Criteria for dynamic aperture limits and impact of the multipolar errors: summary of the simulations with beam-beam for levelling scenarios at 5 and 7.5x10^{34}

T. Pieloni, D. Banfi, J. Barranco
for the LHC and HL-LHC Beam-Beam Teams

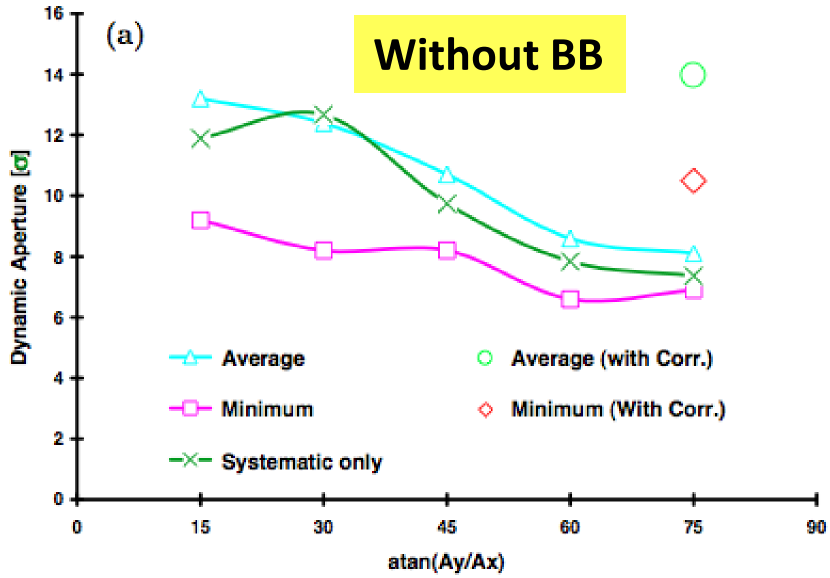
Acknowledgements: X. Buffat, C. Tambasco, G. Arduini, A. Valishev, W. Herr, M. Giovannozzi

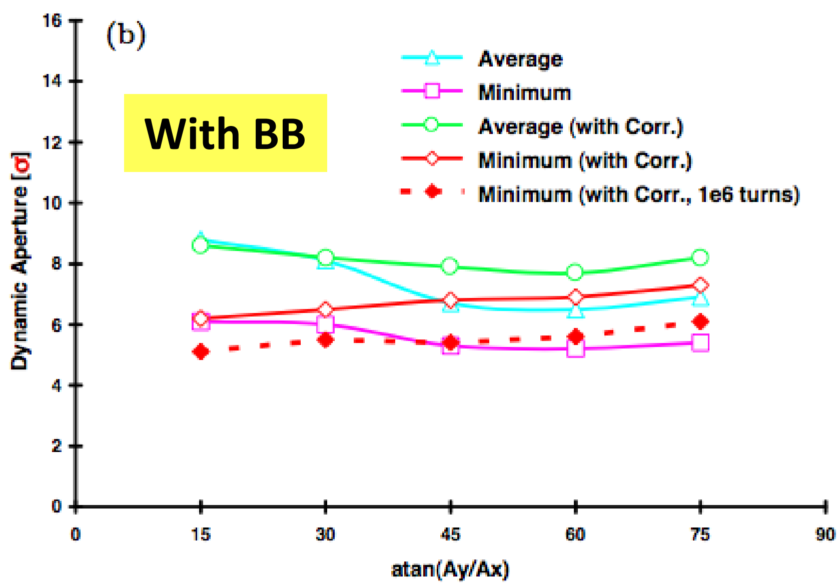
4th Joint HiLumi LHC-LARP Annual Meeting
Nov 17-21 KEK, Tsukuba, Japan

Outline

- **DA studies for the LHC**
- **Experiments in the LHC 2011/2012 runs**
- **HL-LHC criteria and studies**
  - **IP1&5**
  - **IP8&2**
  - **Multipolar Errors**
- **Non-colliding bunches and instabilities: Q’ & Octipoles**
- **Summary**

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

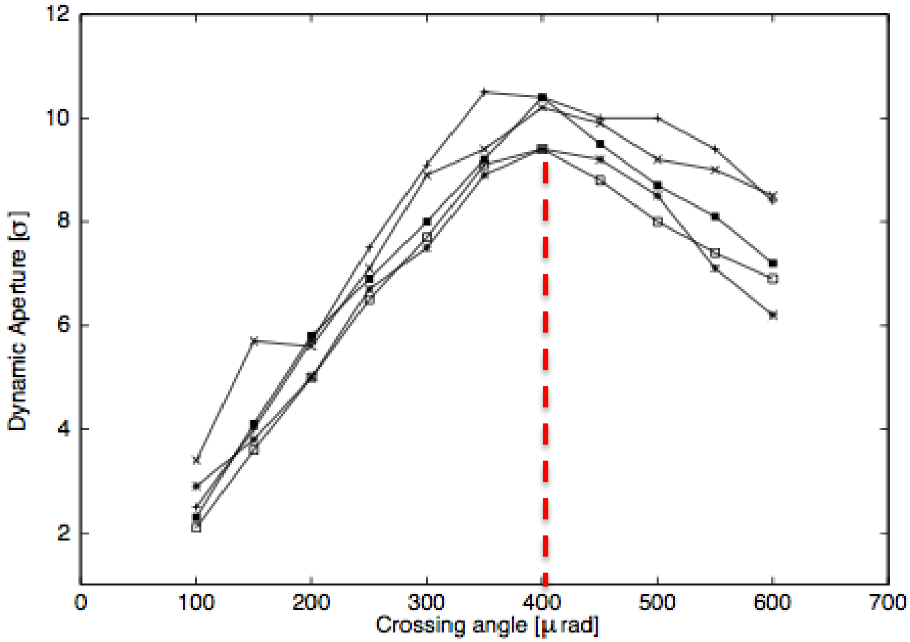


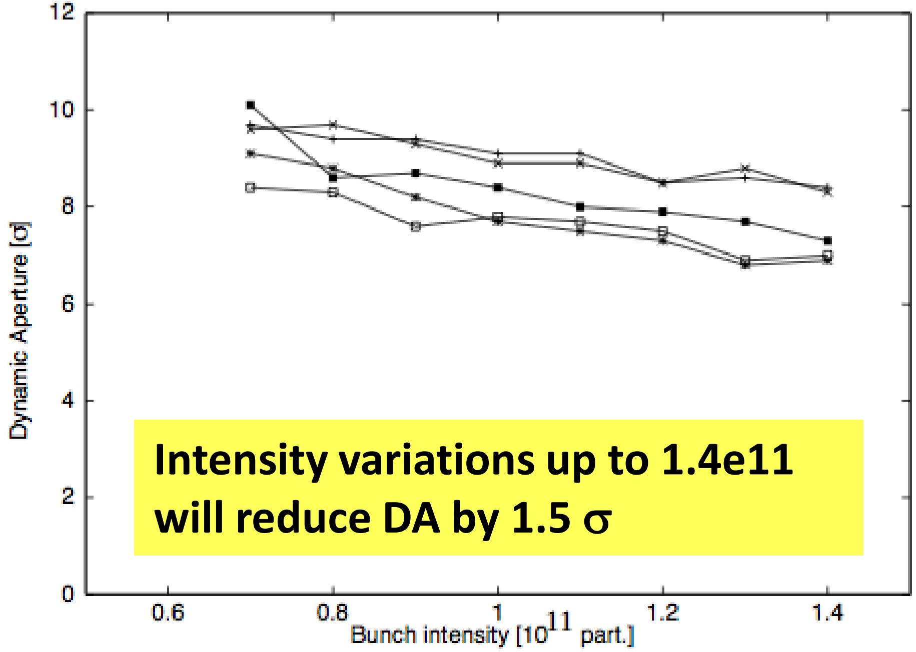


SIXTRACK Simulations set-up

- 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

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





New limit from triplet errors

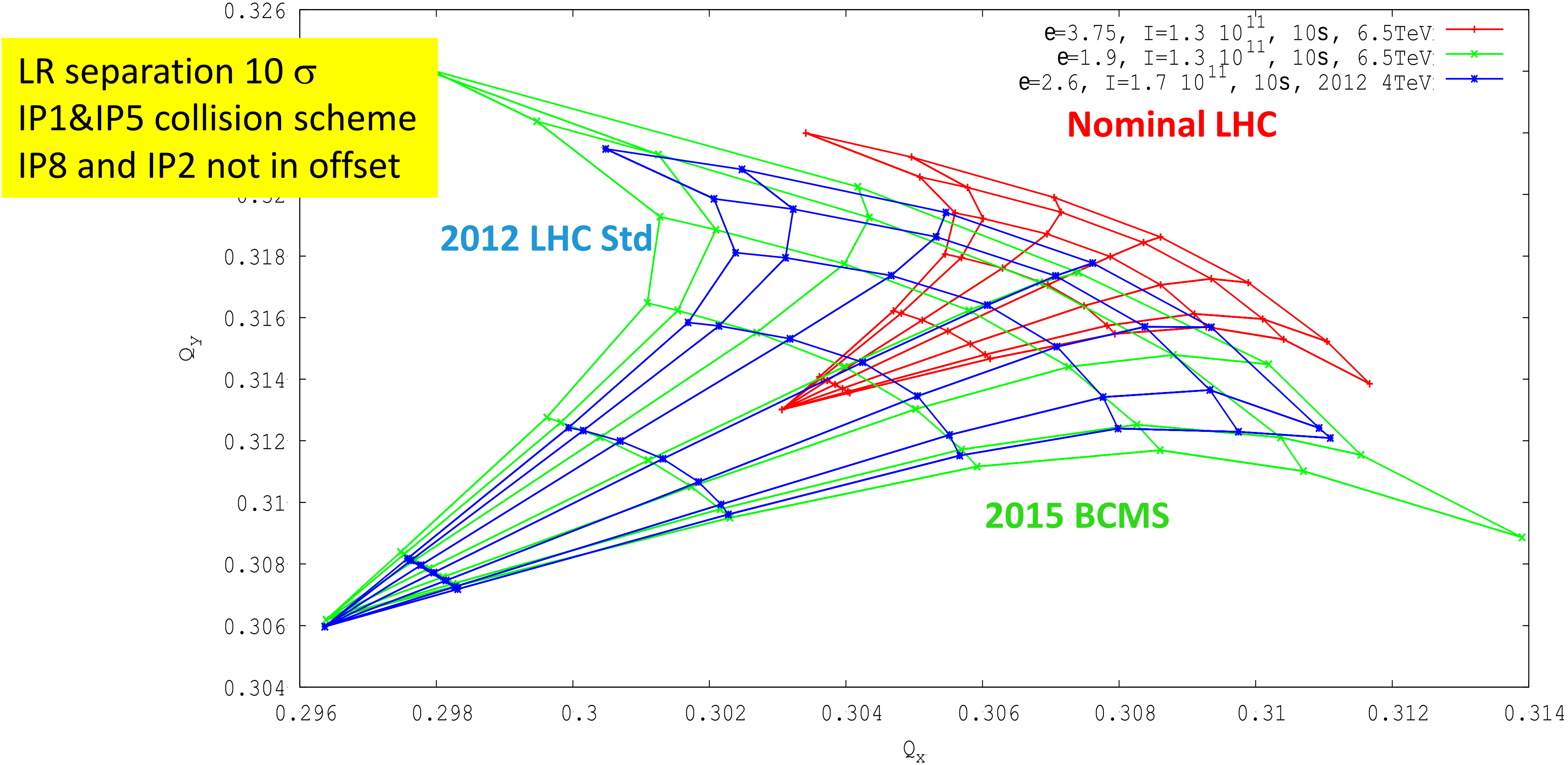
effective for the case without the beam–beam interaction. But there is also a considerable improvement when this interaction is included, resulting in a minimum dynamic aperture of some 6 σ for 10^5 turns. However, as the motion becomes strongly chaotic at just 4 σ the minimum dynamic aperture reduces 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 interactions: scaling laws

Tune shift scaling		DA scaling laws
$\Delta Q_{LR} \propto N_p$	**Intensity**	$DA \propto \frac{1}{N_p}$
$\Delta Q_{LR} \propto \epsilon$	**Emittances**	$DA \propto d_{sep} \propto \frac{1}{\sqrt{\epsilon}}$
$\Delta Q_{LR} \propto 1/d_{sep}^2 \propto \frac{1}{\alpha^2}$	**Crossing-angle**	$DA \propto d_{sep} \propto \alpha$
$\Delta Q_{LR} \propto 1/d_{sep}^2 \propto \frac{1}{\beta *}$	**β***	$DA \propto d_{sep} \propto \sqrt{\beta *}$
$\Delta Q_{LR} \propto \#LR$	**Number of LRs**	$DA \propto \frac{1}{\#LR}$

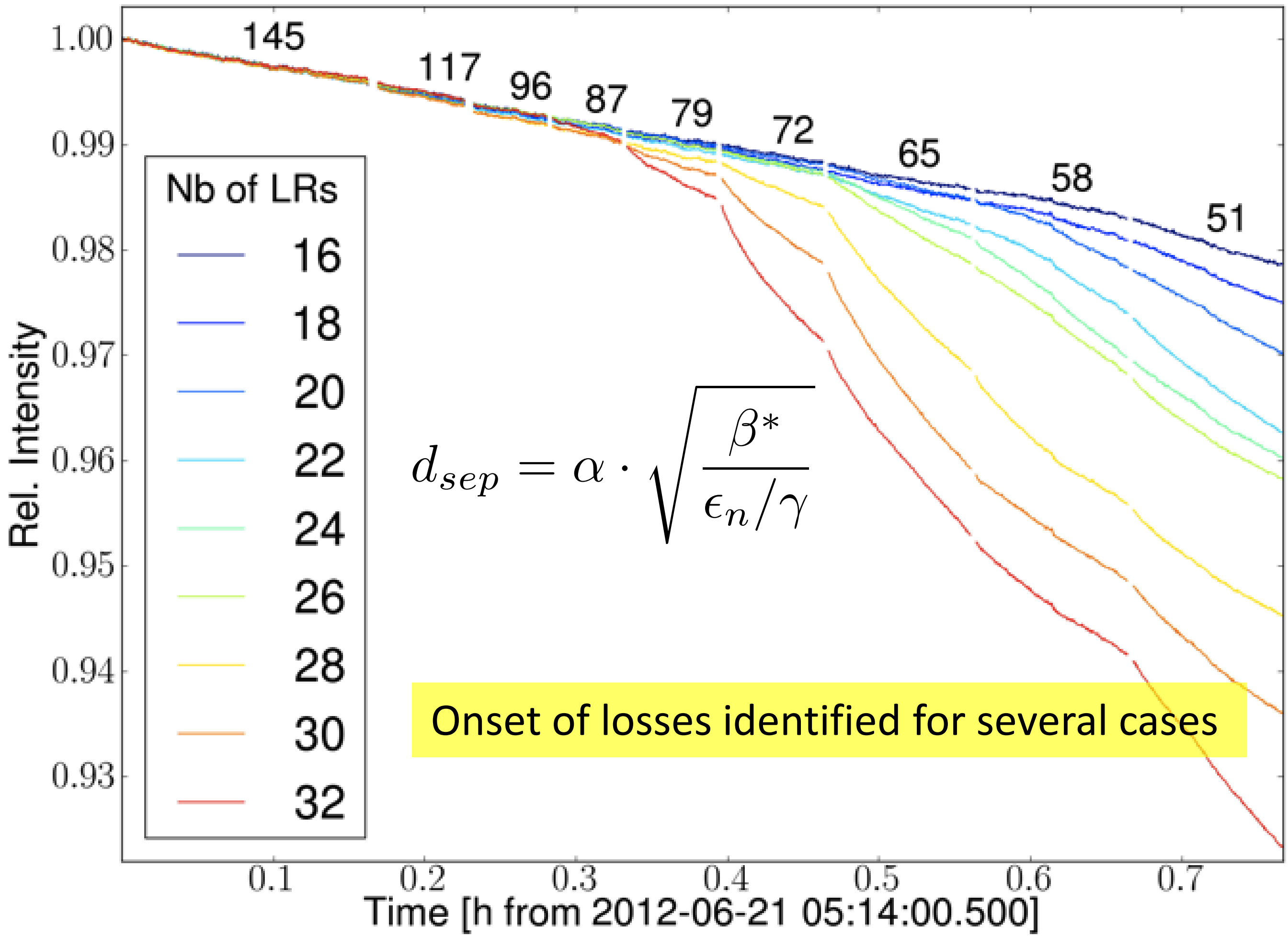
Defined a Head-on set-up then
DA is fully dependent on Long-range Beam-beam interactions as shown in Luo&Schmidt Project note 290

Footprints for Nominal, 2012 run and 2015:



