HL-LHC longitudinal stability

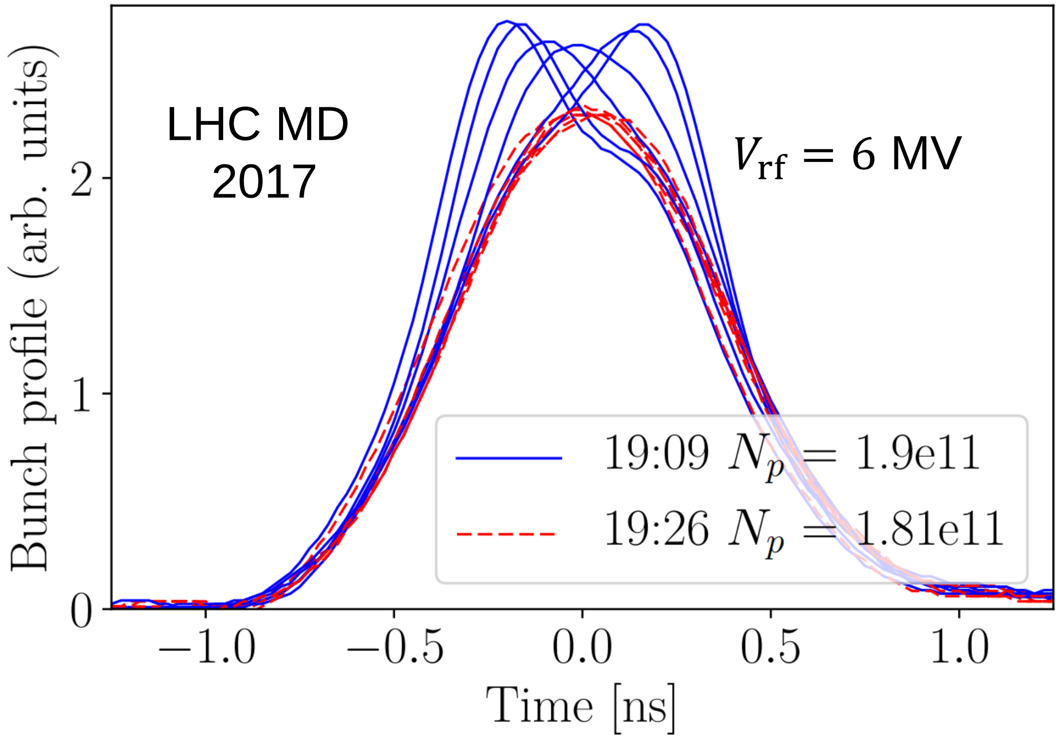
Ivan Karpov, Theodoros Argyropoulos, Rama Calaga, Heiko Damerau, Leandro Intelisano, Birk Karlsen-Baeck, James A. Mitchell, Nicolas Mounet, Sigurd Nese, Elena Shaposhnikova, and Helga Timko

12th HL-LHC Collaboration Meeting, CERN, 19-22 September 2022

Recap on single-bunch stability

- Persistent oscillations after injection indicate that we are above the threshold of loss of Landau damping (LLD)

Persistent oscillations after injection



H. Timko et al., HB2018

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- The LLD threshold is defined as*

$$N_{\mathrm{th}} \propto \frac{V_{\mathrm{rf}} \tau^4}{(\mathrm{Im}Z/k)_{\mathrm{eff}}\, f_c}$$

Effective impedance

Effective cut-off frequency

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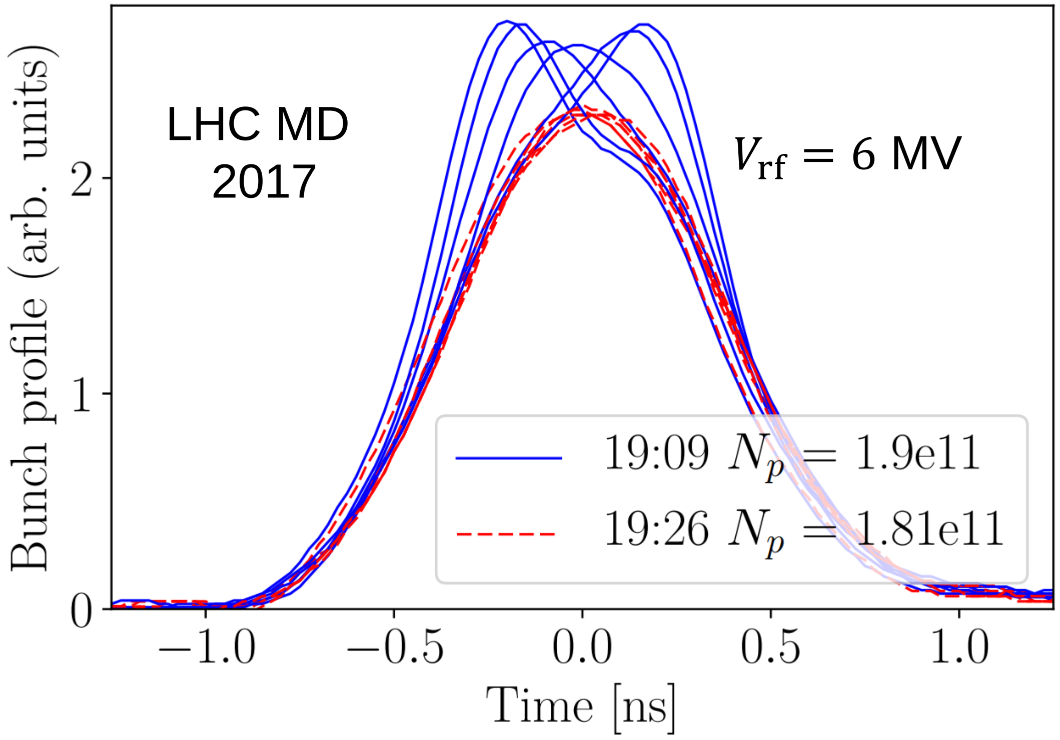

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**IK, T. Argyropoulos, and E. Shaposhnikova, PRAB 2021*

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Effective impedance — Effective cut-off frequency

- Complicated impedance model can be substituted by an effective broad-band (BB) impedance**

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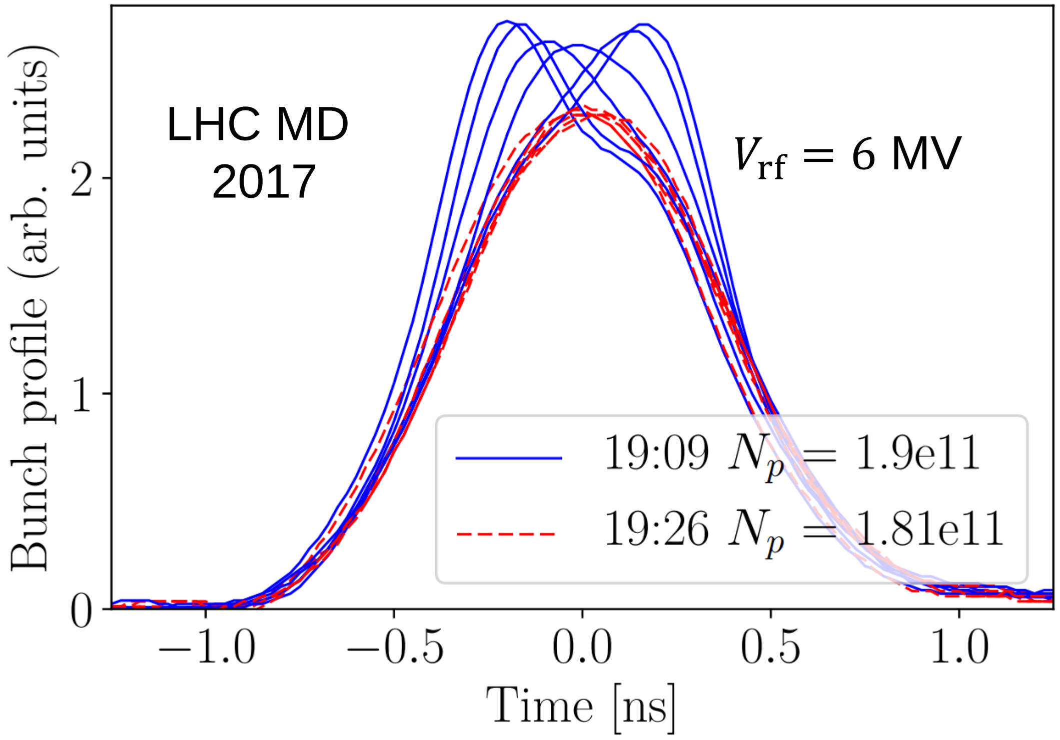

