# Long-range limit in the LHC: Lifetimes and dynamic aperture

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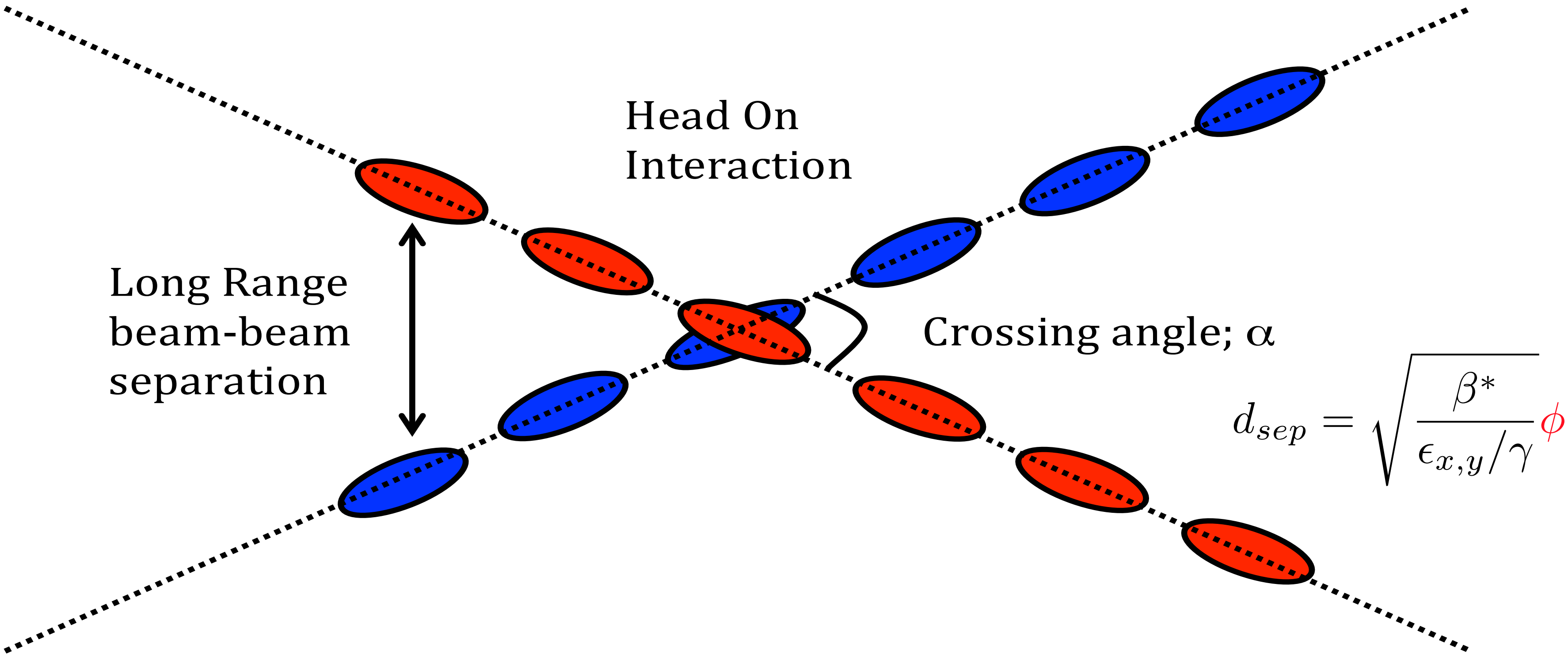
# Outline

- Long-range beam-beam machine study 2016
  - Long-range beam-beam studies at $\beta^* = 40$ cm
- Calculation of dynamic aperture from measured intensity loss
- Comparison of measured dynamic aperture to tracking simulations
- Summary and outlook

# Long-range beam-beam machine study 2016

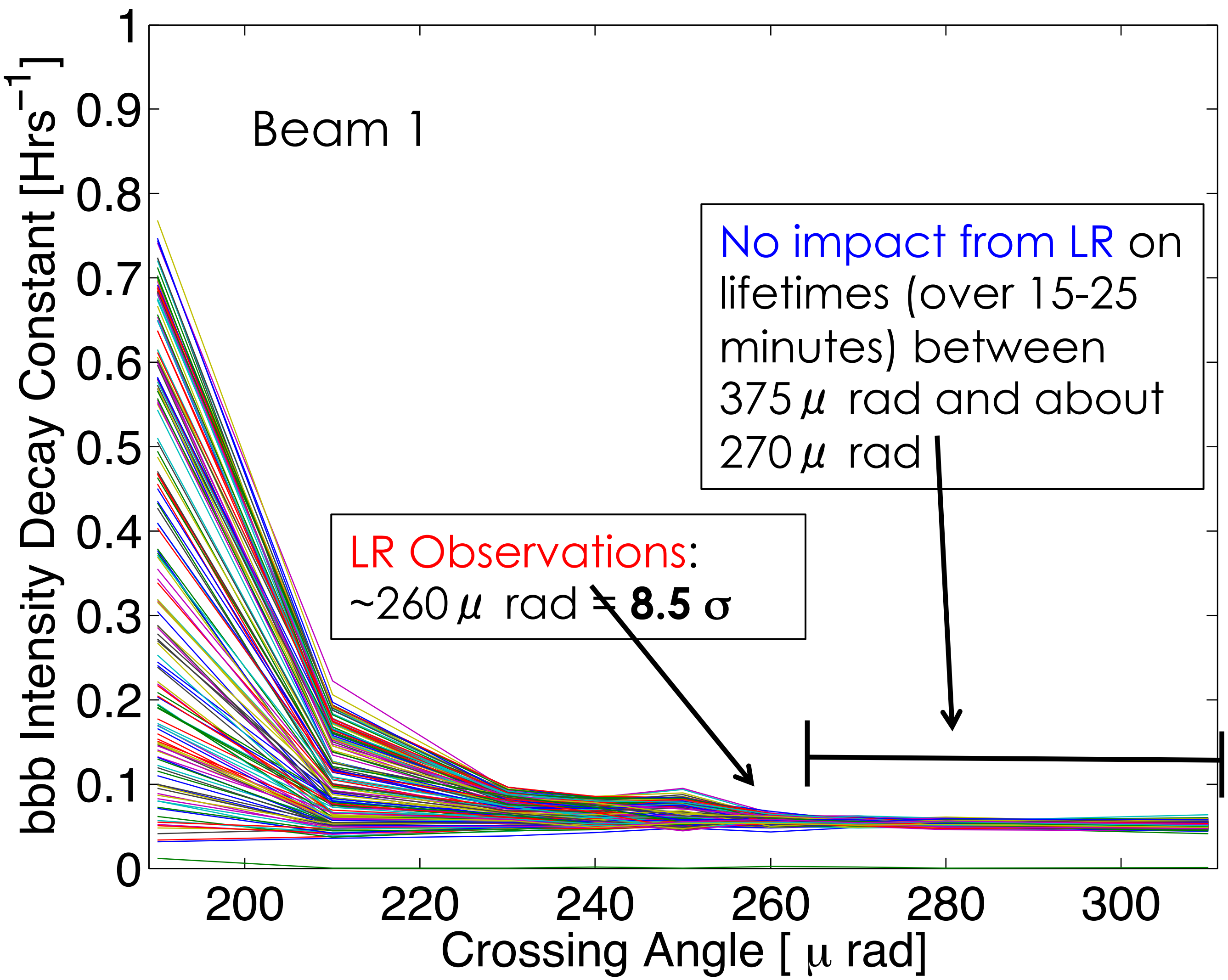
- Long-range beam-beam machine study performed during the 2016 run II of the LHC
- Three trains of bunches were collided at IP1/5, IP1/5/8, and IP1/5/2/8 to investigate the impact of collisions at different IPs.
- The crossing angle was then reduced from the nominal operational in sequential steps whilst the beam intensity and luminosity lifetimes were monitored.

# The long-range beam-beam limit




- Reducing the crossing angle reduces the beam-beam separation and hence increases the strength of the long-range beam-beam interaction
- This defines the minimum operational crossing angle and hence helps to define the maximum luminosity reach before long-range effects begin to impact the particle losses.
- Two experiments analysed performed: one in 2015 at $\beta^*$= 80 cm, a second during 2016 at $\beta^*$= 40cm.

