Taming the high intensity beam-beam and impedance

X. Buffat

Acknowledgments : L. Barraud, S. Fartoukh, W. Herr, N. Mounet, E. Métral, T. Persson, T. Pieloni*, A. Ribes Metidieri, B. Salvant, C. Tambasco*, R. Tomas, S.M. White**

* EPFL ** ESRF The European Synchrotron

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- Why beam-beam and impedance needs taming ?
- Amplitude detuning and Landau damping of head-tail modes
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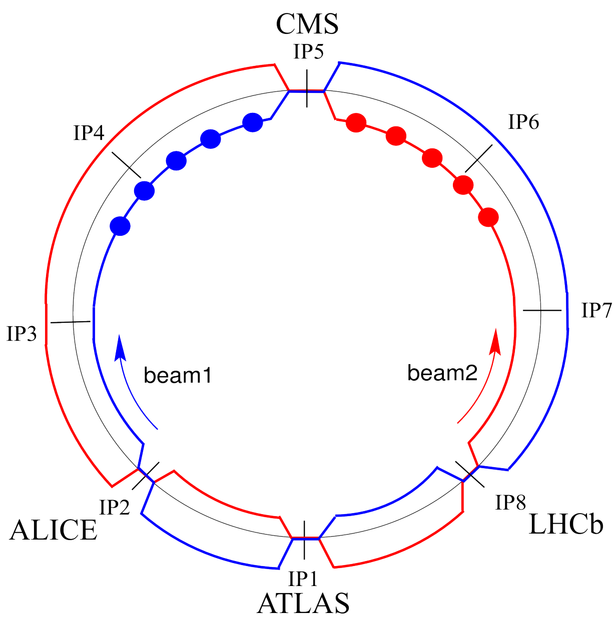
Why beam-beam and impedance needs taming

- Modern high energy hadron colliders require a collimation system to cope with high intensity beams, leading to a high impedance also at top energy
- The complexity of the IP configuration, crossing scheme and beam structure leads to a variety of mechanisms that can generate coherent instabilities



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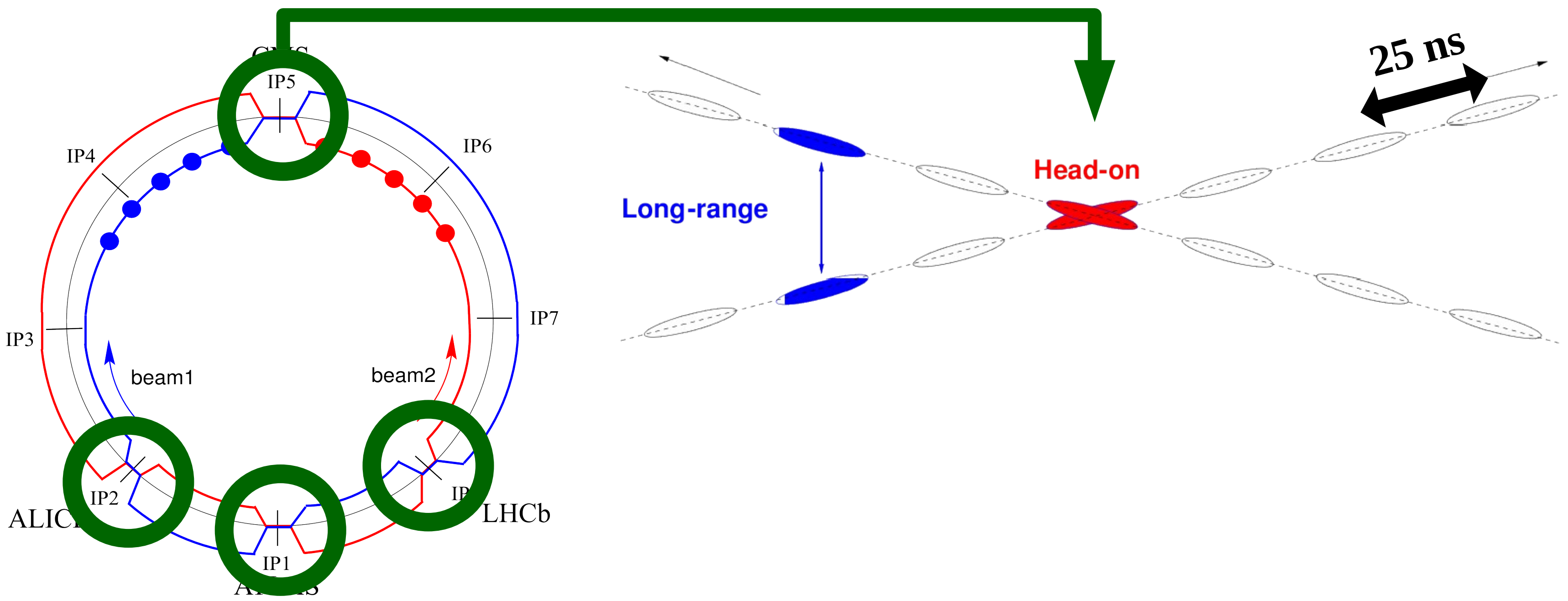

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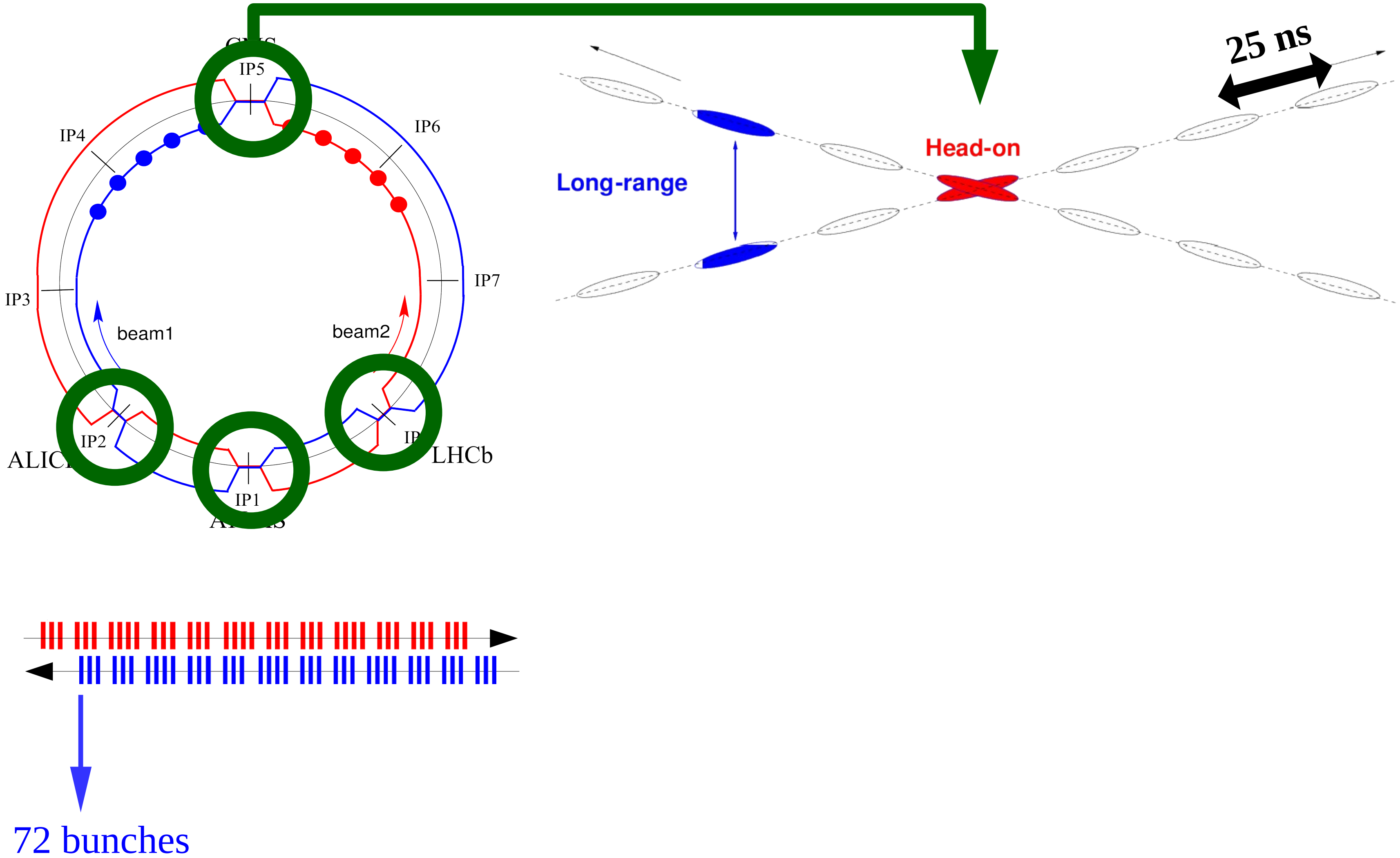

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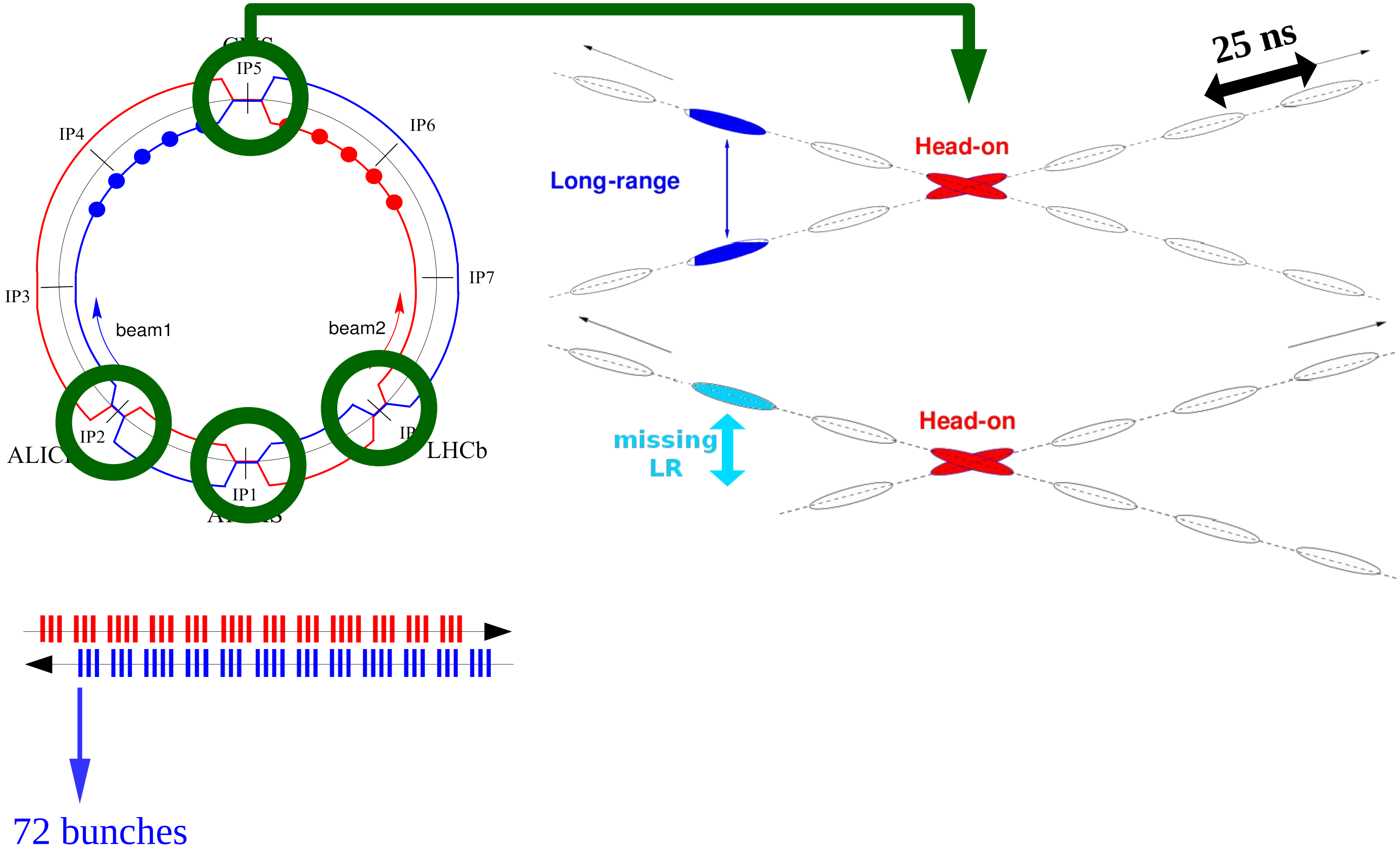

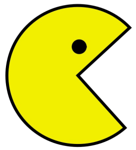

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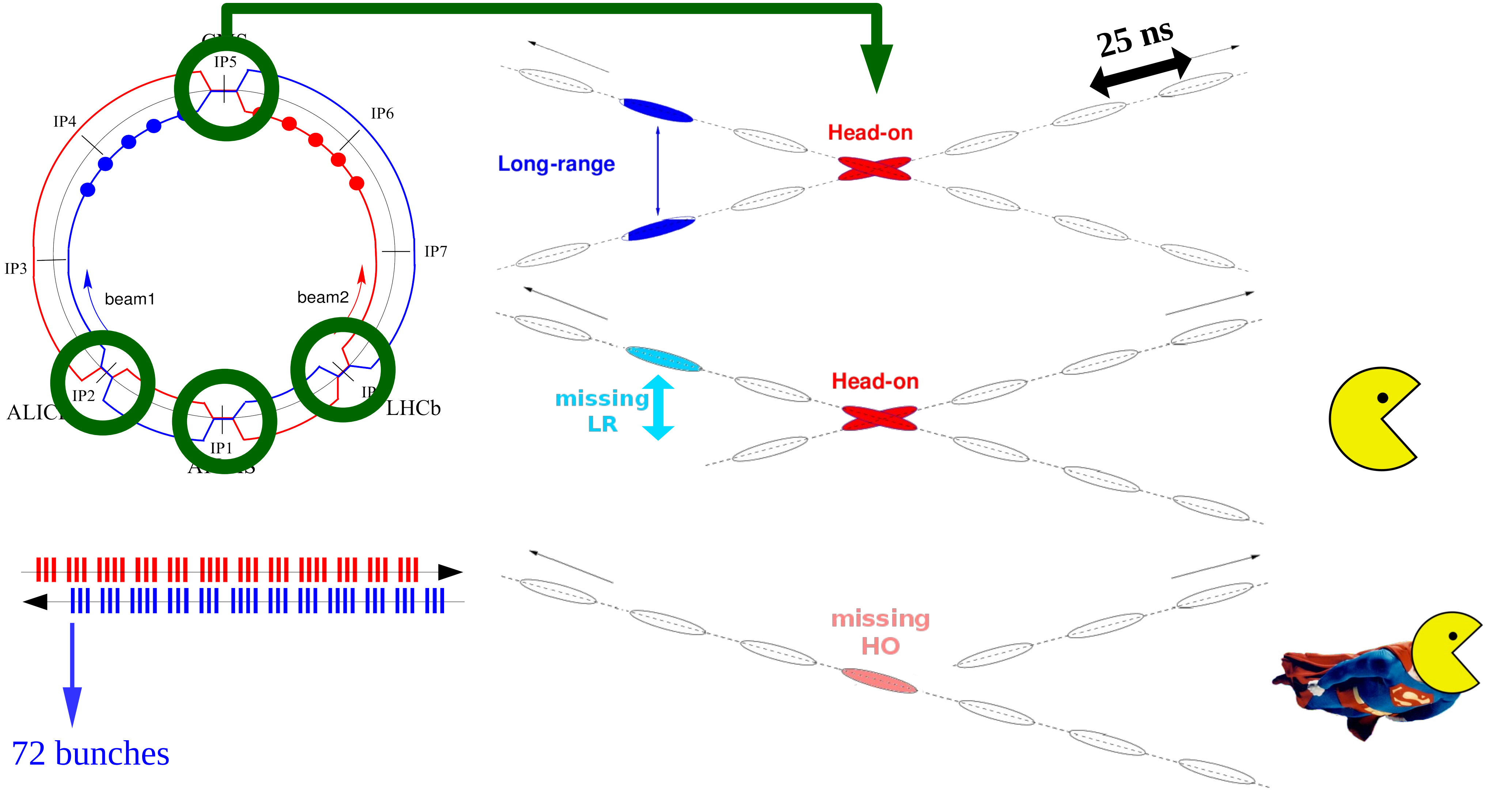

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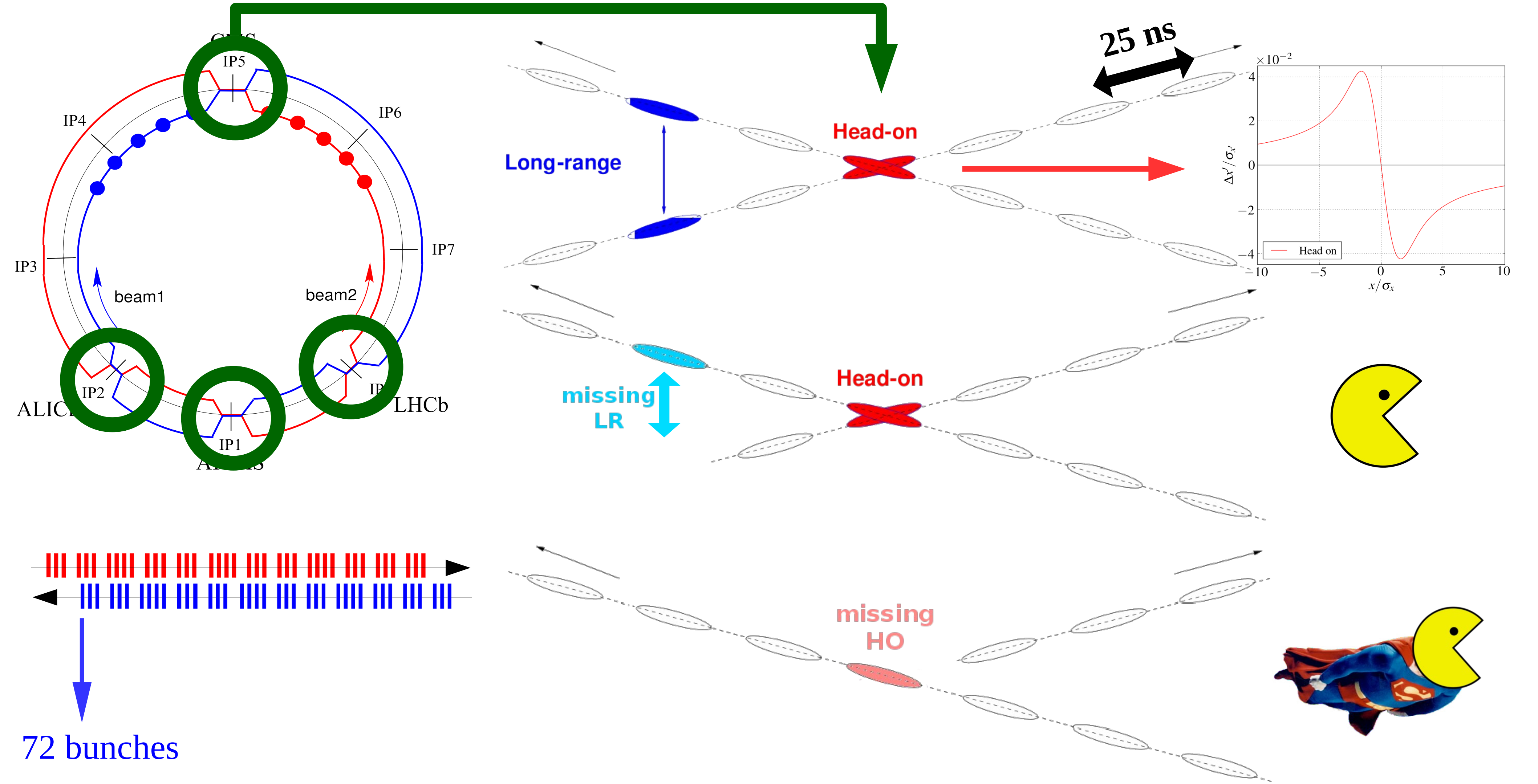

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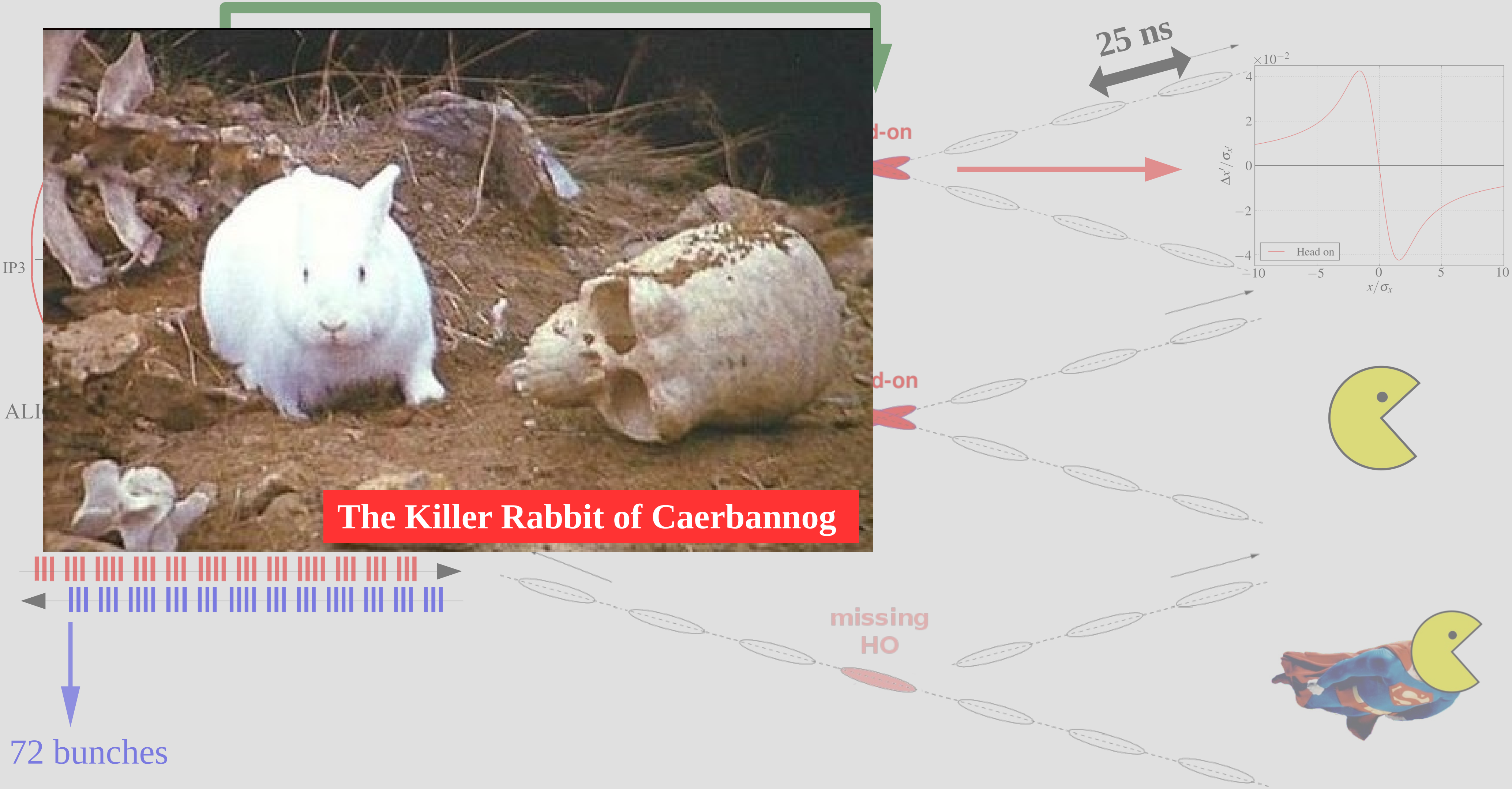

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IP3

72 bunches

Landau damping of head-tail modes

- In a first step we neglect the oscillations of the two beams against each other, i.e. the beam-beam force experienced by each beam is assumed frozen

  → Beam-beam interactions impact the beam stability through their impact on the amplitude detuning and consequently Landau damping

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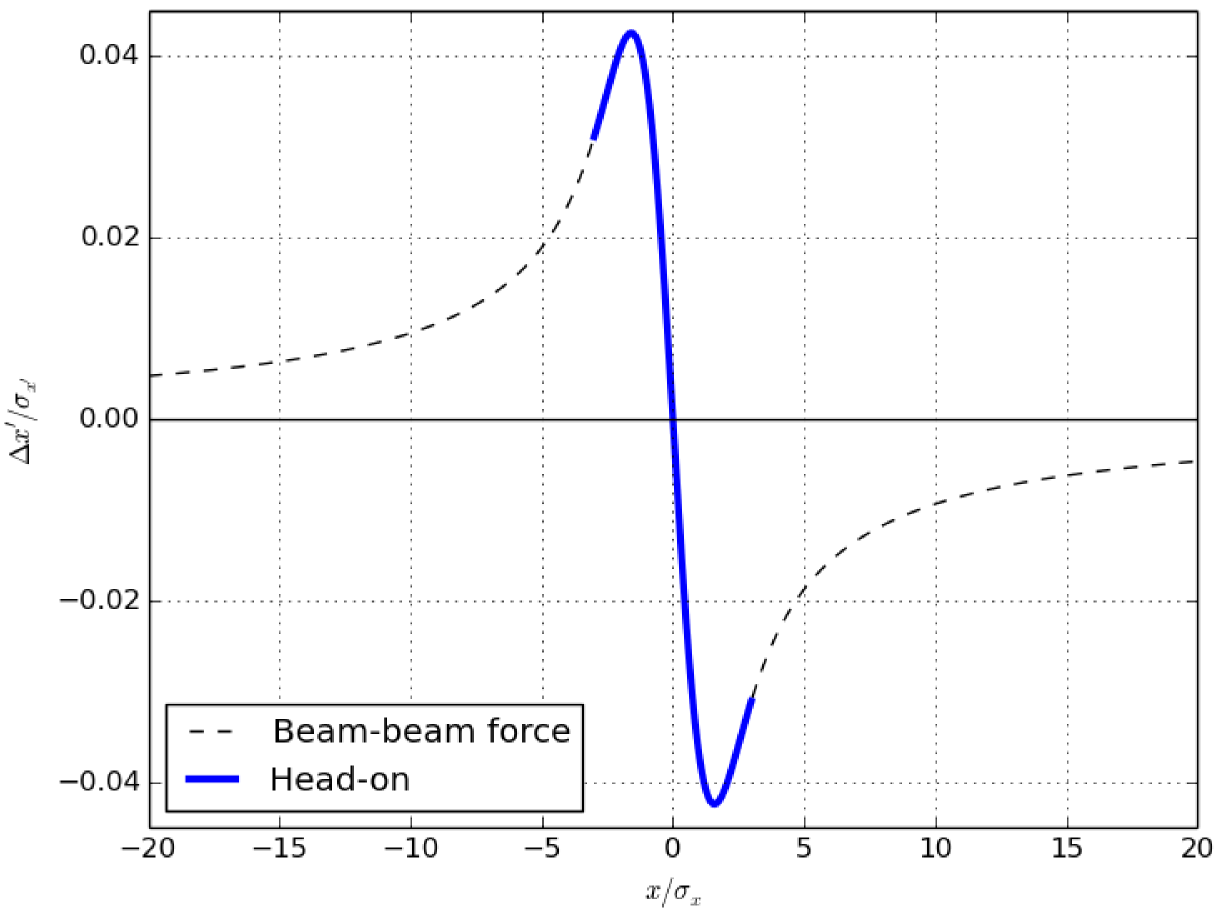
- Equivalently, one may also use the output of tracking codes such as MAD-X X. Buffat, et al., Phys. Rev. ST Accel. Beams 17, 111002