H. Timko et al., HB2018

***IK, T. Argyropoulos, S. Nese, and E. Shaposhnikova, HB2021*

Destabilizing effect of broad-band impedance

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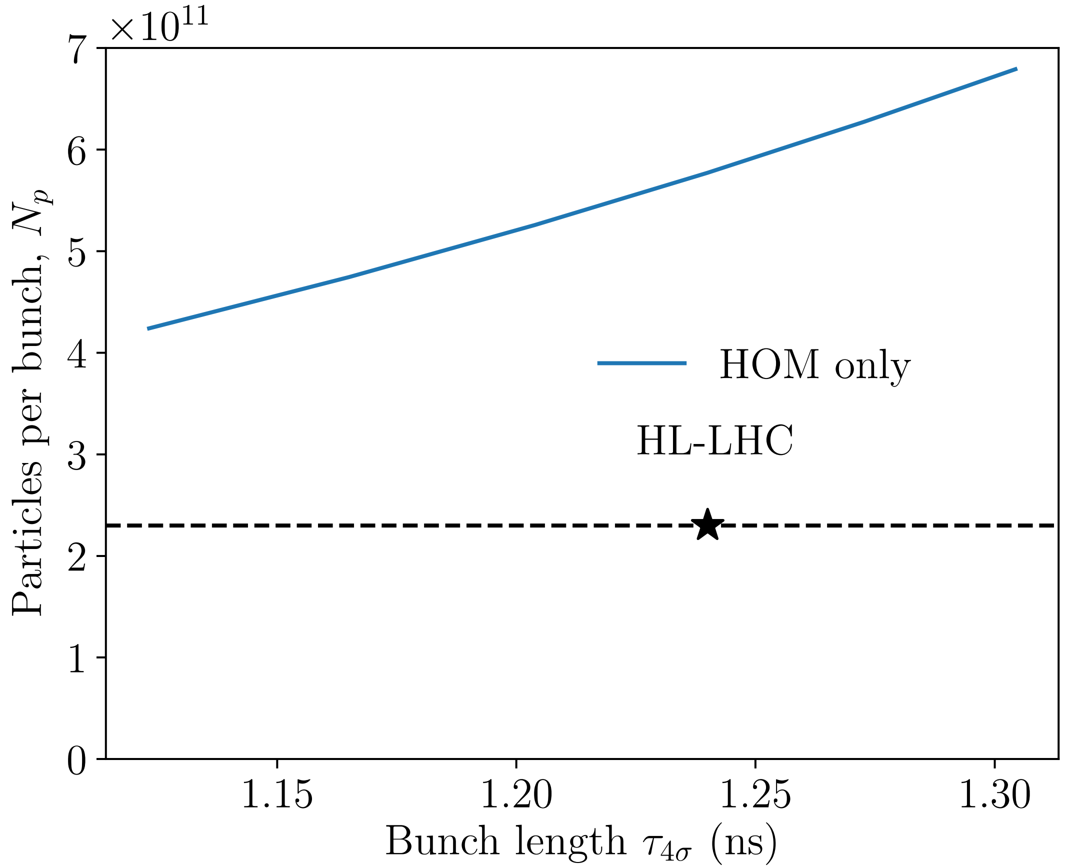
Instability thresholds at $E = 450$ GeV for V_{rf} = 8 MV:
HOM - $R_{\mathrm{sh}} = 4 \times 71$ kΩ, f_r = 582 MHz



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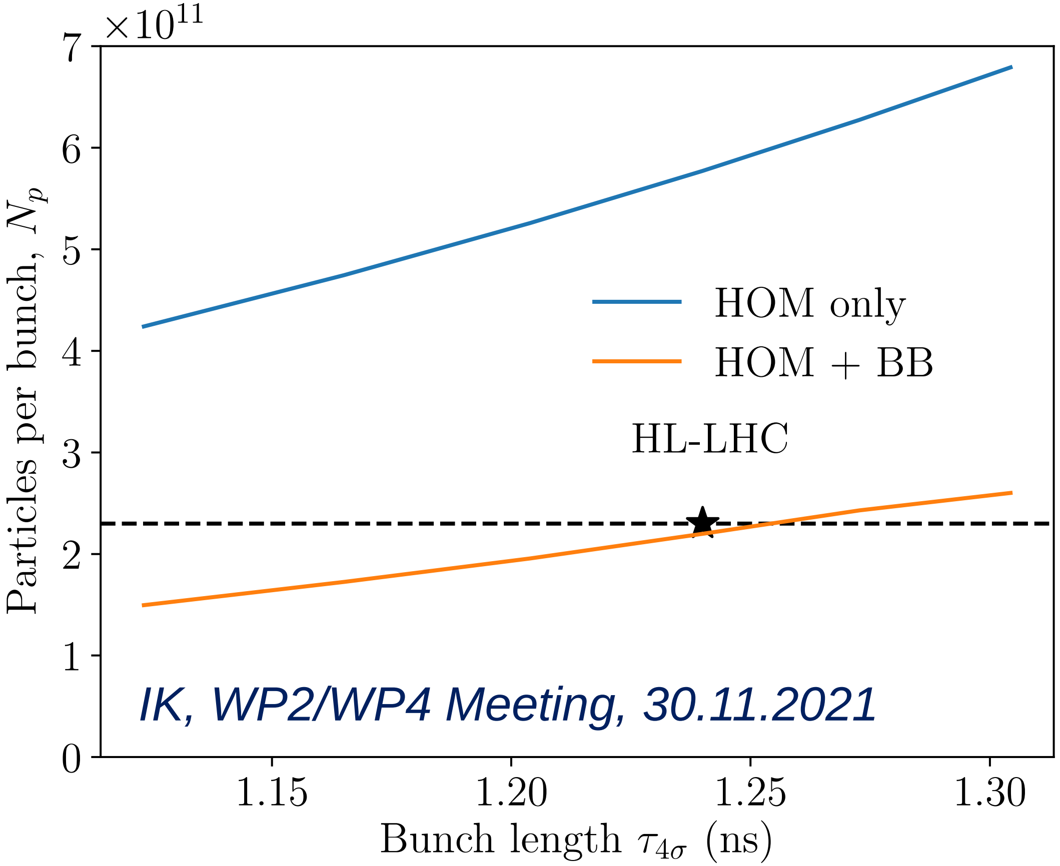

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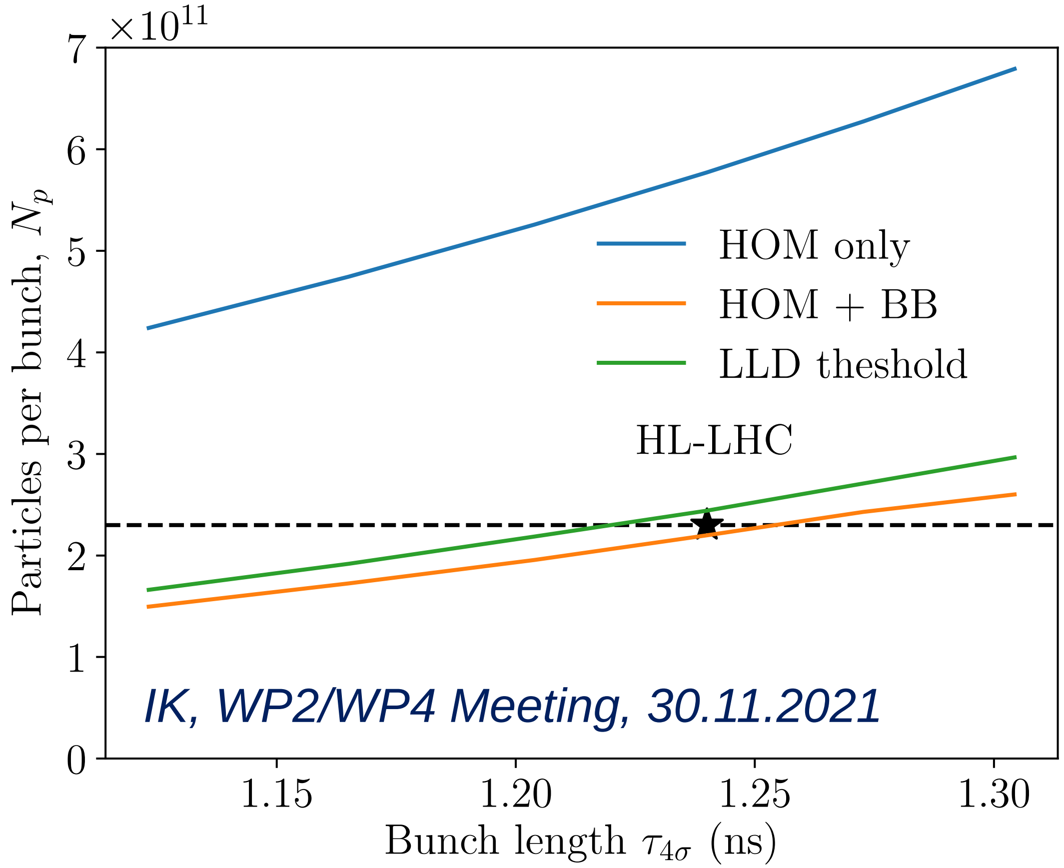

Theoretical model

$$\text{Instability threshold*} \propto \frac{1}{\text{Contribution of BB impedance} + \text{Contribution of HOM impedance}}$$

Contribution of BB impedance $\propto (\mathrm{Im}Z/k)_{\mathrm{eff}}$ and f_c

Contribution of HOM impedance $\propto R_{\mathrm{sh}}/f_r$

***IK and E. Shaposhnikova, IPAC 2022**

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Possible scenarios	BB impedance	HOM impedance
Threshold is defined by BB imp., slow instability	Strong	Weak

**IK and E. Shaposhnikova, IPAC 2022*

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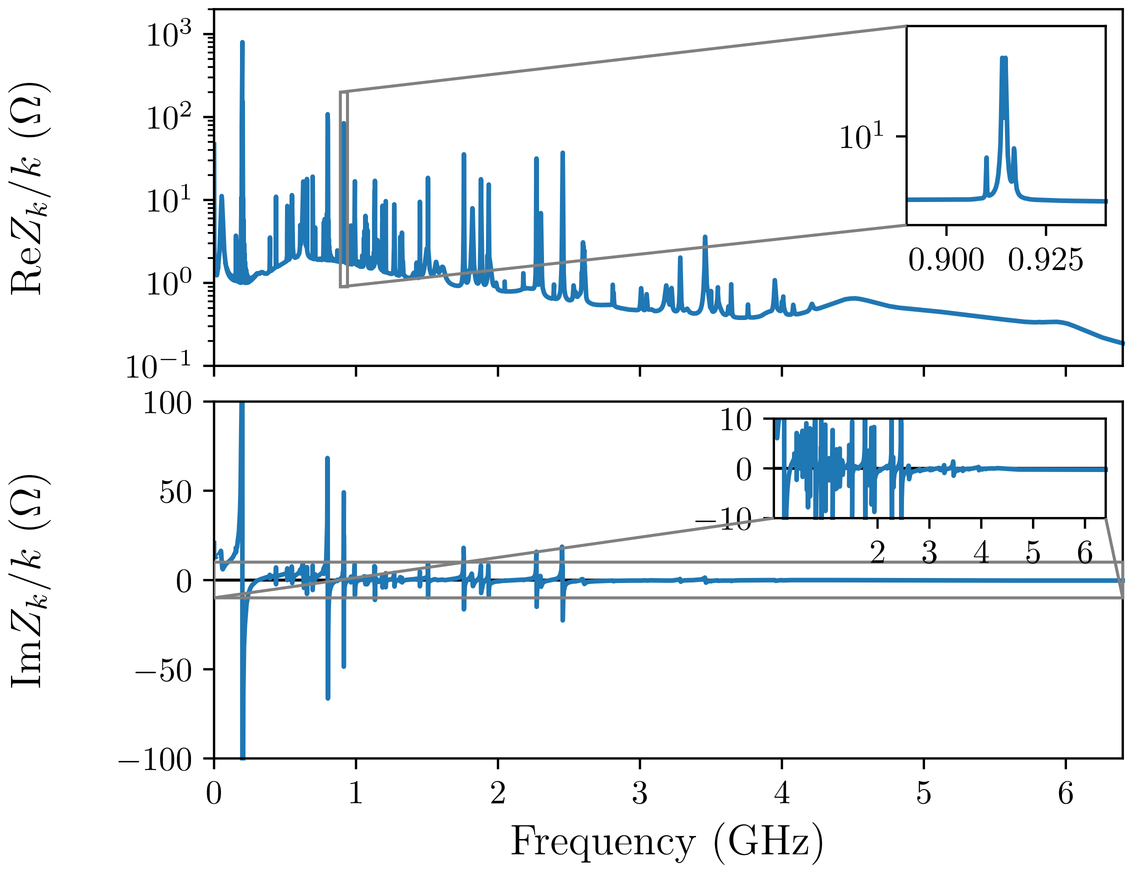
Threshold affected by both imp., fast instability	Strong	Strong

