Beam-beam effects and limitations in the HL-LHC

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Acknowledments: E. Mcintosh, I. Zacharov and all the LHC@home volunteers, G. Arduini, R. Calaga, R. De Maria, M. Giovannozzi,

LARP-HiLUMI Collaboration Meeting
May 7-9 Brookhaven National Laboratory

Outlook

- Code development and benchmarks
- Learning case the LHC 2012 Physics RUN
- The HL-LHC baseline scenario different contributions
- Baseline: β^* leveling
- PACMAN effects
- Strong-strong studies: see J. Qiang talk later
- Summary
- What's next?

Codes development:

CERN Sixtrack:
J. Barranco and D. Banfi (EPFL), T. Pieloni (CERN)

- DA
- Element by element tracking
- FMA
- Lifetimes
- Crab Cavities
- Beam-beam LR wire compensator

Lifetrac:
S. Valishev, D. Shatilov

- DA
- Element by element tracking
- FMA
- Lifetimes
- Crab Cavities
- Beam-beam LR wire compensator

Beambeam3D:
J.Qiang (LBNL)

Ohmi code:
K. Ohmi (KEKB)

COMBI code:
J. Barranco (EPFL), M. Crouch (Manchester) and T. Pieloni (CERN)

- **General effort to reproduce LHC 2012 run observables**
- **Benchmark: emittance growth studies in the presence of crab cavities**
- **Benchmark: the impact of feedback model on colliding beams**

Lifetrac benchmark: DA
test case without beam-beam

slhcv3.1b, 7 TeV, β*=10 cm, beam-beam off

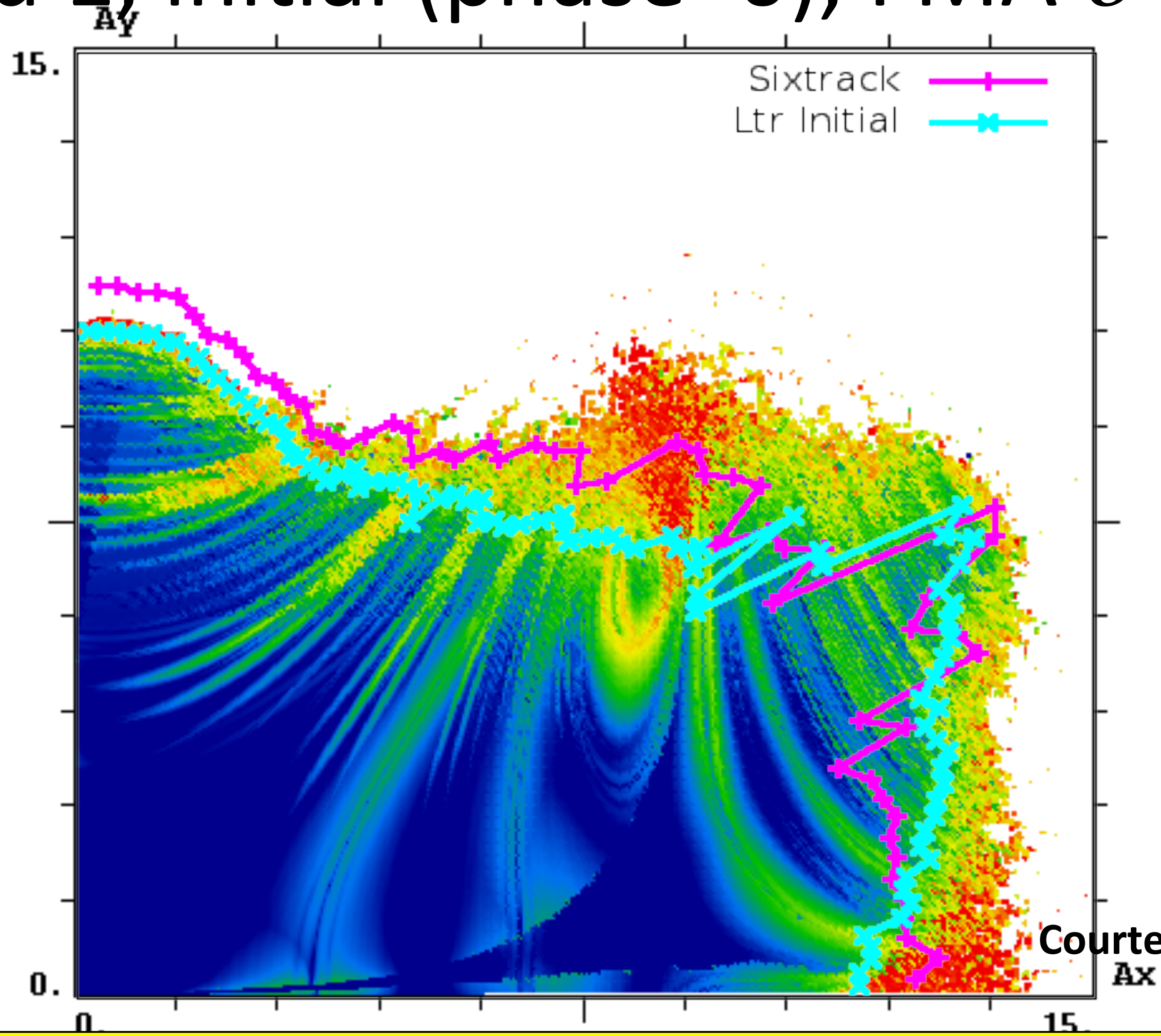
- emittance 3.75 μm, Δp/p=2.7E-4, 10^5 turns DA

- Sixtrack data provided by Task 2.3 M.Giovannozzi
  - 60 seeds
  - 59 angles
  - 30 particle pairs for 2 sigma intervals

- Lifetrac
  - Same seeds
  - 59 angles
  - 22 particle pairs for 2 sigma intervals

Courtesy S. Valishev

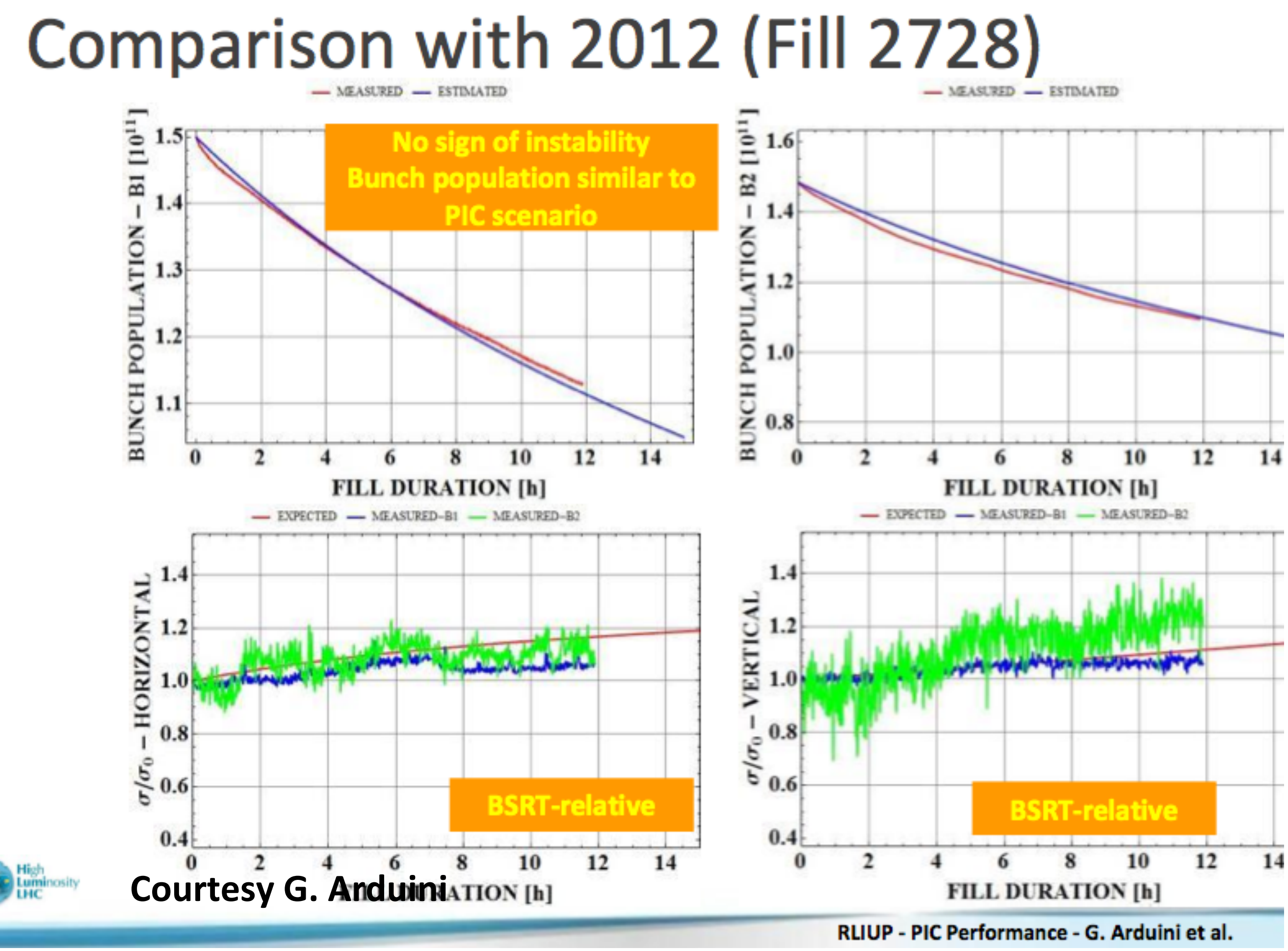
Seed 1, initial (phase=0), FMA δ=2σ



Courtesy S. Valishev

Comparison over several seeds (60), results in within 10% difference
Very good agreement!

Reproducing LHC lifetimes with Lifetrac: special fill.



Courtesy G. Arduini

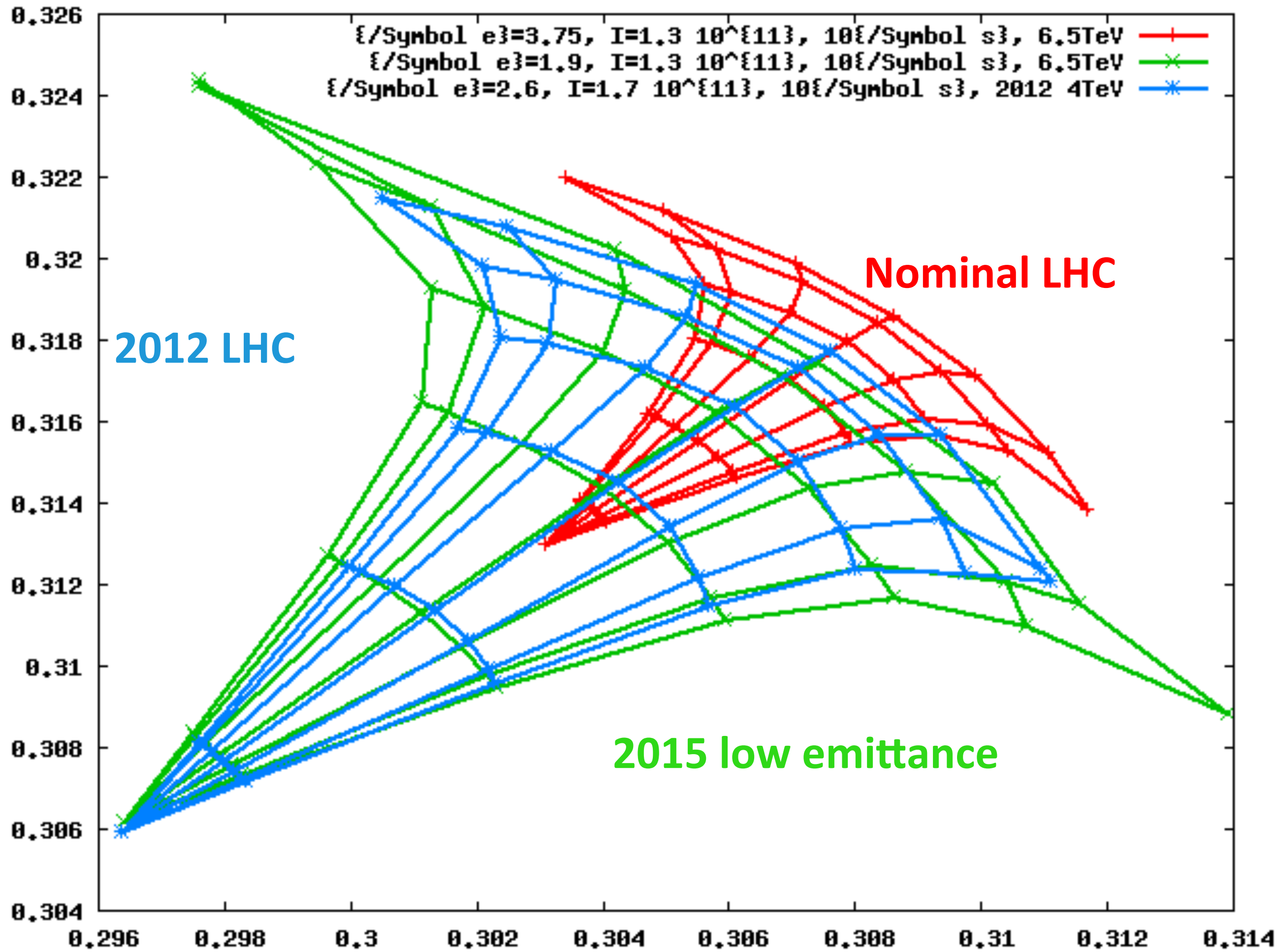
DATA
Int lifetimes = 1.5 %/hr
Lumi lifetimes = 2%/hr

