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Beam-Beam Studies for FCC-HH

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- FCC-hh beam-beam effects
- Baseline and Ultimate scenario
- LHC observations
- Low Luminosity Experiments
- Alternative solutions: flat versus round optics
- Compensation techniques
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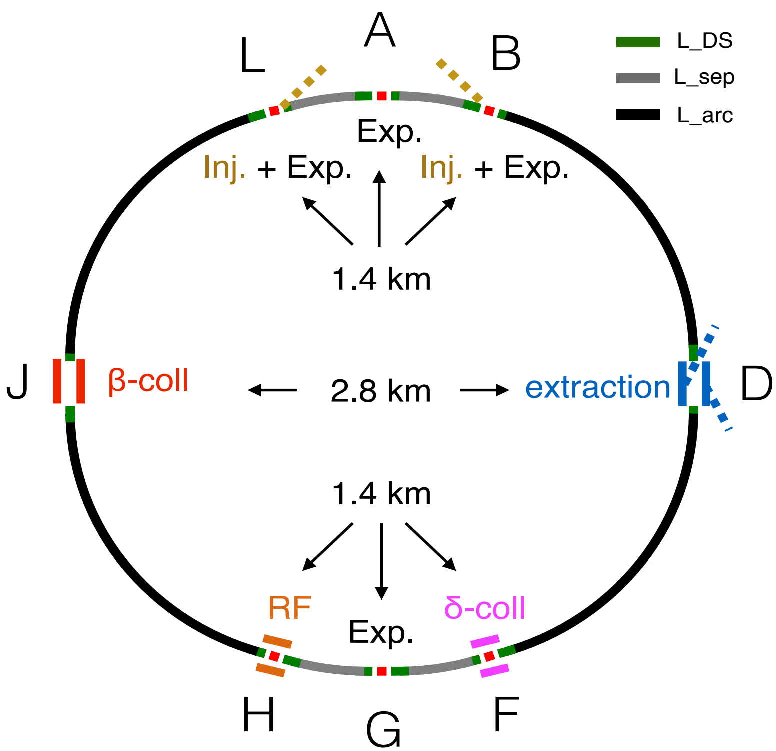
Collider parameters



	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

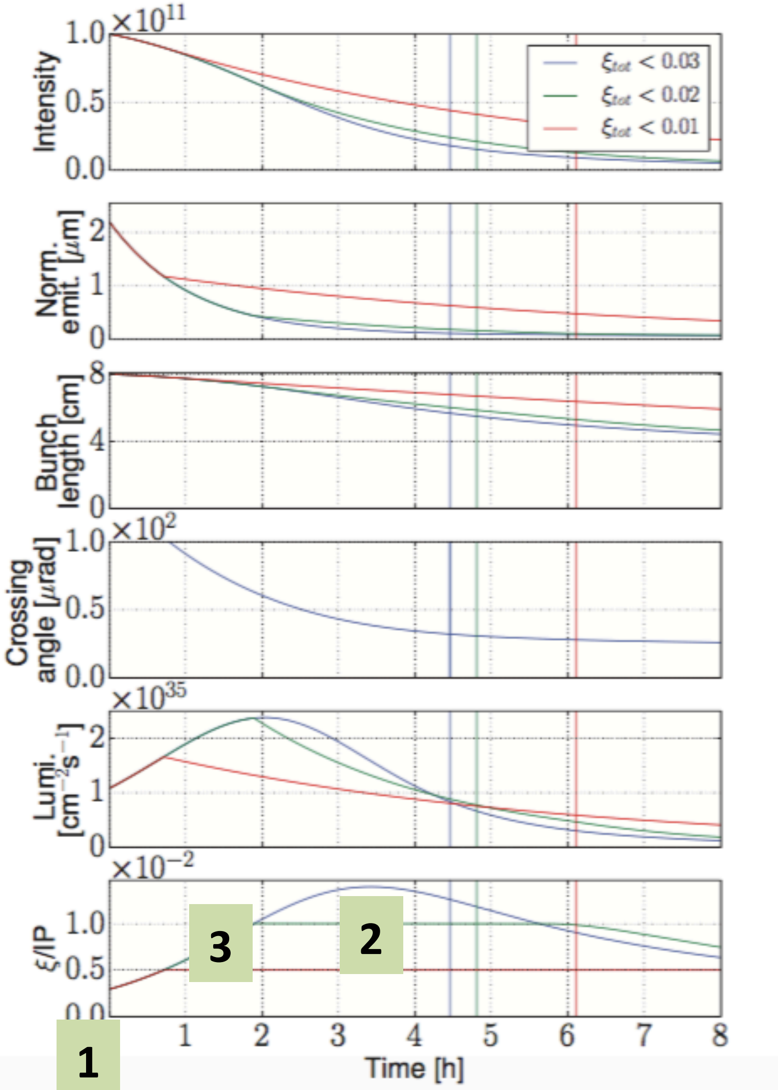
IPA and IPG main high luminosity experiments:

Goal → maximum luminosity with good lifetimes → maximum integrated luminosity

IPL and IPB low luminosity Ips:

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

Beam-Beam Effects



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

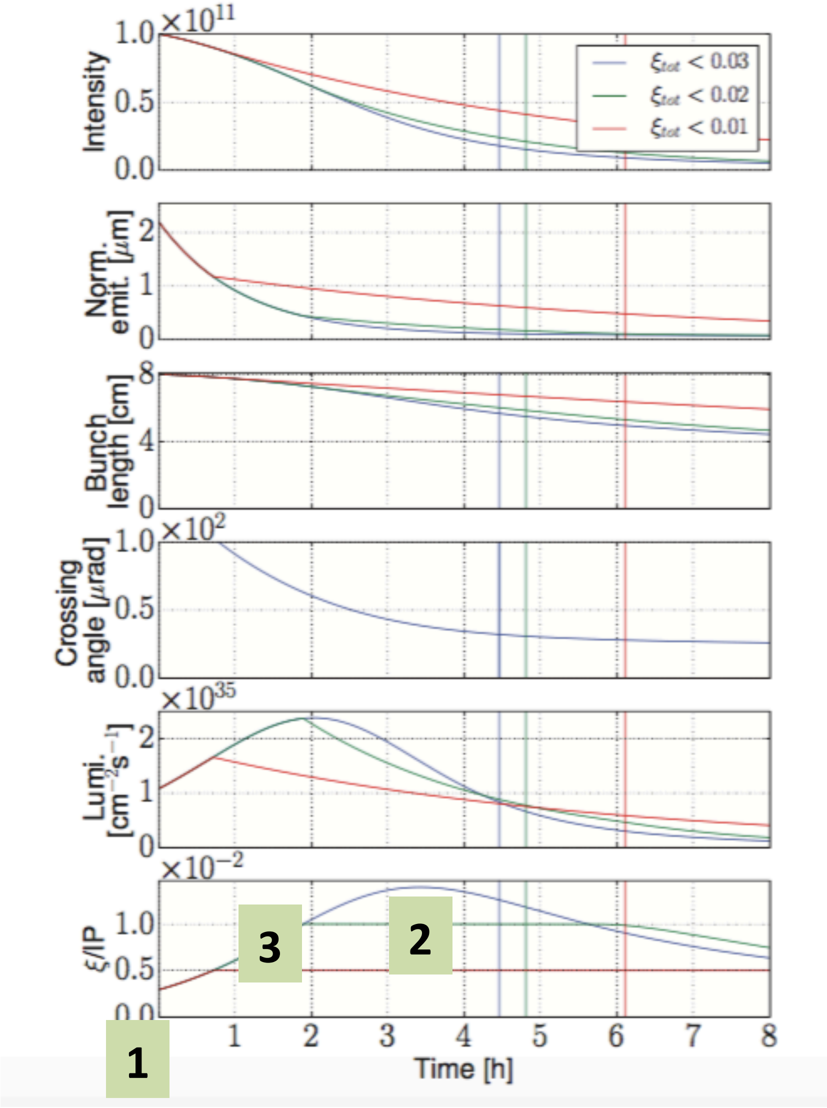
1. LHC/HL-LHC beam-beam dynamics ξ_{bb} = 0.06→0.01
   LHC experience and long-range effects

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

X. Buffat & D. Schulte

Beam-Beam Effects



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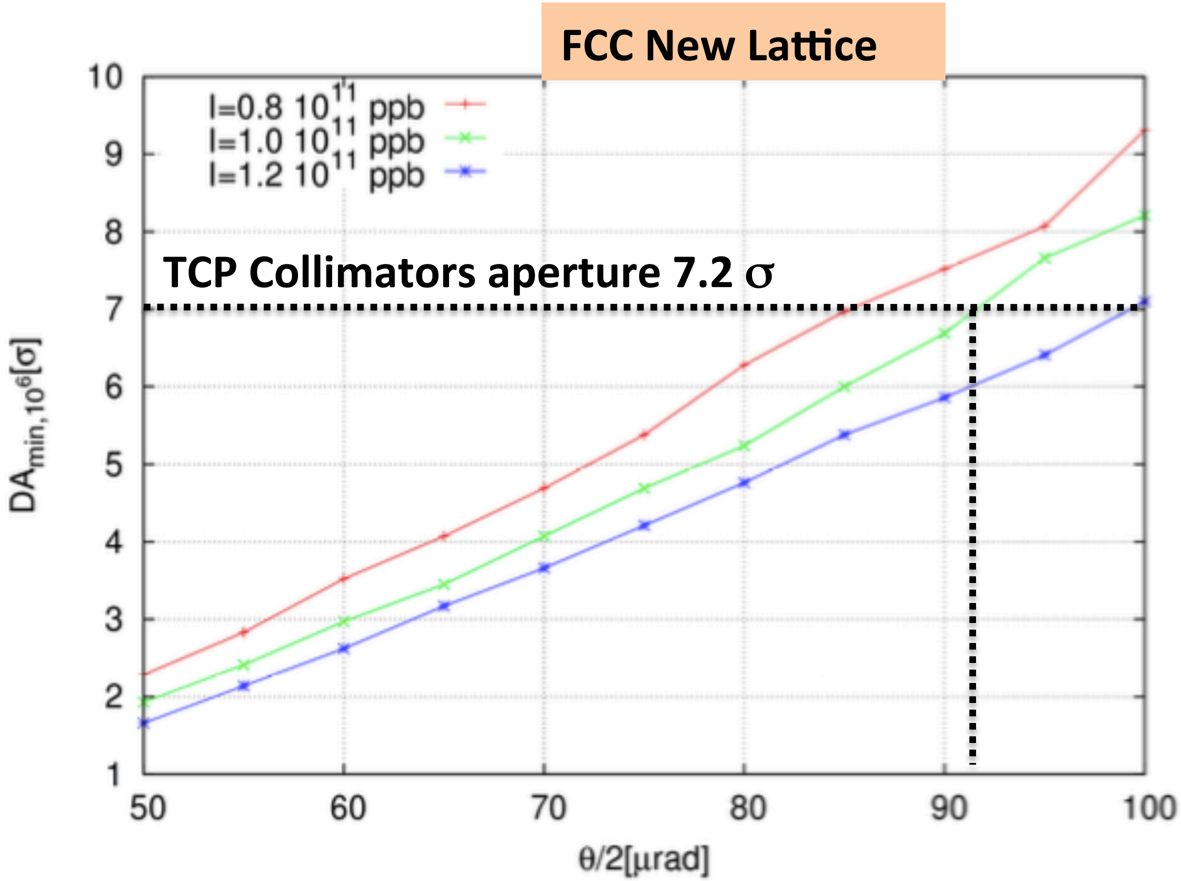
All cases with 25 ns bunch spacing

