# Interplays with beam-beam in circular hadron collider

X. Buffat

Many thanks to L. Barraud, H. Bartosik, S. Fartoukh, S.V. Furuseth, W. Herr, P. Kicsiny, N. Mounet, E. Métral, T. Persson, T. Pieloni, A. Ribes Metidieri, B. Salvant, R. Soos, R. Tomas, N. Triantafyllou, D. Valuch and S.M. White

# Content

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  - Collimation (F. van Der Veken, et al., C.E. Montanari, et al.)
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# Weak head-tail instability in the weak-strong regime

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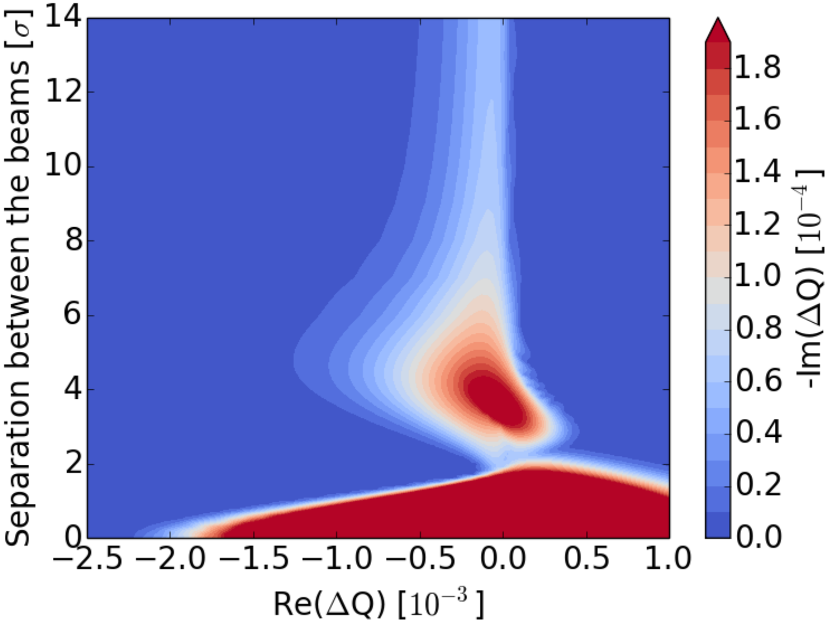

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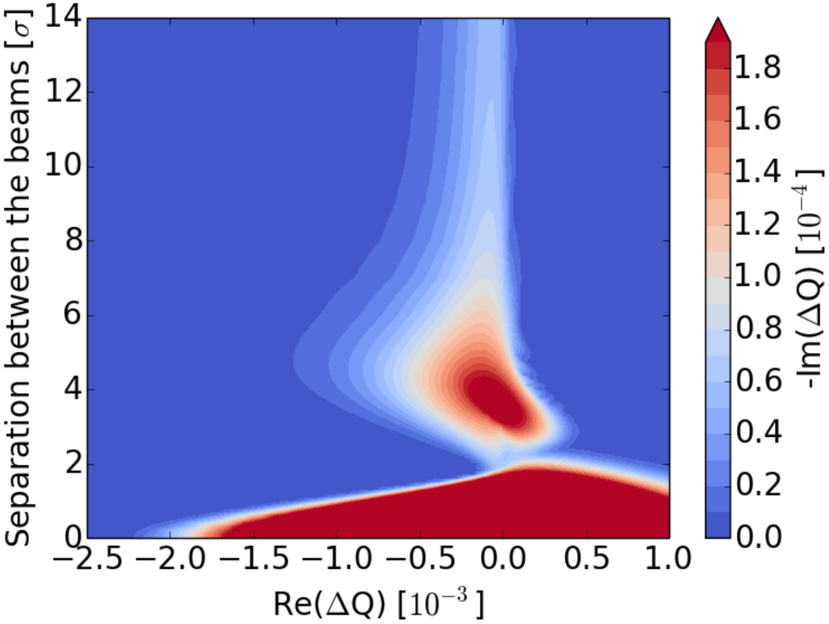

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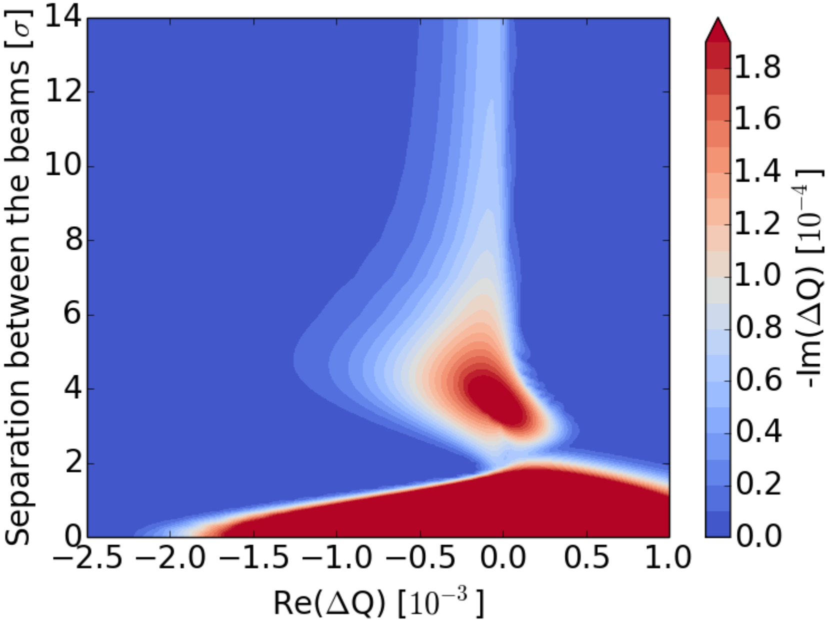

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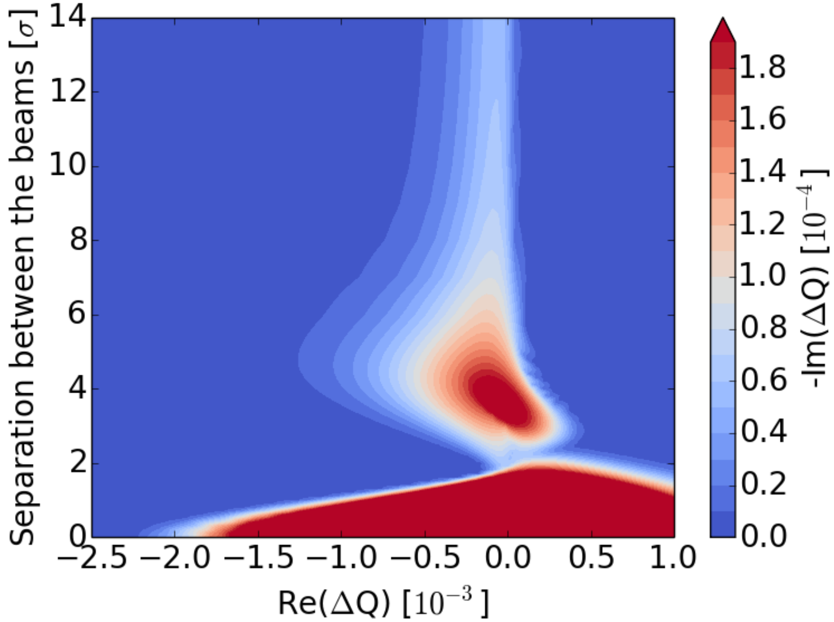


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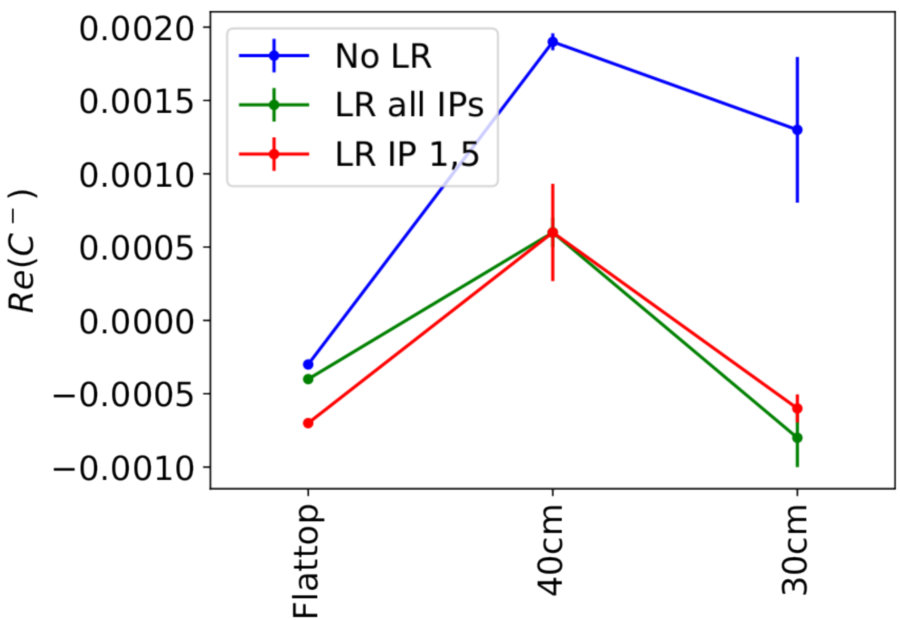


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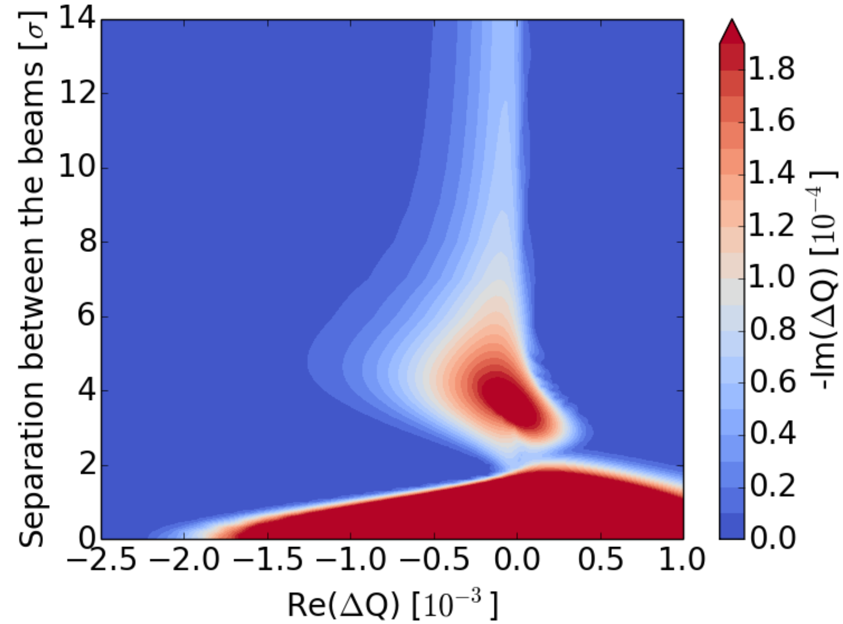


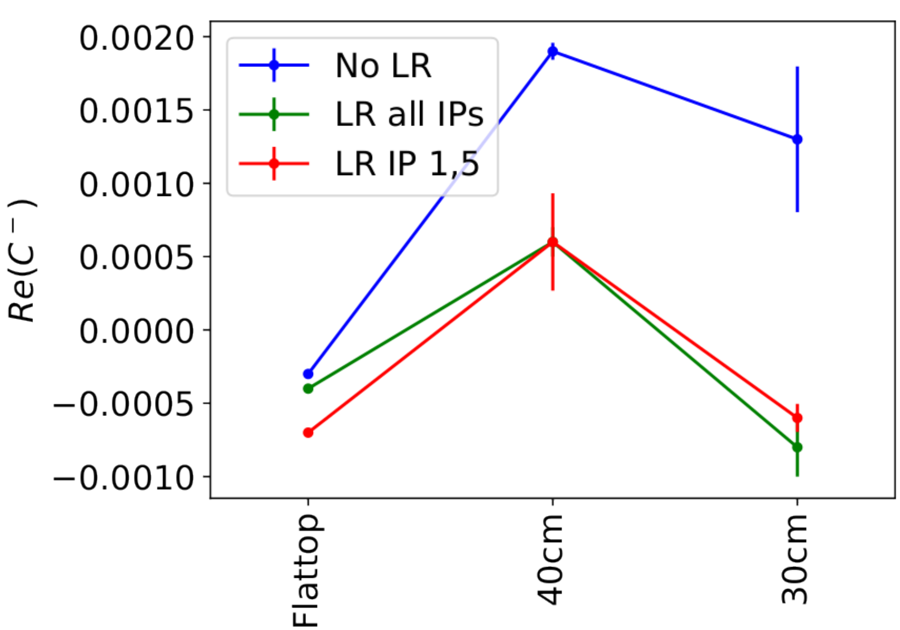


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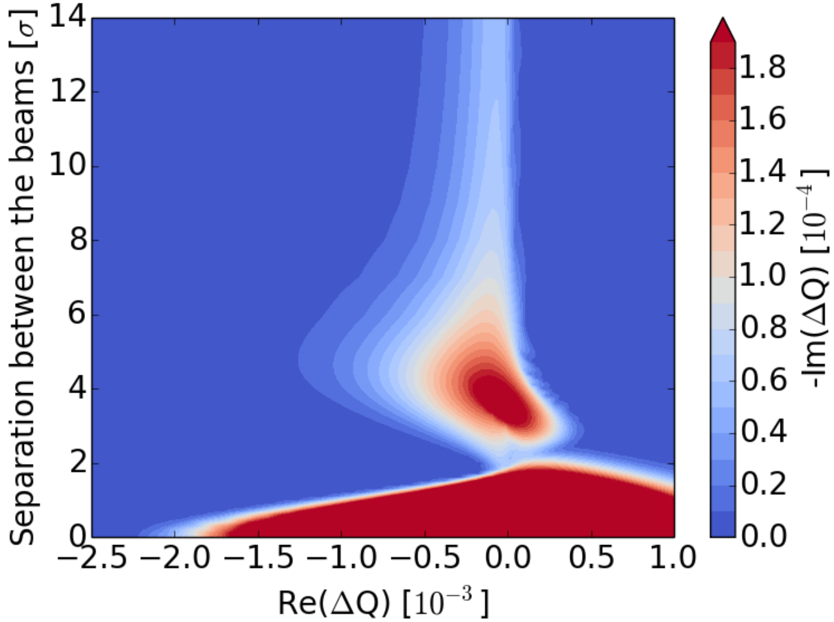


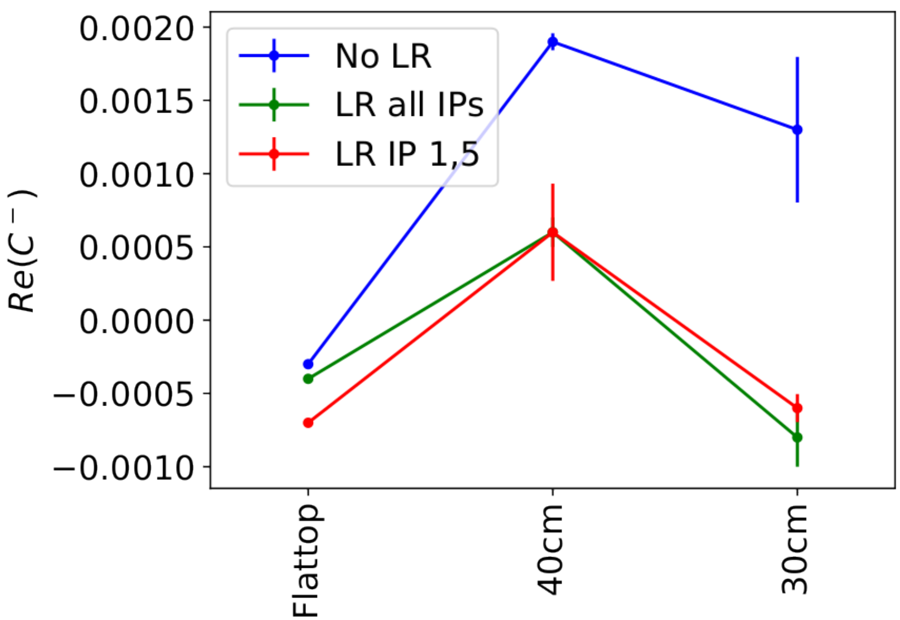


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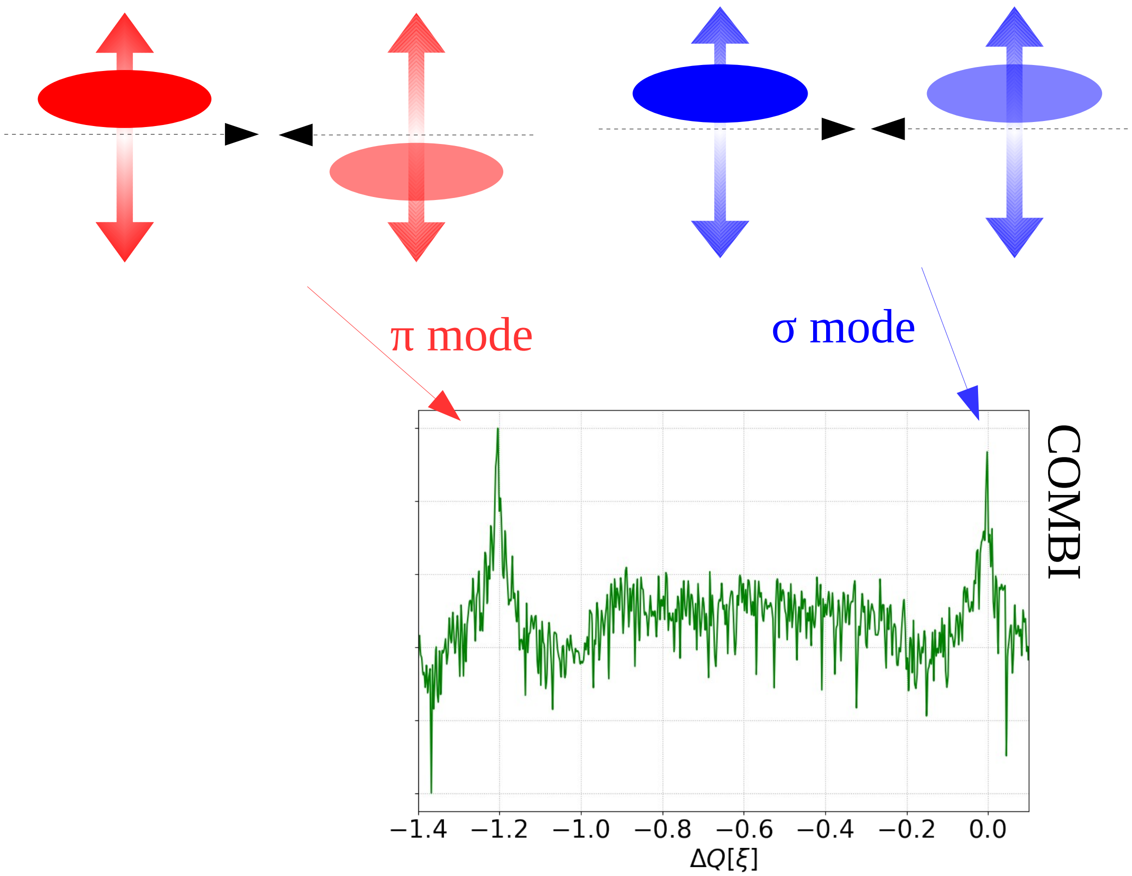
- Weak head-tail approx is often broken since often the beam-beam tune spread is much lager than the synchrotron tune
- Electron cloud instabilities were still observed in the LHC in collision, in spite of the large beam-beam in collision tune spread [Romano18]

# Coherent beam-beam modes

- If we now consider the oscillation of the two beams consistently, we find new modes of oscillation [Yokoya90]



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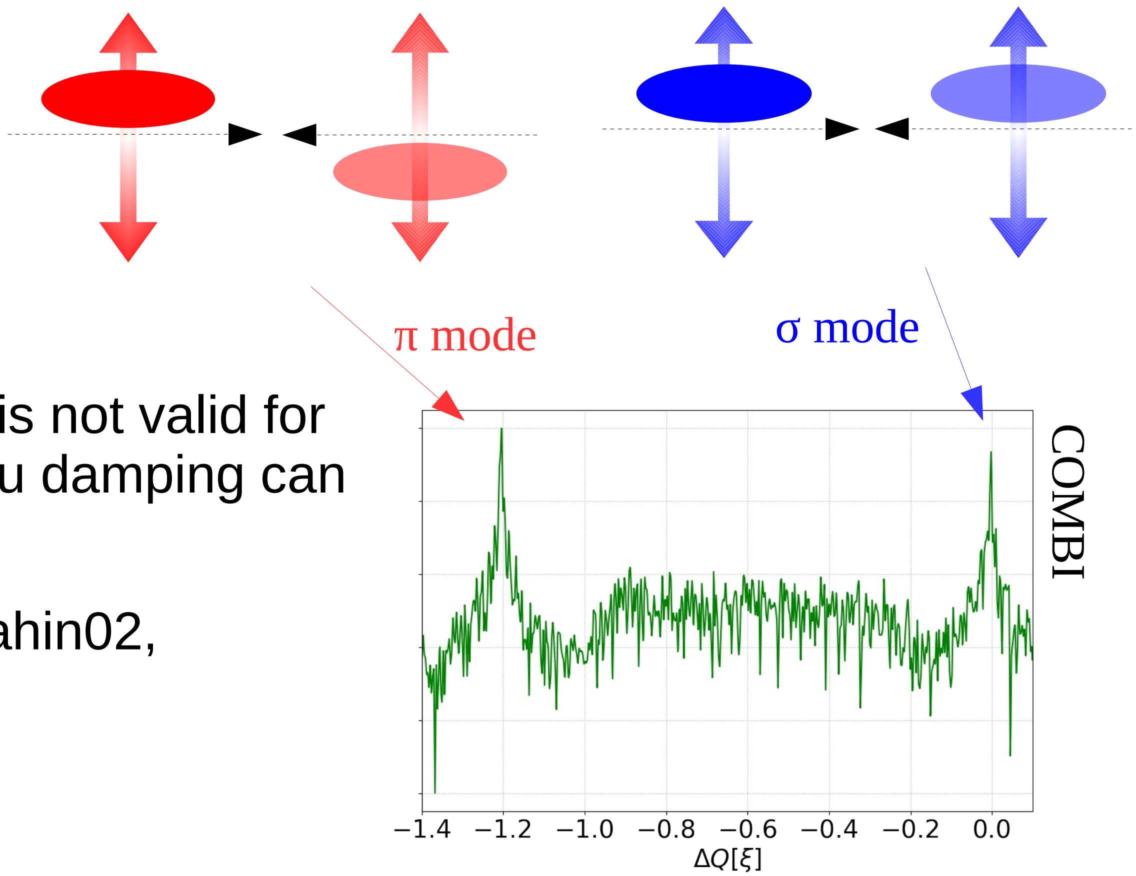


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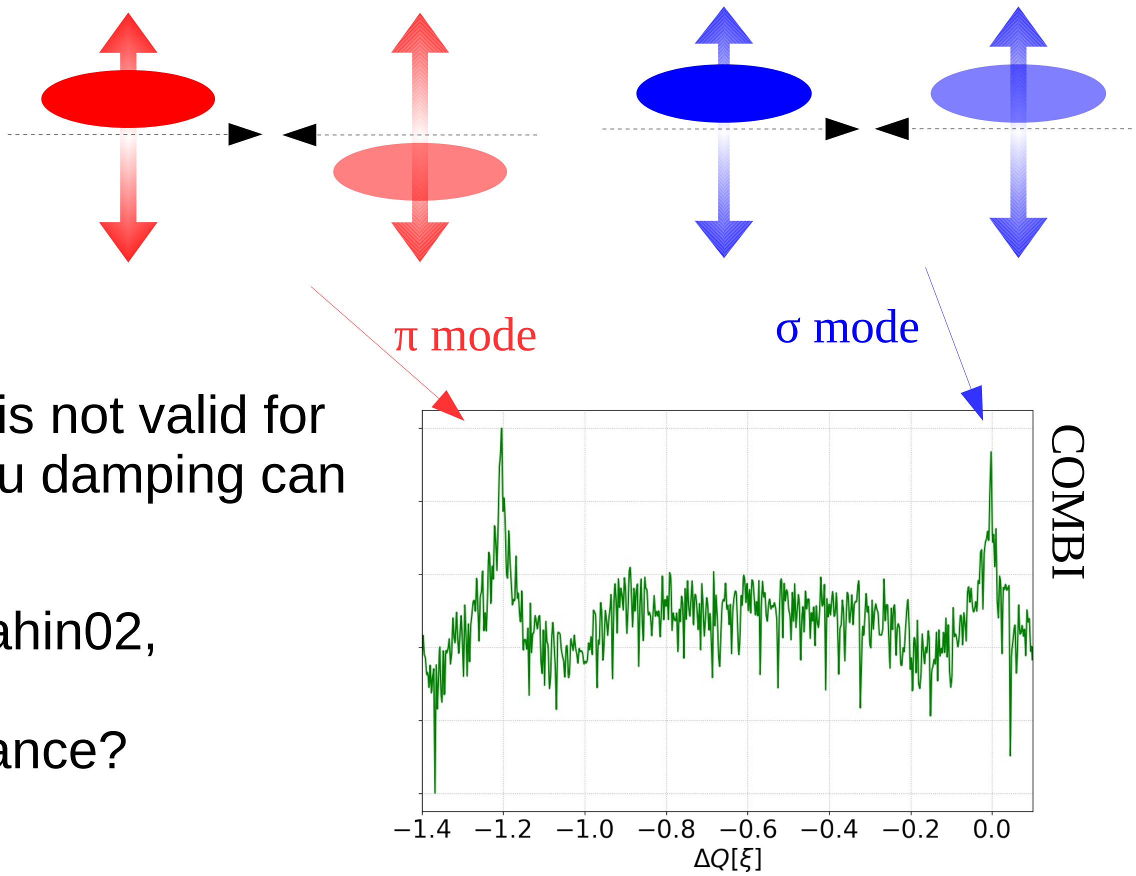


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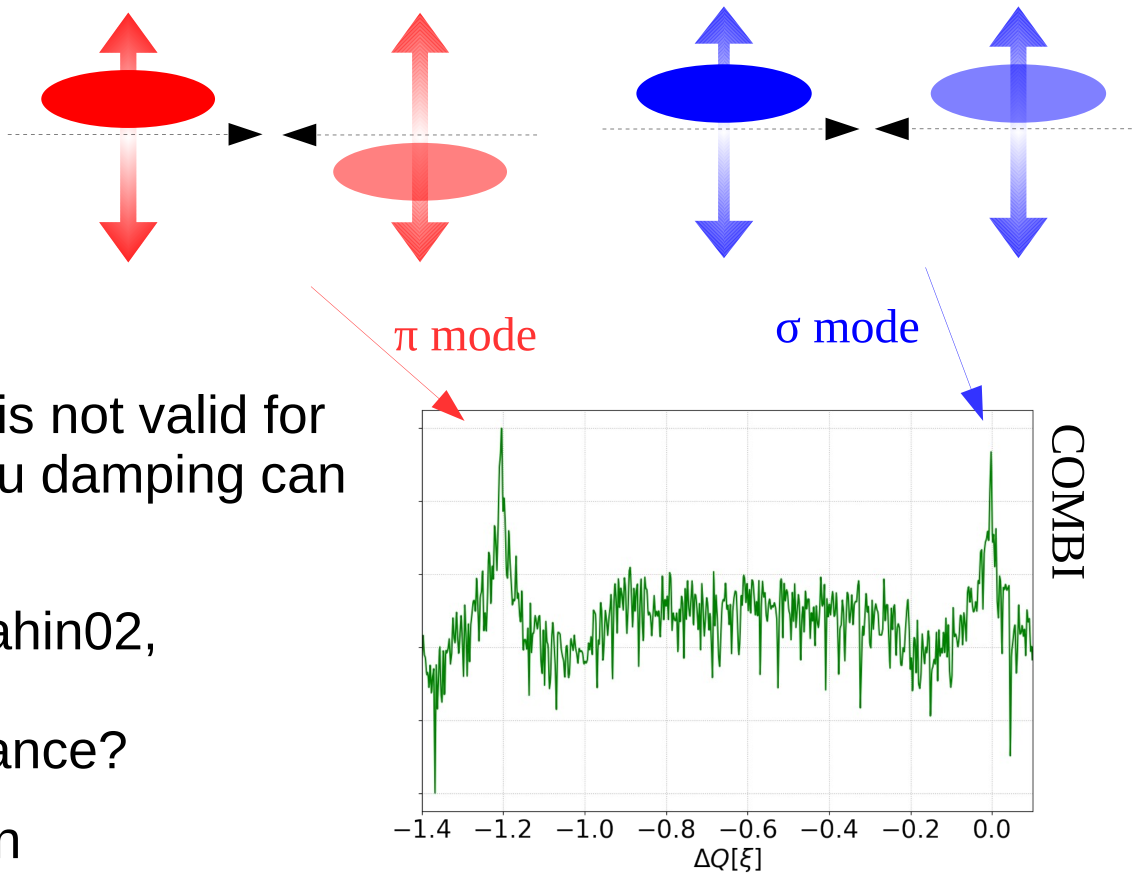


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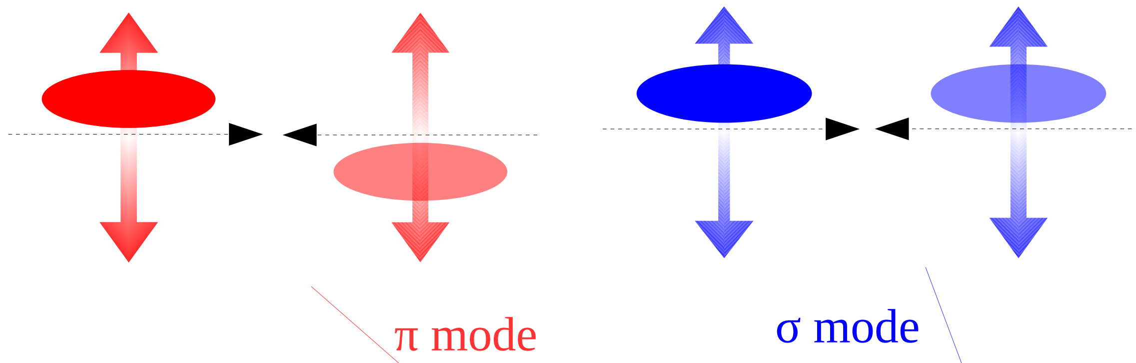


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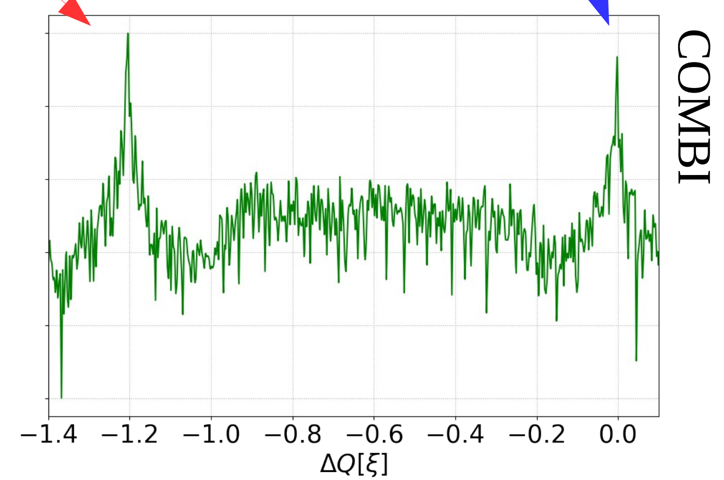
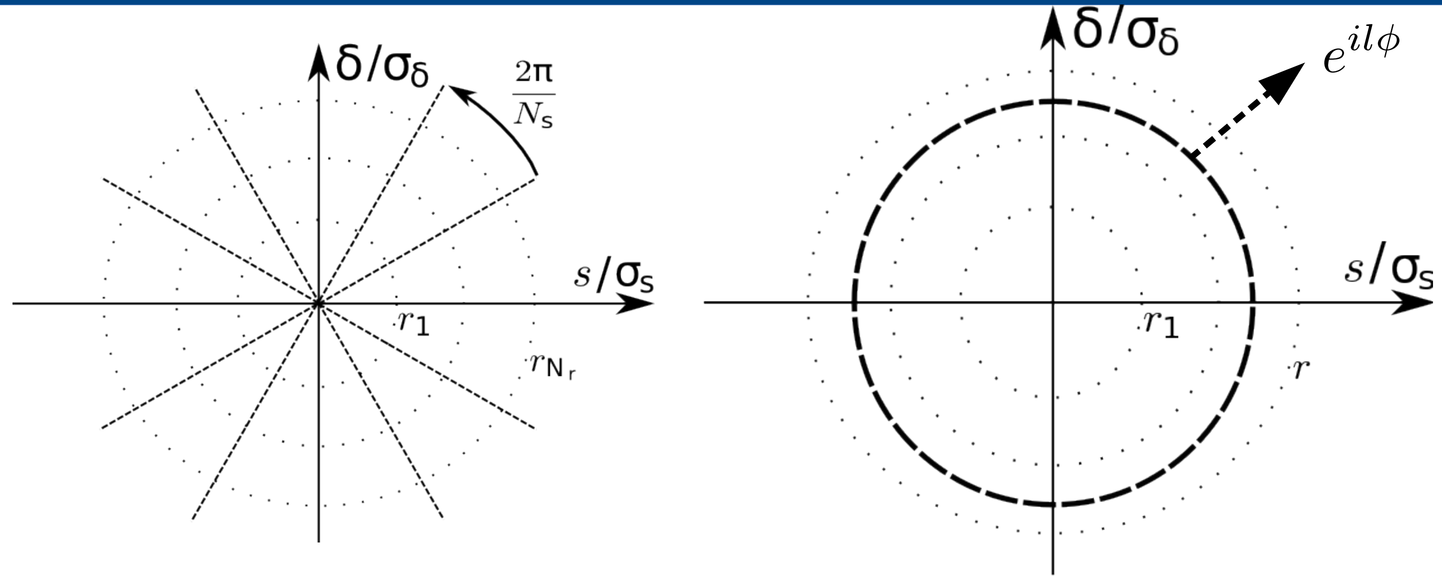



- The interaction of coherent beam-beam mode with the transverse impedance can result in strong mode coupling instabilities
  - Two main linear approaches:
    - [White14], based on the circulant matrix model (CMM) [Perevedentsev01]
    - [Zhang23] based on the cross-wake approach (CWA) [Ohmi17]

# The circulant matrix model vs the cross-wake approach

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| Dynamical variables | Transverse coordinates of each cell | Transverse amplitude and phase of each mode |
| Radial decomposition | Uniform discretisation | |
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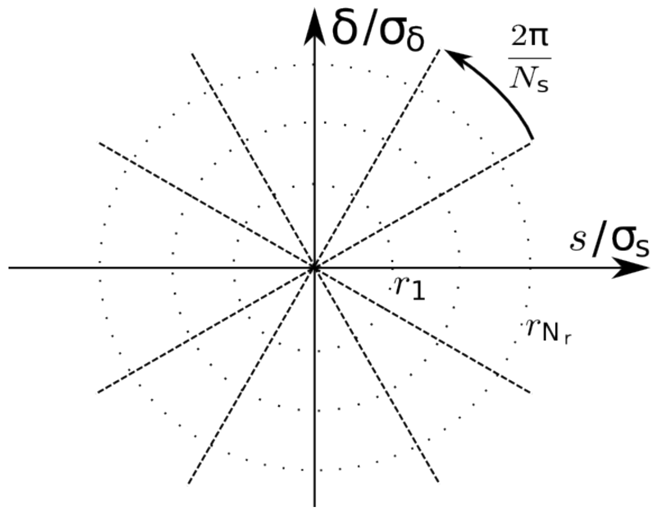


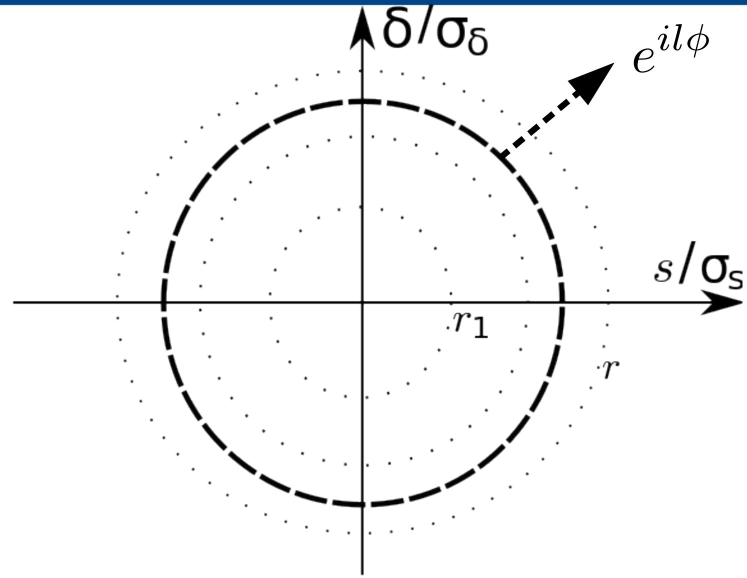


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→ Eigenvalue problem yielding the stability of the transverse modes of oscillation

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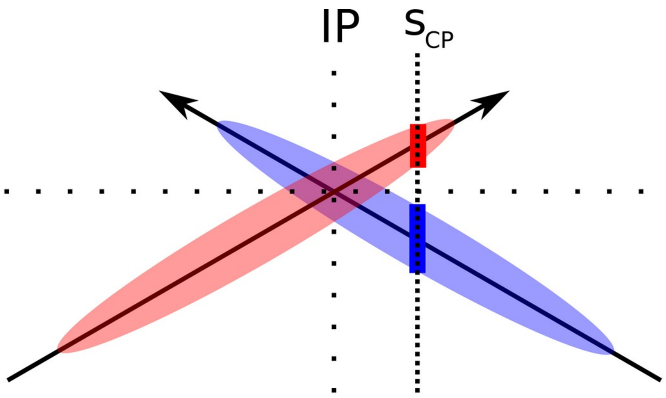


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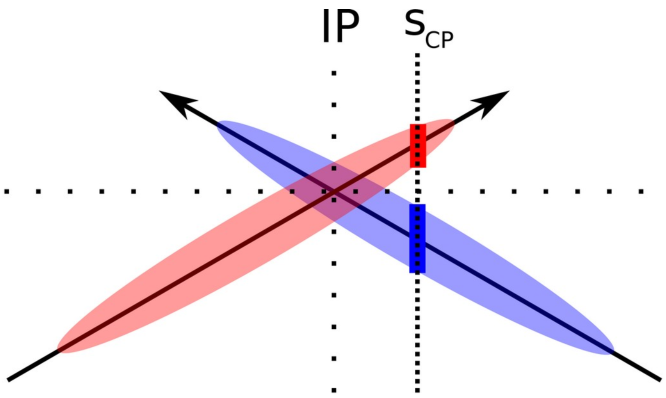


