First beam-beam considerations on crossing angles: 2012 experience and possible 2015 scenarios

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Outline:

- History of long-range separations and DA
- DA studies for LHC Nominal
- 2012 configuration
- 2015 possible parameters
- Summary&Outlook
- Strategy

BB Separation: LHC design Report

$$Energy = 7\ TeV$$

$$\beta^* = 0.55m$$

$$\epsilon = 3.75\mu m$$

$$\epsilon_n = \epsilon/\gamma = 16.62\mu m$$

$$\alpha/2 = \pm 142.5\mu rad$$

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

$$d_{sep} = 9.42\ \sigma$$

The high luminosity requires a large number of bunches (2808) and to avoid unwanted collisions, a crossing angle is needed to separate the two beams in the part of the machine where they share a vacuum chamber. The size of the crossing angle is limited by the available aperture in the final quadrupole triplet and for high luminosity operation a crossing angle of 285 μrad is planned. For $\beta^* = 0.55$ m this provides a separation d_{sep} above 9 σ. With the bunch spacing of 25 ns this leads to a total of 120 long-range beam-beam interactions

Chou W. & Ritson D. LHC Project Report 123 (1997)

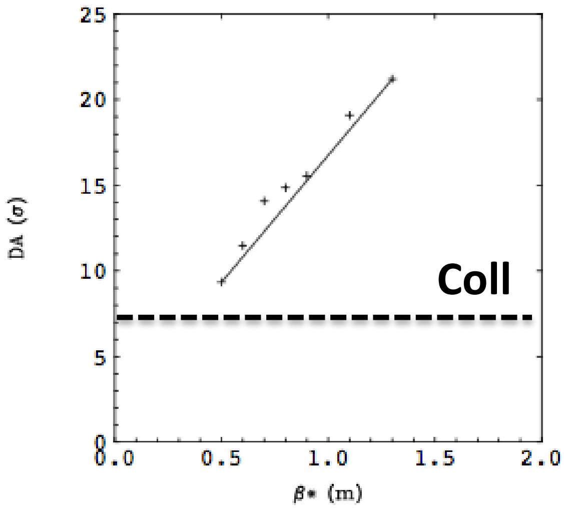


Figure. 1. The scaling of dynamic aperture *vs.* β^* when the beam separation is kept constant at 9.5σ. It is approximately linear.

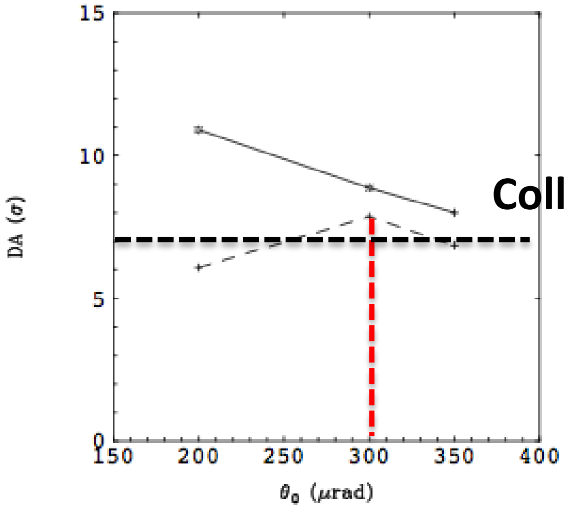
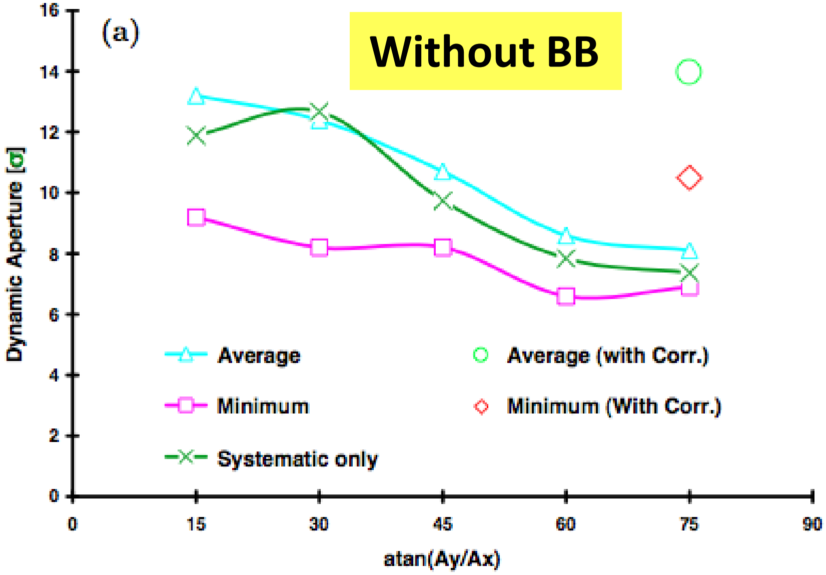


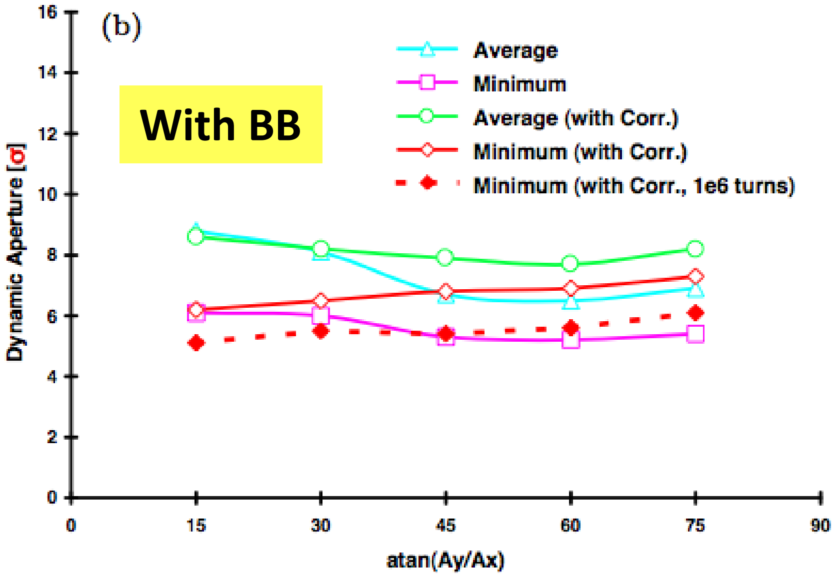
Figure. 3. Dynamic aperture *vs.* crossing angle: The solid curve is the case when there are magnet errors but no beam-beam. The dashed one is when both magnet errors and beam-beam interactions are present. Below 300 μrad, the beam-beam is dominating, while above that, the triplet errors seem to take over.

JJIP code
Intensity 1 e11 ppb
30 LR per IP (IP1 and IP5)
10^5 turns DA
Requirements: DA > 7σ (primary collimator location)

Maximum DA achieved at 300 μrad equivalent to 9.5 σ

H. Grote, F. Schmidt et Leunissen
LHC Version 5: Project Note 197





SIXTRACK Simulations

Spike of chaotic behavior are not representative of long term losses

Particles show spikes of chaotic motion between 4-6 σ

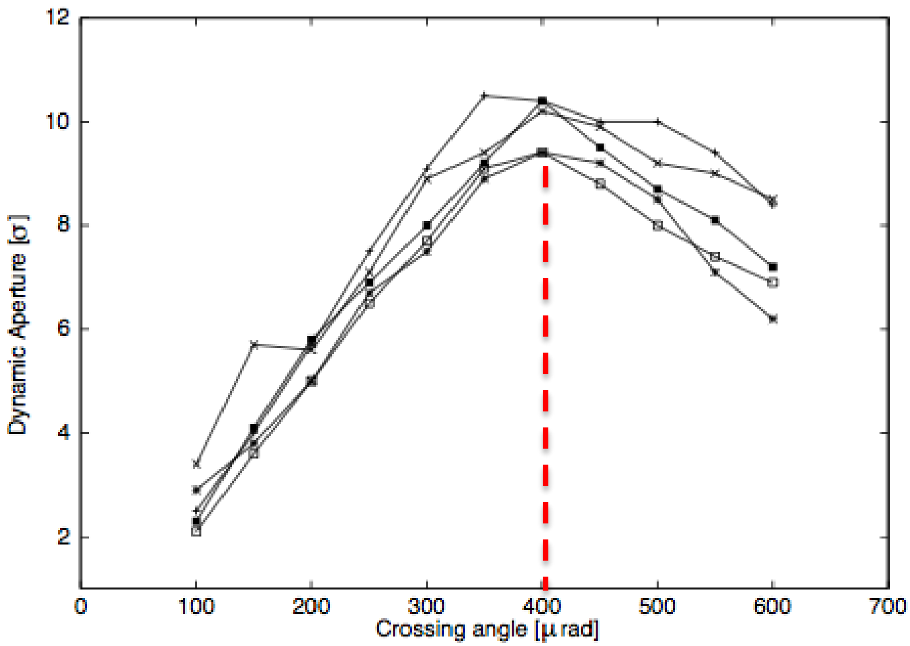
Introduce the concept of 10^6 turns for long term tracking with beam-beam, actually longer is the better!

Studies showed loss of DA of 1 σ

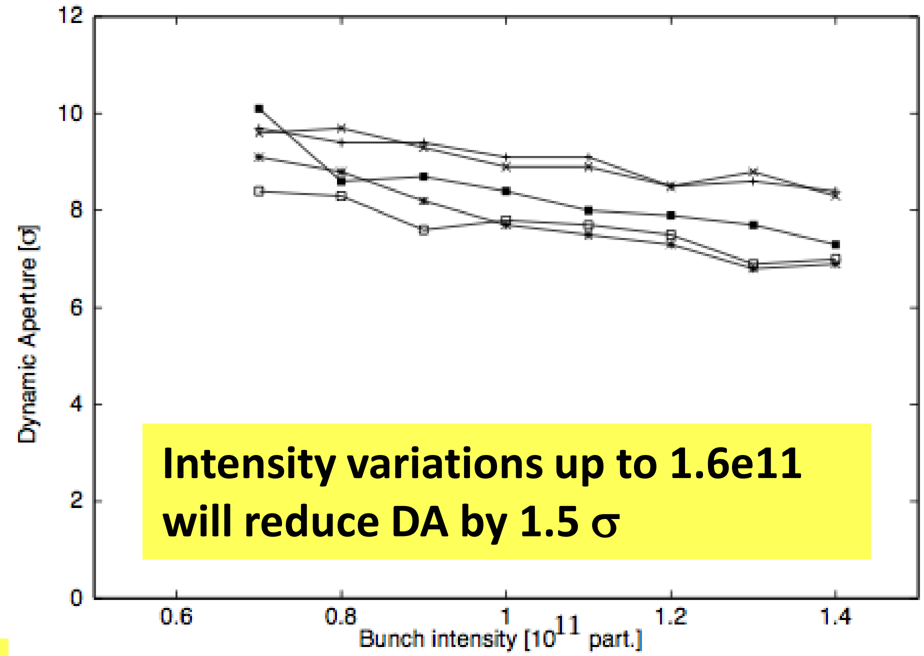
New BB standards…10^6

Nominal 1e11 ppb, emittances 3,75 μm

H. Grote, F. Schmidt et Leunissen
LHC Version 5: Project Note 197



New limit from triplet errors at 400 μrad



Intensity variations up to 1.6e11 will reduce DA by 1.5 σ

effective for the case without the beam–beam interaction. But there is also a considerable improvement when this interaction is included, resulting in a minimum dynamic aperture of some 6 σ for 10^5 turns. However, as the motion becomes strongly chaotic at just 4 σ the minimum dynamic aperture reduces further to 5 σ when the tracking is prolonged to 10^6 turns. It is therefore advisable to increase the total crossing angle to 400 μrad which results in a net gain of roughly 2 σ. This gain should not lead to a substantial loss in luminosity since the particle intensity can be adjusted without noticeable change in the dynamic aperture.

