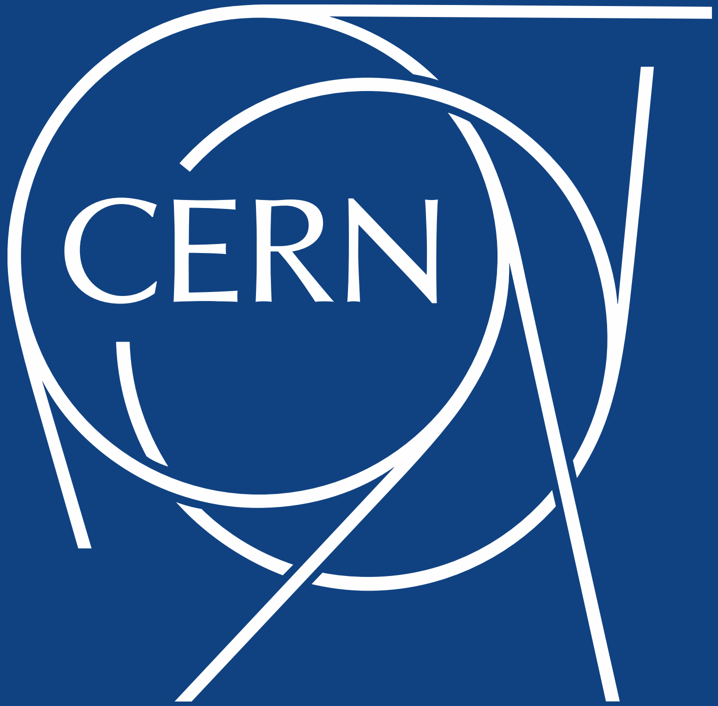
CERN

Rigid Waist Shift for Local Coupling Correction in the LHC IRs

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Felix Soubelet

(For more details see: PhysRevSTAB.26.051001)

Talk Outline

- Intro & Context.
- Overview of IR Local Coupling in the LHC and Limitations of our Existing Methods.
- Developped Solution: Rigid Waist Shift.
- Experimental Results from the LHC 2022 Commissioning.
- Relevance to other colliders & Conclusions.

The Missing ALICE Events of 2018 (1/2)

- In the late 2018 ion run “missing collisions” were noticed at ALICE.
- A human mistake led to a strong coupling bump in IR2.
- Coupling bump led to a beam size blowup.

➢ Observed about 50% loss of luminosity!

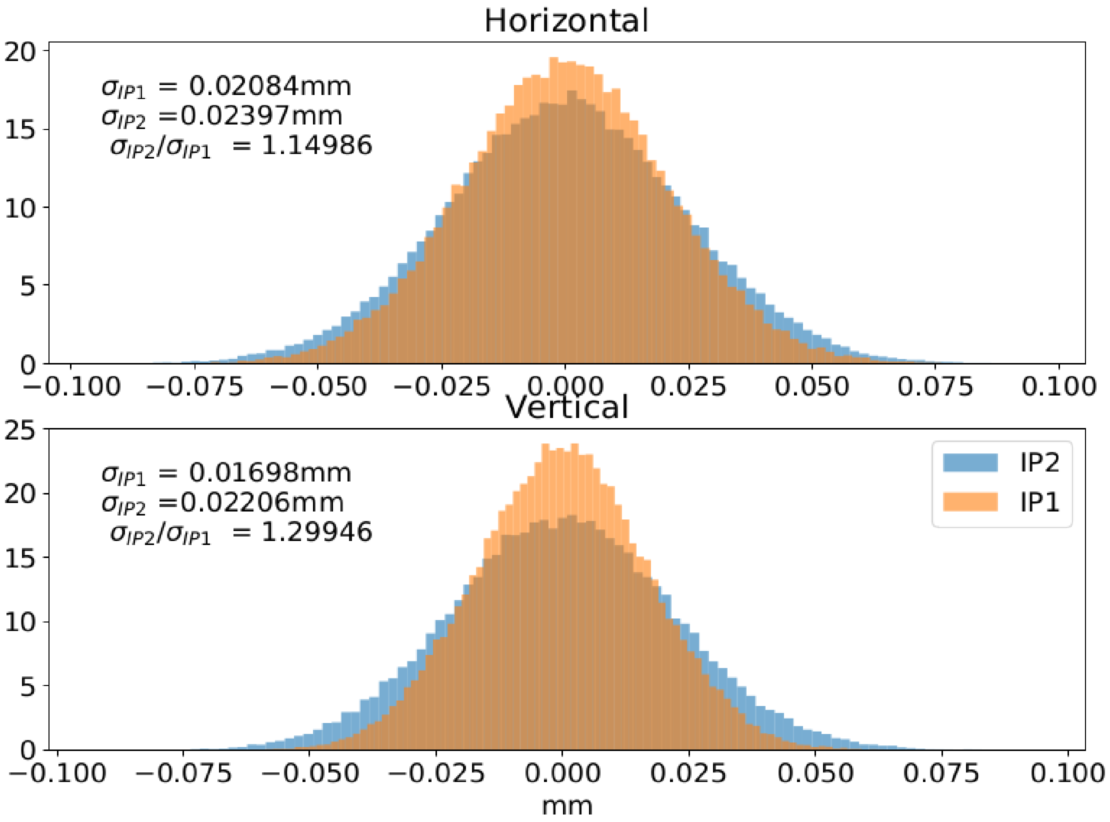

Figure: IP2 vs IP1 particle distributions from tracking simulations with a coupling bump implemented at IP2. Courtesy of T. Persson.

The Missing ALICE Events of 2018 (2/2)

- We can usually think of coupling's effect on the beam as tilting the beam ellipse.

- In the LHC we operate with round beams.

➢ Effect of coupling is felt as an increase of beam size.

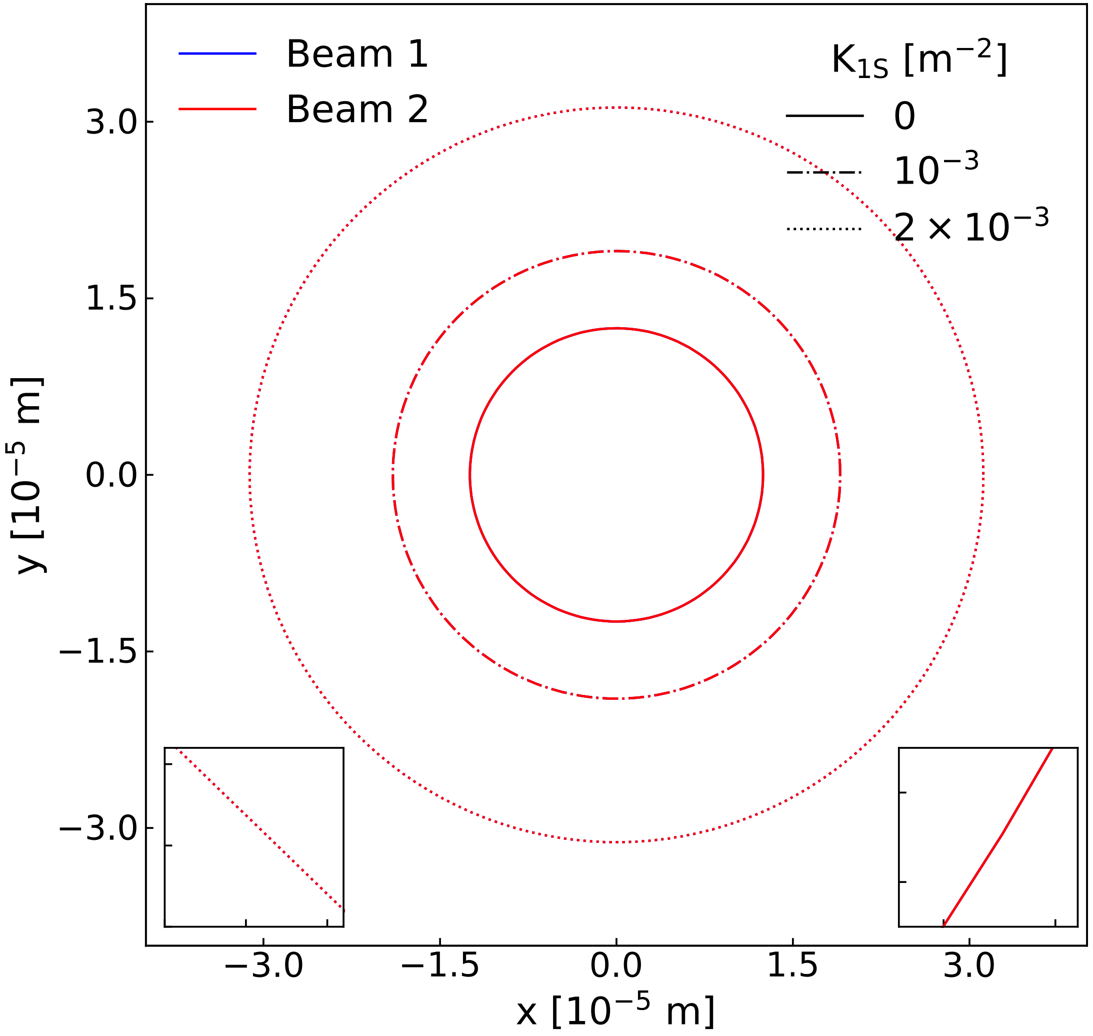

Figure: Transverse beam ellipses reconstructed at IP5 for different strengths of a coupling bump around the IP.

Local Linear Coupling to Luminosity

- Similar coupling bumps at IP1 or IP5 would lead to serious drops in luminosity.

- In case of the HL-LHC with even more squeezed beams, the situation would be drastically worse.

➢ There is a need for a reliable way to measure and correct linear coupling at the IPs.

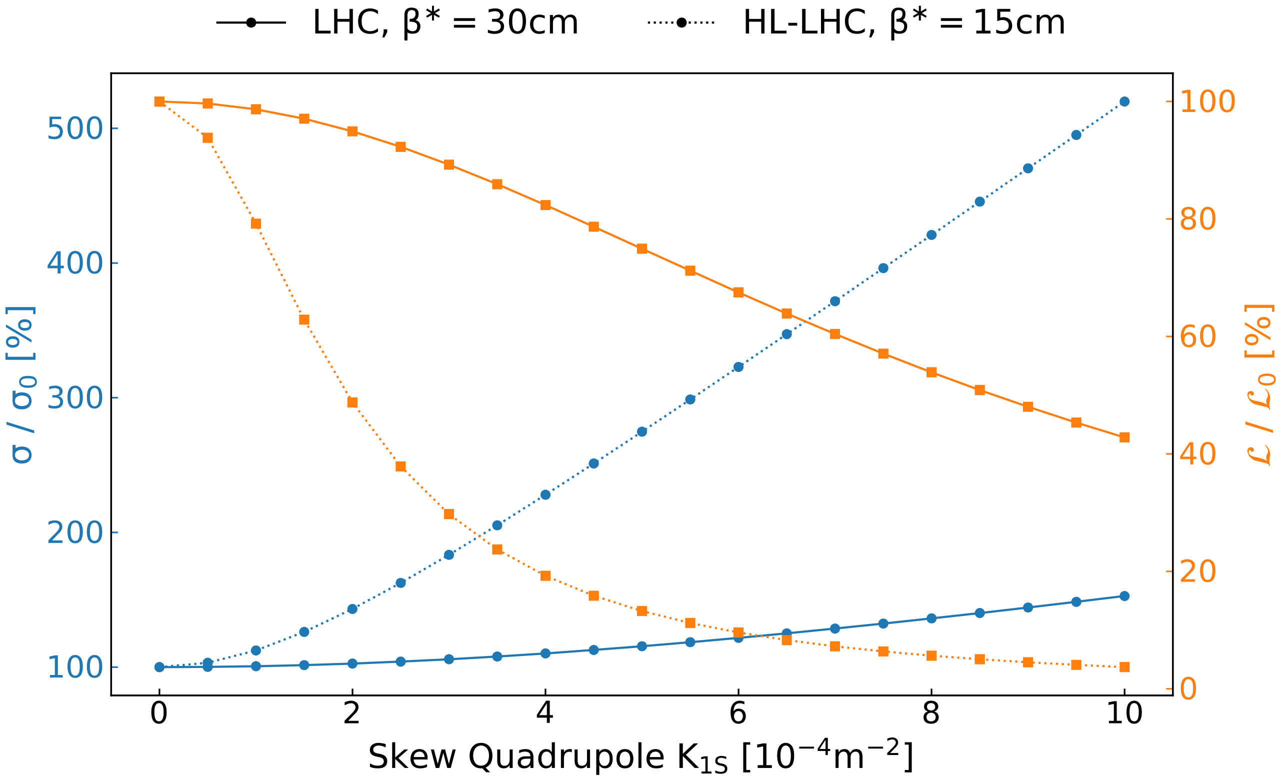

Figure: Relative RMS beam size increase and instant luminosity at IP1 for different strengths of coupling bump around the IP.

