Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI

FCC-hh Design and benchmarking on LHC

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Contents

- FCC-hh parameters and beam-beam effects
- Dynamic aperture studies for Ultimate scenario
- Compensation of beam-beam long-range
- Low Luminosity Experiments
- LHC experimental observations
- Summary and outlook

High Energy Colliders: Present/Future

PARAMETERS	LHC HL-LHC
Center of Mass Energy [TeV]	14
Dipole Fields [T]	8.33
Circumference [Km]	27
Beam-Beam Interactions	120 LR + 4 HO
Lattice Elements	23000
Beam Current [A]	0.58 - 1.12
Bunch Intensity [10^{11}]	1.15 - 2.2
Bunch spacing [ns]	25
RMS bunch length [cm]	7.55 – 8.1
Luminosity [10^{34} cm^{-2}s^{-1}]	1 - 5
Events/bunch crossing	27 - 135
Stored Energy [GJ]	0.36 – 0.7
β^* [m]	0.55 – 0.2
Transverse beam size [μm]	3.75-2.5

High Energy Colliders: Present/Future

PARAMETERS	LHC HL-LHC	High Energy LHC
Center of Mass Energy [TeV]	14	27
Dipole Fields [T]	8.33	16
Circumference [Km]	27	27
Beam-Beam Interactions	120 LR + 4 HO	120(600) LR + 4 HO
Lattice Elements	23000	30000
Beam Current [A]	0.58 - 1.12	1.12
Bunch Intensity [10^{11}]	1.15 - 2.2	2.2 (0.44)
Bunch spacing [ns]	25	25 (5)
RMS bunch length [cm]	7.55 – 8.1	7.55
Luminosity [10^{34} cm^{-2}s^{-1}]	1 - 5	25
Events/bunch crossing	27 - 135	800 (160)
Stored Energy [GJ]	0.36 – 0.7	1.3
β^* [m]	0.55 – 0.2	0.25
Transverse beam size [μm]	3.75-2.5	2.5 (0.5)

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High Energy Colliders: Present/Future

PARAMETERS	LHC HL-LHC	High Energy LHC	FCC-hh Baseline - Ultimate	
Center of Mass Energy [TeV]	14	27	100	
Dipole Fields [T]	8.33	16	16	
Circumference [Km]	27	27	100	
Beam-Beam Interactions	120 LR + 4 HO	120(600)LR + 4 HO	352 LR + 4 HO (1764)	
Lattice Elements	23000	30000	100000	
Beam Current [A]	0.58 - 1.12	1.12	0.5	
Bunch Intensity [10^{11}]	1.15 - 2.2	2.2 (0.44)	1	1 (0.2)
Bunch spacing [ns]	25	25 (5)	25	25 (5)
RMS bunch length [cm]	7.55 – 8.1	7.55	7.55	
Luminosity [10^{34} cm^{-2}s^{-1}]	1 - 5	25	5	30
Events/bunch crossing	27 - 135	800 (160)	170	1k (200)
Stored Energy [GJ]	0.36 – 0.7	1.3	8.4	
β^* [m]	0.55 – 0.2	0.25	1.1- 0.3	
Transverse beam size [μm]	3.75-2.5	2.5 (0.5)	2.2 (0.4)	

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High Energy Colliders: Present/Future

PARAMETERS	**LHC HL-LHC**	**High Energy LHC**	**FCC-hh** **Baseline - Ultimate**
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B			
RMS			
Lum			
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Stored Energy [GJ]	0.36 – 0.7	1.3	8.4
β* [m]	0.55 – 0.2	0.25	1.1- 0.3
Transverse beam size [μm]	3.75-2.5	2.5 (0.5)	2.2 (0.4)

Can we control such beams? Which losses can we allow? How can we make predictions?

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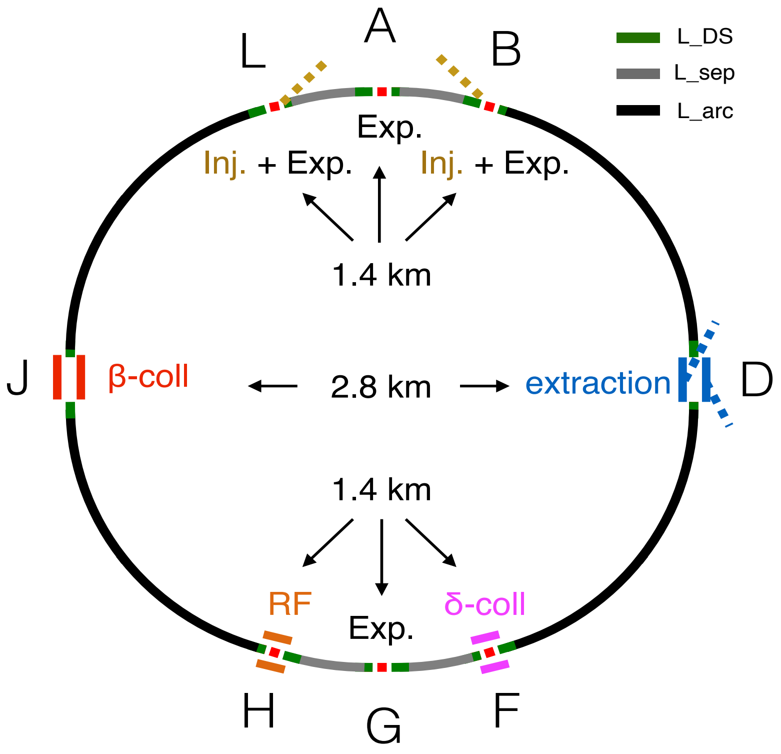
Collider collision schemes



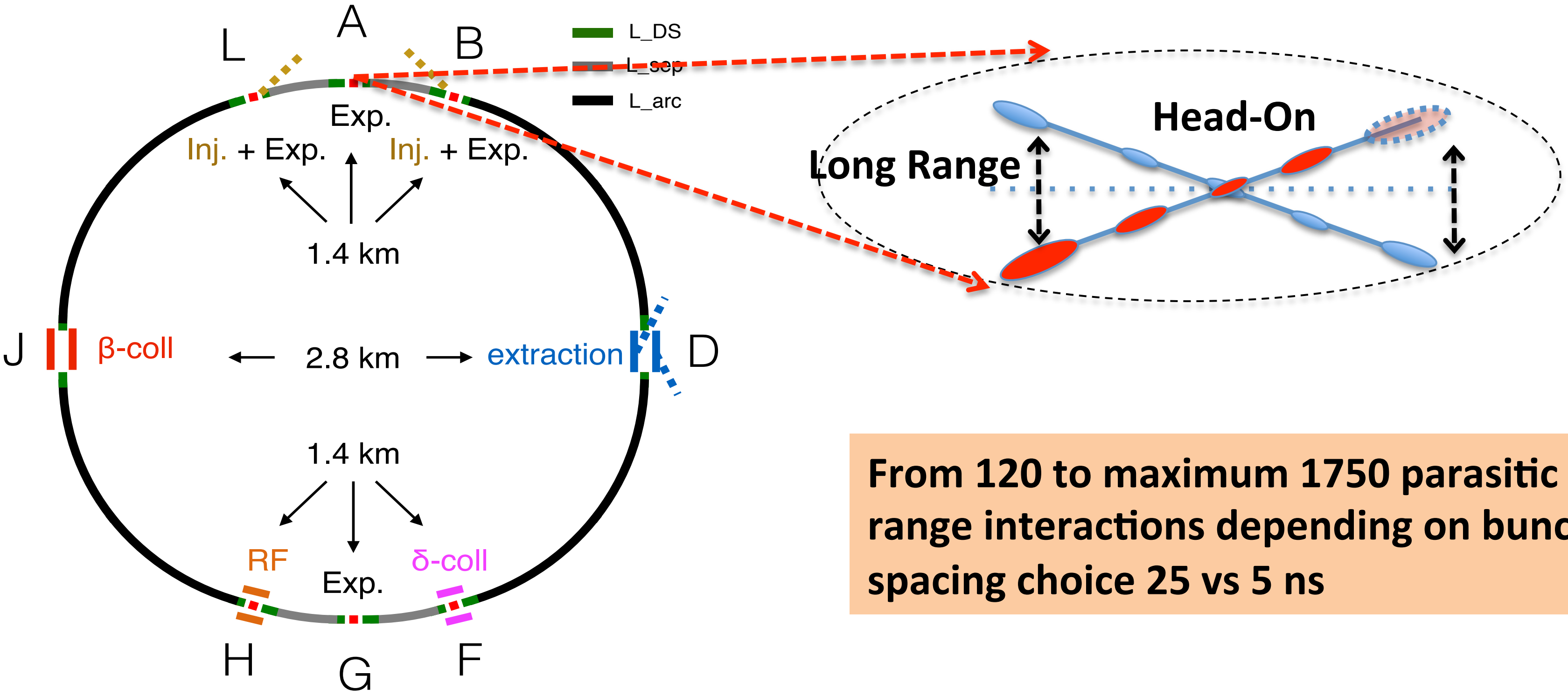
IPA and IPG main high luminosity experiments:

Goal → maximum luminosity with good lifetimes → maximum integrated luminosity

IPL and IPB low luminosity IPs:

Goal → in shadow on main IPs where possible → will define luminosity operation

Collider beam-beam interactions



From 120 to maximum 1750 parasitic long-range interactions depending on bunch spacing choice 25 vs 5 ns

IPA and IPG main high luminosity experiments:

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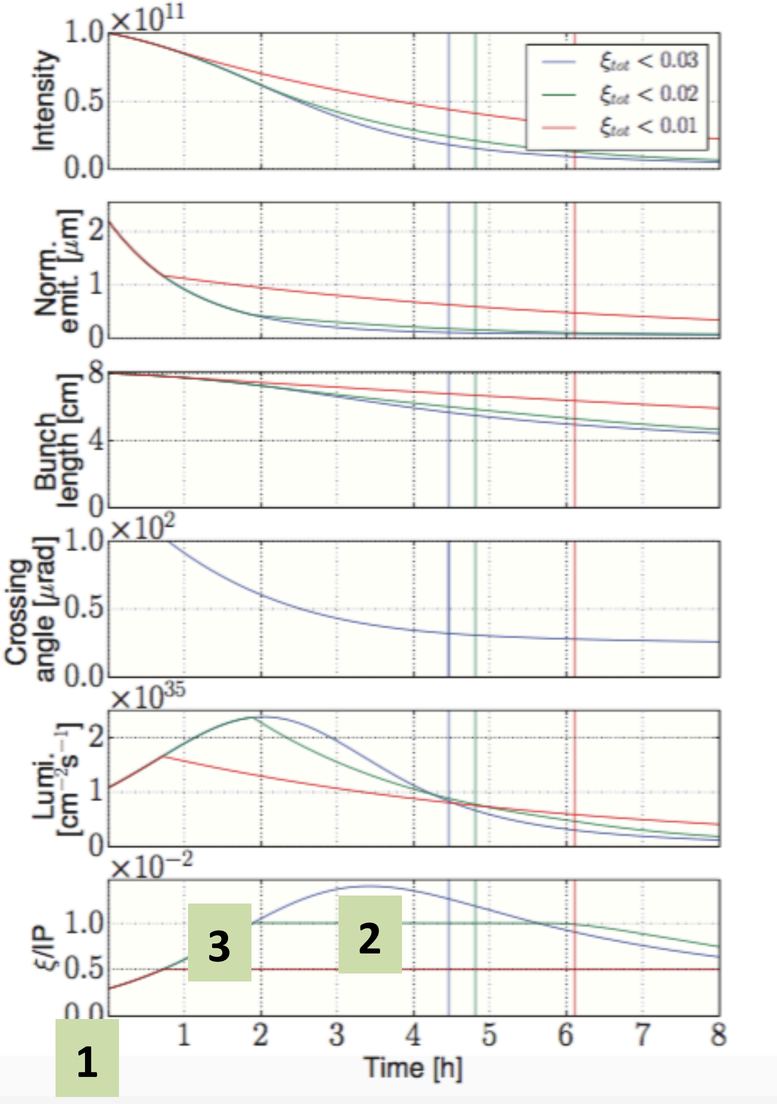
IPL and IPB low luminosity IPs:

Goal → in shadow on main IPs where possible → will define luminosity operation

Parameter evolutions



X. Buffat & D. Schulte

Due to strong radiation damping we have quite some different regimes from beam-beam point of view:

1) LHC/HL-LHC beam-beam dynamics

ξ_{bb} = 0.06 → 0.01

LHC experience and long-range effects

2) Head-on driven dynamics with beam-beam parameter ξ_{bb} = 0.01 → 0.02
plus 2 low luminosity IPs ξ_{bb} = 0.04

Need R&D in LHC and HL-LHC

3) Mixed status, radiation damping and possible operational scenarios

Need new developments in models

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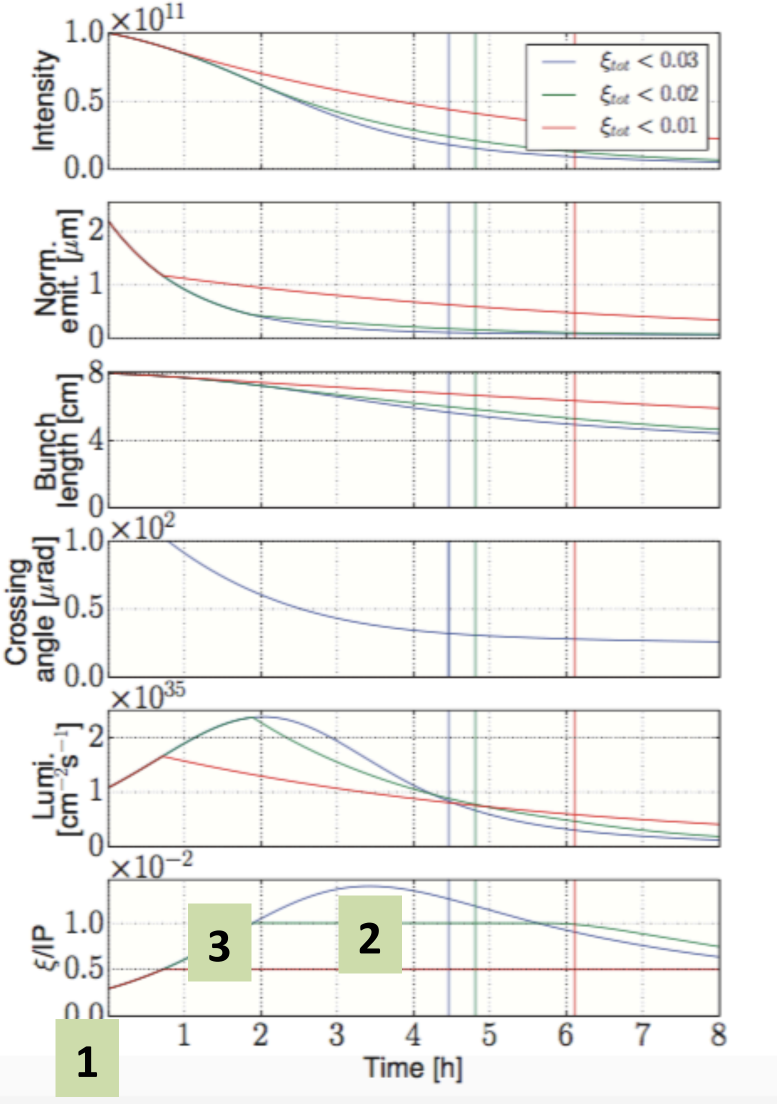
Parameter evolutions



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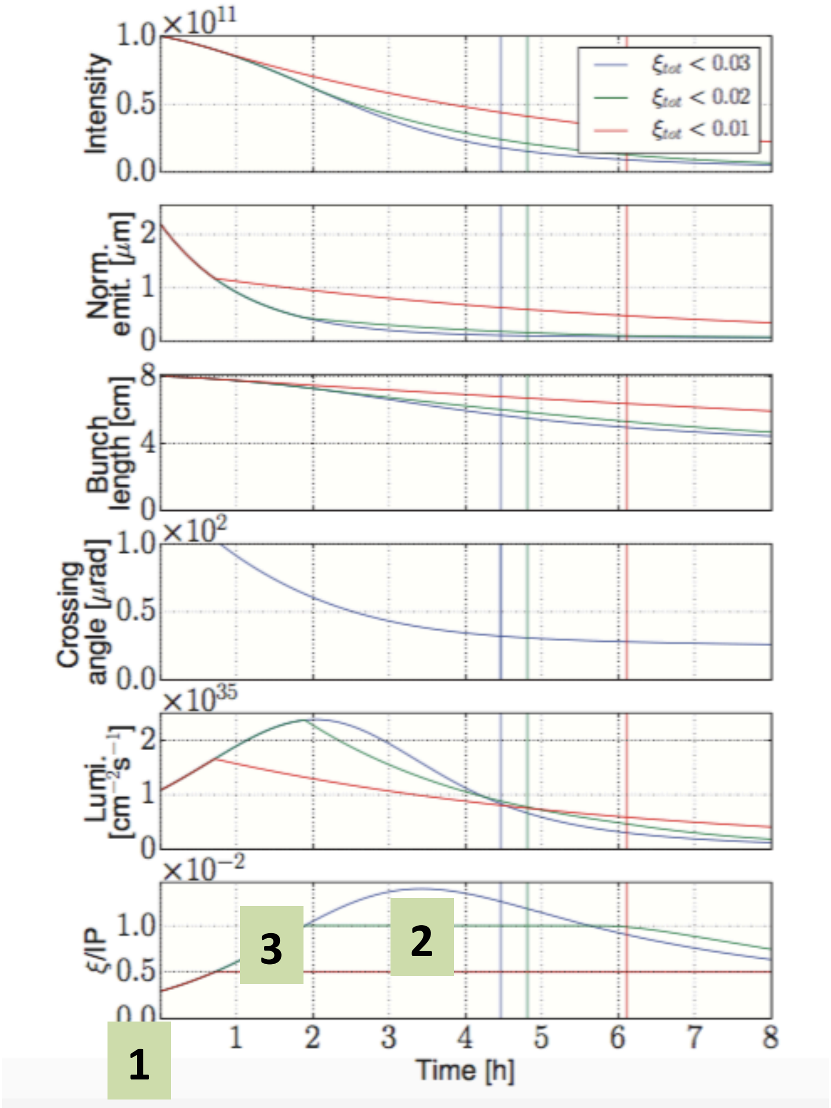

