LHC Luminosity Follow-up for 2016 - Summary

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Acknowledgements to G. Arduini, X. Buffat, K. Li, G. Trad,
R. Tomas, ATLAS collaboration, CMS collaboration

Beam-beam and Luminosity studies meeting, 24 Feb. 2017

Outline

- Model description
- Emittance evolution from injection to stable beams
- Peak luminosity along the year
  - Calculated vs measured
- Luminosity evolution
  - Luminosity evolution prediction
  - Emittance evolution during Stable Beams
  - Losses during the first hours at Stable Beams
  - Impact on integrated luminosity loss
- Summary

Model description

Luminosity model description

- Self consistent bunch by bunch luminosity model
  - **Emittance evolution:**
    - Intrabeam scattering (IBS), Synchrotron Radiation (SR) elastic scattering due to the proton-proton collisions

$$\left(\frac{d\epsilon_x}{dt}, \frac{d\epsilon_y}{dt}, \frac{d\sigma_s}{dt}\right)_{IBS+SR} = f(En, N_b(t_0), \epsilon_x(t_0), \epsilon_y(t_0), \sigma_s(t_0), dt)$$

$$\left(\frac{d\epsilon_{x,y}}{dt}\right)_{elastic} = N_{IP}\beta^*_{x,y}\mathcal{L}\sigma_{el} < \theta^2_{x,y} > /(n_b N_p)$$

$$\frac{d\epsilon}{dt} = \left(\frac{d\epsilon}{dt}\right)_{IBS+SR} + \left(\frac{d\epsilon}{dt}\right)_{elastic}$$

- Or using the empirical evolution from the data

Luminosity model description

- **Bunch intensity evolution:**
  - Luminosity burn-off due to the p-p collisions:

$$\tau_{nuc} = \frac{N_{b0}}{kL_0\sigma_{tot}}$$

$$N_b = N_{b0}/(1 + t/\tau_{nuc}).$$

  - Or using the empirical bunch intensity evolution from the data

- **Bunch length evolution:**
  - Intrabeam scattering and synchrotron radiation (see previous slide)
  - Or using the empirical bunch length evolution from the data

- Iteration of the equations in a self-consistent way and in small timesteps (10-15min) such the bunch intensity can be considered constant
- Any of the modes can be called at each time step
  - Theoretical or empirical evolution of the bunch parameters and luminosity

Luminosity model description

- The model can be applied bunch-by-bunch both for **colliding** and **non-colliding** bunches
- The emittance evolution function can be applied both at **injection** and **flat top energies**
- Can be applied under different assumptions:
  - **Pure model:**
    - Initial values of bunch intensities, emittances and bunch length taken from the data
    - Model iteration to compute intensity, emittance, bunch length and luminosity evolution
  - **EmpiricalBlowUpBurnOff**:
    - Emittance evolution taken from the data
    - Model iteration to compute bunch intensity, bunch length and luminosity evolution
  - **IBSEmpiricalLosses**:
    - Intensity evolution taken from the data
    - Model iteration to compute emittance, bunch length and luminosity evolution
  - **EmpiricalBlowUpEmpiricalLosses**:
    - Intensity and emittance evolution taken from the data
    - Model iteration to compute luminosity evolution

Data used as input

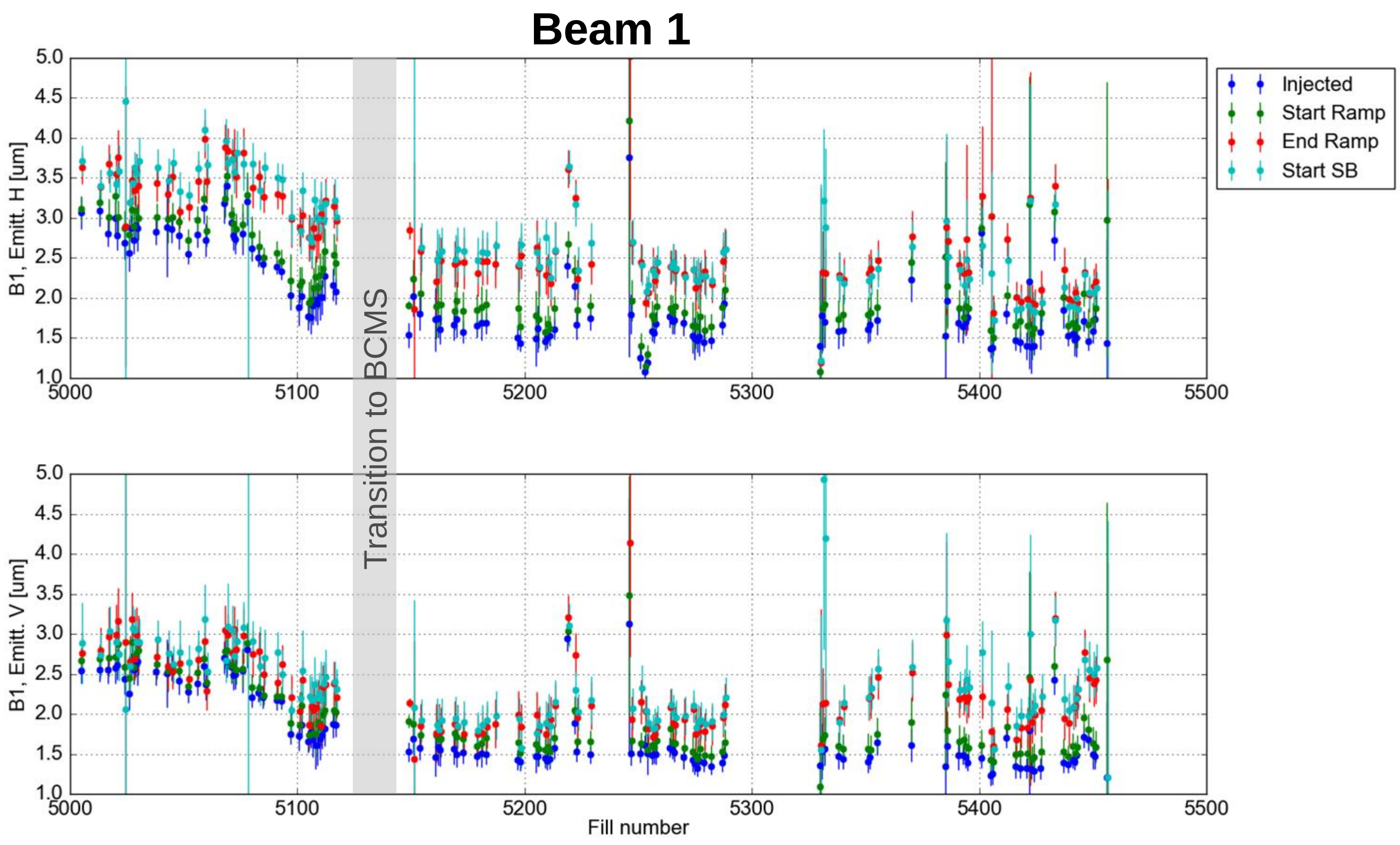
- Bunch by bunch intensity data from fBCT
- Bunch by bunch emittance data from BSRT
- Bunch by bunch bunch length data from BQM
- Bunch by bunch luminosities from ATLAS and CMS (Massi files are used)

➔ A set of tools have been developed to ease the follow up of the beam quality and luminosity evolution in the LHC and the comparison against models.
  - ◆ Extended the python tools used for the scrubbing follow up and integrated the luminosity simulation in the same framework
  - ◆ **Many thanks to Gianni for this!!!**

➔ The idea is to use the same tools for the weekly follow up of the fills of 2017

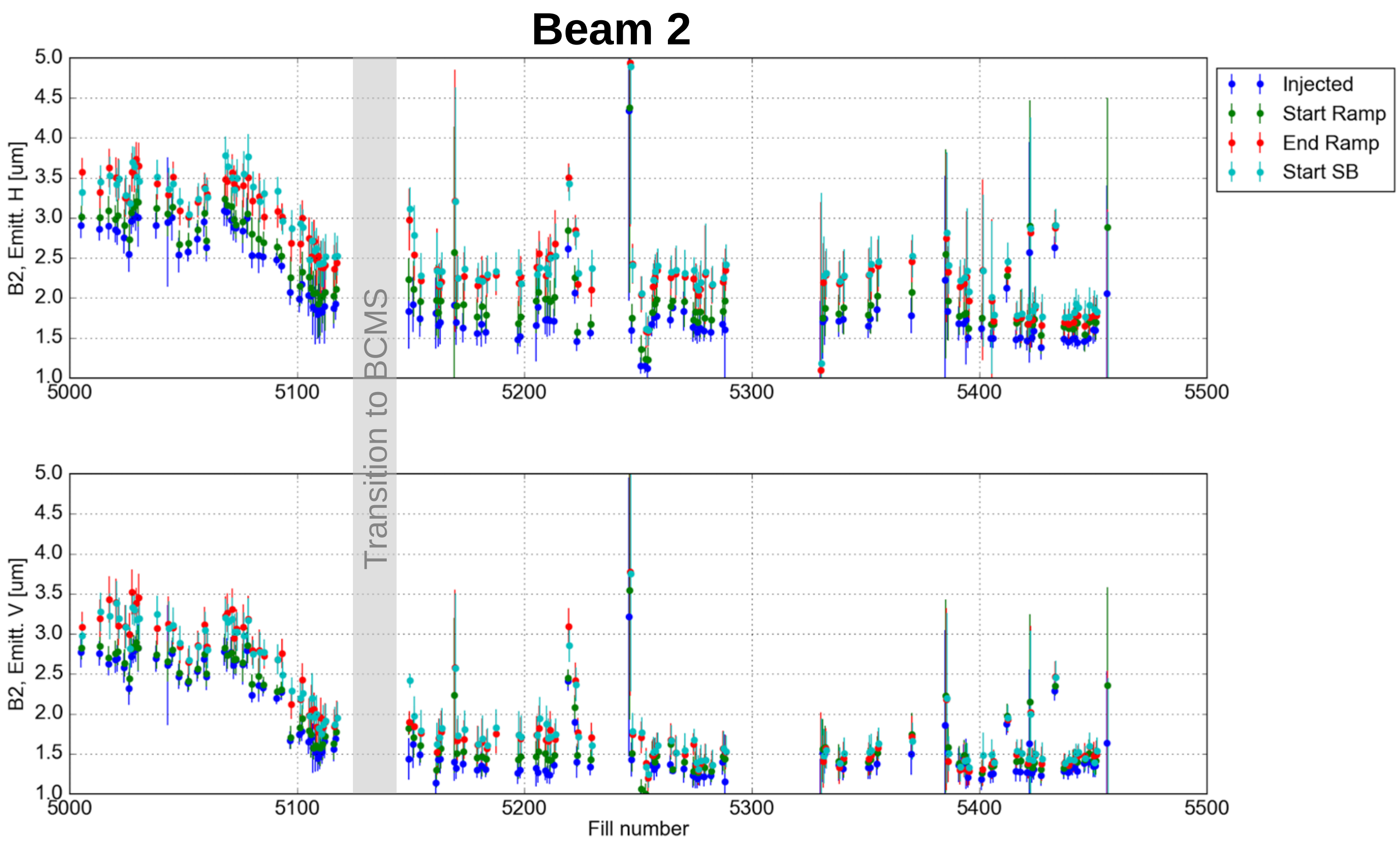
Injection to Stable Beams Analysis

Emittance evolution from injection to stable beams



- Larger part of the blow up induced during the Ramp
    - Cannot be explained by IBS+SR

Emittance evolution from injection to stable beams



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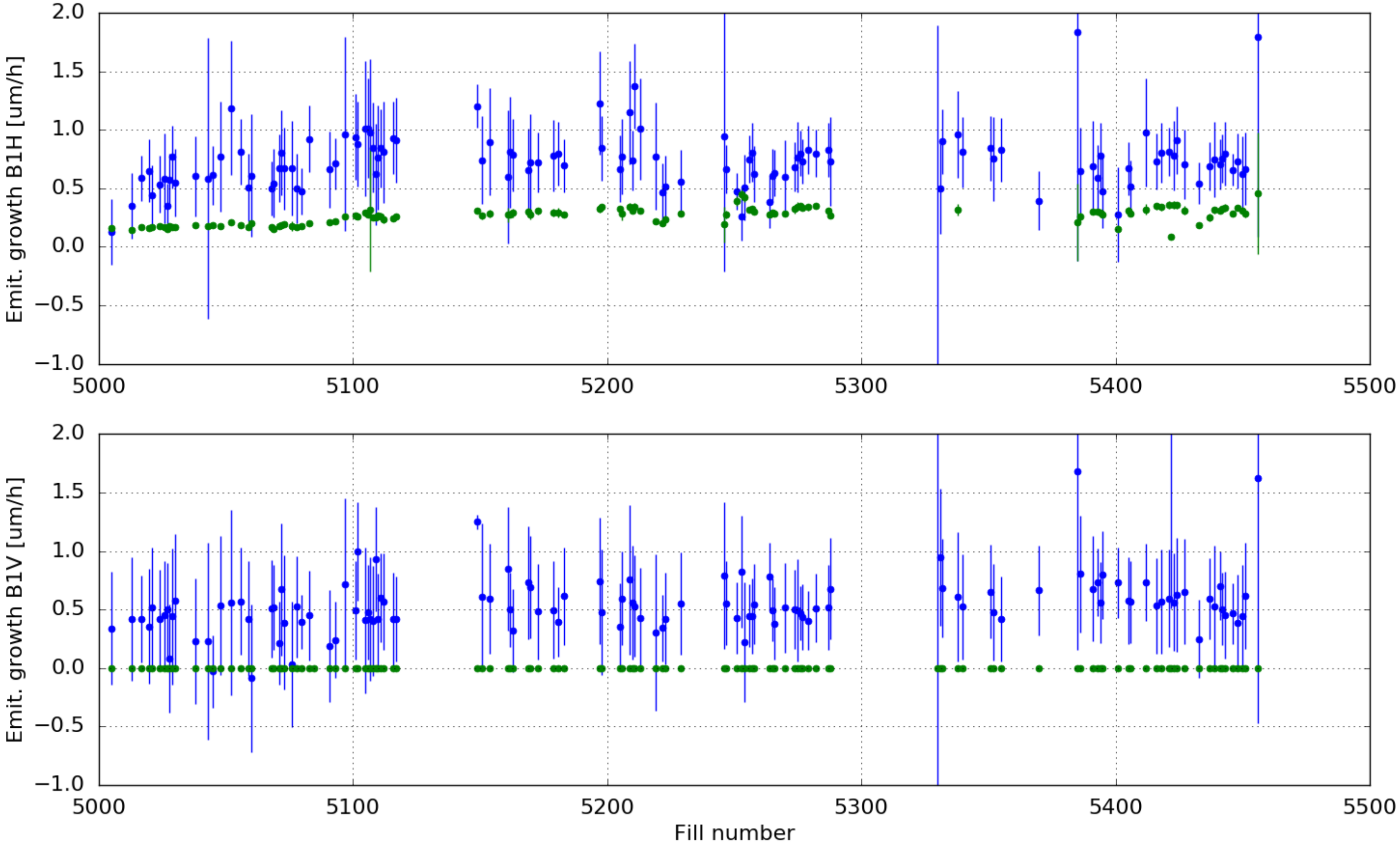
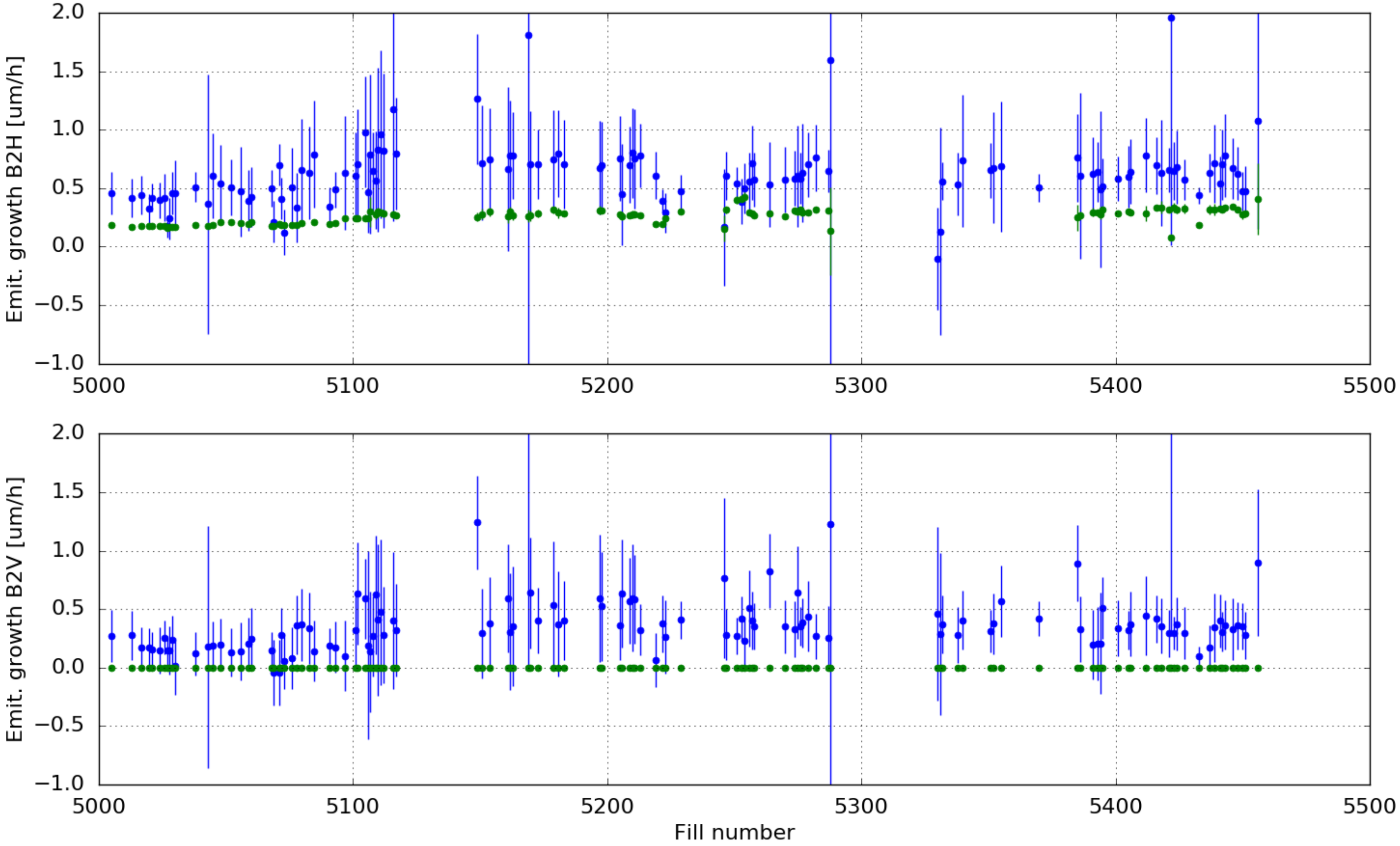
Emittance evolution during Flat Bottom – Beam 1



