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Beam-Beam Studies for FCC-HH

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LHC@home SixTrack

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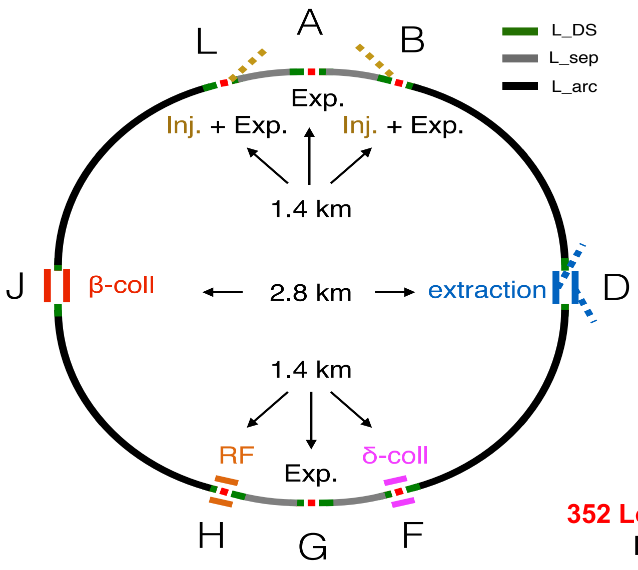
EuroCirCol A key to New Physics

Contents

- Dynamic aperture studies for Round optics
- Low Luminosity Experiments
- Alternative crossing scheme
- Global compensation and Phase advance optimization
- Head-on studies
- Alternative solutions
- Summary and outlook

Collider parameters



352 Long-Range interactions
For 4 Experiments

	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. [μm]	2.2(0.44)	
Max ΔQ_{bb} (for 2 IPs)	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ']	12	Crab. Cav.

Interaction Point A and G main **high luminosity experiments**:

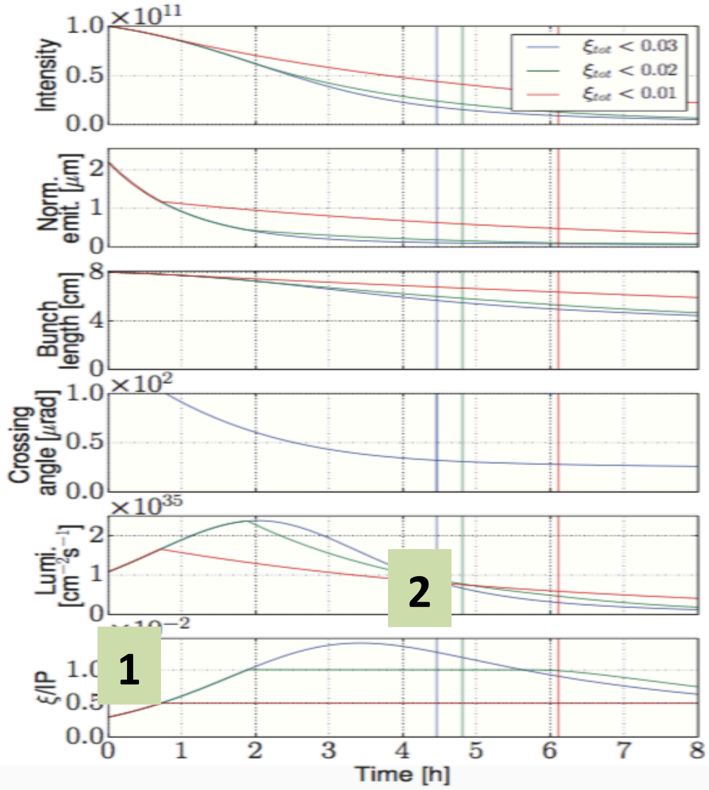
Goal → maximum luminosity with good lifetimes

Interaction Point L and B **low luminosity experiments**:

Goal → in shadow on main IPs where possible → Defined luminosity operation

From D. Schulte

Beam-Beam Effects



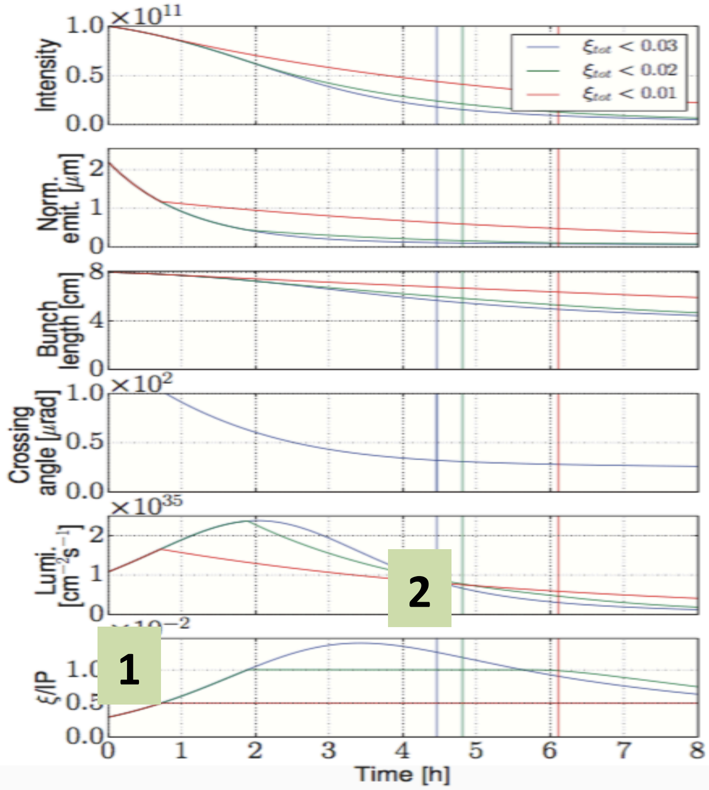
Due to strong radiation damping we have quite some different regimes from beam-beam point of view:

1. LHC beam-beam dynamics ξ_{bb} = 0.06→0.015
   LHC experience and long-range effects

2. HL-LHC Head-on driven dynamics with beam-beam parameter ξ_{bb} = 0.02→ 0.03 plus 2 low luminosity IPs
   LHC experience with HL-LHC experiments

Very difficult to address studies for all configurations

Beam-Beam Effects



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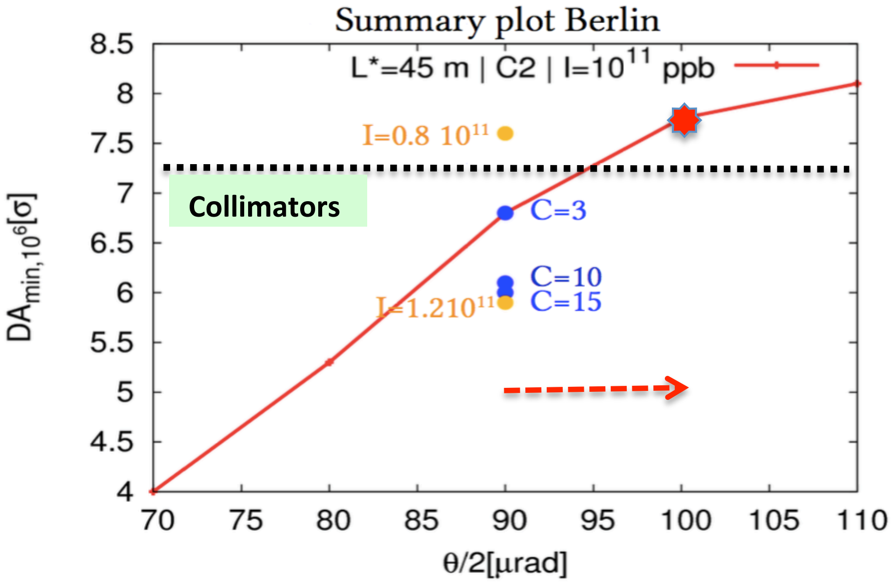
   LHC experience with HL-LHC experiments

We focus on the most challenging scenario from beam-beam point of view → Luminosity highest reach and performances (other points will/should just be better)
All cases with 25 ns bunch spacing

Ultimate case Round Optics Berlin results

FCC L* 45 meters optics 2 IPs and H-V alternating crossing



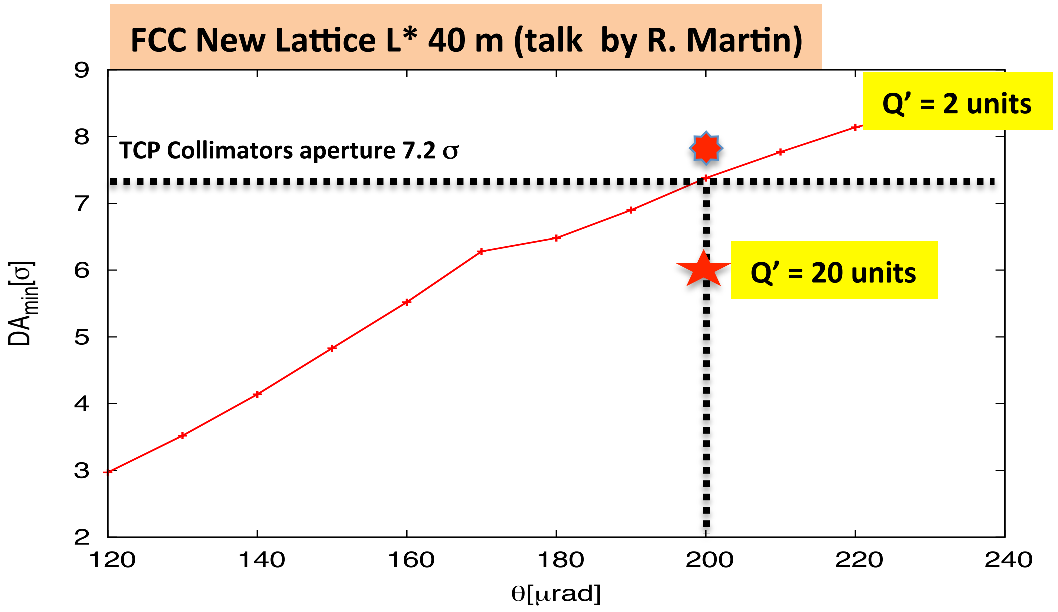
Dynamic Aperture from beam-beam effects larger than collimation aperture to do not increase the particle impact on collimation system due to BB diffusive mechanisms

