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Beam-Beam Studies for Future Circular Hadron Colliders

T. Pieloni (EPFL),

J. Barranco, P. Goncalves, C. Tambasco, L. Rivkin (EPF Lausanne)

M. Crouch, R. Appleby (Manchester University)

X. Buffat, S. V. Furuseth, M. Giovannozzi (CERN)

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- FCC-hh parameters and options
- Beam-Beam effects for a FCC
  - Dynamic aperture and proton losses
  - Orbit Effects
  - Losses and Emittance effects
  - Coherent instabilities
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  - Compensation schemes
- Alternative scenarios studies
- Summary and outlook

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

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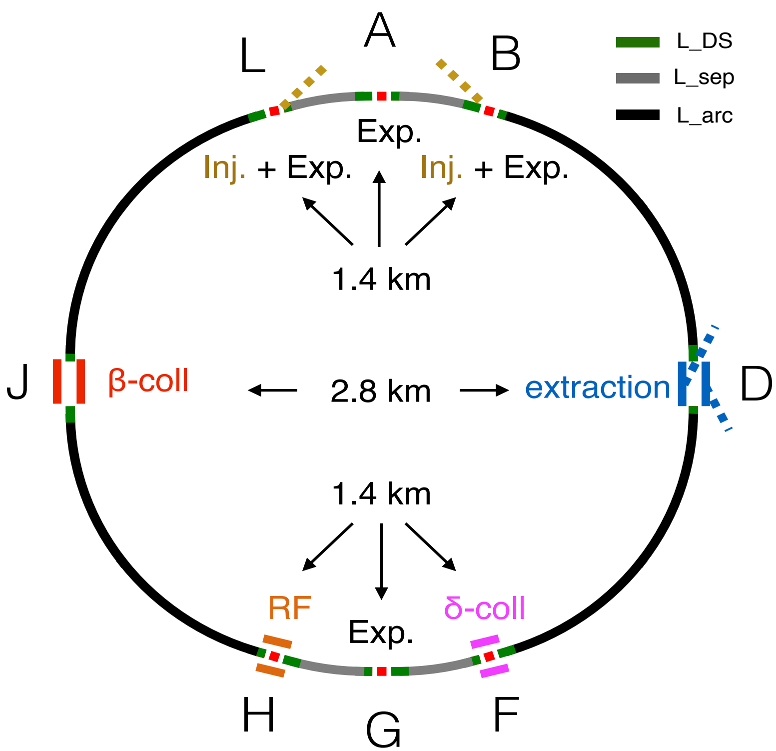
Collider Baseline and ultimate



	FCC-hh Baseline	FCC-hh Ultimate
Luminosity L [$10^{34}cm^{-2}s^{-1}$]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [mm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [mm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [s']	12	Crab. Cav.
Turn-around time [h]	5	4

IPA and IPG main high luminosity experiments:

Goal → maximum luminosity with good lifetimes → maximum integrated luminosity

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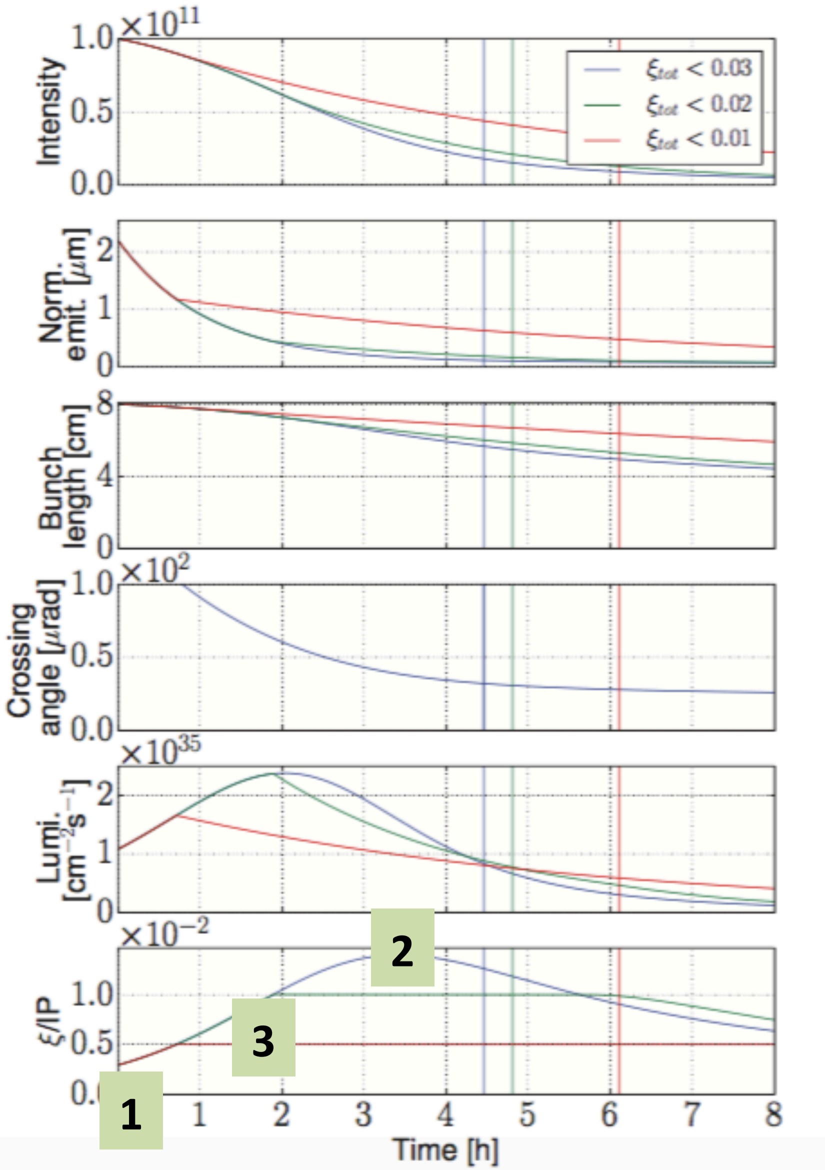
Parameter evolution



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
   LHC experience with HL-LHC MDs

3. Mixed status, radiation damping and possible operational scenarios
   Need new developments in models

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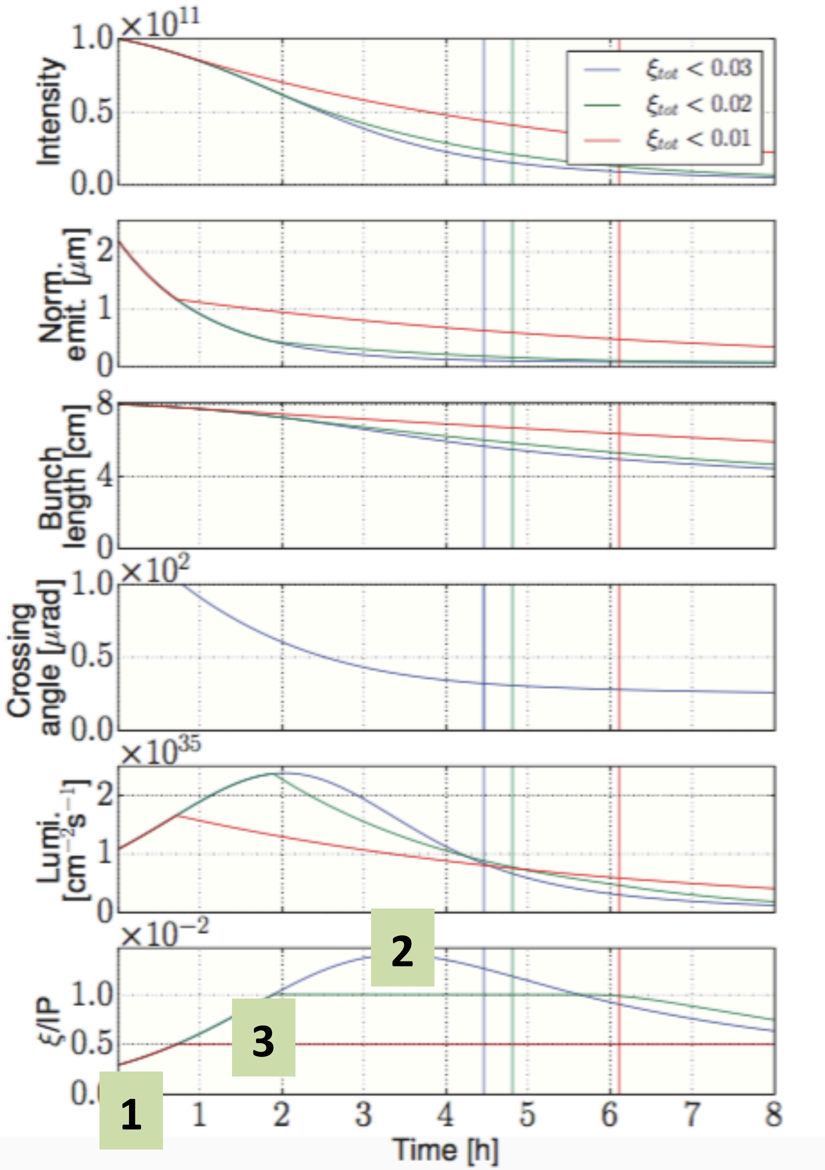
Parameter evolution



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All cases with 25 ns bunch spacing

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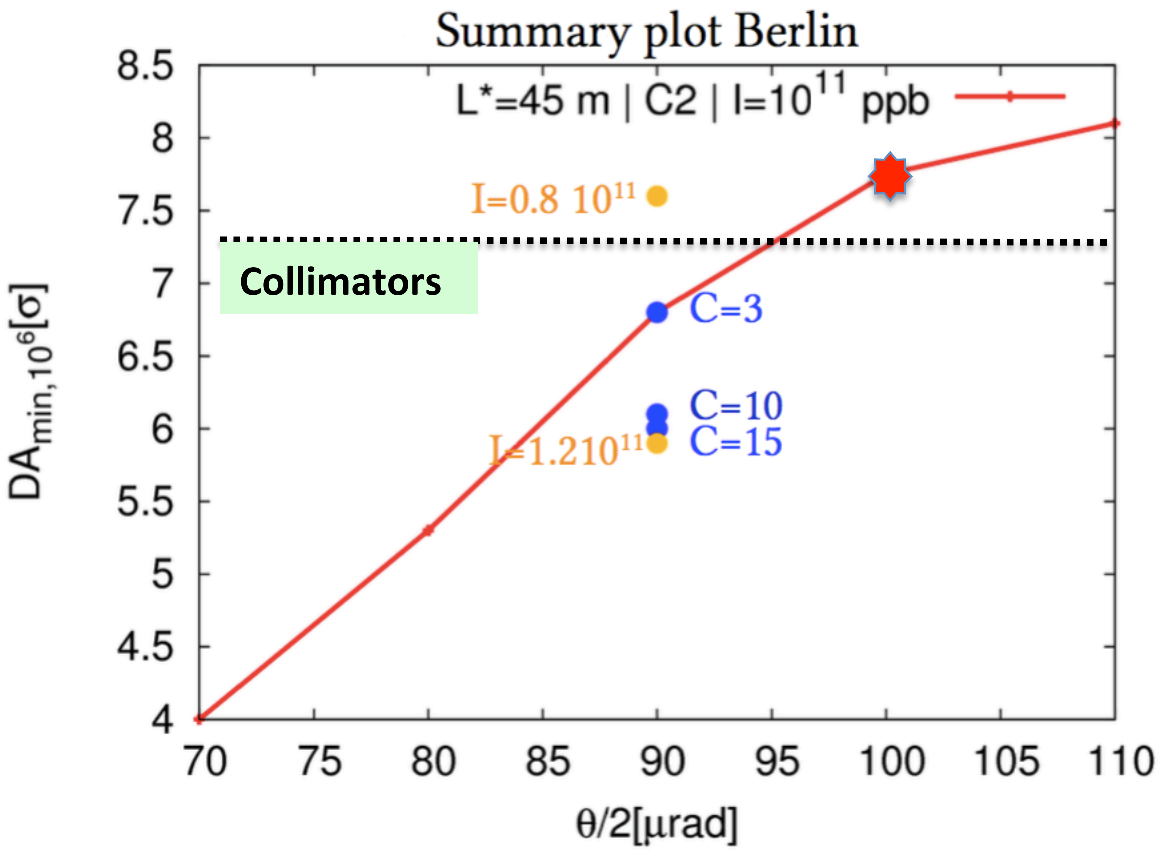
Dynamic aperture studies

