Update on the beam-beam effects for HL-LHC: Landau damping (octupoles and Long-Range) and PACMAN Effects (orbit, chroma, tunes)

T. Pieloni and C. Tambasco (CERN-EPFL)

Acknowledgements: X. Buffat (CERN-EPFL), D. Banfi (EPFL), J. Barranco (EPFL), G. Arduini, W. Herr, H. Grote, R. Tomas, E. Metral, S. Fartoukh.

4th Joint HiLumi LHC-LARP Annual Meeting
Nov 17-21 KEK, Tsukuba, Japan

Outline

- Beam-Beam and Landau Octupoles
- PACMAN Effects: orbit, Q and Q'
- Summary

Scenarios :

Baseline1 : Luminosity of 5e34

- Round optics: from 70cm down to 15cm β^* (also 10cm β^*)
- Full crab crossing in IP1 and IP5
- Leveling luminosity with β^* in IP1, IP5.
- Adding contribution of IP8 and IP2
- Minimum crossing angle/Maximum Intensity

Ultimate : Luminosity of 7.5e34

- Round optics: from 33cm down to 10cm β^*
- Full crab crossing in IP1 and IP5
- Leveling luminosity with β^* in IP1 & IP5
- Adding contribution of IP8 and IP2

Extreme Case: no β^* leveling

- Extreme case of 15cm β^* Round optics
- No β^* leveling
- Nominal crossing angle 590 μrad IP1&5

Scenarios from BB view :

Baseline1 : Luminosity of 5e34
Head-on strong ΔQ = max 0.033 to → 0.01
Long Range:
IP1&5 From 26σ → 12.5σ (Int 2.2e11 → 1.1e11)
IP8 2 LR at 5s (others > 20σ)
IP2 all > 30σ

Ultimate : Luminosity of 7.55e34
Head-on strong ΔQ = max 0.033 to → 0.01
Long Range:
IP1&5 From 18σ → 12.5σ (Int 2.2e11 → 1.5e11)
IP8 2 LR at 5s (others > 20σ)
IP2 all > 30σ

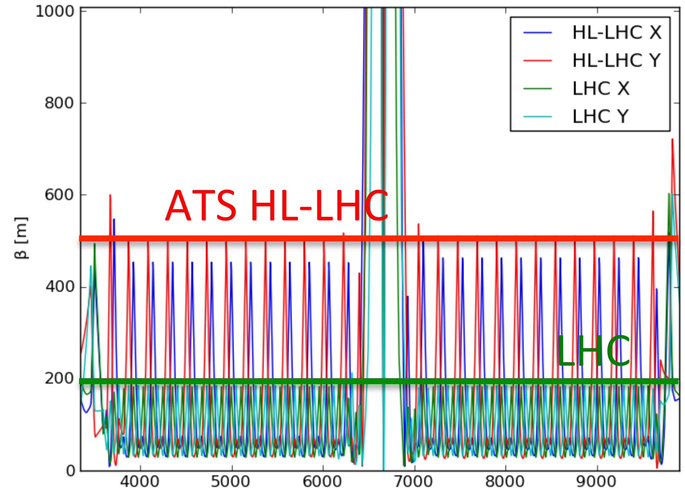
Extreme Case: no β^* leveling
Head-on strong ΔQ = max 0.033 to → 0.01
Long Range:
IP1&5 at 12.5σ separation and 2.2e11ppb

Outline

- **Beam-Beam and Landau Octupoles**
- PACMAN Effects: orbit, Q and Q’
- Summary

Landau Damping and ATS optics

HL-LHC vs LHC (I=2.2E11, ε=2.5μm)



Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade

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(Received 26 July 2013; published 19 November 2013)

Landau Damping, Dynamic Aperture and Octupoles in LHC

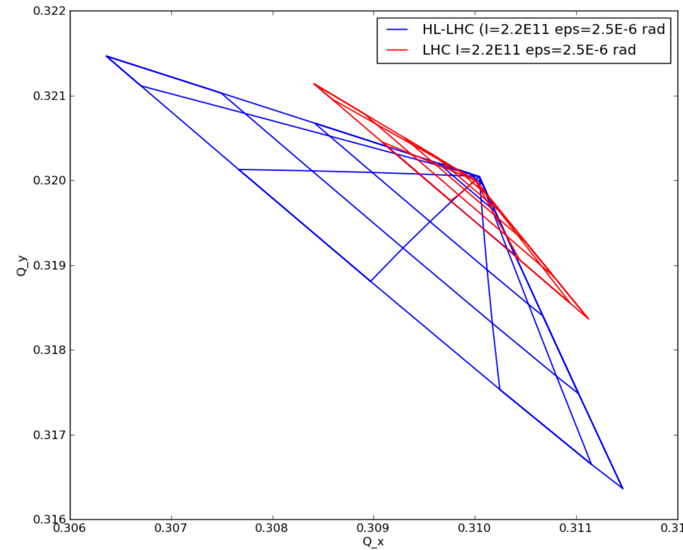
J. Gareyte, J.P. Koutchouk and F. Ruggiero

$$\Delta Q_x = \left[\frac{3}{8\pi}\int \beta_x^2 \frac{O_3}{B\rho}\,ds\right] J_x - \left[\frac{3}{8\pi}\int 2\beta_x\beta_y \frac{O_3}{B\rho}\,ds\right] J_y,$$

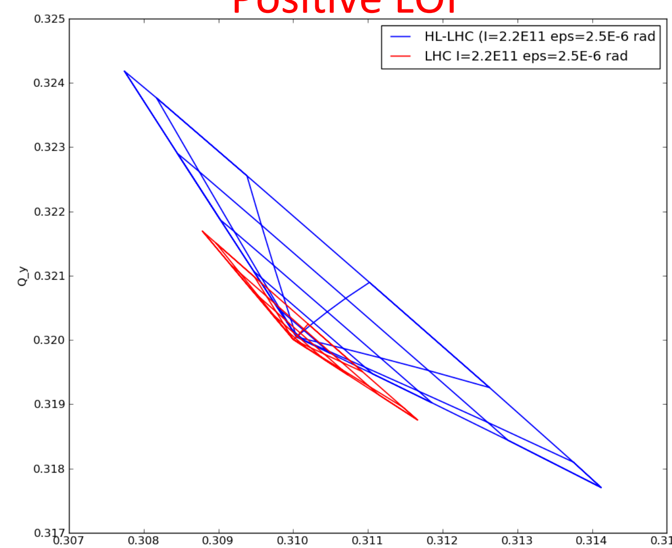
2.5 times larger than LHC

C. Tambasco PhD student CERN&EPFL

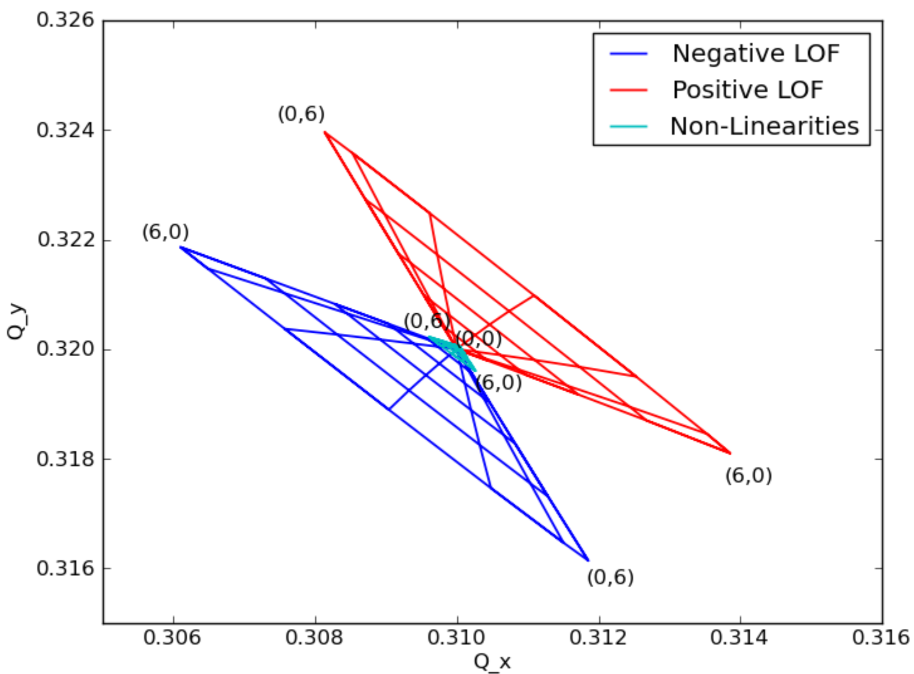
Negative LOF

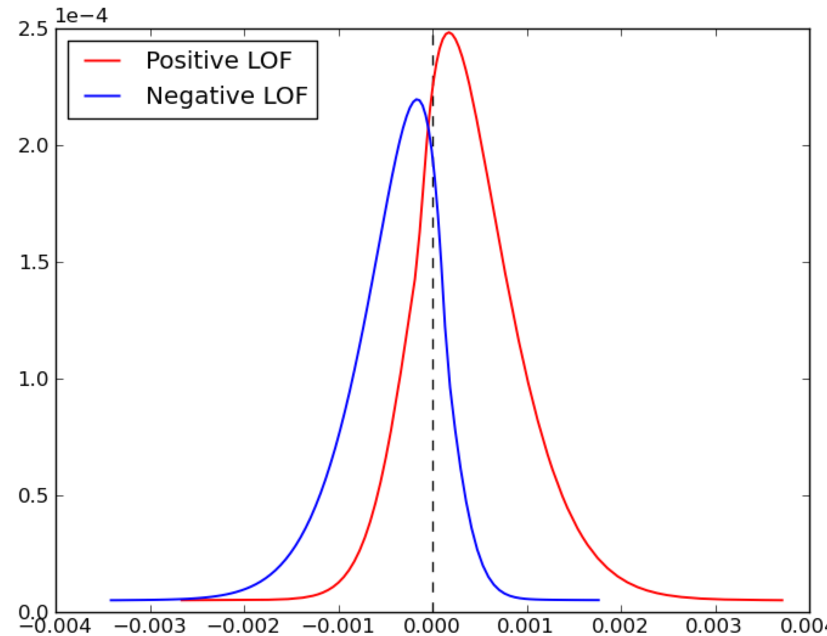


Positive LOF



Stability diagrams with Octupoles ATS (15cm β*)





2.5 times larger than LHC

Landau Damping, Dynamic Aperture and Octupoles in LHC

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$$\Delta Q_x = \left[\frac{3}{8\pi}\int \beta_x^2 \frac{O_3}{B\rho}\,ds\right] J_x - \left[\frac{3}{8\pi}\int 2\beta_x\beta_y \frac{O_3}{B\rho}\,ds\right] J_y,$$

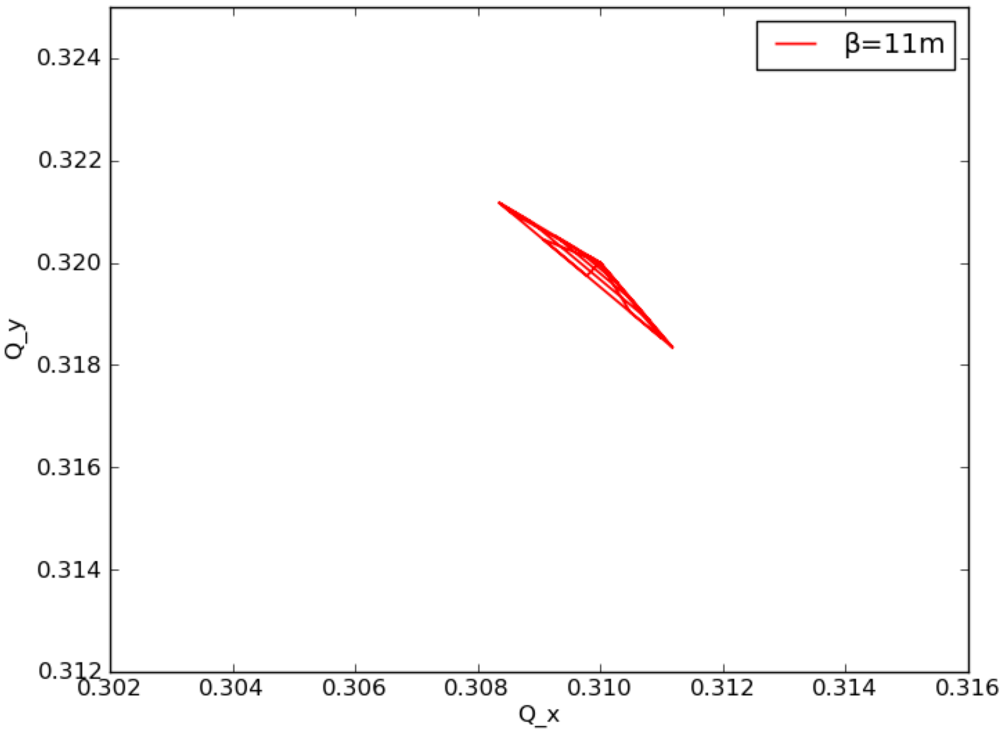
X. Buffat, Pyssd code: numerically solves the dispersion integral EPFL PhD Thesis 2014

Translated in Stability diagrams:

- Negative polarity of octupoles gives larger area
- Asymmetry between two polarities due to non-linearities (sextupoles under investigation)

Optics during betatron squeeze: FP

- Negative LOF



Optics during betatron squeeze: FP

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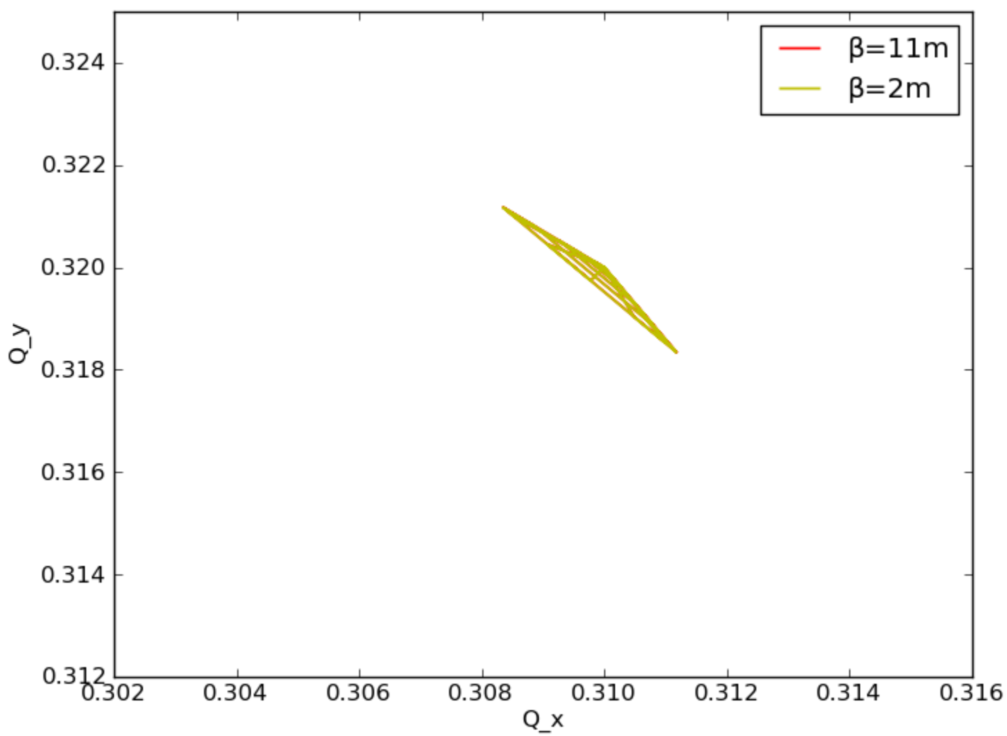
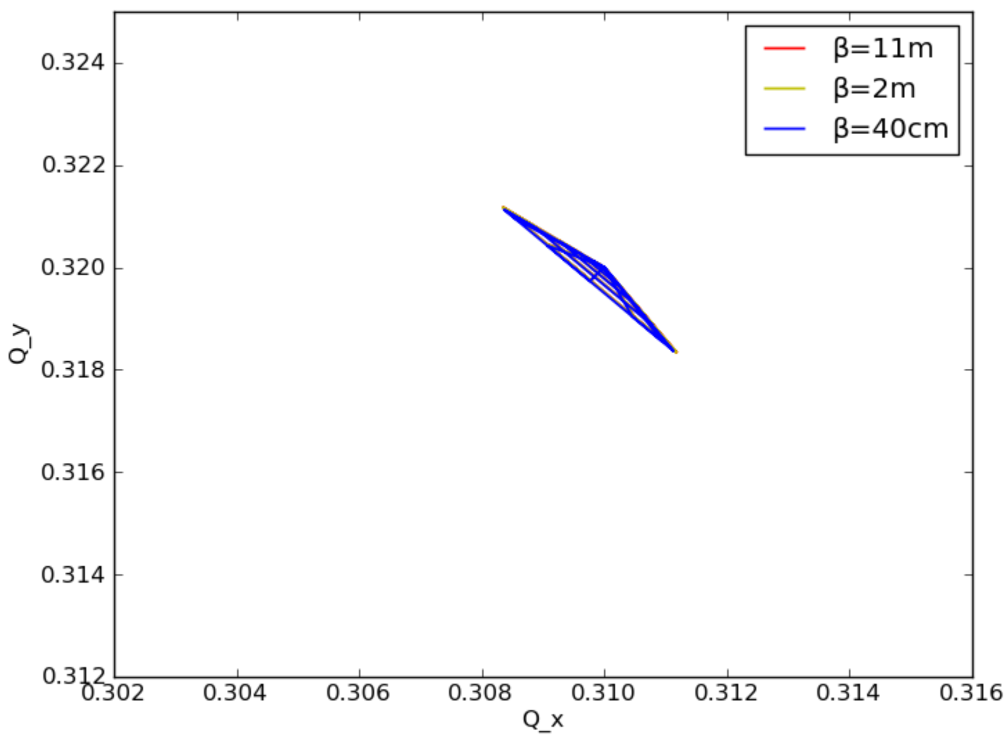


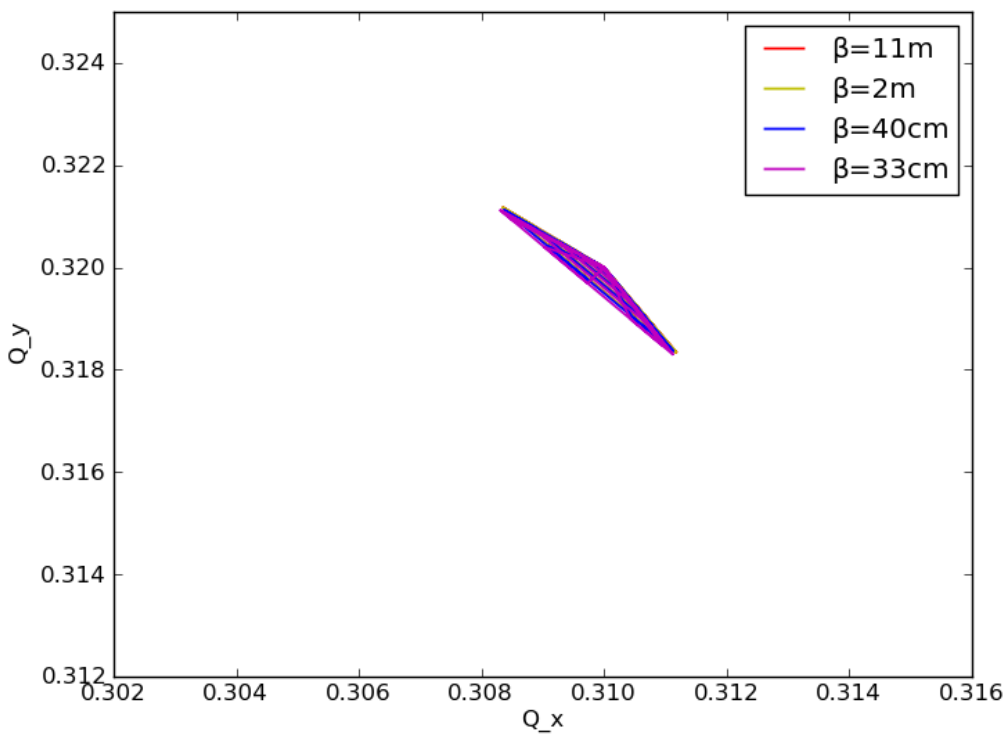
Optics during betatron squeeze: FP

- Negative LOF



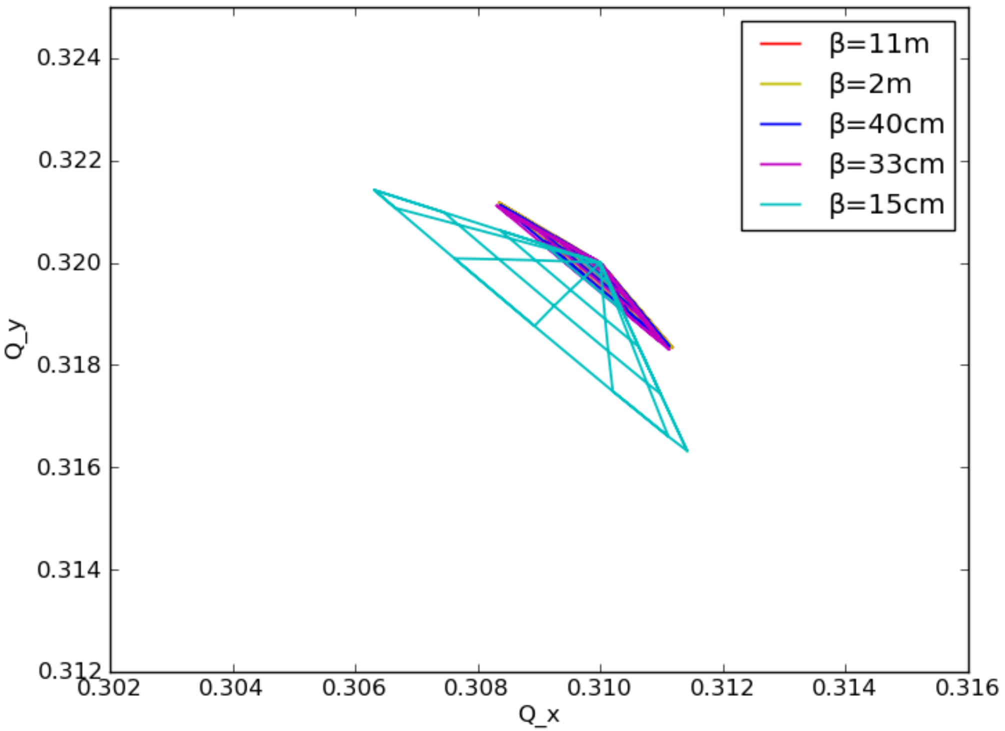
Optics during betatron squeeze: FP

- Negative LOF



Optics during betatron squeeze: FP

- Negative LOF



Optics during betatron squeeze: FP

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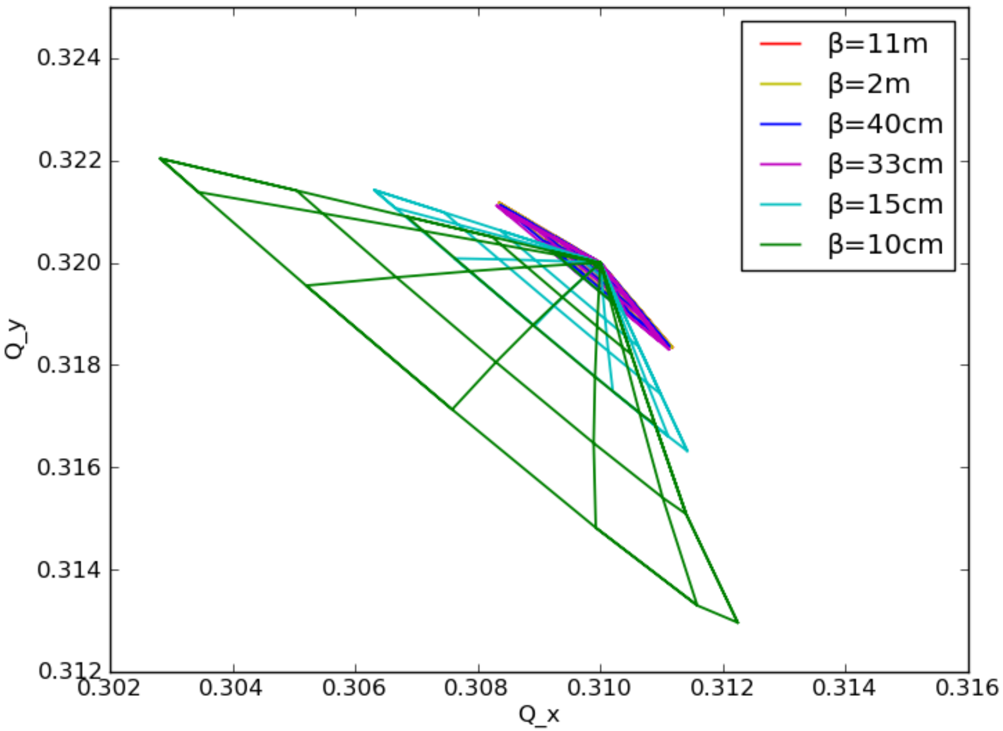