**IK and E. Shaposhnikova, IPAC 2022*

Instabilities in the SPS as testbed

SPS impedance model after LS2



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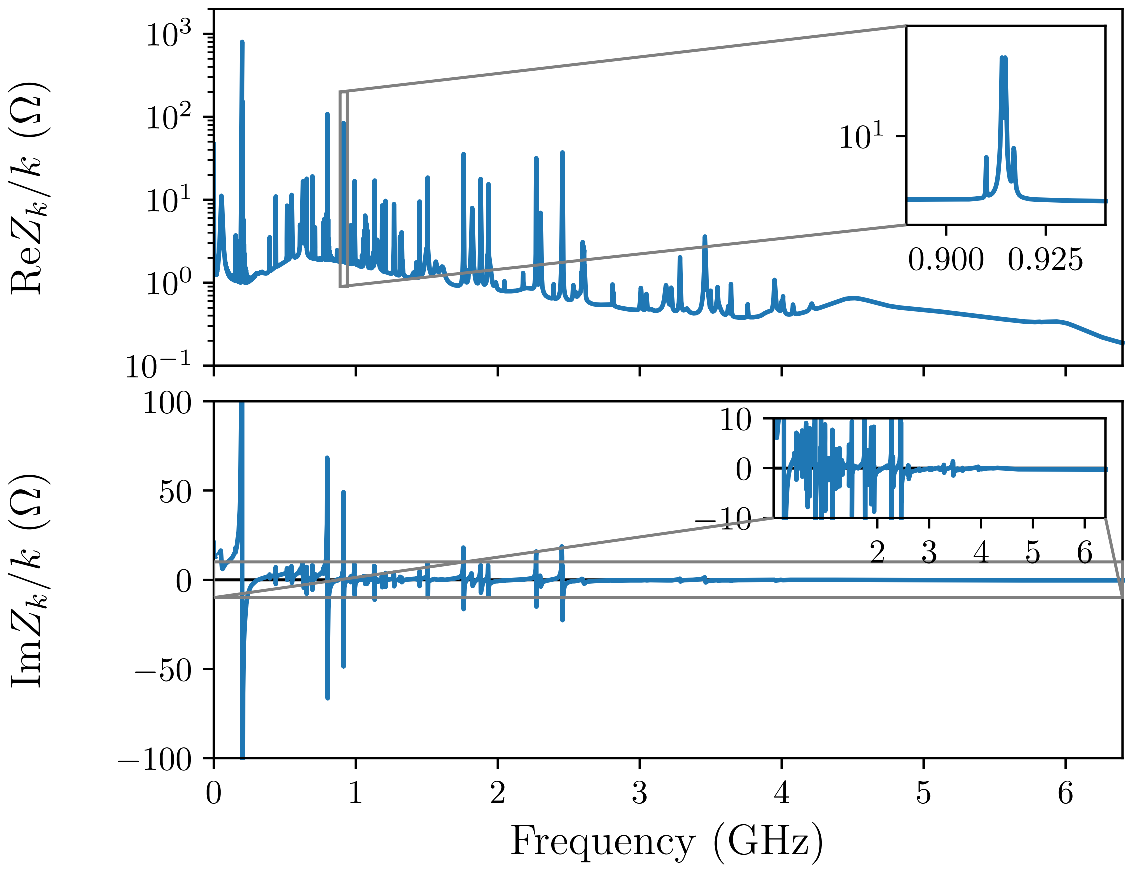
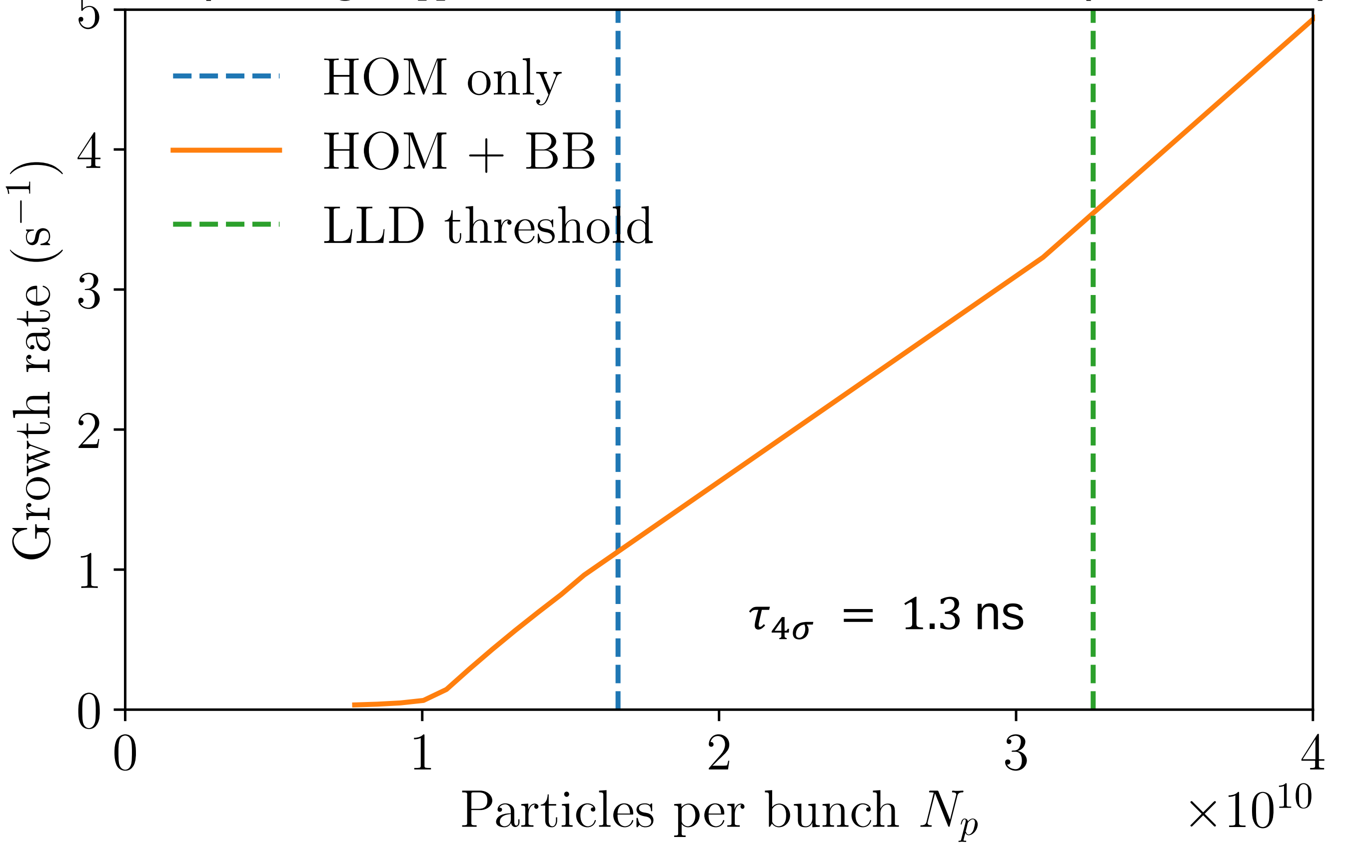


Coupled-bunch instability in **SPS** uniform filling with 25 ns spacing, V_{rf} = 7.2 MV, E = 450 GeV (MELODY)

