Can we predict luminosity?

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Acknowledgements: R. Alemany Fernandez, G. Arduini, R. Bruce, K. Li, X. Buffat, E. Efthymiopoulos, M. Lamont, G. Papotti, B. Salvachua Ferrando, W. Kozanecki, ATLAS collaboration, CMS collaboration

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Outline

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

Luminosity model description

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

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

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

    - Or using the data evolution
  - **Bunch intensity evolution:**
    - Luminosity burn-off:

$$\frac{dN}{dt} = \left(\frac{dN}{dt}\right)_{BOff}$$

    - Or using data evolution
  - **Bunch length evolution:**
    - Intrabeam scattering and synchrotron radiation:

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

    - Or using data evolution
  - Iteration in small timesteps (10-15min) and any of the modes can be called at each time step

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

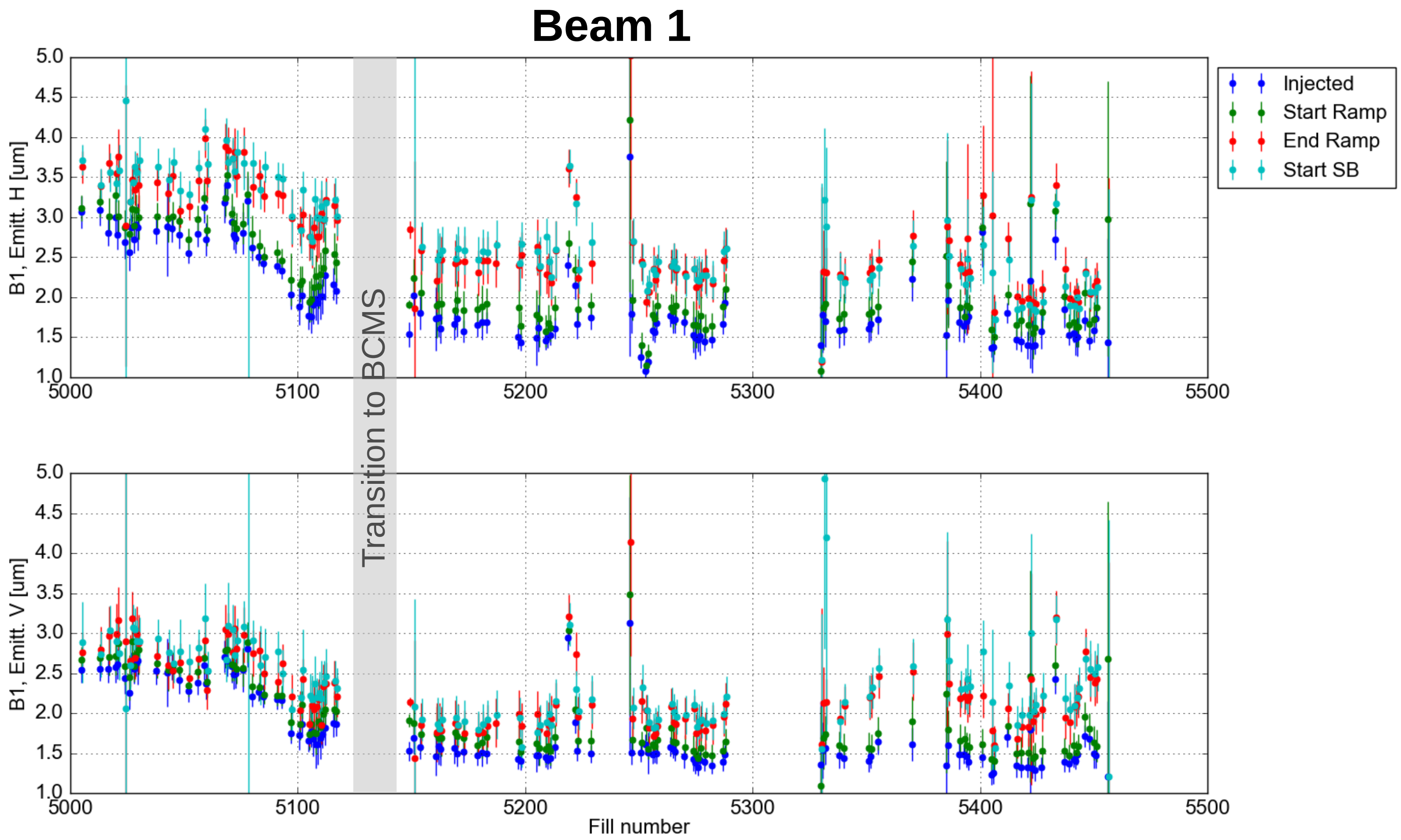
Data used as input

- 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

Emittance evolution from injection to stable beams



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

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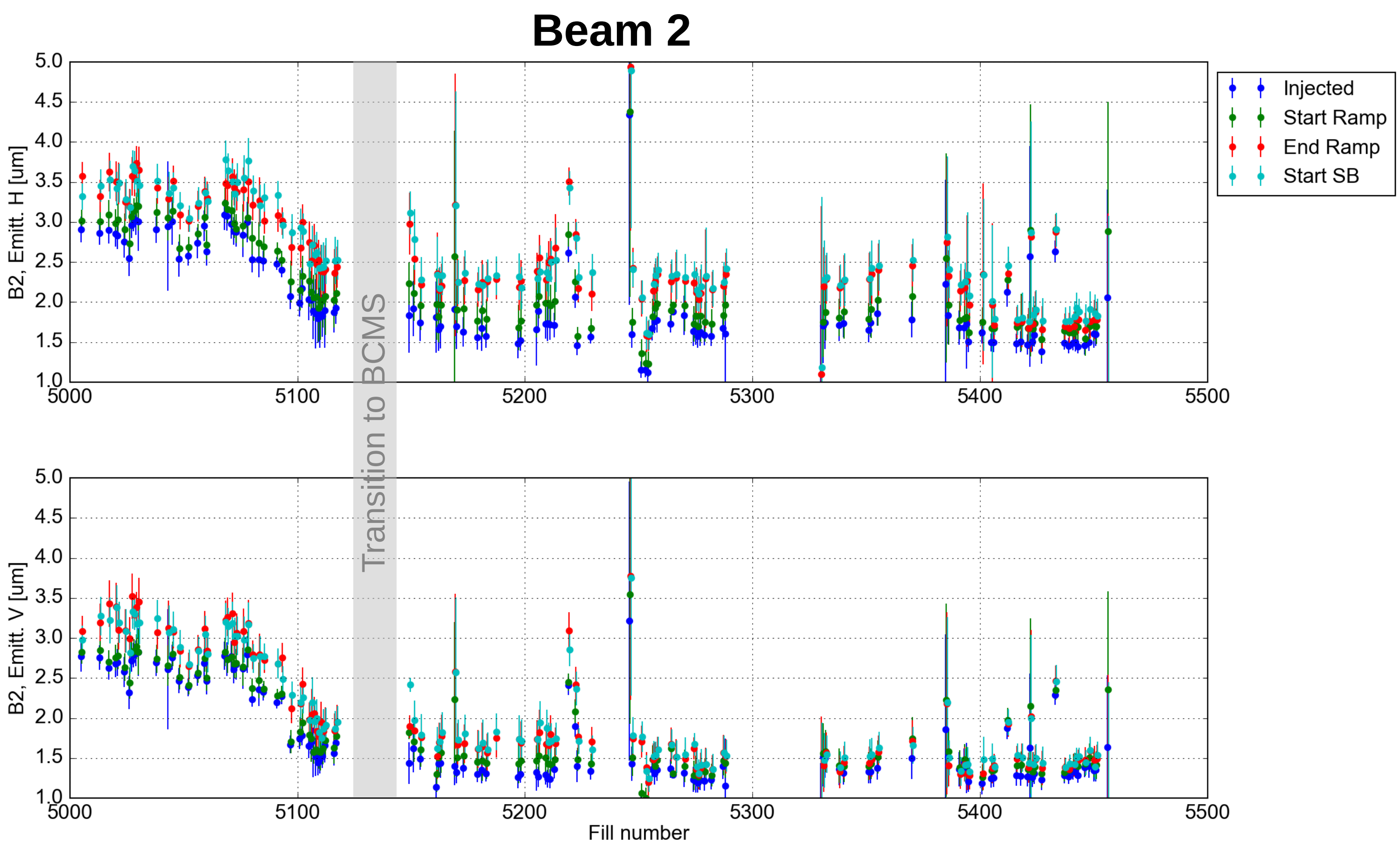

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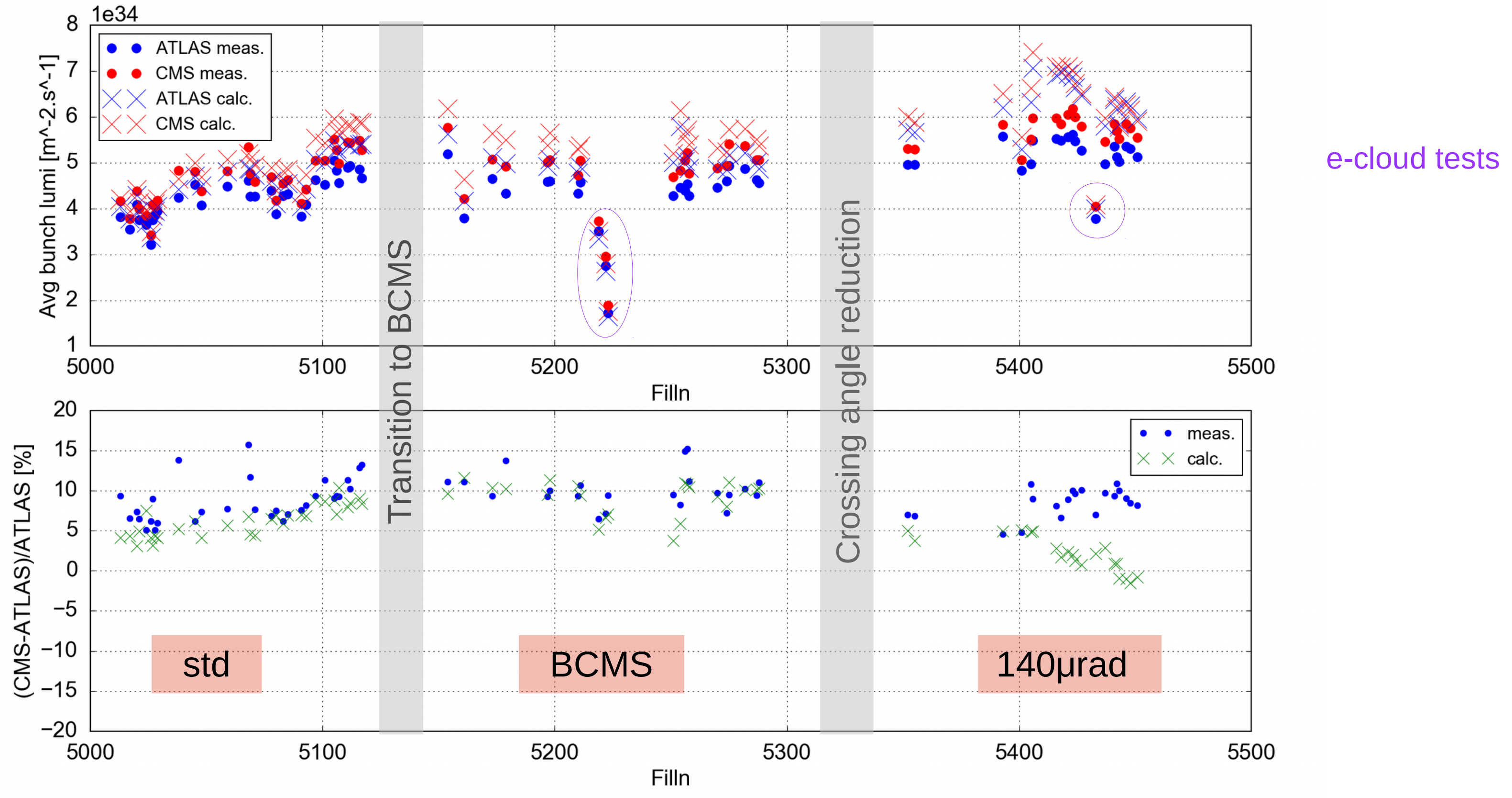
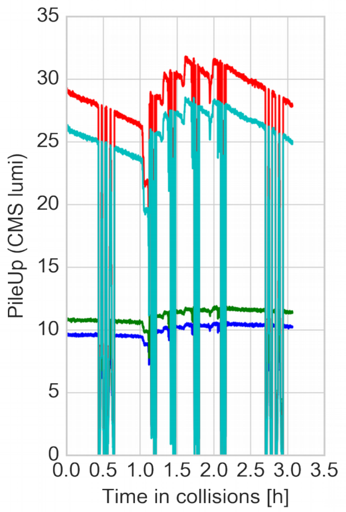
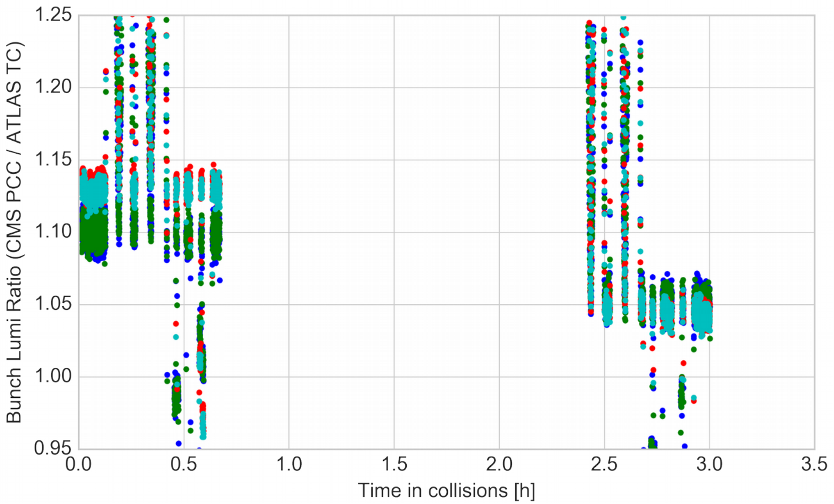
Peak luminosity along the year



- 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)