Several Beam-Beam Long Range experiments 2011-2012

CERN-ATS-Note-2012-070 MD



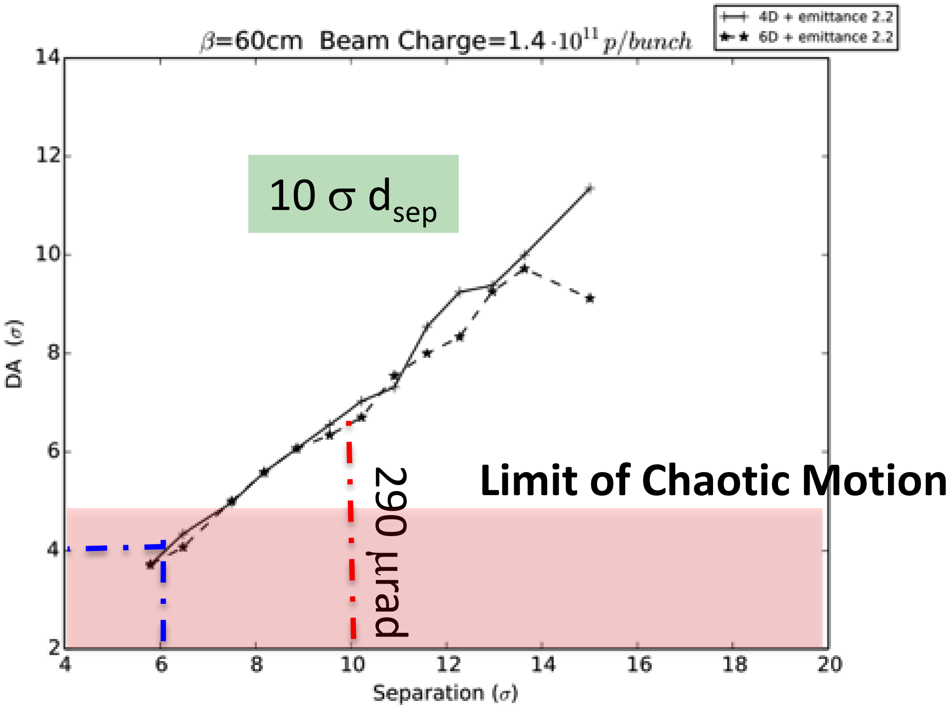
Biggest uncertainty are emittances: bunch to bunch differences(instability, e-cloud…) and instruments

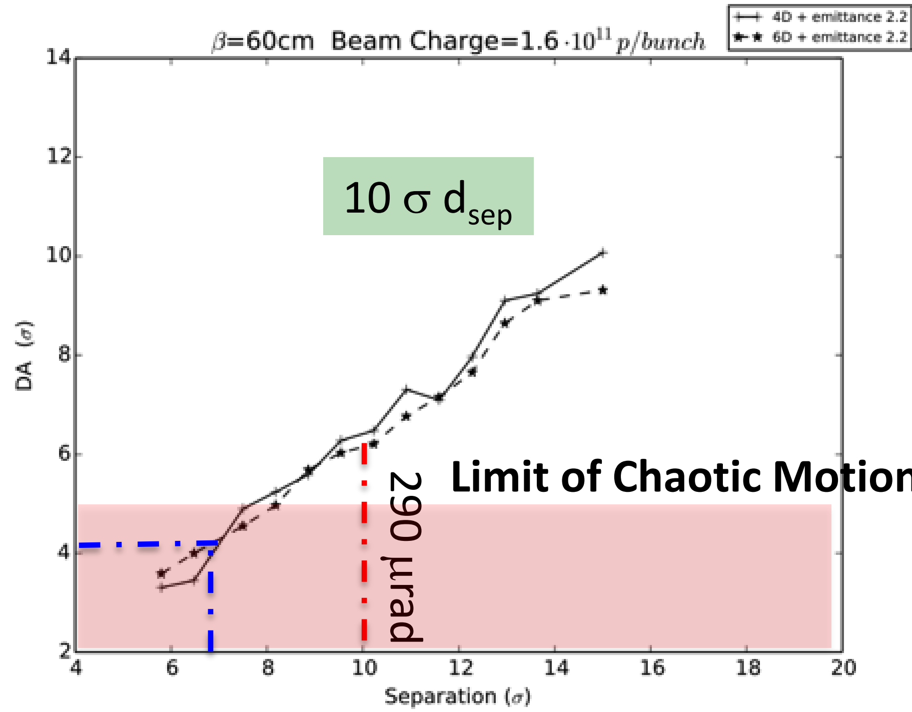
Several cases and all consistent with expectations from scaling laws : β^*, N_p, α

LR Experiments in LHC vs Simulations

50 ns beams: different β*, Intensity (1.2-1.6e11 ppb), crossing angle scan 2-2.5 μm emittances and 2 units Q'

Also Independent study W. Herr & D. Kaltchev





- **All experiments show significant losses and lifetime drops at 7-6 σ BB separations depending on conditions**
- **Corresponds to 4 σ DA, simulations +/- 1 σ error bar (emittance & intensity fluctuations 10%)**

LHC DA 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

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

Changes also HO

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

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

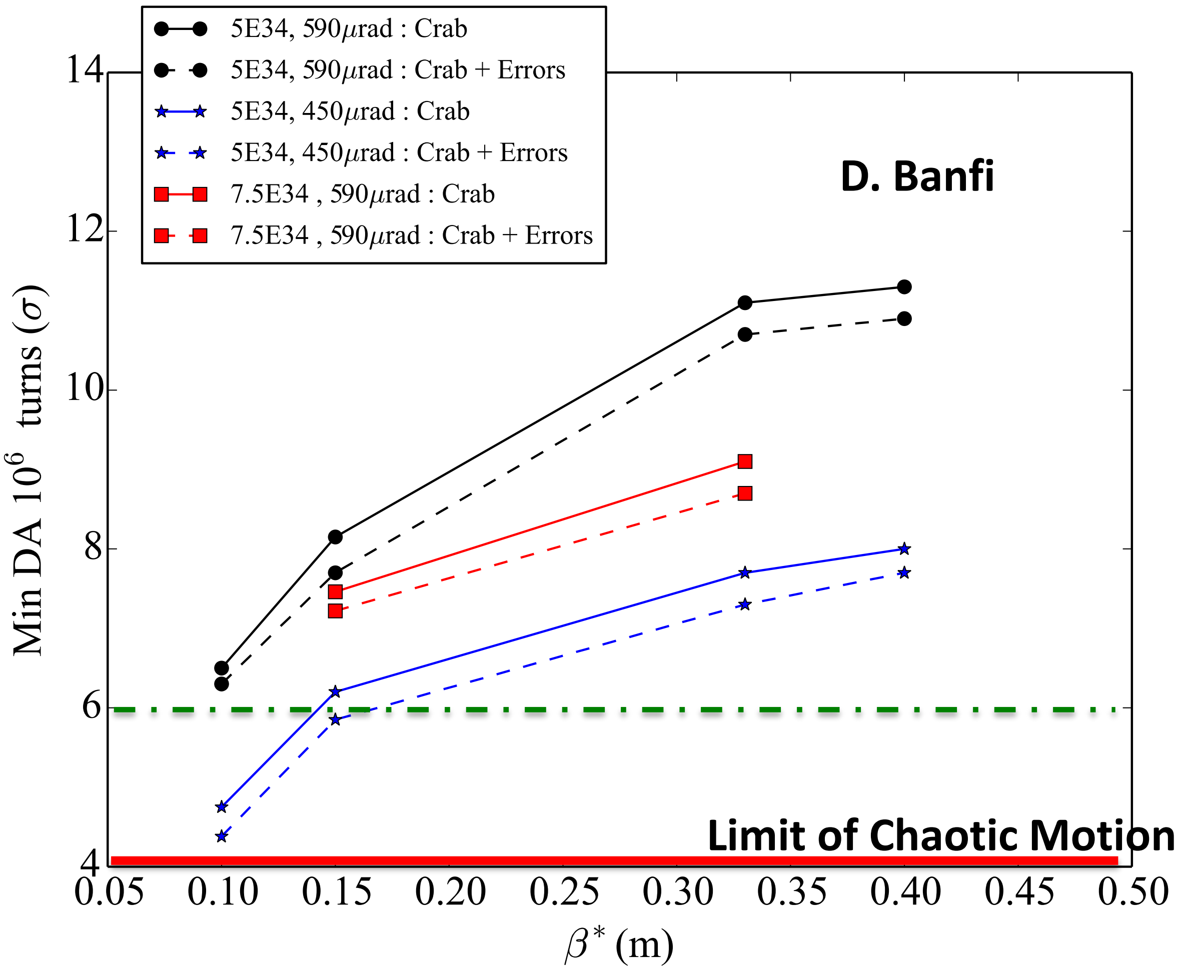
$$DA \propto d_{sep} \propto \sqrt{\beta*}$$

50→25 ns experiment not conclusive due to e-cloud

$$\Delta Q_{LR} \propto \#LR \qquad DA \propto \frac{1}{\#LR}$$

Establish scaling laws for HL-LHC conditions
Identify different contributions
Ensure DA > 6 σ
In the LHC we have not yet shown the LR limit for 25ns! 2015 will identify it!

The beauty of β* leveling



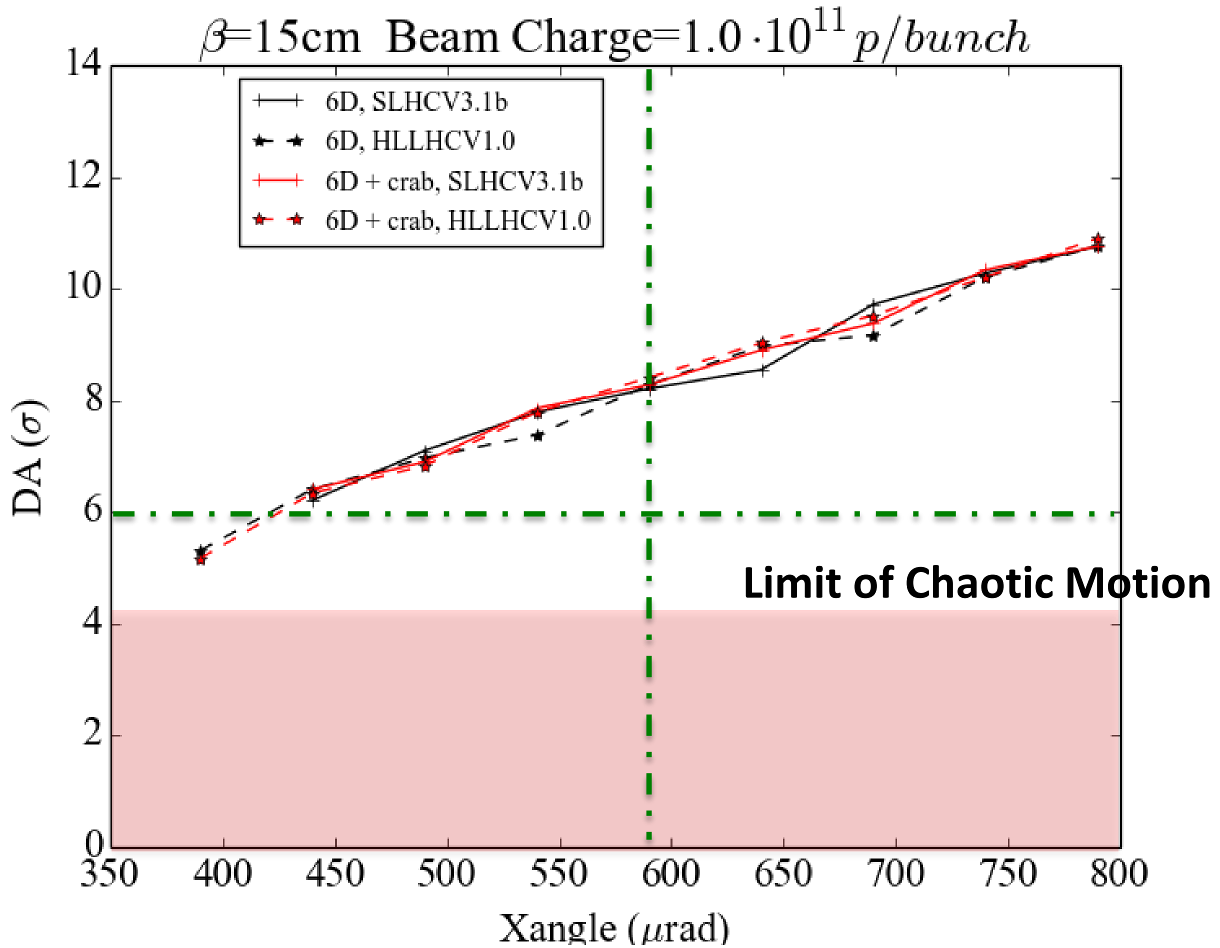
Baseline 1
5e34 leveled Luminosity
β* leveling

Ultimate
7.5e34 leveled Luminosity
β* leveling

Extreme case:
NO β* leveling

β* leveling is extremely "beautiful" for beam-beam dynamics
Gives higher potentials for the HL-LHC

