Joint Accelerator Performance Workshop 2023

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Emittance Evolution and Stability in Run 3

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Outline

- **Data sets used for the analysis**
  - Data from **2022** : **BCMS-type** beams and from **2023** : hybrid **STANDARD-type** beams
- **Our basis of understanding: "The Model", i.e. emittance evolution and luminosity model - reminder**
- **Emittance**
  - Studies at injection energy
  - Evolution during acceleration
  - Evolution during collisions

Bunch-by-bunch analysis on emittance, intensity, luminosity
Bunch-to-bunch fluctuations

- **Beam lifetime and Luminosity**
- **Beam stability**
- **Summary & Outlook**

Data sets

Data and Fills selection – p-p data

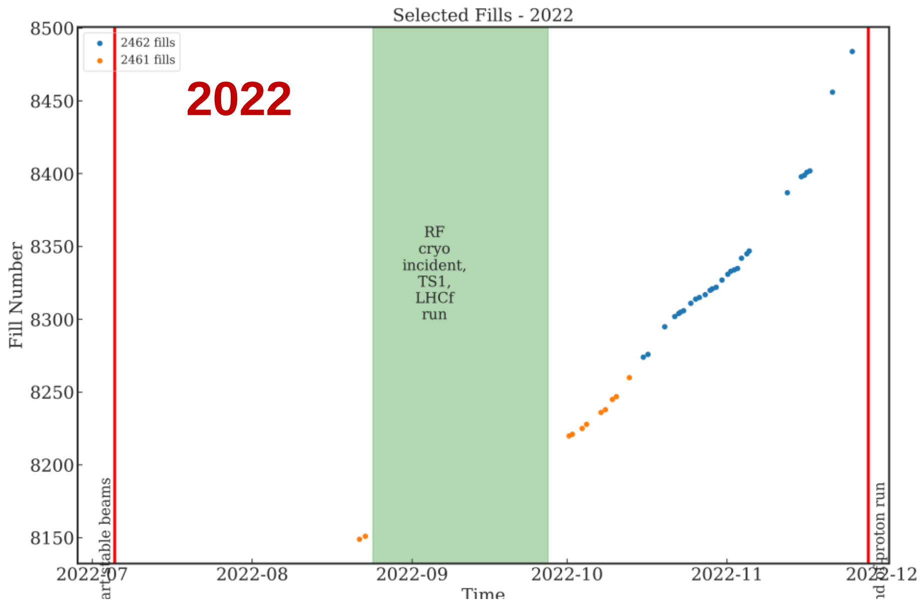
- **Analysis based on NXCALS data**
- **Selection of fills with:**
  - > 5 h in collisions (STABLE), > 600 bunches / beam
- **40 fills in 2023, 68 fills in 2022**

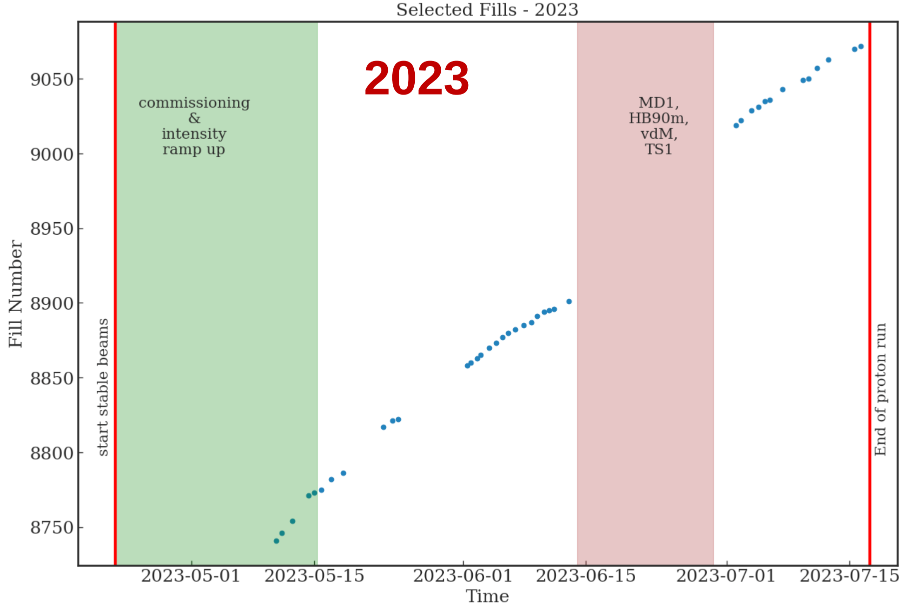
Main filling schemes - 2022	Fills
25ns_2462b_2450_1737_1735_180bpi_17inj_2INDIV	29
25ns_2461b_2448_1737_1733_180bpi_16inj_1INDIV	11
25ns_1935b_1922_1602_1672_192bpi_14inj_3INDIVs	5
25ns_2413b_2400_1836_1845_240bpi_12inj_1INDIV	4

5× 36b trains
BCMS-type beams

7×8b4e + 5× 36b trains
STANDARD-type beams

Main filling schemes - 2023	Fills
25ns_2358b_2345_1692_1628_236bpi_14inj_hybrid_2INDIV	17
25ns_2464b_2452_1842_1821_236bpi_12inj_hybrid	8
25ns_2374b_2361_1730_1773_236bpi_13inj_hybrid_2INDIV	7





The Emittance and Luminosity Model

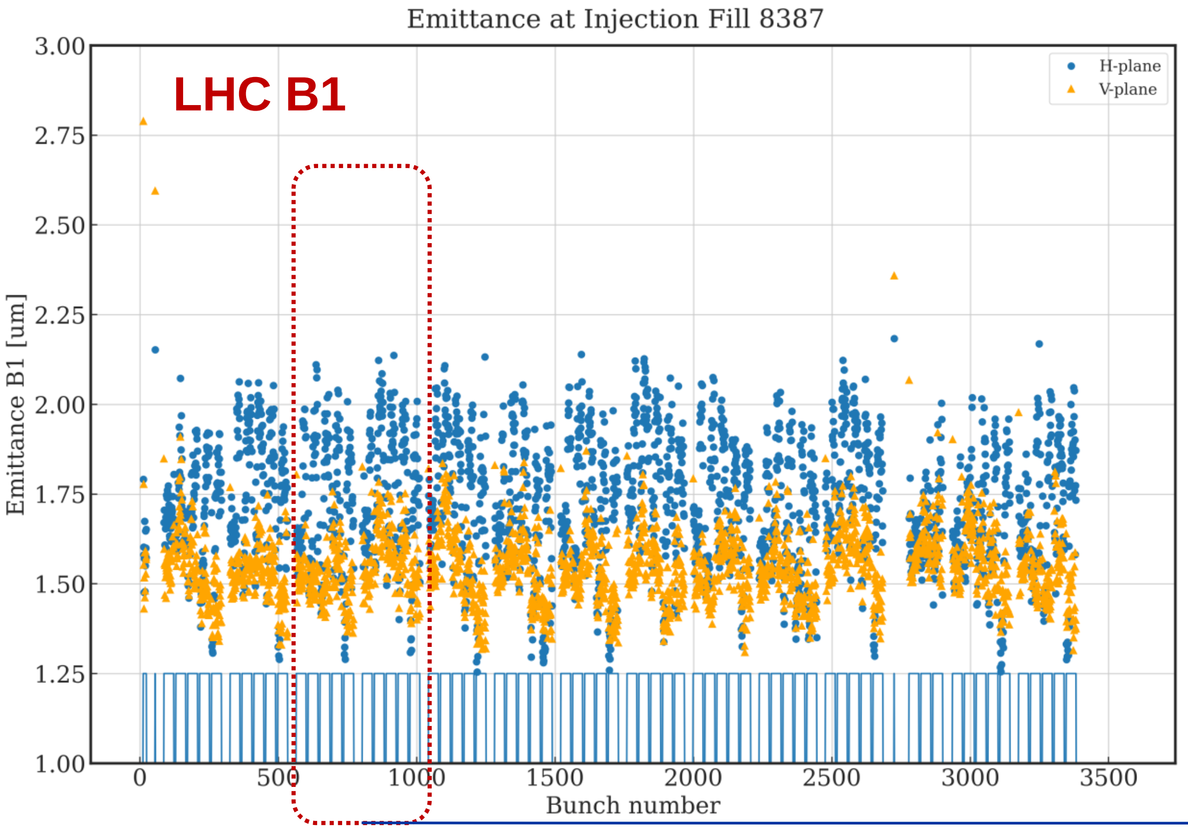
…in a nutshell

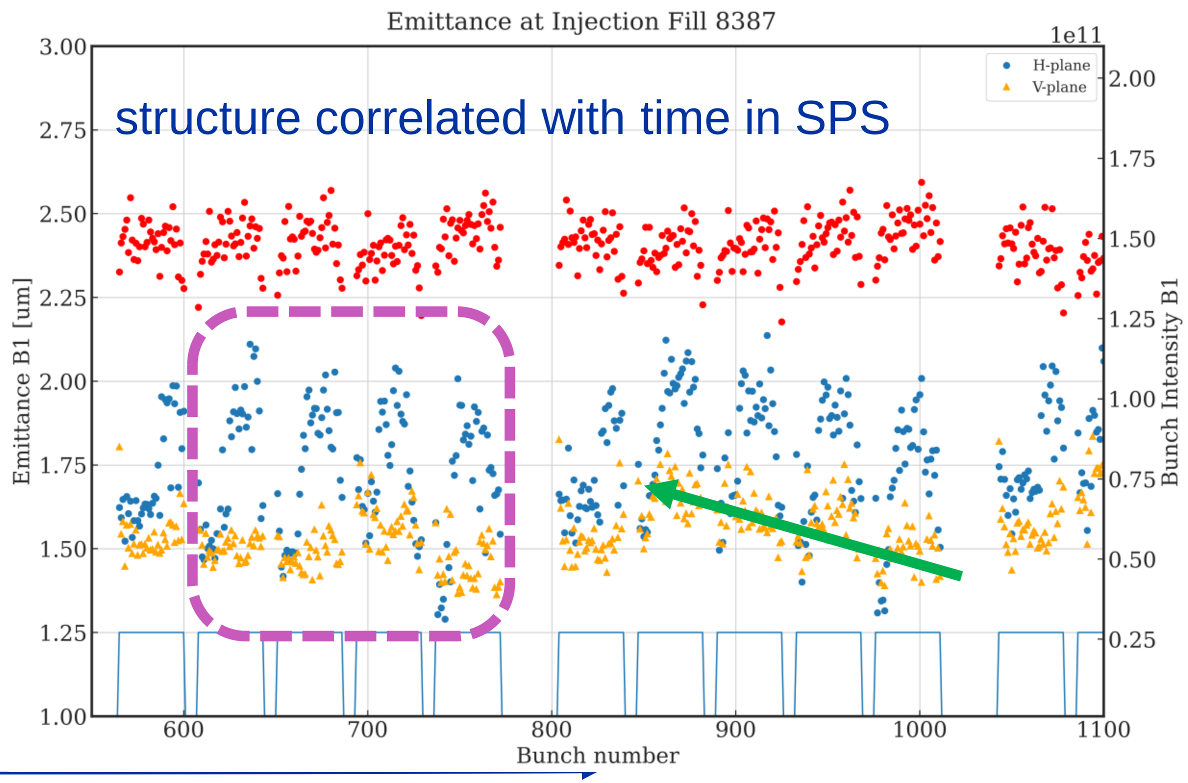
- **Simulation tool aimed to understand the LHC beam emittance evolution and support optimization studies and operational scenarios towards the maximization of the delivered luminosity to the experiments**
- **Initial development in 2017, with constant evolution throughout Run 2**
- **The ingredients:**
  - uses MAD-X and LHC optics, can combine input from data for combined studies, can simulate single bunch or full beam effects
  - effects included: IBS, synchrotron radiation, elastic cross-section, coupling, noise, luminosity burn-off (intensity losses + emittance blow-up), factors for extra emittance emittance growth or burn-off
- **Detailed presentation and performance in previous Evian workshops**
  - Latest update for **2018**: 50% of the observed emittance blow-up at injection unexplained (0.24 (H-plane, 0., extra emittance blow-up (0.02 μm/h H and 0.08 μm/h V) during collisions added to match the data
- **Updated for Run 3 to include the optics and levelling scenarios,**
  - correct follow up of the conditions: optics changing, crossing angle, β* steps – separation to be done

Emittance @ Injection
Example 2022 fill

Observations:

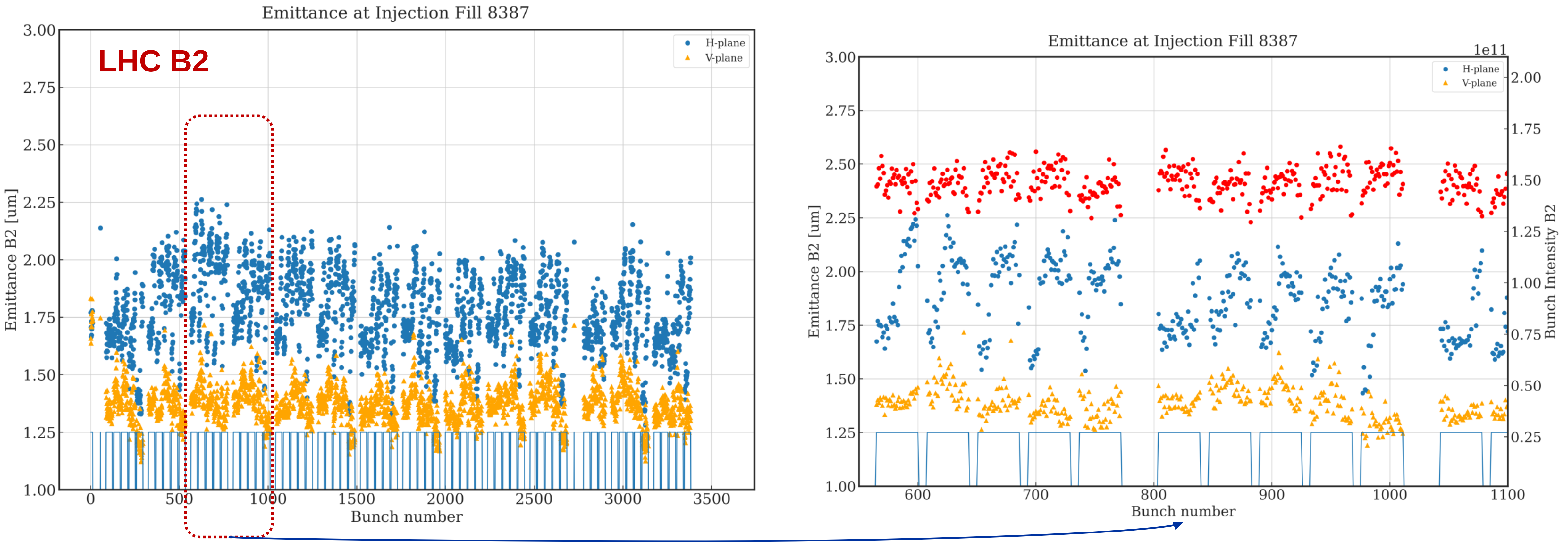
structure correlated with time in SPS – an Λ-shape, most likely due to e-cloud within the train





Emittance @ injection
Example 2022 fill

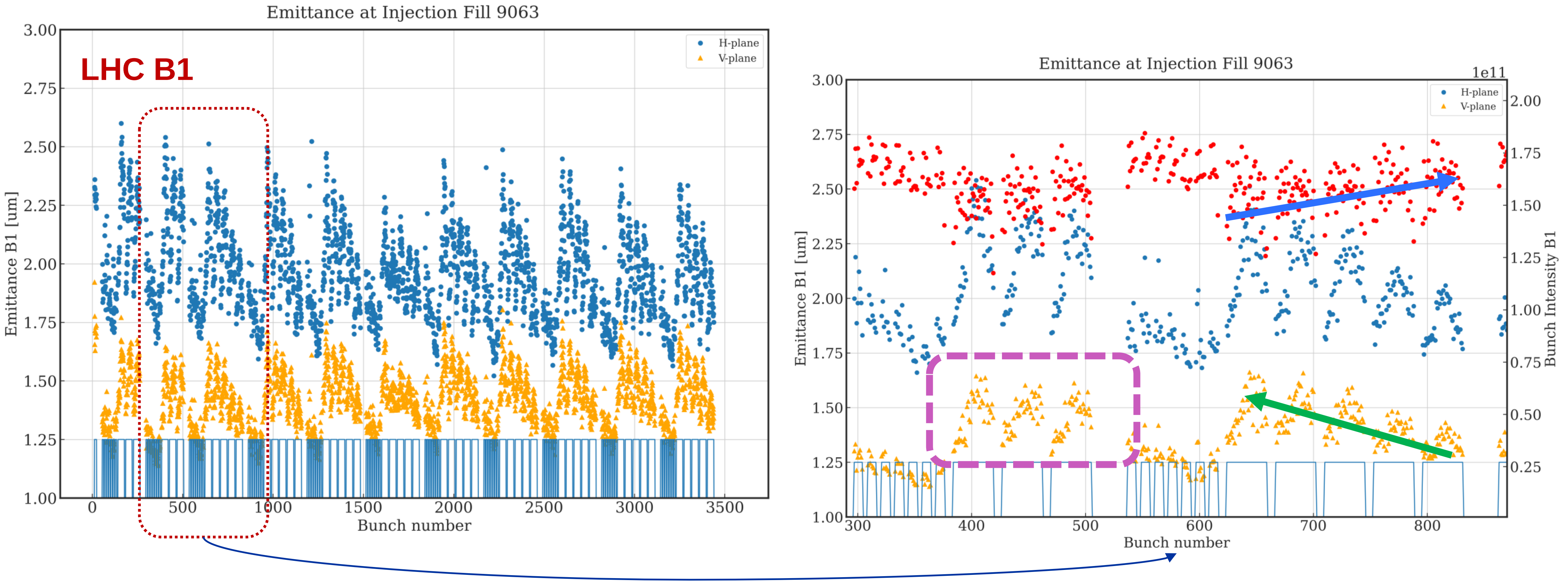
Observations: H-plane worse than vertical, small trend with number of injections



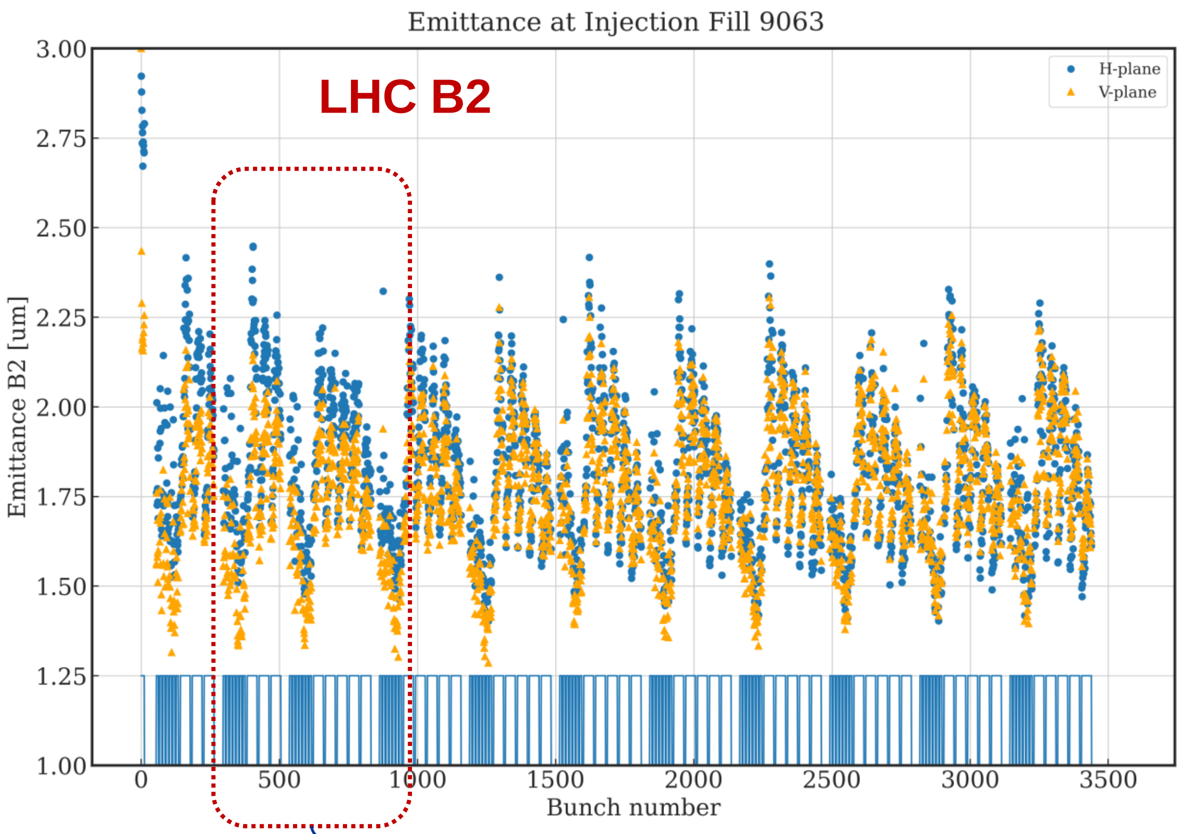
Emittance @ injection

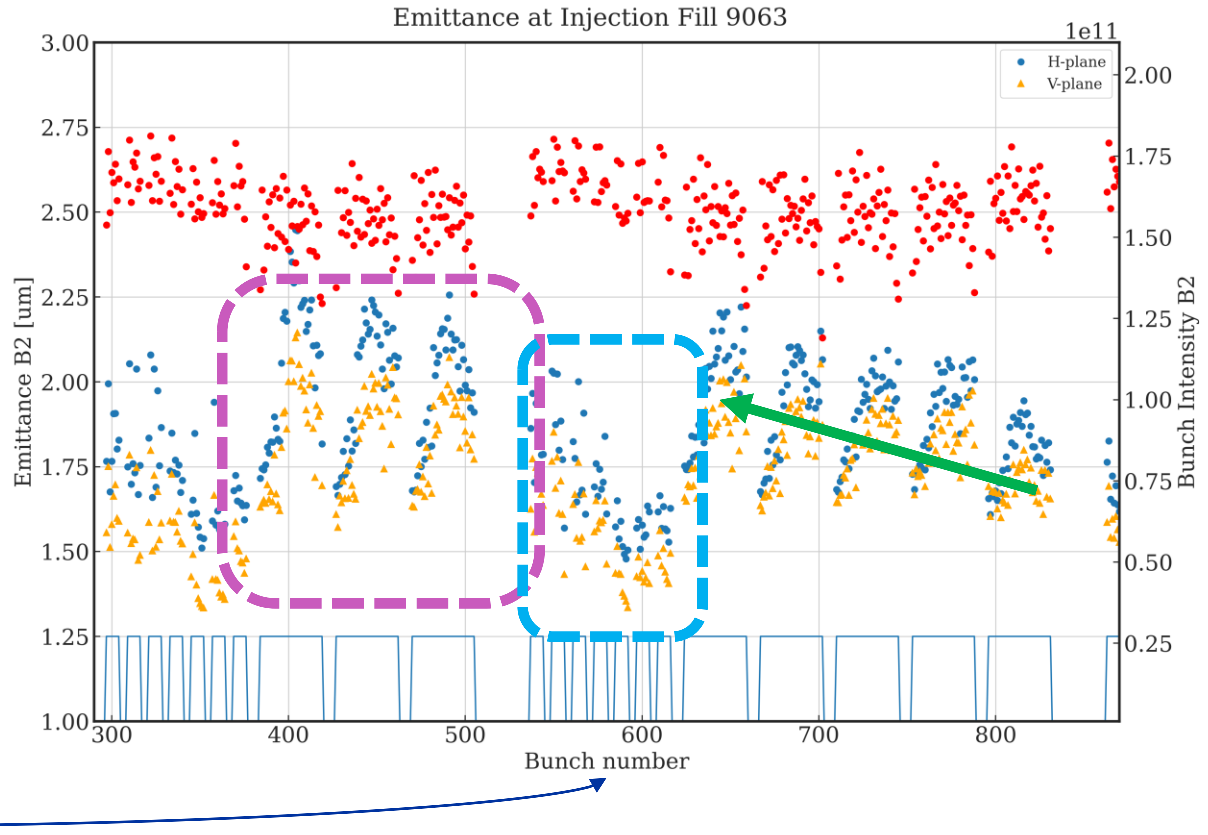
Example 2023 fill

Observations: similar to 2022 but effects substantially enhanced, 8b4e lower emittances, small variation in intensity per train due to scraping?