LHC IR Skew Quadrupole Correctors

- We have 1 skew quadrupole corrector on each side of the IPs.

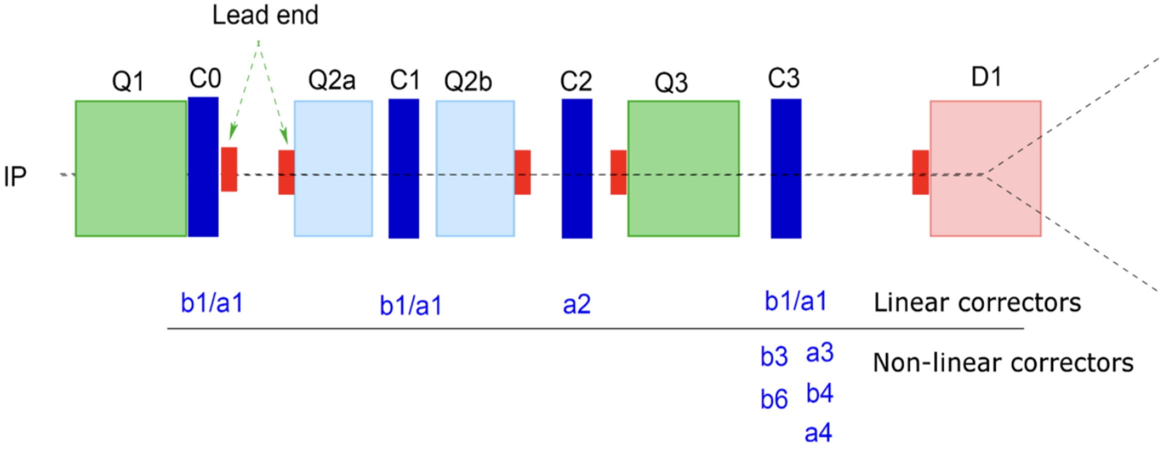

Figure: Schematic layout of triplet magnets and linear + non-linear correctors in the LHC experimental insertions.

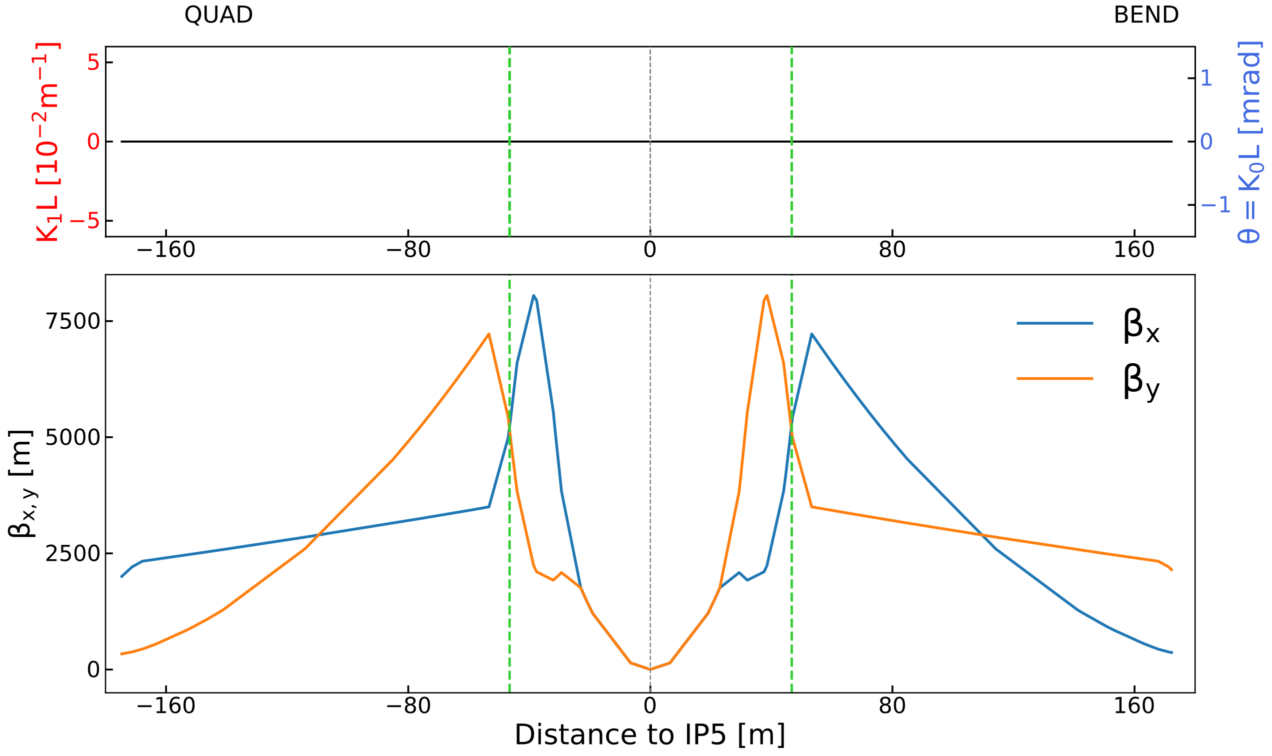

Figure: Layout and β–functions of IR5, and location of the skew quadrupole correctors.

➢ How do we determine how to power them?

Local Corrections in the LHC

- We use the Segment-by-Segment (SbS) technique.
  - Treat part of the machine as an independent beam line.
  - Propagate measured properties at the entry of the line with MAD-X.
  - Find settings matching the measured deviations.
  - ➢ Apply these in reverse in the machine for correction.
- SbS is used to compensate for the IR contribution to global coupling.

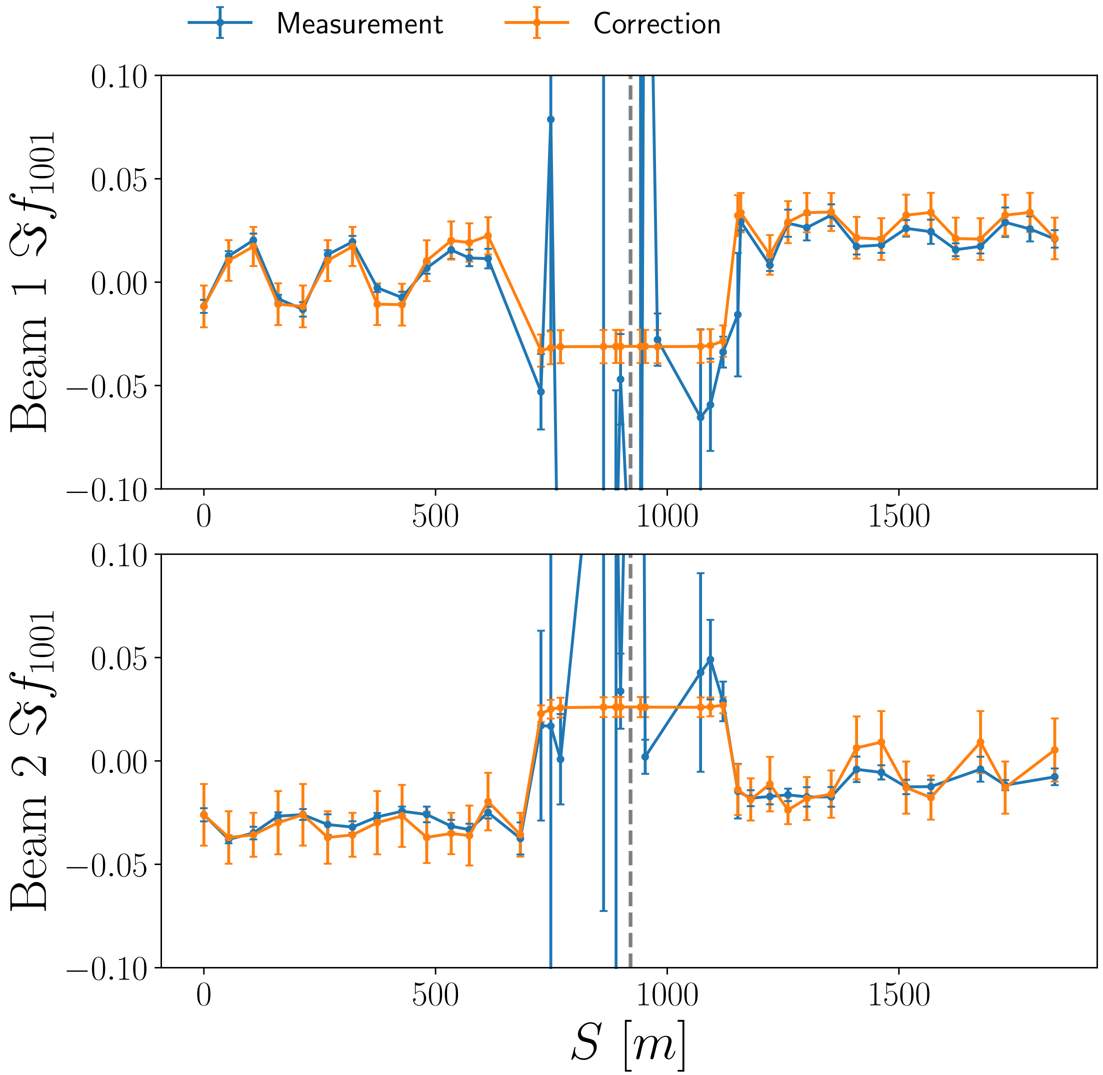

Figure: SbS correction of the imag. part of the f_{1001} RDT in the IR1 segment during the 2022 commissioning.

Current Methods’ Limitations

- SbS corrections are very important as they allows us to safely squeeze to low β^* optics.

- However:
  - Difficult to get good coupling RDT measurements in the IPs vicinity.
  - Does not allow distinguishing the contributions of left and right corrector magnets -> how to balance?
  - There is no information (no BPM) at the IP location.

- K-modulation is robust against local coupling (PhysRevSTAB.23.094001, PhysRevSTAB.20.011005).