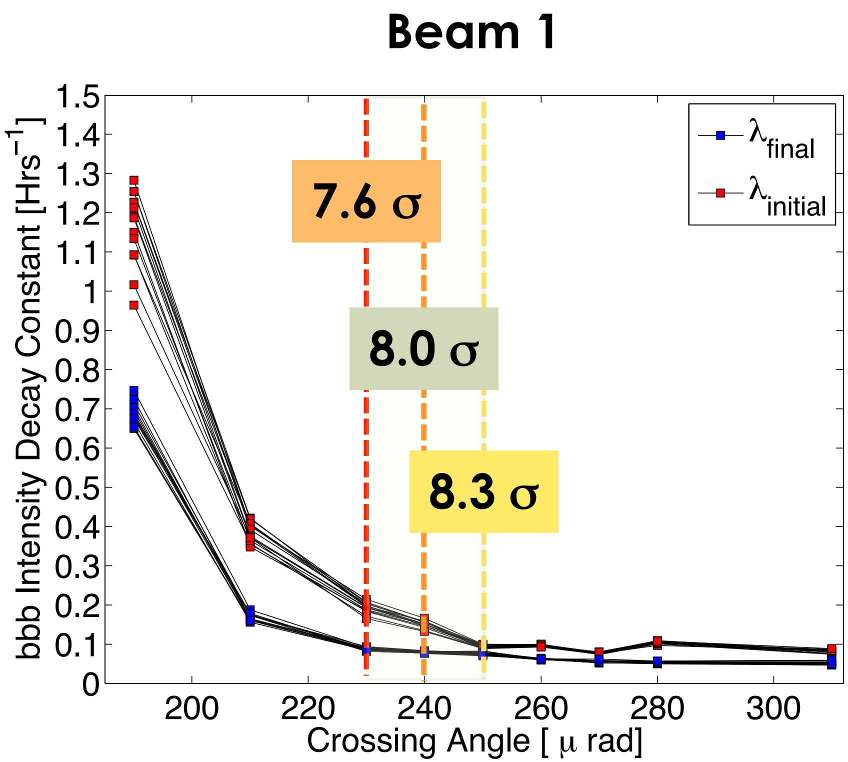
# Bunch by bunch intensity decay rates as a function of crossing angle




- In beam 1, the LR BB begins to impact decay rates at about $\alpha$=260 $\mu$ rad. This corresponds to a beam-beam separation at the first long-range interaction of about 8.5$\sigma$.
- However at crossing angles larger than this there is no impact from the crossing angle on the decay rates
- This indicates that there is scope to reduce the crossing angle.
- However not all bunches are effected the same.

# Intensity losses versus long range separation

First 5 minutes losses versus losses after 15 minutes



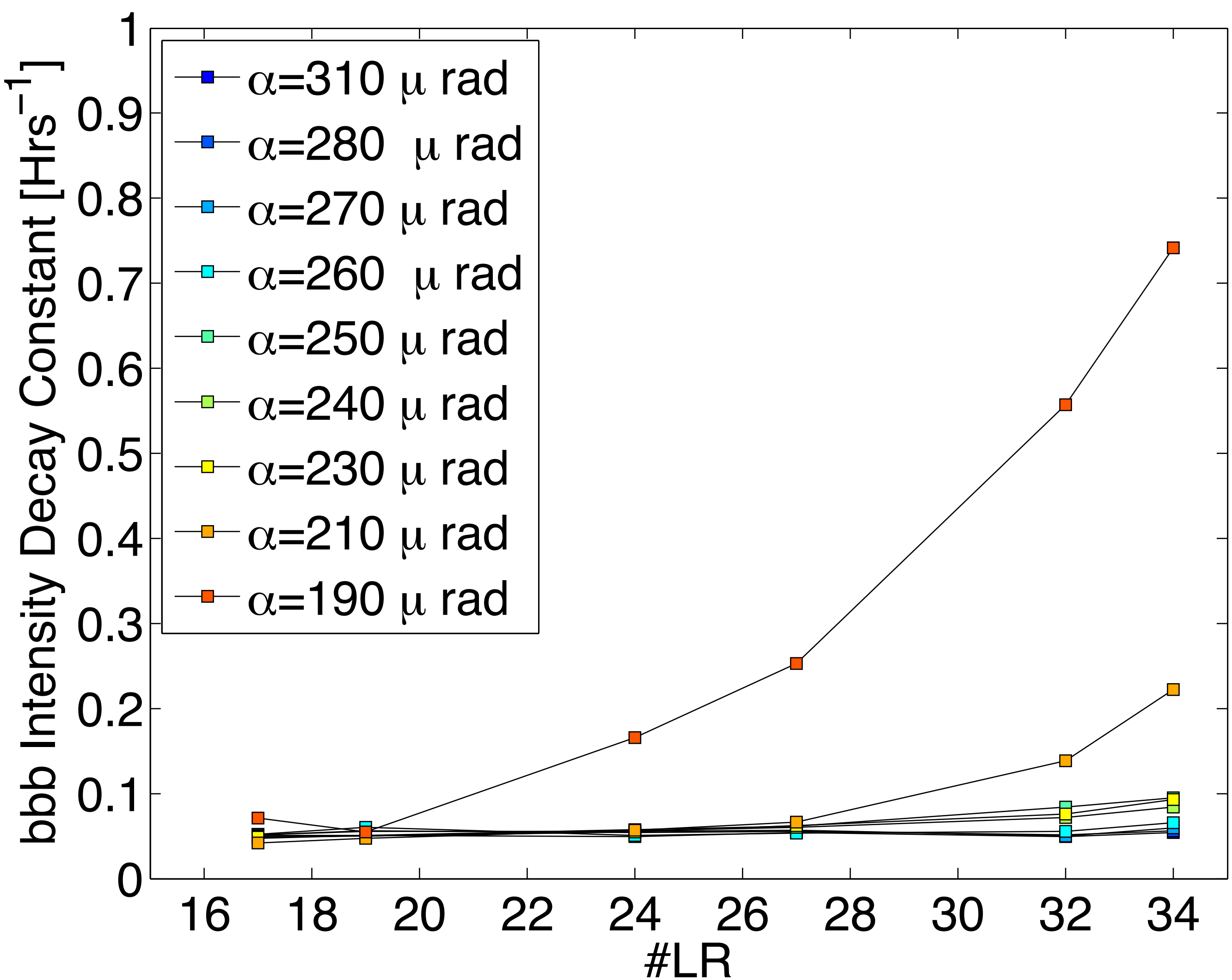

$$d_{sep} = \sqrt{\frac{\beta^*}{\epsilon_{x,y}/\gamma}}\phi$$

| $\phi$ |
|---|
| 310 |
| 280 |
| 270 |
| 260 |
| 250 |
| 240 |
| 230 |
| 210 |
| 190 |

Different regimes are present :

1. Weak Long-range beam-beam
2. Middle observable effects
3. Stron Long-range beam-beam effects

# Lifetimes as a function of the number of LR BB interactions




- Nominal bunches with the most number of long-range beam-beam interactions suffer the most at smaller crossing angles.
- The LRBBI causes particles to diffuse from the core of the bunch to the halo where they are then lost
- The LRBBI is strongest when the beam-beam separation is smallest which corresponds to the smallest crossing angle.
- NON-LINEAR scaling with the LR number

# Dynamic aperture from Intensity decay

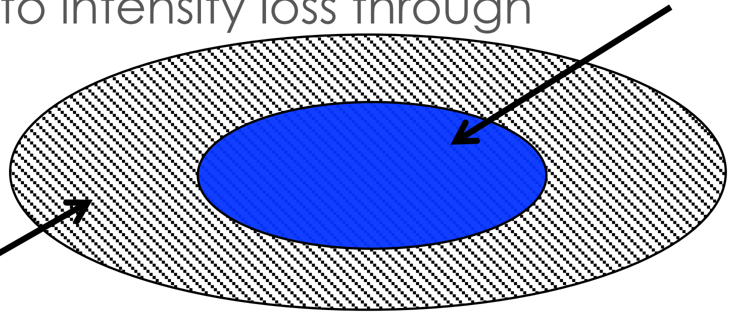
Using the method proposed by M.Giovannozzi (Phys Rev Spec Top-AB, 15(2): 024001, 2012)

- Partitioning of phase space.
  - When $r < D_\infty$ defines the motion of the particles to a KAM surface
  - When $r > D_\infty$ where chaotic motion occurs and the escape rate to infinity is determined by a Nekhoroshev like estimate
- Assuming a Gaussian charge density distribution

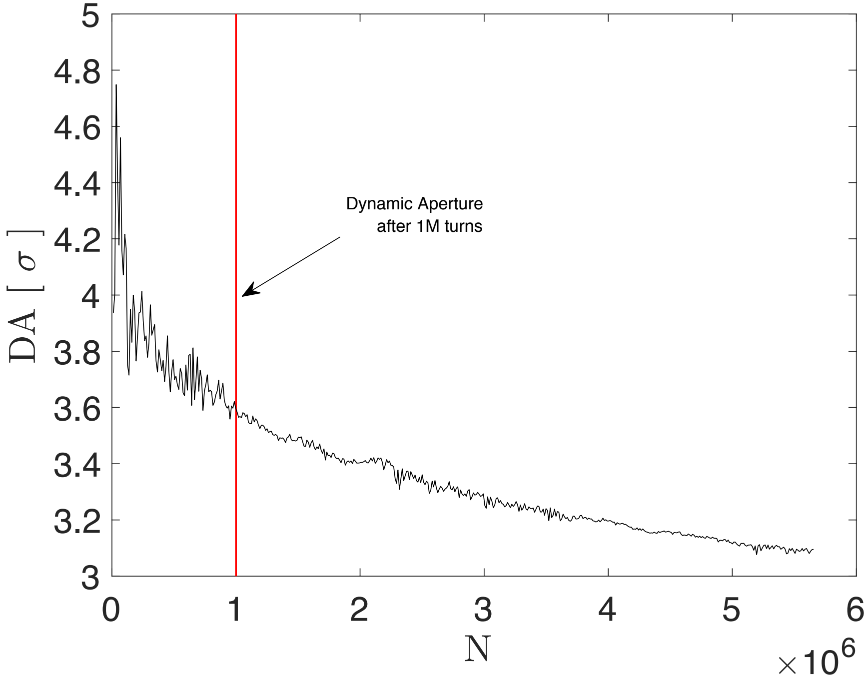
$$\frac{I}{I_0} = 1 - \int_{D(N)}^{\infty} r e^{-\frac{r^2}{2}} dr$$

