Beam-Beam Effects Long Range and Head-on

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LHC Operational Workshop, EVIAN 2015

Outline

- 2012 Beam Beam effects data and simulations
- 2015 set-up strategy and 2015 Long Range MD
- 2016 crossing angles
  - IP1&5
  - IP2 with possibility to swap spectrometer
  - IP8 as in 2015
- Stable beams
  - Weak-strong BB Head-on
  - Separation scans and stability of beams
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  - Beam Transfer Functions
  - Noise on colliding beams
  - Beta-beating
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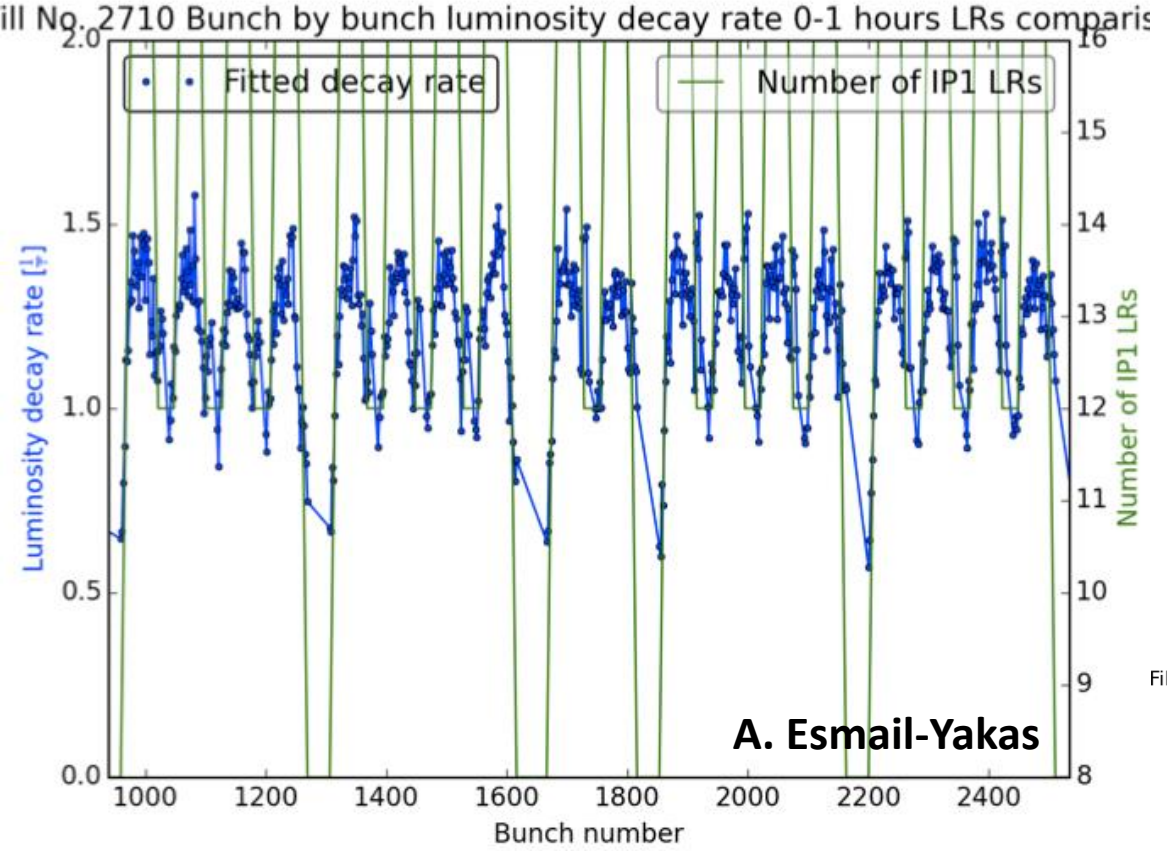
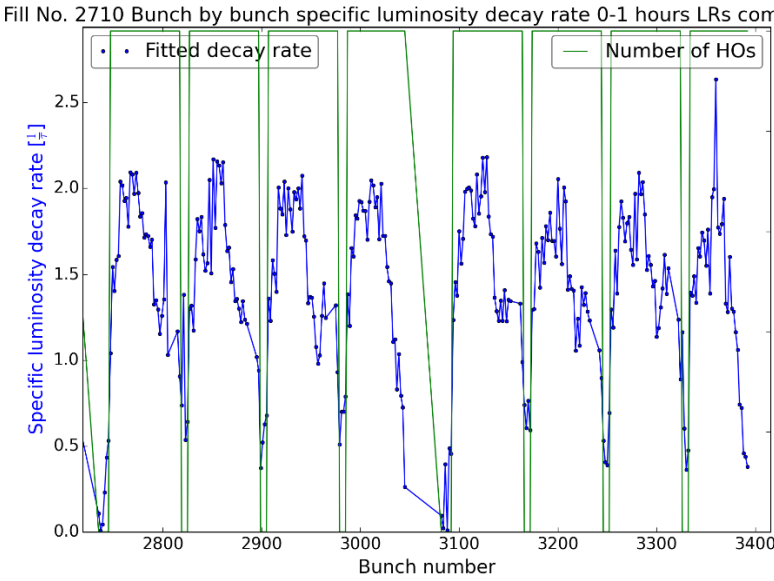
Long Range effect 2012

Regular Physics Fill of 2012 RUN LHC



Clear Long Range pattern in the Luminosity and Specific luminosity decay rates

Losses and emittance blow-up has a clear BB pattern



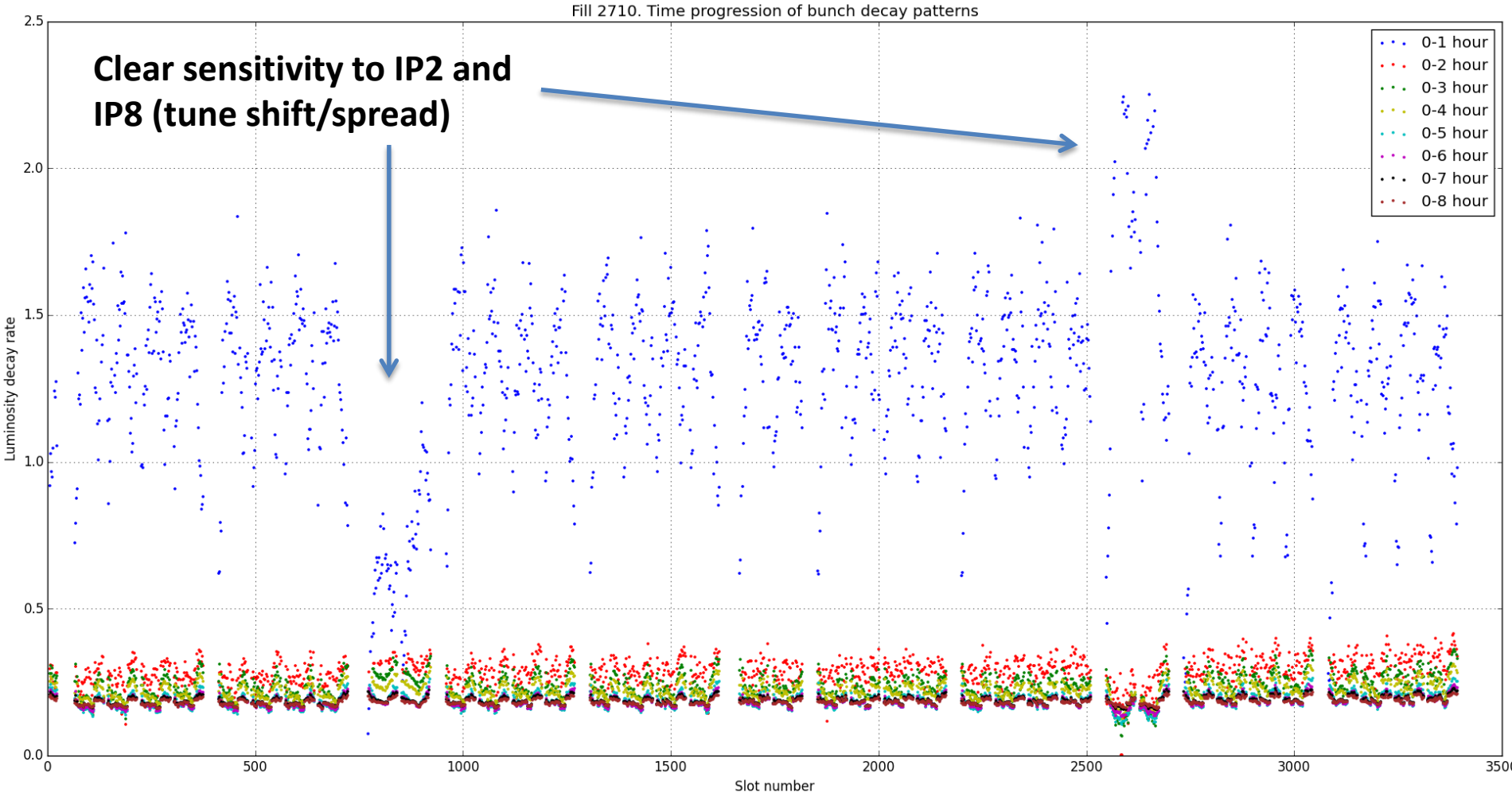
2012 Beam-Beam parameter of 0.0067/IP

- **2 HO 0.015 total**
- **IP2 and IP8 with relevant long ranges**
- **Octupoles at maximum current…**
- **Chromaticity to 20 units….**
  - **“see also analysis of F. Antoniou”**

Long Range effect 2012

Regular Physics Fill of 2012 RUN LHC

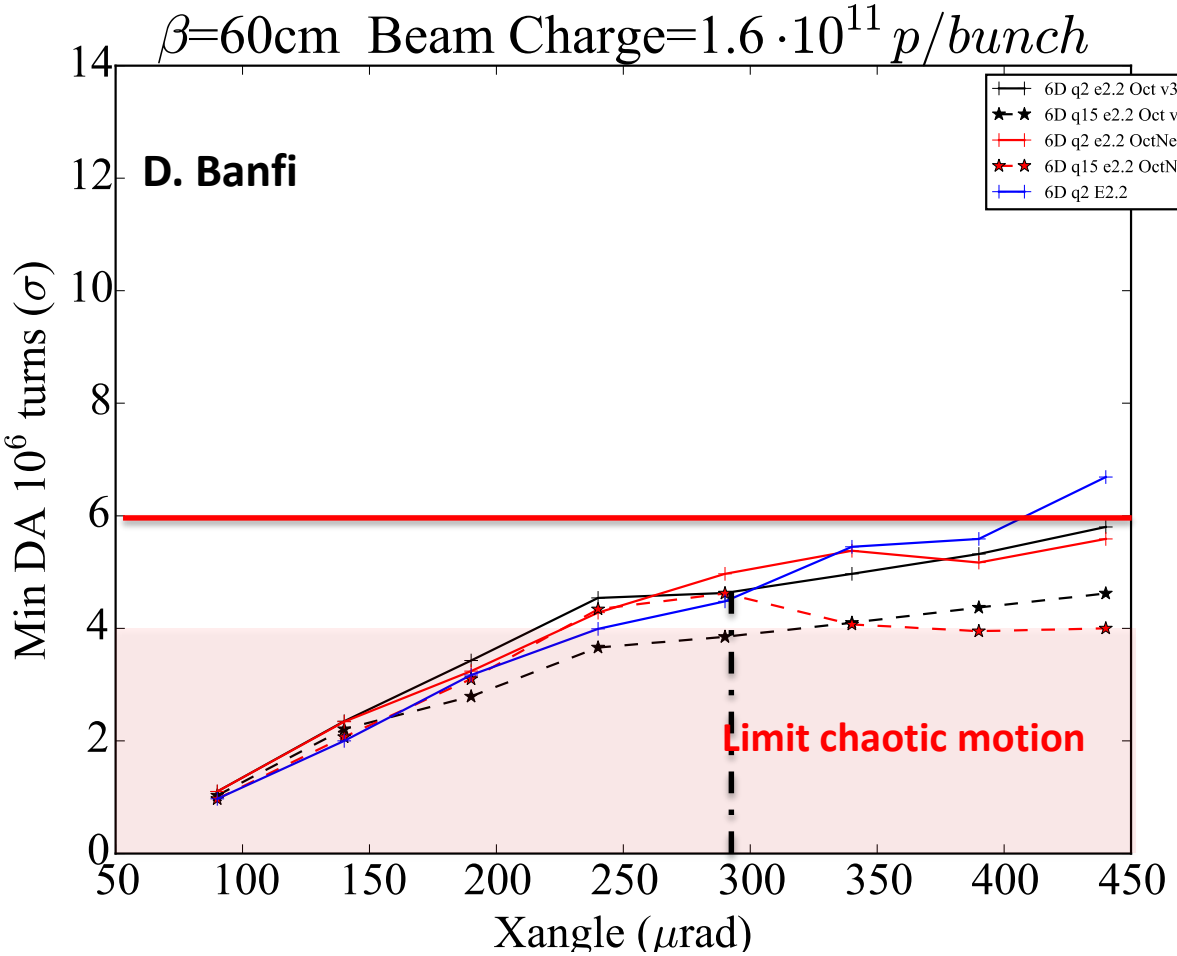
A. Esmail-Yakas



Beam-Beam pattern visible in first 2 Hours of physics fills

Also special IP2 and IP8 effects visible missing head-on collision and/or long ranges

2012 Physics RUN



Beam parameters:
N_b = 1.6/1.7 e11 ppb
ε = 2.5-3.5 μm
IP8 leveled offset = 2.5 σ
Q' = **15** units
Oct 550A

Beam-Beam separation at first LR

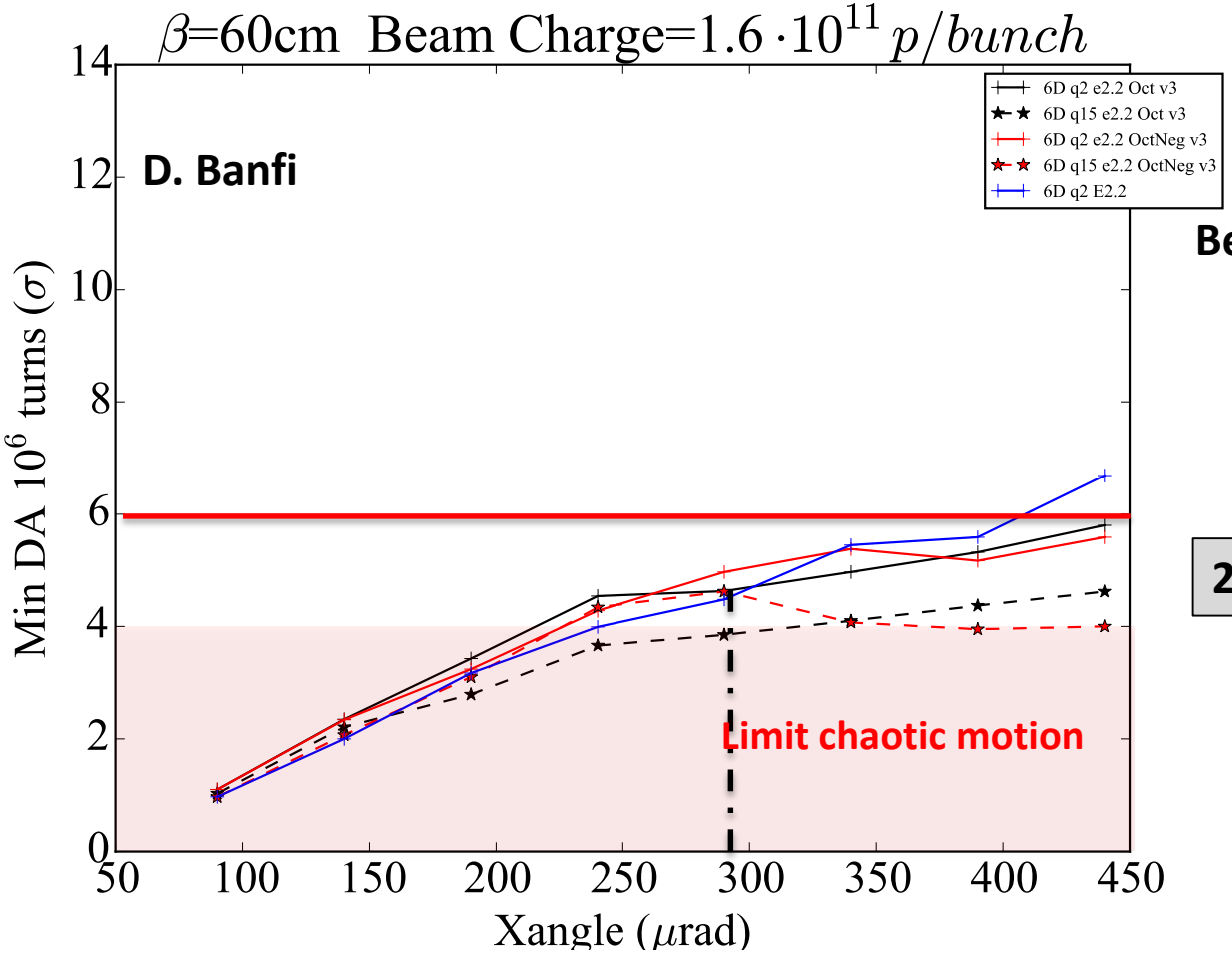
$$d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon}}$$

2.2 μm beams → d_{sep} = 10 σ

- **High Chromaticity (15-20) has very BAD impact on Dynamic Aperture!**
- **High Octupoles (550 A) has very BAD impact on Dynamic Aperture!**

All needed to fight coherent instabilities in the squeeze…

2012 Physics RUN



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Oct 550 A

Beam-Beam separation at first LR

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

2.2 μm beams → d_{sep} = 10 σ

We were at the limit!

Chaotic motion due to beam-beam+Q'+Oct drives diffusive mechanism (particle losses and emittance blow-up)

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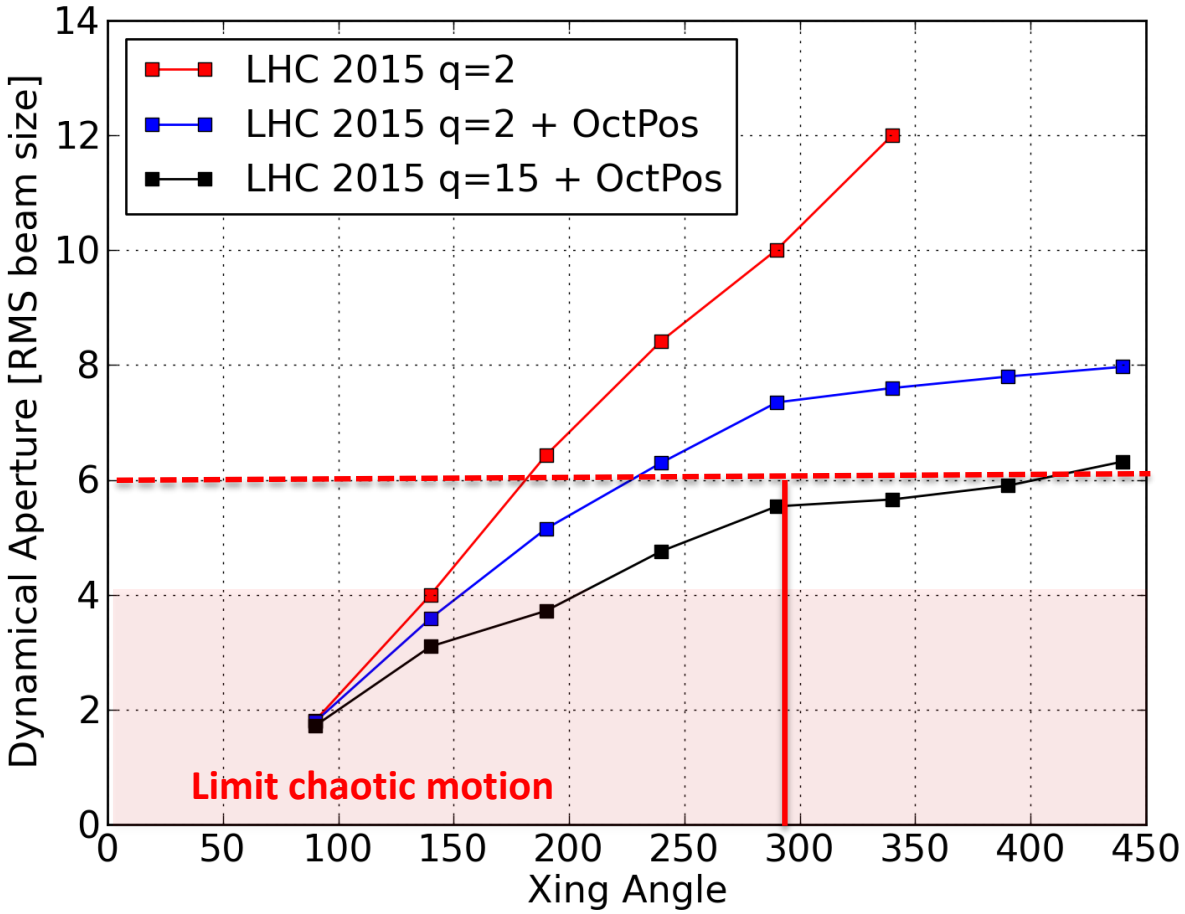
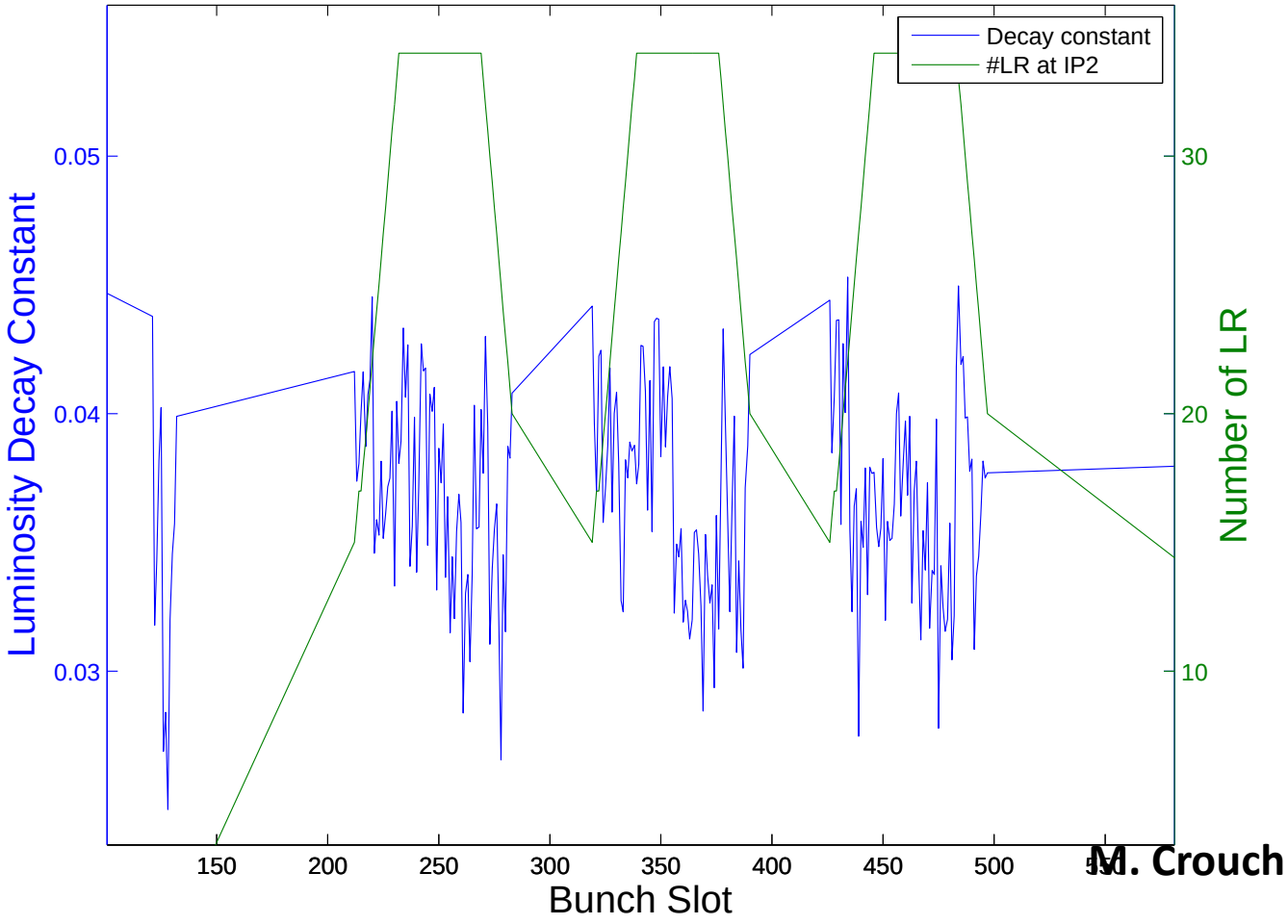
2015 Strategy



- **Beam-Beam parameter 0.0037/IP (half of what we had in 2012)**
- **Long Range weaker to allow high Octupoles and high Chromaticity operation**
- **11 σ beam-beam separation (3.75 μm emittances and 1.3 e11ppb)**
- **Tight control on tune shifts from Beam-Beam Long Range of IP2&8**
- **1 Angle for high-low brightness beams (DA depends on Head-on as well)**

Long Range beam-beam effects 2015

Regular LHC Physics Fill of 2015

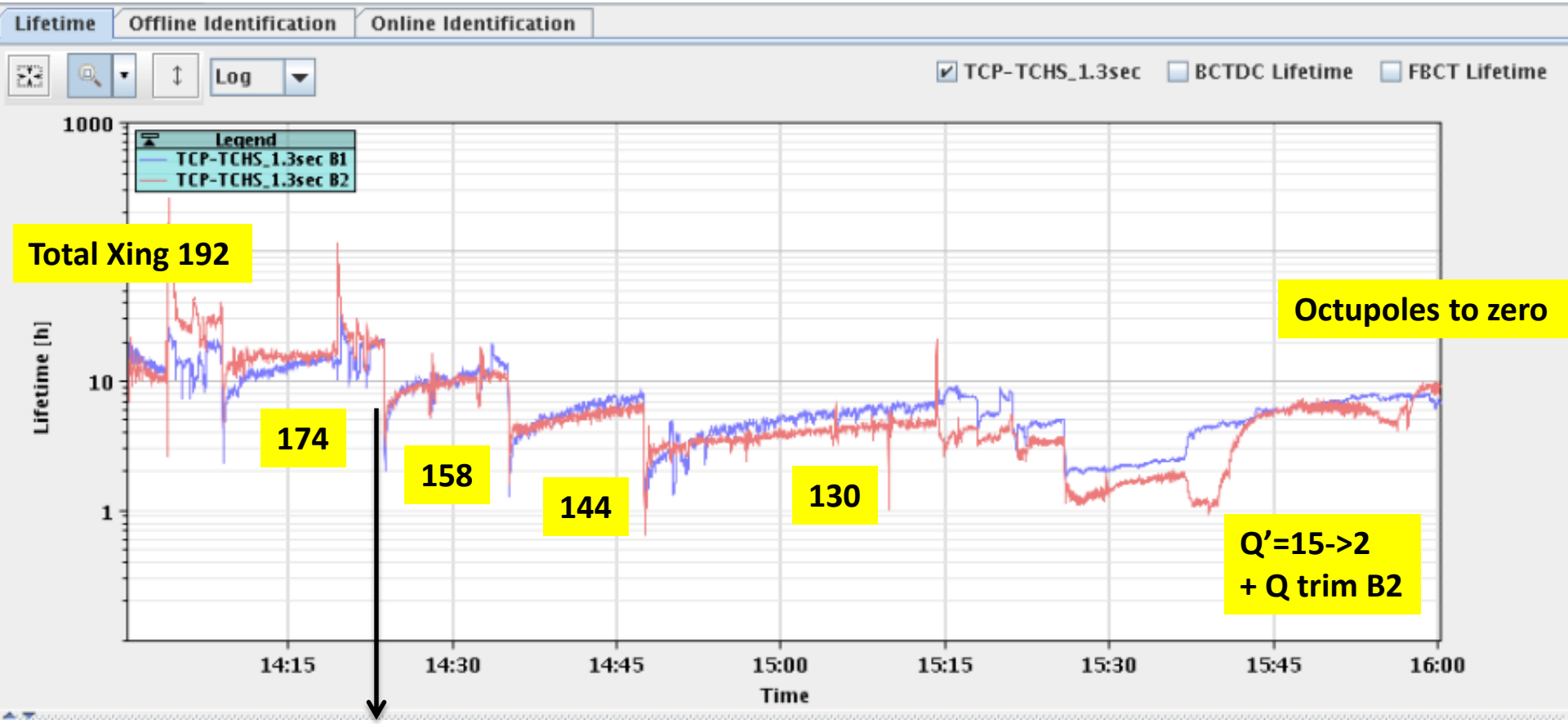


No clear evidence of beam-beam long range and Head-on signature in physics fills

Beautiful Beams and Lumi lifetimes (above 20 hours)!