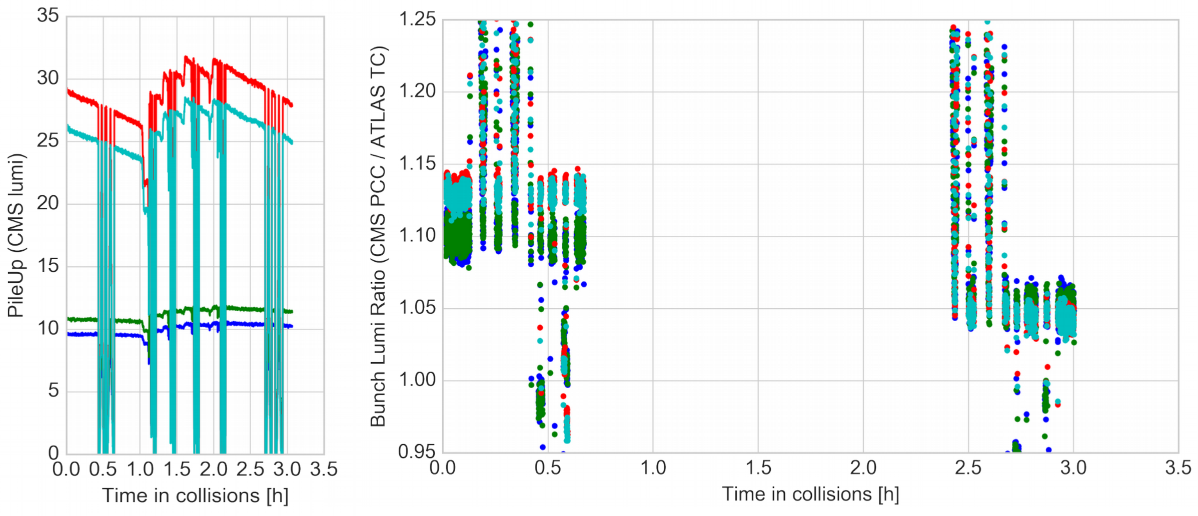
Peak luminosity along the year





- 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

Peak luminosity along the year



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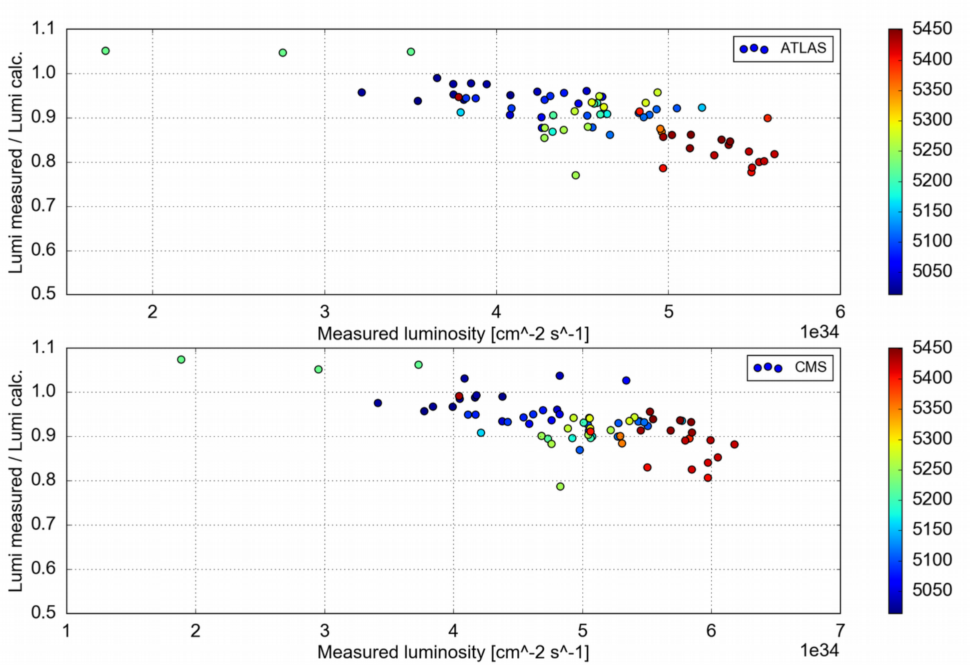
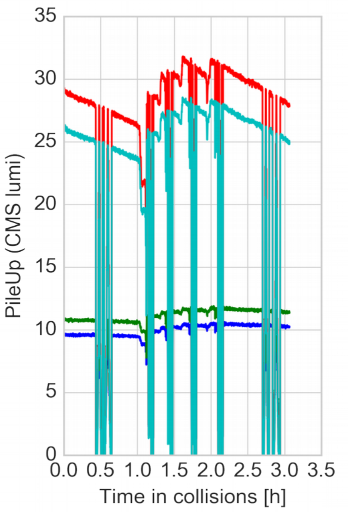
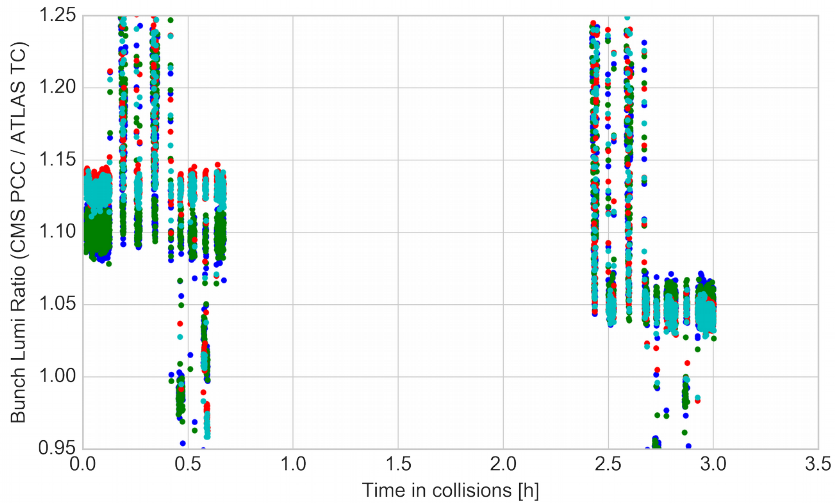
- Correlation of the difference between the measured and calculated luminosity with the measured peak luminosity observed
  - Valid also in the same BSRT calibration factor periods



Peak luminosity along the year





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- 4 bunches with different brightness were brought to collision
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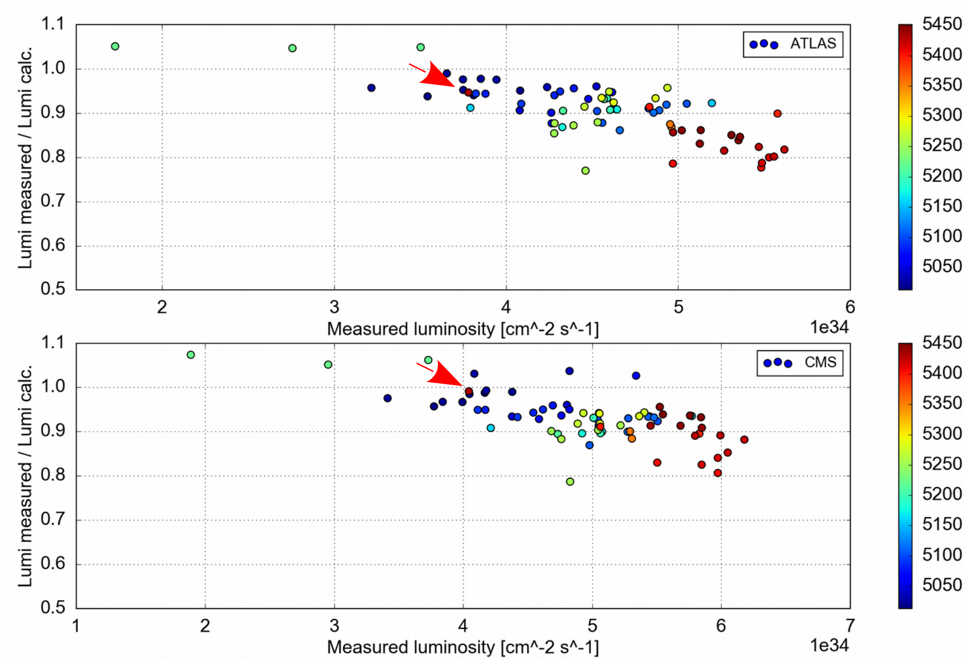
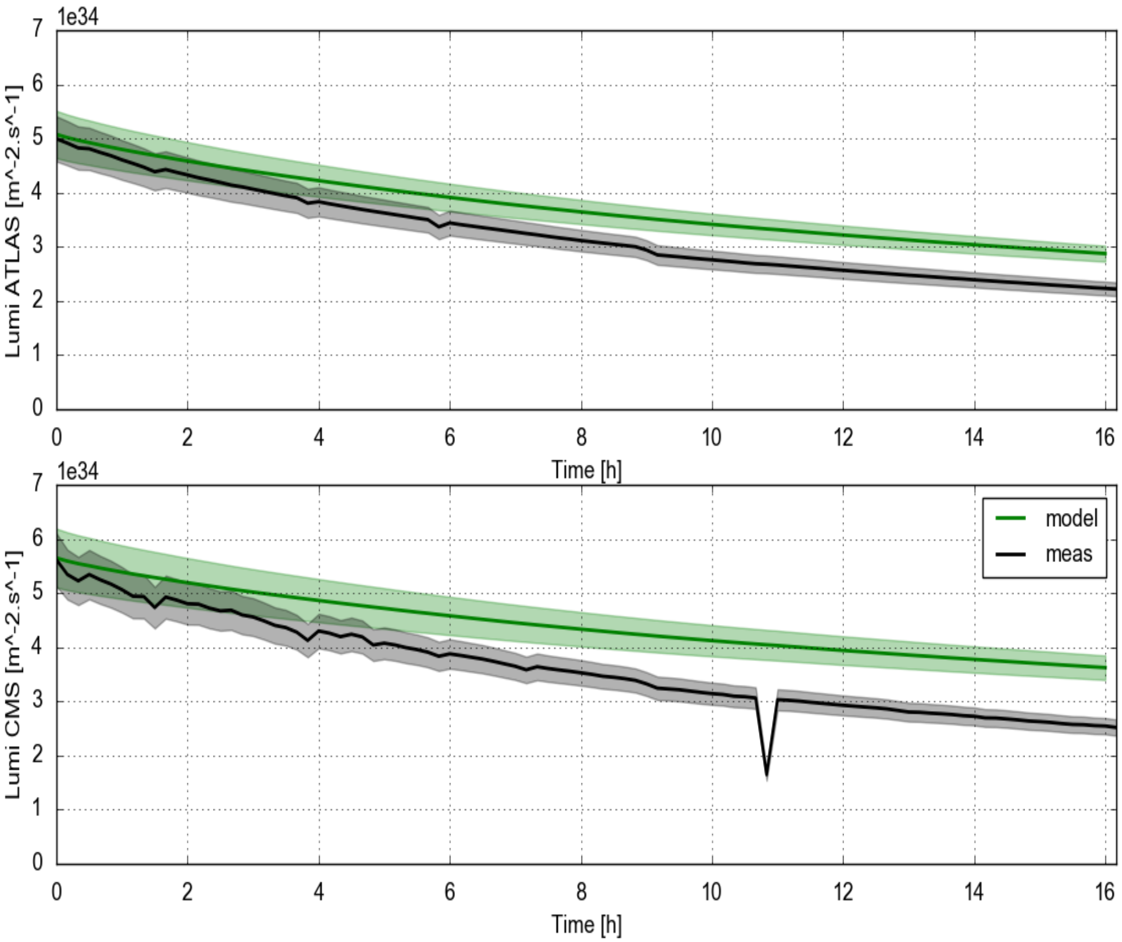
- Correlation of the difference between the measured and calculated luminosity with the measured peak luminosity observed
  - Valid also in the same BSRT calibration factor periods
  - Notice the red dot (last BSRT calibration period) with lower peak luminosity
  - Analysis is ongoing..