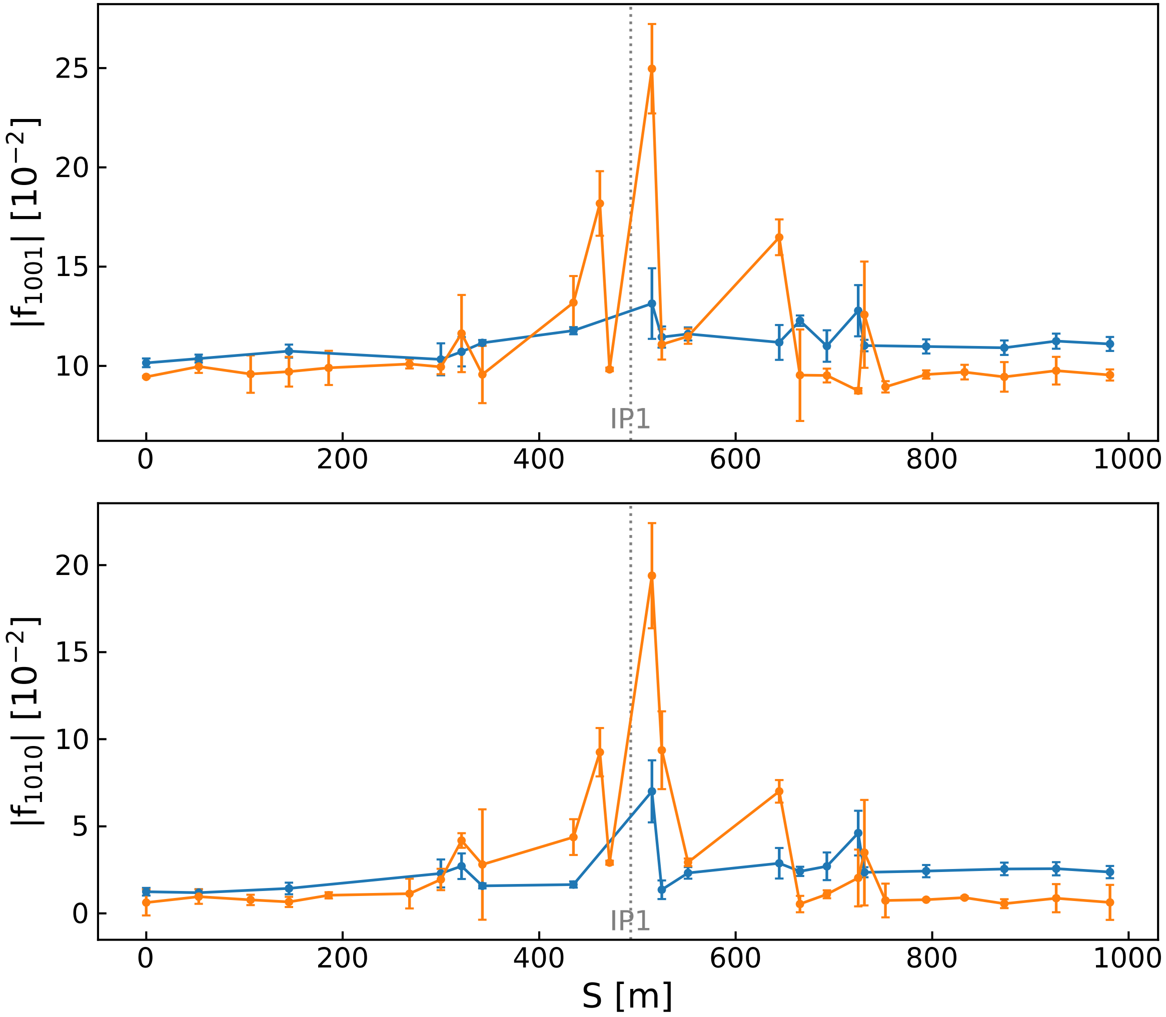

Figure: Propagation (B1) of the measured $|f_{1001}|$ and $|f_{1010}|$ with SbS around IP1 for two different correction settings.

Quick Recap So Far

To summarize

- Control of local linear coupling in the LHC IRs is important.
- Current methods do not provide a way to measure coupling at the IP.
- Existing SbS corrections are crucial for squeezing to collision optics and safe machine operation, and cannot be removed.

We need two things:

- ➢ A way to adjust the coupling at the IP without affecting the rest of the machine.
- ➢ A reliable way to measure coupling at the IP so we can determine corrections.

Tool 1: The Colinearity Knob

- Close to difference resonance, contribution of individual sources:

$$\Delta|C^-| = \left|\frac{1}{2\pi}\sum_w \sqrt{\beta_x^w \beta_y^w} J_w \, e^{-i(\Phi_x - \Phi_y)}\right|$$

➢ Powering setting of left and right correctors that acts anti-symmetrically.

Magnet	$\Delta \mathbf{K}_{1S}$ $[\mathbf{m}^{-2}]$
MQSX.3R[IP] → K_{1S}	10^{-4}
MQSX.3L[IP] → K_{1S}	-10^{-4}

Table: Definition of 1 unit of the colinearity knob.

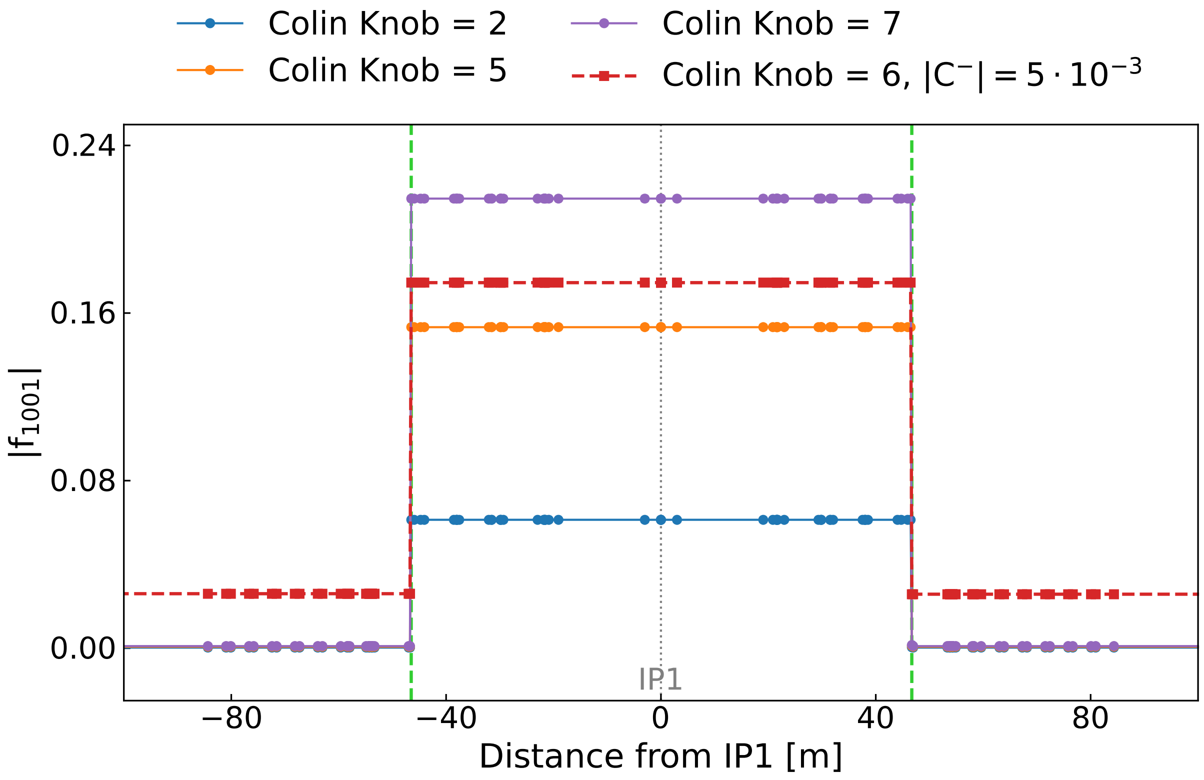

Figure: Effect of the colinearity knob on the f_{1001} coupling RDT, with and without global coupling.

Tool 2: The Rigid Waist Shift

- Rigid Waist Shift = moving all 4 betatron waists simultaneously.
- Achieved by unbalancing the powering knobs of the triplets left and right of the IP.

Circuit	Powering Δ
KQX.R[IP]	$-0.5\,\%$
KQX.L[IP]	$0.5\,\%$

Table: Definition of one unit of the rigid waist shift knob.

➢ Allows us to break the (anti)-symmetry of the optics functions in the IR.

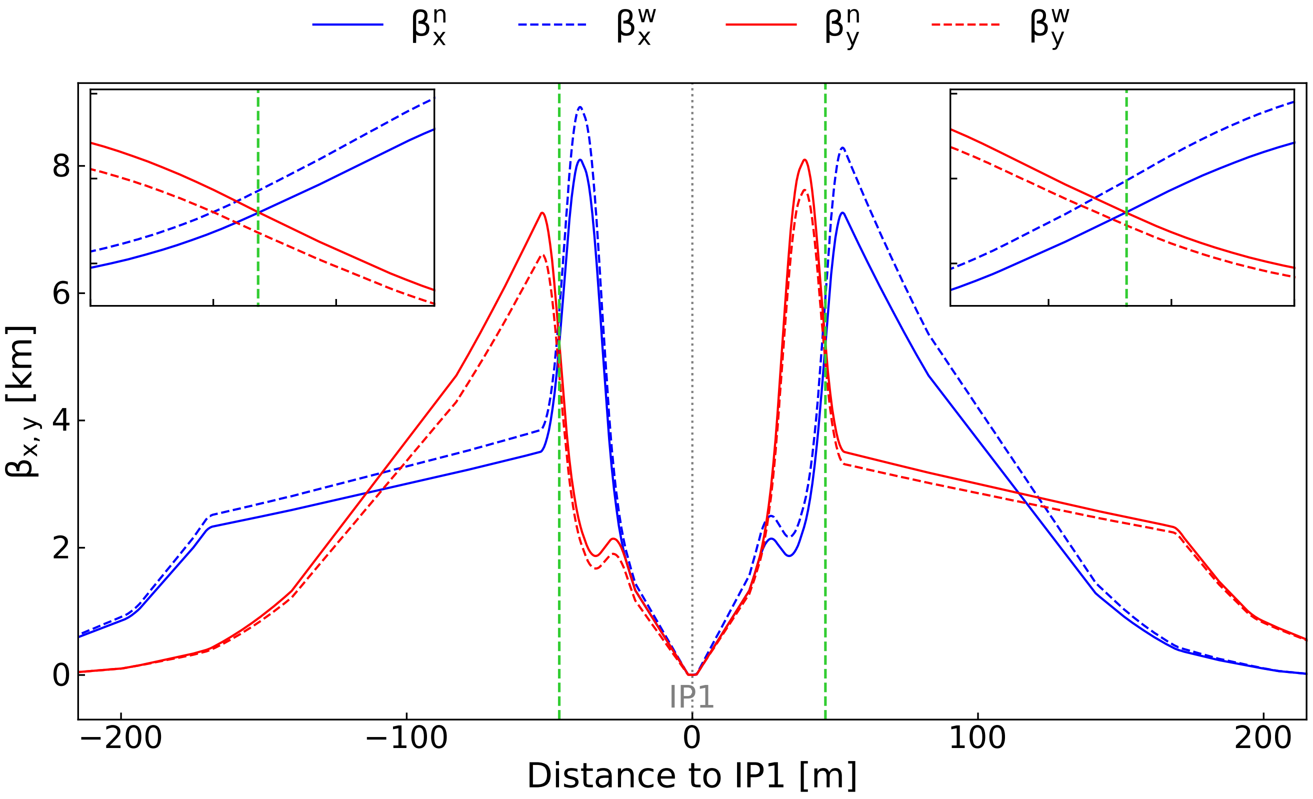

Figure: Change of β–functions in the IR when applying a RWS (dashed lines) compared to nominal optics (full lines).

Rigid Waist Shift – Application (1/4)

- Breaking the symmetry of the IR breaks the locality of any coupling bump.

- Example with fully closed bump from the colinearity knob:

$$\Delta|C^-| = \frac{1}{2\pi}\left(\sqrt{\beta_x^l\beta_y^l}k_s^l L + \sqrt{\beta_x^r\beta_y^r}k_s^r L\right)$$

- This makes the impact of even truly local coupling errors measurable everywhere.