Dynamic aperture HL-LHC IP1&5: the beauty of β*leveling

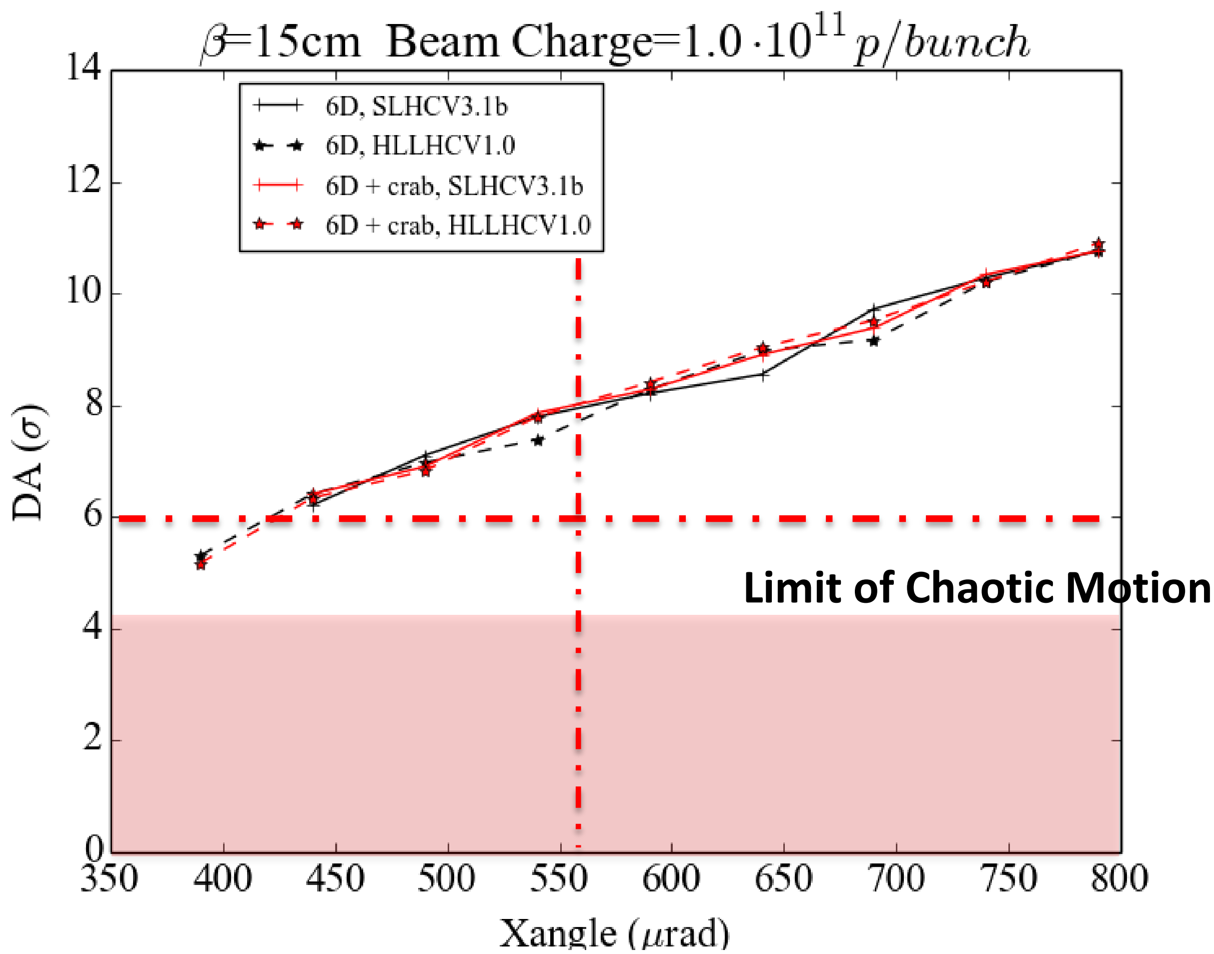


$$d_{sep} = \alpha \cdot \sqrt{\frac{\beta^*}{\epsilon/\gamma}}$$

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

In nominal condition 590 mrad DA=8.4 Sixtrack
Plenty of margin but…

Dynamic aperture HL-LHC IP1&5: the beauty of β*leveling



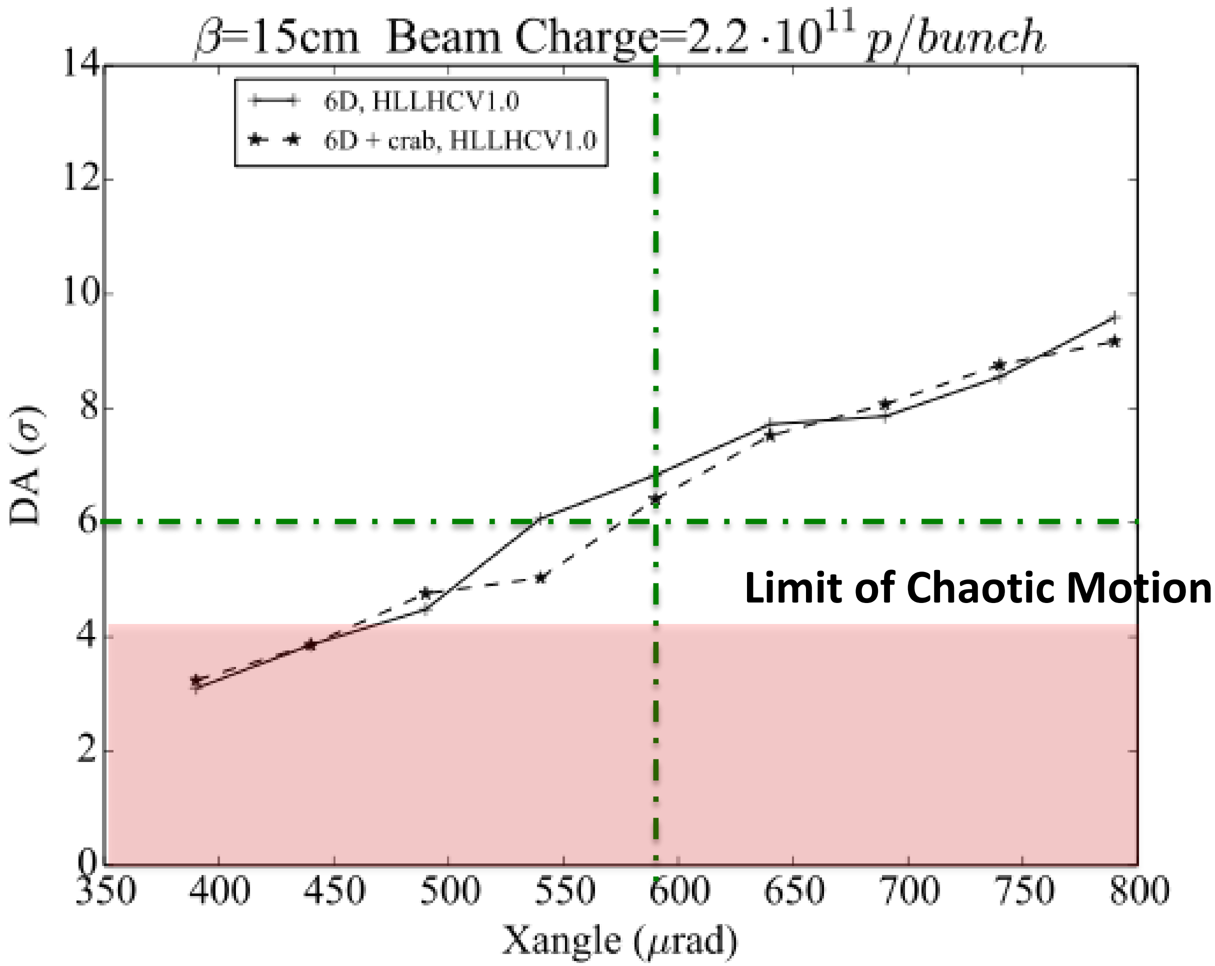
$$d_{sep} = \alpha \cdot \sqrt{\frac{\beta^*}{\epsilon/\gamma}}$$

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

1. **10% larger ε_n (2.5→2.75)**
2. **Equivalent to reduction of the angle 590μrad→560μrad**
3. **Equivalent to reduction of DA 1σ**

10% increase ε_n (bbb fluctuations injectors, growth) → reduces DA 8.5 → 7.5 σ

Dynamic aperture HL-LHC IP1&5:
NO β* leveling

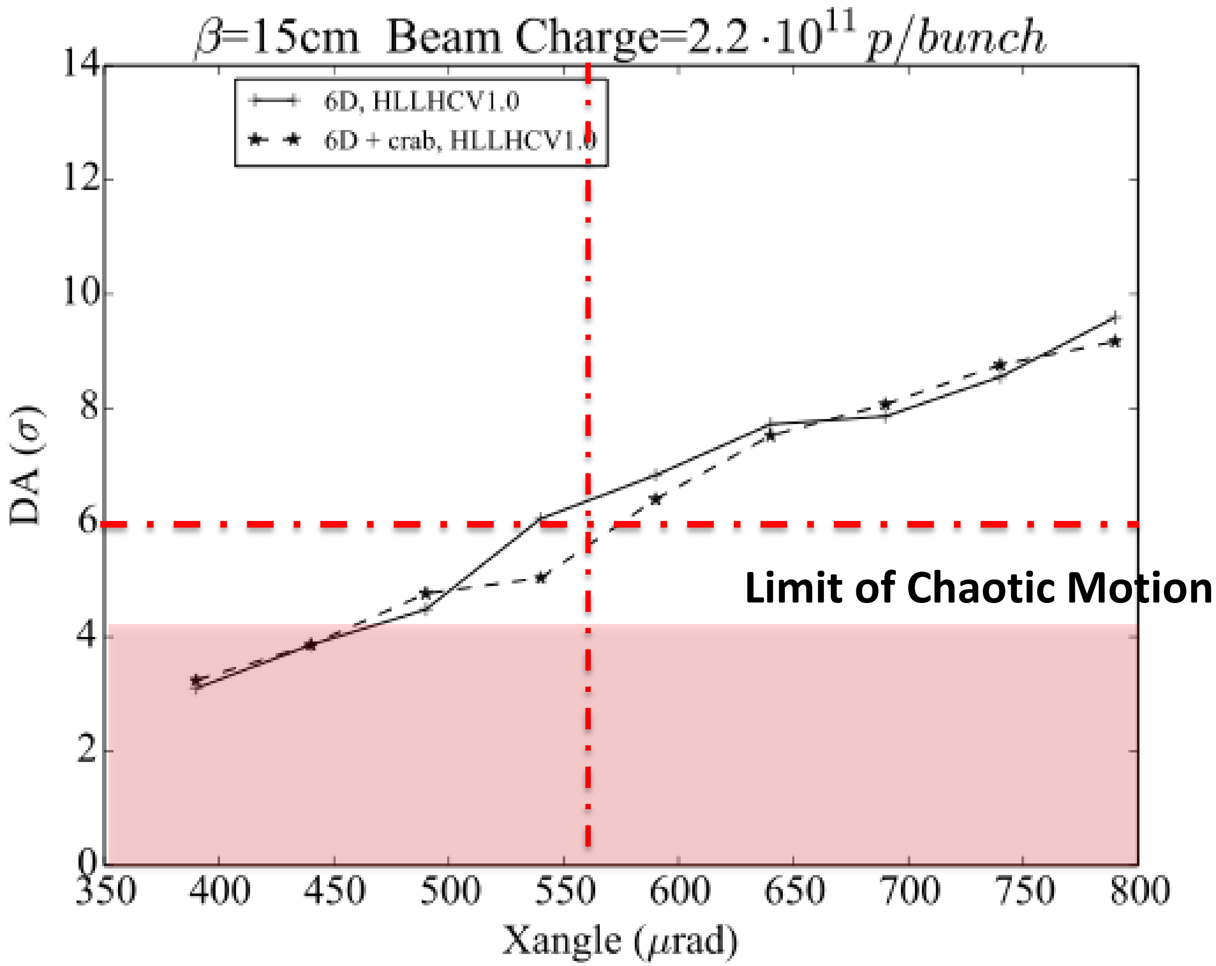


$$d_{sep} = \alpha \cdot \sqrt{\frac{\beta^*}{\epsilon/\gamma}}$$

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

In nominal condition 590 μrad DA=6.4

Dynamic aperture HL-LHC: IP1&5



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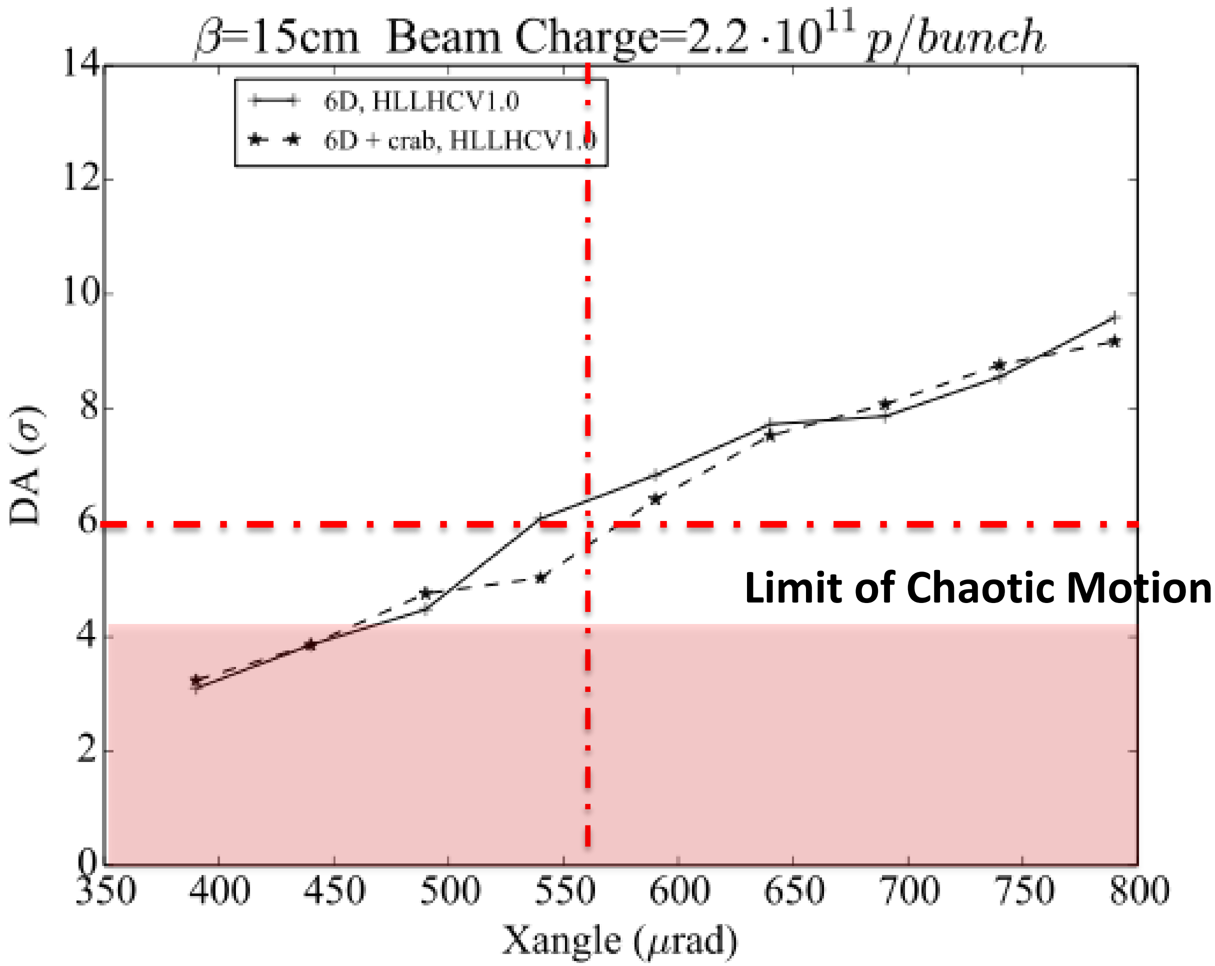
10% increase ε_n reduces DA 6.4 → 5.5 σ

Dynamic aperture HL-LHC: IP1&5



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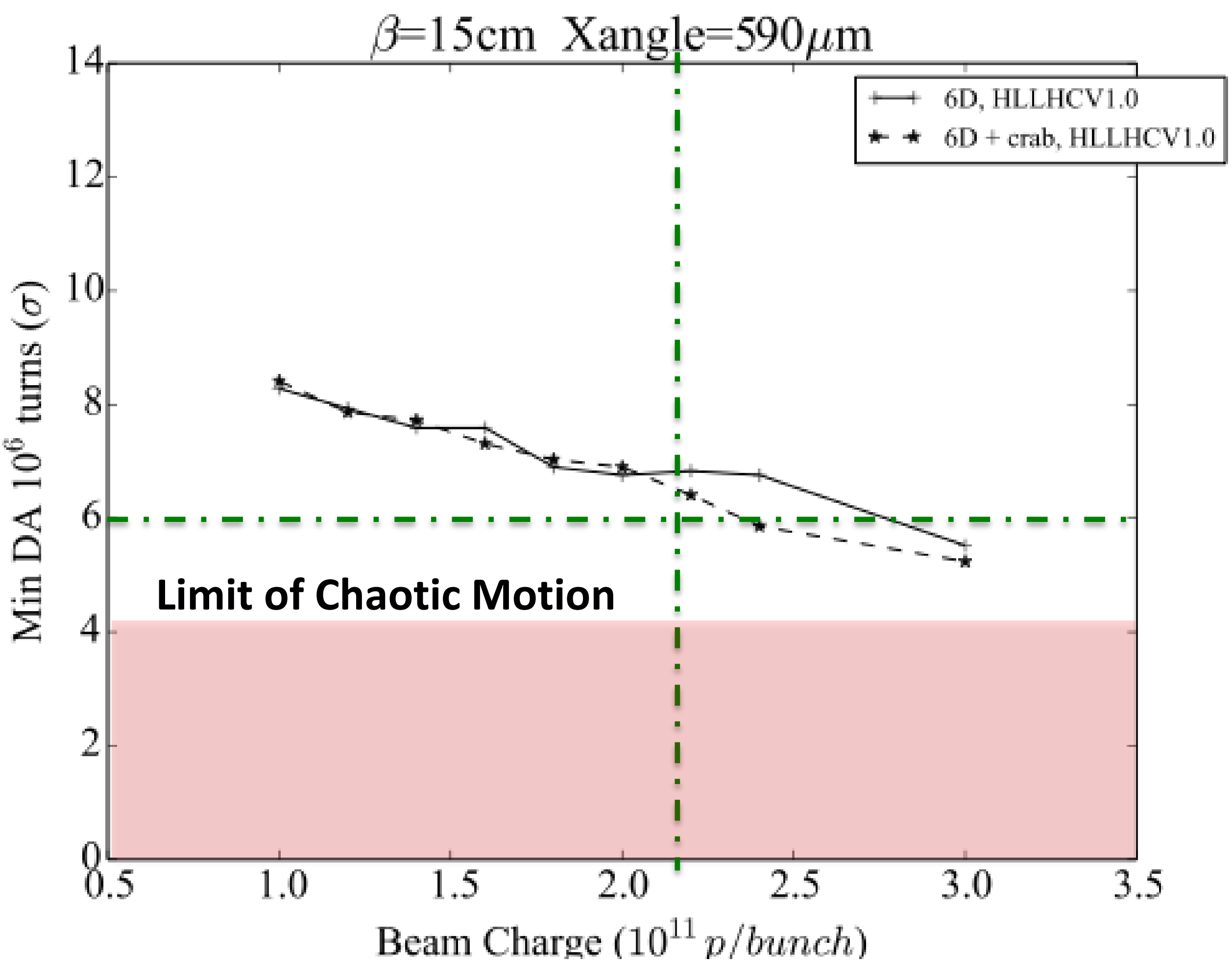
3. **Equivalent to reduction of DA 1σ**

Margins can be lost very fast with Beam-beam if not attentive!
Beams will not explode but integrated Luminosity reduced!

