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FCC hh ee he

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

Beam-Beam Studies for Future Circular Hadron Colliders

T. Pieloni,
J. Barranco, P. Goncalves, C. Tambasco, L. Rivkin (EPF Lausanne)
X. Buffat, S. V. Furuseth, M. Giovannozzi (CERN)
M. Crouch, R. Appleby (Manchester University)

LHC@home SixTrack

Acknowledgements: R. Tomas, L. Medina, D. Schulte, A. Seryi, EIR team, M. Roman, B. Dalena, S. Antipov, D. Amorin, M. Hofer, I. Zackarov, E. Metral, F. Zimmermann, R. DeMaria, W. Herr, B. Salvant, S. Antipov, S. Arsinev and all the FCC-hh and HE-LHC collaborators.

The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

EuroCirCol A key to New Physics

Contents

- FCC hadron colliders parameters and options
- Beam-Beam effects for a FCC-hh
  – Incoherent studies
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    - Landau damping and impacts on DA
- Beam-Beam studies for HE-LHC
- Summary and outlook

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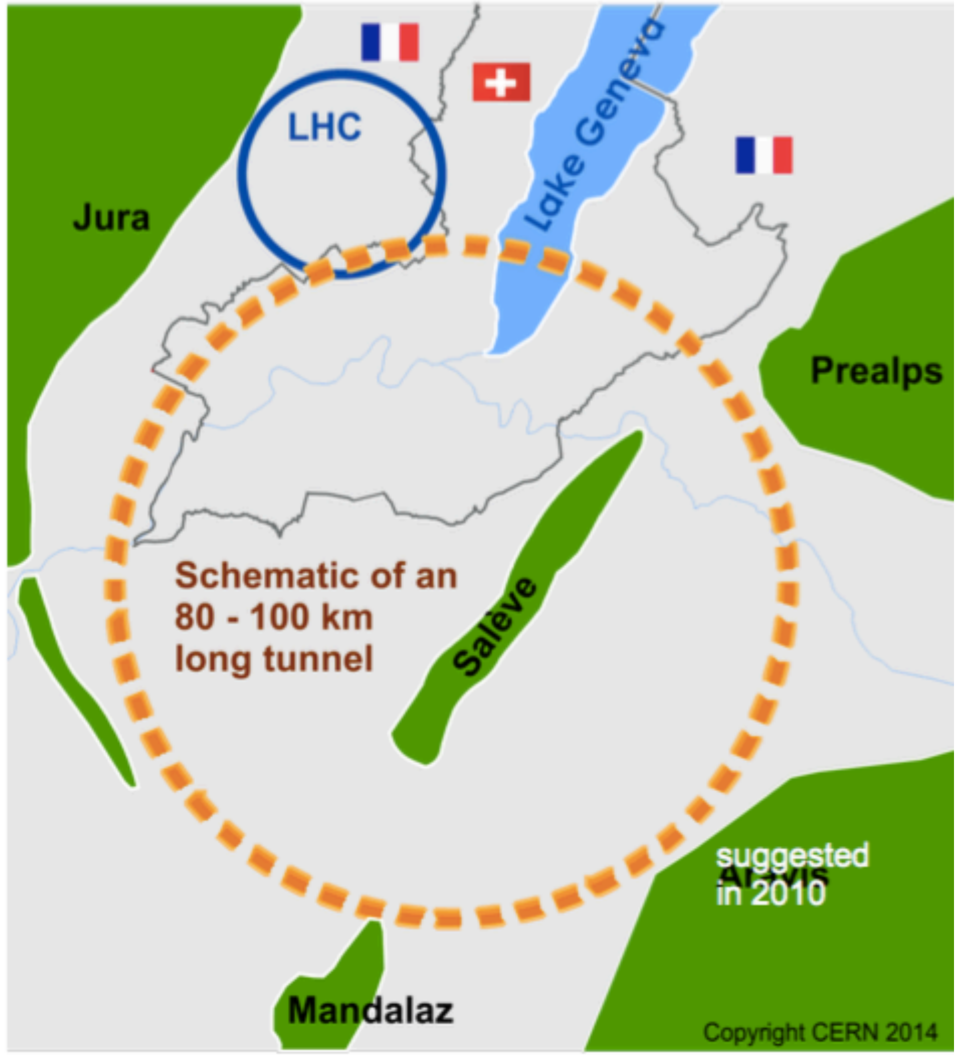
Future Circular Collider Study
CDR for European Strategy Update 2019/20

international FCC collaboration (CERN as host lab) to design:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as a possible first step
- ***p-e* (*FCC-he*) option,** one IP, FCC-hh & ERL
- **HE-LHC** w *FCC-hh* technology



F. Zimmermann HE-LHC review Dec 2017

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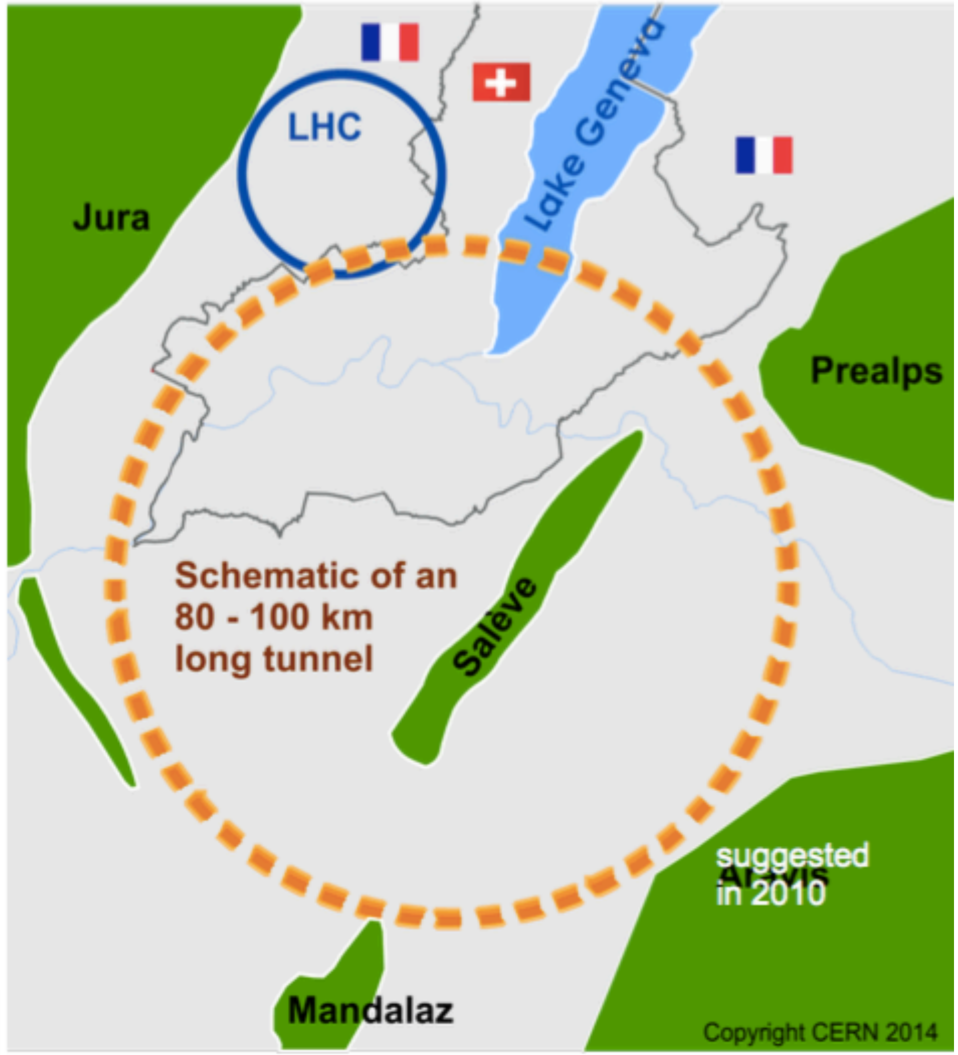

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High Energy Colliders: Present/Future

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	60(300)LR + 2 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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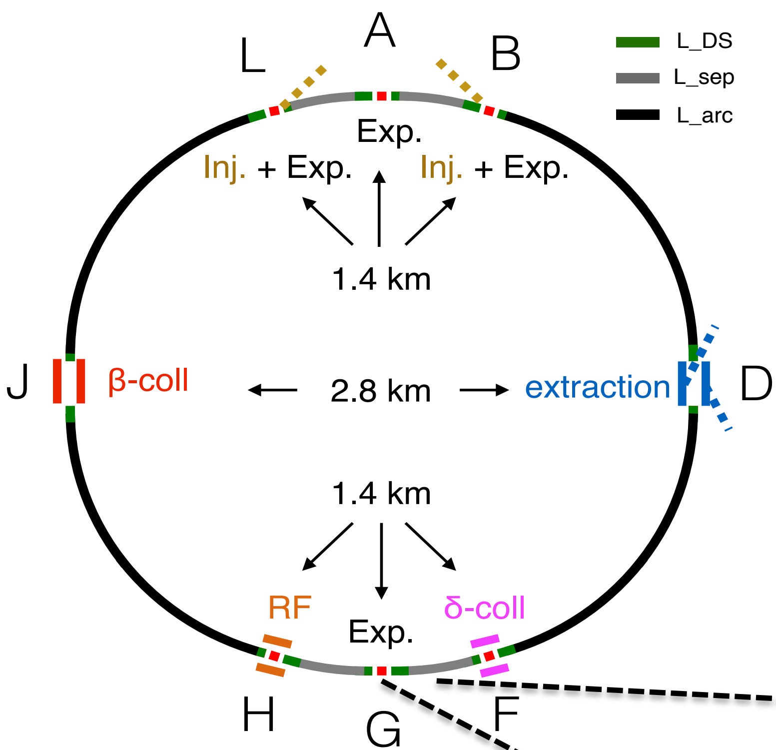
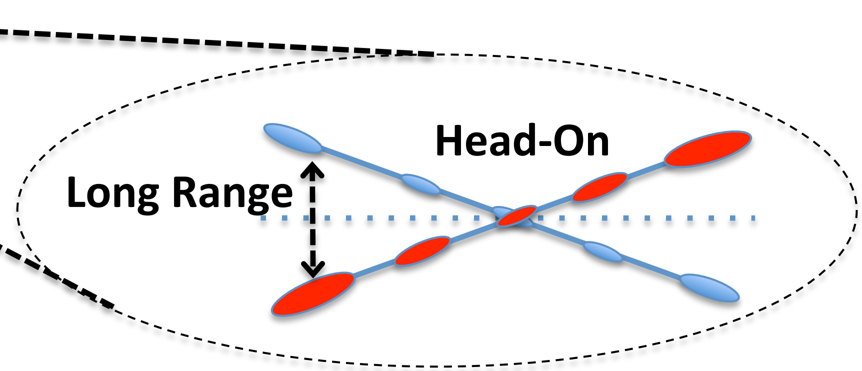
Total ξ_{bb}	**0.017 -0.02**	**0.017 -0.02**	**0.01/0.02-0.03/0.05**	