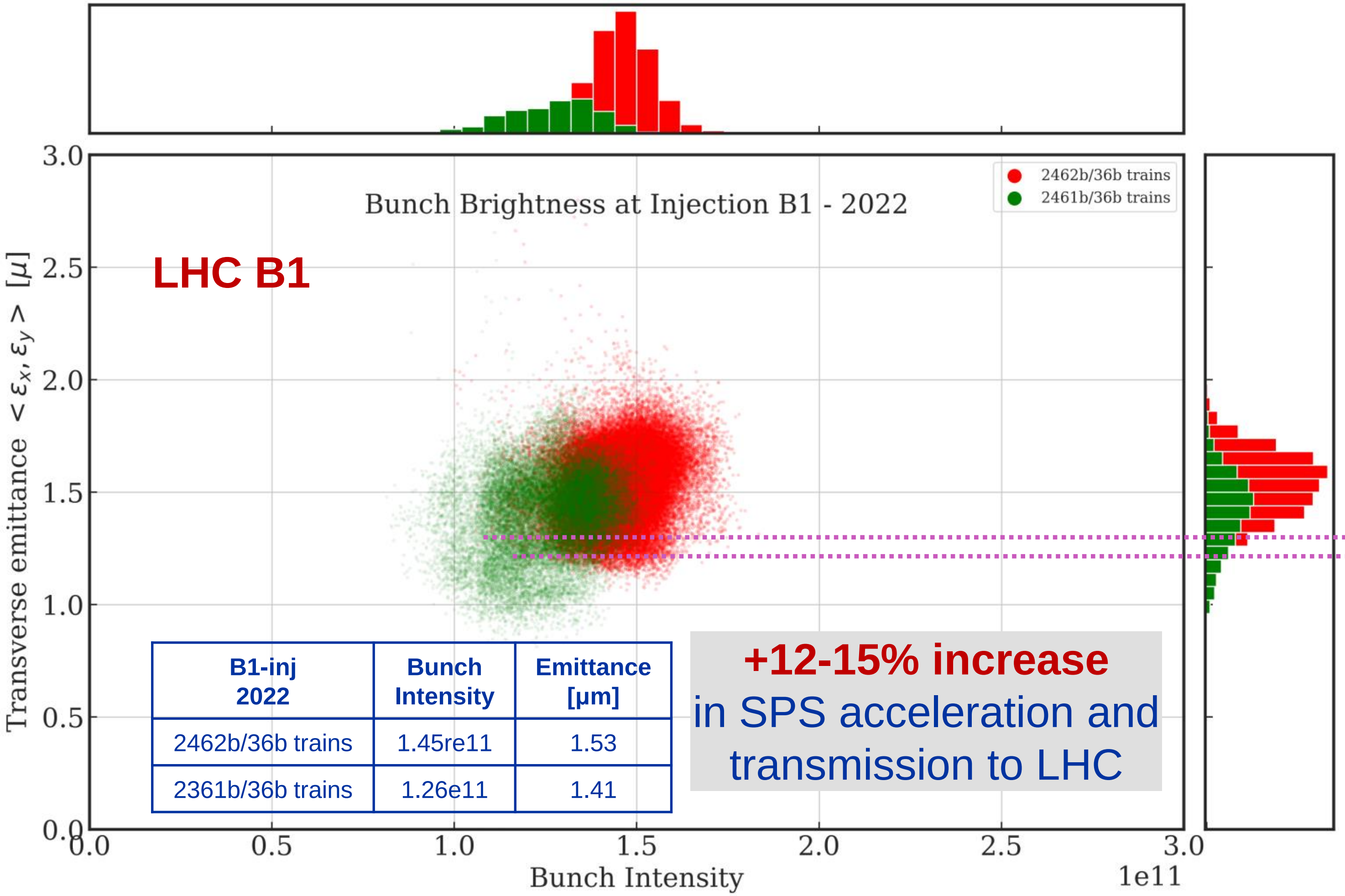
Emittance @ injection
Example 2023 fill





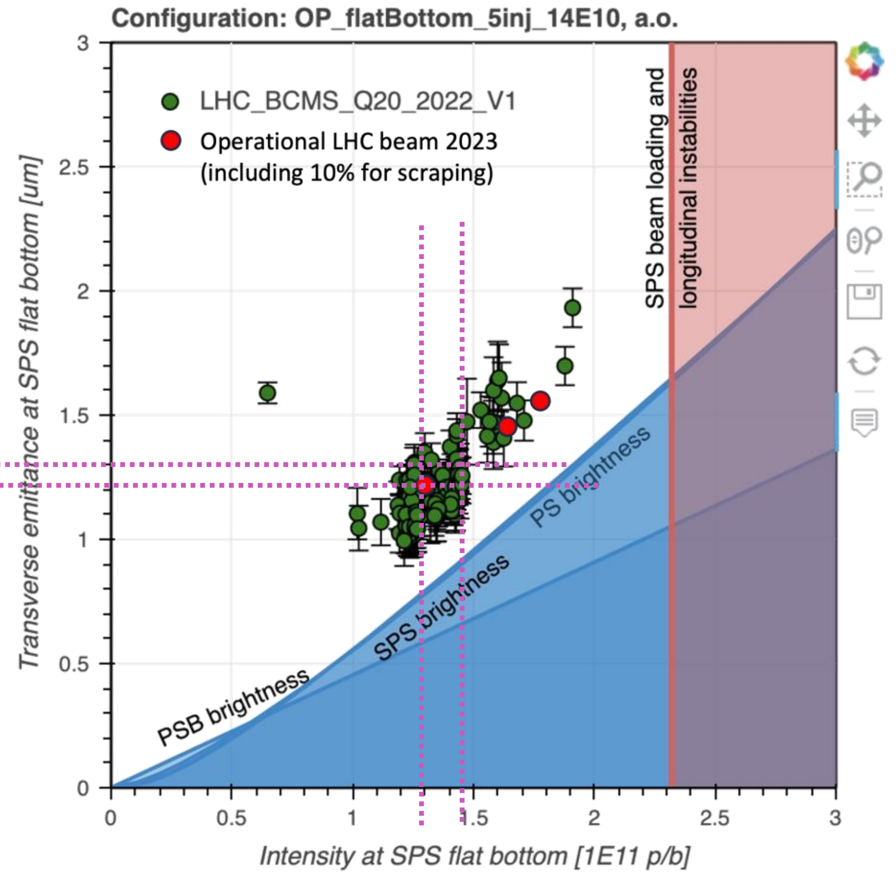
Emittance @ injection

Summary 2022 fills



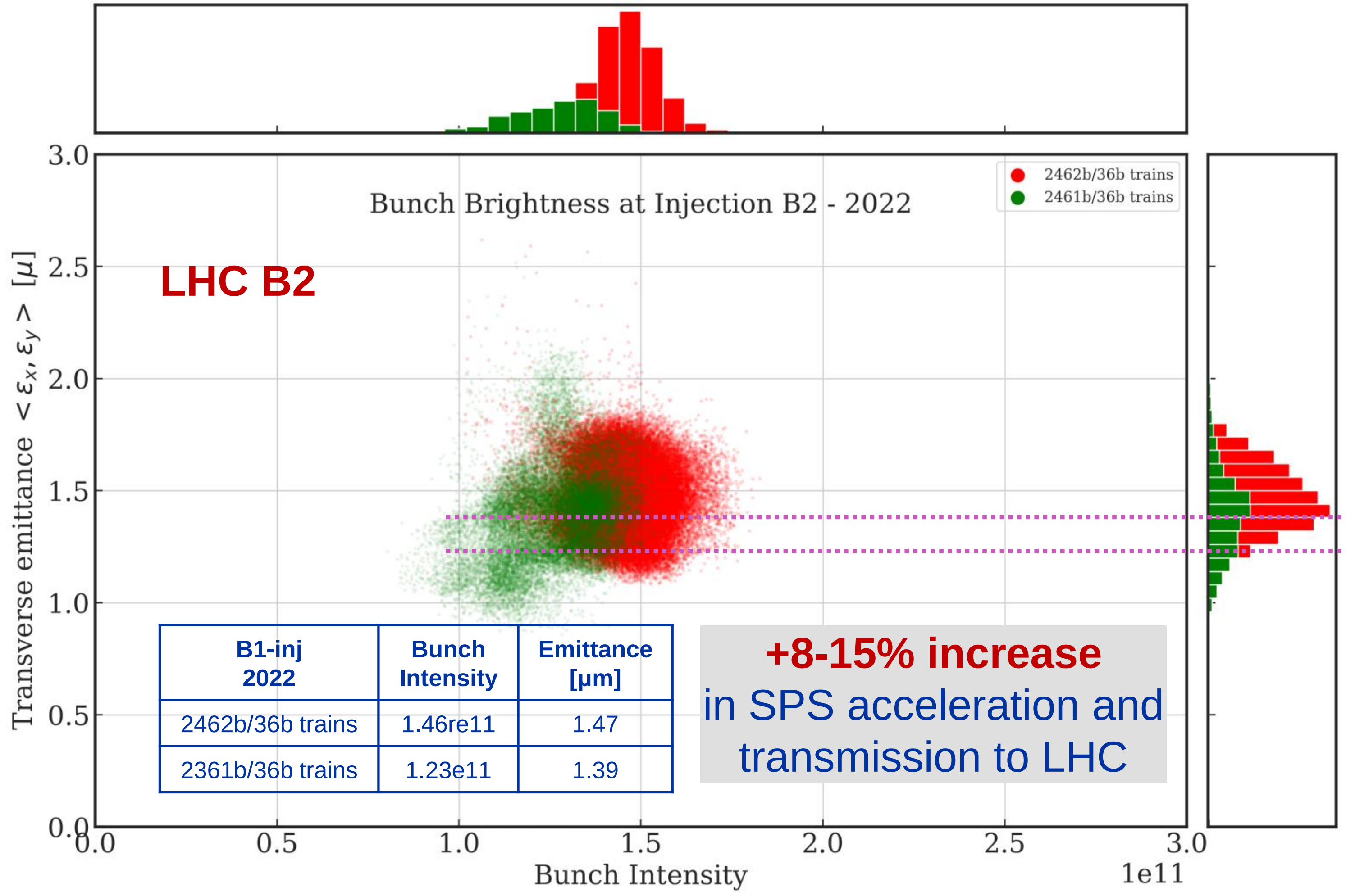
B1-inj 2022	Bunch Intensity	Emittance [μm]
2462b/36b trains	1.45re11	1.53
2361b/36b trains	1.26e11	1.41

+12-15% increase
in SPS acceleration and transmission to LHC



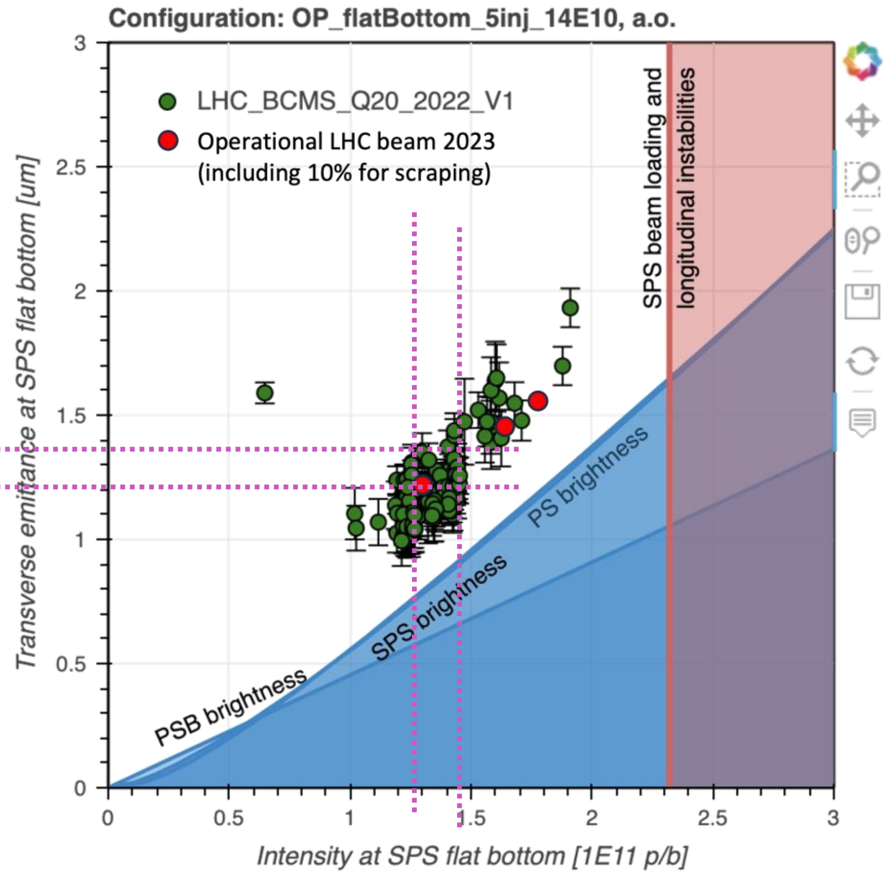
Emittance @ injection

Summary 2022 fills



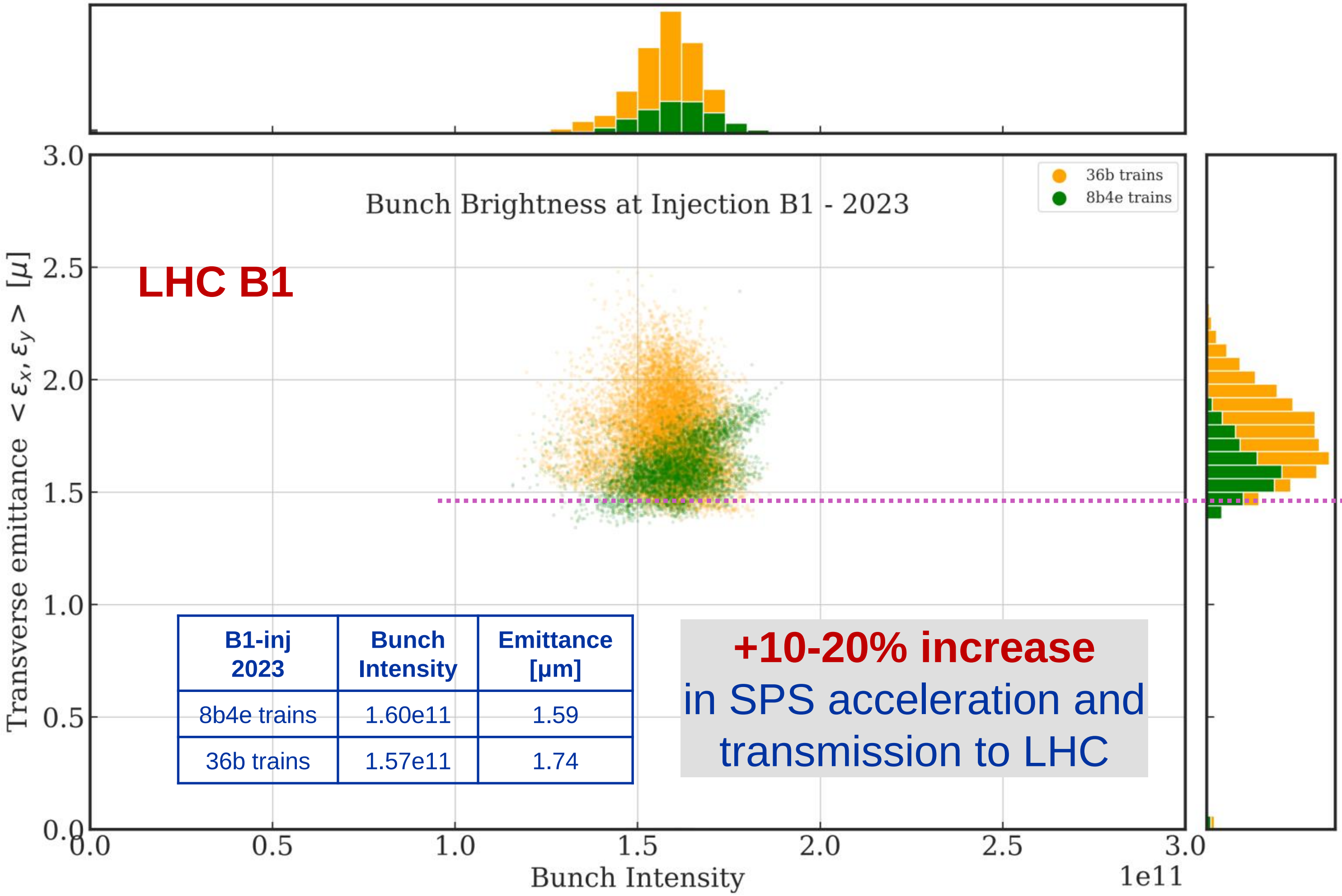
B1-inj 2022	Bunch Intensity	Emittance [µm]
2462b/36b trains	1.46re11	1.47
2361b/36b trains	1.23e11	1.39

