Expectations (extrapolated from LHC operation) for the beam lifetime and halo population based on scaling from the LHC observations for radiation damping and IBS excitation

F. Antoniou, G. Iadarola, S. Papadopoulou, Y. Papaphilippou

Acknowledgements: R. Alemany Fernandez, G. Arduini, I. Efthymiopoulos, M. Hostettler, M. Lamont, G.Trad

Review on the needs for a hollow electron lens for the HL-LHCCERN, 6-7 Oct. 2016

Outline

- LHC Luminosity model
- LHC observations
  - RunI 2012
  - RunII 2016
- Impact on beam distributions
  - IBS simulations
  - LHC beam profiles evolution
- Extrapolations or the HL-LHC
  - Impact on luminosity evolution based on the above observations

LHC Luminosity model

- Python scripts built for extracting TIMBER data for parameter evolution observations, luminosity reconstruction and comparison with model
  - We can follow all the fills bunch by bunch
- Modelling of **emittance evolution**
  - **IBS evaluation** based on multi-parametric fit functions depending on 3D emittances, bunch current, energy and synchrotron radiation damping
  - At **stable beams**, adding a self-consistent evaluation of:
    - current decay due to **burn-off** (only inelastic interactions considered, see "Where do the protons go?" by M. Lamont)
    - emittance growth due to **elastic cross section**

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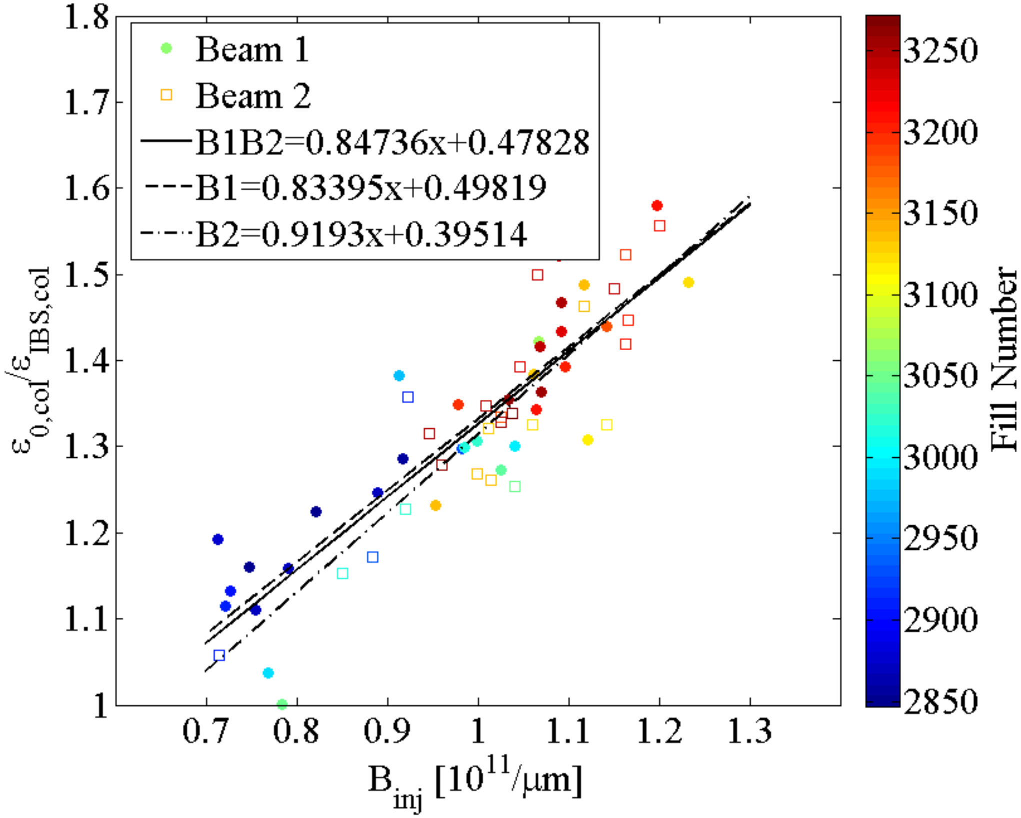
LHC Observations
RunI 2012

Emittance evolution from Injection to Stable Beams

- Fills with WS data at Flat Bottom
  - Not always data for both beams and both plane
  - The convoluted emittance is used
- The IBS model from injection to the beginning of collisions is applied
  - The expected conv. emittance of the selected 144 bunches (with WS data) at the beginning of collisions is calculated
  - Comparison with the measured one
- The data from many Fills were put together

Emittance evolution from Injection to Stable Beams

- Fills with WS
  - Not always ... lane
  - The convol
- The IBS moc ... g of collisions is
  - The expect ... ed 144 bunches (w ... collisions is calculated
  - Compariso



- The data from many fills were put together
- Brightness depented effect which blows up the transverse emittance on top of IBS
  - Same effect for both beams

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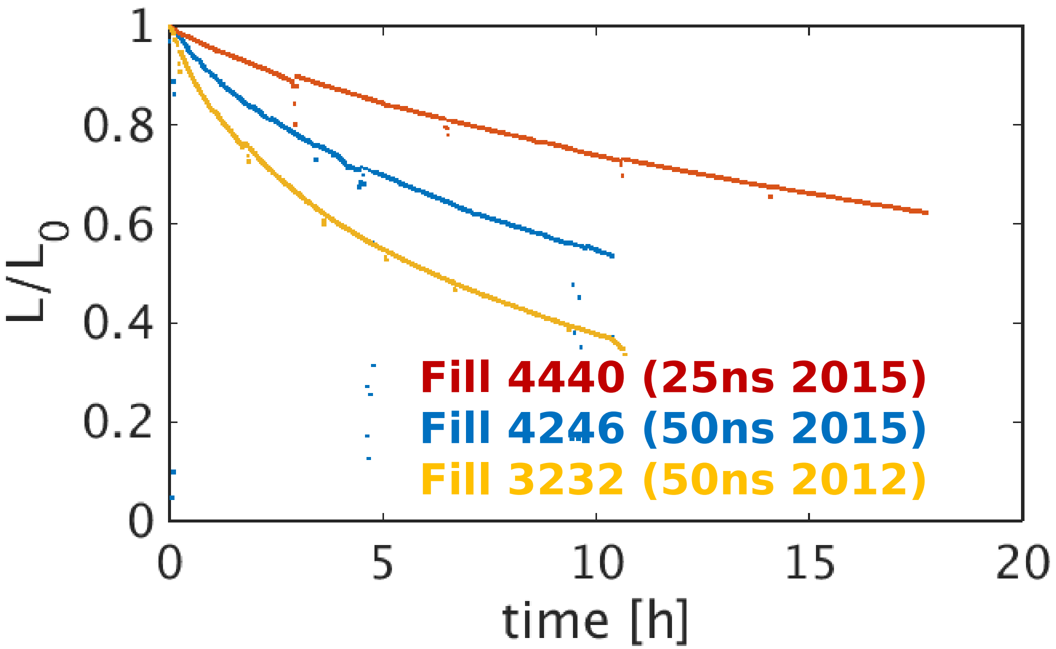
Lumi evolution: LHC RunI Vs RunII



- Luminosity decay from ATLAS data
- The luminosity lifetime much better in 2015
  - Lower bunch brightness
  - Weaker beam-beam effect

- Mean bunch characteristics at the beginning of Stable Beams:
  - Fill 4440
    - N_{b0} =1.08e11ppb
    - ε_0 = 3.08 μm-rad
  - Fill 4246
    - N_{b0} =1.2e11 ppb
    - ε_0 = 2.1 μm-rad
  - Fill 3232
    - N_{b0} =1.6e11ppb
    - ε_0 = 2.8 μm-rad

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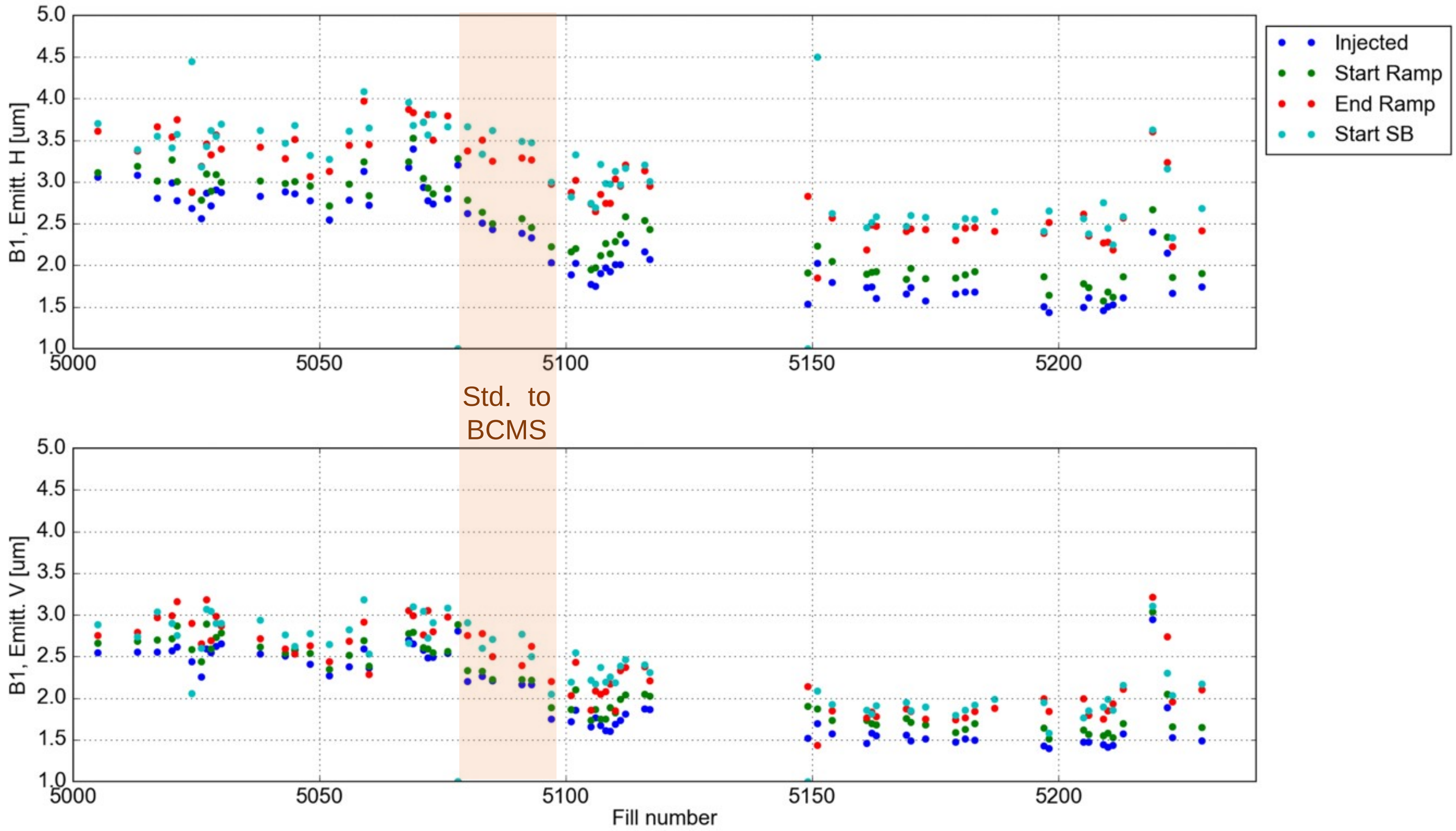
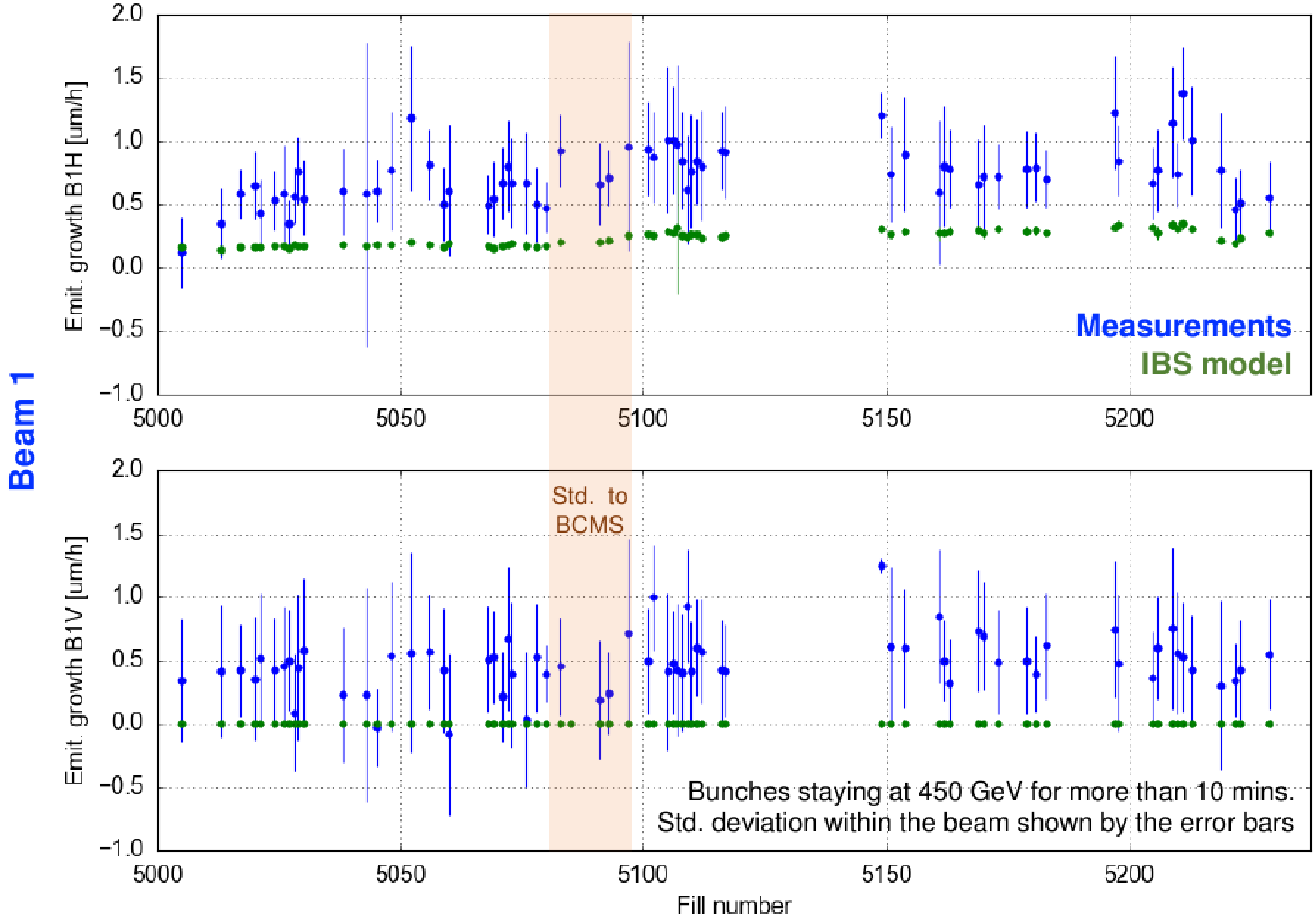
LHC Observations
RunII 2016

