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IPAC22

Suppression of Crab Cavity RF Noise-Induced Emittance Growth by Beam Transverse Impedance

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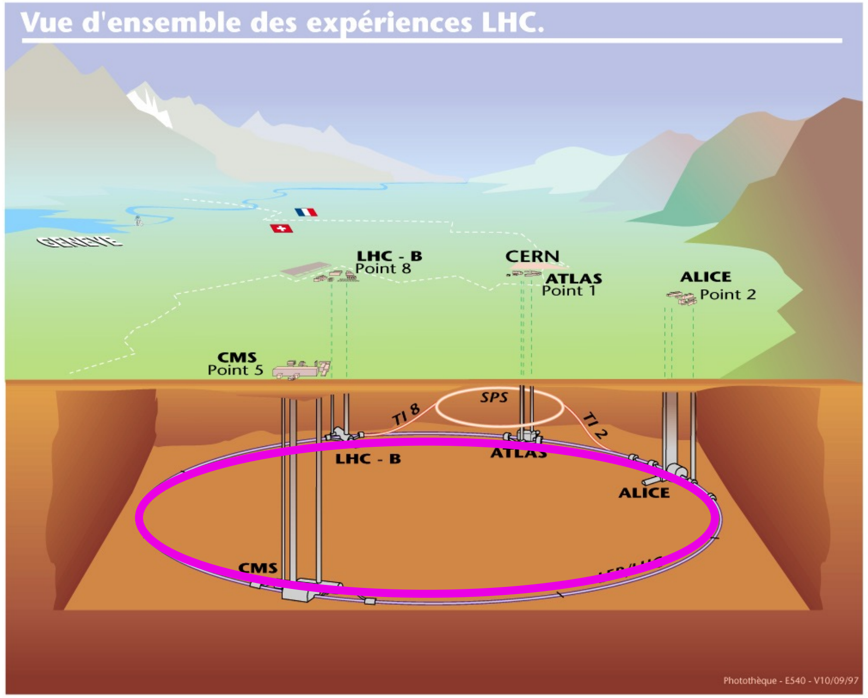
Introduction

Crab Cavities for the HL-LHC

HiLumi HL-LHC PROJECT

- High Luminosity (**HL-LHC**) project is the **upgrade of the LHC machine**, which aims to increase its integrated luminosity by a factor of 10.



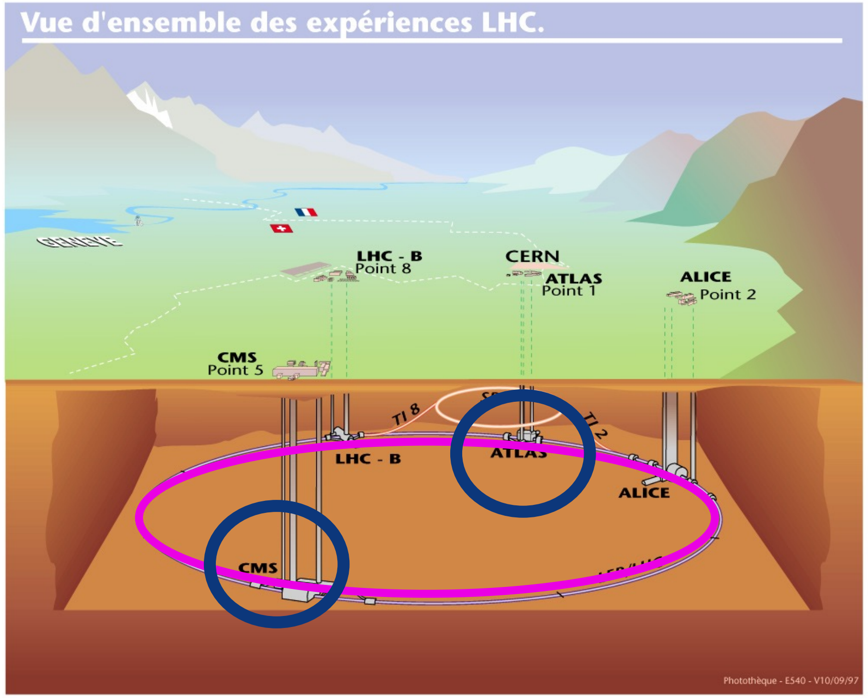
Luminosity in a collider

$$\mathcal{L} = \frac{n_b f_{\rm rev} N_1 N_2}{4\pi \sigma_x \sigma_y} \frac{1}{\sqrt{1 + (\frac{\sigma_z}{\sigma_{\rm xing}} \frac{\alpha}{2})^2}}$$

where f_{rev} the revolution freuency of the machine, n_b the number of colliding bunch pairs, $N_{1,2}$ the bunch intensities, $\sigma_{x,y}$ the transverse beam size at the interaction point, σ_z the rms bunch length, σ_{xing} the transverse beam size in the crossing plane and α is the full crossing angle.

Crab Cavities for the HL-LHC

- High Luminosity (**HL-LHC**) project is the **upgrade of the LHC machine**, which aims to increase its integrated luminosity by a factor of 10.
- **Crab Cavities** are a key component for the HL-LHC as they will **restore the luminosity reduction** caused by the crossing angle, in the interaction points of **ATLAS** and **CMS.**



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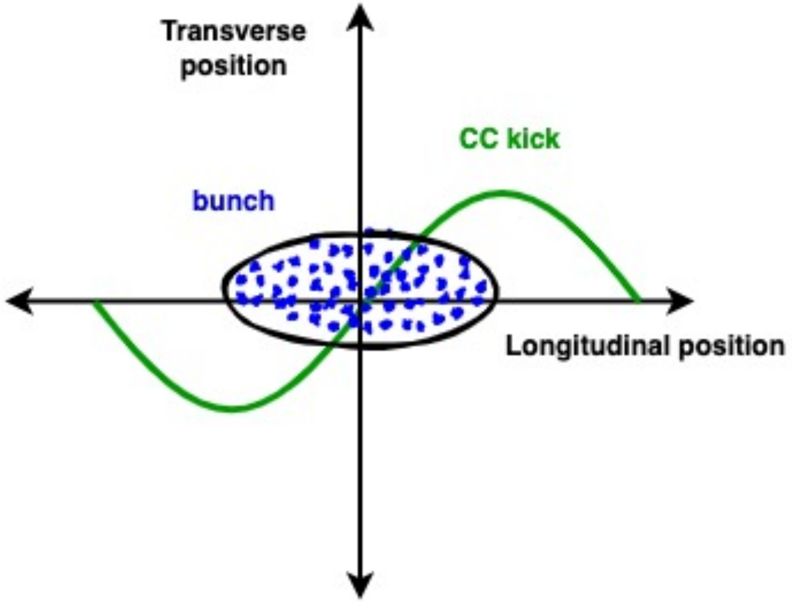
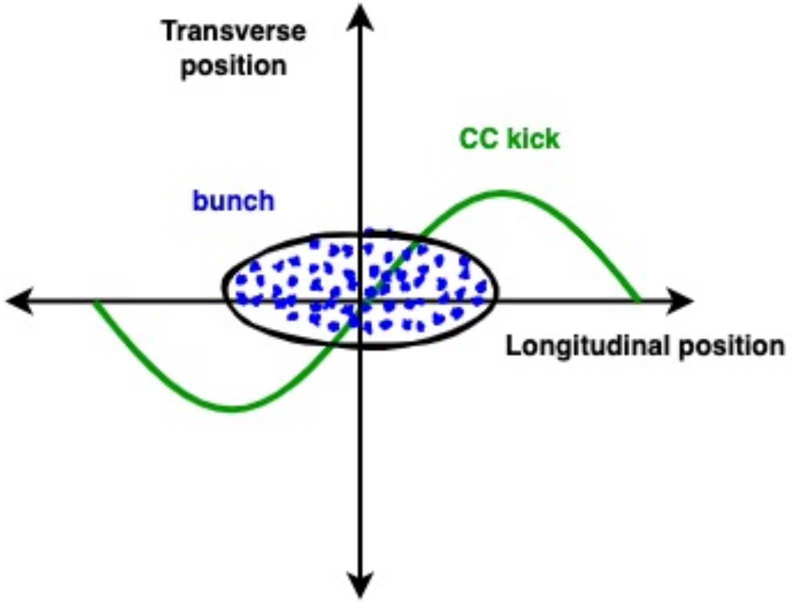
Crab Cavity technology

