LHC optics model, measurements and corrections

R. Tomás

Acknowledgements

β-beating team: M. Aiba[∗], R. Calaga[†], A. Franchi[Υ], R. Miyamoto[†] and G. Vanbavinckhove.

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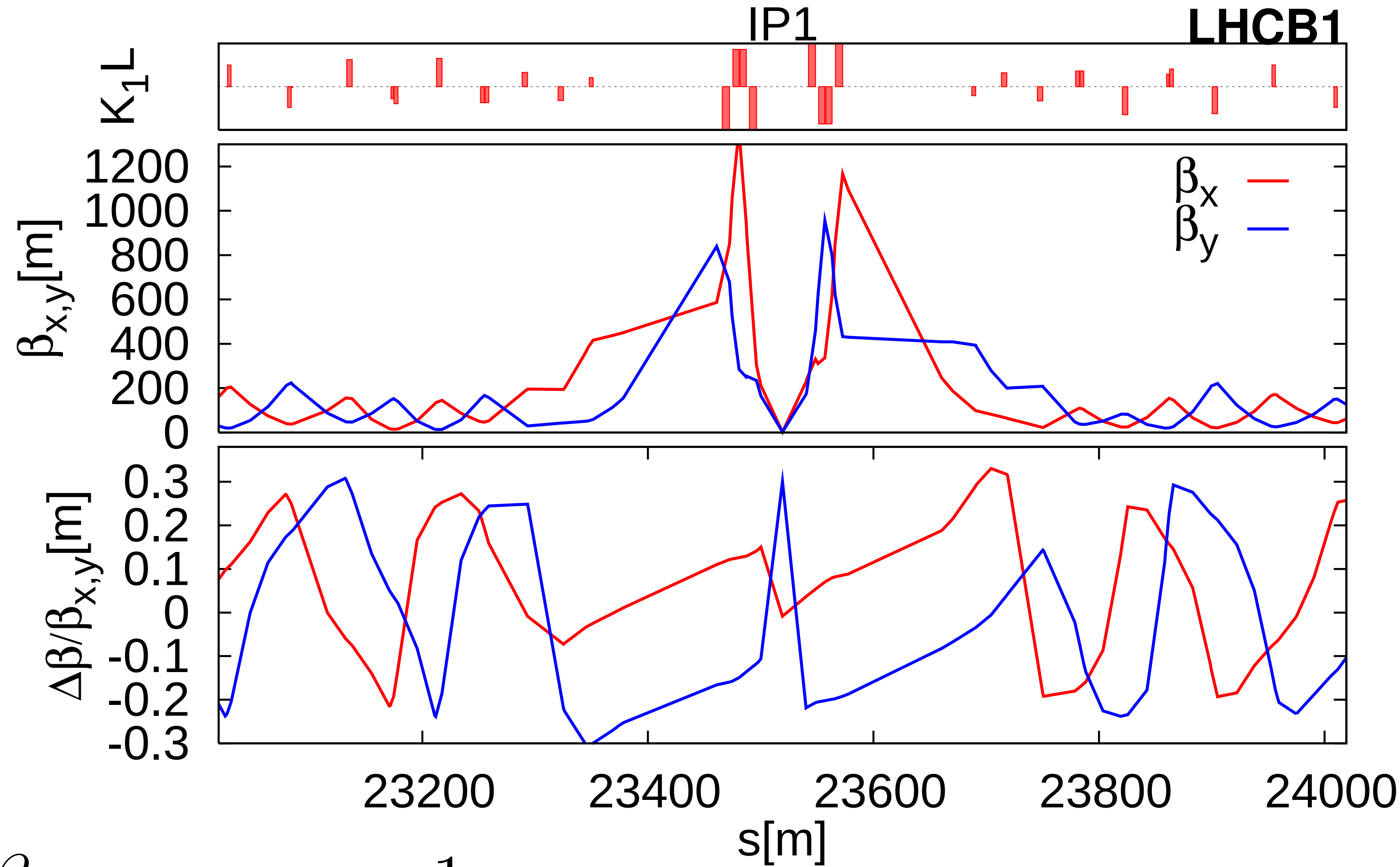
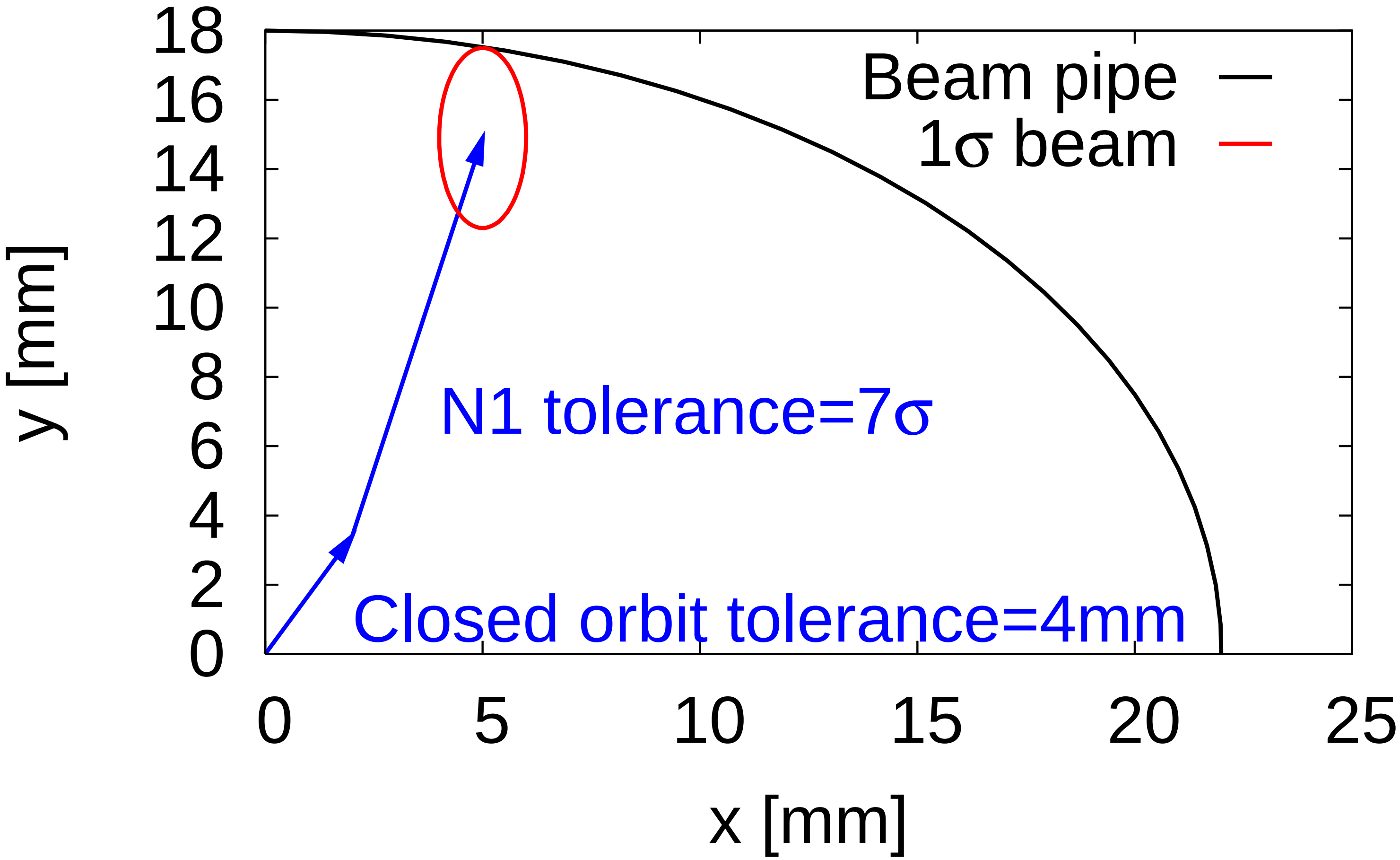
Optics errors



$$\frac{\Delta\beta}{\beta}(s) = \frac{1}{2\sin(2\pi Q)}\beta_0 \Delta KL \cos(2|\phi(s)-\phi_0| - 2\pi Q)$$

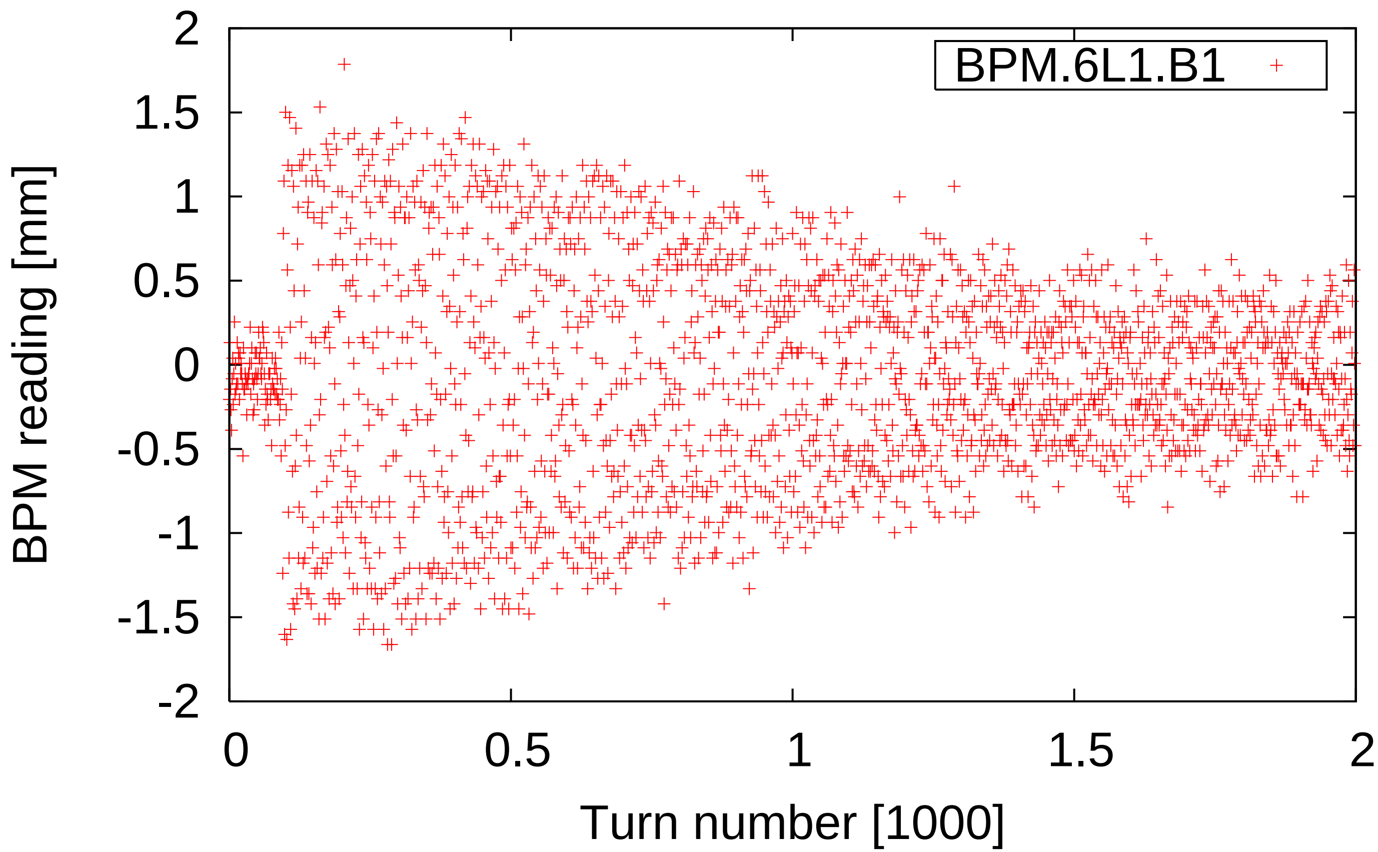
$$\Delta\phi_{rms} = \frac{1}{\sqrt{2}}\frac{\Delta\beta}{\beta}\Big|_{rms} \quad \text{(for the LHC)}$$

Tolerances: a simplified view



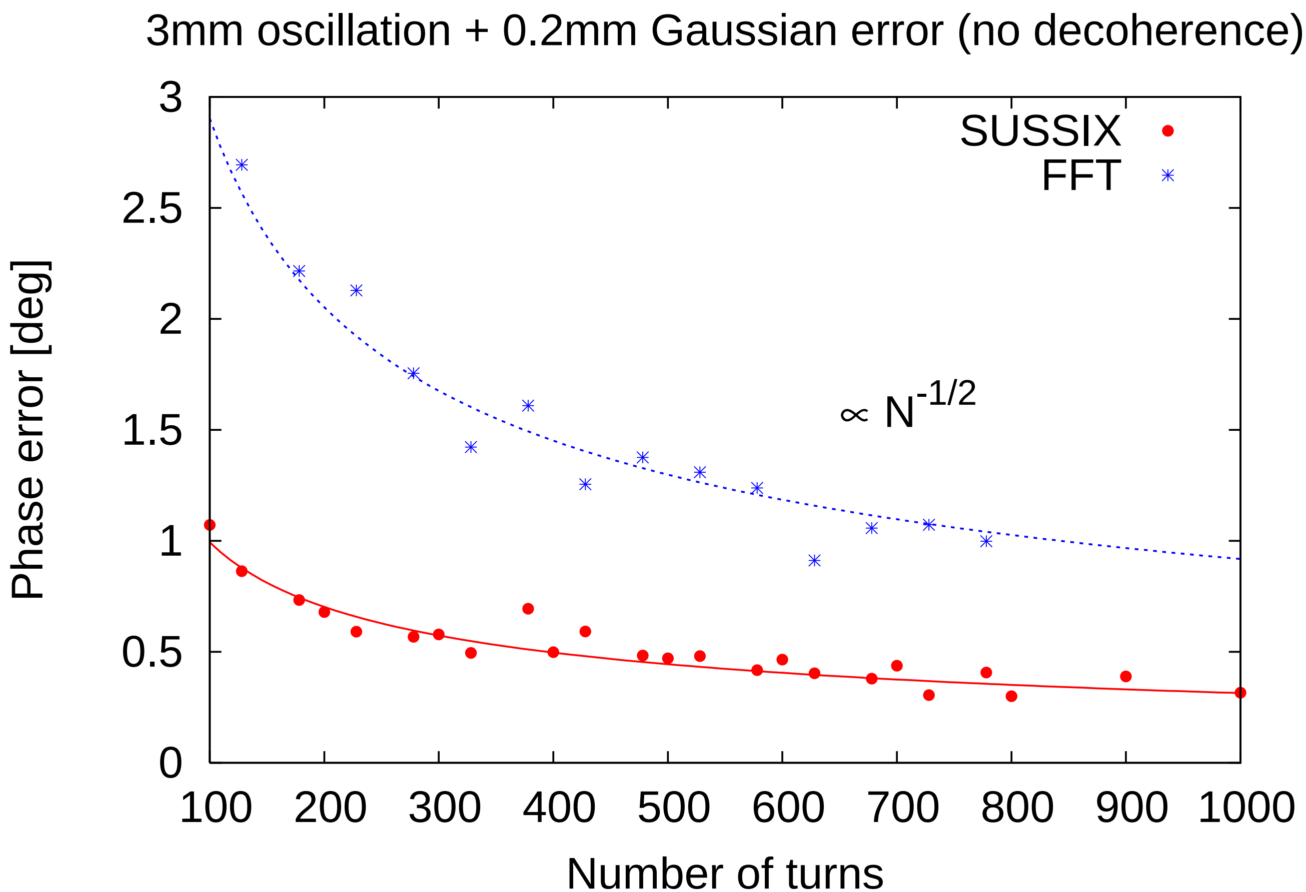
$$\left(\frac{\Delta\beta}{\beta}\right)_{\mathrm{peak}} < 14\% - 19\%\text{, depending on the optics}$$