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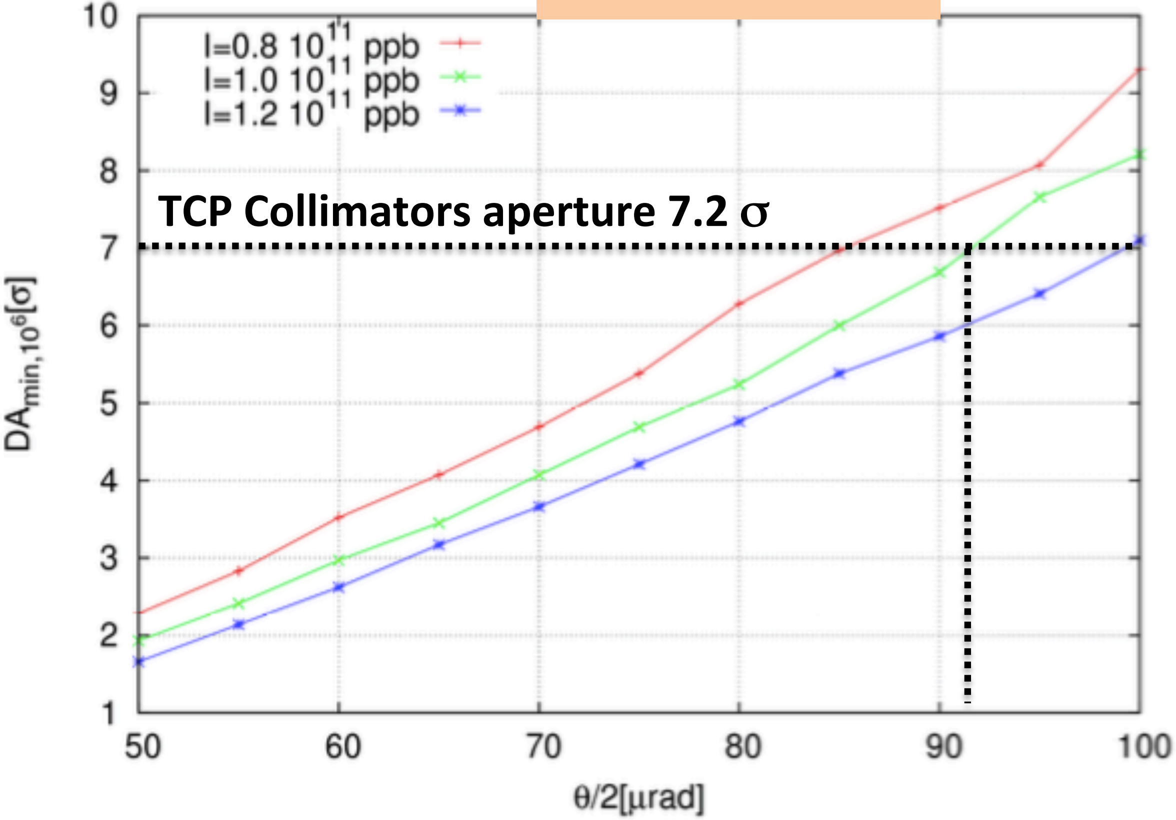
All cases with 25 ns bunch spacing

Ultimate case Round Optics: IPA and IPG

FCC New Lattice



TCP Collimators aperture 7.2 σ

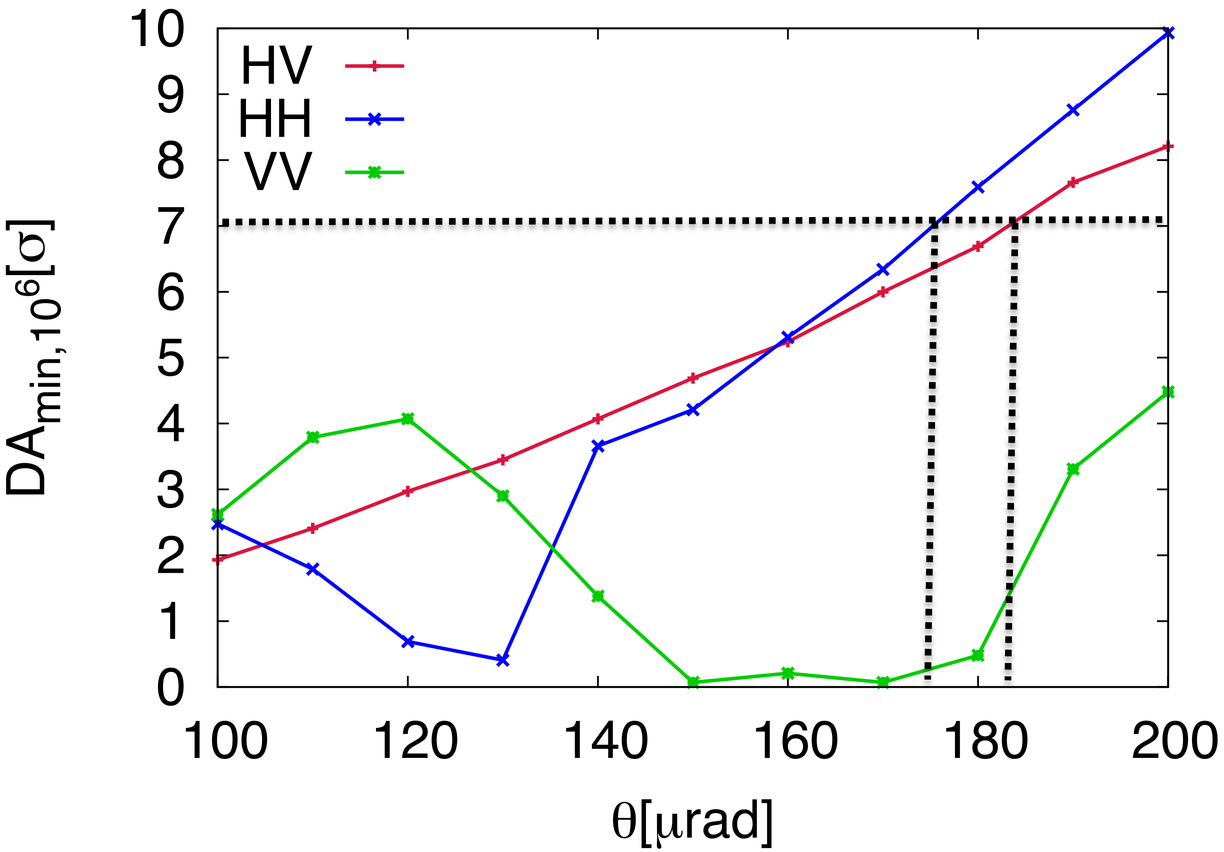
LHC criterion: Dynamic Aperture should be larger or equal than the mechanical aperture defined by the collimation system (TCPs): for LHC 6.0 σ

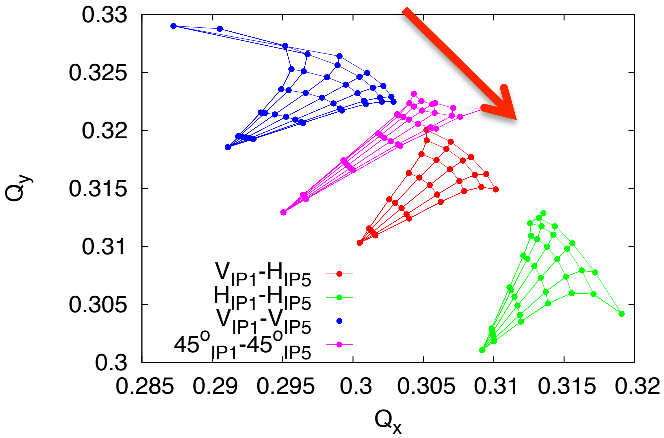
For FCC-hh case TCPs at 7.2 σ
M. Fiascari et al. @IPAC2016

$$DA \geq 7.2\ \sigma$$

- **Crossing angle 180 μrad** needed only from beam-beam non linearities
- **Intensity fluctuations →** requires roughly 5-10 μrad for 10-20% fluctuations

Crossing Schemes: HV versus HH and VV

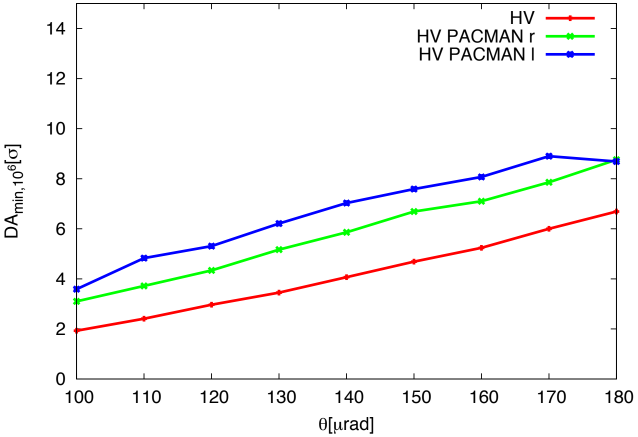


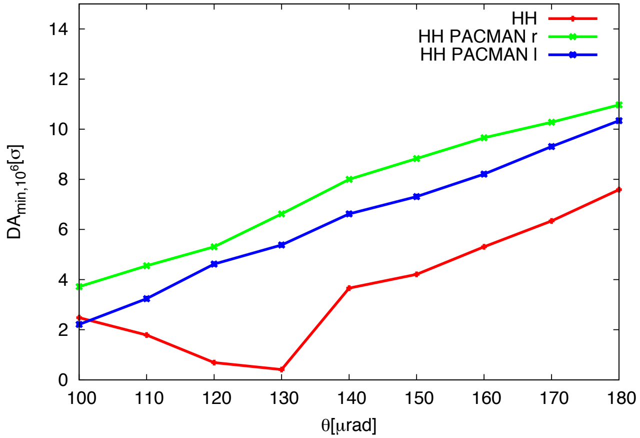


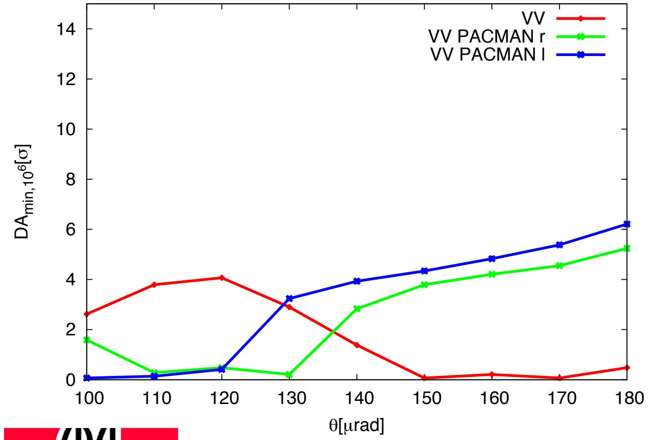
Hor/Ver crossing in place to profit of passive compensation of pacman effects (tune shifts and chromaticity)

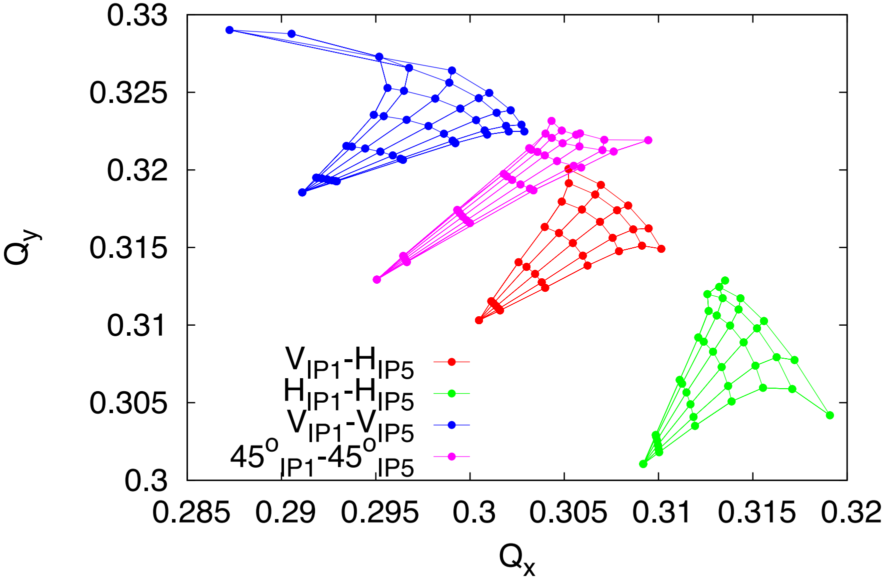
- HH Crossing seems equivalent to HV in terms of DA for nominal bunches
- VV not acceptable at the (0.31-0.32) working point due to strong impact of 3rd order resonance effect → Mirrored tune will solve the problem
- Moving on the mirrored tunes inverts the situation where then HH pushes particles on the 3rd order resonance
- Tilted angle scheme still to be analyzed

PACMAN Bunches





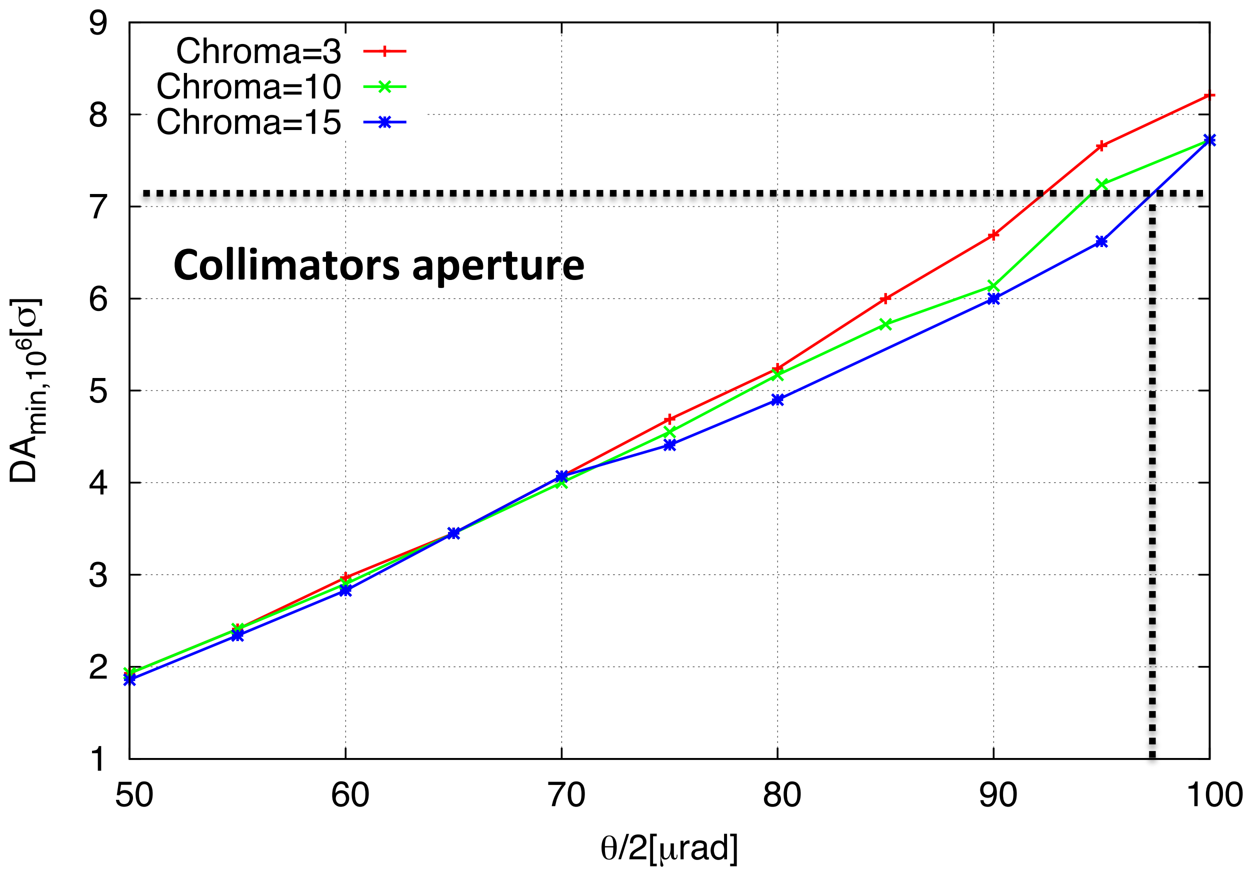




- For all crossing schemes the major impact of long-range effects are on the nominal bunches
- PACMAN bunches always show a better dynamic aperture, DA is defined by nominal bunches