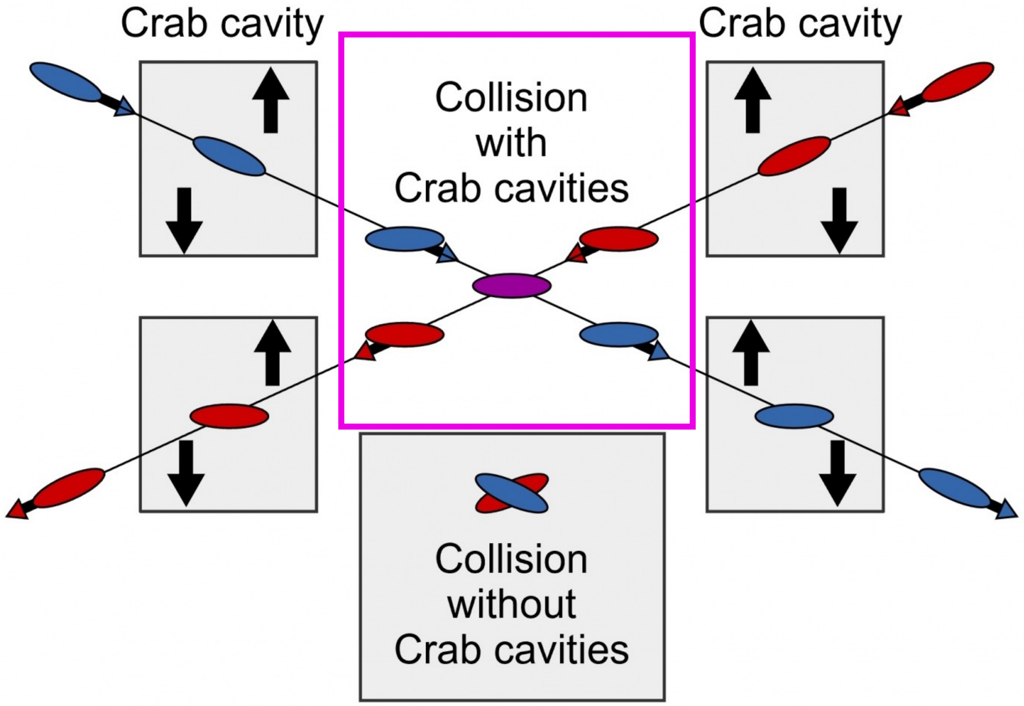
- RF cavity providing **transverse kick** to particles **depending** on their **longitudinal position** within the bunch.
- Head and tail receive opposite deflection while particles at the centre remain unaffected.



Crab Cavity technology

- RF cavity providing **transverse kick** to particles **depending** on their **longitudinal position** within the bunch.
- Head and tail receive opposite deflection while particles at the centre remain unaffected.
- The **bunch rotates,** and the **head-on collision** **is restored** at the interaction points.





Transverse emittance growth from Crab Cavity RF noise

RF noise in the Crab Cavity

- **Noise** in the Crab Cavity RF system results in **undesired transverse emittance growth** and therefore **loss of luminosity**.

RF noise in the Crab Cavity

➢ **Noise** in the Crab Cavity RF system results in **undesired transverse emittance growth** and therefore **loss of luminosity**.

Very tight HL-LHC target values

↓

Maximum luminosity loss from the Crab Cavity RF noise emittance growth → **1%**

↓

Maximum Crab Cavity RF noise induced **emittance growth** → **2%/h**

↓

A good **understanding of the emittance growth** due to Crab Cavity RF noise is **essential**!

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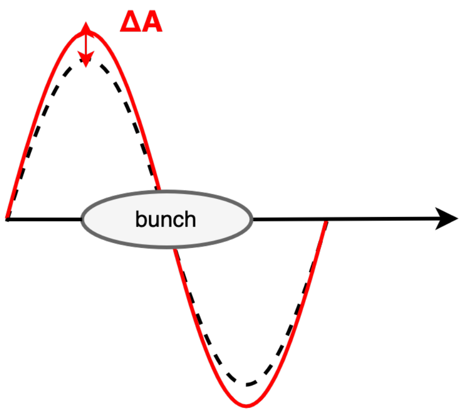
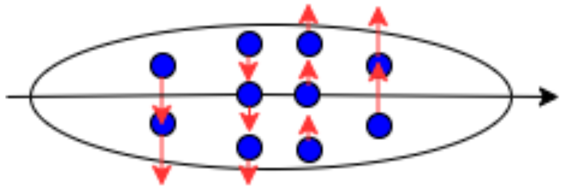
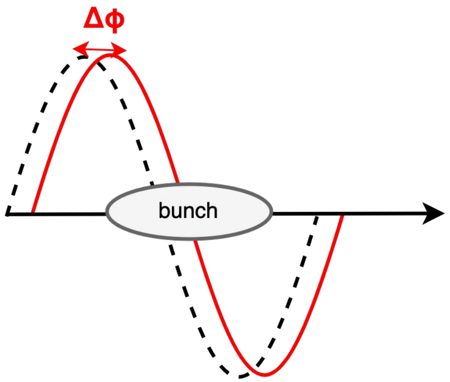
Amplitude noise

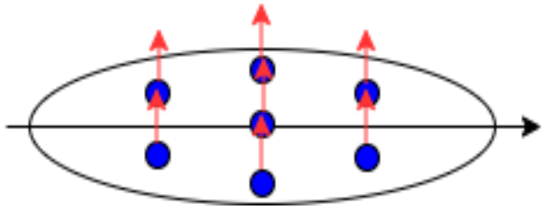




The head and the tail of the bunch are kicked in opposite directions → **Intra-bunch oscillations**

Phase noise





All the particles within the bunch experience kicks that are in phase → centroid shift → **dipole / mode 0 motion**

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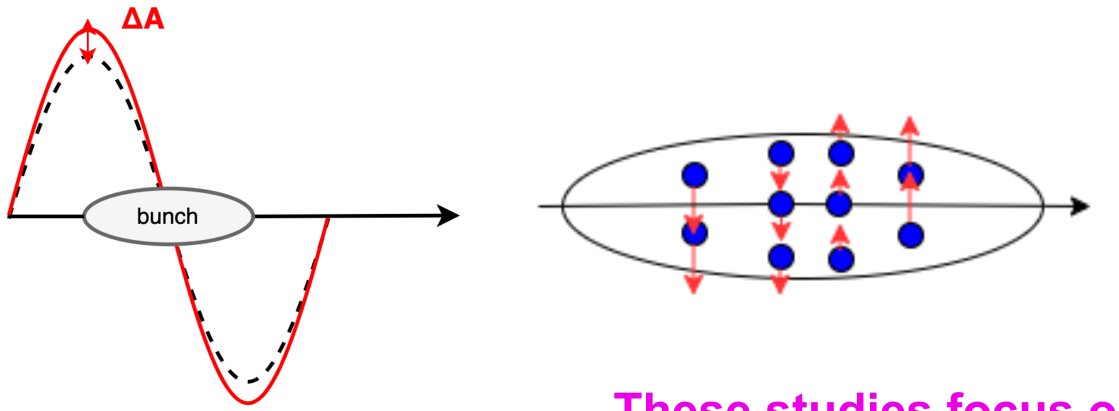
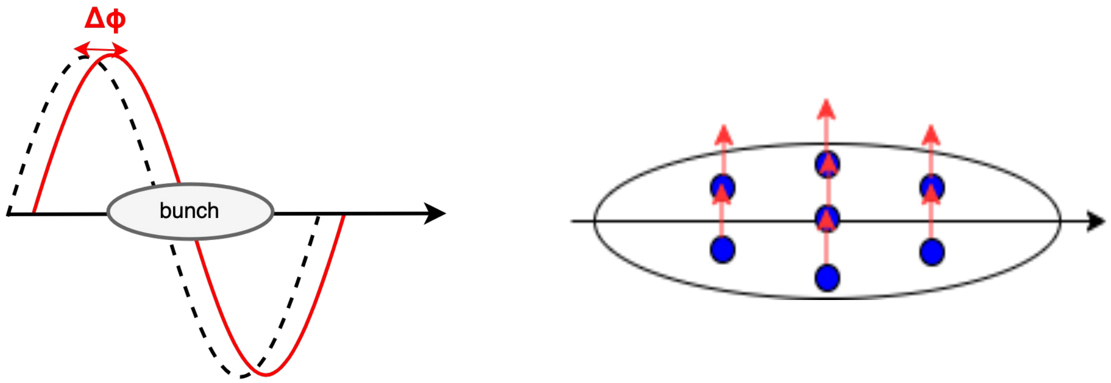


The head and the tail of the bunch are kicked in opposite directions → **Intra-bunch oscillations**

These studies focus on phase noise.

Phase noise



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Theoretical formalism

- The **theoretical model**(*) was derived to **predict the emittance growth** from Crab Cavity noise.

PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 101001 (2015)

Transverse emittance growth due to rf noise in the high-luminosity LHC crab cavities

P. Baudrenghien
CERN, 1211 Geneva, Switzerland

T. Mastoridis
California Polytechnic State University, San Luis Obispo, California 93407, USA
(Received 23 June 2015; published 5 October 2015)

The high-luminosity LHC (HiLumi LHC) upgrade with planned operation from 2025 onward has a goal of achieving a tenfold increase in the number of recorded collisions thanks to a doubling of the intensity per bunch (2.2e11 protons) and a reduction of β^* to 15 cm. Such an increase would significantly expedite new discoveries and exploration. To avoid detrimental effects from long-range beam-beam interactions, the half

- The model was validated through numerical simulations (HEADTAIL).
- **Benchmarking with experimental data is essential! → Tested in SPS in 2018.**

(*) P. Baudrenghien and T. Mastoridis, "Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities," Phys. Rev. Accel. Beams 18, 101001(2015)

Experiment in 2018

- A few important points:

1.	**SPS** was used as a test bed for two **vertical** Crab Cavities **before** their installation in the **LHC**.
2.	**First time** that **proton dynamics with crab cavities** could be studied **experimentally**.
3.	**Different parameters** in SPS than in HL-LHC i.e. damper, beam-beam, energy, collisions, optics → The **results** need to be **scaled for the HL-LHC.**
4.	**Injected artificial noise much larger than targeted for HL-LHC** for better observables.

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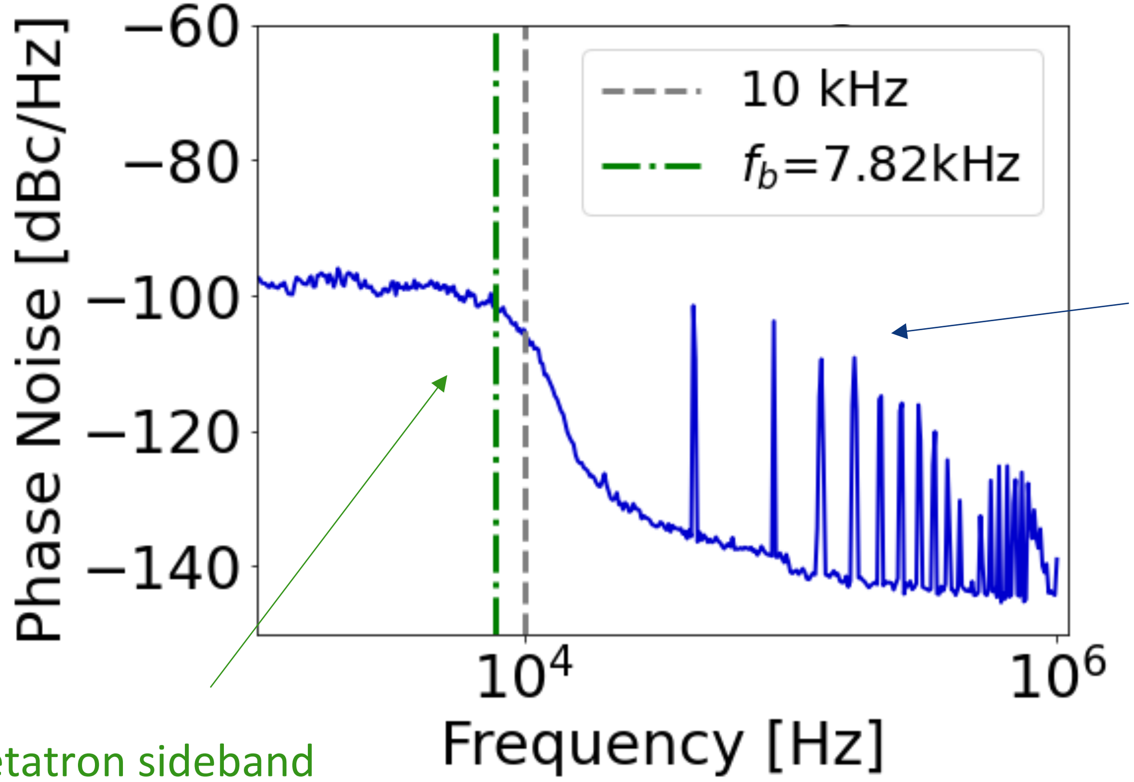
4.	**Injected artificial noise** **much larger than targeted for HL-LHC** for better observables.
5.	The **goal** is to **validate the predictions** from the **theoretical model.** **Scaling** will be needed for the **HL-LHC case**.

scaling

Experiment in 2018 – RF noise spectrum

- Mixture of amplitude and phase noise
- **Phase noise was always dominant**

Example noise power measurement in 2018



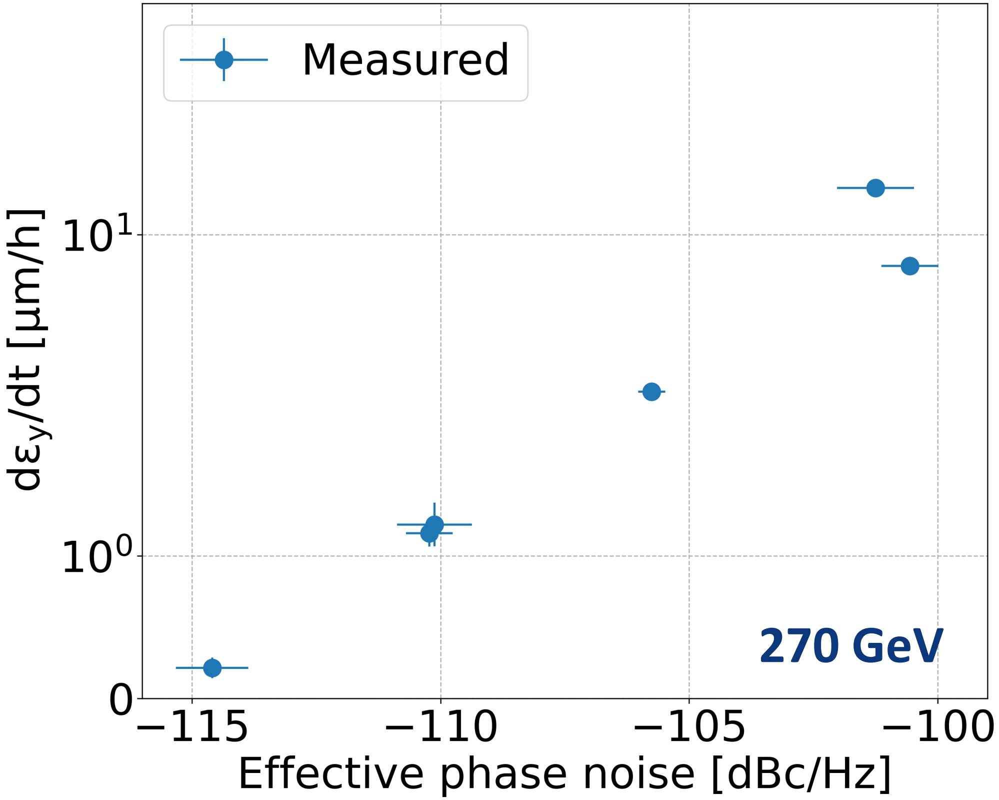
Harmonics of revolution frequency due to bunch crossing

1st betatron sideband

Experiment in 2018 - Results

- Measurements for different (phase) noise levels.

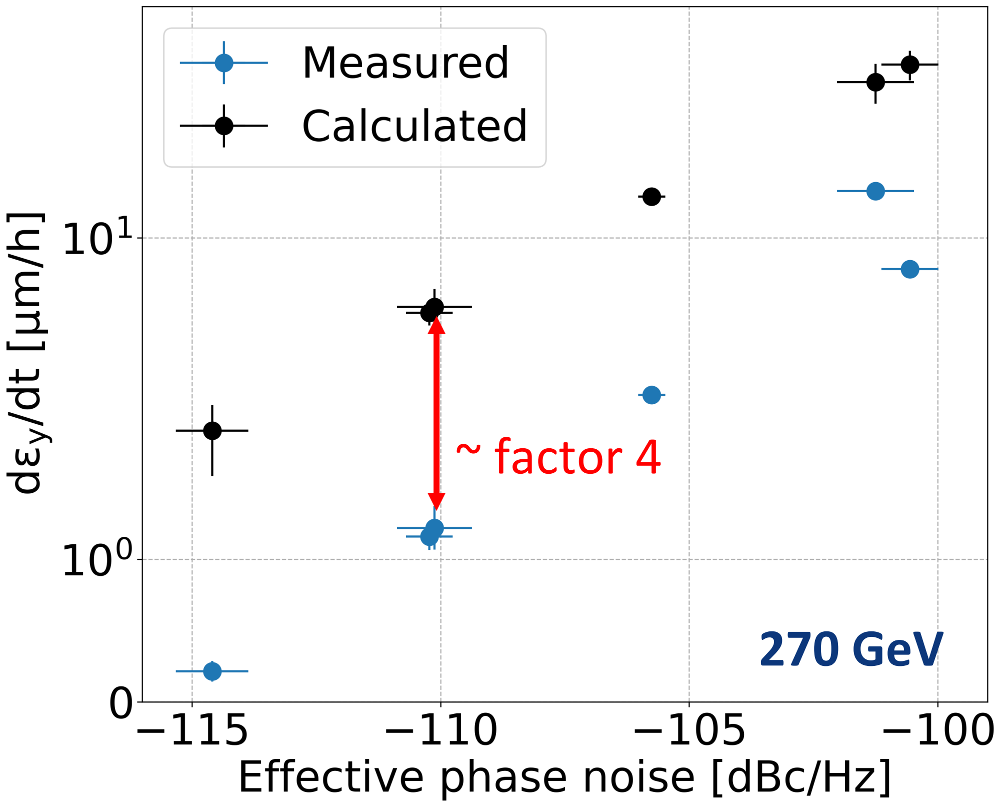
- Observed **scaling** of **measured** emittance growth with **noise power**.