LHC DA dominated by Long-range interactions: scaling laws

Tune shift scaling

$$\Delta Q_{LR} \propto N_p$$

$$\Delta Q_{LR} \propto \epsilon$$

$$\Delta Q_{LR} \propto 1/d_{sep}^2 \propto \frac{1}{\alpha^2}$$

$$\Delta Q_{LR} \propto 1/d_{sep}^2 \propto \frac{1}{\beta *}$$

DA scaling laws

$$DA \propto \frac{1}{N_{LR}}$$

$$DA \propto \frac{1}{N_p}$$

$$DA \propto d_{sep} \propto \frac{1}{\sqrt{\epsilon}}$$

$$DA \propto d_{sep} \propto \alpha$$

$$DA \propto d_{sep} \propto \sqrt{\beta *}$$

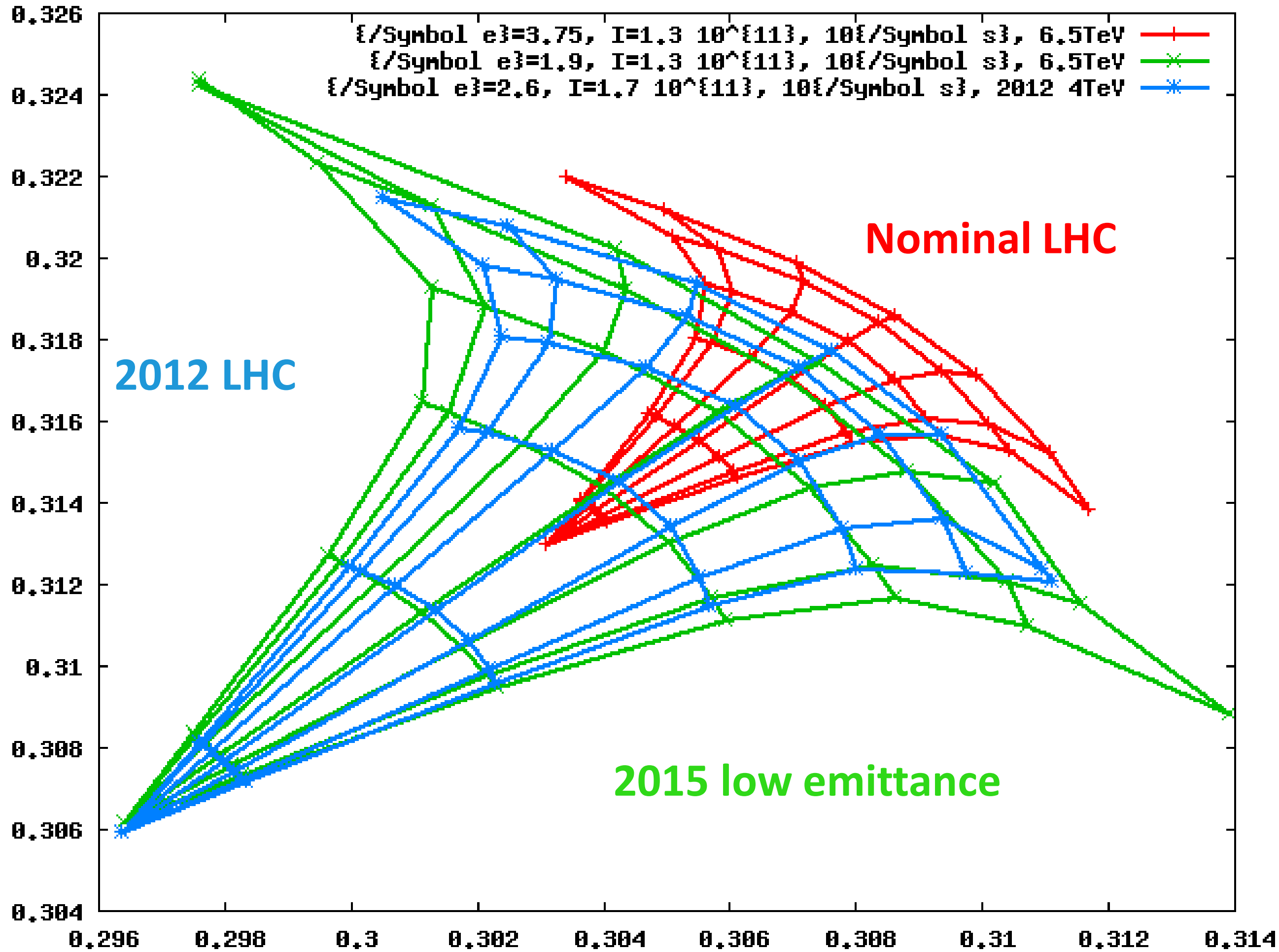
This is valid when the head-on part doesn't change, and DA is fully dependent on Long-range Beam-beam as demonstrated in Luo&Schmidt Project note 290

Example: if emittance (ε) reduced then Intensity (N_p) should be reduced to keep same HO!
Then scaling laws still valid, HO not contributing to DA for nominal LHC!

2012 MDs and physics run

Footprints for Nominal, 2012 run and 2015:

LR separation 10 σ



10-12 σ separation is not an absolute number!

Depends on the beam-beam head-on!

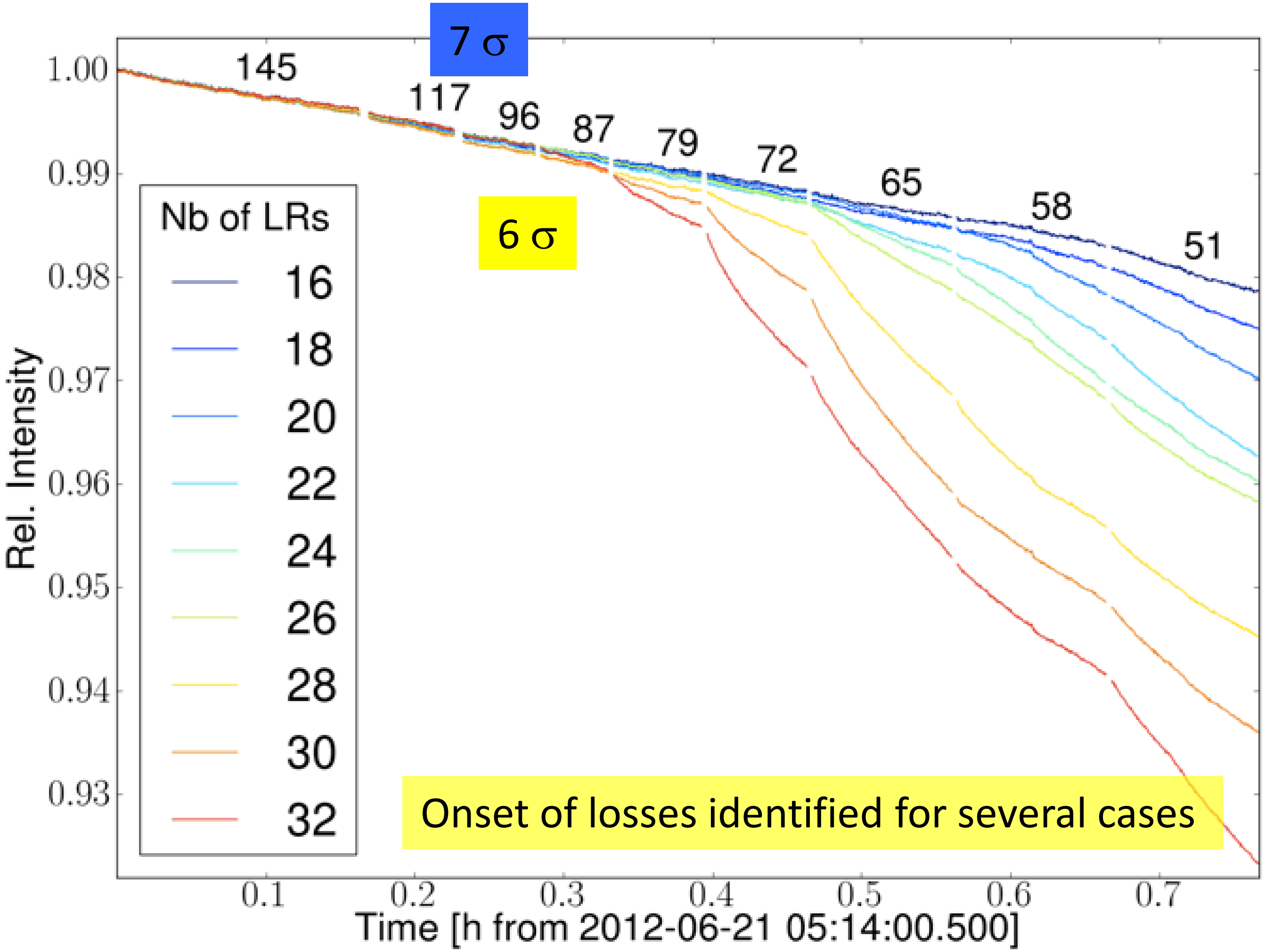
Not the same ΔQ_{LR} if Head-On becomes important!

DA changes and other mechanism could enter!

BB LR experiment Note:

very similar to LHC OP before MYC

1.6 e11 ppb
IP1 crossing angle
Q’ = 2 units



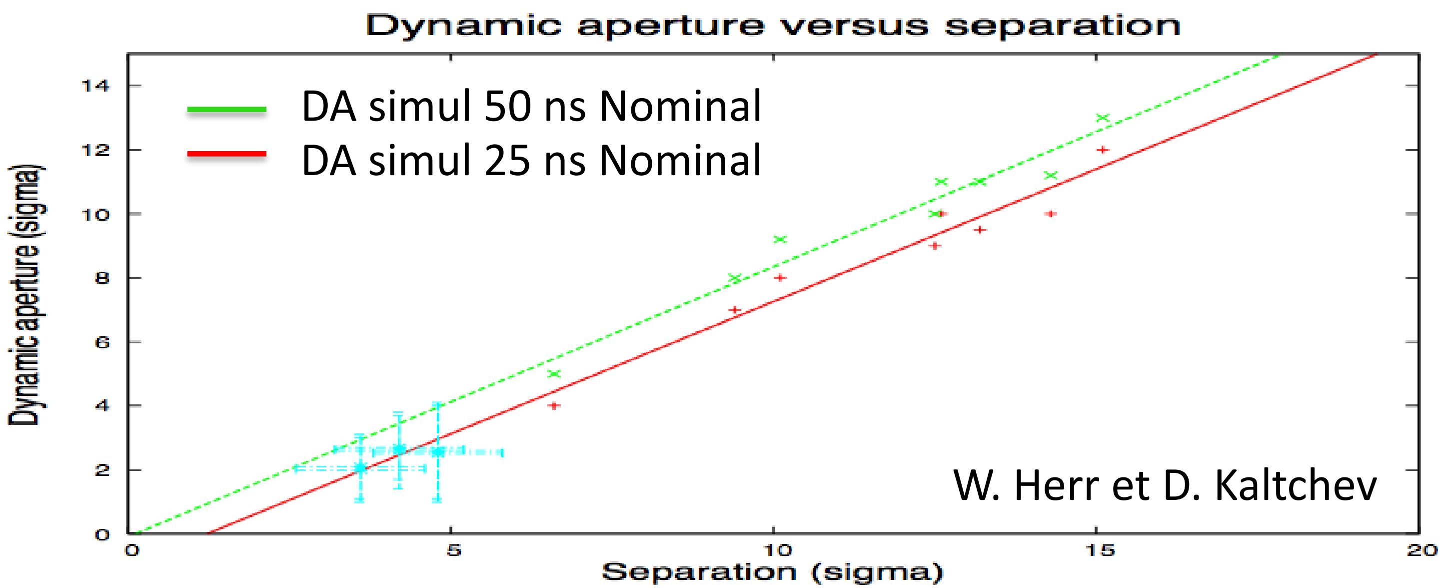
Consistent with expectations from scaling laws : β^*, N_p, α

Lower intensity 1.2e11 showed the onset of losses starting at 6-5 σ separation

25 ns test not conclusive, e-cloud present difficult emittance estimates, big error bars!