Dynamic aperture HL-LHC IP1&5: Intensity

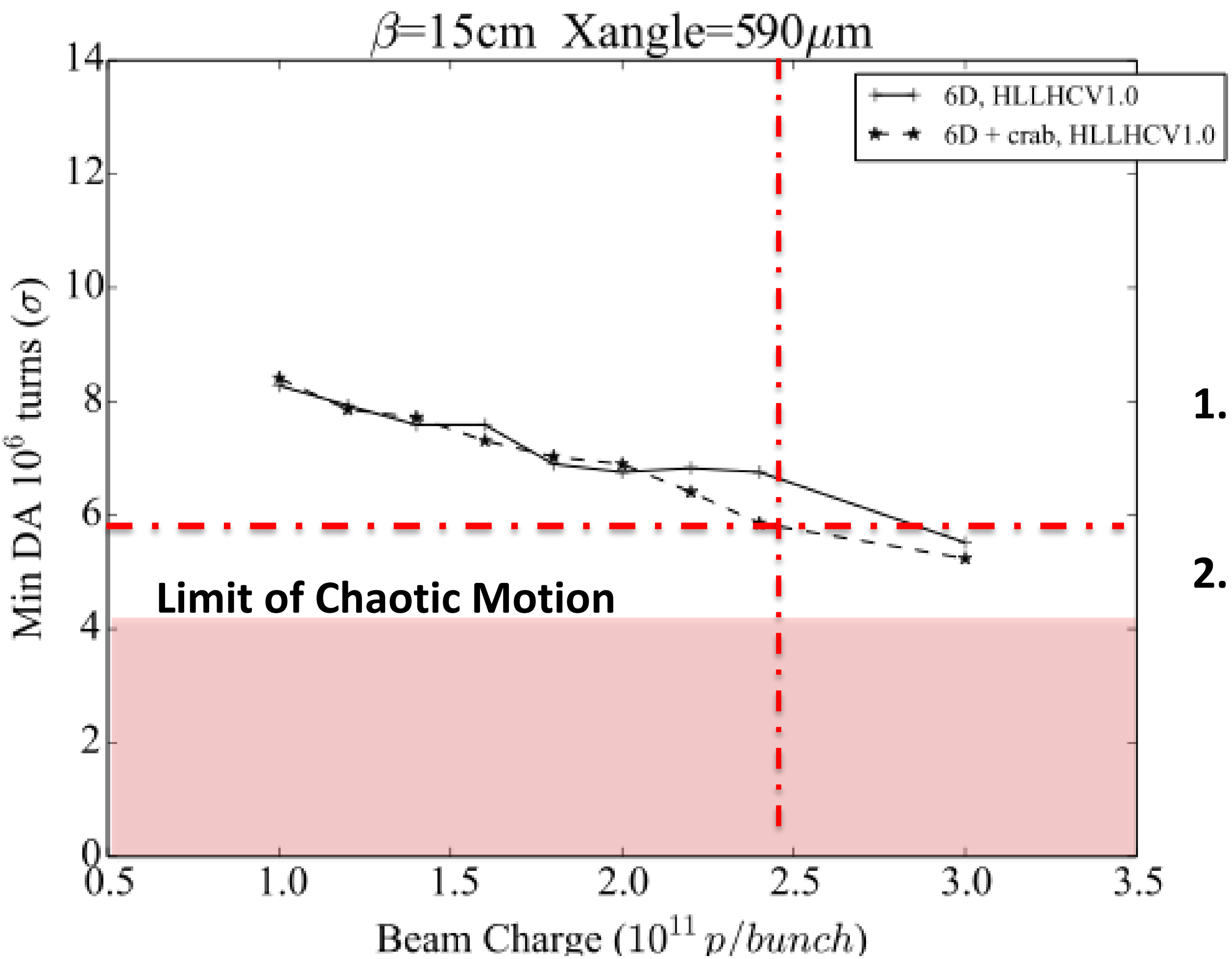


$$F_{bb} \propto Intensity$$

$$DA \propto Intensity$$

In nominal condition 2.2e11ppb DA=6.4 σ

Dynamic aperture HL-LHC IP1&5: Intensity



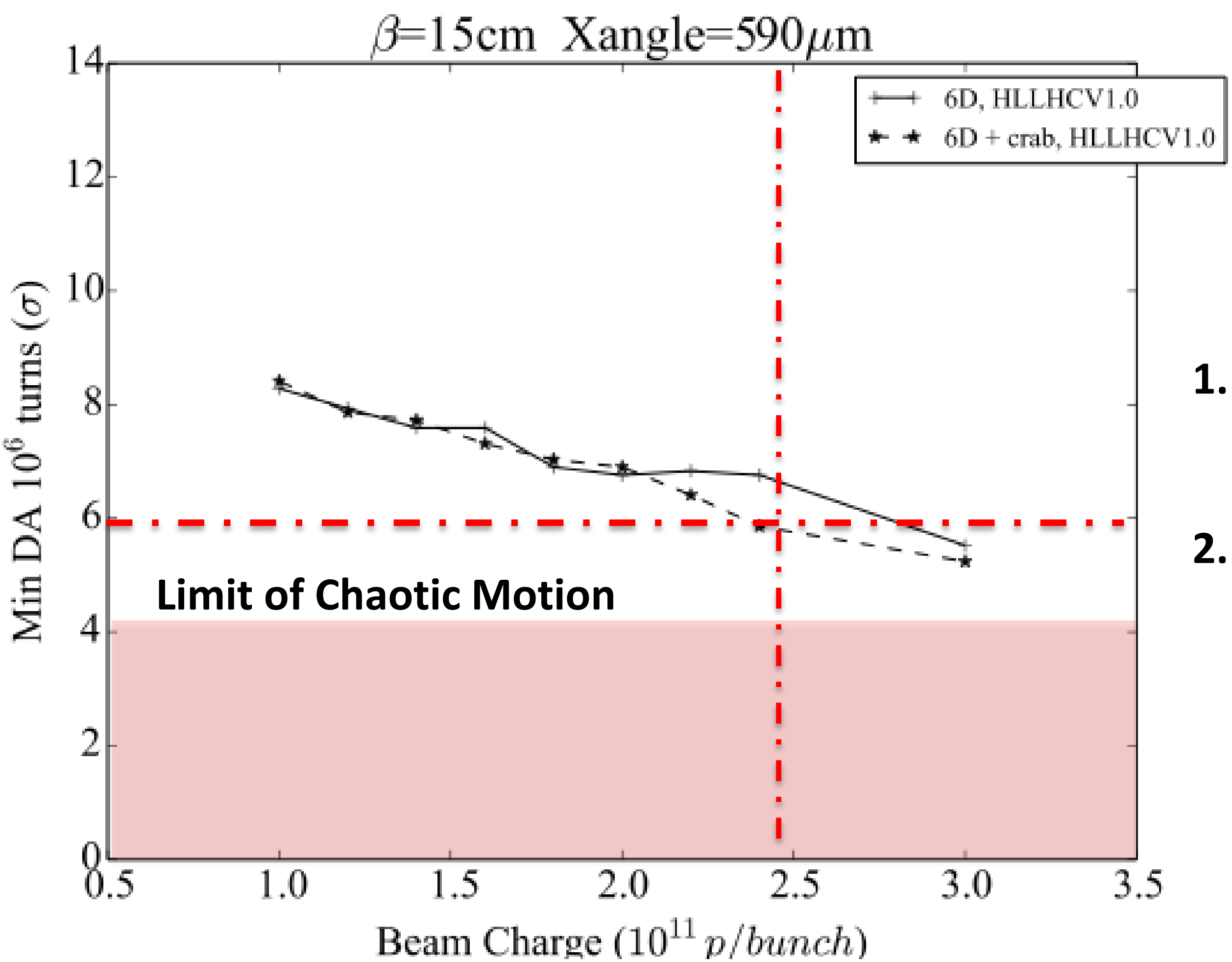
$F_{bb} \propto Intensity$

$DA \propto Intensity$

1. **10% Intensity increase (2.2→2.4)**
2. **Equivalent to reduction of DA 0.6 σ**

10% Intensity fluctuations reduces DA 6.4 → 5.8 σ

Dynamic aperture HL-LHC IP1&5: Intensity



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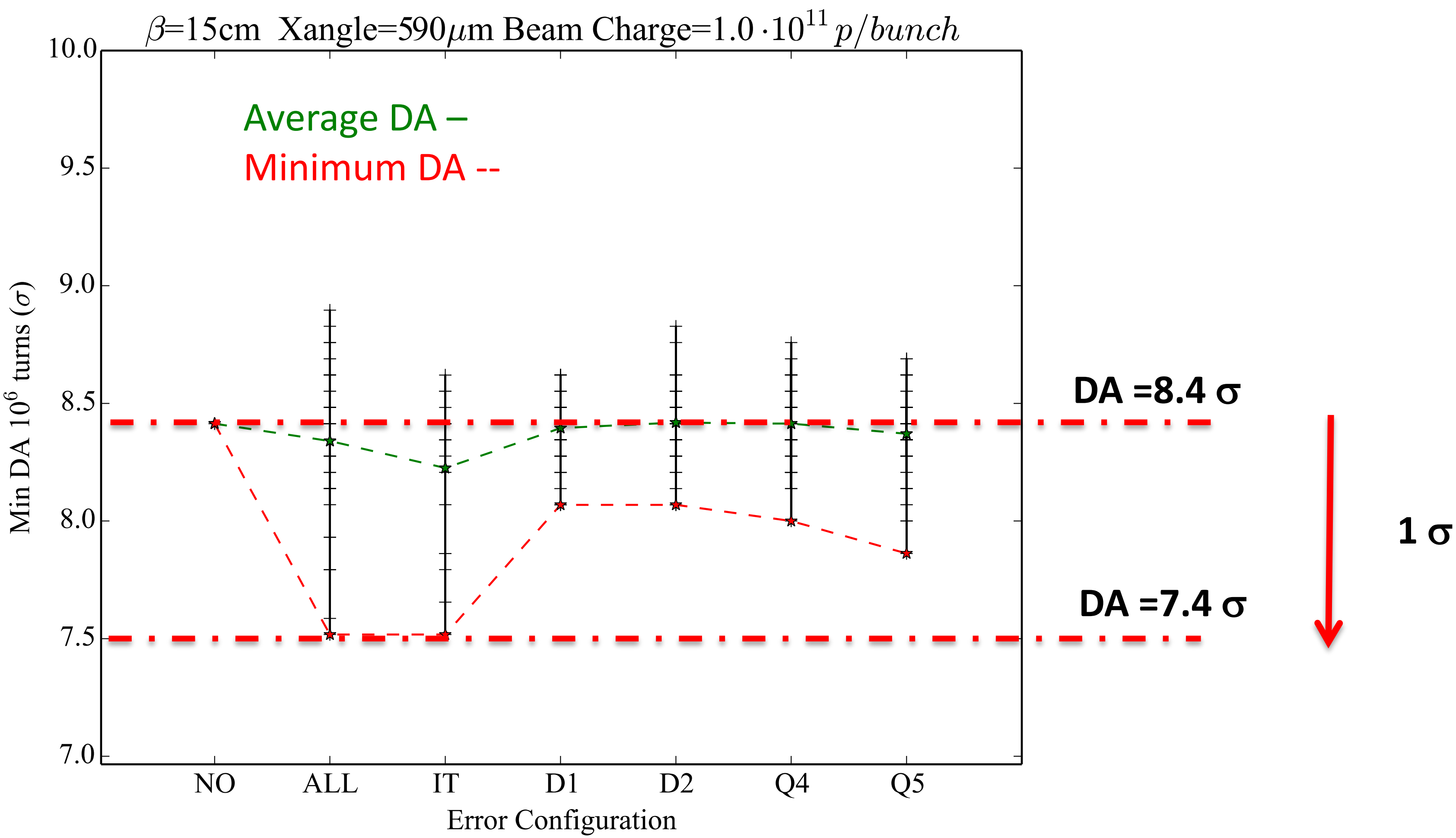
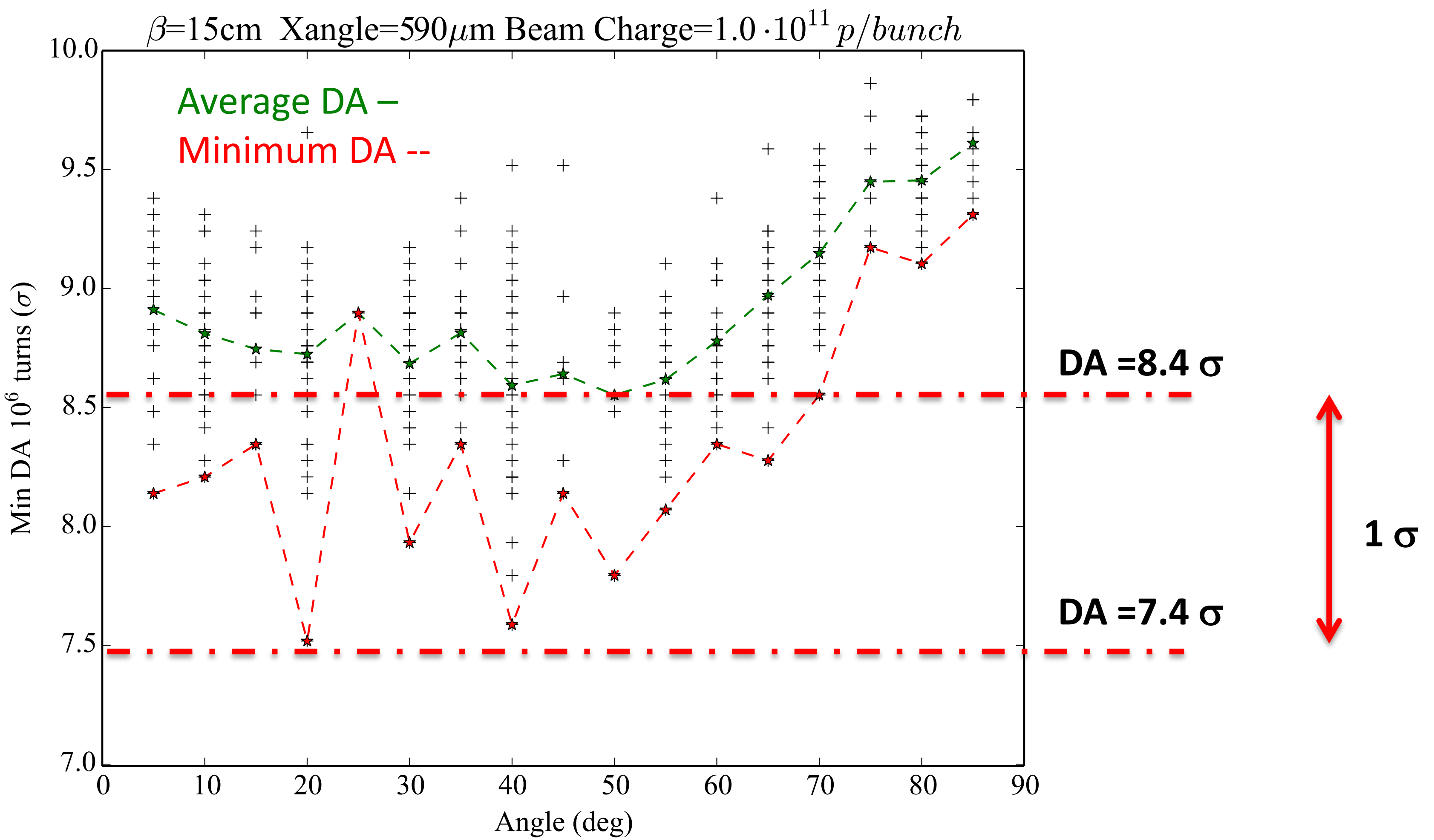
Multipolar errors single element impact: IP1&5 and β* leveling