Dynamic Aperture larger than 6.0 σ with all non linearities in the presence of beam-beam at different stages of the operational cycle

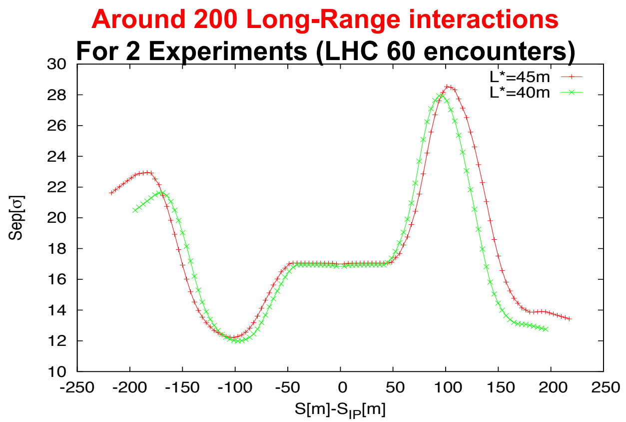
For FCC-hh case TCPs at 7.2 σ
M. Fiascari et al. @IPAC2016

Crossing angle of **200 μrad at IPA and IPG** proposed
→ Still to be added some margins for: Landau Octupoles, High chromaticity operation, Magnets imperfections,Tunability and low luminosity experiments

Ultimate case Round Optics: New optics

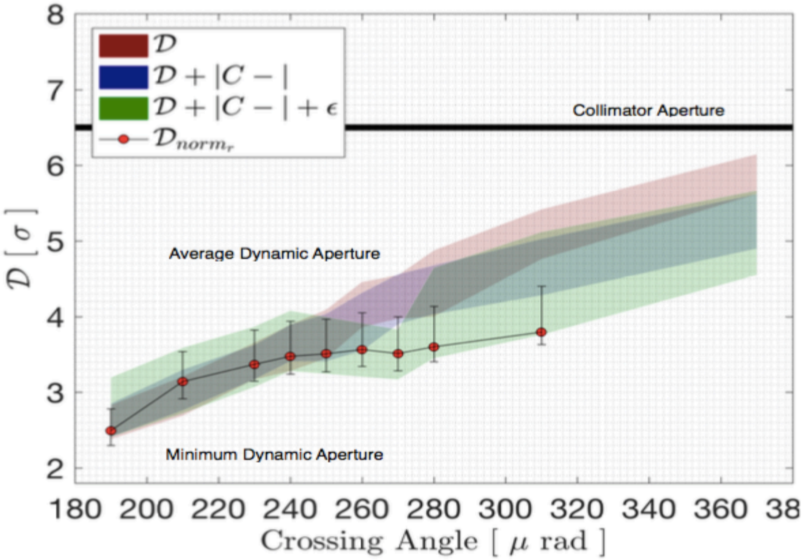


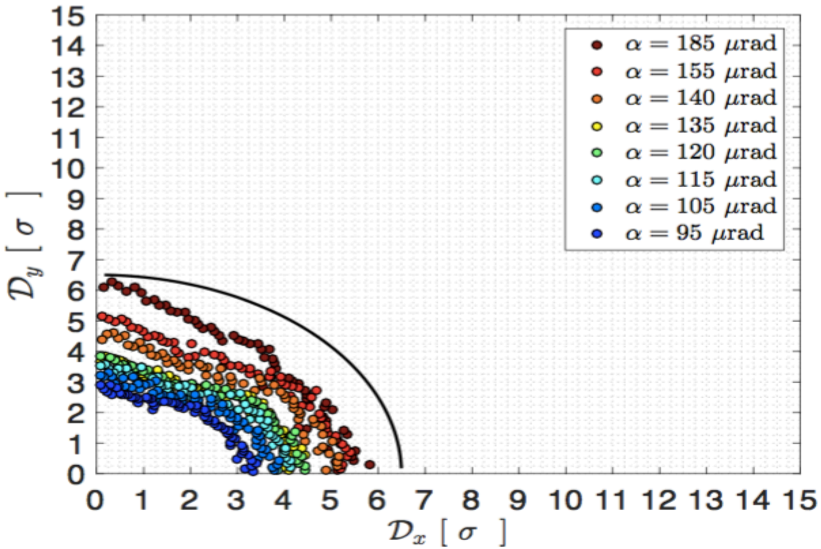
- **New Interaction Region Layout L* 40 m optics**



- New optics have reduced dynamic aperture →fewer encounters but smaller separations
- Crossing angle of **200 μrad at IPA and IPG** proposed allows for high chromaticity operation→ Still to be added :
  - → Landau Octupoles
  - → Magnets imperfections
  - → Tunability and low luminosity experiments

Dynamic Aperture goals and benchmark to LHC





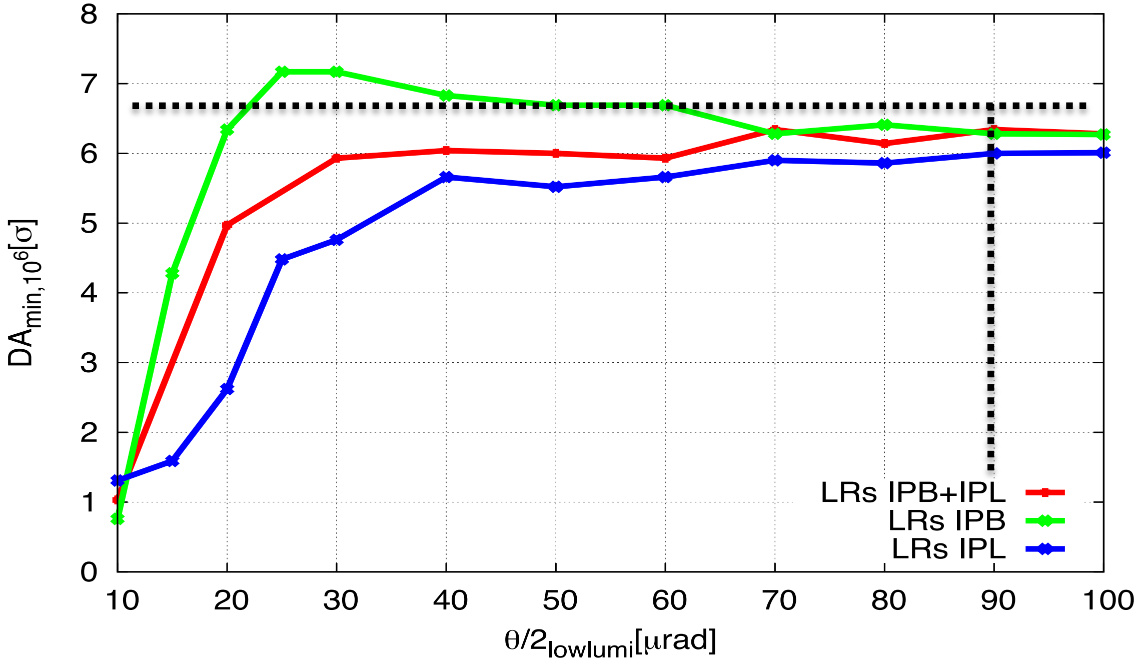
@IPAC 2017 THPAB056

Long-range bb behave like scrapers but non guiding losses for larger separations→ interplay of all non-linearities

Dynamic Aperture in the LHC well correlated to the particle losses

Further studies on particle distributions and implementation into models on-going to understand better

Low Luminosity Experiments: IPL and IPP



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

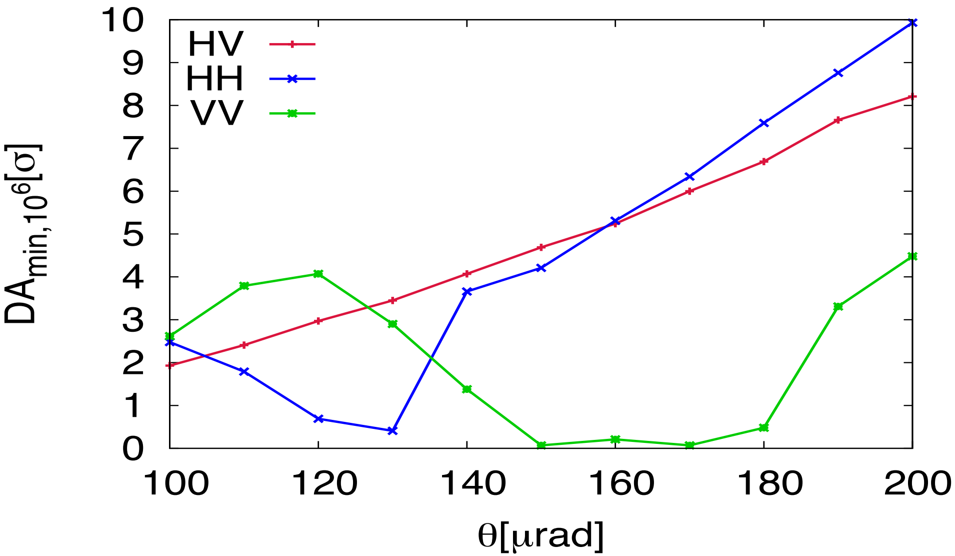
To have them not perturbing the high luminosity experiments should have **angles > 180 μrad**

