Beam-Beam Effects in the LHC

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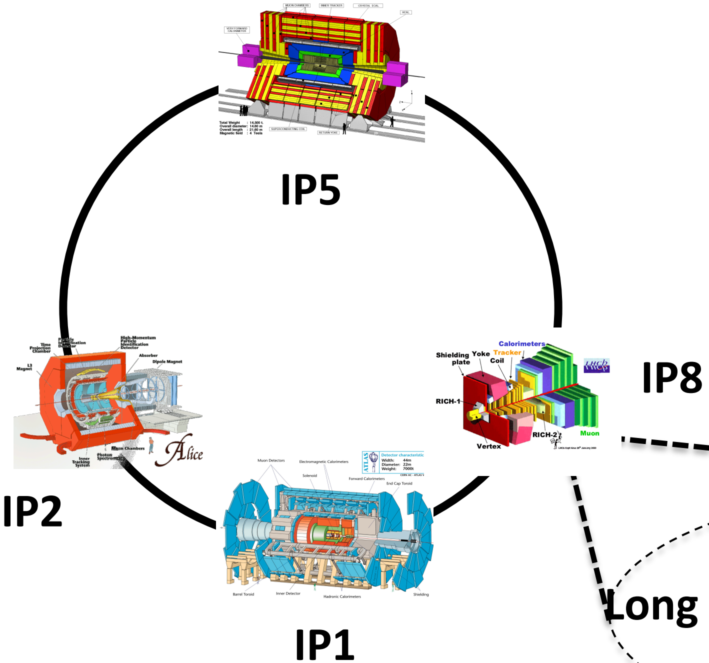
HB Workshop, Malmo 2016

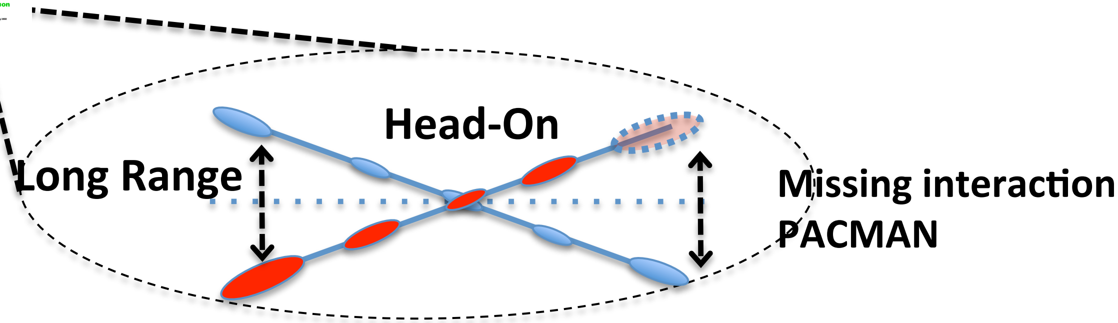
Outline

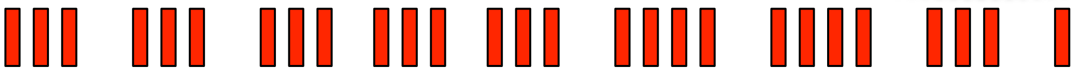
- Beam-Beam Effects past and present LHC
- Long Range experiments
- Instabilities in collision
- Head-on limitations
- Conclusions

LHC

- **Crossing angle operation**
- **High number of bunches in train structures**



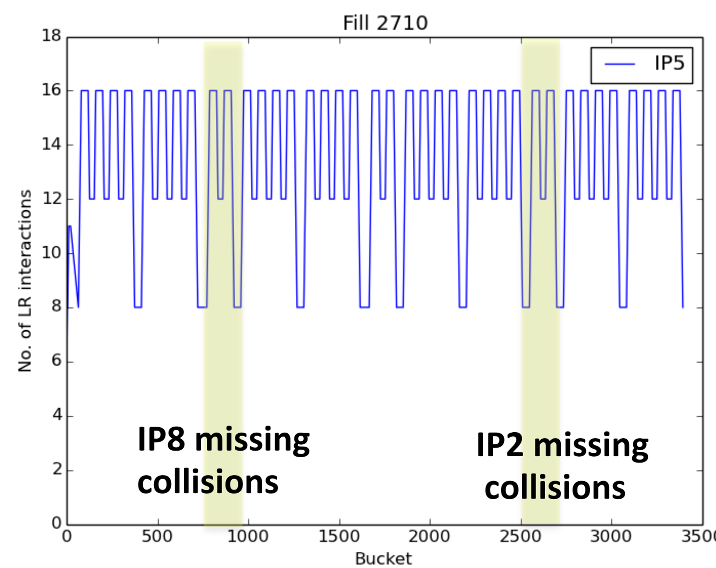




48-72-144 bunch trains

||||||||||| ....

- Many collisions (120 per turn for 25 ns spacing)
- Different type (HO and LR)
- Different separations and leveling…
- Complicate system

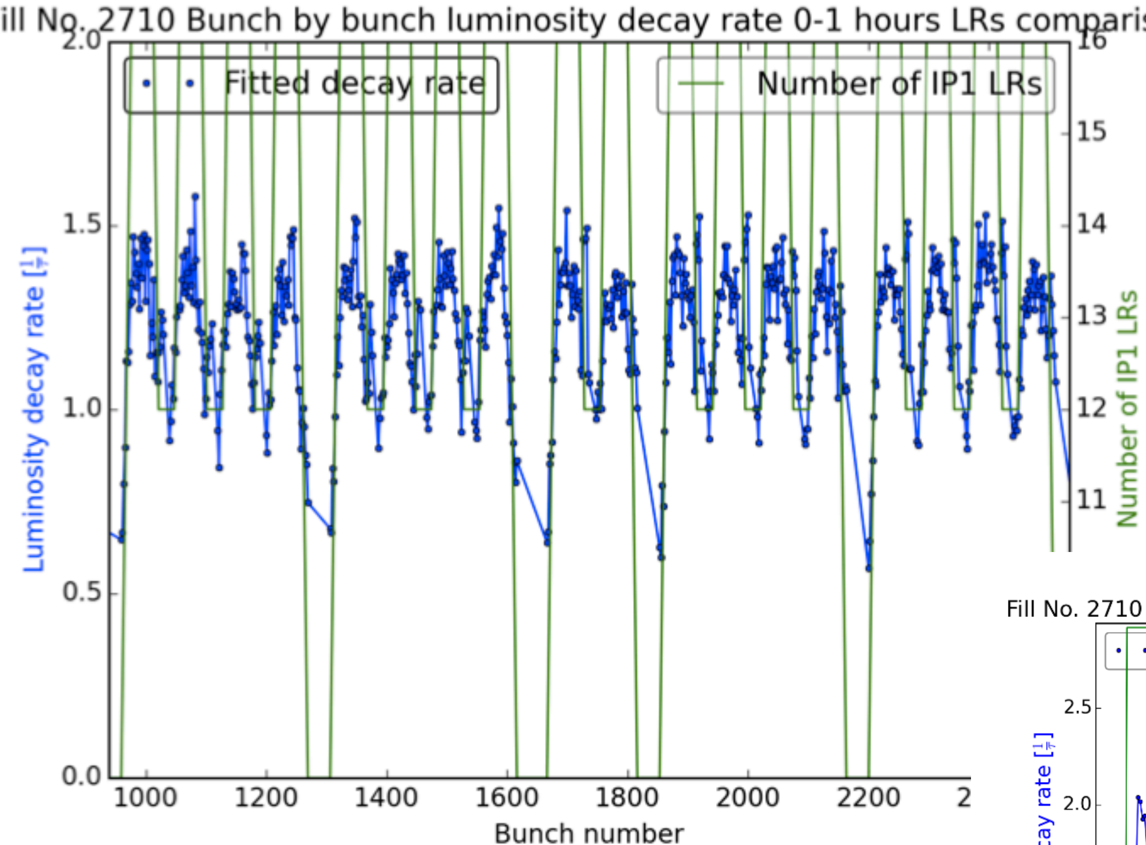


LHC parameters over the last 3 years

	2012	2015	2016
Intensities protons per bunch	1.6-1.7 10^{11}	1.2 10^{11}	1.2 10^{11}
Normalized Emittances	2.5 μm	3.5 μm	3.5 μm
ξ_{bb}	**0.007/IP**	**0.0035/IP**	**0.003/IP**
Bunch spacing/ maximum # LR	50 ns / 60	25 ns / 120	25 ns / 120
IP1/IP5 LR sep	9.5 σ	11.5 σ	**10.5 σ**
IP2 LR sep	> 12 σ	**> 26 σ**	**> 26 σ**
IP8 LR sep	> 10 σ	**> 26 σ**	**> 26 σ**
Energy	4 TeV	6.5 TeV	6.5 TeV
Peak Luminosity	6.6 10^{33}	0.7 10^{34}	1.1 10^{34}
Octupole magnets	550 A	470 A	470 A
Chromaticity	20 units	15 units	22 units

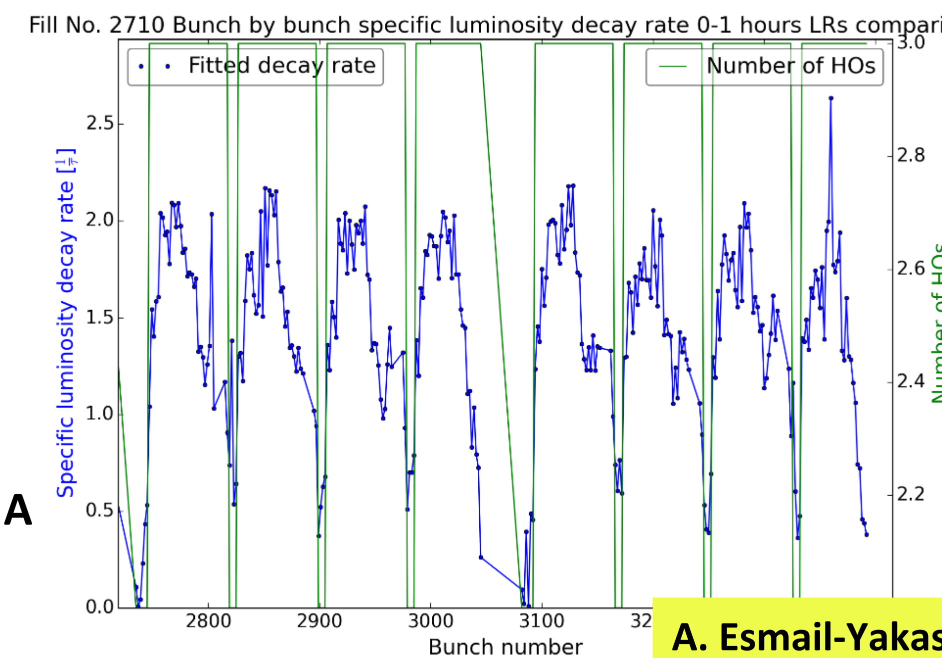
Some Beam-Beam Observations RUN I

Regular Physics Fill of 2012 LHC RUN



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

Losses and emittance blow-up during first 2 hours of collisions had clear beam-beam pattern!



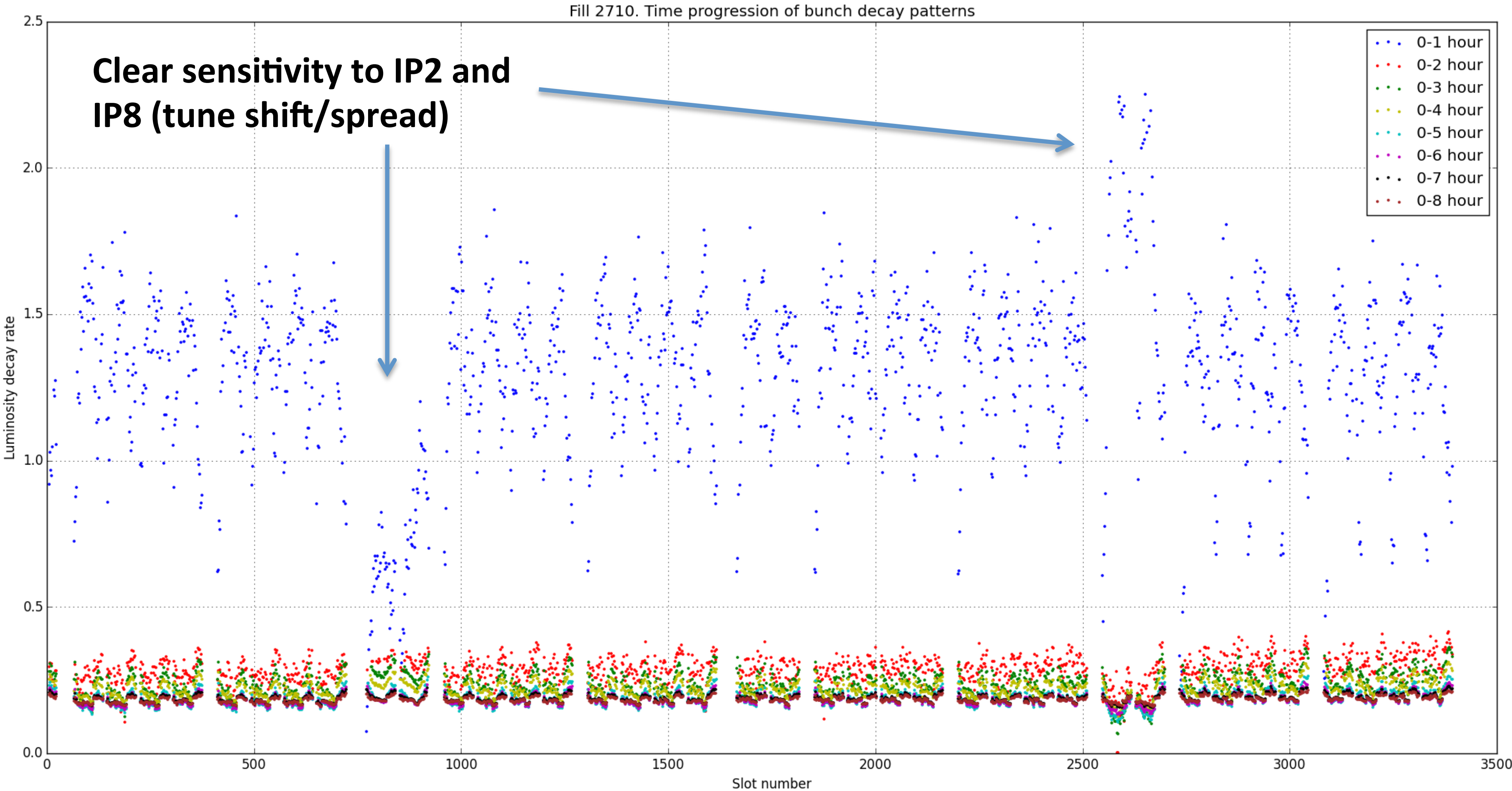
2012 Beam-Beam parameter of 0.007/IP

- **2 HO 0.015 total**
- **IP2 and IP8 with relevant long ranges**
- **Landau Octupoles at maximum current…550 A**
- **Chromaticity above 20 units….**

