Bunch-by-bunch tune shift studies for LHC type beams in the CERN SPS

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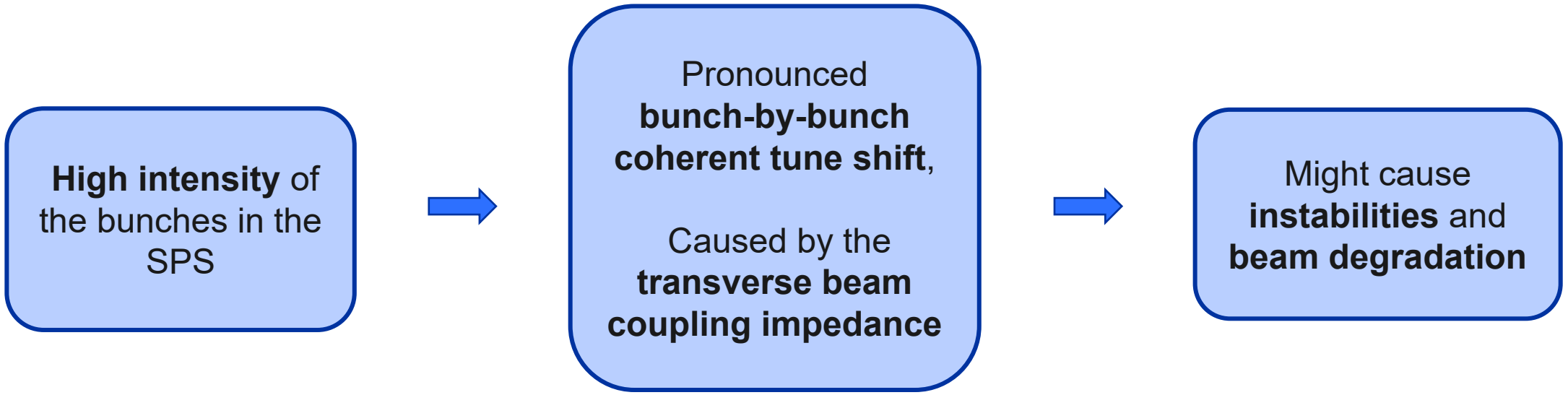
Outline

- INTRODUCTION
- METHODOLOGY OF MEASUREMENTS
- RESULTS FROM MEASUREMENTS AND SIMULATIONS BENCHMARKING
- REMARKABLE OBSERVATIONS
- CONCLUSIONS

MOTIVATION OF THE STUDIES

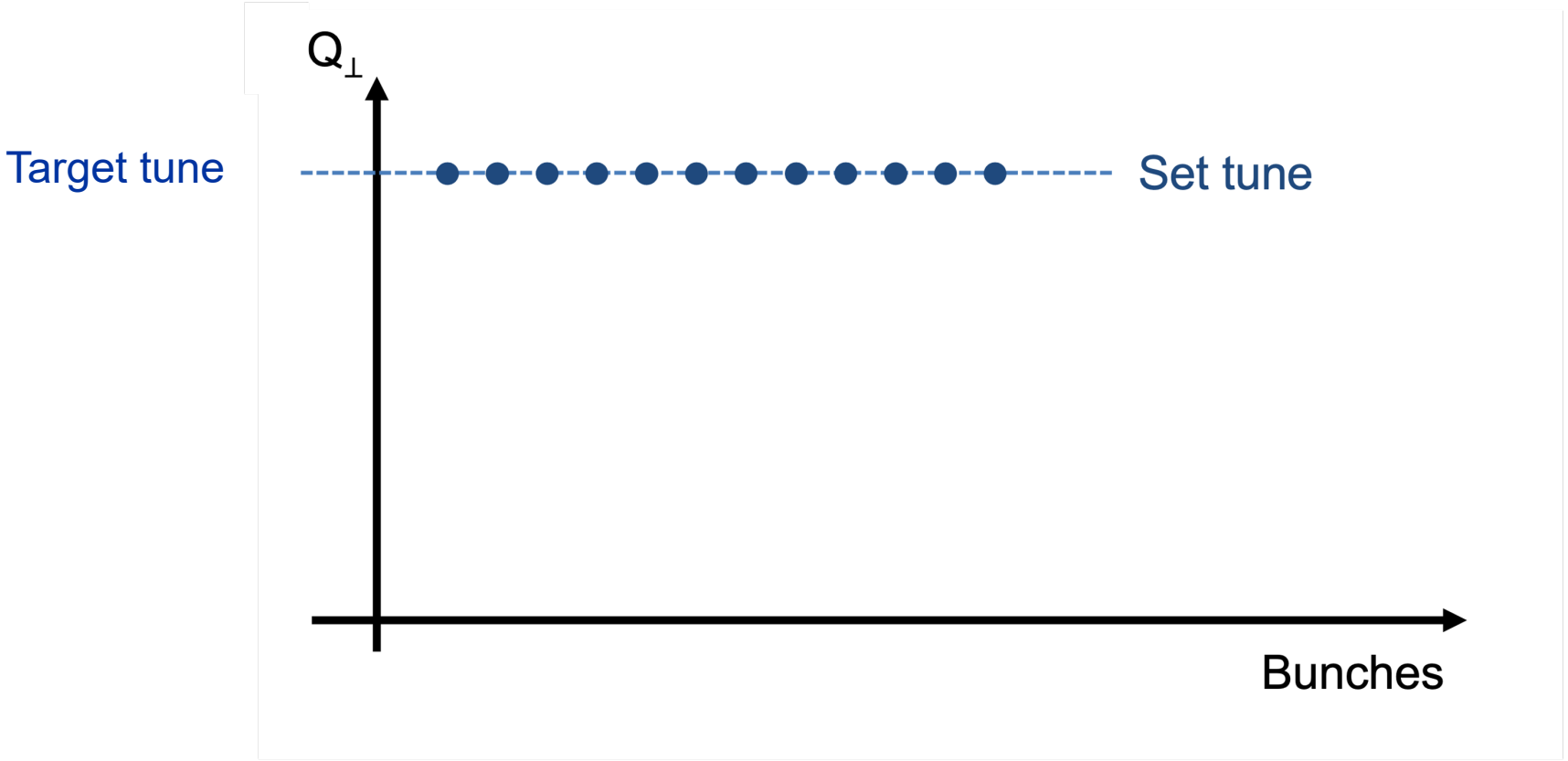
Before the **LHC Injectors Upgrade** (LIU) the SPS was able to deliver LHC-type beams (25 ns bunch spacing) with a maximum intensity of **1.15e11 p/b**.

The **goal** after LIU is to **double the intensity** delivered to the LHC: **2.3e11 p/b**.



INTRODUCTION: Multi-bunch impedance tune shift in the SPS

Vertical plane



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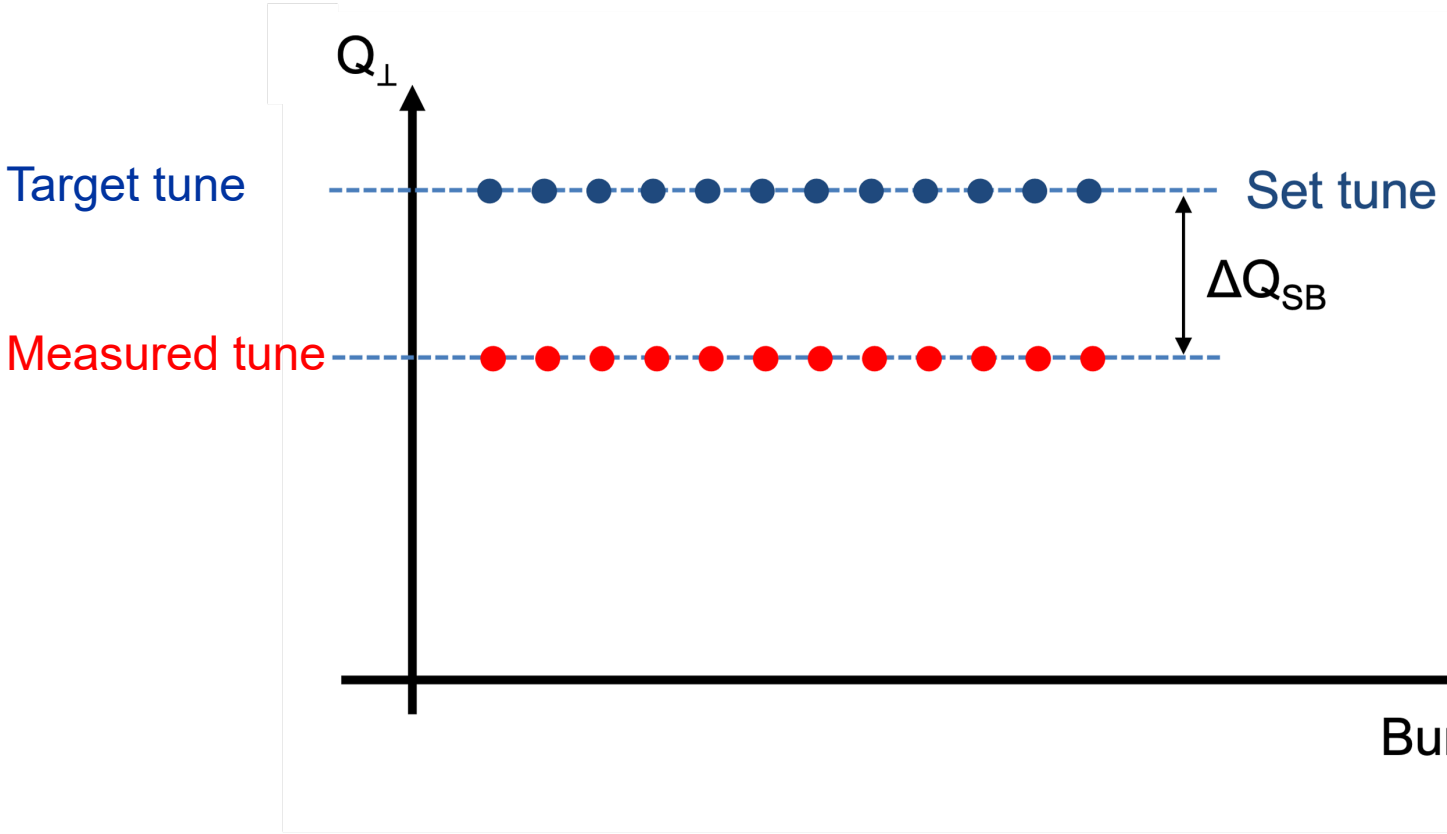
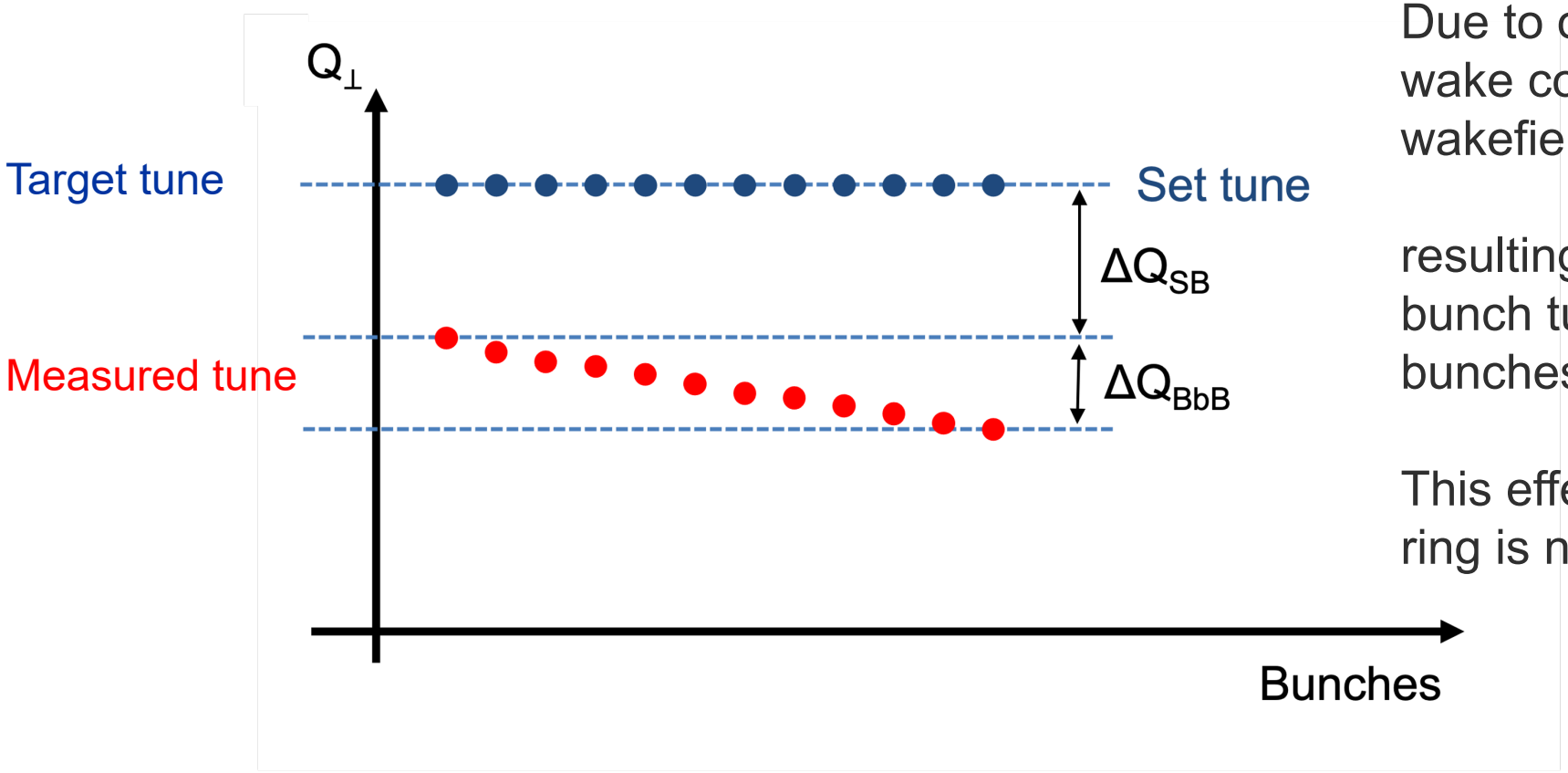


Single bunch tune shift (ΔQ_{SB}):
Some impedance sources result in tune shift already for single bunches.

Wake vanishes over the bunch spacing
(no coupling between bunches).

INTRODUCTION: Multi-bunch impedance tune shift in the SPS

Vertical plane



Single bunch tune shift (ΔQ_{SB})

Bunch-by-bunch tune shift (ΔQ_{BbB}):

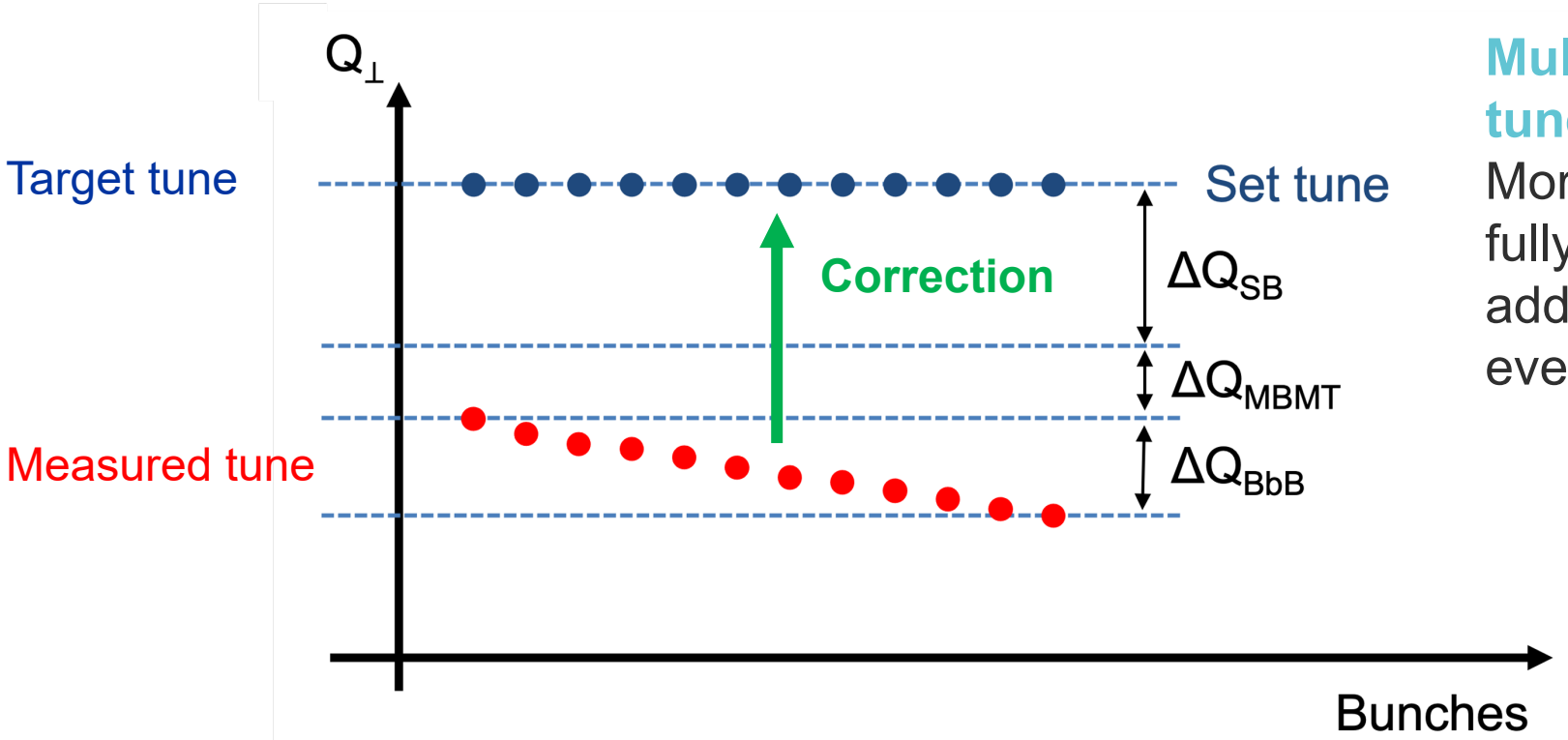
Due to other impedance sources, wake couples over all bunches and wakefield builds up along the train,

resulting in an increasing bunch-by-bunch tune shift for the trailing bunches.