FCC New Lattice 2 IPs and H-V alternating crossing

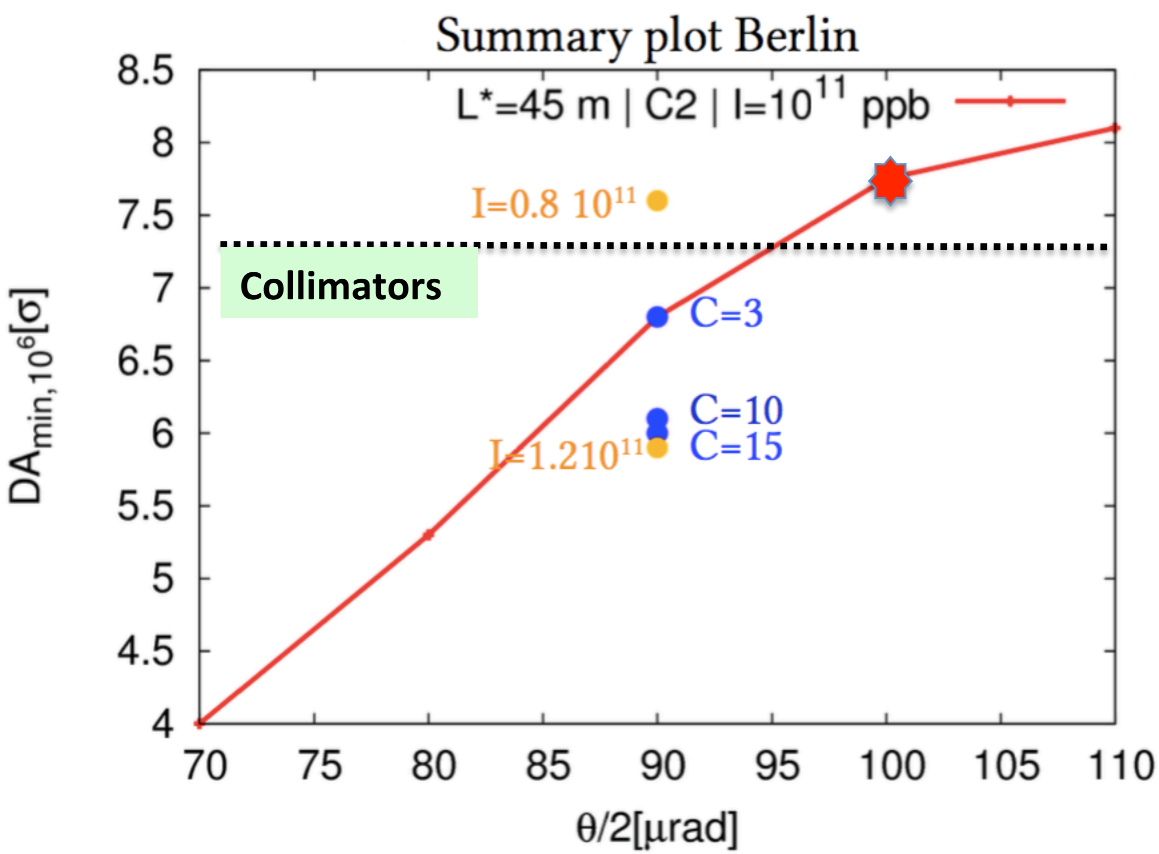


Dynamic Aperture: area in amplitude space with stable motion

Stable area of particles depends on beam intensity and crossing angle

Use of Sixtrack model

Dynamic aperture studies



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

No diffusive mechanism should increase the losses on the collimation system

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 no non-linearities
- **Intensity fluctuations →** requires roughly 5-10 μrad for 10-20% fluctuations

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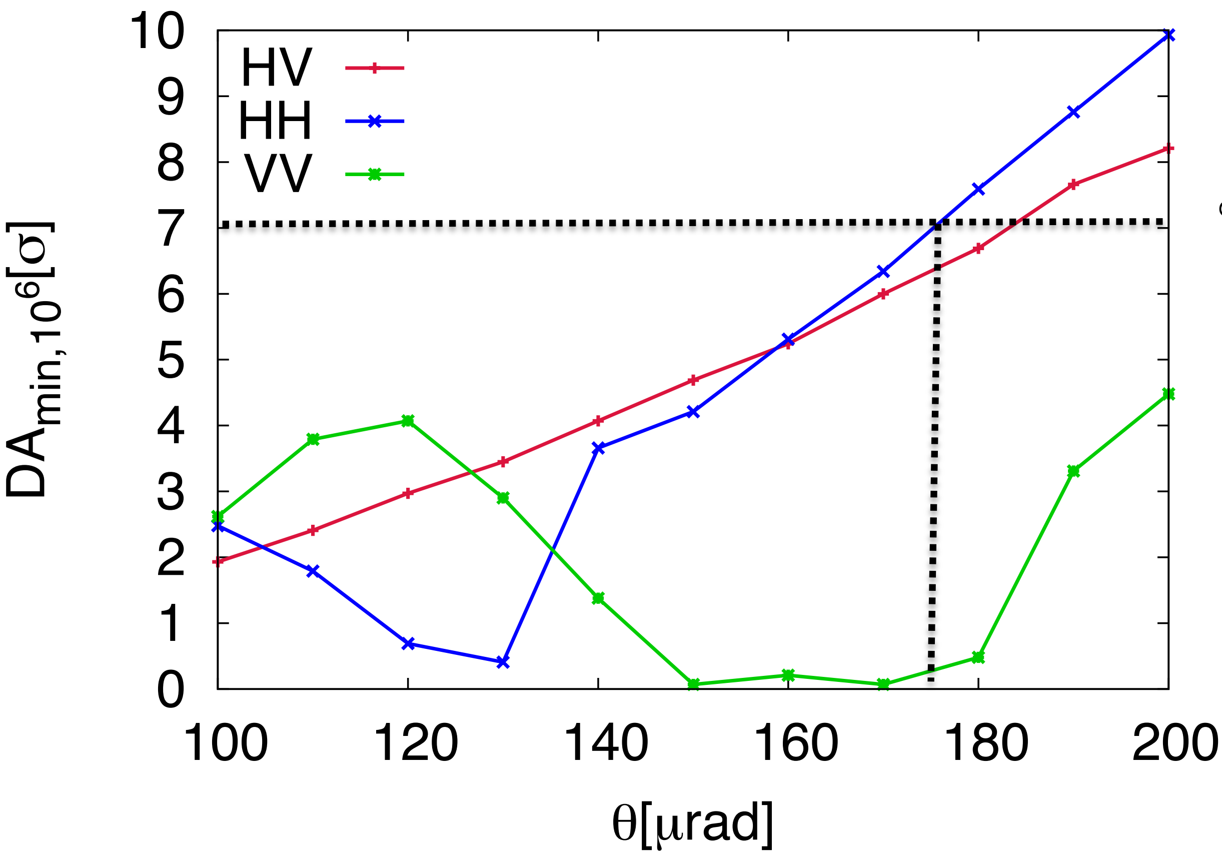
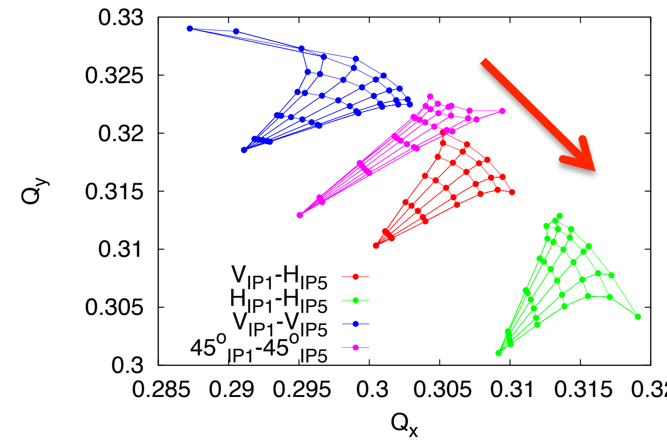
Variable Crossing Schemes: HV, HH and VV





Alternative crossing schemes are explored to overcome energy deposition constrains → changeable angles to dilute the particles losses in the IR. (I. Besana and F. Ceruti)

- HH Crossing is 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 → Mirrored tune will solve the problem
- **Tilted angle scheme still to be analyzed**

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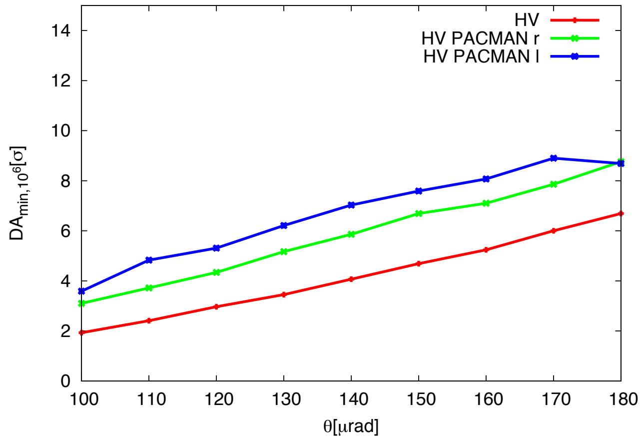
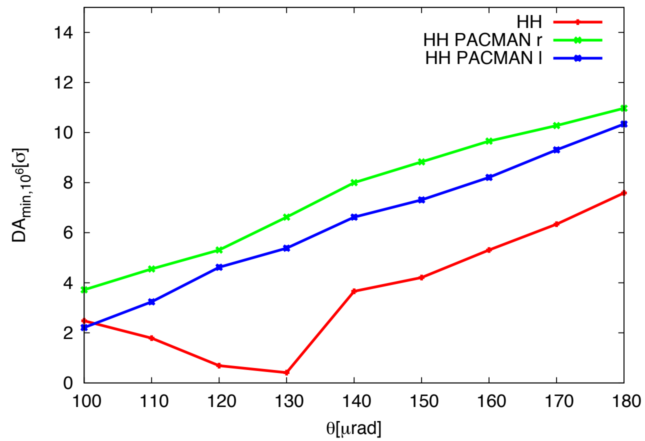
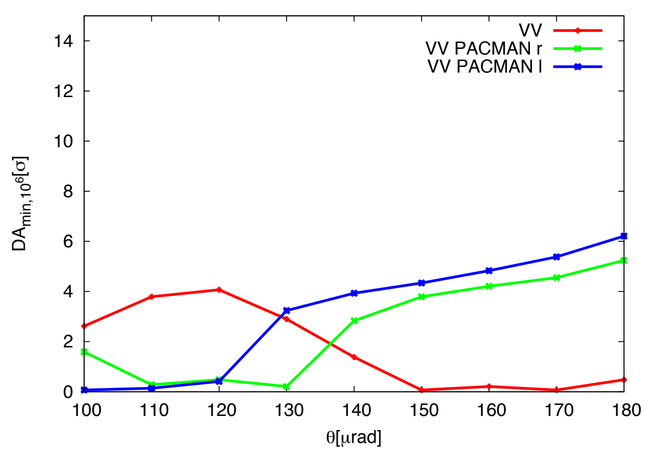
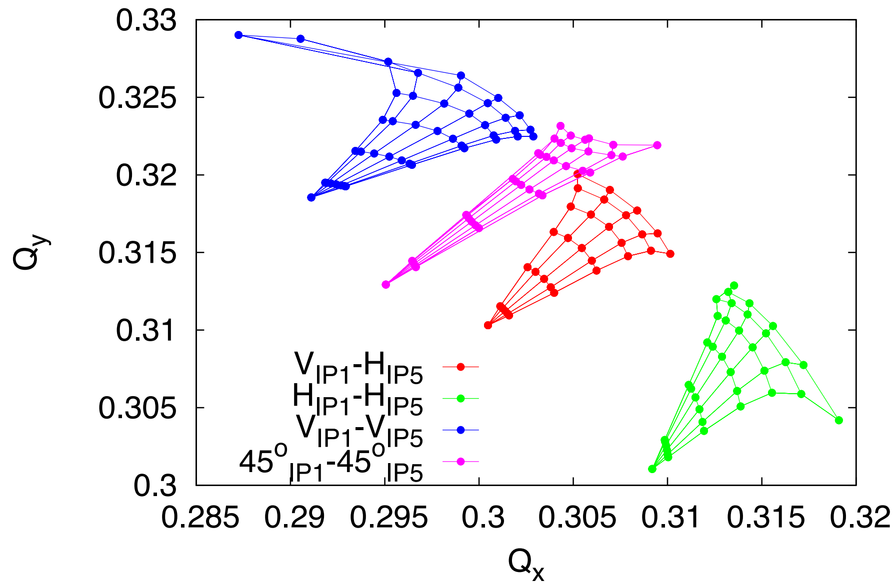






