# Beam Transfer Function (BTF) measurements and transverse stability in presence of beam-beam

C. Tambasco

Acknowledgements: J. Barranco, X. Buffat, E. Mètral, T. Pieloni

*ICFA - Mini Workshop on impedances and beam instabilities in particle accelerators*
*19-22 September, Benevento, Italy*

# Coherent beam instability

**Coherent ➔** centre of mass effects, characterized by imaginary tune shift as the one produced by the **impedance**

**Instability ➔** a moment of the beam distribution exhibits an exponential growth (e.g. mean positions, standard deviations, etc.)

**Beam quality degradation or even partial or total beam losses**

# Coherent beam instability

**Coherent ➔** centre of mass effects, characterized by imaginary tune shift as the one produced by the **impedance**

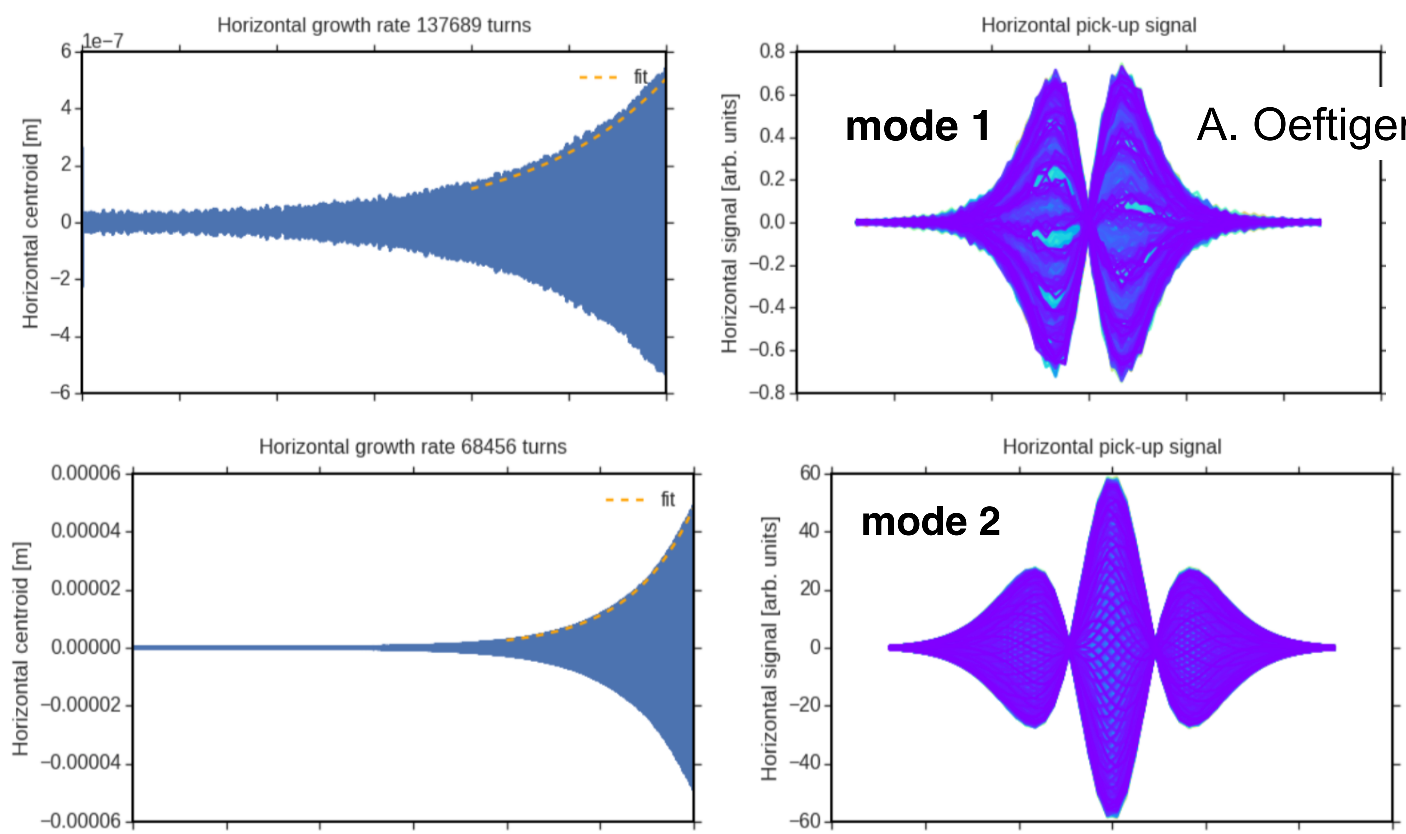
**Instability ➔** a moment of the beam distribution exhibits an exponential growth (e.g. mean positions, standard deviations, etc.)

**Beam quality degradation or even partial or total beam losses**

The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- Im(ΔQ): beam instability rise time
- Re(ΔQ): Impedance coherent real tune shift



# Coherent beam instability

**Coherent ➔** centre of mass effects, characterized by imaginary tune shift as the one produced by the **impedance**

**Instability ➔** a moment of the beam distribution exhibits an exponential growth (e.g. mean positions, standard deviations, etc.)

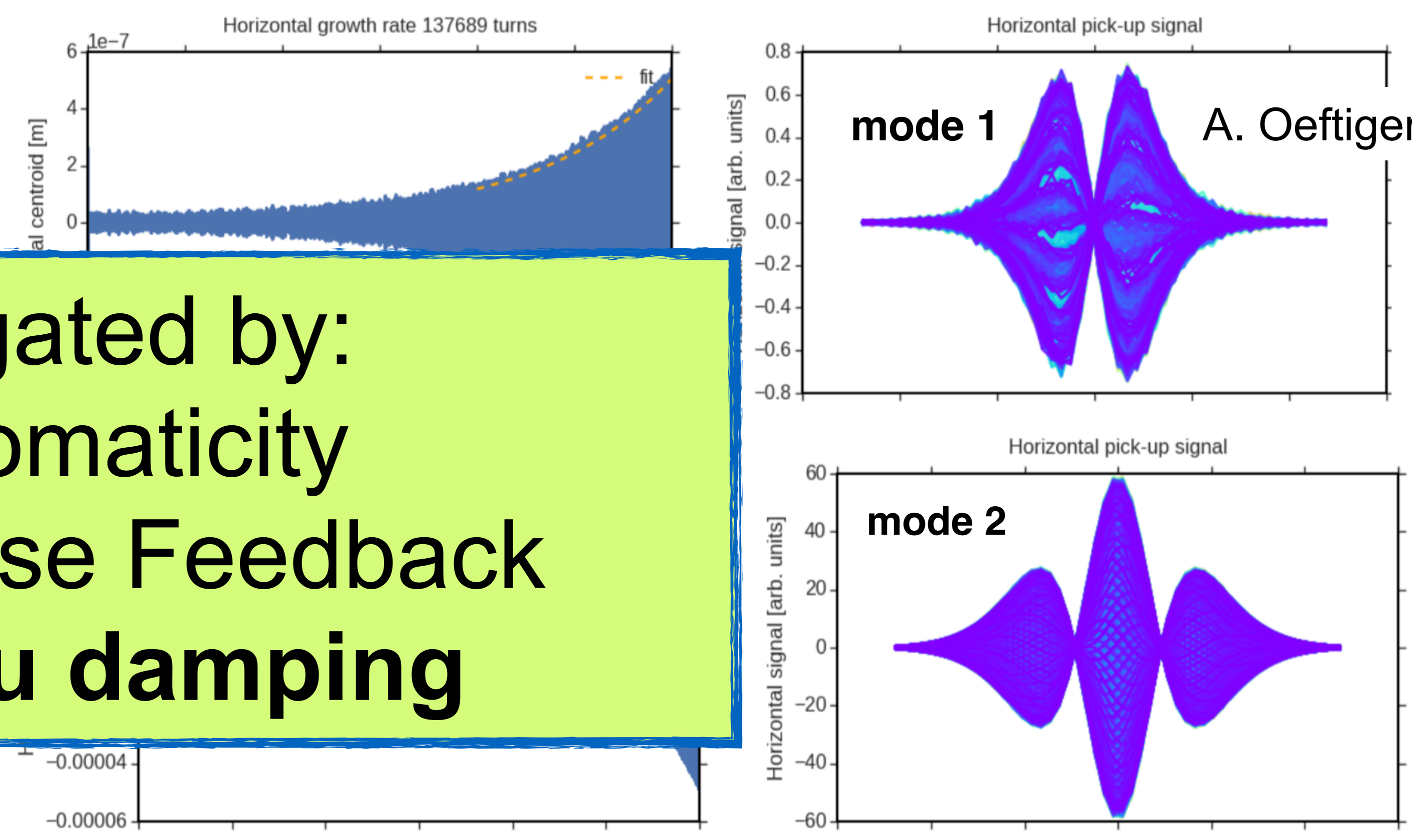
**Beam quality degradation or even partial or total beam losses**

The impedance drives so-called **head-tail instabilities** → different modes of beam oscillations

Complex Tune shifts:

- Im(ΔQ): beam insta
- Re(ΔQ): Impedanc tune shift

Mitigated by:
Chromaticity
Transverse Feedback
**Landau damping**



# Dispersion integral and Stability diagrams

Landau damping of the impedance modes can be quantified by the **dispersion integral [1]**:

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x, J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

[1] J. Berg and F. Ruggero, *Landau damping with two dimensional betatron tune spread*, CERN SL-AP-96-71 (1996)

# Dispersion integral and Stability diagrams

Landau damping of the impedance modes can be quantified by the **dispersion integral [1]**:

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x, J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

Detuning with amplitude [2,3]
($J_x$ - $J_y$ phase space amplitude)

For accelerators, the Landau damping is generated by the **tune spread** (LHC equipped with 168 Landau octupoles to stabilize the beam)


[1] J. Berg and F. Ruggero, *Landau damping with two dimensional betatron tune spread*, CERN SL-AP-96-71 (1996)
[2] X. Buffat, EPFL Thesis 6321 (2015)
[3] X. Buffat et *al*., *Stability diagrams of colliding beams in the Large Hadron Collider*, PRSTAB 111002 (2014)

# Dispersion integral and Stability diagrams

In presence of **diffusive mechanisms the particle distribution changes**

Particle distribution [4,5]

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

Detuning with amplitude [1,2]
($J_x$ - $J_y$ phase space amplitude)

For accelerators, the Landau damping is generated by the **tune spread** (LHC equipped with 168 Landau octupoles to stabilize the beam)


[4] C. Tambasco, EPFL Thesis 7867 (2017)
[5] C. Tambasco *et al.*, *Impact of incoherent effects on stability diagram at the LHC*, IPAC TUPVA031 2017

# Dispersion integral and Stability diagrams

In presence of **diffusive mechanisms the particle distribution changes**

Particle distribution [4,5]

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x, J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

Detuning with amplitude [1,2]
($J_x$ - $J_y$ phase space amplitude)

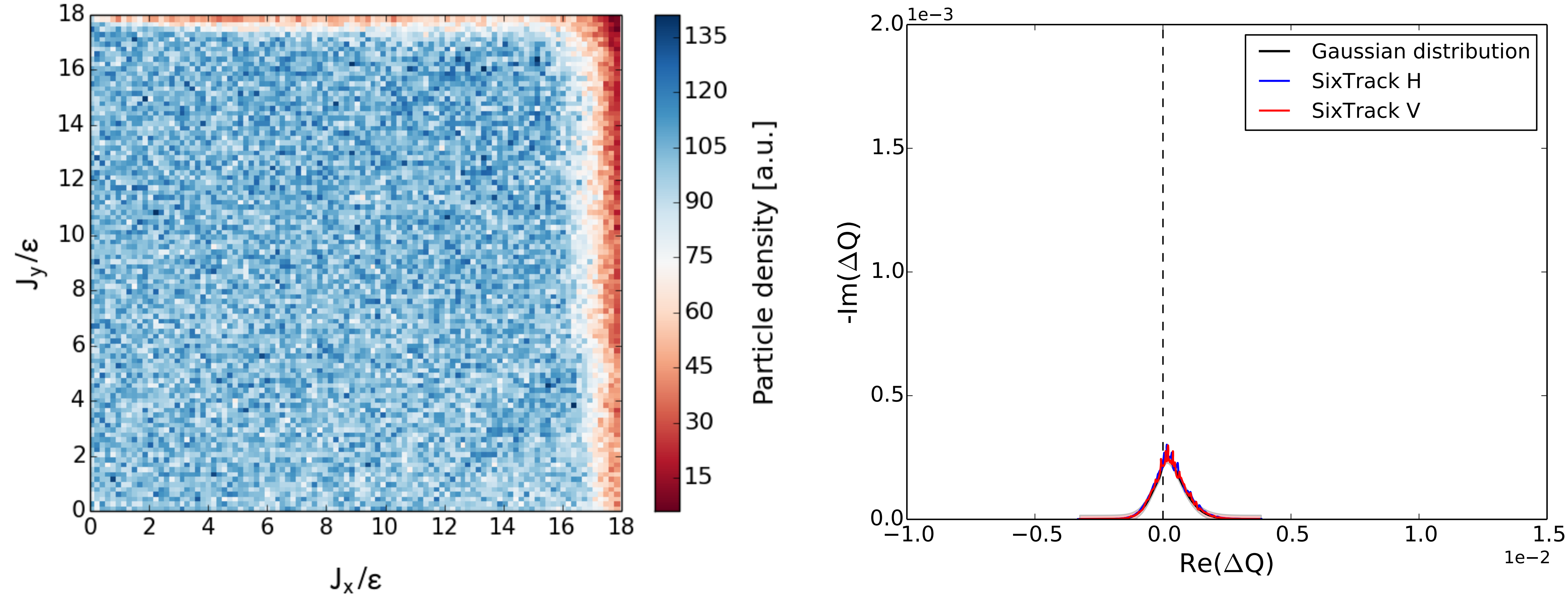
For accelerators, the Landau damping is generated by the **tune spread** (LHC equipped with 168 Landau octupoles to stabilize the beam)

**In case of diffusive mechanisms and/or reduced dynamic aperture with particle losses or redistribution ➔ Characterize the impact of realistic lattice on particle distribution**

# Impact of incoherent effects on the Stability Diagram

Tracking of $10^6$ particles under realistic lattice configuration for $10^6$ turns ➔ Impact of DA, lattice and beam-beam excited resonances

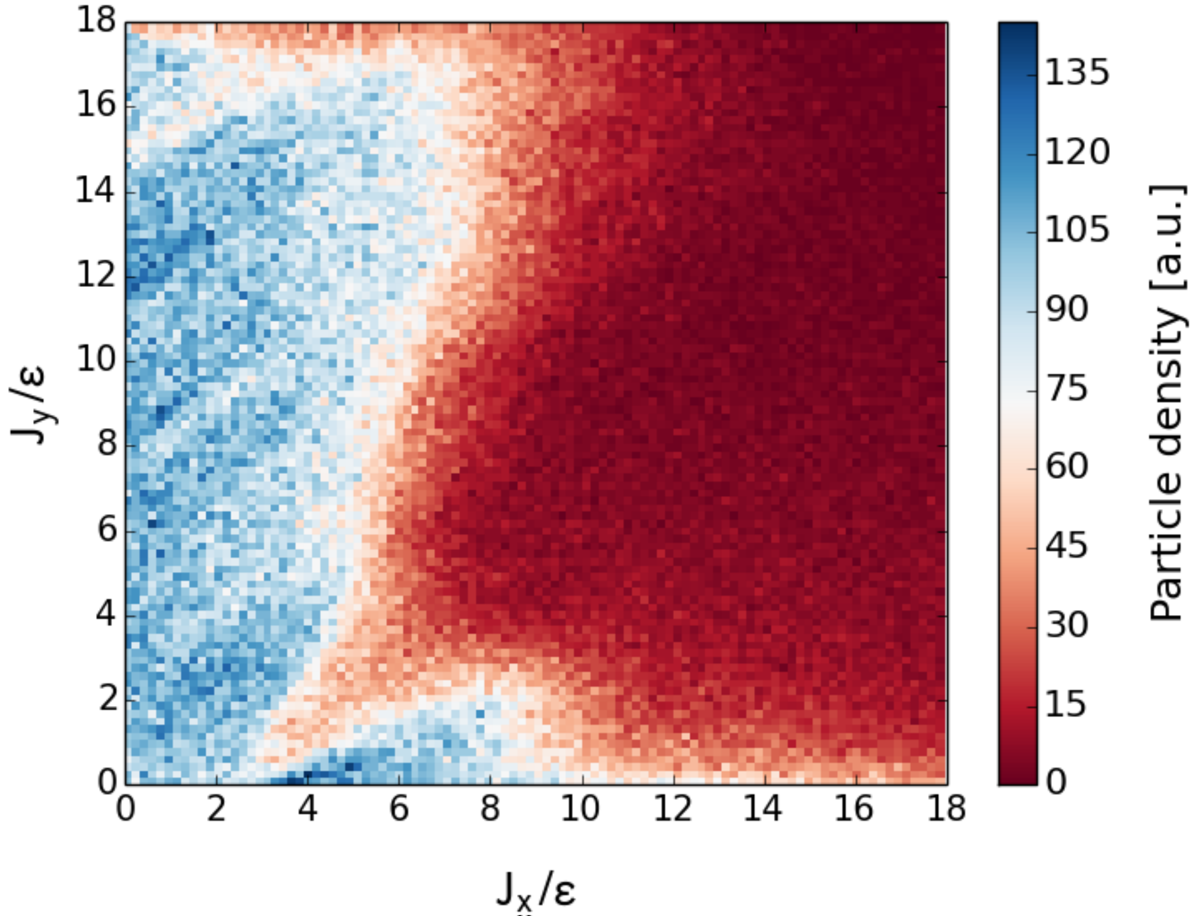
**Tracked distribution (tune spread provided by octupoles current 6.5 A)**

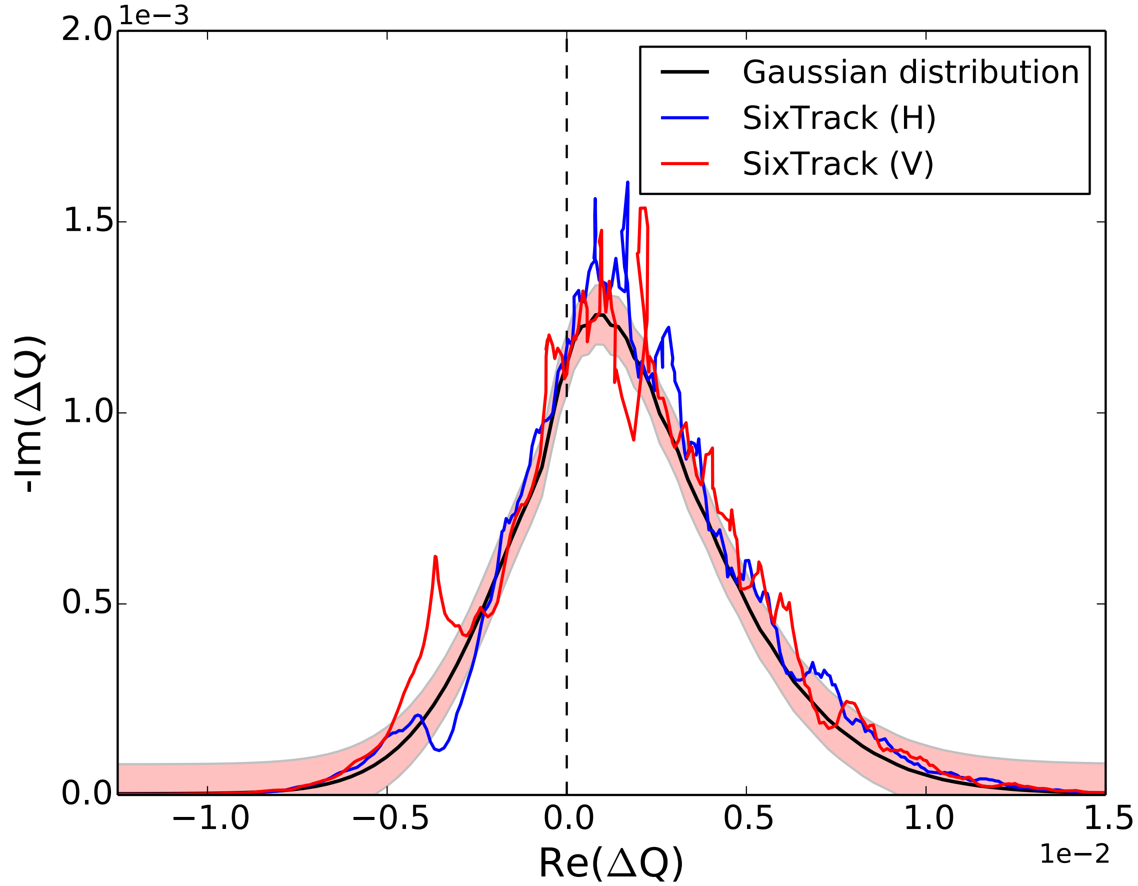



- No evident distortion compared to Gaussian distribution case
- **Red** points represent the particles that are lost (out of the dynamic aperture)

# Impact of incoherent effects on the Stability Diagram

**Tracked distribution (tune spread provided by octupoles current 35 A)**



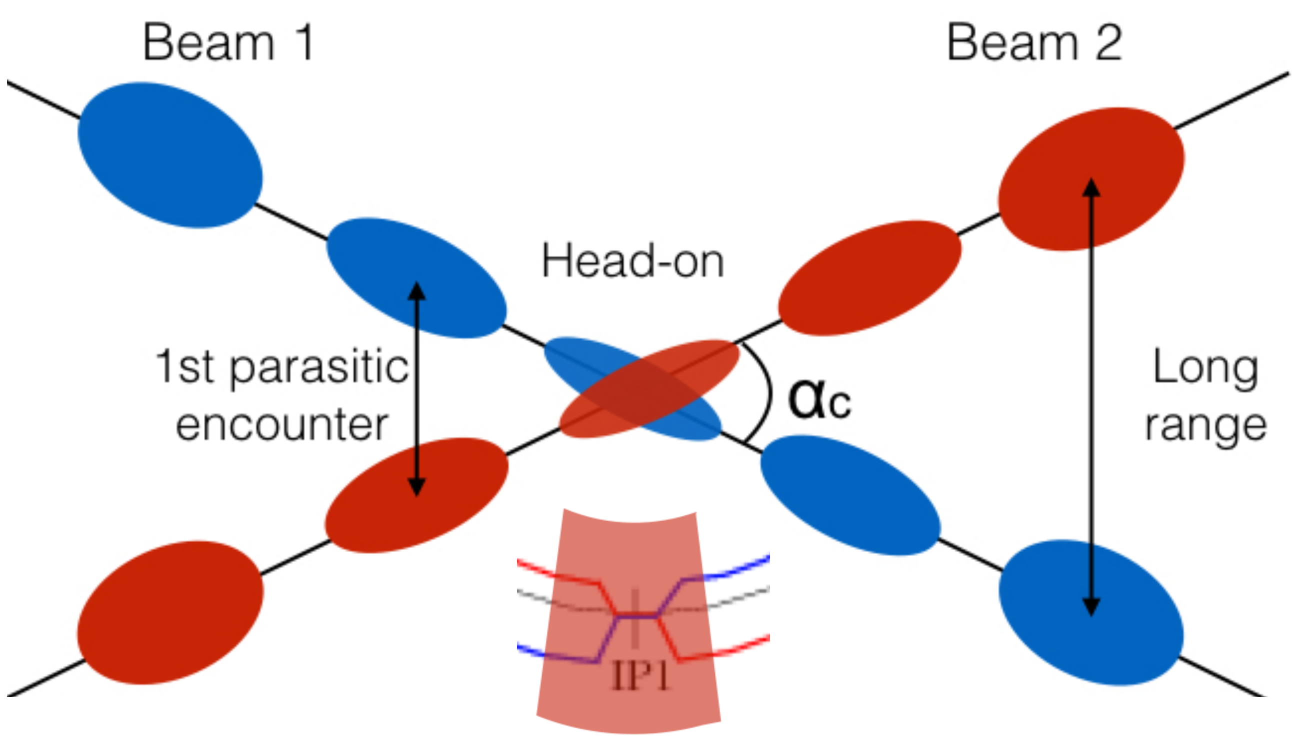




- Small amplitude particles are lost (amplitude < 3.5 σ)
- Distortion visible on the Stability Diagram due to modification of particle distribution (reduced dynamic aperture )

**Incoherent effects on the particle distribution modify coherent stability**

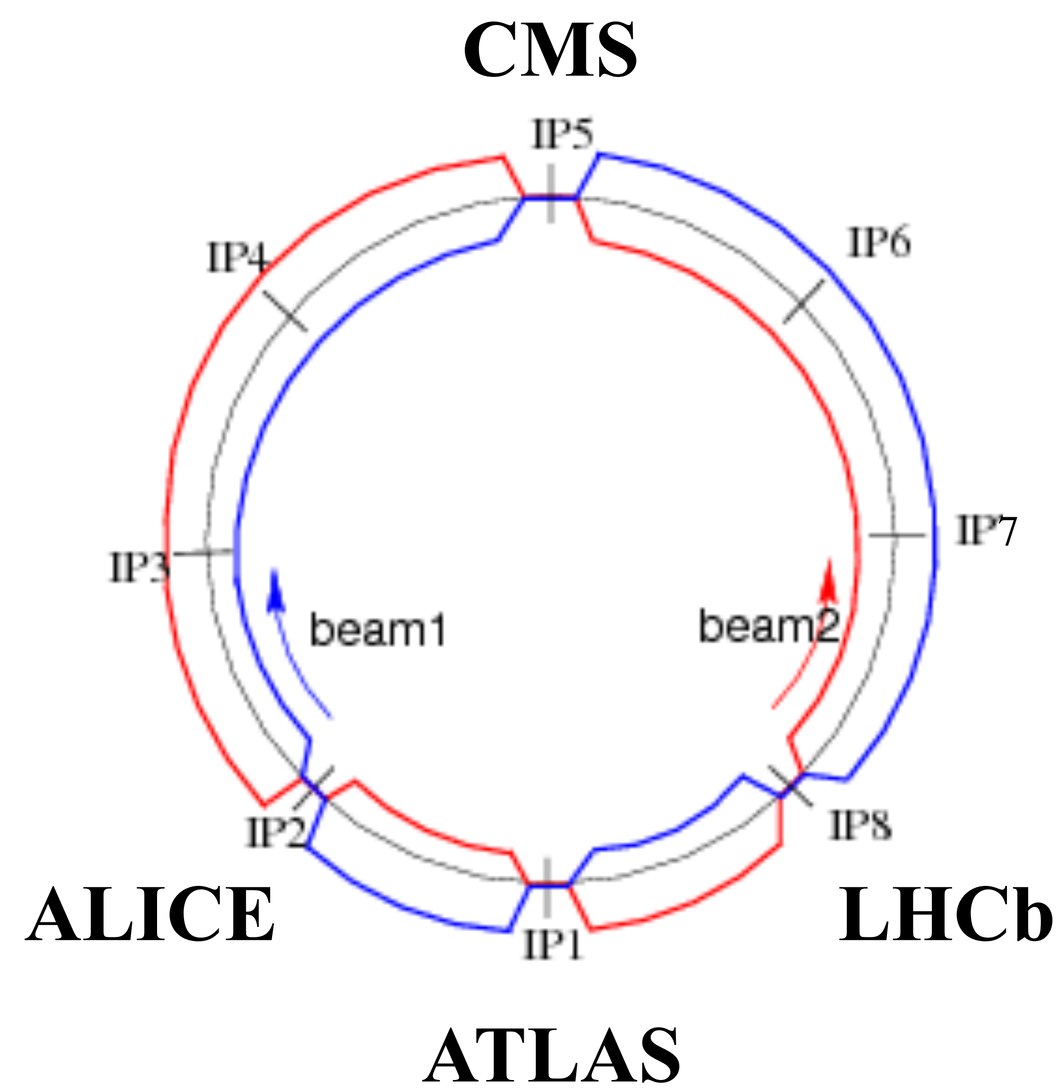
# Collisions at the LHC

**Crossing angle is needed to avoid multiple head-on collisions**



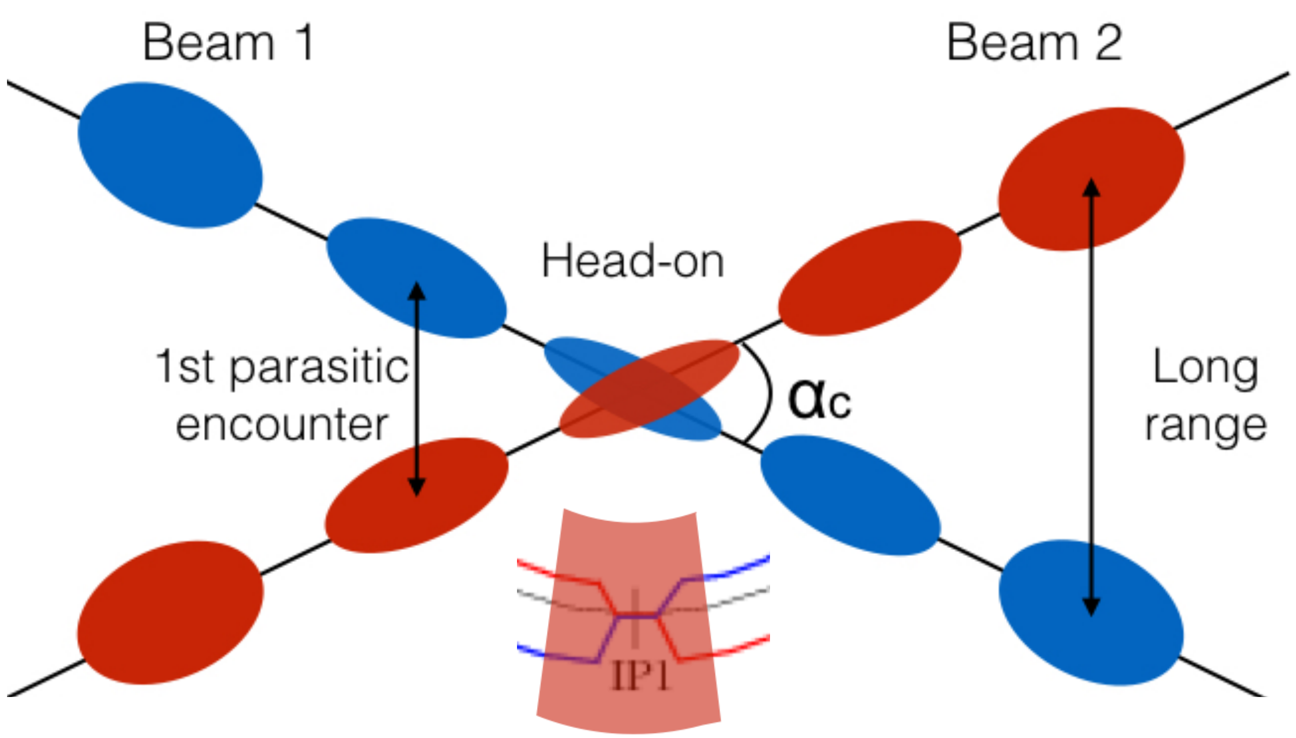

**Interaction Point**

$$d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon}}$$



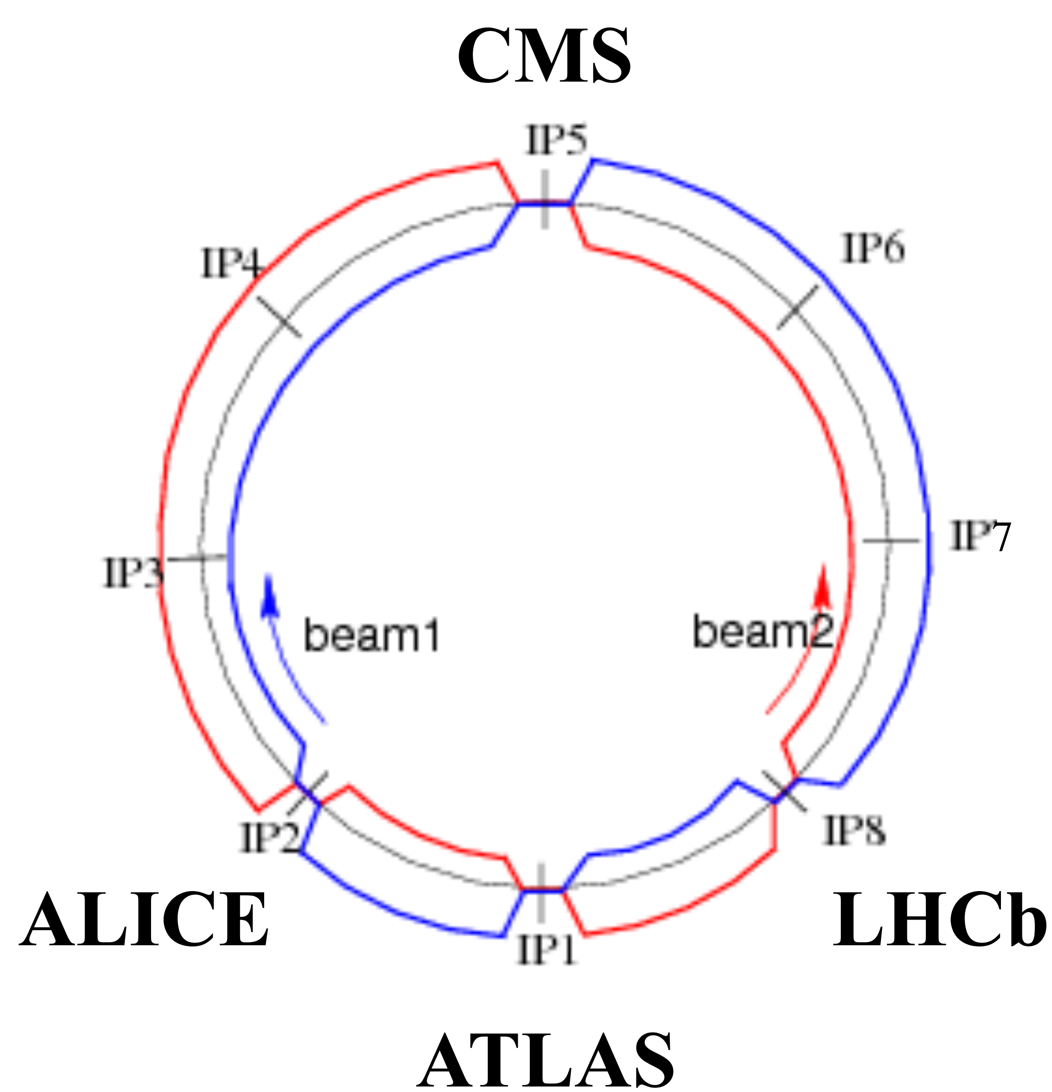
# Collisions at the LHC

**Crossing angle is needed to avoid multiple head-on collisions**




**Interaction Point**

$$d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon}}$$




The crossing angle scheme also apply to: HL-LHC, HE-LHC, FCC…

# The Beam-Beam force

**Stronger for high brightness beams**

Deflection of a test particle due to the Beam-Beam force (incoherent):