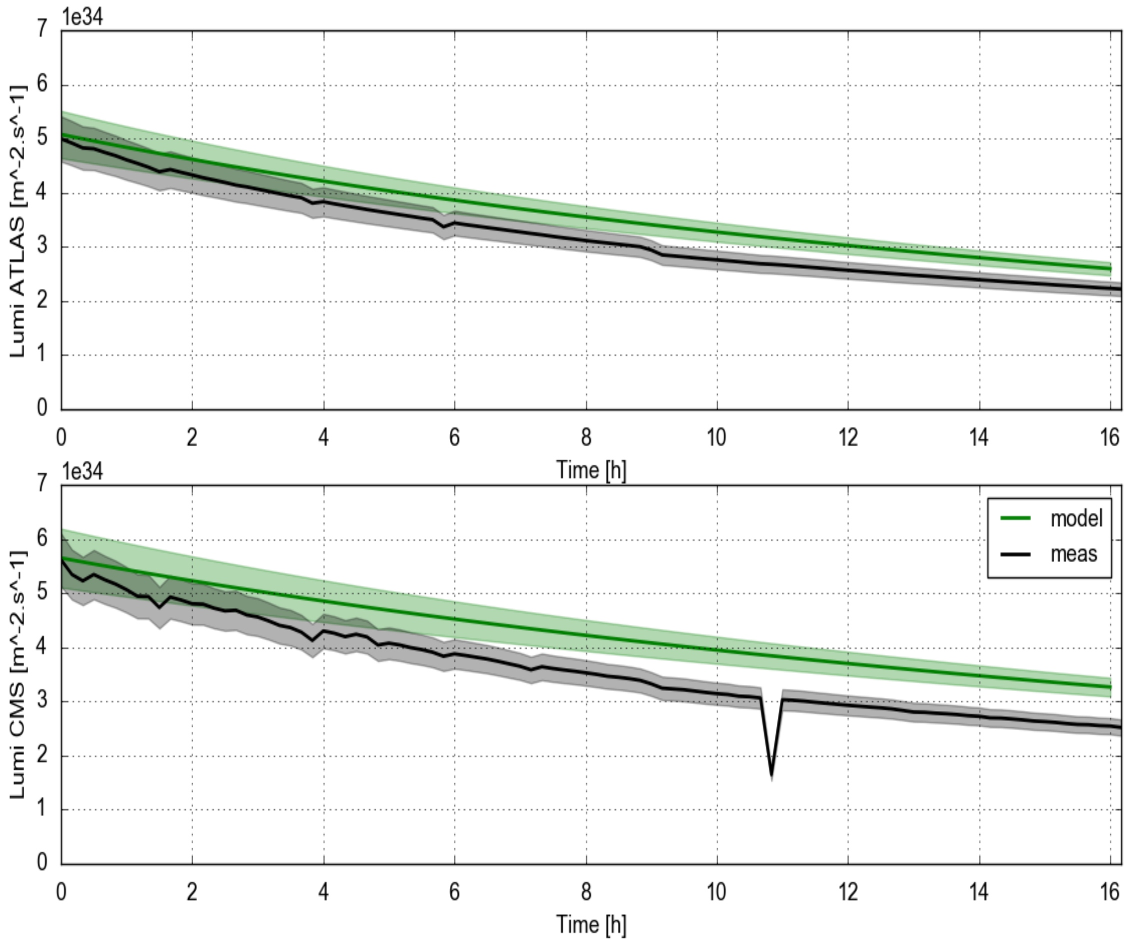


Luminosity evolution prediction



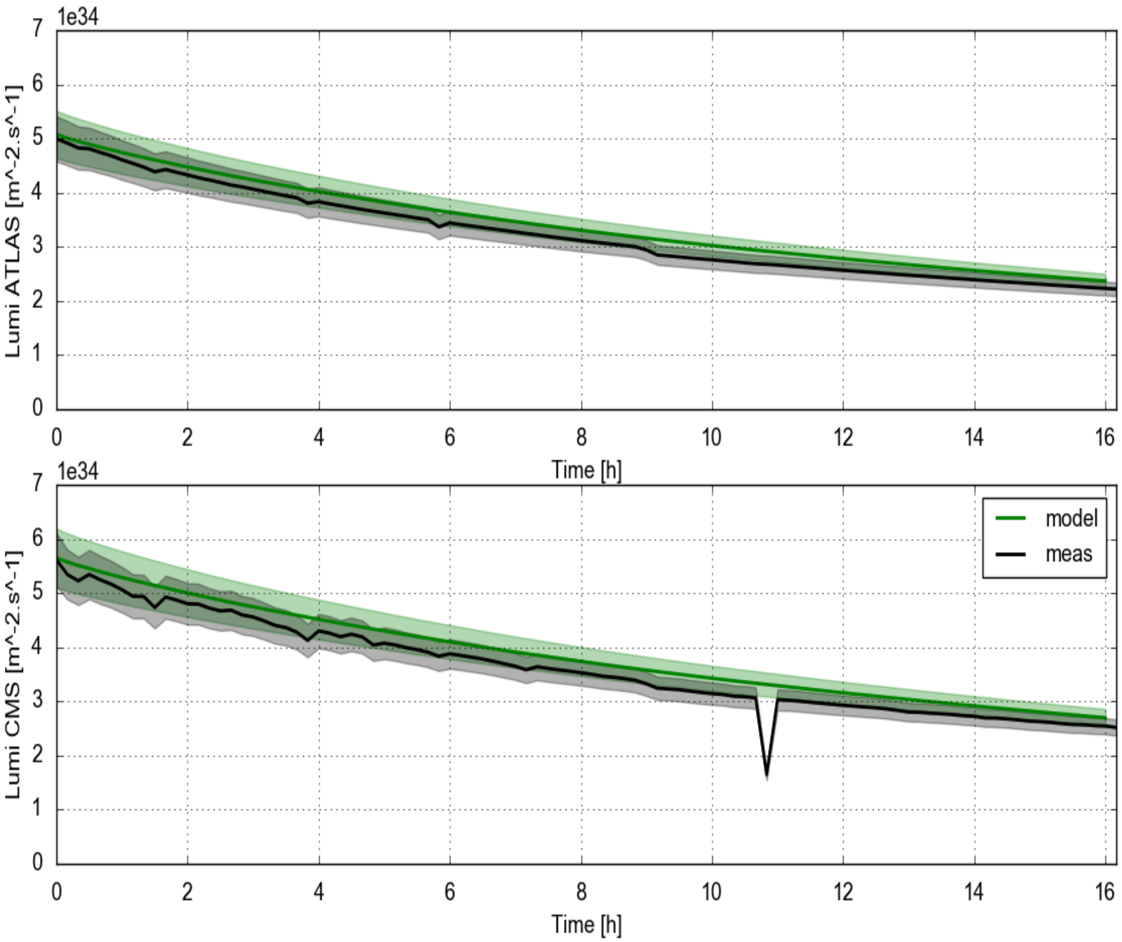
- For each Fill the model is applied under different assumptions and the luminosity evolution is calculated bunch-by-bunch
- Comparison of the averaged evolution assuming the **ideal case**: **IBS+SR+Burn-off**
- Only initial bunch parameters are taken from the data and then the model is iterated to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

Luminosity evolution prediction



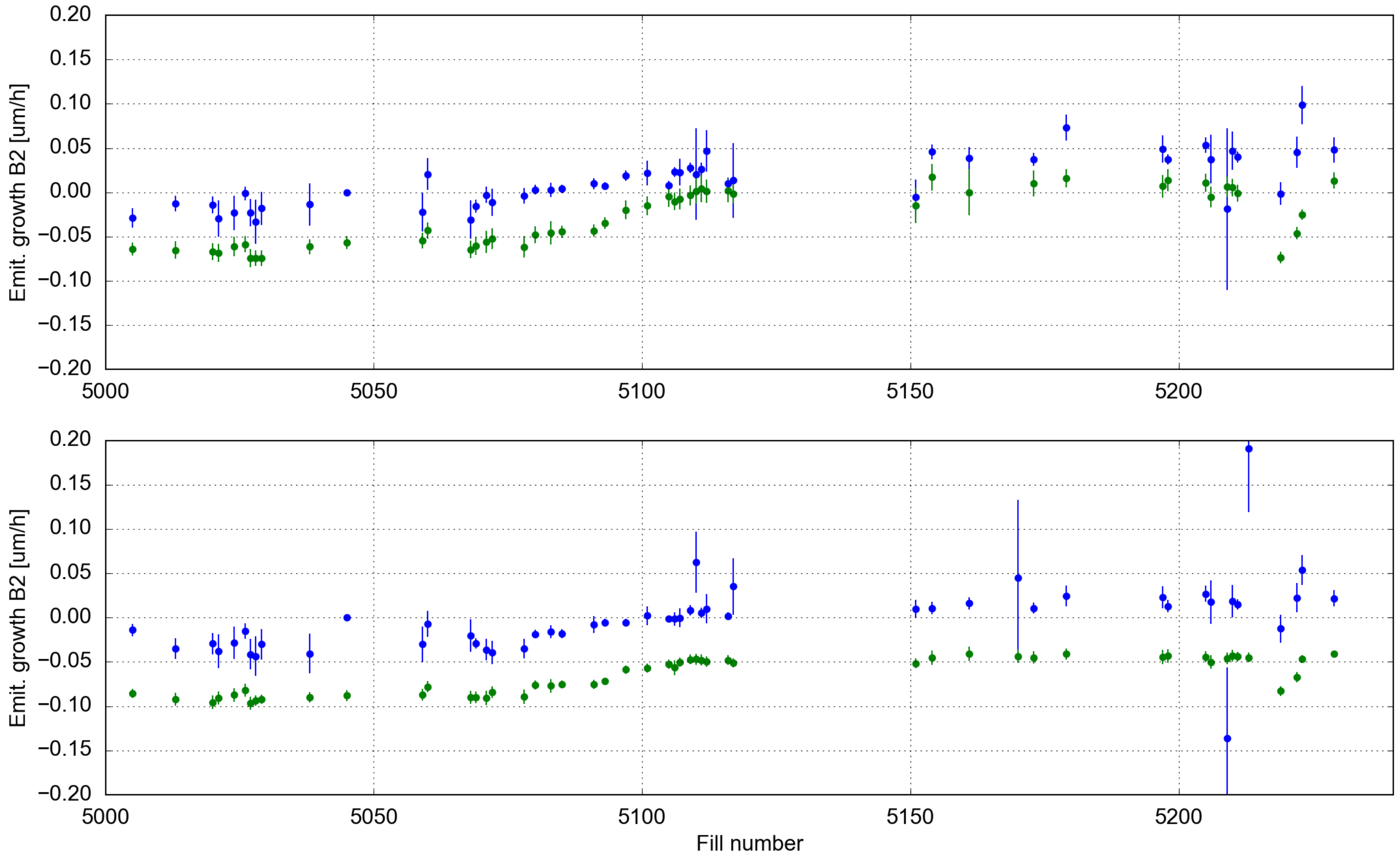
- For each Fill the model is applied under different assumptions and the luminosity evolution is calculated bunch-by-bunch
- Comparison of the averaged evolution using the **empirical bunch intensity** evolution: **IBSEmpiricalLosses**
- Bunch intensity evolution from the data. The model computes the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

Luminosity evolution prediction



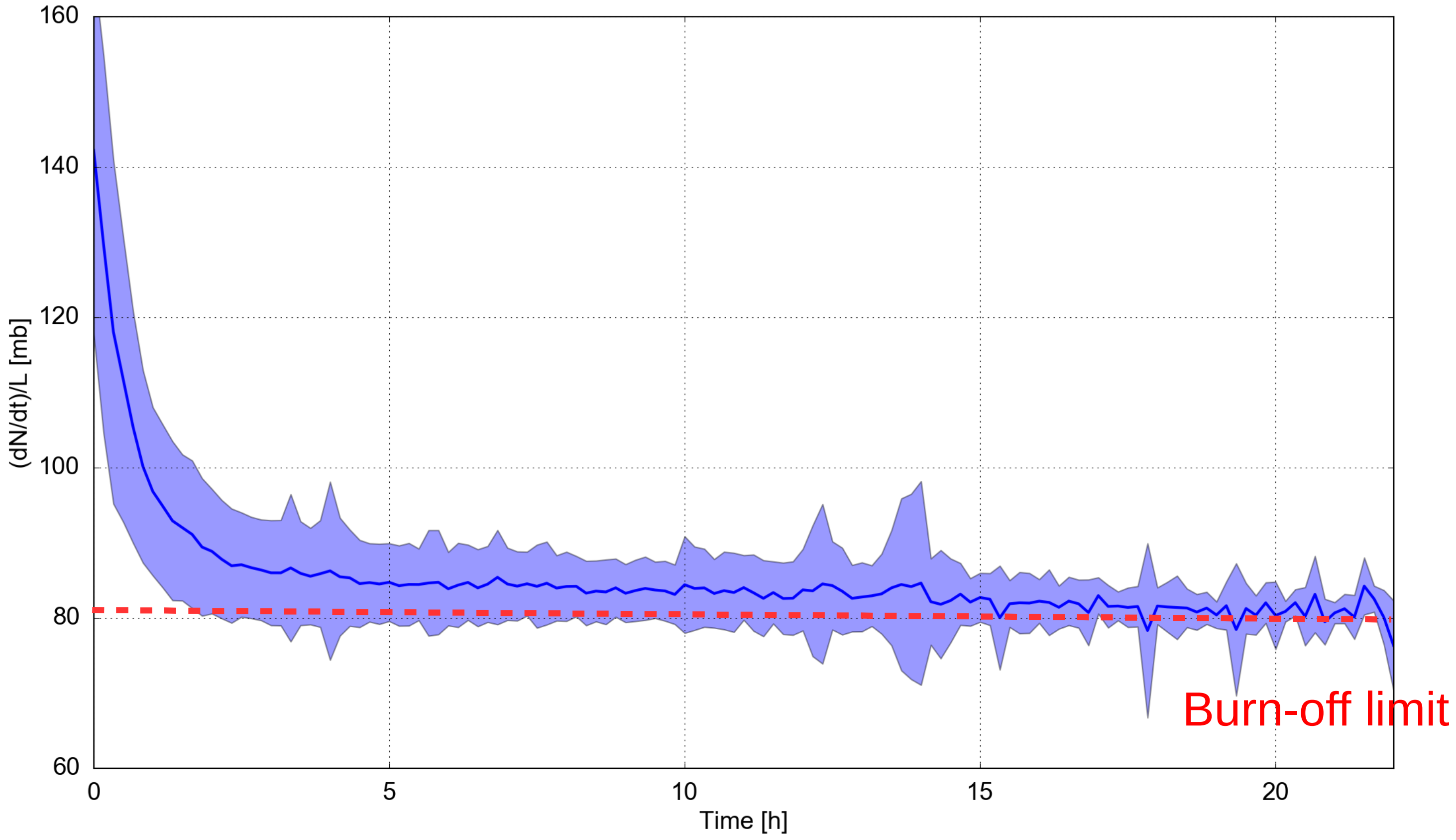
- For each Fill the model is applied under different assumptions and the luminosity evolution is calculated bunch-by-bunch
- Comparison of the average evolution using the **empirical bunch intensity** and **empirical emittance evolution**: **EmpiricalBlowUpEmpiricalLosses**
- Bunch intensity and emittance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