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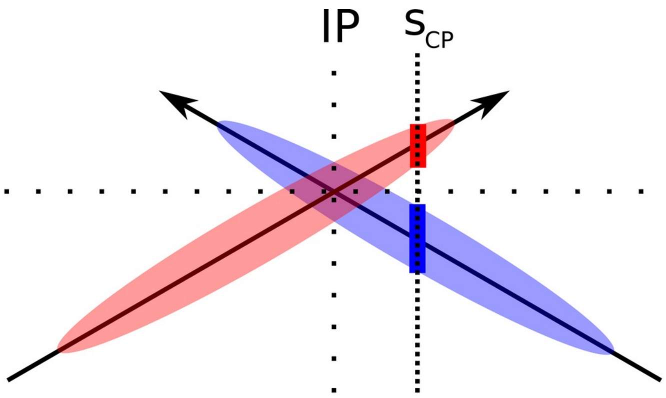


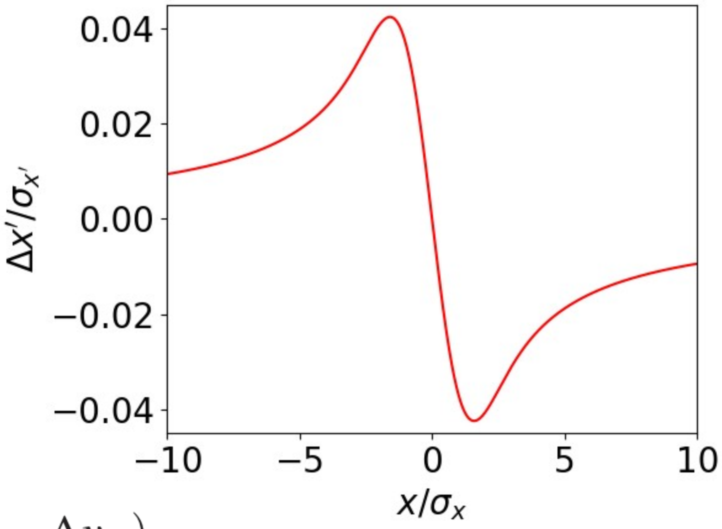


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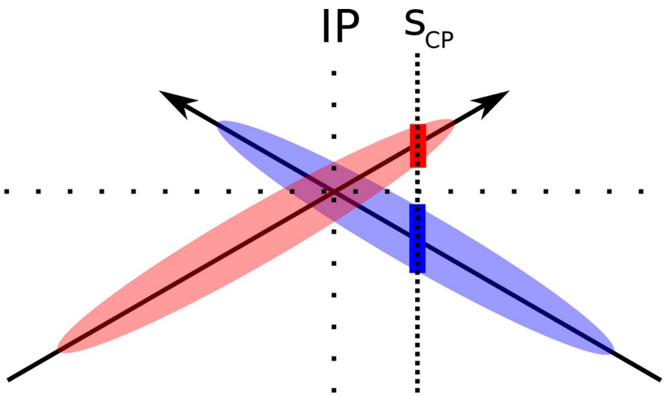
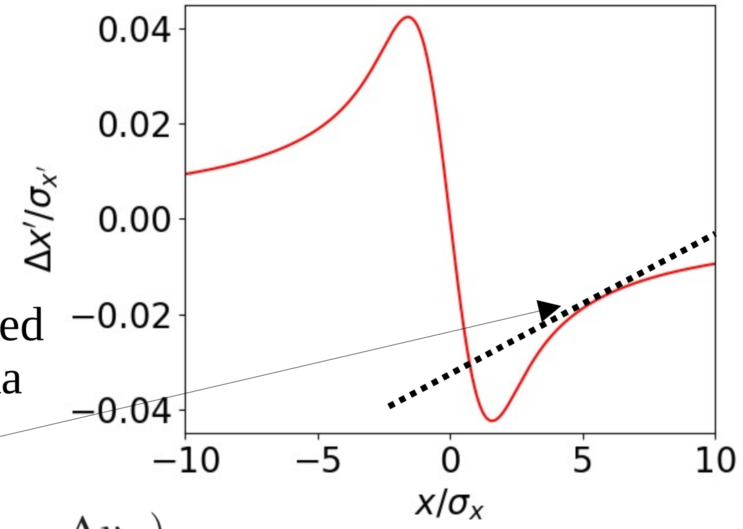



Linearised kick on individual particles based on Bassetti-Erskine (aka incoherent kick)

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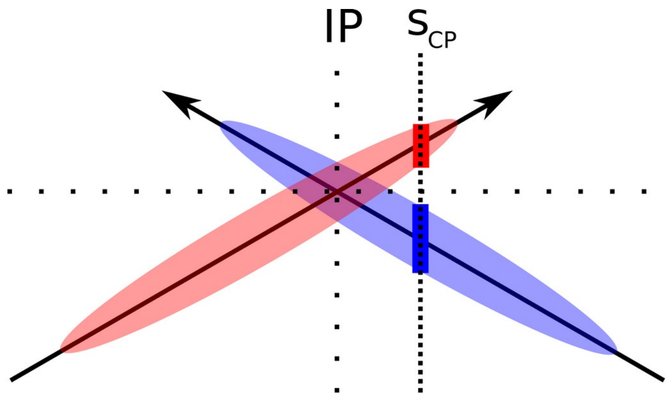


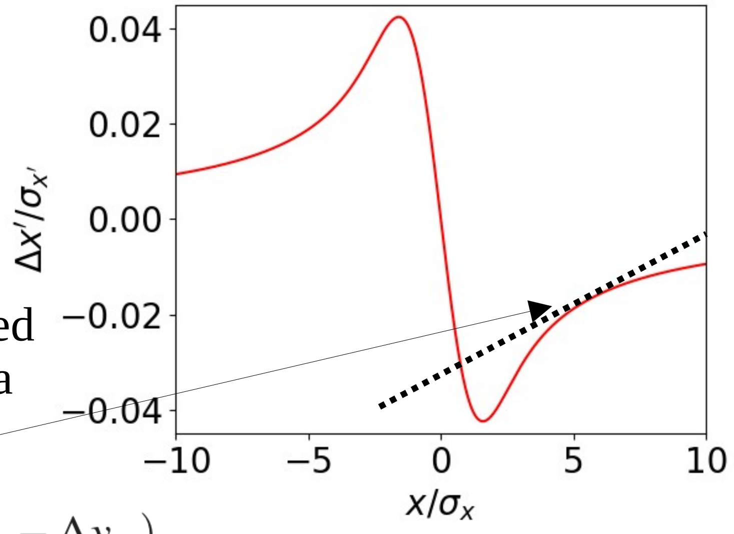


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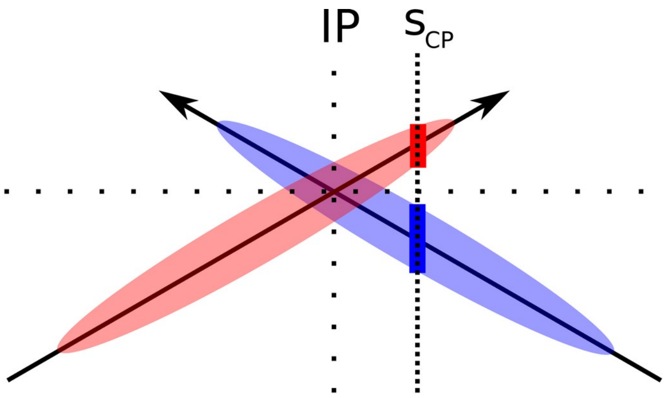


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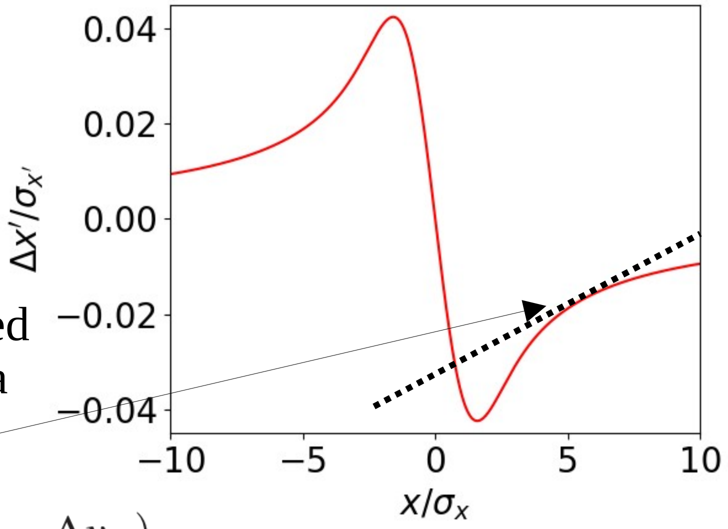


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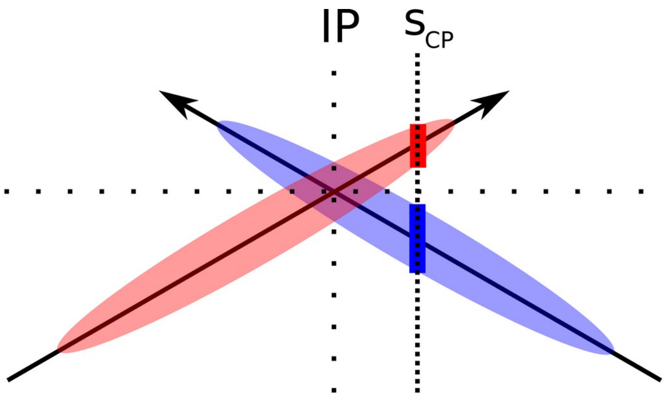


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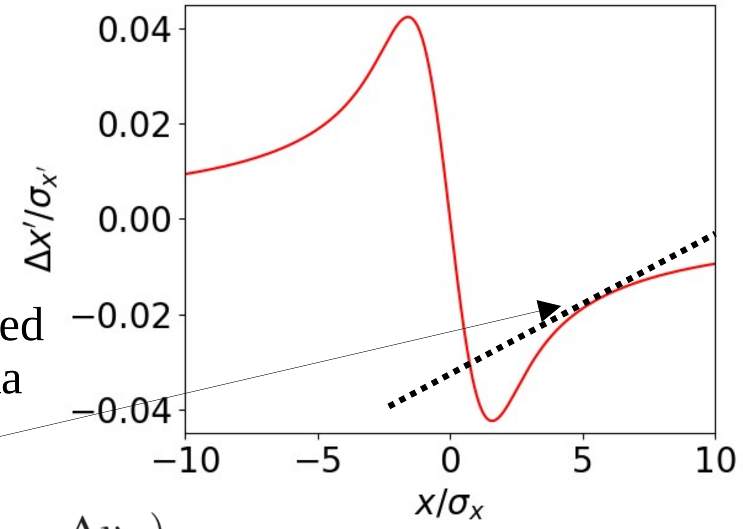


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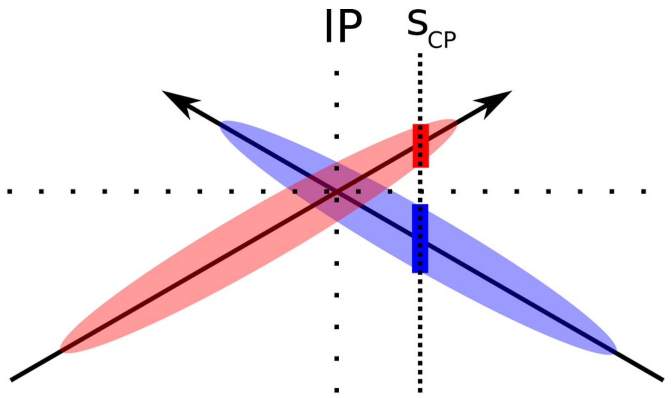


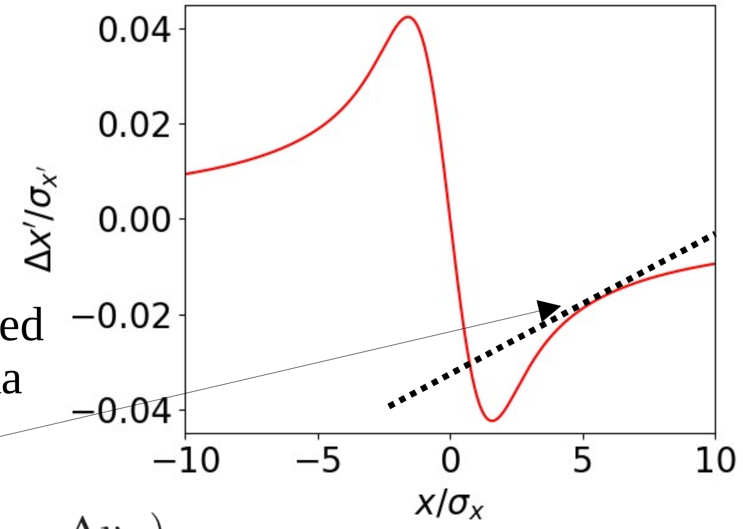


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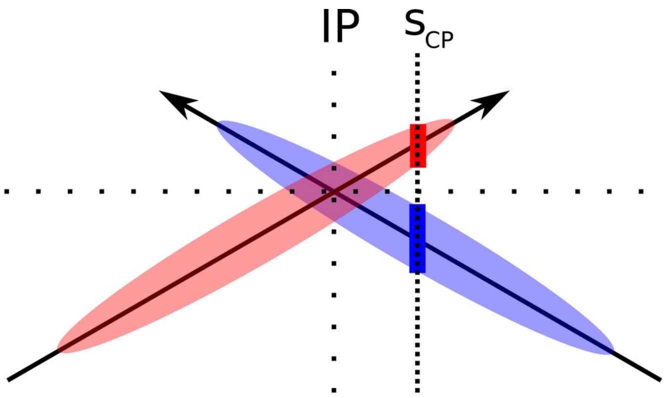


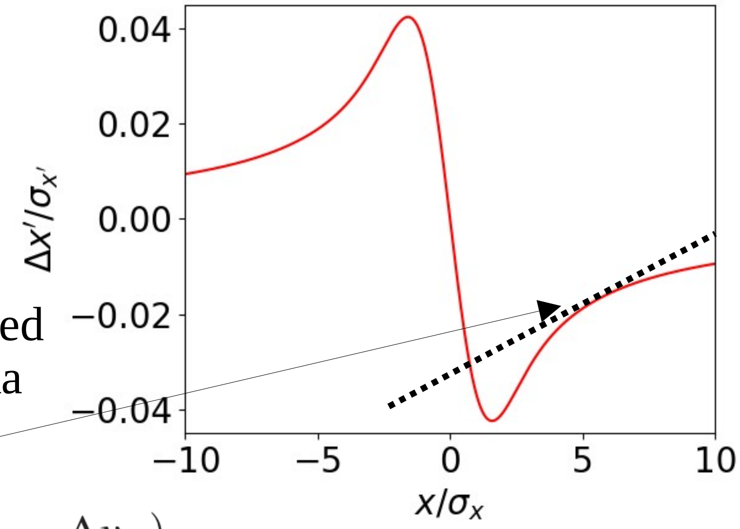


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**Cross-wake approach**

- Integrate the incoherent kick over the transverse distribution

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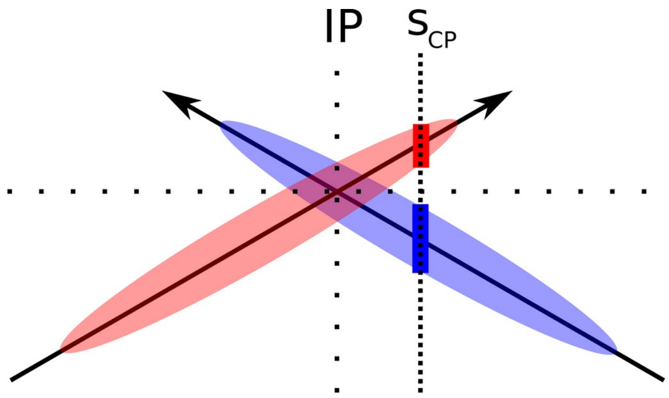


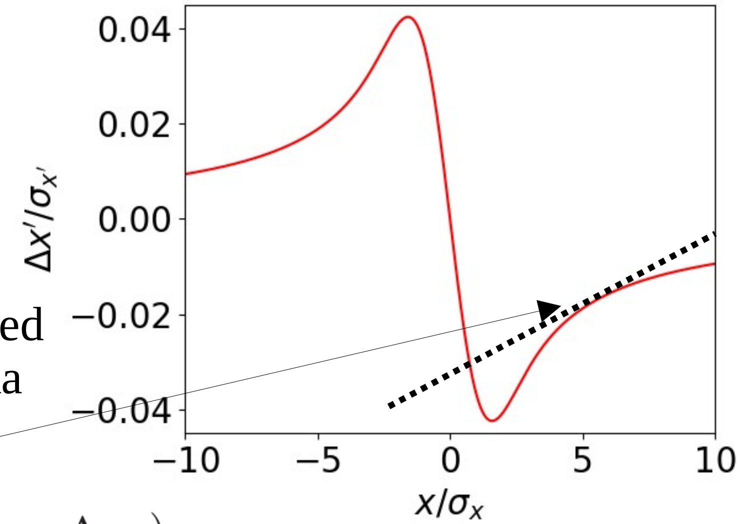


Linearised kick on individual particles based on Bassetti-Erskine (aka incoherent kick)

$$\Delta p_y^{(-)} = -\frac{N^{(+)}\rho^{(+)}(z')\delta z' r_e}{\gamma^{(-)}}\frac{\partial F_y}{\partial y}\Big|_{\substack{x=(z-z')\theta_c \\ y=y_- - y_+}}(\Delta y_- - \Delta y_+)$$

**Hirata-style** (without energy change)

- Integrate the force on the transverse distribution (coherent kick [Hirata88]):

$$F_y^{coh}(\sigma_x, \sigma_y) = F_y(\sqrt{2}\sigma_x, \sqrt{2}\sigma_y)$$

- Build the interaction matrix by considering a succession of drift-kick-drift

$$\prod_i M_{CP\to IP} M_{BB} M_{IP\to CP}$$

Linearised beam-beam kick considering local orbit (crossing angle) and size (hourglass)

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**Cross-wake approach**

- Integrate the incoherent kick over the transverse distribution
- Express it as a wake function

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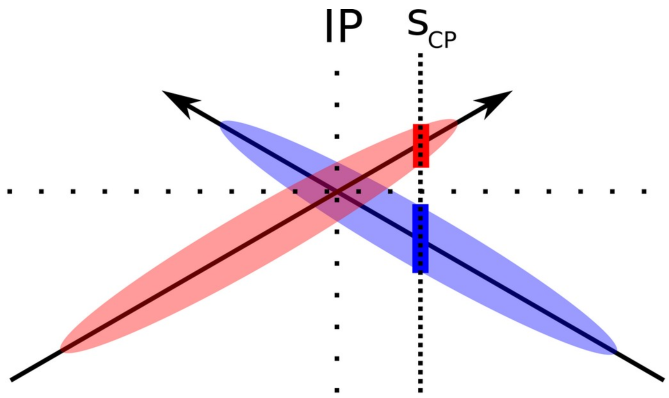


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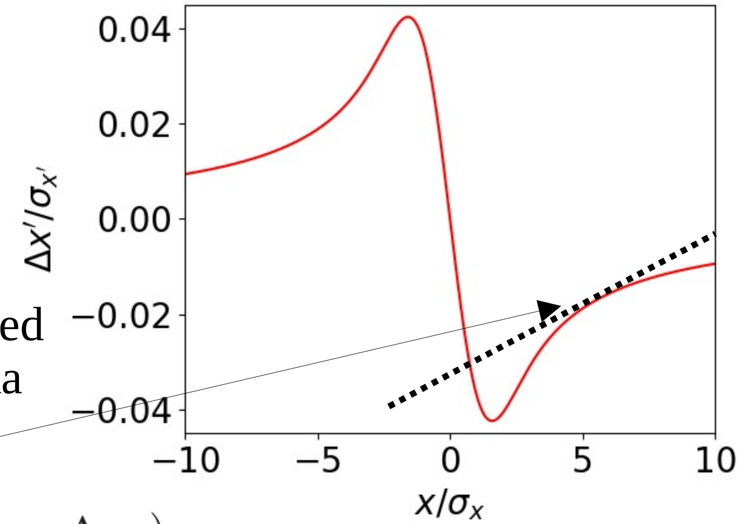


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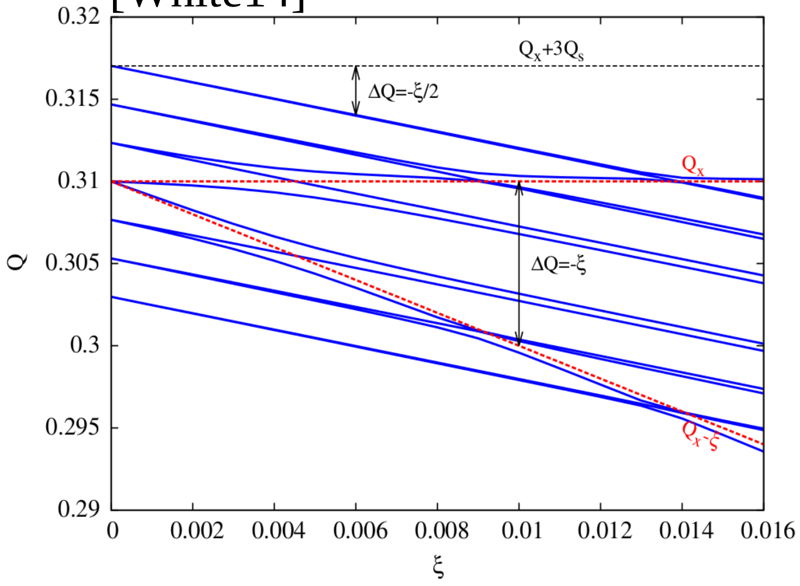

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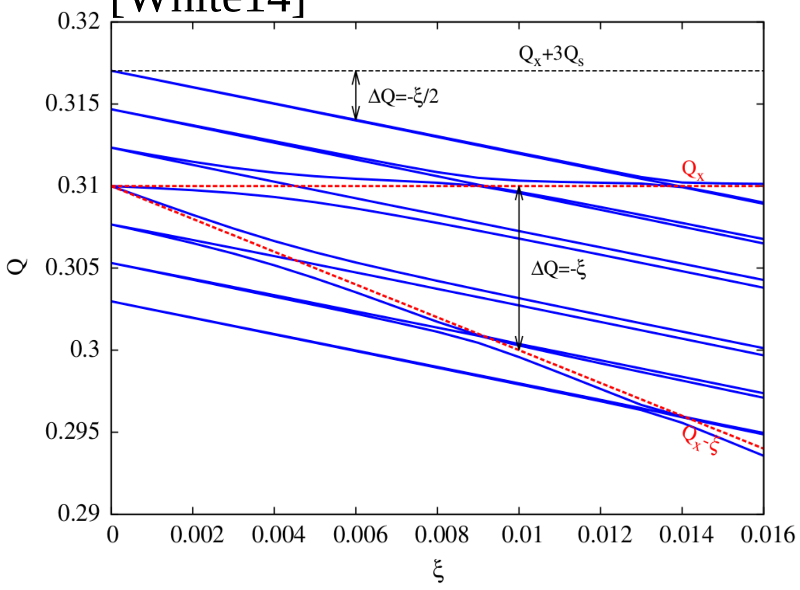


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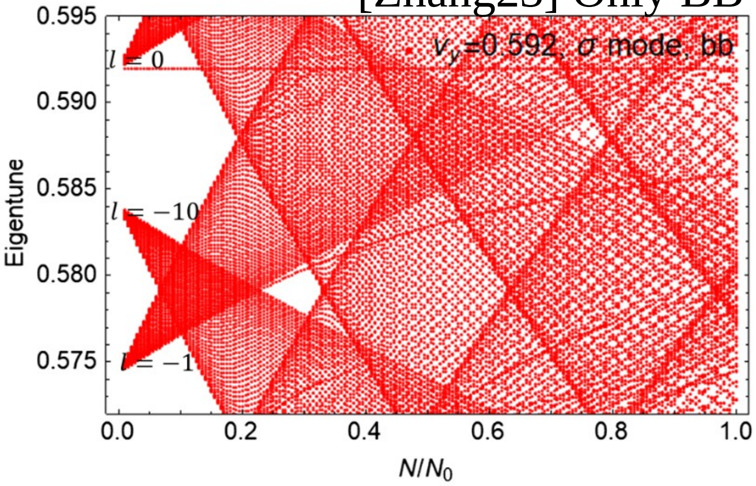

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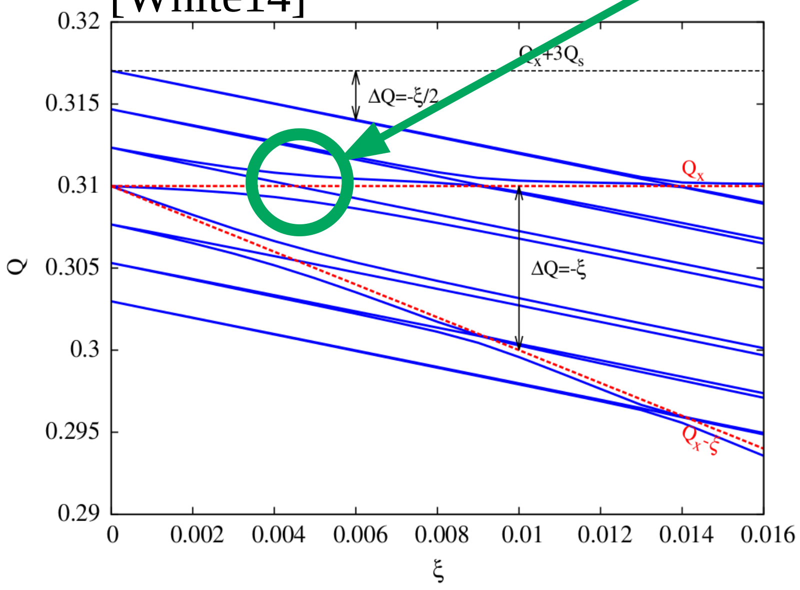


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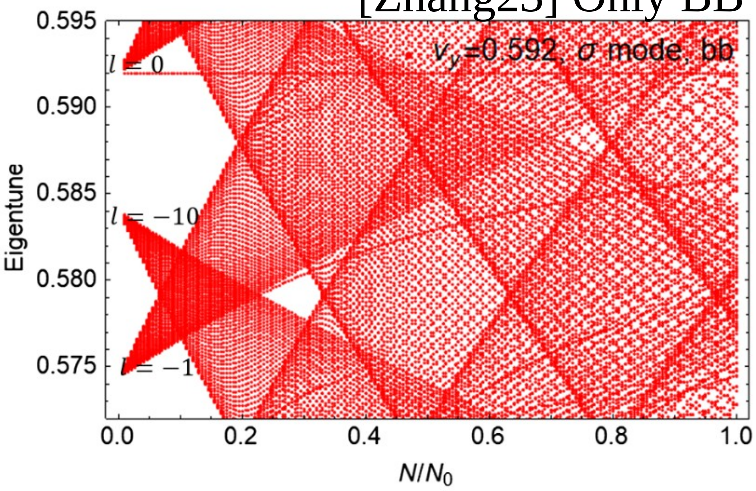

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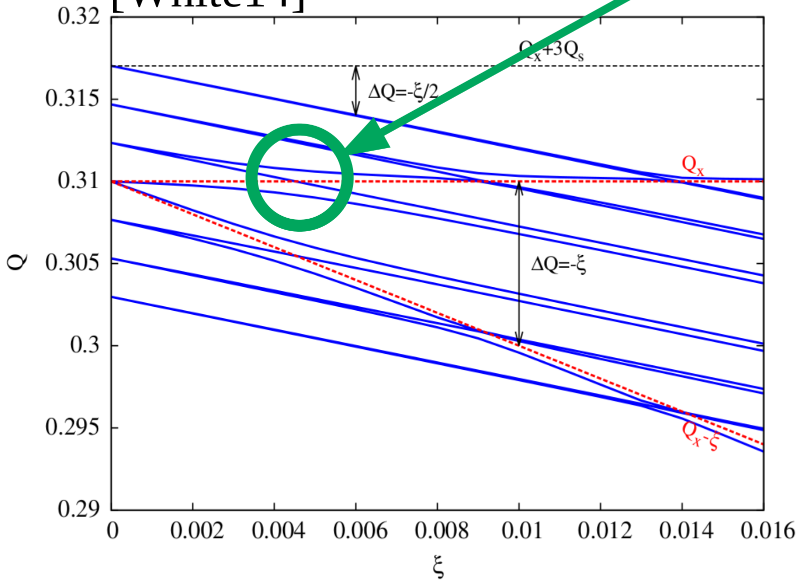


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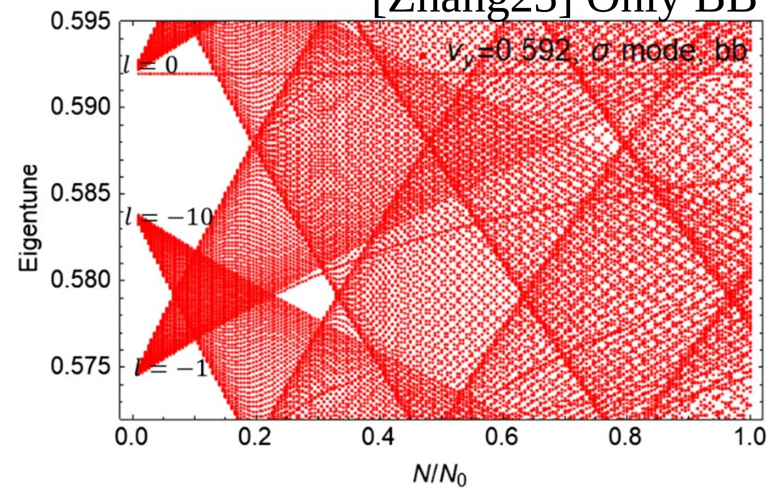

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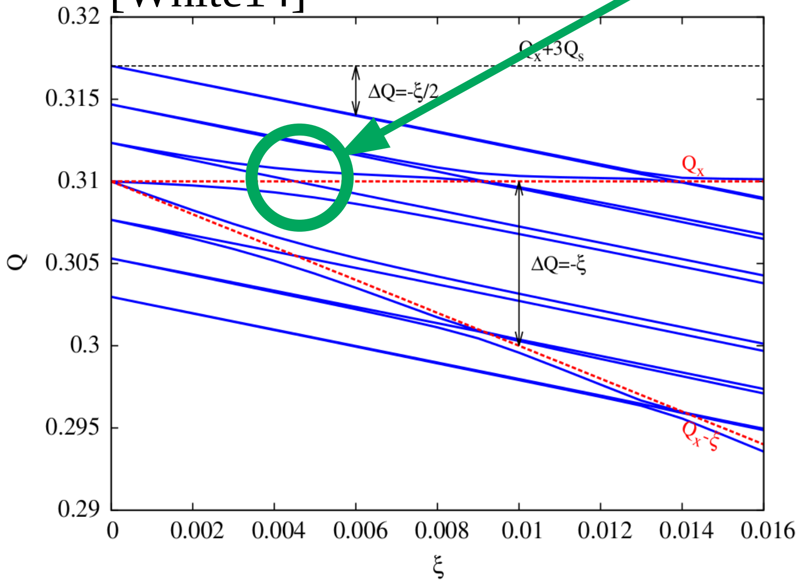


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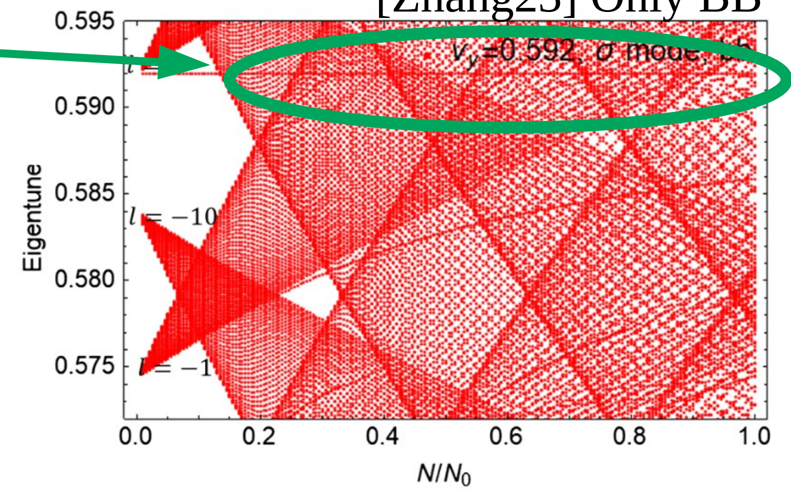

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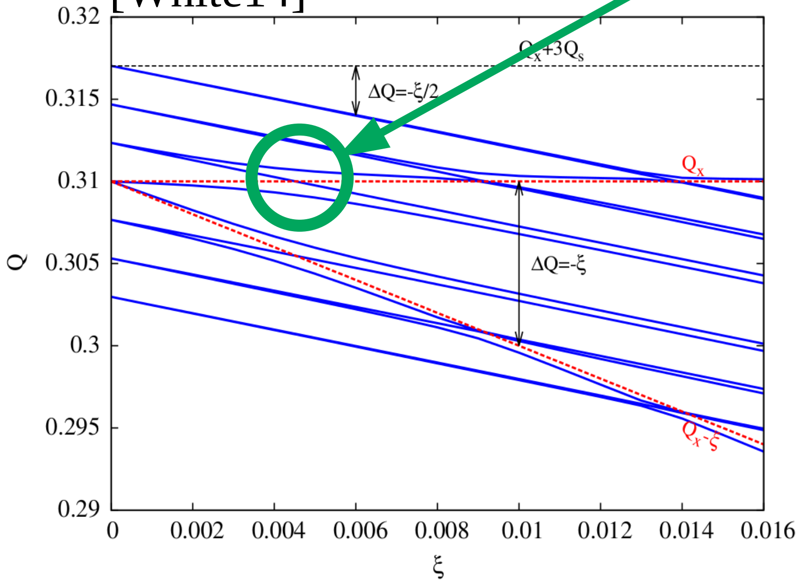


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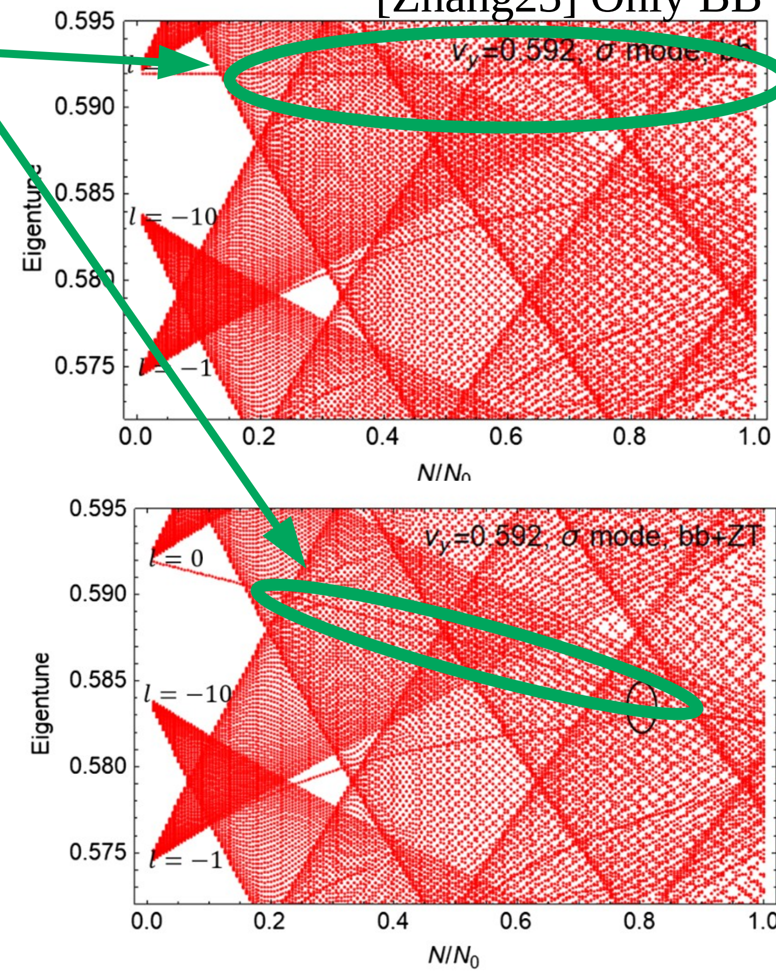

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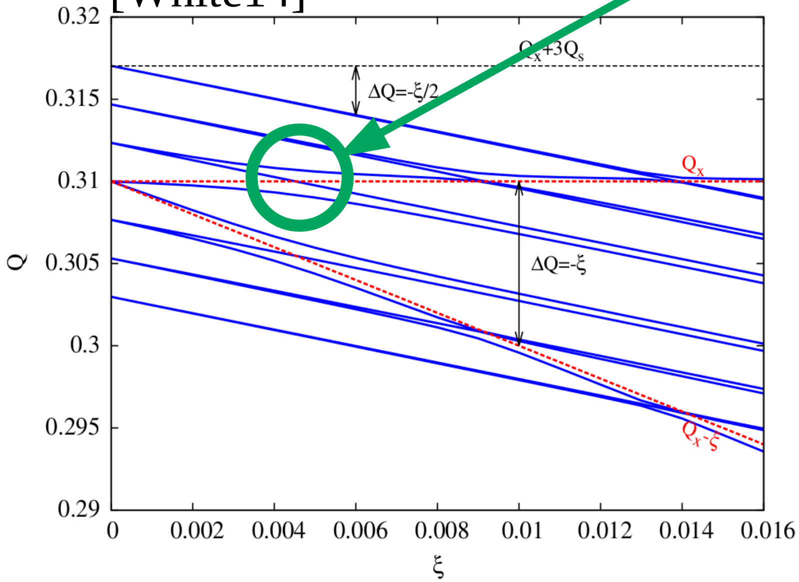


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σ-mode shifted by the impedance

→ Lower TMCI

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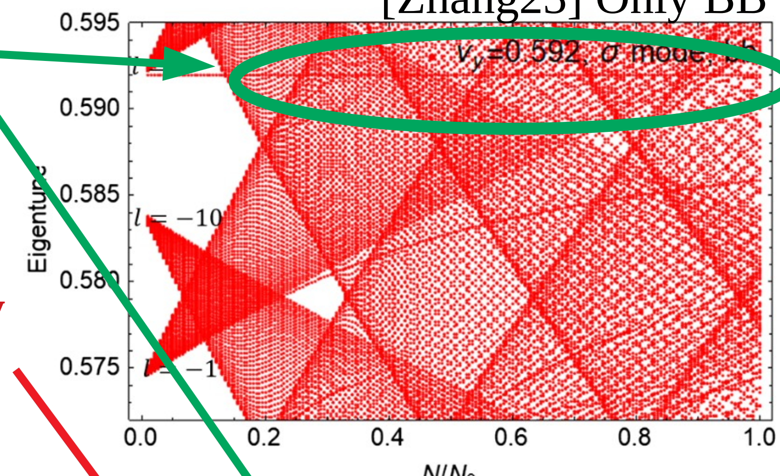