X. Buffat & D. Schulte

Ultimate case Round Optics: IPA and IPG



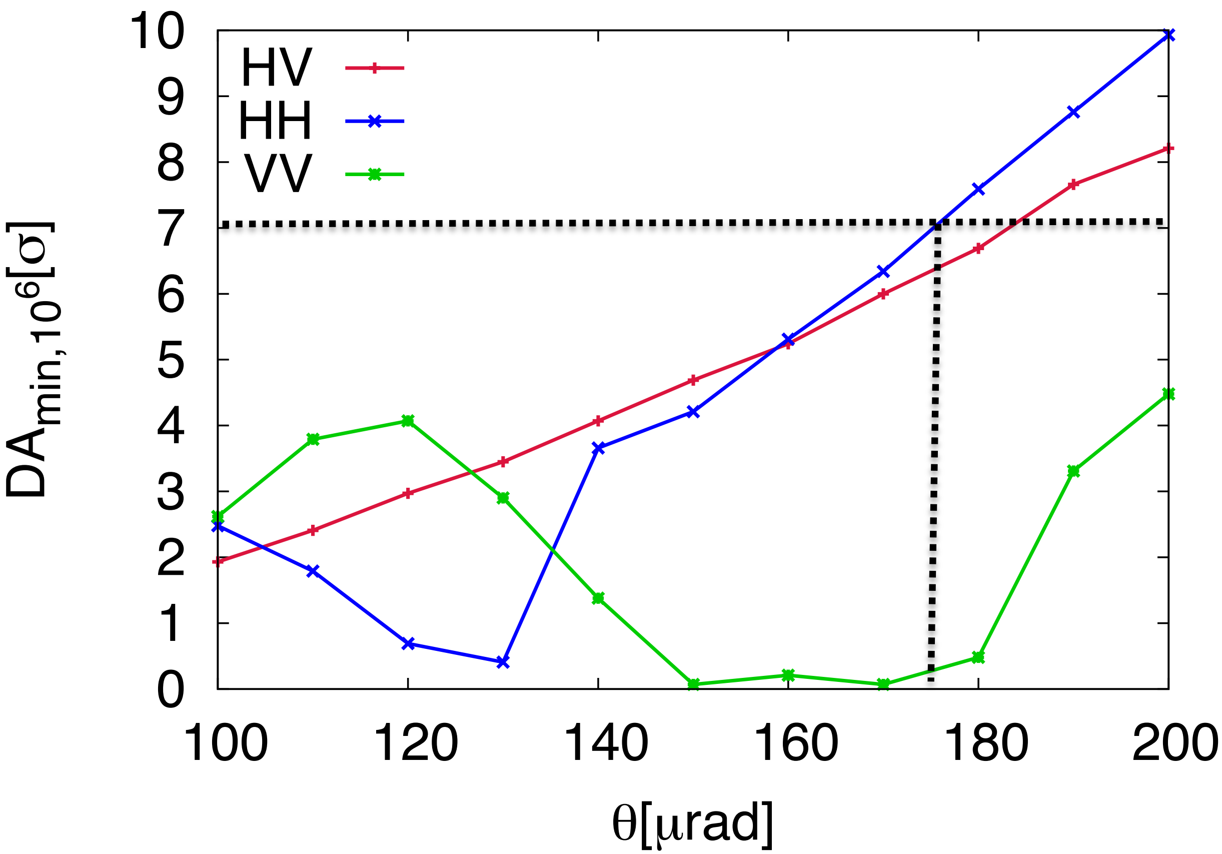
LHC criterion: Dynamic Aperture should be larger or equal than the mechanical aperture defined by the collimation system (TCPs): for LHC 6.0 σ

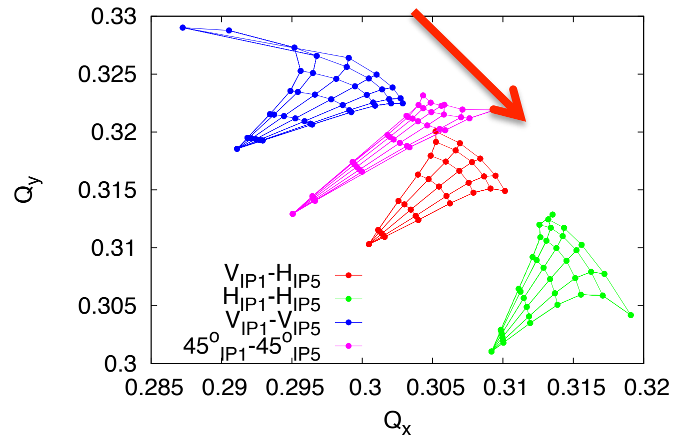
For FCC-hh case TCPs at 7.2 σ
M. Fiascari et al. @IPAC2016

$$DA \geq 7.2\ \sigma$$

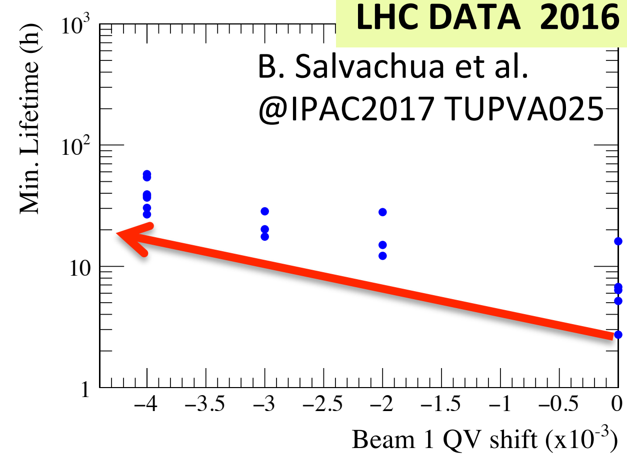
- **Crossing angle 180 μrad** needed only from beam-beam non linearities
- **Intensity fluctuations** → requires roughly 5-10 μrad for 10-20% fluctuations

