Bunch by bunch tune shifts for HL-LHC: tune separation along the bunch train

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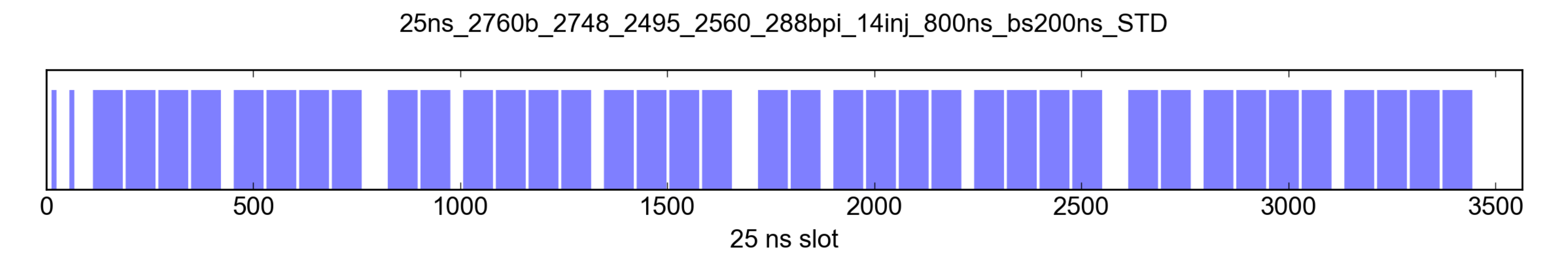
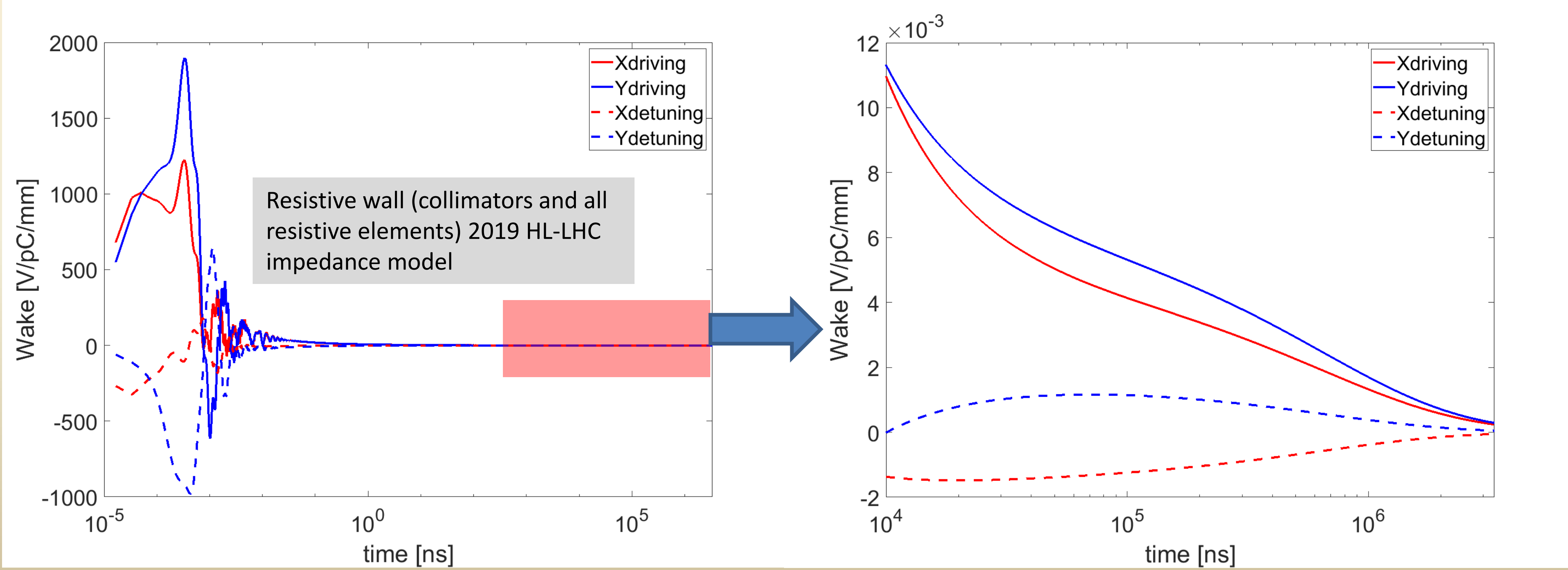
HL-LHC: PyHEADTAIL multi-bunch simulation

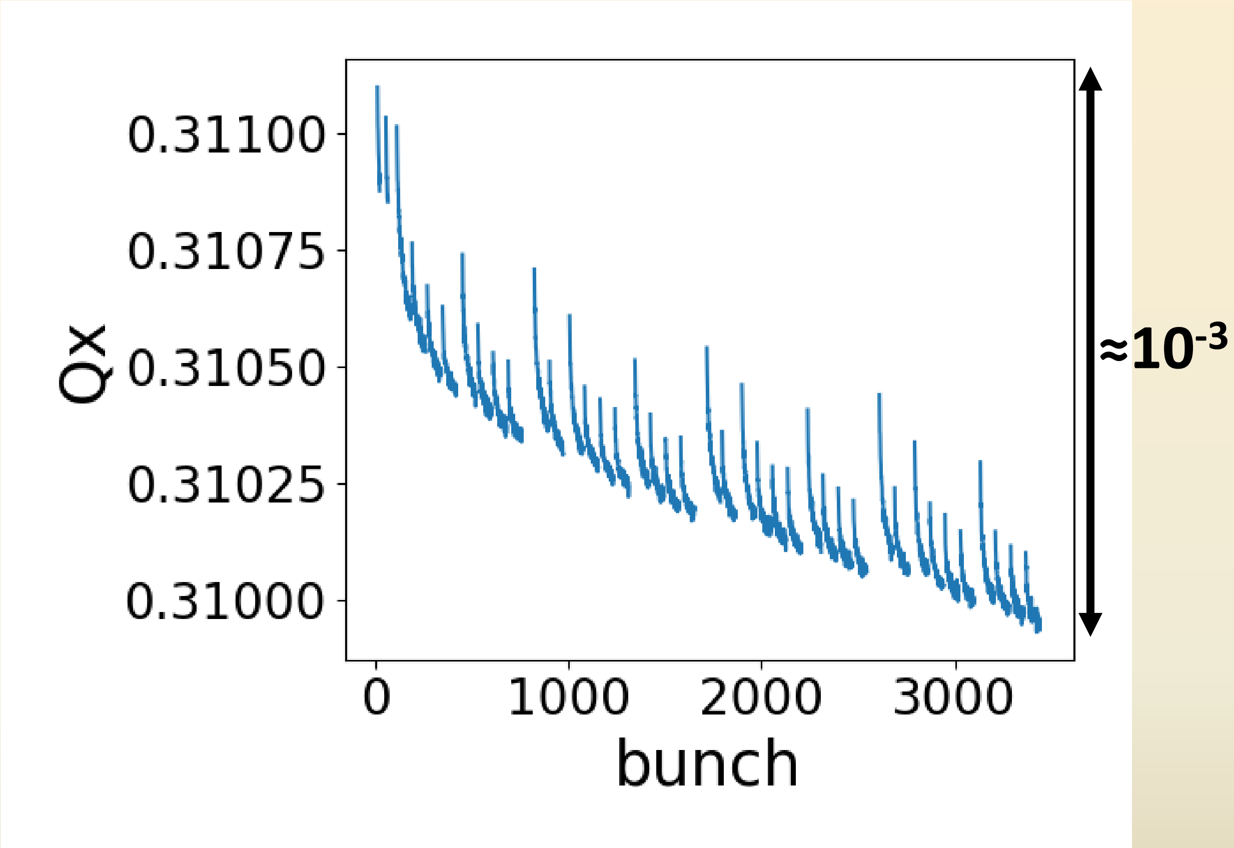
HL-LHC baseline scheme (assumed in TDR)