Alternative crossing schemes are possible to support energy deposition constrains (I. Besana and Cerruti)

High Chromaticity operation: IPA and IPG

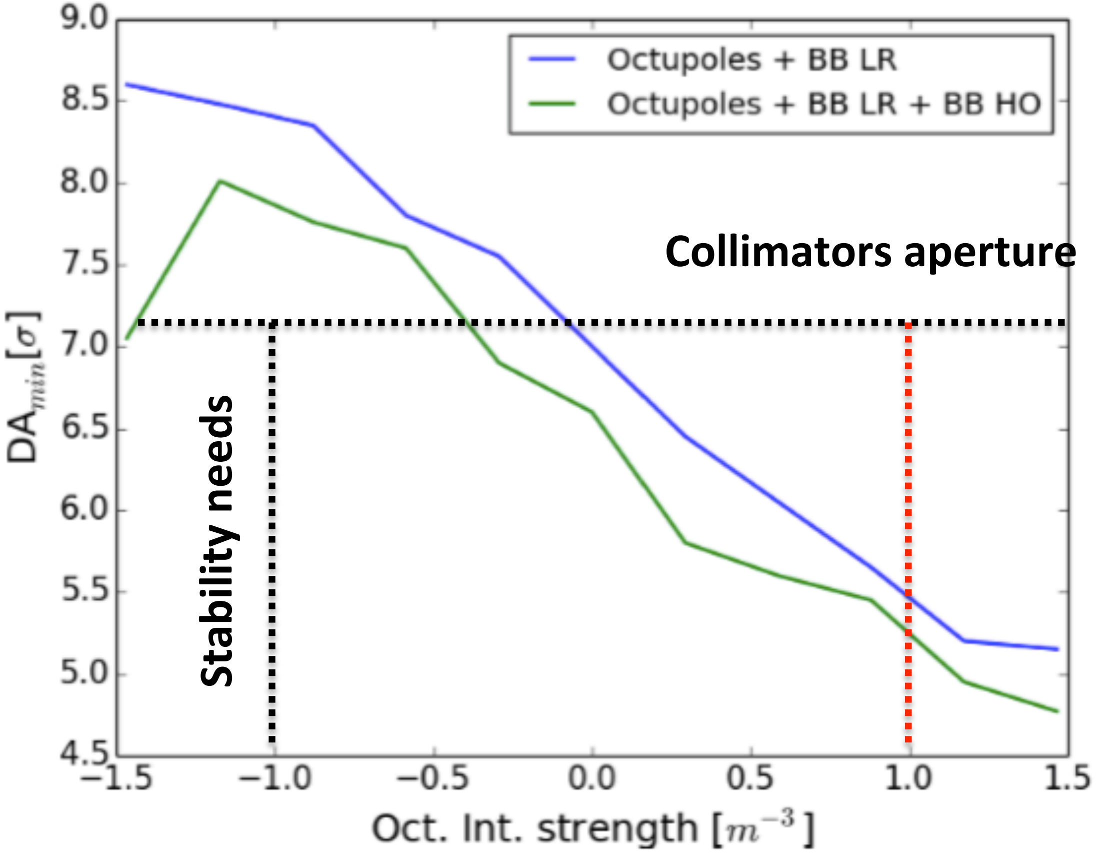


Due to severe stability limitations we are forced to keep **margins for very high chromaticity and Landau damping octupoles operation at a design stage**

High Chromaticity operation will be needed for stability reasons!
5-10 μrad for 15-20 units chromaticity

Will need to add margins to the crossing angles to allow for high chroma and higher spreads

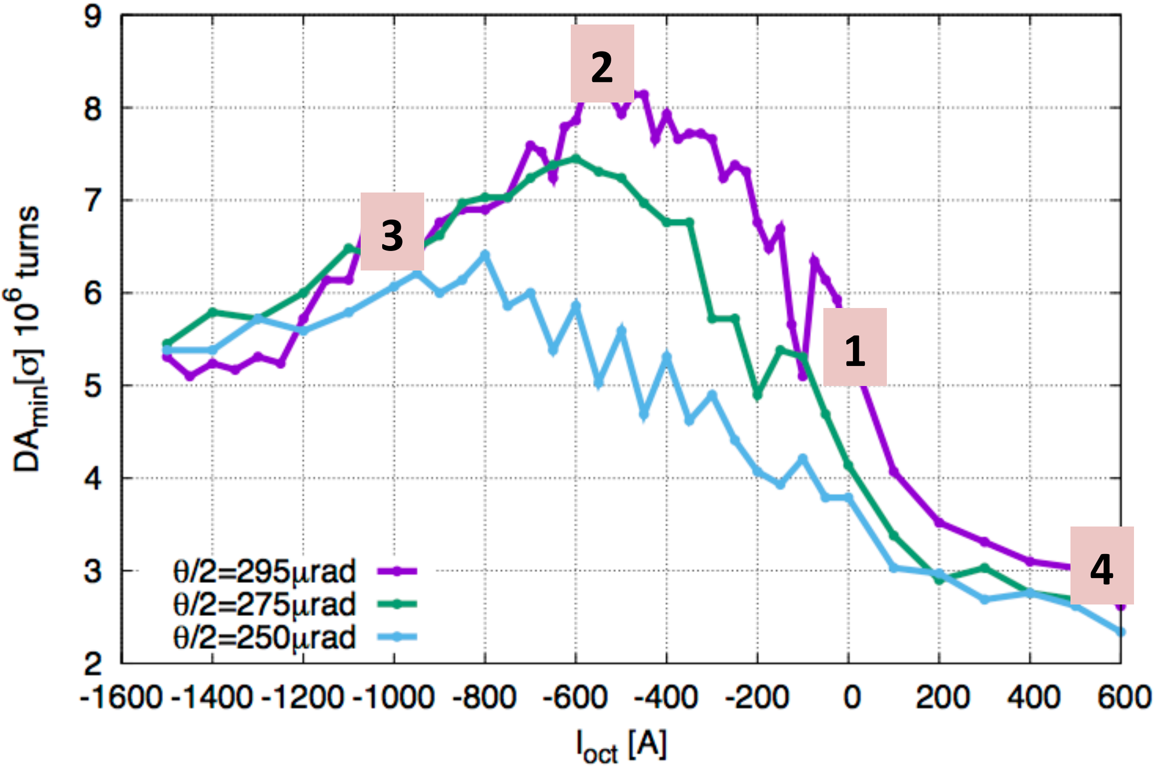
Impact of Landau Octupoles

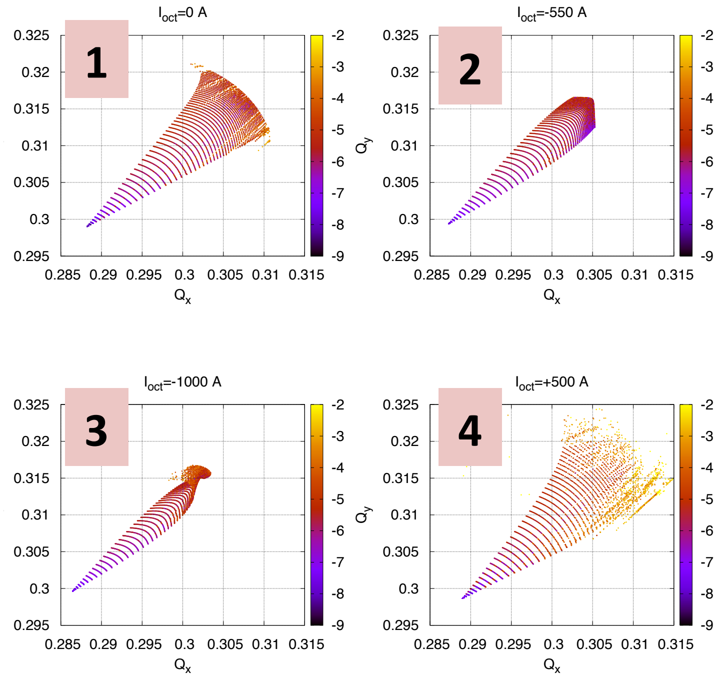


Landau octupoles for FCC give compensation of long-range effects
Global compensation of long-range beam-beam effects from earlier design stage

→ Explore other sources of Landau damping (collisions, elenses as Landau damping objects proposal by V. Schiltzev et al.)

Global Compensation with octupoles

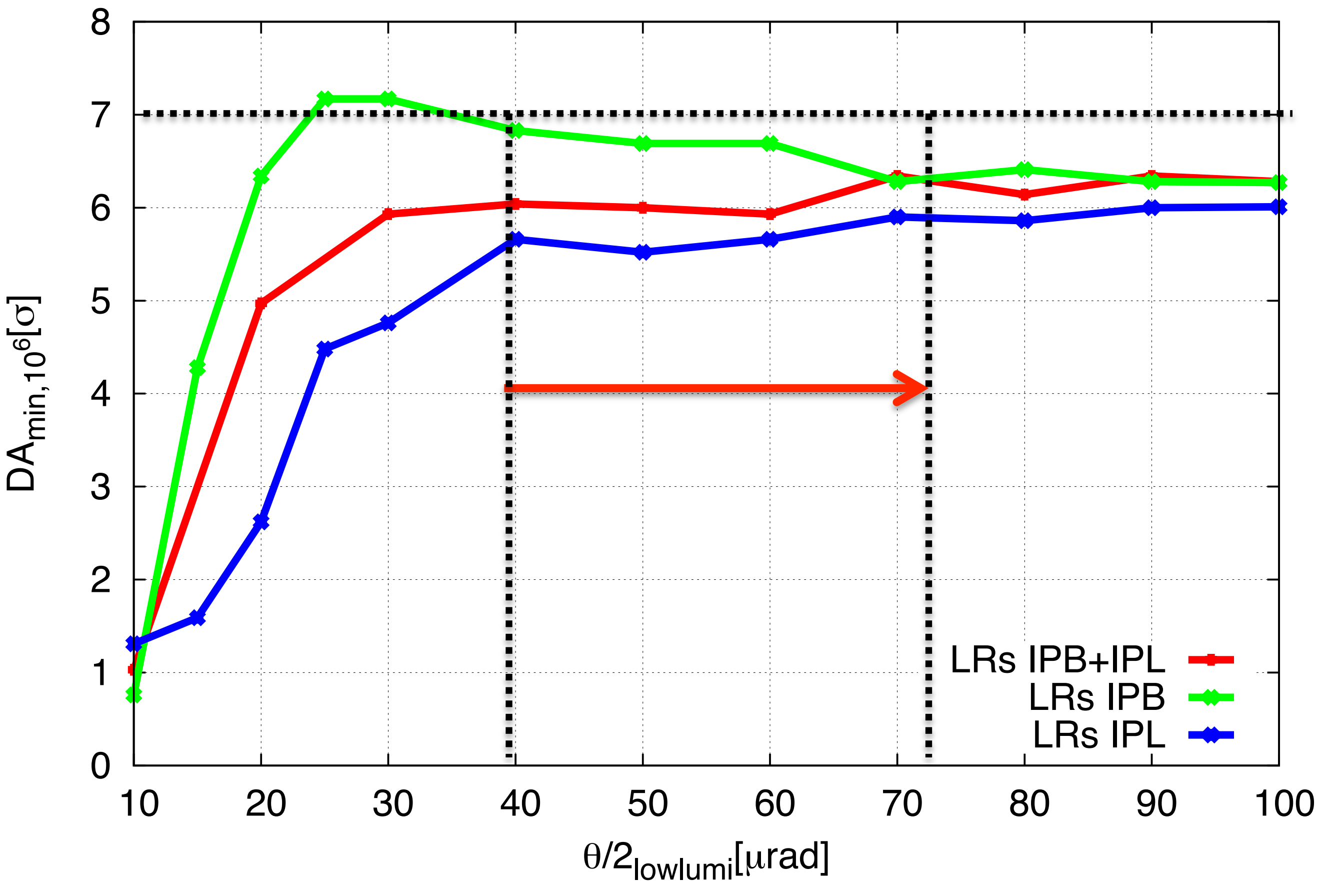




HL-LHC study case
CERN-ACC-NOTE-2017-0035

- Octupole magnets are used/needed to provide tune spread for Landau damping.
- **They have very negative effect on DA if not used with care.**
- **If installed at right location they could help compensating long-range effects!**
- **FCC should allow for these option, design with multipolar compensation as proposed in past from Shi et al. and recently studied for the LHC and HL-LHC**

Low Luminosity Experiments: IPL and IPP



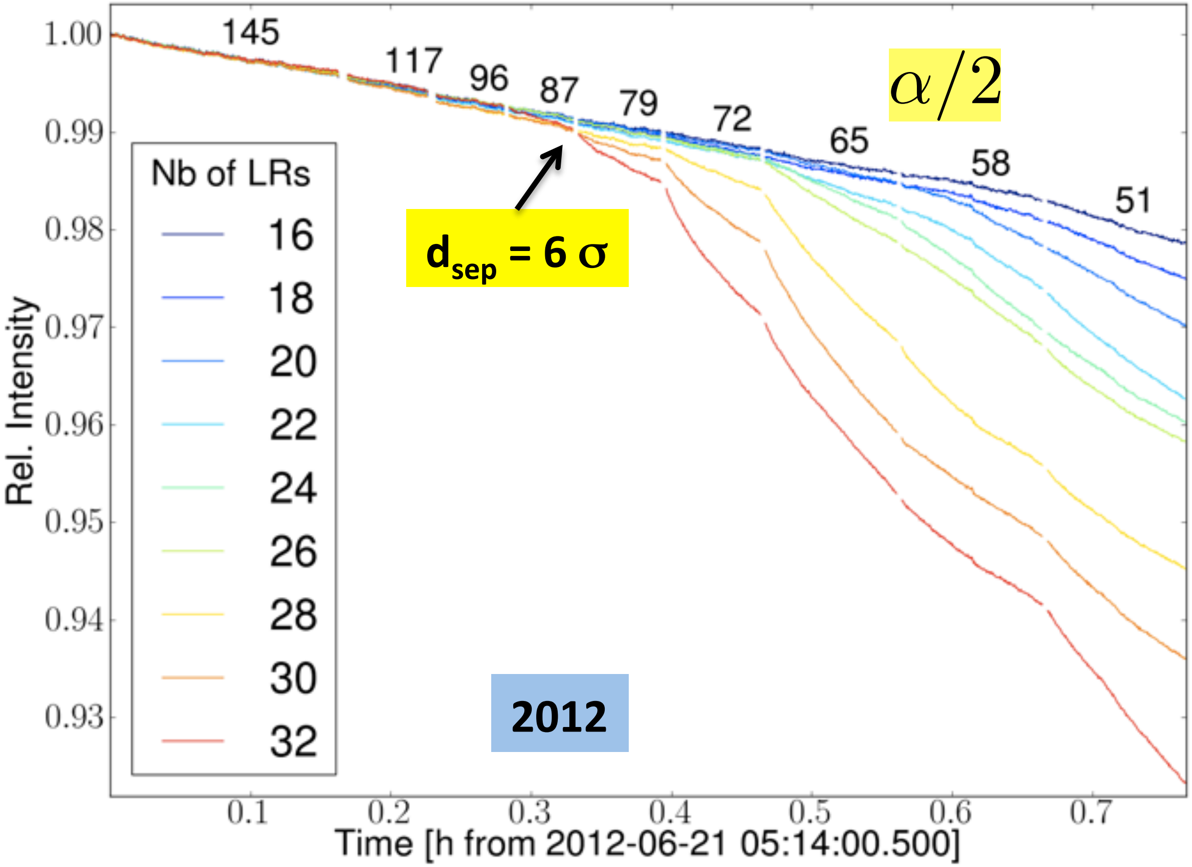
The long-range effects of IPL and B will impact bunches differently (**no passive compensation**)

Reduce the impact of secondary experiments

- **Long-range:** to keep effects weak → larger beam-beam separations
- **Head-on:** clear limit from the energy deposition studies (M. Besana et al.)
  - From beam-beam studies → apply separation leveling → limit on integrated luminosity per year of run!

