Impact of HL-LHC civil engineering work on the LHC: do we see it and what can we learn for HL-LHC

D. Gamba, M. Schaumann, R. Corsini

Many thanks to M. Guinchard, D. Ramos, M. Martos, J. Wenninger, P. Fessia, D. Valuch, S. Redaelli, A. Mereghetti, B.Salvachua, A. Gorzawski, P. Racano, **et al.**

8th HL-LHC Collaboration Meeting – 18/10/2018

Outline

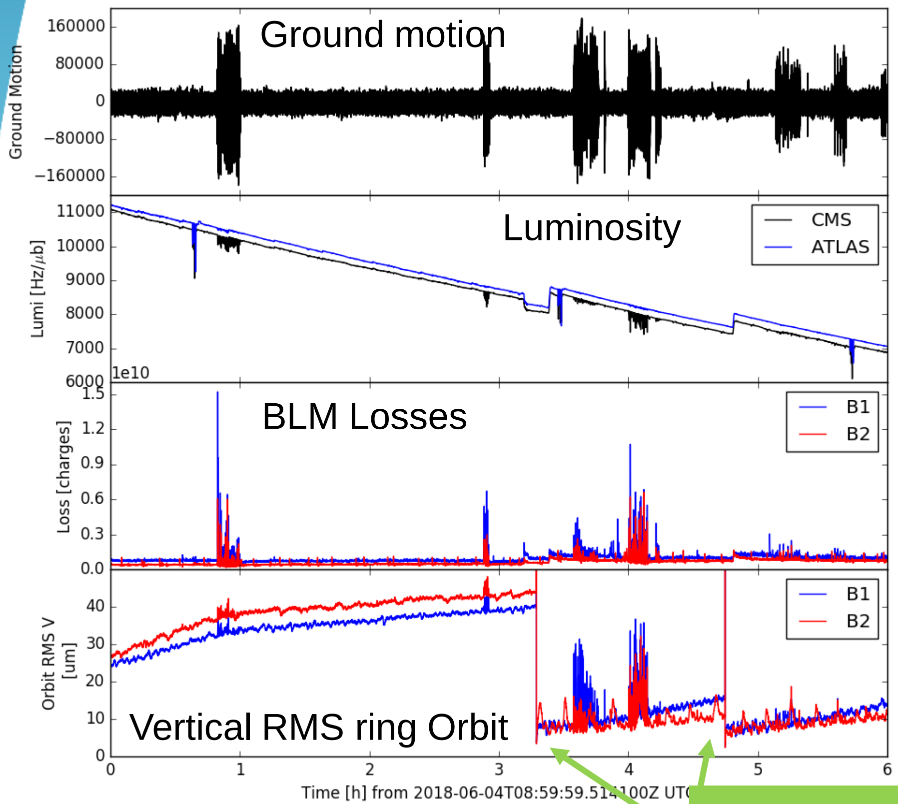
- Do we see it?
  - ...yes!
- Do we understand what we see?
  - Assumptions
  - Optics sensitivity LHC v.s. HL-LHC
  - Trying to quantify the amplitude of the effect we see
- What can we say about HL-LHC?
- Summary

References:

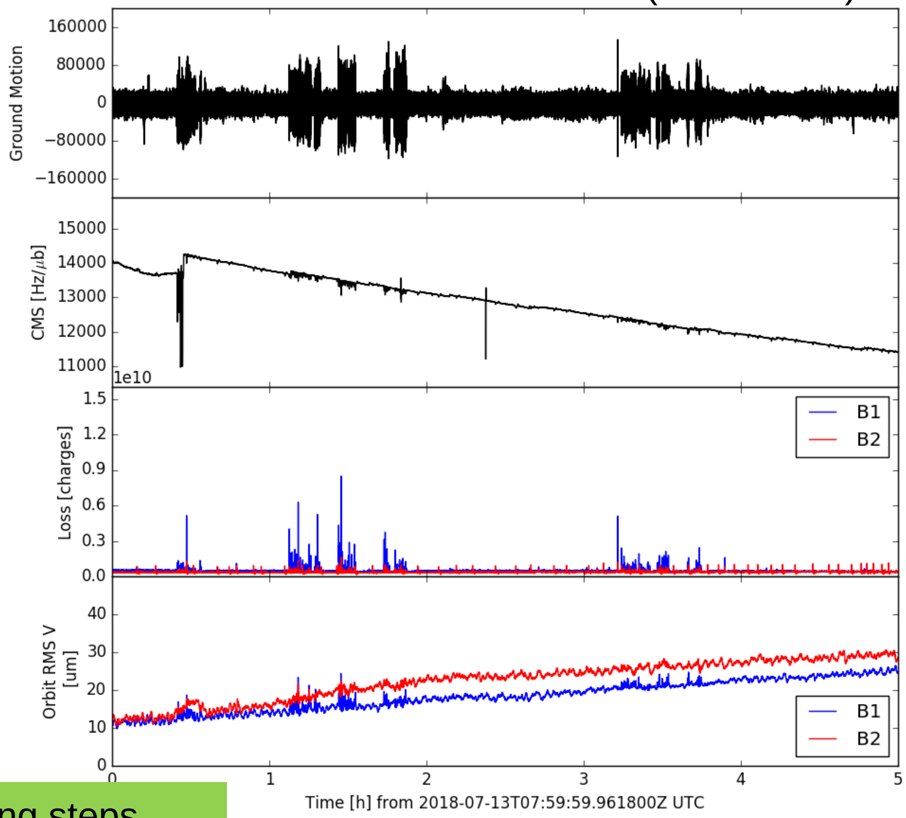
- M. Schaumann – Aug 2018 - LMC – link
- M. Schaumann – Aug 2018 - LBOC- link
- D. Gamba et al. – IPAC2018 link
- D. Gamba et al. – Jul 2017 - WP2 - link
- M. Fitterer et al. – Apr 2015 - WP15 - link
- Many other references available at this page

Main Events Overview (M. Schaumann)

Fill 6757 (4/06/2018)



Fill 6919 (13/07/2018)



Beta* levelling steps and new orbit reference

- **Same scales** on all plots
- Fill 6757 higher excitation amplitude
  - → stronger effect on beams
  - → higher losses, deeper luminosity dips, higher vertical RMS orbit

From: *Observation on HL-LHC CE vibration on the beam*, M. Schaumann (link)

Optics sensitivity: assumptions

- Interested in frequencies (*f*) **above a few Hz**
  - Normally **no spatial correlation**
  - **Not interested** in strong single event, e.g. earthquakes, which can carry strong correlation
  - Motion normally **not caught by** present **orbit feedback**

- Assuming all perturbations induce simply a **closed orbit** variation
  - i.e. considering only $f \ll f_{rev}$

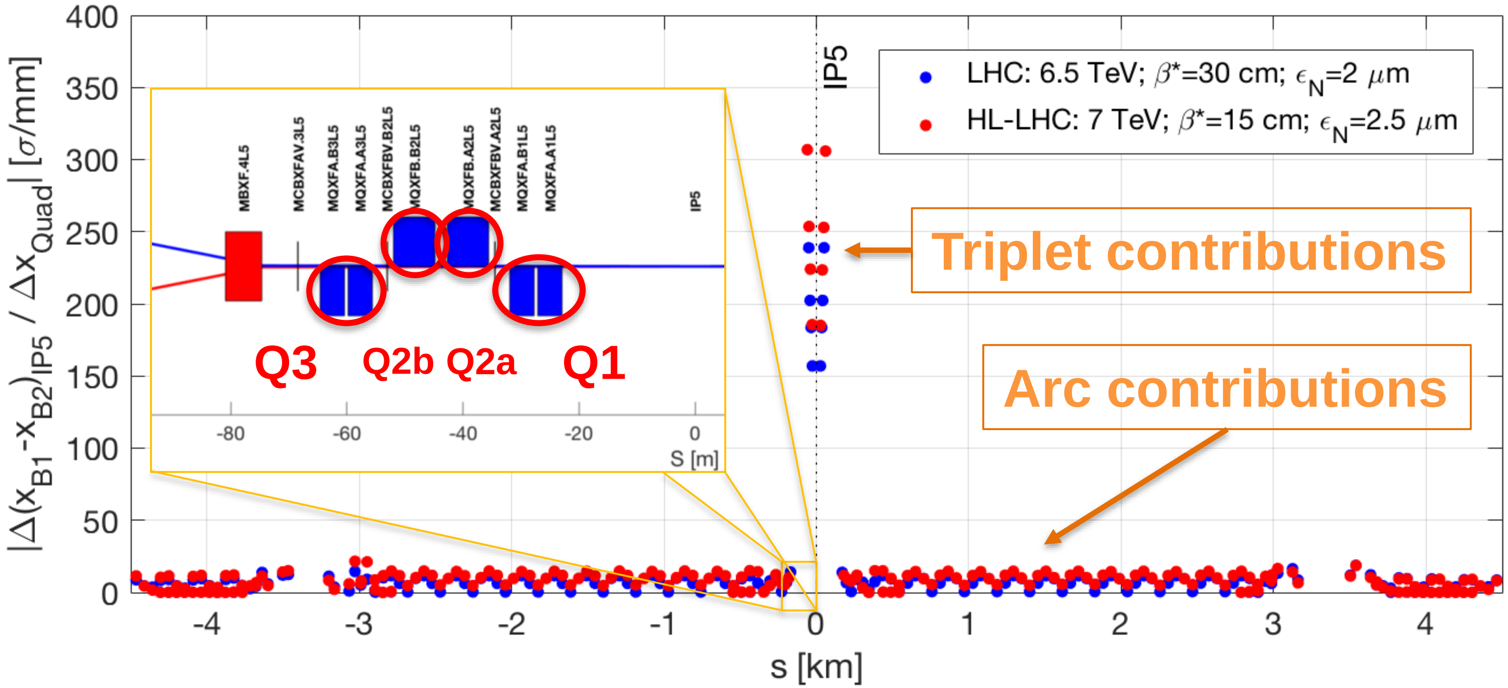
- **Uncorrelated** ground motion distributed along the whole machine with equal amplitude
  - **main players are the triplets in IP1/5**

- Beam/optics parameters
  - **LHC**: ε_N = 2 µm; 6.5 TeV; β^* = 30 cm
  - **HL-LHC**: ε_N = 2.5 µm; 7 TeV; β^* = 15 cm

Impact of quad misalignment on closed orbit

- Expected B1 closed orbit variation at IP5:

$$\frac{\Delta x^*}{\sqrt{\beta^* \epsilon_g}\Delta x_q} = \frac{\sqrt{\beta_q}(K1L)_q}{\sqrt{\epsilon_g}} \frac{\cos(2\pi\phi_{q*} - \pi Q_x)}{2\sin(\pi Q_x)}$$



- **HL-LHC @15cm very similar to present LHC @30 cm**

Possible beam observables

- **Luminosity**
  - Probably the **most sensitive observable**.
- Beam **intensity**
  - Very high dynamic range due to intensity variation along fill
  - More interesting to look at BLM-computed **integrated losses**
    - Very sensitive signal!
- **BPMs**
  - Position acquired at 25 Hz, but available only as **mean over 1 s**
    - **Not suitable** for vibrations of *f* > a few Hz
  - The **rms over 25Hz data** is logged in Timber
    - **Suitable** to look at oscillations of a few Hz
- **DOROS BPMs**
  - Could acquire at much higher frequency, but also normally logging **average over 1 s**
  - Logging of spectra requested by Michaela, will happen soon
- **BBQ**
  - A lot of spectra, **not amplitude calibrated**.
  - **Not very sensitive during standard operation**
- **ADT**
  - Spectra being logged since a few months.
    - **Rough amplitude calibration available**

Luminosity [1]

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} W e^{\frac{B^2}{A}} S H$$

$$W = e^{-\frac{1}{4\sigma_x^2}(d_2-d_1)^2}$$

Reduction due to offset (e.g. horizontal -- x)

$$A = \frac{\sin^2(\frac{\phi}{2})}{\sigma_x^2} + \frac{\cos^2(\frac{\phi}{2})}{\sigma_s^2}$$

$$B = \frac{(d_2 - d_1)\sin(\frac{\phi}{2})}{2\sigma_x^2}$$

$$S = \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_x}\tan(\frac{\phi}{2})\right)^2}}$$

For **LHC**: we can estimate that the **effect** of **crossing angle variation** is **comparable to offset**

For **HL-LHC**: in the **limit** of ideal **full crabbing**, is equivalent to head on collision, i.e. **equivalence between crossing and separation plane**

$$H = \sqrt{\pi}\frac{\beta^*}{\sigma_s} e^{\left(\frac{\beta^*}{\sigma_s}\right)^2} \mathrm{erfc}\left(\frac{\beta^*}{\sigma_s}\right)$$

Reduction due to Hour Glass effect

[1] Concept of Luminosity, W. Herr and B. Muratori, (CERN-2006-002)

Summary: impact on observables

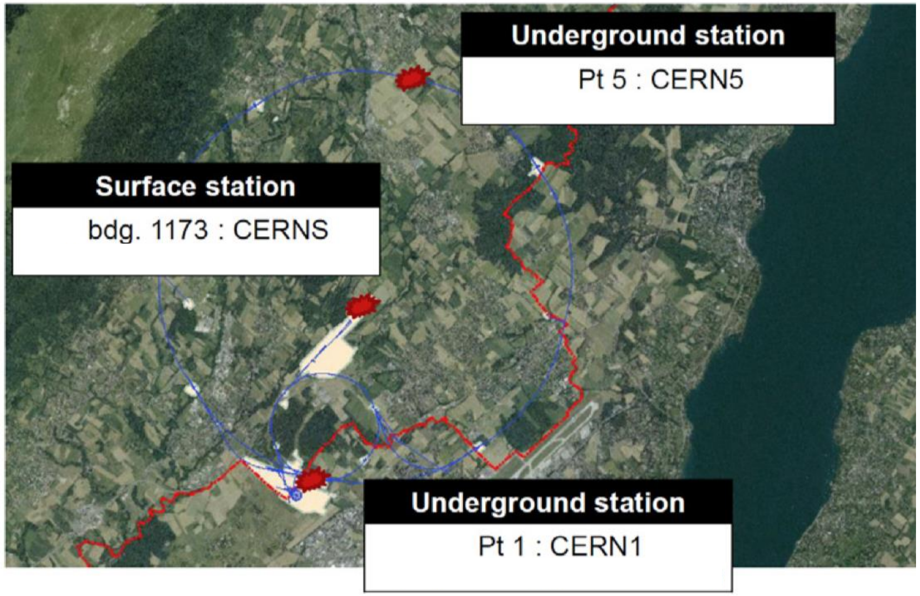
Luminosity loss [%] $W = e^{-\frac{1}{4\sigma_x^2}(d_2-d_1)^2}$	1		10		~2
	LHC	HL-LHC	LHC	HL-LHC	HL-LHC
Orbit sep. IP1/5 [σ_{beam}]	0.2		0.7		0.3
Necessary quad. motion rms [μm]	**0.3**	**0.2**	**0.9**	**0.7**	**0.3**
rms orbit @TCP* [σ_{beam}]	0.1	0.1	0.4	0.4	0.2
rms orbit @BPM* [μm]	~50	~50	~240	~240	~120

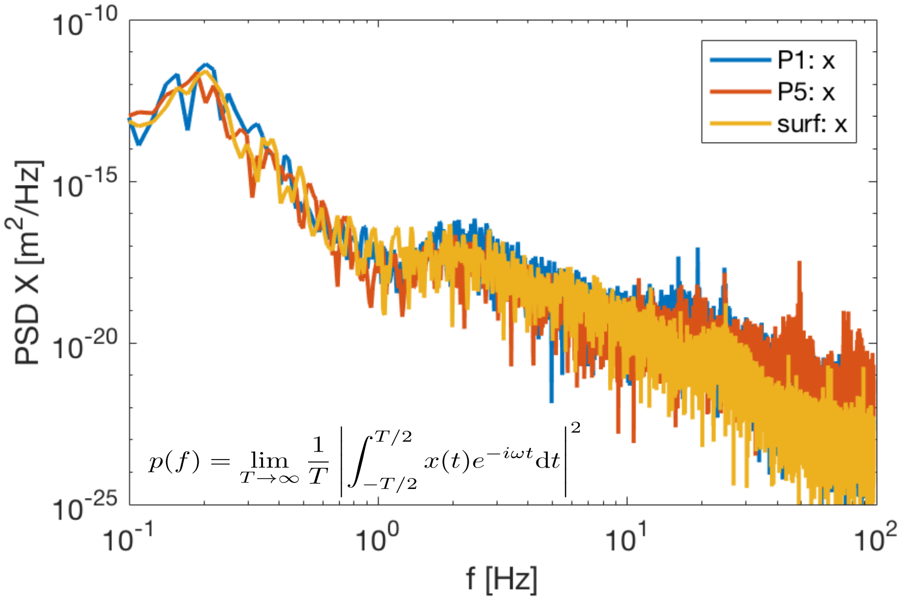
- Numbers computed assuming **IP1/5 triplet only source** of perturbation.
  - **Assuming both IP triplets oscillate by the same rms amplitude in one plane only.**
  - **If only one triplet oscillates => sqrt(2) more quadrupole motion needed to give same effect.**
- A reasonable threshold is **1% instantaneous luminosity loss**, which correspond to about **0.3 (LHC) or 0.2 (HL-LHC) μm triplets motion**.
- An event causing **1%** instantaneous luminosity loss in **LHC** would cause a **2%** luminosity loss in **HL-LHC**

* Considering the most sensitive TCP/BPM/plane

Observables of ground motion

- **Geophones** are logging data since 2017
- Data logged into Timber in the form of PSD





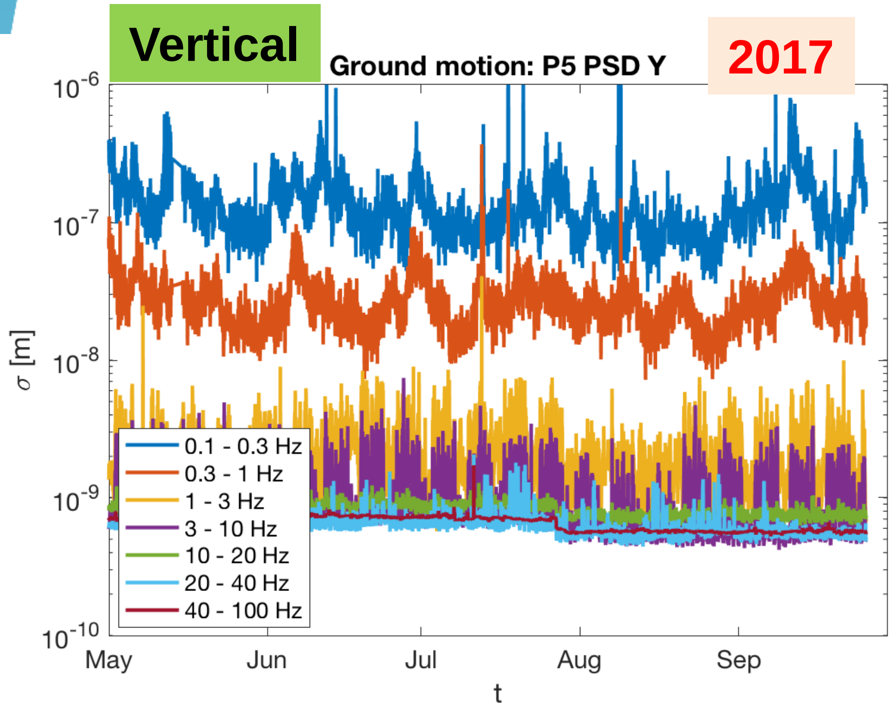
- 15 May 2018: Official start of HL-LHC excavation works.
  - 2018 run is the occasion to see perturbation on the beam due to ground motion
  - It could allow us to see if our expectations for HL-LHC are correct.

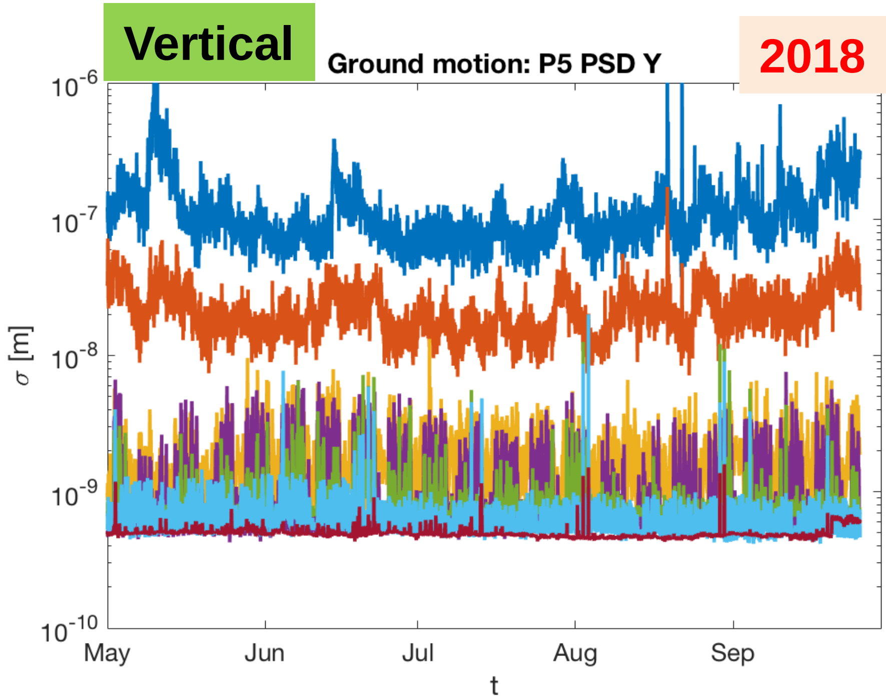
M. Guinchard, Oct. 2017 link

Integrated PSD: 2017 vs 2018 (P5)

- **PSDs integrated over range of frequencies**
  - Gives measured rms motion in that band

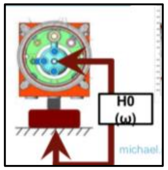
$$\sigma^2(f_0 < f < f_1) = \int_{f_0}^{f_1} p(f)\mathrm{d}f$$



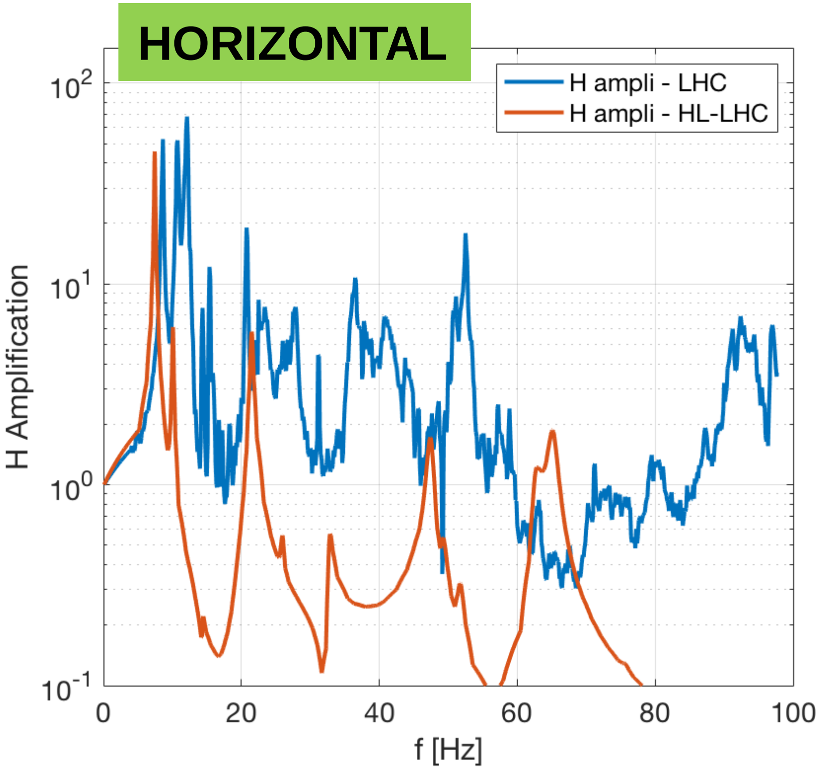


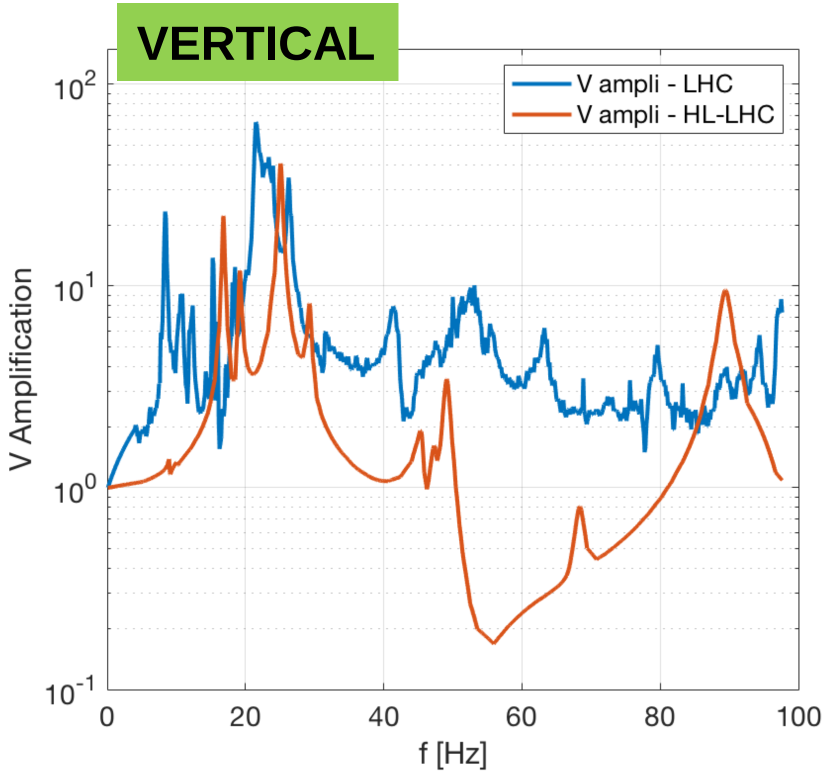
- Possible to see **human activity** in band **3-10Hz** and **above**
- Some **higher activity** (starting in **Oct. 2017** – not in the plot)
- **No obvious sign** of **civil engineering** works started in **May 2018**

Ground motion amplification



- The triplet quadrupole assembly can amplify (or damp) the ground motion:

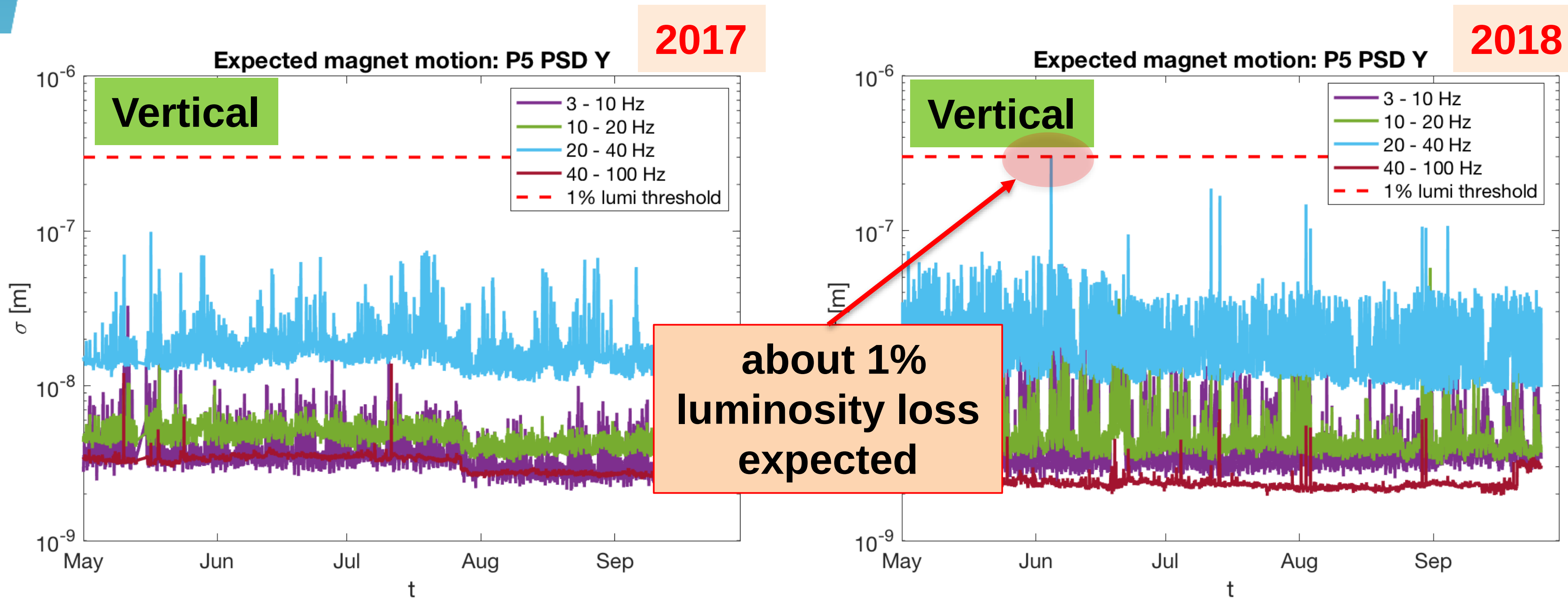




- **LHC: measured** on Q1 spare assembly in SM18 (M. Guinchard, Oct 2017, link)
- **HL-LHC: simulated** (1% damping) by D. Ramos and M. Martos

Integrated Amplified (LHC) PSD: 2017 vs 2018 (P5)

- **PSD amplified** and **integrated** (f > 3Hz) $$\sigma^2_{mag}(f_0 < f < f_1) = \int_{f_0}^{f_1} p(f)T^2(f)\mathrm{d}f$$



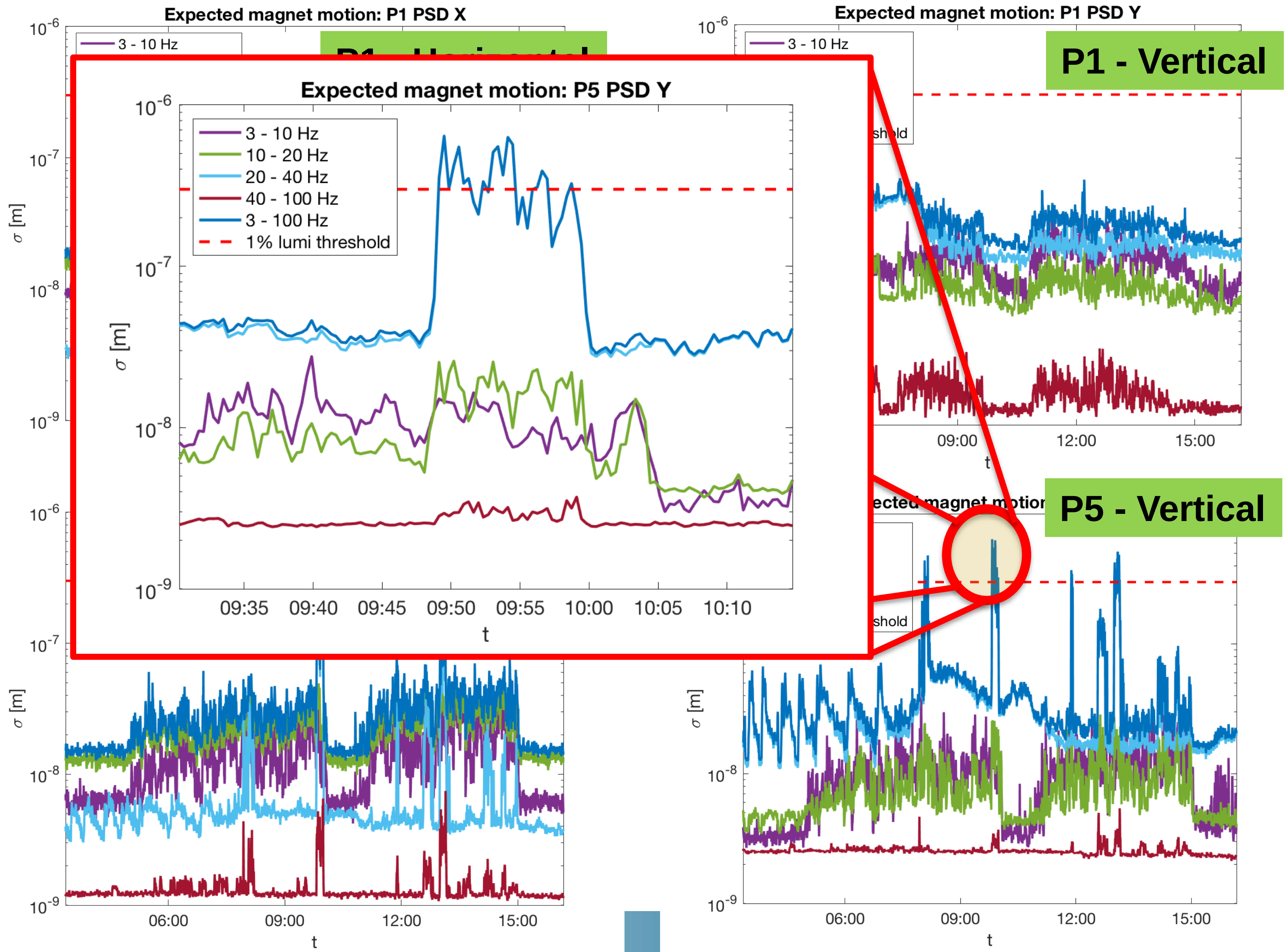
- The 20-40 Hz band is dominant
- 2017: relatively quiet, far from 1% lumi threshold
- 2018: some dangerous spikes

“Interesting” fills

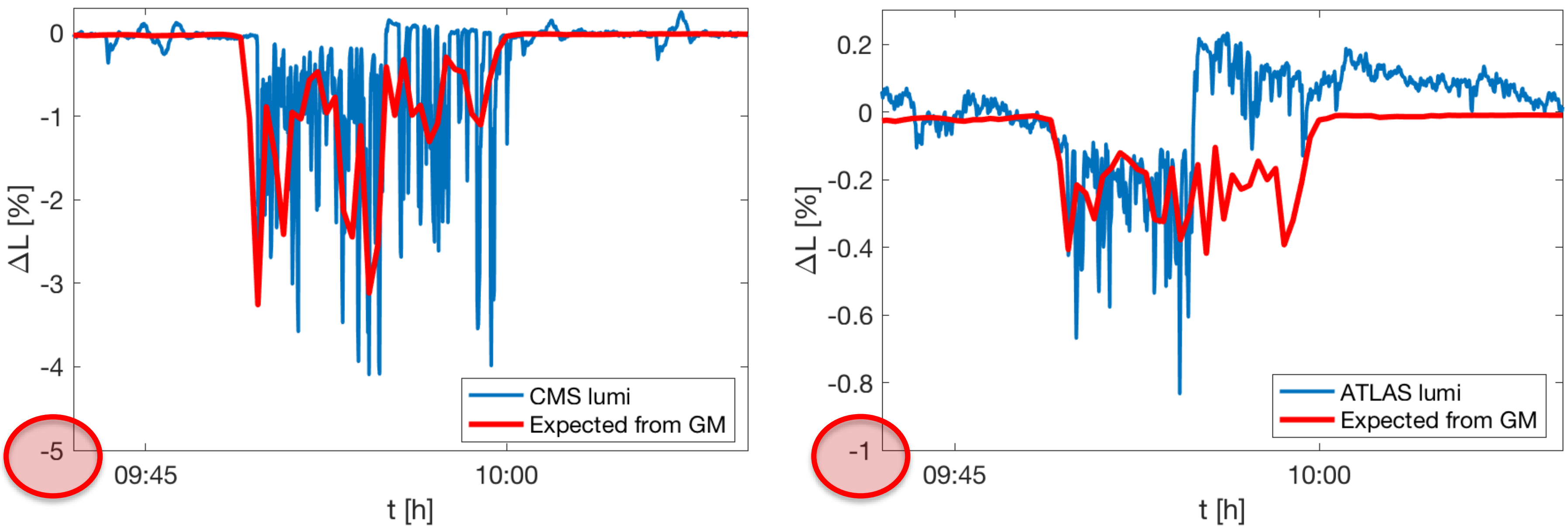
- **Alarm system** set up by M.Guinchard and L.G.Scislo (EN-MME) **on geophones** to eventually stop the excavation works.