The beam-beam force for round beams



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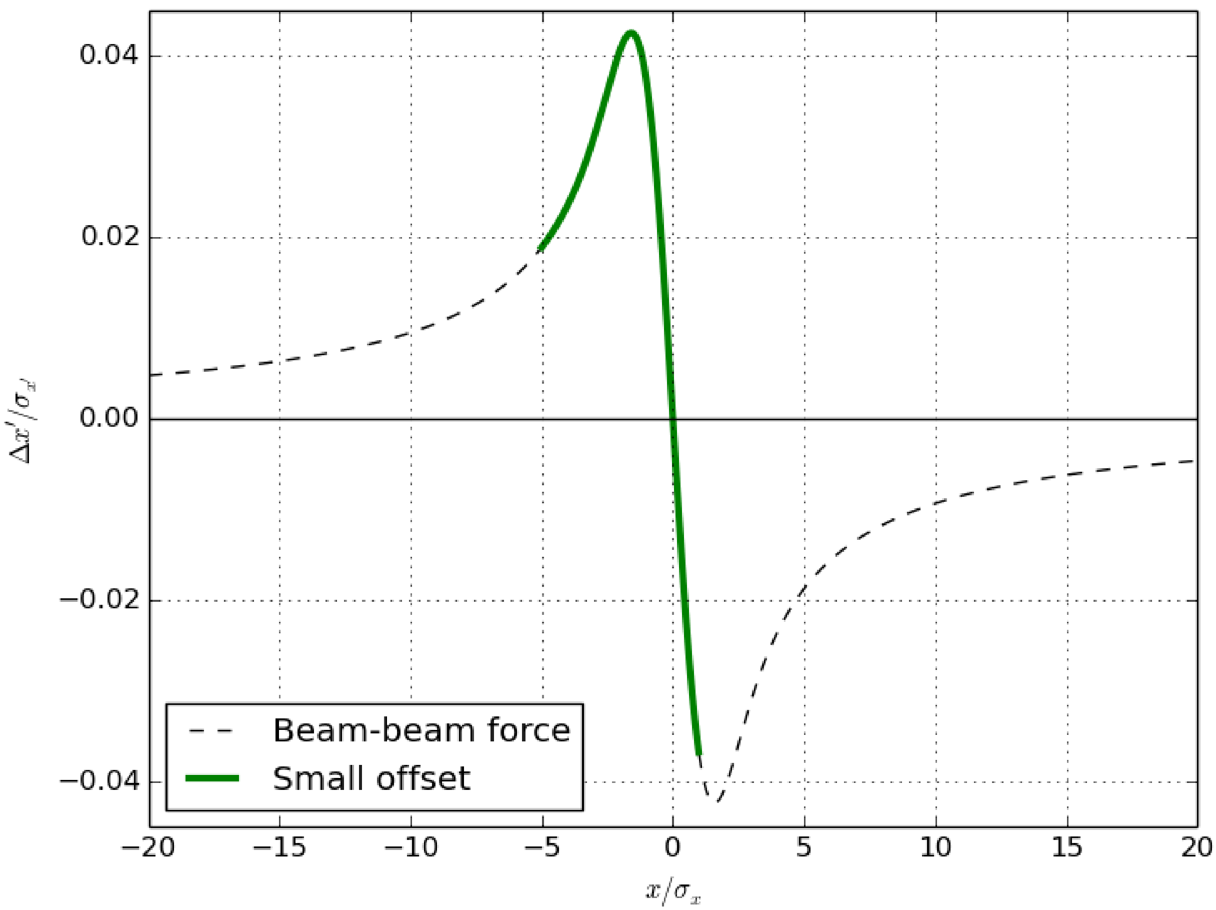

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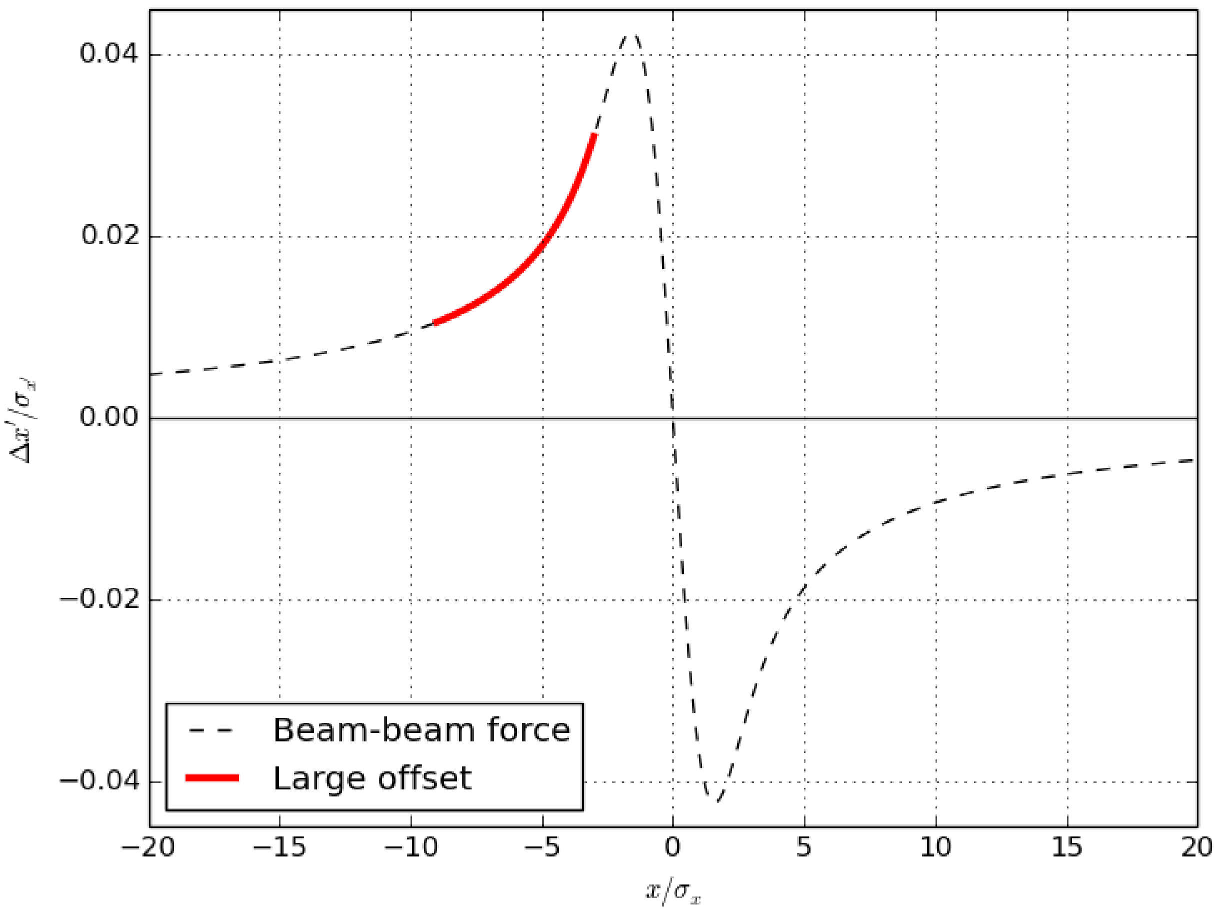

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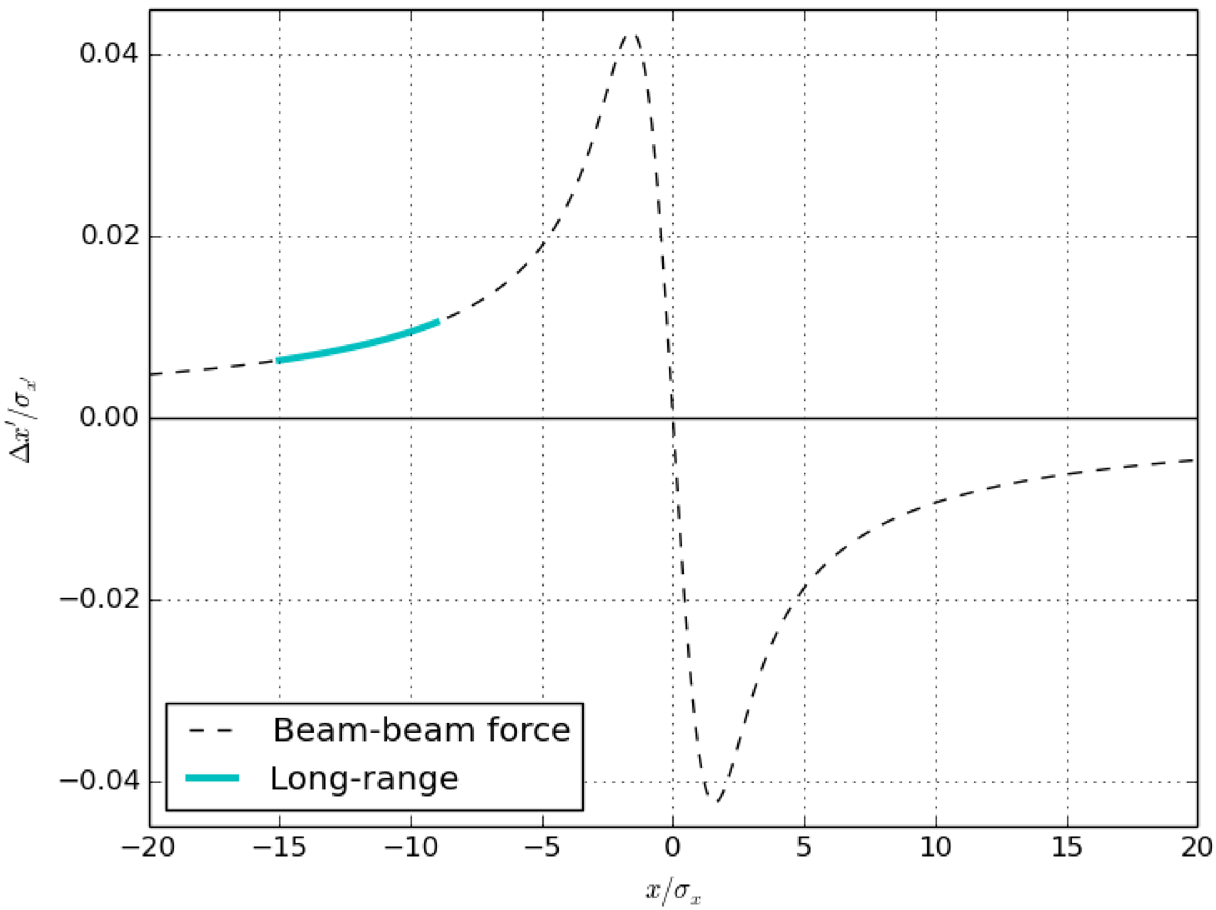
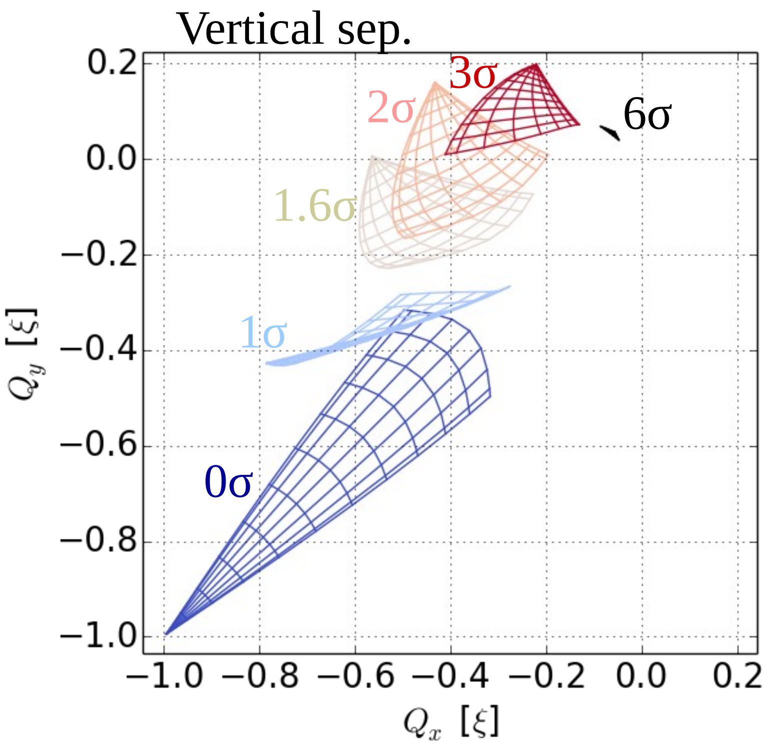


The beam-beam force for round beams

Landau damping with beam-beam interactions



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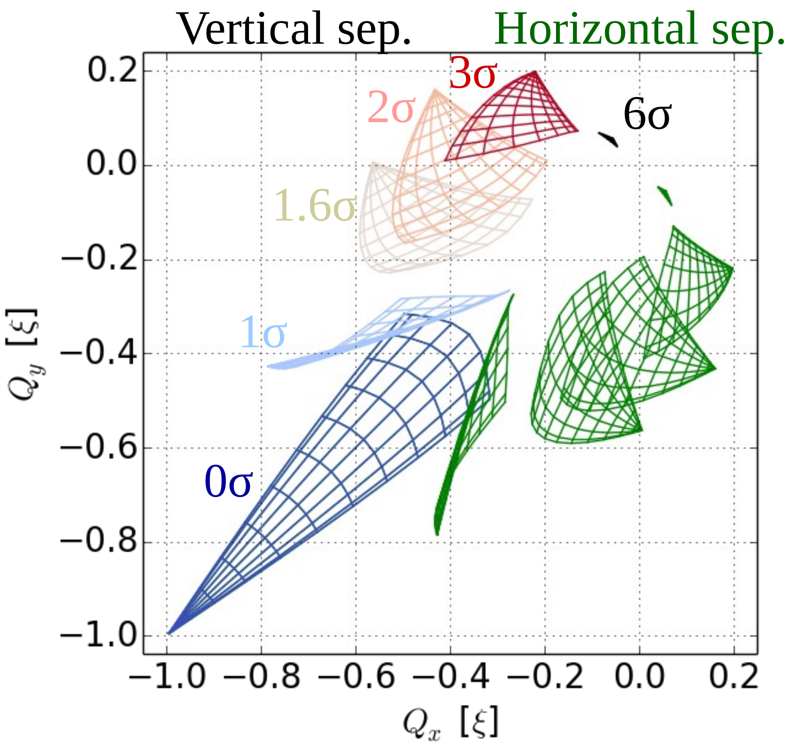

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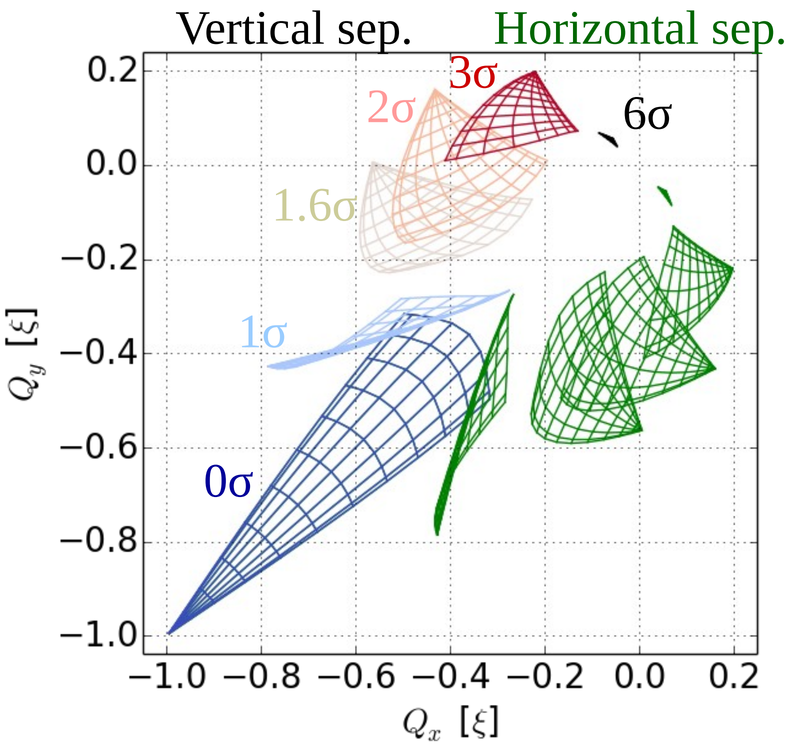

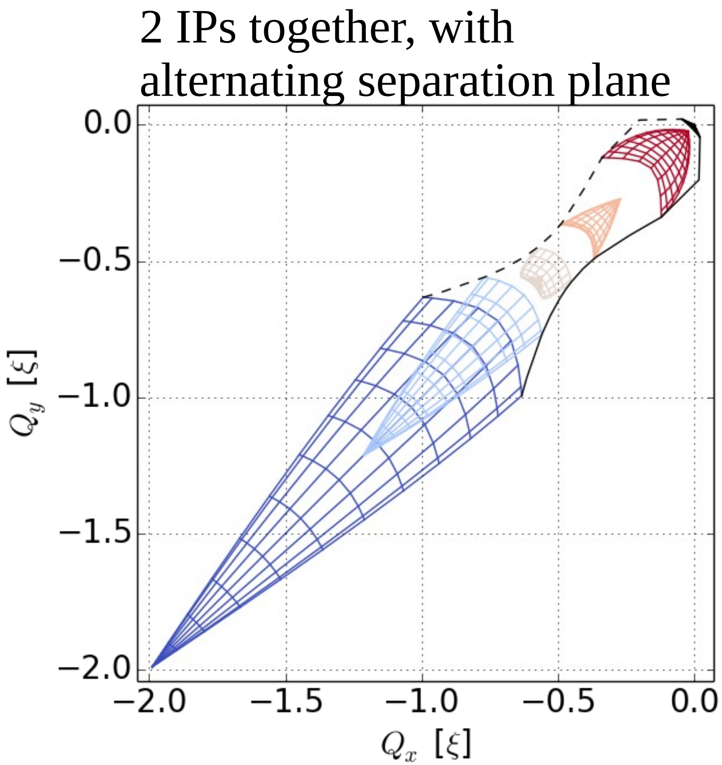

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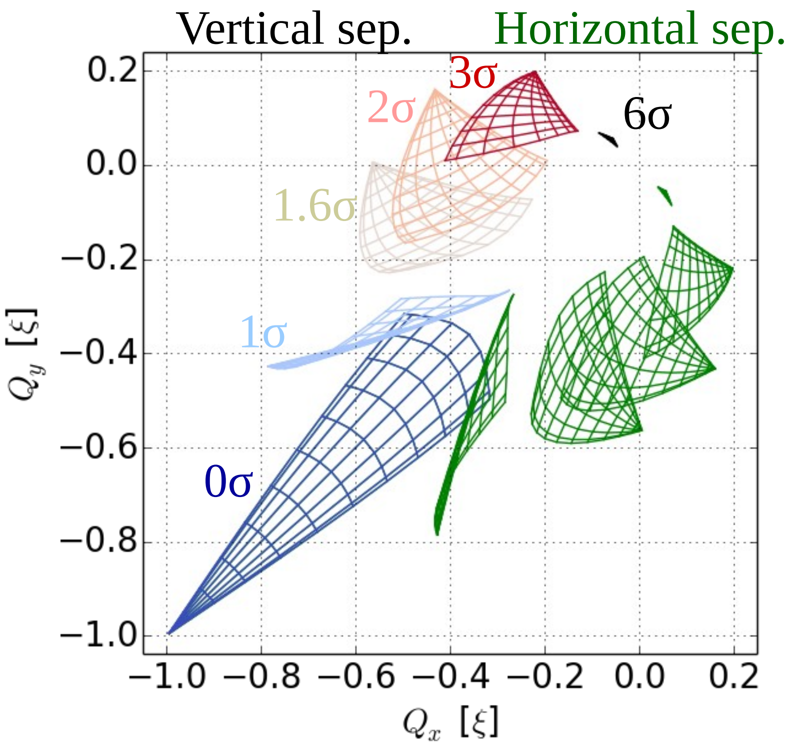
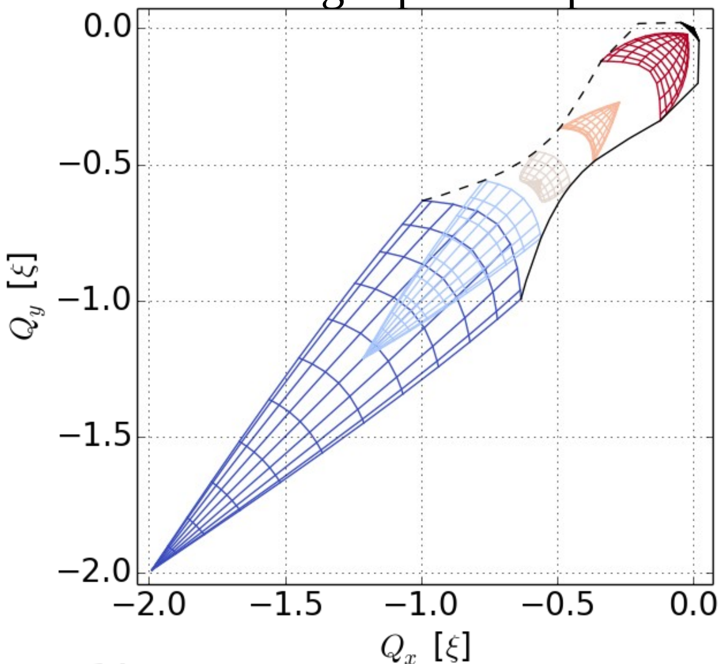
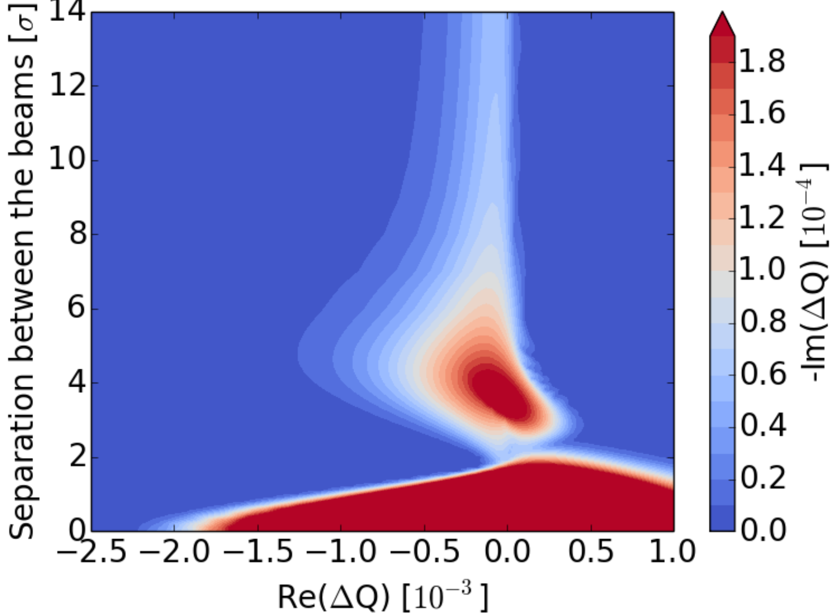


2 IPs together, with alternating separation plane





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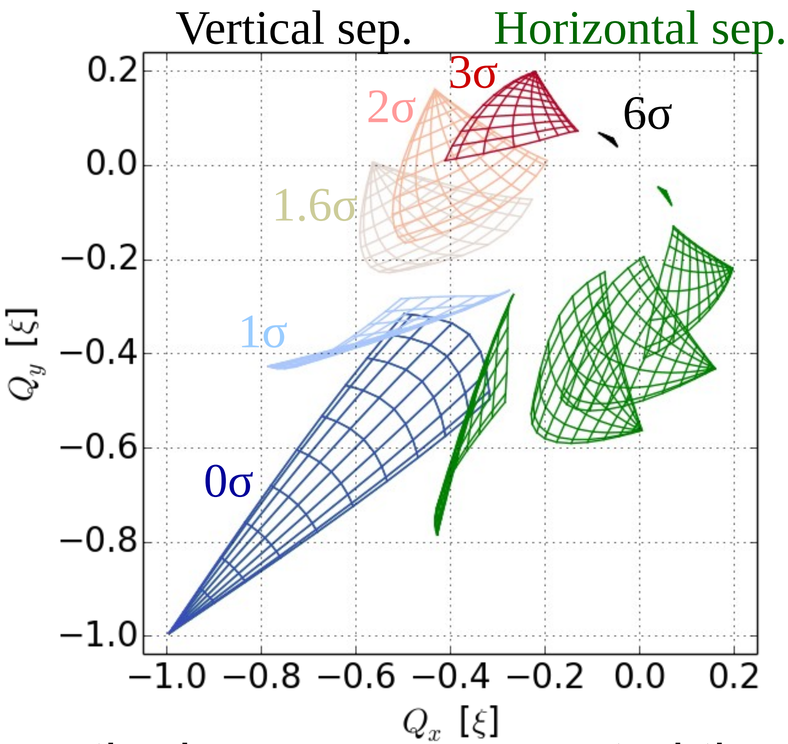

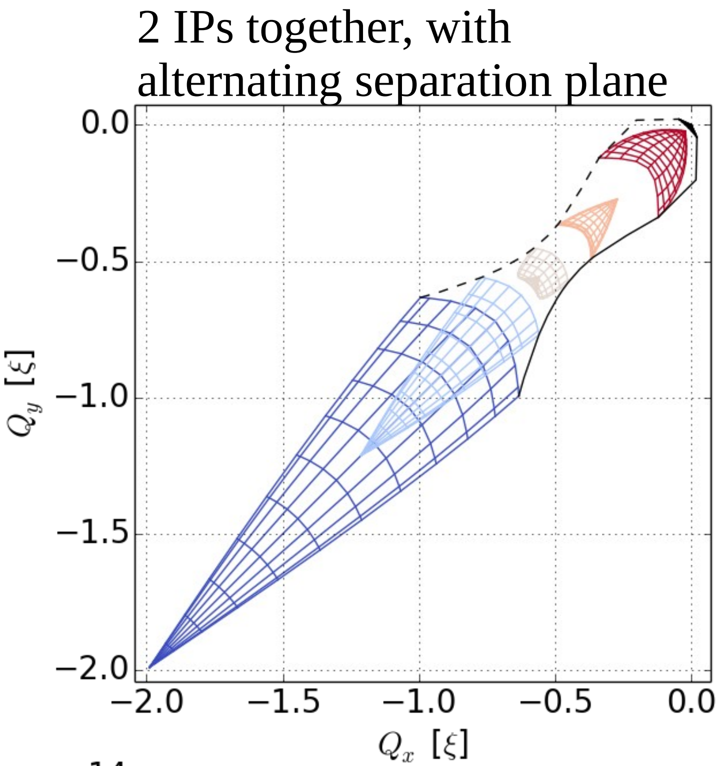

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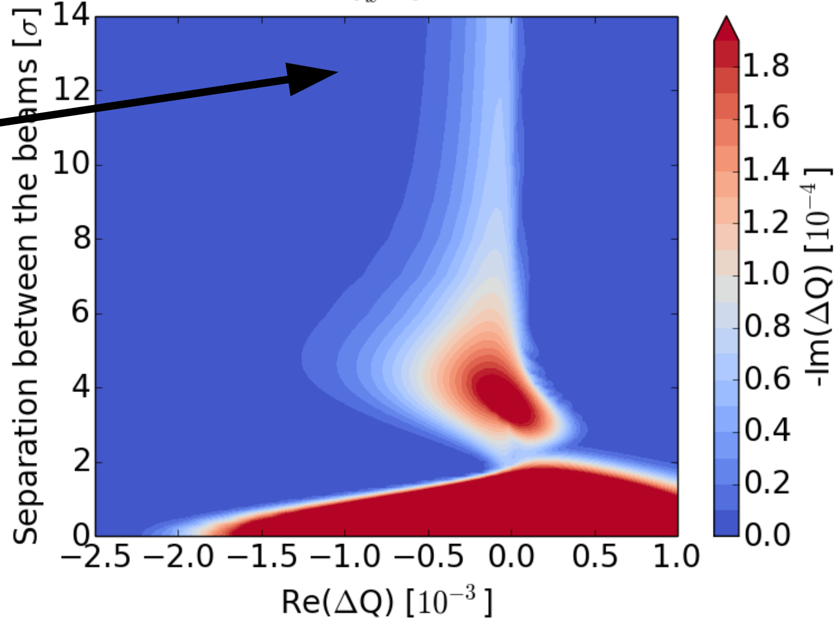