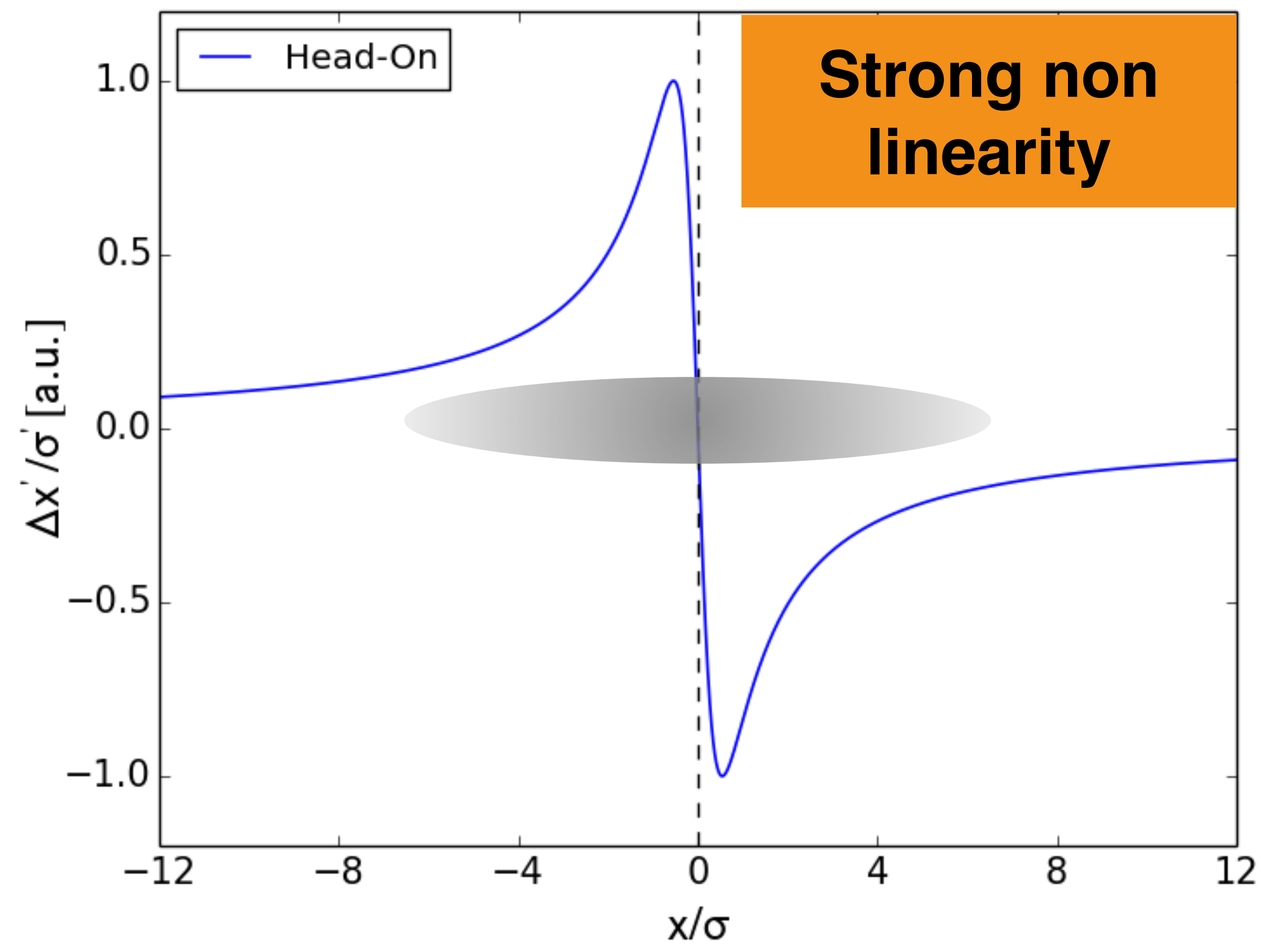
$$\Delta x' = -\frac{2 r_0 N}{\gamma} \frac{x}{r^2} \left(1 - \mathrm{e}^{-\frac{\mathrm{r}^2}{2\sigma^2}}\right)$$

# The Beam-Beam force

**Stronger for high brightness beams**

Deflection of a test particle due to the Beam-Beam force (incoherent):

$$\Delta x' = -\frac{2r_0N}{\gamma}\frac{x}{r^2}(1-\mathrm{e}^{-\frac{\mathrm{r}^2}{2\sigma^2}})$$



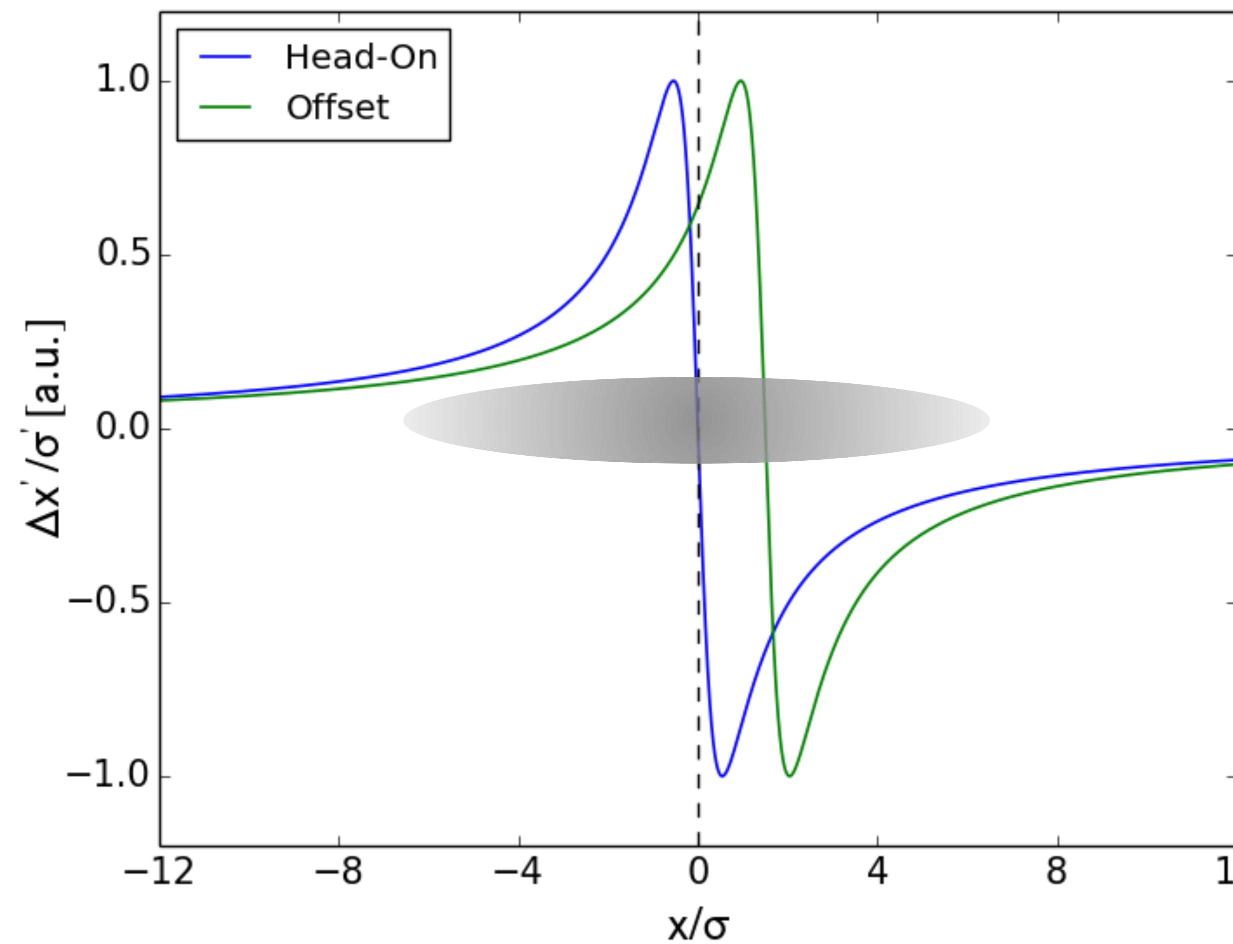

**Head-on**

# The Beam-Beam force

**Stronger for high brightness beams**

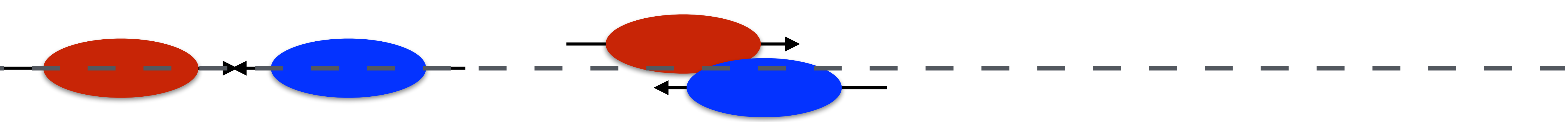
Deflection of a test particle due to the Beam-Beam force (incoherent):

$$\Delta x' = -\frac{2 r_0 N}{\gamma}\frac{x}{r^2}\left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)$$




**Head-on**

**Offset** (sep ~ σ)

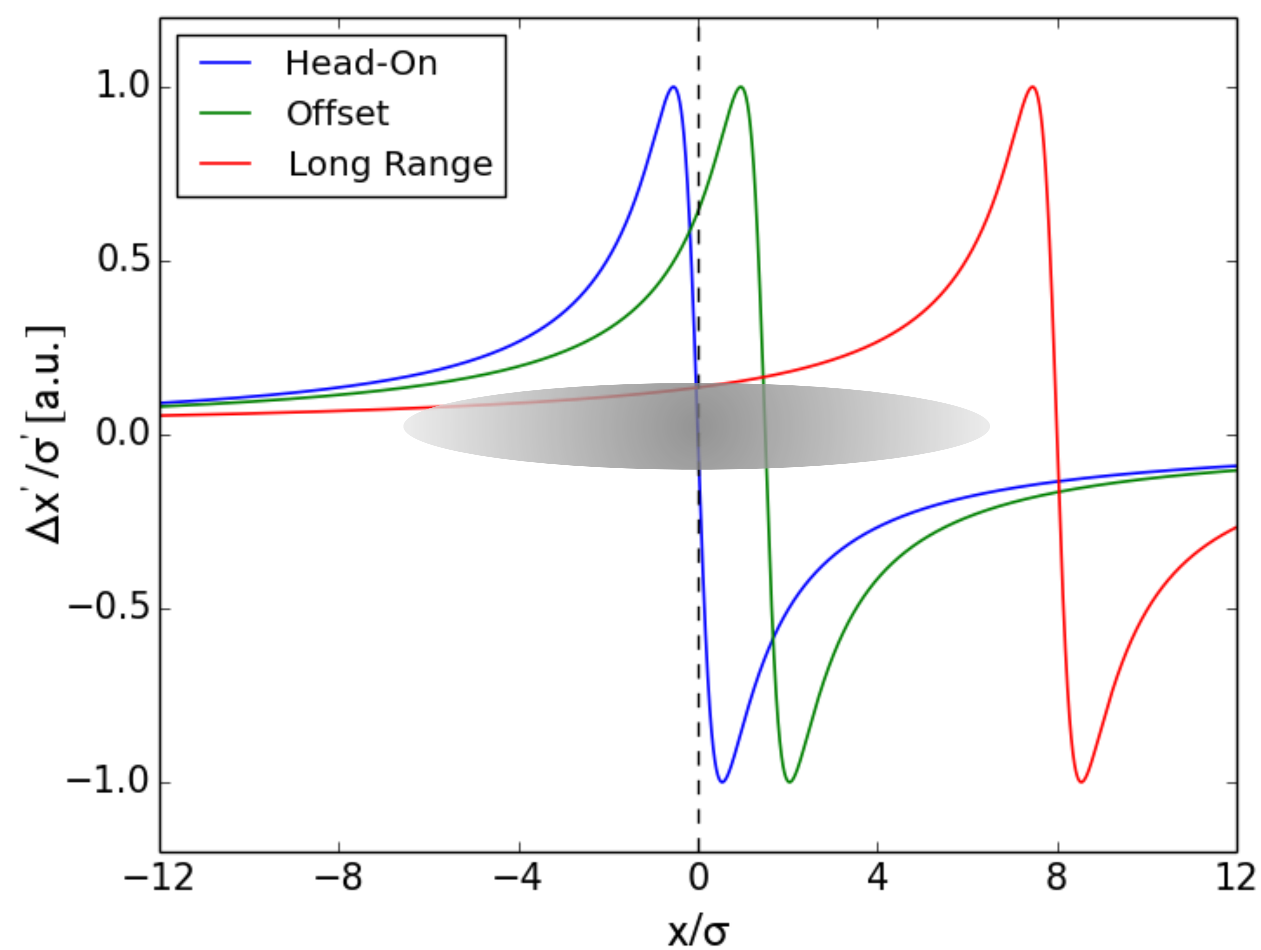


# The Beam-Beam force

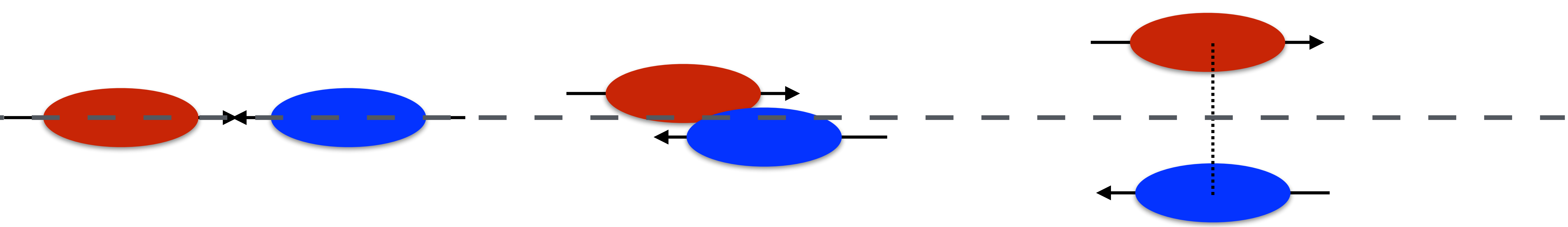
**Stronger for high brightness beams**

Deflection of a test particle due to the Beam-Beam force (incoherent):

$$\Delta x' = -\frac{2r_0 N}{\gamma}\frac{x}{r^2}(1-\mathrm{e}^{-\frac{\mathrm{r}^2}{2\sigma^2}})$$




**Head-on** **Offset** (sep ~ σ) **Long range (LR)** (sep >> σ)

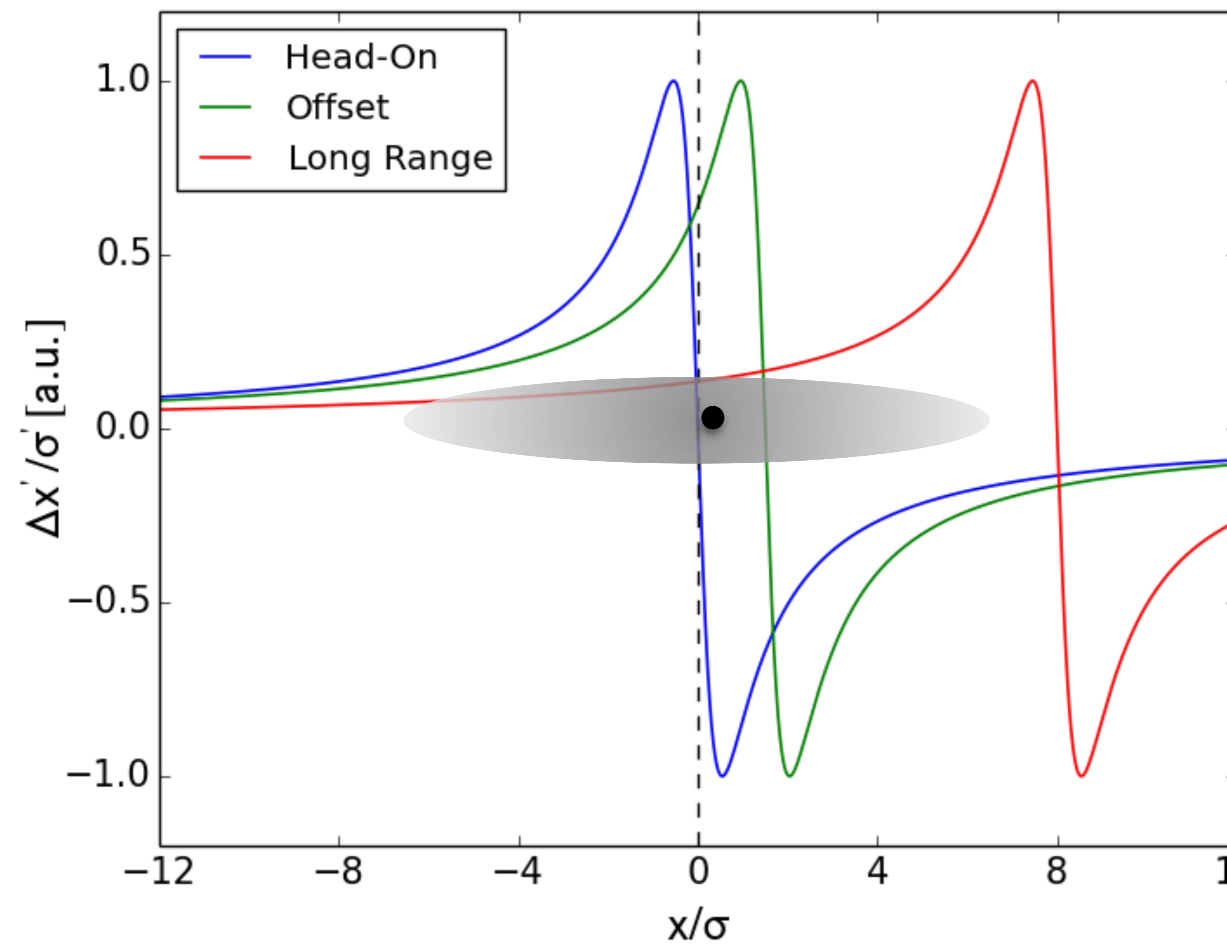


# The Beam-Beam force

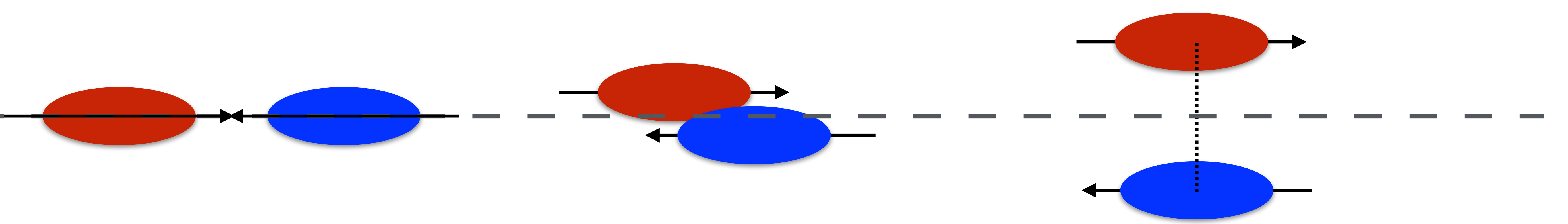
**Stronger for high brightness beams**

Deflection of a test particle due to the Beam-Beam force (incoherent):

$$\Delta x' = -\frac{2 r_0 N}{\gamma} \frac{x}{r^2} (1 - e^{-\frac{r^2}{2\sigma^2}})$$




**Head-on** **Offset** (sep ~ σ) **Long range (LR)** (sep >> σ)

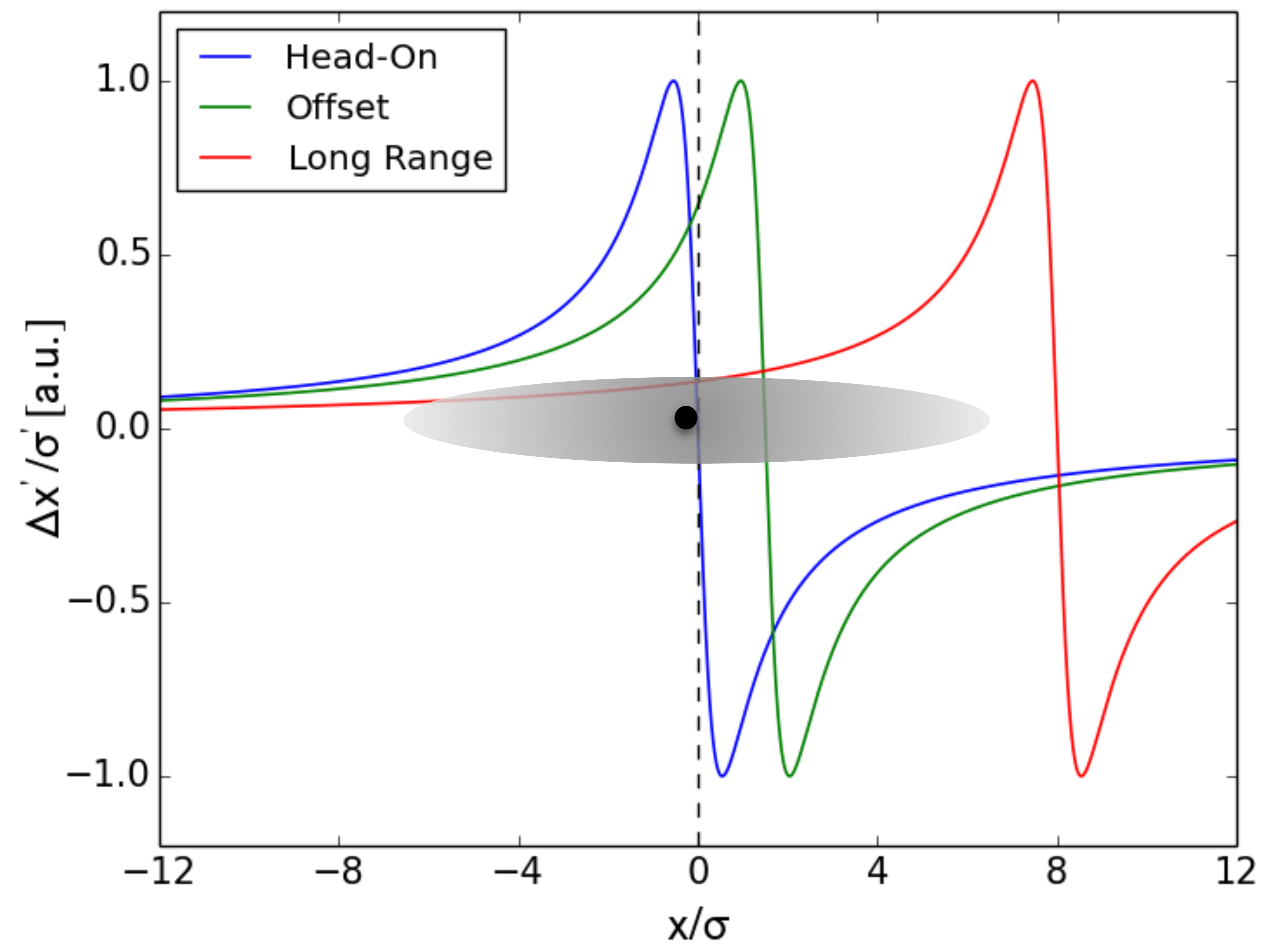


# The Beam-Beam force

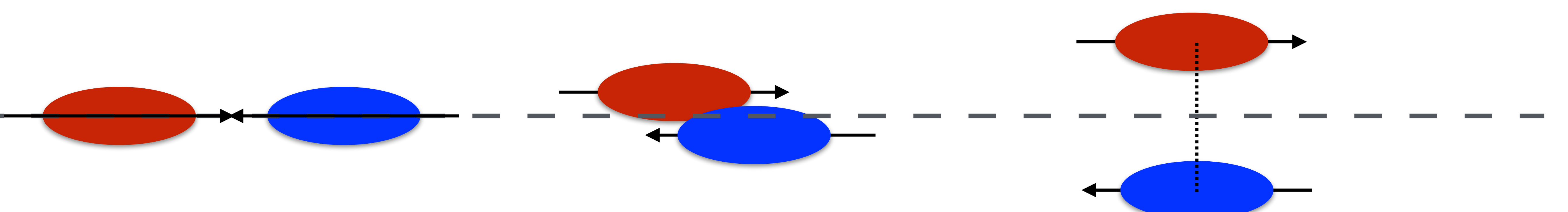
**Stronger for high brightness beams**

Deflection of a test particle due to the Beam-Beam force (incoherent):

$$\Delta x' = -\frac{2 r_0 N}{\gamma}\frac{x}{r^2}\left(1 - \mathrm{e}^{-\frac{\mathrm{r}^2}{2\sigma^2}}\right)$$




**Head-on** **Offset** (sep ~ σ) **Long range (LR)** (sep >> σ)

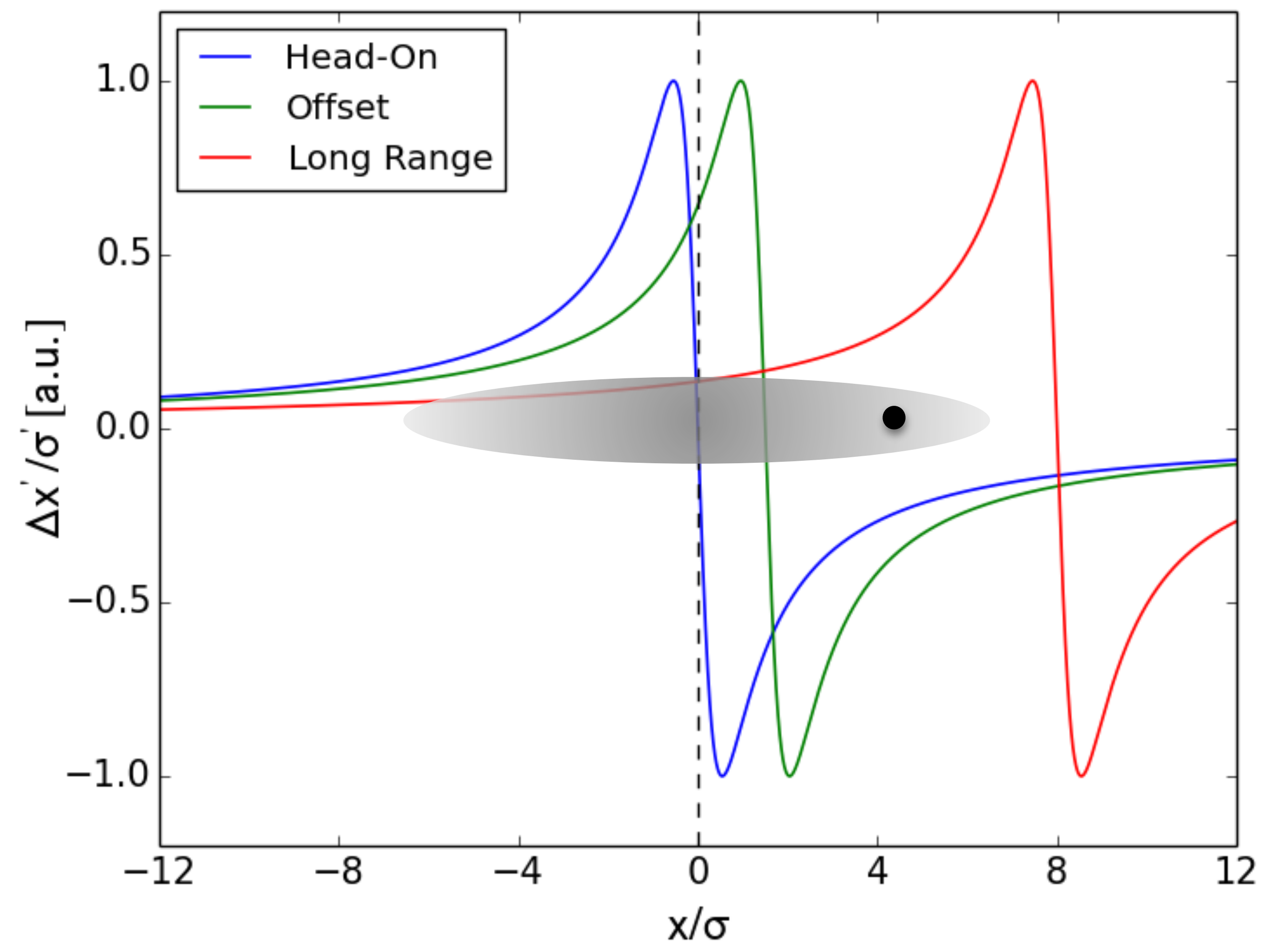


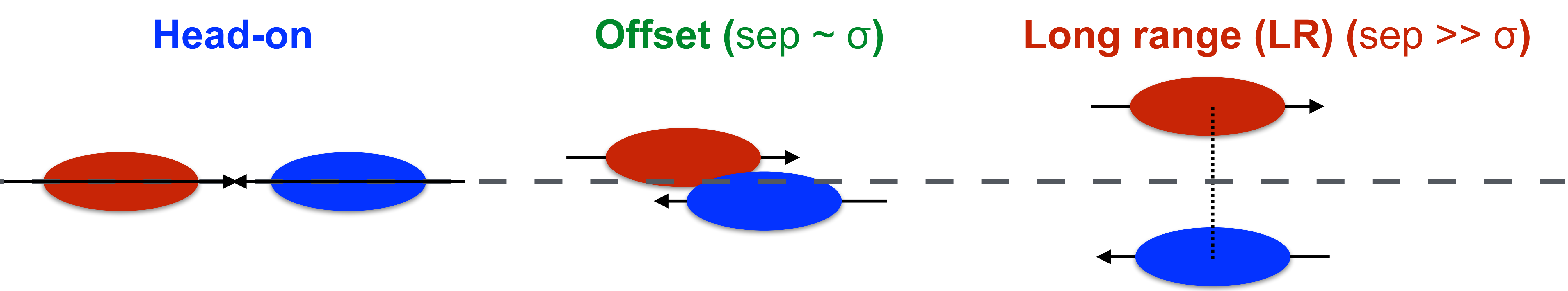
# The Beam-Beam force

**Stronger for high brightness beams**

Deflection of a test particle due to the Beam-Beam force (incoherent):

$$\Delta x' = -\frac{2r_0 N}{\gamma}\frac{x}{r^2}(1 - e^{-\frac{r^2}{2\sigma^2}})$$