- **Fills with beam that could have been affected by Ground Motion:**
  - Point 1
    - 30/05/18: 13:00 -> fill **6741 (very small GM excitation)**
    - 01/06/18: 08:00-13:00 -> fill **6749 -> considered**
    - 10/09/18: 6:30-7:00 -> fill **7145 (very small GM excitation)**
  - Point 5
    - 11/10/**17**: around 8:00 fill **6291 (a few small spikes only)**
    - 19/10/**17**: around 8:00 -> fill **6308 -> considered**
    - 20/10/**17**: around 9:00 -> fill **6311 -> considered**
    - 04/06/18: 08:11 -> Fill **6757 -> considered**
    - 13/07/18: Day -> Fill **6919 -> considered**
    - 30/08/18: 5:50-13:20 -> Fill **7105 (very small GM excitation)**
    - 03/09/18: 7:00 - 7:25 -> Fill **7122 -> considered**
    - 04/09/18: 6:43 - 7:10 -> Fill **7124 (very small GM excitation)**

Fill 6757 P1/P5 Amplified – LHC



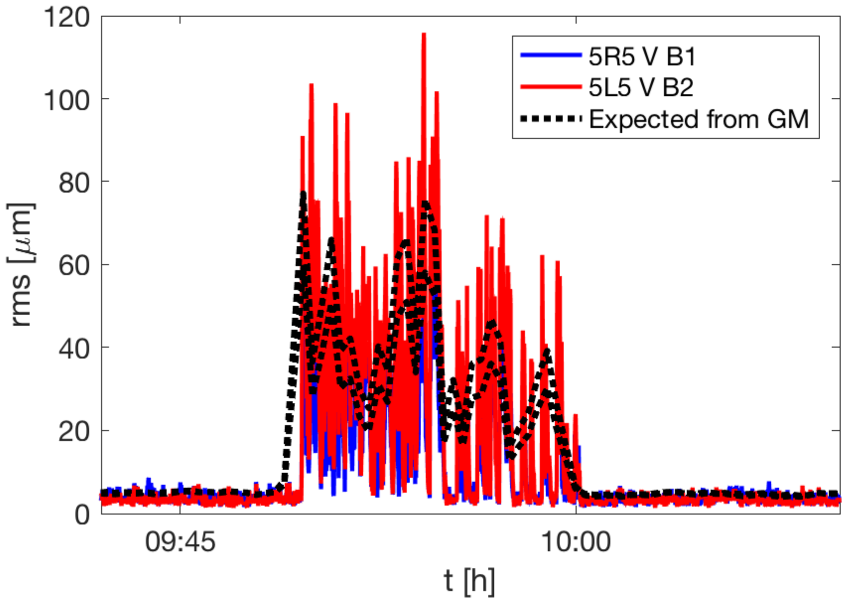
Fill 6757 impact on luminosity

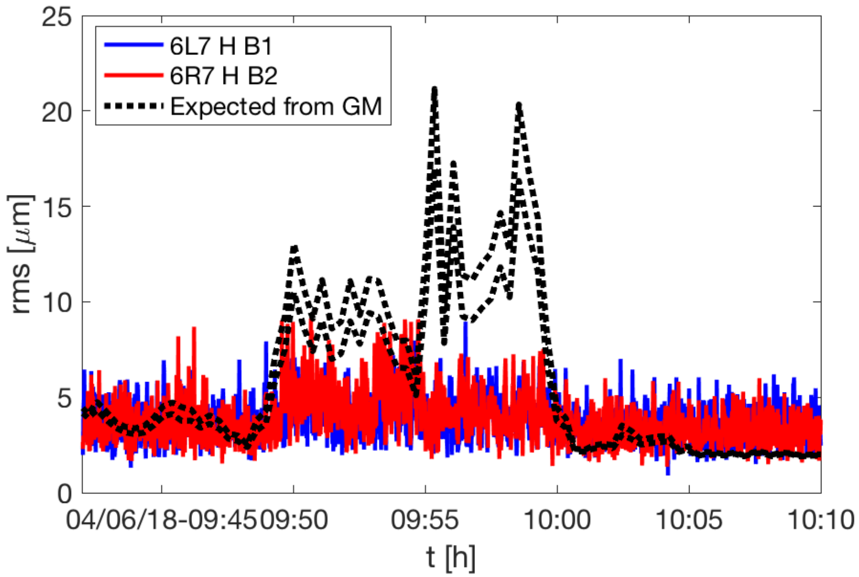


- **Luminosity dips compatible with expectation** from ground motion measured, amplified, converted into orbit separation at IPs

- **ATLAS** much less sensitive to vertical ground motion generated next to CMS

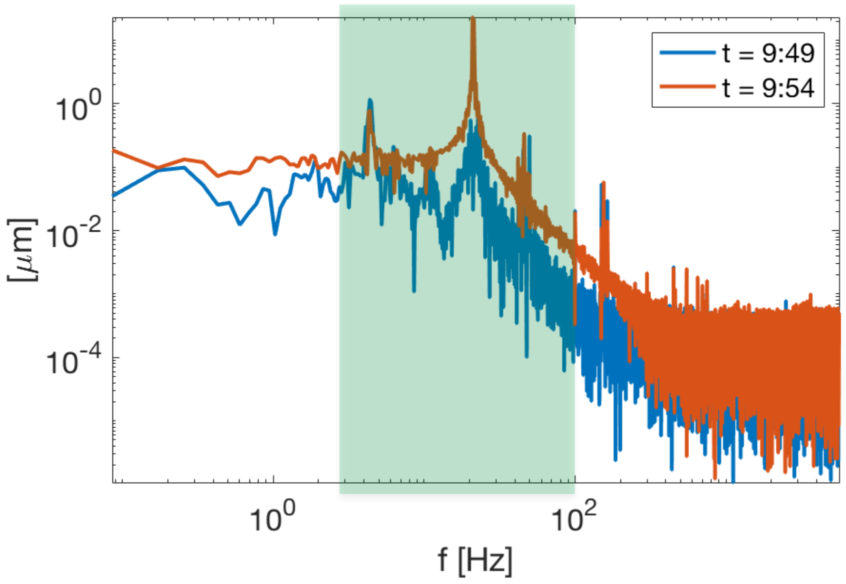
Fill 6757 impact on orbit @BPMs



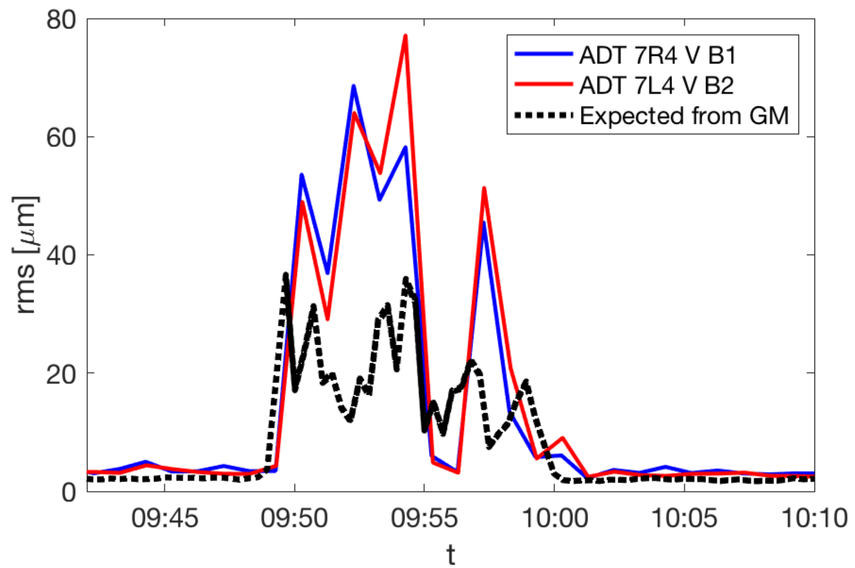


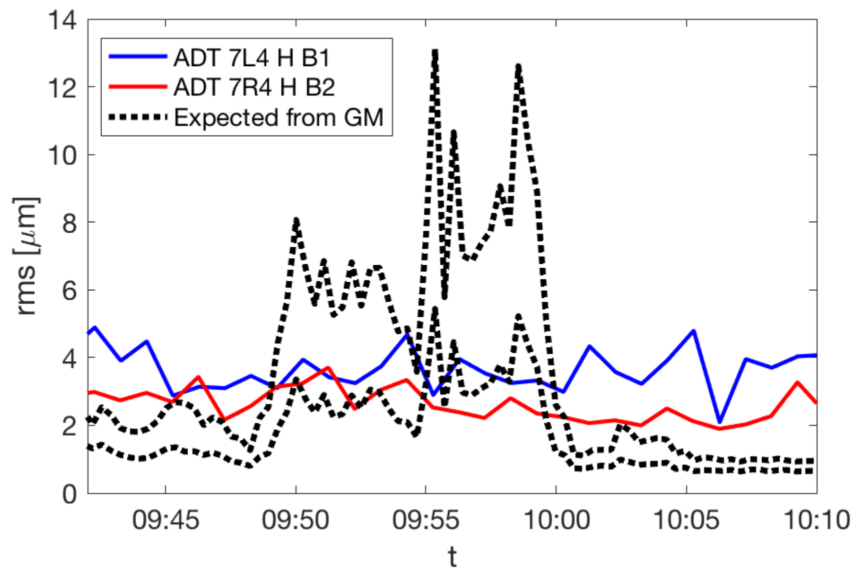
- **BPM** system logs data at 1 Hz, but it also provides the **rms computed over 25 Hz data**.
- **Vertical** rms orbit **compatible with expectations**
- It looks like we are **over-estimating the horizontal motion**
  - Possible discrepancy in the quadrupole transfer function?

Fill 6757 impact on orbit @ADT

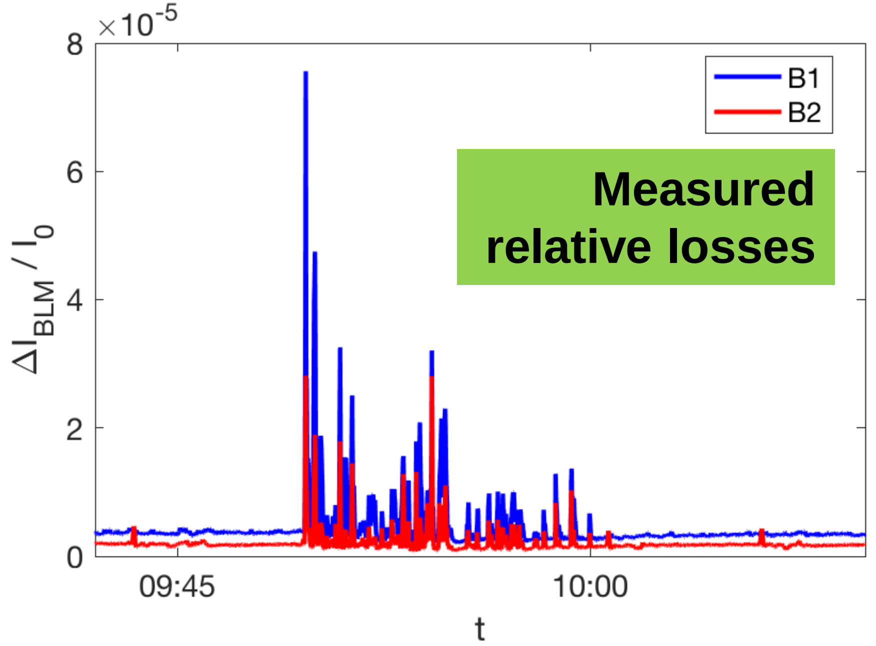


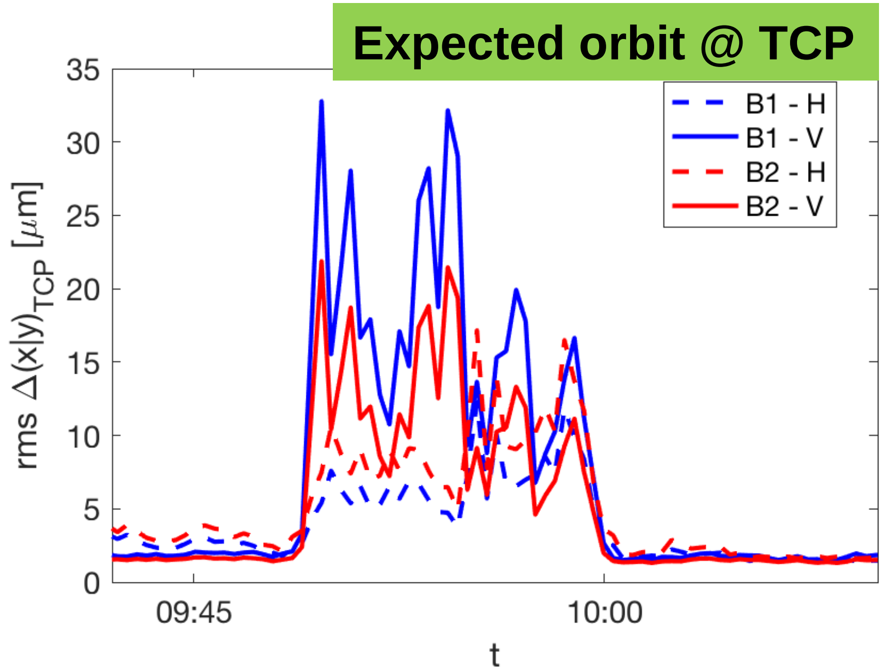
- **ADT** data **logged as spectra**
- **Integrating** over band **3-100 Hz** we get similar matching with expectation as for the BPMs
- Still "off" in horizontal





Fill 6757 impact on beam losses @TCP





- **Losses** of the order of **a few 10^{-5}** wrt beam intensity.
  - **Difficult** to **translate losses into orbit** variation at collimators
  - From ground motion, we would expect 20-30 um orbit jitter wrt to total aperture of TCP (2.7 mm H; 2 mm V)
    - If correct, losses **compatible** with **over-population of tails** wrt simple Gaussian

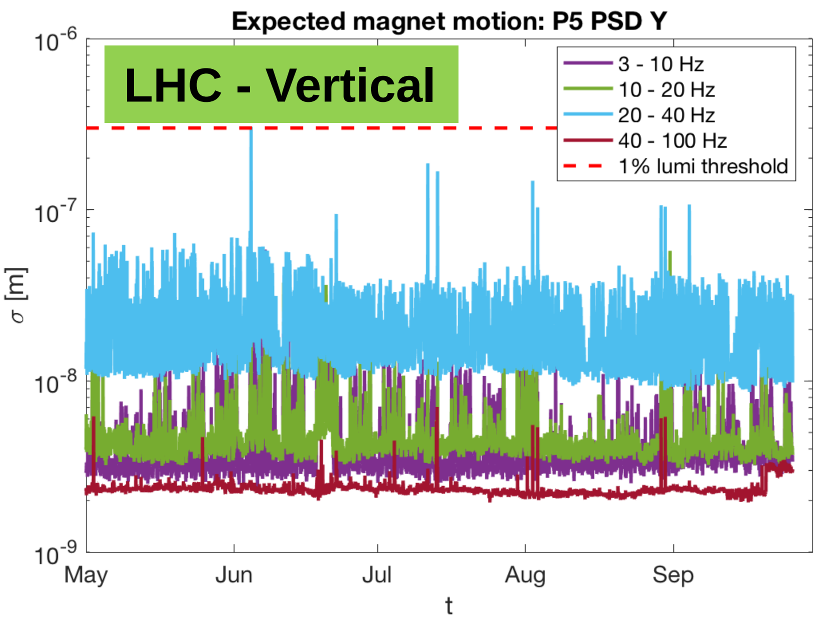
Summary of observations

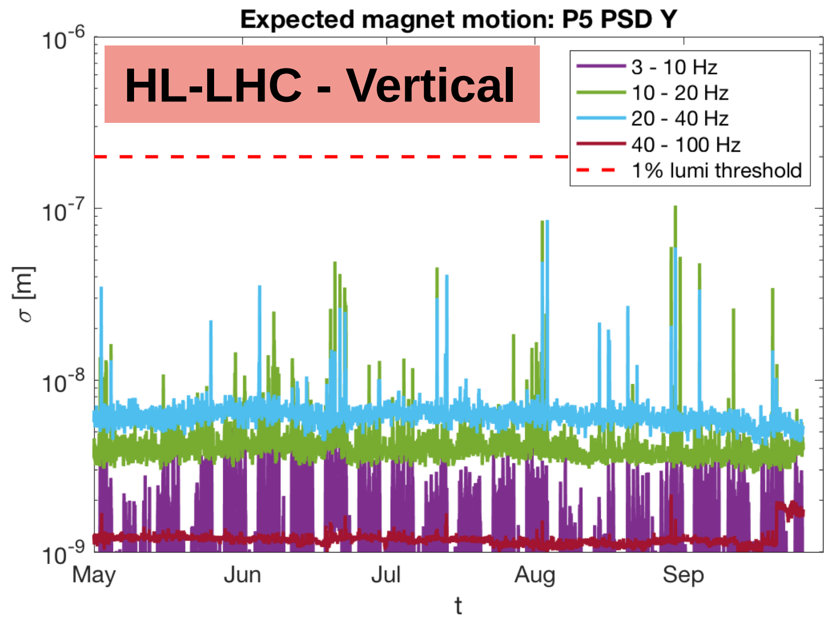
- Looking (by eye => **very rough estimates**) at different fills (see appendix)

Fill #	Obs. V GM rms [μm]		Lumi loss [%]				Losses [1e-5]		Orbit [um]			
	P1	P5	P1		P5		TCP	TCP	ARC BPMs		ADT pickup	
	Obs.	Obs.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
6308	<0.1	**0.2**	<0.1	0.1	0.4	0.2	0.2	9	20	20	20	10
6311	<0.1	**0.3**	0.2	0.3	1	1	0.5	15	50	40	25	15
6749	**0.8**	<0.1	<0.1	1	0.2	1.5	0.8	30	25	100	20	20
6757 (1)	<0.1	**0.6**	0.5	0.5	3	3	3	20	80	70	60	30
6757 (2)	<0.1	**0.4**	0.4	0.3	6	2	4	20	70	50	70	20
7122	<0.1	**0.4**	0.3	0.3	1.5	1.5	1	20	50	50	60	20

- Fill **6749** is the only affected by ground motion in P1, but is also the one “less predictable”: impact smaller than expected.
- **Predictions on luminosity drops and orbit at BPMs well within a factor 2**
- **Prediction on orbit at ADT seems to be a factor 2 off**
  - **Information from this morning: factor 2 in the data published in Timber…**

2018: LHC vs HL-LHC





- **HL-LHC slightly more sensitive, but triplet more forgiving (on paper!)**
- Very **important** to **measure** the **transfer function** of the **new** triplet **quadrupoles**:
  - A factor 2 would be enough to show ground motion into the beam
  - **Plan to measure a main dipole in 2019, then the first quad prototype as soon as it is available.**

Conclusions

- **HL-LHC civil engineering showed up in LHC…**
  - From July 2018, 11 days with multiple alarms linked to surface activity [M.Guinchard]
  - Events caused **luminosity dips** of the order of a few %, mainly at CMS.
    - Hardly noticeable for typical LHC operation

- The **ground motion sensors** + **transfer function measurements** + **optics simulation** allow to **understand the observations**

- **Actual LHC** is **very close to HL-LHC** in terms of optics sensitivity
  - Still, **main players remain the IP1/5 triplets**.
  - Estimated triplet transfer function seems to be a bit more forgiving that present triplet
    - **Important to verify the transfer function estimate on actual hardware.**

- Thanks for your attention and comments -

Appendix

From losses to orbit at TCP?!

Parameters Vertical plane

CONSTRAINS →
- Double Gaussian : $I_1 > I_2$ and $\sigma_1 < \sigma_2$
- Lèvy Student : $n > 2$

B1

DATA ACQUISITION	SCRAPING	MODEL					
		DOUBLE GAUSSIAN				LEVY STUDENT	
		I_1	I_2	σ_1	σ_2	n	a
30/07/2018	FULL	0,69	0,3	0,6	1,37	4,1	1,38
	FULL	0,73	0,26	0,58	1,42	4,11	1,3
	FULL	0,54	0,45	0,11	0,34	2	0,2

DOUBLE GAUSSIAN MODEL	
I_1/I_2	σ_2/σ_1
2,23	2,25
2,79	2,43
1,2	3,01

FLAT TOP

B2

DATA ACQUISITION	SCRAPING	MODEL					
		DOUBLE GAUSSIAN				LEVY STUDENT	
		I_1	I_2	σ_1	σ_2	n	a
30/07/2018	FULL	0,79	0,2	0,62	1,31	7,36	1,82
	FULL	0,57	0,42	0,5	1,08	4,53	1,31
	FULL	0,77	0,22	0,14	0,35	4,96	0,35

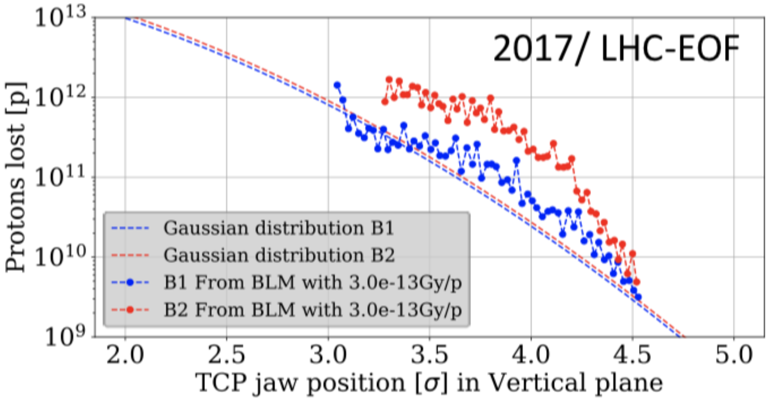
DOUBLE GAUSSIAN MODEL	
I_1/I_2	σ_2/σ_1
3,95	2,08
1,33	2,13
3,5	2,4

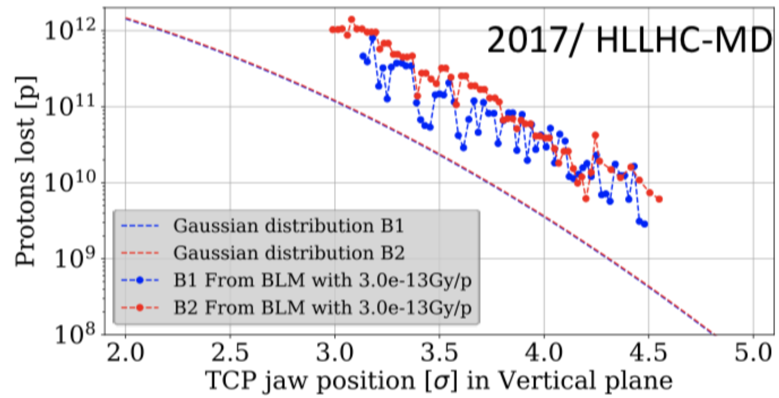
FLAT TOP

From: *Review of halo measurements at LHC with collimator scans*, P. Racano(link)

From losses to orbit at TCP?!

Beam tails reconstruction (2017)



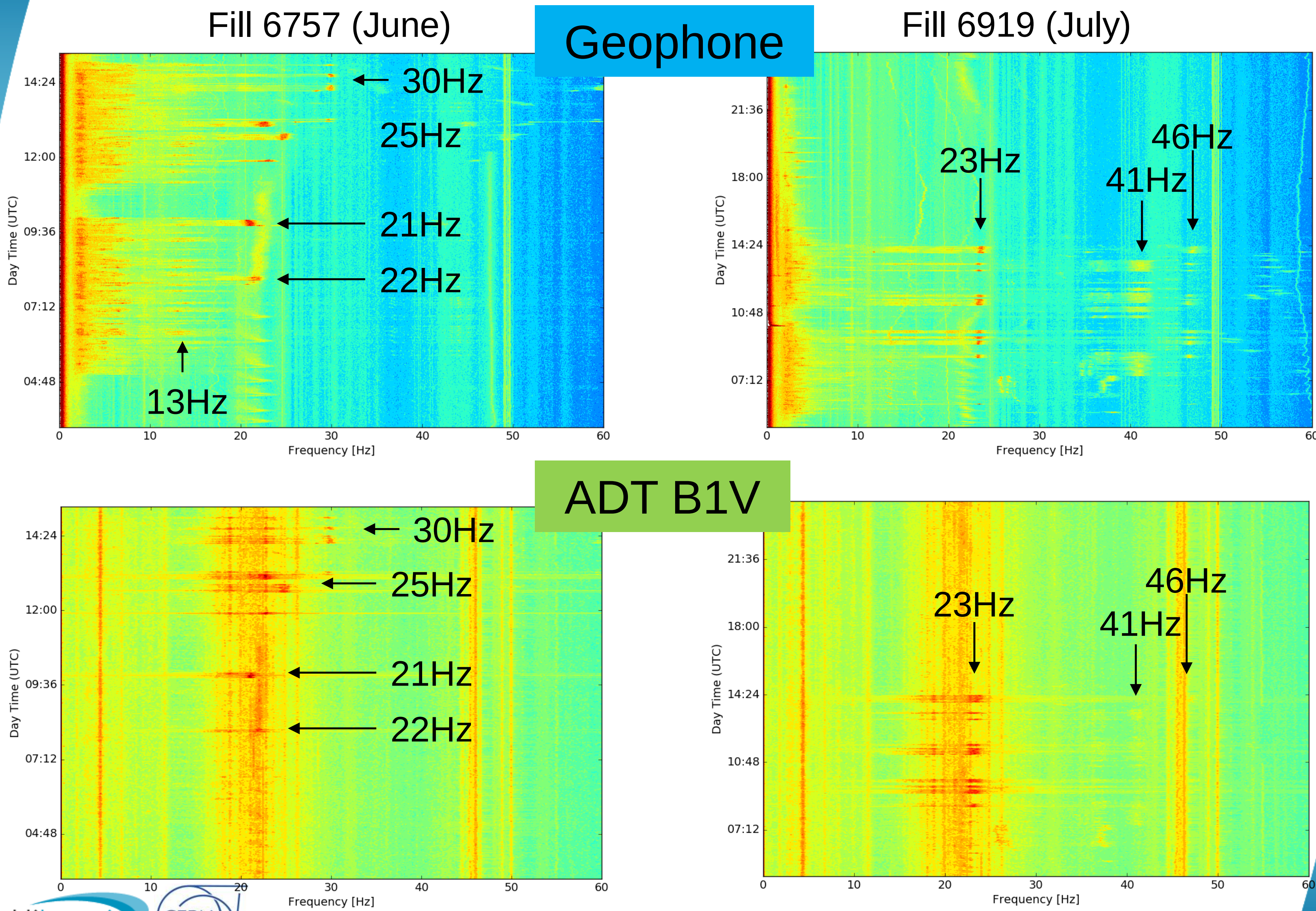


- The regular LHC beam tails profile (left) consistent for the measurements in 2016/2017
- In general, there is **visible tail over population** especially for the HL-LHC like bunches (right)
- Profiles in the plots for the **emittance of 2um**

10/12/2018 ColUSM: Results of the beam diffusion measurements in the LHC at 6.5TeV 15

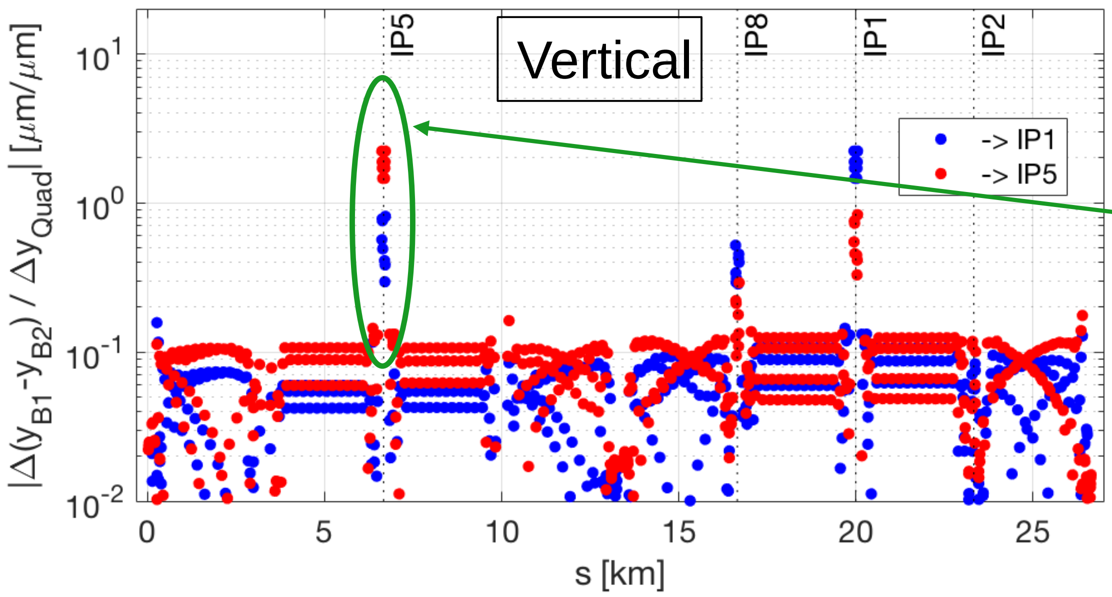
From: ***Results of the beam diffusion measurements in the LHC at 6.5TeV***, A. Gorzawski (link)

GM and Beam Spectrum Evolution



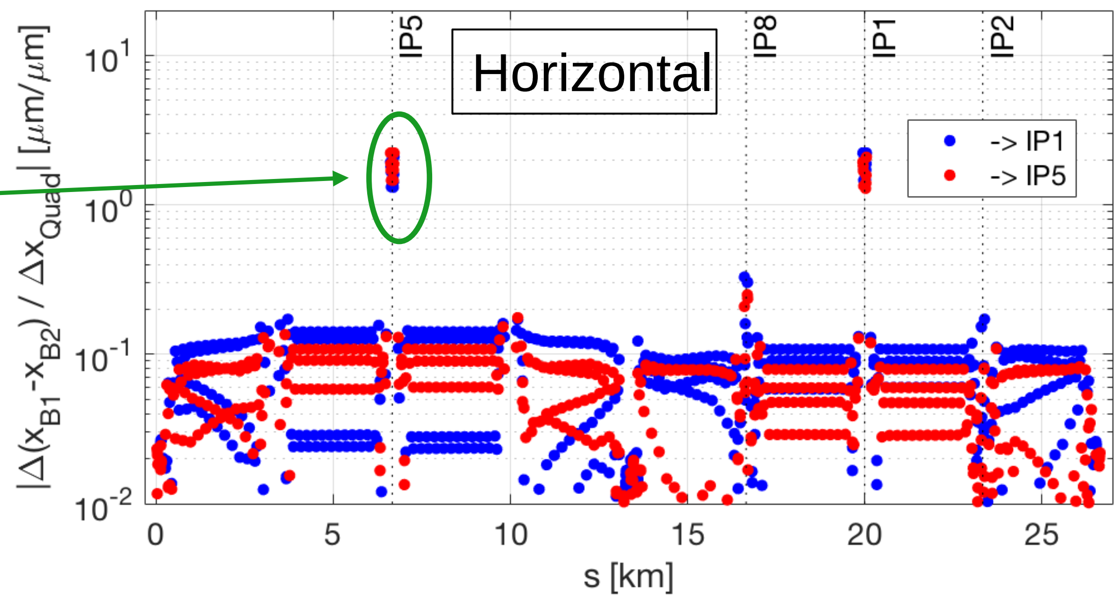
From: *Observation on HL-LHC CE vibration on the beam*, M. Schaumann (link)

Beam Separation at IP1/5 due to Quadrupole Offset



Assumption:
30cm optics, 2um emittance

Vertical offset of triplet in IP5 introduces a larger orbit effect in the IP5 compared to IP1 and vice versa



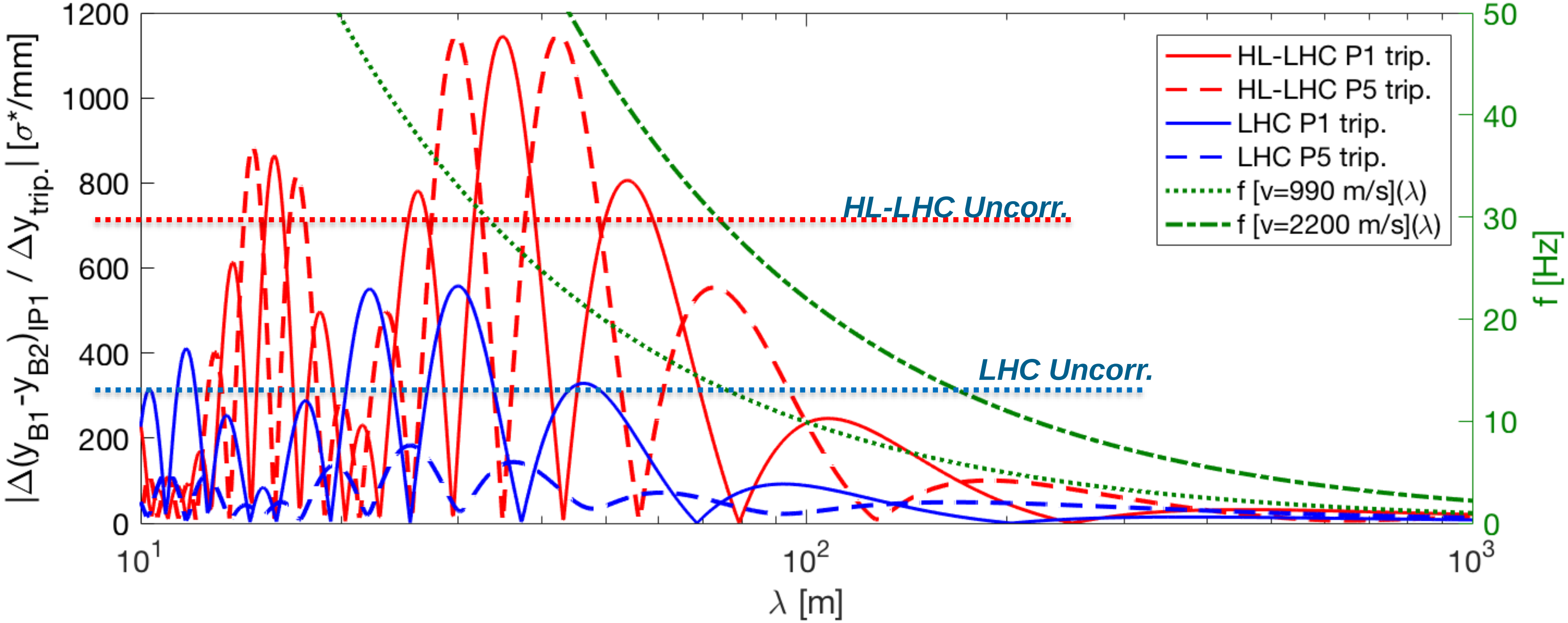
Horizontal offset of triplet in IP1/5 introduces a similar orbit effect in the both IPs.