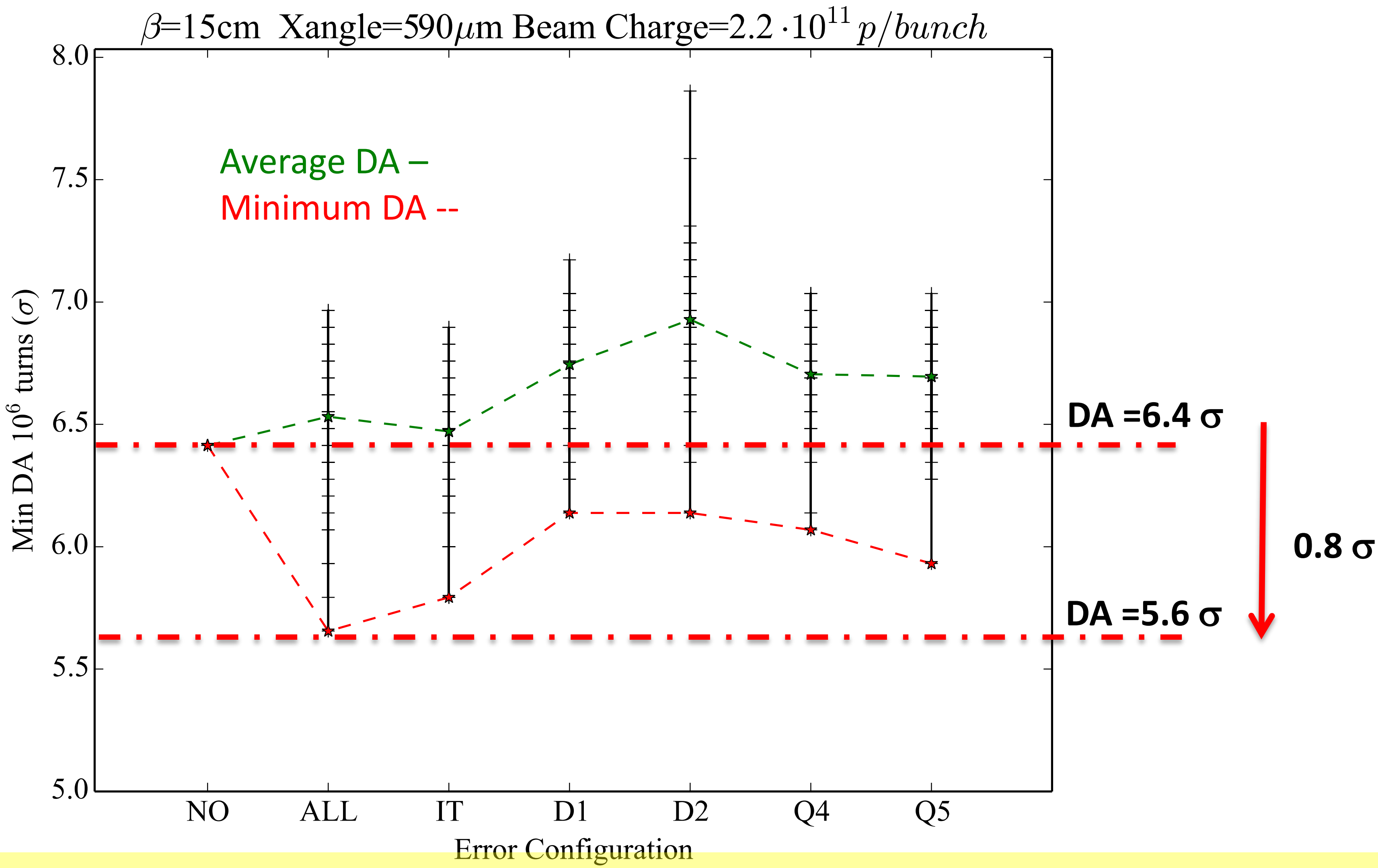
Errors do have an impact (1 σ reduction)
Driven by Inner Triplet element errors

Multipolar errors impact IP1&5: β* leveling



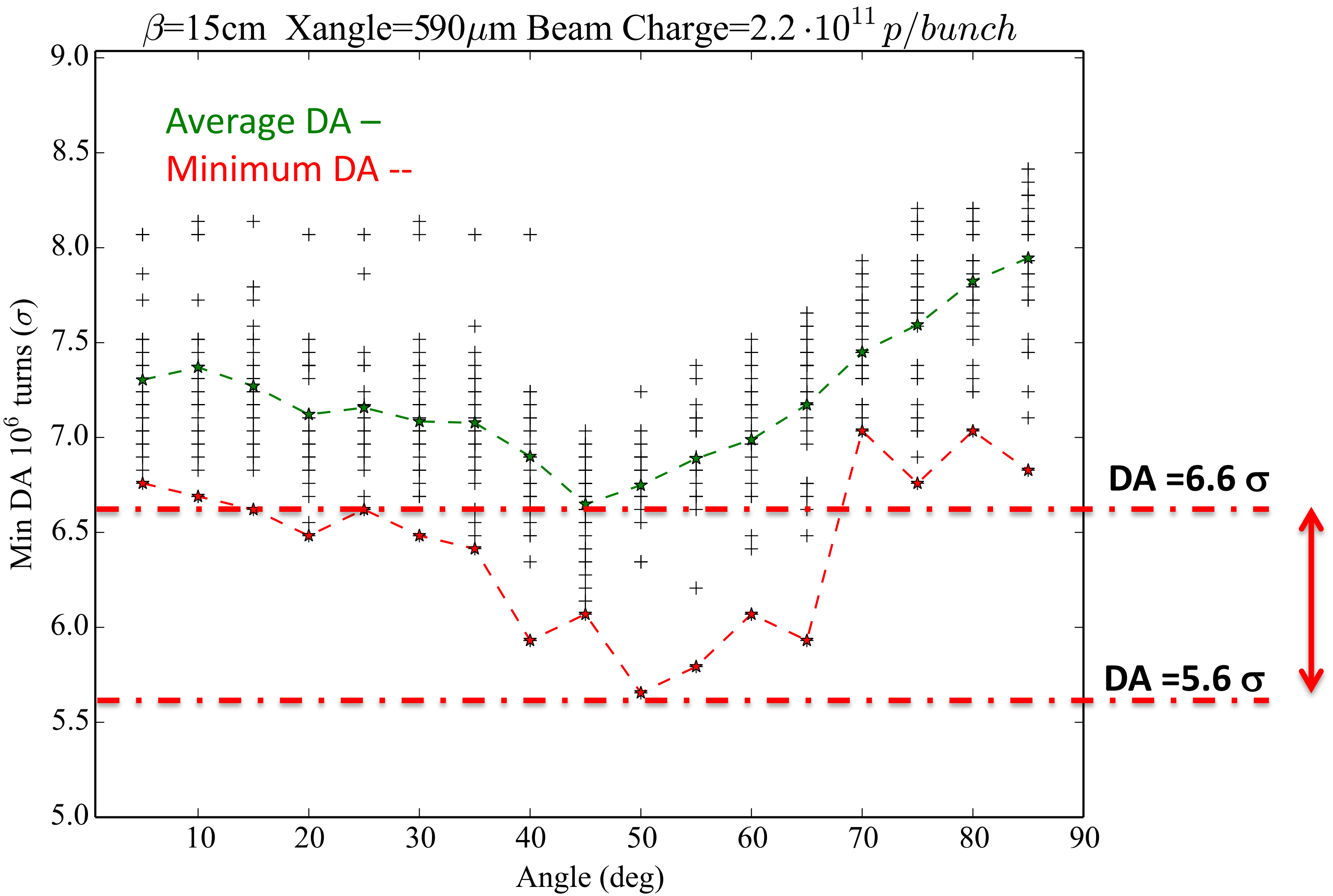
Minimum DA rigorous criteria for LHC design we all profited of in 2012. Intensities up to 1.6e11 and emittances of 2-2.5μm

Multipolar errors impact IP1&5:
NO β* leveling



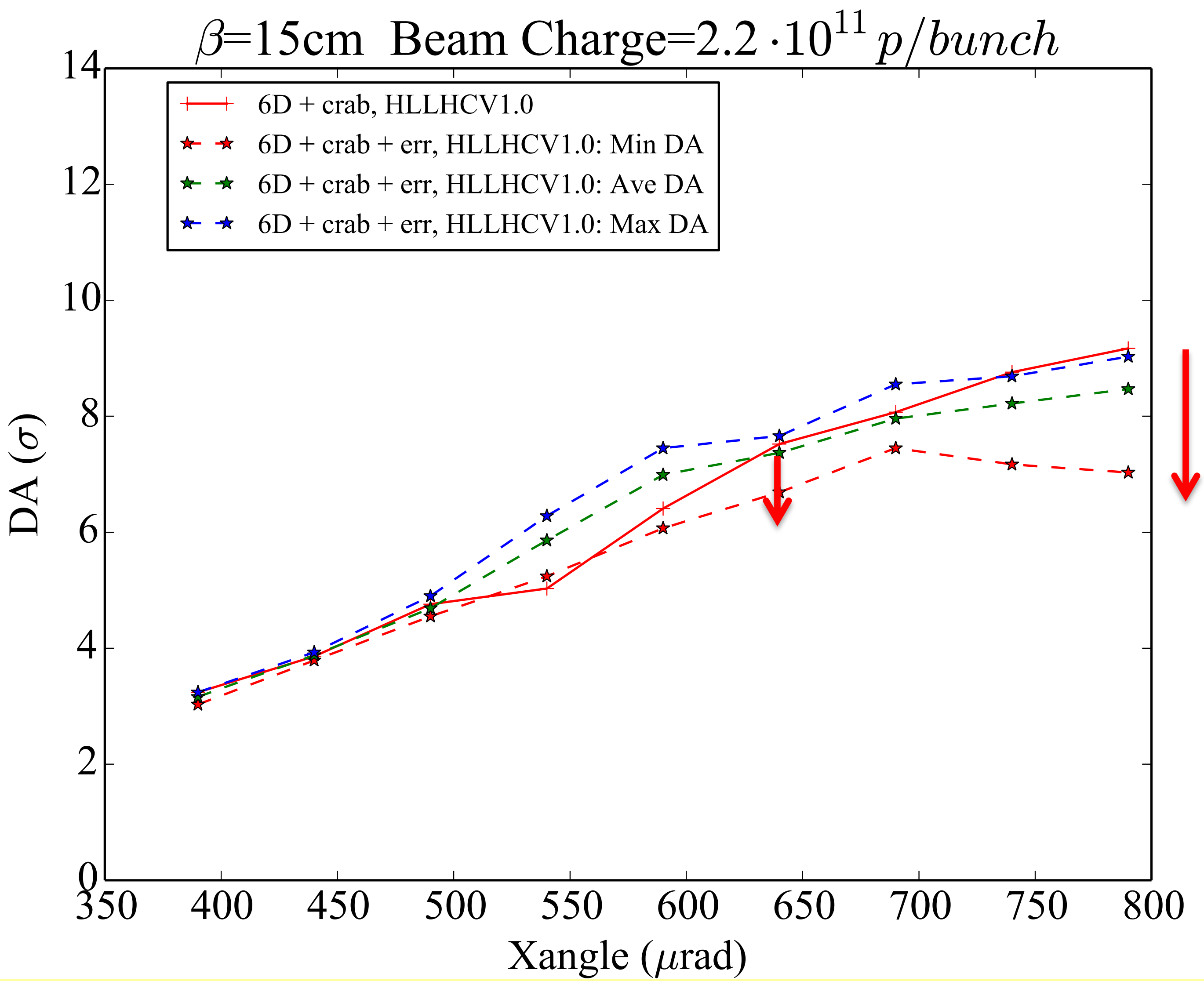
Errors do have an impact (0.8 σ reduction)
Dominated by Inner Triplet element and Q5…

Multipolar errors impact IP1&5: NO β* leveling



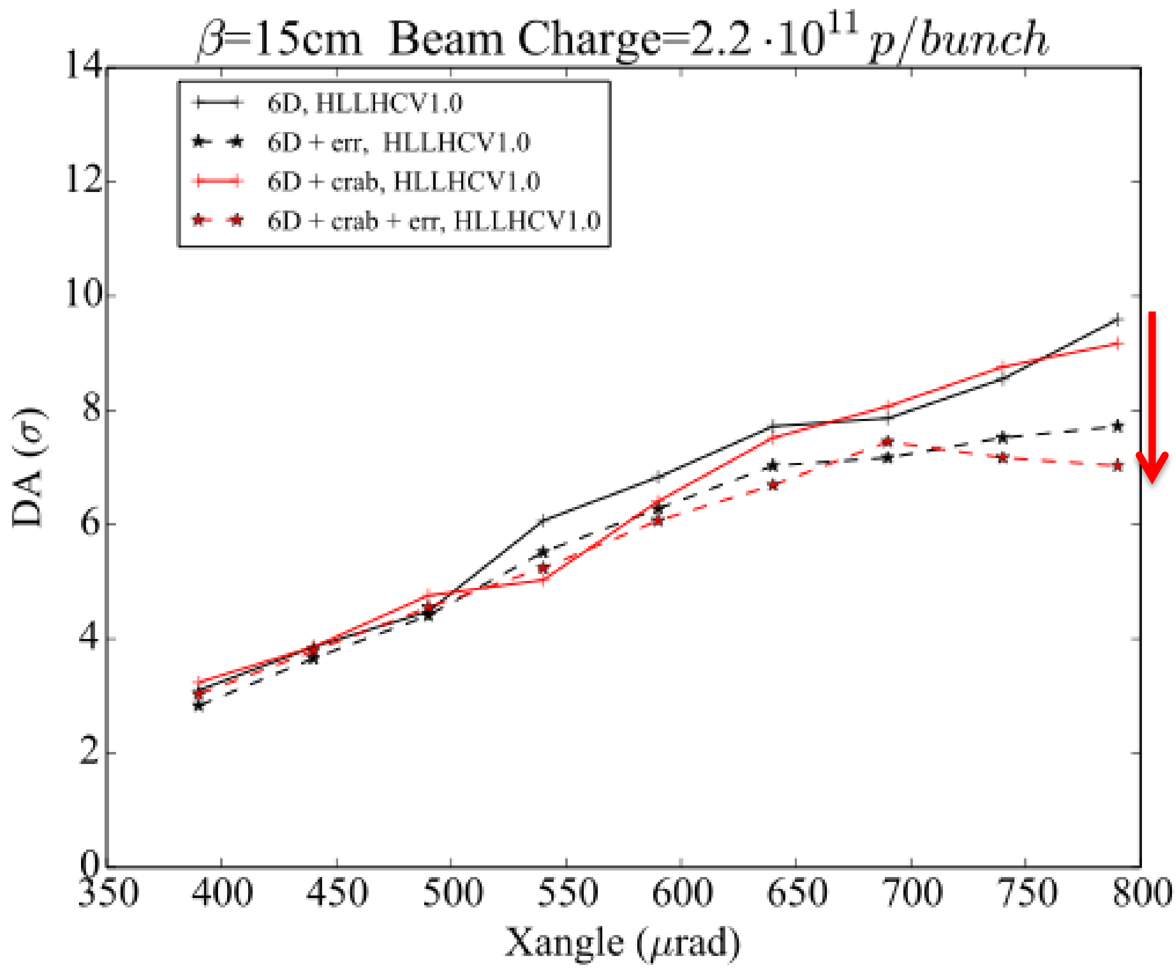
Minimum DA criteria → LHC design criteria shown to be successful

Multipolar Errors and crossing angle



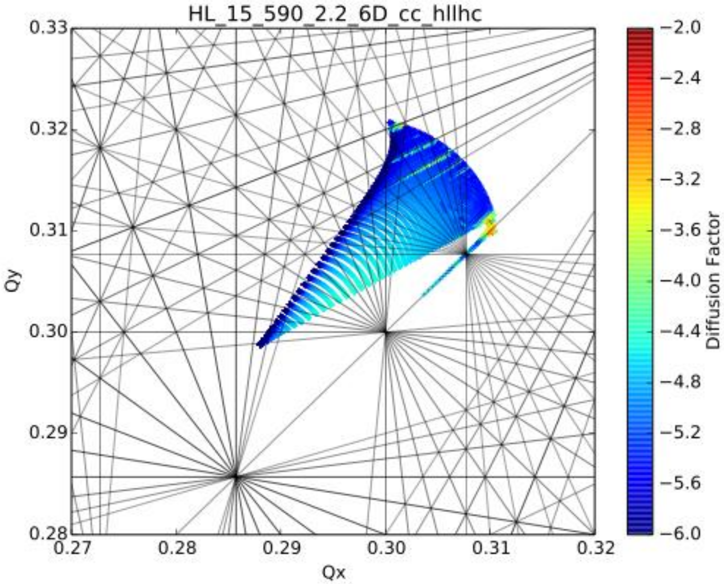
The impact of the errors becomes stronger for larger angles
If we need larger angle for BB problems then we might even loose in DA…

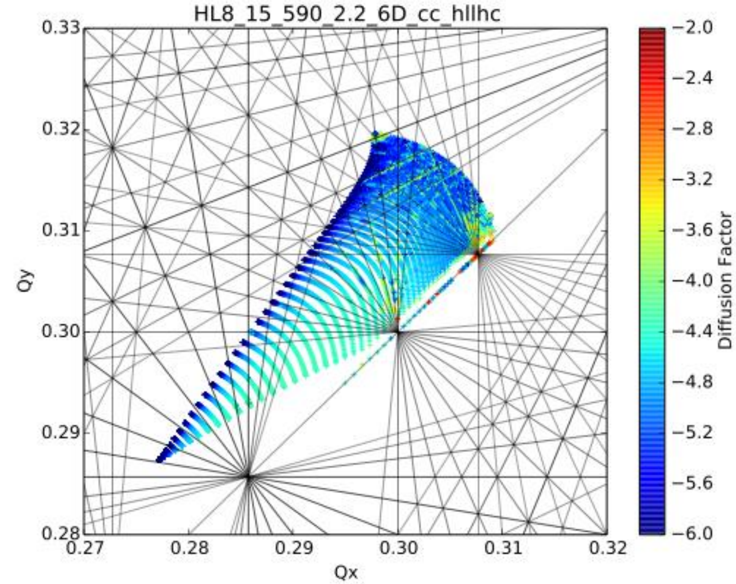
Multipolar Errors and crossing angle



The impact of the errors becomes stronger for larger angles
If we need larger angle for BB problems then we need stronger CC and it is not granted we will gain if multipolar errors are not tightly controlled!