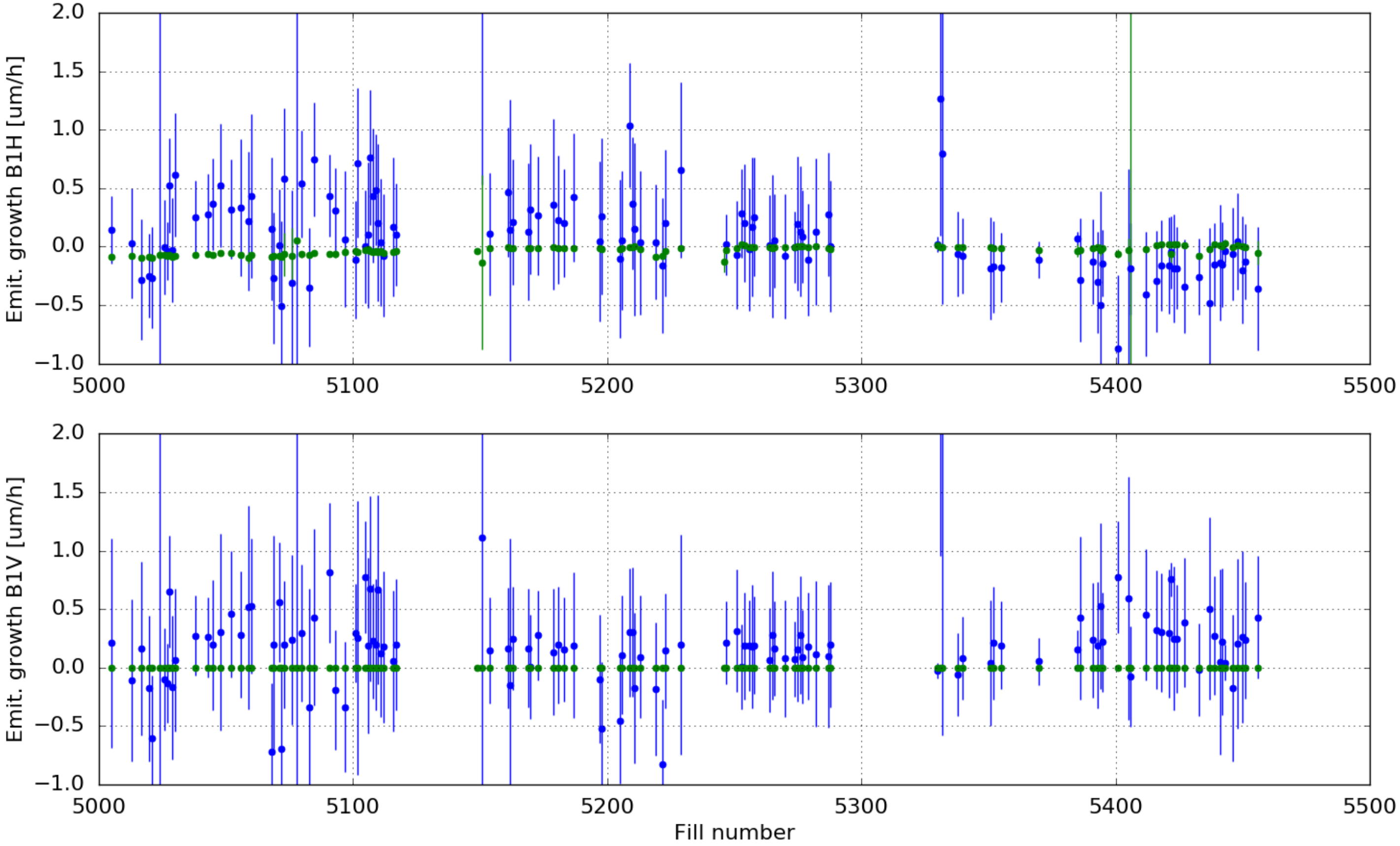
BSRT data
model

Emittance evolution during Flat Bottom – Beam 2



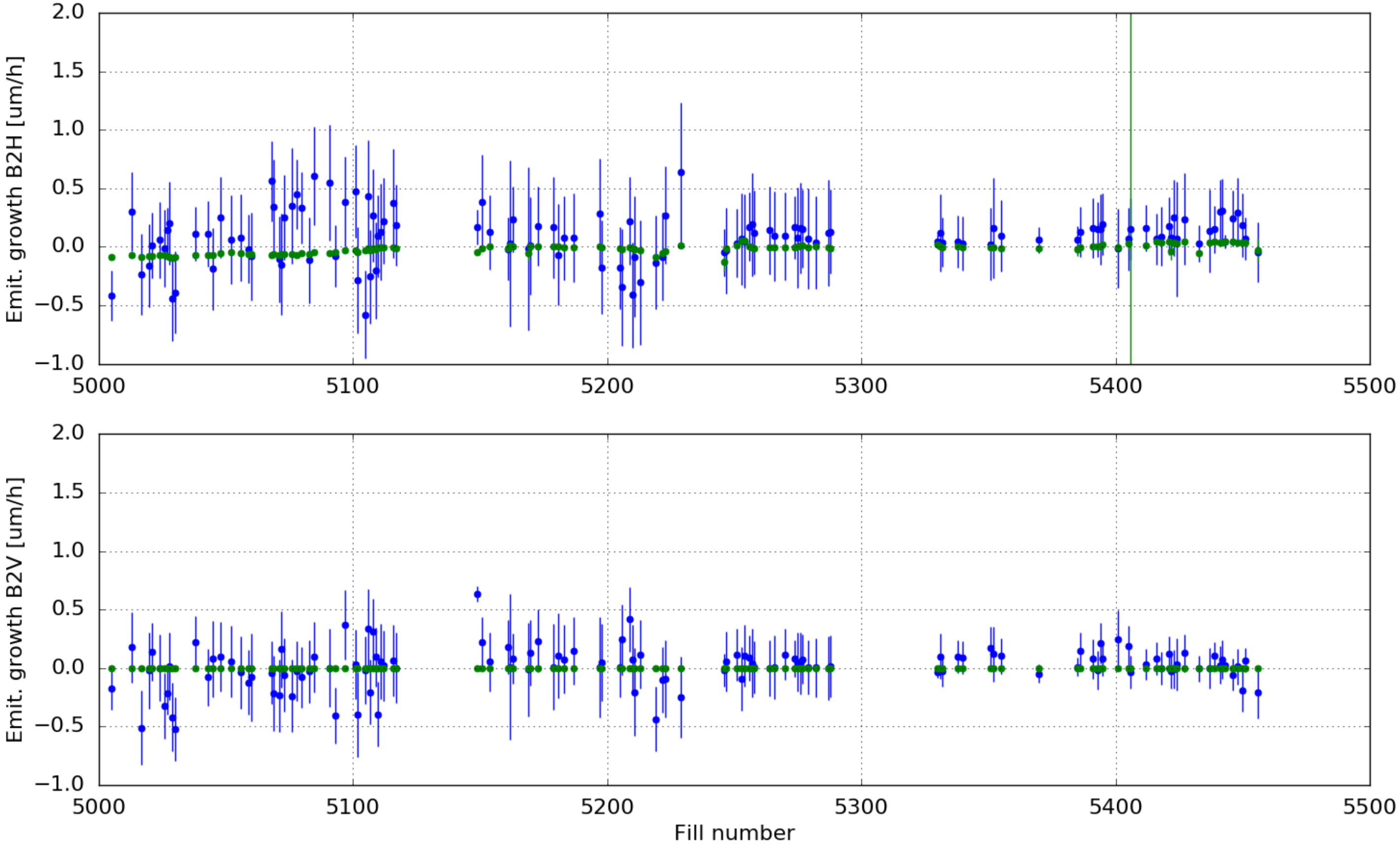
BSRT data
model

Emittance evolution during Flat Top – Beam 1



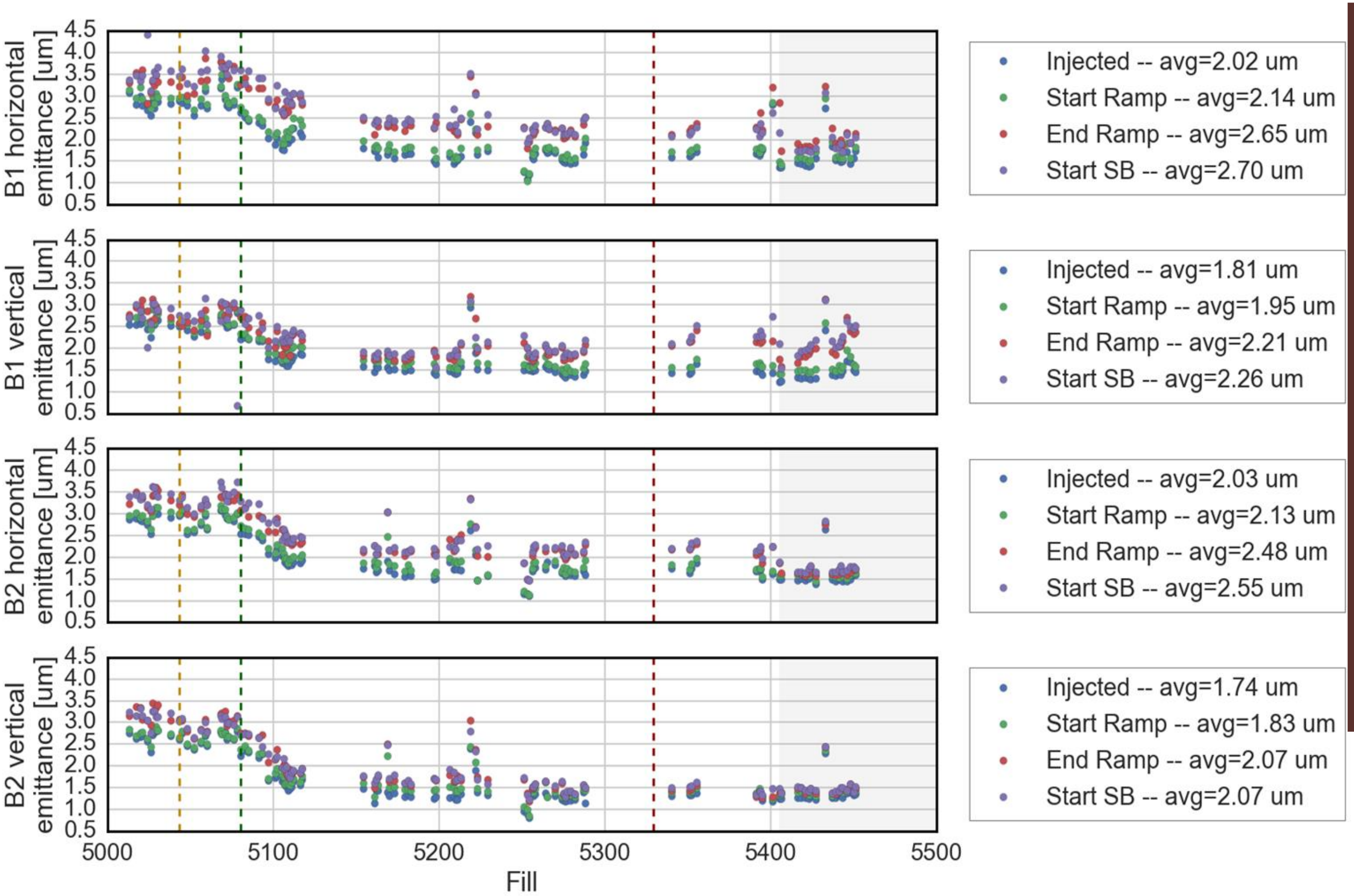
BSRT data
model

Emittance evolution during Flat Top – Beam 2



BSRT data
model

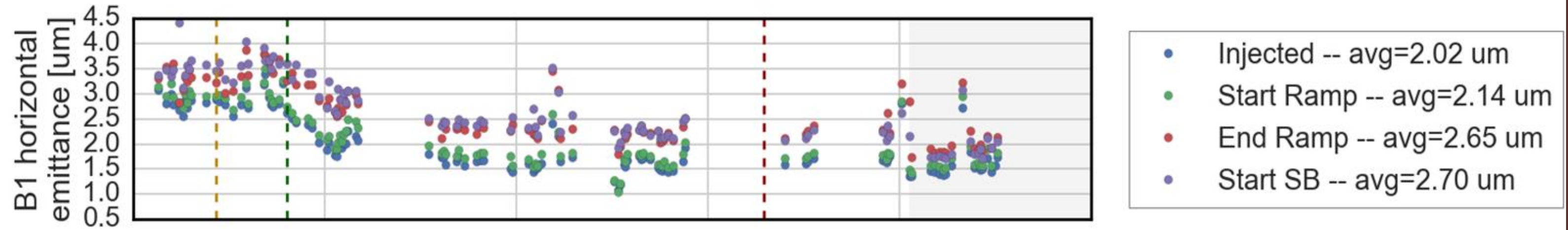
Emittance evolution from injection to stable beams – model corrected



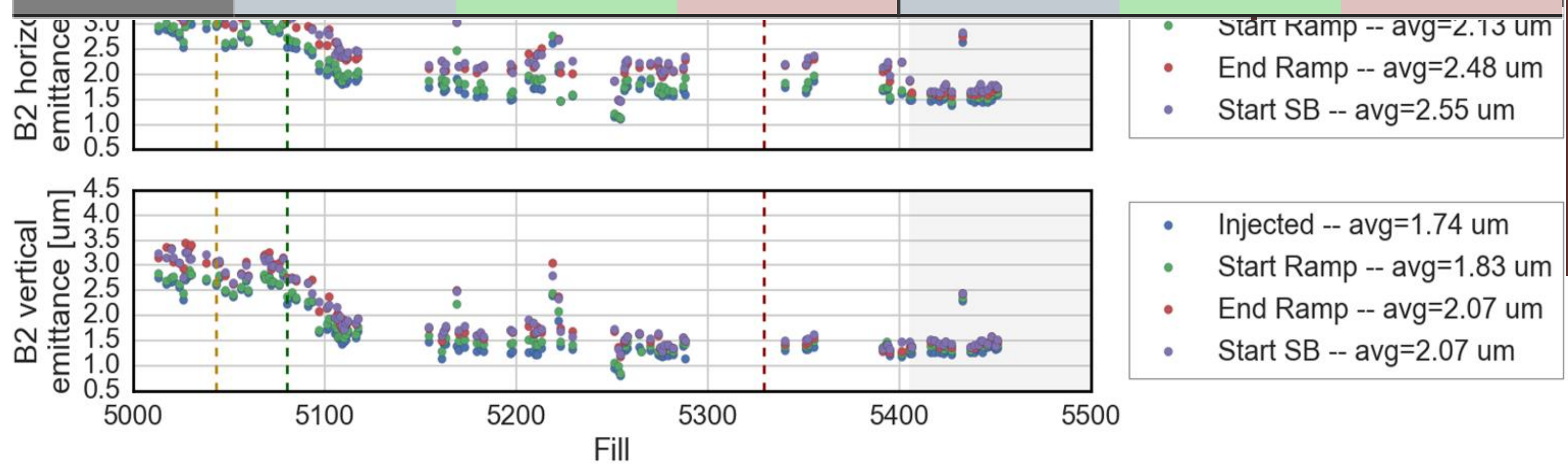
- Good **emittance preservation** for the small beams (~ 1.5 um injected)
- On average, B1 worse than B2, H worse than V – largest blow-up observed during ramp (up to 0.5 um)
- Additional blow-up **under investigation** – no apparent correlation with brightness (noise as possible source?)

From K. Li, Chamonix 2017

Emittance evolution from injection to stable beams – model corrected



	B1 blow-up			B2 blow-up		
	Injection	Ramp	Flat-top	Injection	Ramp	Flat-top
H	0.12 um	0.51 um	0.05 um	0.10 um	0.35 um	0.07 um
V	0.14 um	0.26 um	0.05 um	0.09 um	0.24 um	**0.00 um**



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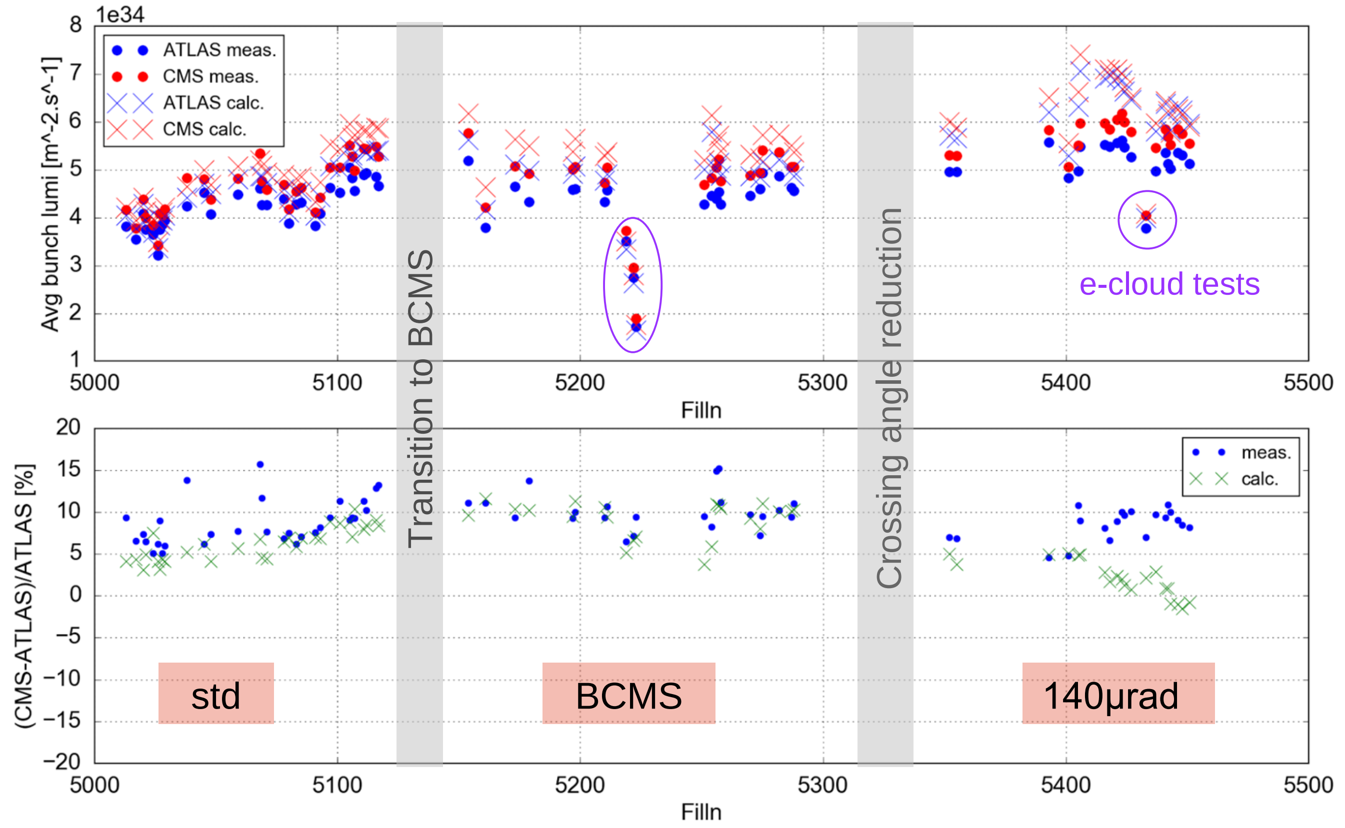
From K. Li, Chamonix 2017

Emittance evolution from injection to stable beams

- Remain **to be done**:
  - Add the model during the ramp (for the LHC parameters the effect is very small, of the order of 2-3%)
  - Estimate the peak luminosity loss per fill due to the extra emittance blow up during the cycle
    - It is almost ready.. needs to be finalized

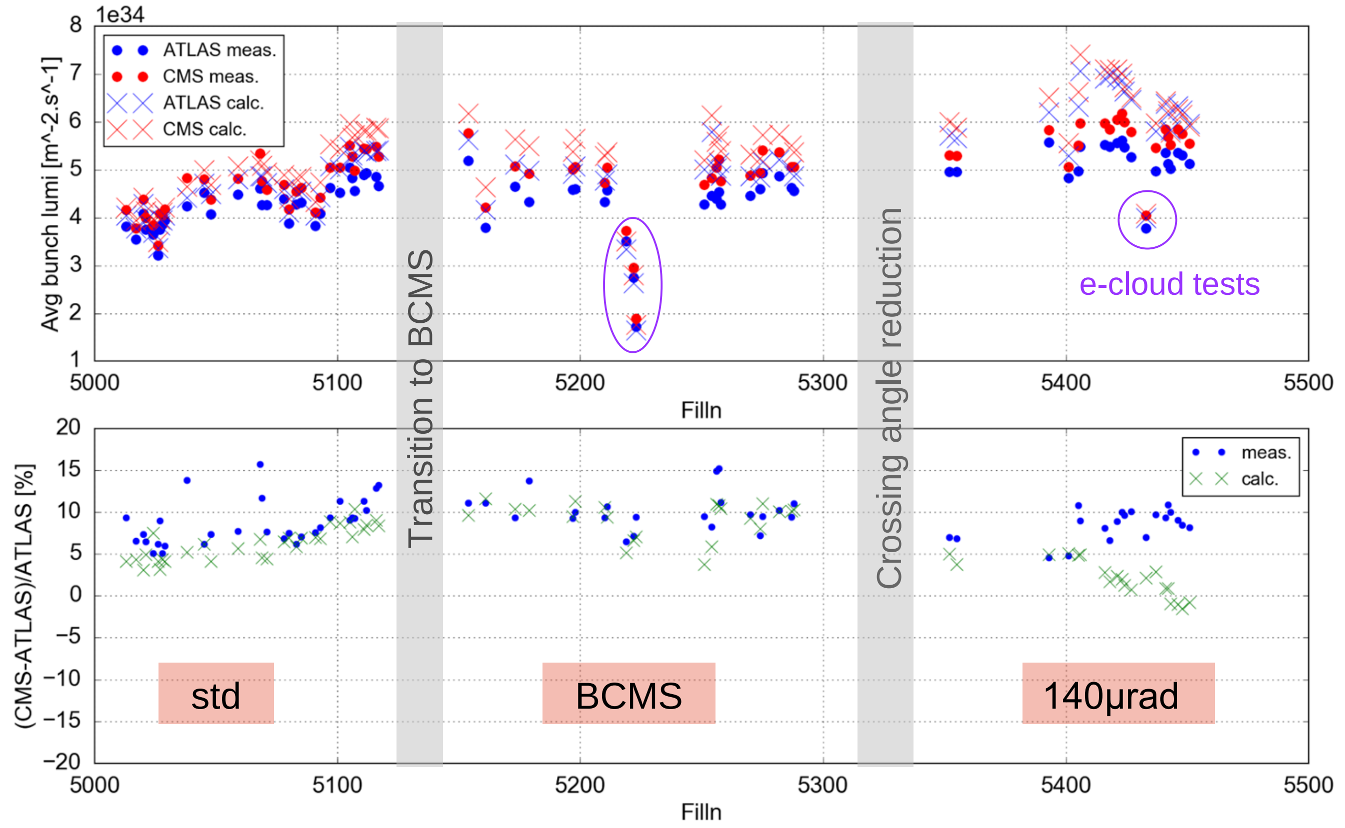
Stable Beams Analysis

Peak luminosity along the year



- Comparison of average peak luminosity as measured by the experiments (dots) and calculated by beam parameters (crosses)
- Fairly good agreement for large part of the run
  - Some discrepancy for the last fills (to be understood)