Lifetrac
Int lifetimes = 2 %/hr
Lumi lifetimes = 0.5%/hr

Simulations in within a factor 2-4 from data. We still need to understand the LHC data

Sixtrack Learning case: the LHC 2012 Physics RUN

LR separation 10 σ for different beams



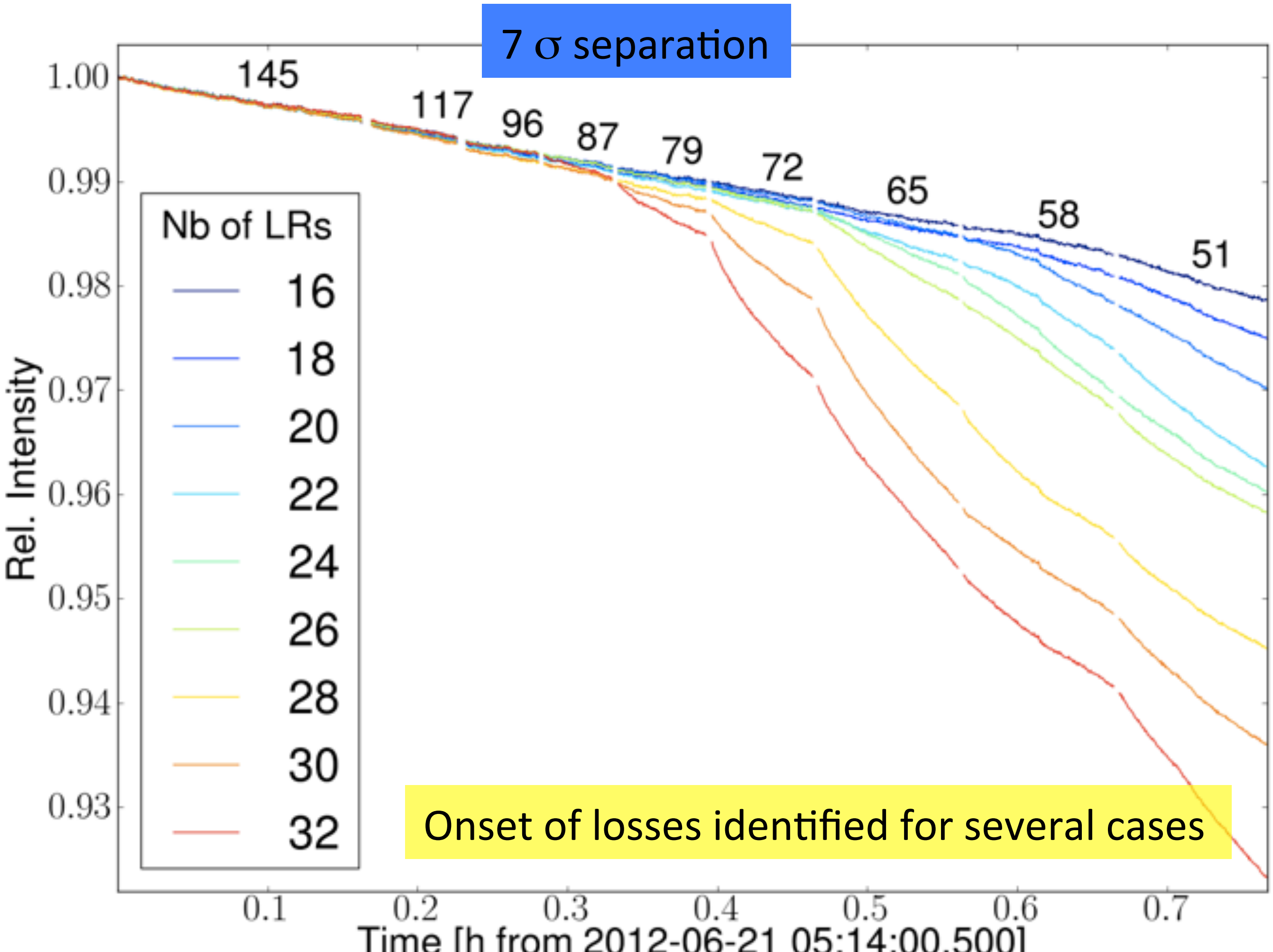
12-10 σ separation is not an absolute number!

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

DA changes and other mechanism could enter!

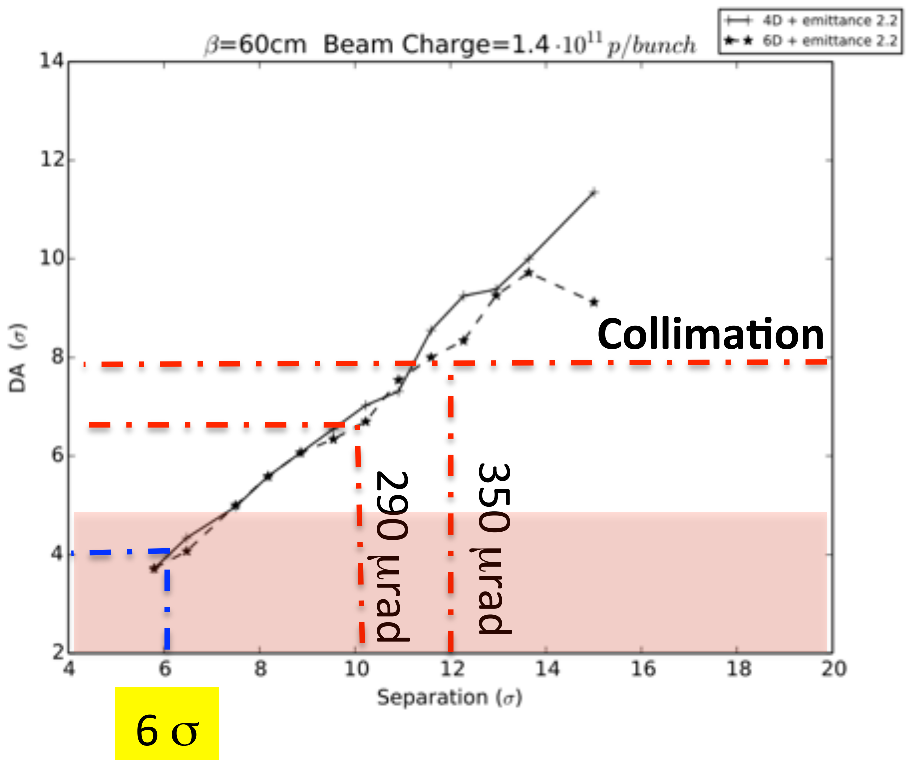
BB LR experiments Note:
very similar to LHC OP first part year

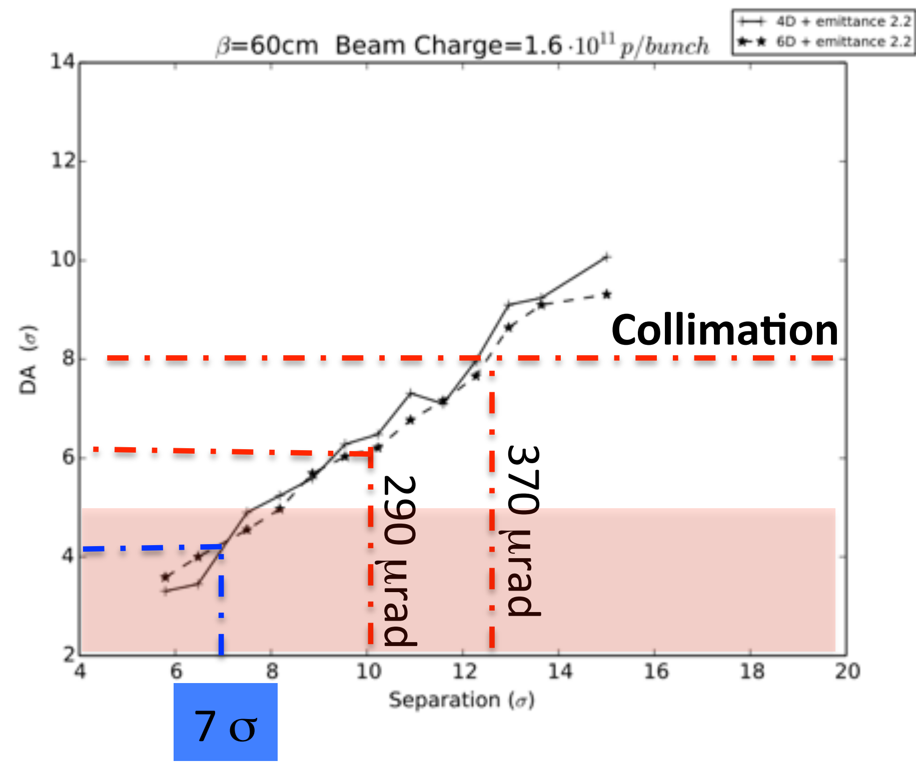
1.6 e11 ppb
IP1 crossing angle
Q' = 2 units



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 seems agreeing with onset of losses at 6 σ separation, e-cloud present

DA for the Long-range MDs Intensity effect:



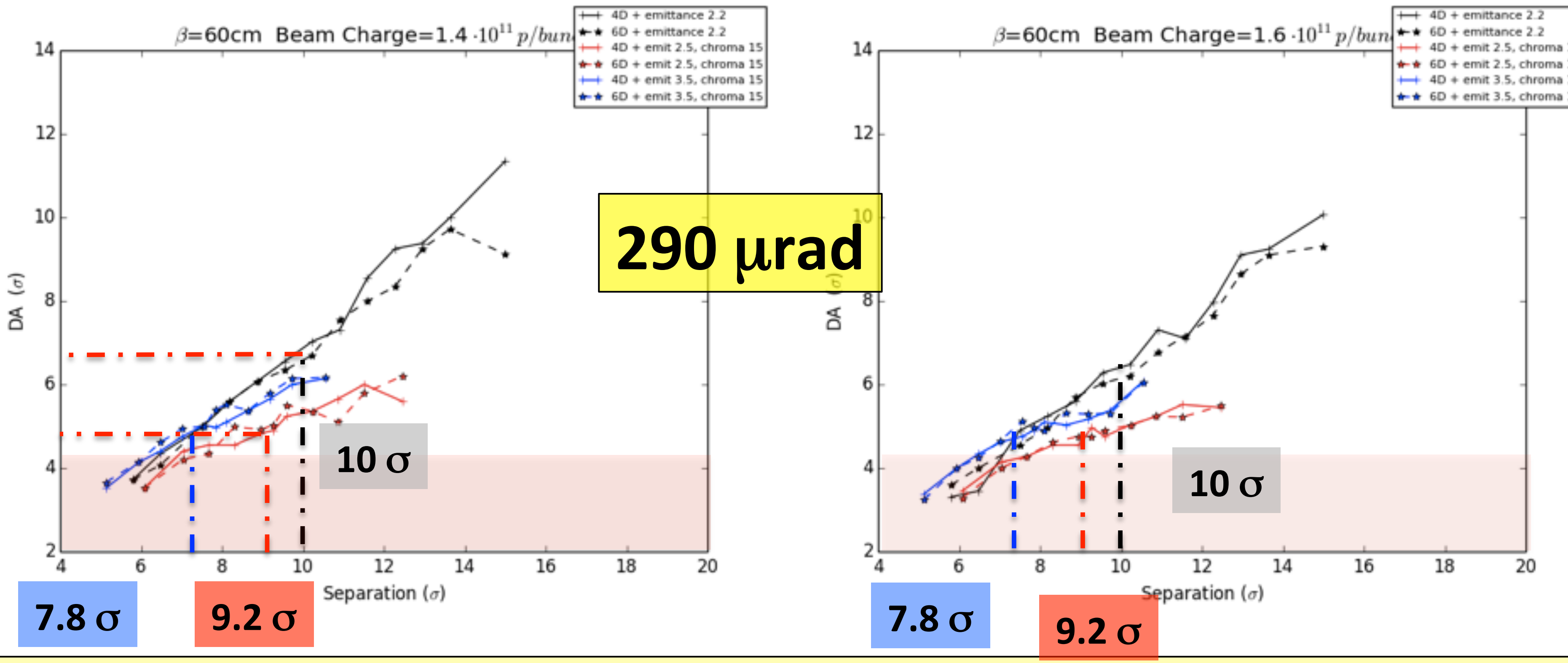


LR MDs:

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

Significant losses and lifetime drop at different 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

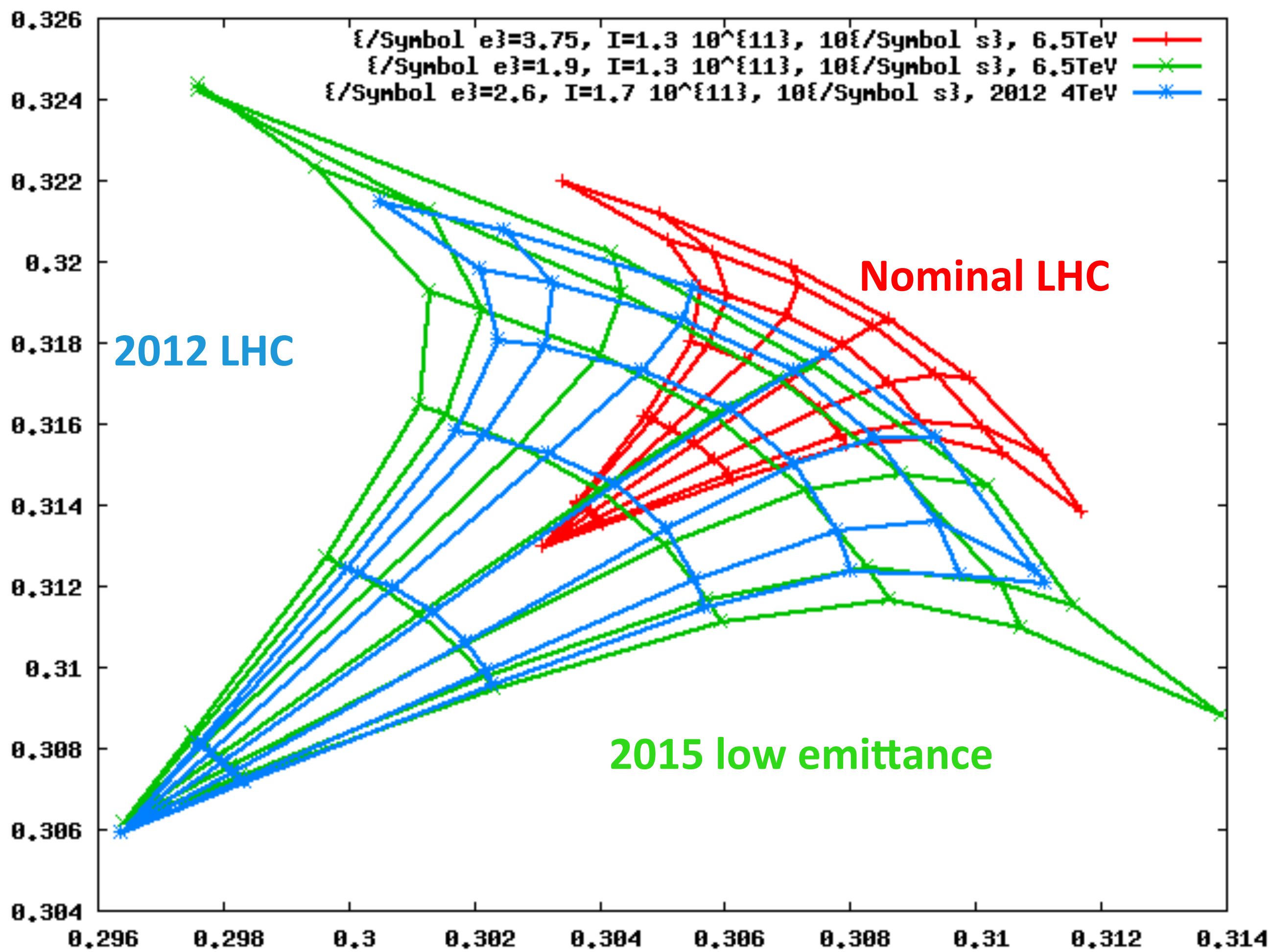
LHC 2012 physics run case second part of the year: Q’ = 15 Bad Lifetimes



Chromaticity has a BAD impact on DA!
During physics fills we were on the limit: any particle at 4-5 sigma was lost!
Chaotic spikes start before 2-3 σ! Bad lifetimes and emittance growth.
DA should be larger than 6 σ if it is BB dependent!

Footprints for Nominal, 2012 run and 2015:

LR separation 10 σ



12-10 σ separation is not an absolute number!

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

DA changes and other mechanism could enter!

HL-LHC baseline parameters

	LHC nominal	HL-LHC 25 ns
# Bunches	2808	2808
p/bunch [10^{11}]	1.15 (0.58A)	**2.2 (1.11 A)**
Energy in one beam [MJ]	360	**690**
$\gamma\varepsilon_{x,y}$ [μm]	3.75	**2.5**
σ_z [cm], $\sigma_{\delta p/p}$ [10^{-3}]	7.5, 0.1	7.5, 0.1
β^* [cm]	55	**15 (→ 10)**
X-angle [μrad], separation	300, (10.0 σ)	**590 (→ 720), (12.5 σ)**
Geometrical luminosity loss factor	0.83	0.31
Peak lumi [10^{34}] (with full Piwinsky angle)	1.0	7.4
Virtual lumi [10^{34}] (w/o Piwinsky angle)	1.2	21.9
$T_{leveling}$ [h] @ 5E34	n/a	**9.0**
#Pile up @5E34	25	**140**

Courtesy S. Valishev

Scenarios analyzed:

Baseline 1

- Round optics 15 cm
- Full crab crossing in IP1 and IP5
- Leveling luminosity with beta* and/or transverse offset in IP1, IP5 and IP8

Baseline 2

- Flat optics 30 cm/7.5 cm
- Long-range wire BB compensators
- Leveling luminosity with beta* and/or transverse offset in IP1, IP5 and IP8

Baseline 3

- 10 cm round optics
- Full crab crossing in IP1 and IP5
- Leveling luminosity with beta* and/or transverse offset in IP1, IP5 and IP8

Baseline 4

- Flat optics 20 cm/5 cm
- Long-range wire BB compensators
- Leveling luminosity with beta* and/or transverse offset in IP1, IP5 and IP8

Sixtrack simulation Standards: DA studies

SixTrack Simulations

Our default simulations :

- 4 HL-LHC optics (β*=15/15cm, β*=10/10cm, β*=7.5/30 cm, β*=5/20cm)
- Collision in IP1 and IP5 only, IP8 off
- 15 X-angles (from 200 to 900 mrad, step 50 mrad)
- 17 xy plane angles (from 5 to 85deg, step 5deg)
- 6 initial amplitudes (from 2 to 12 sigma, step 2 sigma)
- 14 beam intensity (from 0.9 to 3.0 10^{11} p/bunch)
- 60 seeds (for multipoles)
- tune scan (for beta=10cm and 7.5/30cm)
- BeamBeam lenses:
  - 4D+5slices: standard lens for the LHC studies
  - 6D Hirata lens: already implemented but never used for DA studies
- All LR encounters and No LR after D1

Various physics cases to be simulated:	Daresbury	Port Jeff
Beam-Beam only	~~DONE~~	DONE
BB + Multipoles Errors	~~DONE~~	DONE
Crab Cavities	~~ONGOING..~~	DONE
BB + Crab Cavities	~~ONGOING..~~	DONE
BB + Crab + Multipoles	~~TO BE DONE~~	DONE
Wire compensation	~~TO BE DONE~~	ON-GOING

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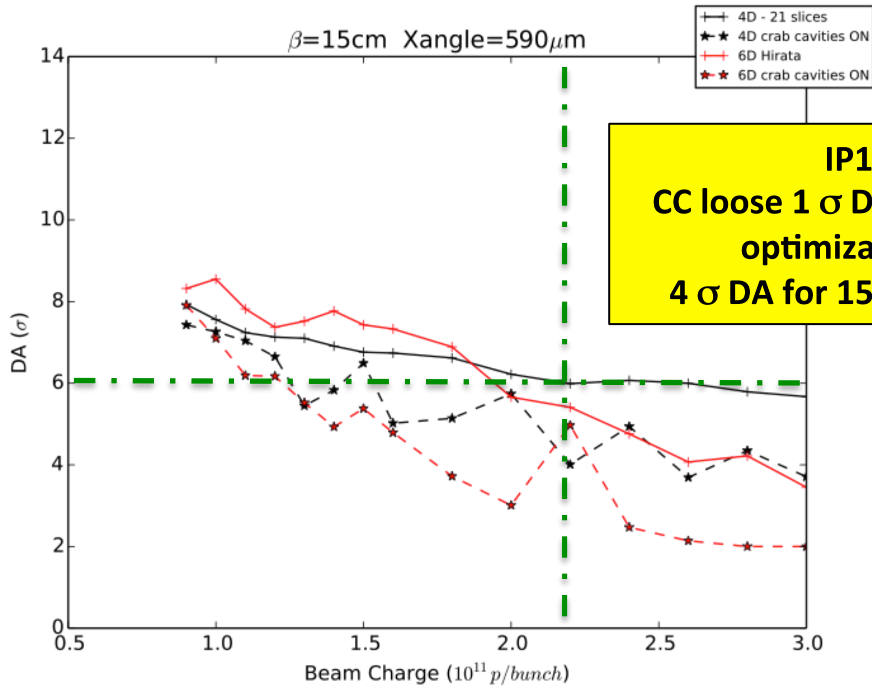
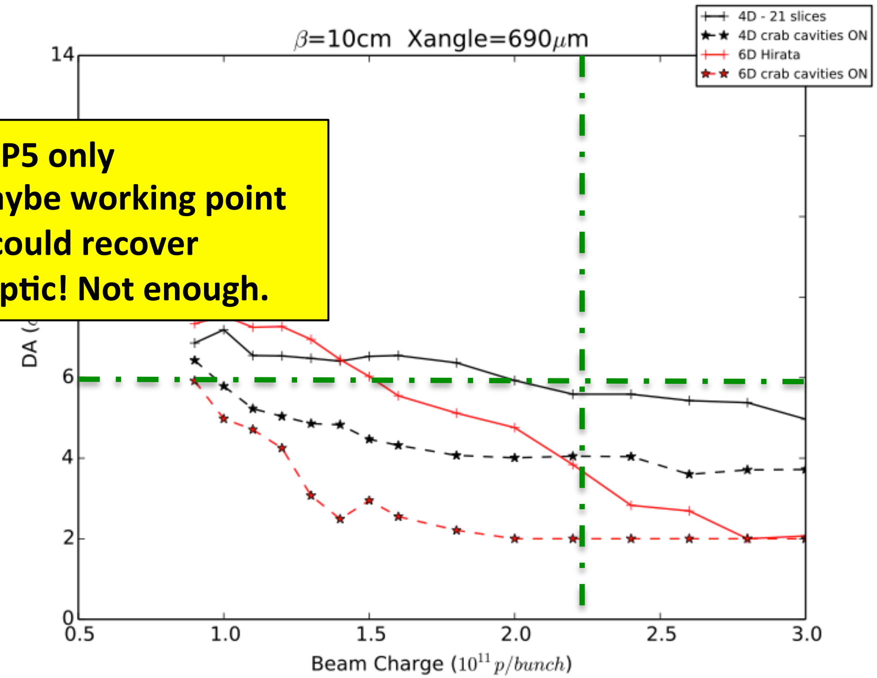
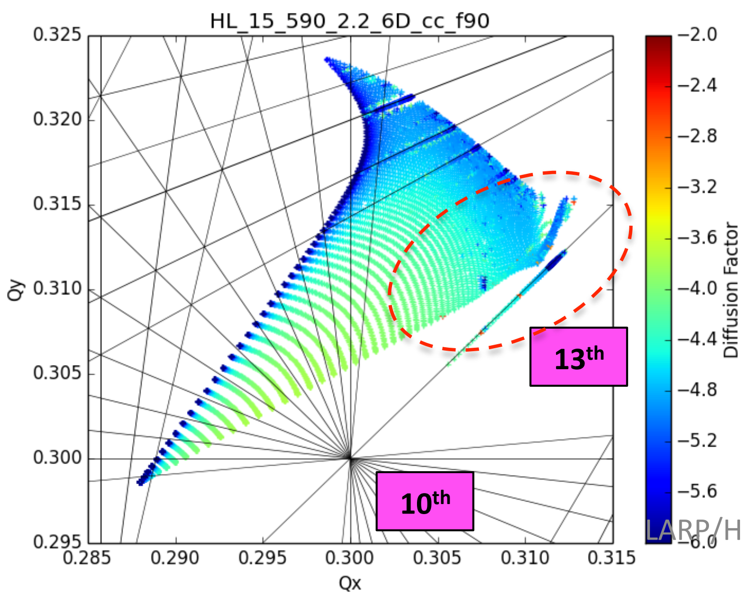
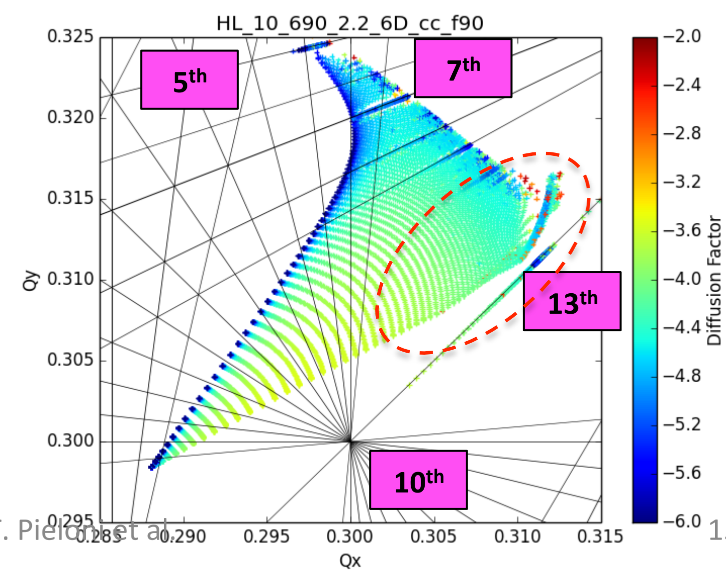
HL-LHC Round Optics CC on/off