This effect is visible in the SPS as the ring is not full of bunches.

INTRODUCTION: Multi-bunch impedance tune shift in the SPS

Vertical plane



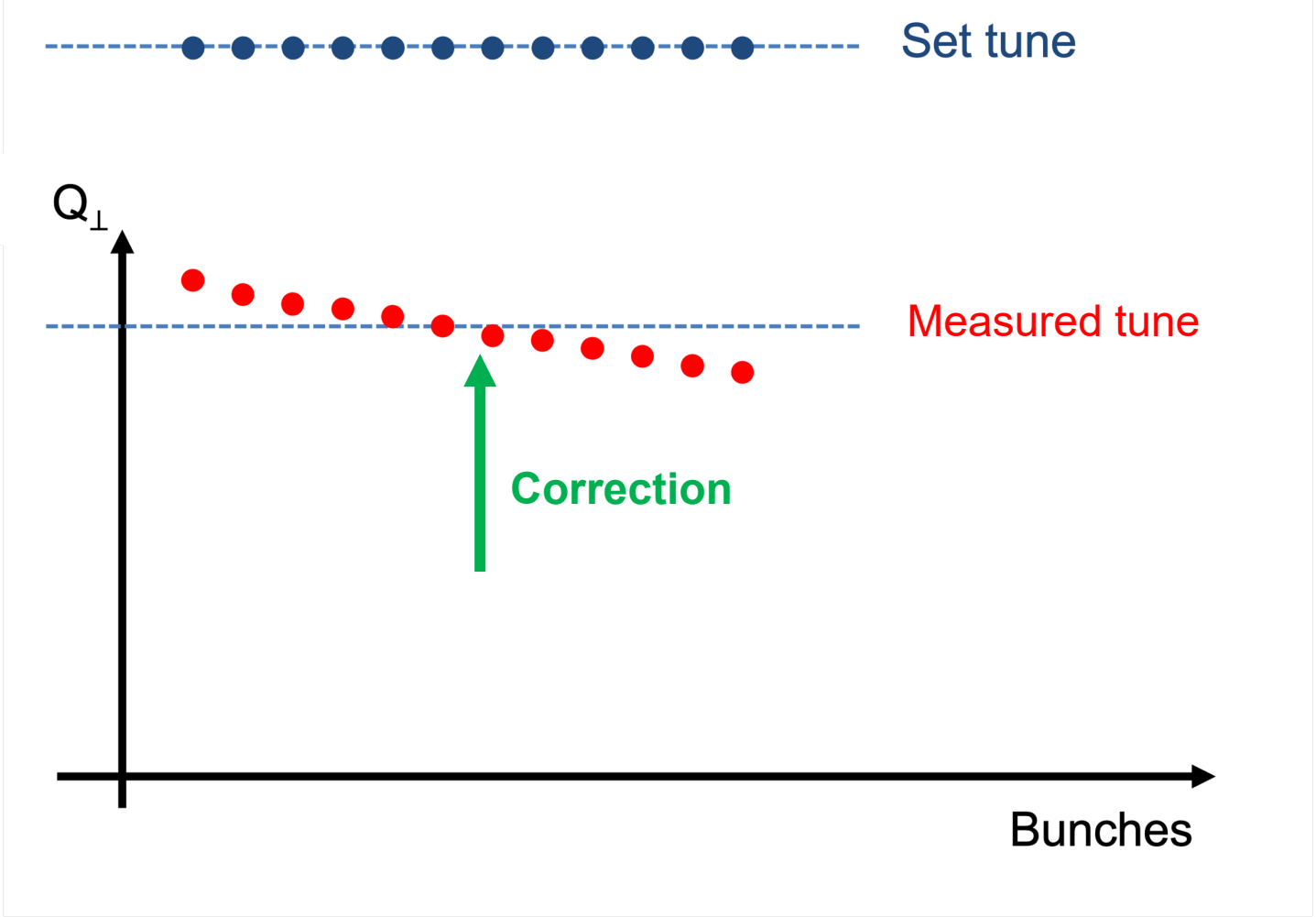
Single bunch tune shift (ΔQ_{SB})

Bunch-by-bunch tune shift (ΔQ_{BbB})

Multi-bunch multi-turn tune shift (ΔQ_{MBMT}):
Moreover, if the wakefield does not fully decay within one turn, an additional tune shift is experienced even by the first bunches of the train.

Tune shift depends on :
- **Bunch intensity**
- **Total intensity**
- **Separation between bunches and trains of bunches**

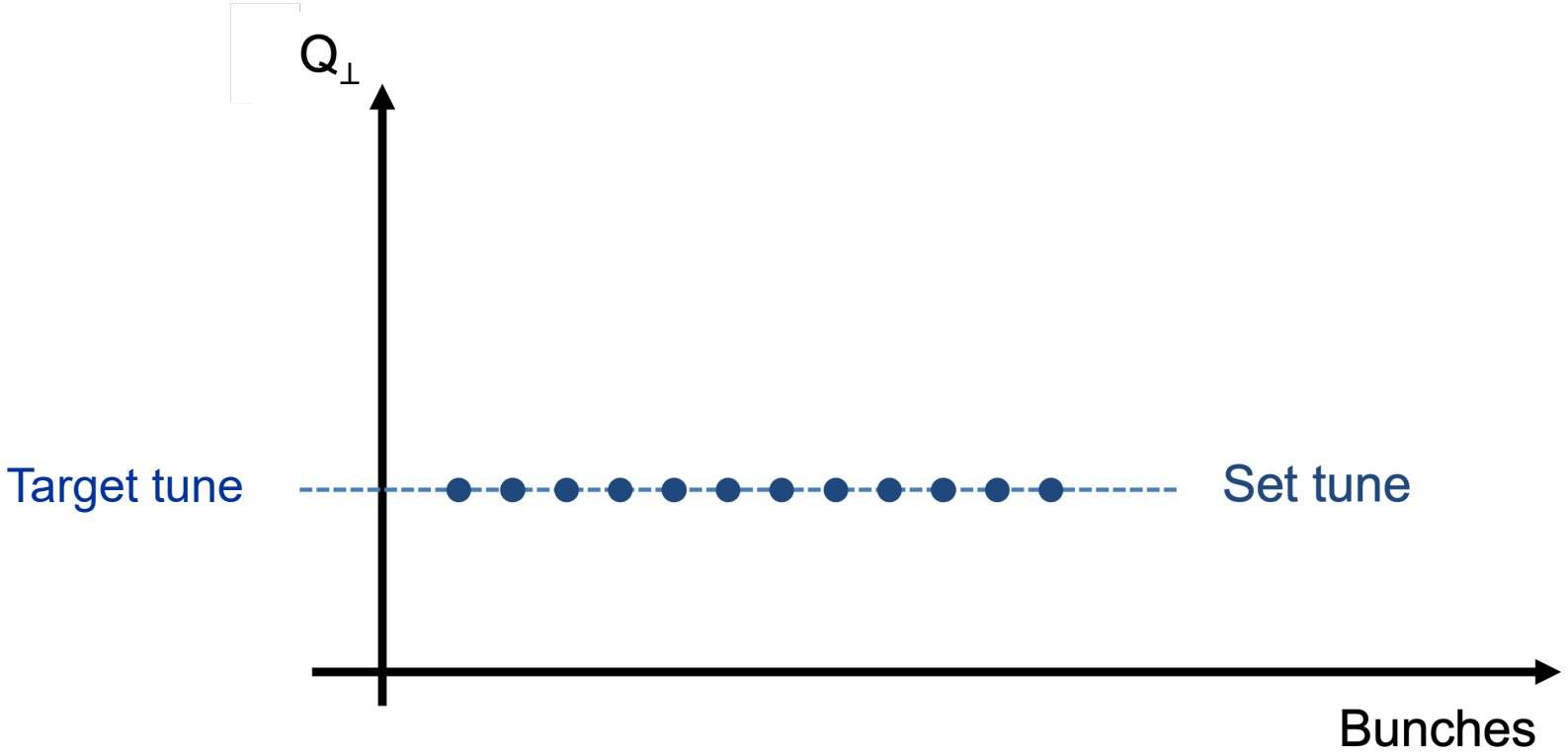
INTRODUCTION: Multi-bunch impedance tune shift in the SPS



Correction of the **coherent** tune shift

INTRODUCTION: Multi-bunch impedance tune shift in the SPS

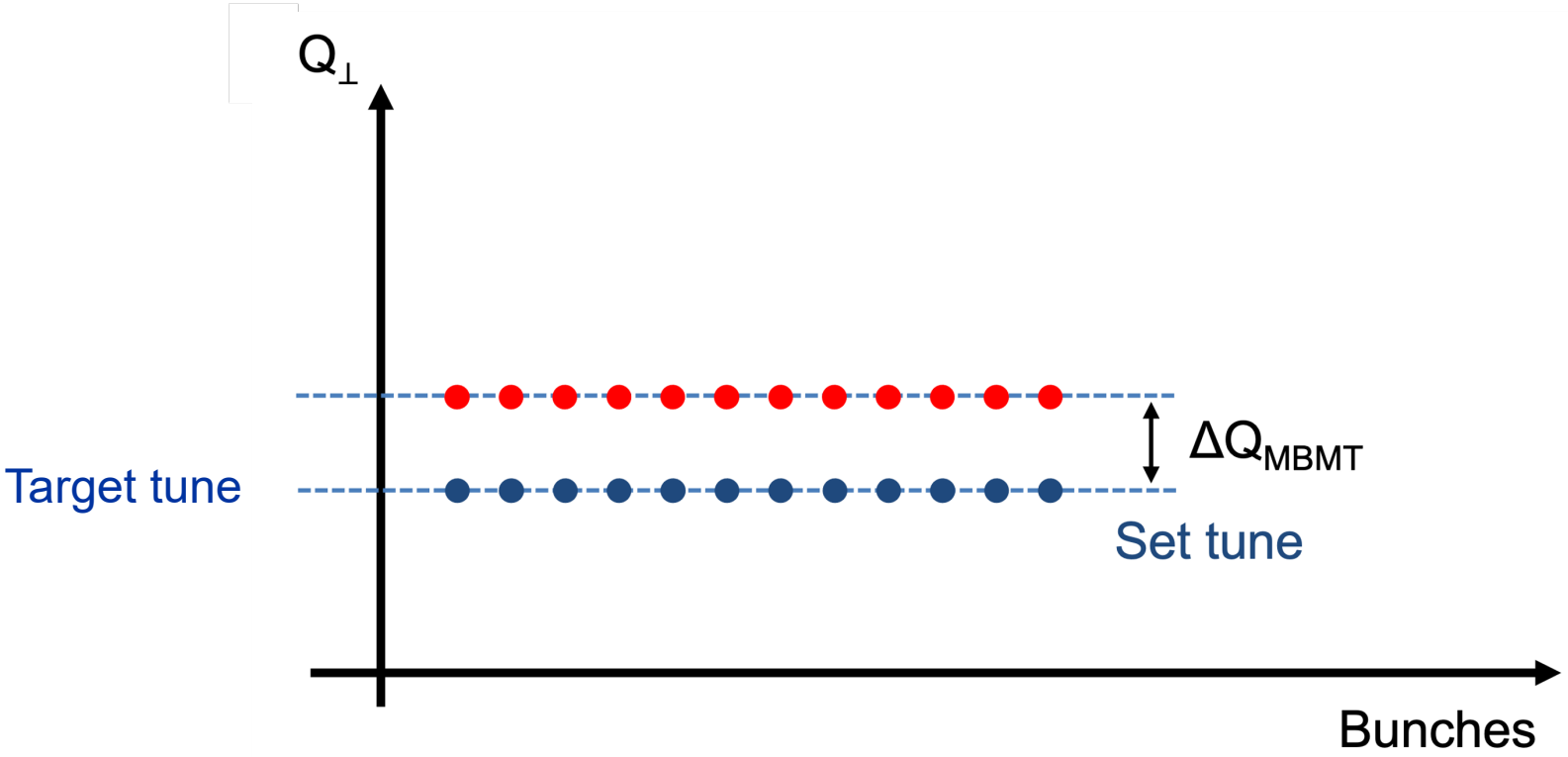
Horizontal plane



Horizontal and vertical impedances are different in the SPS, resulting in **different bunch-by-bunch tune shifts in the transverse planes**:

INTRODUCTION: Multi-bunch impedance tune shift in the SPS

Horizontal plane



Horizontal and vertical impedances are different in the SPS, resulting in **different bunch-by-bunch tune shifts in the transverse planes**:

$$\Delta Q_{SB,\,hor} \sim 0$$

$$\Delta Q_{BbB,\,hor} \sim 0$$

INTRODUCTION: Multi-bunch impedance tune shift in the SPS

- **Tune shift from impedance** is larger at **higher intensities.**
- At **injection**, the proton beam is sensitive to instabilities,
  so, tunes must be **measured** and **corrected** to the **nominal values** (central tunes programmed for the transverse damper) to **ensure beam stability and quality**.

Measuring the tune shift
at high intensities
(> 2.0e11 p/b)
is **not transparent**

Goal: to build a **model** describing the
tune shift experienced by each train injected in the SPS
as function of beam configuration.

Dedicated measurements and simulations

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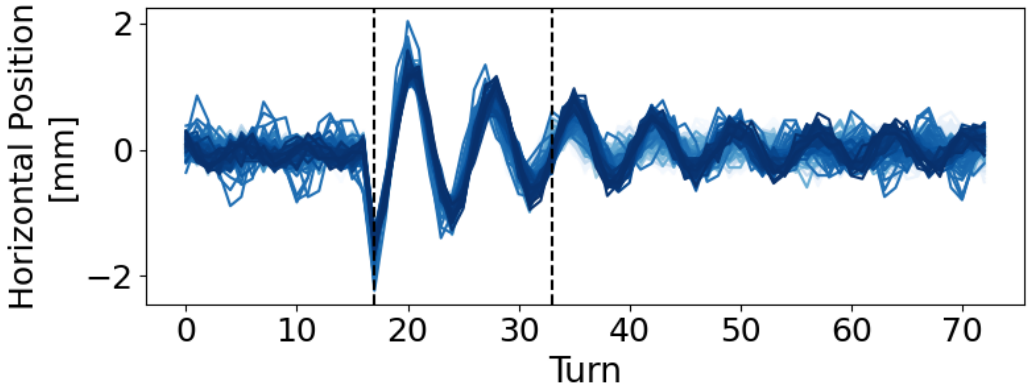
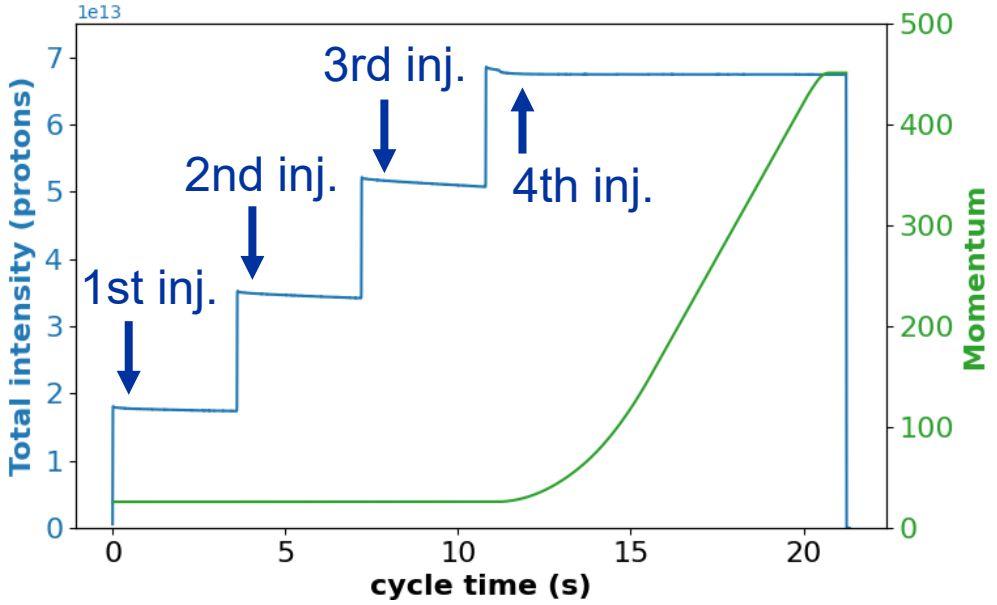
MEASUREMENTS METHODOLOGY

Bunch-by-bunch tunes are computed by means of refined Fourier analysis of the transverse position of the beam

1. Acquisiton of the turn-by-turn positions for each bunch with the LHC type BPMs in the SPS.
2. A kick needs to be applied in both planes to enhance the oscillations.
3. The kick is applied some miliseconds after injection (far from injection oscillations).
4. Transverse damper gain is set to zero for the first 2 ms after the kick (to obtain cleaner turn-by-turn position data).





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PyHEADTAIL simulations

Multi-bunch impedance induced tune shifts have been simulated with PyHEADTAIL (a macro-particle tracking code for simulating beam dynamics with collective effects).