What do we need these margins for?





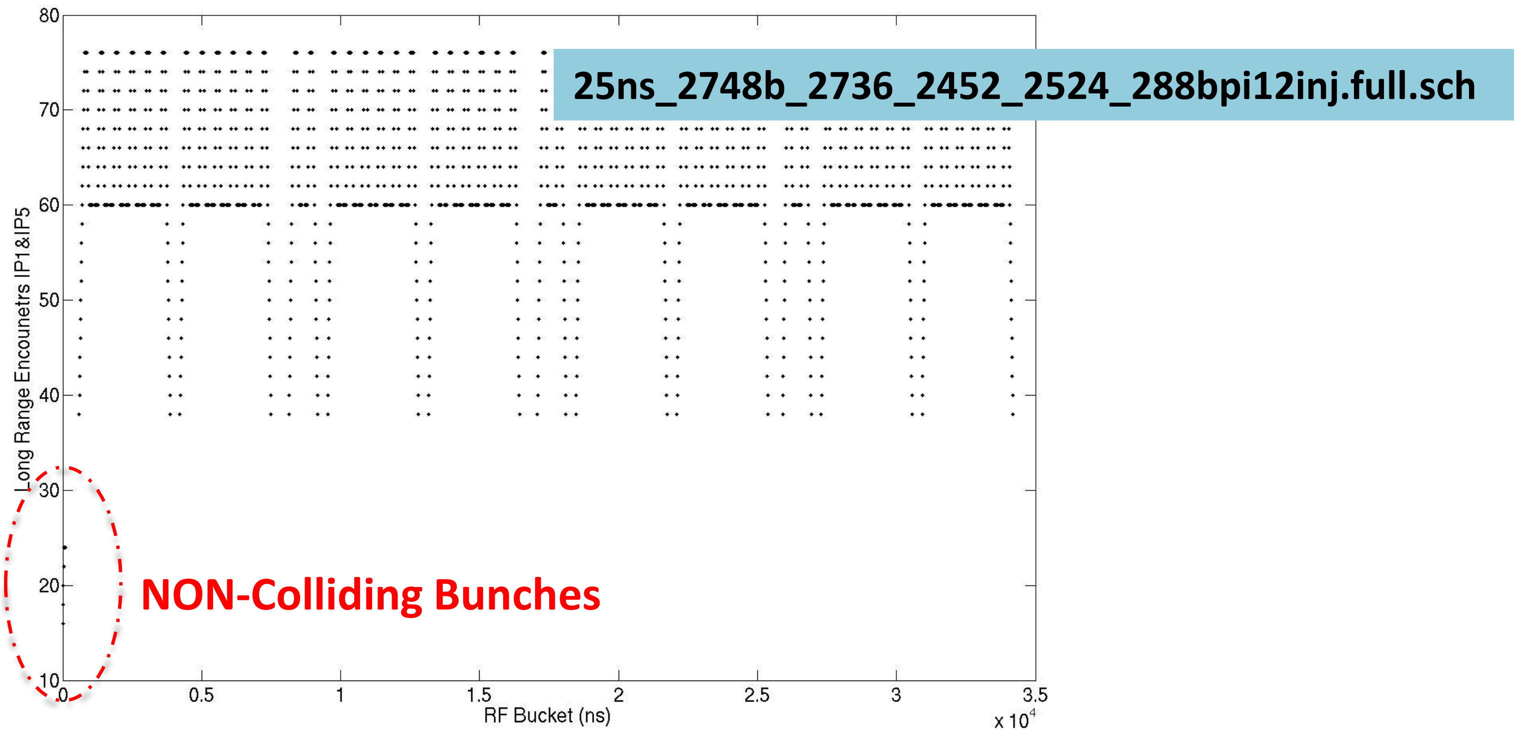
Intensity 10^{11} ppb	IP1&5	IP8 (-340mrad ext x-angle -270μrad septrometer)	IP8 (-560μrad ext x-angle + 270μrad spectrometer)	IP8 (-340μrad+270μrad spectrometer)
1.0	8.41	8.07	7.93	7.72
2.2	6.42	6.28	6.06	5.86

→ **ΔDA = -0.5 σ**

We optimize the scenarios to put IP8 (LHCb) in the shadow of the two main IP1&5 (ATLAS and CMS) but they do take part of the margins!
Then IP2 (ALICE)…. Something else?...

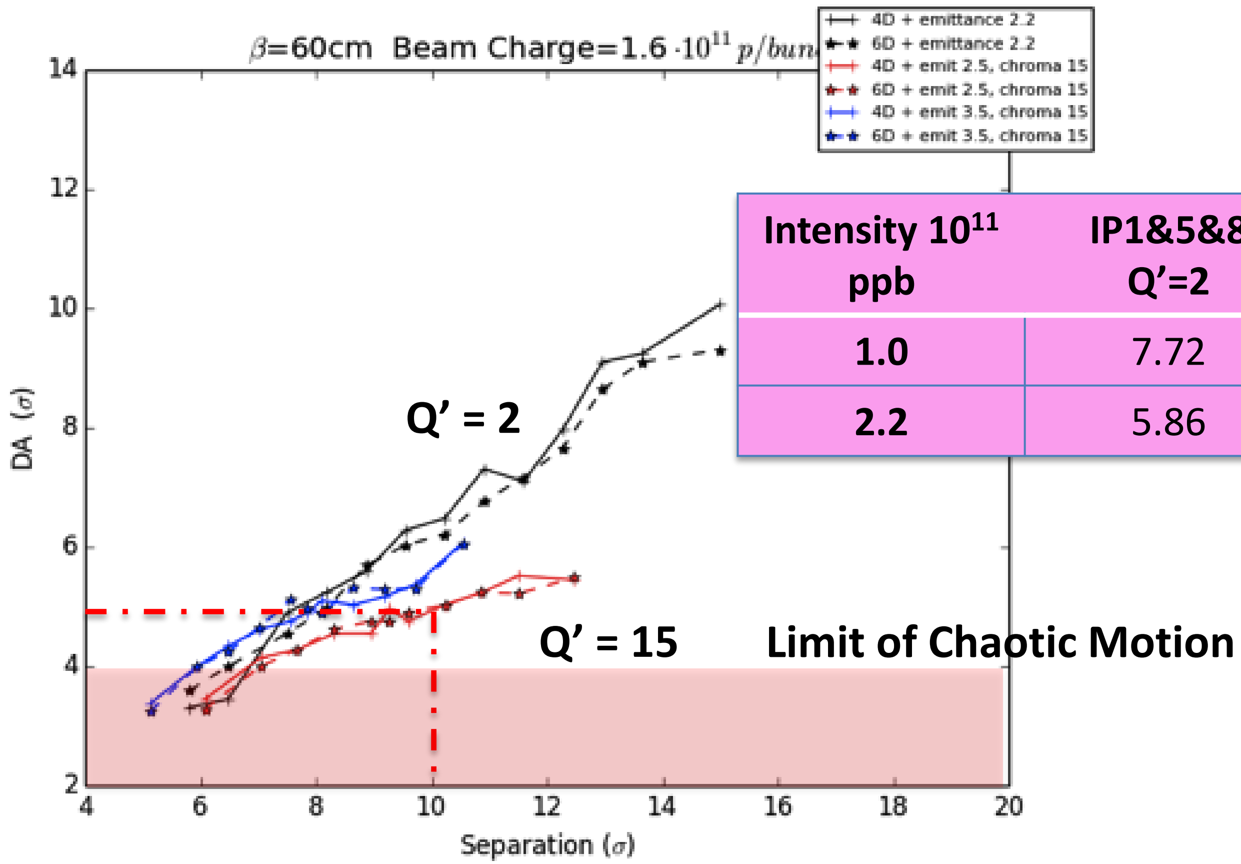
INSTABILITIES: NON-Colliding Bunches & chromaticity

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



- **Non-Colliding Bunches will have very little Landau Damping (NO-Head-on collision) need to be kept stable by other means→ Q' & octupoles….**
- **These few bunches stability will define important parameters in collision CHROMATICITY and LANDAU Octupoles (visible in 2012 for IP8 bunches in LHC)**

What do we need these margins for?



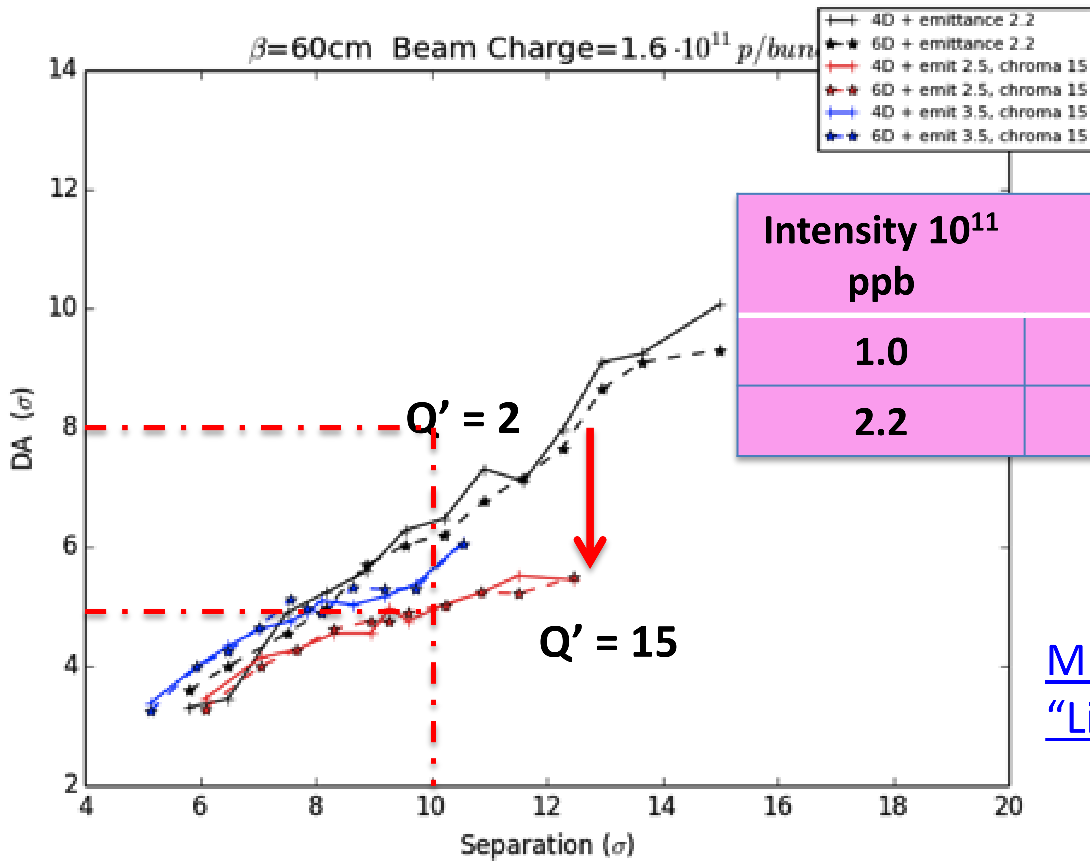
Intensity 10^{11} ppb	IP1&5&8 Q'=2	IP1&5&8(-) Q'=15	IP1&5&8(+) Q'=15
1.0	7.72	6.48	4.83
2.2	5.86	4.83	4.76

CHROMATICITY HAS A VERY STRONG IMPACT!

If for any reason we need to use high chroma (i.e. stability in collision) then no margins! Have we seen this in 2012? Yes!

With high chroma integrated lumi per fill much smaller despite higher brightness

What do we need these margins for?



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M. Lamont
"Lifetimes in Stable Beams Revisited"

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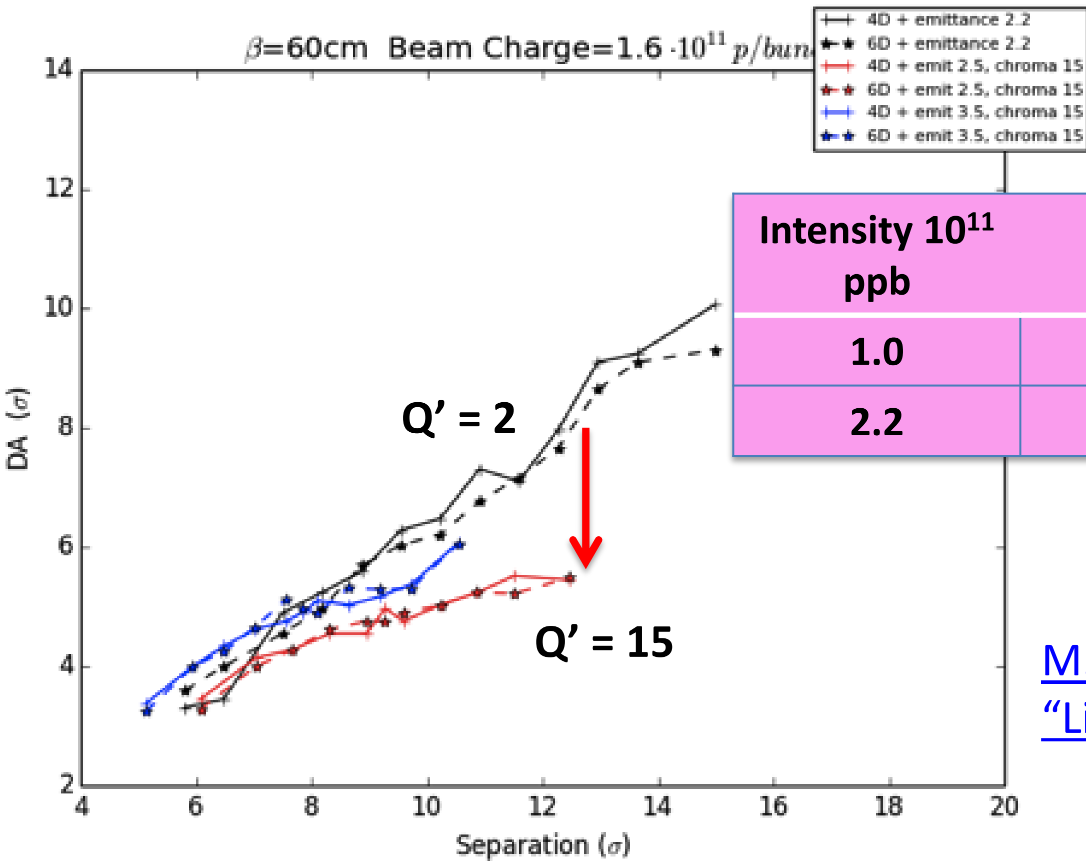

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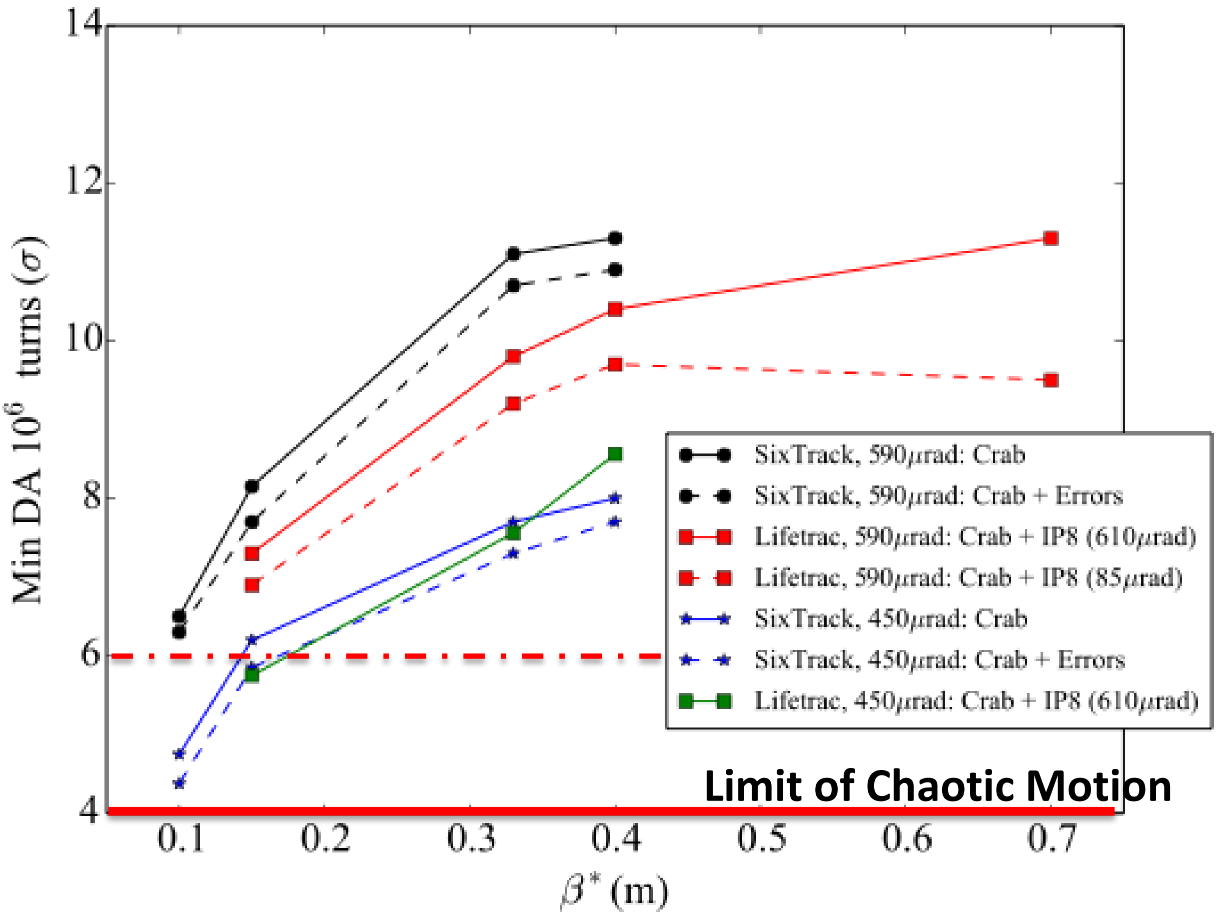
M. Lamont
"Lifetimes in Stable Beams Revisited"

OCTUPOLES not yet in the picture!
But they will also contribute….reducing margins!