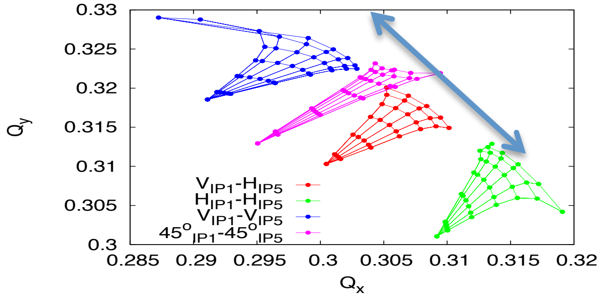
Level by separation the head-on collision to avoid strong tune shifts

Same strategy as for in LHC and HL-LHC

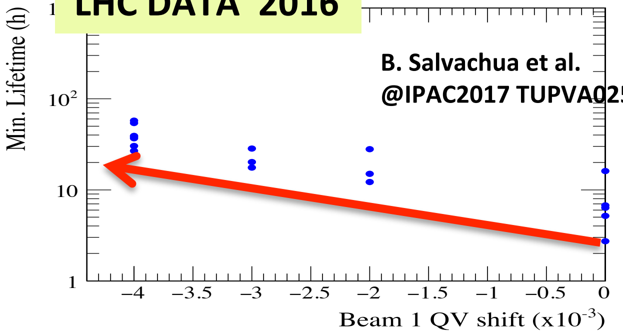
- **Long-range:** crossing angles larger than 180 μrad (enough aperture from **M. Hofer**)
- **Head-on** apply separation leveling of luminosity = limit on integrated luminosity per year of run!
  To be defined with tune optimization!

Alternative Crossing Schemes: HV versus HH and VV





LHC DATA 2016

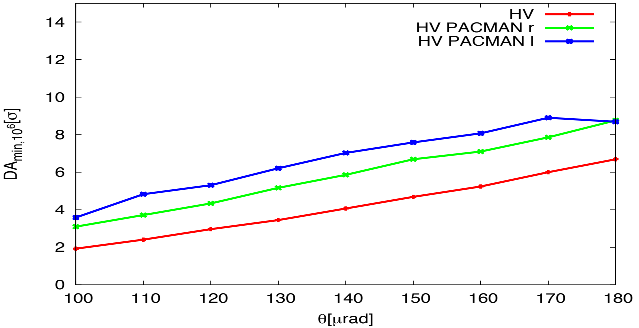


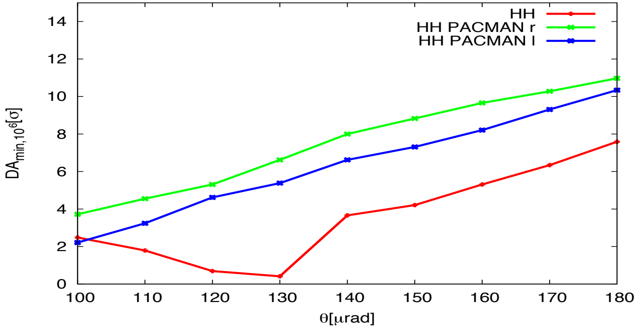
Pacman Bunches?

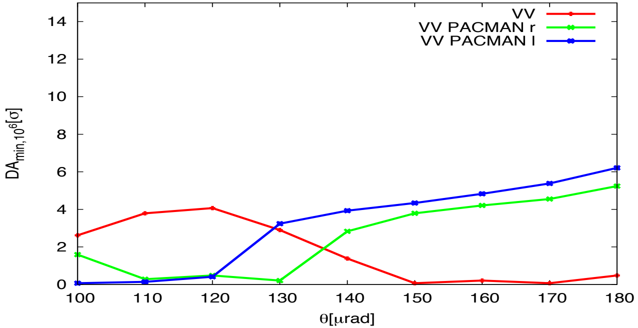
Alternative crossing schemes have been explored and show larger flexibility in terms of dynamic aperture with optimized tunes

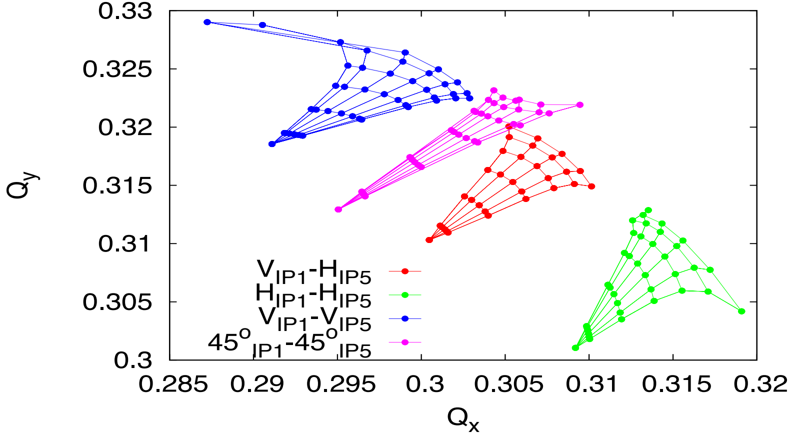
- HH Crossing is equivalent to HV
- VV not acceptable at the (0.31-0.32) working point due to strong impact of 3[rd] order resonance effect → Mirrored tune will solve the problem

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**

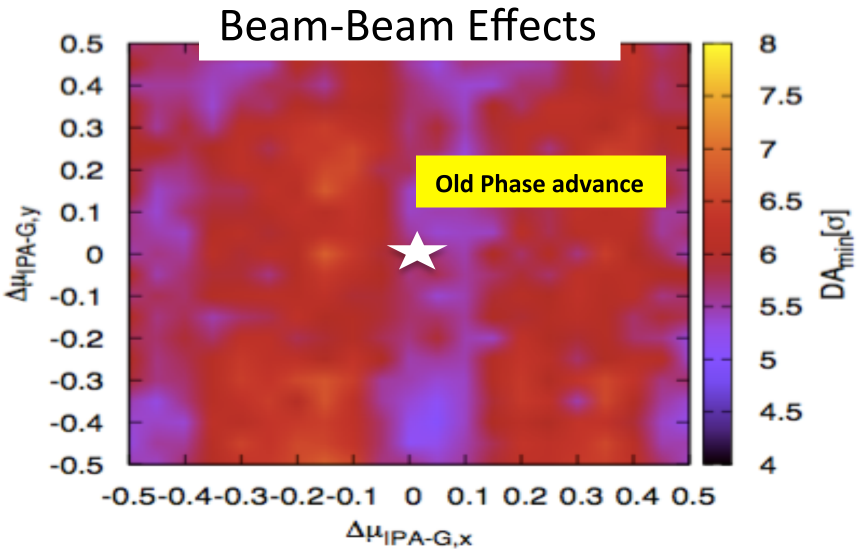
Room for flexible configurations if needed by energy deposition studies
Tilted crossing schemes also under study

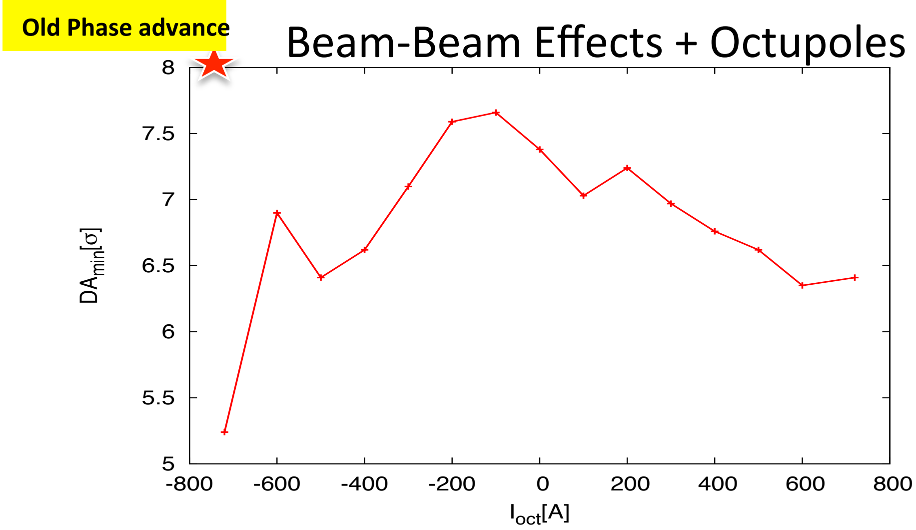
Optimization based on dynamic aperture

Landau Octupole magnets fundamental for beam stability (see talks O. Boine-Frankheim and C. Tambasco)

→they have very important impact on dynamic aperture

→ optics optimization as to be applied at different stages of collider cycle using DA

