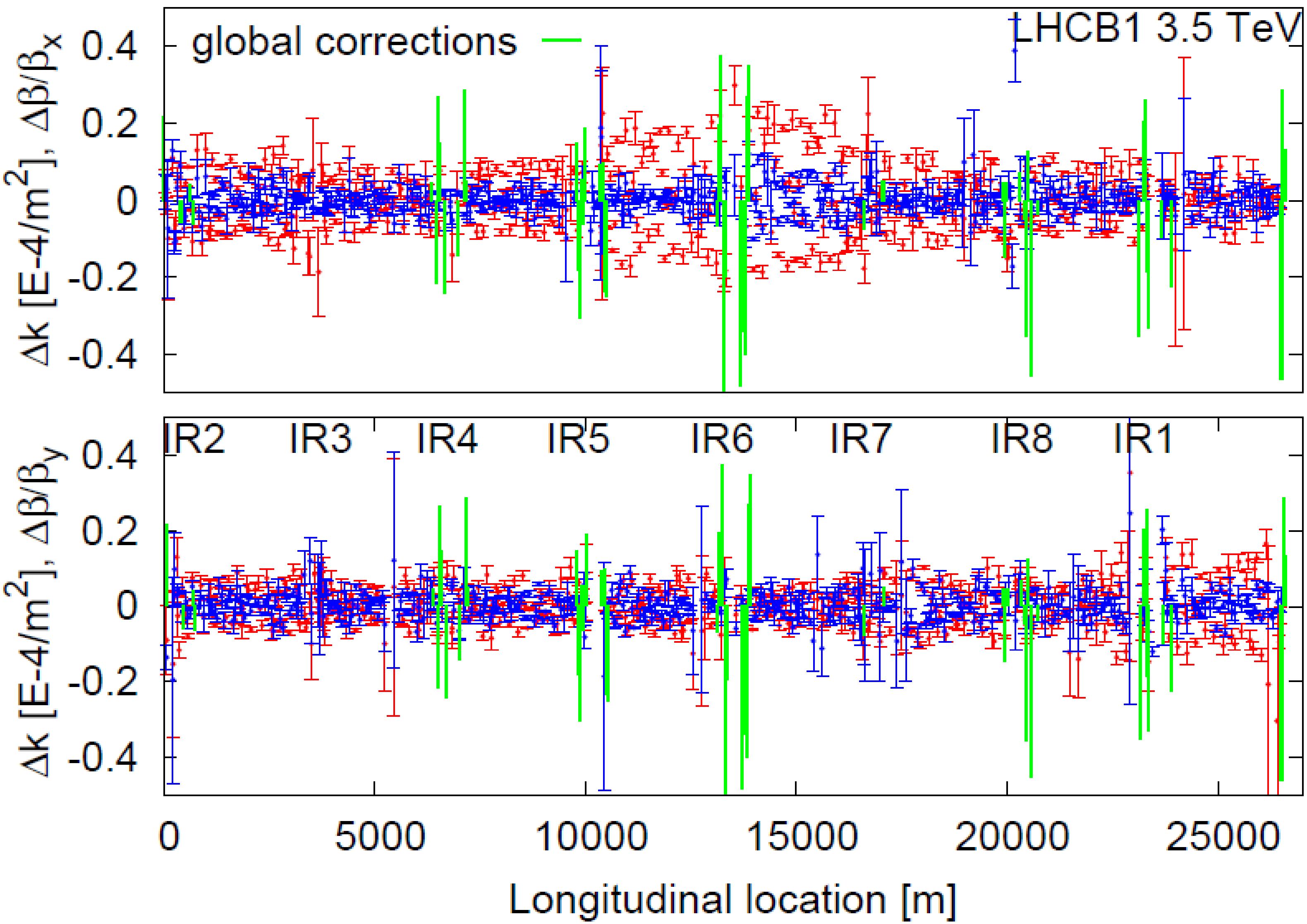
Works for 3.5-1.5 m β^*. The knob starts at 4 m and becomes 100% at 3.5 m.