Crossing Schemes: HV versus HH and VV



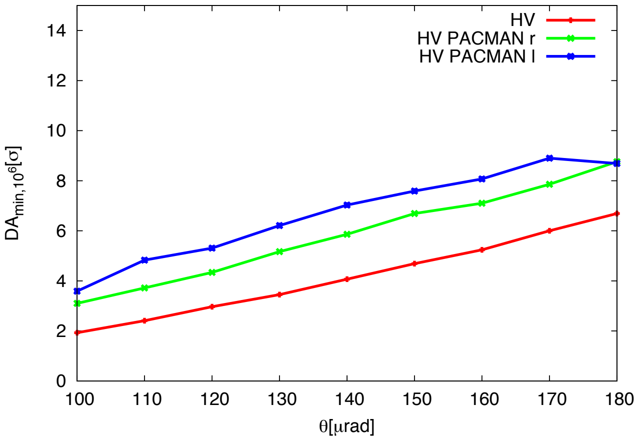


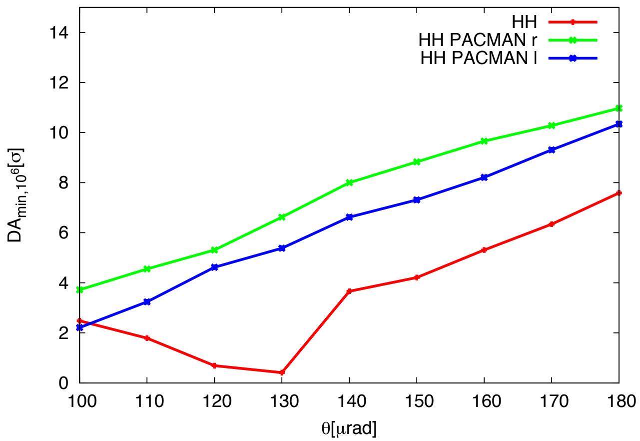
LHC DATA 2016

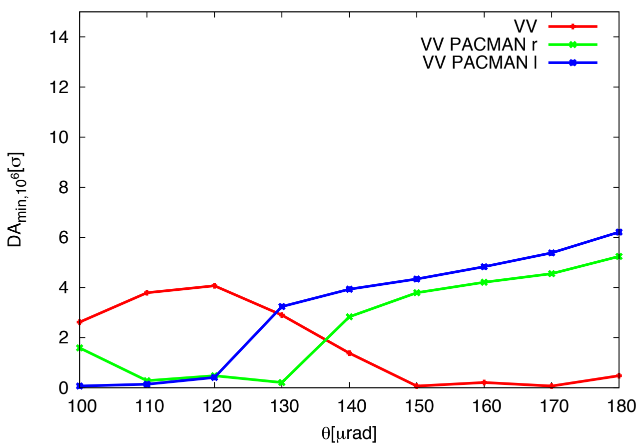


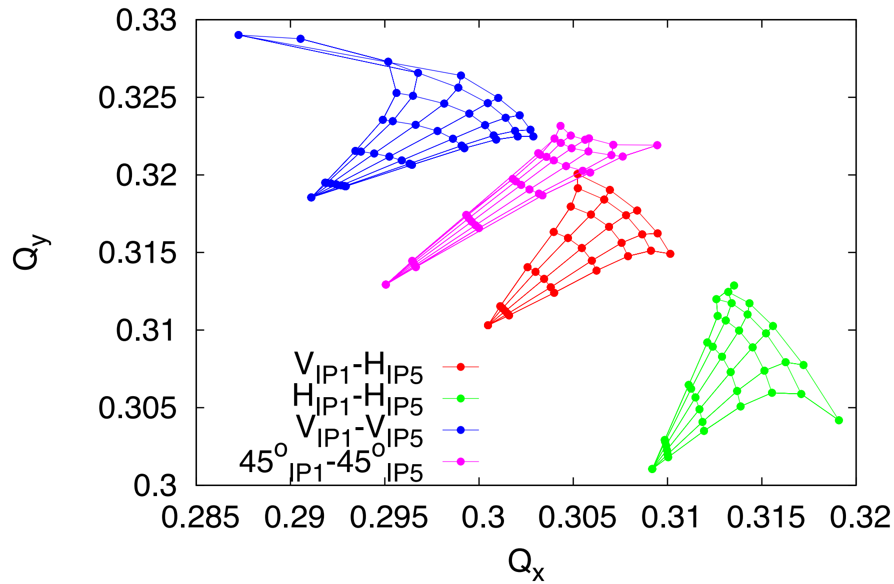
- HH Crossing is equivalent to HV in terms of DA for nominal buncnes
- VV not acceptable at the (0.31-0.32) working point due to strong impact of 3rd order resonance effect → Mirrored tune will solve the problem
- Moving on the mirrored tunes inverts the situation where then HH pushes particles on the 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
- **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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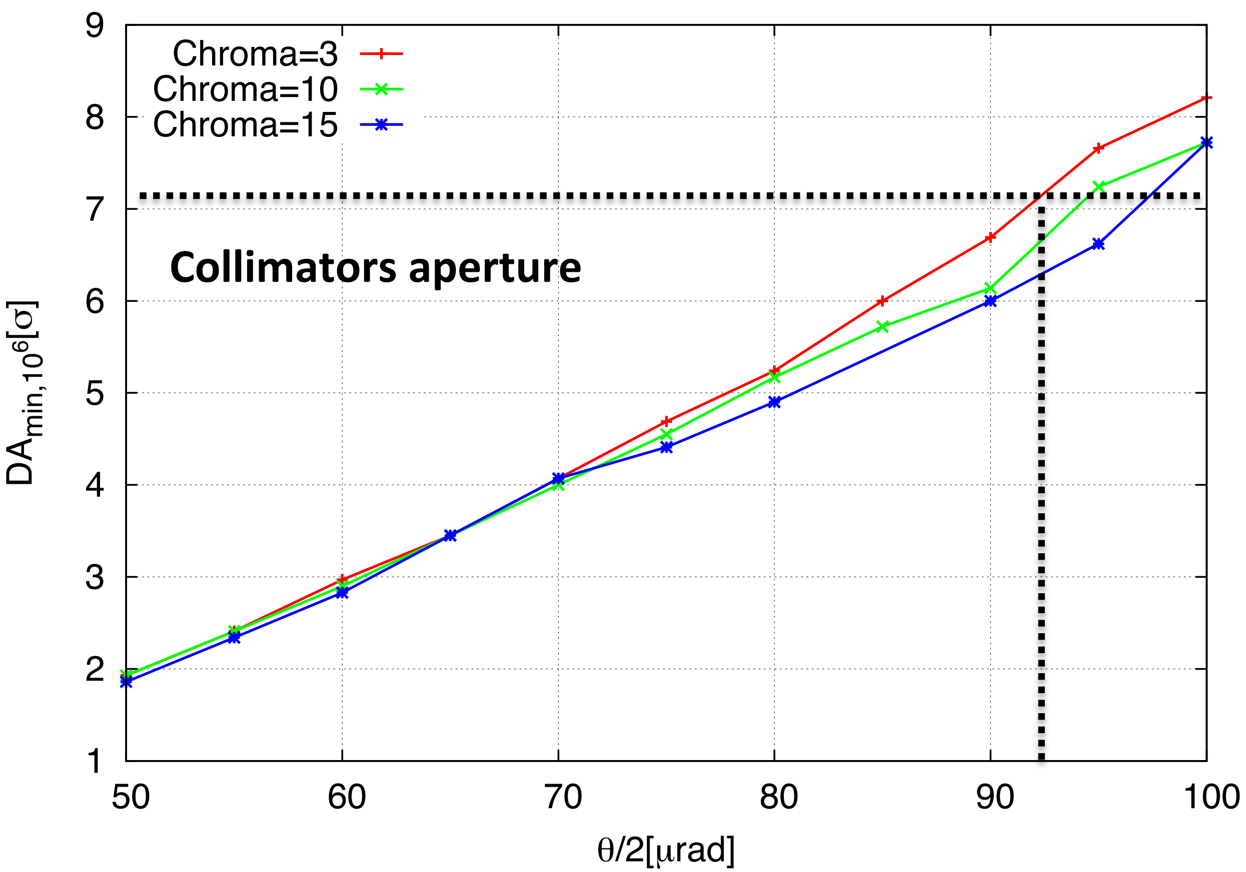
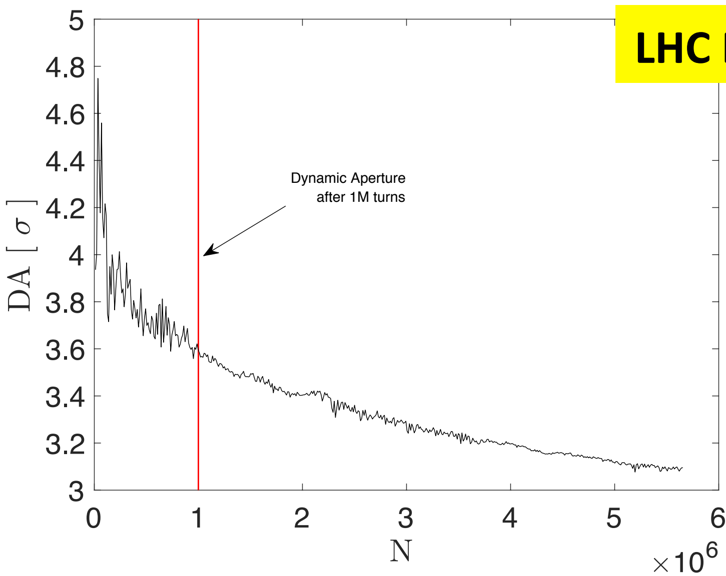
High Chromaticity: IPA and IPG



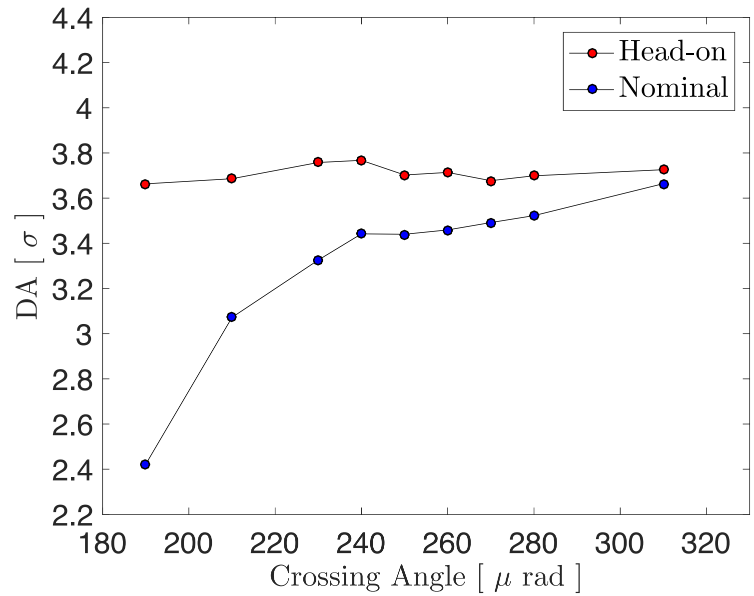
High Chromaticity operation will be needed for stability resons!
5-10 μrad for 15-20 units chromaticity

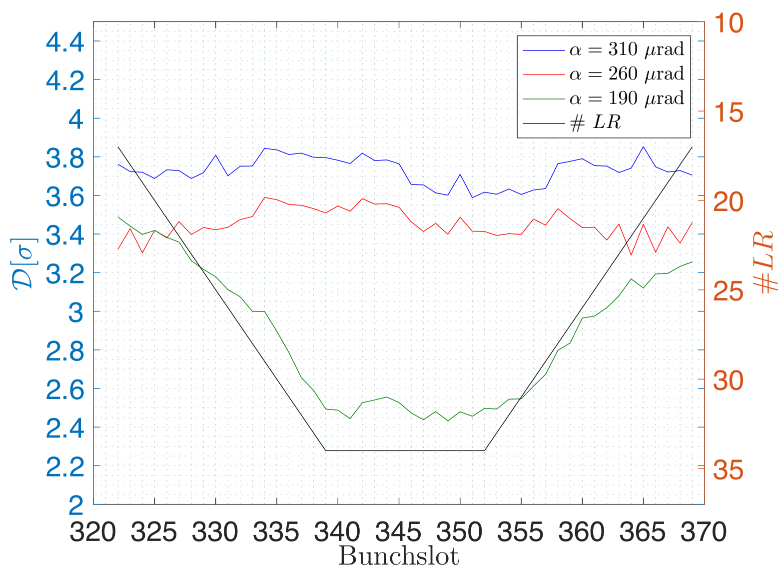
Will need to add margins to the crossing angles to allow for high chroma and higher spreads

What have we learned from LHC and DA?