Optics measurement: single kick



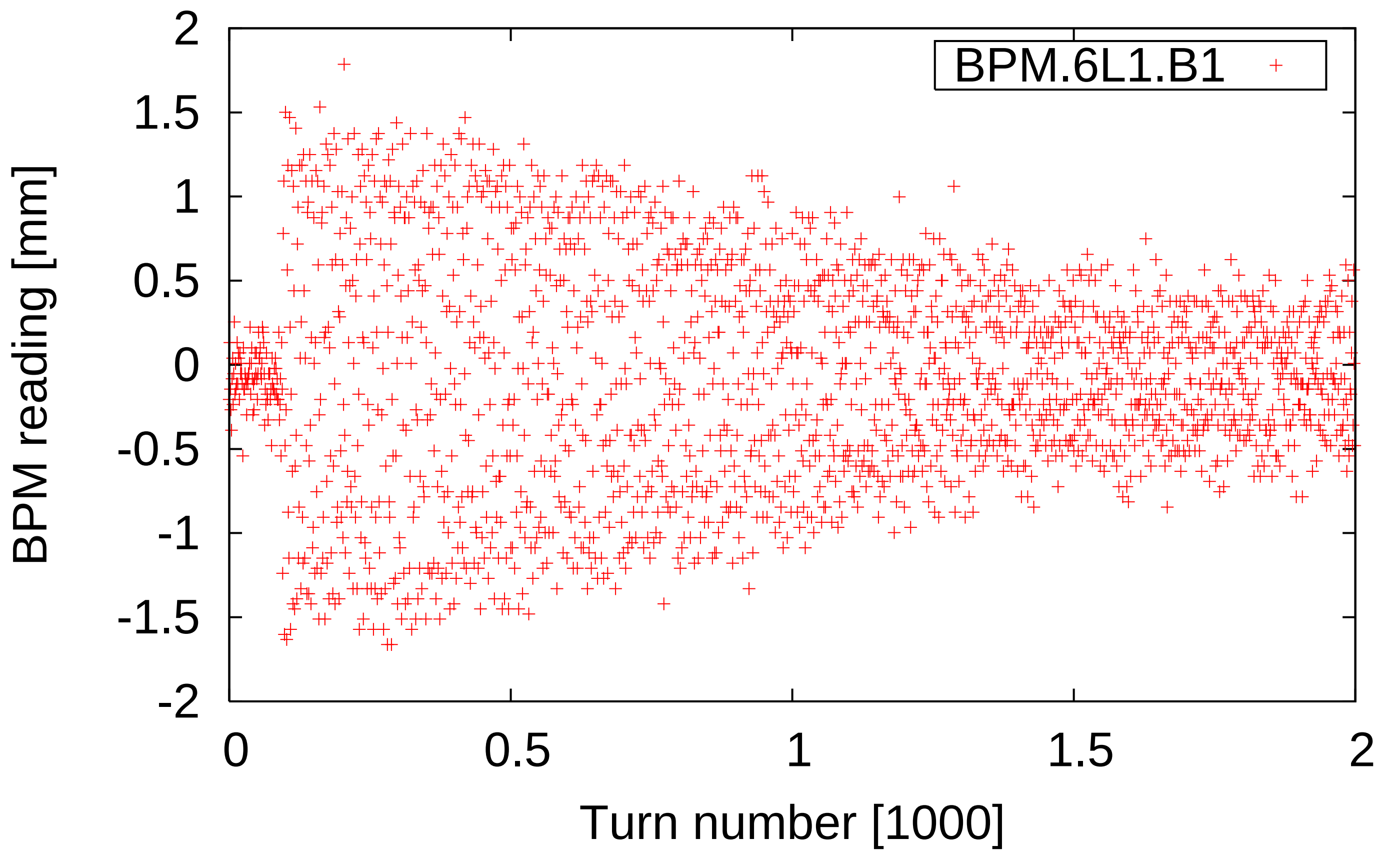
FT and SVD of data from $\approx$500 double plane BPMs yield the ϕ around the ring.

Resolution of Fourier Analyses



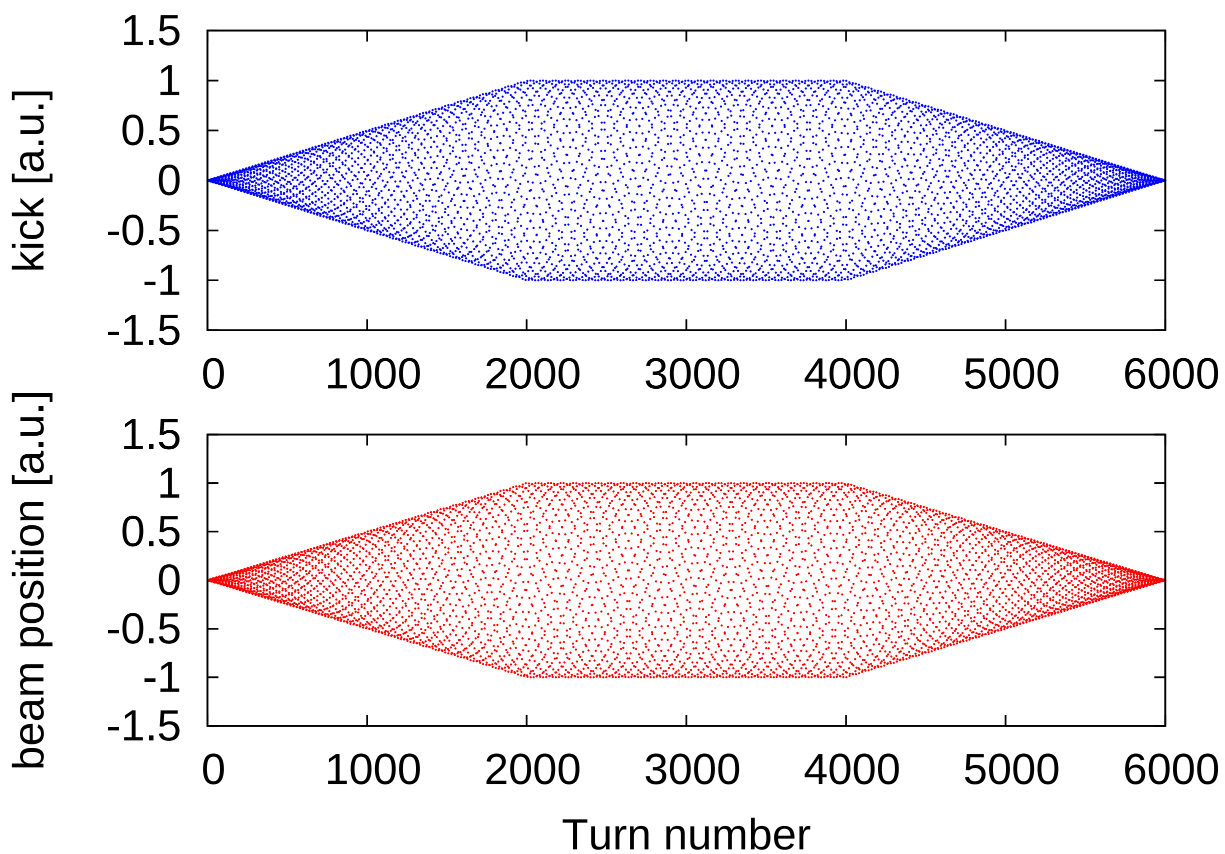
SUSSIX is an interpolated FT with better resolution than the FFT (SVD beats SUSSIX in some regimes).

Optics measurement: single kick



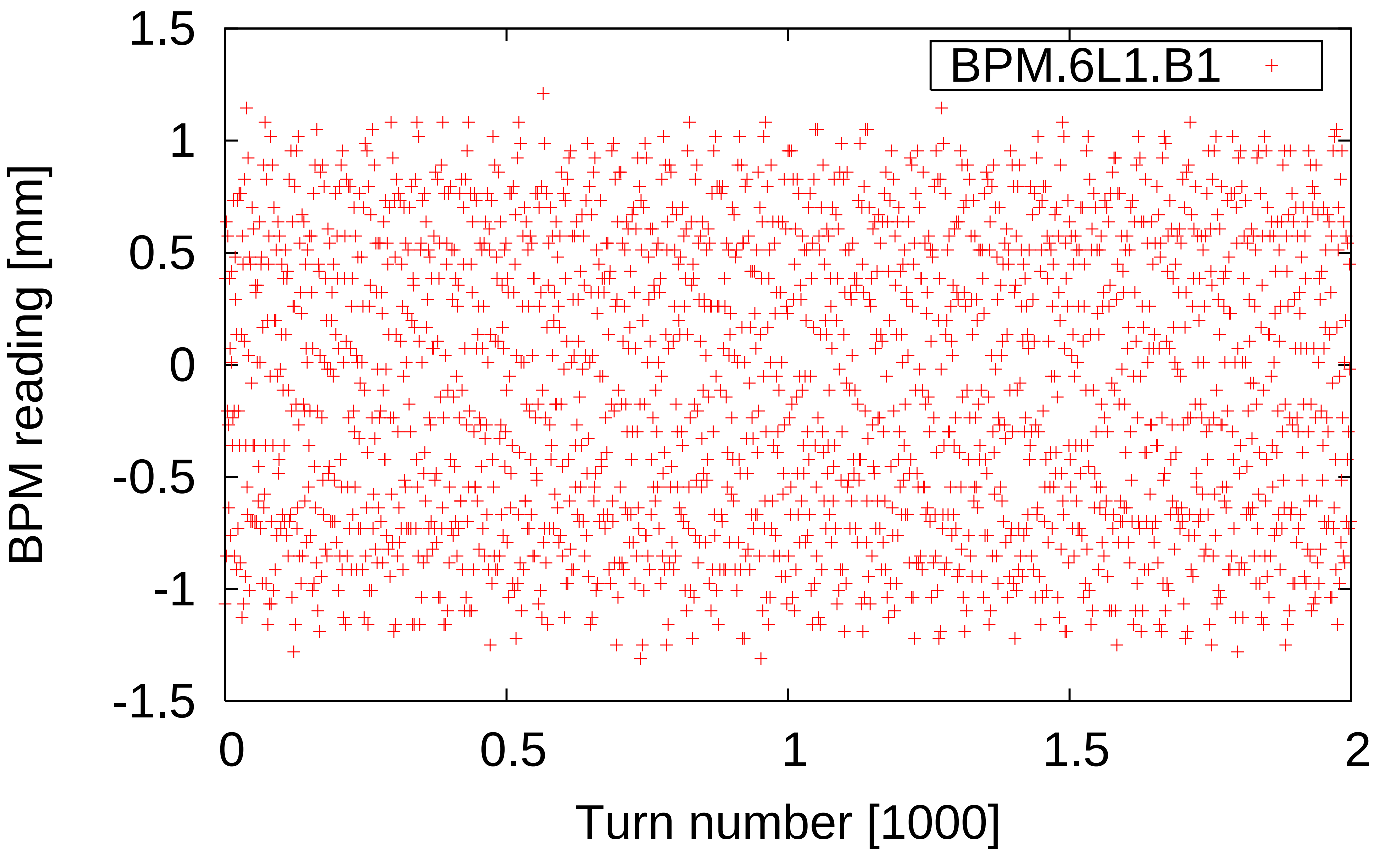
Limitation: [decoherence]

Optics measurement: AC dipole

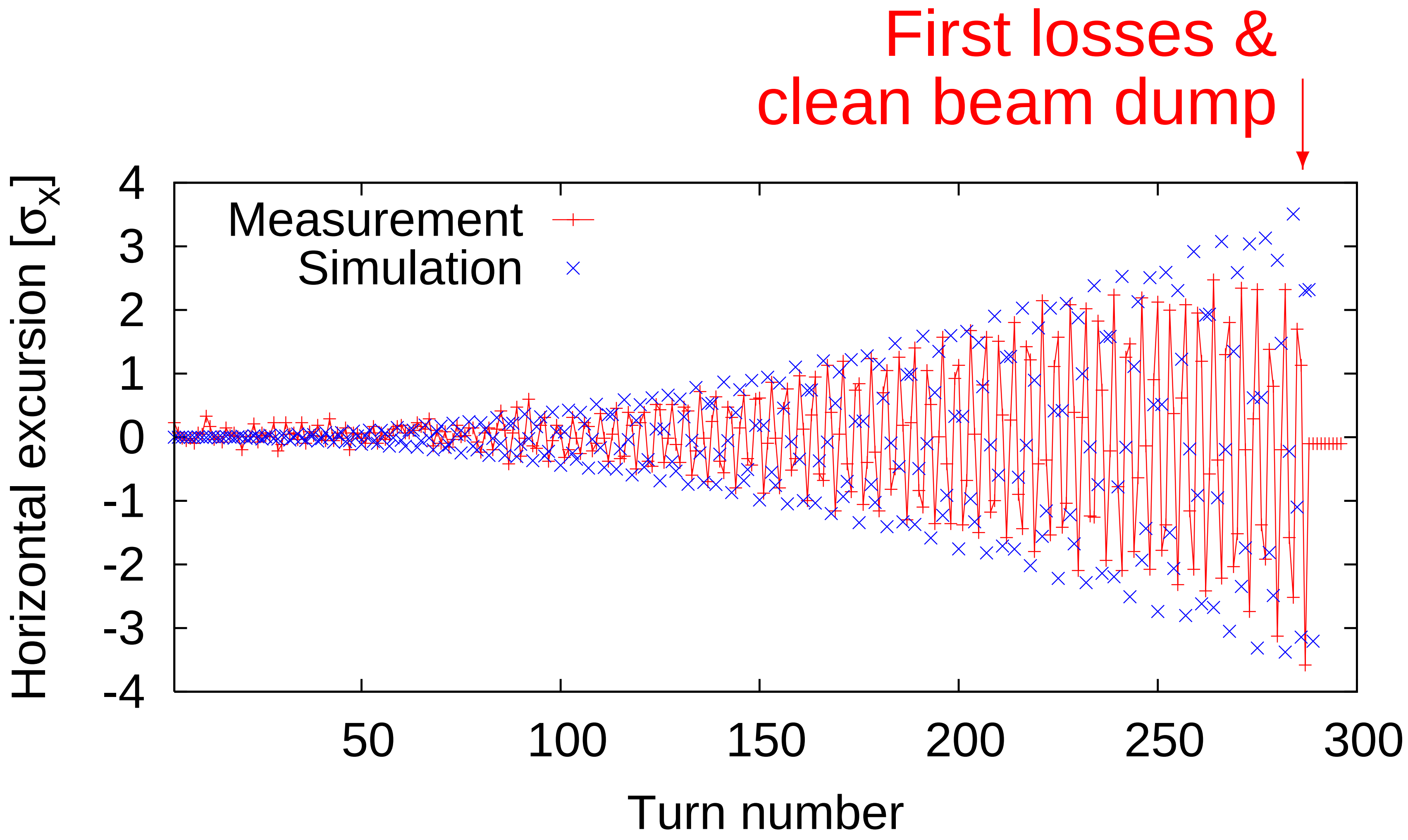


Long-lasting forced oscillations adiabatically ramped up and down$\longrightarrow$ no emittance growth!