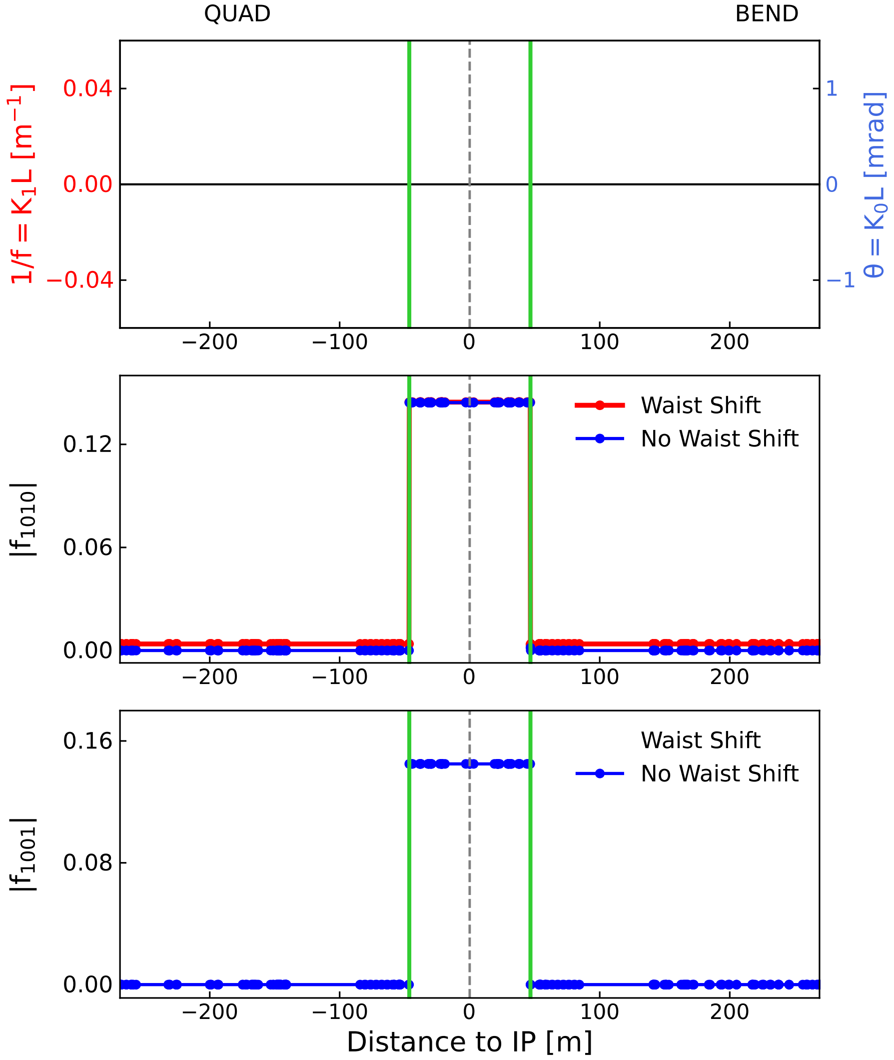

Figure: Coupling RDTs in the IR from a closed coupling bump, with and without an RWS.

Rigid Waist Shift – Application (2/4)

- Breaking the symmetry of the IR breaks the locality of any coupling bump.

- The influence of truly local sources is leaked to RDTs throughout the machine and can be picked up as the $|C^-|$ from turn-by-turn measurements.

➢ Opens the possibility to probe local coupling errors through global coupling.

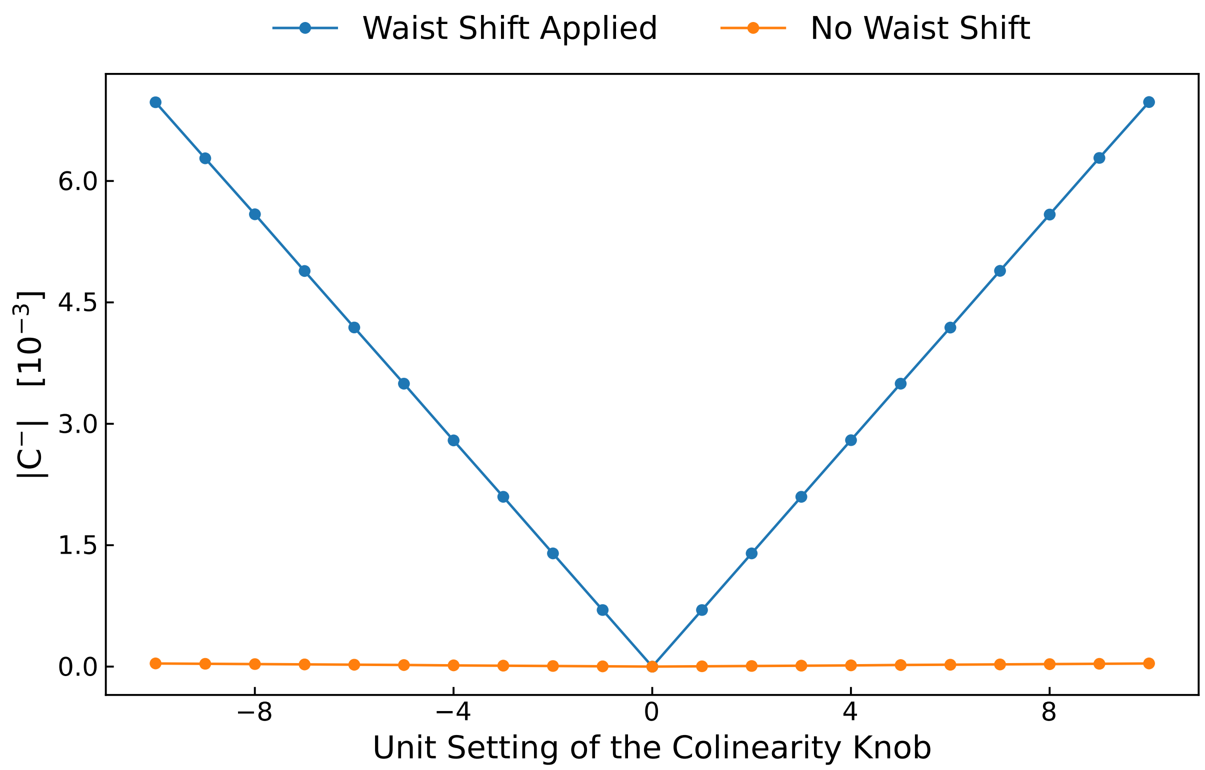

Figure: Impact of a fully closed coupling bump on the $|C^-|$ with and without an RWS.

Rigid Waist Shift – Application (3/4)

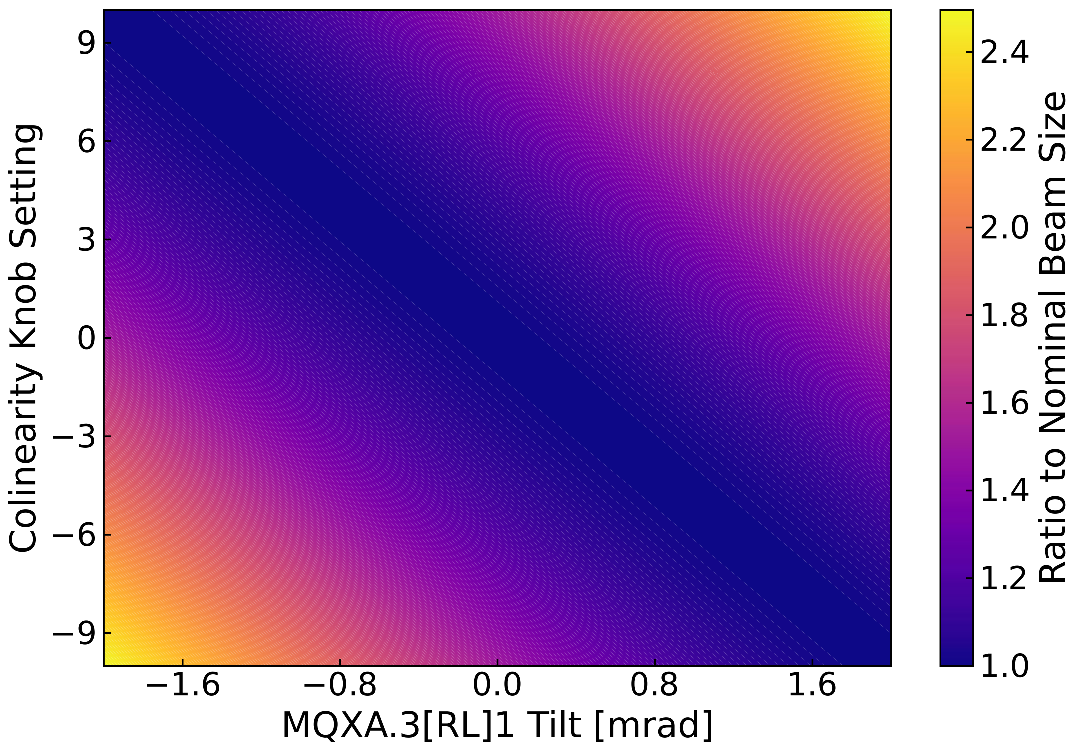

Figure: Resulting beam size increase for identical settings of tilt error and colinearity knob, but without an RWS.

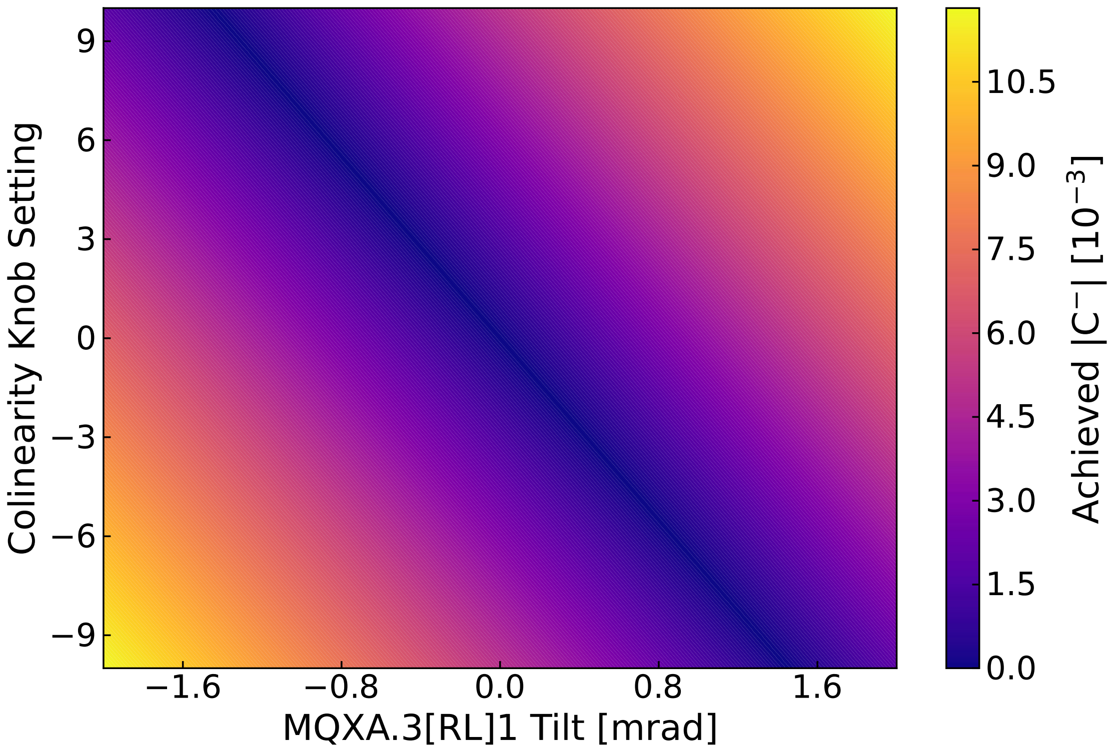

Figure: Resulting $|C^-|$ for various combinations of tilt error and colinearity knob settings, when applying an RWS.

- Great correlation across the parameter space.

➢ Settings minimizing the $|C^-|$ *with* an RWS also minimize the beam size growth from local coupling *without* an RWS.

Rigid Waist Shift – Application (4/4)

- A more realistic scenario:
    - Local tilt errors in triplets
    - Tilt errors in Q4-Q6.
    - Tilt errors in other IR's triplets.
    - Global coupling sources so that $|C^{-}| \sim 10^{-2}$.
    - Rountine of global coupling correction so that $|C^{-}| \sim 3 * 10^{-3}$.
    - Parametric scan with/without RWS.
    - Again, great correlation (0.96 Pearson coefficient).

➢ Thanks to the RWS:

- ✓ We can probe the local errors through global coupling.
- ✓ We can find settings to minimize coupling at IP.