A. Esmail-Yakas

Some Beam-Beam Observations RUN I

Regular Physics Fill of 2012 RUN LHC

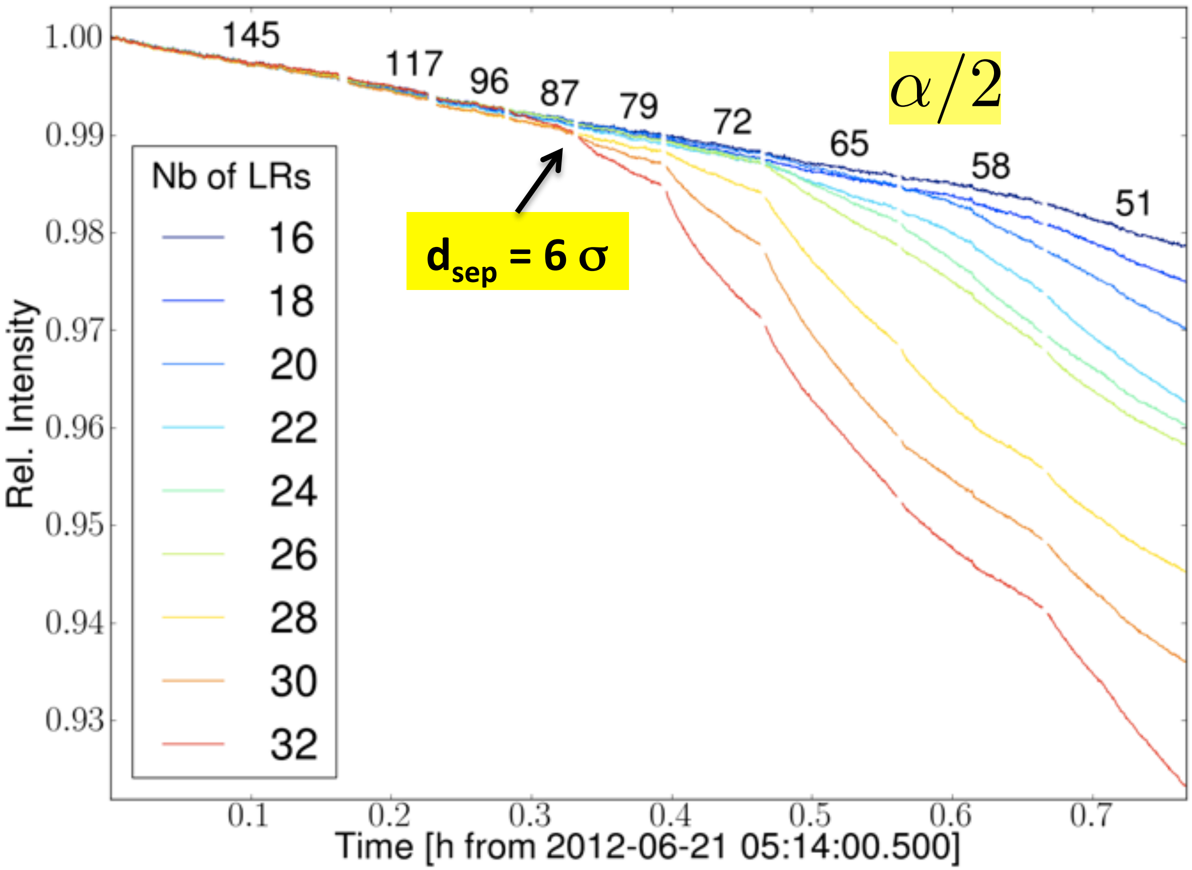


Beam-Beam pattern visible in first 2 Hours of physics fills

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

Long Range Experiments

Bunch losses for different families of Long-Range encounters



Beam-Beam separation at first LR

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

Small crossing angle = small separation

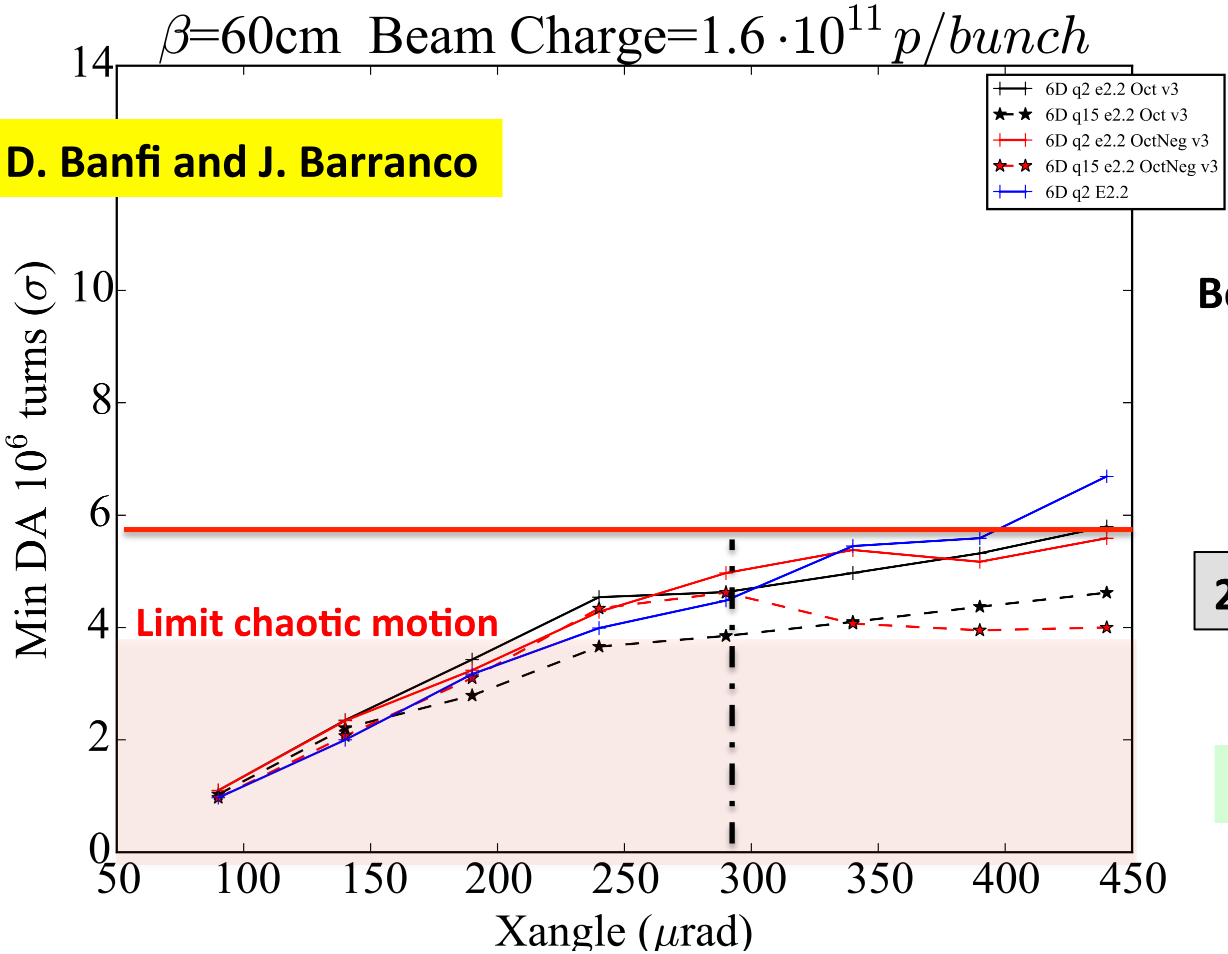
At small separations particles motion becomes chaotic and particles are lost.
The loss rate depends on number of long range encounters

The on-set of losses has been empirically related to the reach of 4 σ dynamic aperture

Dynamic Aperture RUN I

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

D. Banfi and J. Barranco



Beam-Beam separation at first LR

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

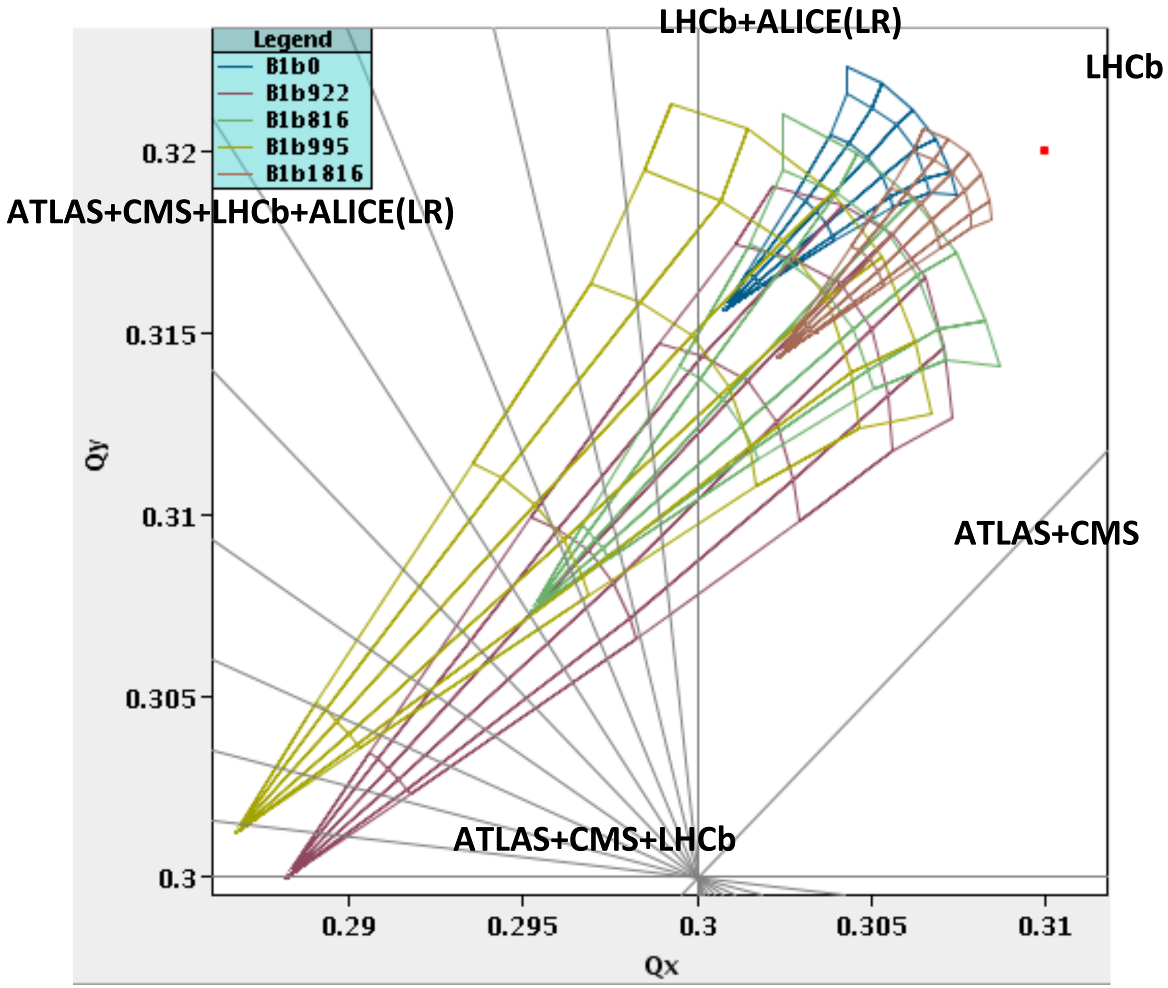
2.2 μm beams → d_{sep} = 10 σ

Dynamic Aperture at 4 σ

- **Beam-beam parameter → 0.007/IP**
- **High Chromaticity (15-20) → BAD impact on Dynamic Aperture!**
- **High Octupoles (550 A) → BAD impact on Dynamic Aperture!**

Footprint

LHC 2012

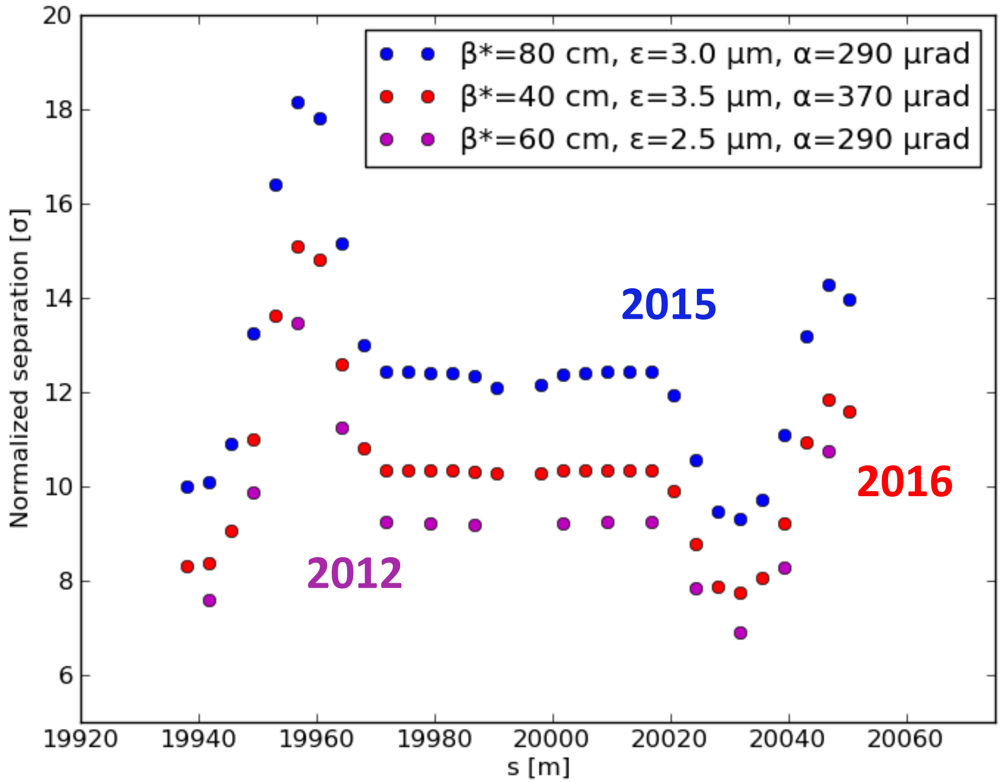


Different families of bunches!

Very difficult to find the best set-up for all families!

LHC configuration 2012→2015-2016

- Move from **50 to 25 ns spacing** → **double long-range numbers**
- **Electron cloud effects** → big uncertainty on final **emittances in collision**
- **Instabilities** during squeeze → allow for safe **High chromaticity and high octupoles operation**
- **β*** → to probe potential **luminosity reach** commissioning the final optics



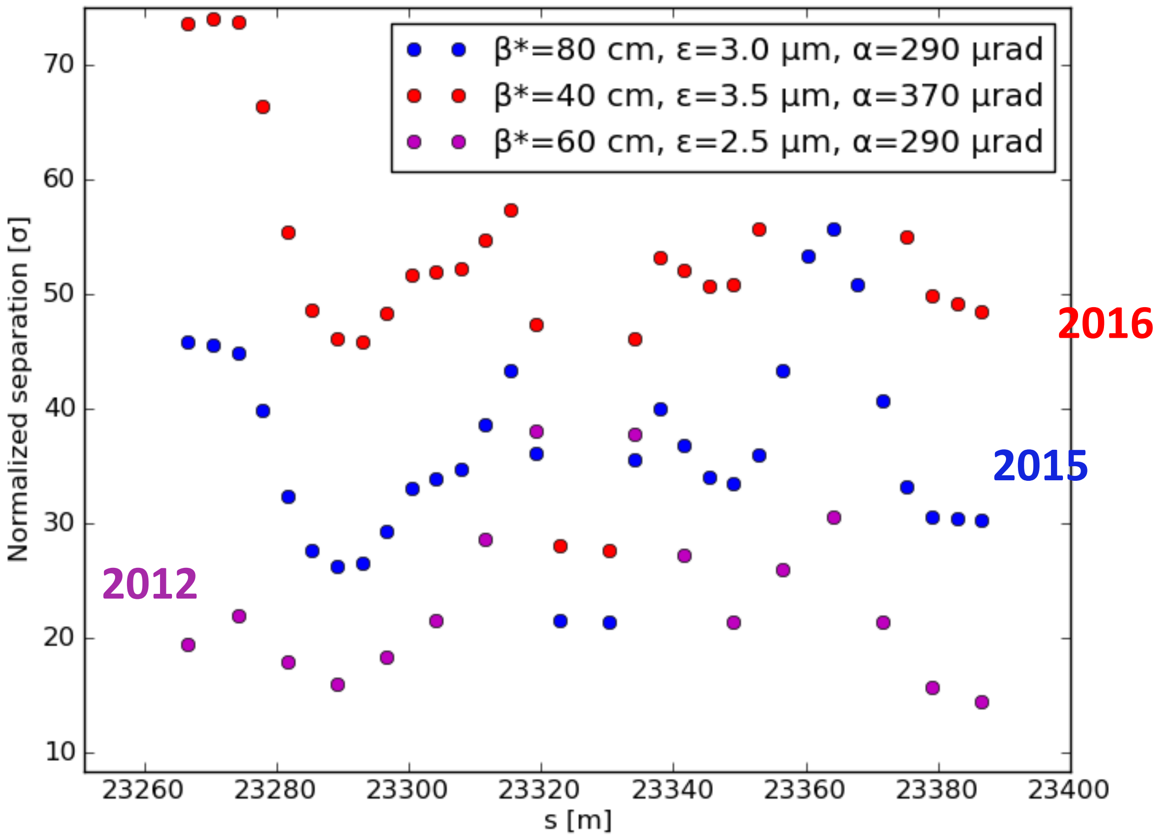
IP1 IP5

IP1 and IP5 at 10 σ beam-beam separation for emittance of 3.75 μm → relaxed configuration

Dynamic Aperture from 4 to 5-6 σ

When emittances stable and at the smallest values → room for reducing crossing angles!