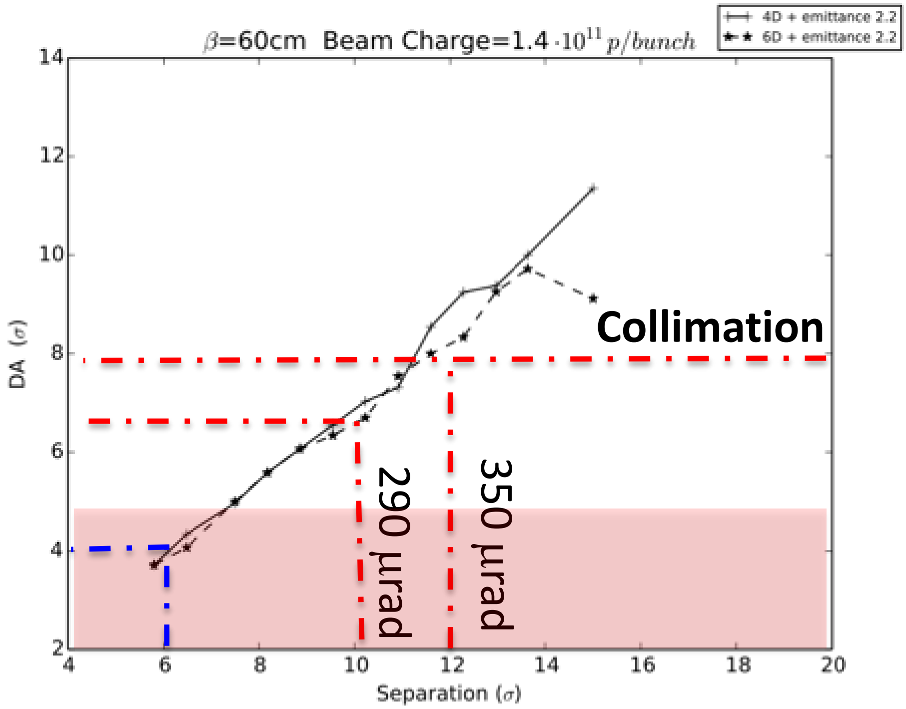
Long Ranges MDs analysis on MD note 70-2012

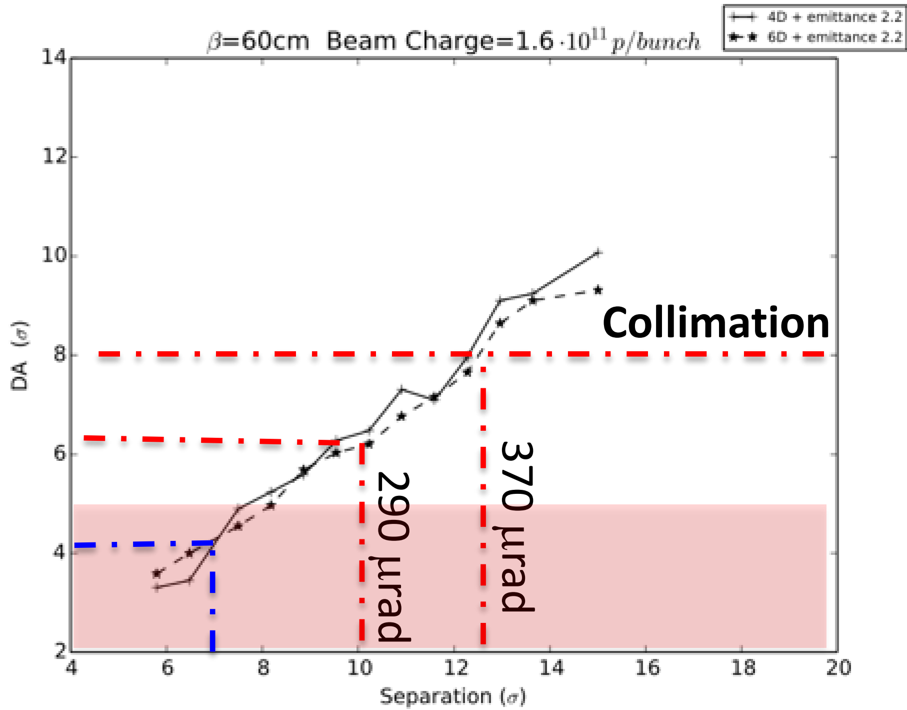
Comparison with our expectations



- **Data estimated from separation scan (50 ns, 3.5 TeV, 1.25 10^{11}p)**
- **Dynamic aperture as function of normalized separation (W.Herr, D.Kaltchev, LPN 416, (2008))**

DA for the Long-range MDs only 50 ns:



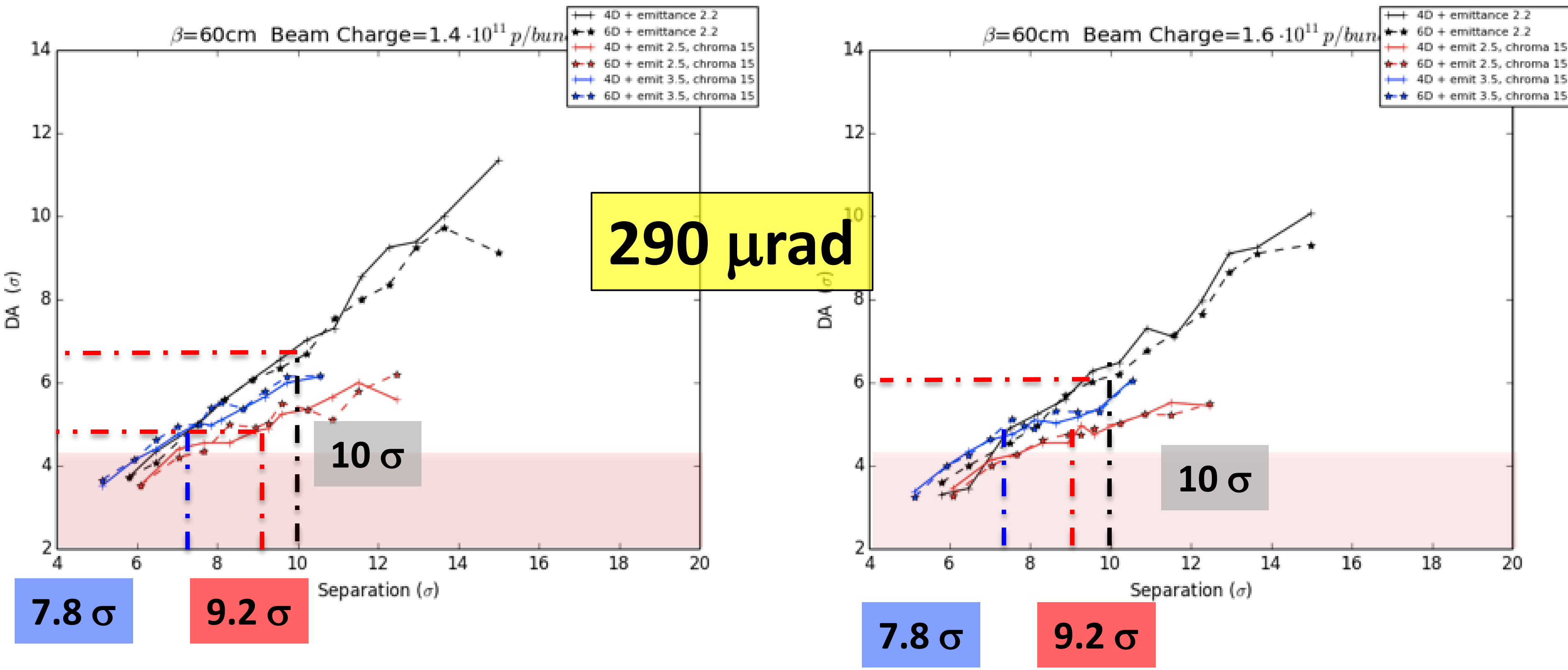


LR MDs:

- **2.2 μm emittances**
- **2 units Q'**
- **Intensities: 1.2 and 1.6 e11**

Significant losses and lifetime drop at 7-6 σ BB separation
Corresponds to 4 σ DA, simulations +/- 1 σ error bar
To guarantee the same DA as Nominal LHC we should have been already at 13 σ