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





Head-on colliding bunch and nominal have similar losses at larger angles

For separation below 8.3 σ long-range effects take over

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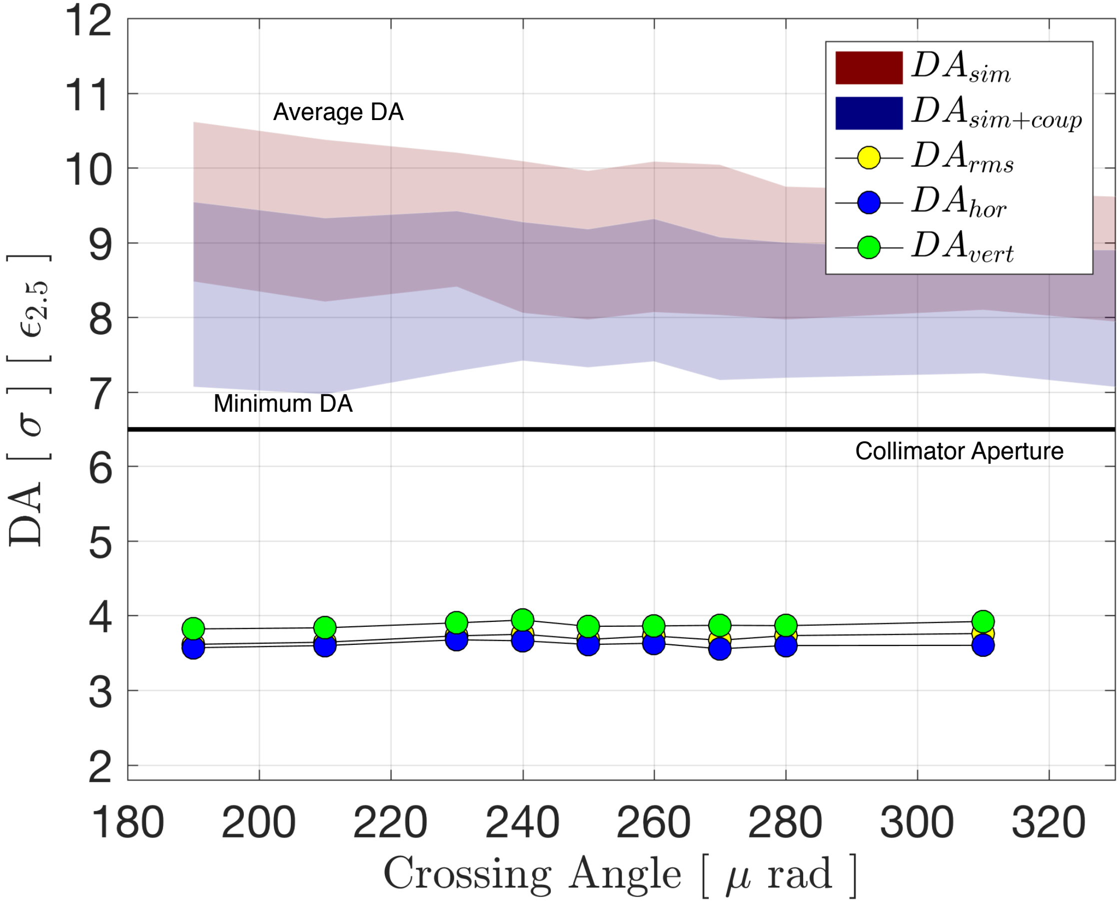
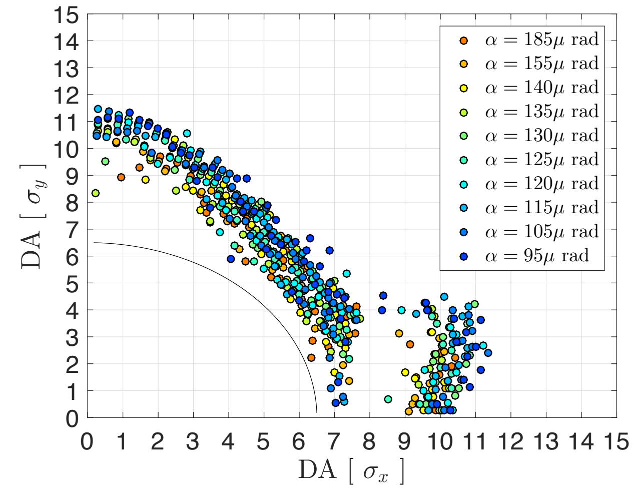
Head-on Beam-Beam losses





Head-on alone cannot justify the losses observed!

Losses are much larger than those expected by collimation cut

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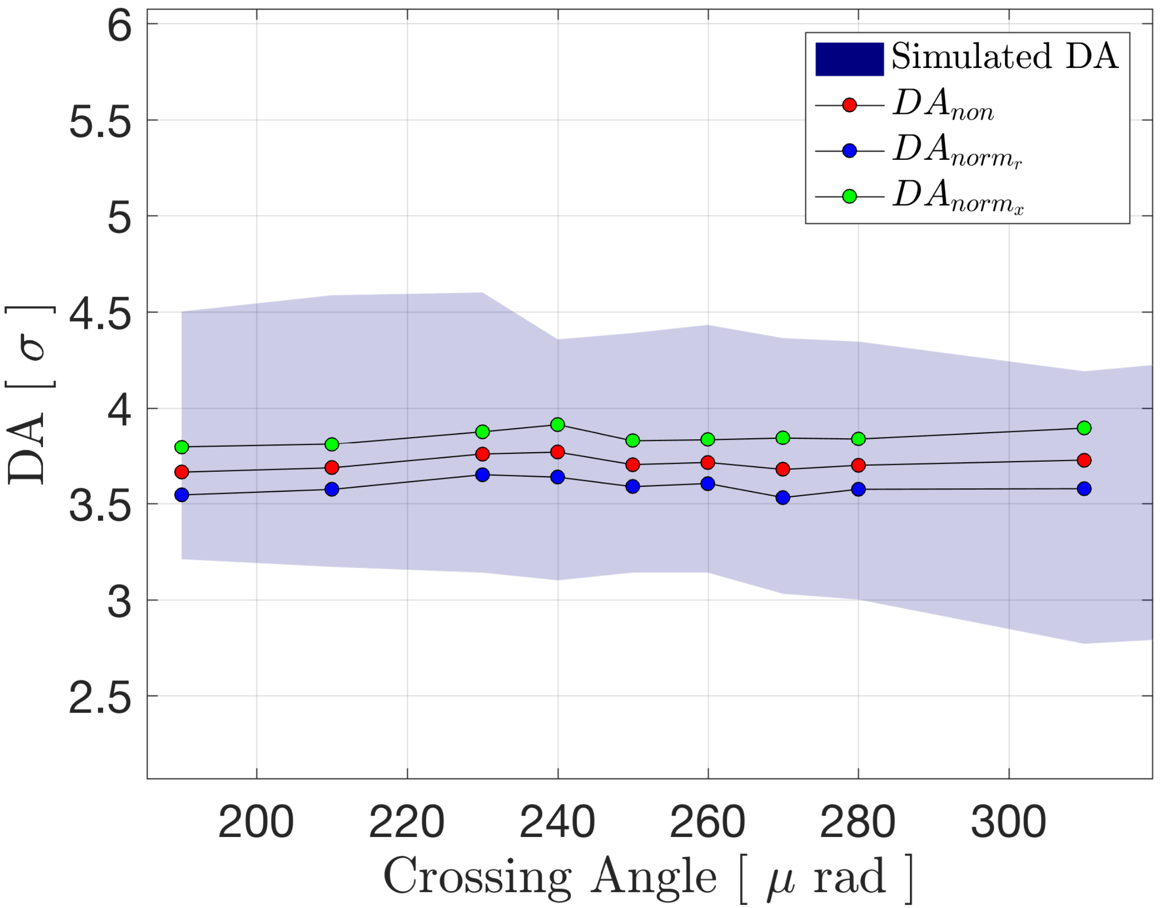
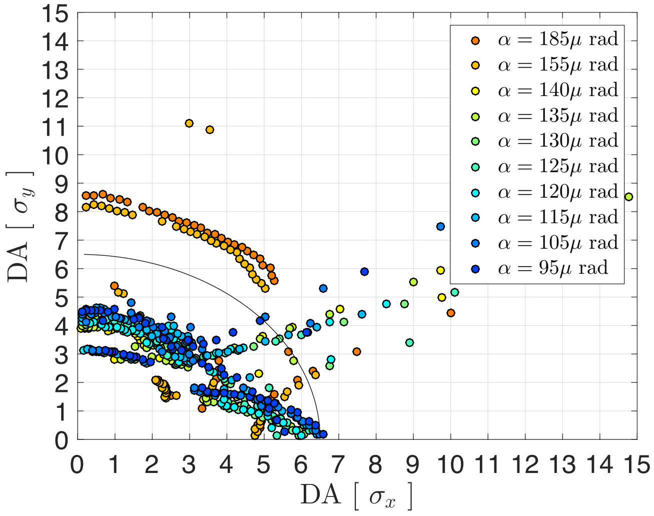
Head-on beam-beam and multipolar errors





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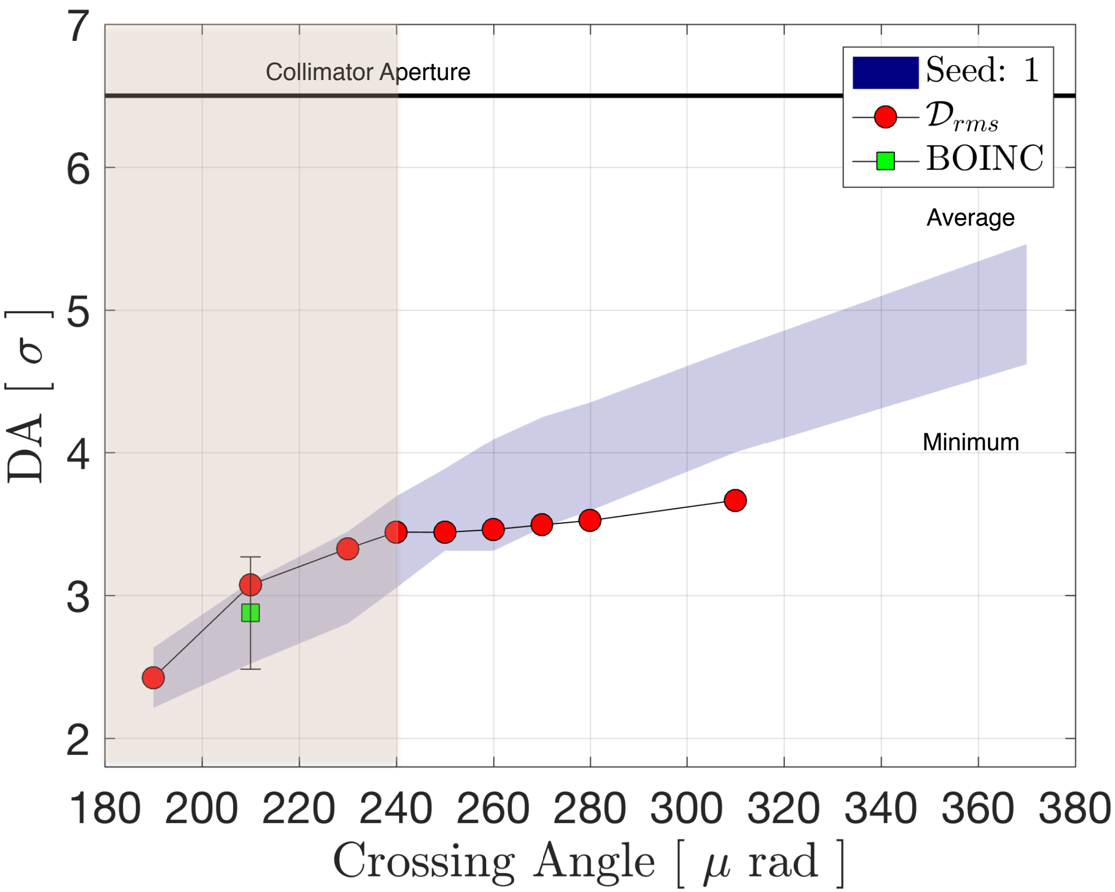
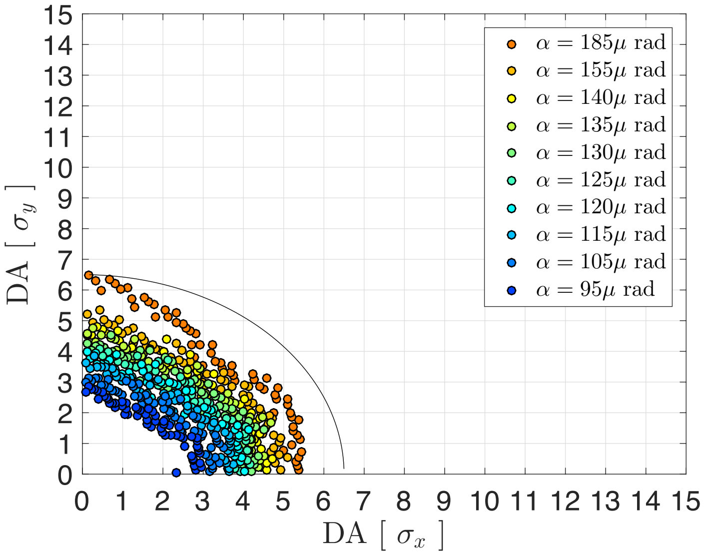
- **Head-on with magnets multipolar errors can justify the losses measured on colliding beams**
- Minima DA is conservative, average should be the the right figure of merit with standard deviation over seeds!
- Magnets Field quality is fundamental to control losses, tolerances should be defined with beam-beam effects → not what makes single beam DA better is good with beam-beam!