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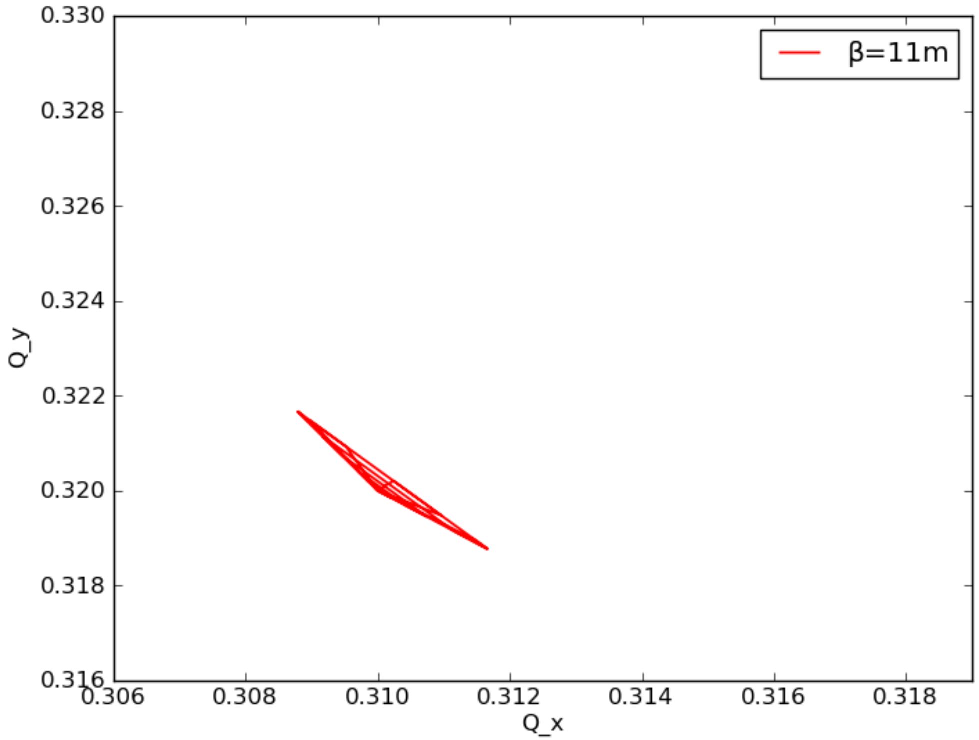
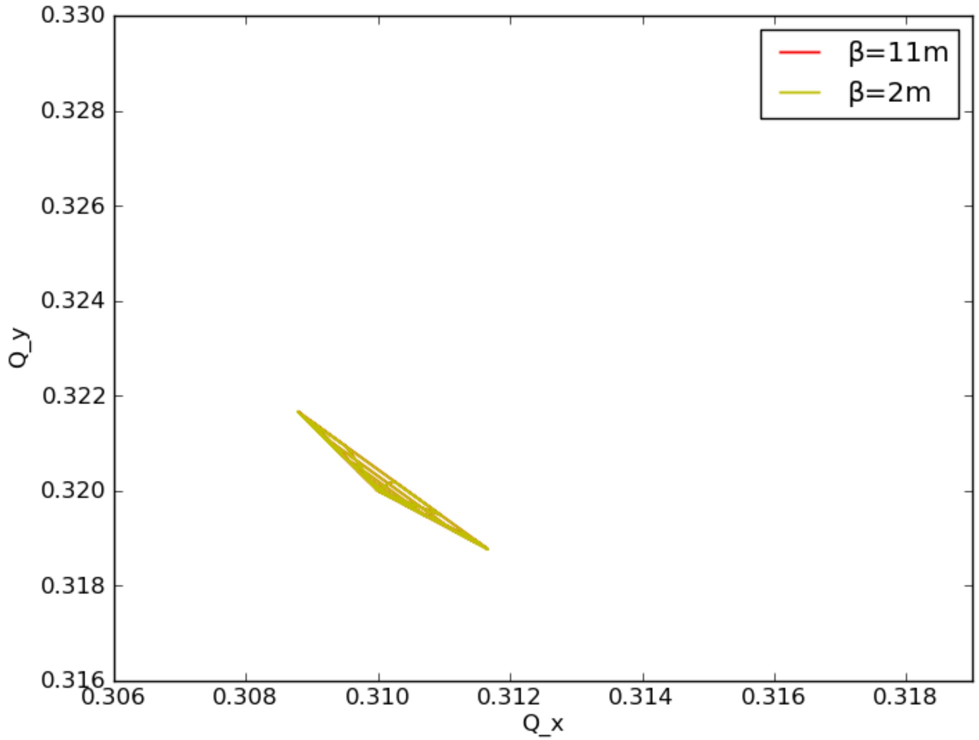
- Positive LOF



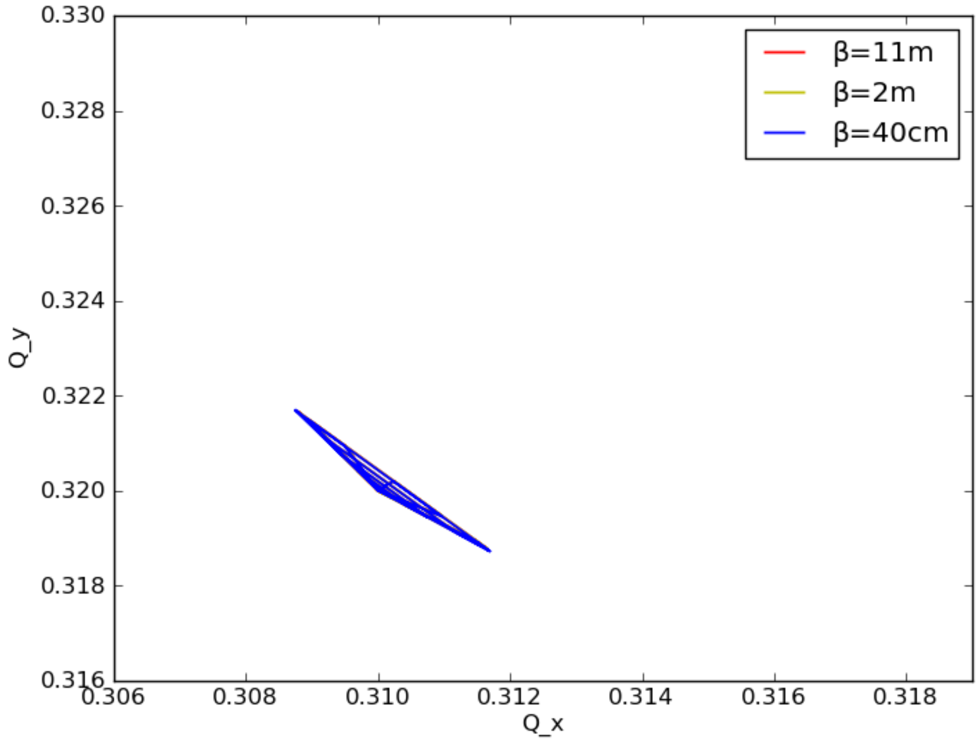
Optics during betatron squeeze: FP

- Positive LOF



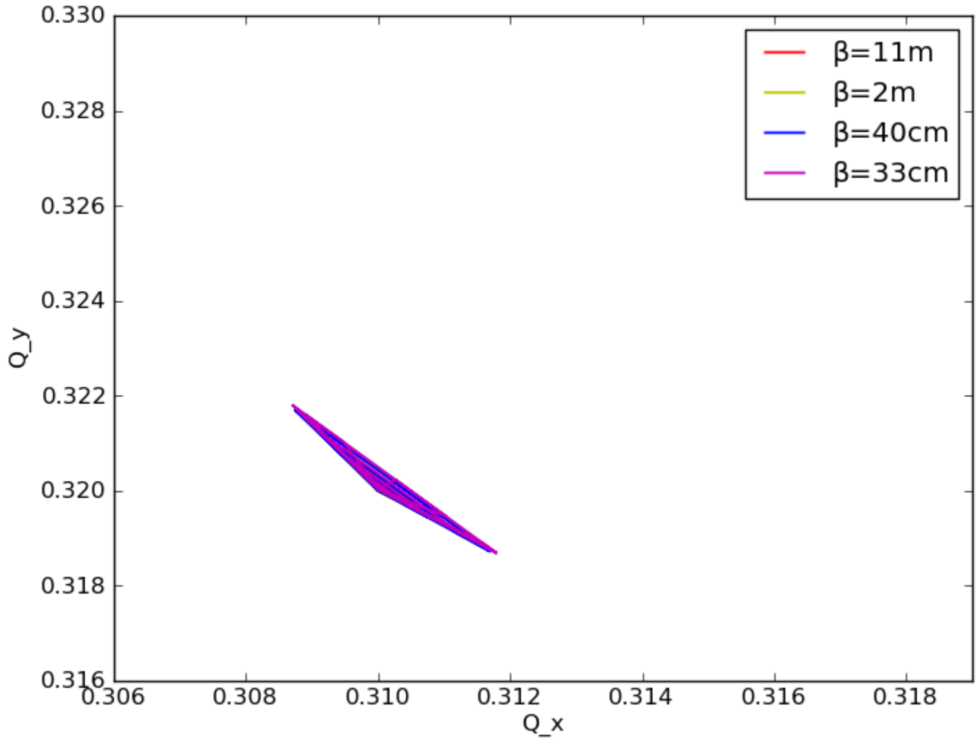
Optics during betatron squeeze: FP

- Positive LOF



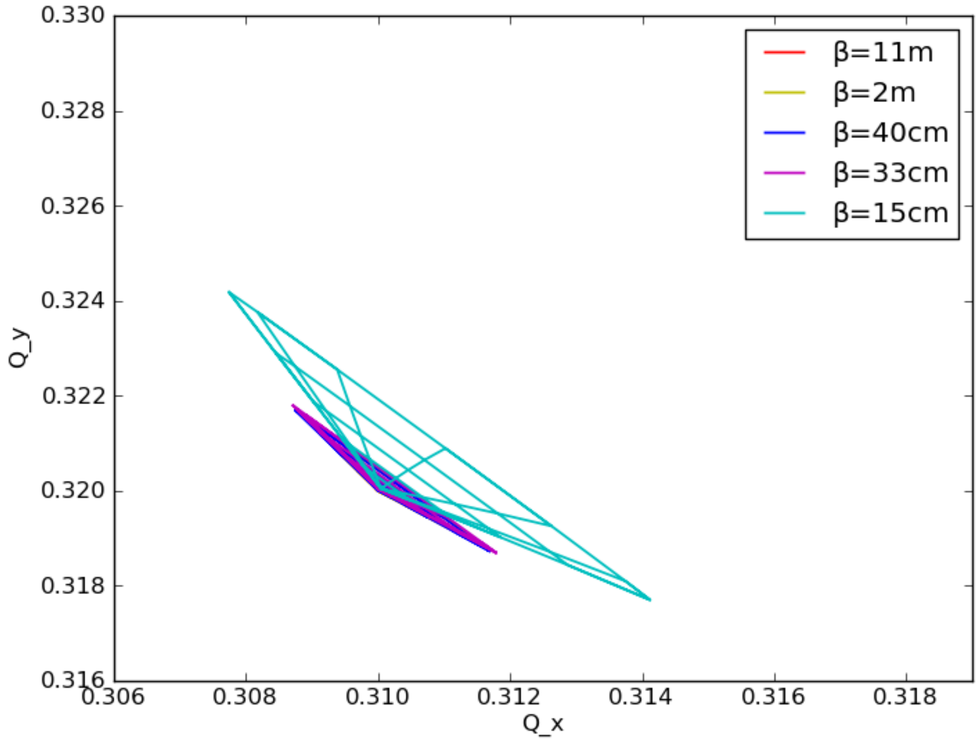
Optics during betatron squeeze: FP

- Positive LOF



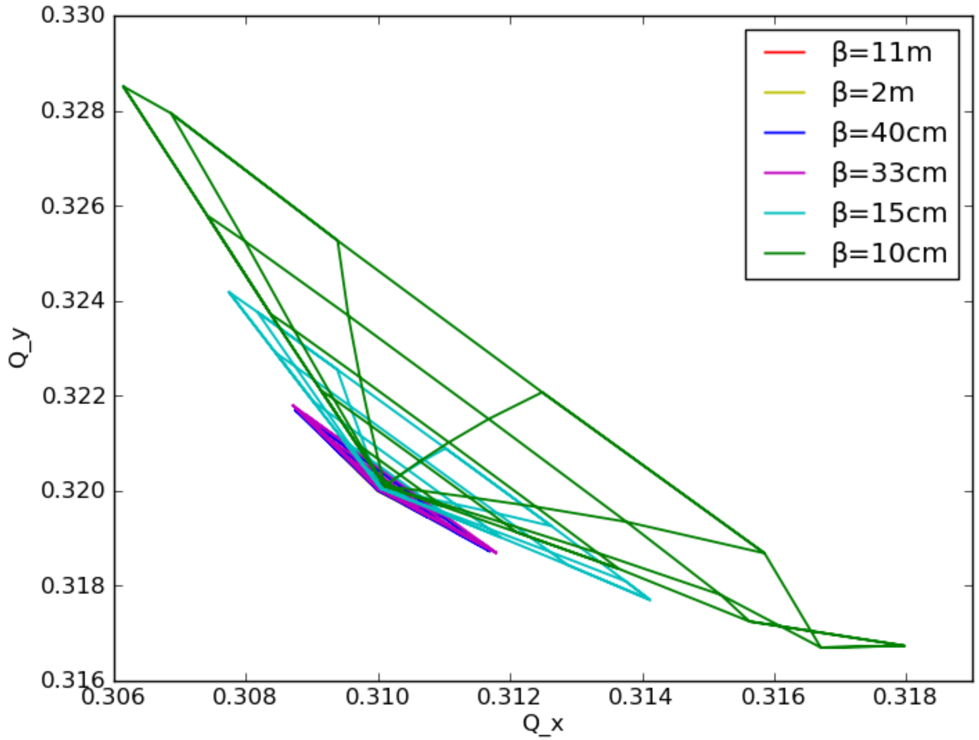
Optics during betatron squeeze: FP

- Positive LOF

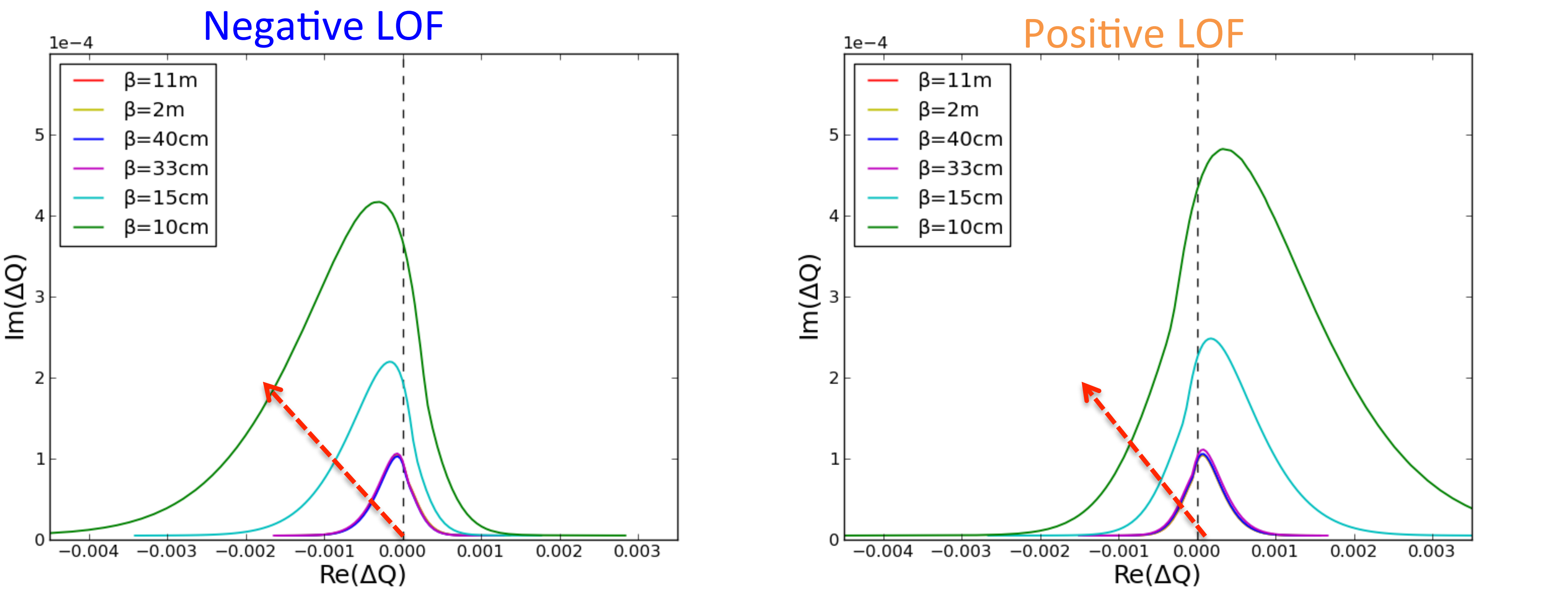


Optics during betatron squeeze: FP

- Positive LOF



The beauty of ATS on stability diagrams



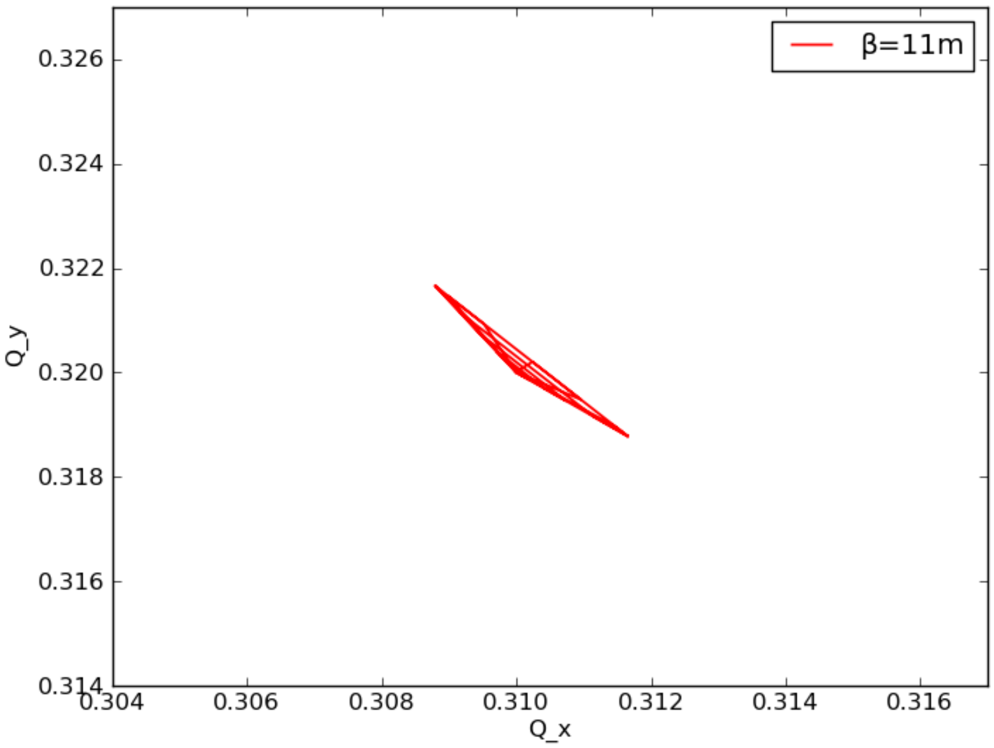
Larger betas in arcs (ATS) increase the stability area:

- LHC optics type range: β* [11 m-33 cm] (2.5 μm ε_n and 2.2e11ppb int)
- ATS optics: β* < 33cm (2.5 μm ε_n and 2.2e11ppb int)

The telescopic part of ATS optics can increase the stable area by a large factor!