LHC 2012 physics run case after MYC:
Q’ = 15
No Octupoles

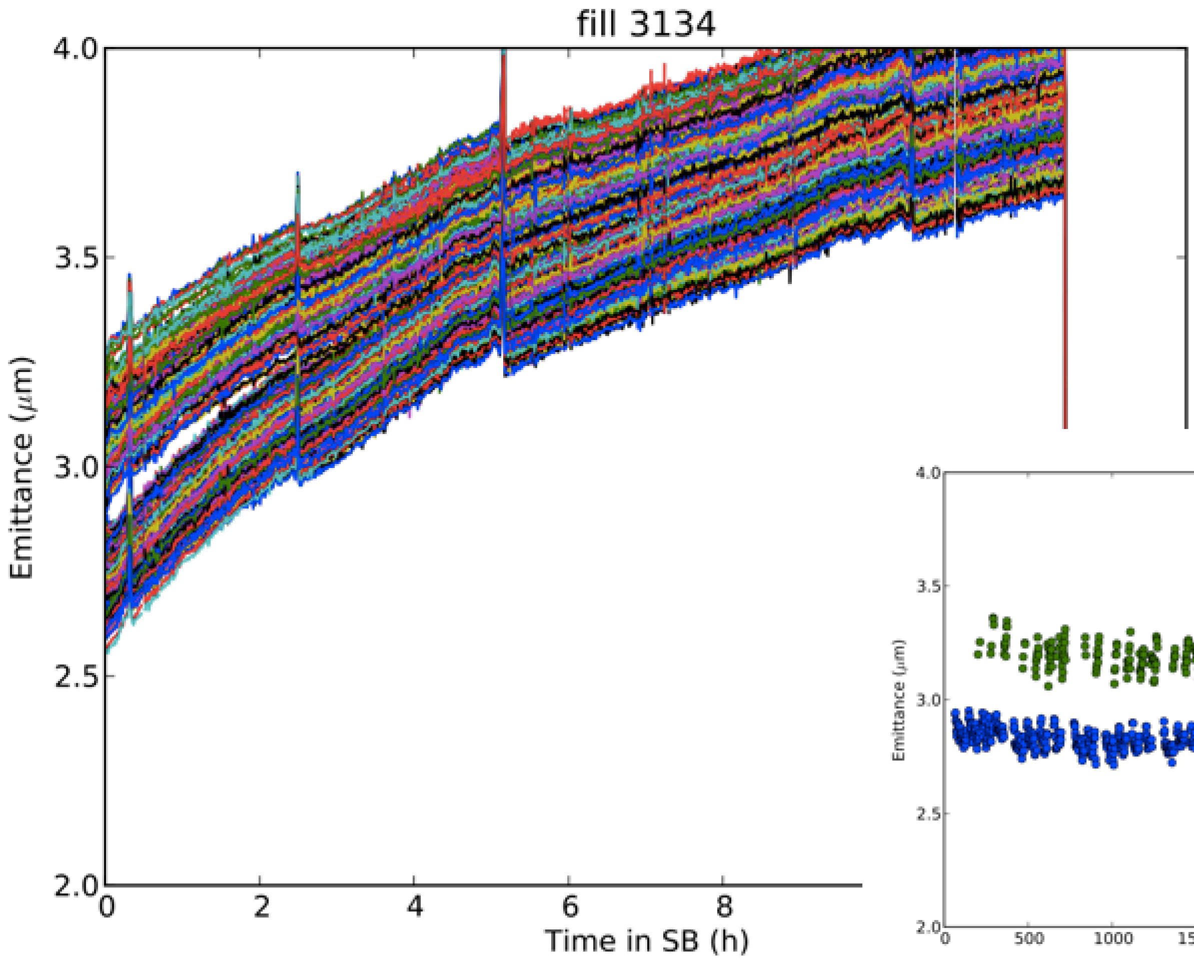


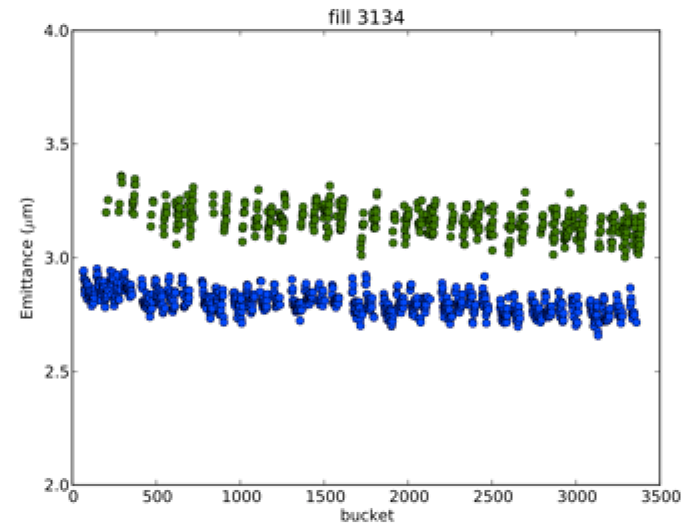
Chromaticity has a BAD impact on DA!

During physics fills without octupoles we were on the limit any particle at 4-5 sigma was lost!

Chaotic motion starts before, 2 sigma particles.

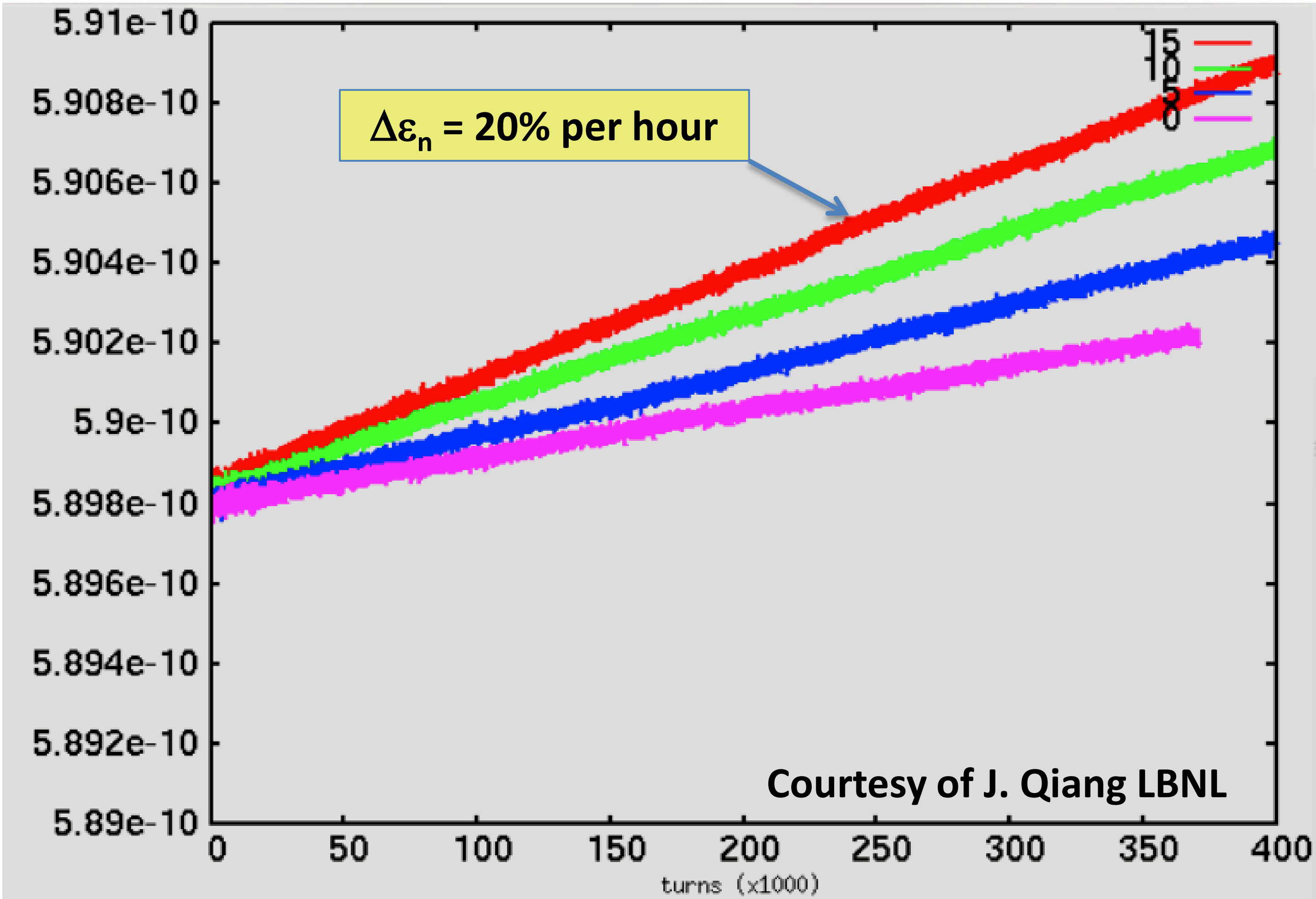
During physics fills also emittance blow-up after MYC:





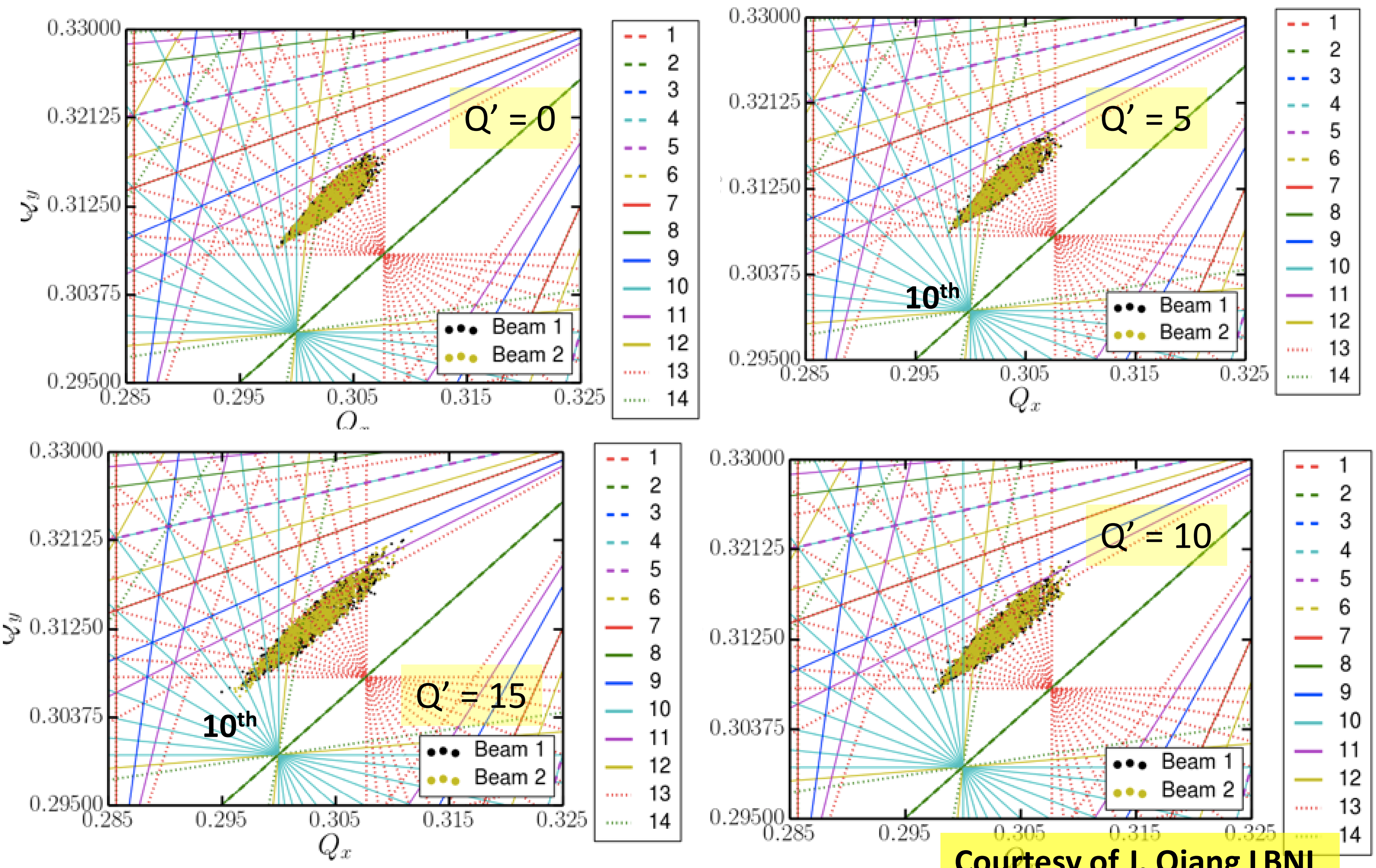
We had emittance blow-up in collision of around 10% per hour
Is it BB related?