LHC AC dipole data example



AC dipole: safety test at $Q_{ac} = Q_x$



and safer than single kicks! *a dream come true!*

Above 1.2 TeV AC dipole is the only exciter.

AC dipoles: too dangerous to be free

Engineer In Charge unlocking the AC dipoles

Optics corrections

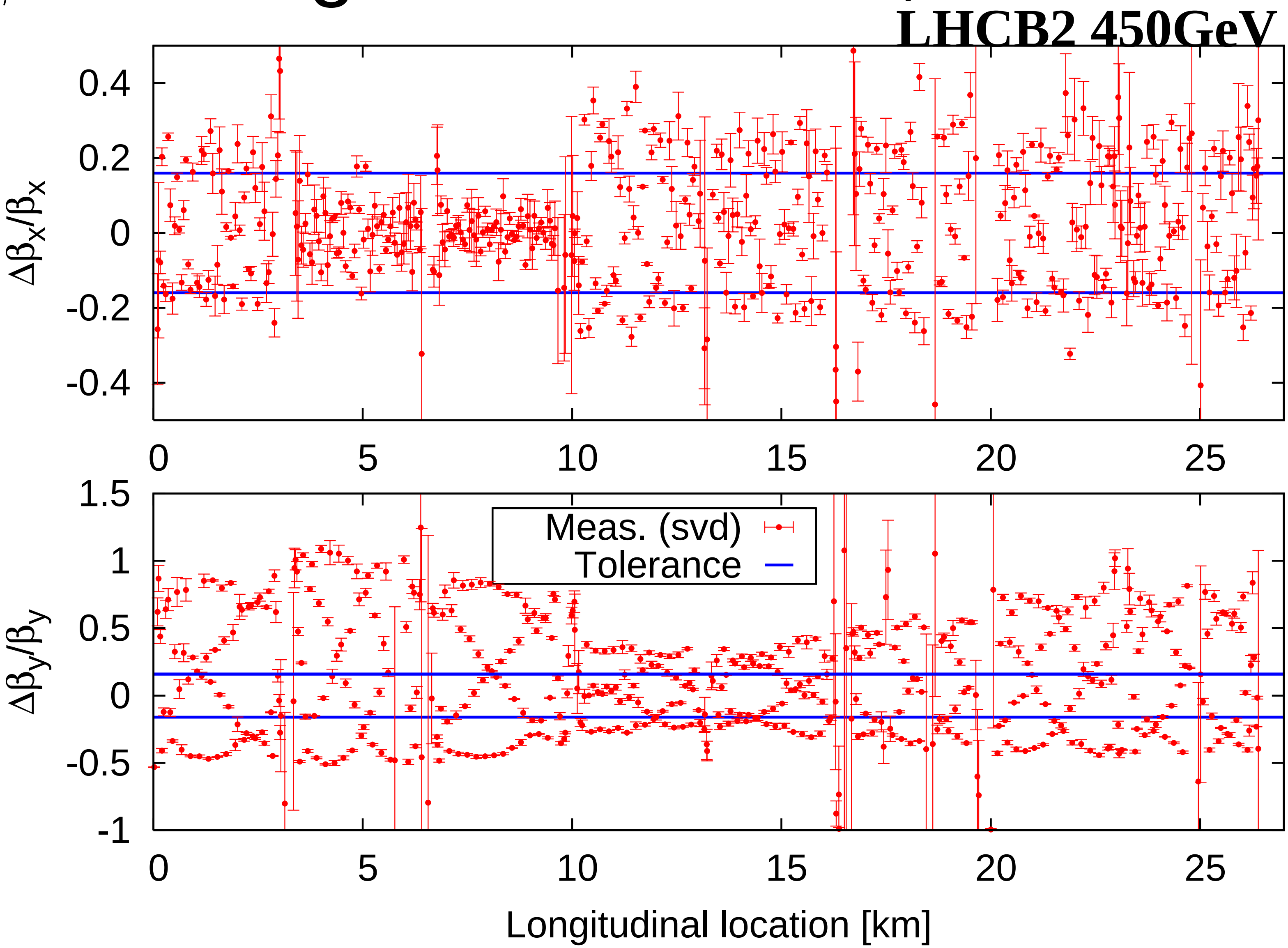
$$\begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \Delta\phi_3 \\ \vdots \\ \Delta\phi_N \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & R_{13} & \cdots & R_{1M} \\ R_{21} & R_{22} & R_{23} & \cdots & R_{2M} \\ R_{31} & R_{32} & R_{33} & \cdots & R_{3M} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ R_{N1} & R_{N2} & R_{N3} & \cdots & R_{NM} \end{pmatrix} \begin{pmatrix} \Delta K_1 \\ \Delta K_2 \\ \Delta K_3 \\ \vdots \\ \Delta K_M \end{pmatrix}$$

$N \approx$ 1000 H&V BPMs per beam,
$M \approx$ 200 quad circuits per beam

$$\Delta\vec{K} = \mathbf{R}^{-1}\Delta\vec{\phi}_{meas} \text{ (pseudoinverse)}$$

This works for moderately low optics errors but...

1^{st} β-beating measurement, 2008



...here the $\mathbf{R}^{-1}$ method did not really work.

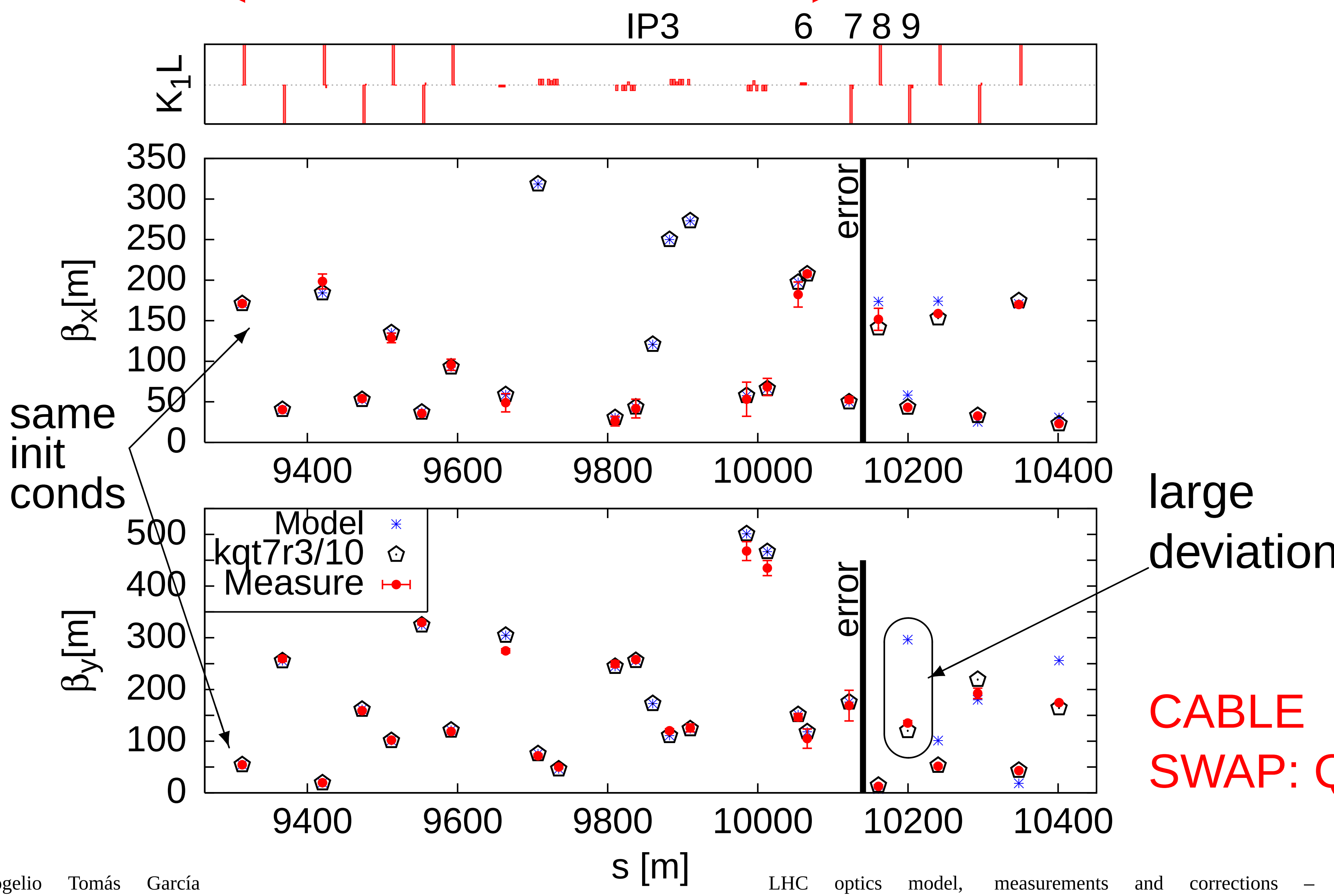
The segment-by-segment technique

Concept: split the LHC into segments and treat them as independent transfer lines by using the measured $\beta_{x,y}$ and $\alpha_{x,y}$ as the initial optics conditions at the starting points $\rightarrow$ Results in a block diagonal $\mathbf{R}$:

$$\begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \Delta\phi_3 \\ \vdots \\ \Delta\phi_N \end{pmatrix} = \begin{pmatrix} \mathbf{R_1} & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{R_2} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{R_3} & \cdots & \mathbf{0} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{R_n} \end{pmatrix} \begin{pmatrix} \Delta K_1 \\ \Delta K_2 \\ \Delta K_3 \\ \vdots \\ \Delta K_M \end{pmatrix}$$