Alice Experiment

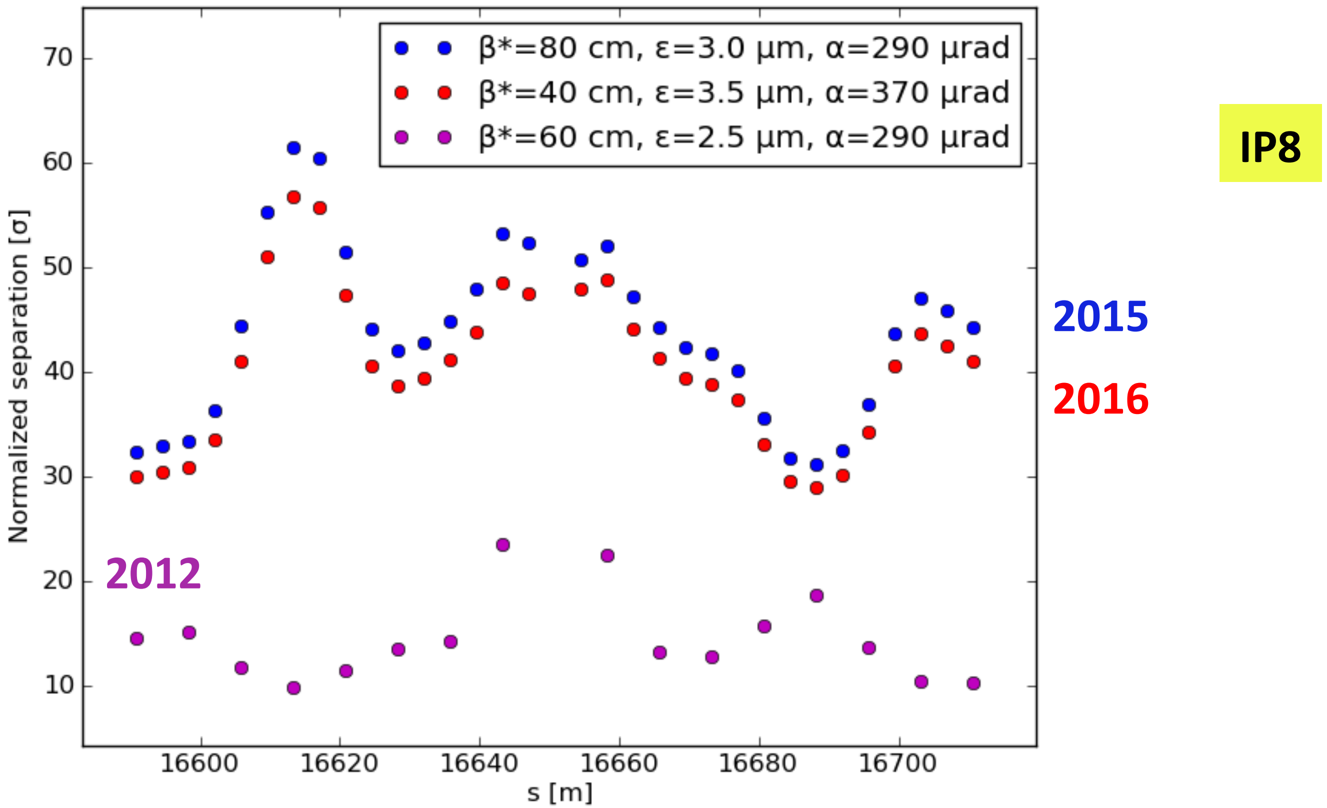


IP2

- **Tune shift** from BB effects of this experiment below 10^{-4} units of the tune
- **Tune spread** below 10^{-4} level
- **No impact on Dynamic Aperture**

Larger beam-beam separations in IP2

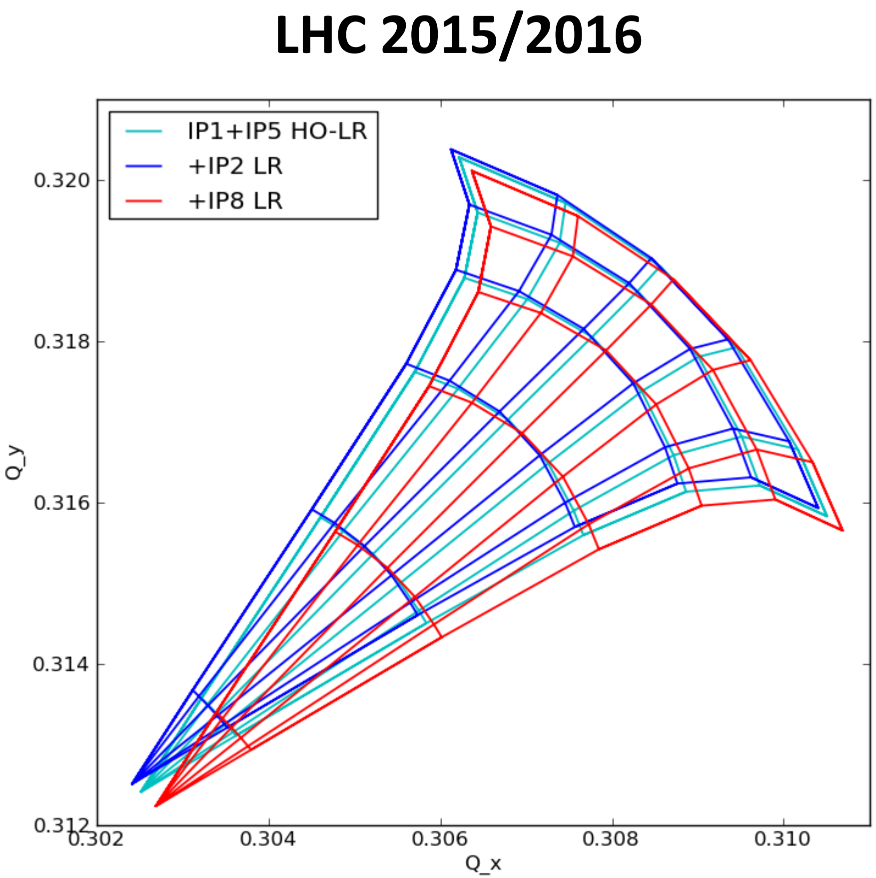
LHCB Experiment



- **Tune shift** from BB effects of this experiment below 10^{-4} units of the tune
- **Tune spread** below 10^{-4} level
- **No impact on Dynamic Aperture**

Larger beam-beam separations in IP8

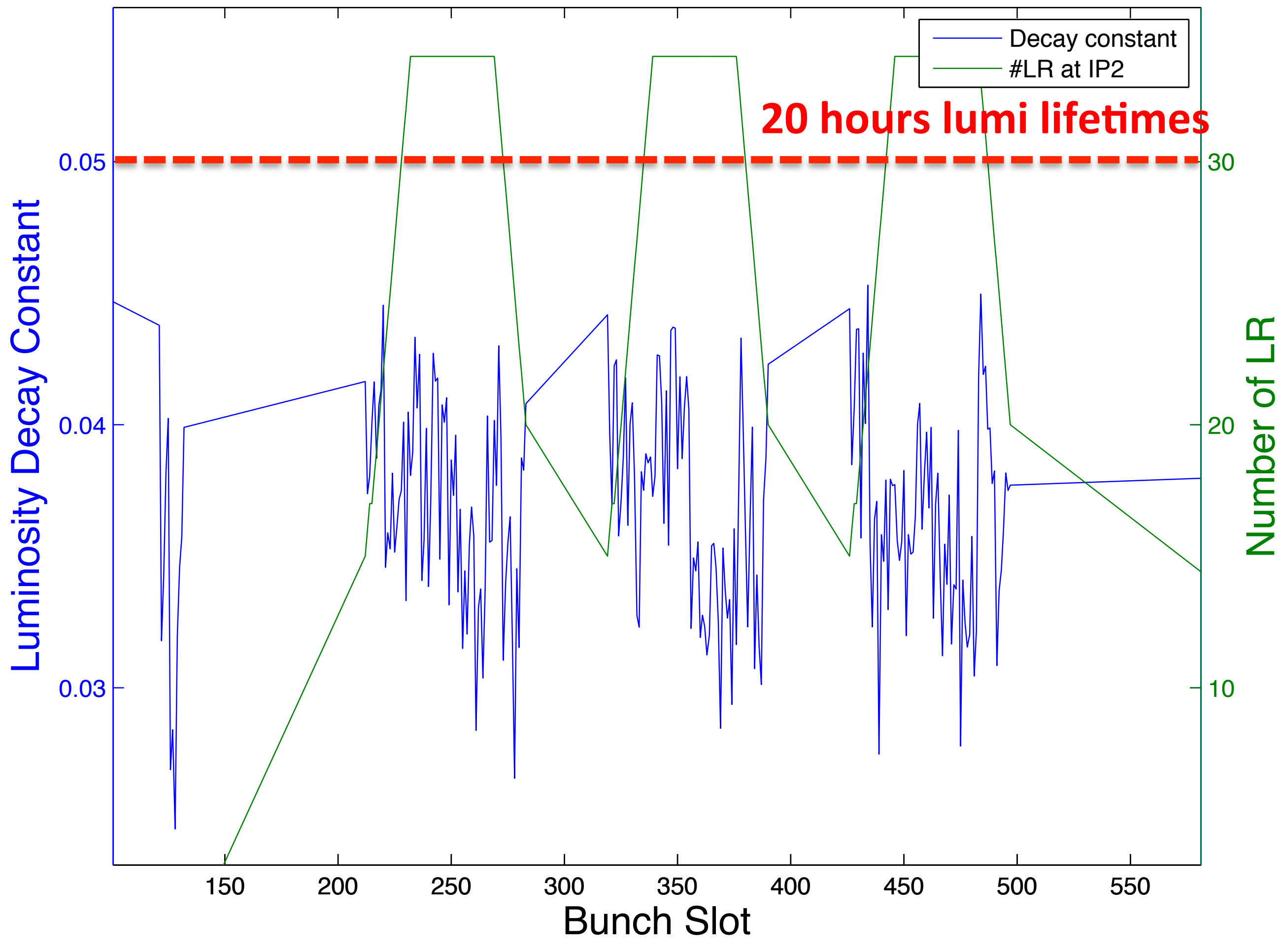
Footprint 2015/2016



LHCB and ALICE Experiments have to stay in the shadow of ATLAS and CMS!

LHC simpler to optimize operation and all margins go for high luminosity experiments

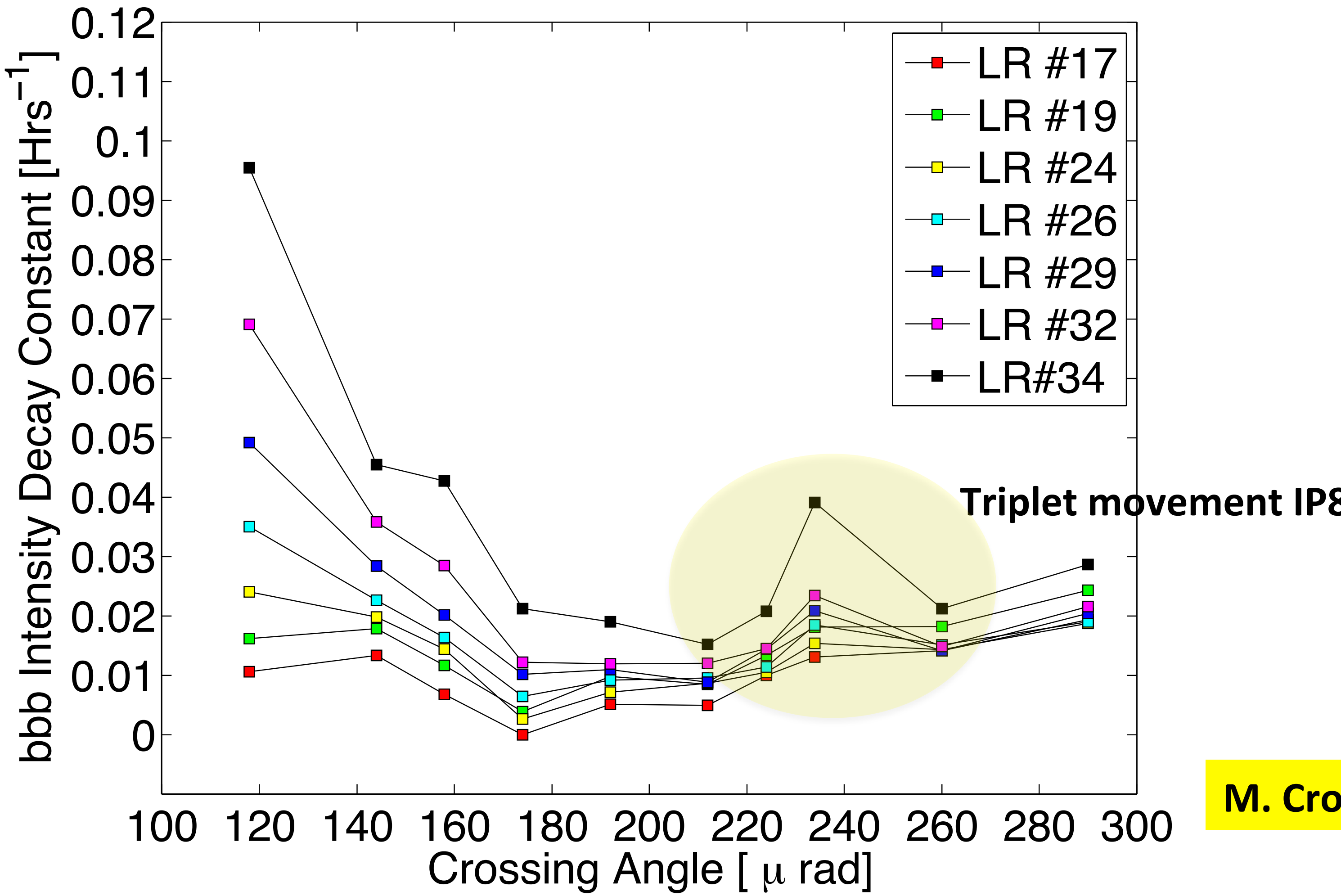
Long Range beam-beam effects 2015/16



No clear evidence of beam-beam long range and Head-on signature on luminosity lifetimes

Beautiful Intensity and Luminosity lifetimes (above 20 hours)!