FCC-hh Interaction Points

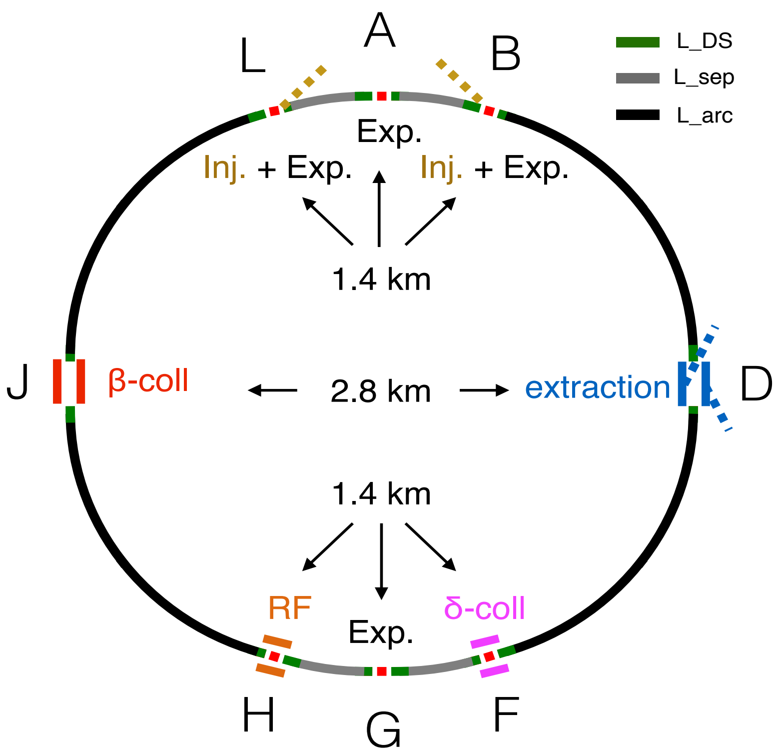


4 experiments:

- 2 high luminosity IPA and G (5-30 x LHC_{nom})
- 2 low luminosity IPL and B (tbd with negligible impact on performances of IPA and G)



FCC-hh 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

All cases with 25 ns bunch spacing

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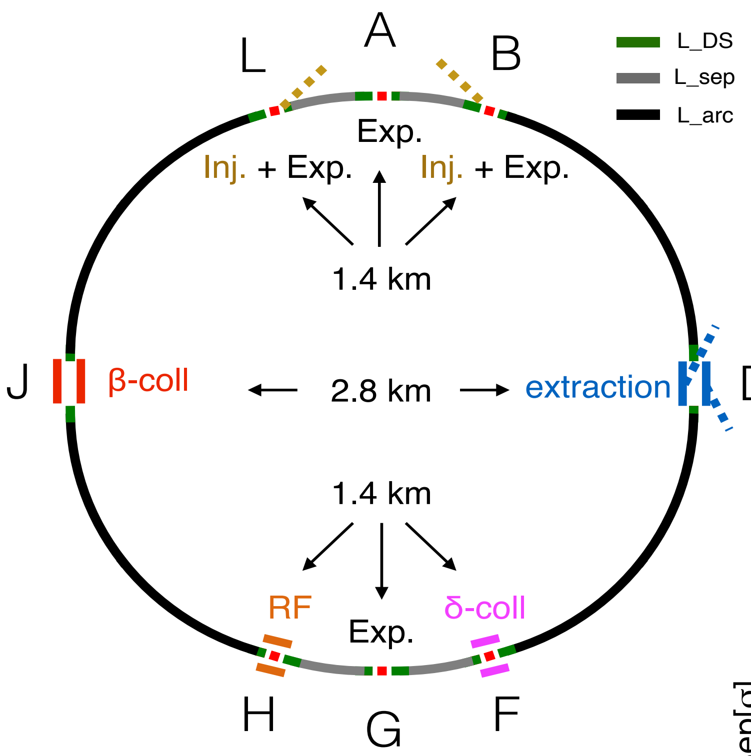
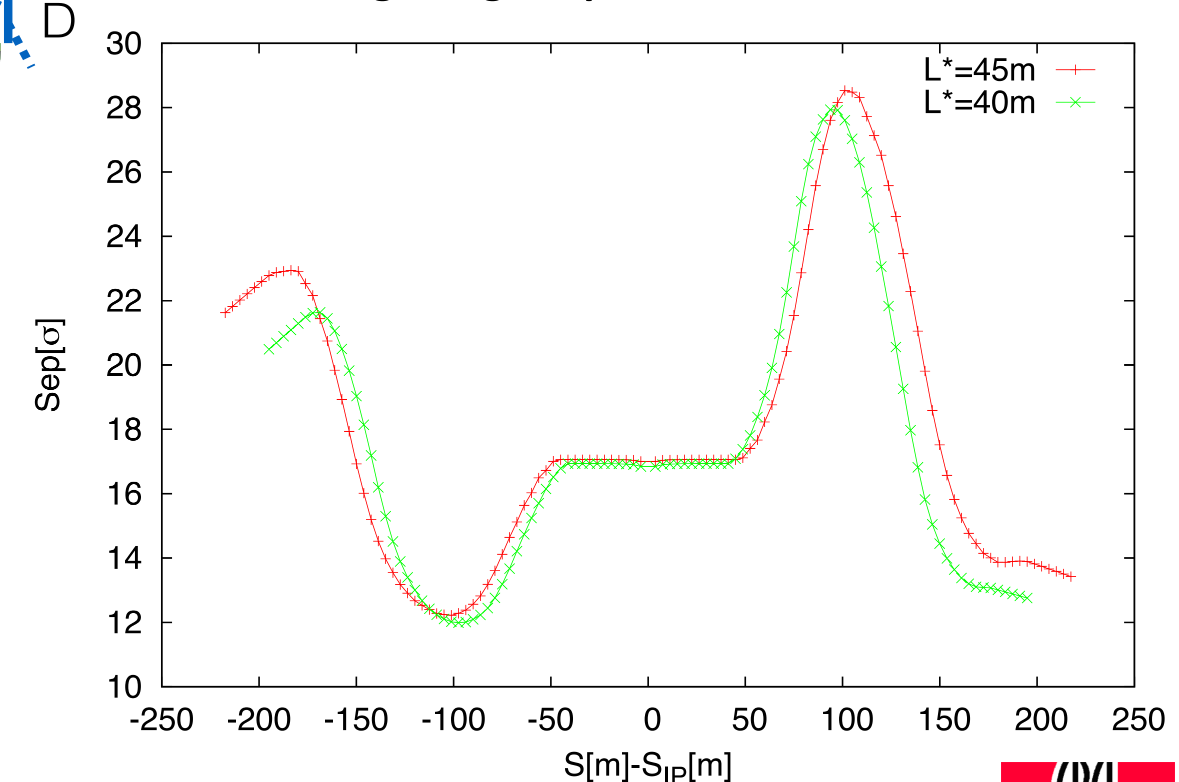
FCC-hh Baseline and ultimate



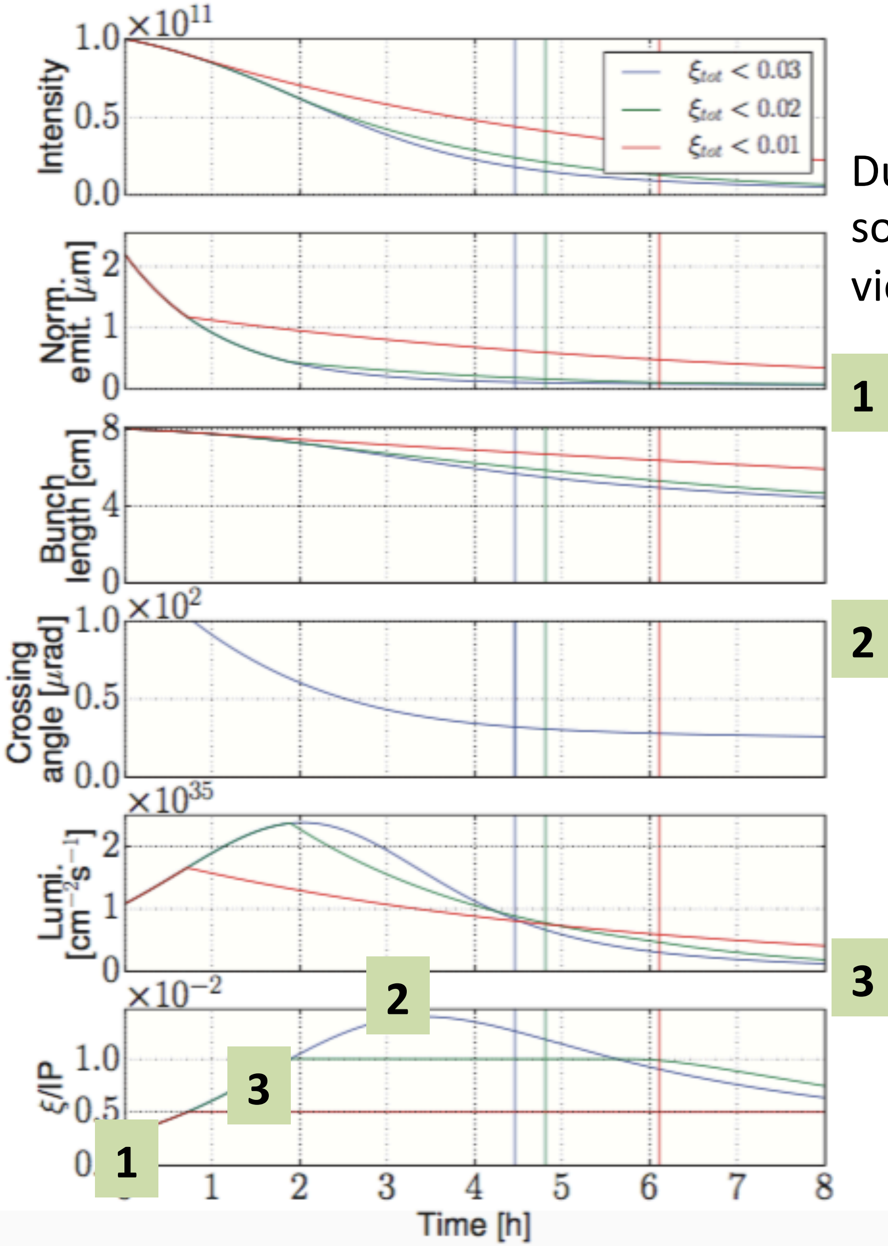
Beam-Beam Interactions:

- 2 Head-on collisions IPA and G
- Leveled with separation IPL and B
- 352 Long Range encounters

Long Range separations at main IPs



Parameter evolution



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

1 LHC/HL-LHC beam-beam dynamics **HO + LR effects** **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→ 0.03** plus 2 low luminosity IPs

LHC experience, Machine Developments studies and simulations

3 **Mixed status**, radiation damping and possible operational scenarios

Need new developments in models and studies

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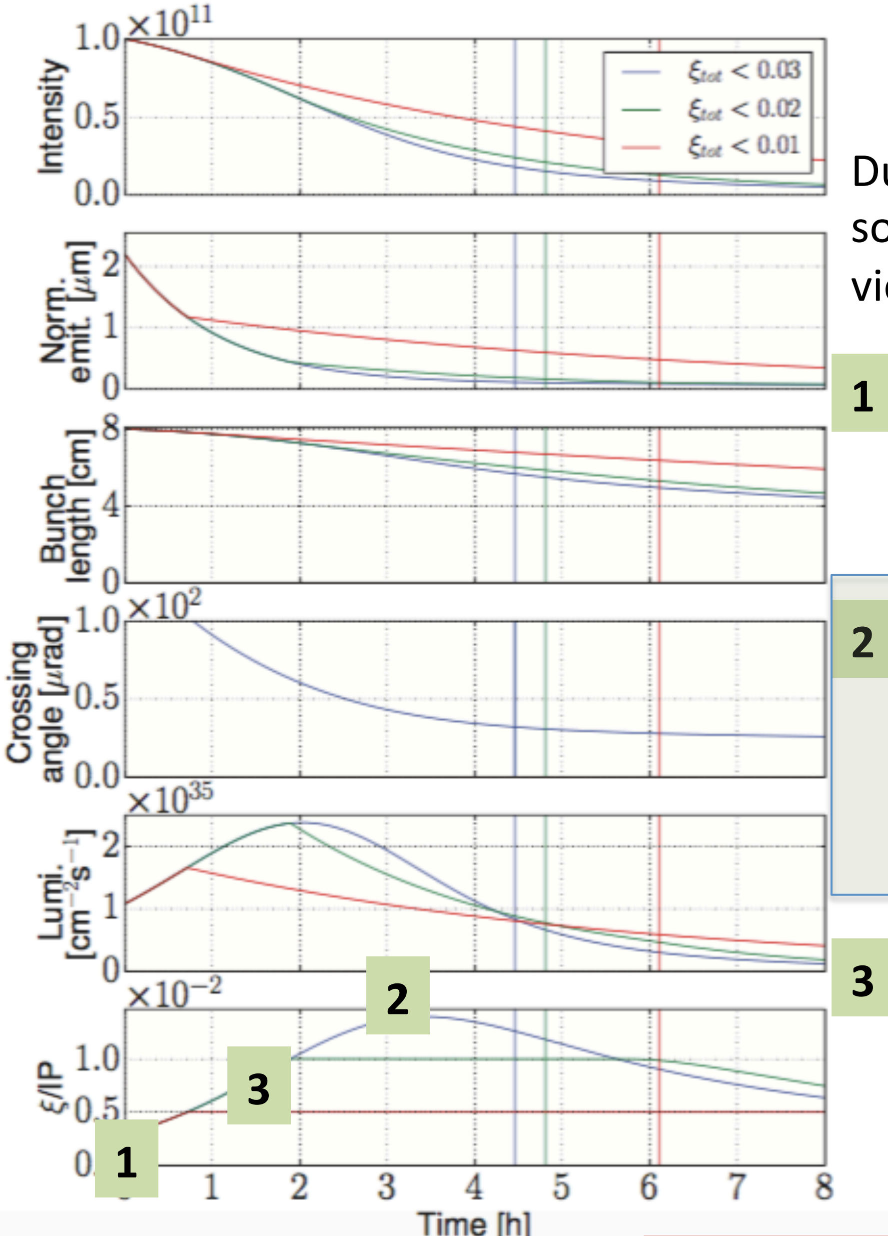
Parameter evolution



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LHC experience, Machine Developments studies and simulations

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

We will focus on this scenario most challenging

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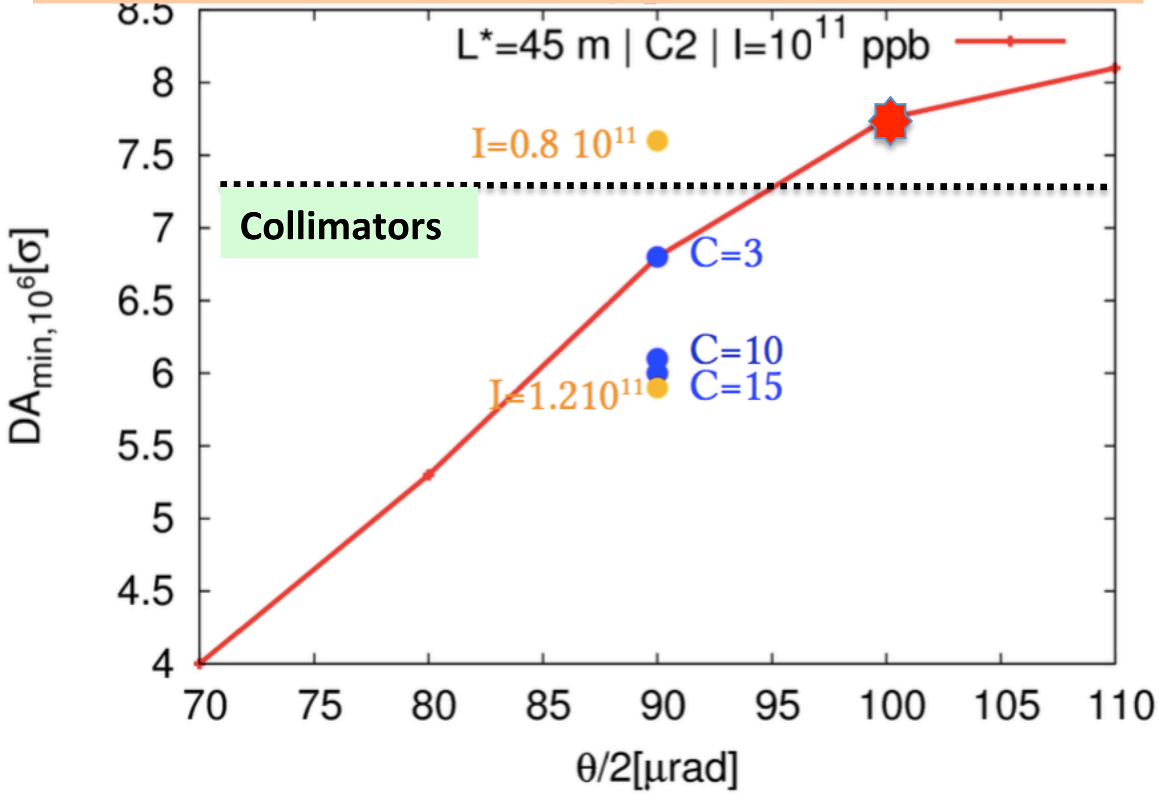
Dynamic aperture studies