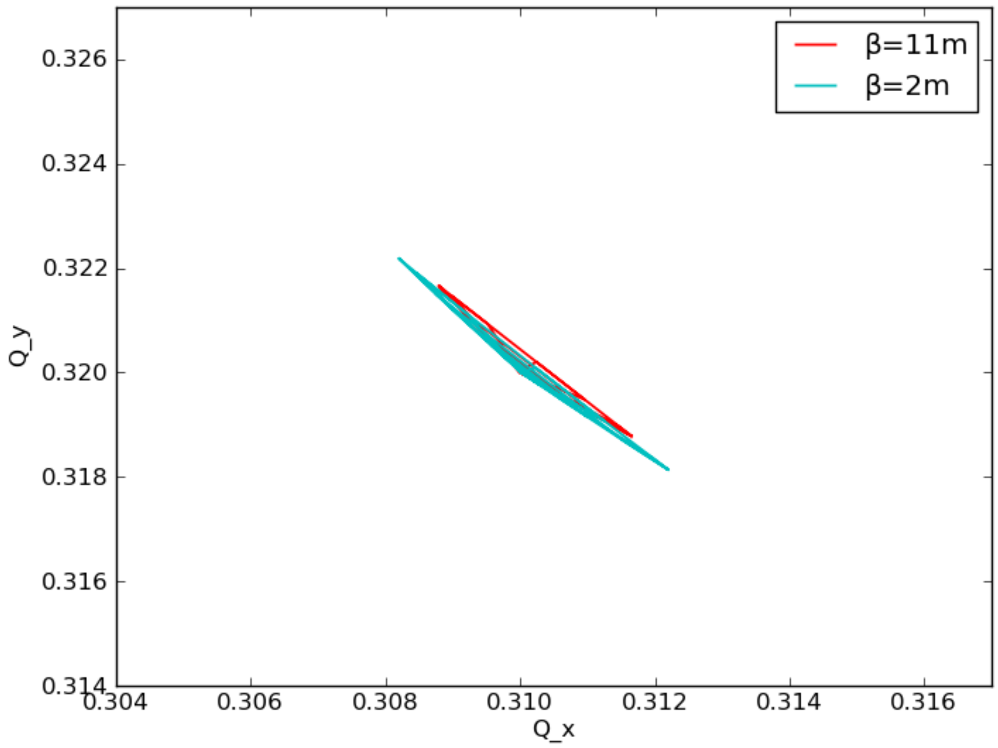
Effects of different optics + beam beam LR: footprints

- Positive LOF



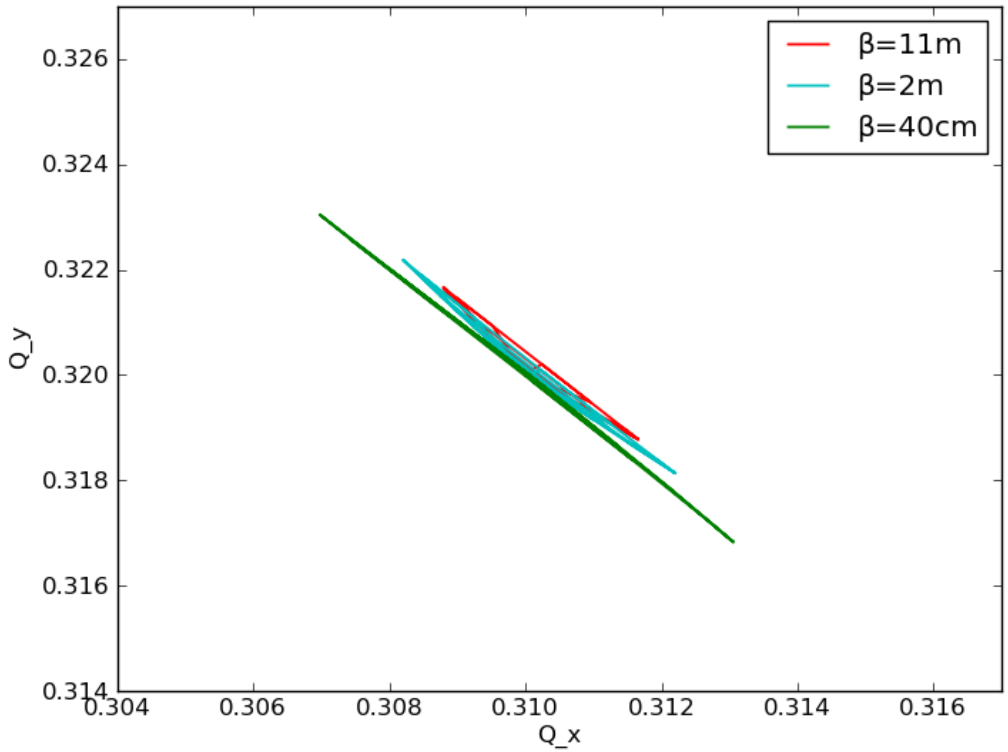
Effects of different optics + beam beam LR: footprints

- Positive LOF



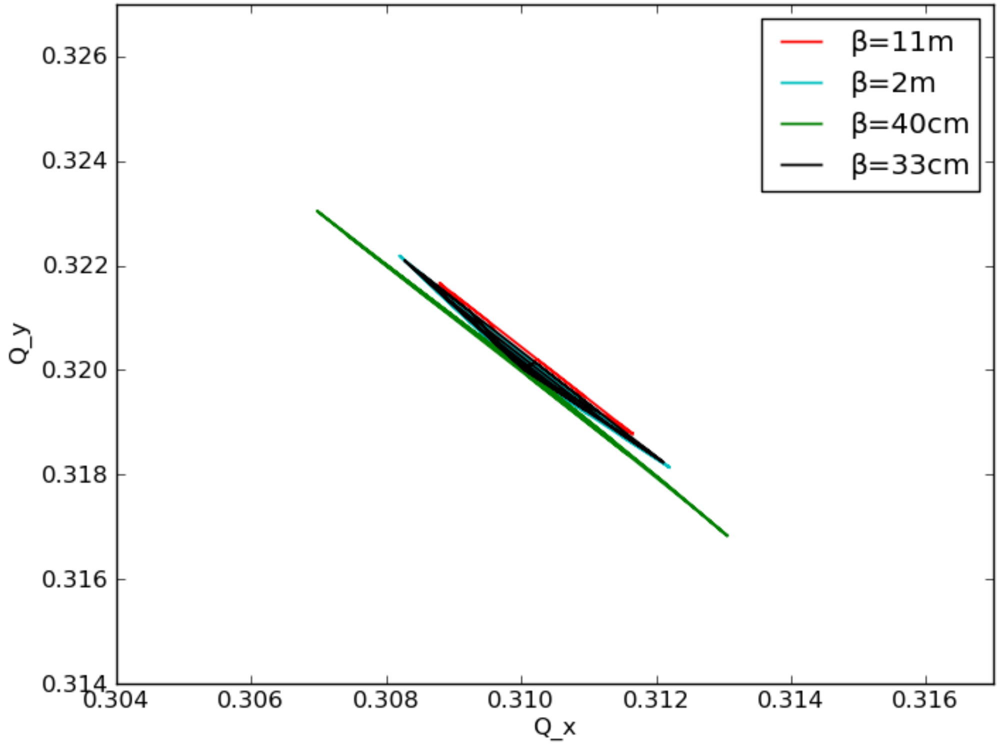
Effects of different optics + beam beam LR: footprints

- Positive LOF



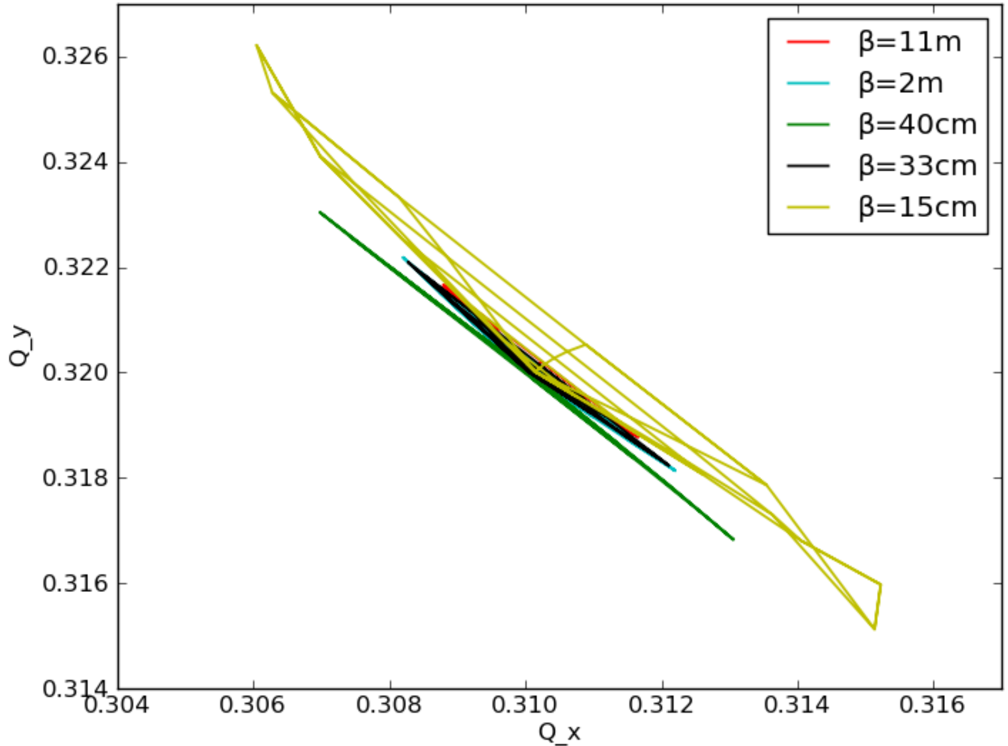
Effects of different optics + beam beam LR: footprints

- Positive LOF



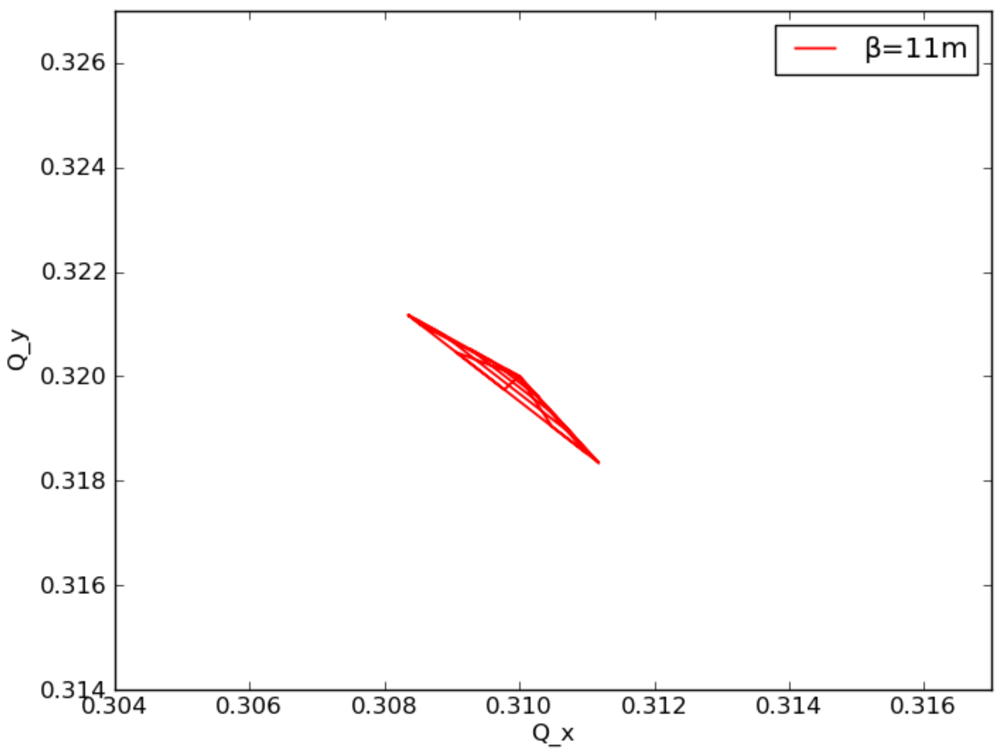
Effects of different optics + beam beam LR: footprints

- Positive LOF



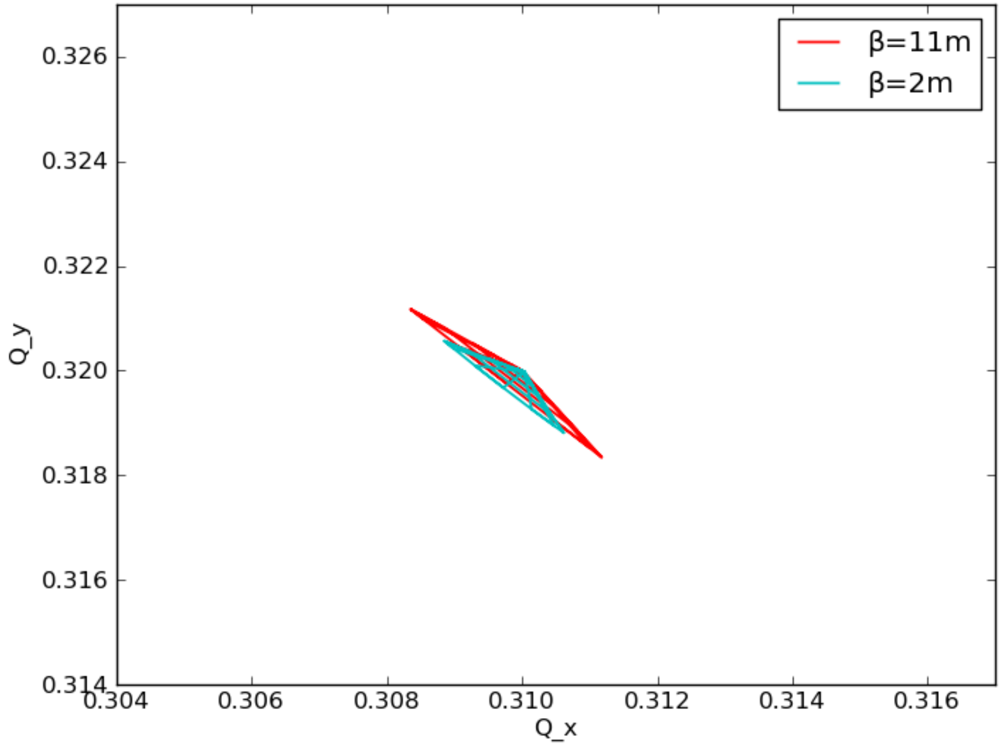
Effects of different optics + beam beam LR: footprints

- Negative LOF



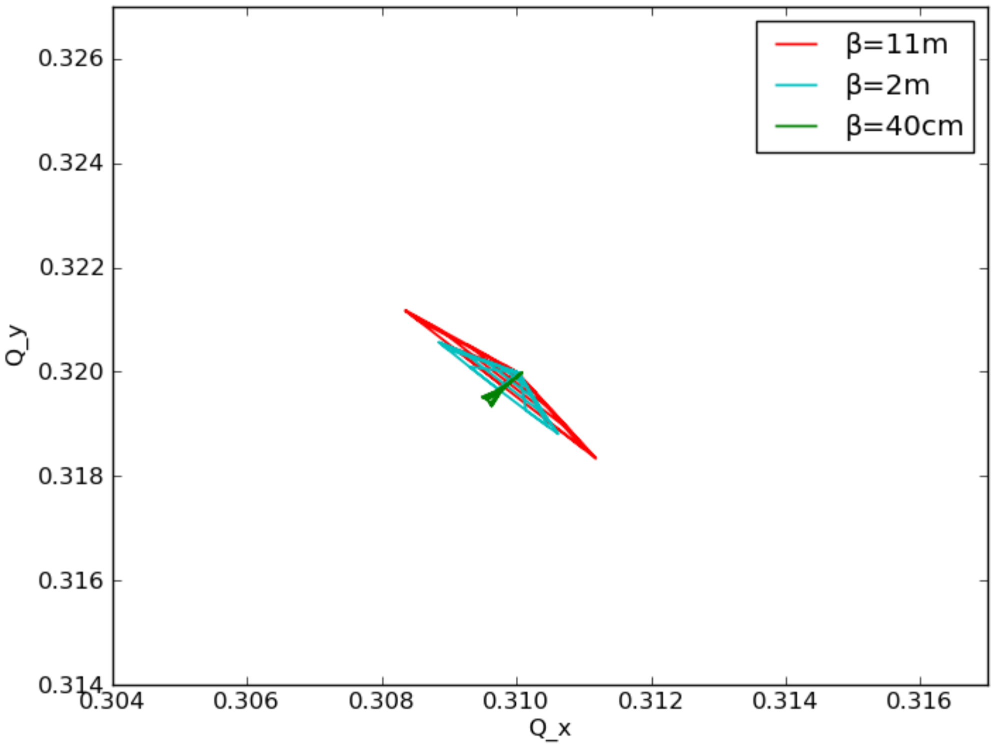
Effects of different optics + beam beam LR: footprints

- Negative LOF



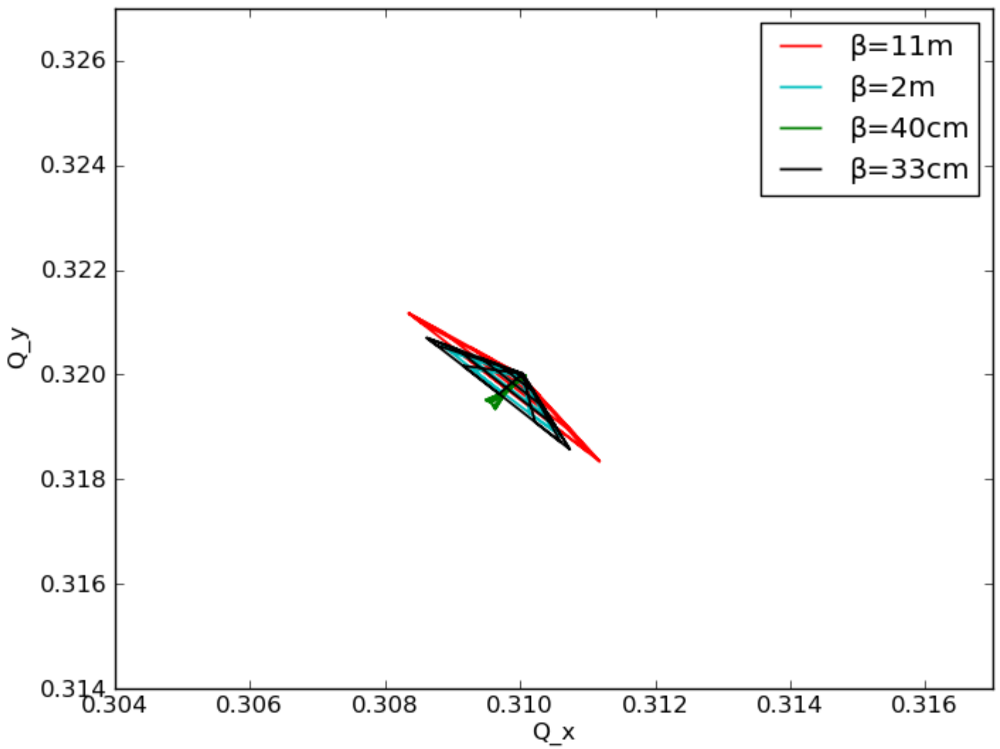
Effects of different optics + beam beam LR: footprints

- Negative LOF



Effects of different optics + beam beam LR: footprints

- Negative LOF



Effects of different optics + beam beam LR: footprints

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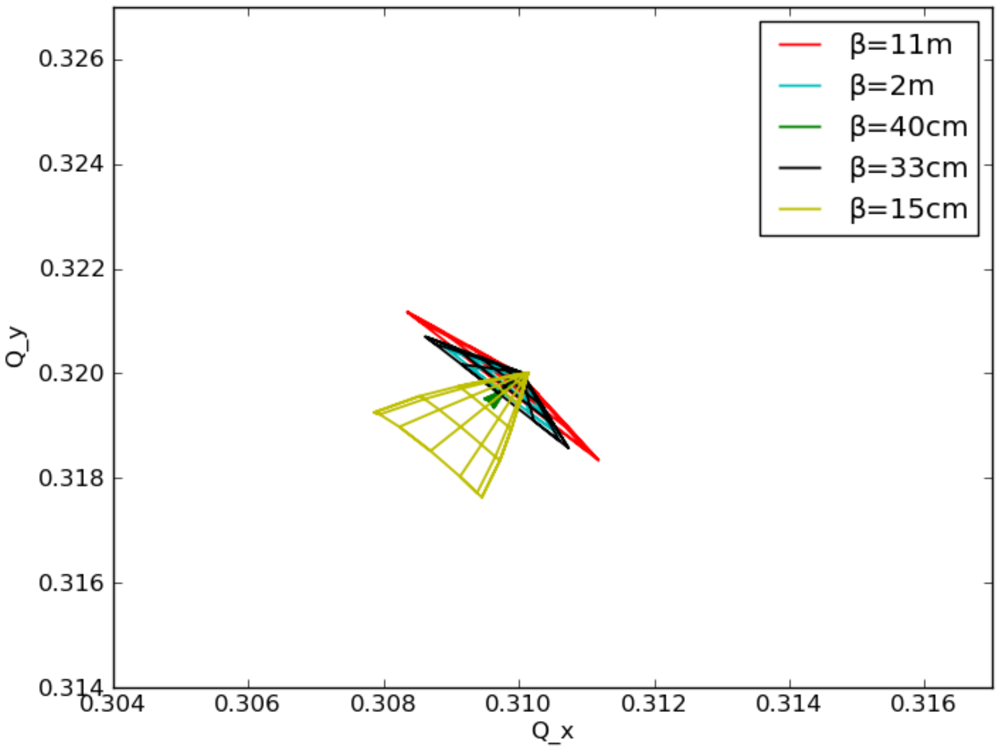
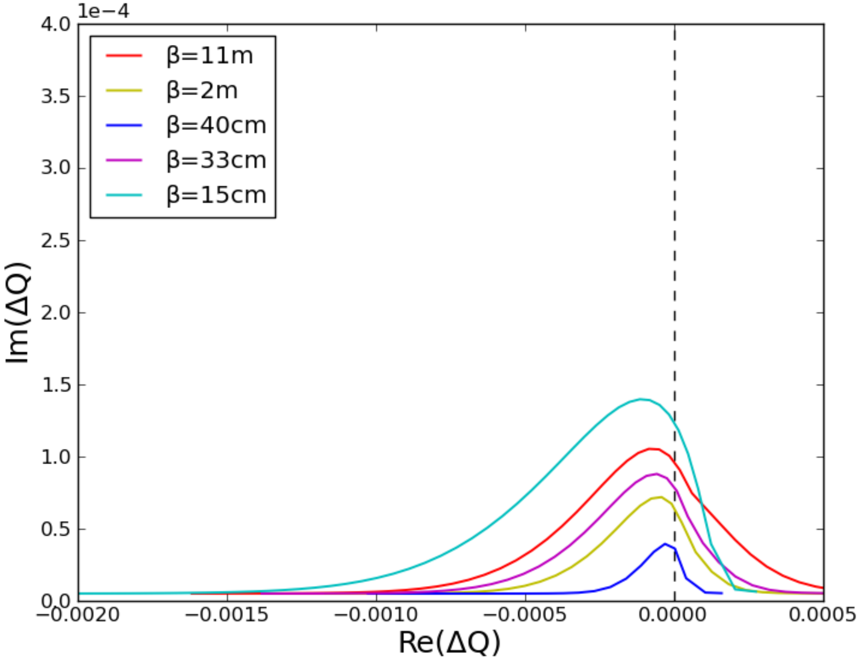
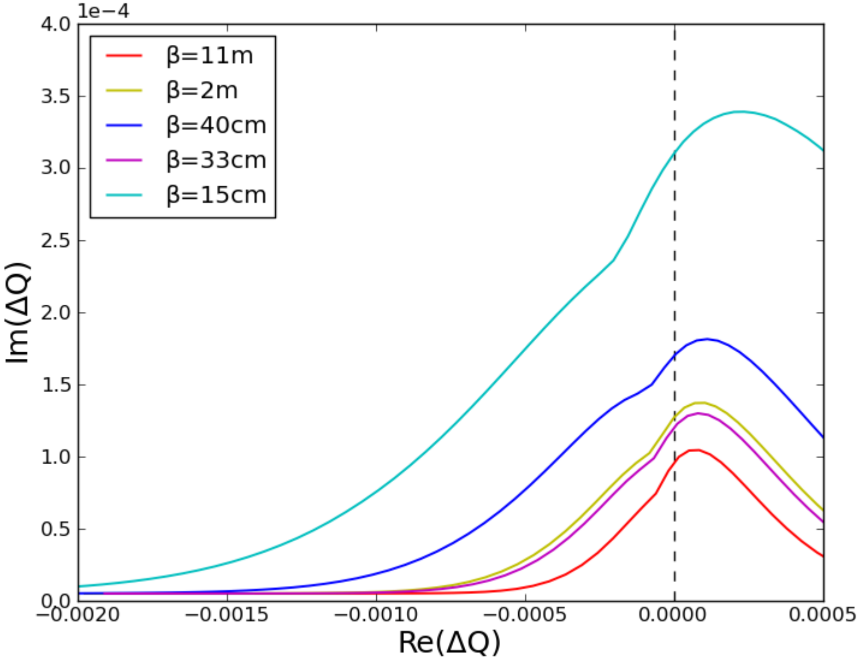


Effects of different optics+beam beam LR: stability diagrams

- Negative LOF



- Positive LOF



Non-monotonic behaviour

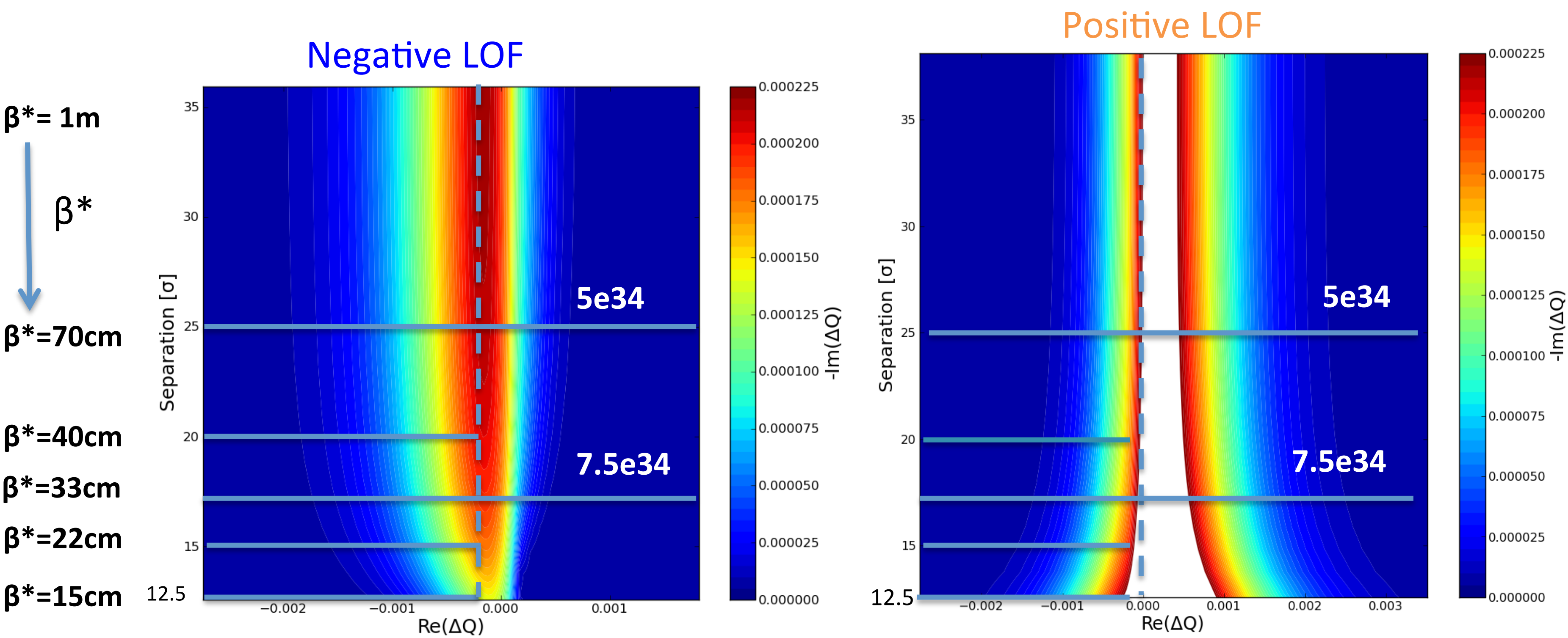
Difficult to decide +/- LOF and keep clean control of effects

Positive LOF and long-range BB gives larger stability area when fully squeezed.