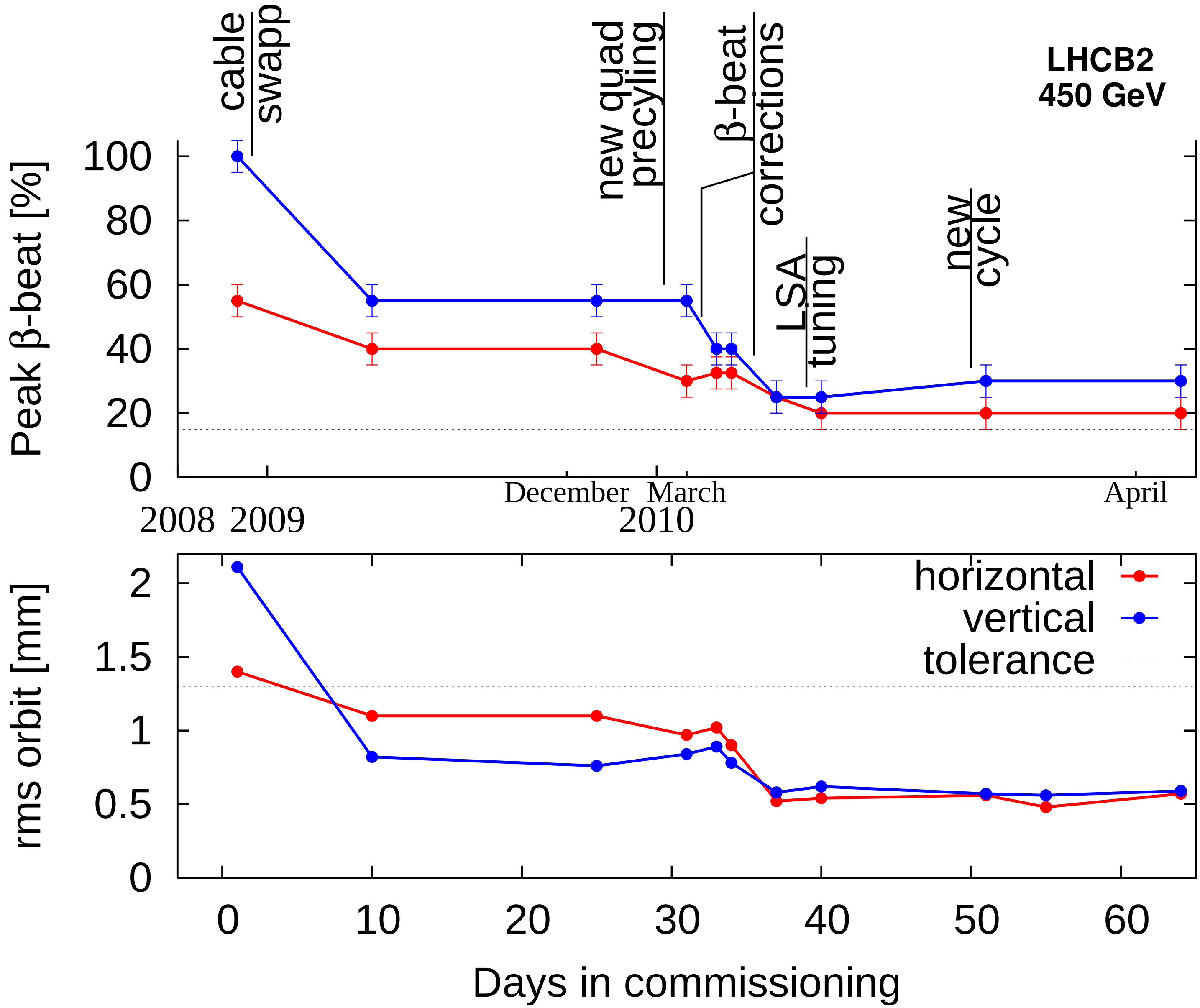
Application to the 2008 data

Measurement=propagated model



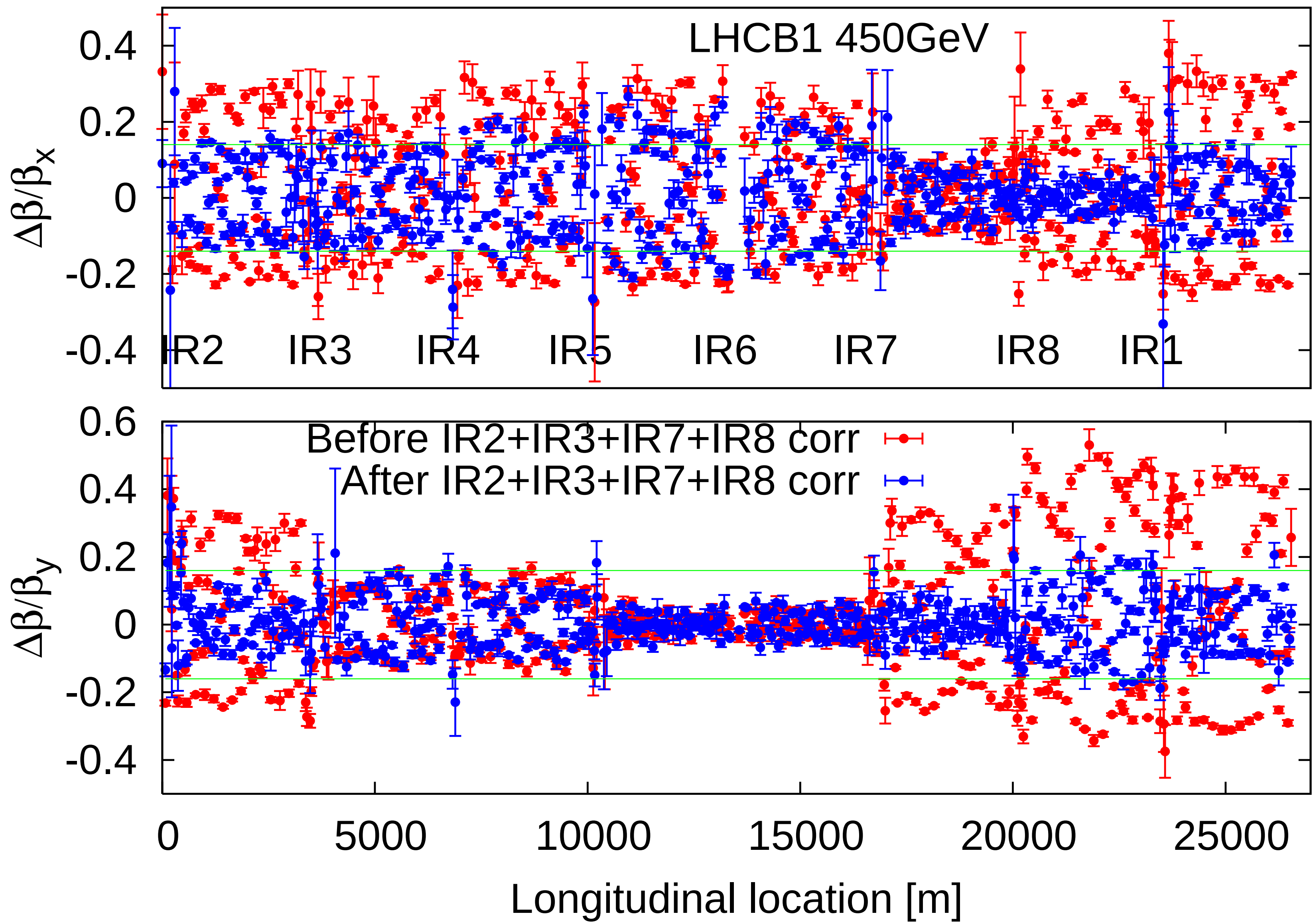
CABLE SWAP: QT7

History of optics errors at injection

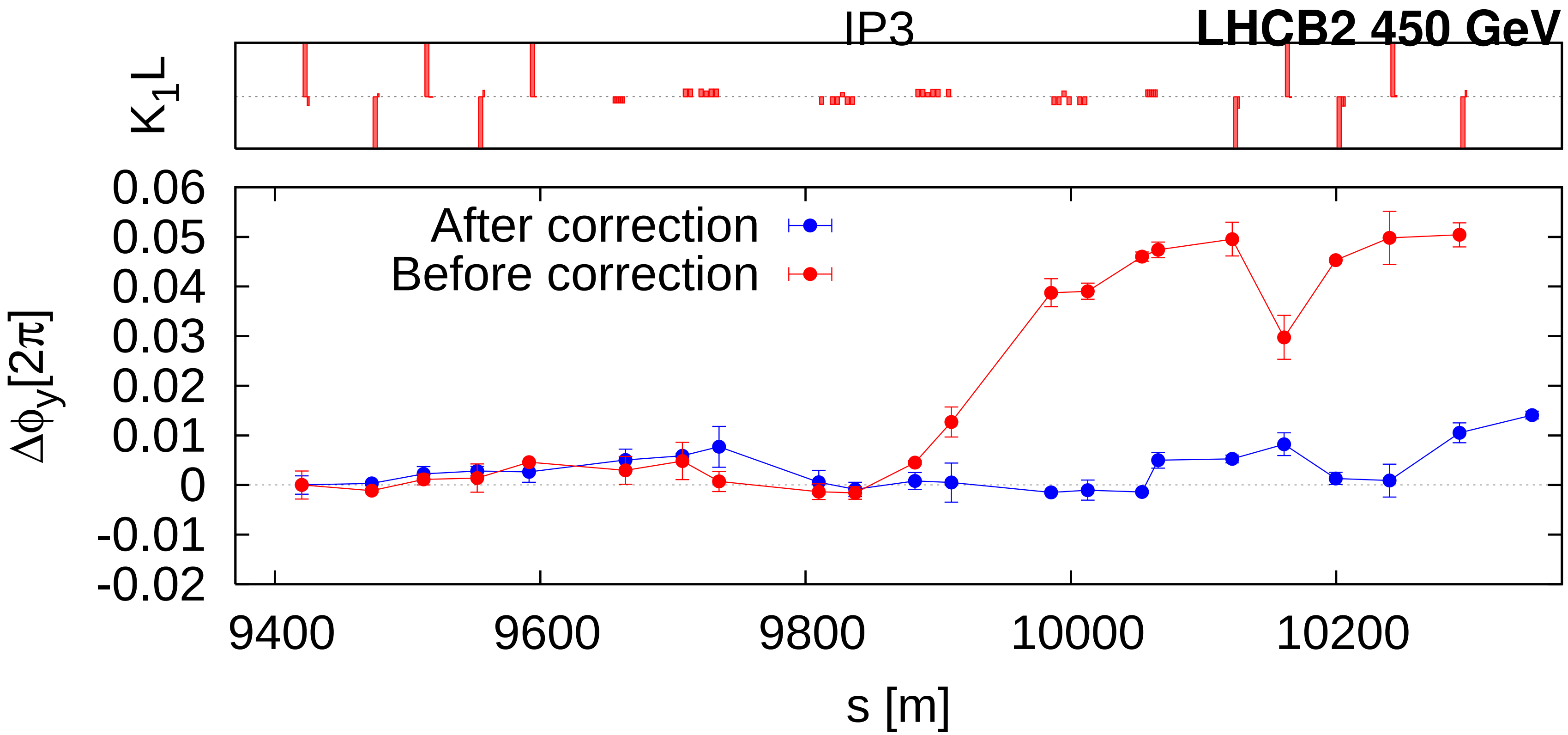


Orbit and β-beat tolerances can be rebalanced

Corrections at injection in 2010



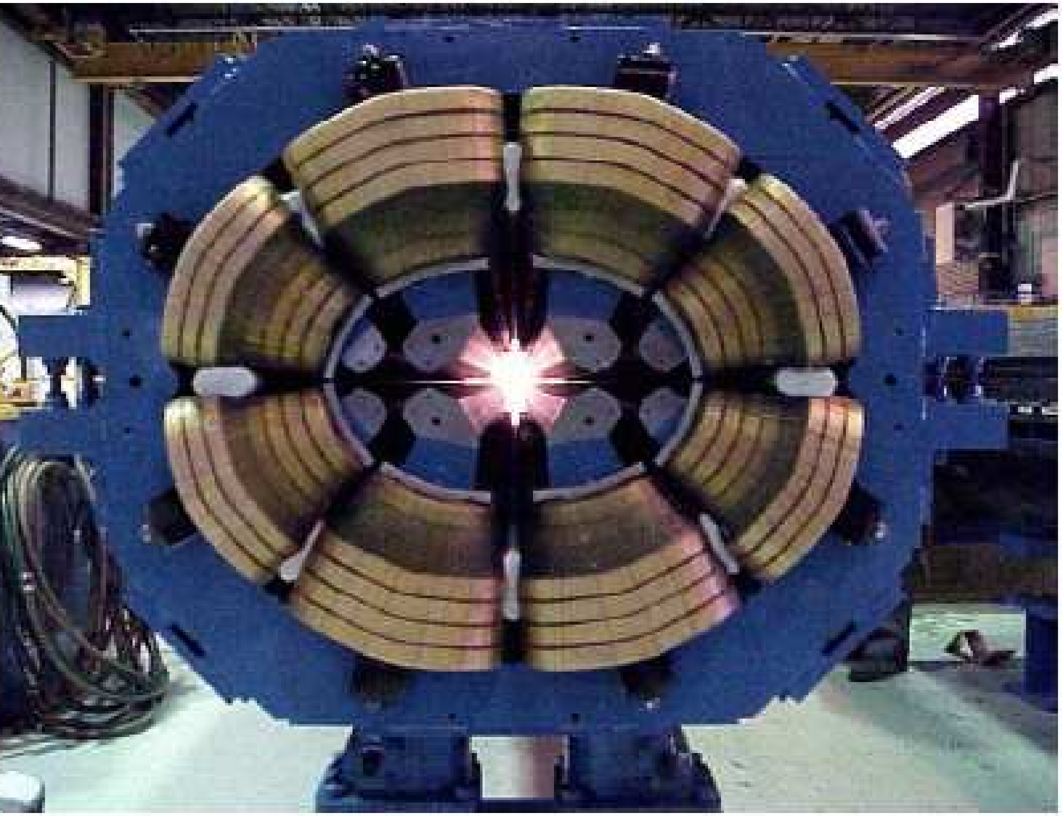
Segment-by-segment correction

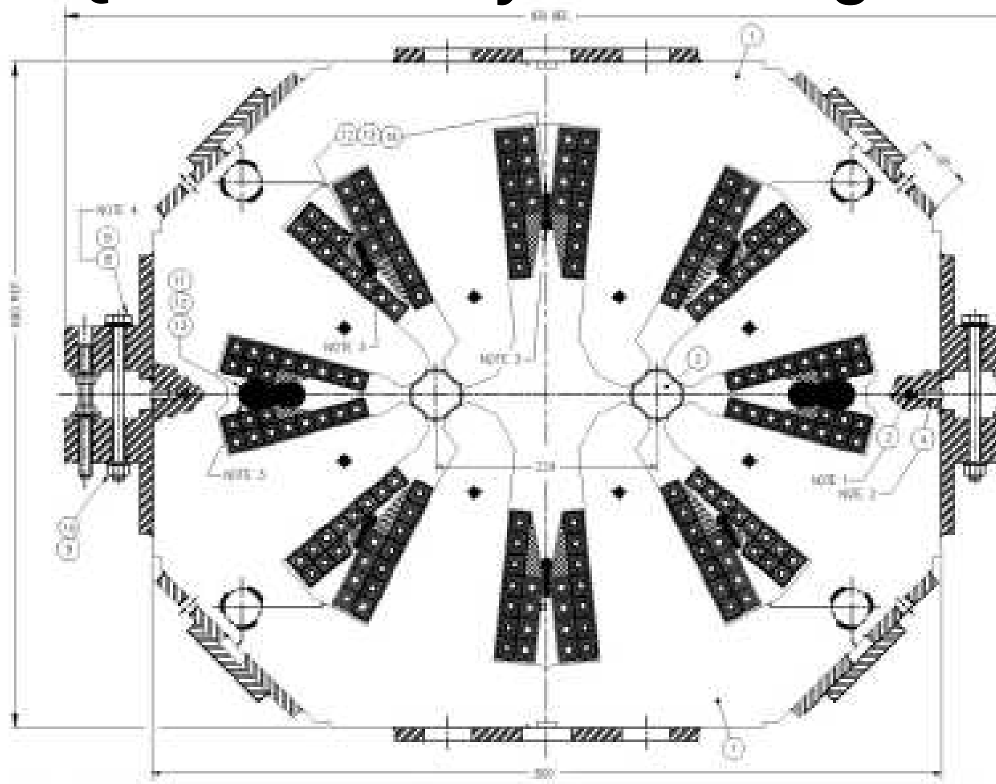


Corrections in the order of 3% were required in main warm magnets and 250% in trim magnets!