Experiment in 2018 - Results

- Measurements for different (phase) noise levels.
- Observed **scaling** of **measured** emittance growth with **noise power**.
- The **measured emittance growth** was a **factor 4** (on average) **lower** than expected from the **theory** (*).

Triggered a series of studies!



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Investigating possible explanations for the discrepancy

- **Points** that were checked but **did not explain the discrepancy**:

1.	Benchmarking of the theory with different simulation codes.
2.	Sensitivity to the non-linearities of the SPS.
3.	Possible errors in the analysis of the experimental data.
4.	Possible errors in the actual noise levels of the Crab Cavities.

Big effort: 2018-2020

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Big effort: 2018-2020

- Finally, simulations showed that the **transverse beam impedance** (not included in the theory (*)) has a **significant impact on the emittance growth**.

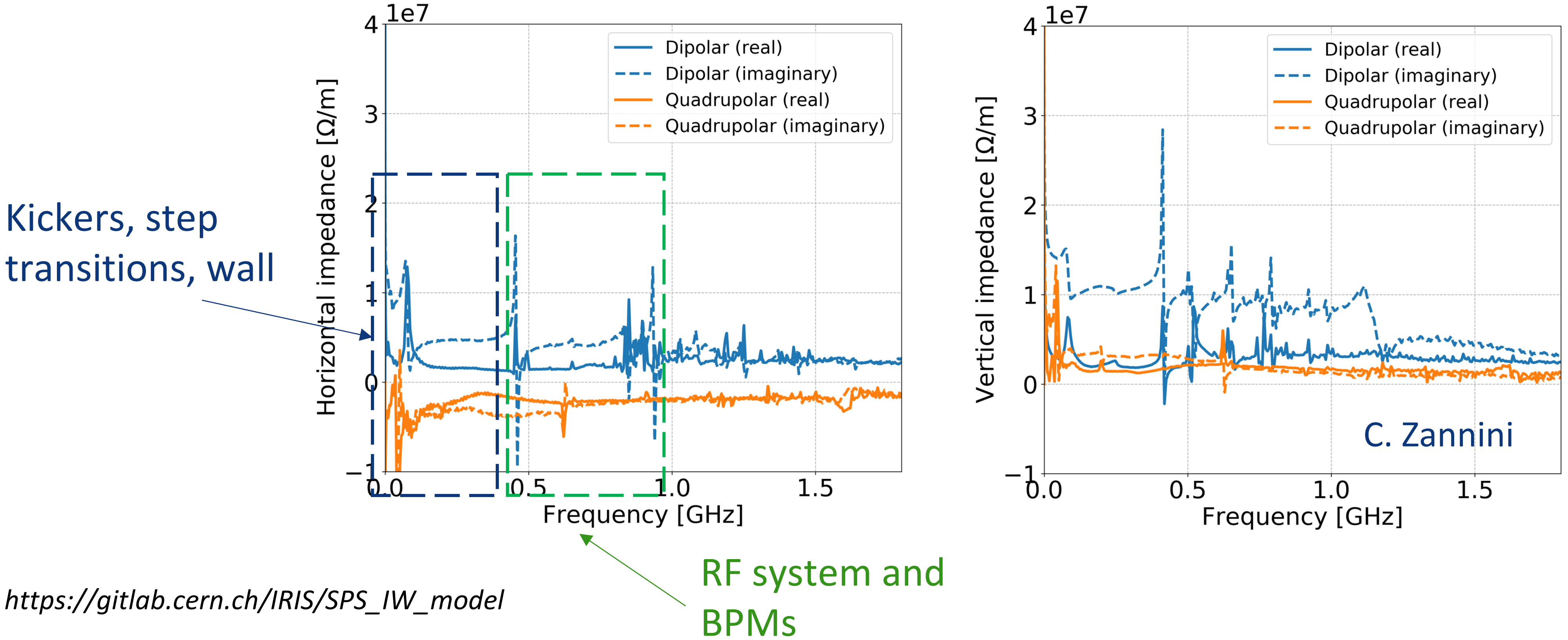
(*) P. Baudrenghien and T. Mastoridis, "Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities," Phys. Rev. Accel. Beams 18, 101001(2015)

Emittance growth suppression from the beam transverse impedance

SPS transverse impedance model

- The **complete SPS transverse impedance model**(*) provided from detailed electromagnetic simulations is used.
  - Kickers, resistive wall, step transitions, BPMs, RF cavities, indirect space charge, etc.

SPS transverse impedance

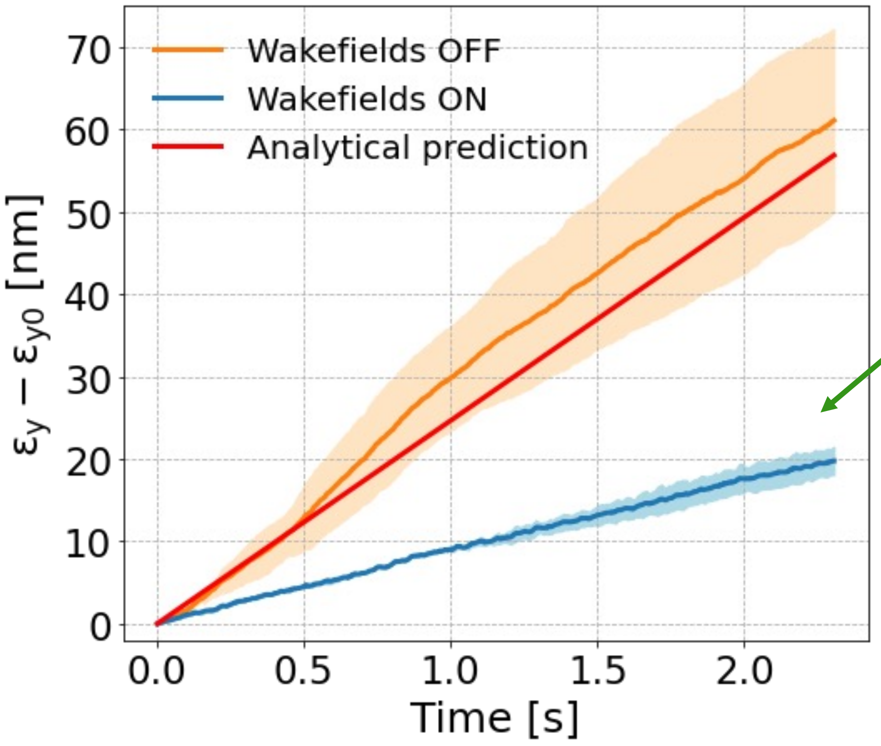


(*) *https://gitlab.cern.ch/IRIS/SPS_IW_model*

First simulation results

Simulations with **PyHEADTAIL** and the **complete SPS transverse impedance model**.