Long Range Beam-Beam MD 15 September

Quantifying the impact of reduced crossing angle on beam parameters

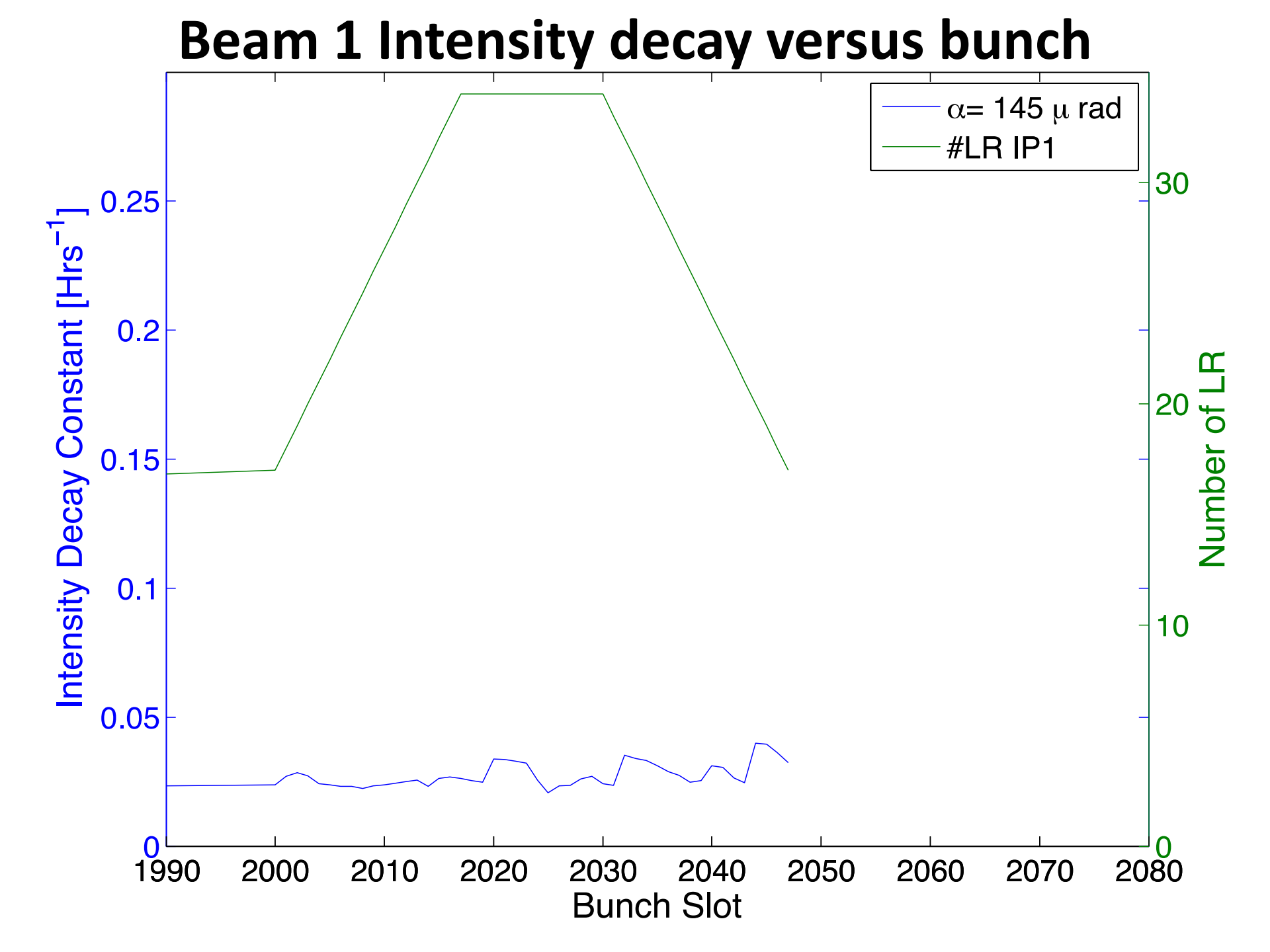


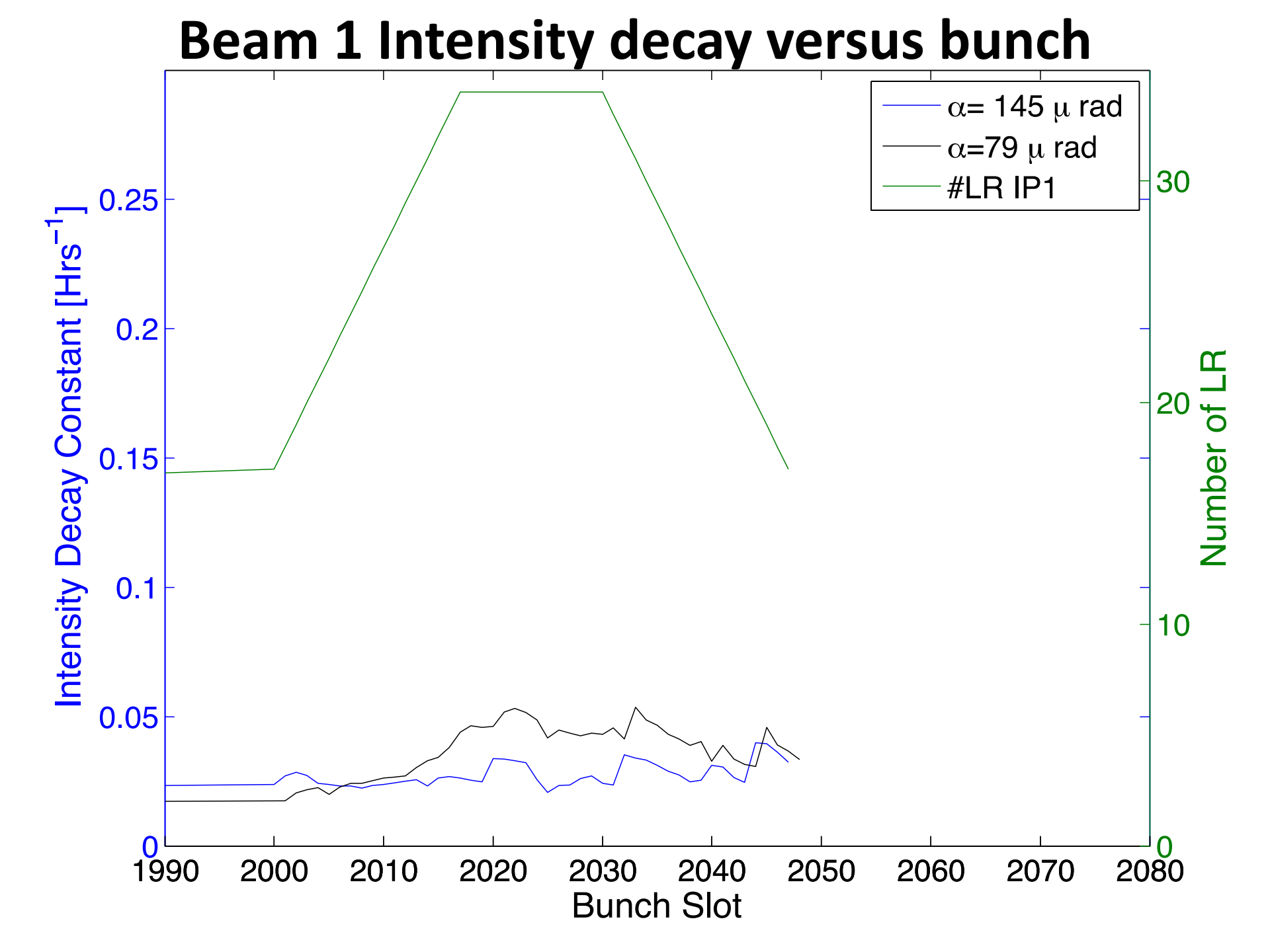
Beam emittances 2.4 μm, intensities 1.1e11ppb 48 bunches train

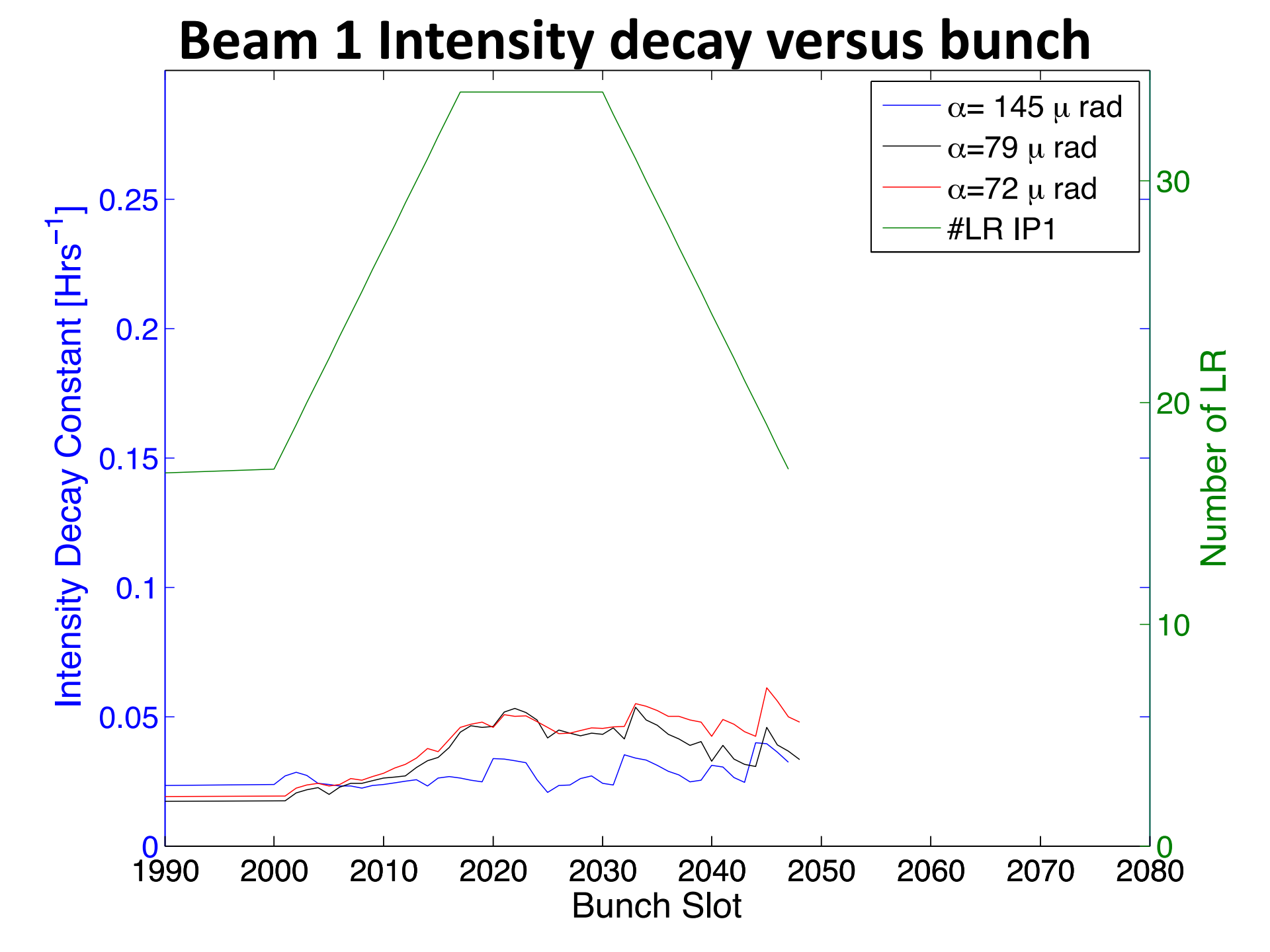
Reduce crossing angle in steps from Total angle 290→130 μrad and quantify impact on beam intensity, emittances and luminosity lifetimes

Reduce Q' and Octupoles

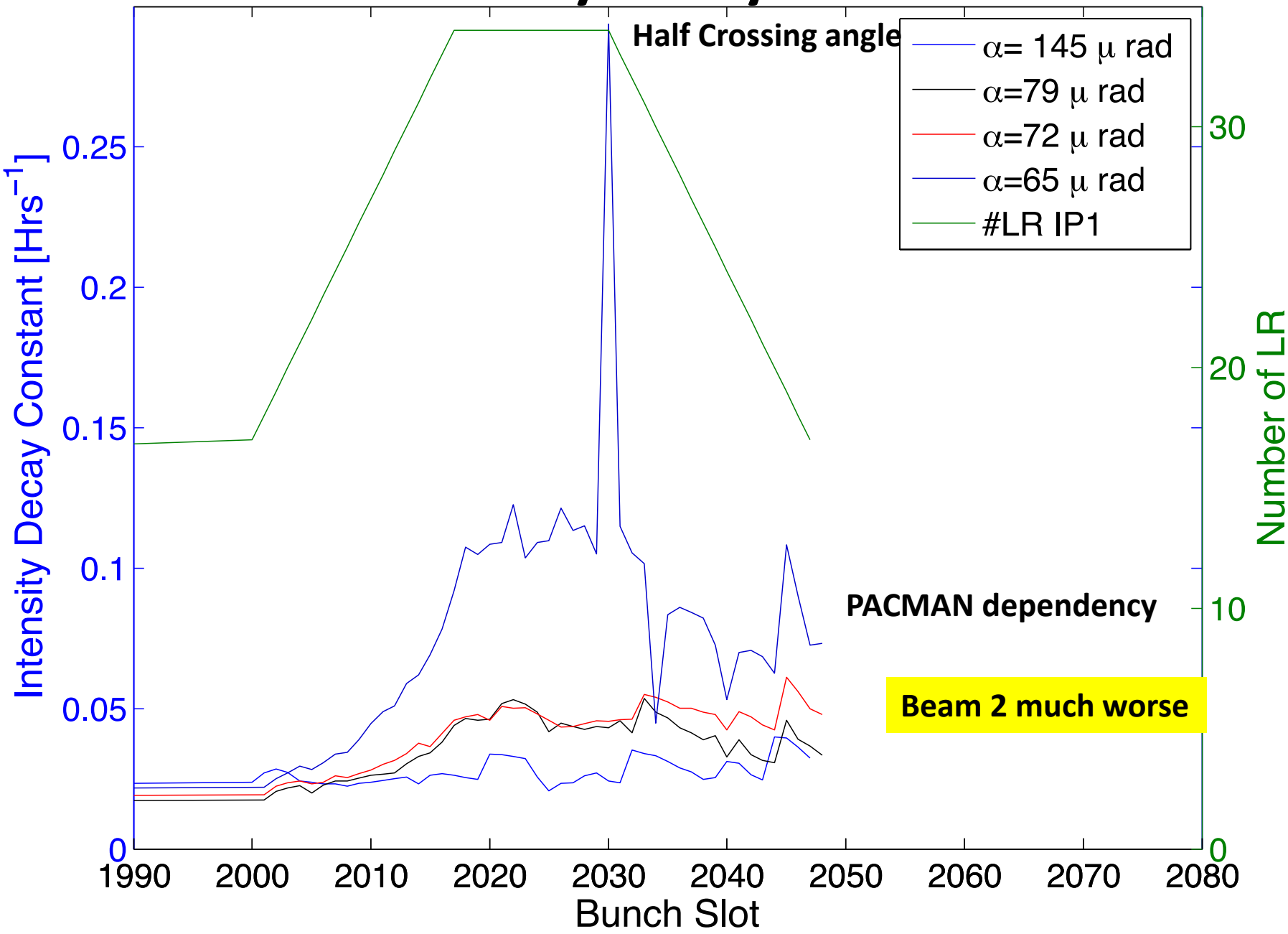
Large orbit drifts during large part of MD→ loosing collisions


Beam 1 Intensity decay versus bunch
α= 145 μ rad
#LR IP1
Intensity Decay Constant [Hrs^{-1}]
Number of LR
Bunch Slot
0
0.05
0.1
0.15
0.2
0.25
0
10
20
30
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080

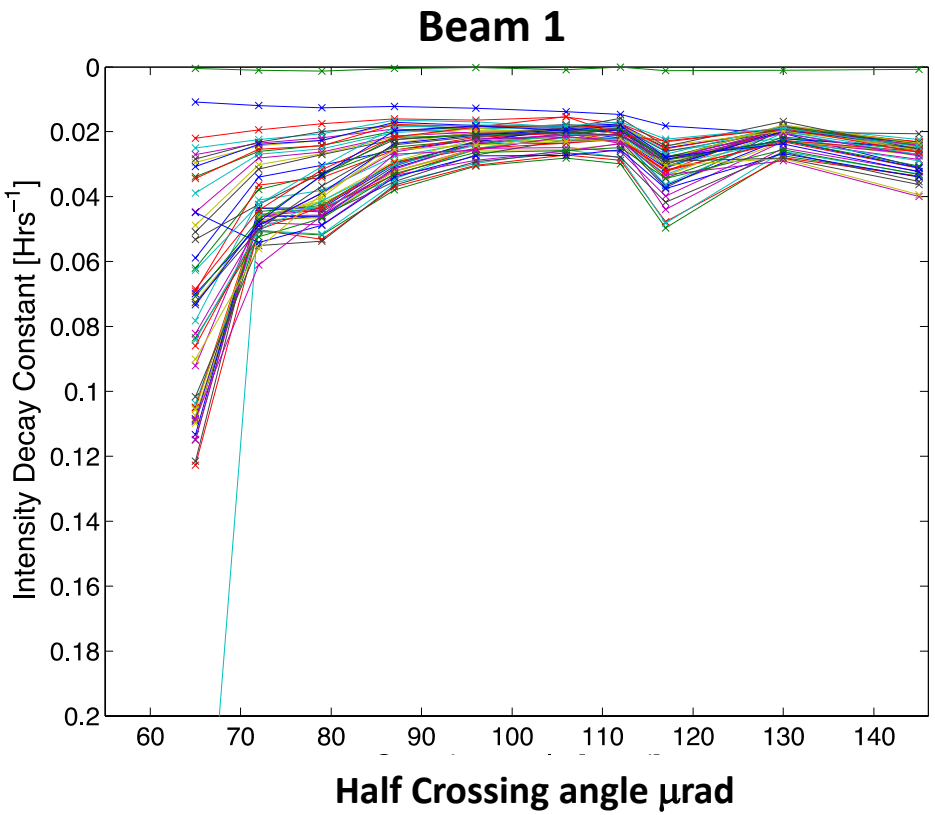

Beam 1 Intensity decay versus bunch
α= 145 μ rad
α=79 μ rad
#LR IP1
Intensity Decay Constant [Hrs^{-1}]
Number of LR
Bunch Slot
0
0.05
0.1
0.15
0.2
0.25
10
20
30
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080

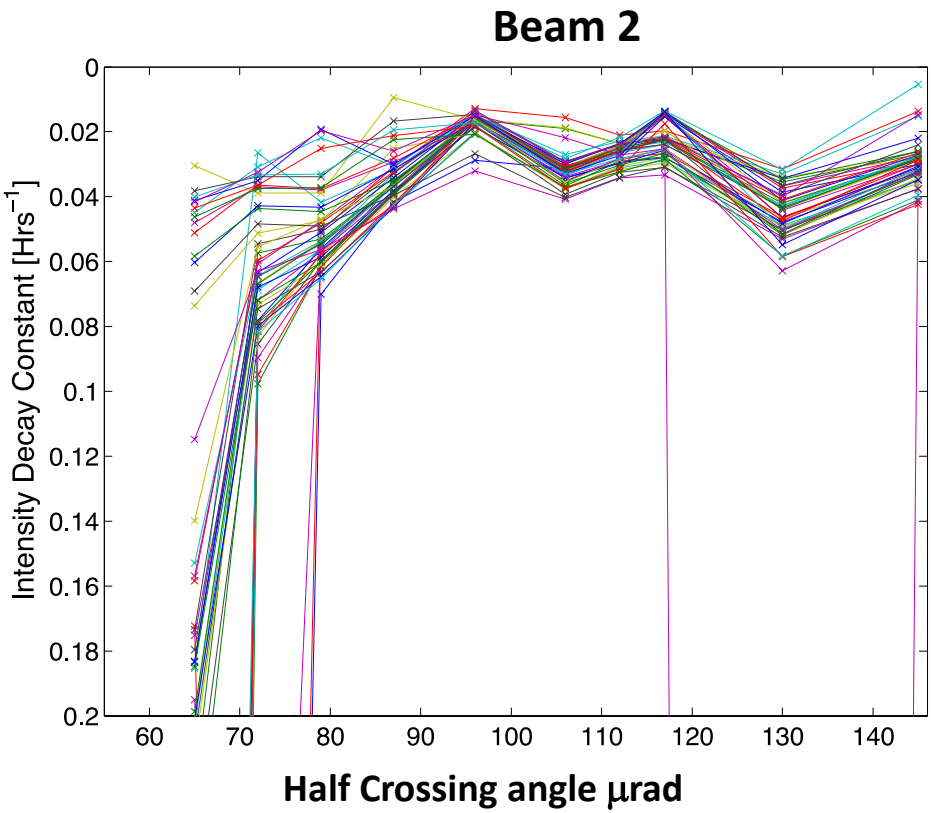

Beam 1 Intensity decay versus bunch
α= 145 μ rad
α=79 μ rad
α=72 μ rad
#LR IP1
Intensity Decay Constant [Hrs^{-1}]
Number of LR
Bunch Slot
0
0.05
0.1
0.15
0.2
0.25
10
20
30
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080

Beam 1 Intensity decay versus bunch



Intensity lifetimes versus crossing angle



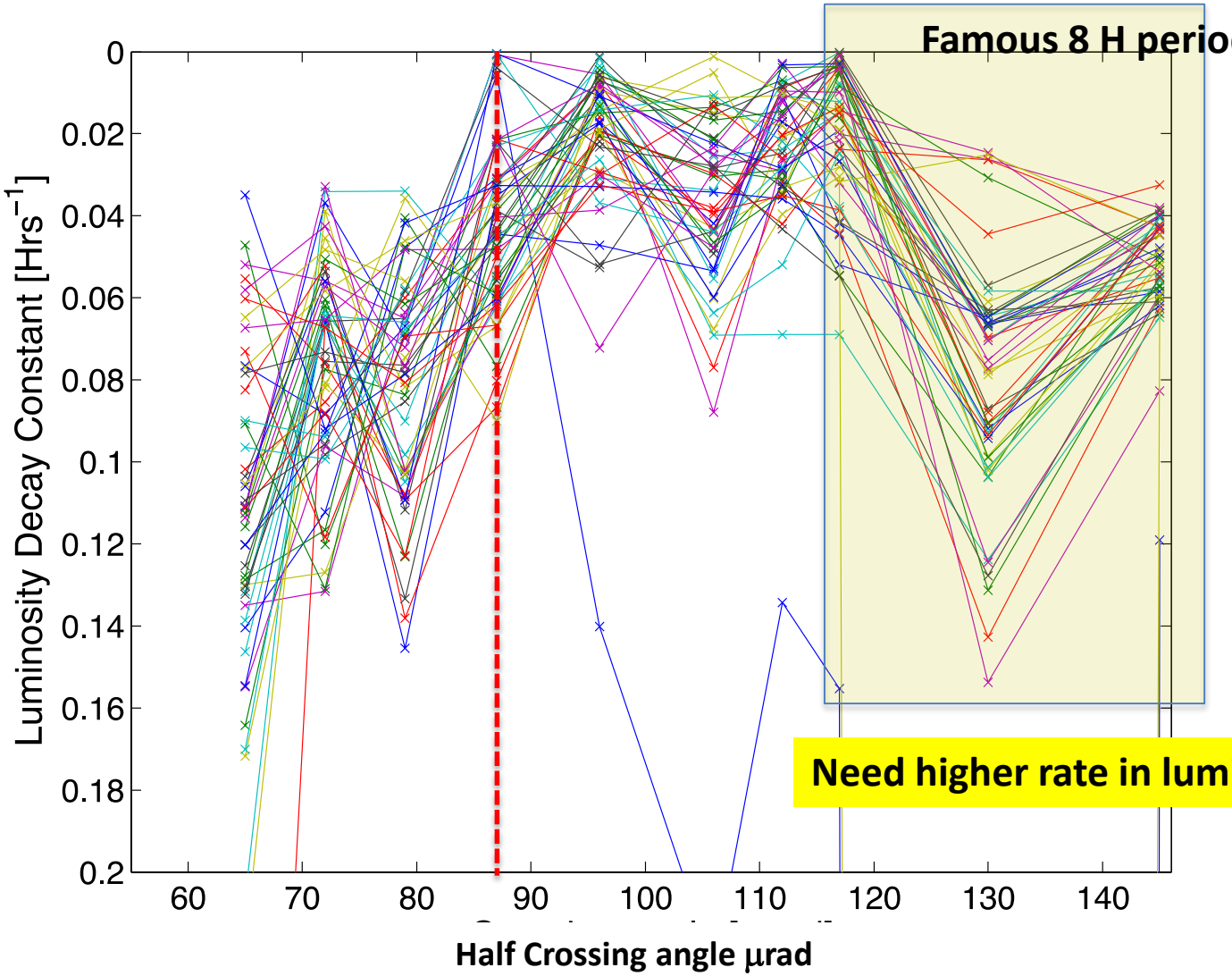


M. Crouch

Reducing the crossing angle Beam lifetimes are reduced from 30→8-5 hours
Beam 2 more sensitive (could be slightly different tune? Different emittances?)