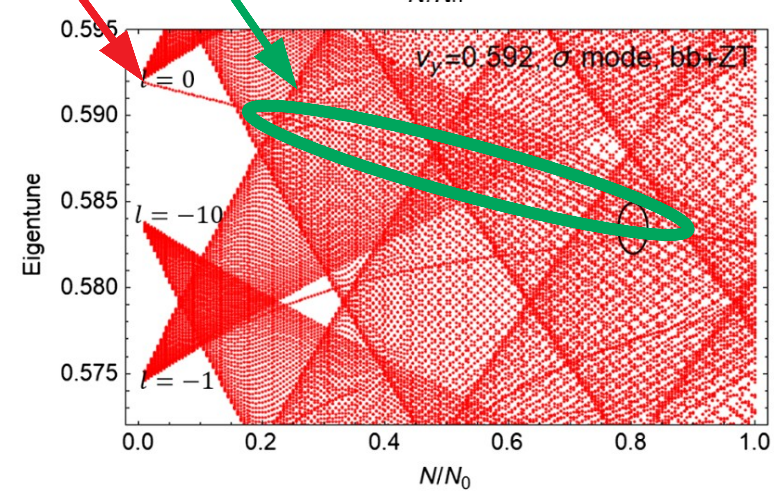

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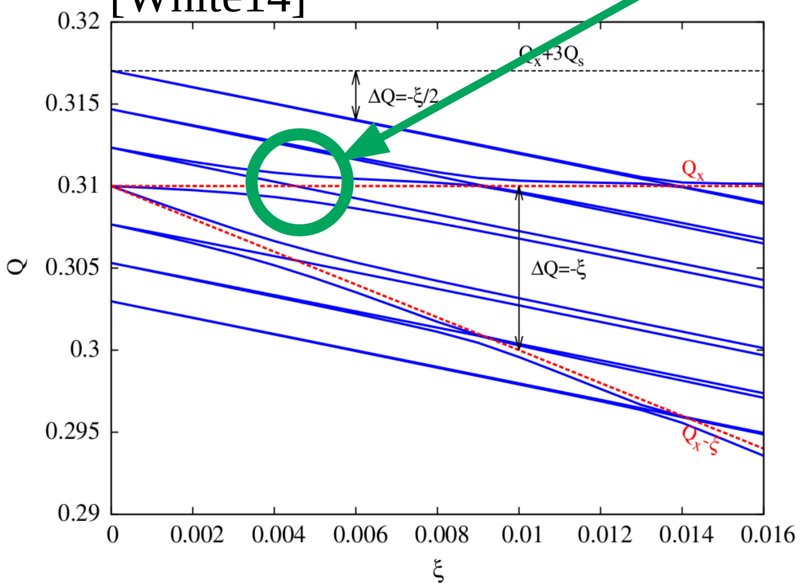


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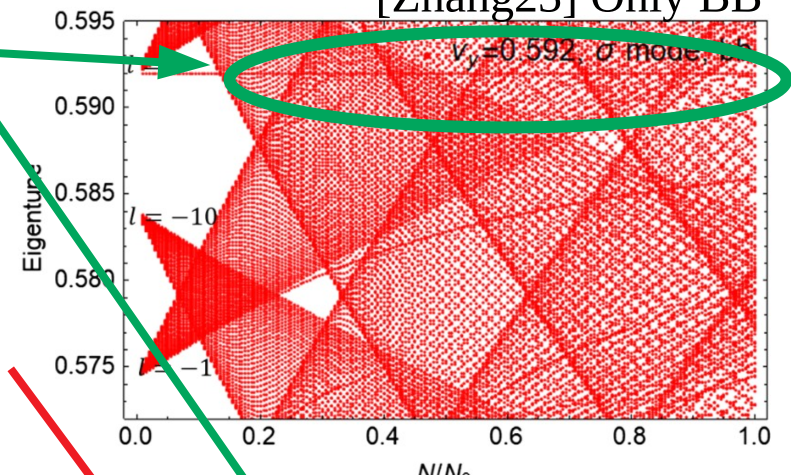


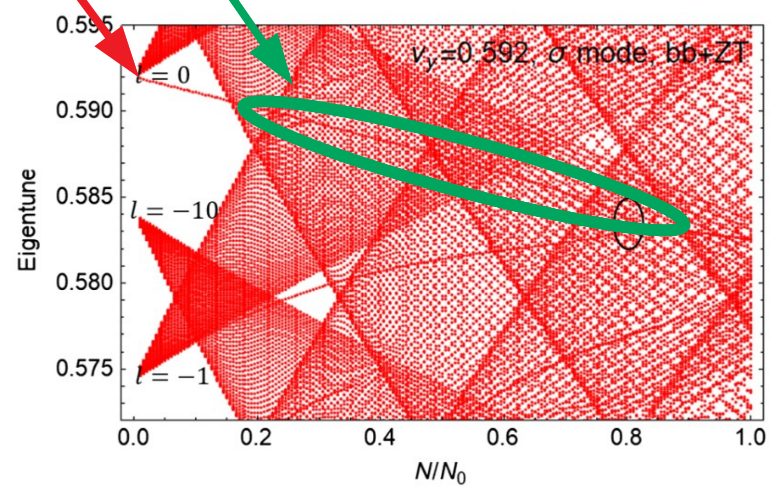


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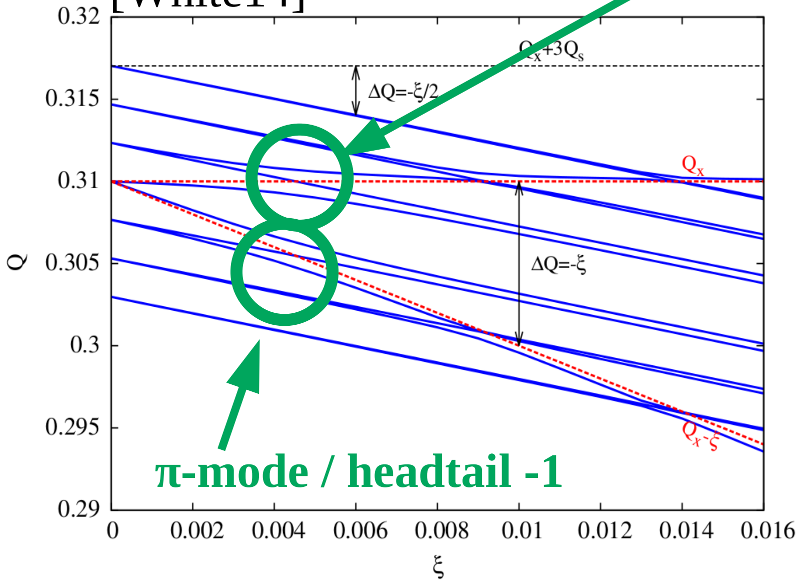


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π-mode / headtail -1

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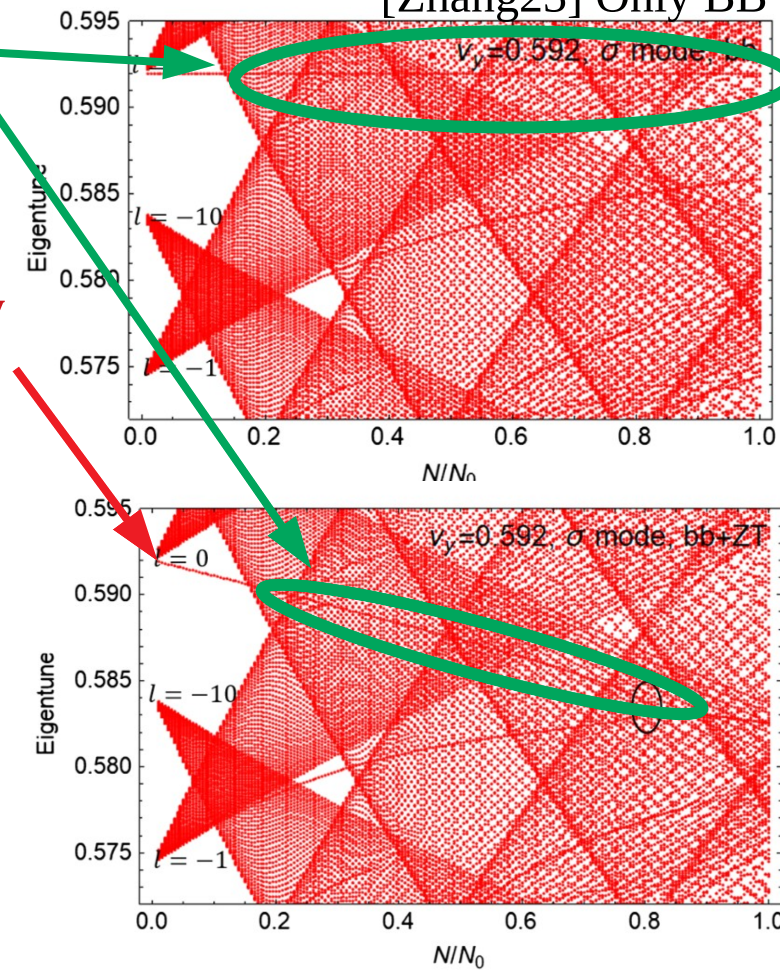


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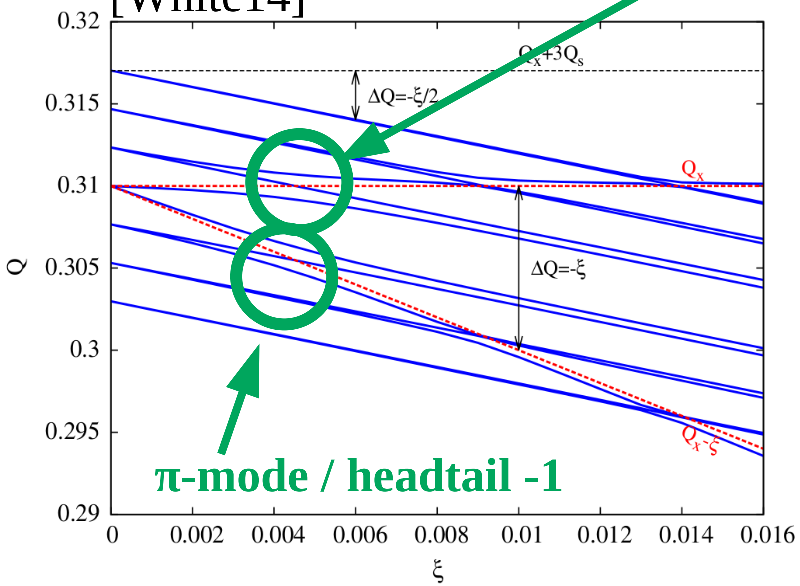


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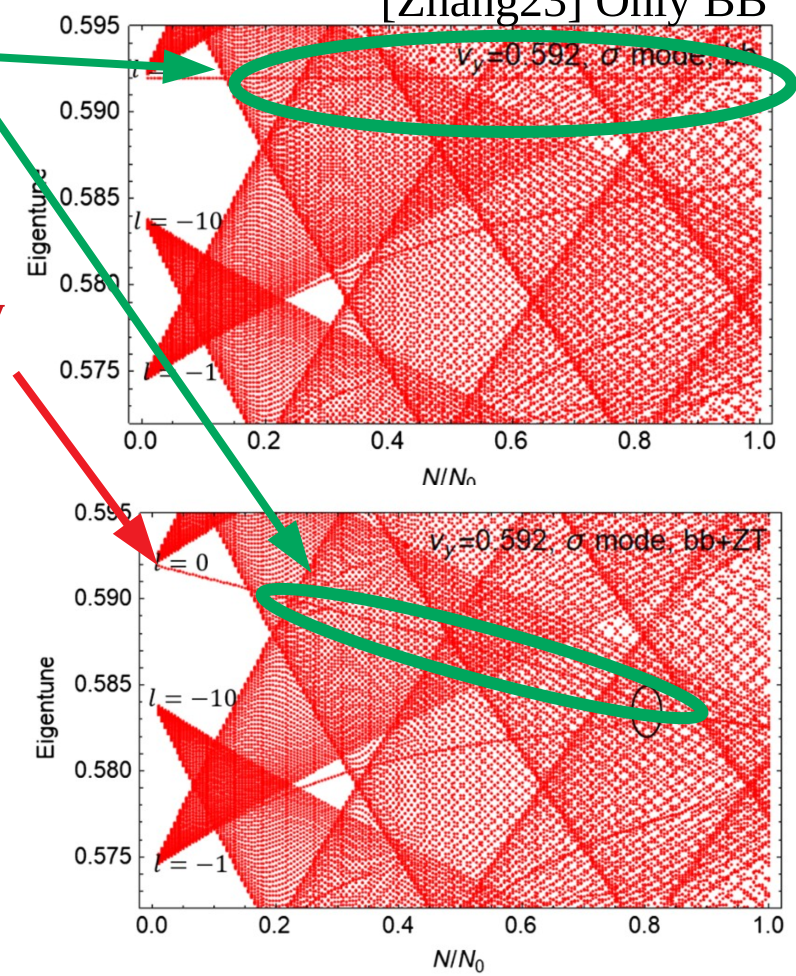


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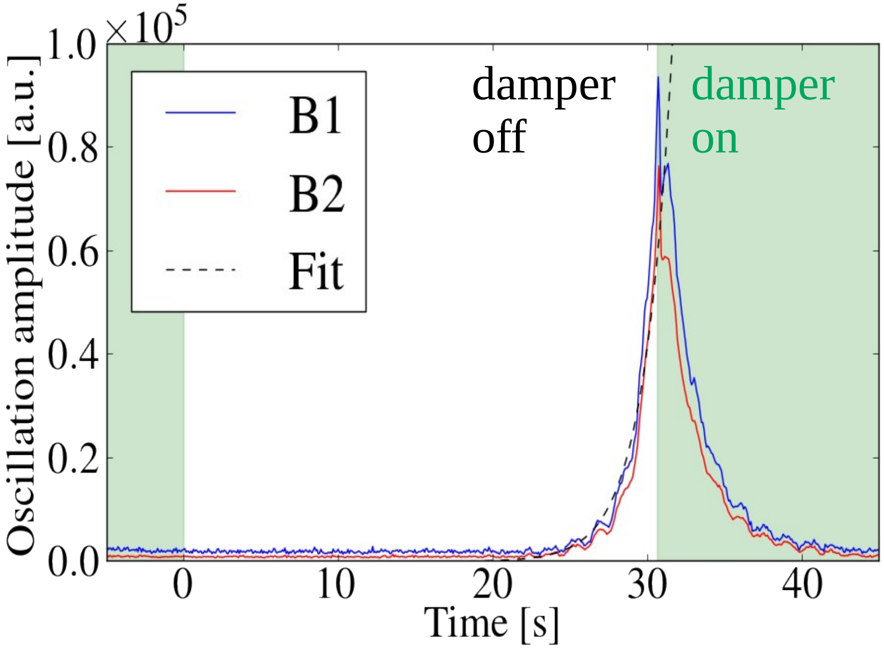
  - The coupling of the π-mode appears at lower intensity → Similar issue in both machines, but not necessarily with the same mode

# Mode coupling instability of colliding beams

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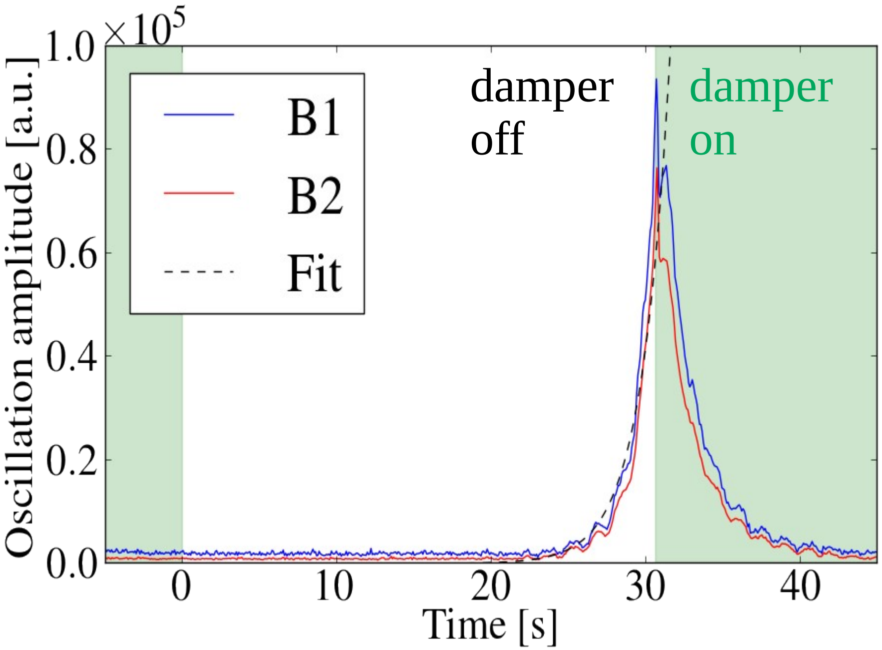


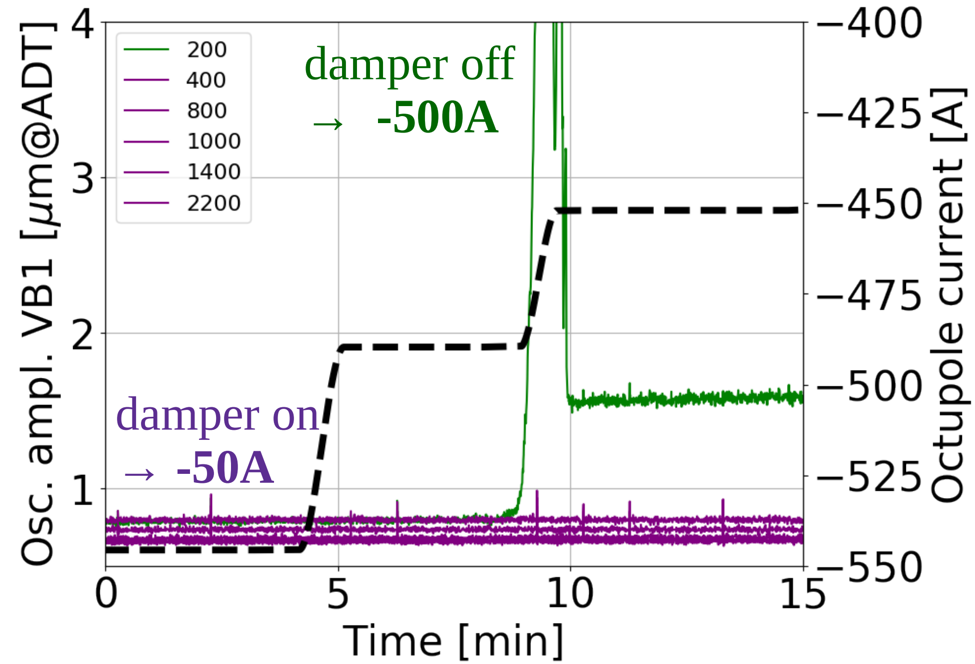


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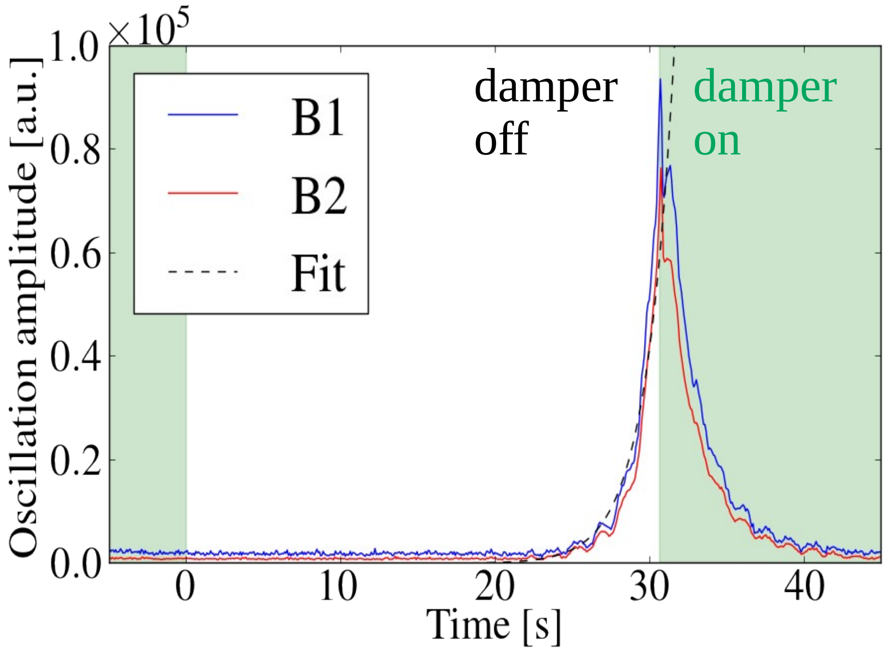


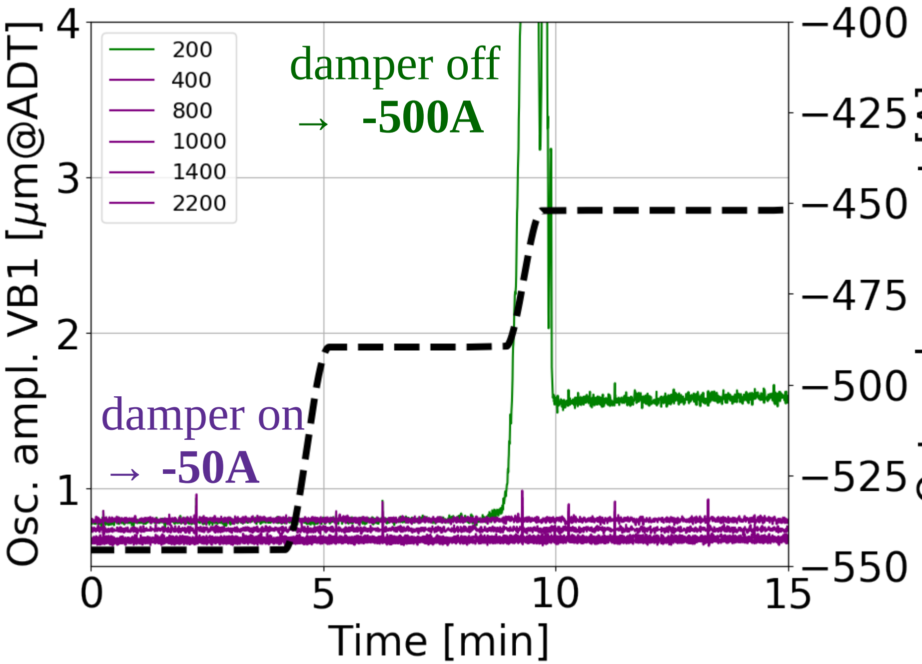


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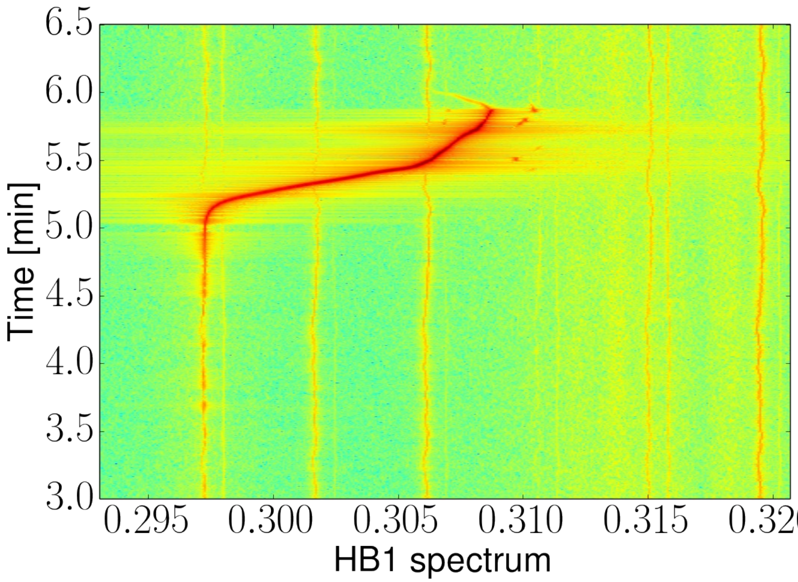

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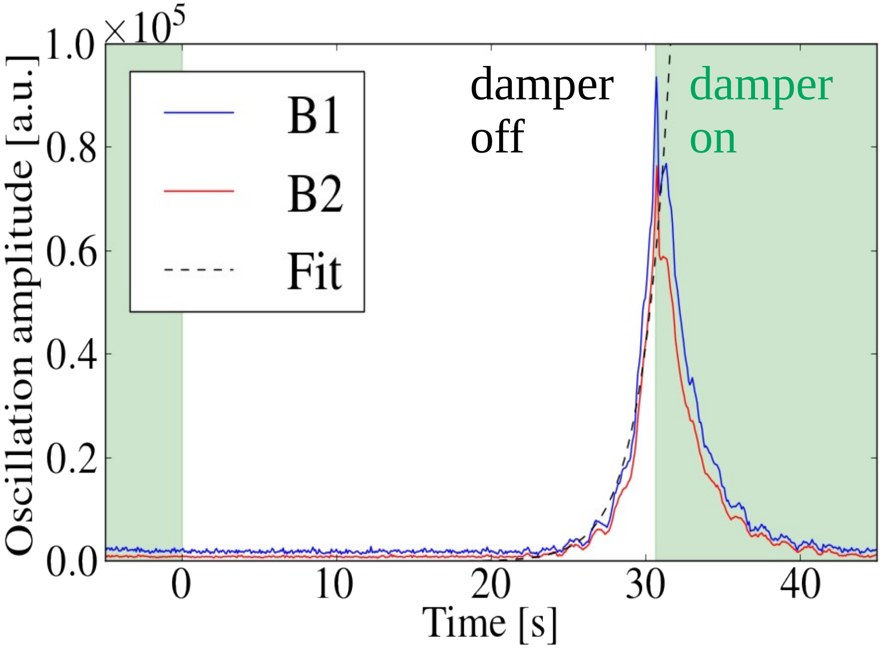


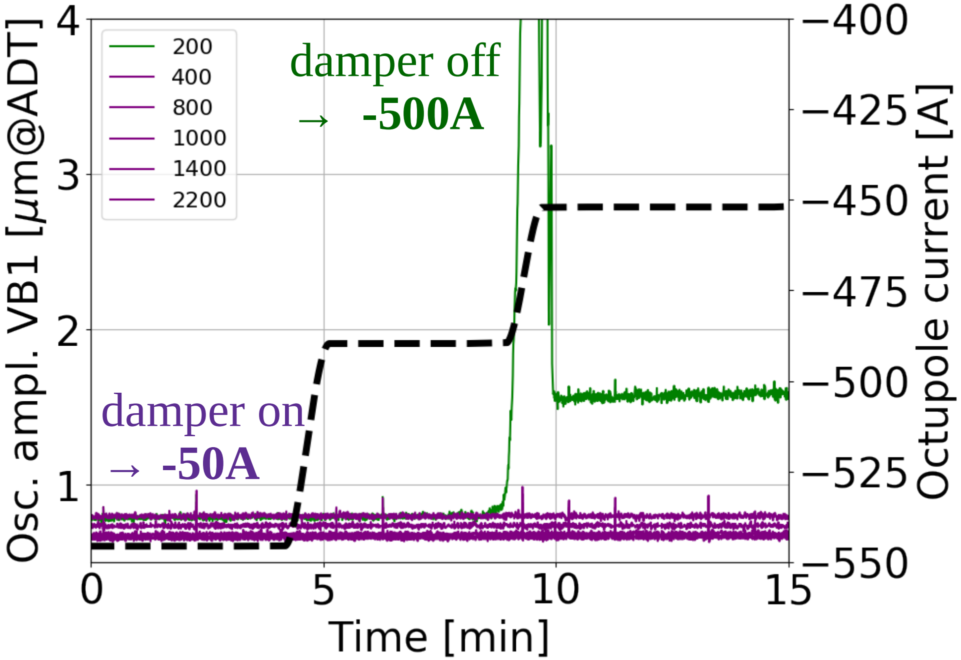


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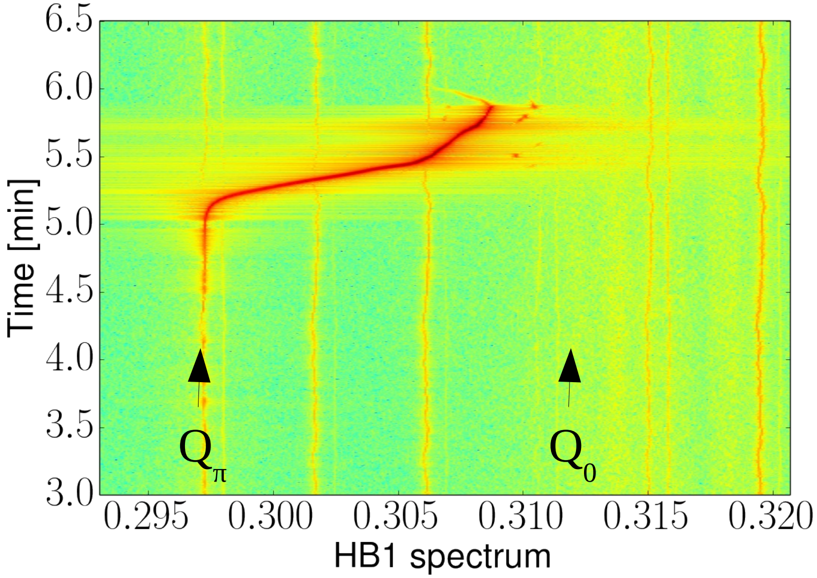
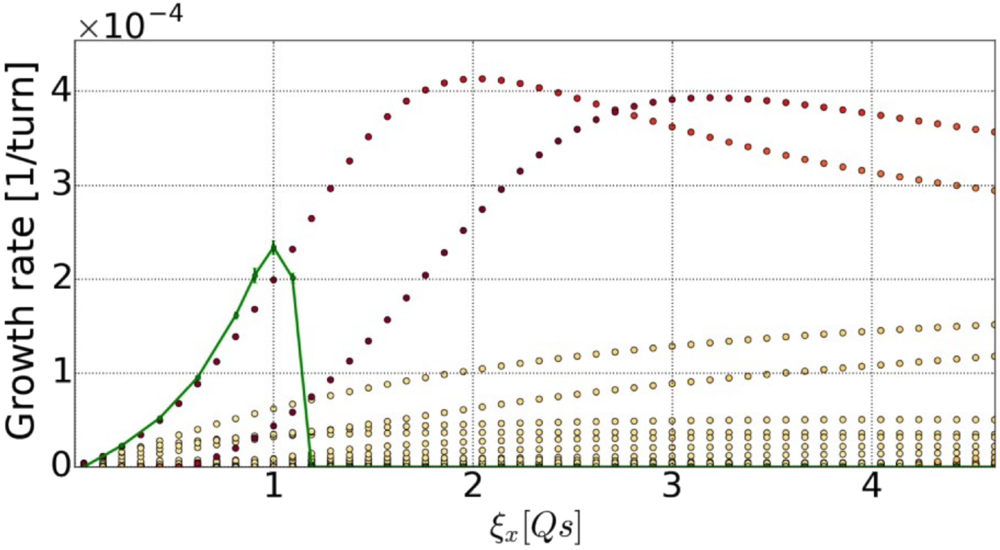


# Mode coupling instability at the HL-LHC

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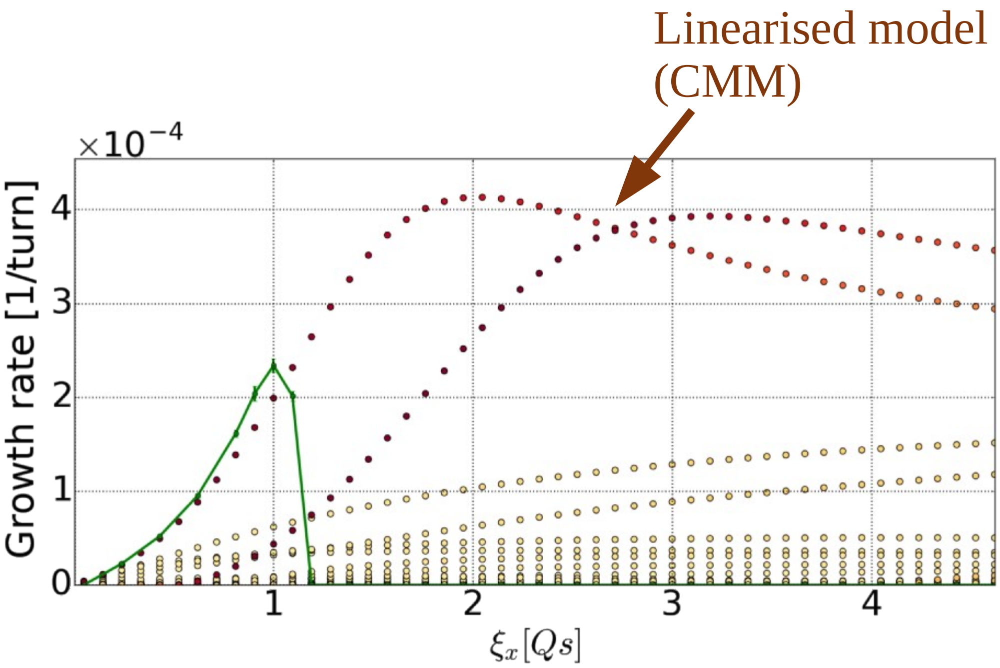


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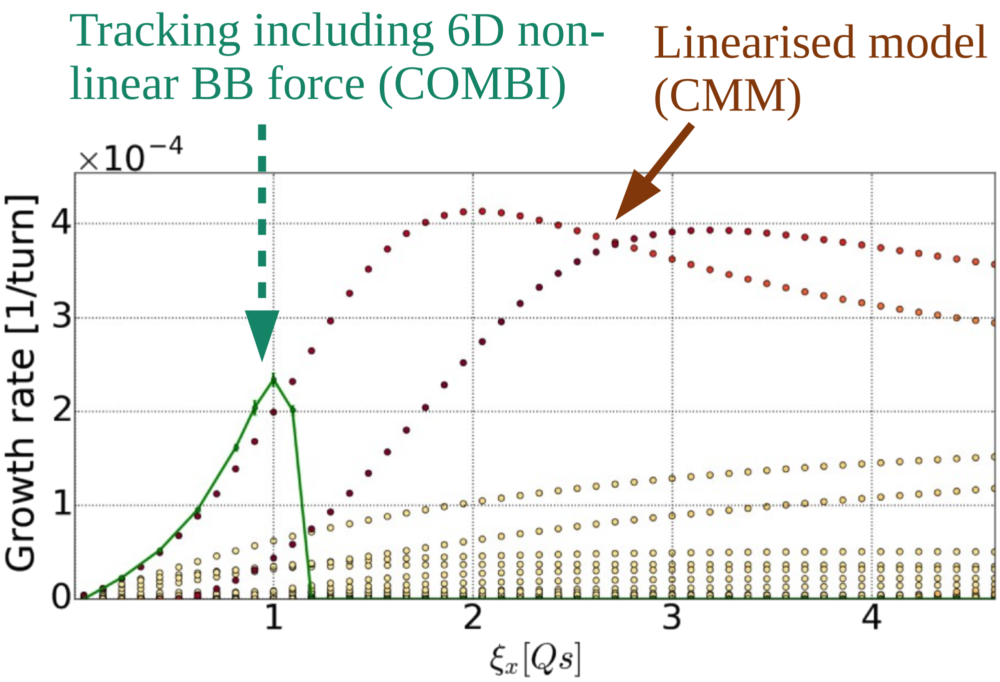


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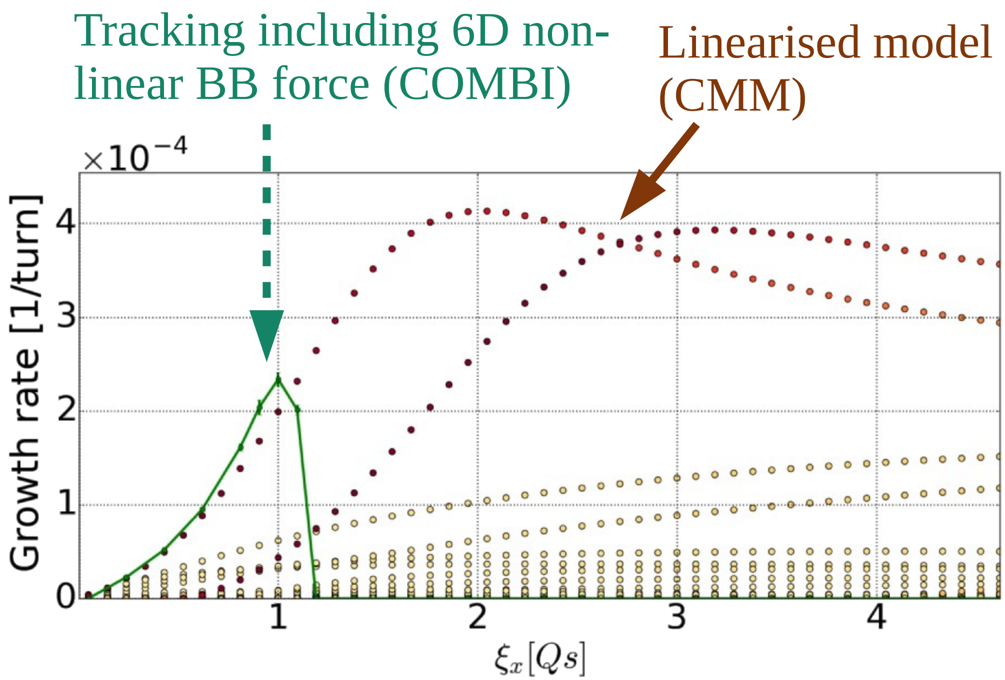


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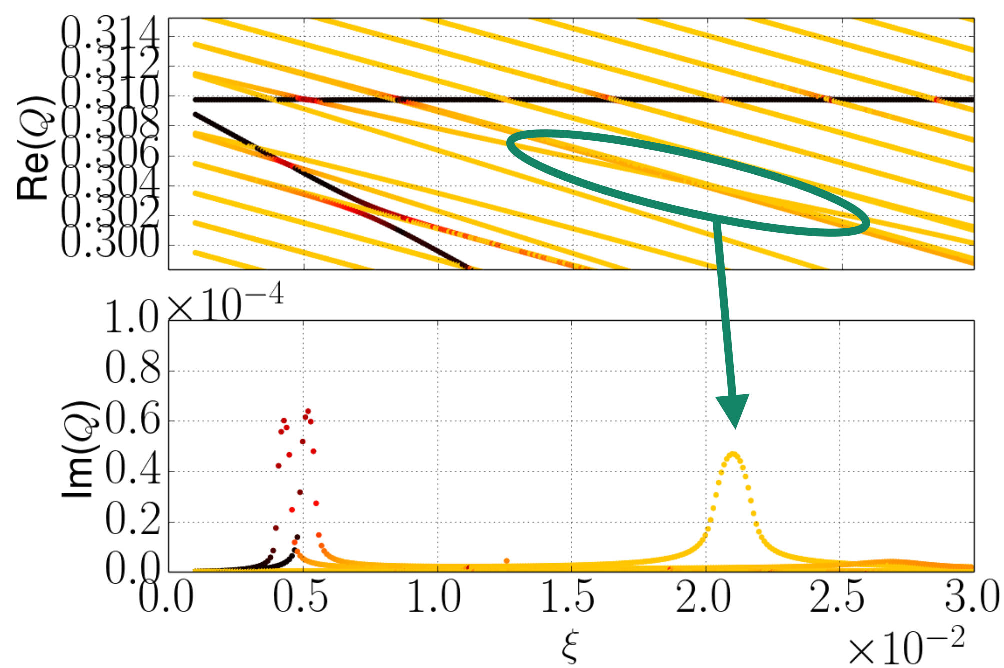
- Coupling of higher order head-tail mode is also observed on in the linearized model