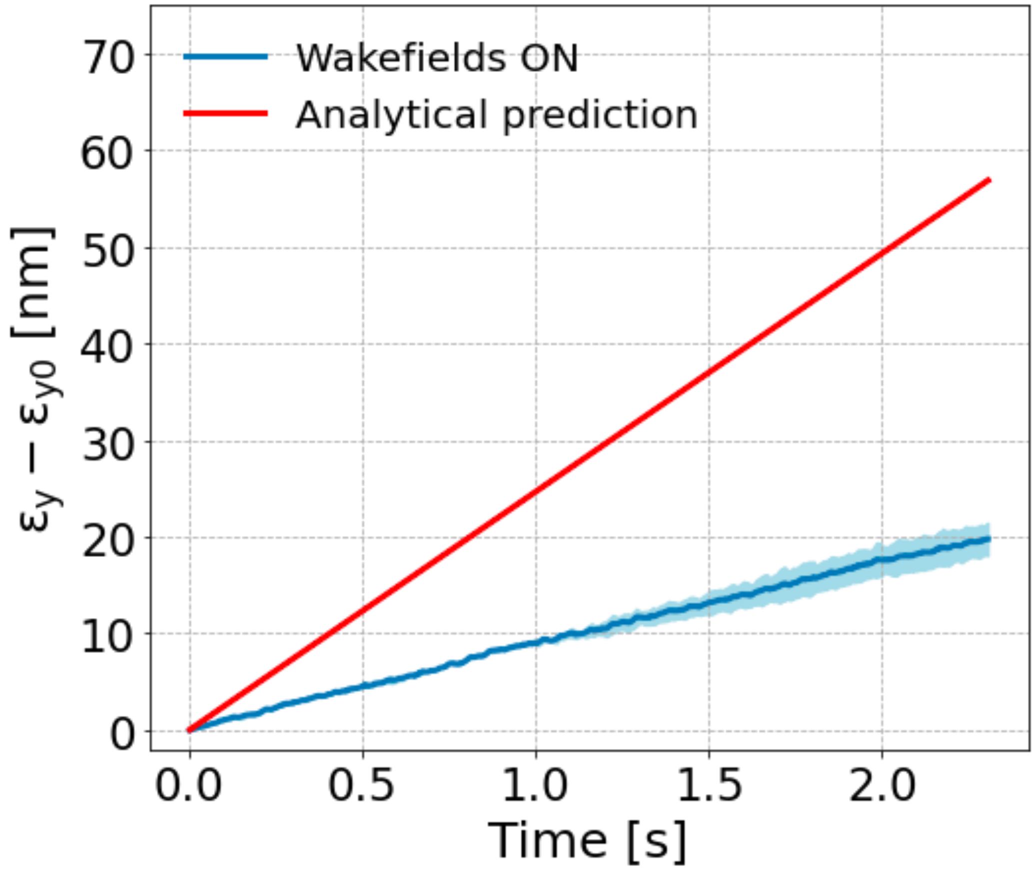
- Beam and machine conditions as in the 2018 SPS experiment.
- Crab Cavity RF **phase noise** for ~ 25 nm/s.
  - Even **stronger than in the SPS experiments**, for observables in the simulation time → **Scaling**.

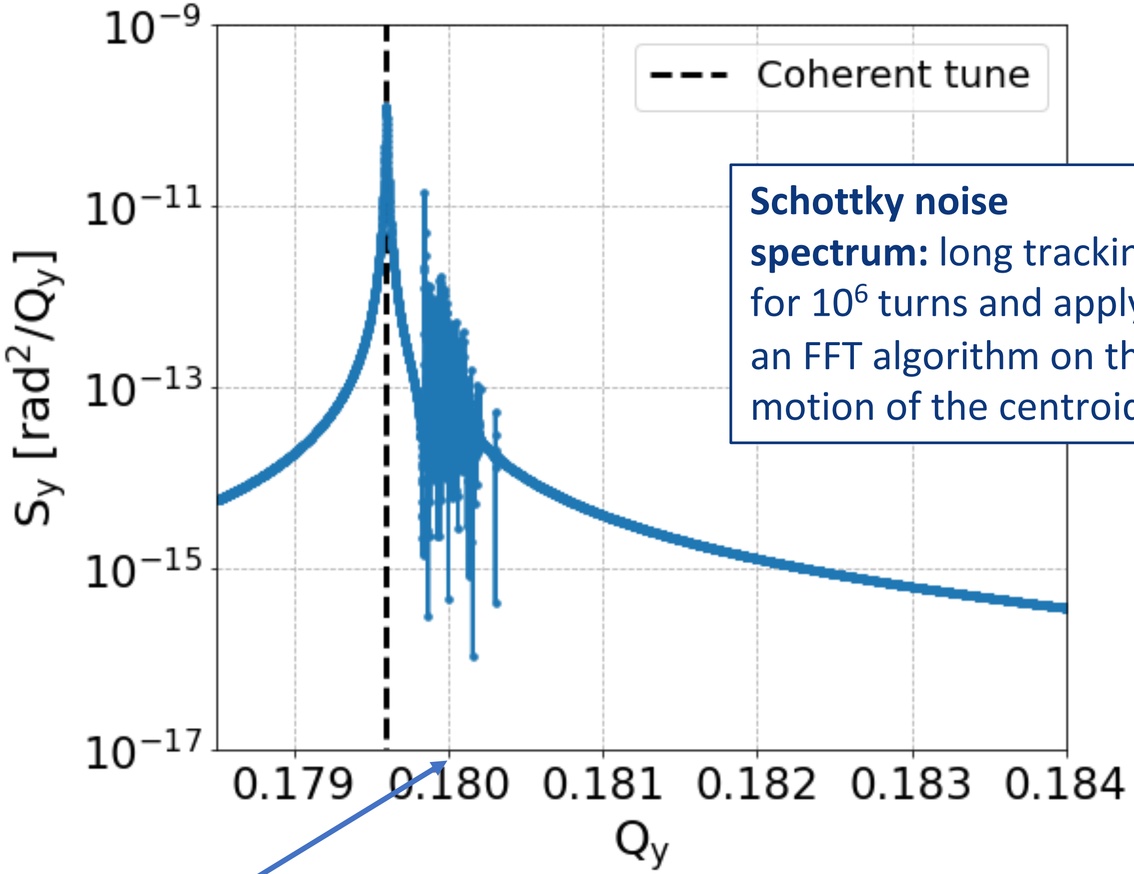


Clear suppression of the **phase noise** induced **emittance growth** in the presence of **wakefields**.

Suppression mechanism - I

The **transverse impedance separates the coherent tune from the incoherent spectrum** which leads to an **effective suppression of the Crab Cavity phase noise induced emittance growth**.





Schottky noise spectrum: long tracking for 10^6 turns and apply an FFT algorithm on the motion of the centroid.

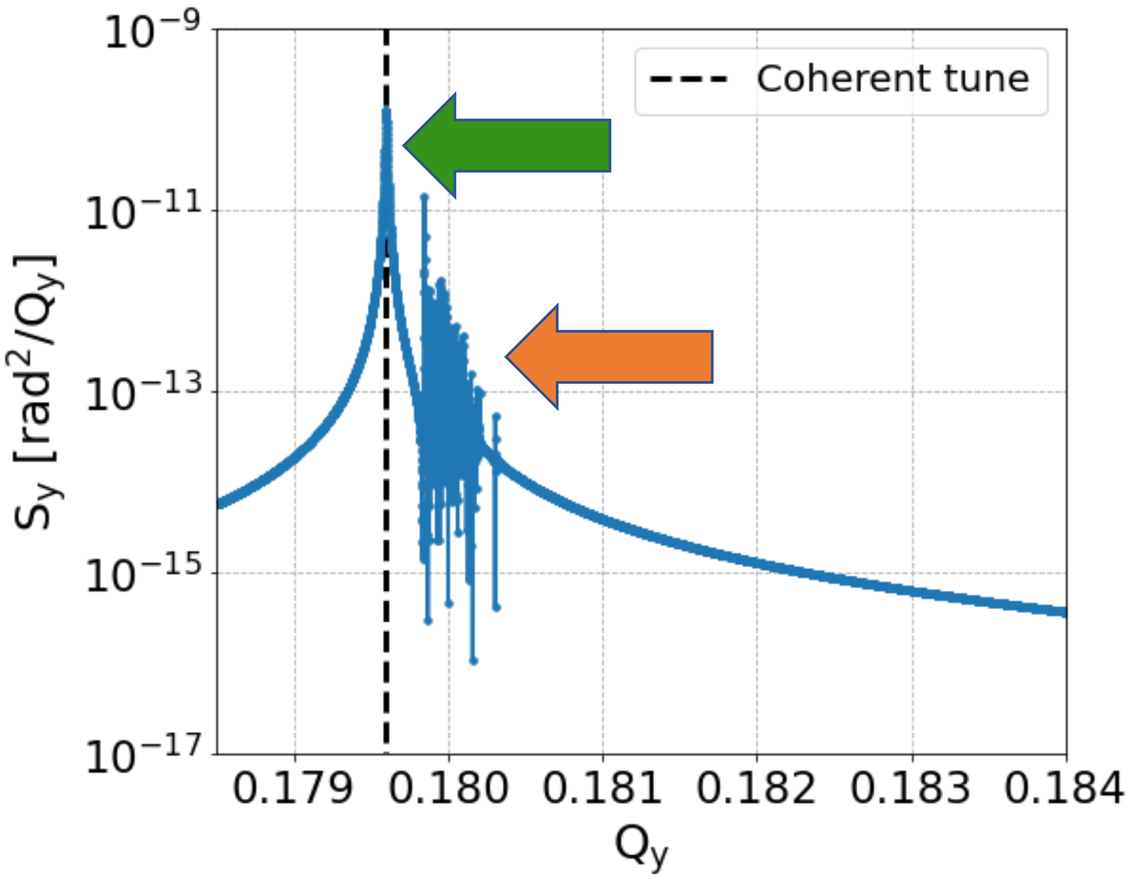
Nominal SPS tune 0.18

Suppression mechanism - II

The **transverse impedance separates the coherent tune from the incoherent spectrum** which leads to an **effective suppression of the Crab Cavity phase noise induced emittance growth.**

- **Only part** of the **energy** from the **noise kicks** drives **incoherent motion** and leads to **irreversible emittance growth.**

- **The rest of the energy** is absorbed by the **coherent mode**, which is **damped** by the **impedance without leading to emittance growth**.