Luminosity Lifetime

ATLAS Data

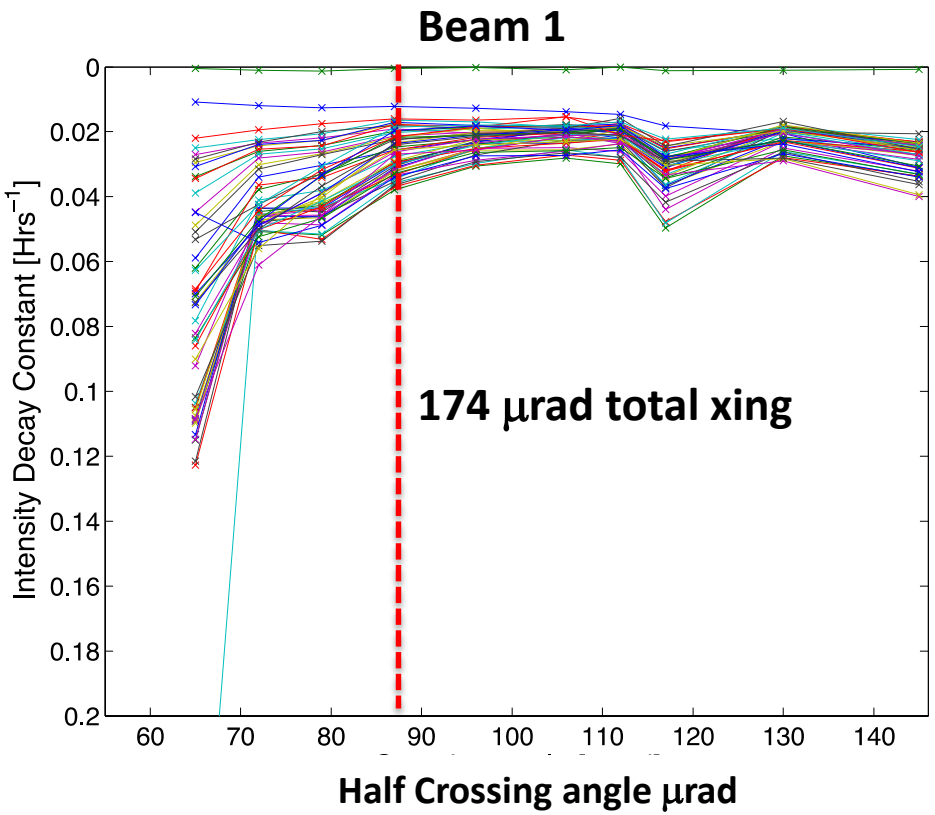


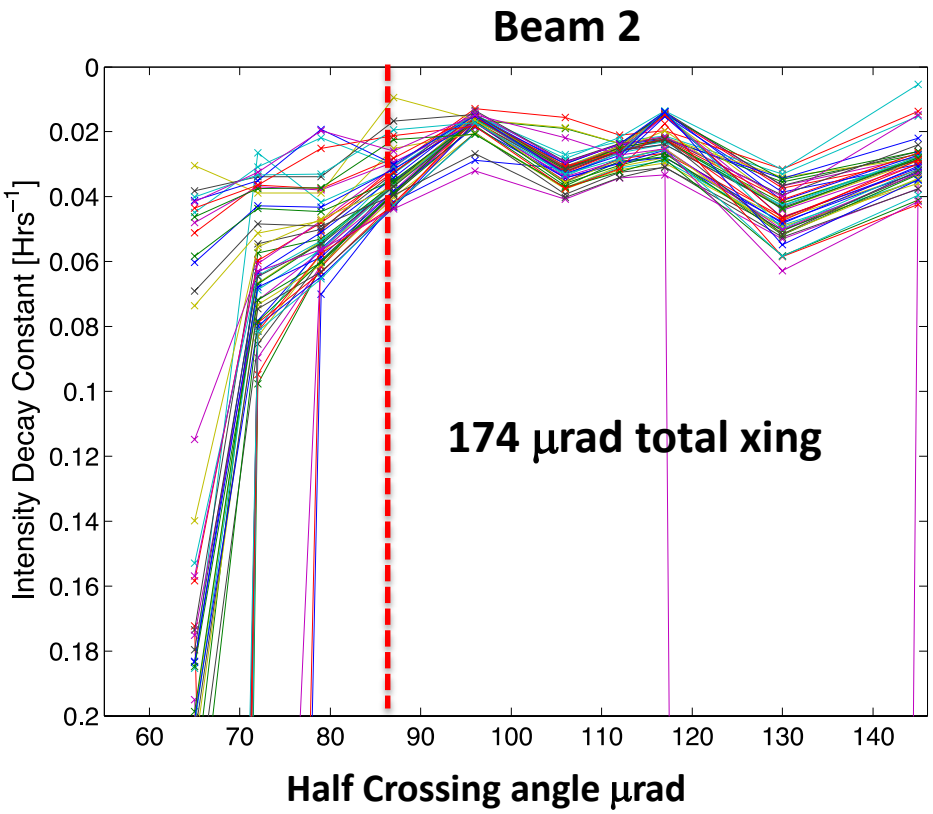
Need higher rate in luminosity data

M. Crouch

Reducing the crossing angle Luminosity lifetime reduces from 30 → 12 → 5 hours

Intensity lifetimes versus xing angle

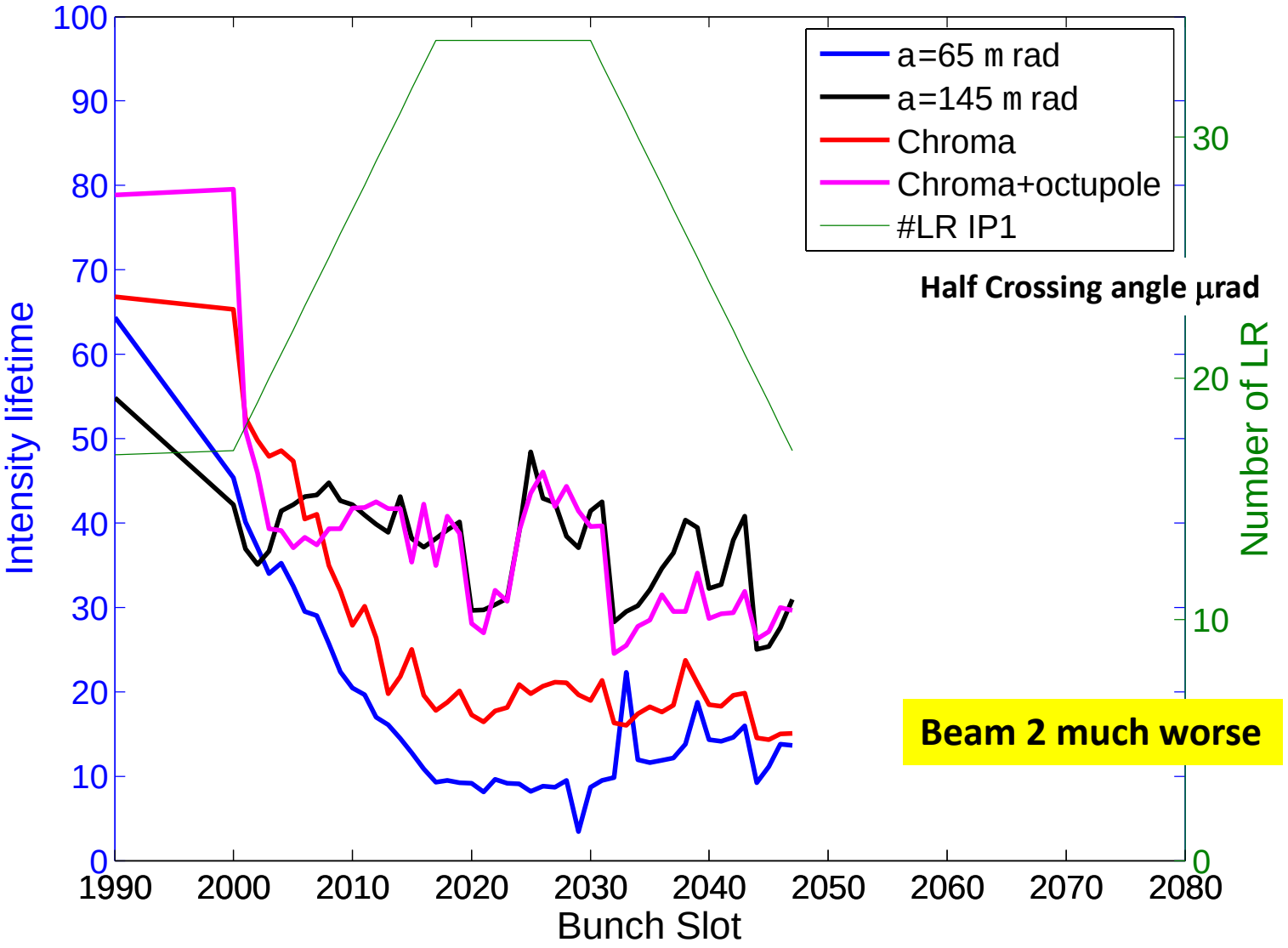




M. Crouch

For angles below this limit Beam lifetimes go below 20 hours Lumi lifetime at 12 hours
Onset of losses with Long Range patterns occurs at a beam-beam separation of 8.5 σ

Beam 1 Intensity lifetimes versus Q' and Octupoles

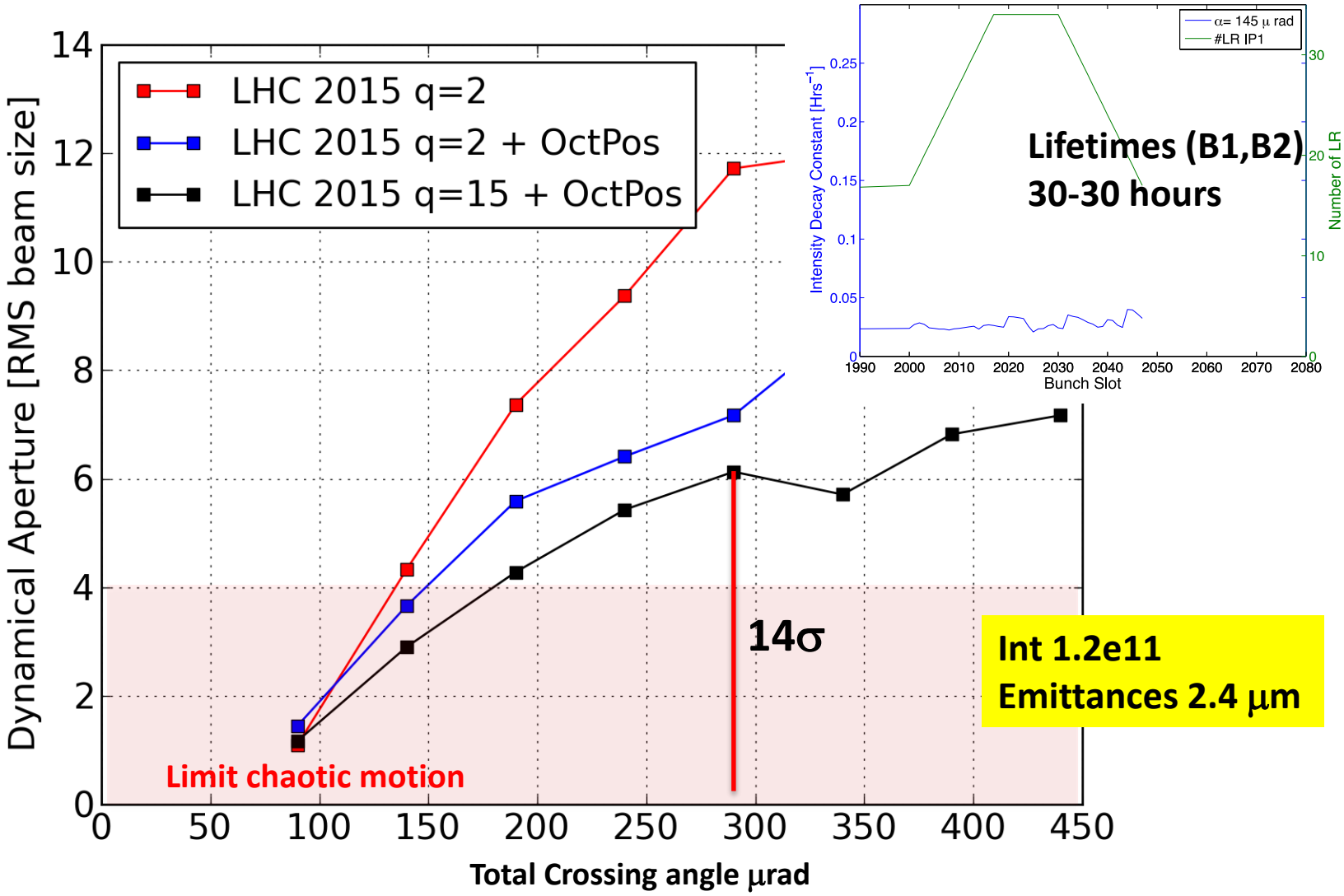


Reducing Q' 15→ 2 units

Landau Octupoles from 476 → 0 A

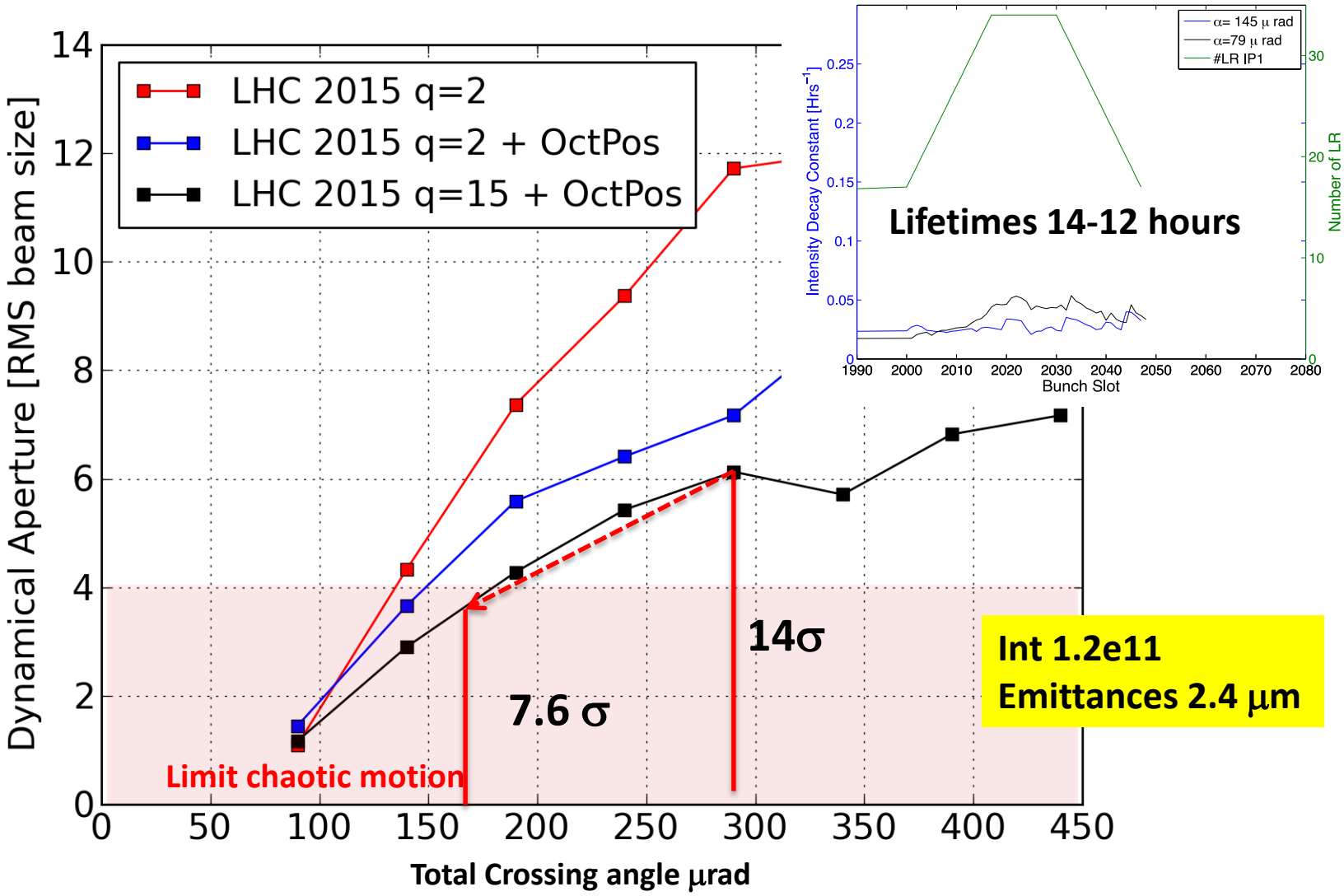
Lifetimes improves going back to 30 hours

2015 MD



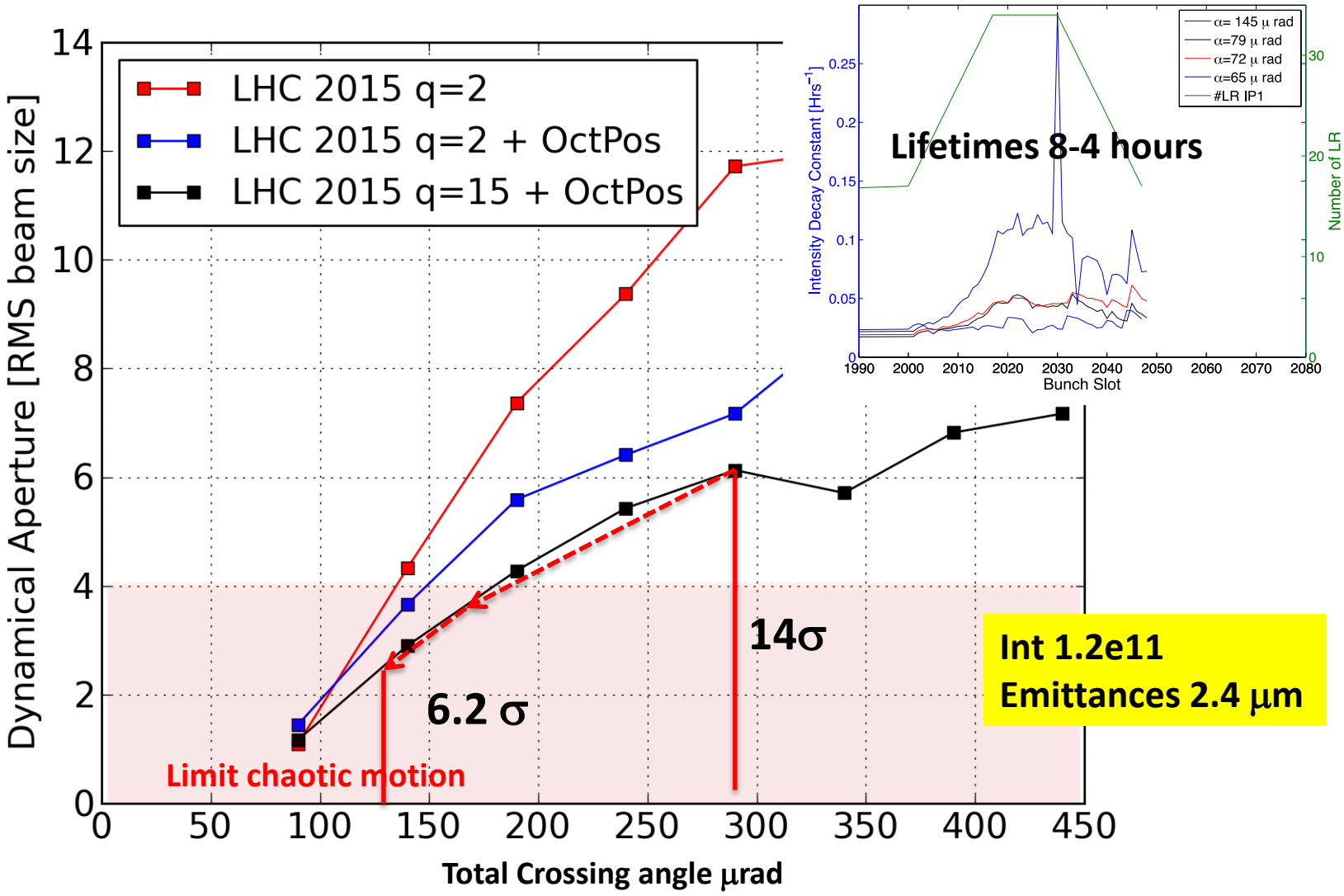
No Evidence of Long Range beam-beam dependent lifetimes

2015 MD



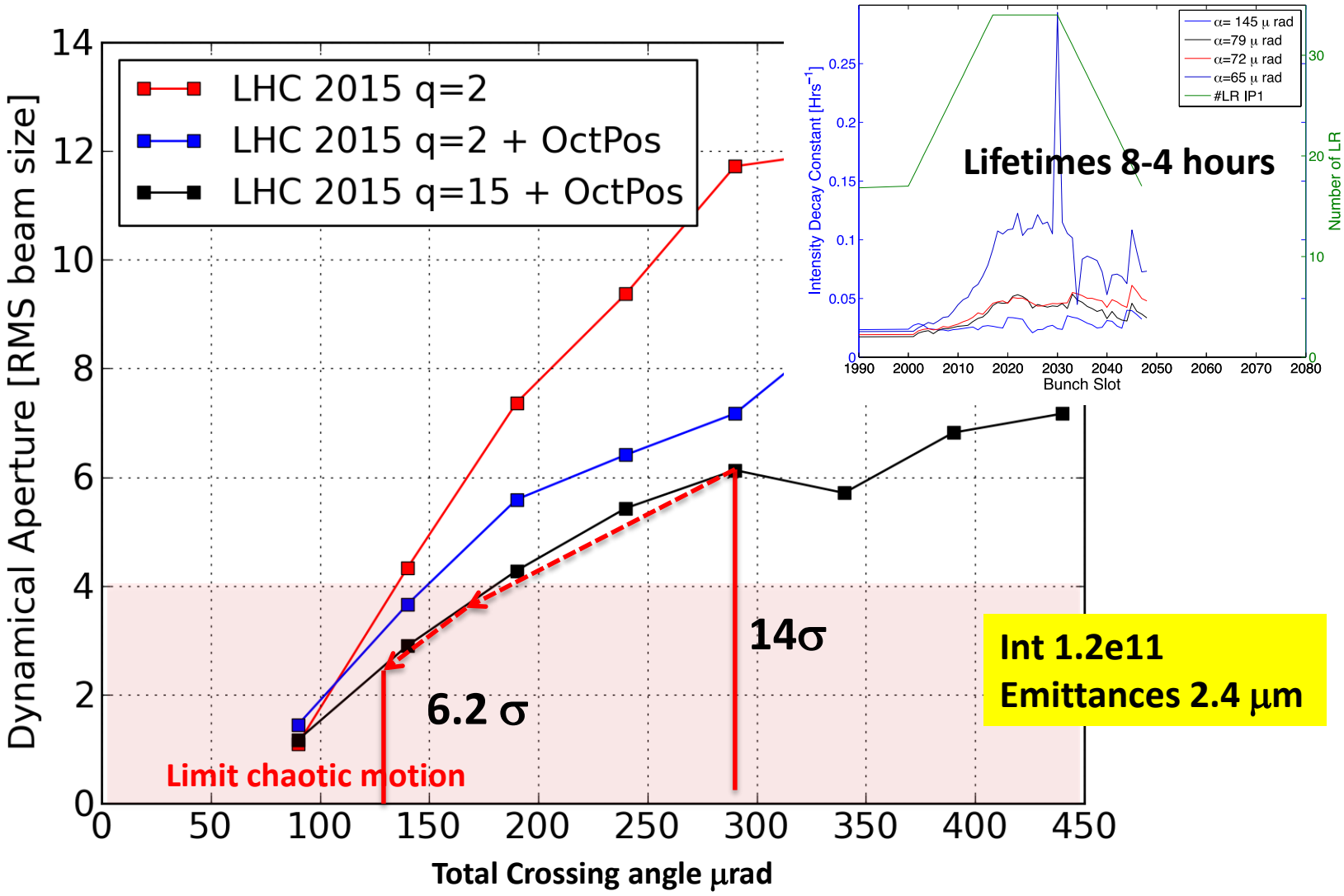
Onset of losses starts between 174-158 μrad equivalent to 8.4-7.6 σ beam-beam separation at first LR encounter → consistent with previous observations 50 ns (4 σ DA)

2015 MD



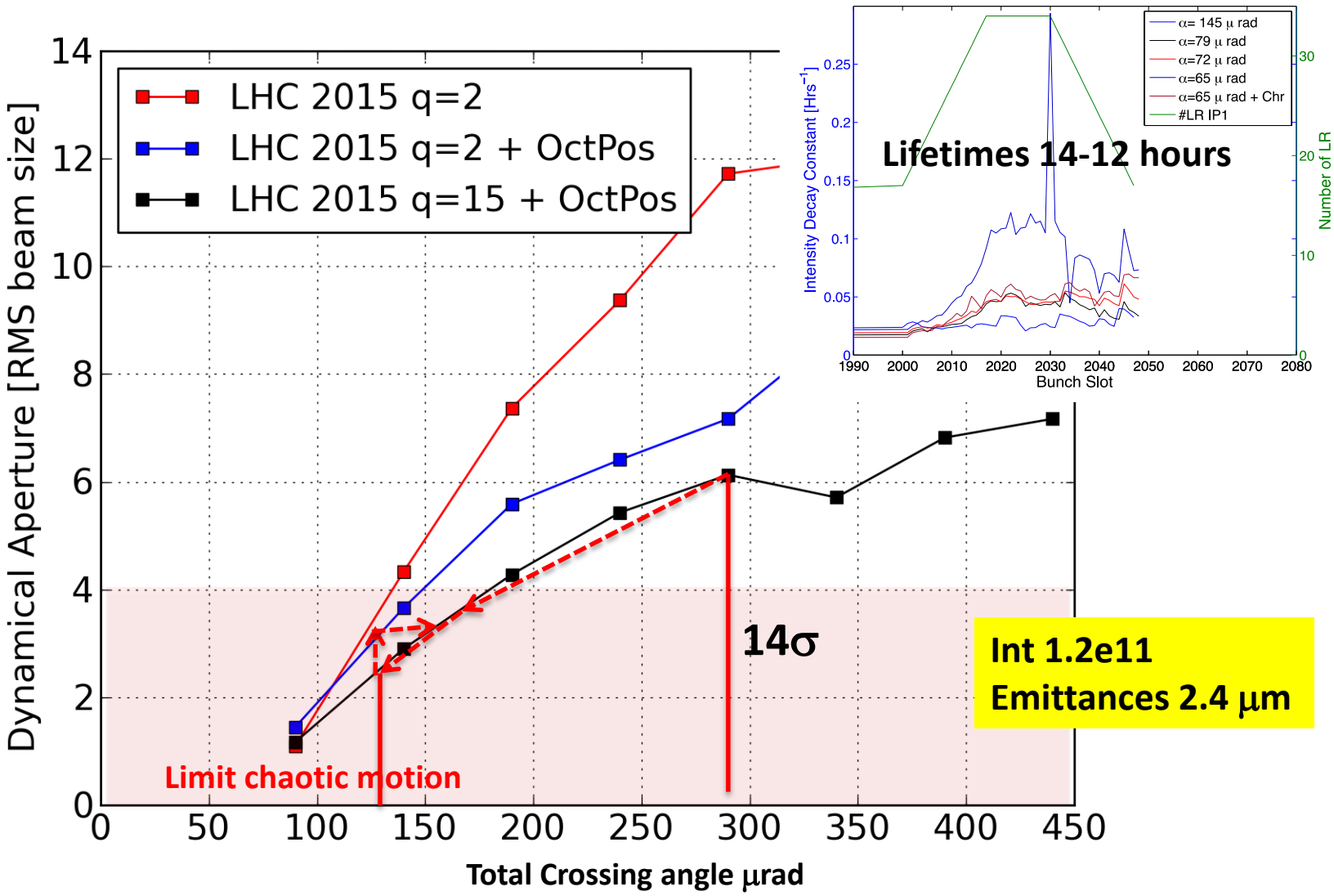
Reduce further the crossing angle to quantify impact on beam lifetimes
Large losses at 130 μrad equivalent to 6.2 σ separation

2015 MD



Reduce Chromaticity from 15→ 2 units + Correct Beam 2 lifetime drop (Feed-Down Effects?)