  → They are not damped by the existing ‘dipole’ damper

  → They are not observed in tracking, probably also due to Landau damping by sidebands



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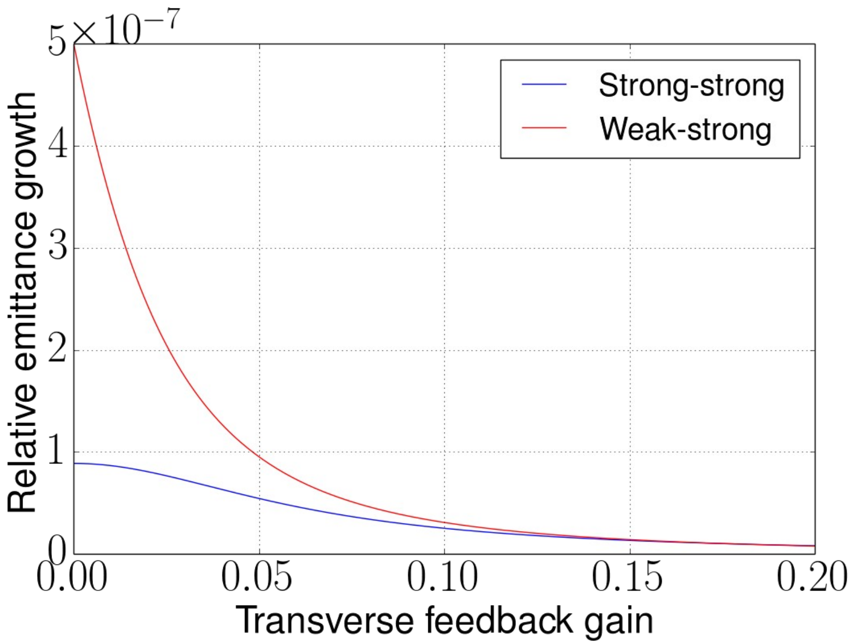

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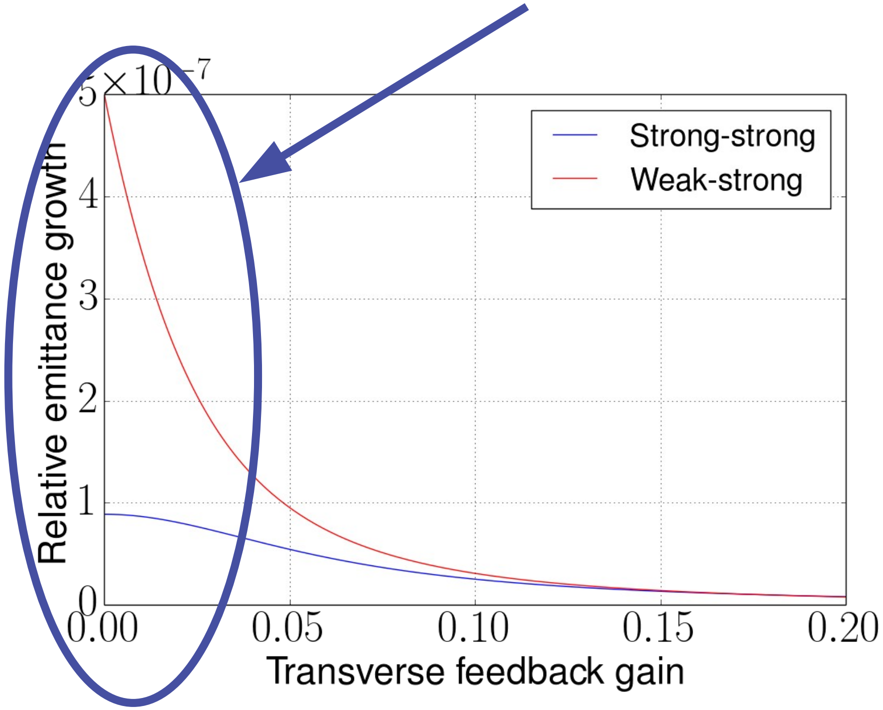

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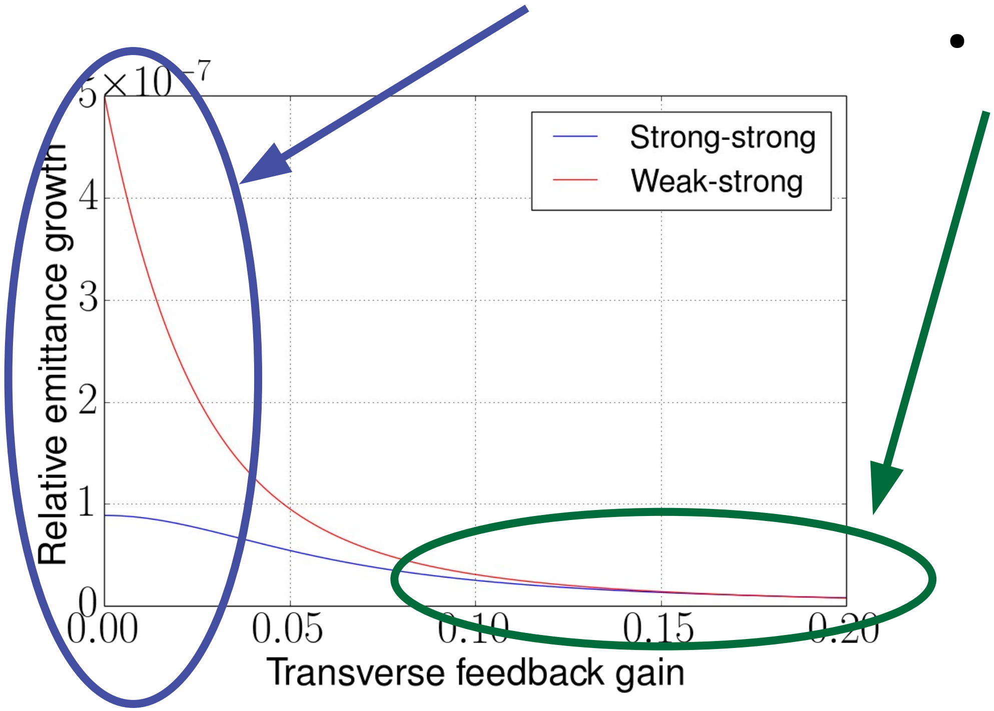


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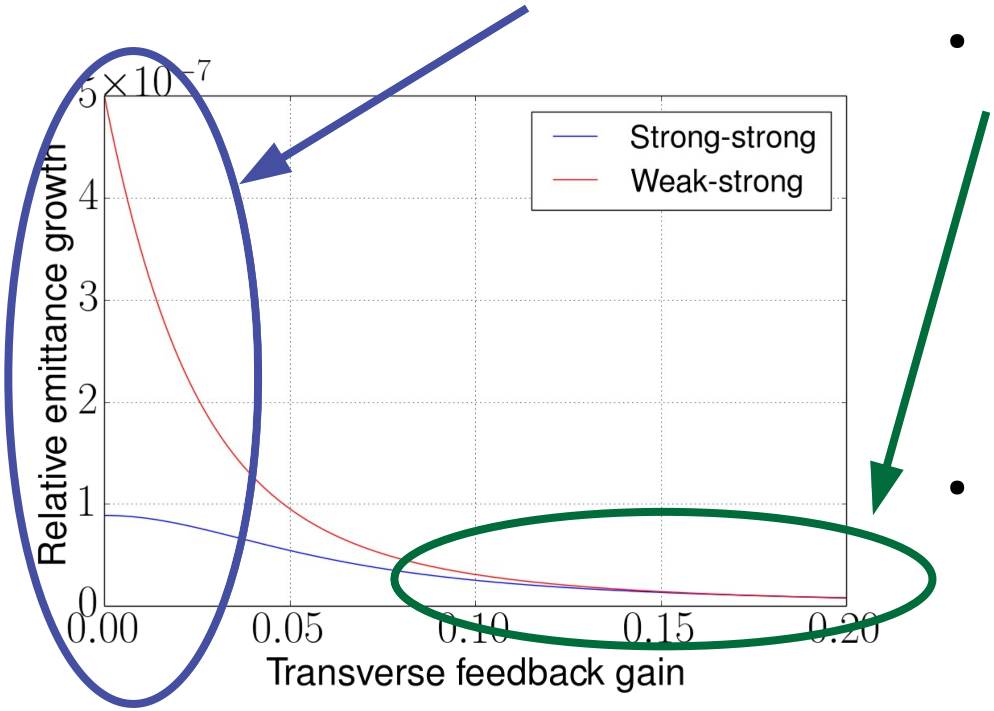


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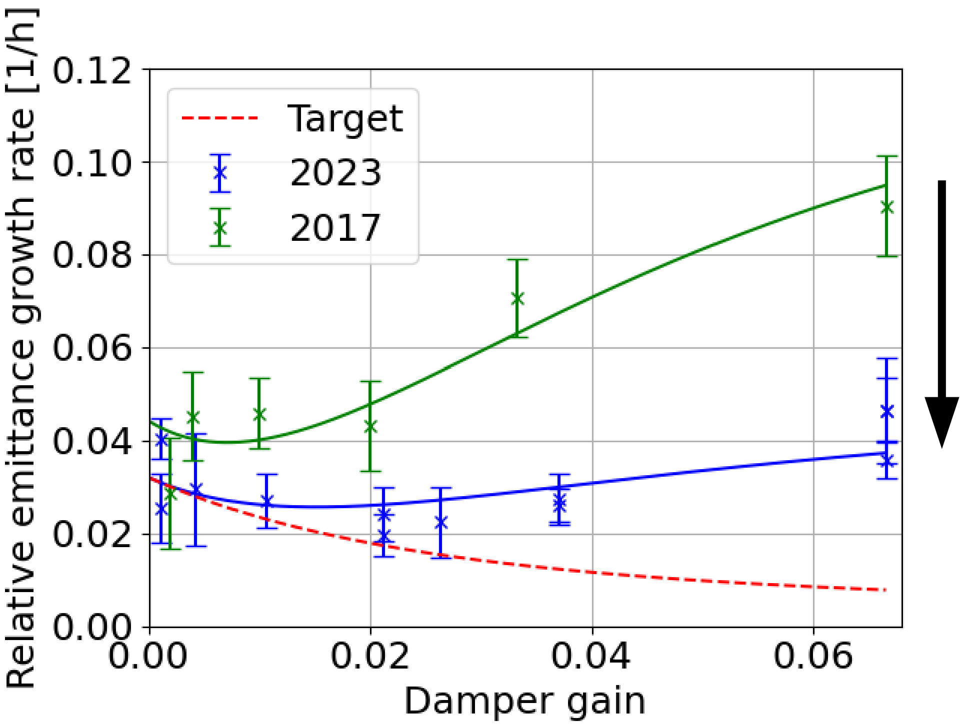
- Potentially many other aspects break coherent modes [Alexahin02, Pieloni08], such that the weak-strong model may be sufficiently accurate even in a strong-strong configuration

# Emittance growth reduction at the LHC




- New low-noise pickup electronics, doubling the number of pickups (now 8 per beam and per plane) [Valuch22]

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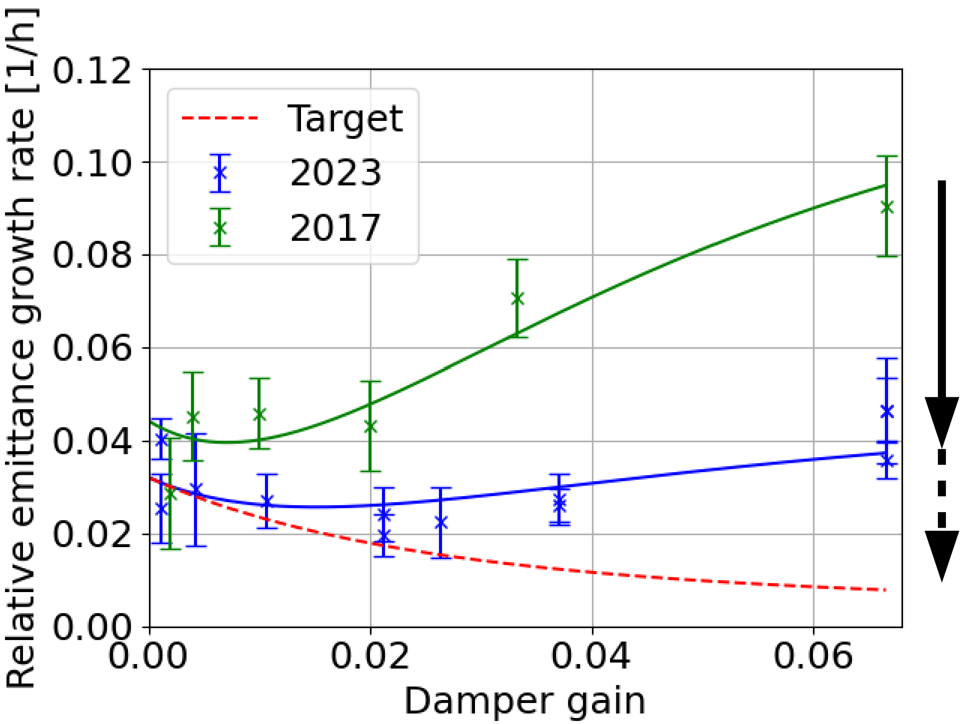


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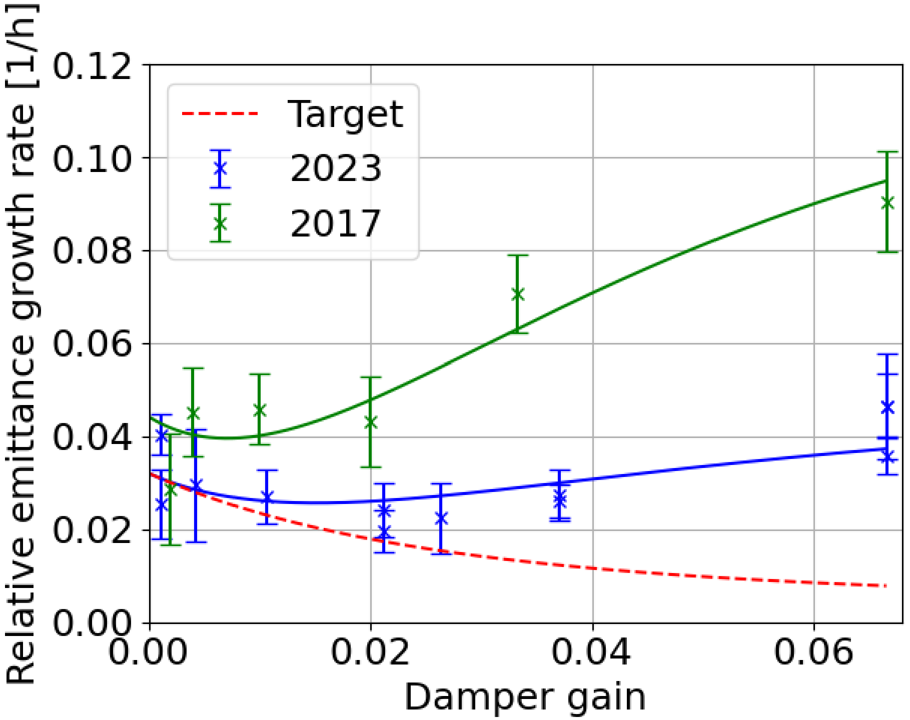


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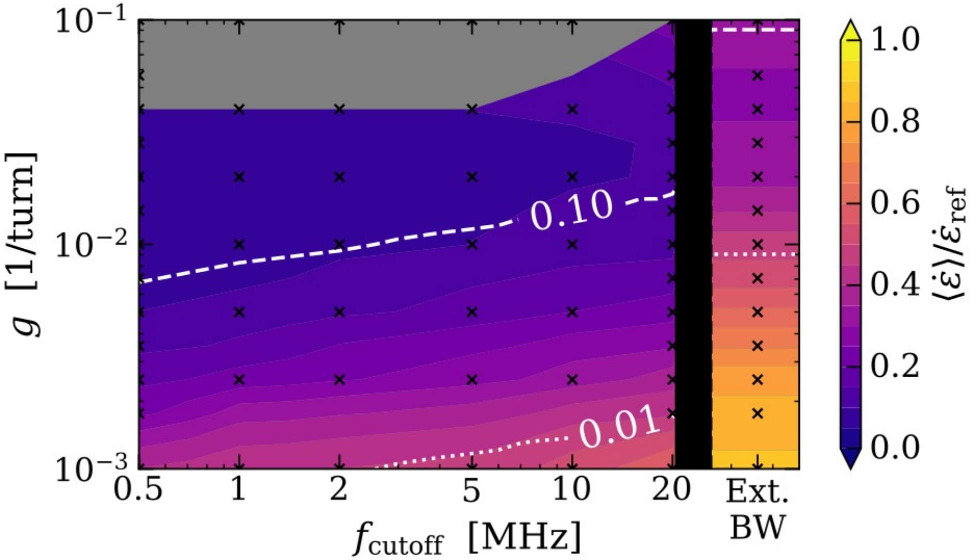

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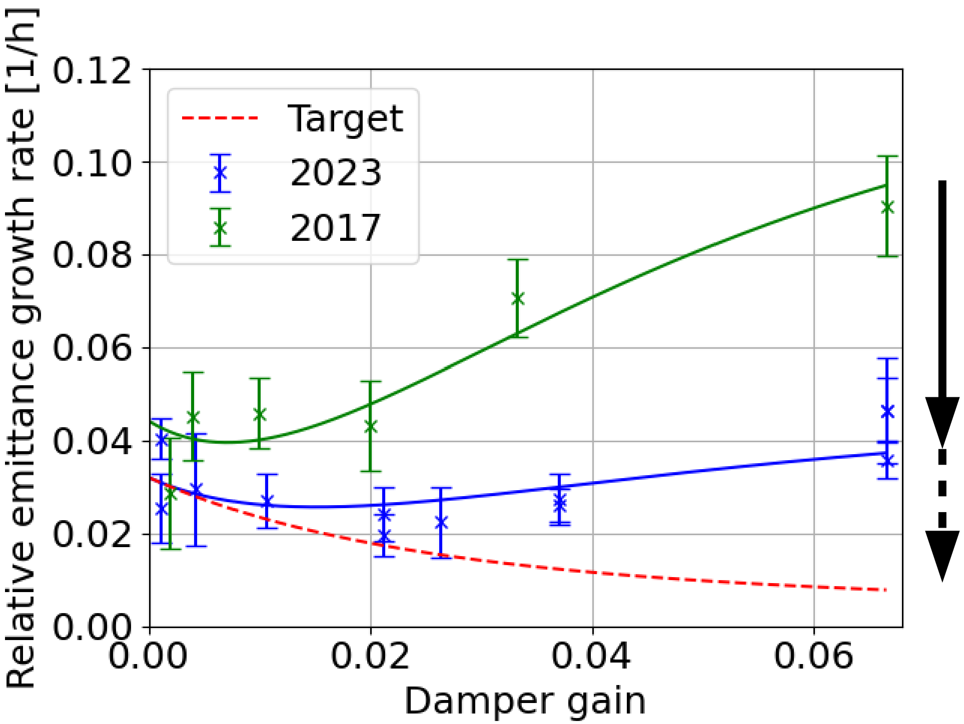


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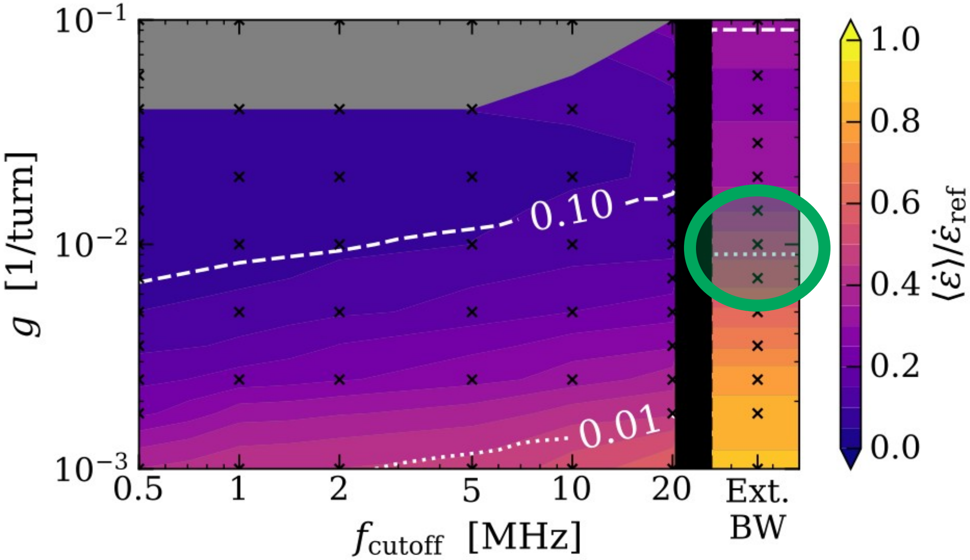

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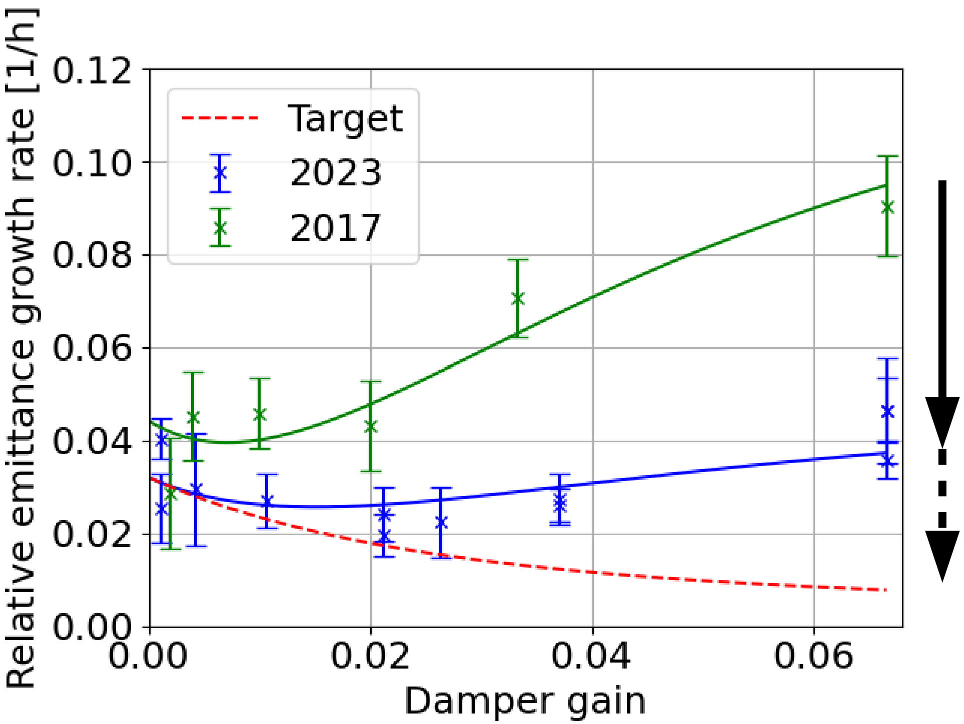


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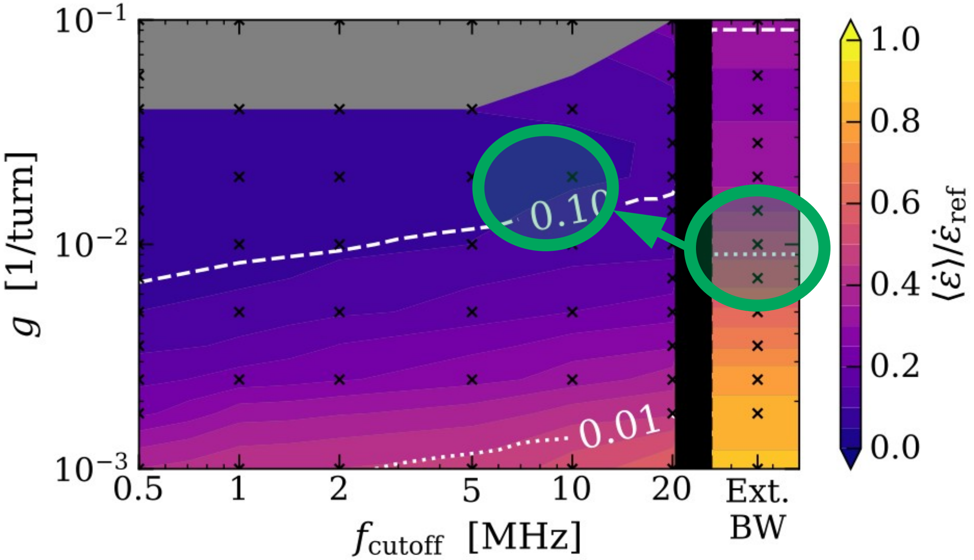
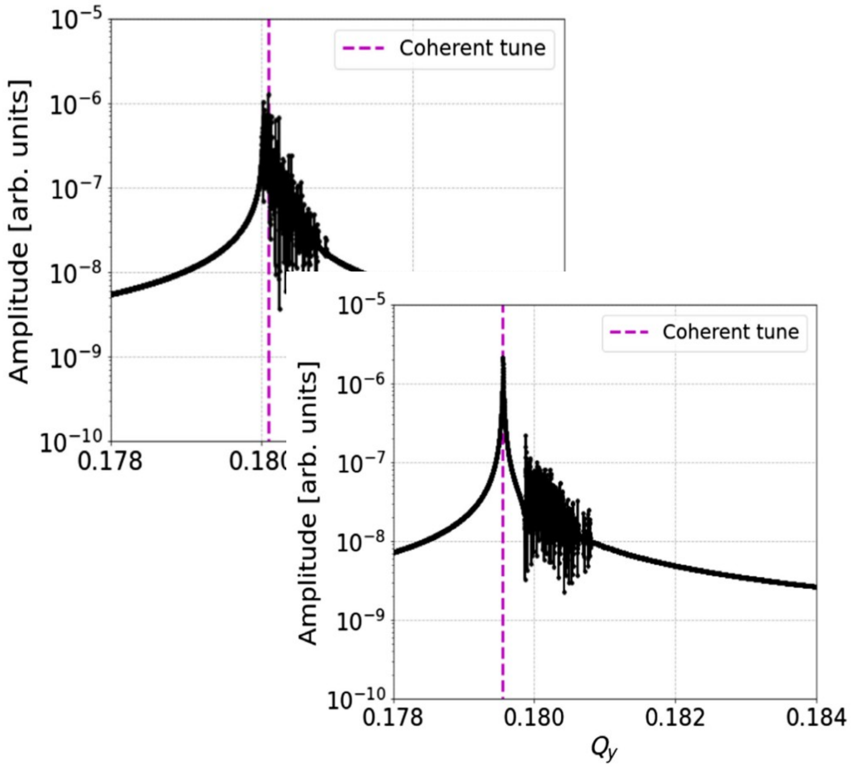


# Validation at the SPS
## [Triantafyllou24]

- The SPS looked like a good *weak-strong-like* case for tests with a crab cavity prototype. In terms of emittance growth, the reality turned out closer to a strong-strong case
  - Analogously to a strong-strong beam-beam force, the impedance can shift coherent modes of oscillation outside of the incoherent spectrum
  - In the realm of instabilities, this would be called a loss of Landau damping, but here the mode 0 is stabilised by the impedance → Natural ***damper***



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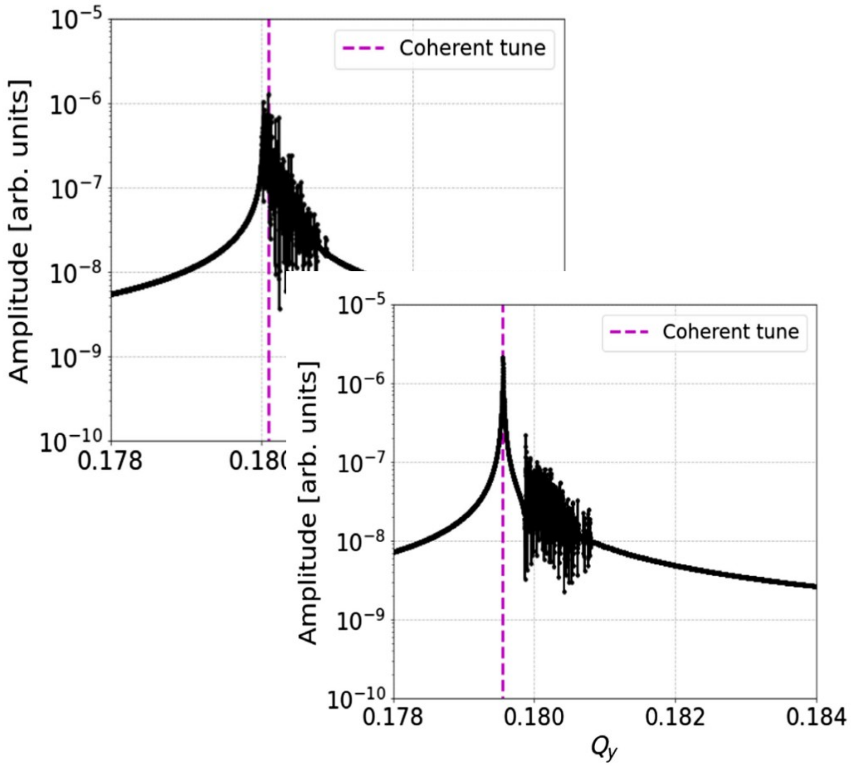


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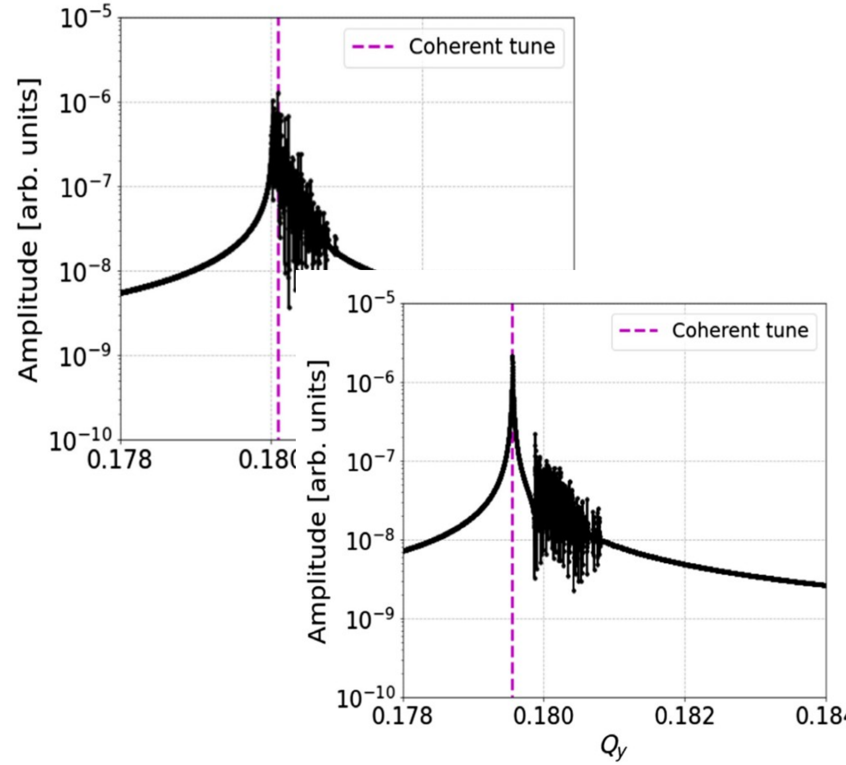


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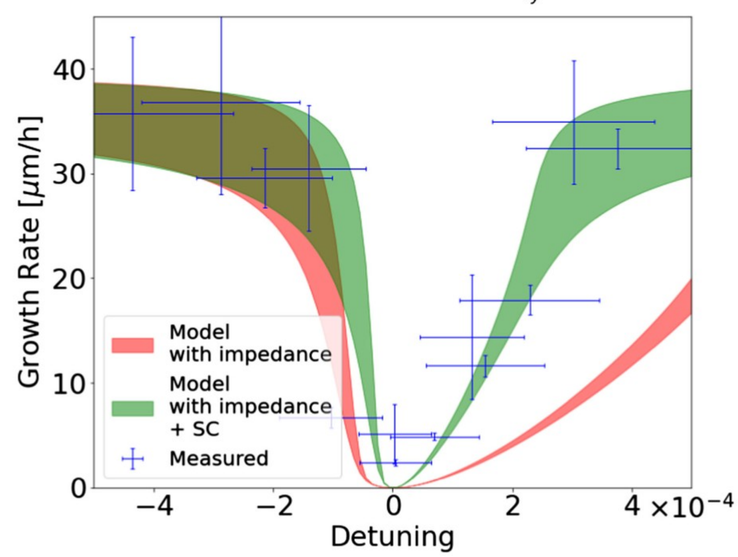

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  - The circulant matrix model was used to describe these instabilties, the instability is comparable to those under study in lepton colliders.
- The suppression of emittance growth predicted by strong-strong models (with discrete modes outside of the incoherent spectrum) was observed experimentally in a different yet analogous setup without beam-beam at the SPS
  - A suppression by up to a factor 10 was observed. It is unfortunately not useful in the *high damper gain* regime required in colliders with many bunches

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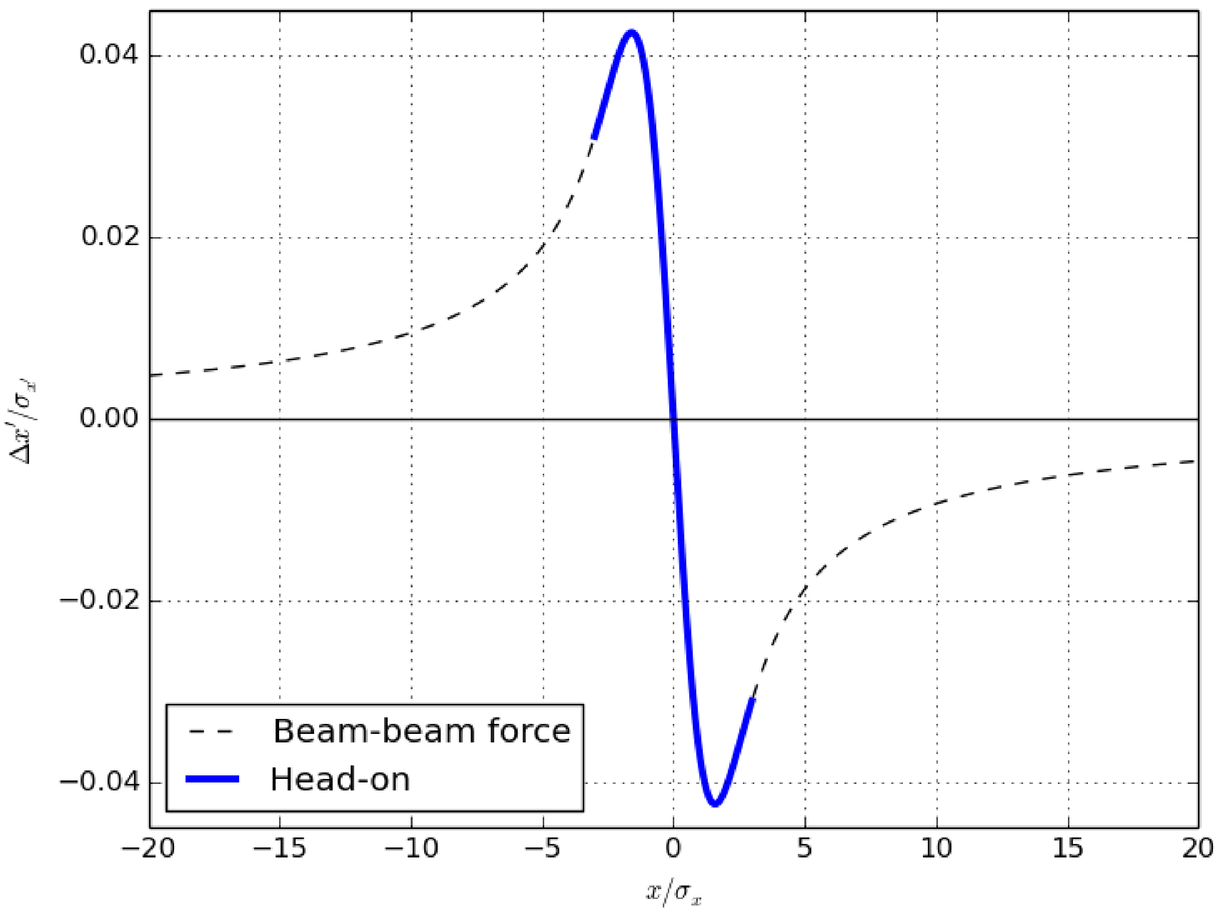