From: *Observation on HL-LHC CE vibration on the beam*, M. Schaumann (link)

Note: correlated IR motion

Computed for LHC @ ε_N=3.75 μm; β*=40cm

Impact of a wave propagating along the local IR1 or remote IR5 on IP1 orbit separation: amplification factor as a function of λ



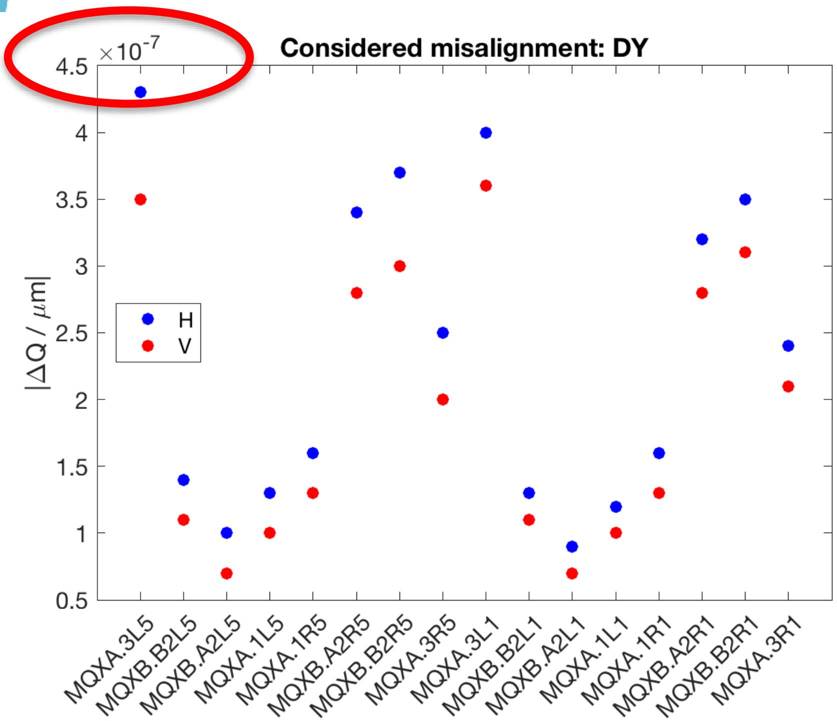
- Typical wave speed measured in the CERN tunnels:
  - 990 m/s (shear); 2200 m/s (pressure)
- ***f* below a few Hz** (most likely *f* to be correlated) **have "small" amplification factor w.r.t. fully uncorrelated case.**

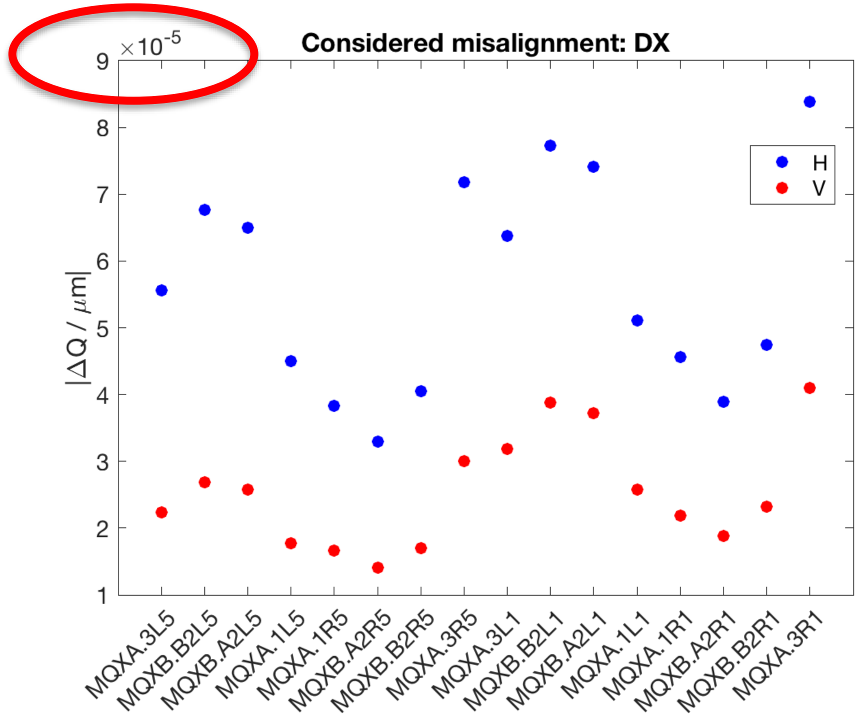
HiLumi HL-LHC PROJECT CERN

From 119th WP2 meeting (link) - sqrt(2) factor missing everywhere

Impact on Tune

- Impact of the orbit induced by 1 um offset of each triplet (P5) element on Tune – **LHC case**





Detailed appendix

Optics sensitivity tables and plots

Optics sensitivity tables

- Amplification factors from magnet motion to **IP orbit separation**

	IP1 [σ^*_{beam}/µm]		IP5 [σ^*_{beam}/µm]		IP2 [σ^*_{beam}/µm]		IP8 [σ^*_{beam}/µm]	
	Δx	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**
LHC all quads	**0.783**	0.616	0.771	0.621	0.338	0.354	0.425	0.516
LHC IR1/5 only	0.754	0.587	0.753	0.587	0.176	0.184	0.251	0.403
LHC IR5 only	**0.506**	**0.180**	0.559	0.559	0.041	0.139	0.147	0.146
HL-LHC all quads	1.054	**1.063**	1.051	1.059	0.392	0.515	0.499	0.832
HL-LHC IR1/5 only	1.028	1.033	1.029	1.031	0.309	0.464	0.344	0.771
HL-LHC IR5 only	0.755	0.762	0.696	0.697	0.276	0.376	0.255	0.527

- If we consider only one triplet we should get a sqrt(2) smaller impact, with the exception of the **vertical plane in LHC** where the “remote” impact is smaller.

sqrt(2) bigger than WRONG values presented at early WP2 meetings (link)

Optics sensitivity tables

- Amplification factors from magnet motion to **IP half/crossing variation**

	IP1 [μrad/μm]		IP5 [μrad/μm]		IP2 [μrad/μm]		IP8 [μrad/μm]	
	$\Delta\theta_x/2$	$\Delta\theta_y/2$	$\Delta\theta_x/2$	$\Delta\theta_y/2$	$\Delta\theta_x/2$	$\Delta\theta_y/2$	$\Delta\theta_x/2$	$\Delta\theta_y/2$
LHC all quads	9.09	10.98	8.73	11.45	1.14	0.86	2.42	3.27
LHC IR1/5 only	8.38	10.67	8.38	10.68	0.67	0.49	1.87	2.96
LHC IR5 only	6.04	9.19	5.81	5.42	0.38	0.33	0.84	2.70
HL-LHC all quads	14.46	13.15	13.99	13.11	1.25	1.18	7.69	5.05
HL-LHC IR1/5 only	13.43	12.50	13.34	12.61	0.88	0.89	3.42	1.70
HL-LHC IR5 only	7.51	6.97	11.11	10.39	0.69	0.61	1.91	0.95

Impact on angle is preferentially local

IR1/5 triplets **not** main source

Optics sensitivity tables

- Impact at **primary collimators** (max rms orbit at any TCP)

	B1				**B2**			
	[σ_{beam}/μm]		**[μm/μm]**		**[σ_{beam}/μm]**		**[μm/μm]**	
	Δx	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**
LHC all quads	0.432	0.384	93	60	0.492	0.376	105	60
LHC IR1/5 only	0.386	0.343	83	53	0.462	0.325	98	52
LHC IR5 only	0.243	0.323	52	51	0.344	0.226	73	34
HL-LHC all quads	0.519	0.492	120	84	0.611	0.202	140	33
HL-LHC IR1/5 only	0.476	0.449	110	77	0.575	0.132	131	21
HL-LHC IR5 only	0.274	0.327	63	56	0.409	0.132	93	21

Single triplet has "same" impact than both triplets… => asymmetry

Optics sensitivity tables (LHC only)

- Impact at “arc” **BPMs** (most sensitive BPM location in parenthesis)

	B1 [µm/µm]		B2 [µm/µm]	
	Δx (BPM)	**Δy (BPM)**	**Δx (BPM)**	**Δy (BPM)**
LHC all quads	122 (6L7)	198 (5R5)	128 (6R7)	170 (5L1)
LHC IR1/5 only	111 (6L7)	181 (5R5)	119 (6R7)	152 (5L1)
LHC IR5 only	78 (11R7) 72 (6L7)	140 (5R1) 92 (5R5) 30 (11R5)	96 (6L2) 90 (6R7)	120 (5L1) 31 (11L5)

- Impact at **Q1 IP1/5 BPMs** (most sensitive location in parenthesis)

	B1 [µm/µm]		B2 [µm/µm]	
	Δx	**Δy**	**Δx**	**Δy**
LHC all quads	183 (1L5)	287 (1R1)	263 (1R1)	252 (1R5)
LHC IR1/5 only	150 (1L5)	256 (1R1)	232 (1R1)	219 (1R5)
LHC IR5 only	129 (1L5)	226 (1R1)	194 (1R1)	183 (1L1) 119 (1R5)

Optics sensitivity tables (LHC only)

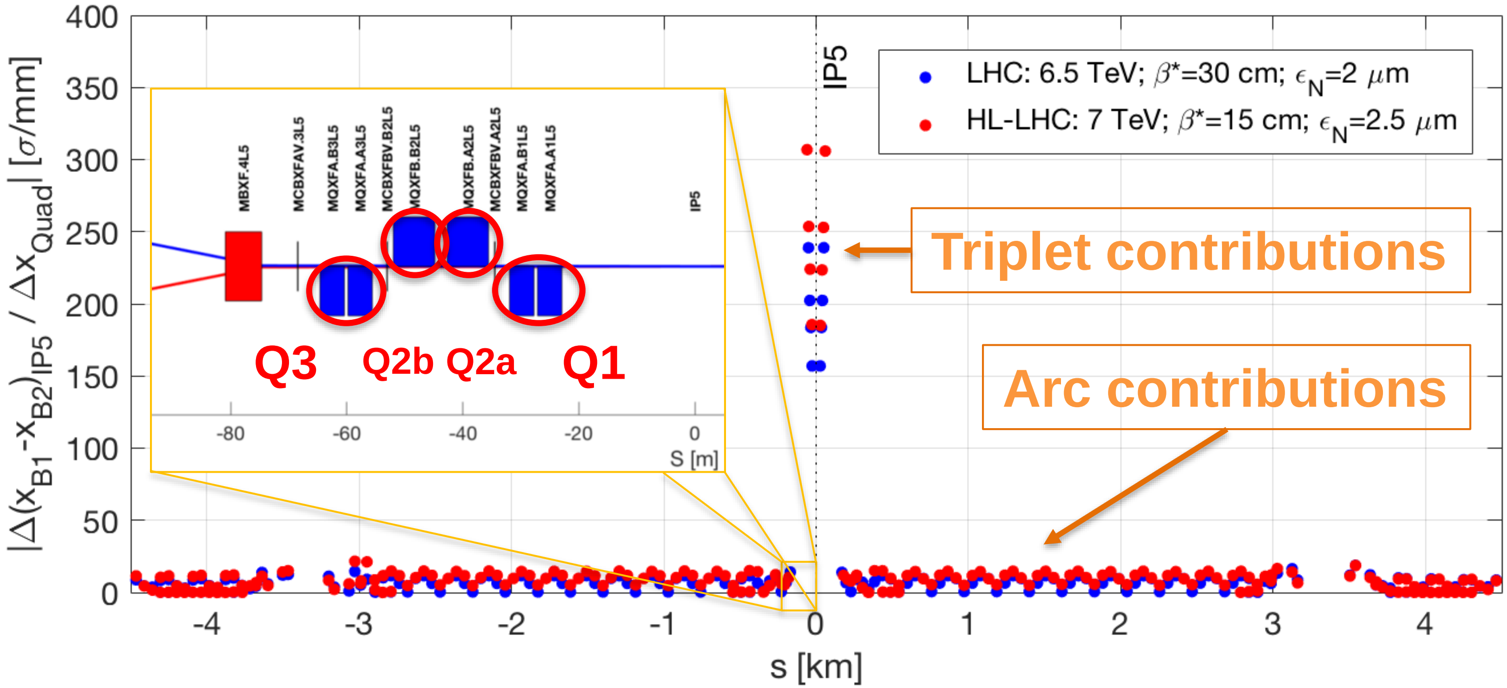
- Impact at **ADT pickup** (pickup location in parenthesis)

	B1 [µm/µm]		B2 [µm/µm]	
	Δx (7L4)	**Δy (7R4)**	**Δx (7R4)**	**Δy (7L4)**
LHC all quads	45	69	69	73
LHC IR1/5 only	37	61	61	63
LHC IR5 only	23	57	56	56

Impact of quad misalignment on closed orbit

- Expected B1 closed orbit variation at IP5:

$$\frac{\Delta x^*}{\sqrt{\beta^*\epsilon_g}\Delta x_q} = \frac{\sqrt{\beta_q}(K1L)_q}{\sqrt{\epsilon_g}}\frac{\cos(2\pi\phi_{q*}-\pi Q_x)}{2\sin(\pi Q_x)}$$

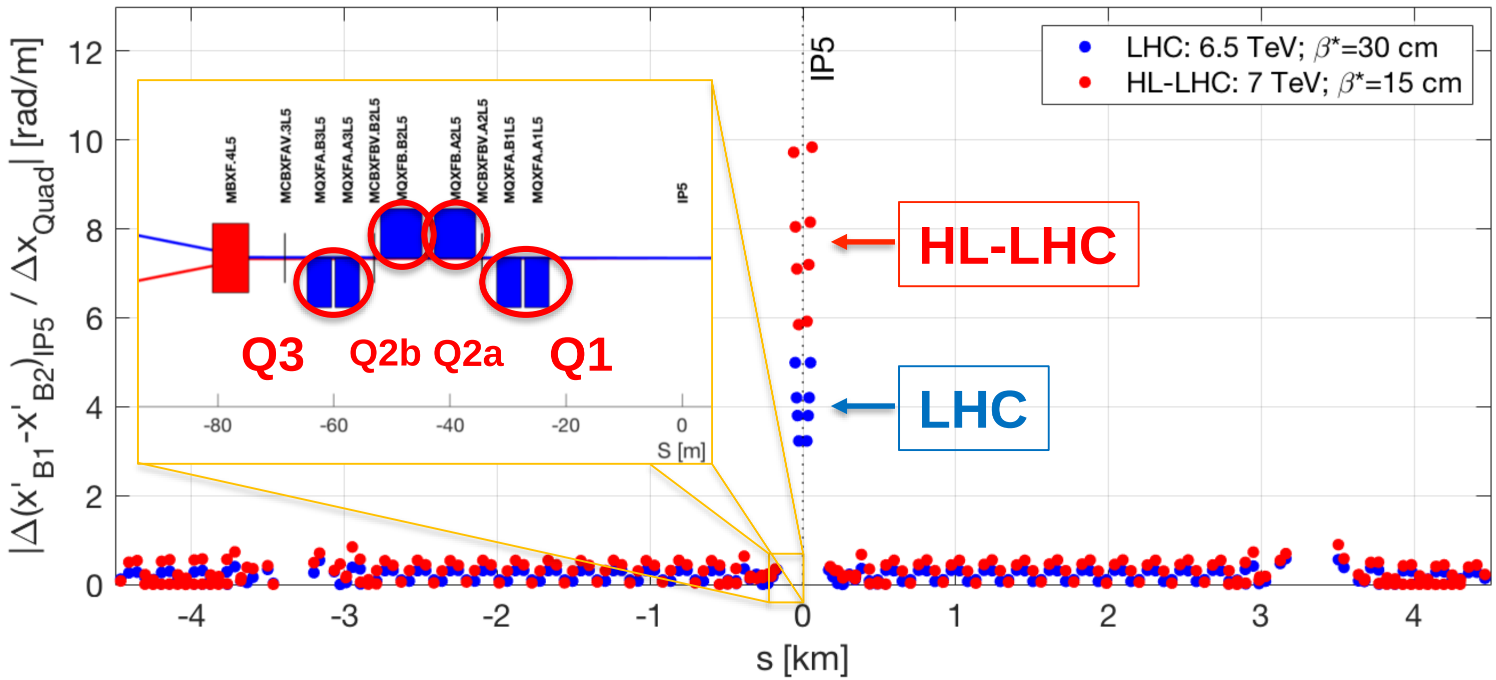


- **HL-LHC @15cm very similar to present LHC @30 cm**

Impact of quad misalignment on closed orbit

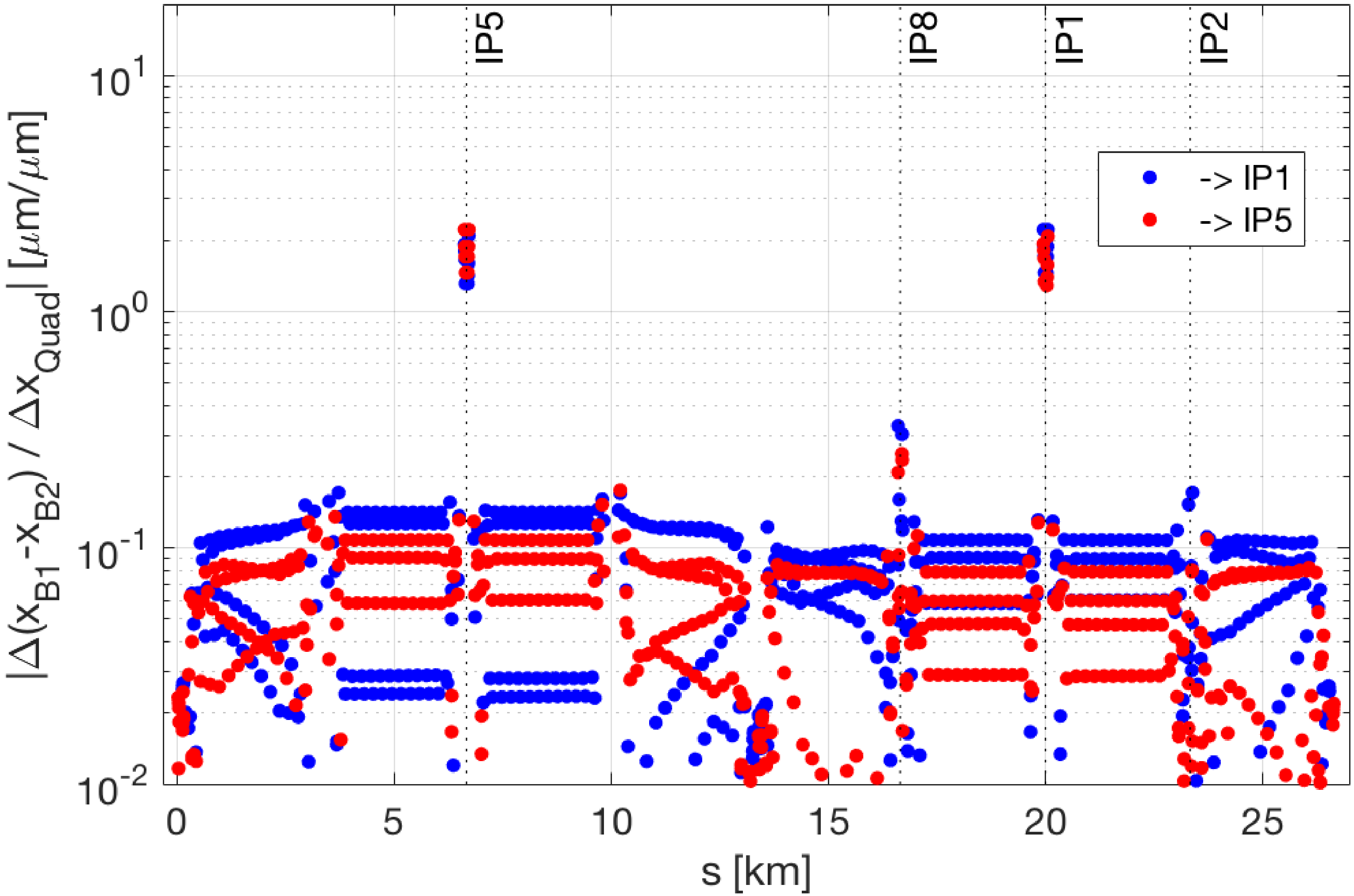
- Expected B1 closed orbit (**angle**) variation at IP5:

$$\frac{\Delta p_x^*}{\Delta x_q} = \frac{-(K1L)_q}{2\sin(\pi Q_x)}\sqrt{\frac{\beta_q}{\beta^*}}\left[\sin(2\pi\phi_{q*} - \pi Q_x) + \cancel{\alpha^* \cos(2\pi\phi_{q*} - \pi Q_x)}\right]$$

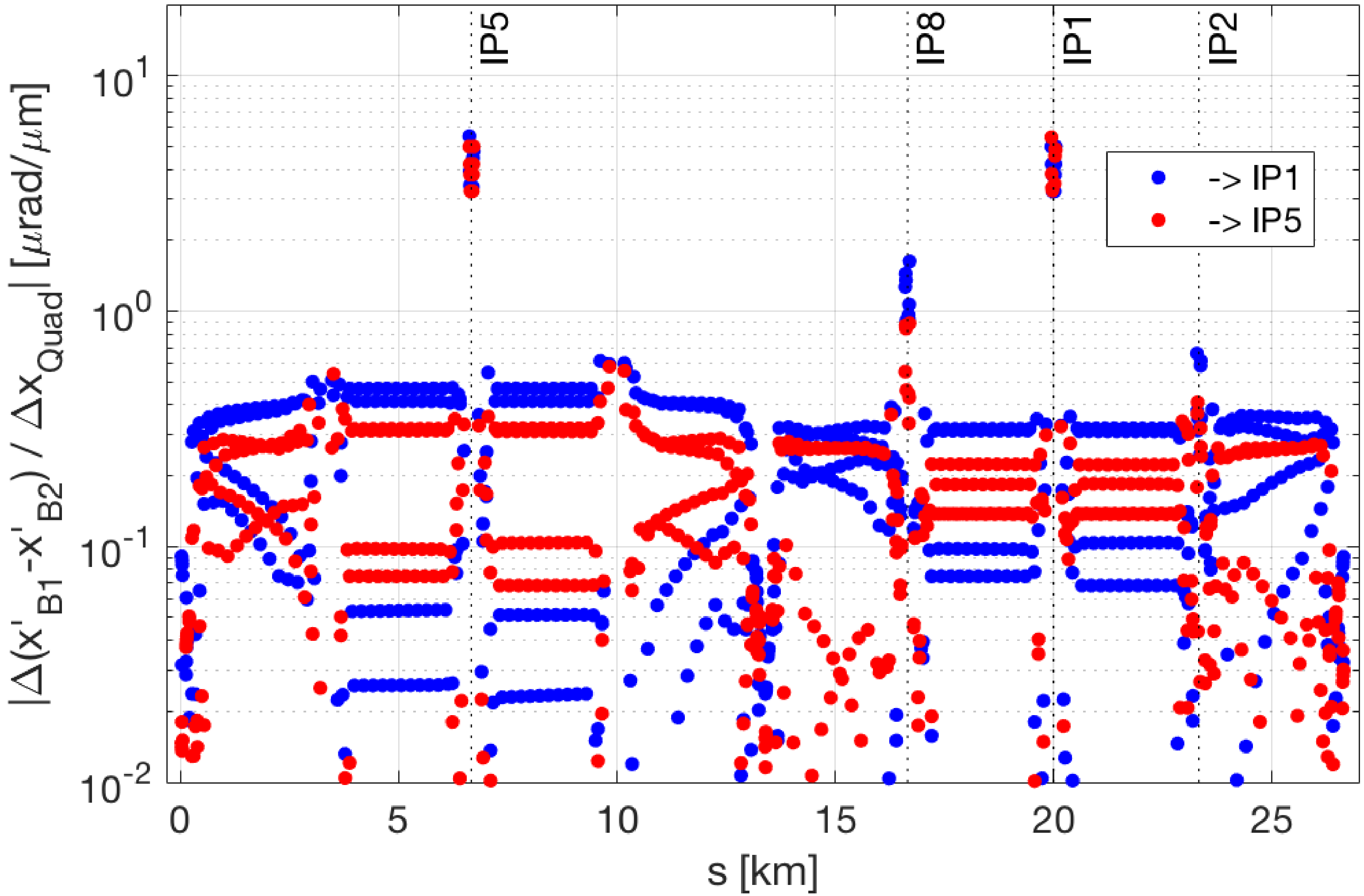


- HL-LHC up to **x2 more sensitivity** to than LHC to be expected

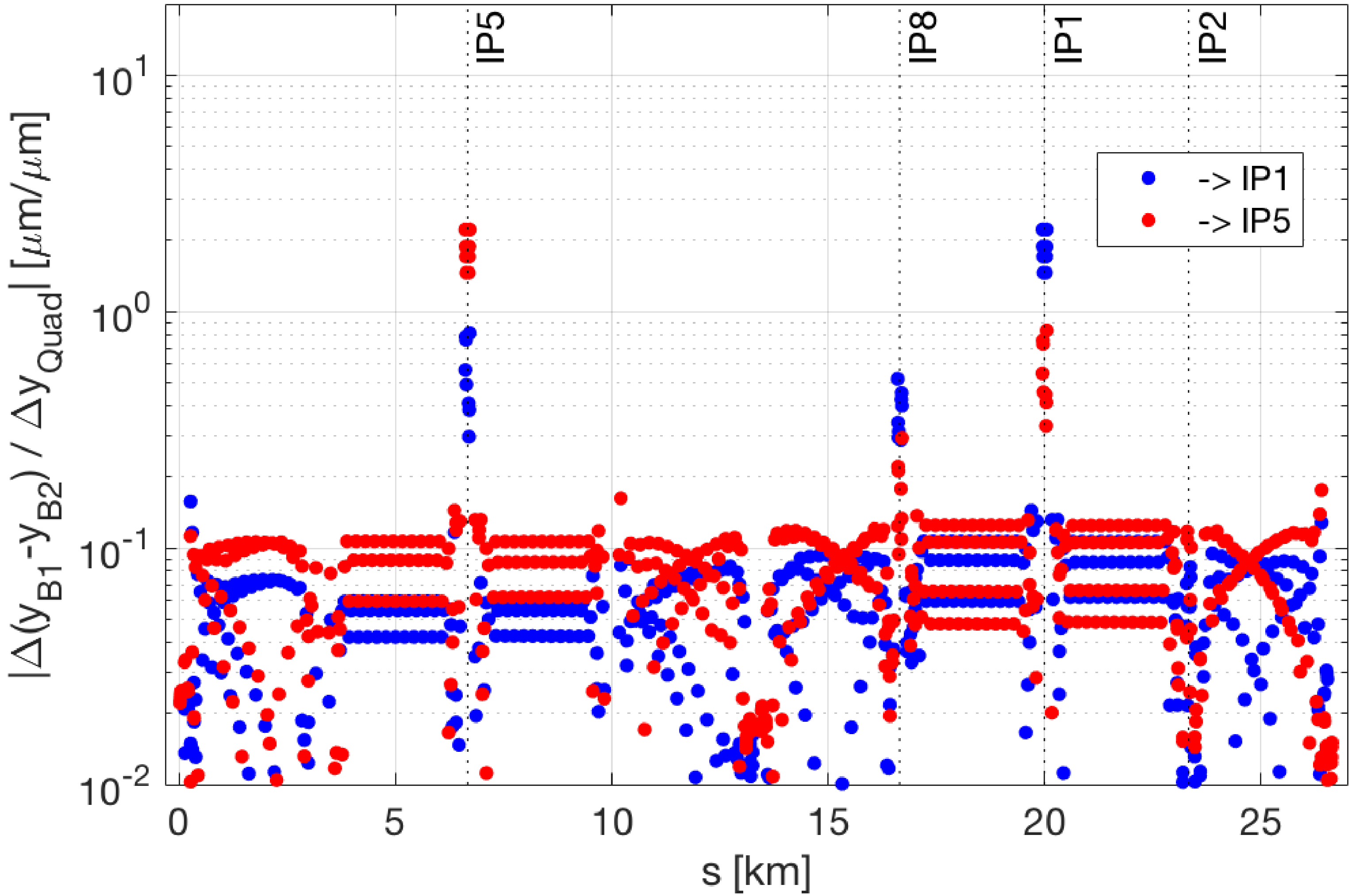
LHC: impact of misalignments on Δx



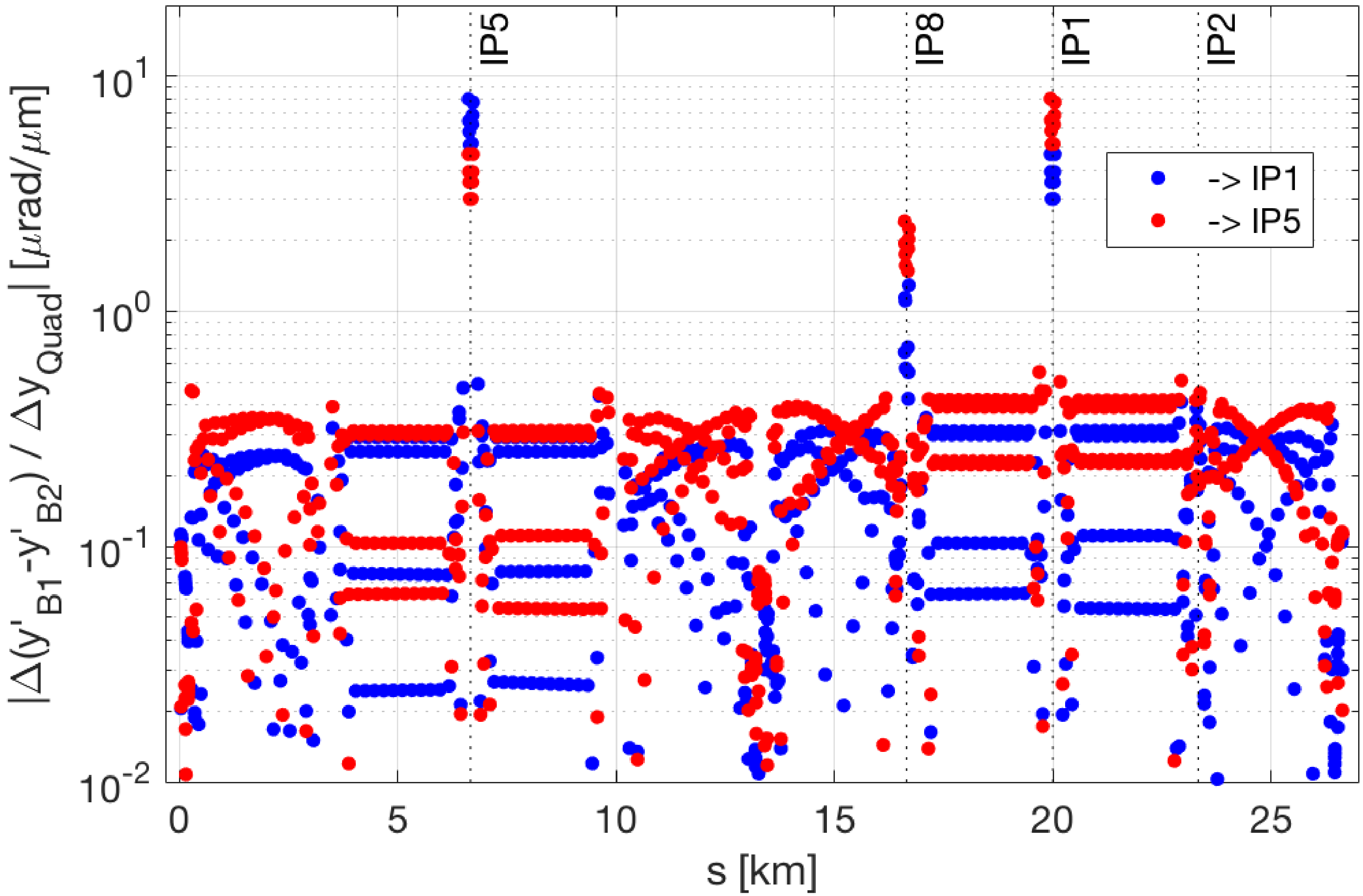
LHC: impact of misalignments on Δx’