Simulations case : Squeeze with ATS at 1 m β*

The telescopic part (larger betas in the arc) can be partially in place from 2 m onwards if needed (S. Fartoukh) still to be proved but interesting!

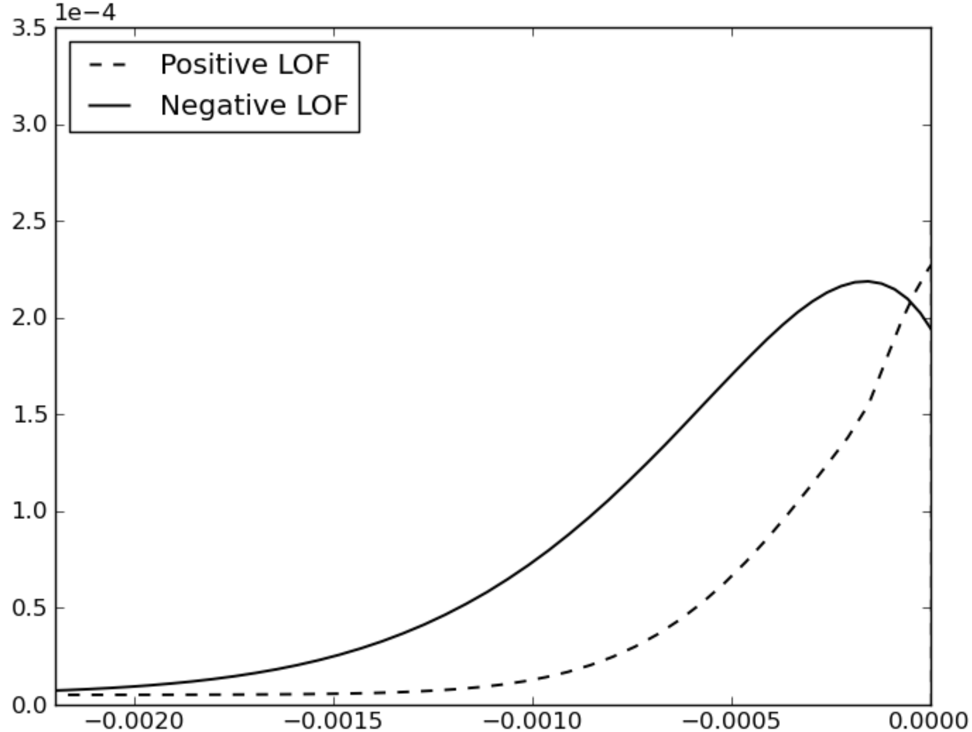
LR beam-beam in IP1 and IP5 **I=2.2e11 ε=2.5e-6 m**



With telescopic part in place from 1 m β* the squeeze is very similar to the LHC case
With larger betas before BB LR arrive LOF negative preferred for stability without BB
With BB LRs the stable area is reduced

SD evolution during the β-squeeze

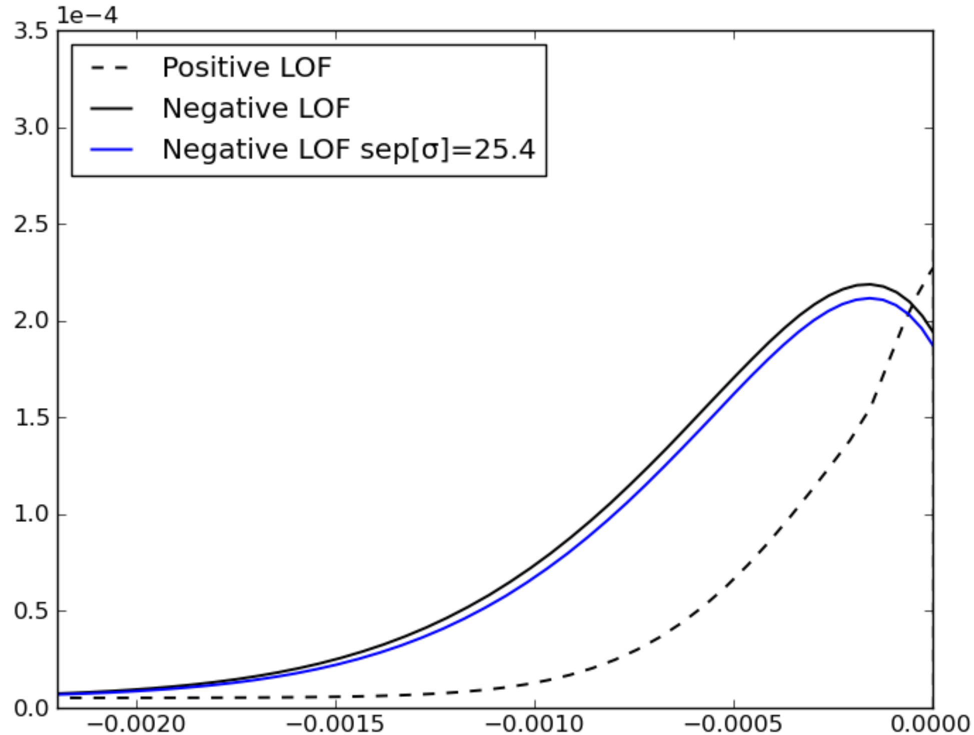
Octupoles only



- Single Beam Negative polarity preferred

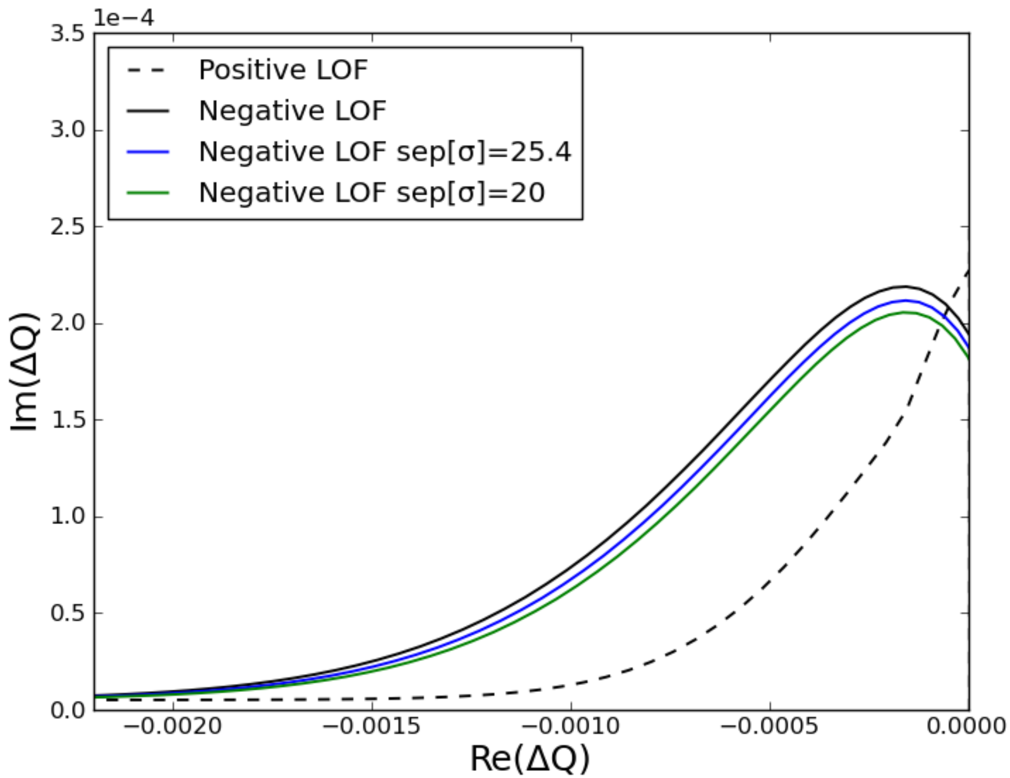
SD evolution during the β-squeeze

LR beam beam added 70cm β*



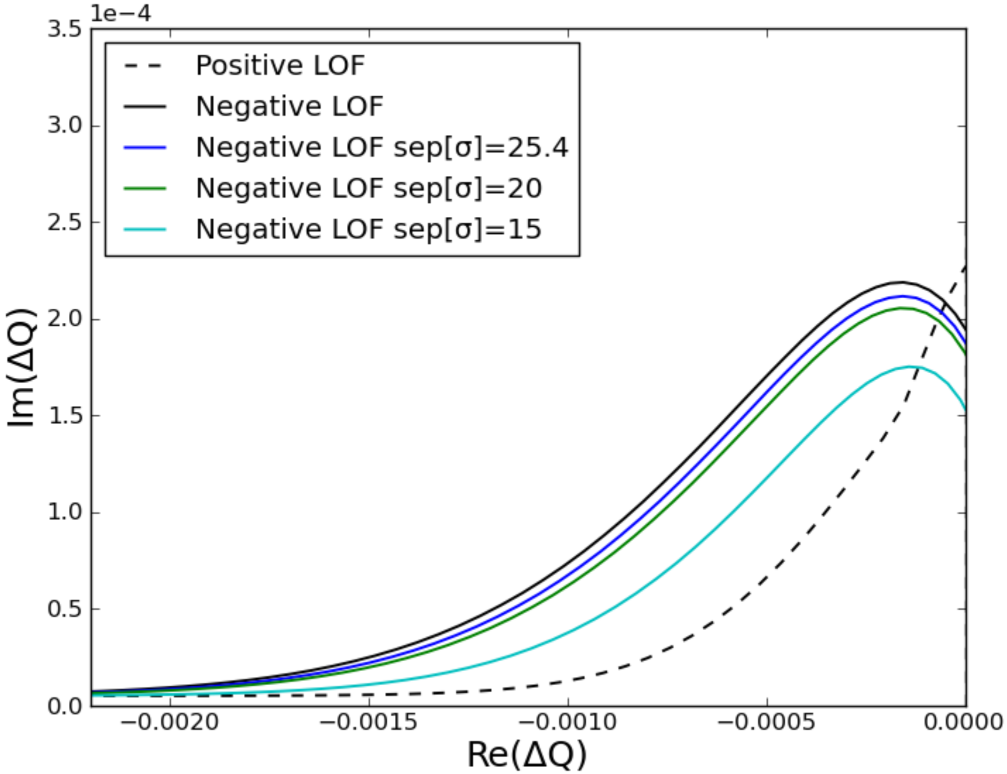
SD evolution during the β-squeeze

LR beam beam added 40cm β*



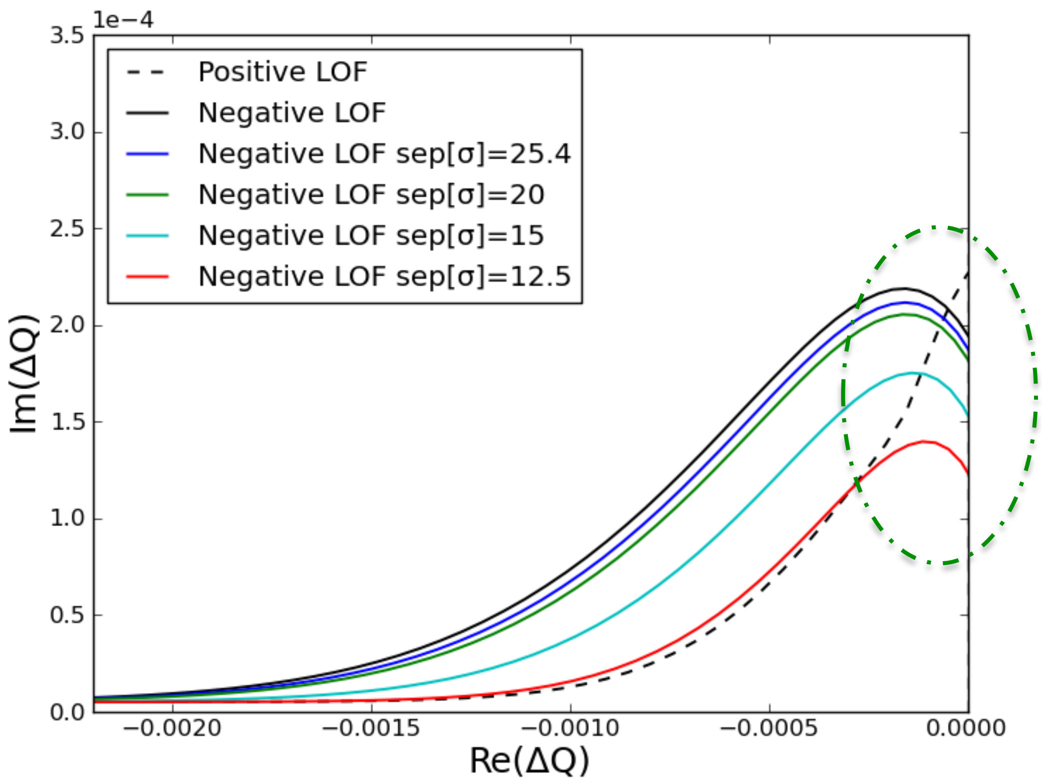
SD evolution during the β-squeeze

LR beam beam added 22cm β*



SD evolution during the β-squeeze

LR beam beam added 15cm β*

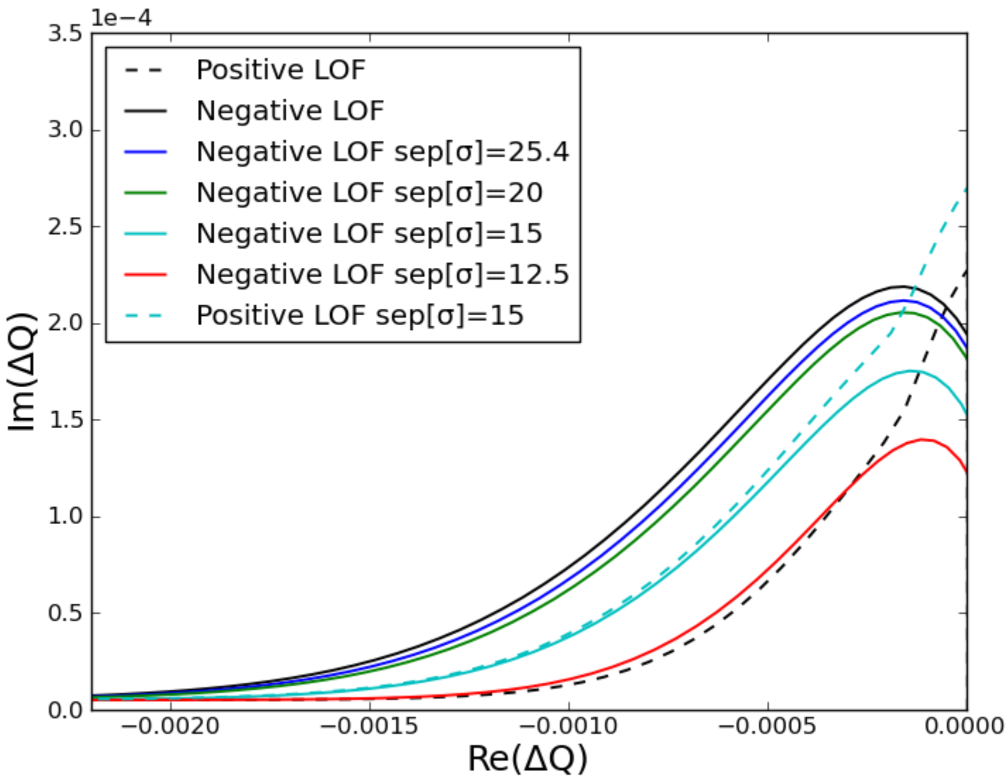


Different behaviour of LOF pos: if coherent modes have small Re (ΔQ) but large Im(ΔQ) then important area

- At 12.5σ the positive LOF (without LR contribution) gives a "similar" SD w.r.t. the negative LOF

SD evolution during the β-squeeze

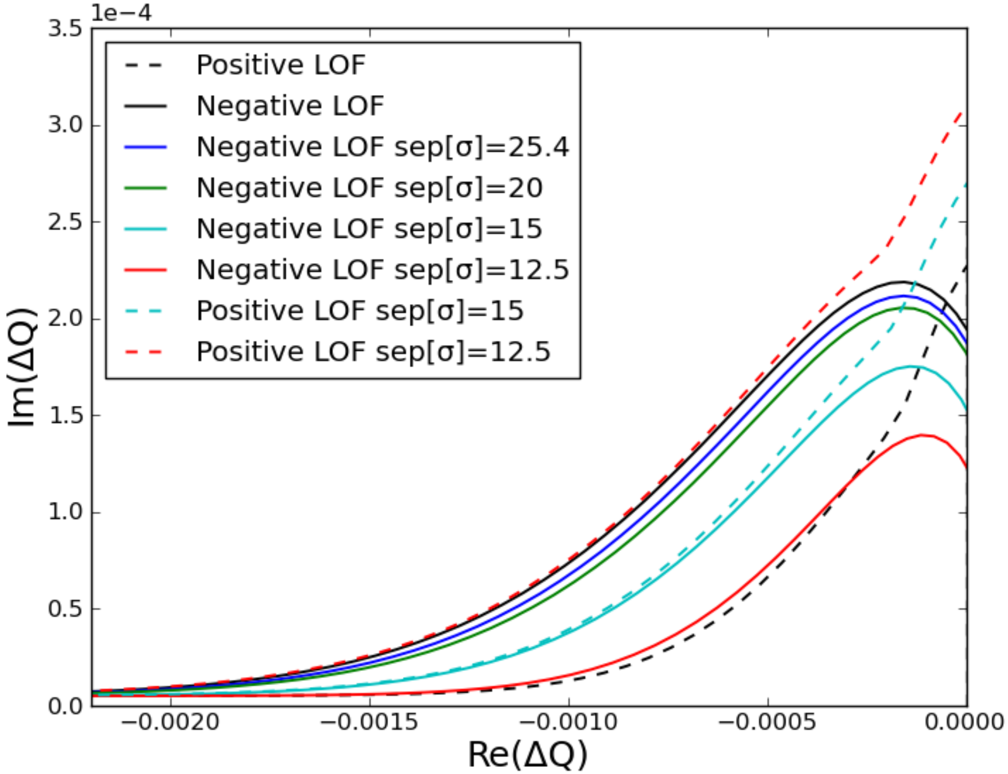
LR beam beam added 22 cm β*



- At 15σ the positive LOF with LR contribution is equal to the negative LOF at the same separation

SD evolution during the β-squeeze

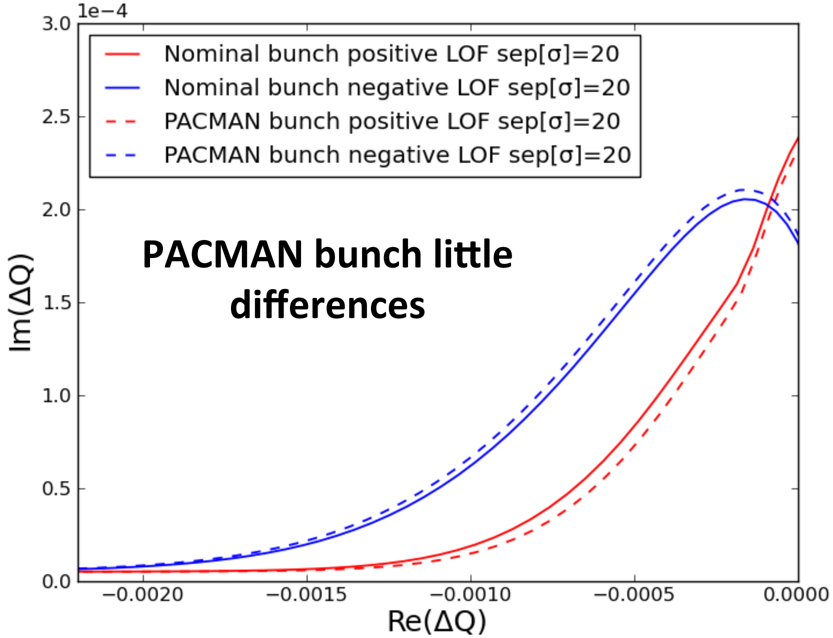
LR beam beam added 15 cm β*



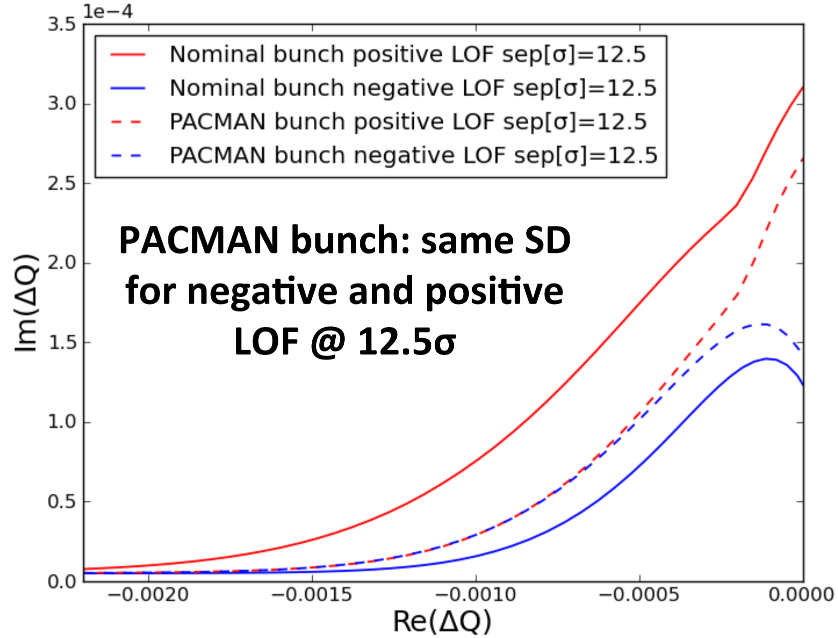
- At 12.5σ the positive LOF with LR contribution gives a larger SD w.r.t. the negative LOF at the same separation