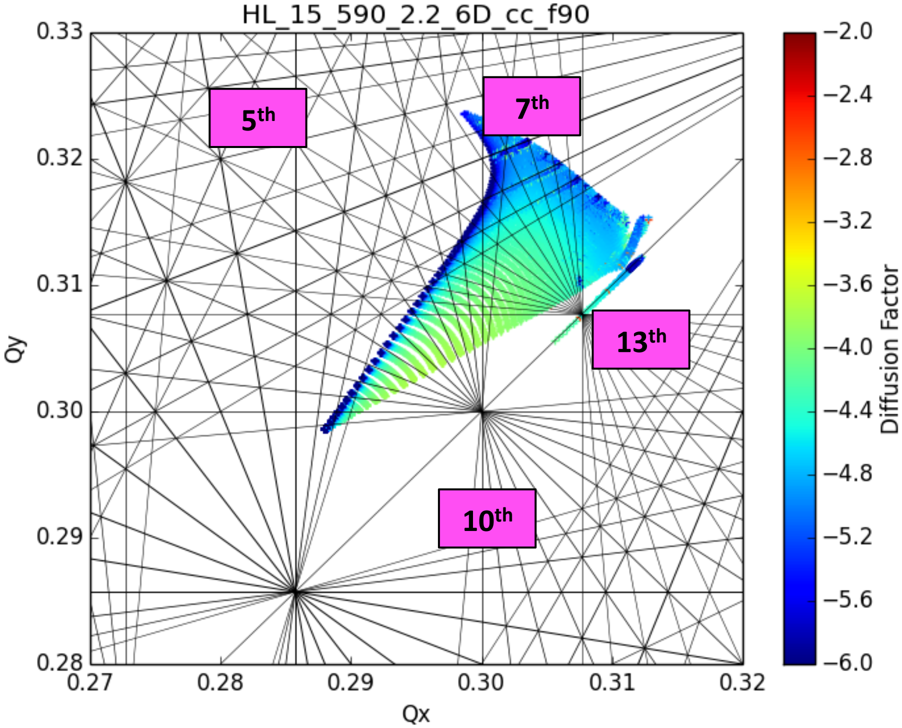


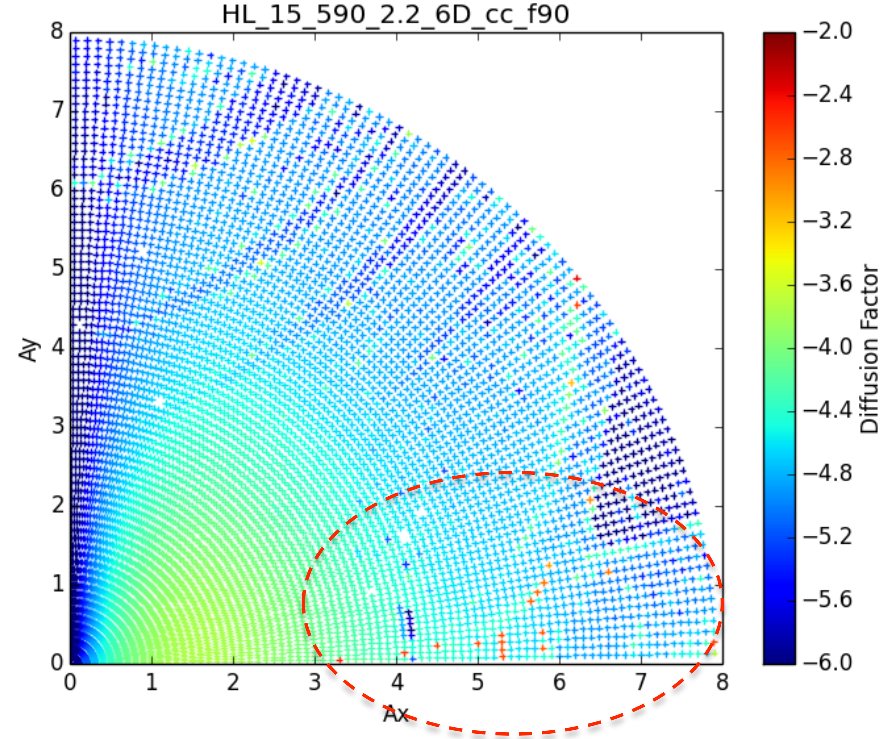
IP1 and IP5 only
CC loose 1 σ DA, maybe working point optimization could recover
4 σ DA for 15 cm optic! Not enough.





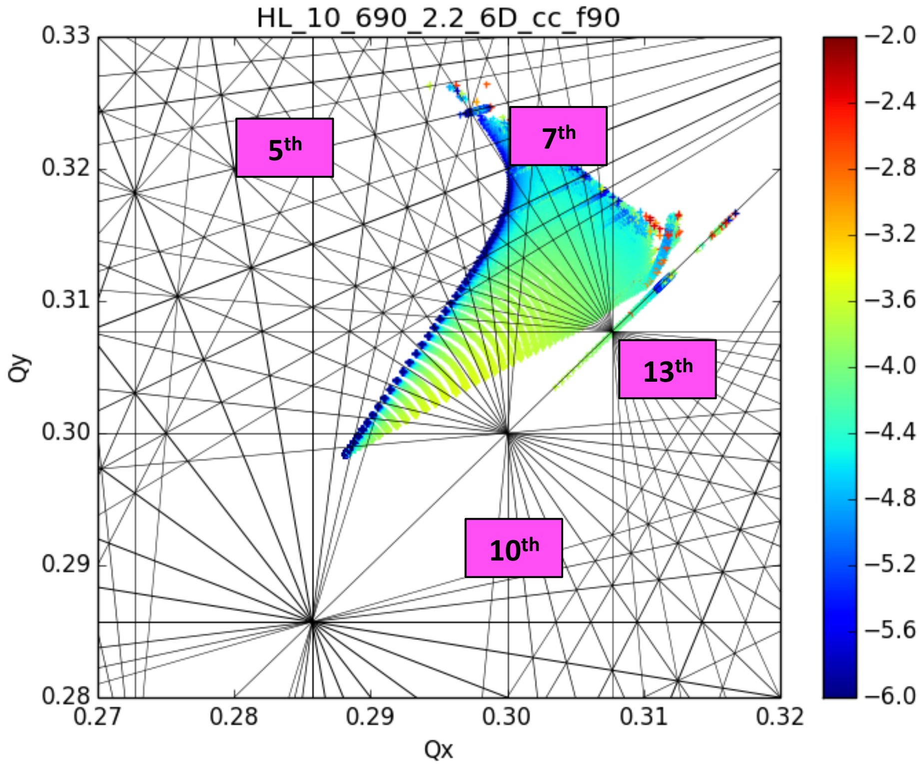
Details 15 cm β* optics at maximum intensity 2.2 e11 ppb

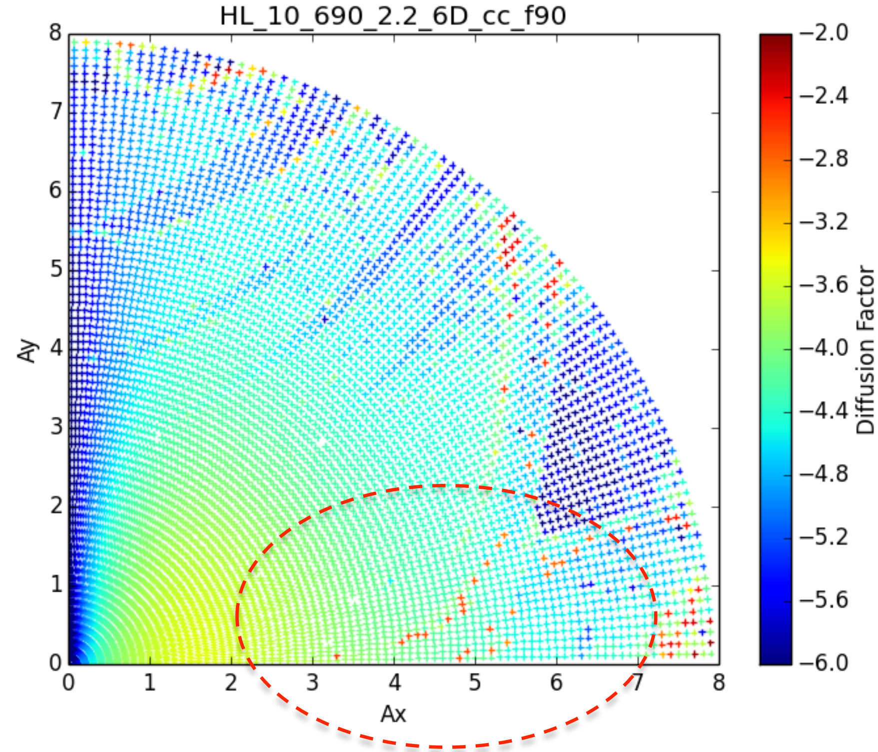




Particles at 3-4 s show chaotic motion and are lost.
Effect driven by 13th order resonance