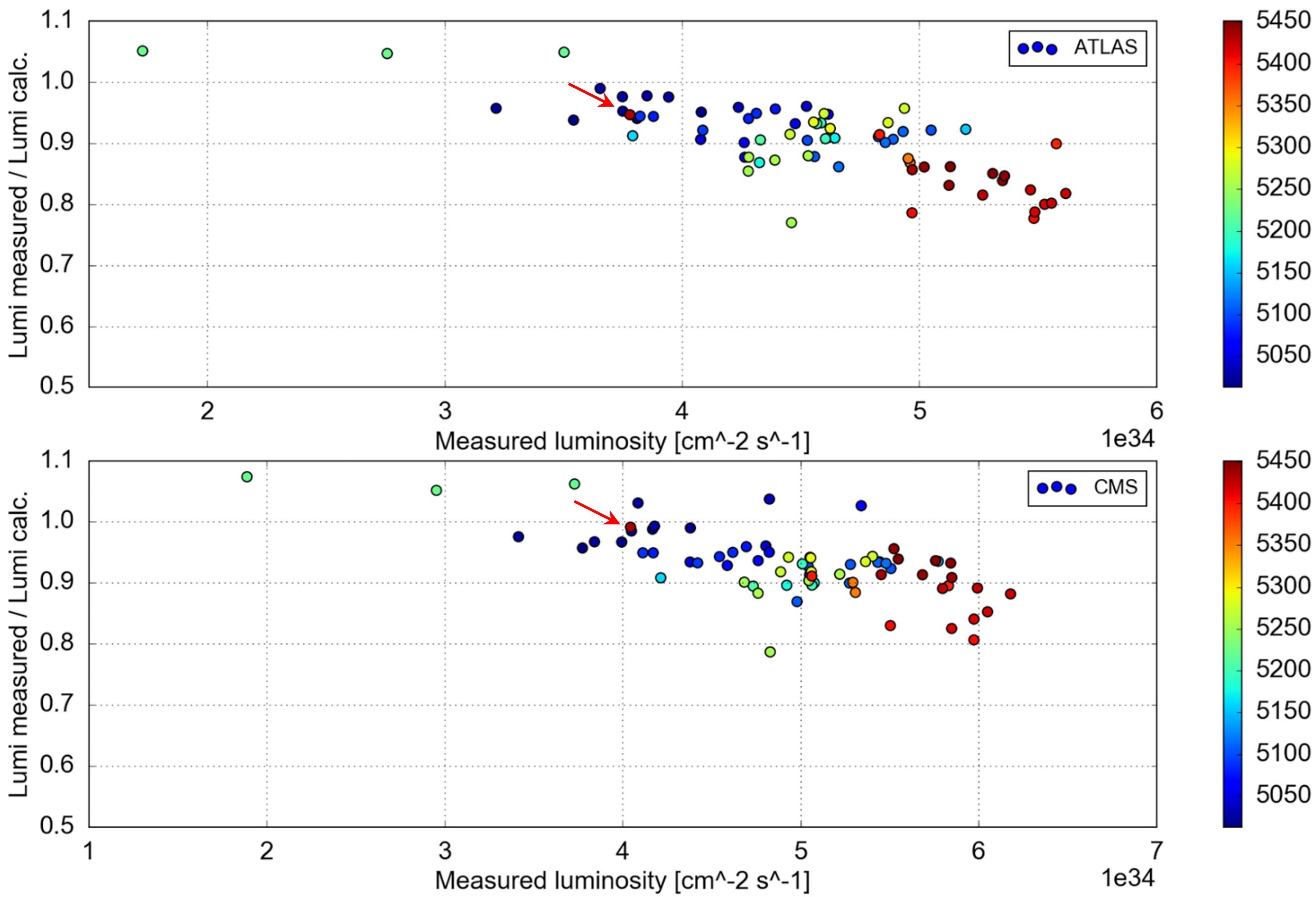
Peak luminosity along the year



To be done:

- Repeat the same plot with different set of BSRT calibration as requested by Jamie and Cristoph
  - Rescale the middle part to the last calibration factors
- Follow-up with the experiments to understand their limitations

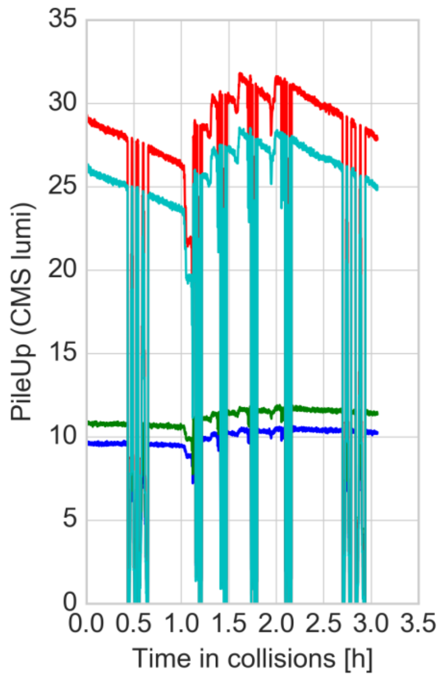
Peak luminosity along the year

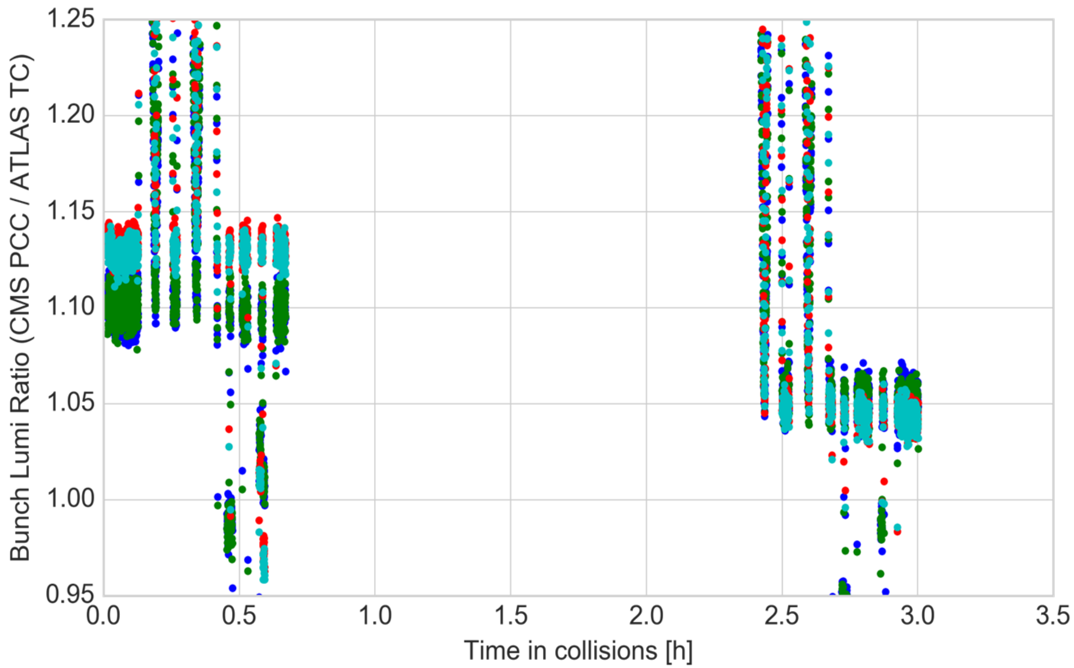


- Correlation of the difference between the measured and calculated luminosity with the measured peak luminosity observed
  - Valid also in the same BSRT calibration factor periods

- **To be done**:
  - verify with the other set of BSRT calibration factors
  - Check within the same calibration periods

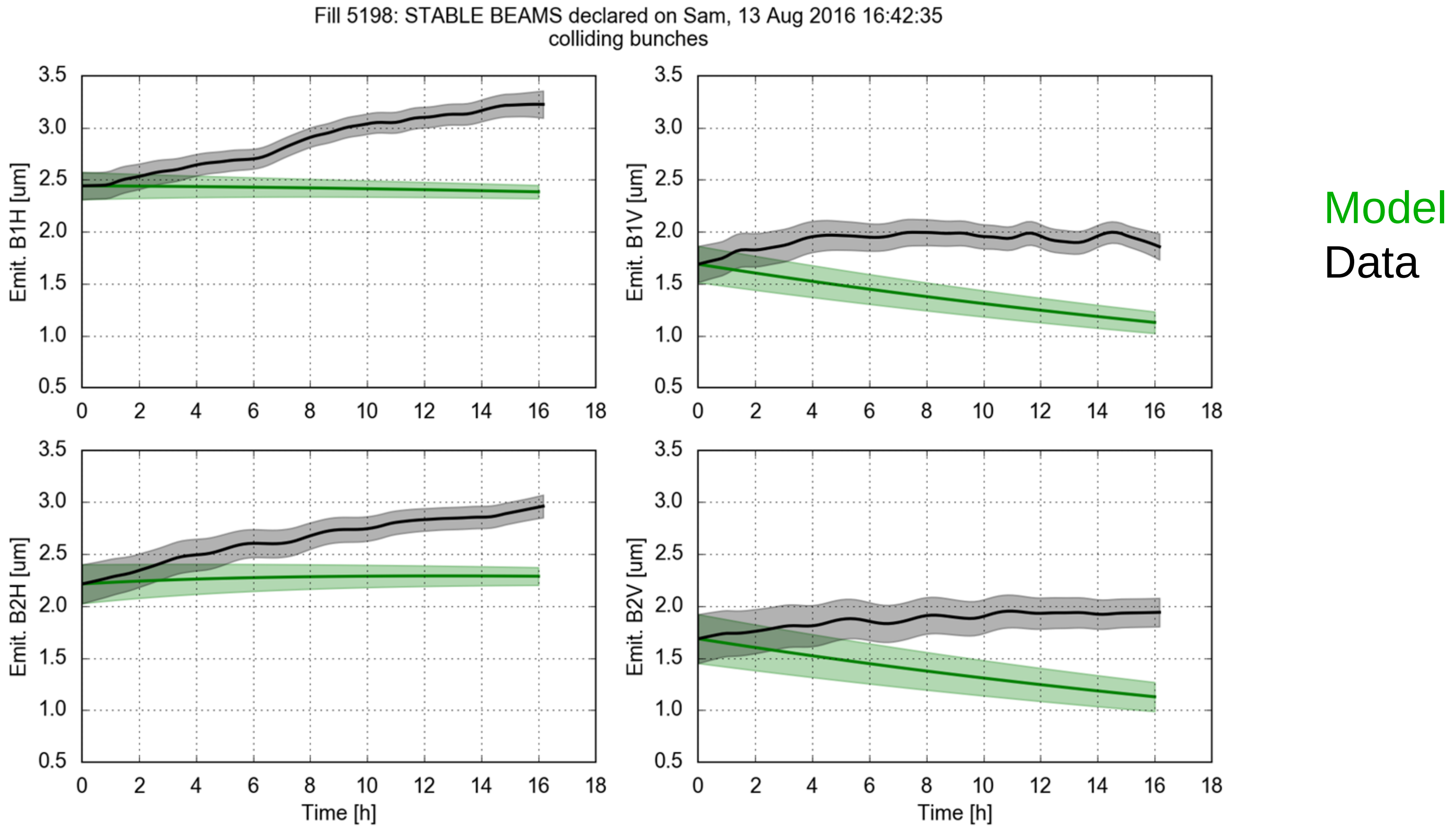
Peak luminosity along the year





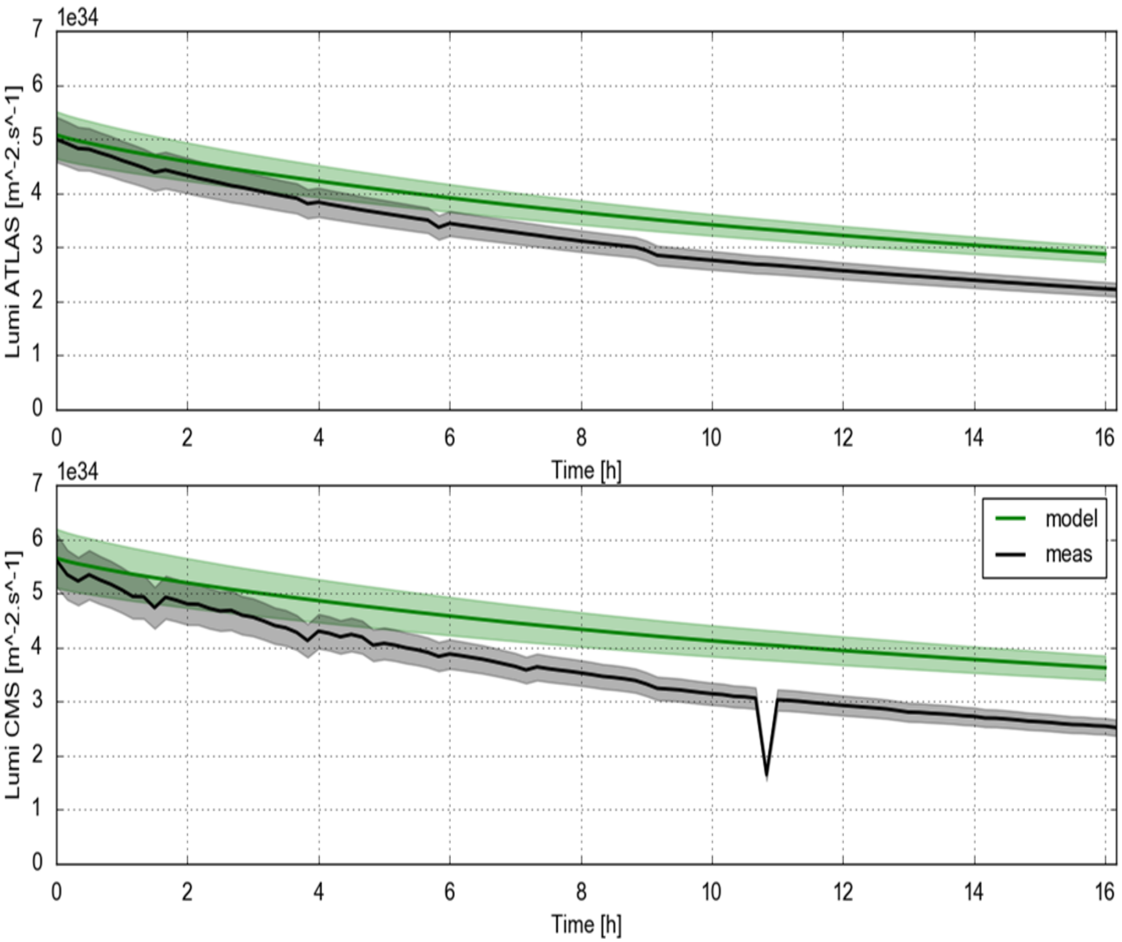
- A very interesting experiment followed up by Michi and W. Kozanecki
  - Crossing angle scan test
  - 4 bunches with different brightness were brought to collision
  - ~5-8% geometric effect (larger for lower emittance bunches)
  - ~5% imbalance still observed at zero crossing angle

Bunch parameters evolution



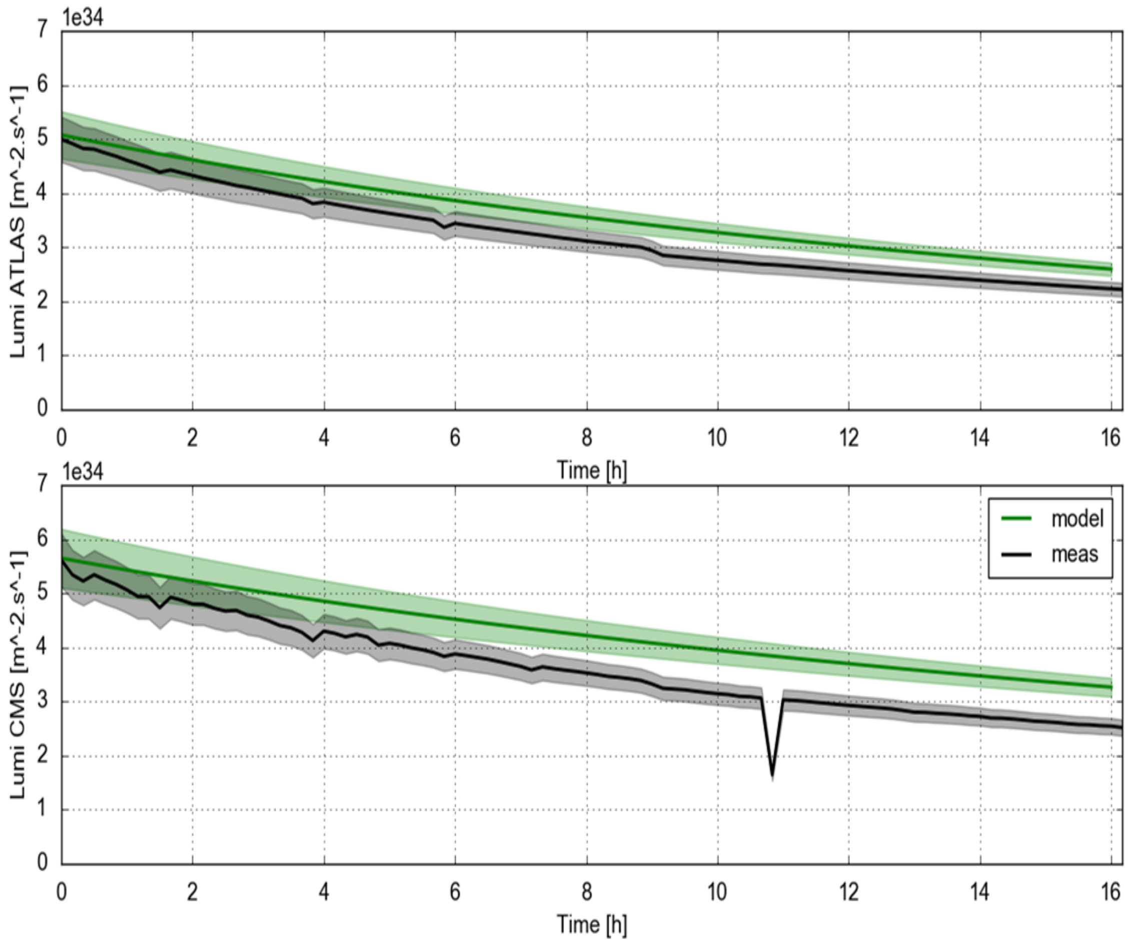
- Using as input only the initial values for the transverse emittance, bunch length and bunch intensity
- Larger emittance blow up observed than expected
- The prediction is not good also for the bunch length and bunch intensity
- Missing sources of extra emittance blow up and losses to be understood

Luminosity evolution prediction



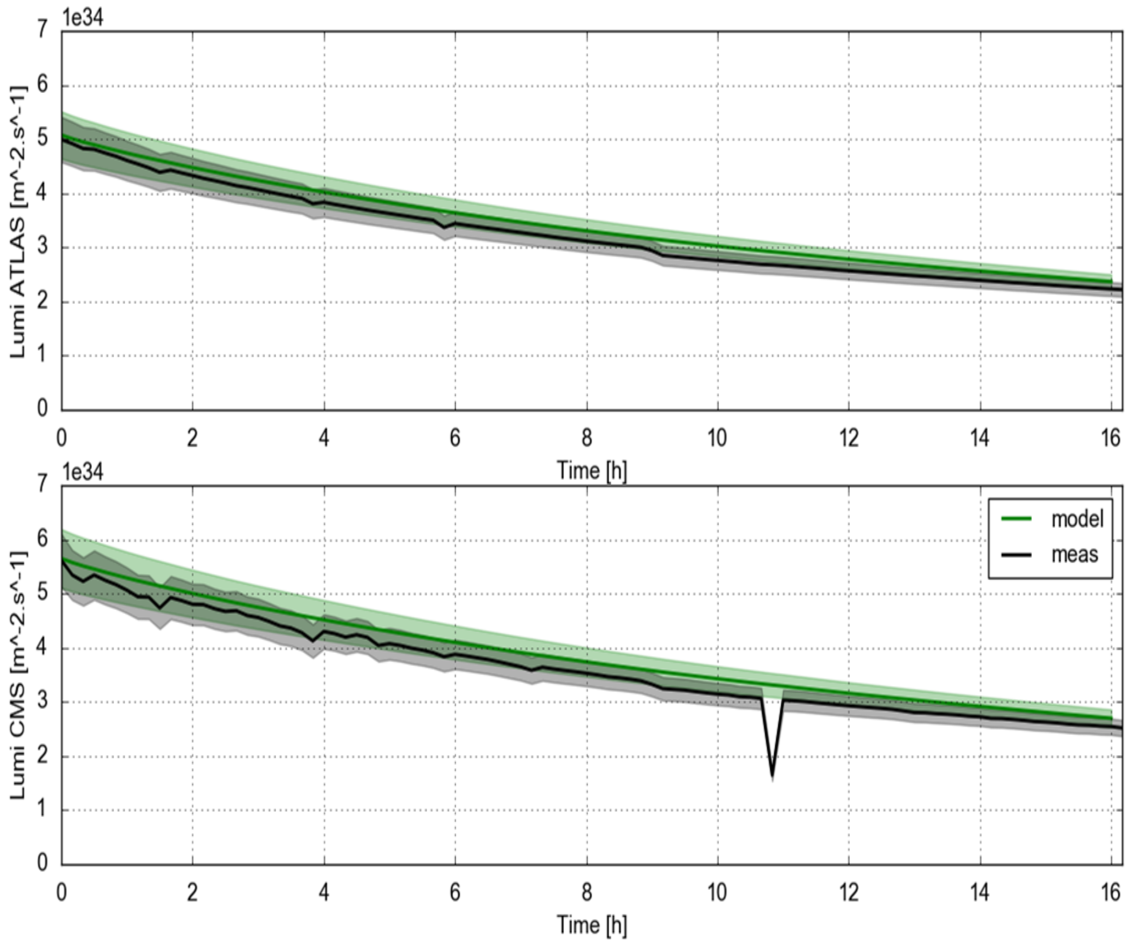
- For each Fill the model is applied under different assumptions and the luminosity evolution is calculated bunch-by-bunch
- Comparison of the average evolution assuming the **ideal case**: **IBS+SR+Burn-off**
- Only initial bunch parameters are taken from the data and then the model is iterated to predict the evolution of emittances, bunch length, bunch intensity and luminosity