Extra emittance blow-up



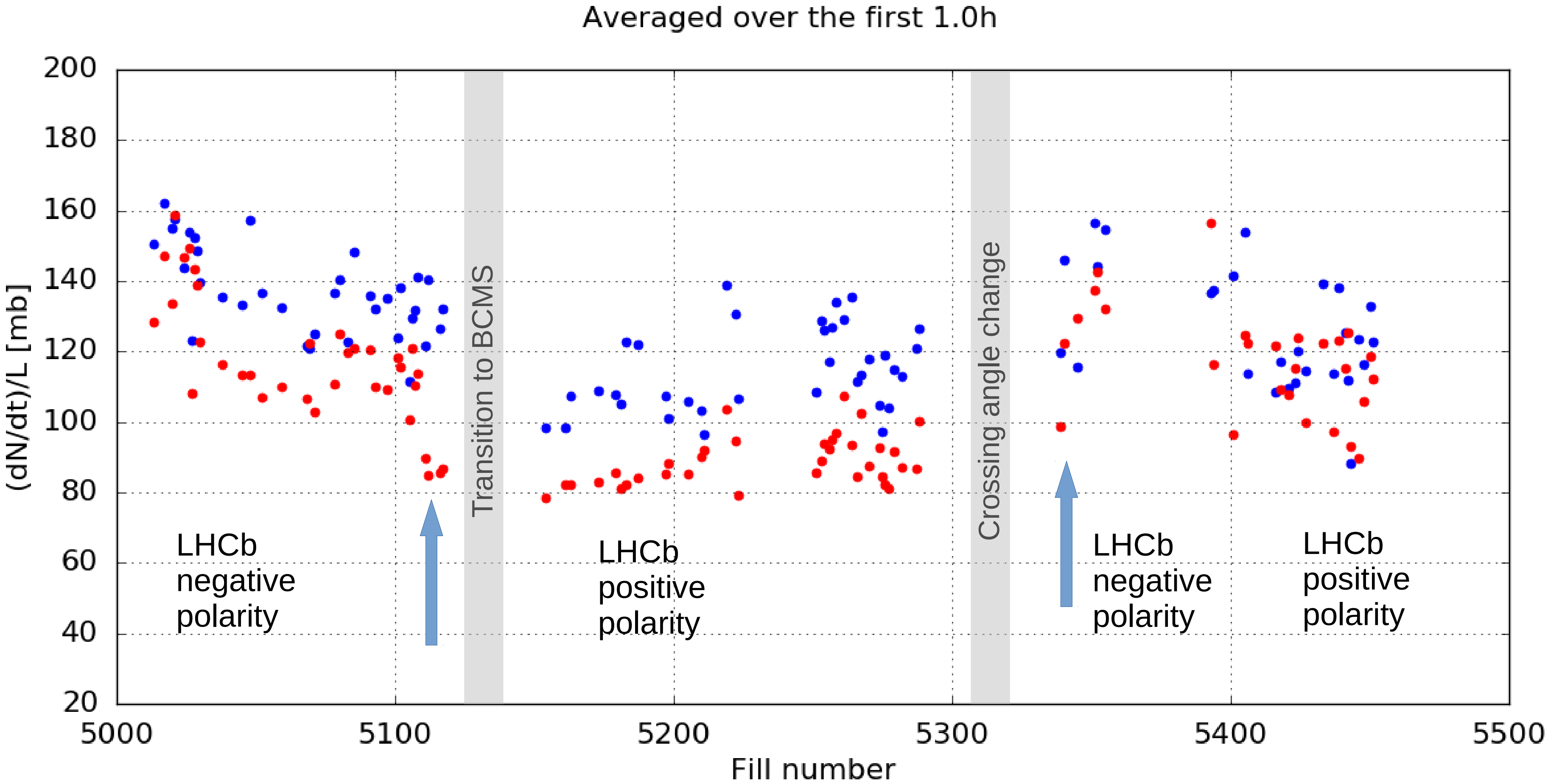
- Emittance growth within **±0.1 um/h**
- Both planes show an **additional blowup of ~0.05 um/h** with respect to the model
  - → The **difference between H and V is consistent with IBS**

Beam Losses



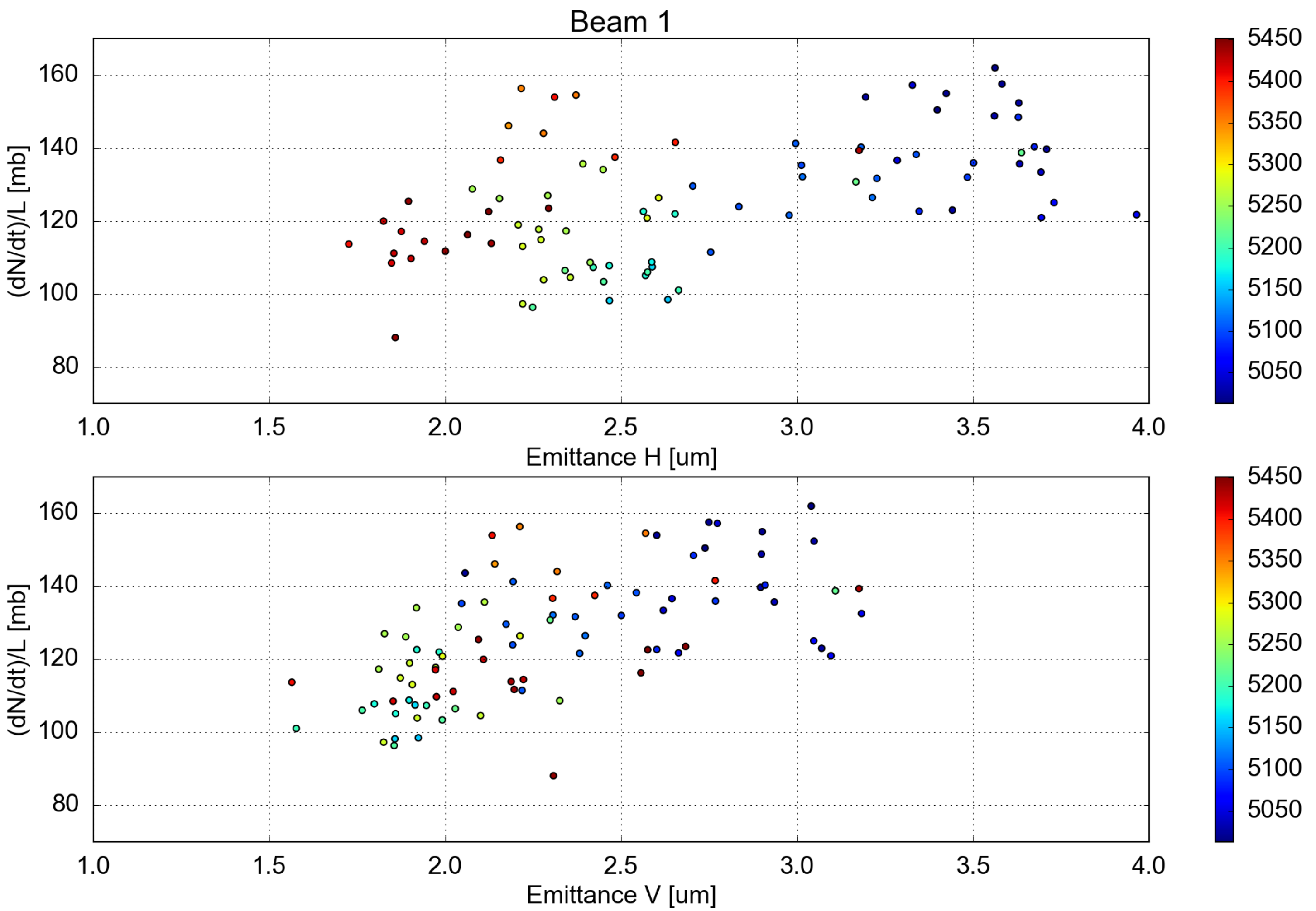
- Normalized loss rate for all fills
- Losses on-top of Burn-off were observed for many fills
- Mainly the first 3h and then become burn off dominated

Beam Losses



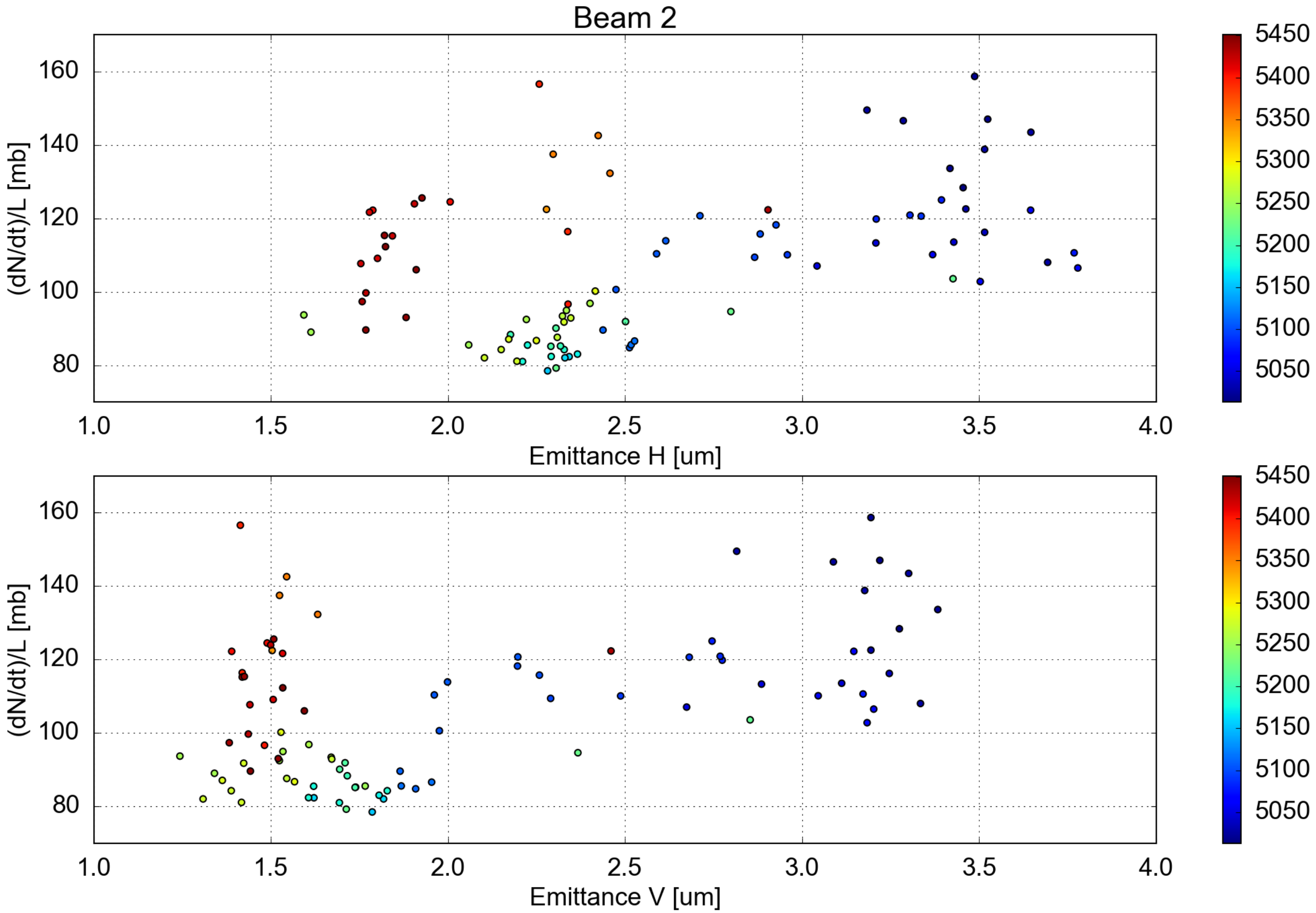
- Evolution of the average normalized losses (after one hour in SB) along the run
- Beam 1 losses higher than Beam 2 losses
- Minimum losses after the transition to BCMS (Beam 2 losses become burn-off dominated)
- Increase of losses after the crossing angle change followed by an improvement trend
- Clear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

Beam Losses



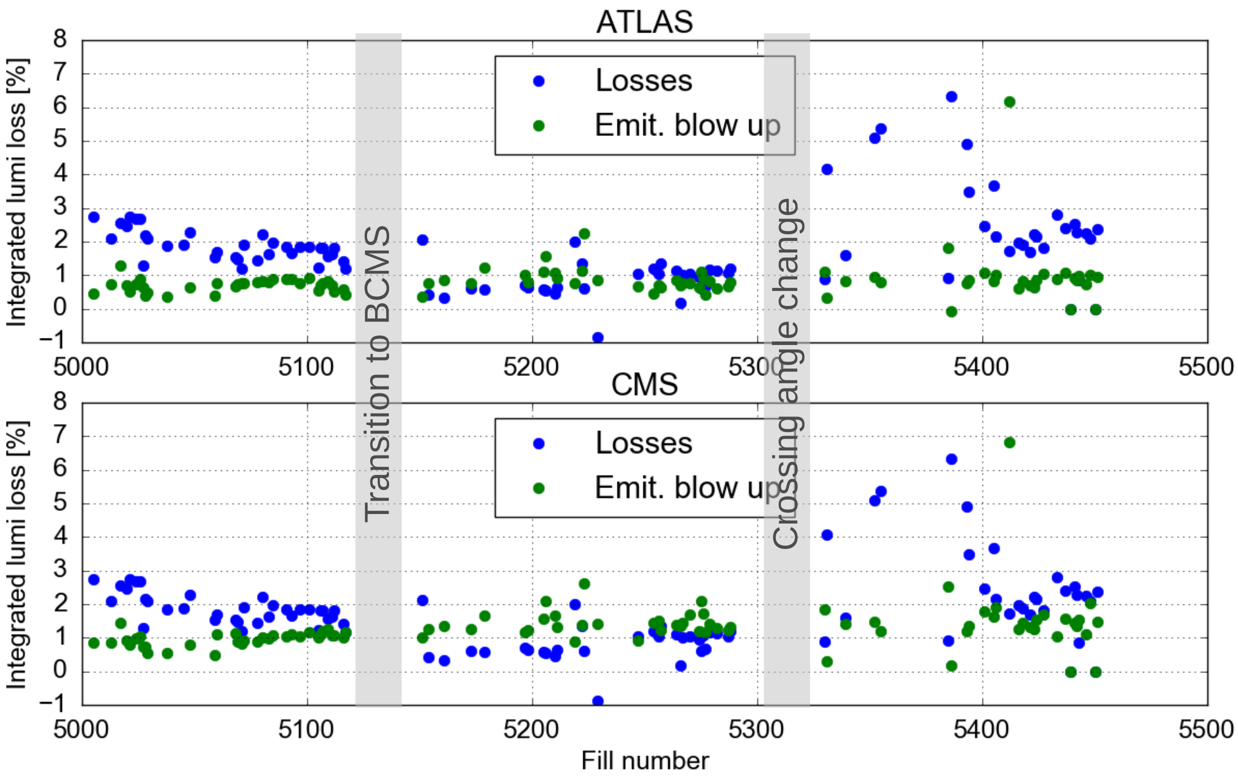
- Losses correlation with the emittance at the beginning of Stable Beams