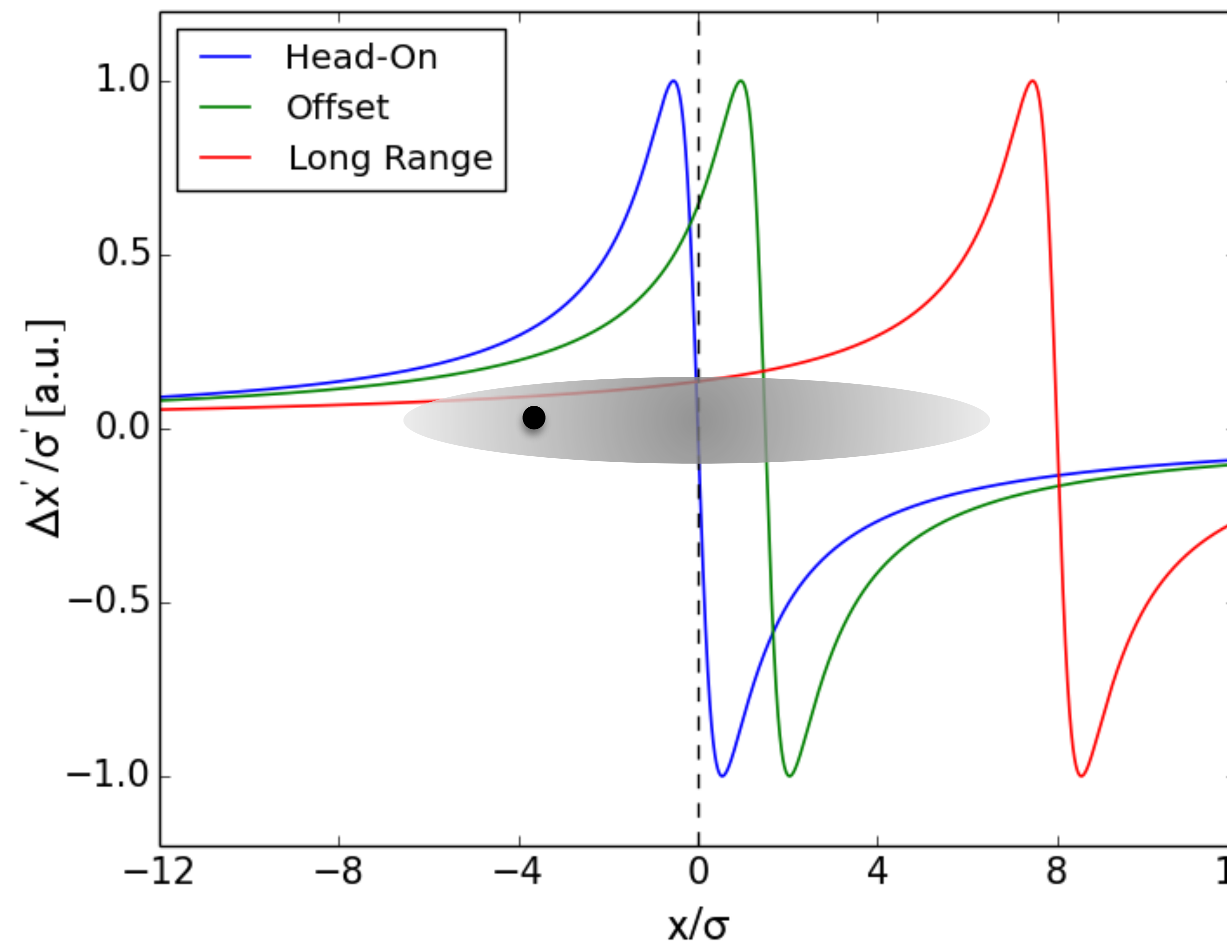



# The Beam-Beam force

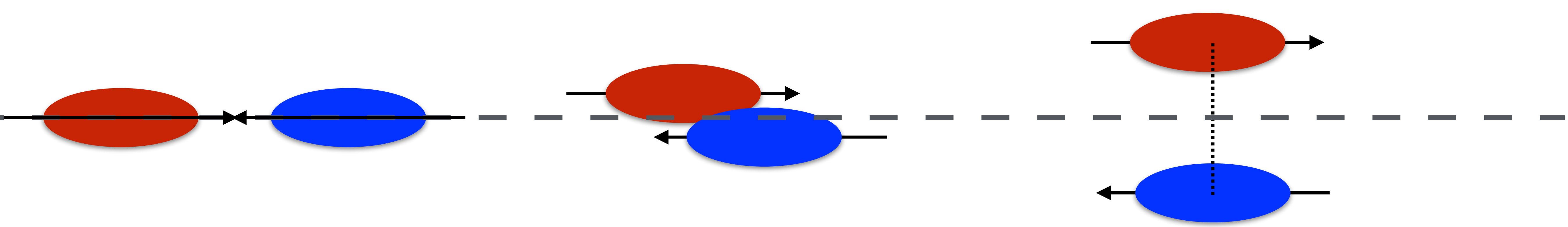
**Stronger for high brightness beams**

Deflection of a test particle due to the Beam-Beam force (incoherent):

$$\Delta x' = -\frac{2r_0 N}{\gamma}\frac{x}{r^2}\left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)$$



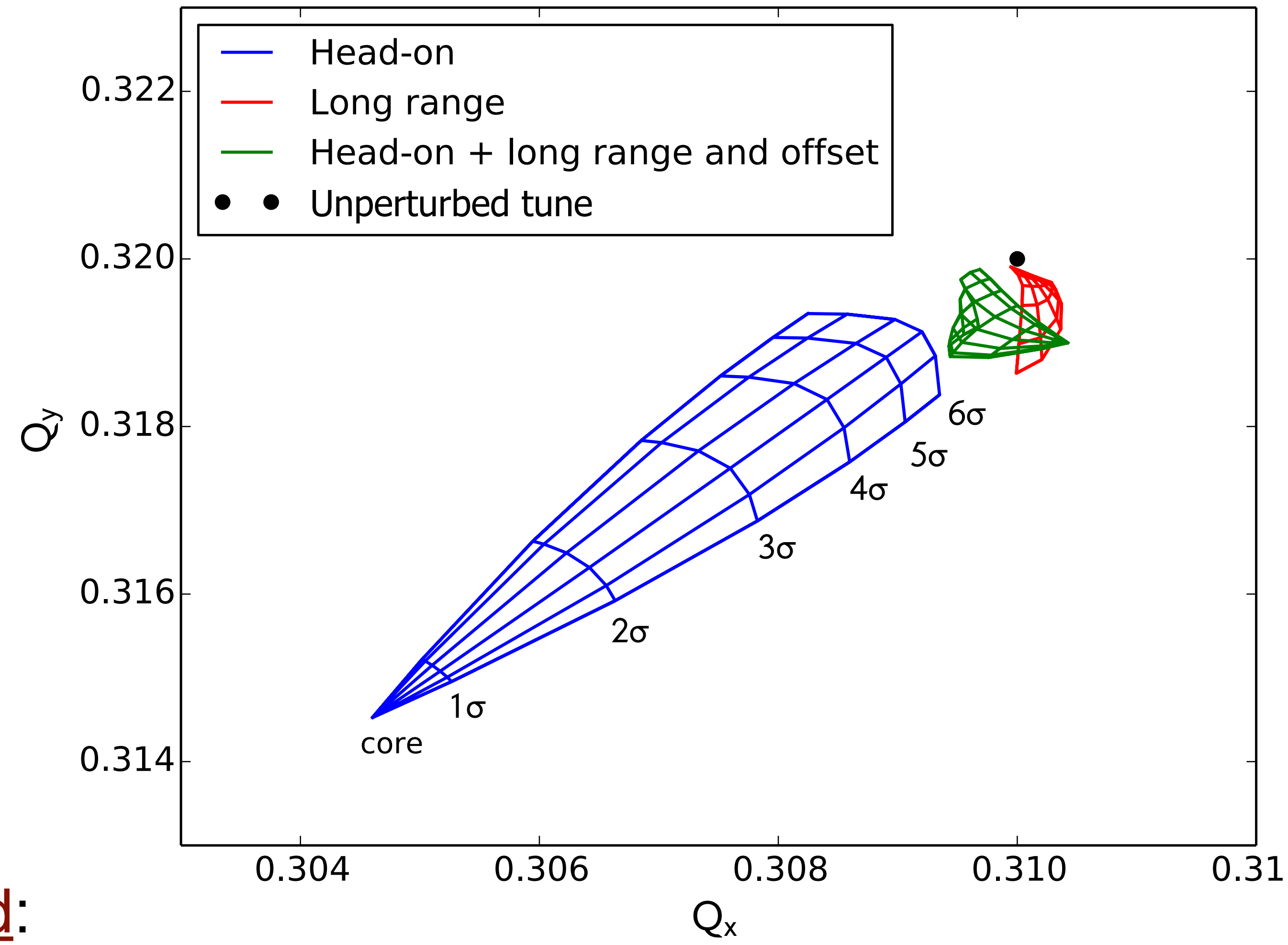

**Head-on** **Offset** (sep ~ σ) **Long range (LR)** (sep >> σ)



# Beam-Beam incoherent effects

- Particles with different amplitudes oscillate at different betatron frequencies → **detuning with amplitude (tune spread)**
- Each type of beam-beam interaction (LR, HO) produces different incoherent effects

**Tune Footprint with beam-beam**



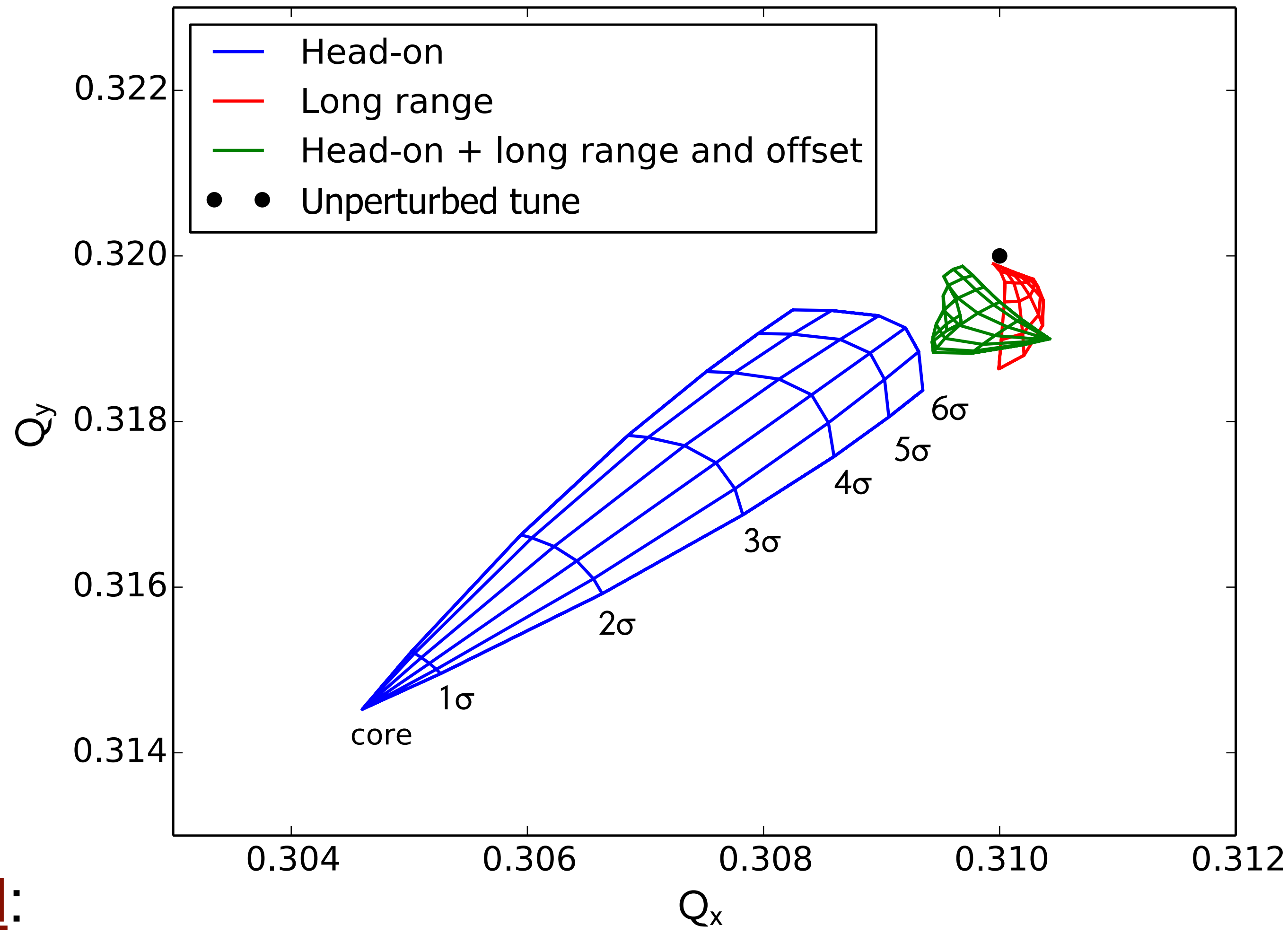

Some sources of (transverse) tune spread:

- Beam-beam interaction (**strongest**)
- Octupole magnets ➔ Used to provide Landau damping in the LHC

# Beam-Beam incoherent effects

- Particles with different amplitudes oscillate at different betatron frequencies → **detuning with amplitude (tune spread)**
- Each type of beam-beam interaction (LR, HO) produces different incoherent effects

**Tune Footprint with beam-beam**



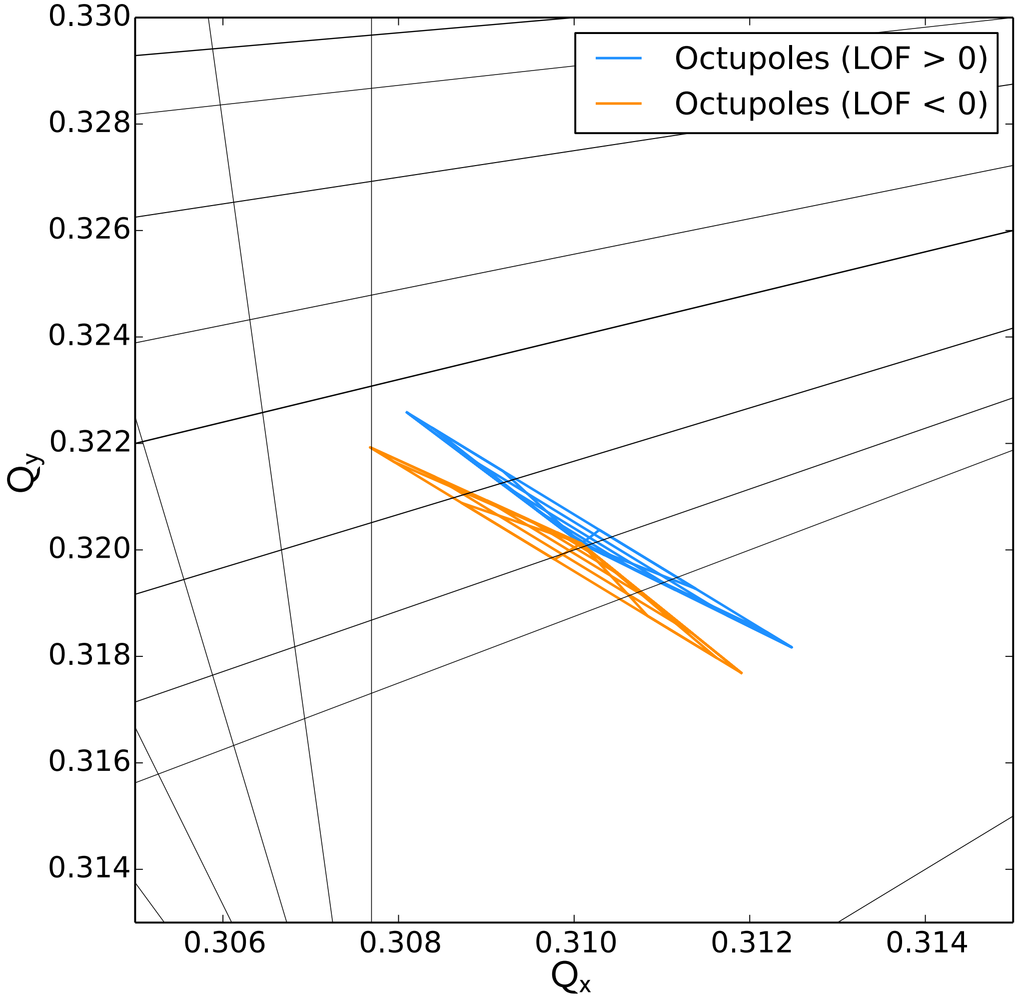

Some sources of (transverse) tune spread:

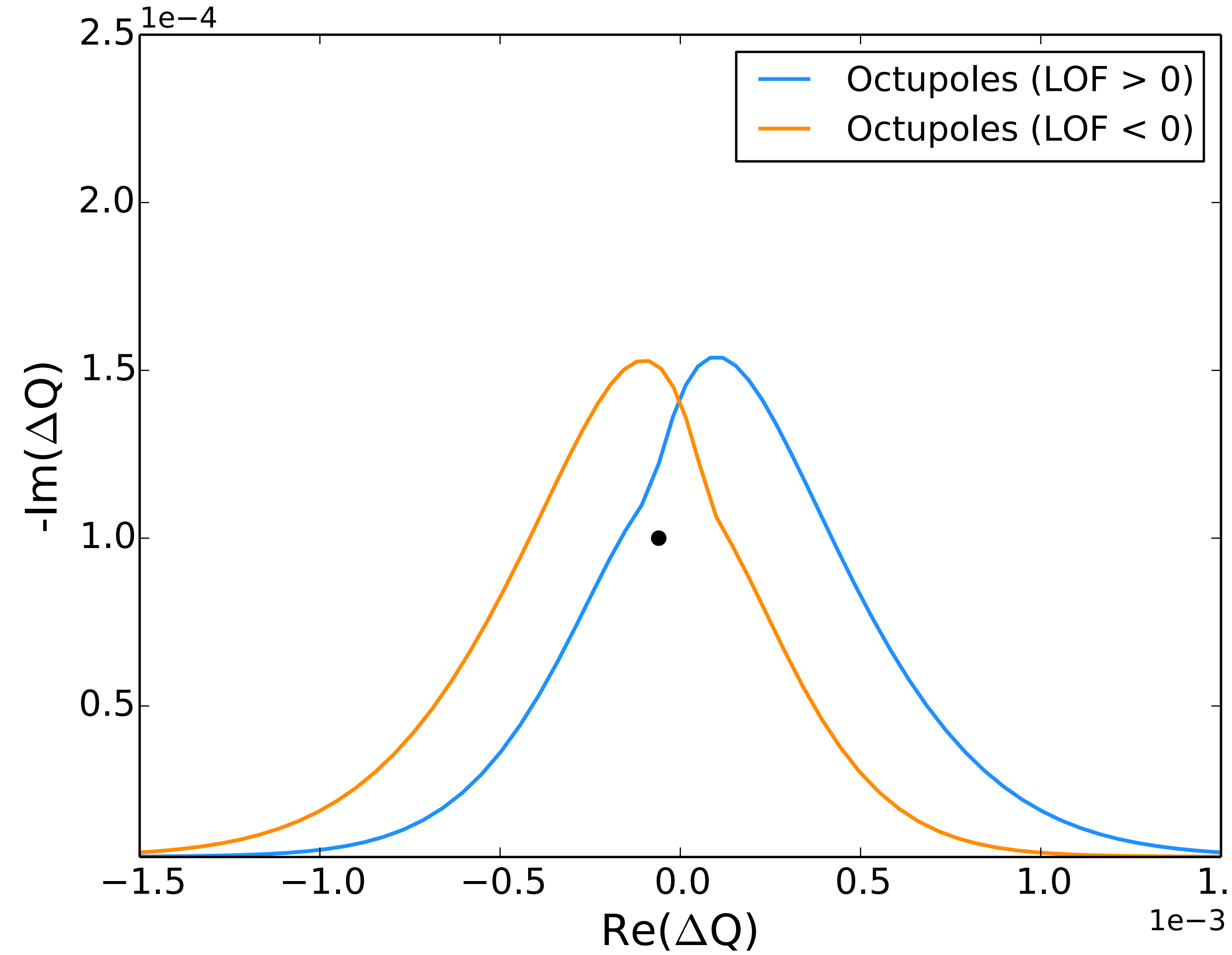
- Beam-beam interaction (**strongest**)
- Octupole magnets ➔ Used to provide Landau damping in the LHC

Beam-beam interactions modify the stability provided by the Landau octupoles

# Transverse stability in presence of beam-beam interaction

## FCC case (50 TeV)

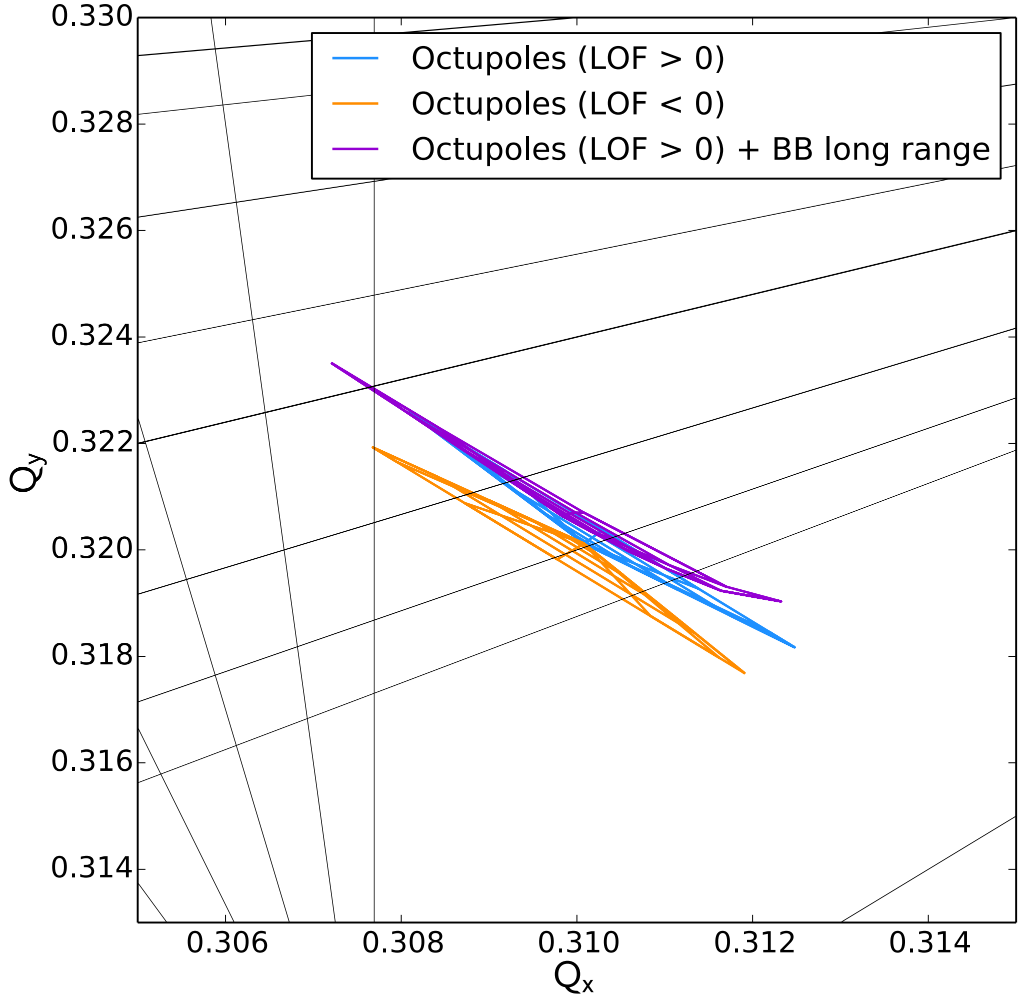


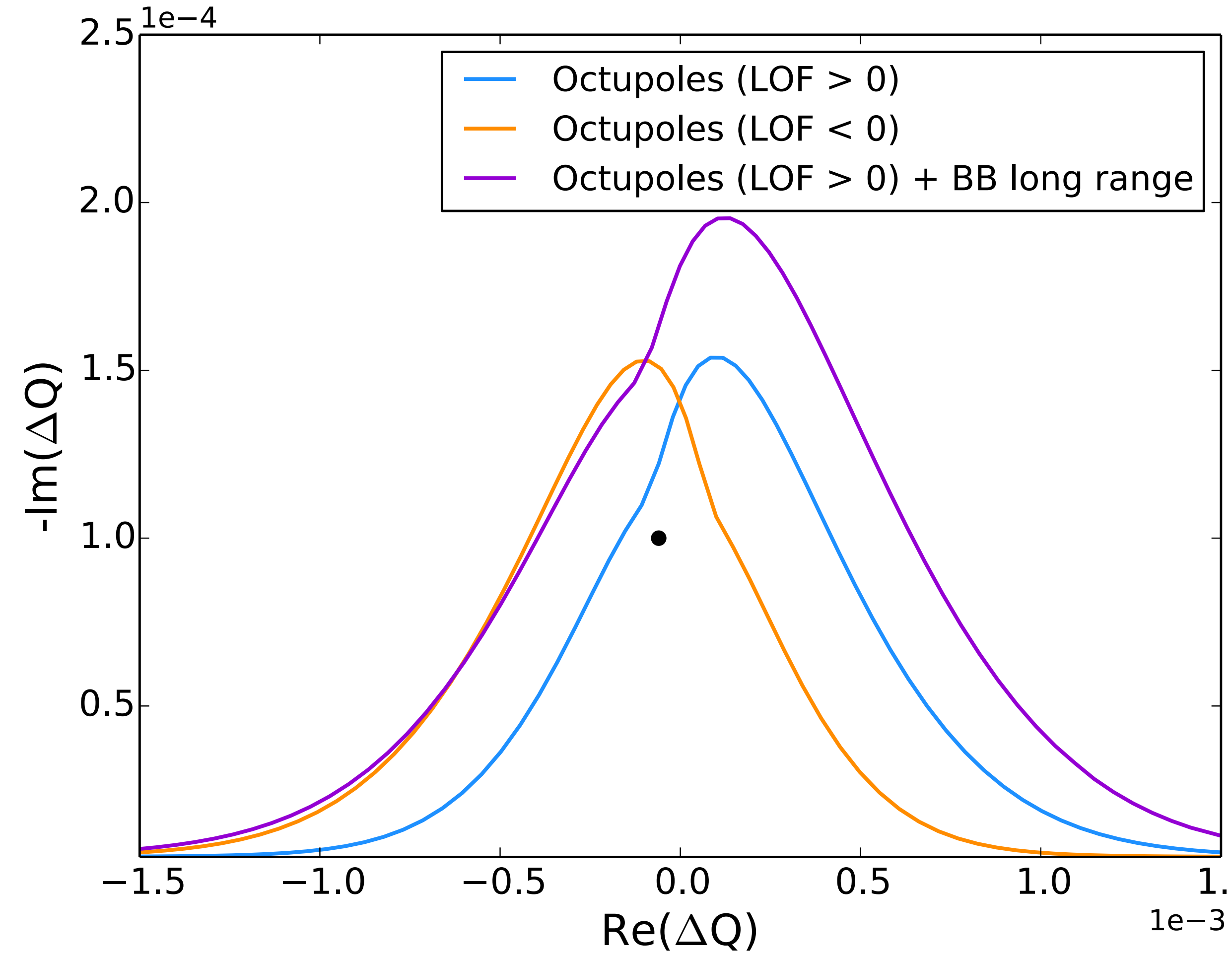




- The octupoles strength is chosen to provide sufficient tune spread to damp coherent impedance mode in the complex plane
- According to octupoles polarity the tune footprint is reversed
- Negative polarity (LOF < 0) provides larger stability than positive polarity

# Transverse stability in presence of beam-beam interaction

## FCC case (50 TeV)

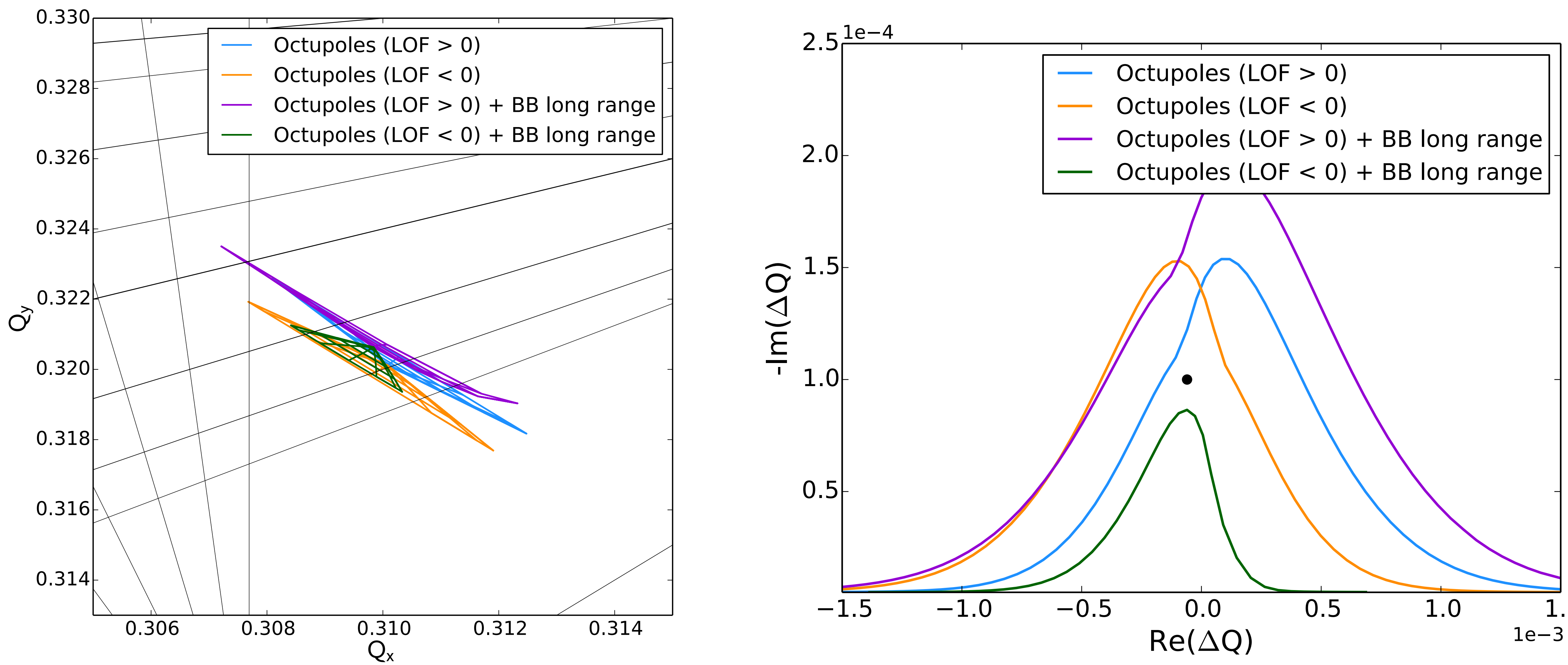



- Beam beam long range interaction (end of squeeze configuration) modifies the stability provided by the Landau octupoles
- With positive octupole polarity and BB long range interactions ➔ the stability with negative polarity is recovered