2015 MD

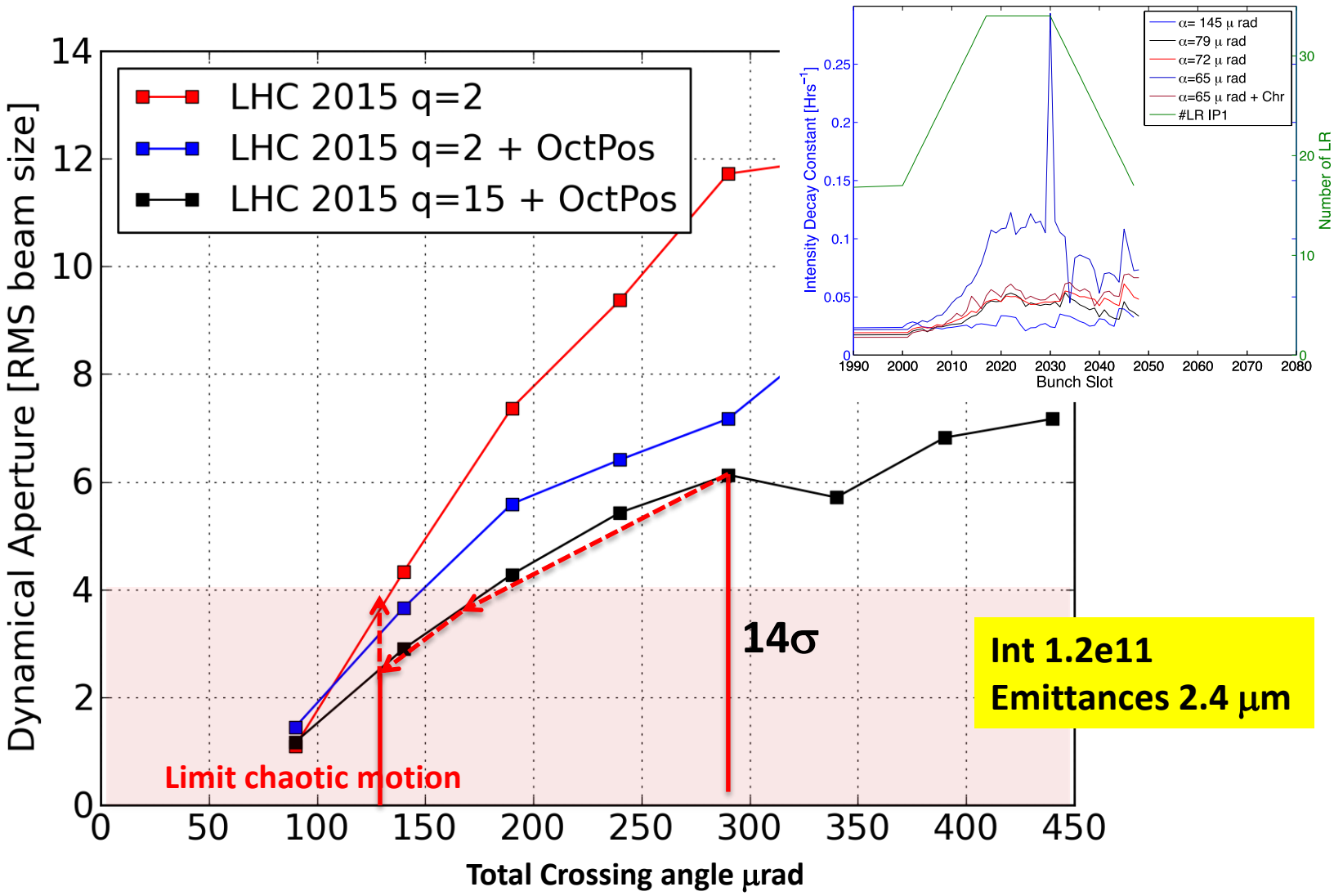


Lifetimes equivalent to case at xing angle 158 μrad

6.3 σ → 7-7.5 σ

1 σ sep →High Q'

2015 MD

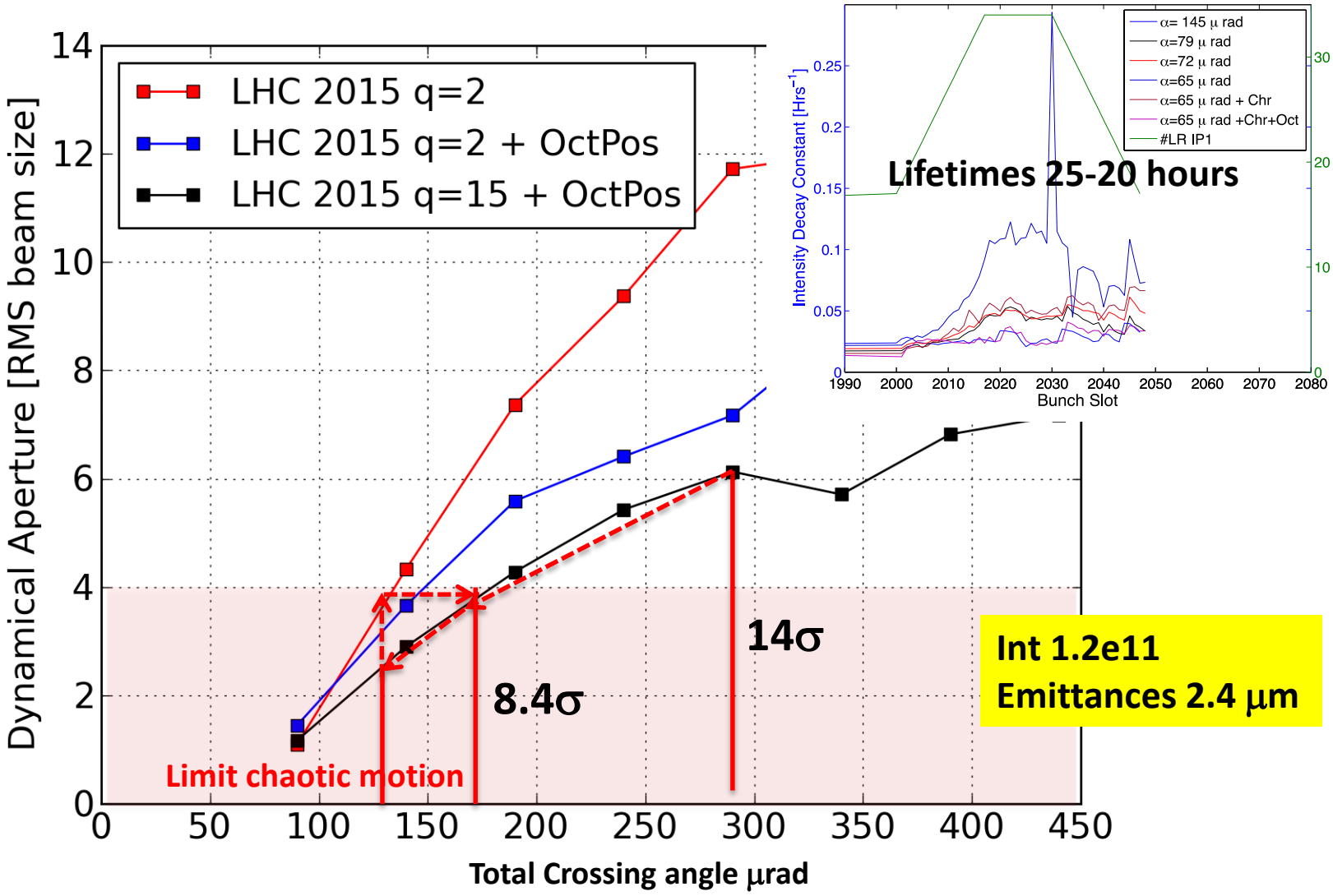


Reduce Landau Octupoles to zero current

Colliding beams Rock stable!

Only non-colliding bunch unstable at zero

2015 MD

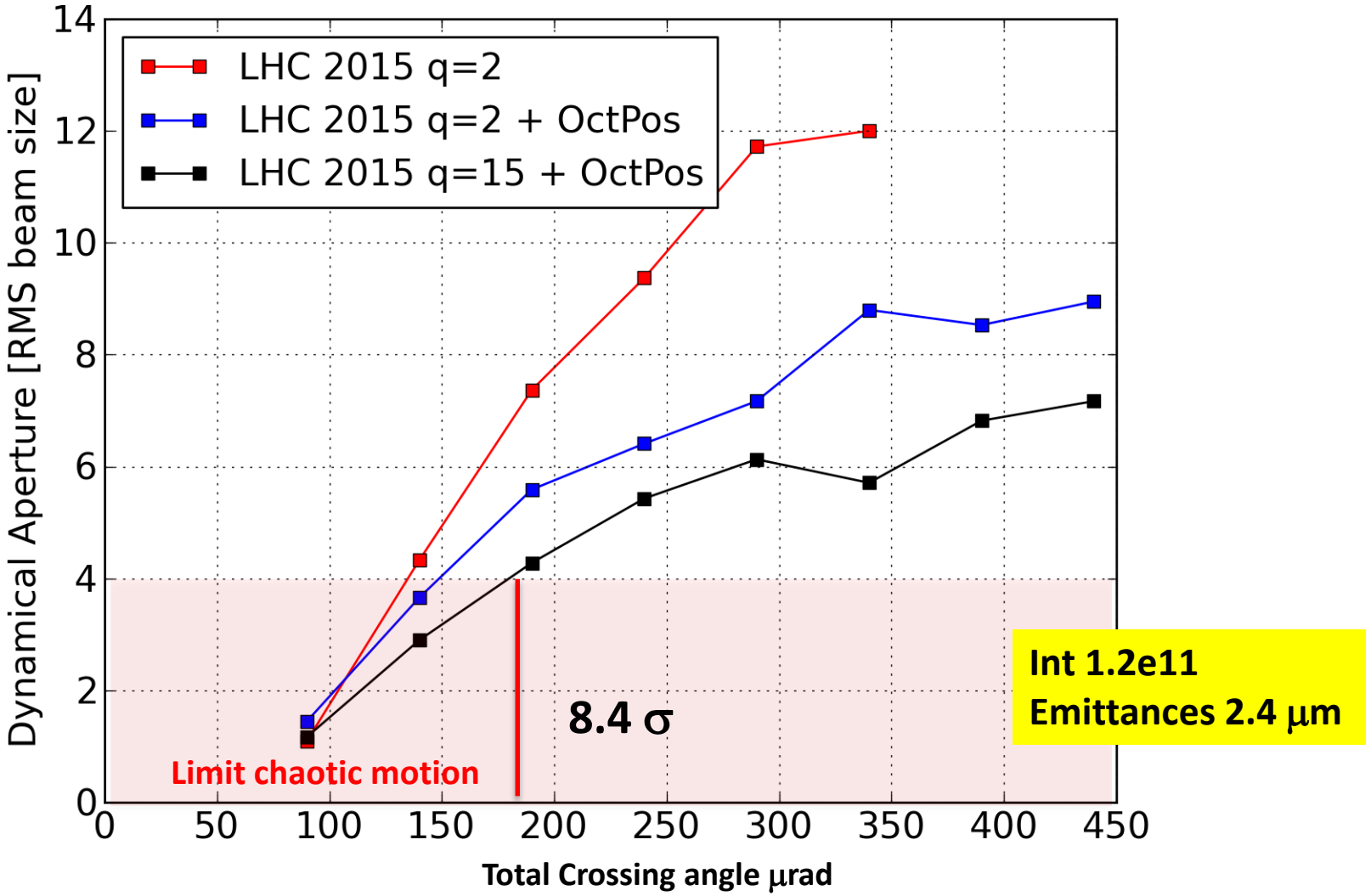


Lifetimes with zero octupoles equivalent to lifetimes at larger xing angle

6.3 σ sep case + Oct=0 → equivalent to 8.4 σ sep case + Oct=476 A

1 σ →Octupoles

2015 MD

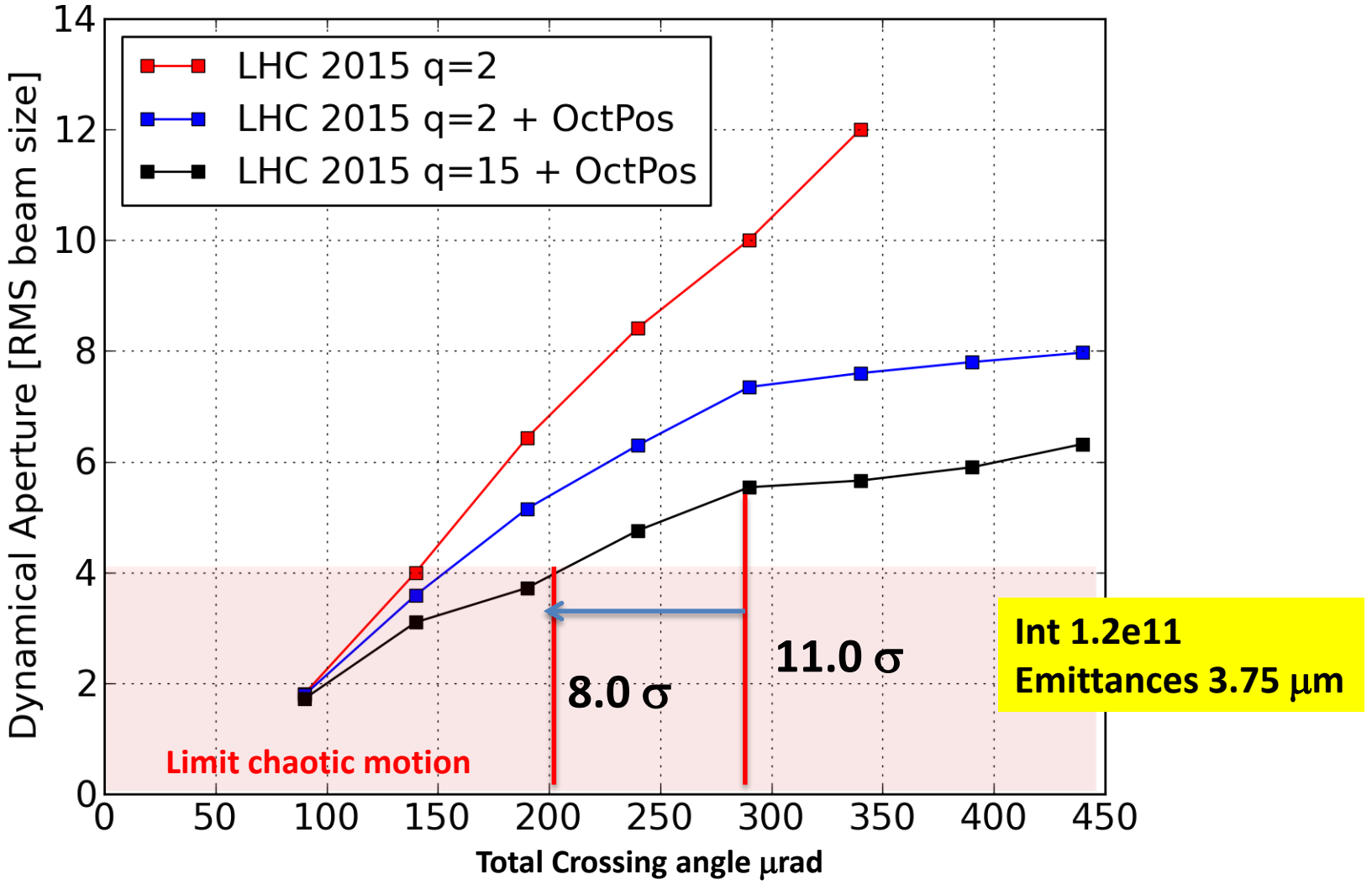


8.4 σ Beam-Beam separation + Oct + 15 units Q' equivalent to 4 σ DA

Beam and Lumi lifetimes are reduced: below 10 hours for smaller angles

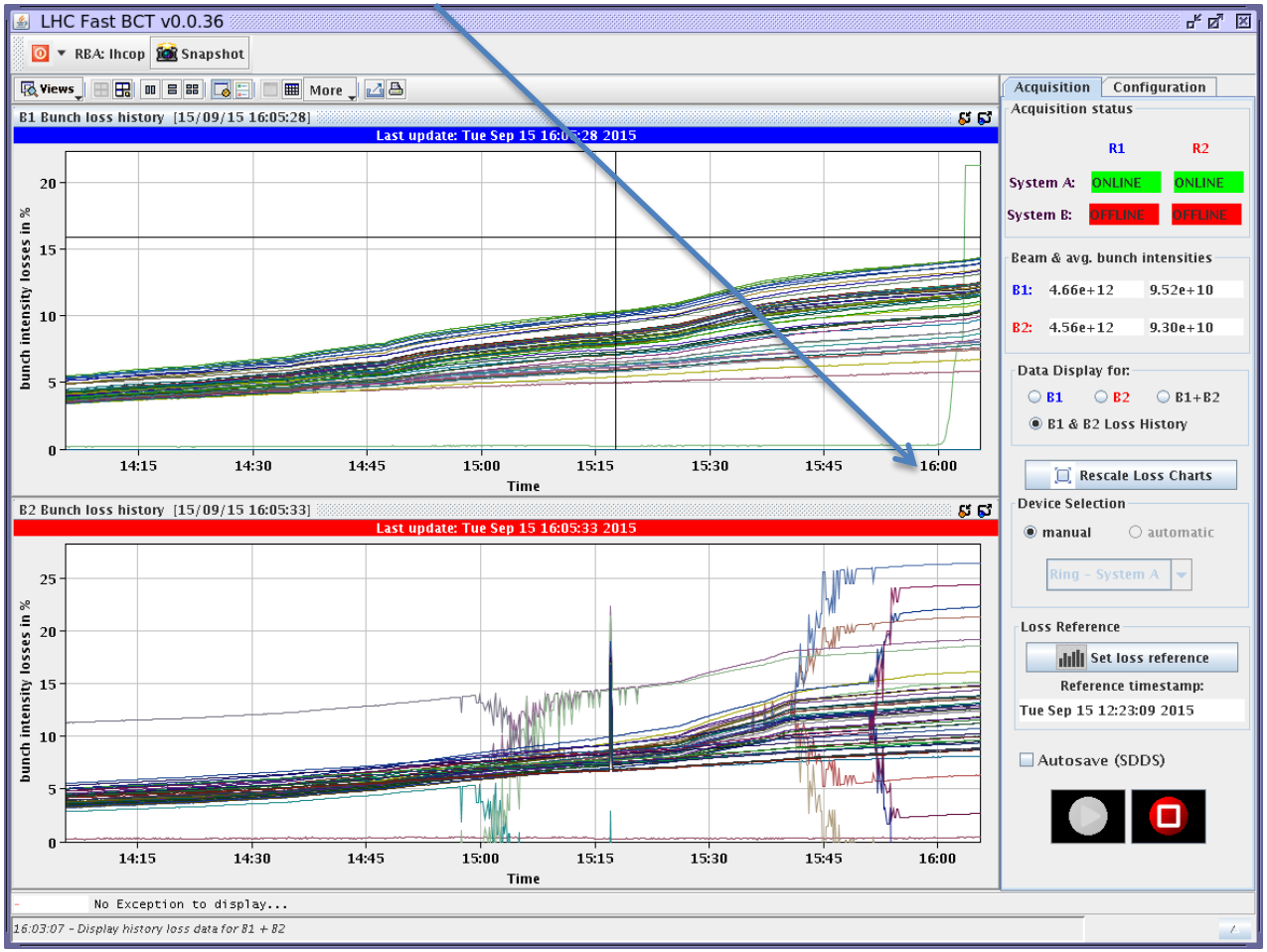
Operational beams (3.75 mm emittances) are 2.6 σ away from this limit

2015 Strategy: 6 σ DA for 3.75 emittance beams



6 σ DA criteria robust for commissioning phase (e-cloud, instabilities…)
Smaller Separations possible with Octupoles and Q' reduced in stable beams!

Non-colliding bunches



Q' at zero and Octupoles reduced to zero current

Colliding bunches rock stable - Non-colliding bunches unstable.

We should aim at reducing Q' and Landau Octupoles in stable beams!

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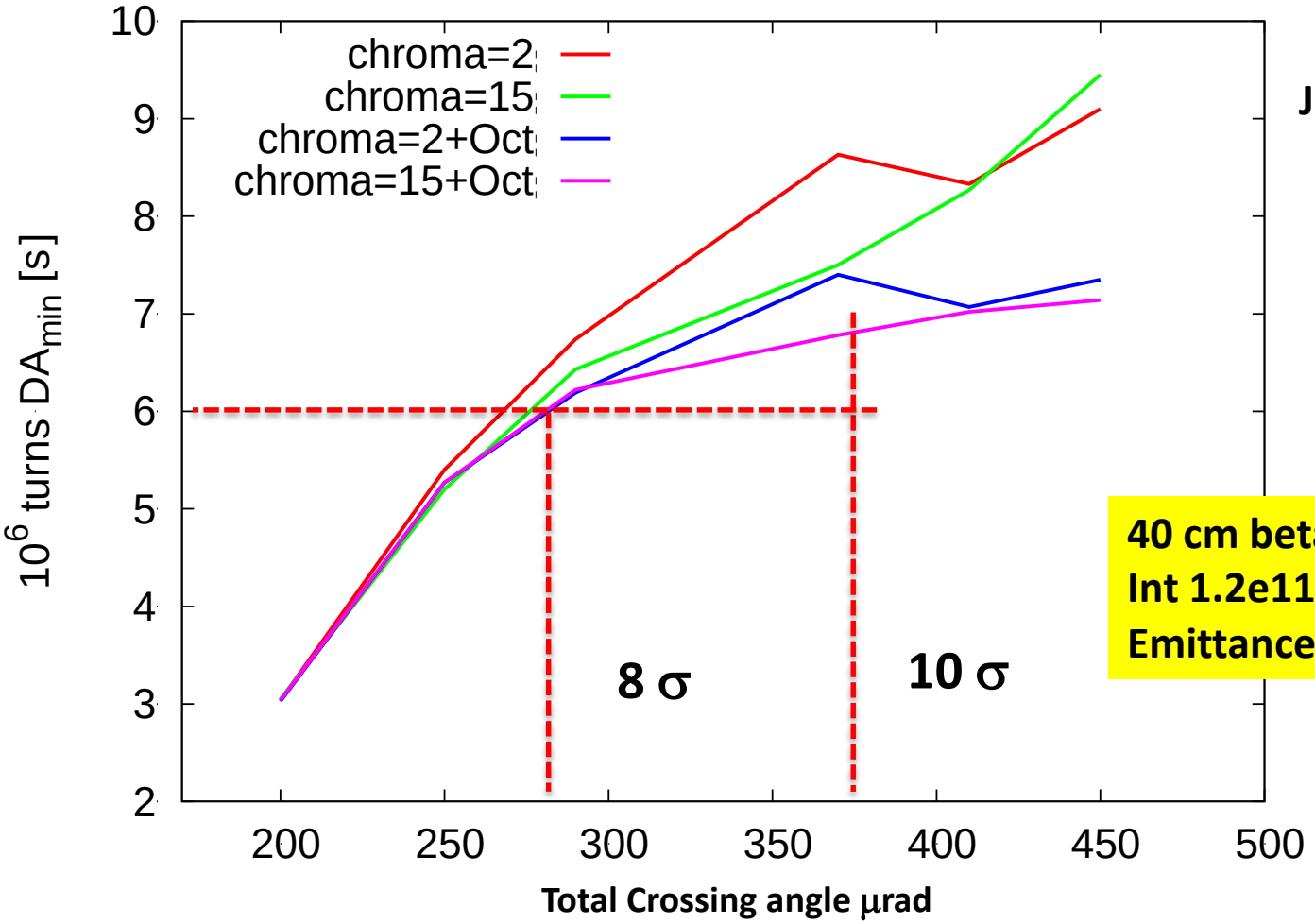
2016 Xing angles IP1&5: Dynamic Aperture

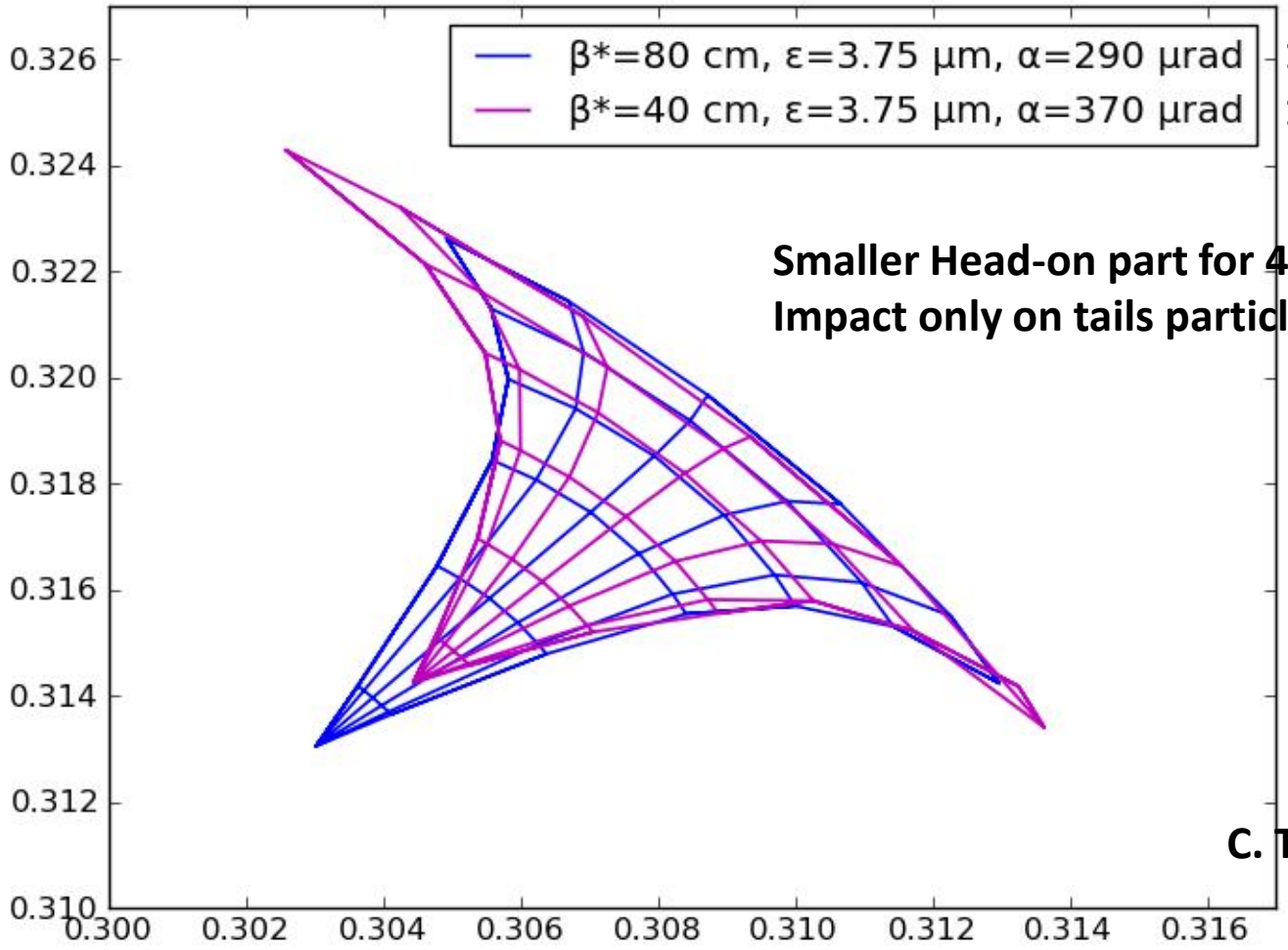


DA above 6 σ with margins to allow for 1.3e11 ppb

Possibility to reduce angle only when:

- **beams emittances are stable (e-cloud, instabilities)**
- **Octupoles and Chroma reduced**
- **MD on crossing angles**