Global β-beating corrections at collision



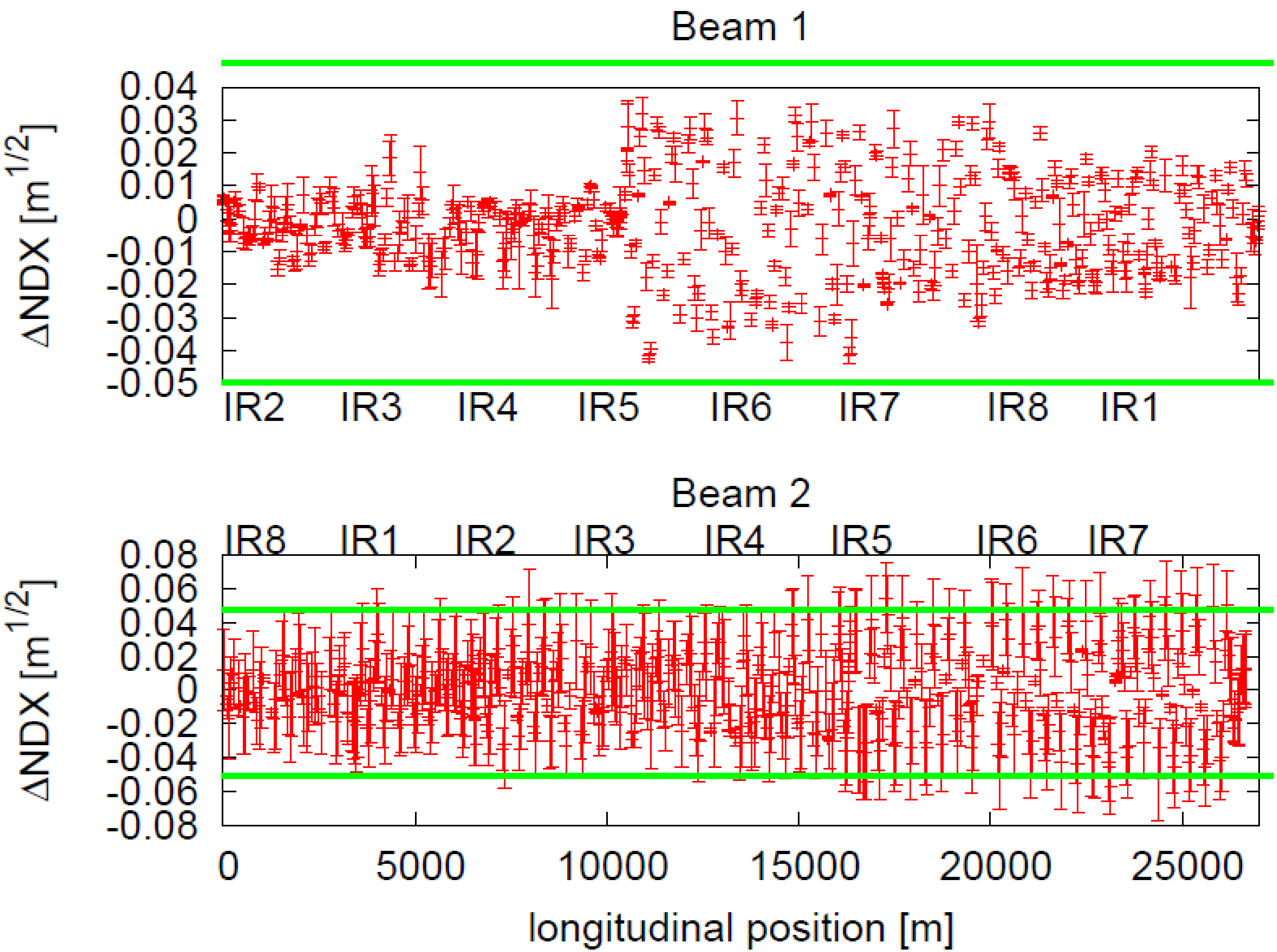
Achieved ~10% peak β-beating for both planes of both beams !!
(Last year, only tried for B2)