Some preliminary and simplified Strong-strong simulations show emittance increase, tails are populated !



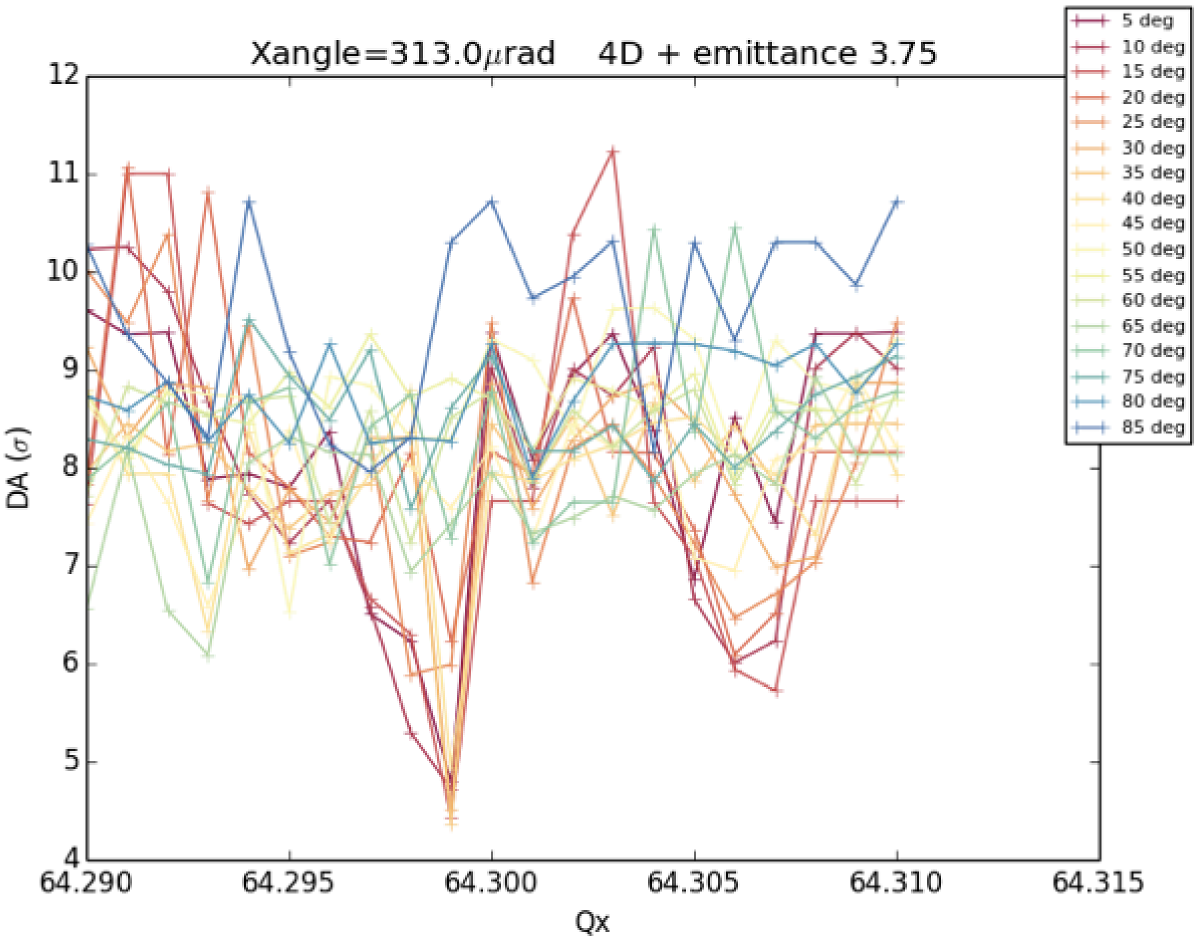
2 Head-on collisions, 2.5 μm emittance, 1.6e11 N_p, ADT on.
Is it driven only by high chroma and resonances? 10th order? 13th order? Which resonance…

Effect of Chromaticity and 10th /13th … order?
Tune is modulated by Q’, particles oscillates and sample further resonances



Courtesy of J. Qiang LBNL

Tune scan of nominal LHC footprint along diagonal

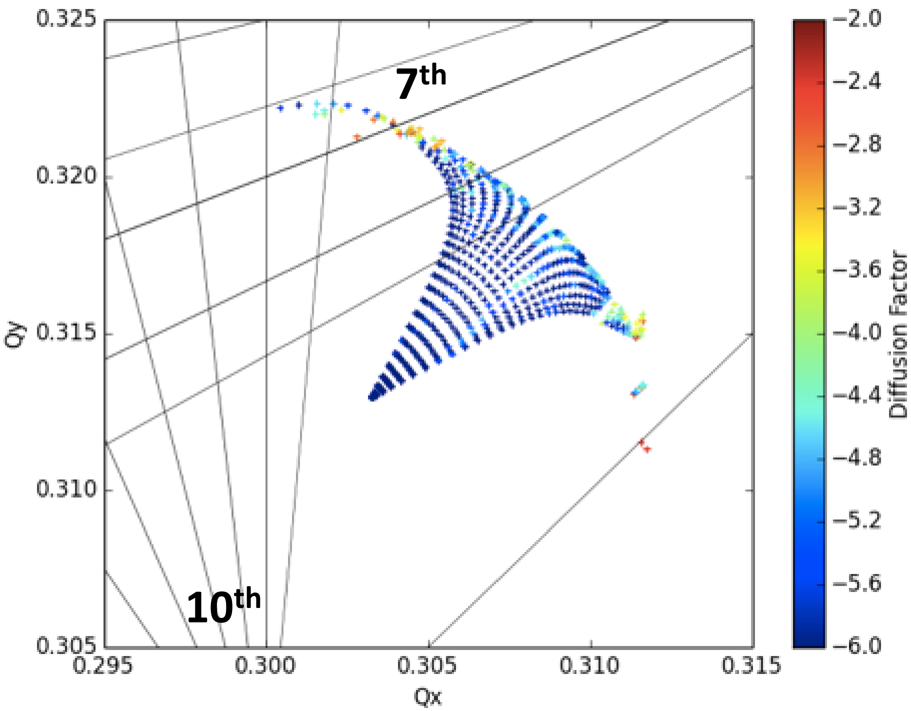


Tune scans with LHC nominal reproducing
W. Herr, D. Kaltchev, E. McIntosh and F. Schmidt LHC-Project-Report 927

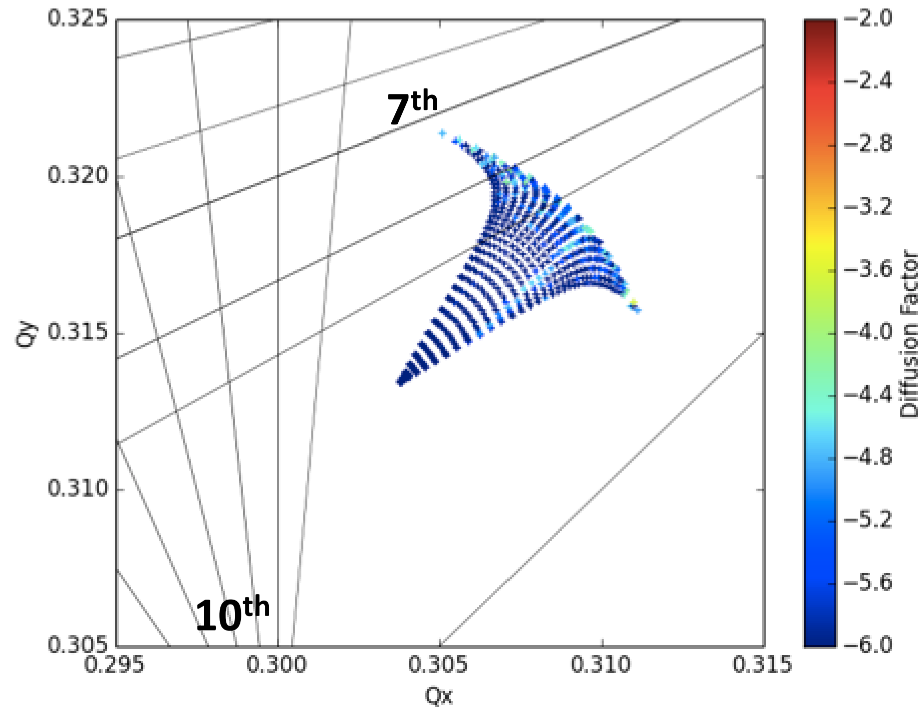
Footprints Nominal LHC 1.3e11

ε = 3.75 μm
N_p = 1.3 e11
β^* = 0.55 m

d = 10 σ



d = 12 σ



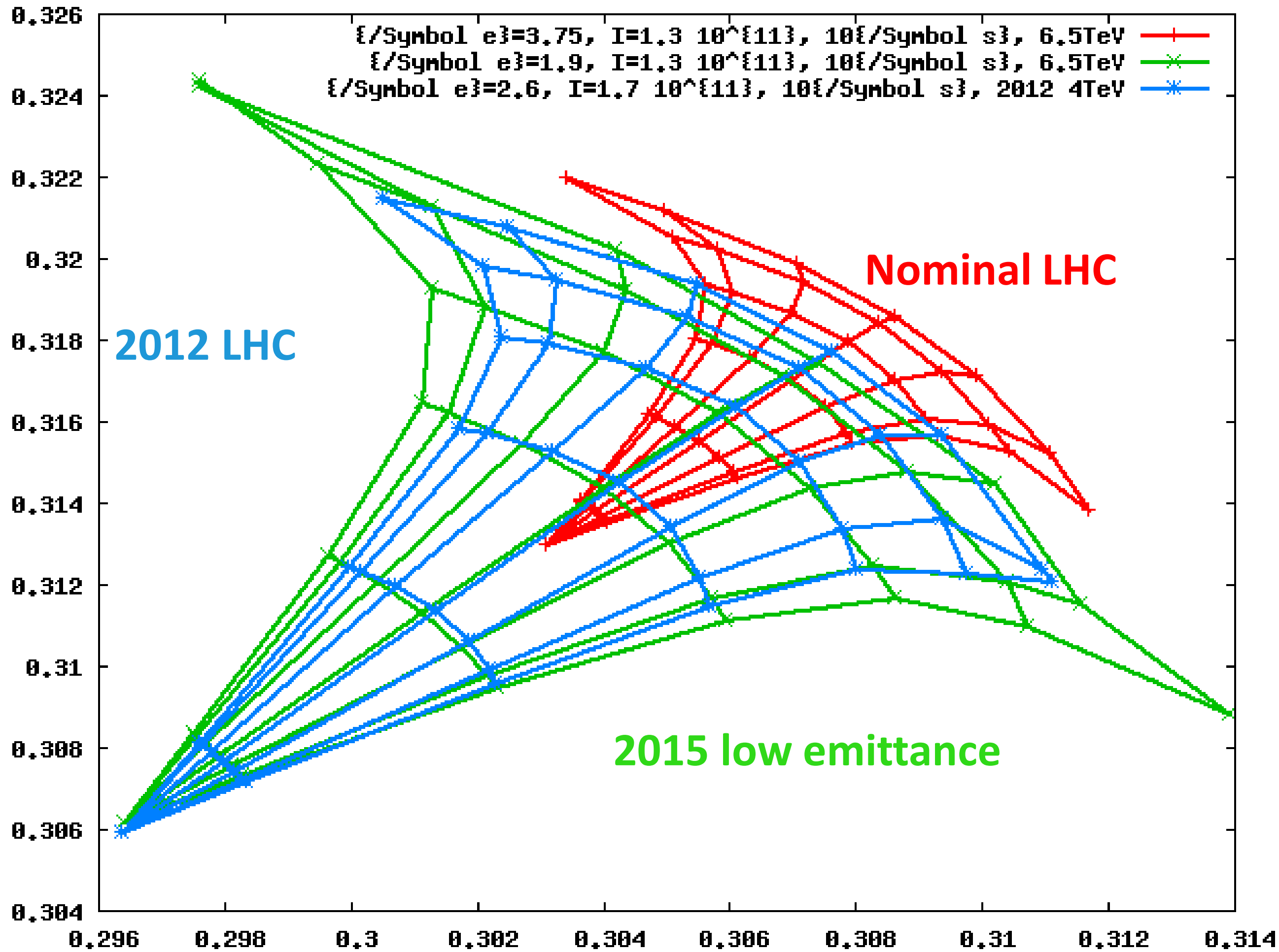
7 – 8 σ particles show chaotic behaviour!