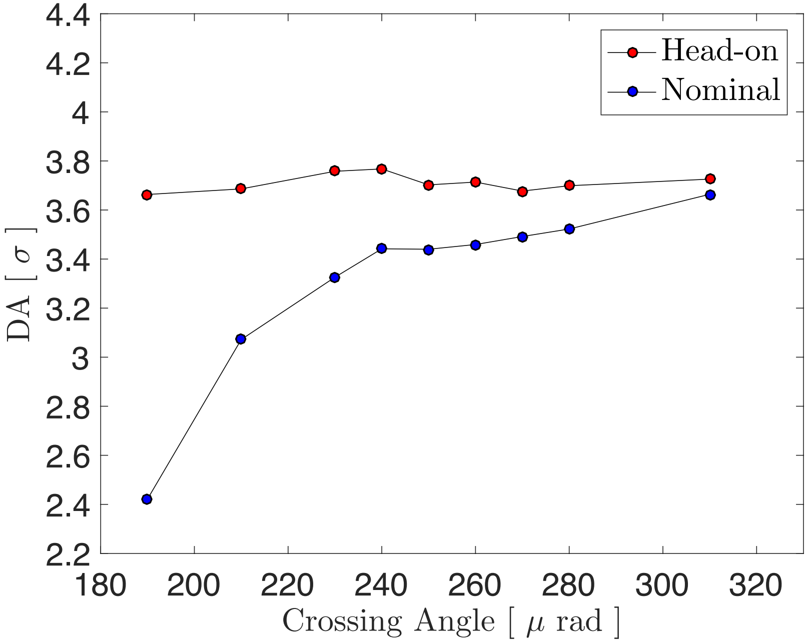
- The losses are given by the particles in the bunch outside of the dynamic aperture at turn N.
- The dynamic aperture is related to intensity loss through

$$D(N) = \sqrt{-2 * log\left(\frac{\Delta I}{I_0}\right)}$$



# Measured dynamic aperture from bunch intensity measurements as a function of turn number.




- Dynamic aperture as a function of turn number is calculated from the bunch intensity data where the proton losses due to luminosity have been subtracted
- We then take the value of the measured DA at $N=1x10^6$ in order to directly compare to tracking simulations which are now limited to this time length

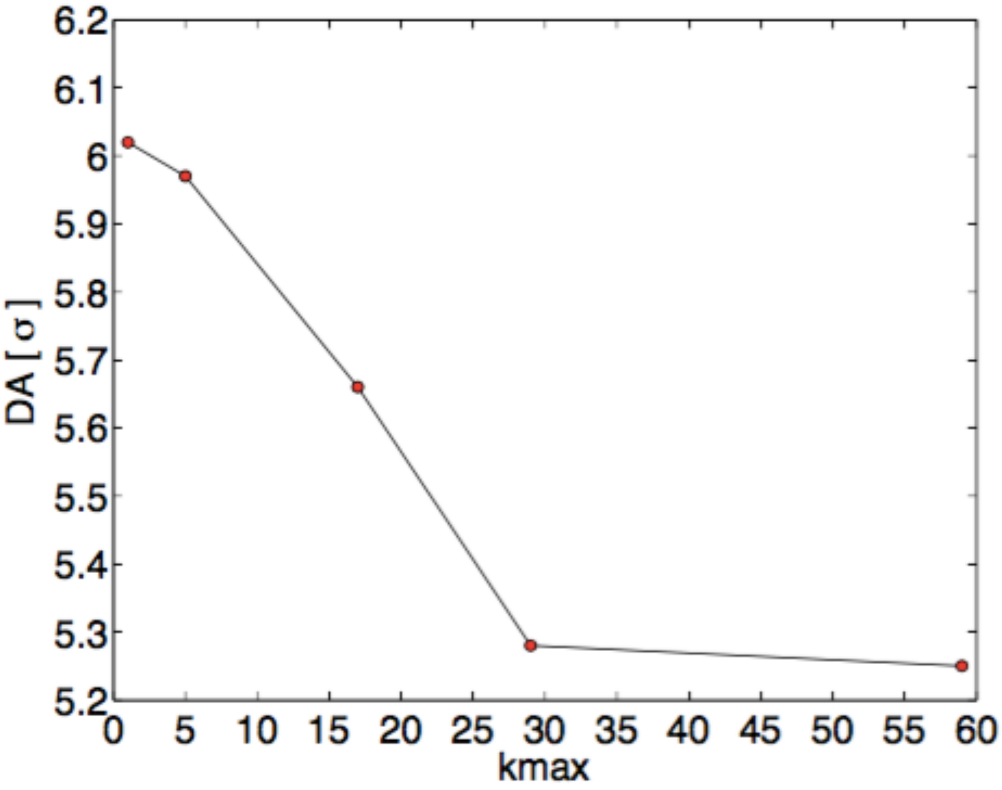
# How to describe the particle transverse space

**Simulation set-up with Sixtrack**

Converged DA from simulations

→ Well described x/y space to well define the associated losses 60 x/y particles

The $10^6$ turns DA is used minimum (used for design) and average (to relate to real machine)