SPS impedance model:
- **Resistive wall**
- **Kickers**
- **Transitions**

Multi-turn wake fields

Non-linear chromaticity and non-linear synchrotron motion

No electron cloud in these simulations

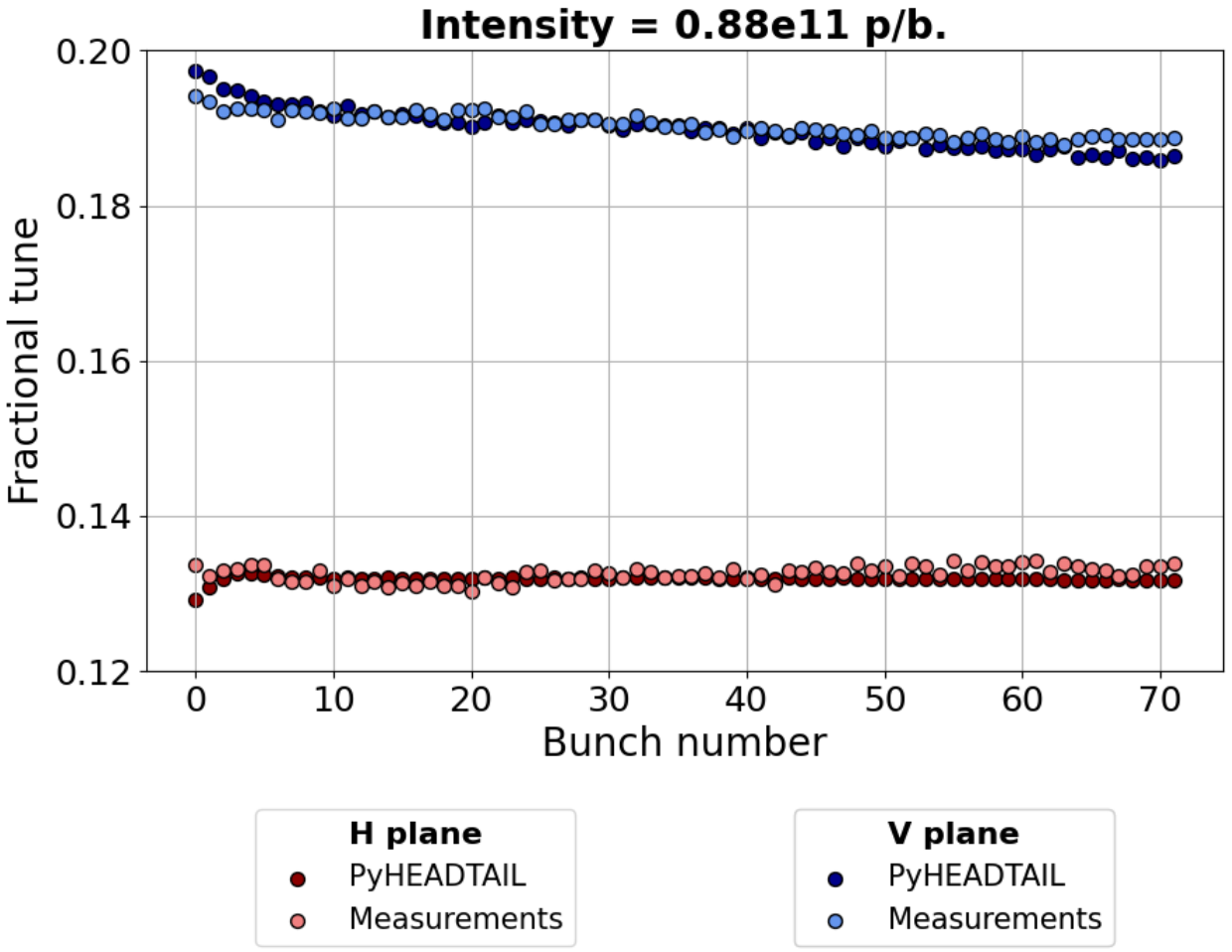
COMPARISON MEASUREMENTS AND SIMULATIONS

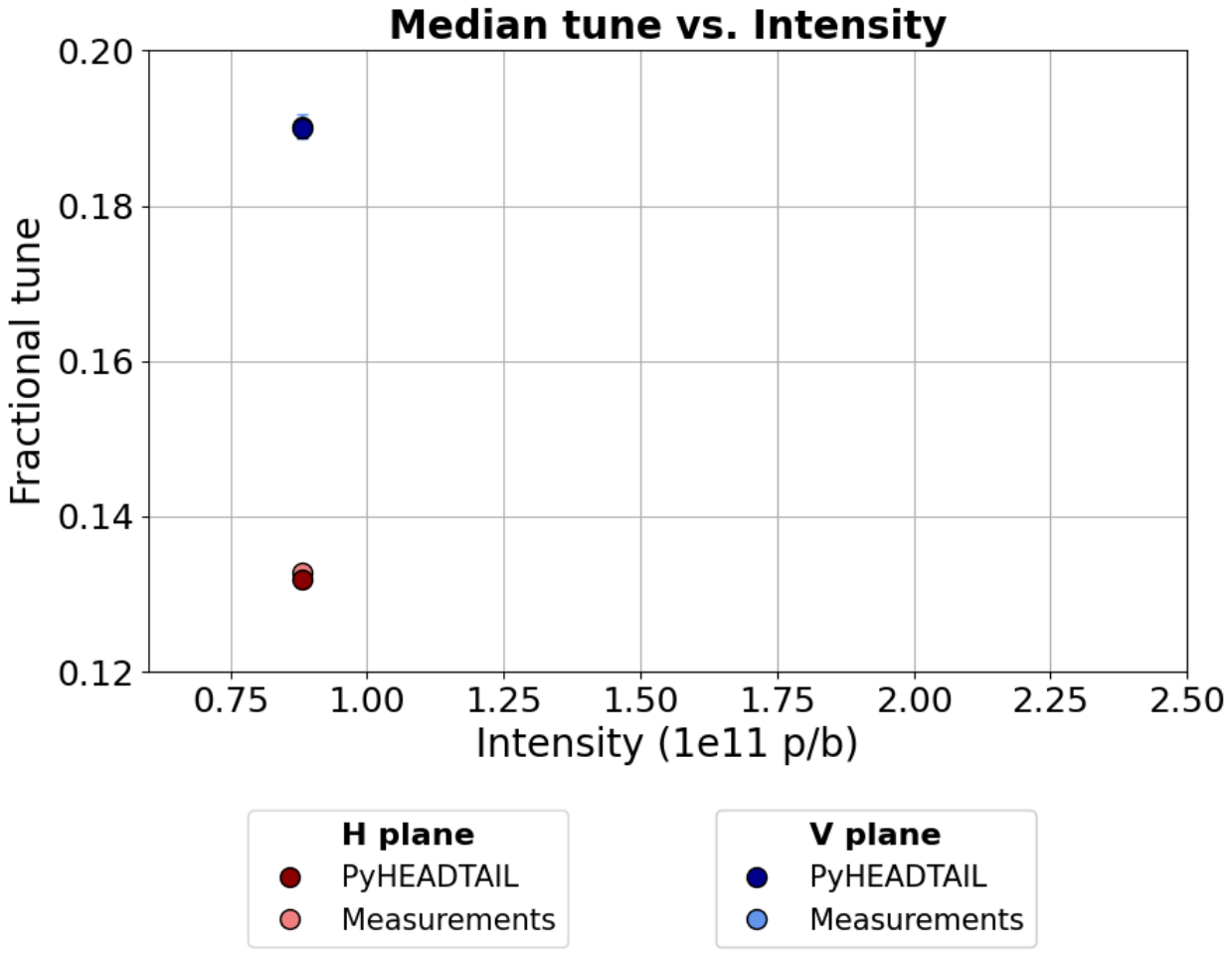
Measuring tune shift with intensity

- **1 x 72 bunches**
- **Intensity scan** from **0.88e11 p/b** to **2.32e11 p/b** (in steps of ~0.2e11 p/b)
- **Set the tunes at low intensity and then they were not changed during the intensity scan:**
  No corrections, just measuring tune shift with intensity.

COMPARISON MEASUREMENTS AND SIMULATIONS

Measuring tune shift with intensity (1x72 bunches)





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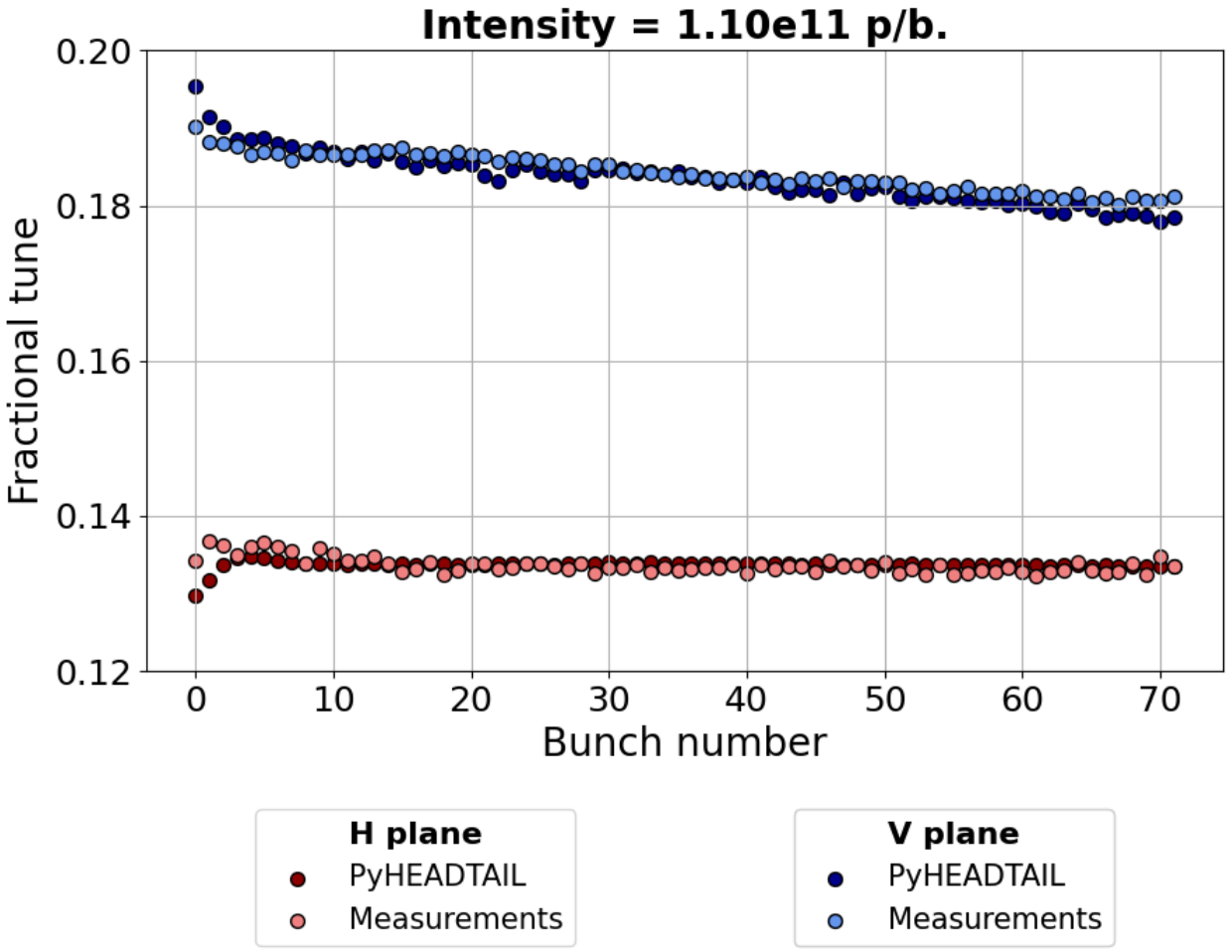

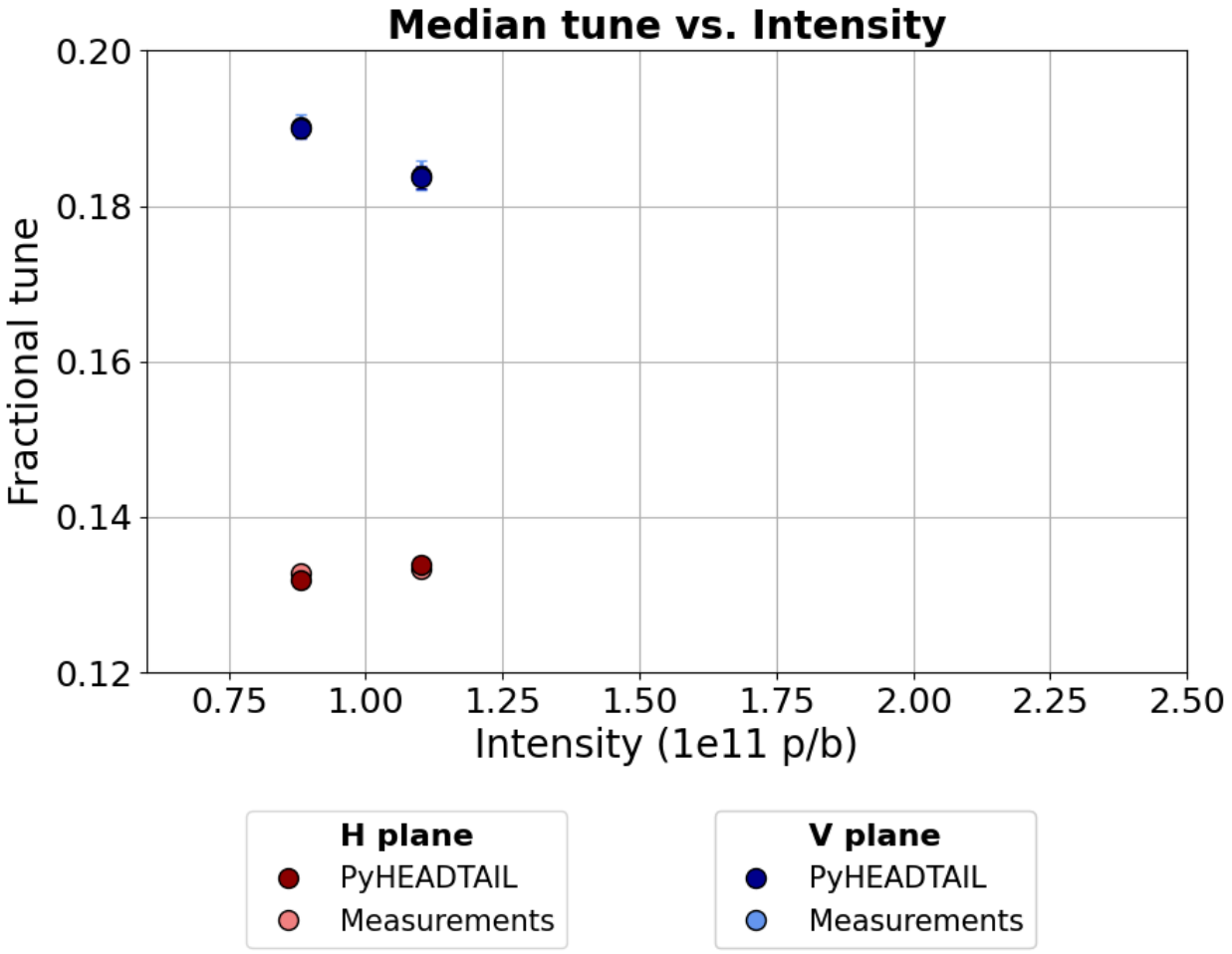

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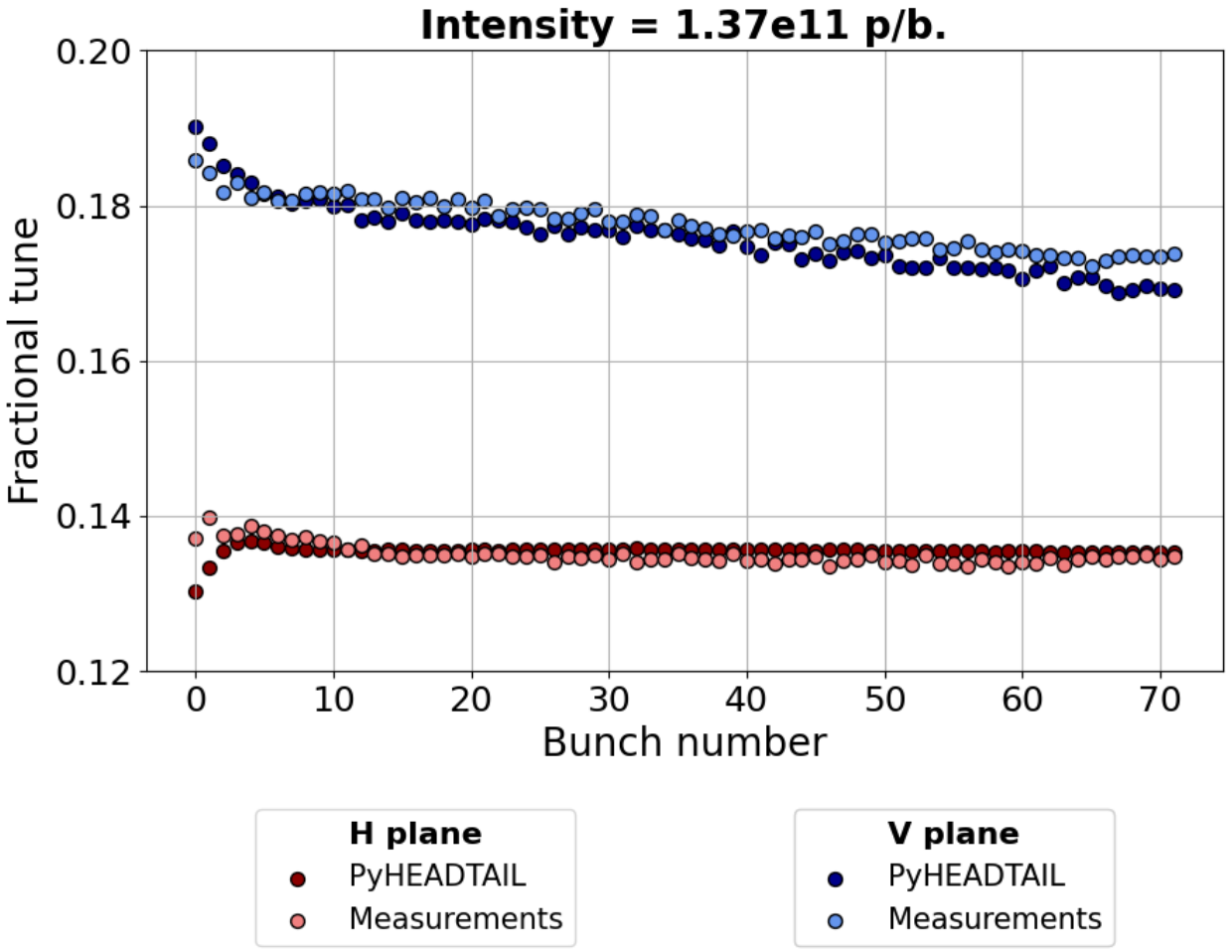