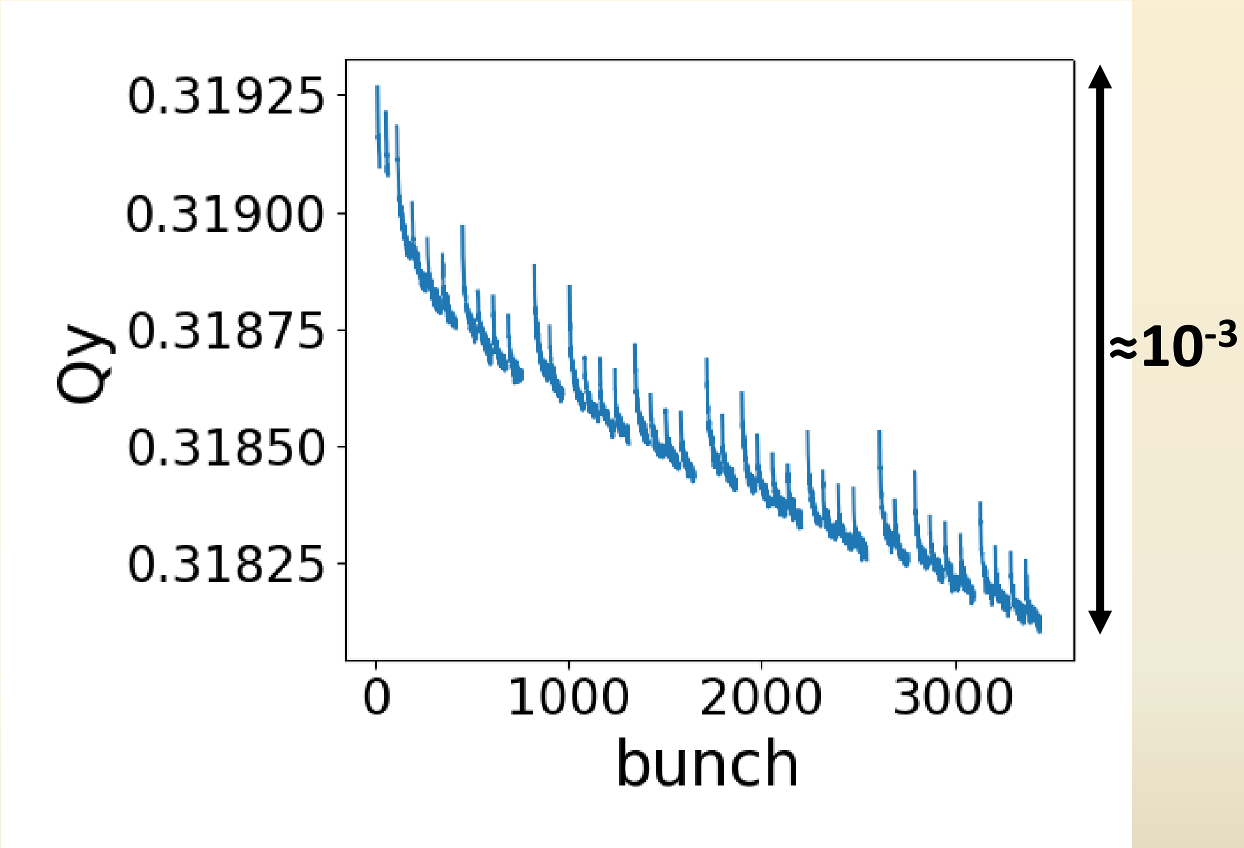
Flat top
N=2.3e11 ppb
Q'=15
σ= 0.08994
Qx=62.31
Qy=60.32





HL-LHC: PyHEADTAIL multi-bunch simulation





Full tune shift over the bunch train is in the order of 10^{-3}

Maximum tune shift along the train due to impedance

Courtesy of S. Antipov

Machine	LHC - 2017	LHC - 2017	HL-LHC	HL-LHC	HE-LHC	HE-LHC
Cycle state	Injection	Flat-top	Injection	Flat-top	Injection	Flat-top
Energy, GeV	450	6500	450	7000	1300	13500
Intensity, ppb	1.05×10^{11}	1.05×10^{11}	2.3×10^{11}	2.3×10^{11}	2.2×10^{11}	2.2×10^{11}
Current full, A	0.67	0.67	1.47	1.47	1.4	1.4
Imp, MΩ/m	100	900	100	800	250	2000
Tune shift full	**8.8×10^{-4}**	**5.5×10^{-4}**	**1.9×10^{-3}**	**1.0×10^{-3}**	**1.6×10^{-3}**	**1.2×10^{-3}**