+8-15% increase
in SPS acceleration and transmission to LHC



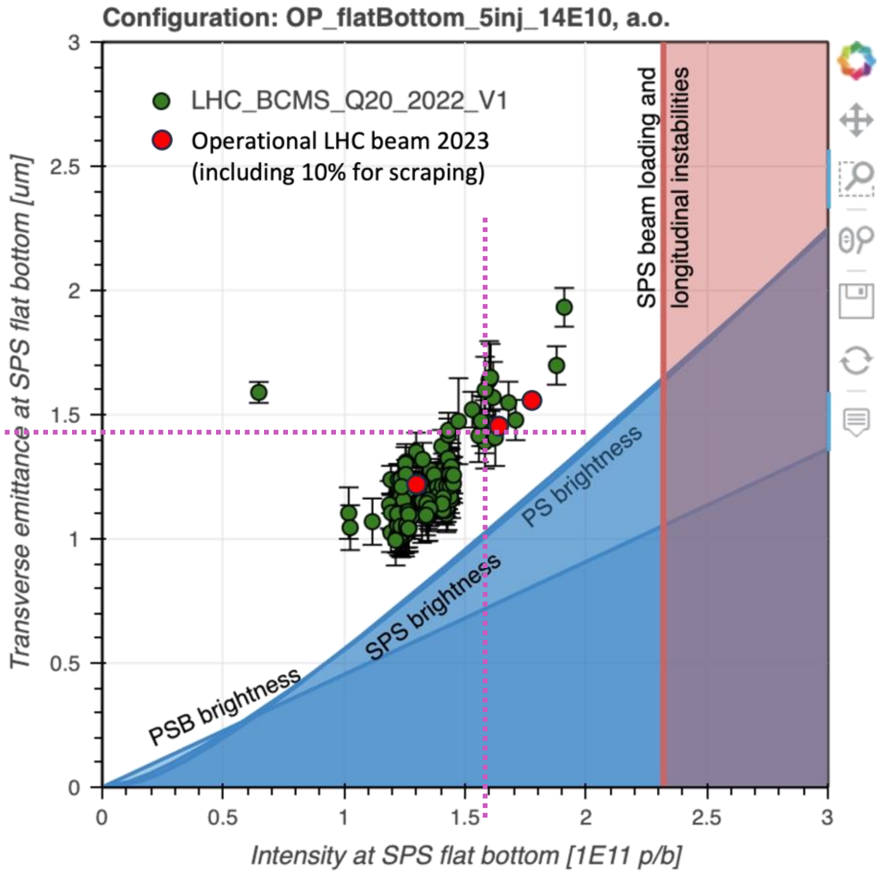
Emittance @ injection

Summary 2023 fills



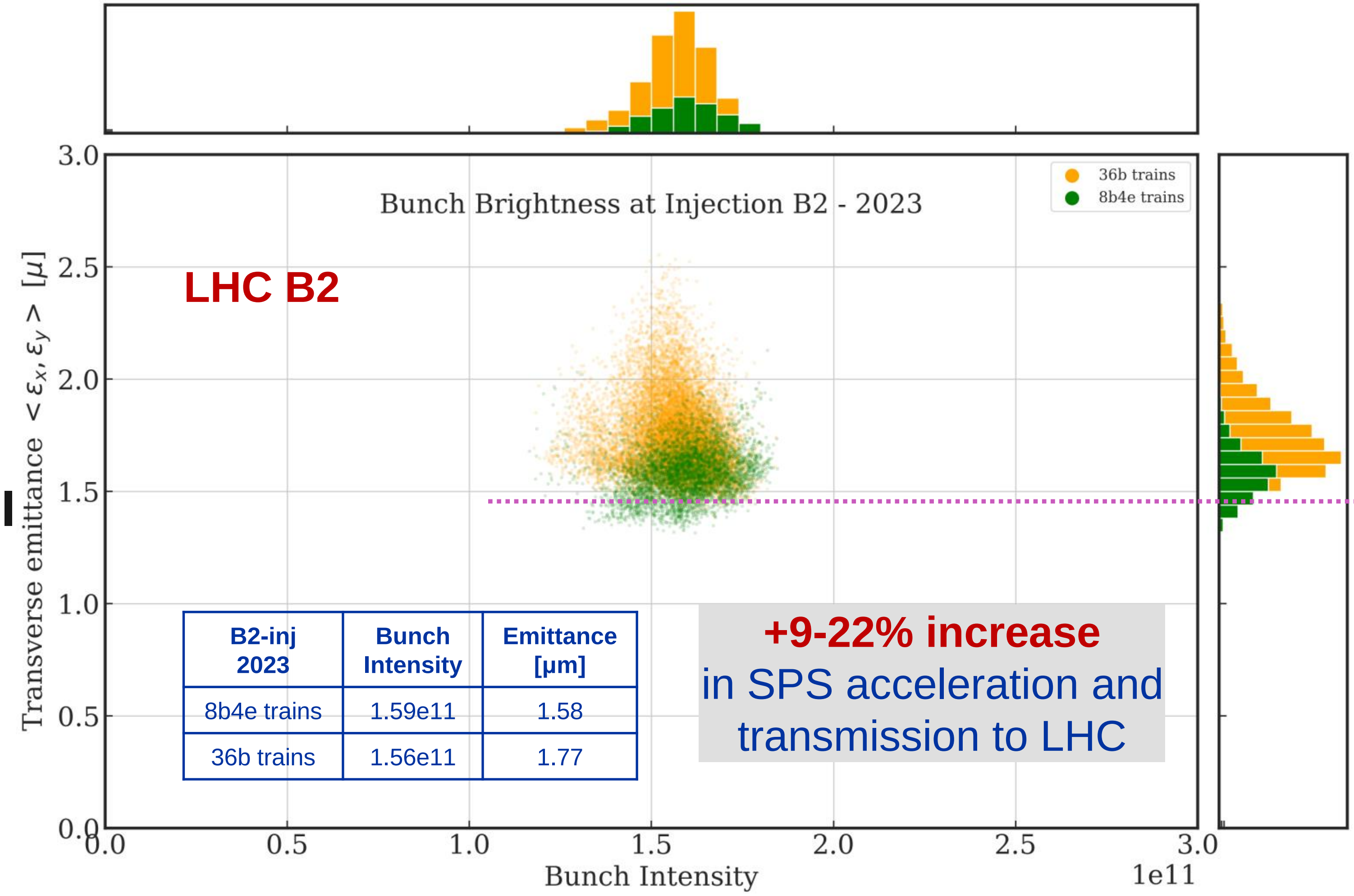
B1-inj 2023	Bunch Intensity	Emittance [µm]
8b4e trains	1.60e11	1.59
36b trains	1.57e11	1.74

+10-20% increase
in SPS acceleration and transmission to LHC



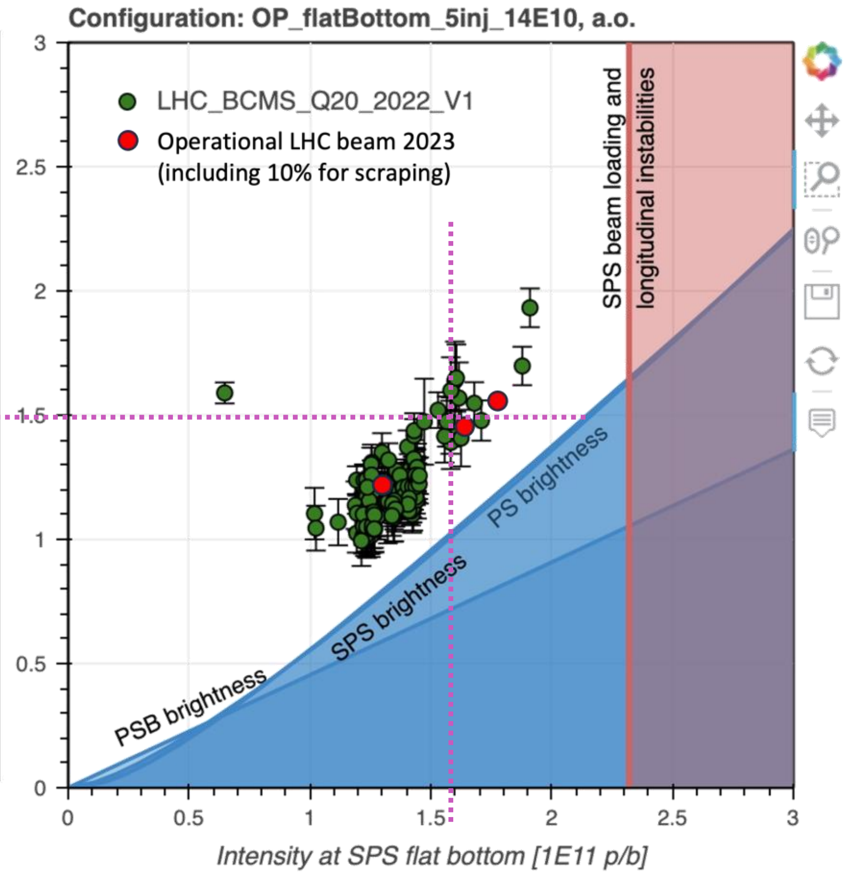
Emittance @ injection

Sumary 2023 fills



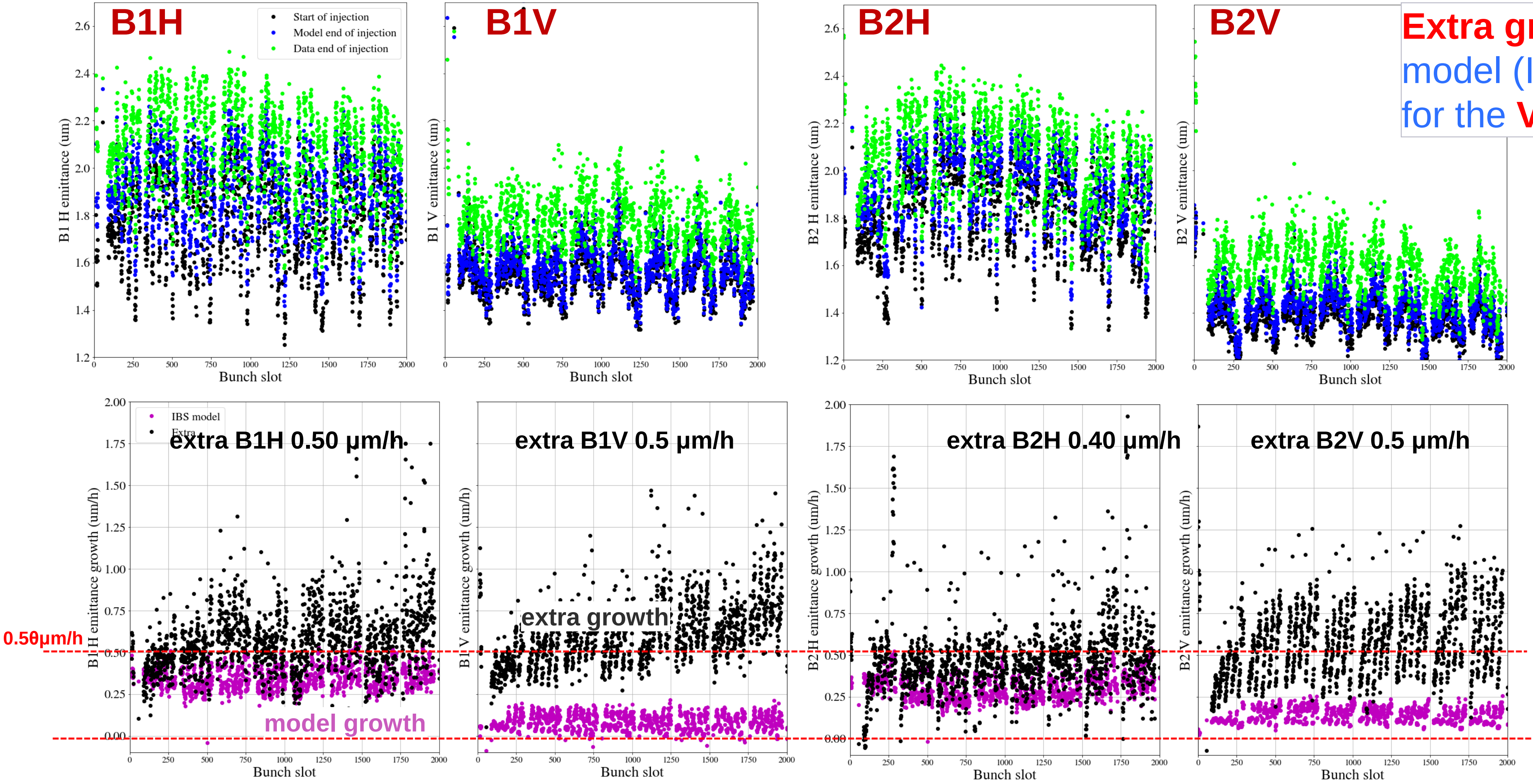
B2-inj 2023	Bunch Intensity	Emittance [μm]
8b4e trains	1.59e11	1.58
36b trains	1.56e11	1.77

+9-22% increase in SPS acceleration and transmission to LHC



Emittance growth at injection energy (FB)

Compare with Model – example 2022 fill



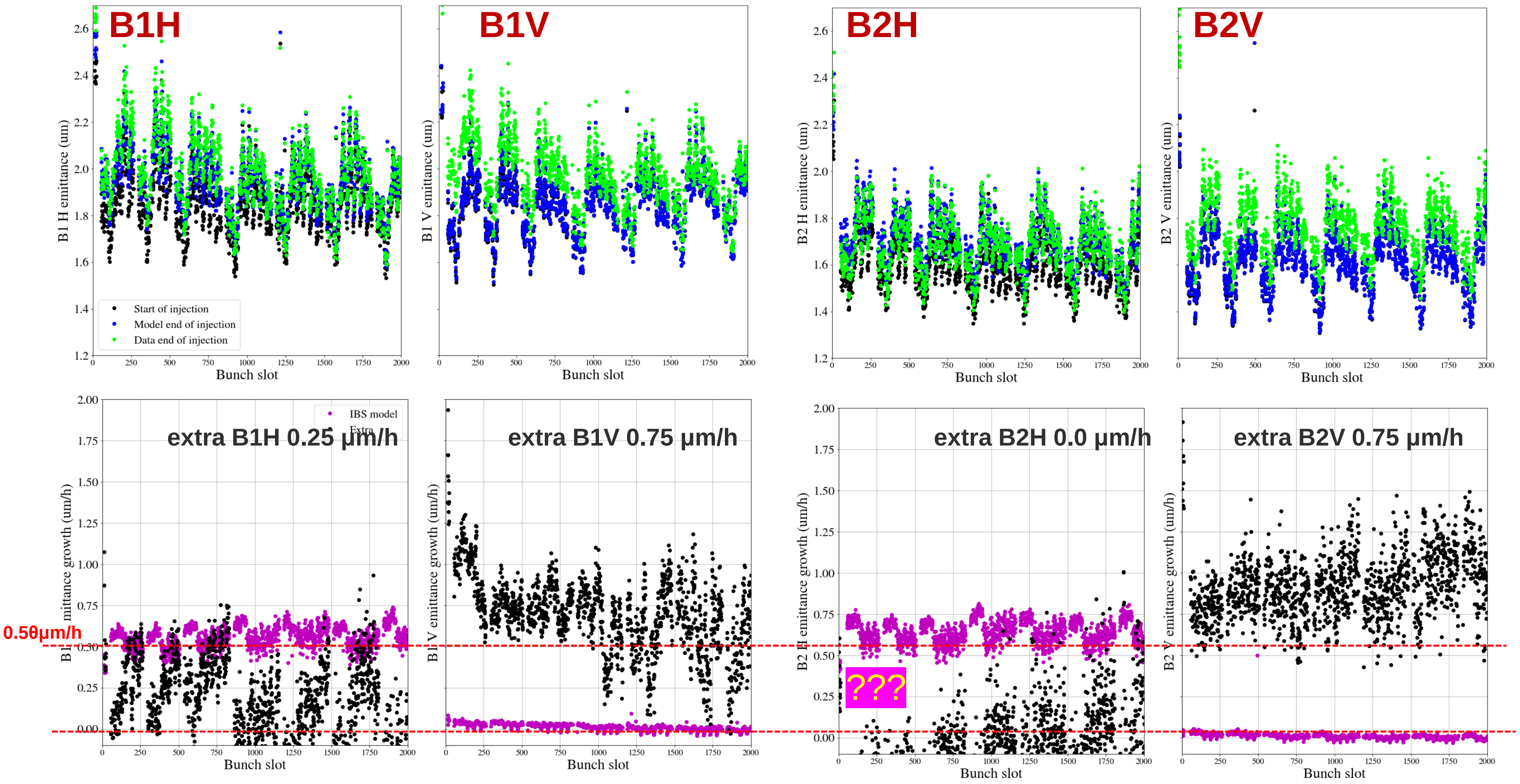
Extra growth on top of the model (IBS + coupling) mainly for the **V-plane**

Adding **noise** and **coupling** to the model we expect to partially explain the discrepancy, as in Run 2 2bdone

1.49E+11

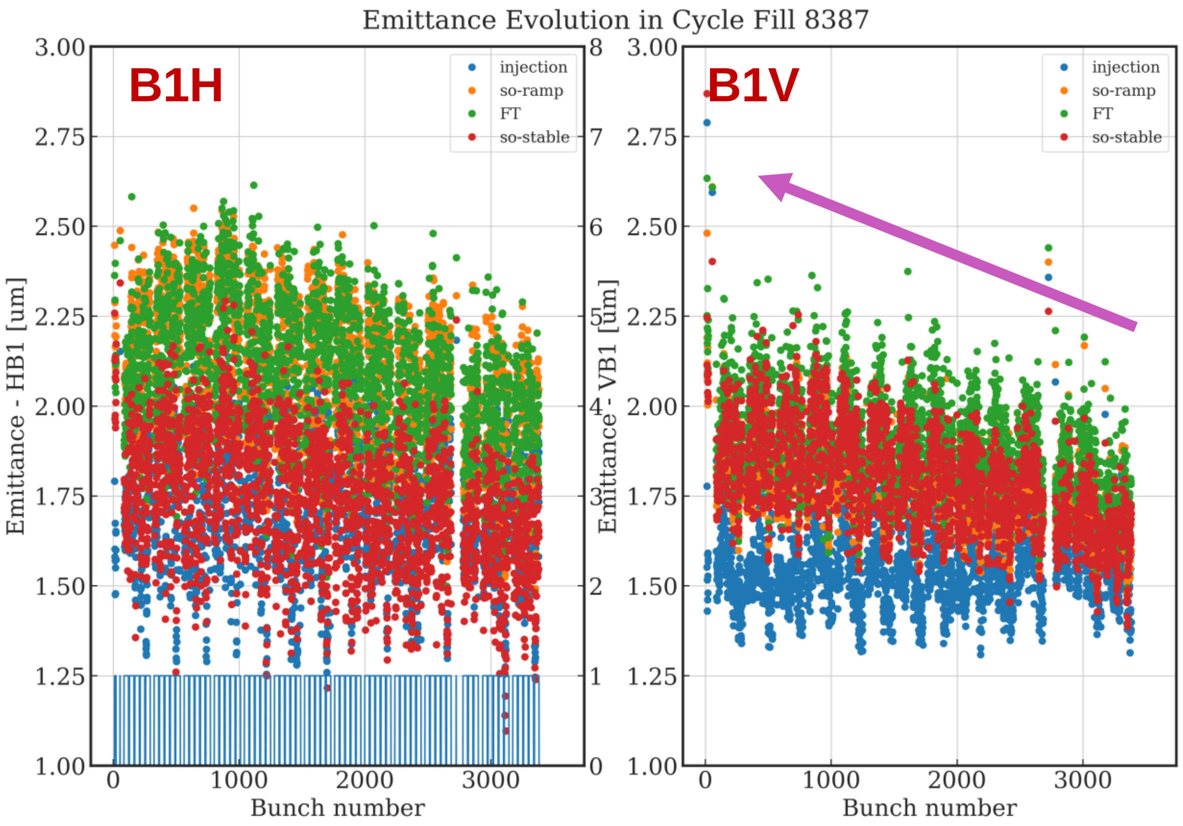
Emittance growth at injection energy (FB)

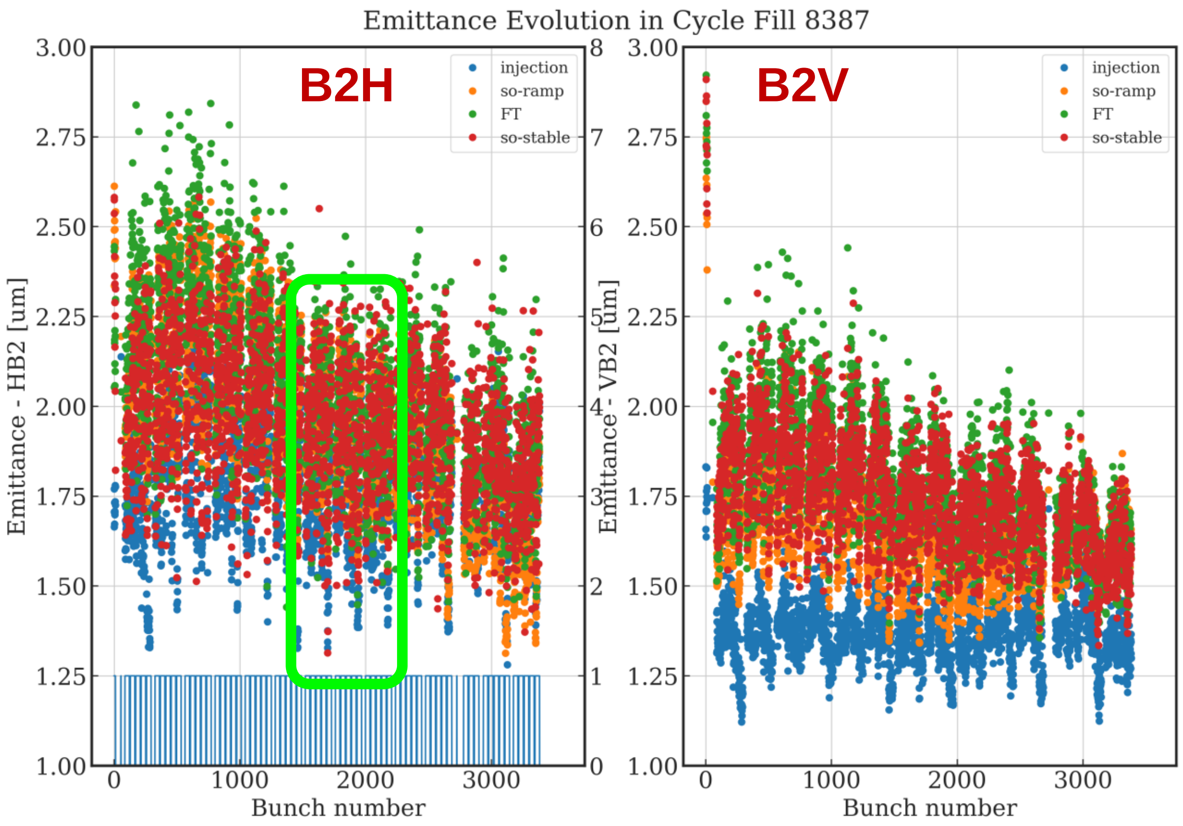
Compare with model – example 2023 fill



Emittance evolution in the cycle
from injection to collisions – example 2022 fill

Observations: slope from FB preserved during acceleration – train structure from injection also preserved