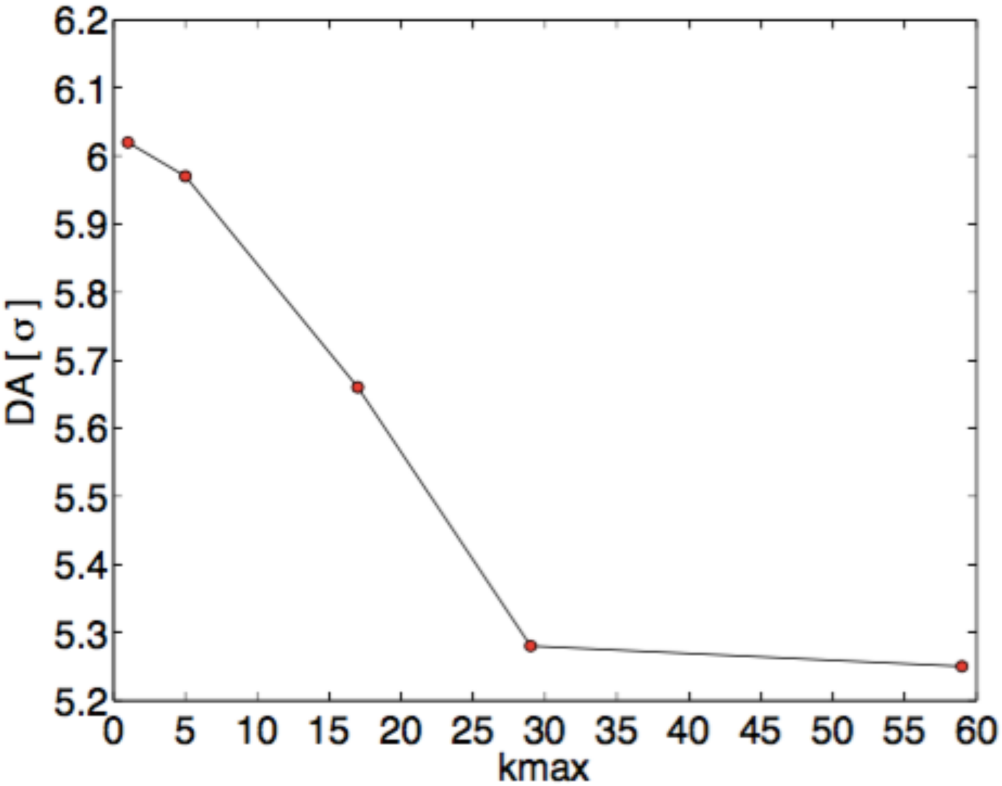


# How to describe the particle transverse space

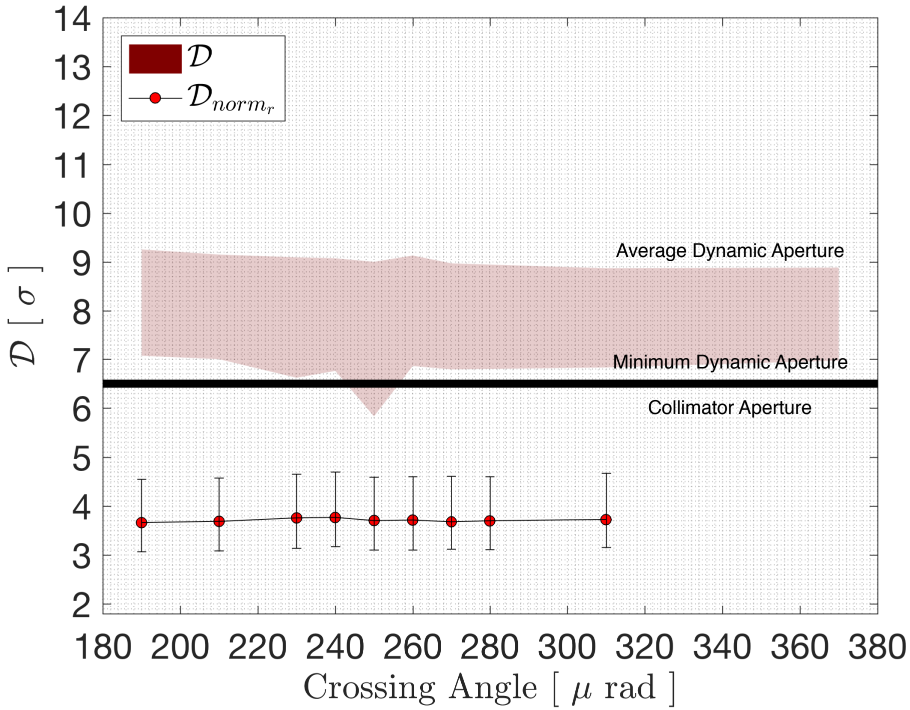
**Simulation set-up with Sixtrack**

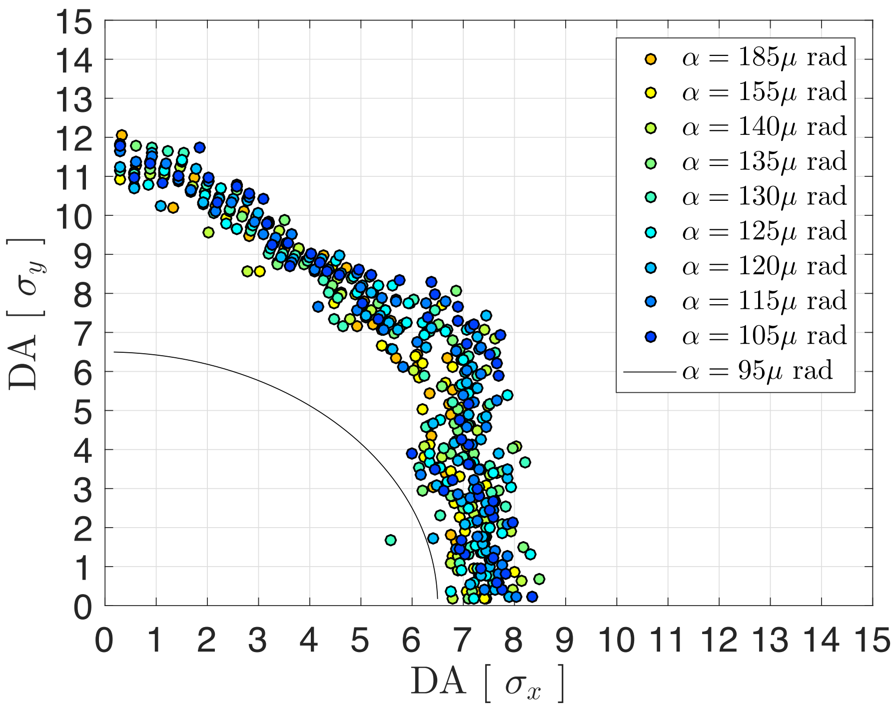
Beam-beam effects computed with measured parameters (emittances and intensities) and well detailed machine configuration from measurements (tunes, crossing angles, multipolar errors, IR description…)