PACMAN Bunches



- 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
- **Orbit effects still to be addressed for conclude on PACMAN**
- **Should allow for flexible tuning**

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

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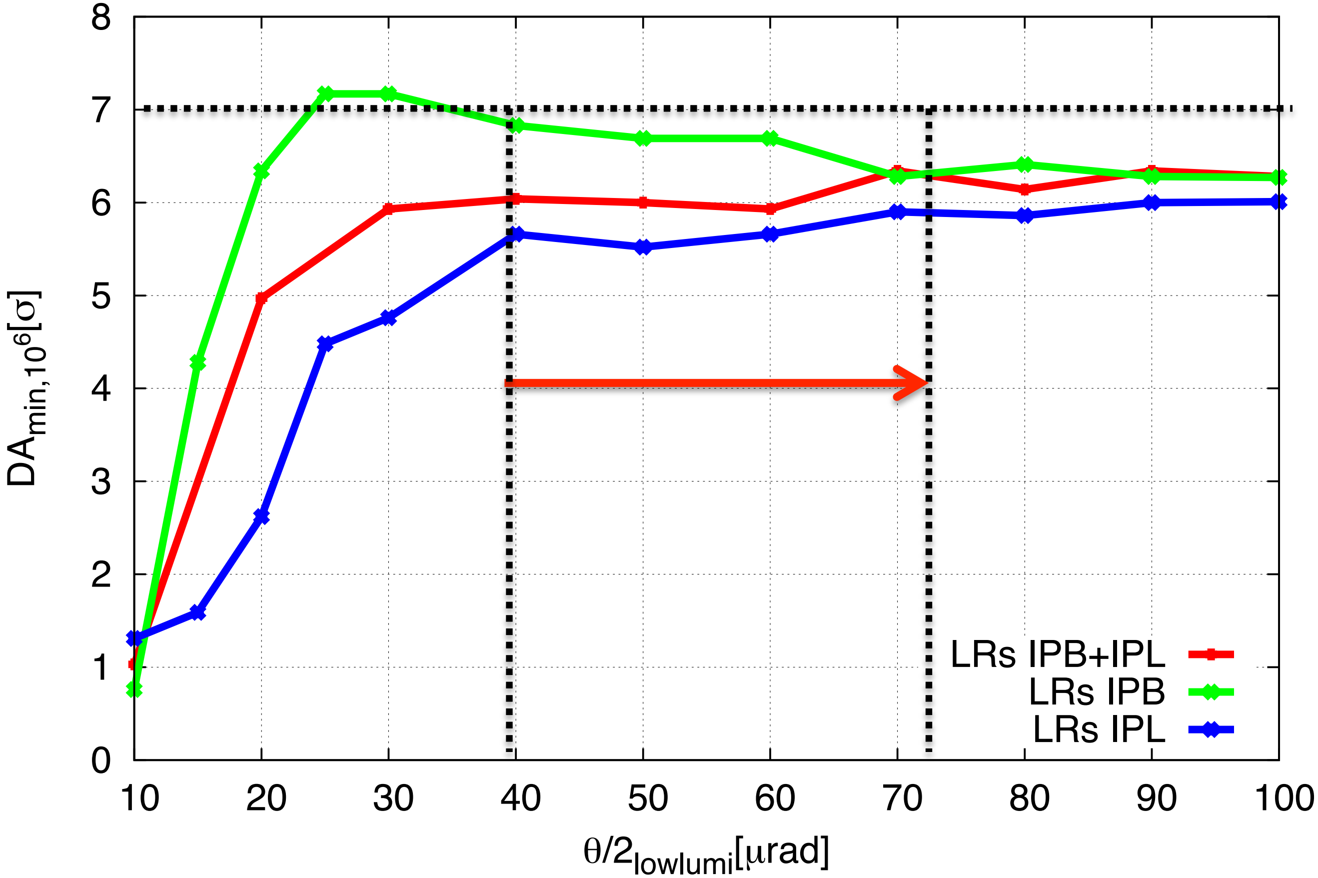
Low Luminosity Experiments to be added

Request for integrating low luminosity experiments IPB and IPL



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

Have to be designed in the shadow of the main high luminosity experiments

- **Long-range:** to keep effects weak → leave margins for larger angles
- **Head-on:** clear limit from the energy deposition studies

  From beam-beam studies → apply separation leveling → for physics programs they will have limit on integrated luminosity per year of run!

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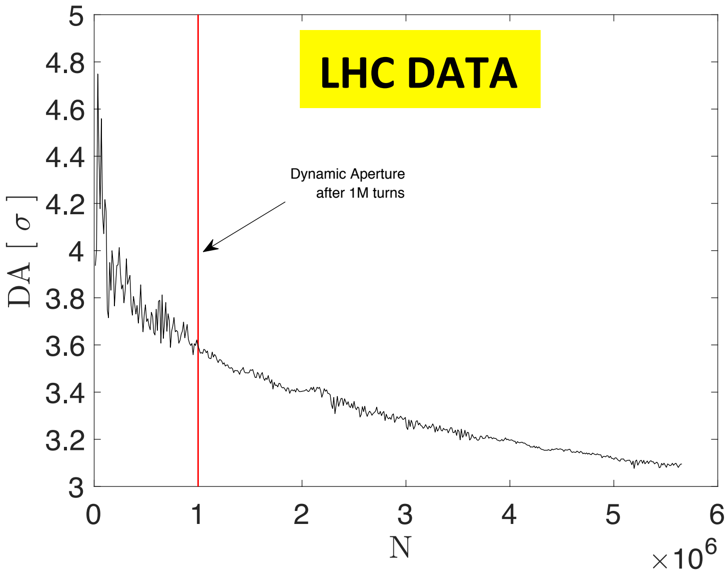
Can we translate dynamic aperture in losses?



Using the method proposed by M.Giovannozzi (Phys Rev Spec Top-AB, 15(2):024001, 2012) we extrapolate the DA to longer time scales → simulate beam lifetimes

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

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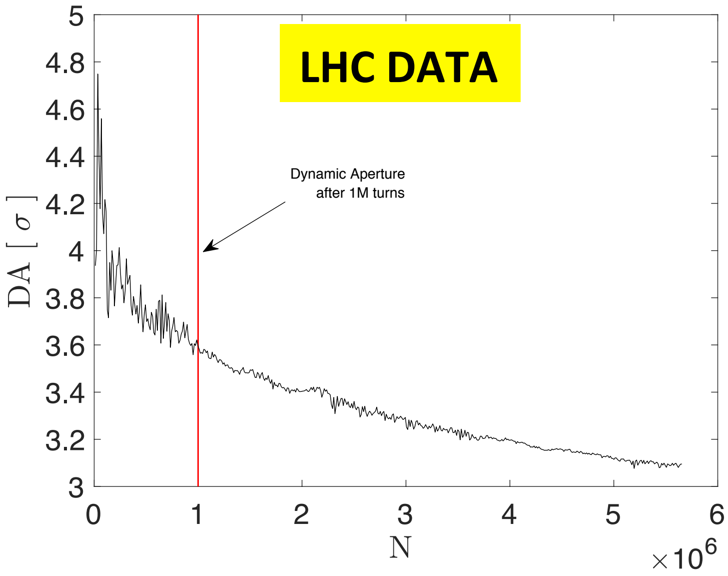
Can we translate losses in dynamic aperture?



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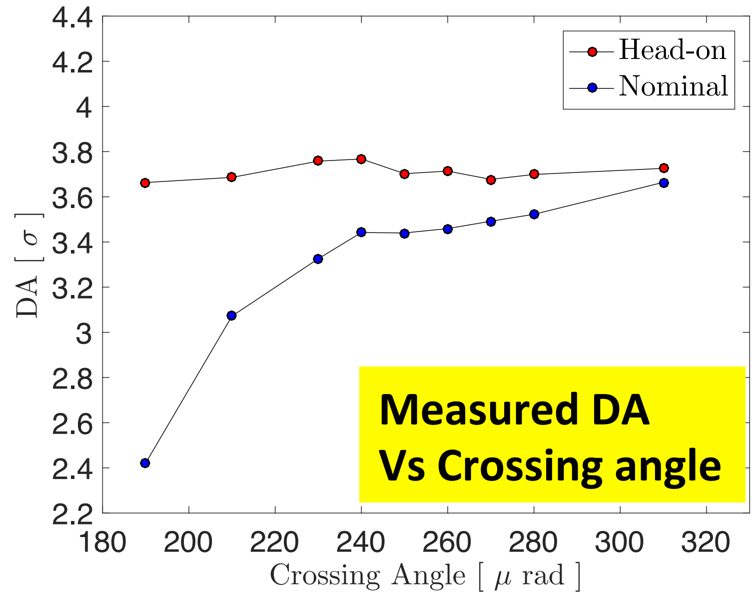
We applied to beam-beam experiments (lifetime evolution as a function of beam-beam parameters)
M. Crouch Manchester PHD Thesis 2017



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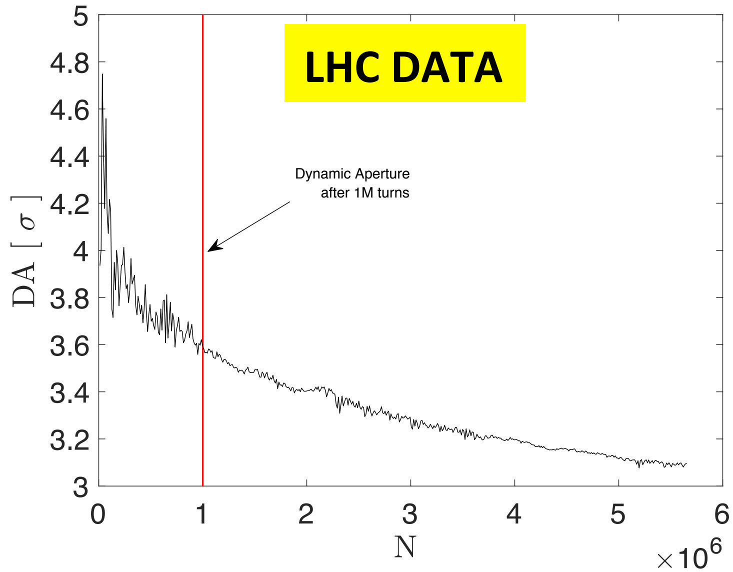
Can we translate losses in dynamic aperture?