Stability Diagrams for PACMAN bunches

At 40 cm b* → 20 σ separation

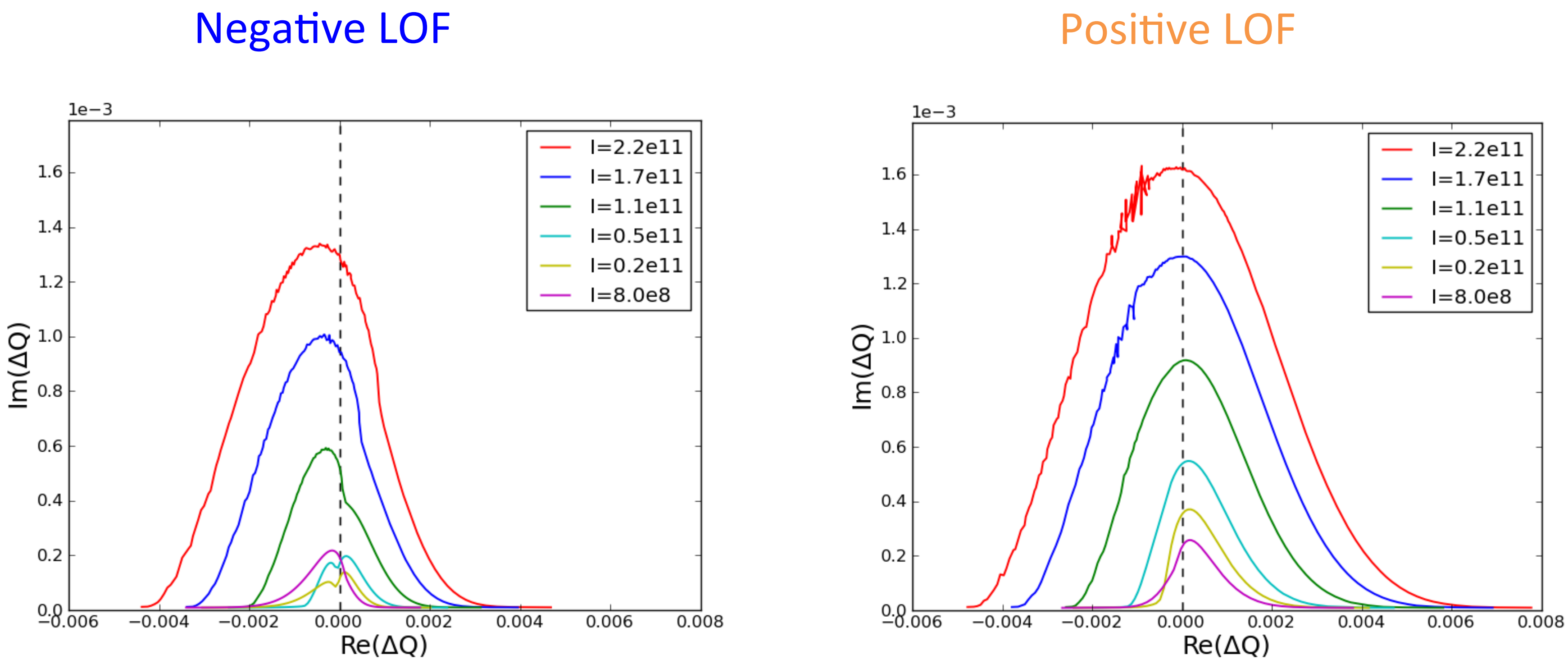


At 15 cm b* → 12.5 σ separation



- **Baseline 1: leveled lumi at 5e11 negative polarity preferred with Telescopic part from 1 m β* compensating LR effects (to be computed minimum required beta in arcs)**
- **Ultimate: leveled lumi at 7.5e11 negative polarity preferred with Telescopic part from 1 m β* compensating LR effects (to be computed minimum required beta in arcs)**
- **Extreme case: full squeeze will depend on single beam needs: if single beam ok with LOF positive before squeeze then positive polarity preferred with BB if not we might need to collide for stability or find other means for providing tune spread?**

Crab crossing 1 head-on only: stability diagrams vs beam intensity



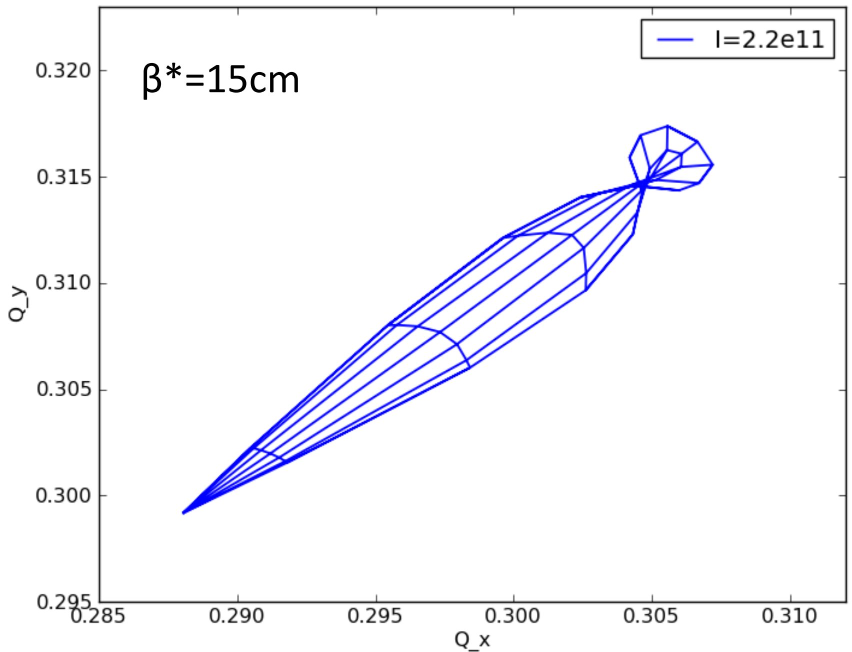
Negative polarity reduces stable area of head-on this might help in collision reducing the detuning with amplitude coming from the LR interactions?!

Needs DA studies with octupoles to evaluate possible cases (on-going)

Need to study effect of high chromaticity (>2units), strong impact!

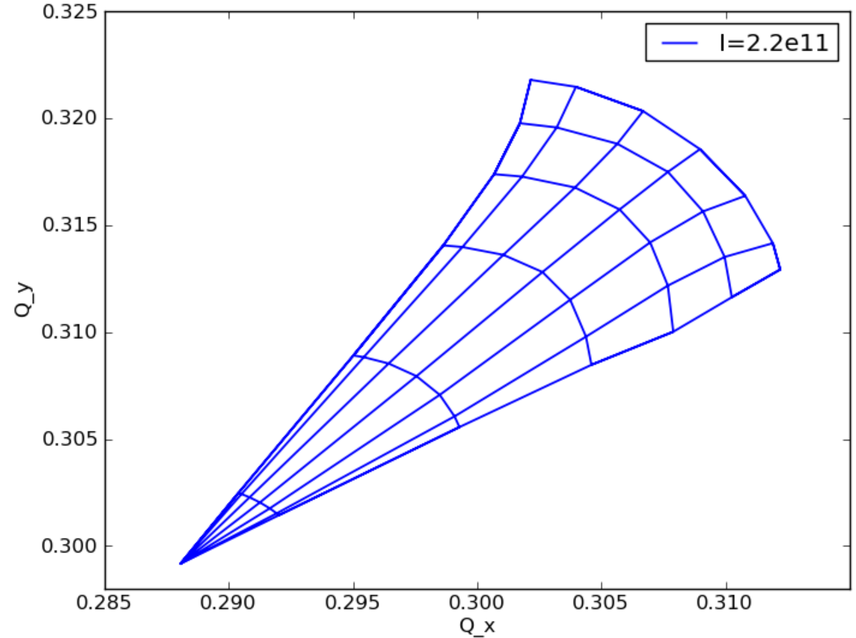
Head-on footprint + Octupoles

Negative LOF



2 H-0 I=2.2e11

Positive LOF



2 H-0 I=2.2e11

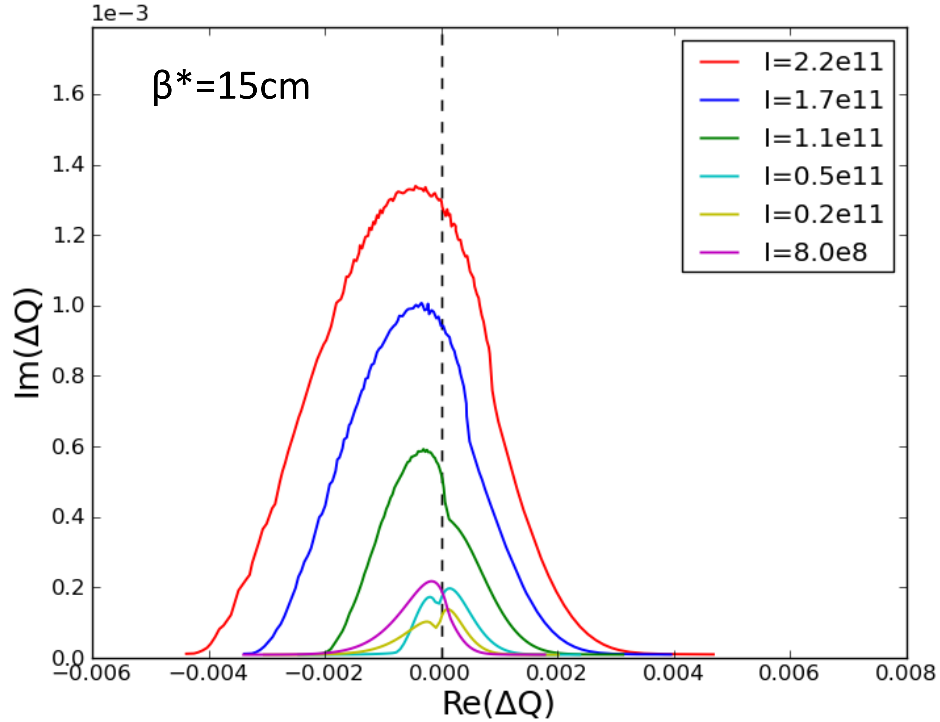
Octupoles with ATS very strong detuning

→ strong reduction of the tail particles detuning for negative polarity

→ Strong increase for pos polarity

SD evolution with intensity HO

Negative LOF



Octupoles with ATS very strong detuning

→ strong reduction of the tail particles detuning for negative polarity: could this be beneficial for DA? (to be studied)

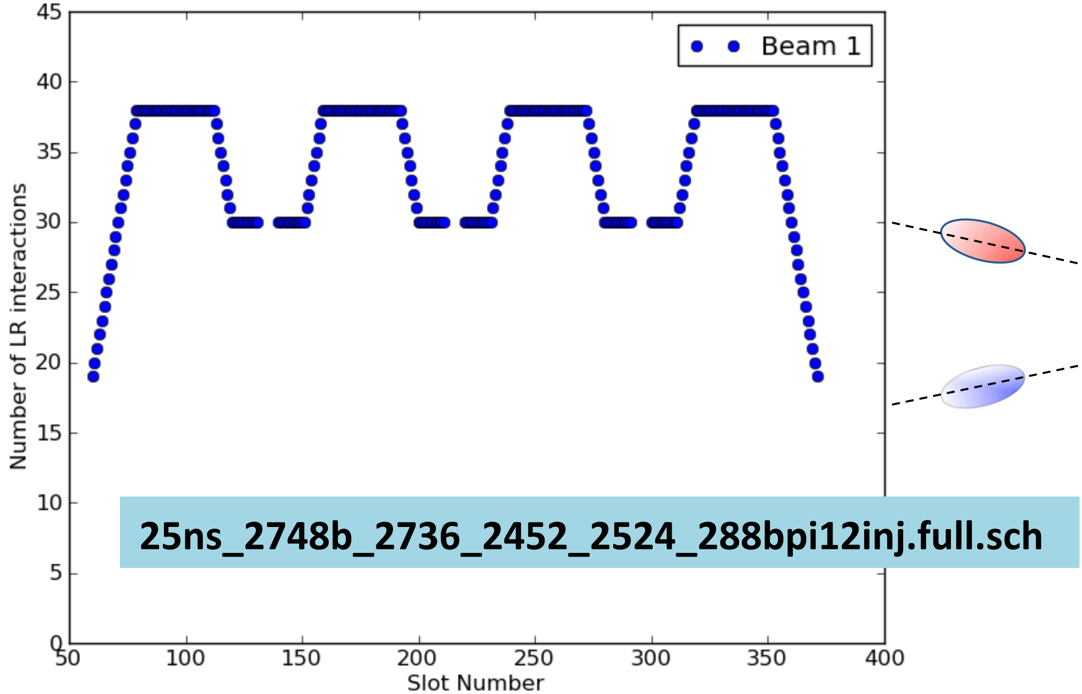
→ Strong increase for positive polarity:

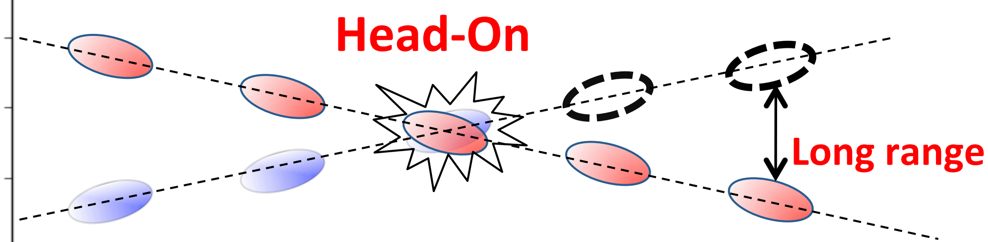
Outline

- Beam-Beam and Landau Octupoles
- **PACMAN Effects: orbit, Q and Q’**
- Summary

HL-LHC PACMAN Effects

B. Gorini : /afs/cern.ch/user/l/lpc/public/FILLSCHEMES/Run2/



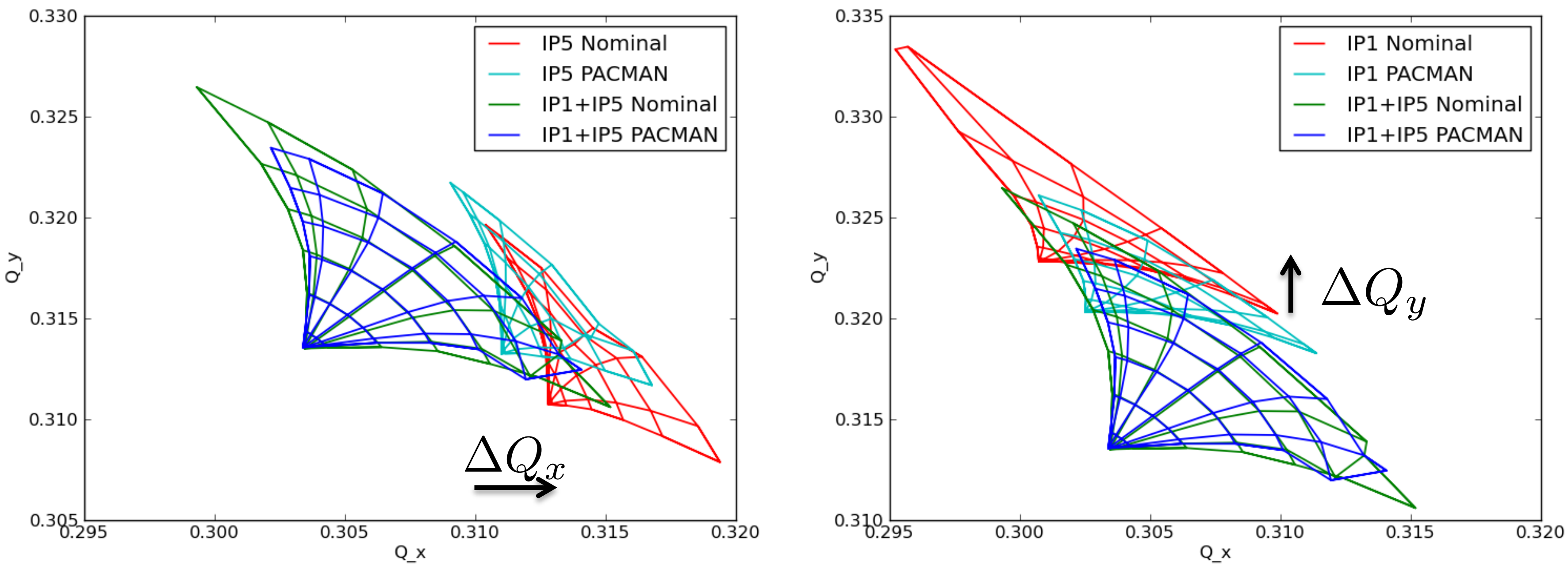


NOMINAL bunches: bunches maximum number of Long ranges (center of a train)
PACMAN bunches: reduced number of long ranges (head and tails of TRAIN)

- Different DA (negligible effect LARP meeting BNL)
- Different tune shift
- Different chromaticities
- Orbit effects

HV crossings IP1/5 compensates for these 2 effects for round optics

HL-LHC case: HV passive compensation



With HV Passive compensation tune shifts (and Q') compensated only spread different (blue/green footprints) and orbits

Without HV crossing : PACMAN bunches will see a tune shift (and chromaticity shift) respect to nominal bunches (red/cyan footprints)

LHC example IP5: Qx

Intensity= 1.15e11 ppb d_{sep} = 9.5 σ
The long-range interactions in IP5 only in V plane

Tune shifts 0.0015 units

IP1 and IP5 HH crossing 2 times the effect

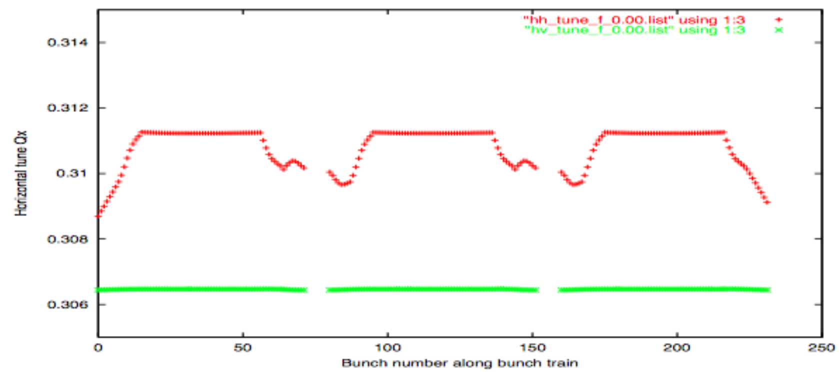
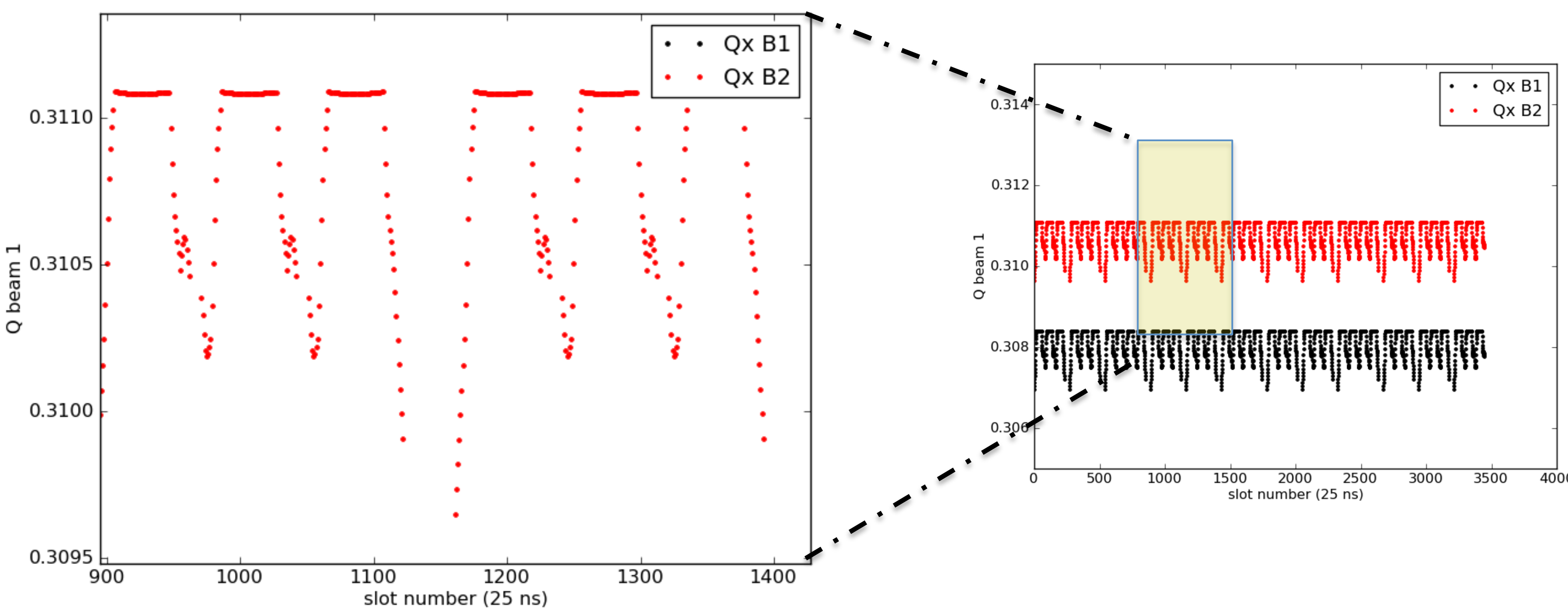


Figure 30: Horizontal tune variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.

Courtesy of W. Herr



LHC IP5:Q’ x

IP1 and IP5 HH crossing 2 time the effect

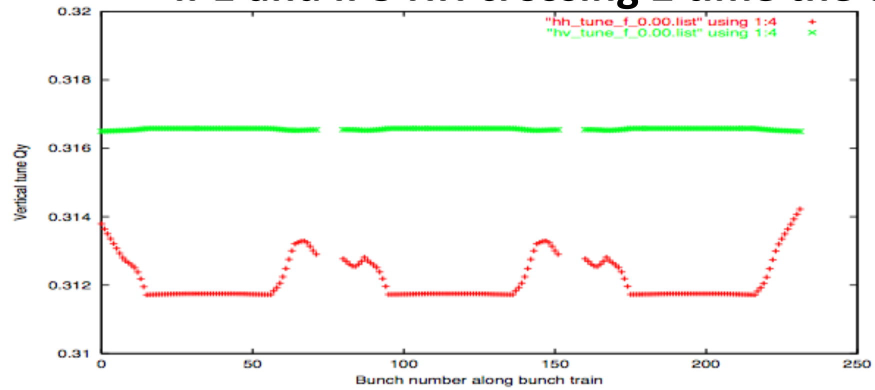
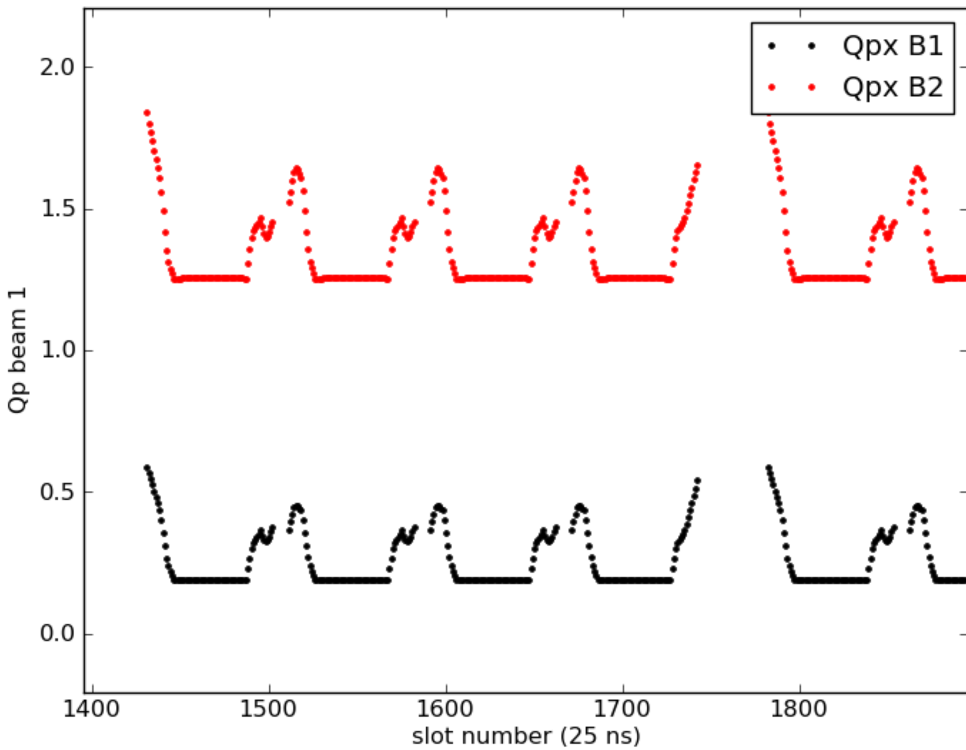


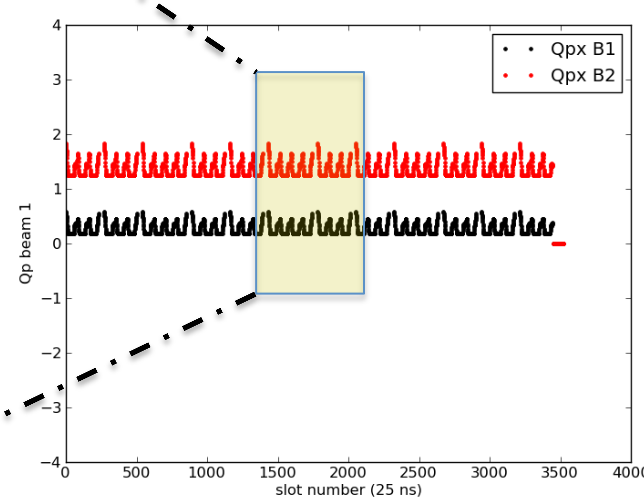
Figure 31: Vertical tune variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.