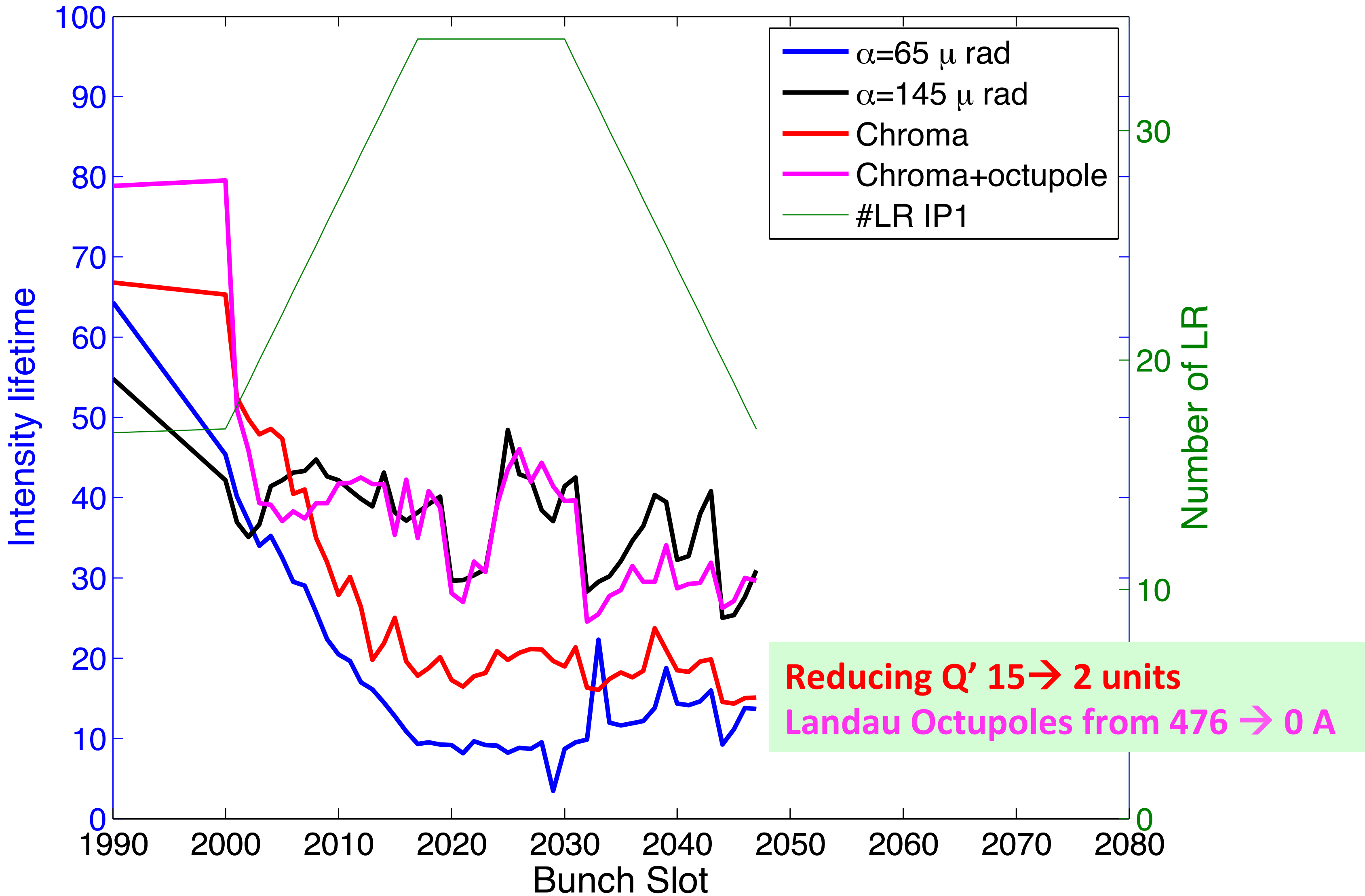
Long-range experiment 2015



M. Crouch

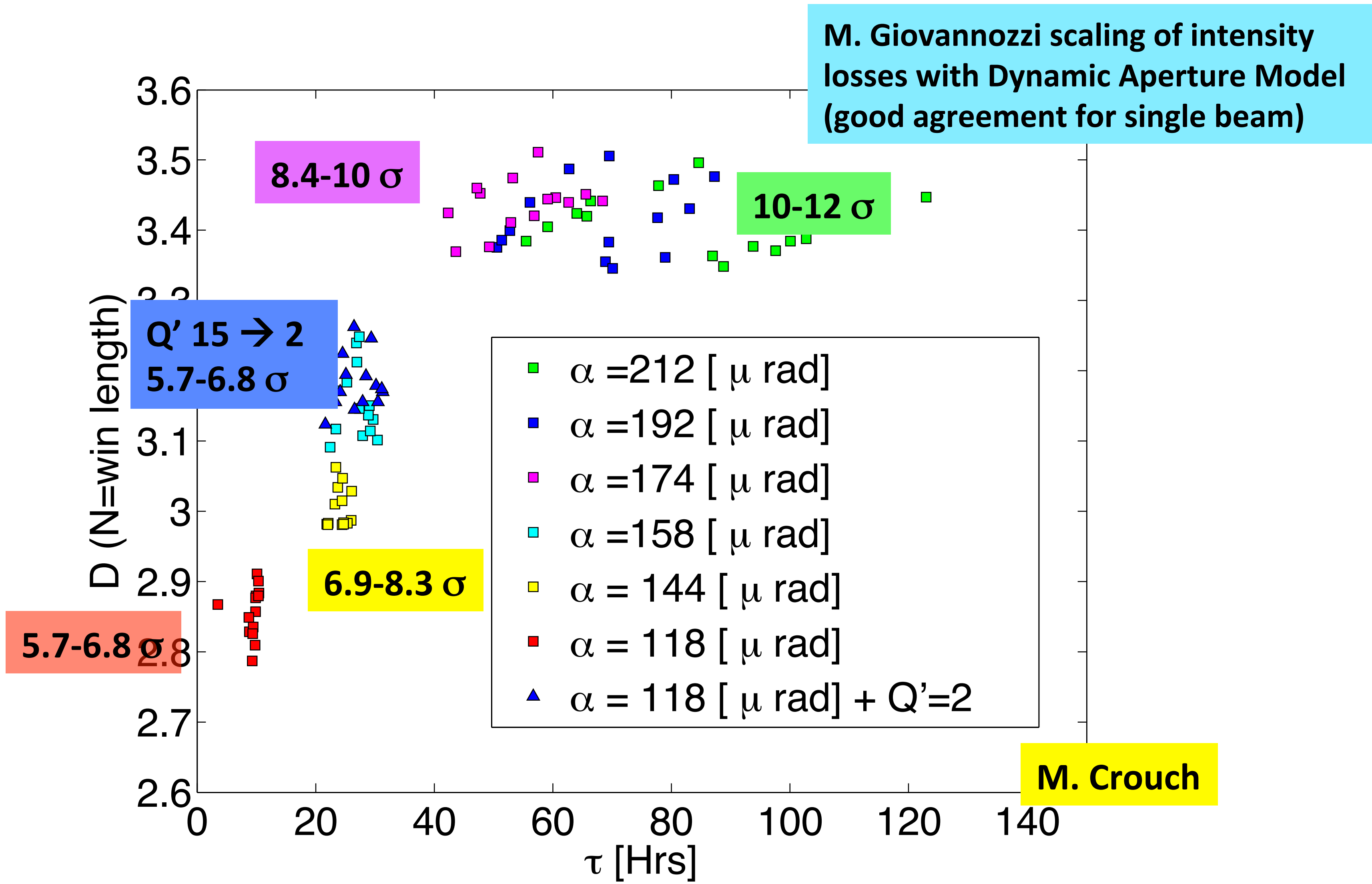
Beam intensity decay (cleaned by burn off) versus crossing angle

Long Range Limit: experiments in 2015



At the minimum angle: Reducing chromaticity → lifetimes at 20-30 h
Reducing octupoles →lifetimes at 30-40 h

Lifetimes versus estimated Dynamic Aperture

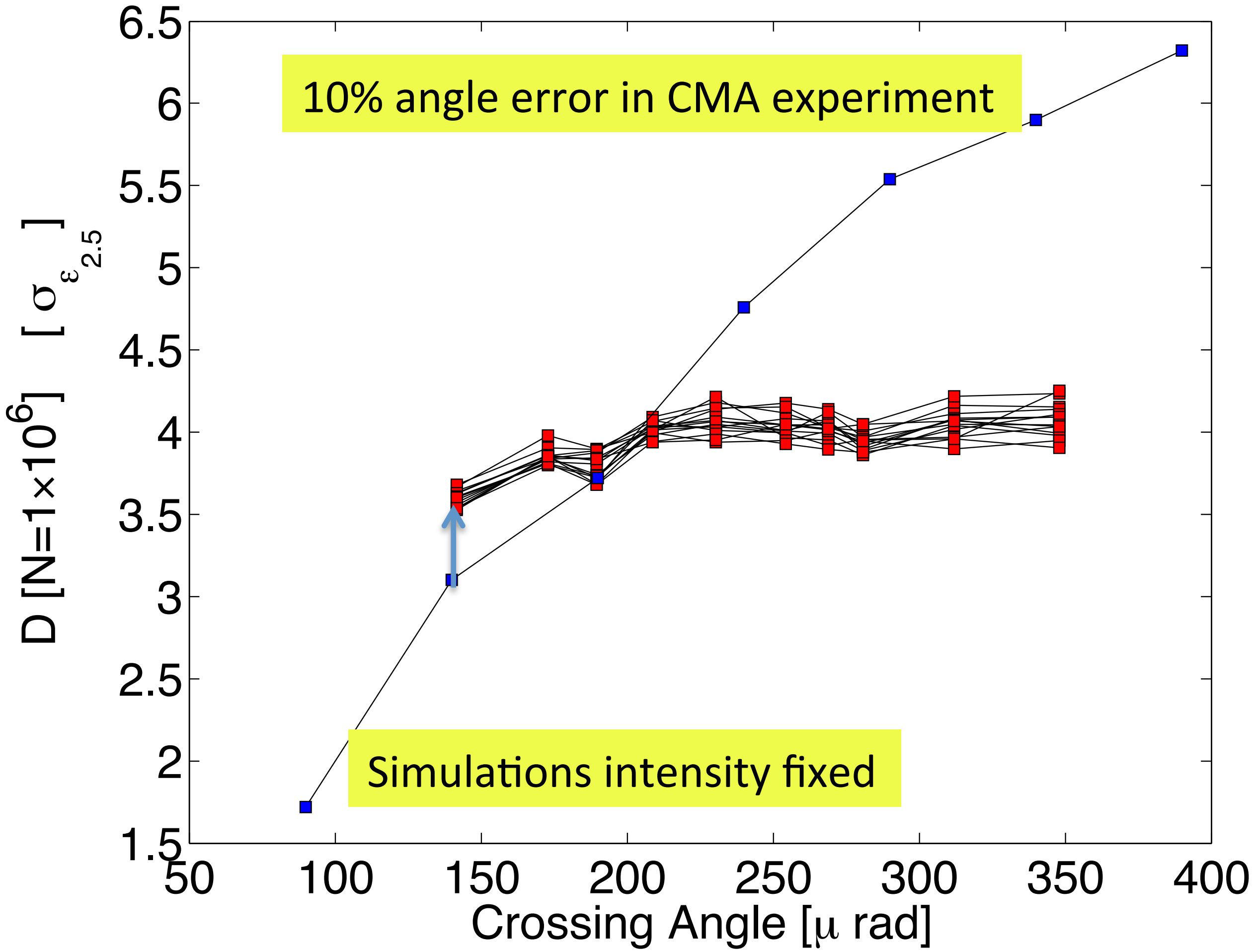


Down to 8 σ beam-beam separation seems feasible 20 h lifetimes!

→ Frees some aperture → 35 cm β* not out of reach!

Big uncertainties on emittances and crossing angle → Experiment at end of July!

Measurements versus simulations

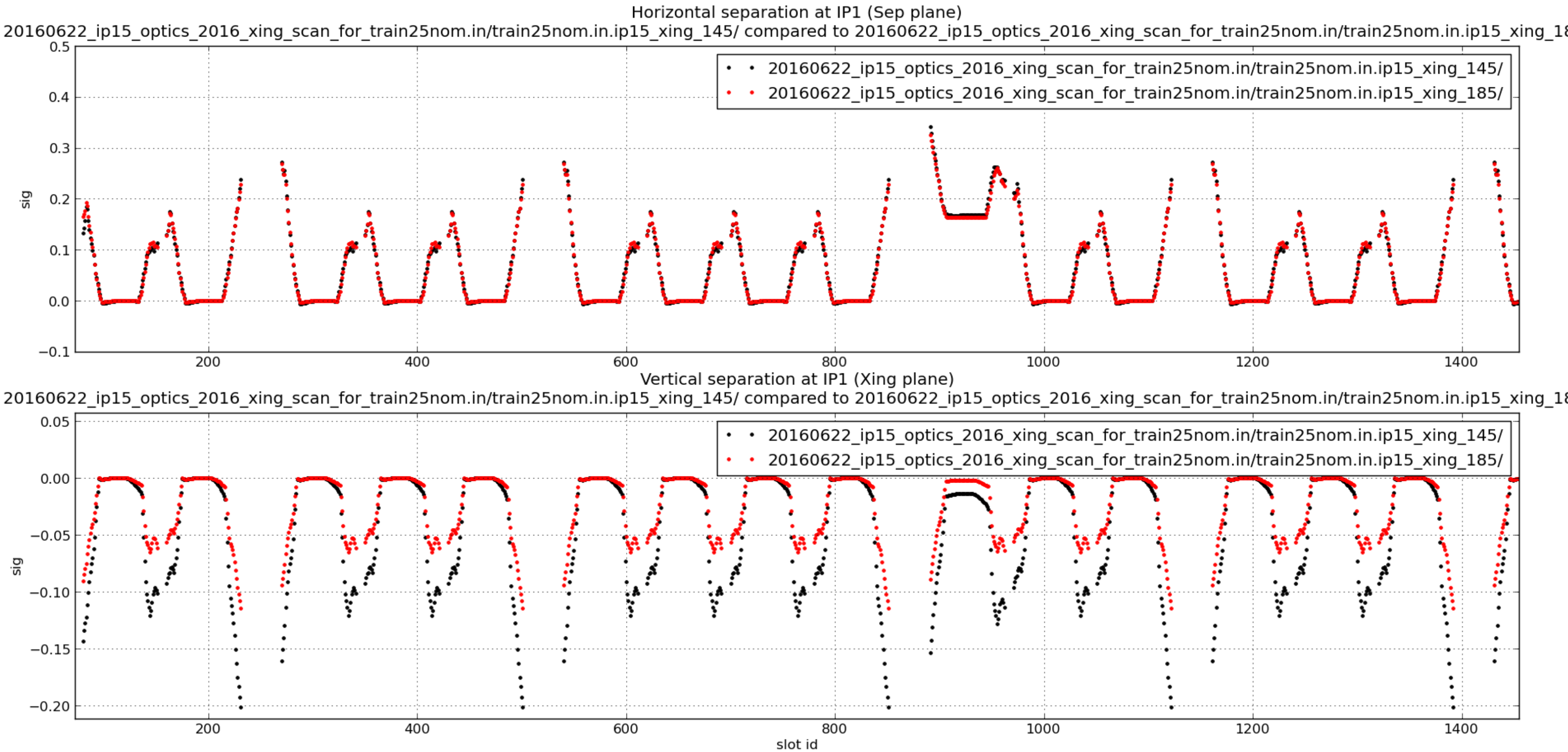


M. Crouch

- **non-linear errors in DA model specially for larger angles!**
- **refining DA at smaller angles for reduced intensities and emittances**

Still far…work on going….

Orbit effects at reduced crossing angle

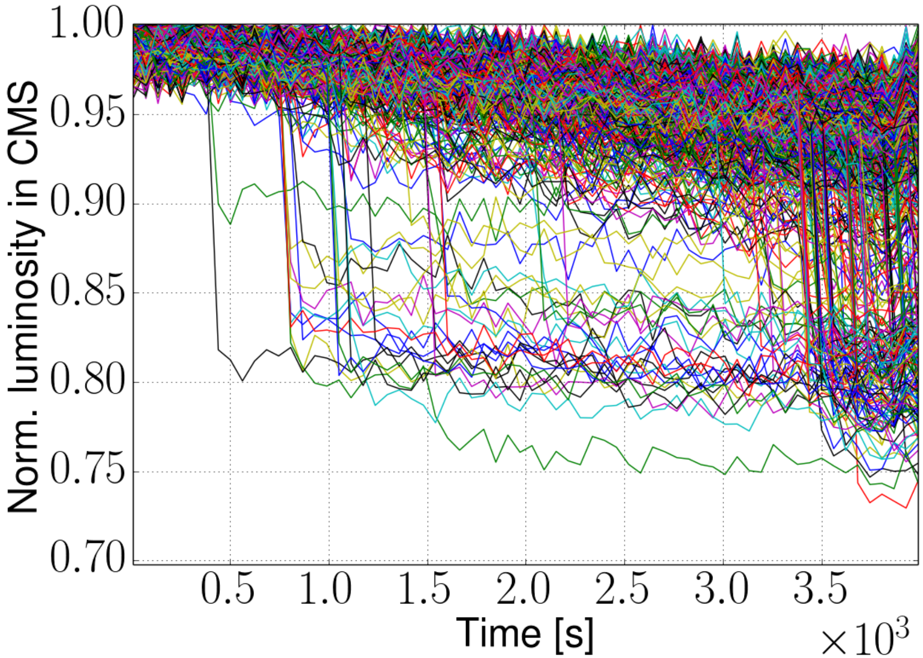


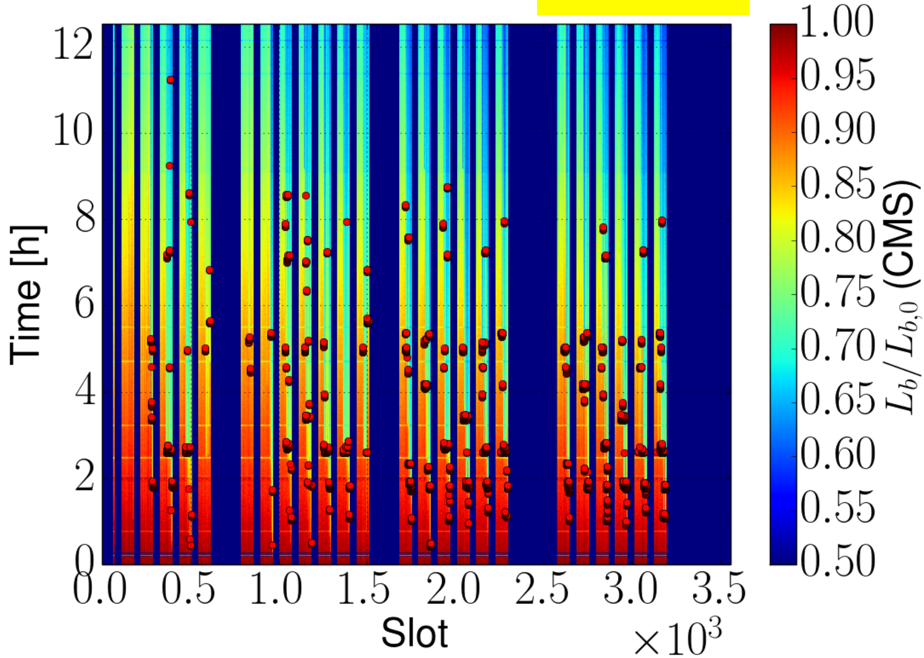
A. Gorzawski

Orbit effects might limit lower crossing angle reach
At 8 sigma separation one should expect up to 0.2 s separation at IP1&5