Beam Losses



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

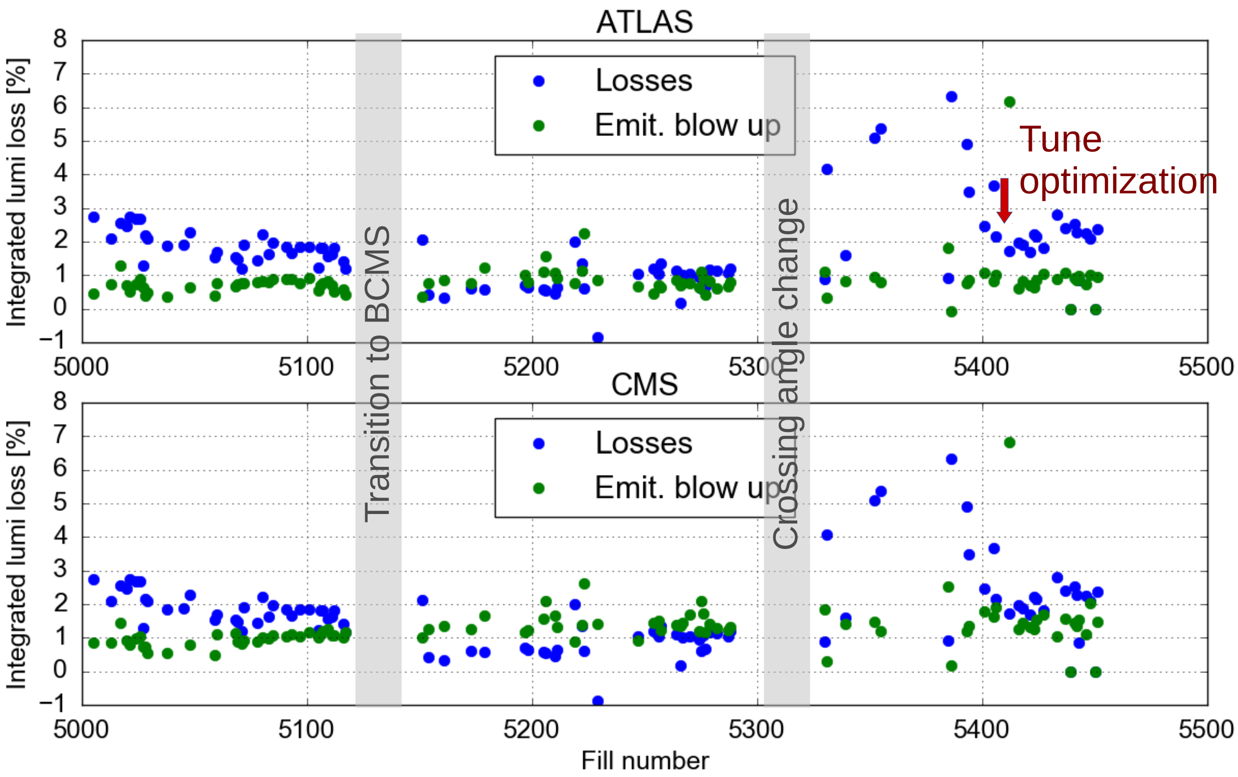
Integrated luminosity loss due to different degradation mechanisms



- 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



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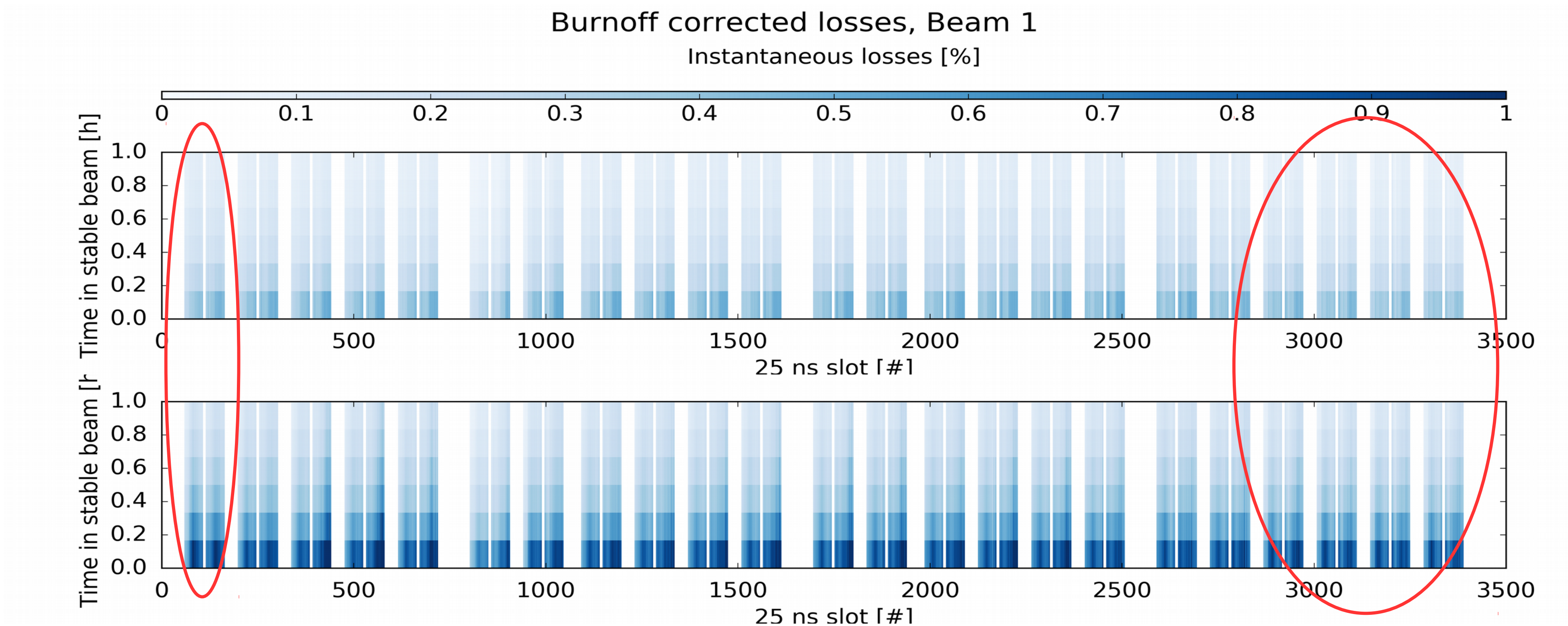
➔ Contribution of the extra **emittance blow-up** is **constant** over the year

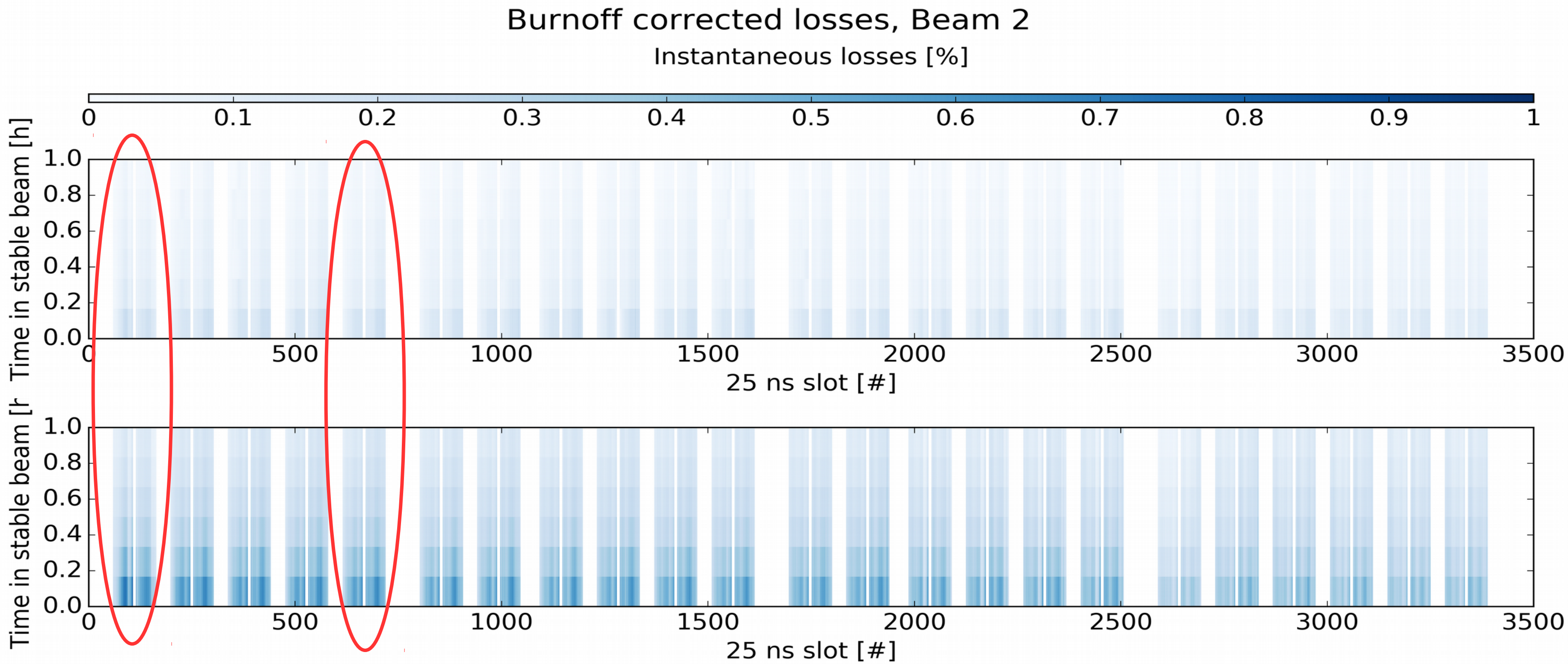
➔ Contribution of extra **losses** is **sensitive to changes in the machine**

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

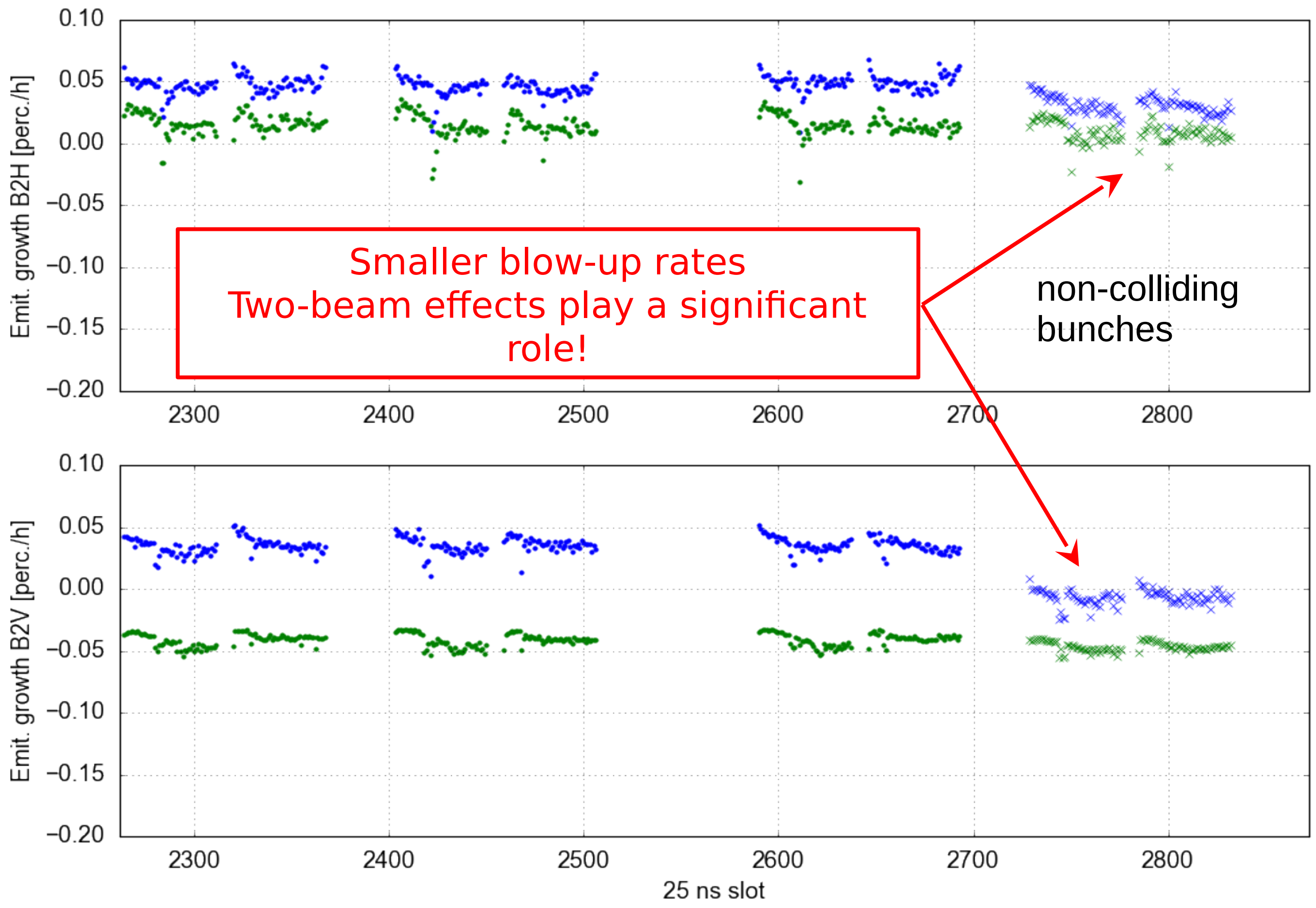
Summary

- Luminosity follow up tools are set up profiting from the consolidated experience with the scrubbing follow up (thanks to Gianni!)
- Peak luminosity evolution along the run can be reproduced fairly well for the biggest part of the run
  - Discrepancy observed in the last fills needs further investigation
- Extra losses observed at the beginning of all fills, sensitive to the machine changes
  - Larger losses for standard beams with larger emittances
  - Minimum losses for the BCMS and larger crossing angle period
  - Losses increased after the crossing angle reduction
  - Losses were improved after the tune optimization
  - Higher losses for the LHCb negative polarity
- Impact of the extra losses on the integrated luminosity, sensitive to machine changes
- Impact of extra emittance blow up on the integrated luminosity is constant along the year
- LR traces observed after the crossing angle reduction
  - Analysis ongoing to verify if this is the source of losses increase after the reduction of crossing angle
  - One should keep this in mind for the operation of next year

Thank you for you attention!