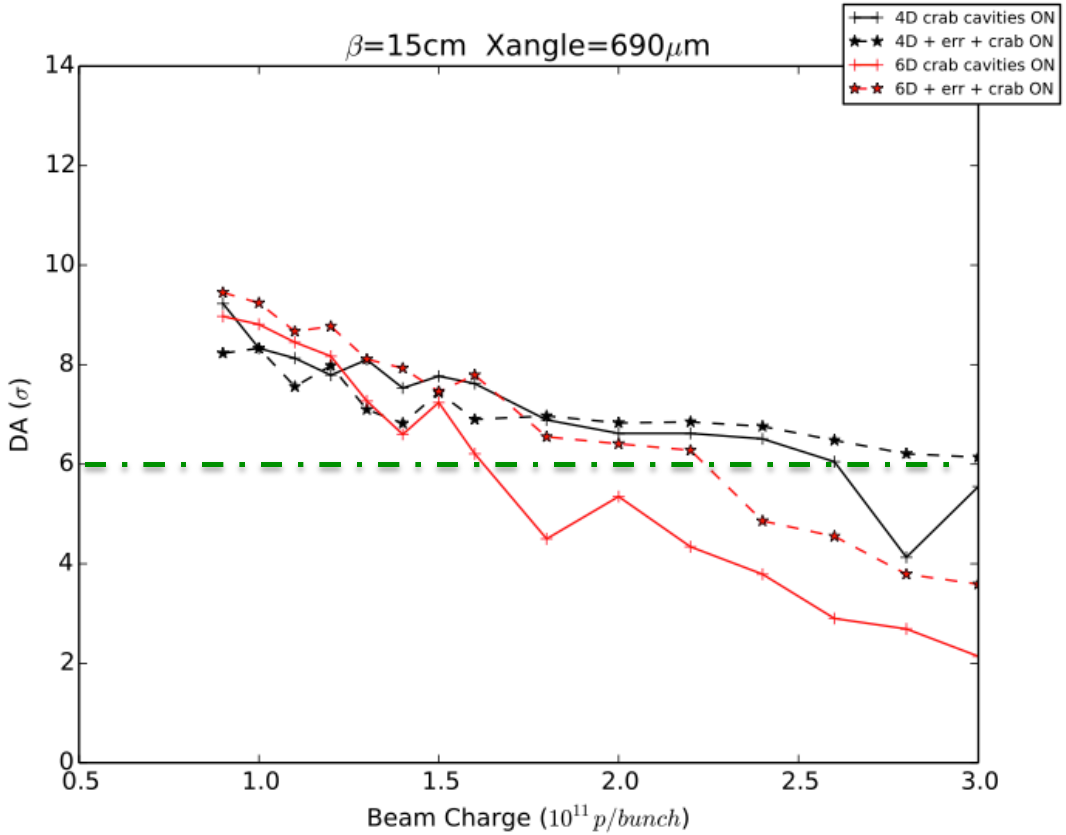
Details 10 cm β* optics at maximum intensity 2.2 e11 ppb

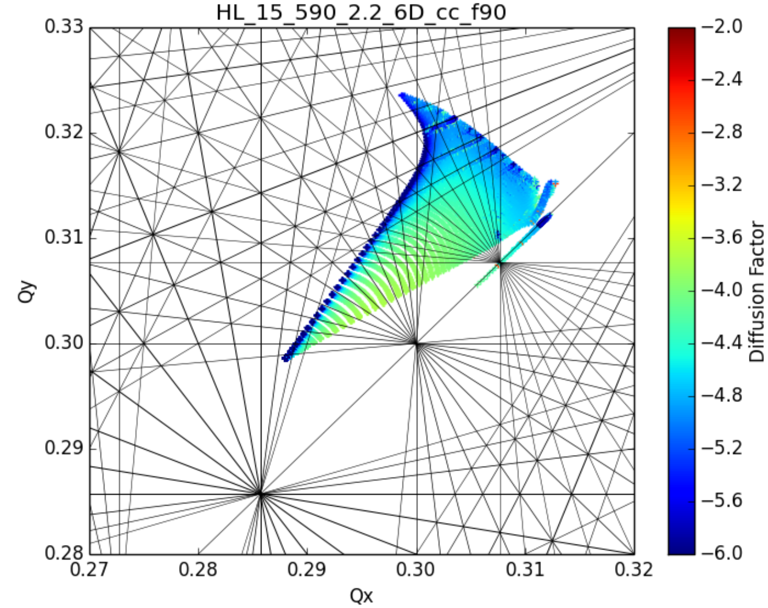


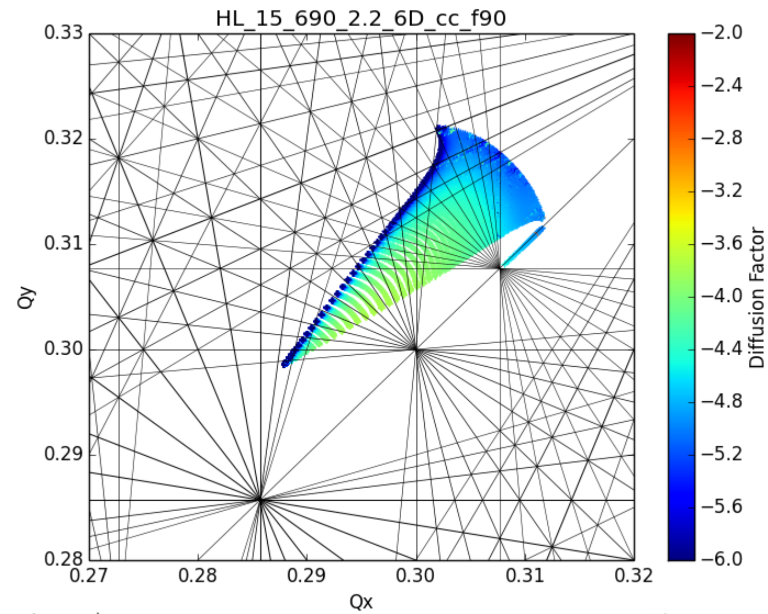


Particles at 3-4 s show chaotic motion and are lost.
Effect driven by 13th order resnance

Larger crossing angle?

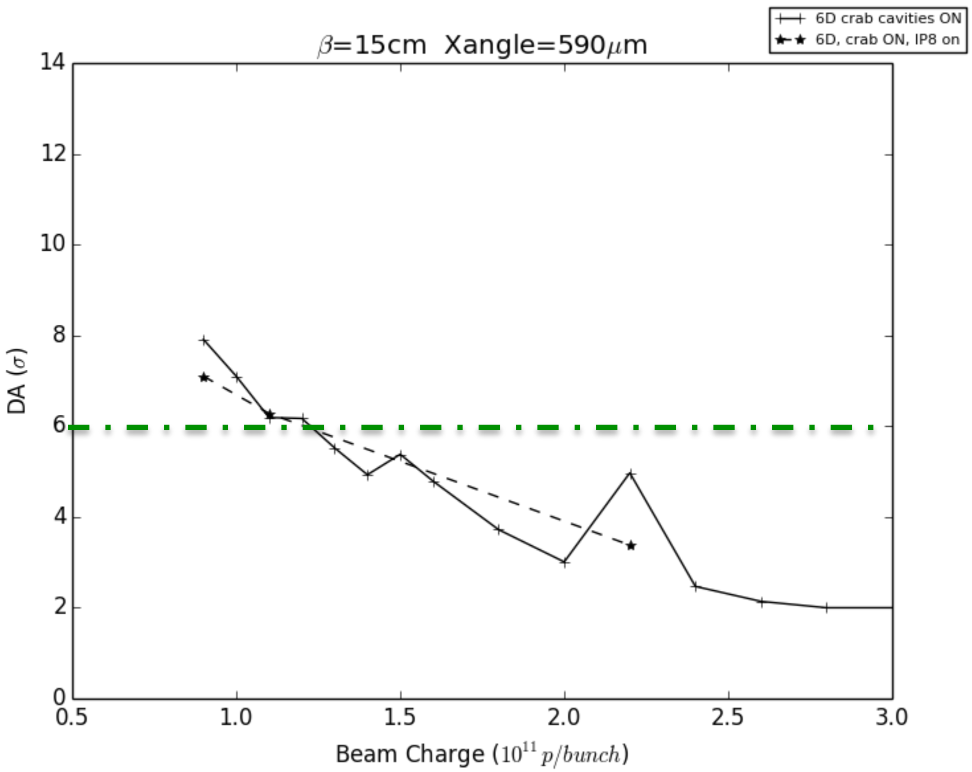


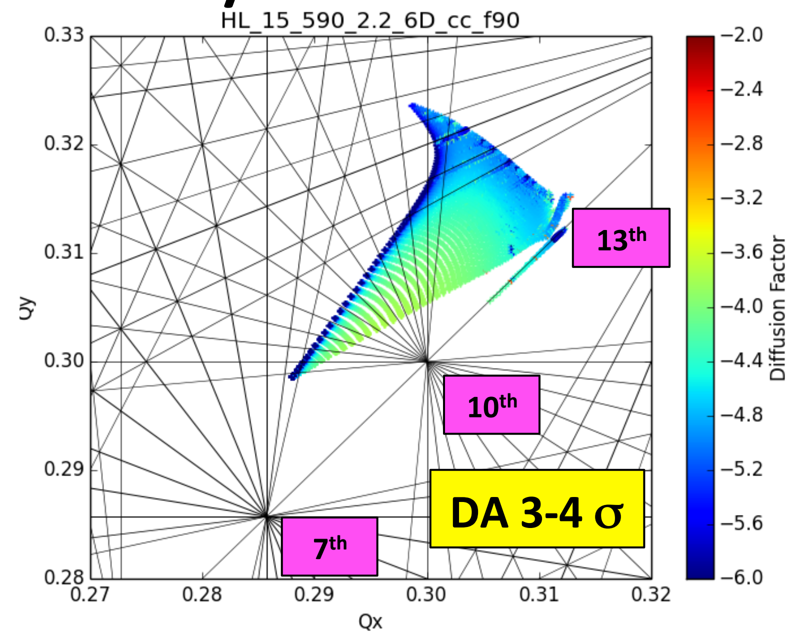


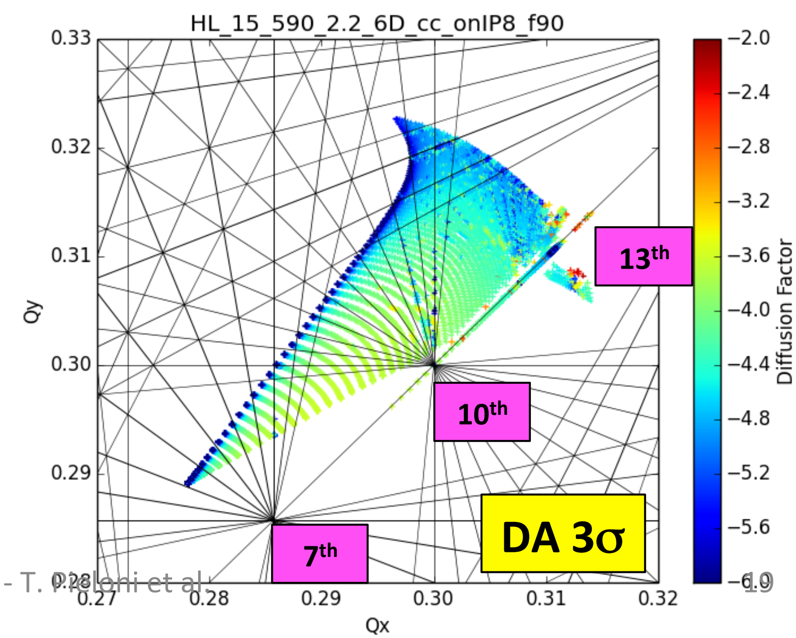


Needs to be increased significantly to be rubust 690 μrad! Larger separations!

HL-LHC Round Optics CC on/off with IP8?