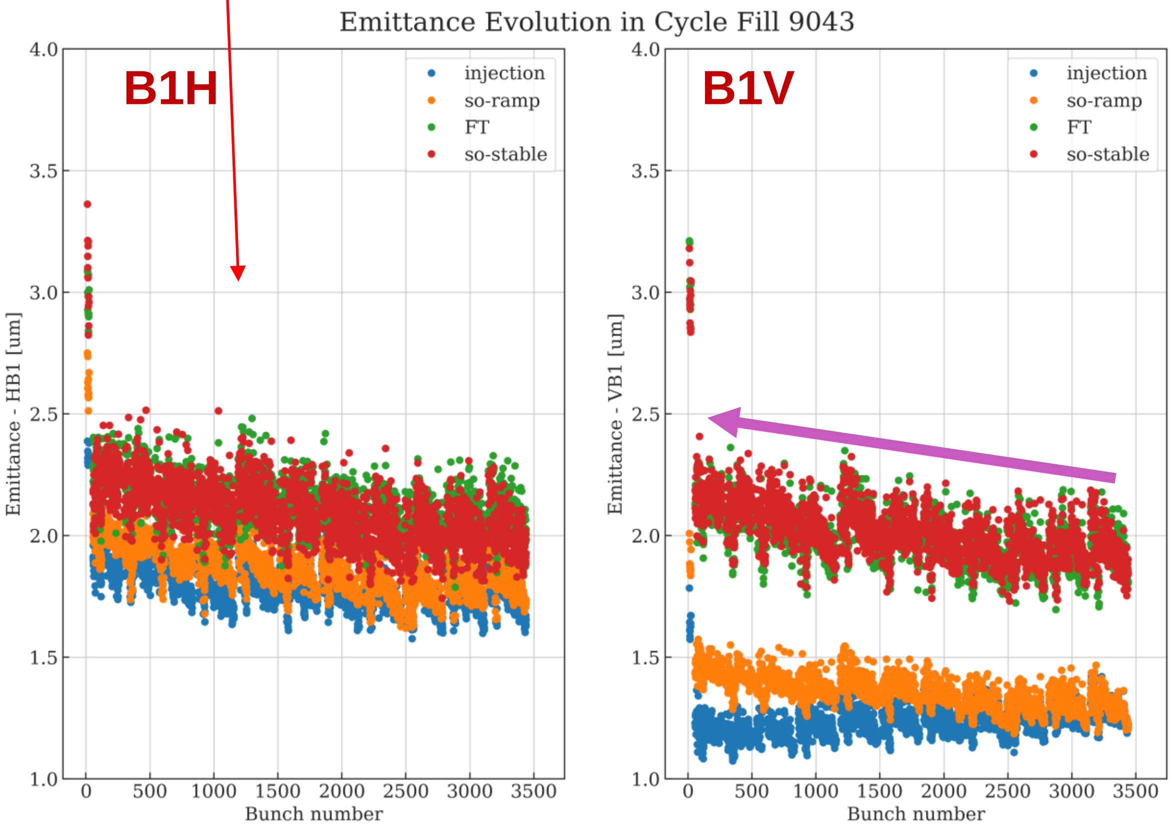


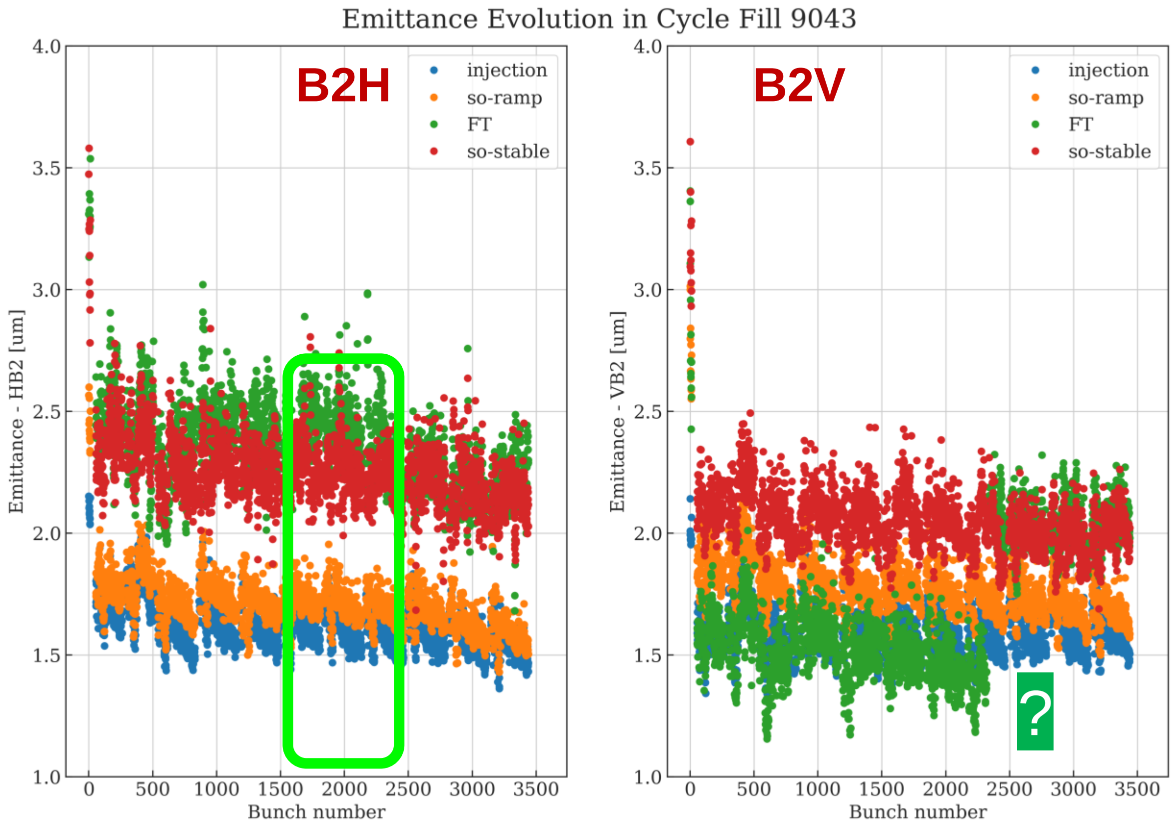


Emittance evolution in the cycle

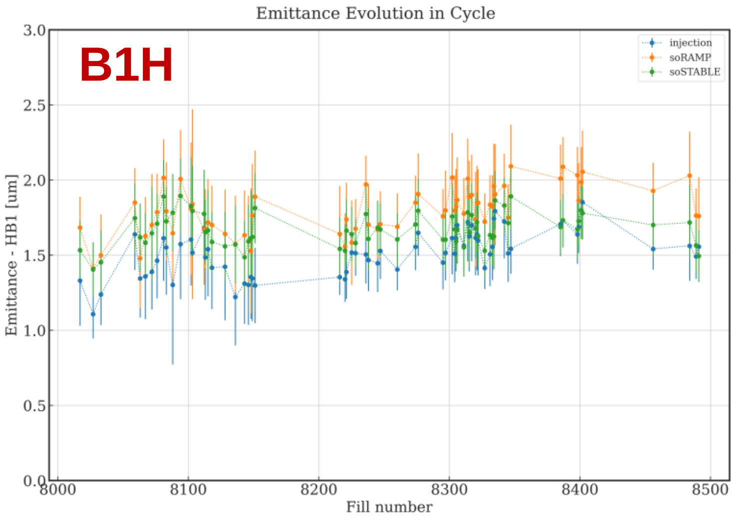
from injection to collisions – example 2023 fill

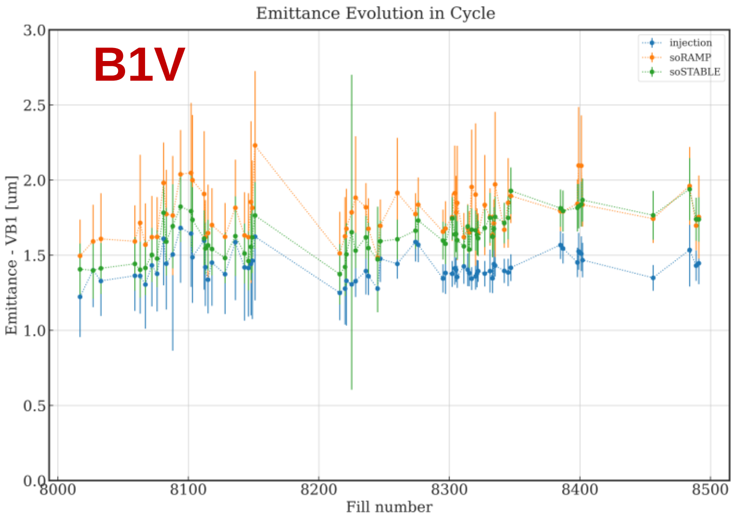
Observations: slope from FB preserved during acceleration – train structure from injection also preserved

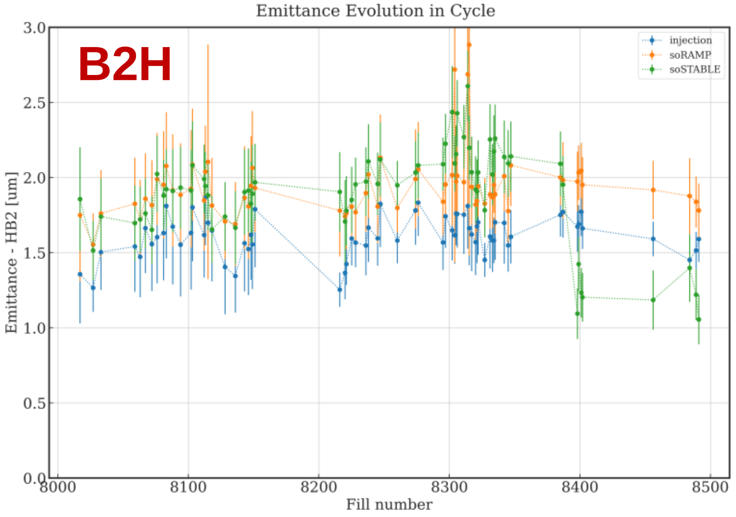


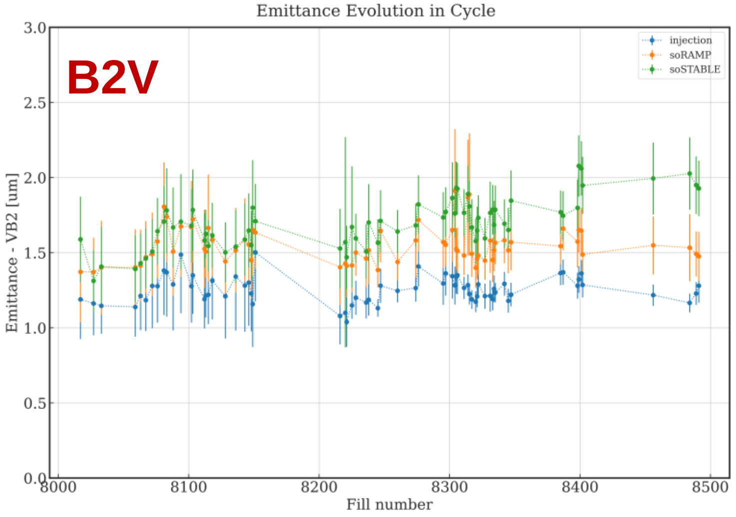


Emittance evolution in the cycle
from injection to collisions – all 2022 fills







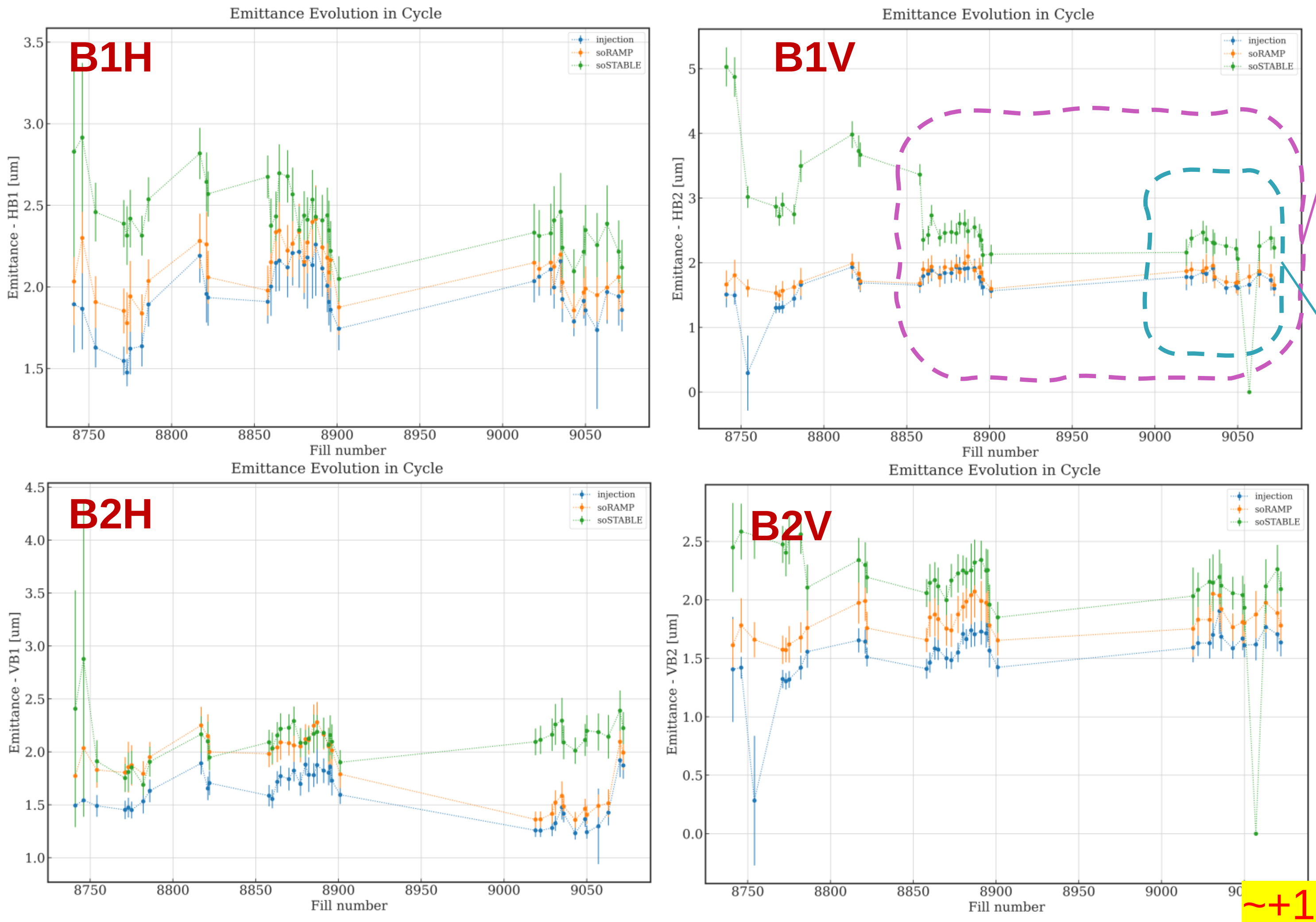


2022 fills	B1H	B1V	B2H	B2V
Injection	1.52	1.62	1.42	1.25
Start of Ramp	1.79	1.94	1.77	1.55
Start of SB	1.67	1.89	1.63	1.70

Average @ SB :
1.72 µm for 1.3e11 ppb

Emittance evolution in the cycle

from injection to collisions – 2023



Fills >8800	B1H	B1V	B2H	B2V
Injection	2.02	1.60	1.78	1.63
Start of Ramp	2.14	1.84	1.84	1.87
Start of SB	2.37	2.15	2.40	2.14

29%

17%

Average @ SB
2.26 µm for 1.49e11 ppb

Fills > 9000	B1H	B1V	B2H	B2V
Injection	1.95	1.41	1.74	1.67
Start of Ramp	2.04	1.54	1.81	1.87
Start of SB	2.29	2.18	2.28	2.10

30%

21%

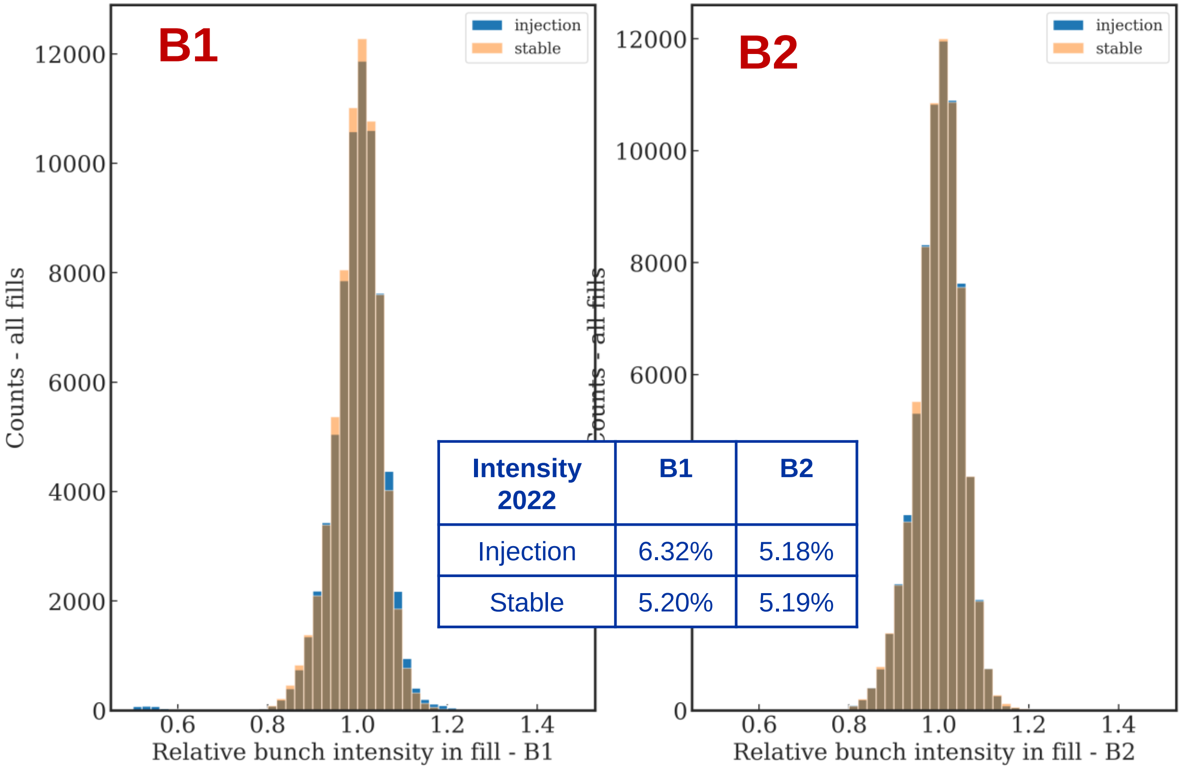
Average @ SB
2.21 µm for 1.49e11 ppb

~+10% from scale with intensity wrt 2022 data

Bunch Fluctuations

Emittance and Intensity bbb variations - 2022

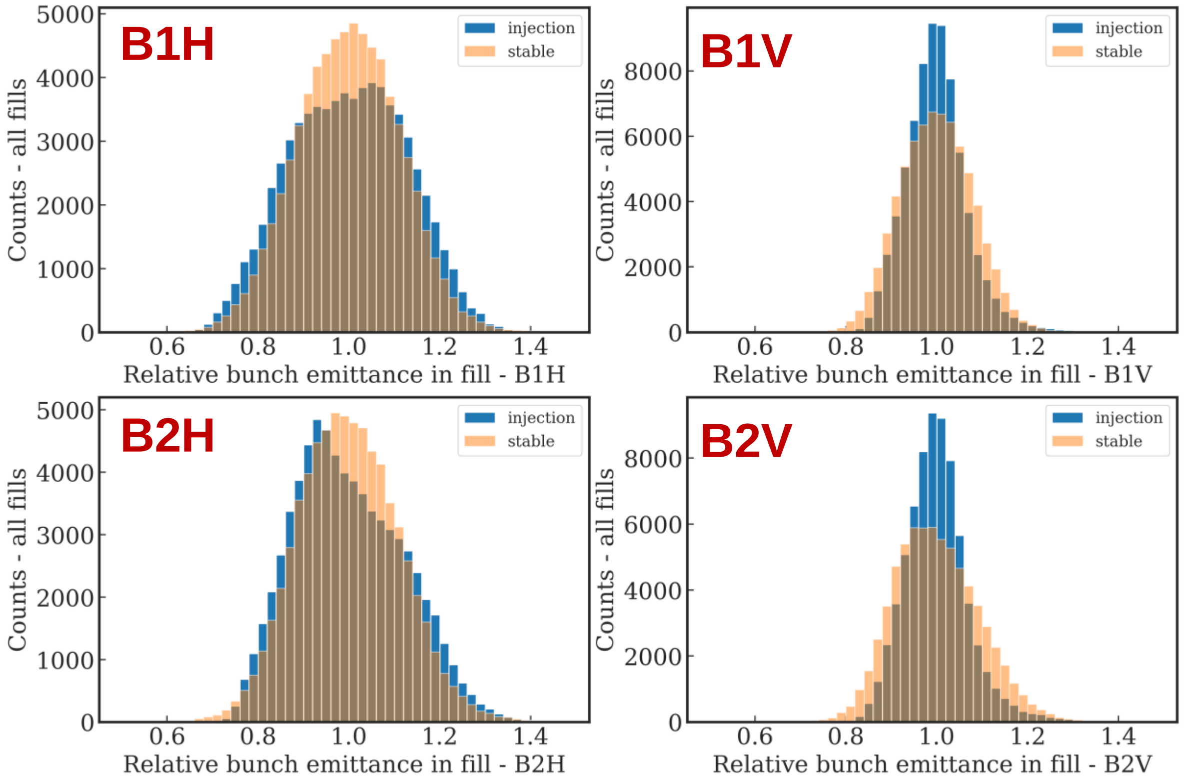
Intensity - all fills



Intensity 2022	B1	B2
Injection	6.32%	5.18%
Stable	5.20%	5.19%

These would translate to >10% b2b luminosity fluctuation!