Related studies

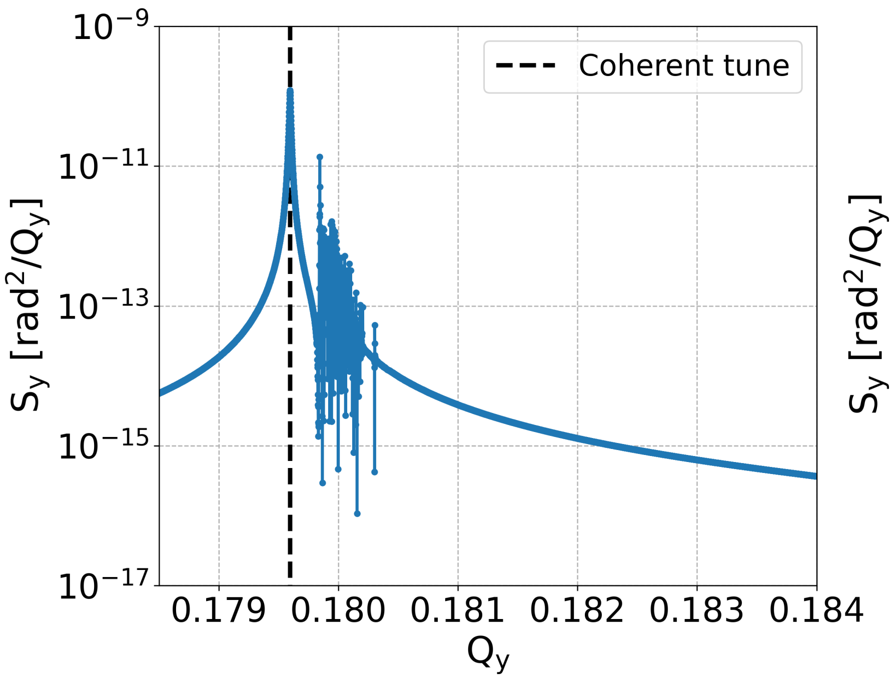
- In the context of the beam-beam modes it has been observed that the **efficiency of a transverse feedback** system at suppressing emittance growth depends on the **overlap between the coherent mode and the incoherent spectrum** in **past** theoretically(*1) and in simulations(*2).

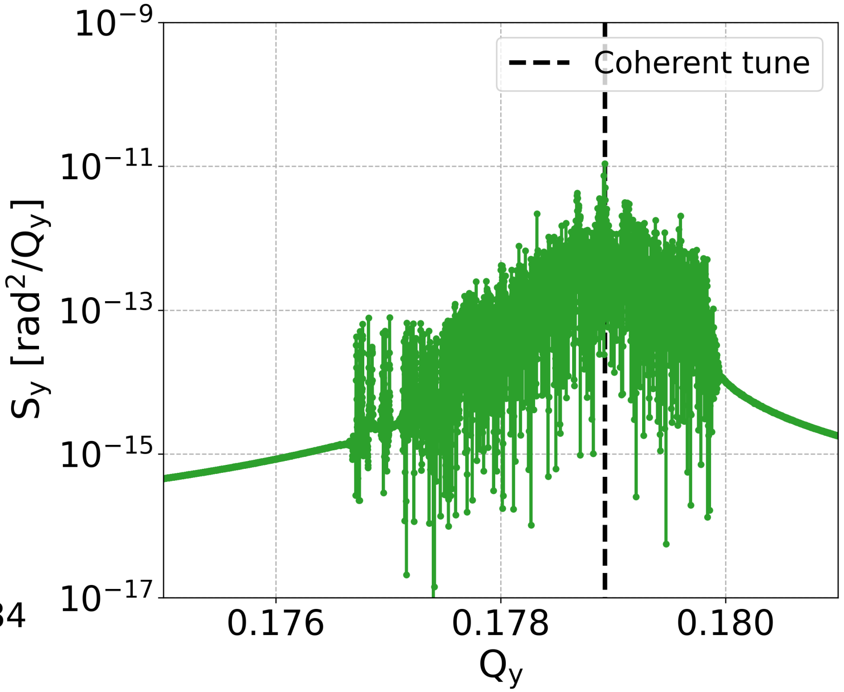
- Recently, this approach was adapted for configurations featuring linear detuning and a complex tune shift from a collective force, supporting the simulation results shown here.
  - **X. Buffat, "Suppression of Emittance Growth by a Collective Force: Van Kampen Approach", IPAC'22: paper WEPOTK059.**

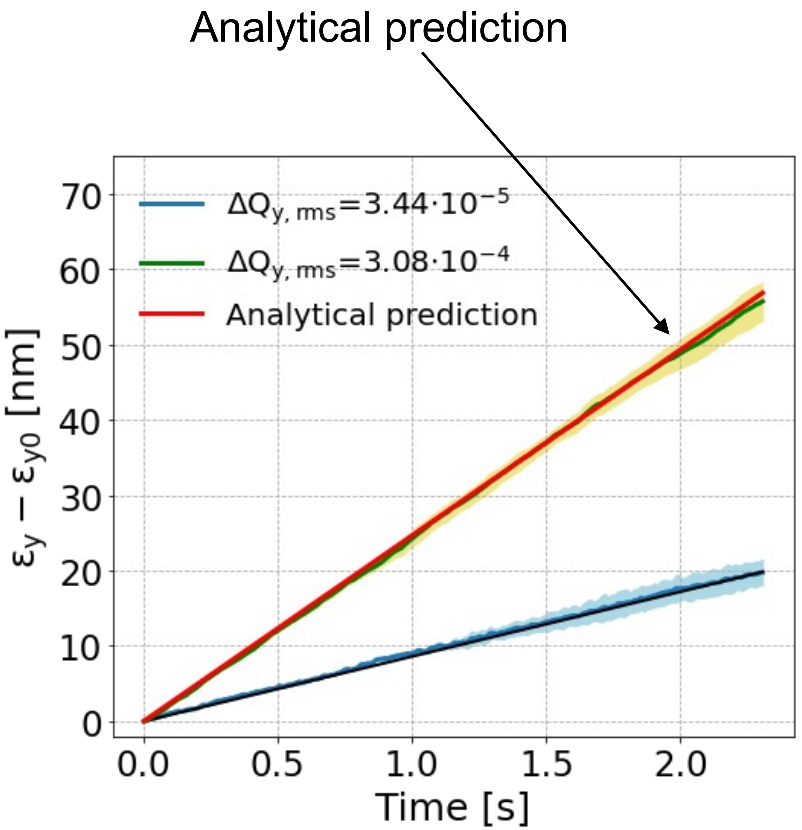
*(*1) Y. Alexahin, "On the Landau Damping and decoherence of transverse dipole oscillations in colliding beams"*
*(*2) X. Buffat, "Modeling of the emittance growth due to decoherence in collision at the Large Hadron Collider", Phys. Rev. Accel. Beams 23, 021002 (2020)*

Impact of tune spread

- Simulations studies showed that increasing the tune spread through detuning with amplitude can **bring the coherent mode inside the incoherent spectrum restoring** the emittance growth expected from the theory of T. Mastoridis and P. Baudrenghien (without impedance effects).