Summary for 5e34 leveled lumi



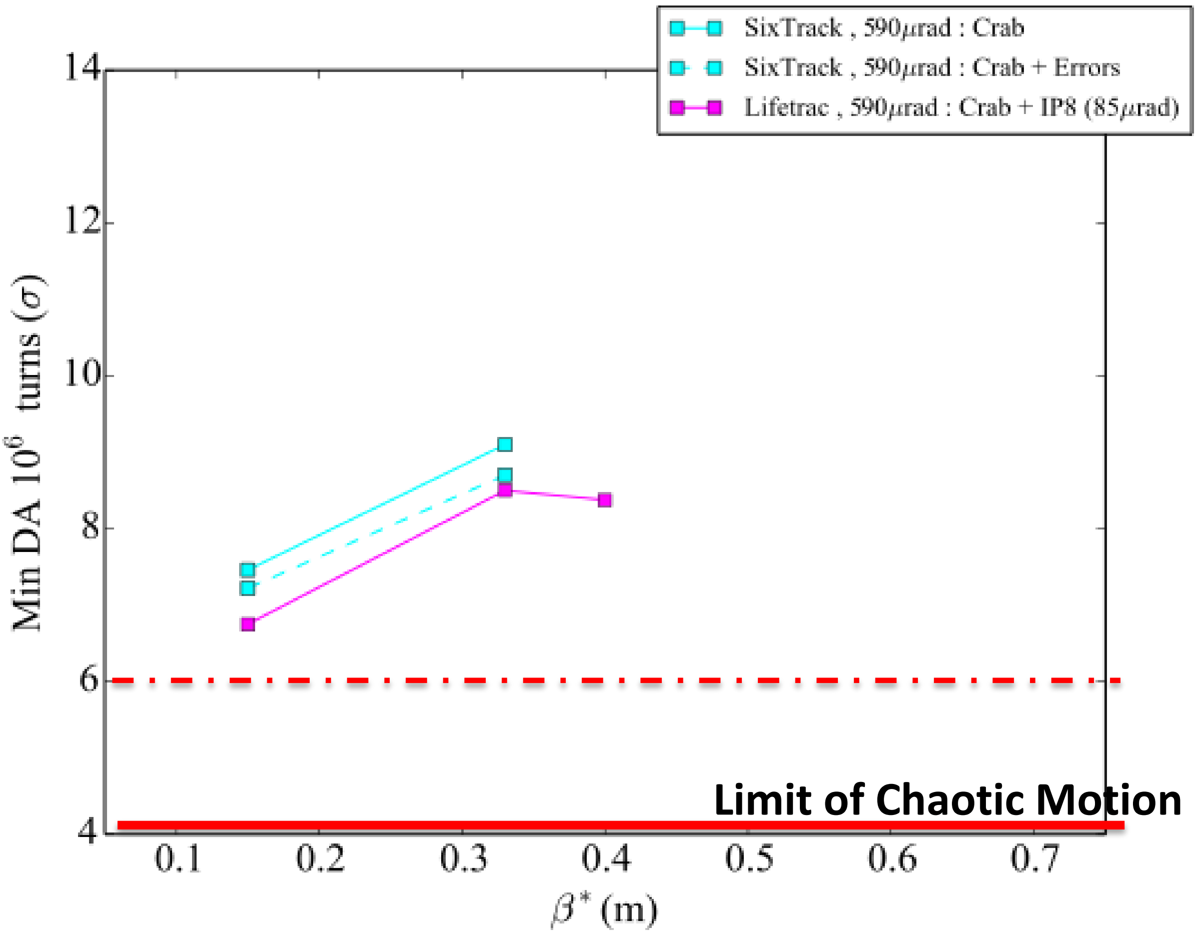
Baseline

IP1&5	8.2
Mult Errors	-0.7
IP8	-0.6
Chroma 15	-2
IP2	-0.2
Octupoles	?
=================	
Total DA	4.7

Nominal scenario with leveled lumi at 5e34 at 590μrad is robust thanks to β* leveling: DA always above 7.5σ

Margins can be lost fast still many uncertainties on running conditions!

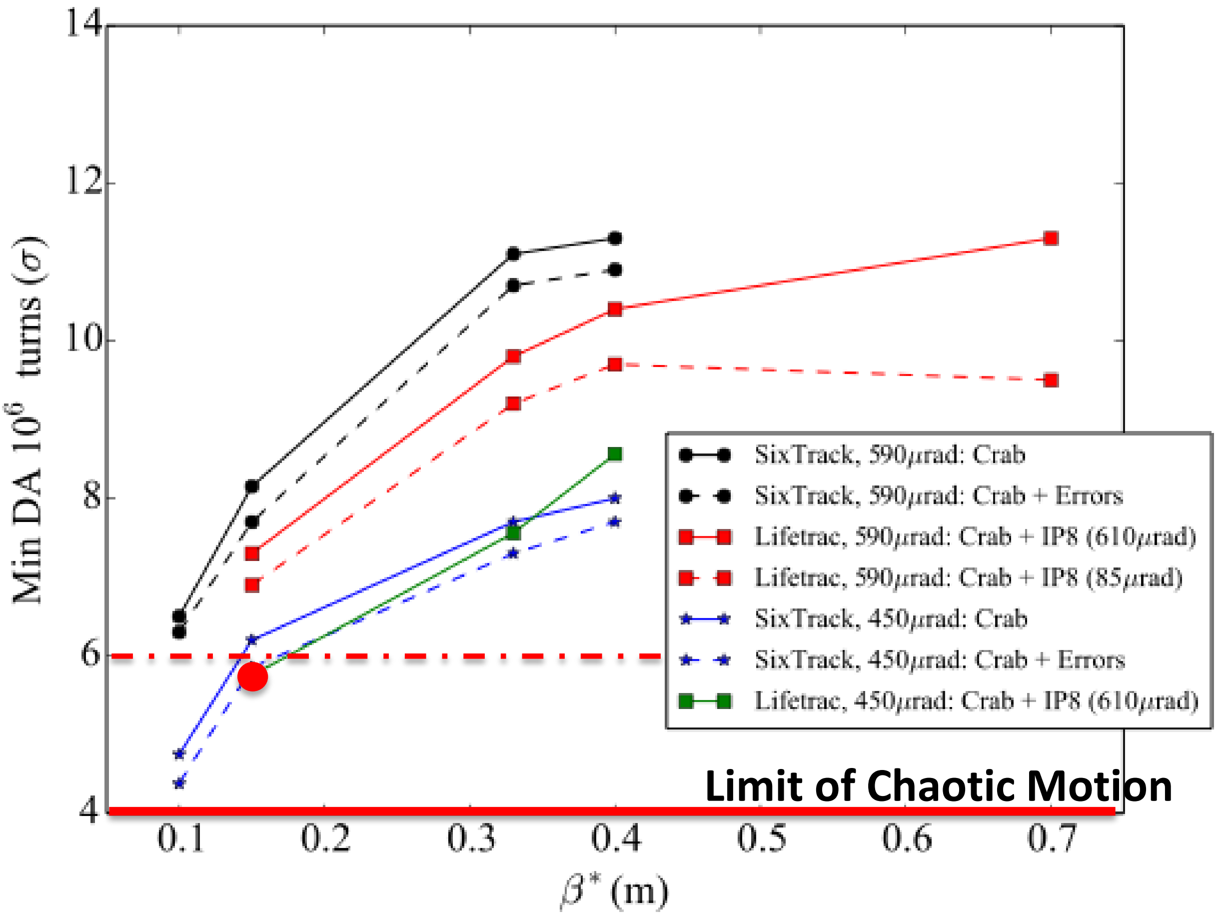
Summary for 7.5e34 leveled lumi



Nominal scenario with leveled lumi at 7.5e34 at 590µrad is robust thanks to b* leveling DA always above 7σ

Margins reduced by 1 σ, we need to keep IP2-8 in the shadow.

No β* leveling



Extreme case

IP1&5	6
Mult Errors	-0.5
IP8	-0.6
Chroma	-2
IP2	-0.2
Octupoles	?
=================	
Total DA	3…

Extreme case NO β* leveling needs to be guaranteed! DA is below 6 σ → Fundamental to keep all contributions at MINIMUM (Multipolar Errors, other IPs)

Conclusions

- No margins for the **7.5e34 leveled luminosity scenario**, no margins if we assume **10% fluctuations in emittances and/or intensities**
  - **IP8** has an impact (0.1-0.7s DA) and we are studying a scenario to minimize the impact on DA
  - In case **of instabilities** (present all 2012 in collision for IP8 bunches) → need **high chromaticity** → strong impact on DA! Detrimental…
- For case **5e34 level lumi** better situation but the need of **high chroma and octupoles** might take away all margins
- **2012 experience instabilities** show need for flexible use of chroma and octupoles, margins needed for this!
- **IP2&8 studies** will aim to minimize the impact of these IPs (sep leveling, larger x-angles…)
  - **IP8 x-angle constrained:** by the correctors magnets strengths

Conclusions

Magnets multipolar errors do have an effect also in the presence of beam-beam.

→ The **tight constrains on the field quality are essential** to guarantee the necessary margins **for the HL-LHC scenarios to be robust**!

→ **The Inner Triplet errors seem dominating** the reduction of DA (but depends on the scenario)

→ We are working now on identifying the specific contributions of different multipoles to feedback to the field quality team (on-going work)

Round optics - Simulation Details

optics files:

SLHC optics:

/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/opt_0400_0400thin.madx beta*=40cm in IR1/5, beta*=10 m in IR2/8
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/opt_0330_0330thin.madx beta*=33cm in IR1/5, beta*=10 m in IR2/8
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/opt_0150_0150thin.madx beta*=15cm in IR1/5, beta*=10 m in IR2/8
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/opt_0100_0100thin.madx beta*=10cm in IR1/5, beta*=10 m in IR2/8

HLLHC optics:

/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/opt_round_thin.madx

error tables:

for old simulations:

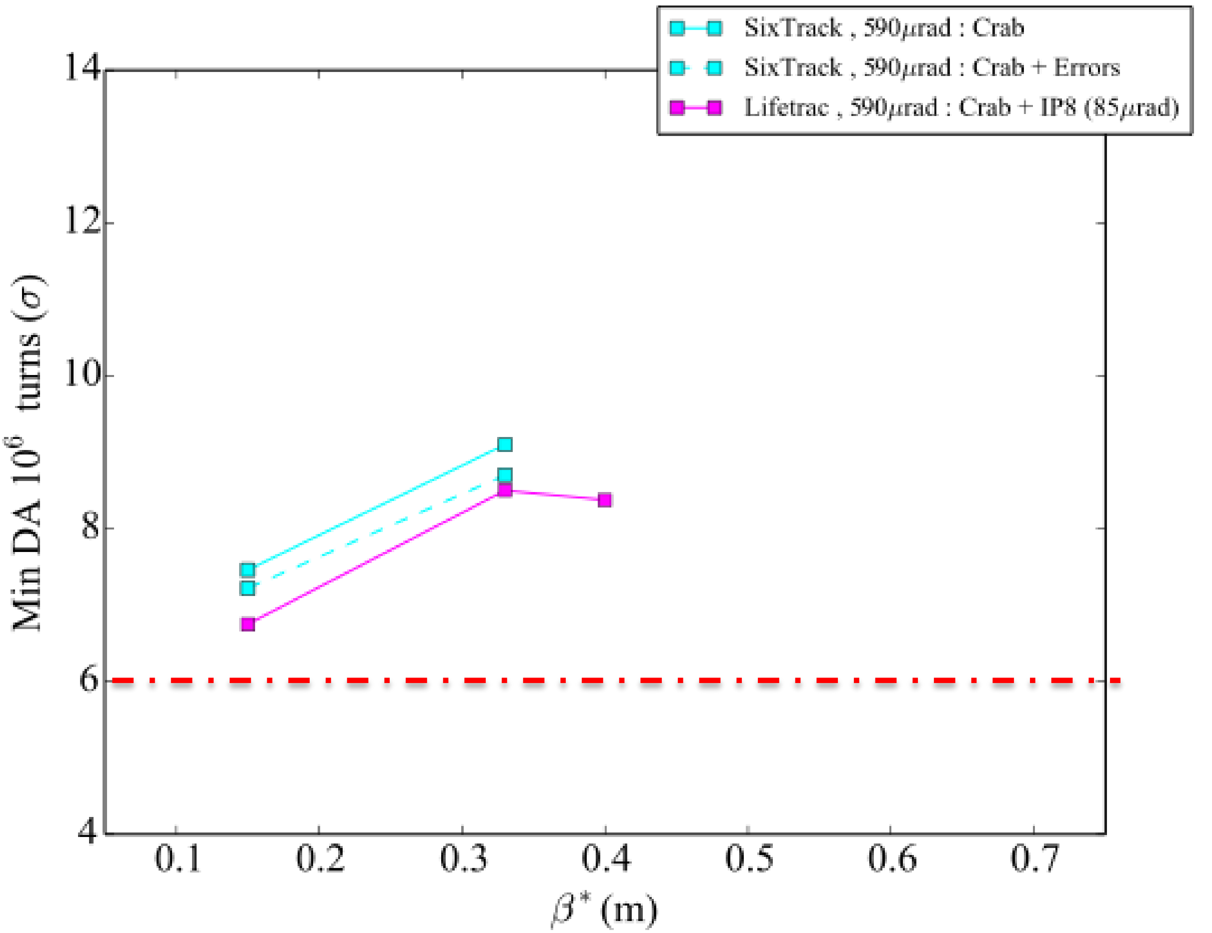
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors/IT_errortable_v3 target error table for the new IT
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors/D1_errortable_v1 target error table for the new D1
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors/D2_errortable_v1 target error table for the new D2
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors/Q4_errortable_v1 target error table for the new Q4 in IR1 and IR5
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors/Q5_errortable_v0 target error table for the new Q5 in IR1 and IR5 and IR6

new error study:

/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors/IT_errortable_v3_spec";! target error table for the new IT
/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors/D1_errortable_v1_spec";! target error table for the new D1
/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors/D2_errortable_v5_spec ";! target error table for the new D2
/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors/Q4_errortable_v1_spec";! target error table for the new Q4 in IR1 and IR5
/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors/Q5_errortable_v0_spec";! target error table for the new Q5 in IR1 &IR5 & IR6