B1 global corrections via SVD fit



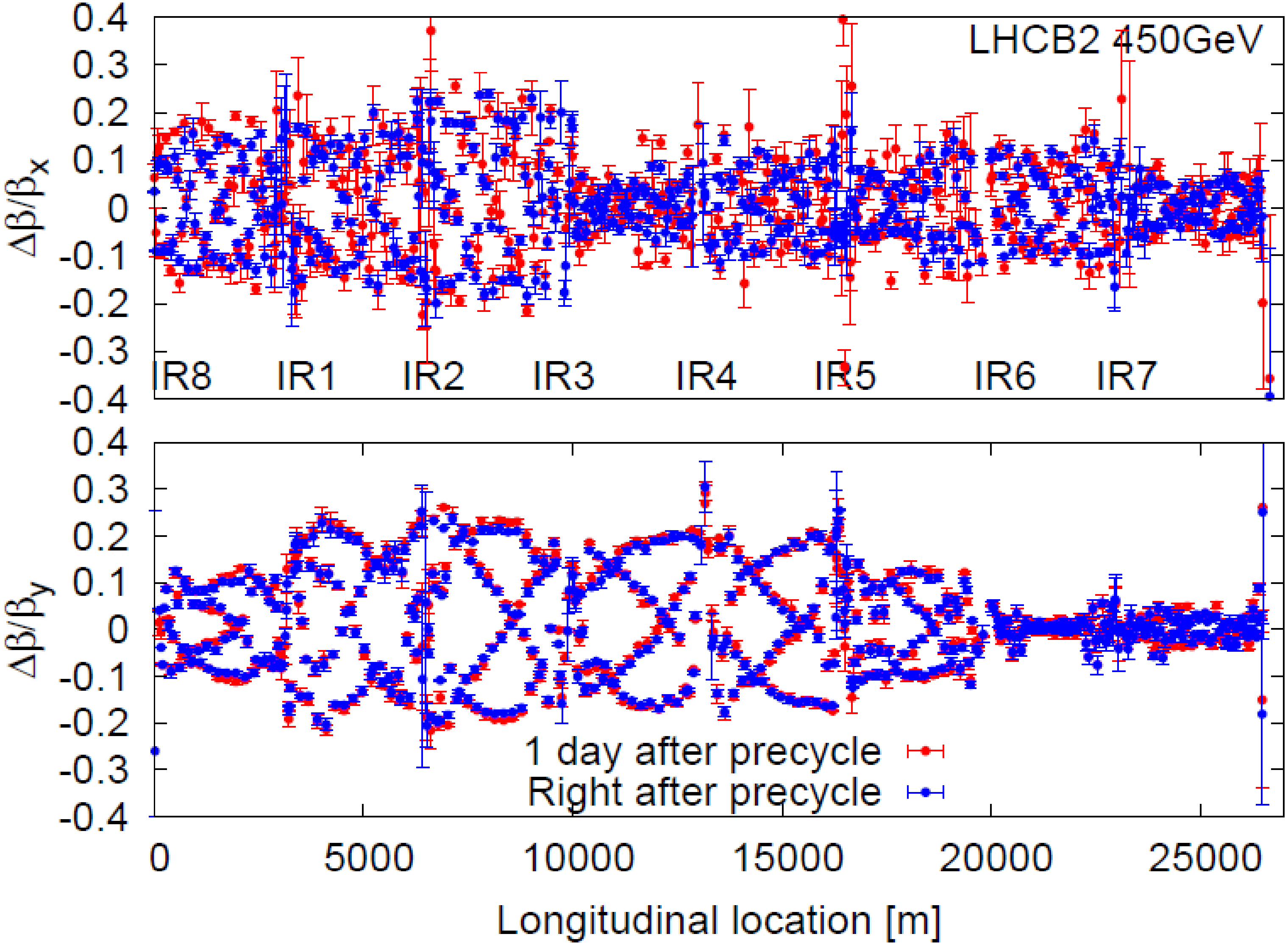
- With quads Q4-7 (MS), Q8-11 (DS), and QT12-13 (trim quads).
- The knob starts at 2 m and becomes 100% at 1.5 m.

Normalized dispersion at collision



Good dispersion and off-momentum β-beating measurements missimg.
(Dispersion is important input for the global correction).