Apply collimation cut to particle distribution in x/y space



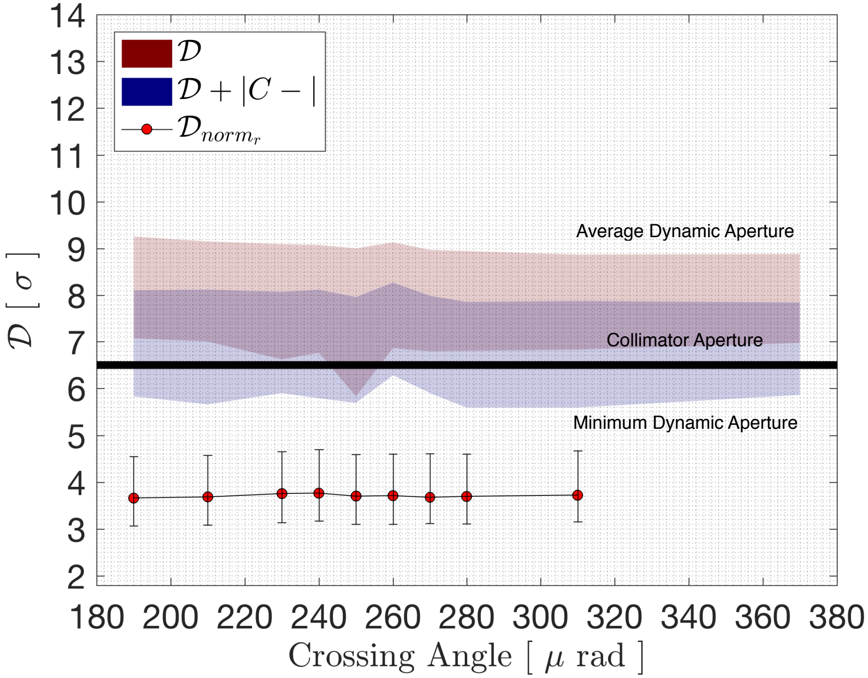
# Head-on beam-beam alone

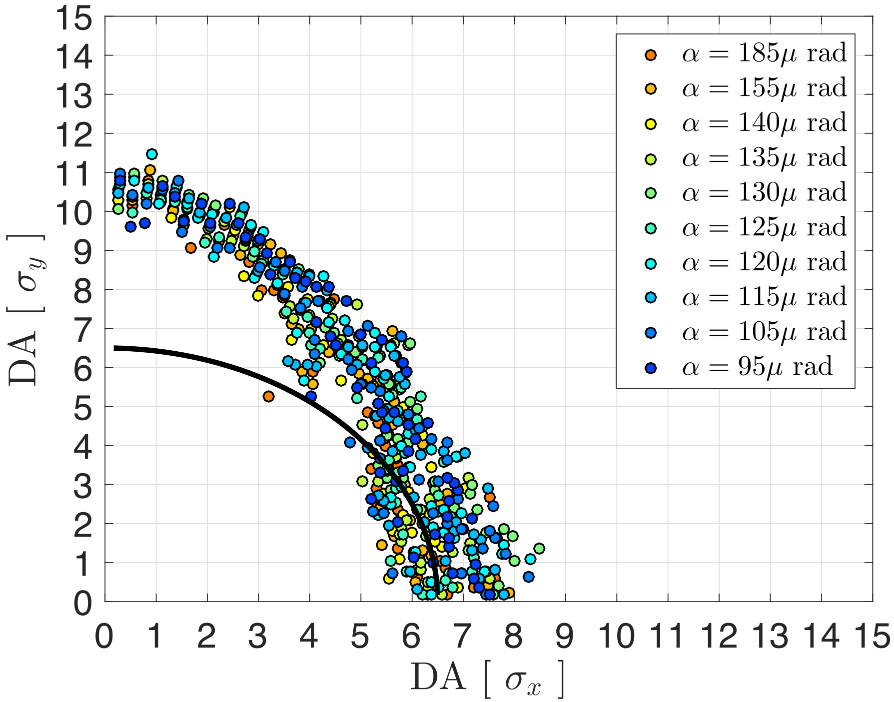



- Head-on Dynamic aperture only beam-beam

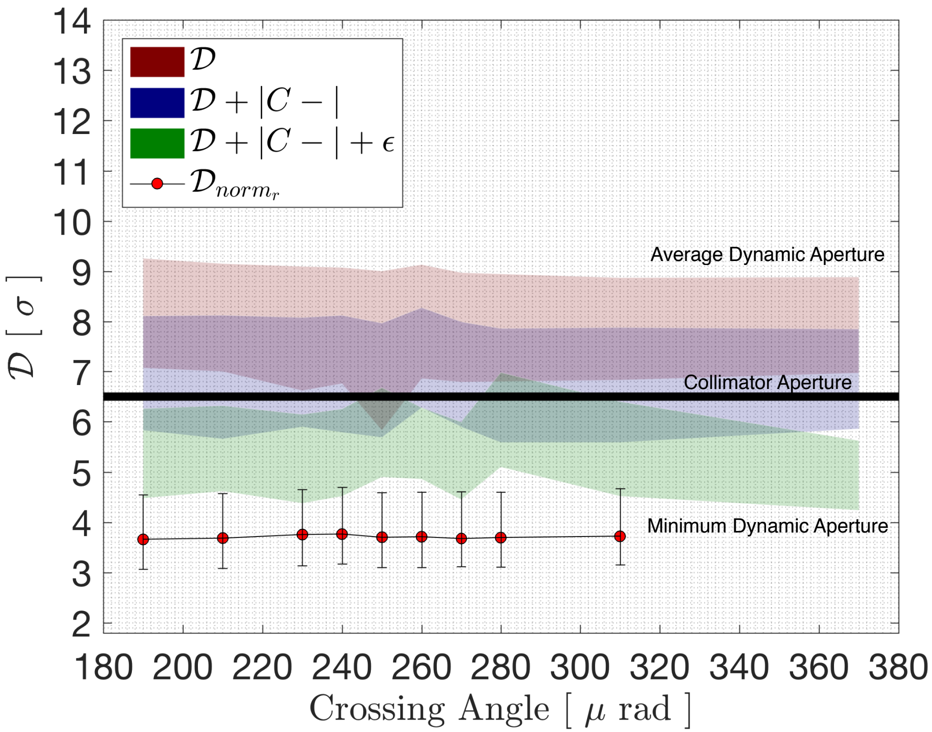
# Head-on BB + Linear coupling

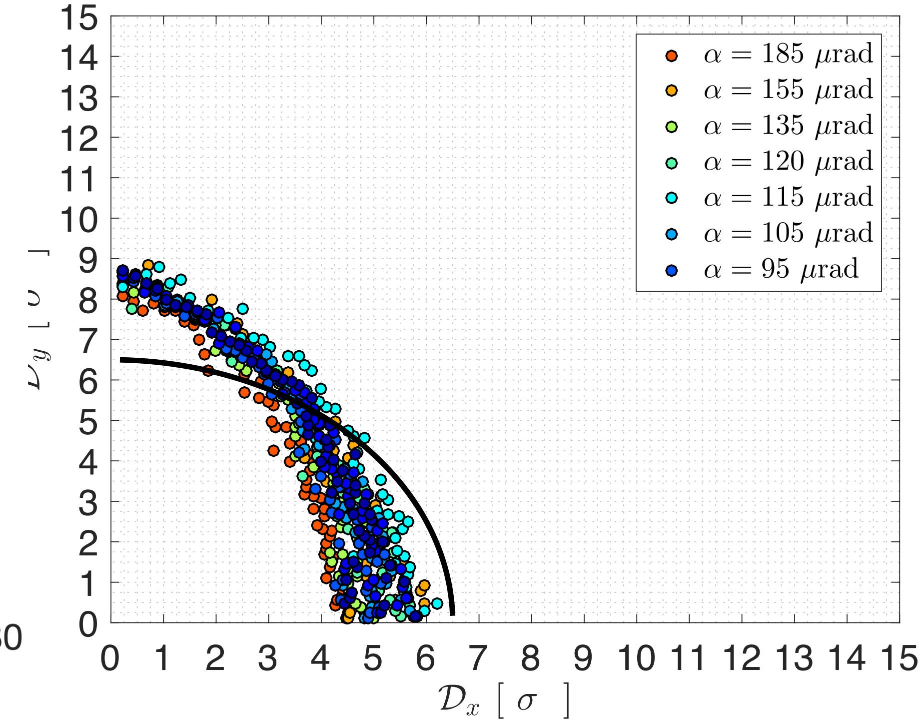



- Head-on Dynamic aperture beam-beam head-on and linear coupling

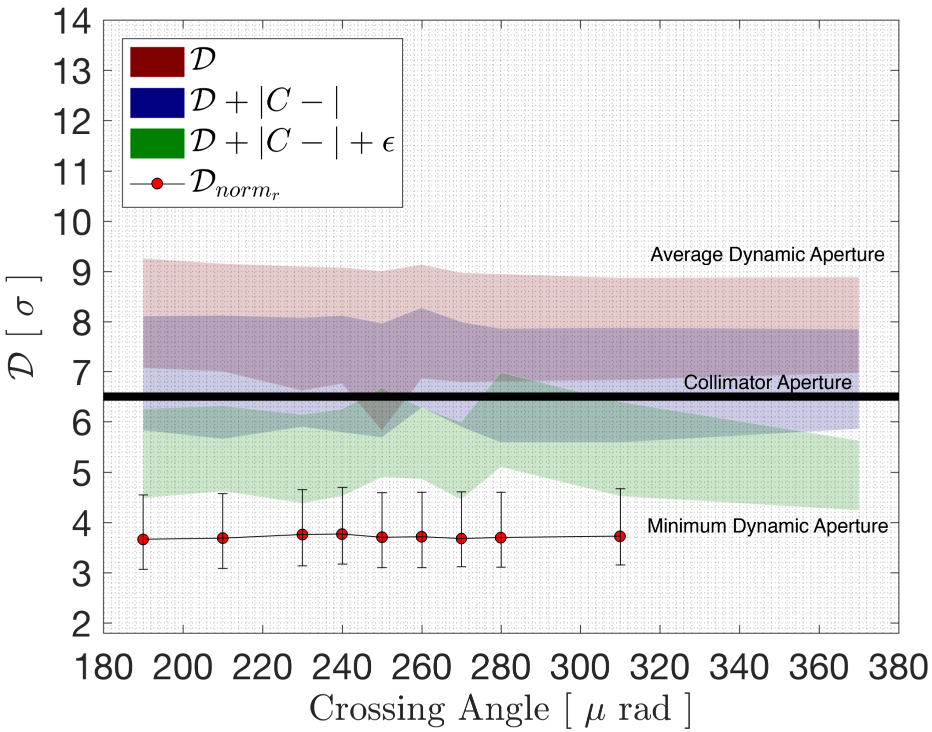
# Head-on BB + Linear coupling + Magnetic errors

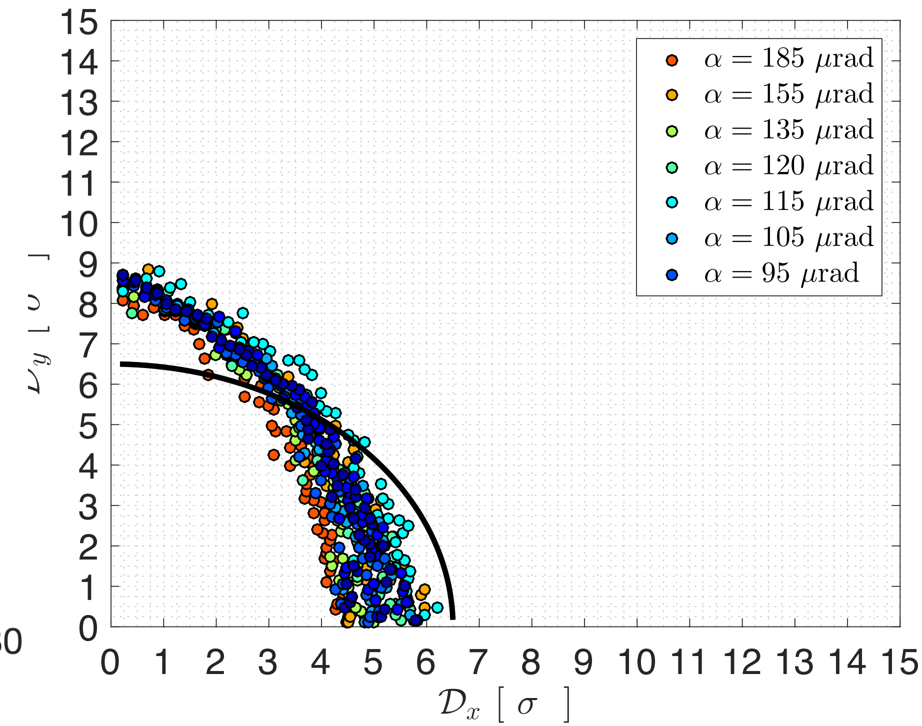



- Tracking simulations including head-on beam-beam interactions, linear coupling ($4 \times 10^{-3}$) and magnetic errors.
- Still some difference between the measured DA and the tracking simulations that still needs to be understood.