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

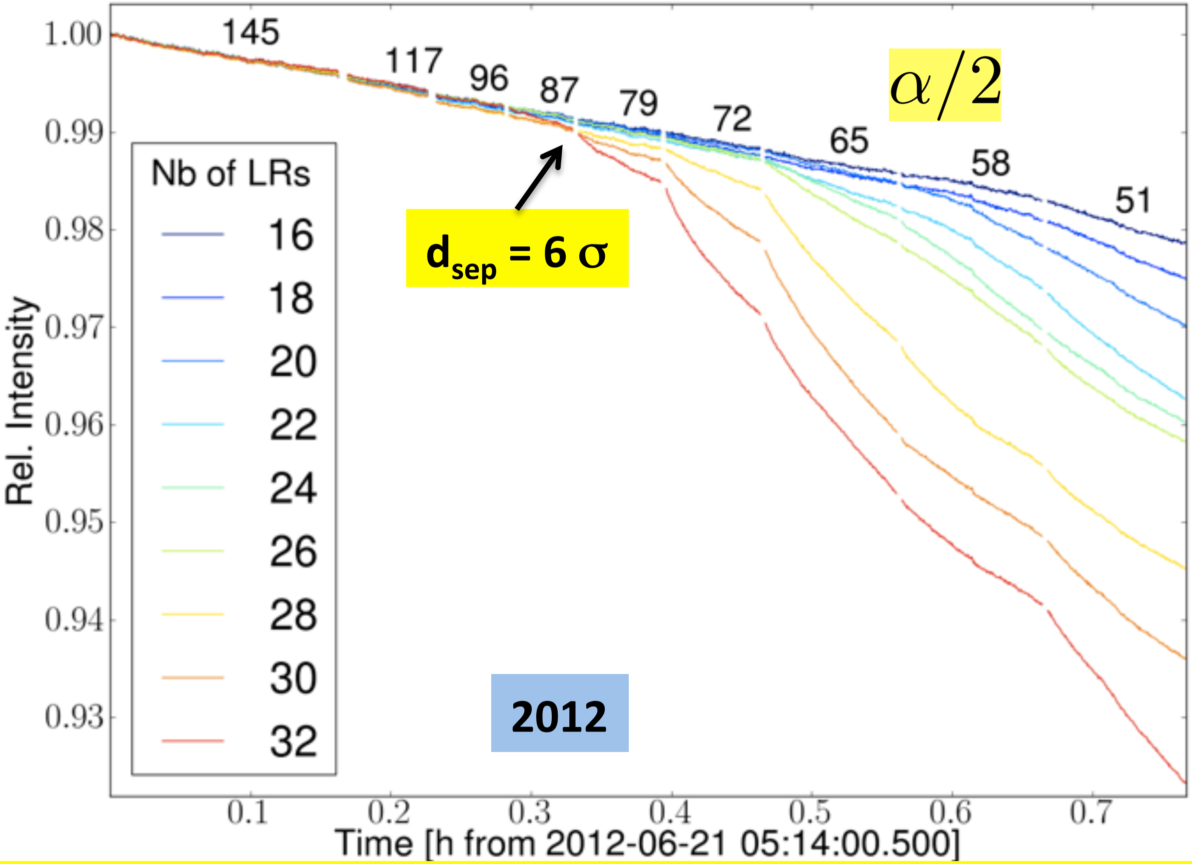
At small separations particles motion becomes chaotic and particles are lost.
The loss rate depends on number of long range encounters and separation

The on-set of losses has been empirically related to the reach of 4 σ dynamic aperture → for DA equal or below this value losses appear

W. Herr et al.

Long Range Experiments

Bunch losses for different families of Long-Range encounters



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

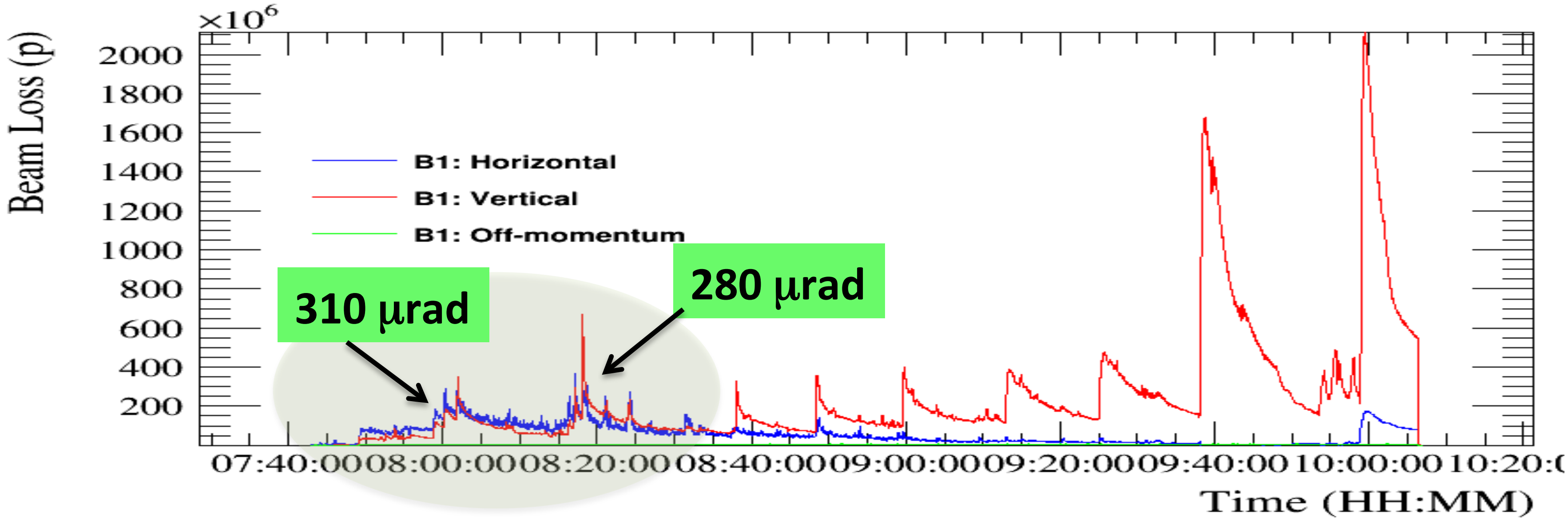
Small crossing angle = small separation

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

Not all losses are relevant for operation and integrated luminosity: it is always a balance between luminosity gain and allowed losses

Long Range Experiments

2015 and 2016 experiments were done differently to understand the longer term losses to extrapolate the beams lifetimes

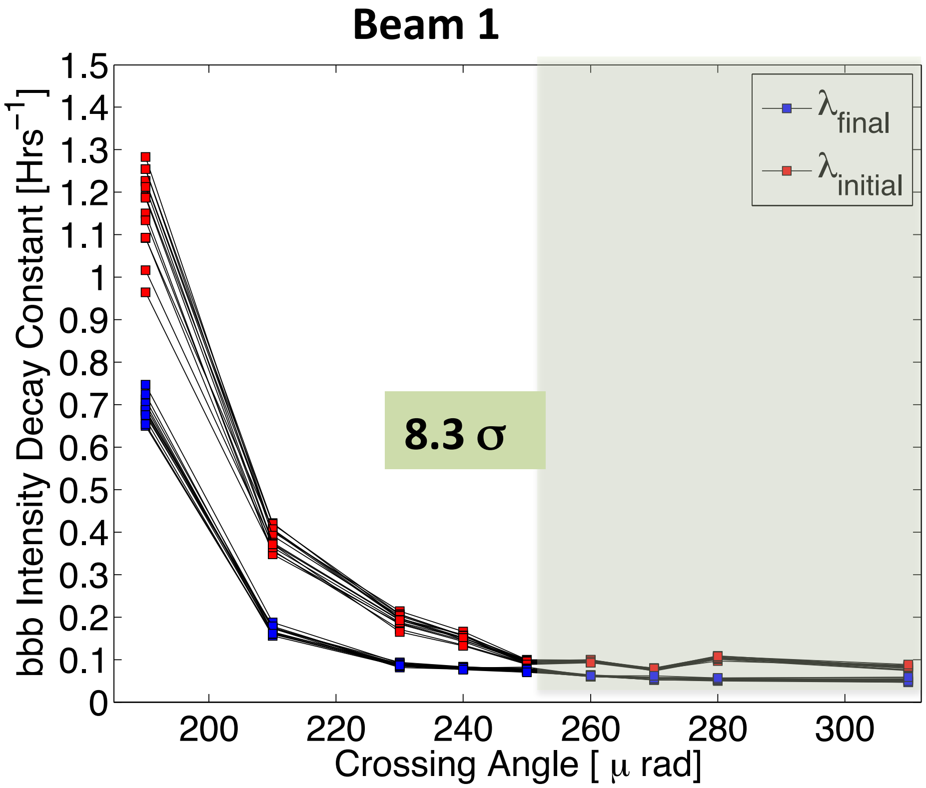


Evaluate the beam lifetimes and correlate to losses expected from dynamic aperture as a function of the different beam-beam separations

Distinguish between fast transient losses and long-term losses

Using the method proposed by M. Giovannozzi Phys Rev Spec Top-AB, 15(2):024001, 2012

Long Range experiment of 2016: intensity decays



$$d_{sep} = \sqrt{\frac{\beta^*}{\epsilon_{x,y}/\gamma}}\phi$$

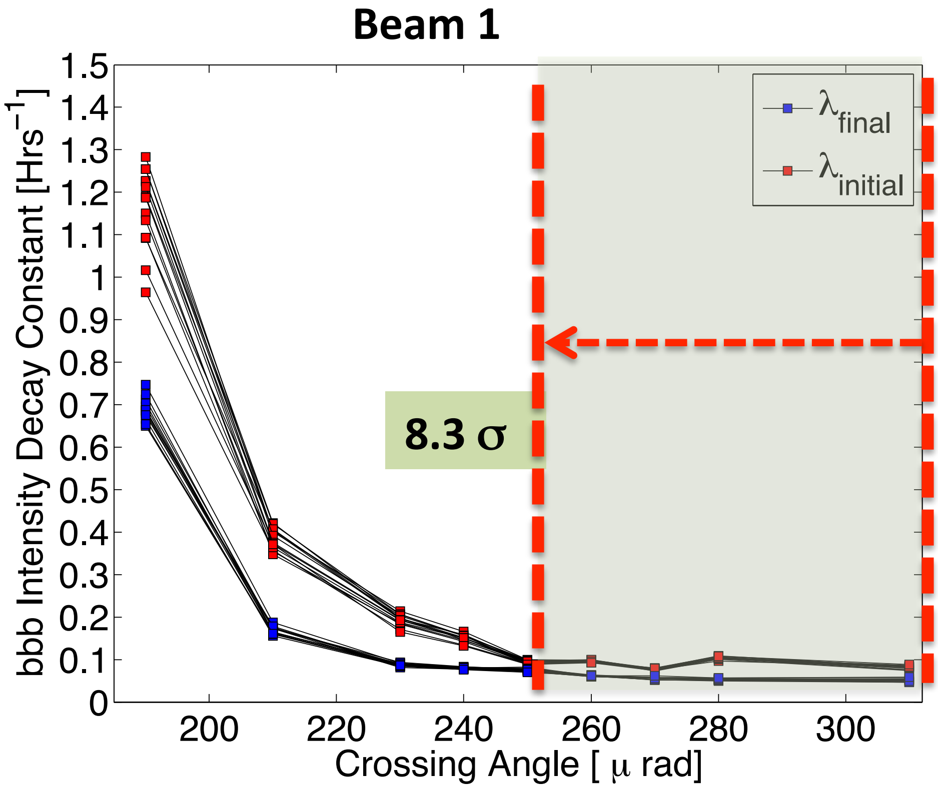
ϕ
310
280
270
260
250
240
230
210
190

Angles range 370-280 μrad:

1. **Fast losses at first time window of 5 min increases with long-range pattern,**
2. **Slower losses after 10-15 minutes at new angle negligible**

→ Transient effect due to change of conditions

Long Range experiment of 2016: intensity decays



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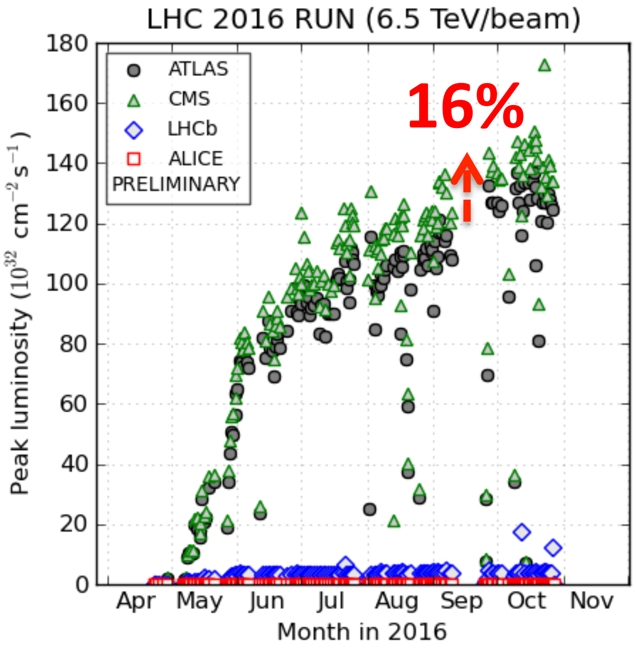
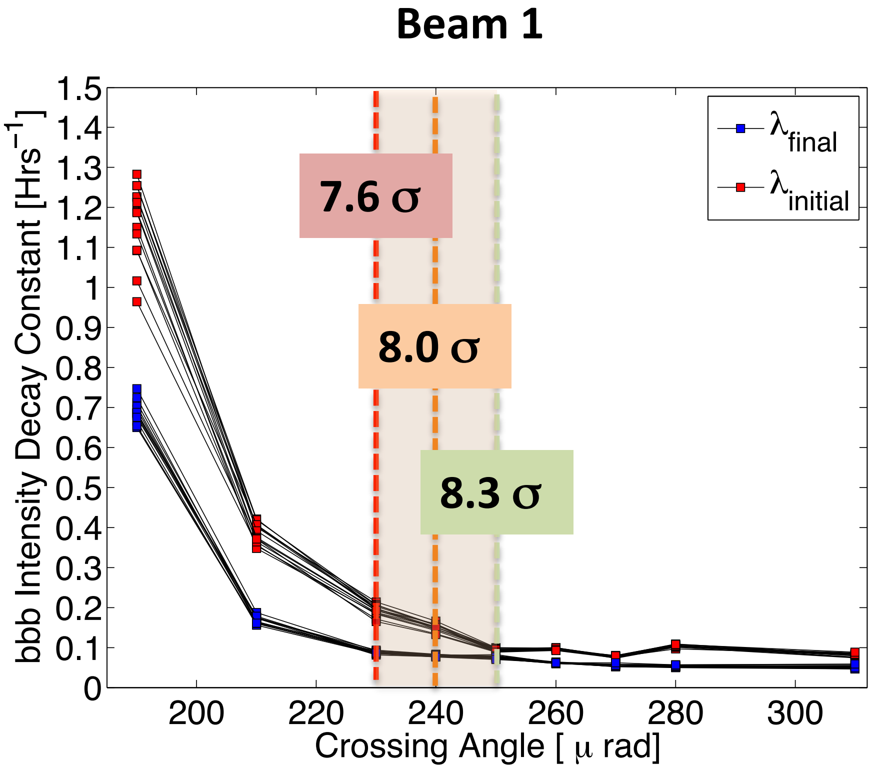


Gain of 16% peak luminosity and beam lifetimes above 20 hours in 2016, sets the LHC RUN II luminosity reach!

Long Range experiment 2016: intensity decays

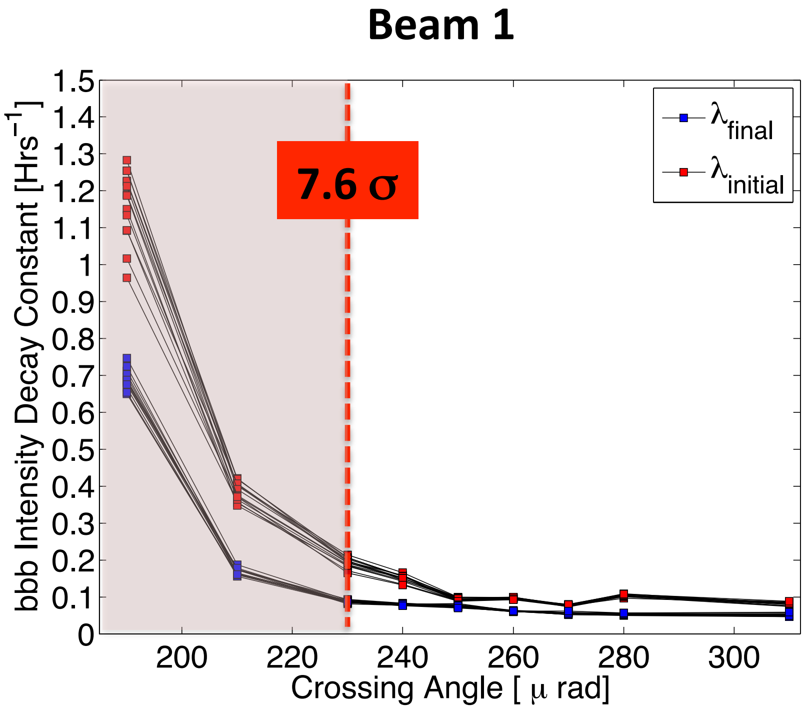


$$d_{sep} = \sqrt{\frac{\beta^*}{\epsilon_{x,y}/\gamma}}\phi$$

ϕ
310
280
270
260
250
240
230
210
190

Moderate beam-beam effects with visible impact on transients losses as a function of angle and as a function of number of long-range interactions.