$$\Delta Q_{full} = \frac{1}{4\pi Q} \frac{R}{E/e} Z_{\perp} I_b$$

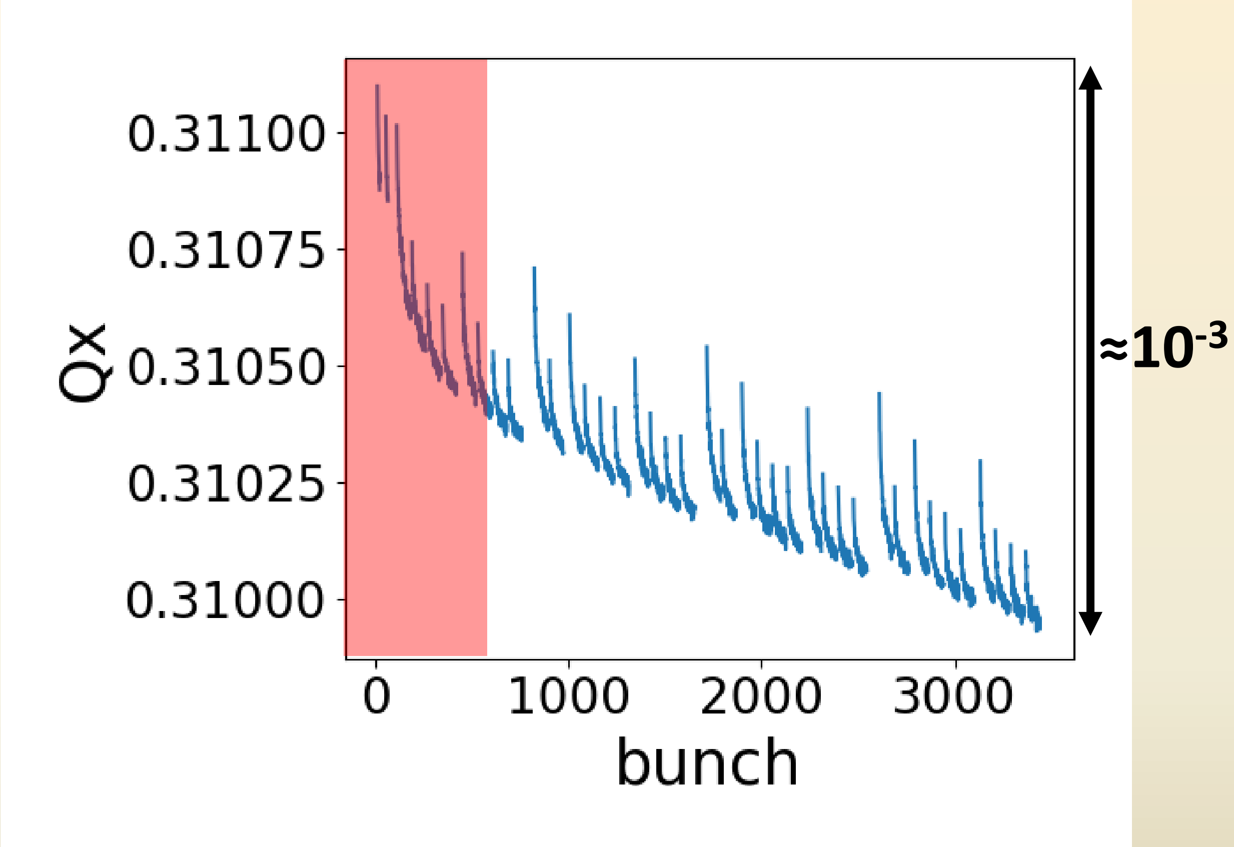
L. Vos, *EPAC 2000*

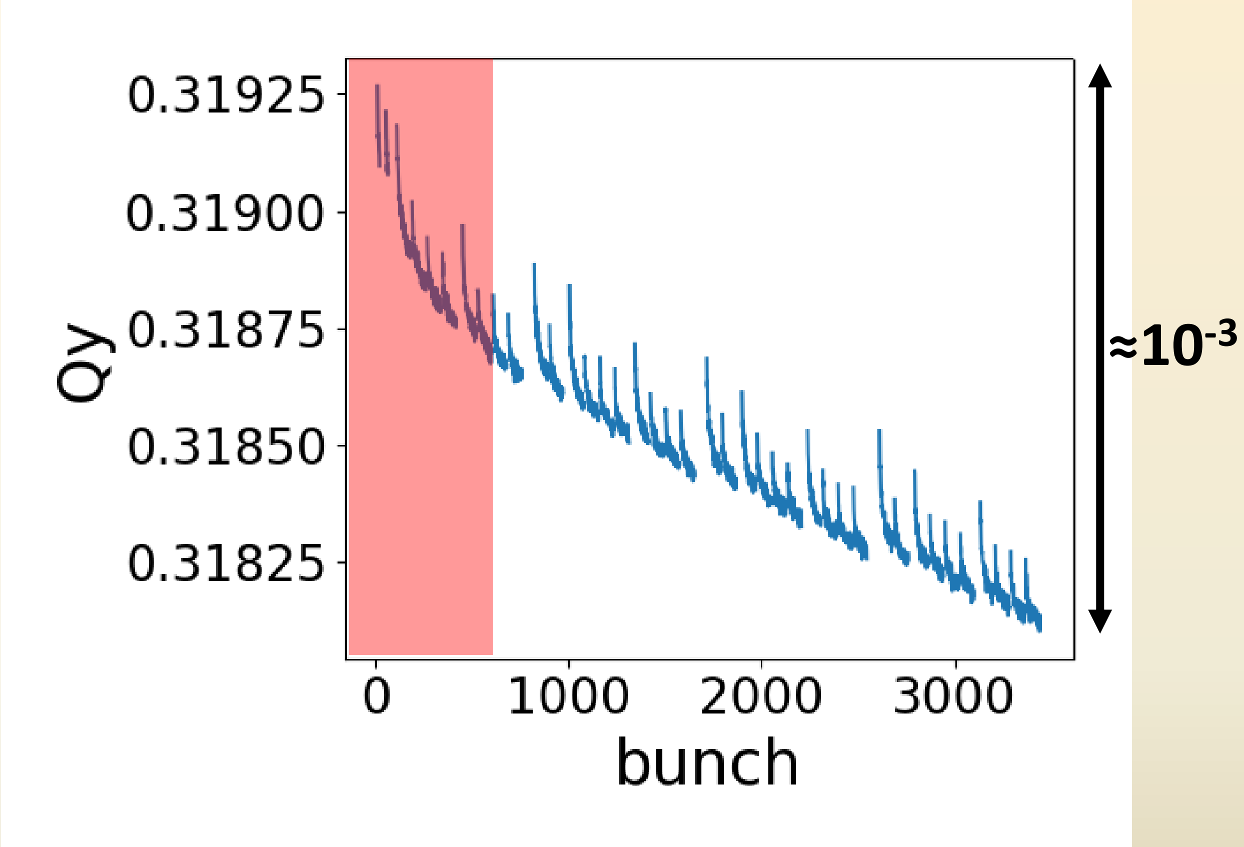
Approximations:

Uniform bunch train of length τ

Resistive wall impedance $Z \sim (j/\omega)^{1/2}$

HL-LHC: PyHEADTAIL multi-bunch simulation





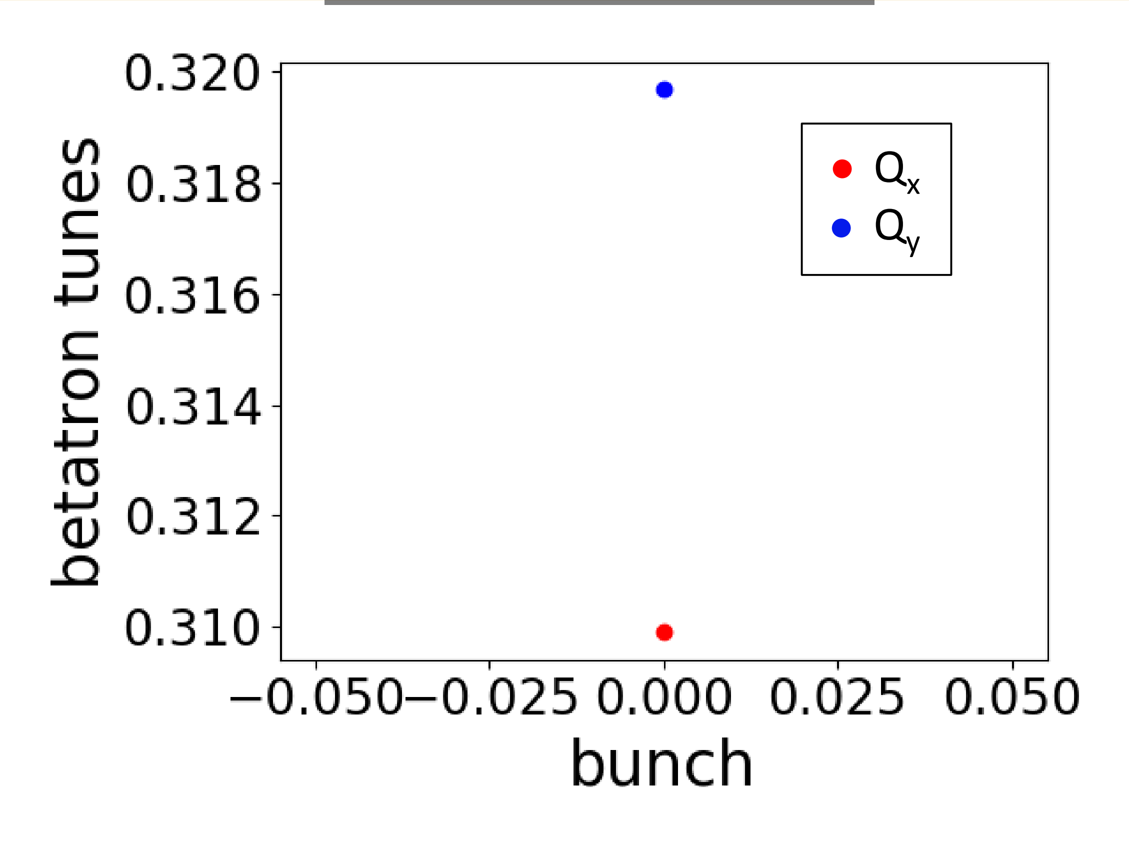
Full tune shift over the bunch train is in the order of 10^{-3}

What about the tune separation along the bunch train?

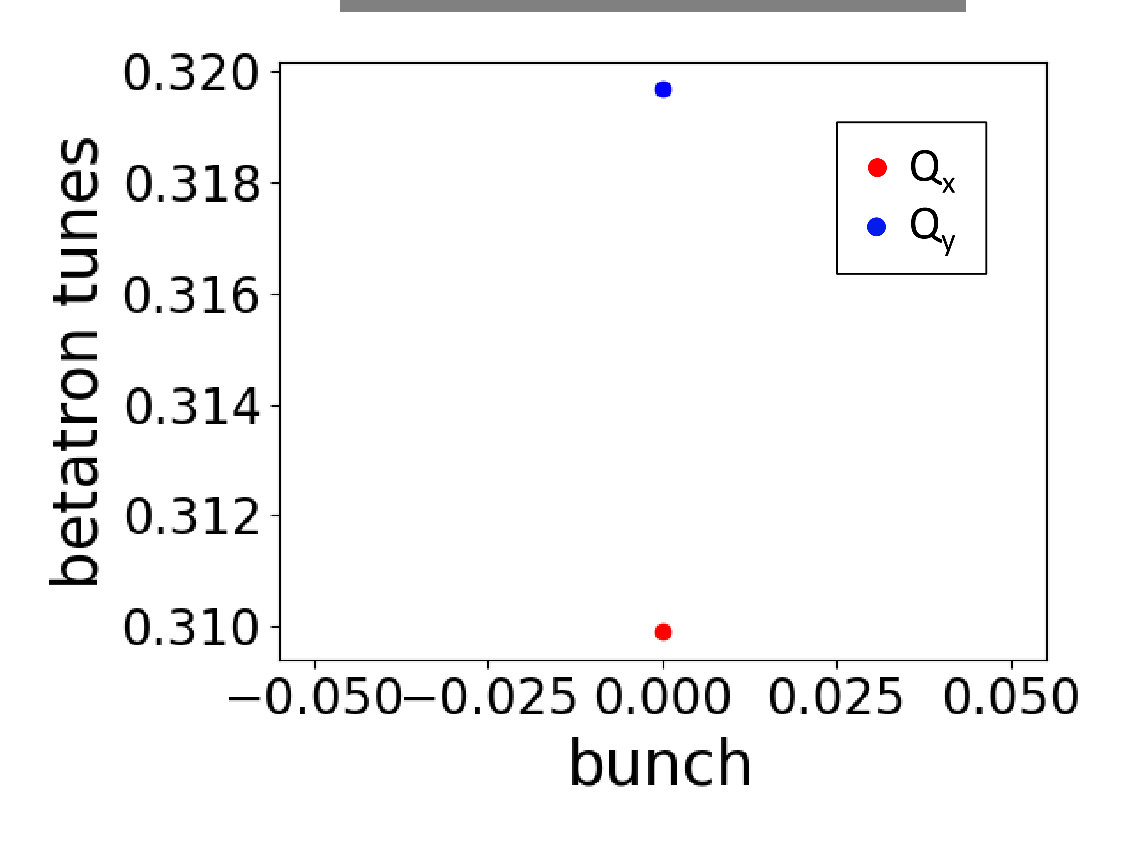
Requires absolute accuracy of the simulated tunes