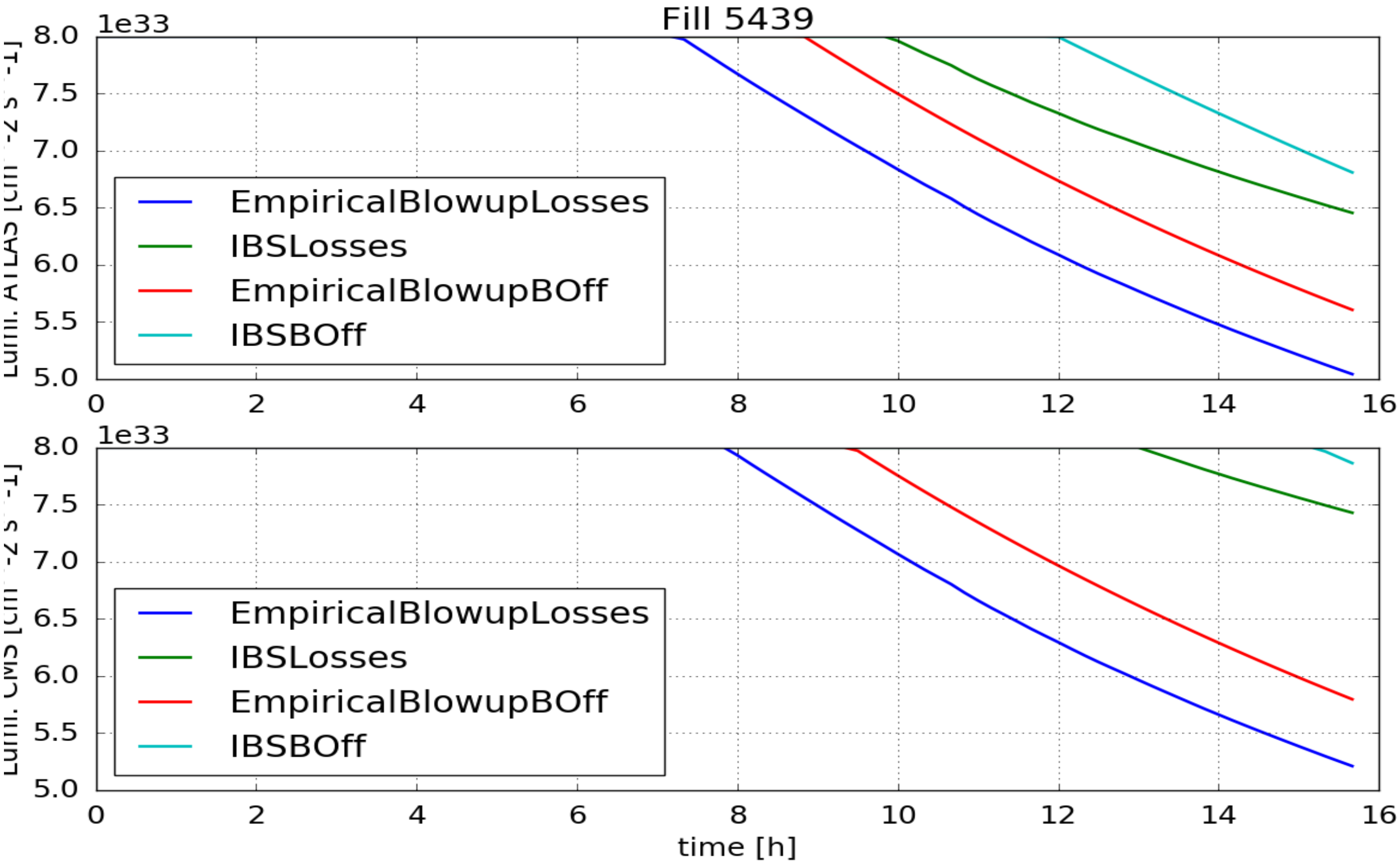
Extra slides

Extra emittance blow-up

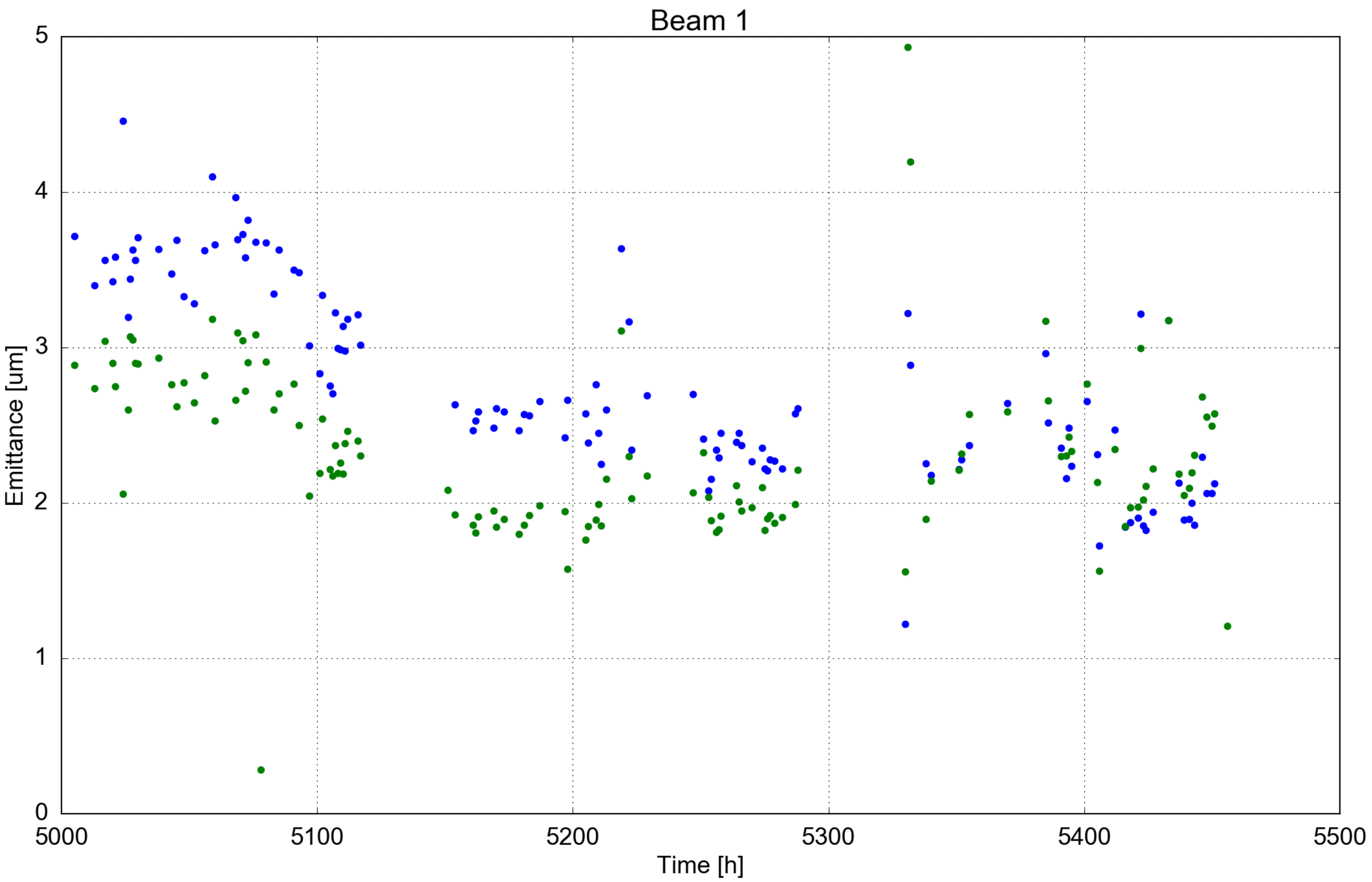


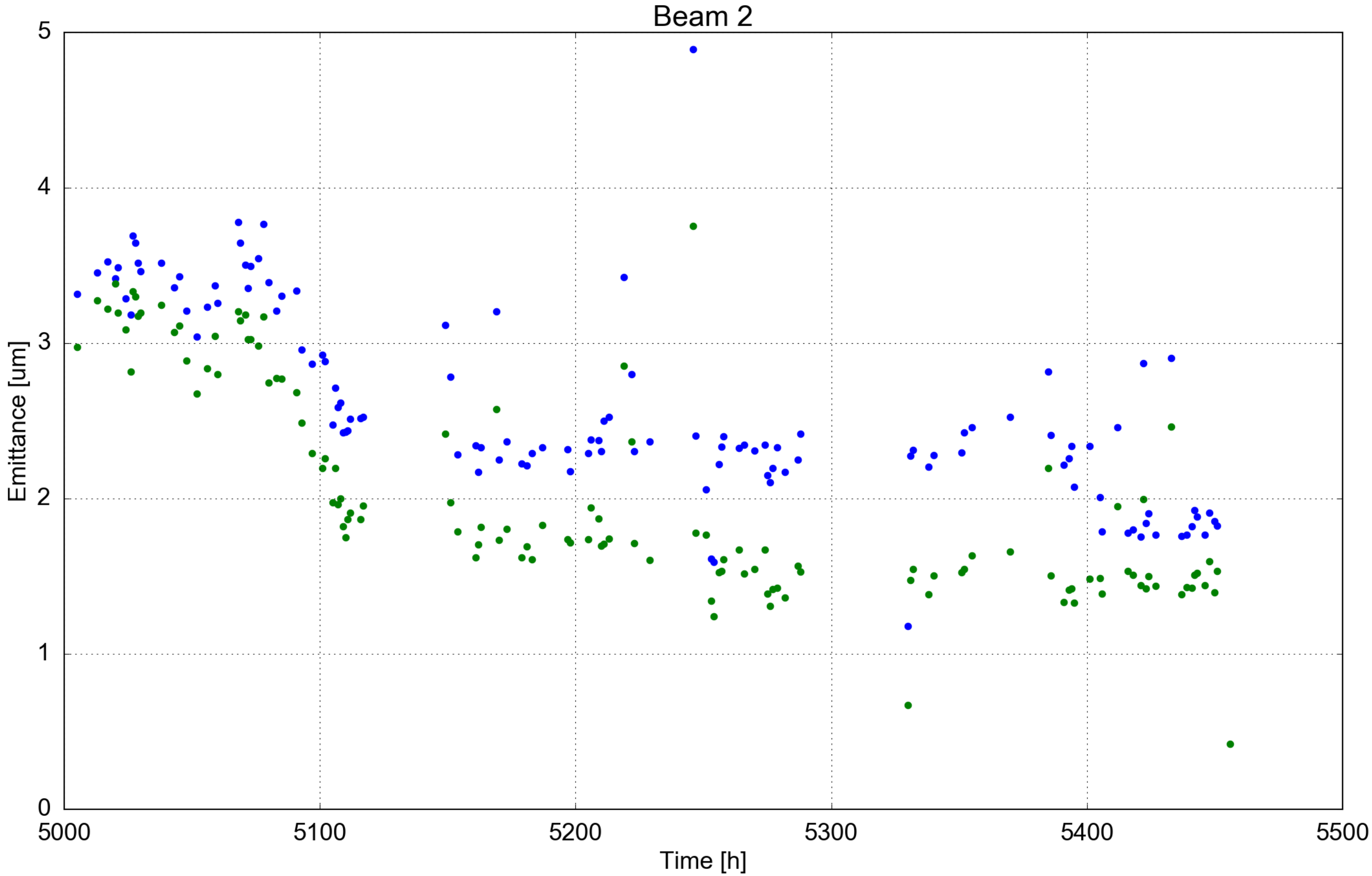
- **Fill 5205** went in collision with **one non-colliding BCMS train in B2** Ideal to make comparisons
- Non-colliding bunches blow-up less → 2-beam effects play a significant role