Instabilities in collision

X. Buffat

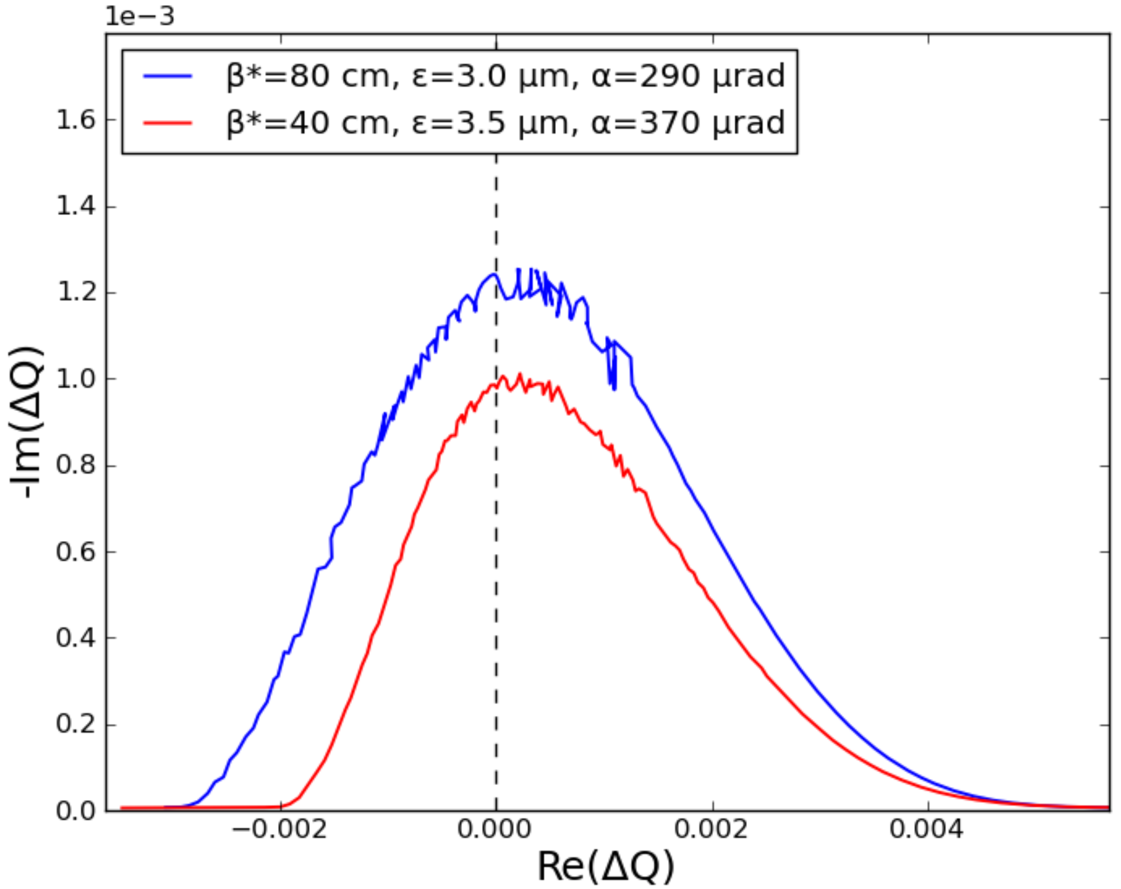




- **For the first time several Instabilities on colliding bunches!**
- **Higher chromaticity makes instability rise time longer**
- **Emittance blow-up but no important losses**
- **Last bunches of the trains most affected**

Need to operate with high chromaticity (22 units) in collisions!

Landau Damping in collision



C. Tambasco

The amplitude detuning, and the corresponding stability diagram, is significantly larger in stable beam (respect to Landau Octupoles) due to head-on collisions in IP1 and 5

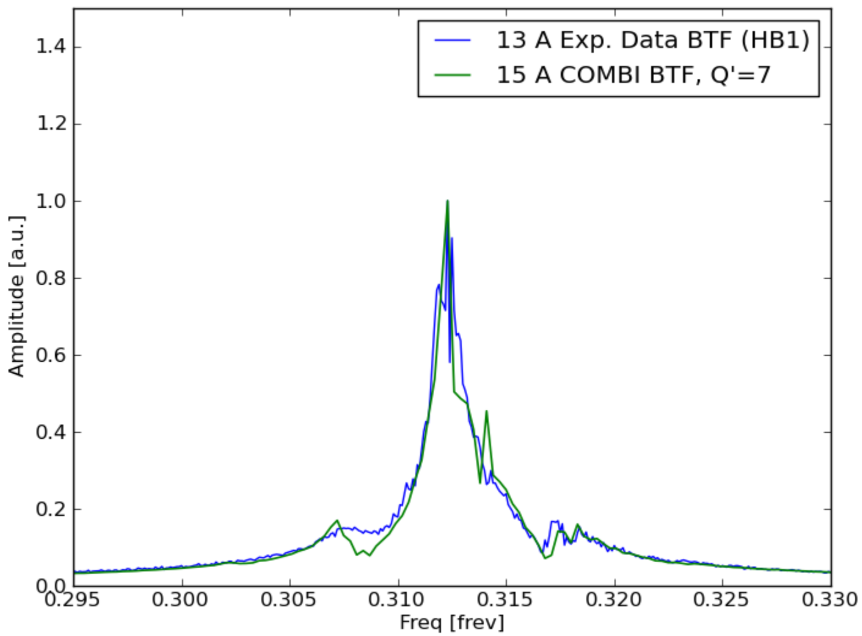
→ The instability mechanism does not seem to be sensitive to the large amplitude detuning but much reduced thanks to high chromaticity 22 units (E. Metral talk)

Beam Transfer Function → Stability Diagram

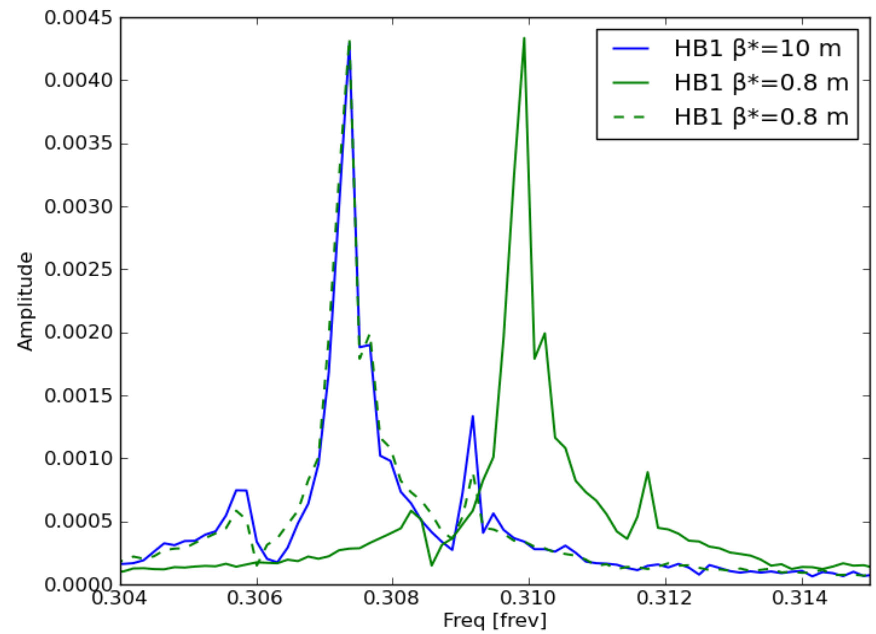
Tune spread and Particle distribution variations

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



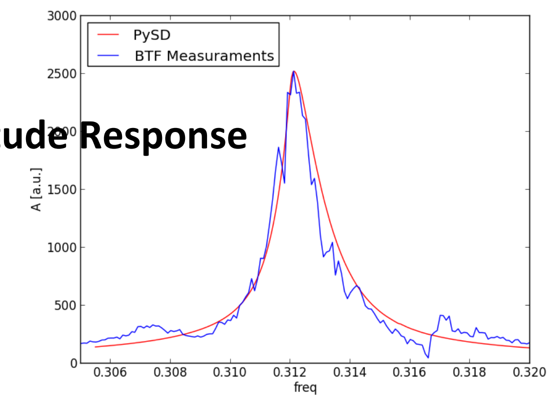
Long Range effects at end of squeeze (14 σ)
NO effect!

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

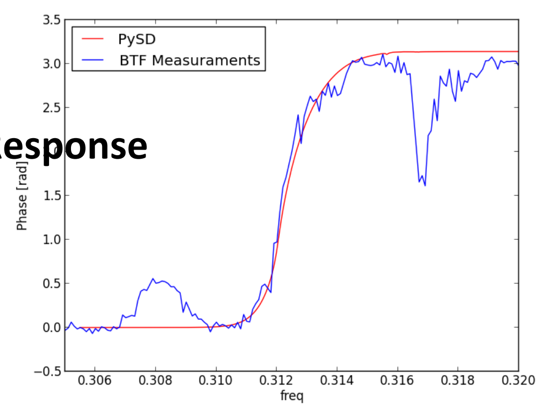
First attempt to reproduce Stability Diagram

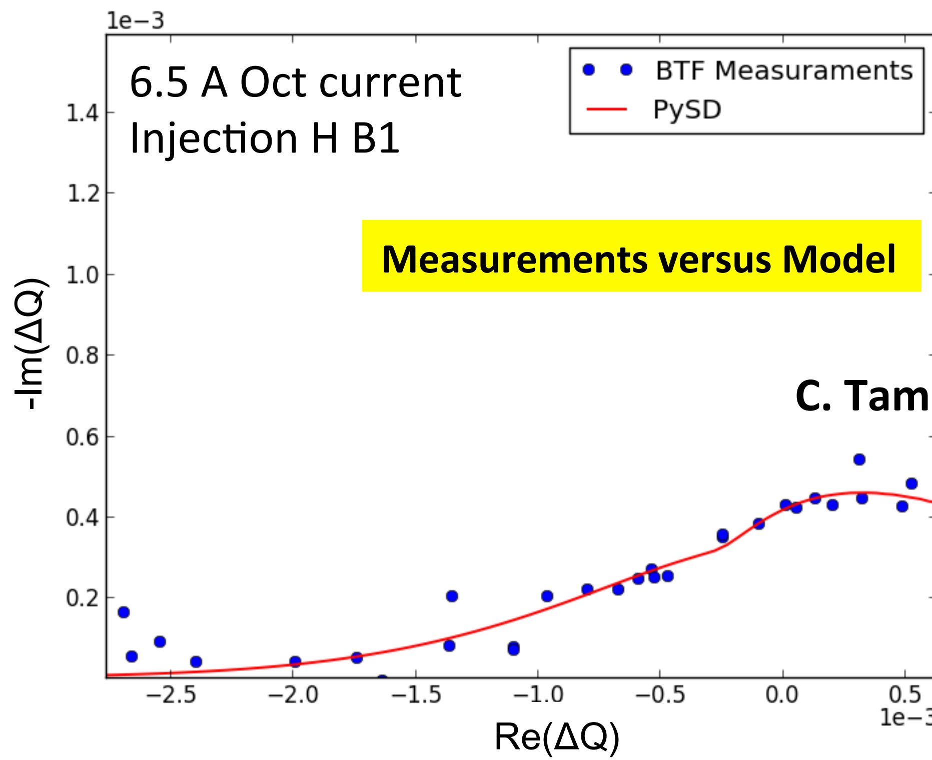
- Very challenging already in simple cases, but powerful tool→ octupole, chroma scans
- Spread from octupoles and Chromaticity effects under study
- Transparent to beams!
- **Still need a lot of work to understand (kick amplitude, resolution)**
  → tools in place but need more data in 2016 !

Amplitude Response



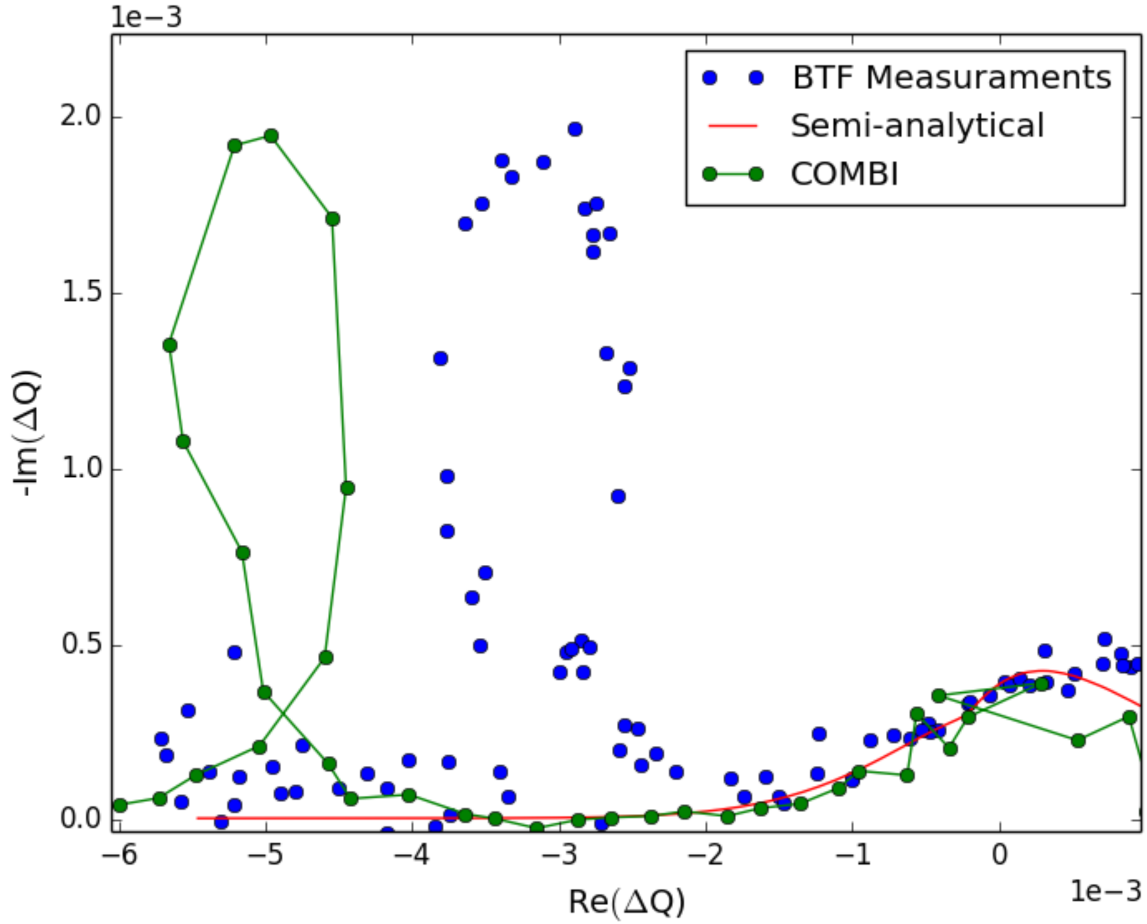
Phase Response





C. Tambasco

Longitudinal plane to transverse

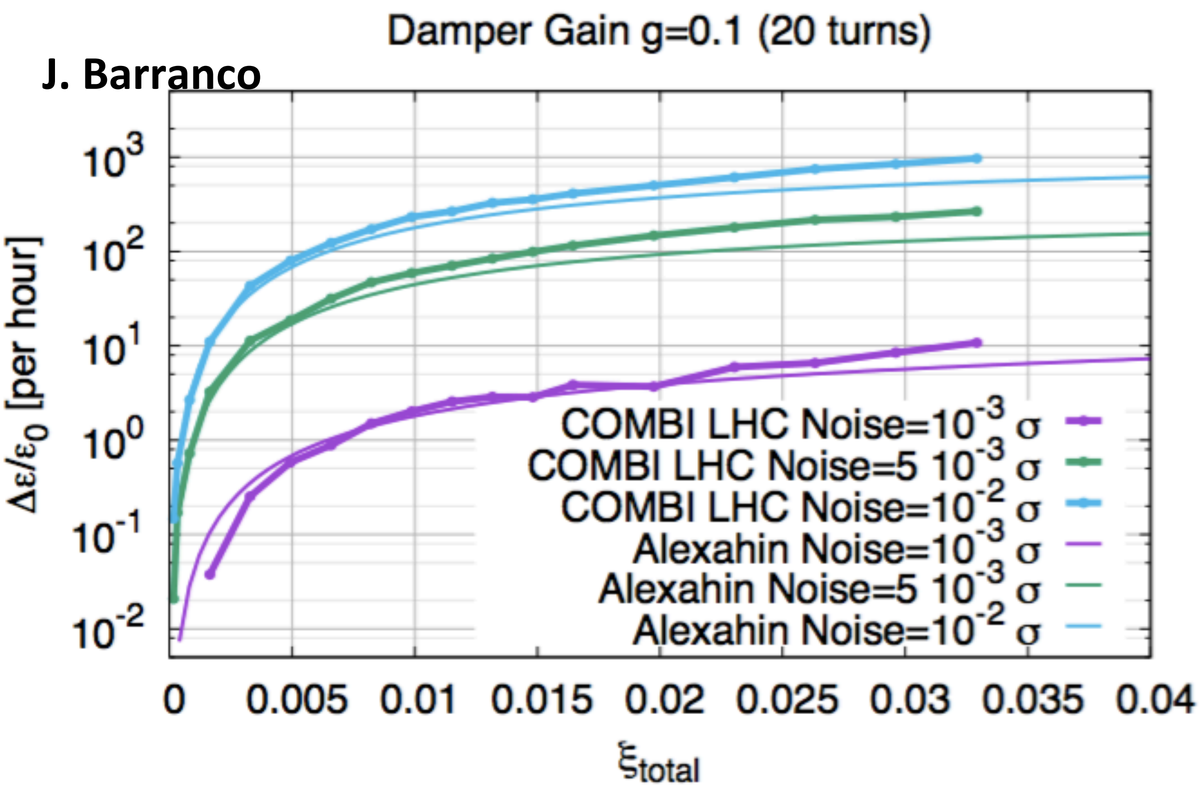


C. Tambasco

Longitudinal contribution visible in transverse response
need some deeper understanding→ very promising tool !
Work in progress!