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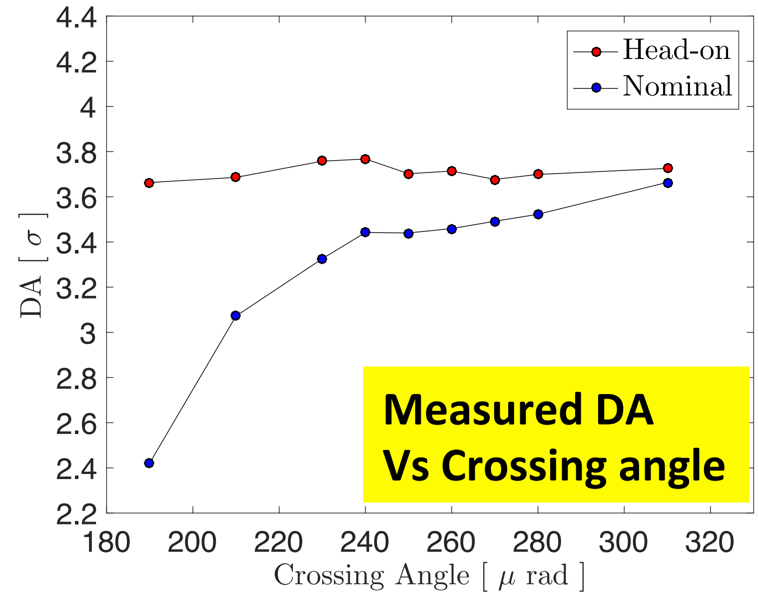

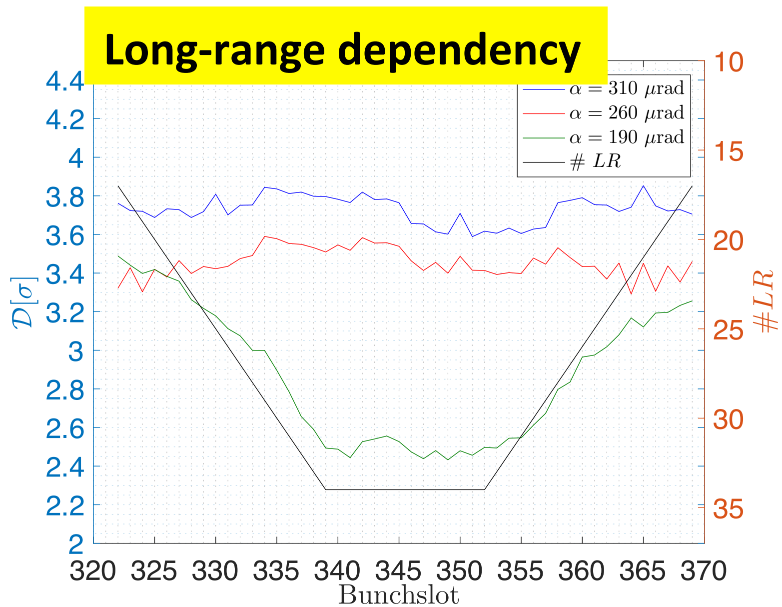

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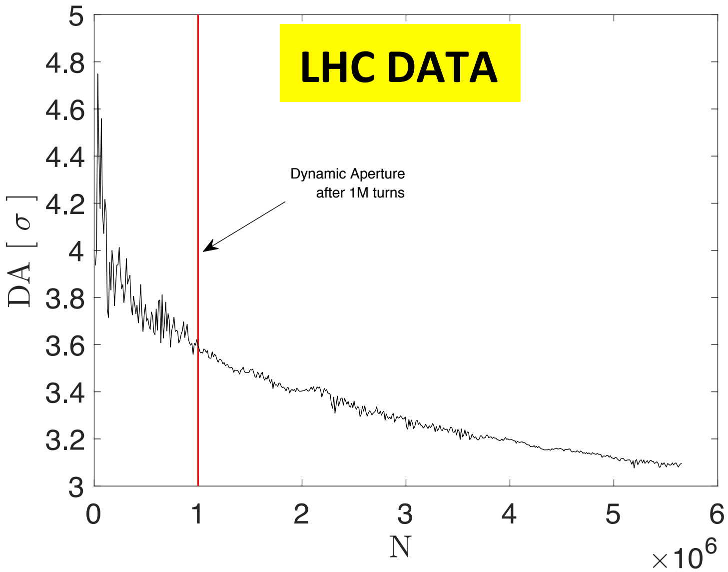

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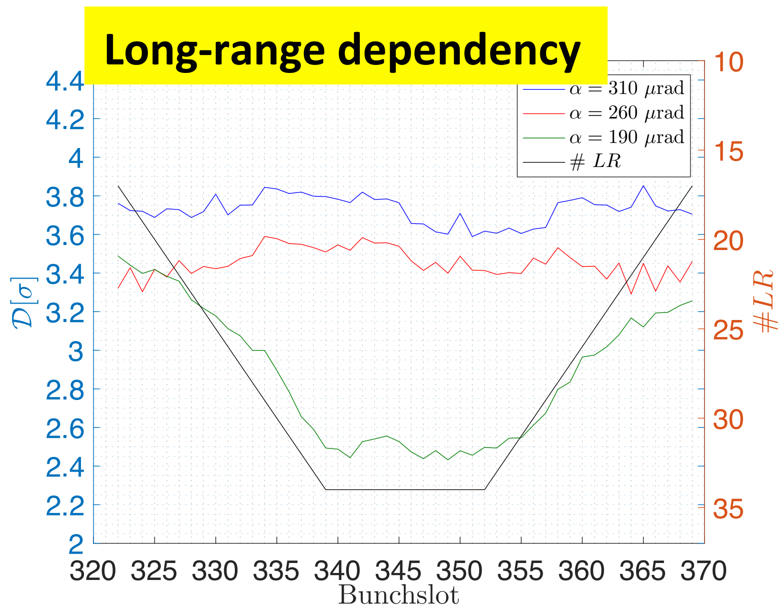

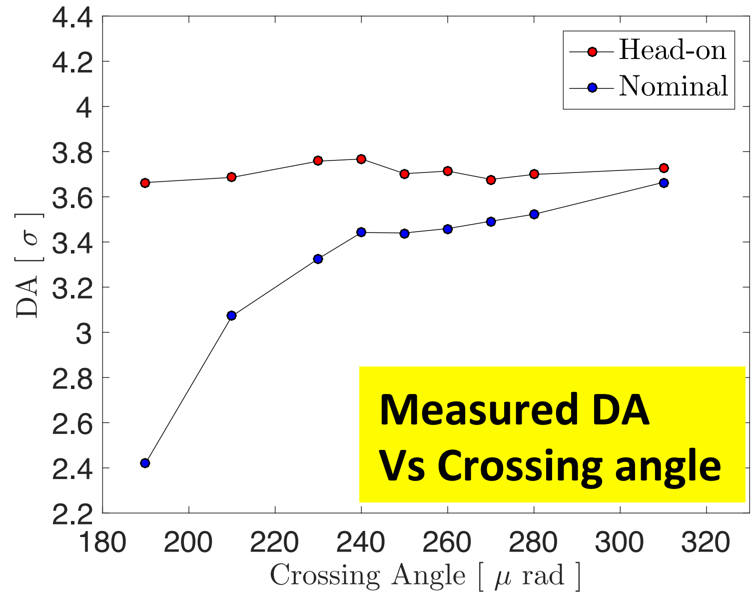

For separation below 8.0 σ long-range effects losses too high (lifetimes below 10 h)

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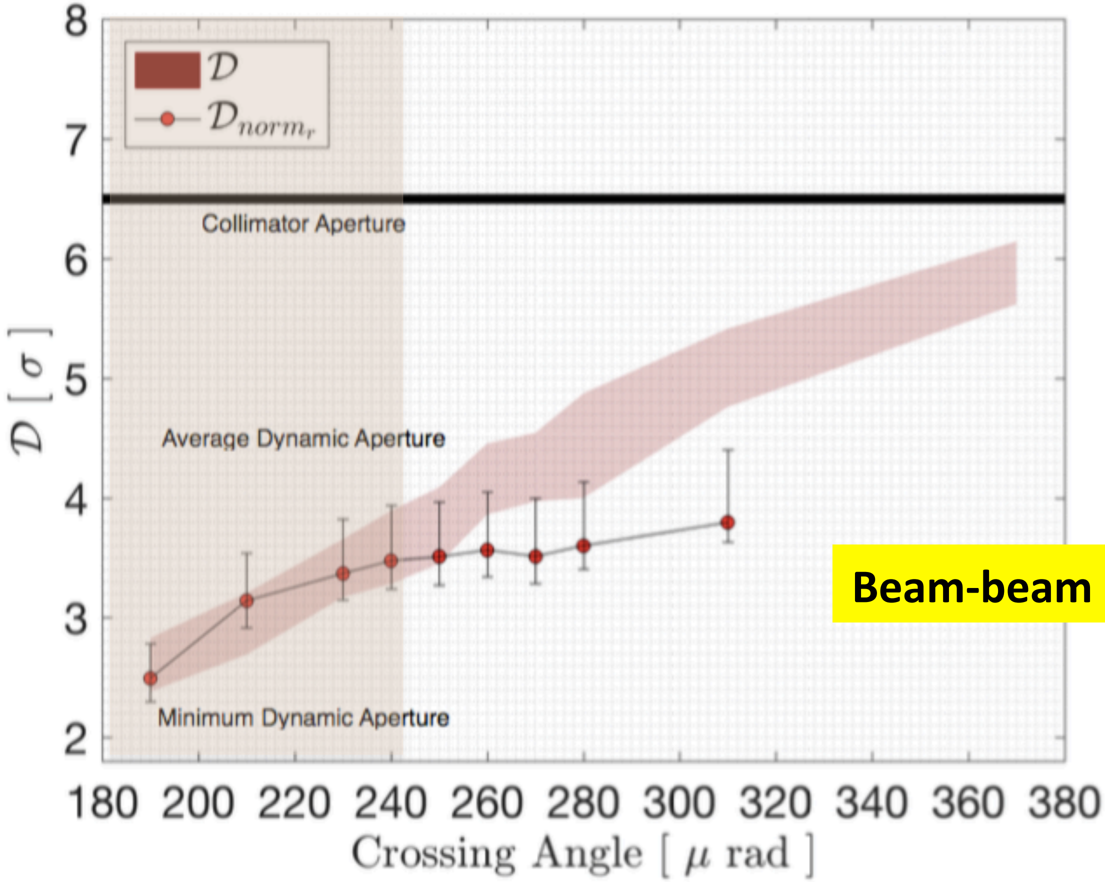
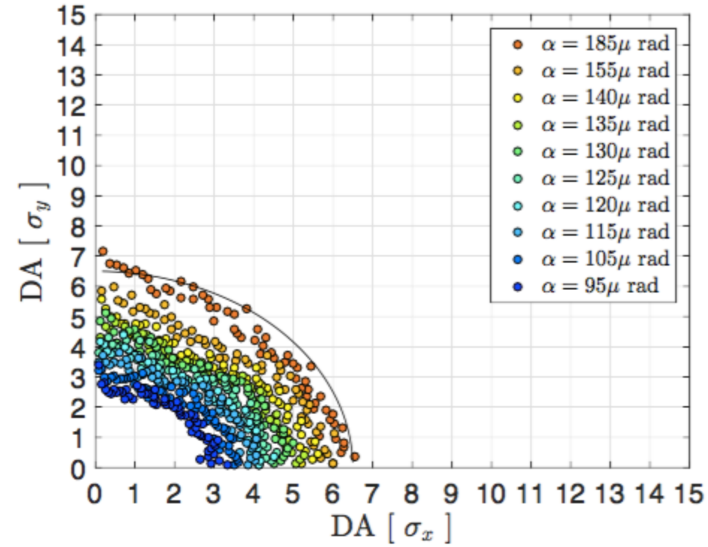
Long-range beam-beam Effects





Beam-beam

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

Cannot describe alone the losses observed at larger angles → other effect dominates!