No dynamical *β*-beating at injection



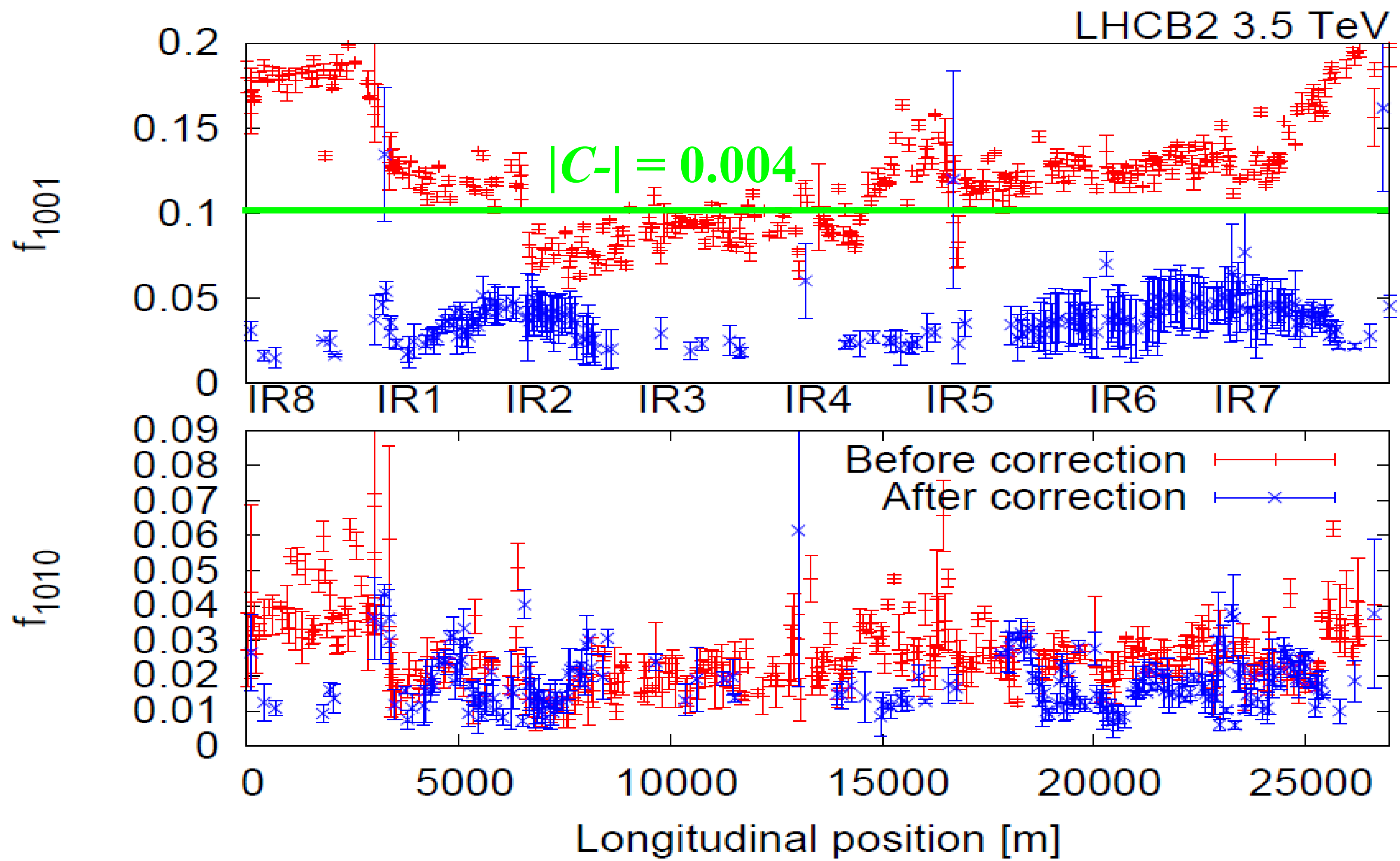
- Last year, ~10% dynamical *β*-beating was observed in measurements separated by 5 days (one at the beginning of a fill and the other at the end).
- Tolerances for dynamical and long-term *β*-beating well defined ??

β^* from K-modulation

case	IR1		IR5	
	Ave	rms	Ave	rms
B2H	1.57	0.11	1.48	0.11
B2V	1.57	0.09	1.52	0.09
B1H	1.53	0.15	1.50	0.15
B1V	1.50	0.06	1.52	0.06