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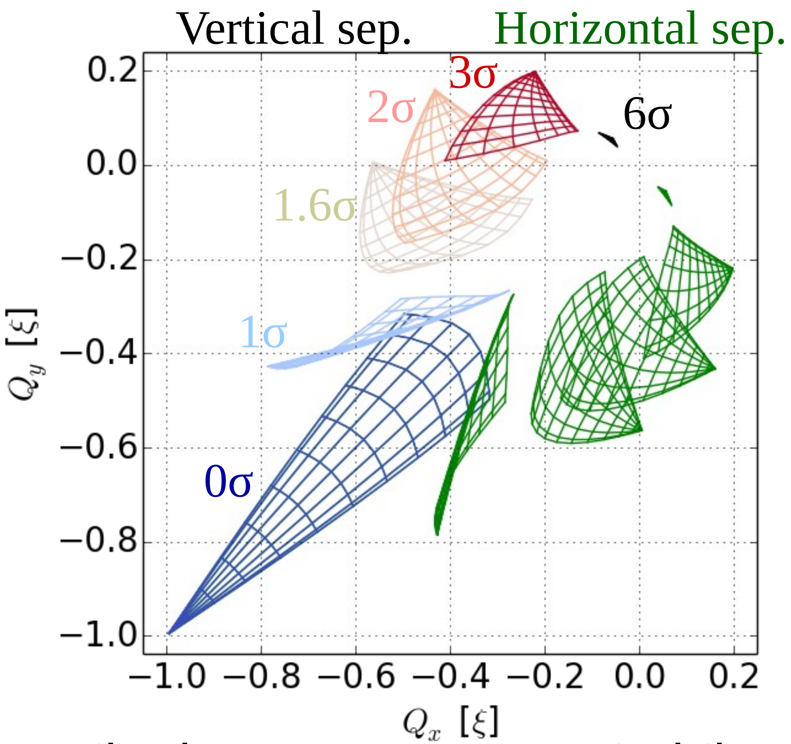

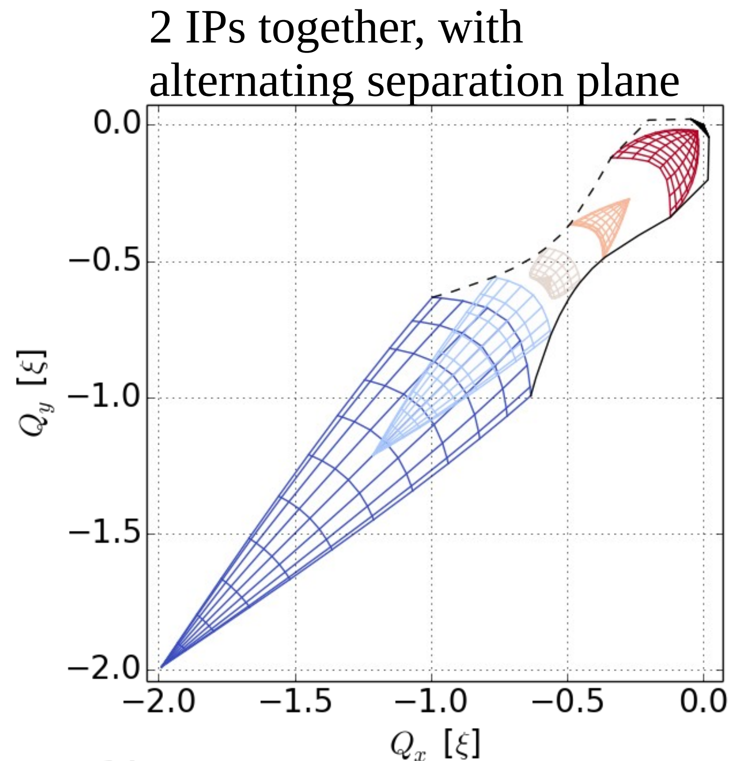

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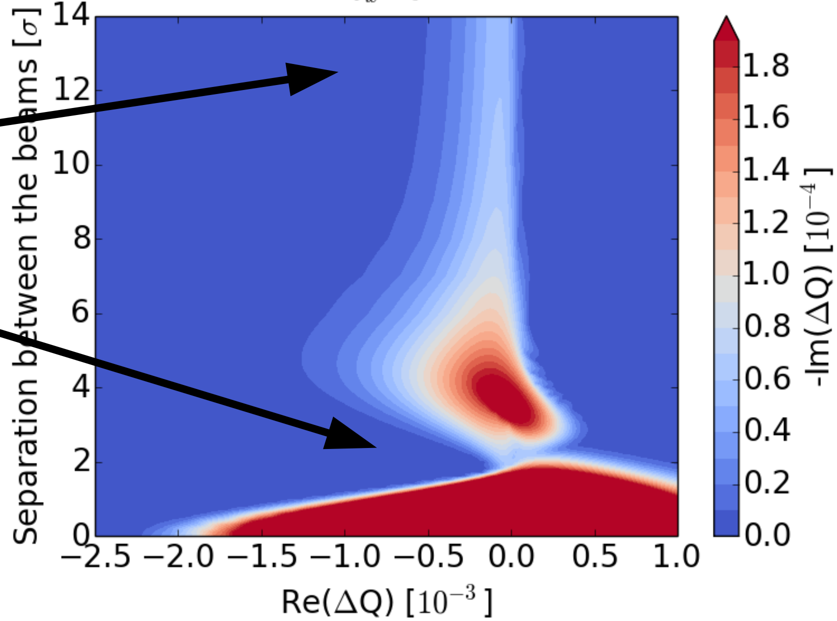

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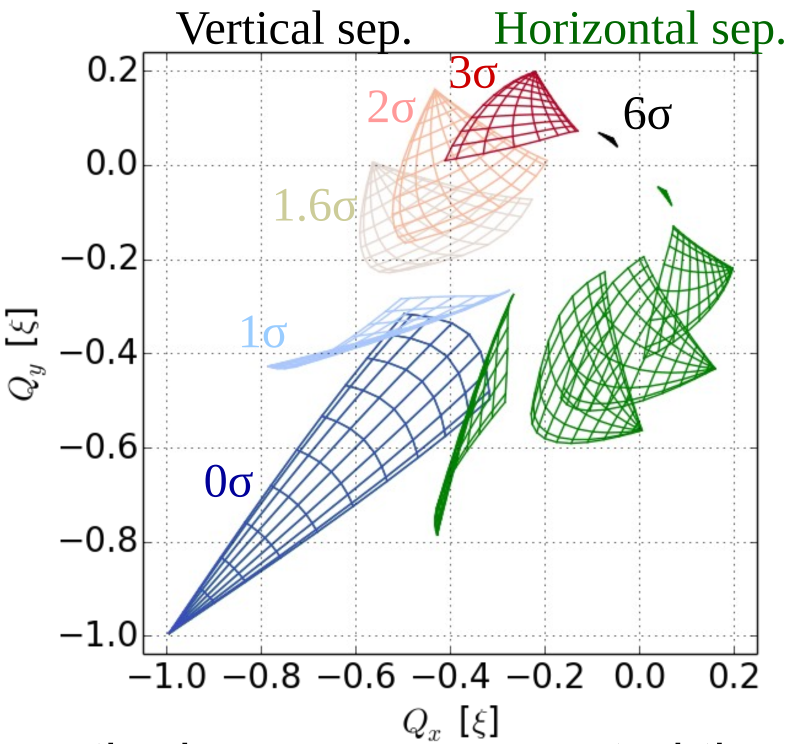

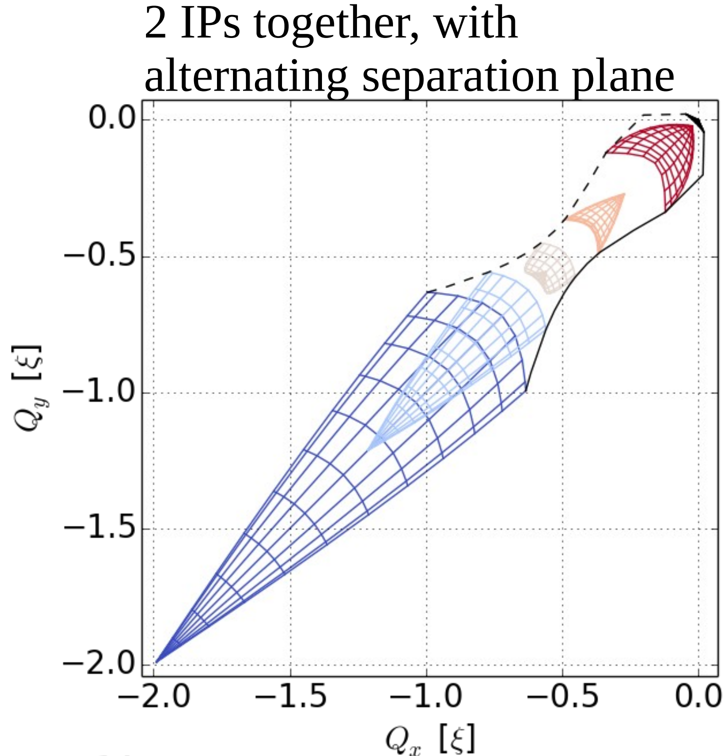

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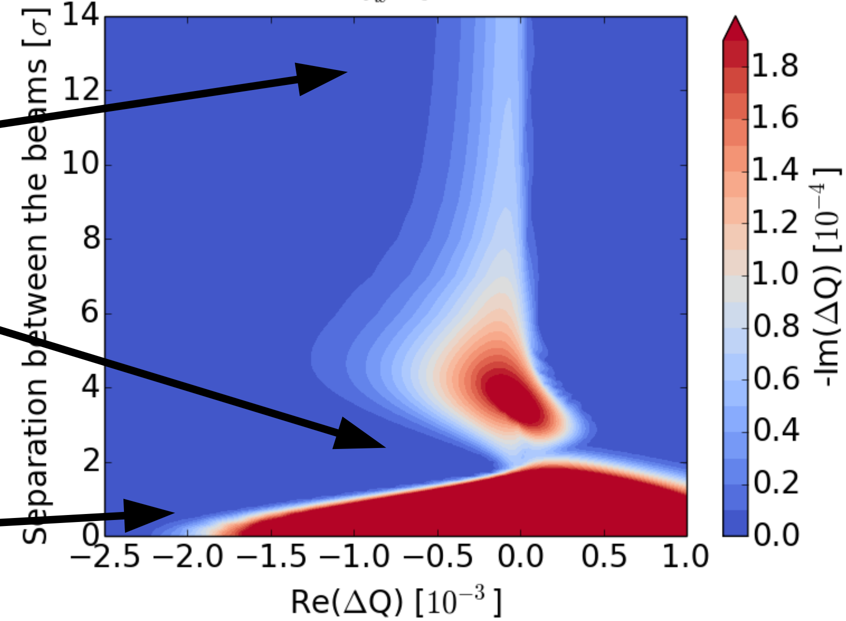
- Once head-on collision the beam profits form strong Landau damping



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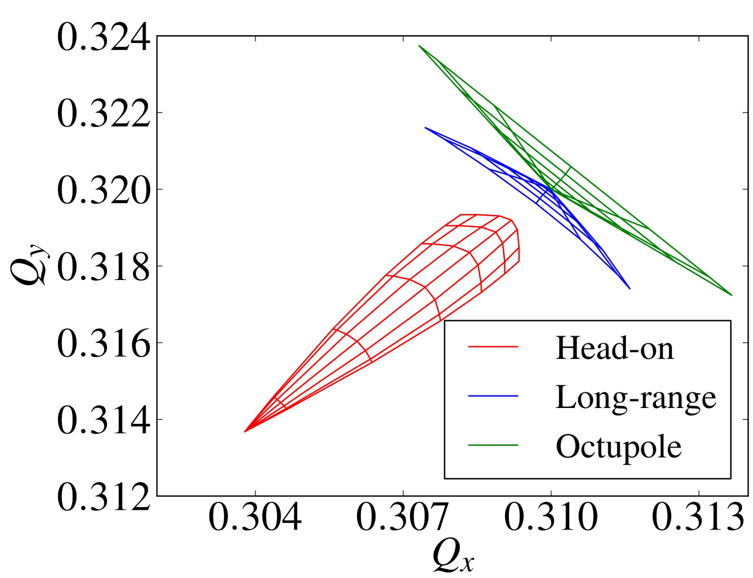

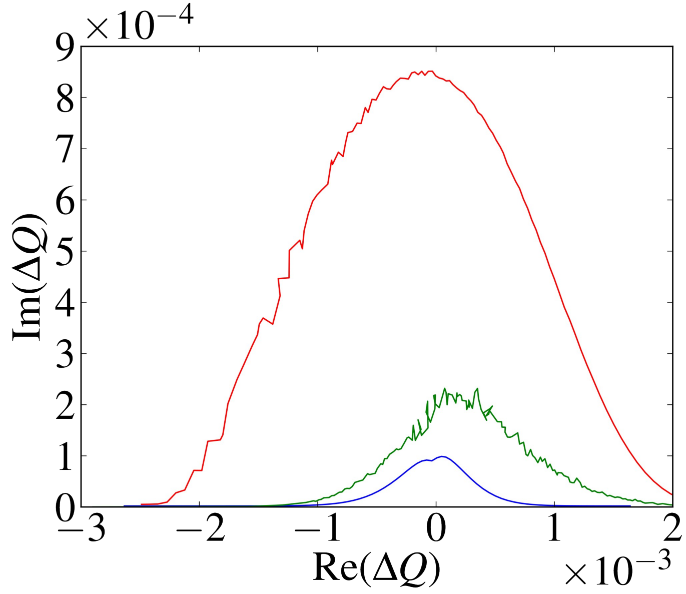

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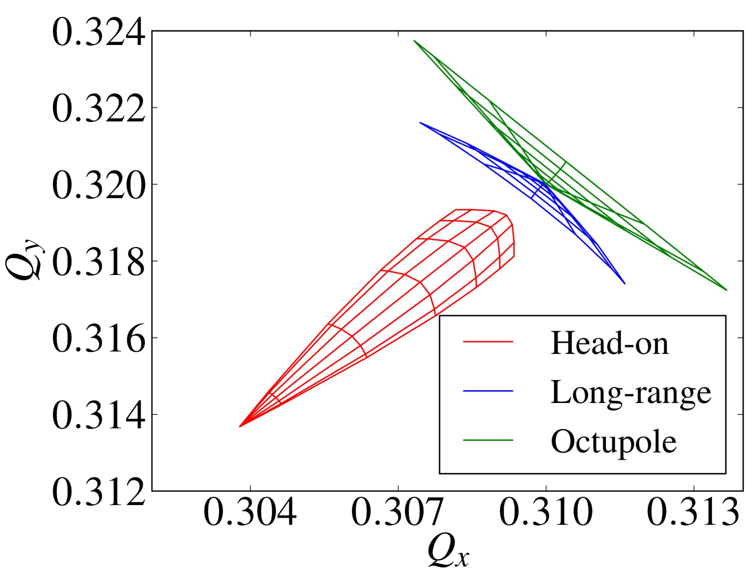

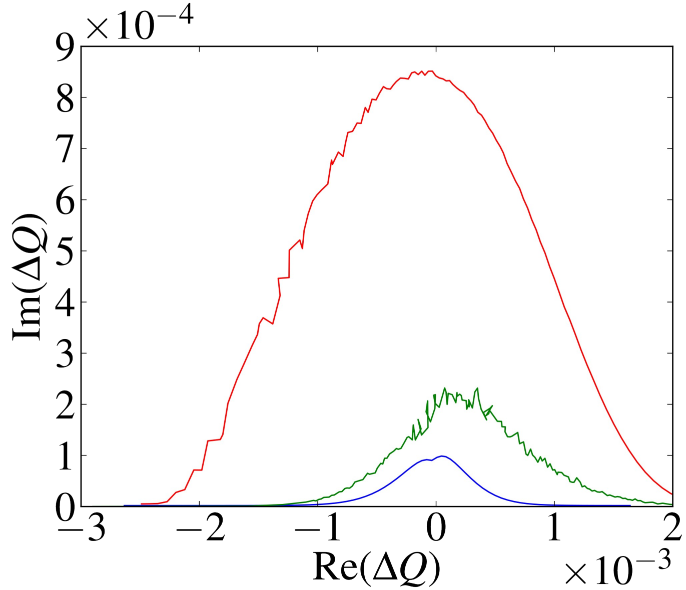

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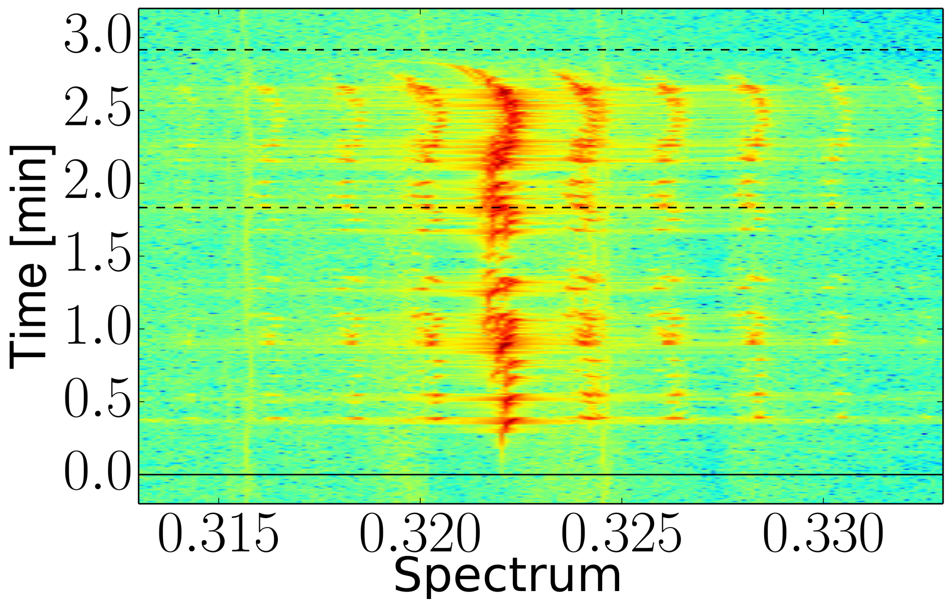

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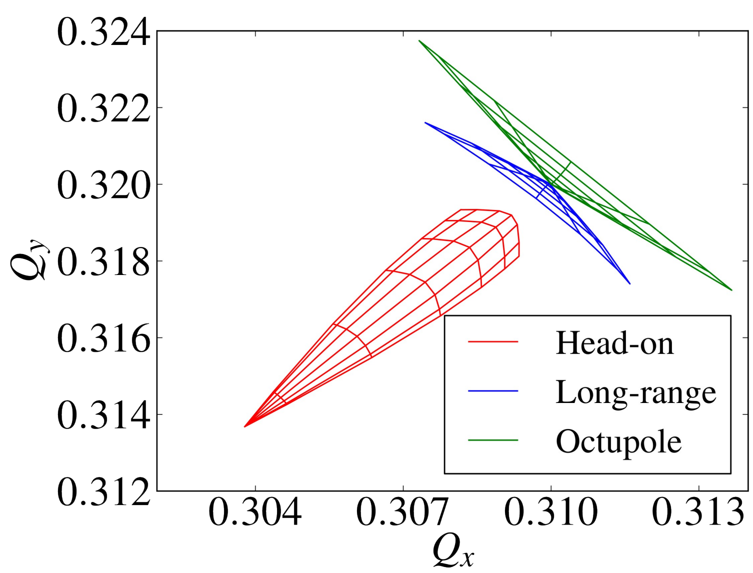

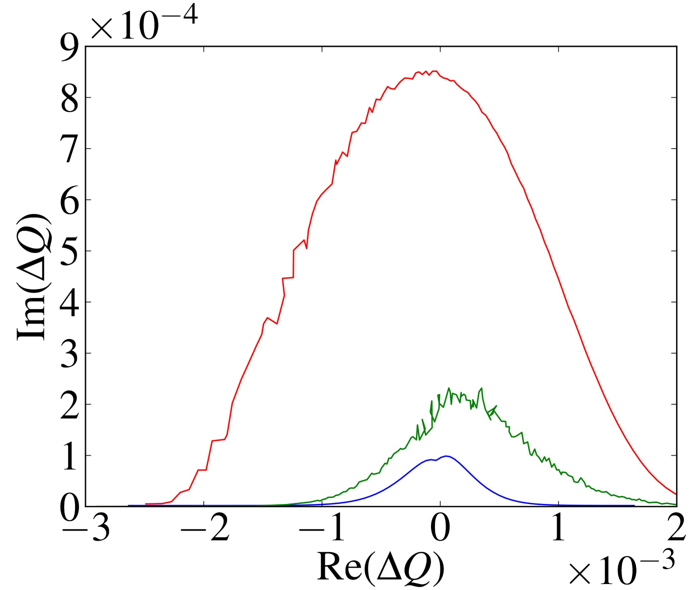

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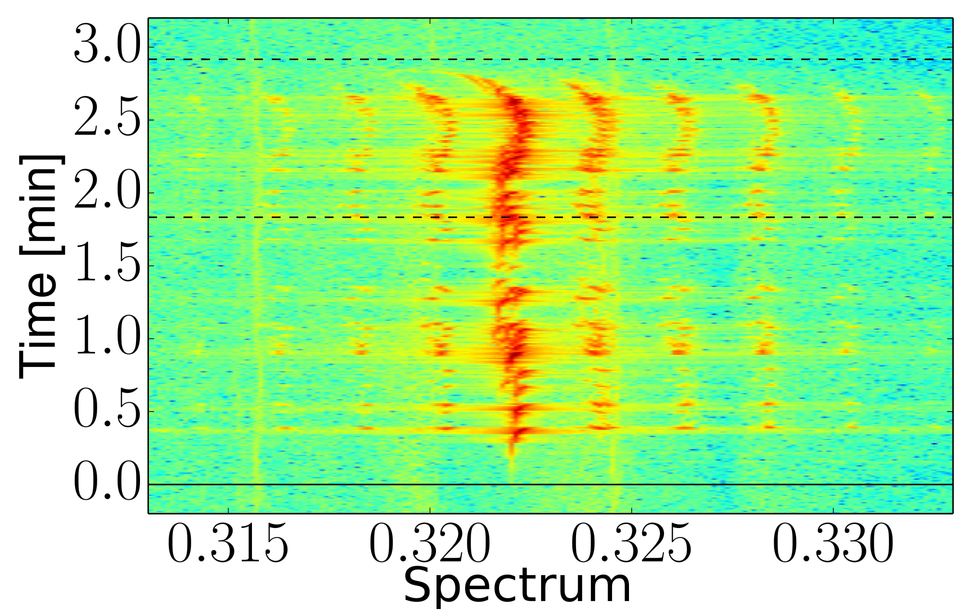

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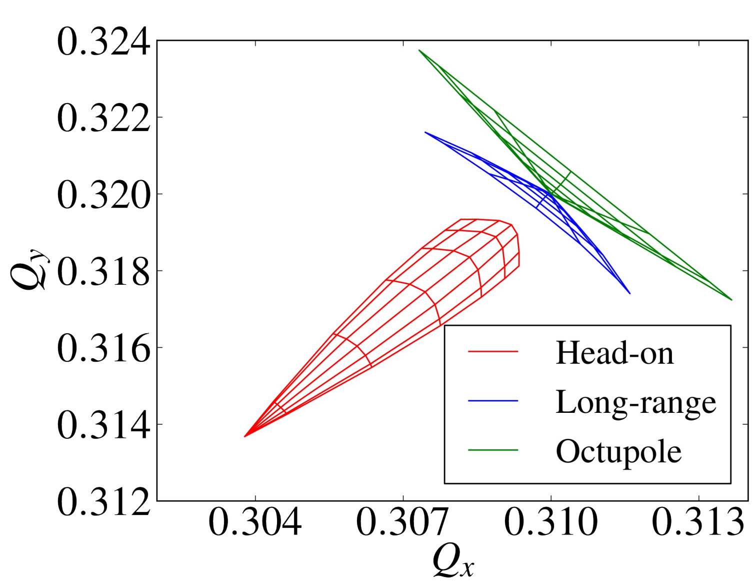

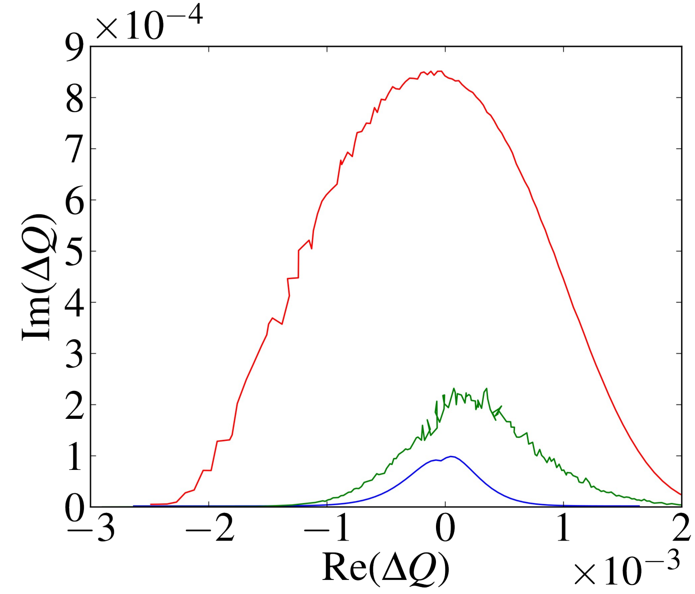

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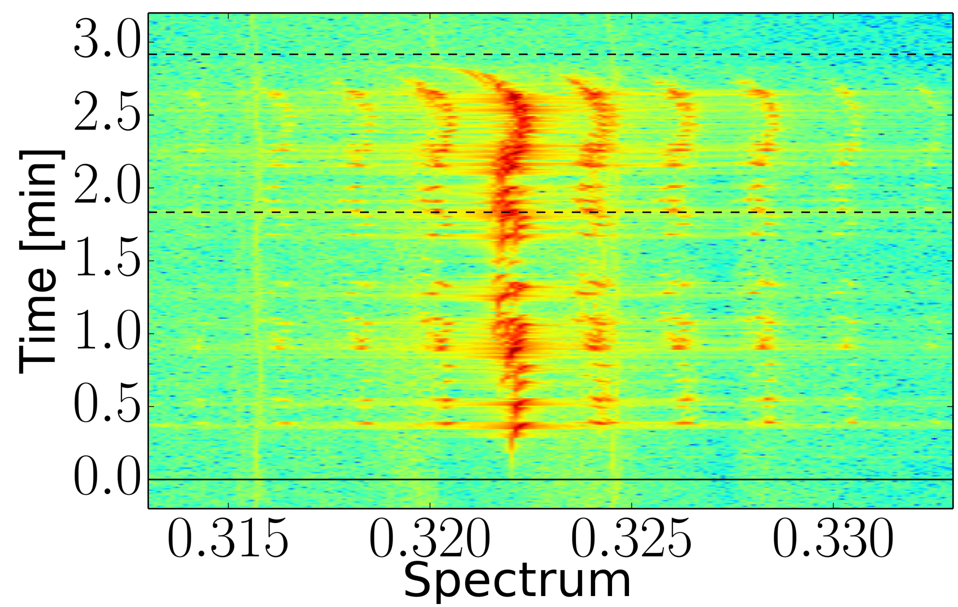

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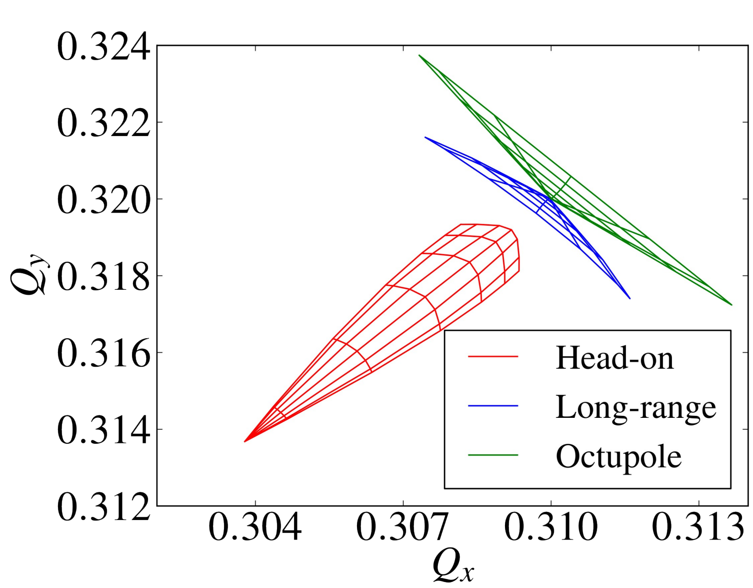