The long-range interactions in IP5 or plane

Q’ spread of less than 1 unit

Courtesy of W. Herr





Alternating crossing

The long-range interactions in IP5 only in V and IP1 in H compensates the tune and chromaticity effects of long ranges interactions

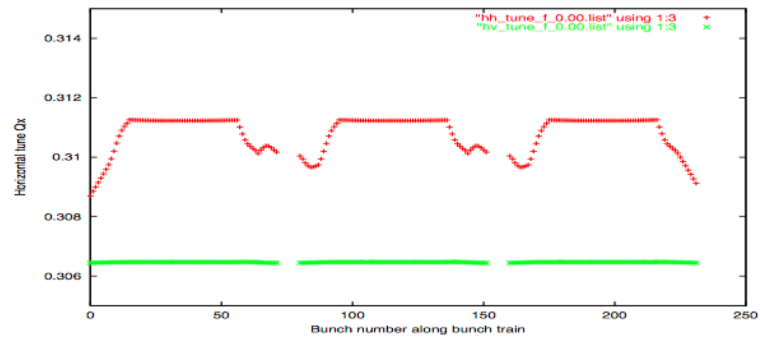
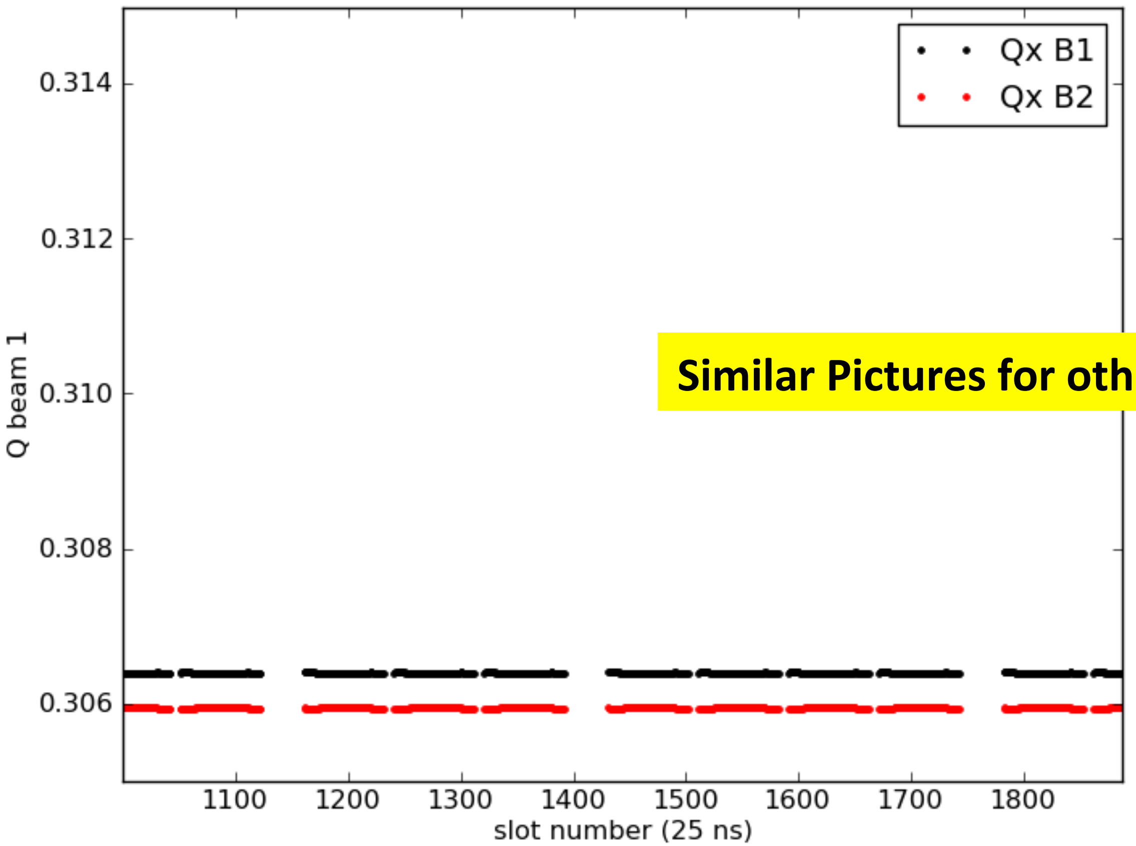


Figure 30: Horizontal tune variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.



Courtesy of W. Herr

Similar Pictures for other plane and chromaticity

LHC IP5 only: orbits

- Intensity 1.15e11 ppb
- Emittance 3.75 (16.6 μm at IP)
- Nominal LHC optic β* 0.55 collision
- 15 LR per side of IP
- IP5 only: H crossing (285 μrad)
- Nominal LHC filling scheme 25 ns

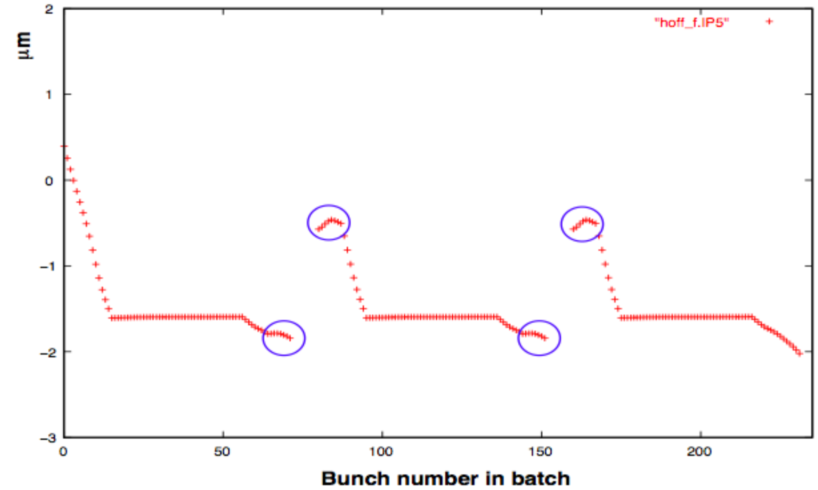
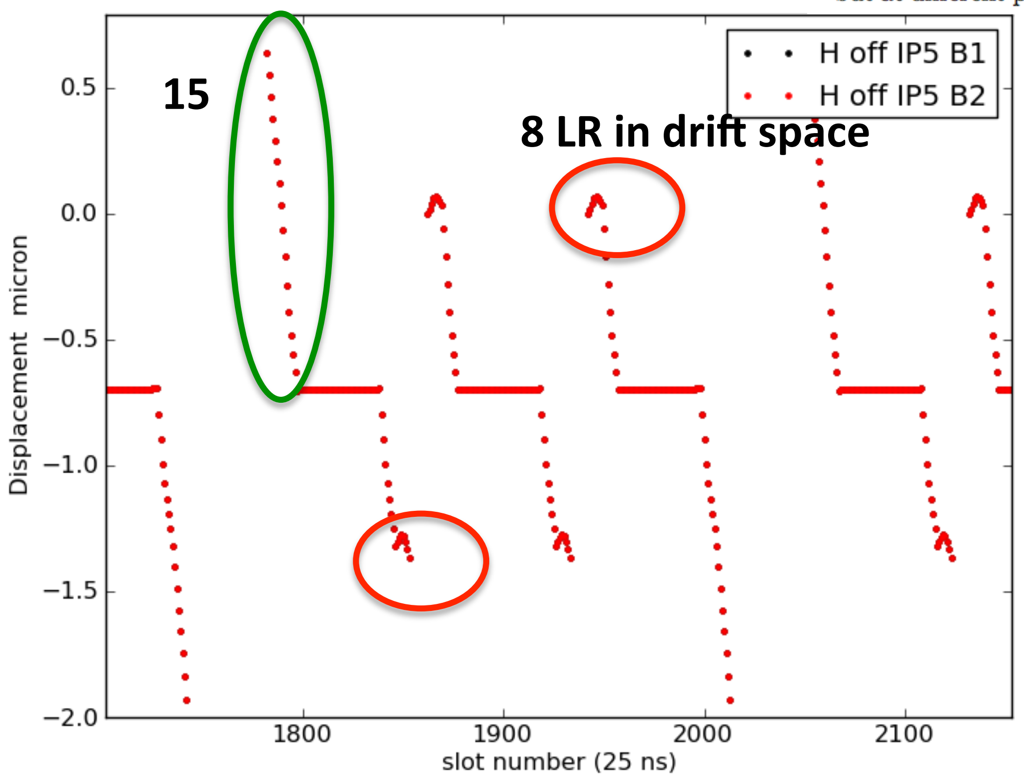


Figure 8: Horizontal offset in IP5 with horizontal-horizontal crossing. Details in first three batches. Indicated bunches have all the same number of long range interactions (i.e. 22), but at different positions. Leftmost and rightmost bunches miss 15 long range interactions.

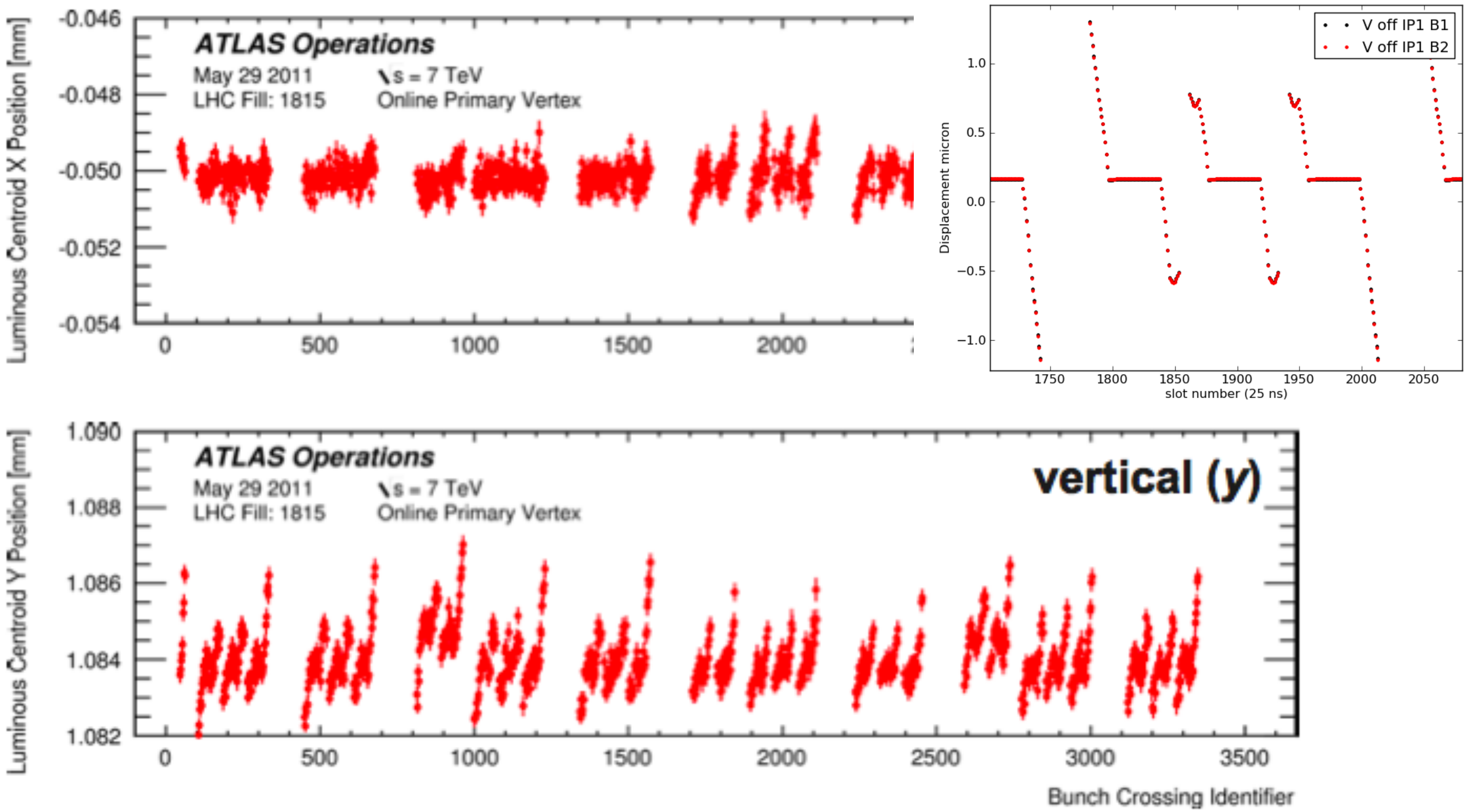


LHC filling scheme:

38-39 empty slots for LHC injection kicker
And 8 empty slots between trains of 72
due to SPS injection kicker

Orbit variation of 2.5 μm due to long-range deflection

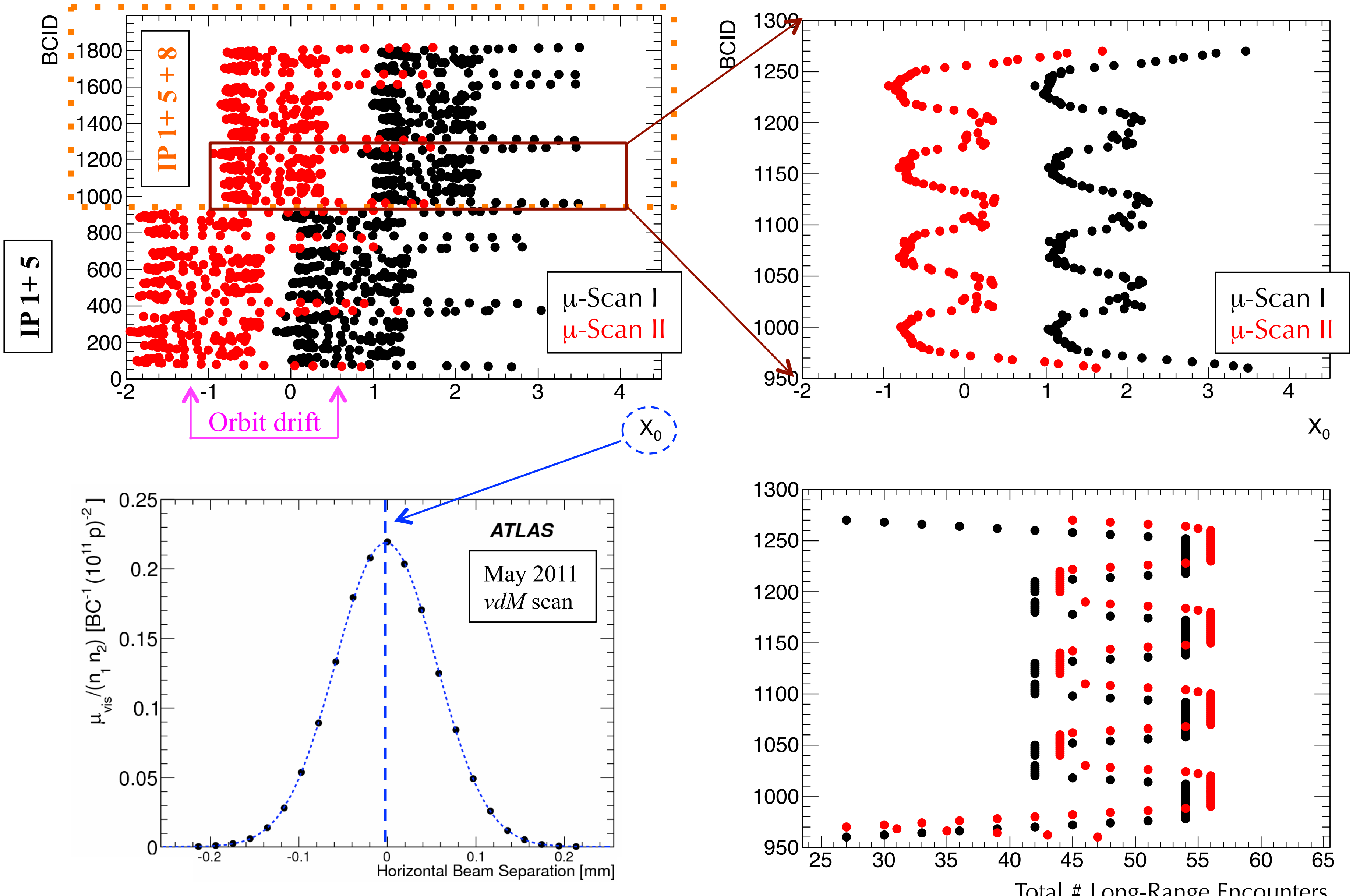
Can we cross check with data? ATLAS vertex detector 2011 data



Courtesy of R. Bartoldus and W. Kozanecki ATLAS collaboration

Vertical centroid displacement can be measured and we can check few cases

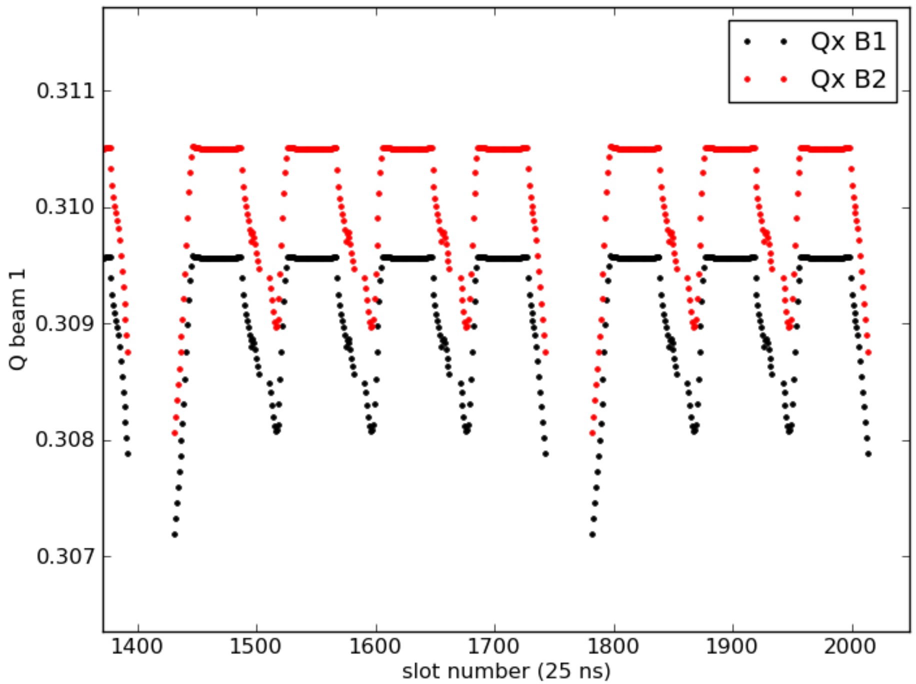
ATLAS data 2012 April VdM Horizontal plane



Courtesy of W. Kozanecki

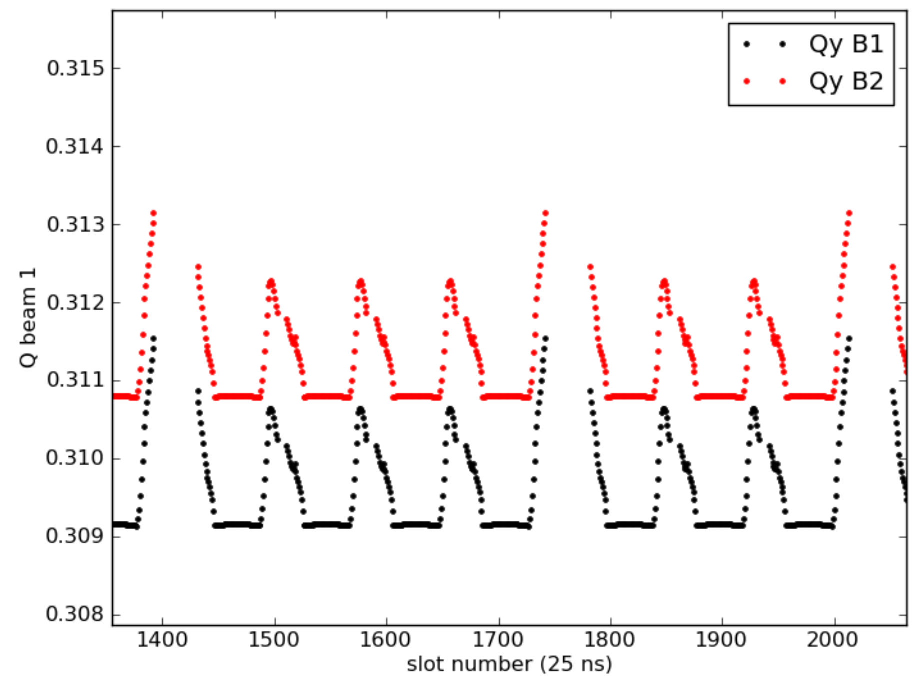
HL-LHC: 1 IP tune shifts

Int 2.2e11



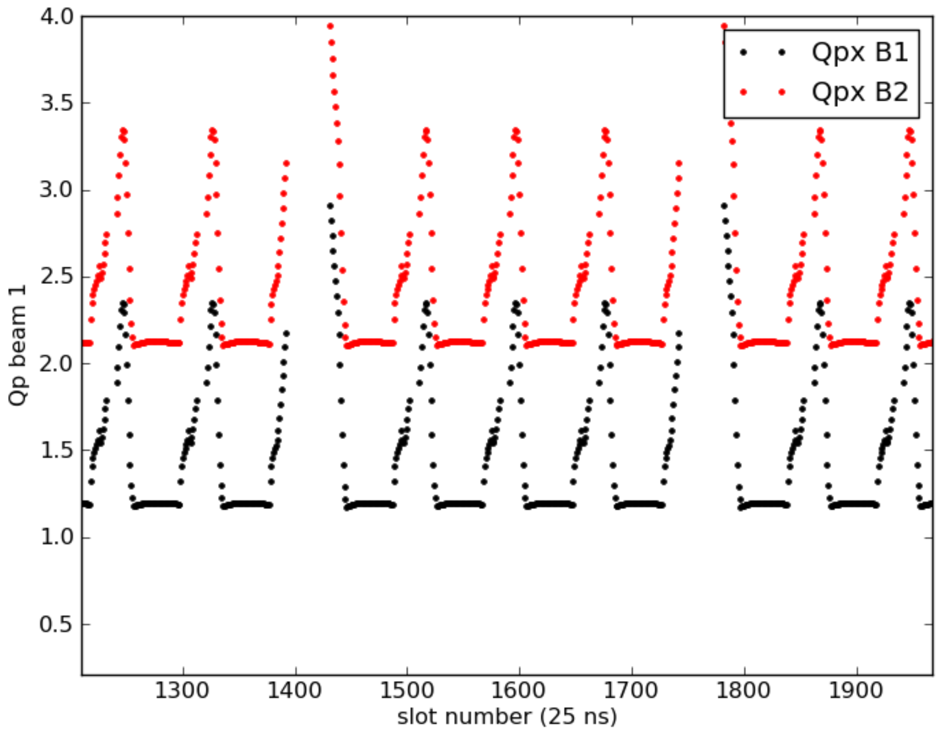
- **Intensity 2.2e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**