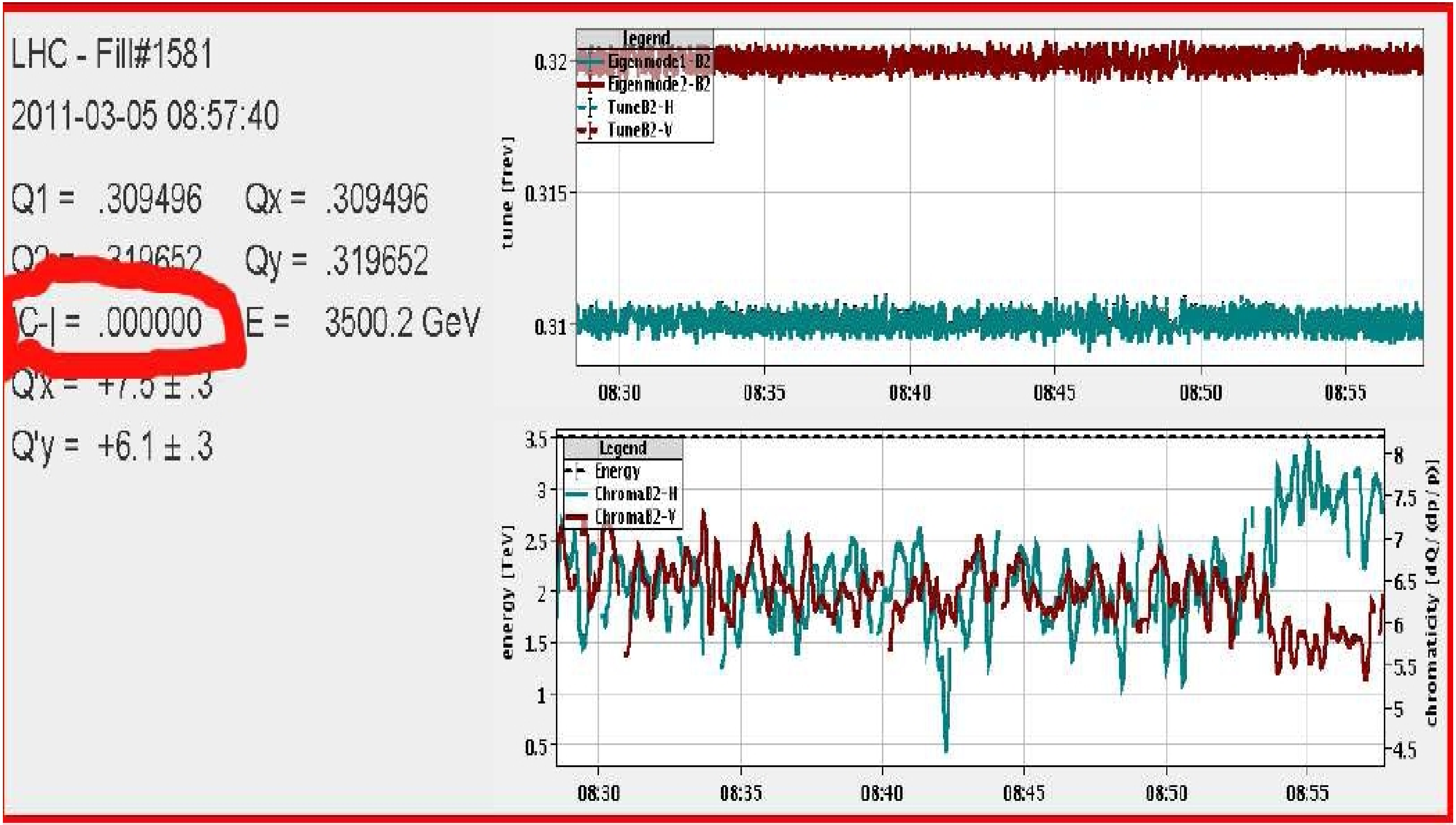
- K-modulation gives β^* with better precision/accuracy than the AC dipole (as long as coupling is well corrected).
- ATLAS loosing ~2.8% and CMS gaining ~0.3% ??
- Should "statistically properly" combine different methods ??

Local coupling corrections at collision



- Local corrections with kqsx3 applied at IPs 1, 5, and 8.
- The corrections reduced the ranges of the global knobs by about half: (-170,100) → (-110,60) A

“Instantaneous” coupling record in LHC



Motion with Coupling + AC dipole not so trivial...

1st order mode due to the coupling:

$$\tilde{x}^{(1)}(n;\bar{s}) = 2iA_y f_-(\bar{s})\sqrt{\beta_x(\bar{s})}e^{-2\pi i\nu_y n - i\psi_y(\bar{s}) - i\phi_y} + 2iA_y f_+(\bar{s})\sqrt{\beta_x(\bar{s})}e^{2\pi i\nu_y n + i\psi_y(\bar{s}) + i\phi_y}$$
$$\tilde{y}^{(1)}(n;\bar{s}) = 2iA_x f_-^*(\bar{s})\sqrt{\beta_y(\bar{s})}e^{-2\pi i\nu_x n - i\psi_x(\bar{s}) - i\phi_x} + 2iA_x f_+(\bar{s})\sqrt{\beta_y(\bar{s})}e^{2\pi i\nu_x n + i\psi_x(\bar{s}) + i\phi_x}$$

Characterized by resonance driving terms:

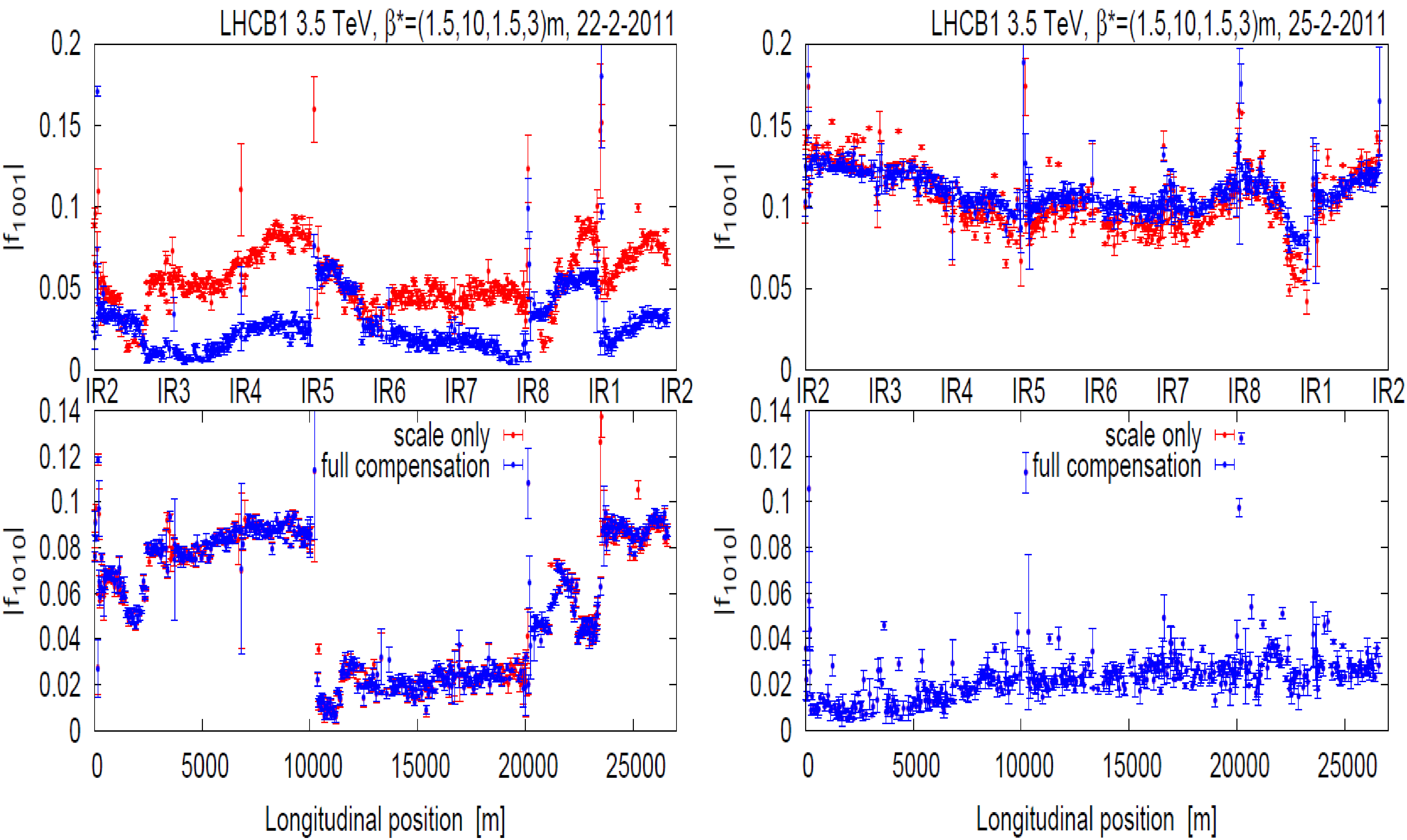
$$f_\mp(\bar{s}) = \frac{1}{8i\sin[\pi(\nu_x \mp \nu_y)]}\sum_{j=1}^{N}\kappa_j\sqrt{\beta_x(\bar{s}_j)\beta_y(\bar{s}_j)}e^{-i[\Psi_x(\bar{s},\bar{s}_j)\mp\Psi_y(\bar{s},\bar{s}_j)]}$$

With AC dipole...

$$\begin{aligned}
\tilde{x}^{(1)}(n;\bar{s}) = \quad & 2iA_{y,v}\frac{\sin[\pi(\nu_x-\nu_y)]}{\sin[\pi(\nu_x-\nu_{y,v})]}\left[f_-(\bar{s}) - 2\pi i\delta_v f_-(\bar{s};\bar{s},\bar{s}_v)\right]\sqrt{\beta_x(\bar{s})}e^{-2\pi i\nu_{y,v}n - i\psi_y(\bar{s},\bar{s}_v) - i\phi_v} \\
& + 2iA_{y,v}\frac{\sin[\pi(\nu_x+\nu_y)]}{\sin[\pi(\nu_x+\nu_{y,v})]}\left[f_+(\bar{s}) + 2\pi i\delta_v f_+(\bar{s};\bar{s},\bar{s}_v)\right]\sqrt{\beta_x(\bar{s})}e^{2\pi i\nu_{y,v}n + i\psi_y(\bar{s},\bar{s}_v) + i\phi_v} \\
& - 2iA_{y,v}\frac{\sin[\pi(\nu_x+\nu_y)]}{\sin[\pi(\nu_x-\nu_{y,v})]}\left[\lambda_v f_+(\bar{s}) - 2\pi i\delta_v e^{-2\pi i\nu_y \mathrm{sgn}(\bar{s}-\bar{s}_v)} f_+(\bar{s};\bar{s},\bar{s}_v)\right]\sqrt{\beta_x(\bar{s})}e^{-2\pi i\nu_{y,v}n + i\psi_y(\bar{s},\bar{s}_v) - i\phi_v} \\
& - 2iA_{y,v}\frac{\sin[\pi(\nu_x-\nu_y)]}{\sin[\pi(\nu_x+\nu_{y,v})]}\left[\lambda_v f_-(\bar{s}) + 2\pi i\delta_v e^{2\pi i\nu_y \mathrm{sgn}(\bar{s}-\bar{s}_v)} f_-(\bar{s};\bar{s},\bar{s}_v)\right]\sqrt{\beta_x(\bar{s})}e^{2\pi i\nu_{y,v}n - i\psi_y(\bar{s},\bar{s}_v) + i\phi_v}
\end{aligned}$$