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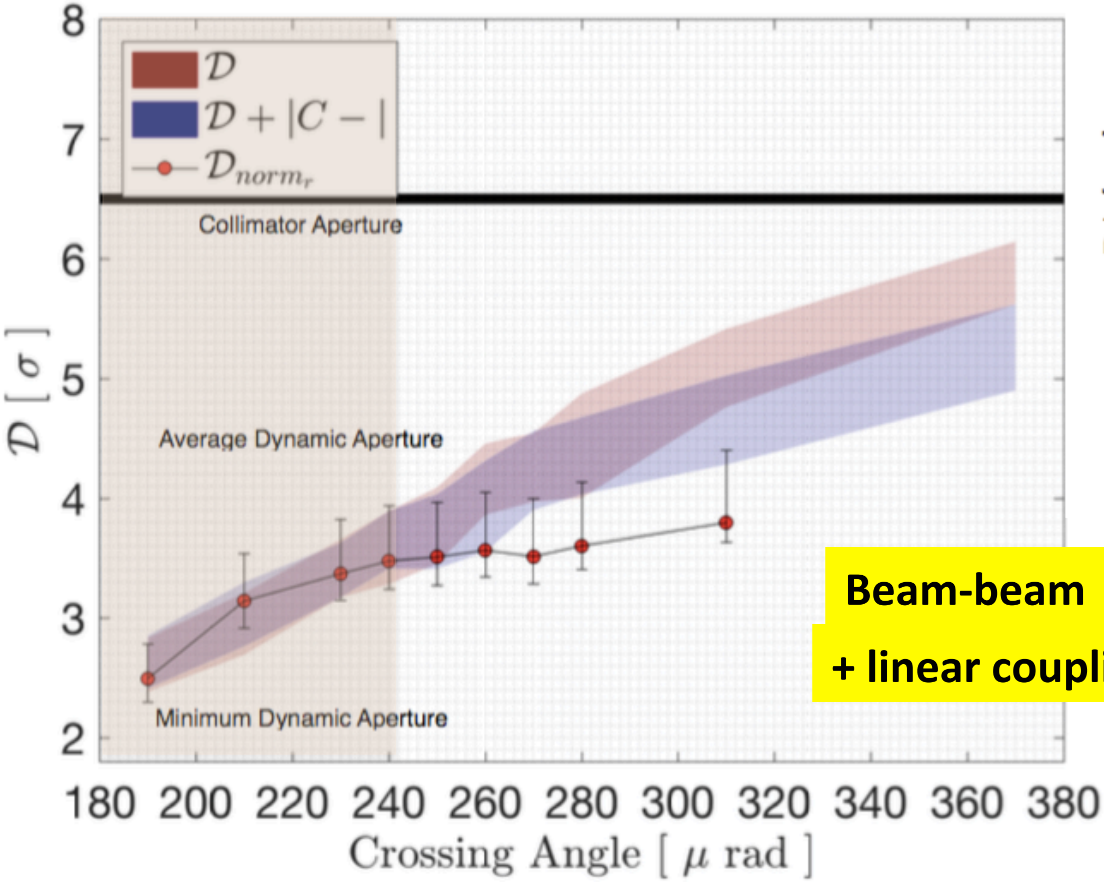
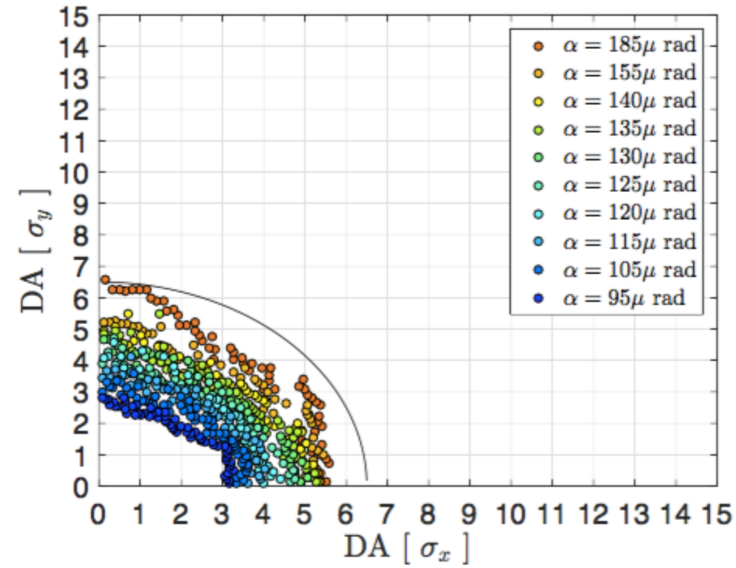
Long-range beam-beam losses





Beam-beam

+ linear coupling resonance

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

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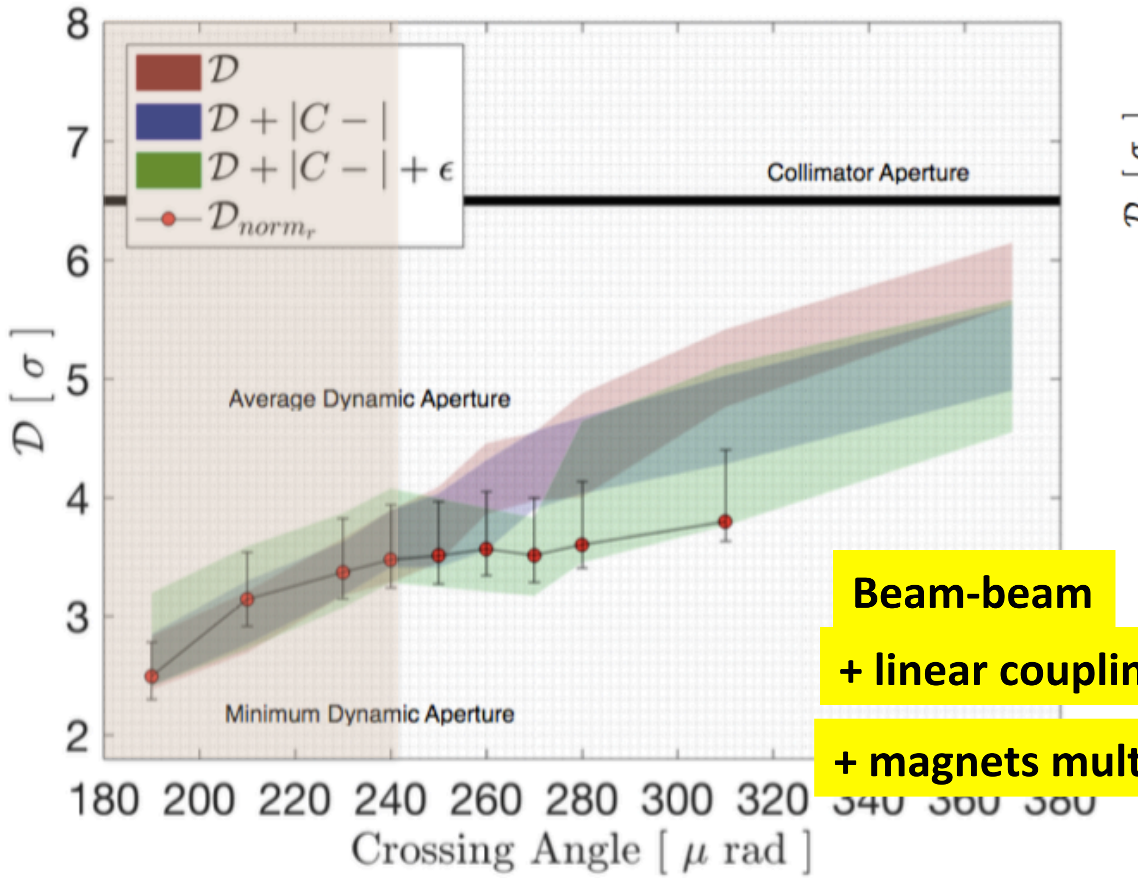
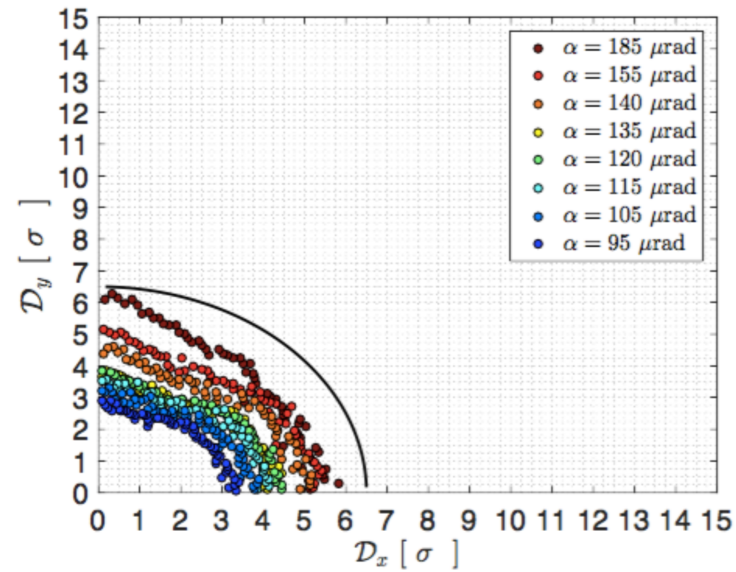
Long-range beam-beam losses





@IPAC 2017 THPAB056
Manchester Thesis 2017 M. Crouch

Beam-beam

+ linear coupling resonance

+ magnets multipolar errors

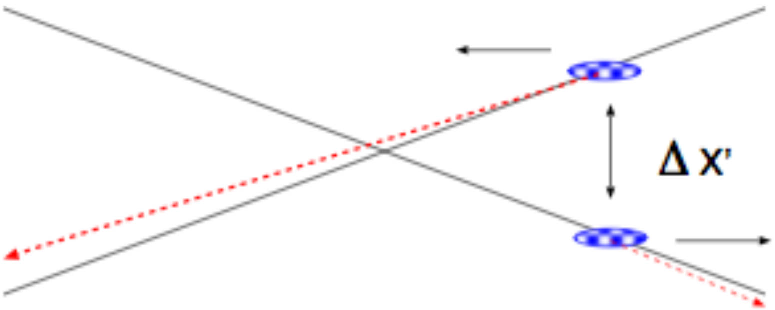
Multipolar Errors have a non negligible impact at larger angles where long-range beam-beam are weaker →can represent the losses observed in the LHC.

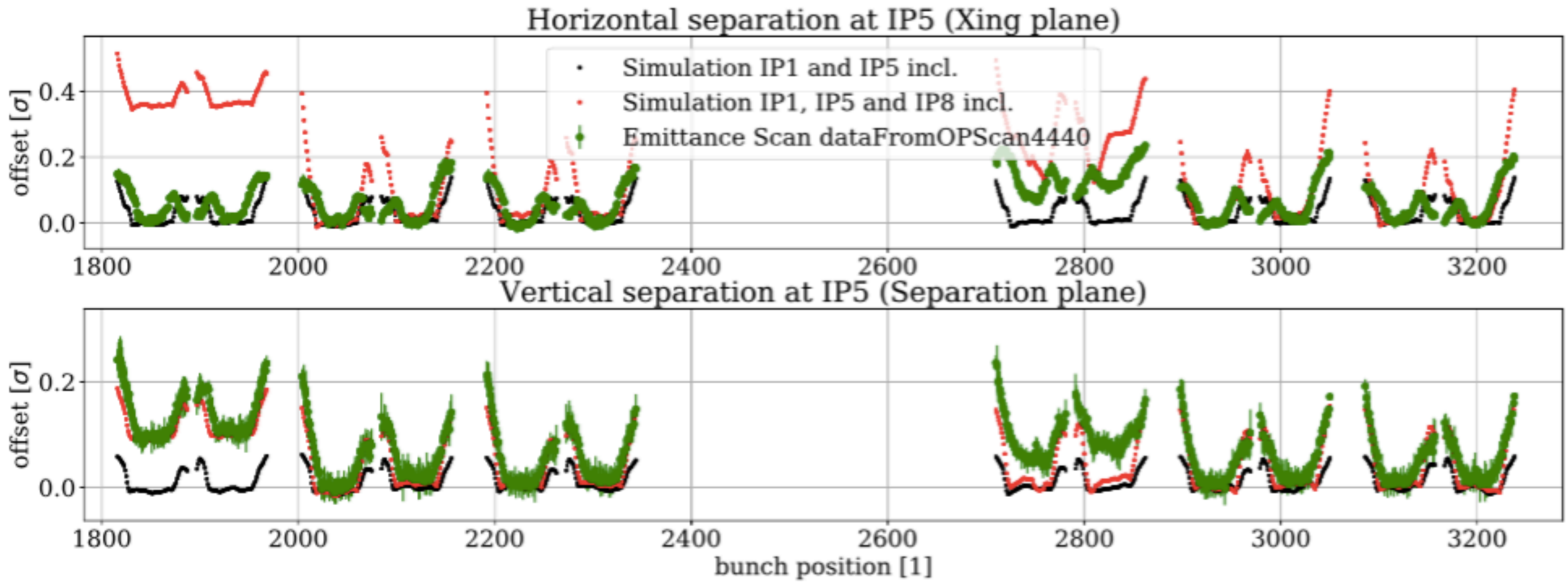
Magnets errors fundamental if we want to reproduce realistic losses!