# Head-on BB + Linear coupling + Magnetic errors

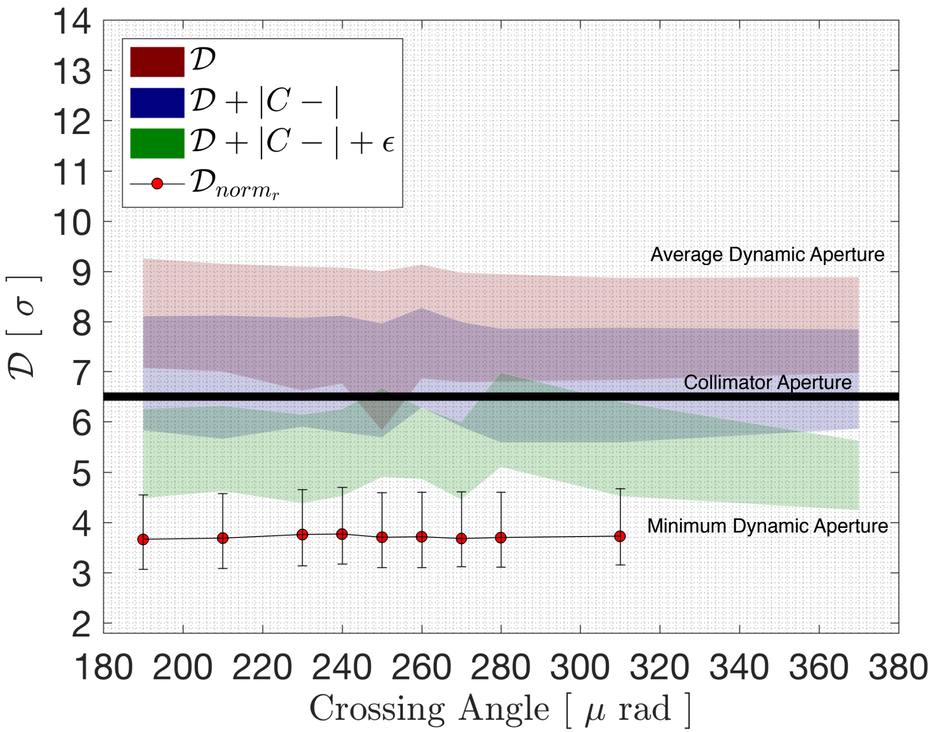


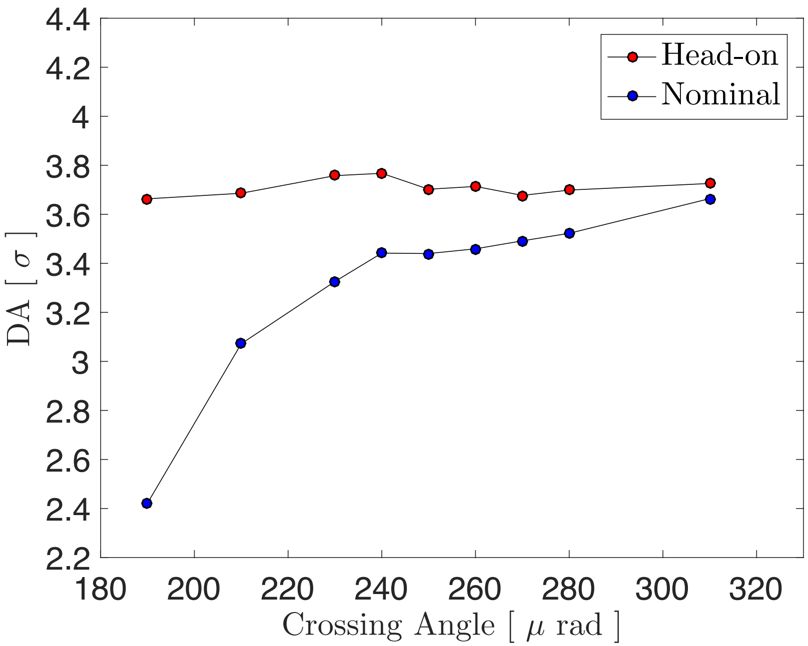




- Tracking simulations including head-on beam-beam interactions, linear coupling (4x10$^{-3}$) and magnetic errors.

- Still some difference between the measured DA and the tracking simulations that still needs to be understood.

# Head-on BB + Linear coupling + Magnetic errors

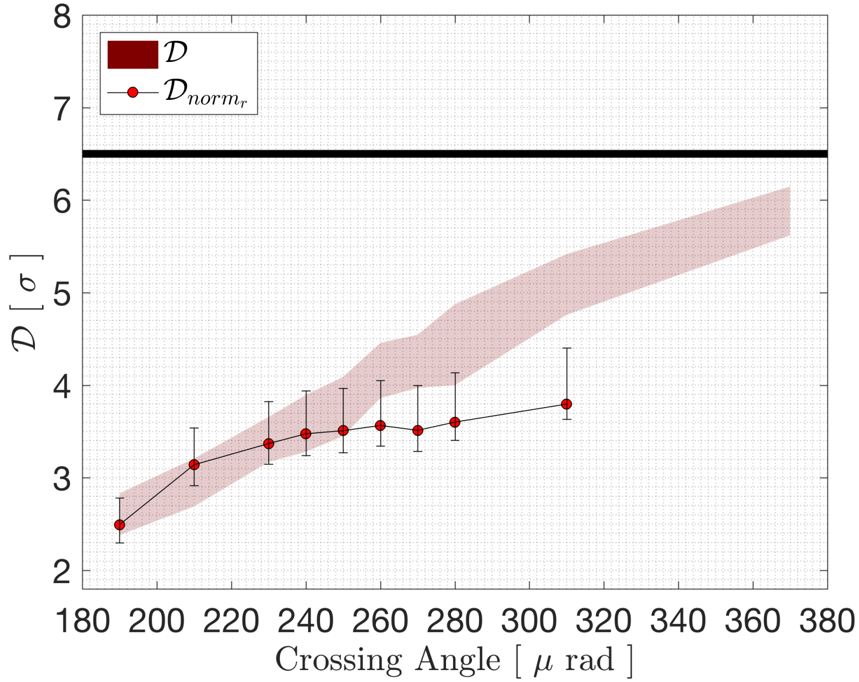


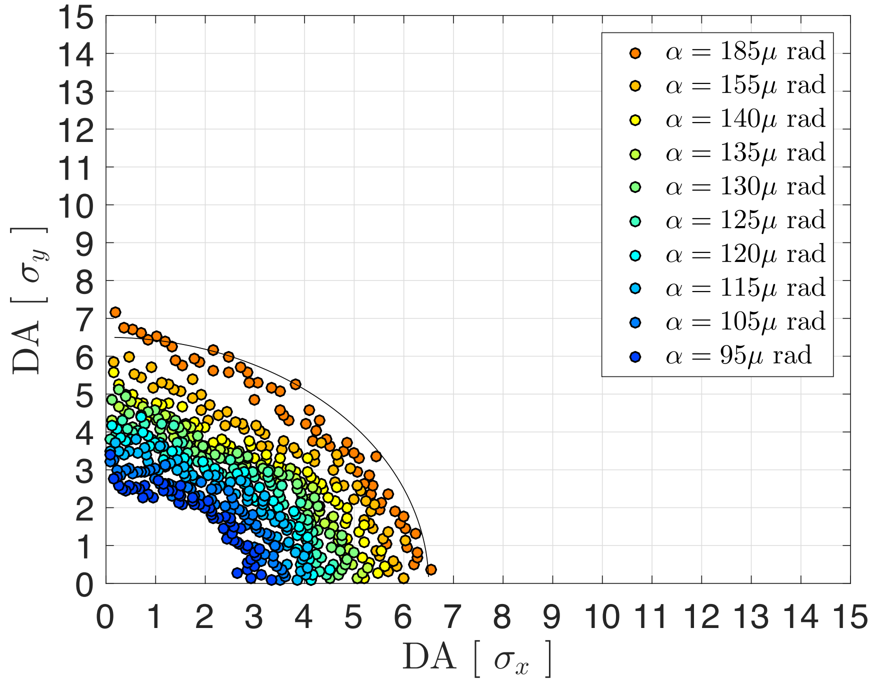




- Losses due to head-on with errors are similar to the one of long-ranges in the time scale analyzed