Luminosity evolution prediction



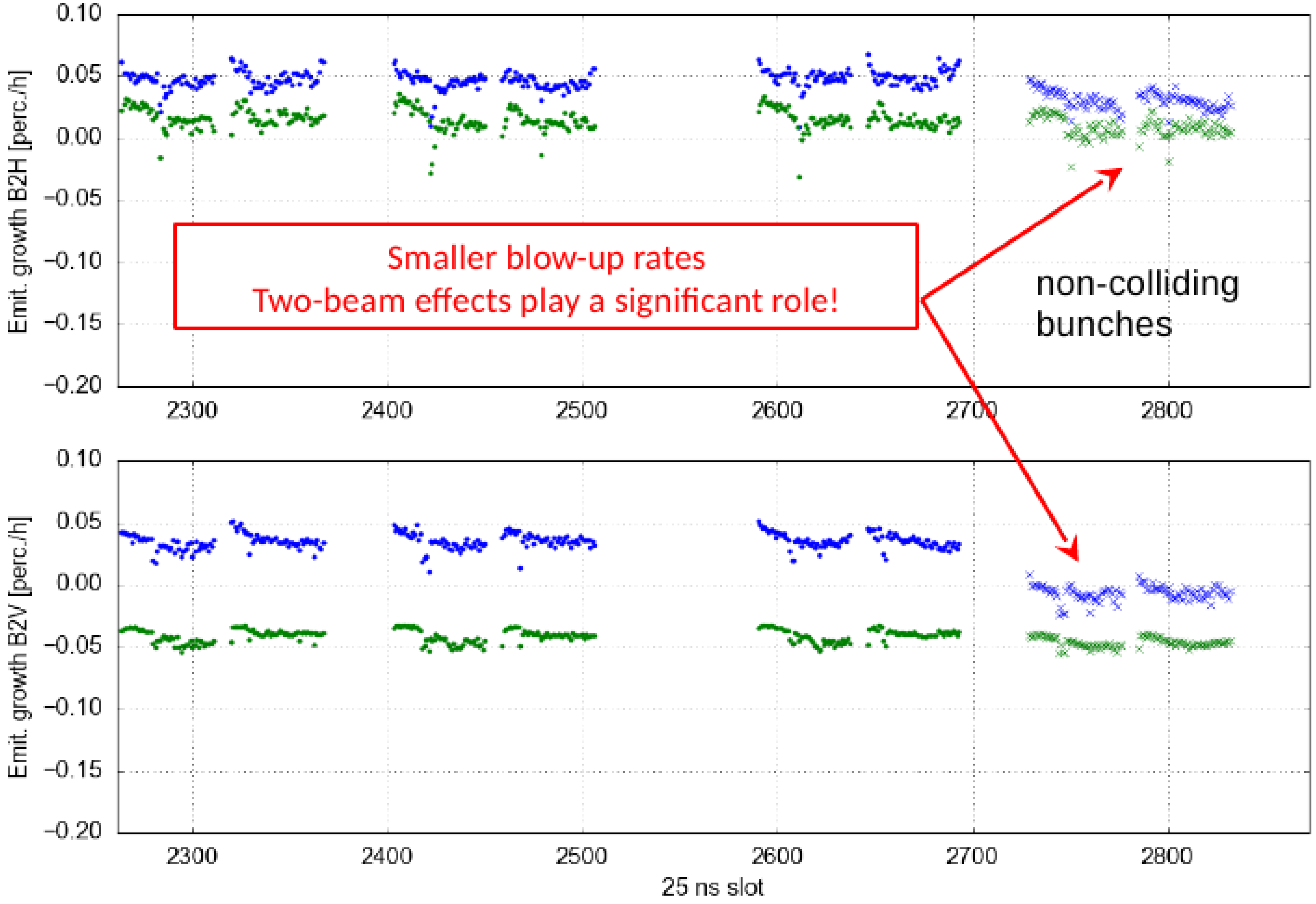
- For each Fill the model is applied under different assumptions and the luminosity evolution is calculated bunch-by-bunch
- Comparison of the averaged evolution using the **empirical bunch intensity** evolution: **IBSEmpiricalLosses**
- Bunch intensity evolution from the data. The model computes the emittance, bunch length and luminosity evolution

Luminosity evolution prediction



- For each Fill the model is applied under different assumptions and the luminosity evolution is calculated bunch-by-bunch
- Comparison of the average evolution using the **empirical bunch intensity** and **empirical emittance evolution**: **EmpiricalBlowUpEmpiricalLosses**
- Bunch intensity and emittance evolution from the data. The model computes the bunch length and luminosity evolution

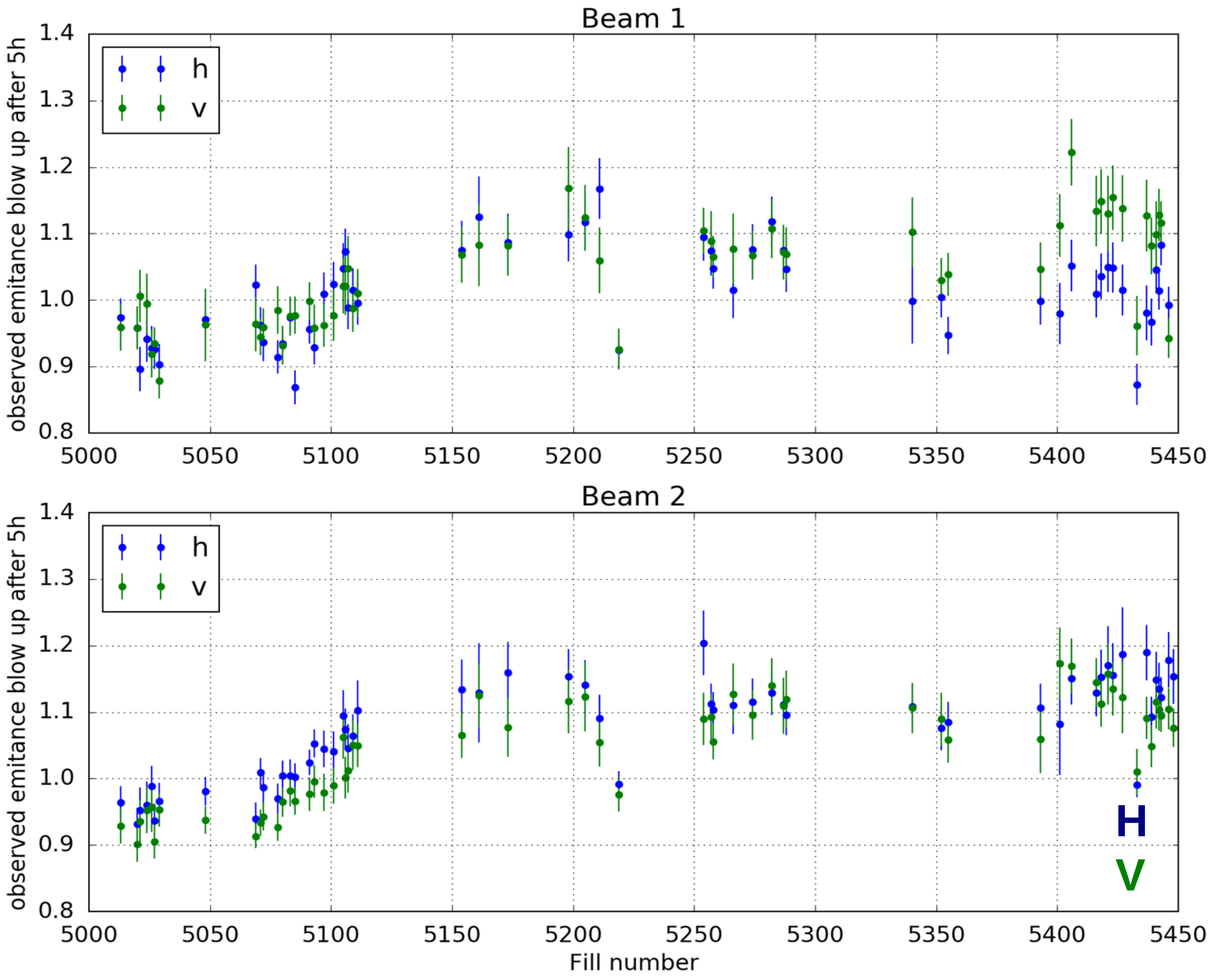
Extra emittance blow-up



•**Fill 5205** went in collision with **one non-colliding BCMS train in B2** Ideal to make comparisons

•Non-colliding bunches blow-up less → 2-beam effects play a significant role

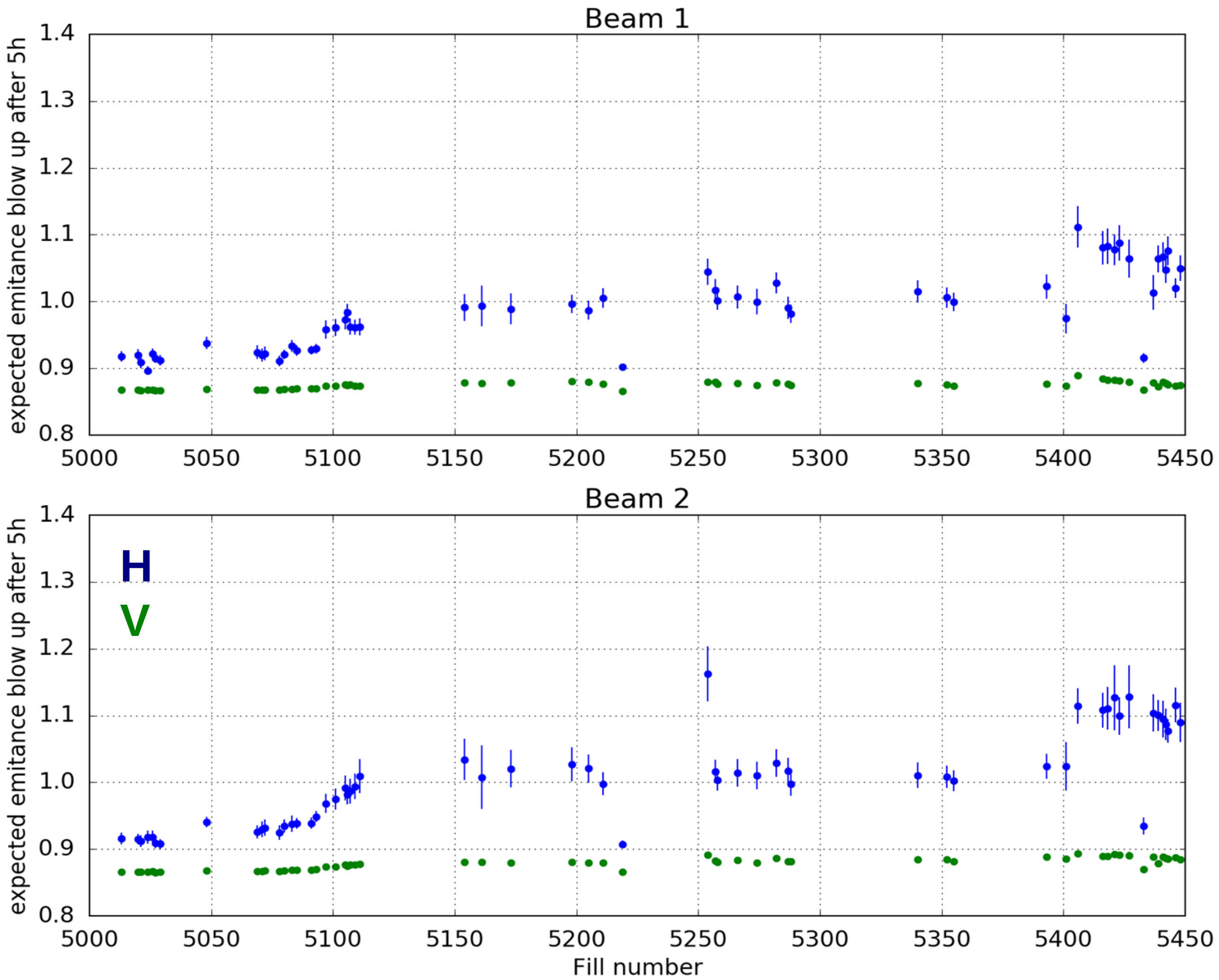
Observed emittance blow-up



- Emittance growth within **±0.1 um/h**

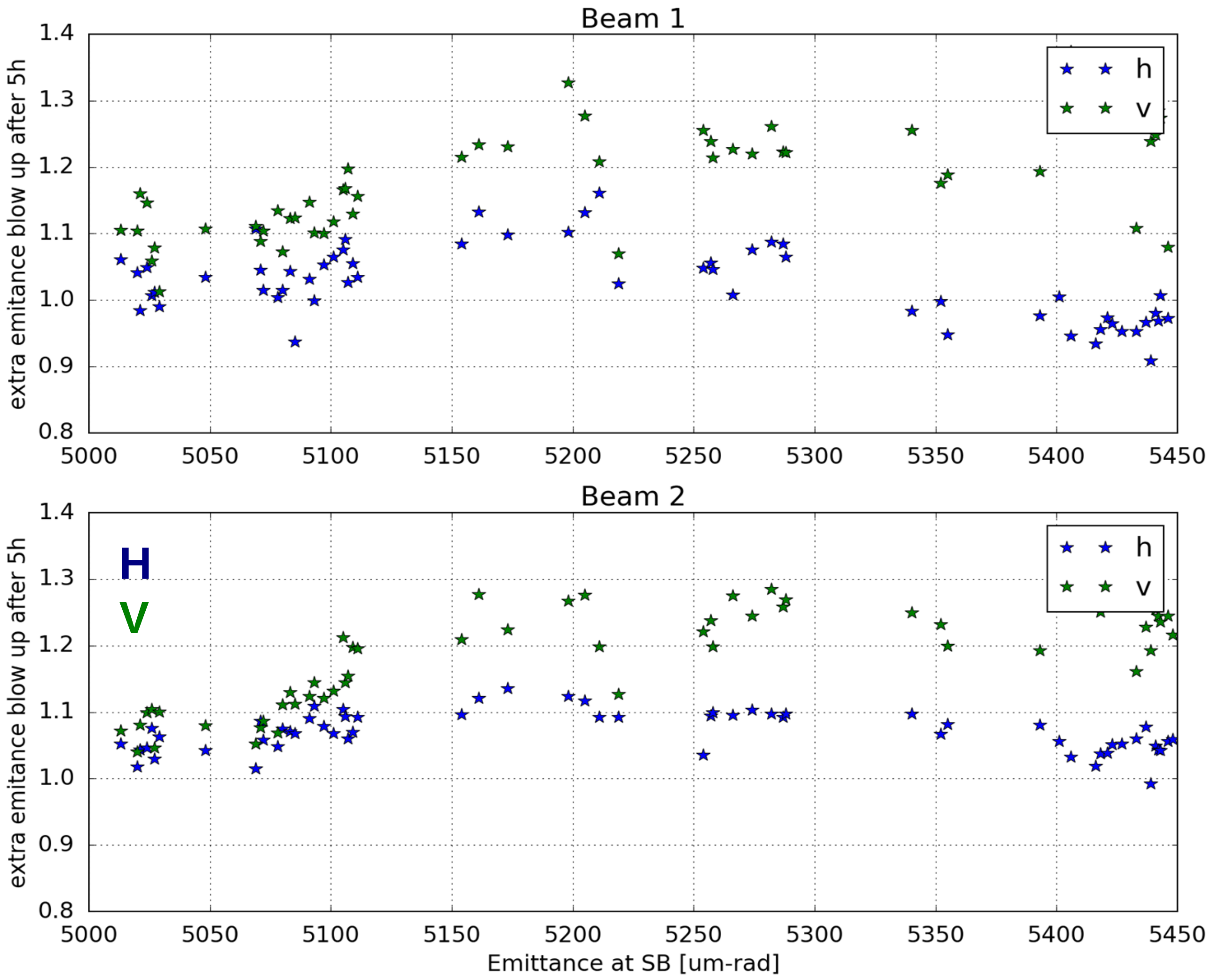
*Observed emittance blow up = emittance after 5h in SB / emittance at the beginning of SB

Expected emittance blow-up



*Expected emittance blow up = pure model prediction after 5h in SB / emittance at the beginning of SB

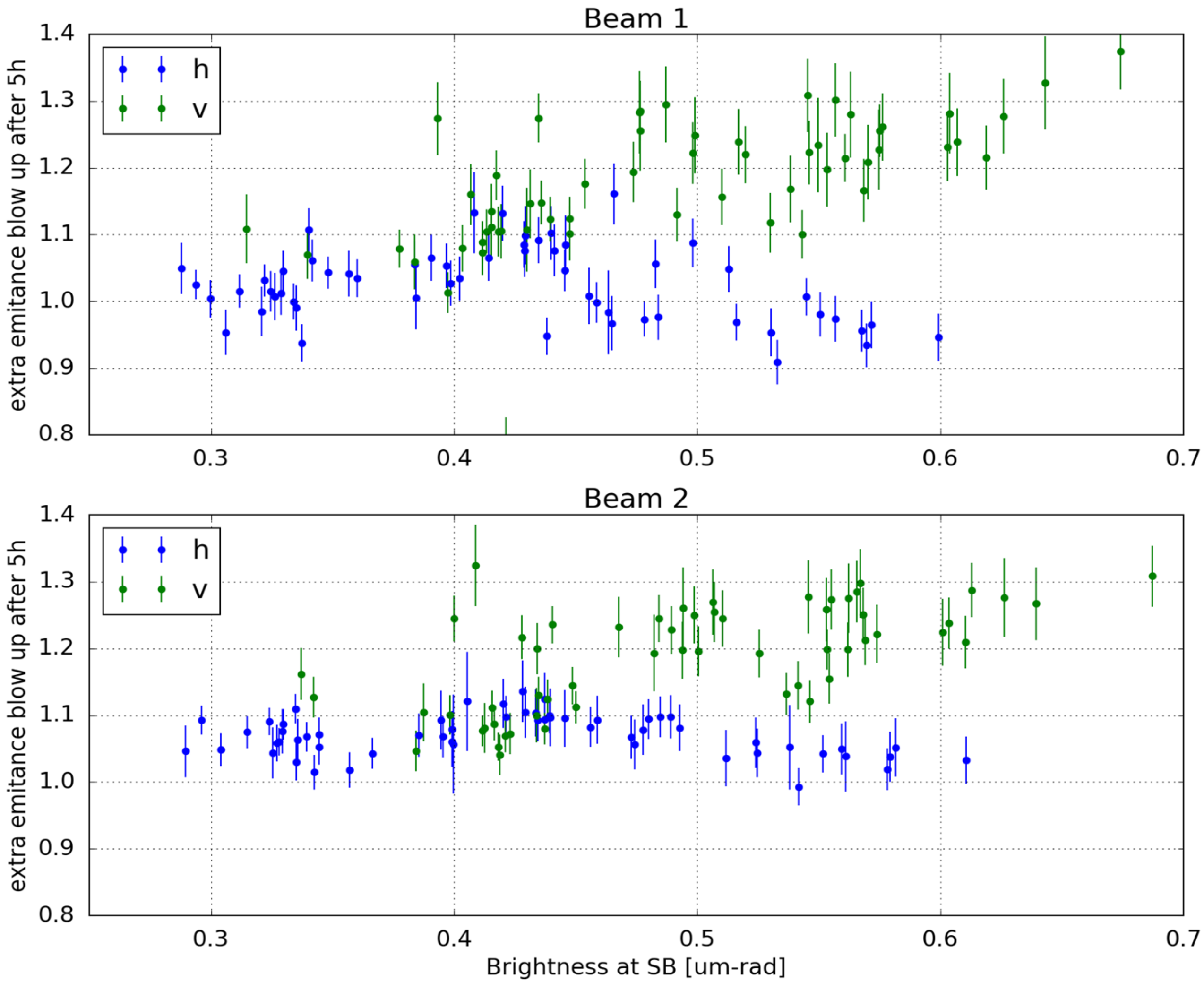
Extra emittance blow-up



- More blow up observed in the vertical plane

*Extra emittance blow up = observed emittance blow up / expected emittance blow up

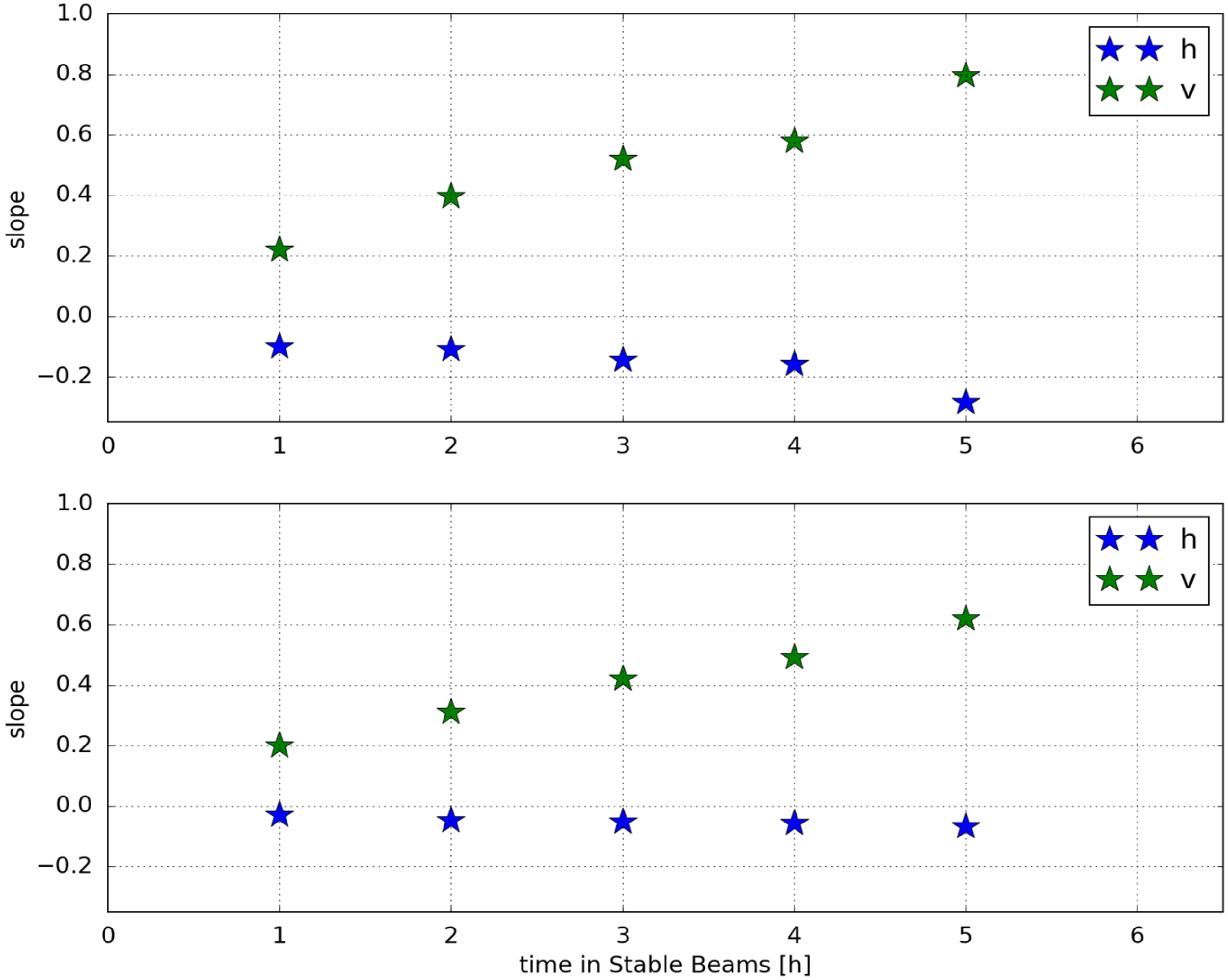
Brightness correlations



- Very weak brightness dependance
  - Mainly in the vertical plane

*Extra emittance blow up = observed emittance blow up / expected emittance blow up