HL-LHC: PyHEADTAIL single bunch simulation

Single bunch, 1 turn wake



Single bunch, multi-turn wake

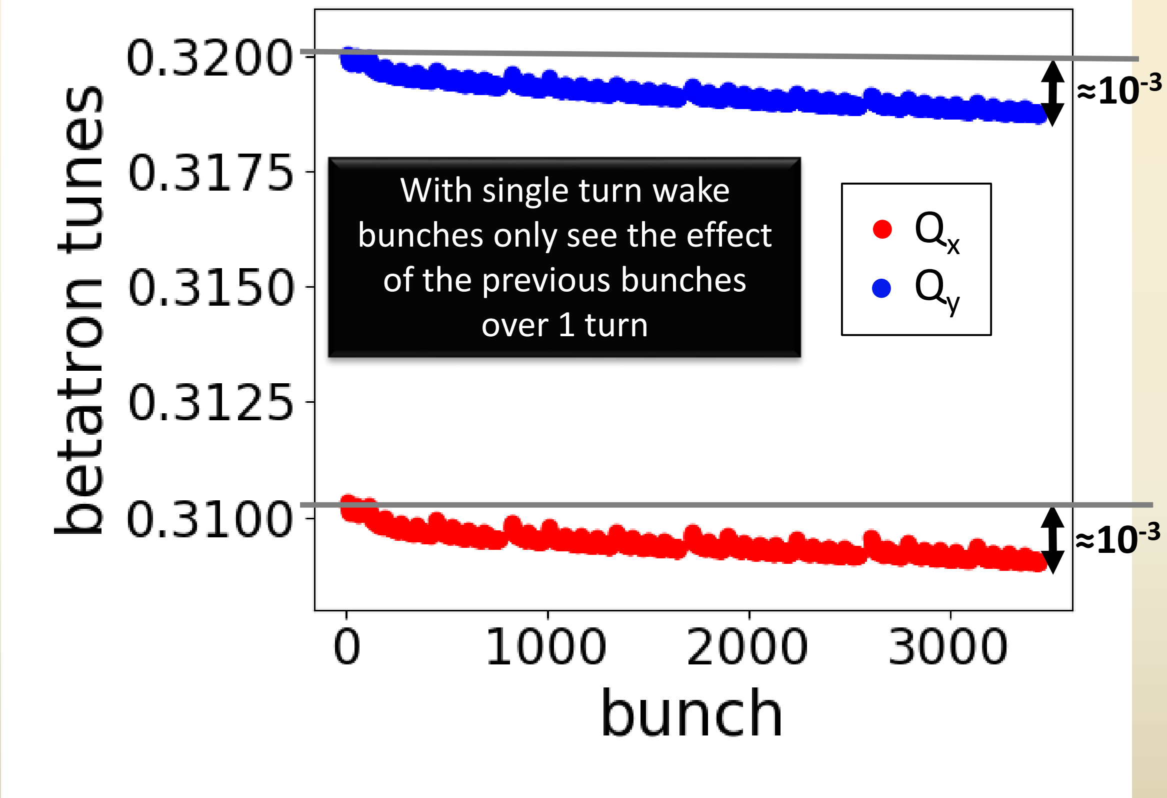


Single bunch tune shift significantly smaller compared to the tune shift experienced by the first bunch of the train

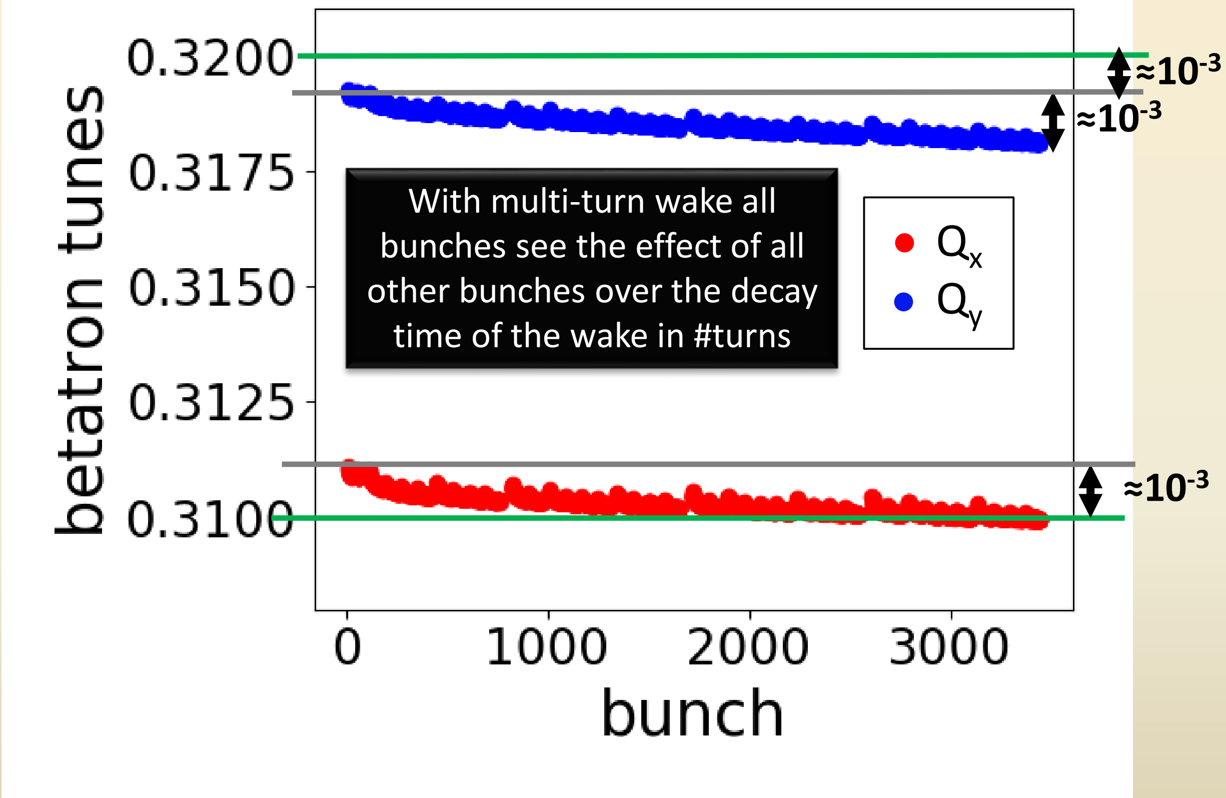
Negligible effect of the multi-turn wake