→ In a weak long-range regime what is dictating the losses are other mechanisms

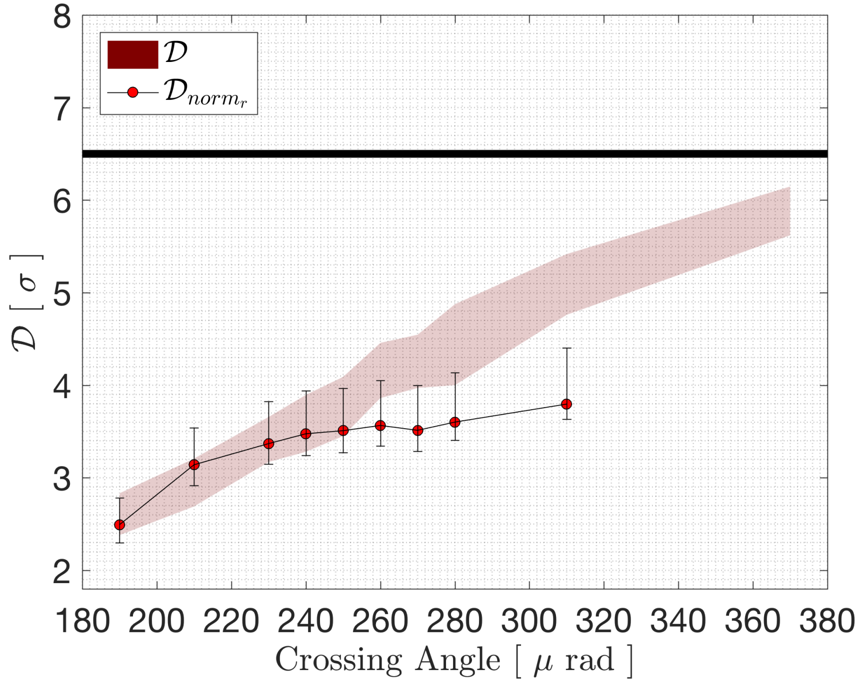
# Head-on + Long-Range Beam-Beam

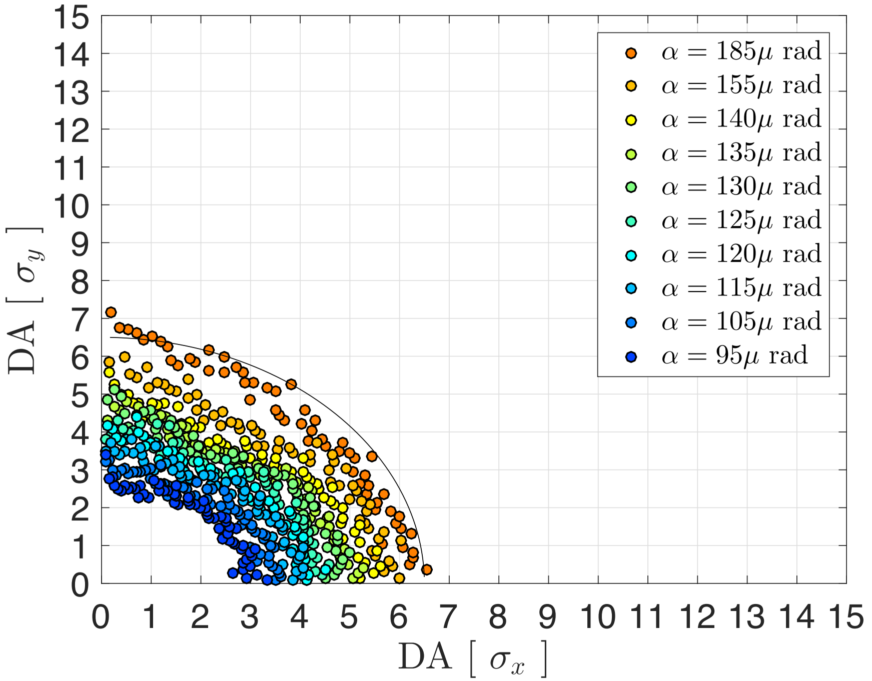



- Head-on + Long-range interactions Dynamic aperture
  - → DA is below the collimation cut
  - → Losses cannot be explained by DA alone at large angle

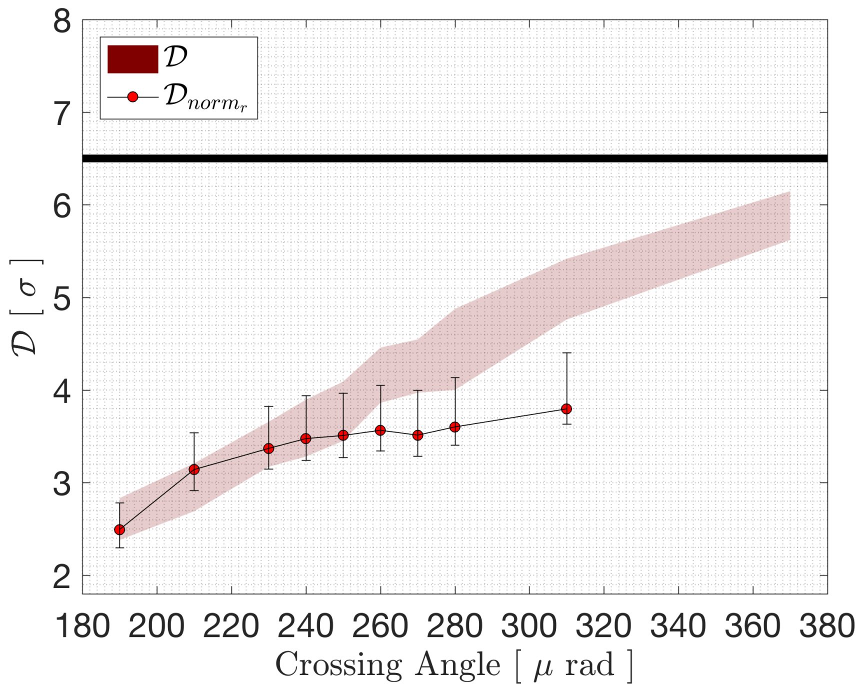
# Head-on + Long-Range Beam-Beam

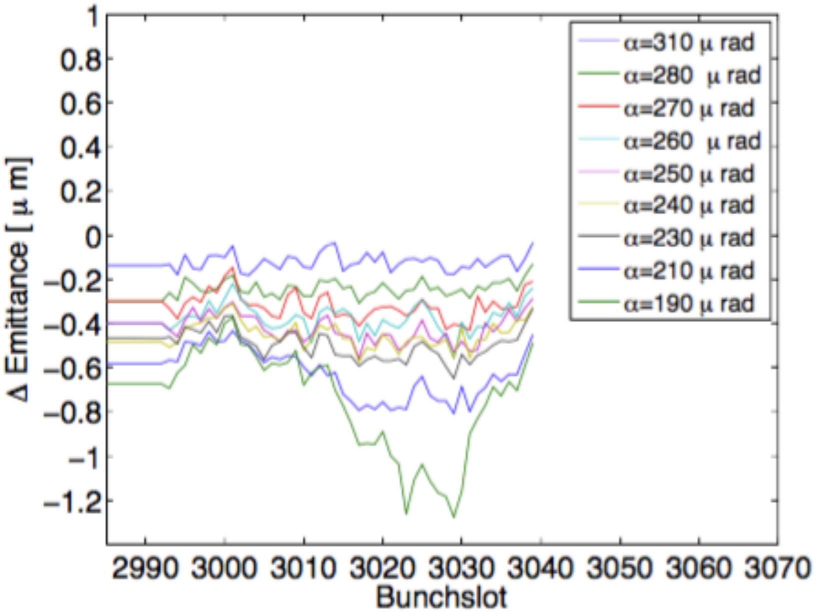



- Head-on + Long-range interactions Dynamic aperture
  - → DA is below the collimation cut
  - → Losses can be explained by DA alone at lower angles where Long-range beam-beam scrap the beams

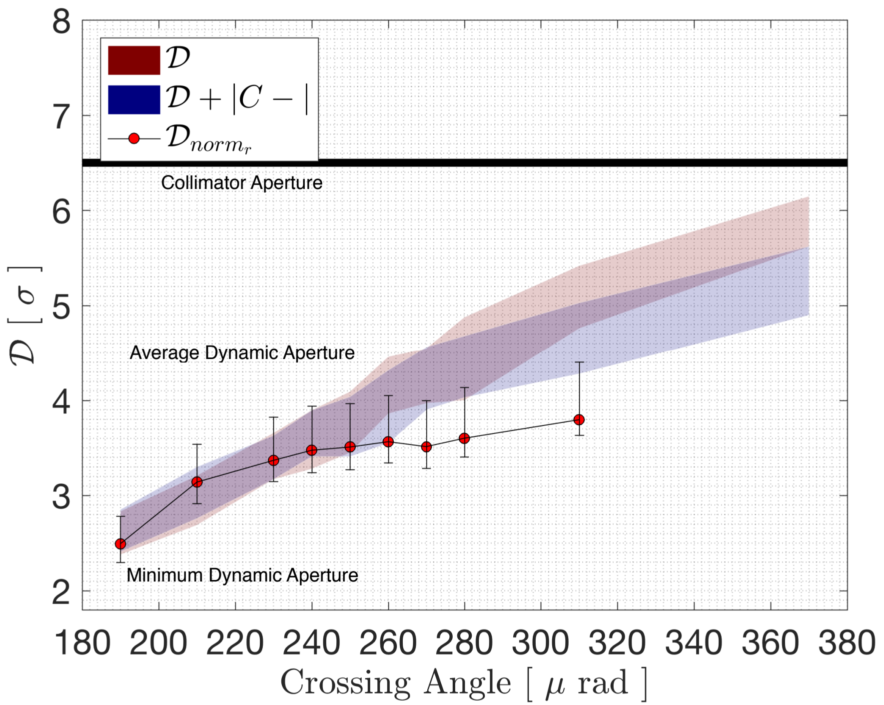
# Head-on + Long-Range Beam-Beam

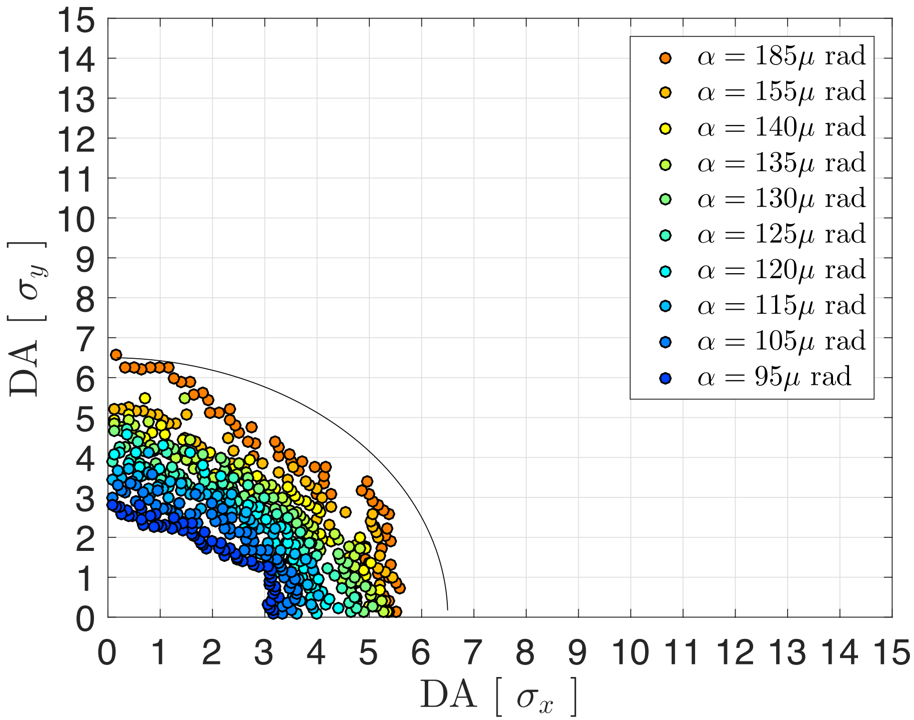



- Head-on + Long-range interactions Dynamic aperture
- → DA is below the collimation cut
- → Losses can be explained by DA alone at lower angles where Long-range beam-beam scrap the beams (we loose faster and depends on transverse dimensions and encounters)