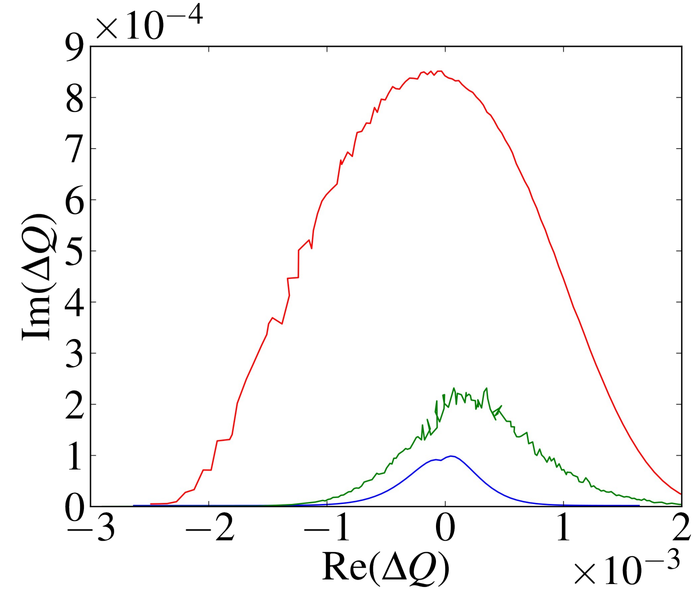

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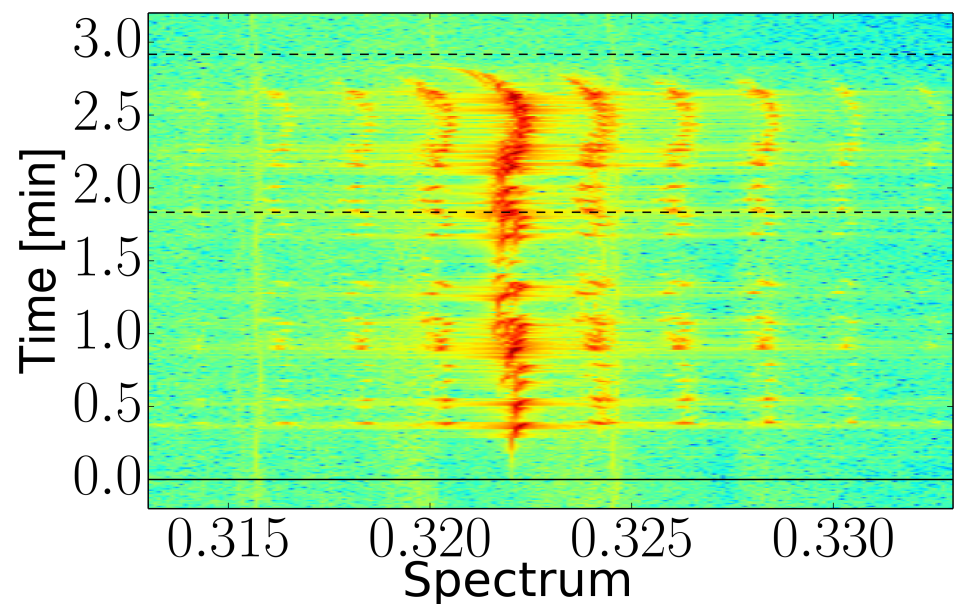
    V. Shiltsev, el al., Phys. Rev. Lett. 119, 134802 (2017)



Observations of instability with offset beams

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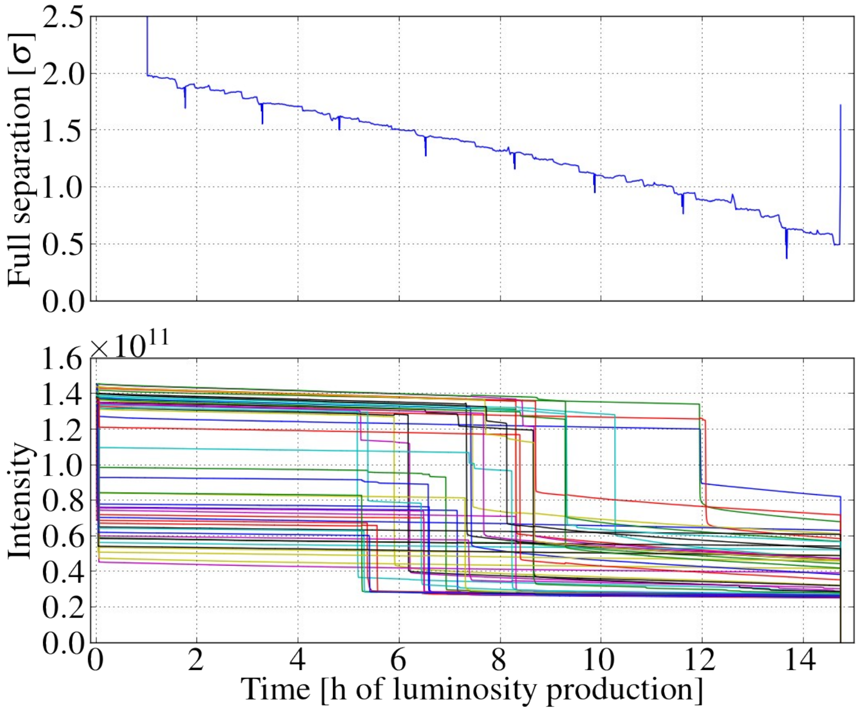

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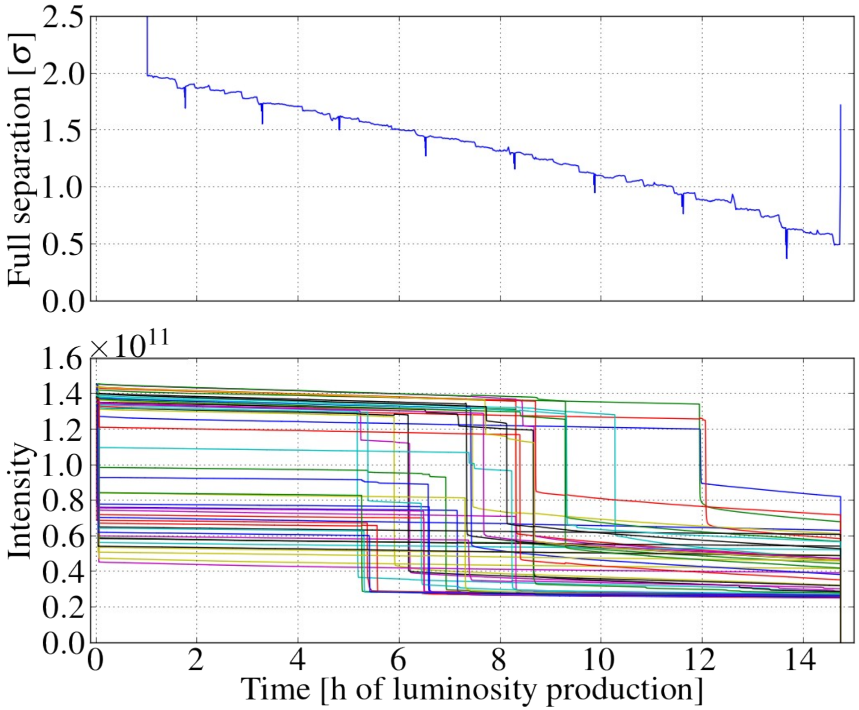

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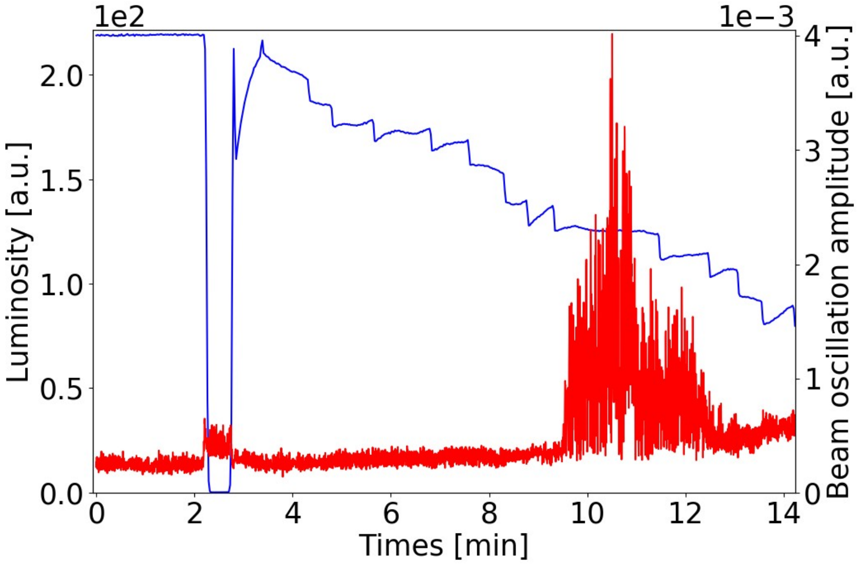

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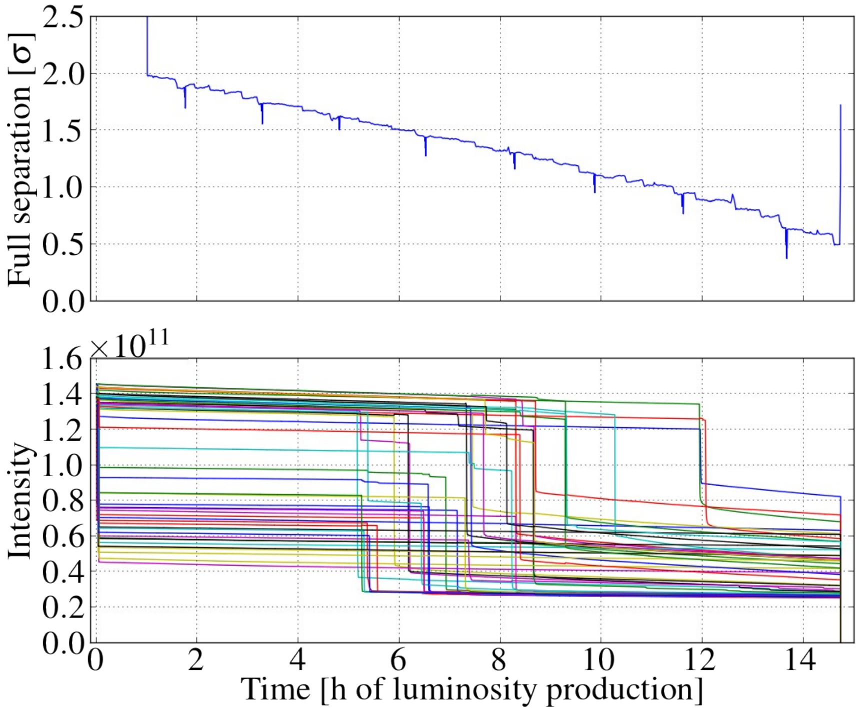

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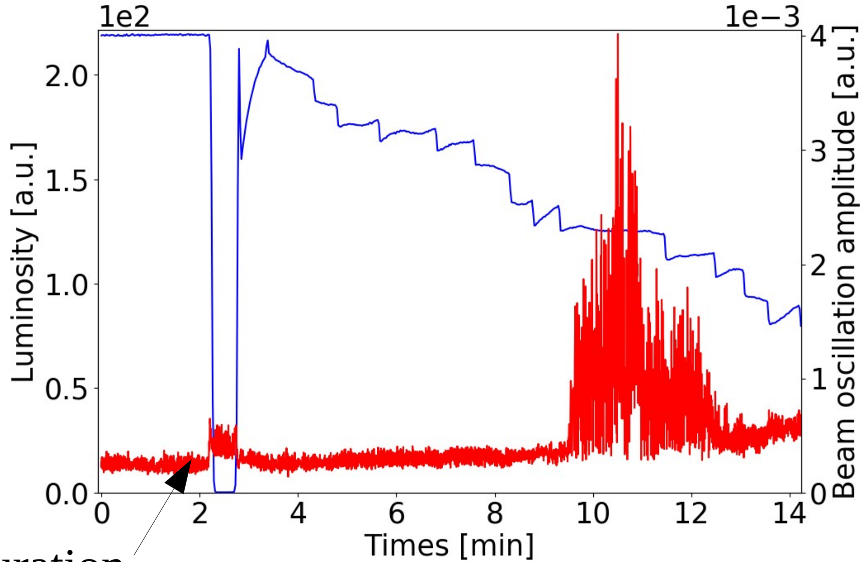

Fast crossing of transient unstable configuration

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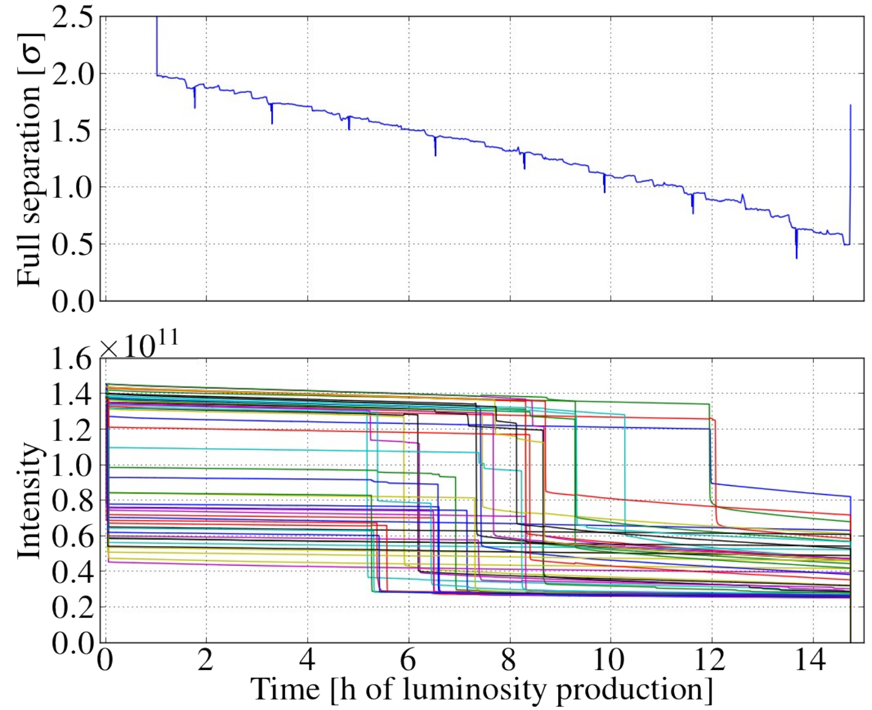

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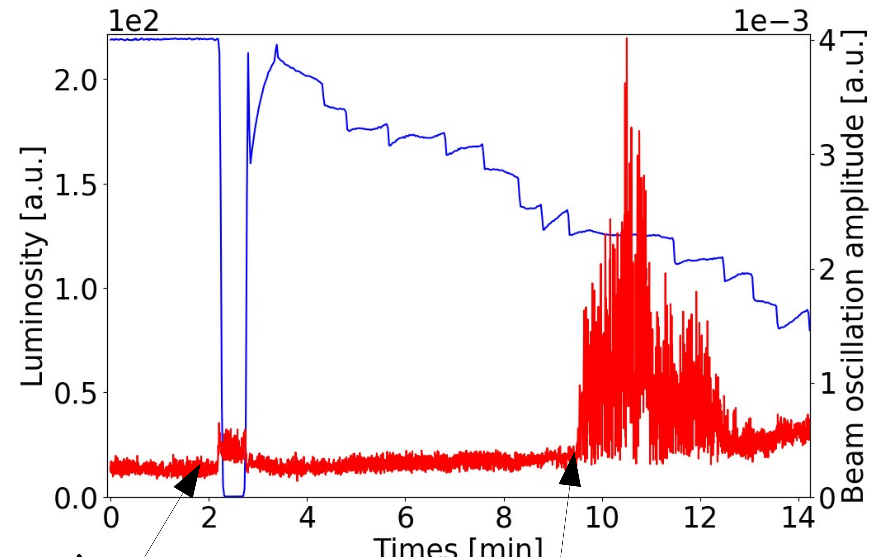

Fast crossing of transient unstable configuration

Instability when steady at 1.6σ full separation between the beams

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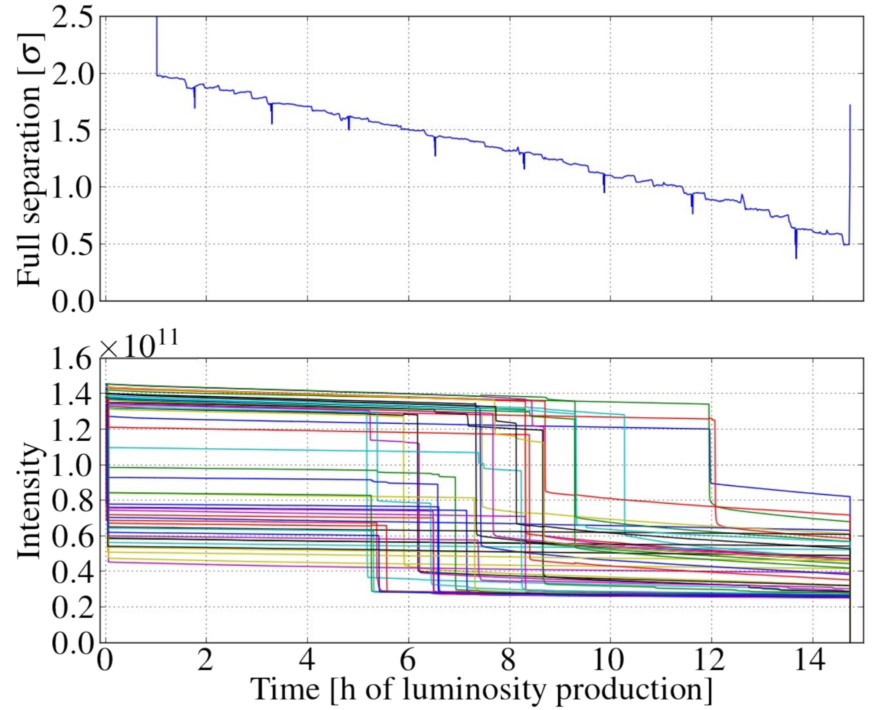
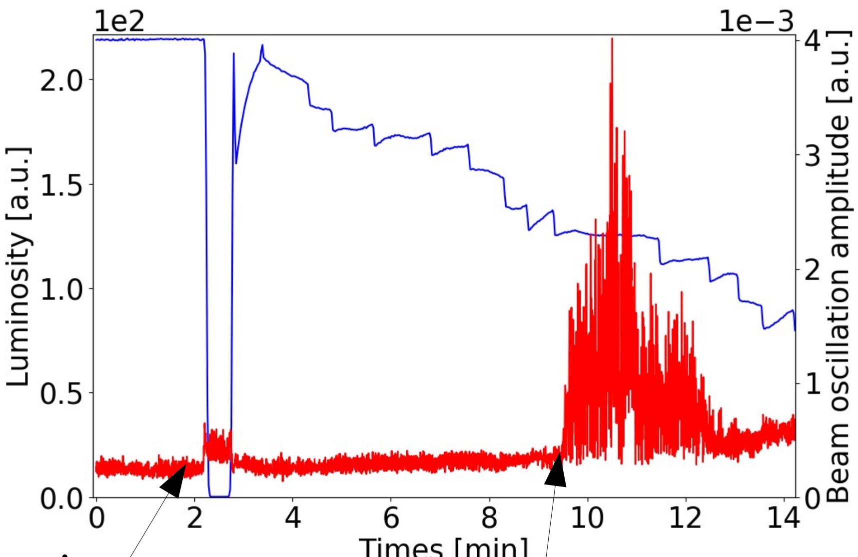


- Dedicated experiment in 2018, demonstrating mitigation by fast crossing of the unstable condition
  S. Fartoukh, et al., CERN-NOTE-2019, in prep.

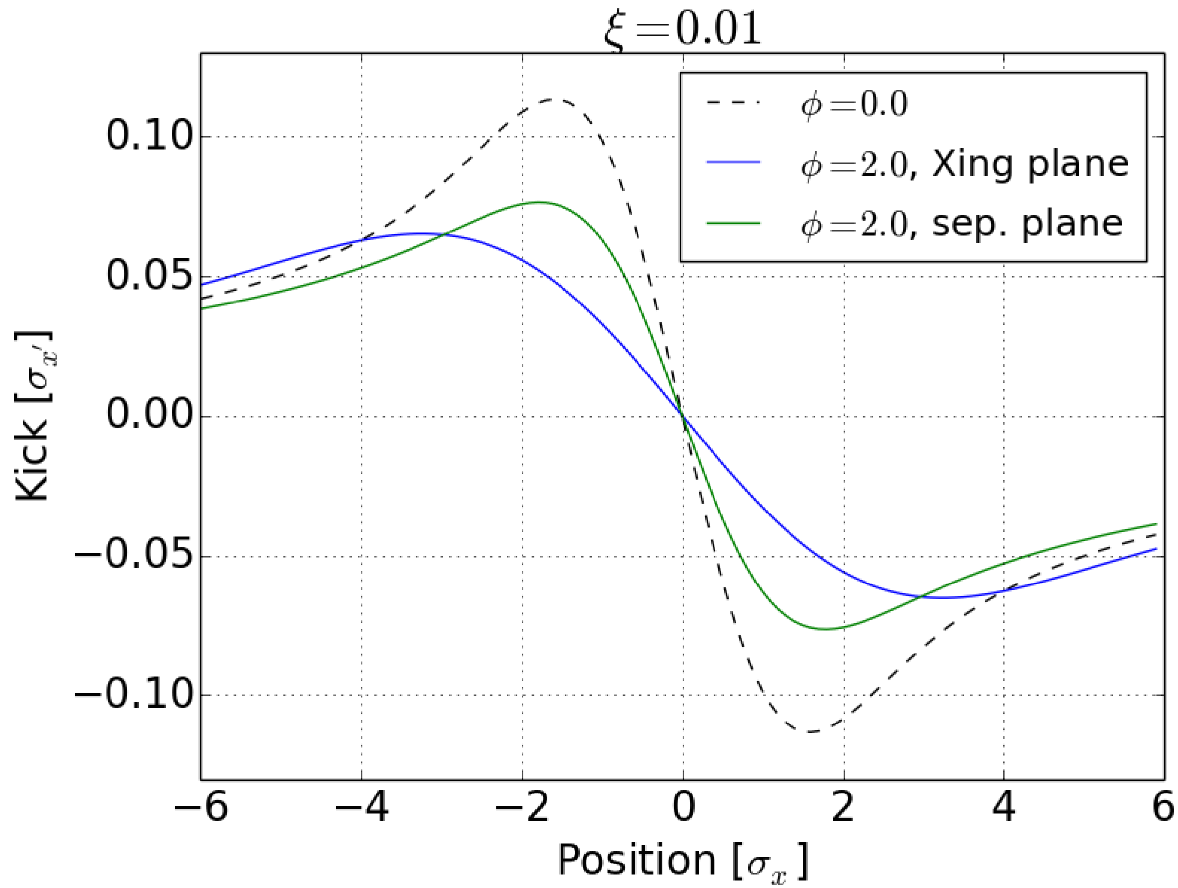
  → This mitigation can work for a standard operational cycle, but it is not suitable for luminosity levelling with an offset



Fast crossing of transient unstable configuration

Instability when steady at 1.6σ full separation between the beams

Beam-beam interaction with a crossing angle



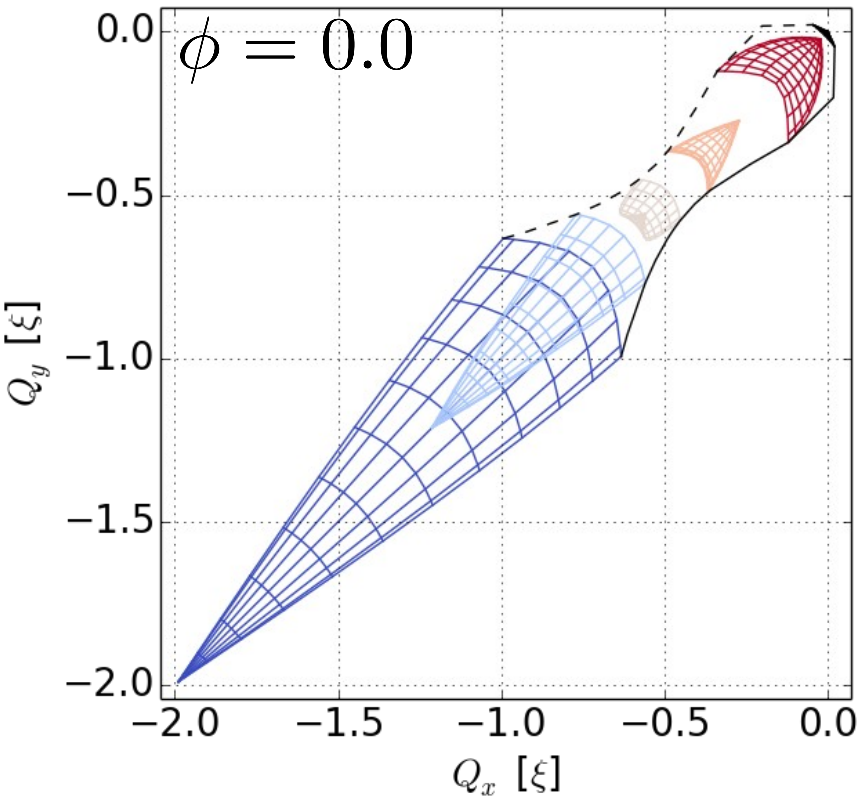
$$\xi = \frac{r_0 N}{4\pi\epsilon_n}$$

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

- 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



- 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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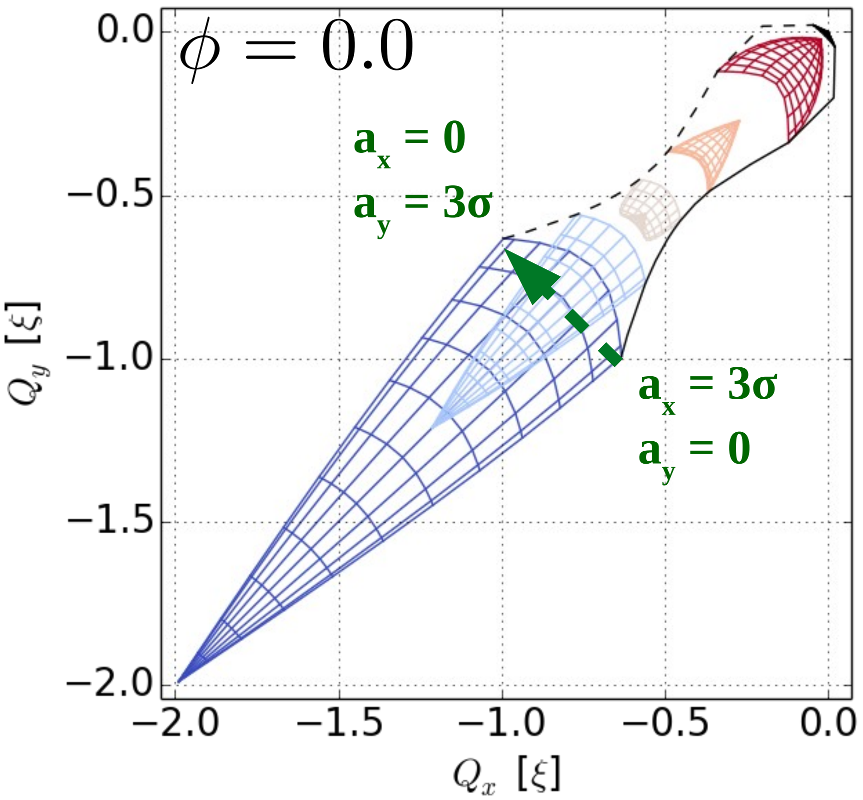

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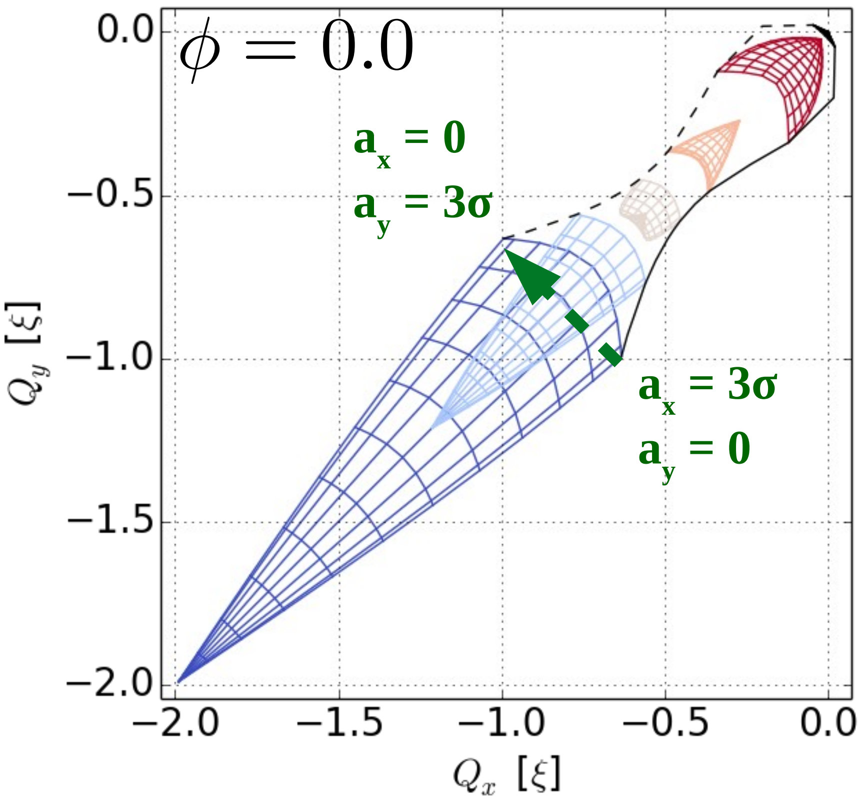