Long-range beam-beam losses





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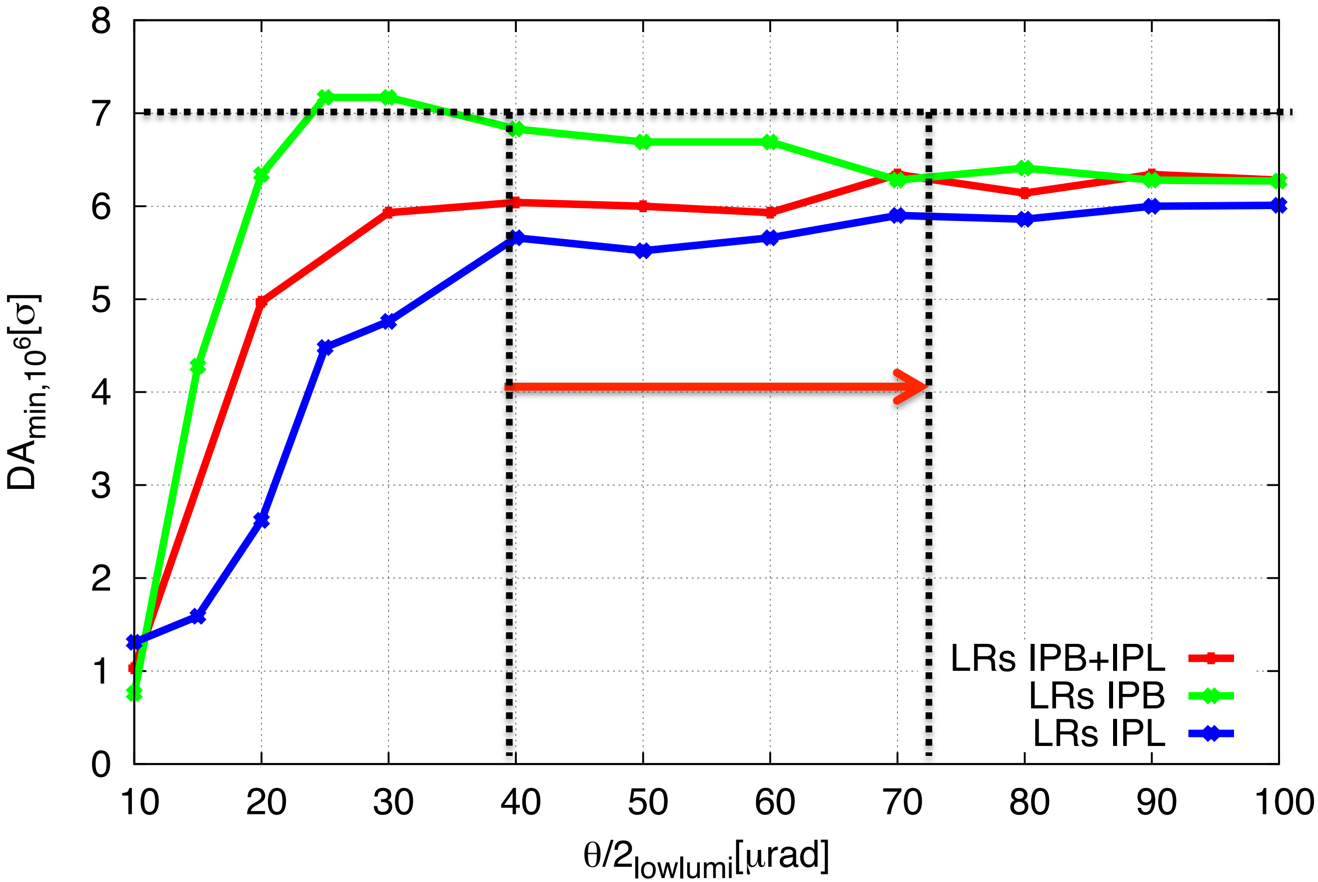
Long-range behave like scrapers (losses well defined by DA) no emittance blow-up

Dynamic Aperture well represents the losses

Work in progress (PhD Thesis Manchester University)

Low Luminosity Experiments: IPL and IPP



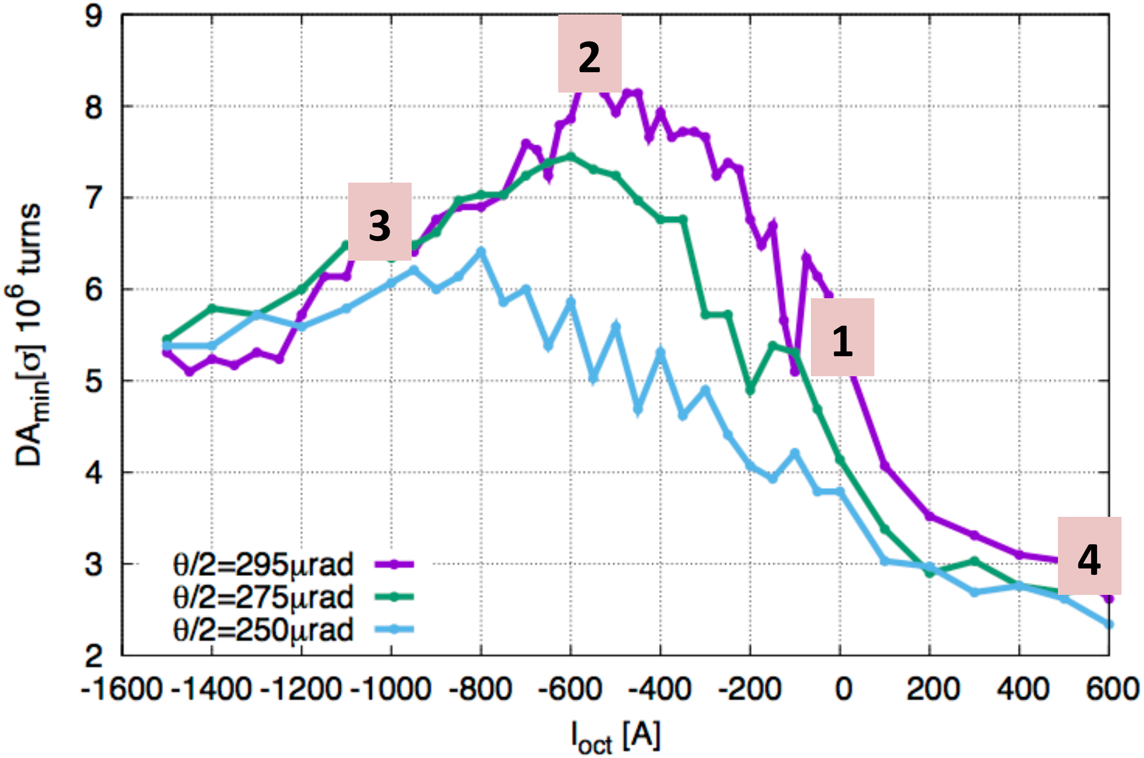
The long-range effects of IPL and B will impact bunches differently (**no passive compensation**)

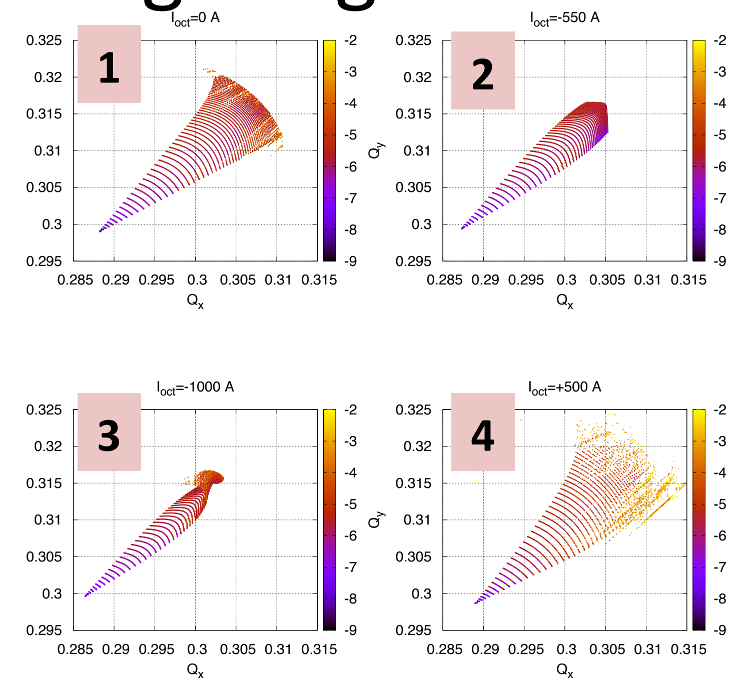
To have them not perturbing the high luminosity experiments should have **angles > 75 μrad**

Margins are available (M. Hofer) to go up to 90 μrad

- **Long-range:** to keep effects weak larger angles needed →larger than 75 μrad
- **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!