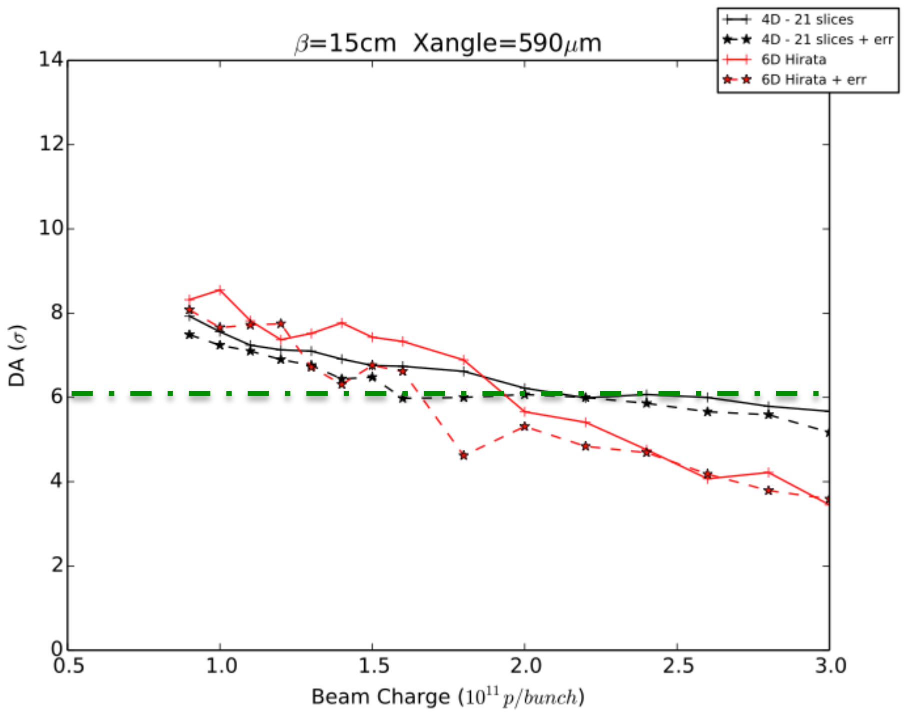


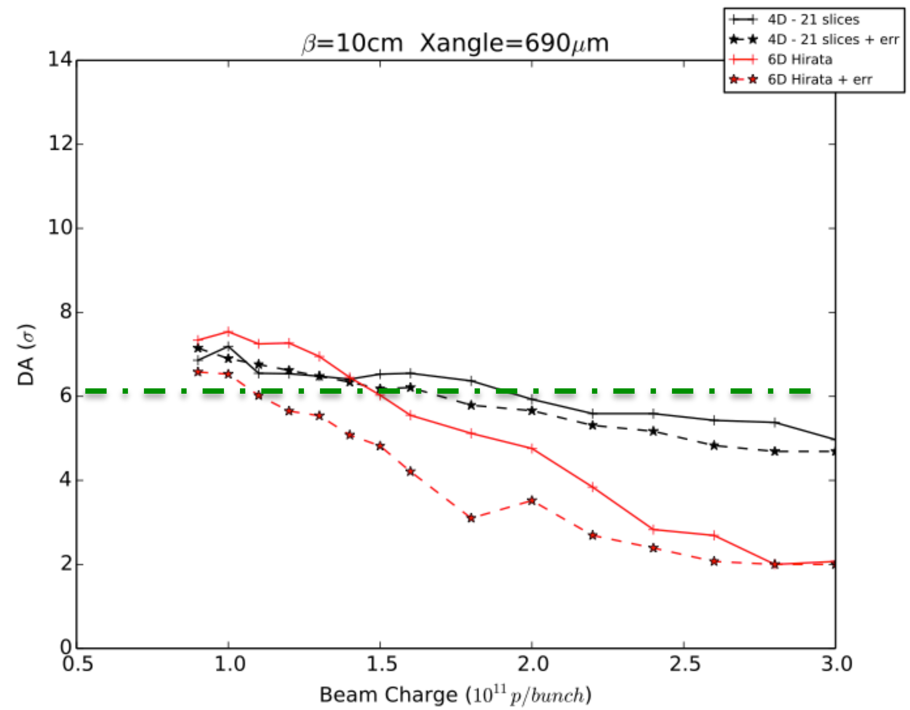




If we have also IP8 colliding head-on
results do not change
3-4 σ particles lost due to 10th and 13th
order resonances.

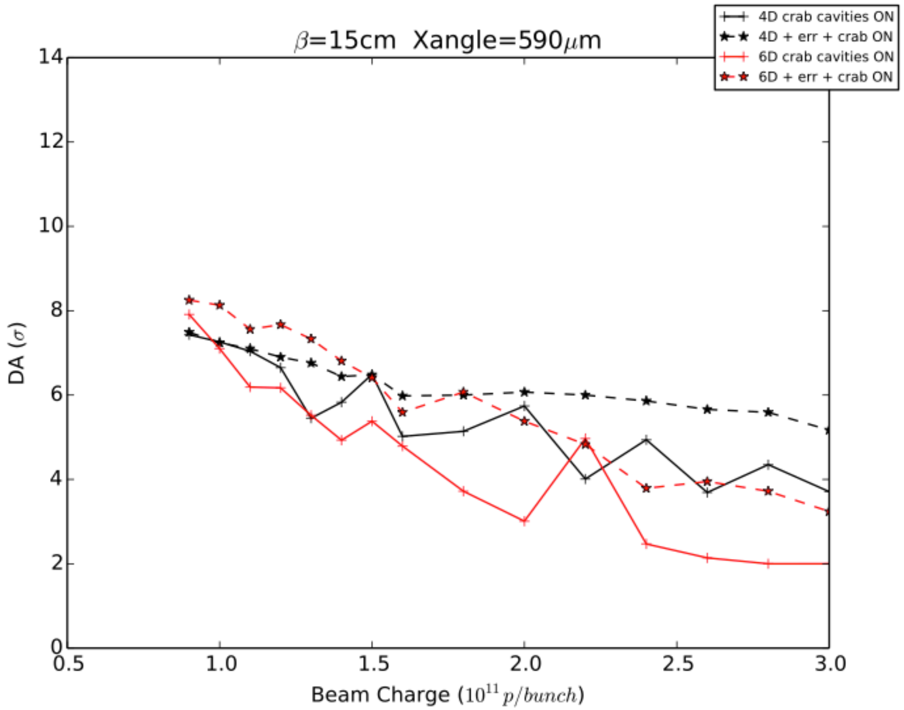
HL-LHC Round Optics errors on/off

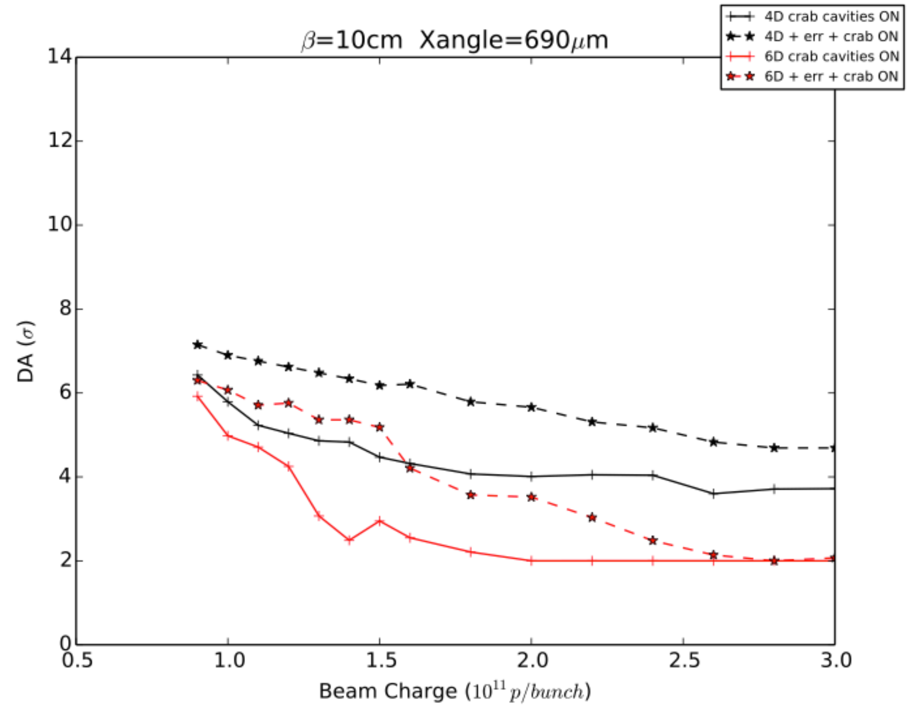




Multipolar Errors do have an impact 1 σ for 15 cm optics, 2 σ for 10 cm.
We need to identify the impact of each multipole error (b_{10}, b_{14}…)!
On-going!

HL-LHC Round Optics CC + errors on/off

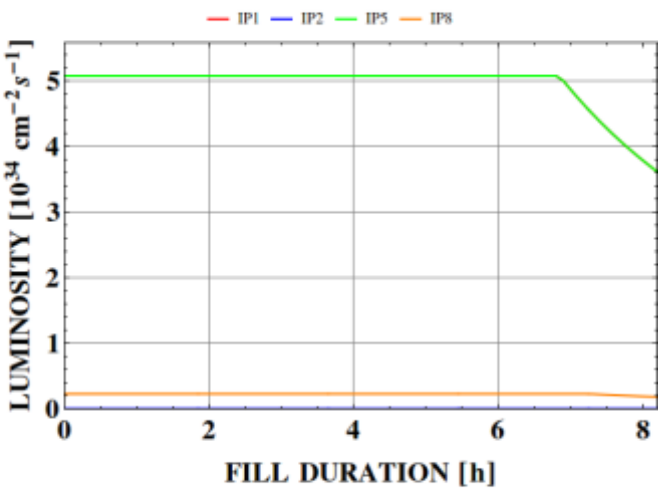


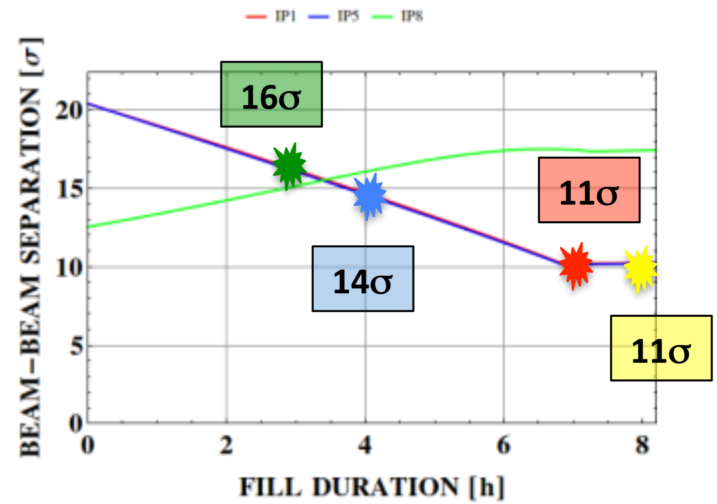


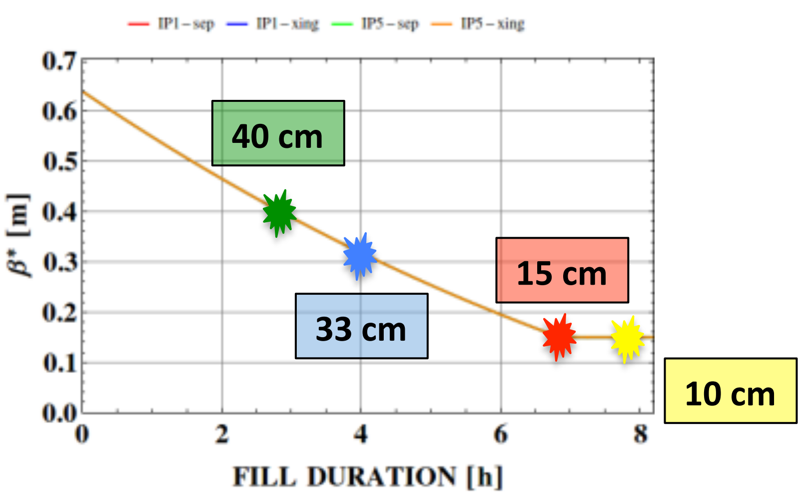
Multipolar Errors do have an impact respect to CC case improve the DA.
Need a working point optimization. On-going!