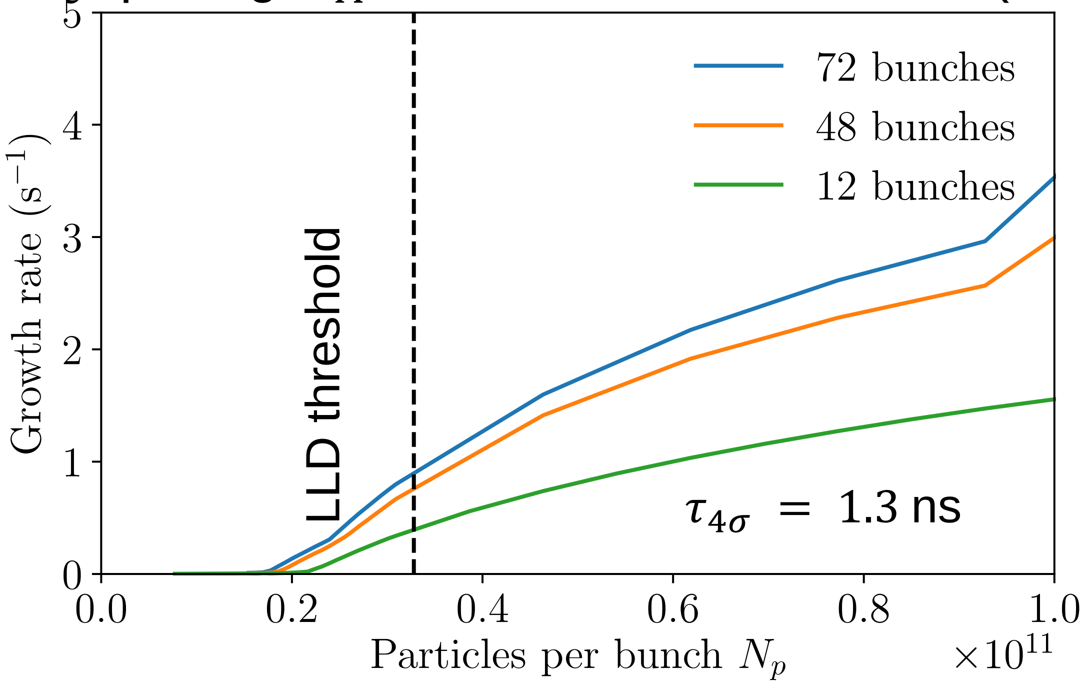


→ The lowest CBI threshold is due to HOMs at 915 MHz

→ BB impedance impacts multi-bunch stability

Comparison with simulations

Coupled-bunch instability for bunch trains with 25 ns spacing, $V_{\mathrm{rf}} = 7.2$ MV, $E = 450$ GeV (MELODY)



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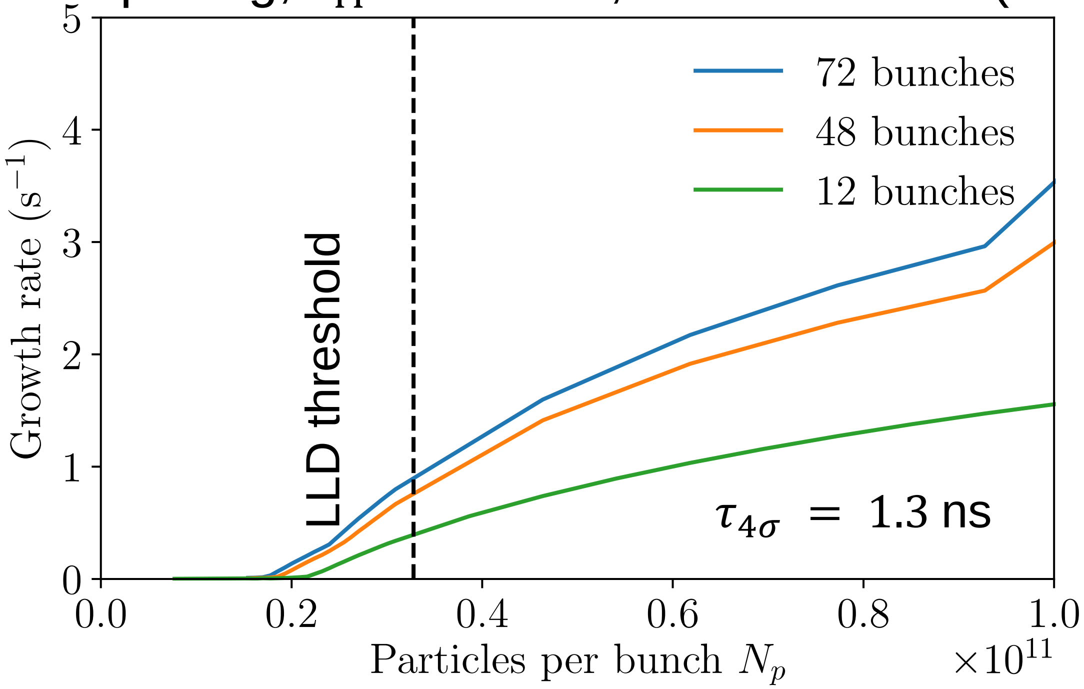
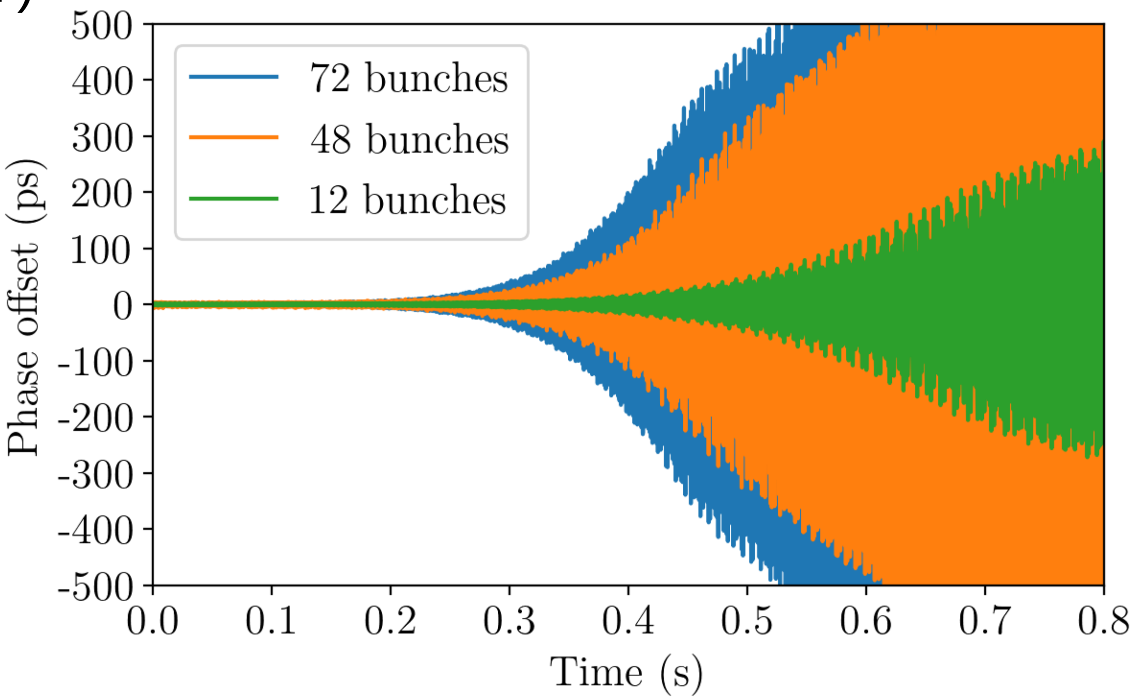


Example of simulations using BLonD



- Overall good agreement with some discrepancies
- Consistent with beam observations, as higher-harmonic RF system (800 MHz) is necessary to reach even LHC nominal intensity
- More accurate measurements to be done

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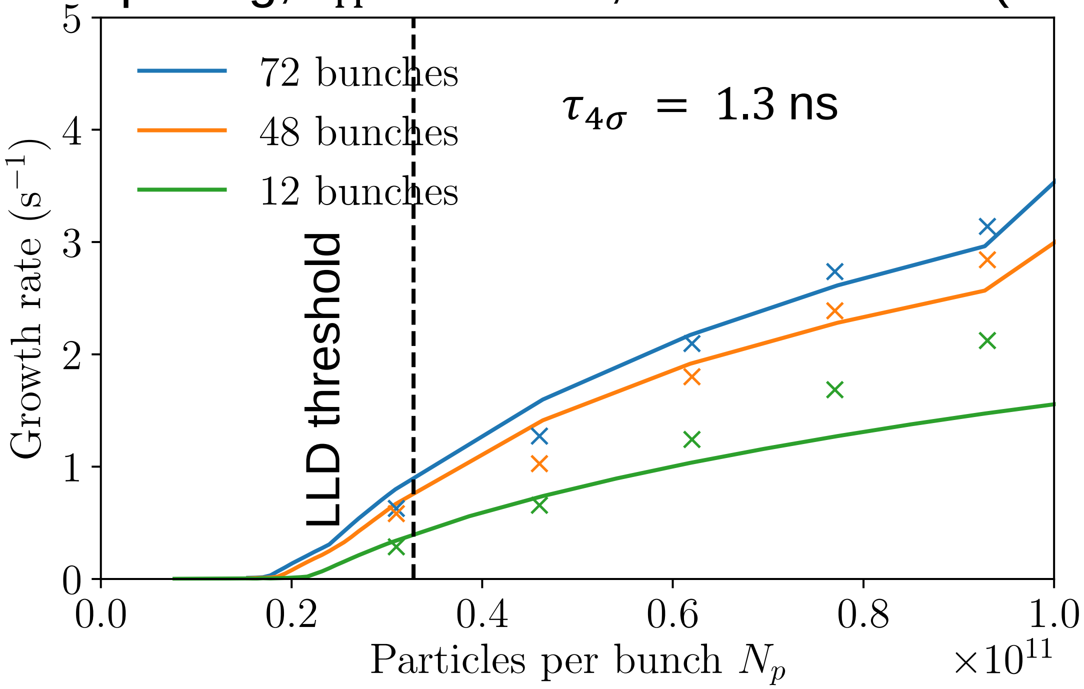