Culprit at injection

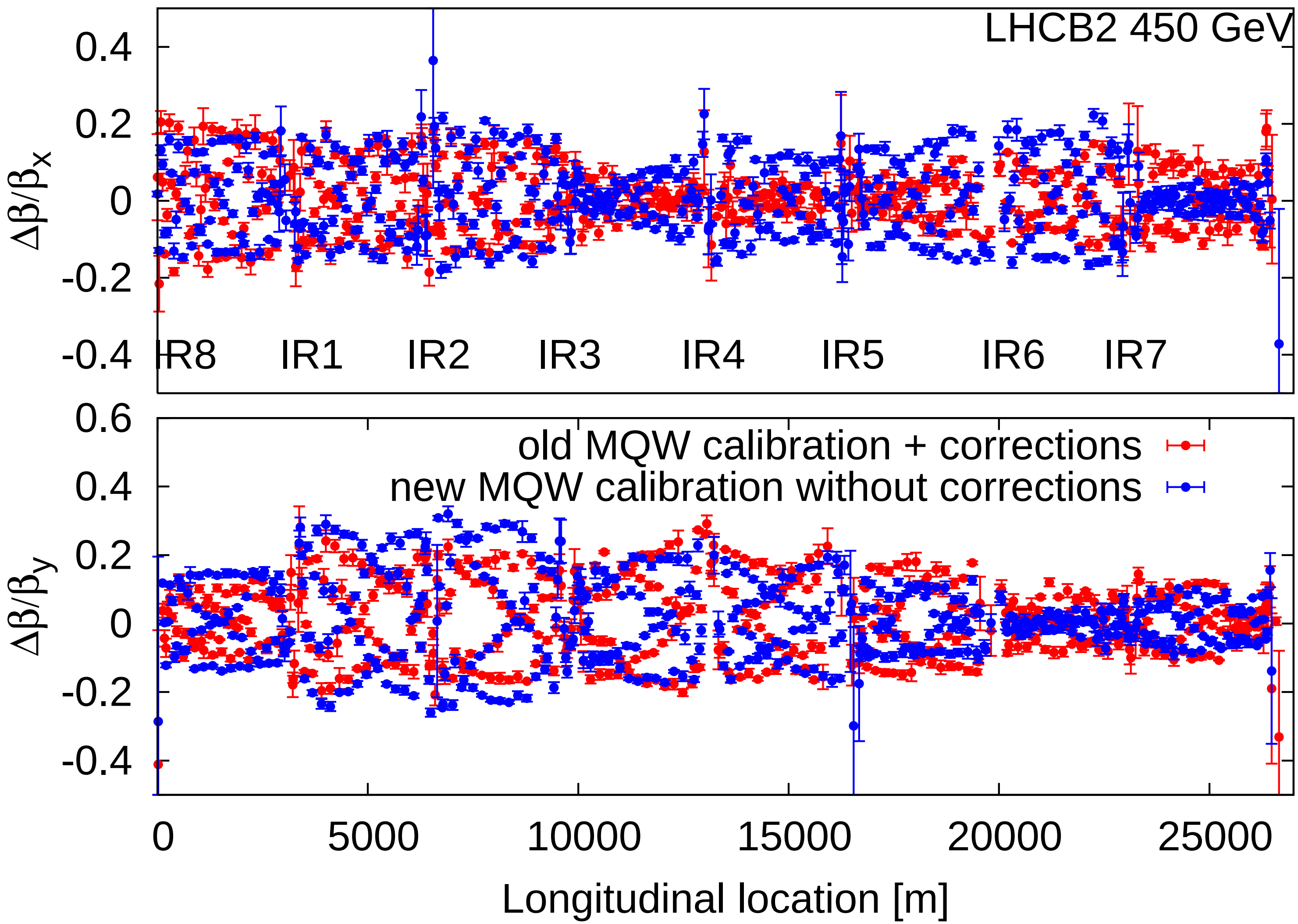
MQW, courtesy of P. Hagen





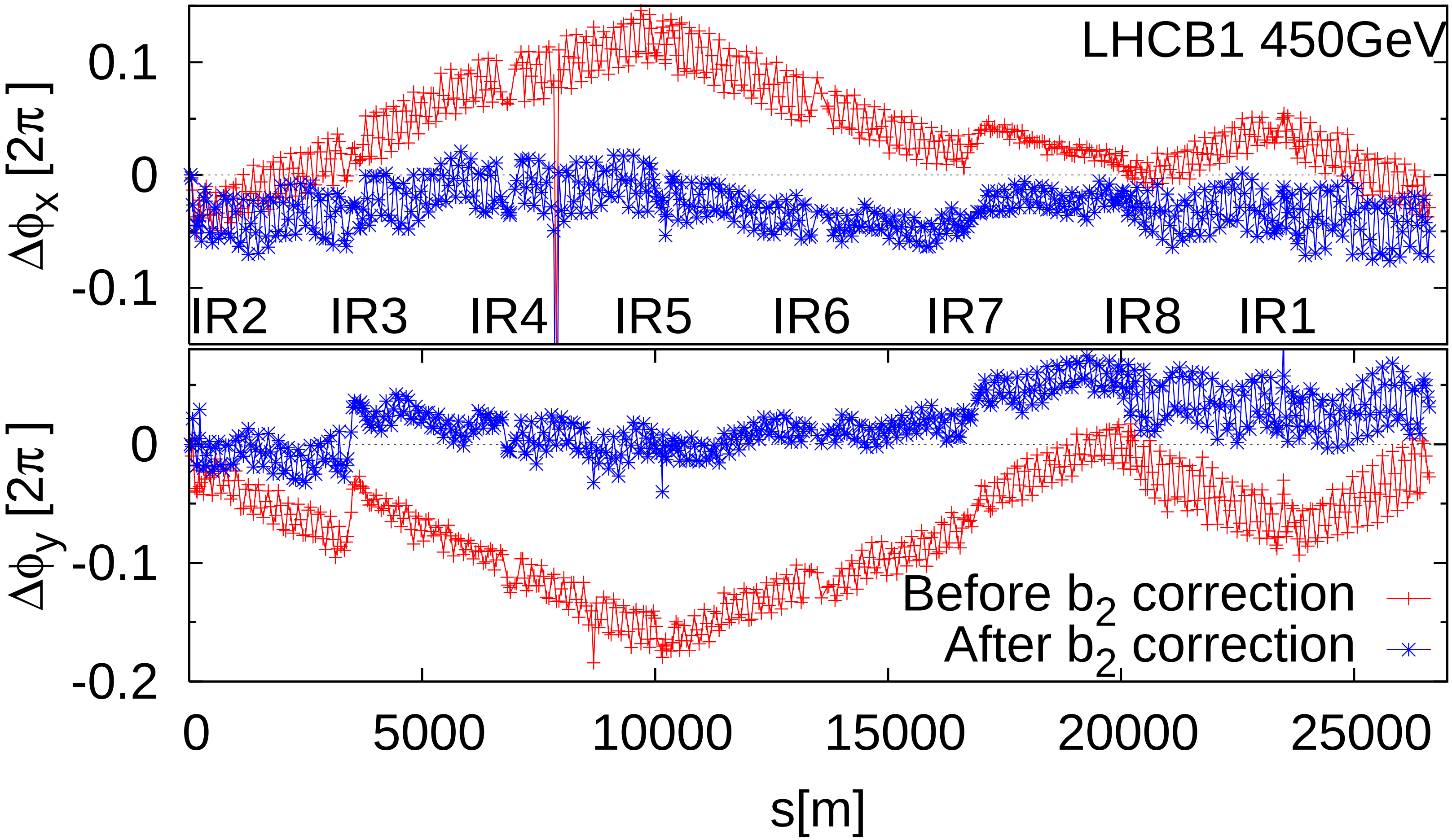
New magnetic measurements of MQWs explain rather well the observed errors → Update MQW calibrations.

New MQW calibrations



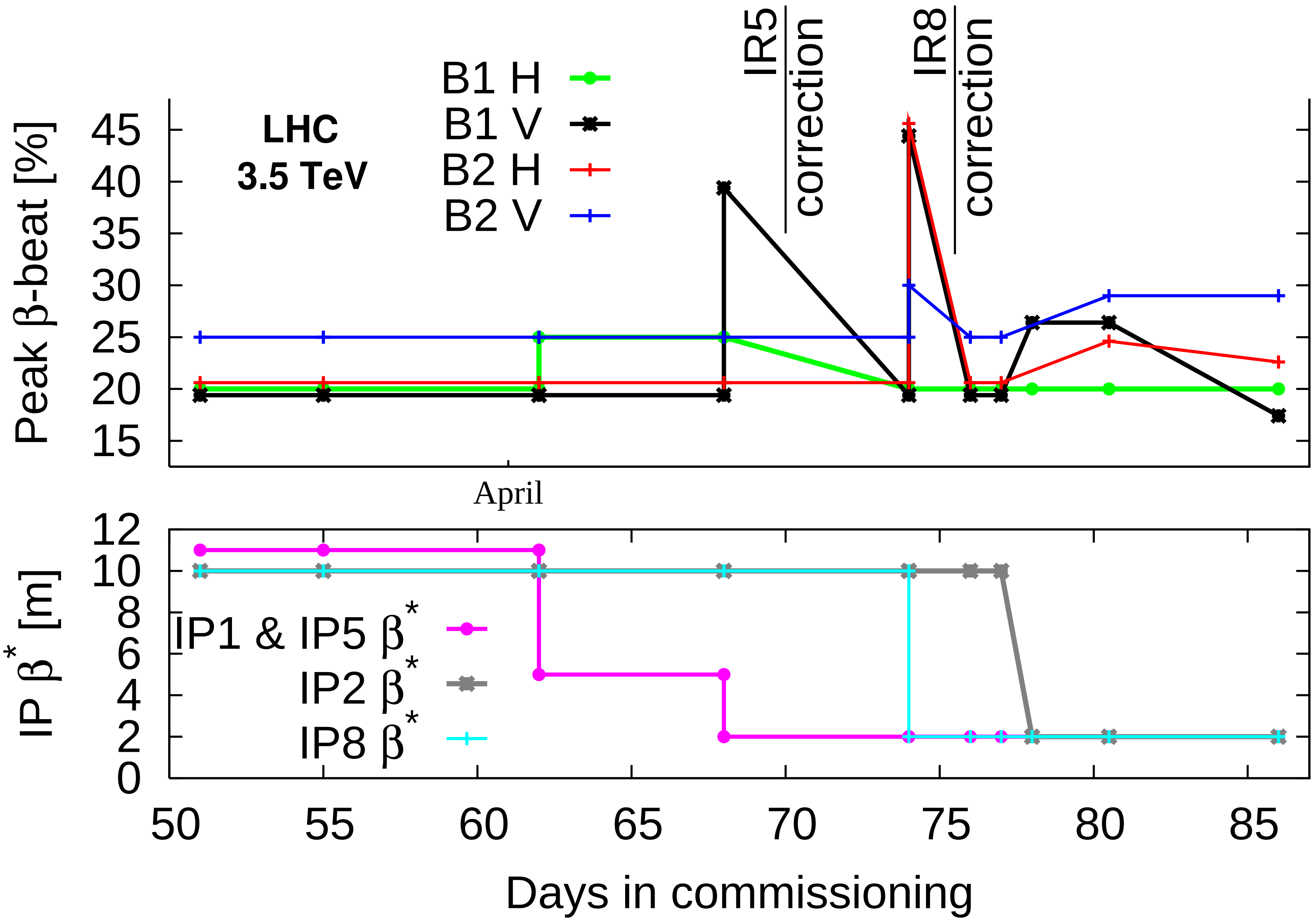
Similar performance!→Problem understood!

The systematic b_2 error in the SC dipoles

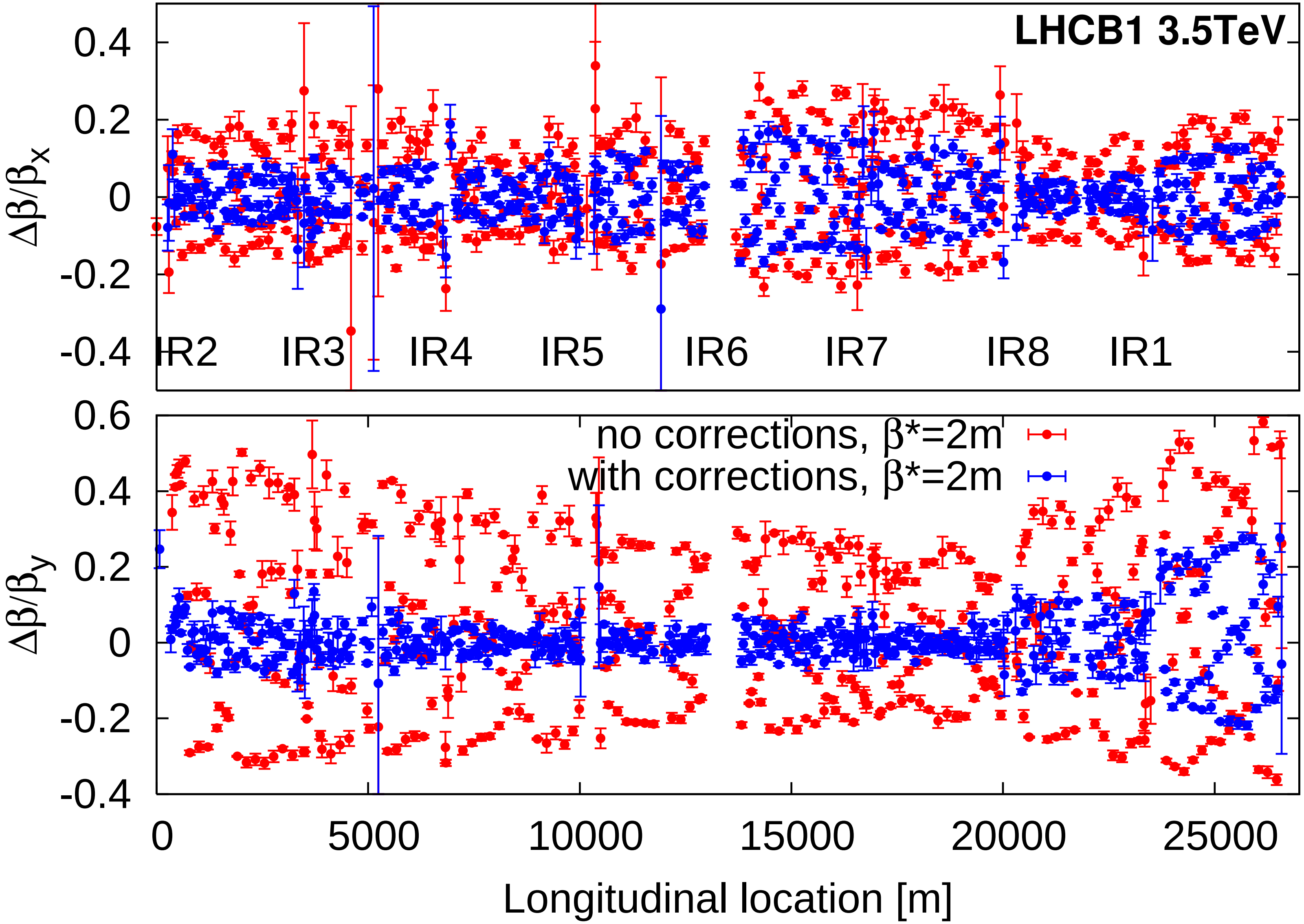


The correction is directly computed from magnetic measurements!