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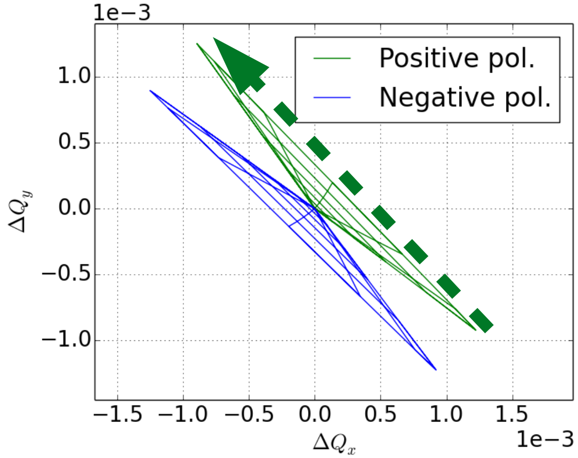

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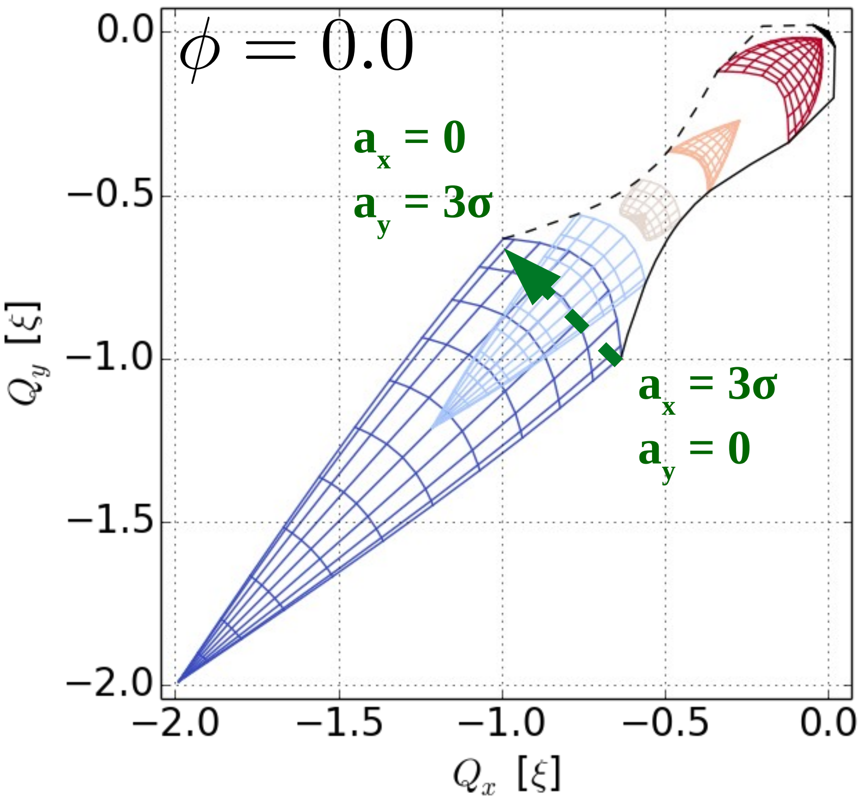

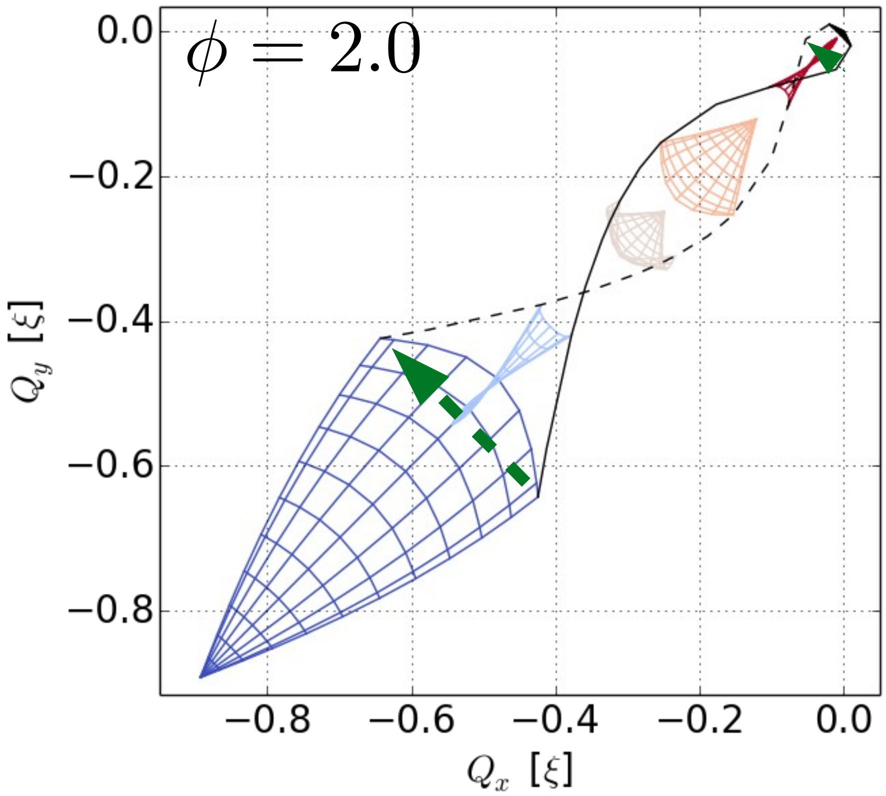

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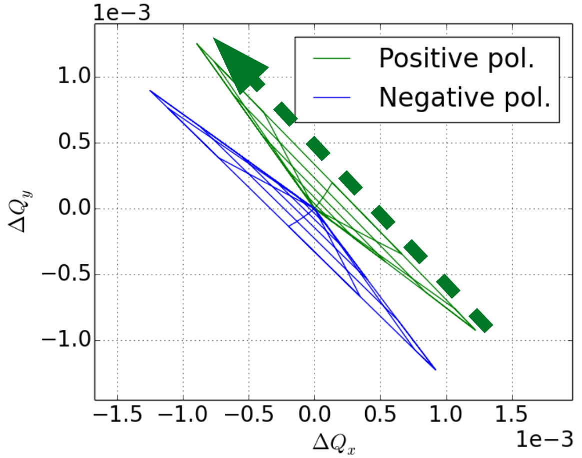
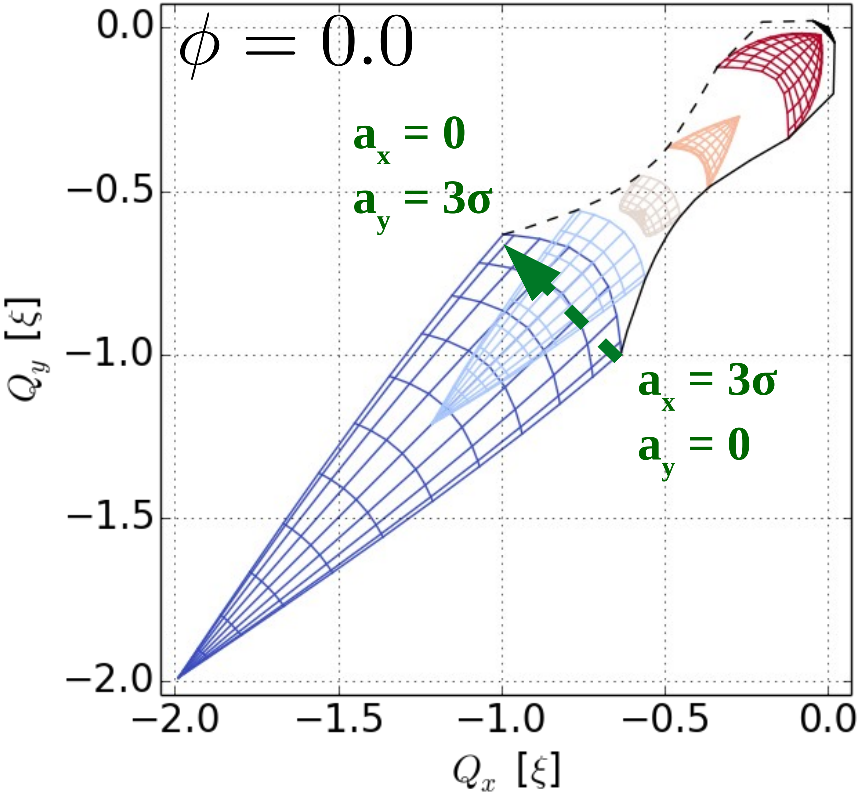
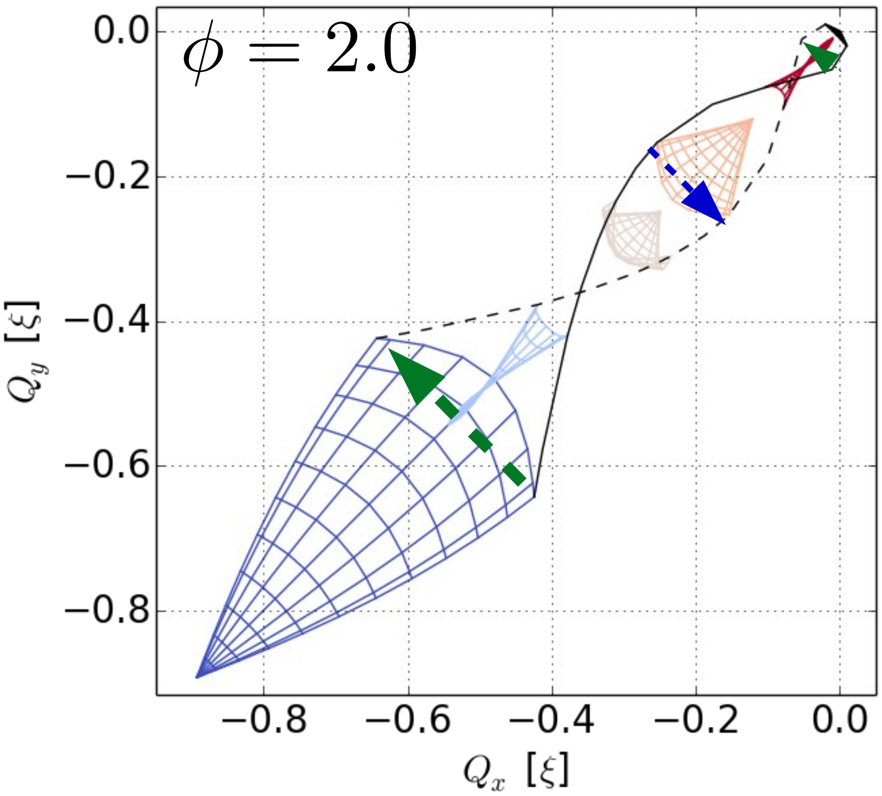


Tune footprint with a crossing angle and an offset

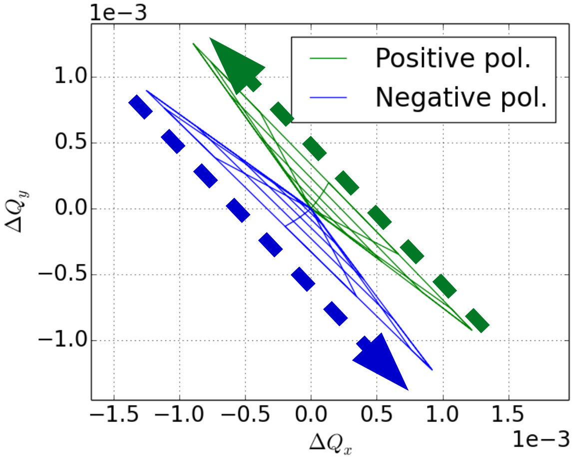
2 IPs with alternating crossing planes



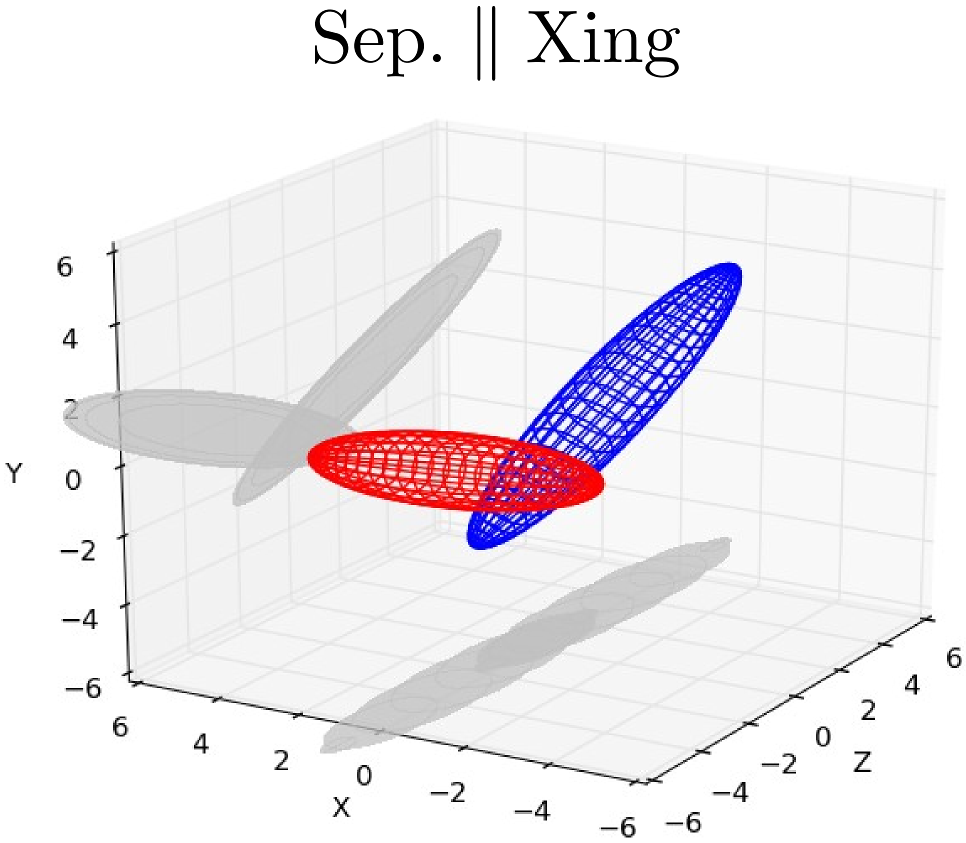


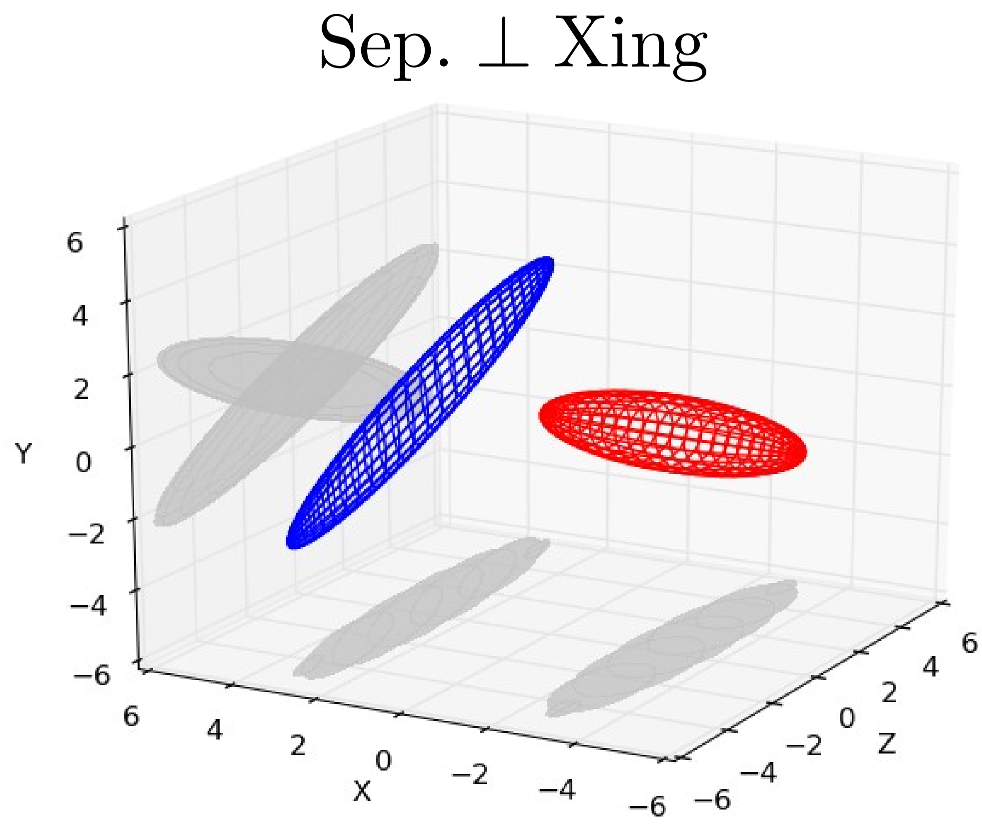
- Without crossing angle, the octupoles setup which generate a positive direct detuning term (the so-called positive polarity) is favourable from long-range to head-on
- With a Piwinski angle larger than 0.8, the positive polarity remains mostly favourable except for separations ~1.5-2σ

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



An effective mitigation





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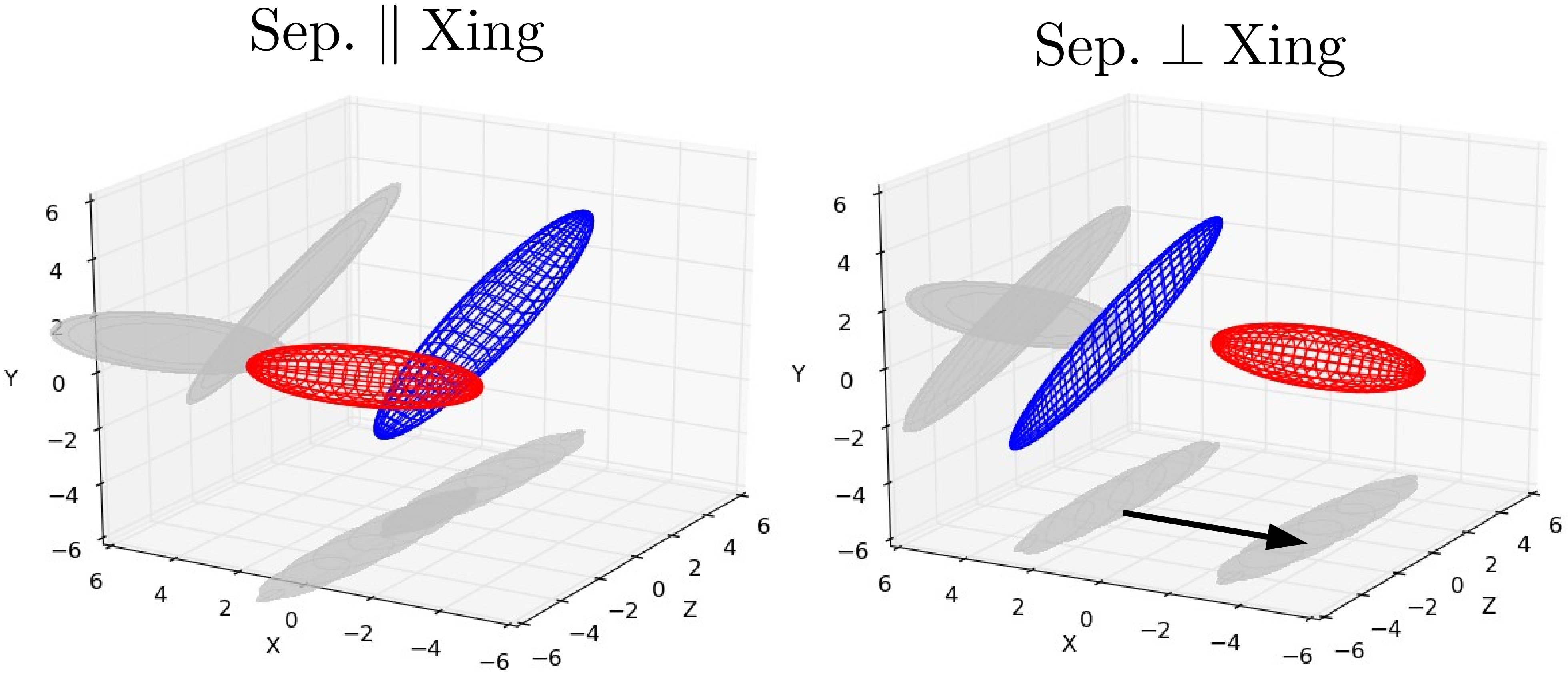
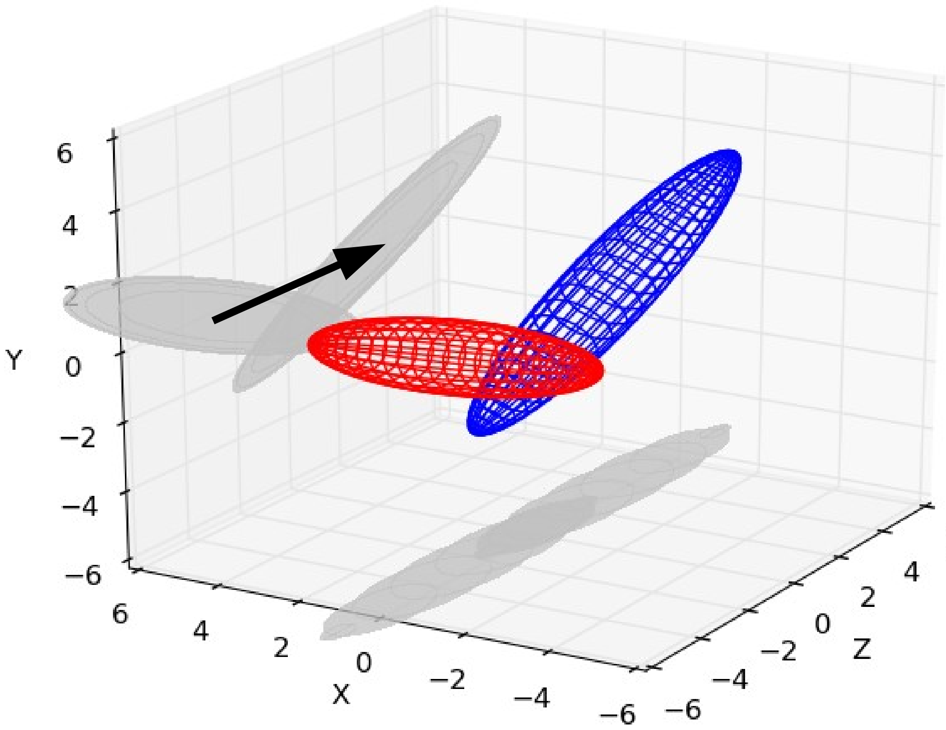
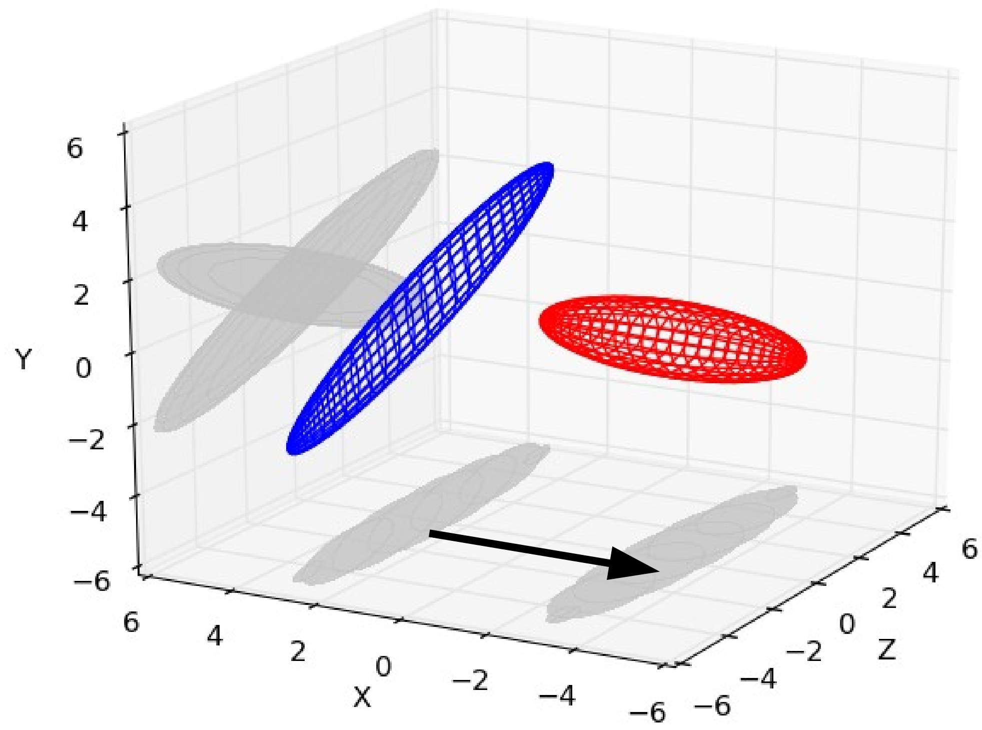