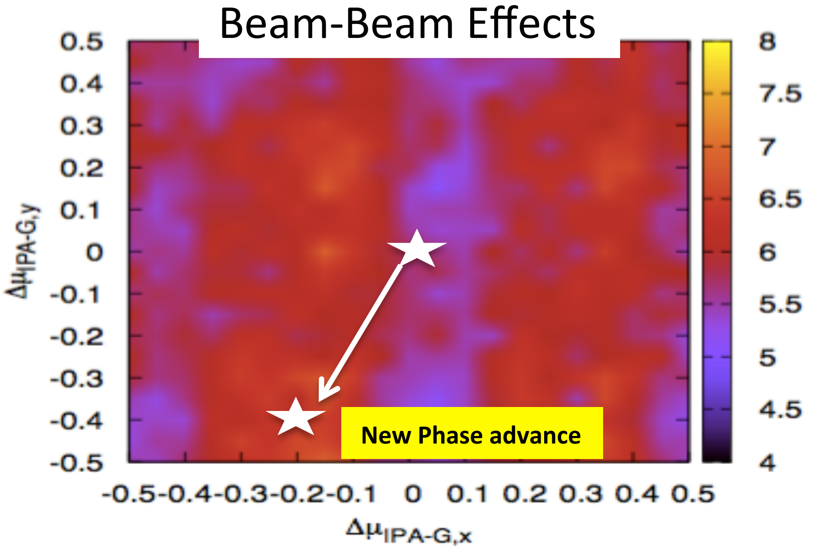


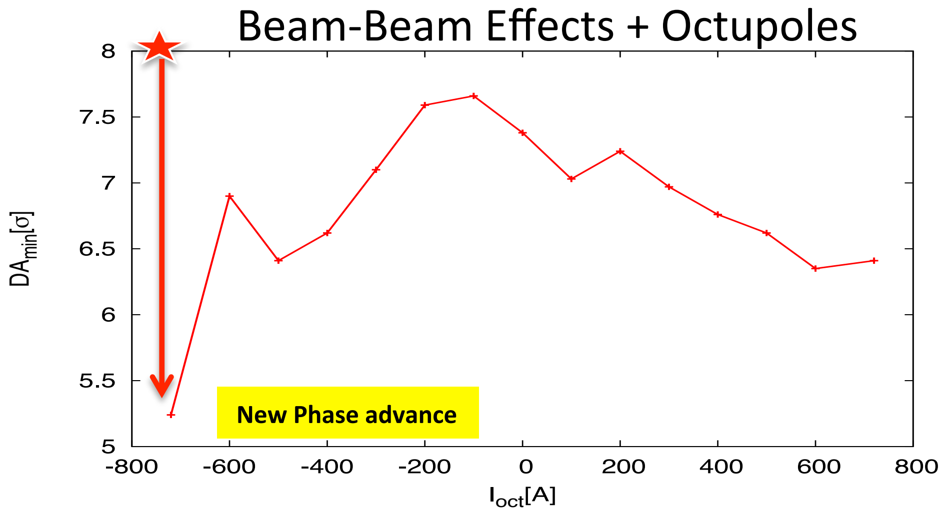


Strong dependency on IPs phase advance observed with beam-beam

Optimization of optics based on dynamic aperture

Optimum phase advance for optics (E. Cruz talk) not always the best when other non-linearities are added

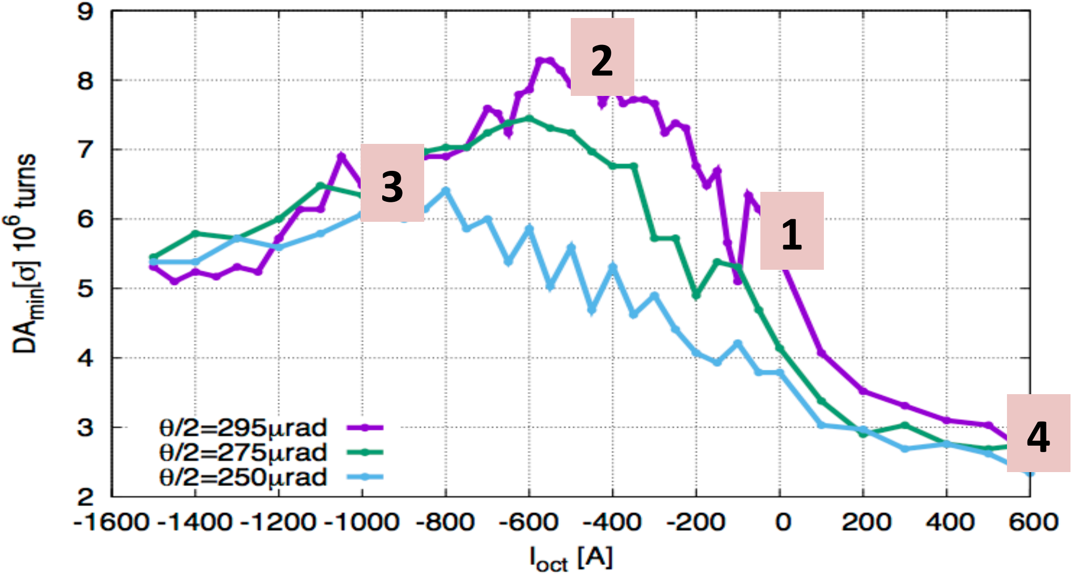


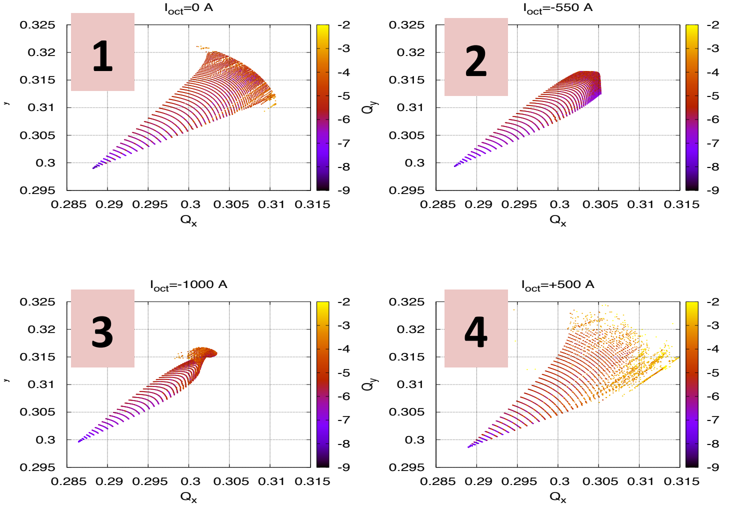


New Phase advance better for optics and beam-beam effects alone but breaks global compensation with octupole magnets (J. Barranco from Eurocircl 2017)

Optimized phase advance to have maximum Dynamic Aperture with beam-beam is not optimum in presence of Landau octupoles

Global compensation with Octupoles

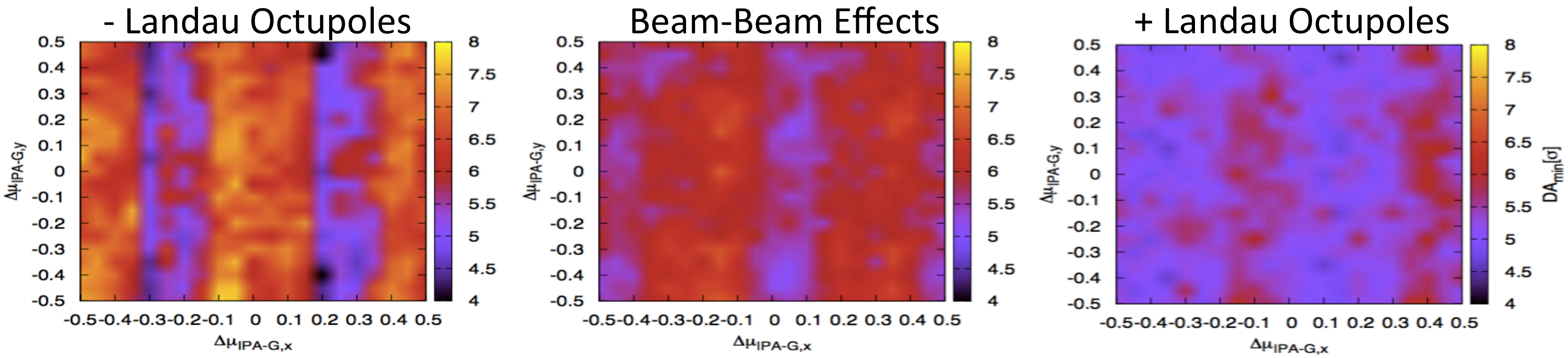




- Octupole magnets are used/needed to provide tune spread for Landau damping.
- **They have very negative effect on DA if not used with care.**
- **If installed at right location they could help compensating long-range effects!**

FCC-hh will be optimized to allow for global compensation!

Landau Octupoles and IP phase advance



We choose to have Landau Octupoles powered in negative octupole polarity

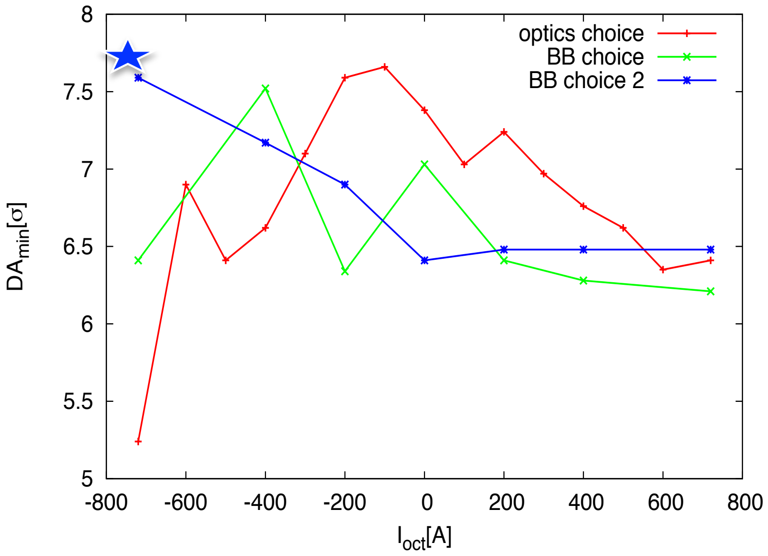
→ **provides larger stability for single beam (see C. Tambasco talk)**