Emittance evolution from Injection to Stable Beams



- Almost constant growth along the run
- More blow-up in B1H, then B2H, followed by V for both beams

Emittance evolution @ 450 GeV



- Significant growth already **at injection**, as compared to the model
- **Input emittance** and **IBS** seems to explain the difference between H/V at start of SB

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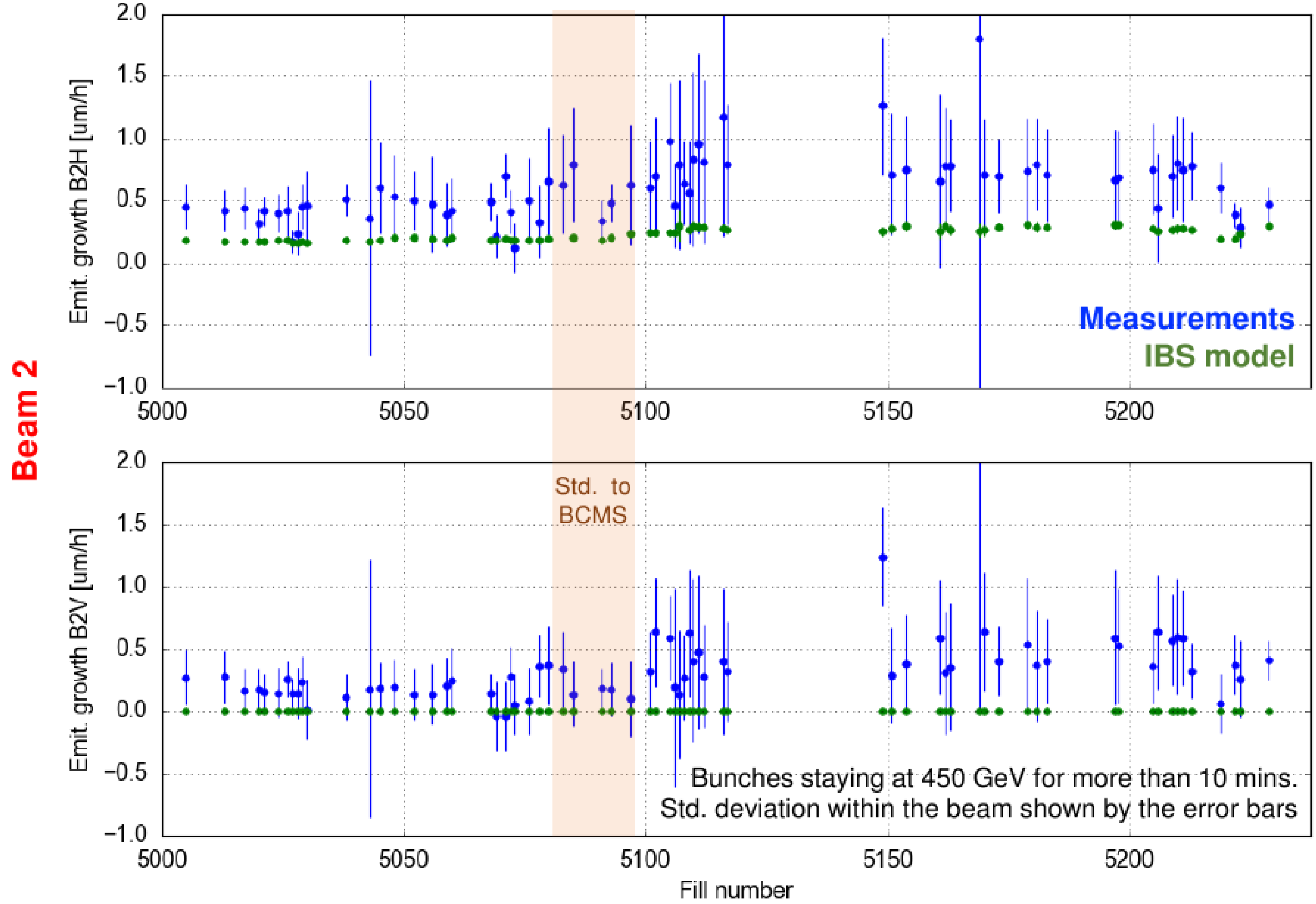
Emittance evolution @ 450 GeV



- Significant growth already **at injection**, as compared to the model
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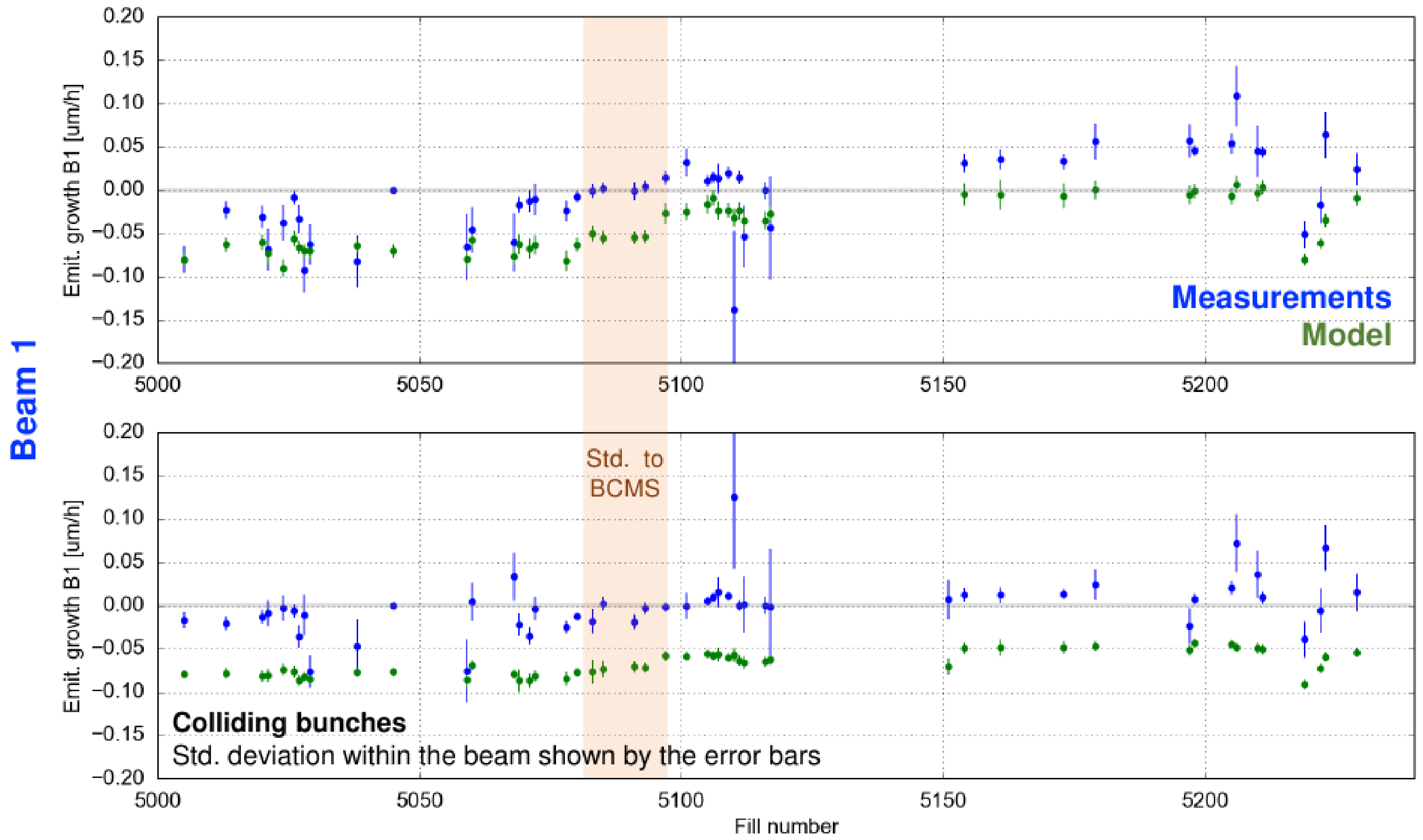
Emittance evolution in Stable Beams



- **Emittance growth** within **±0.1 μm/h (10 times less** than **@ injection**), changing with the beam brightness
- Additional blowup of around **0.05 μm/h** in both planes with respect to the model

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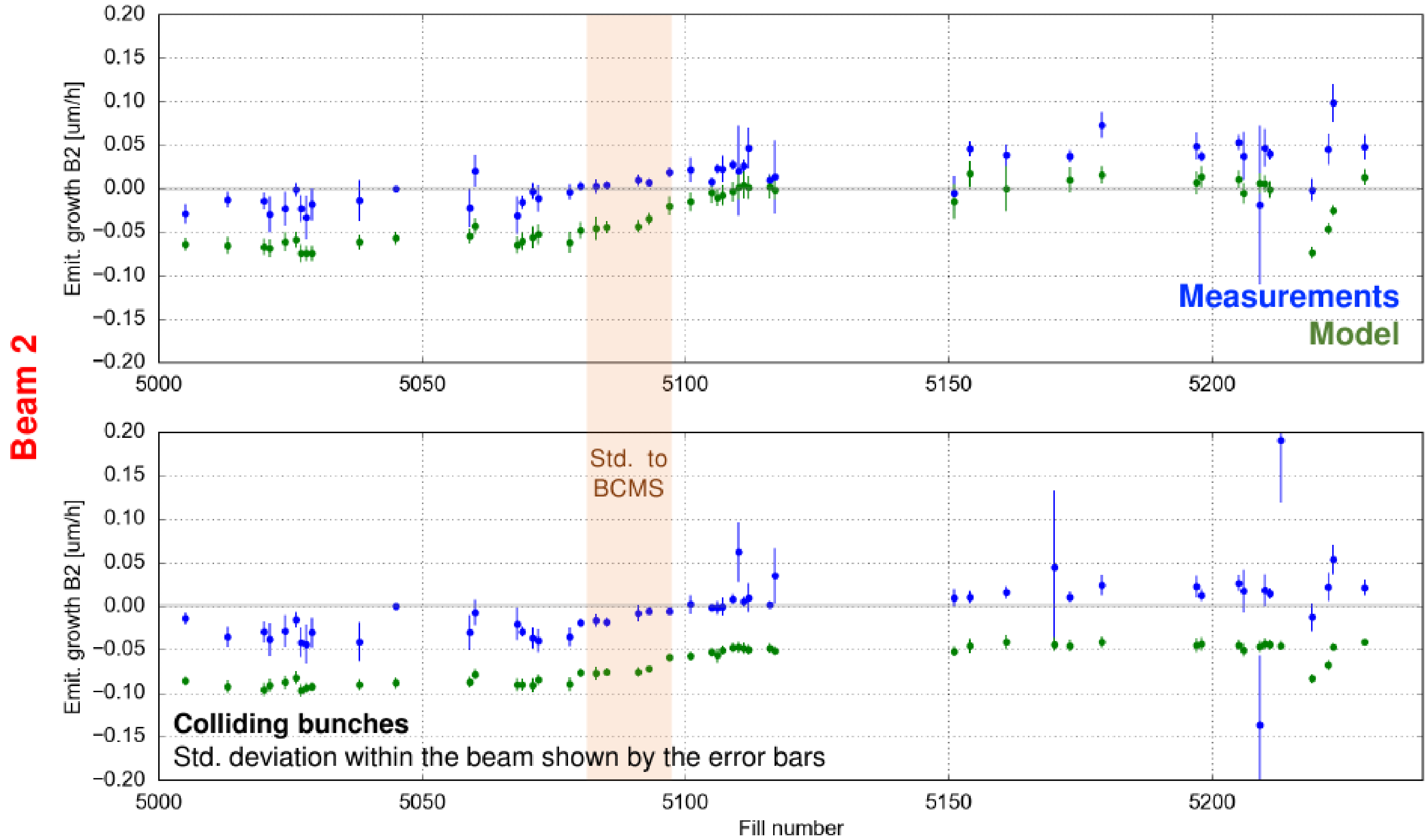
Emittance evolution in Stable Beams