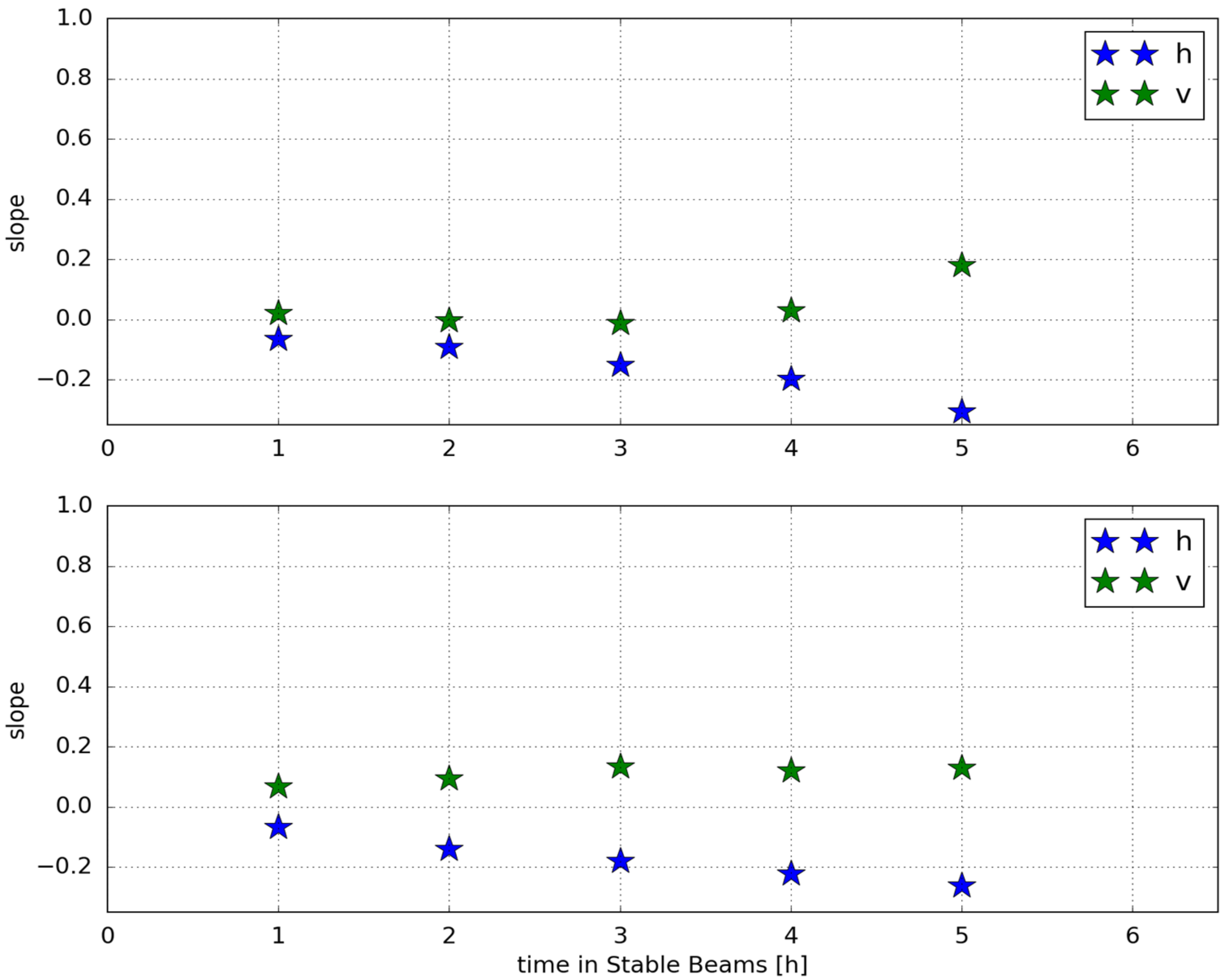
Brightness correlations – colliding bunches



- For every fill a linear fit was applied to the extra emittance blow up versus initial brightness, after 1-5h in Stable Beams
- Only colliding bunches are used
- The slope of the linear fit versus the time in stable beams is shown in the plots
- Brightness dependence of the extra emittance blow up in the vertical plane

*Extra emittance blow up = observed emittance blow up / expected emittance blow up

Brightness correlations – non-colliding bunches

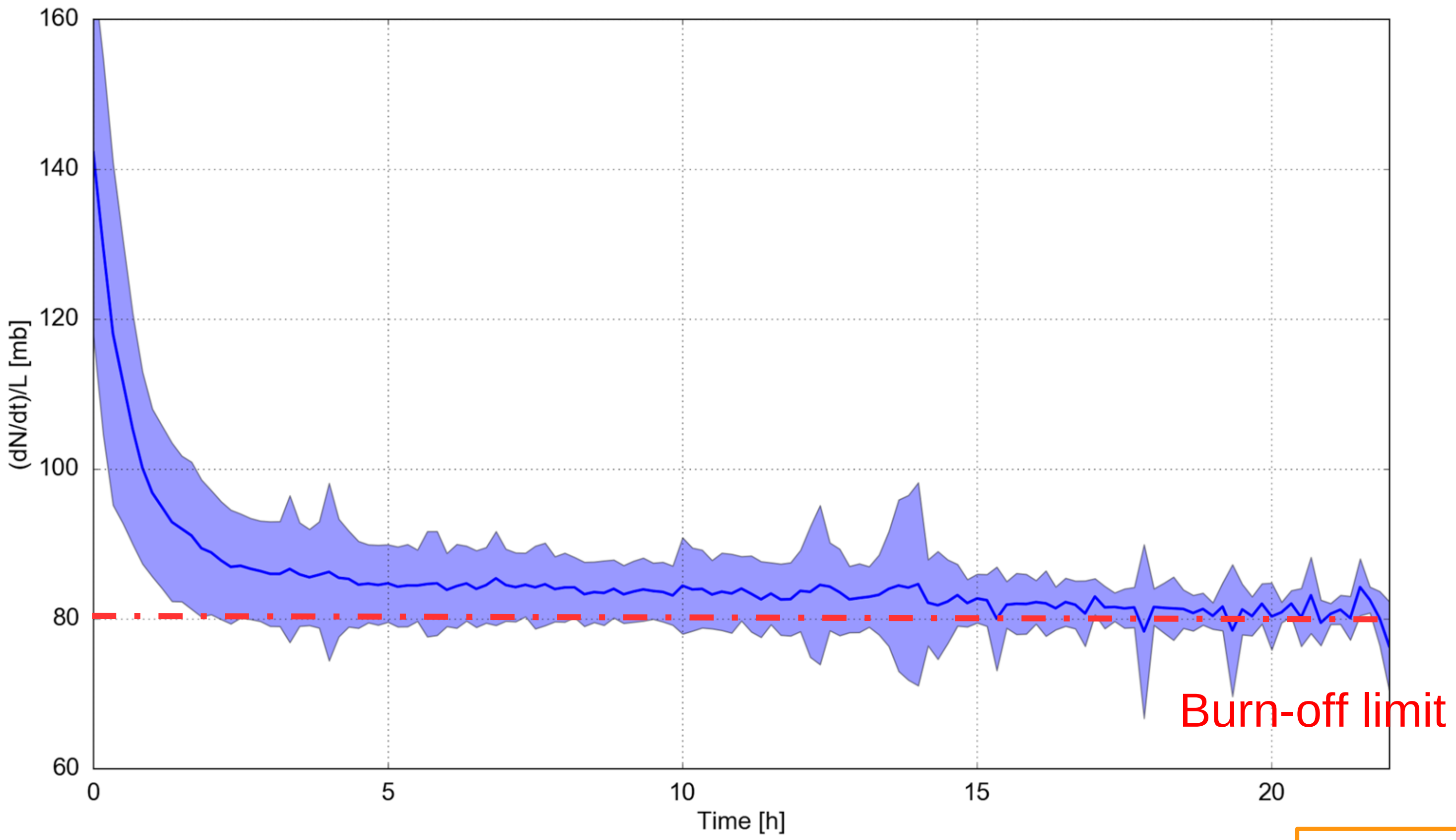


*Extra emittance blow up = observed emittance blow up / expected emittance blow up

- For every fill a linear fit was applied to the extra emittance blow up versus initial brightness, after 1-5h in Stable Beams
- Only non-colliding bunches are used
- The slope of the linear fit versus the time in stable beams is shown in the plots
- No brightness dependence is observed in both planes

To be done:
Further investigation of the observations
More detailed bbb analysis

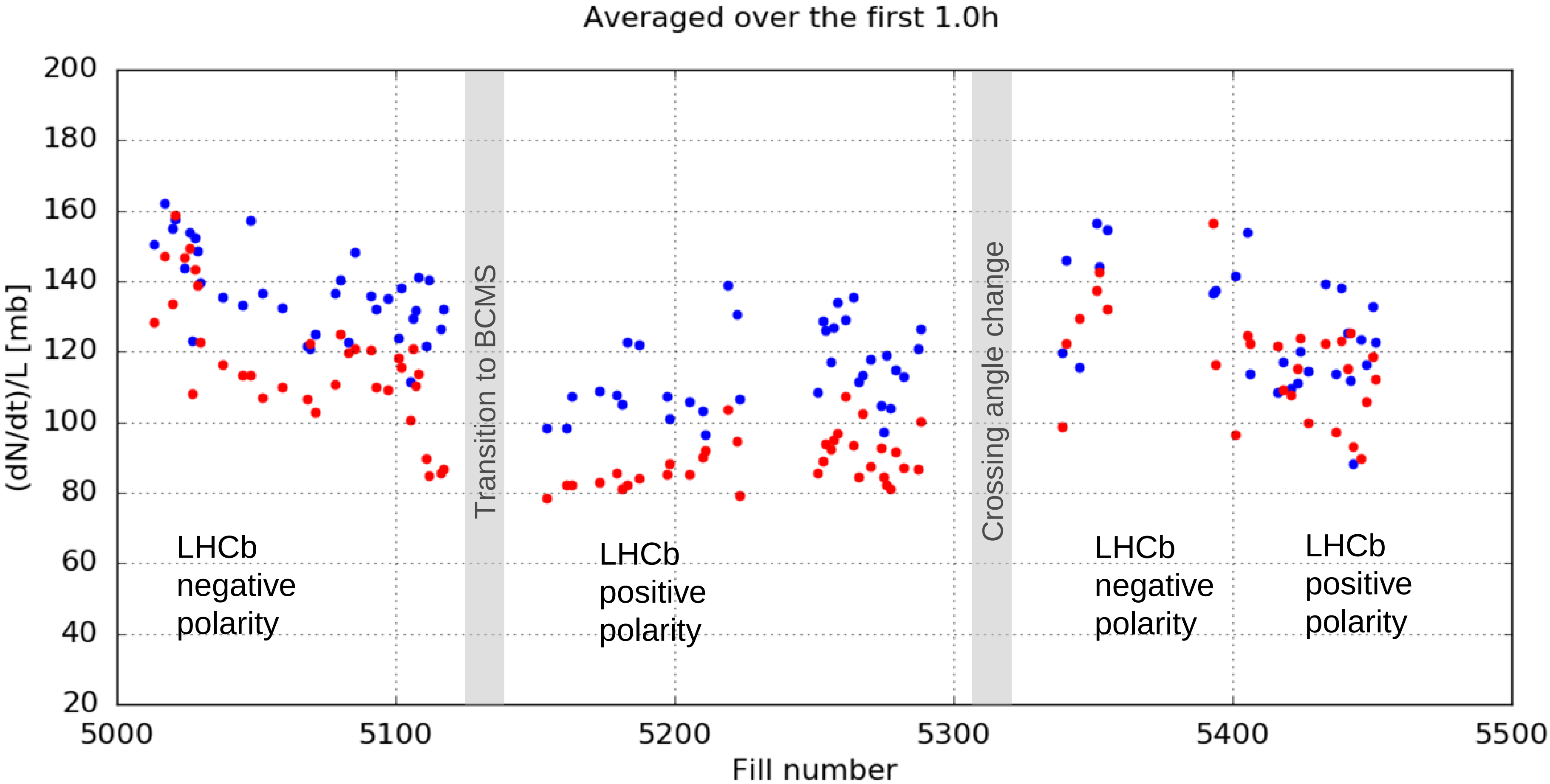
Beam Losses



- Normalized loss rate for all fills
- Losses on-top of Burn-off were observed for many fills
- Mainly the first 3h and then become burn off dominated

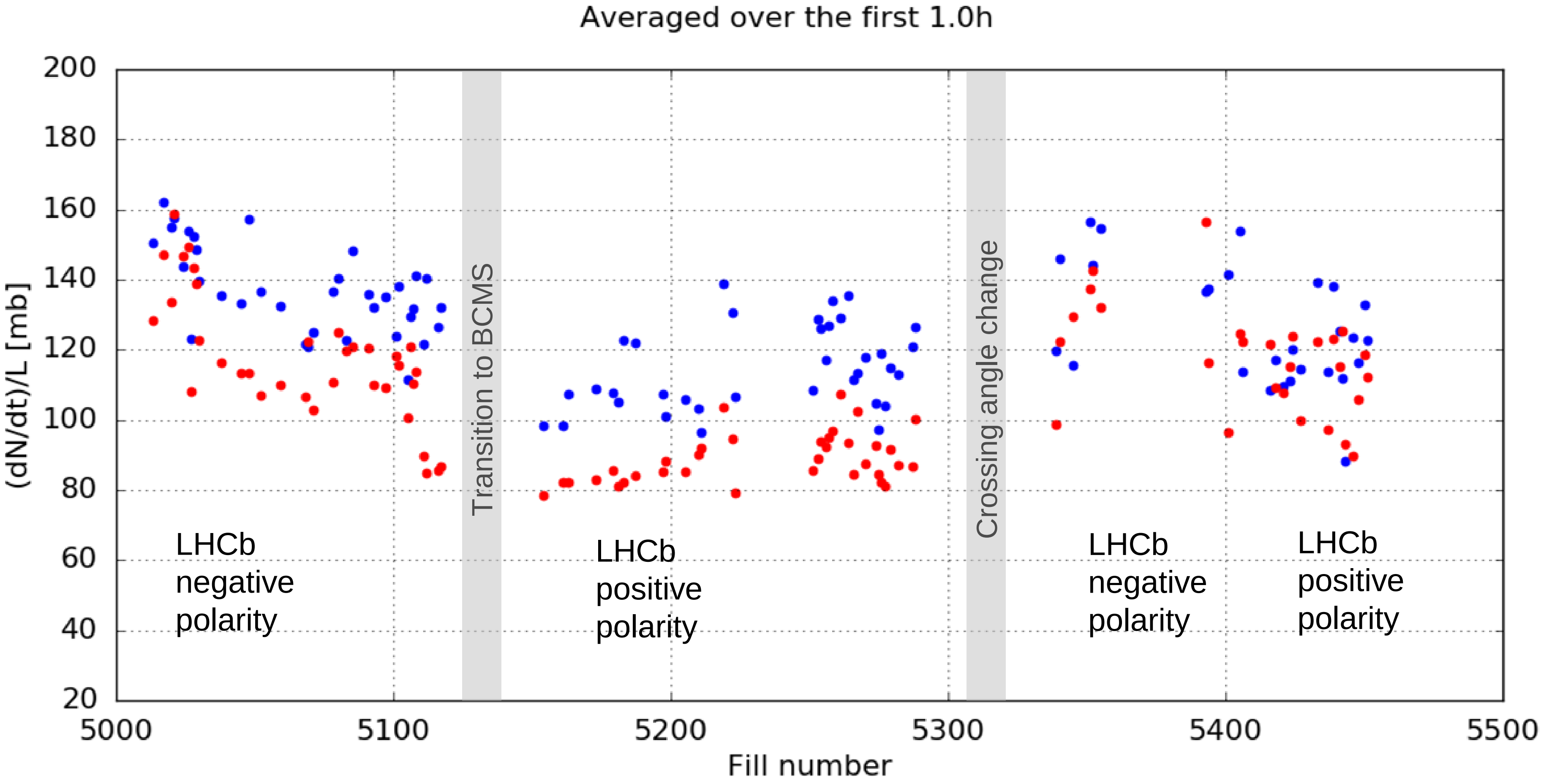
To be done:
Check the convergence limit bunch-by-bunch and fill by fill

Beam Losses



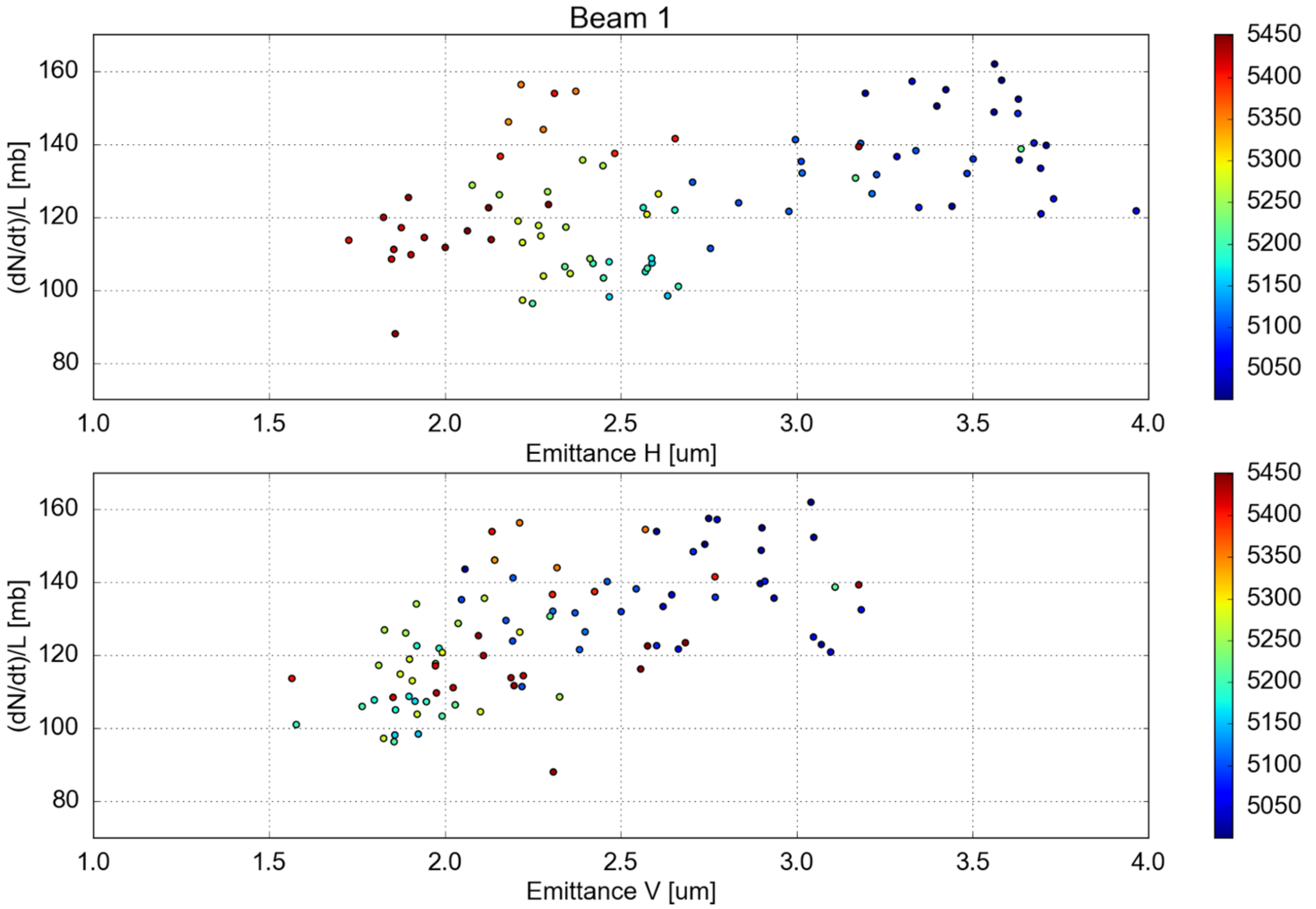
- Evolution of the average normalized losses (after one hour in SB) along the run
- Beam 1 losses higher than Beam 2 losses
- Minimum losses after the transition to BCMS (Beam 2 losses become burn-off dominated)
- Increase of losses after the crossing angle change followed by an improvement trend
  - Clear impact of the LHCb polarity changes