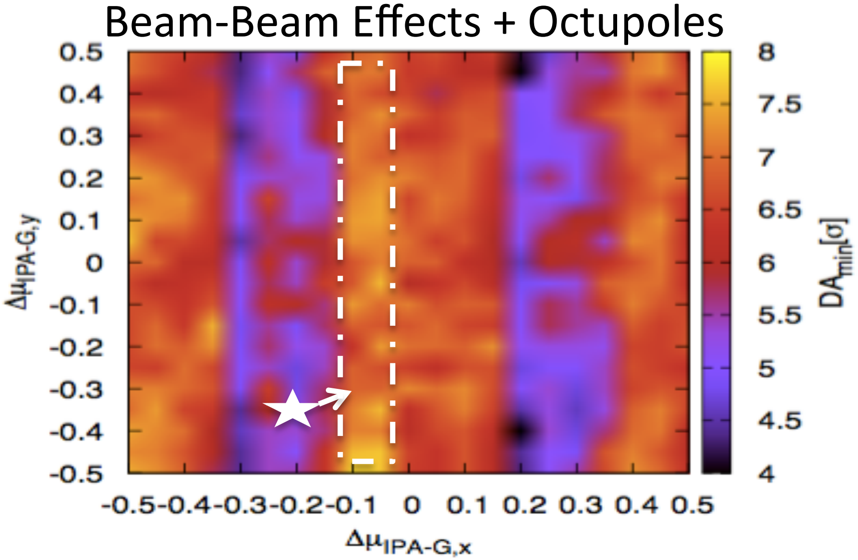
→**allows for larger DA with optimized phase advance thanks to compensation (J. Shi et al.,** CERN-ACC-NOTE-2017-036**) → large dynamic aperture margins**

Need to optimize the optics to keep compensation!

Different Phase advances at different stages of the operational cycle to maintain compensation

Optimization of optics based on dynamic aperture



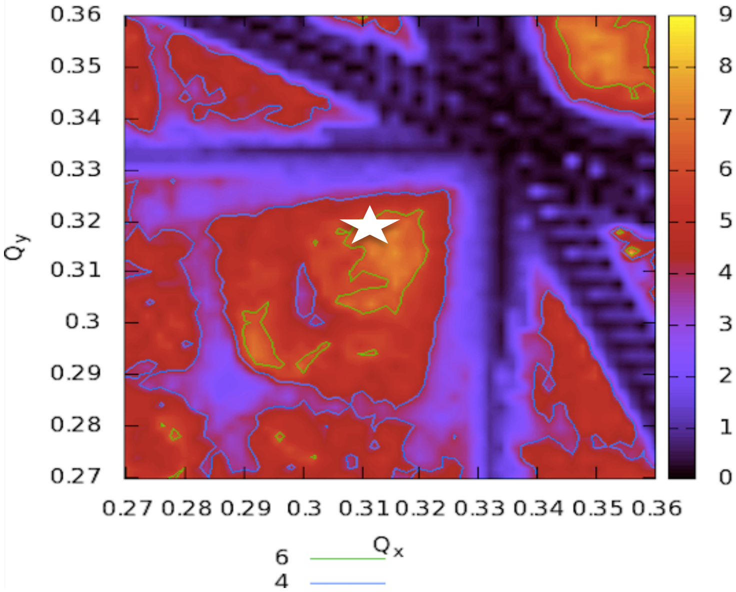


Further optimization of phase advance with beam-beam and octupoles compensation

→ Will further change with multipolar errors

Phase advance between IPs changes over the operational cycle of the collider to have maximum Dynamic Aperture

Dynamic Aperture dependency on tune



Define **robust baseline scenario with Dynamic Aperture above 6 σ** with all non-linearities (magnets errors, Landau octupoles, high chromaticity and beam-beam effects) and some margins for parameter fluctuations (10%)

Tune optimization to find optimum and large area in tune diagram (on-going work)
→ host low luminosity experiments contributions (tune shifts) and multipolar errors

Dynamic Aperture with multipolar errors

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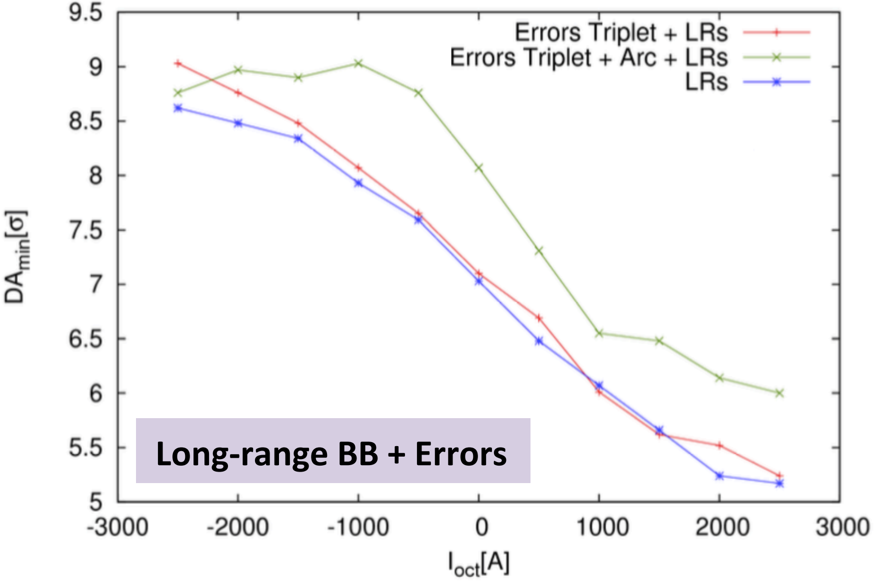
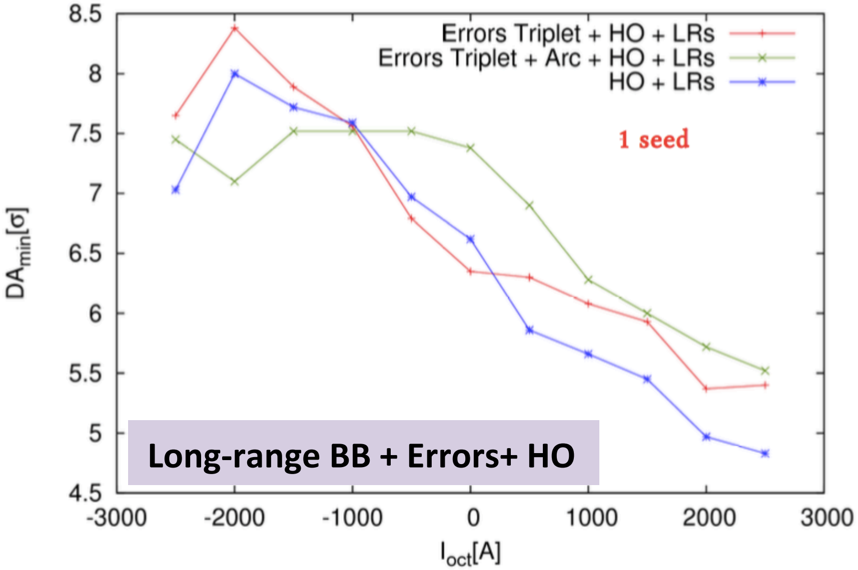
FCC L* = 45 meter optics only one seed



Long-range BB + Errors



Long-range BB + Errors+ HO

Break of long-range global compensation scheme in collision → need further studies and lattice optimization
L* 40 meter optics under study with full seed statistics

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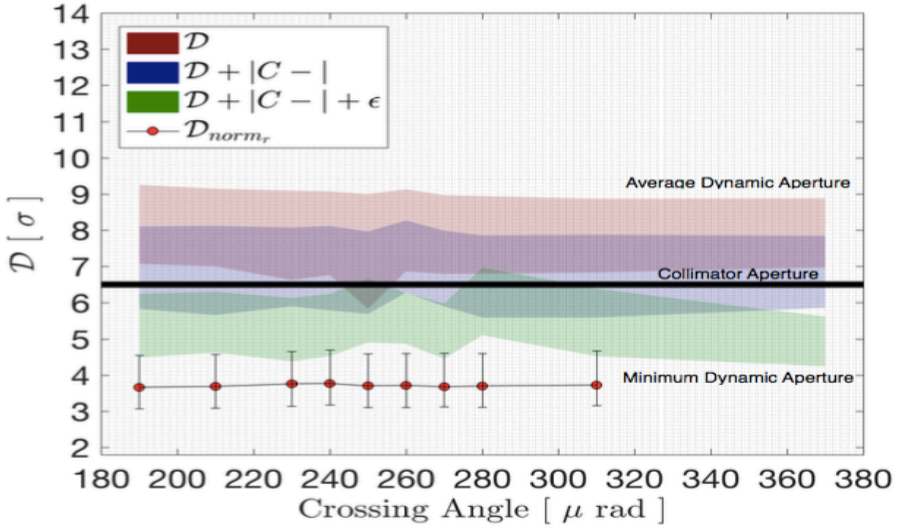
Head-on Limit: Losses and Emittance growth

Head-on beam-beam can result in losses and emittance growth. FCC pushed to beam-beam tune shifts of 0.02-0.03 total.

From LHC experience head-on losses not fully described by dynamic aperture model as for long-range effects!

Machine Non-linearities fundamental!