Head-on limits: Noise

J. Barranco



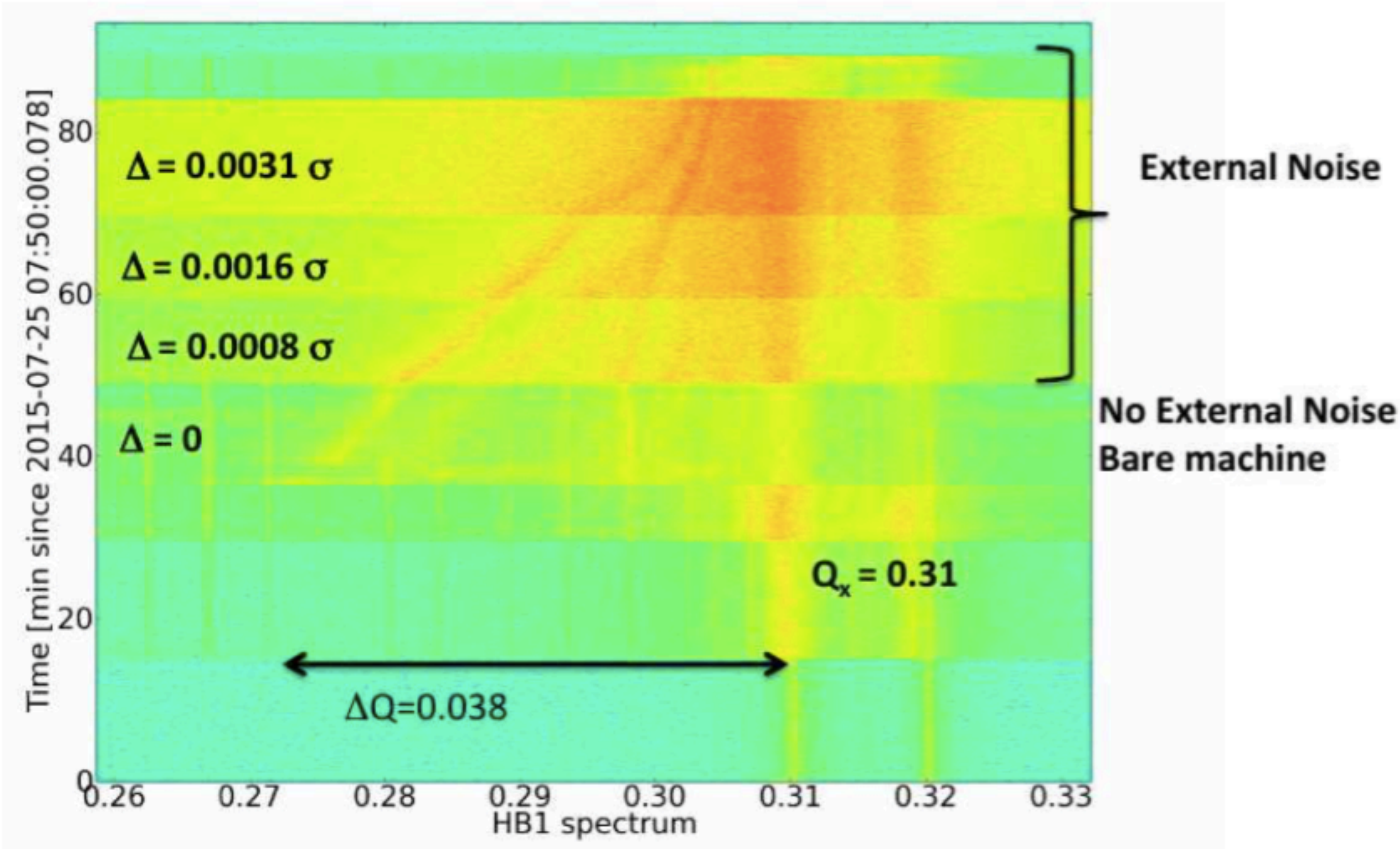
Crab cavity tolerances, estimates of emittance growth…

$$\frac{1}{\epsilon_0}\frac{d\epsilon_x^{1,2}}{dN} = \frac{1-s_0}{4}\left(\Delta^2\right) S\left(\frac{g}{2\pi|\xi|}\right)$$

Y. Alexahin derivation

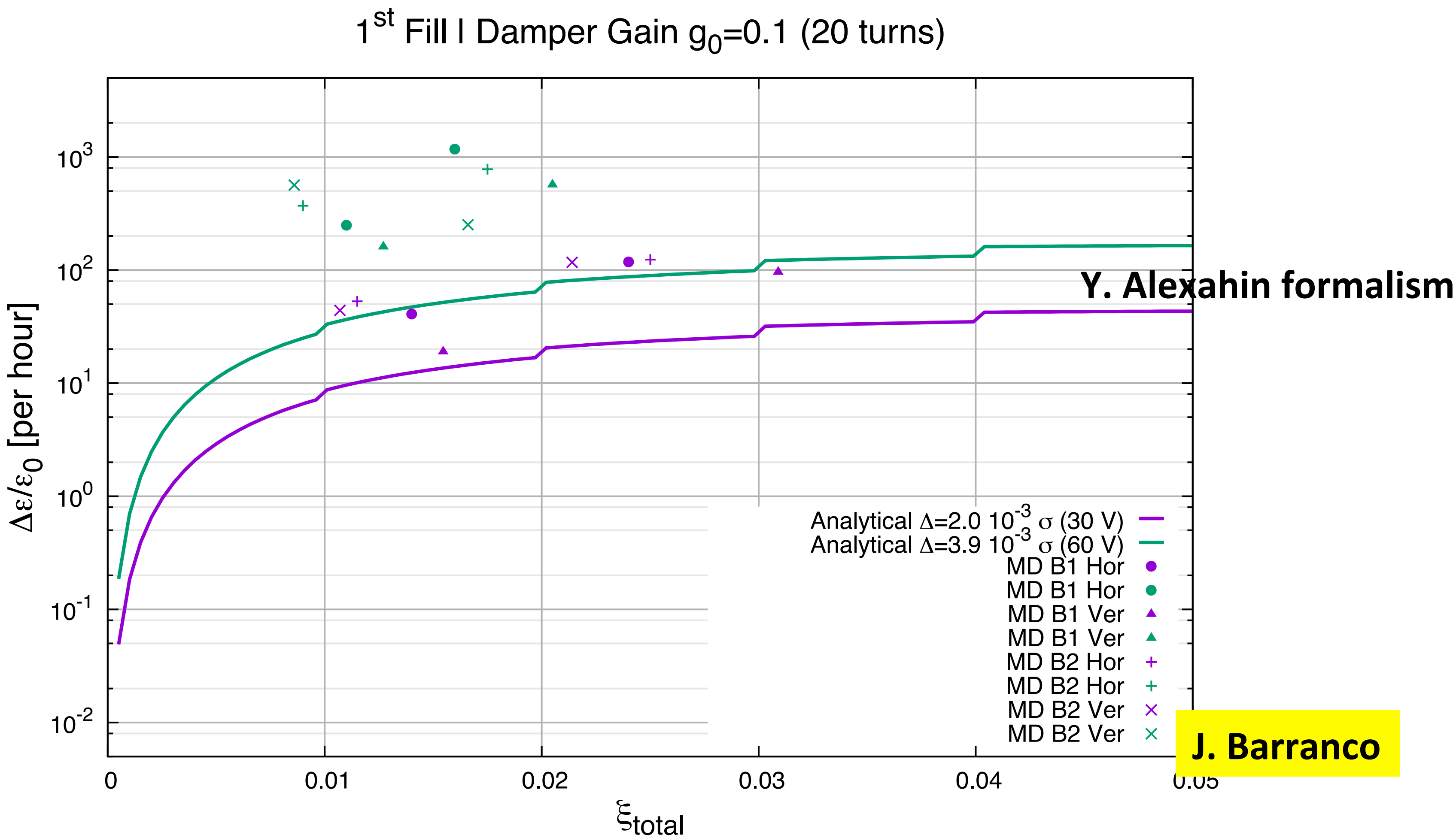
How far are we from reality?

High brightness Colliding beams spectrogram



Collisions at injection energy for different transverse damper gain, beam-beam parameter and amplitudes of the noise!

Noise on colliding beams at injection

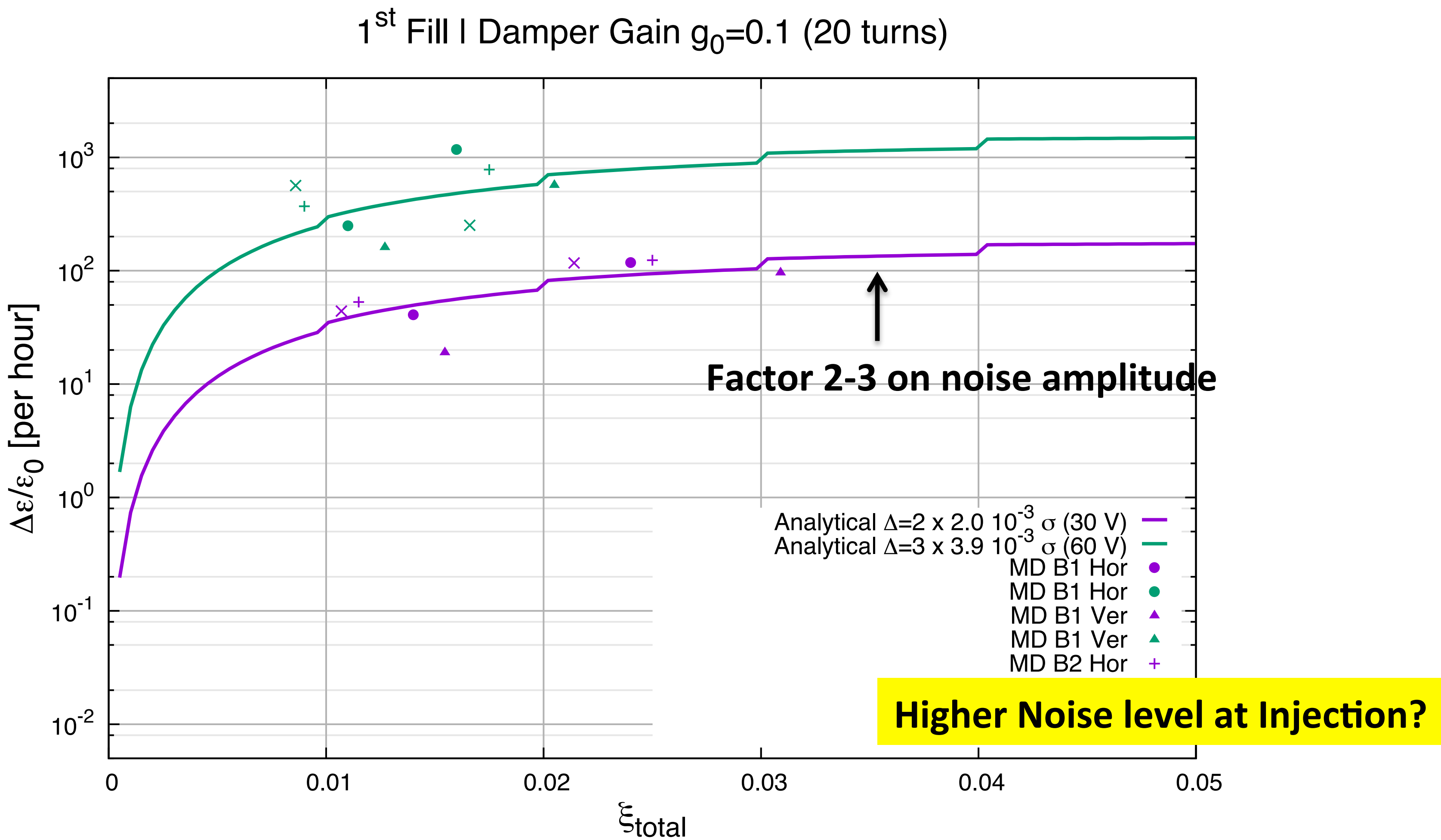


Injection Energy: introduce white noise different amplitudes

Single bunches with different BB parameter in collision

Different white noise amplitude used

Noise on colliding beams at injection



Missing ingredients in the model, beam-beam dependency consistent with expectations!
Very reproducible! Noise source at injection energy?
Is this the same at 6.5 TeV?→ experiments foreseen in August!

Conclusions

- RUN I at limits of DA (transverse blow-up and losses) and severe instabilities (chroma and oct at high values)→ several lesson learned and tools developed

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  - Cancel effects of IP2 and IP8
  - Wait for e-cloud scrubbing to have defined transverse emittances in collision
  - Learn about aperture limitations $\beta^* = 40$ cm

Key elements under control! Beautiful Luminosity lifetimes in collision, with controlled conditions!

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- Next steps: further boost in performance! Potential to reduce crossing angle to 7-8 σ for bunches with 2.5 mm emittances and 1.25 10^{11} ppb

  → RUNII 1.52-1.75 10^{34} (40cm-35cm beta*) peak luminosity with lifetimes above 20 hours.

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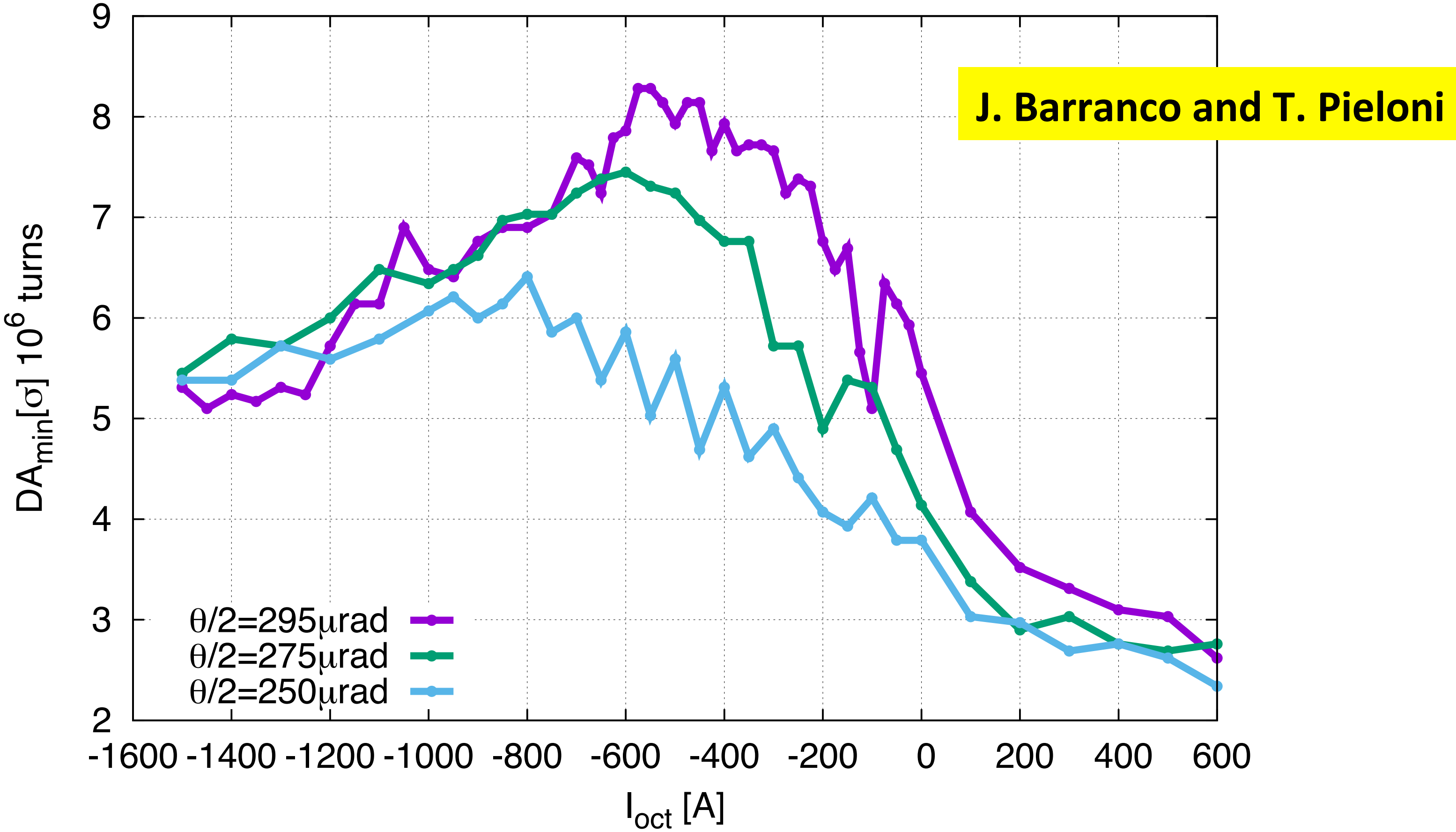
  → RUNII 1.52-1.75 10^{34} (40cm-35cm beta*) peak luminosity with lifetimes above 20 hours.
- **Measurement campaign** to define possible limits of higher brightness :
  - **Dynamic aperture**: measurements and simulations to be refined
  - **Noise impact** still to be understood, models underestimates (factor 2-5)
  - **Developing BTF**: unique tool to understand dynamics of Landau damping

Thanks you!