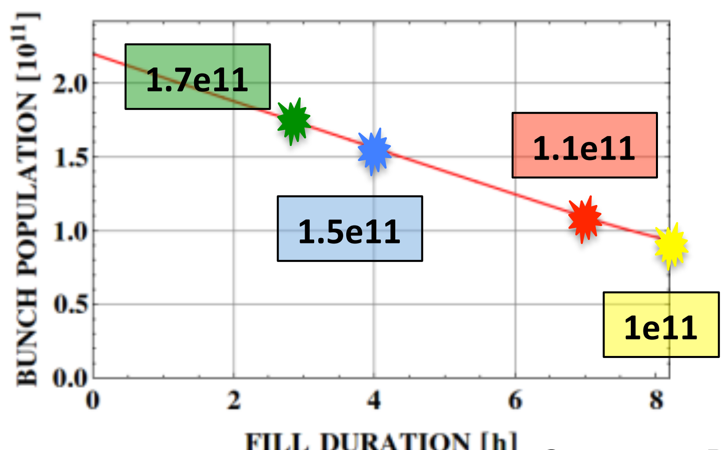
β* leveling

α = 473 μrad and emittances 2.5 μm





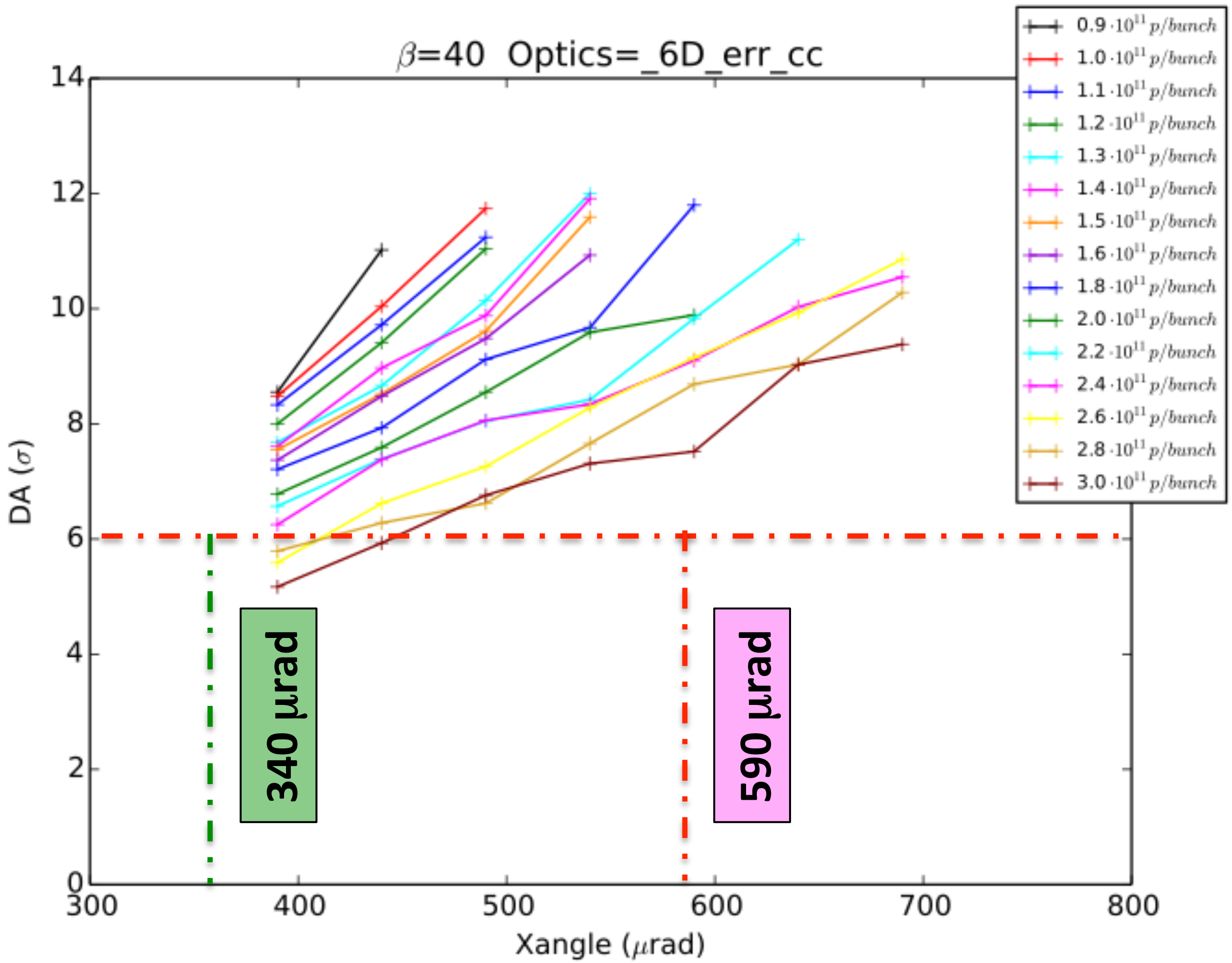




Courtesy R. De Maria

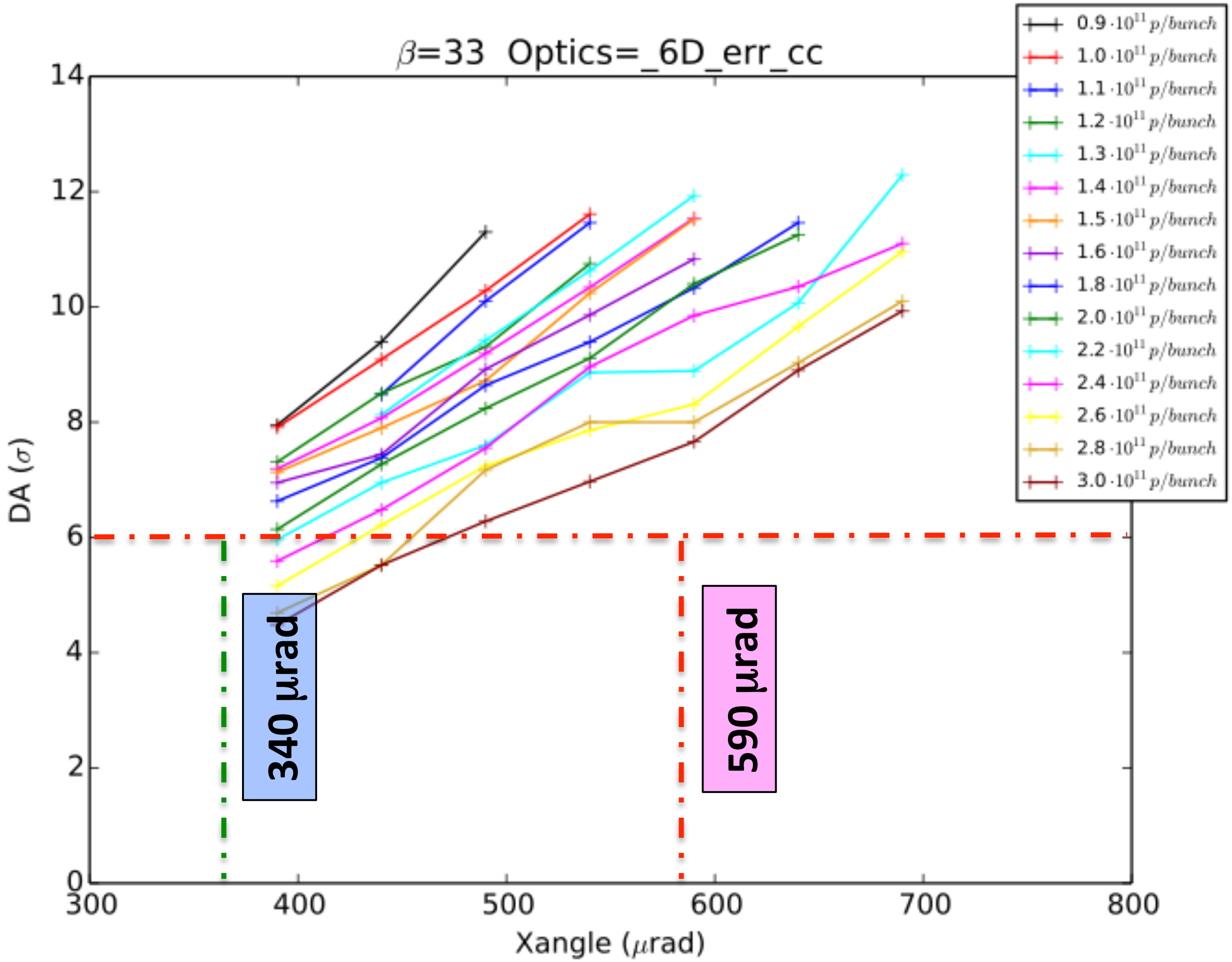
We modeled 4 optics during betatron squeeze beam parameters follow the luminosity leveling