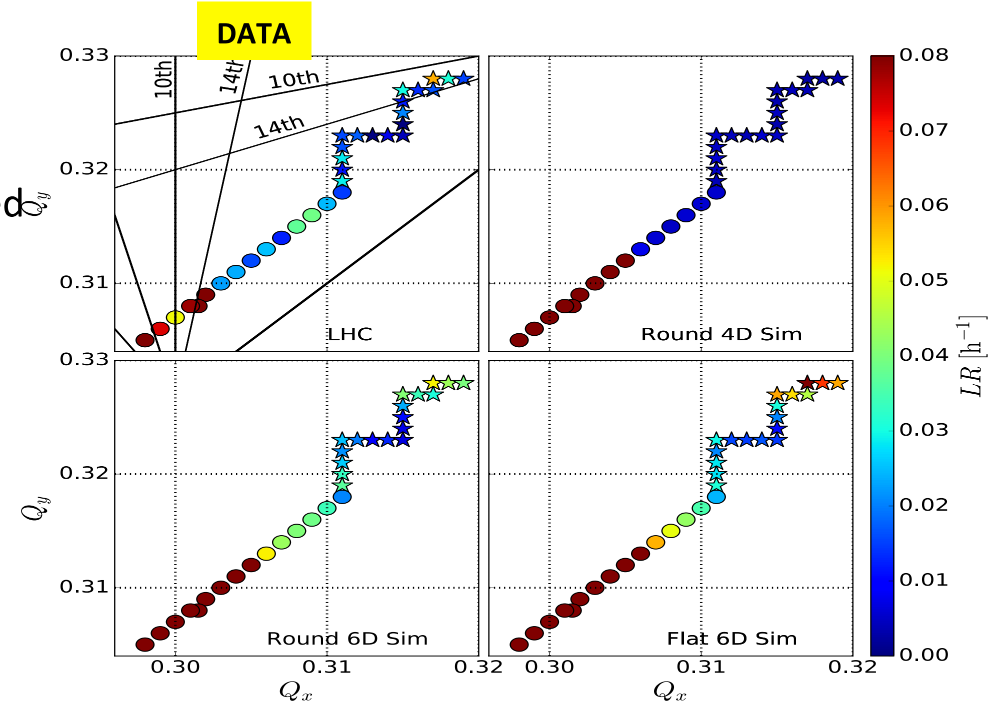
M. Crouch
Manchester Universisty PHD Thesis 2017

Head-on Limit: Losses and Emittance growth

Model developed for FCC-hh of loss rates with 6D beam-beam and simplified lattice!

First comparisons to LHC losses data during dedicated experiment

- Total Beam-Beam tune shift of 0.02
- GPU accelerated 6D simulations (CABIN) 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**)



Poster by S. Vik Furuseth
Strong Head-on Beam-Beam Interactions

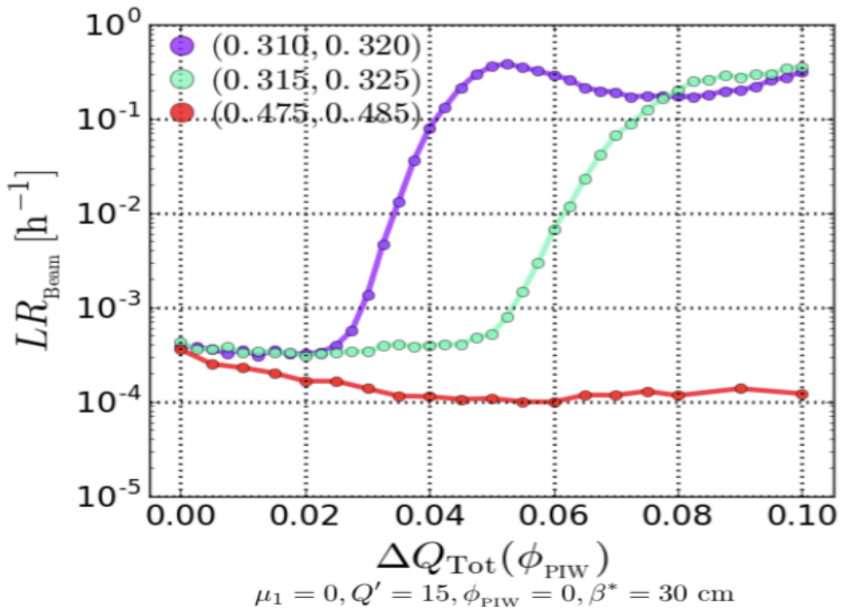
Head-on Limit: Losses and Emittance growth

Baseline scenario (total beam-beam tune shift 0.02) shows no limitations

Ultimate (total beam-beam tune shift 0.03) is not given!

Working point optimization could increase the beam-beam maximum tune shift reach to 0.046

Further optimization between dynamic aperture studies and head-on studies are foreseen



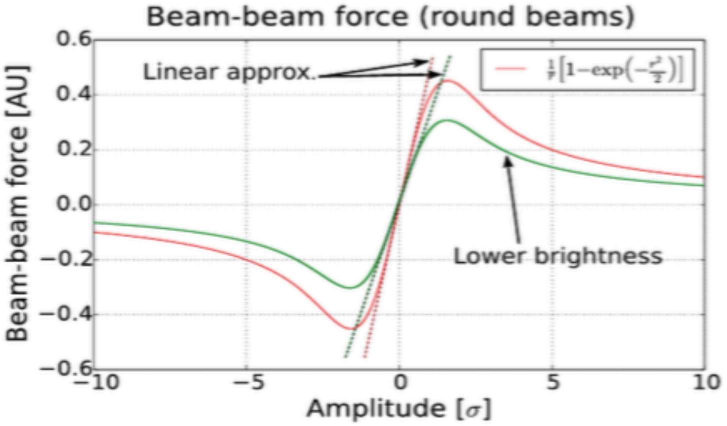
Poster by S. Vik Furuseth
Strong Head-on Beam-Beam Interactions

Further studies needed to explore possible limitations linked to head-on beam-beam: LHC data benchmark fundamental!

Head-on Limit: beta-beating

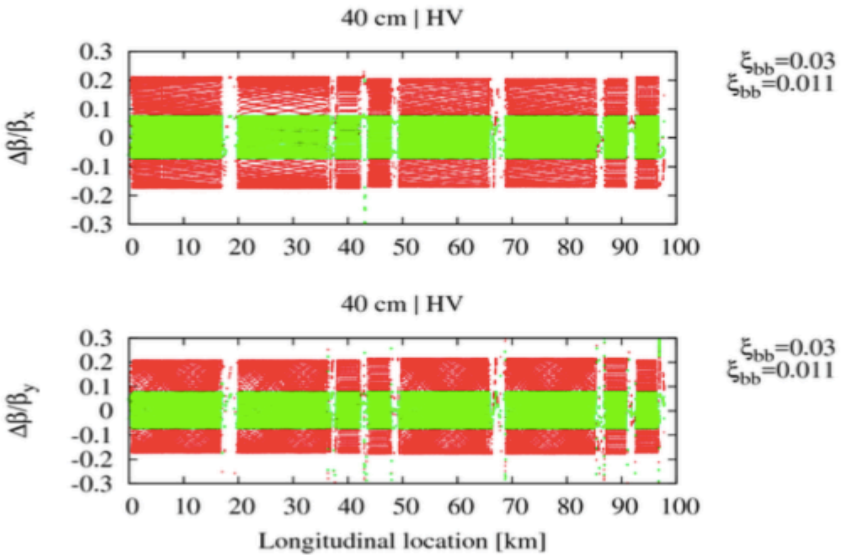
- The BB interaction non-linearity will cause non-linear amplitude detuning.
- However for small amplitude particles (< 1 σ) the kick is **linear** (quad-like).
- The change of the β-function assuming a series of small quadrupole errors is given by:

$$\frac{\Delta\beta(s)}{\beta_0(s)} = \frac{2\pi\xi}{\sin(2\pi Q_0)} \sum_{i=0}^{N} \cos(2\,|\mu_0(s) - \mu_0(s_i)| - 2\pi Q_0)$$



- The expected beating is directly proportional to the beam-beam parameter. HLLHC and FCC are designed to increase the ξ_{bb} by 2-3 times
- Operationally the LHC β-beating from lattice errors is routinely measured and corrected during commissioning to 5-7% level.

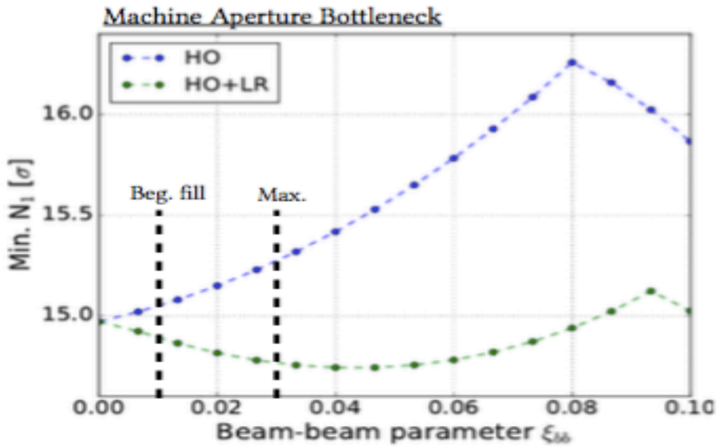
Head-on Limit: beta-beating

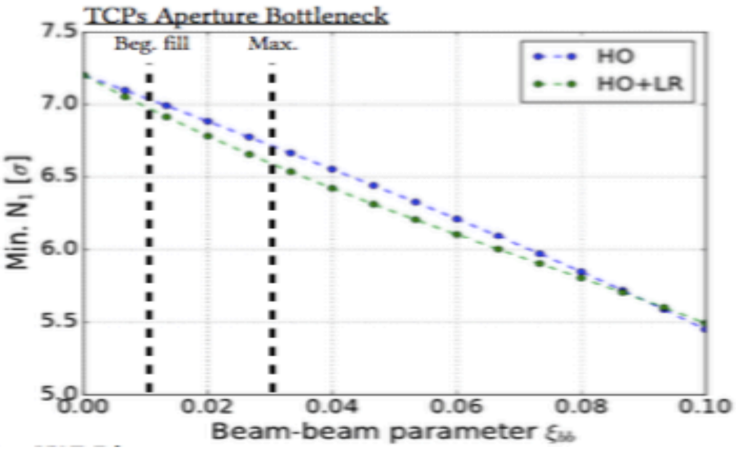


- Linear beating from MADX (0σ particles) with head on (HO) interactions in IPA and G and no lattice errors.
- Using L*=40m and β*=0.3m optics with full crab crossing.
- FCC adds new feature since the ξ_{bb} **changes over the fill** and so the beating.
  - $\xi_{bb,tot}$=0.011 (beg. Fill) - $\Delta\beta/\beta_{max}$=8 %
  - **$\xi_{bb,tot}$=0.03 (max)-$\Delta\beta/\beta_{max}$=22 %.**
- FCC is currently optimizing the phase advances between main experiments @ collision to maximize DA. This optics distortion becomes yet another parameter on the optimization (HO, octupoles,…).
- Collimation experts request $\Delta\beta/\beta_{max}$ <10 % as in the LHC.