Long Range experiment 2016: intensity decays



$$d_{sep} = \sqrt{\frac{\beta^*}{\epsilon_{x,y}/\gamma}}\phi$$

ϕ
310
280
270
260
250
240
230
210
190

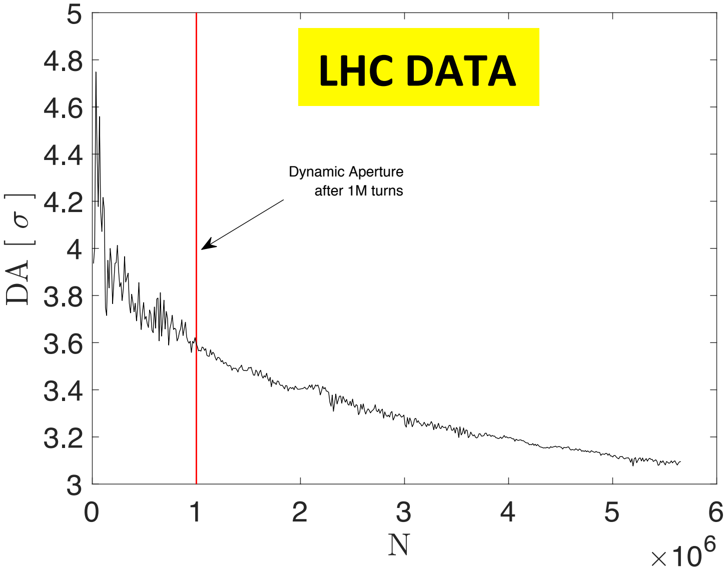
Below 230 μrad:

1. **Fast losses at first time window of 5 min increases**
2. **Slow losses increase and do not improve after 15 minutes**

→ Transient effect + strong deterioration of intensity lifetimes

Beam-beam effects visible with strong impact on losses

Can we translate losses in dynamic aperture?

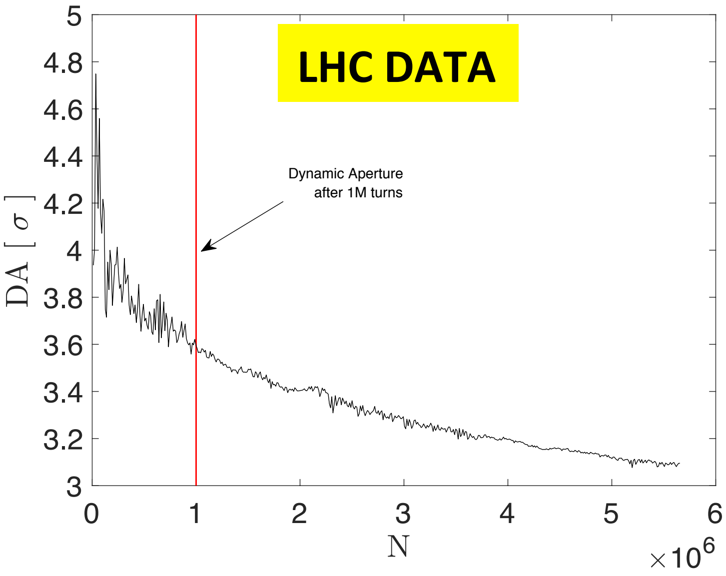


Using the method of M.Giovannozzi

Phys Rev Spec Top-AB, 15(2):024001, 2012

$$D(N) = \sqrt{2 log \Delta I}$$

Can we translate losses in dynamic aperture?



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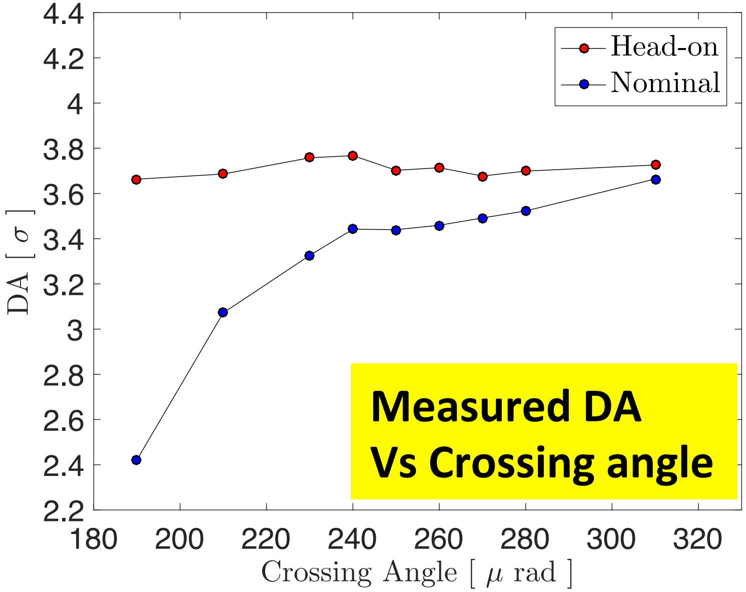
We applied to beam-beam experiments

M. Crouch Manchester PHD Thesis 2017



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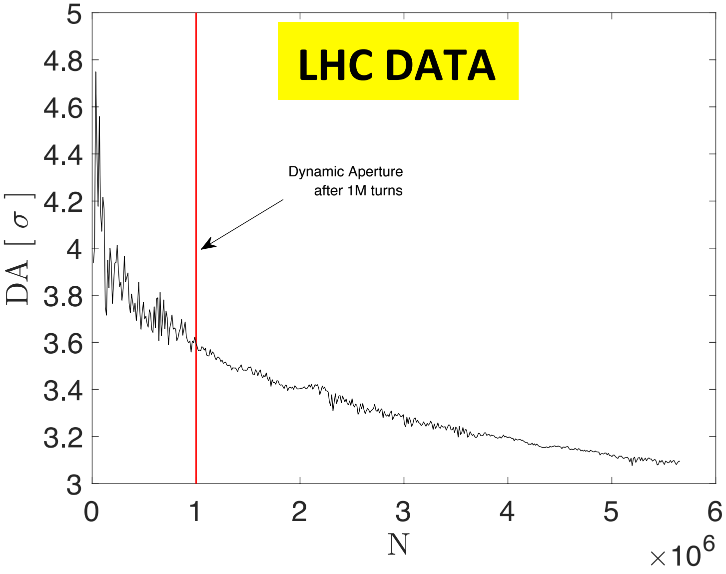

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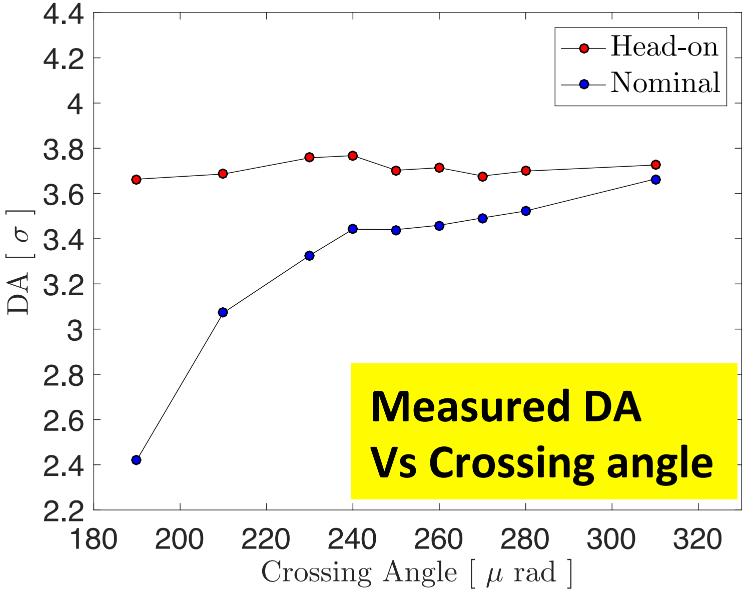

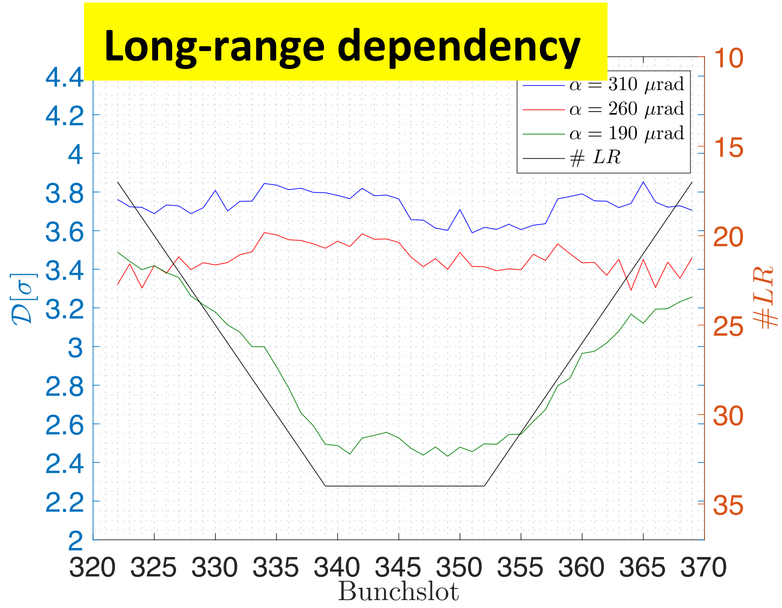

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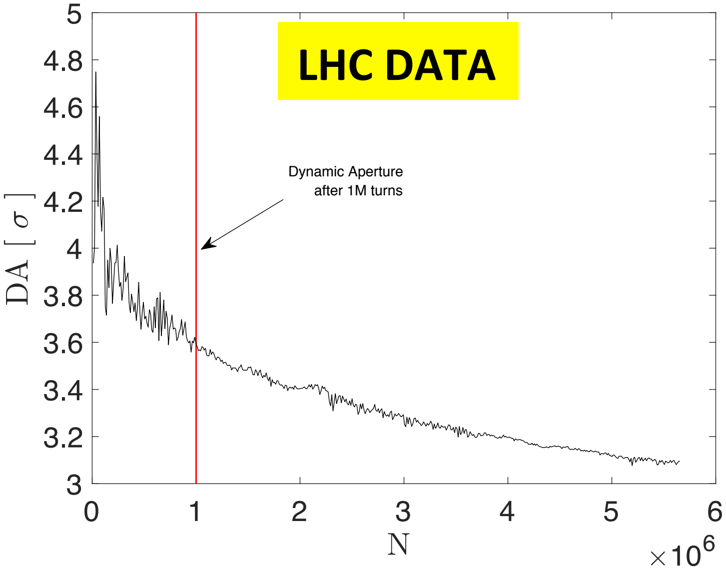

LHC DATA

Using the method of M.Giovannozzi
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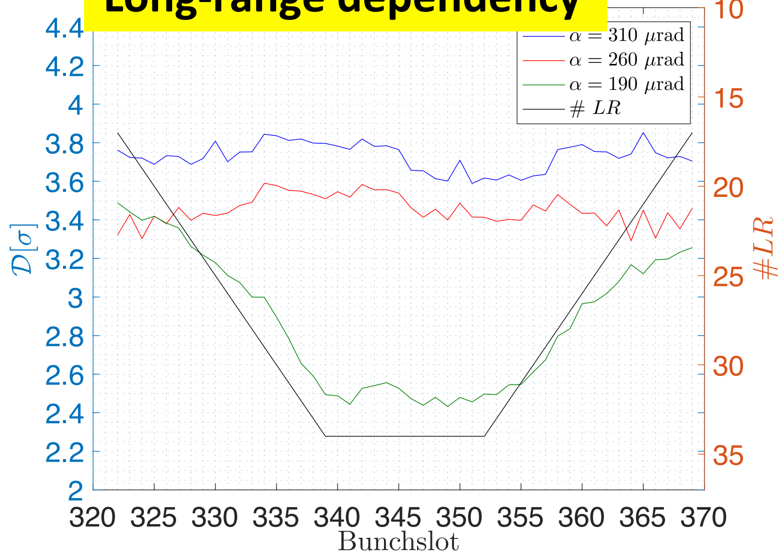
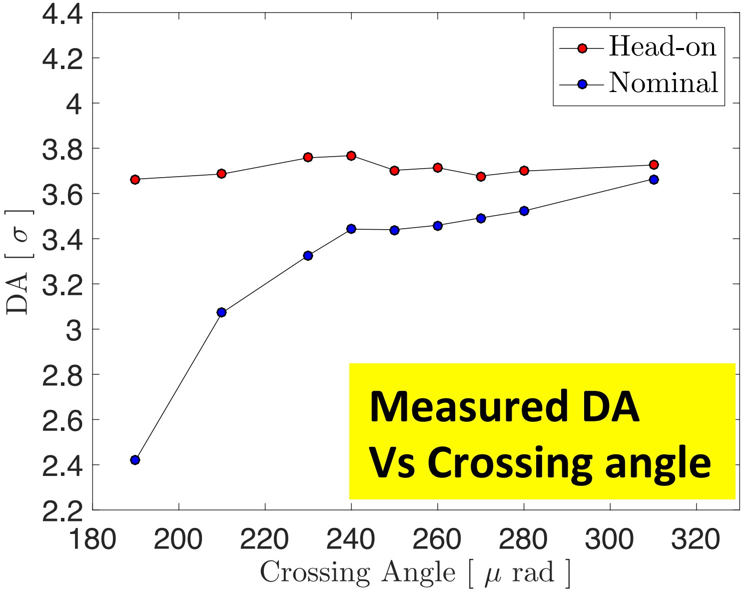
Long-range dependency

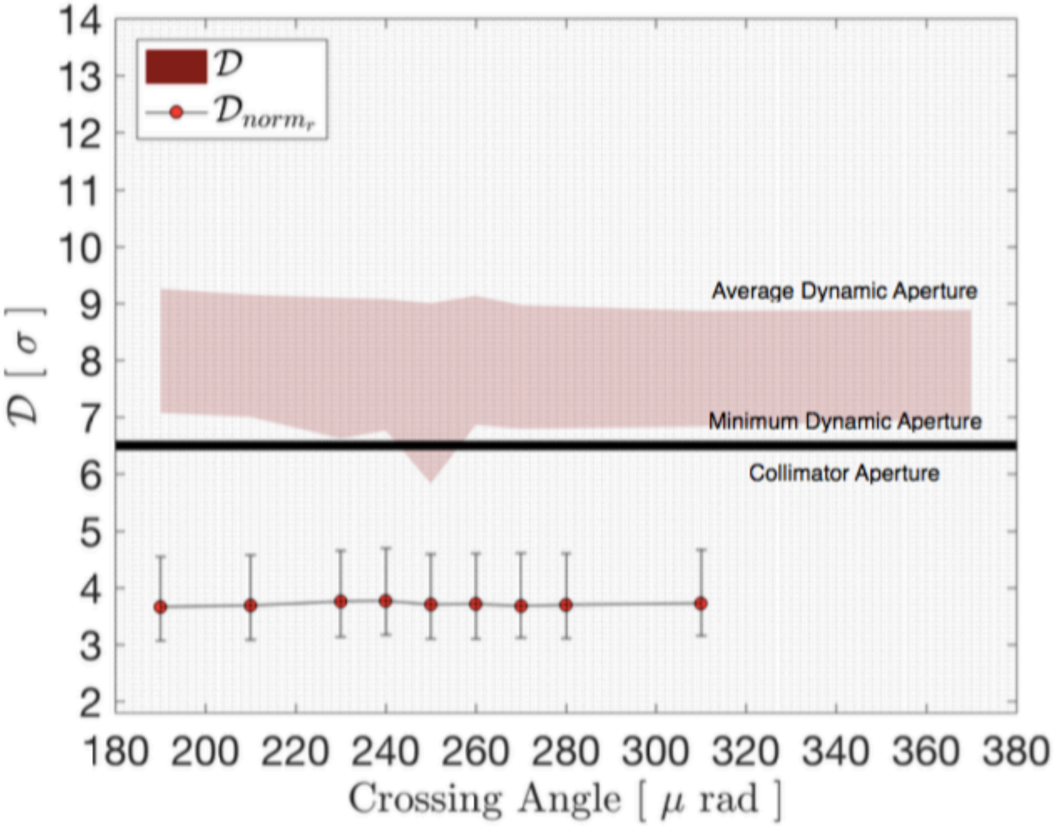


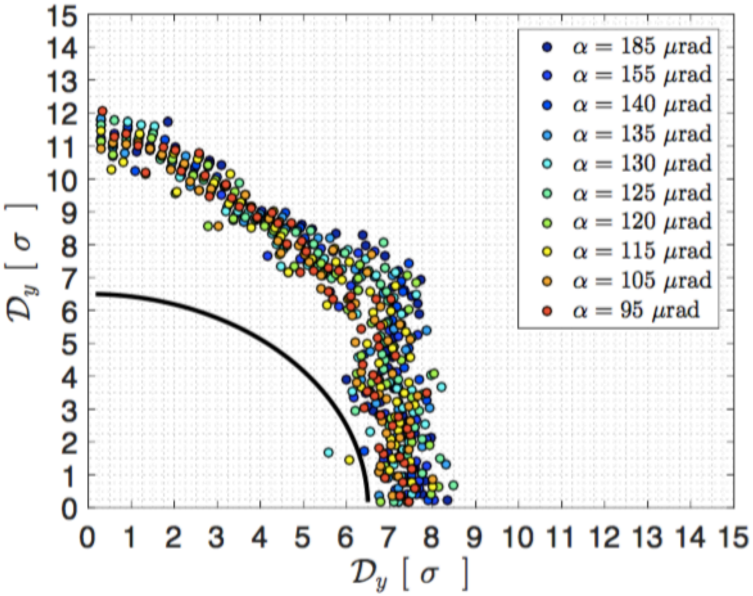


Measured DA
Vs Crossing angle

Head-on colliding bunch and nominal have similar losses at larger angles
For separation below 8.3 σ long-range effects take over