HL-LHC: PyHEADTAIL multi-bunch simulation

Multi-bunch, 1 turn wake



Multi-bunch, multi-turn wake

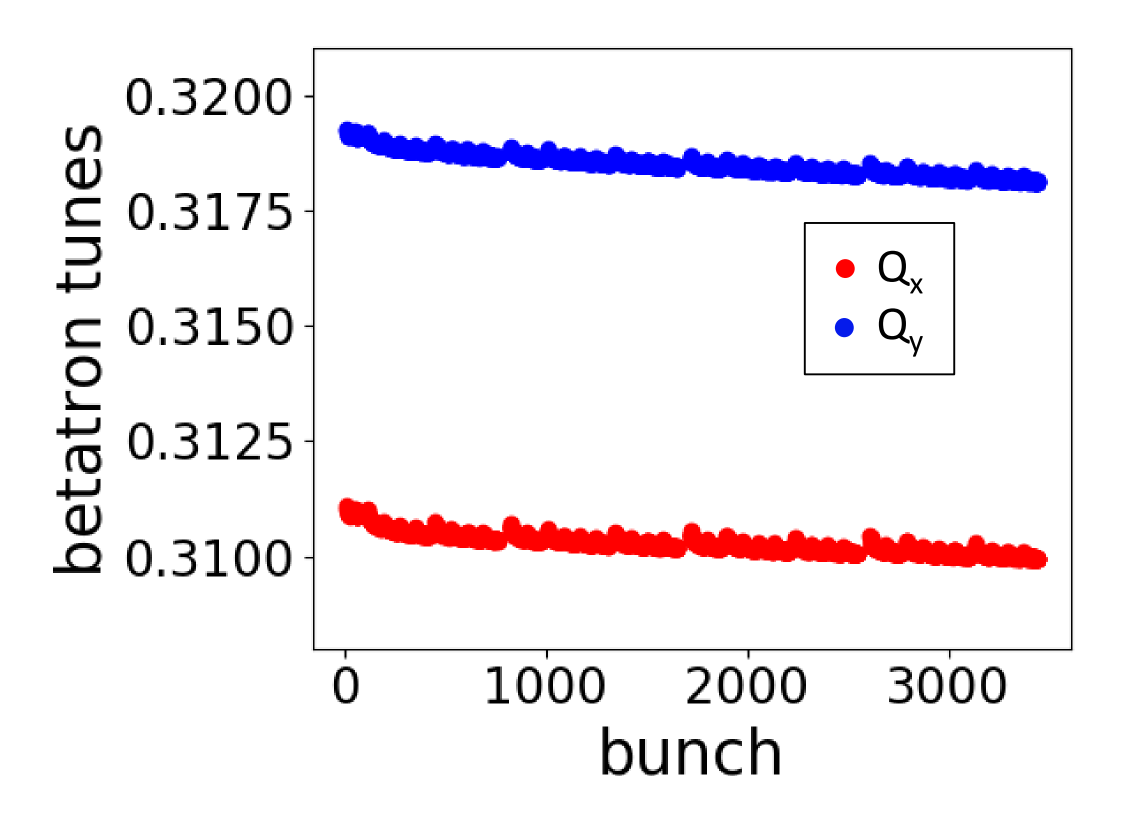


The bunch by bunch tune shift along the train is a single-turn wake effect

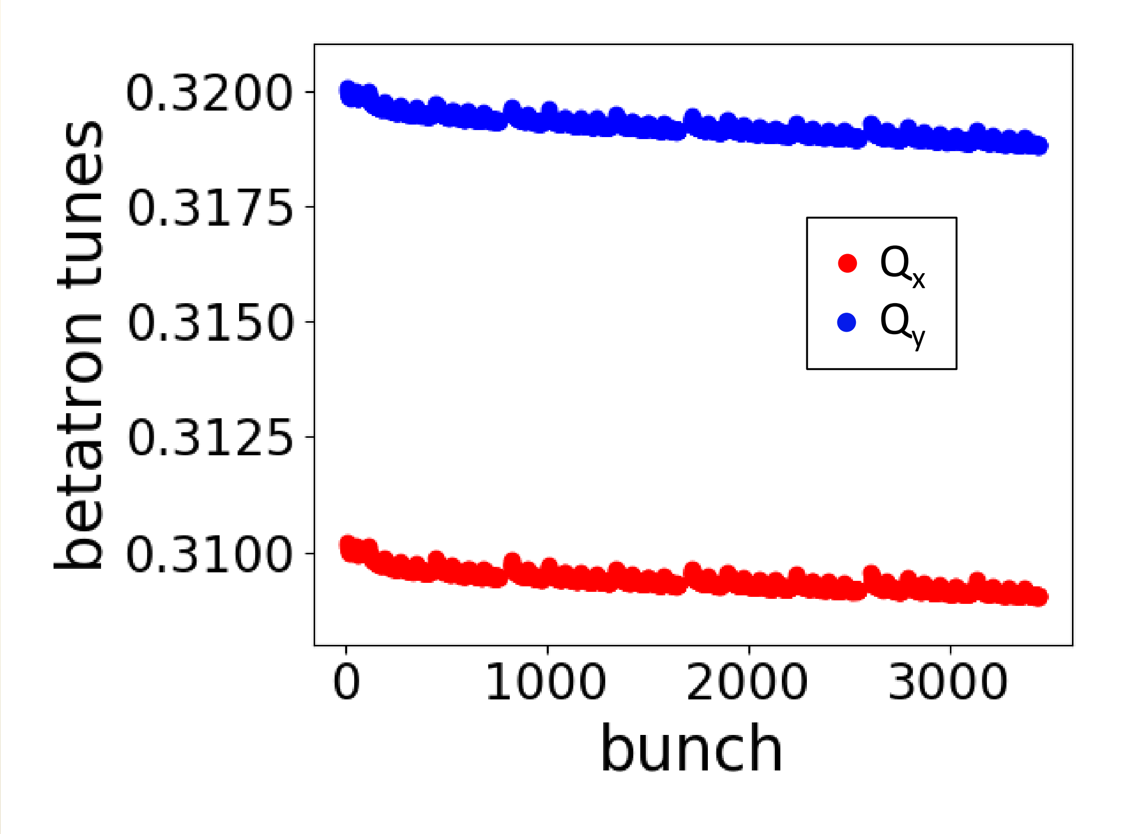
The additional tune shift in the order of -10^{-3} in y and 10^{-3} in x appears only in the case of multi-bunch (multi-turn wake)