Emittance - all fills

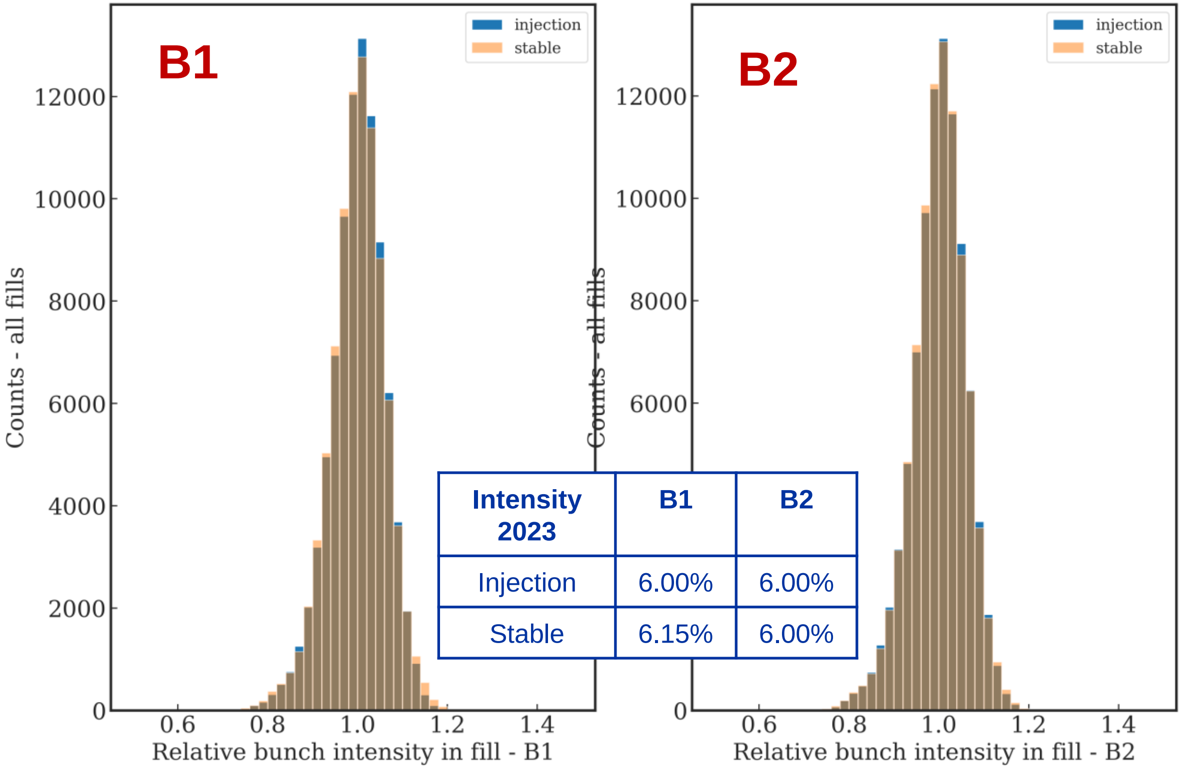


Emittance 2022	B1H	B1V	B2H	B2V
Injection	12.77%	7.04%	12.02%	7.00%
Stable	11.31%	8.00%	11.17%	9.39%

Bunch Fluctuations

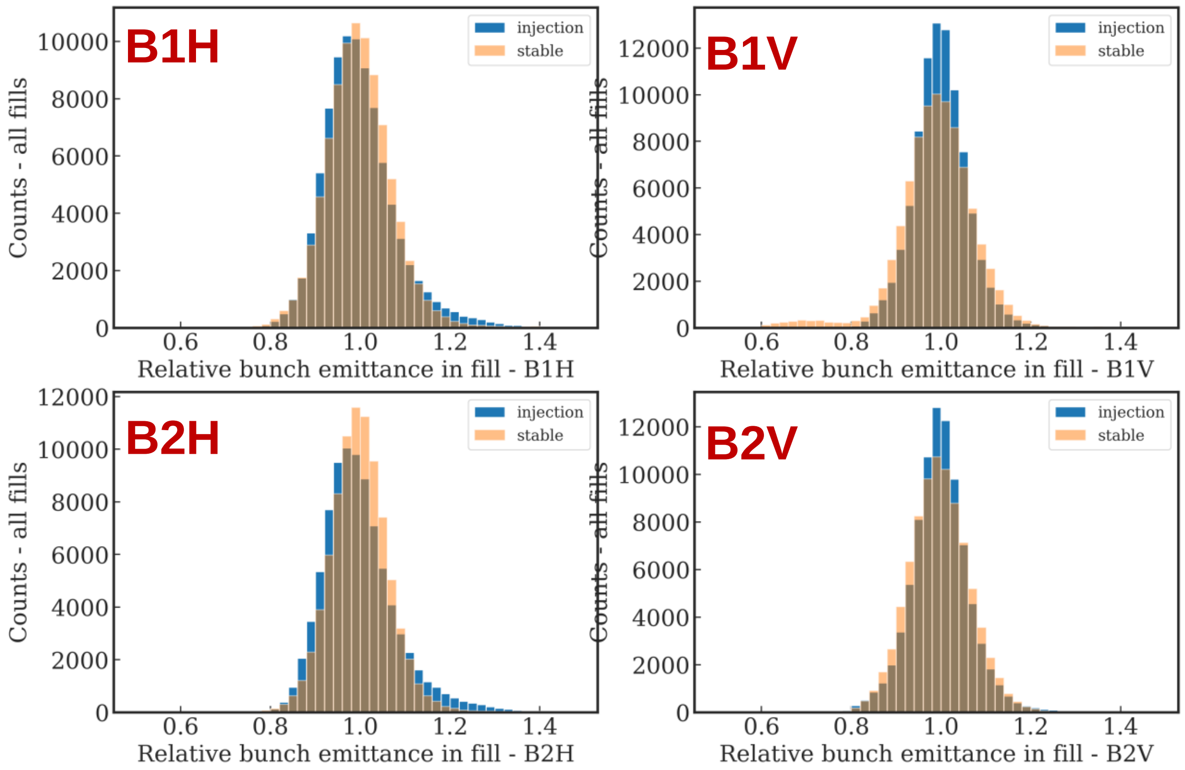
Relative emittance and Intensity bbb variations - 2023

Intensity - all fills



Intensity 2023	B1	B2
Injection	6.00%	6.00%
Stable	6.15%	6.00%

Emittance - all fills



Emittance 2023	B1H	B1V	B2H	B2V
Injection	8.17%	5.95%	8.19%	7.89%
Stable	7.77%	12.75%	6.41%	7.07%

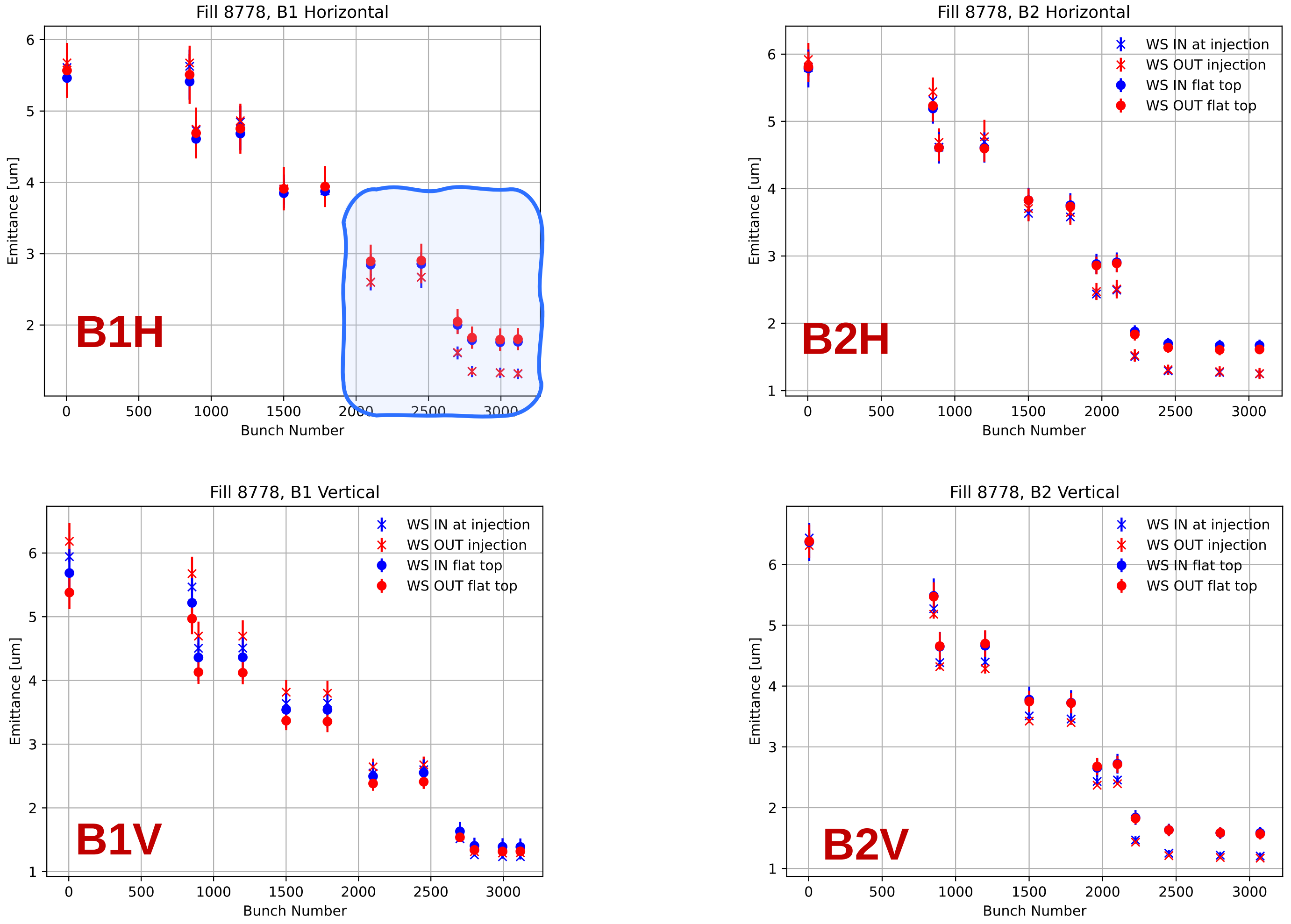
Emittance evolution in the cycle
Acceleration ramp

From the data, ~half of the emittance blow up form injection to collisions is happening during the acceleration ramp.

Analysis of BSRT calibration data

- **set of single bunches with variable emittances**
- **can help to distinguish between single bunch and train effect contributions.**
- **WS data for the full cycle**

Result : the blow-up is it is clearly present in the bunches that have similar emittance as in normal fills and of similar amplitude

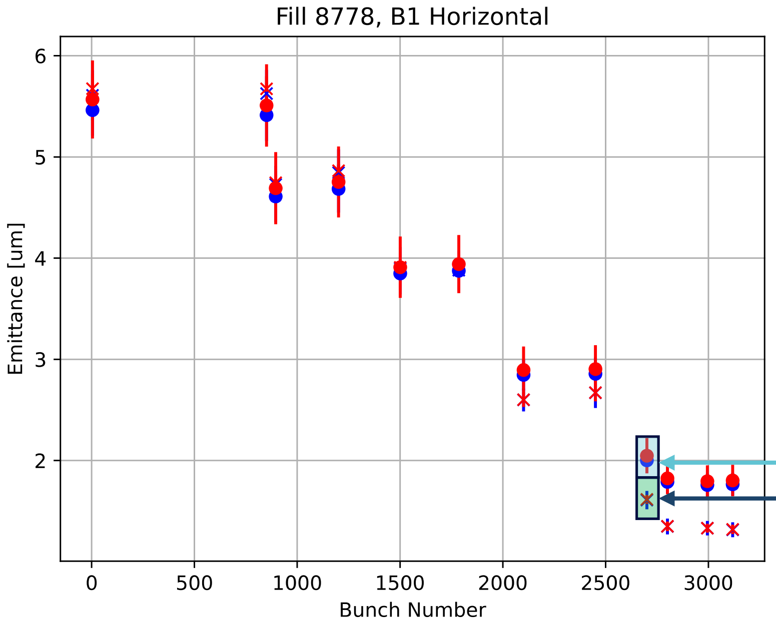


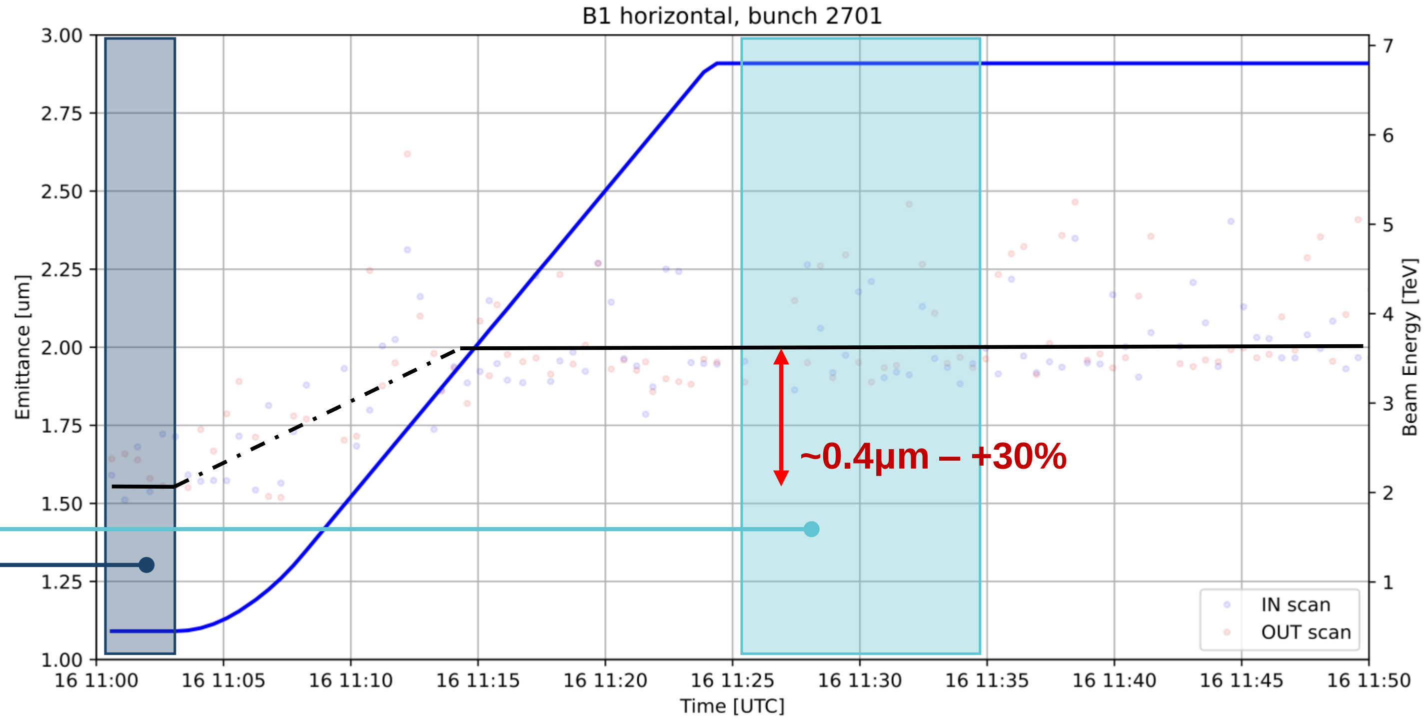
Emittance evolution in the cycle

acceleration ramp

Can we localize the blow-up on a particular part of the ramp?

It seems mainly to develop between 0.45 and 3.5 TeV



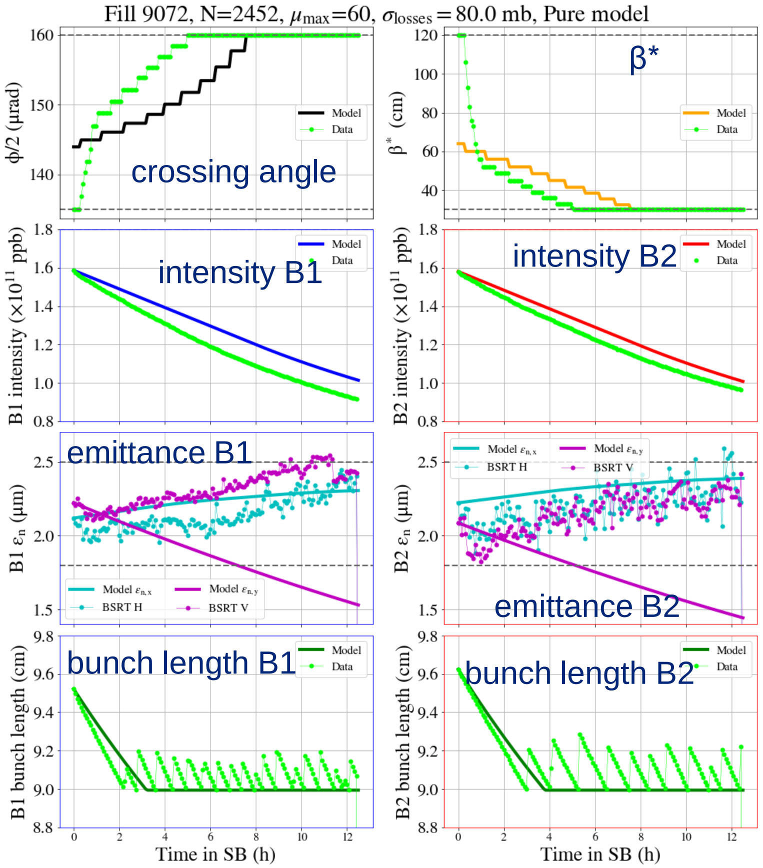


Emittance evolution in collisions

Compare data with the model - 2023

Case 1 Pure model : emittance and intensity calculated by the model – step 1

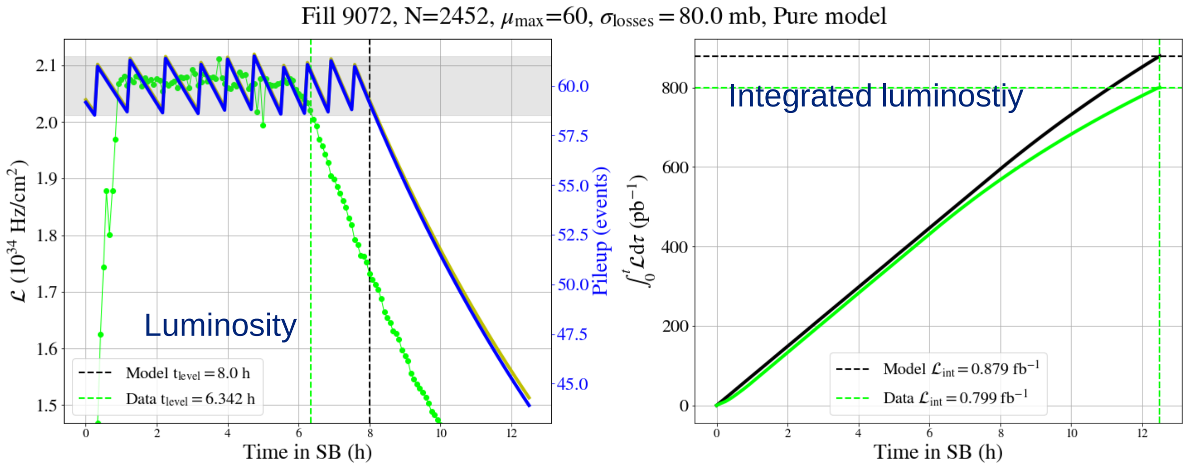
2023	soSB	eoL	10h
B1H	2.2	2.25	2.3
B1V	2.3)	2.45	2.5
B2H	2.0	2.2	2.3
B2V	2.0	2.2	2.3



ε-H good for start/end points(!) not the evolution

ε-V the model predicts dumping!

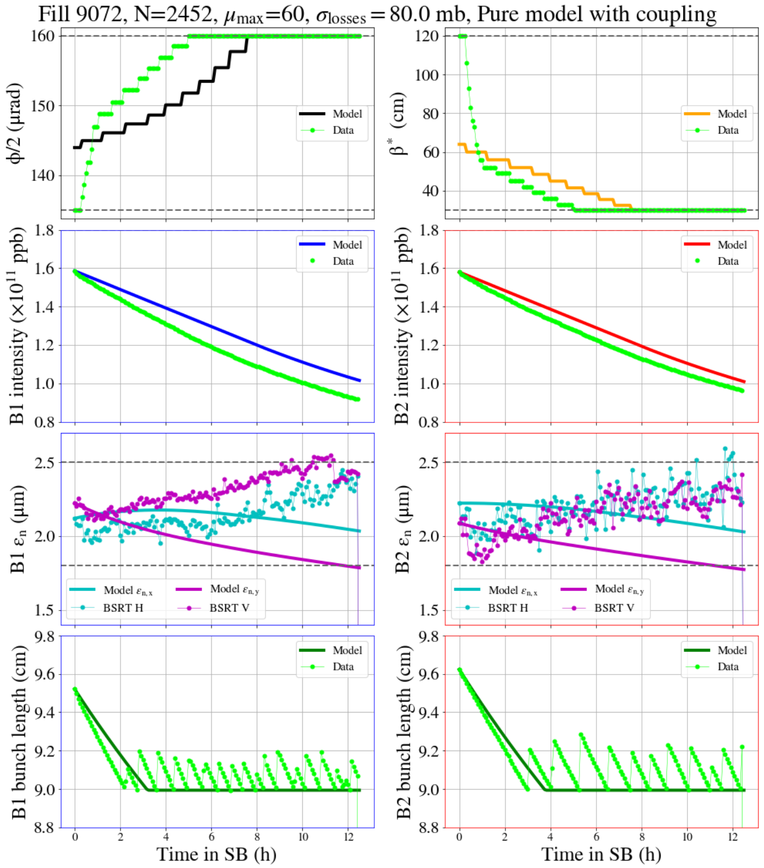
Model components	
base (*)	Yes
Burn-off	80 mb
Coupling	No
Noise	No
ε-growth from burn-off	No
Extra emittance growth	No



Emittance evolution in collisions

Compare data with the model - 2023

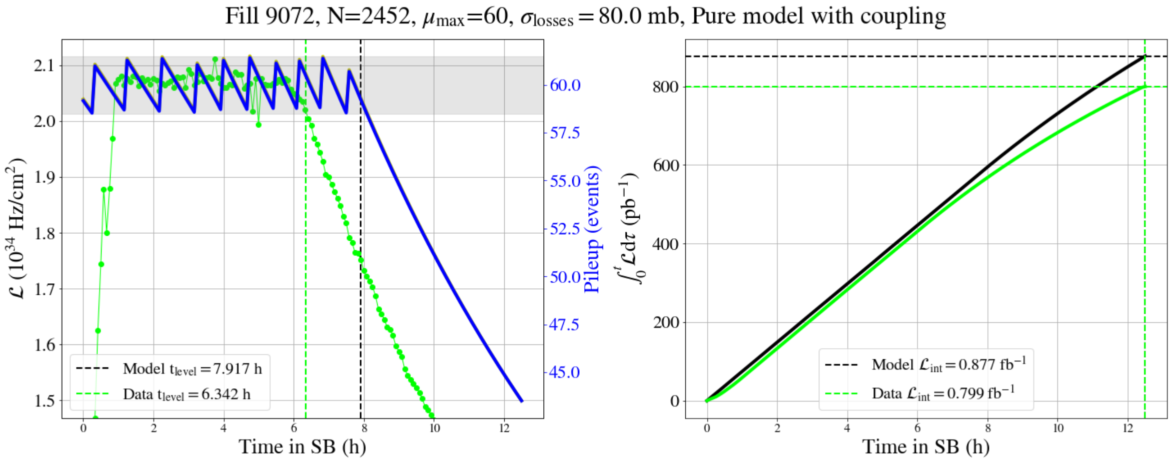
Case 1 Pure model : emittance and intensity calculated by the model – step 2