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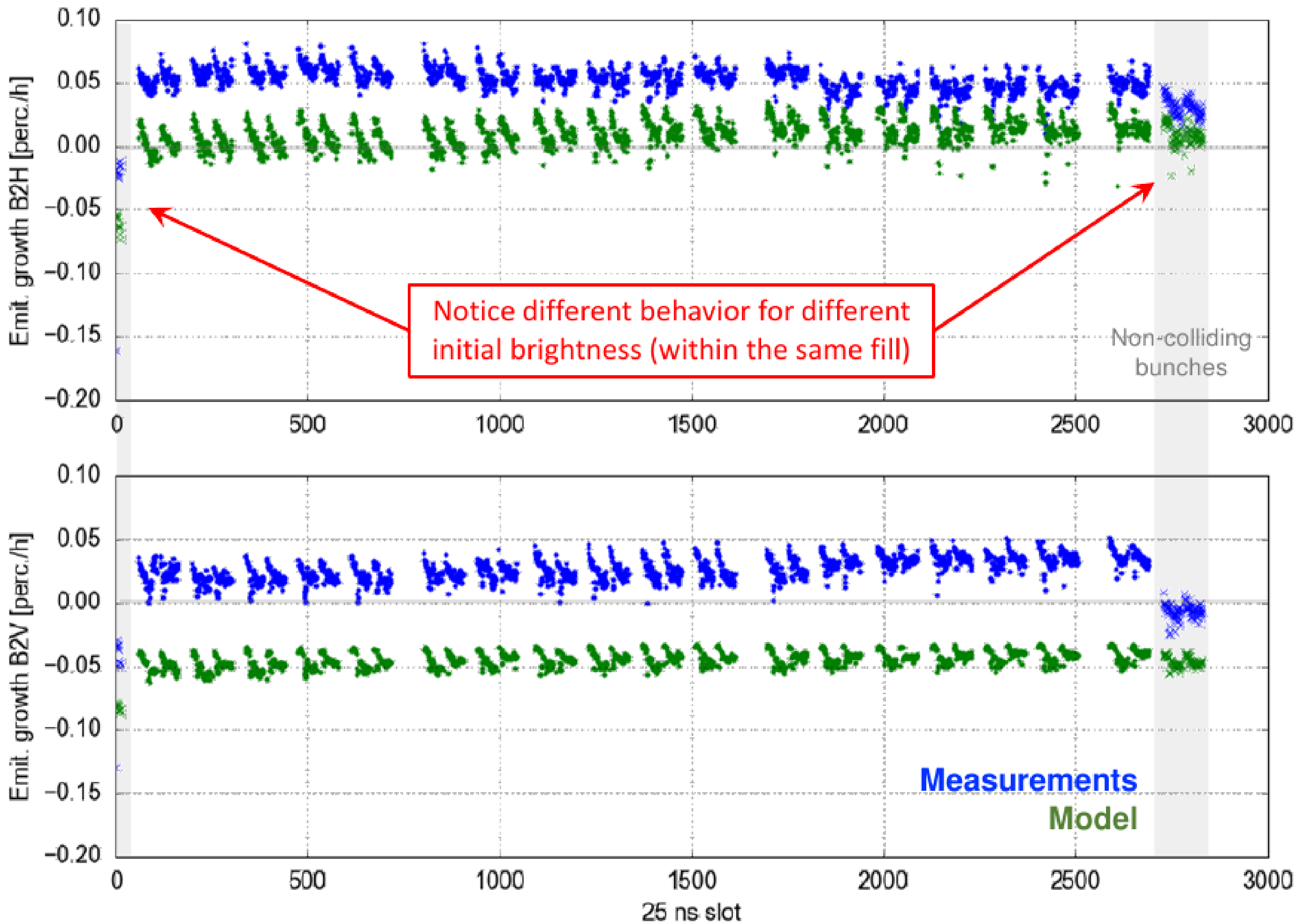
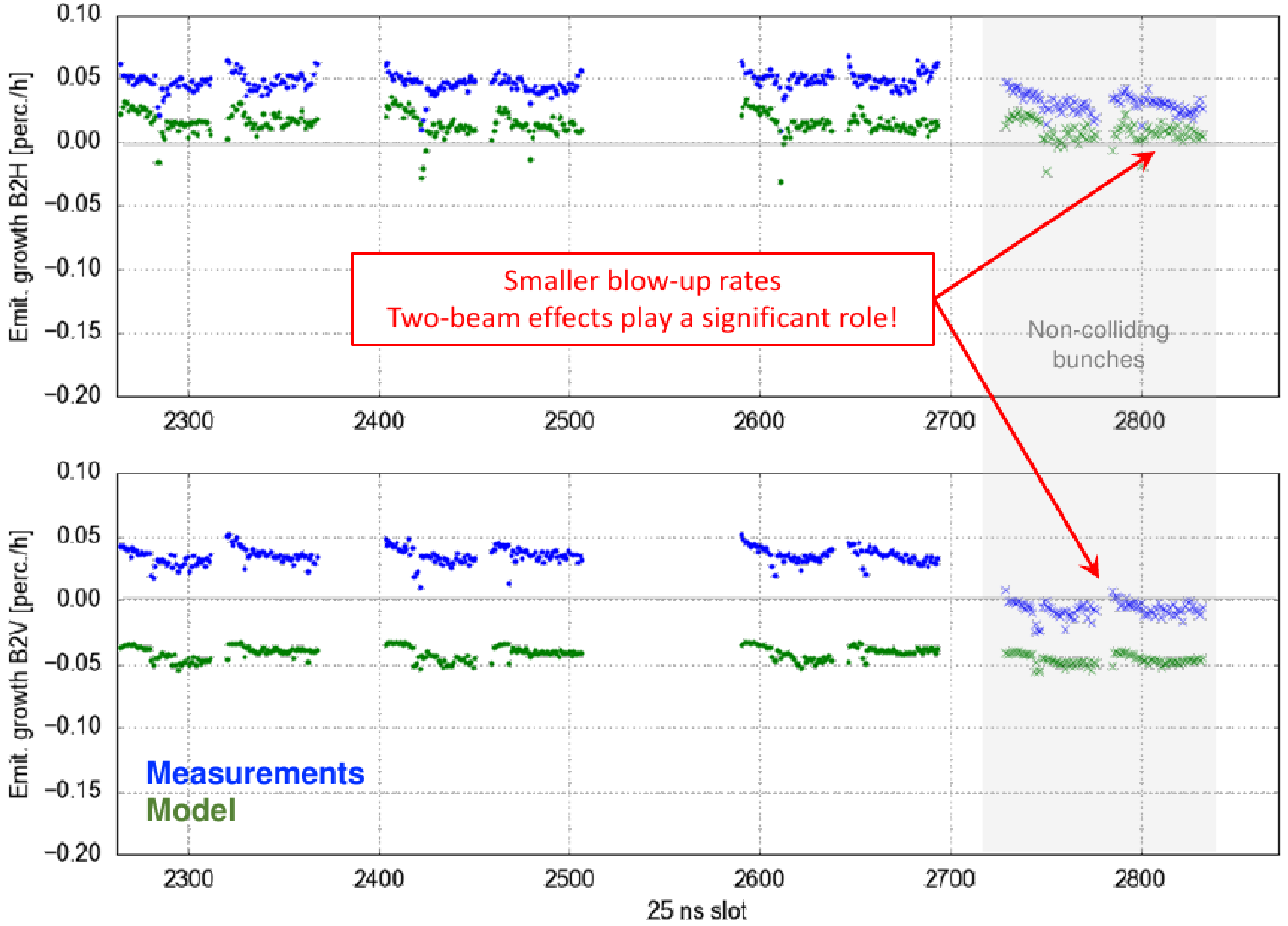
Colliding Vs non-colliding bunches



- Fill 5205 went to collisions with one non-colliding BCMS train in B2
  - Ideal for comparisons

Colliding Vs non-colliding bunches



- Fill 5205 went to collisions with one non-colliding BCMS train in B2
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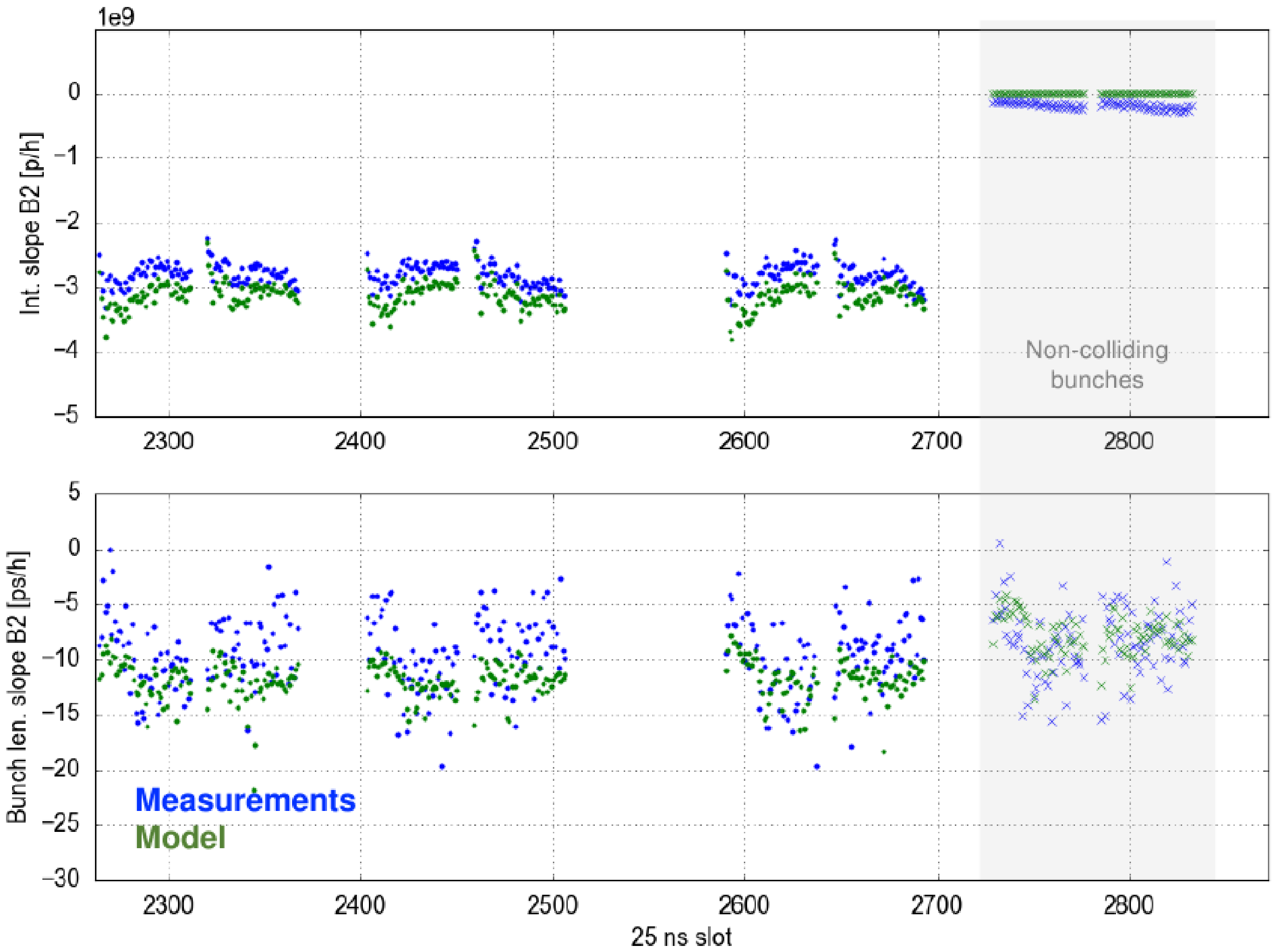
Colliding Vs non-colliding bunches



- Fill 5205 went to collisions with one non-colliding BCMS train in B2
  - Ideal for comparisons (burn-off and bunch length evolution very consistent with the model)