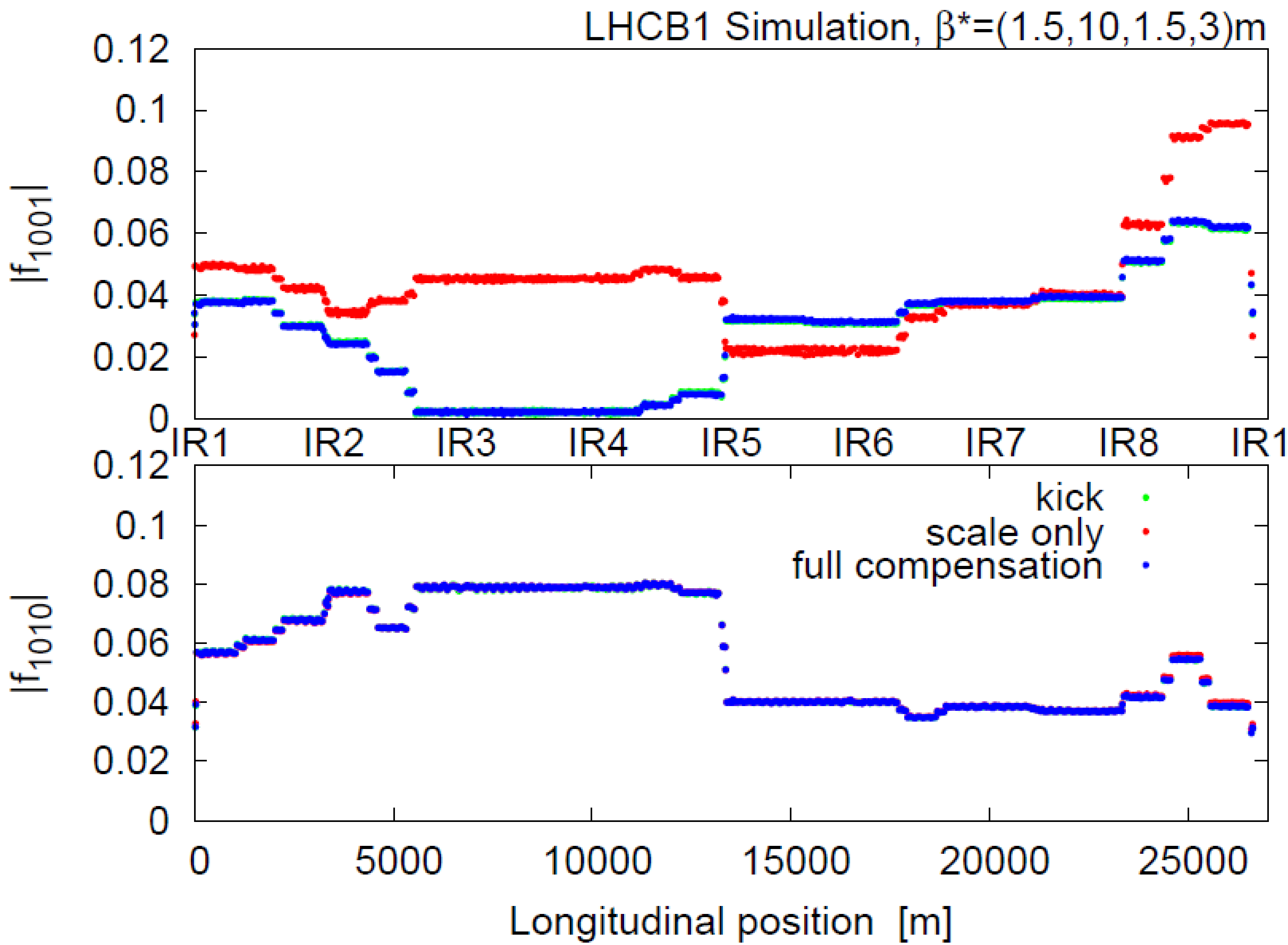
Used to be based on a simple approximation. Analytic formulae found recently (BNL CAD-AP-Note 410).