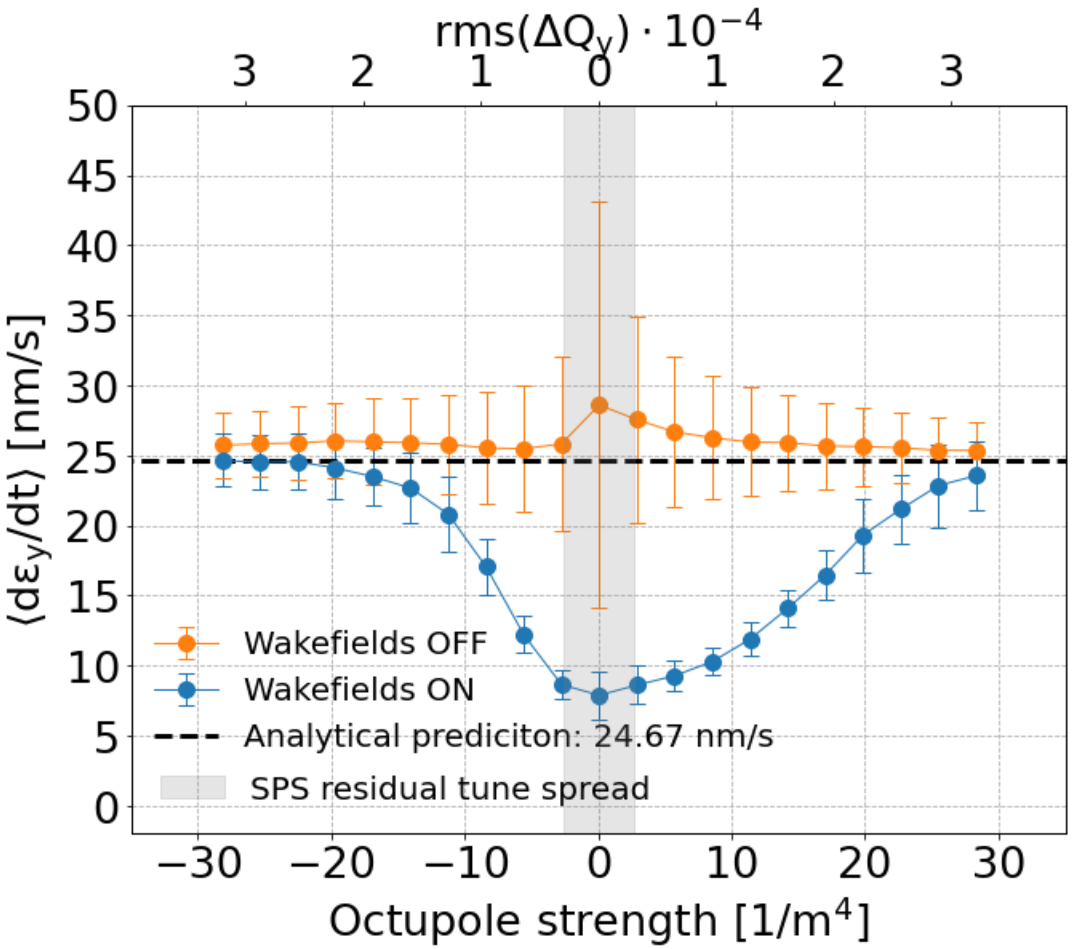




Parameters: 270 GeV, 3e10 protons per bunch, Q’y=0.5

Sensitivity to tune spread

- In the presence of **wakefields**, there is a **clear dependence** of the emittance growth on the **tune spread value** and thus the overlap of the coherent tune and the incoherent spectrum observed in the simulations.



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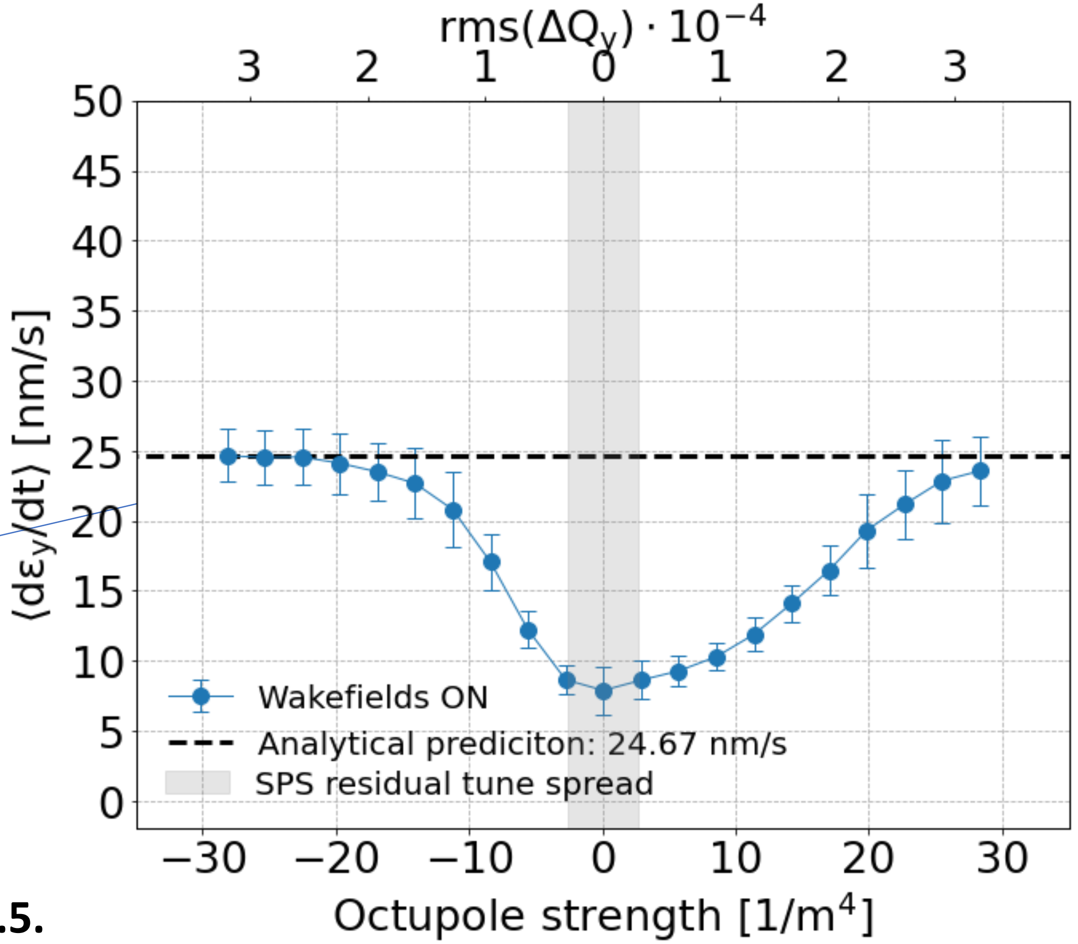
This **behavior** was **tested experimentally** in the **SPS in 2022.**

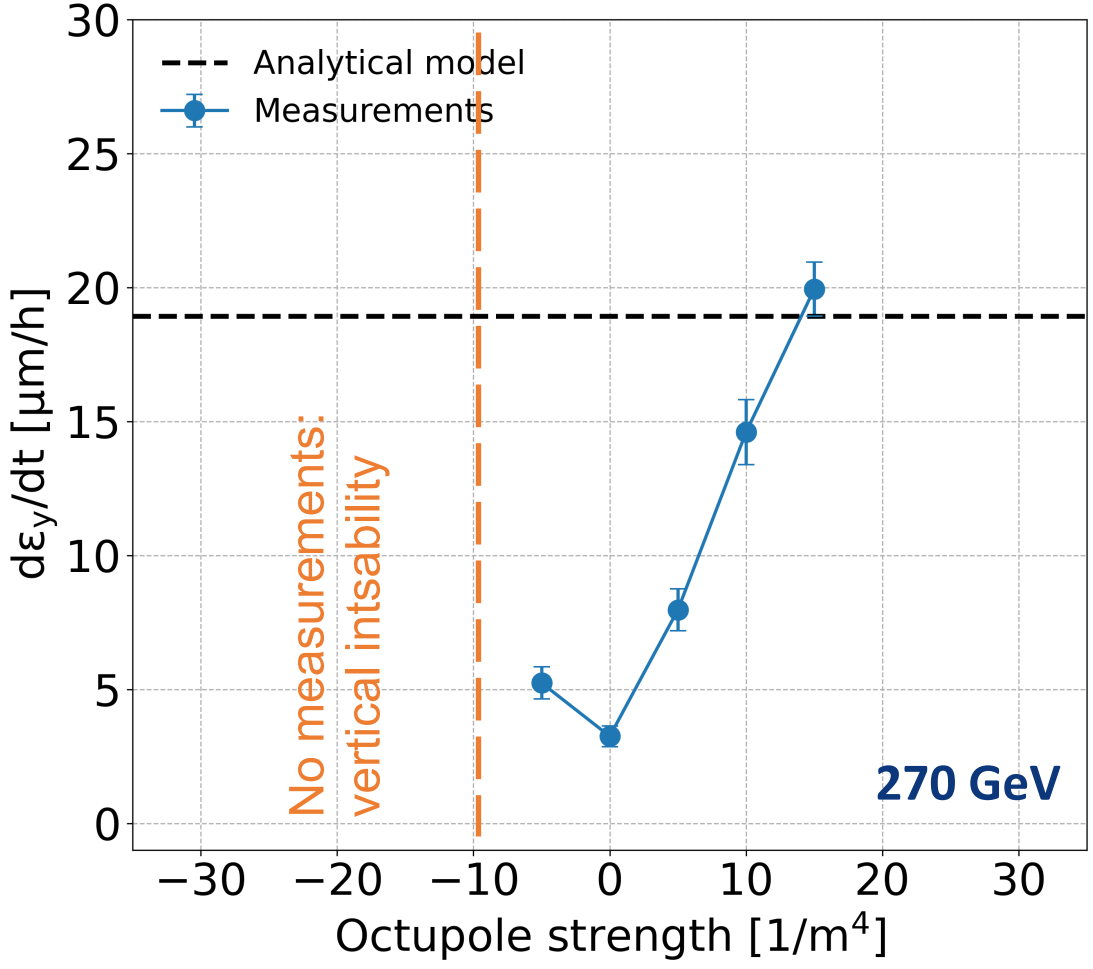
- **Use of SPS octupole families.**
- **Goal: Reproduce the behavior only (due to scaling).**
- **For the residual SPS tune spread: suppression of a factor ~ 3.5.**



SPS measurements in 2022

Experimental results 2022 - I

Measurements



- ➢ Very limited machine time: Full scan not possible.
- ➢ **Clear dependence of the measured emittance growth on the octupole strength.**
  - ➢ Goal of the experiment achieved.