Compensation techniques: Octupoles magnets for Long-range

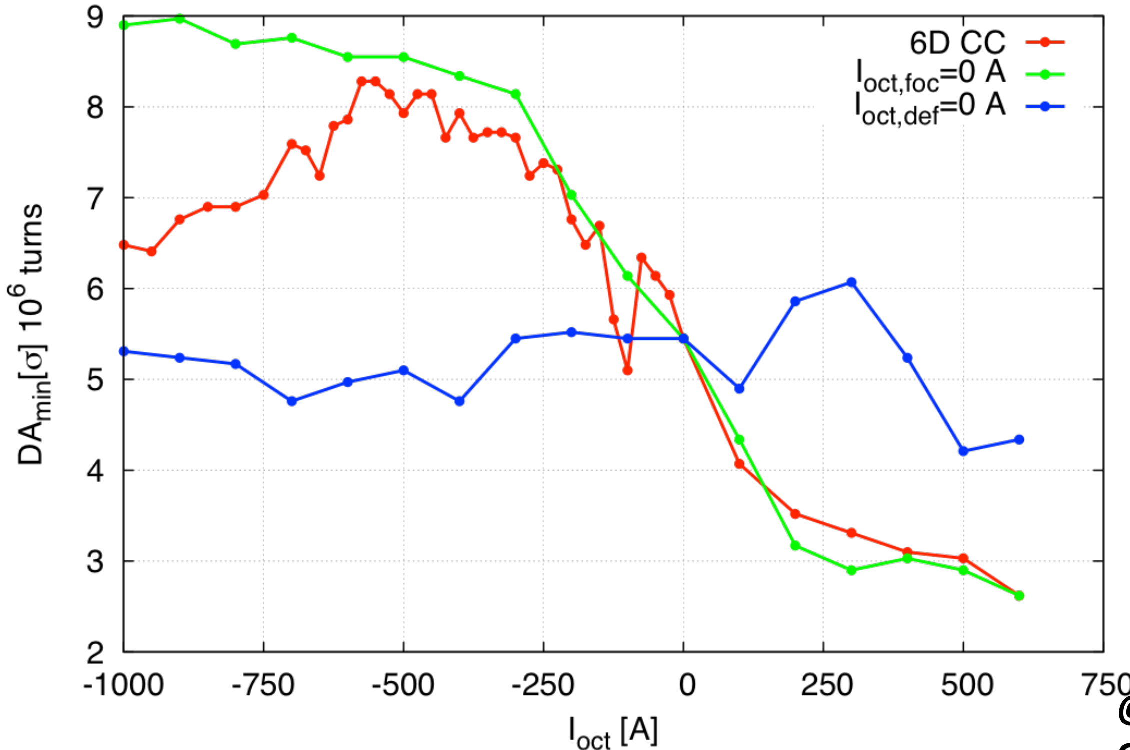




HL-LHC study case
CERN-ACC-NOTE-2017-0035

- 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

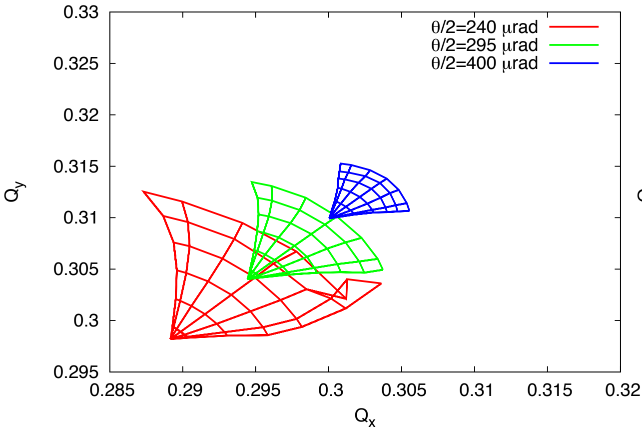
Octupoles studies: using HLLHC as study case

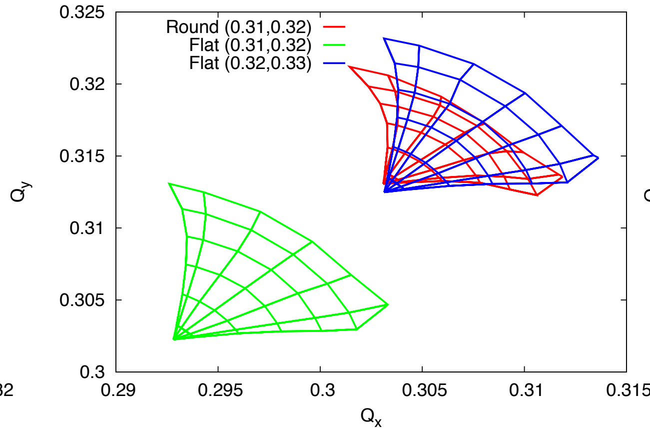


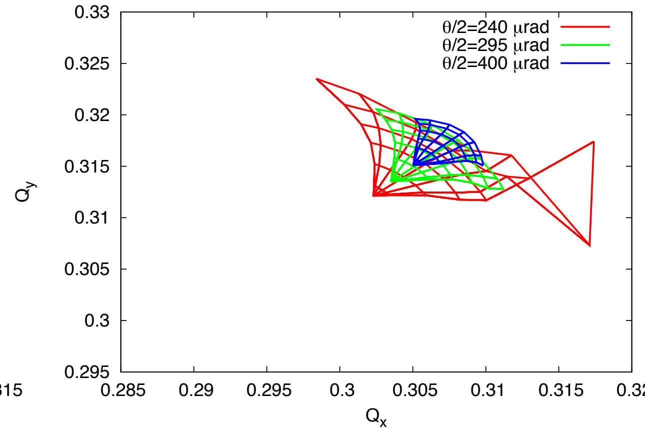
@IPAC2017 TUPVA027
CERN-ACC-NOTE-2017-0035

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

Alternative solutions: Flat optics versus round







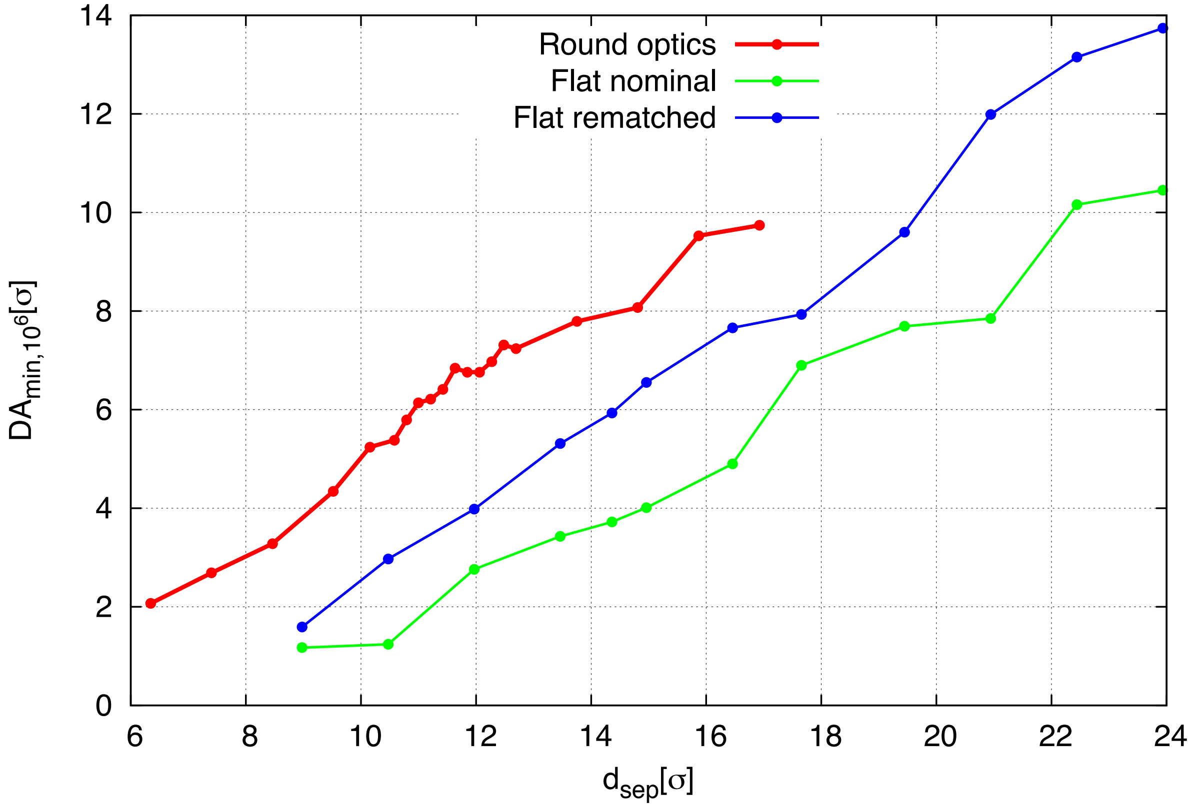
Flat optics is the natural back up solution in case crab cavities do not work, because for same normalized separation one has smaller geometric loss factor.

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!**

Head-on Limit: Losses and Emittance growth

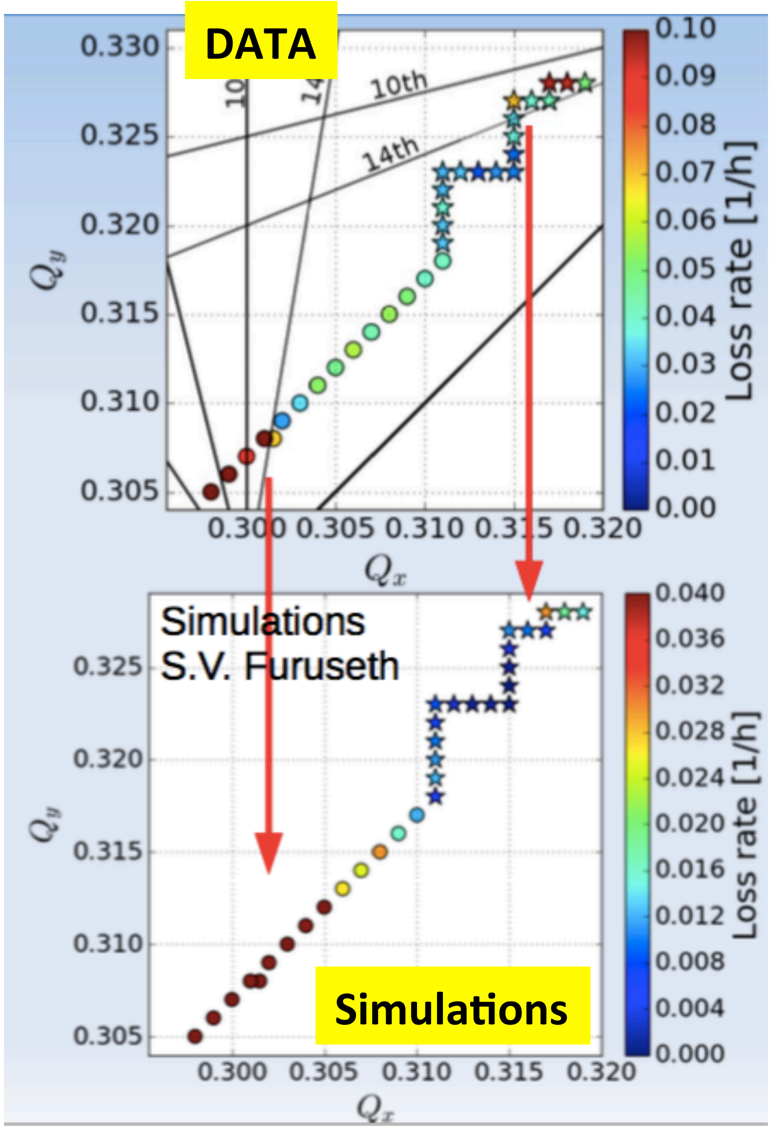
Head-on beam-beam can result in losses and emittance growth. FCC pushed 0.03 total and two experiments to add.