# Transverse stability in presence of beam-beam interaction

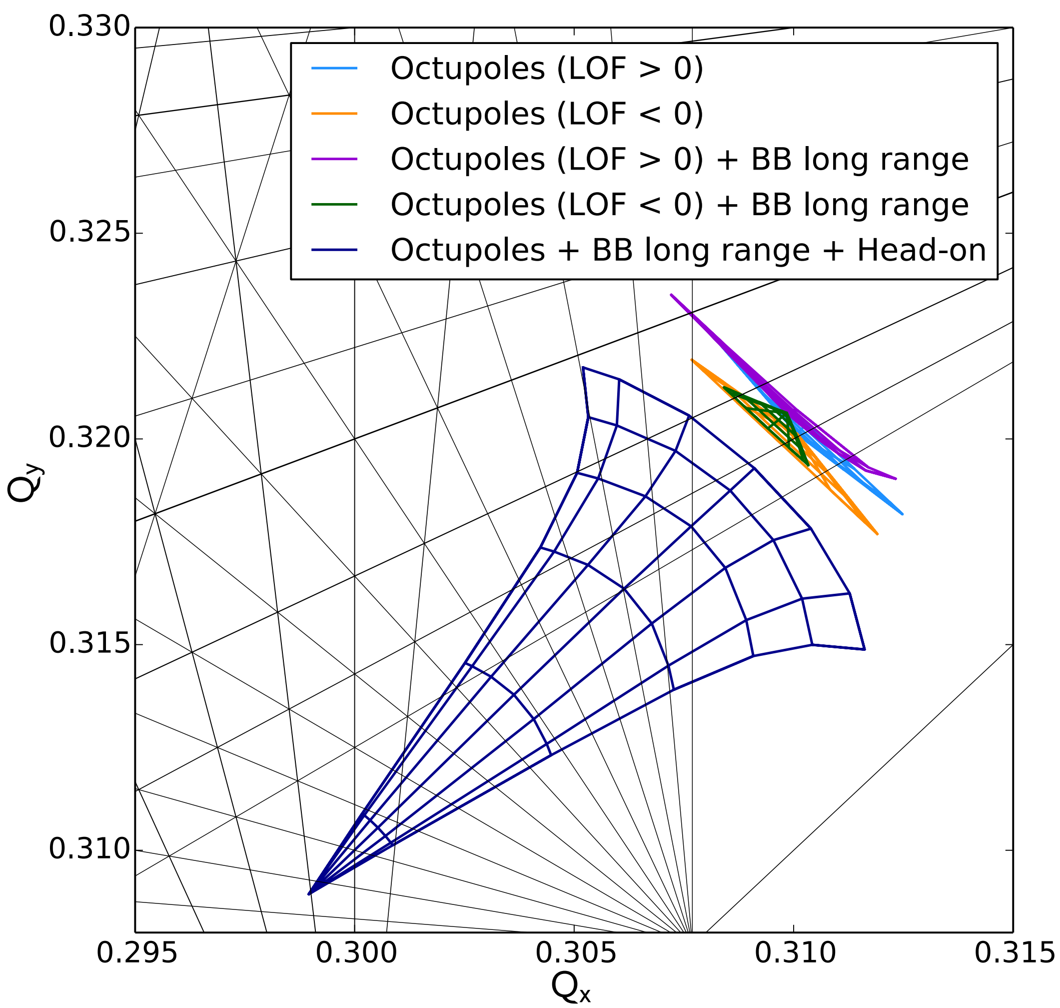
## FCC case (50 TeV)

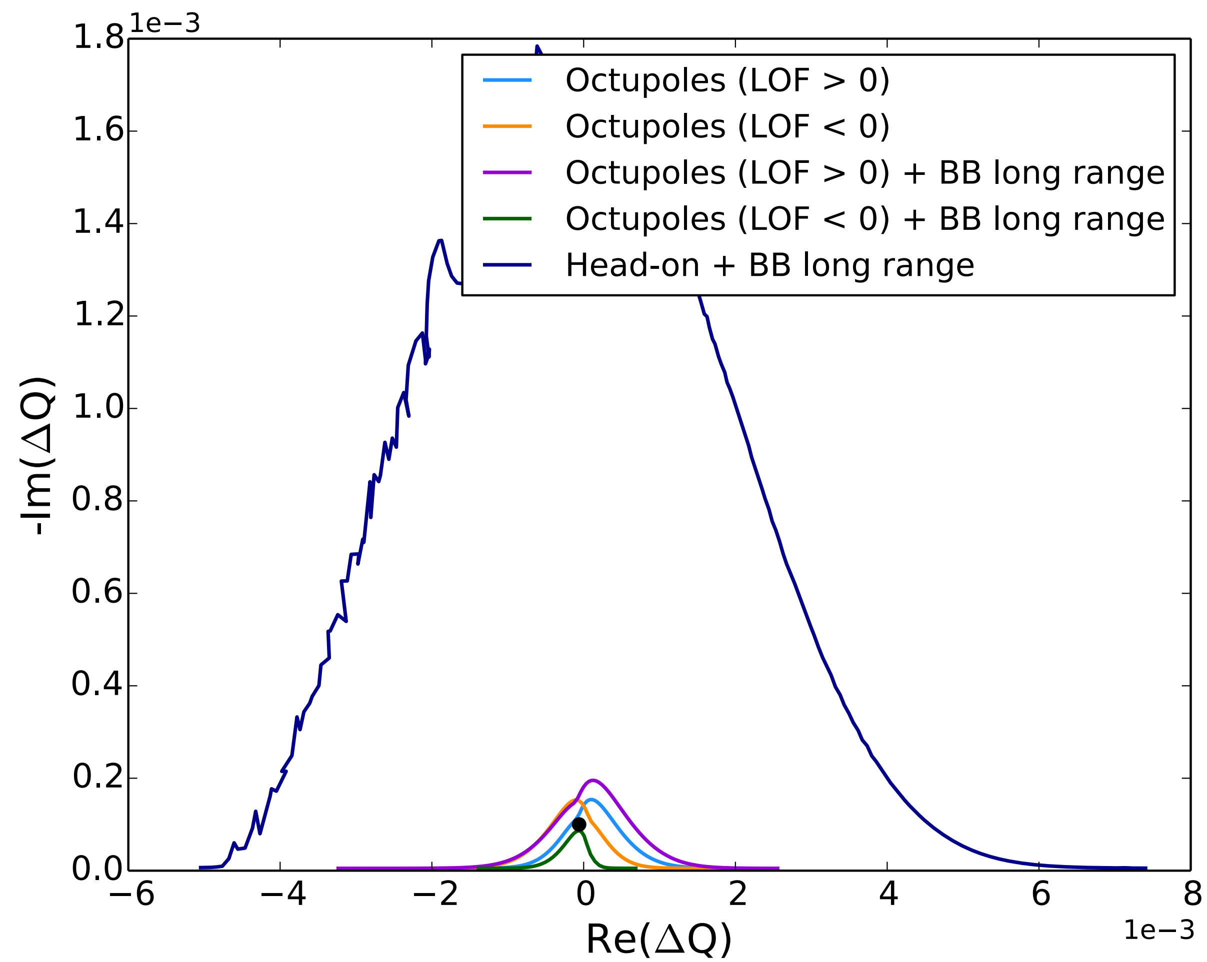



- With negative octupole polarity and BB long range interactions, the stability is strongly reduced ➔ **the expected coherent impedance mode is not Landau damped**

# Transverse stability in presence of beam-beam interaction

## FCC case (50 TeV)




- The large tune spread caused by the beam-beam head-on interaction (most effective because core particles are involved) provides the largest stability [3]

[3] X. Buffat et *al.*, *Stability diagrams of colliding beams in the Large Hadron Collider*, PRSTAB 111002 (2014)

# BTF to measure transverse beam stability

**B**eam **T**ransfer **F**unction measurements are direct measurements of the dispersion integral

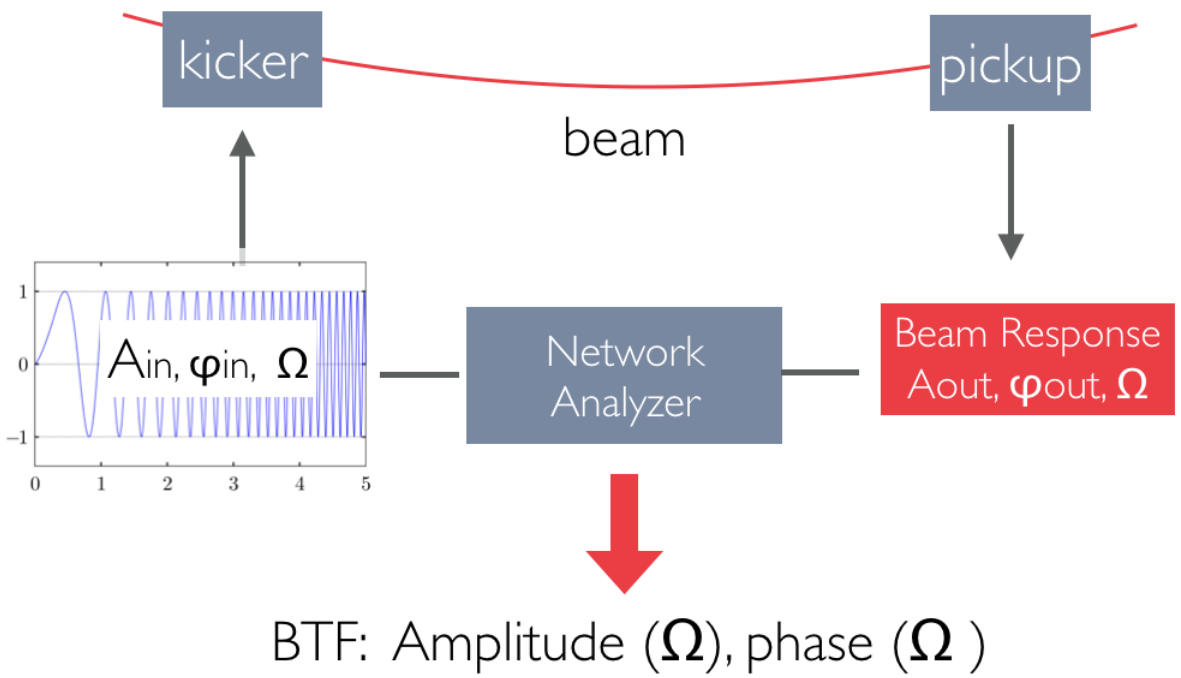
$$\mathrm{BTF} \propto \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x,J_y) - i\epsilon} dJ_x dJ_y$$

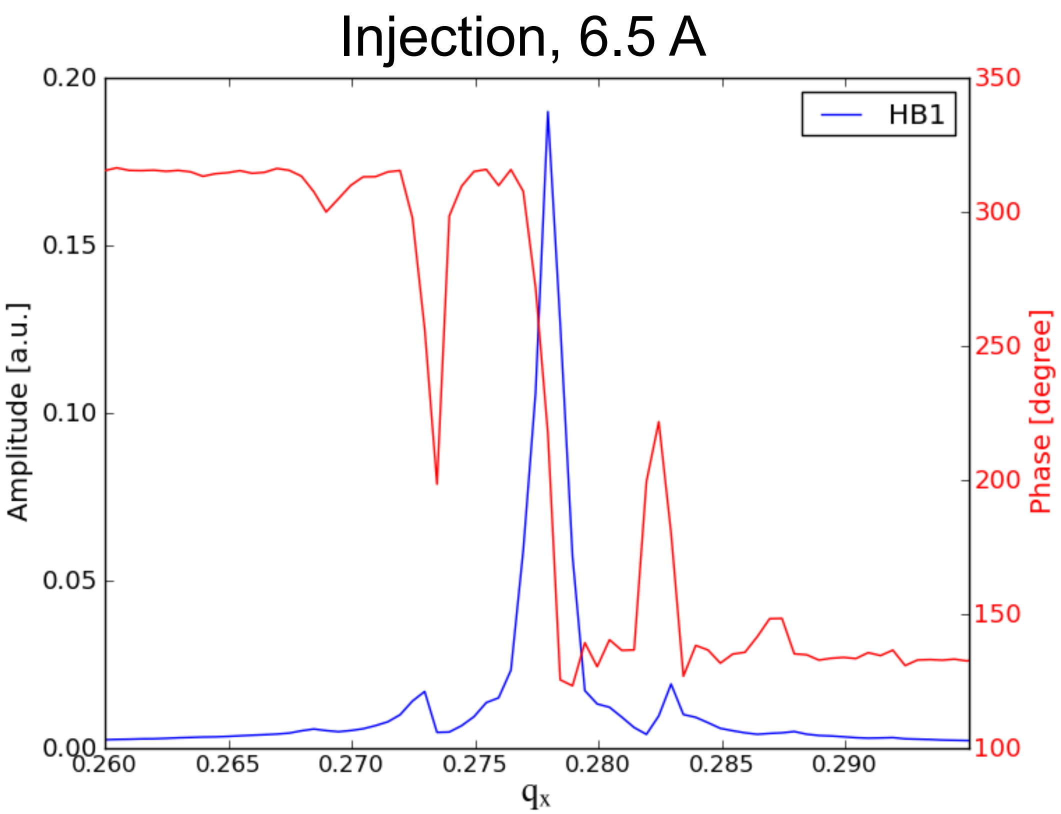
**BTF can experimentally verify the stability → direct measurements of SD!**

- Tune (high resolution, operationally used at RHIC), chromaticity measurements
- Coherent mode observations
- **Sensitive to particle distribution changes**
- **Tune spread of the beams**

# The transverse BTF system at the LHC

**Beam Transfer Function:**
beam amplitude response per driving excitation frequency




- Installed in **LHC** in the 2015 for the **first time**
- Small excitation, **small impact on the beam quality**
- **Uncalibrated system (dependency on measurement conditions)**

# Stability diagram reconstructed from BTFs in the LHC

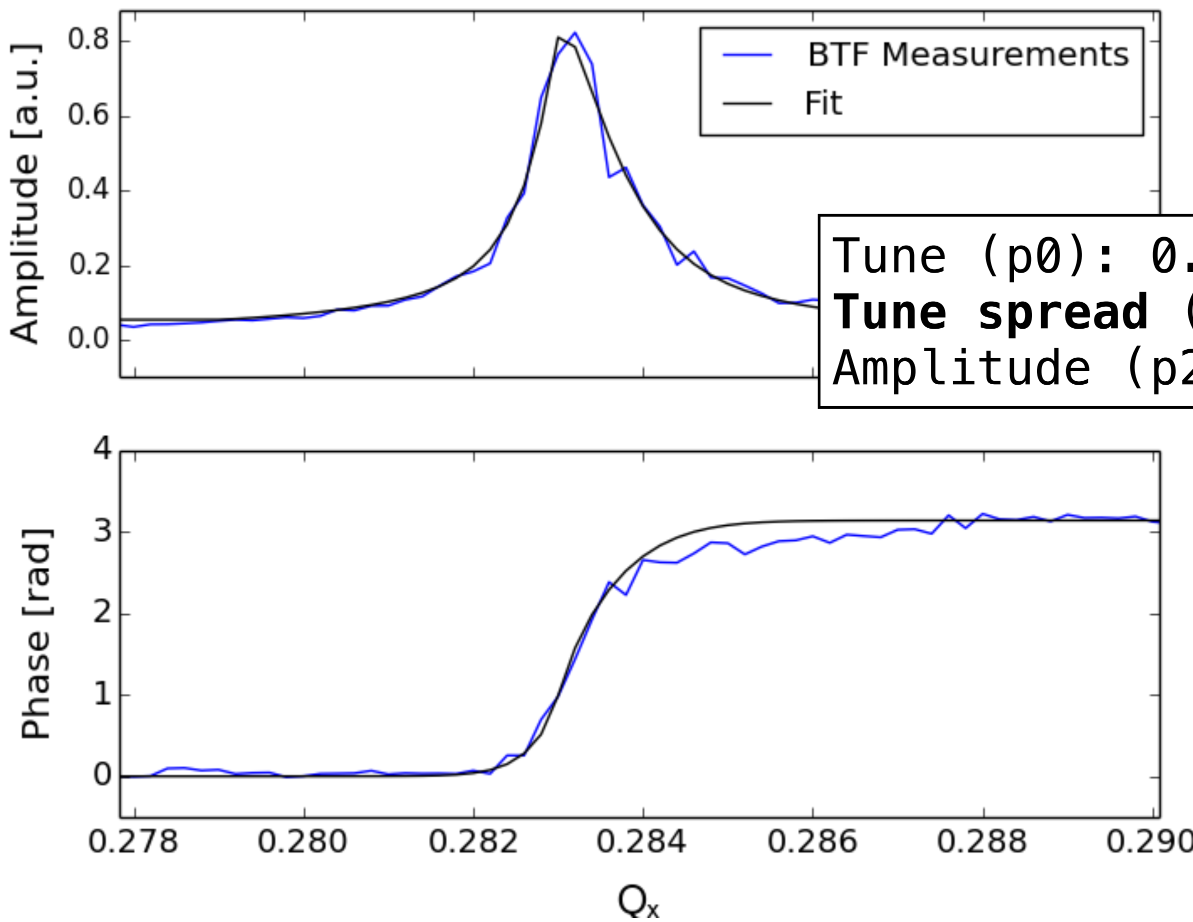
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

CERN

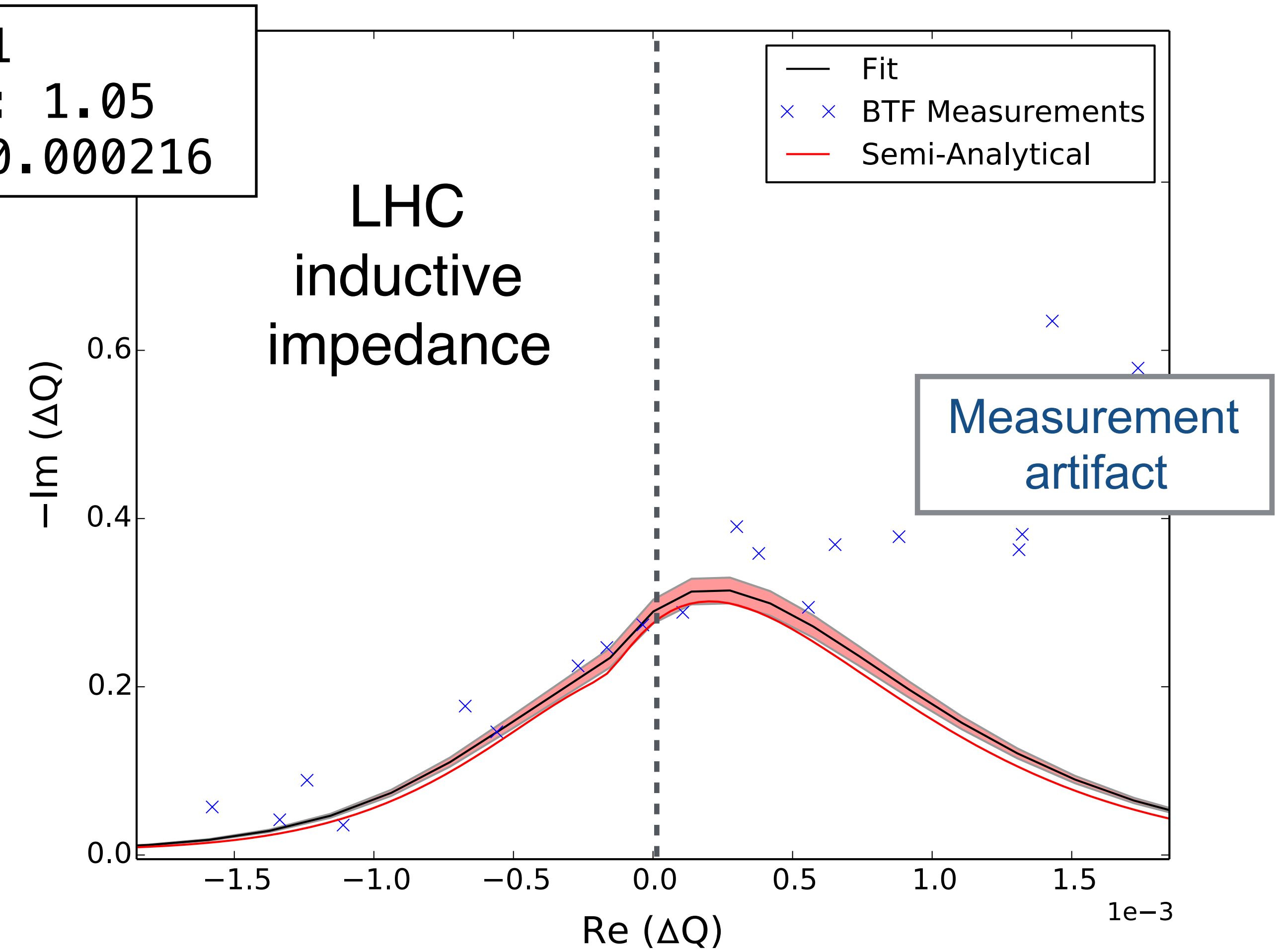
$$Q_{fit} = p_0 + p_1 \cdot (Q_{analyt} - Q_0)$$

$$A_{fit} = p_2 / p_1 \cdot A_{analyt}$$

Single bunch, Injection, 6.5 A (2016)



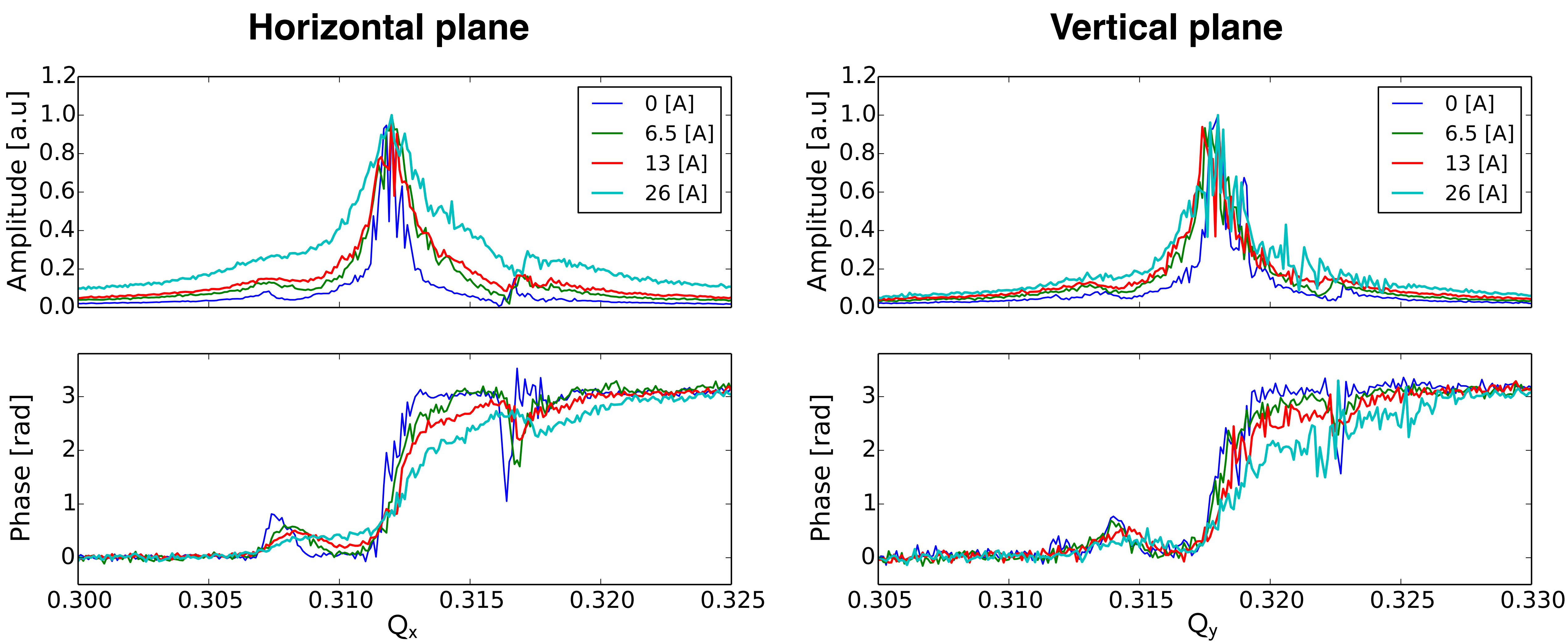

Tune (p0): 0.2831
**Tune spread** (p1): 1.05
Amplitude (p2): 0.000216




**Good agreement between measurements and expectations for the 2016 measurements**

# Single beam: stability at injection

Tune spread given by Landau octupoles and lattice non linearities

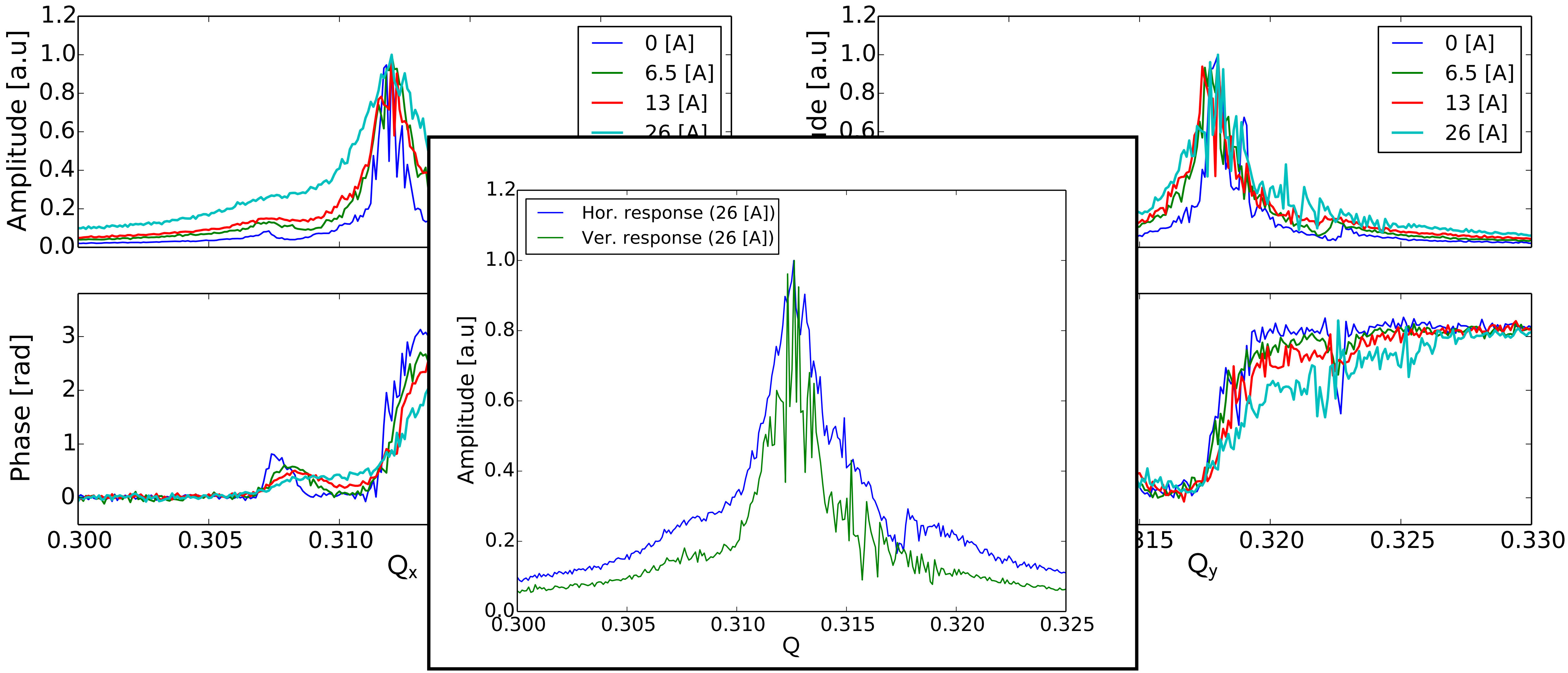



For the largest octupole strength (26 A) larger spread in the horizontal plane, smaller in the vertical plane

# Single beam: stability at injection

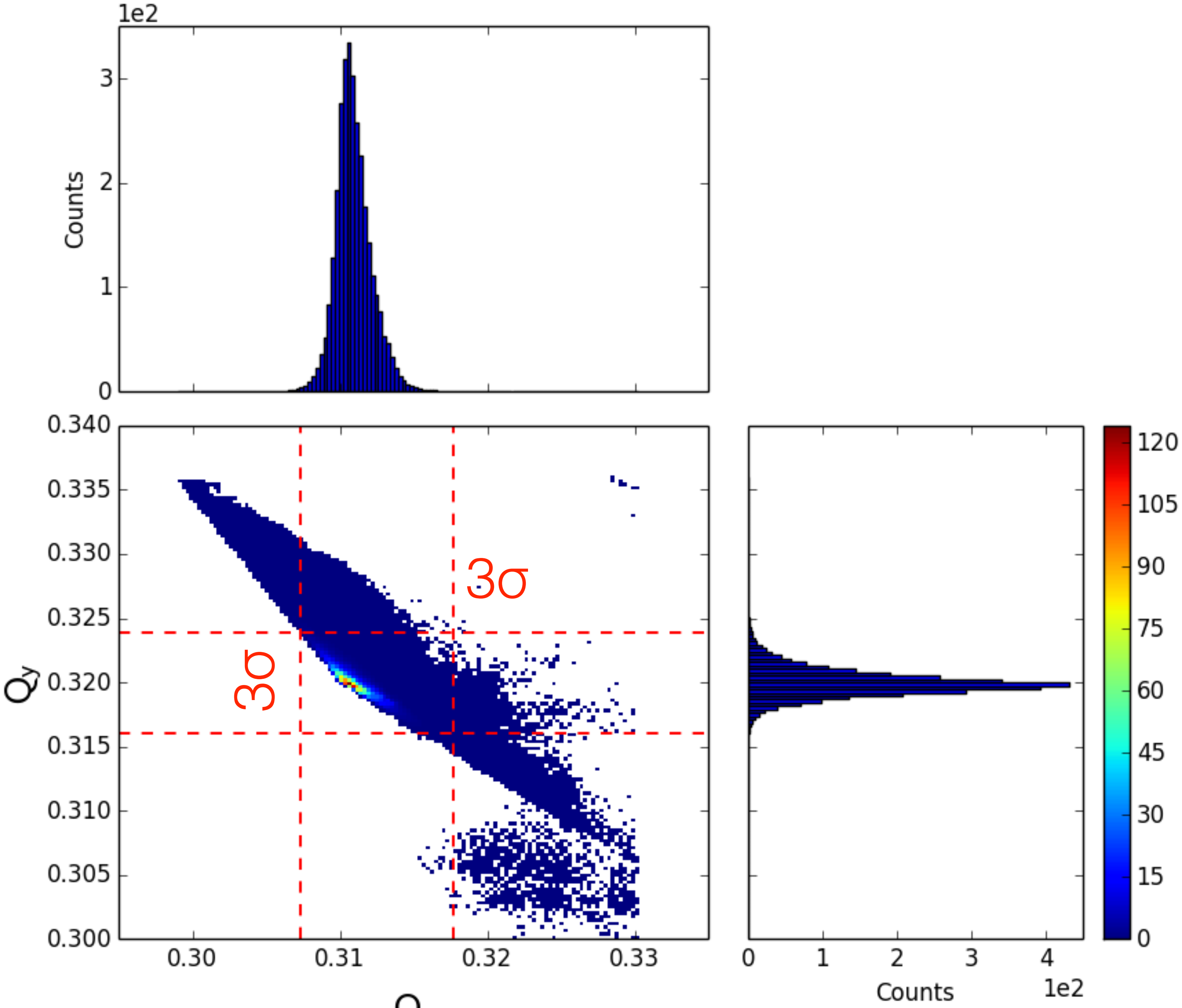
Tune spread given by Landau octupoles and lattice non linearities