LHC: impact of misalignments on Δy



LHC: impact of misalignments on Δy’



Luminosity

Luminosity [1]

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} W e^{\frac{B^2}{A}} S H$$

$$W = e^{-\frac{1}{4\sigma_x^2}(d_2-d_1)^2}$$

Reduction due to offset (e.g. horizontal -- x)

$$A = \frac{\sin^2(\frac{\phi}{2})}{\sigma_x^2} + \frac{\cos^2(\frac{\phi}{2})}{\sigma_s^2}$$

$$B = \frac{(d_2 - d_1)\sin(\frac{\phi}{2})}{2\sigma_x^2}$$

Reduction due to offset AND angle in the same (e.g. horizontal -- x) plane

$$S = \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_x}\tan(\frac{\phi}{2})\right)^2}}$$

Reduction due to crossing angle

$$H = \sqrt{\pi}\frac{\beta^*}{\sigma_s} e^{\left(\frac{\beta^*}{\sigma_s}\right)^2} \operatorname{erfc}\left(\frac{\beta^*}{\sigma_s}\right)$$

Reduction due to Hour Glass effect

[1] Concept of Luminosity, W. Herr and B. Muratori, (CERN-2006-002)

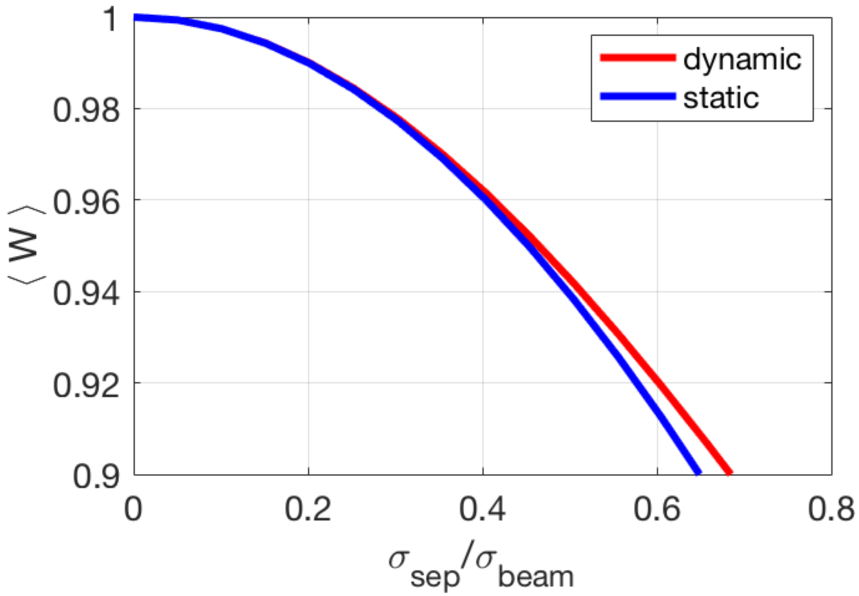
Instantaneous* luminosity reduction - offset

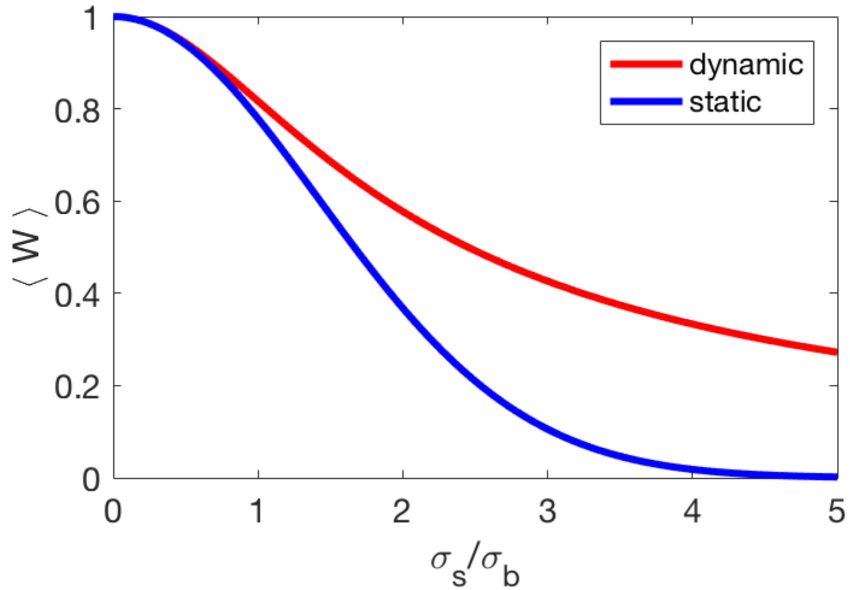
$$W = e^{-\frac{1}{4\sigma_x^2}(d_2 - d_1)^2}$$

Factor due to "static" orbit separation (d_2-d_1)

$$\langle W \rangle = \frac{\sqrt{2}}{\sqrt{\sigma_d^2/\sigma_b^2 + 2}}$$

Factor due to "dynamic" orbit separation σ_d i.e. assuming beam separation is oscillating around zero.





=> Static ≈ dynamic for small amplitudes

* Instantaneous compared to LHC fill, integrated compared to revolution frequency

Luminosity reduction factors

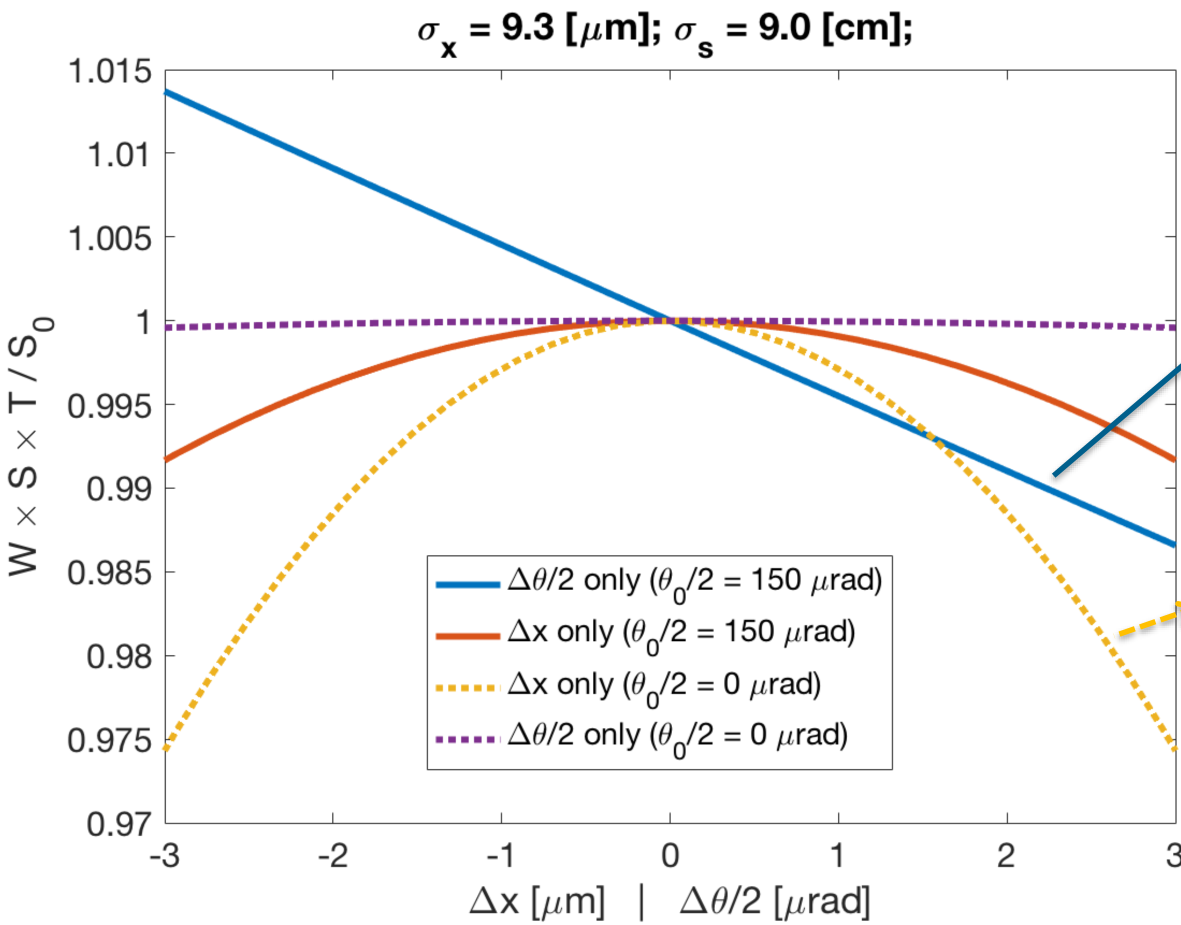
	LHC (Design Report) [1]	LHC (Actual) [2]	HL-LHC [2]
Norm. Emit. [um]	3.75	2	2.5
Energy TeV	7	6.5	7
Bunch length rms [cm]	7.55	9	9
Beta* [m]	0.55	0.3 to 0.25	0.64 to 0.15
Half Cros. angle [urad]	142.5	150 to 130	250 **(0 with full CC)**
S (crossing)	**0.84**	**0.57 to 0.59**	**0.55 to 0.30 (1 with full CC)**
H (hour glass)	**0.99**	**0.95 to 0.95**	**0.99 to 0.88**

- Note: in **HL-LHC** with **full crabbing** it would be as **head-on collision**.
  - In reality we will have 60 [urad] residual half crossing angle.

[1] LHC Design Report – EDMS 445830
[2] Update of the HL-LHC op. scenarios for proton op. - CERN-ACC-NOTE-2018-0002

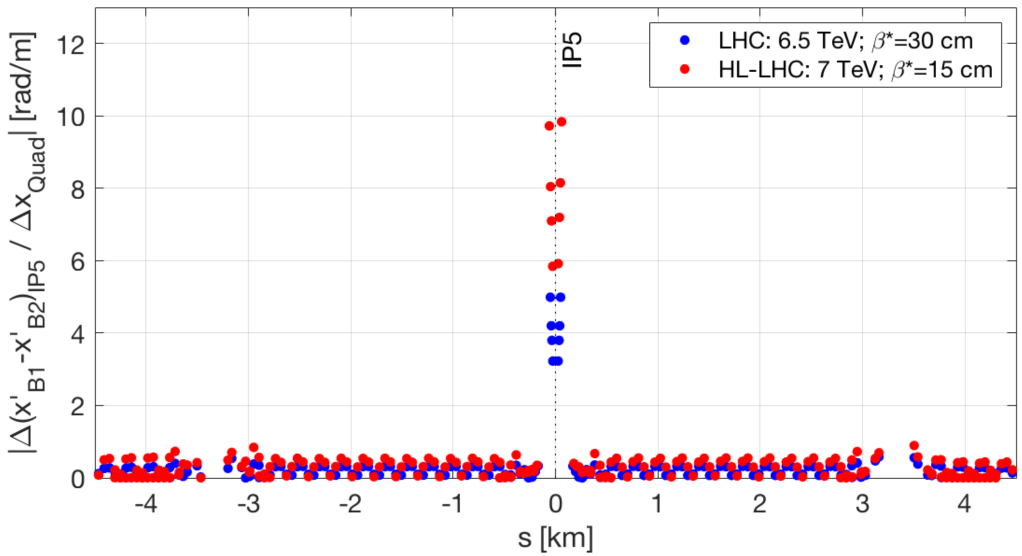
Luminosity reduction factors - imperfections

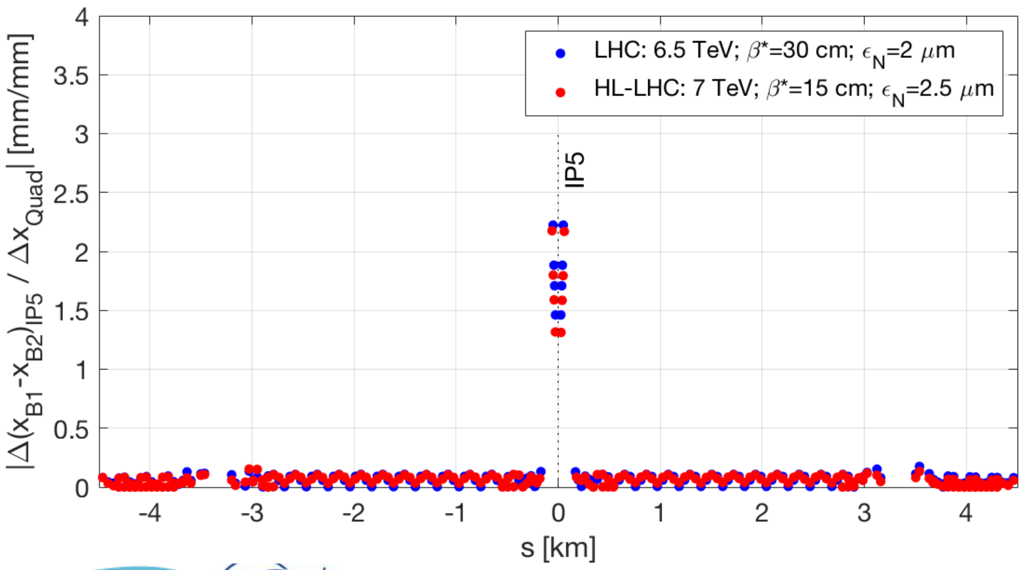
- Case of LHC (ε_N = 2 µm; 6.5 TeV; β* = 30 cm)



- Assuming similar impact on orbit and **half** cros. angle, i.e.: **~0.1 σ_x ≈ 1 µm ≈ 1 µrad**
- **Crossing plane** dominated by **angle variation**
  - can increase inst. luminosity
  - on average, no luminosity loss in case of oscillation
  - **valid for small Δθ/2**, otherwise the separation contribution becomes relevant…
- **Separation plane** dominated by **orbit separation**
  - Basically unaffected by residual Δθ/2

Luminosity reduction factors - imperfections

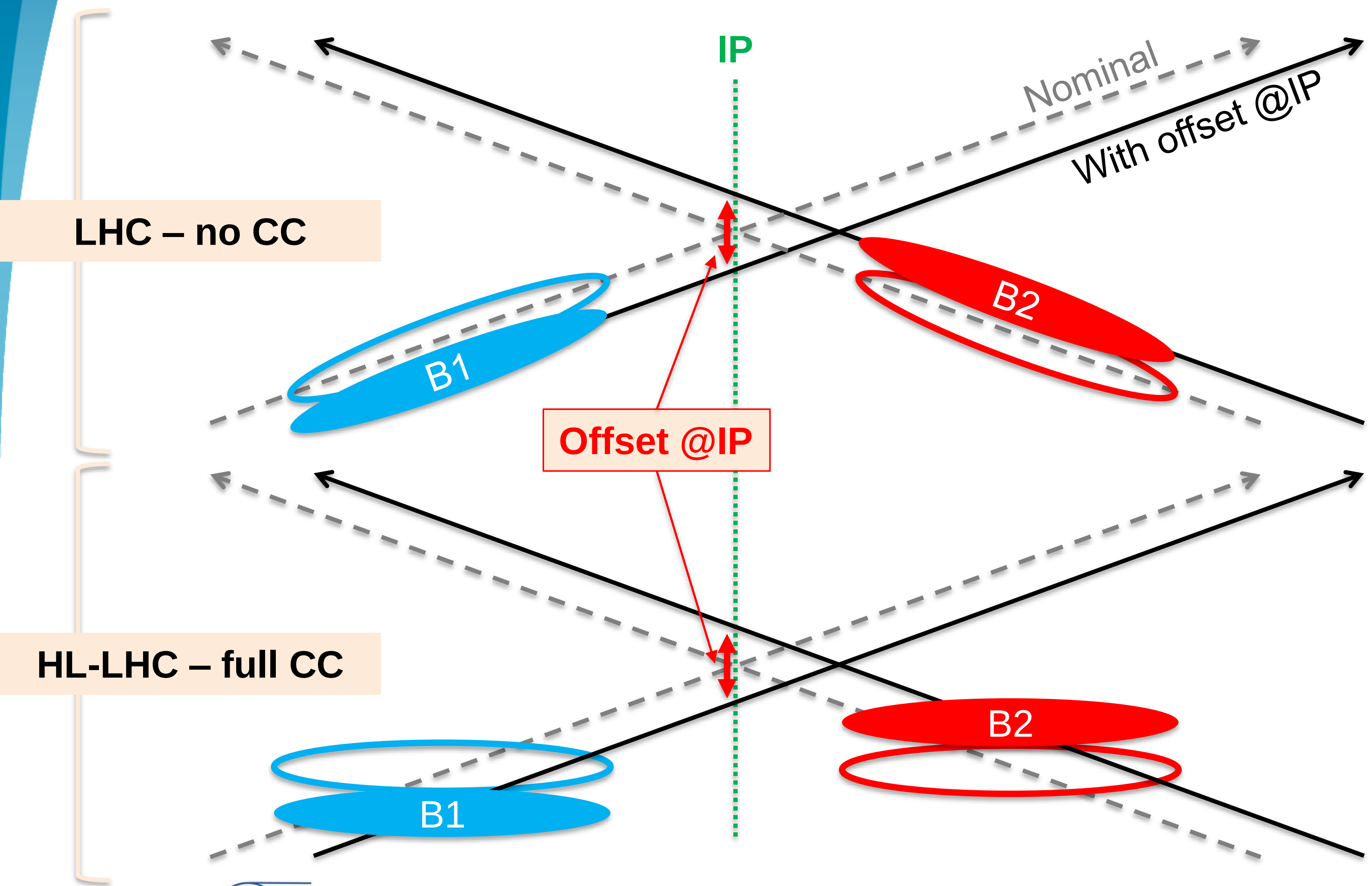




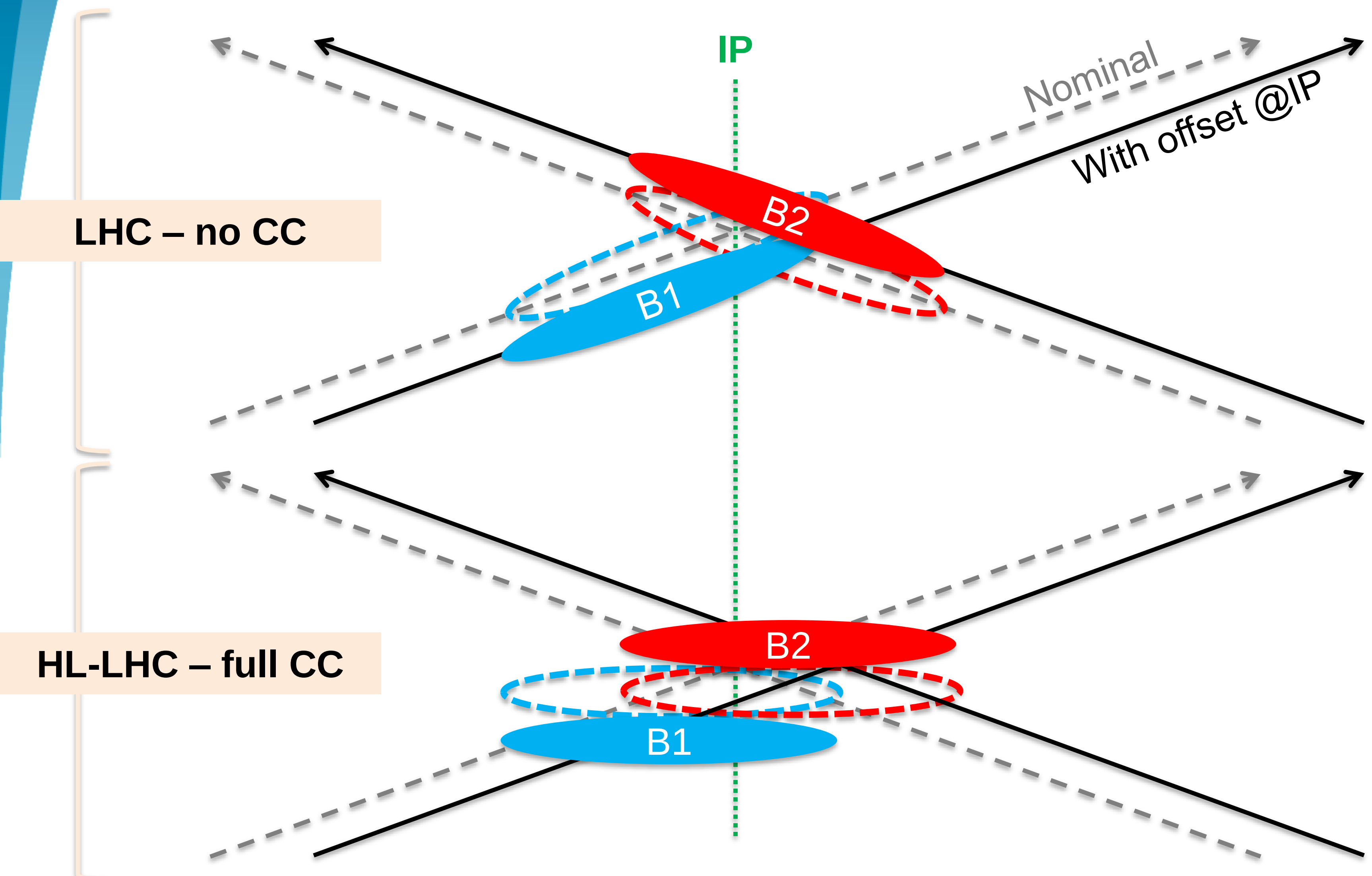
NOTE:

- The impact of each 1 um displacement of each triplet element on **total crossing angle** variation is of the order of **4 urad in LHC** and **8 urad in HL-LHC**
- The impact on **total orbit separation** is of the order of 2 um for both LHC and HL-LHC

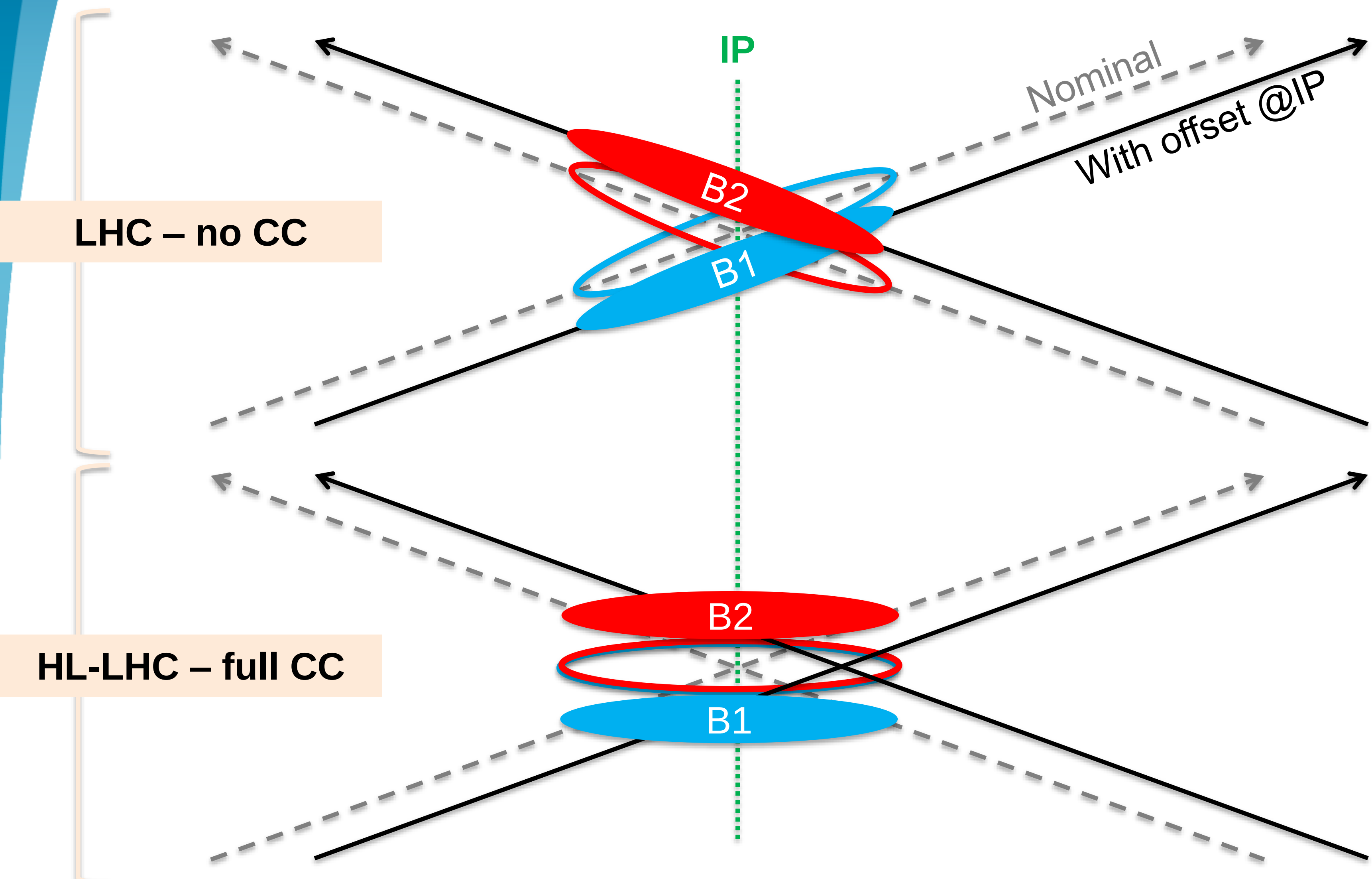
Luminosity with offset in crossing plane



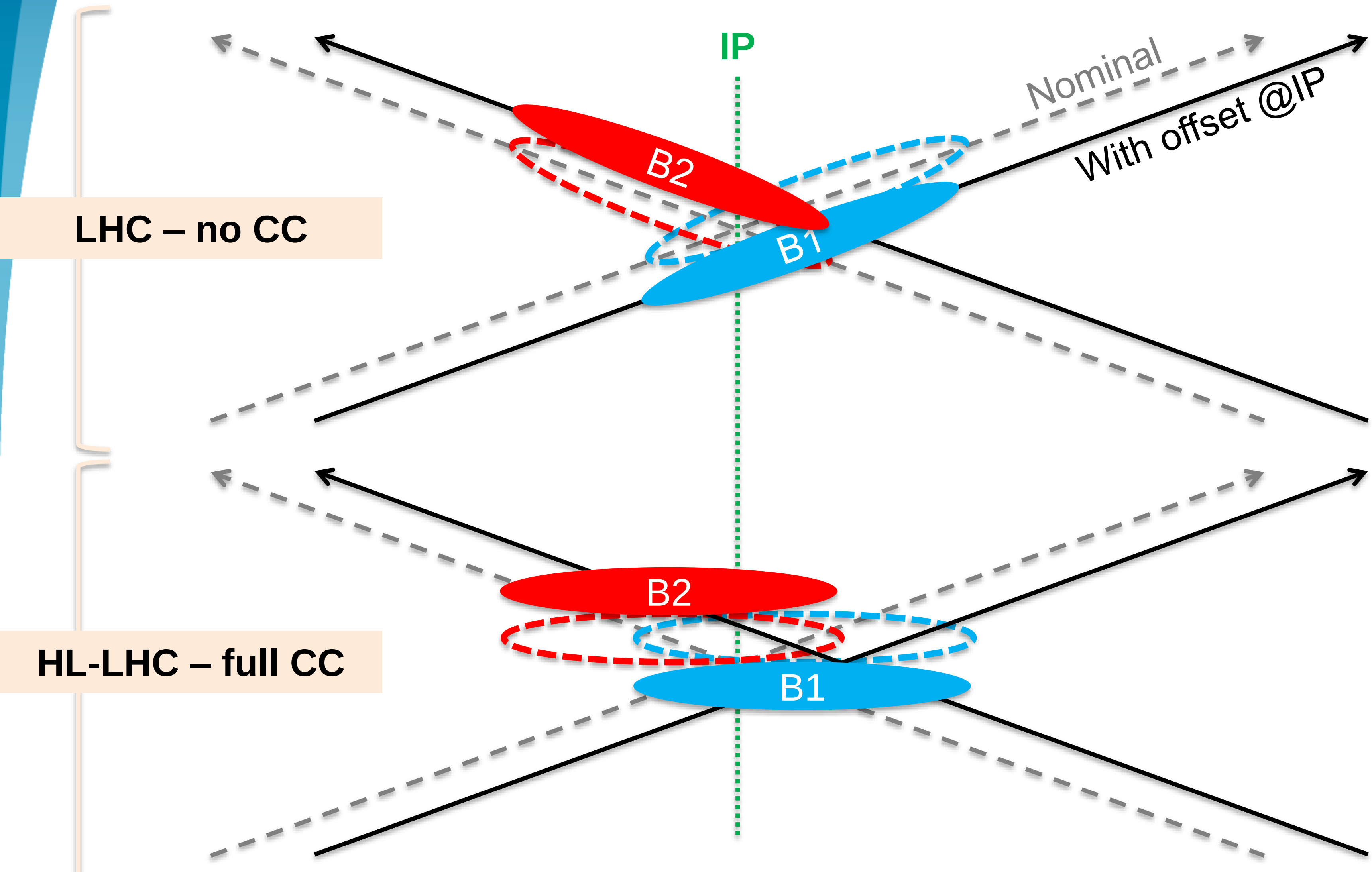
Luminosity with offset in crossing plane



Luminosity with offset in crossing plane



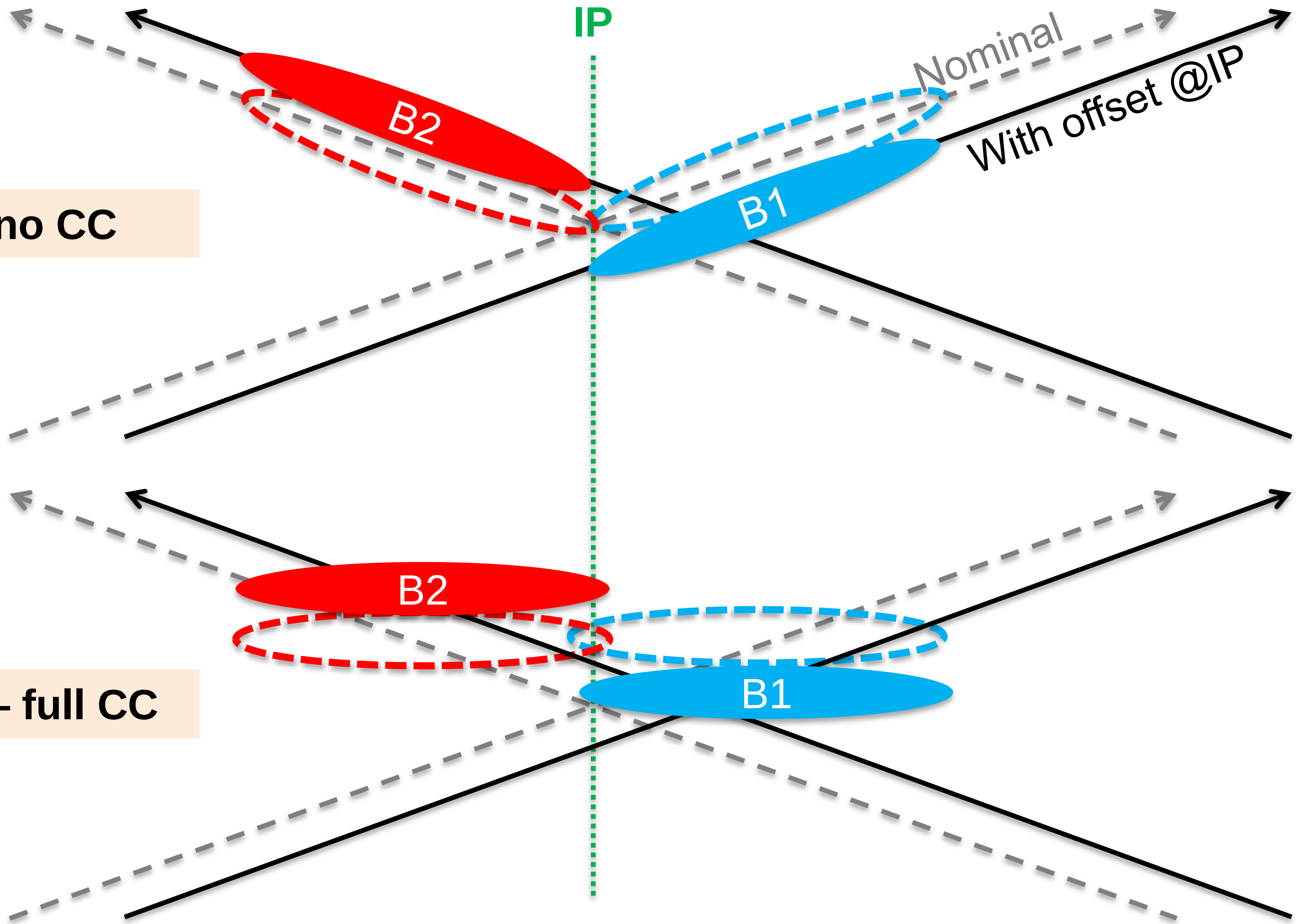
Luminosity with offset in crossing plane