An effective mitigation

Sep. $\parallel$ Xing



Sep. $\perp$ Xing



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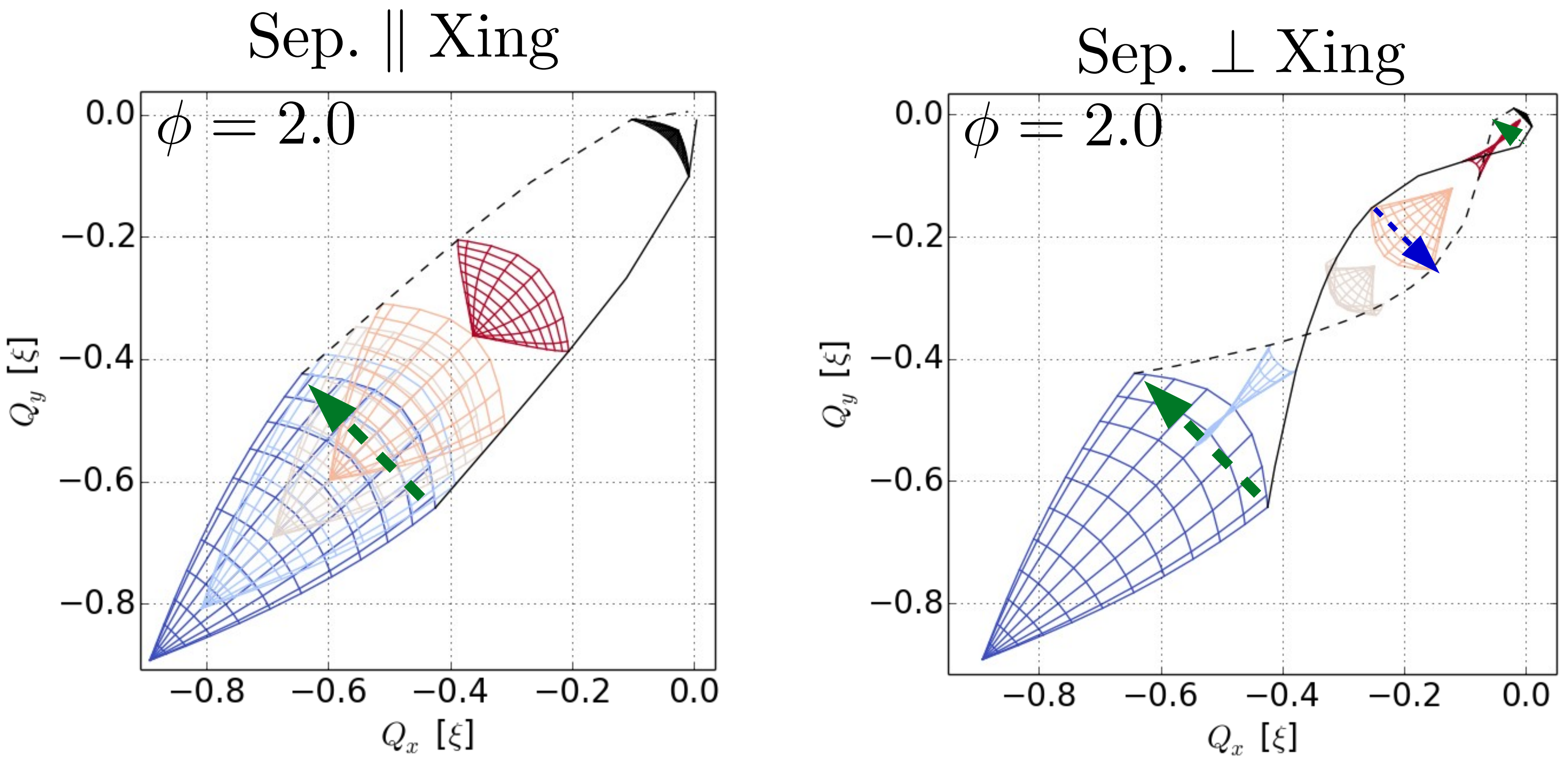
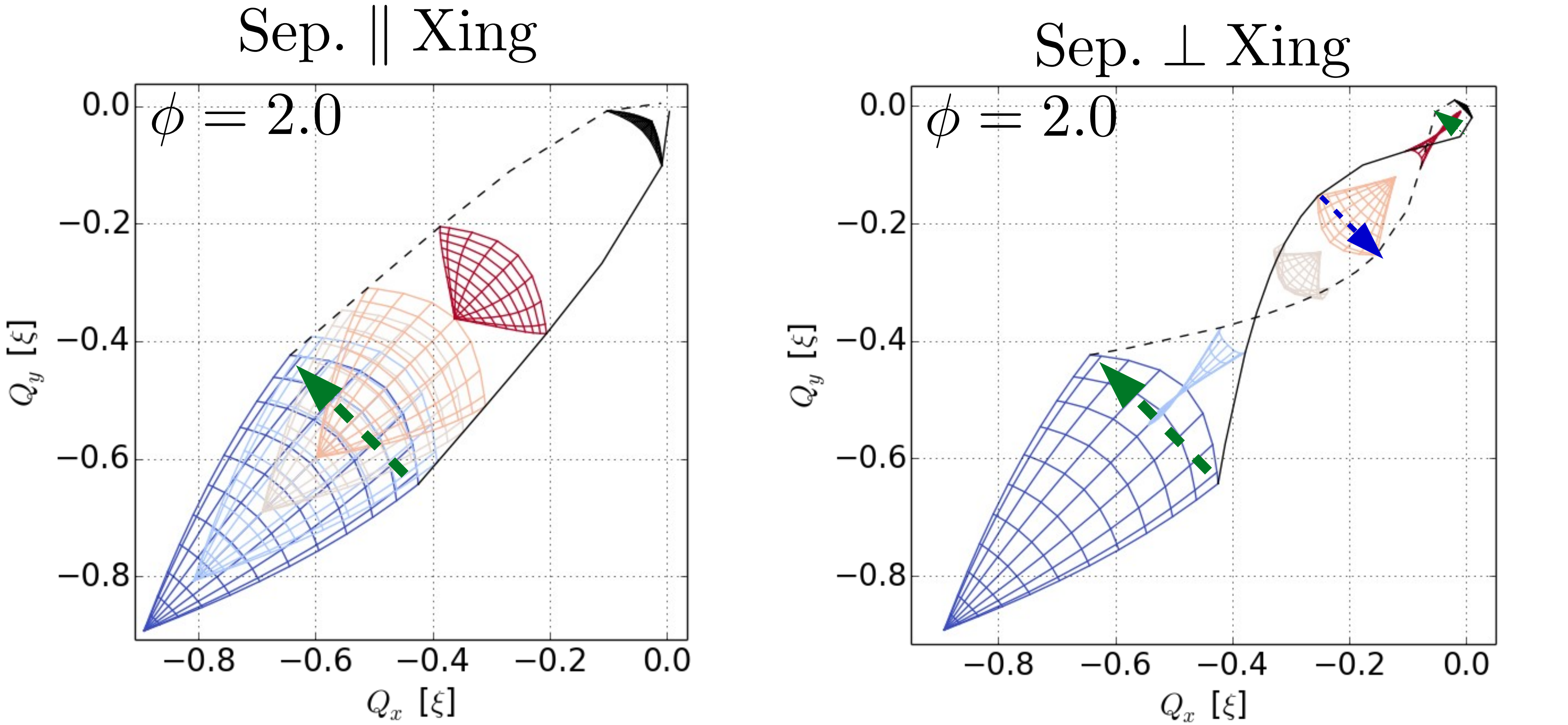


- By introducing a separation bump parallel to the crossing angle bump, instead of perpendicular, the positive polarity of the octupoles remains favourable all along the process

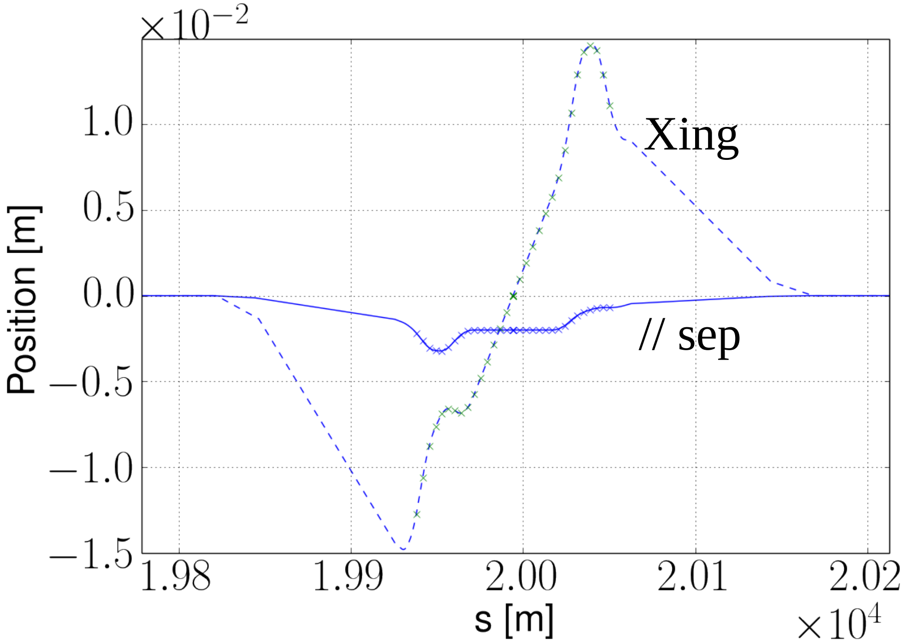
An effective mitigation

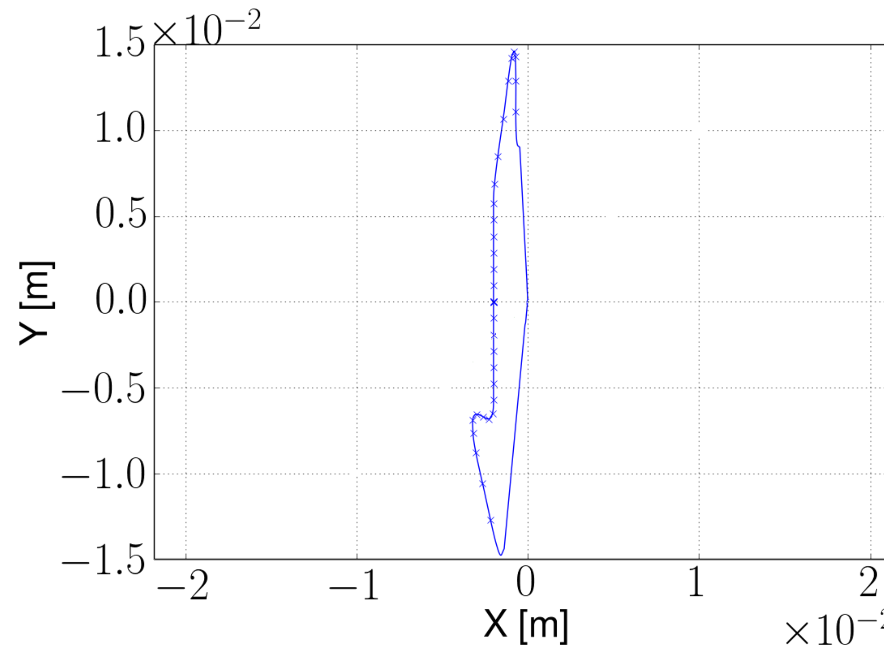


- By introducing a separation bump parallel to the crossing angle bump, instead of perpendicular, the positive polarity of the octupoles remains favourable all along the process

  → 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

Linear coupling due to long-range interactions





- Long-range beam-beam interactions on a skew plane generate coupling and therefore can reduce Landau damping
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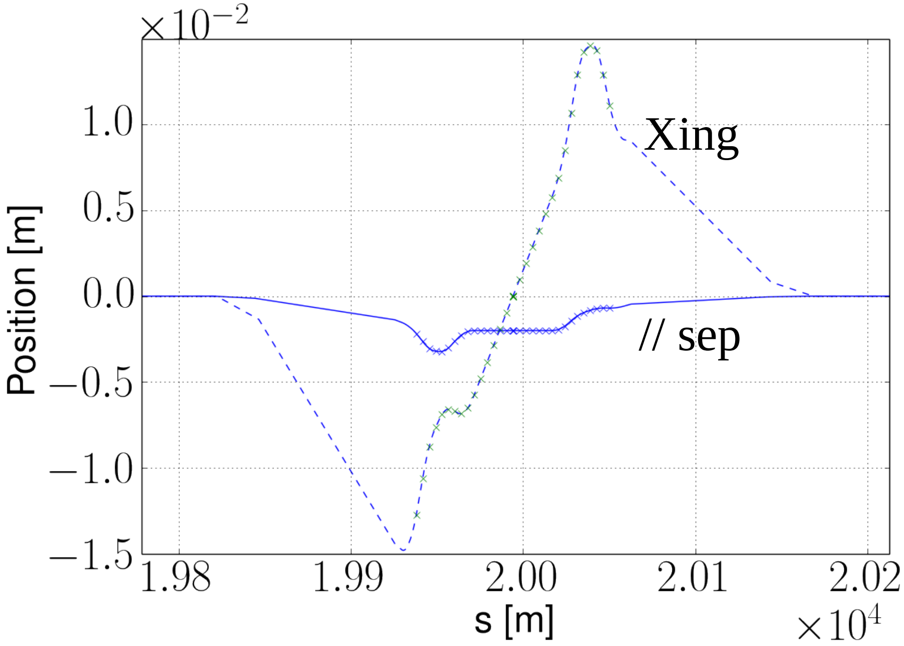
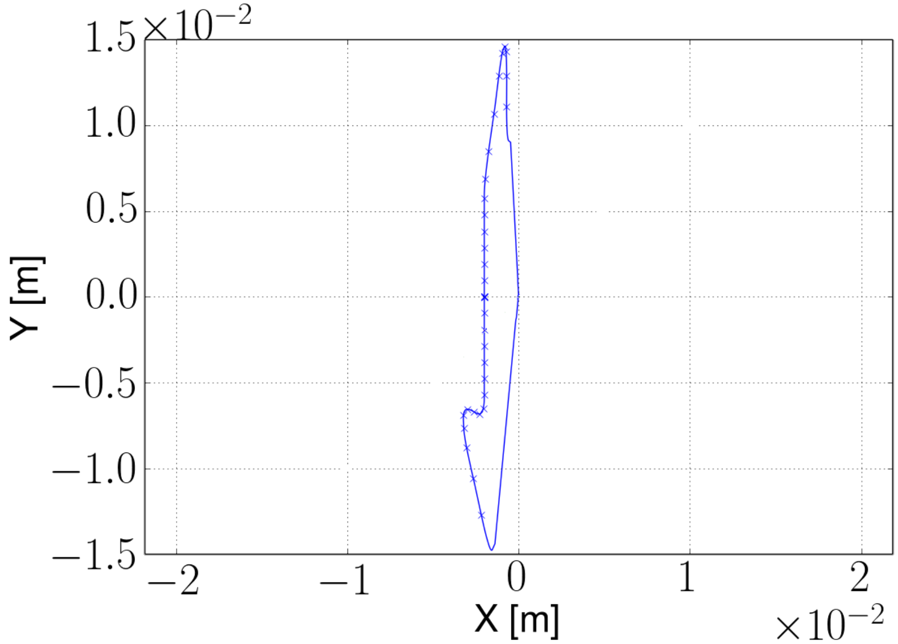
Linear coupling due to long-range interactions





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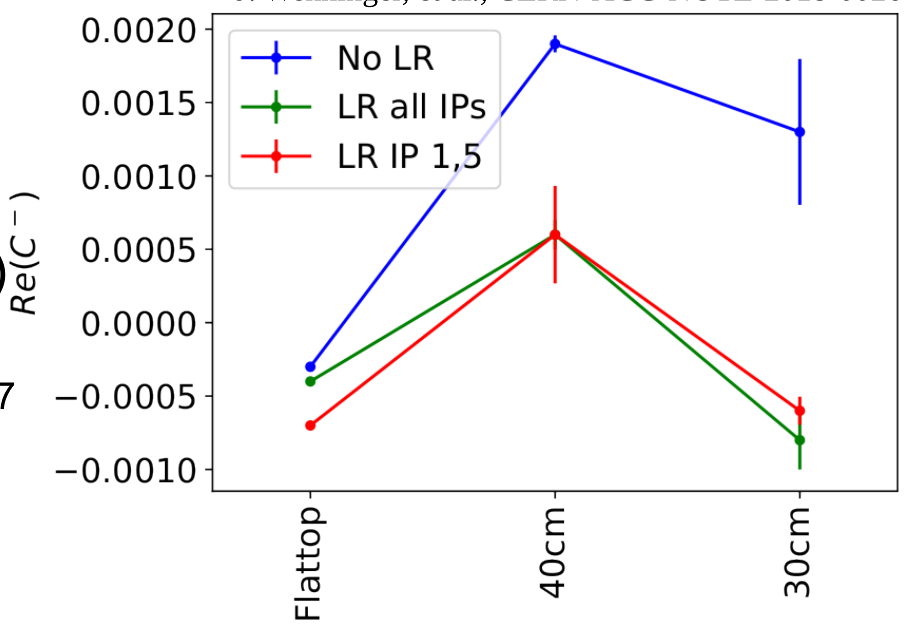
J. Wenninger, et al., CERN-ACC-NOTE-2018-0026



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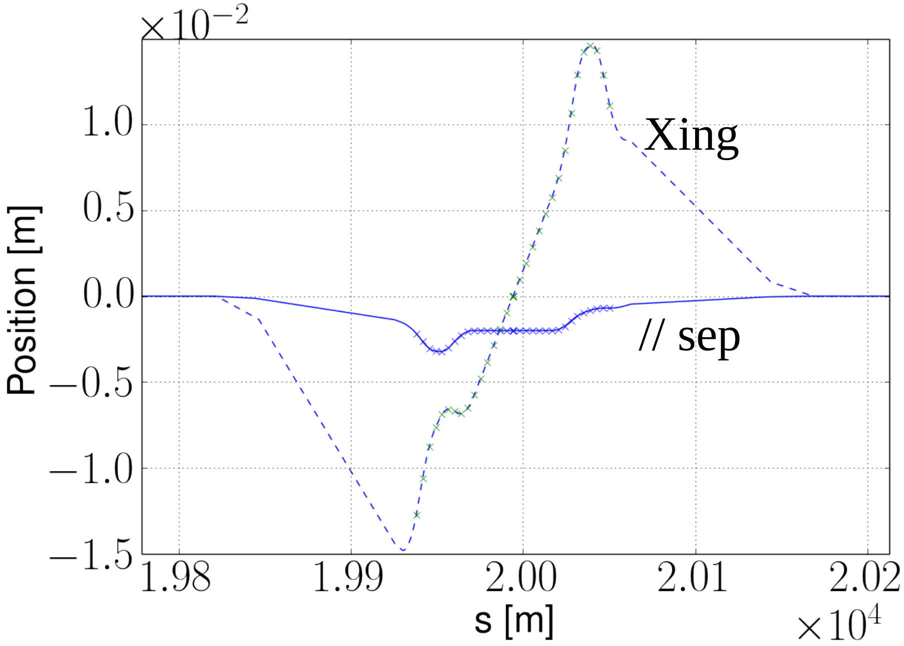

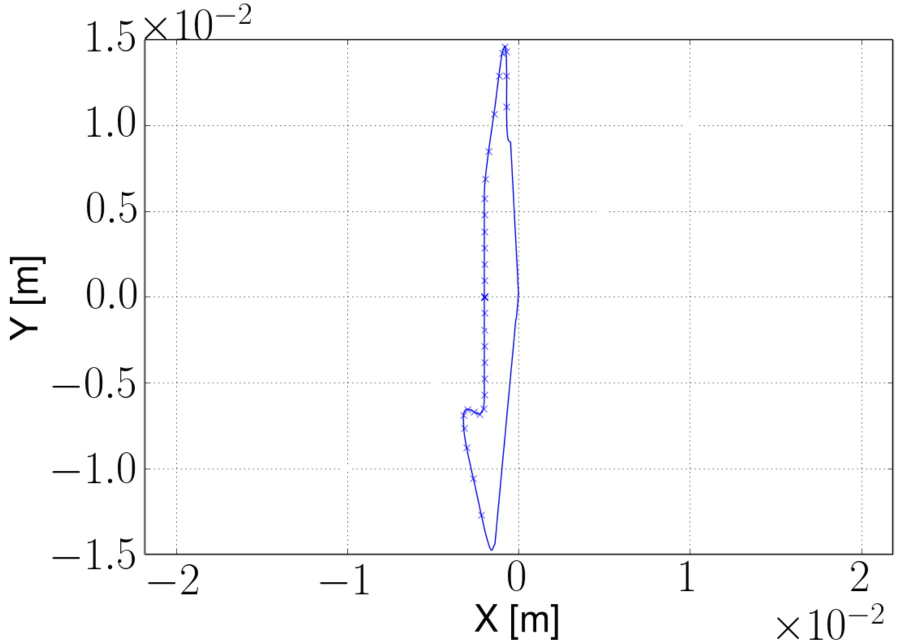

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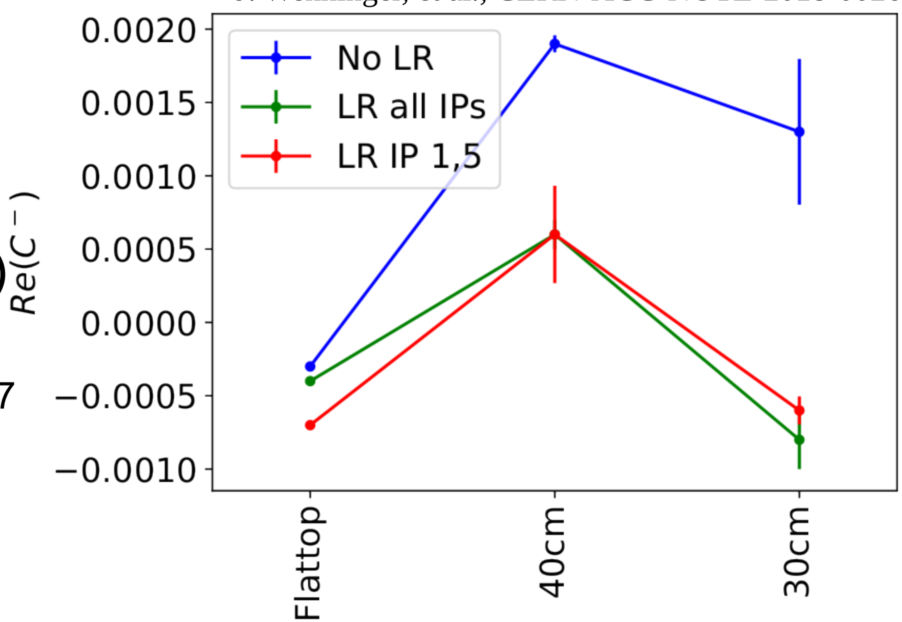
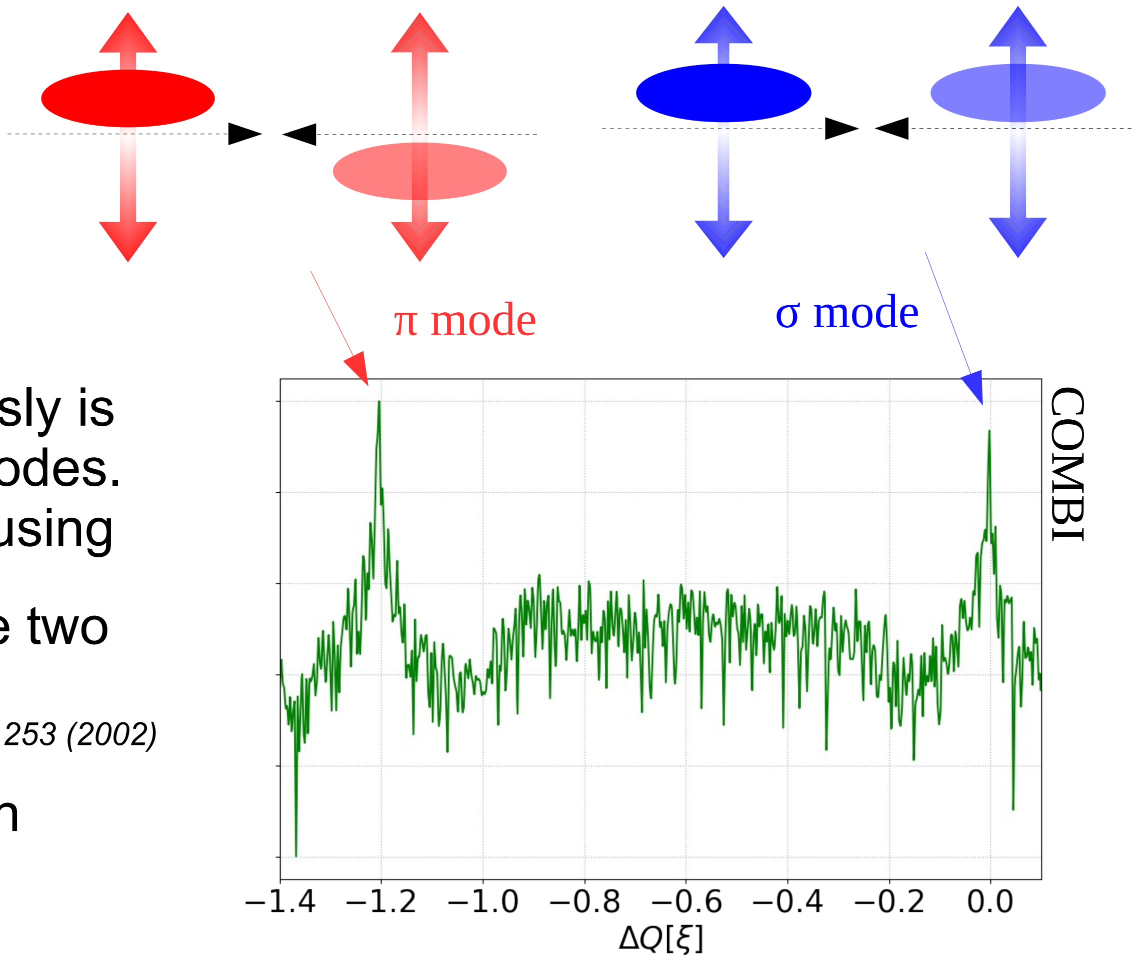
- The mitigation of this issue is based on tight control of the orbit in the interaction region

J. Wenninger, et al., CERN-ACC-NOTE-2018-0026



Coherent beam-beam modes

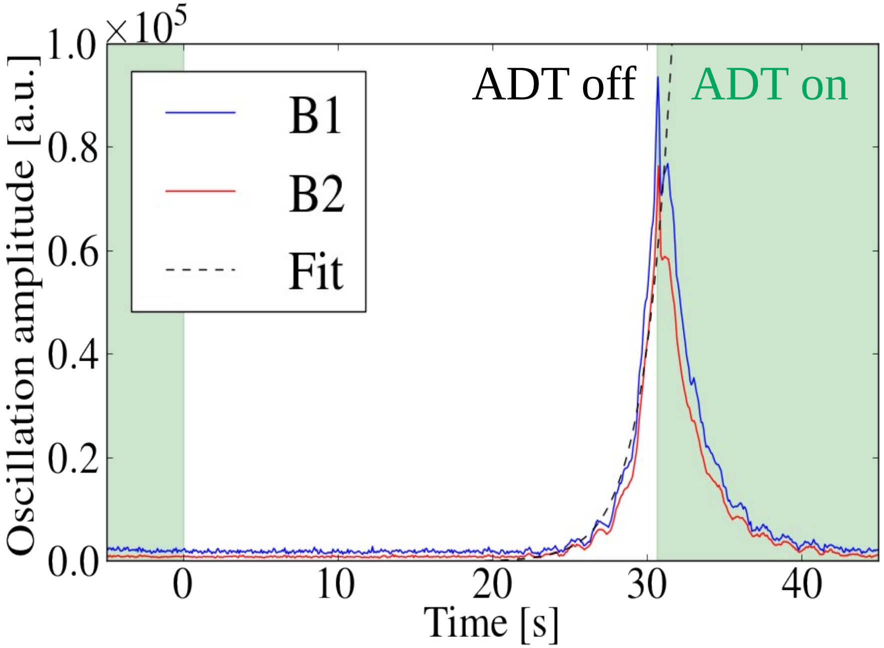
- If we now consider the oscillation of the two beams consistently, we find new modes of oscillation
  K. Yokoya and H. Koiso, Part. Acc. 27, 181 (1990)



- The dispersion integral used previously is not valid for coherent beam-beam modes. Landau damping can be addressed using
  - Coupled Vlasov equations for the two beams
    Y. Alexahin, Nucl. Instrum. Methods Phys. Res. A 480, 253 (2002)
  - Macro-particle tracking simulation
    COMBI, BeamBeam3D

- The interaction of coherent beam-beam mode with the machine impedance can result in strong mode coupling instabilities
  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)

Mode coupling instability of colliding beams



- As predicted by the models, experimentally it could be verified in the LHC that:
  - The transverse feedback is effective against this instability
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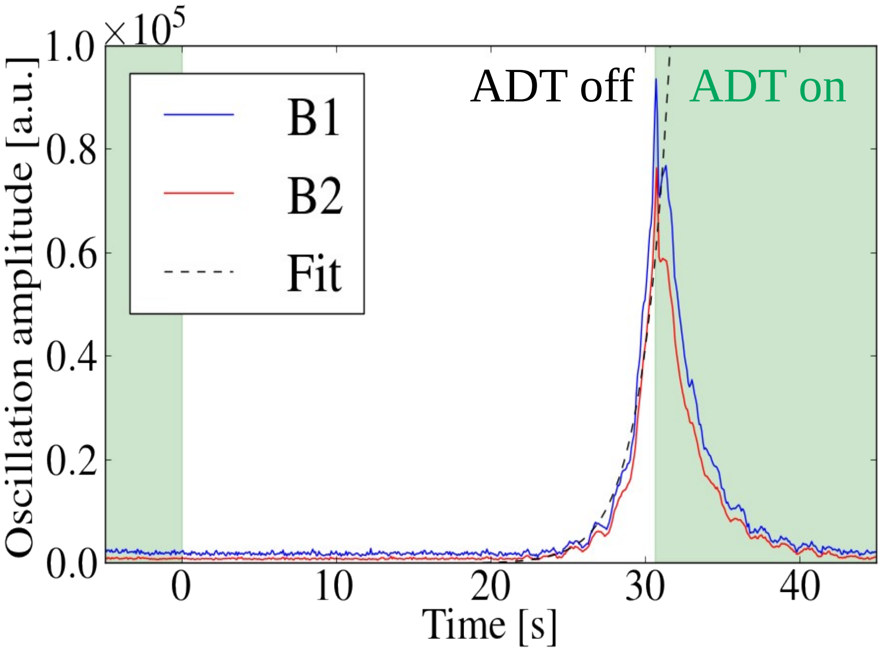