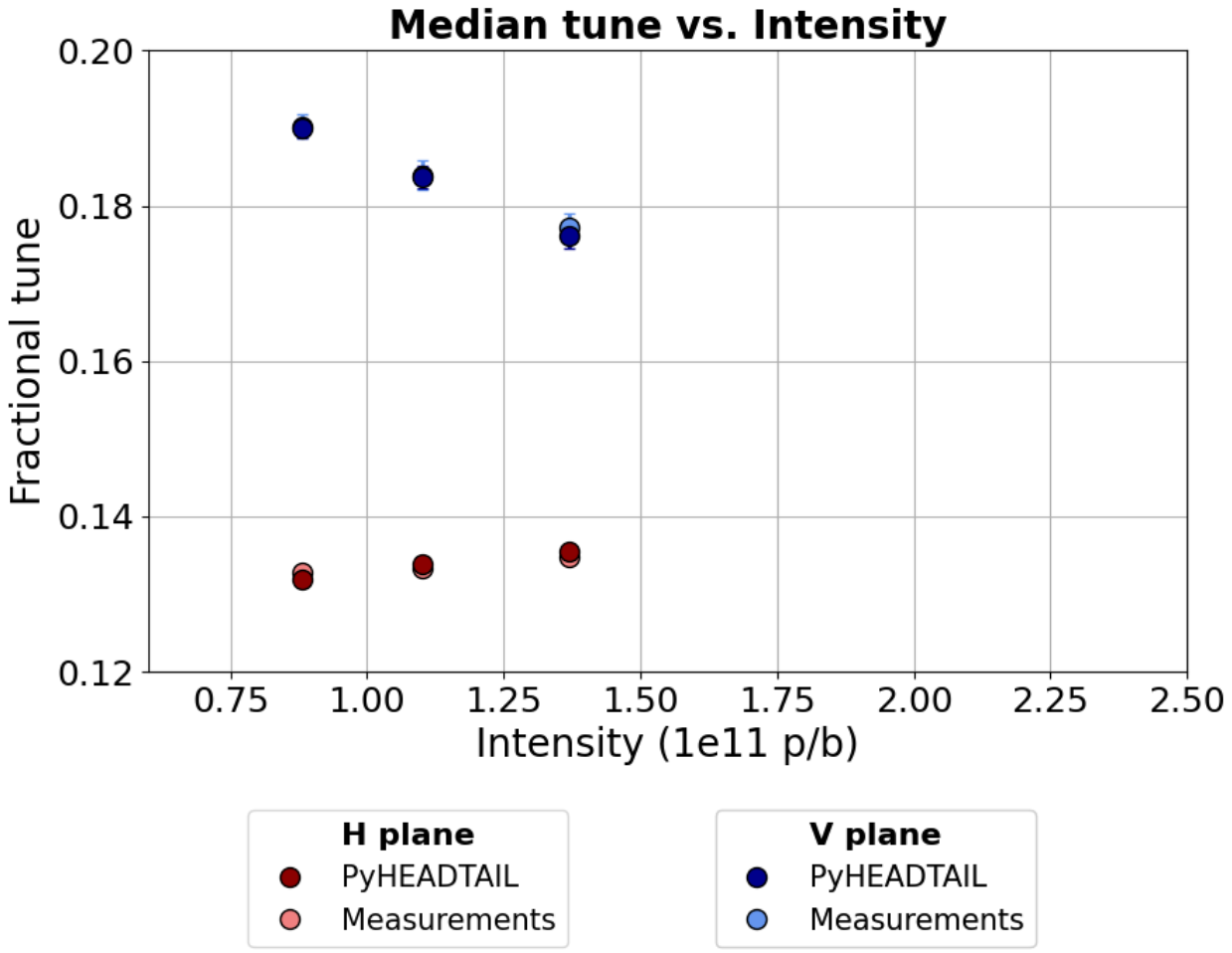

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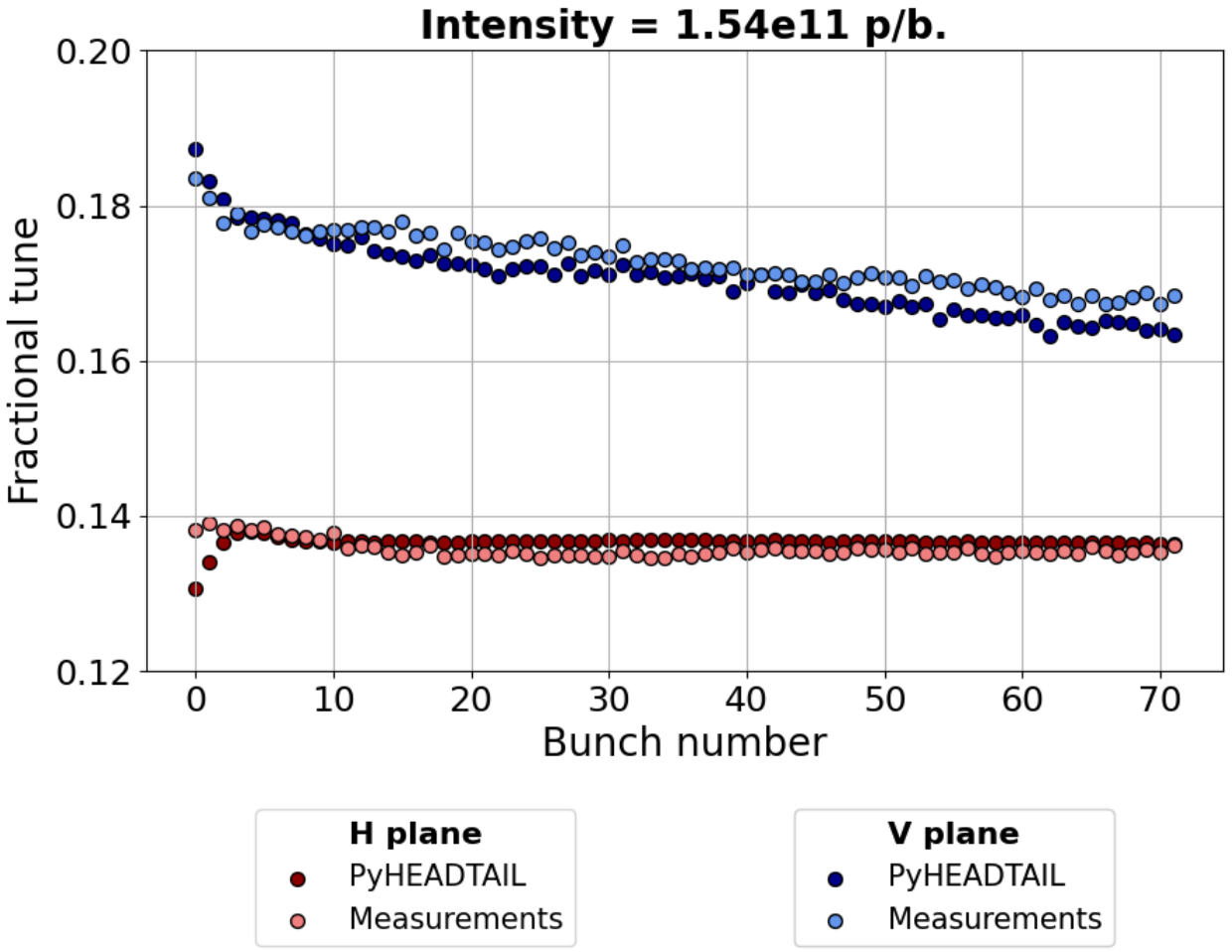

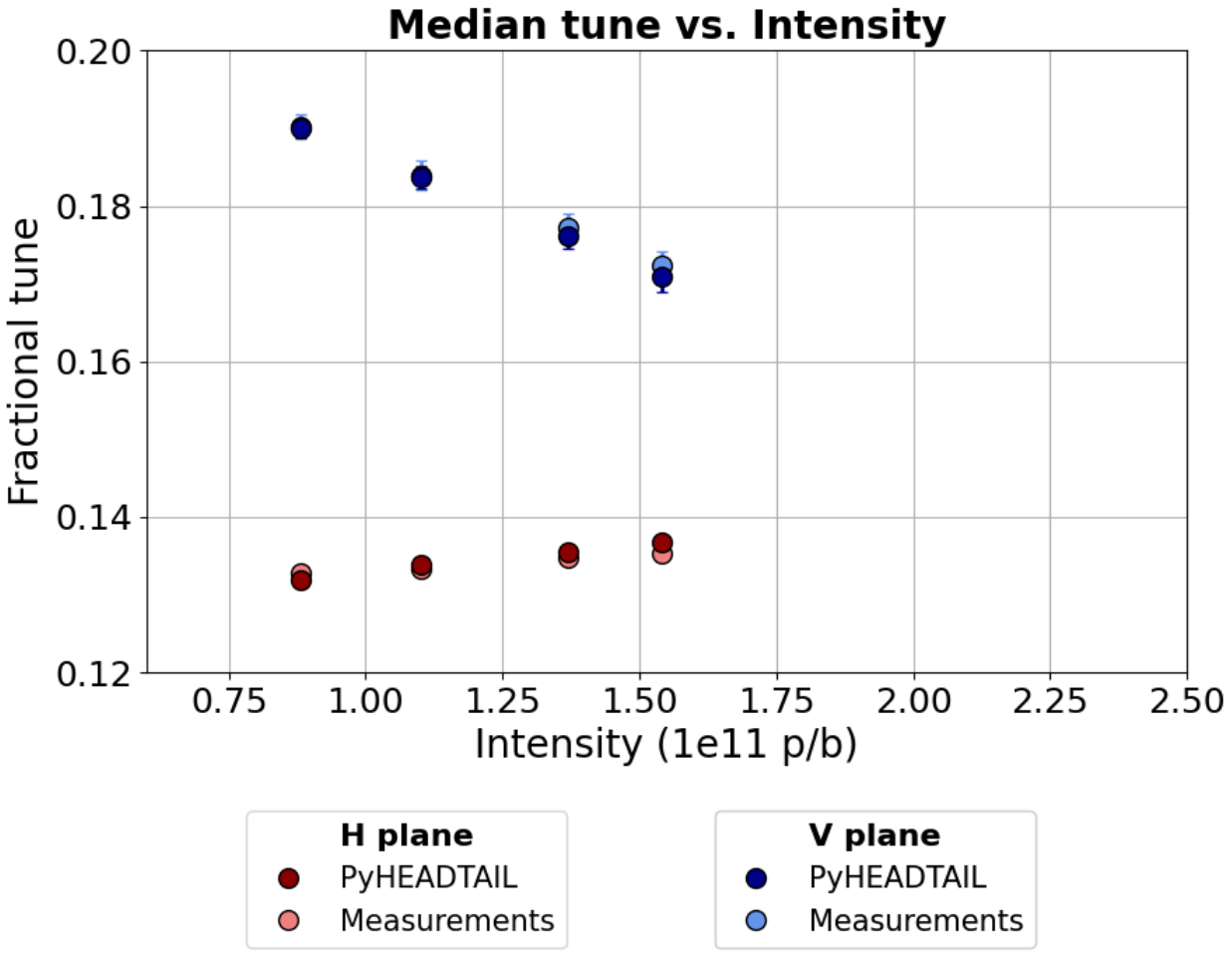

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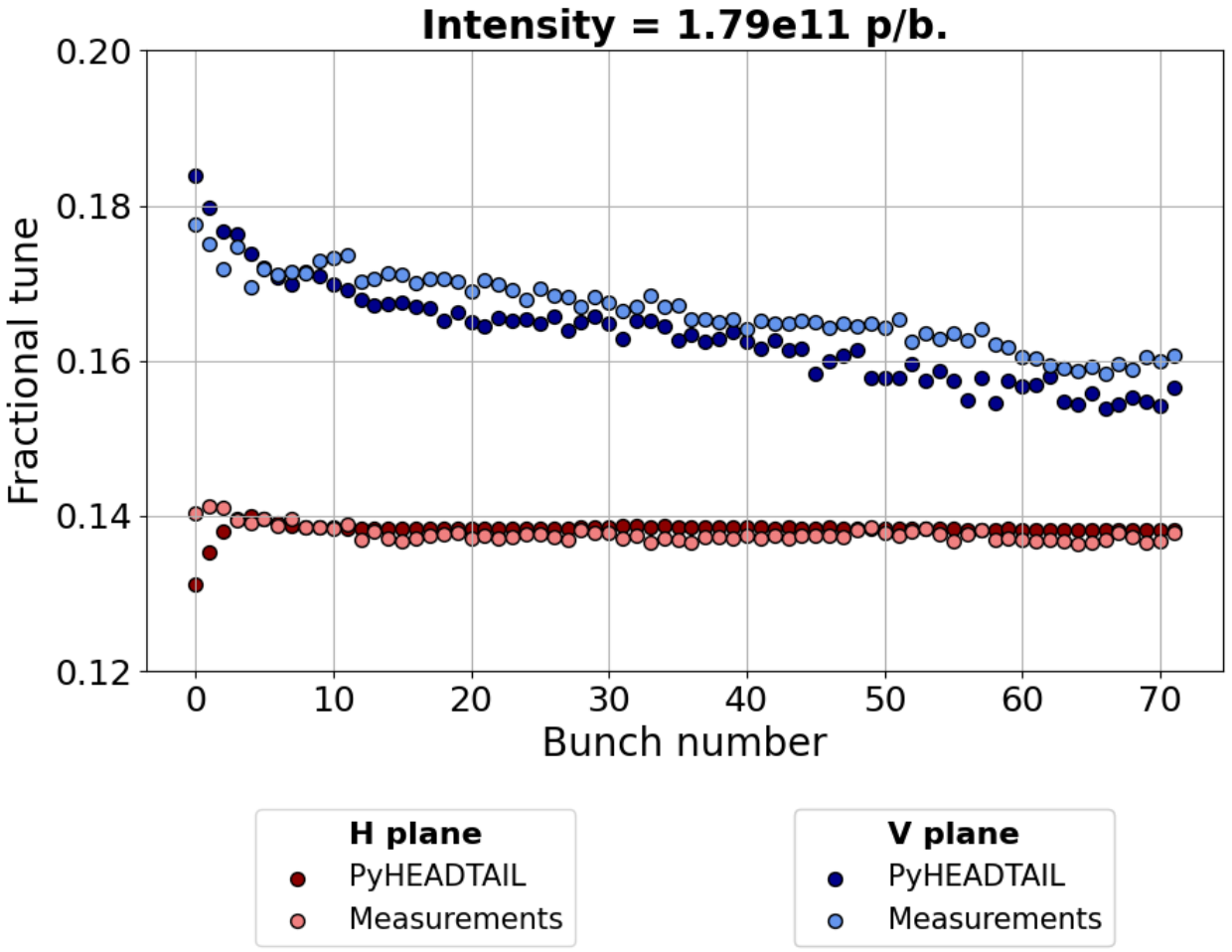