ε-H worse prediction – blow-up shared with V-plane

ε-V some blow-up but not sufficient

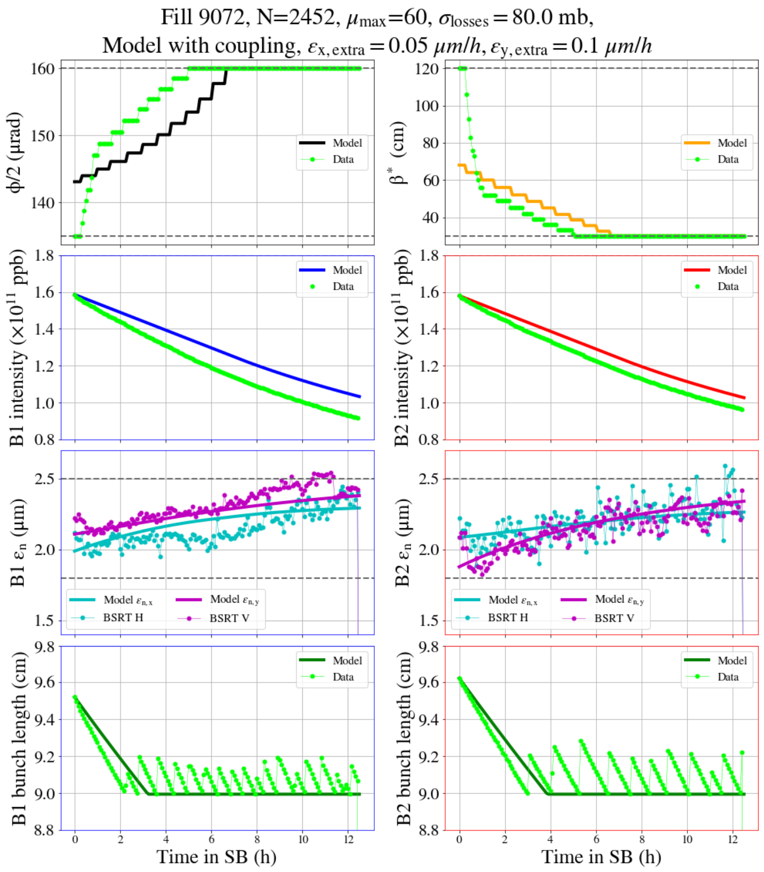
Model components	
base (*)	Yes
Burn-off	80 mb
Coupling	Yes
Noise	No
ε-growth from burn-off	No
Extra emittance growth	No



Emittance evolution in collisions

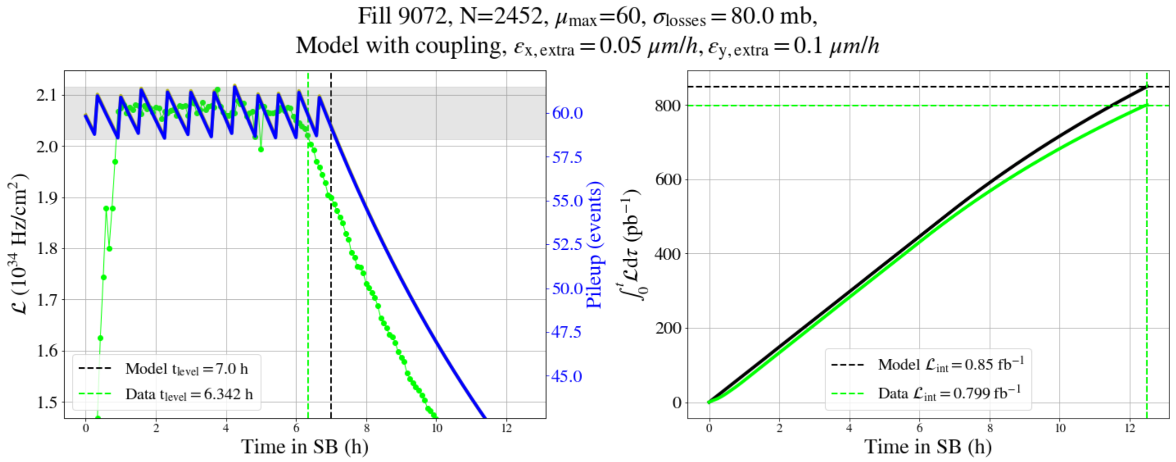
Compare data with the model - 2023

Case 2 Data driven : intensity from the model, extra emittance growth



- **Extra emittance growth adjusted to best match the data :**
  - **ε_H → 0.05 μm/h**
  - **ε_V → 0.1 μm/h**

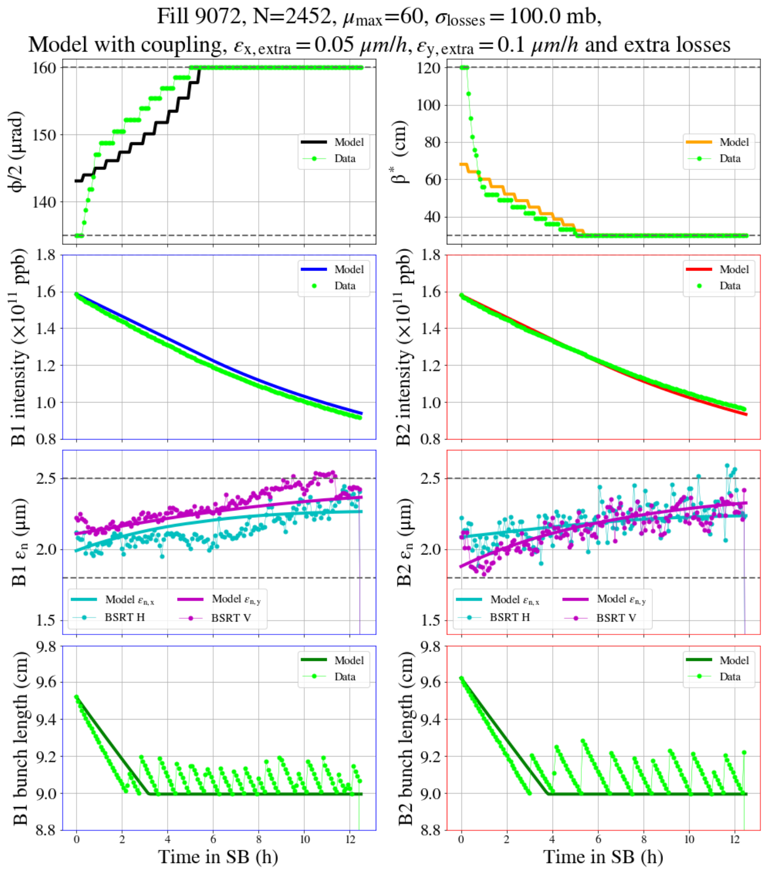
Model components	
base (*)	Yes
Burn-off	80 mb
Coupling	Yes
Noise	No
ε-growth from burn-off	No
Extra emittance growth	**Yes**



Emittance evolution in collisions

Compare data with the model - 2023

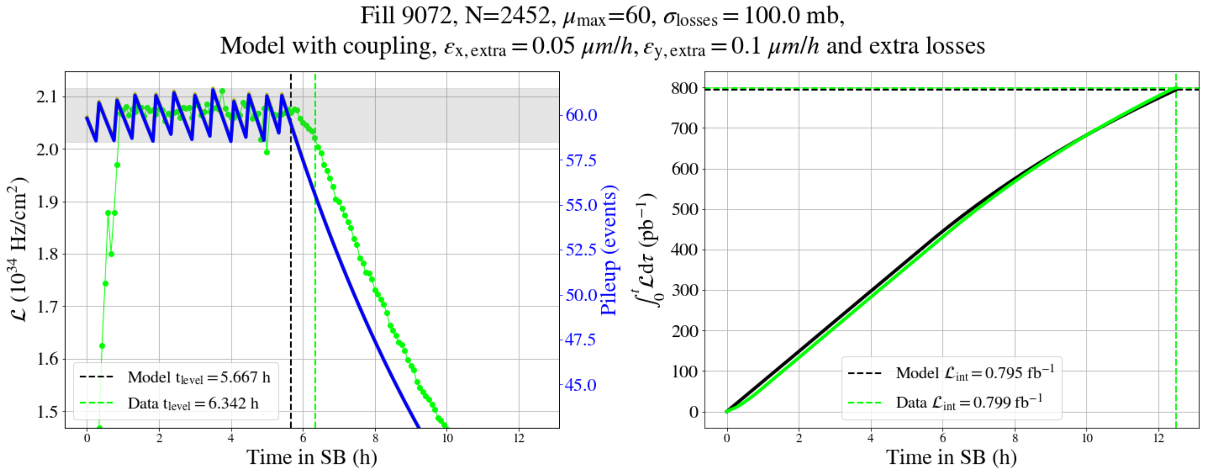
Case 3 Data driven: increased burn-off, extra emittance growth



Emittances : good agreement for B2 H&V, B1 still off in the final values but also during evolution

Intensity : well matched to the data

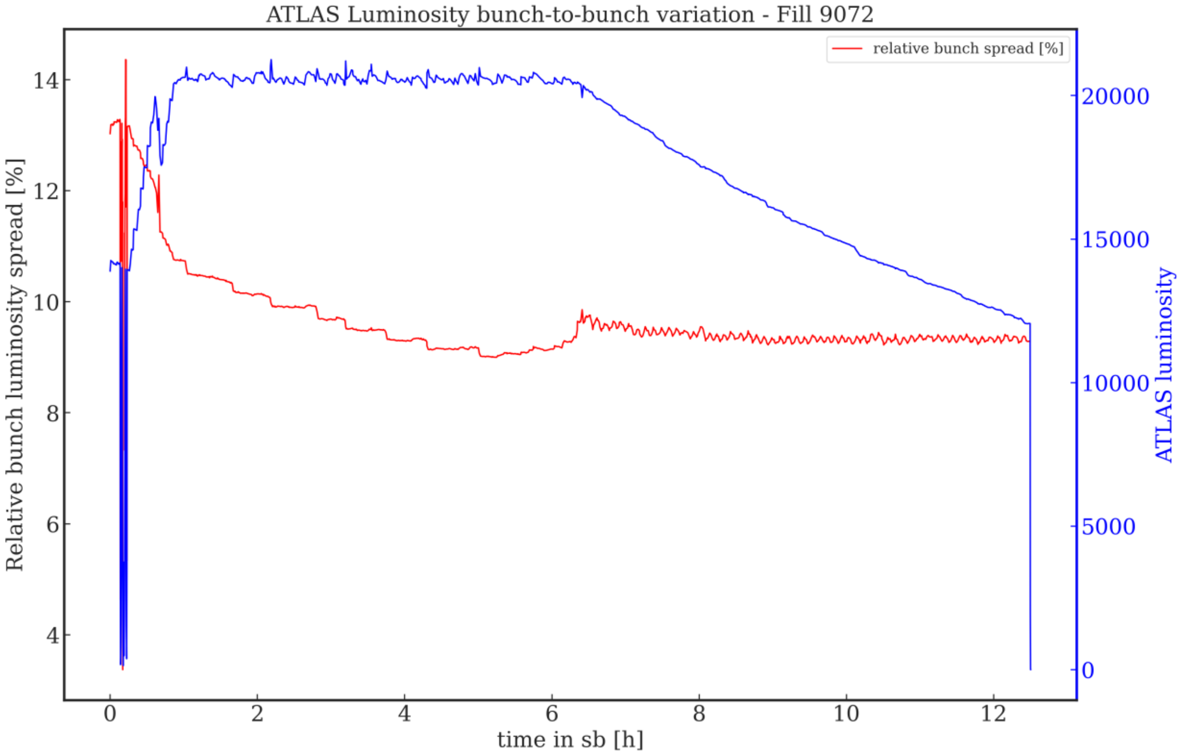
Model components	
base (*)	Yes
Burn-off	100 mb
Coupling	Yes
Noise	No
ε-growth from burn-off	No
Extra emittance growth	Yes



Beams in collision

Bunch-to-bunch variations – 2023

Luminosity bunch-to-bunch variations – example fill 9072



- **Initial bunch-to-bunch luminosity fluctuations ~13%**
- **Reduced fast at start of collisions to ~11% at start of levelling**
- **B2B fluctuations further reduced during levelling, and constant during the luminosity decay**
- **For the moment the values are below the natural fluctuations due to PU**

$$\frac{1}{\sqrt{N}} = \frac{1}{\sqrt{60}} = 13\%$$

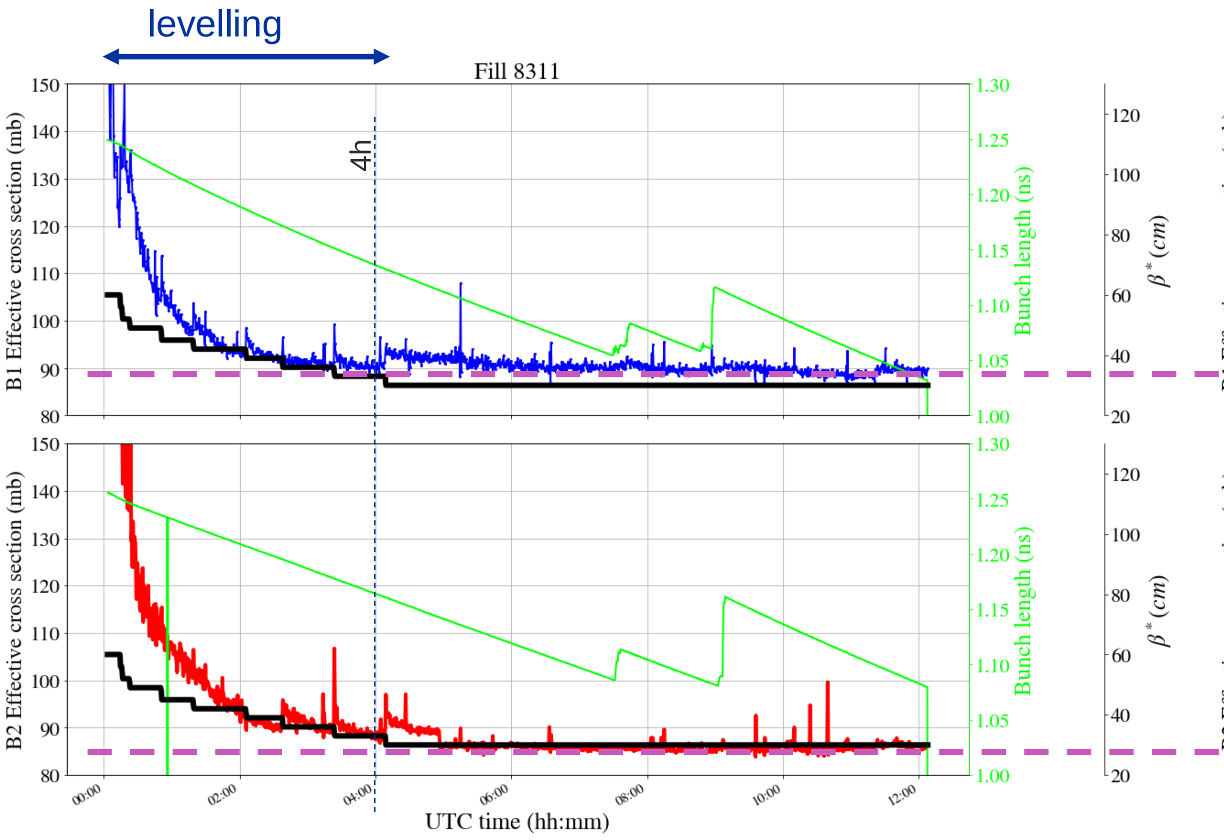
- **but certainly not compatible with future HL-LHC requirements with increased PU**

Beams in collision

Beam lifetime – effective cross section

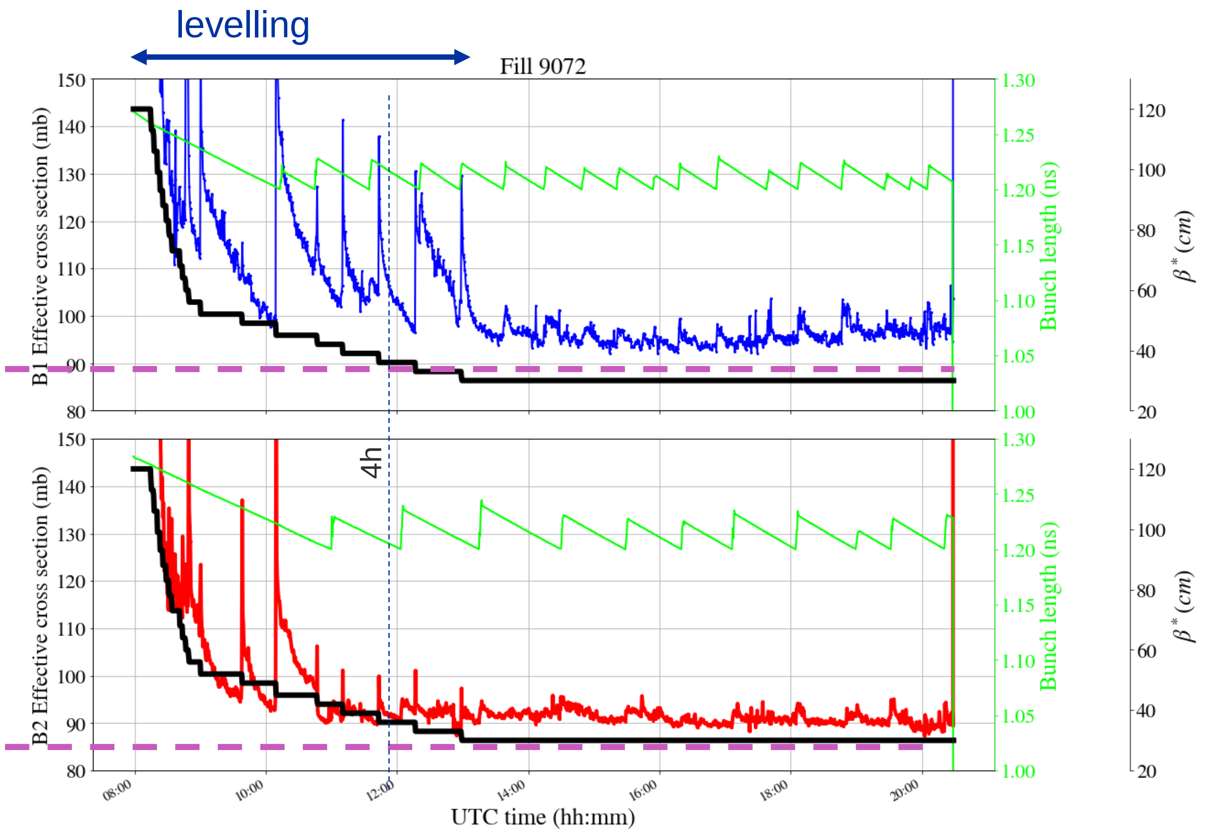
Example 2022 fill

Extra losses at start of collisions, but no loss spikes during leveling steps to 30cm β*



Example 2023 fill

Extra losses during leveling steps, correlated with the β* and beam length changes(?)