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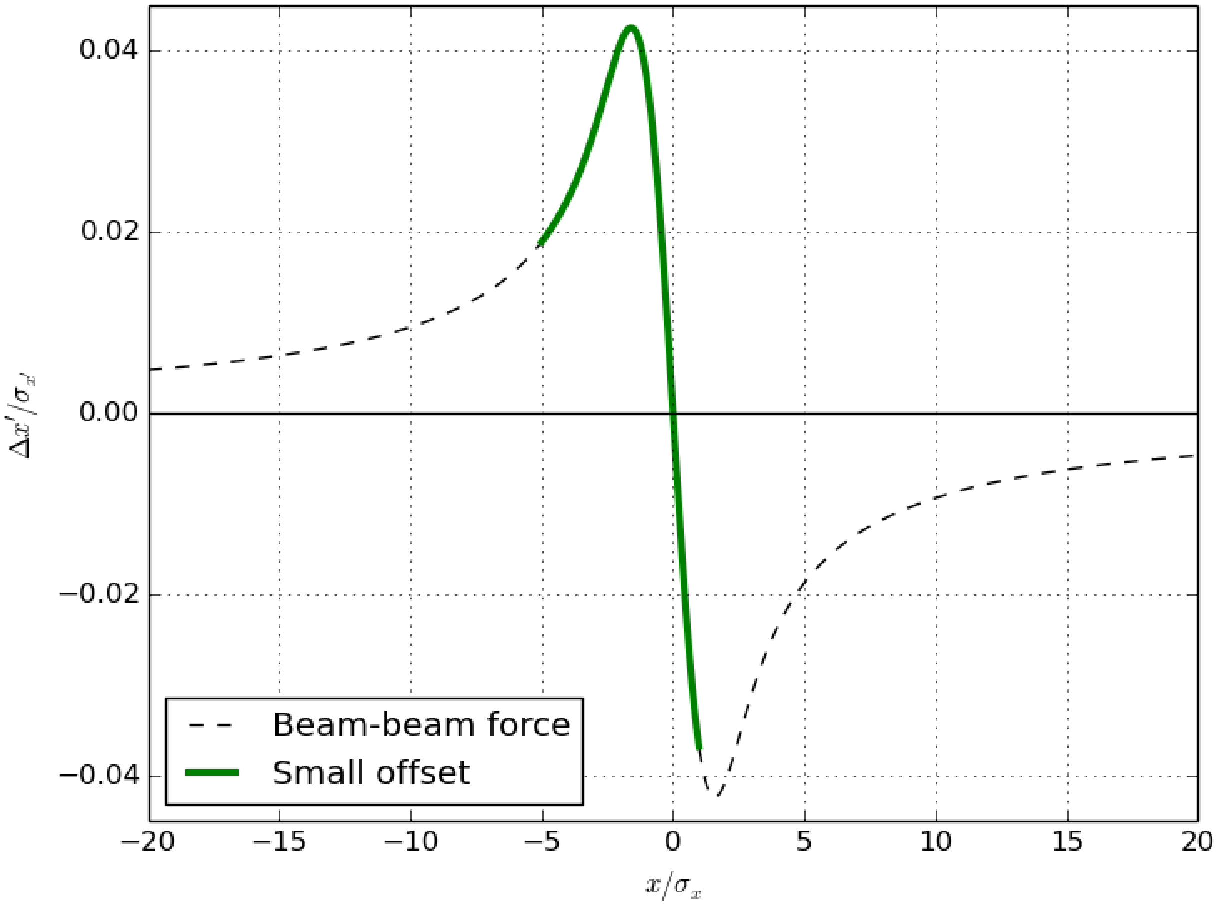

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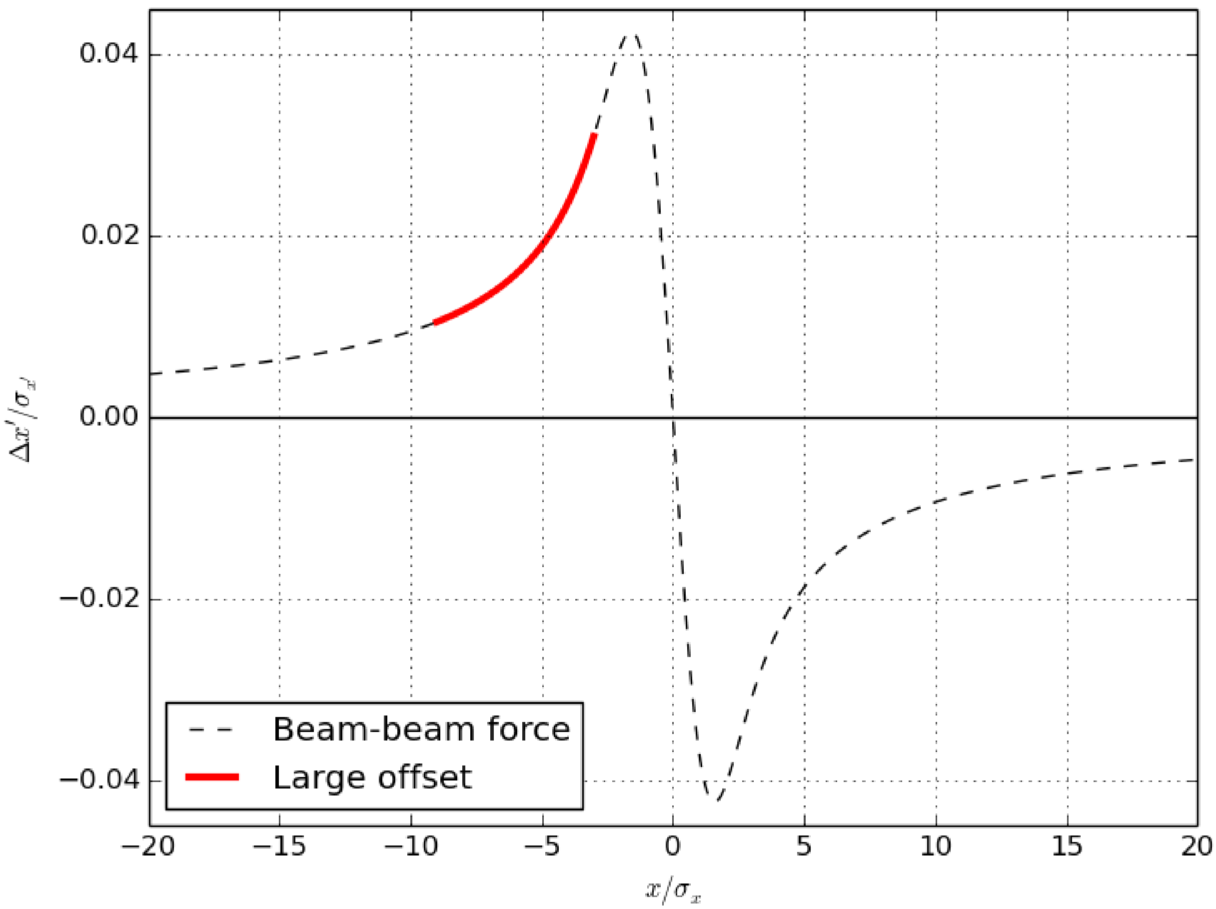

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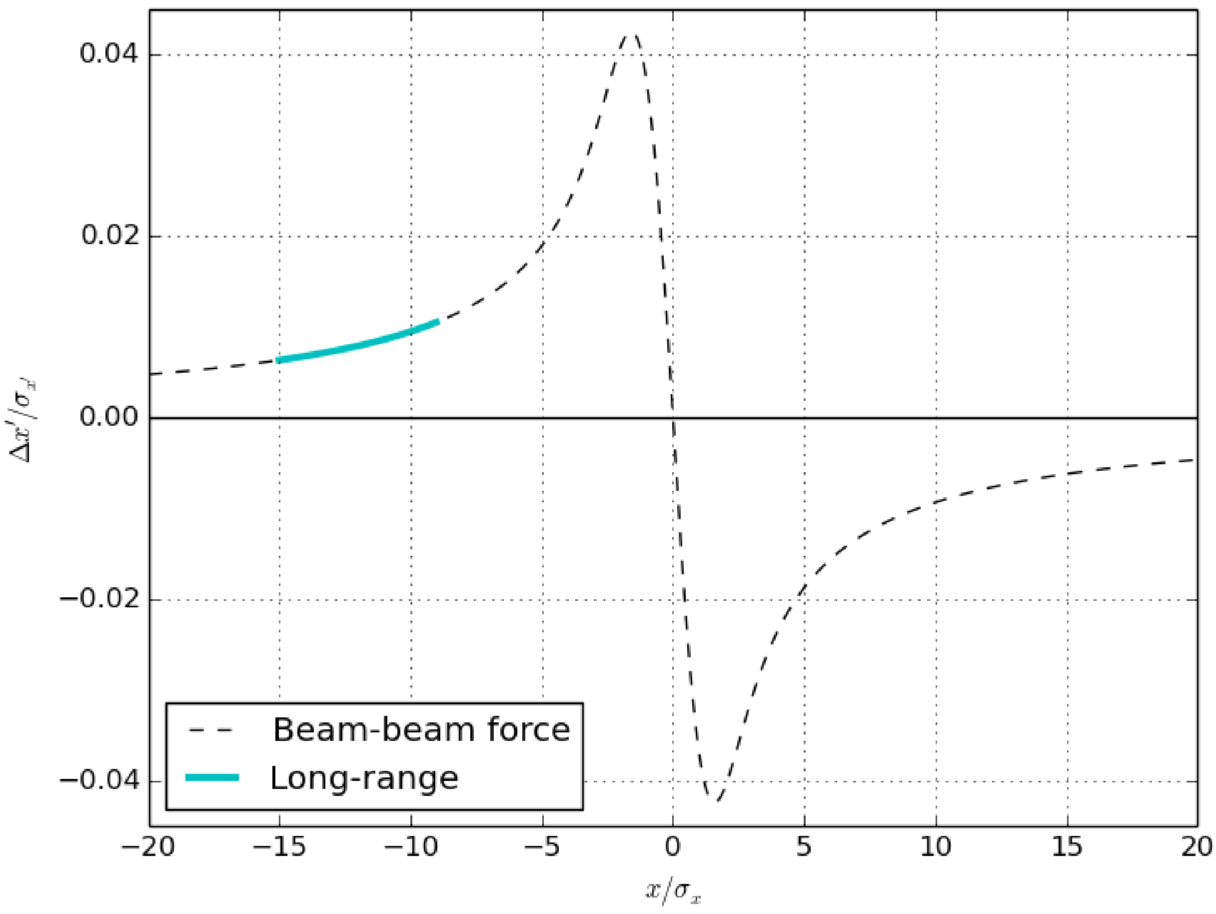
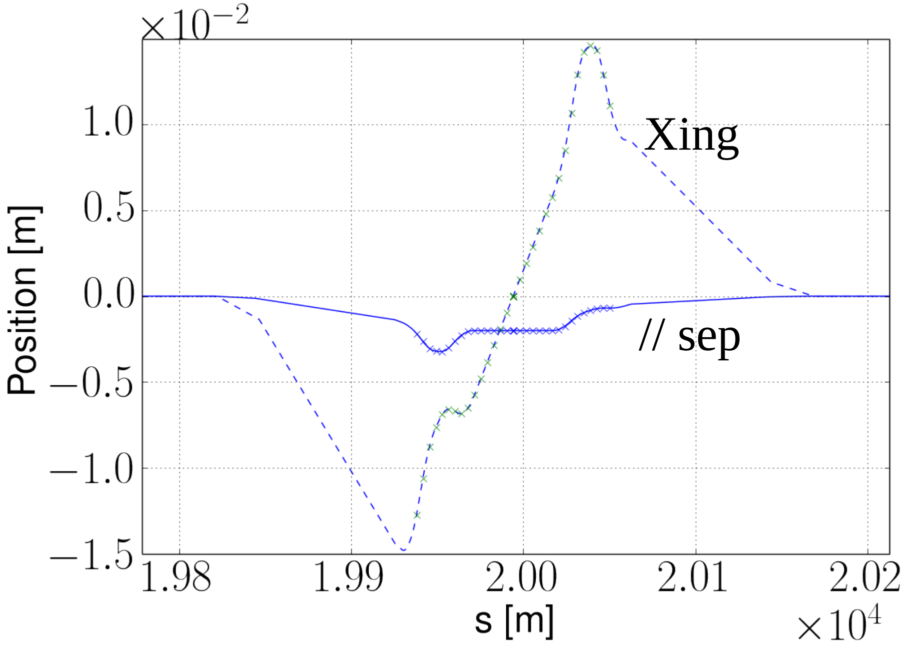
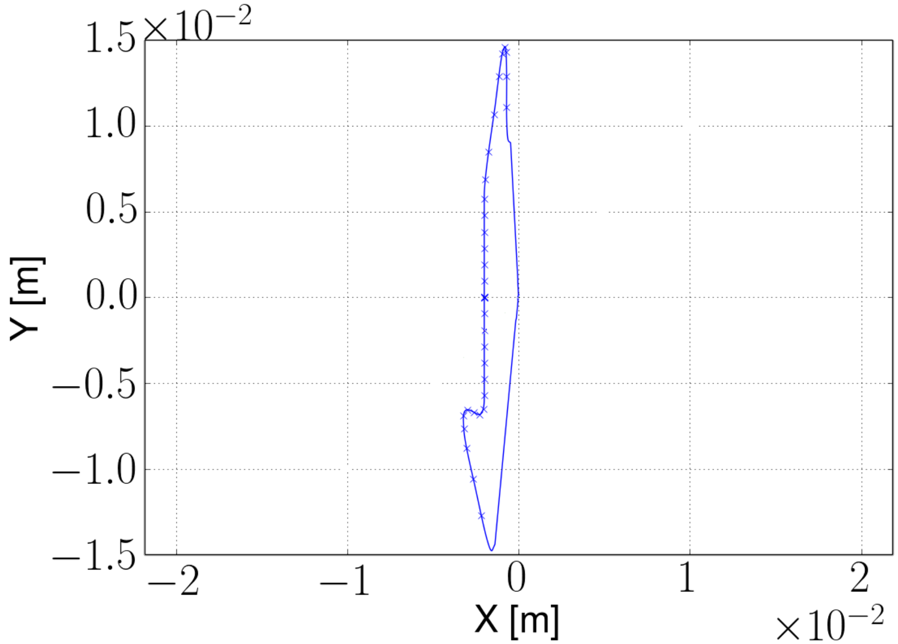


# The beam-beam force for round beams

# Linear coupling due to long-range interactions

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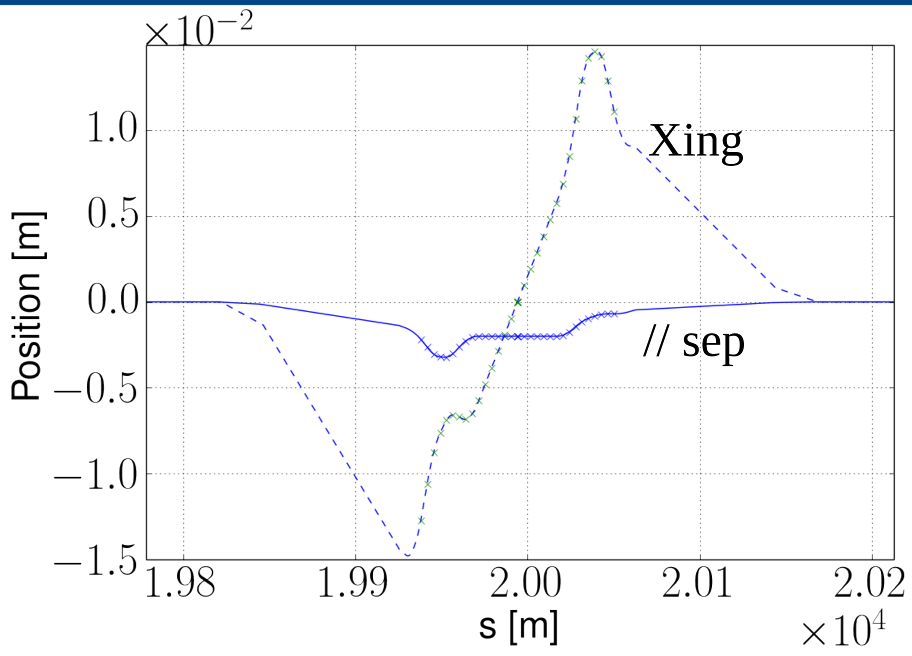


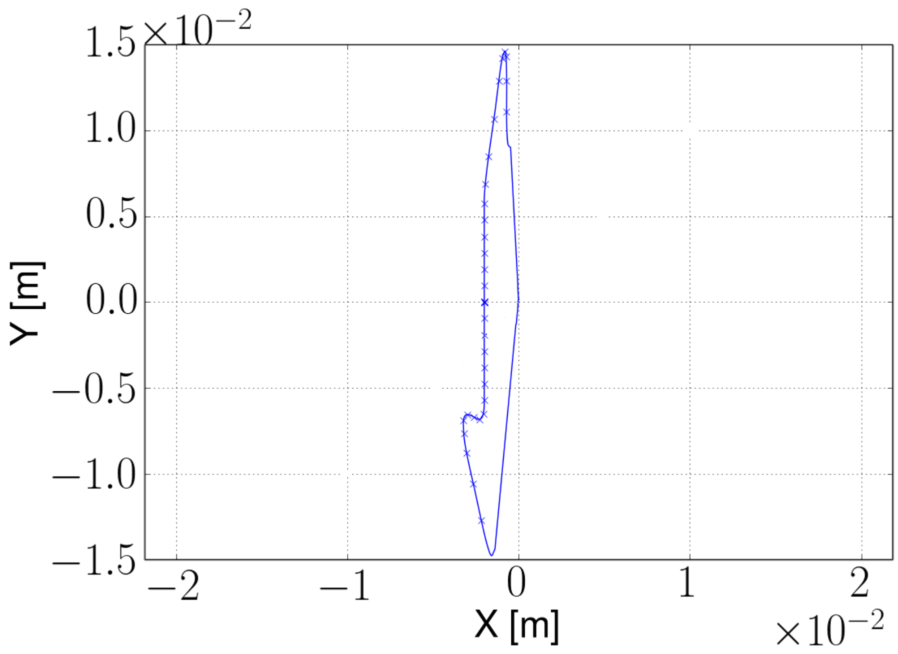


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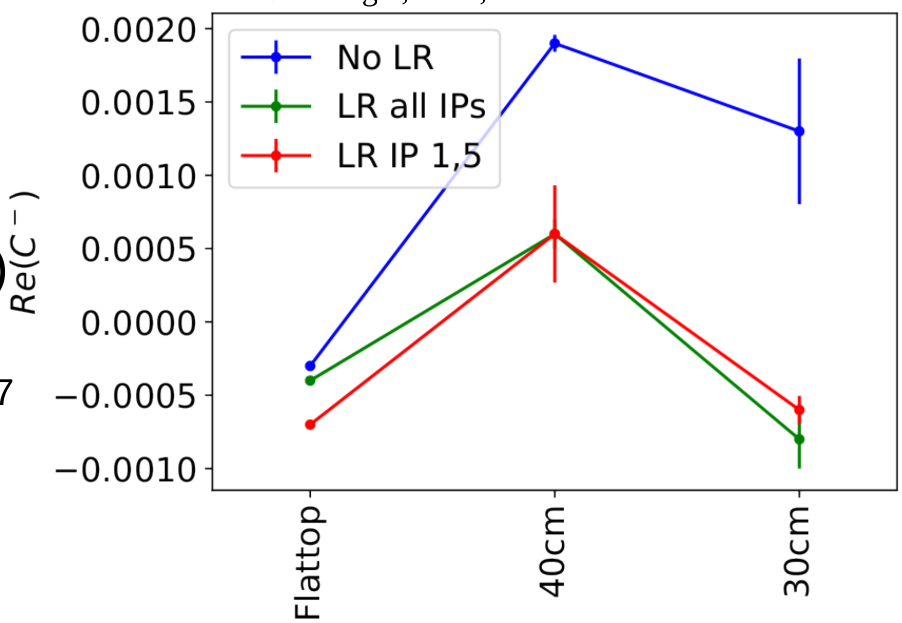

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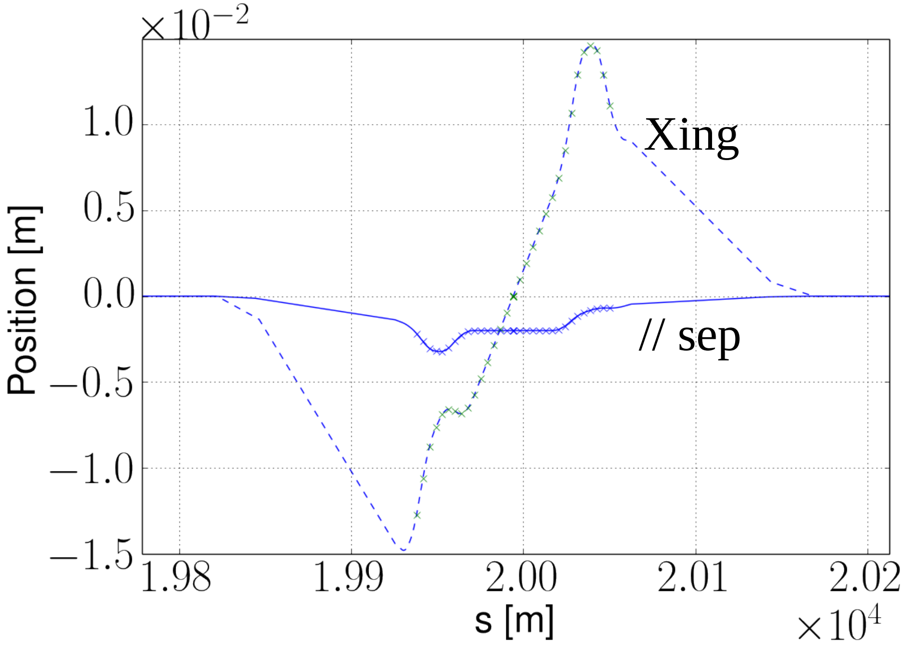


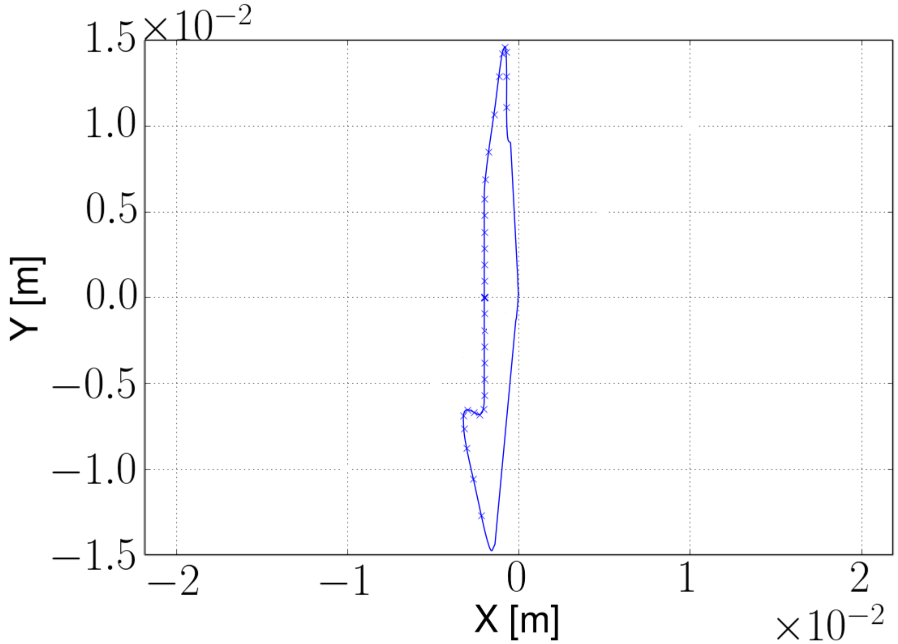


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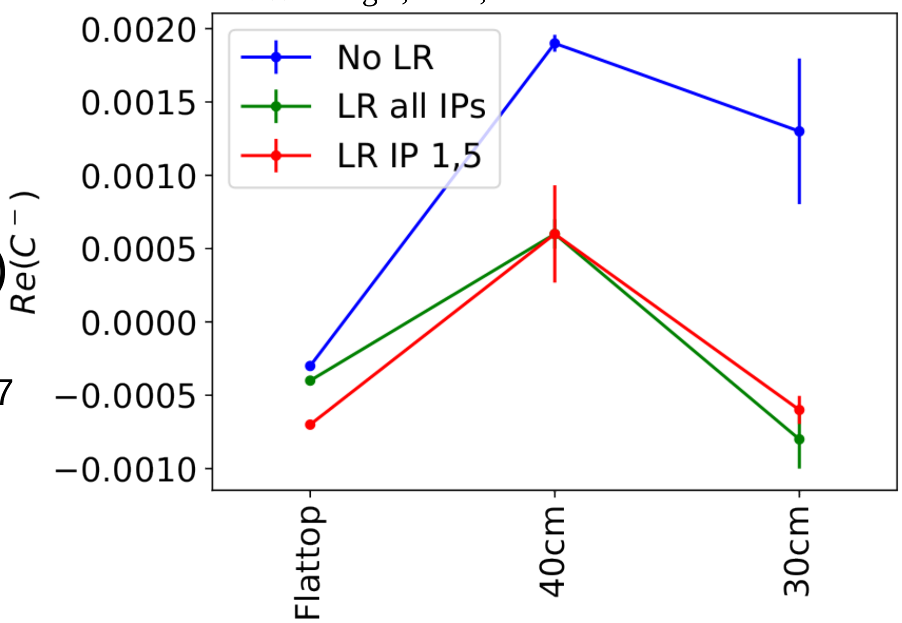

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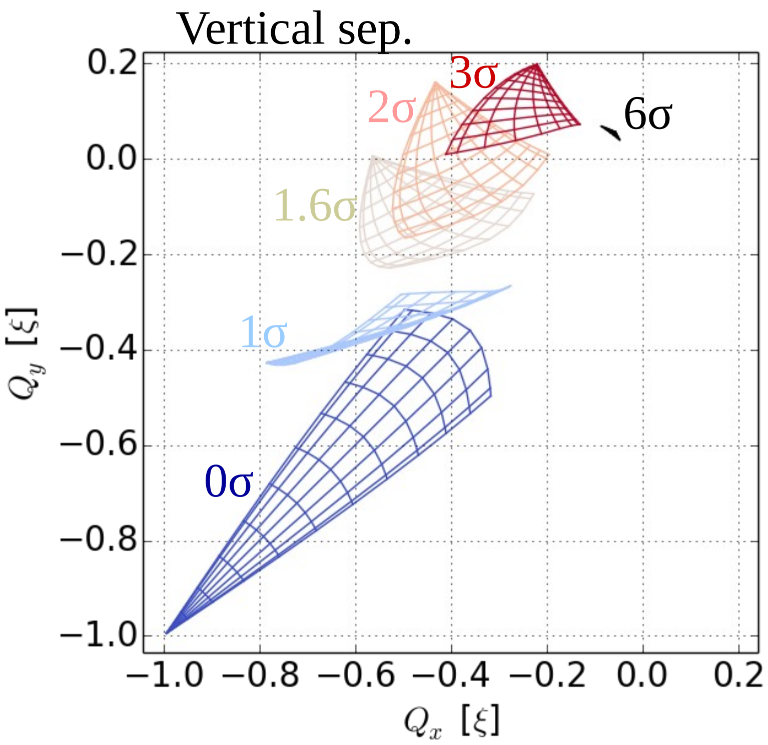

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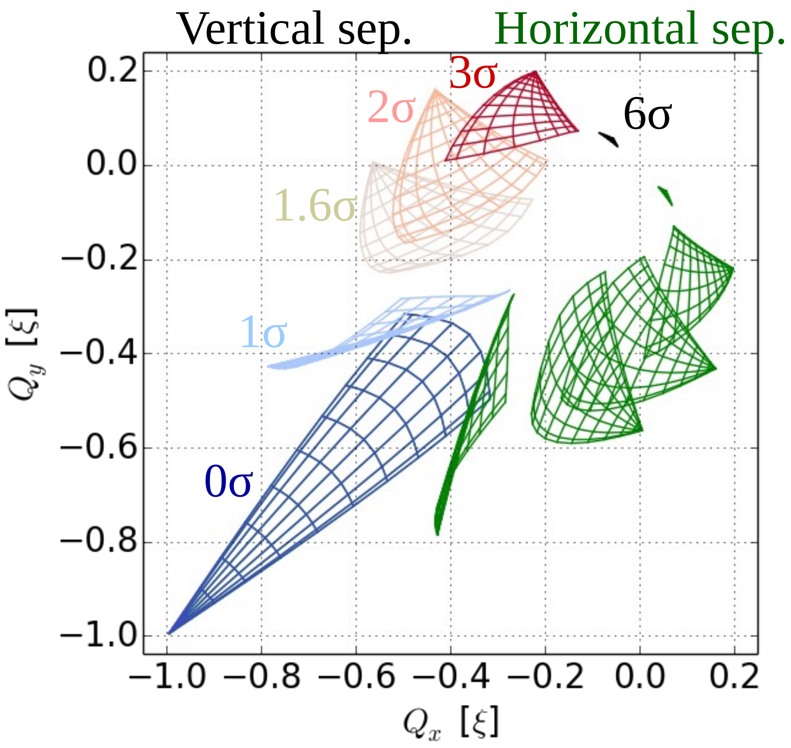

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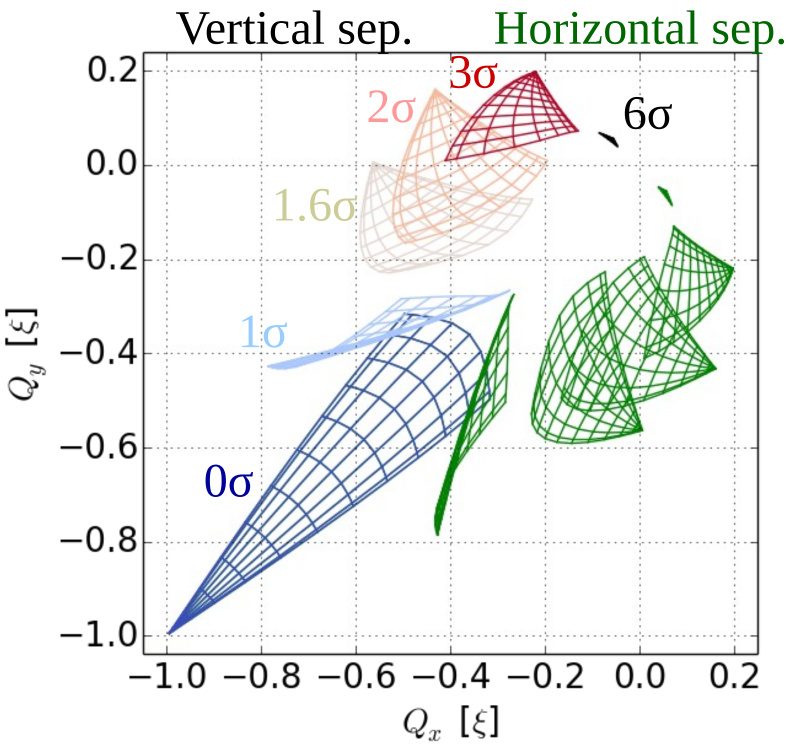
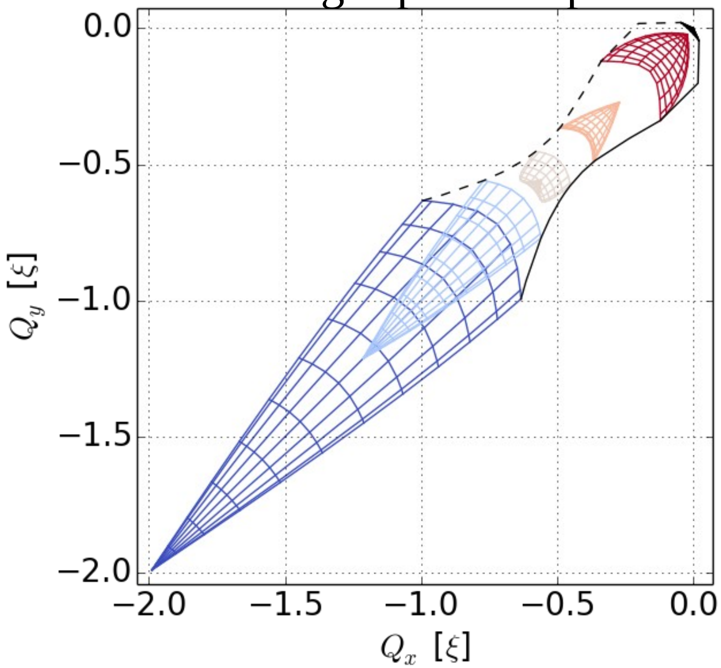



2 IPs together, with alternating separation plane



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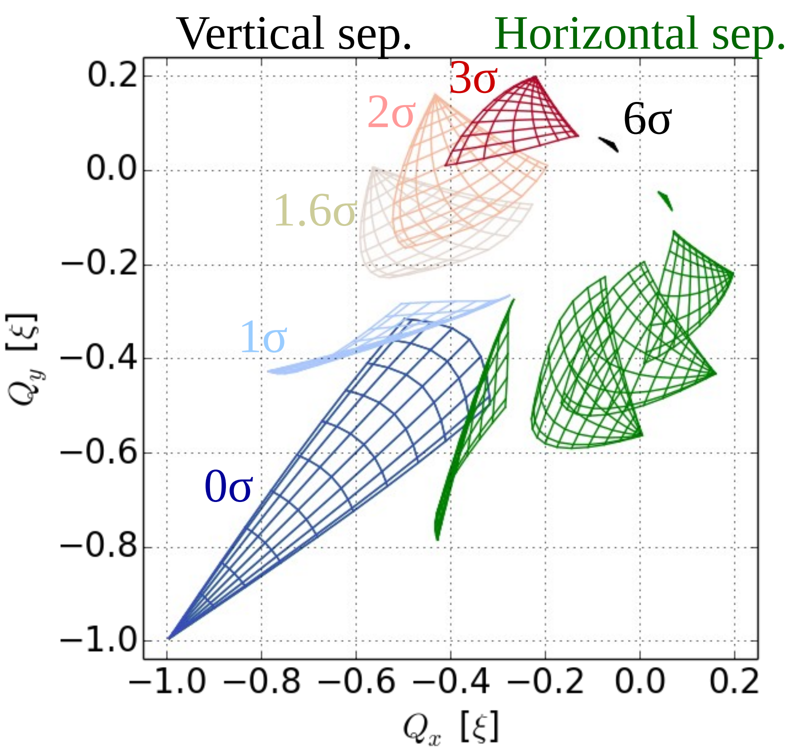


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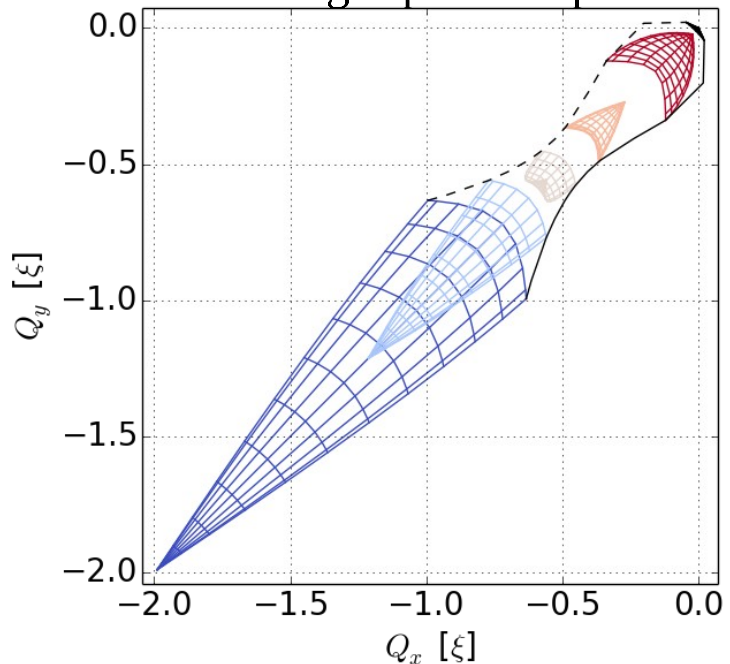


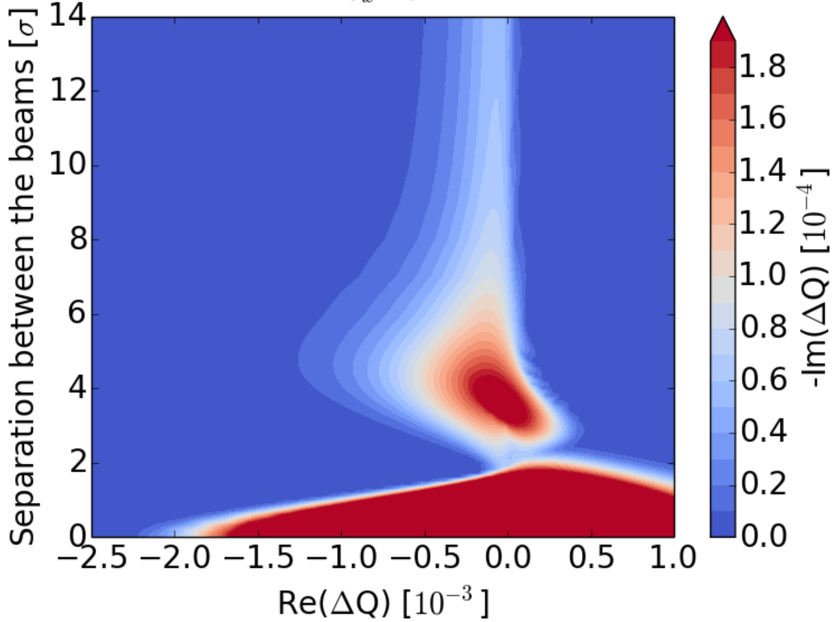

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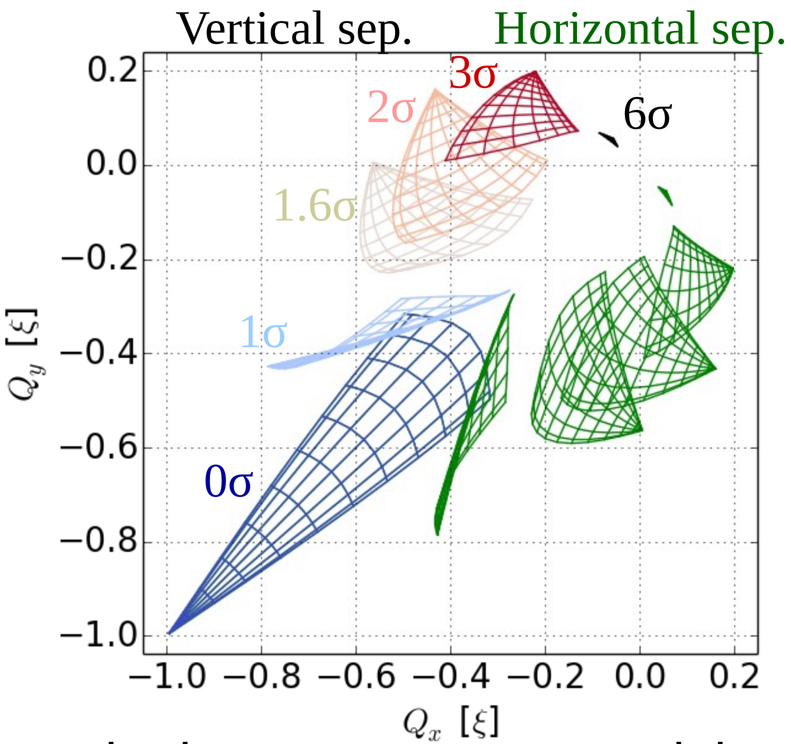