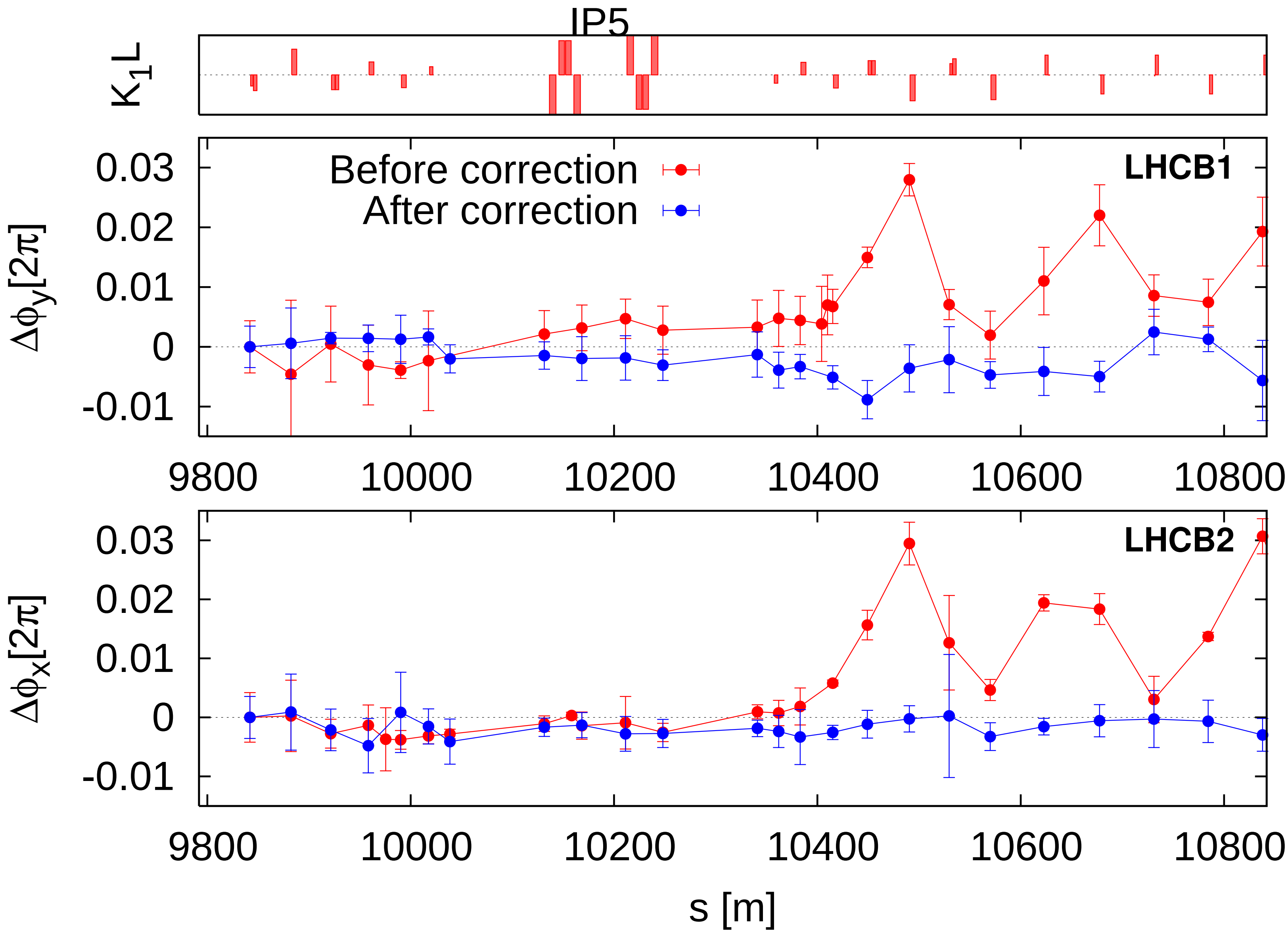
Optics errors during the squeeze



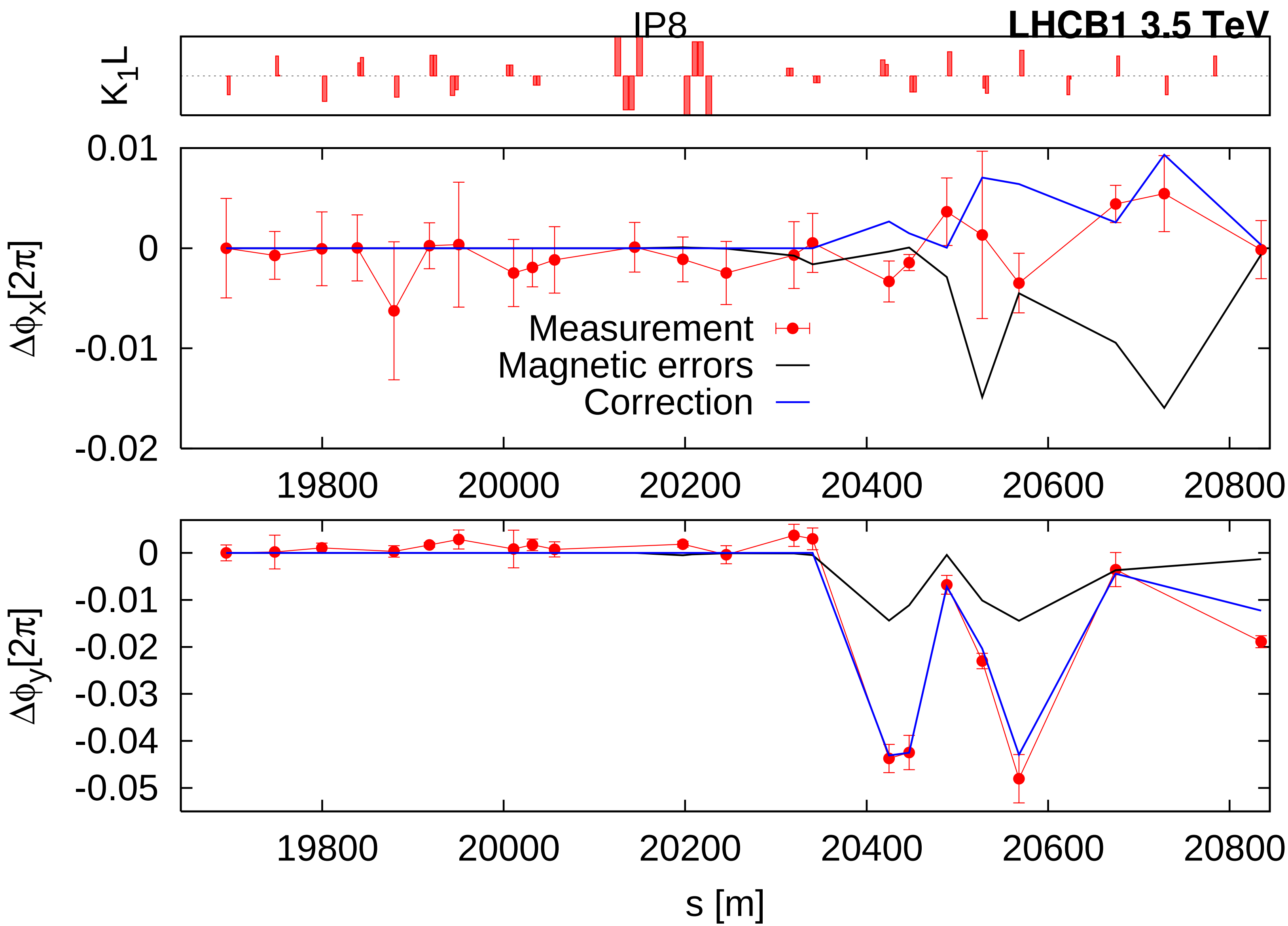
Corrections at $\beta^* = $2m



IP5 correction using the triplet



IP8, the largest error



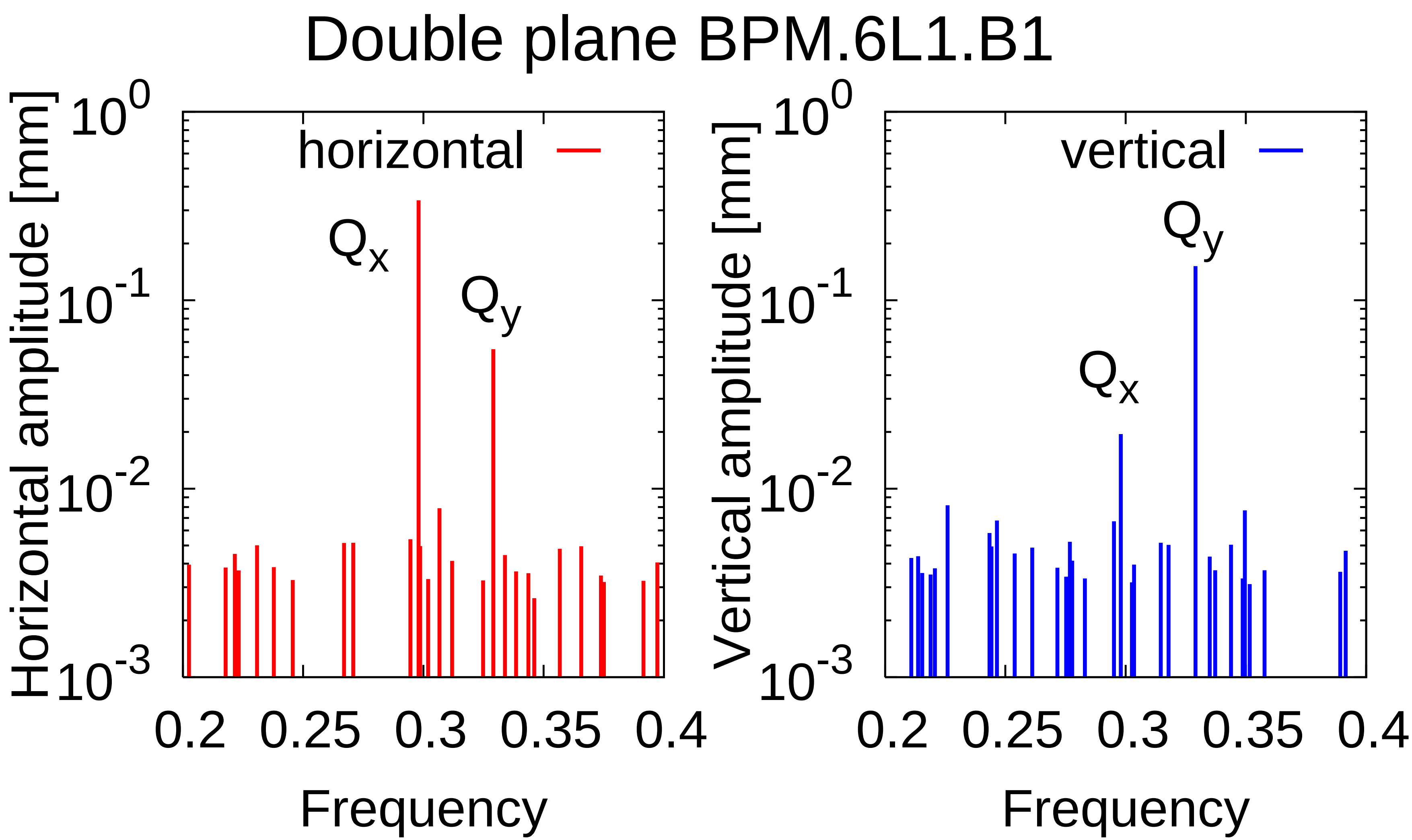
Known triplet errors explain part of the deviation...

The corrections at 3.5 TeV

Magnet	Value[m^{-1}]	Max[m^{-1}]	Correction[%]
MQXB2.R5	-0.0087	0.018	-0.15
MQXB2.L5	0.0087	0.018	0.12
MQ5.R8B1	-0.0029	0.013	5→3.3
MQ6.L8B2	0.0056	0.013	1.8

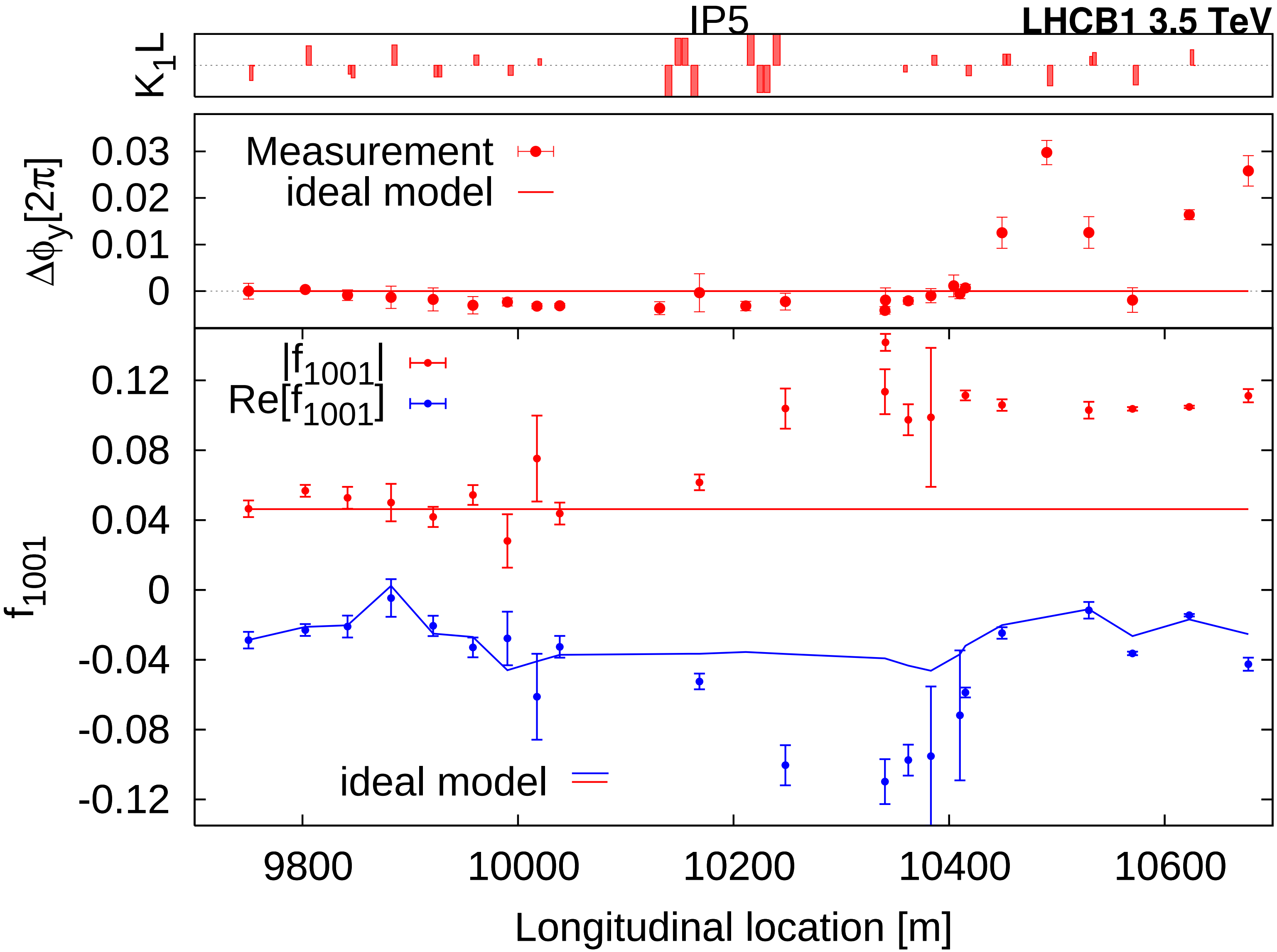
The IR8 errors need further investigation.