2016 Xing angles IP1&5: Footprints



11 σ

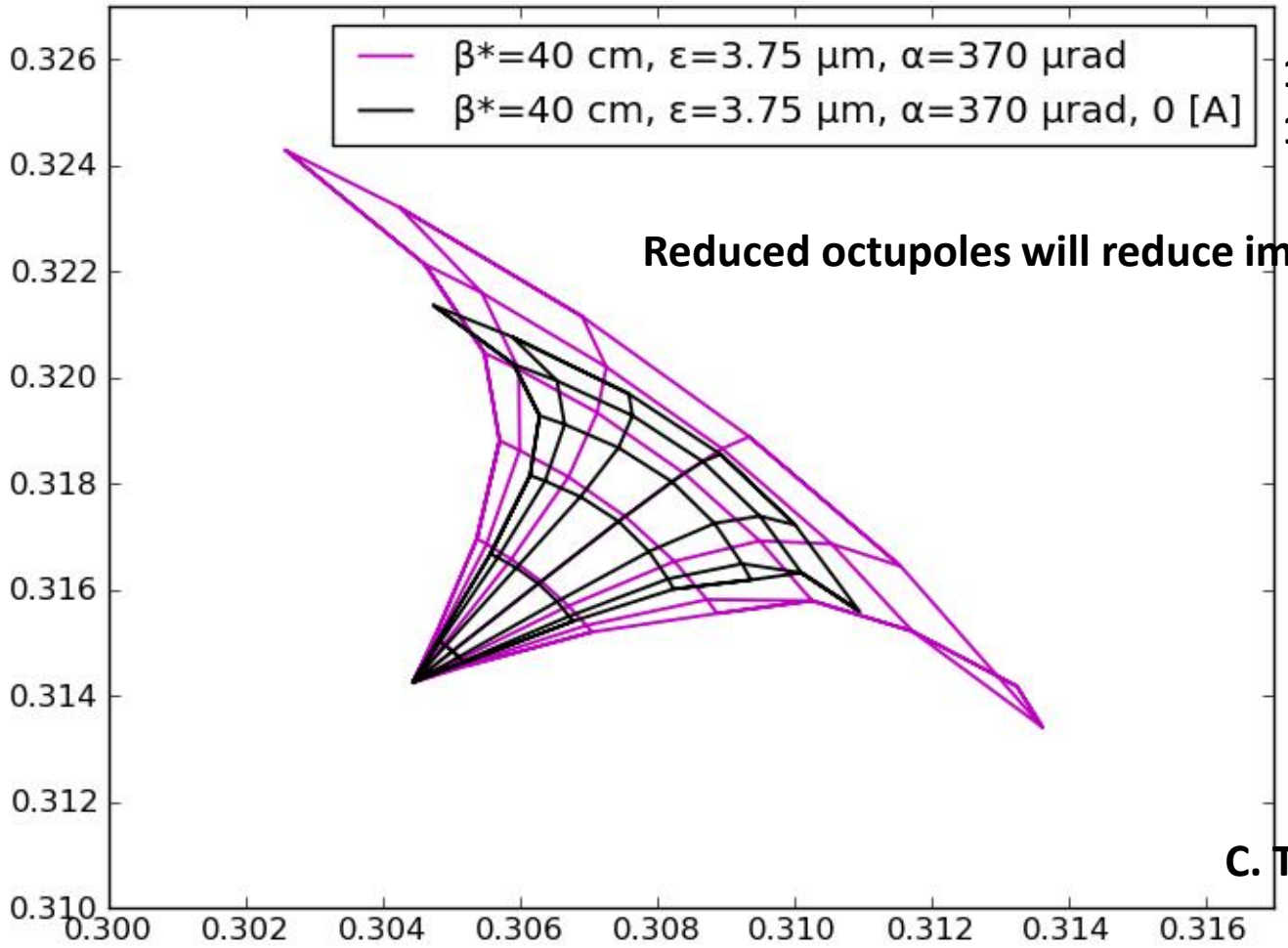
10 σ

Smaller Head-on part for 40 cm optics
Impact only on tails particle

C. Tambasco

2015 versus possible 2016 with 10 σ separation with 40 cm optics

2016 Xing angles IP1&5: Octupoles effect



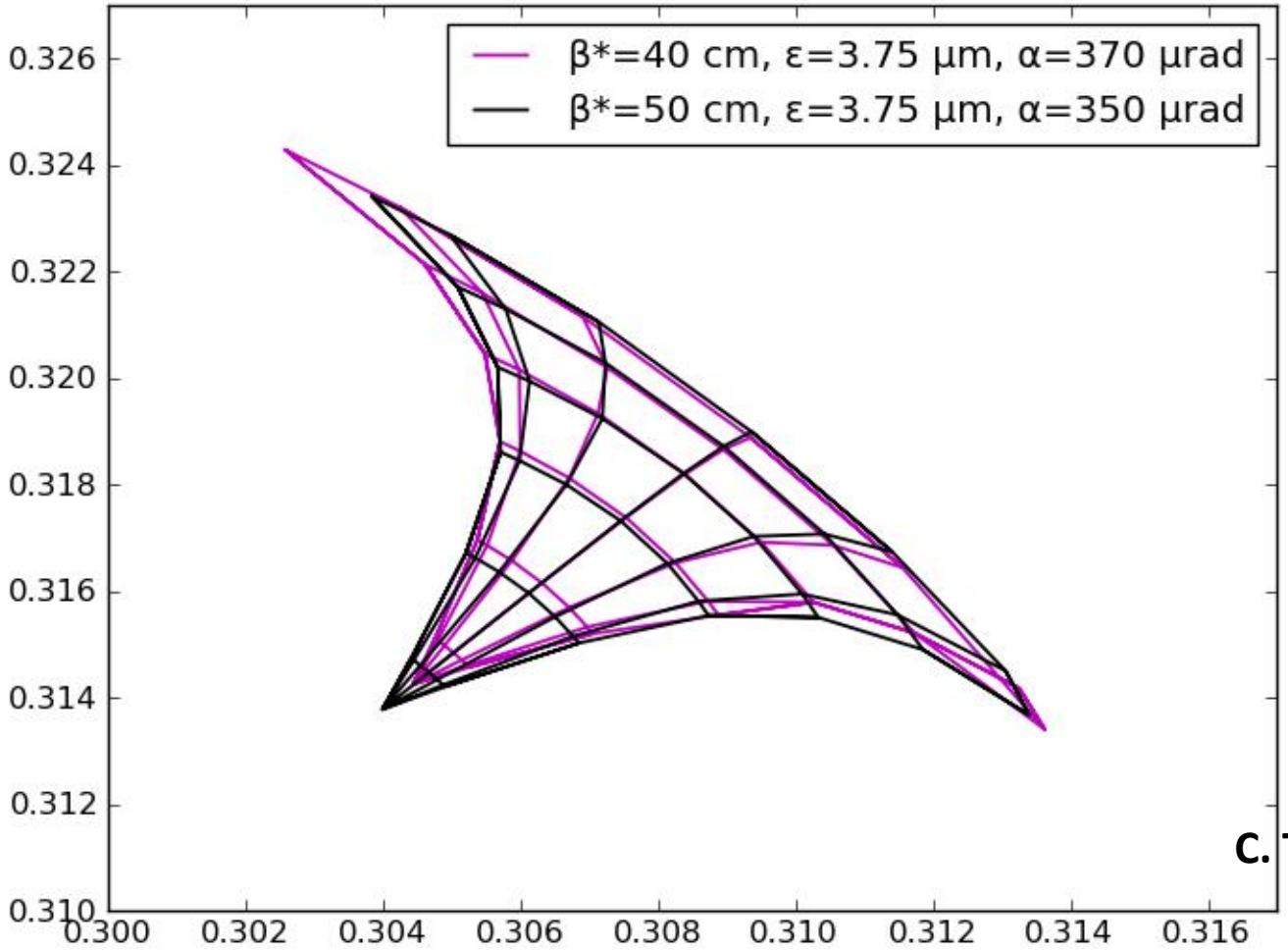
10 σ
10 σ

Reduced octupoles will reduce impact on tails

C. Tambasco

Reducing Landau octupoles reduces the whole spread on tails
→ Similar situation as 2015

2016 Xing angles IP1&5: 40 cm versus 50 cm



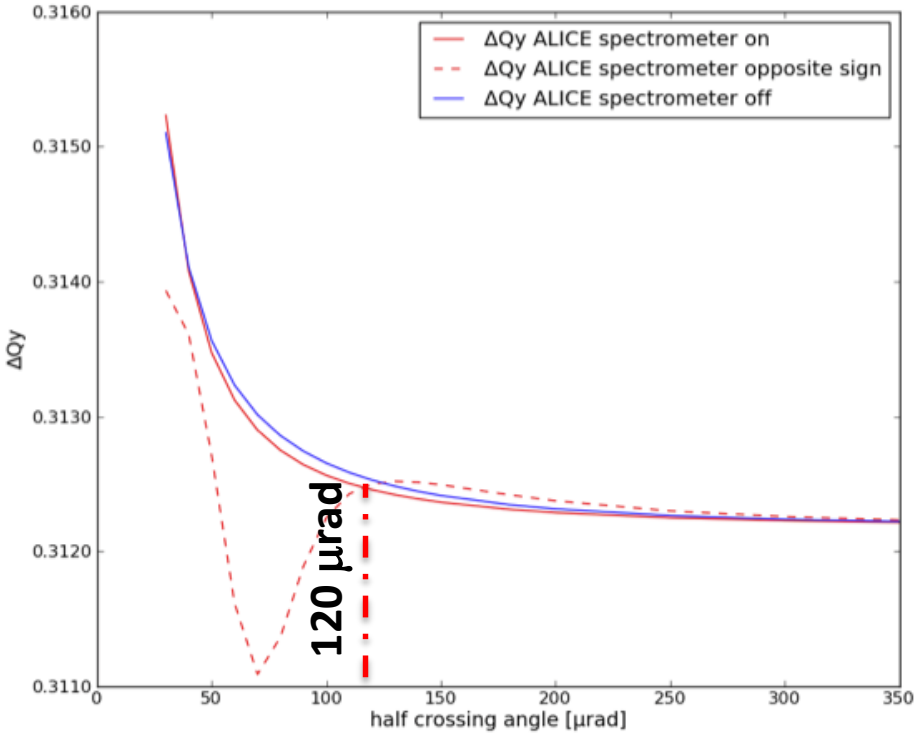
10 σ
10.5 σ

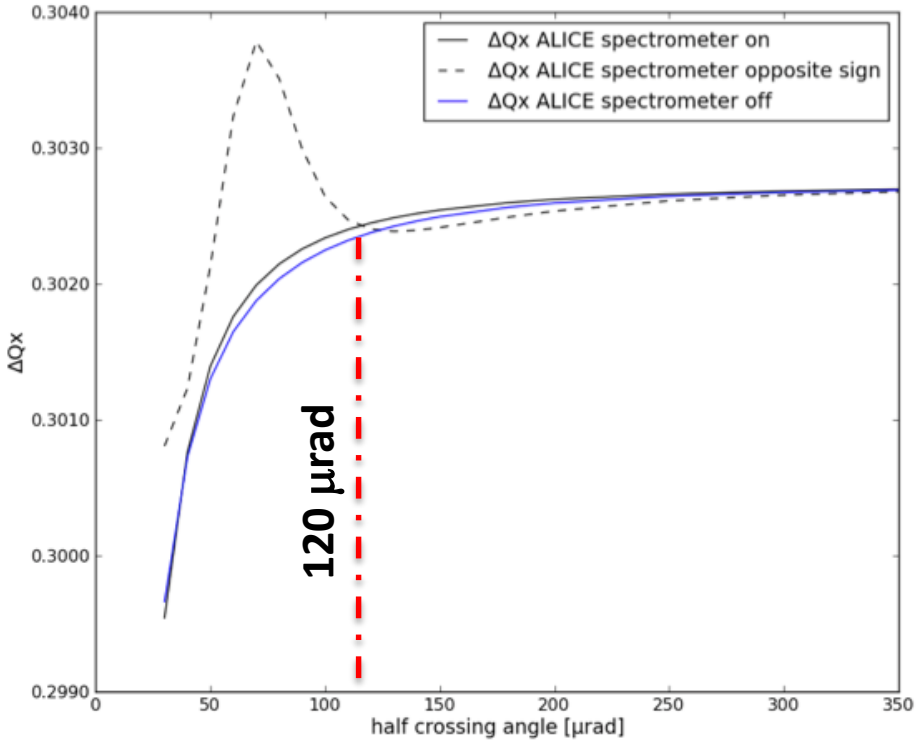
C. Tambasco

40 cm optics or 50 cm are almost identical for beam-beam effects

Alice IP2:
in shadow of the high Lumi experiments

From DA studies 10^{-3} tune shift can have strong impact on DA (2 σ reduction)
→ Tune shift below 10^{-4} effect





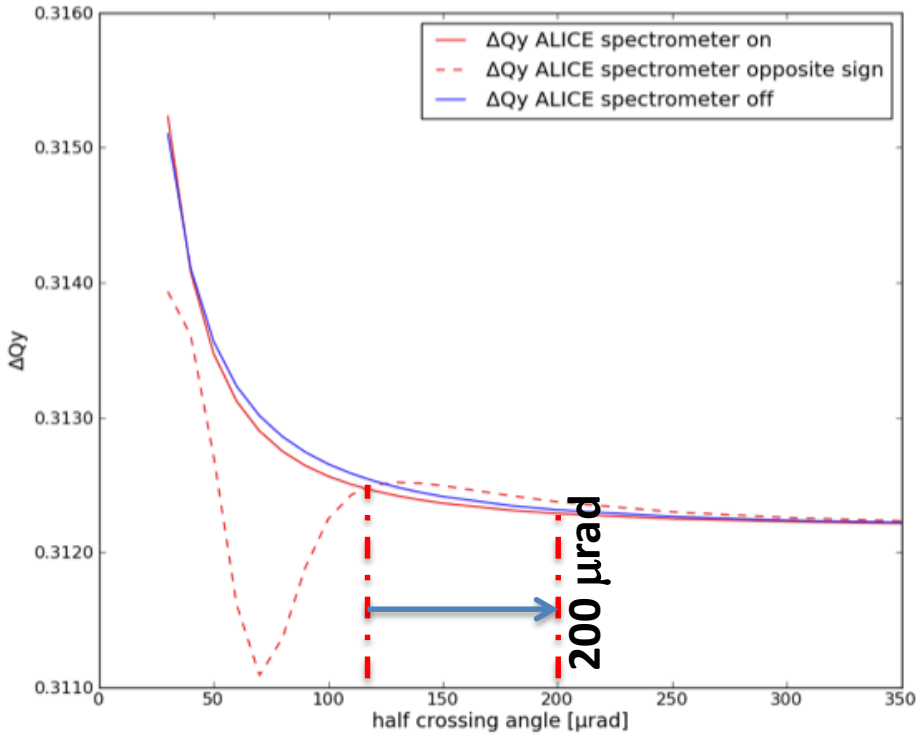
Alice IP2:
in shadow of the high Lumi experiments

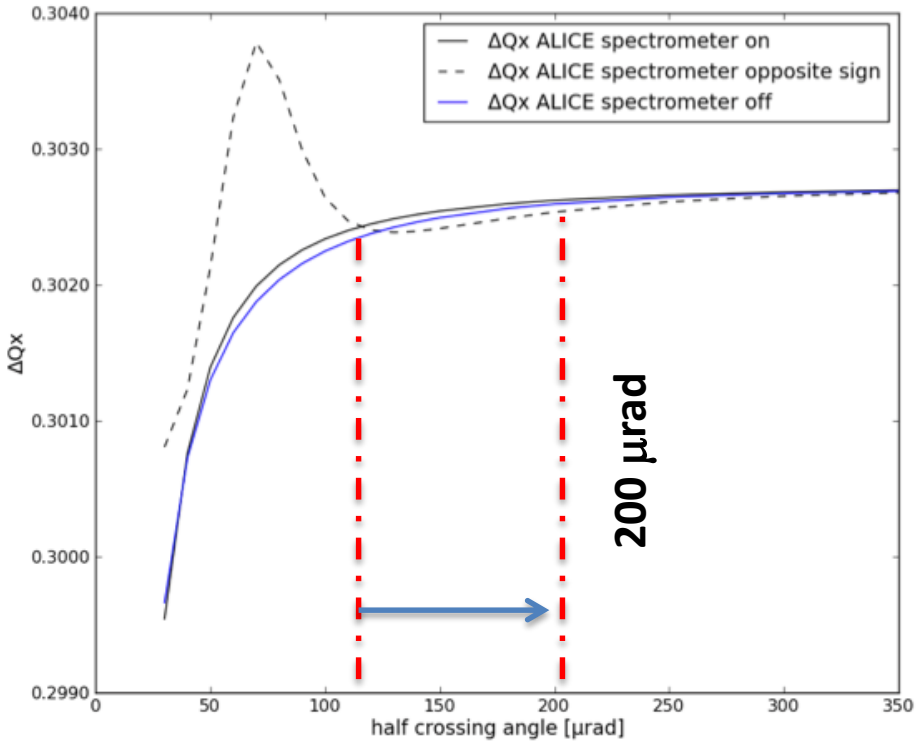
From DA studies 10^{-3} tune shift can have strong impact on DA

→ Tune shift below $5*10^{-4}$ effect

→ for 2016 swap of spectrometer polarity requested

→ Need larger angle (200 µrad half at Collision)





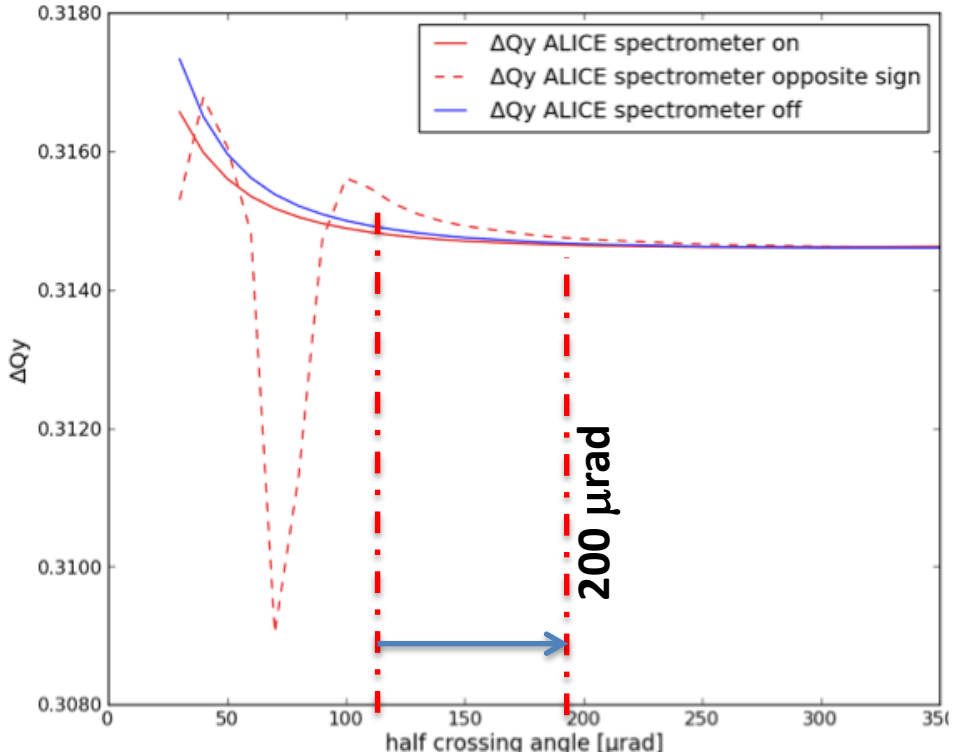
400 mrad external crossing angle

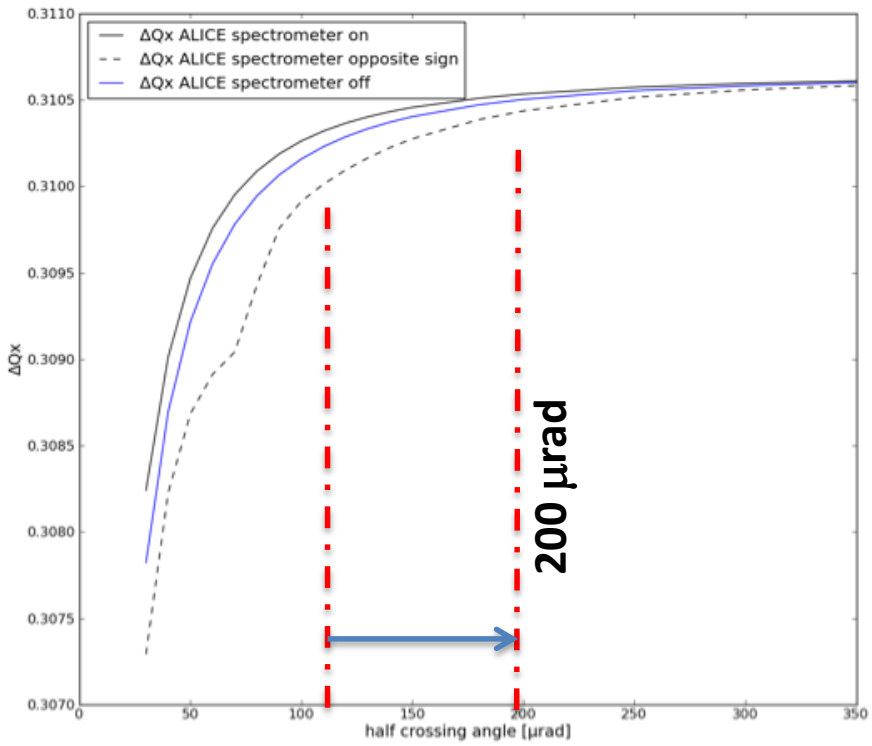
Alice IP2:
in shadow of the high Lumi experiments

From reduce impact of long range from these IP

→ Tune spread below $5*10^{-4}$ effect

→ for 2016 swap of spectrometer polarity option

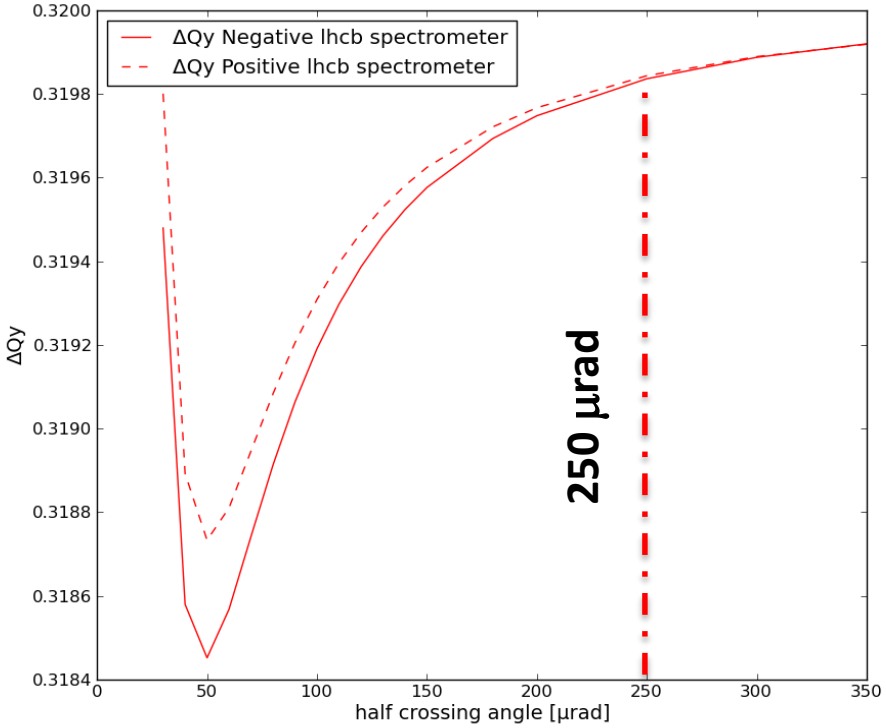


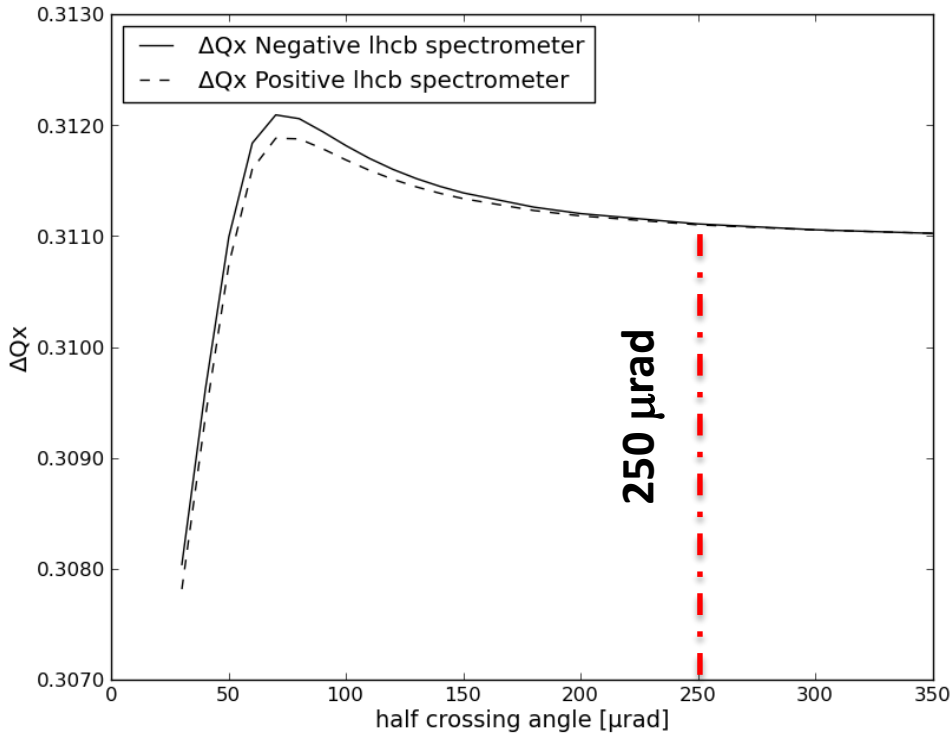


400 mrad external crossing angle

LHCB IP8:
in shadow of the high Lumi experiments

Same considerations set-up as in 2015
→ Crossing angle 250 μrad half





Outline

- 2012 Beam Beam effects data and simulations
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Colliding beams: Stability

Head-on beam-beam is weaker respect to 2015
→ factor 2 reduced BB parameter from 0.0067→0.0033/IP
→ reduced Landau damping depending on separation

Three cases of coherent oscillations in stable beams:

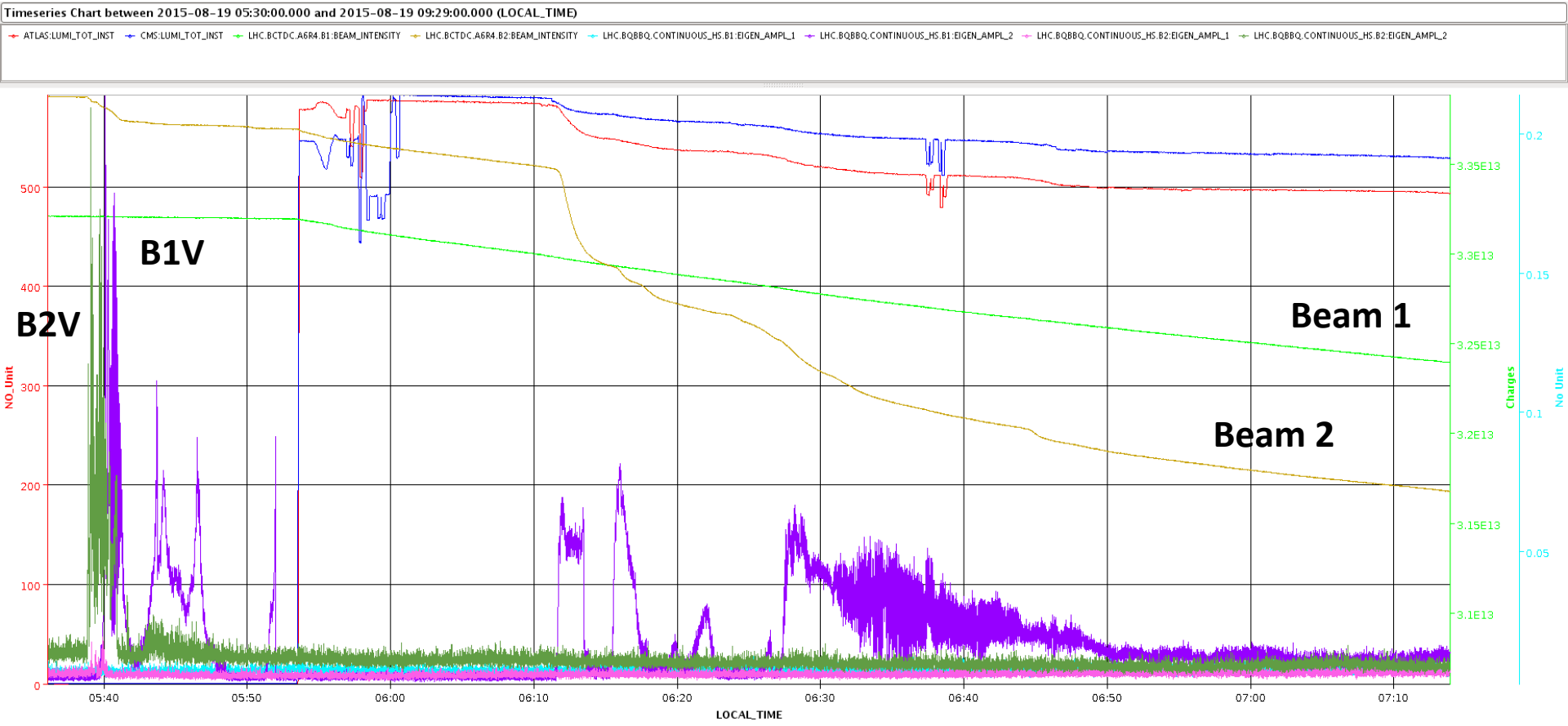
1) Fill 4321 instability in stable beams Beam 1V in squeeze then Beam 2 V in stable beams
→Weak-strong regime

2) OP-scans and ADT reduced gain(several Fills) → instabilities at separation of 2 σ
→ Weaker beam-beam parameter (head-on Landau damping)

3) BCMS beams test
→ **Coherent oscillations during stable beams**→ could be like for Fill 4321 (weak-strong regime) since instabilities observed during squeeze **(L. Carven talk)**

Fill 4231: Instabilities during squeeze and impact in collisions

Instability in the squeeze (9m-3 m):
Beam 2 Vertical (green line) then Beam 1 Vertical (violet line)
In Collision only Beam 1 Vertical shows coherent ”oscillations”?