Beam Losses



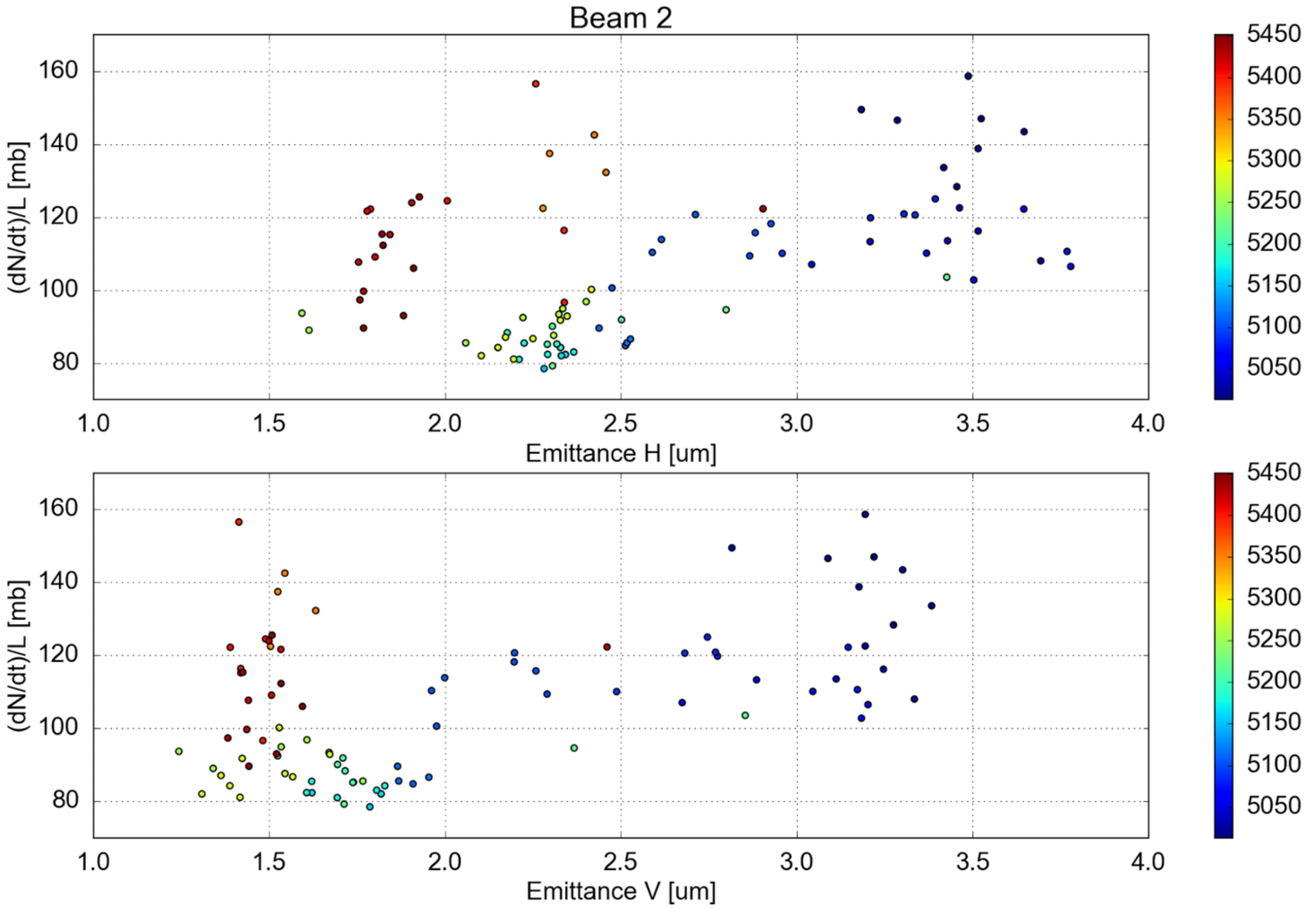
To be done: Estimate the integrated losses bunch-by-bunch and fill-by-fill at different time moments and the end of each fill. How this evolves in time and when does it reach the theoretical burn-off limit?

Beam Losses



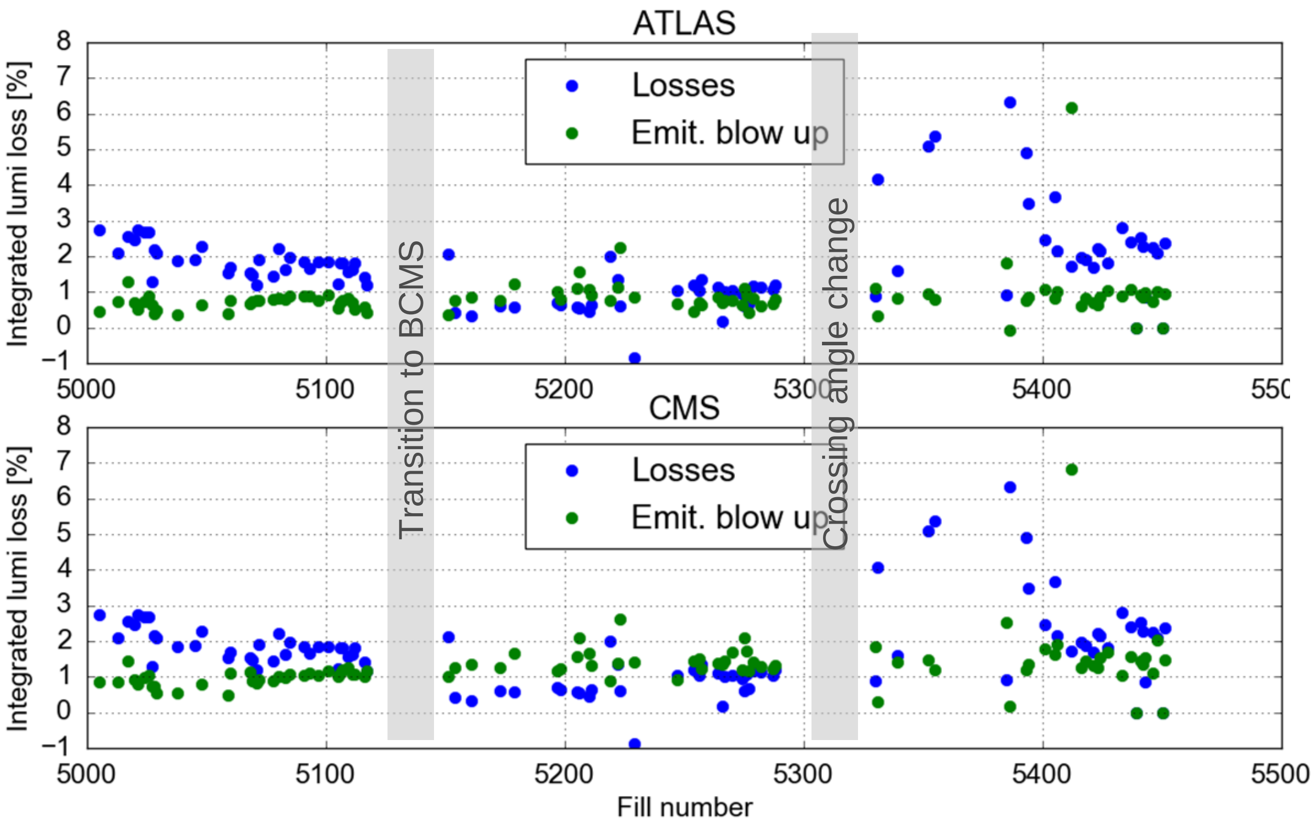
- Losses correlation with the emittance at the beginning of Stable Beams

Beam Losses



- Losses correlation with the emittance at the beginning of Stable Beams

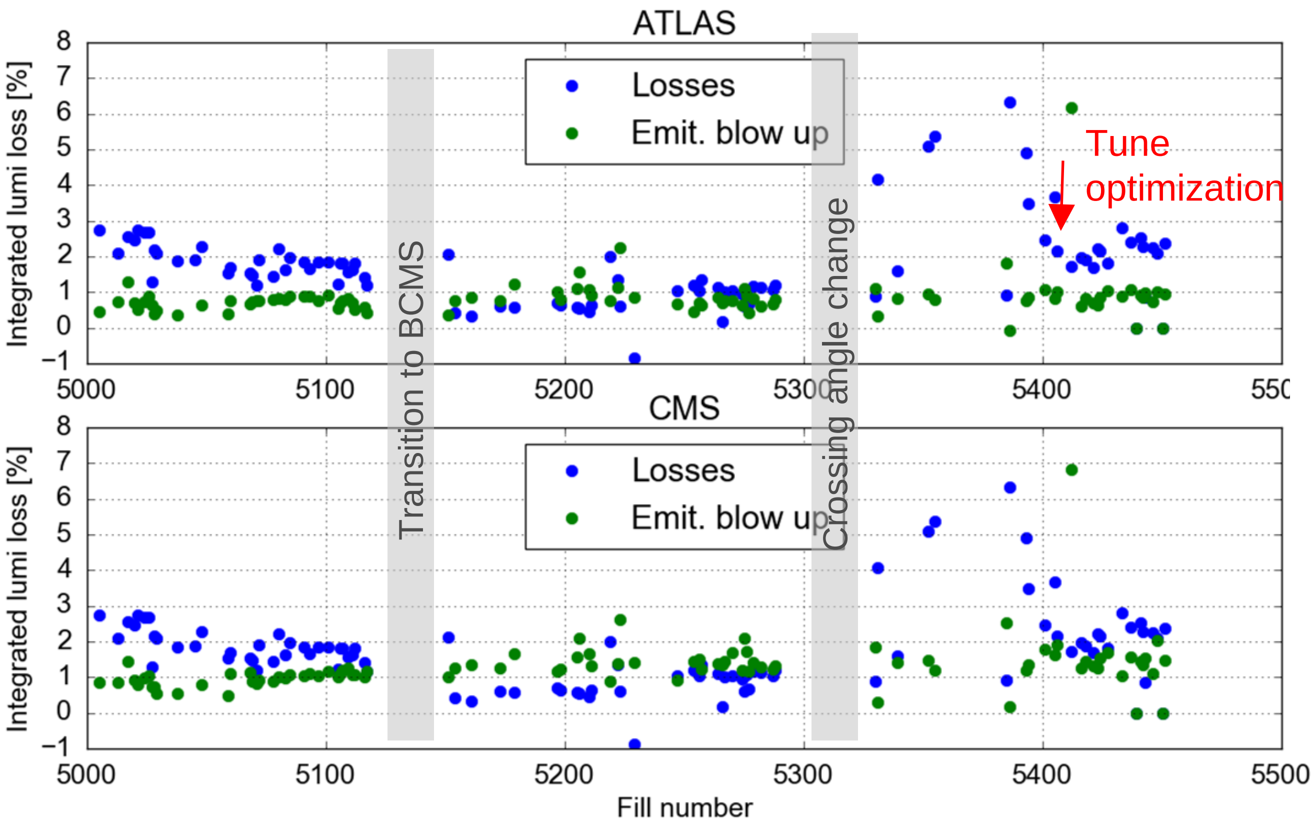
Integrated luminosity loss due to different degradation mechanisms



- The integrated luminosity over the first 3h is calculated for each model assumption
- Integrated luminosity loss due to:
  - **extra losses**
  - **extra emittance blow up**

- Contribution of the extra **emittance blow-up** is **constant** over the year
- Contribution of extra **losses** is **sensitive to changes in the machine**

Integrated luminosity loss due to different degradation mechanisms



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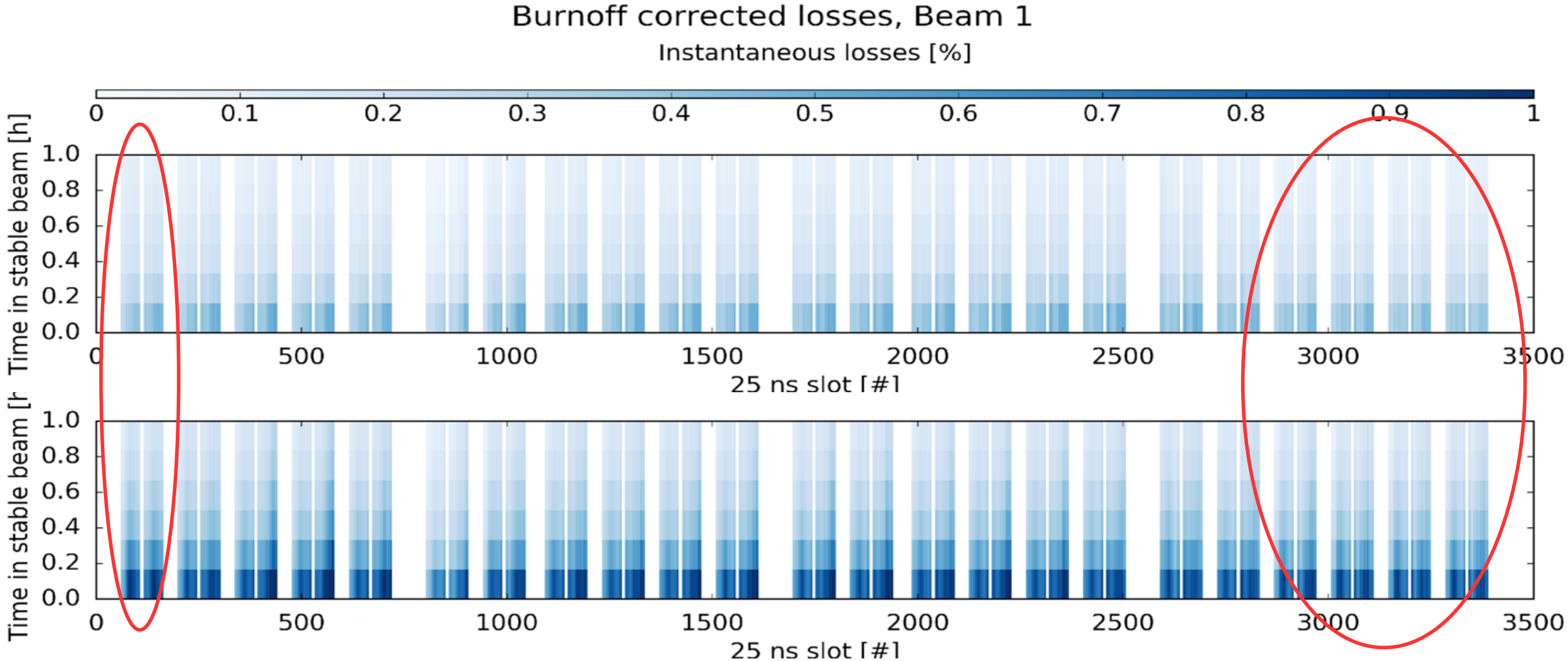
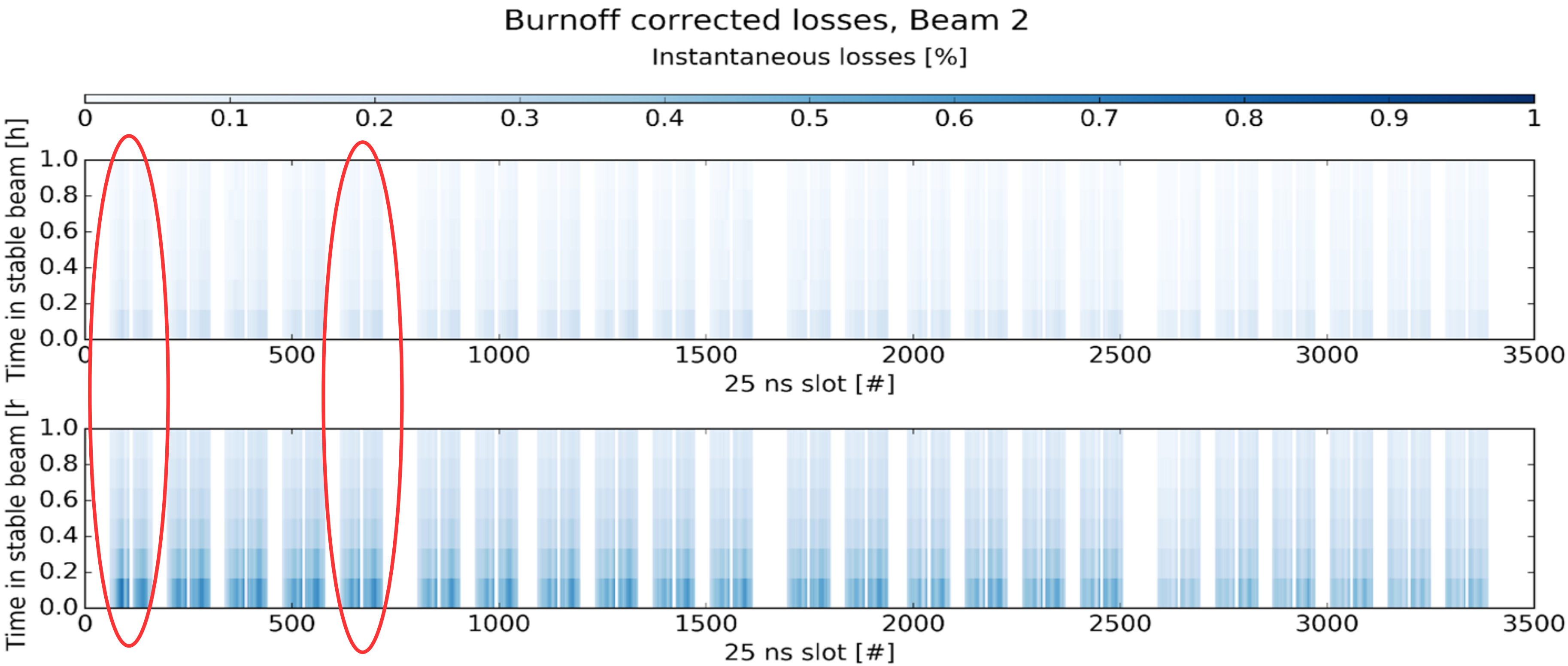
Instantaneous beam losses before and after the crossing angle change



- Burn-off corrected losses averaged over many fills for **Beam 1**
  - Top: crossing angle of 185 murad
  - Bottom: crossing angle of 140 murad
- More losses observed at the end of the trains for the large crossing angle → e-cloud traces
- More losses at the middle of many trains (with full LR encounters) are observed after the crossing angle change
  - The effect is more pronounced during the first 30 min.

Instantaneous beam losses before and after the crossing angle change



- Burn-off corrected losses averaged over many fills for **Beam 2**
  - Top: crossing angle of 185 murad
  - Bottom: crossing angle of 140 murad
- More losses observed at the end of the trains for the large crossing angle → e-cloud traces
- More losses at the middle of many trains (with full LR encounters) are observed after the crossing angle change
  - The effect is more pronounced during the first 30 min.
  - Less pronounced than for Beam 1

To be done: Extend the analysis trying to verify correlations with long ranges

Other interesting studies

- To be done..
  - Application of the analysis to the 2015 data and compare observations
  - Can we put all Run II together?
  - Same with 2012 data

- To be followed up
  - Luminosity predictions for HL-LHC, HE LHC, etc..
    - Nikos already took over this part

Summary

- Luminosity follow up tools are set up profiting from the consolidated experience with the scrubbing follow up (thanks to Gianni!)
  - Cleaning up is needed!
- There are three main parts of the analysis
  - **Emittance evolution from injection to stable beams**
    - Is the observed extra emittance blow-up due to noise effects?
  - **Emittance evolution during stable beams**
    - Interesting observations
    - The effect is different between colliding and non-colliding bunches
    - Is the non-brightness dependent part coming from noise effects?
  - **Extra losses during collisions**
    - After how long in SB the theoretical limit is reached for each fill?
    - Long range correlations? Can we verify the correlation of losses with long ranges?