**Horizontal plane** **Vertical plane**



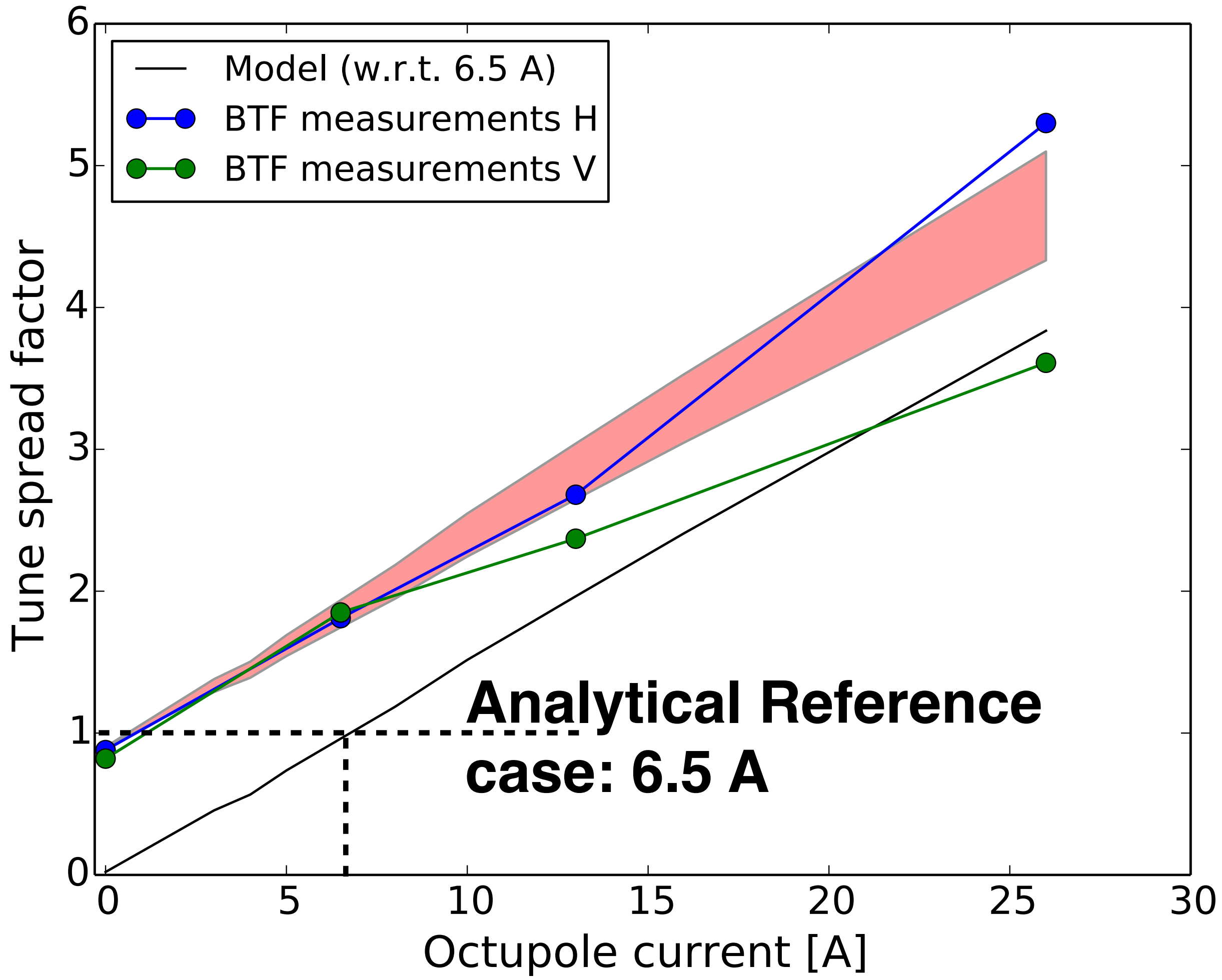

For the largest octupole strength (26 A) larger spread in the horizontal plane, smaller in the vertical plane

# Frequency distribution at injection for 26 A octupole current



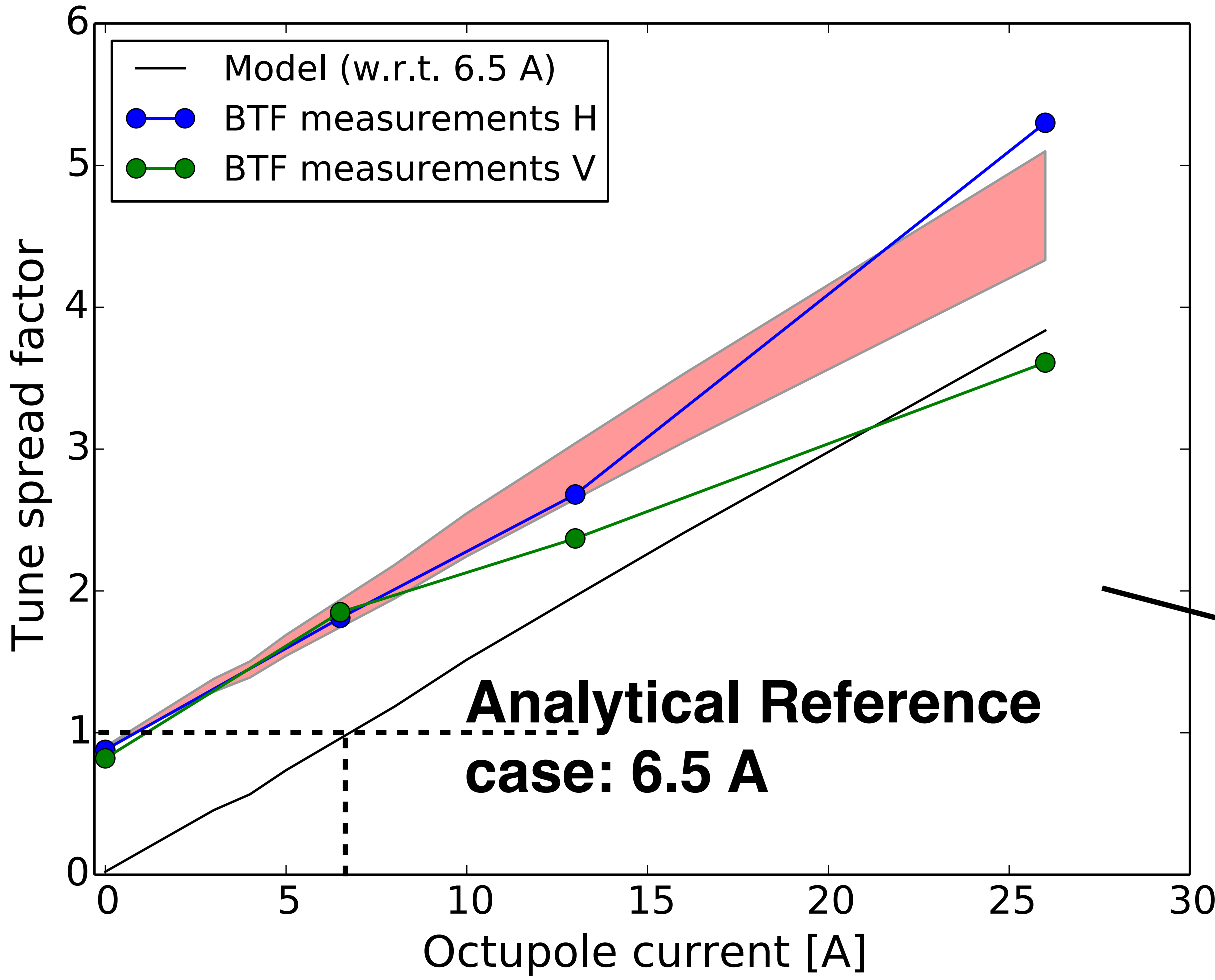

No drastic change in the frequency distribution and it can not explain H-V BTF asymmetry

# Octupole scan at injection: evaluation of beam tune spread



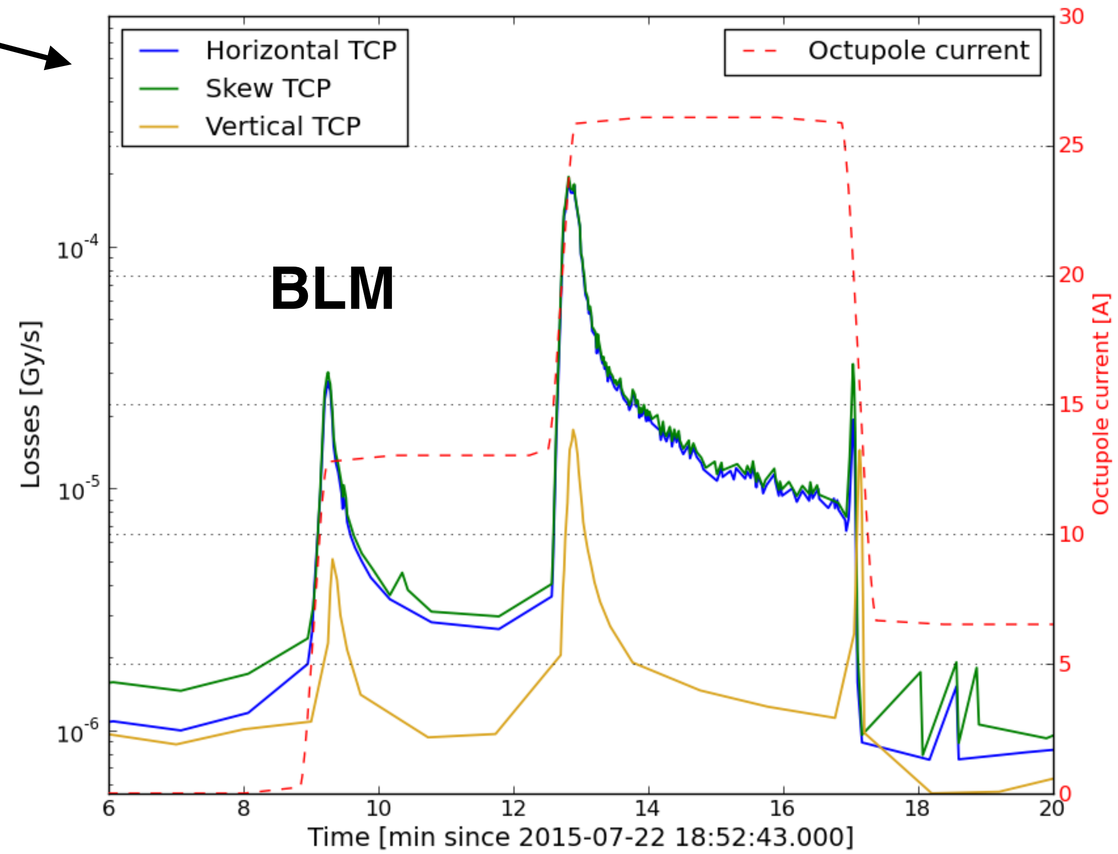

- Fitting method to compare measurements and expectations from model (tune spread factor)
- Case with no octupoles: consistent with optics measurements in the 2015
- Linear trend reproduced

# Octupole scan at injection: evaluation of beam tune spread



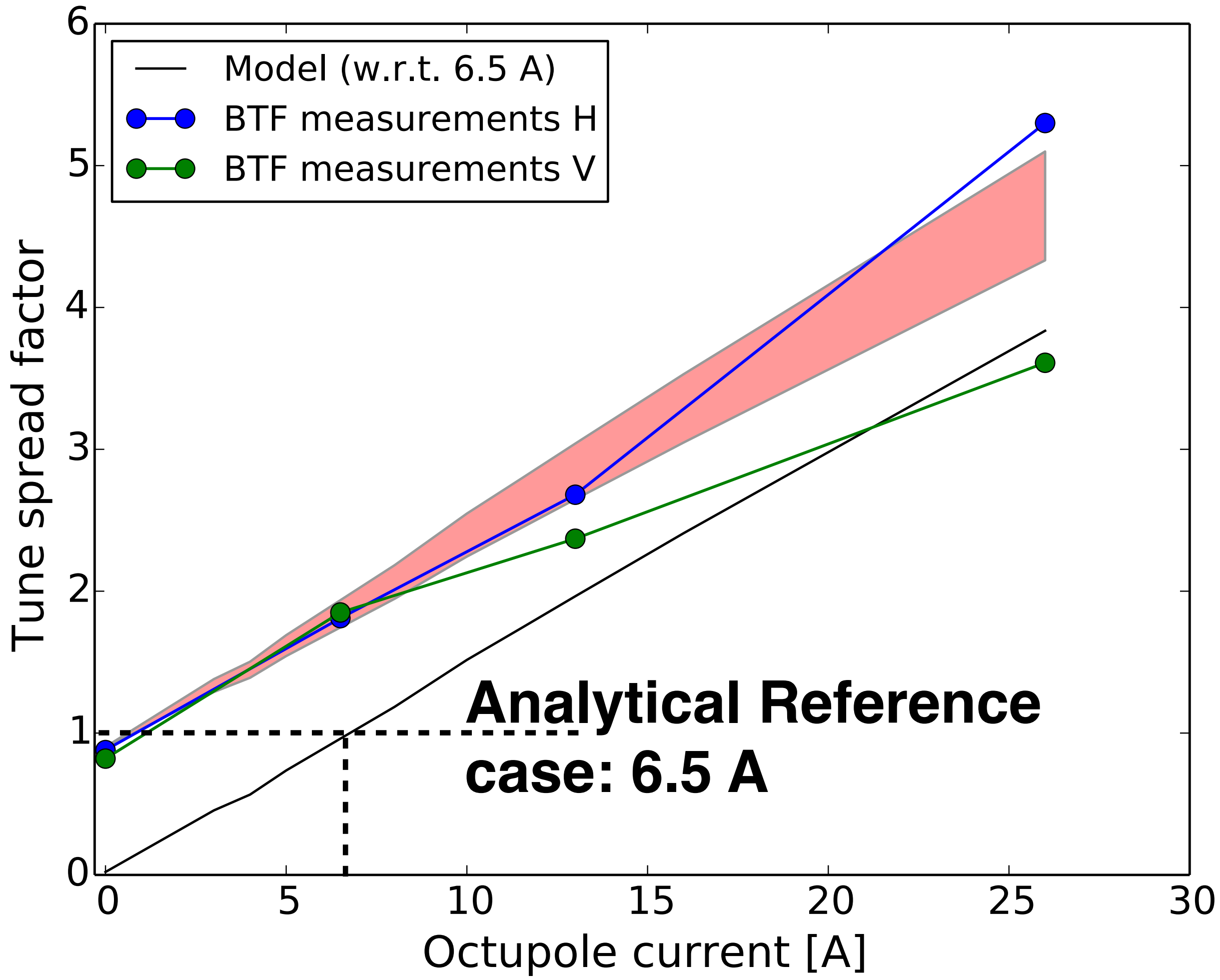

- Fitting method to compare measurements and expectations from model (tune spread factor)
- Case with no octupoles: consistent with optics measurements in the 2015
- Linear trend reproduced

**Losses observed in the vertical plane correlated with octupole current changes**

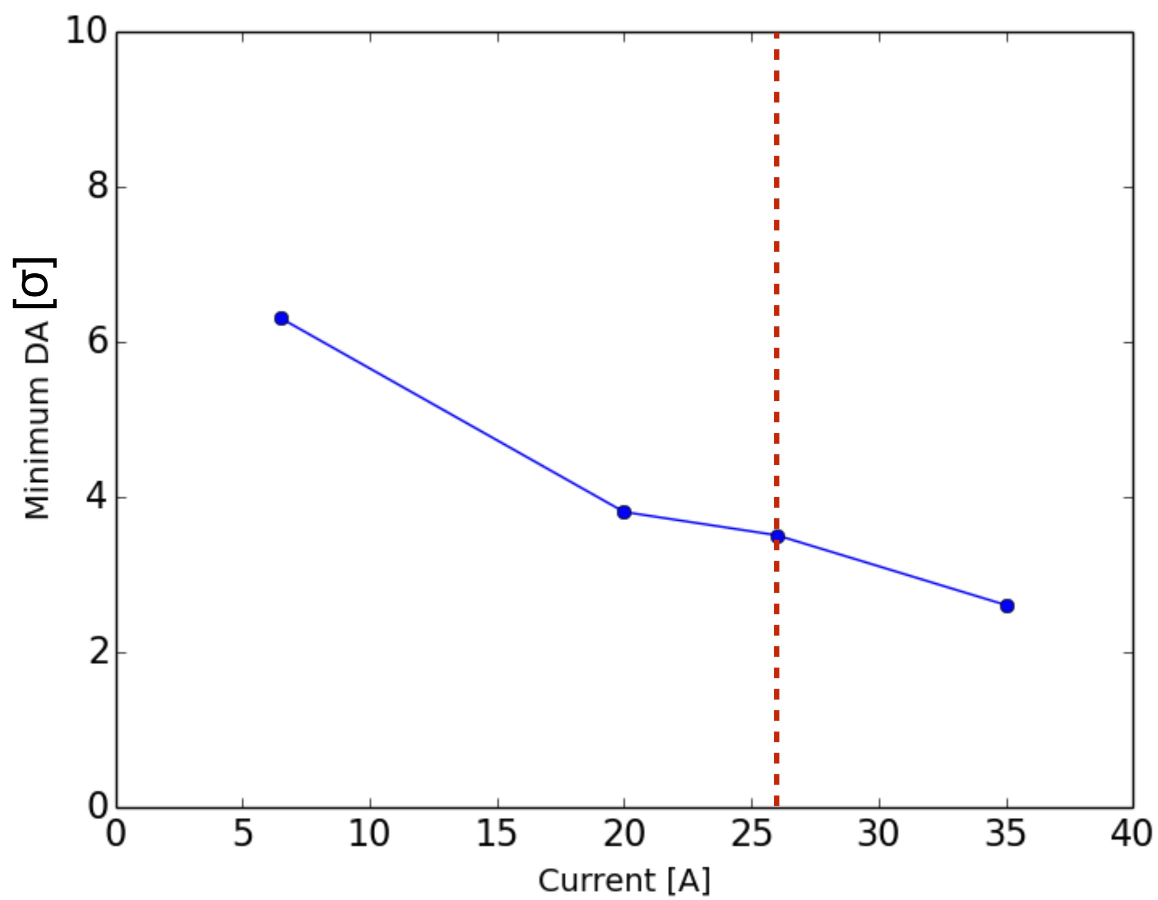



Losses very low➔ **negligible impact on beam lifetimes and collimation system**

# Octupole scan at injection: evaluation of beam tune spread




- Fitting method to compare measurements and expectations from model (tune spread factor)
- Case with no octupoles: consistent with optics measurements in the 2015
- Linear trend reproduced