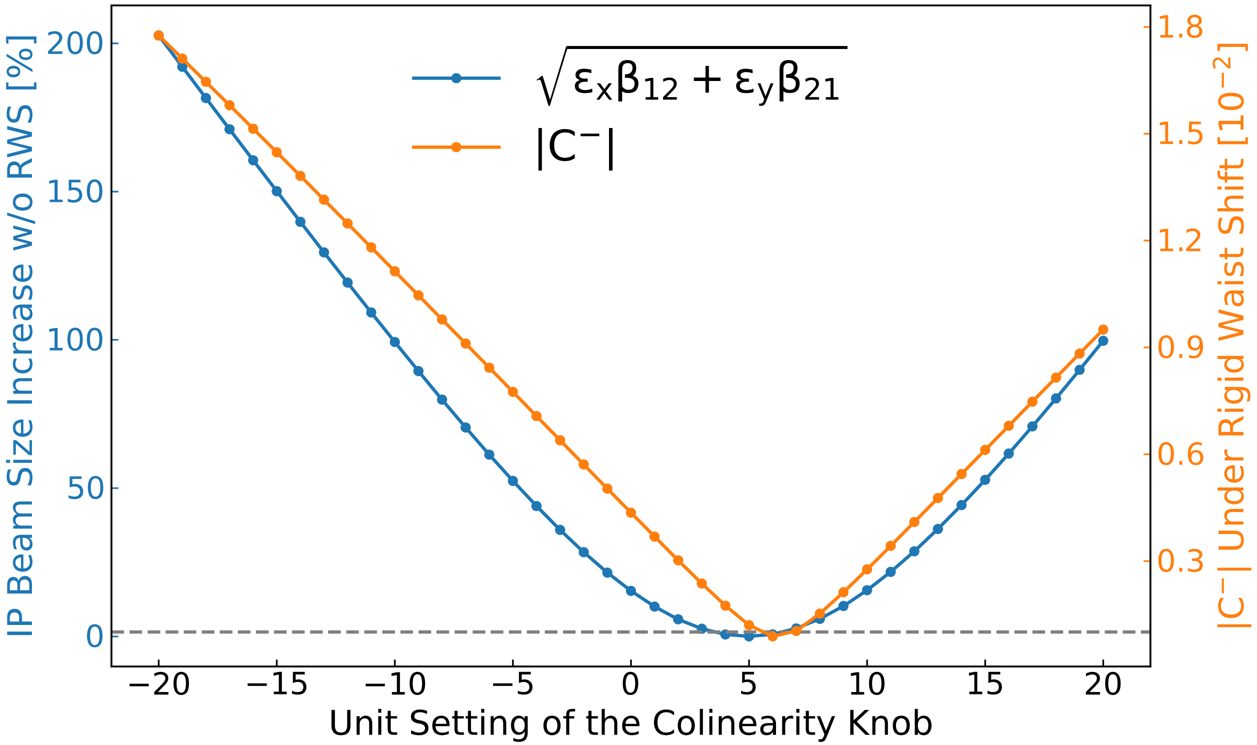

Figure: Resulting $|C^{-}|$ under an RWS and increase in IP1 beam size without RWS. Black dotted line represents a 1% increase in beam size.

Determining Corrections (1/2)

- We want to compensate for *local sources only*, not global or coupling emerging from the RWS setup.

- We replicate the global coupling from the machine in simulations.
- Compare measured $|C^-|$ to these simulations.

- Simulations include no local errors but measurements do.

➢ Find how to match them with the colinearity knob, find the setting that compensates for these local errors.

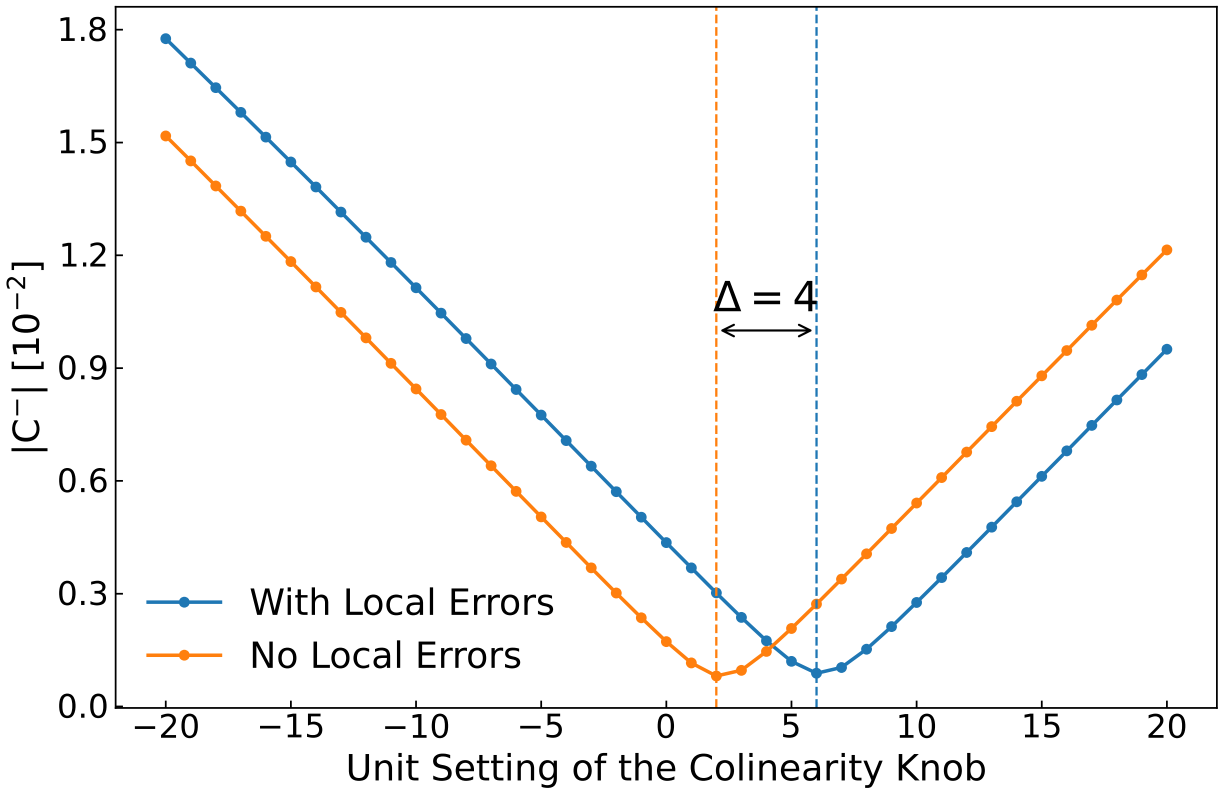

Figure: Resulting $|C^-|$ under RWS from simulations with and without local sources included.

Determining Corrections (2/2)

- We want to compensate for *local sources only*, not global or coupling emerging from the RWS setup.

- We replicate the global coupling from the machine in simulations.
- Compare measured $|C^{-}|$ to these simulations.

- Simulations include no local errors but measurements do.

➢ Find how to match them with the colinearity knob, find the setting that compensates for these local errors.

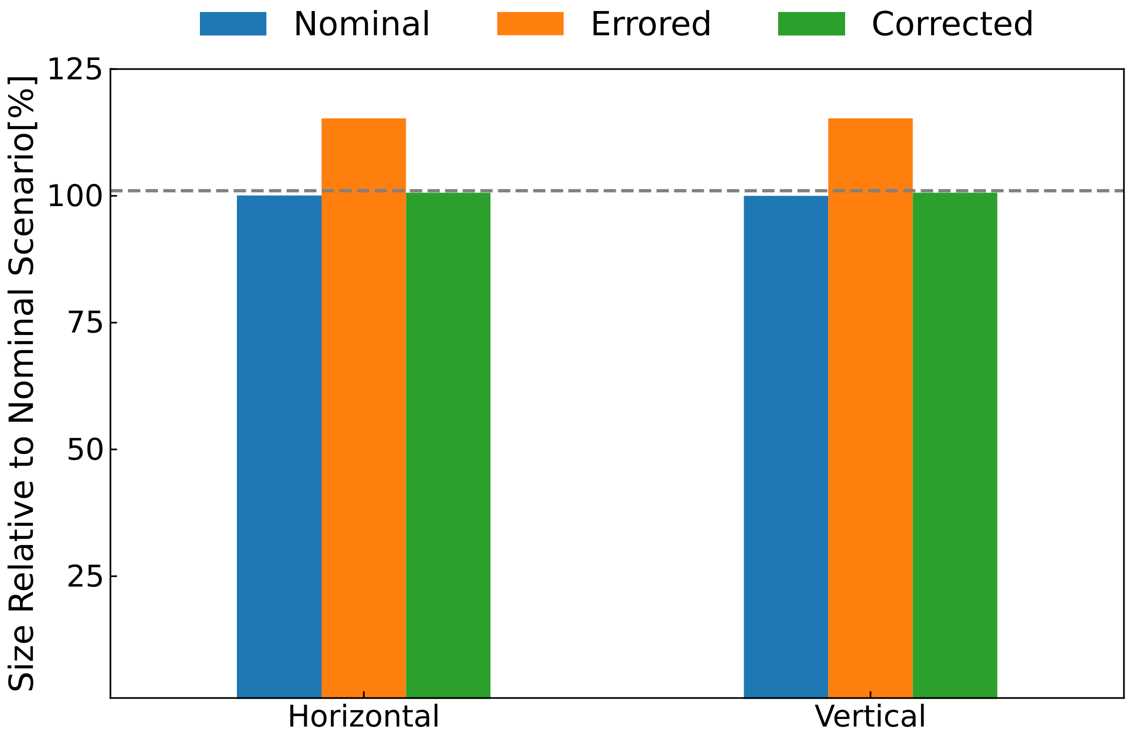

Figure: Relative IP beam sizes when compared to the nominal scenario when inputting the local errors used in the study (prev. slides) and after applying the suggested correction.

Another Recap

We have tools to tackle our needs

✓ The colinearity knob allows us to adjust coupling at the IP without affecting the rest of the machine nor SbS corrections.

✓ The RWS allows us to probe local errors and find a correction setting of the colinearity knob to minimize coupling at the IP.

What’s left to do?

- Applying all of this in the machine.
- Results below are from the LHC 2022 commissioning.