Head-on Beam-Beam effects

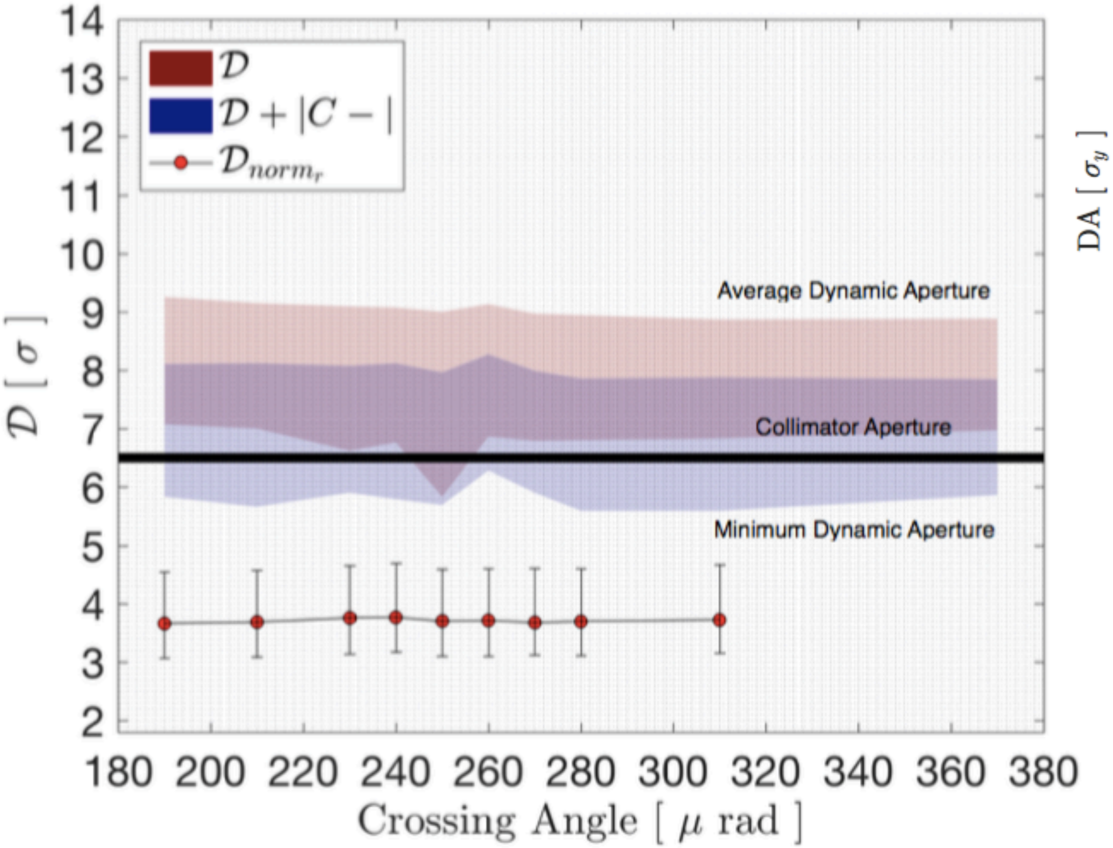


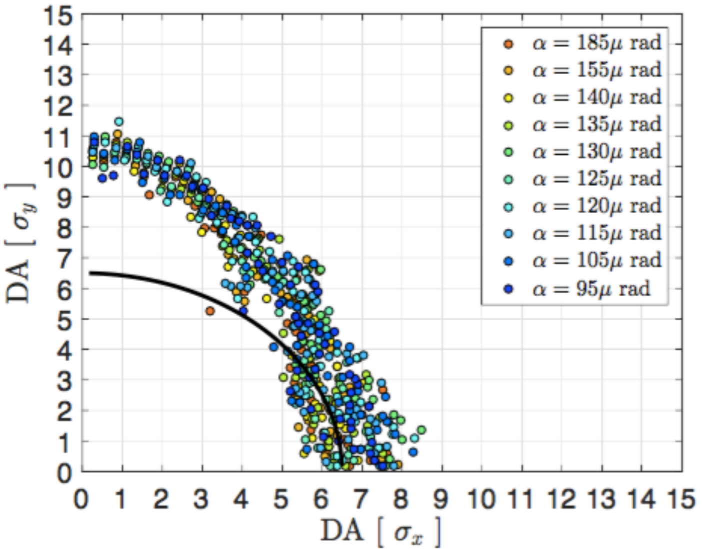


Head-on alone cannot justify the losses observed!
Losses are much larger than those expected by collimation cut

@IPAC 2017 THPAB056
Manchester Thesis 2017

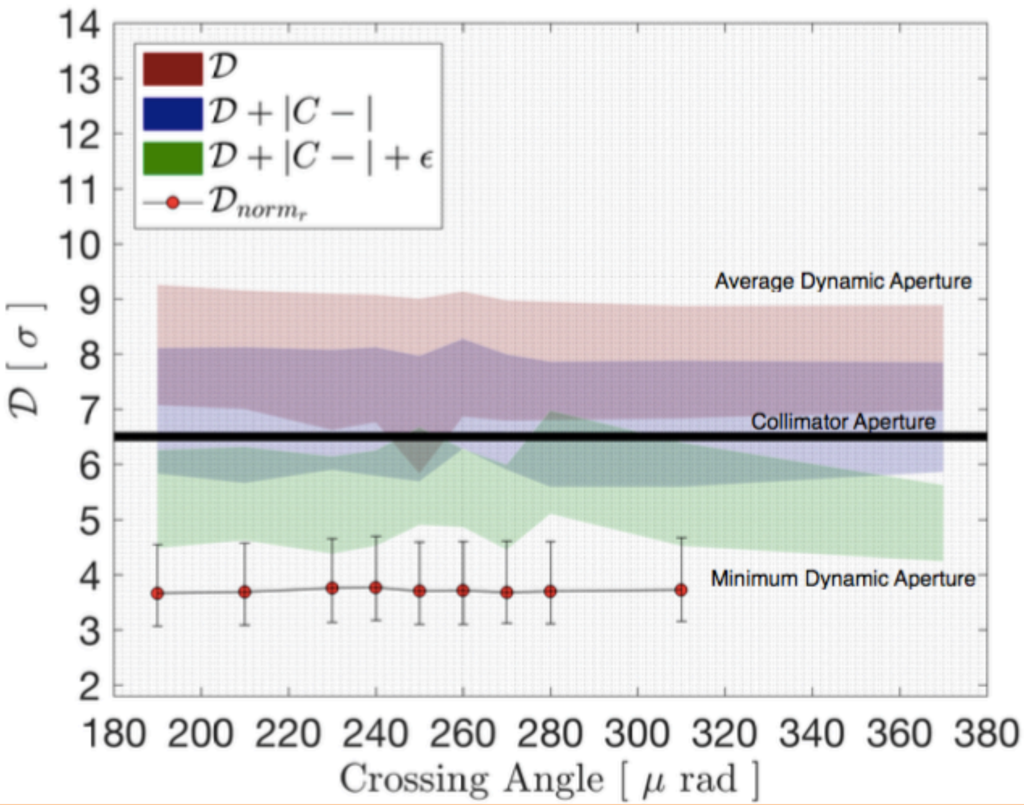
Head-on Beam-Beam Effects

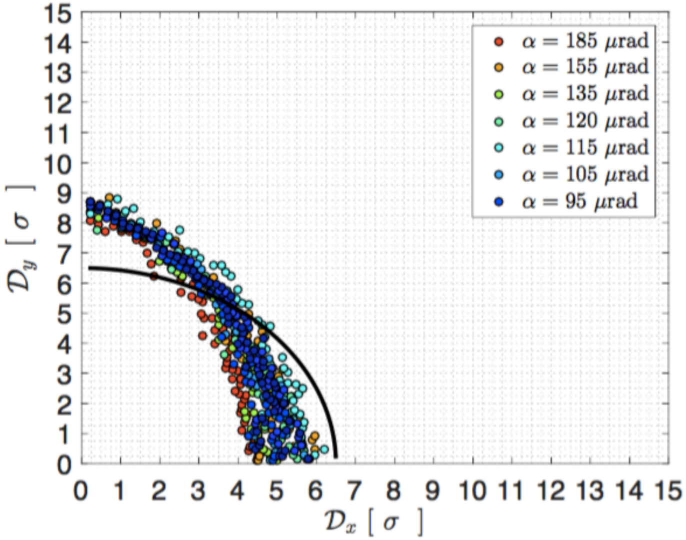




Linear Coupling reduces the DA

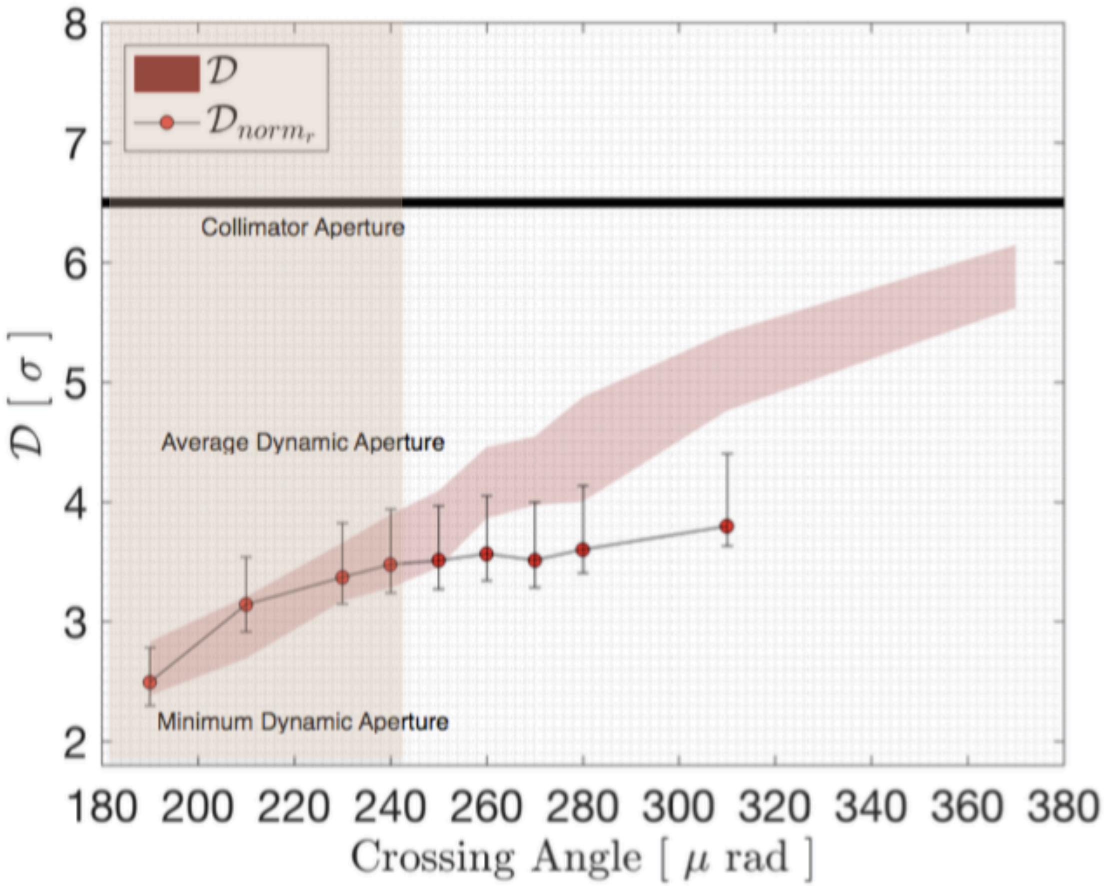
Head-on Beam-Beam Effects

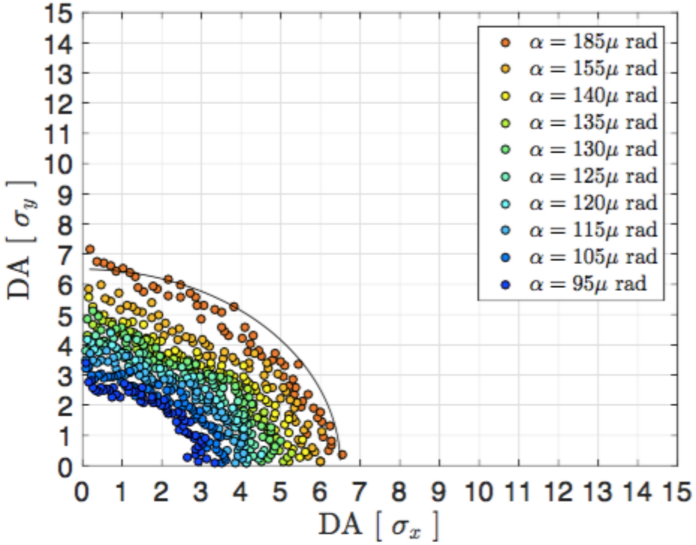




- **Head-on with magnets multipolar errors can partially justify the losses measured on colliding beams**
- **Stilll missing some contributions**
- Minima DA is conservative, average should be the the right figure of merit with standard deviation over seeds!

Long-range beam-beam Effects





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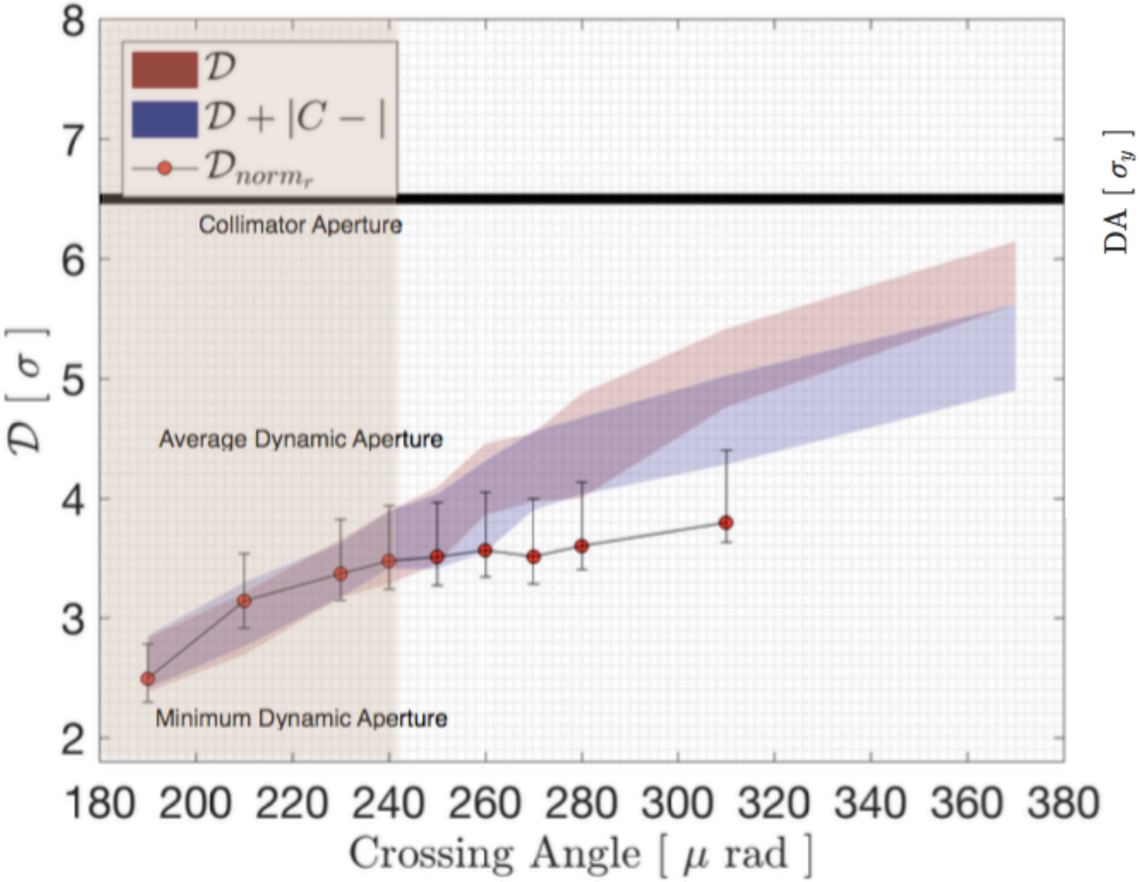
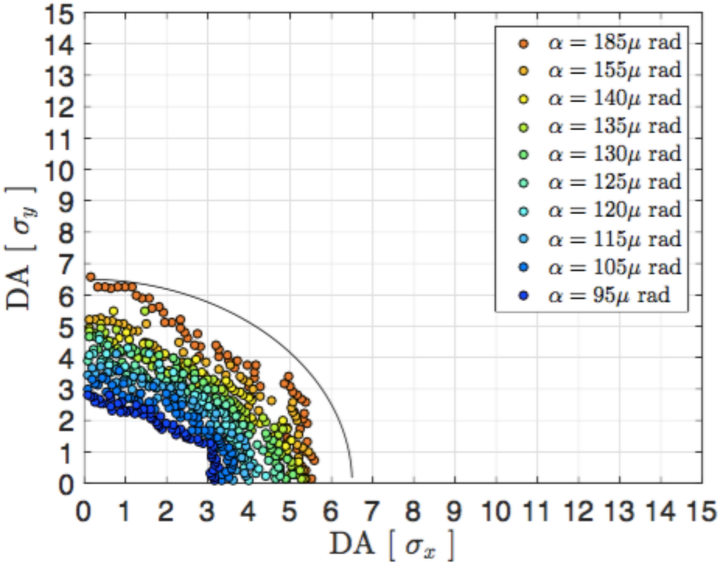
Manchester Thesis 2017 M. Crouch