FCC New Lattice 2 IPs and H-V alternating crossing



Dynamic Aperture Criterion 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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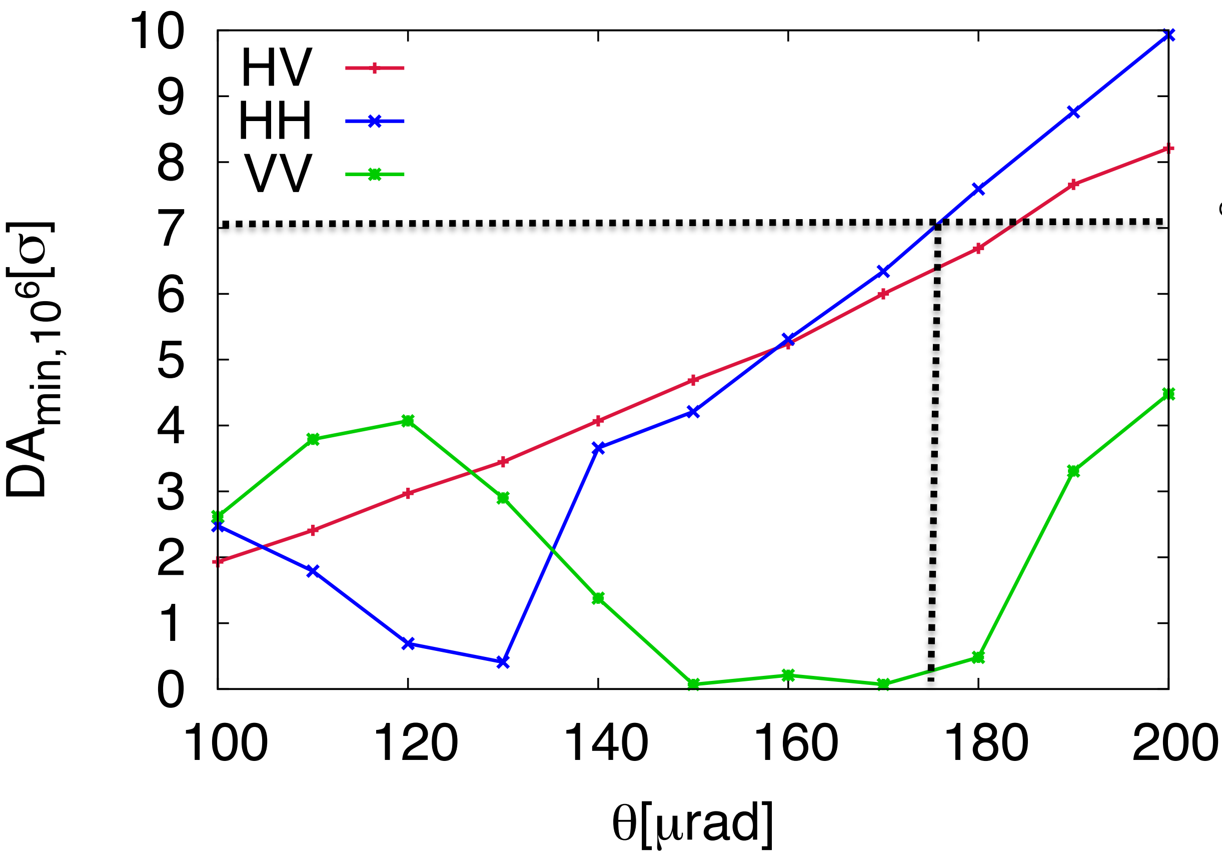
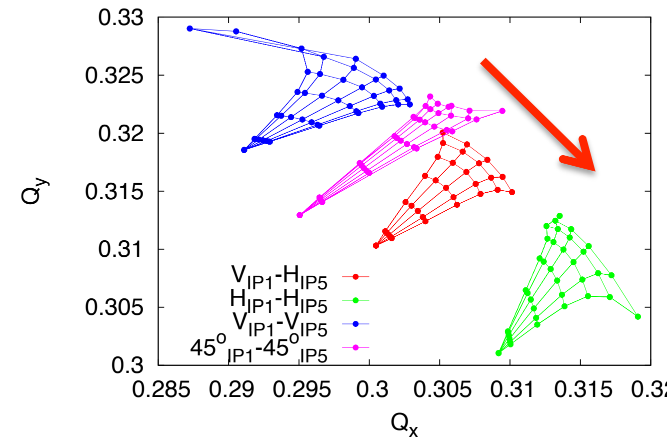
Variable Crossing Schemes: HV, HH and VV





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

- 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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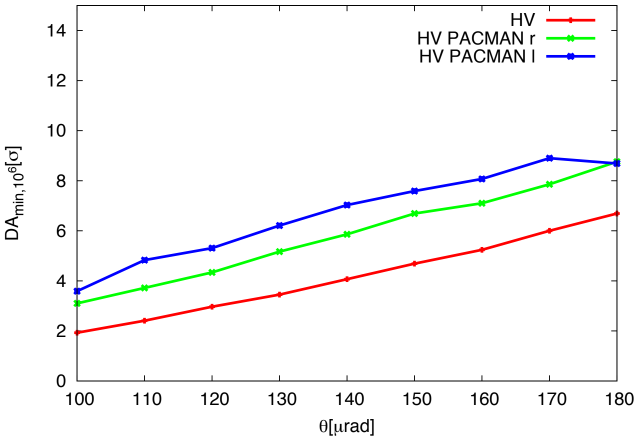
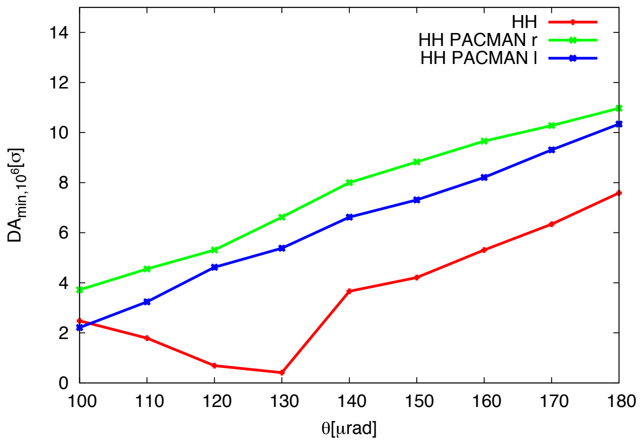
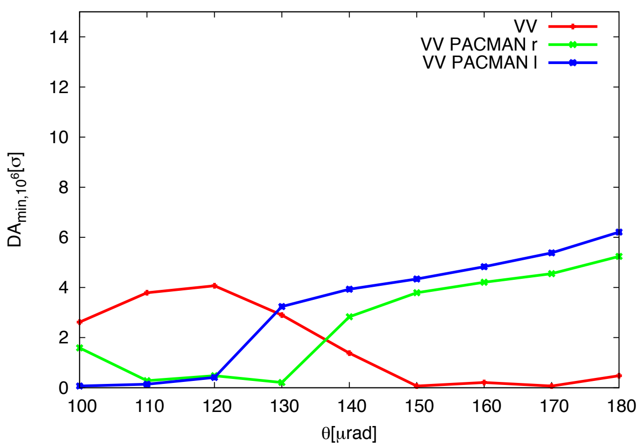
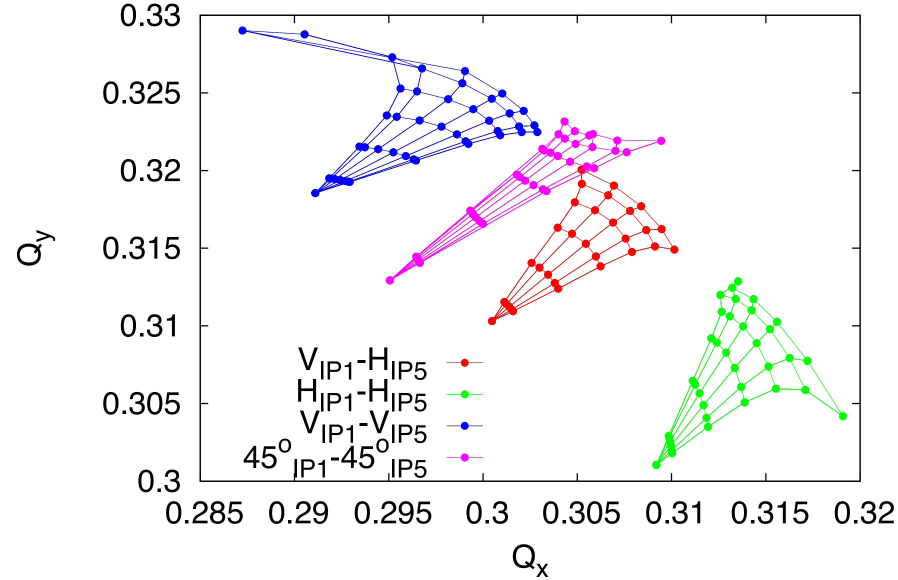
PACMAN Bunches









- 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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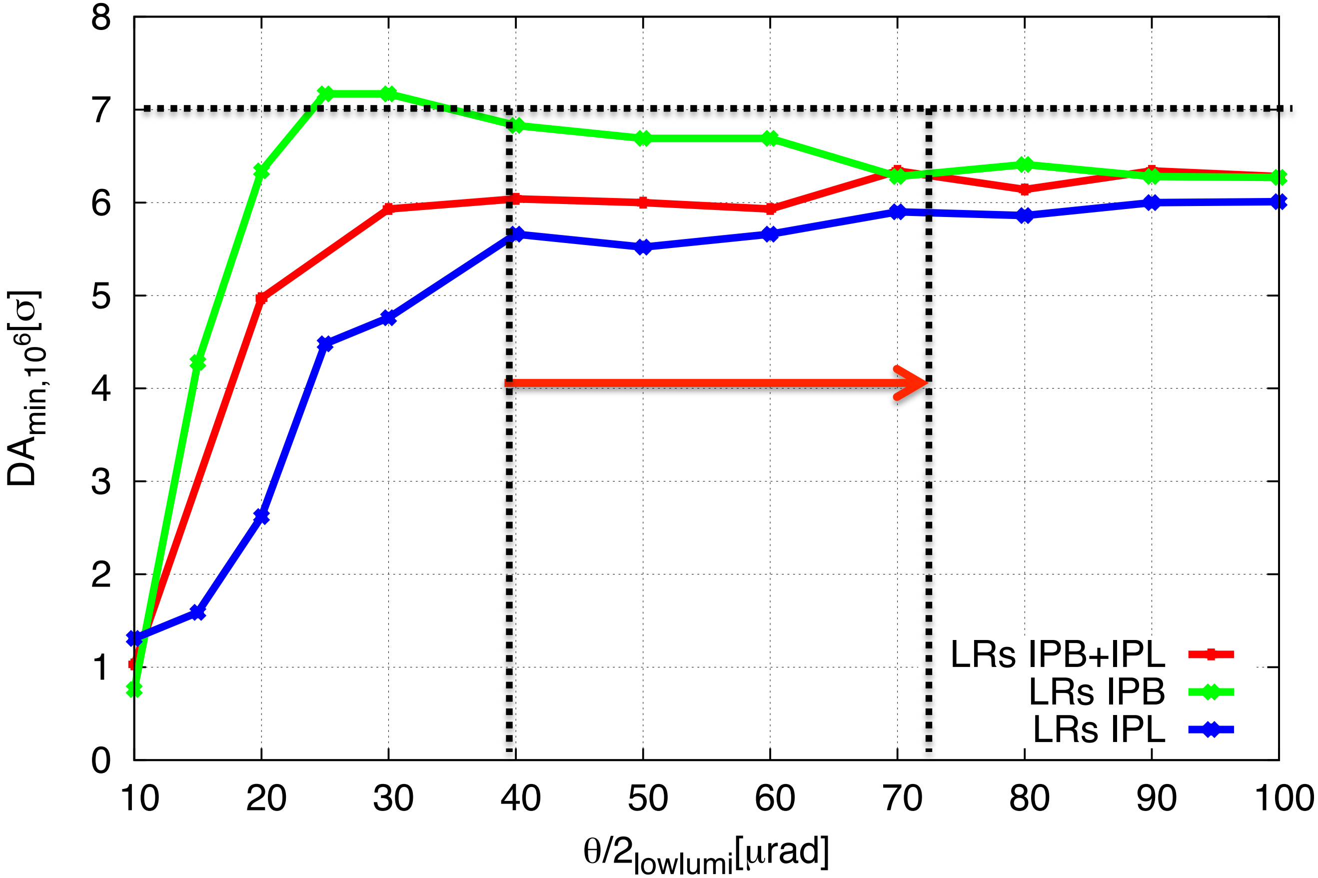
Low Luminosity Experiments to be added