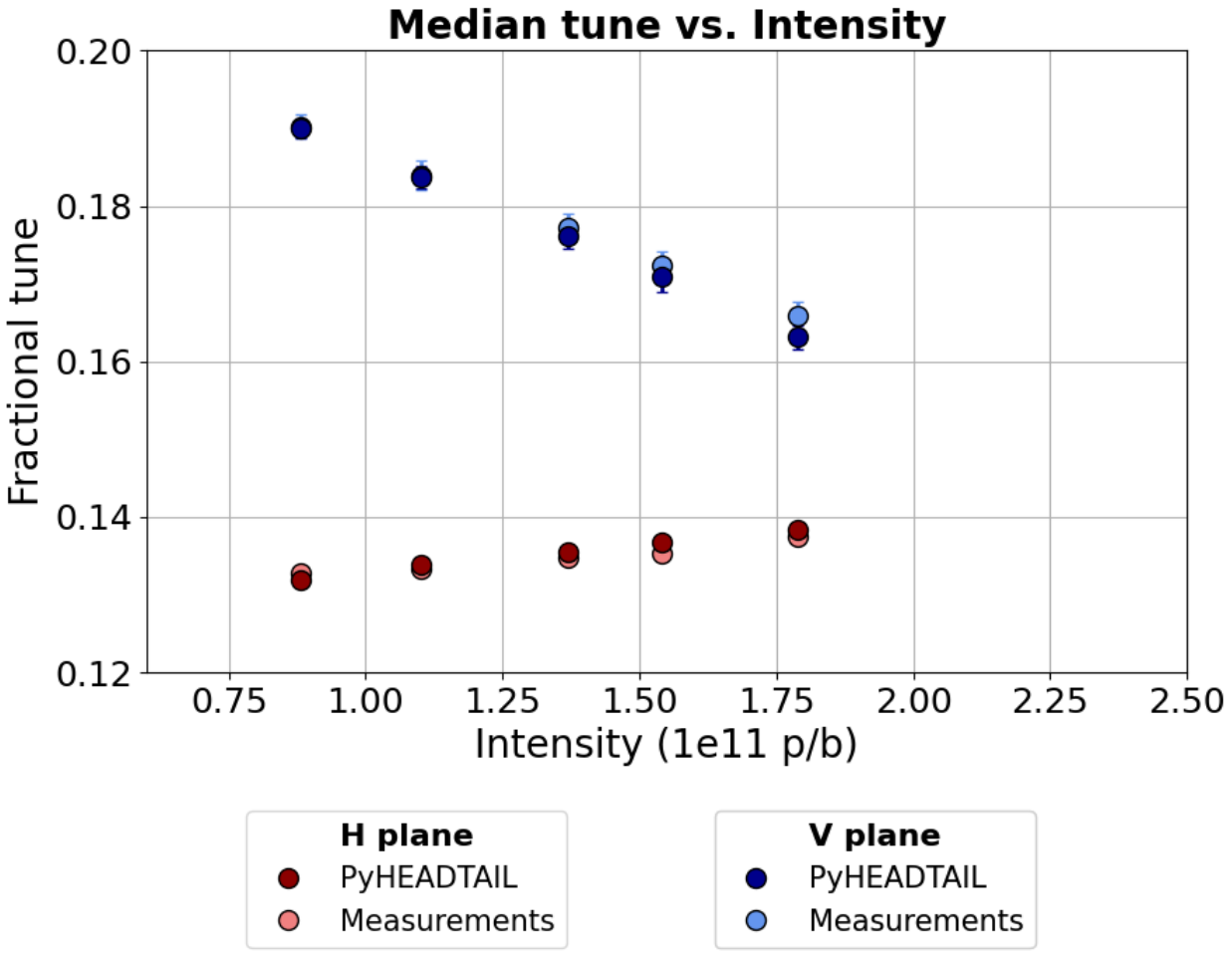

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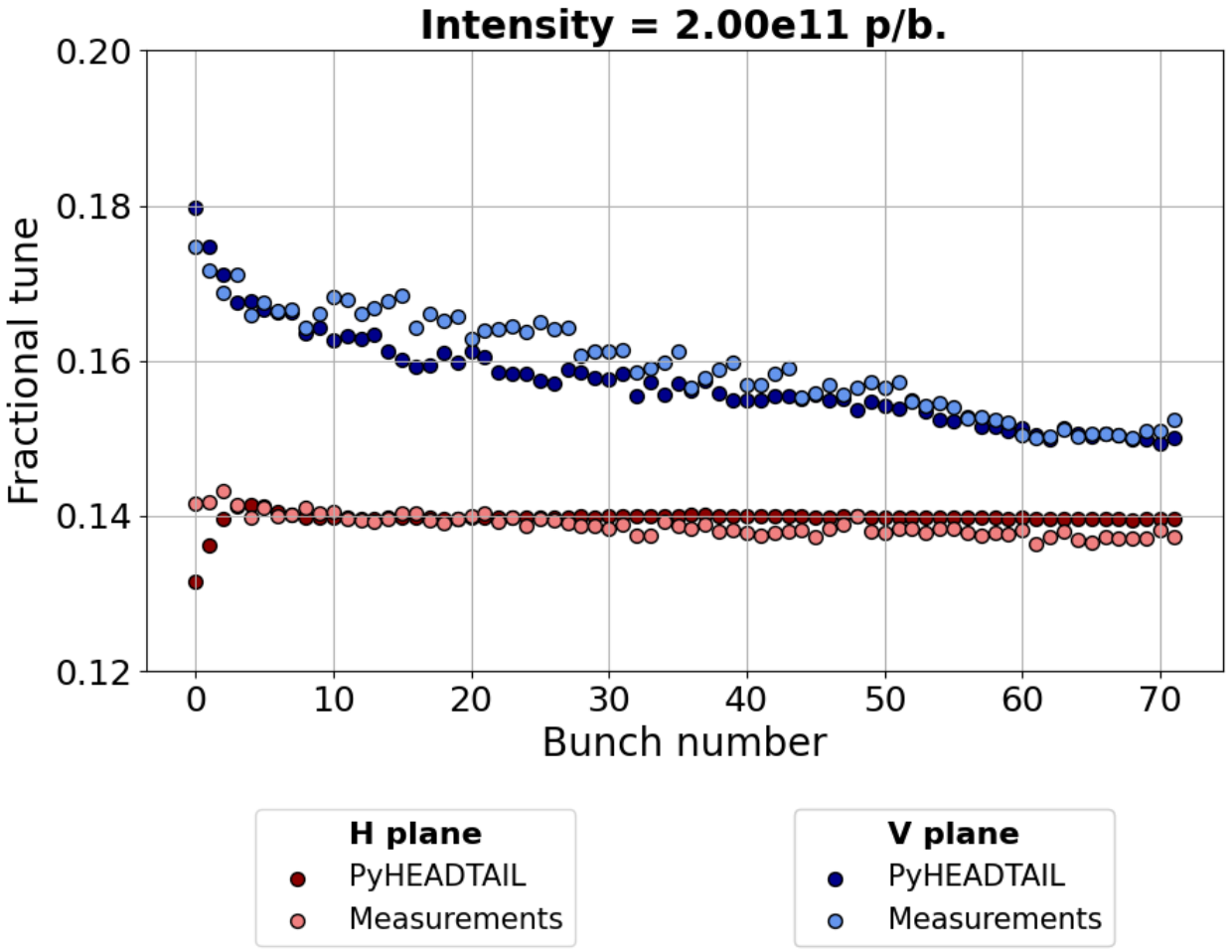

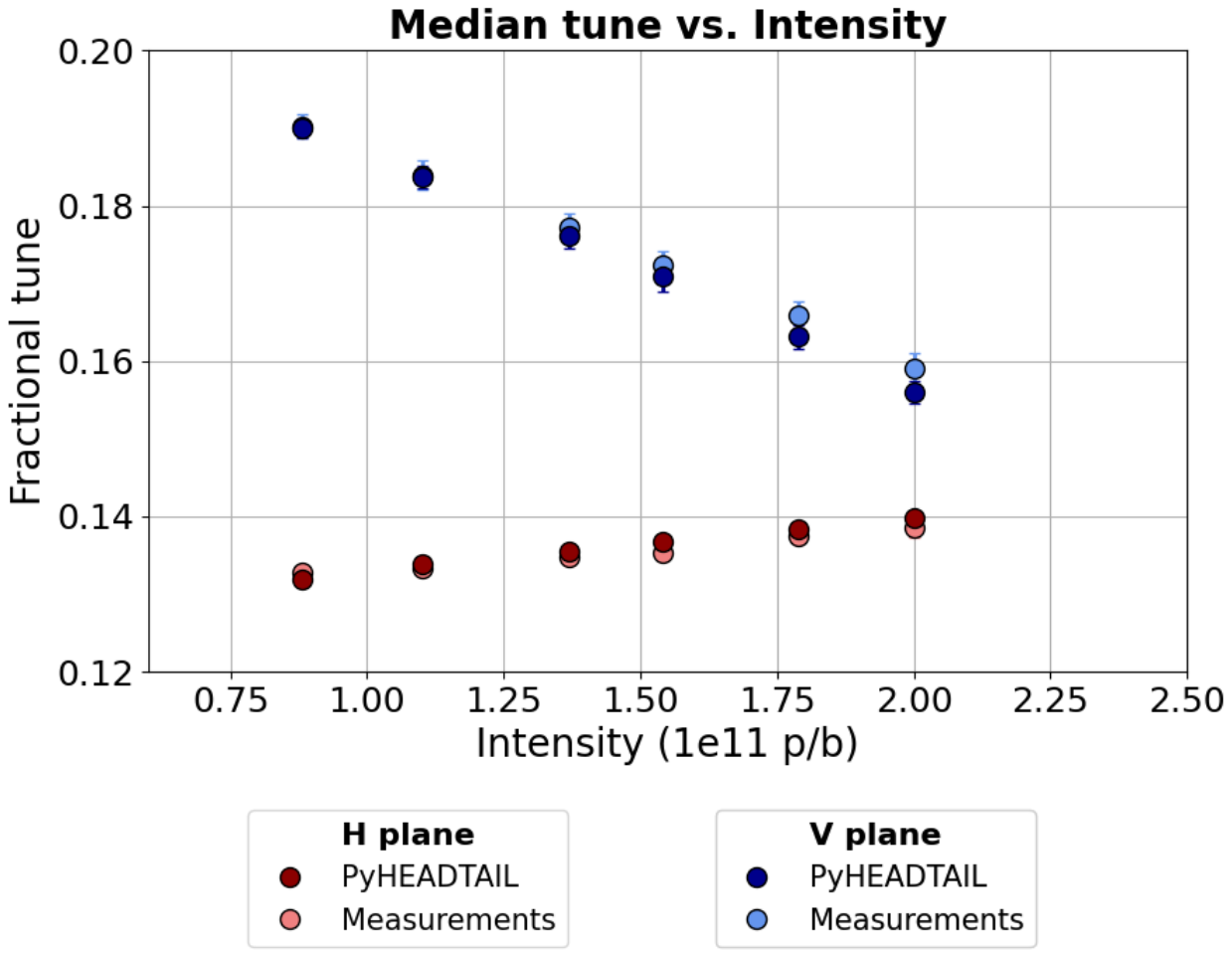

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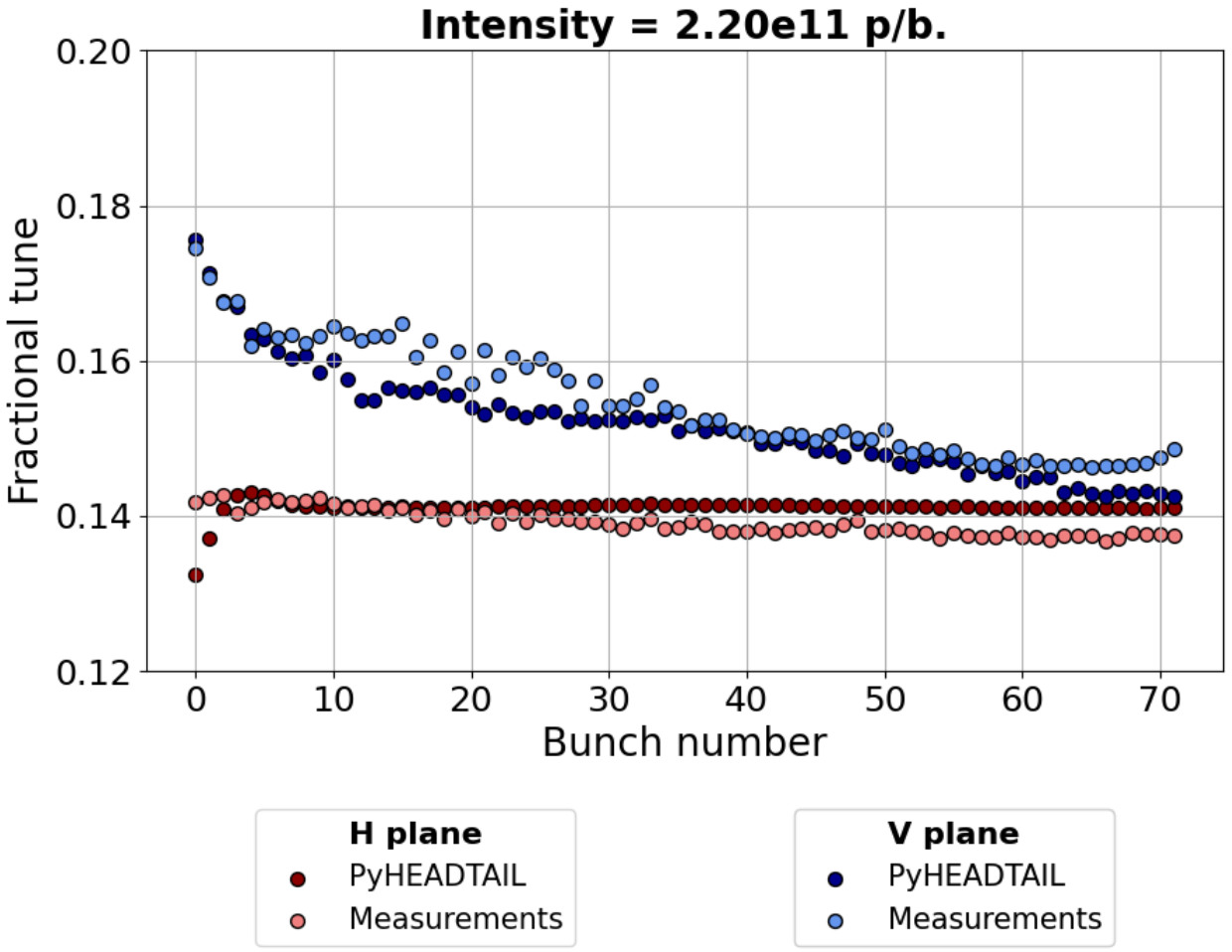