Luminosity with offset in crossing plane

LHC – no CC

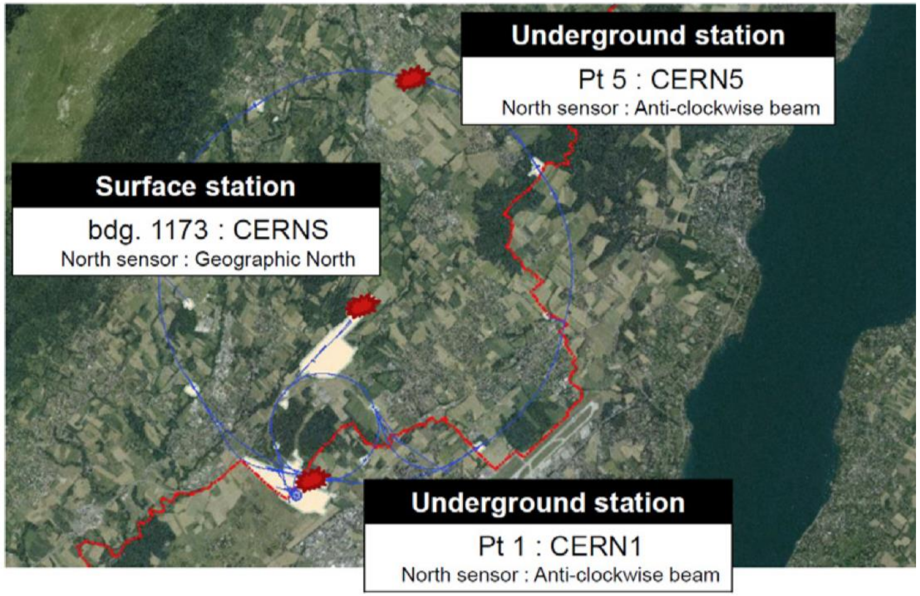
HL-LHC – full CC

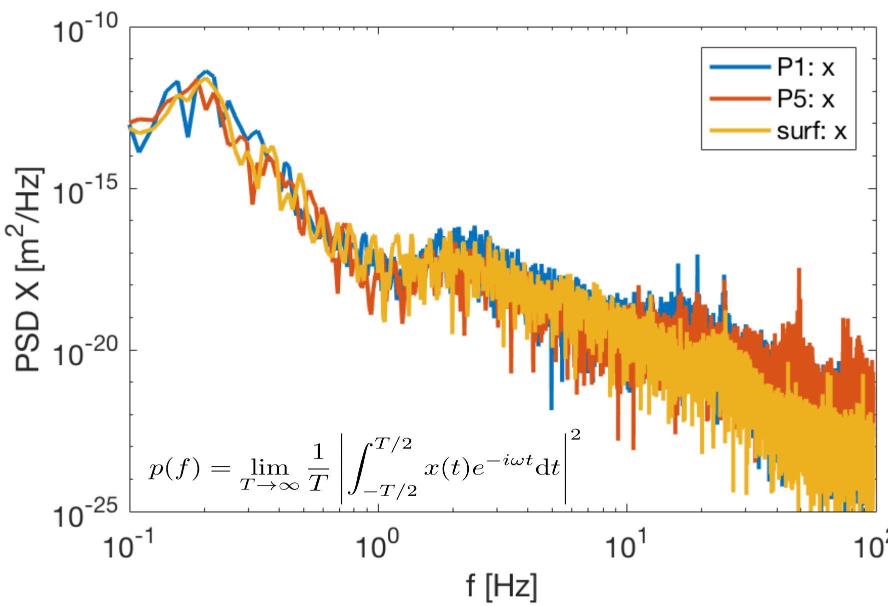


Ground motion sensors

Ground motion observations in LHC

- Geophones are logging data since 2017
- Data logged into Timber in the form of PSD





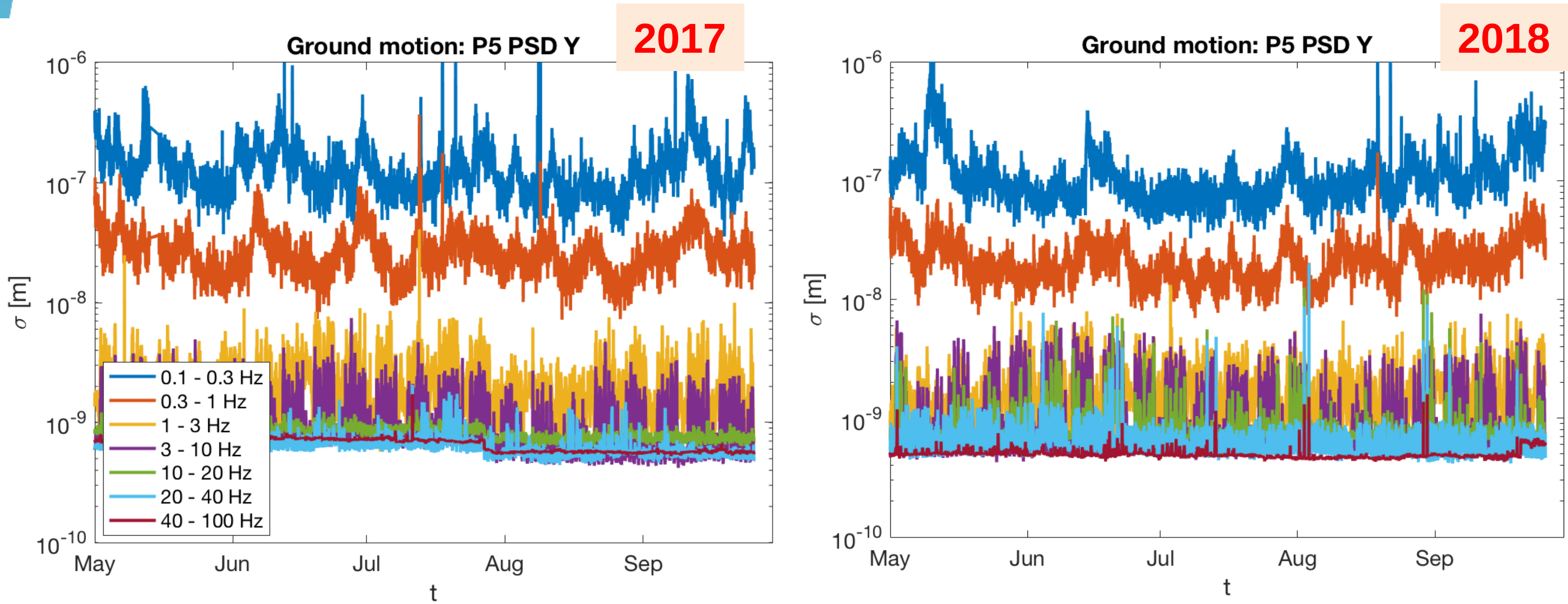
- 15 May 2018: Official start of HL-LHC excavation works.
  - 2018 run is the occasion to see perturbation on the beam due to ground motion
  - It could allow us to see if our expectations for HL-LHC are correct.

M. Guinchard, Oct. 2017 link

Integrated PSD: 2017 vs 2018 (P5)

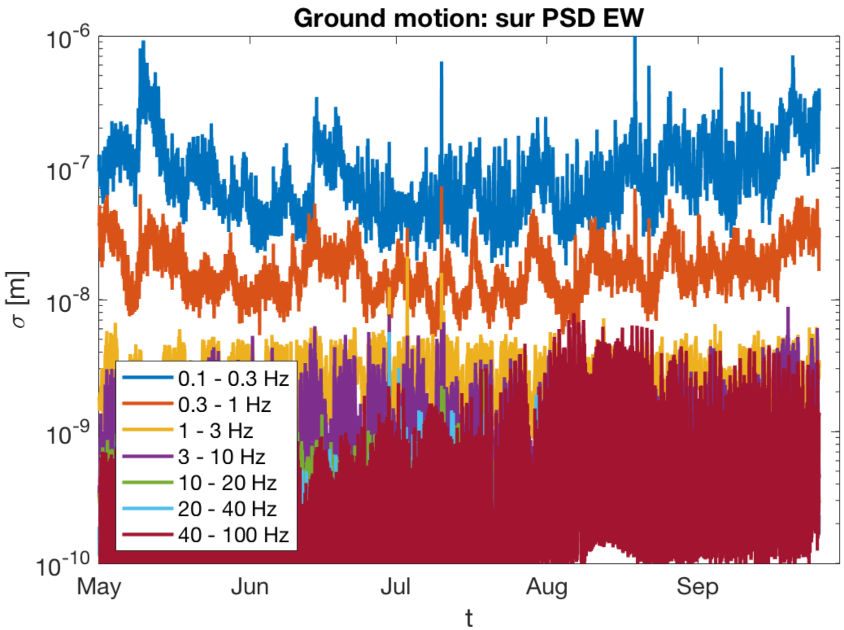
- **PSDs integrated over range of frequencies**
  - Gives measured rms motion in that band

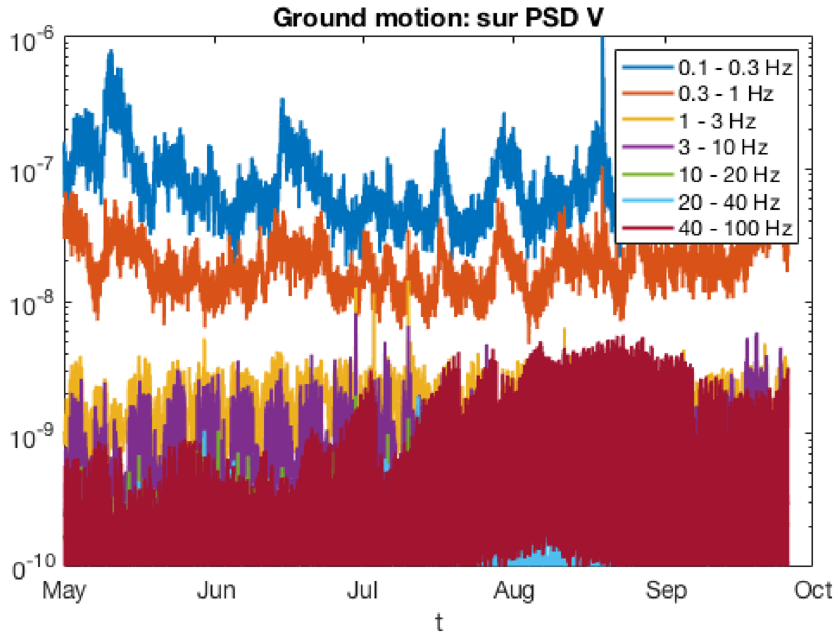
$$\sigma^2(f_0 < f < f_1) = \int_{f_0}^{f_1} p(f)\mathrm{d}f$$

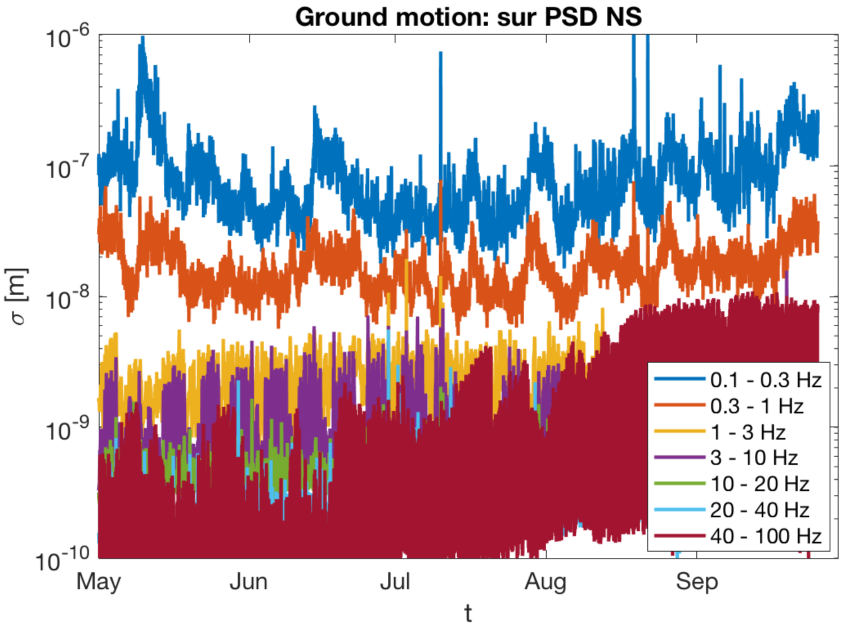


- Possible to see **human activity** in band **3-10Hz** and **above**
- Some **higher activity** starting in **Oct. 2017**
- **No obvious sign** of **civil engineering** works started in **May 2018**

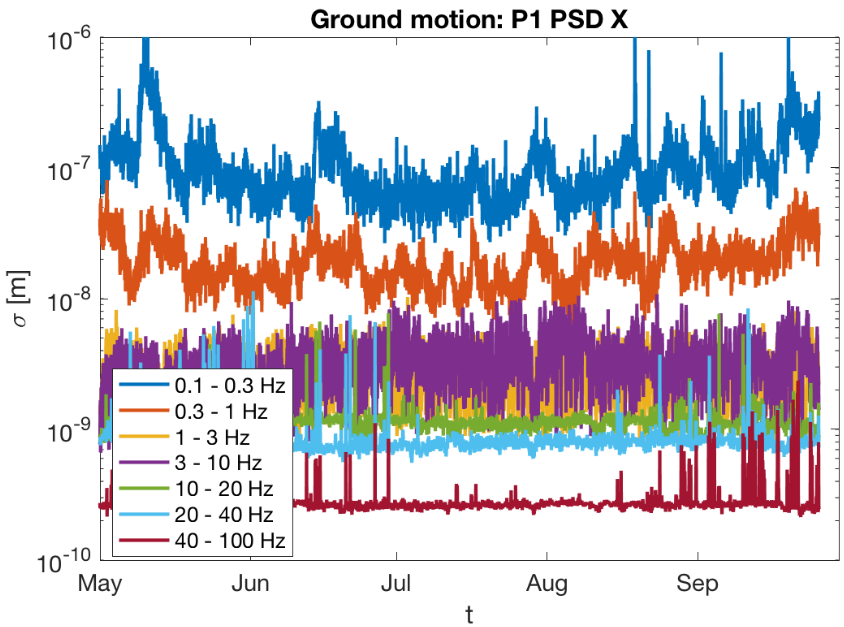
2018 Surface



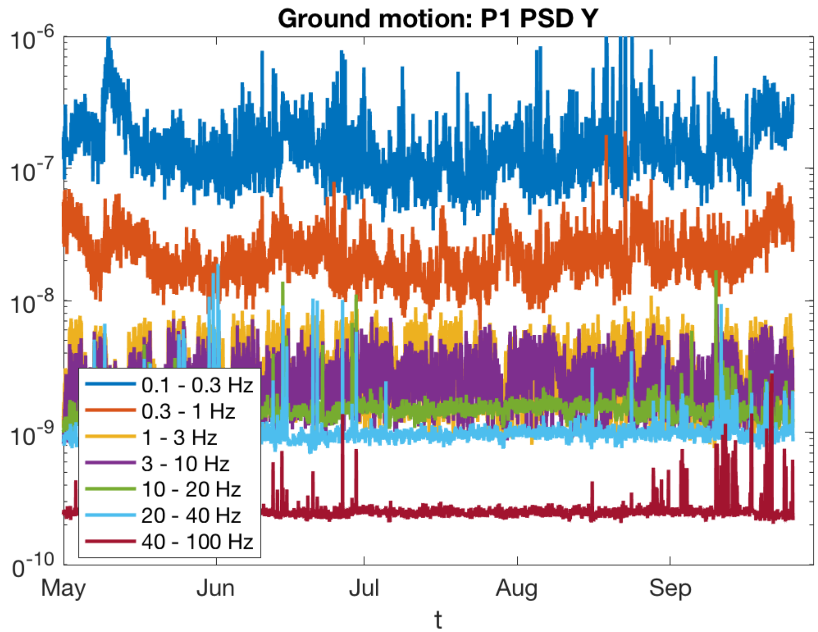




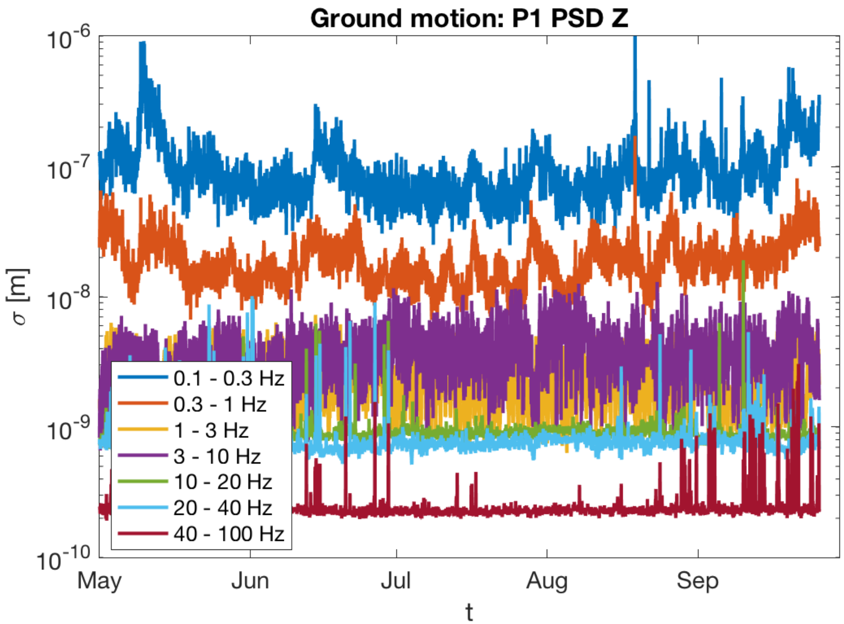
2018 P1



Ground motion: P1 PSD X
σ [m]
10^-6
10^-7
10^-8
10^-9
10^-10
May
Jun
Jul
Aug
Sep
t
0.1 - 0.3 Hz
0.3 - 1 Hz
1 - 3 Hz
3 - 10 Hz
10 - 20 Hz
20 - 40 Hz
40 - 100 Hz

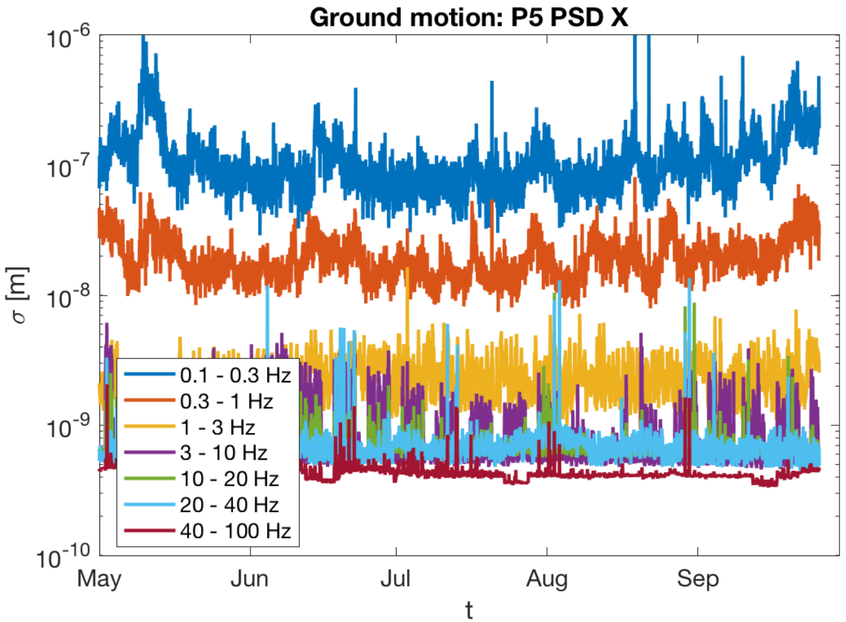


Ground motion: P1 PSD Y
10^-6
10^-7
10^-8
10^-9
0^-10
May
Jun
Jul
Aug
Sep
t
0.1 - 0.3 Hz
0.3 - 1 Hz
1 - 3 Hz
3 - 10 Hz
10 - 20 Hz
20 - 40 Hz
40 - 100 Hz

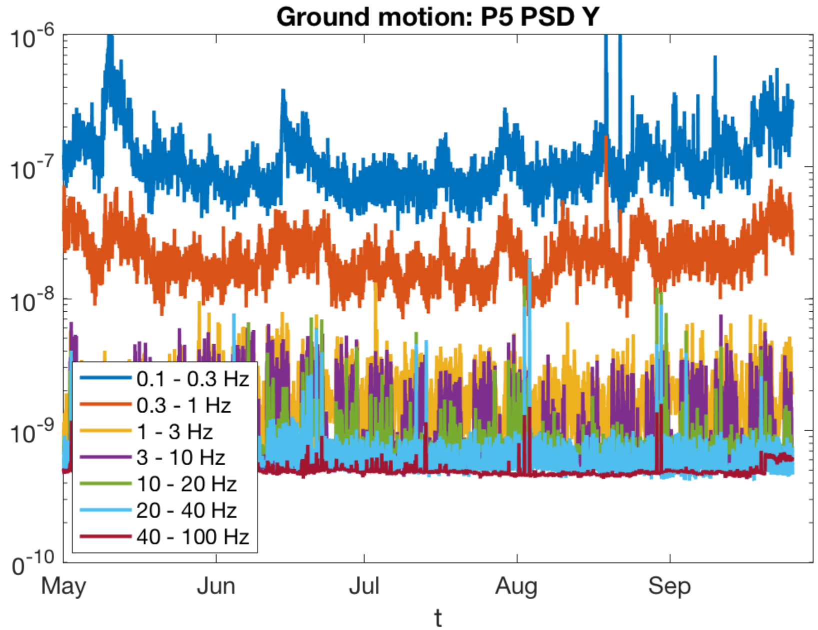


Ground motion: P1 PSD Z
σ [m]
10^-6
10^-7
10^-8
10^-9
10^-10
May
Jun
Jul
Aug
Sep
t
0.1 - 0.3 Hz
0.3 - 1 Hz
1 - 3 Hz
3 - 10 Hz
10 - 20 Hz
20 - 40 Hz
40 - 100 Hz

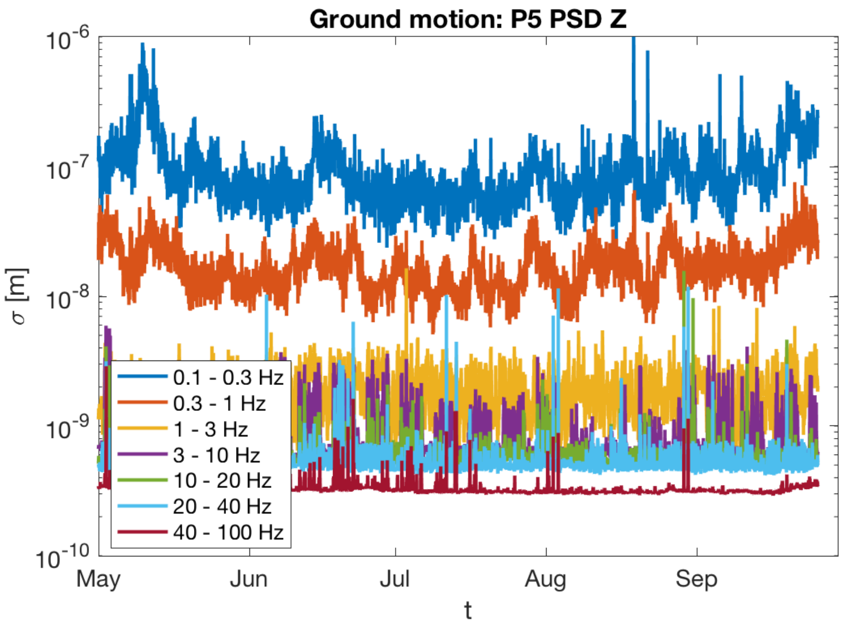
2018 P5



Ground motion: P5 PSD X
10^-6
10^-7
10^-8
10^-9
10^-10
σ [m]
0.1 - 0.3 Hz
0.3 - 1 Hz
1 - 3 Hz
3 - 10 Hz
10 - 20 Hz
20 - 40 Hz
40 - 100 Hz
May
Jun
Jul
Aug
Sep
t



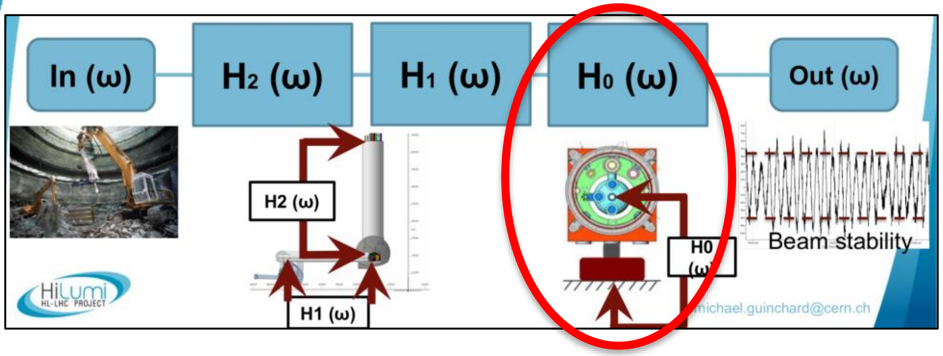
Ground motion: P5 PSD Y
10^-6
10^-7
10^-8
10^-9
0^-10
0.1 - 0.3 Hz
0.3 - 1 Hz
1 - 3 Hz
3 - 10 Hz
10 - 20 Hz
20 - 40 Hz
40 - 100 Hz
May
Jun
Jul
Aug
Sep
t



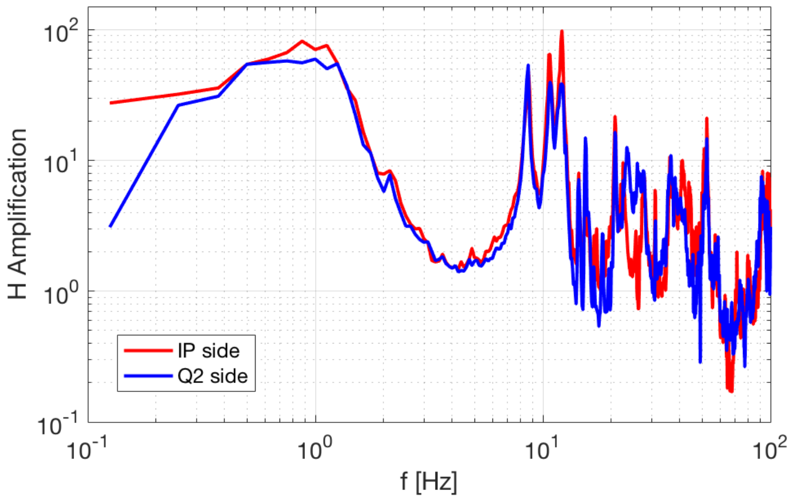
Ground motion: P5 PSD Z
10^-6
10^-7
10^-8
10^-9
10^-10
σ [m]
0.1 - 0.3 Hz
0.3 - 1 Hz
1 - 3 Hz
3 - 10 Hz
10 - 20 Hz
20 - 40 Hz
40 - 100 Hz
May
Jun
Jul
Aug
Sep
t

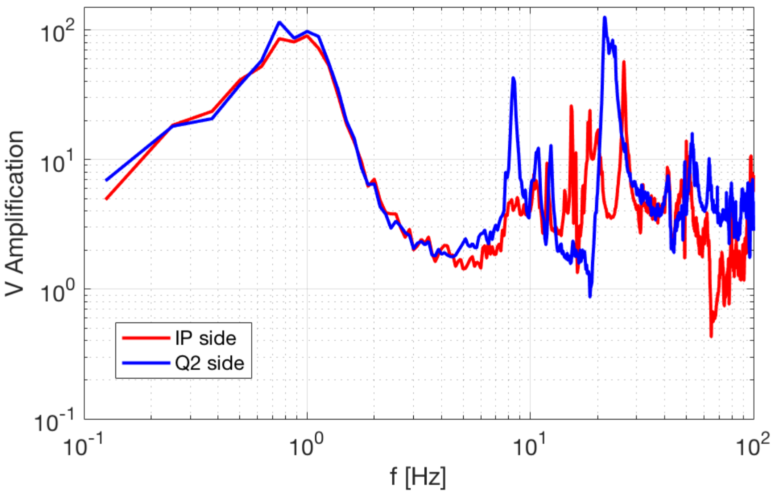
Triplet amplification

Amplification of LHC Q1 assembly



- **Measured** on Q1 spare assembly in SM18 in preparation of civil engineering works
  - See for example M. Guinchard, Oct 2017, link

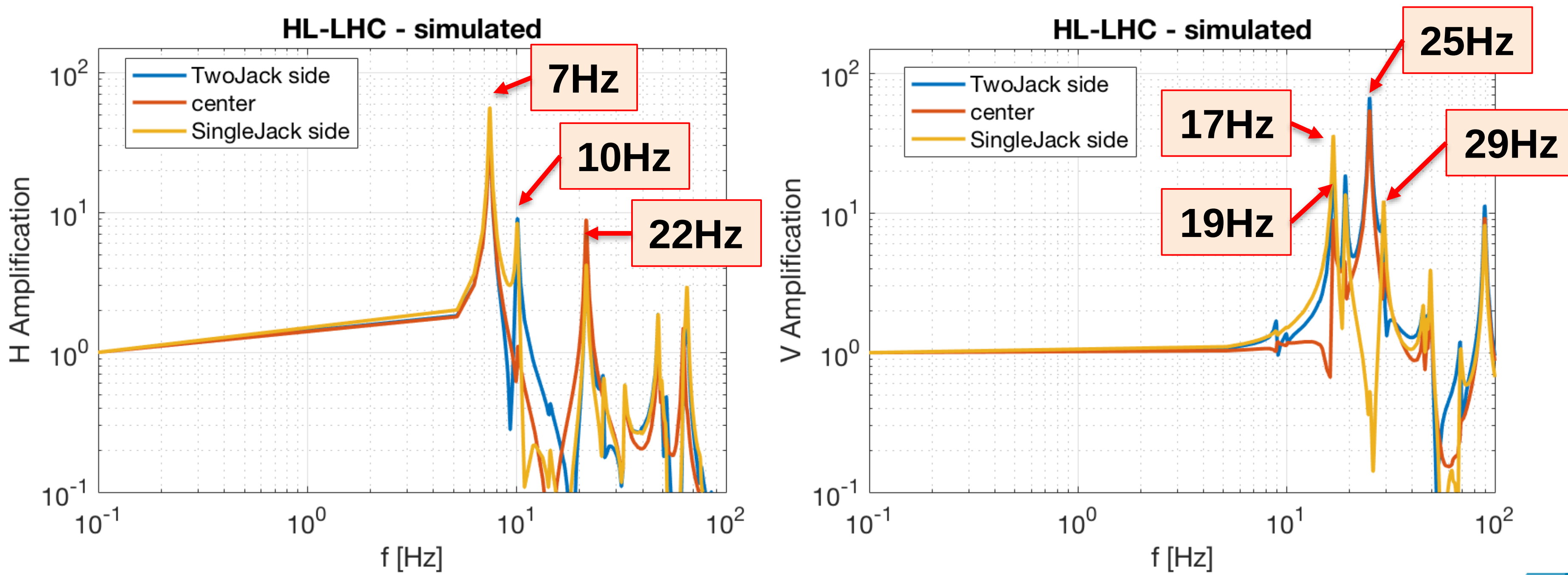




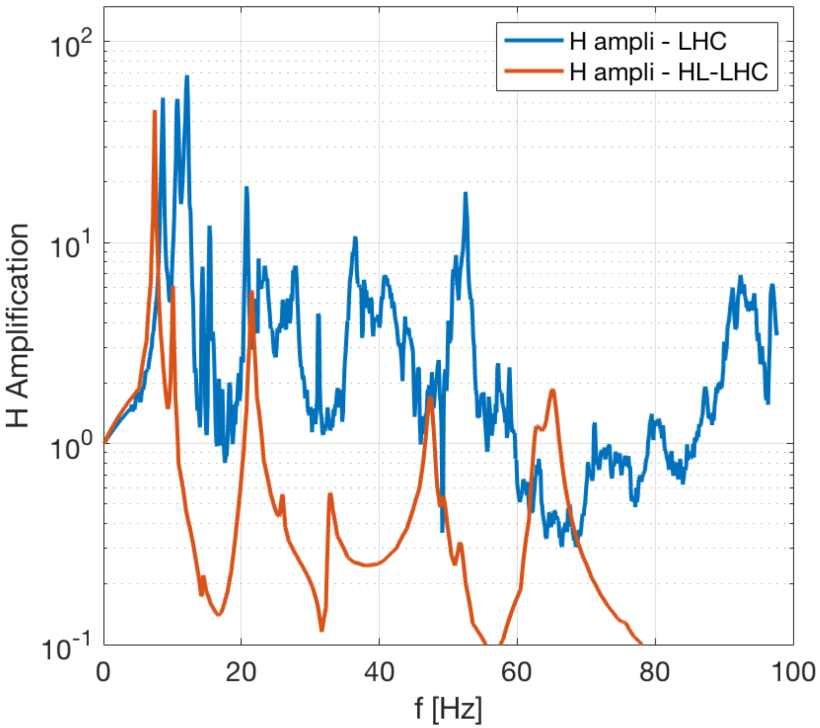
- **Only "valid" for f > 3 Hz**
  - Response below 3 Hz is unknown.
  - **Most likely flat close to 1**

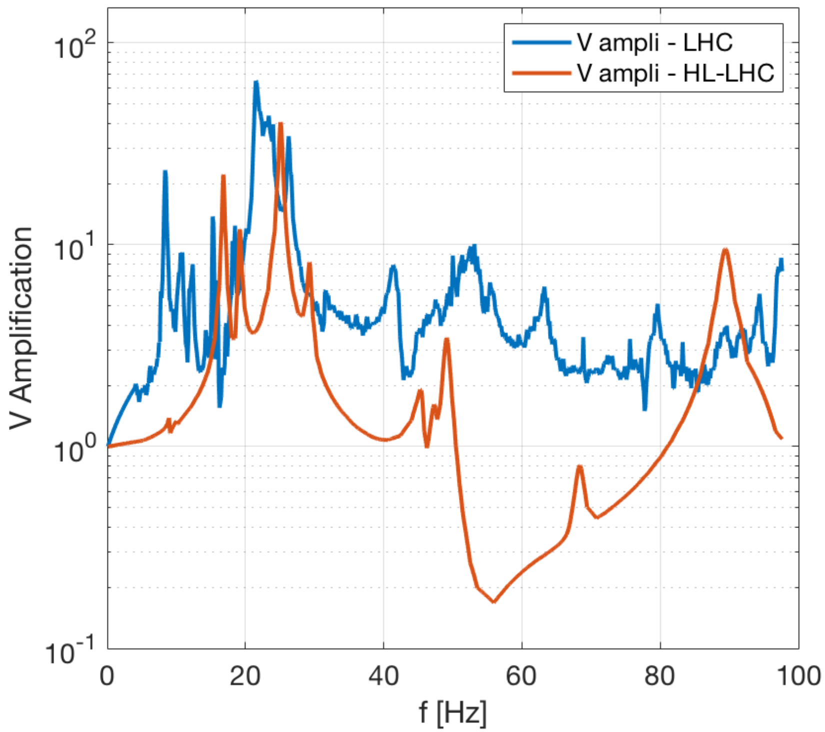
Amplification of HL-LHC triplet quadrupole

- Simplified **model** by **D. Ramos** and **M. Martos**
- Strongly depends on dumping factor assumed in the model. Here a "pessimistic" 1% dumping.
  - **To be crosschecked** with measurement on a LHC dipole (mechanically very similar to new triplets) and on first prototype.