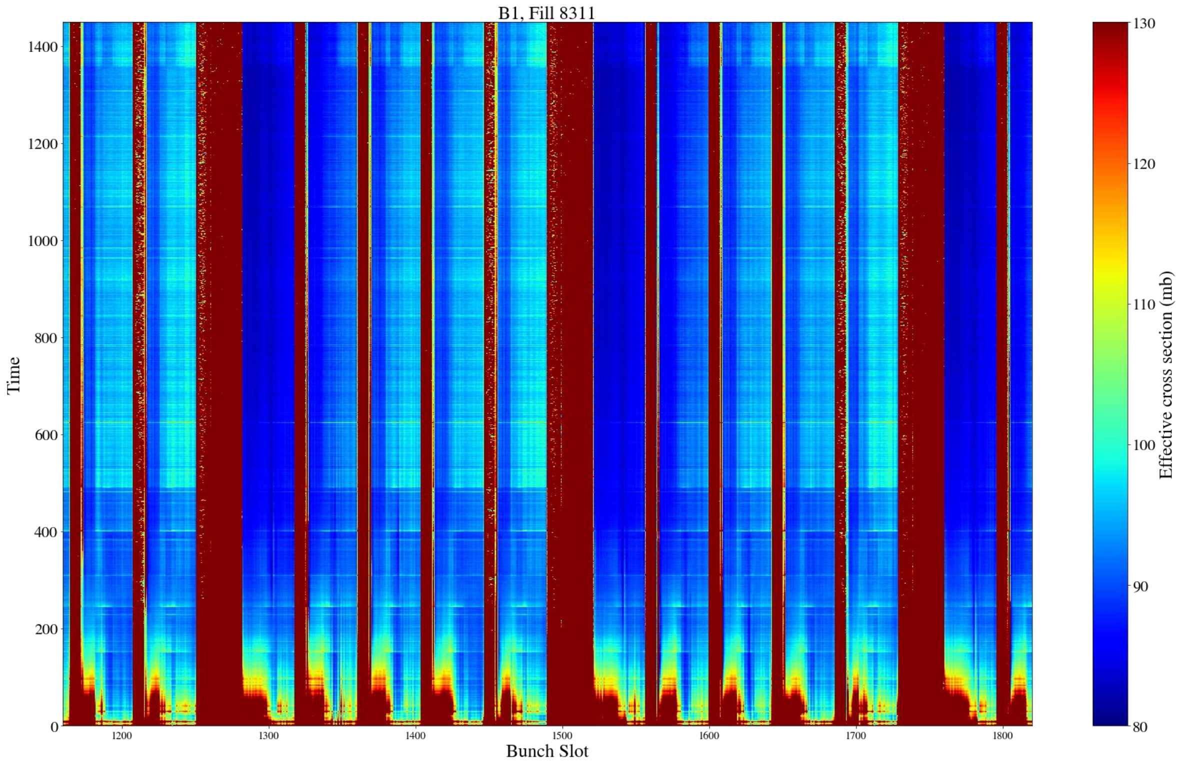


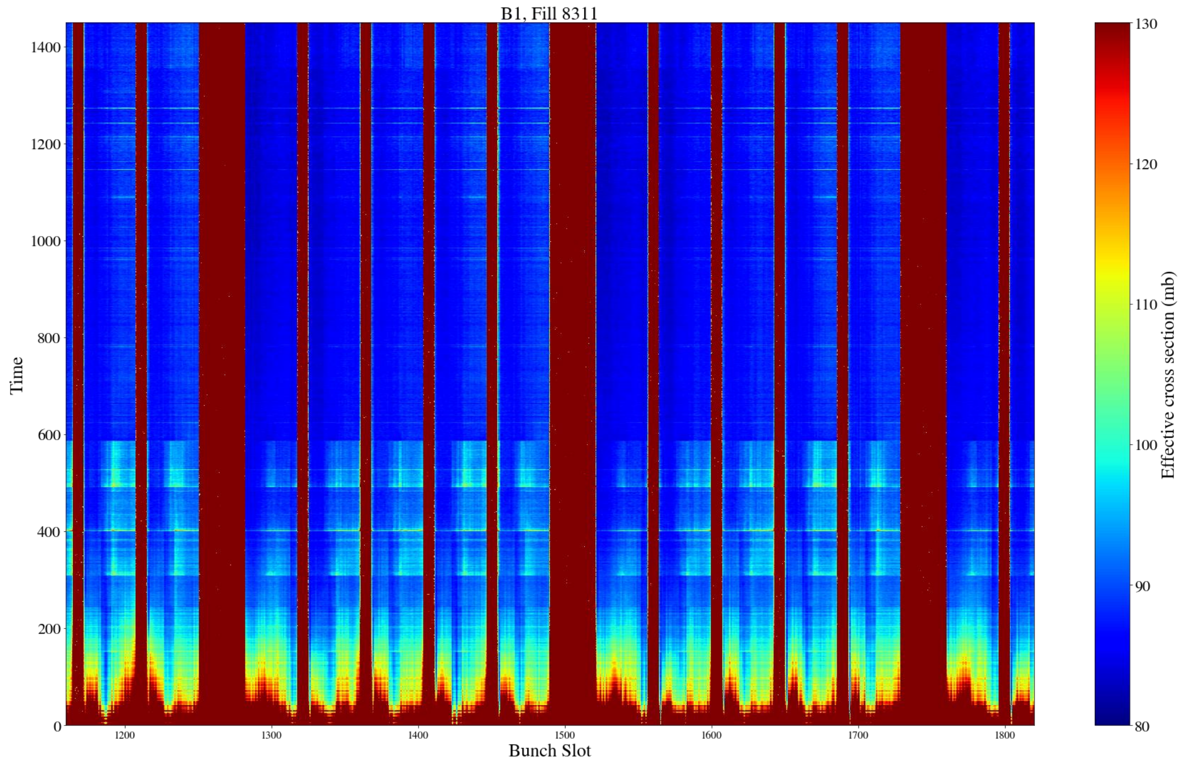
Beams in collision
Beam lifetime – effective cross section

2022 fill – bunch-by-bunch data

large initial losses, no sign of correlation with β* changes

e-cloud pattern in the trains

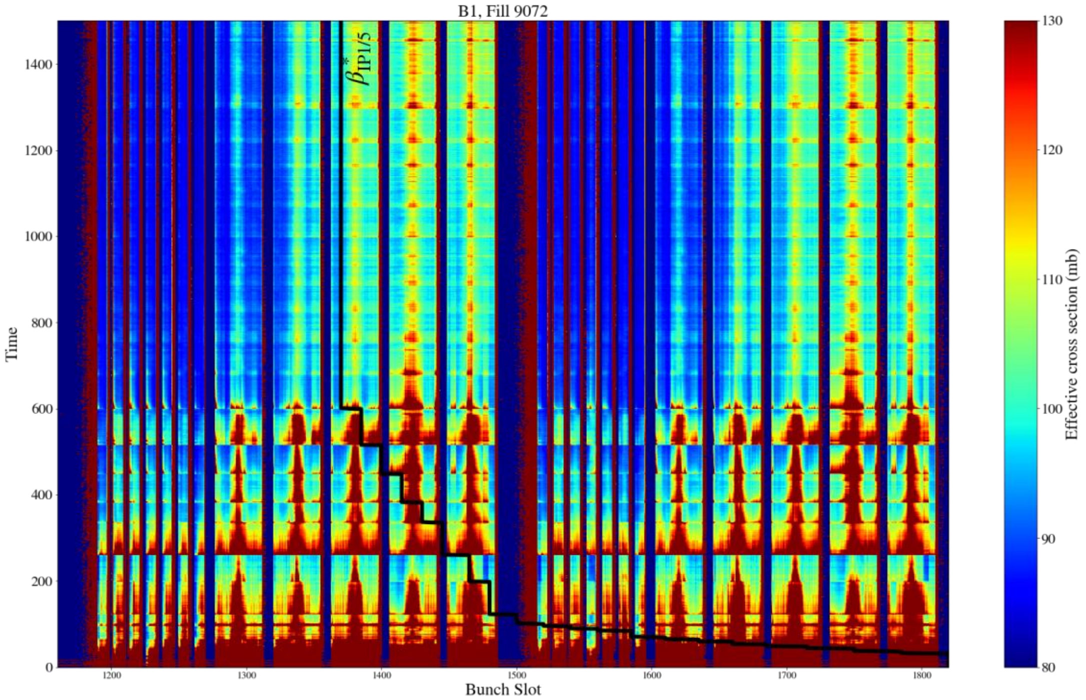


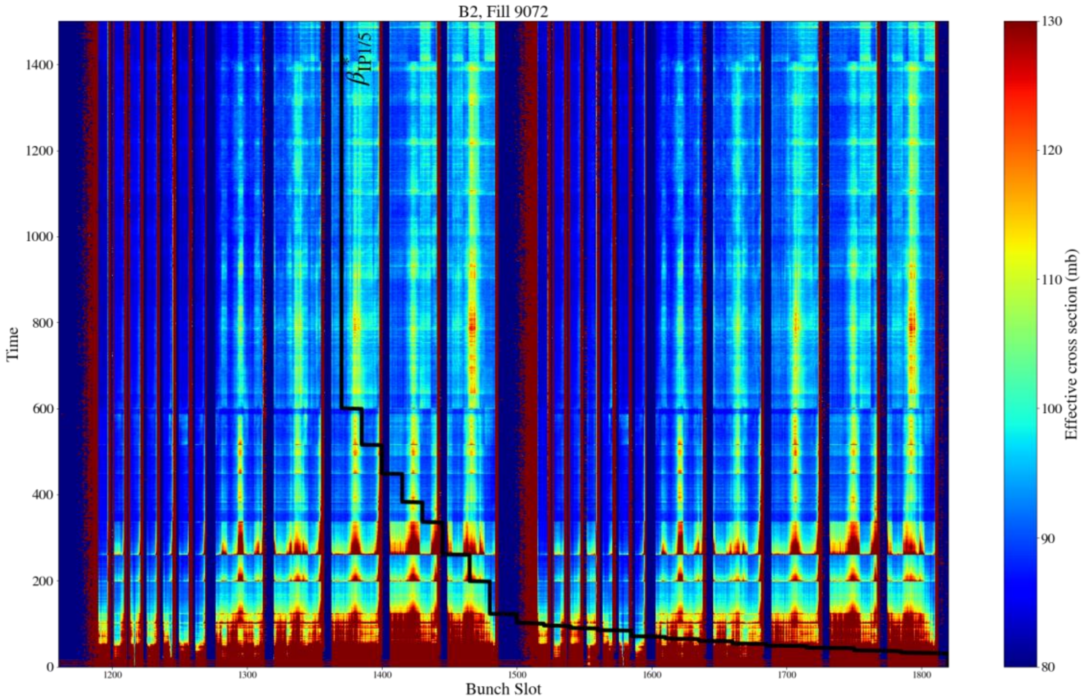


Beams in collision
Beam lifetime – effective cross section

2023 fill – bunch-by-bunch data

- losses correlated with β* changes and BBLR interactions(?)
- loss pattern similar to the Λ-shape observed at injection ?
- late trains in injection seem to have more loses !



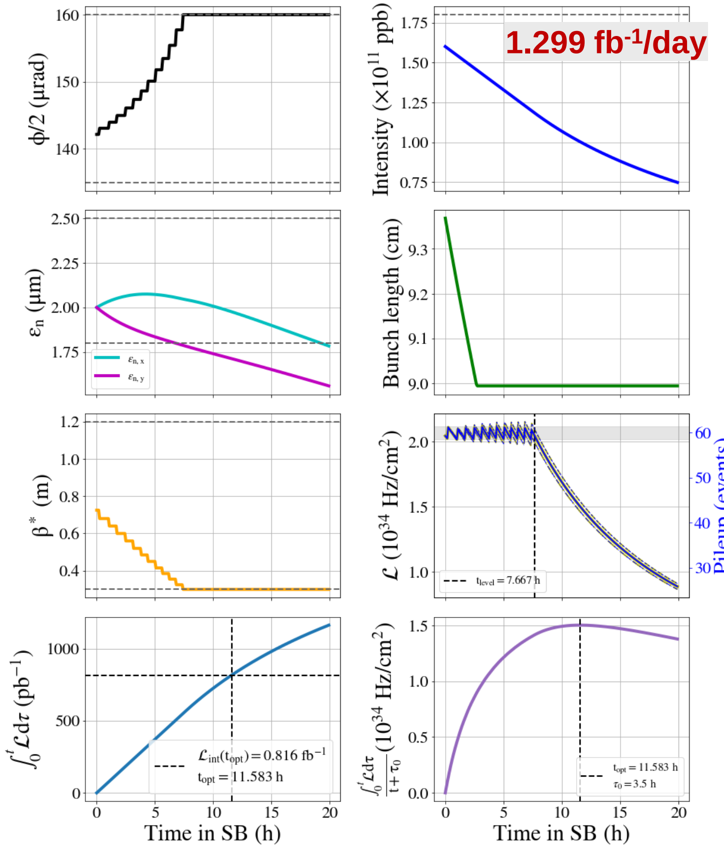


Beams in collision

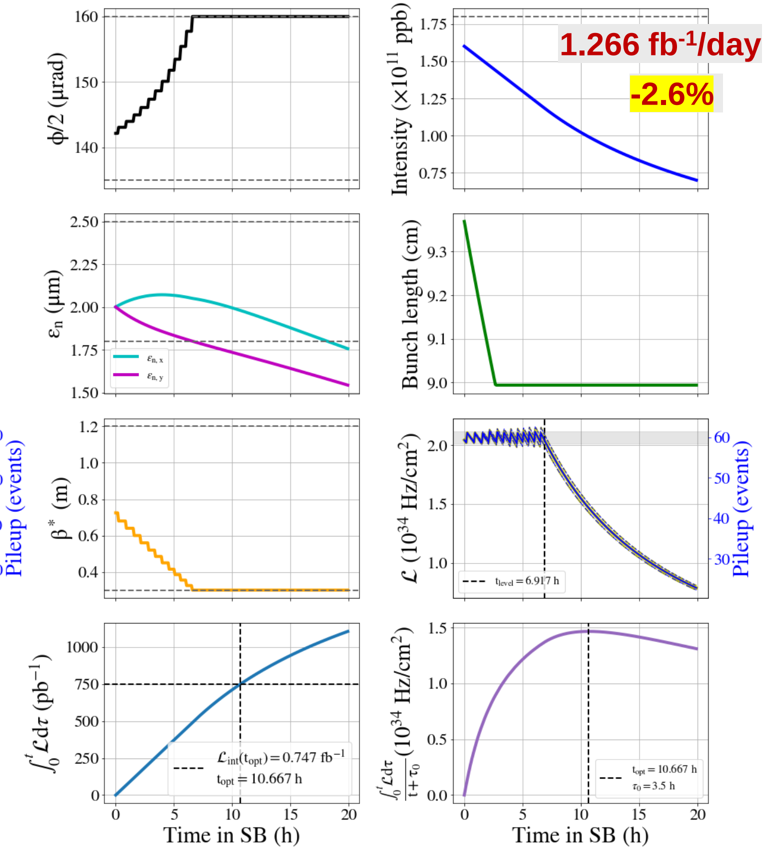
Beam lifetime – effective cross section

Estimate impact of extra losses to integrated luminosity : 3% for 10mb extra losses, 4% for extra blow-up for the same intensity

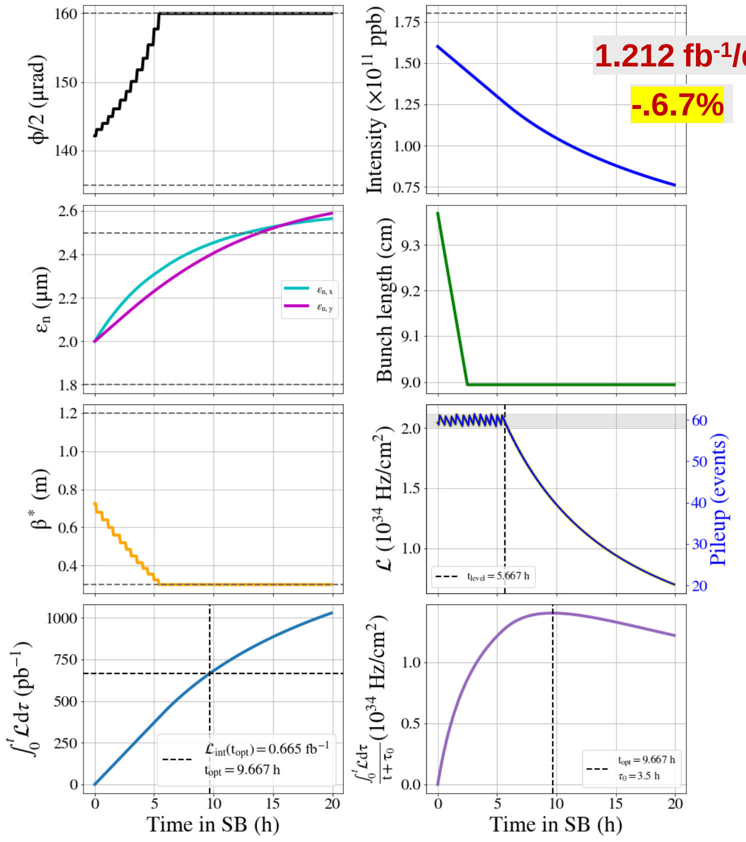
Pure model
1.6e11 ppb – 90mb



Model
1.6e11 ppb – 100mb



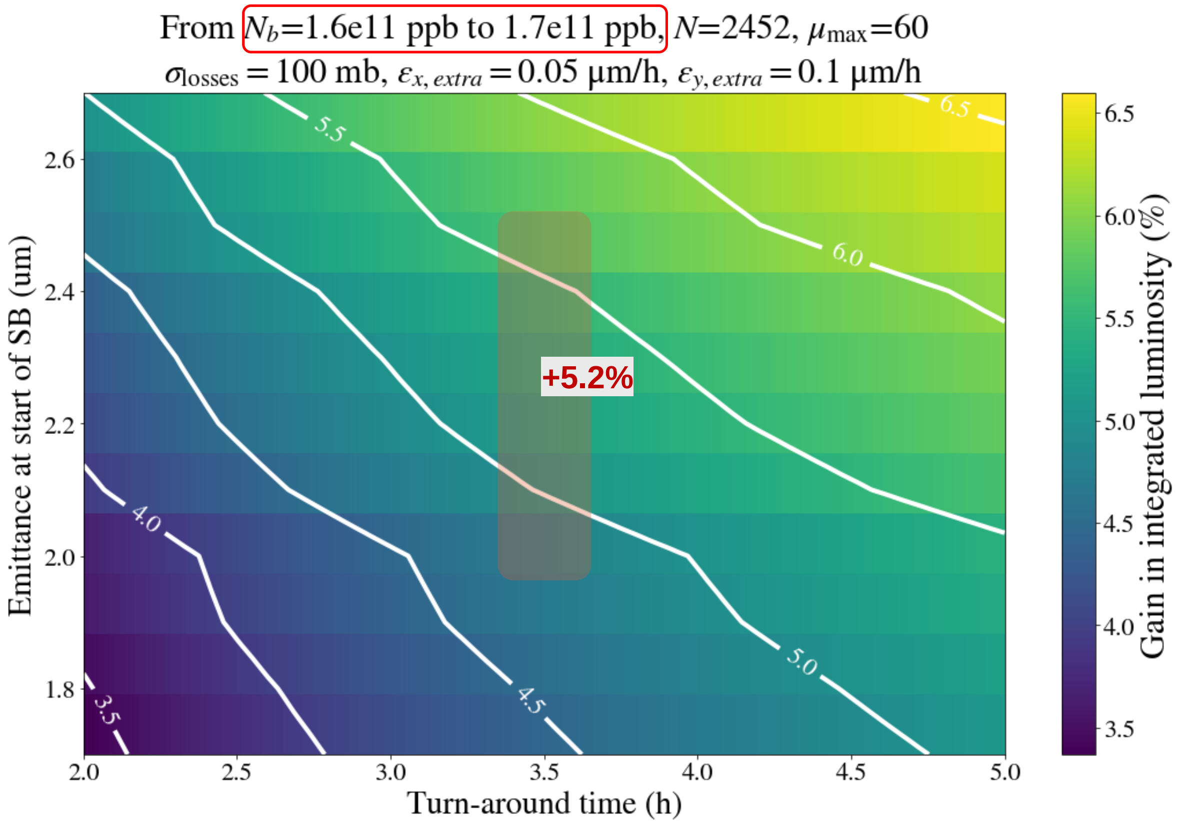
Model
1.6e11 ppb – 100mb – ε-growth :0.1V, 0.05H

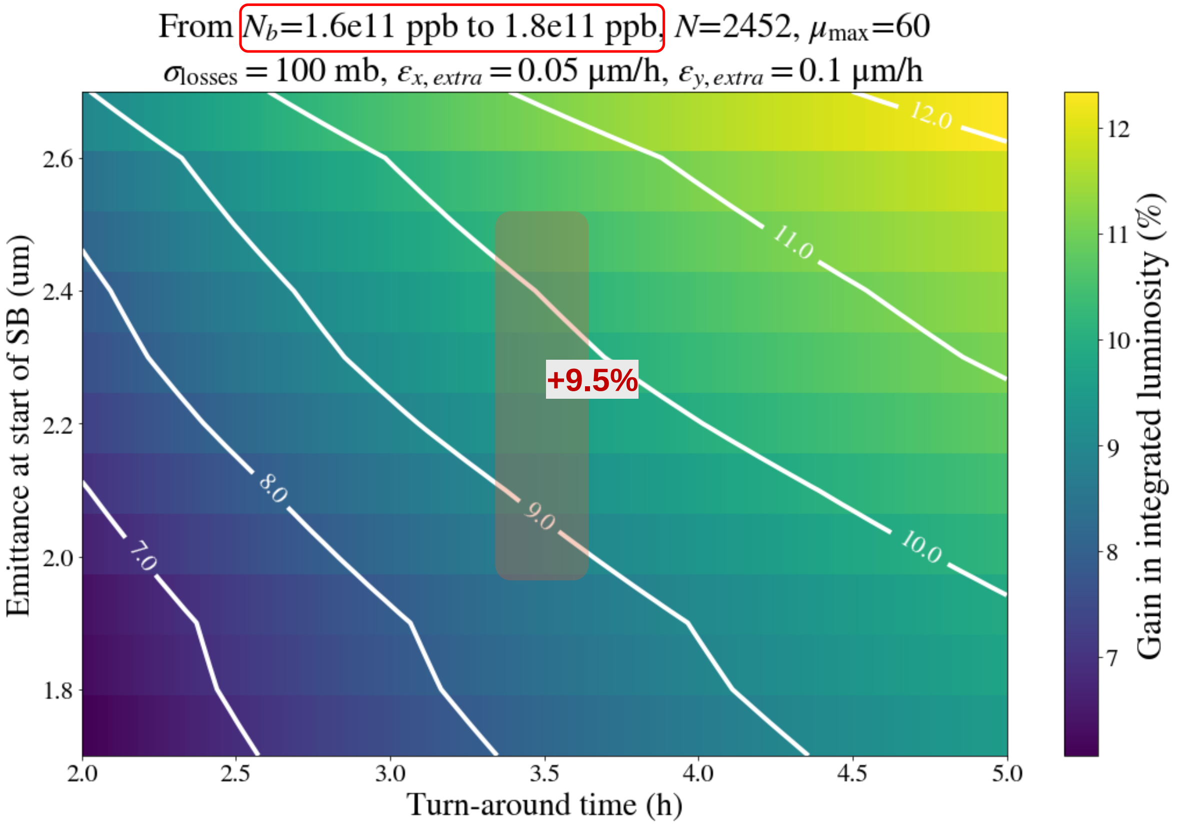


Emittance evolution in collisions

Beam intensity ⟺ integrated luminosity

Gain of 5% for 6.2% (1.6e11 to 1.7e11), and +9.5% for 12.5% (1.6e11 to 1.7e11) increase of intensity