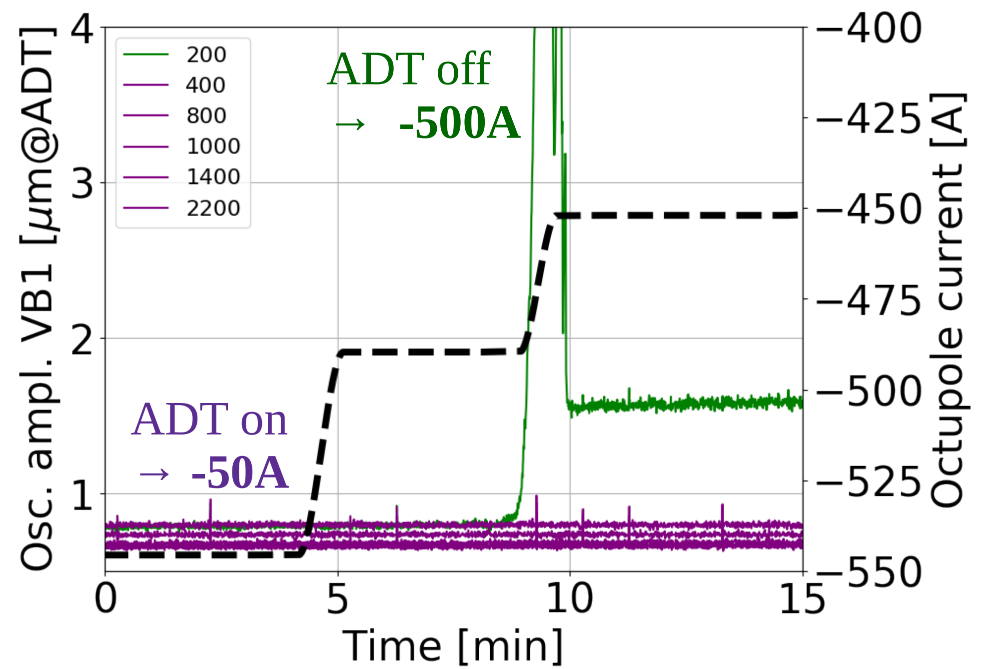

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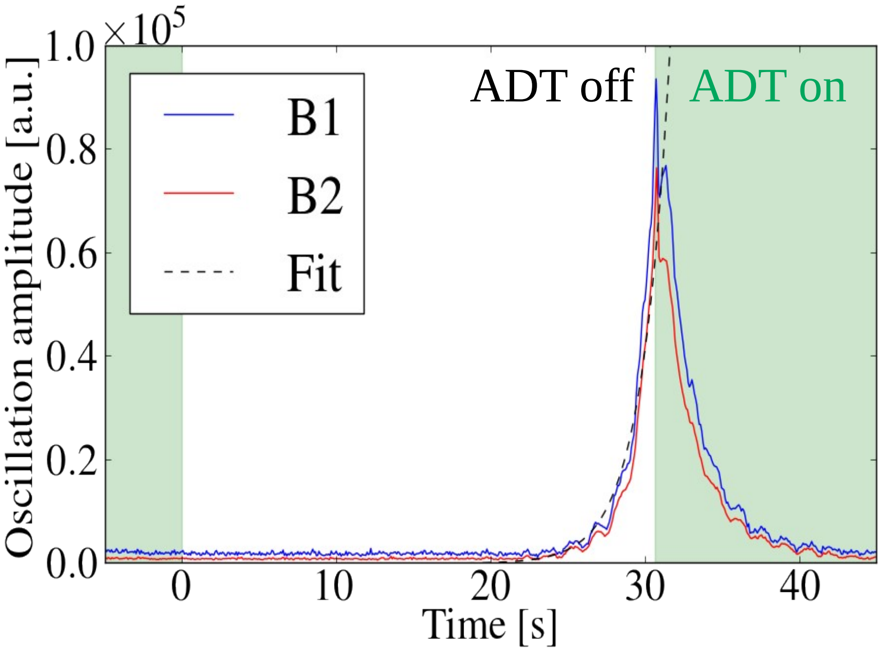

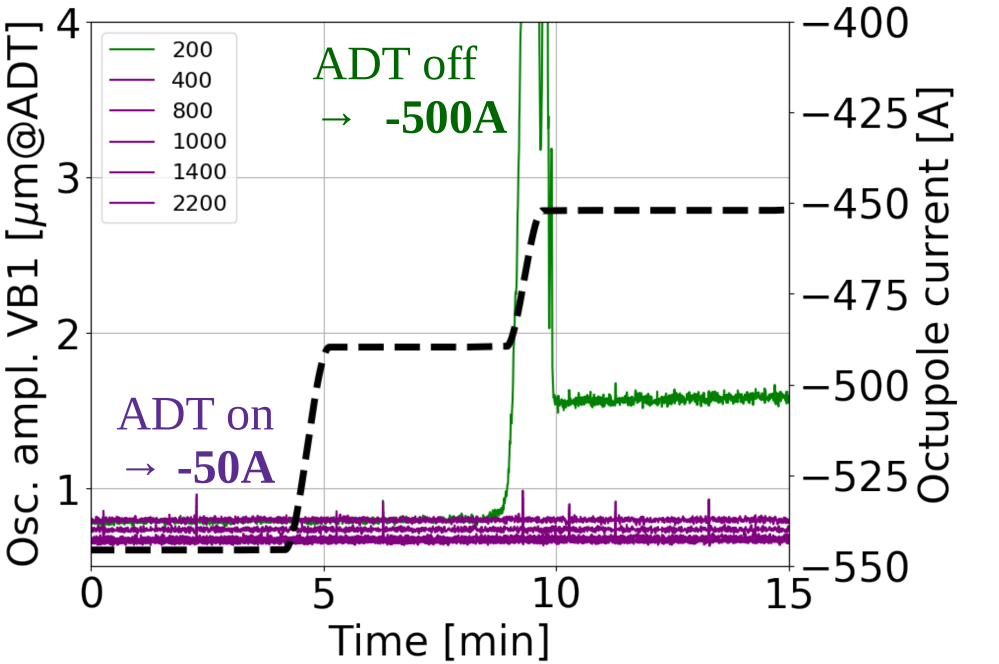

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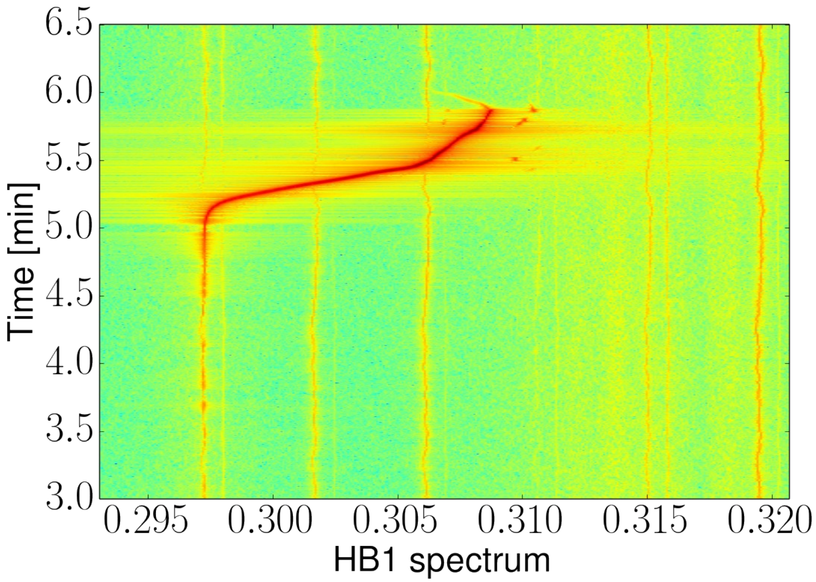

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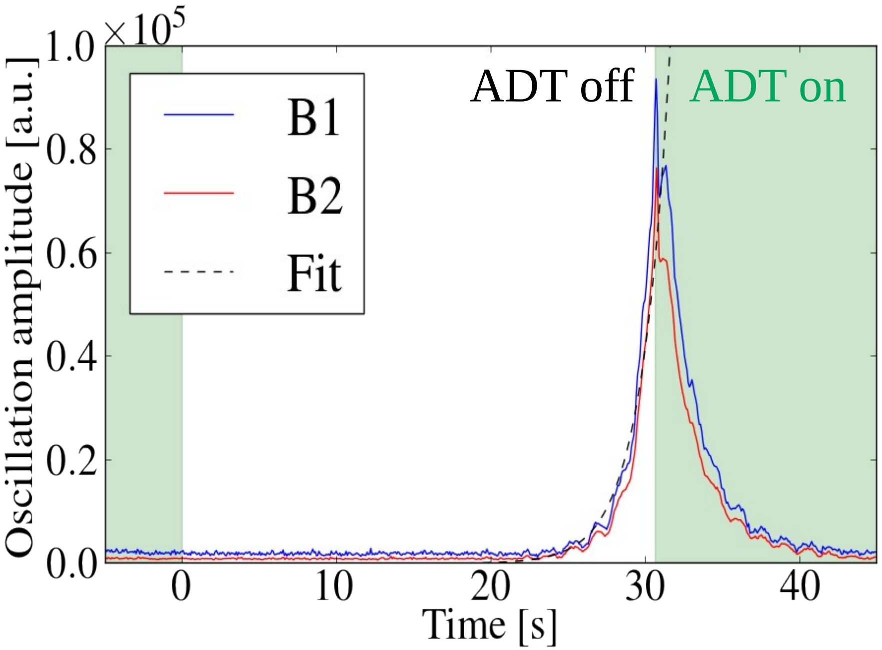

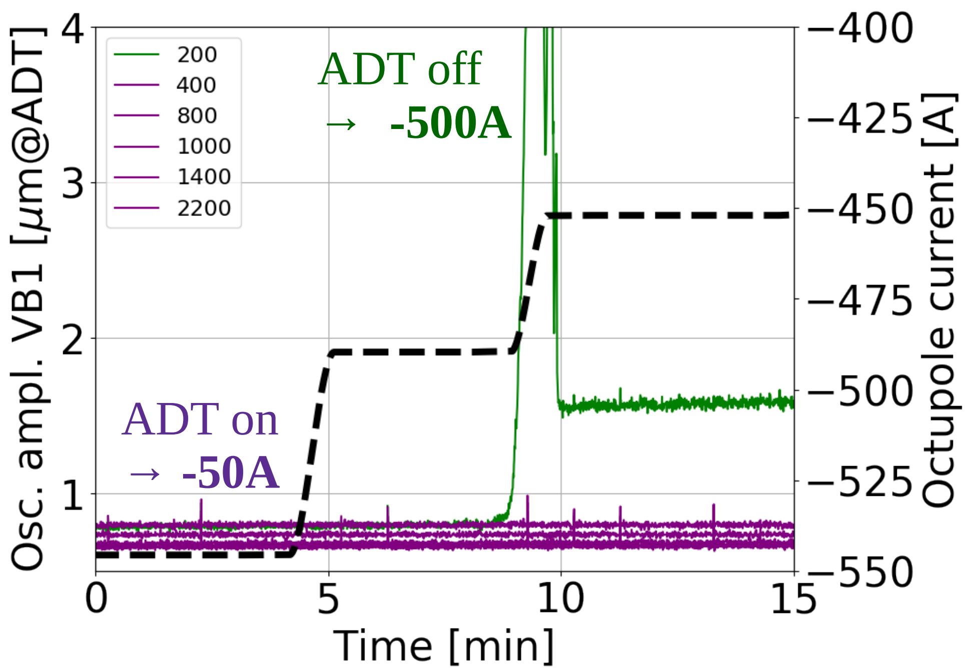

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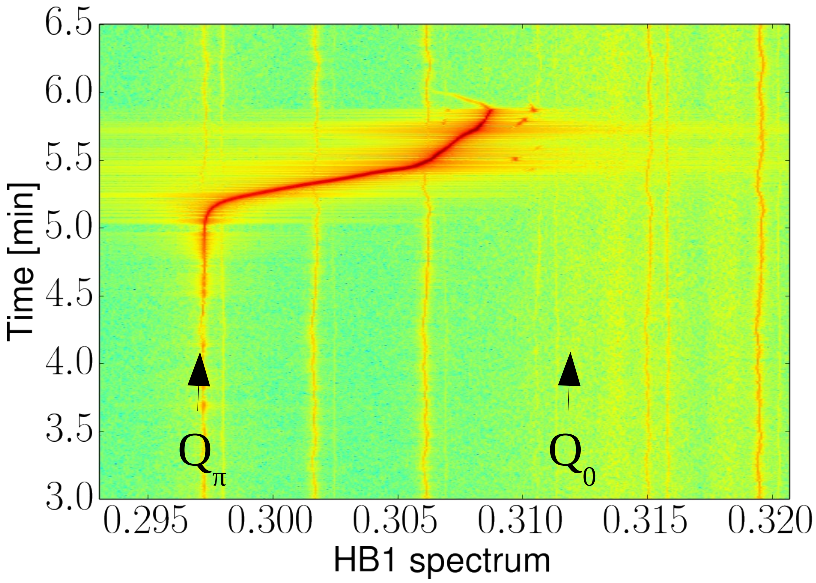
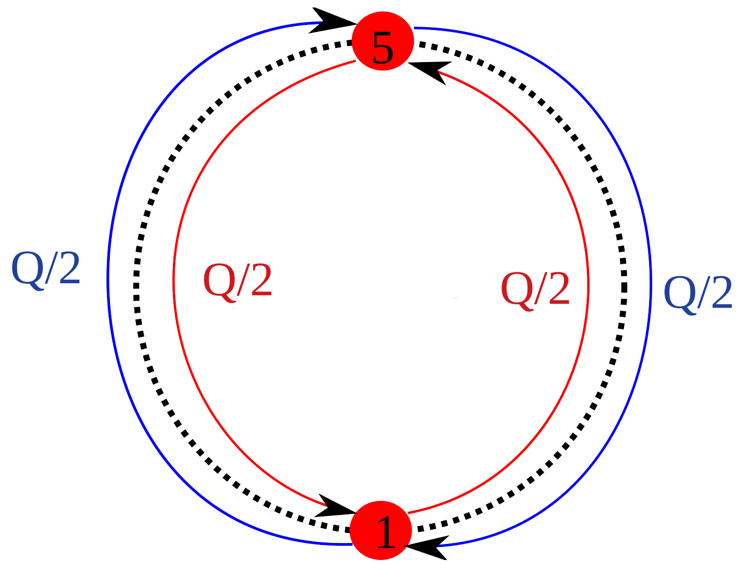
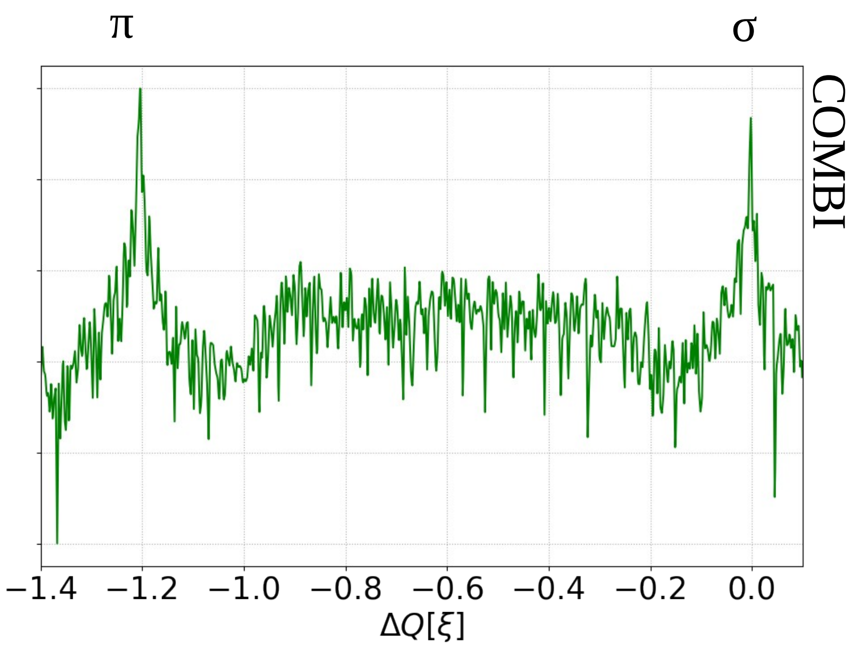


Coherent beam-beam modes





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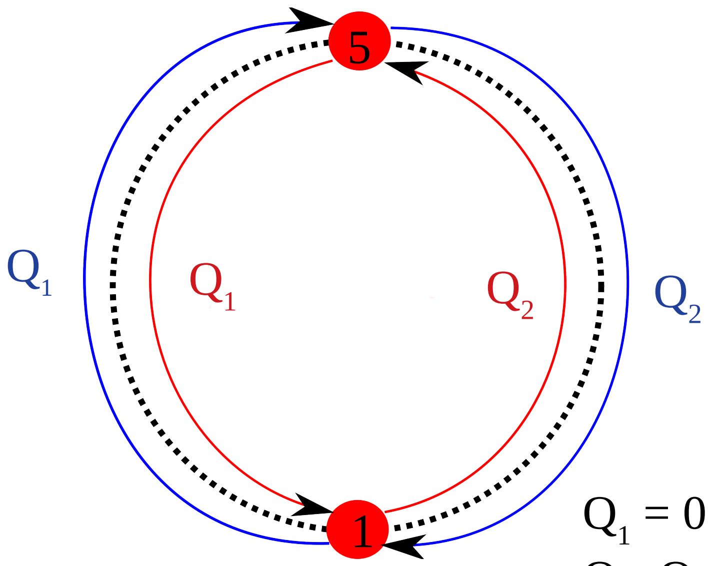
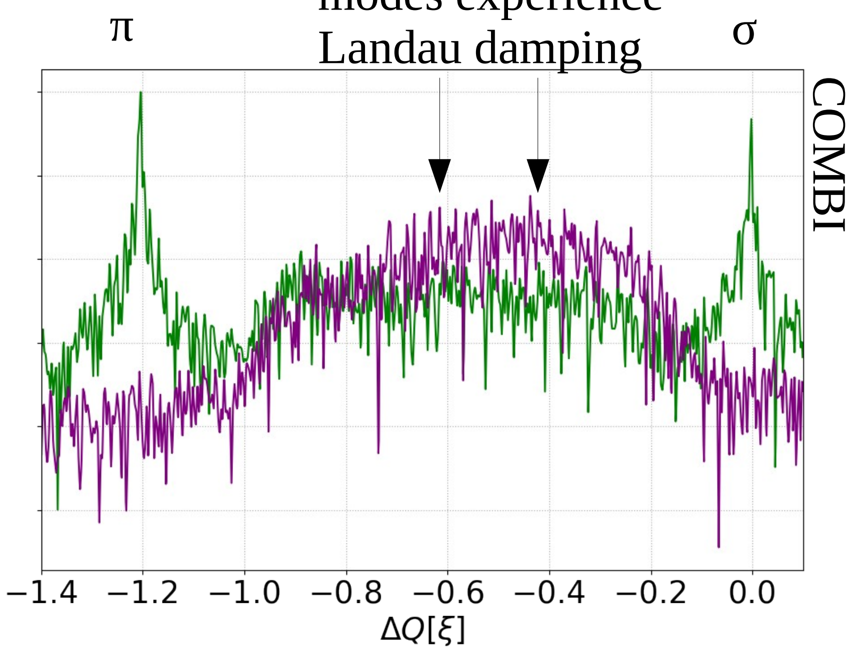


$Q_1 = 0.405$, $Q_2 = 0.905$

$Q_1 + Q_2 = Q$

Expected coherent modes experience Landau damping



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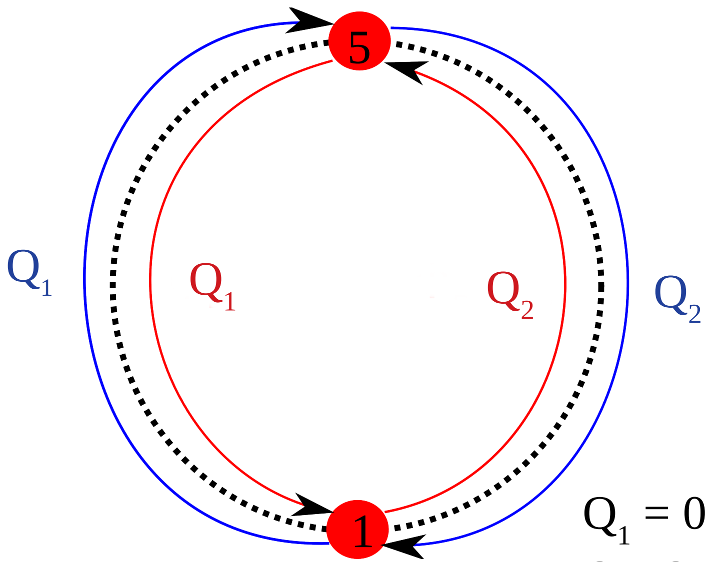

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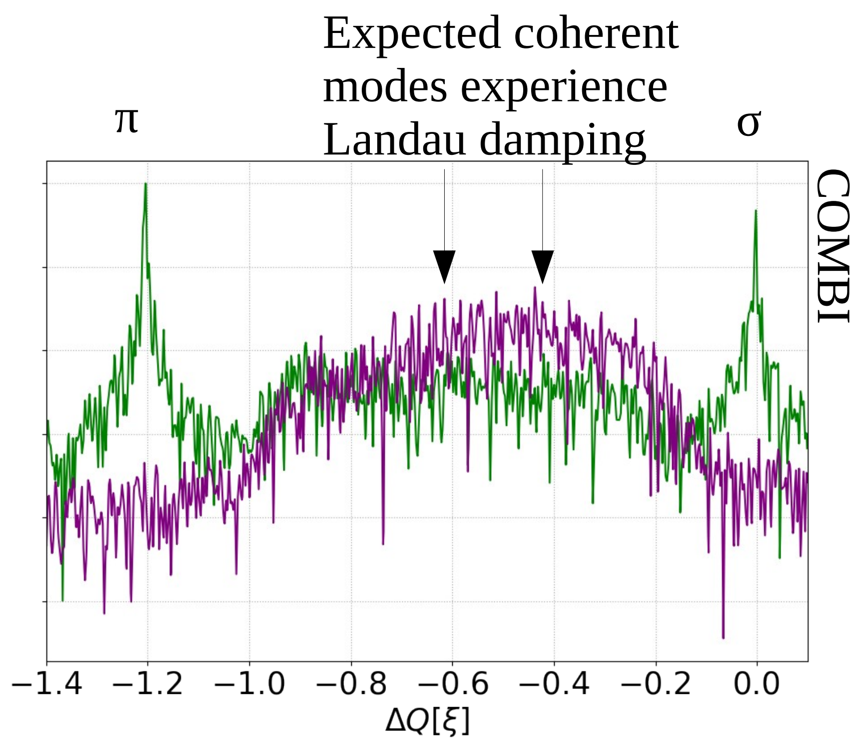
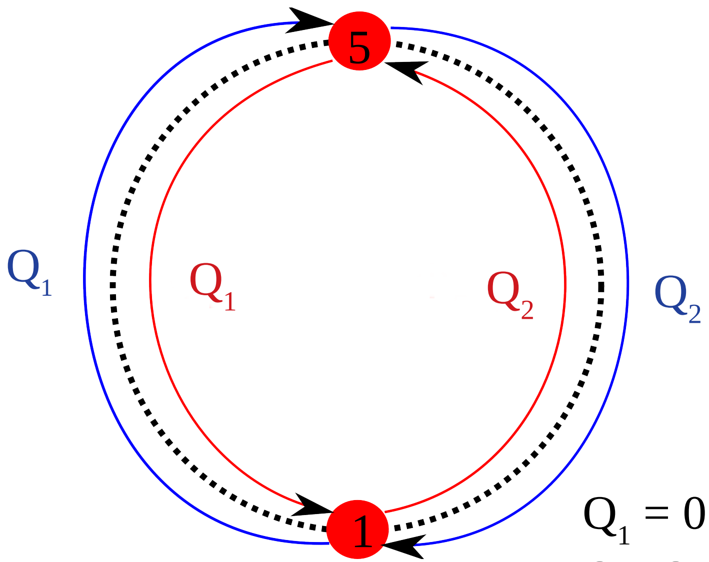


- The spectrum of coherent beam-beam modes strongly depends on the complexity of the machine / beam setup (number of IPs, number of bunches, phase advances between them, asymmetries between the beams) T. Pieloni, PhD Thesis EPFL 2008

Coherent beam-beam modes



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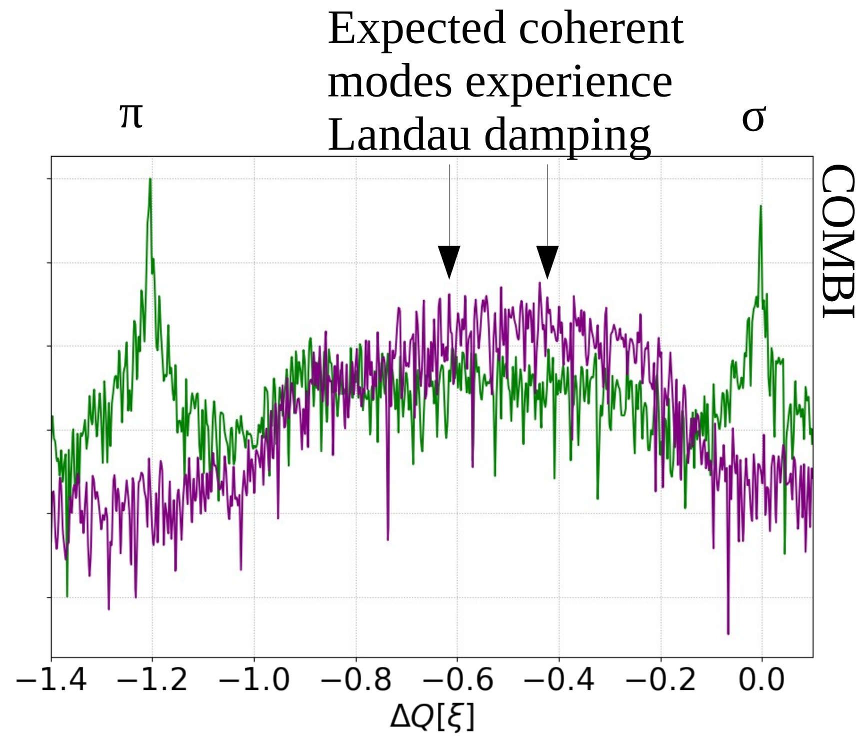