Back up slides

Summary for 7.5e34 leveled lumi

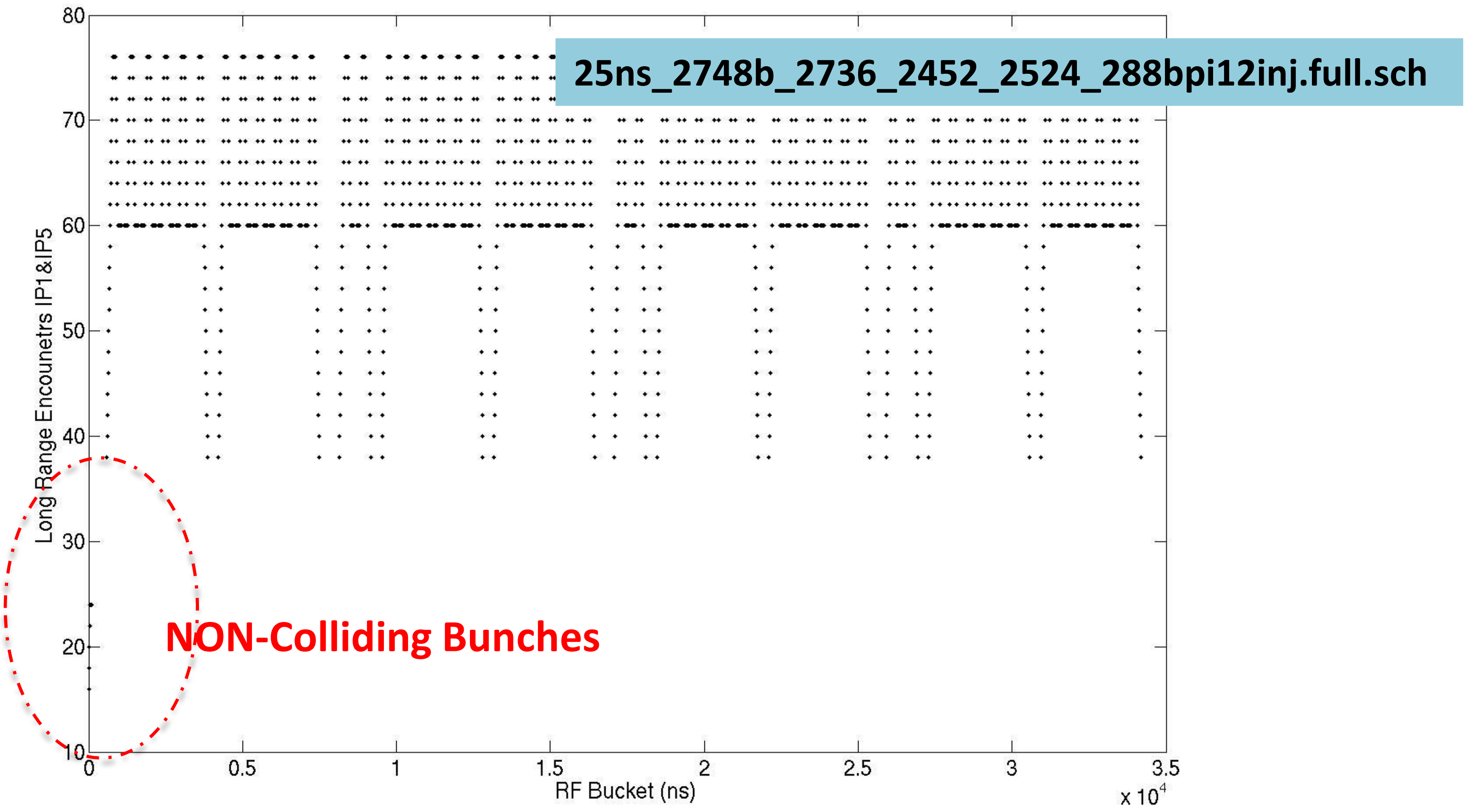


Nominal scenario with leveled lumi at 7.5e34 at 590μrad is robust thanks to b* leveling DA always above 7σ

Extreme case NO β* leveling: DA is below 6 σ → Fundamental to keep all contributions at MINIMUM (Multipolar Errors, other IPs)

Filling Schemes: NON-Colliding Bunches

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



- **Non-Colliding Bunches will have very little Landau Damping (NO-Head-on collision) might become unstable and or reduce other bunches lifetimes**
- **These few bunches stability will define important parameters in collision CHROMATICITY and LANDAU Octupoles (visible in 2012 for IP8 bunches in LHC)**

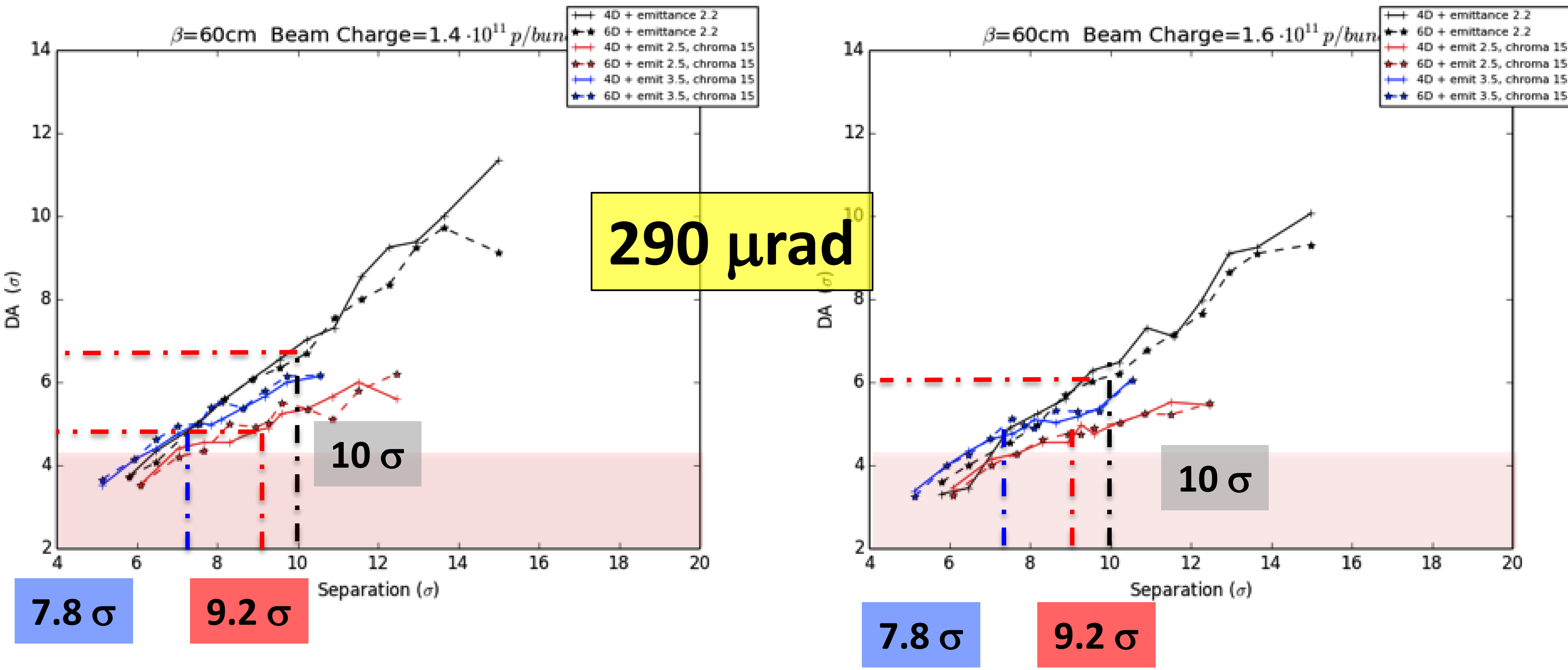
Intensity 10^{11} ppb	IP1&5	IP1&5&IP 8(-lhcb)	IP1&5&8 (+lhcb)	IP1&5&8 (-lhcb)	IP1&5&8 (+lhcb)
1.0	8.41	8.07	7.72	6.48	4.83
2.2	6.42	6.28	5.86	4.83	4.76

Full head-on from IP8 DQ = - 0.01

Three cases for IP8 LRs at 3m β*:

- **α_{IP8} = 610 μrad → ΔDA = -0.35@2.2e11 (0.14@1.1e11) σ**
- **α_{IP8} = 290 μrad → ΔDA = -0.5@2.2e11 (0.36@1.1e11) σ**
- **α_{IP8} = 70μrad → ΔDA = -0.7@2.2e11 (0.56@1.1e11) σ**

2) Second Part Year: 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.

β* leveling scenario at 5E34

Two cases 5e34 and 7.5e34

Leveled Luminosity	**Intensity ppb at β* = 40cm**	**Intensity ppb at β* = 33cm**	**Intensity ppb at β* =15cm**	**Intensity ppb at β* =10cm**
5E+34	1.7E+11	1.5E+11	1.1E+11	1E+11
7.5E+34	x	2.1E+11	1.5E+11	x

We Define:

- **Minimum crossing angle** acceptable to ensure 6σ DA
- **Maximum Intensity** acceptable per β* step during leveling

Filling Schemes

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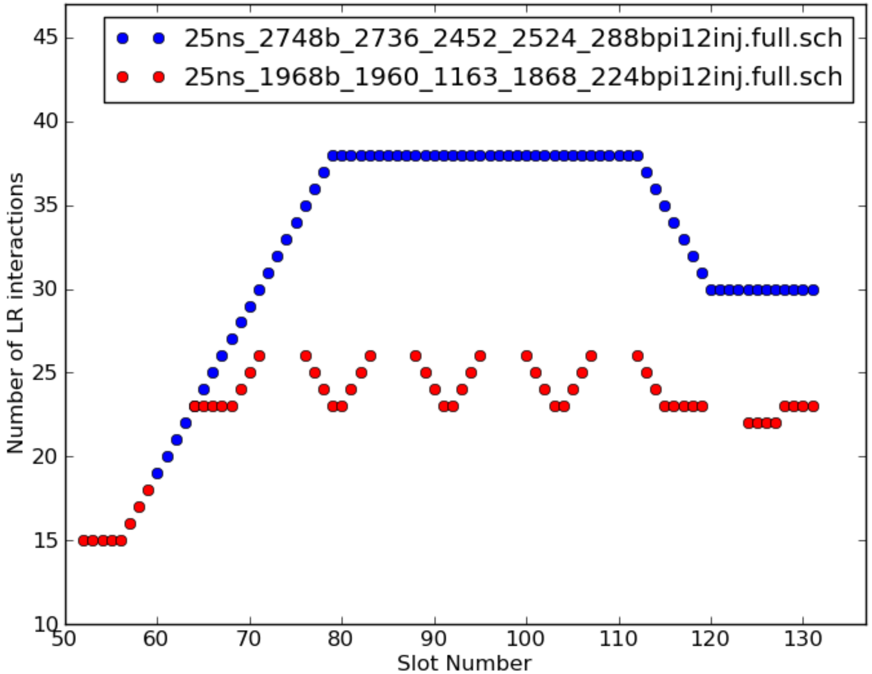
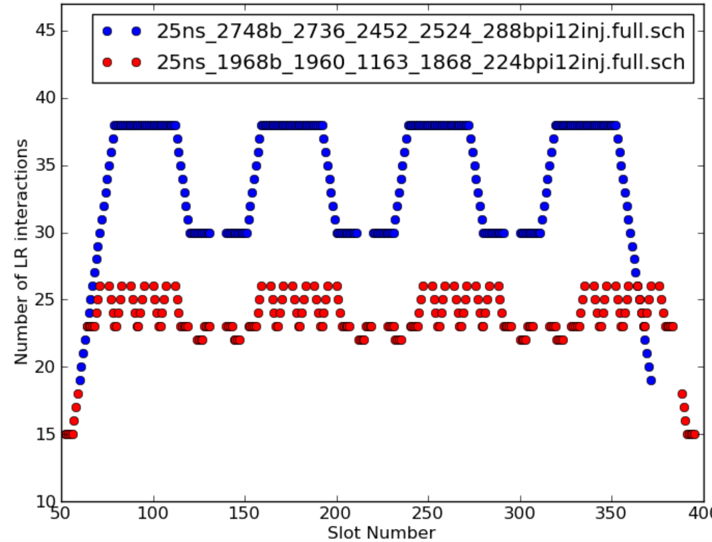




8b+4e Filling schemes:

- 40-30% less LR encounters
- 12 non-colliding bunches

Nominal Filling scheme:

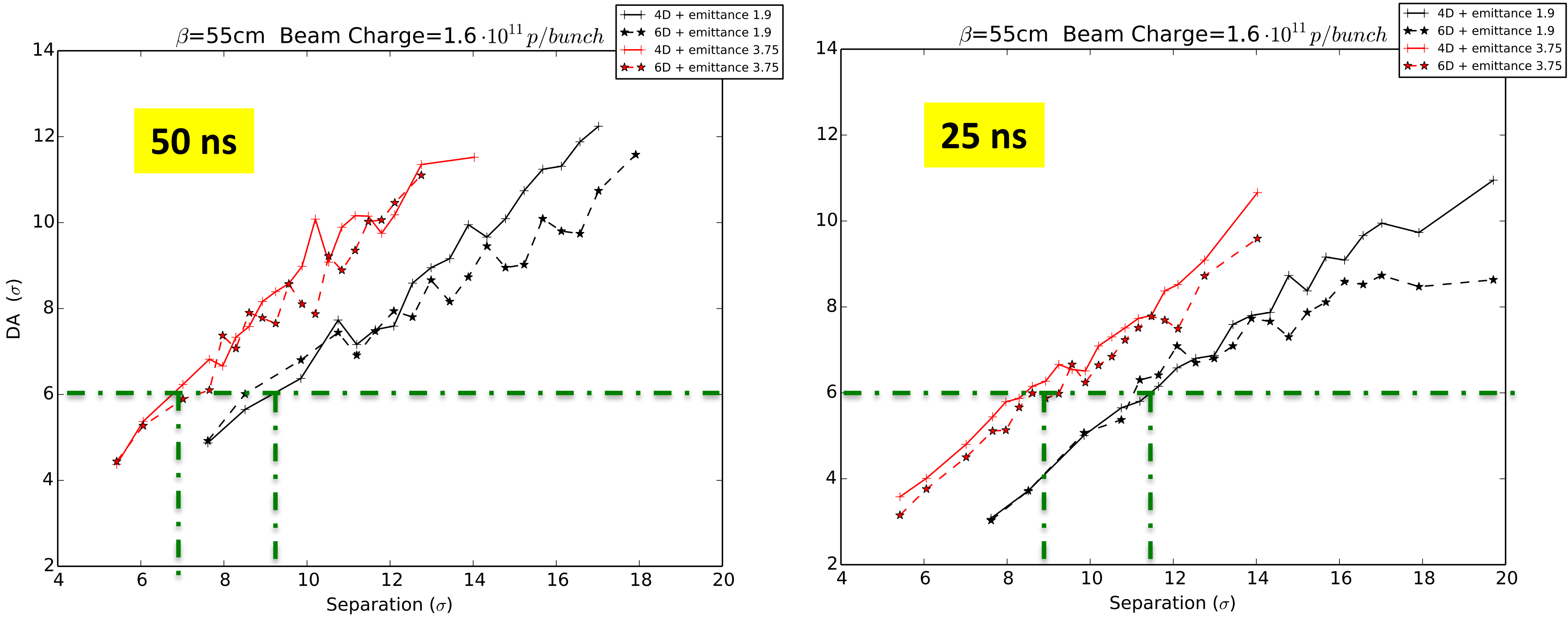
- 38 LRs in IP1&IP5 (after D1 not considered)
- 12 non-colliding bunches

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

Round optics - Simulation Details

optics files:

SLHC optics:

/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/opt_0400_0400thin.madx beta*=40cm in IR1/5, beta*=10 m in IR2/8
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/opt_0330_0330thin.madx beta*=33cm in IR1/5, beta*=10 m in IR2/8
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/opt_0150_0150thin.madx beta*=15cm in IR1/5, beta*=10 m in IR2/8
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/opt_0100_0100thin.madx beta*=10cm in IR1/5, beta*=10 m in IR2/8

HLLHC optics:

/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/opt_round_thin.madx

error tables:

for old simulations:

/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors/IT_errortable_v3 target error table for the new IT
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors/D1_errortable_v1 target error table for the new D1
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors/D2_errortable_v1 target error table for the new D2
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors/Q4_errortable_v1 target error table for the new Q4 in IR1 and IR5
/afs/cern.ch/eng/lhc/optics/SLHCV3.1b/errors/Q5_errortable_v0 target error table for the new Q5 in IR1 and IR5 and IR6

new error study:

/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors/IT_errortable_v3_spec";! target error table for the new IT
/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors/D1_errortable_v1_spec";! target error table for the new D1
/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors/D2_errortable_v5_spec ";! target error table for the new D2
/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors/Q4_errortable_v1_spec";! target error table for the new Q4 in IR1 and IR5
/afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors/Q5_errortable_v0_spec";! target error table for the new Q5 in IR1 &IR5 & IR6