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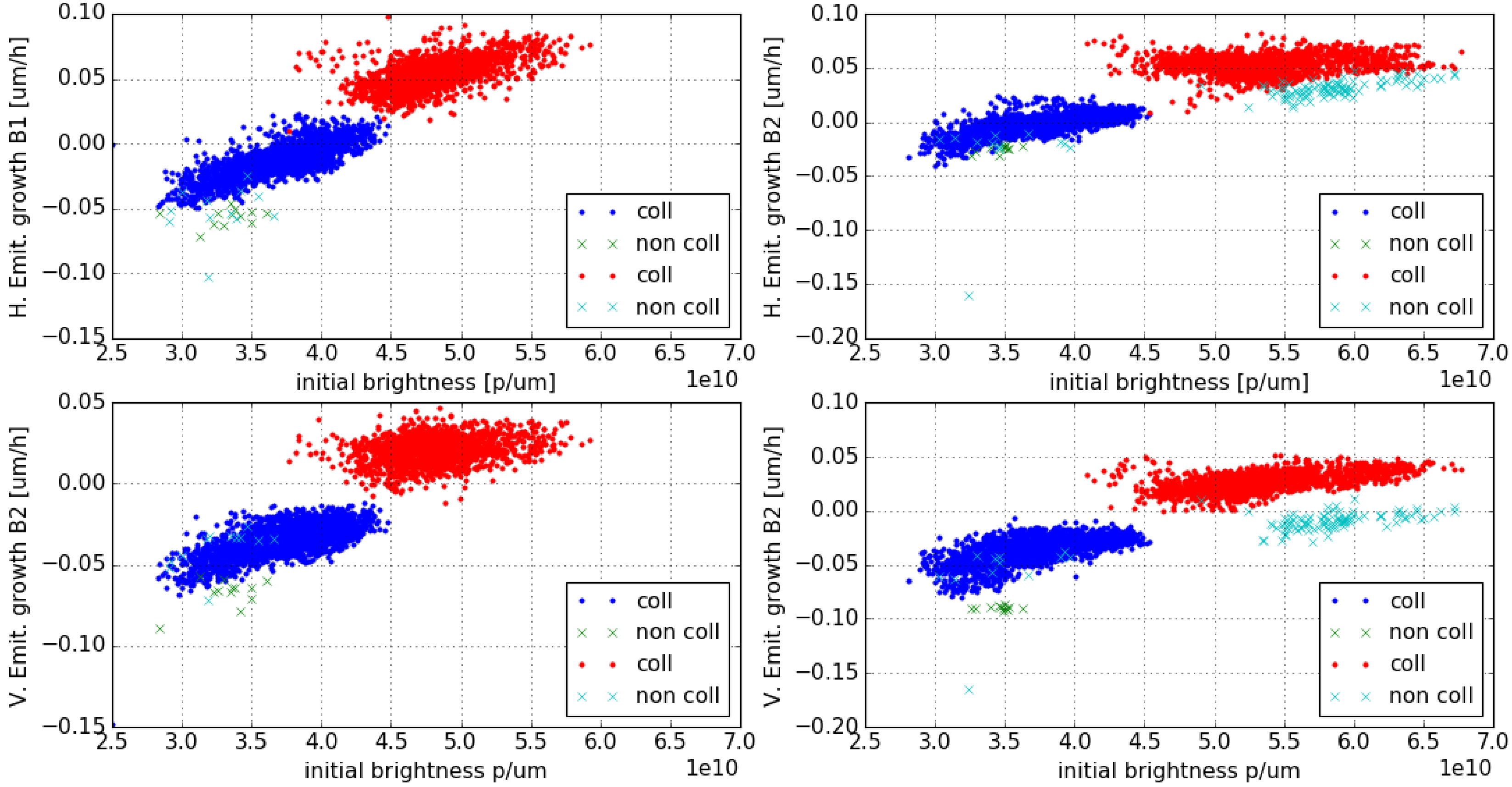
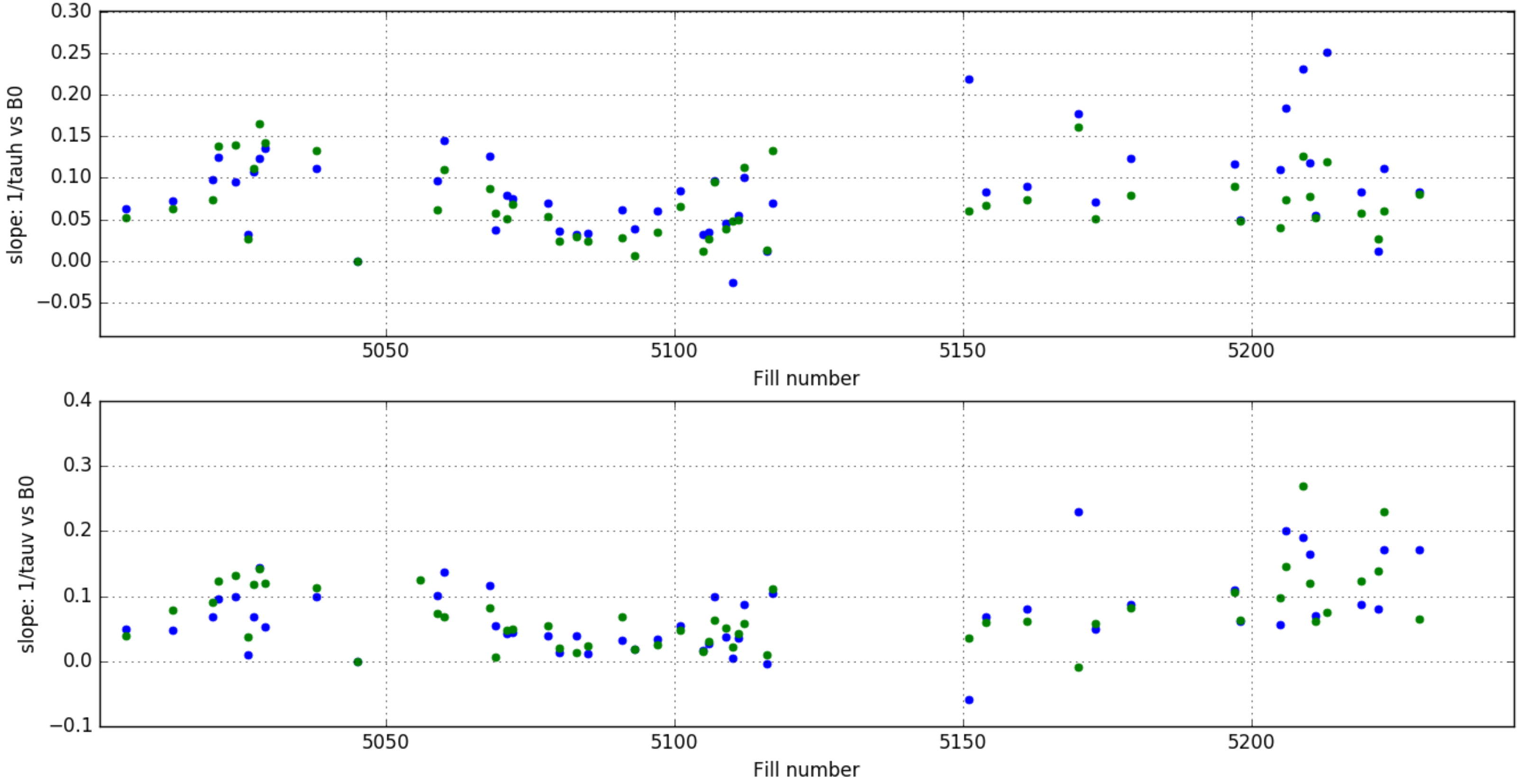
Brightness dependence



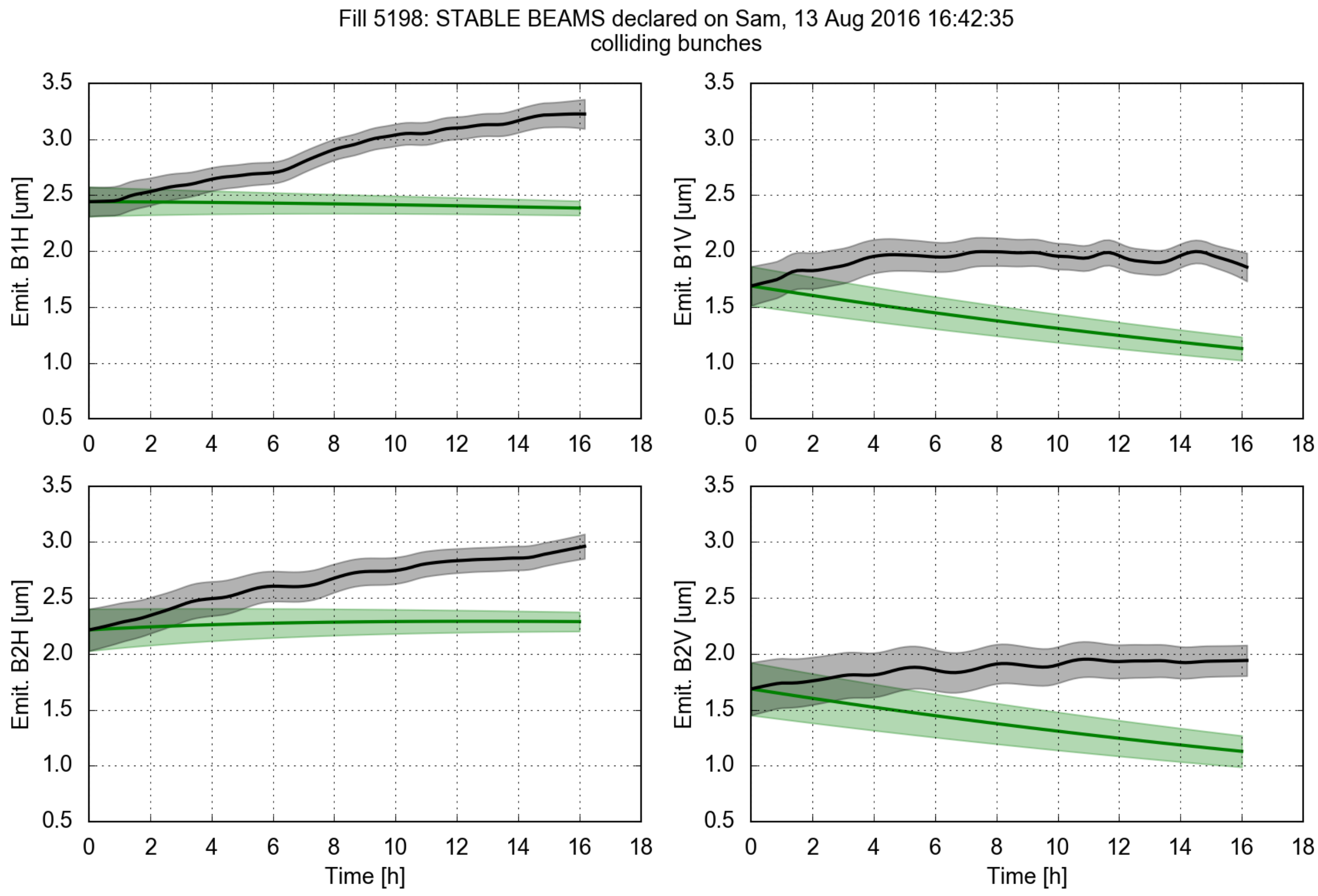
- Brightness dependent blow-up observed for both standard and BCMS beams (also true for non-colliding bunches)
- Model predicts almost no blow-up (or slight damping)

Brightness dependence



- Linear fit to the emittance growth times vs initial brightness
  - For all fills and for both beams and both planes