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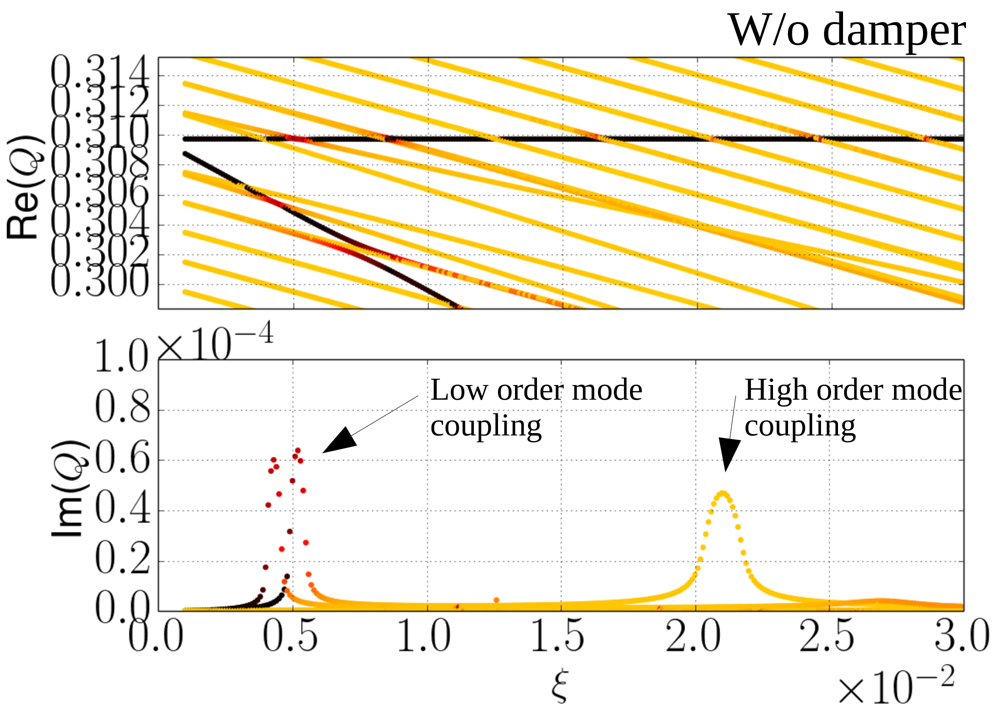
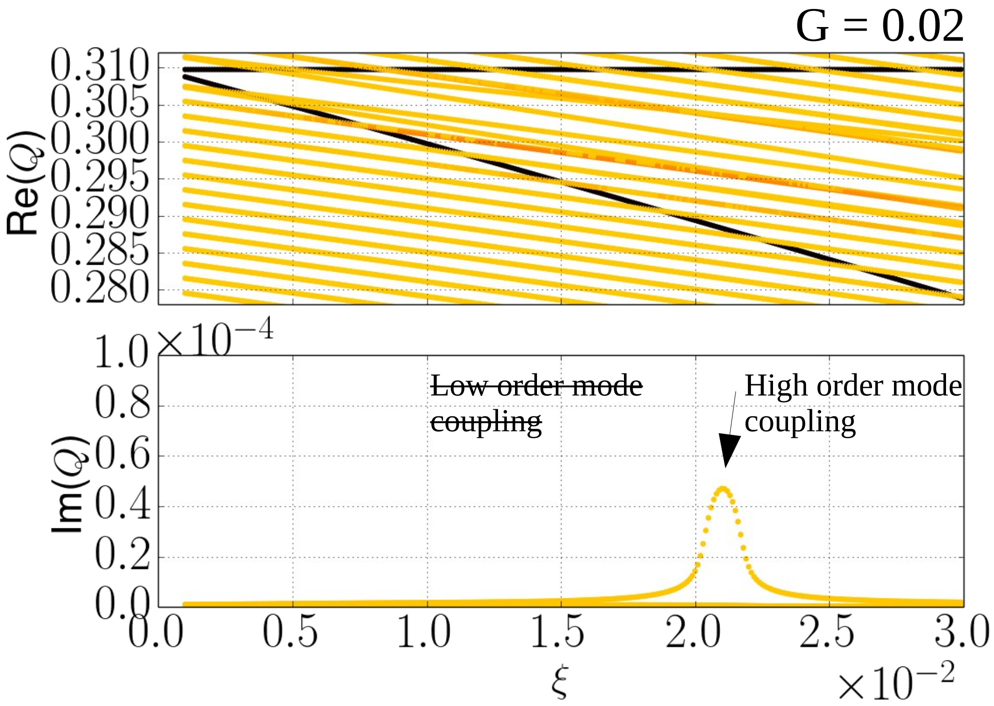
- The circulant matrix model is particularly handy to predict the mode frequency in complex configurations, as well as the effectiveness of other mitigation techniques such as chromaticity or active feedbacks
  E. A. Perevedentsev and A. A. Valishev, Phys. Rev. ST Accel. Beams 4, 024403
  S. White, et al., Phys. Rev. ST Accel. Beams 17 041002 (2014)
  X. Buffat, PhD Thesis EPFL, 2015

Mode coupling instability at the HL-LHC



- In the presence of large Piwinski angle or hourglass effect, we may expect mode coupling of higher order head-tail mode which are not efficiently damped by a feedback based on the bunch centroid

Mode coupling instability at the HL-LHC



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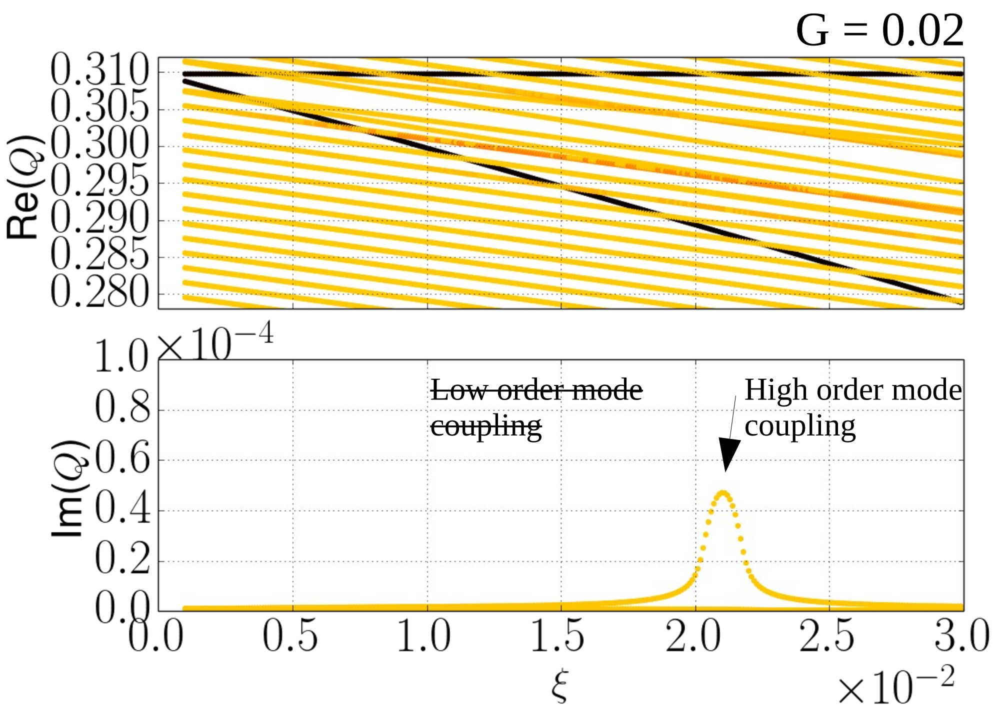

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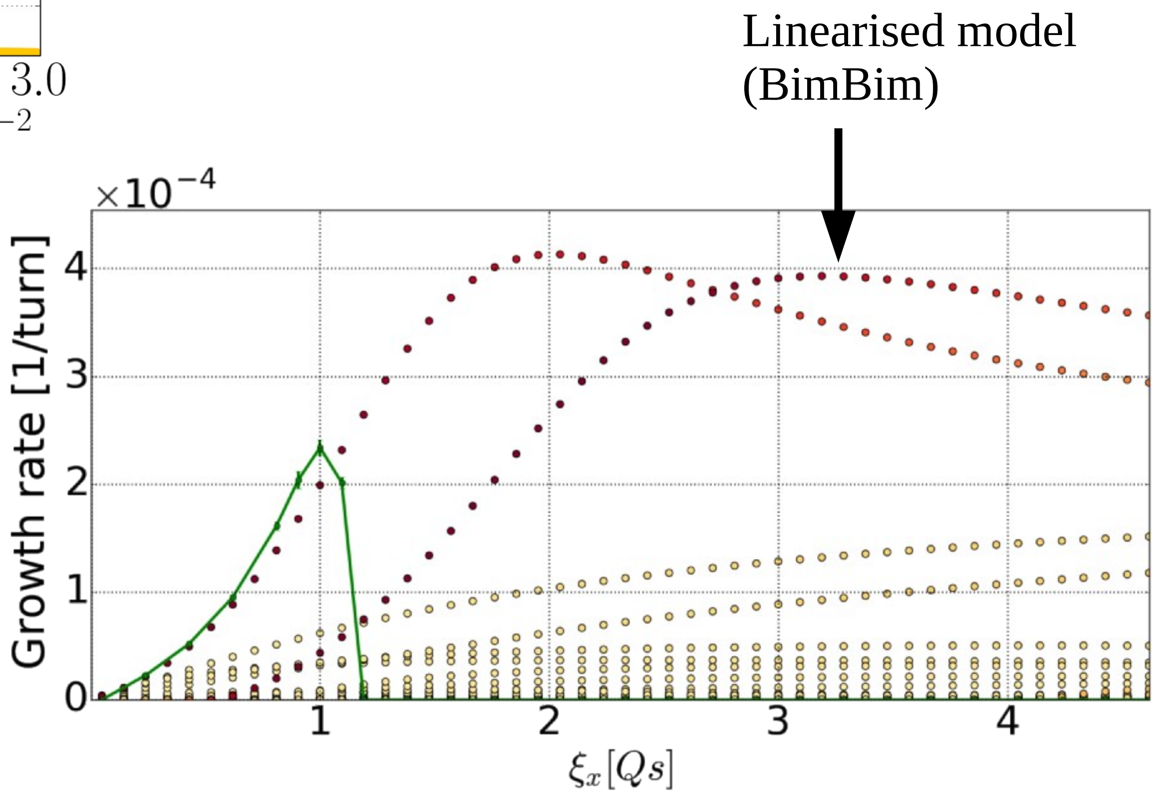

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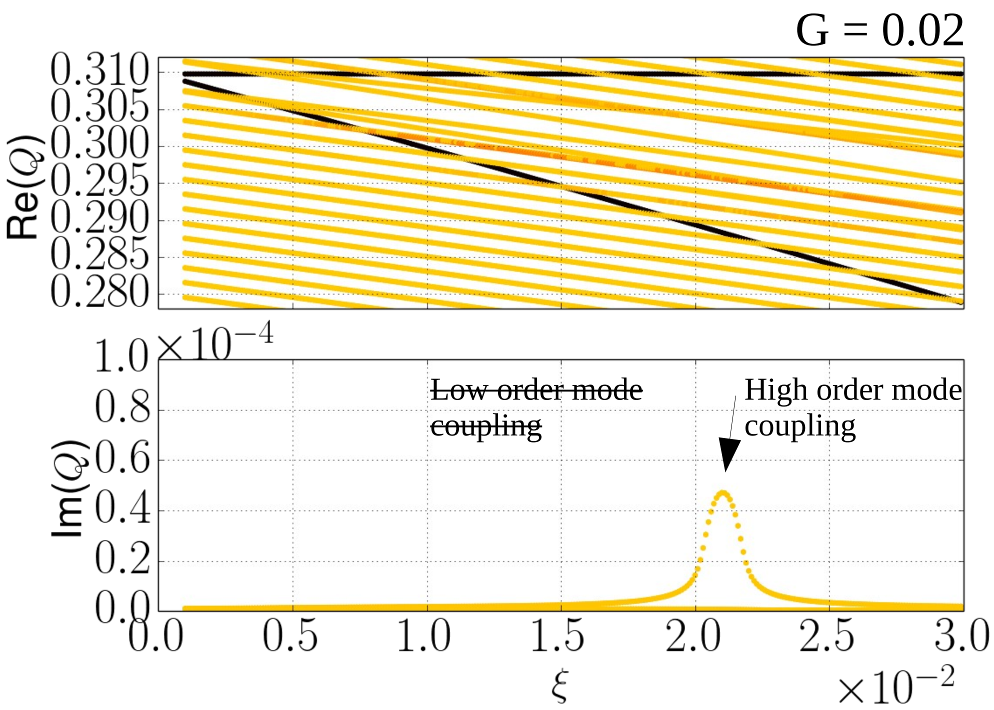

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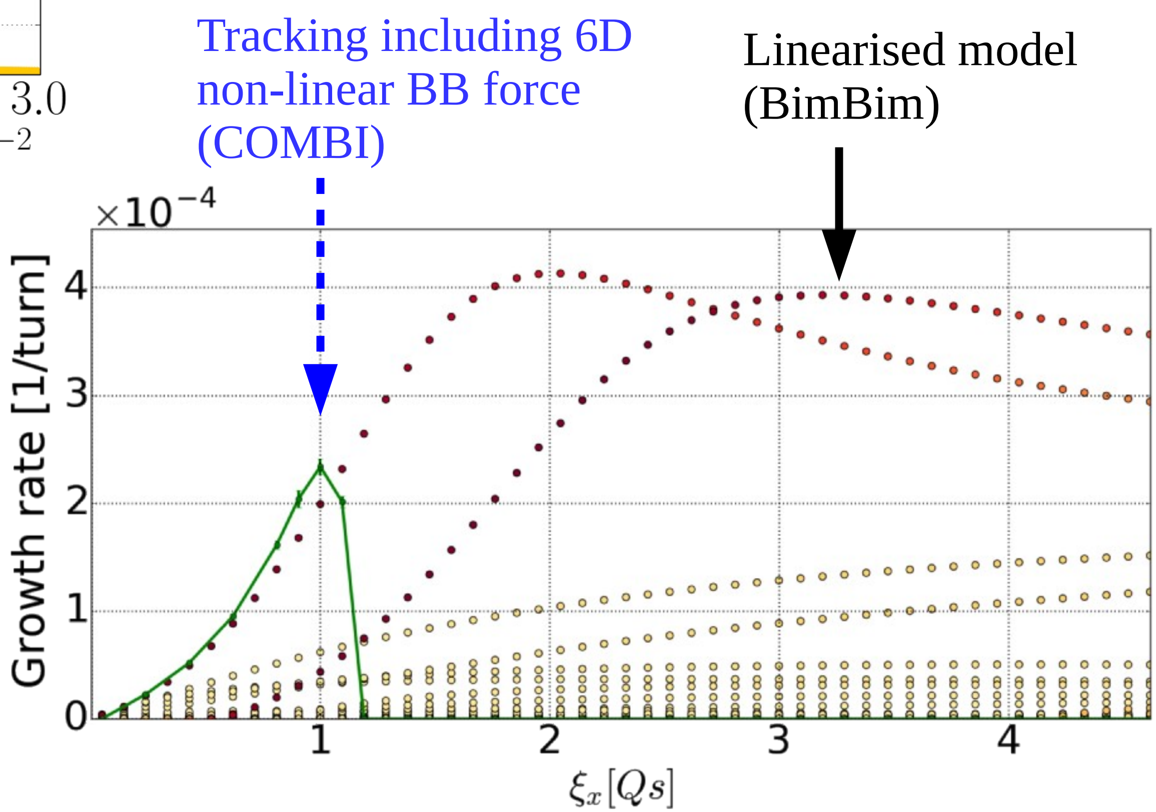
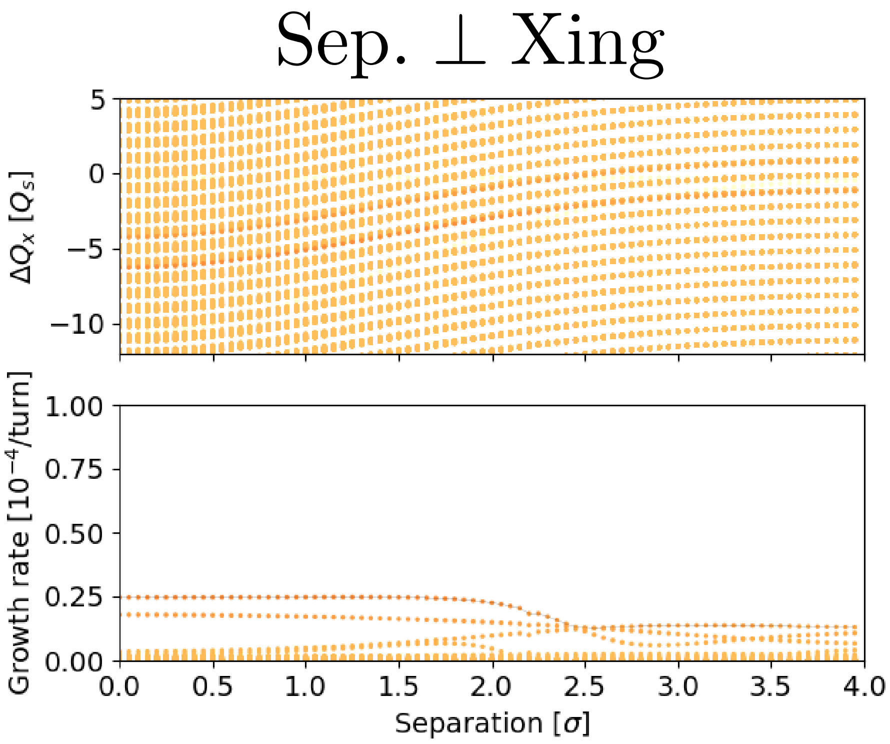


- Landau damping by synchrotron side-bands (enabled by the large Piwinski angle or hourglass effect) is sufficient to ensure stability for beam-beam parameter larger than Q_s in the HL-LHC

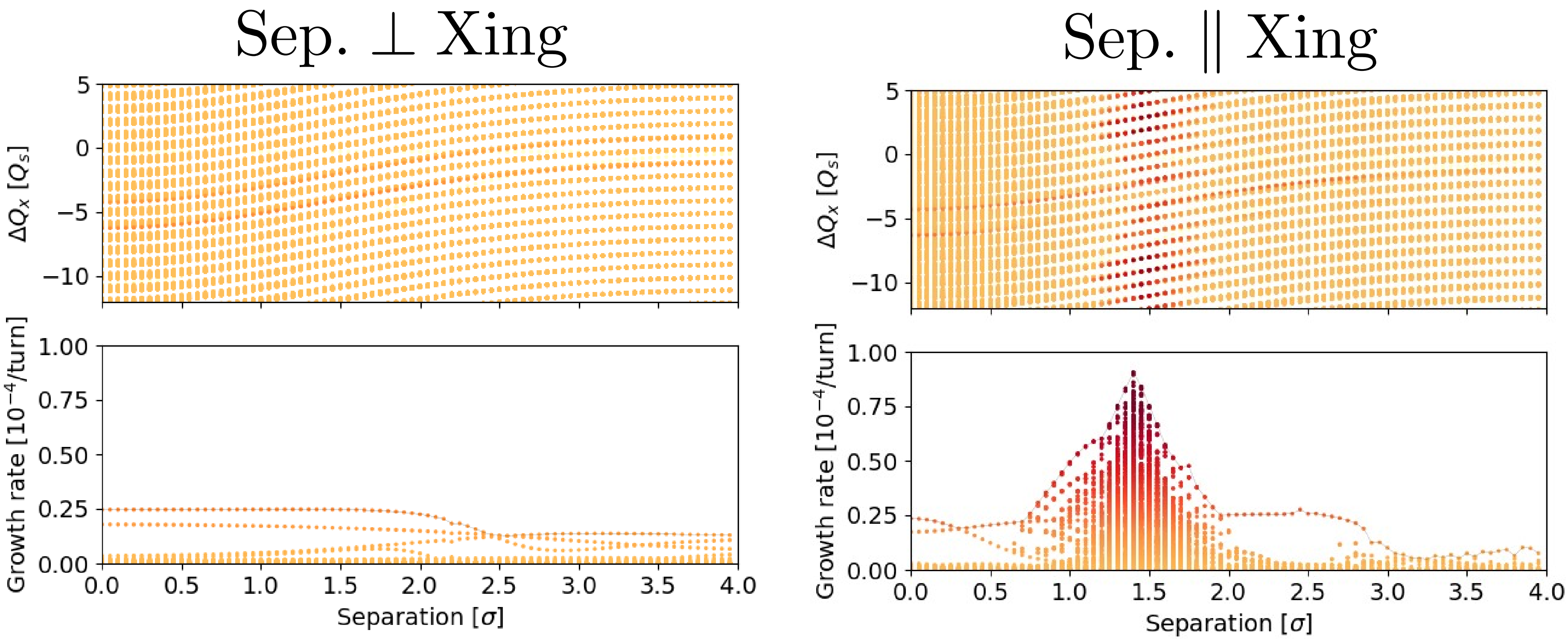
L. Barraud and X. Buffat., CERN-ACC-NOTE-2019-0032

Offset beams + crossing angle



- 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

Offset beams + crossing angle



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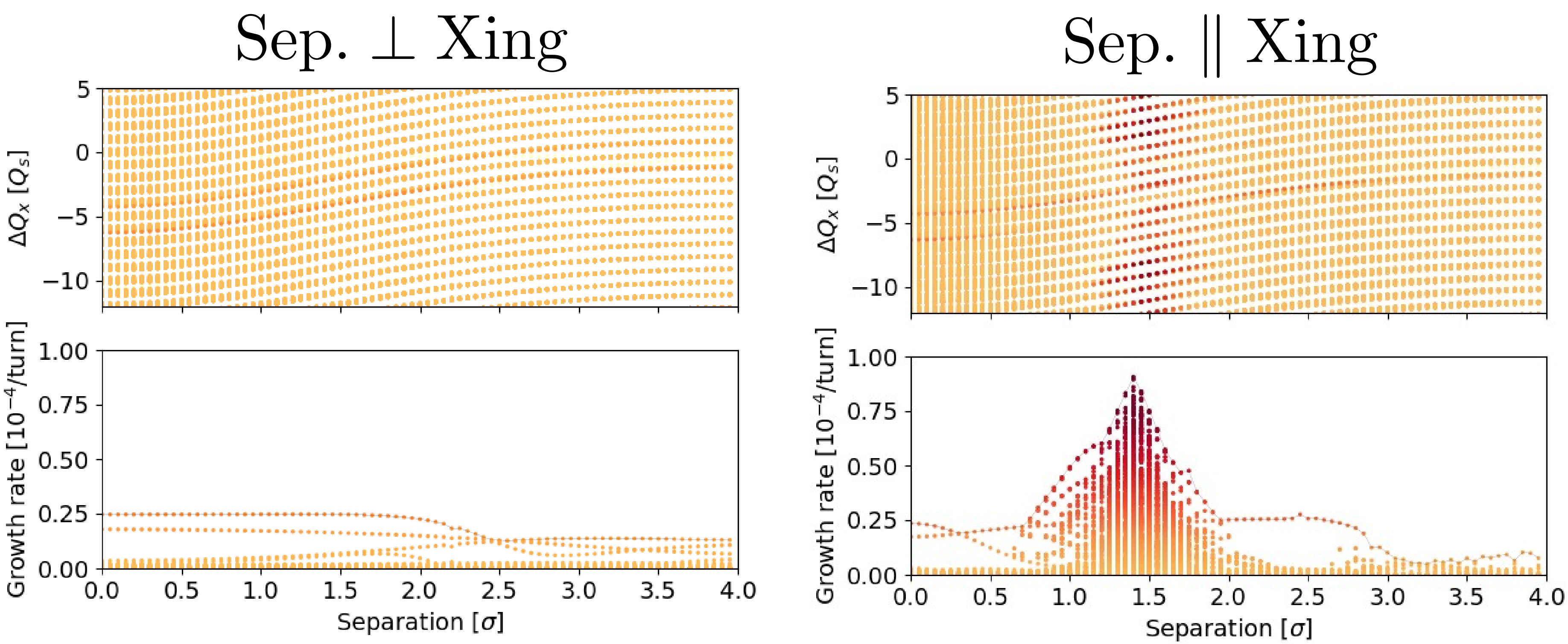

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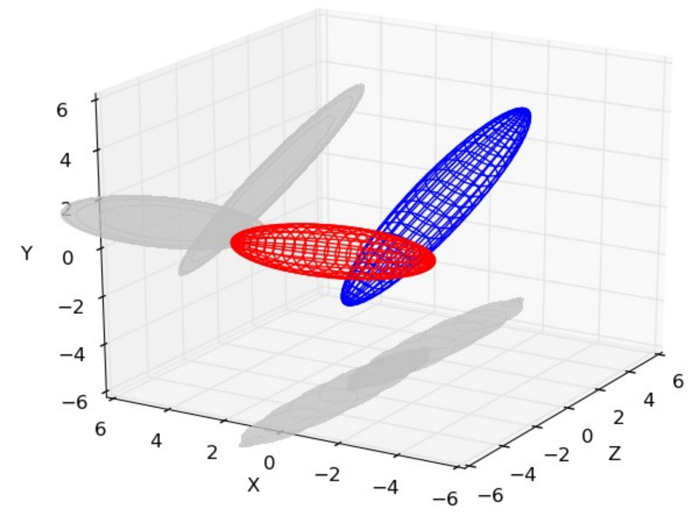

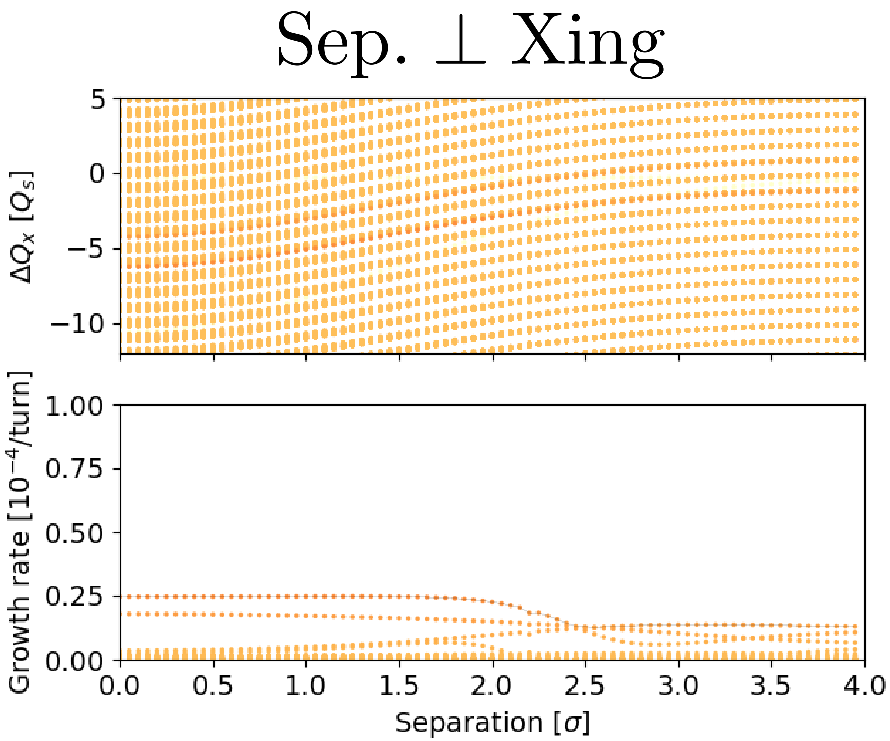

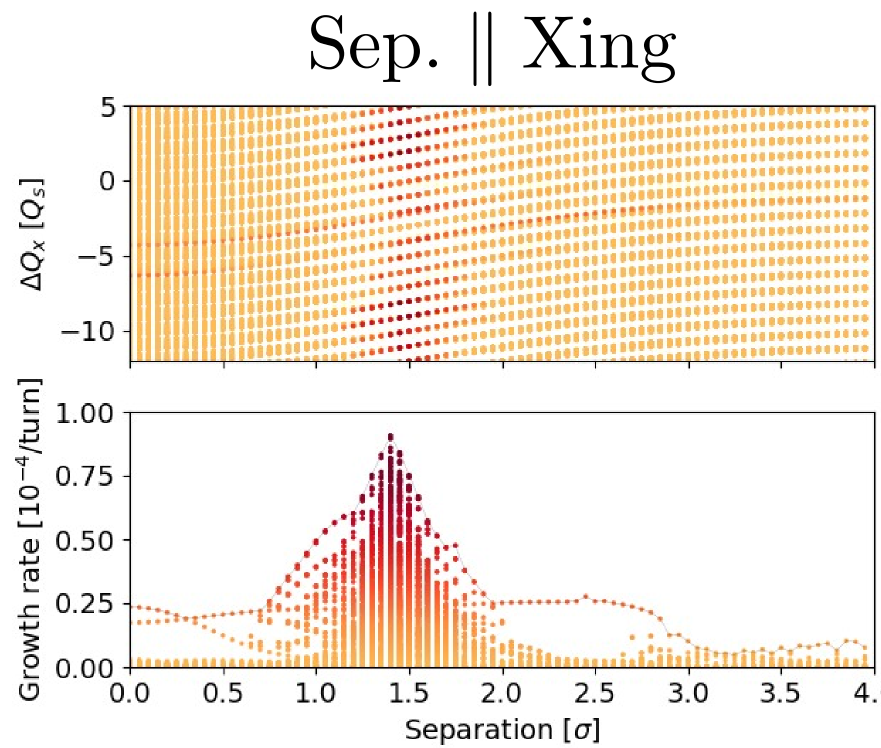

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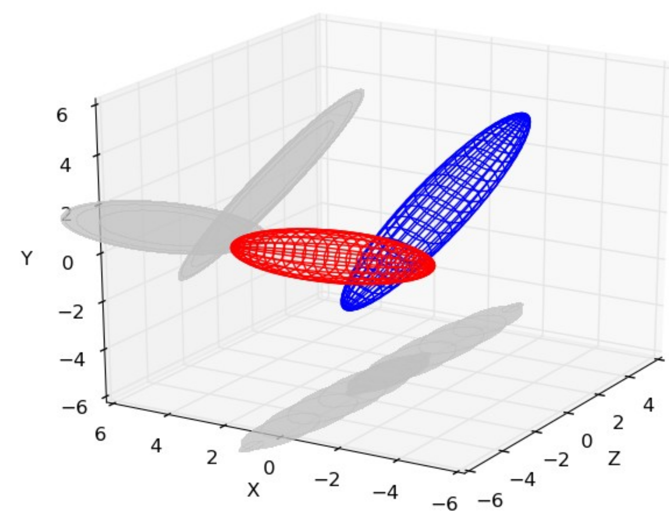
  → Fresh off the press, to be continued...



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- Depending on the operational cycle, one may have to rush through an intermediate unstable configuration (e.g. using fast PC for the separation bumps), similarly to transition crossing in low energy machines