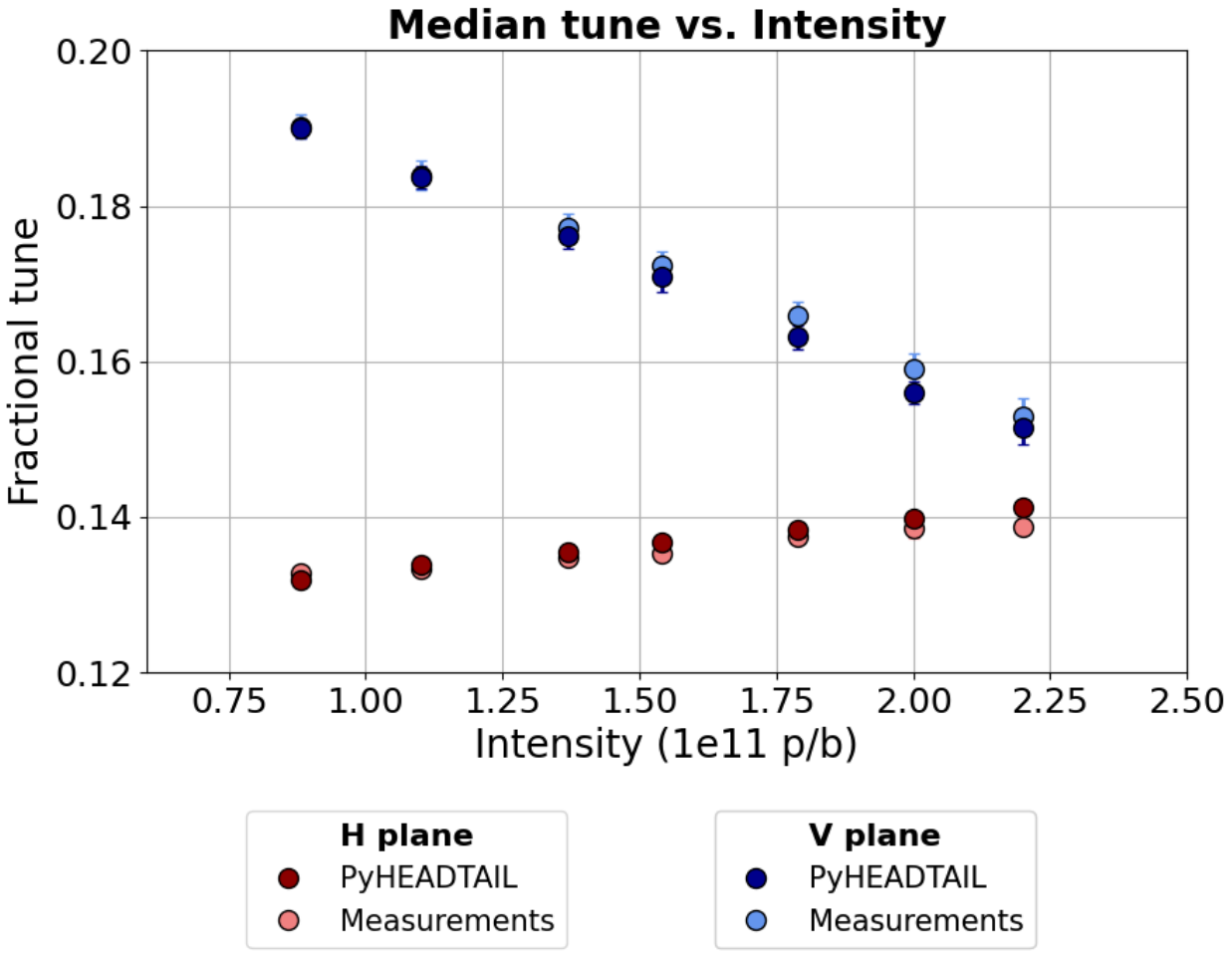

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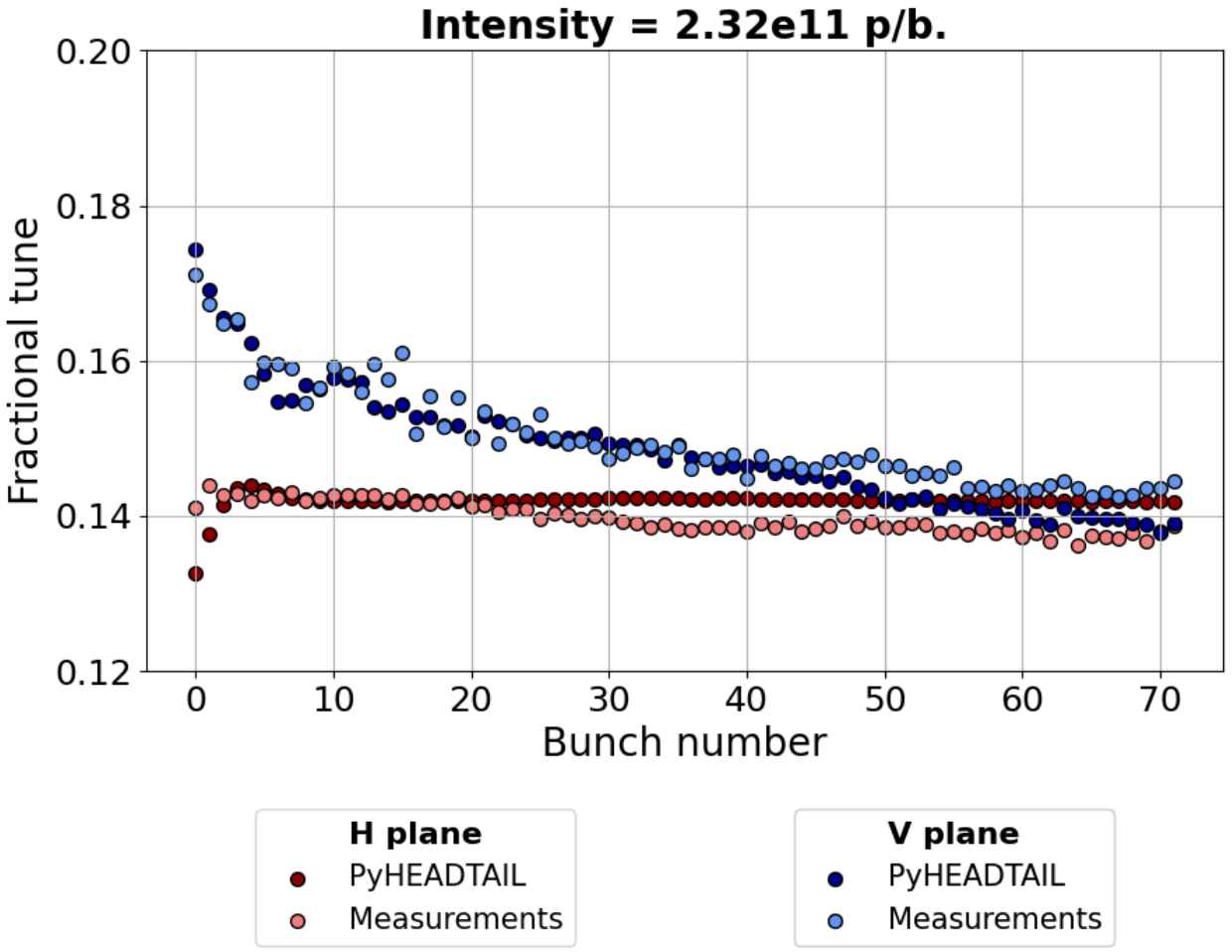
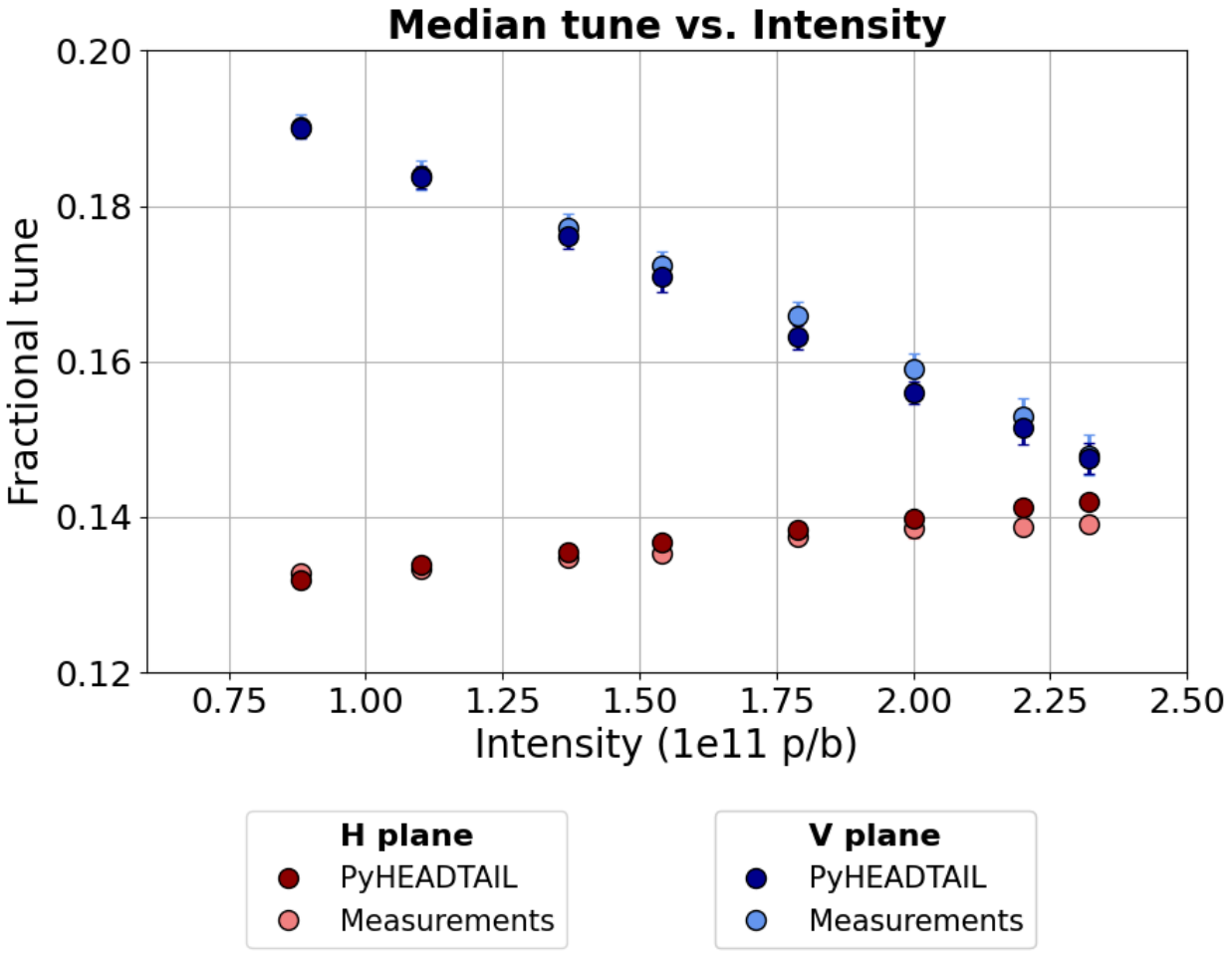
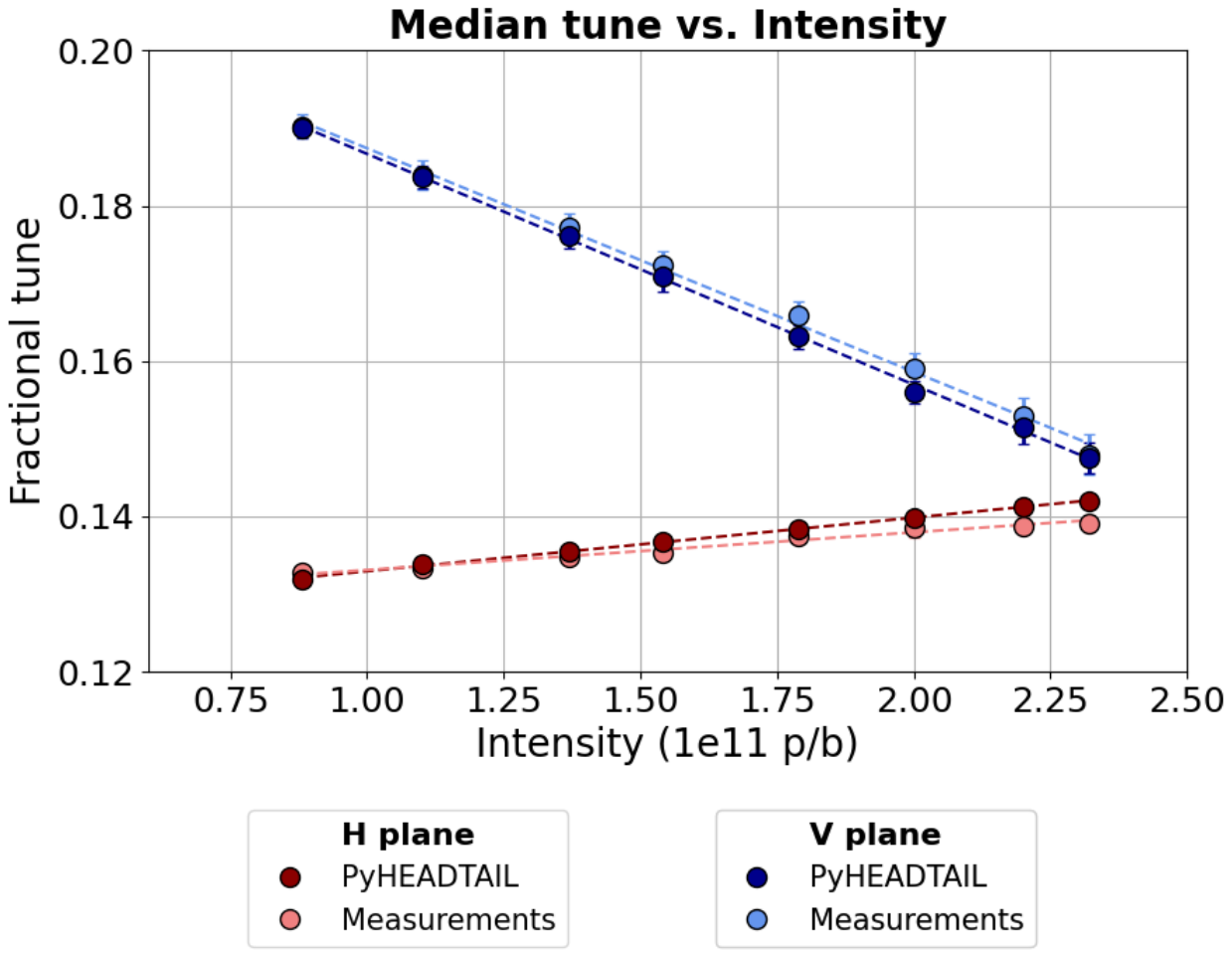




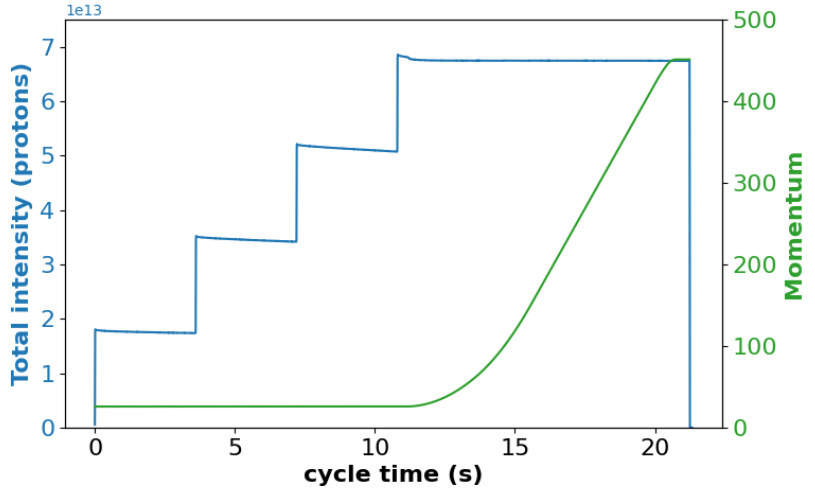
COMPARISON MEASUREMENTS AND SIMULATIONS
Measuring tune shift with intensity (1x72 bunches)

- Good agreement of measurements and simulations
- Significant bunch-by-bunch tune shift well reproduced with PyHEADTAIL multi-bunch simulations



COMPARISON MEASUREMENTS AND SIMULATIONS

Measuring tune shift with intensity



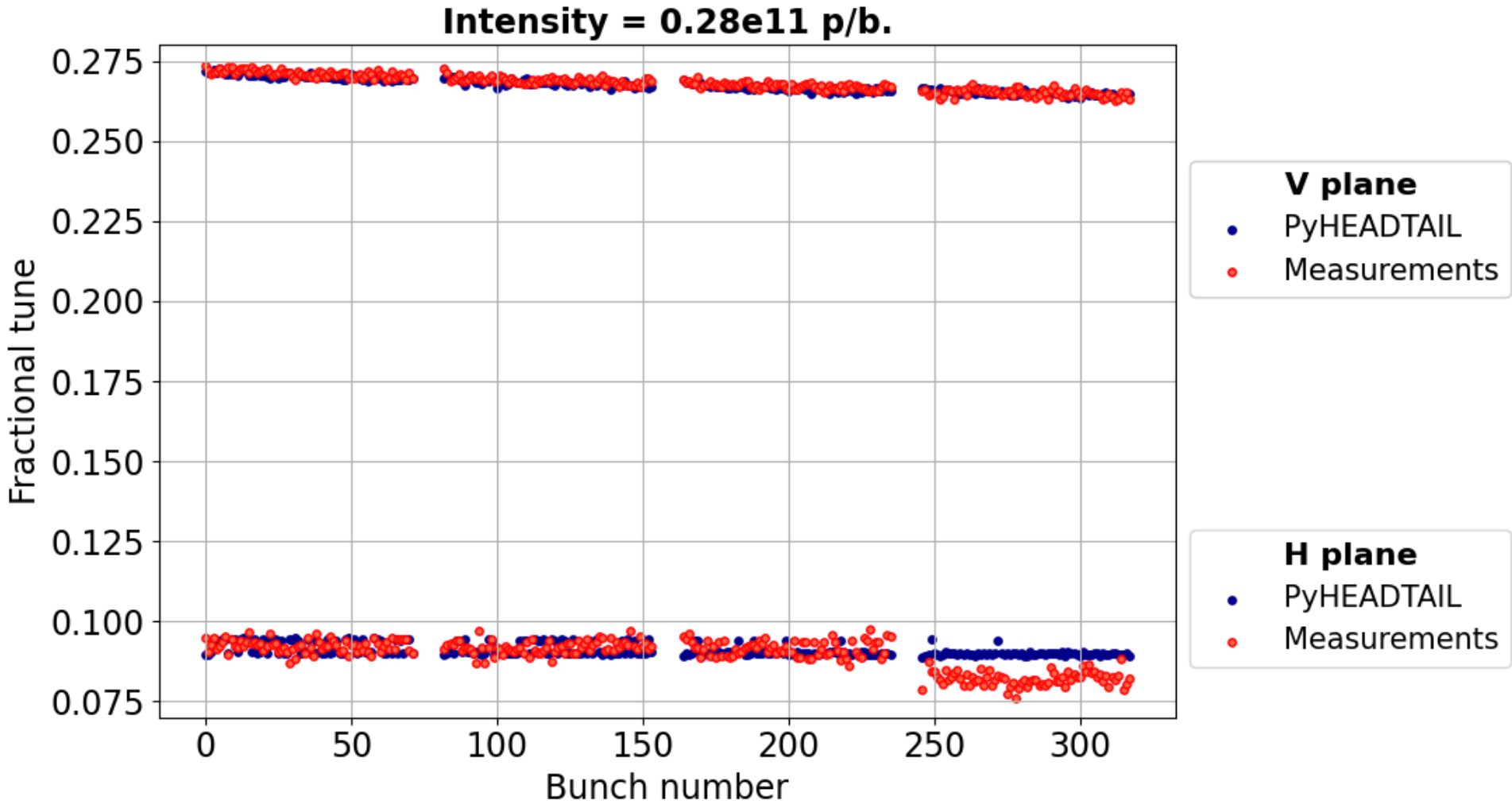
- **4 x 72 bunches**
- **Intensity scan** from **0.28e11 p/b** to **2.15e11 p/b (close to the LIU target intensity)**
- **Set tunes were not changed during the scan:**

- No corrections, just measuring tune shift with intensity.

- Tune measurements done at the injection of the last train.

COMPARISON MEASUREMENTS AND SIMULATIONS

Measuring tune shift with intensity (4x72 bunches)



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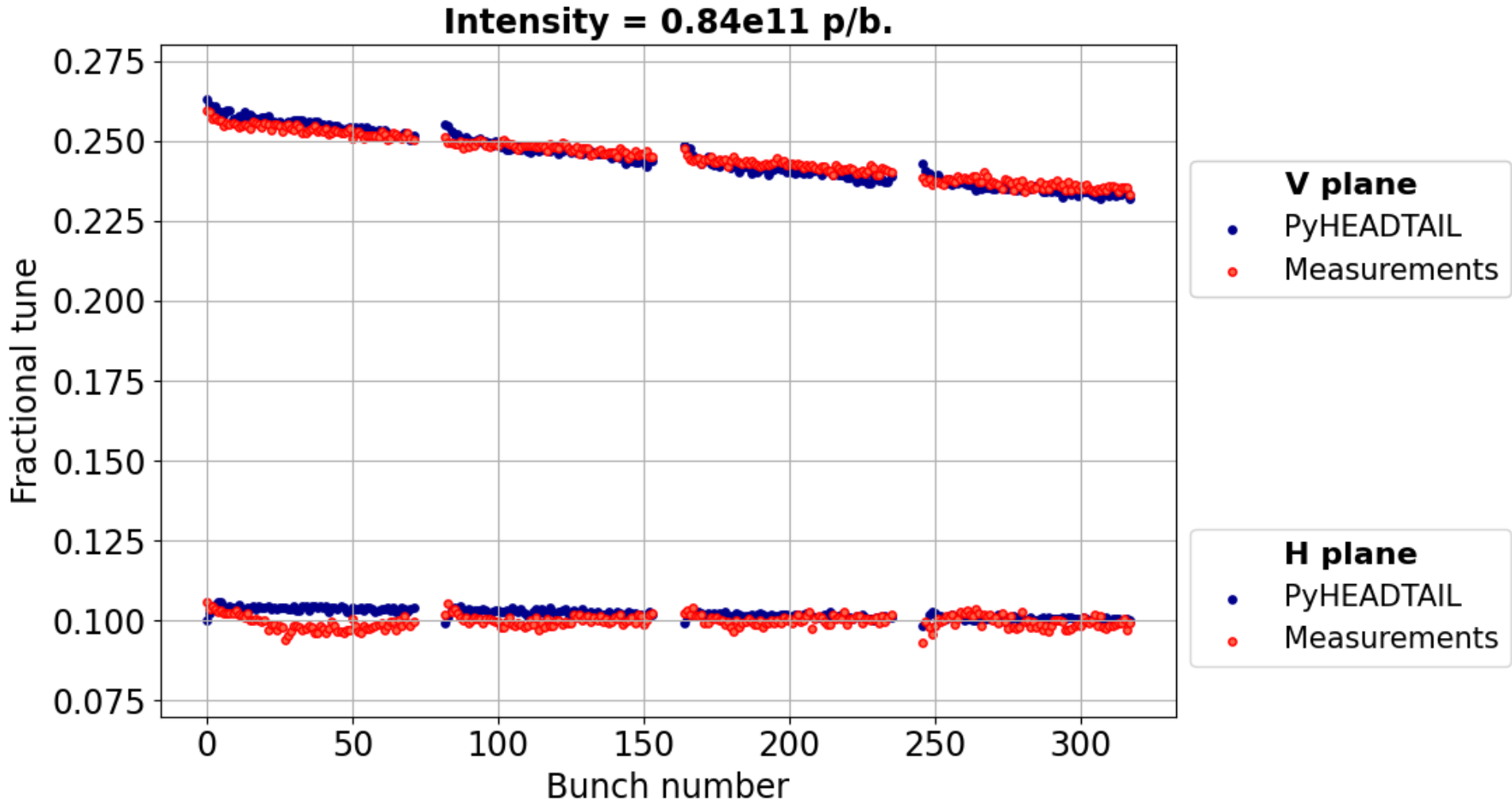