Summary

- It has been a very interesting path, quite busy most of the times :)
- Lots of work has been already done and many open fronts to be continued
- **Ilias Efthymiopoulos** is taking over the activity with the usual suspects around him and hopefully new people to join
  - I am still around if support is needed
- Some documentation has been put together and I will try to clean it up soon

★ **I would like to take this opportunity to give my special thanks to Yannis for his support and to Gianni for all the help and input!!**

Relevant presentations and proceedings

https://indico.cern.ch/event/368172/contributions/1784182/attachments/732013/1004311/LHC_Luminosity_modeling2.pdf

IPAC 2015: http://accelconf.web.cern.ch/AccelConf/IPAC2015/papers/tupty020.pdf

Evian 2015:
https://indico.cern.ch/event/434129/contributions/1917206/attachments/1205402/1830241/LumiModel-Evian2015.pdf

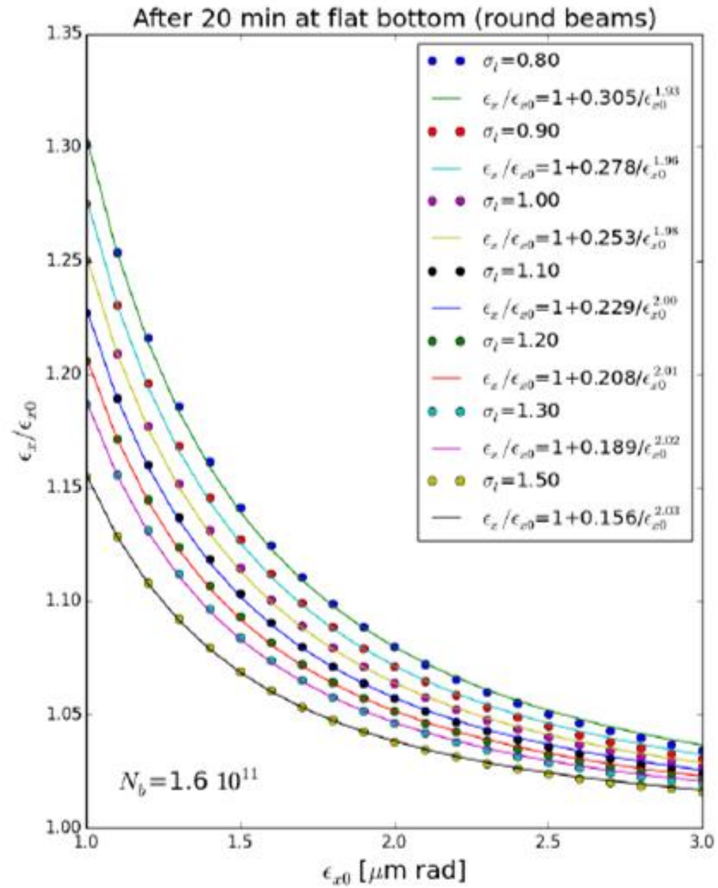
IPAC 2016:
https://cds.cern.ch/record/2207357/files/tupmw002.pdf

Evian 2016:
https://indico.cern.ch/event/578001/contributions/2366376/attachments/1388316/2113783/F.Antoniou_Evian2016.pdf
Evian 2016 proceedings to be published soon

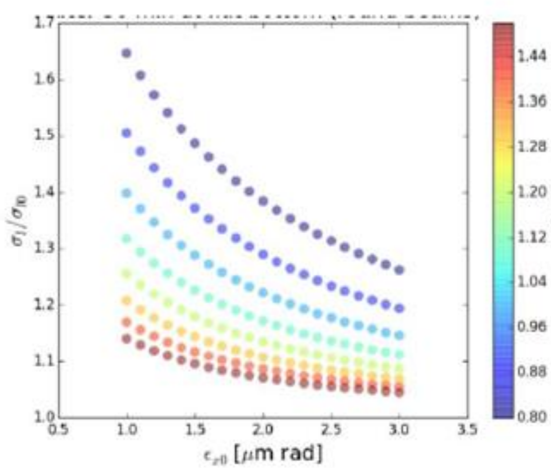
Thank you for your attention!

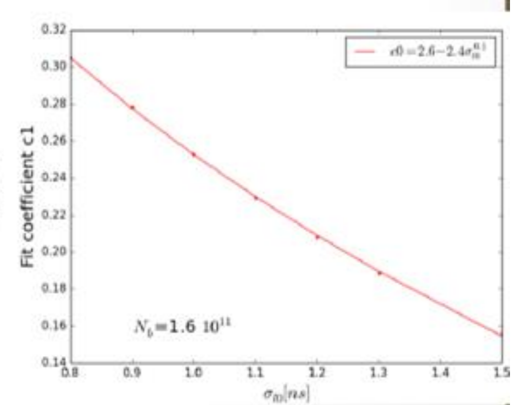
Extra slides

The IBS + SR model

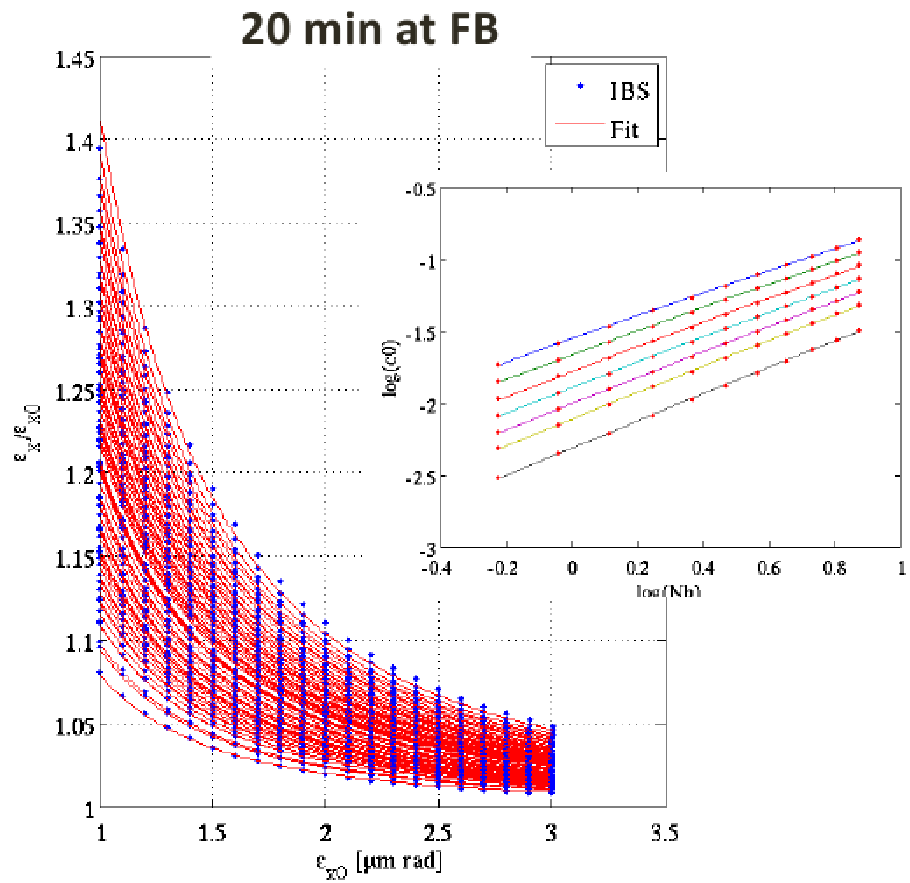


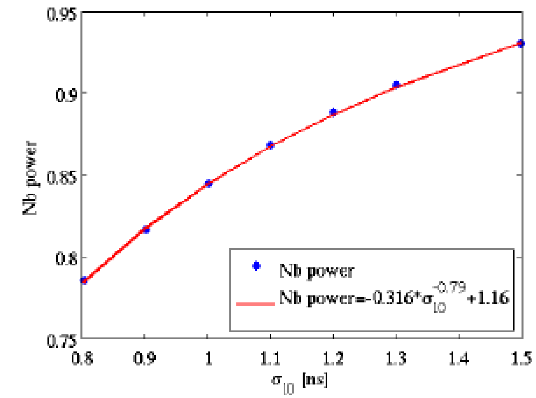
- Parameterization of the IBS effect at the horizontal and longitudinal plane with different initial horizontal emittance and bunch length (N_b=1.6e11)
- Simple scaling laws can be found
- For ε_{t0}=2μm and σ_l=1.2ns (red line) the effect at flat bottom is of the order of 5%

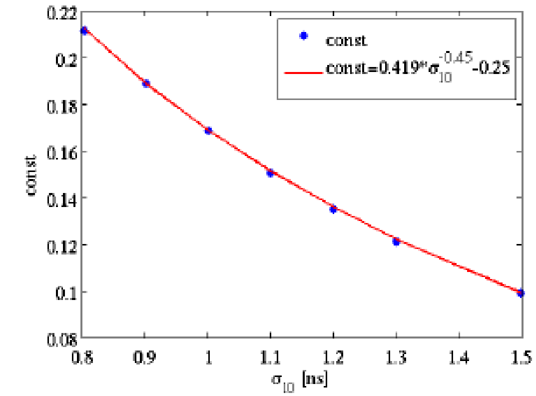




The IBS + SR model







$$\frac{\epsilon_x}{\epsilon_{x0}} = 1 + \frac{C_0(N_b, \sigma_{l0})}{{\epsilon_{x0}}^2}$$

$C_0(N_b, \sigma_{l0}) = a_0(\sigma_{l0})\, {N_b}^{a_1(\sigma_{l0})}$

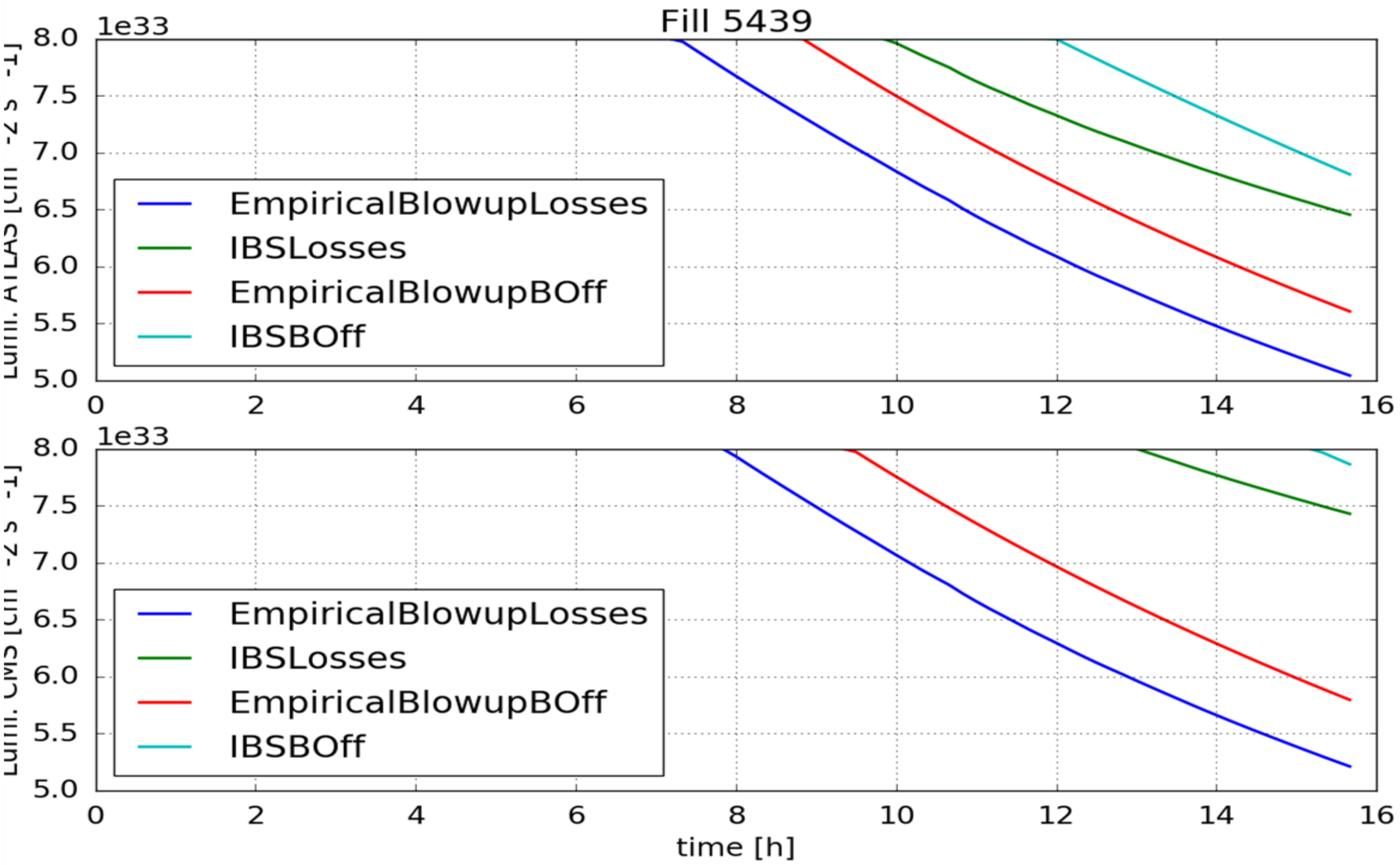
$a_0(\sigma_{l0}) = 0.419{\sigma_{l0}}^{-0.45} - 0.25$

$a_1(\sigma_{l0}) = -0.316{\sigma_{l0}}^{-0.79} + 1.16$

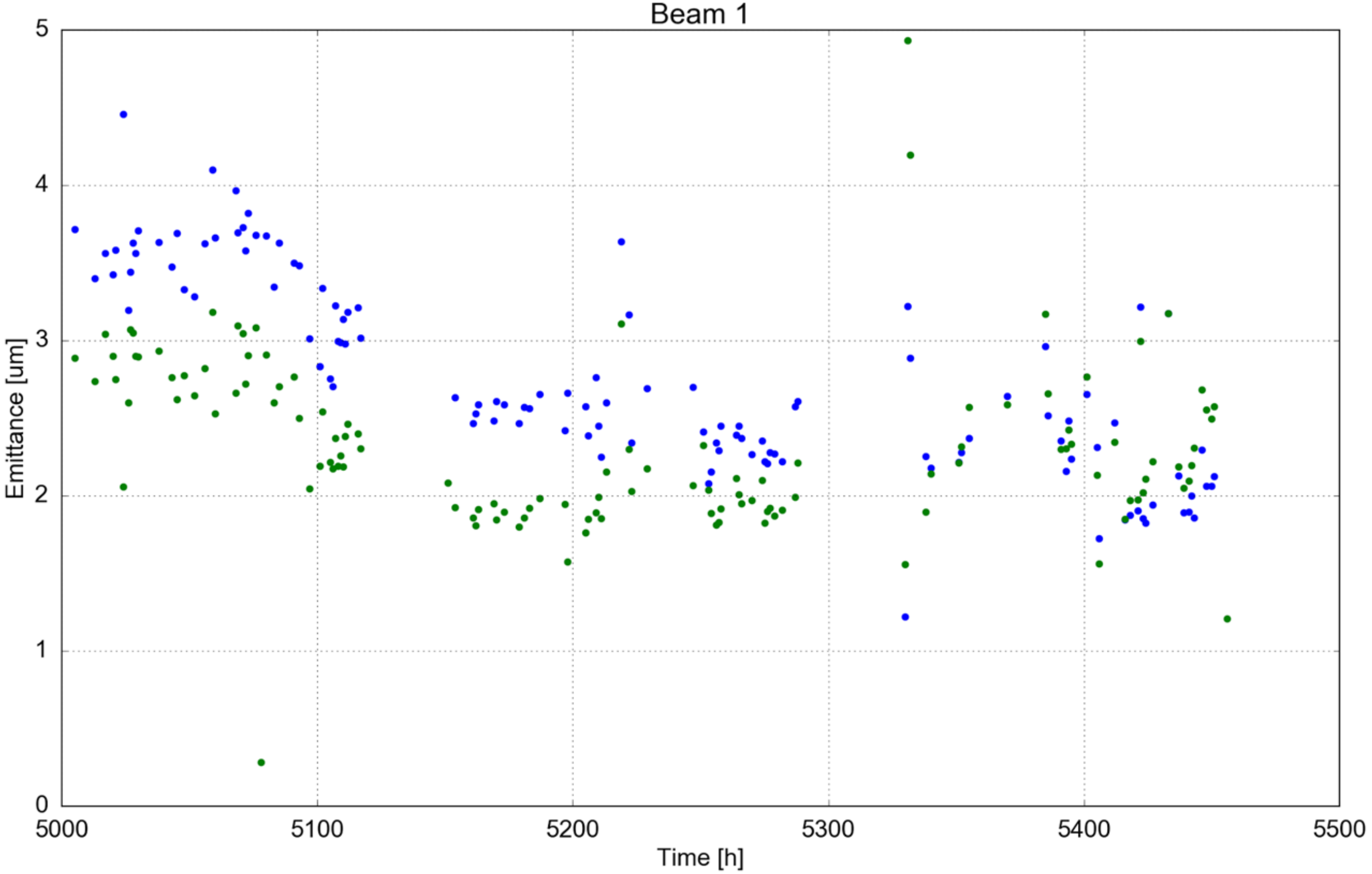
Further comments

- No effect in the vertical plane
- The memory of the IBS effect in the longitudinal plane will be "erased" during the ramp

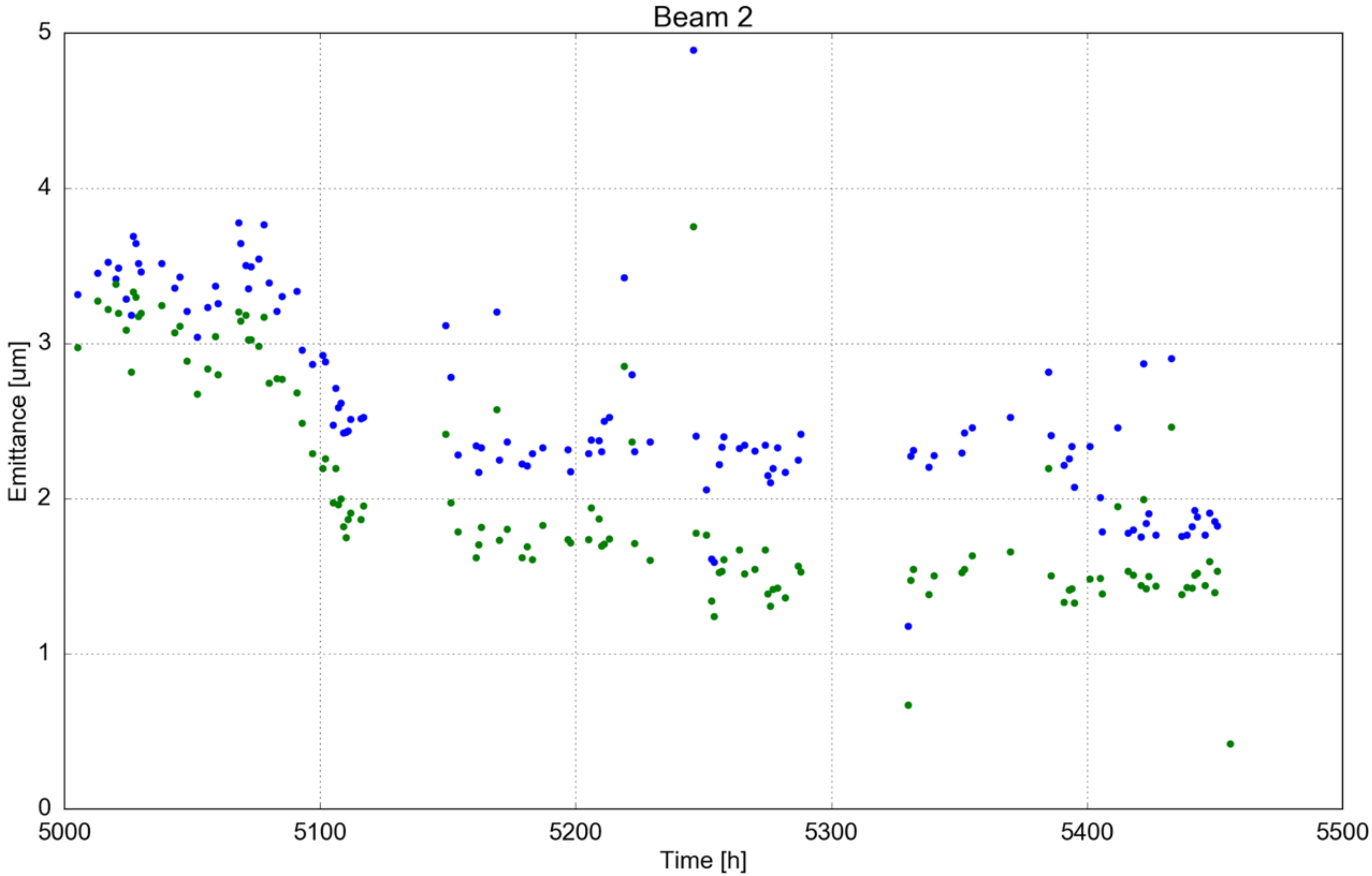
Leveling Fills



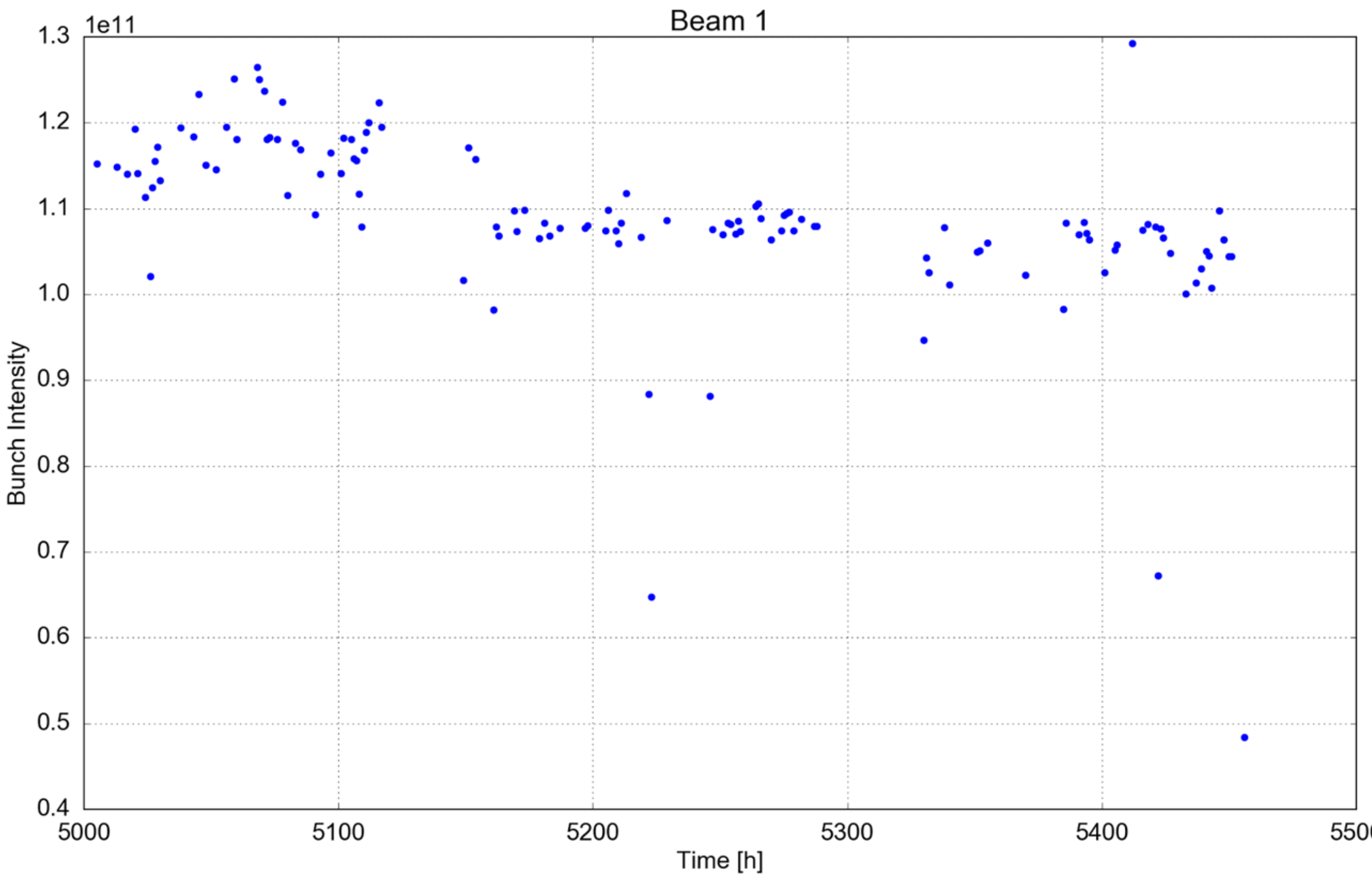
- Impact of the different degradation mechanisms on the leveling time based on the lumi model