Improvement with new analytic formula



- The simple approximation screwed up when the sum resonance (f1010) is not small.
- No impact on the local correction but does effect the global correction.

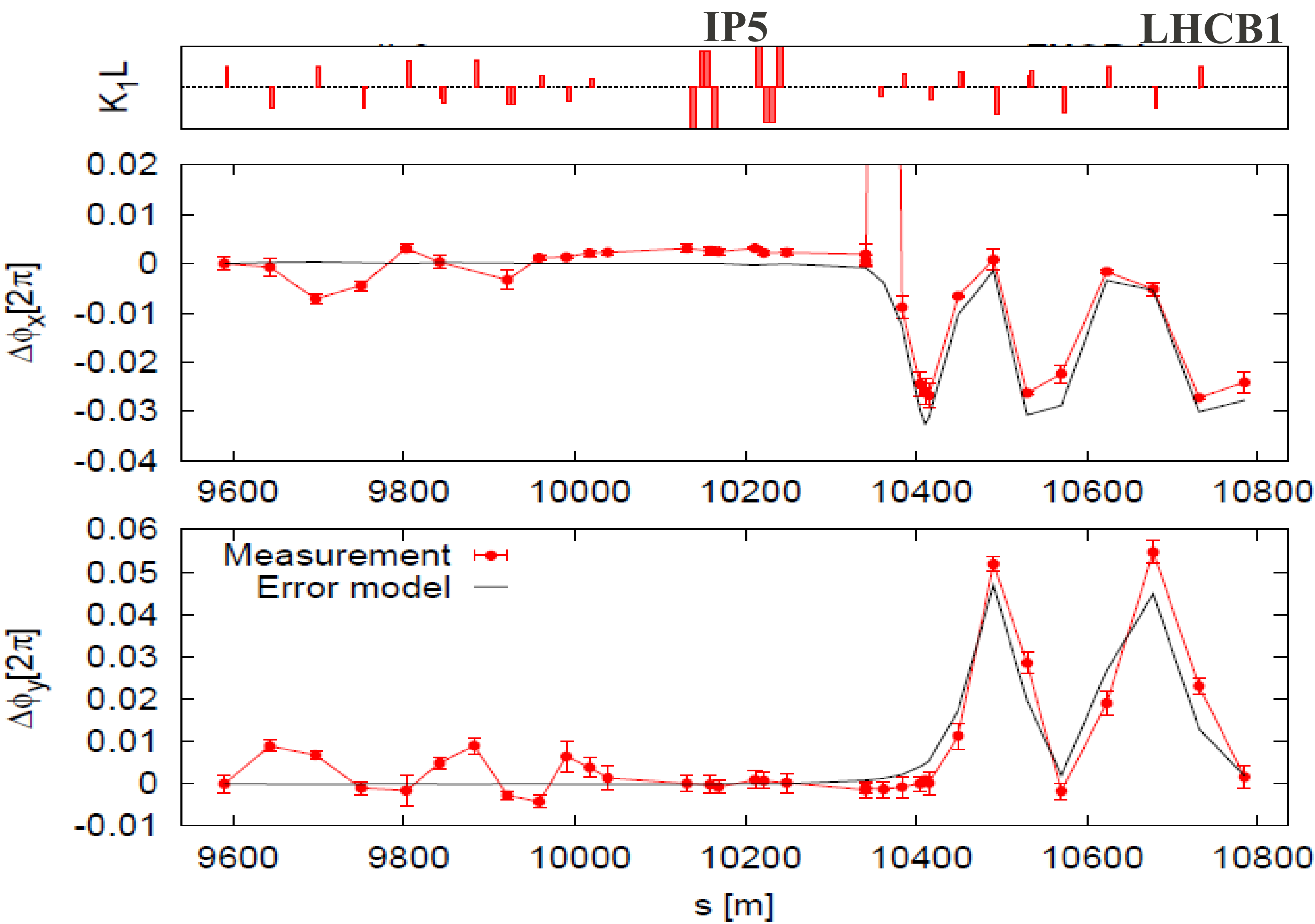
Check with simulations



Summary

- β^* changed to (1.5,10,1.5,3) m at IPs (1,2,5,8) from 3.5 m at all these IPs.
- Peak β-beating is reduced to ~10% at collision. β-beating up to flattop is verified to be good enough (can be improved).
- Coupling corrected at collision and later at injection and ramp for B2. We can improve the injection and ramp of B1 and also during the initial part of squeeze.
- Good machine stability verified.
- Good dispersion and off-momentum β-beating measurements missing.
- β^* measured with K-modulation.
- Diagnosis tools have been improved.
- Supported MDs: collision tunes from injection, 90 m β^*, ATS.

An example of local corrections



Coupling during the ramp