Orbit Effects

The long-range BB force has an amplitude independent contribution:
ORBIT KICK

$$\Delta x' = \frac{const}{d}[1 - \frac{x}{d} + O(\frac{x^2}{d^2}) + \dots]$$





A. Gorzawski et al. @IPAC2017 THPAB042

Need to keep small these effects: TRAIN code adapted to FCC collision schemes

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Head-on Limit: Losses and Emittance growth

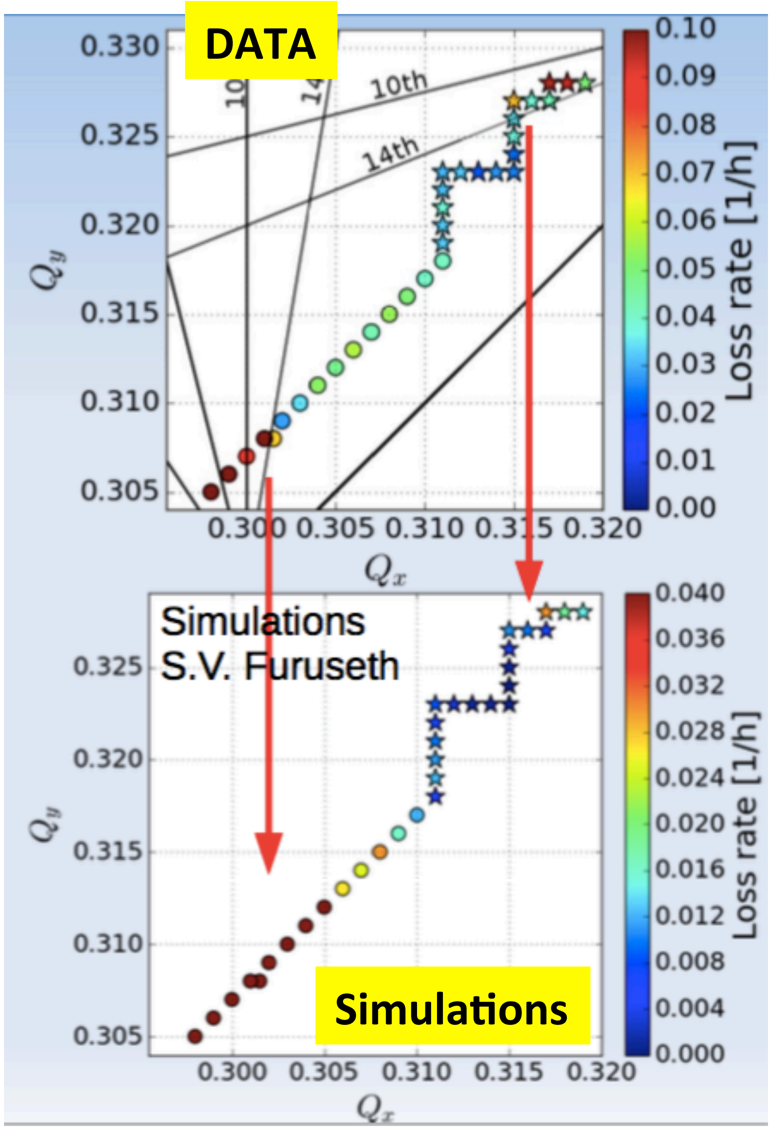
Head-on beam-beam can result in losses and emittance growth.
FCC pushed 0.03 total and two experiments to add.
From LHC experience head-on alone can explain losses in the presence of multipolar errors from magnets!

Model developed for FCC-hh of loss rates with 6D beam-beam (weak-strong a la Lifetrac) and simplified lattice!

First comparisons to LHC losses data during dedicated experiment

- BB parameter of 0.02 (FCC Ultimate is 0.03)
- GPU accelerated 6D simulations compared to measured losses in the LHC.
- Clear impact of Piwinski angle to loss mechanism
- Good qualitative agreements
- Work on going on quantitative estimates (**magnets errors**)

@IPAC2017 TUPVA026, TUPVA029



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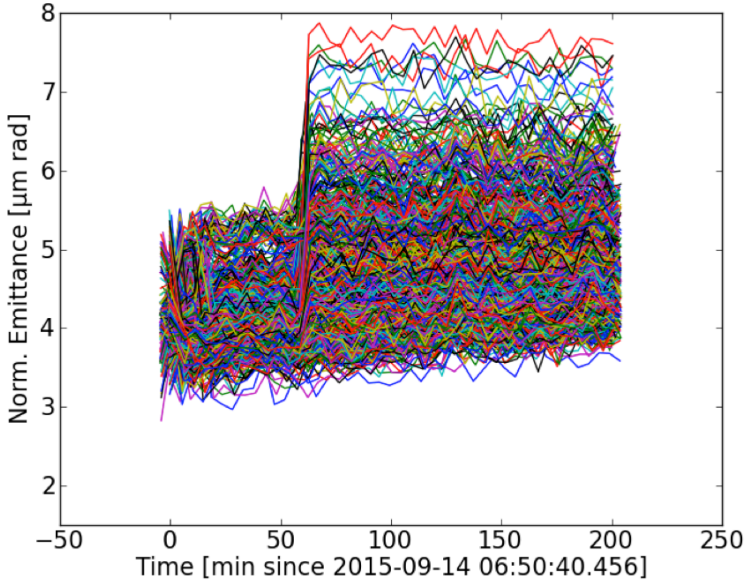
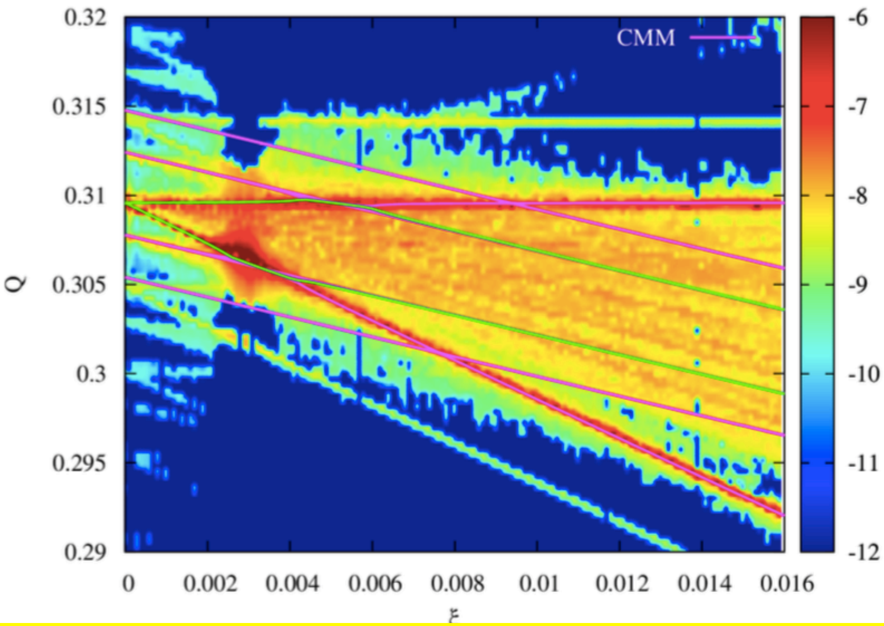
Coherent Instabilities

Coherent Instabilities not yet fully understood have been identified and impact the performances of the LHC from 2012 till today

E. Metral et al.
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 2, APRIL 2016

Several studies have been performed to model such effects and understand why they occur and which effects are behind these observations which can limit the beam brightness specially for a FCC





S. White et al., *Phys. Rev. Spec. Top. Accel. Beams 17, 041002 (2014).*

This represents a major concern
More studies in C. Tambasco talk tomorrow.

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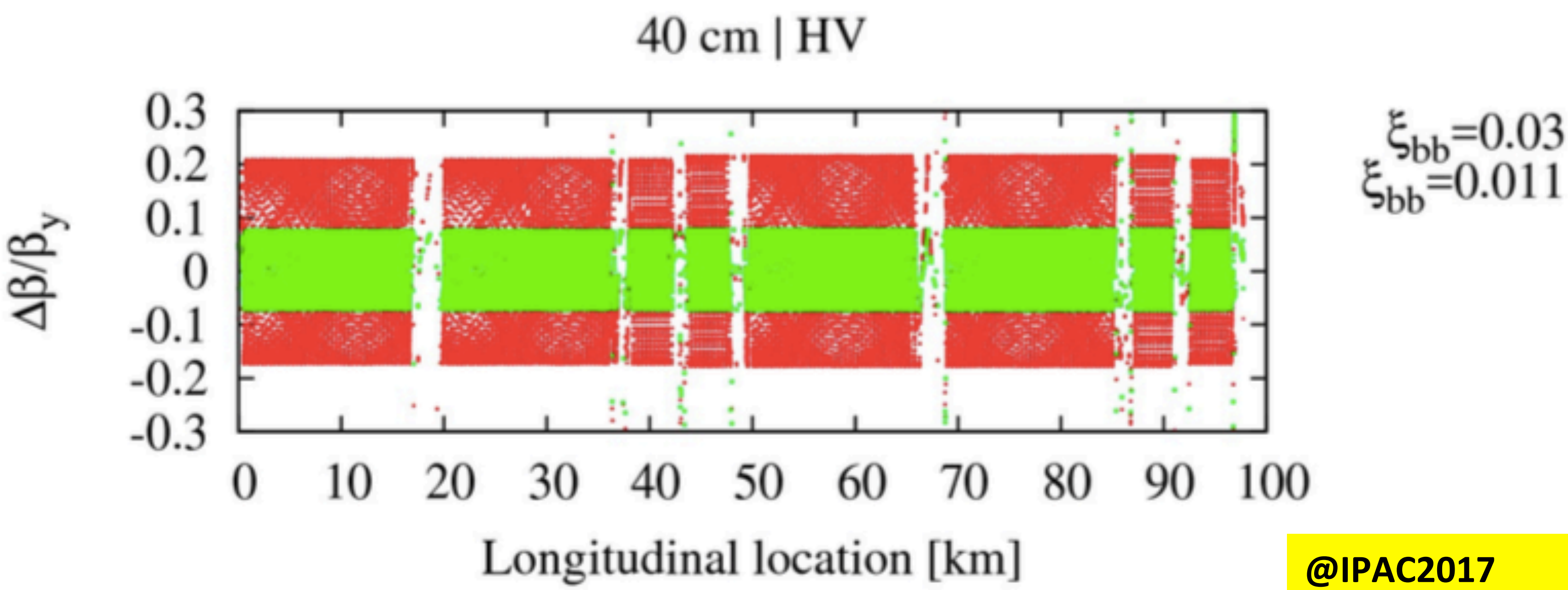
Head-on Beam-beam β-beating

Head-on interaction at two IPs will result in a very important beating of roughly 30%



@IPAC2017
WEOAB2, TUPVA030
Eurocircle Week Oct

FCC-hh: ξ_{bb}= up to 0.03 + 2 low lumi experiments → 0.05

- Impact on collimation system, is it important?
- Impact on performances → luminosity unbalance → will tune to profit from this
- Propose a correction scheme and explore compensation techniques.