Assumed amplification functions



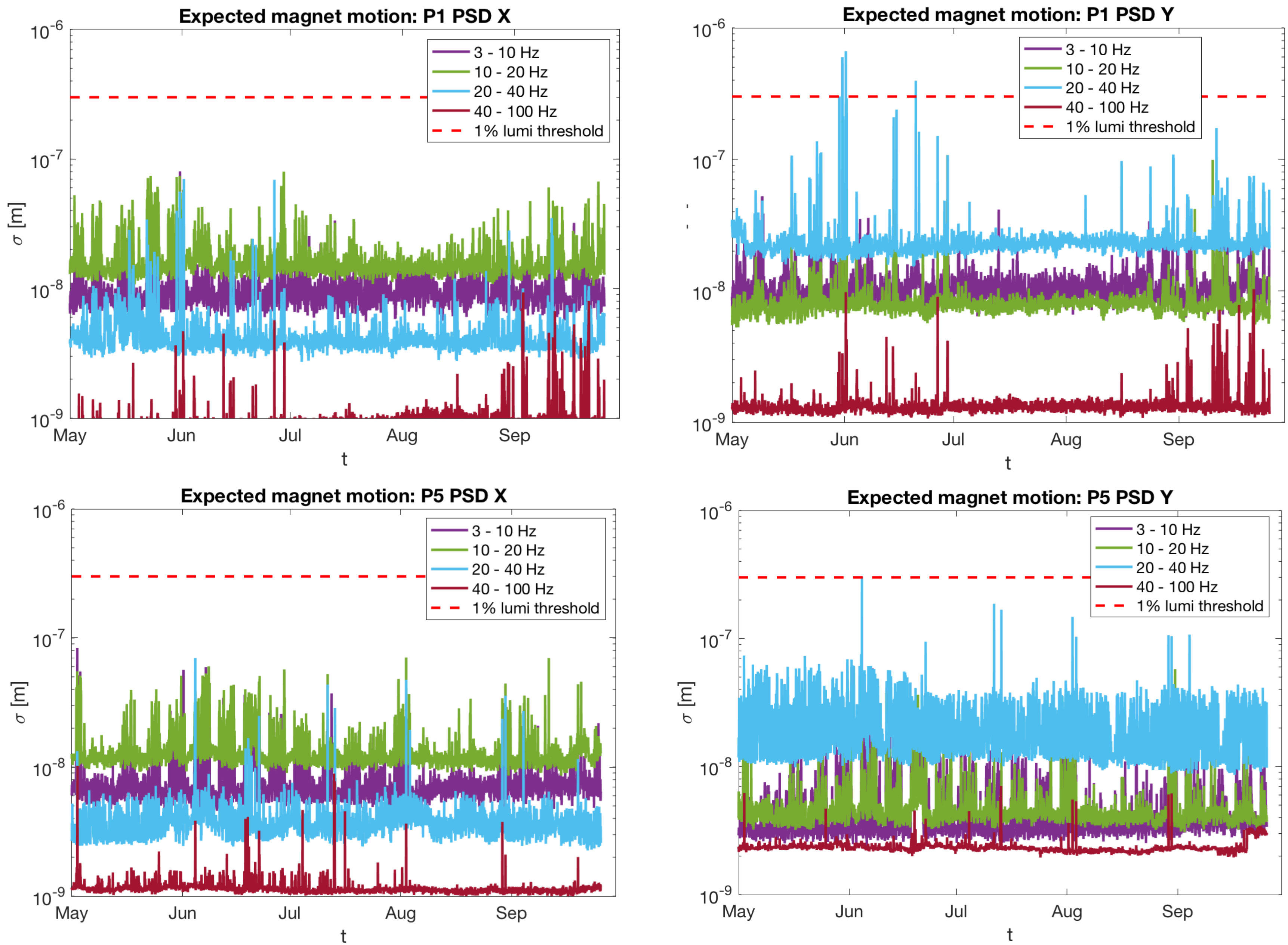


- **LHC: measured** on Q1 spare assembly in SM18 (M. Guinchard, Oct 2017, link)
- **HL-LHC: simulated** by **D. Ramos** and **M. Martos**

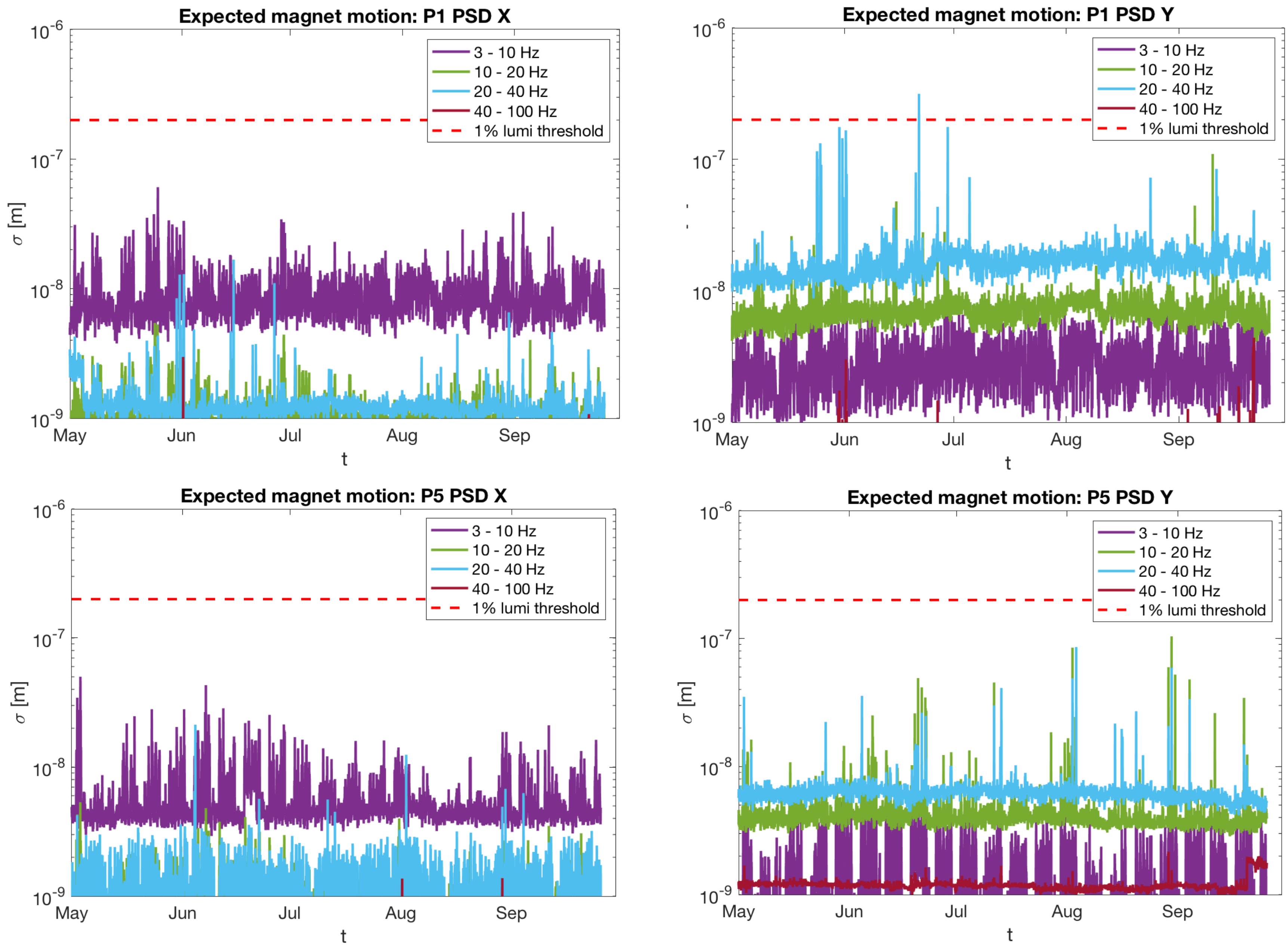
- All **computed** as **mean over different point measured/simulated.**