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

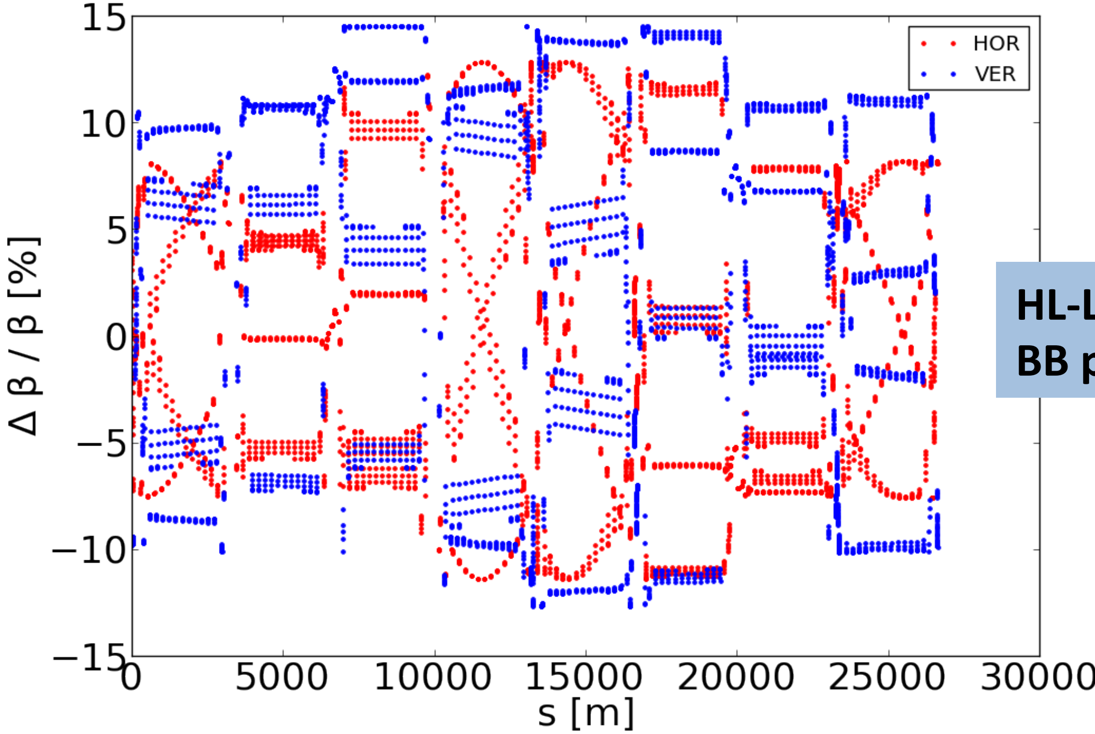
- BB parameter of 0.02 (FCC Ultimate is 0.03)
- GPU accelerated 6D simulations compared to measured losses in the LHC.
- Clear impact of Piwinski angle to loss mechanism
- Good qualitative agreements
- Work on going on quantitative estimates (**magnets errors**)



@IPAC2017 TUPVA026, TUPVA029

Head-on Beam-beam β-beating

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



HL-LHC study case
BB parameter 0.02

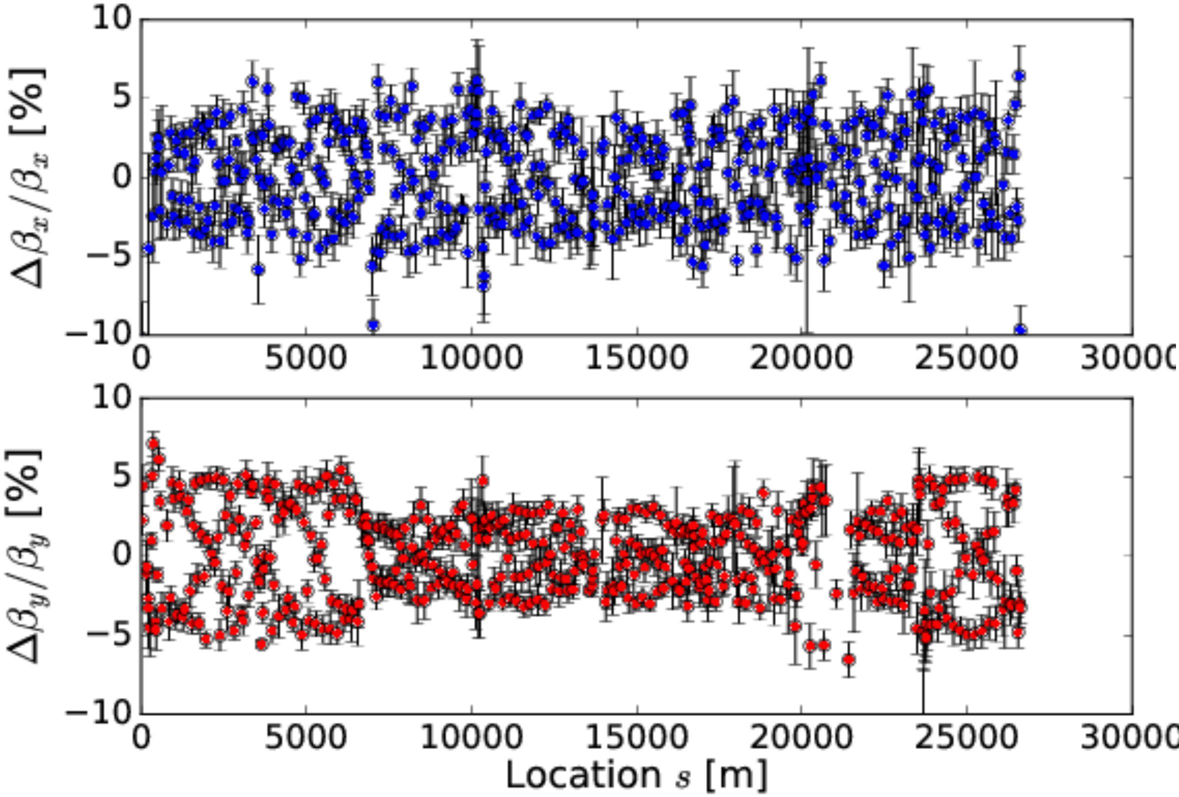
@IPAC2017
WEOAB2, TUPVA030

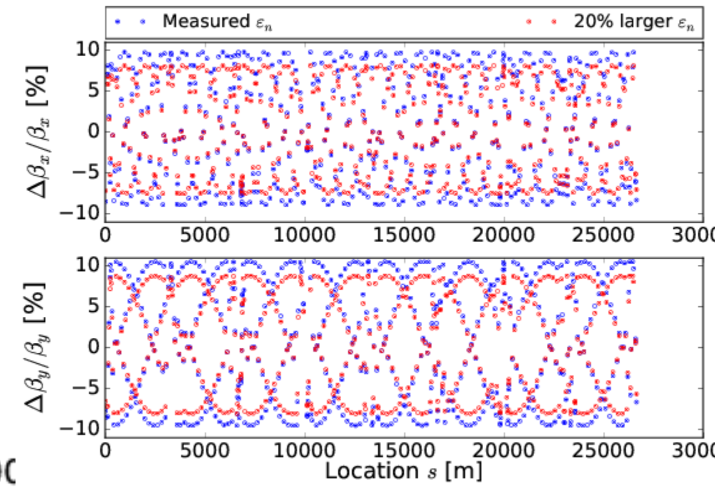
FCC-hh: ξ_{bb}= 0.02 (up to 0.03)

- Impact on collimation system, is it important?
- Impact on performances → luminosity unbalance → will tune to profit from this
- First attempt to measure and correct

Head-on Beam-beam β-beating

First measurements in LHC and tests





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WEOAB2, TUPVA030

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

Summary and Outlook

- For the Ultimate round optics case we will need larger crossing angles: rough estimates now **x-ing angle 200 μrad** will be required, **ultimate value only after studies with octupoles and magnets multipolar errors model**

Angle rough estimates: 90 (nominal) + 5 (15 Units Chroma) + 5 (10% intensity) + 5 (0.5 s effect of Multipolar errors) +/- Octupoles (difficult to judge) = 100 μrad + Landau spread, imperfections…

- **HH (@nominal WP), VV(@mirrored WP) can be made equivalent to HV crossing scheme**
- **Nominal Bunches are the one defining the dynamic aperture** also for the case of broken passive compensation.
- **Still missing estimates of : Octupole magnets, multipolar errors**

- **2 Low Luminosity experiments evaluation**:
  - **Level luminosity by separation** → reduce Head-on contribution (already at 0.03 for ultimate)
  - Larger beam-beam separations at LRs → **x-ing angles larger than 150 μrad**

- **Flat optics requires larger beam to beam separation**. Tune correction can mitigate but still need to assume 25% more angle and depends on betas ratio

Summary and Outlook

- **LHC data** shows that **head-on beam-beam and magnets multipolar error can explain the losses measured during experiments** → keep HO beam-beam smaller will be beneficial **studies needed for head-on limits investigation**

- Models available need to speed-up because of **computational limits** (need of the lattice description and FCC is much larger, parameter space, multiparticles…)

- **Magnets field quality tolerances** should be defined with Beam-beam at design stage to ensure large DA with BB head-on more than with single beam

- **Compensation techniques**:
  - **Octupole magnets compensate BBLR** if well integrated in lattice design otherwise negative impact. Wires studies not yet initiated.
  - **Head-on compensation techniques** (e-lenses) should be studied to compensate head-on beam-beam since it is of major concern

- **Head-on limit models** developed show first **qualitative agreement** with observations, **quantitative comparison only with lattice imperfections**

Outlook

- **Stability studies** will start after Berlin (newer member starting next week)
  - Dynamic aperture effects of Landau spread (EPFL PHD Thesis C. Tambasco)
  - Octupole needs with beam-beam
  - RFQ impact

- **Orbit effects** to be evaluated, work started benchmarking to LHC data (@IPAC2017 THPAB042)