Coupling measurement



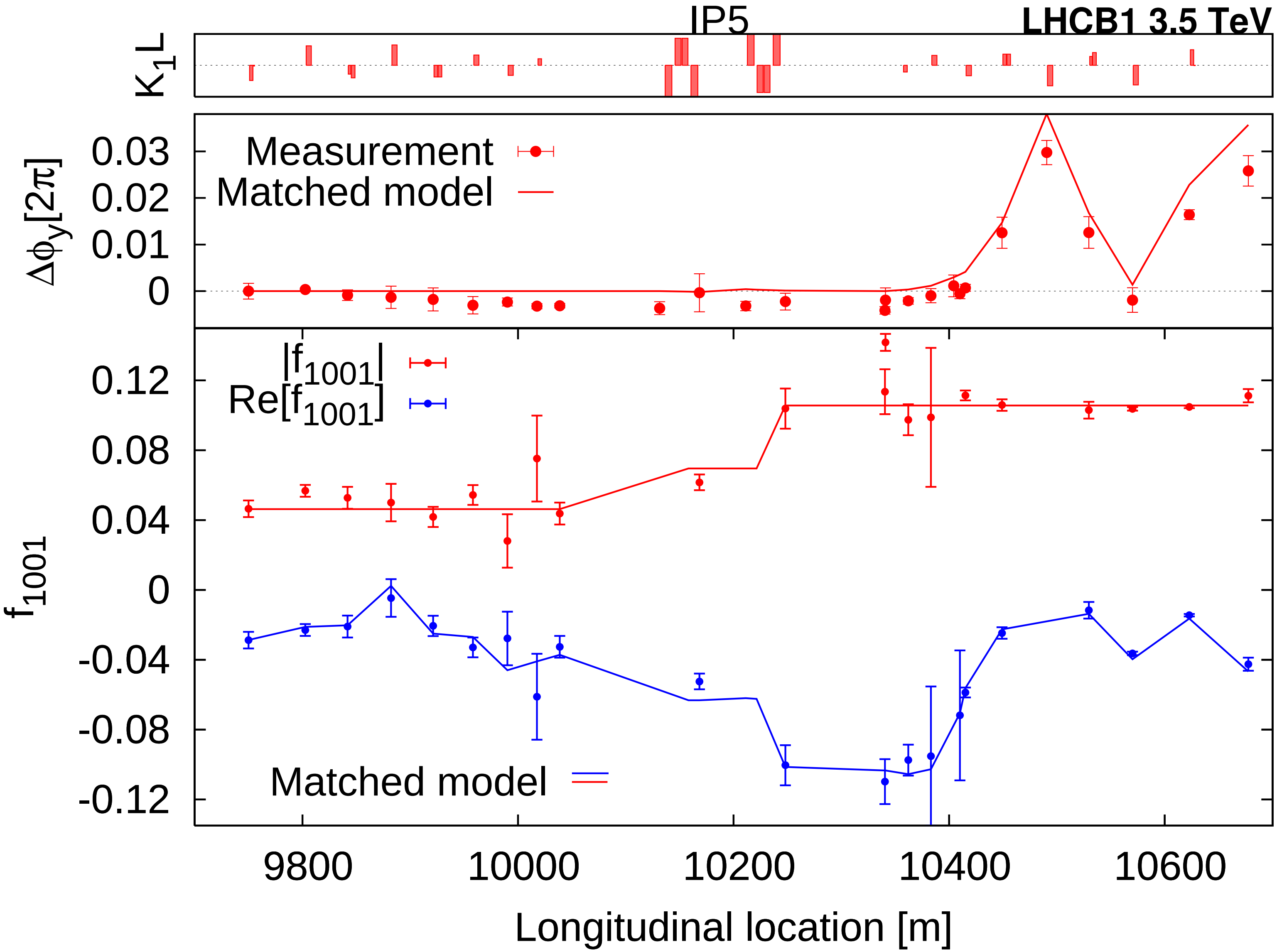
$$f_{1001} = \frac{1}{4\gamma}(\bar{C}_{12} - \bar{C}_{21} + i\bar{C}_{11} + i\bar{C}_{22}),$$

Full segment-by-segment



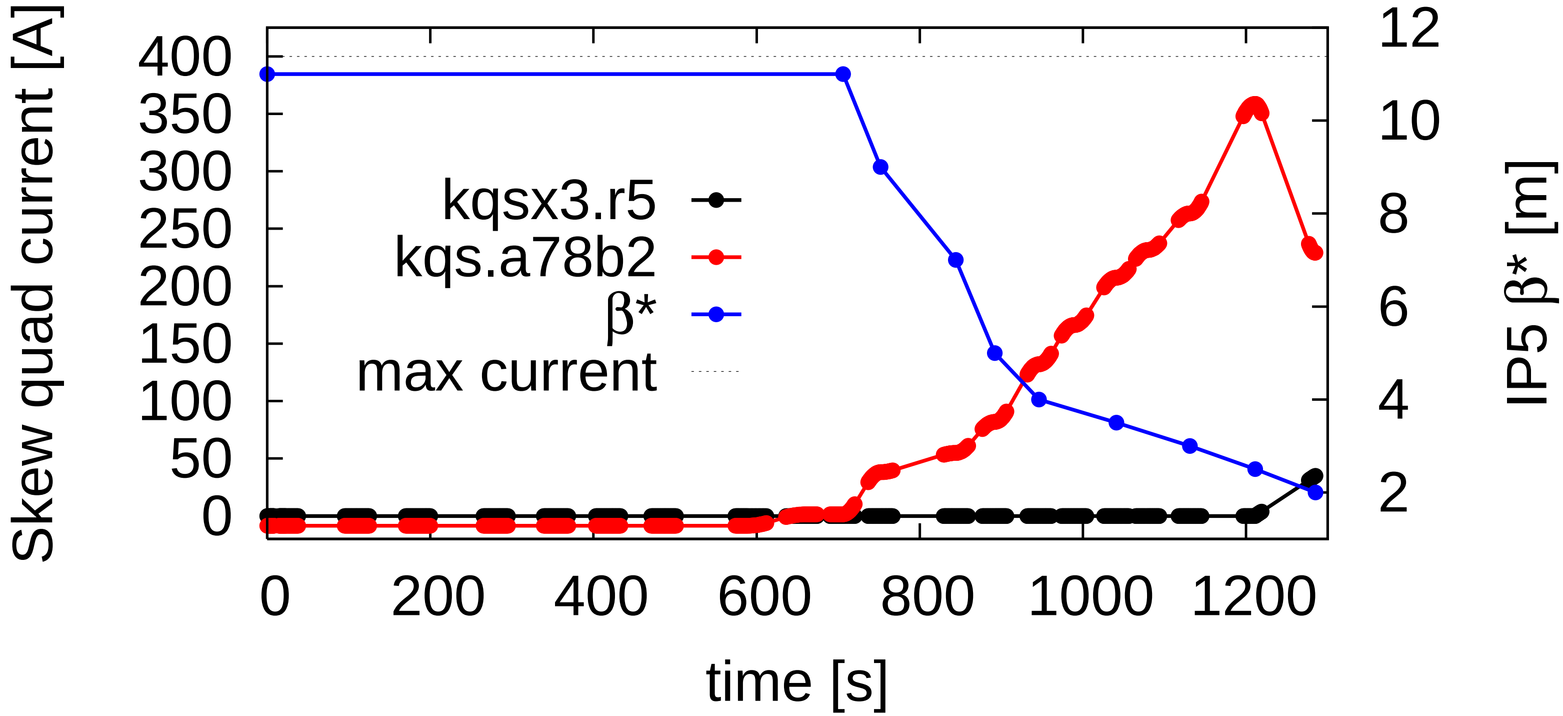
The discrepancy suggest errors in the triplet

Full segment-by-segment: error matching



Matching using normal and skew triplet gradients

Coupling correction during the squeeze



Global knobs are not strong enough at β^{*}=2m and the IR skew quadrupole strengths are computed using the full segment-by-segment technique.

Summary & Outlook

- I hope to have conveyed the excitement and challenge of the LHC optics

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- Cannot wait for the off-momentum and non-linear optics

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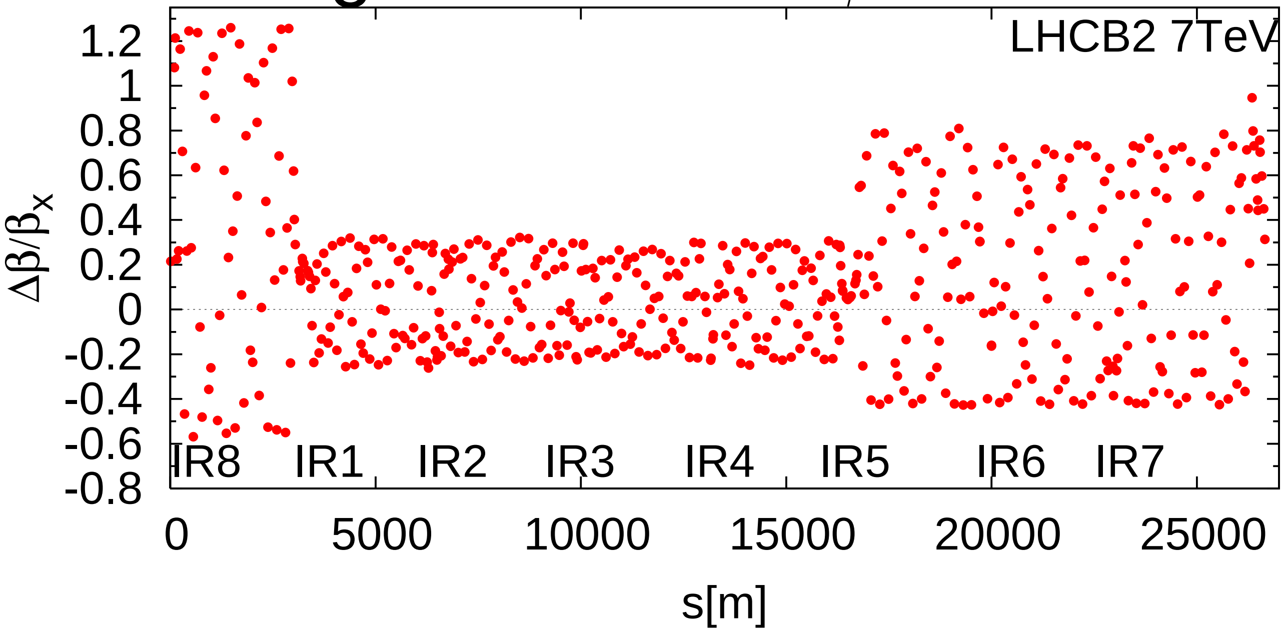
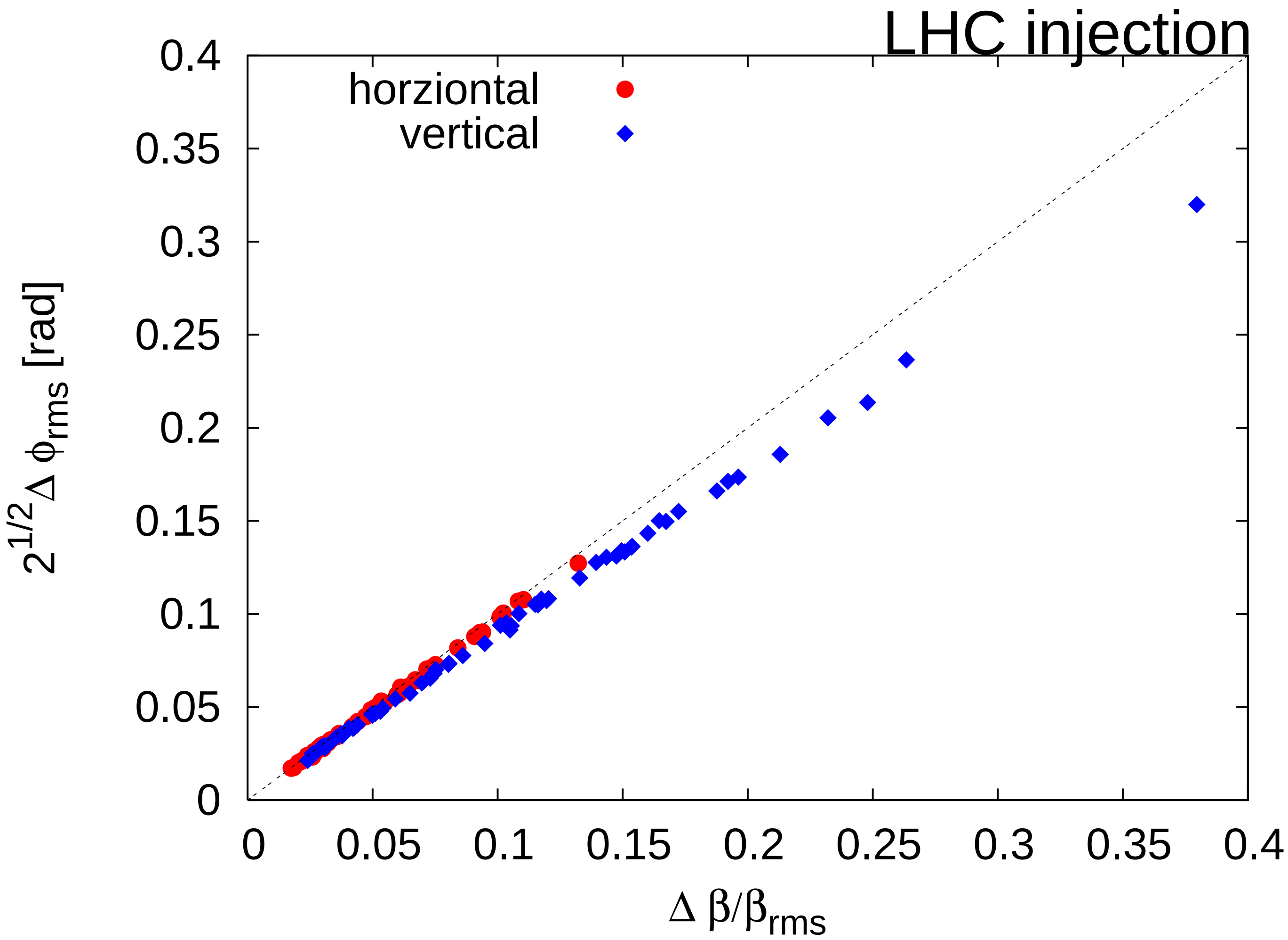
- I hope to have conveyed the excitement and challenge of the LHC optics
- Cannot wait for the off-momentum and non-linear optics
- 2013 challenge: 7 TeV and β^*=0.55 m