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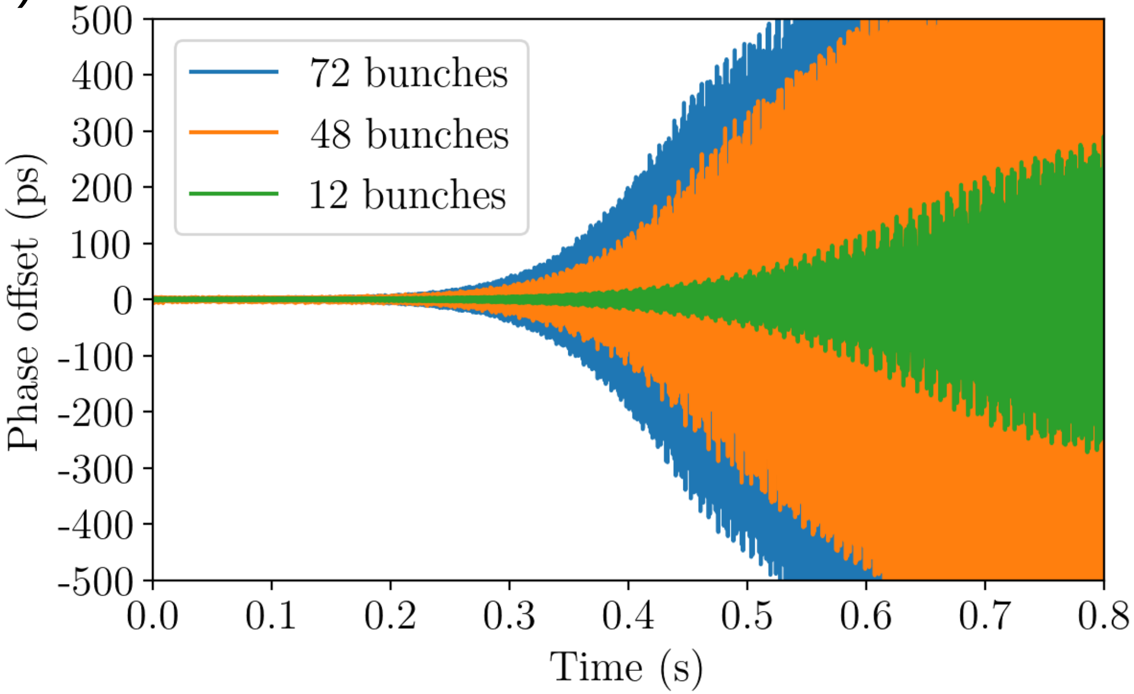

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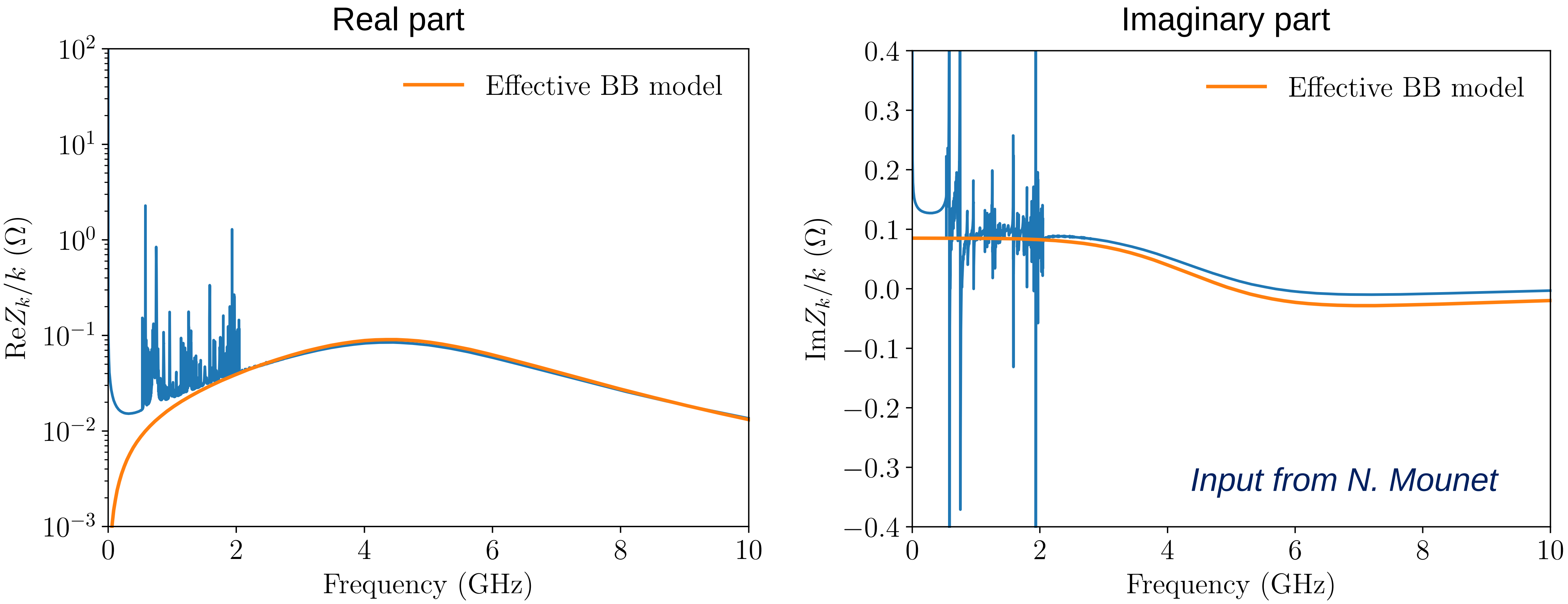
HL-LHC impedance model



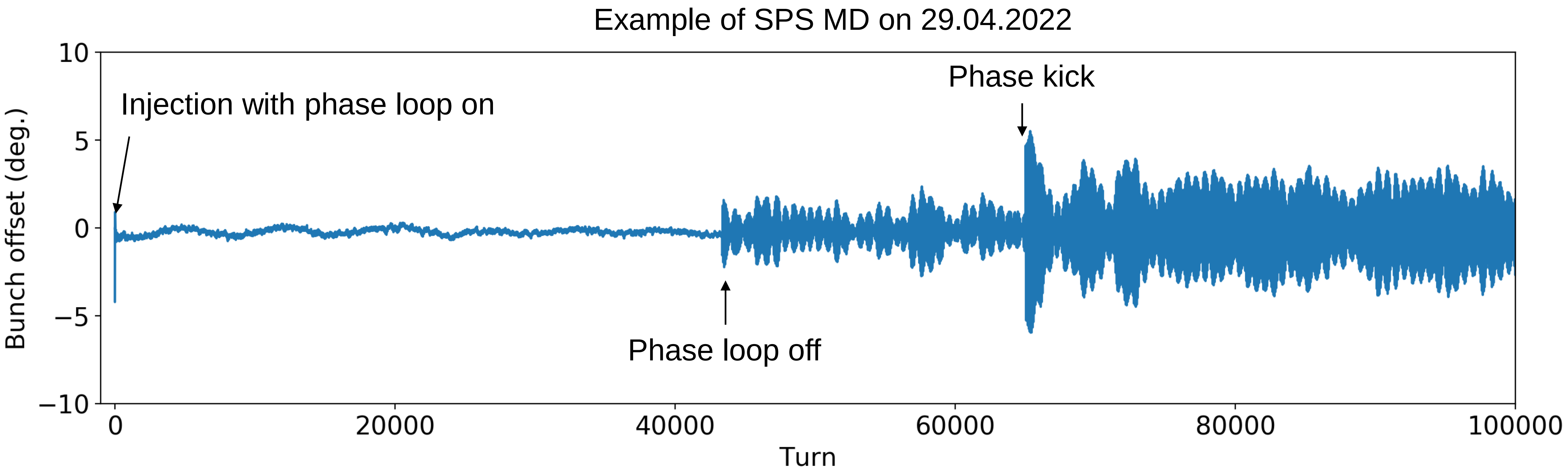
BB contributions from different elements are added as a single BB resonator with f_r = 5 GHz

→ It dominates the effective impedance of HL-LHC

→ Model refinement is necessary for precise predictions of instability threshold (new fellow is arriving)

Beam-based measurements of LLD threshold

Different measurements were performed before LS2 (*J. E. Muller, PhD thesis, 2016)*



→ This technique is already used in the SPS and PS *(PhD project of L. Intelisano)*

→ Precise knowledge of RF voltage is important *(see details in talk by B. Karlsen-Baeck)*