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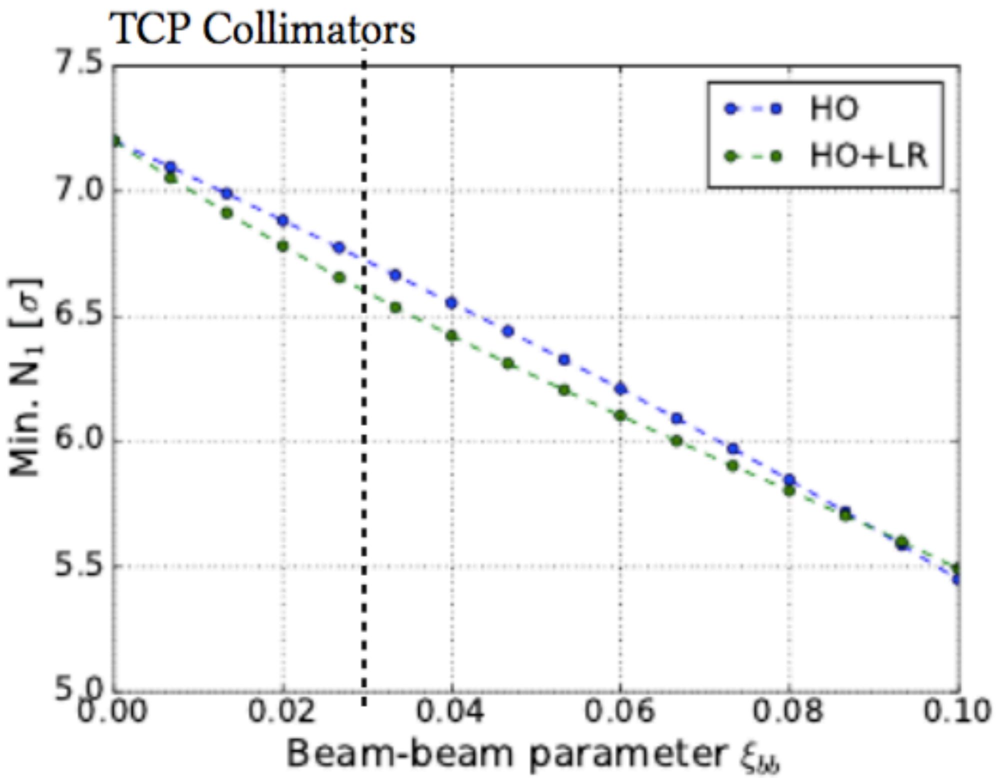

P. Goncalves EPFL Master thesis
Eurocircle Meeting
Oct2017

- Beam-beam beta-beating needs to be reduced!
  - Impact on luminosity
  - Impact on mechanical aperture (→ impact on impedance etc…)

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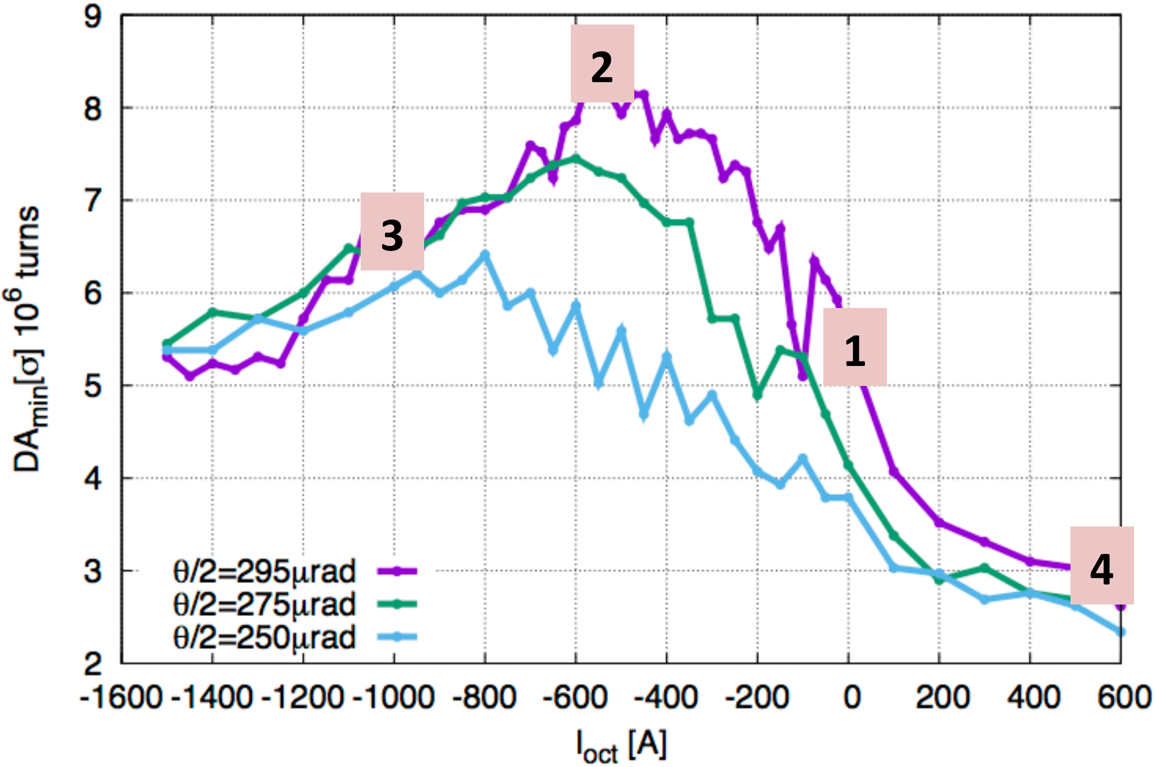
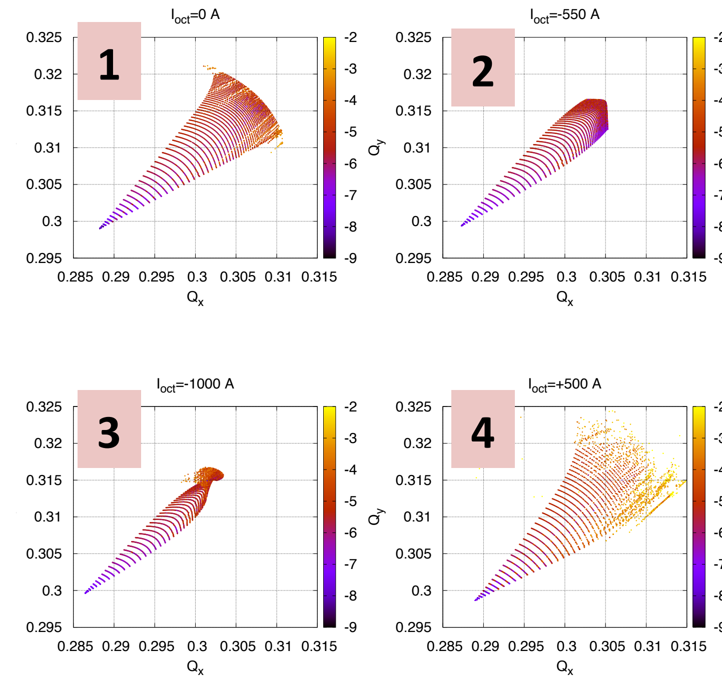
Global compensation with octupole magnets

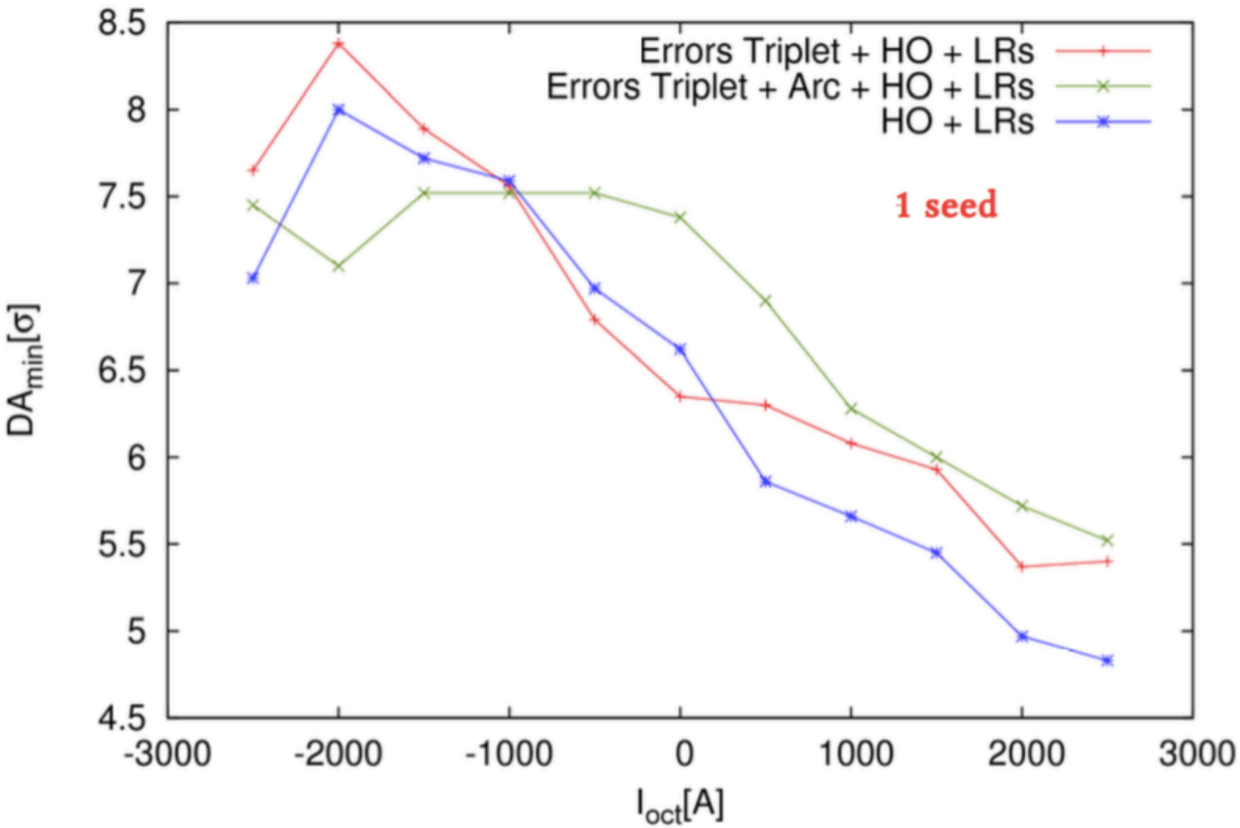




HL-LHC study case
CERN-ACC-NOTE-2017-0035

- 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 with some tunability of the lattice measurements**

Global compensation with octupole magnets



Eurocircle Meeting Oct2017

Octupole could have positive effect on dynamic aperture → should invest at early stage to define lattice properties such that we could use them if needed!

Errors seem to break the effectiveness of such compensation for FCC L*-45 m lattice

Close collaboration with Lattice team (B. Dalena and A. Chance) is fundamental!

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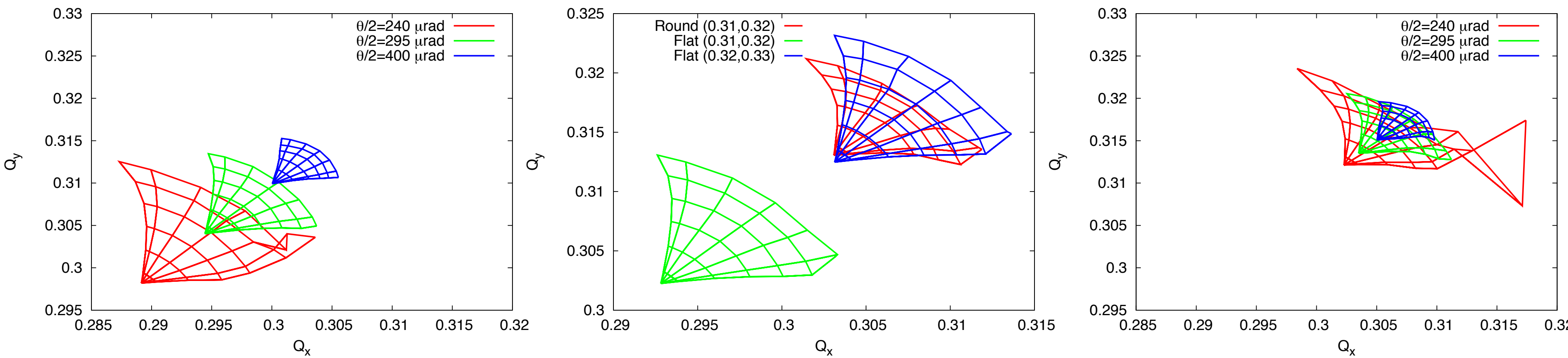
Alternative solutions: Flat optics versus round