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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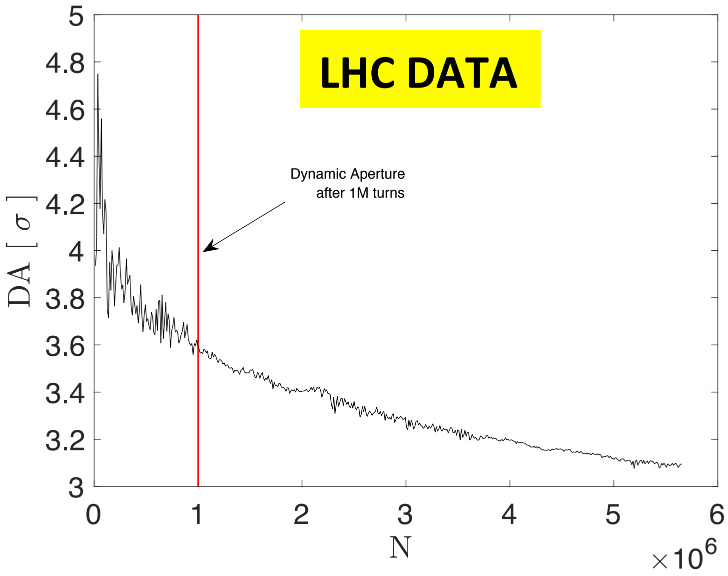
Can we move from dynamic aperture to losses?



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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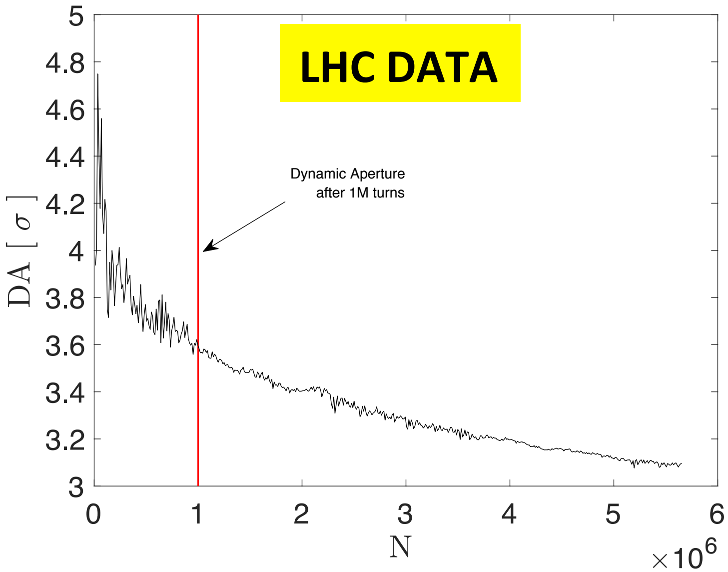
Can we translate losses in dynamic aperture?



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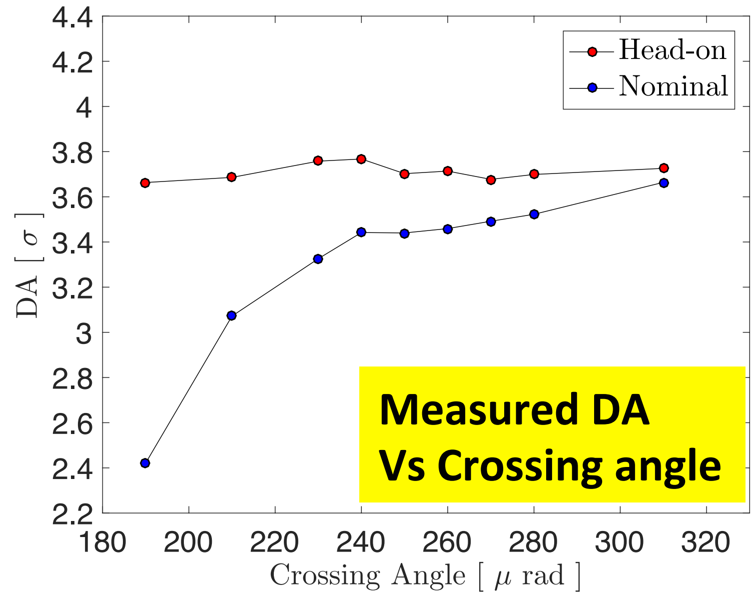
M. Crouch Manchester PHD Thesis 2017



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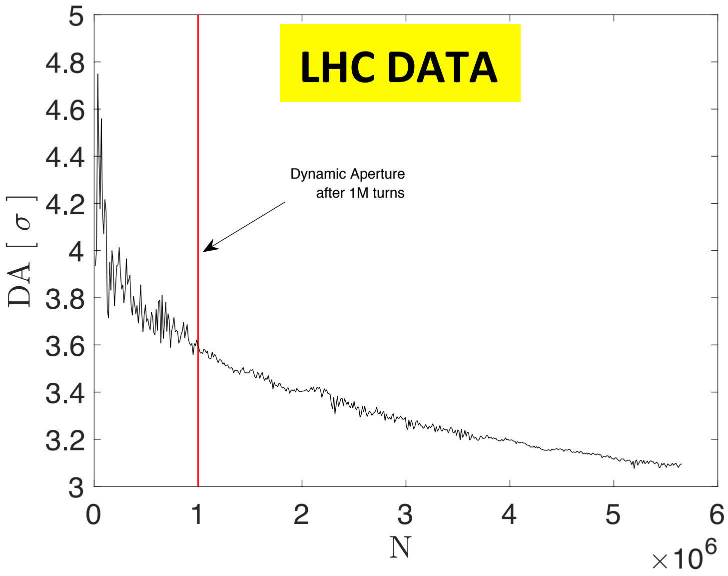

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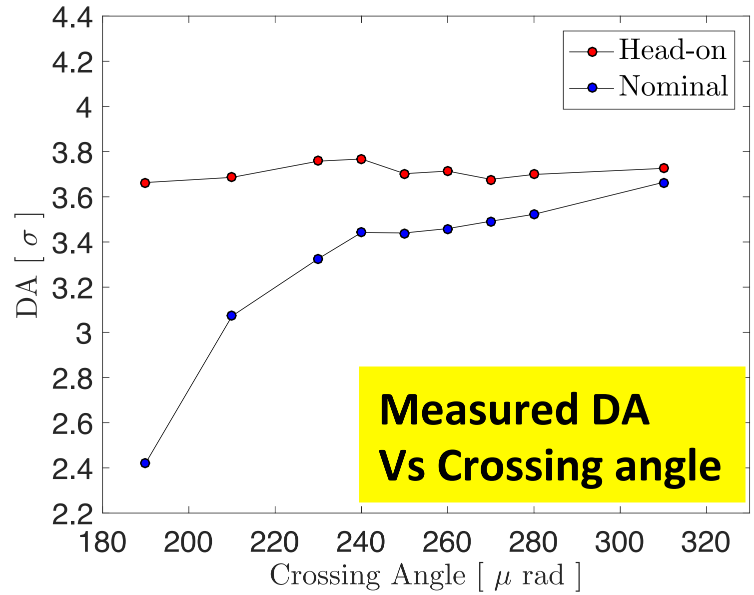