Can we do better? Can we compensate?



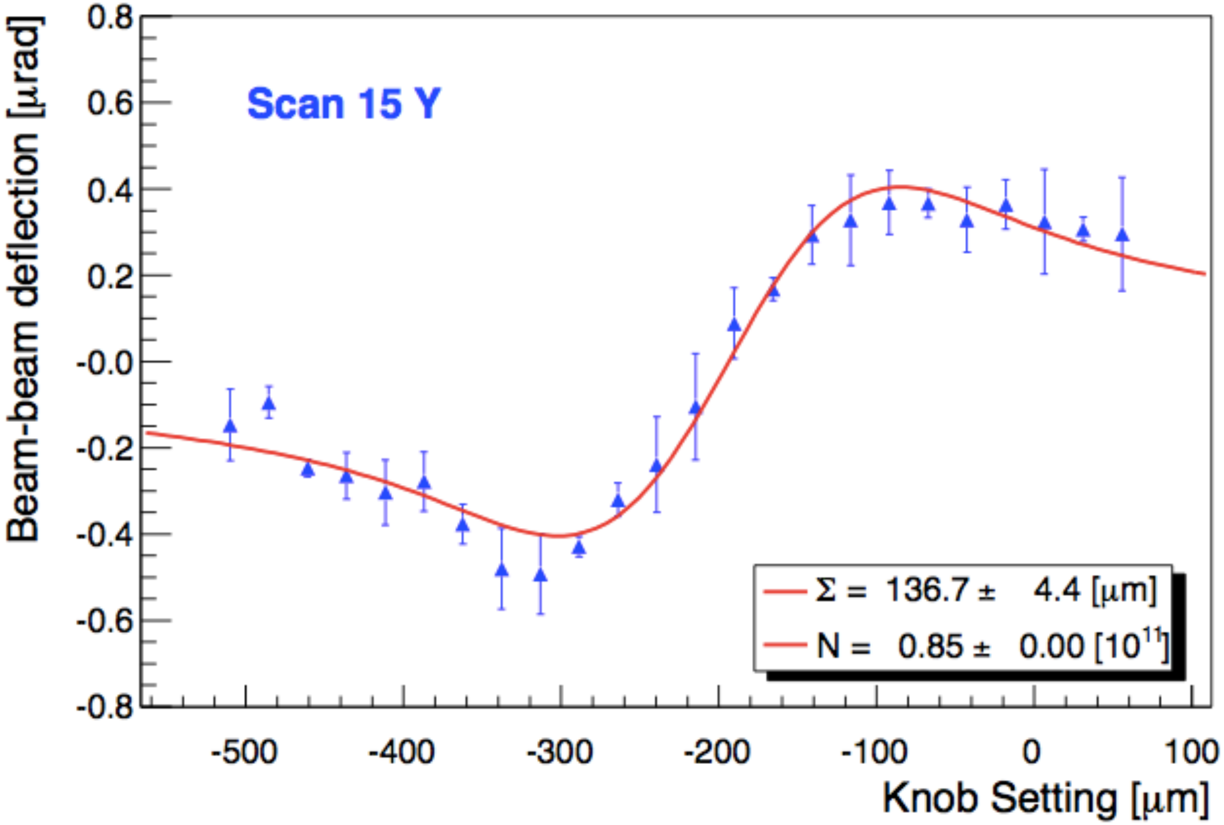
HLLHC studies (thanks to ATS optics) have revealed the possibilities to compensate LR BB with octupoles magnets

→ Octupoles also improve DA when high chromaticity

→ Will need stronger Octupoles (ATS type of optics with right phase advance)!

→ Smaller than 8 σ crossing angle might be possible….!

Orbit effect as a function of separation



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

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

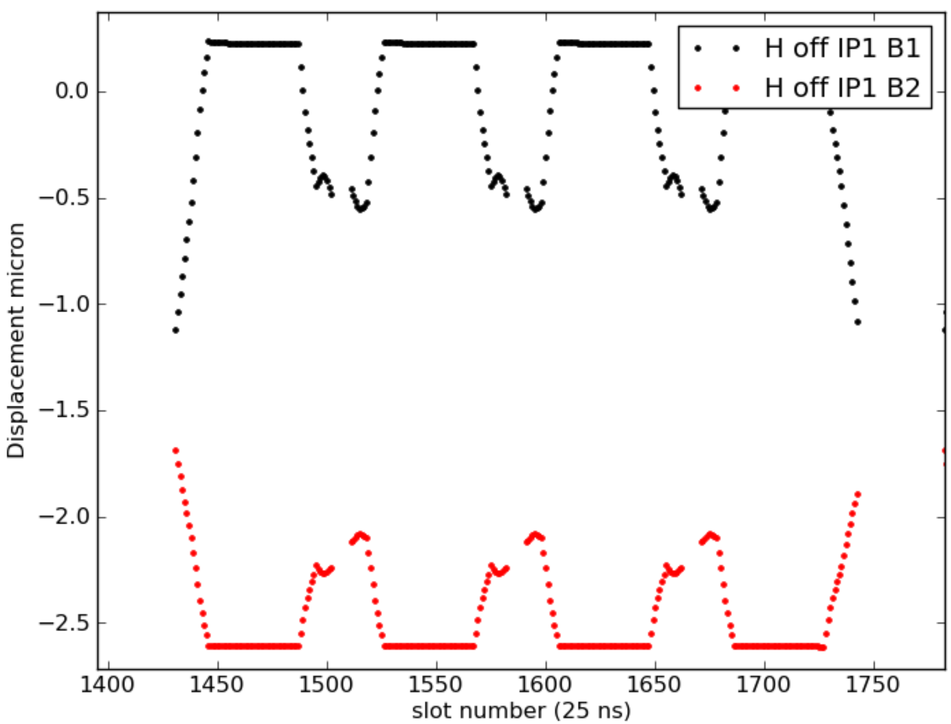
LHC orbit effects

Many long range interactions could become important effect!

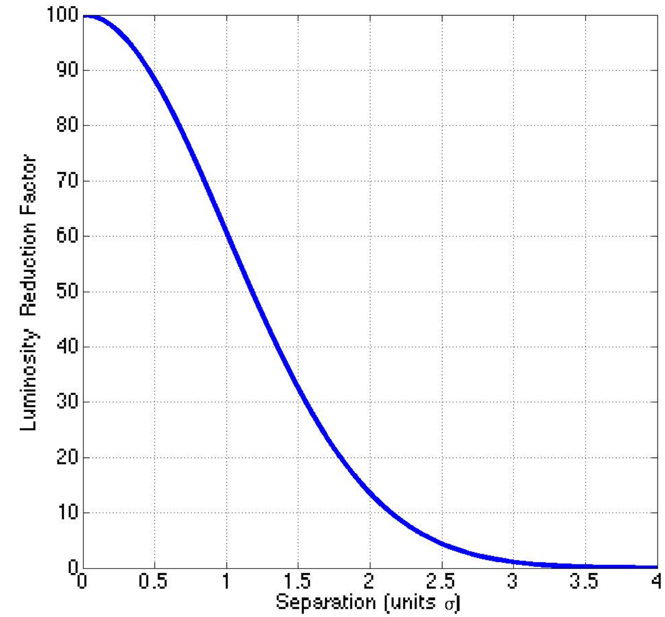
Holes in bunch structure leads to PACMAN effects this cannot be corrected!

$$L = L_0 \cdot e^{-\frac{d^2}{4\sigma_x^2}}$$

Self consistent evaluation



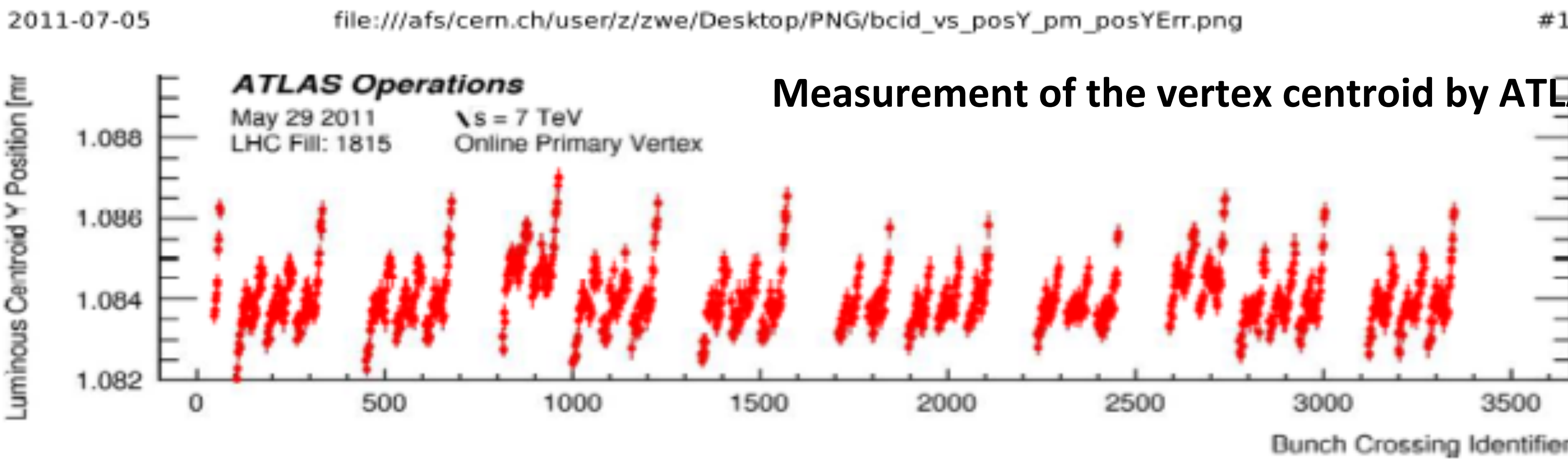
d = 0 – 0.2 units of beam size



Orbit Effect due to PACMAN bunches CANNOT be compensated should be kept SMALL to avoid loss of luminosity!

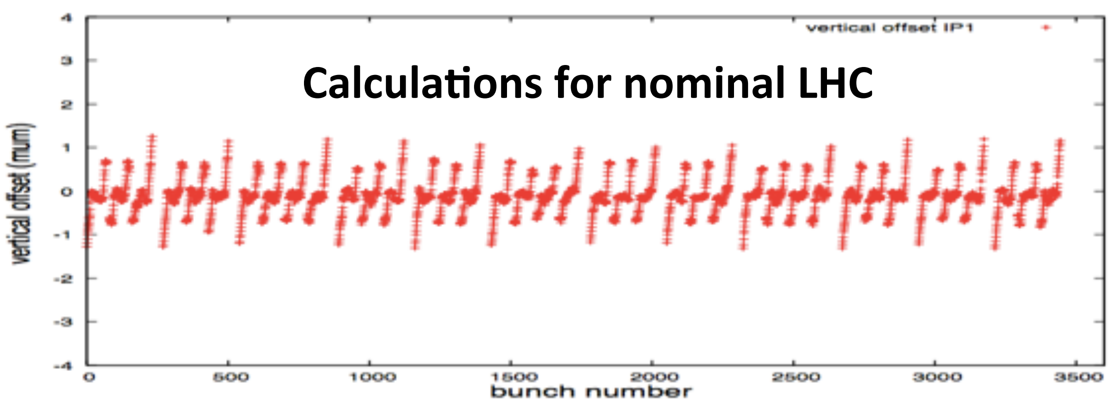
Long range orbit effect

Long range interactions leads to orbit offsets at the experiment a direct consequence is deterioration of the luminosity