Head-on Beam-beam β-beating impact on aperture

- We explore the impact on machine and collimator apertures for various ξ_{bb}. Only linear beating is considered (worst case).
- Machine aperture bottleneck in separation dipole MBRD.B4RA.H1.
  - For HO only no aperture decrease for expected ξ_{bb} FCC range [0.01-0.03].
  - For HO+LRs there is a decrease of ~0.25 σ for max ξ_{bb}=0.03.
- TCPs aperture bottleneck TCP.B6L2.B1 (for ξ_{bb}=0.01 HO, ξ_{bb}=0.016 HO+LRs) then TCP.A6L2.B1. For ξ_{bb}=0.03, a decrease of ~0.6 σ is observed.



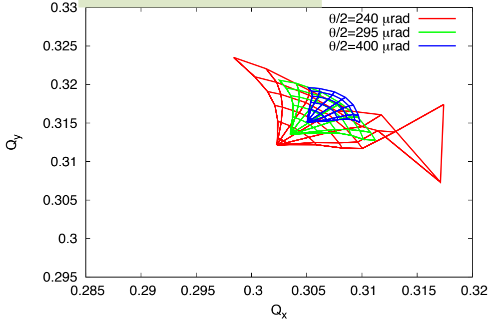


Impact on Collimation aperture of maximum 0.6 σ needs further study to address and identify possible limitations

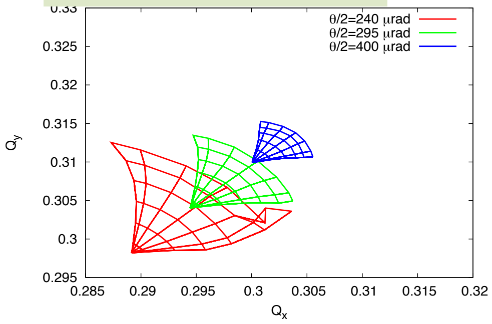
Alternative solutions: Flat optics versus round

Flat optics is the natural back up solution in case crab cavities do not perform as expected.
See HL-LHC project TDR and J. Abellaira talk

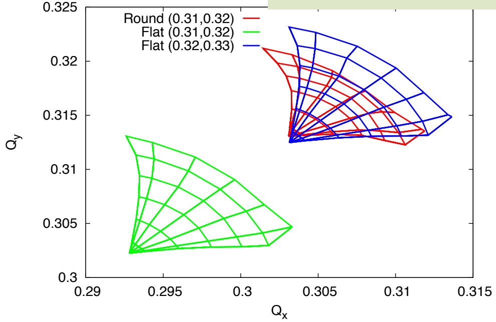
Round optics



Flat optics H/V xing



Flat optimized

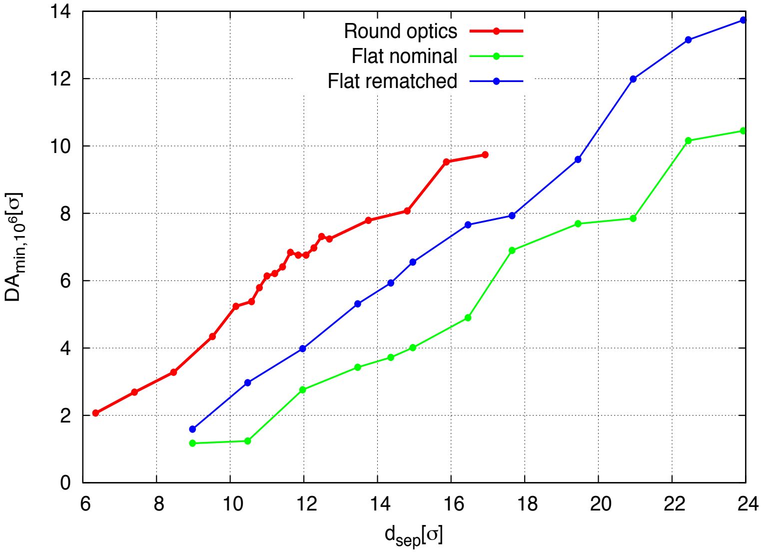


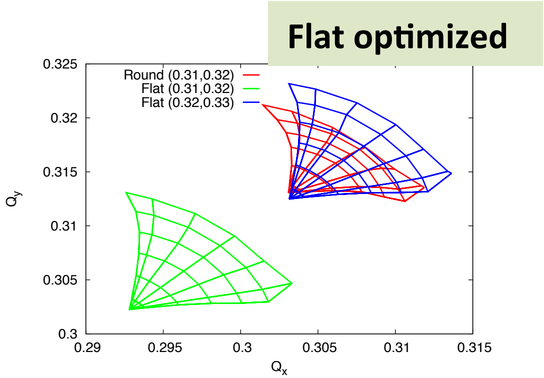
Beam-Beam long-range and head-on behave differently:

- Due to trains and braked passive compensation → tune shifts (for H-V crossing schemes)
- Head-on beam-beam creates larger detuning with amplitude

Flat optics introduces some unwanted effects

Flat versus round optics: tune shift correction

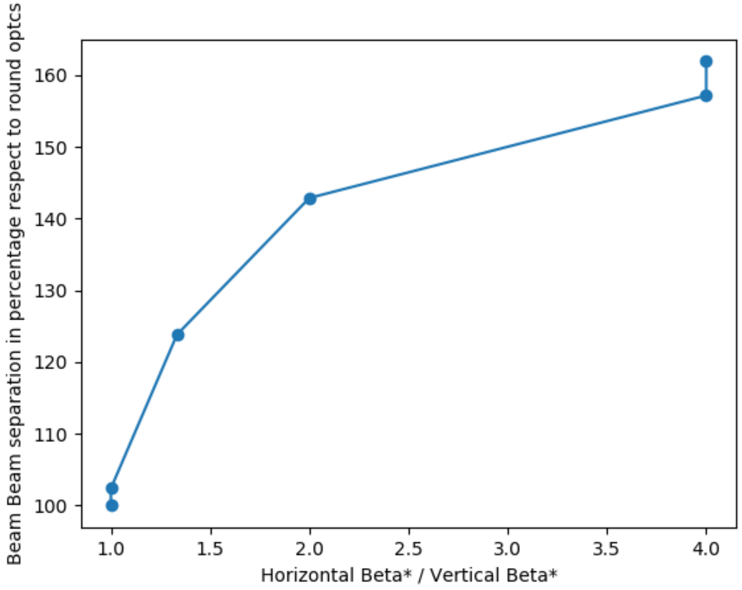




Study case beta ratio of 4 and H-V crossing scheme:

- 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!**

Flat versus round optics: beta ratios



For H/V crossing schemes

The extra separation needed from dynamic aperture studies with a DA goal of 6 σ shows strong dependency on the beta* ratio at the IPs

Alternative crossing schemes become even more difficult→ separation up to factors 3-4 larger

Studies on-going to propose a back up scenario for the CDR!

Summary

A **robust baseline scenarios** has been studied and beam-beam separation proposed based on dynamic aperture studies for the FCC-hh different optics and more challenging beam-beam scenario.

Optimized optics parameters have been shown to allow highest dynamic aperture together with a global compensation scheme using Landau octupoles (see C. Tambasco talk for stability considerations)

Newer optics L* 40 m has to be optimized further with multipolar errors (on-going)

Head-on beam-beam limit seem far away from chosen parameters but studies show optimized working points in parallel to single particle dynamic aperture studies

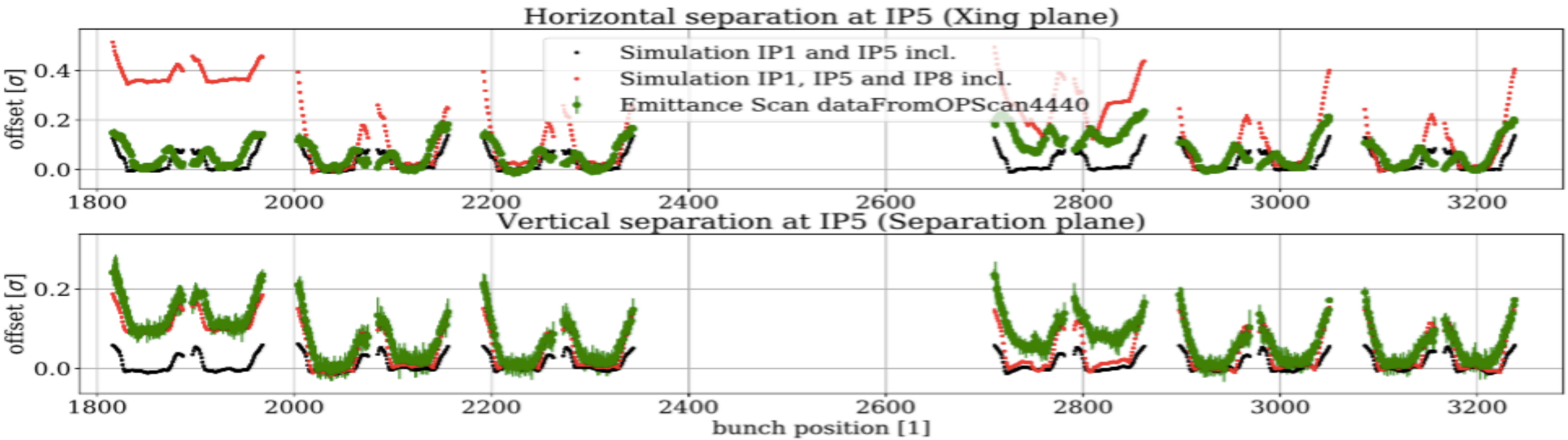
Large beta-beating should be expected (30 %) and needs further understand of implications

Alternative scenarios are explored to allow for flexibility in the presence of other constrains

Continuous benchmark to LHC data is fundamental to understand predictive power of simulations

Thank you!