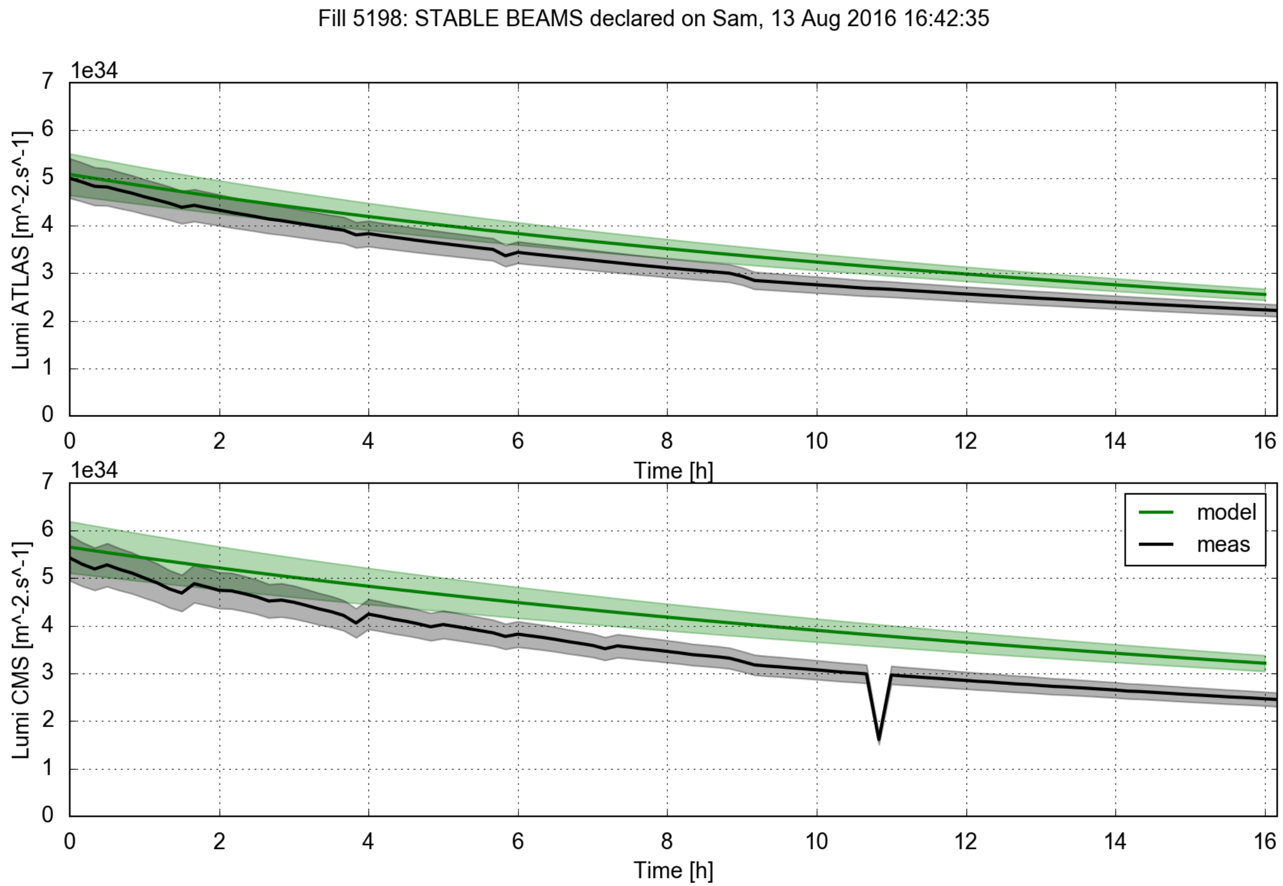
Impact on Luminosity modeling



Measurements
Model

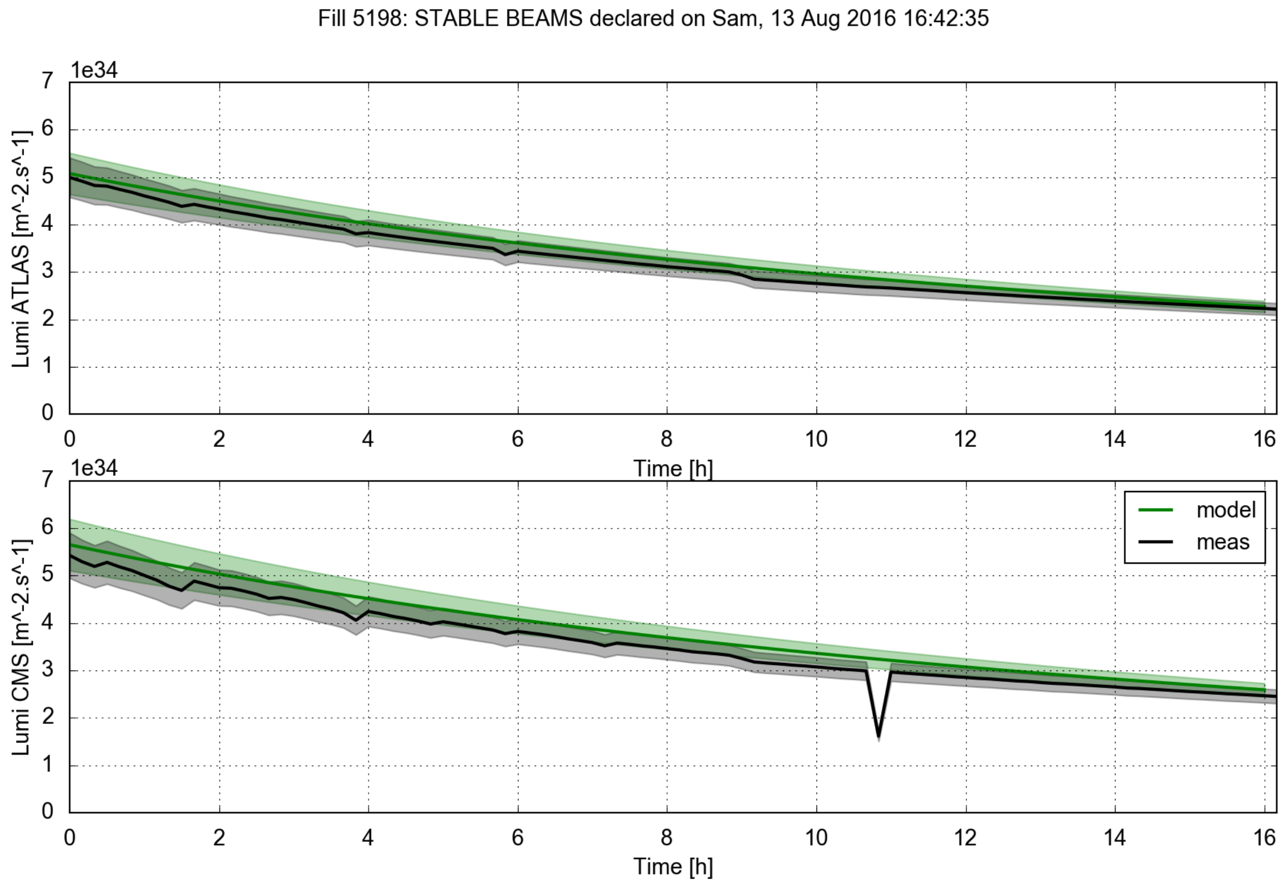
- Model tends to underestimate the emittance blow-up

Impact on Luminosity modeling



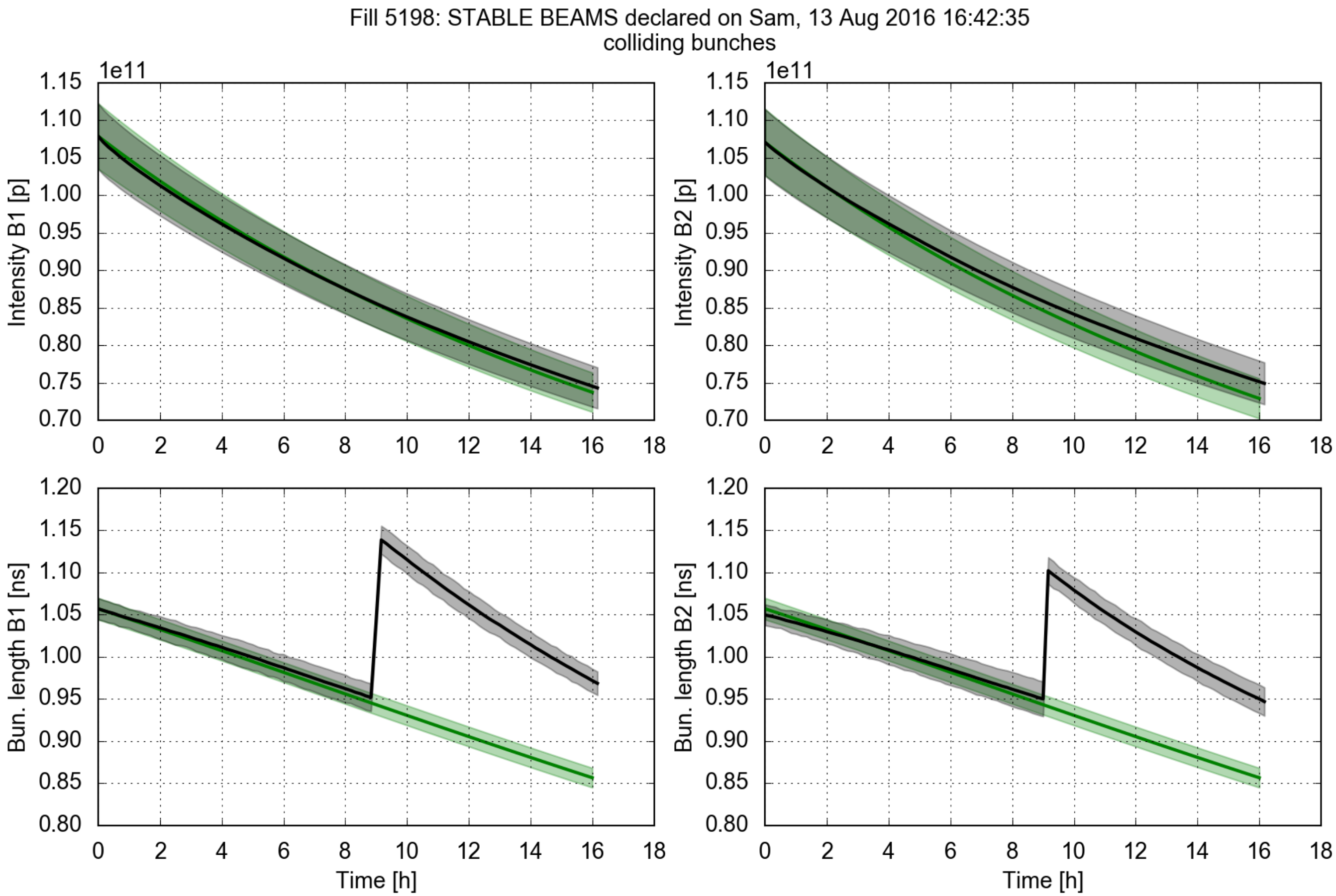
- ... and the luminosity evolution as well..

Impact on Luminosity modeling



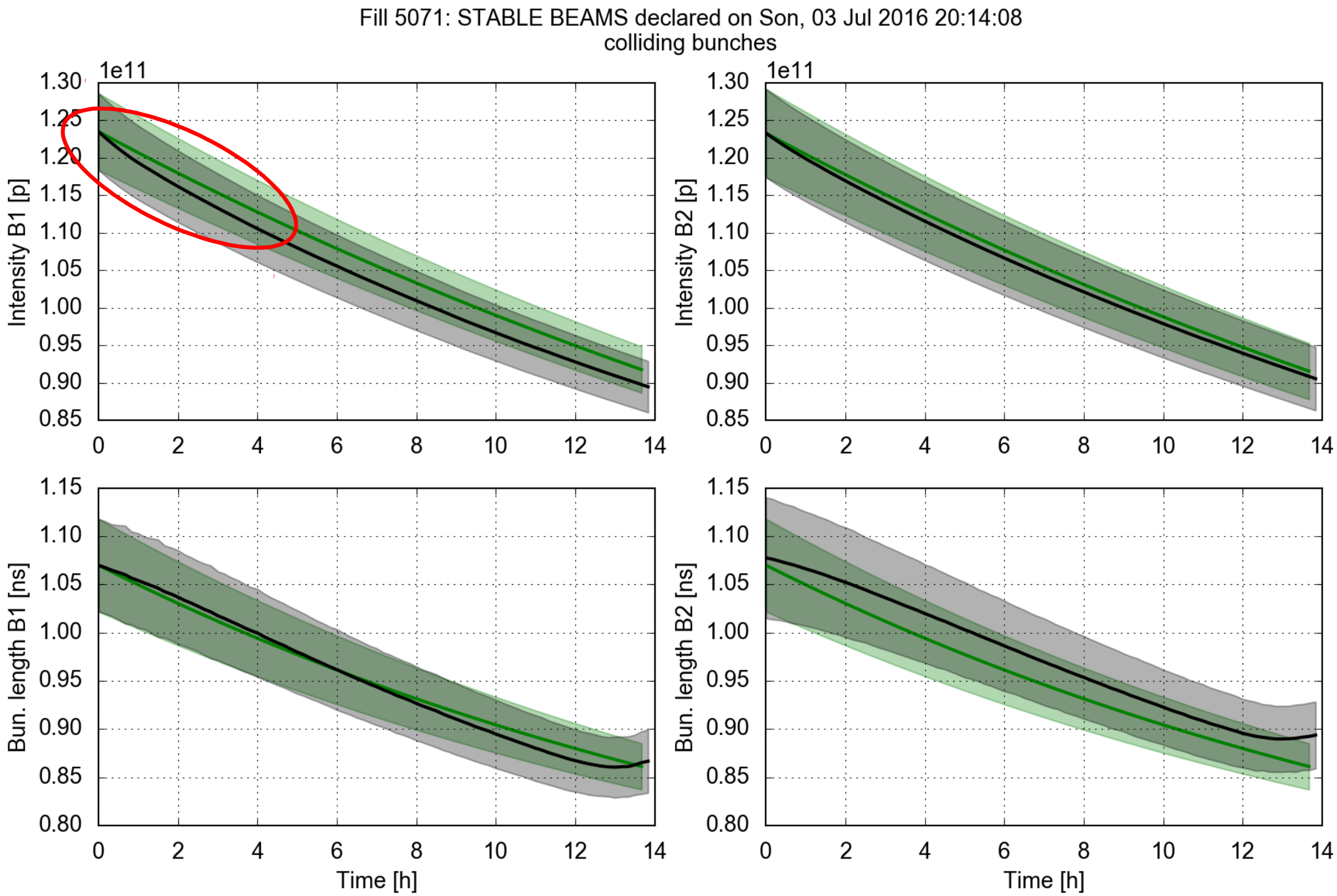
- Adding an additional transverse blow-up term (determined by fitting the measurements) the **luminosity decay** can be **predicted** correctly (similar to 2015)

Impact on Luminosity modeling



- Very good agreement for intensity decay and longitudinal damping (especially for latest BCMS fills)
- Effect of IBS visible also in the longitudinal evolution

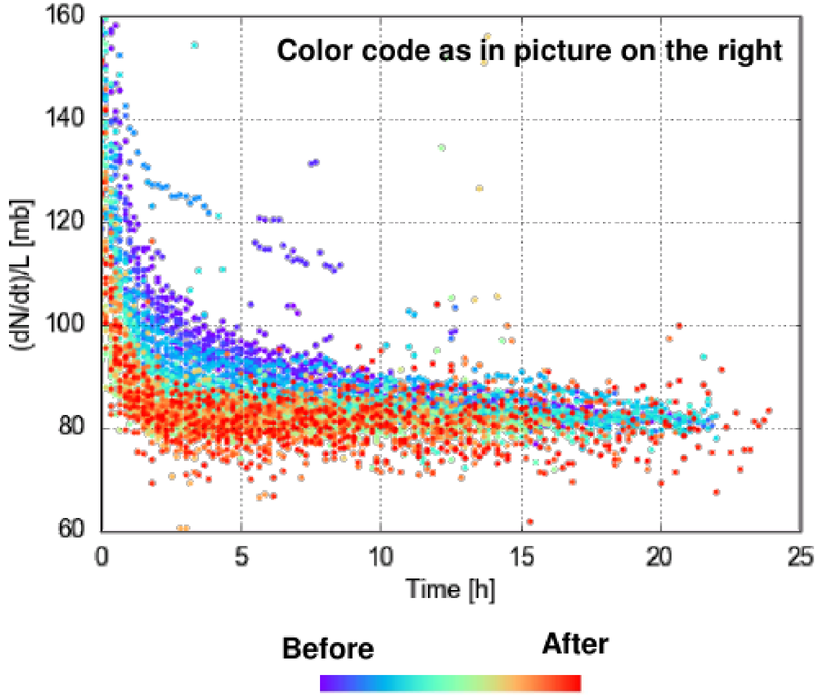
Beam lifetime @ SB

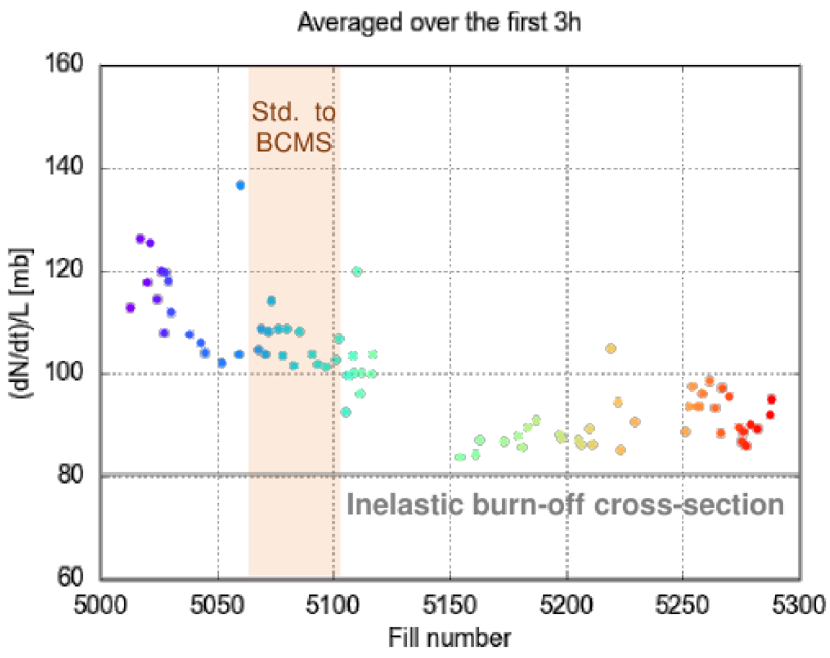


- For earlier fills in the year (non-BCMS) it seems that we have more extra losses on top of burn-off