Measurement of the vertex centroid by ATLAS

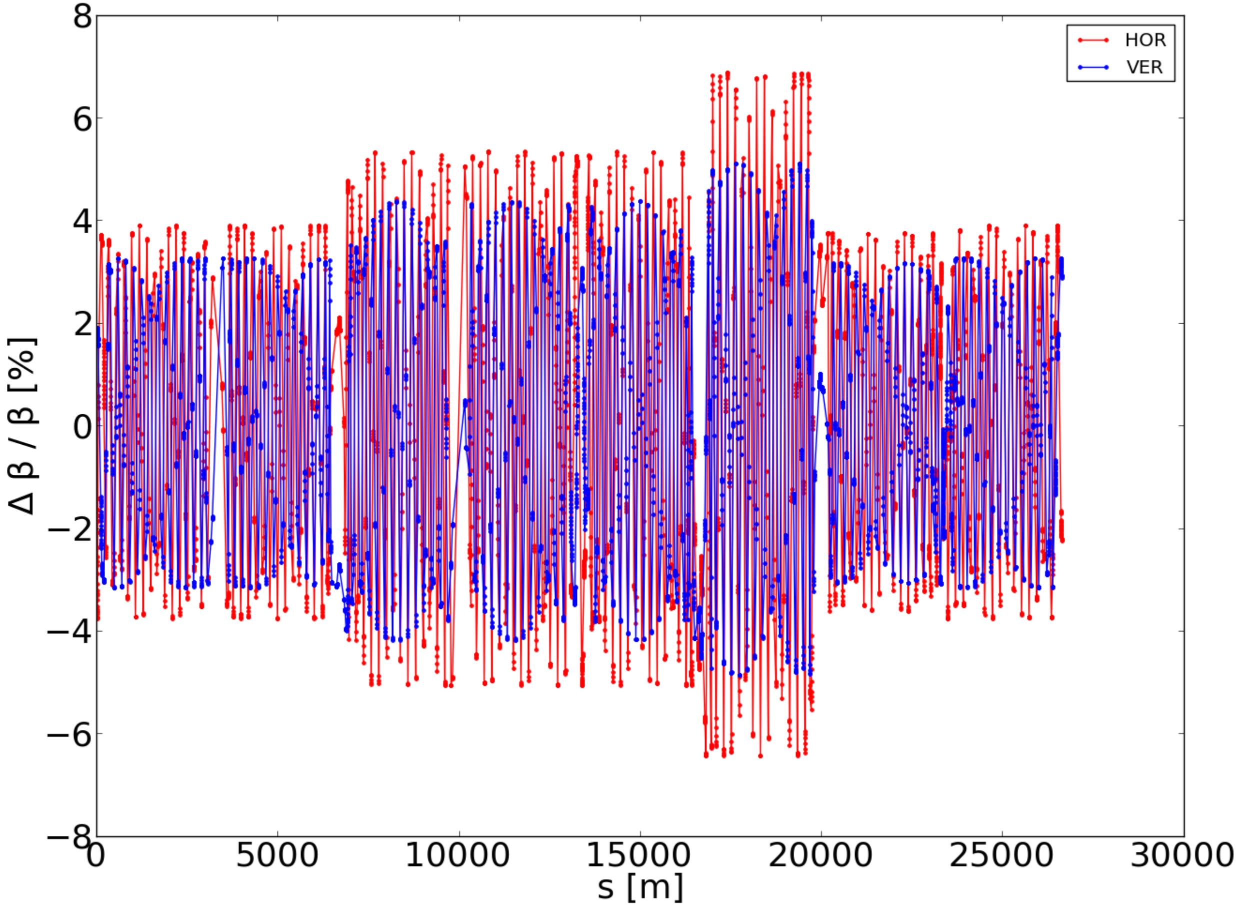
Courtesy W. Kozanecki



Calculations for nominal LHC

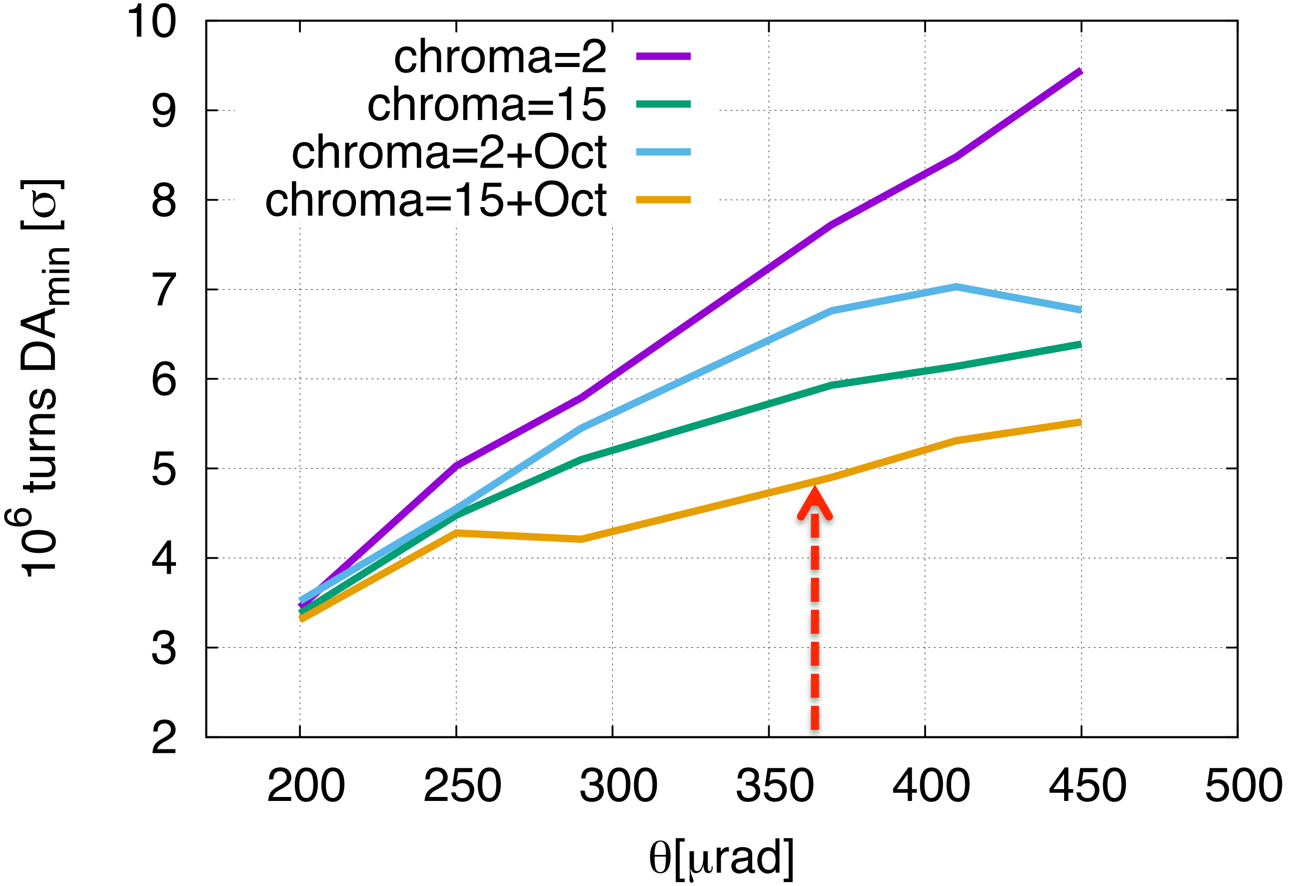
Effect is already visible with reduced number of interactions

Beta beating from Beam-beam HO

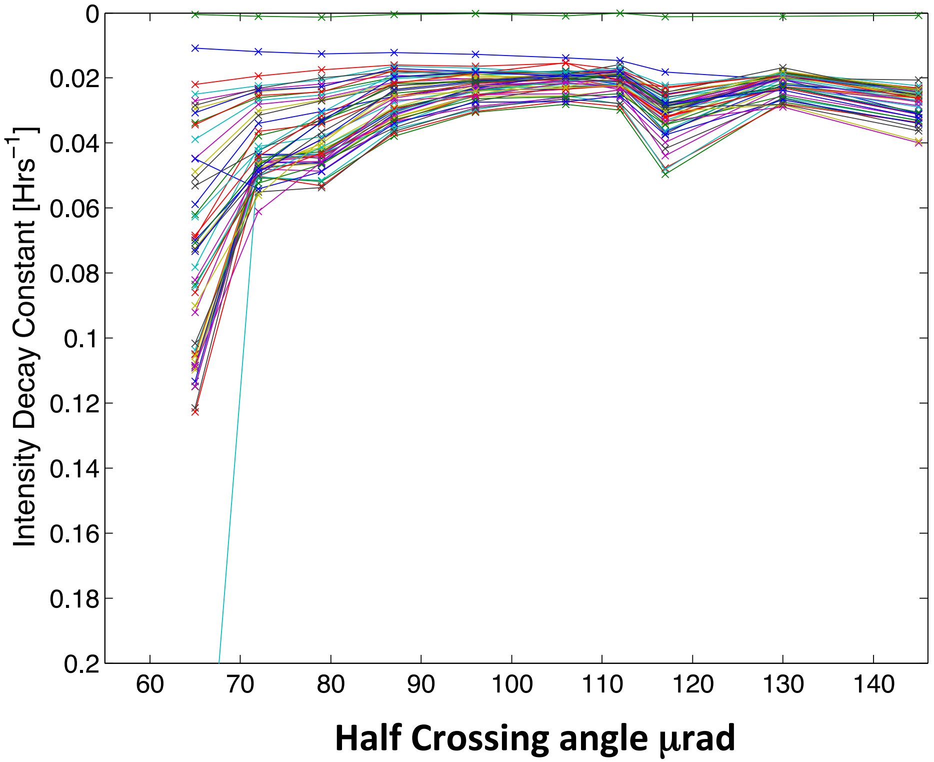


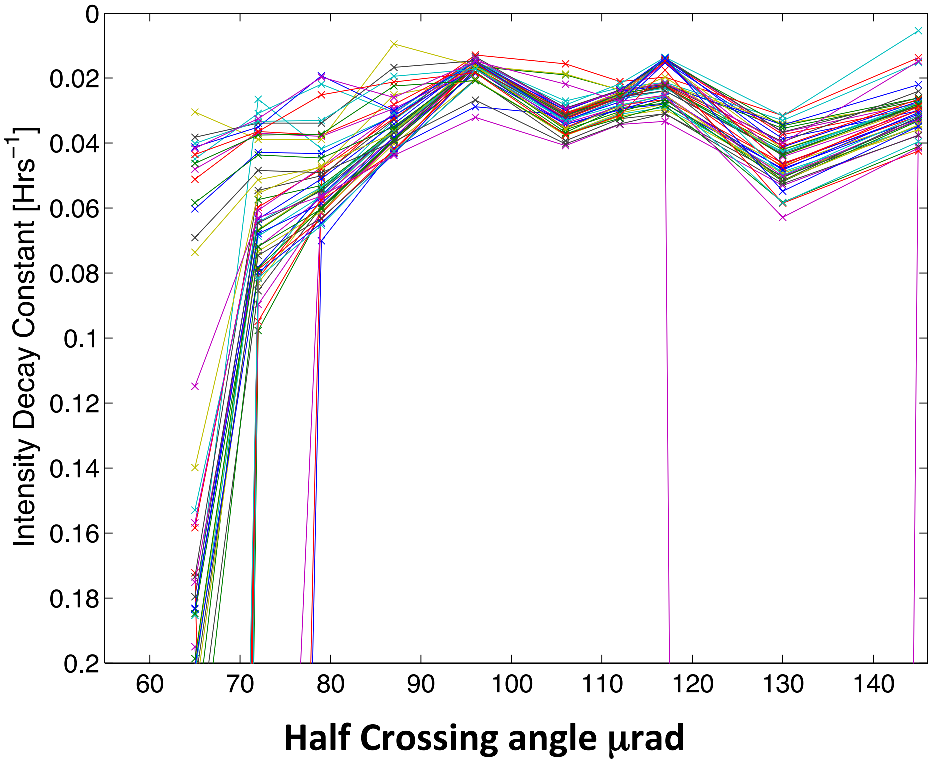
The beam-beam head-on collisions IP1&5 provokes a beating around the accelerator of maximum 7 % 2015 case (very important for larger beam-beam parameters HLLHC 20%)
Very different for core and tail particles… needs further studies.

2016 Dynamic Aperture



Intensity lifetimes versus crossing angle

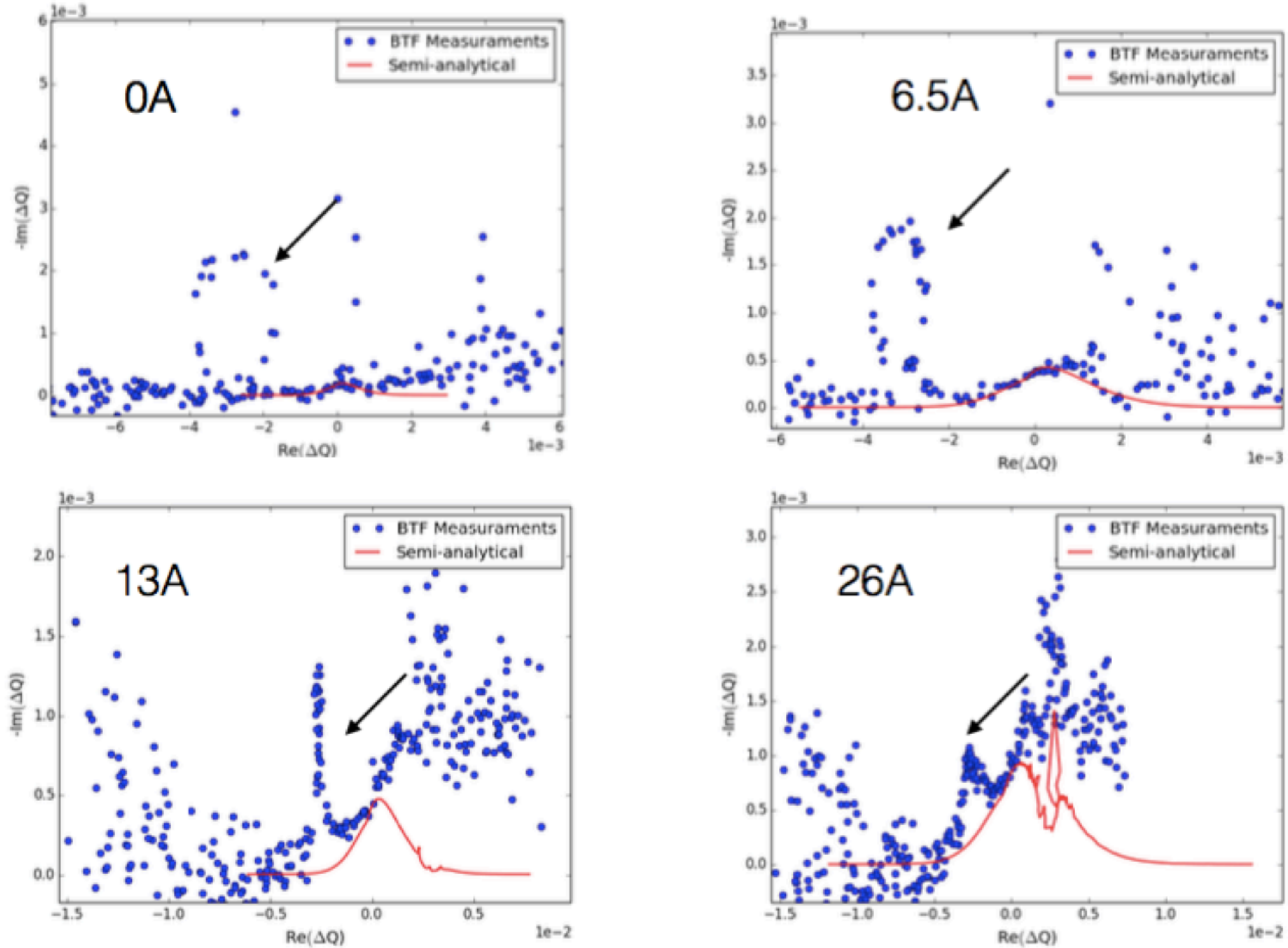




Reducing the crossing angle Beam lifetimes are reduced from 30→8-5 hours
Beam 2 more sensitive (could be slightly different tune? Different emittances?)

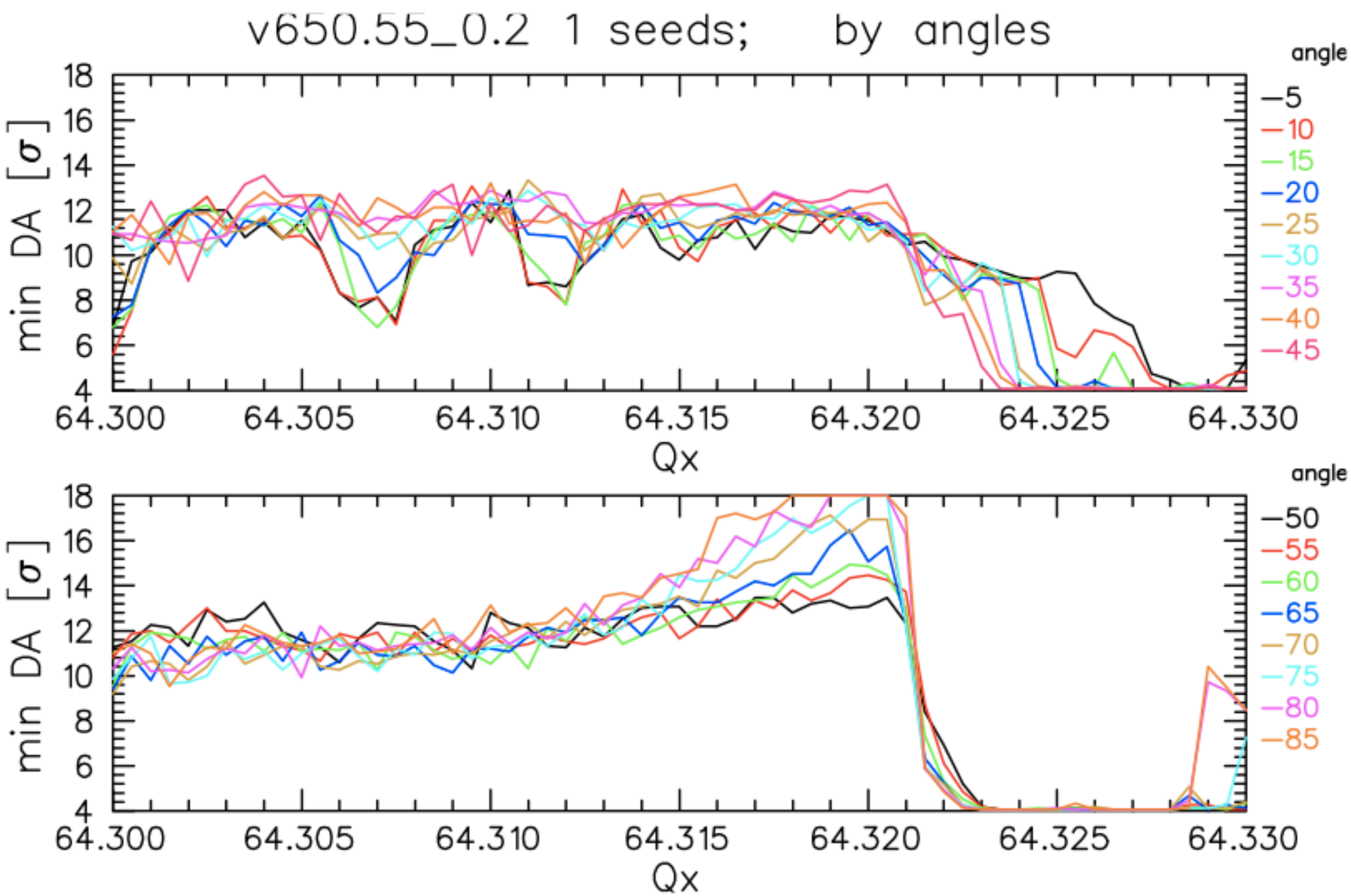
SD octupole scan at injection

- 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)



IP2 and IP8 contributions?

Dynamic Aperture depends on the working point



What does IP2 and IP8 in the picture?

Non-negligible LR encounters → tune shift and spread

Several bunches with different working points→ difficult to optimize!