HL-LHC: PyHEADTAIL multi-bunch simulation

Multi-bunch, multi-turn wake



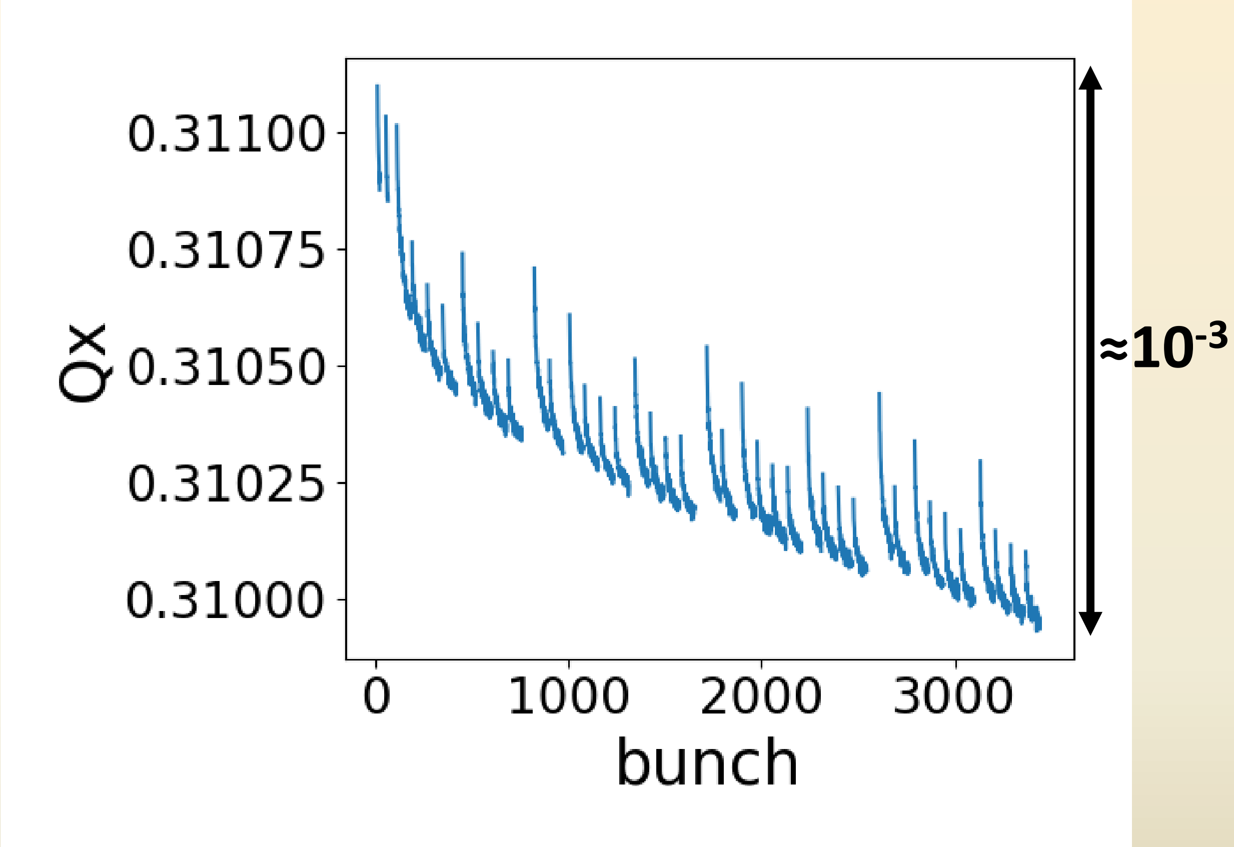
Multi-bunch, multi-turn wake (only driving)