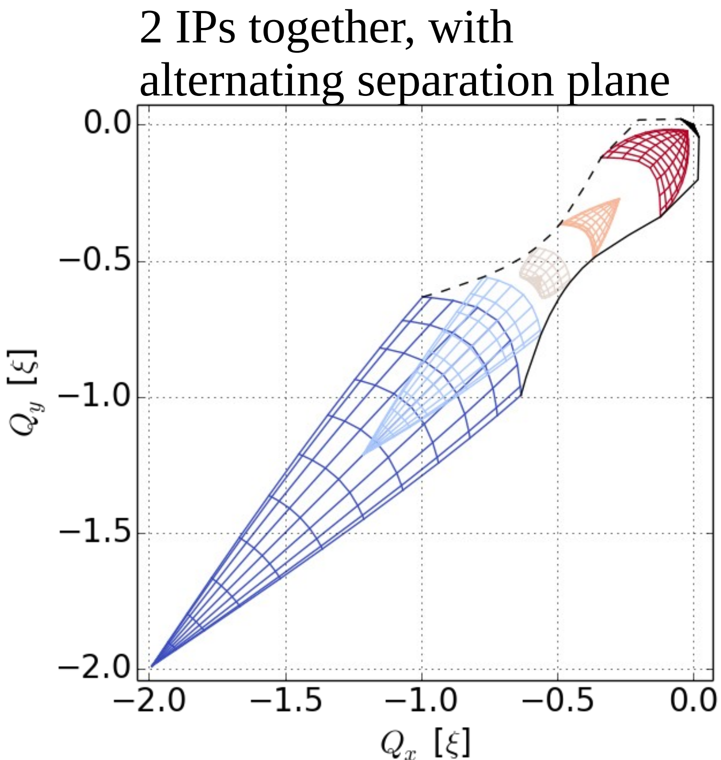


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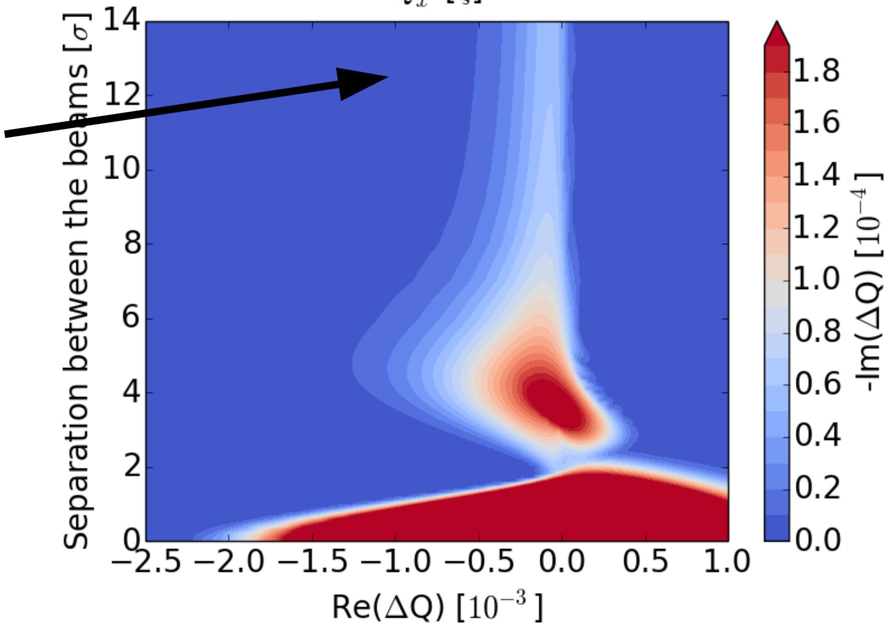

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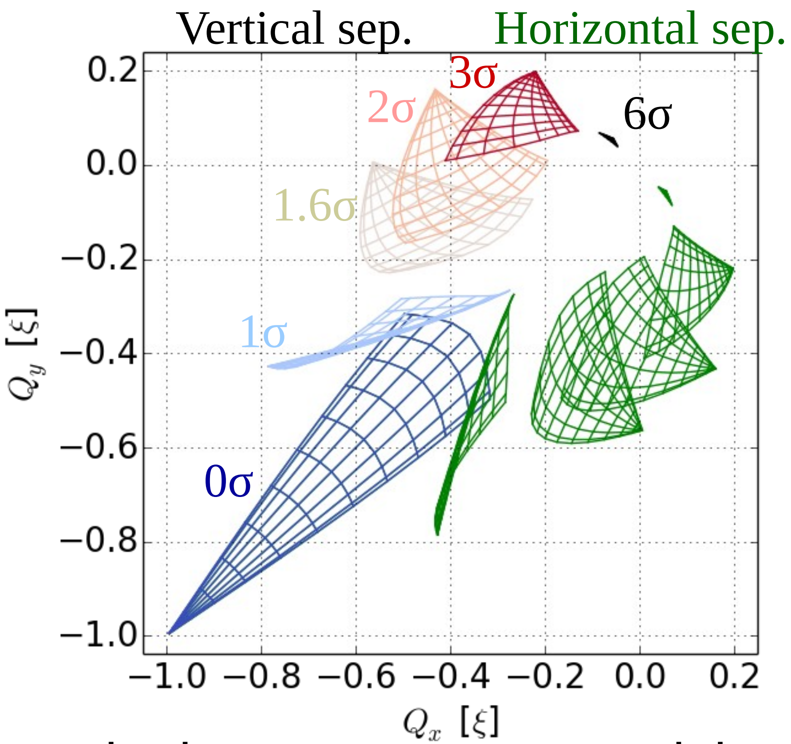


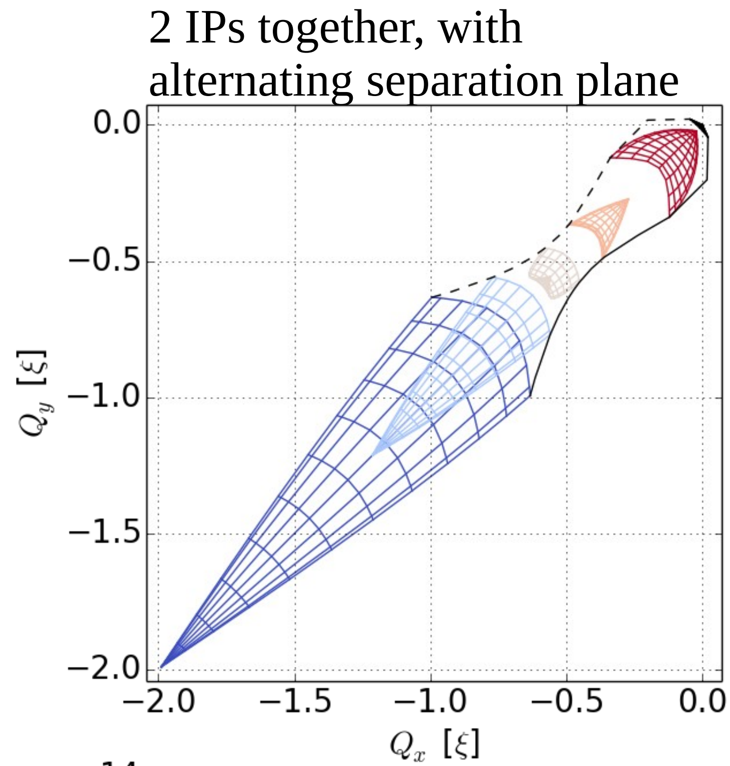


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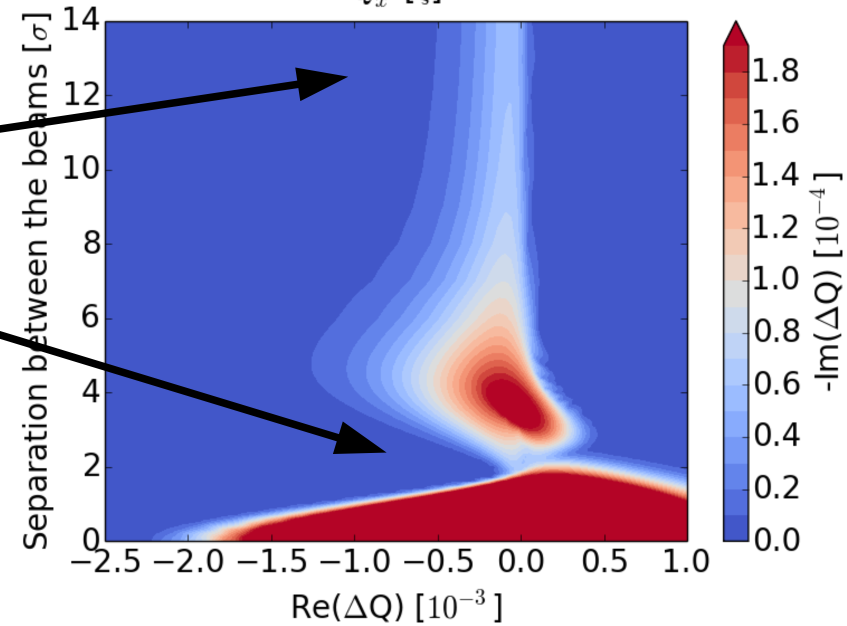

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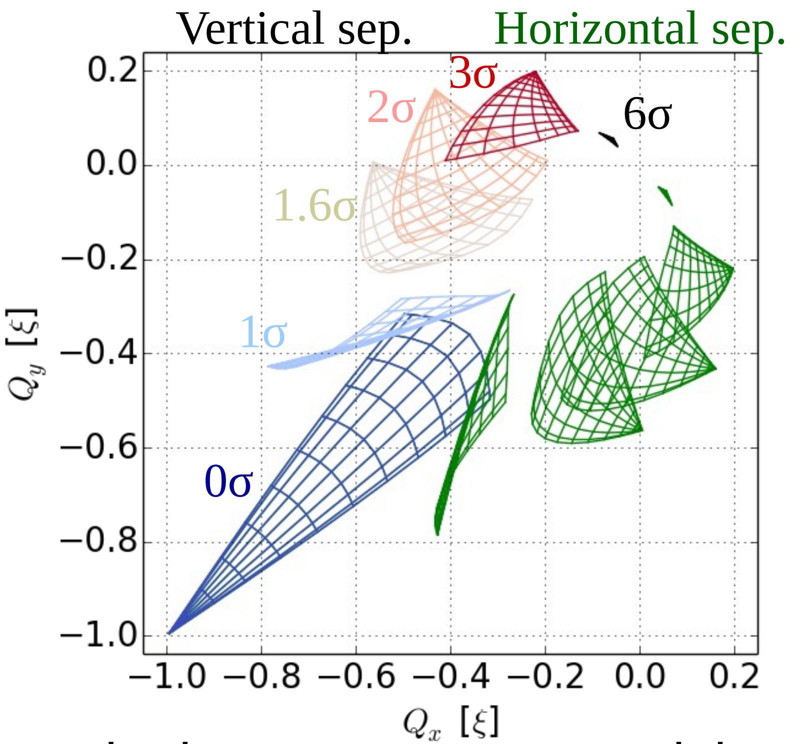


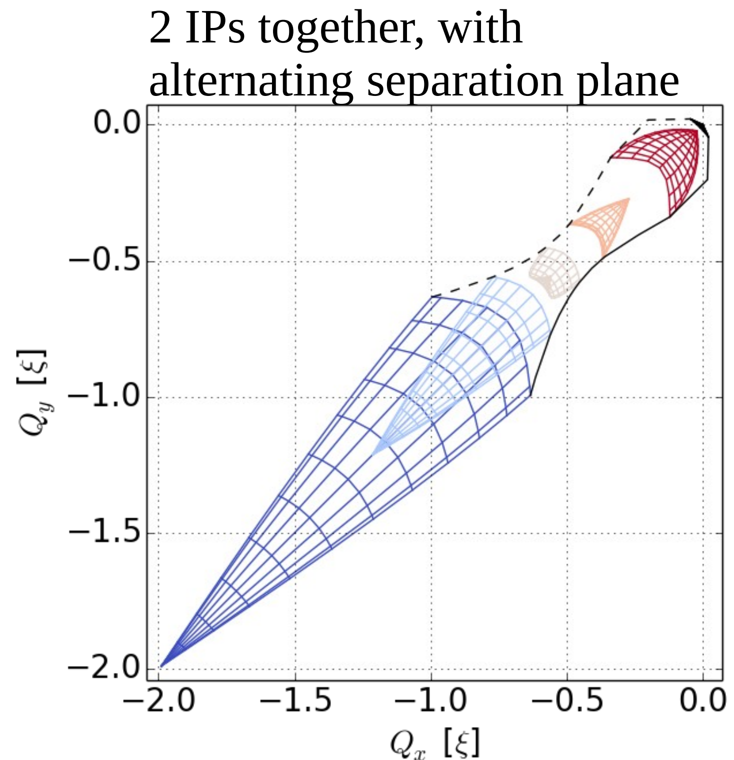


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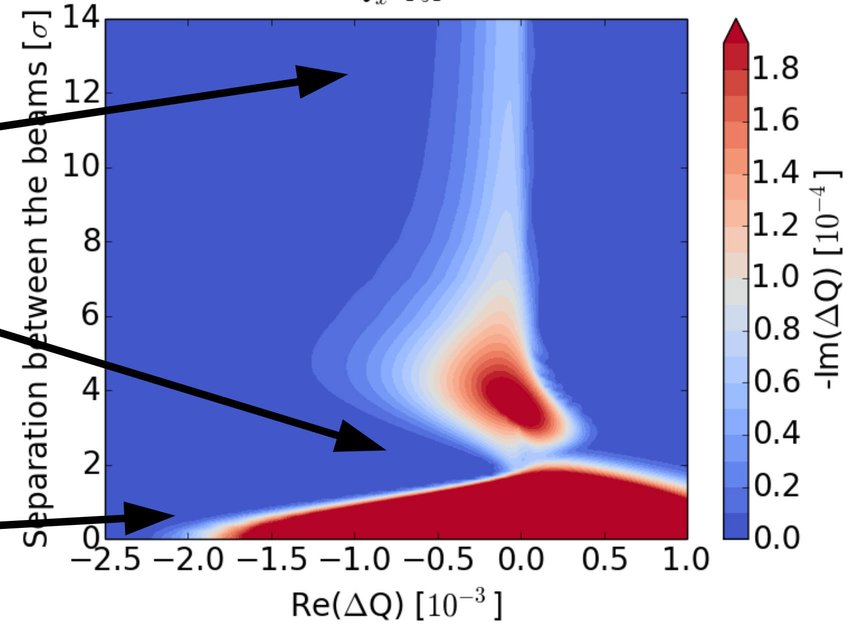
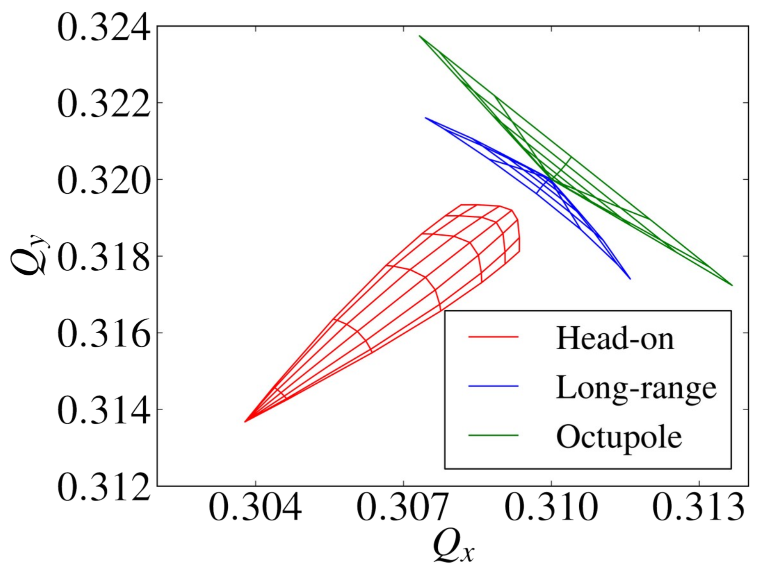
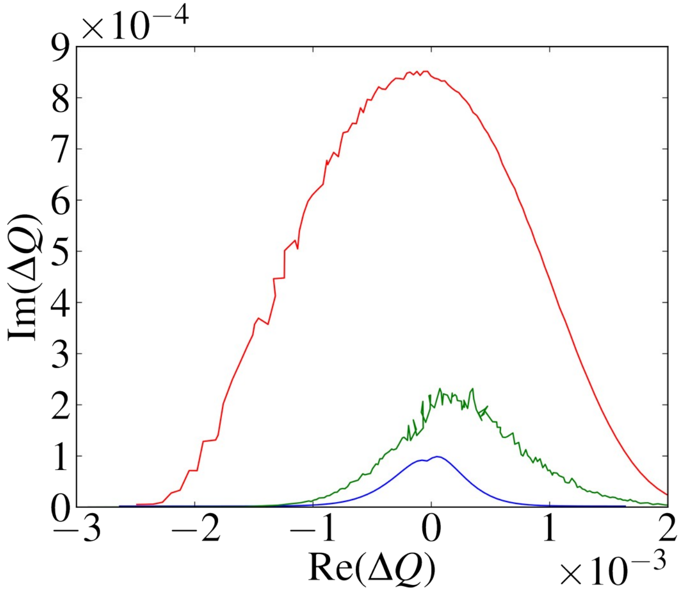
- At intermediate separations (~1.5σ), the flip of the footprint can reduce Landau damping, possibly leading to instabilities
- Once head-on collision the beam profits form strong Landau damping



# Head-on beam-beam saves the day




- By generating a large amplitude detuning for the core of the beam distribution, head-on interaction is very efficient at providing Landau damping

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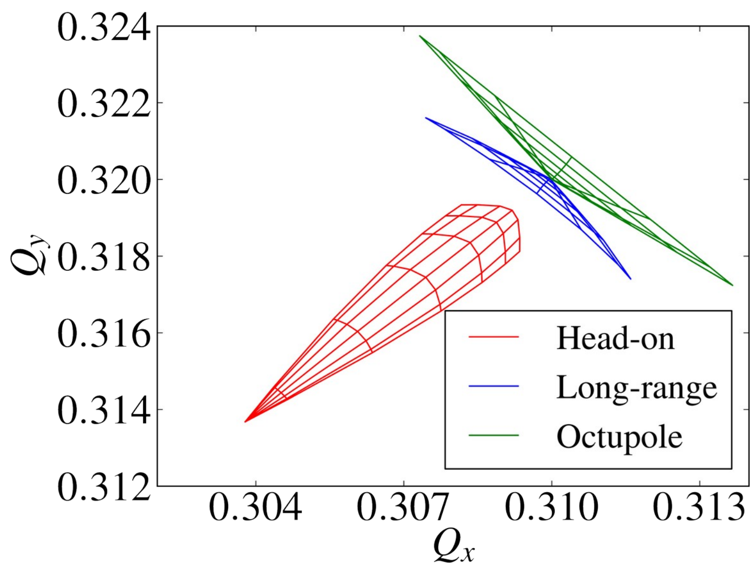


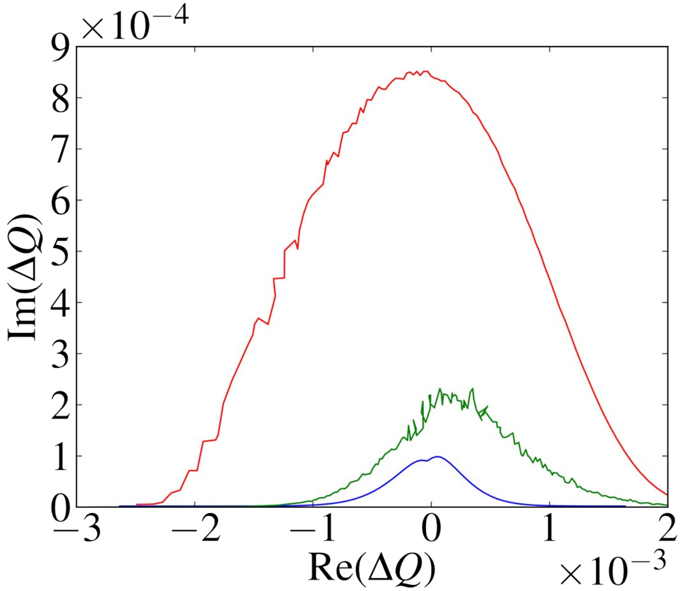


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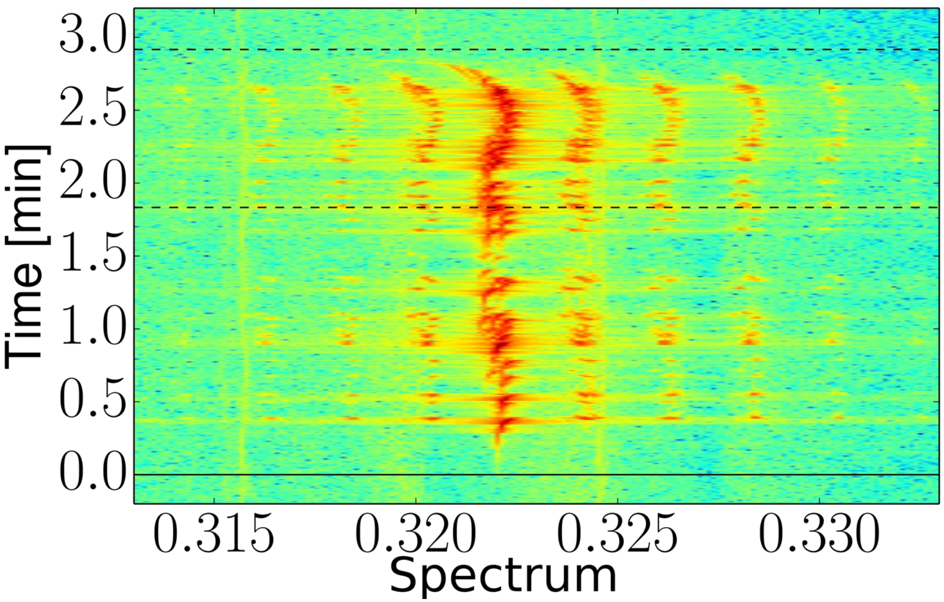

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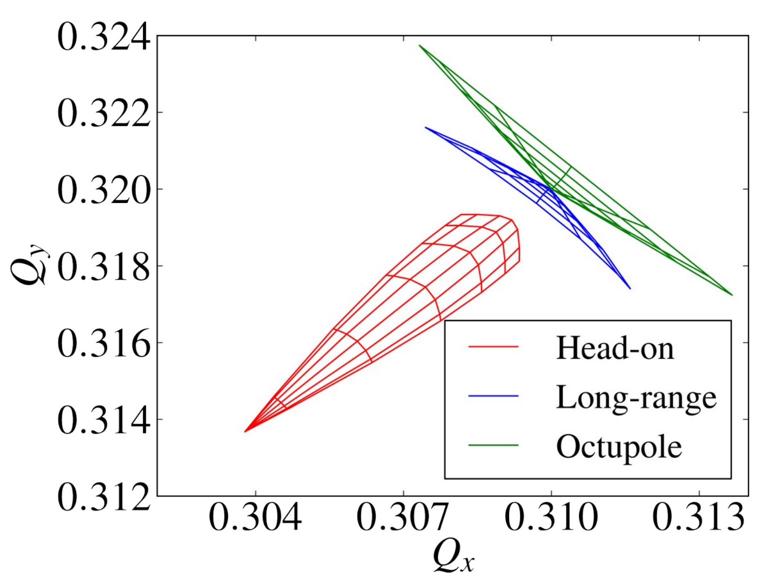


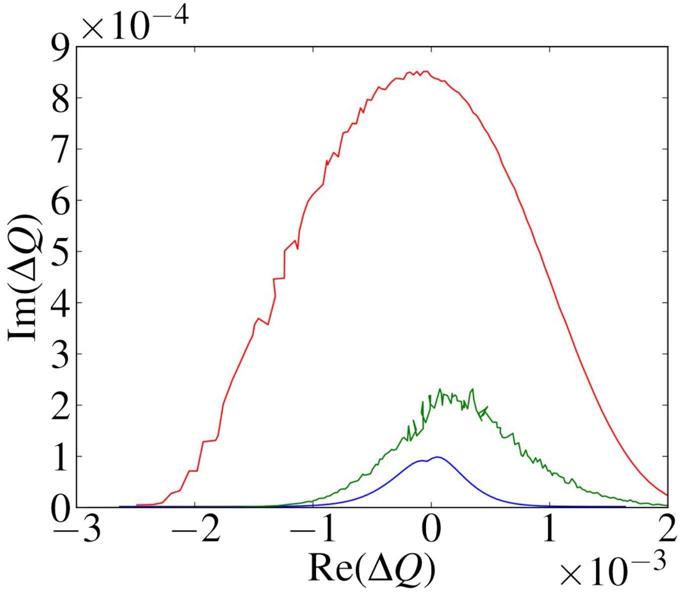


- By generating a large amplitude detuning for the core of the beam distribution, head-on interaction is very efficient at providing Landau damping
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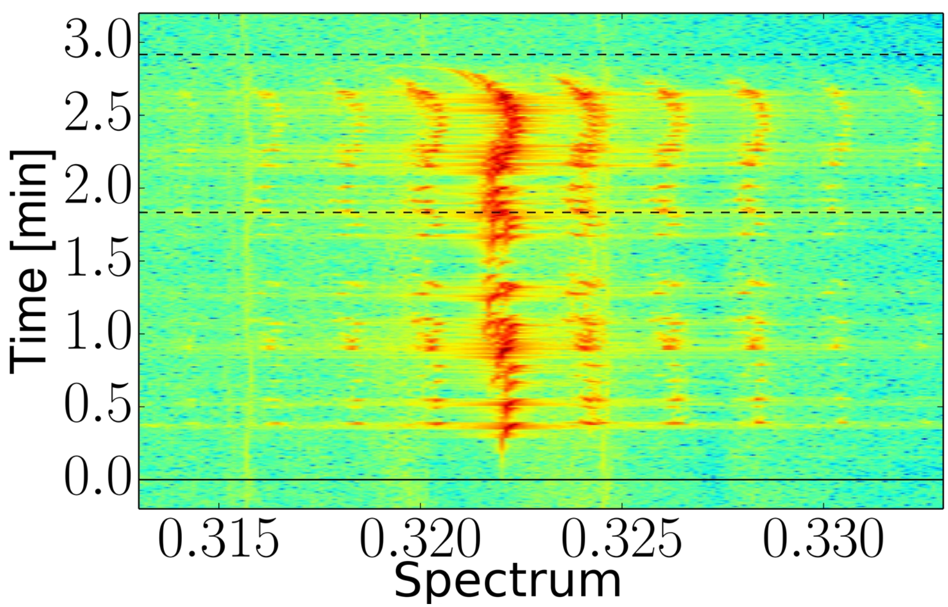
    A. Romano, et al., Phys. Rev. Accel. Beams 21, 061002 (2018)



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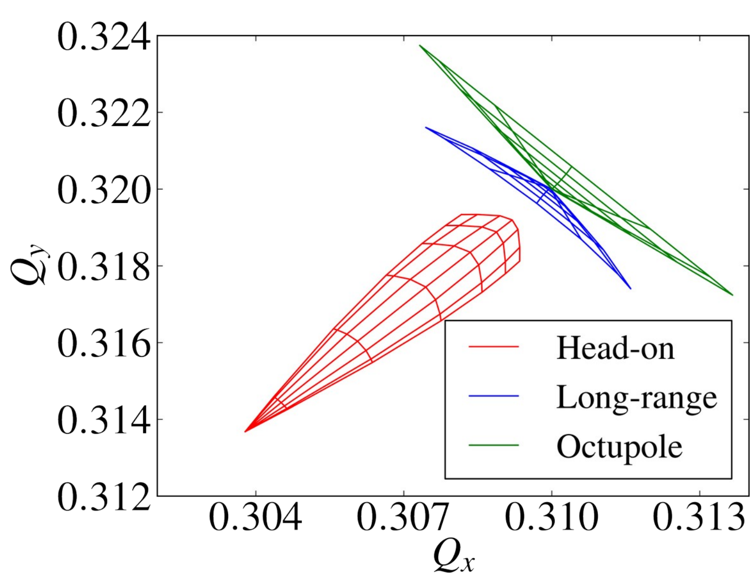


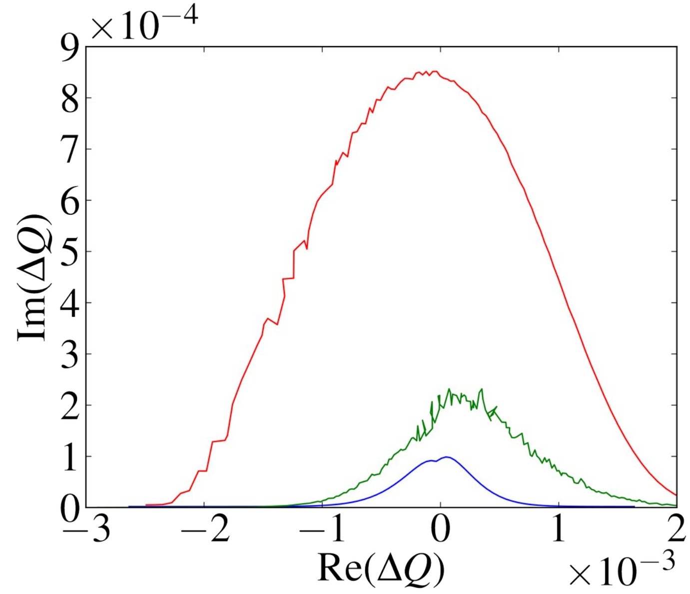


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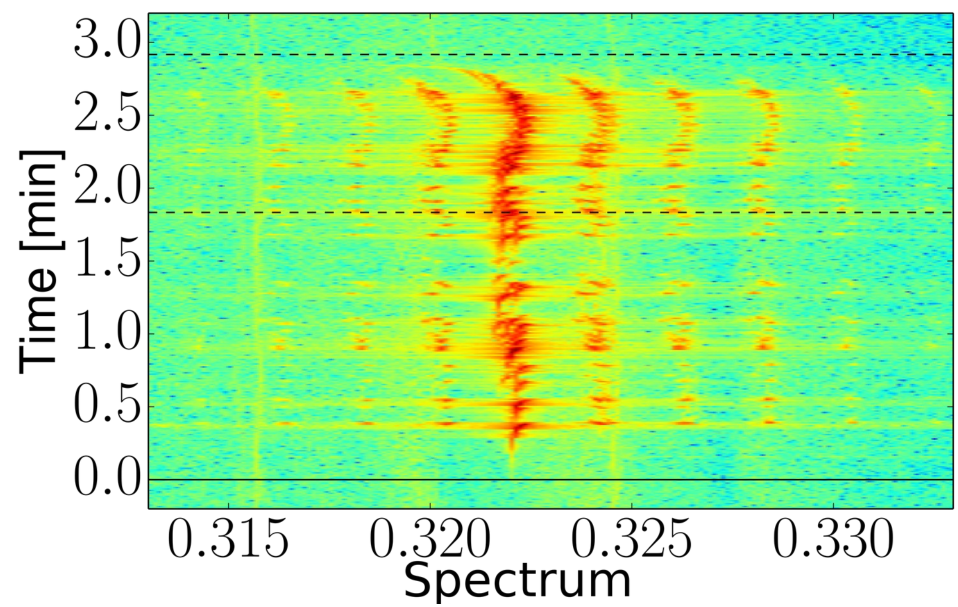

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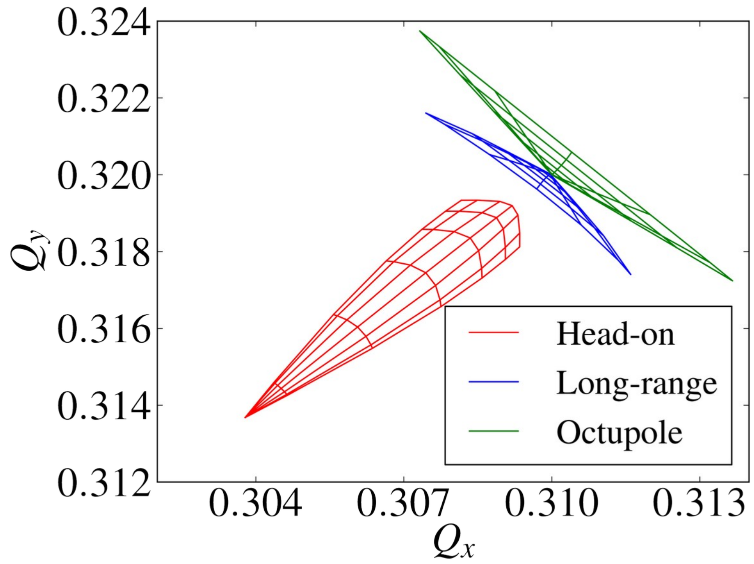


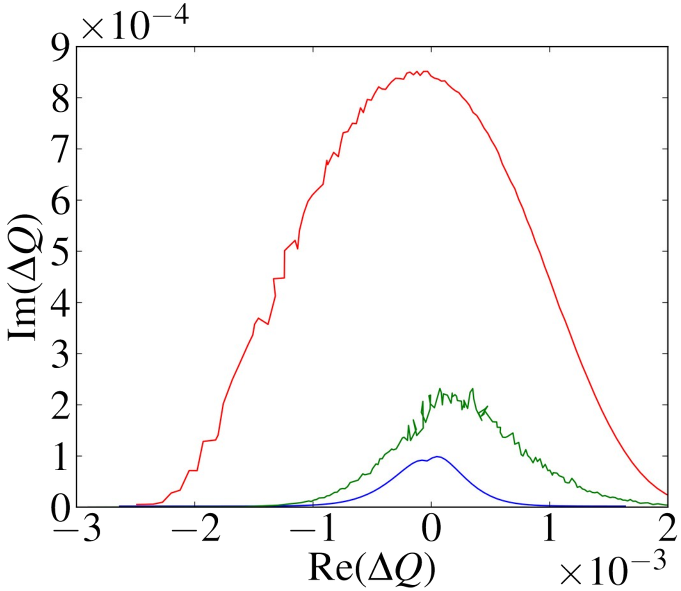


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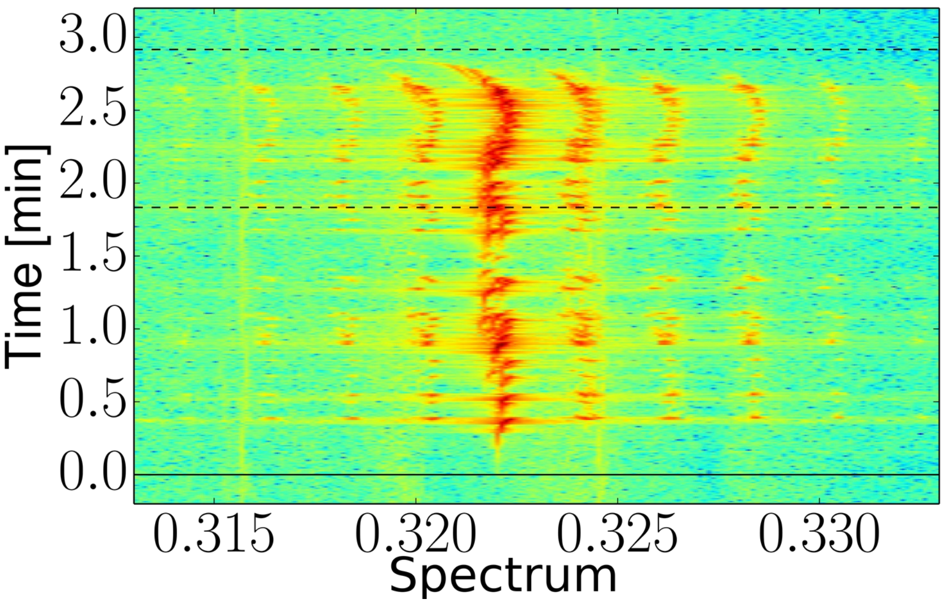
  - An e-lens mimicking this behaviour would have a similar potential as a mitigation
    V. Shiltsev, el al., Phys. Rev. Lett. 119, 134802 (2017)



# Observations of instability with offset beams

- First observations in 2012, due to offset levelling in IP8, only super-PACMAN bunches were affected
  X. Buffat, et al., Phys. Rev. ST Accel. Beams 17, 111002

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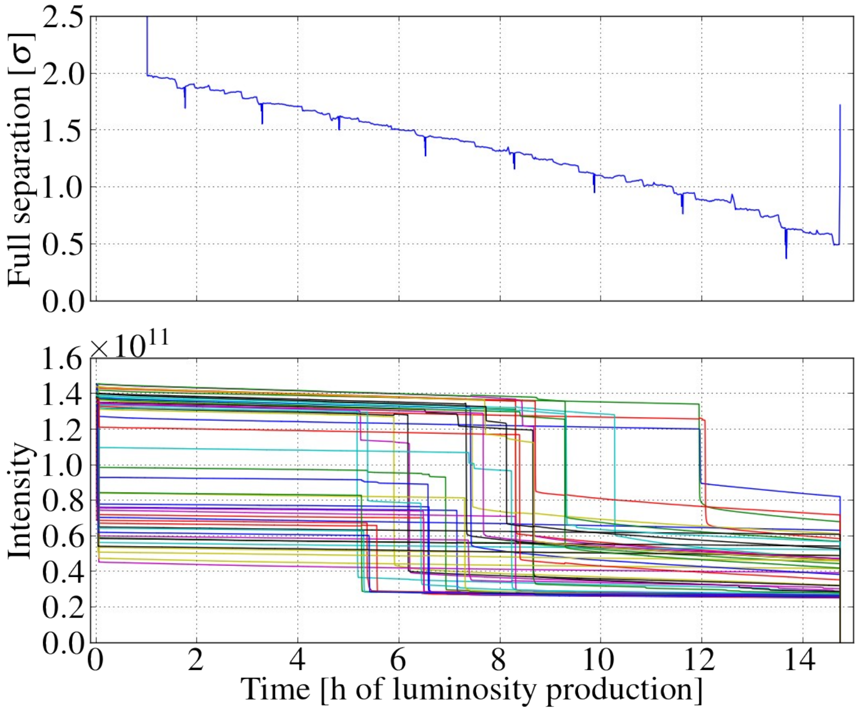

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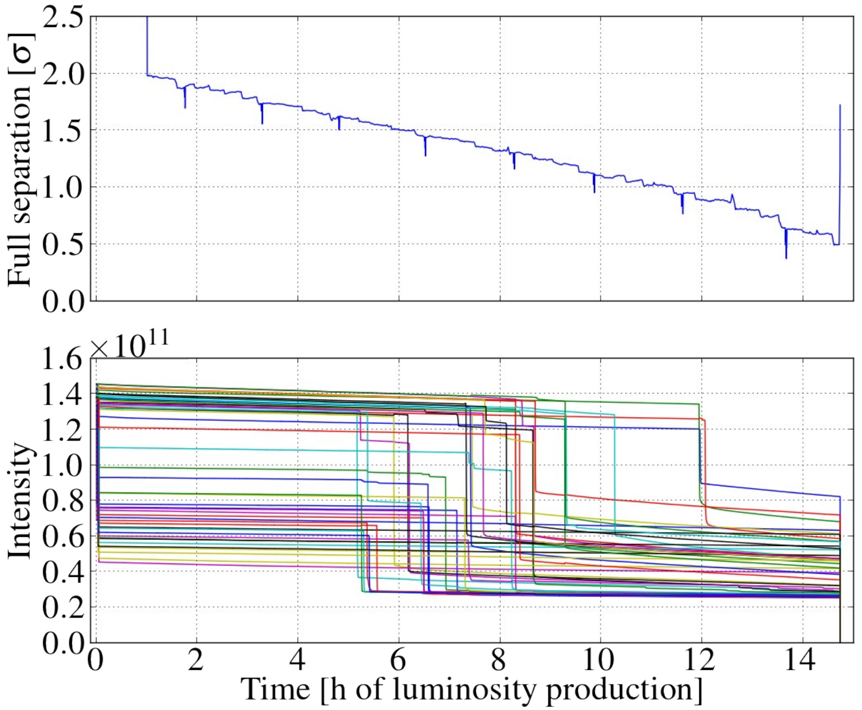