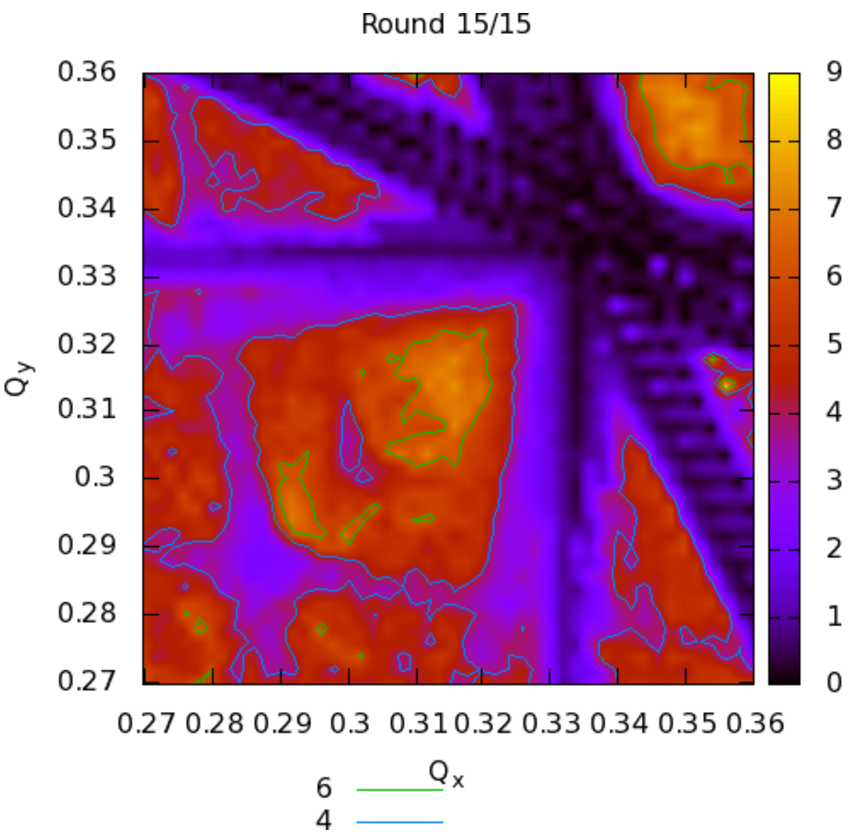
- Start a close **interaction with lattice team** to define lattice properties to improve/compensate beam-beam effects

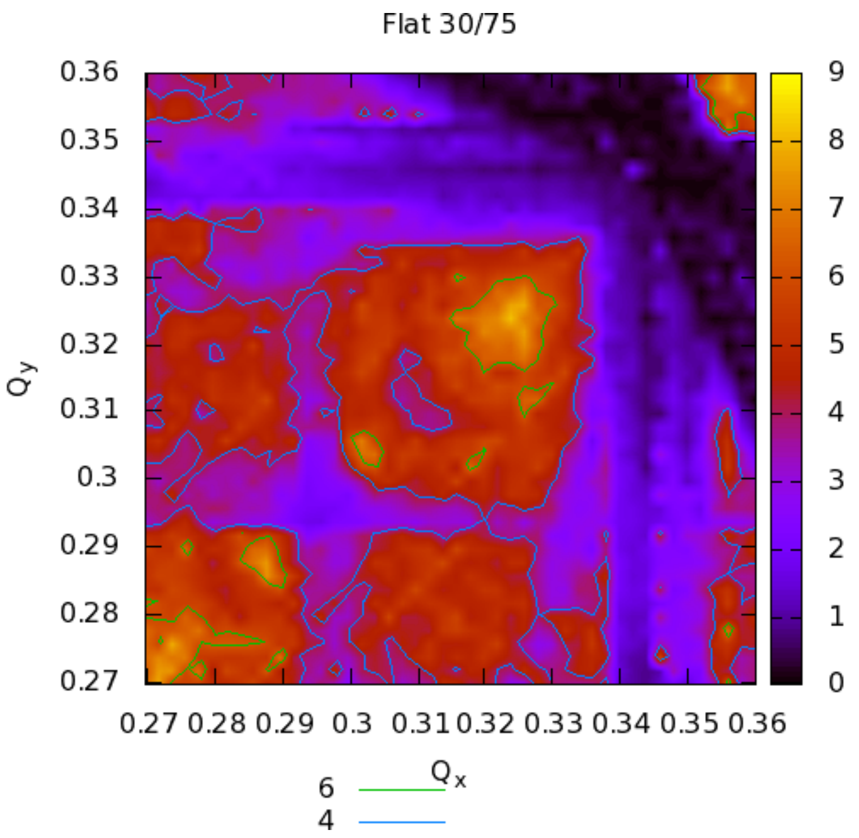
- Deeper study of **head-on limitations and possible compensation (e-lens)** to be able to define possible intensity limitations

- 5 ns scenario to be evaluated

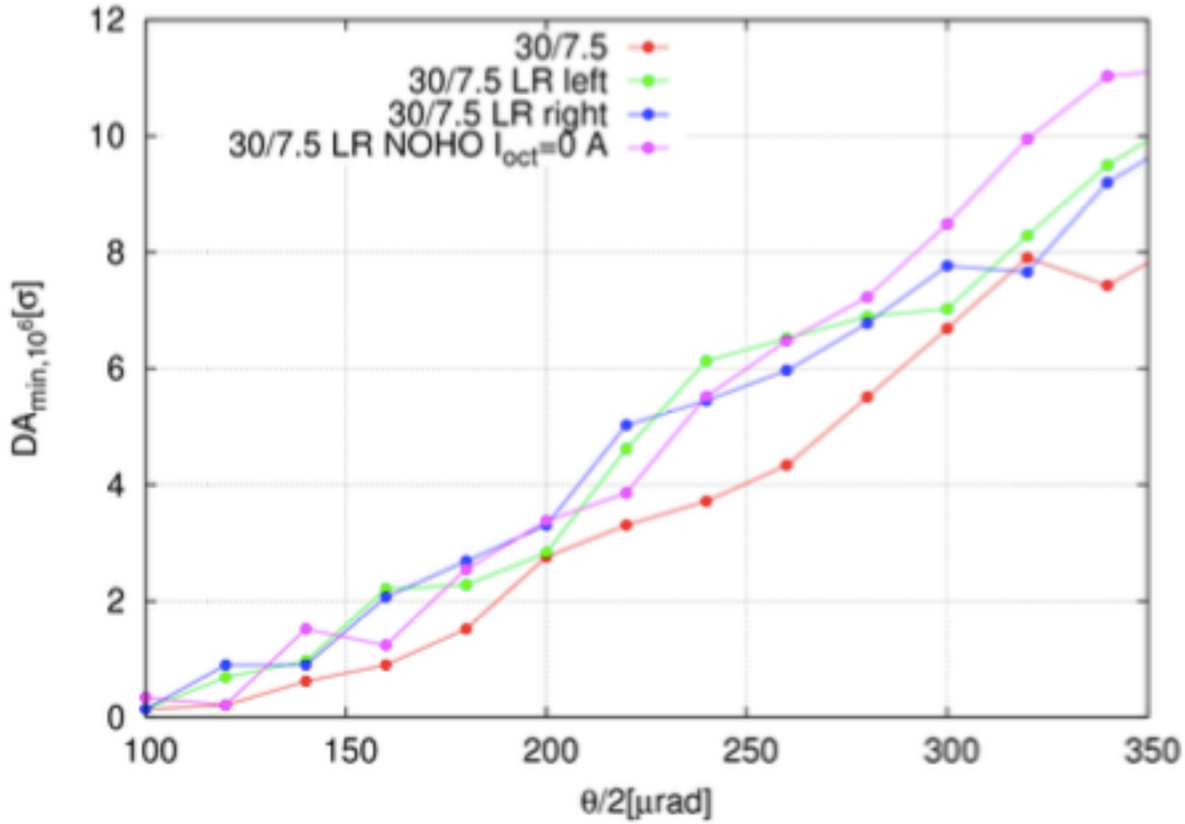
Thank you!

Flat versus round tune space



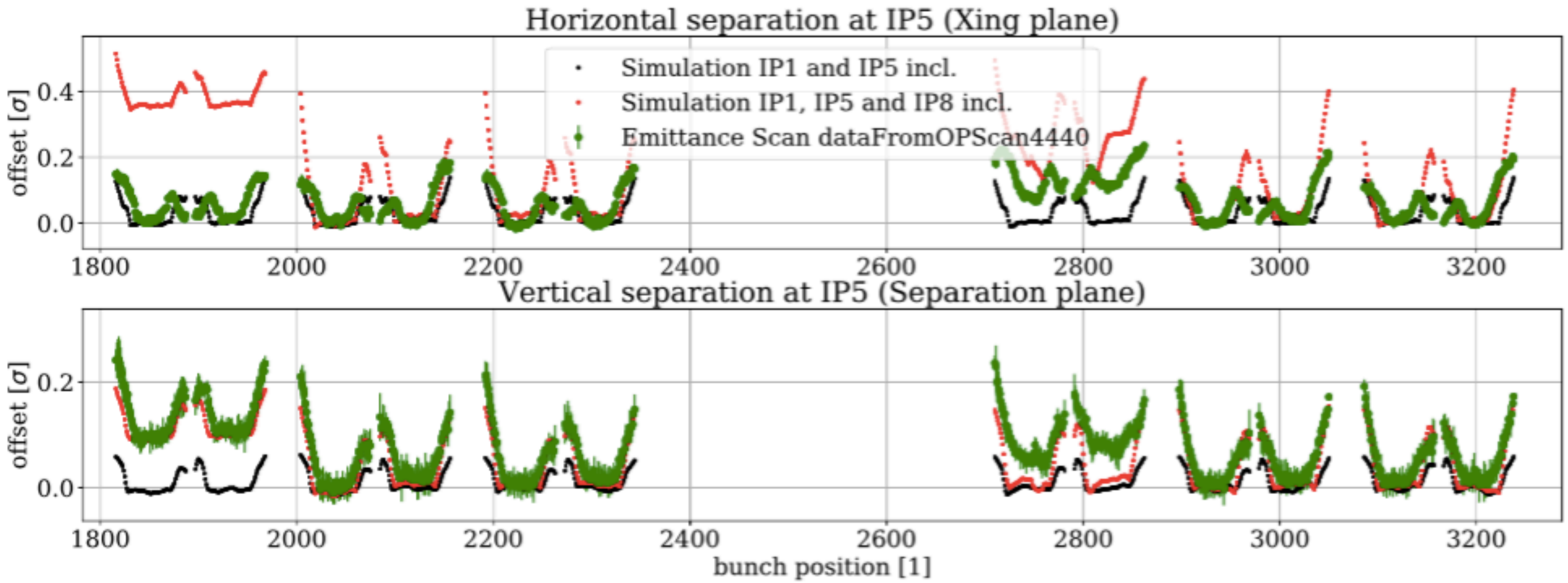


PACMAN effects Flat versus Round



As for the round optics case Dynamic Aperture is defined by nominal bunches
PACMAN bunches will have larger DA

Orbit Effects



@IPAC2017 THPAB042