Due to one IP Long Ranges ΔQ over bunches could be maximum 0.0025

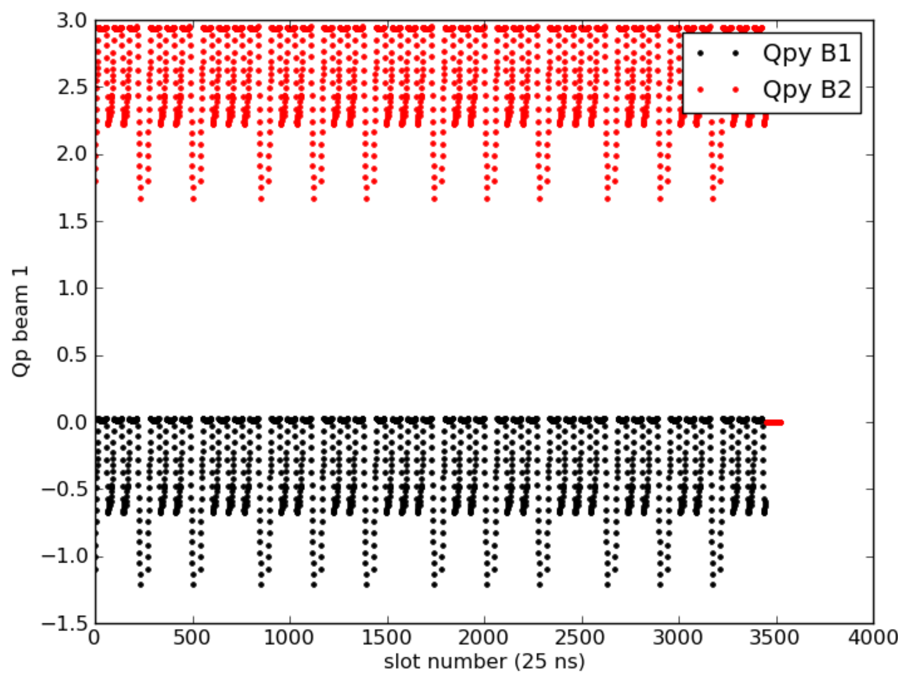


HL-LHC: 1 IP chromaticity

Int 2.2e11



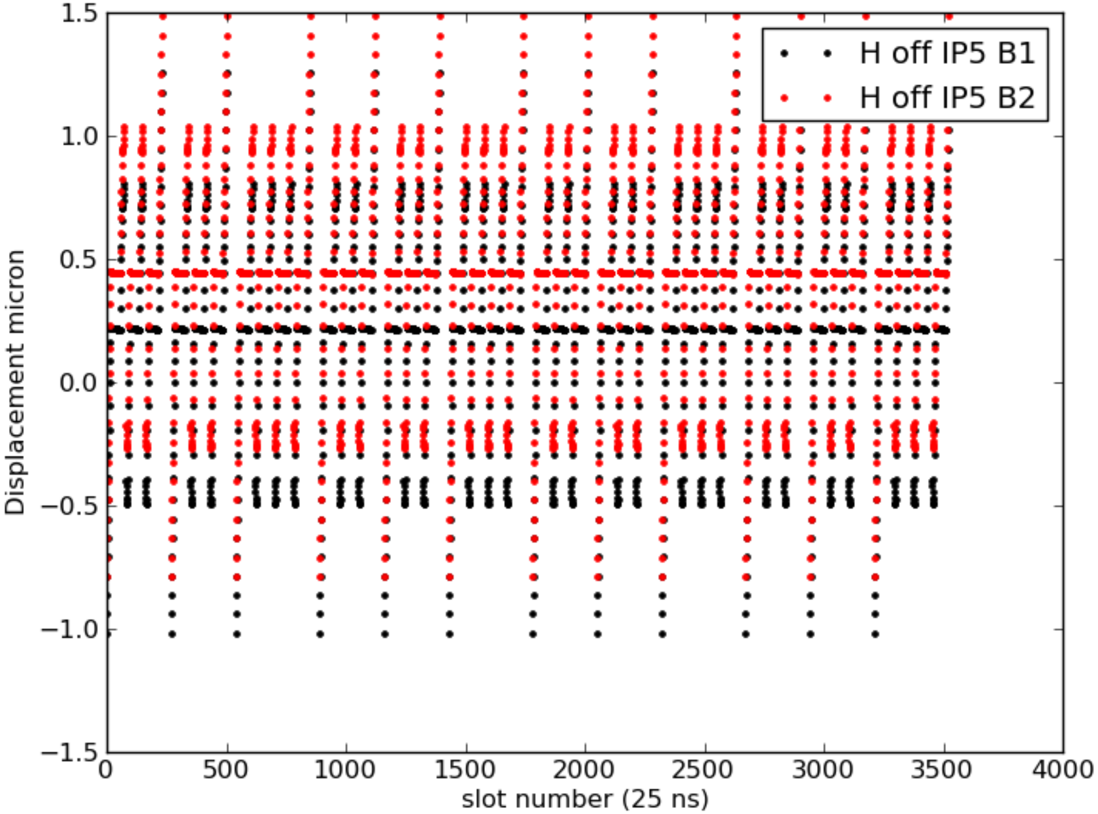
- **Intensity 2.2e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**



Due to one IP Long Ranges Q' spread of 2 units expected

HL-LHC: IP5 only

Int 2.2e11

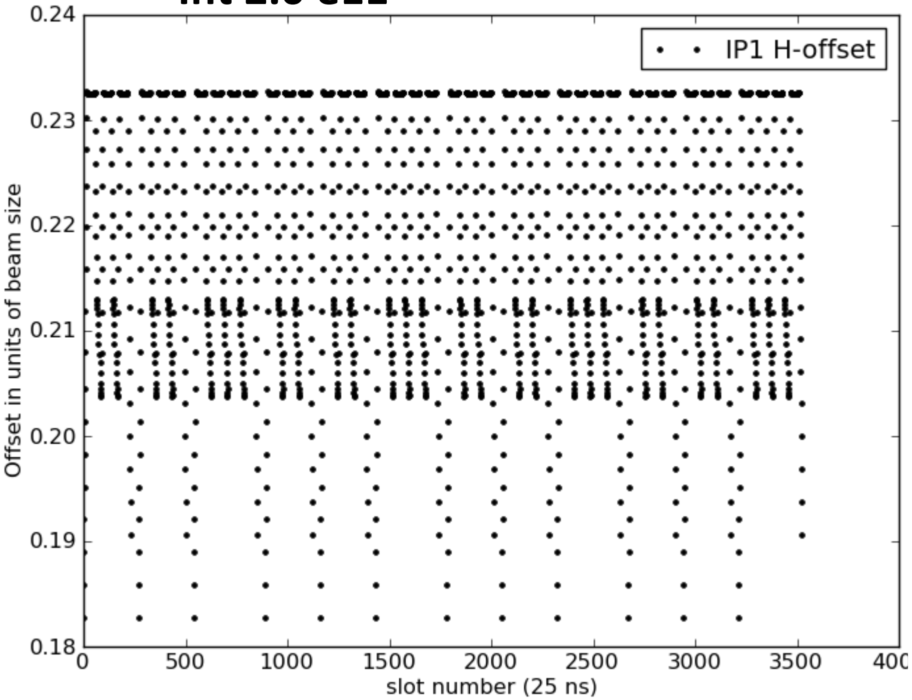


- **Intensity 2.2e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**

Due to one IP5 Long Ranges Expected displacement of collision centroid of:
→ 2.5 μm (0.3 σ)

HL-LHC: IP1&IP5 offsets

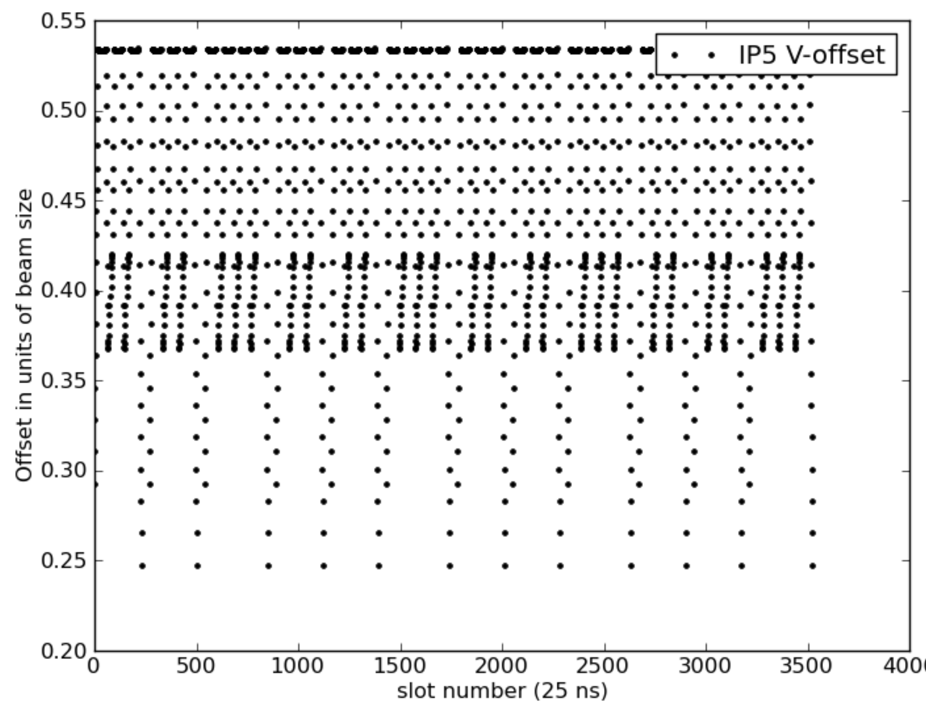
Int 2.0 e11



IP1 (ATLAS) V-crossing
IP5 (CMS) H-crossing

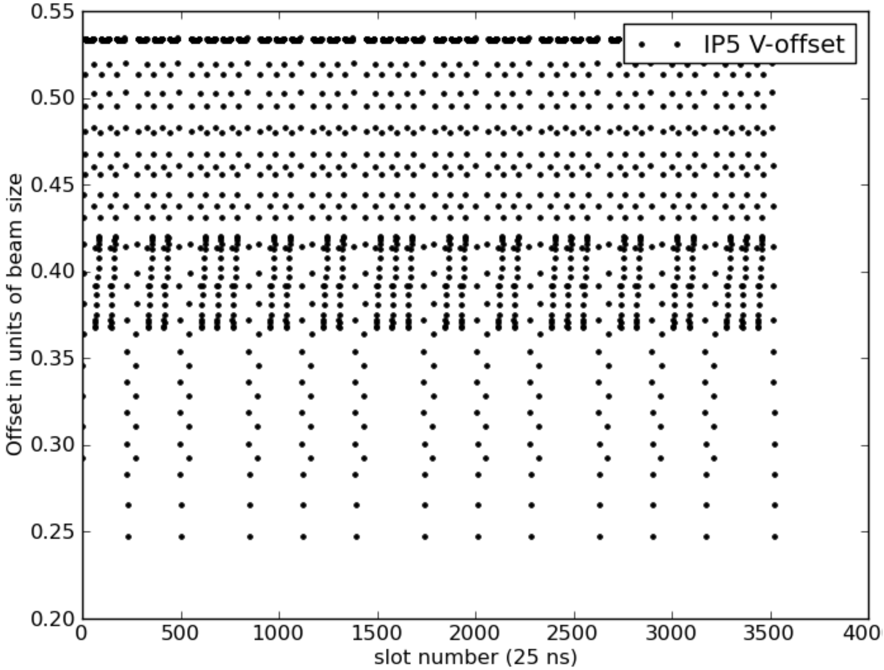
- **Intensity 2.0e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**

Long ranges BB lead to offsets in opposite IP in the plane of separation of maximum 0.3 σ at intensities of 2.0e11 ppb
→IP1 H offsets
→IP5 V offsets
Asymmetry between H and V effects under-investigation



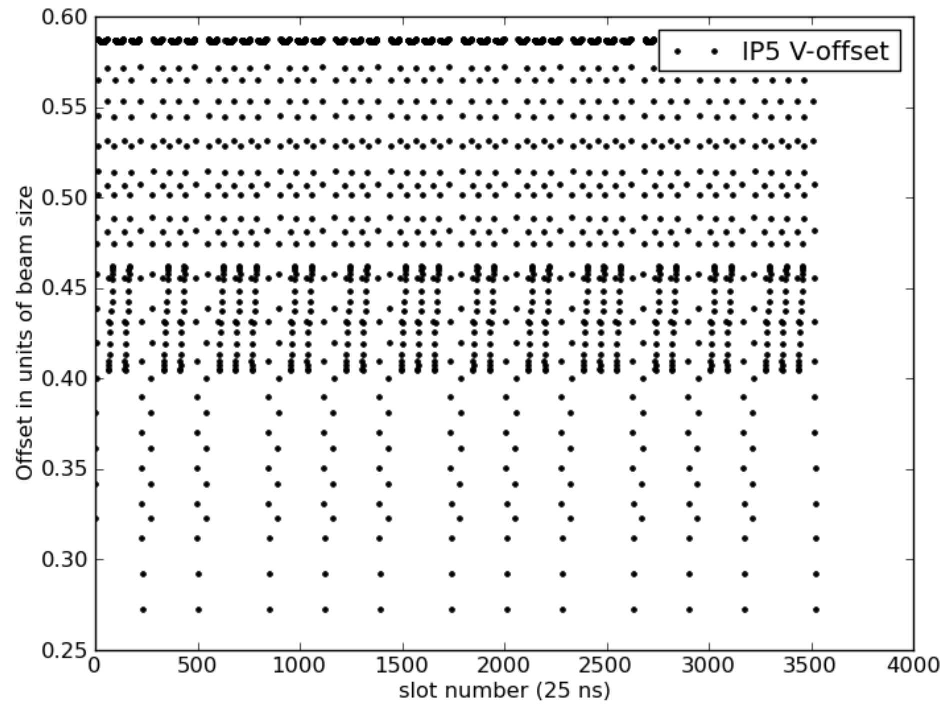
HL-LHC: IP1&IP5 offsets

Int 2.0 e11



- **Intensity 2.0 and 2.2e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**

Int 2.2 e11



Long ranges lead to offsets in opposite IP in the plane of separation of maximum 0.29-0.31 σ at intensities of 2.0-2.2e11 ppb

Luminosity reduction is marginal few %

Summary

- **Stability of beams with Beam-Beam:**
  - **Baseline 1: leveled lumi at 5e11** negative polarity preferred with small/ partial Telescopic part compensating LR effects before β^* = 70 cm collisions
  - **Ultimate: leveled lumi at 7.5e11** negative polarity preferred with Telescopic part from β^* to be defined compensating LR effects
  - **Extreme case**: full squeeze will depend on single beam needs: if single beam ok with LOF positive before squeeze then positive polarity preferred with BB if not we might need to collide for stability or find other means for providing tune spread
- **PACMAN Effects:**
  - H/V alternating crossing in place to compensate Q and Q' variations due to long-range beam-beam at IP1&IP5
  - Orbit effects from long-range beam-beam cannot be compensated:

    Offsets of maximum 0.3 σ should be expected for HL-LHC scenarios fully squeezed (extreme case)

    → Loss of Luminosity of few % should be expected

Back-up slides

IP5&IP1 Collisions HV crossing: we observe in IP1

For IP1

Separation Plane: H
These effects come LR in IP5

Crossing plane: V
These effects come LR in IP1

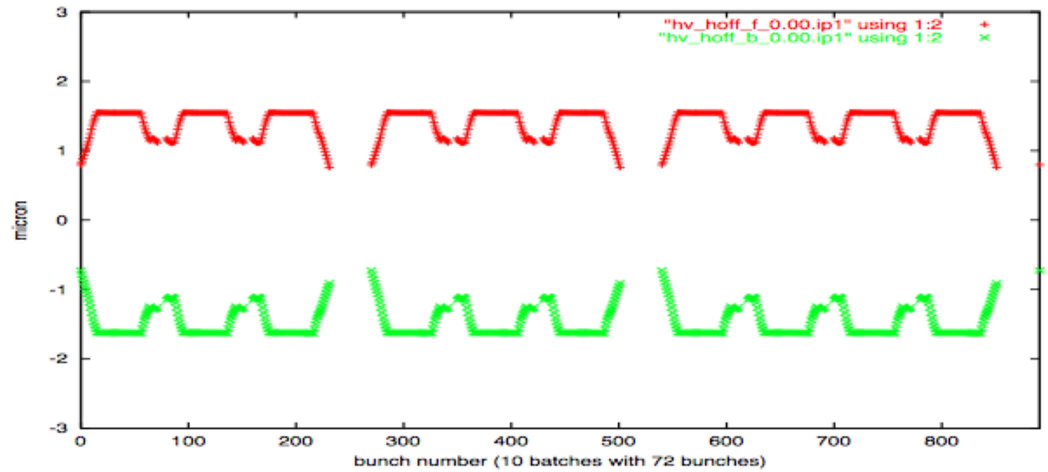


Figure 14: Horizontal offset in IP1 with vertical-horizontal crossing.

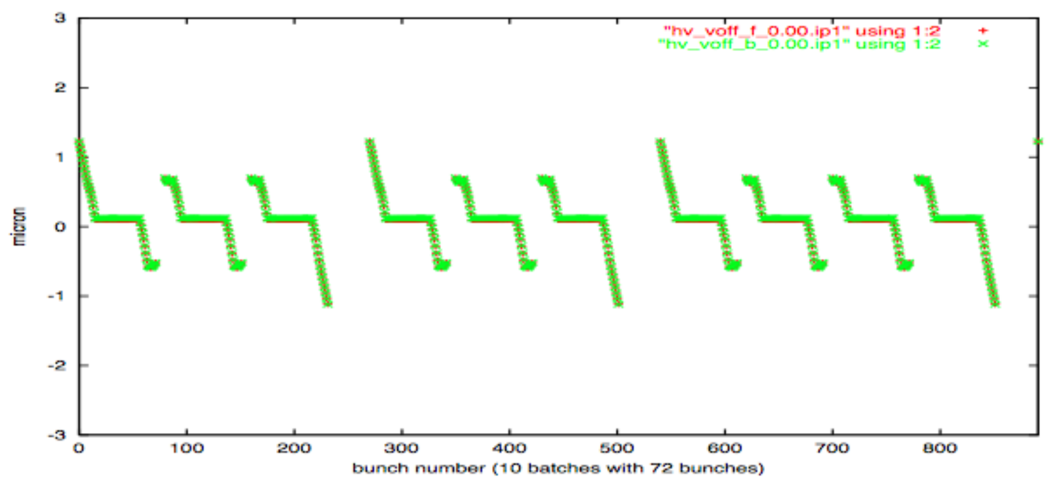


Figure 20: Vertical offset in IP1 with vertical-horizontal crossing.

IP5&IP1 Collisions HV crossing: Observe IP5

For IP5 the opposite

Crossing plane: H
These effects come LR in IP5

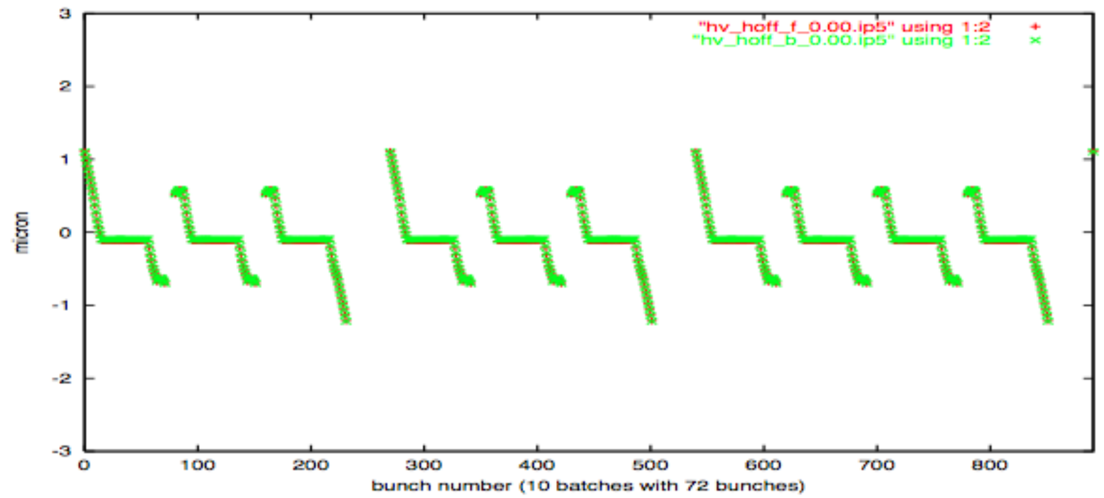


Figure 17: Horizontal offset in IP5 with vertical-horizontal crossing.

Separation Plane: V
These effects come LR in IP1

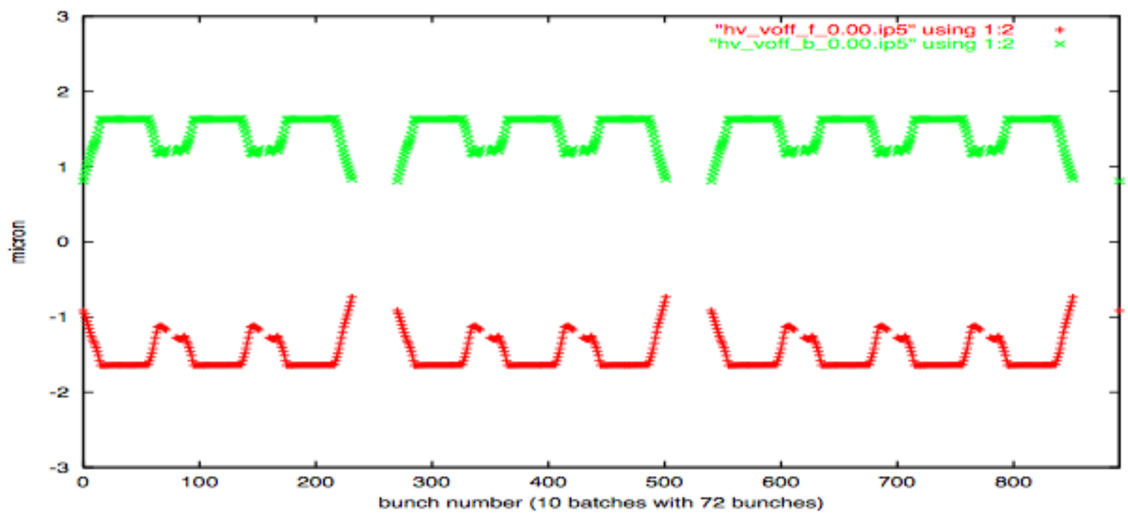
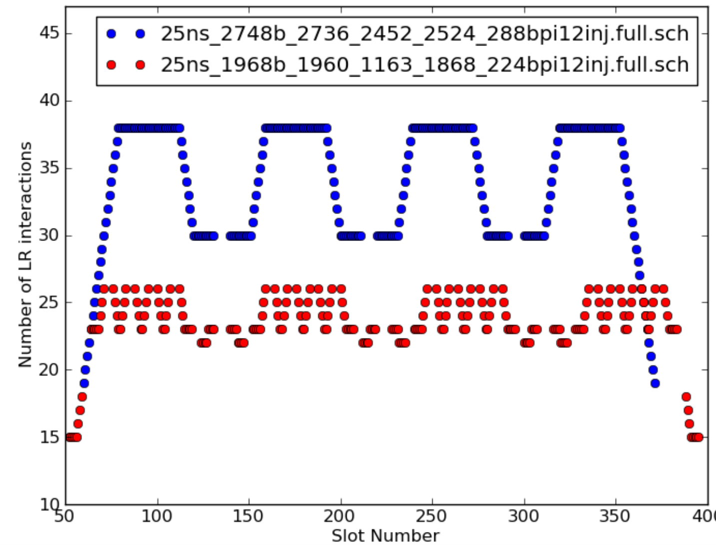
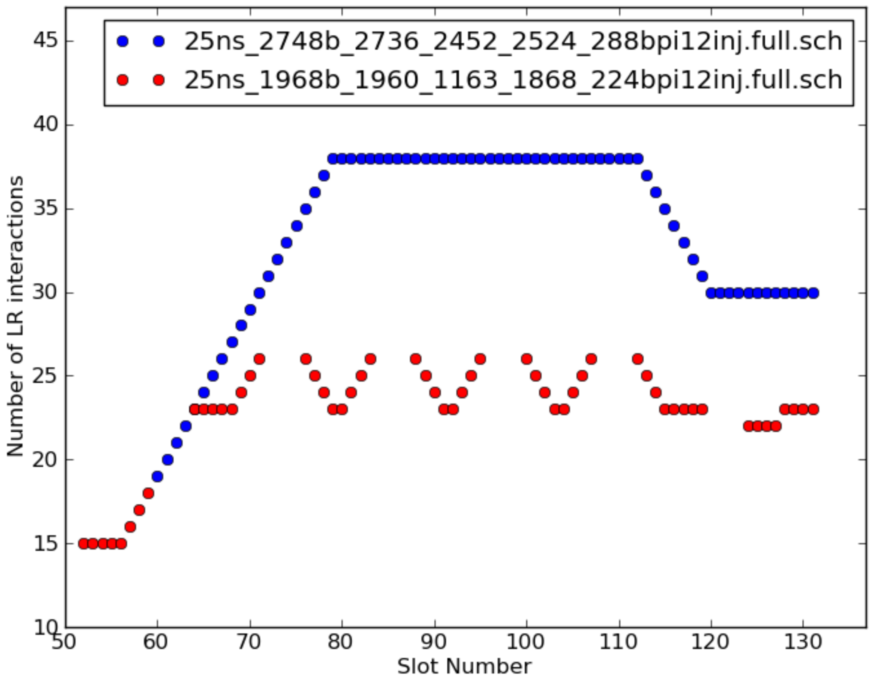


Figure 23: Vertical offset in IP5 with vertical-horizontal crossing.