Leveling Fills

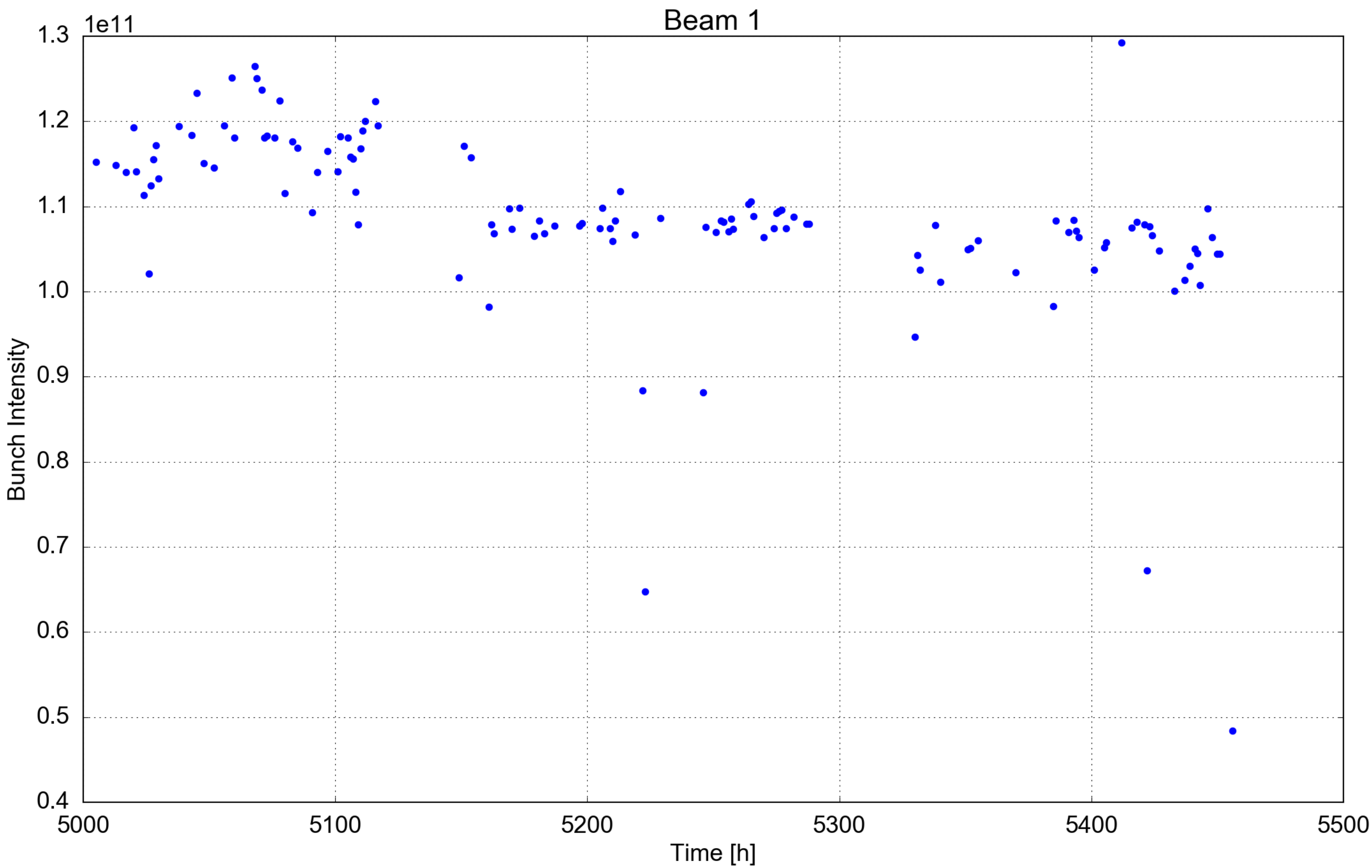


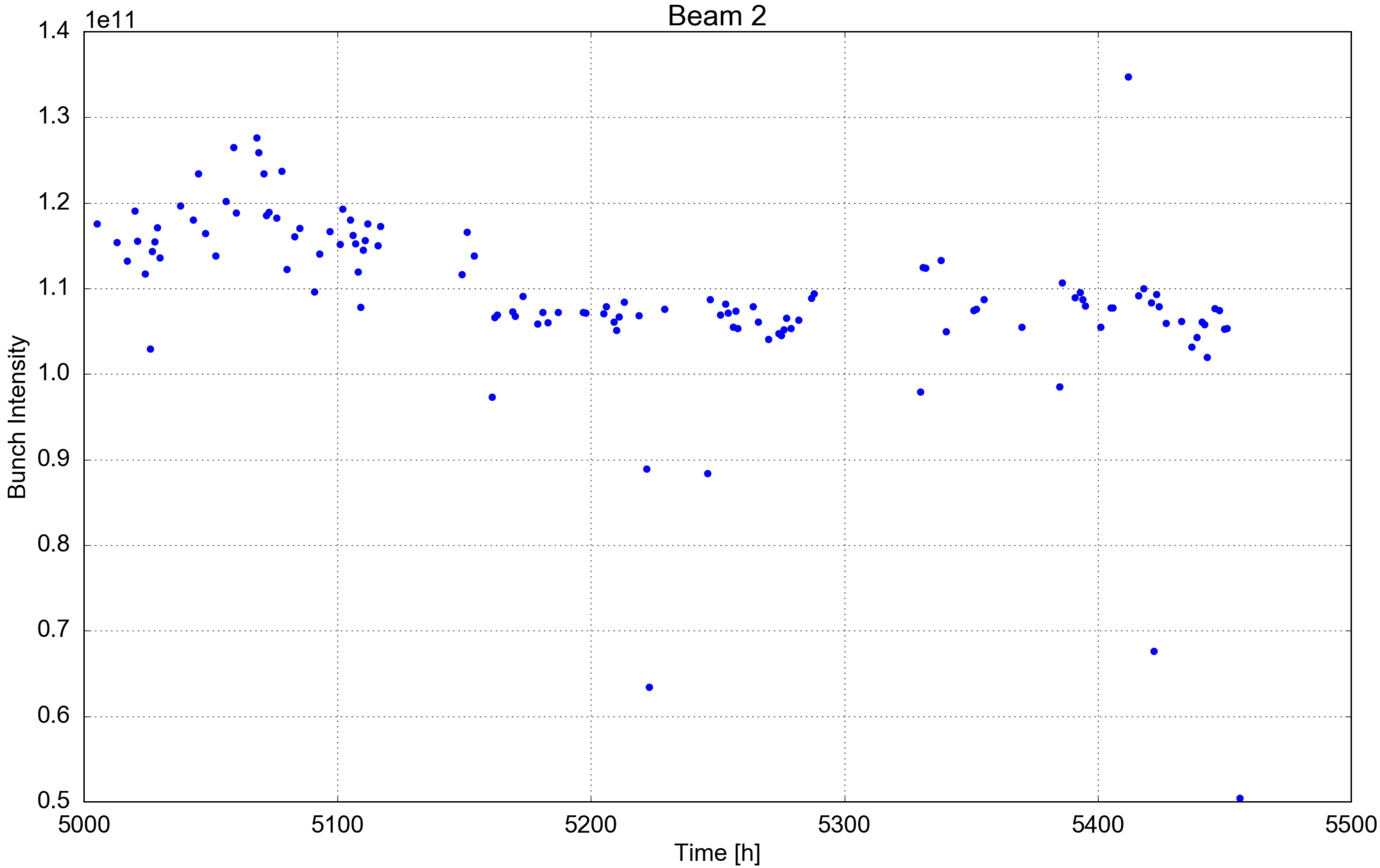
- Impact of the different degradation mechanisms on the leveling time based on the lumi model


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

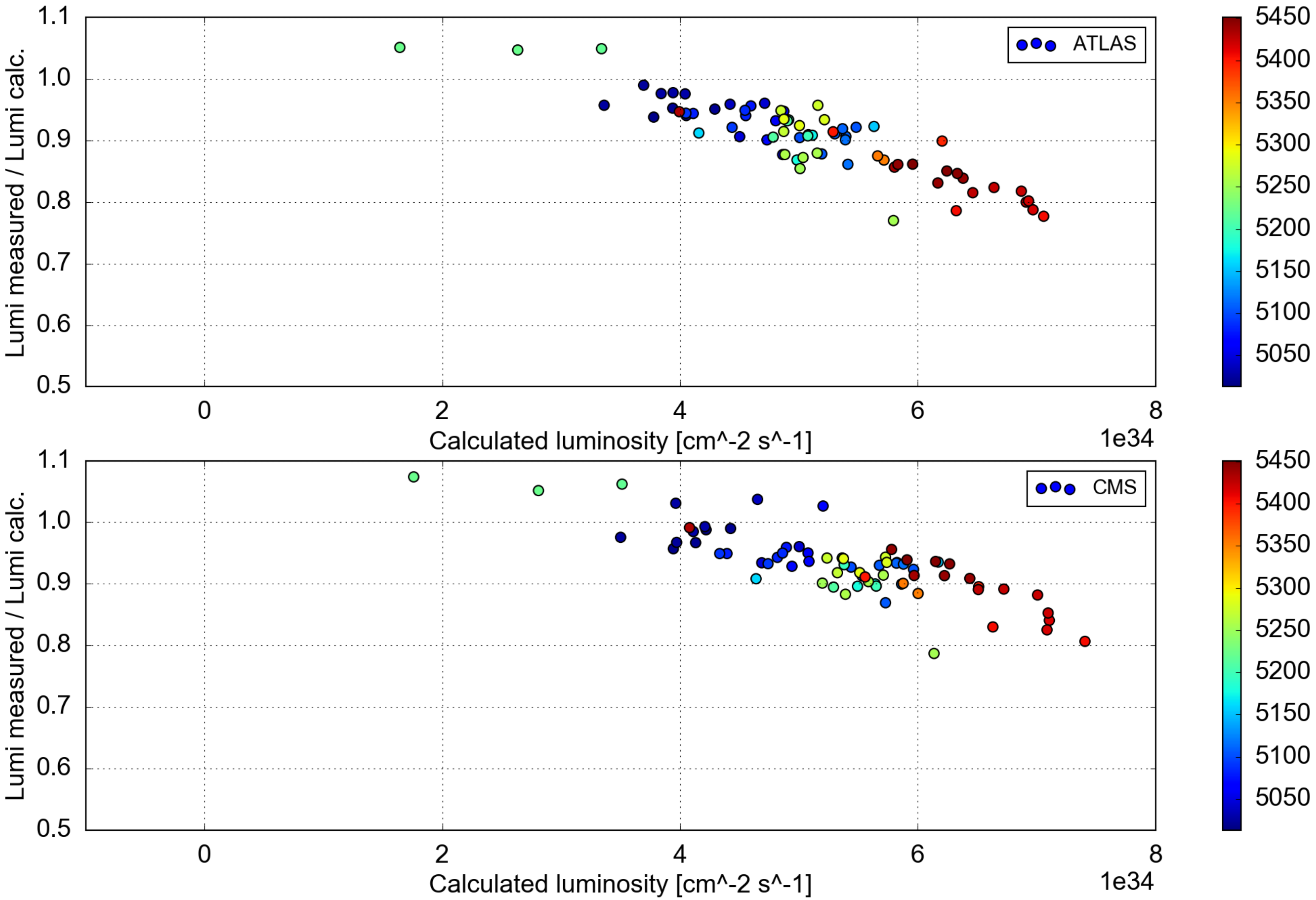


Beam 2
Emittance [um]
Time [h]
0
1
2
3
4
5
5000
5100
5200
5300
5400
5500

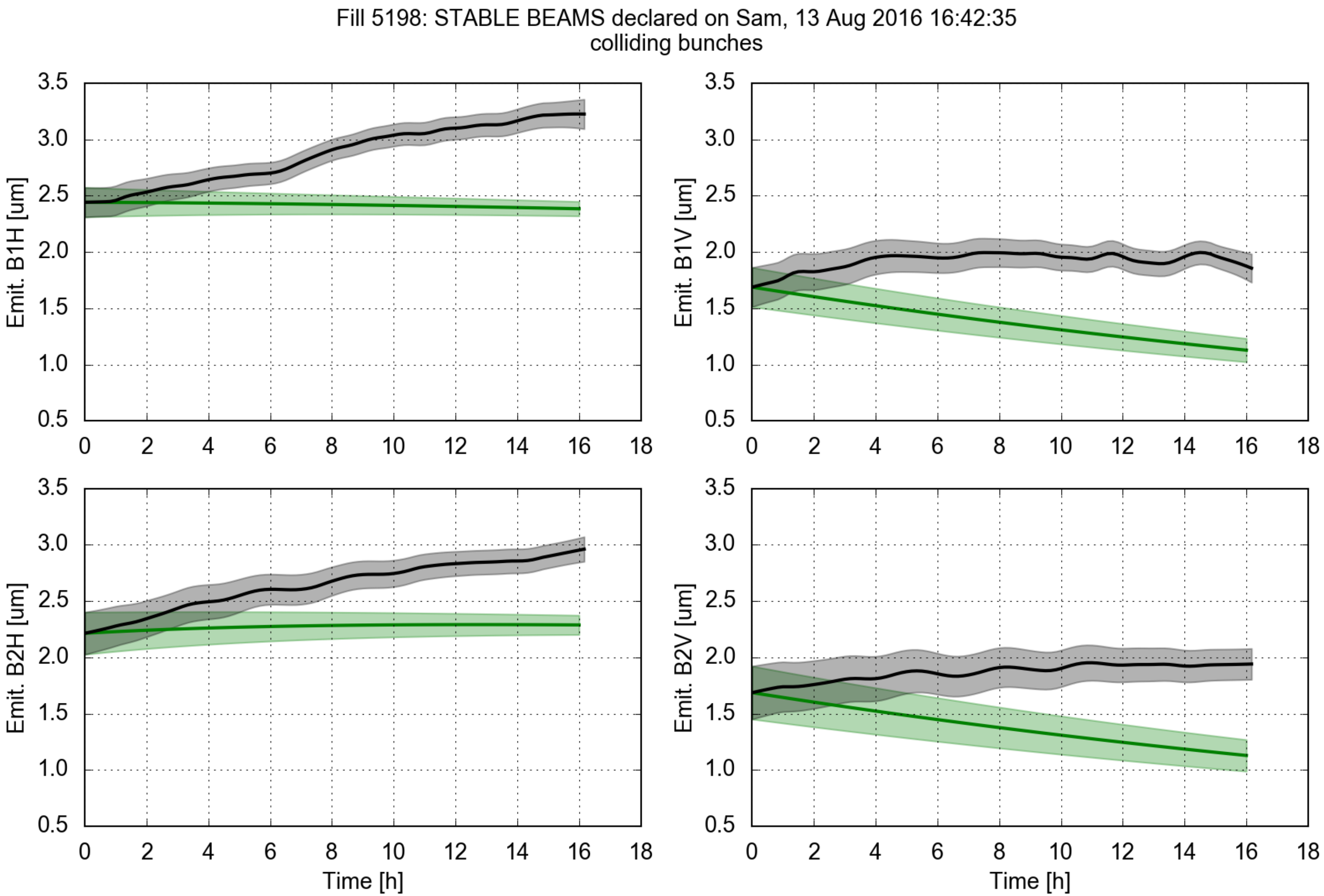

Beam 1
1e11
Bunch Intensity
Time [h]
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
5000
5100
5200
5300
5400
5500



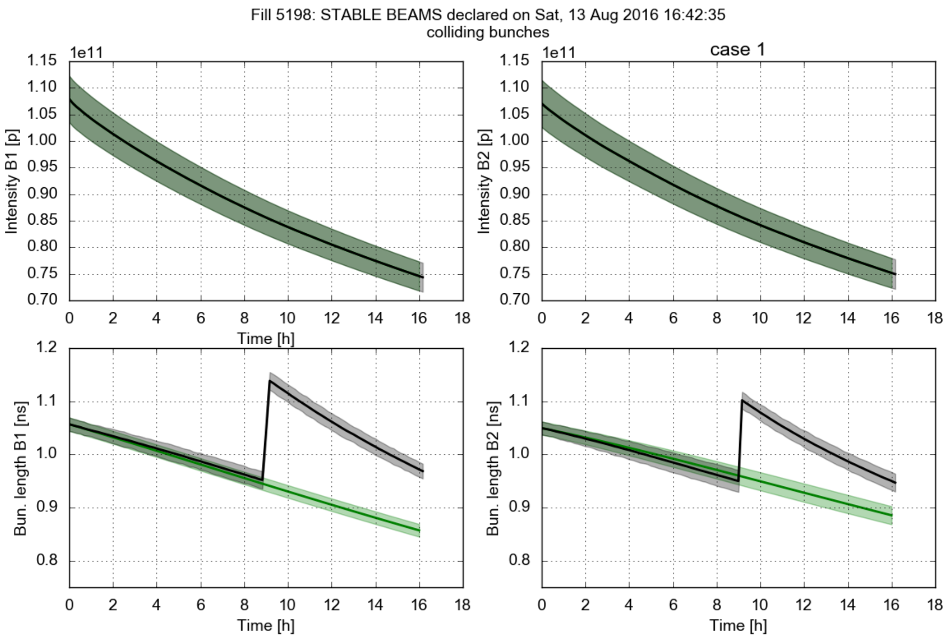
Beam 2
1e11
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
Bunch Intensity
5000
5100
5200
5300
5400
5500
Time [h]