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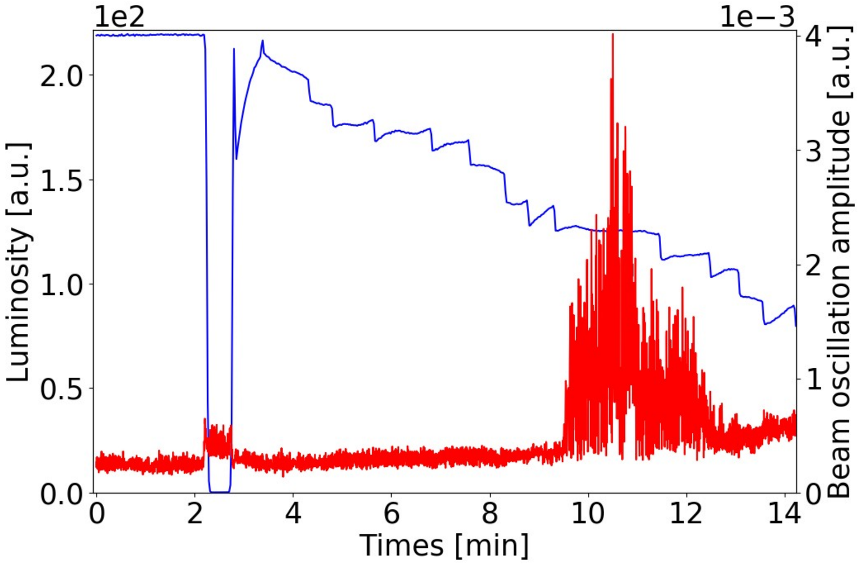

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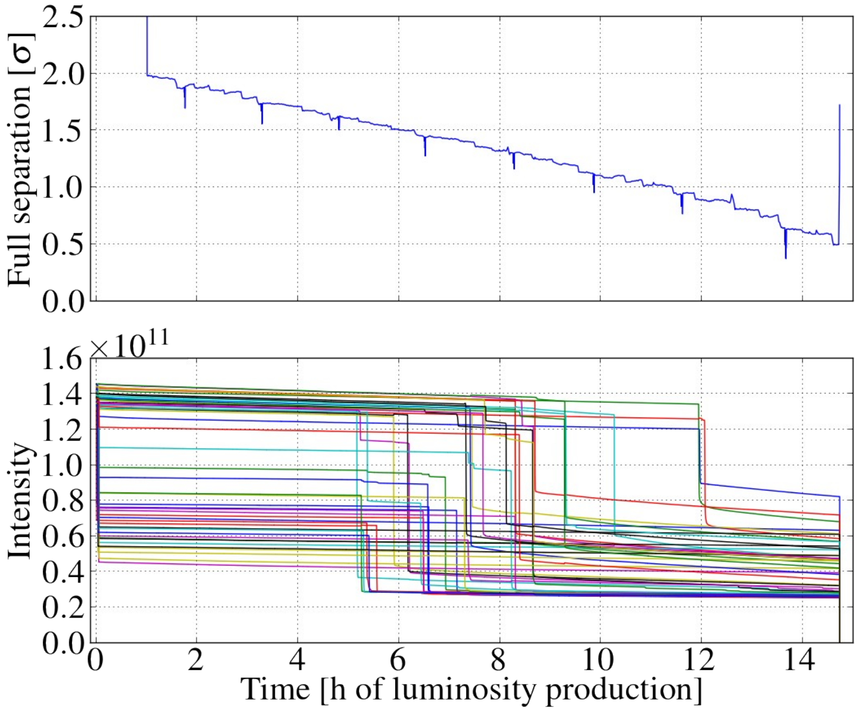


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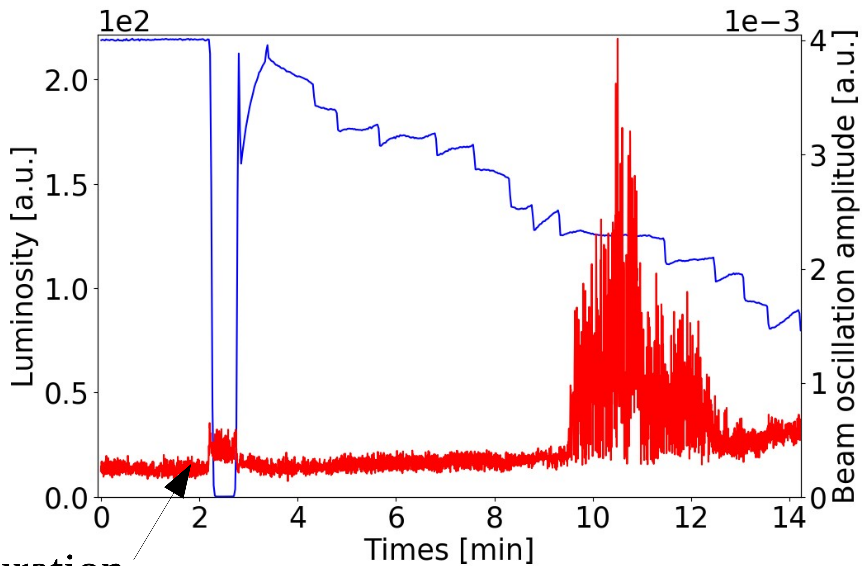


Fast crossing of transient unstable configuration

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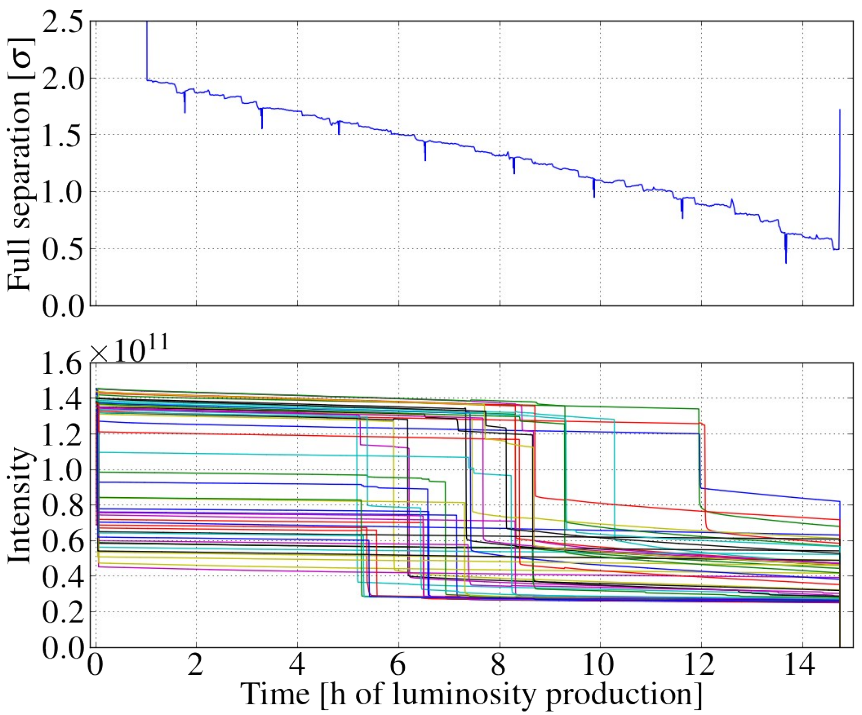


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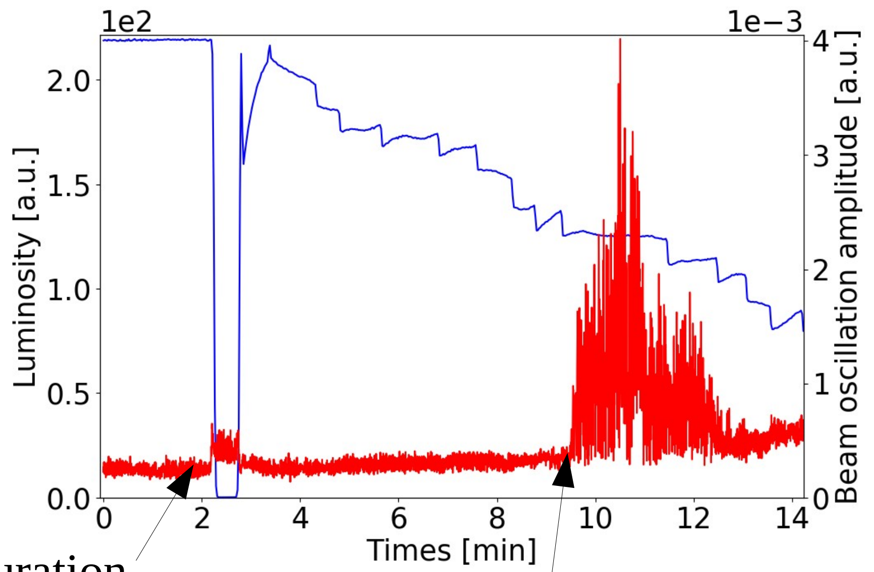


Fast crossing of transient unstable configuration

Instability when steady at 1.6σ full separation between the beams

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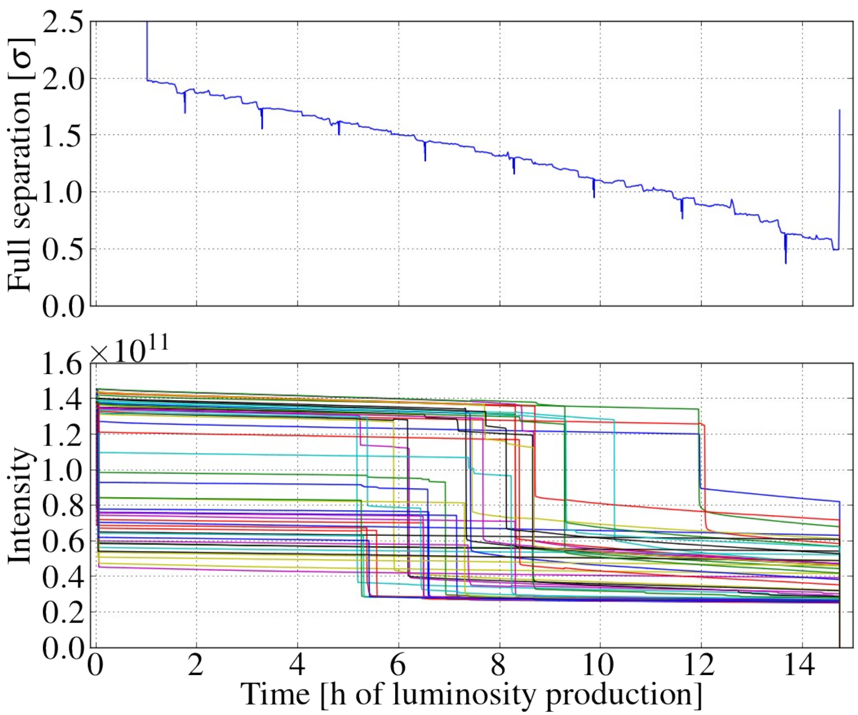


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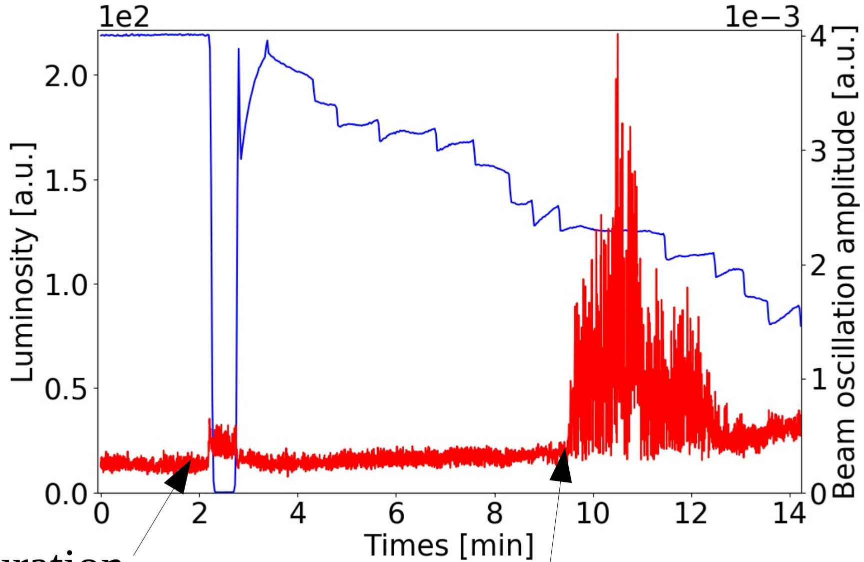
  → This mitigation can work for a standard operational cycle, but it is not suitable for luminosity levelling with an offset




Fast crossing of transient unstable configuration

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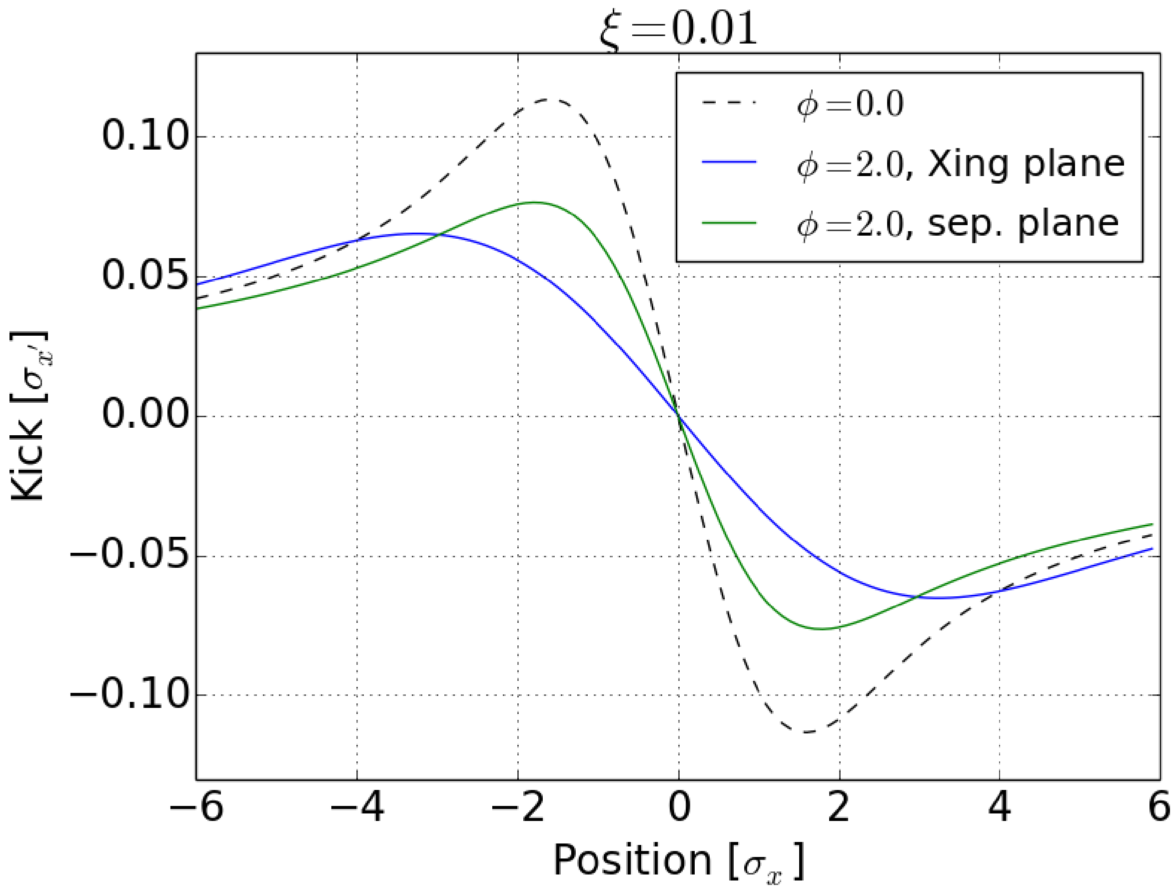
# Beam-beam interaction with a crossing angle




$$\xi = \frac{r_0 N}{4\pi\epsilon_n}$$

$$\phi = \frac{\sigma_s}{\sigma_X}\theta_{half}$$

- In the presence of a crossing angle the beam-beam force differs in the plane parallel and perpendicular to the crossing angle A. Piwinski, IEEE Trans. Nucl. Sci. NS-24 1408
  - The force is comparable to a flatter beam with effective beam size in the crossing plane given by $\Phi\sigma_x$

# Tune footprint with a crossing angle and an offset

## 2 IPs with alternating crossing planes

$$\phi = 0.0$$

- Without crossing angle, the octupoles setup which generate a positive direct detuning term (the so-called positive polarity) is favourable from long-range to head-on

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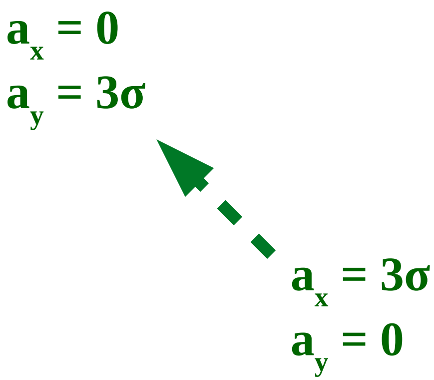


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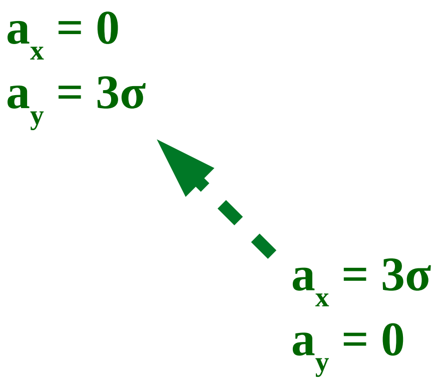


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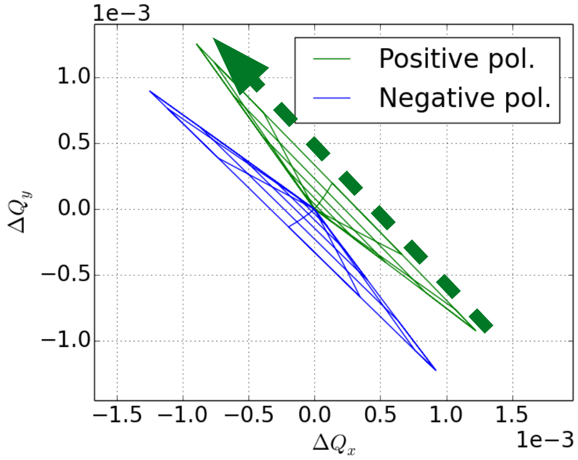

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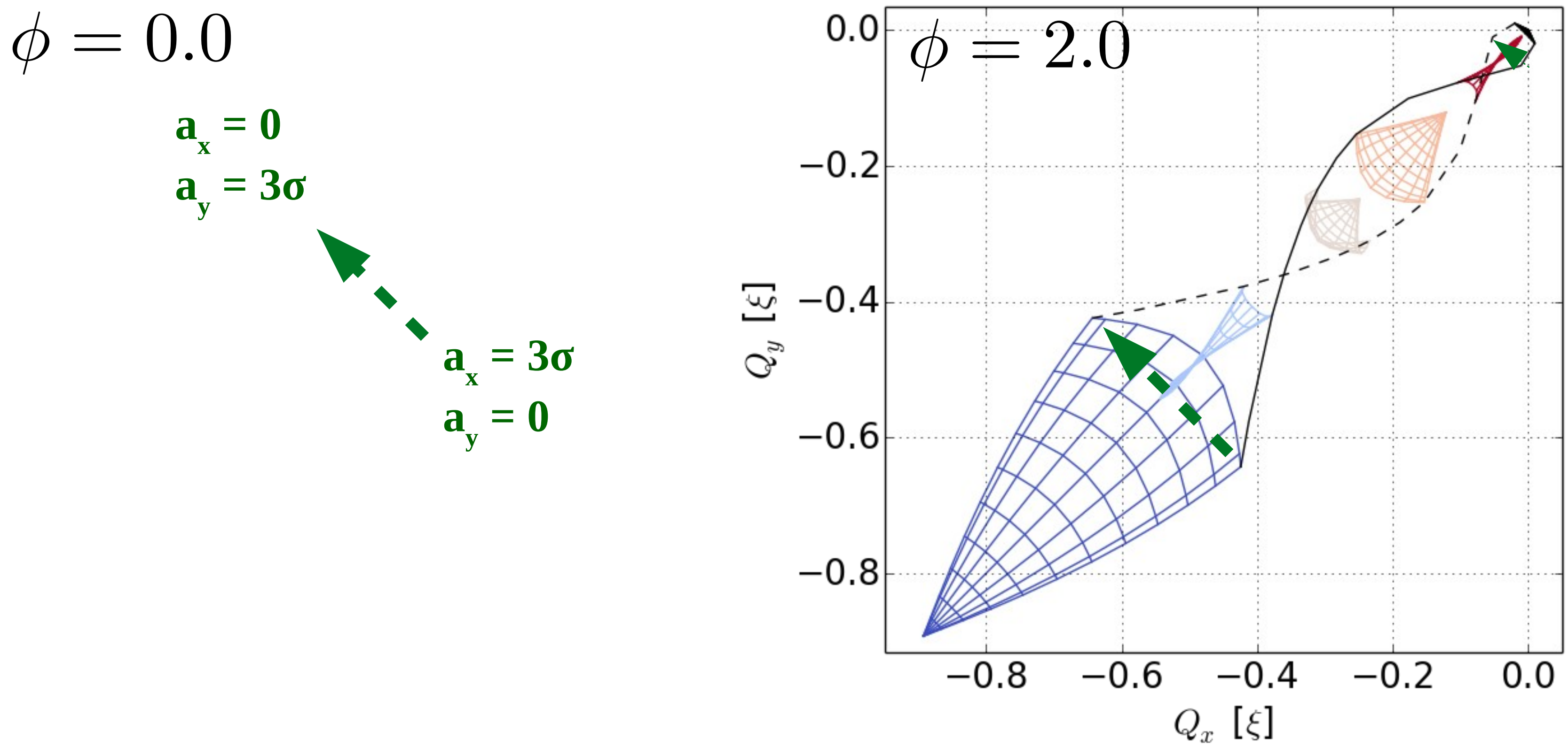


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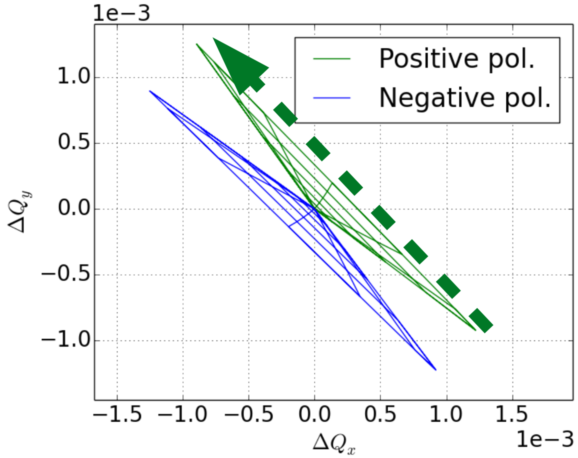

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## 2 IPs with alternating crossing planes

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$a_x = 0$
$a_y = 3\sigma$

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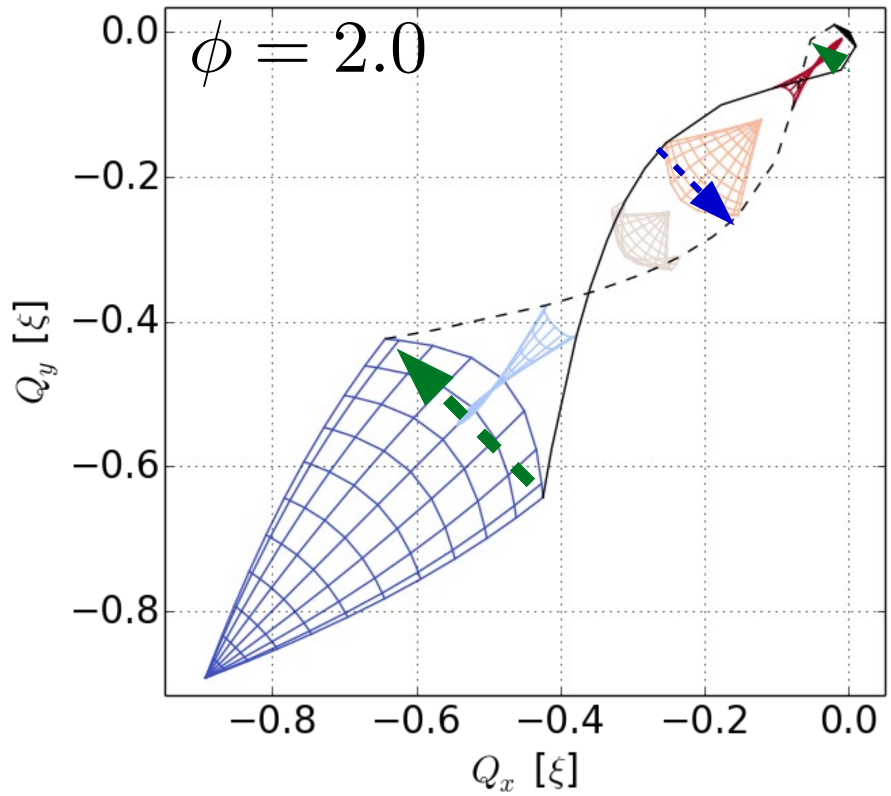
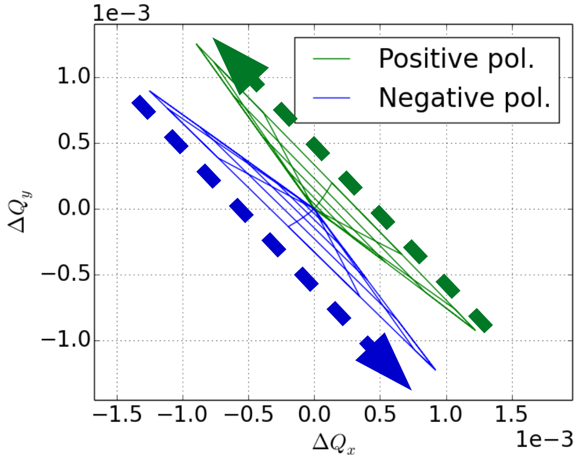
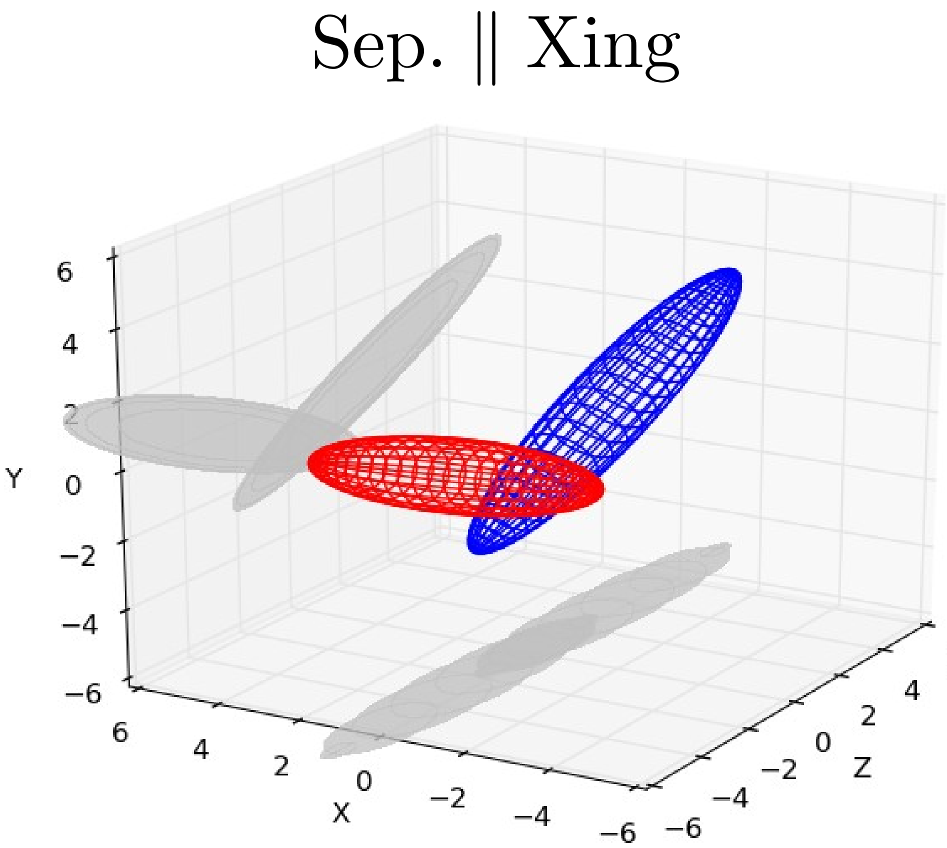


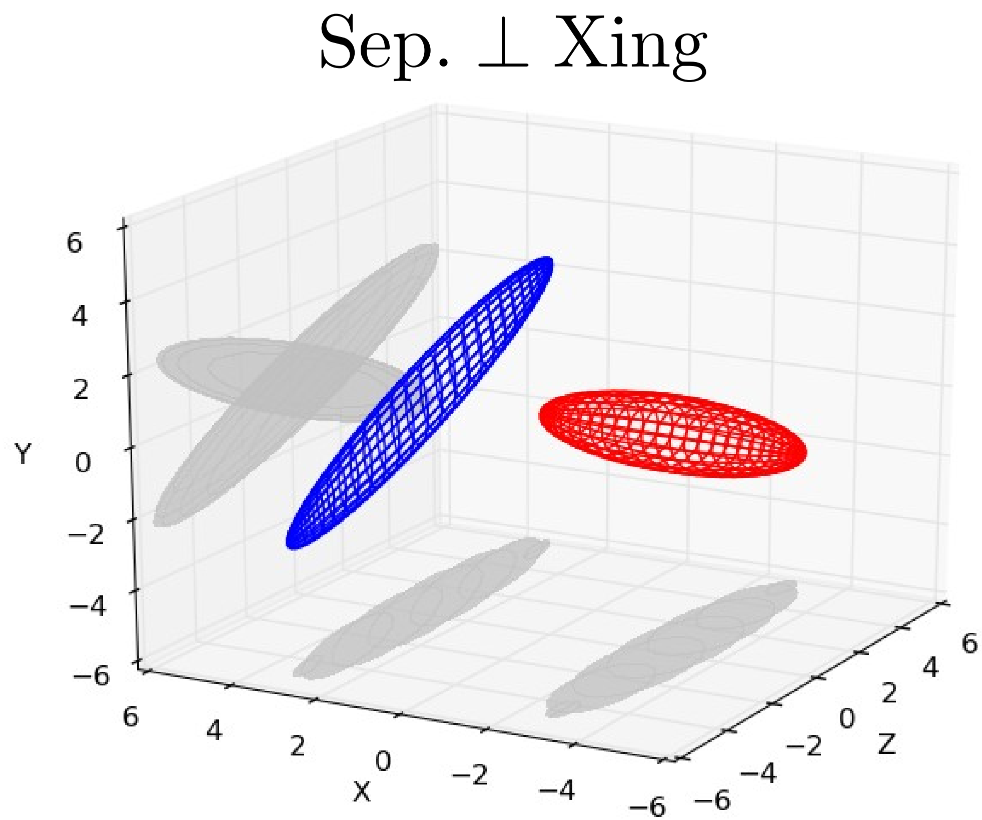

- Without crossing angle, the octupoles setup which generate a positive direct detuning term (the so-called positive polarity) is favourable from long-range to head-on
- With a Piwinski angle larger than 0.8, the positive polarity remains mostly favourable except for separations ~1.5-2σ

  → Exactly at the most critical separations, caused by the flip of the footprint !



# An effective mitigation



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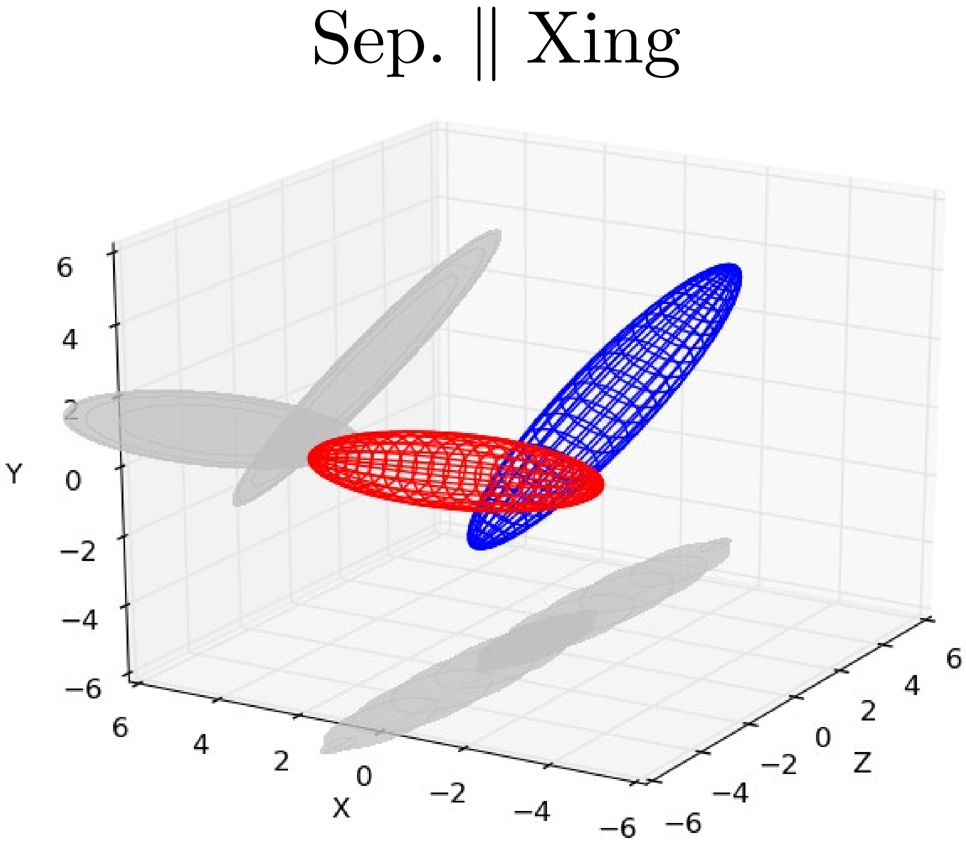


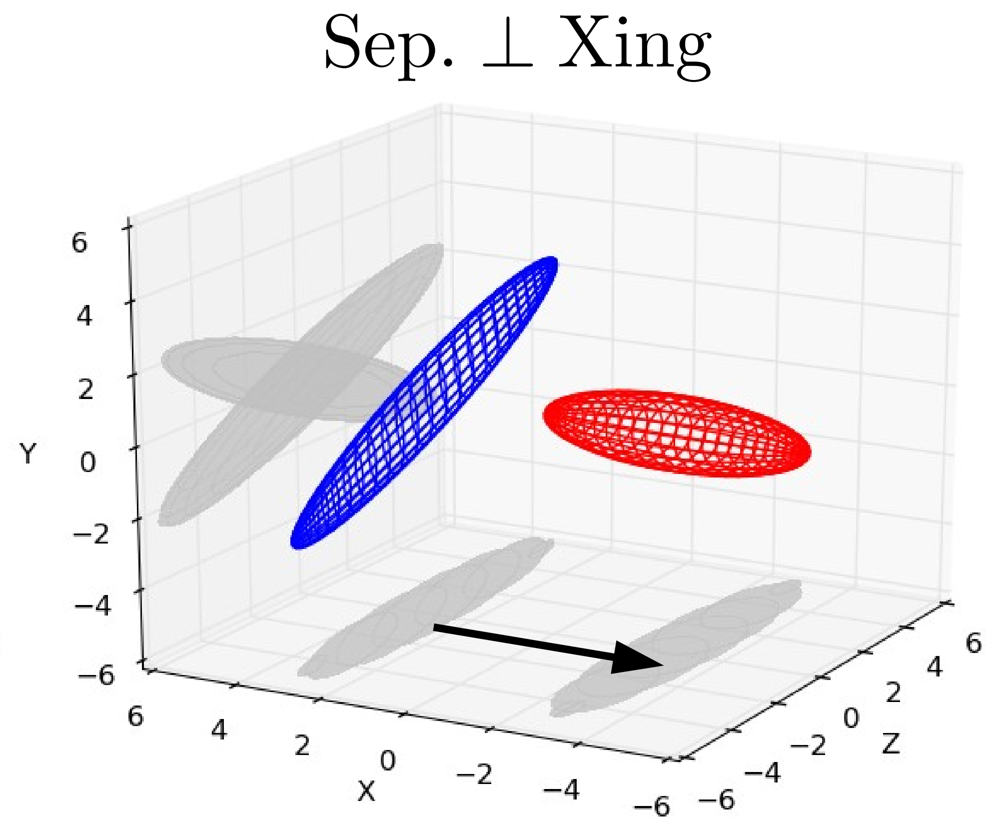

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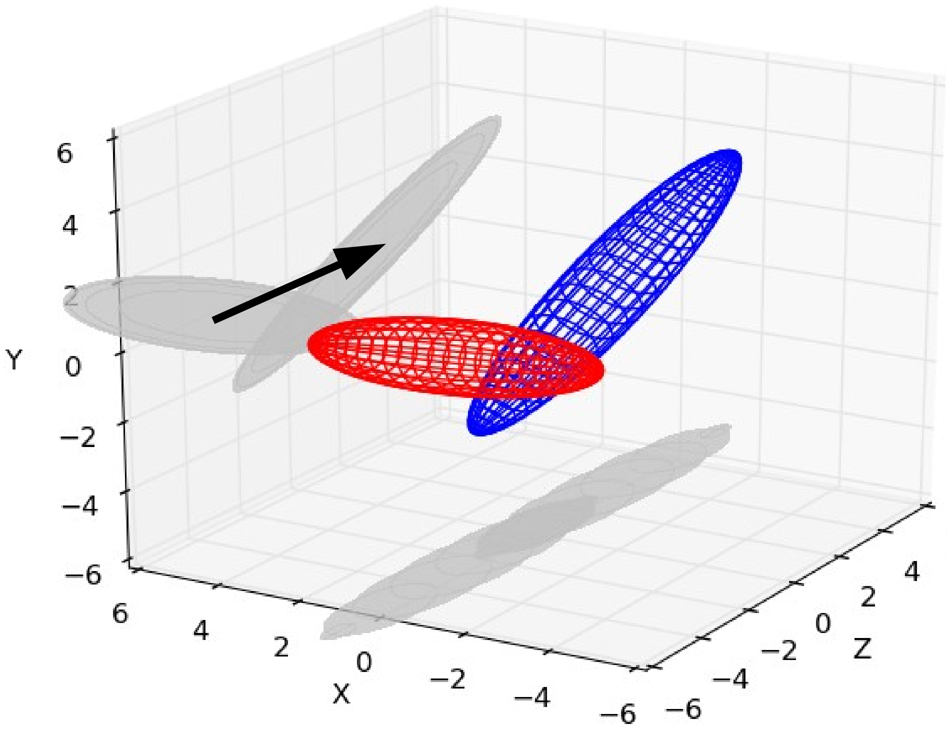
Sep. ∥ Xing