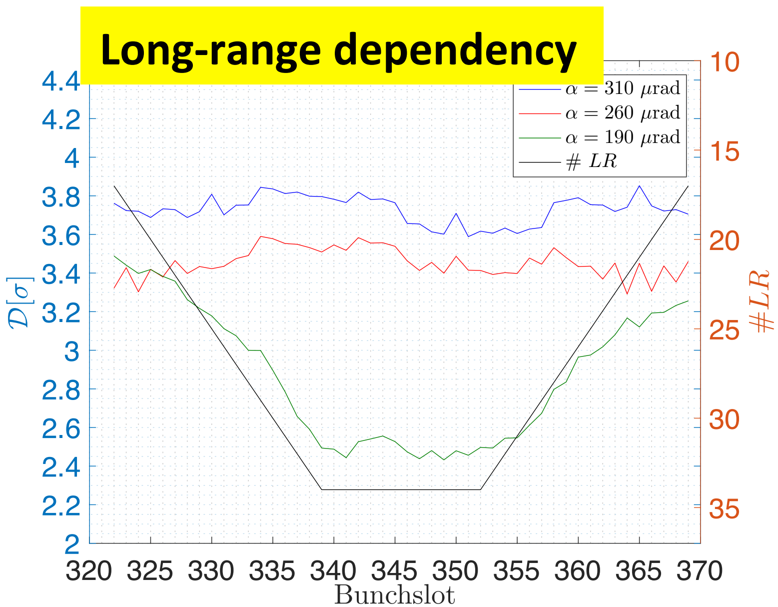

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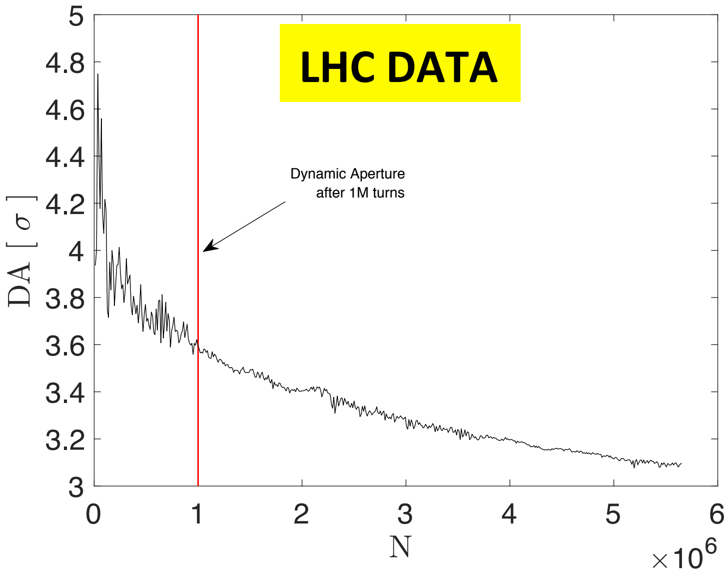

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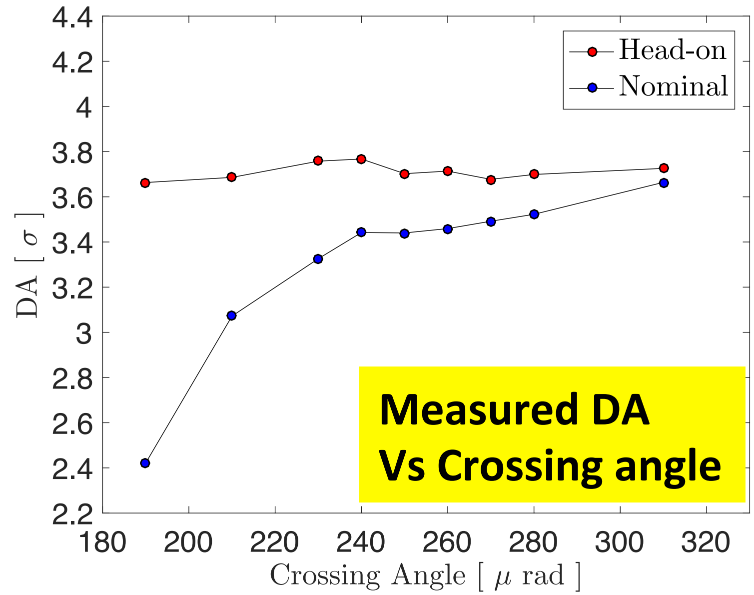

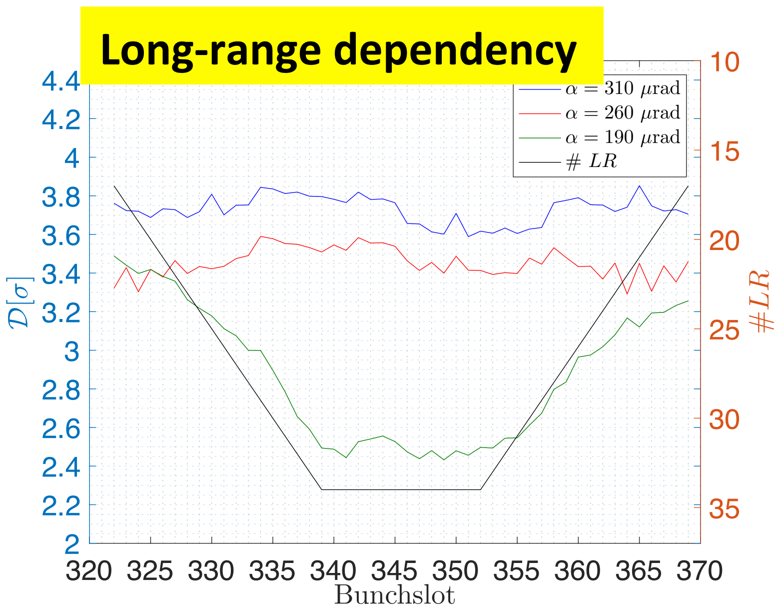

Use the Dynamic Aperture simulation to predict the losses expected per scenario…

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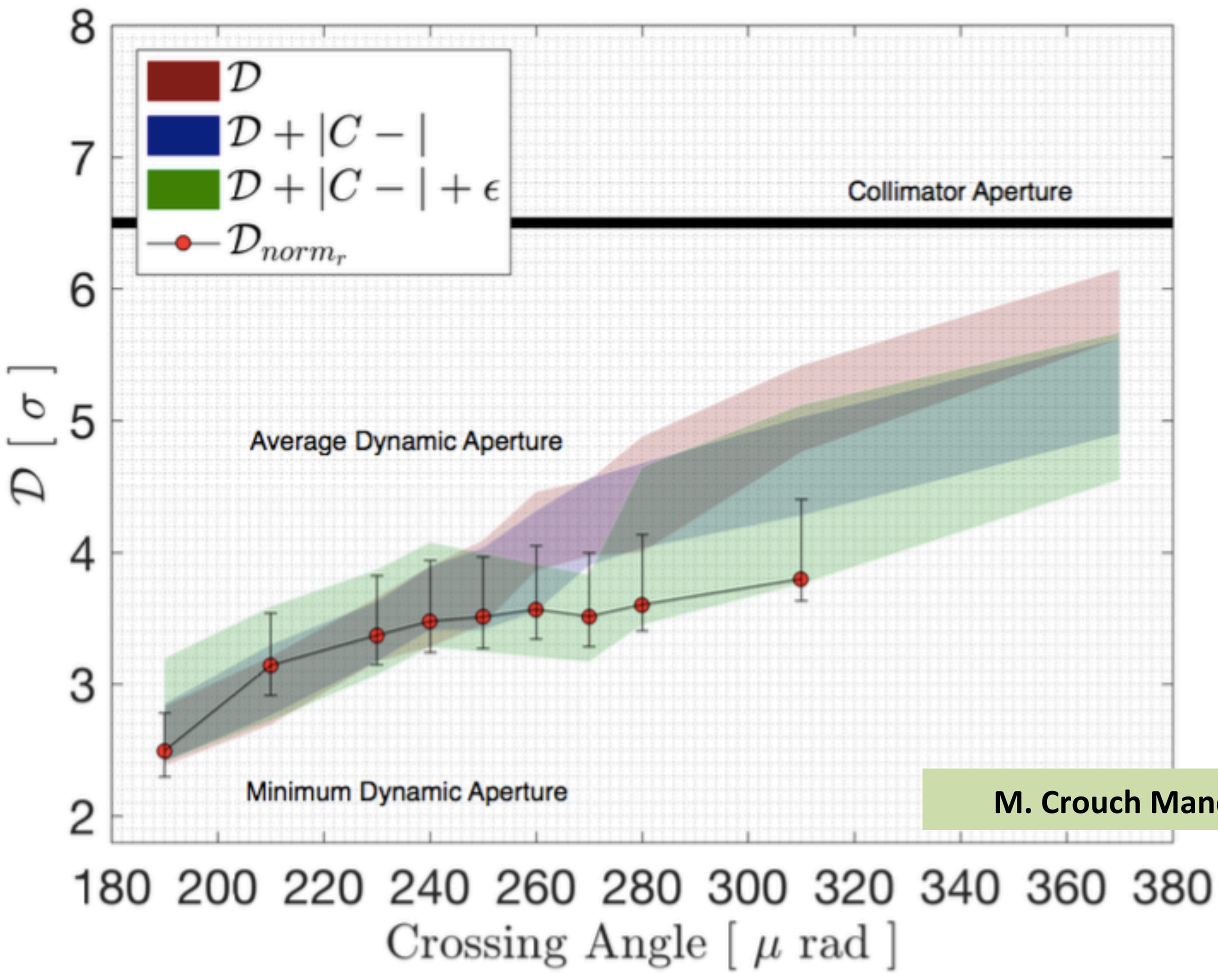
How far are models from reality?