Filling Schemes

B. Gorini : /afs/cern.ch/user/l/lpc/public/FILLSCHEMES/Run2/





8b+4e Filling schemes:
- 40-30% less LR encounters
- 12 non-colliding bunches

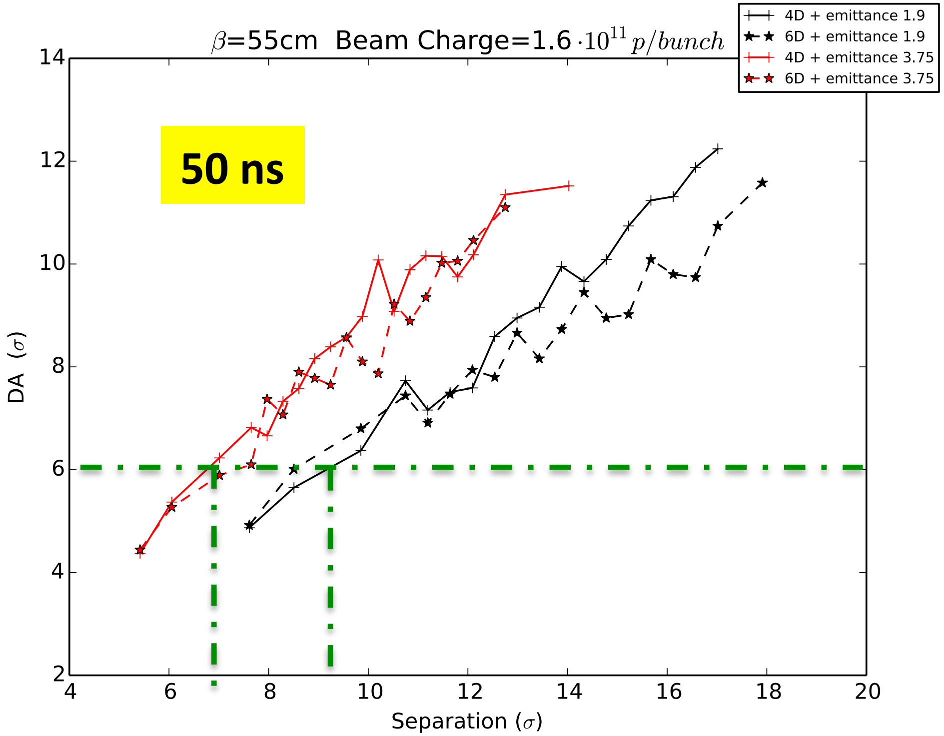
Nominal Filling scheme:
- 38 LRs in IP1&IP5 (after D1 not considered)
- 12 non-colliding bunches

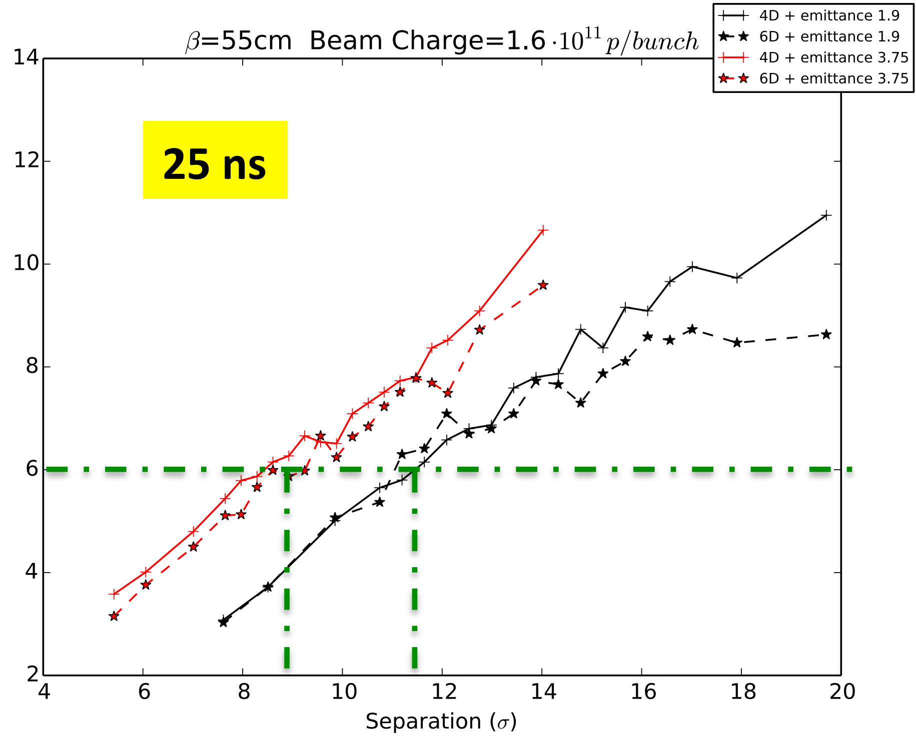
Can we reduce the LR separations?
By how much?
} Let's scale from 50 ns → 25 ns studies

What about the 12 non-colliding bunches? → Might require special setting (chroma, Octupoles) which will impact performances

50 ns versus 25 ns beams

25 ns beams have 38 Long range encounters from IP1&IP5
50 ns beam will have 50% of them (16 LRs)





Roughly 2 σ more separation needed from 50 ns to 25 ns to ensure same 6 DA
If we have 70% of LR (8b+4e filling schemes) we can reduce the BB separation by 1.4 σ
In Crossing angle : 590 μrad → 520 μrad
see Thursday R. Tomas talk

Beam-Beam deflection angles and orbit in the LHC: model for round and non-round beams during VdM

Deflections: $$\theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma)$$

$$\begin{cases} \Sigma_{12} = 0 \\ \Sigma_{11} > \Sigma_{22} \\ \Sigma_{11} = \sigma_{x^1}^2 + \sigma_{x^2}^2 \\ \Sigma_{22} = \sigma_{y^1}^2 + \sigma_{y^2}^2 \end{cases}$$

Bassetti-Erskine formula:

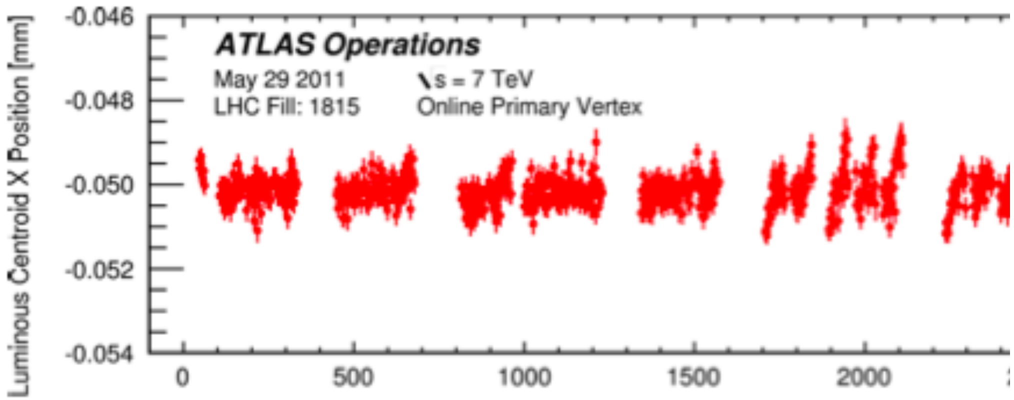
$$F_0(x, y, \Sigma) = \frac{\sqrt{\pi}}{\sqrt{(\Sigma_{11} - \Sigma_{22})}} [w(\alpha_1) - w(\alpha_2) \cdot \exp(-\frac{1}{2}(\Sigma_{11}^{-1} x^2 + \Sigma_{22}^{-1} y^2))]$$

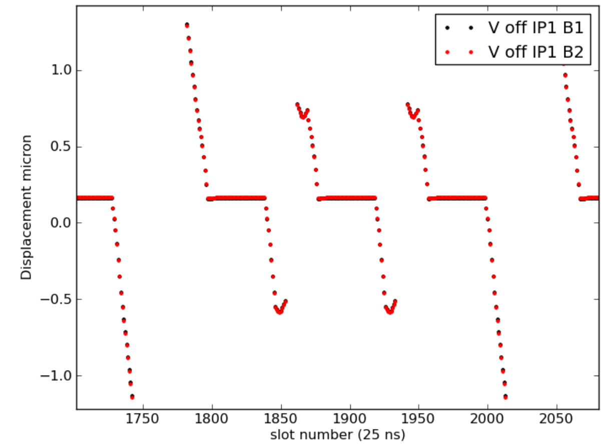
$$\alpha_1 = \frac{x + iy}{\sqrt{2(\Sigma_{11} - \Sigma_{22})}} \qquad \alpha_2 = \frac{(\Sigma_{22} x + i\Sigma_{11} y)}{\sqrt{2\Sigma_{11}\Sigma_{22}(\Sigma_{11} - \Sigma_{22})}}$$

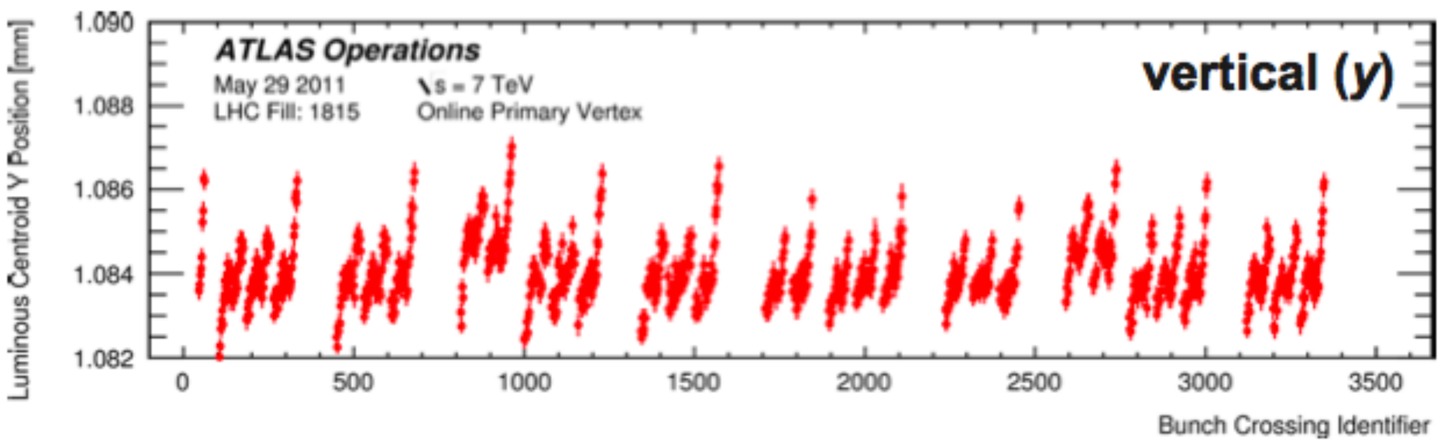
$$w(z) = exp(-z^2) erfc(-iz)$$

Closed Orbit effect: $$Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})}$$

Can we cross check with data? ATLAS vertex detector 2011 data



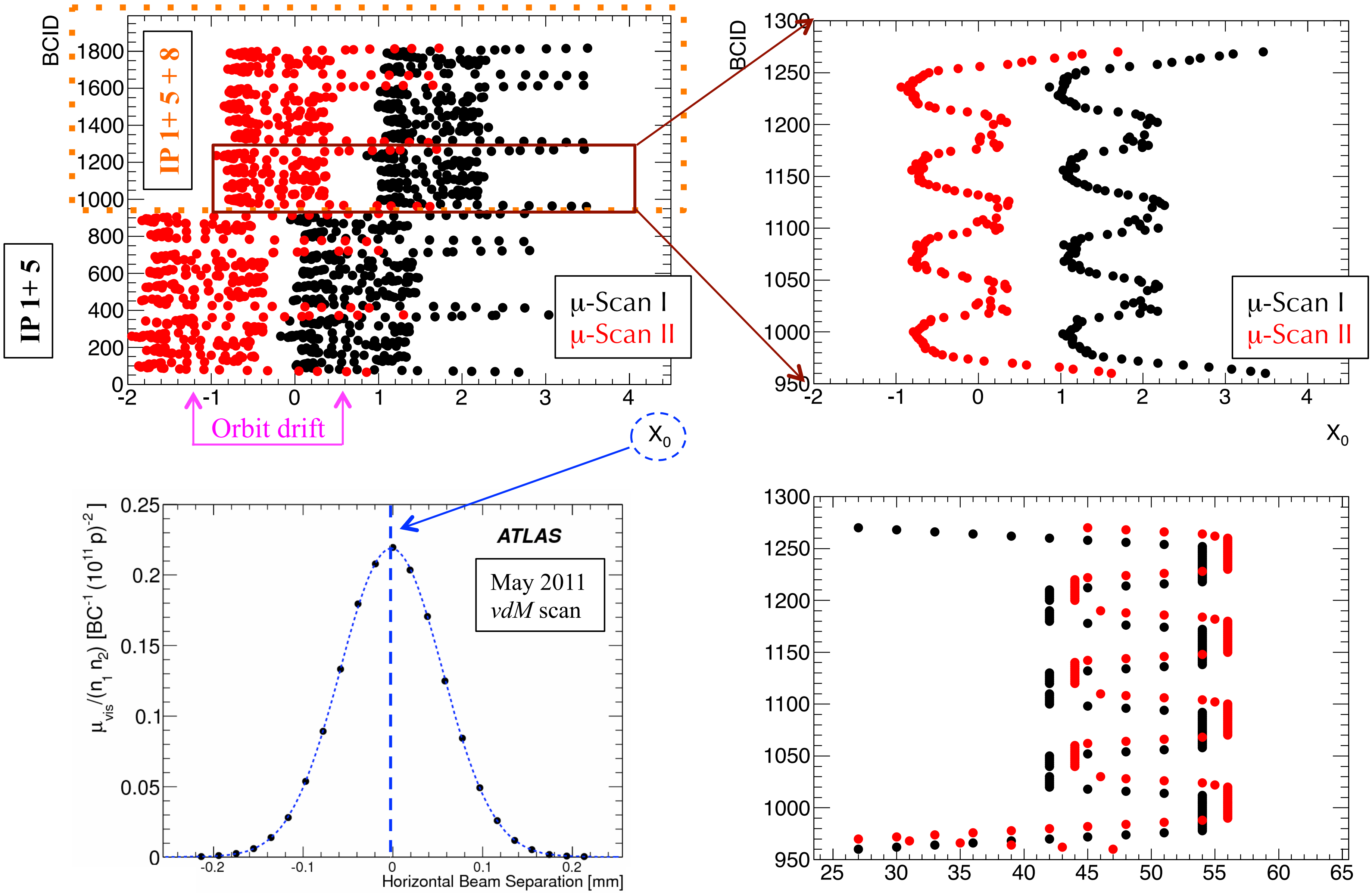




Courtesy of R. Bartoldus and W. Kozanecki ATLAS collaboration

Vertical centroid displacement can be measured and we can check few cases

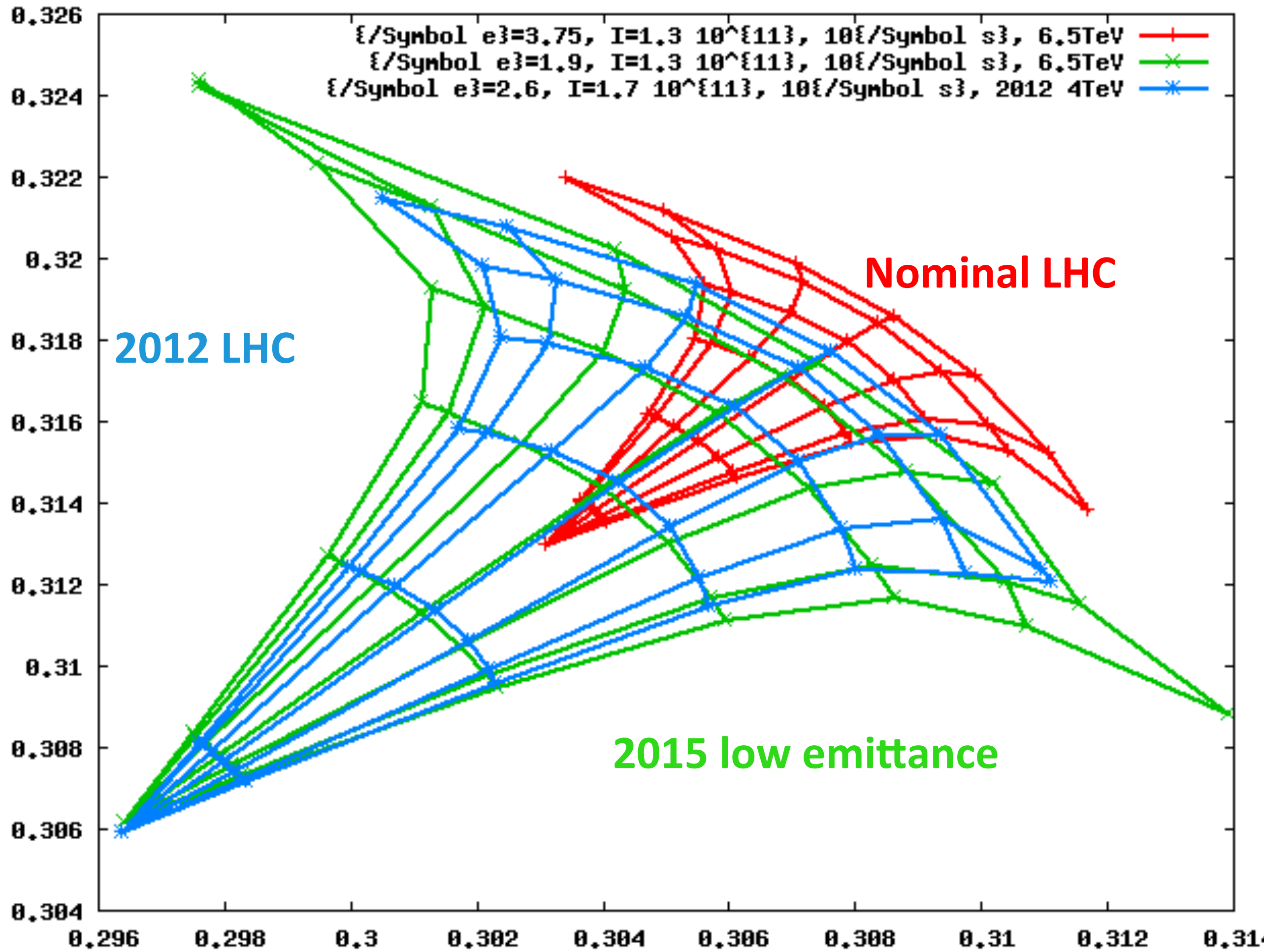
ATLAS data 2012 April VdM Horizontal plane



Courtesy of W. Kozanecki

Footprints for Nominal, 2012 run and 2015:

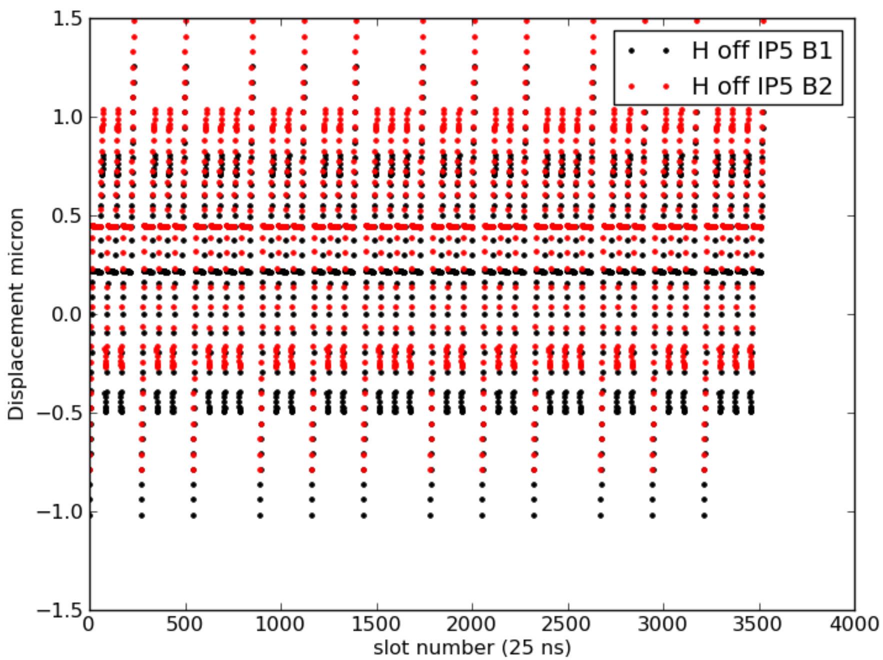
LR separation 10 σ



12-10 σ separation is not an absolute number!
Not the same ΔQ_{LR} if Head-On becomes important!
DA changes and other mechanism could enter!

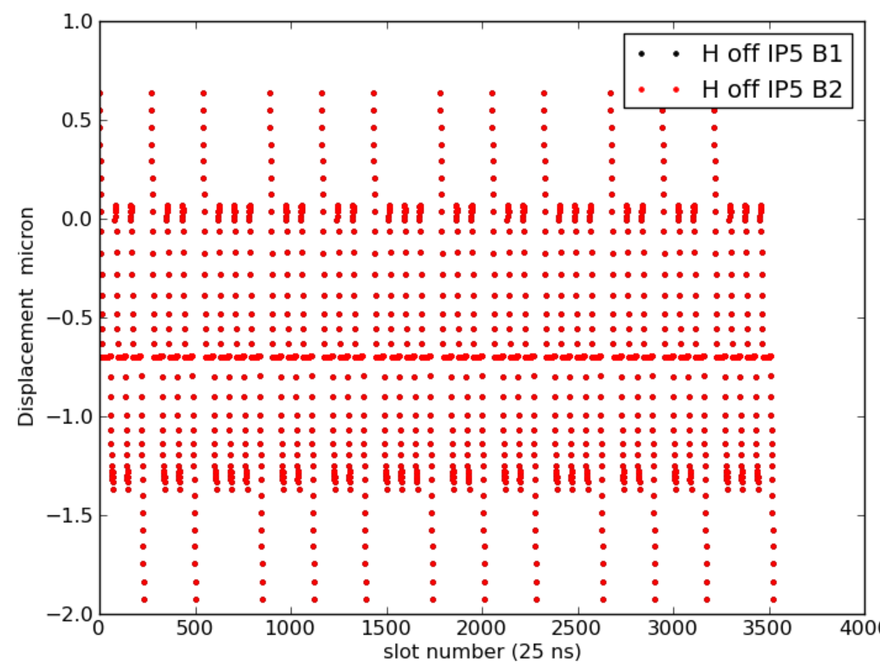
HL-LHC: IP5 only

Int 2.2e11



- **Intensity 2.2e11 ppb and 1.1e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**

Int 1.1e11



Due to one IP Long Ranges Expected displacement of collision centroid of:
→ 2.5 μm for 2.2e11 ppb