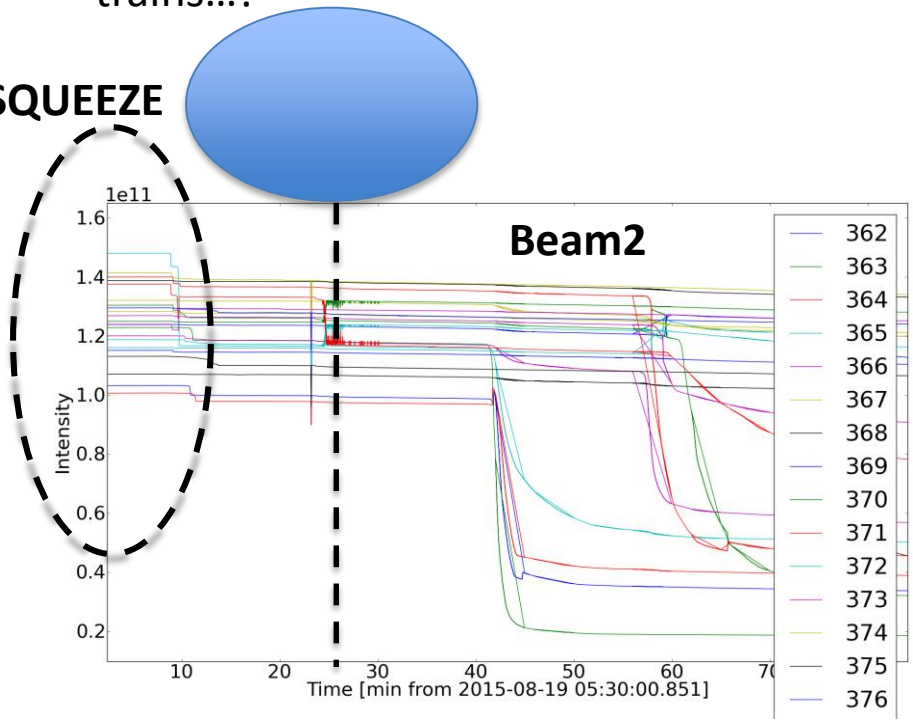


Bam 2 Losses Unstable Bunches

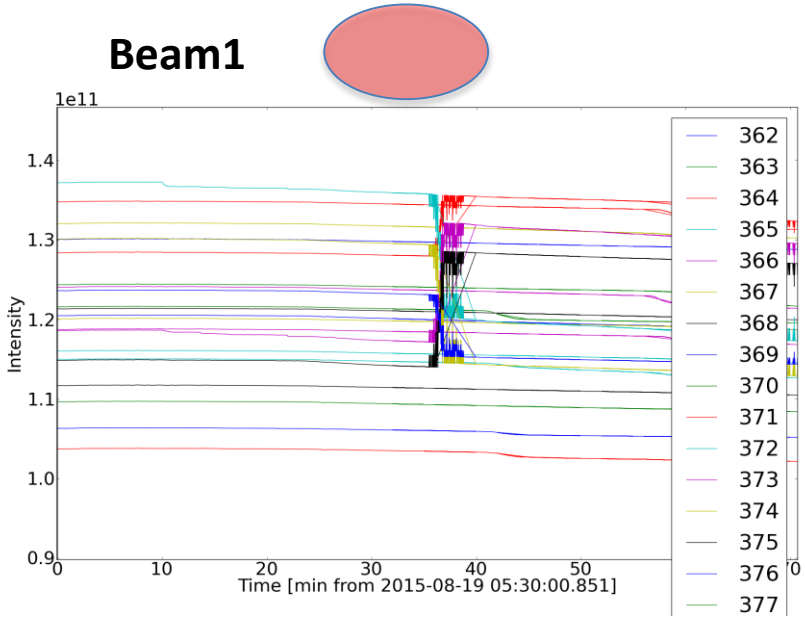
B2 V unstable in Squeeze 1st TRAN of 72 bunches most affected then few individual bunches in other trains

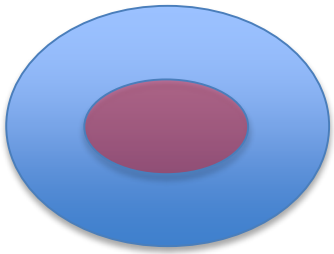
Why? No BB apparent reason, these bunches are like all the central ones in other trains…!

SQUEEZE



Beam1





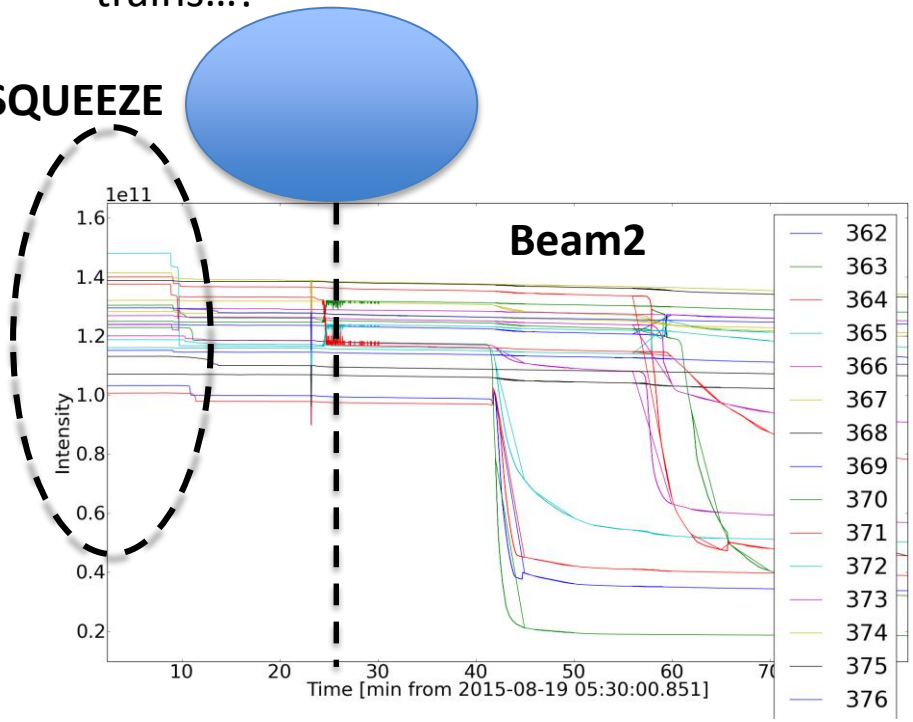
Beam 1 sees BB parameter 0.001 → like "single beam" in squeeze
Oscillations and emittance blow-up due to filamentation

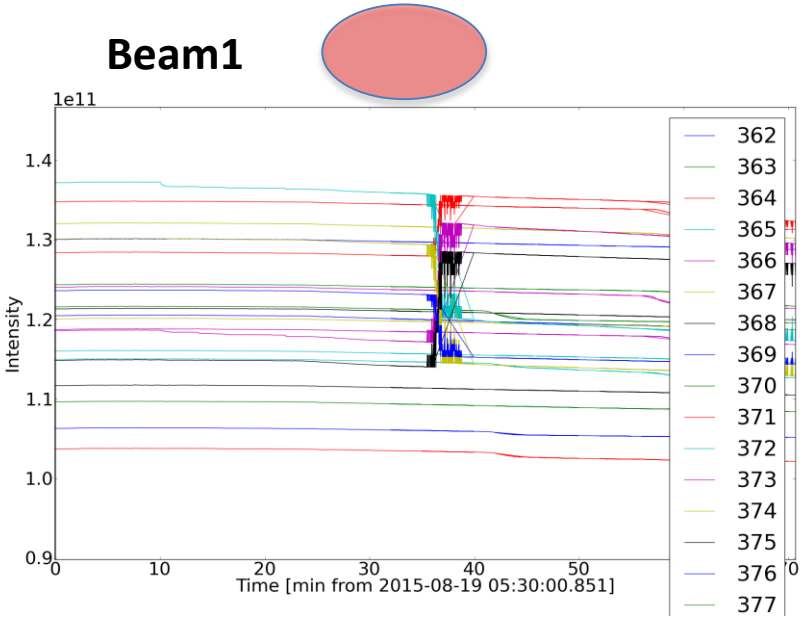
Bam 2 Losses Unstable Bunches

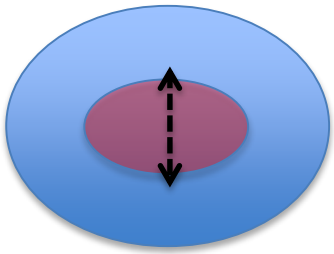
B2 V unstable in Squeeze 1st TRAN of 72 bunches most affected then few individual bunches in other trains

Why? No BB apparent reason, these bunches are like all the central ones in other trains…!

SQUEEZE

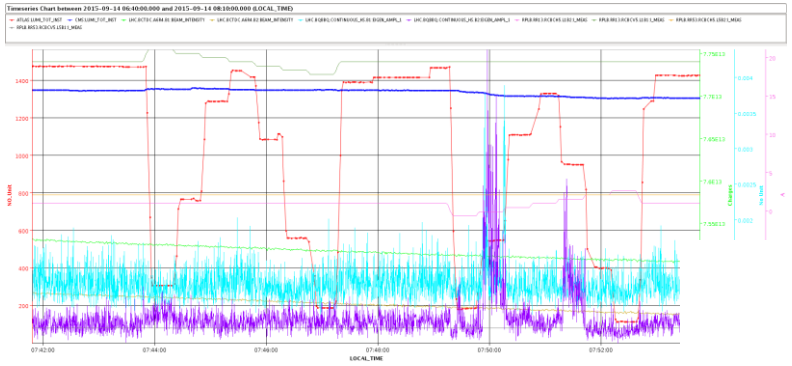




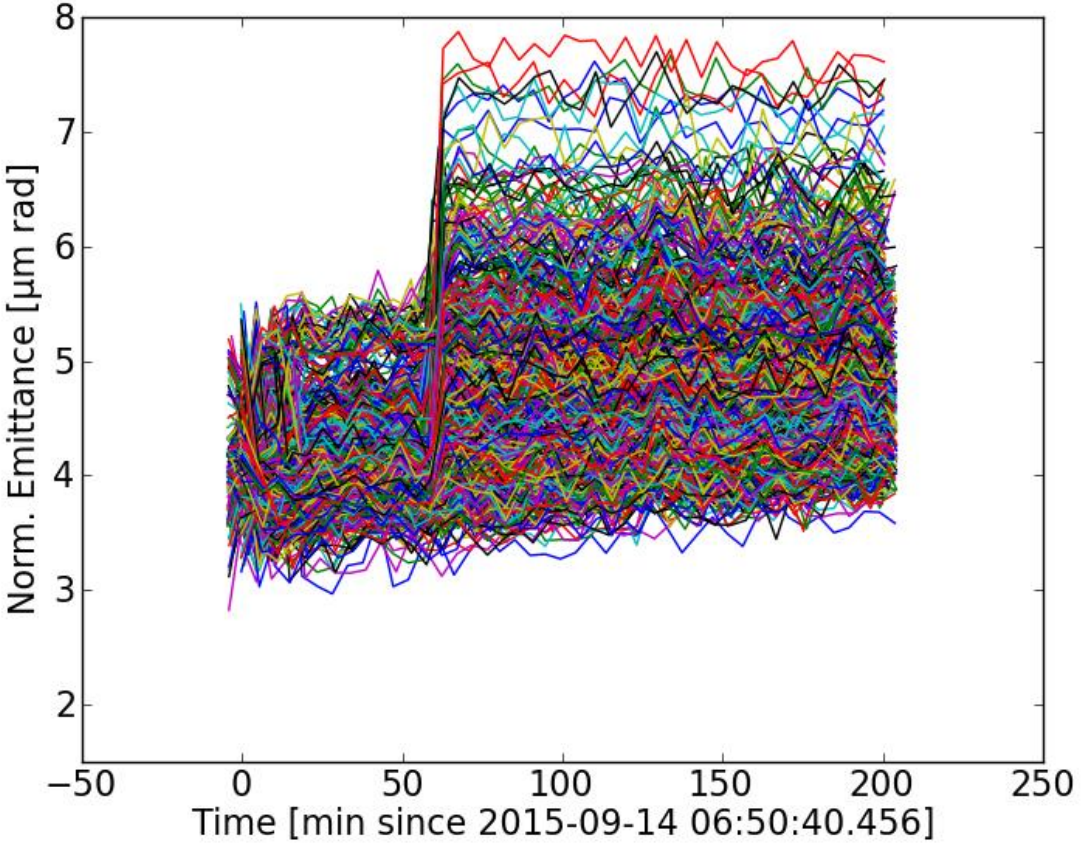


Beam 2 sees BB parameter 0.004 → sees the strong non-linear force of Beam 1 and sees Beam 1 oscillating → Modulated non-linearity scraping away particles since it is already large (emittance reduced) and large losses

Separated beams: instability



Horizontal Plane



Instability develops when beams are separated by 2 σ

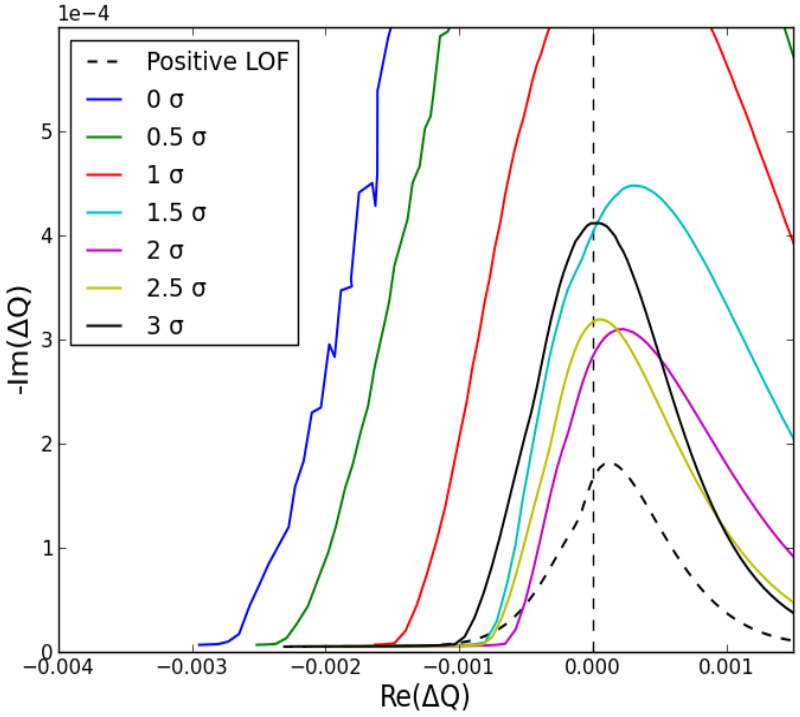
Emittance blow-up of selective bunches

Only on Horizontal plane

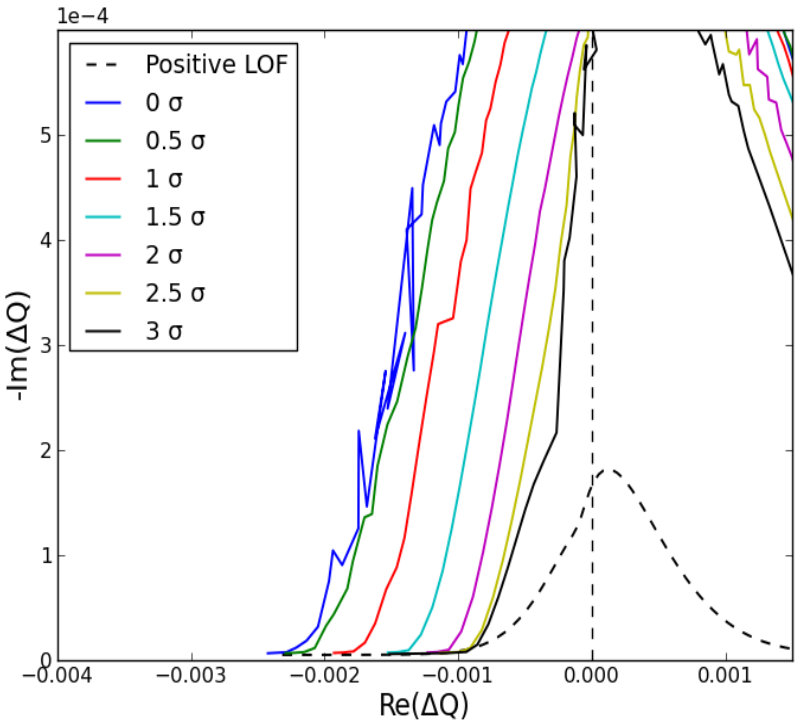
Weaker ADT gain found

Separated beams: instability why at 2 σ ?

Horizontal Plane



Vertical Plane



At 2 σ separation we have minimum of stability even if the other IP is colliding head-on
2 Head-on collisions are needed to guarantee strong stability, at 2 s separation
How are we confident in our understanding of Landau damping?

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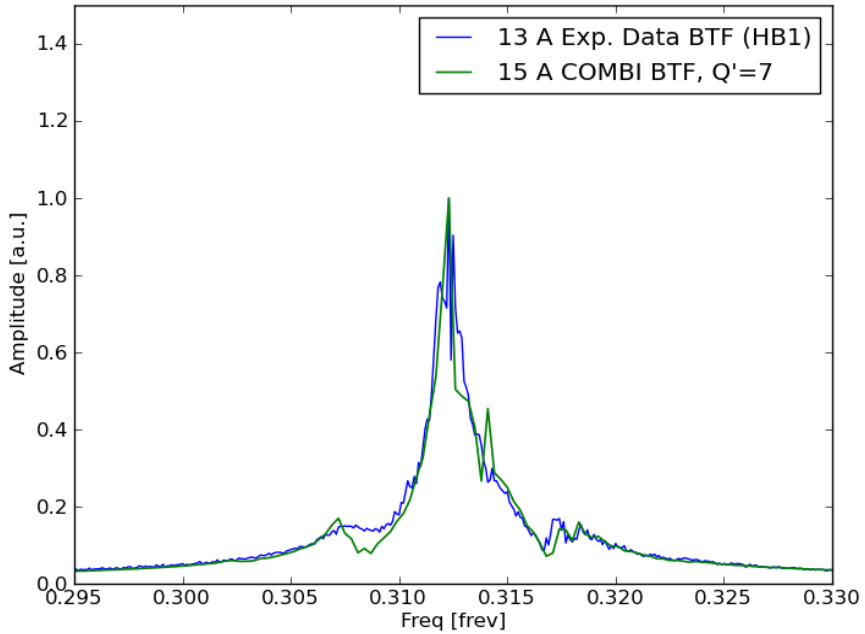
Beam Transfer Function → Stability Diagram

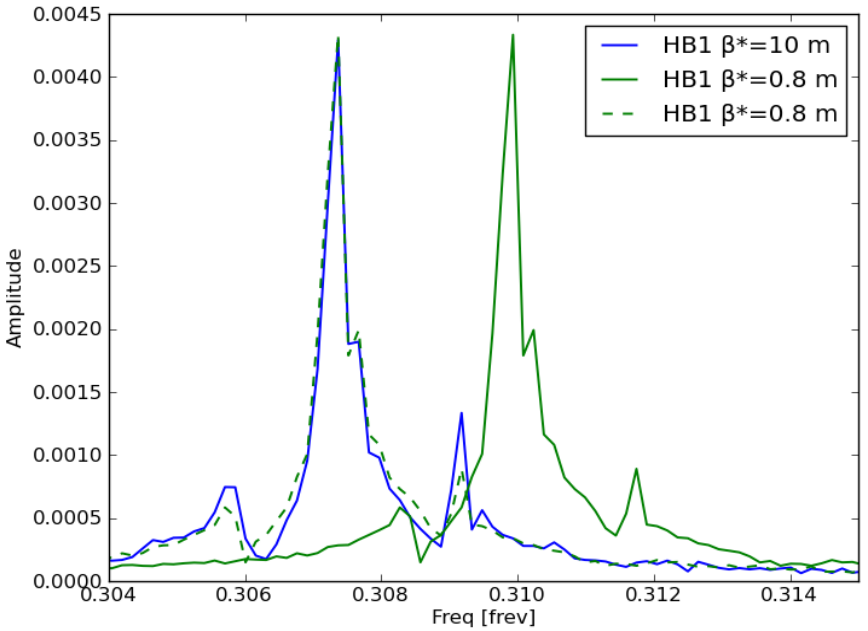
Tune spread and Particle distribution variations

Dispersion Integral

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



Octupole Effects and Chromaticity



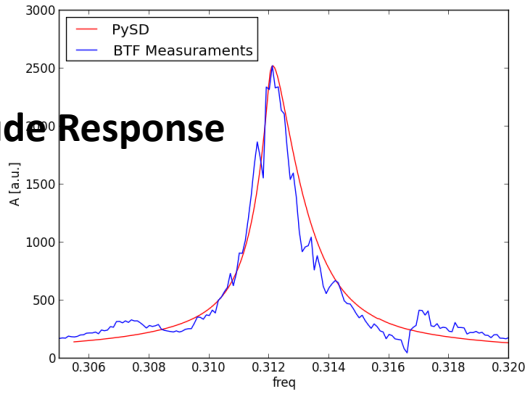
Long Range effects at end of squeeze (14 σ)
NO effect!

Thanks to A. Boccardi, M. Gasior, T. Lefevre, T. Levens, G. Kotzian, W. Hofle

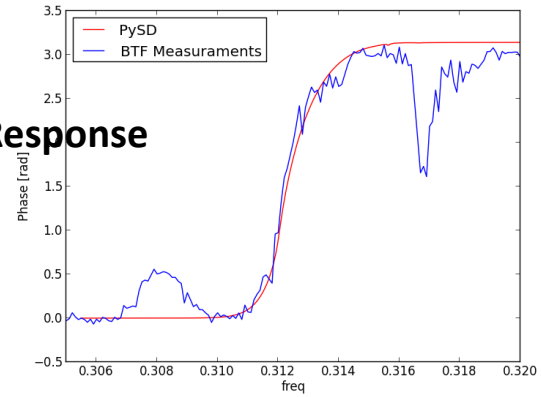
First attempt to reproduce Stability Diagram

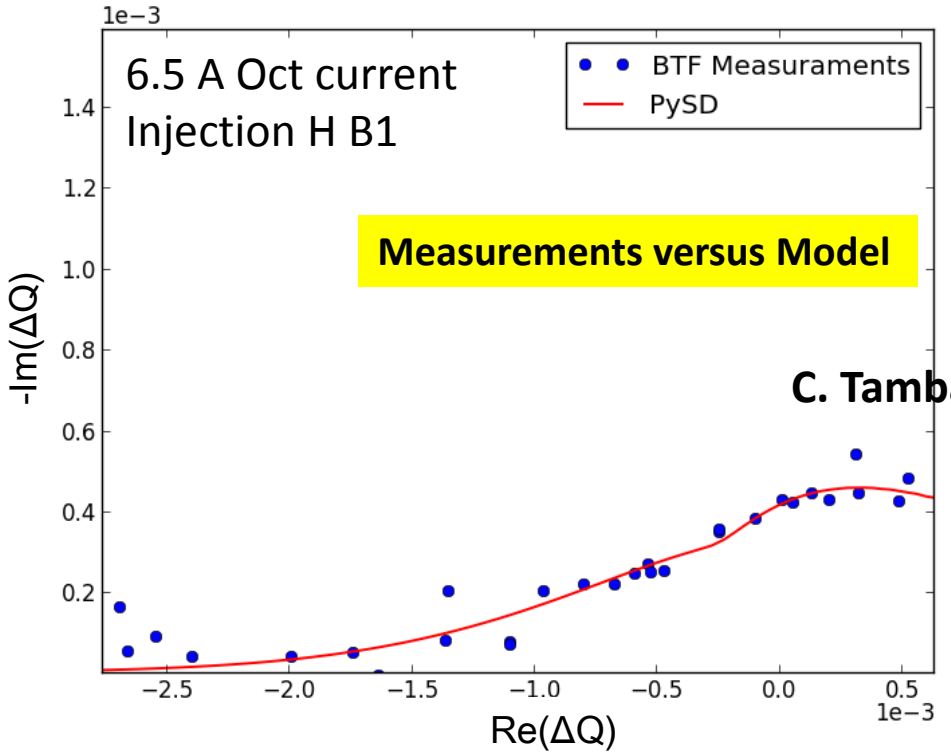
- Very challenging already in simple cases, but powerful tool→ octupole, chroma scans
- Spread from octupoles and Chromaticity effects still under study
- Transparent to beams!
- **Still need a lot of work to understand (kick amplitude, resolution)**
  → tools in place but need more data in 2016 !