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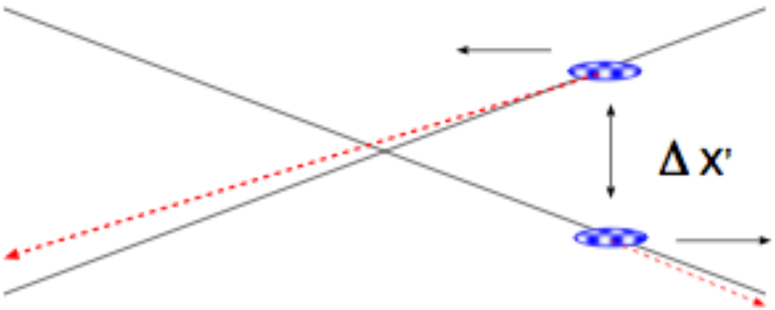
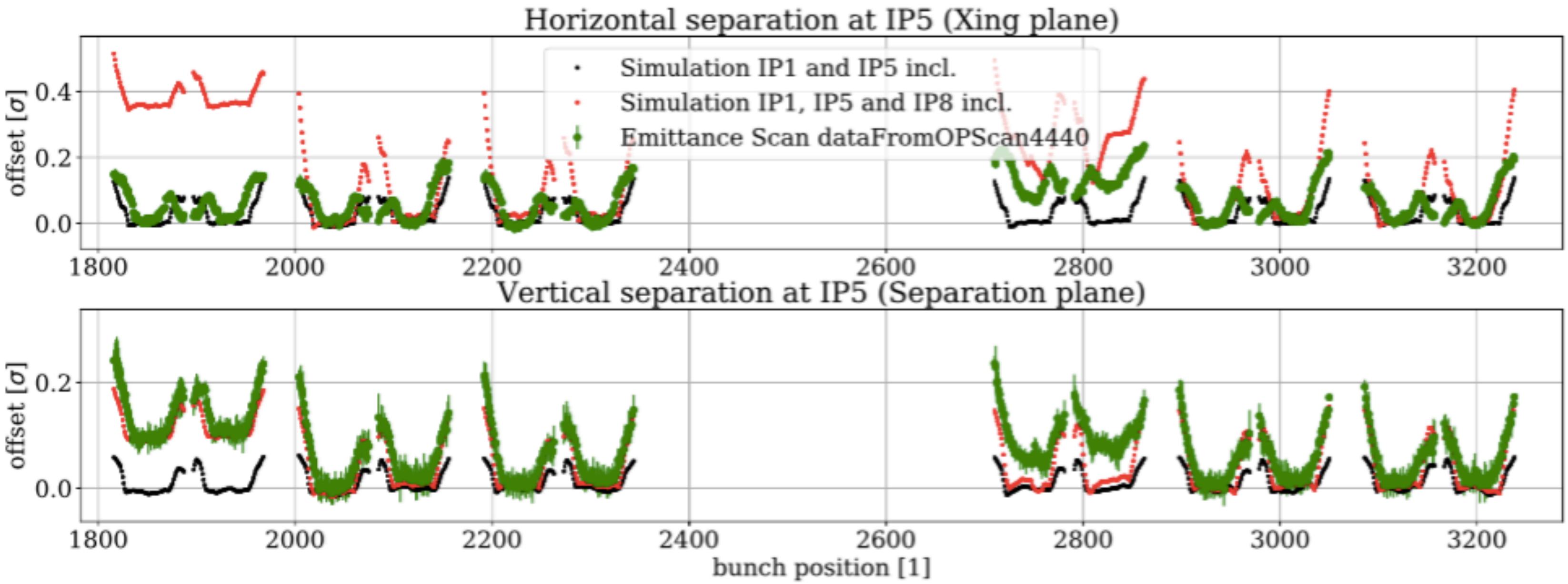
Include in luminosity models losses expected from Dynamic Aperture, to have estimates on impact to collimation system

Orbit Effects

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

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





A. Gorzawski et al. @IPAC2017 THPAB042

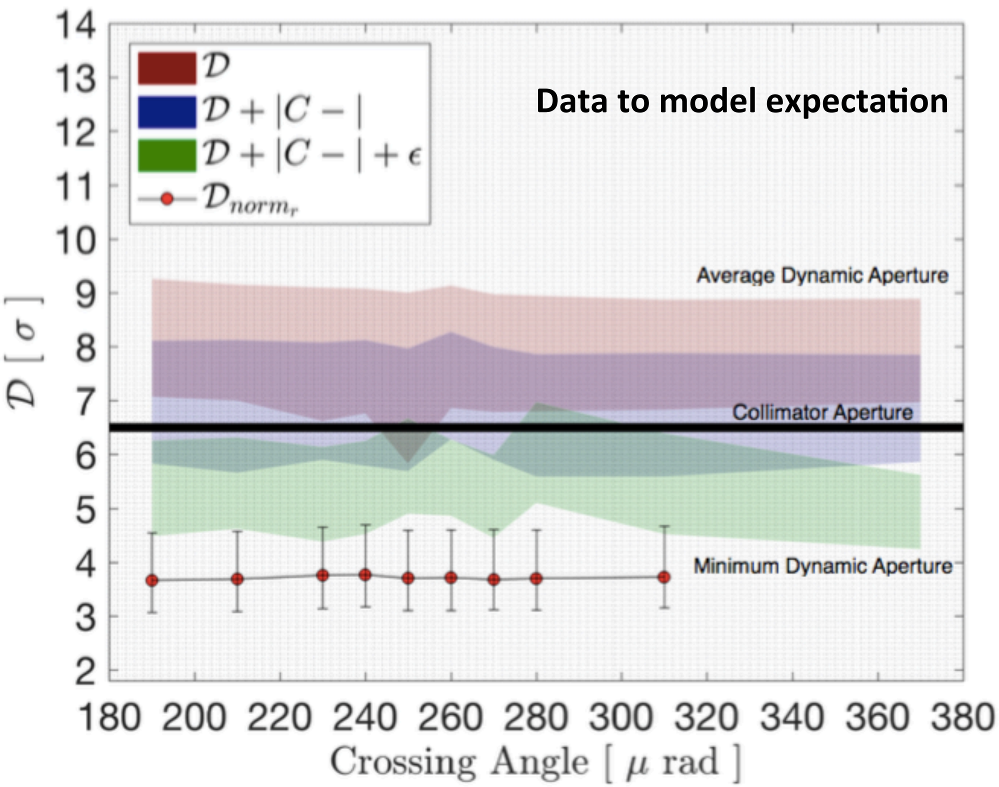
For FCC should be not limited, but effects are evolving since beam sizes are changing. Need to keep small effects: TRAIN code adapted to FCC collision schemes

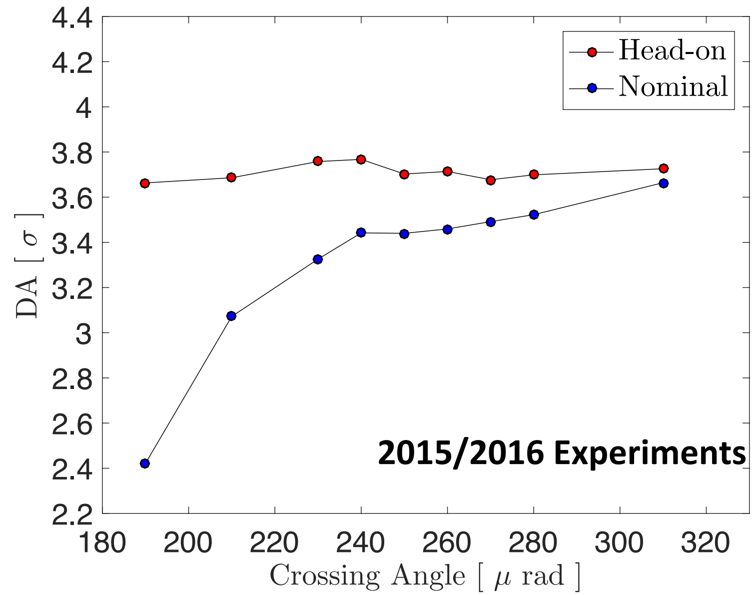
Head-on Limit: Losses and Emittance growth

Head-on beam-beam can result in losses and emittance growth.

FCC pushes to a total beam-beam tune shift of roughly 0.03 and two experiments to add.

From LHC experience head-on colliding bunches losses cannot be explained by only Dynamic aperture losses when in a weal long-range regime…





@IPAC2017 TUPVA026, TUPVA029

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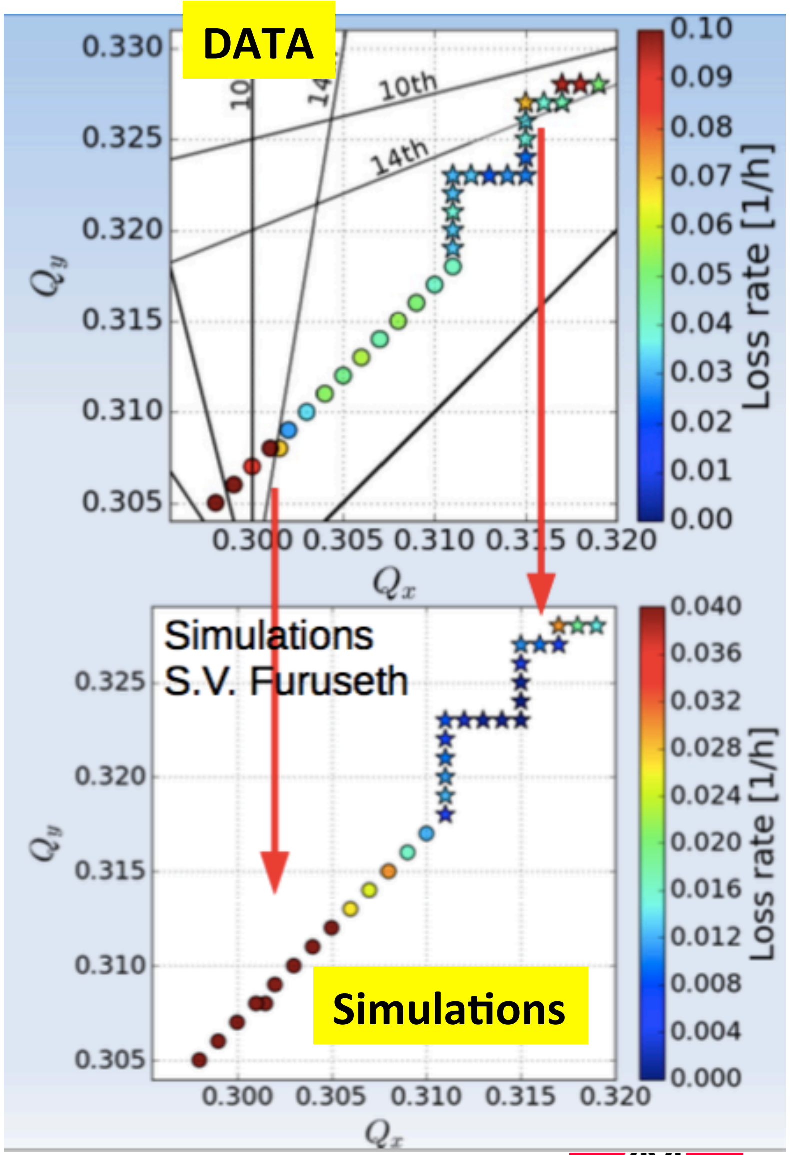
Head-on Limit: Losses and Emittance growth