Beam losses

- Loss rates estimated from the FBCT for many fills along the year indicate that they correspond to significantly more than burn-off in the first three hours
- Seems to evolve during the run towards the inelastic cross-section





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Impact on beam distribution

Software for IBS and Radiation Effects (SIRE)

- A multiparticle monte carlo code developed at CERN by A. Vivoli and M. Martini
  - Based on MOCAC
- **Computing IBS** **(and Radiation Effects)**
  - Particles are tracked from point to point in the lattice by their invariants.
  - At each point of the lattice the scattering routine is called.
  - 6-dim coordinates of particles are calculated.
  - Particles of the beam are grouped in cells.
  - The intrabeam collisions between pairs of macro-particles are iteratively computed, the momentum of particles is changed because of scattering.
  - Invariants of particles are recalculated.
  - Radiation damping and excitation effects are evaluated at the end of every loop.
- **Outputs**
  - The beam distribution is updated and the rms beam emittances are recomputed, giving finally **the evolution of the emittance and particle distribution in time.**

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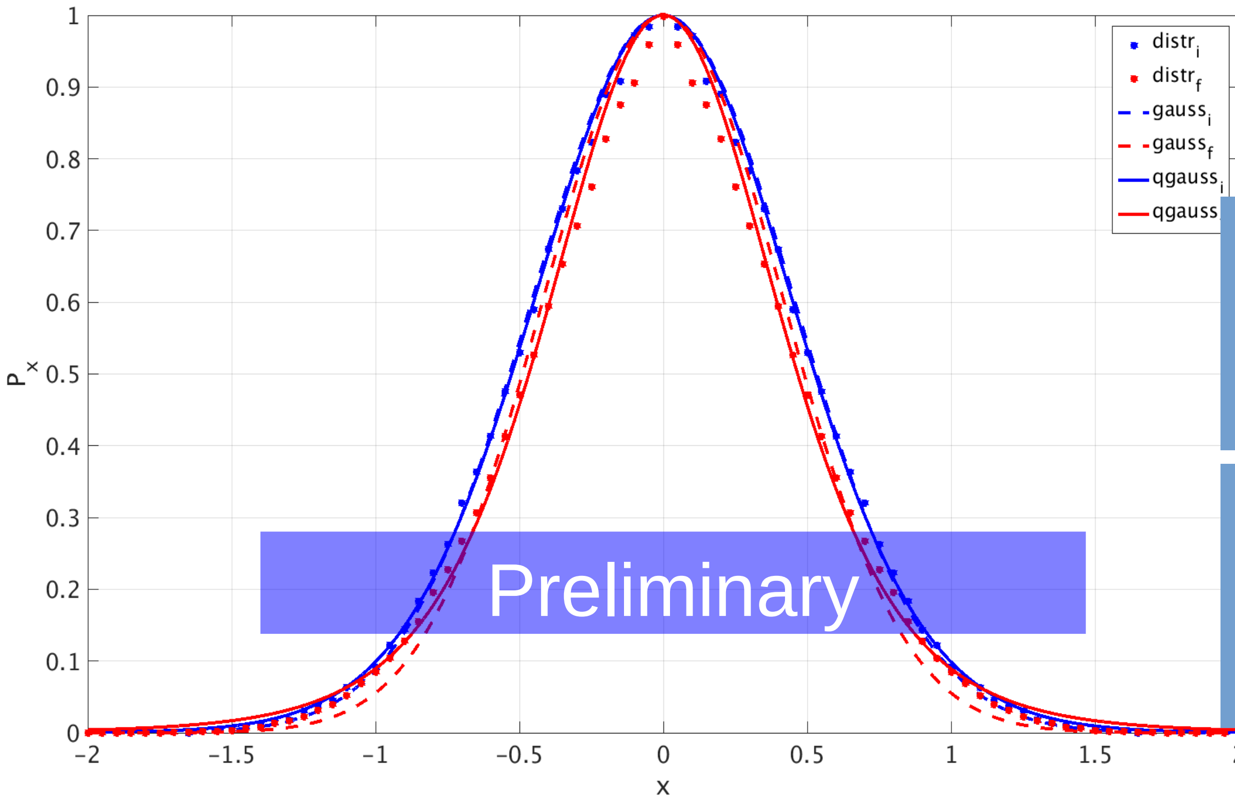
IBS impact on the evolution of beam distributions in LHC @ 450 GeV



Initial parameters	sigma	q
Gauss	0.454±0.003	1
qGauss	0.335±0.002	1.09±0.03

Final parameters	sigma	q
Gauss	0.416±0.005	1
qGauss	0.357±0.002	1.30±0.06

- **Tracking with SIRE** for the LHC lattice at injection energy (450 GeV)
  - The results are preliminary but interesting!
- Input distribution Gaussian (blue)
- Final distribution q-Gaussian (red)
  - Tail development due to IBS

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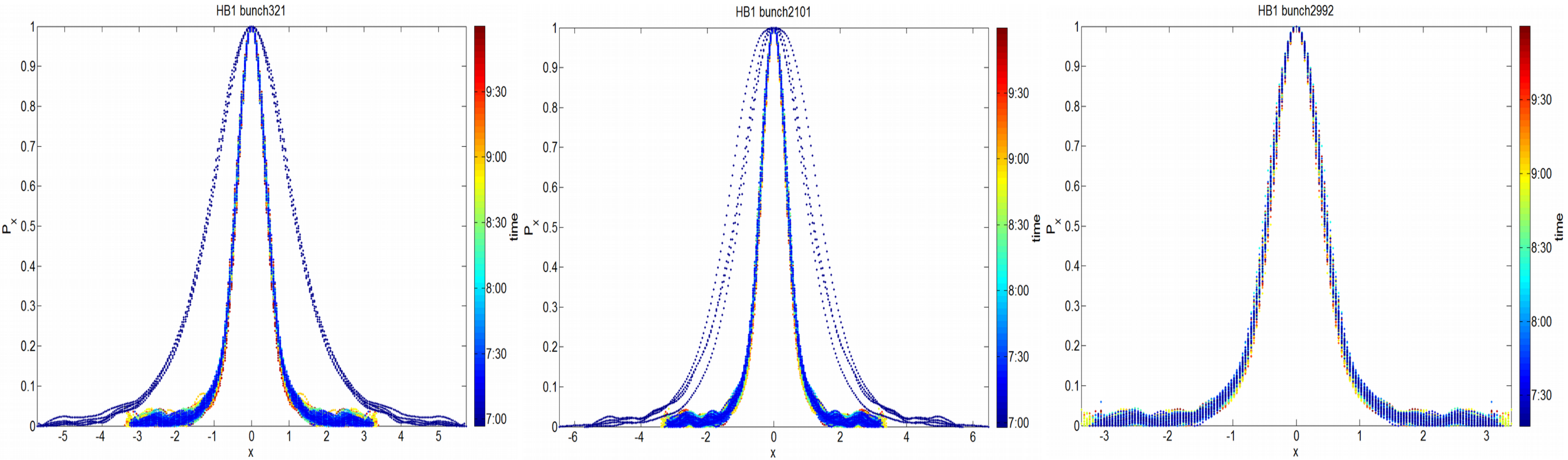
Evolution of beam distributions in LHC (2016)



- Data from crossing angle scan MD (Fill 5137)
- Horizontal plane profiles evolution (for 3 different bunches) from injection to Stable Beams
- Profiles significantly non-Gaussian
  - At Flat Top Energy the interplay between IBS+SR → the beam profiles become Gaussian
  - Simulations and data analysis are on-going

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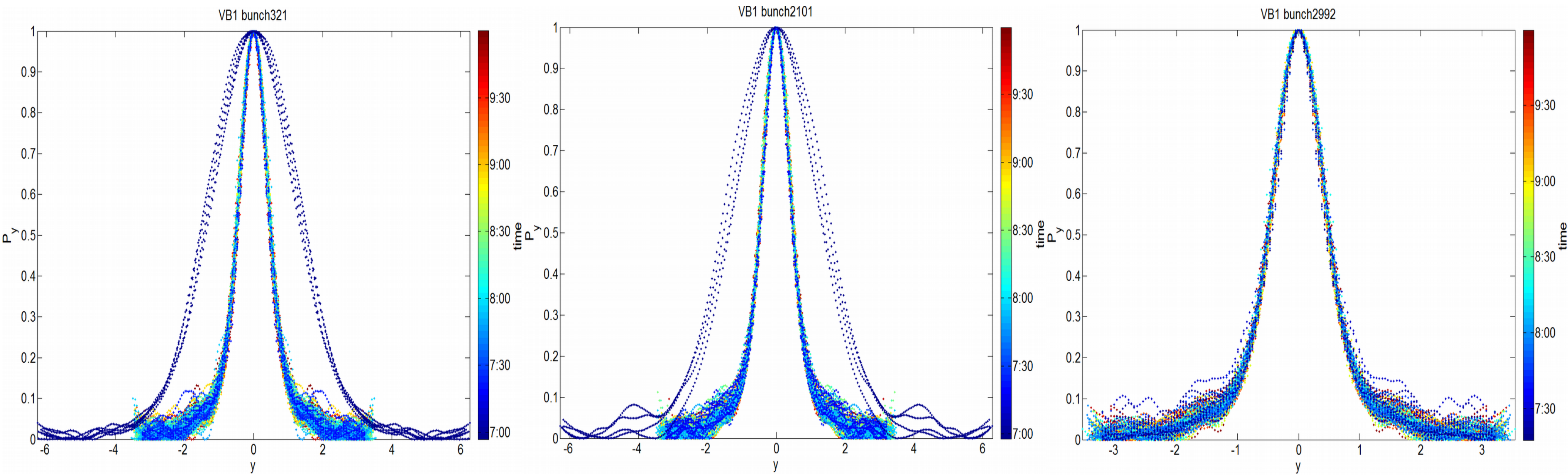
Evolution of beam distributions in LHC (2016)



- Data from crossing angle scan MD (Fill 5137)
- Vertical plane profiles evolution (for 3 different bunches) from injection to Stable Beams
- Profiles significantly non-Gaussian
  - At Flat Top Energy the interplay between IBS+SR → the beam profiles become Gaussian
  - Simulations and data analysis are on-going