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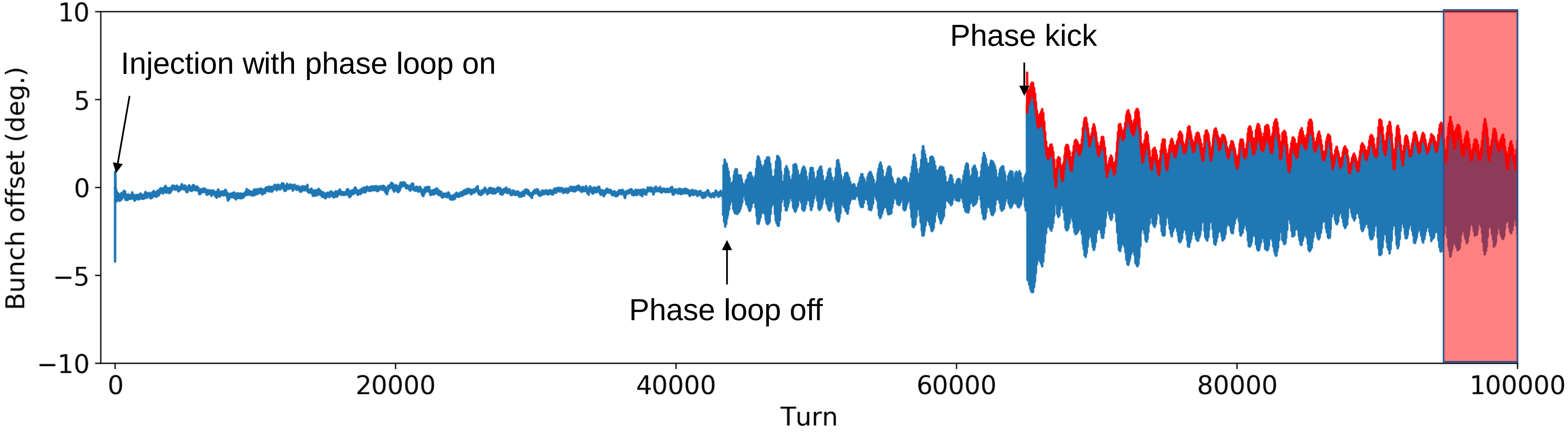
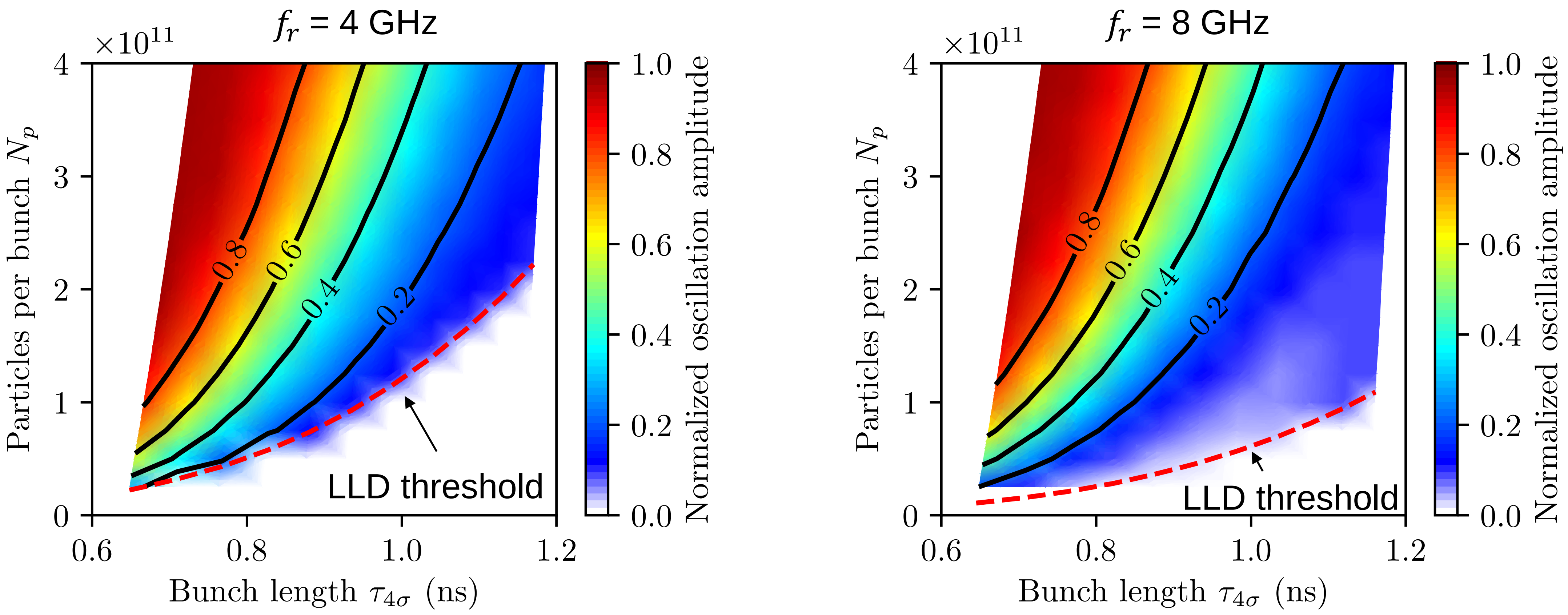
Example of SPS MD on 29.04.2022



→ This technique is already used in the SPS and PS *(PhD project of L. Intelisano)*
→ Precise knowledge of RF voltage is important *(see details in talk by B. Karlsen-Baeck)*
→ Residual oscillation amplitude contains information about impedance
(IK, T. Argyropoulos, and E. Shaposhnikova, PRAB, 2021)

Sensitivity to the cut-off frequency

MELODY results for single BB impedance at LHC flatbottom



→ Oscillation amplitude after the kick strongly depends on the effective cut-off frequency

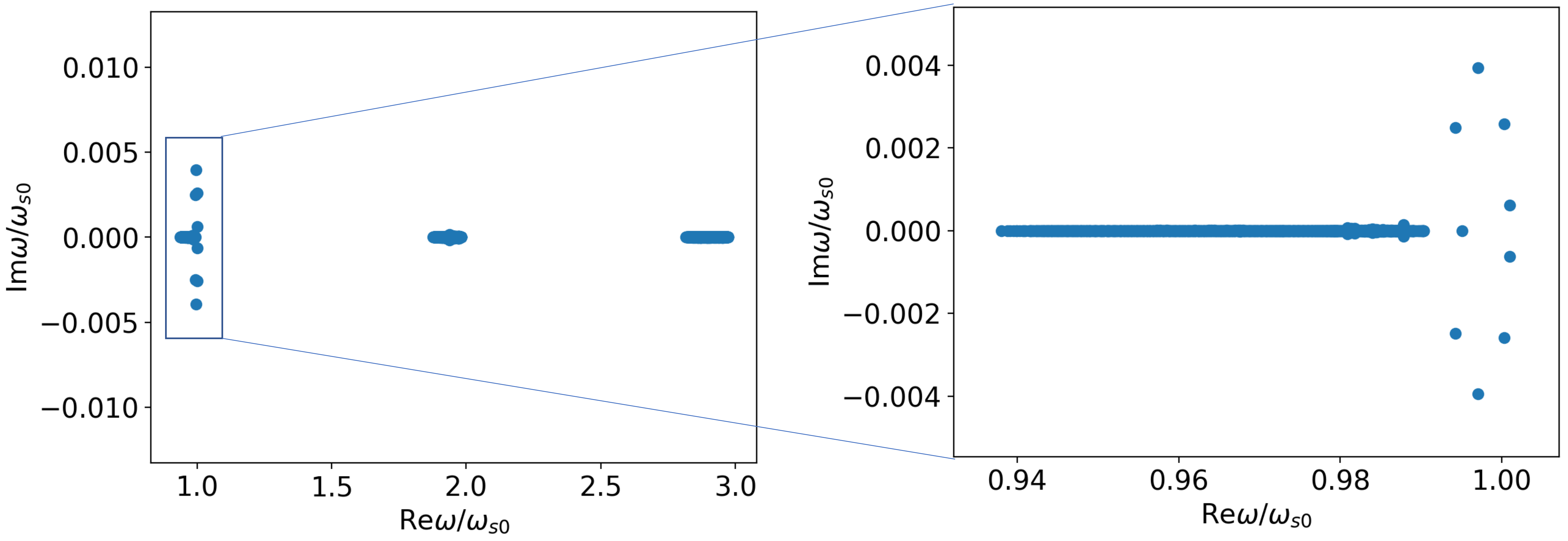
→ Scanning parameter space allows to probe longitudinal impedance

Summary

- Loss of Landau damping and coupled-bunch instability are closely related in the longitudinal plane
- The theoretical model is developed to describe semi-analytical results and confirmed by simulations
- Instability driven by HOMs of crab cavities could be a serious performance limitation since LLD was already observed in LHC
- Good knowledge of the (HL-)LHC impedance (especially broad-band part) is crucial: MDs in the LHC and CST simulations are necessary

Thank you for your attention!

Explanation of discrepancy

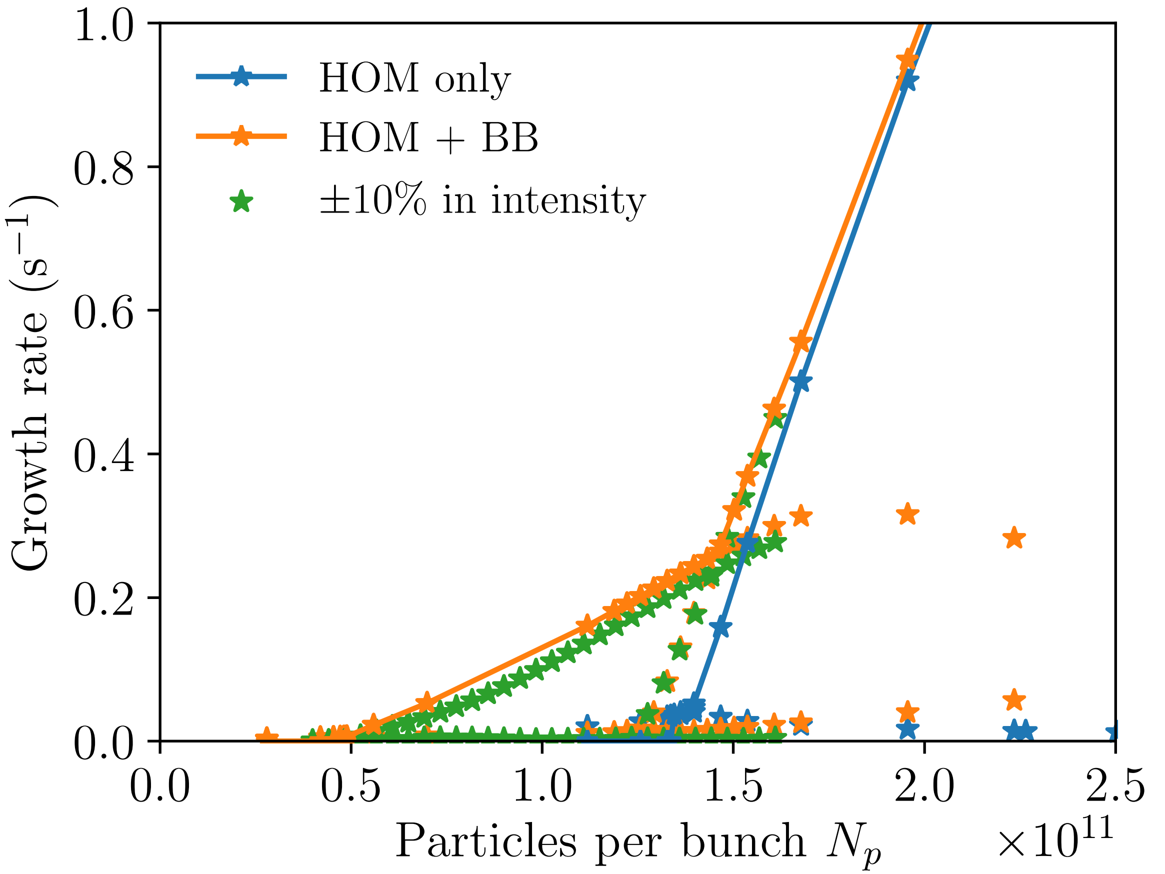


Possible cures (1/3)

Synchrotron frequency variation due to bunch-by-bunch parameter variation (bad for luminosity, but unavoidable) and transient beam loading can help to suppress LLD type instability