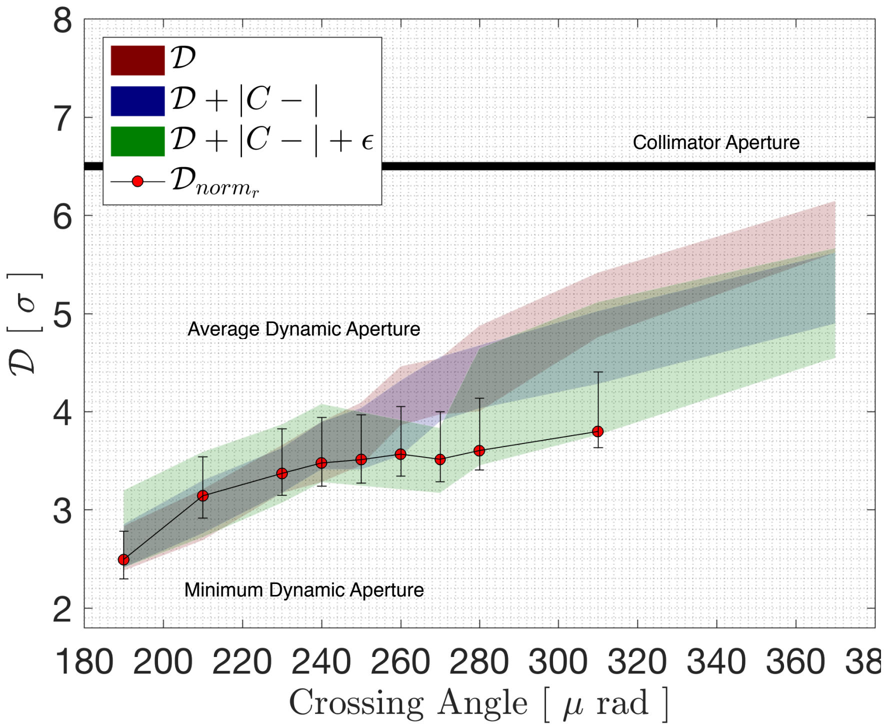
# Head-on + Long-Range+ Linear Coupling

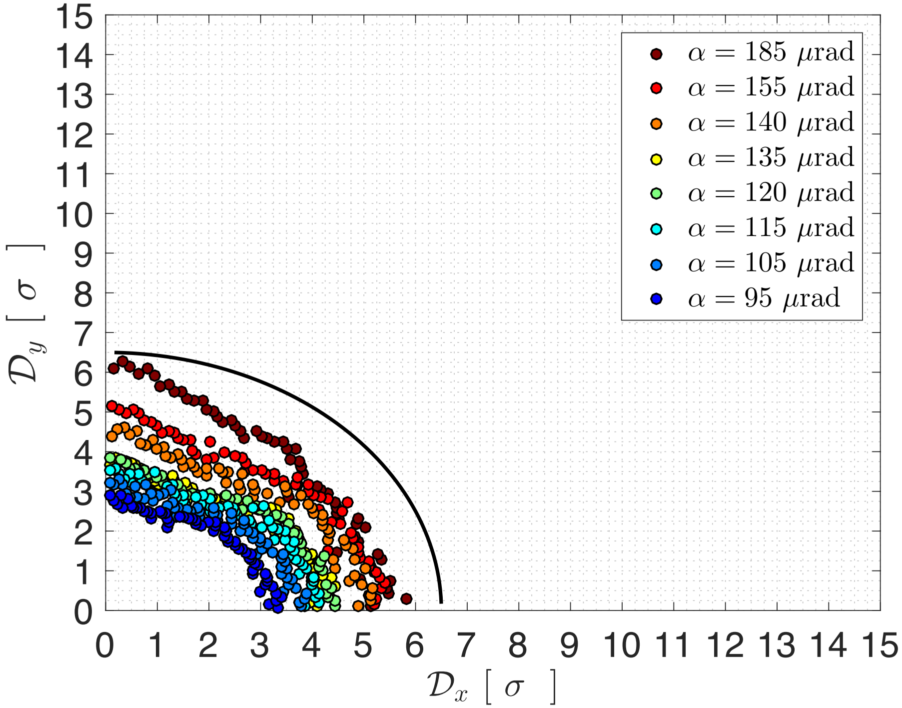



- Head-on + Long-range interactions Dynamic aperture
  - → DA is below the collimation cut
  - → Losses cannot explain the large crossing angles neither in the presence of strong (measured) linear coupling

# Head-on + Long-range + Linear Coupling + Magnetic errors




- Head-on + Long-range interactions Dynamic aperture + Coupling and multiple errors in the lattice
  - → DA is below the collimation cut
  - → Losses can explain the large crossing angles losses and do not impact the behaviour at small beam-beam separations

# Summary

- Experiments in controlled way are very useful to understand the limitations and to benchmark the available models
- Sixtrack has been benchmarked to the LHC using a model for the losses associated to dynamic aperture
- Qualitatively agreement between the measurements and the simulations
- Head-on interaction alone not fully understood
  - Noise of 2-3%/h growth rate?
  - Weak strong modeling non fully describing the whole picture.
- Head-on and Long-range interactions well described
  - Low crossing angle losses dominated by beam-beam effects
  - Larger crossing angle machine non-linearities and head-on...

# Outlook

Continue the benchmark for other cases (i.e. 2015 data)

Look into the PACMAN differences and to bunch by bunch fast losses

Refine the model introducing diffusive mechanisms in the DA evolution from losses (i.e. noise effects)

Understand the H/V asymmetry in losses seen also in simulations

Benchmark to LHC data in different configurations of DA (from 2012 to today) single and two beams

Add to the FCC-hh luminosity model and evaluate impact on performances

# Outlook

Continue the be

Look into the PA … losses

Refine the mode … volution from
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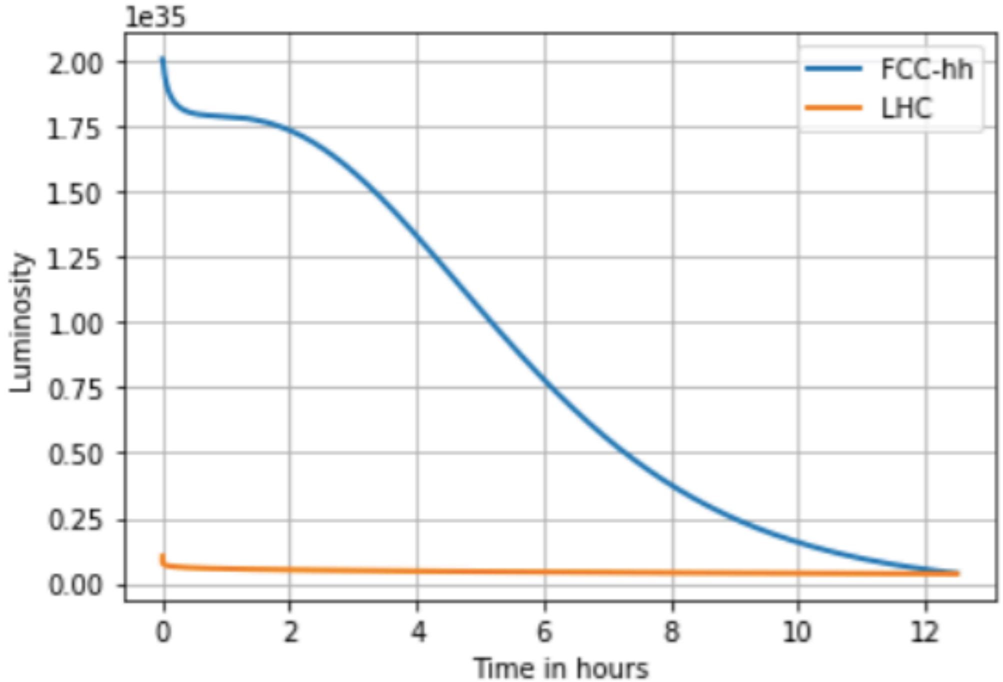
Benchmark to LH … 2012 to today)

Add to the FCC- … erformances



Thank you