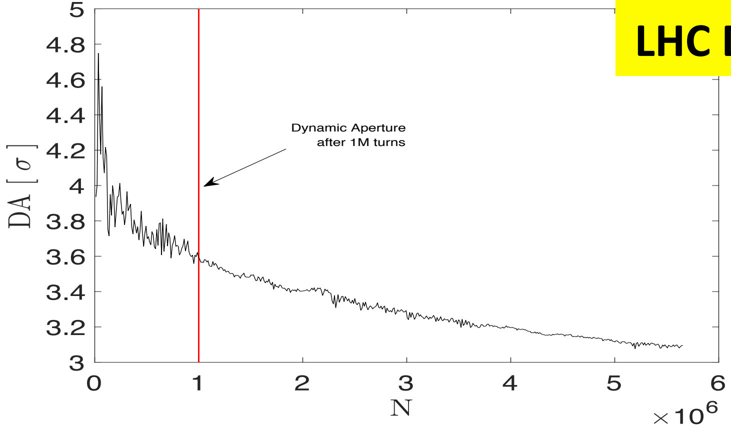
Orbit Effects



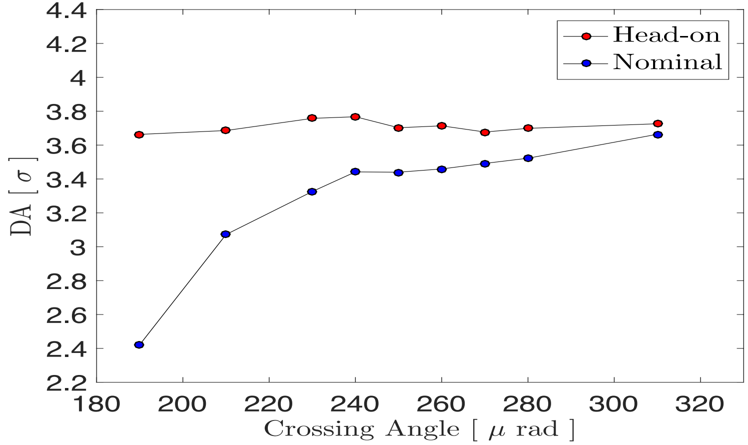
@IPAC2017 THPAB042

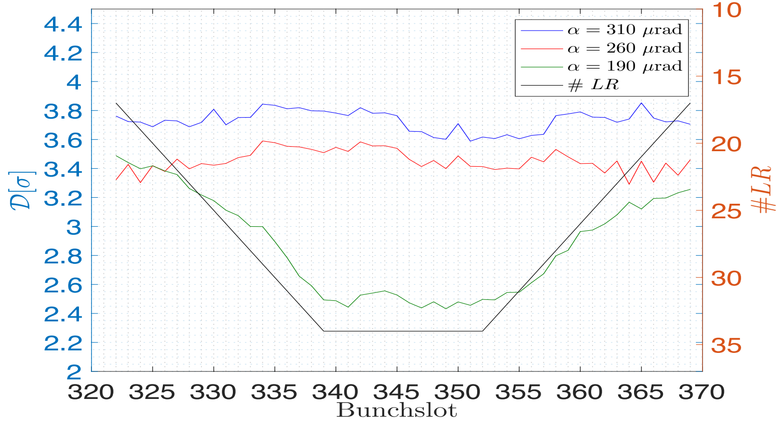
What have we learned from LHC and DA?

LHC DATA



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





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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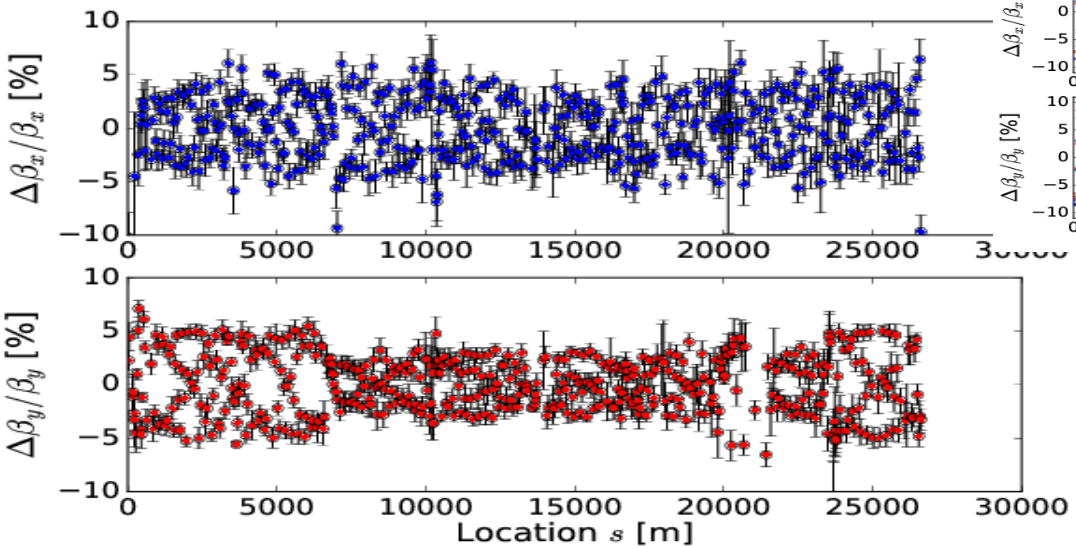
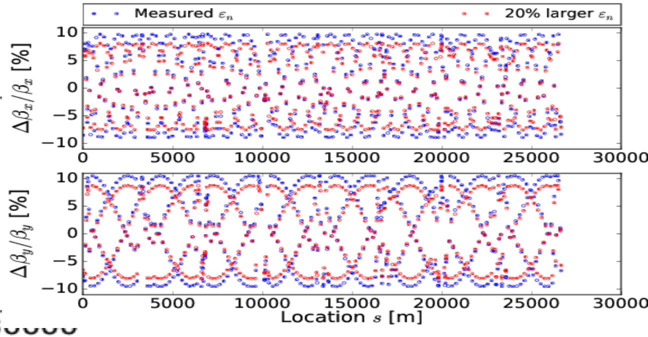
Head-on Beam-beam β-beating

First measurements in LHC and tests





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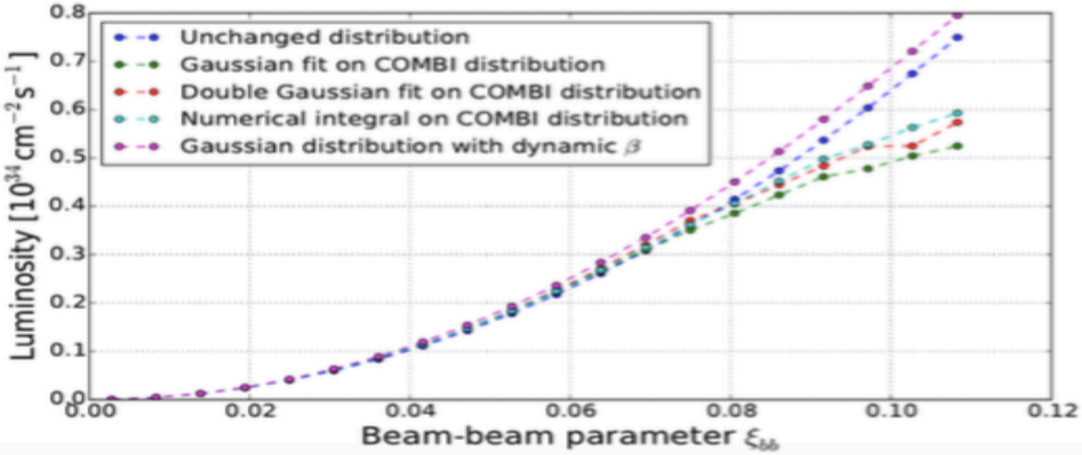
Measurements consistent with expectation
First attempt to correct, results under evaluations

Head-on Beam-beam β-beating impact on Luminosity

- The BB interact will not only modify the optics @ the IP (β^*) but as well the distribution itself.
- Luminosity is typically evaluated assuming Gaussian distributions. **Is this the case in strong ξ_{bb} regimes?**
- Gain in luminosity predicted by dynamic β distribution valid for all cases for $\xi_{bb} < 0.07$
- Deviation from Gaussian regime above $\xi_{bb} \sim 0.07$
- Luminosity from double Gaussian ≈ numerical integration ∀ ξ_{bb}



Impact on Luminosity marginal for FCC beam-beam parameters