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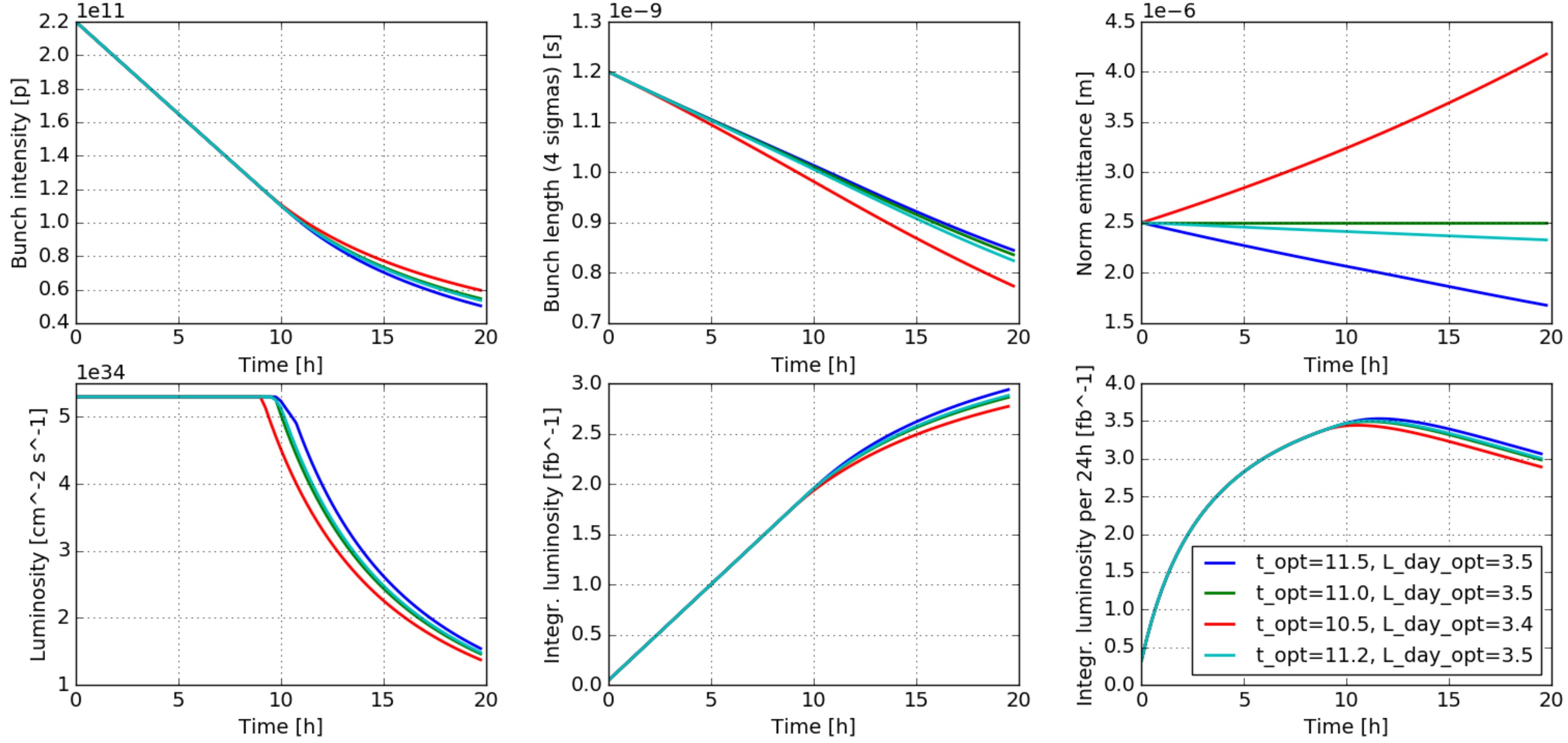
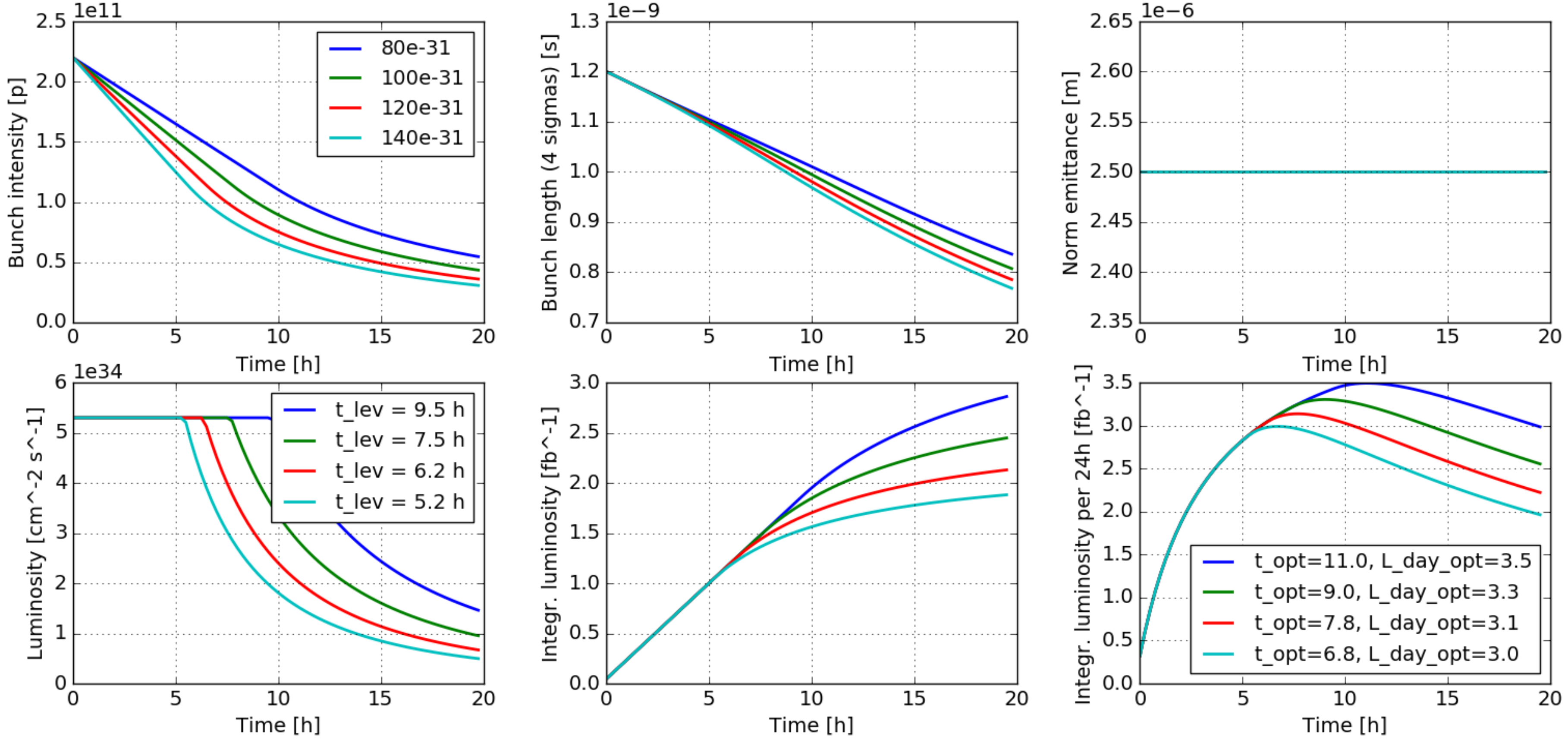
Extrapolations for the HL-LHC

Impact of observations on HL-LHC: Emittance blow up



- Small sensitivity to the emittance evolution

Impact of observations on HL-LHC: Bunch current losses



- High sensitivity to losses

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Summary

- A luminosity model including **IBS**, **synchrotron radiation** and **luminosity burn off** is used for the analysis of the LHC data
- **2012 analysis**
  - Brightness depended emittance blow up on top of IBS predictions
  - Losses and emittance blow up in the first hour dominated by the long range effects
- **2016 analysis**
  - Emittance blow up from injection to stable beams
  - Both at injection and in **collision IBS explains the different growth rate observed between H/V** and the relative change observed with the brightness increase but an **additional source of blow-up** needs to be identified
  - A significant **transverse blow-up** takes place in the **energy ramp** (provided that all cross calibrations are correct) → to be further investigated
  - Additional blow-up in collision is different for **colliding and non-colliding bunches** with similar brightness → **two beam effect** play a significant role in the emittance evolution
  - Once the additional transverse blow-up is included in the simulation, our relatively "ideal" luminosity **model predicts quite well intensity, bunch length and luminosity evolution**, especially for BCMS fills
  - **Losses on top of burn-off seem to evolve during the run**

Summary

- Simulations of beam profiles evolution due to IBS and SR are on-going
  - First simulations shows tails population at Injection (the result is preliminary)
- Beam profiles analysis from LHC
  - Non-Gaussian bunches
  - Work in progress to understand and quantify the impact of SR on the evolution of beam distributions
    - How fast SR damps the tails (due to absence of IBS at these amplitudes)?
    - Does the extra emittance blow-up impacts halo?
- Extrapolations to HL-LHC
  - Assuming similar behavior for the emittance evolution and extrapolating to the HL-LHC brightness → Small impact on integrated luminosity
  - Assuming similar behavior of losses as in 2016 → Significant impact on beam lifetime, leveling time and integrated luminosity

Thank you!

Backup slides

Parameters

Parameters @ FB	Nominal (BCMS)	HiLumi
E [GeV]	450	450
$\varepsilon_{x,y}$ [μm]	1.5	2.0
4σ bunch length [ns]	1.0	1.2
Bunch population [10^{11}]	1.2	2.3

Parameters @ FT	Nominal (BCMS)	HiLumi
E [GeV]	6.5	7.0
$\varepsilon_{x,y}$ [μm]	2.5	2.5
4σ bunch length [ns]	1.0	1.2
Bunch population [10^{11}]	1.1	2.2

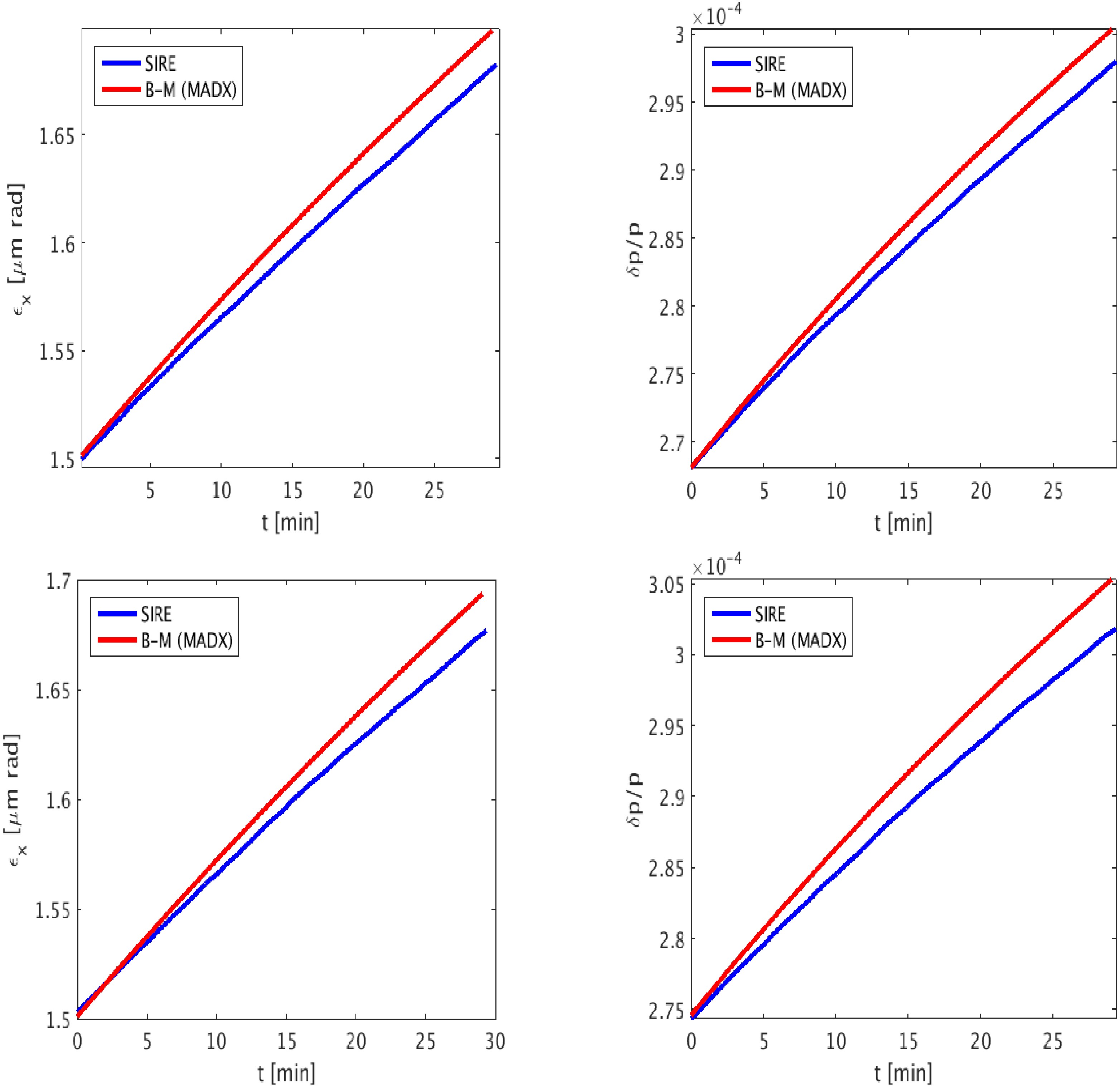
EMITTANCE AND BUNCH LENGTH EVOLUTION

Nominal

30min at FB, reduced lattice

Gaussian

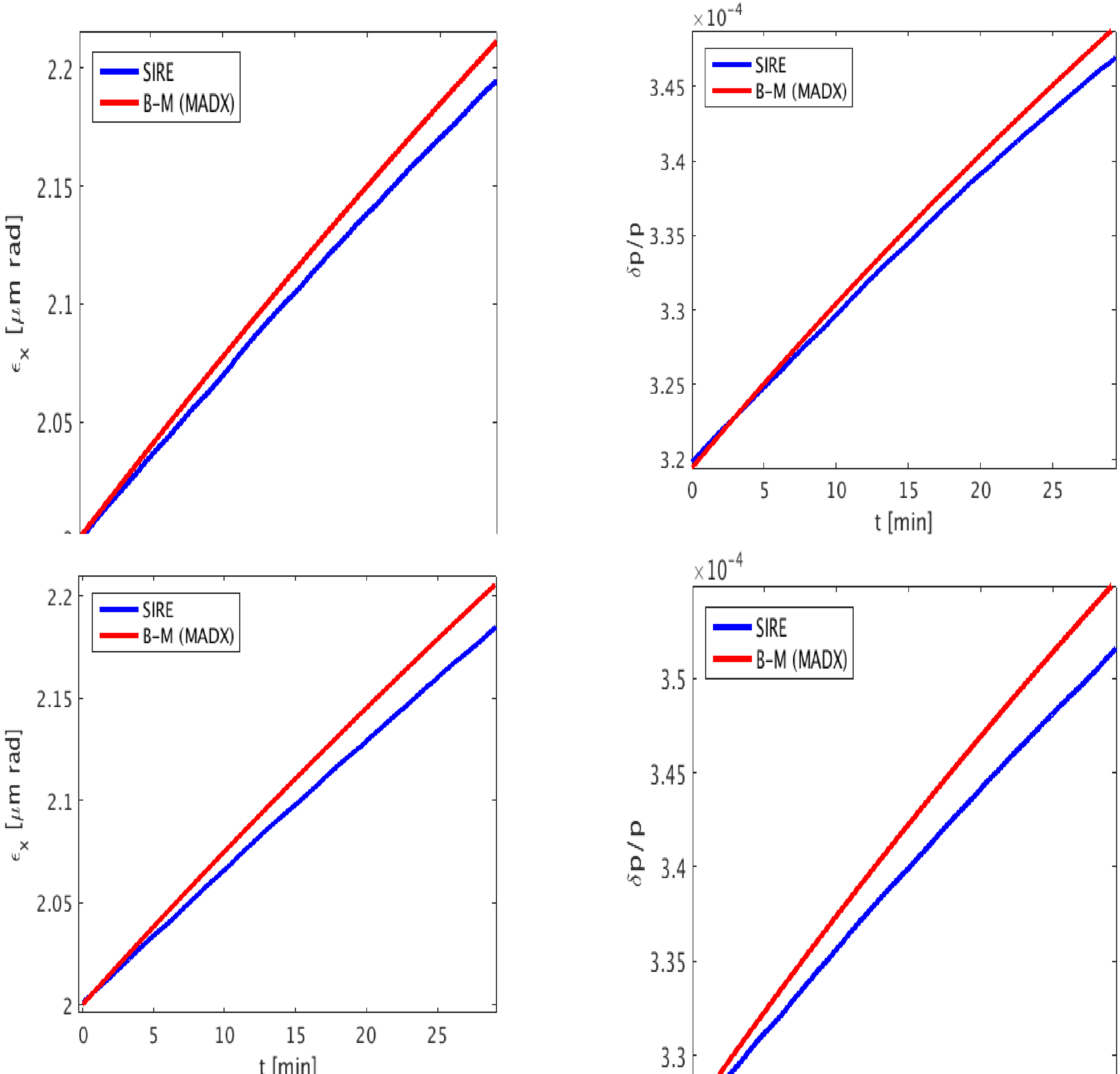
q Gaussian (q=1.2)



30min at FB, reduced lattice

Gaussian

q Gaussian (q=1.2)



The q Gaussian distribution

- The emittance evolution at LHC FB energy is dominated by the IBS effect.
- In the case of LHC, the interplay between IBS and a series of other effects, can enhance the tails of the beam distributions, which may become non-Gaussian.