Amplitude Response

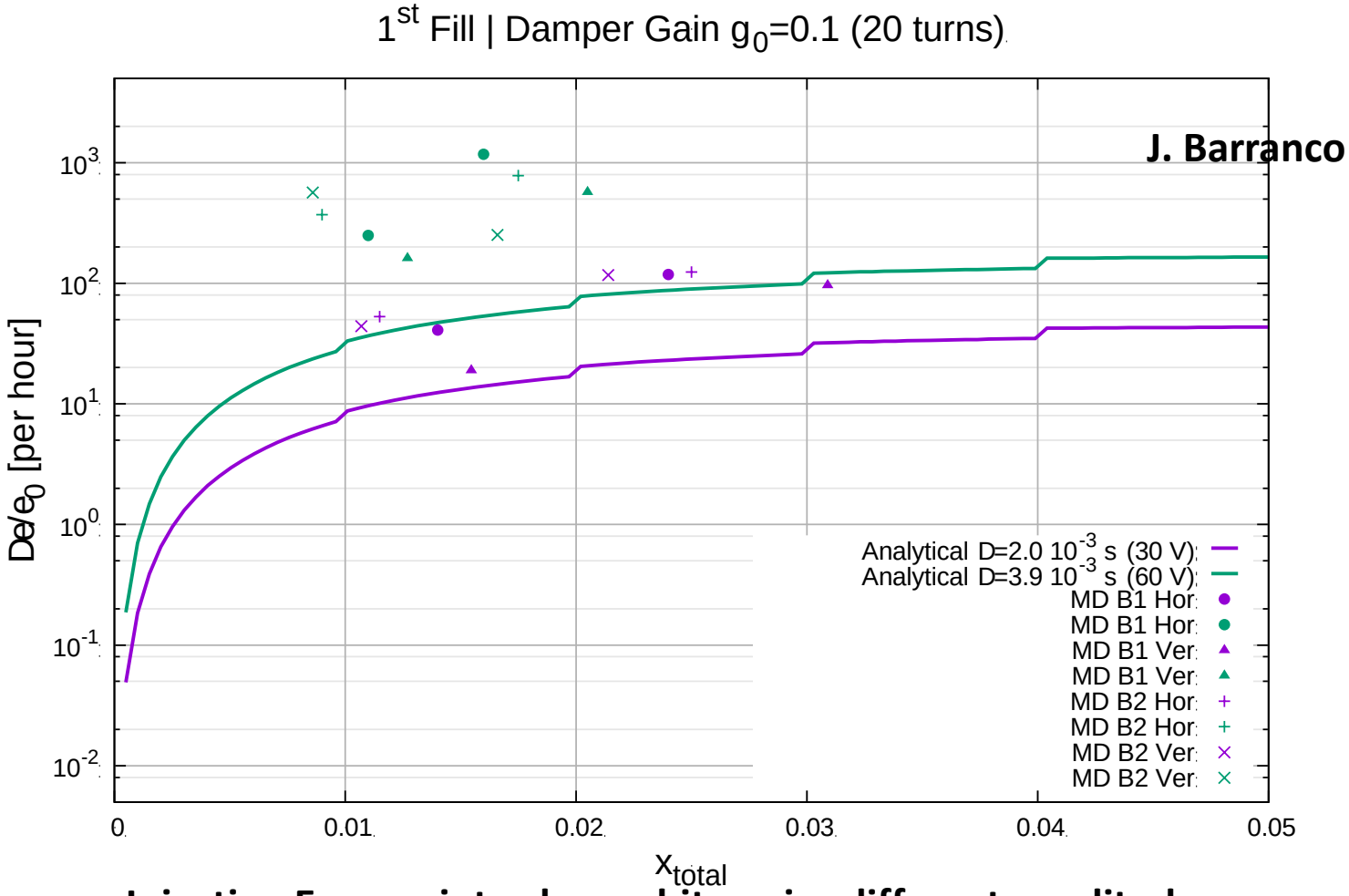


Phase Response





Noise on colliding beams at injection



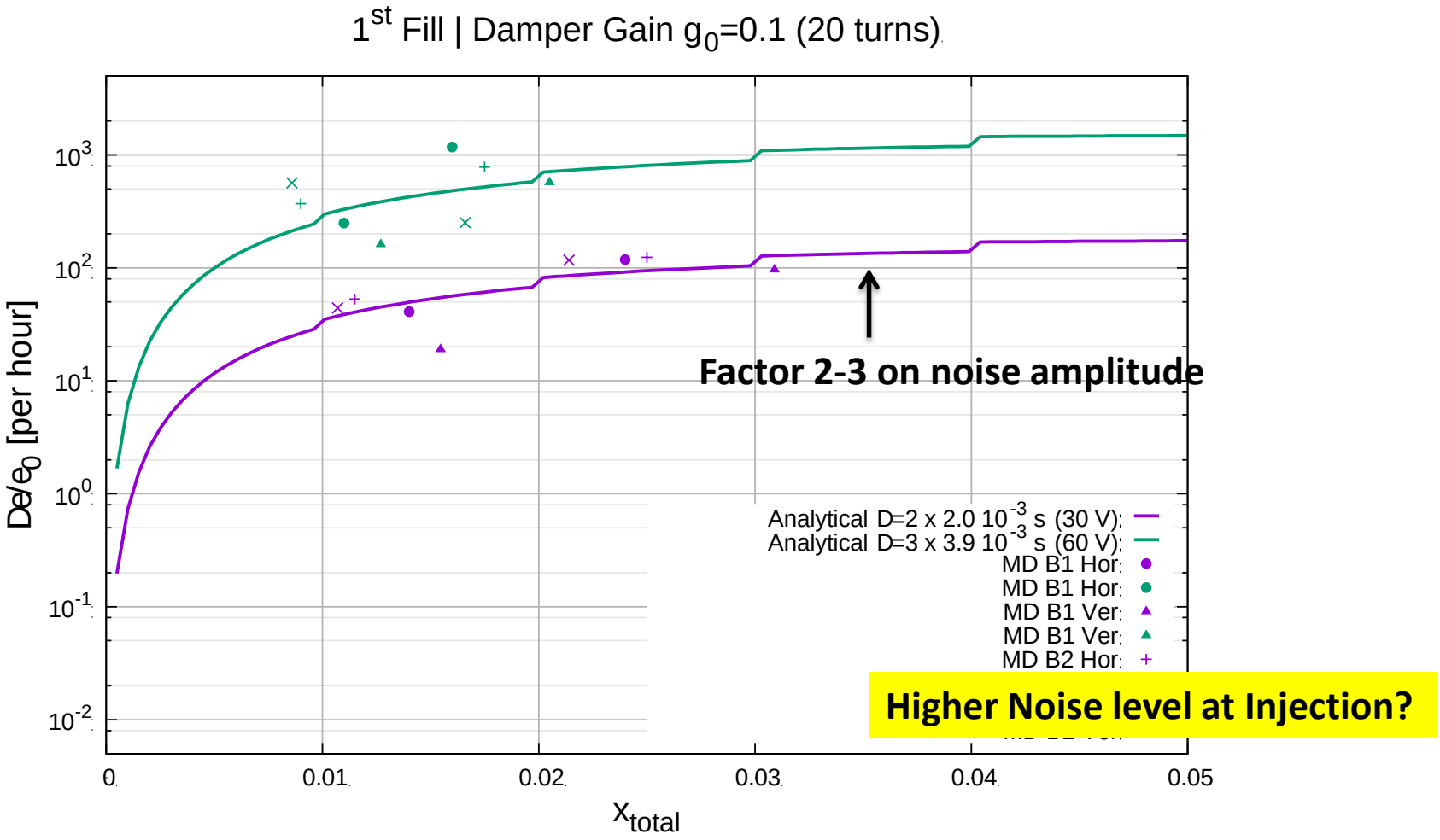
Injection Energy: introduce white noise different amplitudes

Single bunches with different BB parameter in collision

Different white noise amplitude used

Thanks to D. Valuch

Noise on colliding beams at injection



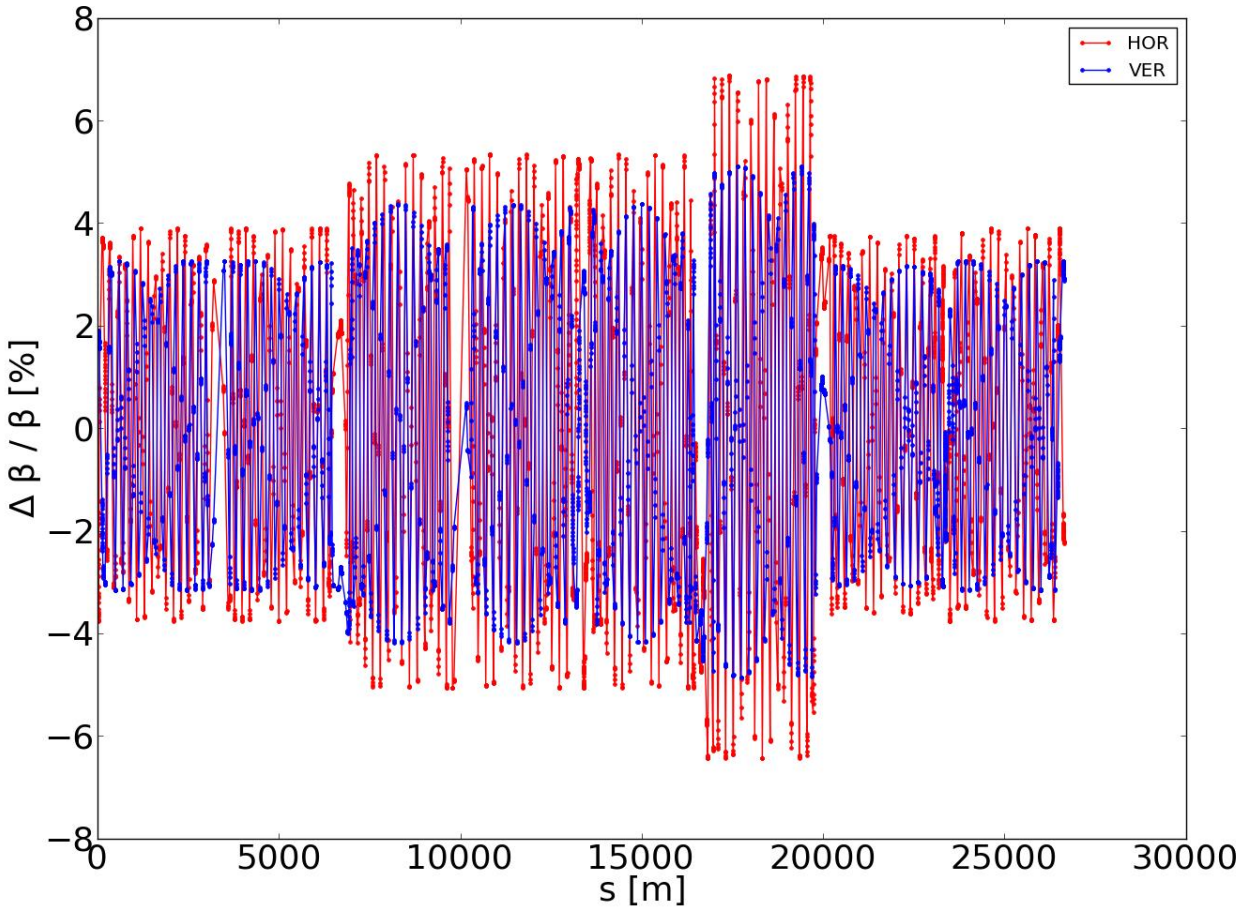
Missing ingredients in the model, beam-beam dependency consistent with expectations!

Very reproducible 3 case MD1!

To be understood to estimate HO limits → Is this the same at 6.5 TeV?

Growth present on non-colliding bunches …

Beta beating from Beam-beam HO



The beam-beam head-on collisions IP1&5 provokes a beating around the accelerator of maximum 7 % 2015 case (very important for larger beam-beam parameters HLLHC 20%)

Very different for core and tail particles… needs further studies.

Summary

- **2012 luminosity lifetime was strongly affected by beam-beam effects** (together with Oct and Q') → **DA was very close to 4 σ limit** were losses increase and lifetime reductions are observed

- 2015 strategy was to allow for High Chroma and Octupole operation
  - **IP1&5 DA BB+Oct+Q' around 6 σ** (high brightness and nominal beams 290 μrad)
  - **IP2& IP8 in the shadow** of IP1&5 → larger beam-beam separations (shift-spread 10^{-4})
  - **Identify Limit and Quantify the impact** of crossing angle on beam and lumi lifetimes

  →**Limit @ 4 σ Dynamical Aperture** → 8.4 s separation→ **2.6 σ margins**

- 2016 apply same strategy (**50 and 40 cm optics are very similar**)
  - 10 σ **beam-beam separation** (**330-370 mrad**) gives **DA above 6σ** (**40cm slightly smaller head-on improves**)
  - **IP8** will stay identical as 2015 RUN (**500 μrad external crossing in collisions**)
  - **IP2 will need 400 μrad external xing angle in stable beams** to allow for spectrometer polarity change (At Injection copy and paste of IP8 with proper xing V plane)
  - **If Octupoles and Chromaticity reduced in stable beams → still room for reduction after quantifying impact on lifetimes and losses**
  - **Could non-colliding bunches have reduced intensities?**

Summary

- **Colliding beams are rock stable**
  - **Weak-strong configuration** leaves strong beam without Landau damping from head-on collisions, colliding companions of unstable bunches will still be sensitive in stable beams
  - **Separated beams at 2 σ** we will have **minimum of stability** → possible ADT gainreduction, reduced Octupoles and Chroma might lead to instability (beams should be separated with care!)

- **Beam Transfer Function Measurements with BB: powerful tool** :
  - Promising first results of amplitude response (Octupole and Q' scans)
  - Quantify long range effects (Stability diagrams, resonance excitation etc).

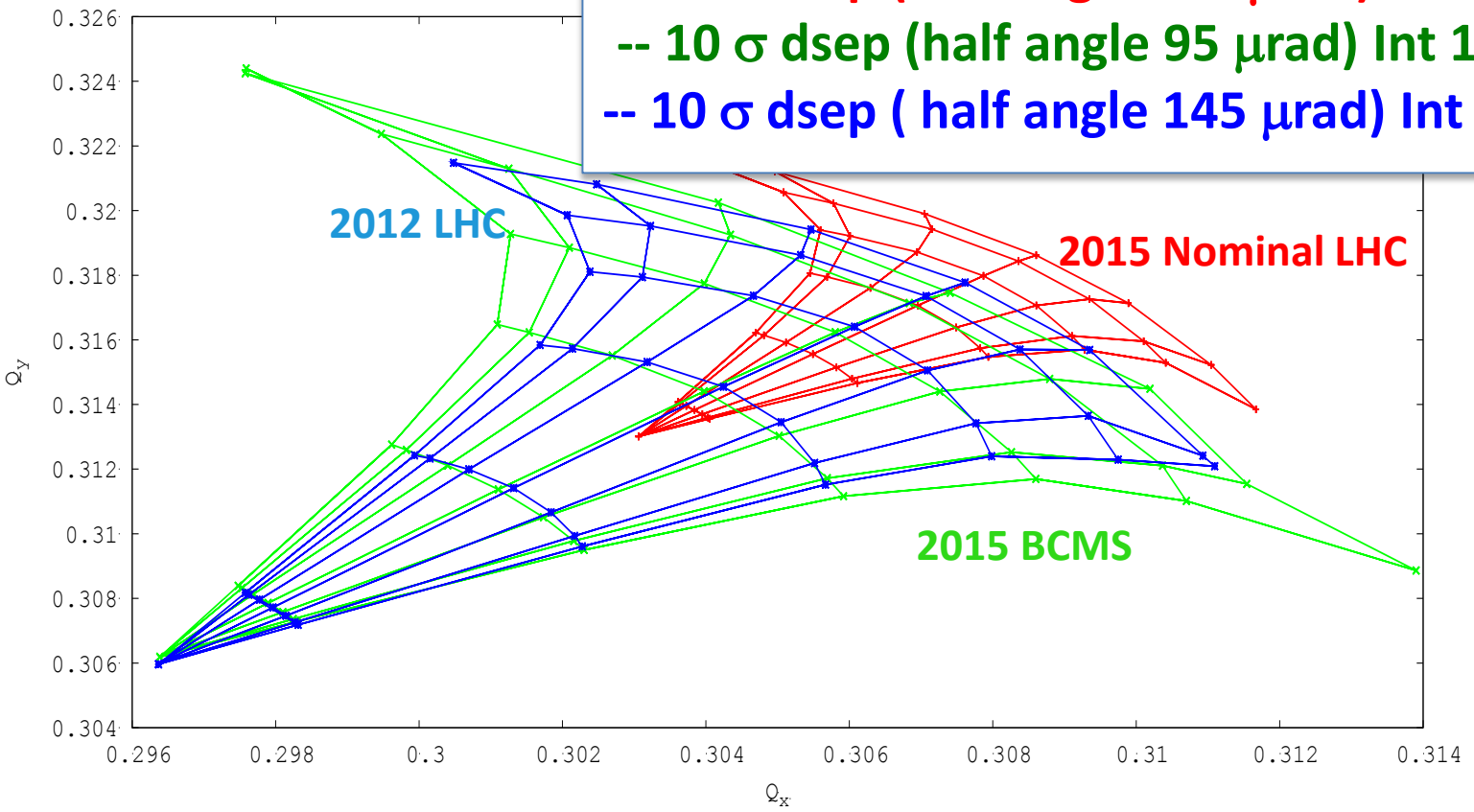
  Need more systematic data in 2016 to explore the sensitivity to particle distribution variations and to understand possible use of this device.

- **Noise on colliding beams** had highlighted important missing ingredient at injection energy → needs to verify at top energy to identify head-on limit!

- **Beta beating from beam-beam** is not negligible in stable beams 7%
  - pushing the beam brightness will make it stronger→ need to measure
  - On-going studies to understand the implications and the possible correction

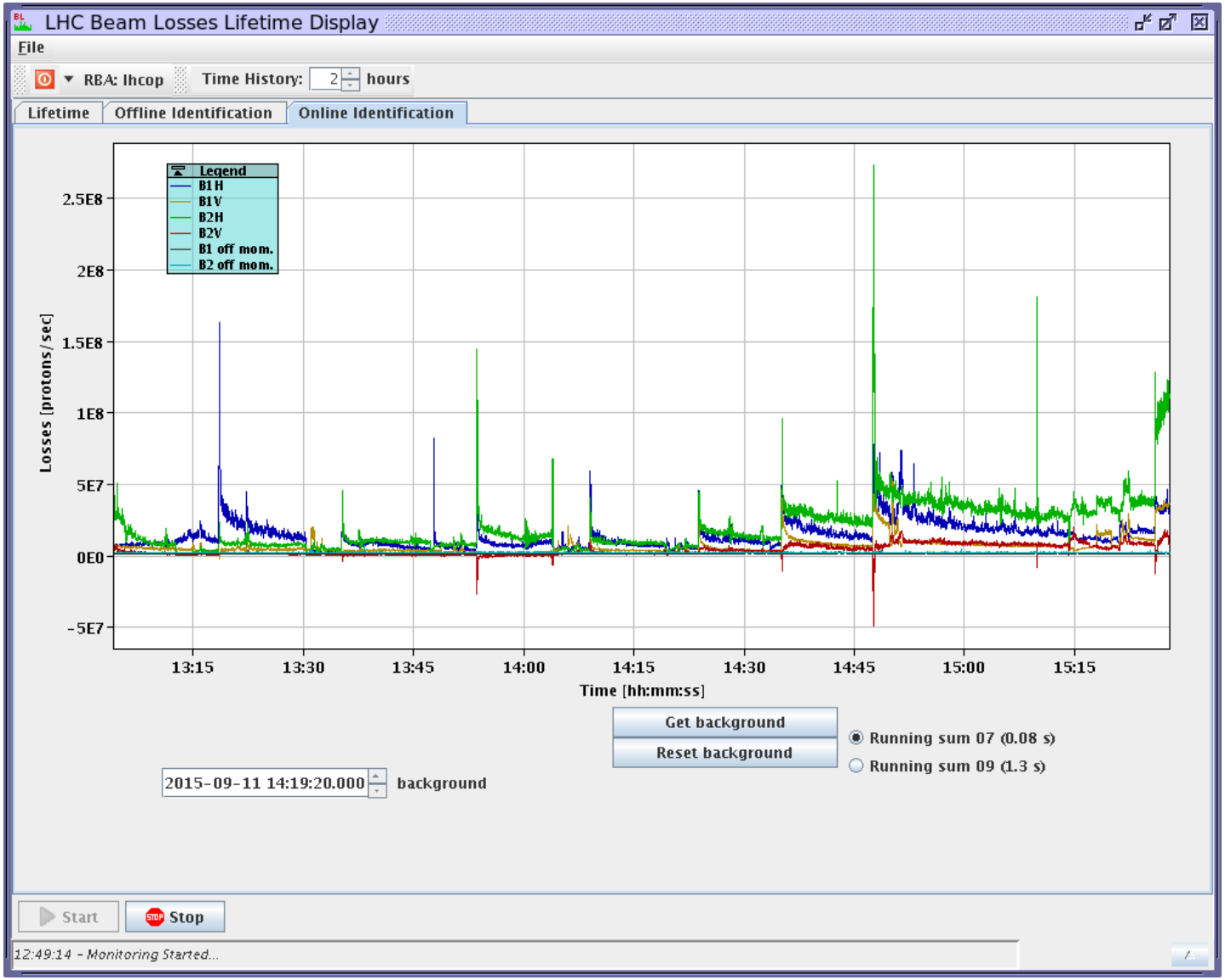
Footprints for 2012 run and 2015 Beams:

Intensities 1.3 e11

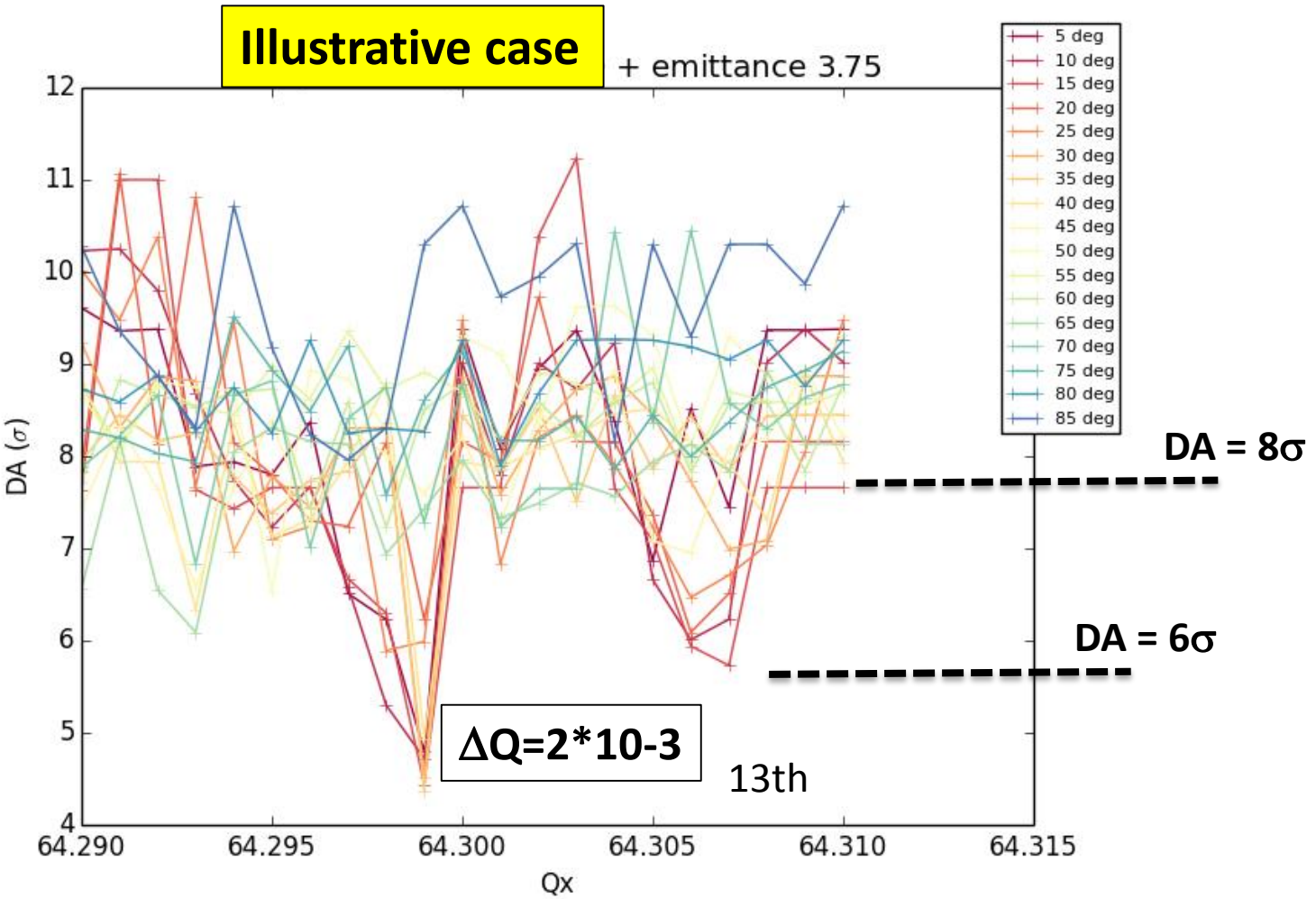


- **BB parameter half of 2012!**
- **Long Range Separation requires changes (10 to 15 σ) depending on the head-on to have similar configurations!**
- **Xing angle for LHC standard valid for BCMS beams**