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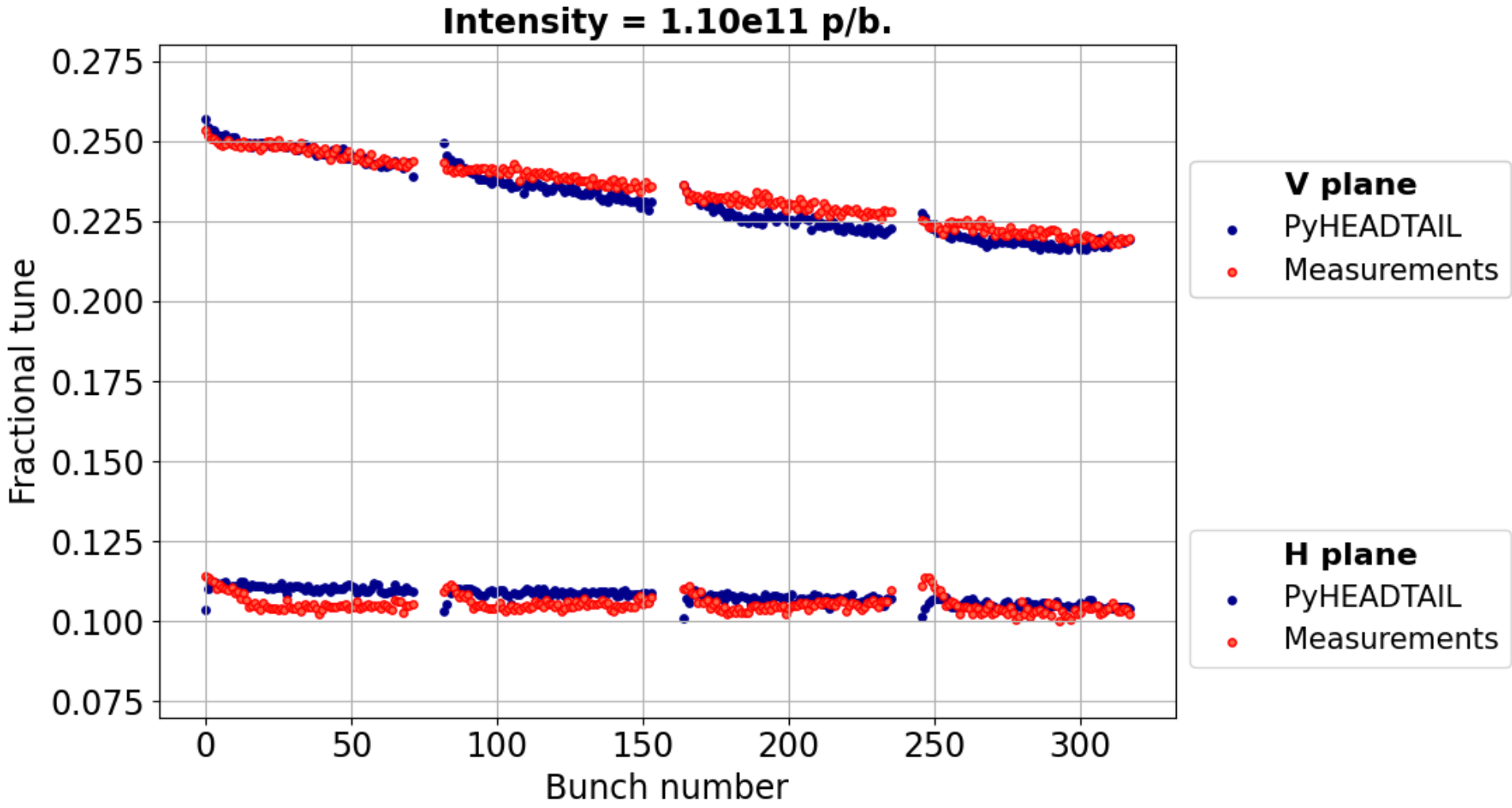

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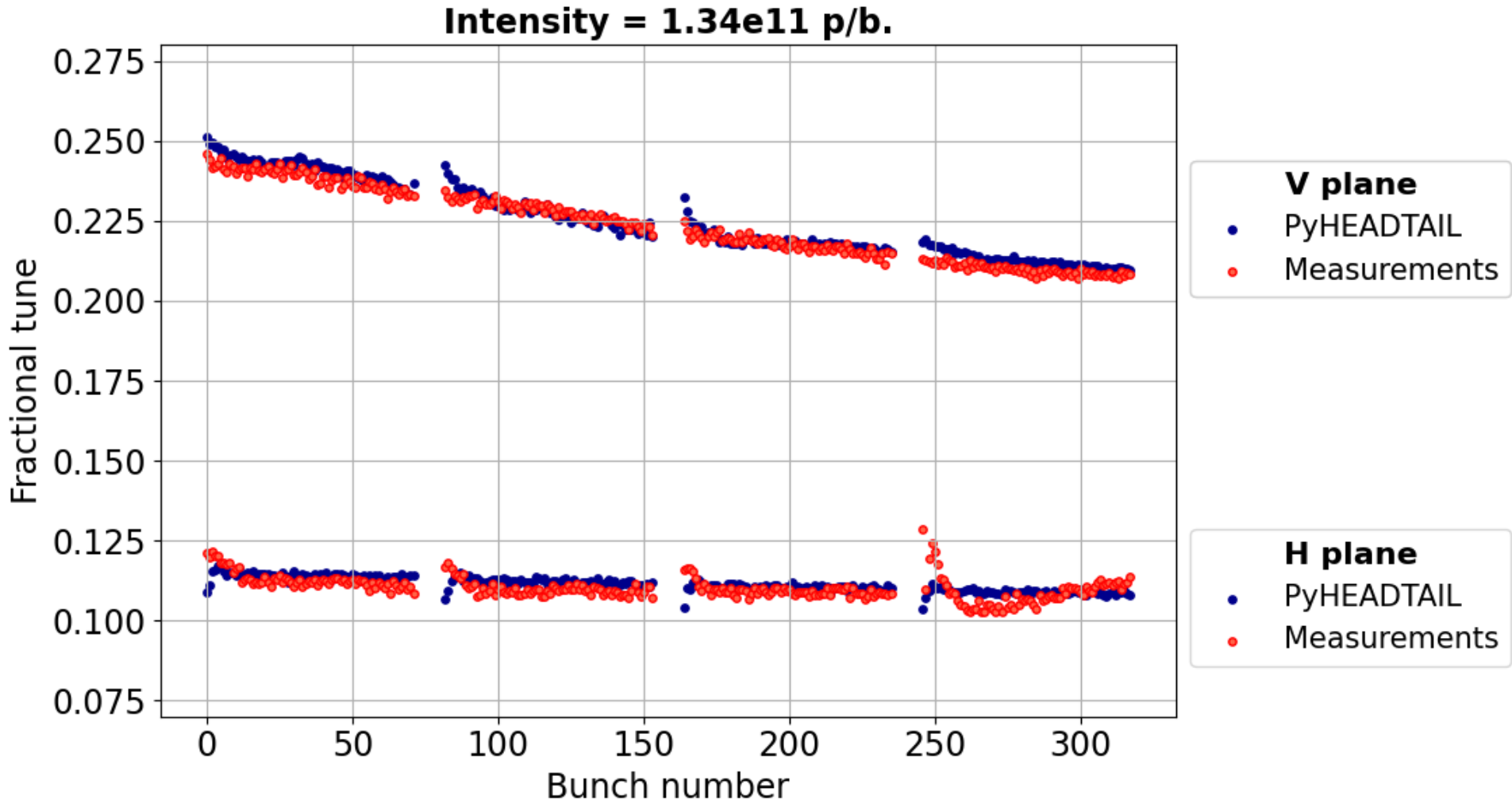

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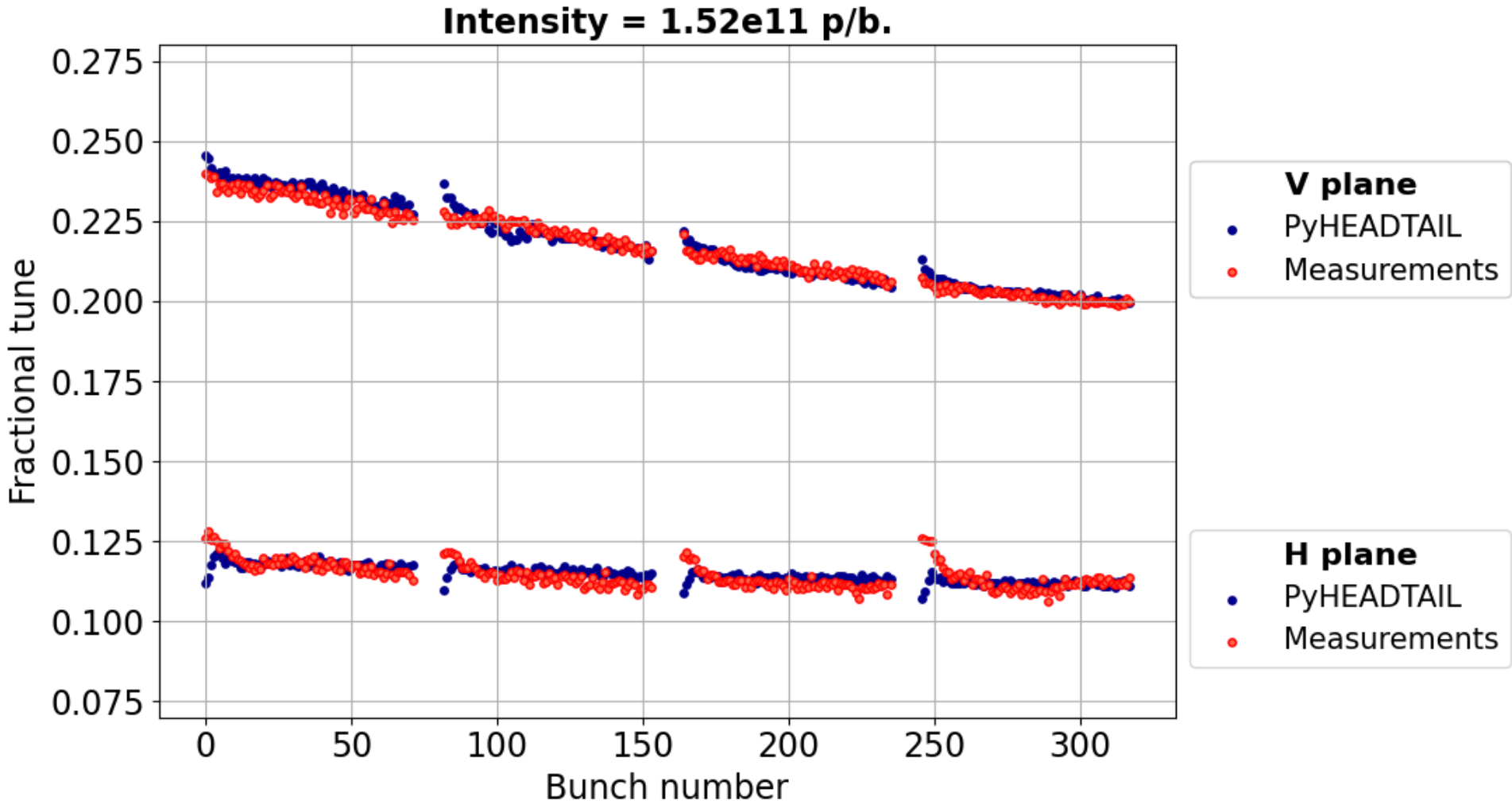

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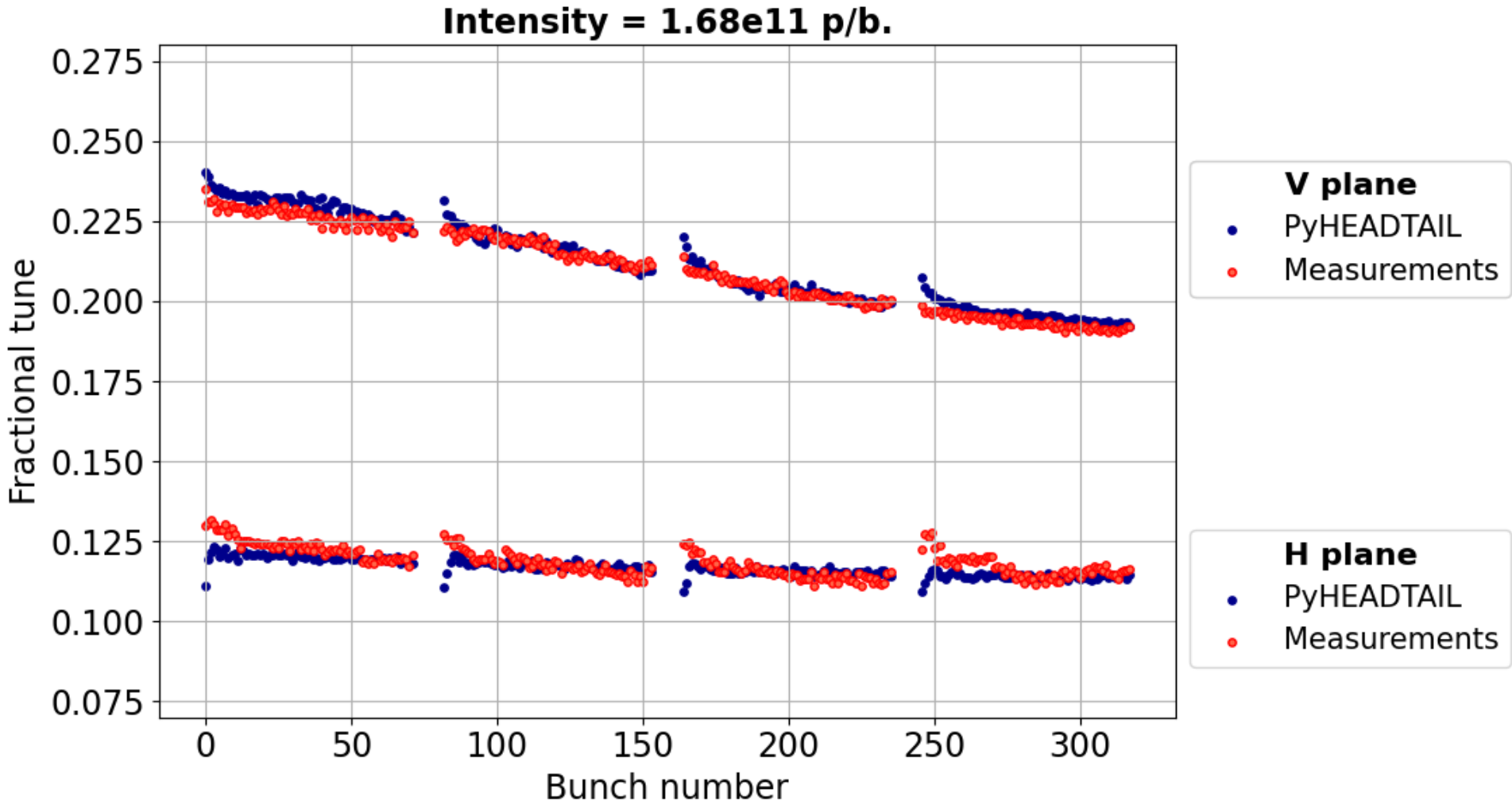

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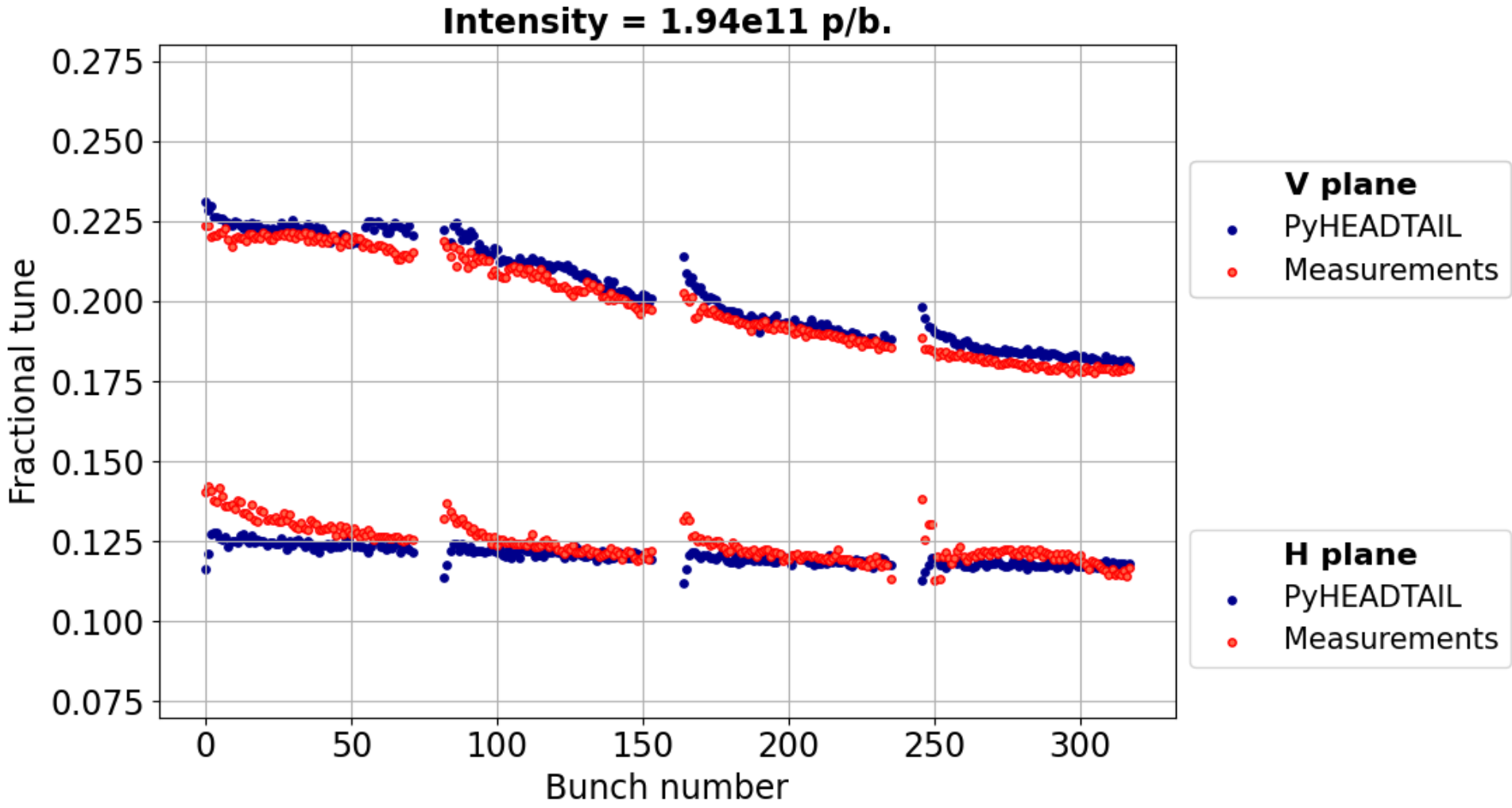