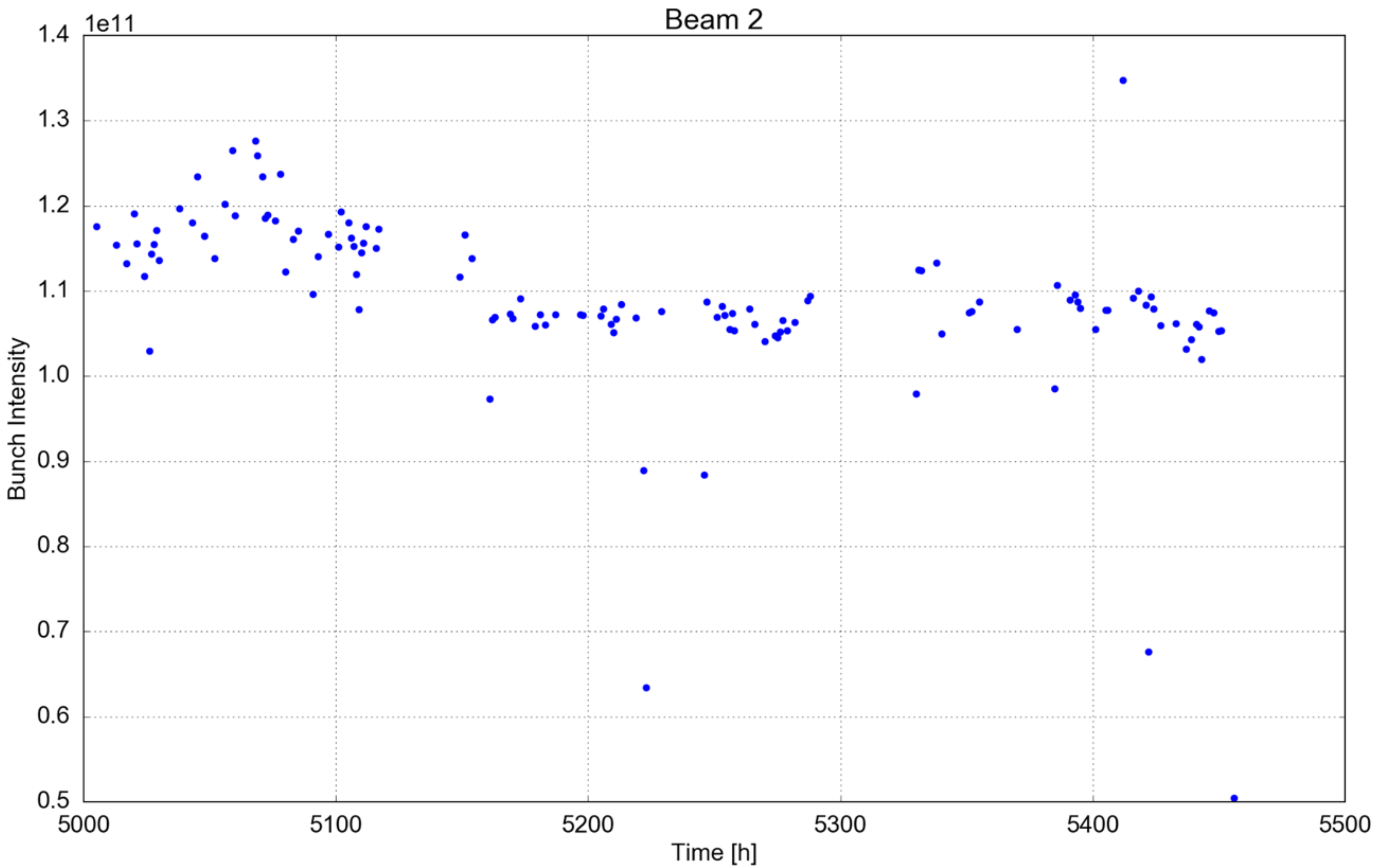
Beam 1
Emittance [um]
Time [h]
0
1
2
3
4
5
5000
5100
5200
5300
5400
5500



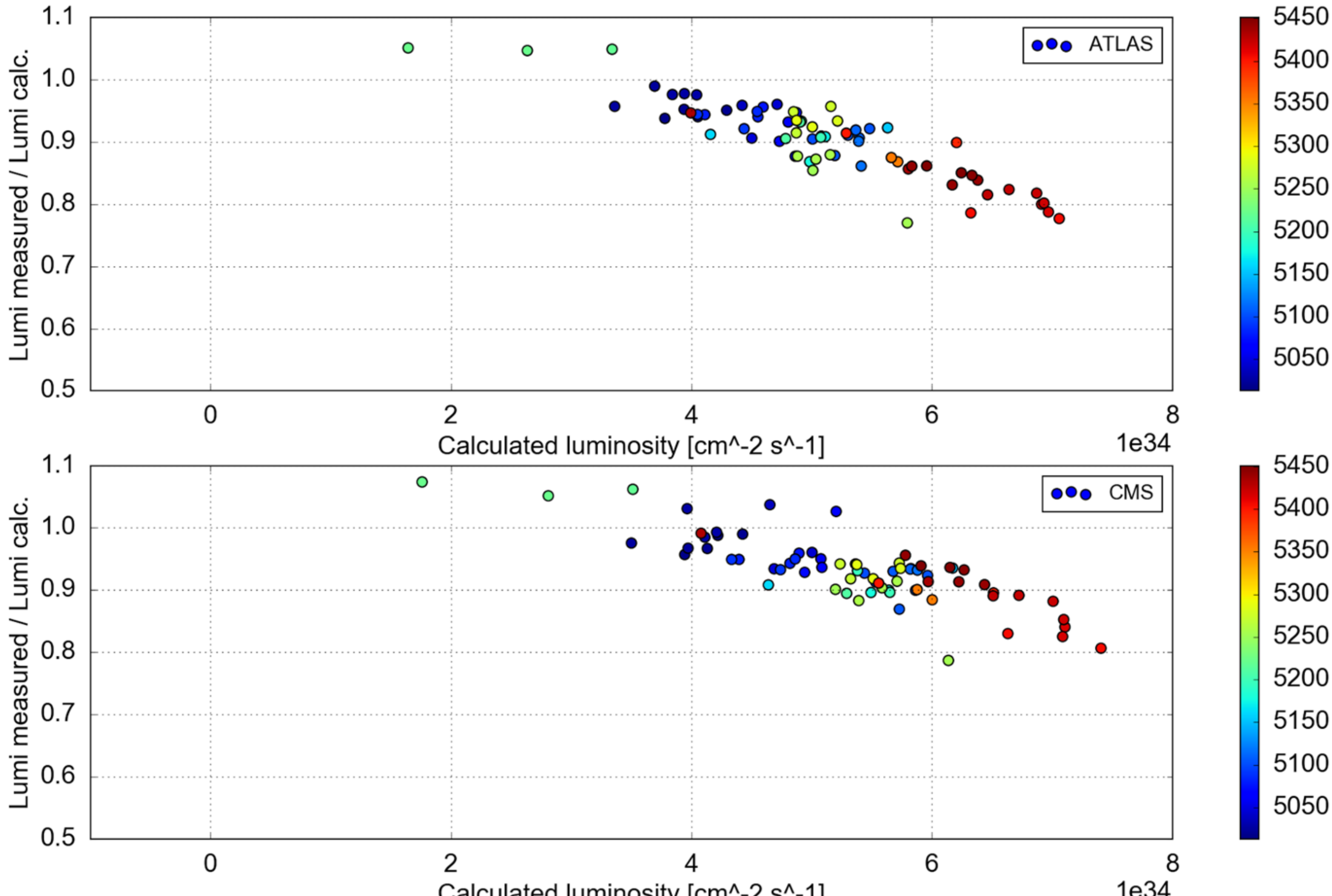
Beam 2
Emittance [um]
Time [h]
0
1
2
3
4
5
5000
5100
5200
5300
5400
5500



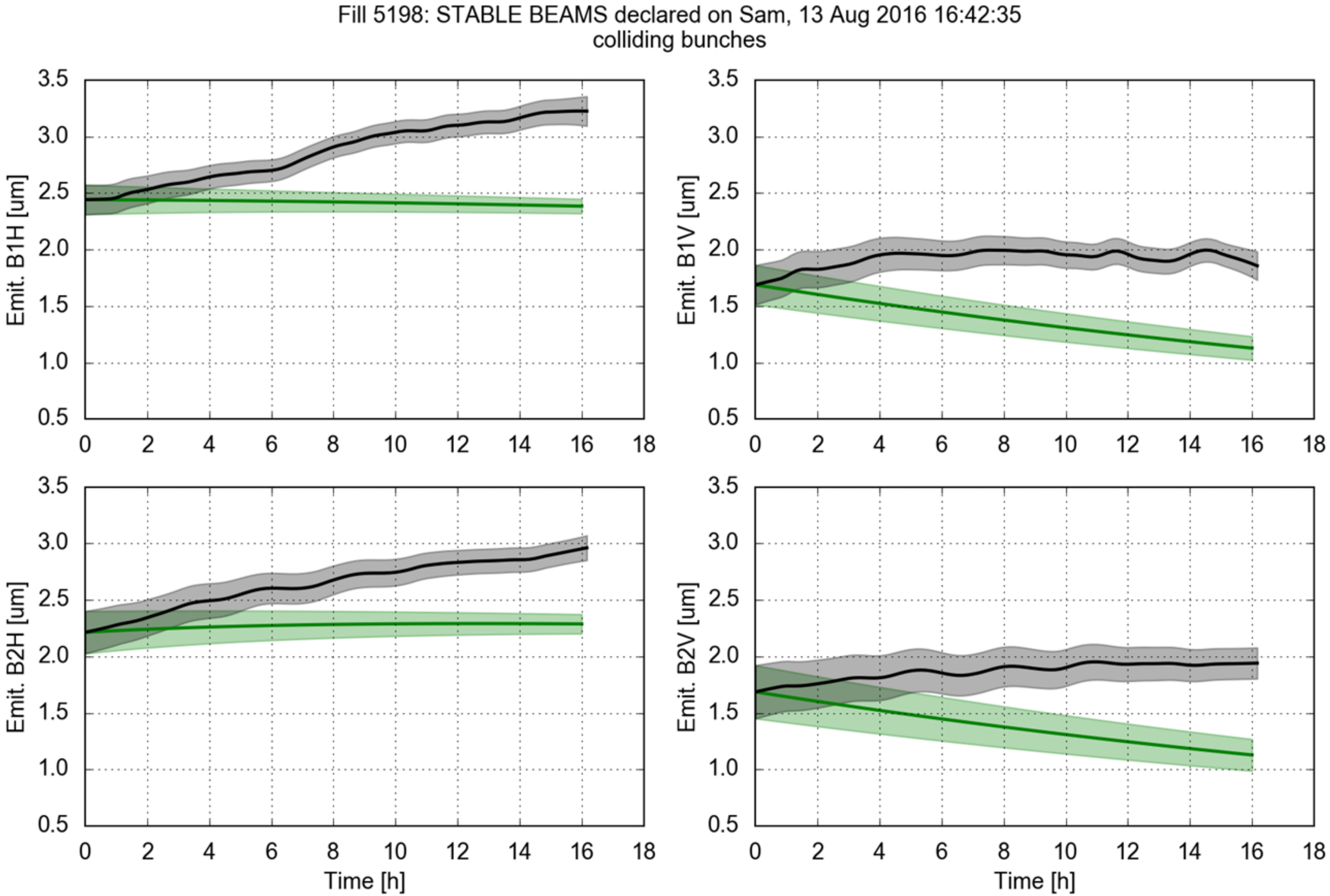
Beam 1
1e11
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
Bunch Intensity
5000
5100
5200
5300
5400
5500
Time [h]



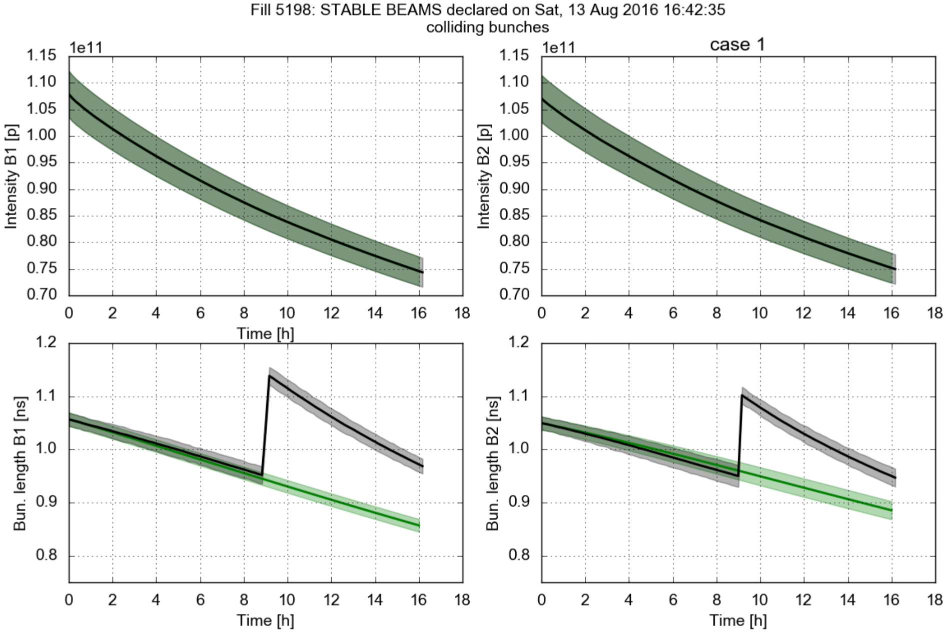
Beam 2
1e11
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
Bunch Intensity
5000
5100
5200
5300
5400
5500
Time [h]

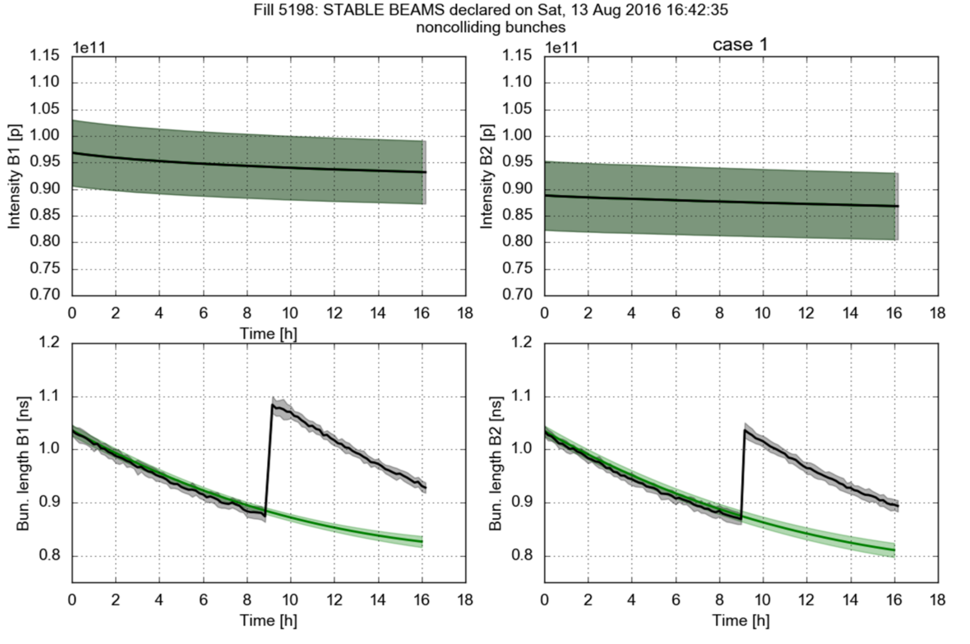

ATLAS
Lumi measured / Lumi calc.
Calculated luminosity [cm^-2 s^-1]
1e34
CMS
Lumi measured / Lumi calc.
Calculated luminosity [cm^-2 s^-1]
1e34

Luminosity modeling



Luminosity model comparison with data: Bunch length



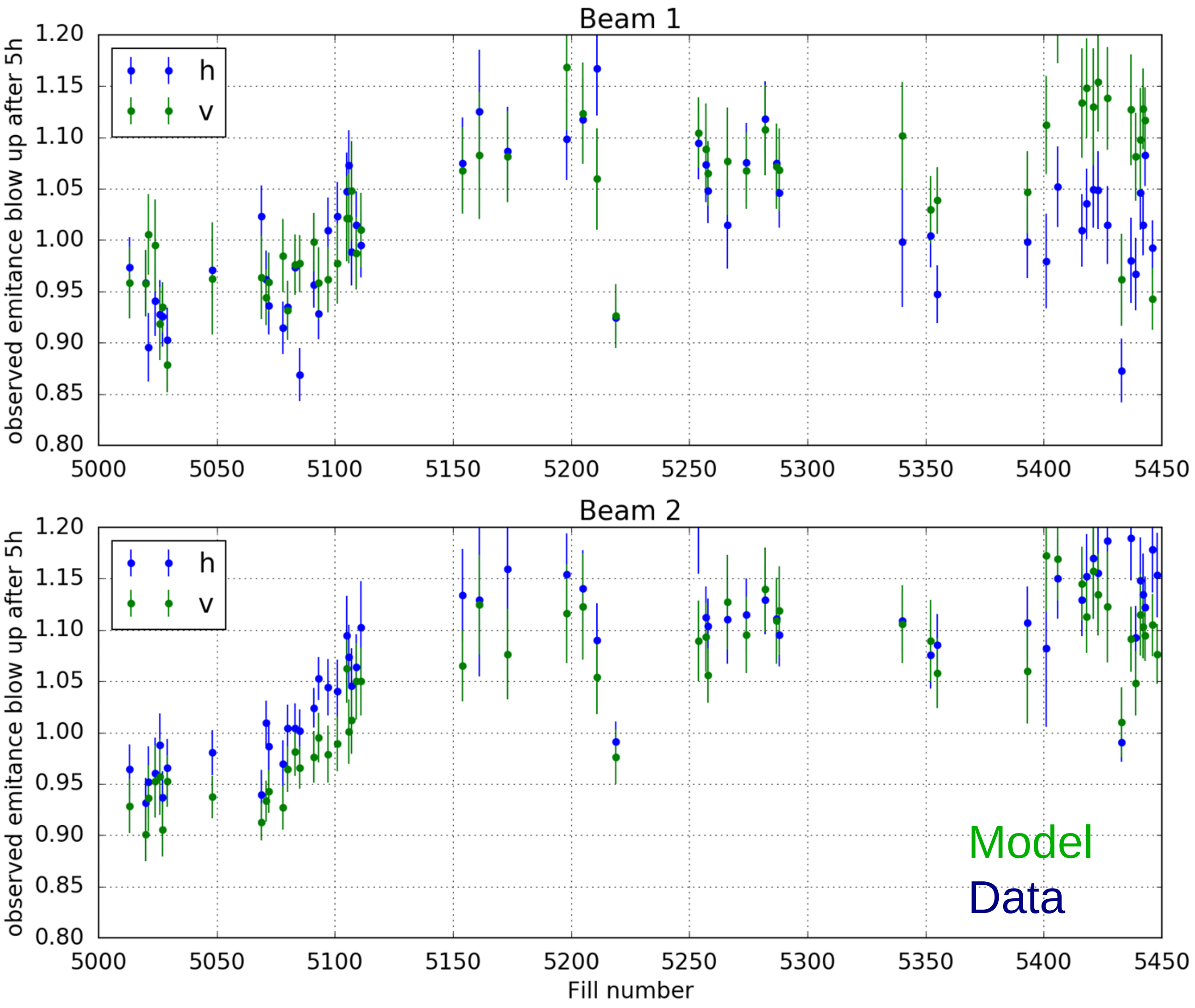


Emittance evolution in Stable Beams

- Emittance growth within **±0.1 um/h** (~10 times less than injection), **changing with the beam brightness**
- Both planes show an **additional blowup of ~0.5 um/h** with respect to the model

  →The **difference between H and V is consistent with IBS**

Observed emittance blow-up



- Emittance growth within **±0.1 um/h**
- Both planes show an **additional blowup of ~0.05 um/h** with respect to the model

→The **difference between H and V is consistent with IBS**