→ Some reduction of growth rates is observed for a toy model (9 bunches)

Example for short bunches of ~0.8 ns



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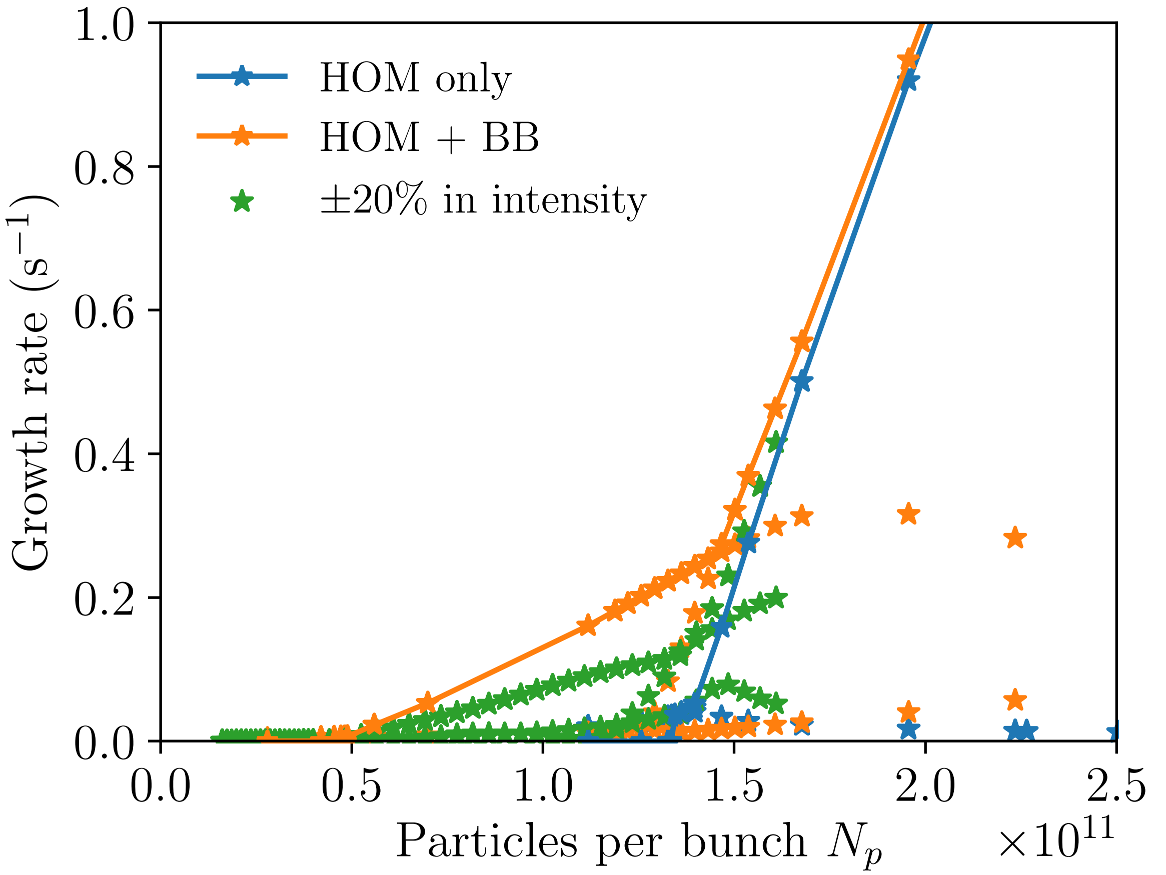
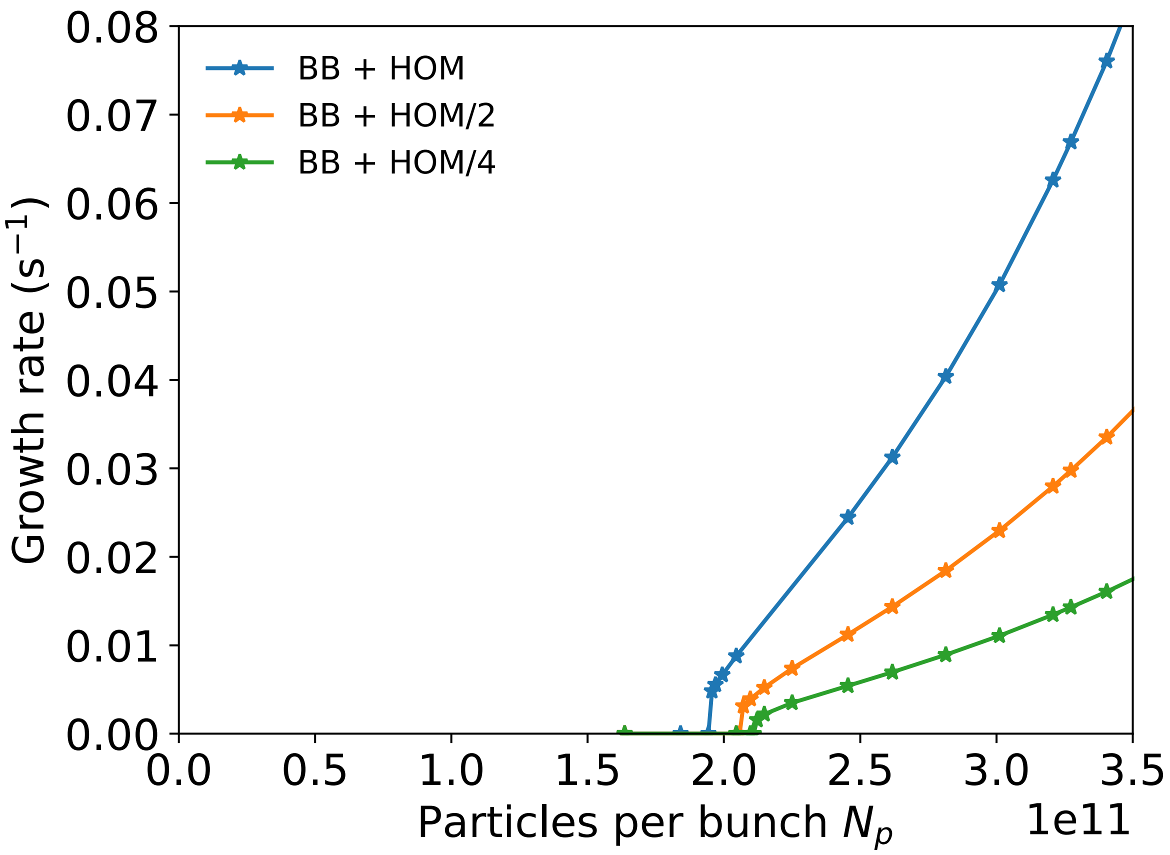


Possible cures (2/3)

Further damping of HOM impedance

→ Threshold slightly increases, and growth rate reduces, but instability might still develop due to time spent at flat-bottom

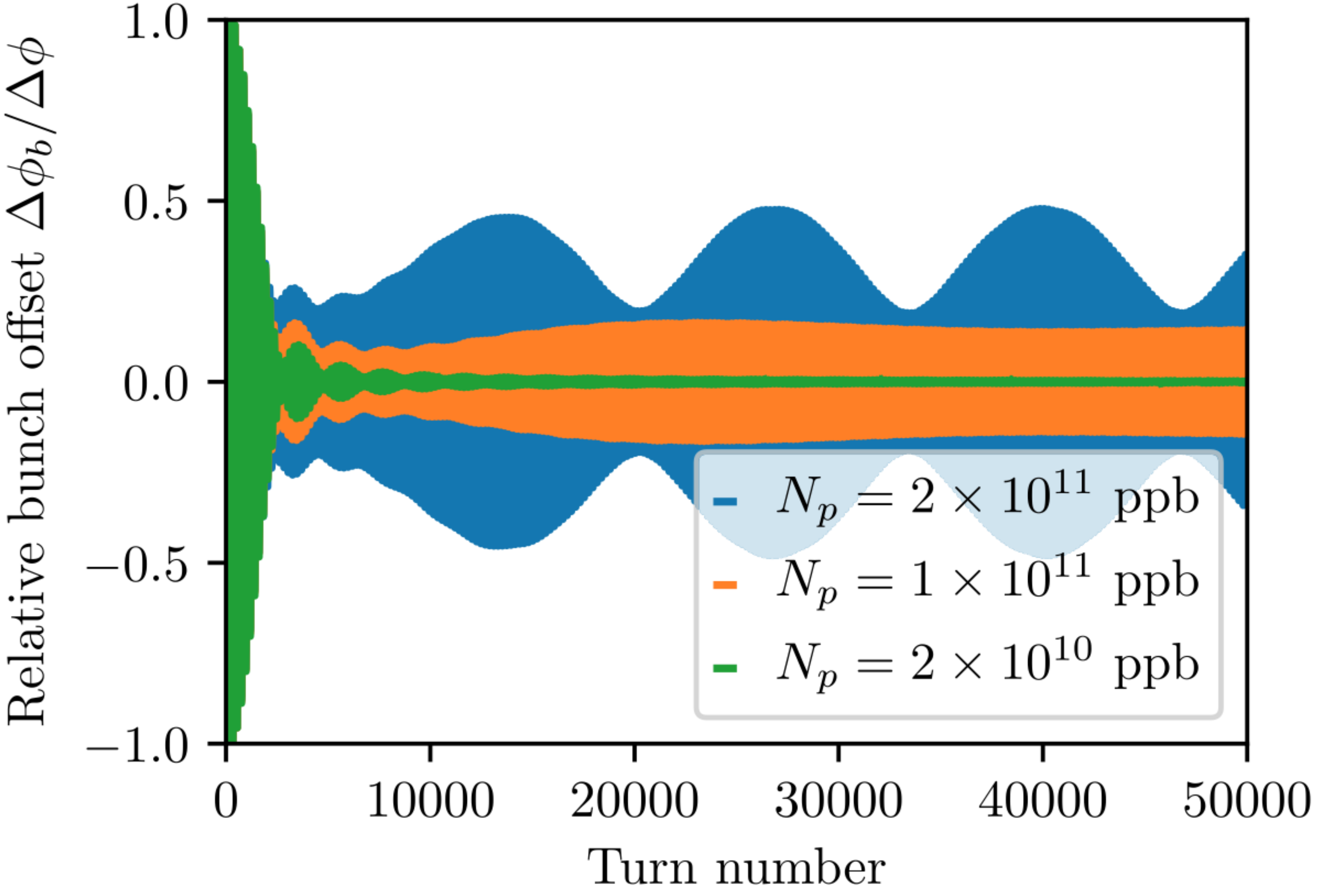


$E = 450$ GeV, $V_{\mathrm{rf}} = 8$ MV, $\mu = 2, \tau_{4\sigma} \approx 1.2$ ns