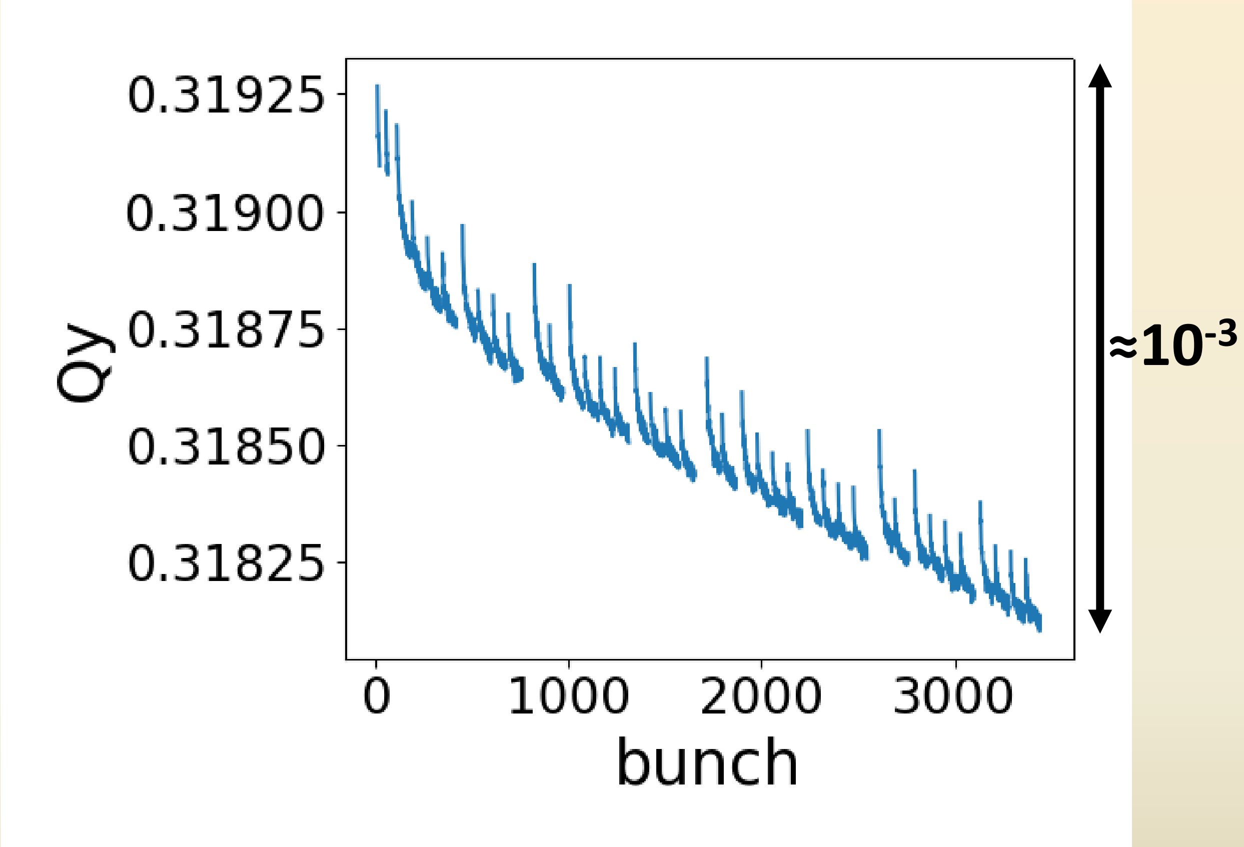


The multi-bunch multi-turn effect is associated with detuning impedance

A. Chao, S. Heifets, and B. Zotter, *Tune shifts of bunch trains due to resistive vacuum chambers without circular symmetry*

HL-LHC: PyHEADTAIL multi-bunch simulation

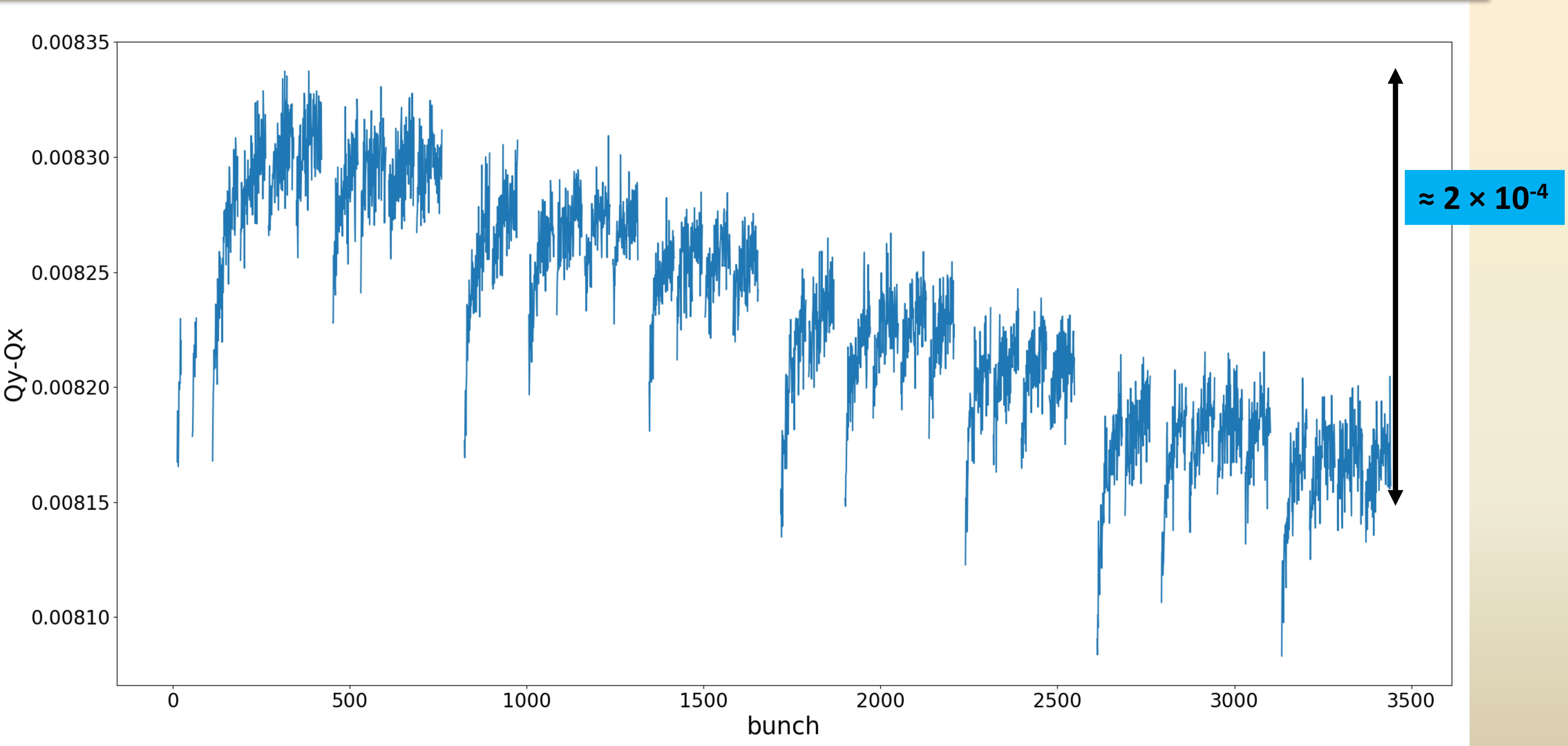




Full tune shift over the bunch train is in the order of 10^{-3}

Additional tune shift in the order of -10^{-3} in y and 10^{-3} in x due to detuning impedance (multi-bunch multi-turn wake effect)

Tune separation along the bunch train



Reduction in tune separation dominated by the additional tune shift in the order of -10^{-3} in y and 10^{-3} in x

Summary

- PyHEADTAIL multi-bunch simulations predict the maximum tune shift of the full train of bunches for HL-LHC beam at flat top to be in the order of 10^{-3}
  - In good agreement with the numbers obtained from L. Vos formula

- In the case under study (Q_x=62.31, Q_y=60.32) the tune separation between horizontal and vertical plane is in the order of 8×10^{-3}
  - Without correction the tune separation is reduced by about 2×10^{-3} due to the additional tune shift of all bunches from detuning impedance.

- Along the train the tune separation is reduced by about 2×10^{-4}.

Thank you for your attention