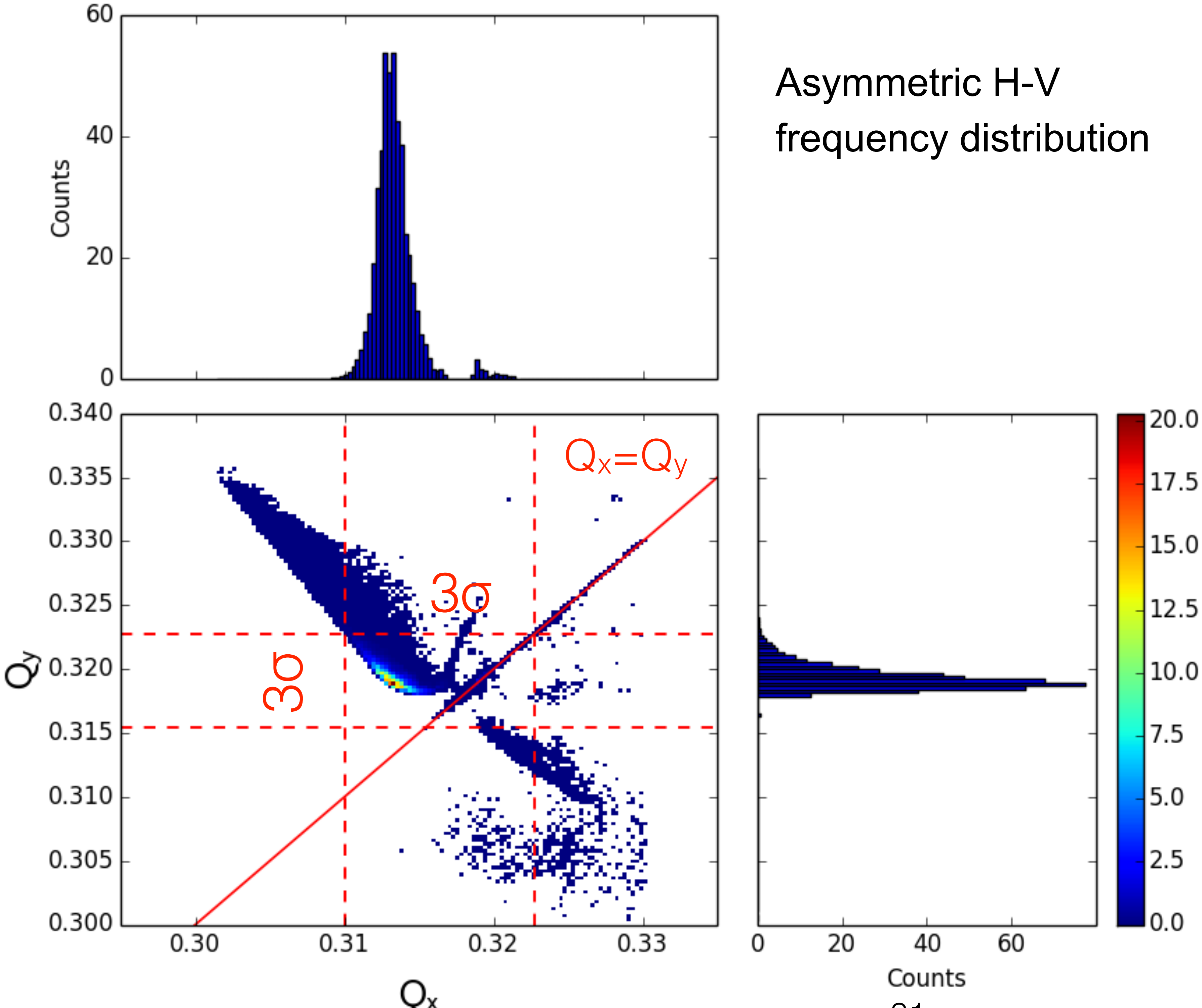



Losses observed as a function of octupole strength due to a reduction of DA

**→ Increasing the tune spread is beneficial for Landau damping as long as any diffusion mechanism is not present**

# Frequency distribution at injection with linear coupling

Effect of **linear coupling**: coupled motion between H-V plane

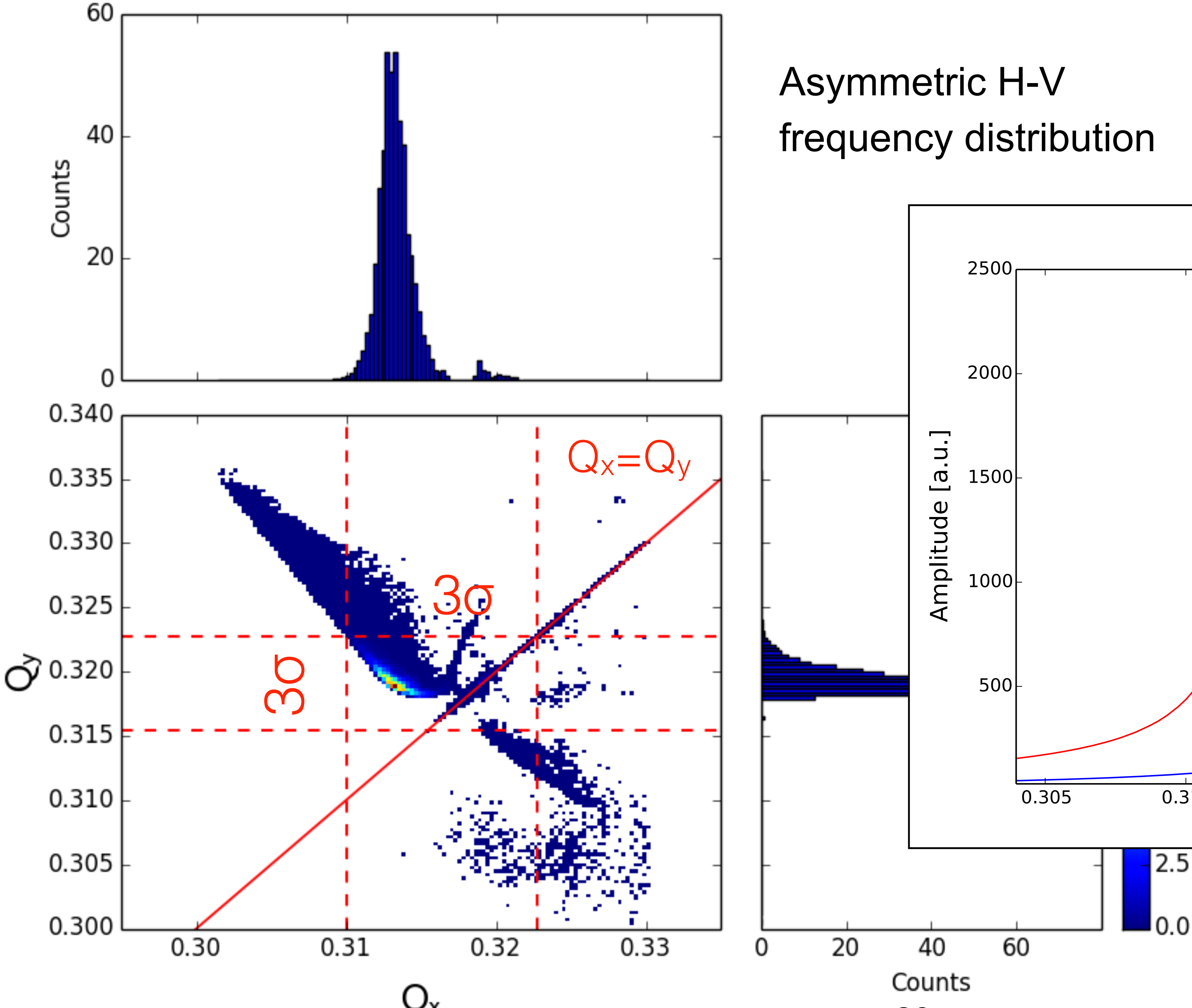


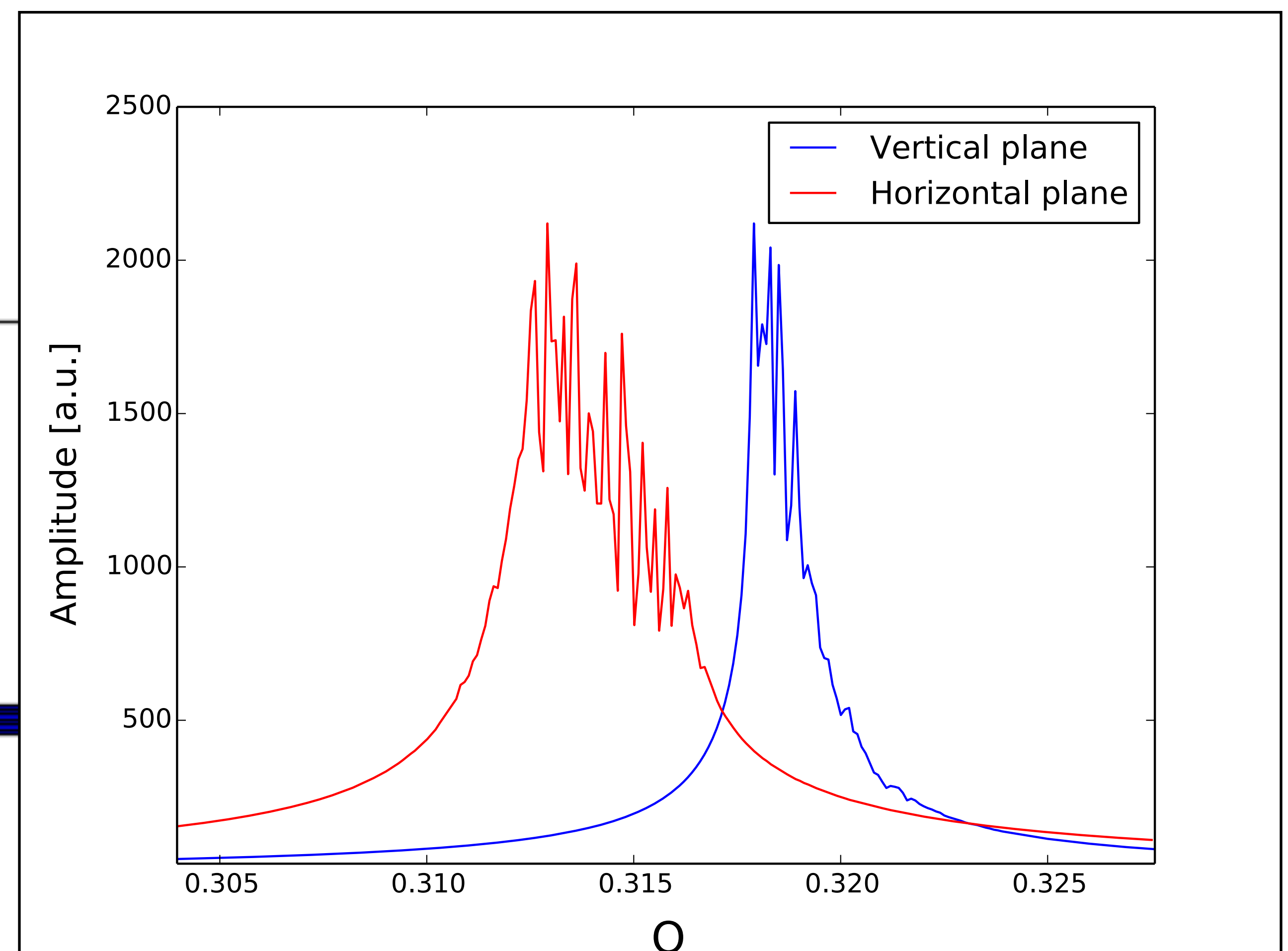

Asymmetric H-V frequency distribution

# Frequency distribution at injection with linear coupling

Effect of **linear coupling**: coupled motion between H-V plane

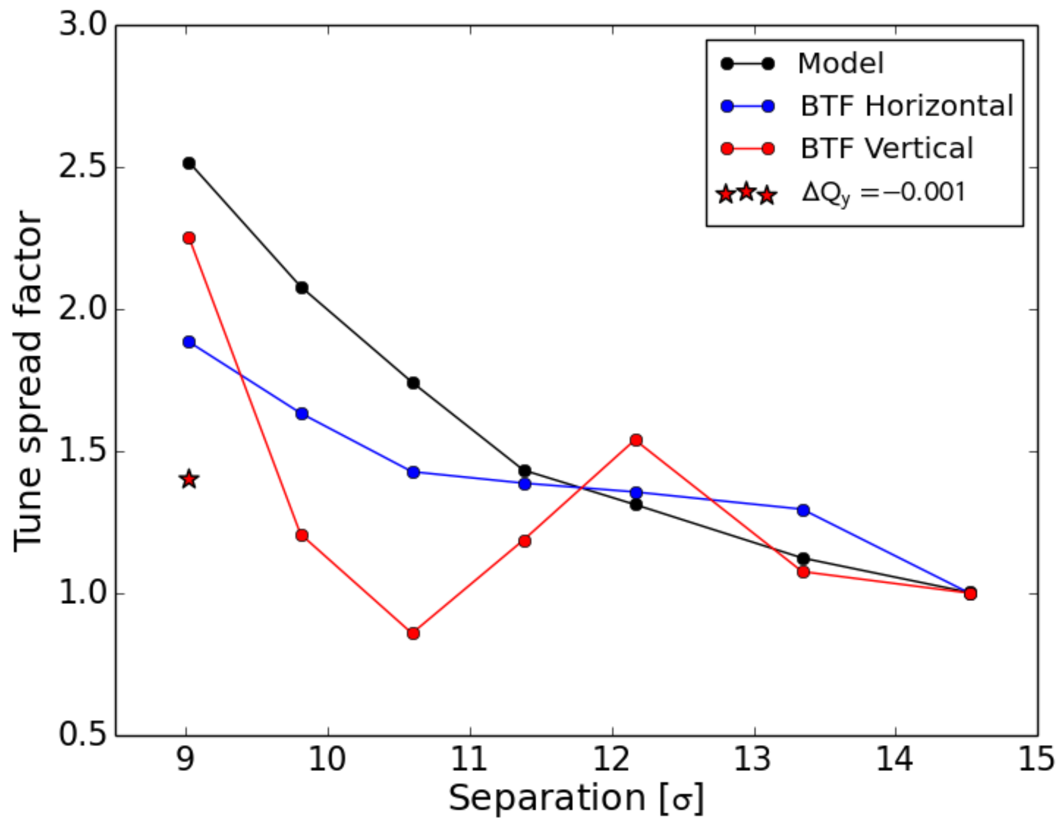
Asymmetric H-V frequency distribution



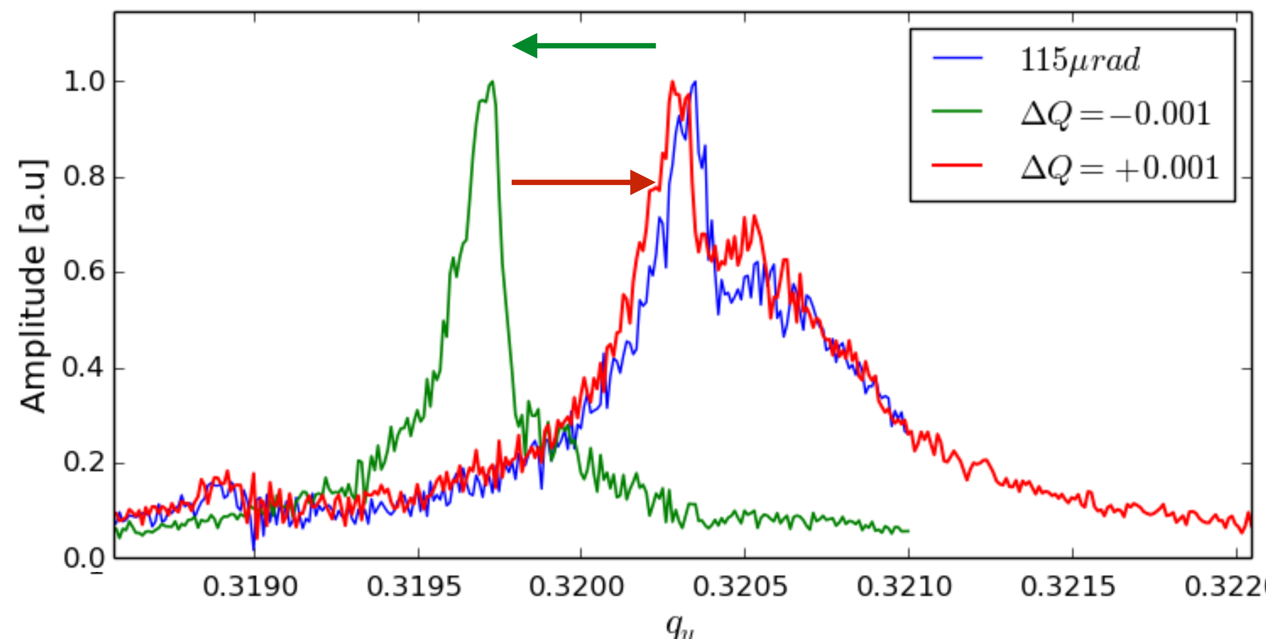



# Beam-beam long range interactions contribution to Landau damping

**Measured multi-bunch bb LR contribution on single bunch as a function of bb LR separation**




**Tune scan in V plane**

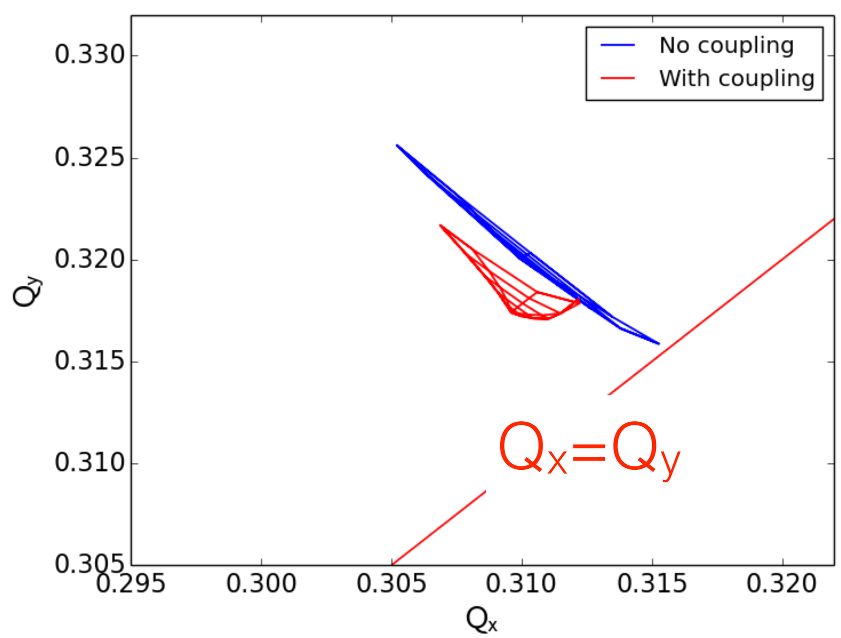


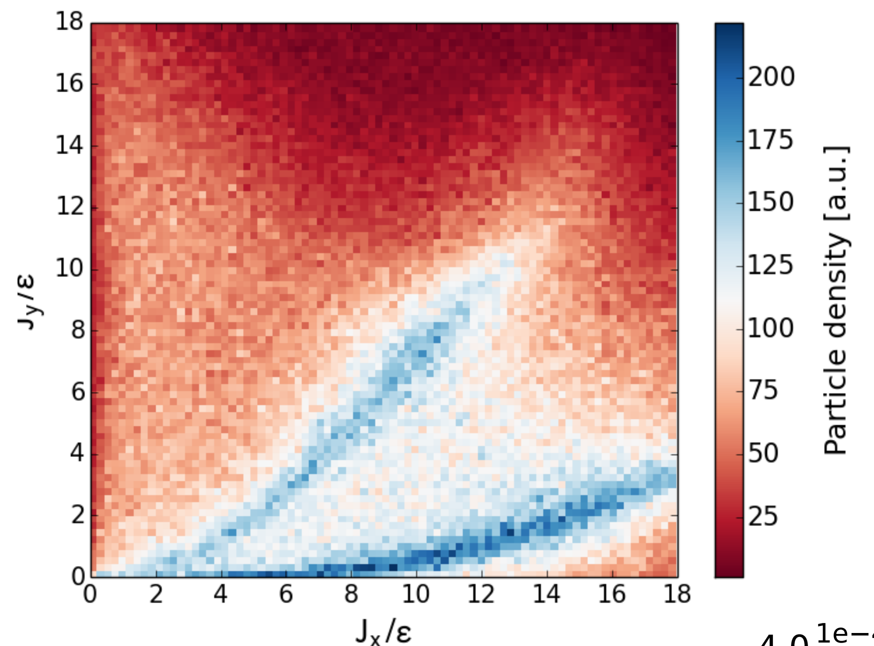

- Unexpected behavior respect to models
- Dependence on working point
- Not expected from models, it may have strong impact on actual Landau damping (stability diagram)

**→ Other mechanisms should play a role**

# Effects of linear coupling and BB long range interactions on Landau damping

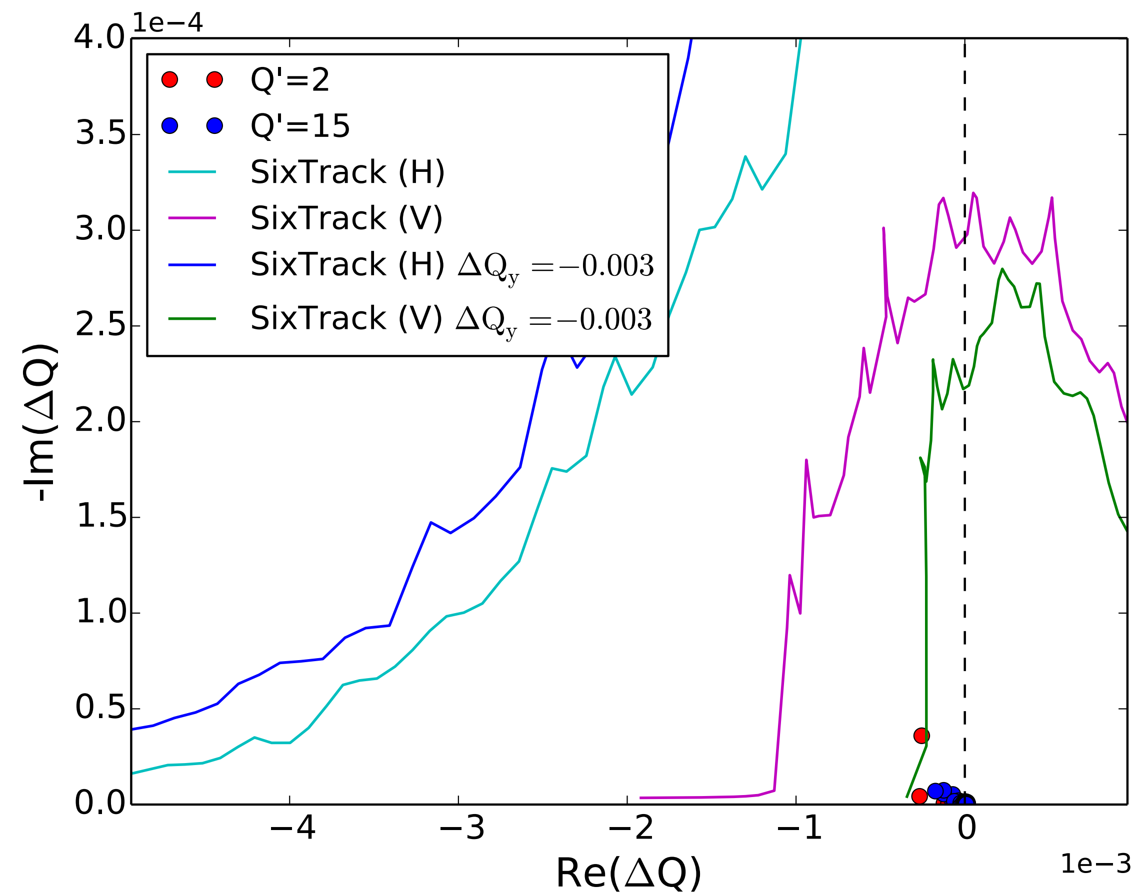
**Vertical tune shift: $\Delta Q_y$= -0.003**




Particles approach more the diagonal and the effects are stronger

- Large effects of working point
- Sharp cut visible in the vertical SD (0 - 3 σ particles approach the diagonal)
- Modes can become unstable



# Conclusions

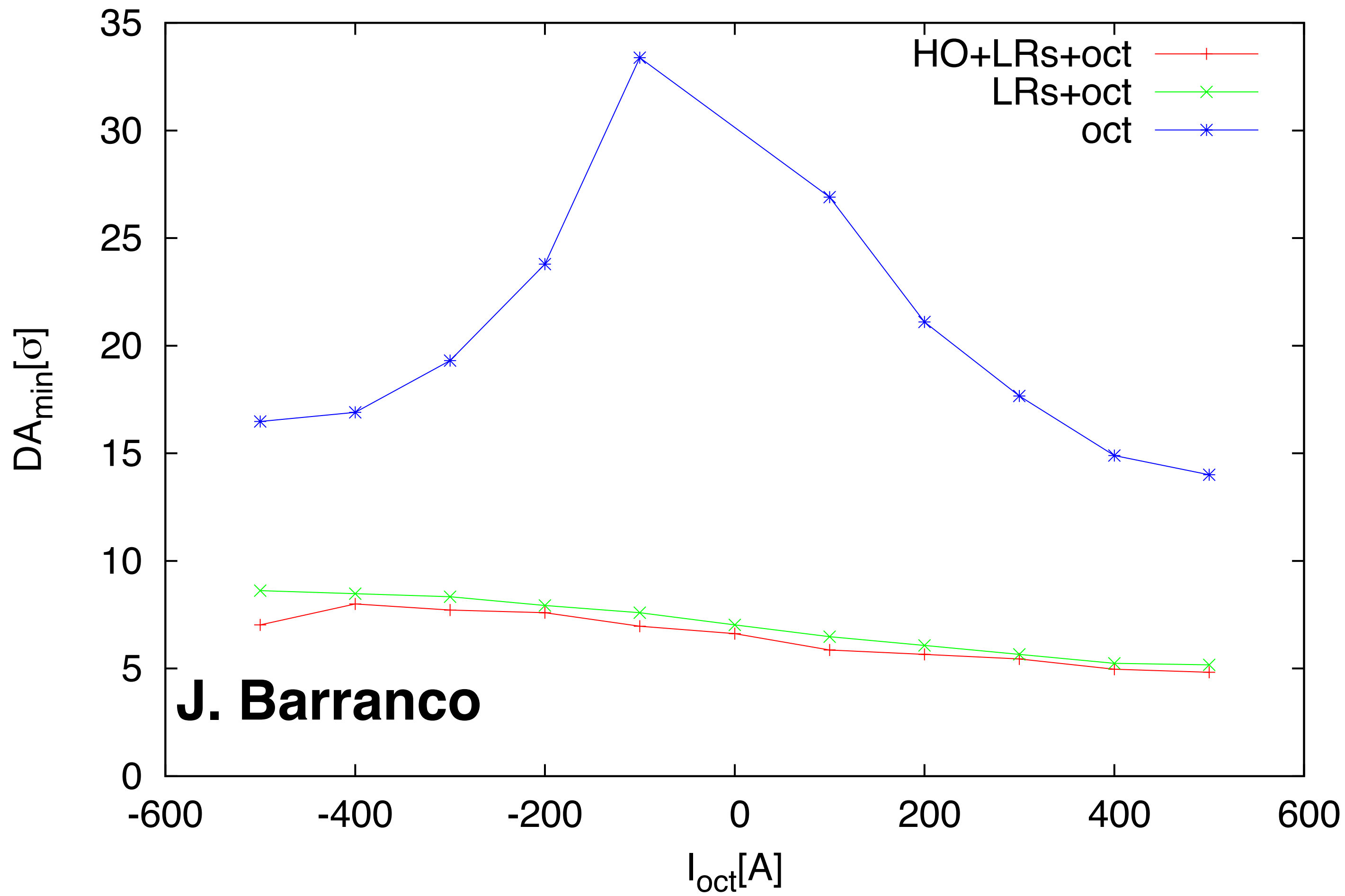
- **Beam-beam interactions can modify the Landau damping from octupoles** according to octupole polarity and type of beam-beam interaction (LR, HO)
- In presence of positive octupole polarity, BB long range interactions provide larger stability ➔ however impact on **DA must be taken into account**
- **BTF measurements show good agreement w.r.t. expectations** with single beam in the LHC ➔ first stability diagram measured in the LHC
- **Linear coupling + high octupole current provoke frequency cut and diffusive mechanisms** that reduce Landau damping compared to expectations and produce important H-V asymmetry ➔ **measured for the first time**
- The particle distribution (DA, losses or redistribution) may have strong impact on stability diagram:
    - **Distortion of shape** compared to a Gaussian distribution
    - **Asymmetric Landau damping in H-V** plane as in presence of linear coupling ➔ a larger stability is expected in the direction of the particle clustering

# Thanks for your attention

# Back-up Slides

# DA in presence of Landau octupoles (FCC)

50 TeV




- Large DA with octupoles only (> 15 σ)
- In presence of BB, DA reduced up to 5σ for high octupole polarity (positive)
- Larger DA for negative octupole polarity

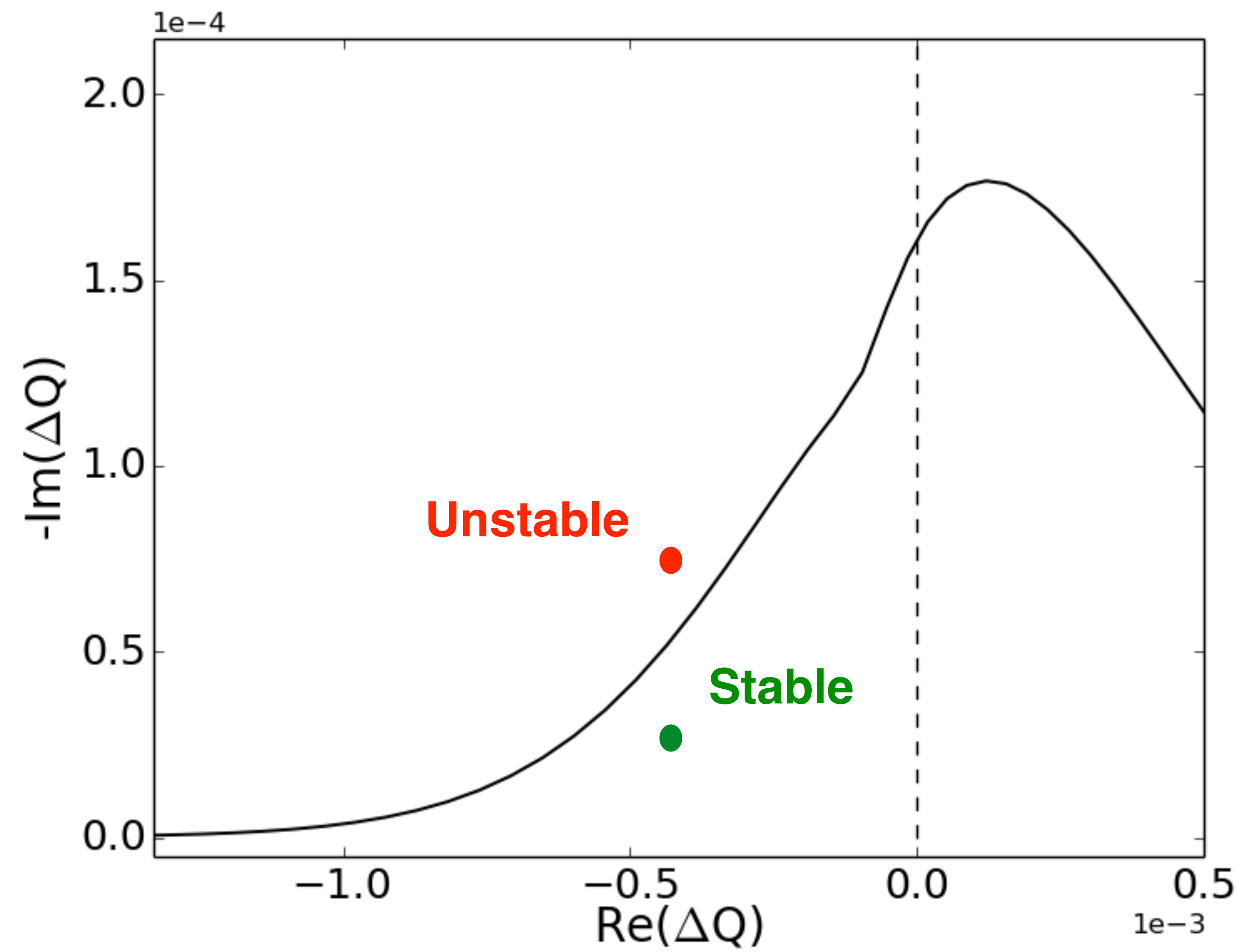
# Landau Damping: Stability diagrams

The Landau damping is generated by the diversification of oscillation frequencies in the beams:

**Tune spread**

Octupoles    Beam-beam

Landau damping is quantified by the Stability Diagram



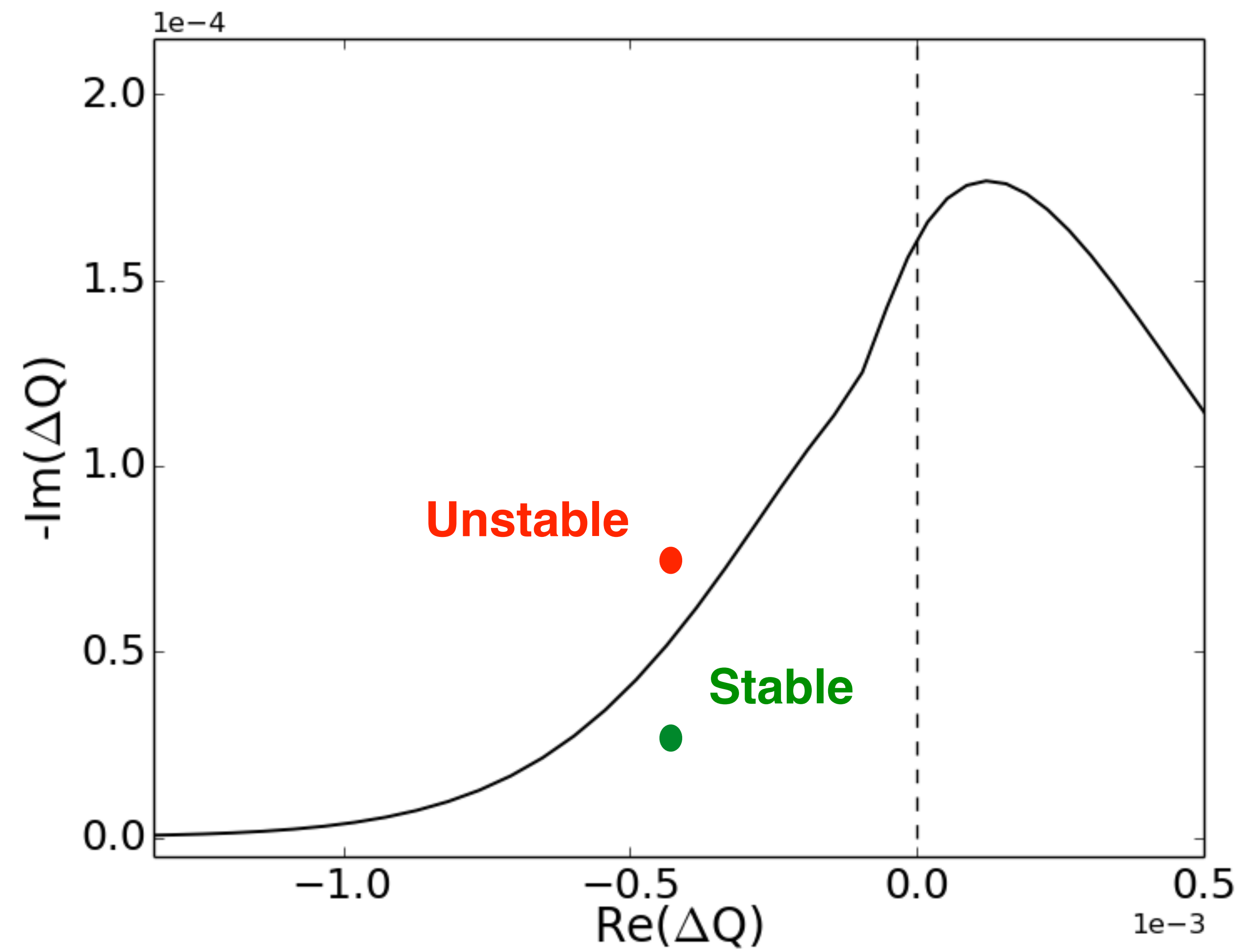
# Landau Damping: Stability diagrams

The Landau damping is generated by the diversification of oscillation frequencies in the beams:

**Tune spread**

Octupoles | Beam-beam

Landau damping is quantified by the Stability Diagram




In presence of **diffusive mechanisms the particle distribution changes**

$$\frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}$$

# Fitting method to reconstruct Stability Diagram from measurements

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

BTF (complex) → **Amplitude (Q)**, **Phase (Q)**

SD ∝ $1/BTF = A^{-1} e^{-i\varphi}$

**Fitting method** allows to compare measurements respect to models (reference case, i.e. octupoles)

$$Q_{fit} = p_0 + p_1 \cdot (Q_{analyt} - Q_0)$$
$$A_{fit} = p_2 / p_1 \cdot A_{analyt}$$

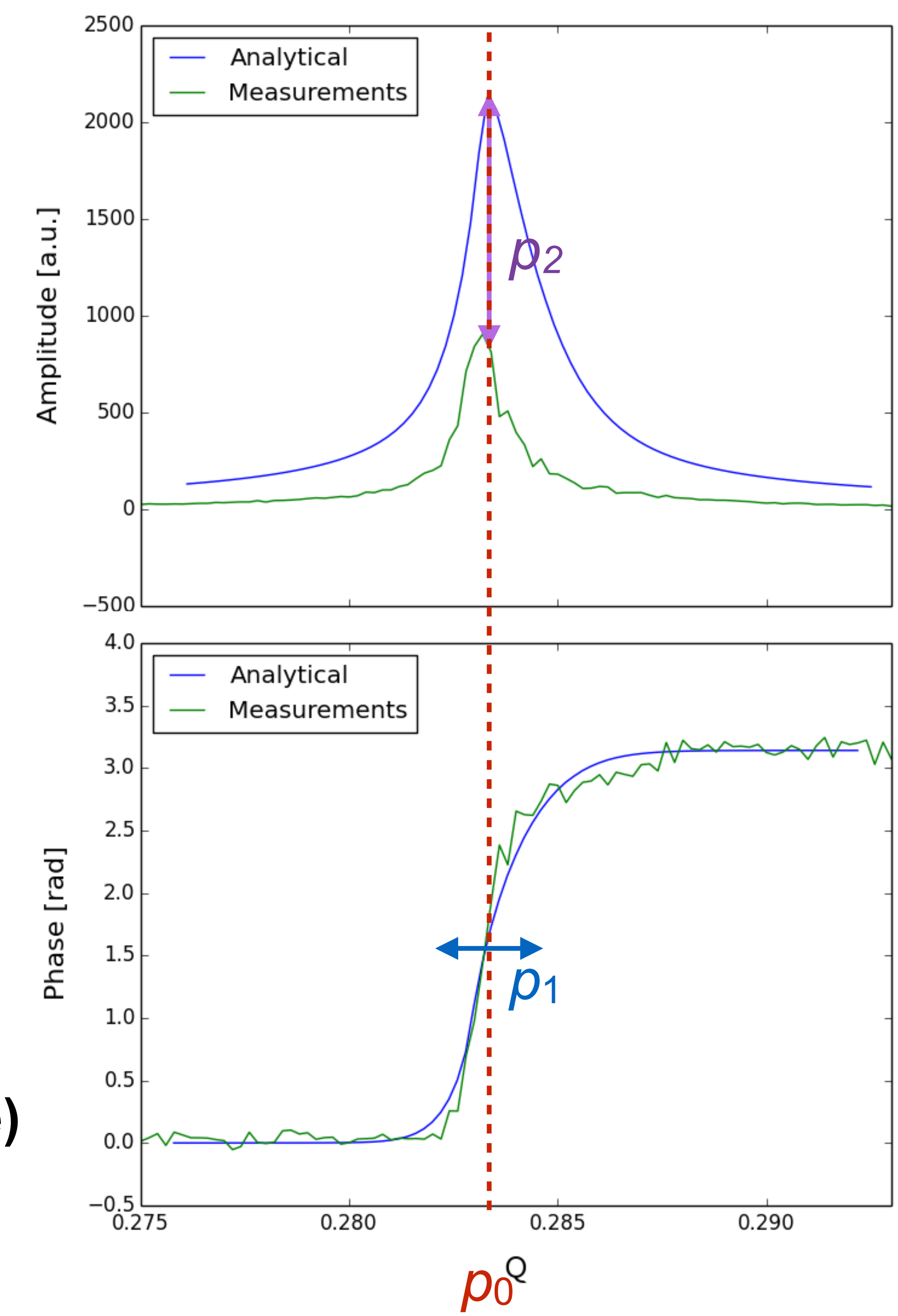
$p_0$ = Tune

$p_1$ = Tune spread factor respect to a reference case

**independent from calibration factor, (phase slope)**

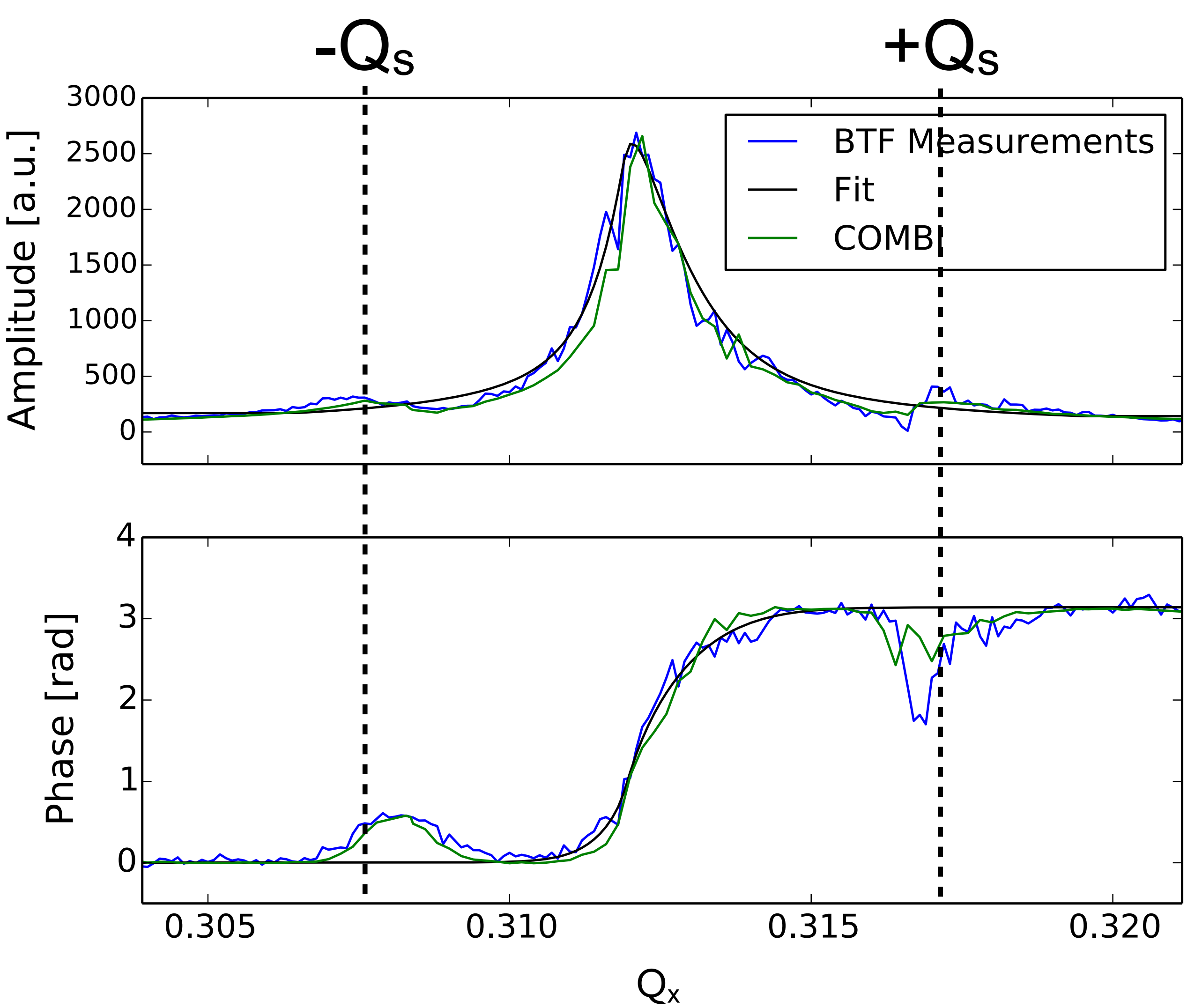
$p_2$ = Amplitude factor:

**calibration, proportionality constant**



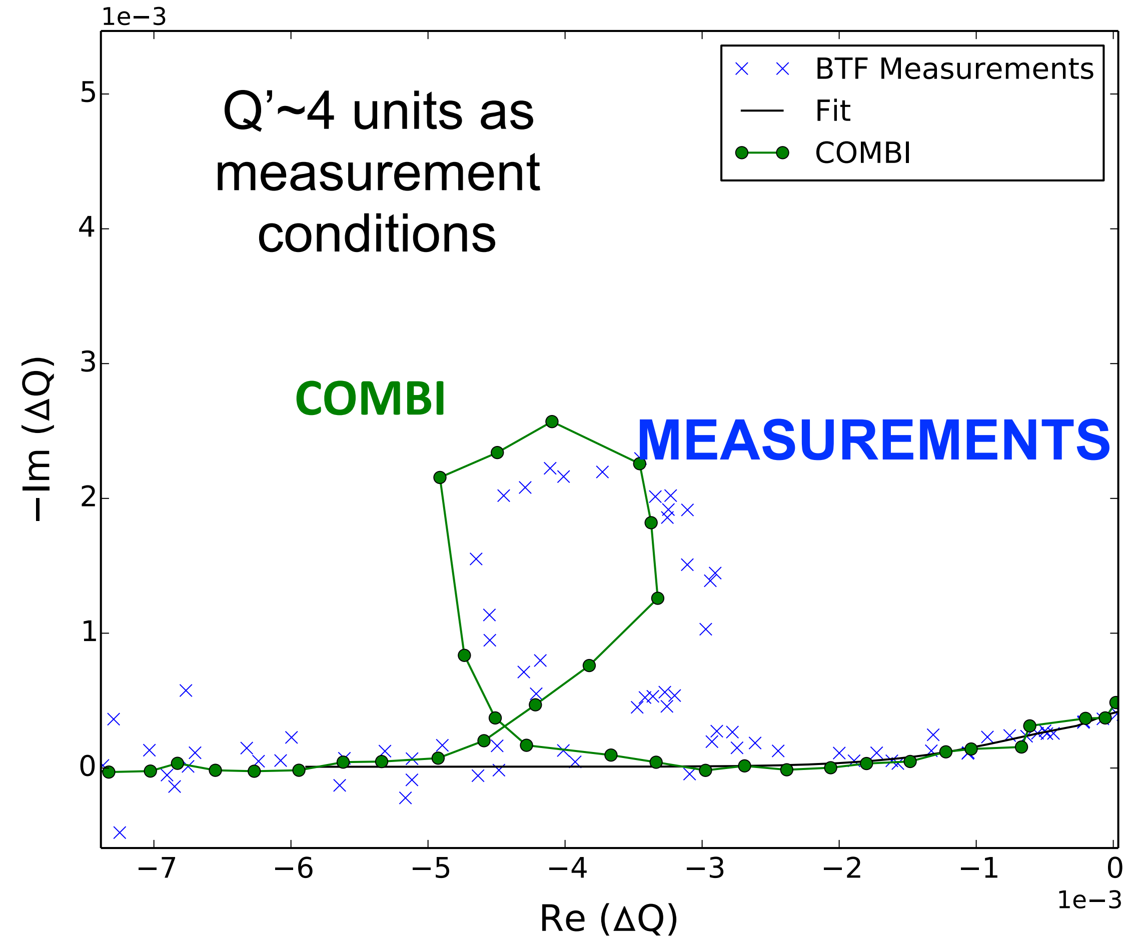
# Effects of chromaticity on BTF

Synchrotron sidebands appear in the BTF amplitude and phase jumps (at ±n · Qs from tune)




COMBI → Multi-particles code

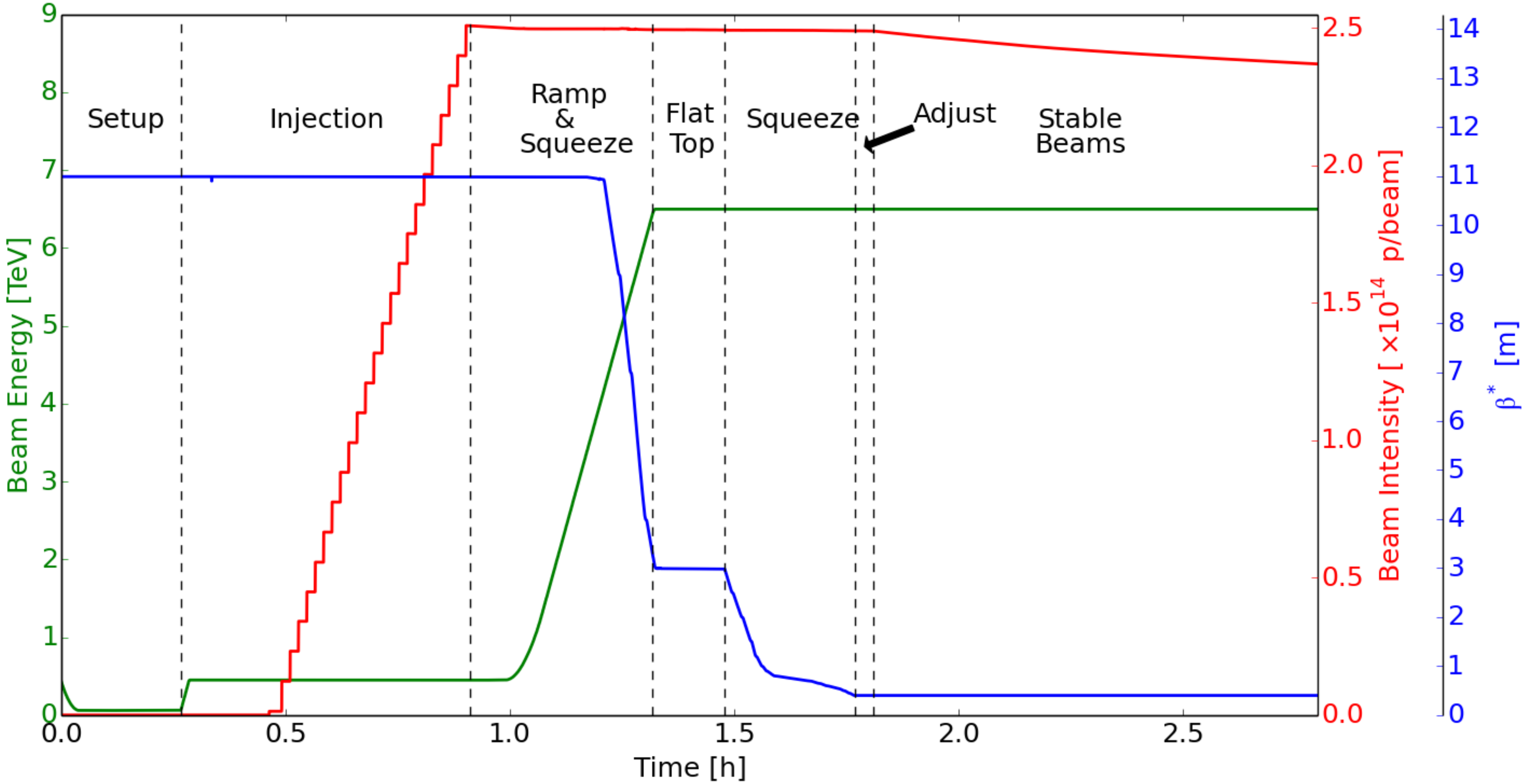
↳ **Implemented BTF module** to simulate response of the beams




3D model simulations (**COMBI**) well reproduce the longitudinal contribution in the BTF

# Beam stability during the operational cycle

**LHC Operational cycle**

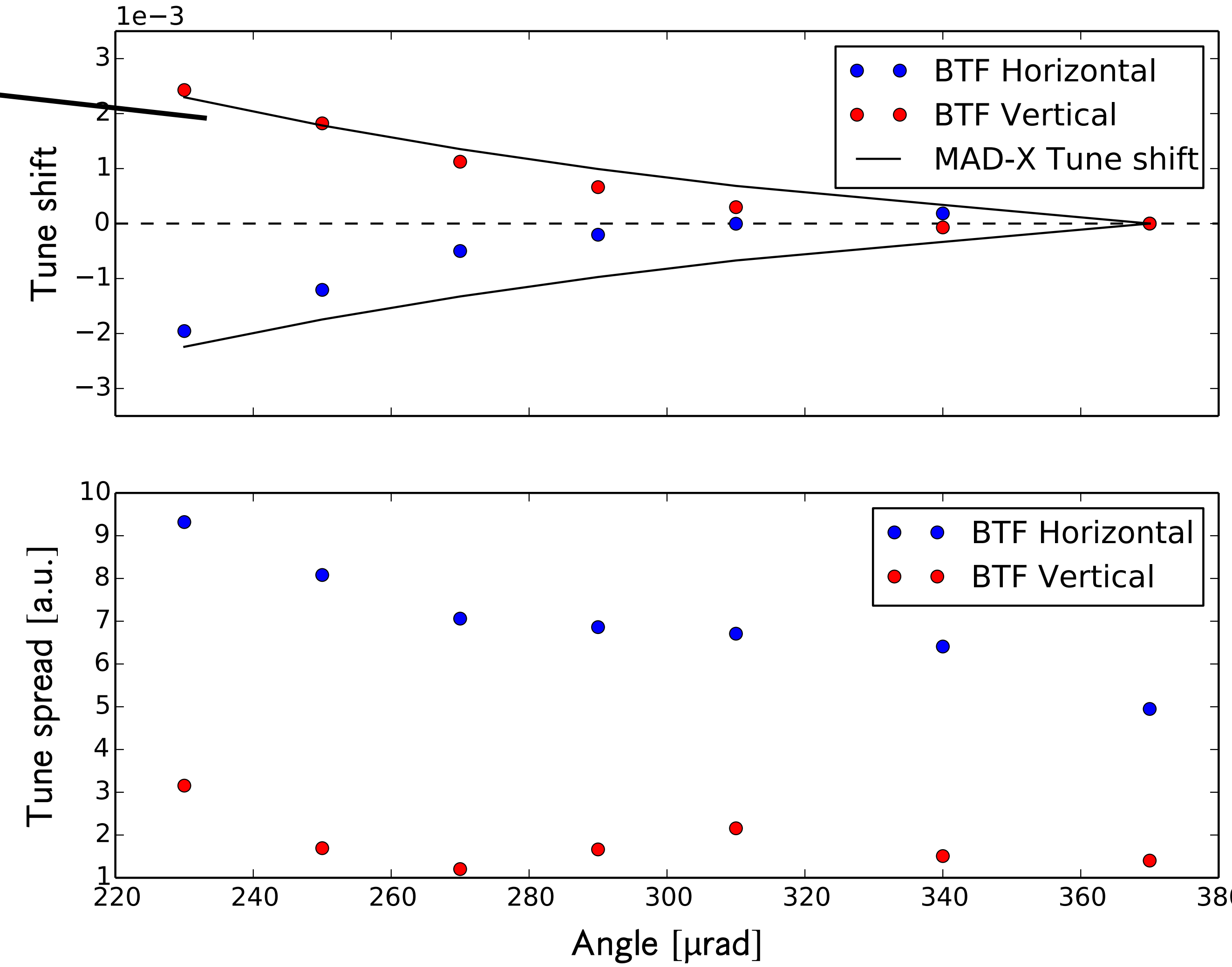



Beam stability has to be ensured during the full operational cycle

# Tune spreads and tune shifts due to beam-beam long range interactions

Crossing angle scan at the IPs → **Beam-beam long range separation scan to measure beam-beam long range contribution to stability**

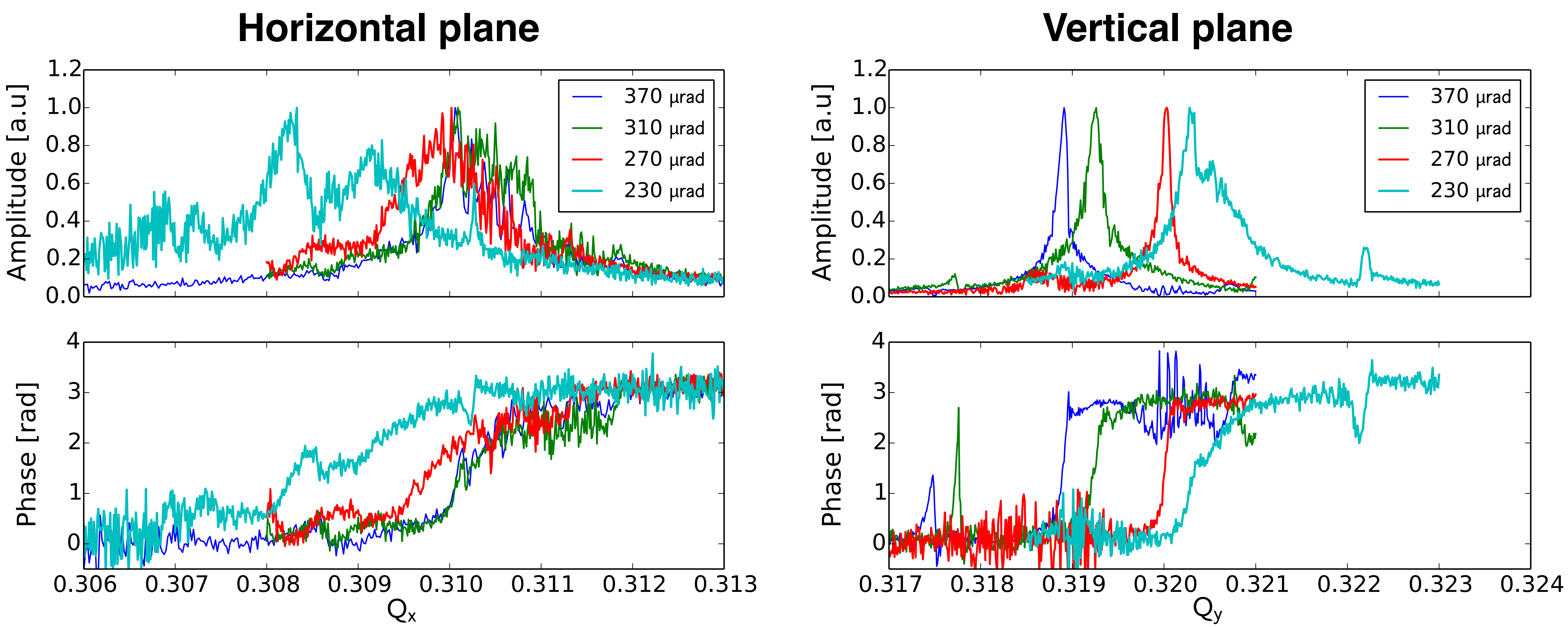
Tune shift can be compatible with breaking long range passive compensation between IP1 and IP5




- Asymmetric tune spread and shifts in horizontal/vertical planes
- Tune shifts are comparable with measured tune shifts from beam-beam LR

*"Observations of Beam Losses at the LHC During Reduction of Crossing Angle"* IPAC 2017 (TUPVA025)

# Measurements with beam-beam long range interactions (1)



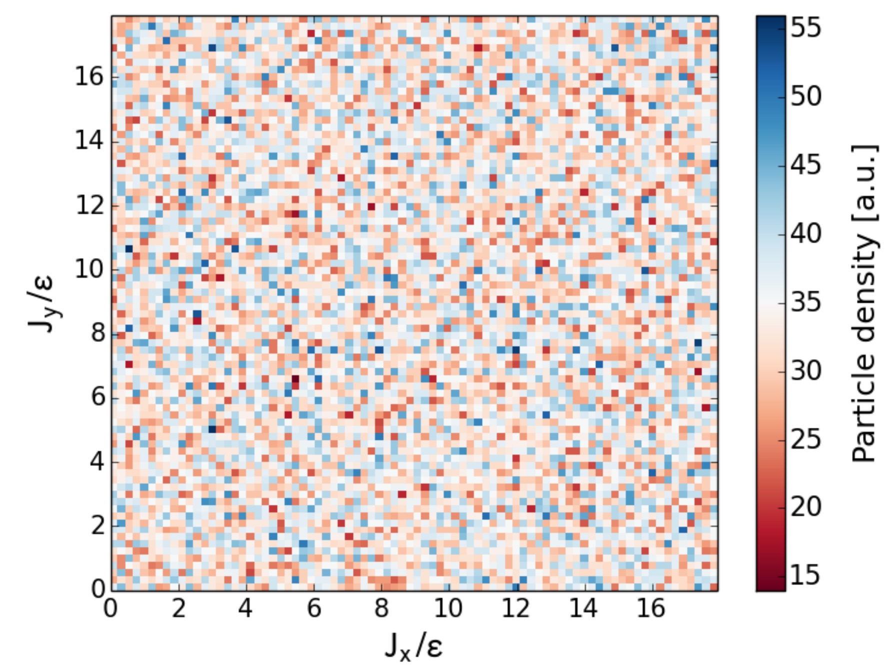

- Strong asymmetry H - V plane, **not expected from models**, tune spread in horizontal plane larger than vertical plane
- Unexpected tune shifts as a function of crossing angle (LHC collisions set up to have full beam-beam long range compensation)

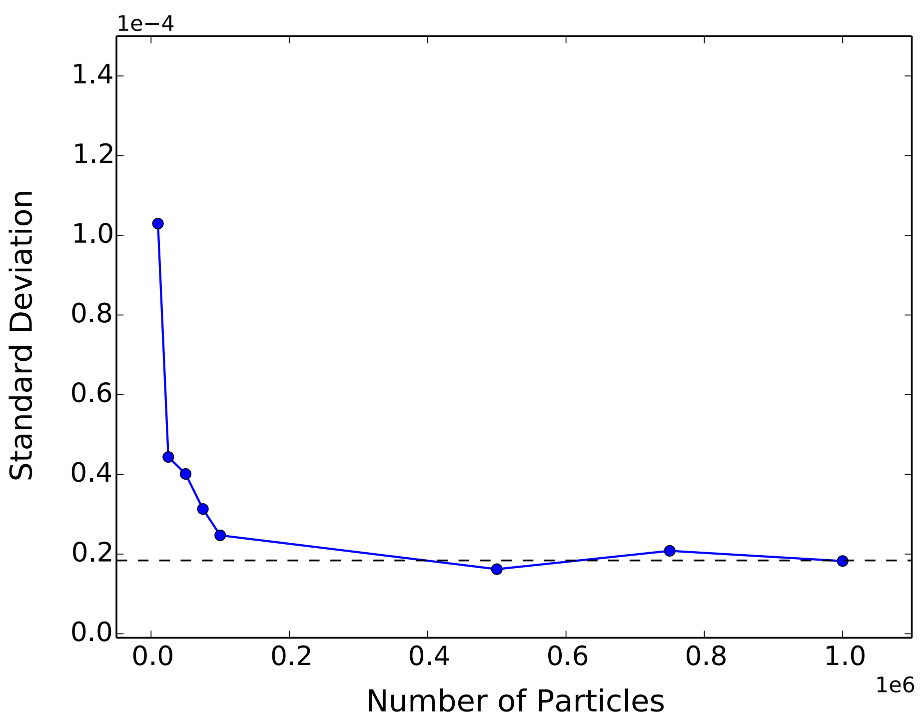
# SixTrack tracked distribution

Extended PySSD to integrate particle distribution from SixTrack Tracking:

- $1 \times 10^6$ particles generated at the first turn (uniform)
- $1 \times 10^6$ turns, (16000 jobs —> 2-3 days required to be executed on Lxplus)
- Weighted with a Gaussian function before the integration
- Large number of particles is required when big losses are present

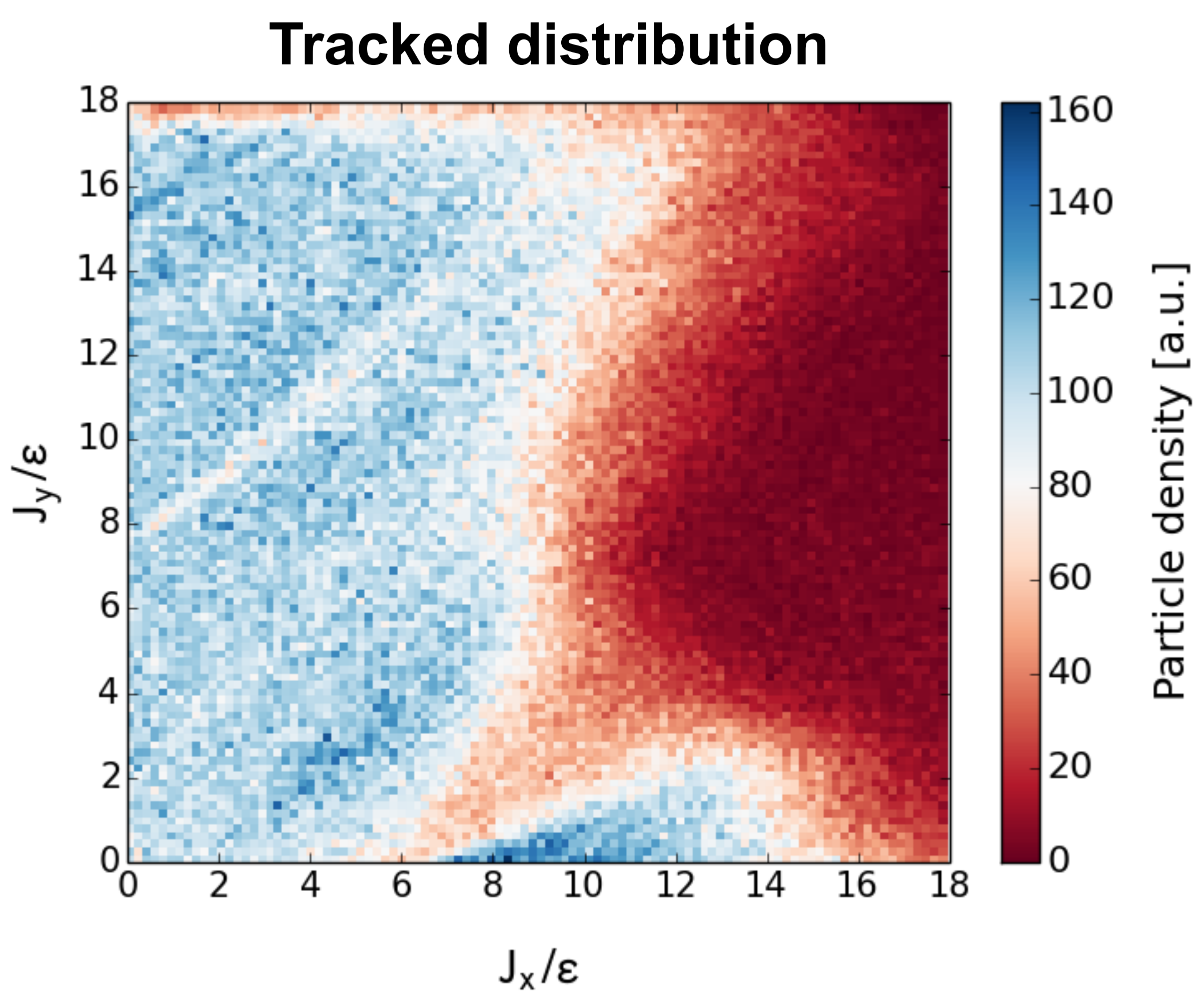
→ BOINC simulations

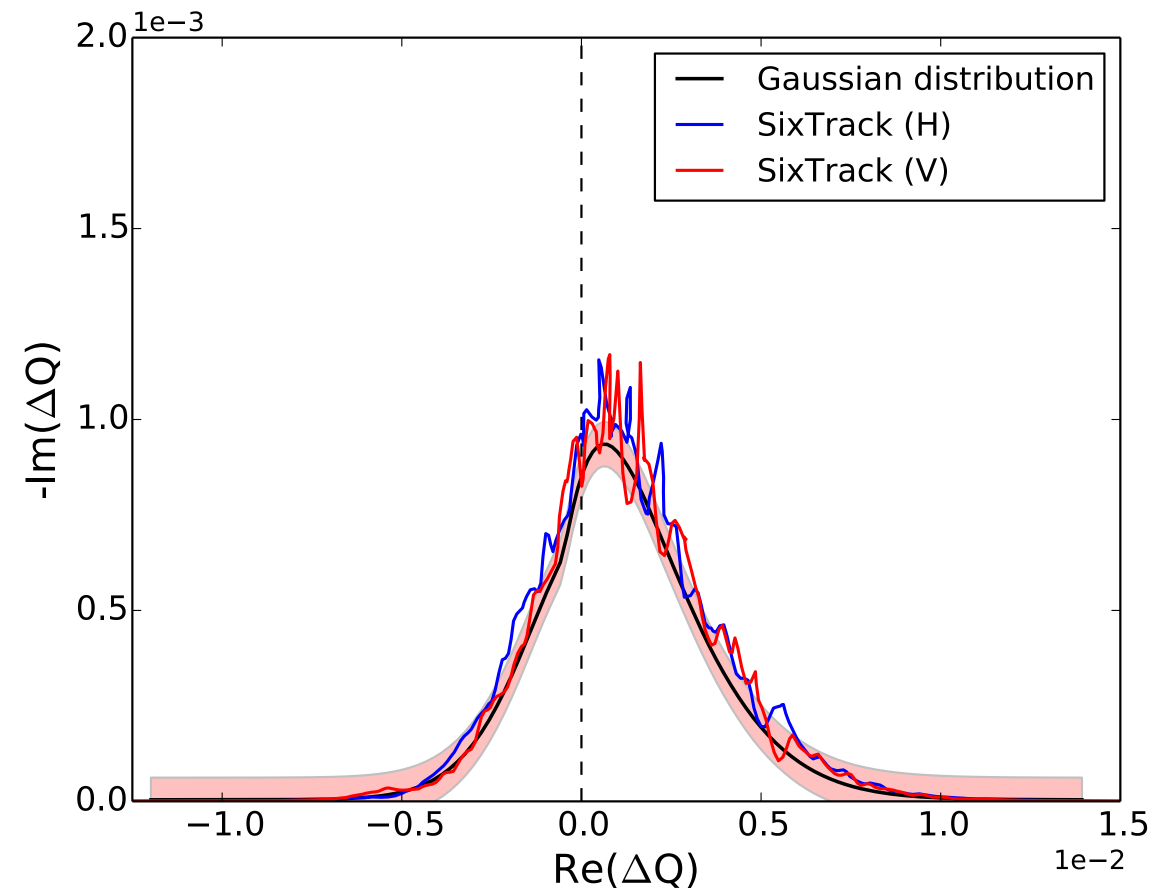


# Impact of incoherent effects on the Stability Diagram

Tune spread provided by octupoles (current **26 A**)




- Landau damping increases with the octupole strengths
- The cut in the distribution does not produce distortion on the stability diagram (particles at amplitudes > 3.5 σ does not contribute)

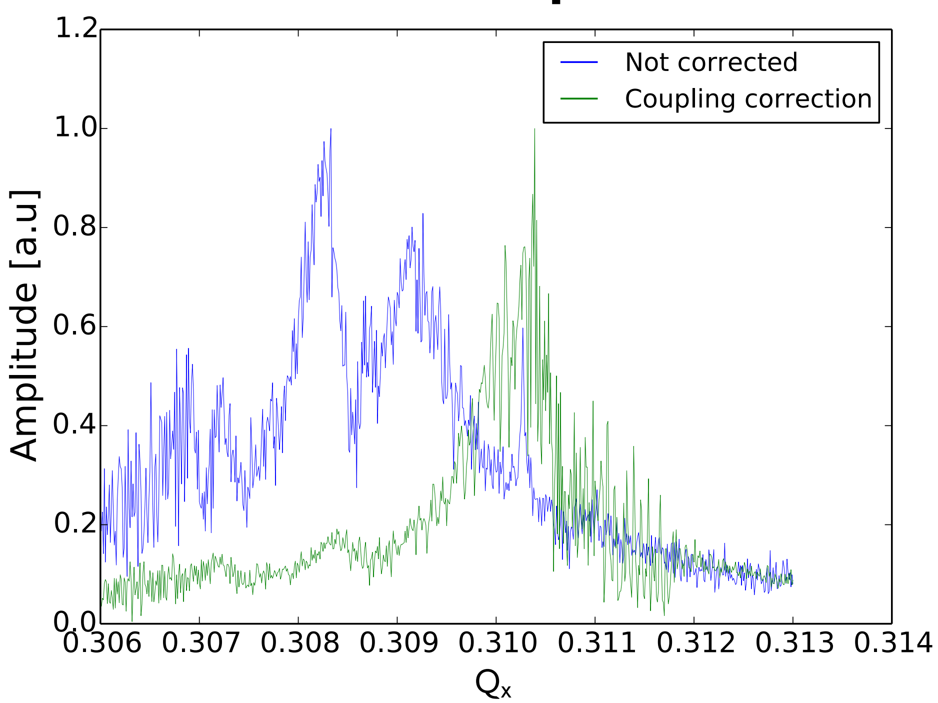
# Linear coupling as a possible mechanism for H-V plane asymmetry

**BTF measurement results** at the end of the betatron squeeze:

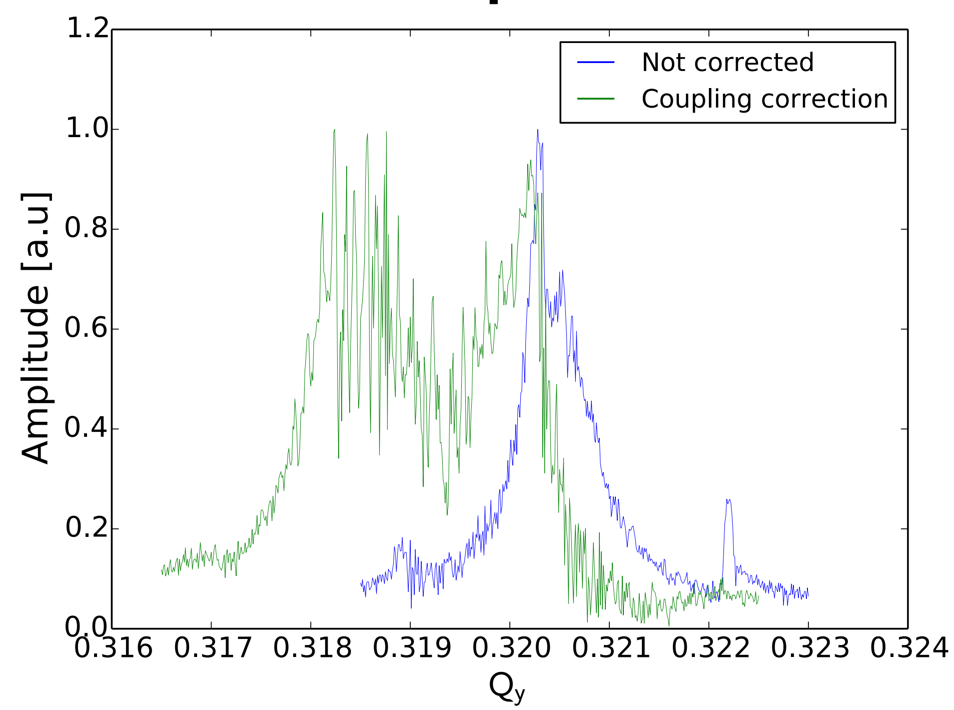
- Larger spread in the horizontal plane respect to models
- Smaller spread in the vertical plane respect to models
- Strong dependency on working point