Ground motion in 2018 – LHC vs HL-LHC

2018 P1/P5 Amplified - LHC



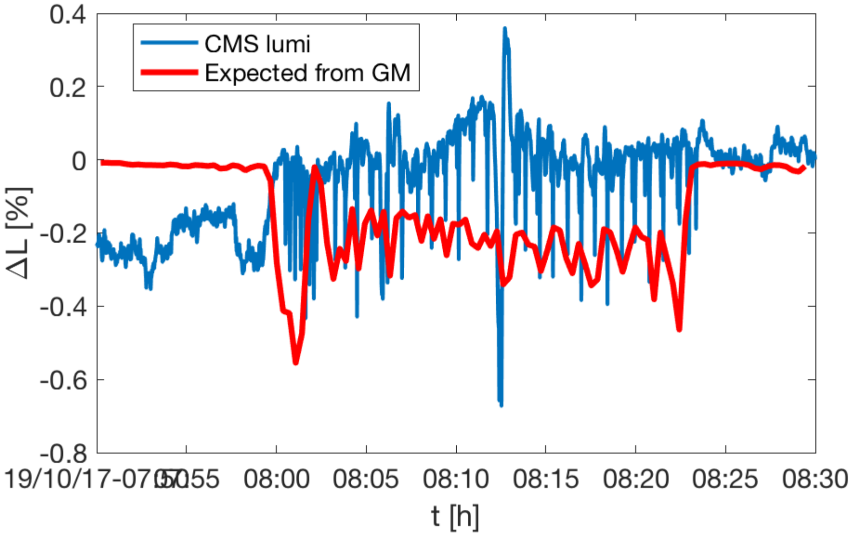
2018 P1/P5 Amplified – HL-LHC

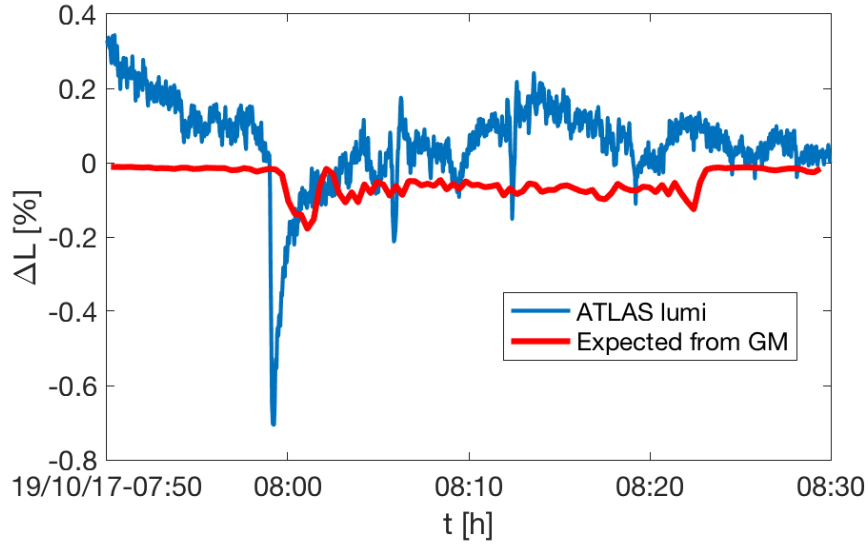


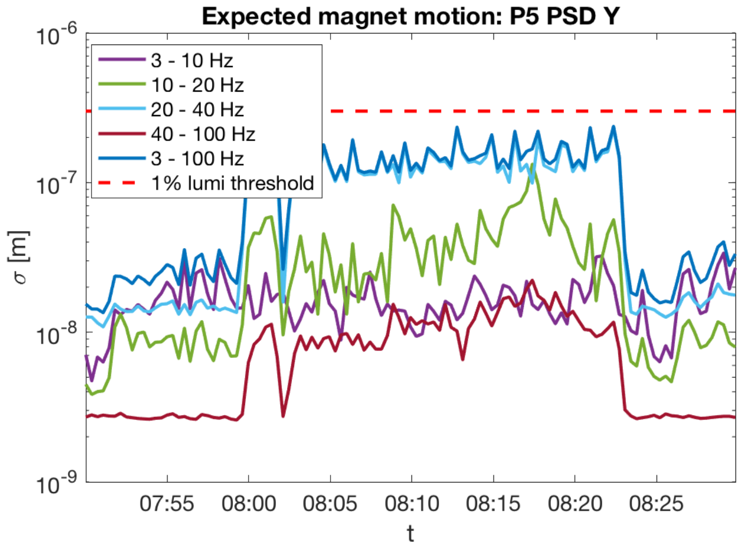
Fills analysis

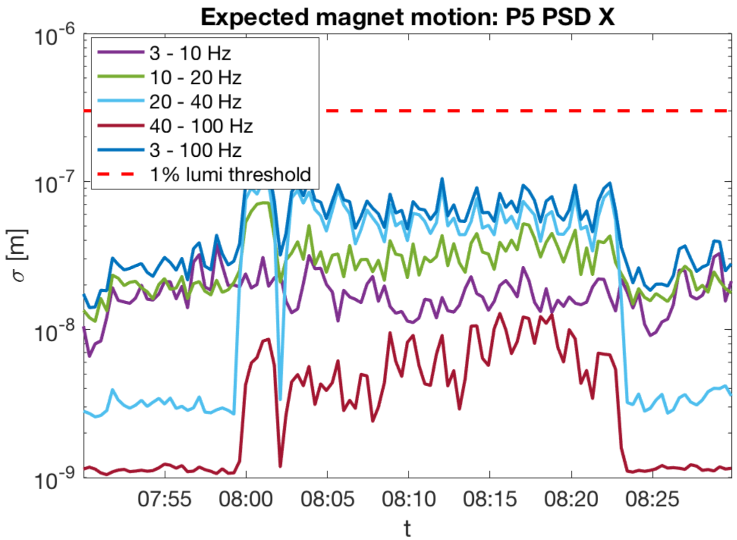
Fill 6308

Fill 6308 (t ≈ 8) impact on luminosity

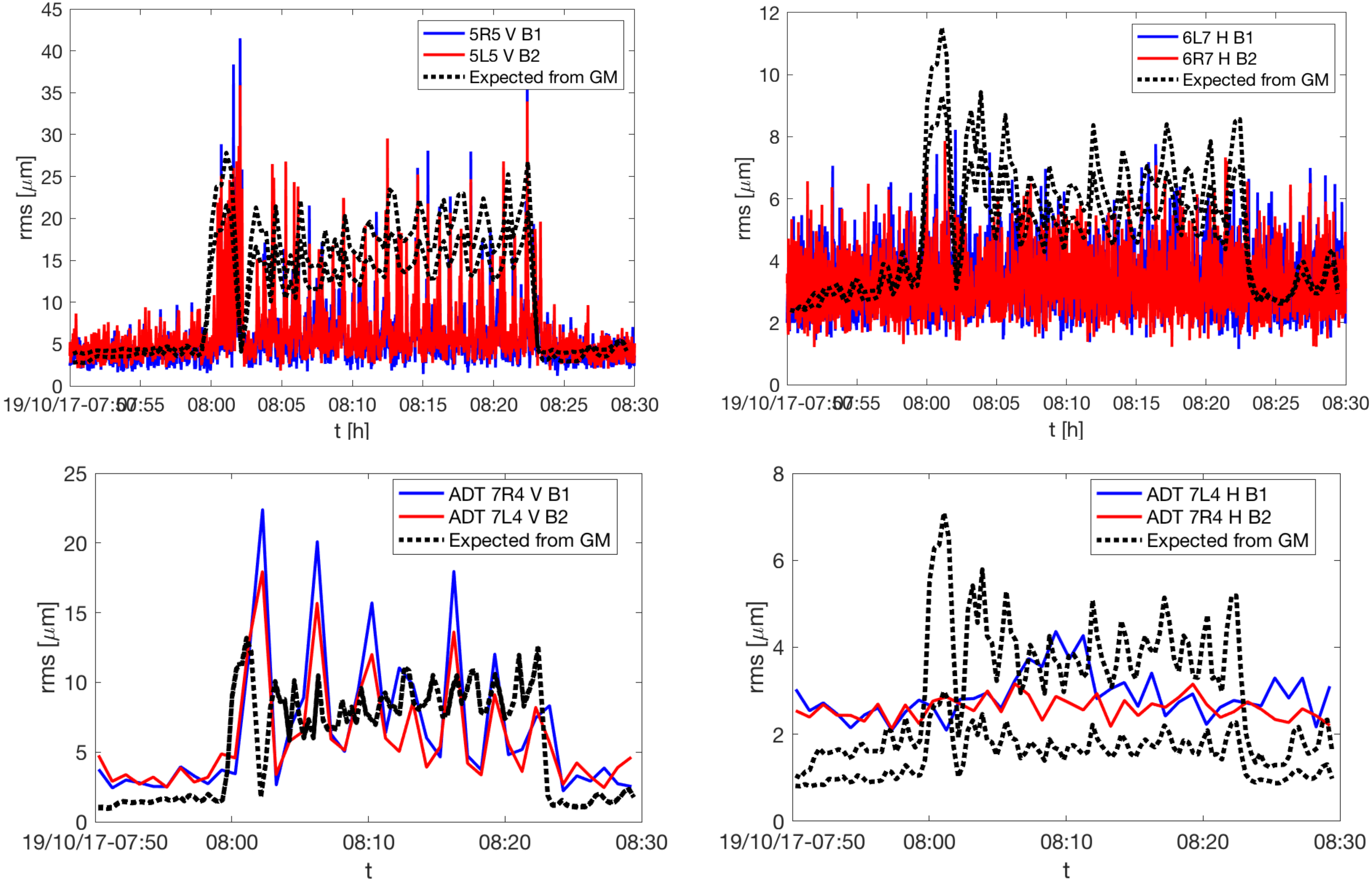




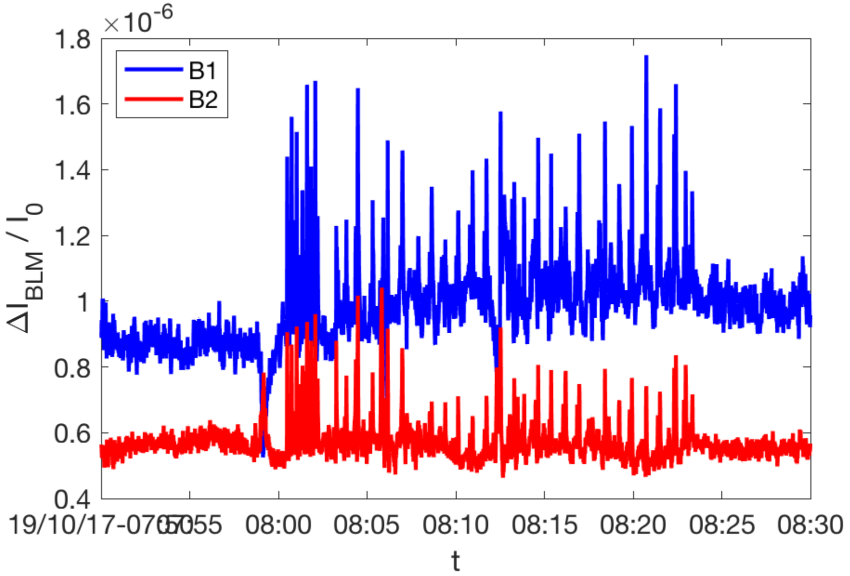


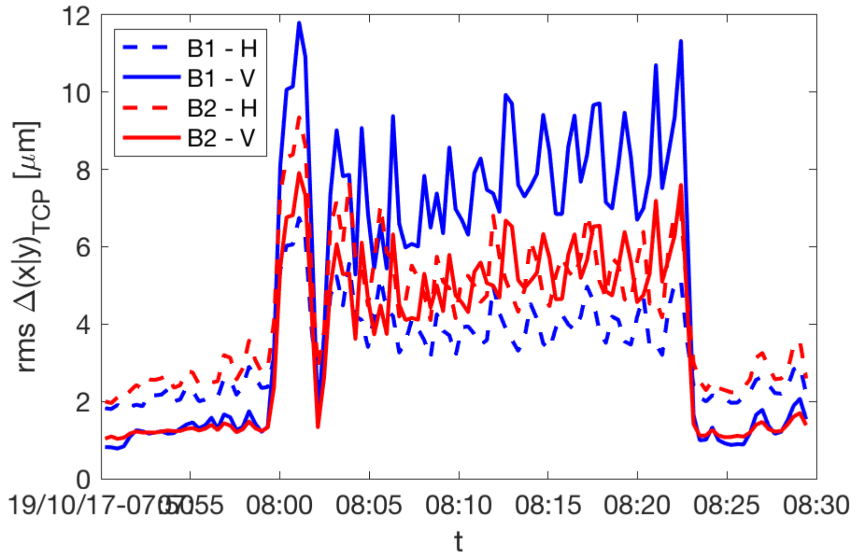


Fill 6308 (t ≈ 8) impact on orbit @BPMs



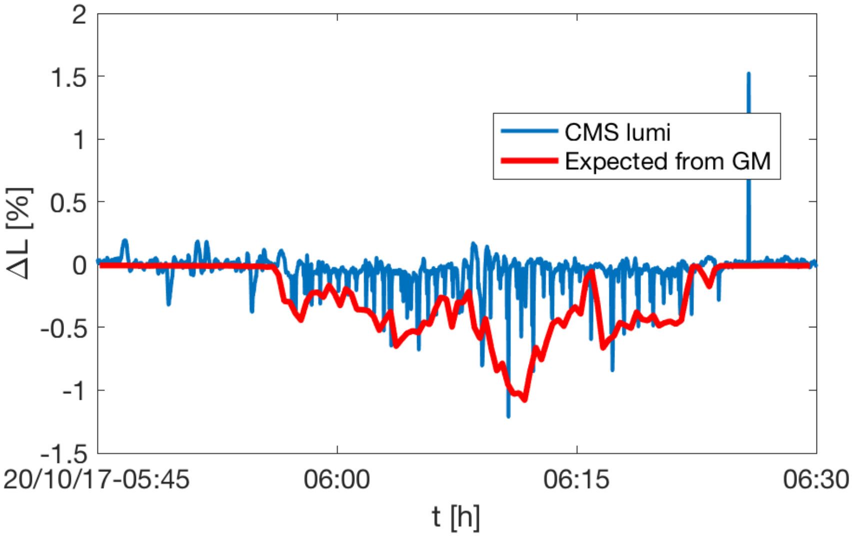
Fill 6308 (t ≈ 8) impact on orbit @TCP

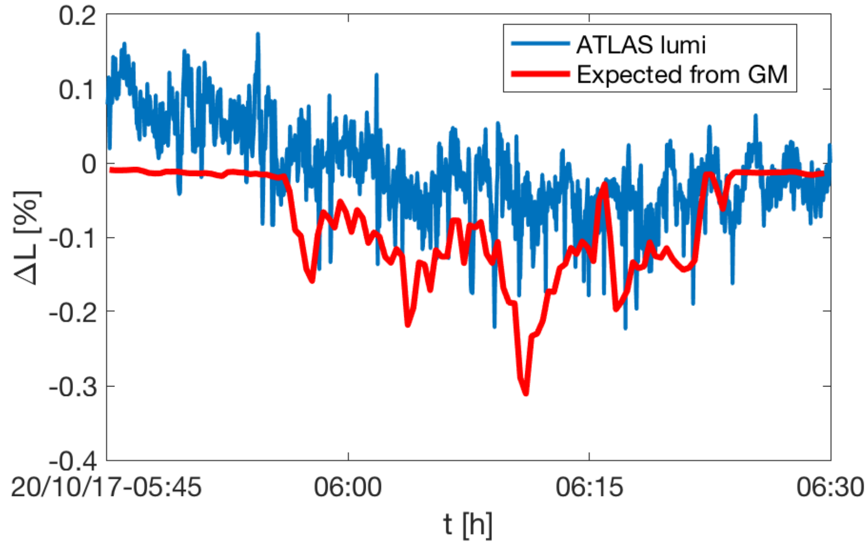


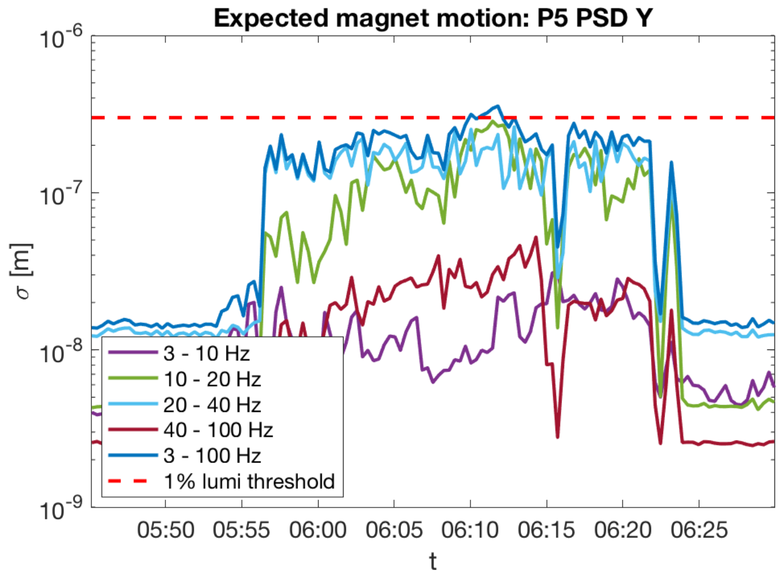


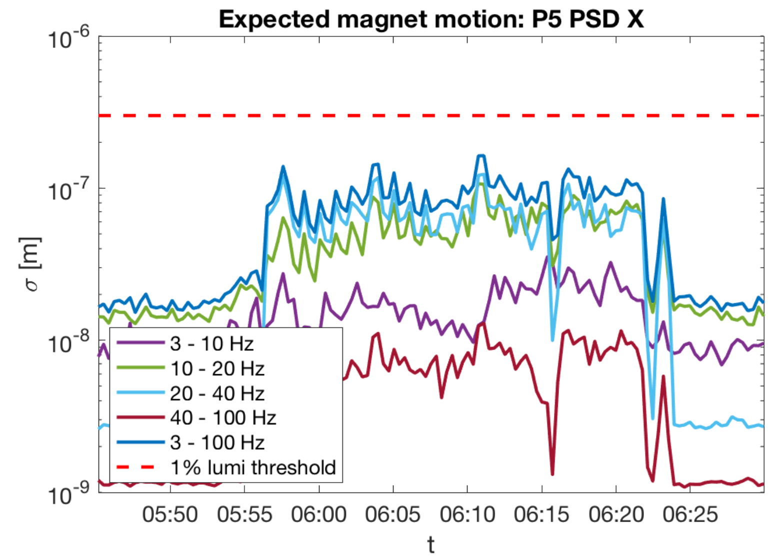
Fill 6311

Fill 6311 (t ≈ 6) impact on luminosity

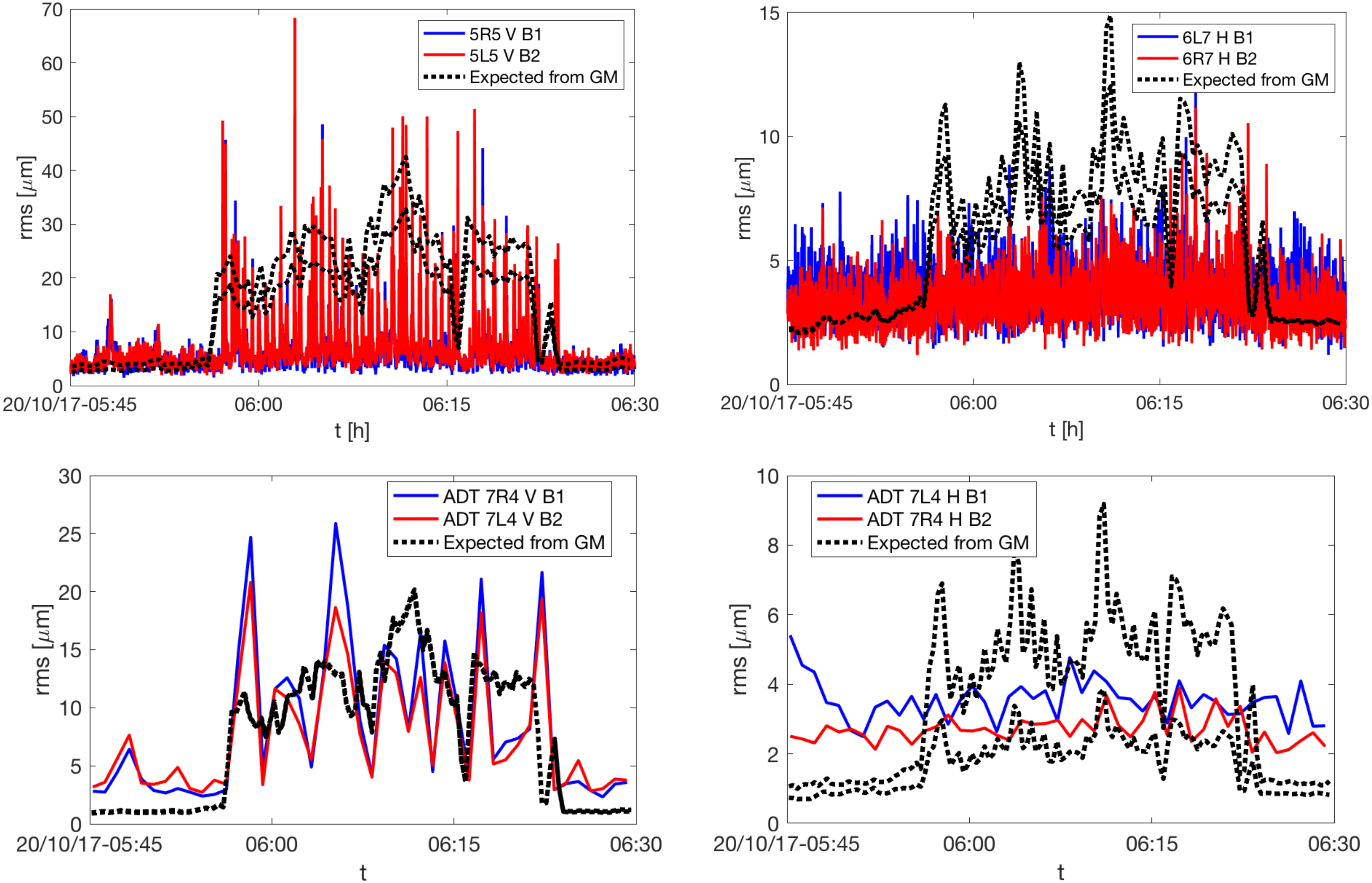




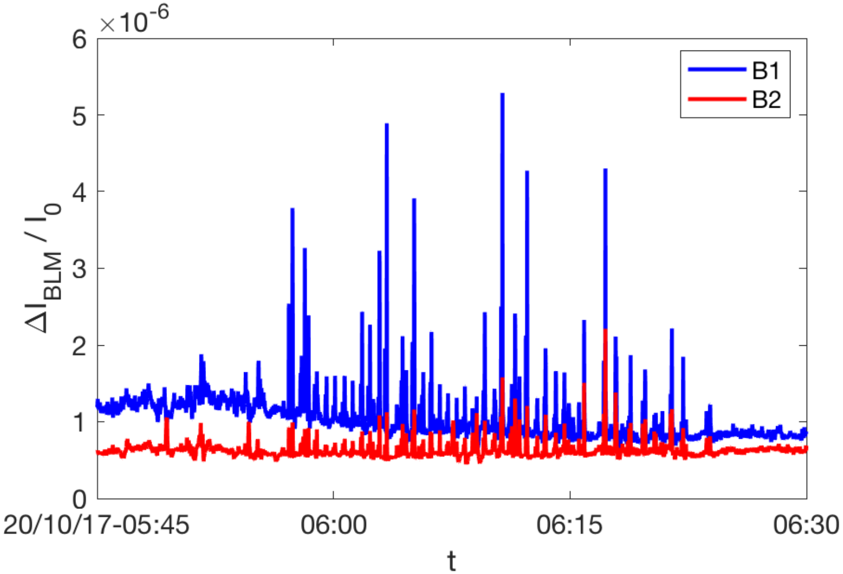


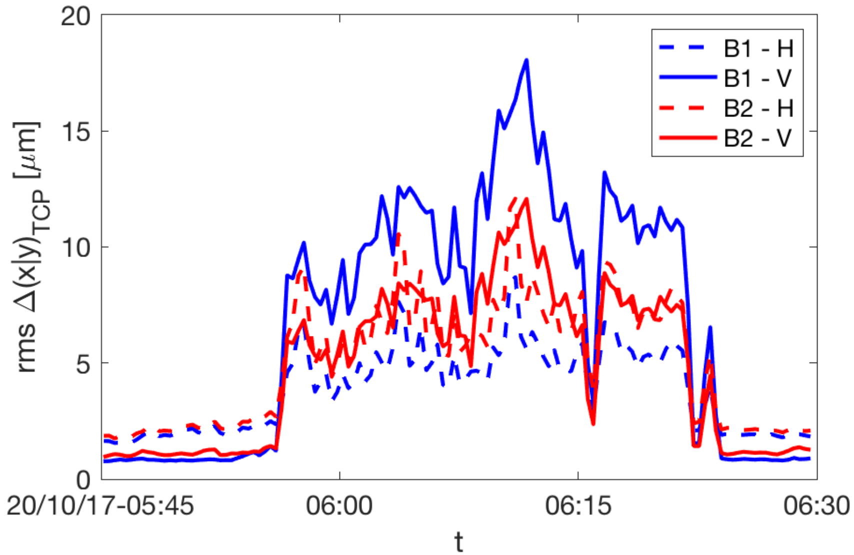


Fill 6311 (t ≈ 6) impact on orbit @BPMs



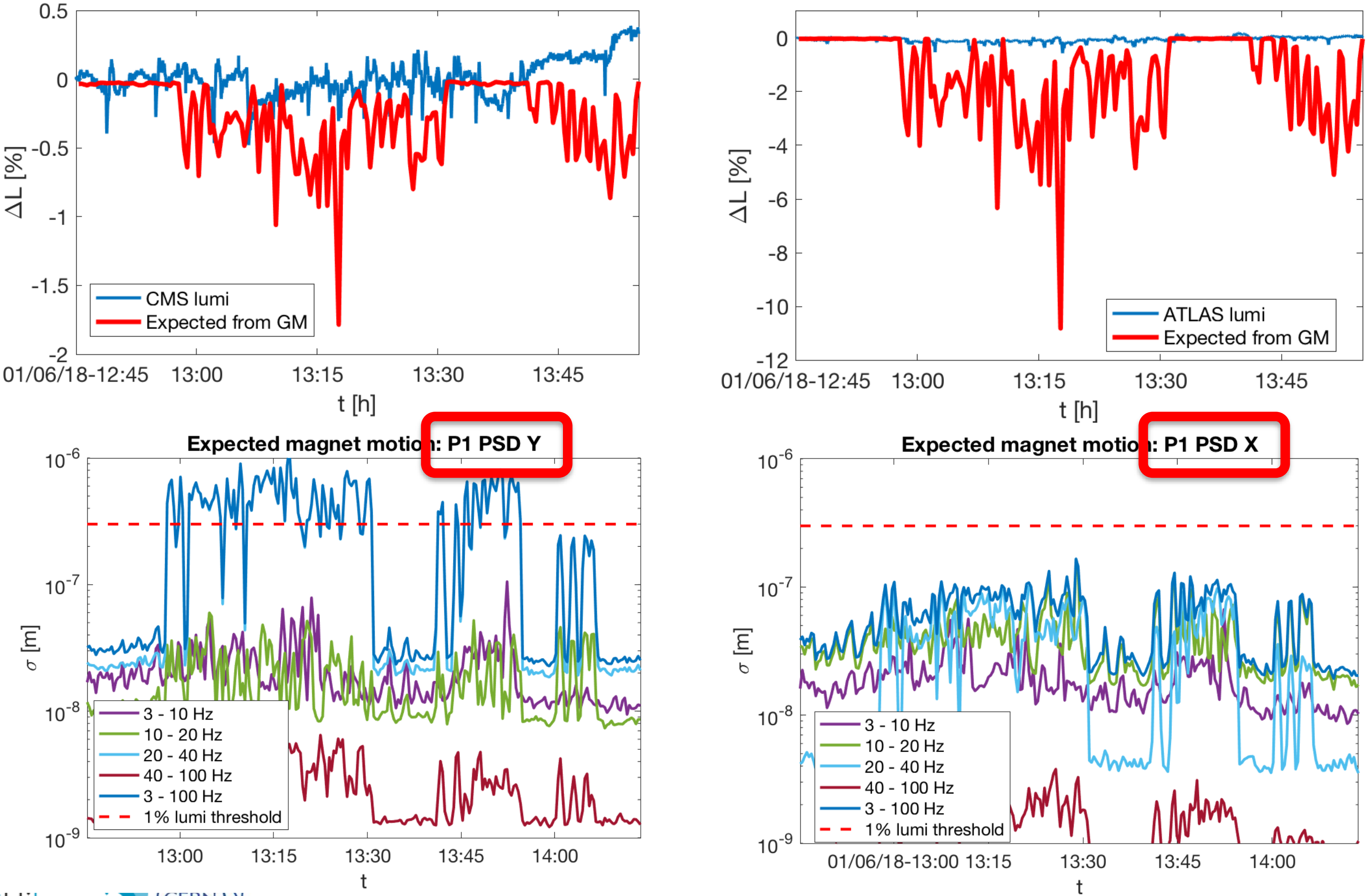
Fill 6311 (t ≈ 6) impact on orbit @TCP



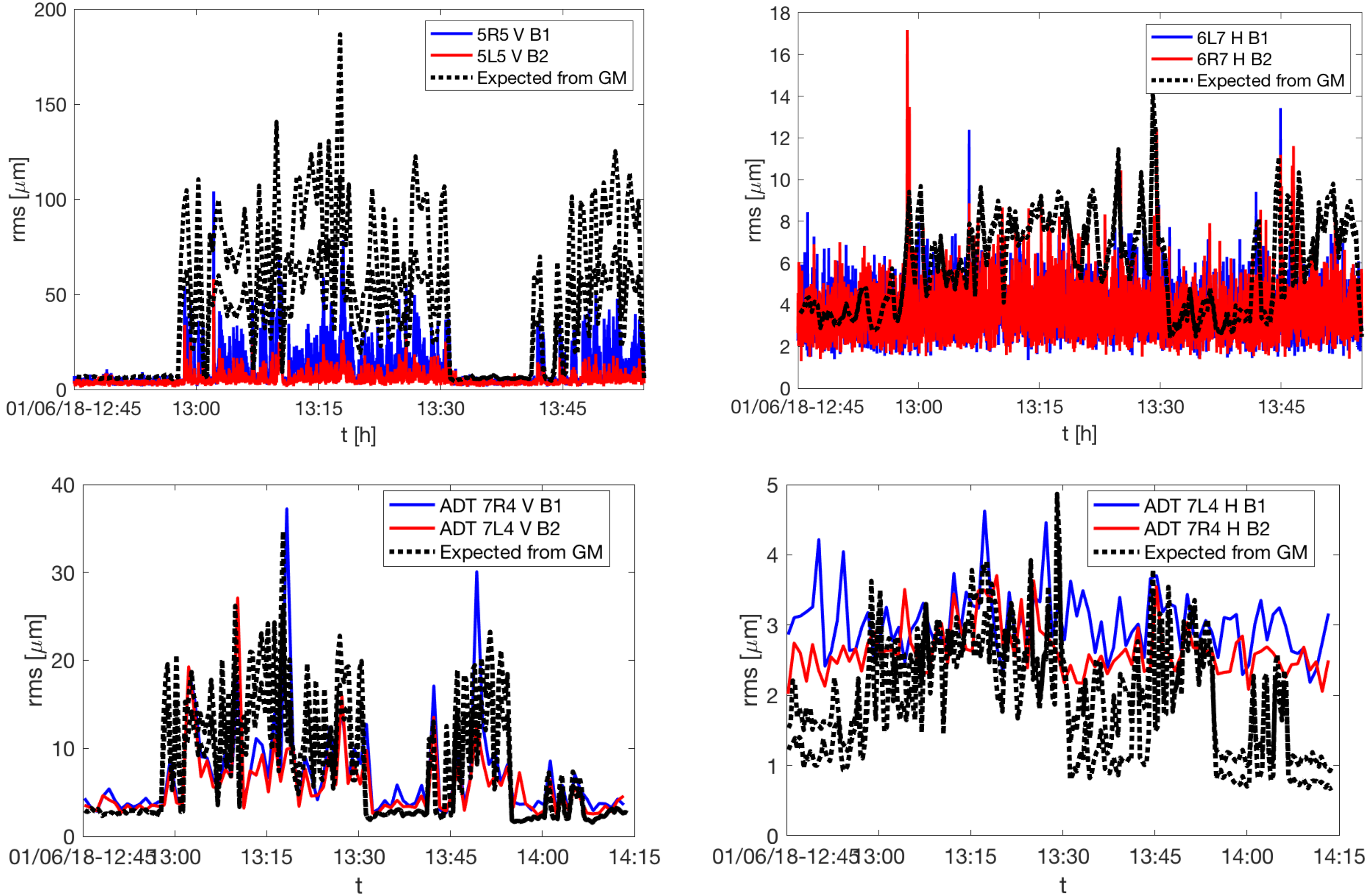


Fill 6749

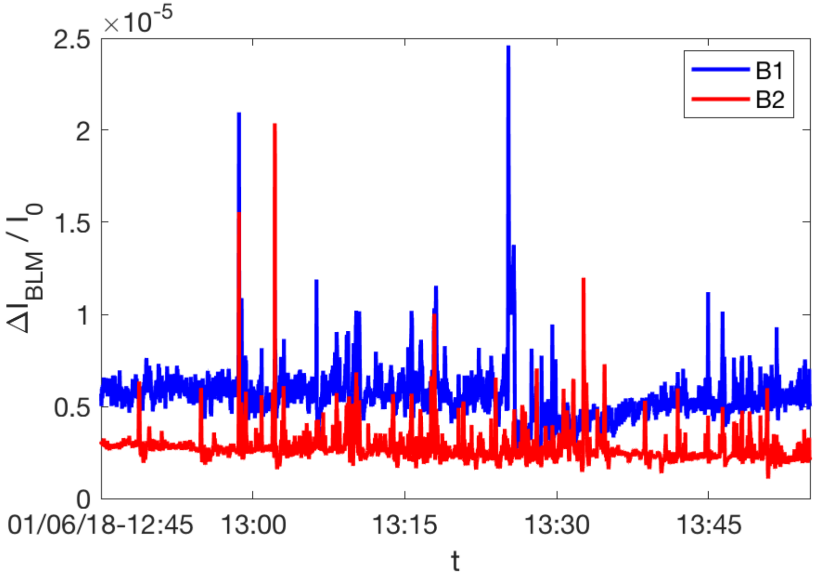
Fill 6749 (P1) (t ≈ 13) impact on luminosity

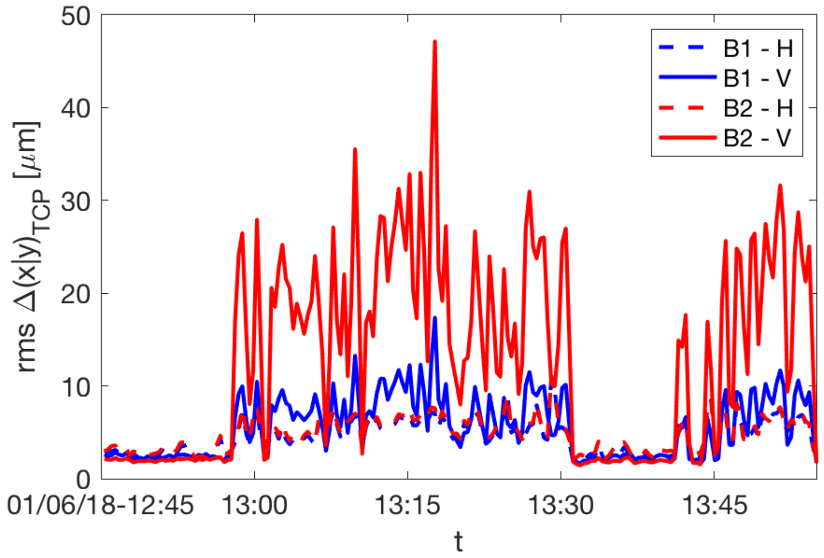


Fill 6749 (t ≈ 13) impact on orbit @BPMs



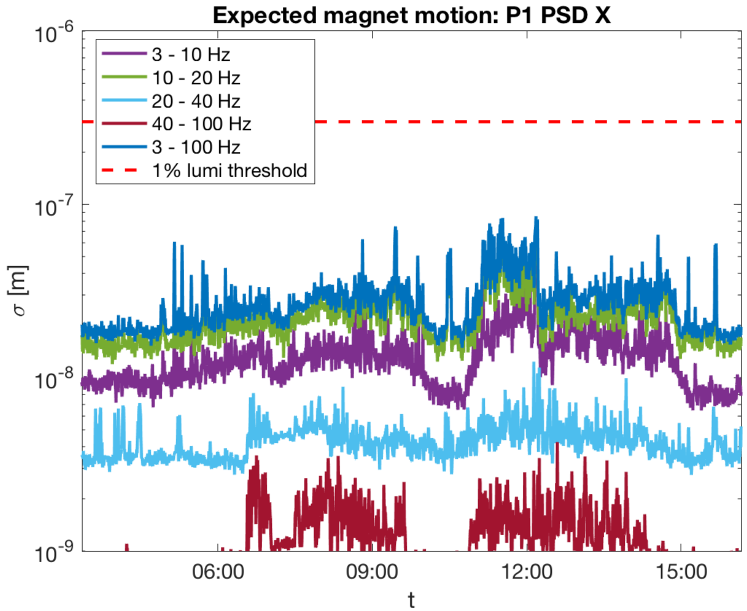
Fill 6749 (t ≈ 10) impact on orbit @TCP

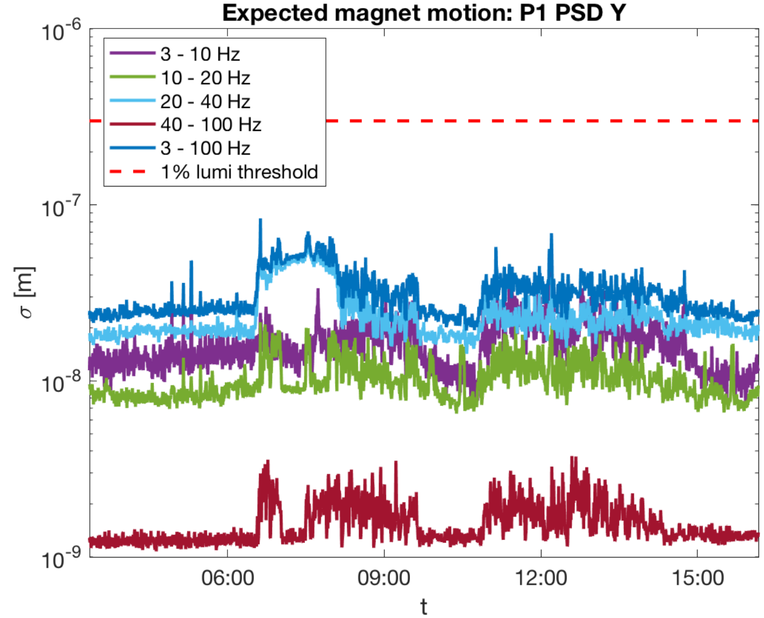


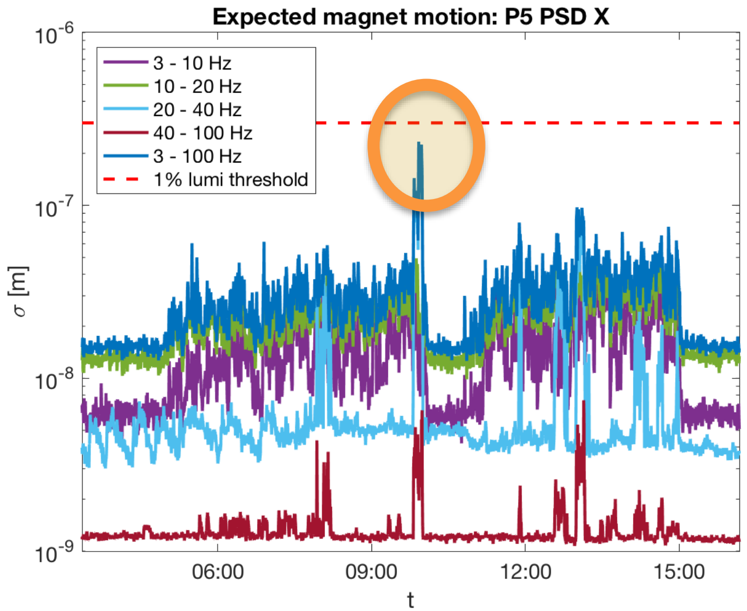


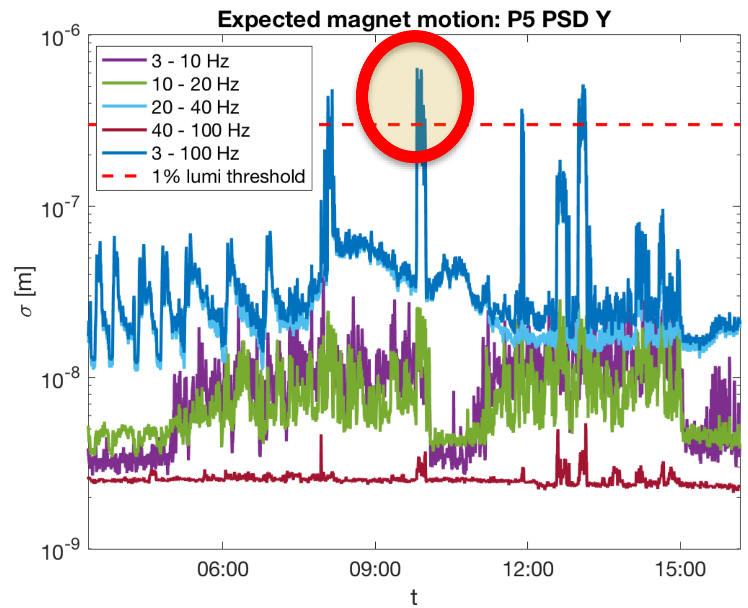
Fill 6757 (1)