Long-range behave like scrapers (losses well defined by DA) for small separations → no emittance blow-up

Long-range beam-beam losses





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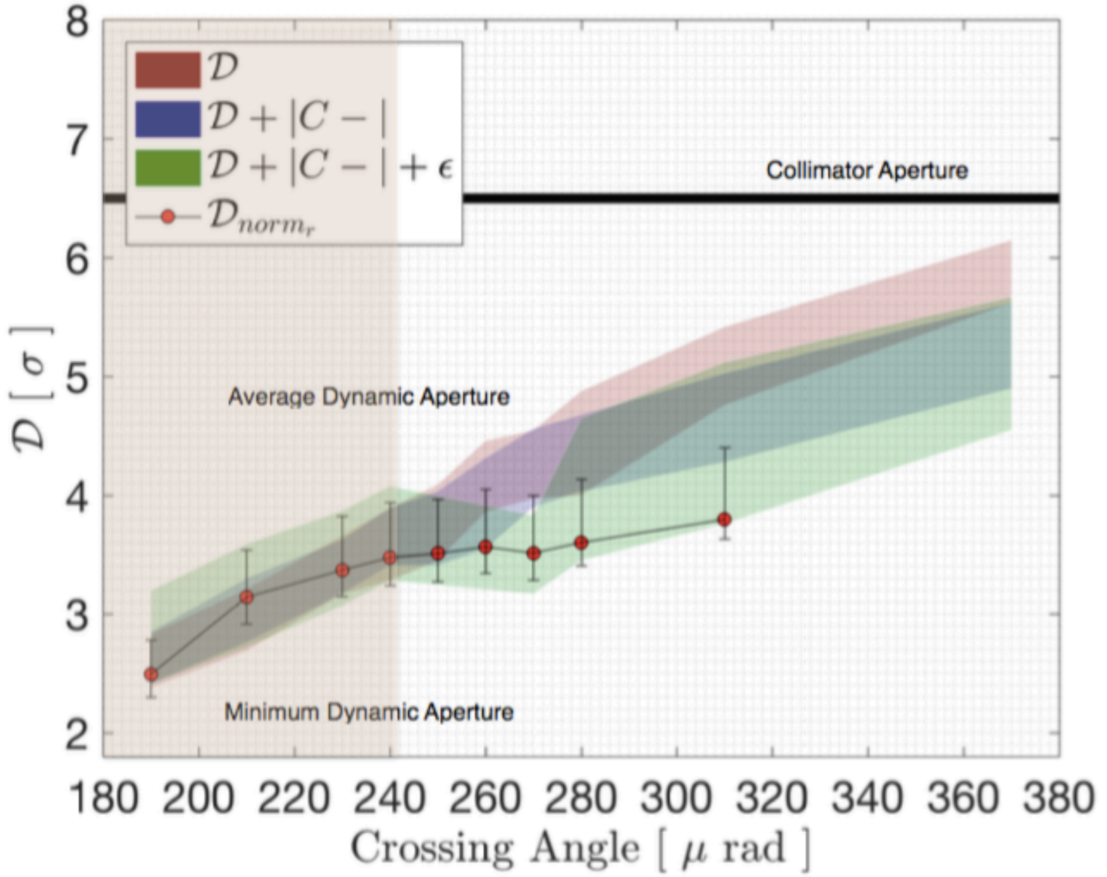
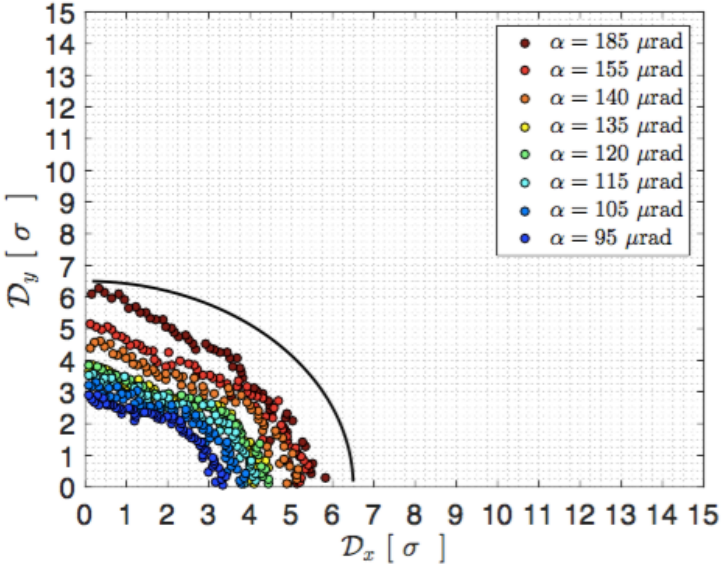
Linear Coupling has an effect for angles were long-range is not dominating → larger angles

Long-range beam-beam losses





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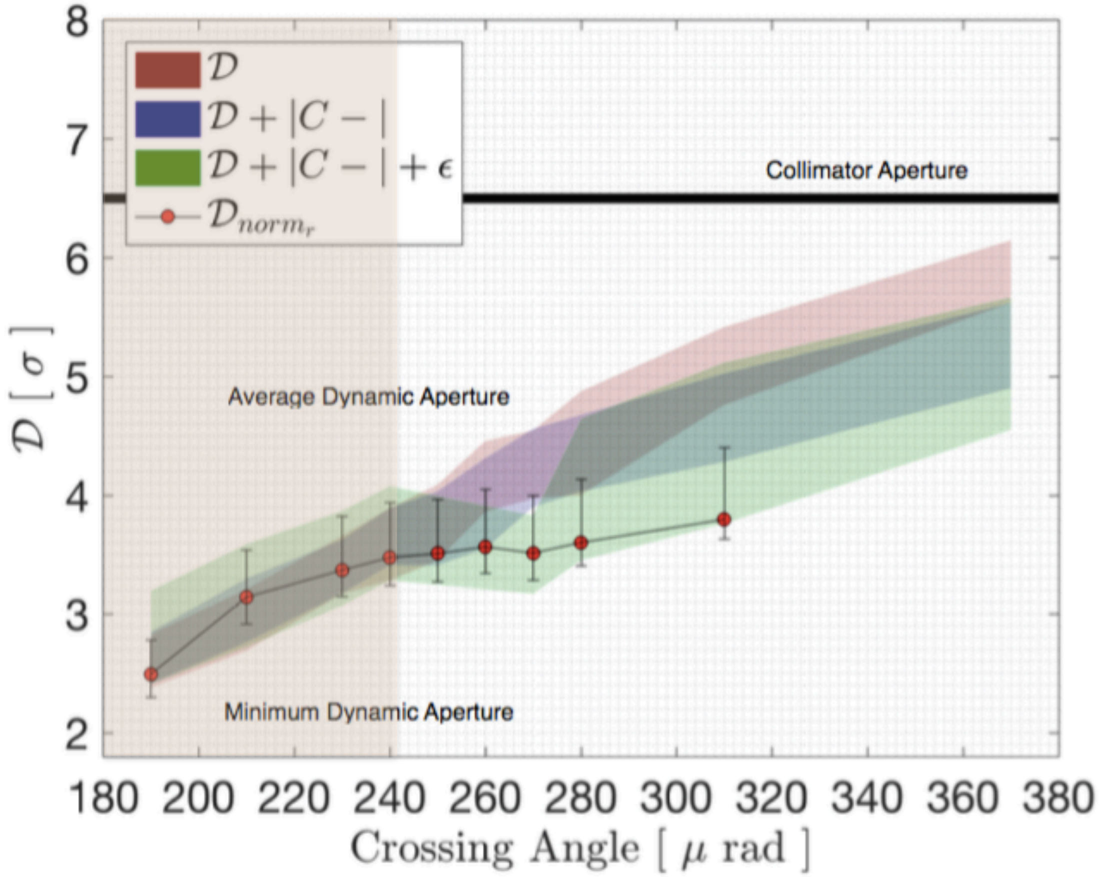
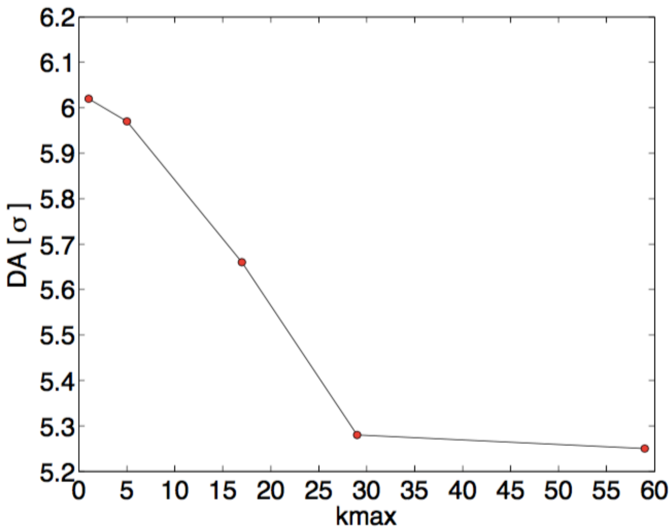
Multipolar Errors have a non negligible impact and can represent the losses observed.

Long-range beam-beam losses





LHC@home
SixTrack

Possible only with the LHC@home volunteers
- **LXBATCH** (300-1000 CPUs) → **8.3 – 2.5 days**
- **LHC@HOME** (4000 CPUs) → **0.63 days**

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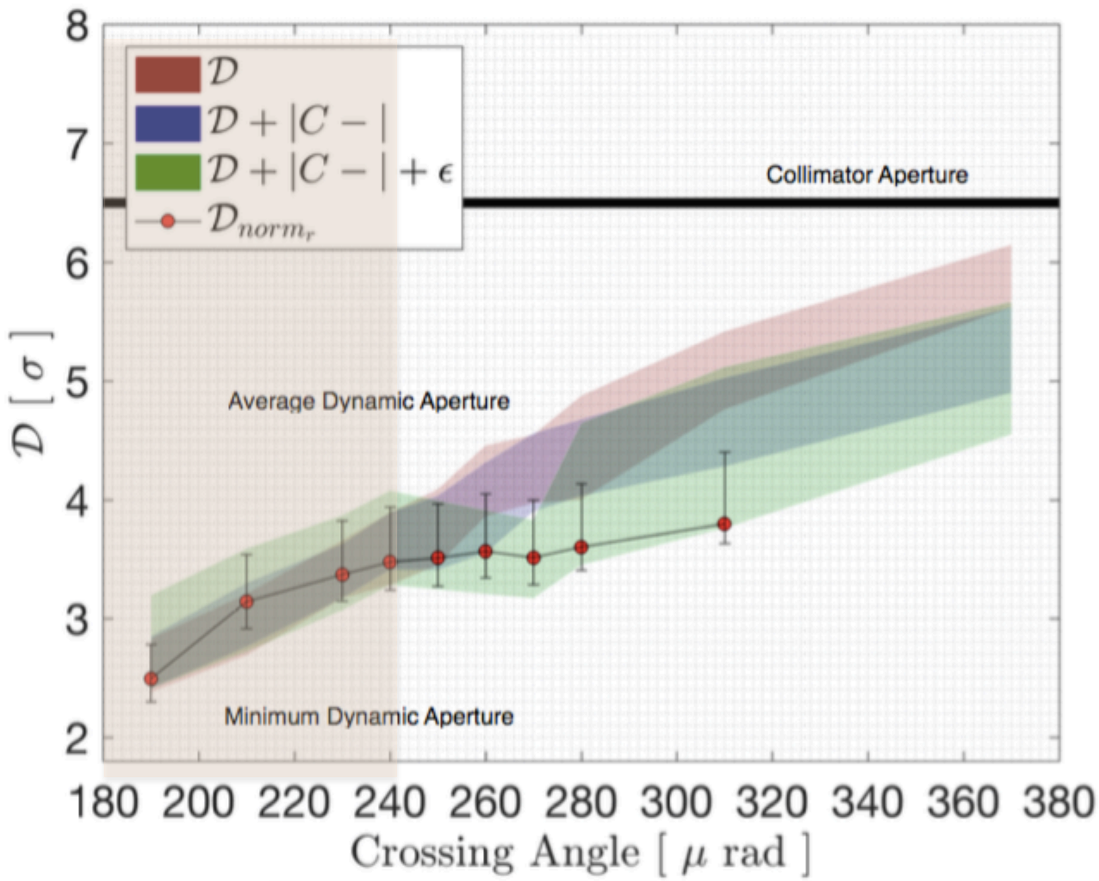
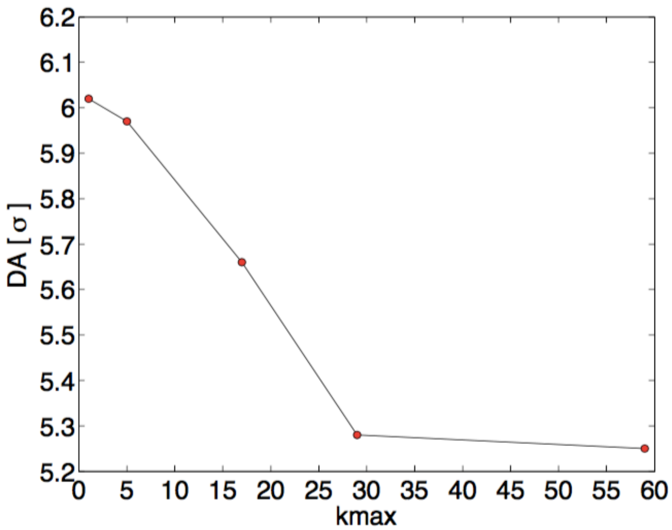
Long-range beam-beam losses





LHC@home
SixTrack

Extremely Demanding computationally factor 3-10 in computing steps (lattice, BB elements…)

- **LXBATCH → 41-12.5 days**
- **LHC@HOME → 3.15 days**

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Summary and Outlook

- **FCC-hh dynamic aperture studies have started using the criterion to keep DA beyond the machine aperture and looking for the largest DA**
  - **Different scenarios are under investigation**
  - **Design of the lattice is done to make use of compensation of beam-beam long-range with multipolar magnets**
  - **Margins are allocated to allow the use of strong non-linear elements (Landau damping and high chromaticity) for coherent stability purposes (C. Tambasco)**

- **Understanding and modeling the LHC case is fundamental to possibly extrapolate to the FCC machines and beams**

- **Big effort has been made to benchmark the LHC data, model keep improving but needs more work:**
  - Beam beam dynamic aperture alone cannot explain the observed losses in weak regime
  - Linear coupling, multipolar errors… have an important impact on DA
  - The head-on interaction is still difficult to model: what are we missing? Newer model will include emittance blow-up from noise sources
  - To model the particle phase space (minimum 60 x/y particles) we need large scale computing facilities (LHC@home) for FCC this will become extremely challenging

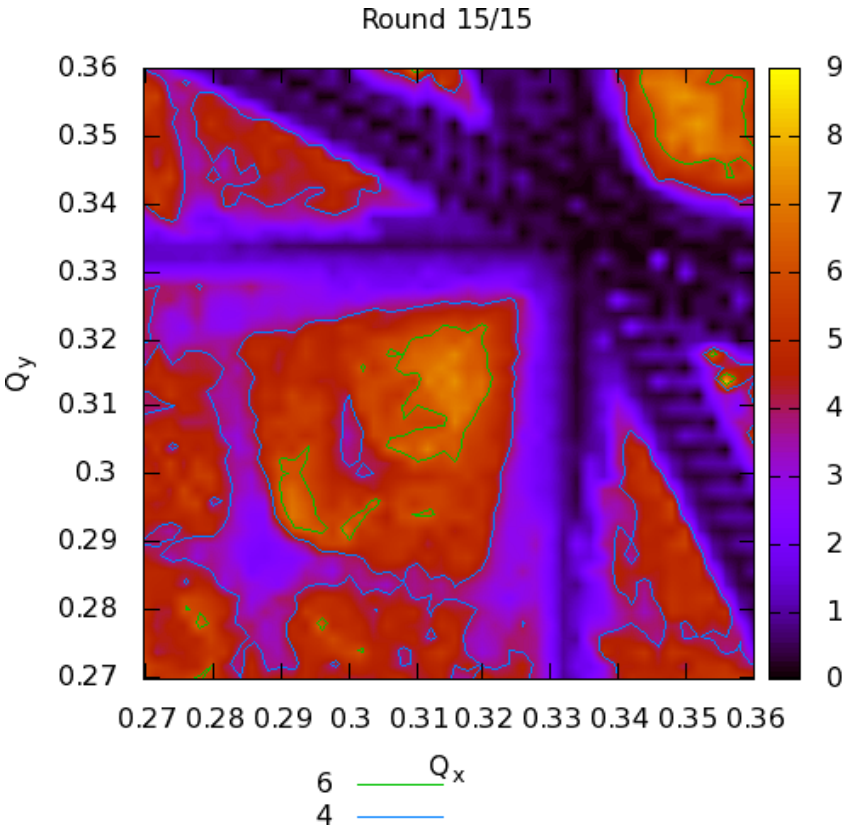
- **To design HE-LHC or FCC will be challenging from computational point of view!**

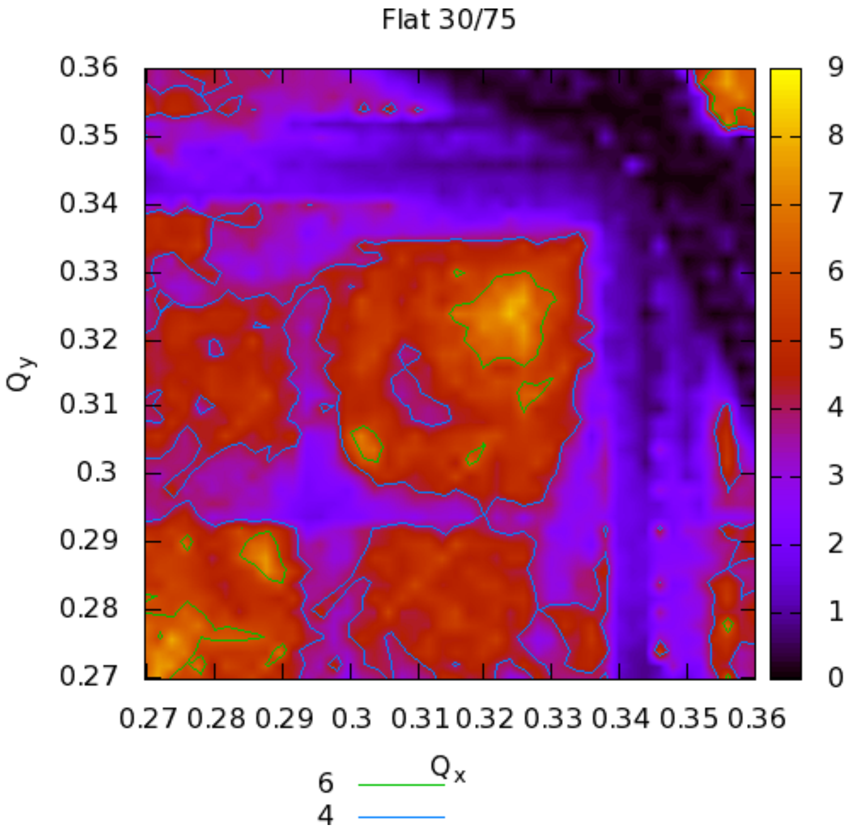
We need to explore the possibility of applying more modern computational techniques

→ speed-up calculations, simplify the collider description without loosing precision

Thank you!