Local Coupling: Experimental Procedure

1. Use SbS to find and apply corrections that compensate for the IR’s contribution.

2. Apply an RWS and perform a scan of the colinearity knob for each beam.

3. Compare scan results to simulations to determine correction settings.

4. Trim in the corrections.

Experimental Measurements (1/2)

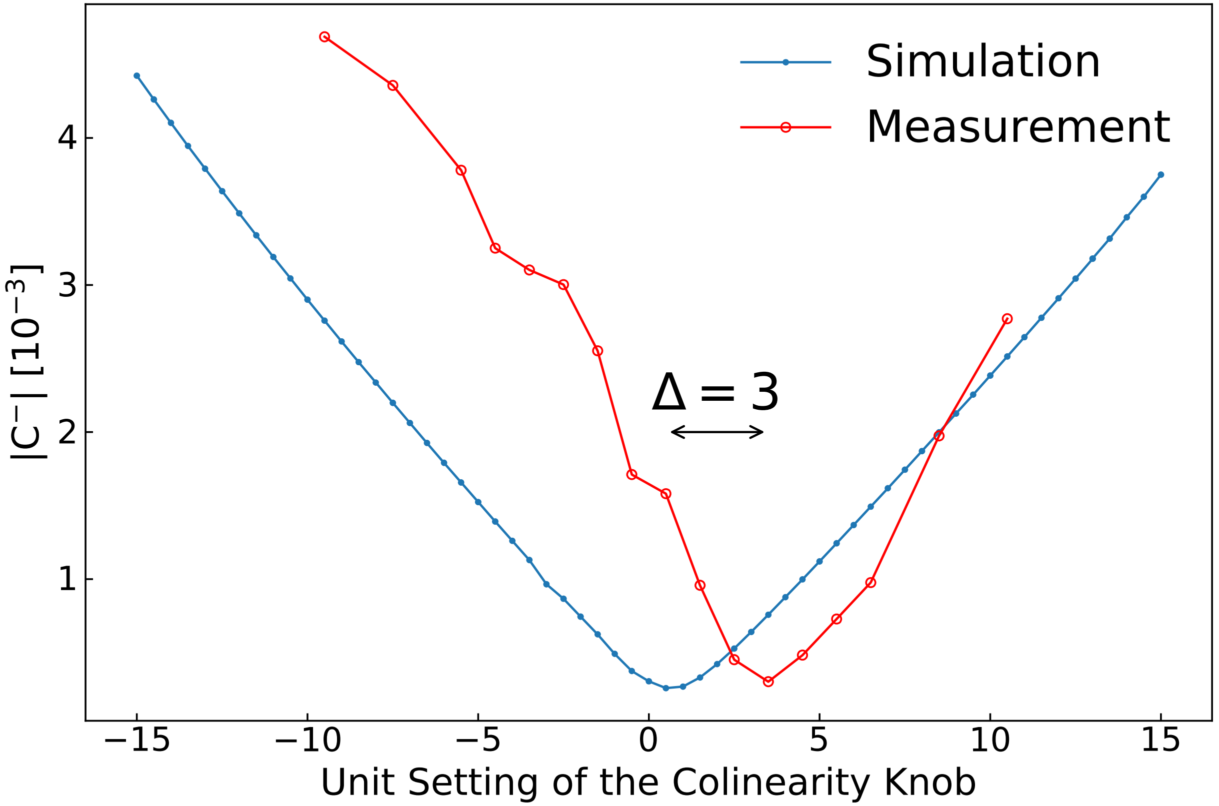

Figure: Measurement scan done at IR1 for beam 2 and simulations for the same setup.

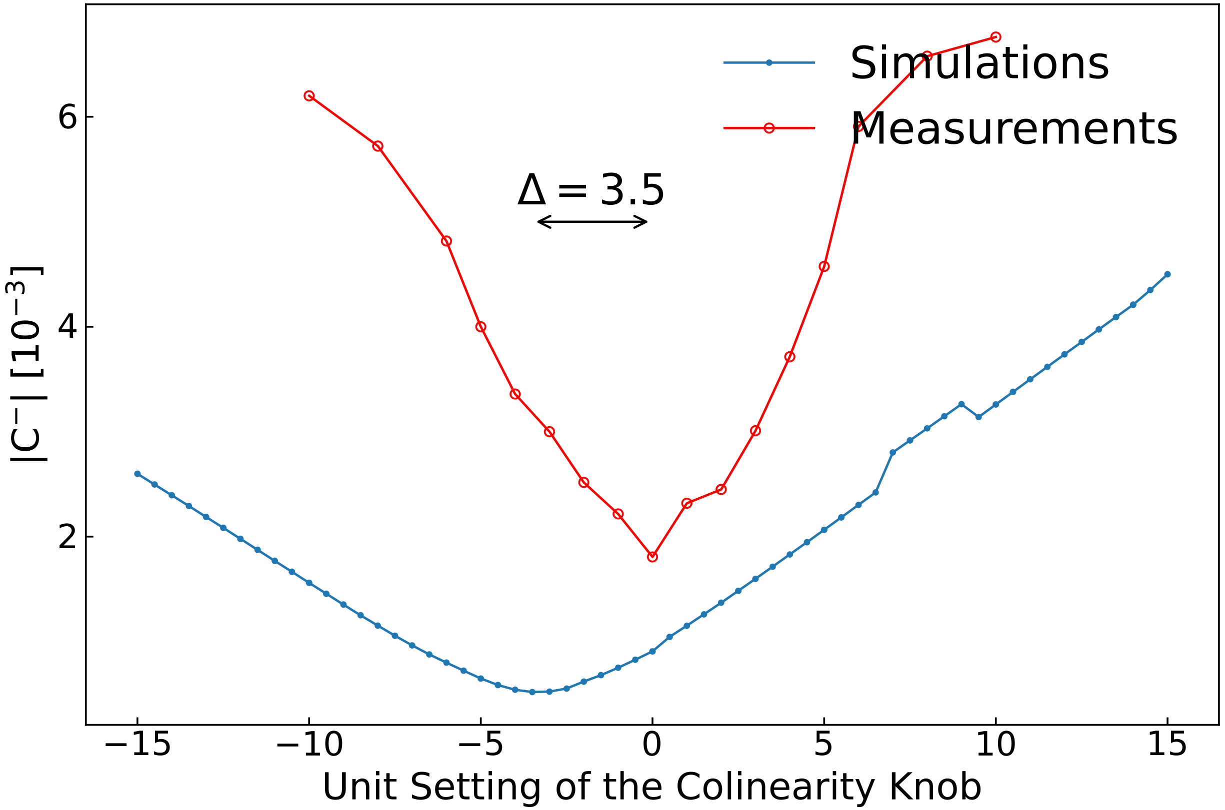

Figure: Measurement scan done at IR1 for beam 1 and simulations for the same setup.

Experimental Measurements (2/2)

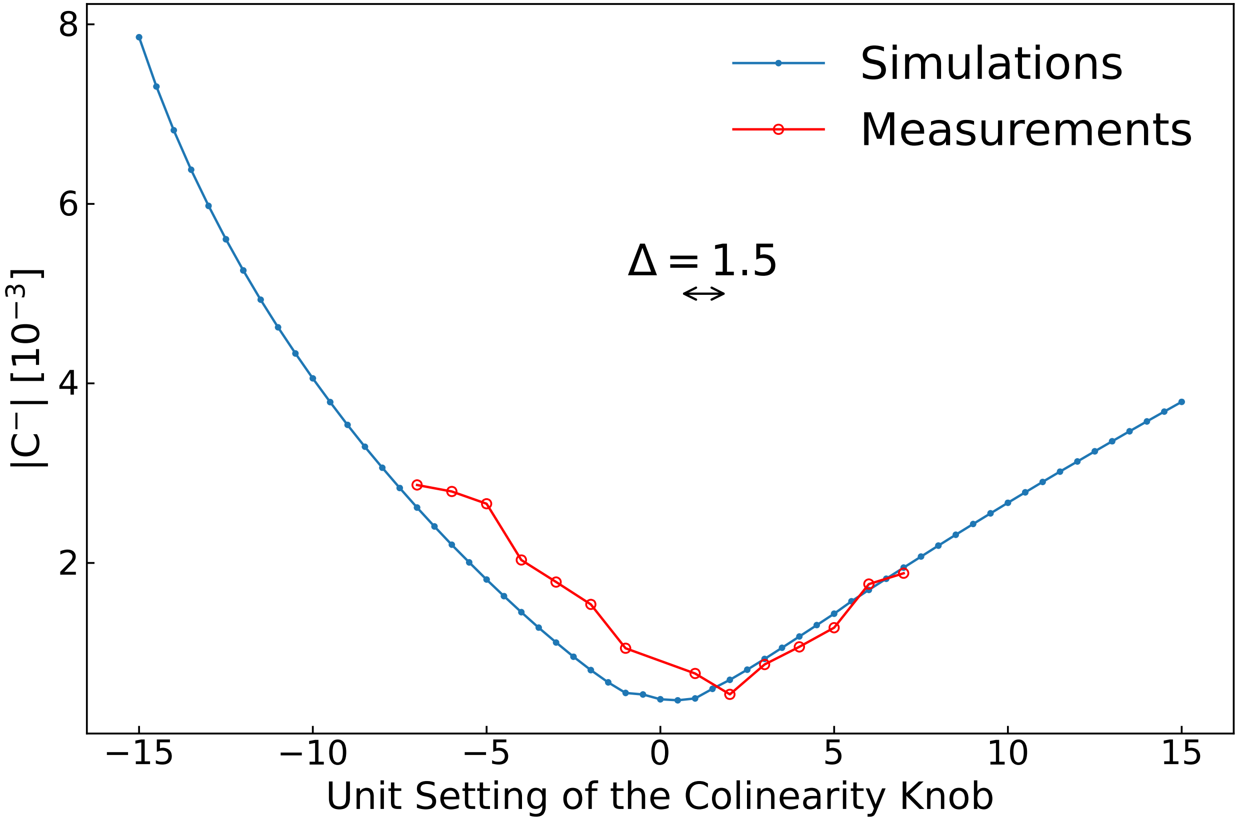

Figure: Measurement scan done at IR5 for beam 2 and simulations for the same setup.

Scan	Suggested $\Delta k\ [10^{-4}\mathrm{m}^{-2}]$	
	Beam1	**Beam2**
IR1	-3.5	-3
IR5	-2	-1.5

Table: Correction adjustments suggested by Rigid Waist Shift scans, on top of the existing Segment-by-Segment corrections that were in the machine.

Trimming Corrections

- Trim of the suggested corrections were done at end of fills, with collisions.
- Measurements done at β*=30cm and β*=42cm.
- Subsequent luminosity changes were observed.

Experiment	**Luminosity Gain [%]**	
	$\beta^* = 30\,\mathrm{cm}$	$\beta^* = 42\,\mathrm{cm}$
ATLAS (IP1)	9.7	5.2
CMS (IP5)	3.5	1.5

Table: Instantaneous luminosity gains observed at the main experiments ATLAS and CMS from trimming the suggested corrections.

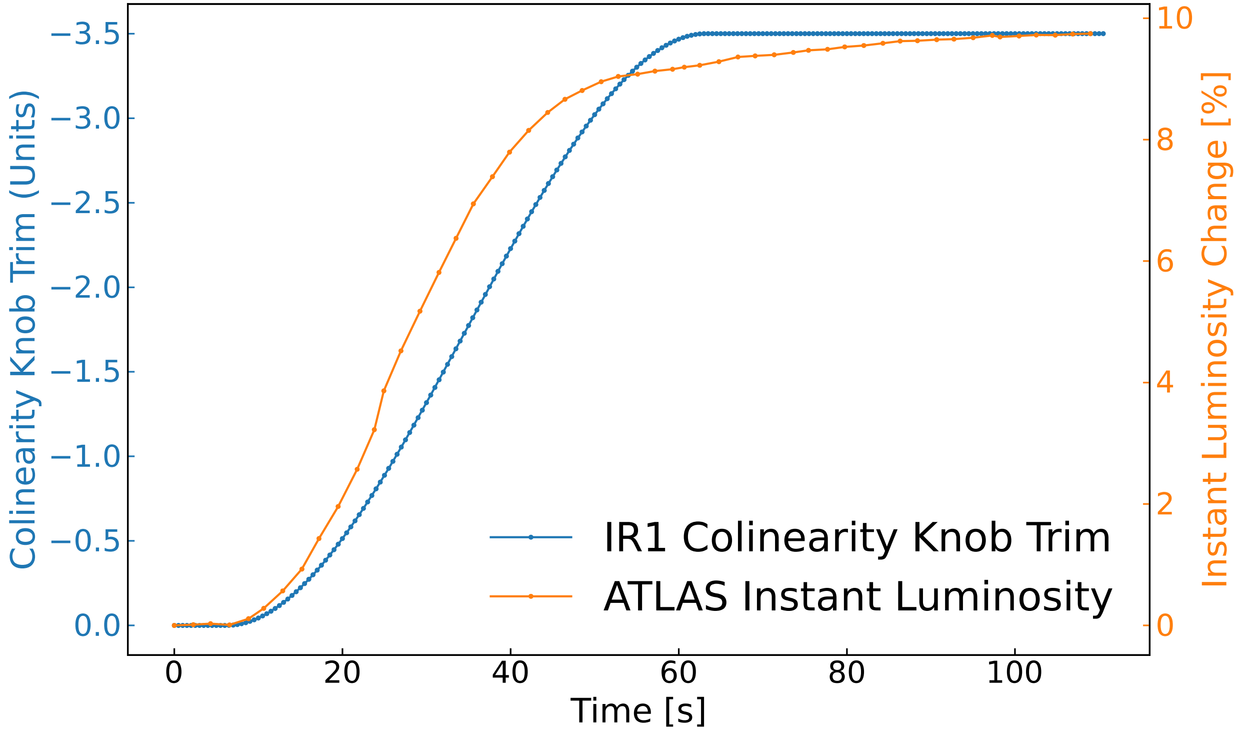

Figure: Trim of the colinearity knob setting and observed IP1 instantaneous luminosity change at $\beta^* = 30cm$.