Above 8 - 9 σ particles show chaotic behaviour!

Nominal LHC good but Intensity Maximum 1.4 and emittance 3.75 μm
Other beams need different separations!

Footprints for Nominal, 2012 run and 2015:

LR separation 10 σ

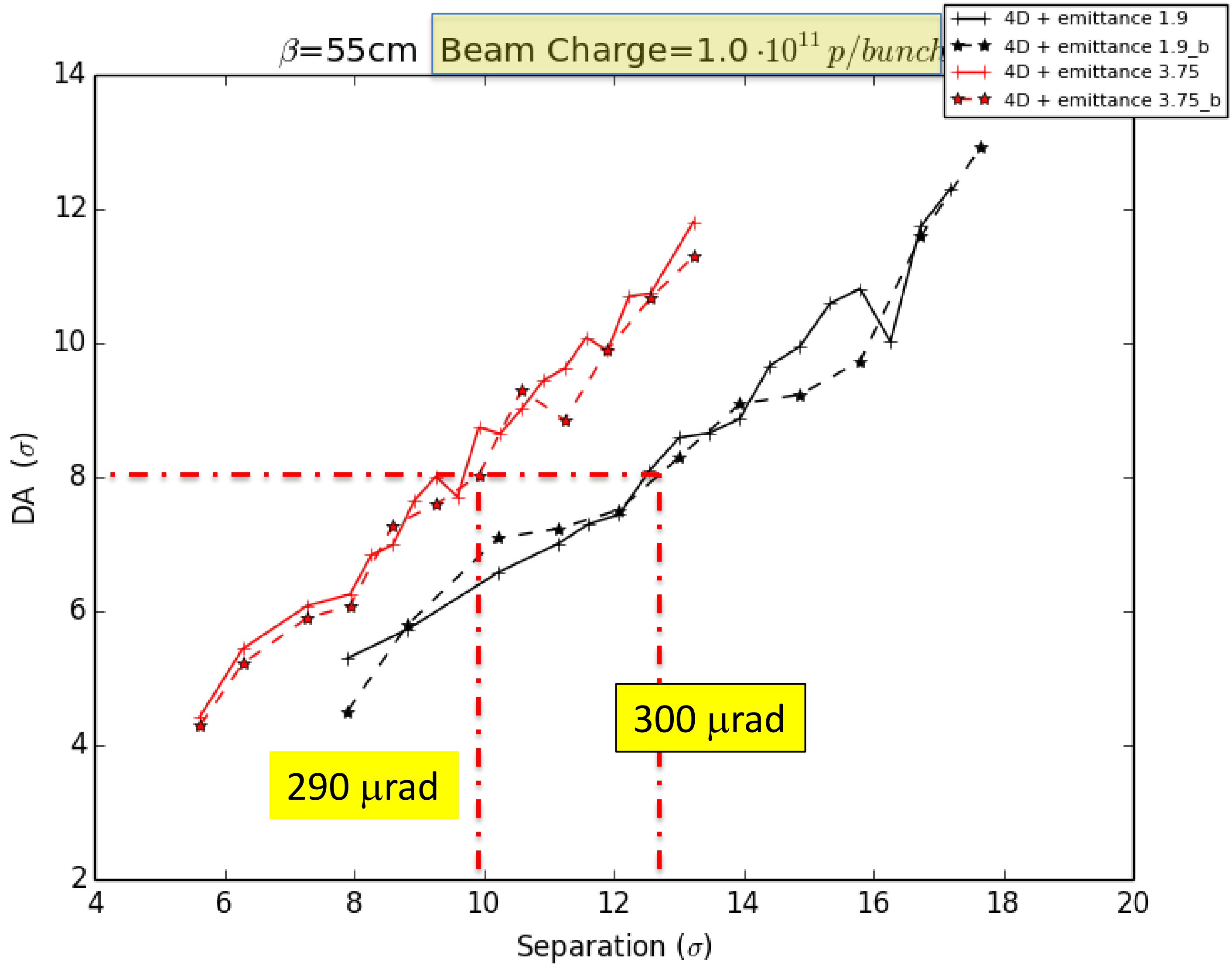


10-12 σ separation is not an absolute number!

Not the same ΔQ_{LR} if Head-On becomes important!

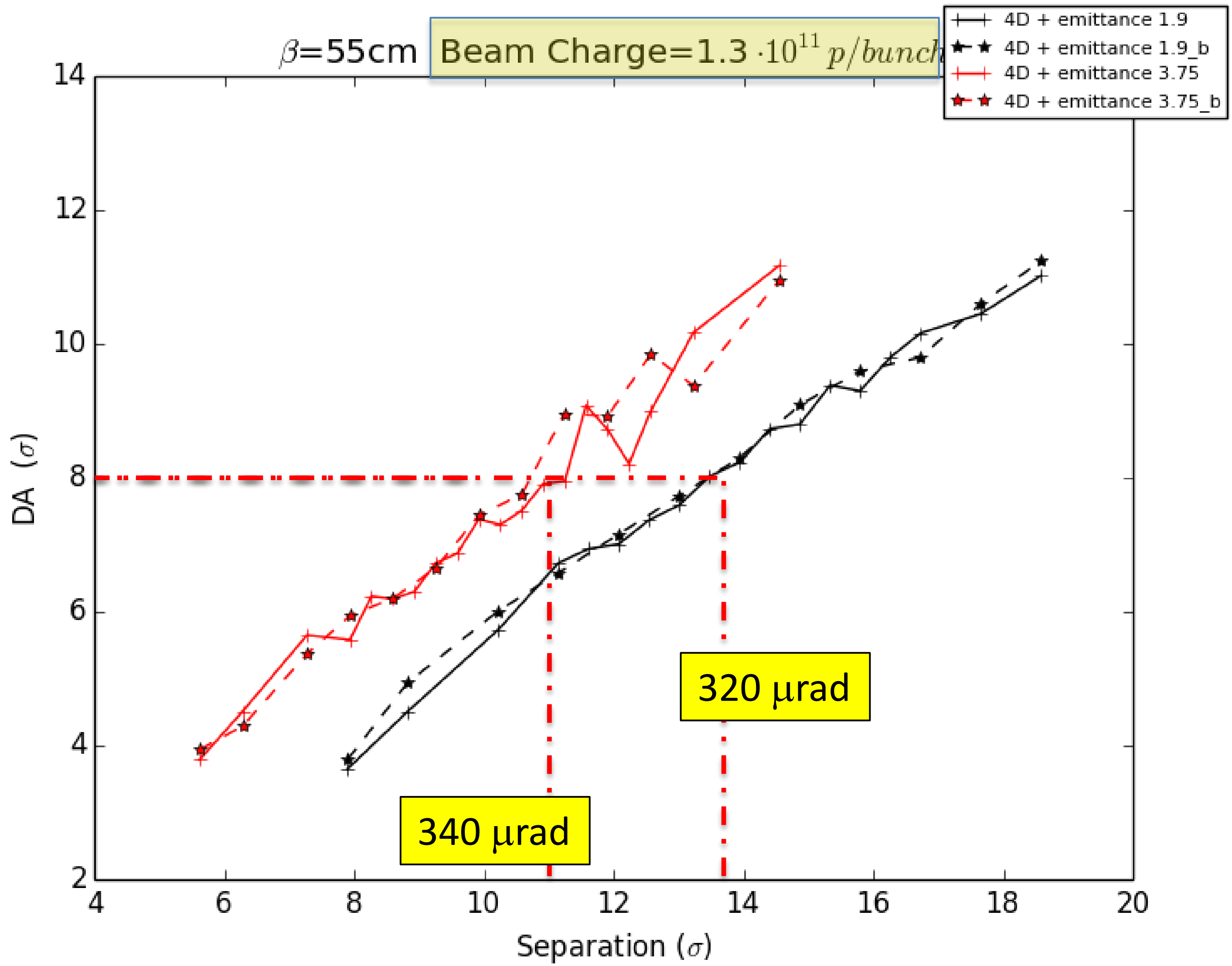
DA changes and other mechanism could enter!