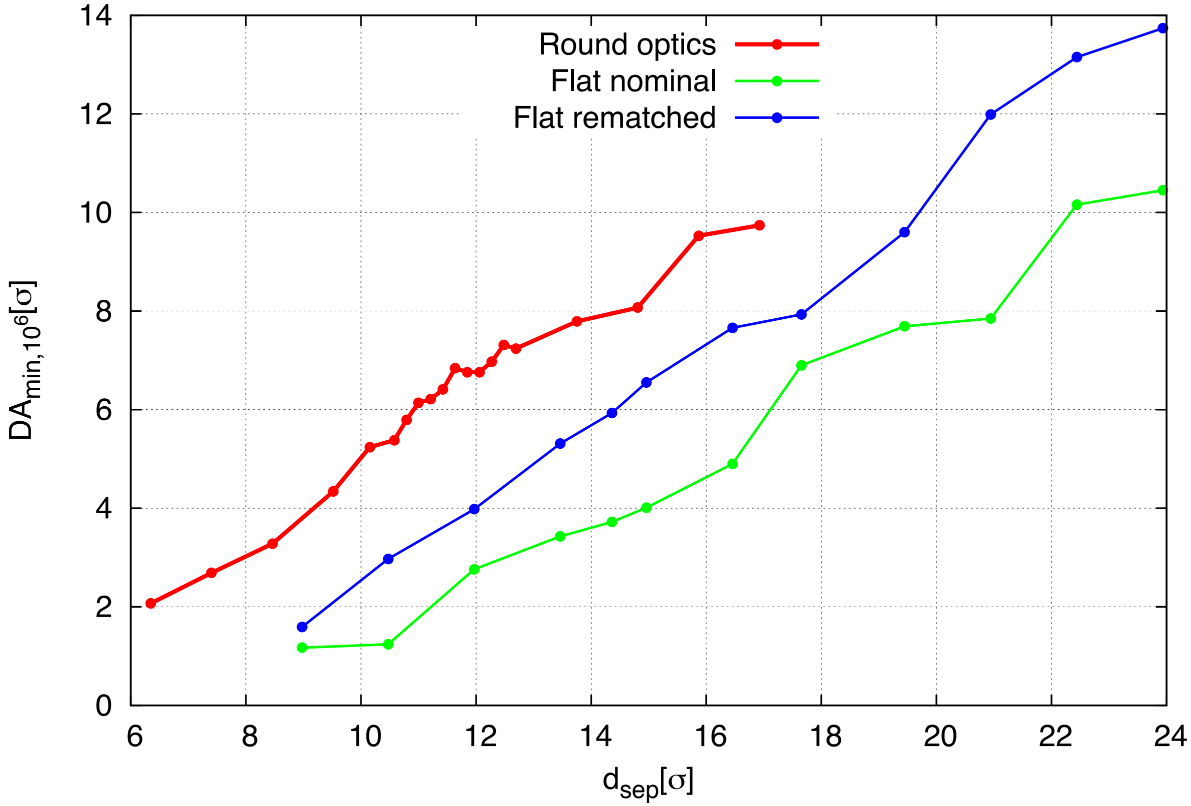
Flat optics is the natural back up solution in case crab cavities do not work, because for same normalized separation one has smaller geometric loss factor.

Beam-Beam long-range and head-on behave differently:

- Due to trains and braked passive compensation → tune shifts
- Head-on beam-beam creates larger detuning with amplitude

Flat optics introduces some unwanted effects

Flat versus round optics: beam-beam effects



HL-LHC study case 30/7.5 versus 15/15:

- Flat optics will need **43%** more separation respect to round
- Correcting for the tune shift reduces the needs but still need **26%** larger separations

- **Larger aspects ratios of betas make things worse!**

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Summary I

- **For the Ultimate round optics case we have a good scenario based on dynamic aperture simulations :**
  - Beam-beam separations have been defined keeping margins for all needed non-linearities (magnets errors), experiments (2 low lumi IPs introduced) and to allow for alternative scenarios (i.e. rotating collision plane)
  - **Benchmark to the LHC data show the limits of models and the possibility to use DA to estimate losses**

Extremely Demanding computationally factor 3-10 in computing steps (lattice, BB elements…)
- **LXBATCH → 41-12.5 days**
- **LHC@HOME → 3.15 days**

Need to upgrade to larger scale studies respect to LHC and HL-LHC

Summary II

- **Orbit effects have to be kept small → code extended and benchmarked to LHC data**
- **First models for predicting losses and emittance evolution are in place for FCC extrapolations with direct benchmark to LHC**
- **Coherent instabilities are an important concern → C. Tambasco talk**
- **Beta-beating due to large beam-beam parameter could excided the tollerances on beating defined by protection system**
  - Need for correction (correction scheme of linear part testing on LHC) or elenses.
- **Compensation techniques**
  - Global compensation using magnets (i.e. octupoles) will be explored and lattice designed accordingly.
  - The study of an electron lens to compensate for the large head-on beam-beam effect will also be covered for the CDR
- **Alternative scenarios are also studied to explore different options**

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Outlook

- **Stability studies**
  - Dynamic aperture effects of Landau spread (EPFL PHD Thesis C. Tambasco)
  - Octupole needs with beam-beam
  - RFQ impact

- Noise studies, need to define tolerances.

- Start a close **interaction with lattice team** to define lattice properties to improve/compensate beam-beam effects by introducing non-linear magnets (octupoles, sextules…)

- Deeper study of **head-on limitations and possible compensation (e-lens)** to be able to define possible intensity limitations

- 5 ns scenario to be evaluated

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Thank you!

Simulation Summary

Explore the parameter range:

- round optics (10,15,33,40 cm)
- flat optics (30cm/7.5cm, 40/10,40/20,40/30,40/40)
- 4D/6D BB lens
- X-angle scan from 190 —>790urad
- Normalized Emittance = 2.5 μm
- Initial amplitude from 0—>12σ
- Beam intensity from 0.9E11—>3.0E11 ppb
- 17 angle in xy plane (every 5 deg)
- w & w/o multipolar errors
- w & w/o Crab Crossing
- 2 Ips
- IP8 contribution
- single multipolar error family contribution
- HLLHCV1.0 and SLHCV3.1b optics

To be done:

- IP2 not in the picture yet but marginal effects (d_{sep} > 30σ)

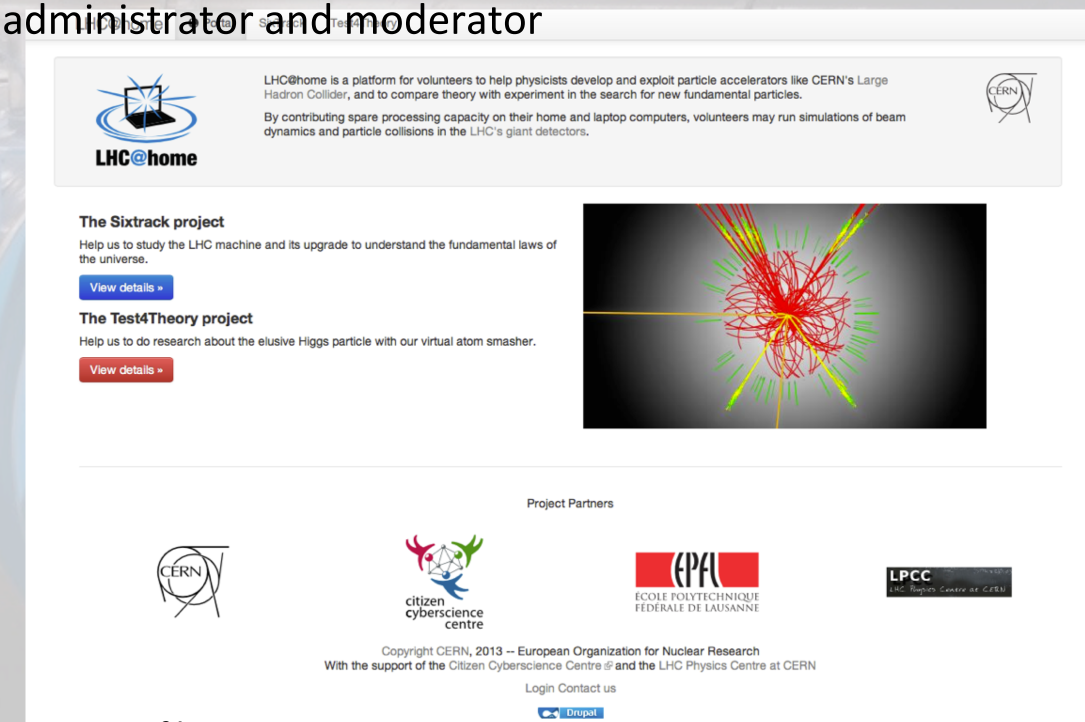
LHC@Home

Close to 10Mjobs to cover all possible cases!
It's impossible to run such number of jobs on CERN lsf: BOINC is the only way to go! **EPFL** is proud sponsor of the LHC@Home project on BOINC platform!

We are at present :

- Testing existing and developing new features
- Extensive use (more than 30M jobs up to now…)
- Forum administrator and moderator

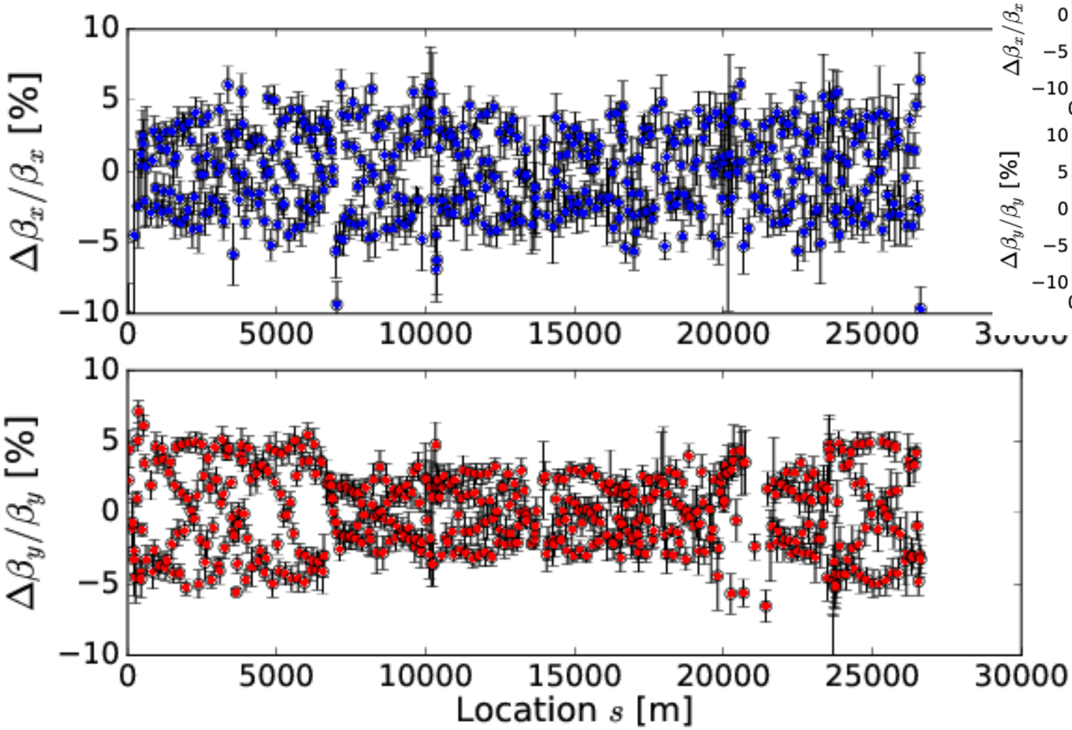
http://lhcathomeclassic.cern.ch/sixtrack/
http://lhcathome.web.cern.ch

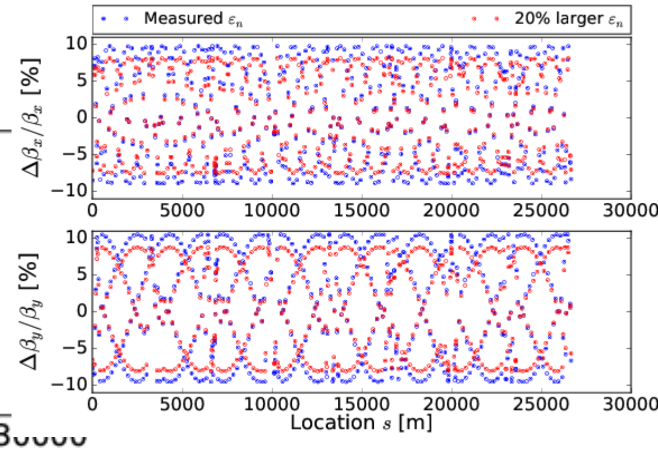


Thanks to LHC@Home Team for the support (E.McIntosh, R.Demaria, I.Zacharov, N. Hømyr et al.)
and to CERN-IT team.

Head-on Beam-beam β-beating

First measurements in LHC and tests





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Measurements consistent with expectation
First attempt to correct, results under evaluations

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