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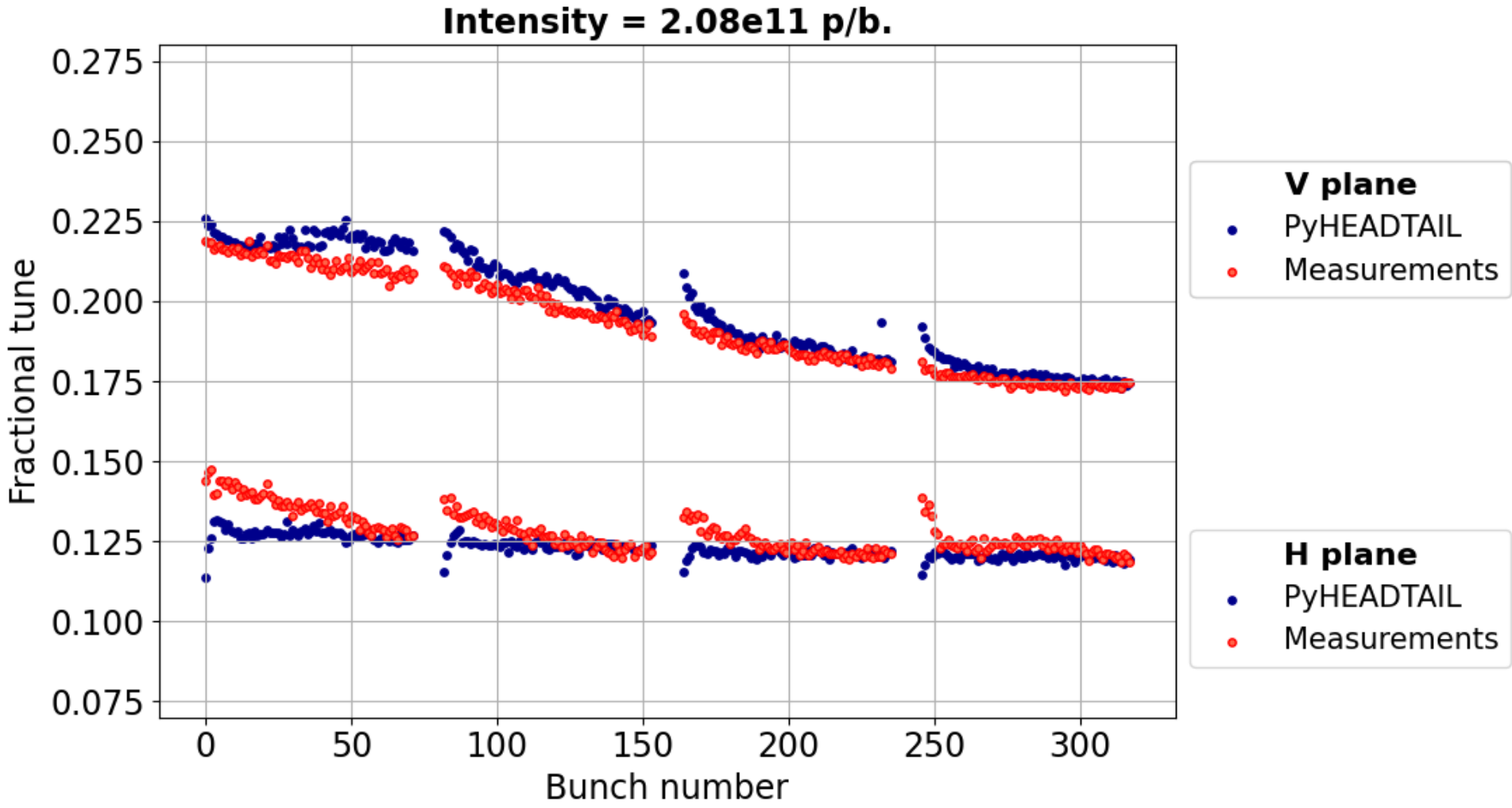

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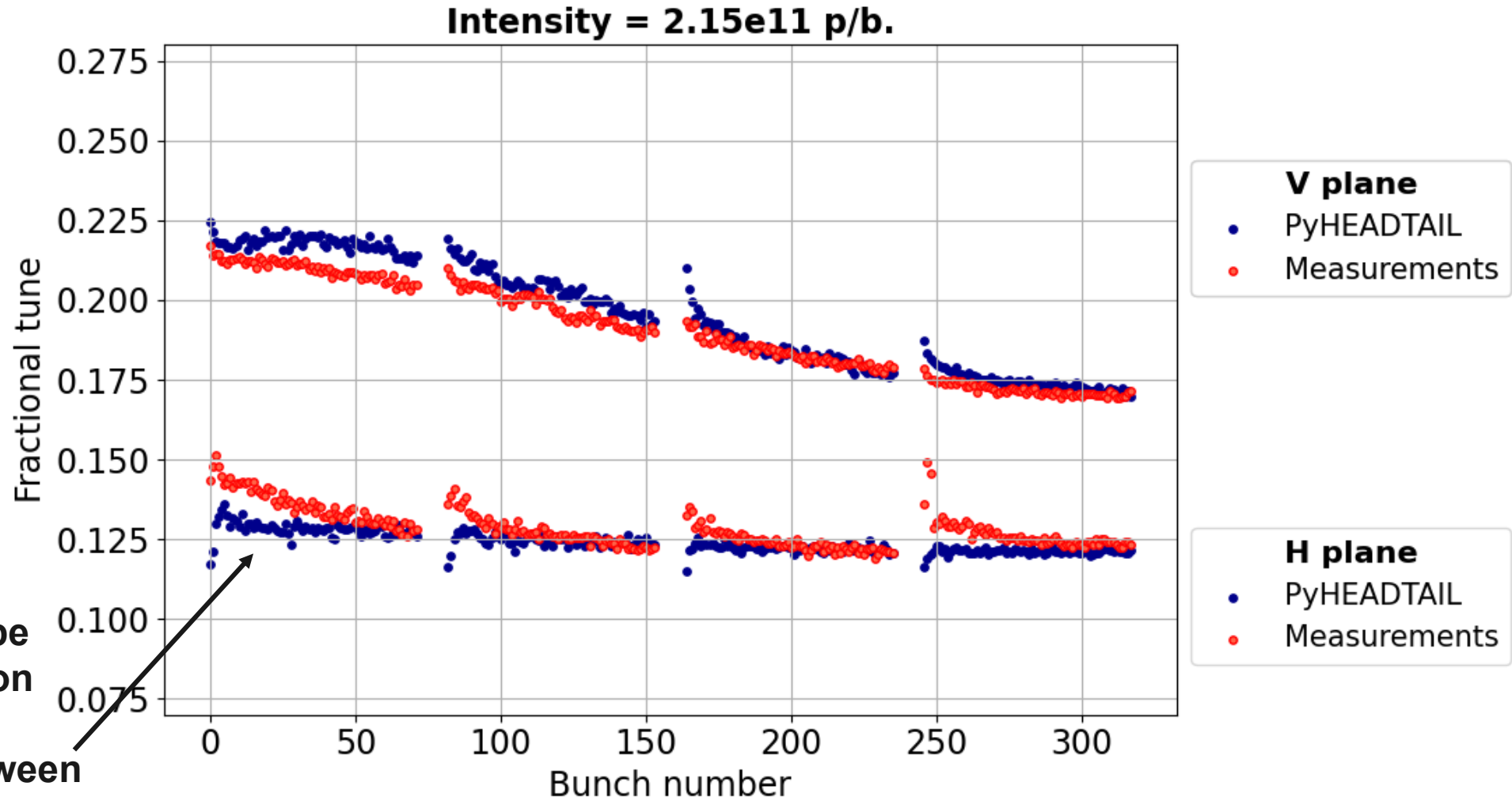
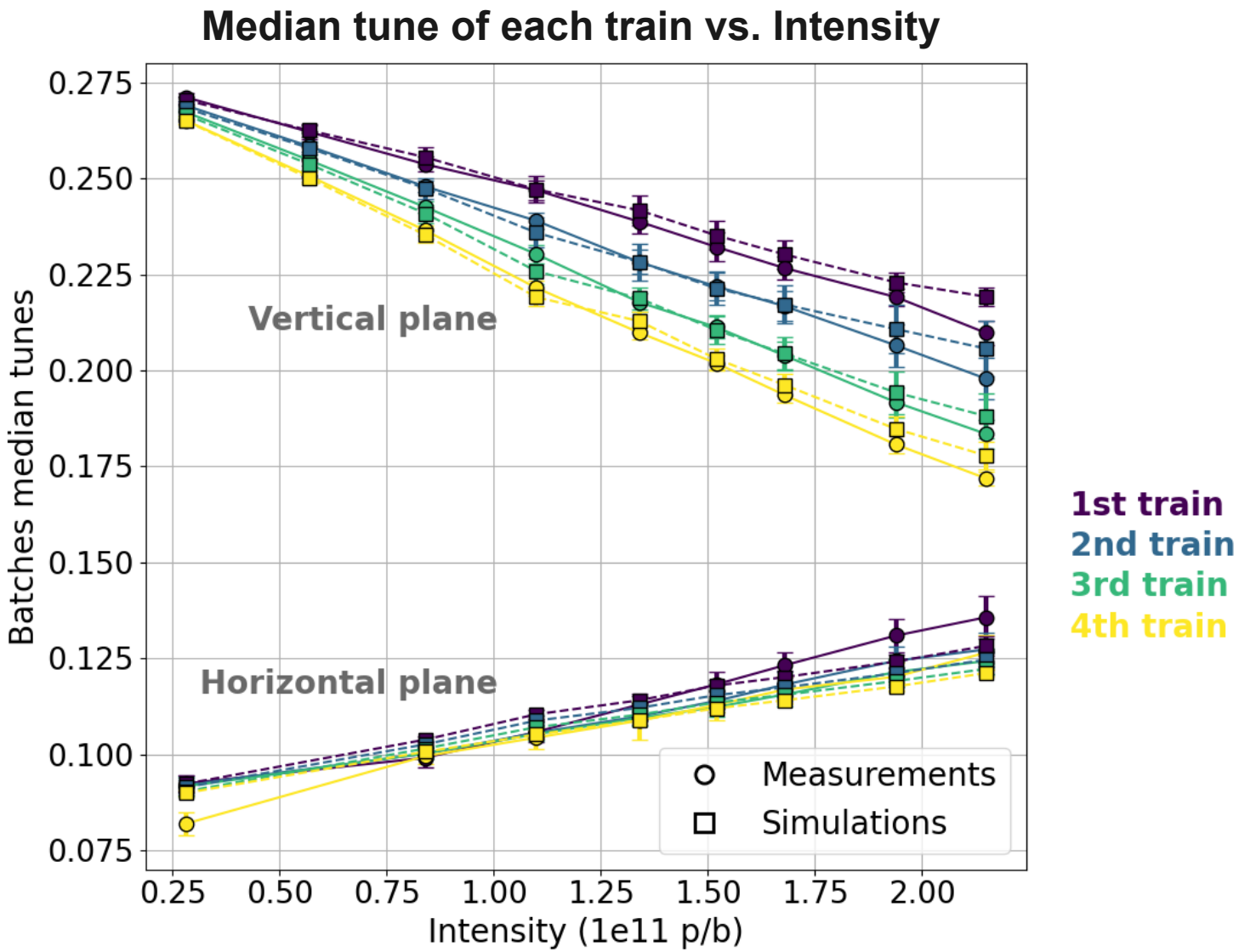


Difference in slope might be due to electron cloud or coupling between transverse planes.

COMPARISON MEASUREMENTS AND SIMULATIONS



Good agreement: Bunch-by-bunch tunes computed from simulations exhibit the same behavior with respect to intensity as observed in the measurements.

Results used to develop a predictive model for tune shift, of LHC-type beams, in the SPS.

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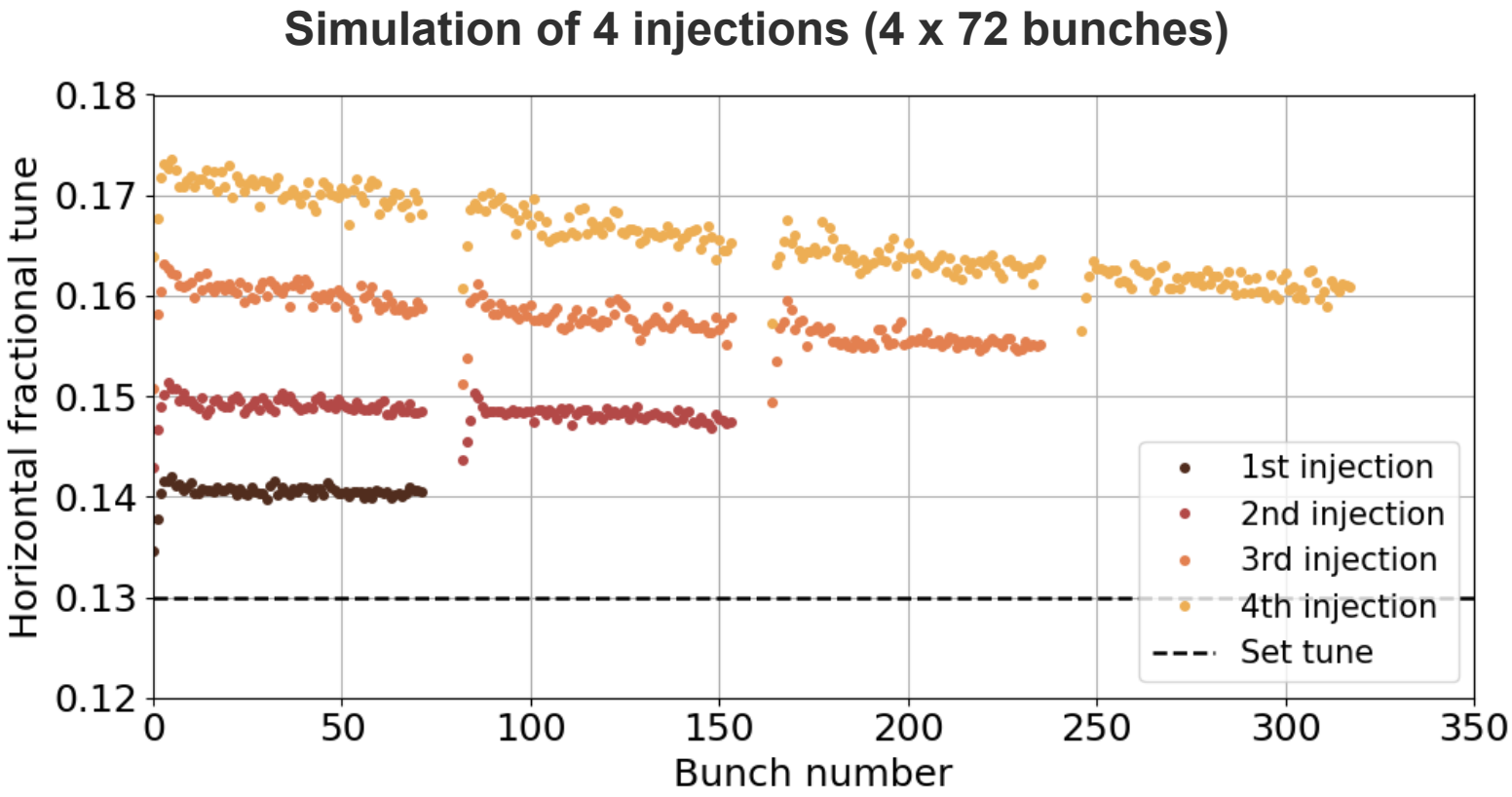
HORIZONTAL PLANE: TUNE SHIFT EVOLUTION WITH NEW INJECTIONS OF TRAINS

All bunches undergo a **positive tune shift** every time a **new train is injected**.

Observed in **measurements** and **simulations**.

Not observed in the vertical plane.

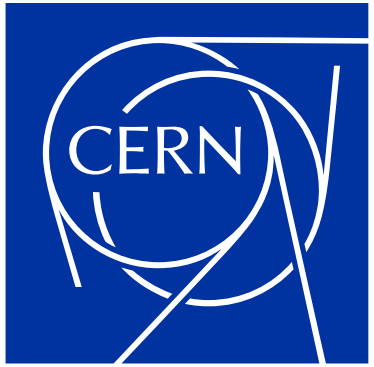
The mechanism responsible for this tune shift is under study: quadrupolar impedance plays a big role.



CONCLUSIONS

- Tune shift effects are important when the SPS operates at high intensities.
- Characterisation of the transverse tune shifts at a wide range of intensities.
- Good agreement between measurements and simulations with the SPS impedance model.
- Small discrepancies are under study.
- These results are being used to develop a predictive model for tune shift correction in the SPS.

Thank you!



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