LHC 25 ns nominal and low emittance beams

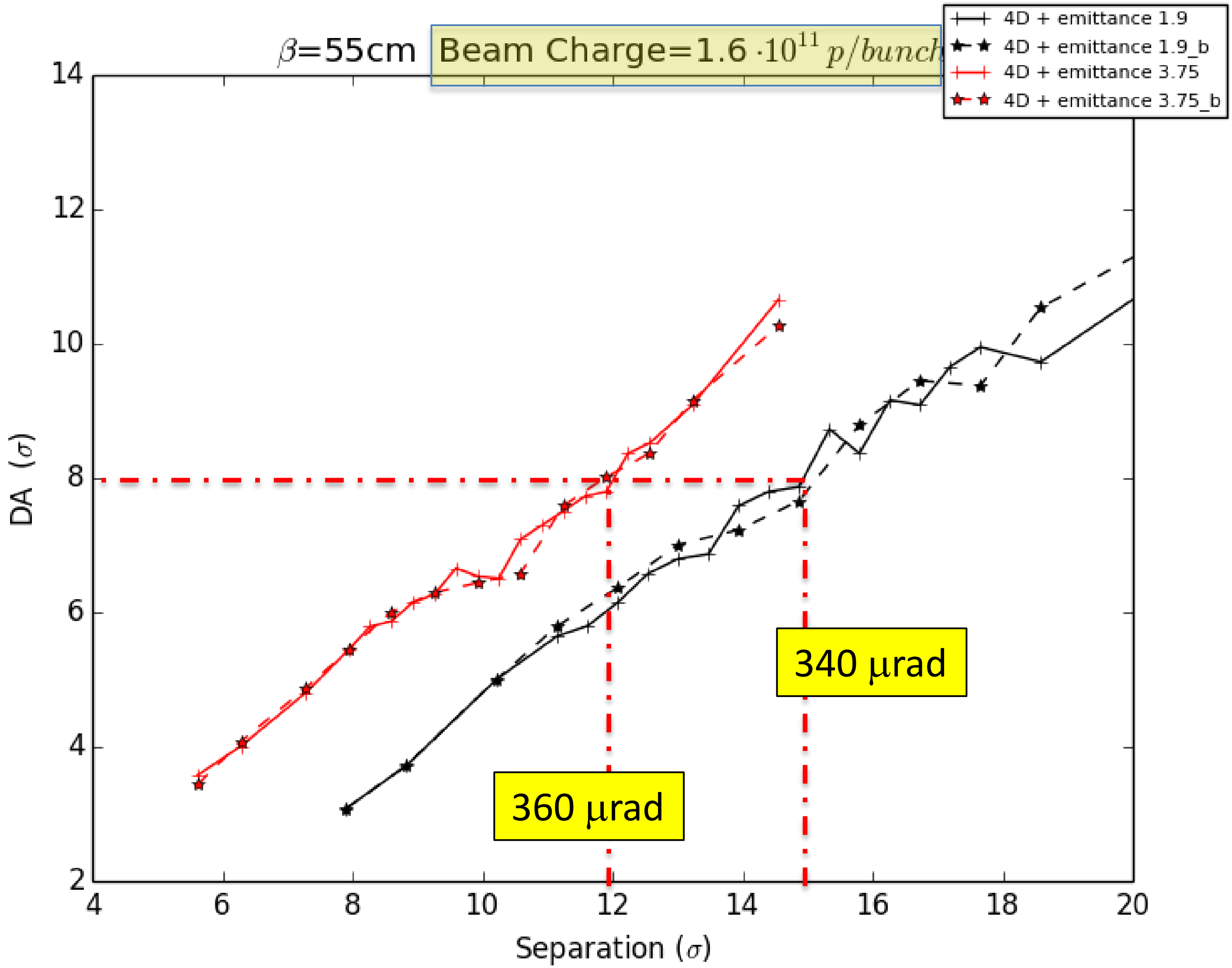


Nominal LHC 10 s separation corresponds to 7-8 s DA for nominal parameters, to obtain the same with smaller emittance beams one needs 13 sigma (HO and long ranges adds-up)

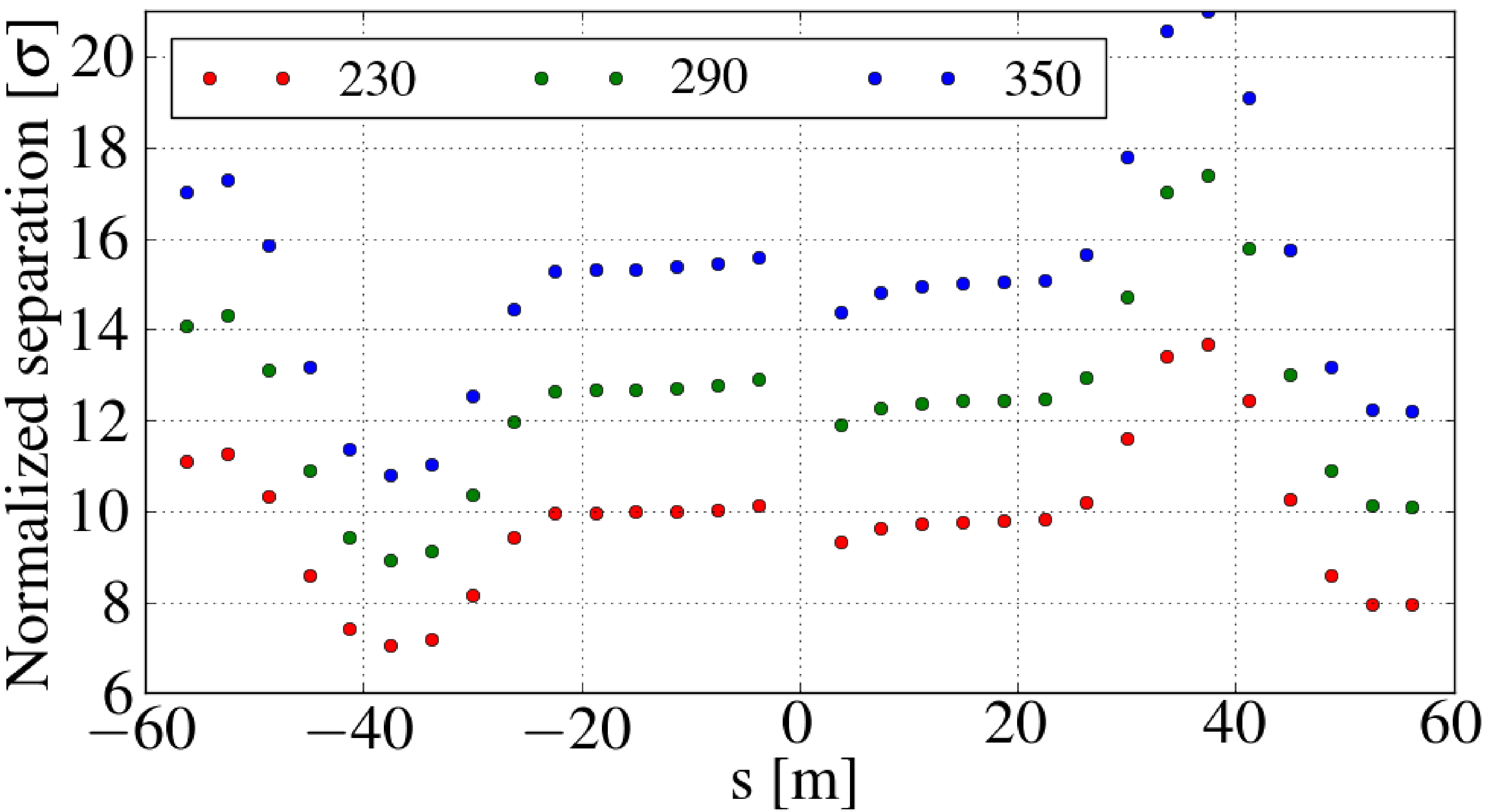
LHC 25 ns nominal and low emittance beams



LHC 25 ns nominal and low emittance beams



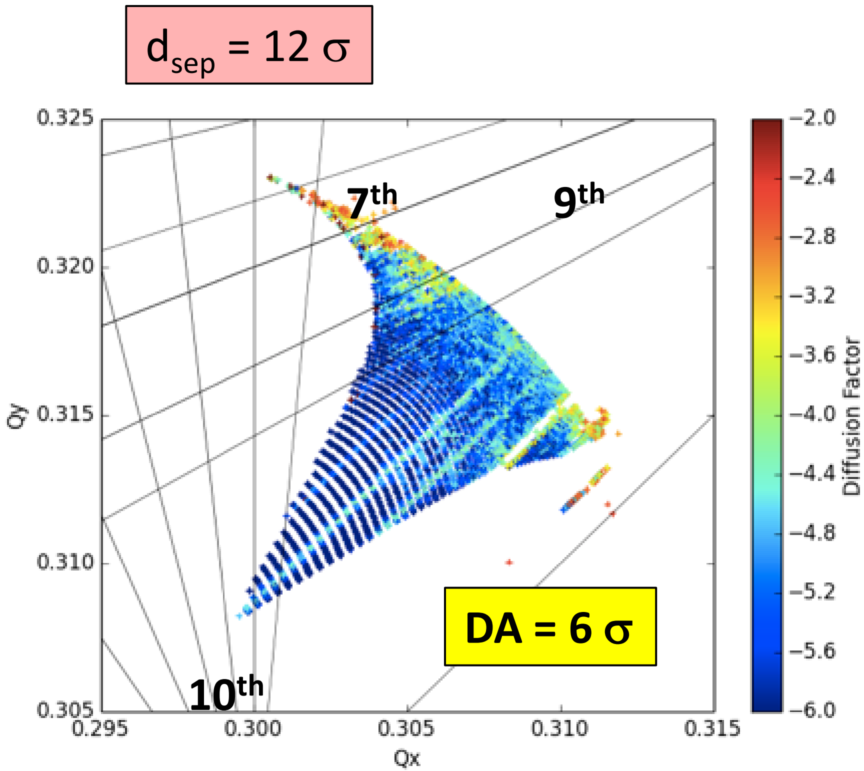
BB separations

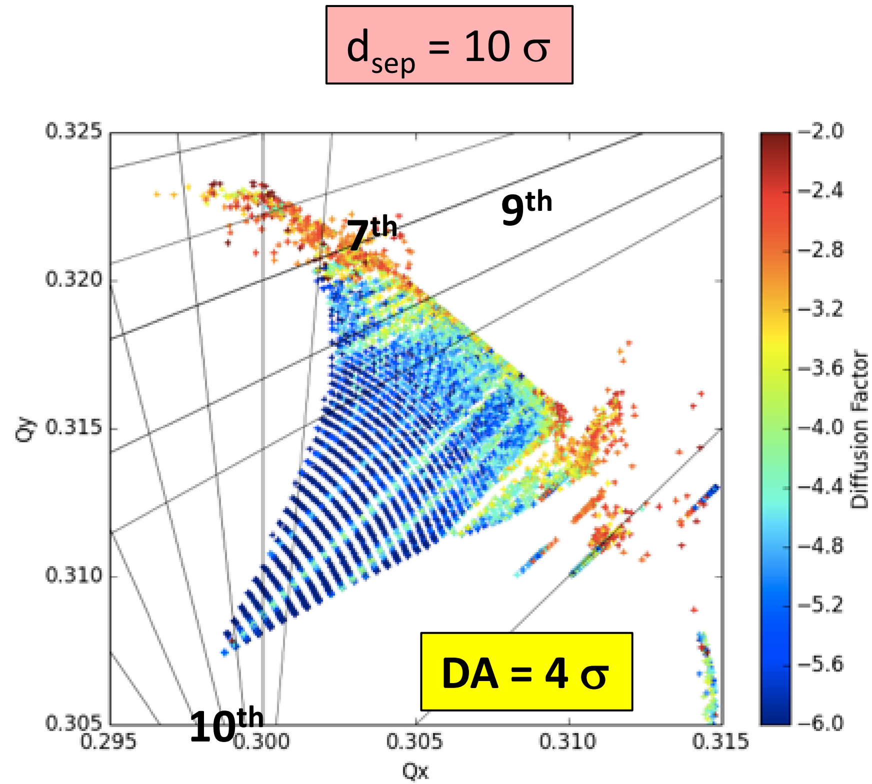


2015 configuration 2 μm emittance and 55 cm β^*

2015 FMA

ε = 1.9 μm
N_p = 1.3 e11
β^* = 0.55 m





We need to identify the resonances and the effects: emittance blow-up, losses…

Specially if have go for high brightness beams (step back to 50 ns or low emittance 25 ns (8b+4e scheme))

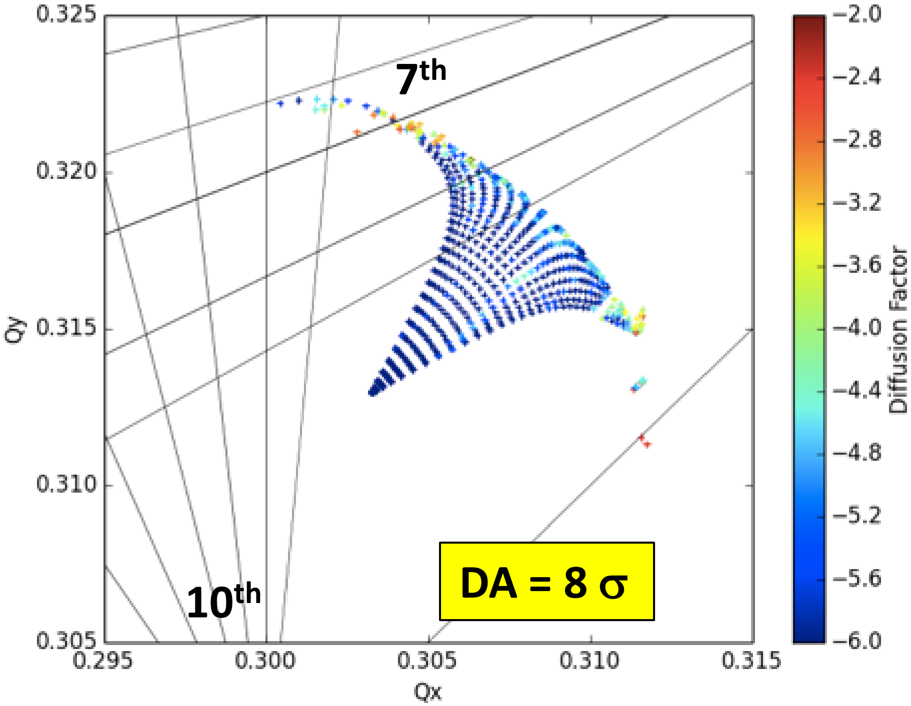
Tune scan needed to find the optimum for head-on!