In many cases, the bunch profiles in the LHC, appear to have **heavier tails than a normal distribution**.
In order to describe them more accurately, the **q-Gaussian function**, is used. This distribution has a probability density function given by:

$$f(x) = \frac{\sqrt{\beta}}{C_q} e_q(-\beta x^2),\ e_q(x) = [1 + (1-q)x]^{\frac{1}{1-q}}$$

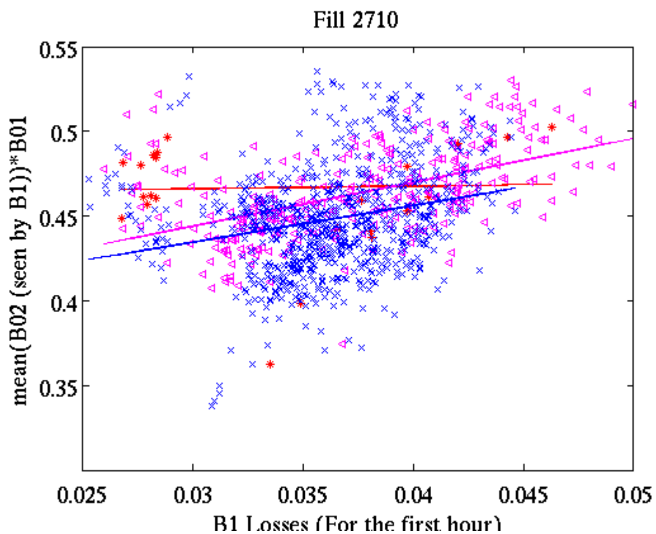
In the heavy tail domain (1 < q < 3)

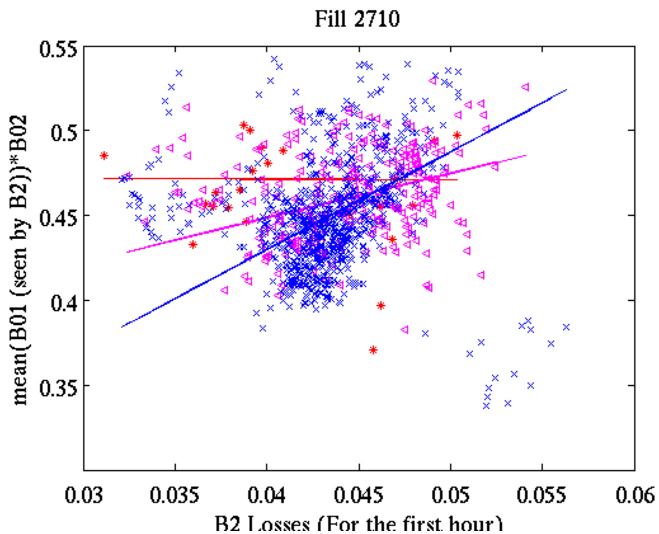
$$C_q = \sqrt{\pi}\,\Gamma\left(\frac{3-q}{2(q-1)}\right) / \left[\sqrt{q-1}\,\Gamma\left(\frac{1}{q-1}\right)\right]$$

for q =1 **Gaussian function**

Variance	$\frac{1}{\beta(5-3q)}$ for $q < \frac{5}{3}$ ∞ for $\frac{5}{3} \le q < 2$ Undefined for $2 \le q < 3$

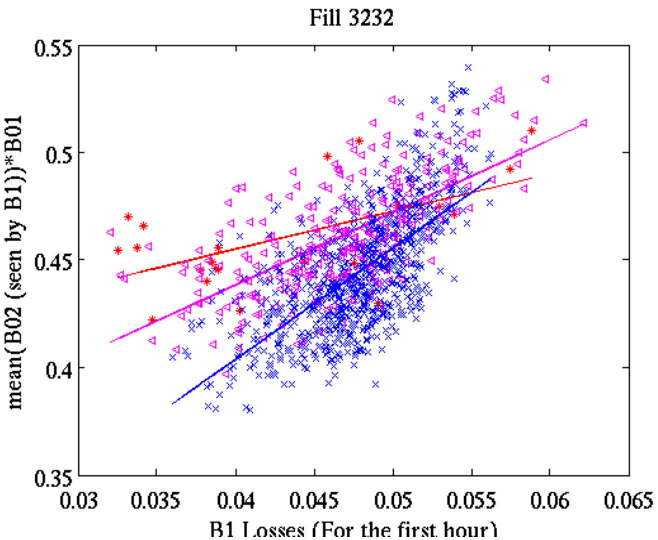
Losses correlated with Long Ranges

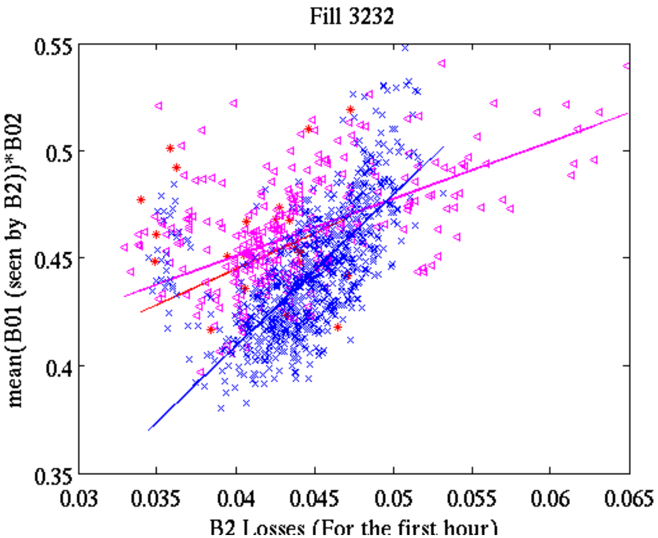




- The product of the mean brightness of the long-range encounters seen by B1 (top) or B2 (bottom) and the brightness of B1 (top) or B2 (bottom) versus the Beam losses after 1h of run
- Bunches with **8**, **12** and **16** longrange encounters are plotted with different colors
- Linear correlation is observed with different slope for different number of longrange encounters
  - The slope is steeper for larger longrange encounters
  - Same trend for both B1 and B2

Losses correlated correlated with Long Ranges





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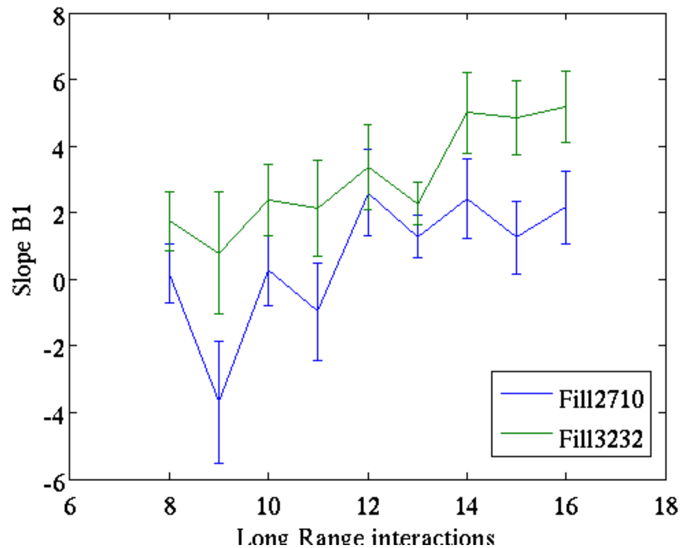
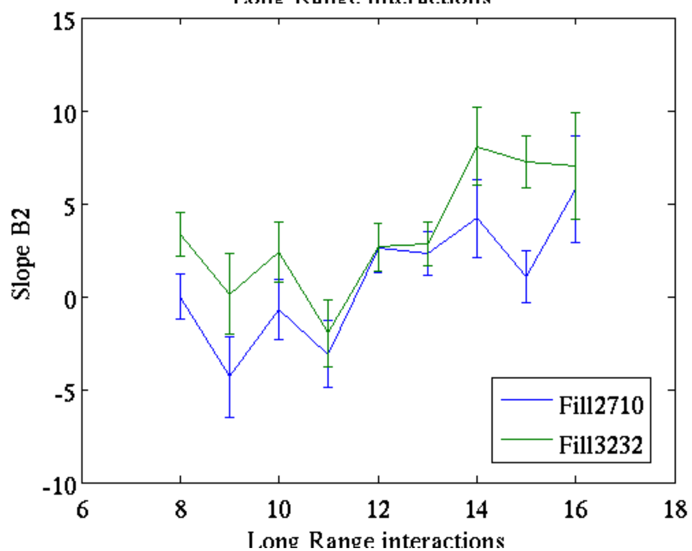
Losses correlated correlated with Long Ranges





- Calculating the slope for each of those curves for all different cases of long-range encounters (8-16)
  - Clear trend of **slope increase with the number of long-range encounters**
  - The effect is enhanced for Fill3232 where the brightness is higher
- Data need carefull cleaning due to **large number of unstable bunches**
- The brightness estimation was not accurate because the **convoluted emittance (from luminosity)** is used

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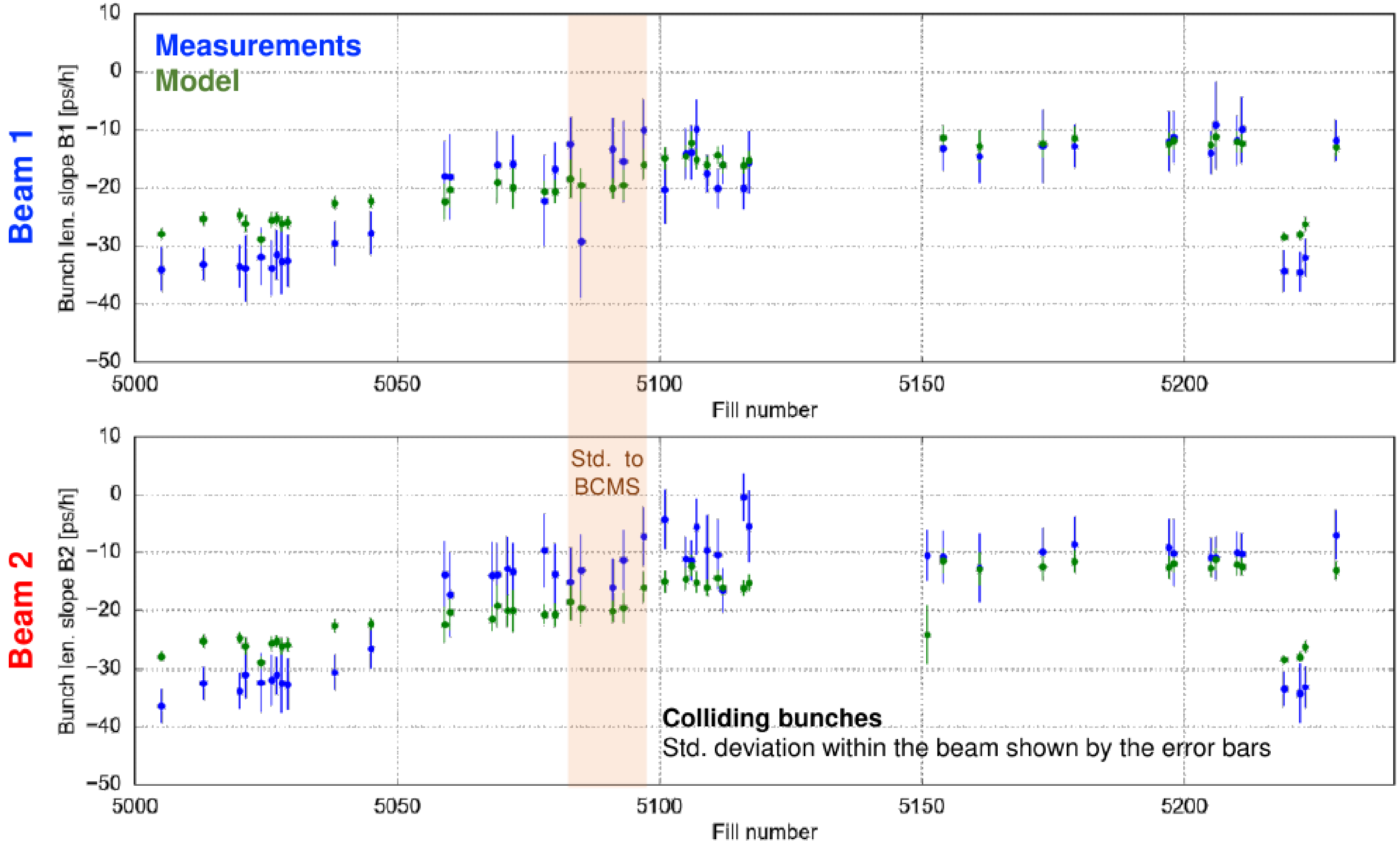
Emittance evolution in Stable Beams



- **Bunch length** evolution **predicted very well by the model**