What about other colliders?

- Typical collider uses quadrupole triplet / doublet for final focusing.
- IP to Q1 phase advance (with $L^* \gg \beta^*$):

$$\mu = \int_0^{L^*} \frac{1}{\beta(s)}\, ds = \beta^* \left[\frac{1}{\beta^*}\tan^{-1}\left(\frac{s}{\beta^*}\right)\right]_0^{L^*} = \tan^{-1}\left(\frac{L^*}{\beta^*}\right) \approx \frac{\pi}{2}$$

- Similar issues present:
  - Can easily get a closed coupling bump
  - No observation device at the IP
  - Phase advance from element to element ~ 0
- These are seen in FCC-ee, FCC-hh, HL-LHC, SuperKEKB HER.
- The RWS should be able help ☺

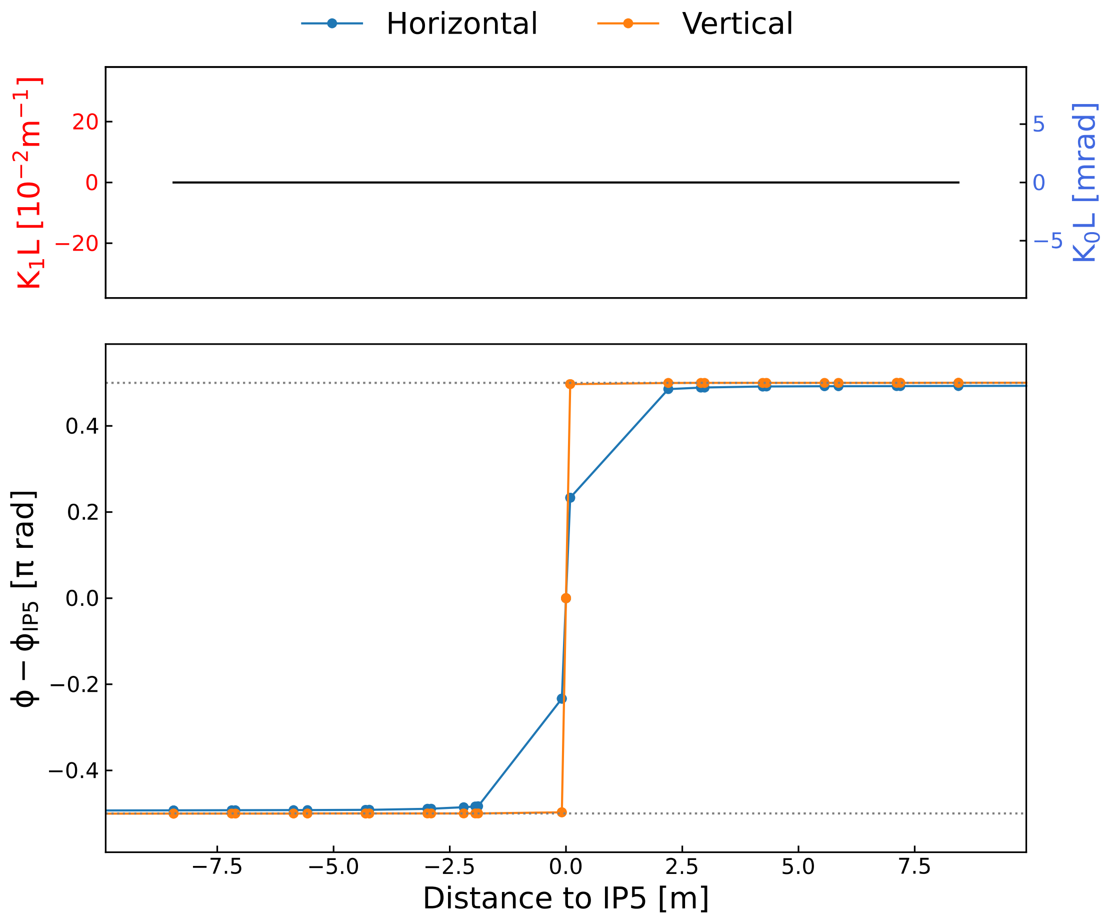

Figure: Phase advances relative to IP5 in FCC-ee V22 lattice, Z operation, 45.6GeV and $\beta^* = 10cm$.

Conclusions

- A good correction of local coupling in the LHC IRs is essential.

- Existing correction methods are crucial for safe machine operation & squeezing of the beams but do not provide an accurate way to measure and minimize coupling at the IP locations.

➢ We developed a new method to determine these correction settings that relies on the application of a Rigid Waist Shift.

✓ The method was implemented during the LHC 2022 commissioning, and corrections were successfully determined from beam-based measurements.

✓ Determined corrections were applied in the machine, and lead to substantial instantaneous luminosity gains.

✓ Seems to be relevant for other existing and future colliders.

Thank you for your attention!

Any Questions?

Linear Coupling in the LHC

- We look at the linear coupling Resonance Driving Terms.
- Global Coupling (difference resonance) quantified with:

$$|C^-| = \left| \frac{4\Delta}{2\pi R} \oint f_{1001} e^{-i(\Phi_x - \Phi_y) + is\Delta/R} ds \right|$$

PhysRevSTAB.17.051004

➢ Looking at RDTs across the machine is not enough to get information on coupling at IPs, we need to look locally.

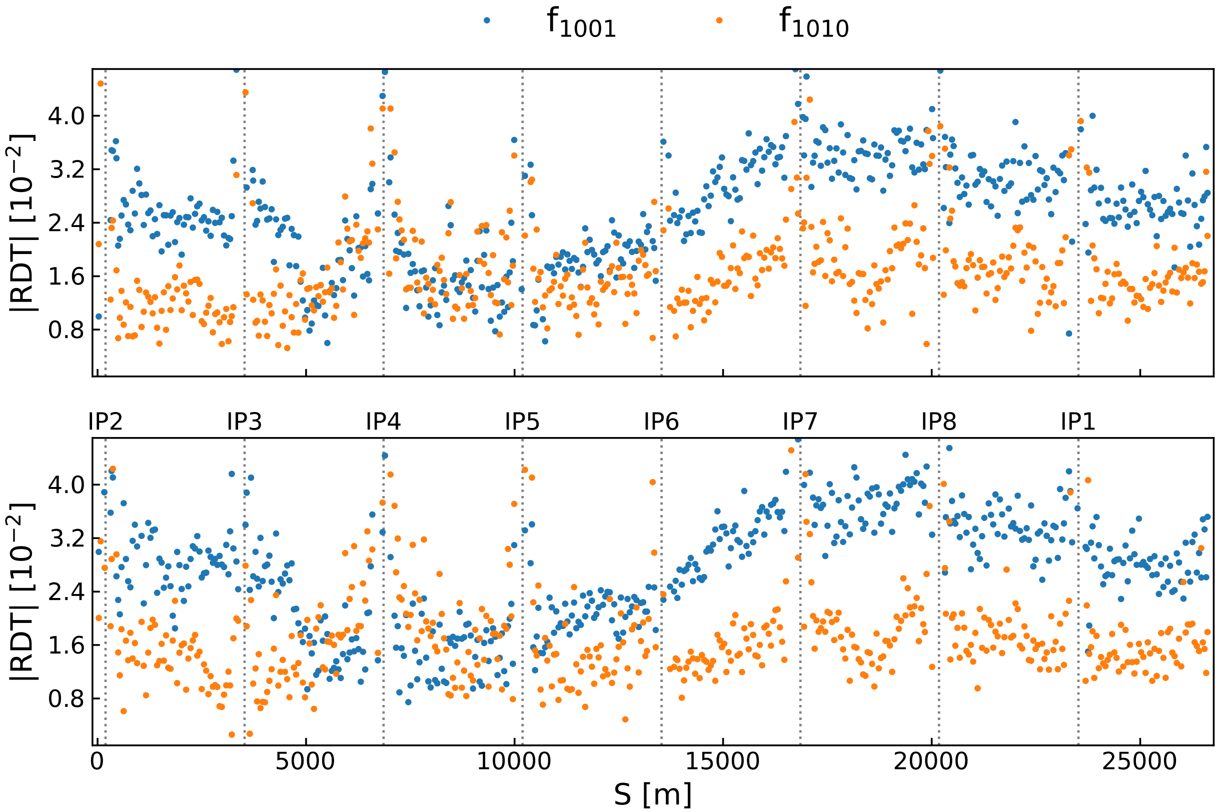

Figure: Similar looking coupling RDTs from two LHC measurements in 2022 (top vs bottom). One scenario leads to a 20% instant luminosity decrease at IP1 compared to the other.

Local Corrections in the LHC

- We use the Segment-by-Segment (SbS) technique.

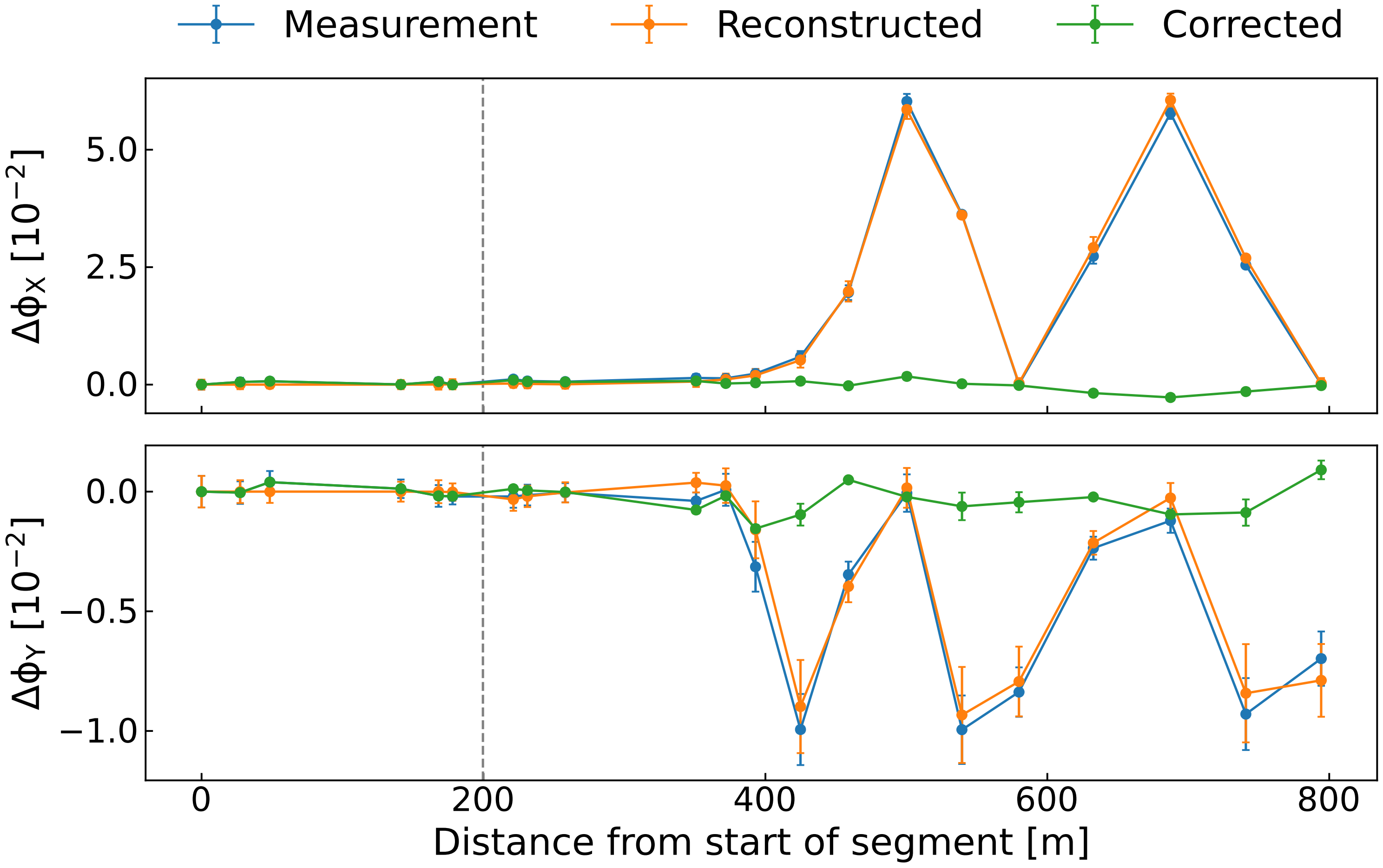

Figure: Illustration of a phase correction with the segment-by-segment technique.