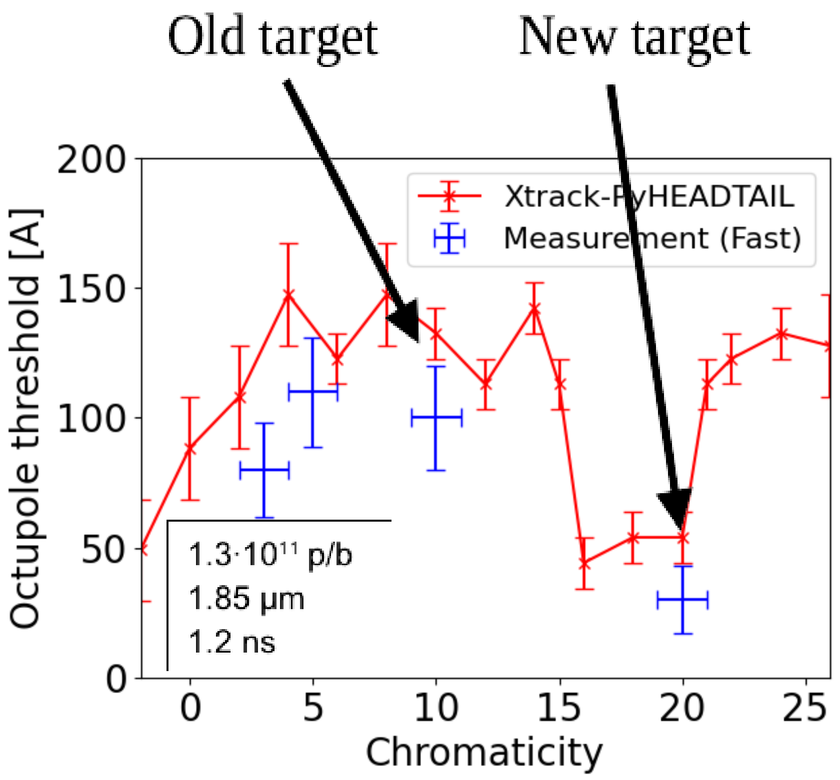


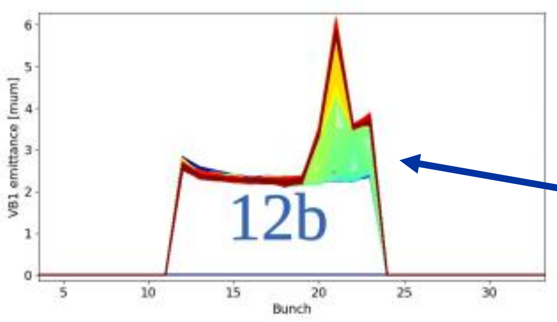
Transverse Stability

To mitigate electron cloud instabilities, talk by K.Paraschou@this workshop, the chromaticity target was increased from 10-15 to 20 units at top energy in Run 3

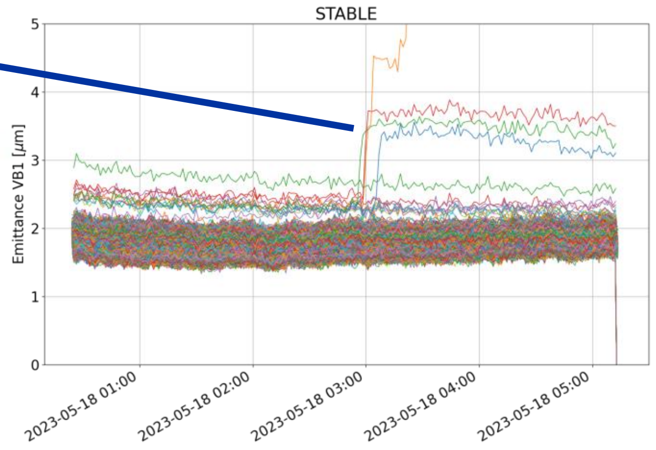
→ Reduced need for octupole if the chromaticity can be controlled to ±2 units (requires further development)

→ In 2023, the octupole current was kept 'high' (395A) to account for noise effects and allow for uncontrolled chromaticity variations





Fill 8784



Few instabilities of the witness bunches were observed and remain not understood.

Nevertheless, they are stabilised by emittance blow-up featuring negligible amount of beam losses → Not an issues for operation

There is no showstopper for operation with $1.8{\cdot}10^{11}$ p/b and 1.8 μm

Summary

- The findings from an initial study on the emittance evolution in Run 3 were presented, including information from 2022 and 2023 fills
- On the injected emittances from SPS, an increase by 15-20% compared to the values measured at SPS FB is found. But more importantly, a structure is visible along and within the trains, enhanced for the 2023 beams.
- These structures, are maintained through the LHC cycle, correlated to the pattern of losses during levelling
- At start of collisions, a ~10% net increase in the bunch emittances is observed for the 2023 beams compared to 2022.
- During the cycle (injection + acceleration), a 30% blowup in the emittances is observed with about half of it during the ramp

Summary

- The model is updated for the Run 3 configuration (optics, levelling) and is used to optimization studies. Still work ahead to further improve it and further include beam (compared to bunch)-related effects, and fully tune it to the Run 3 data
- From the results so far, the extra emittance blow-up at injection and top energy is similar with the Run 2 data. Namely, 0.5 μm/h at injection energy and 0.05(0.1) μm/h for H(V) in collisions.
- For the 2023 beams, we observe a substantially higher level of extra losses during collisions, correlated to the changes in conditions during levelling.
- Using the model, we could evaluate the impact of losses (effective cross section) and intensity on the integrated luminosity: reducing by 10mb the extra losses, assuming the same emittance blow up in collisions, results in a gain of ~4% integrated luminosity, comparable to the gain of going from 1.6e11 to 1.7e11 in intensity.
- We want to correlate the extra losses to the increased emittances at soSB – further work is needed to fully quantity this.

Thus, understanding and possibly reducing the losses during collisions is vital to optimally operate LHC for the rest of Run 3, and should go along with the efforts to increase the bunch intensity

Outlook

- **The emittances at soSB have two components:**
  1. The injected emittances to LHC
  2. The emittance blow-up in the ramp.
- **For the first, we propose for 2024 a comparative test is done between the BCMS and STANDARD type beams**
  - Most likely hybrid filling schemes need to be maintained so we should test both in same conditions
  - **Tests of few (2-3 fills) with both configurations and stable beam conditions in LHC and injectors**
    - Should be transparent for the experiments
    - This implies work to commission both schemes in the injectors but the potential gain in integrated luminosity will pay well the effort
- **For the second, we could further investigate with MDs and profit from the new BSRT fills**

Begin at the beginning," the King said, very gravely, "and go on till you come to the end: then stop

Alice – Lewis Carroll

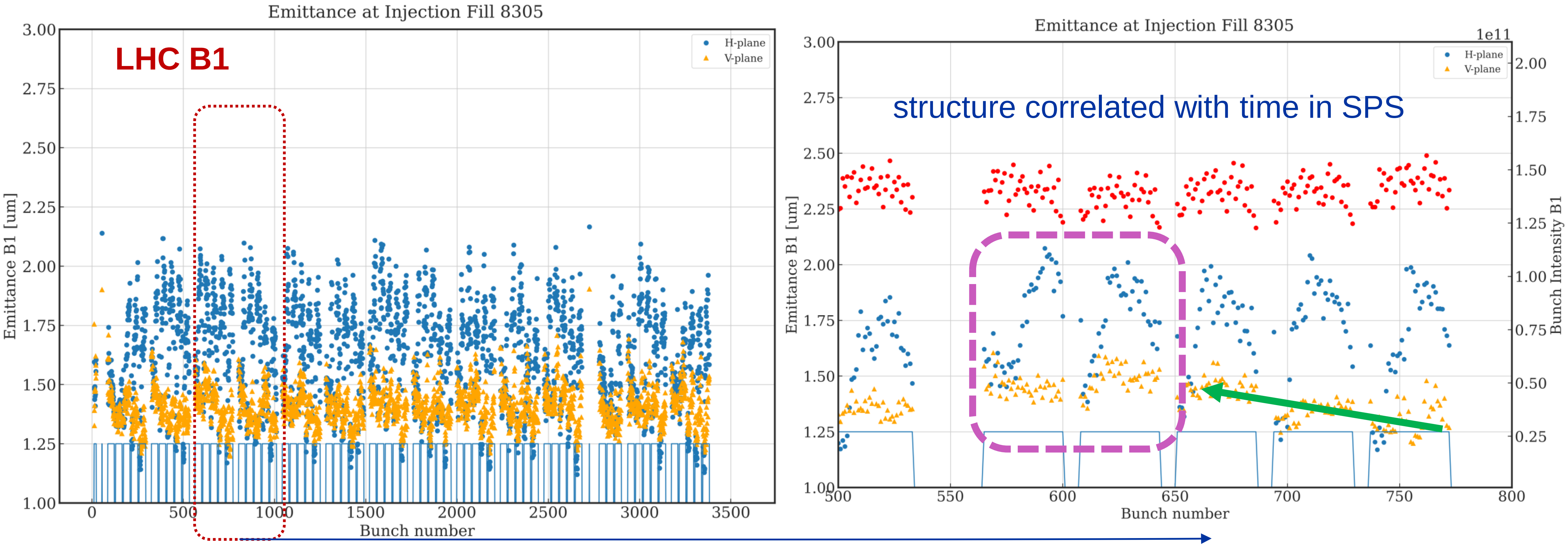
Thank you!

Backup slides

Emittance @ Injection
Example 2022 fill

Observations:

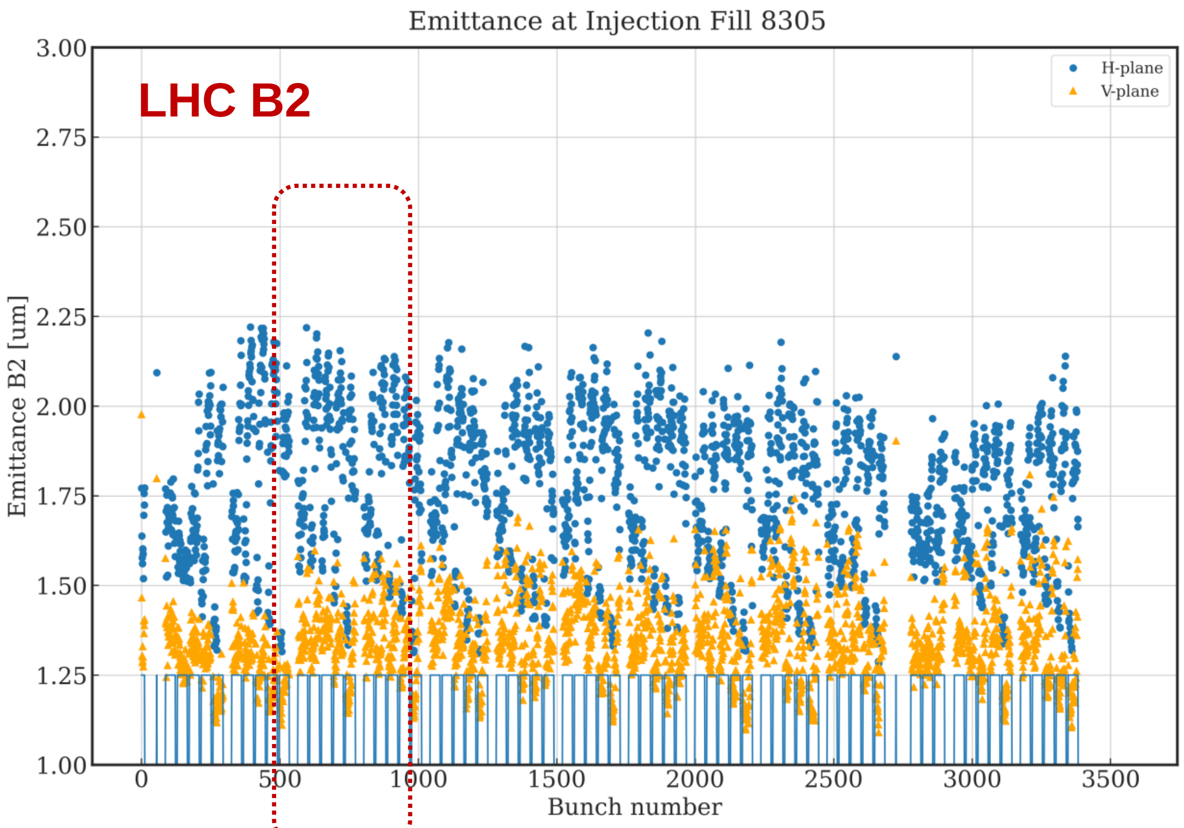
structure correlated with time in SPS – an Λ-shape, most likely due to e-cloud within the train

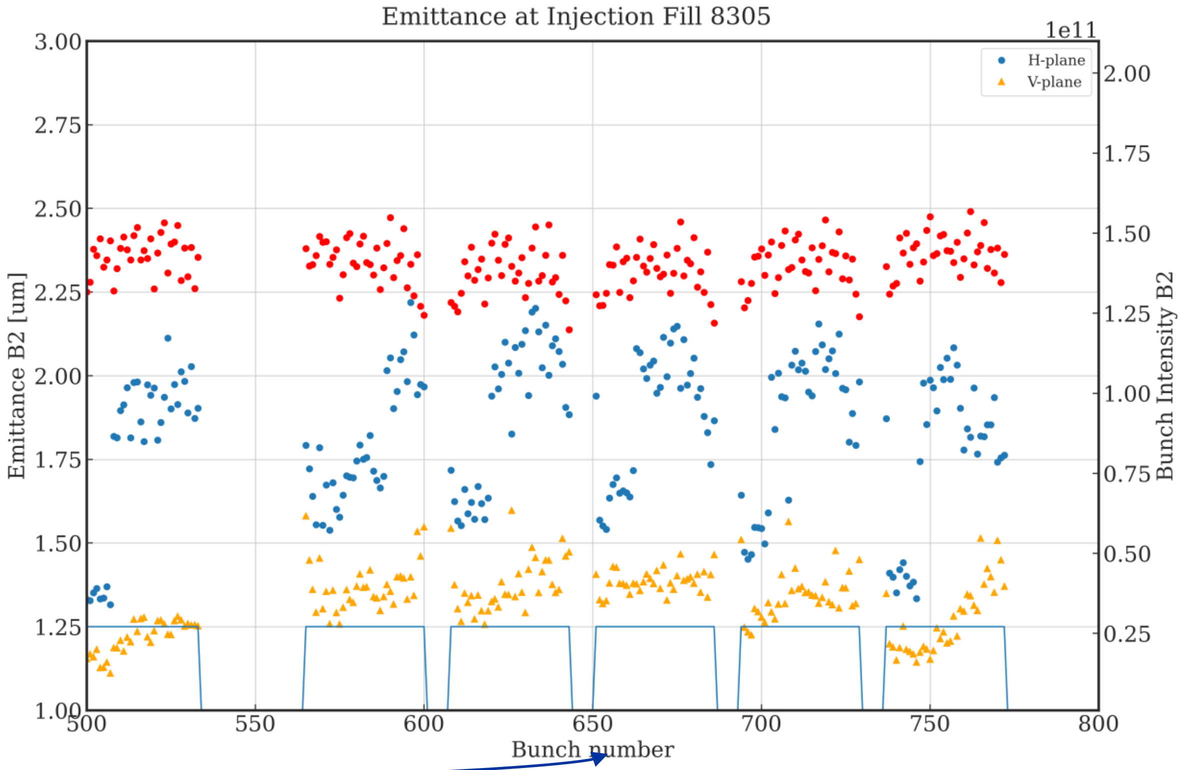


Emittance @ injection

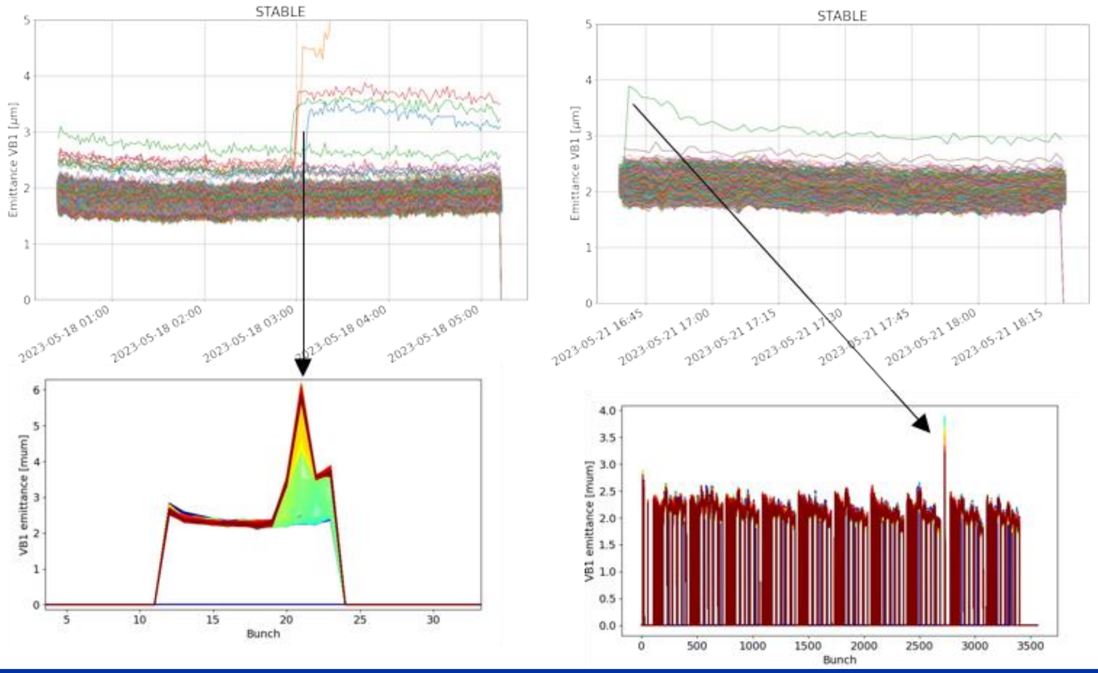
Example 2022 fill

Observations: H-plane worse than vertical, small trend with number of injections





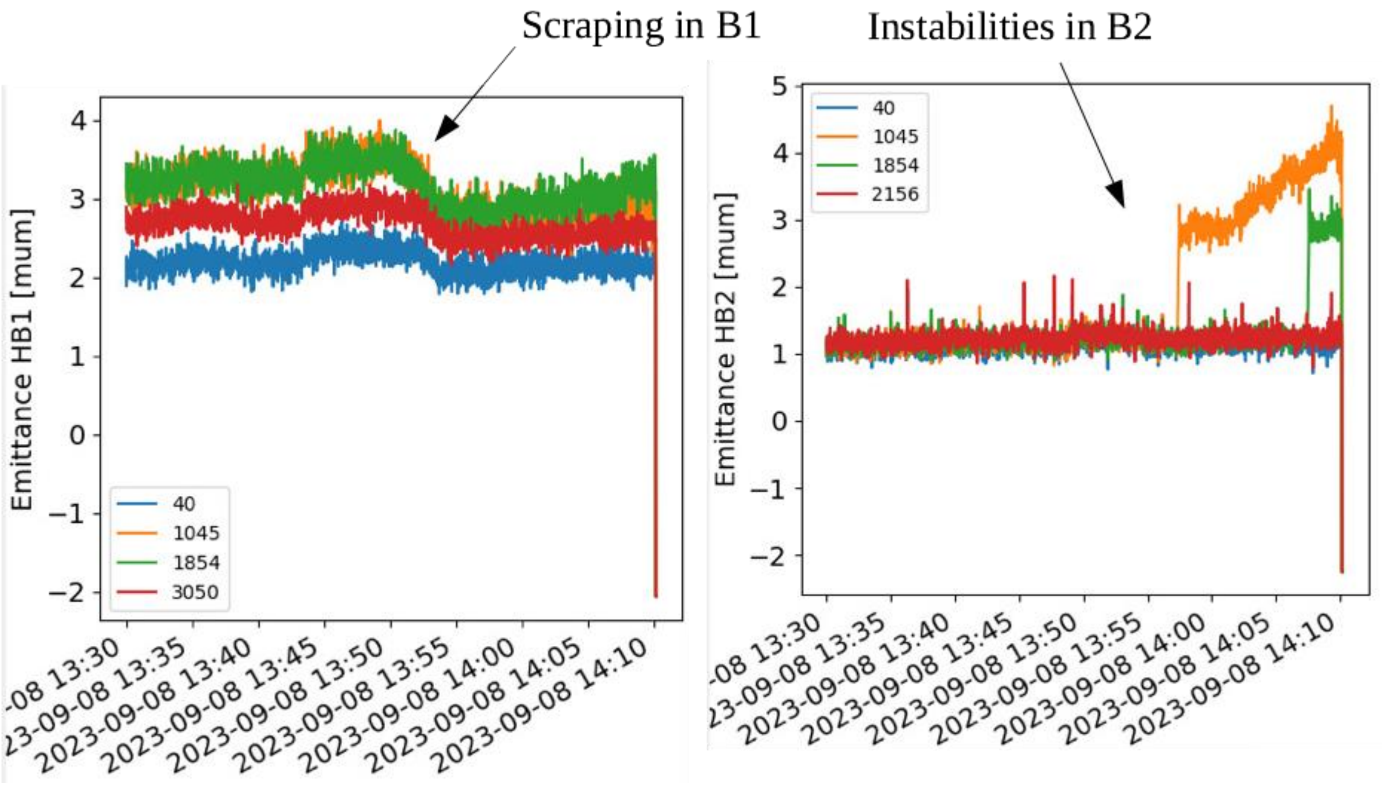
Instability of witness bunches



- **Few witness bunches became unstable during STABLE BEAM, no clear correlation with the optics, e-cloud or beam-beam**
    - Important to note that we operate with 395 A in the octupoles, whereas in MD (fast octupole scan) the threshold is only 50 A

Fill	Plane	beam	β*[cm]	Bunches	LR IP1 / 5	HO* IP2	LR IP2	HO* IP8	LR IP8
8784	V	1	45	Few last of 12b	~8	1	~31	0	~12
8786	V	1	45	Few last of 12b	~8	1	~31	0	~12
8807	V	1	120	INDIV	1	1	0	1	27
8850	V	1	100	Few first of 12b	12	0	24	1	~32
8850	V	2	64	Few first of 12b	~8	1	27	1	~20
8858	V	1	33	Few last of 12b	~8	1	~25	0	0

Instabilities during high beta run



- **Instabilities were observed during the high beta run, though the beams were colliding**
- **→ Possible explanation: Larger beam size and cut tails tend to 'linearise' the head-on beam-beam force, thus reducing Landau damping**
- **→Instabilities no longer observed once B1 quality was restored (to the level of B2)**