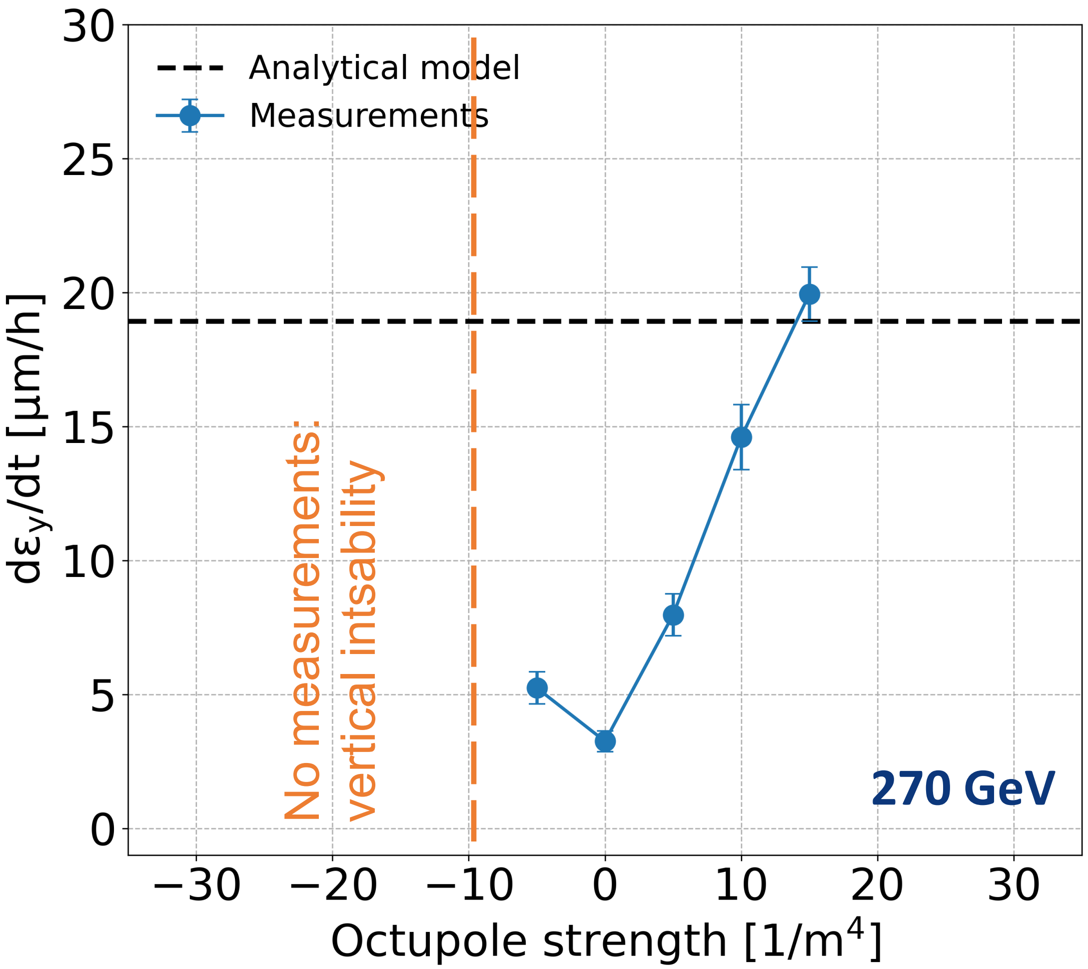
Confirmation of damping mechanism from the impedance!

- ➢ Without octupoles → **suppression factor ~4-5**. **Similar to what is expected from impedance.**

Parameters: 270 GeV, 3e10 protons per bunch, Q'y~0.0

Experimental results 2022 - II

Measurements



Very complicated studies

1.	**Limited machine time**

- 5 points are great success

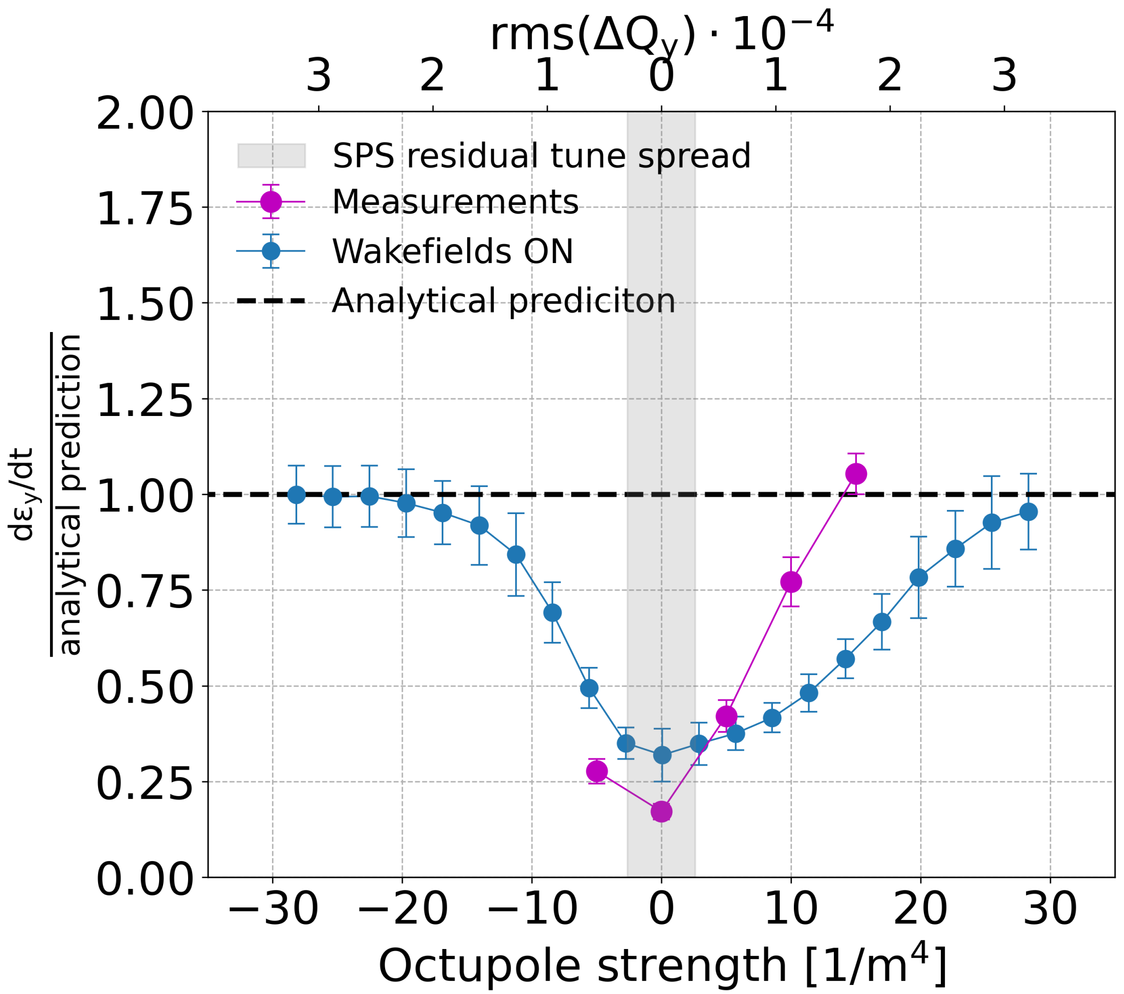
2.	**SPS not in the usual operation mode**

- Crab Cavity operation
- Noise in the Crab Cavity RF
- Stored beam
- Octupoles operation out of the usual regime
- Clear dependence on the octupoles strength is great success

Parameters: 270 GeV, 3e10 protons per bunch, Q'y~0.0

Experimental results 2022 - III

Simulations vs measurements



- **Qualitative agreement** with the simulations **confirming the damping mechanism from impedance!**
- Further studies, simulations and measurements, will be needed to investigate the quantitative agreement.
- Possible factors:
  - Contribution from space charge
  - Significantly larger final emittances in the experiment → larger tune spread

Summary and future plans

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- **First experimental beam dynamic studies** with **Crab Cavities** and **proton beams.**
- **First investigation and experimental validation of the suppression mechanism** of the Crab Cavity RF phase noise induced emittance growth by **transverse impedance**.
- **Crucial step forward** on the understanding of the Crab Cavity noise effects which impact the HL-LHC performance.
- **Further measurements** are planned in the SPS **to refine the experimental observations** and obtain **quantitative agreement** between measurements and simulations.
- Understanding obtained from these studies will be applied **for the design of the crab cavity HL-LHC Low-Level RF system.**

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Thank you for your attention!
Questions?