Presence of linear coupling during measurements → impact on BTF

**Horizontal plane**

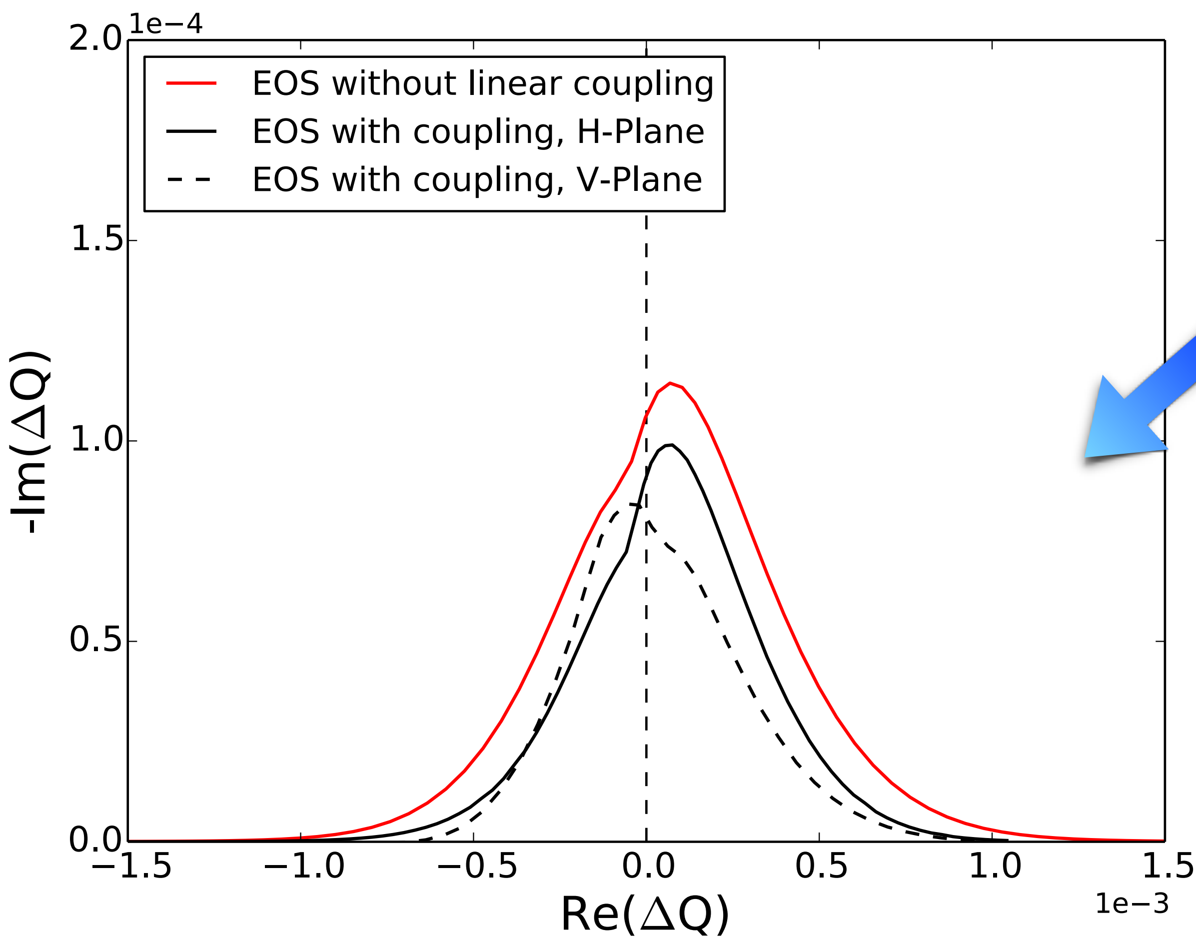


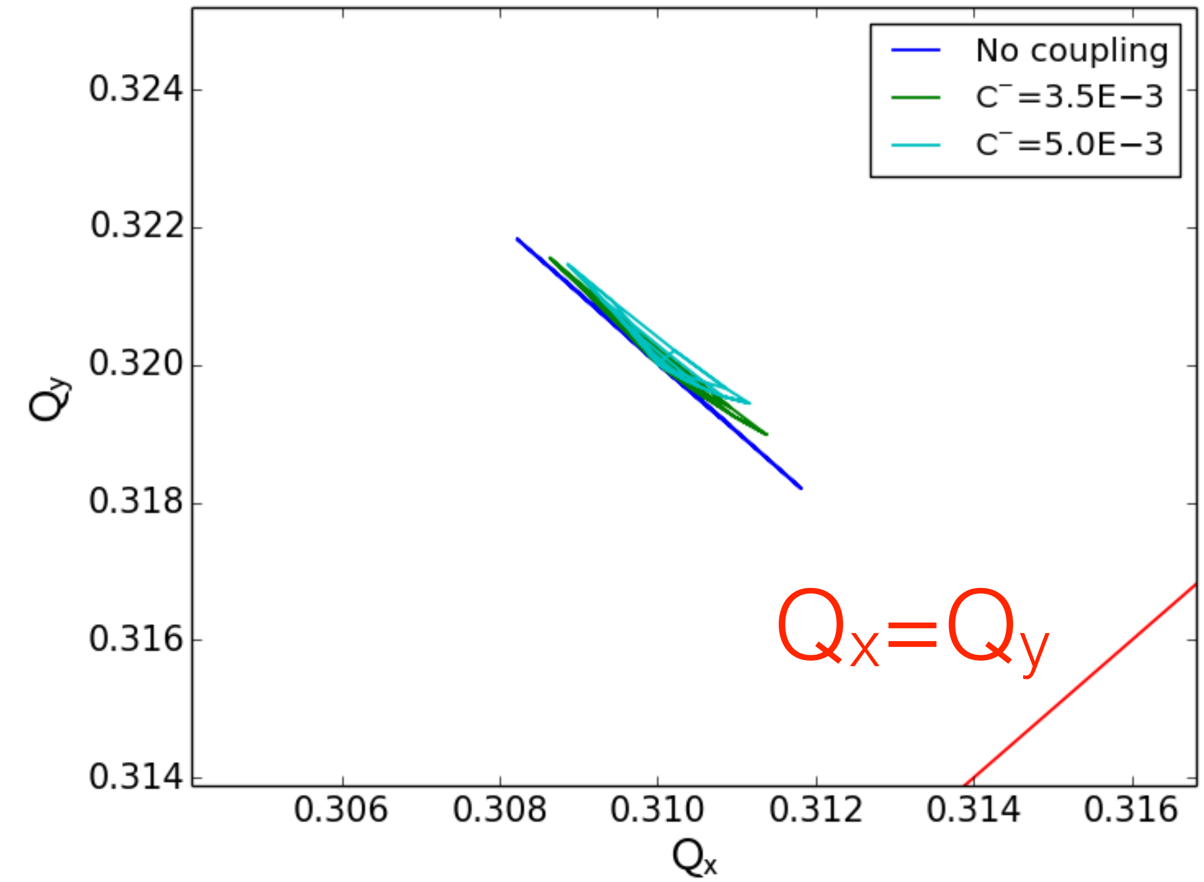

**Vertical plane**



# Effects of linear coupling on the detuning with amplitude

- **Reduction of the overall tune spread**
- With linear coupling footprint is distorted when approaching the resonance

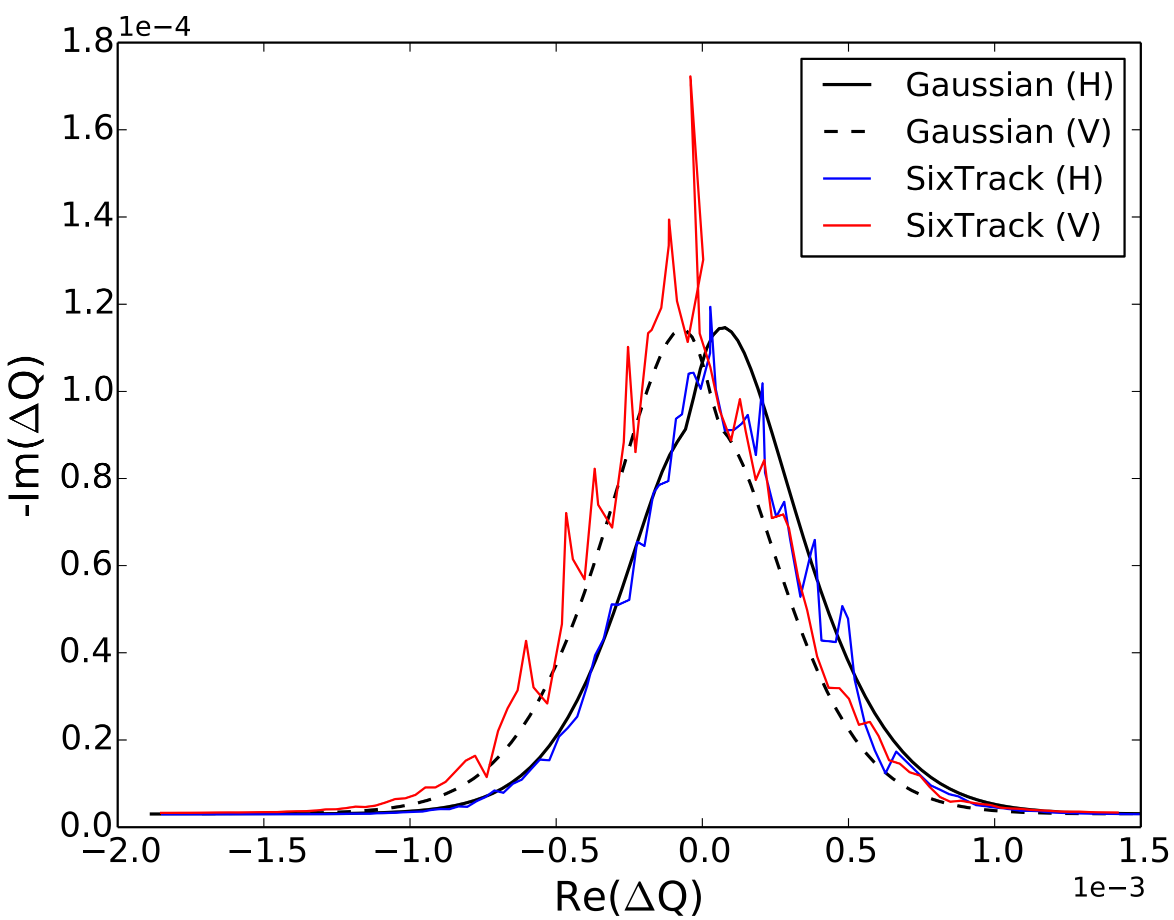


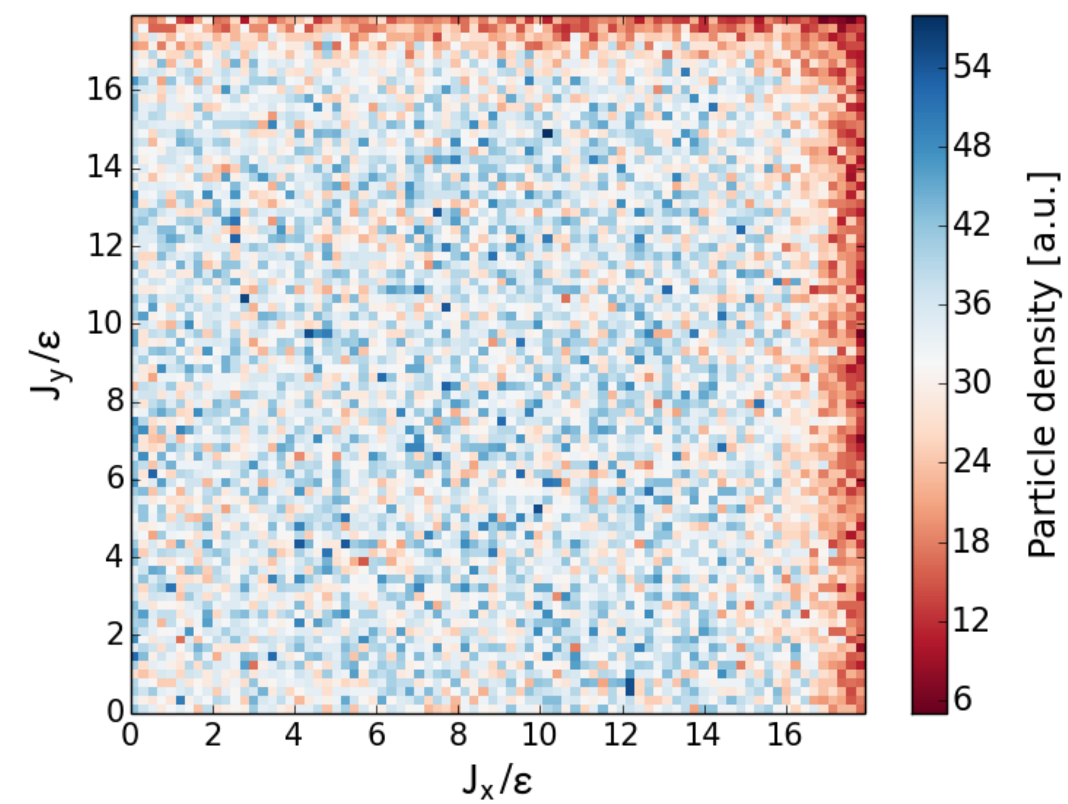




**Reduction of Landau damping** due to the effect of linear coupling on tune footprint

# Effects of linear coupling on particle distribution

- **Integrated tracked distribution**
- End of betatron squeeze (octupoles + BB LR)
- No coupling



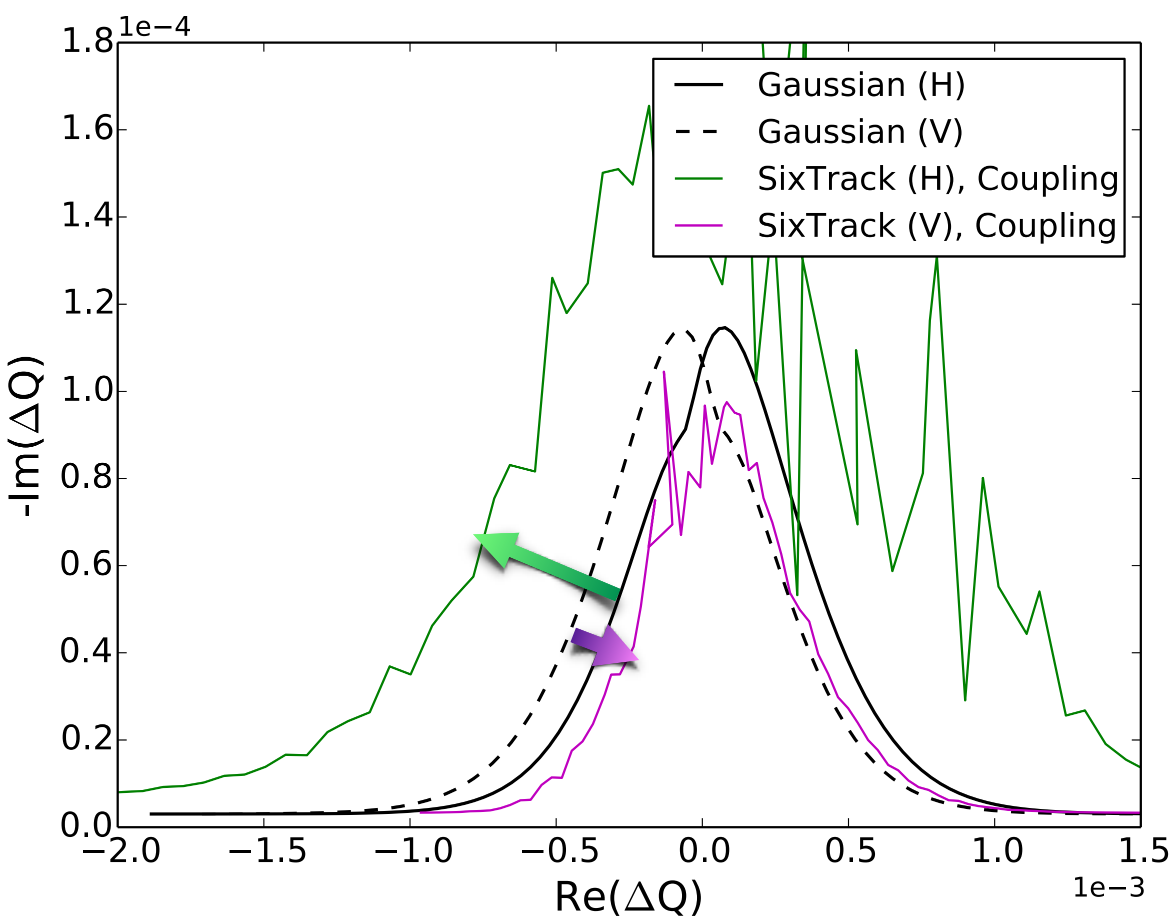

No evident distortion or discrepancy respect to Gaussian case

# Effects of linear coupling on particle distribution

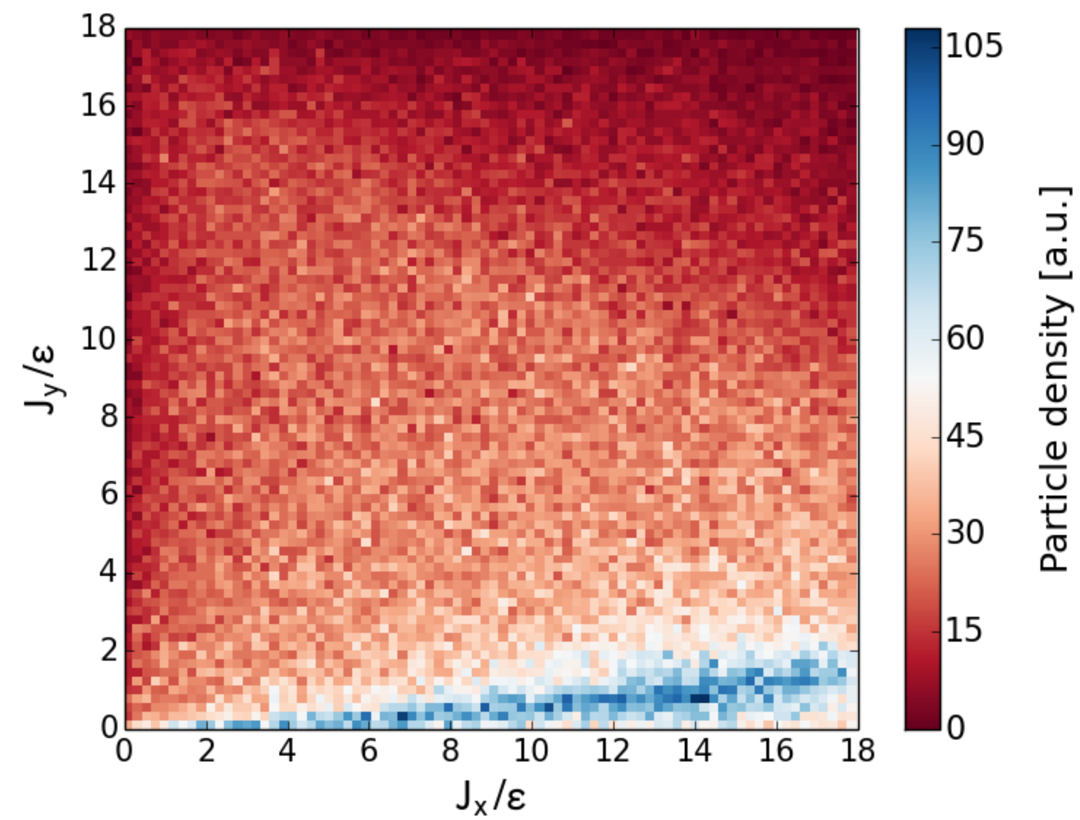
**Effects of Linear coupling:**

- Tune spread reduced ➞ **Smaller SD**
- Particle distribution (extended simulation tools)

  ➞ **Asymmetric H - V** stability diagram



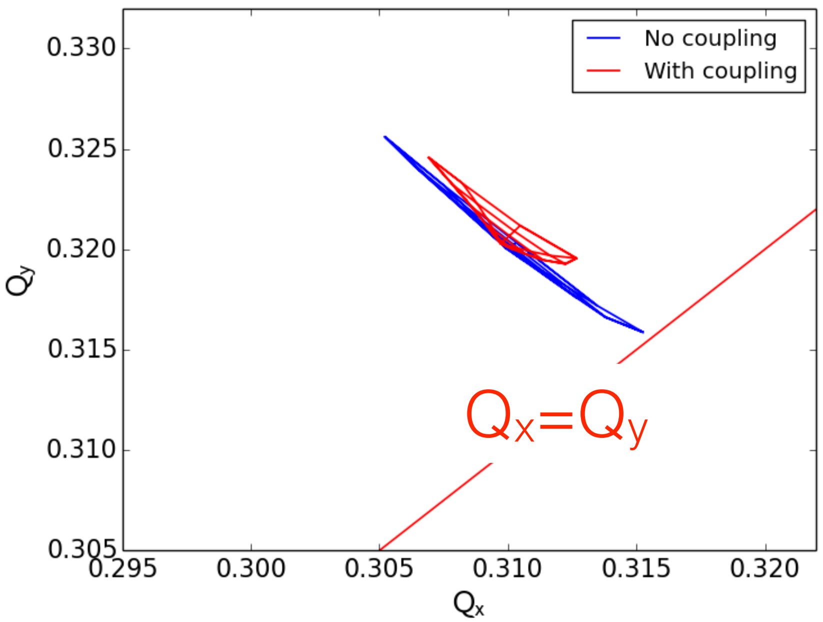

**Tracked distribution**



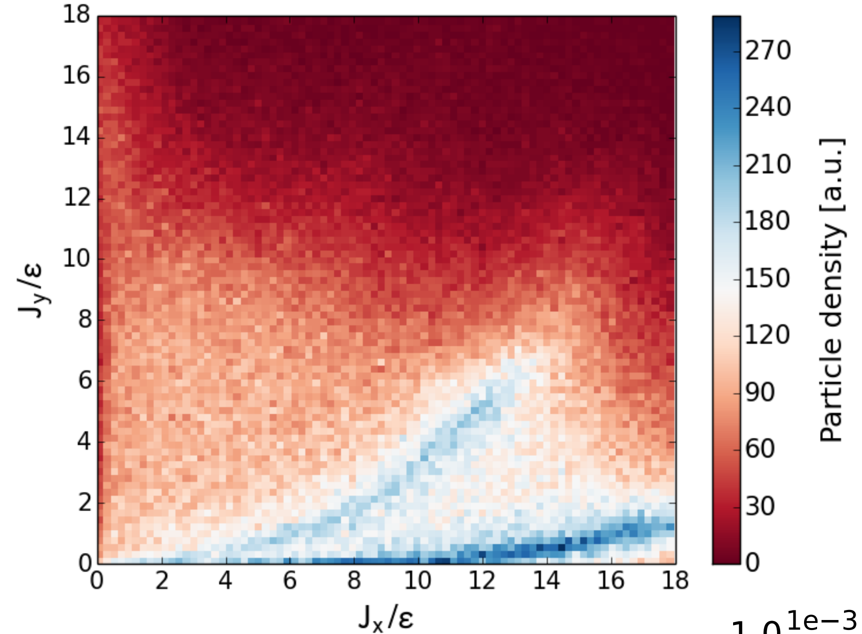

**Consistent with the observations in the LHC**

# 2012 Physics Run configuration at the end of betatron squeeze

**Amplitude Detuning**

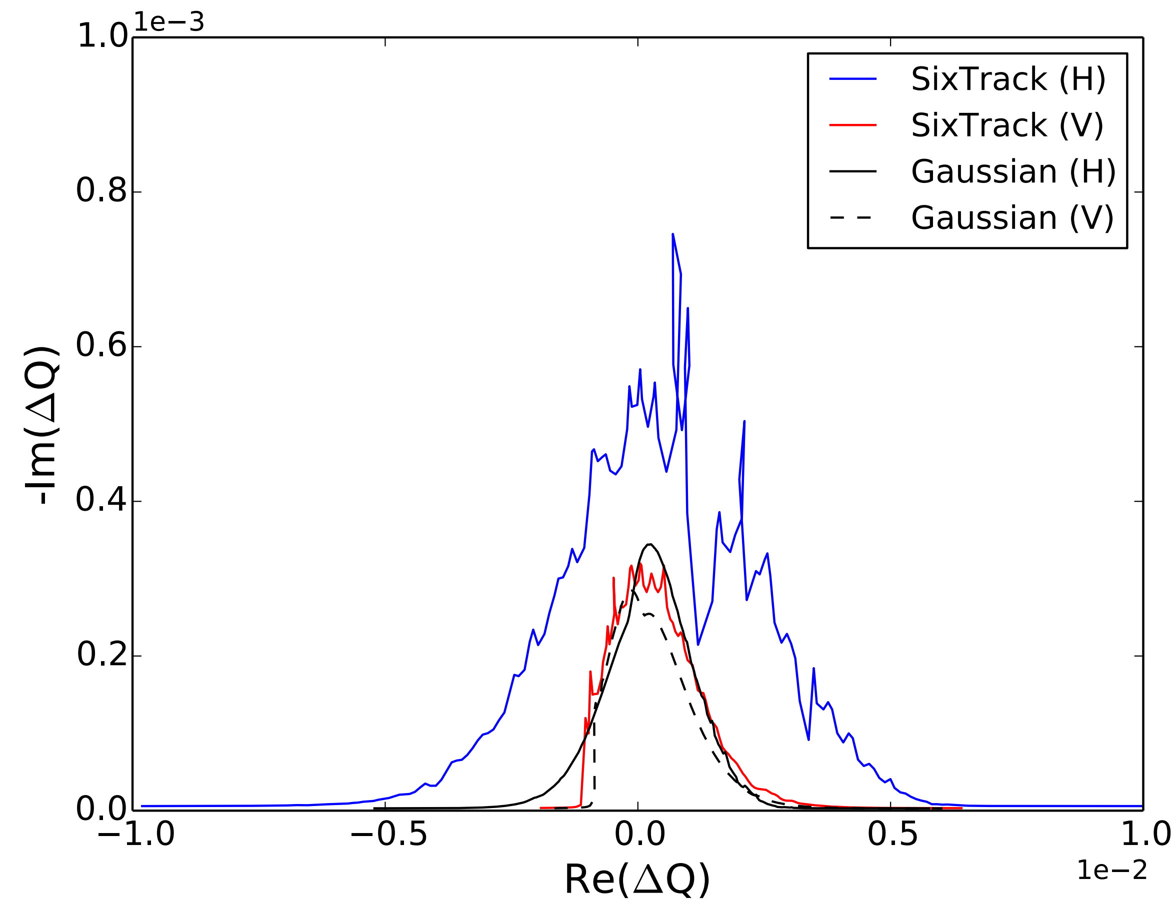



**Tracked distribution**




Important effect visible for larger footprint (as in 2012 end of betatron squeeze)

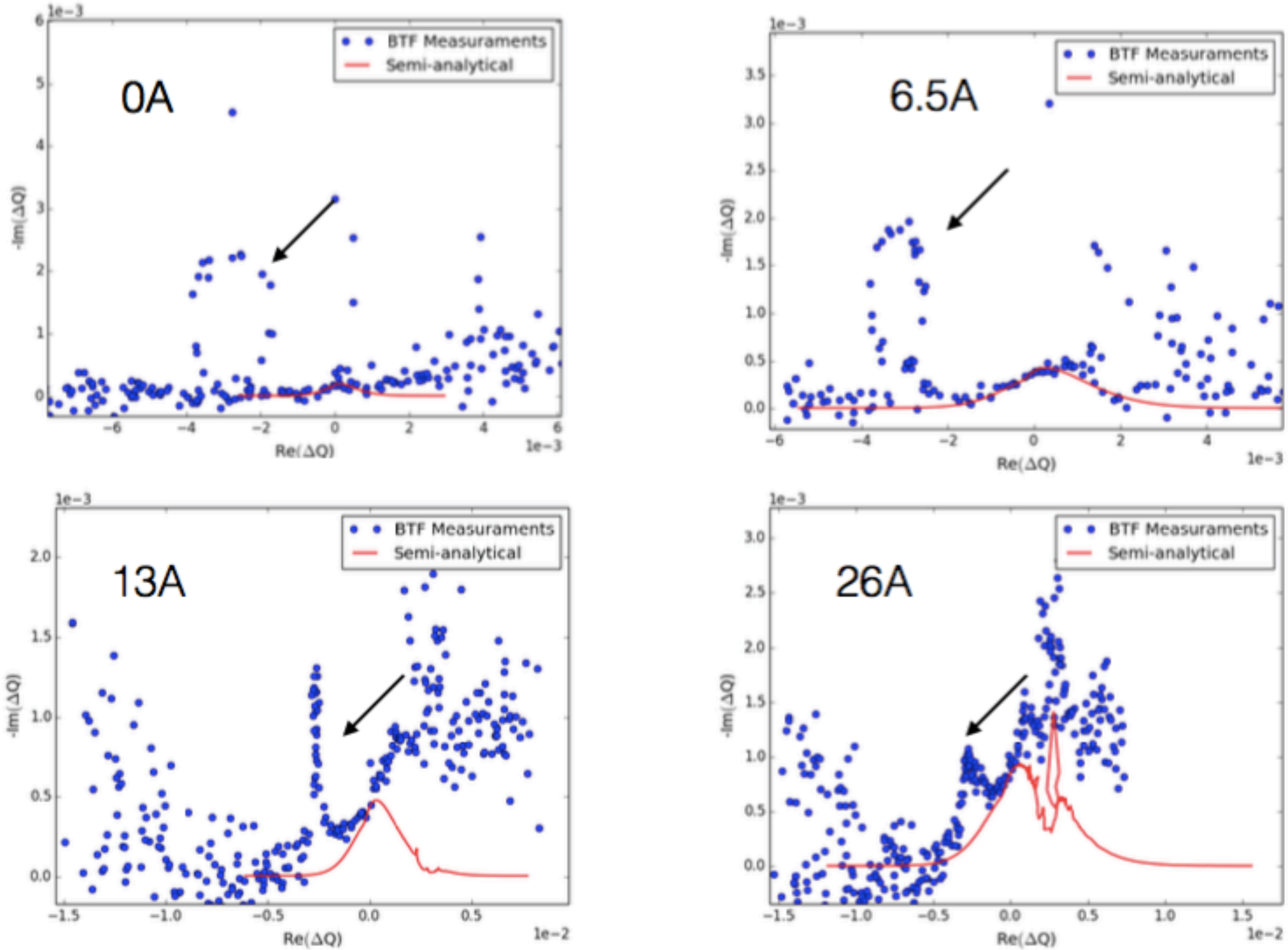
- Visible cut in the computed stability diagram
- Strong effect on the particle distribution



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

# Landau Damping: Chromaticity in BTF

- The loops (and deformations of it) are always present in measurements
- High octupole current: deformation of the SD and loops —> sidebands included in the transverse spread (see next slide)



# Landau Damping: Plasmas vs Accelerators

| Plasmas | Accelerators |
|---|---|
| Velocity distribution (slope of the velocity distribution) | **Frequency distribution (tune spread)** (external nonlinear forces: amplitude dependent ) |
| Coherent motion due to oscillating electrons in plasma | Coherent motion due to accelerator environment (complex tune shifts) |
| Self consistent treatment (Vlasov equation) | Self consistent treatment (Vlasov equation) |
| Velocities close to velocity wake | Coherent modes must be inside tune spread |
| Initial conditions (stable) | Initial conditions (stable) |
| Leads to exponentially decaying oscillations | **Landau damping is the absence of oscillations** |