Possible cures (3/3)

Increase of LLD threshold and CBI threshold by

- Increase of RF voltage in LHC and SPS (more power or additional cavities) to increase emittance
- Adding 800 MHz RF system (smaller than 4 MV might be sufficient to compromise losses)
- Increase bunch length/emittance in SPS and capture in 200 MHz + 400 MHz RF systems *(J., Esteban-Müller, PhD thesis, 2016)*, but rather high RF voltages are needed



Relative bunch offset $\Delta\phi_b/\Delta\phi$
1.0
0.5
0.0
−0.5
−1.0
0
10000
20000
30000
40000
50000
Turn number
$N_p = 2 \times 10^{11}$ ppb
$N_p = 1 \times 10^{11}$ ppb
$N_p = 2 \times 10^{10}$ ppb

Reduction of CBI threshold due to ImZ/k

HL-LHC will operate at higher intensity compared to LHC + crab cavities will be installed with non-negligible longitudinal impedance

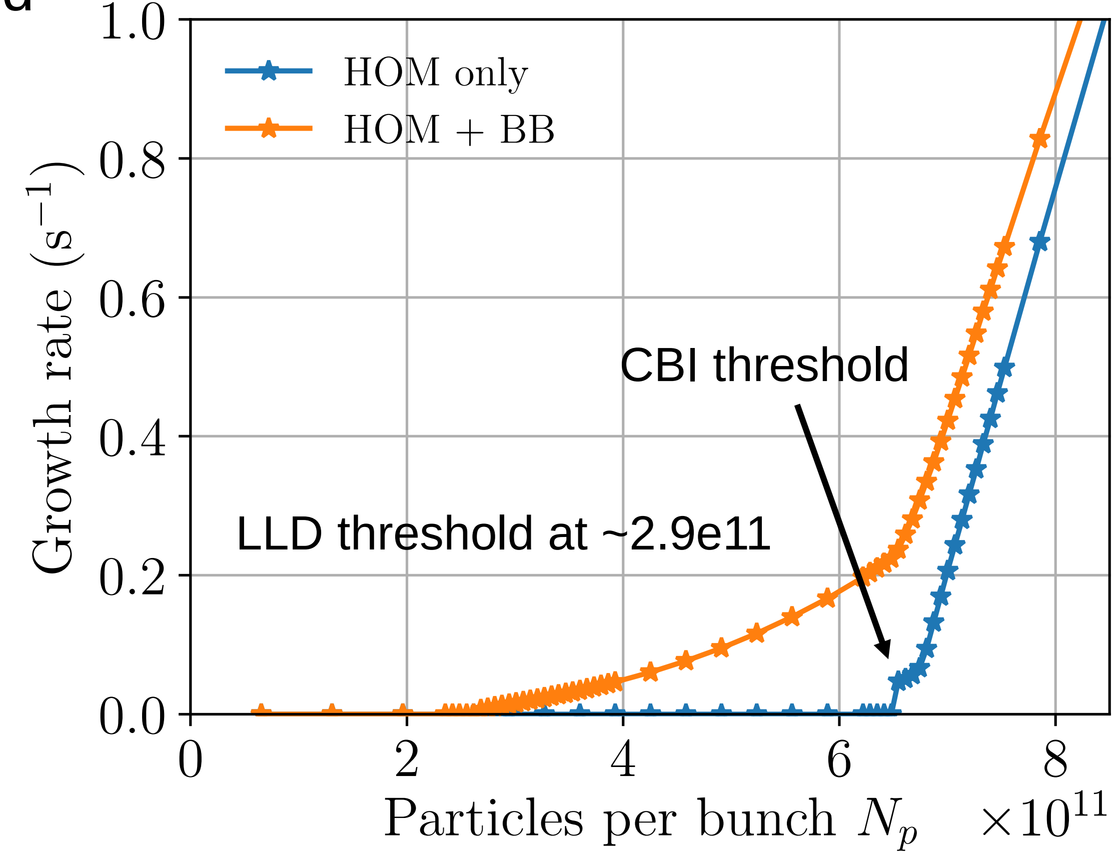
Results for broad-band $(\mathrm{Im}Z/k)_{\mathrm{eff}} \approx 0.075\ \Omega$ + narrow-band (HOM of DQW CC: $R_{\mathrm{sh}} = 4 \times 71\ \mathrm{k}\Omega$, f_r = 582 MHz) resonators

→ For this HOM, the CBI threshold is about ~3 higher than HL-LHC intensity

→ In the presence of BB impedance, the CBI threshold is reduced at ~ LLD threshold

→ Similar effect is seen in SPS

Coupled-bunch instability in **HL-LHC** (MELODY)



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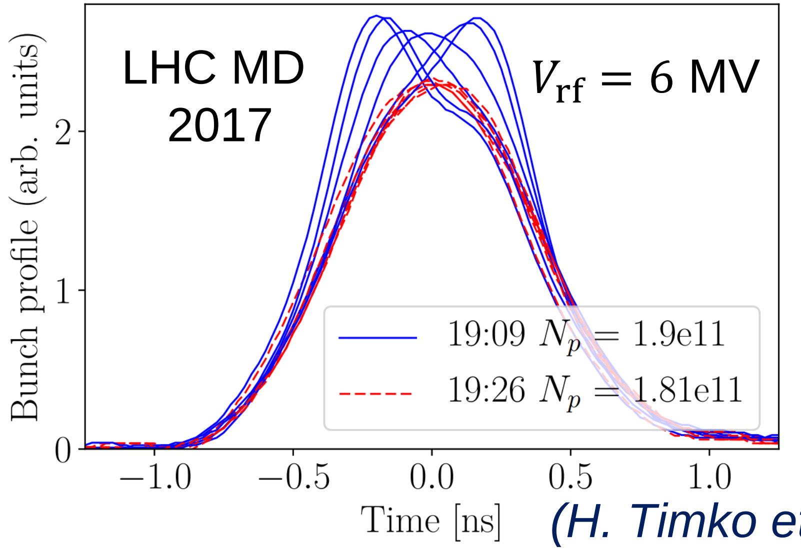
Introduction

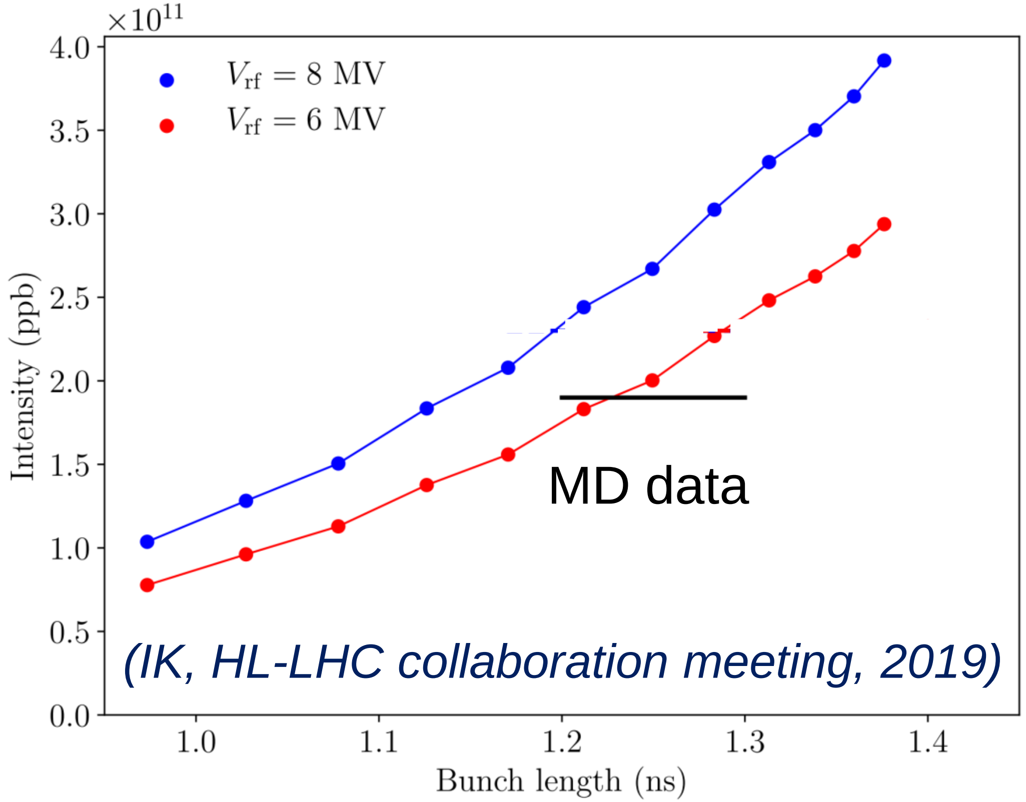
Coupled-bunch instabilities (CBI) were not observed so far, contrary to the loss of Landau damping (LLD) due to inductive impedance $\mathrm{Im}Z/k$ $(k = f/f_0)$

Persistent oscillations after injection



(H. Timko et al., HB2018)

LLD threshold (MELODY) at 450 GeV for smoothed imp. (resistive wall + broad-band model at 5 GHz)



(IK, HL-LHC collaboration meeting, 2019)

→ During 20 min oscillations lead to ~10 % bunch lengthening and ~5% particle loss
→ New approach to compute the LLD threshold was developed *(IK, TA, ES, PRAB 2021)*

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