Fill 6757 P1/P5 Amplified – LHC

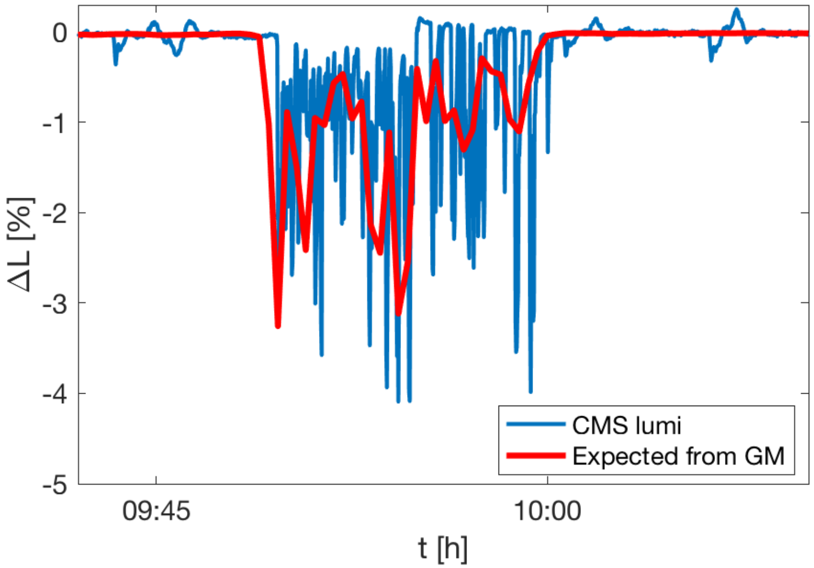


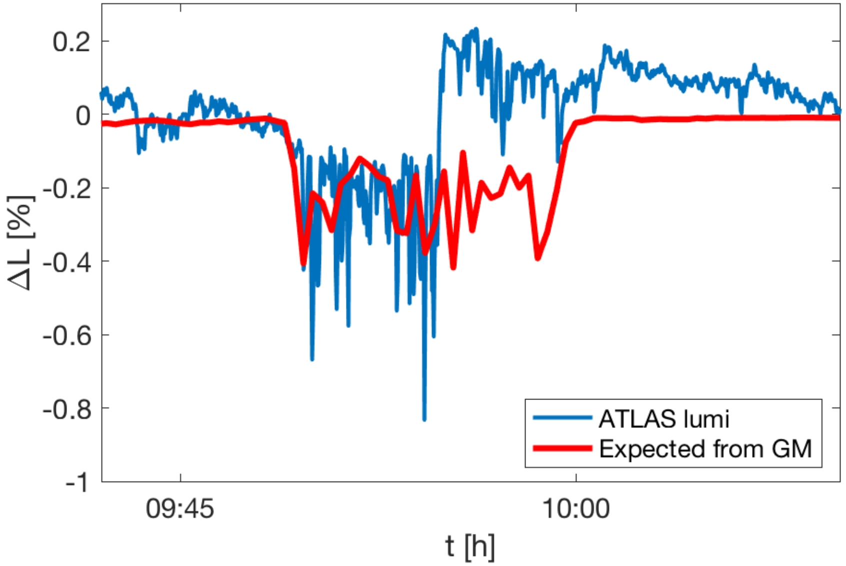


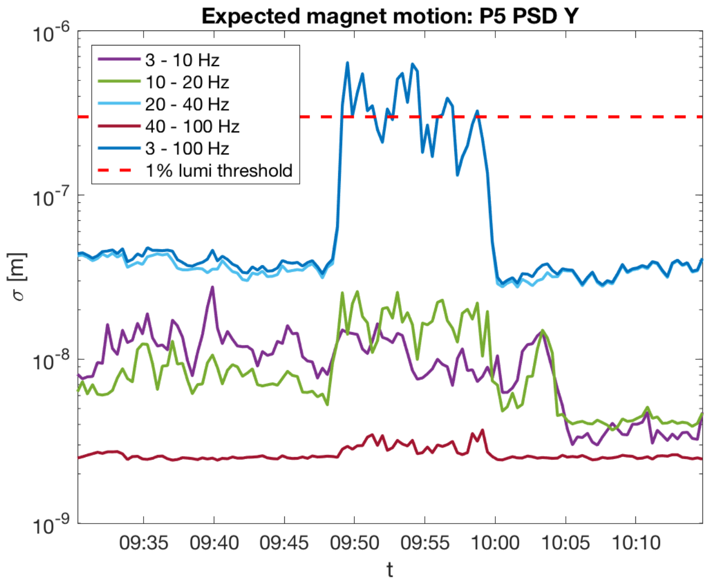


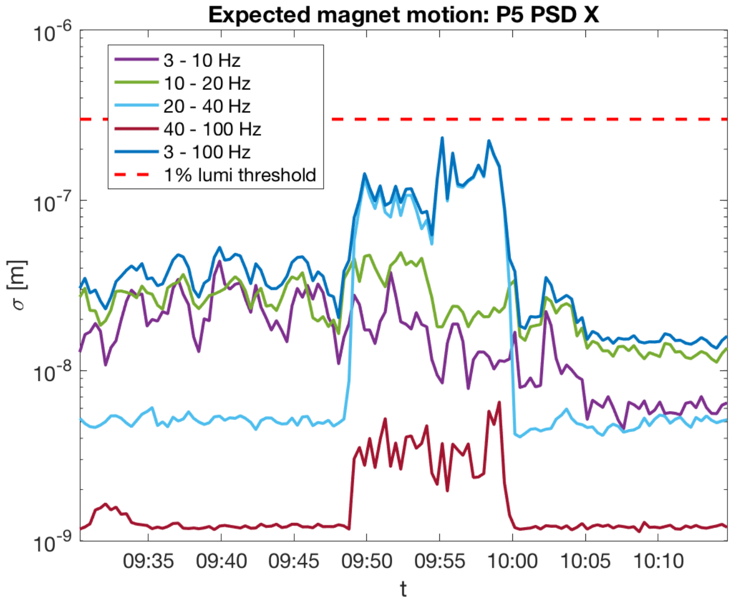


Fill 6757 (t ≈ 10) impact on luminosity

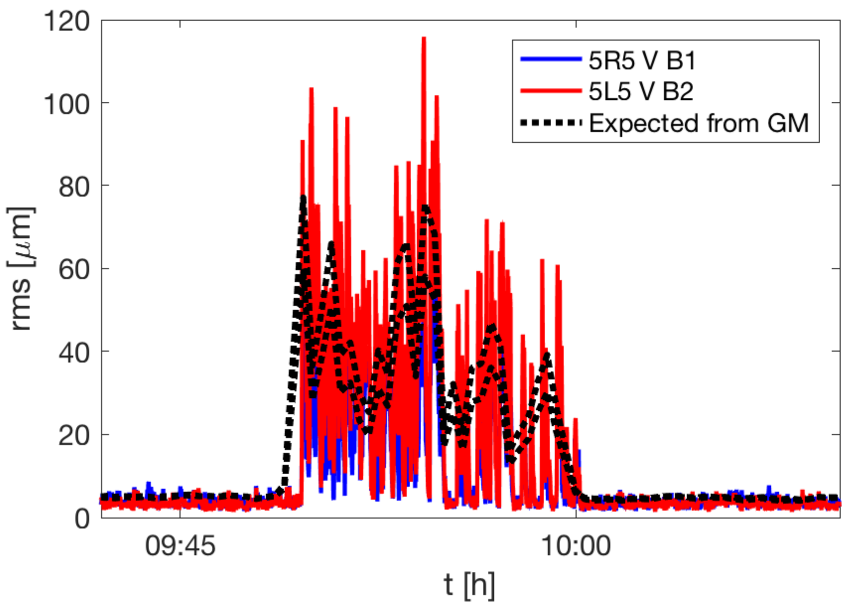


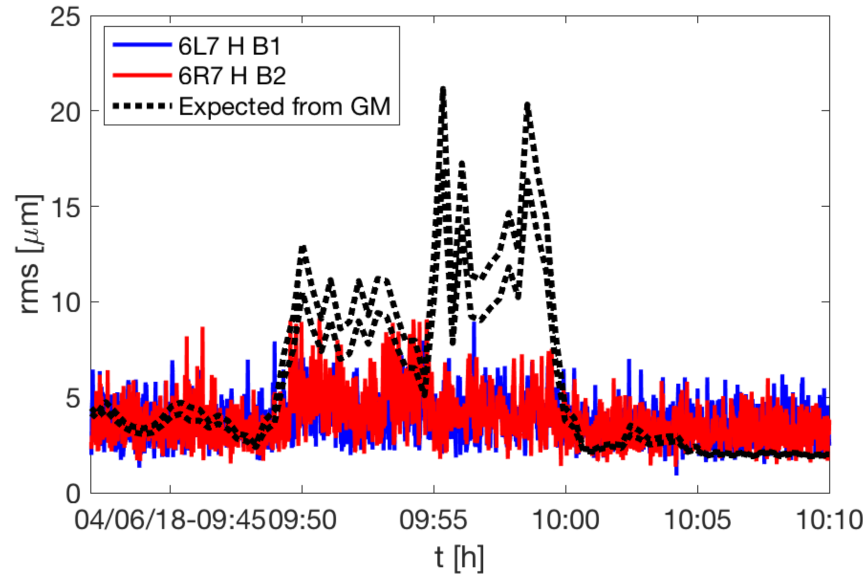


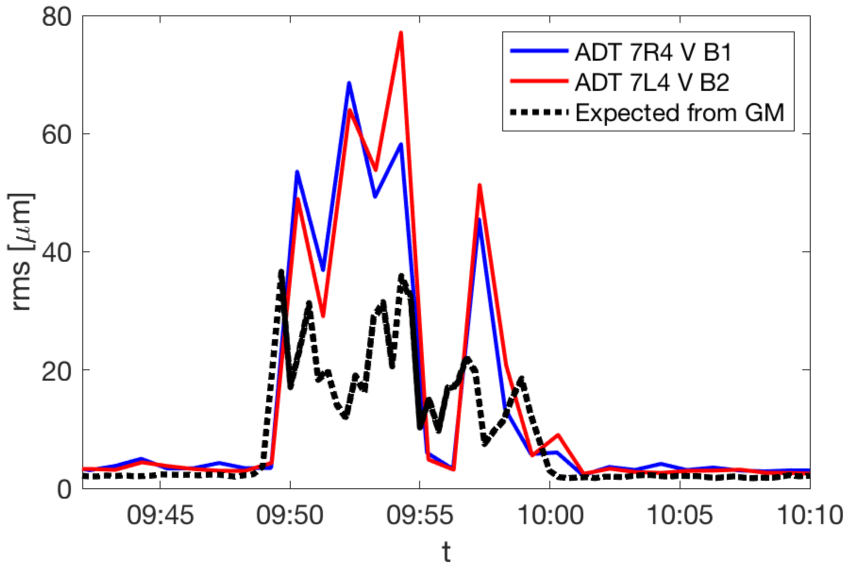


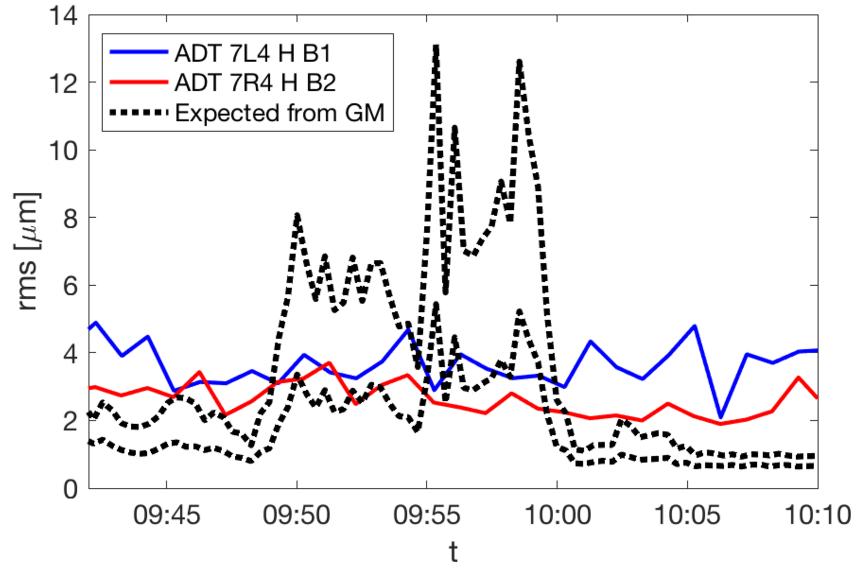


Fill 6757 (t ≈ 10) impact on orbit @BPMs

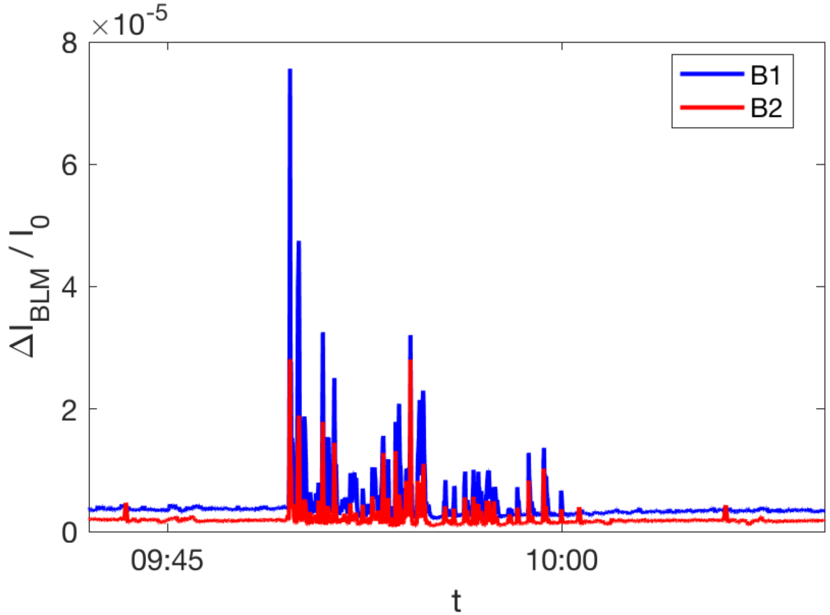


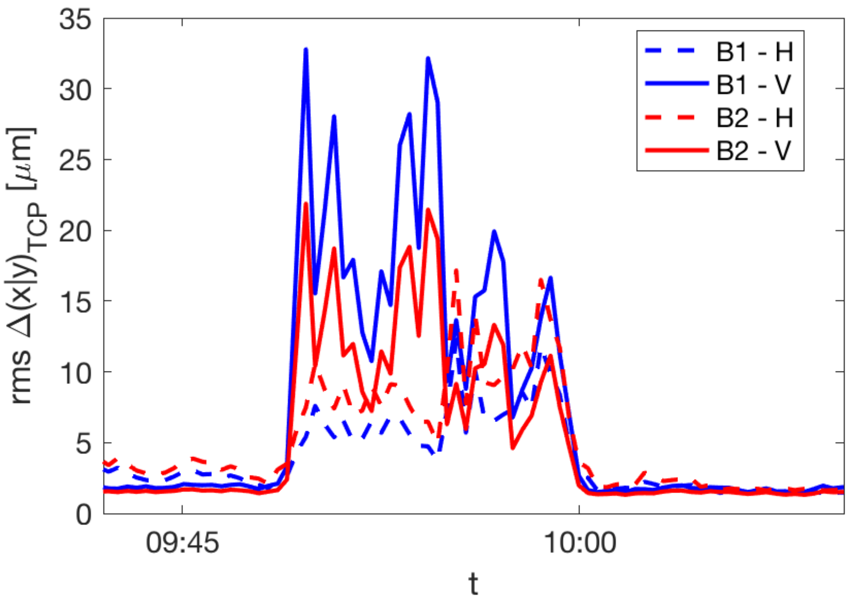






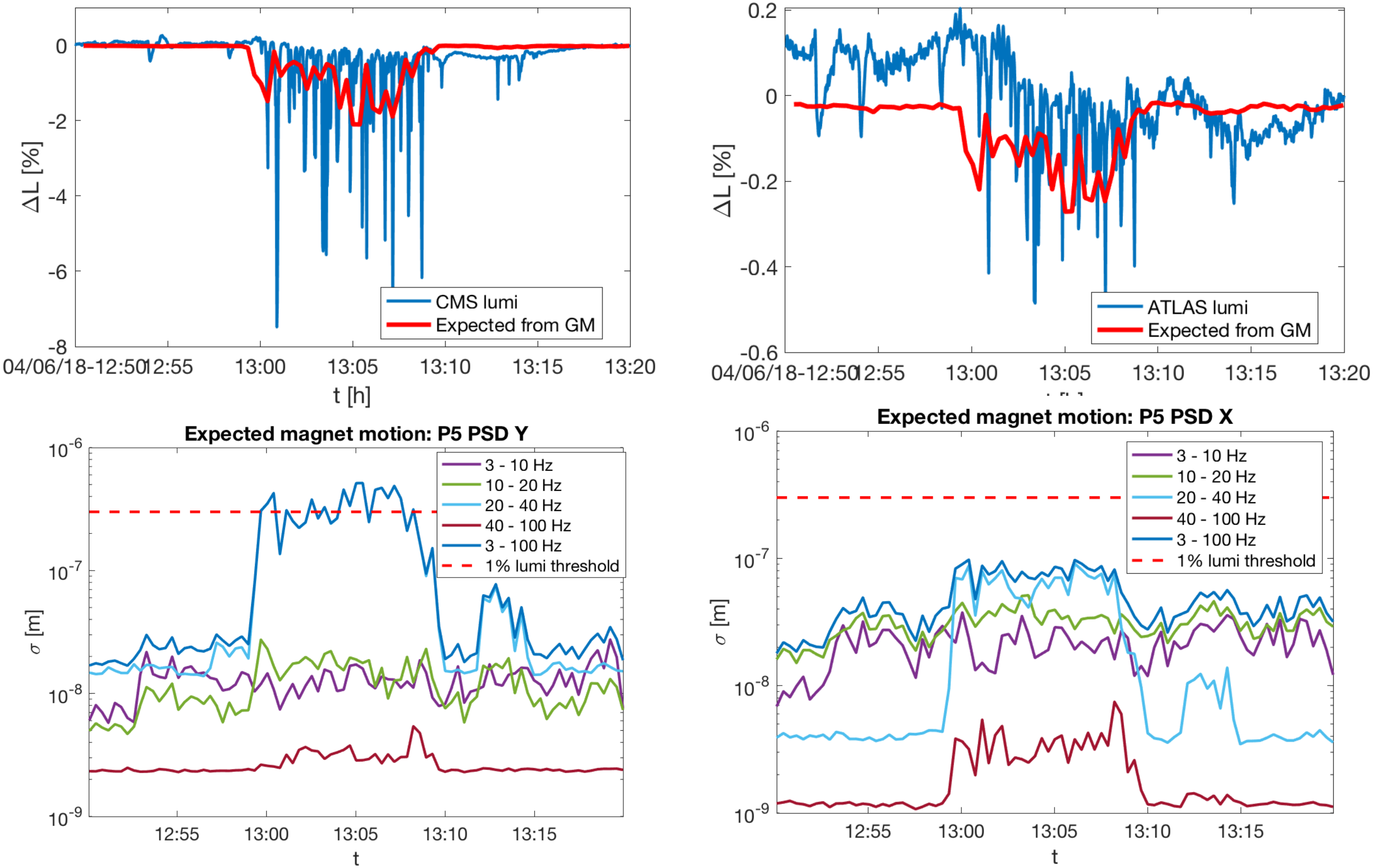
Fill 6757 (t ≈ 10) impact on orbit @TCP



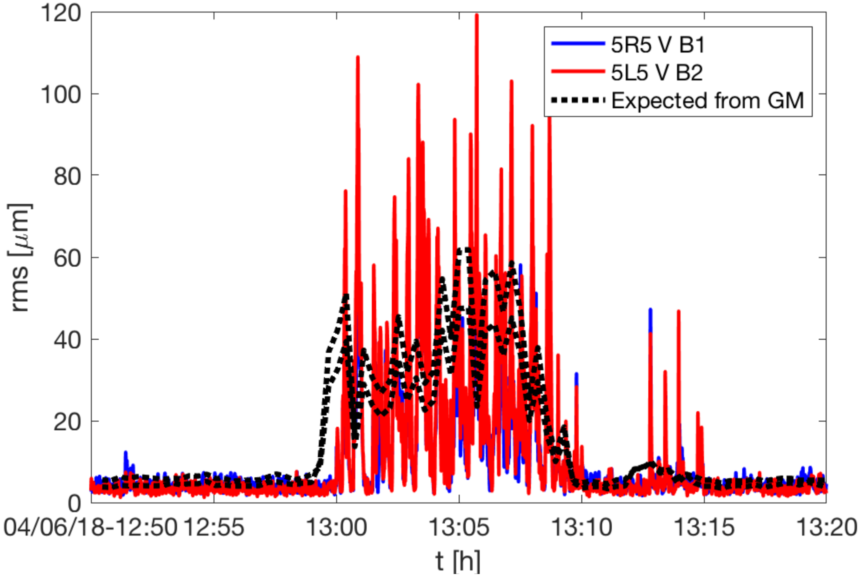


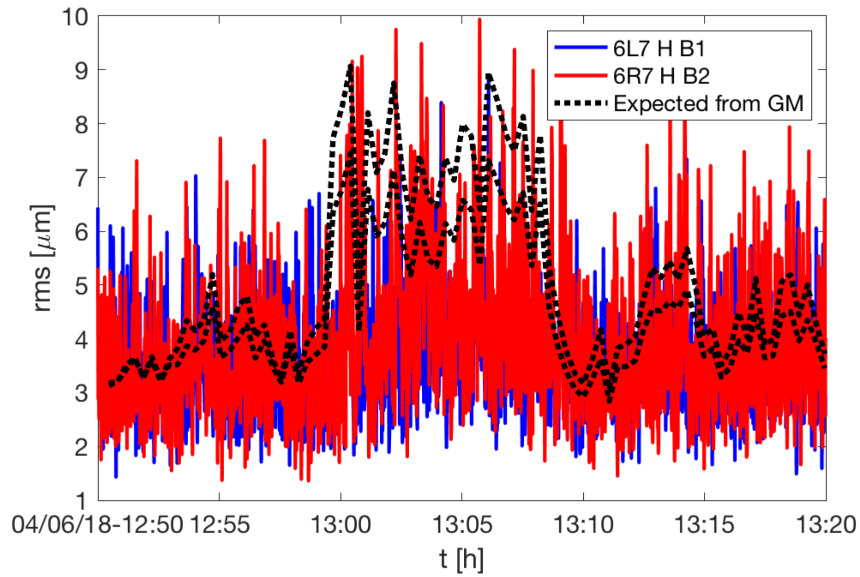
Fill 6757 (2)

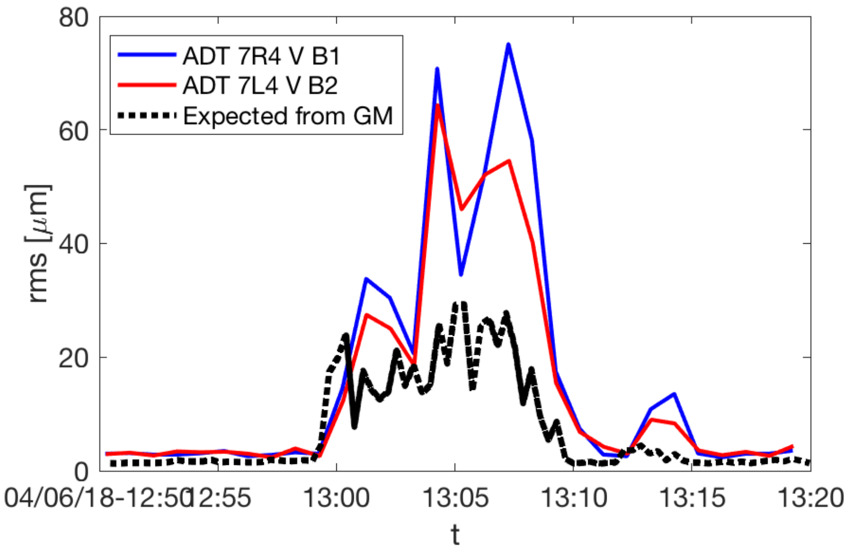
Fill 6757 (t ≈ 13) impact on luminosity

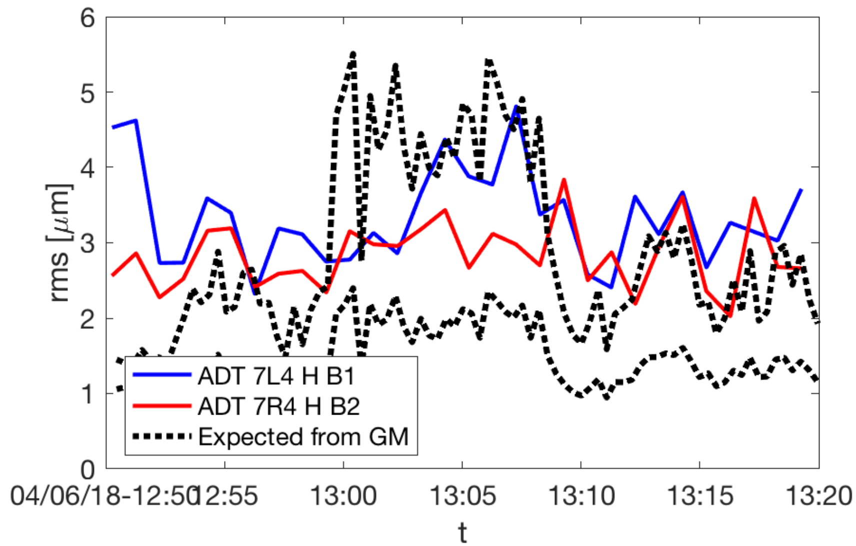


Fill 6757 (t ≈ 13) impact on orbit @BPMs

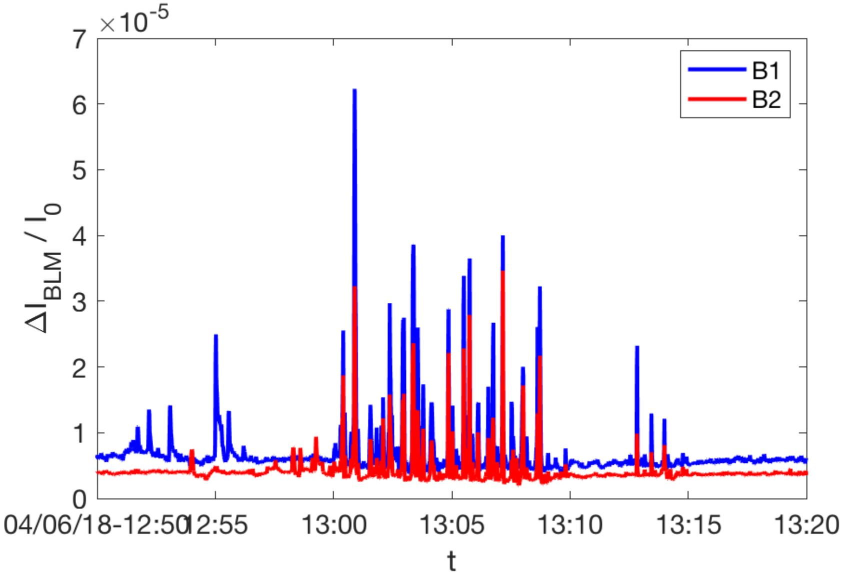


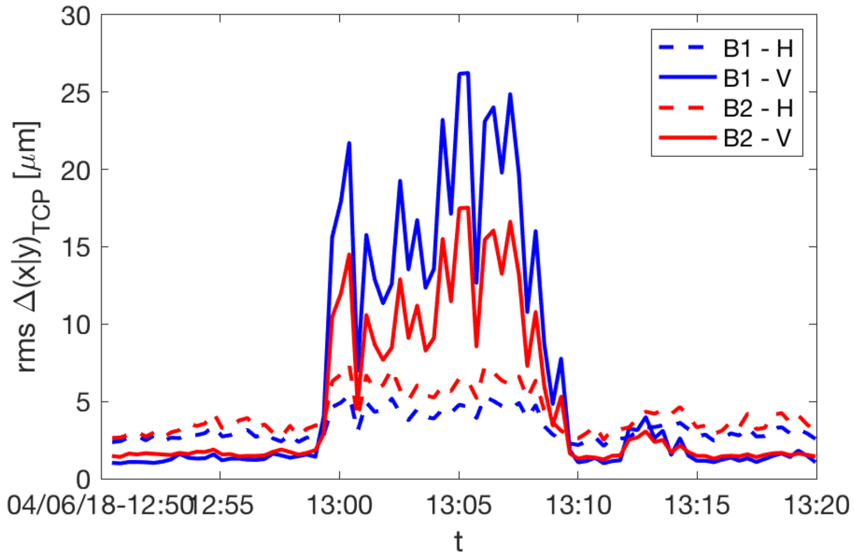






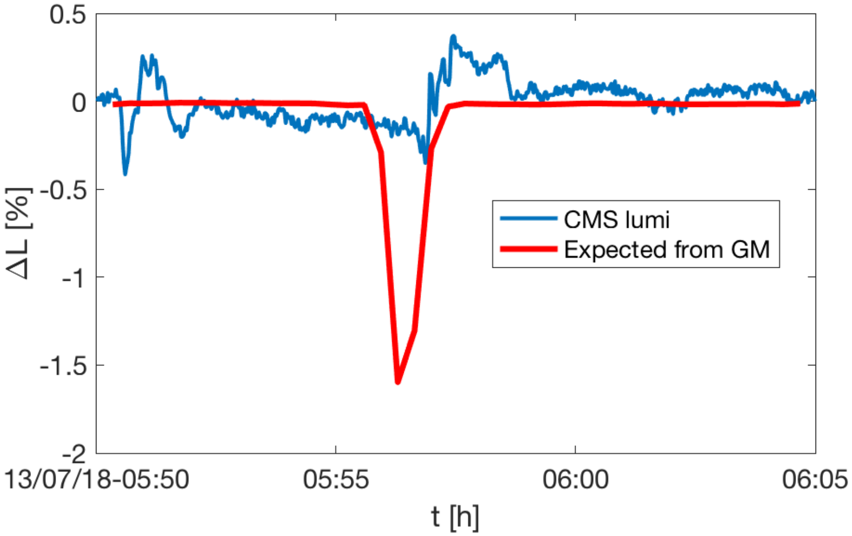
Fill 6757 (t ≈ 10) impact on orbit @TCP

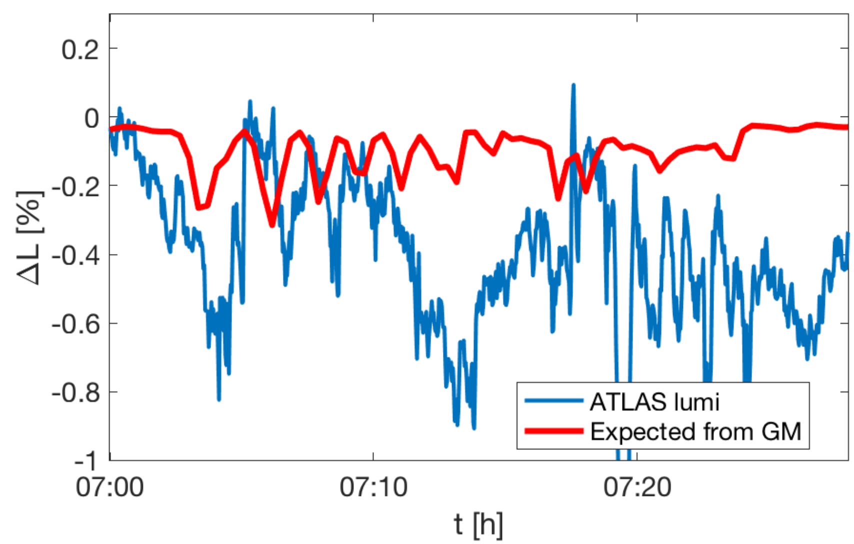


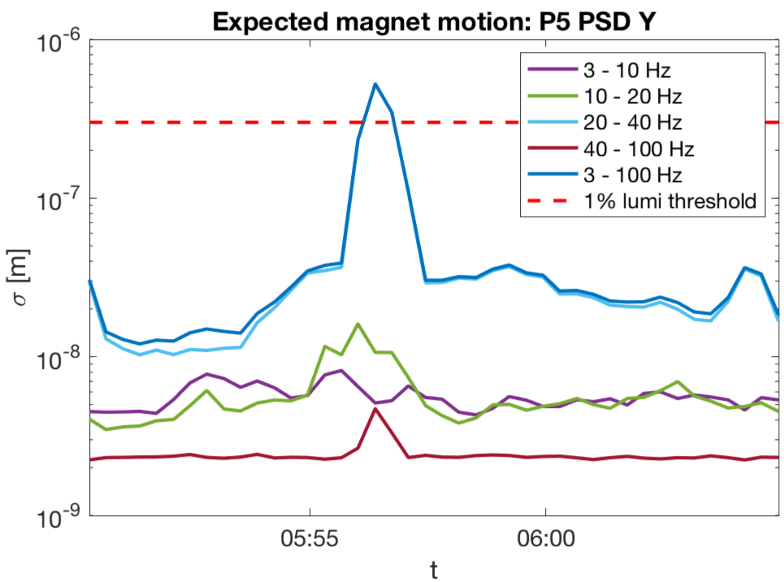


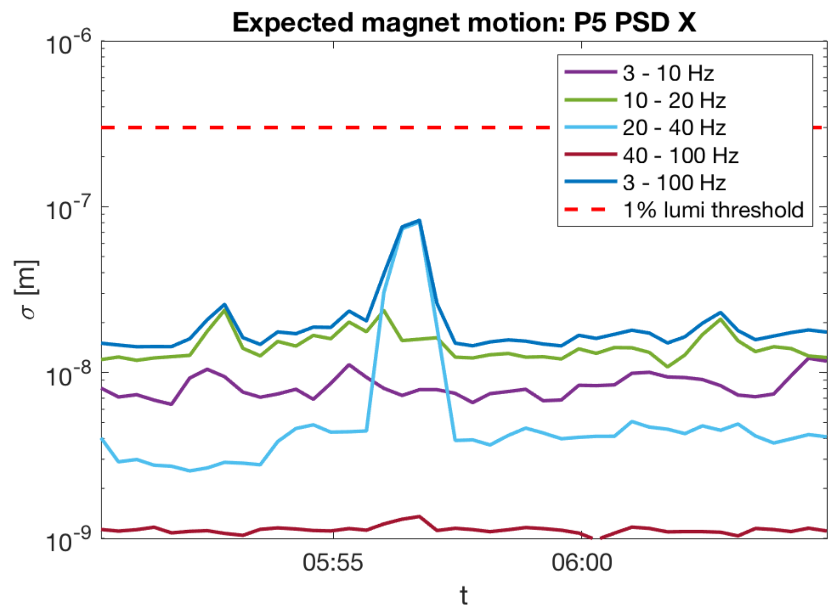
Fill 6919

Fill 6919 (t ≈ 6) impact on luminosity



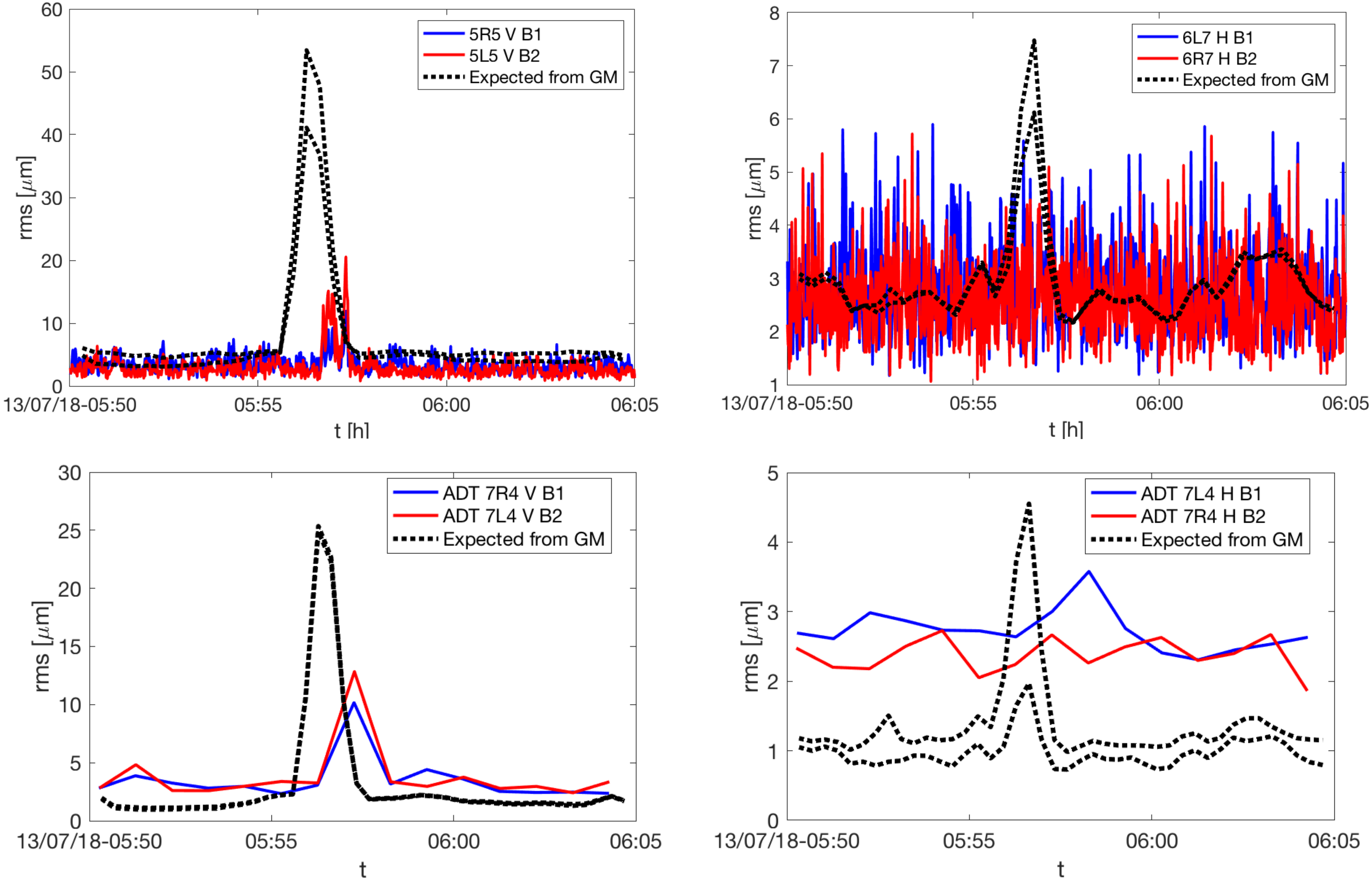






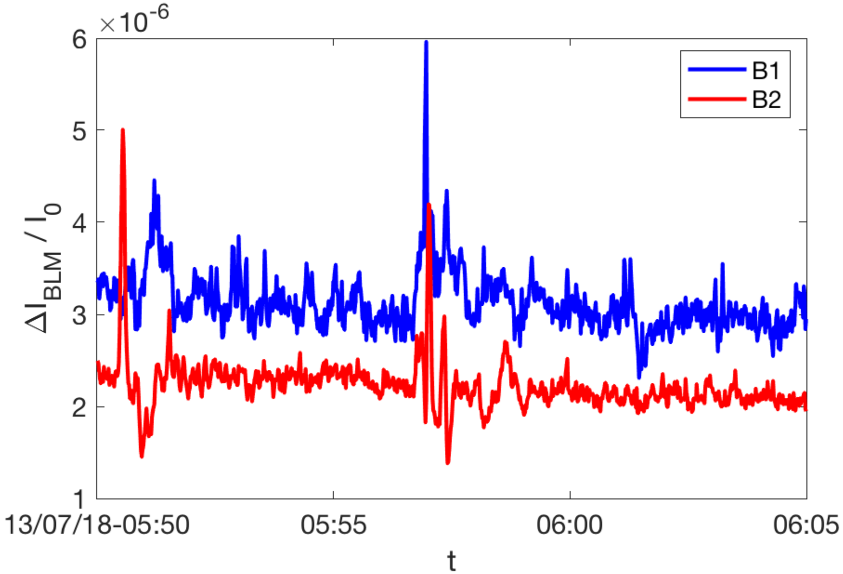
HiLumi HL-LHC PROJECT CERN

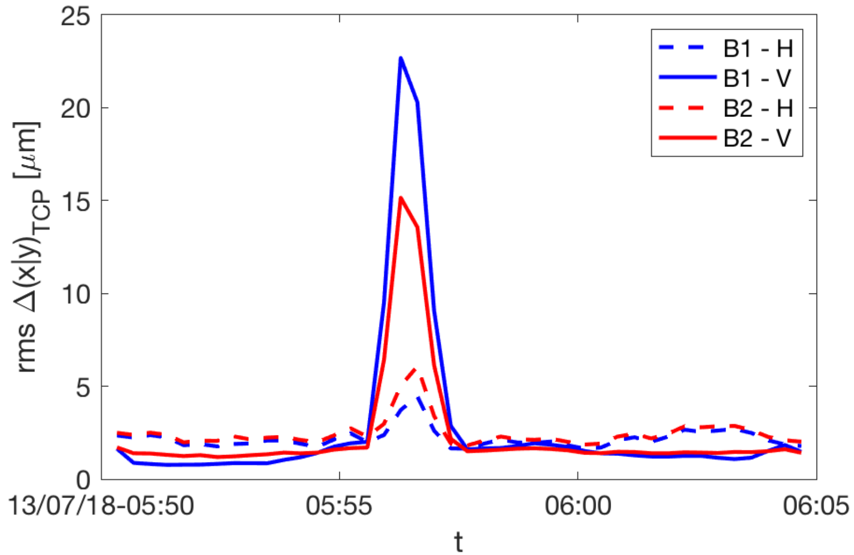
Fill 6919 (t ≈ 6) impact on orbit @BPMs



HiLumi HL-LHC PROJECT CERN

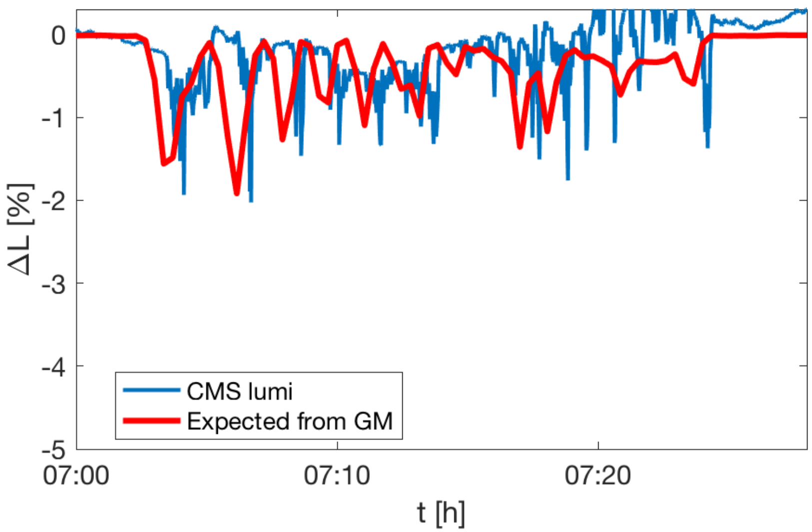
Fill 6919 (t ≈ 6) impact on orbit @TCP

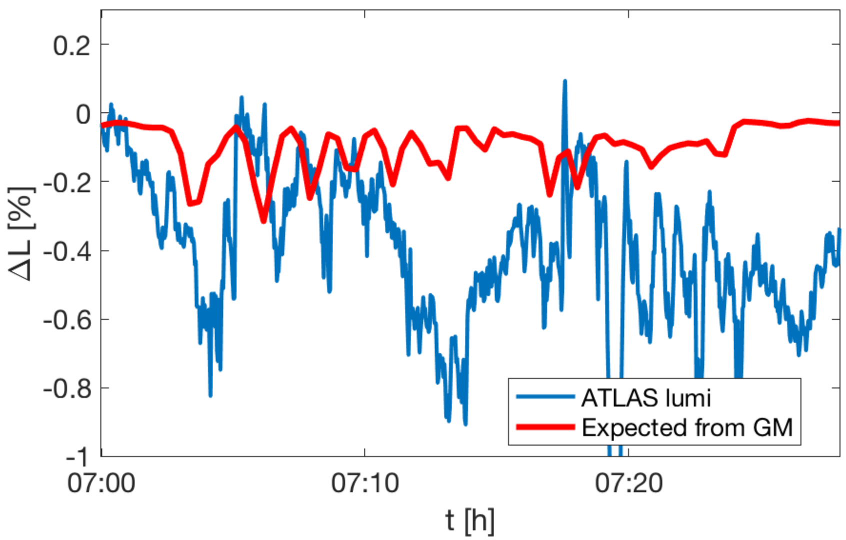


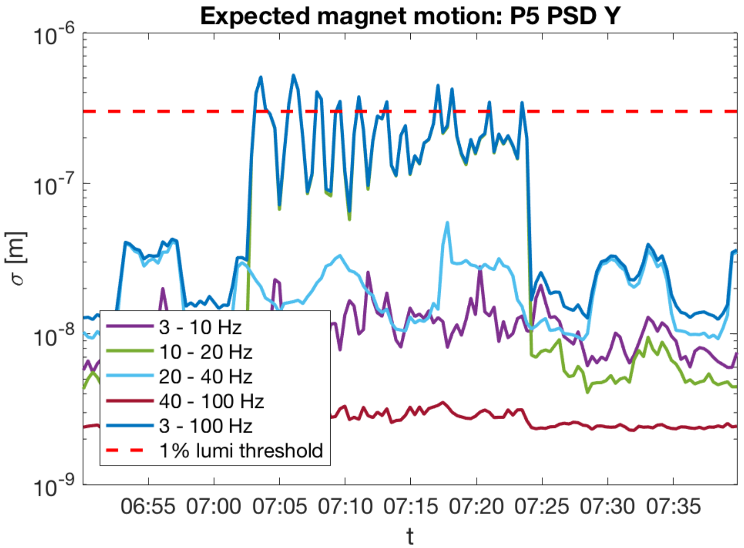


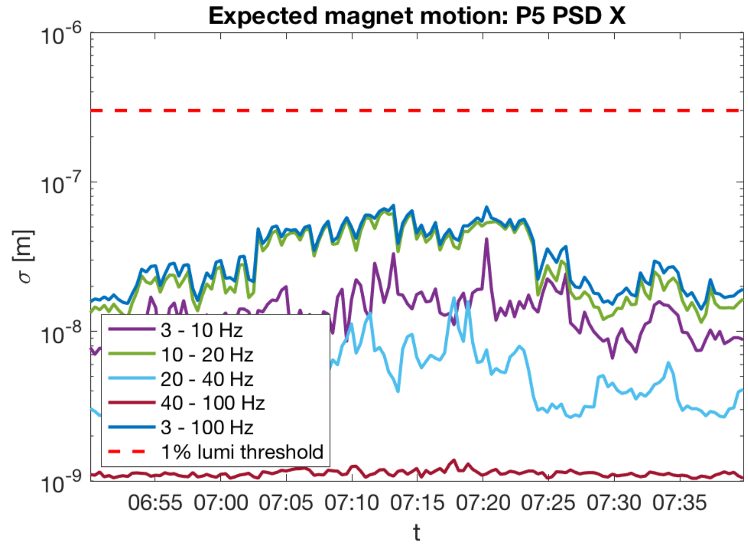
Fill 7122

Fill 7122 (t ≈ 7) impact on luminosity

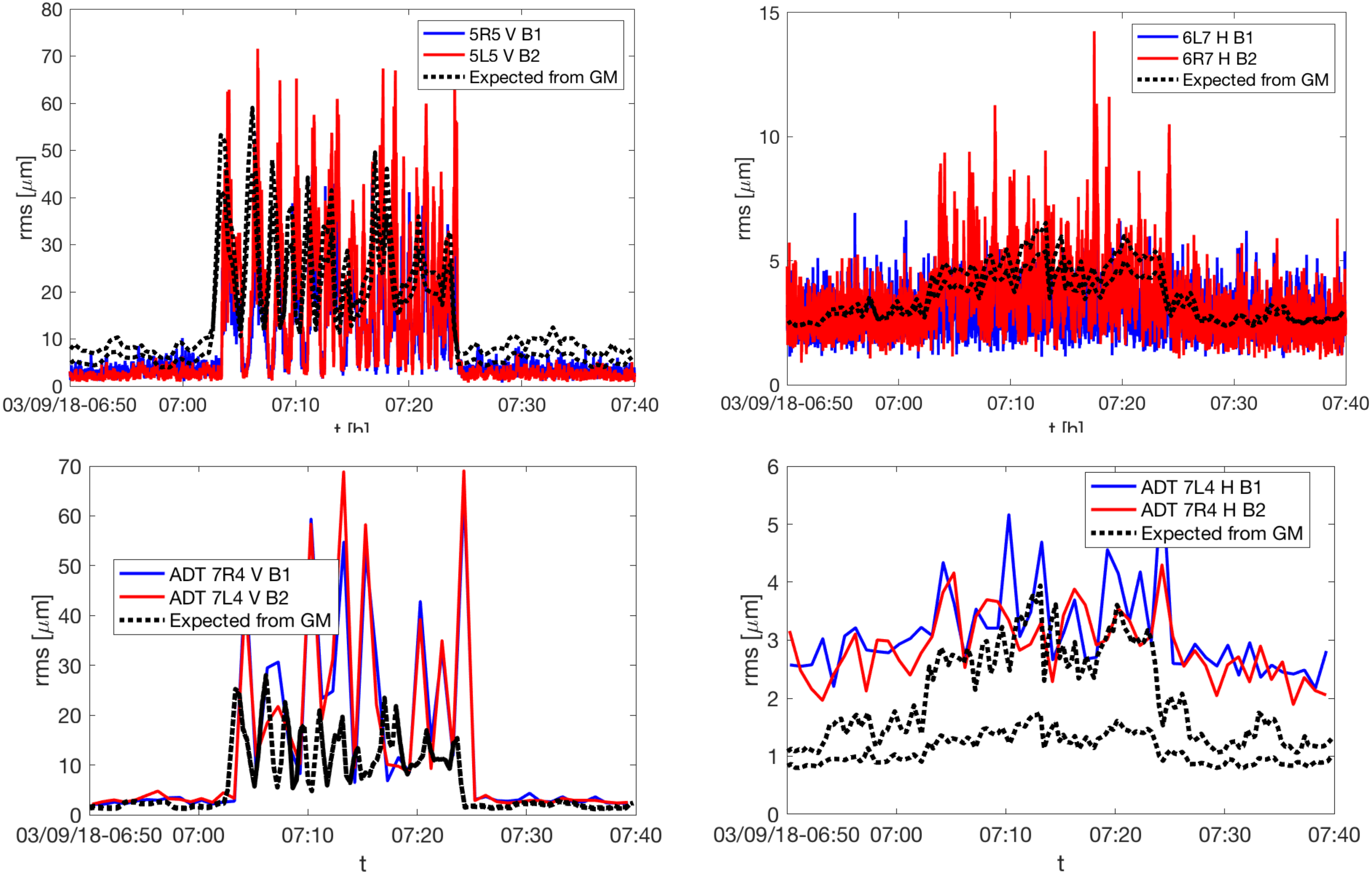








Fill 7122 (t ≈ 7) impact on orbit @BPMs/ADT



Fill 7122 (t ≈ 7) impact on orbit @TCP