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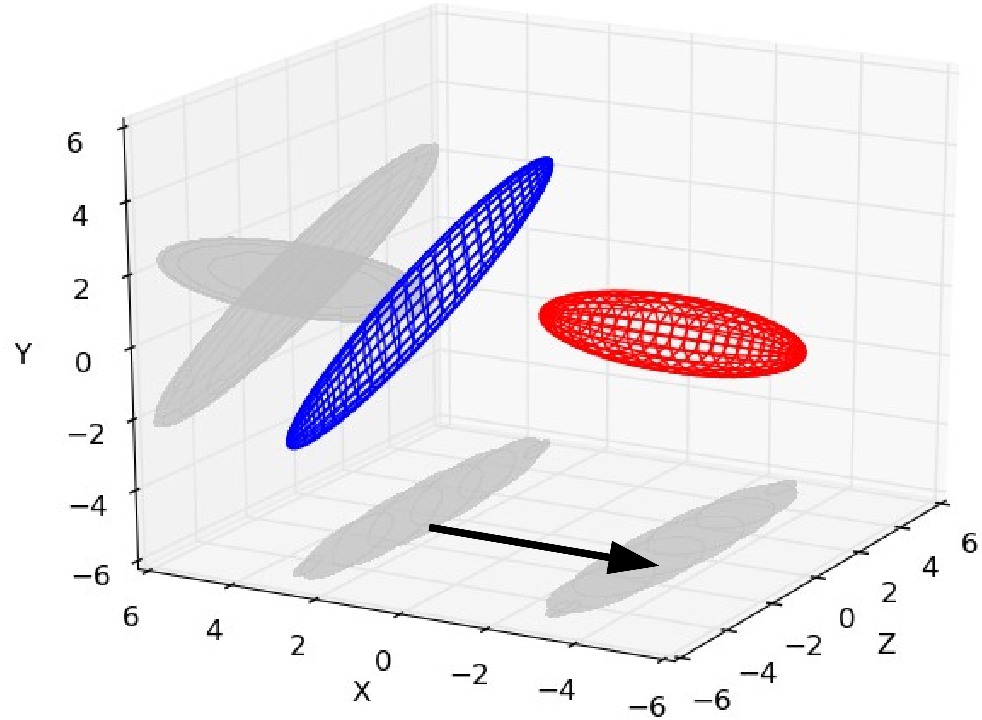

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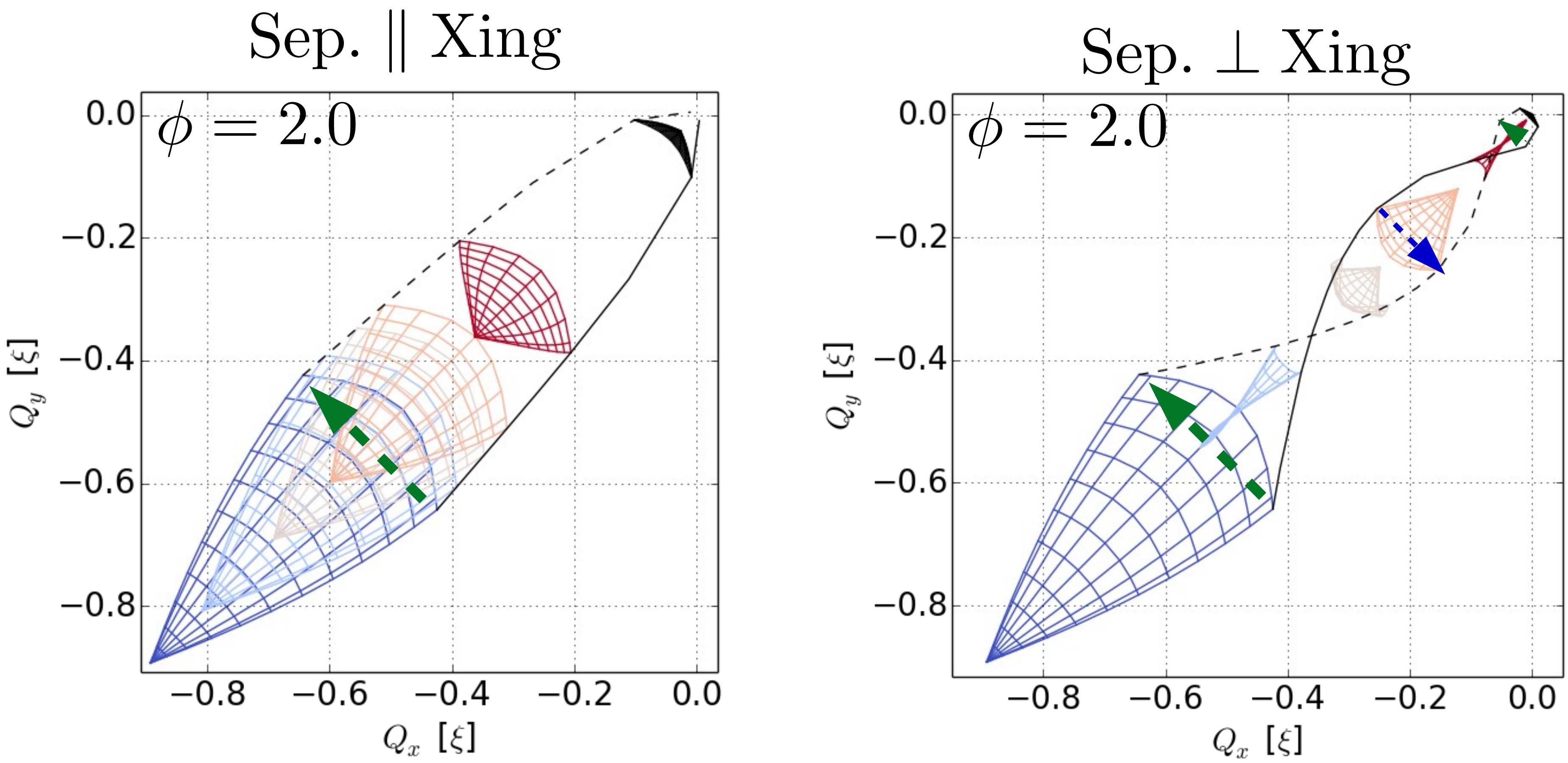


- By introducing a separation bump parallel to the crossing angle bump, instead of perpendicular, the positive polarity of the octupoles remains favourable all along the process

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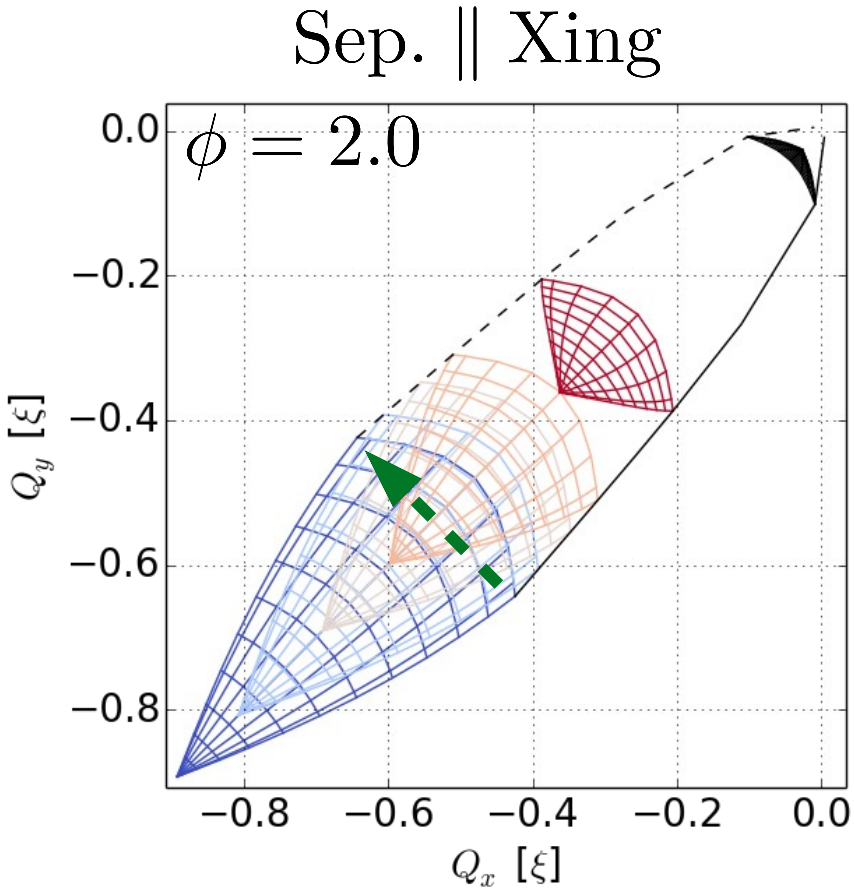


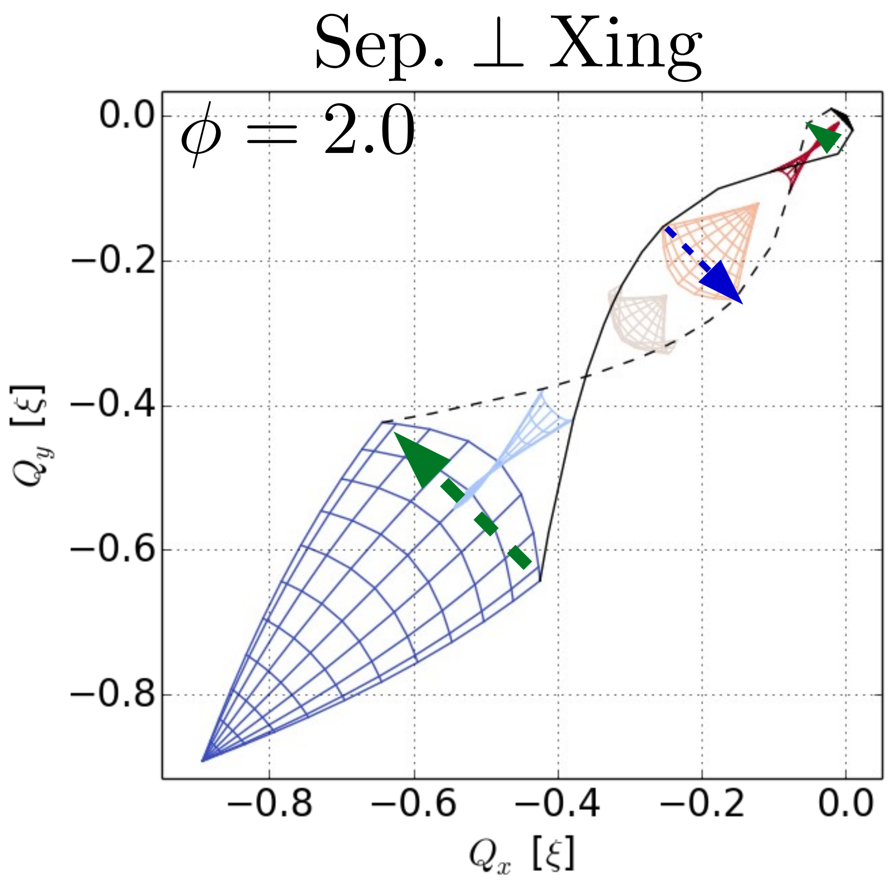


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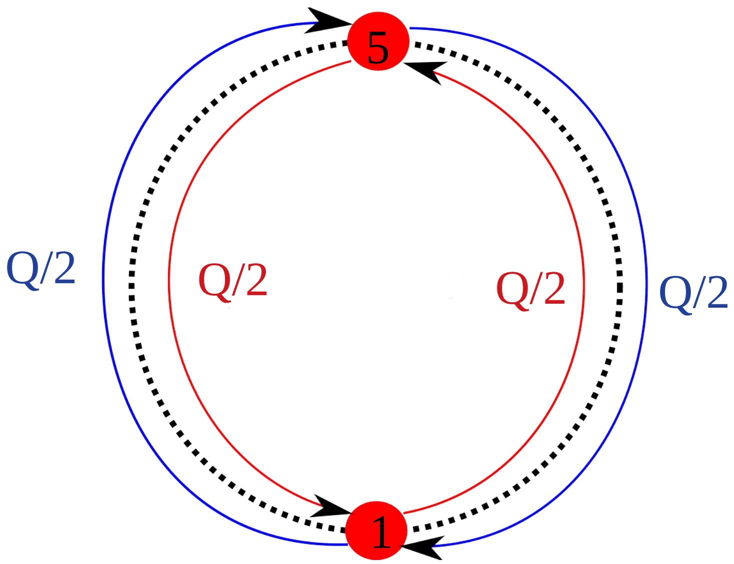
→ The mitigation of instabilities in the presence of beam-beam interaction requires a detailed knowledge of the amplitude detuning, since there are several degrees of freedom that have a significant impact

# Coherent beam-beam modes




π

σ

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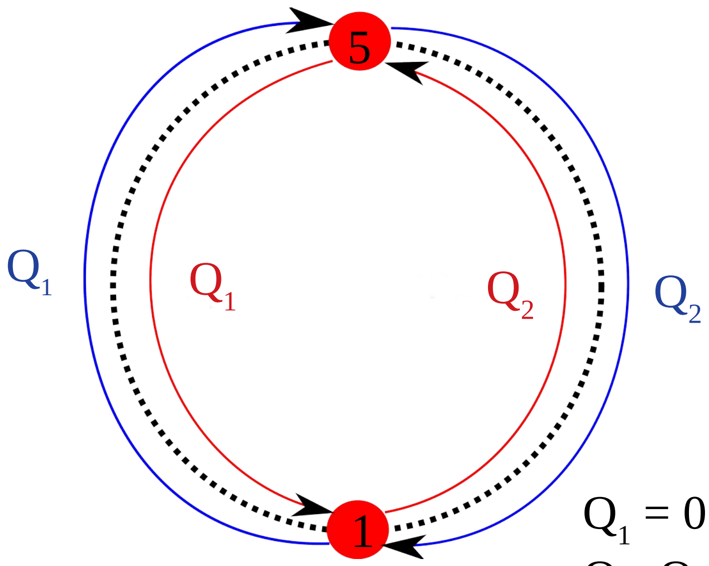
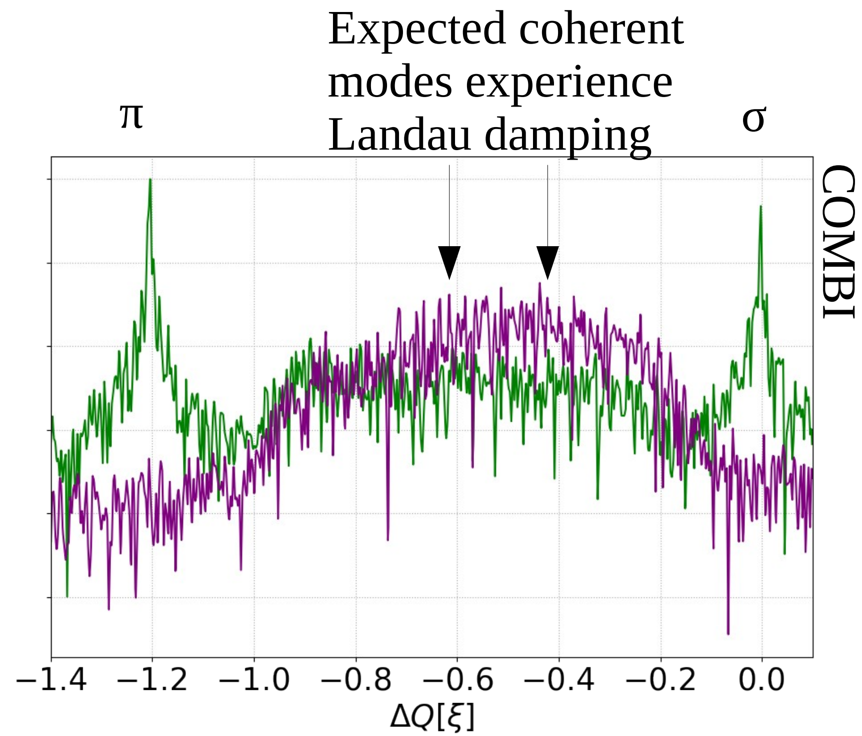
# Coherent beam-beam modes




$Q_1 = 0.405$, $Q_2 = 0.905$

$Q_1 + Q_2 = Q$



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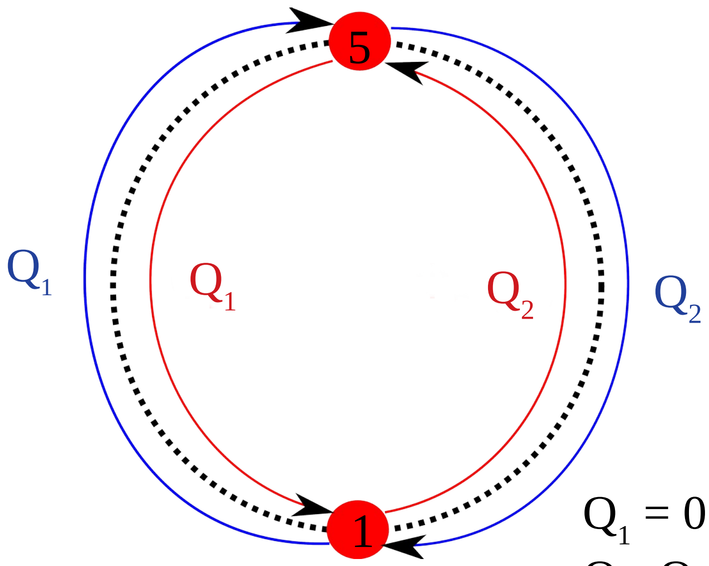


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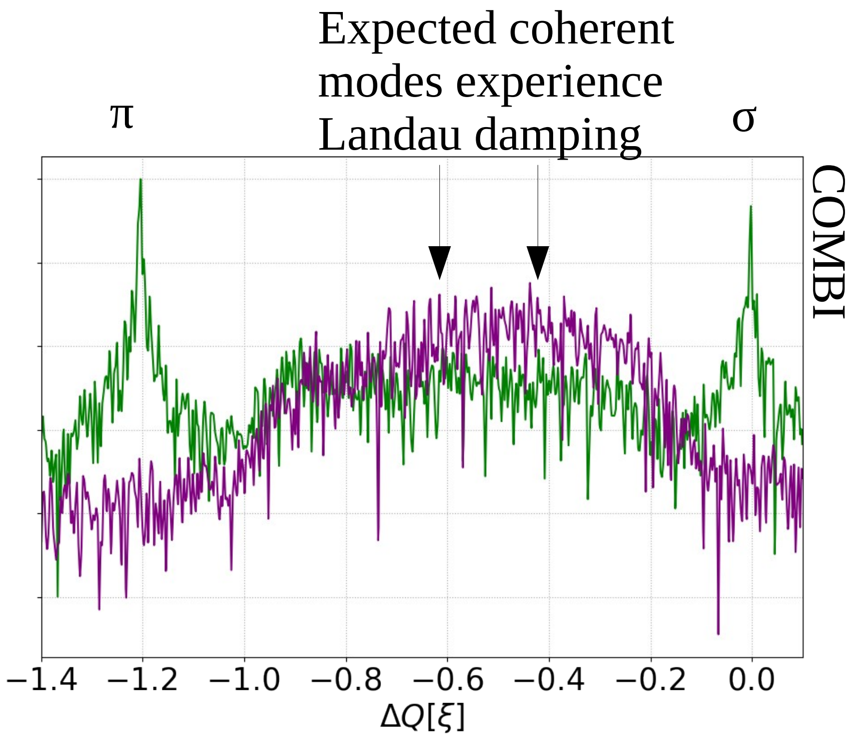


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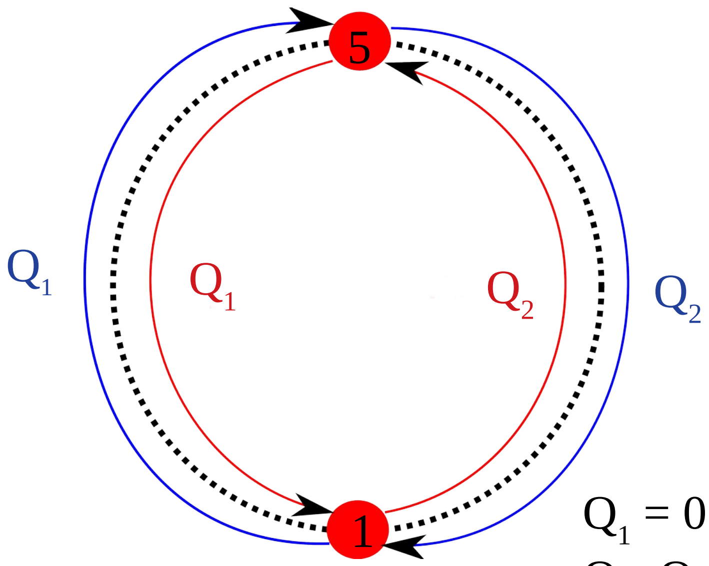


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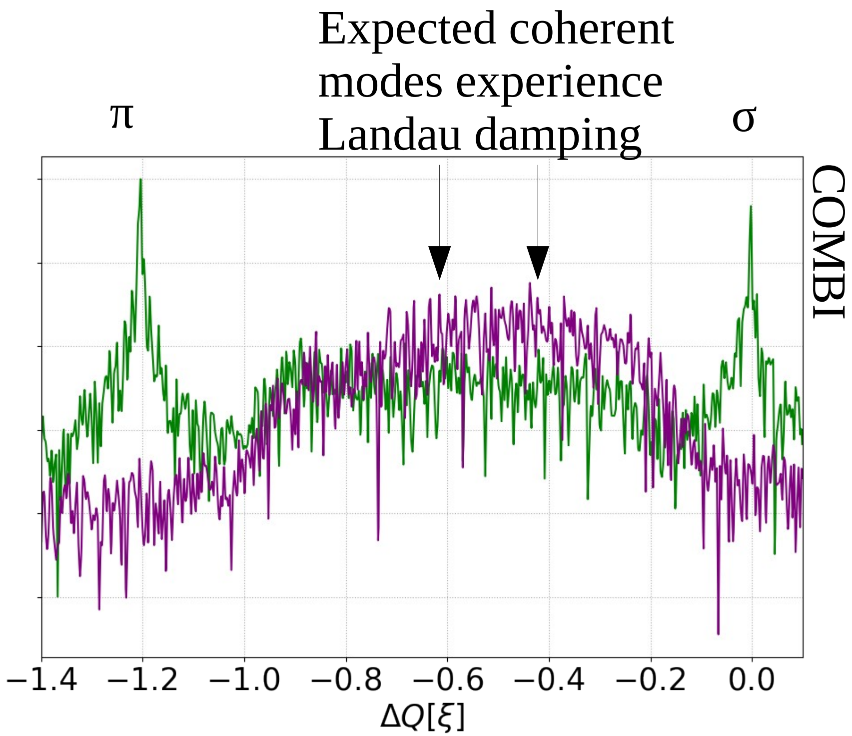


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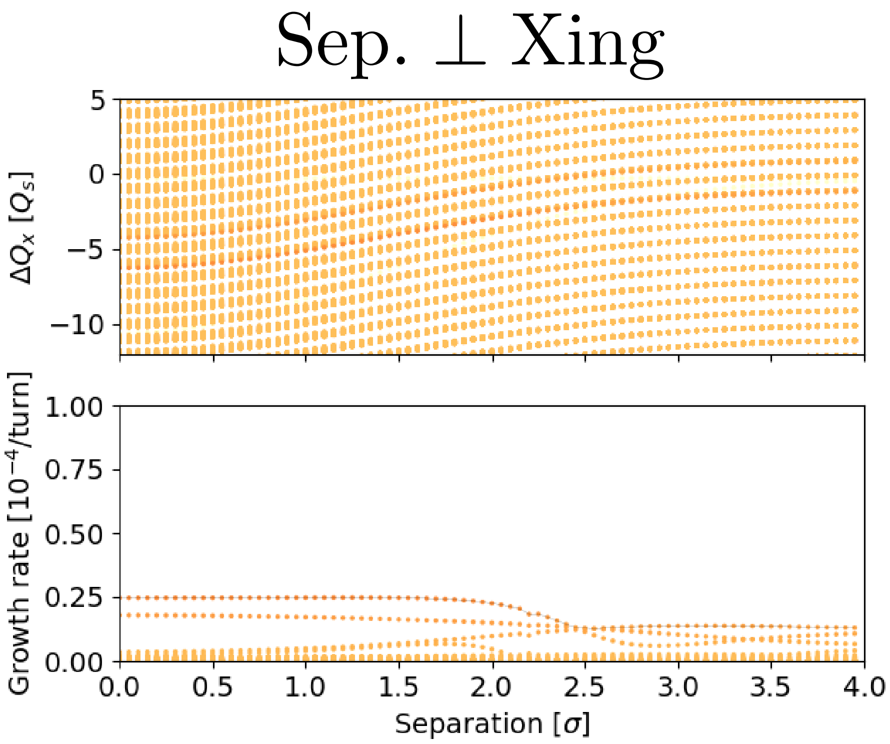
- The circulant matrix model is particularly handy to predict the mode frequency in complex configurations, as well as the effectiveness of other mitigation techniques such as chromaticity or active feedbacks

  E. A. Perevedentsev and A. A. Valishev, Phys. Rev. ST Accel. Beams 4, 024403

  *S. White, et al., Phys. Rev. ST Accel. Beams 17 041002 (2014)*

  *X. Buffat, PhD Thesis EPFL, 2015*

# Offset beams + crossing angle

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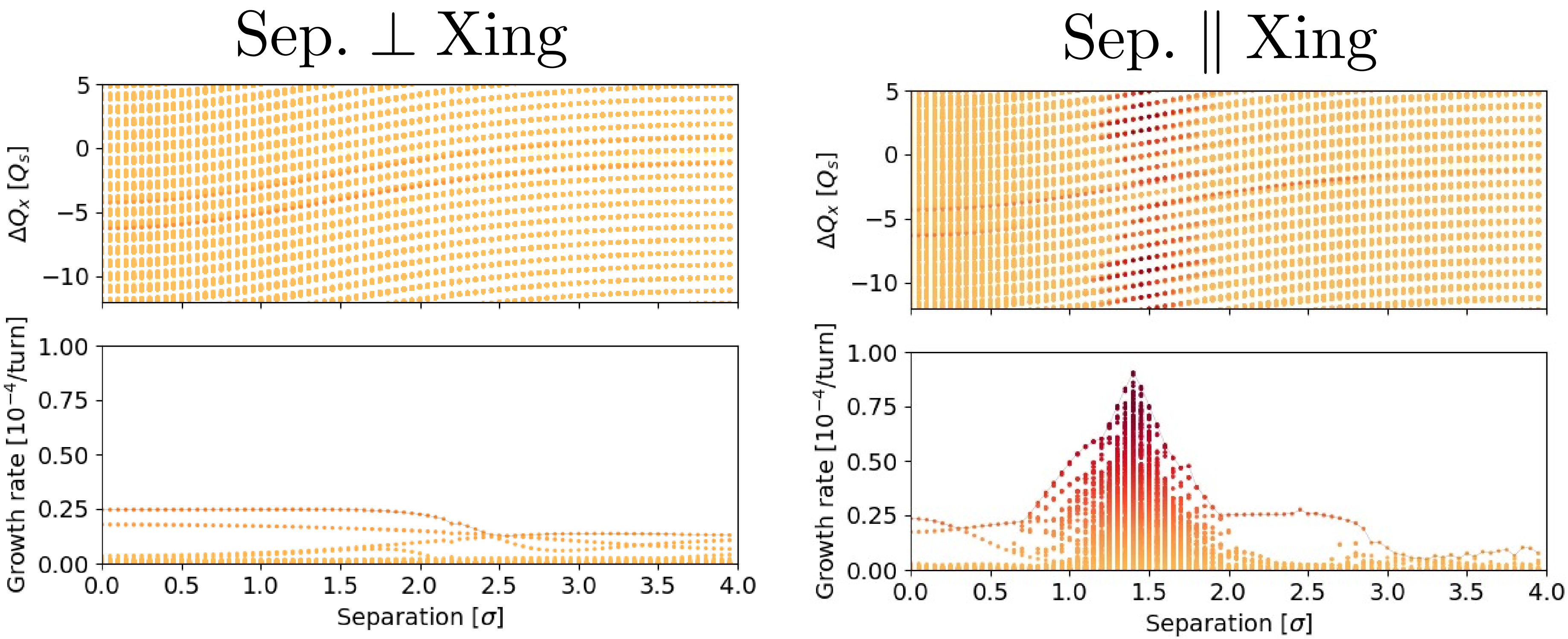


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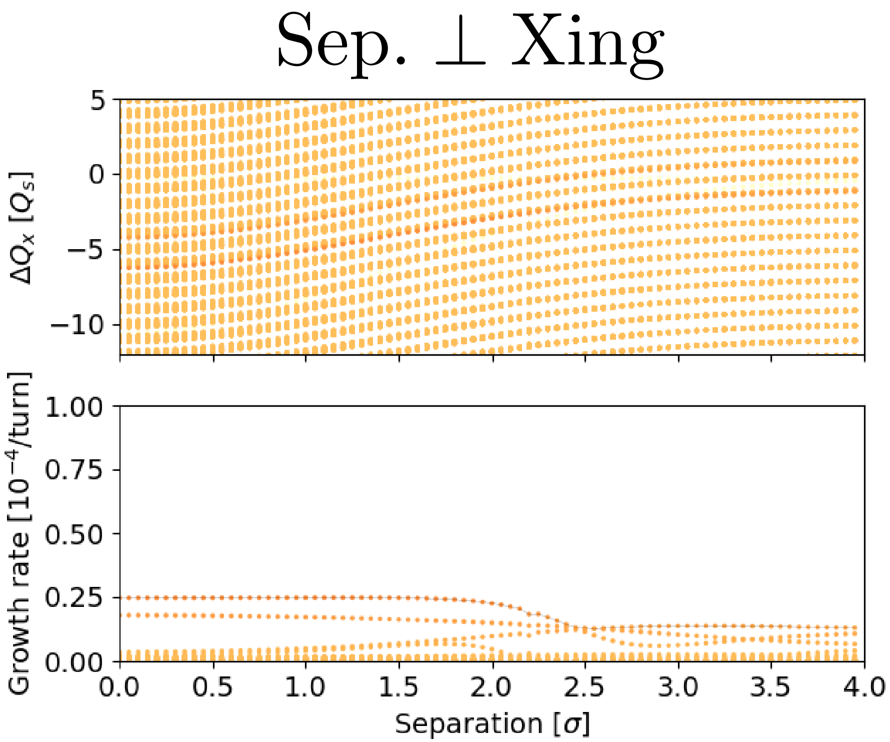


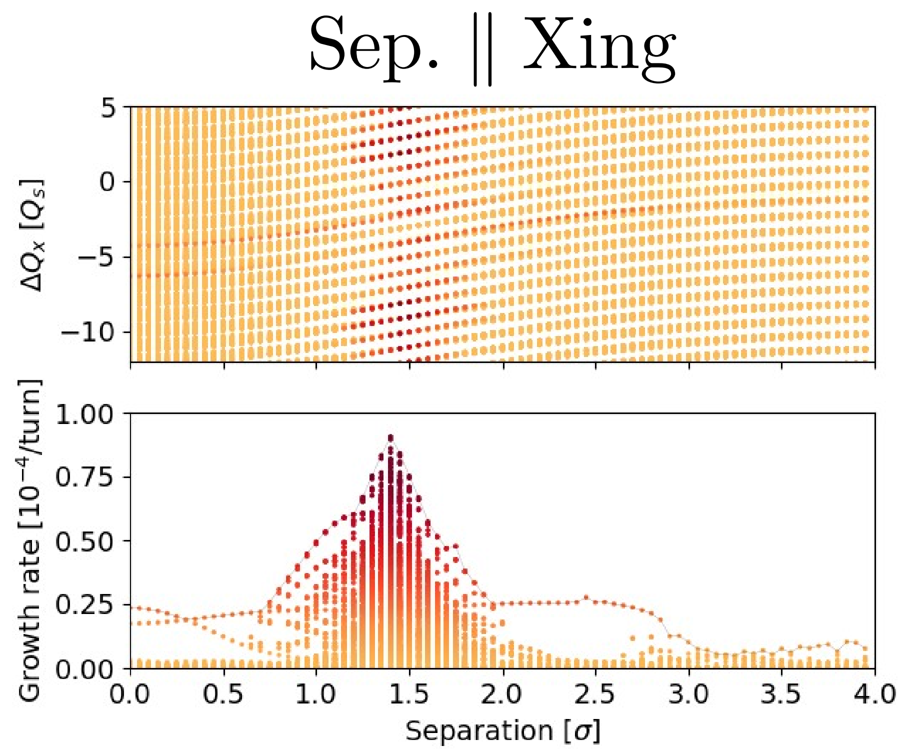


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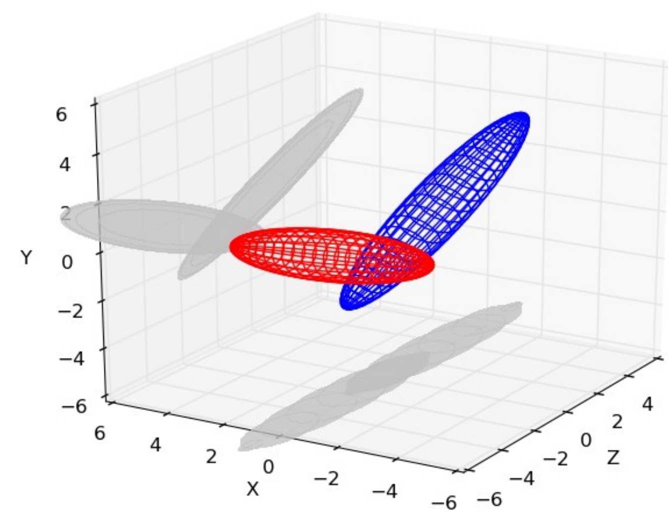

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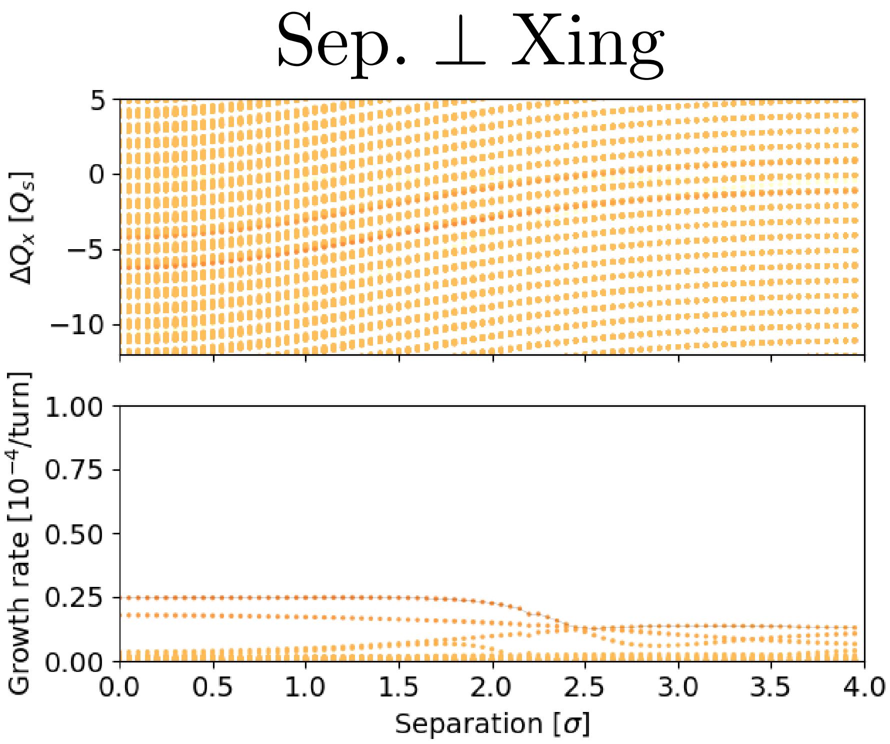


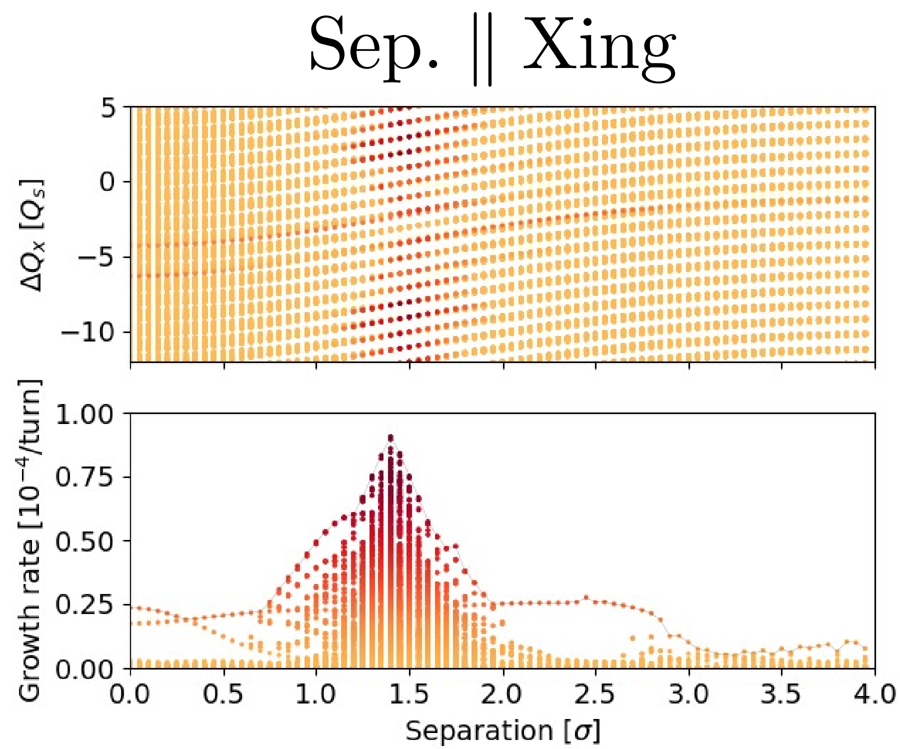


- The mode coupling instability of colliding beam is well suppressed by a transverse feedback in configurations relevant for the HL-LHC with the 'normal' setup of crossing and separation bumps
- With the configuration favourable for Landau damping, we find coupling of high order modes

→ Fresh off the press, to be continued...