Beta* leveling: 40 cm β*



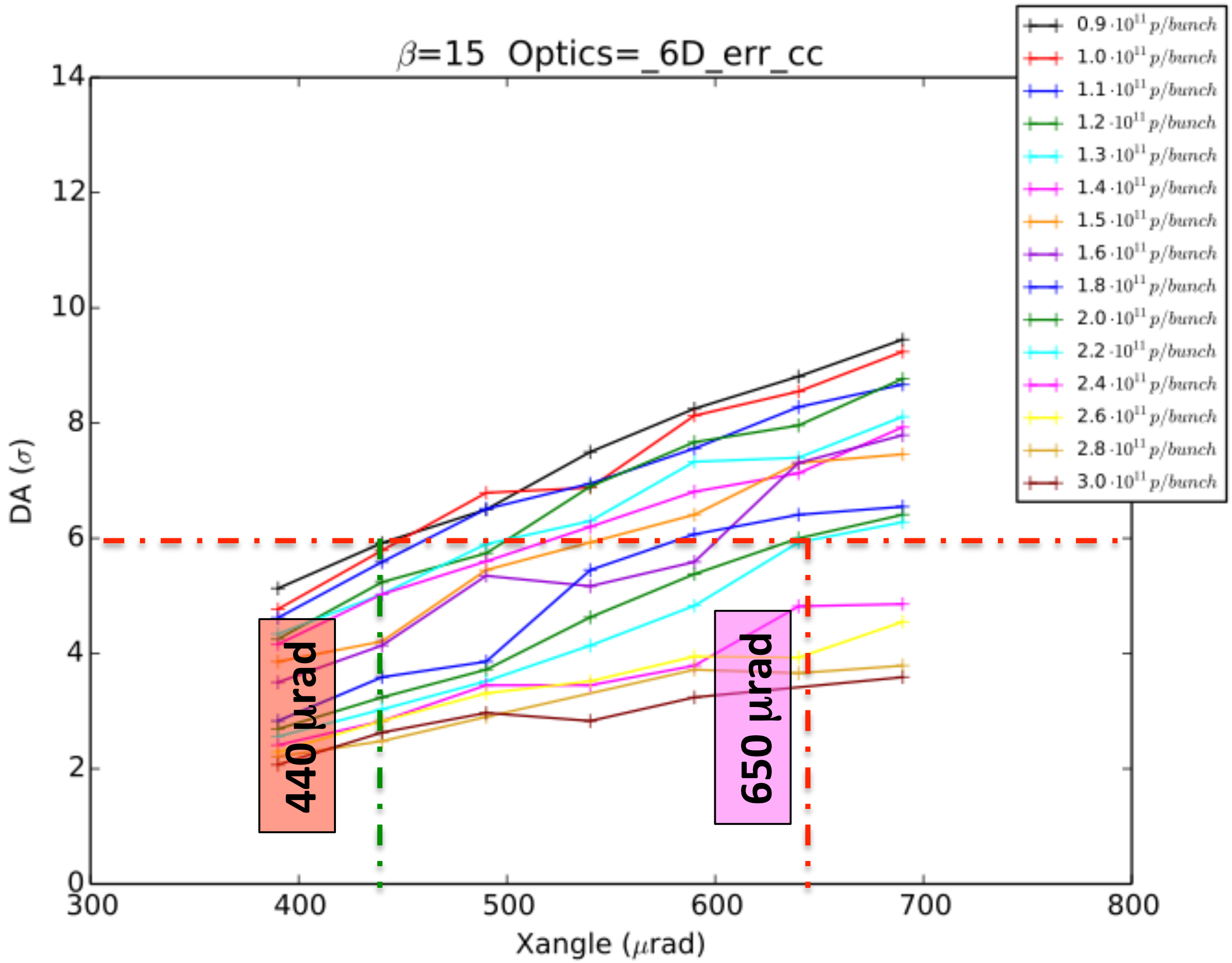
Minimum crossing angle 340 μrad

Beta* leveling: 33 cm β*



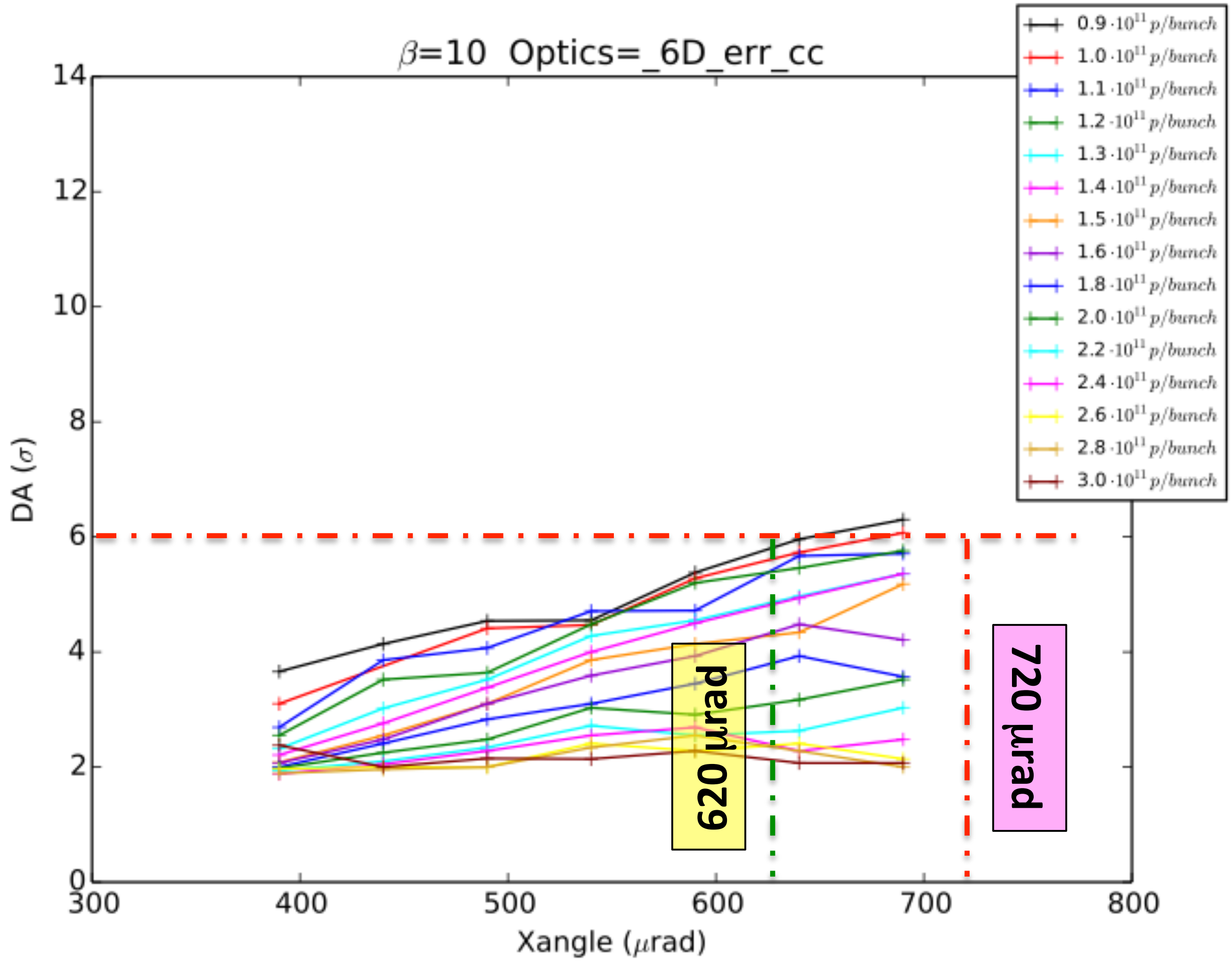
Minimum crossing angle 340 μrad

Beta* leveling: 15 cm β*



Minimum crossing angle 440 μrad

Beta* leveling: 10 cm β*



The 10 cm beta* optics allows a reduction of crossing angle to 620 μrad!
The multipolar errors are very effective and do play an important role.
Only very low intensities are allowed.

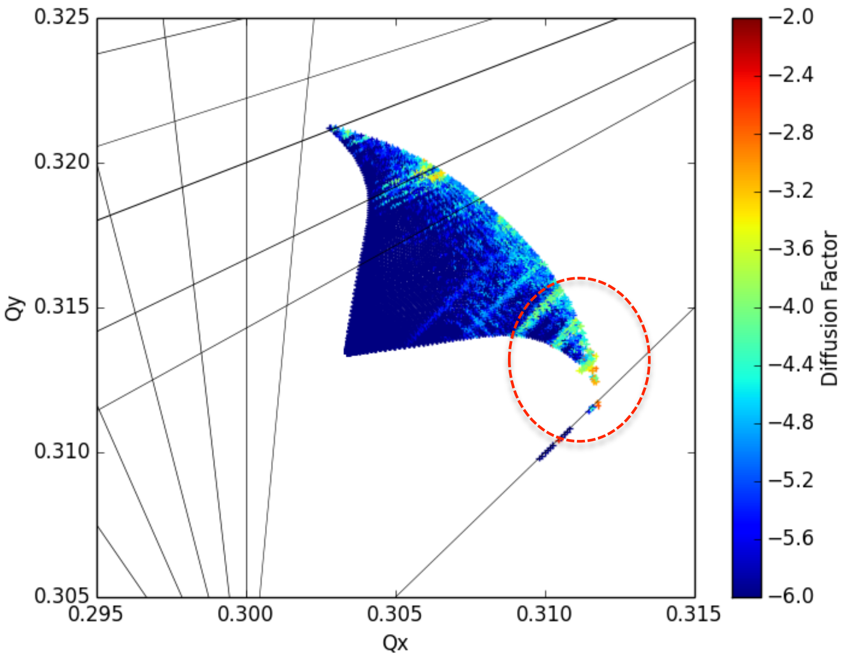
Baseline HL-LHC scheme simulations from Lifetrac

- Beginning of fill is 'trivial' despite large ξ – 3 head-on IPs, very weak long-range (>16 σ separation, compensated IR1-IR5)
- Middle of fill – significant head-on <u>and</u> long range
- End of fill – weak head-on
- <u>Question: how low can the CC voltage be?</u>

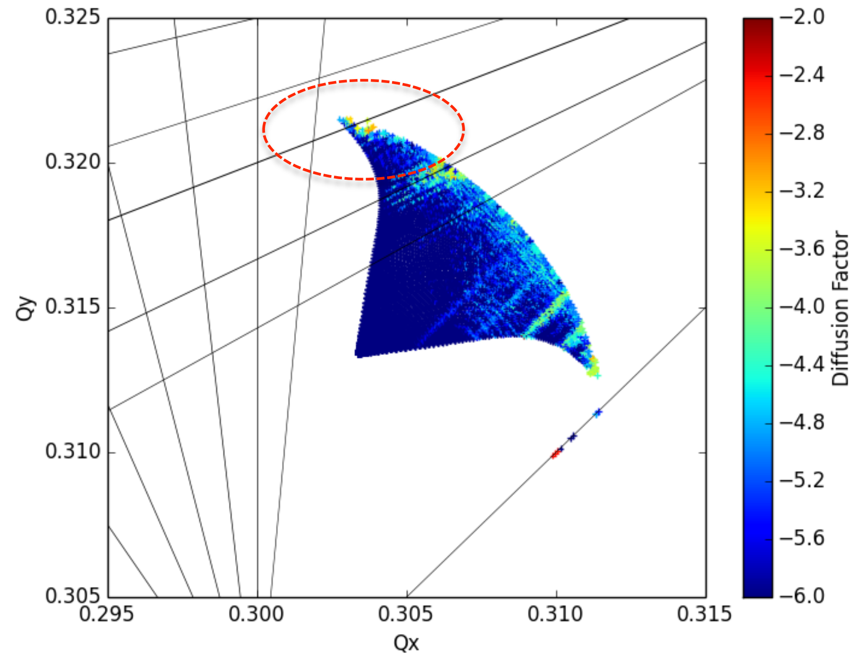
Leveling at L=5E34 (except * case)

β^* (cm)	Np (10^{11})	x-angle (μrad)	bb sep. (σ)	CC (MV)	ξx	ξy
69	2.2	360	16	7.7	0.0306	0.031
40	1.65	360	12	7.7	0.023	0.024
40	2.2*	360	12	7.7	0.0306	0.031
15	1.06	590	12.5	12.5	0.015	0.016
15	1.06	440	9	9	0.015	0.016

Pacman bunches: Left and Right Long-ranges at IP1 and IP5



No left LR at IP1 and IP5



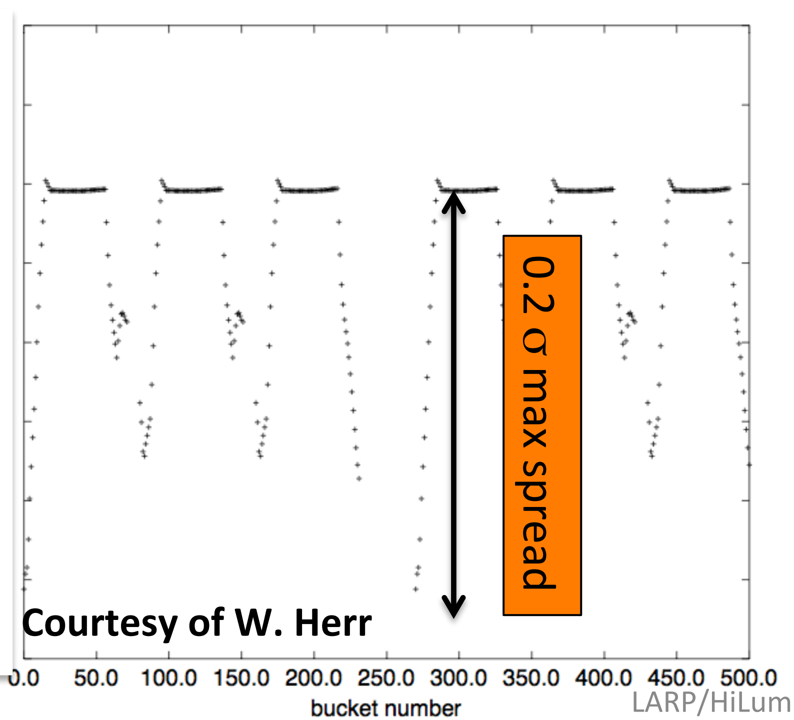
No right LR at IP1 and IP5

No impact on DA for PACMAN bunches
Worse DA for Larger footprint bunches maximum HO and maximum LR interactions

Pacman bunches: orbit effects and chromaticity worse case

β^* (m)	Np (10^{11})	X-angle (μrad)	bb sep (units of σ)	ξx	ξx
15	1.0	590	12.5	0.015	0.016

The worse case brings us back to a very well known and studied case: LHC nominal



Orbit effects from long range results in offset at IPs and therefore deterioration of luminosity
Maximum spread of approx. 0.1-0.2 σ at IP1 and 5 as calculated in Ref

Chromaticity calculations on-going

Strong-strong studies

- Very **demanding** simulations (CPU time, complexity)
- **Reproduce LHC data** to be confident in simulations and define numerical uncertainties
- Study **possible emittance blow up mechanisms**. This could be mainly due to crab cavities noise, transverse feedback and or in general any source of noise.
- This is our new challenge!
- Big effort see talk J. Qiang later

Summary:

- **Important benchmark between Sixtrack and Lifetrac** now complementary tools
- **Several bugs solved in Sixtrack**
- Reproducing observations to tune simulations
- LHC data show the importance of **DA > 6 σ**
- **Sixtrack DA** studies of HL-LHC scenarios **show the impact on DA of different effects (beam-beam, crab crossing, multipolar errors, IP8)** for the round options
- Larger separations than 12 σ are needed because of the strong head-on part
- **β* leveling scenario is RUBUST!** The worse beam-beam configuration is at β* 15 cm where we go back to LHC nominal case with larger separation 11-12 σ and 1e11 ppb
- **Pacman/Superpacman effects on DA are negligible:** worse case LR IP1 and IP5 and IP8 contribution
- **Orbit effects** from long range beam-beam are of the same amplitude of LHC nominal. **Maximum spread below 0.1 s**
- Strong-strong studies: see J. Qiang talk later

Baseline scenario round with β* leveling RUBUST!
Larger β* makes things very simple!
Gives room for brighter beams or reduced crossing angles

What’s next?

- **Crab cavity impact on colliding beams**: strong strong simulations of the interplay of crab cavities and bb. T. Pieloni (CERN), J. Barranco (EPFL), J. Qiang (LBNL) and K. Ohmi (KEKB)
- **Effect of noise on colliding beams**: strong-strong simulations of the J. Barranco (EPFL), M. Crouch (Manchester)
- Study impact of **transverse feedback on colliding beams**
- Move to Plan B: **flat optics** and **wire compensation simulations** (**verify wire implementation, run simulation campaign with Sixtrack**) T. Pieloni (CERN) and J. Barranco (EPFL)
- Multipole errors studies: identify the impact of different multipoles

Thank you!