Caveat – Optics Impact of the RWS

- RWS sends a β-beating wave through the machine.
  - Get to ~20-30% β-beating depending on the beam and plane.
  - Reduces the effectiveness of correction knobs.
  - Changes the impact of probed errors (namely skew quadrupolar impact).

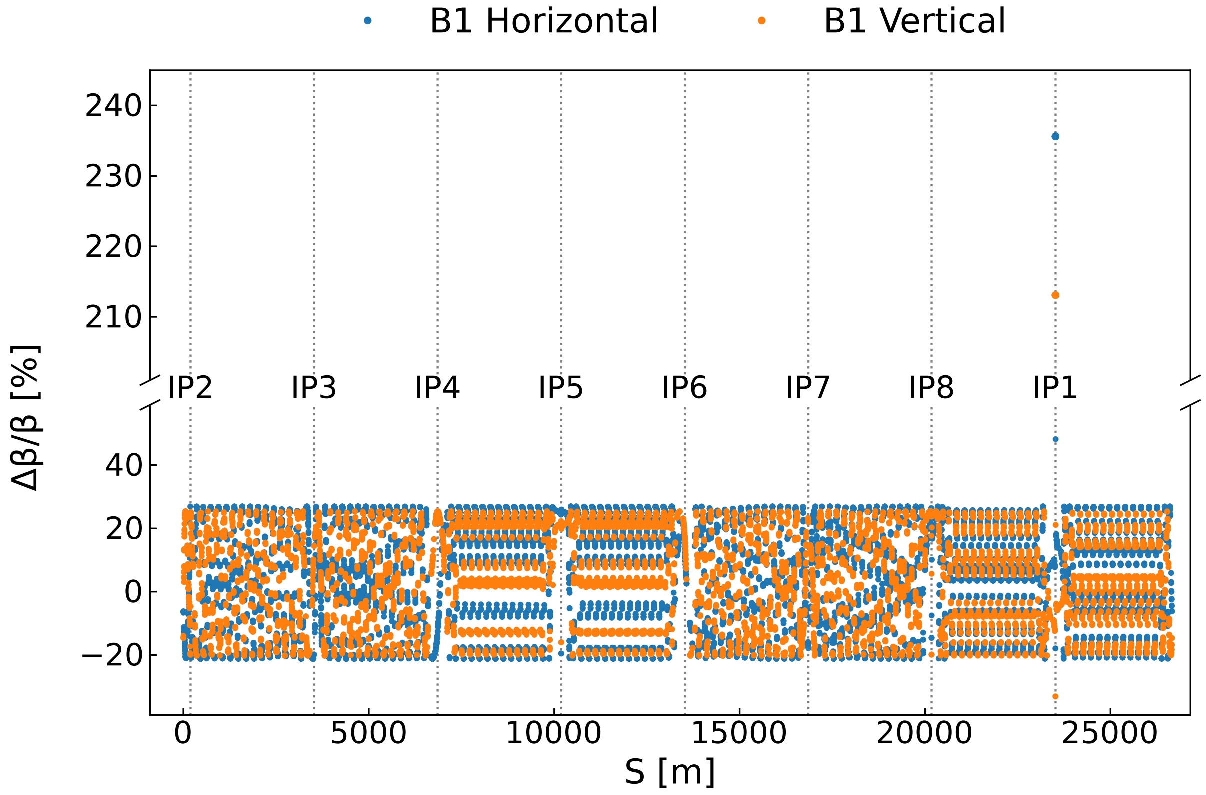

Figure: Simulated β-beating across beam 1 from applying an RWS at IP1.

Caveat – Optics Impact of the RWS

- RWS sends a β-beating wave through the machine.
  - Get to ~20-30% β-beating depending on the beam and plane.
  - Reduces the effectiveness of correction knobs.
  - Changes the impact of probed errors (namely skew quadrupolar impact).

➢ Can rematch the optics:

  - ✓ Rematching knobs designed using independent quadrupoles Q4-Q10.
  - ✓ Minimize the impact on the optics to ~5% β-beating aka control we have in operation.

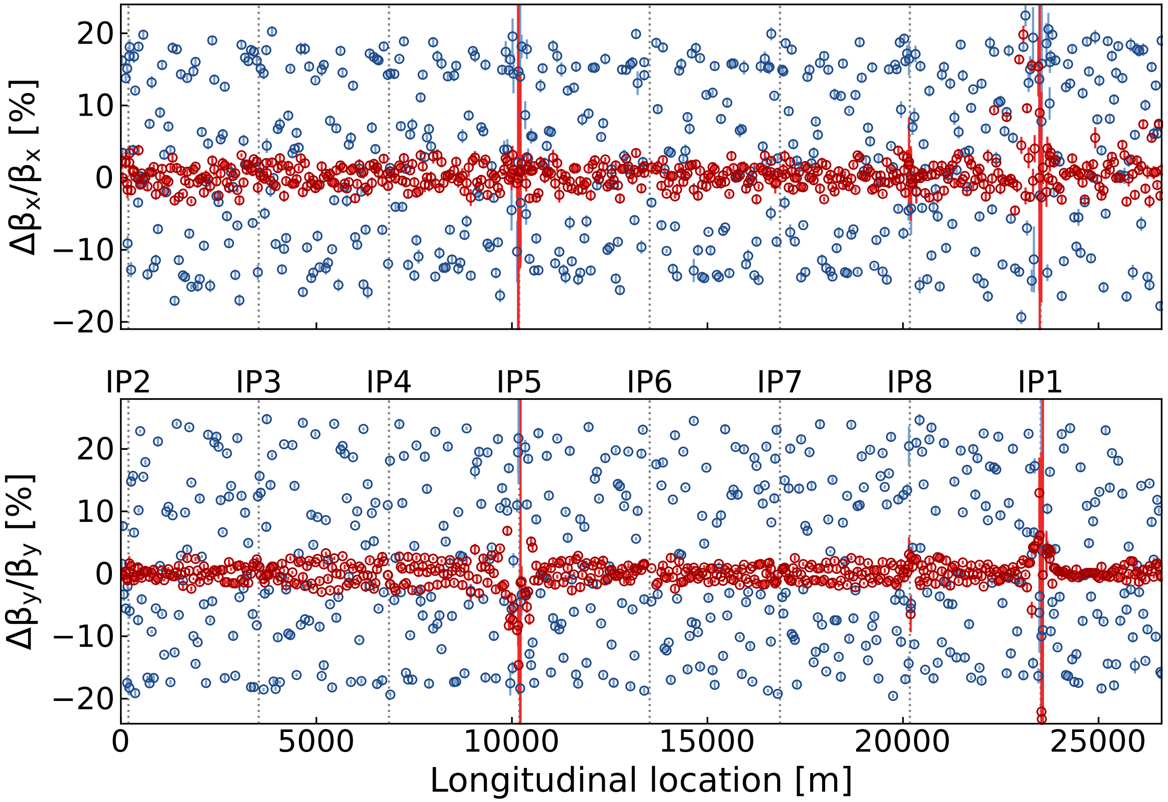

Figure: The beam 1 additional β-beating observed in the machine from an RWS in IP5, before and after applying the optics rematching knob.

Reproducing the Machine’s Coupling

- Need to best reproduce the coupling in the machine in simulations.

- In studies: The distribution of errors has little influence as long as the $|C^-|$ is the same.

➢ In the LHC: we did so by applying the correction knobs used in the machine.

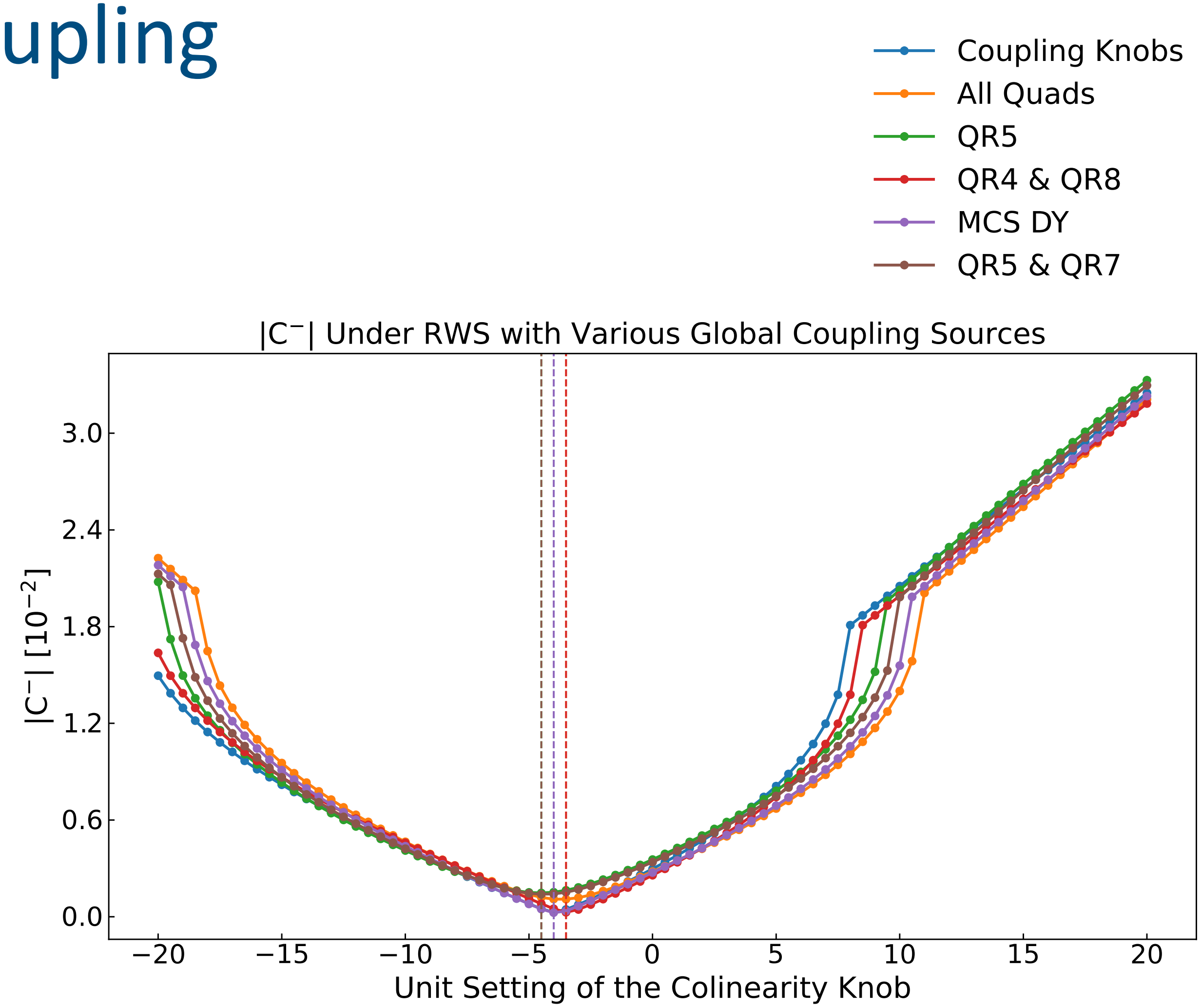

Figure: Minimization of the with an RWS for various distributions of sources for the global coupling.