Losses follows

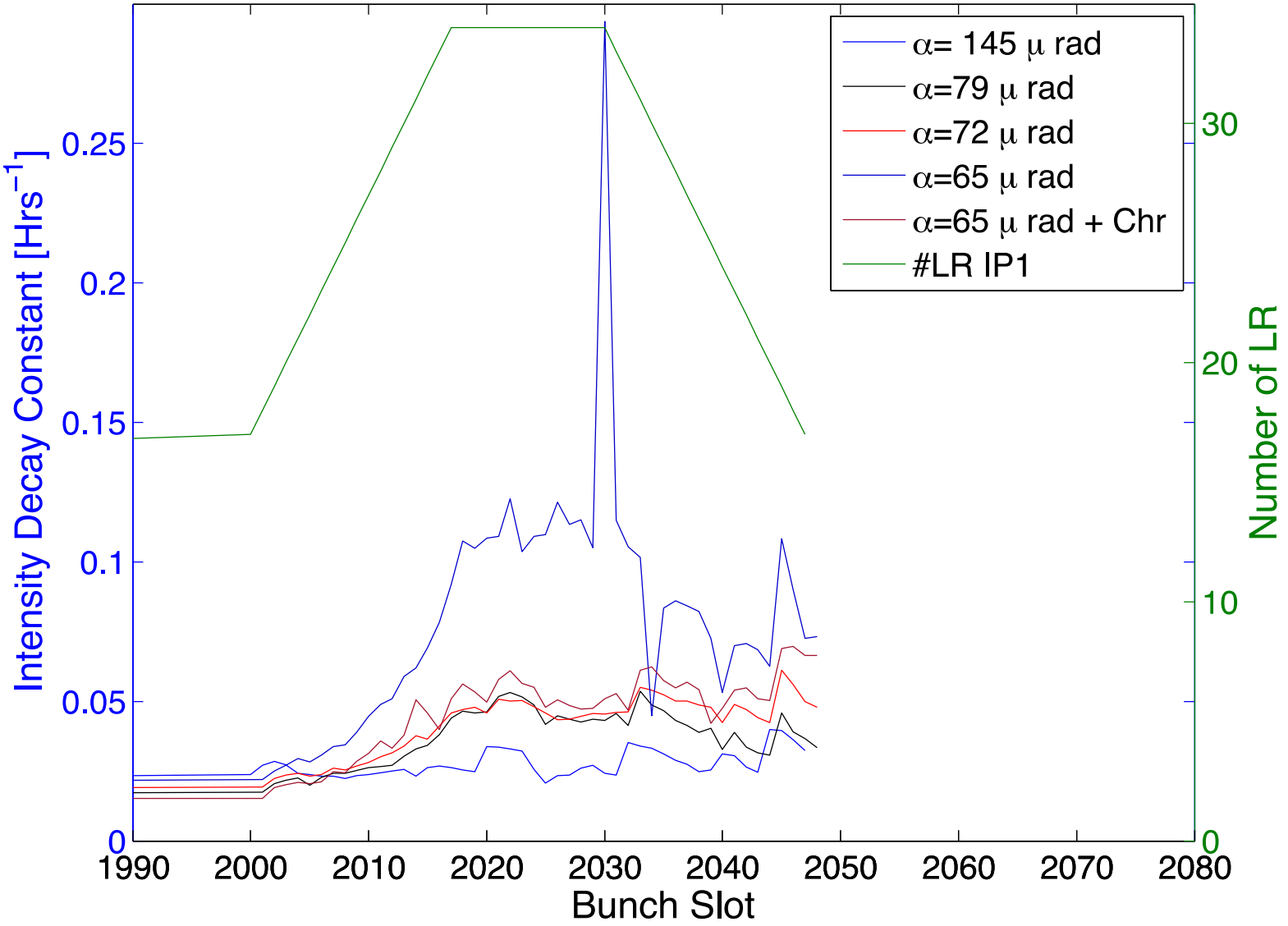


BB dynamics very sensitive to working point



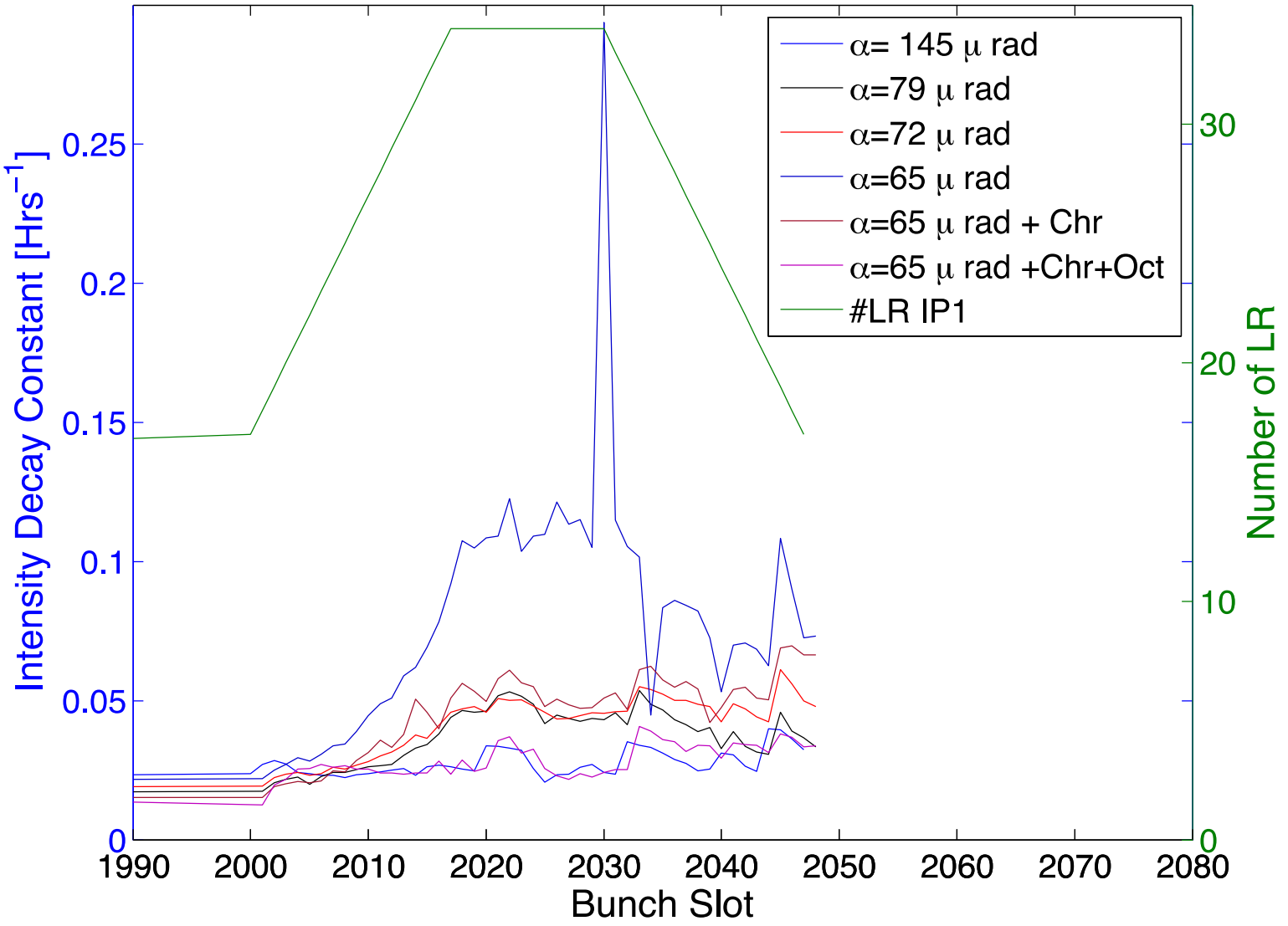
DA can easily drop by 2-3 σ for tune shift of 2*10-3 13th order resonance → Keep IP2 and IP8 tune shift smaller than 10^{-4}

Beam 1 Intensity decay versus bunch



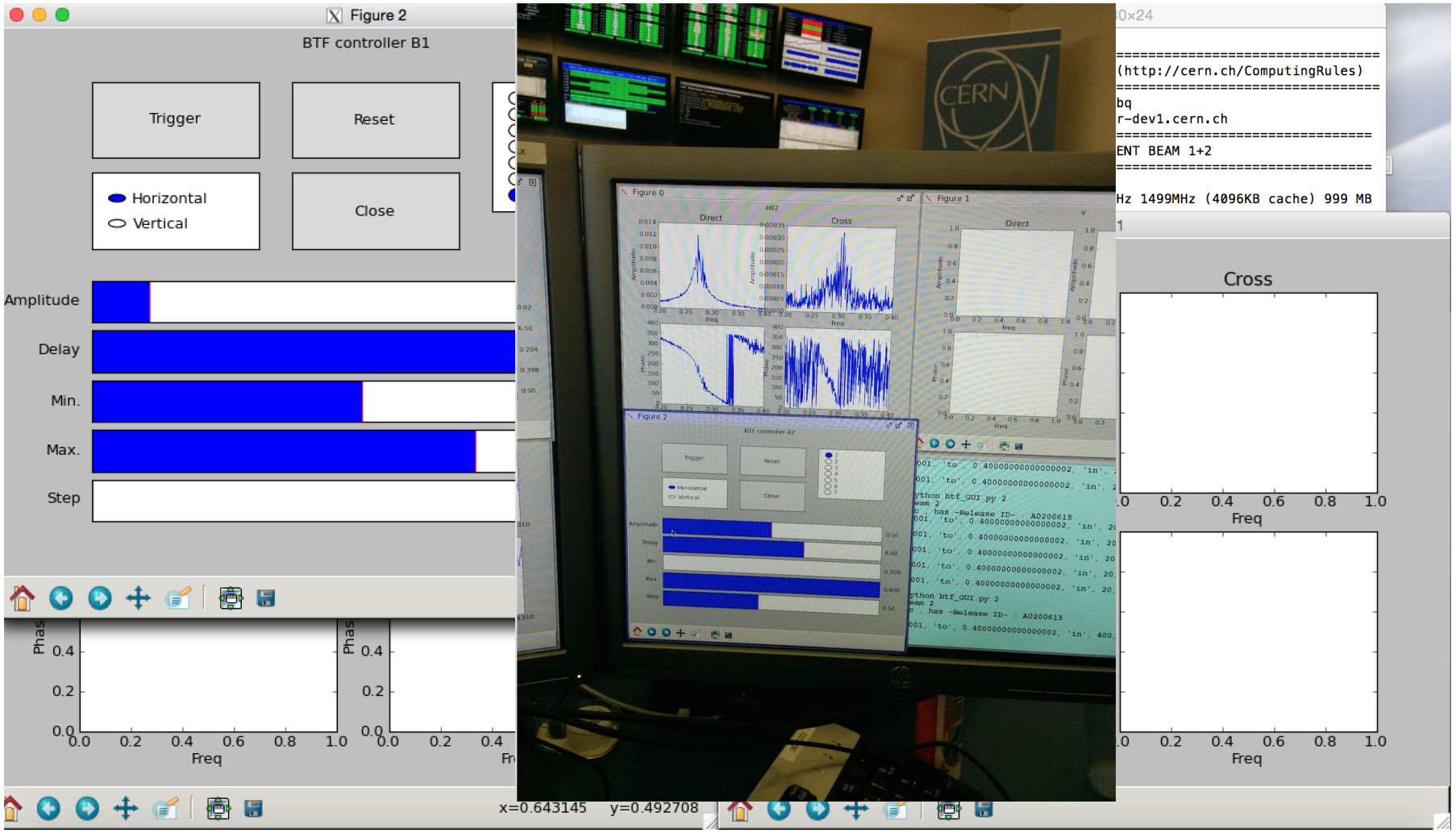
Reducing the crossing angle Beam lifetimes are reduced from 30→8-5 hours
Reducing Chromaticity

Beam 1 Intensity decay versus bunch

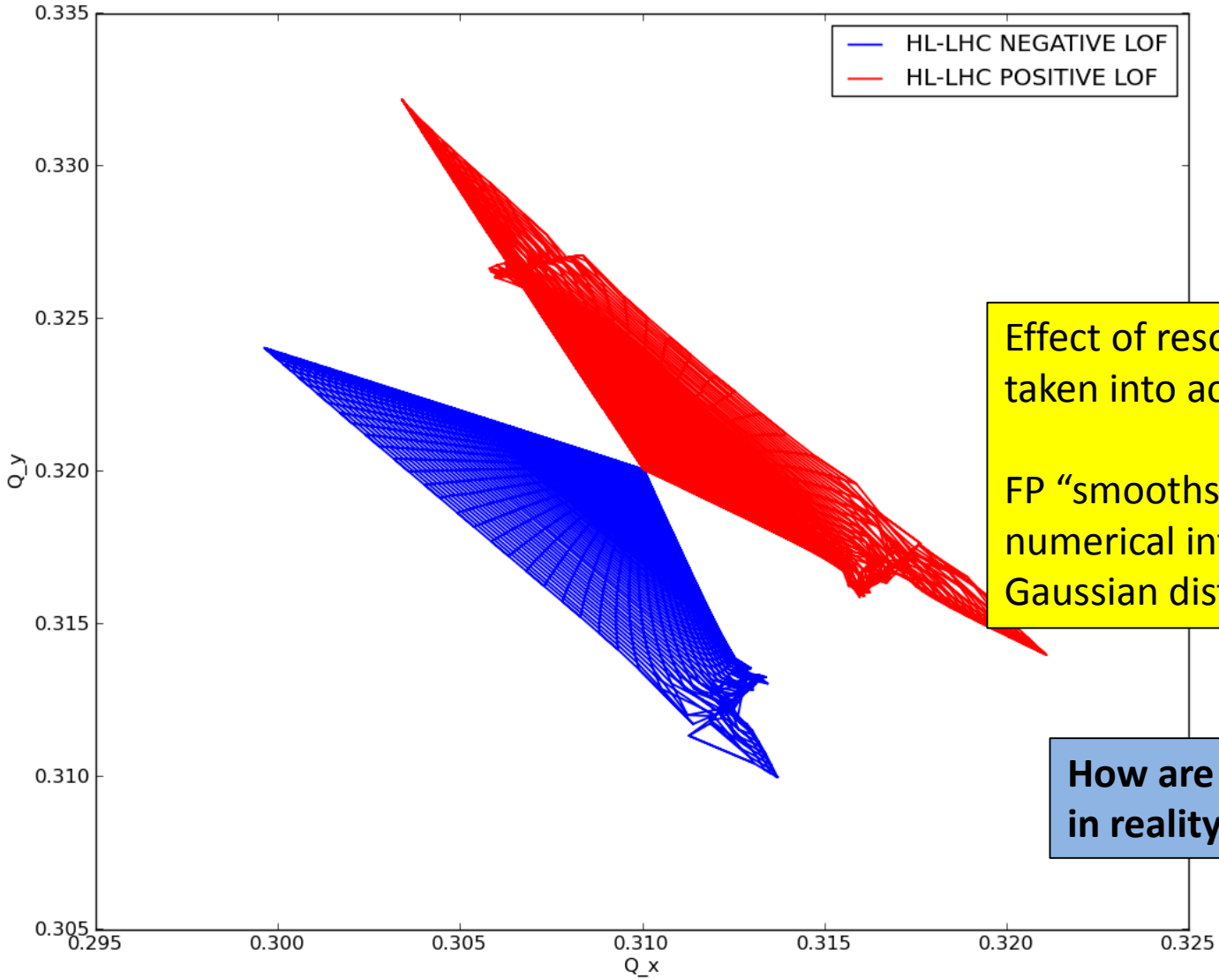


Reducing Q' 15→ 2 units and Landau Octupoles from 476 → 0 A
Lifetimes improves going back to 30 hours

BTF GUI in the CCC: simple and expert based… not yet operational!



Modified distribution: Non-Linear Resonances

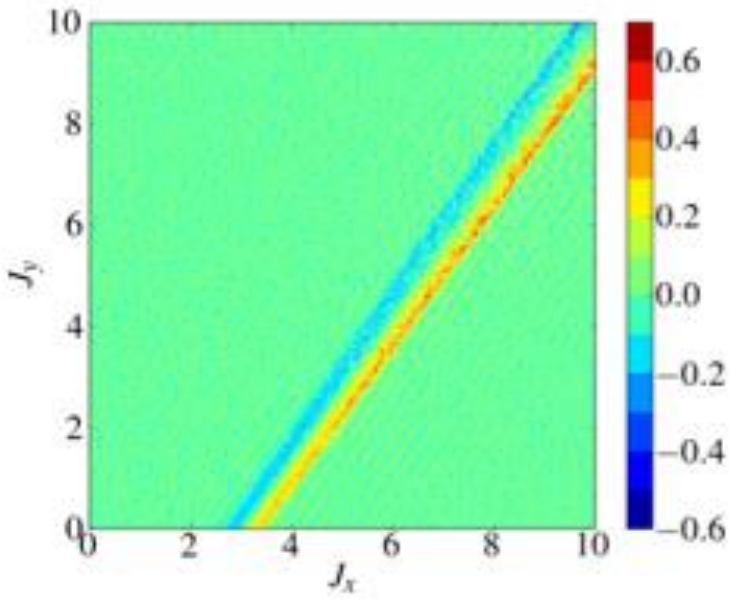


Effect of resonances are not fully taken into account

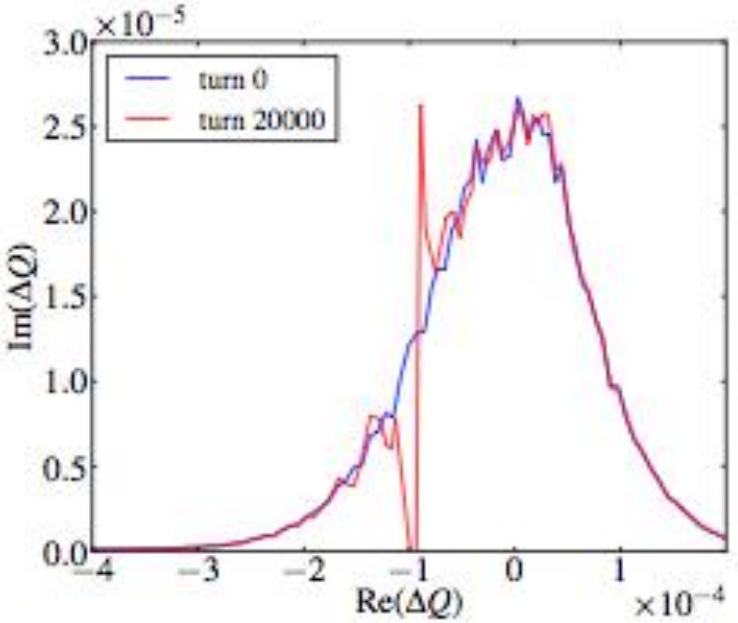
FP “smooths” the resonances and numerical integration assumes Gaussian distributions

How are particles distributed in reality along resonances?

What happens to SD (BTF) if particle distribution modified?



(a) Relative deviation from the initial distribution in action space

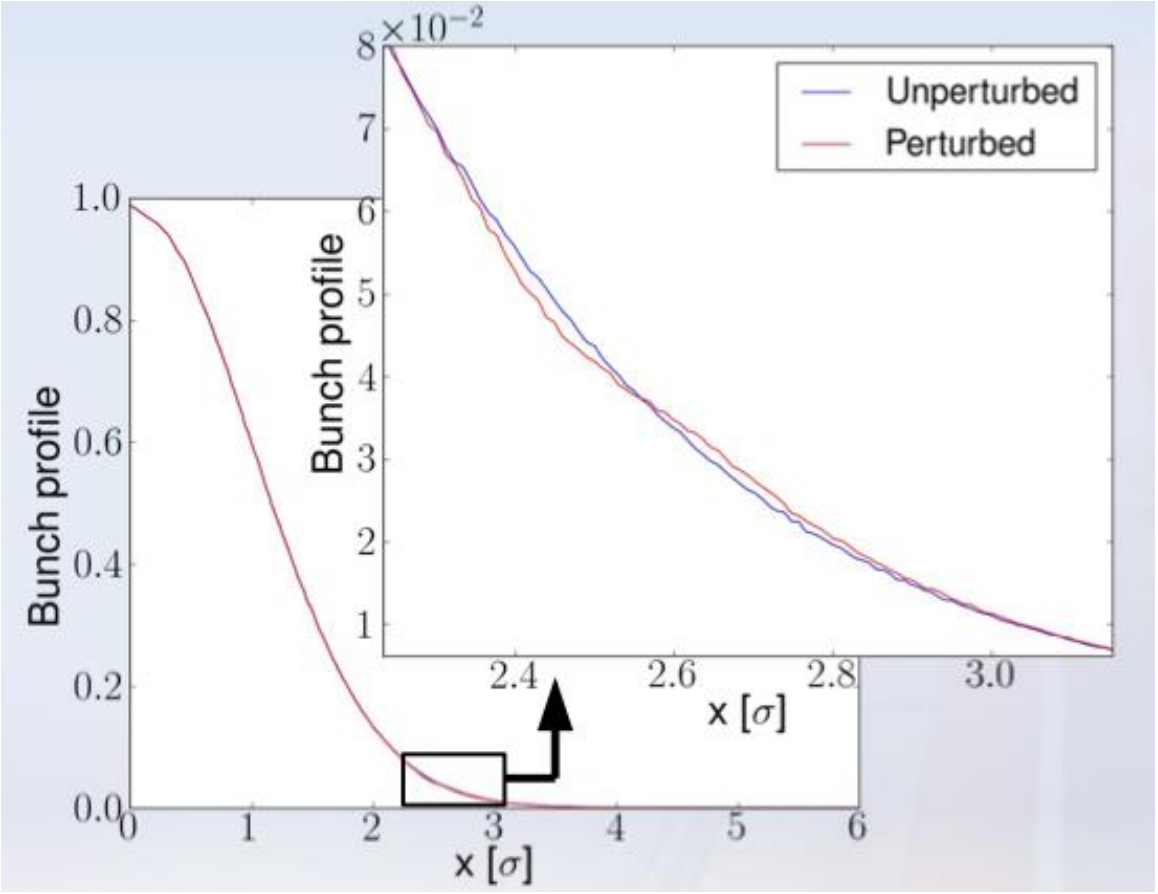


(b) Stability diagram before (blue) and after (red) the distortion of the distribution.

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

- Colored Noise source → Diffusion of resonant particles
- Modification of particle density in action space with time
- **Strong effect on stability diagram at edge of variation (derivative of distribution)**

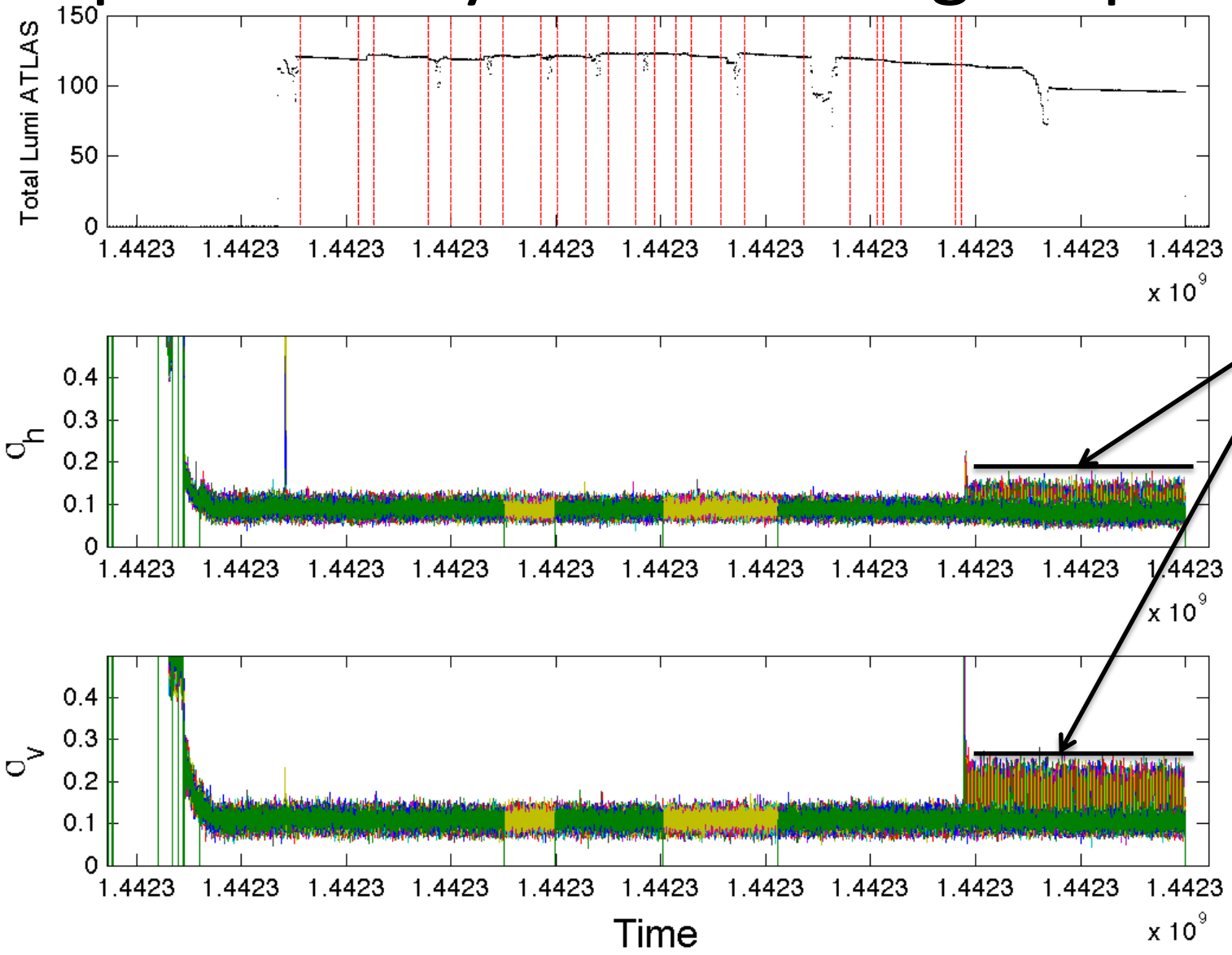
Modified distribution: Colored Noise



- Effect on particle distribution very small (% level)
- Profile measurement dominated by core of beam

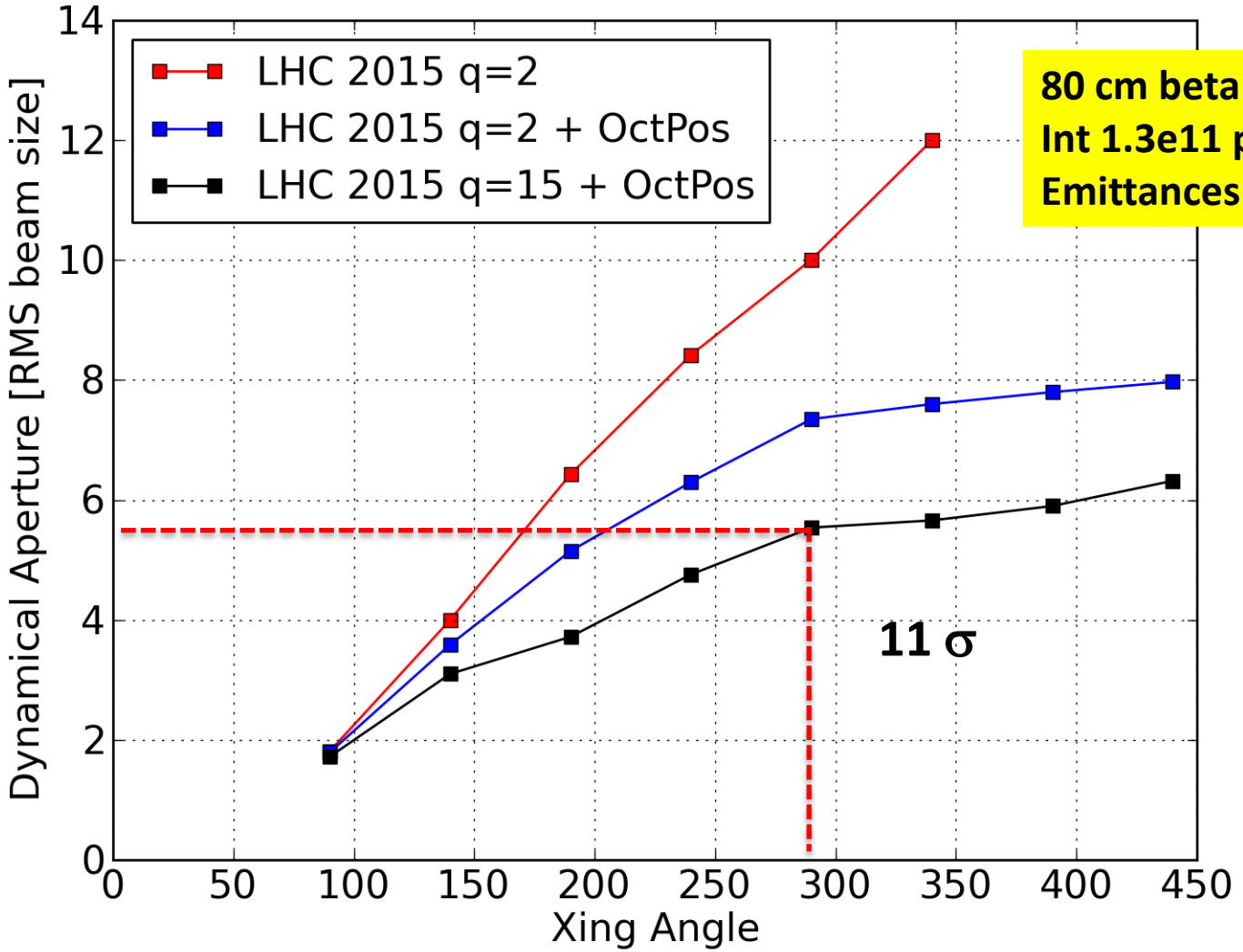
→ **Impossible to measure the effect with profile measurement!**

Preliminary emittance plots (only qualitatively correct of sigma planes)



Emittance growth is outside of the angles of interest

2016 Xing angles IP1&5



2015 Set-up