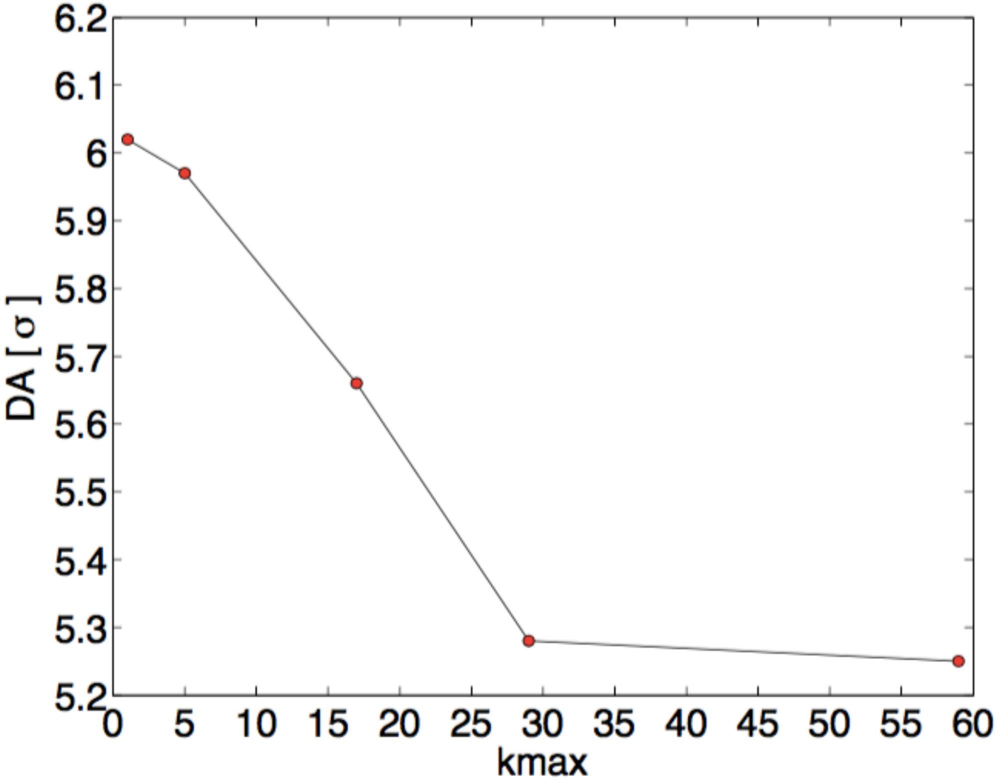
Flat versus round tune space





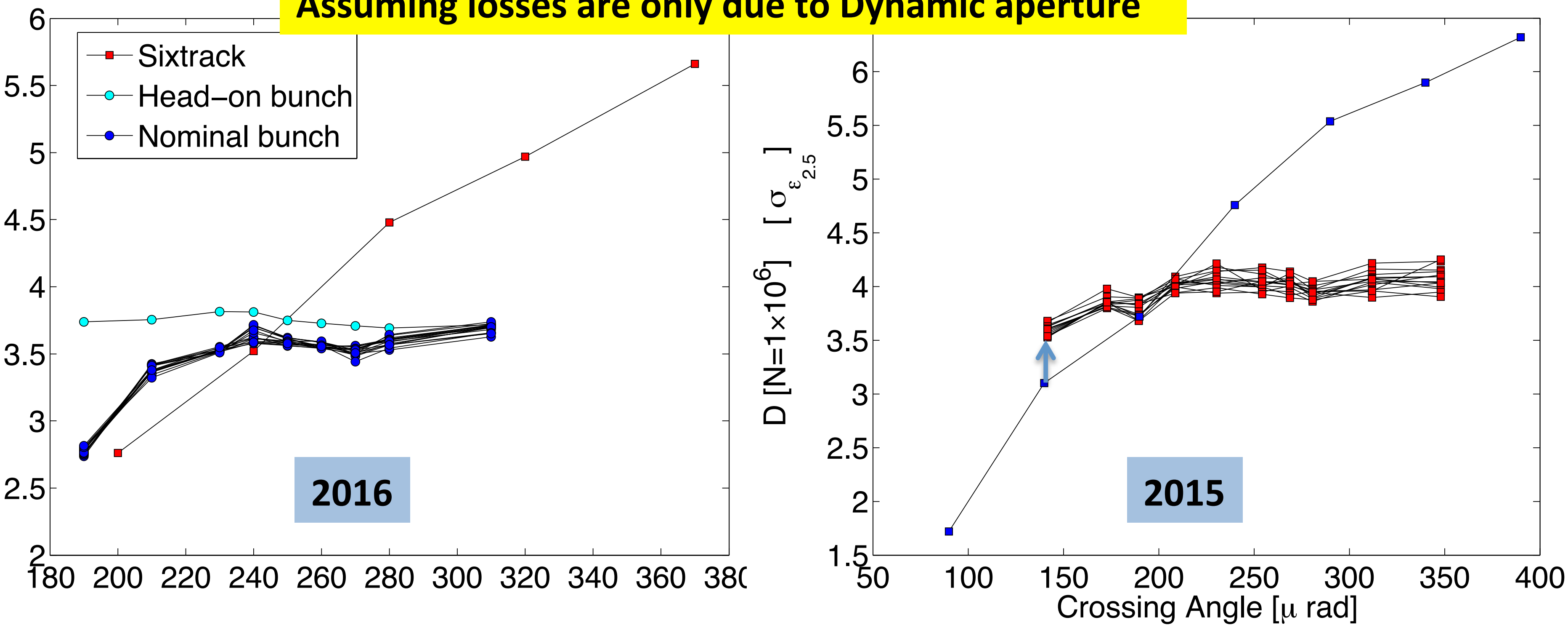
Simulation Set-up

- Use experiment parameters
- 60 x/y particles (normally 19)
- Amplitudes from 0 to 10 σ in steps of 0.2 σ
- Apply:
  - Beam-Beam
  - Linear Coupling (4x10^{-3})
  - Multipolar errors (60 seeds)
- Scan beam-beam separations
- Track 10^6 turn



Measurements versus simulations: Dynamic Aperture

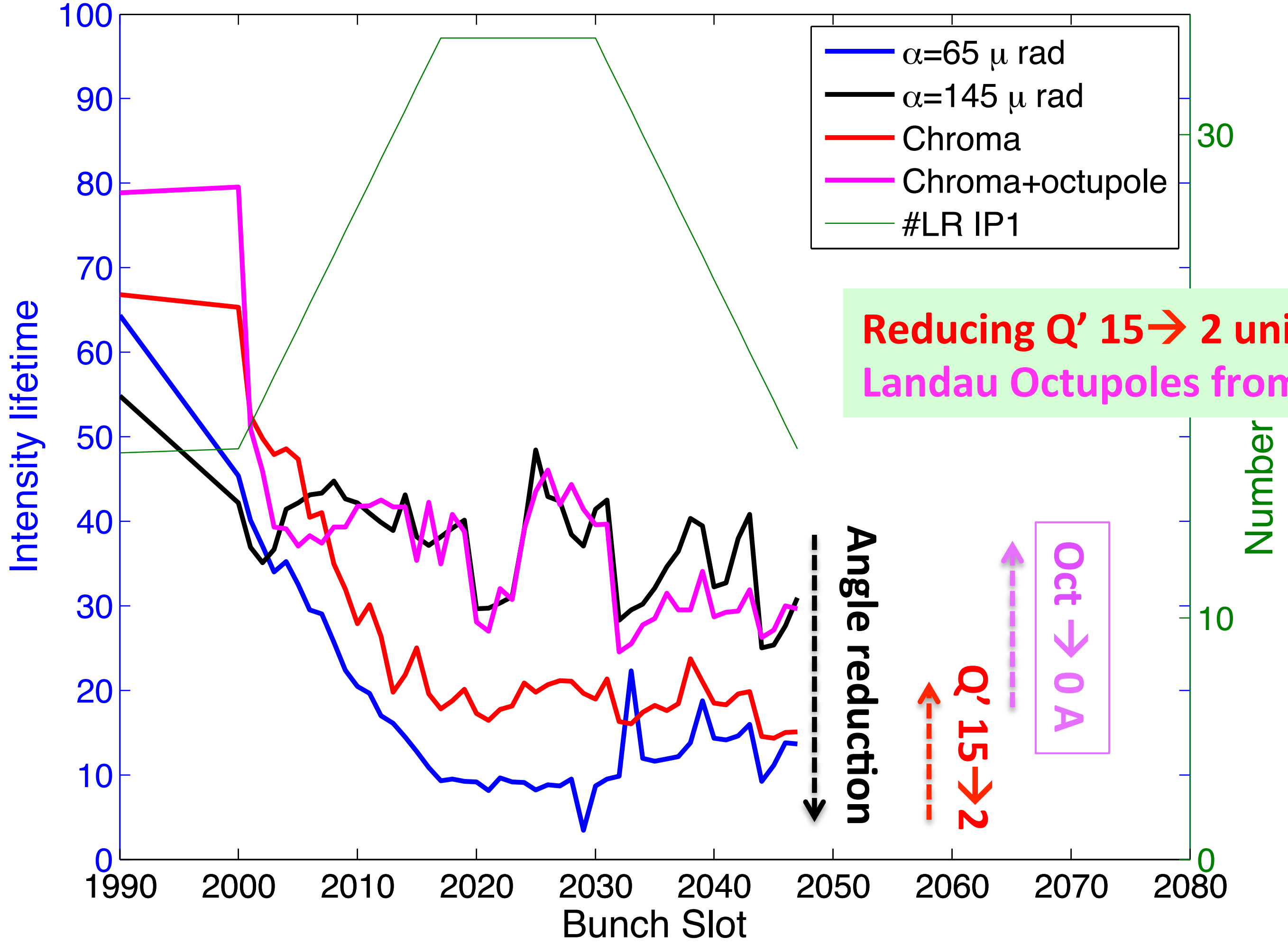
Assuming losses are only due to Dynamic aperture



Dynamic Aperture simulations at larger angles (370→250 μrad) are not representative of the machine! Losses are not dependent on crossing angle!

For smaller angles, separations below 8-8.5 σ Beam-Beam long-range dominates!

Octupoles and chromaticity knobs



Reducing Q' 15→ 2 units
Landau Octupoles from 476 → 0 A

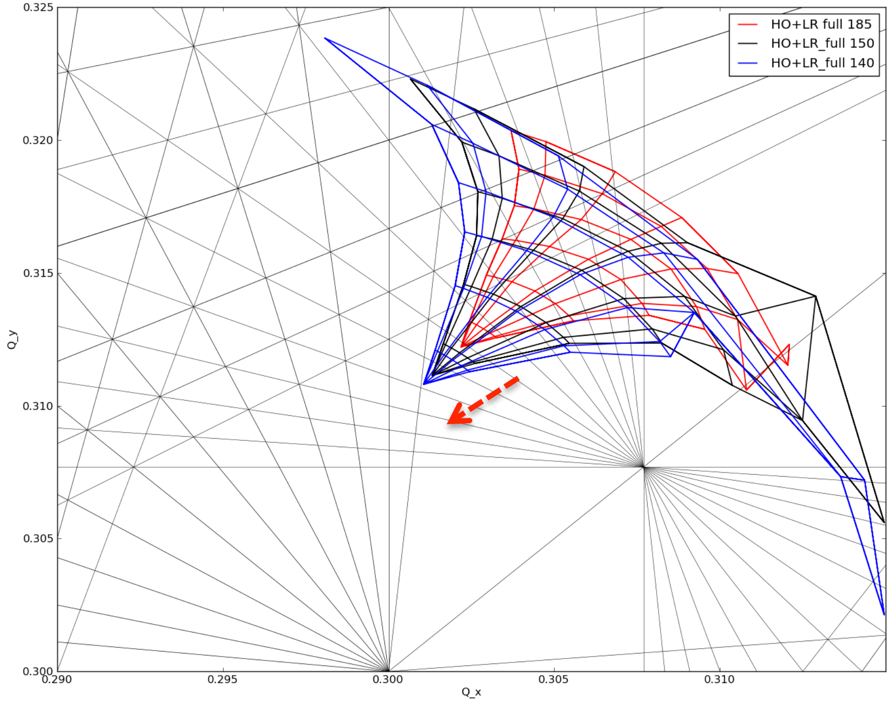
Octupoles and chromaticity knobs can be used to improve beam intensity lifetimes

At the minimum angle: **Reducing chromaticity → intensity lifetimes improve**

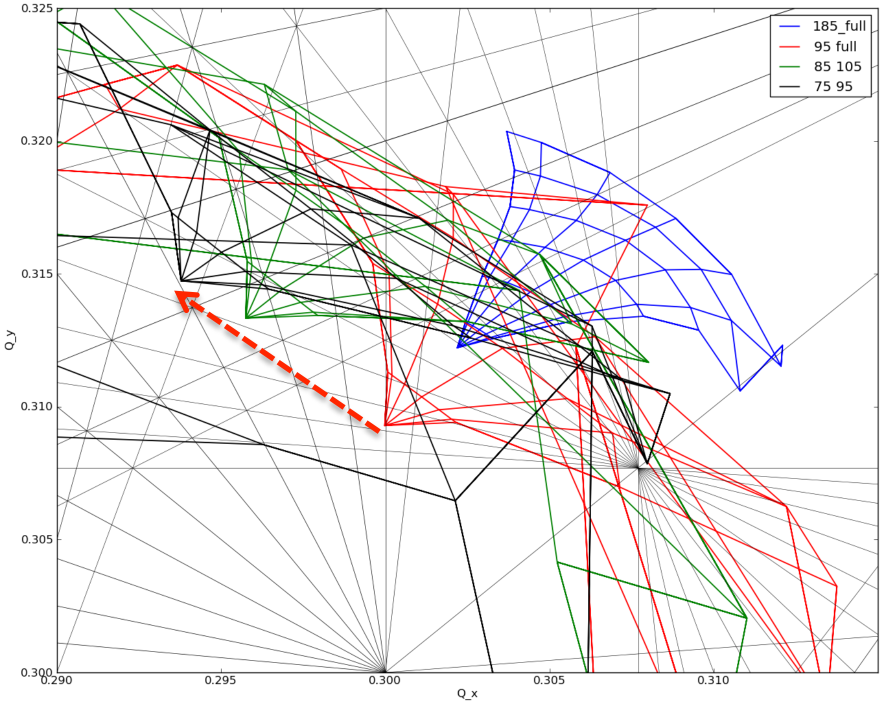
Reducing octupoles →intensity lifetimes improve

Tune shifts and un-compensated long-range

Compensated Long Ranges



Un Compensated Long Ranges



→**Uncompensated long-ranges in Vertical plane?** (smaller crossing angle in ATLAS than in CMS) → **breaking passive compensation** 17% differences between the V and H long-ranges

→**Test on machine**: angles measurement at IP1&IP5 and/or compensate for tune shift!