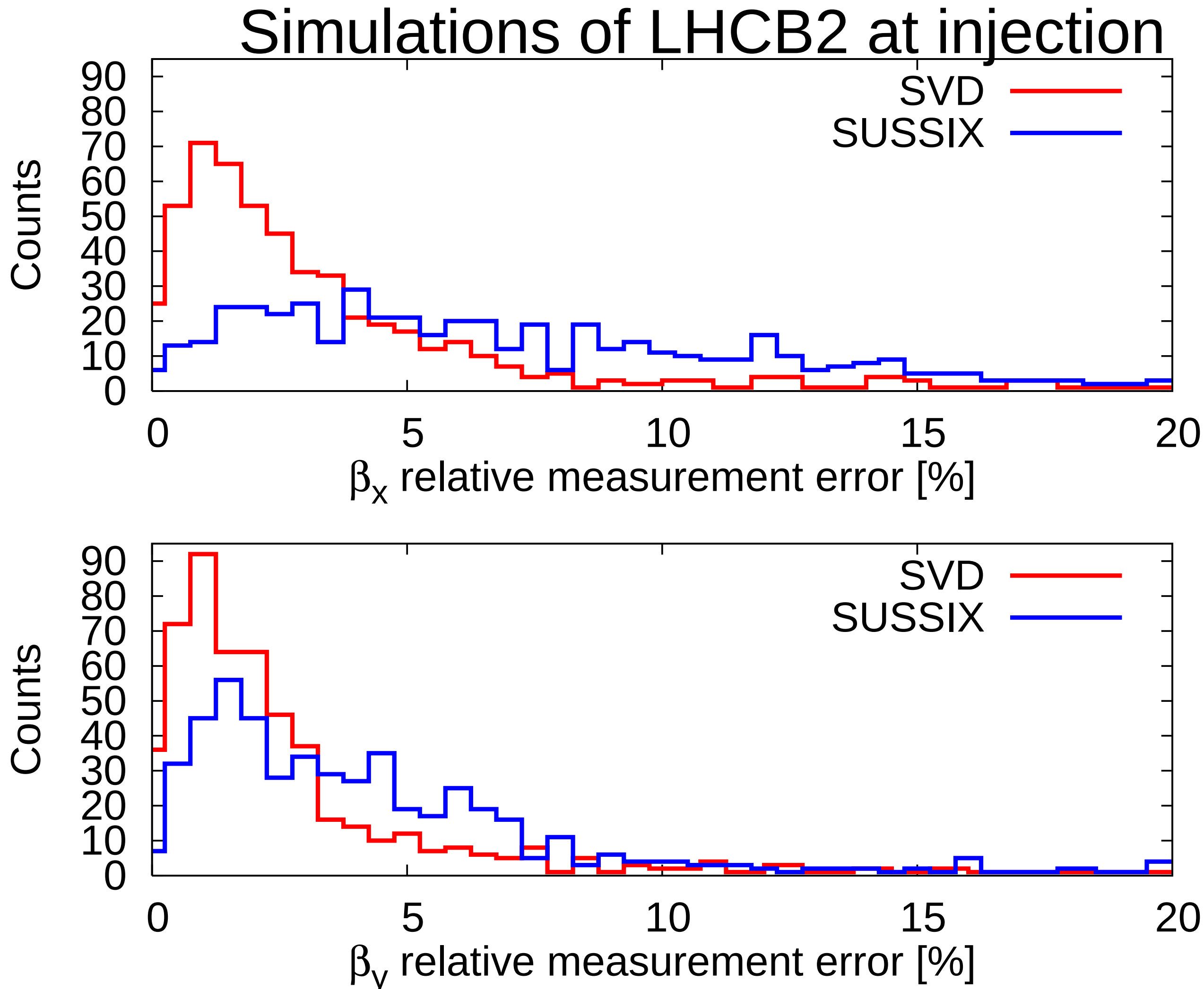
Support slides

Equivalence of ϕ- and β-beatings



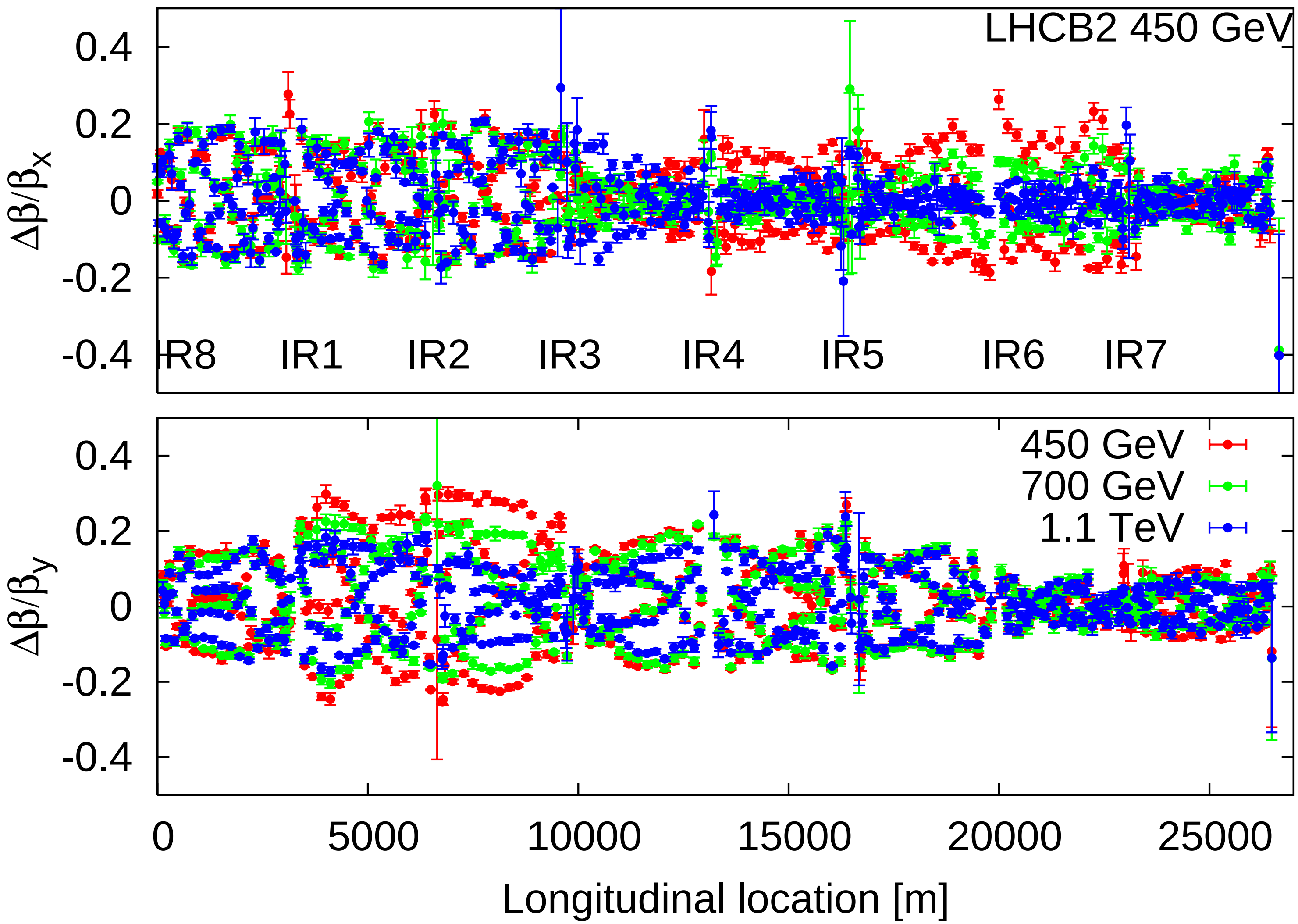
Precise relation between $\Delta\phi_{rms}$ and $\Delta\beta/\beta_{rms}$

SUSSIX Vs SVD for 90 turns



SVD clearly wins at low number of turns! It benefits from the BPM-to-BPM correlation

Along the energy ramp with new MQW cal.



Magnets behave better at higher energies!

Measurements possible thanks to the AC dipole!

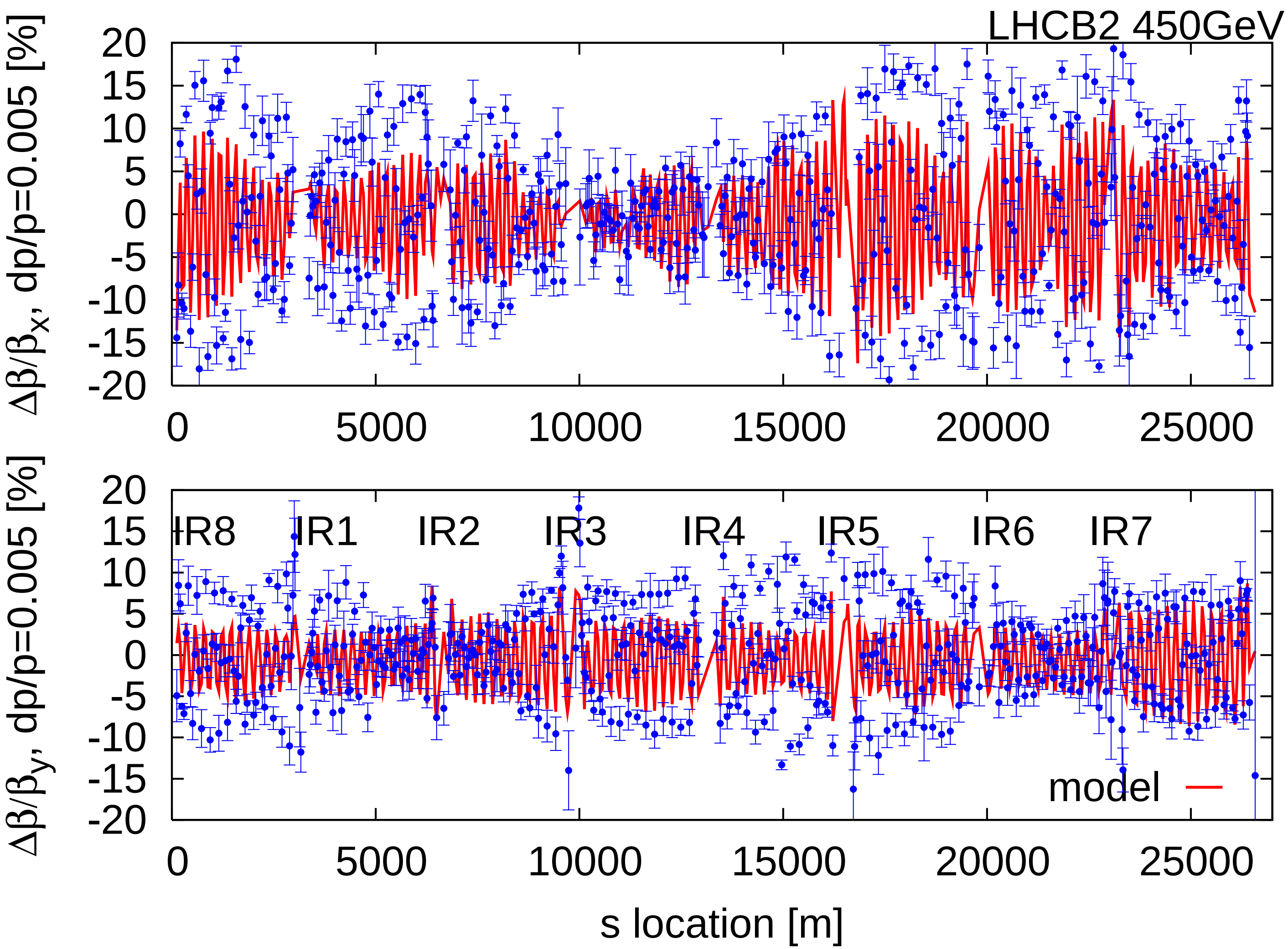
Coupling measurement

$$h_x(N) = \sqrt{2I_x}e^{i\phi_x(N)} -$$
$$i2f_{1001}\sqrt{2I_y}e^{i\phi_y(N)} - i2f_{1010}\sqrt{2I_y}e^{-i\phi_y(N)}$$
$$h_y(N) = \sqrt{2I_y}e^{i\phi_y(N)} -$$
$$i2f^{*}_{1001}\sqrt{2I_x}e^{i\phi_x(N)} - i2f_{1010}\sqrt{2I_x}e^{-i\phi_x(N)}$$

f_{1001} and f_{1010} are measured at every double plane BPM. This allows to extend the segment-by-segment technique to include coupling!

$$f_{1001} \;=\; \frac{1}{4\gamma}(\bar{C}_{12} - \bar{C}_{21} + i\bar{C}_{11} + i\bar{C}_{22}),$$

First off-momentum β-beat measurement



First amplitude detuning measurement