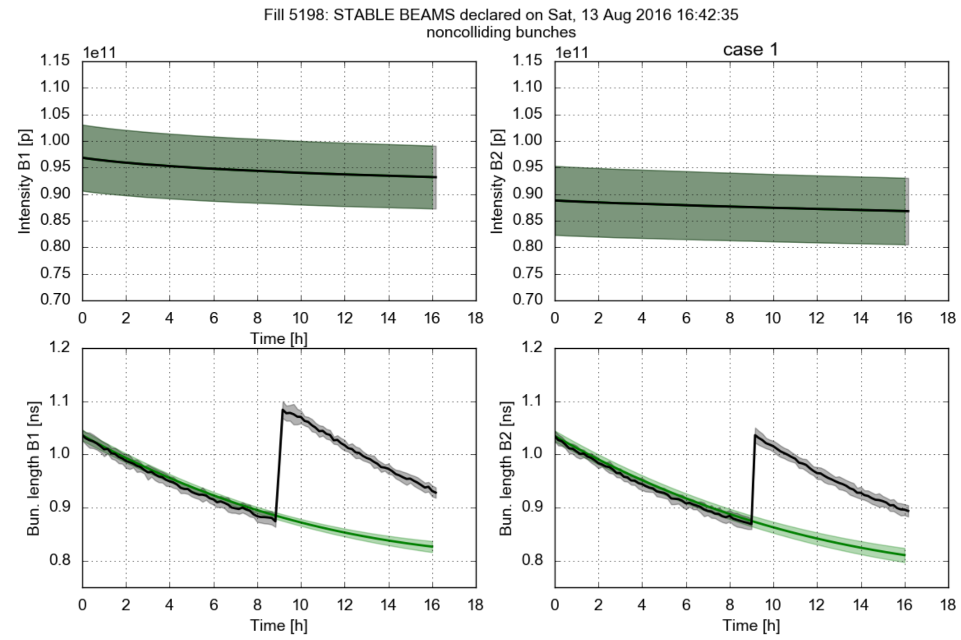

ATLAS
CMS
Lumi measured / Lumi calc.
Calculated luminosity [cm^-2 s^-1]
1e34
0
2
4
6
8
0.5
0.6
0.7
0.8
0.9
1.0
1.1
5050
5100
5150
5200
5250
5300
5350
5400
5450

Luminosity modeling



Luminosity model comparison with data: Bunch length



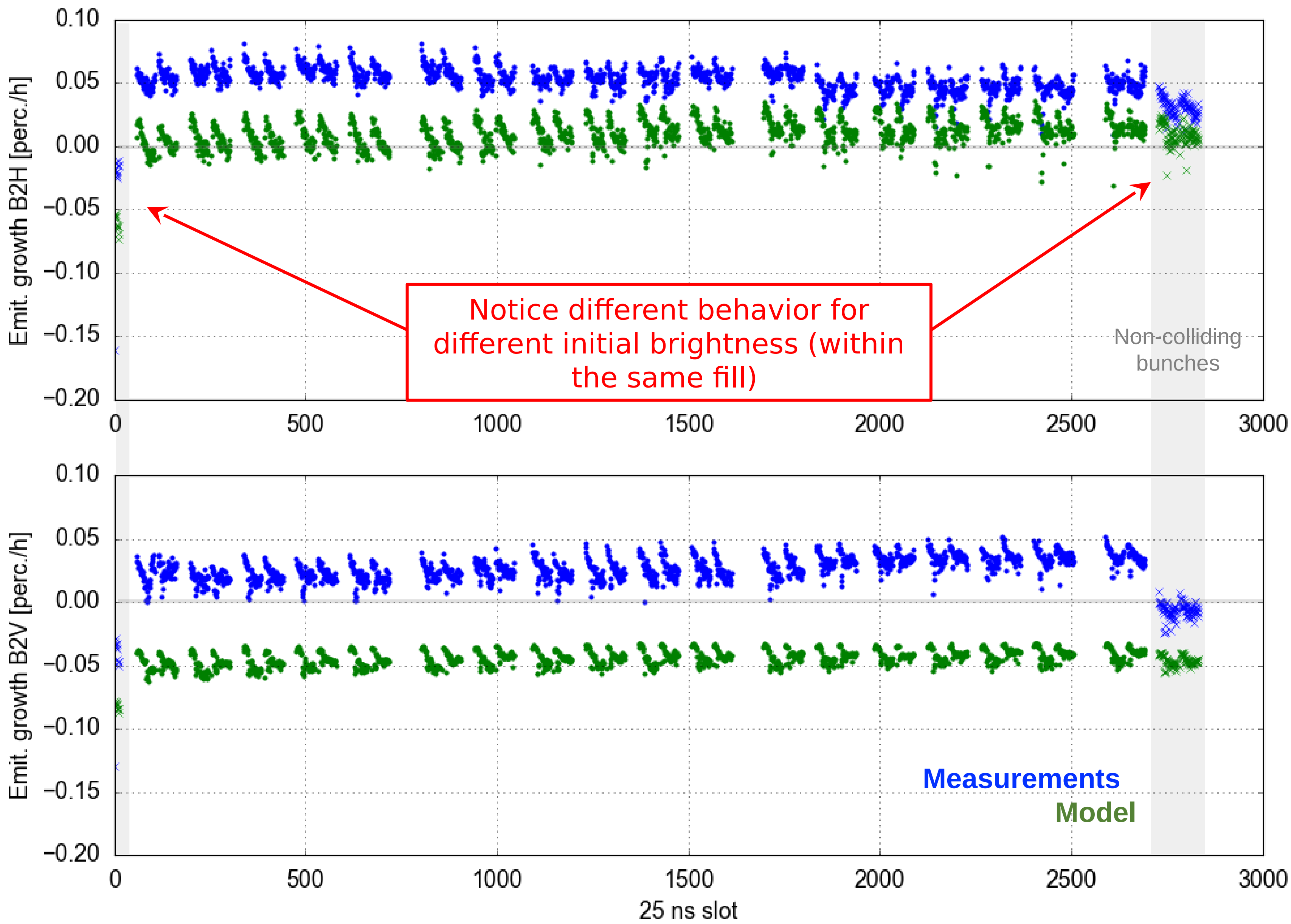


Emittance evolution in Stable Beams

- 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**

Colliding vs non-colliding

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



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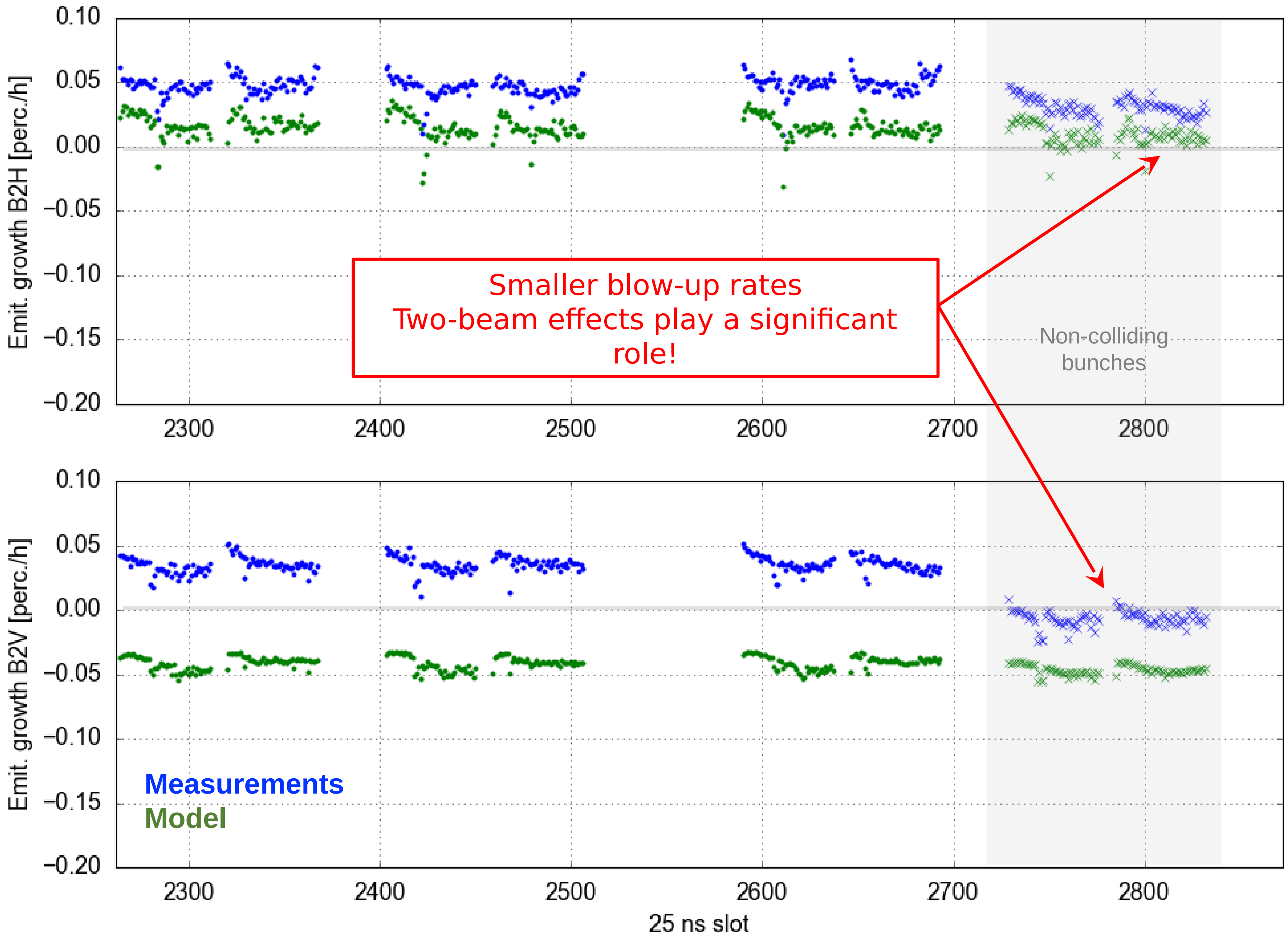

Colliding vs non-colliding

- **Fill 5205** went in collision with **one non-colliding BCMS train in B2**
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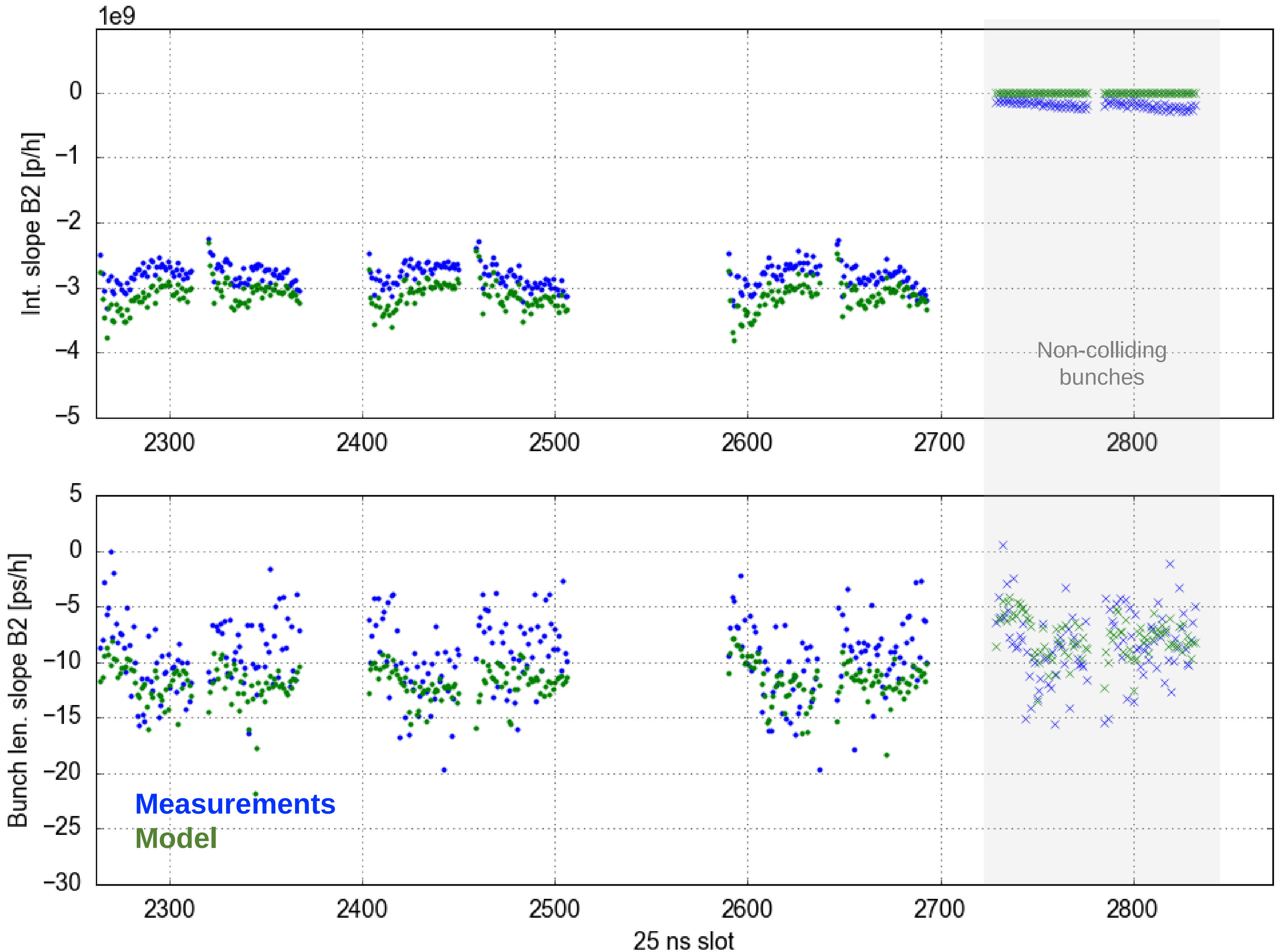

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