Then optimize Long-Ranges reducing crossing angle after MD depending on beam parameters!

Footprints Nominal LHC 1.3e11/versus 2 μm

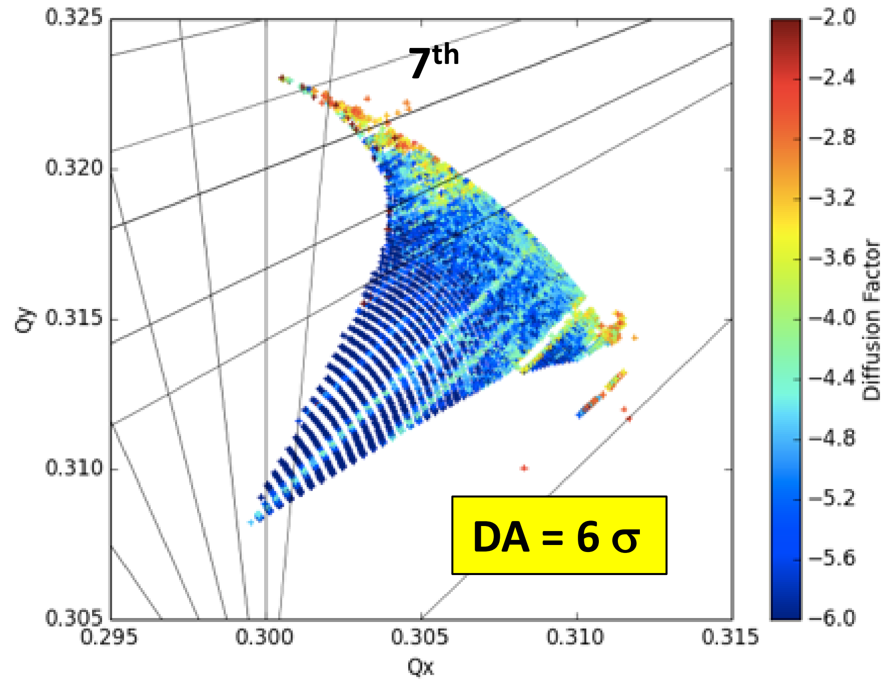
d_{sep} = 10 σ

ε = 3.75 μm
N_p = 1.3 e11
β^* = 0.55 m



d_{sep} = 12 σ

ε = 1.9 μm
N_p = 1.3 e11
β^* = 0.55 m



7 – 8 σ particles show chaotic behaviour!

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Nominal LHC good but Intensity Maximum 1.4 and emittance 3.75 μm
Other beams need different separations!

Summary&Outlook:

- 2012 run:
  - Second part of the year, DA at the limit (4 σ), BB was collimating particles above 4 σ. Q' strong impact on DA.
  - **25 ns MD has to be repeated, emittance estimates big error bars in results!**
  - Emittance blow-up due to Head-on BB, ADT, high chromaticity. Need to find what is causing the blow-up! Is reduced Q' the solution? Are maybe other resonances excited 10^{th} ? Need to find the best working point.

- Nominal LHC is still an optimum scenario (290 μrad) but if we step back to 50 ns and/or want higher brightness beams then we will need larger crossing angle: suggested 340 μrad!
- Crossing angle impact (290 μrad → 340 μrad) on lumi from 84% → 80%.
- Need to analyze data to identify resonance driving the blow-up .
- Make simulations with and without HO but high Q', is it possible that BB was scraping tails?
- What is the impact of other sources of detuning (octupole)?
- In this picture IP8 is transparent, negligible LR contribution (no tune shift)!

Proposed Strategy IP1 and IP5

- Optimize the "head-on" footprint with WEAKER long-range (minimum 340 μrad 12-15 s separation depending on beam parameters)

- Tune scan to identify causes of emittance blow-up: 10th order resonance?

  - Pros: if collide and squeeze required we will have reduced orbit effects!
  - If need to increase chroma for IP8 bunches still some margin

- Test in MD the long-range limit impact when beam parameters are defined, looking also at emittance evolution per step of crossing angle and a tune scan to identify LR driving resonances (7th, 9th, diagonal)

- Reduce in second stage crossing angle accordingly with experiments on 25ns beams

For all cases Chromaticity as low as possible in collision if possible

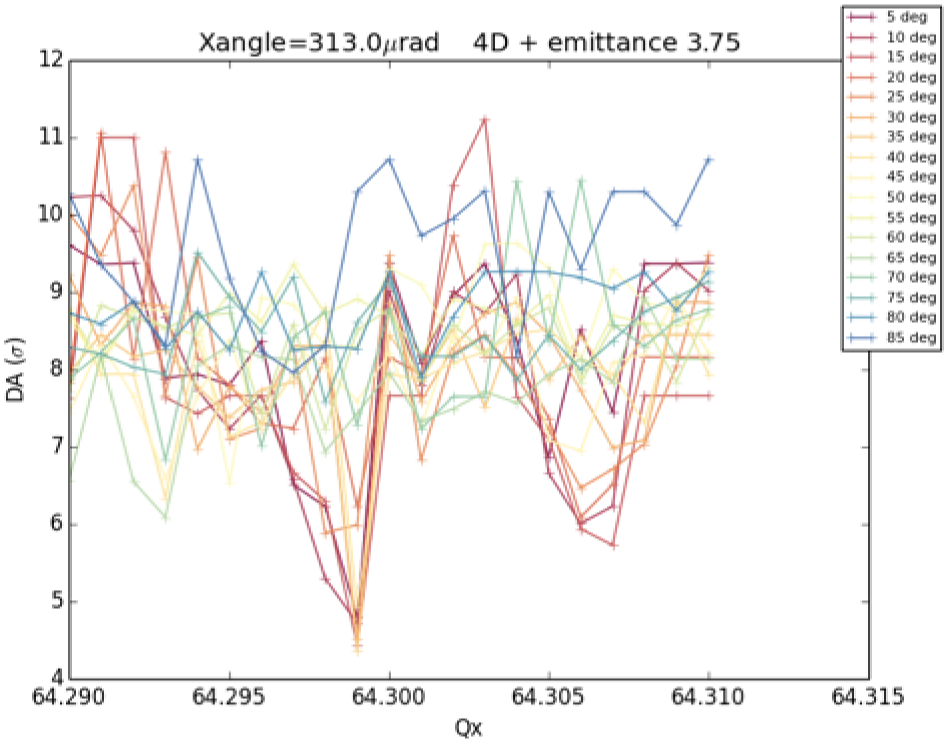
Summary of crossing angle versus beam

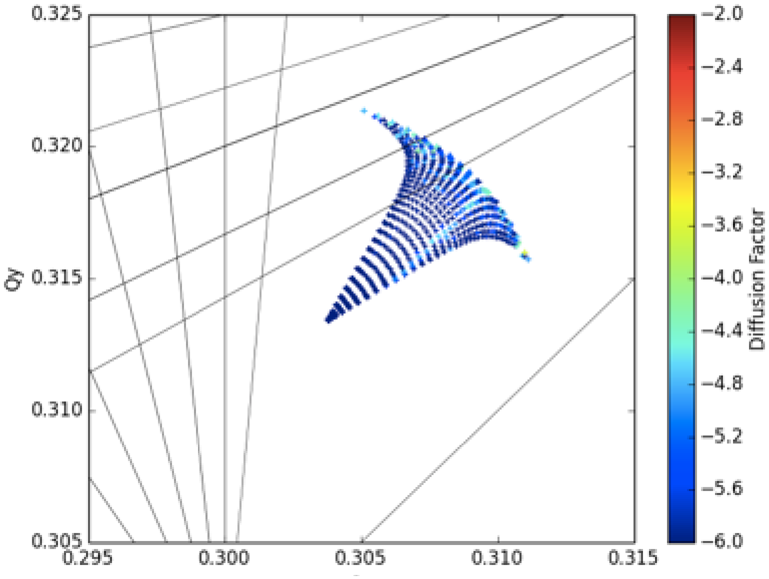
	Crossing angle	BB Separation	Crossing angle	BB Separation
Standard LHC (3.75 μm, 1.3e11 ppb max)	**340 μrad**	**11 σ**	**255 μrad**	**8 σ**
BCMS (1.9 μm,1.3 e11 ppb max	**320 μrad**	**13.5 σ**	**245 μrad**	**11 σ**

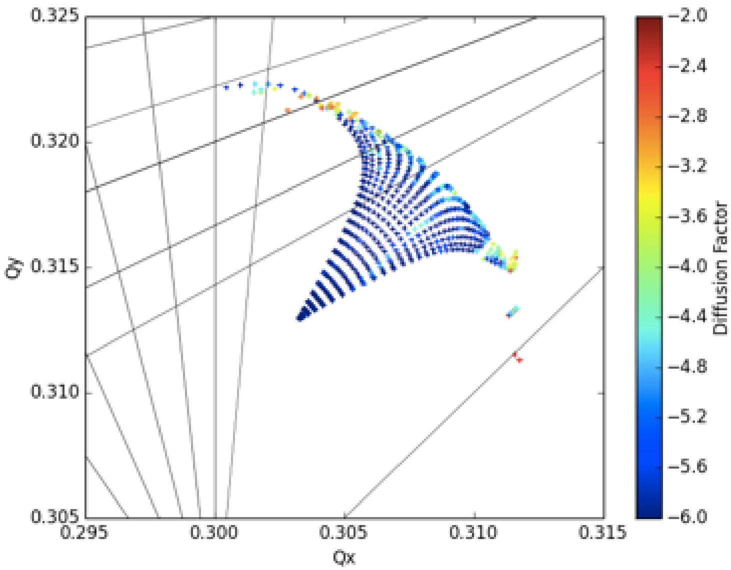
8 σ
Dynamic Aperture

6 σ
Dynamic Aperture

3.75 2012 1.3e11 10 vs 12 sigma







Reference to paper werner with tune scans