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**, **noise impact due to crab cavities and other devises i.e. e-lenses**)



@IPAC2017 TUPVA026, TUPVA029

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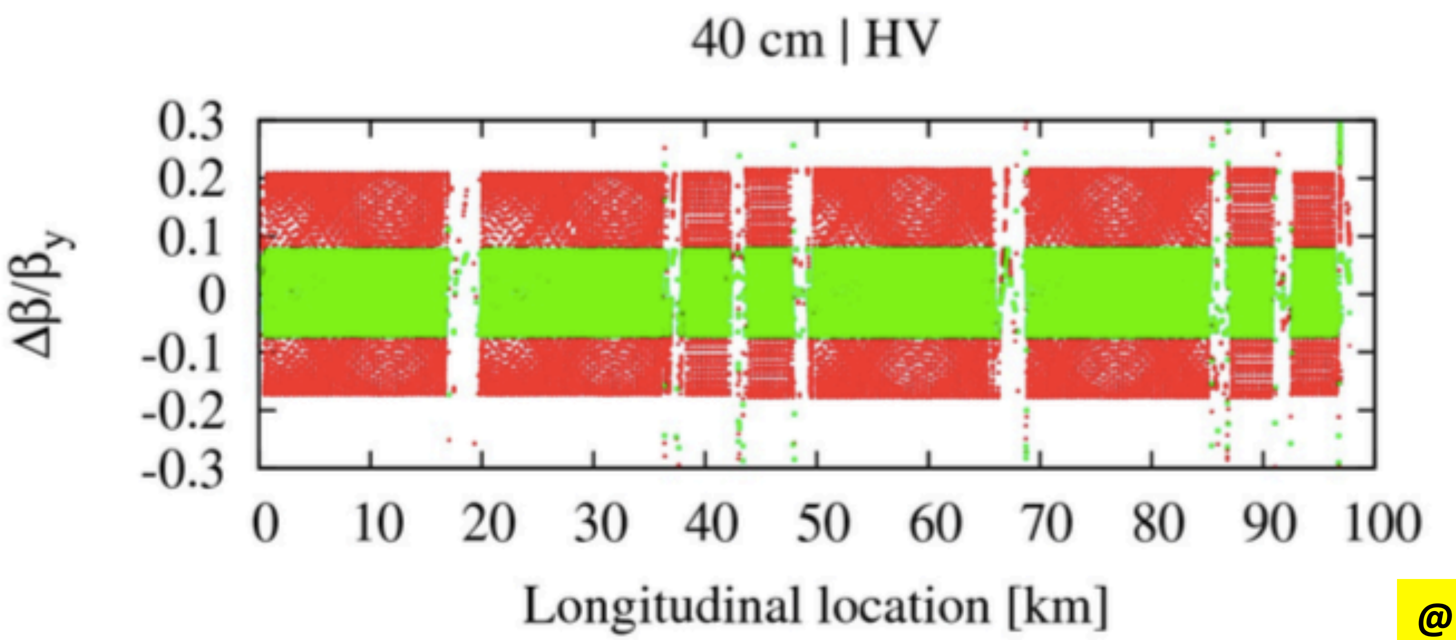
Head-on Beam-beam β-beating is important

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



@IPAC2017
WEOAB2, TUPVA030
Talk after

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

- Study Impact on collimation system, is it important?
- Study Impact performances → luminosity enhancement (like in lepton colliders)

→ **Reduce effect 2 low luminosity IP separated**

→ **Propose a correction scheme and explore compensation techniques.**

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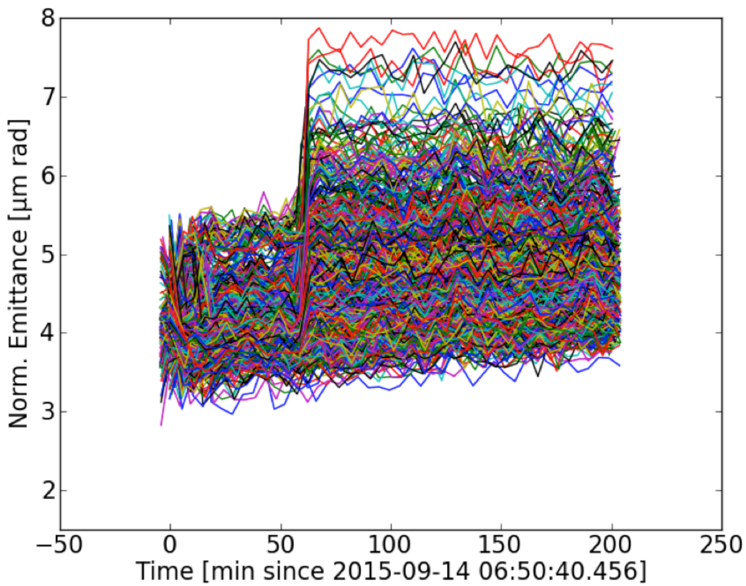
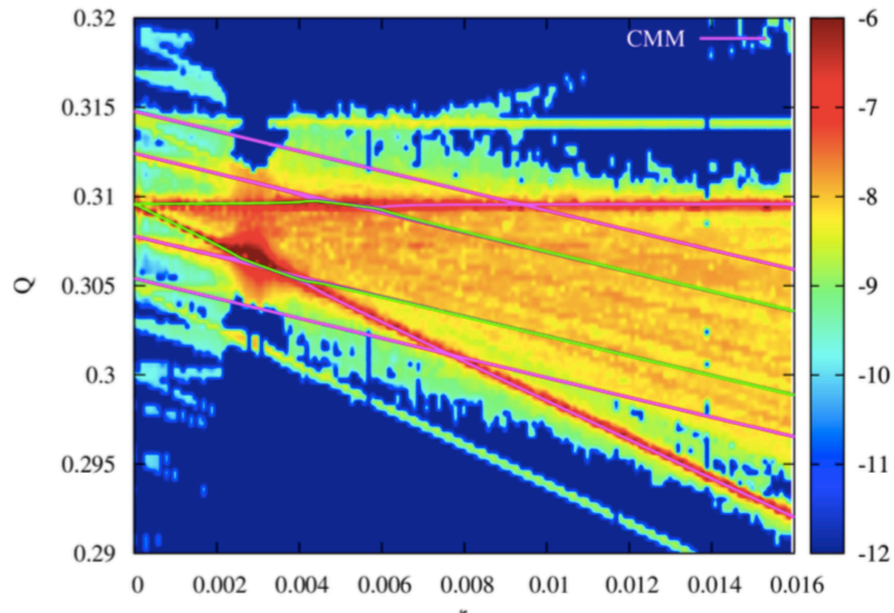
Coherent Instabilities

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 thes e observations which can limit the beam brightness specially for a FCC → baseline operation at 5 units chromaticity and use of **Landau octupoles** or **electron lenses** (V. Shiltzev and Co.) to stabilize head-tails modes and BB and impedance mode coupling.





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

This represents a major concern
More studies in C. Tambasco and X. Buffat talk

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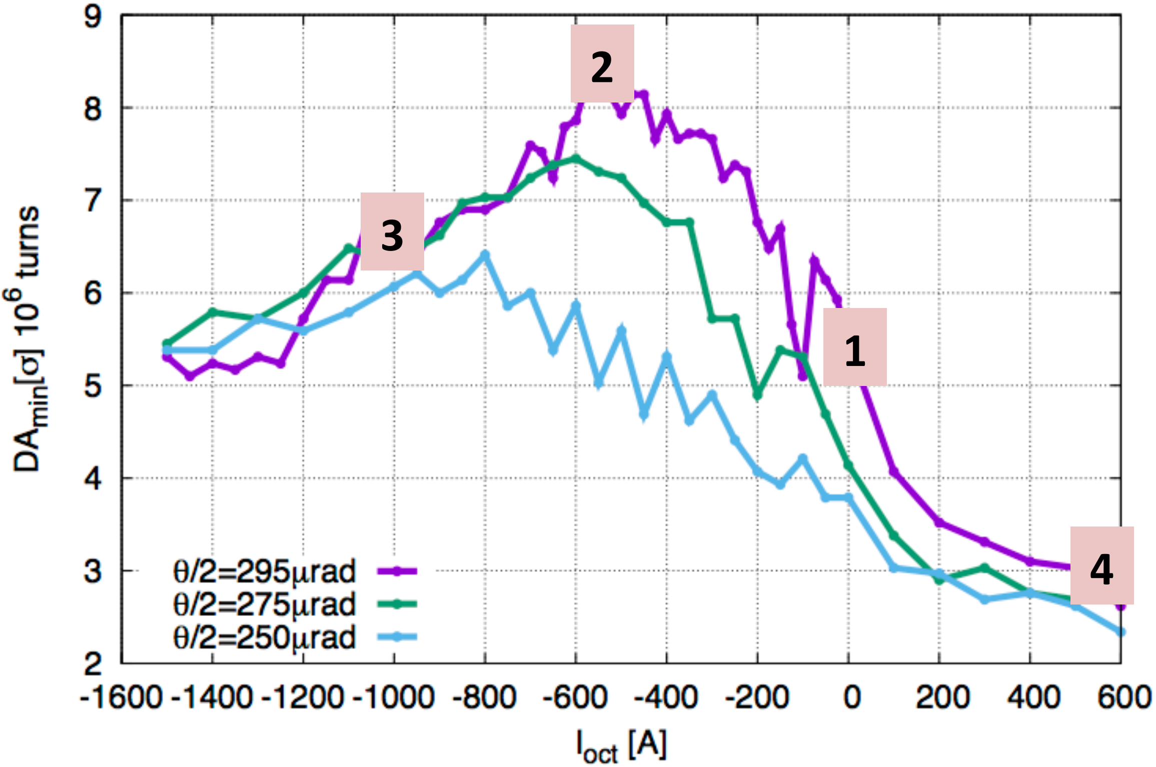
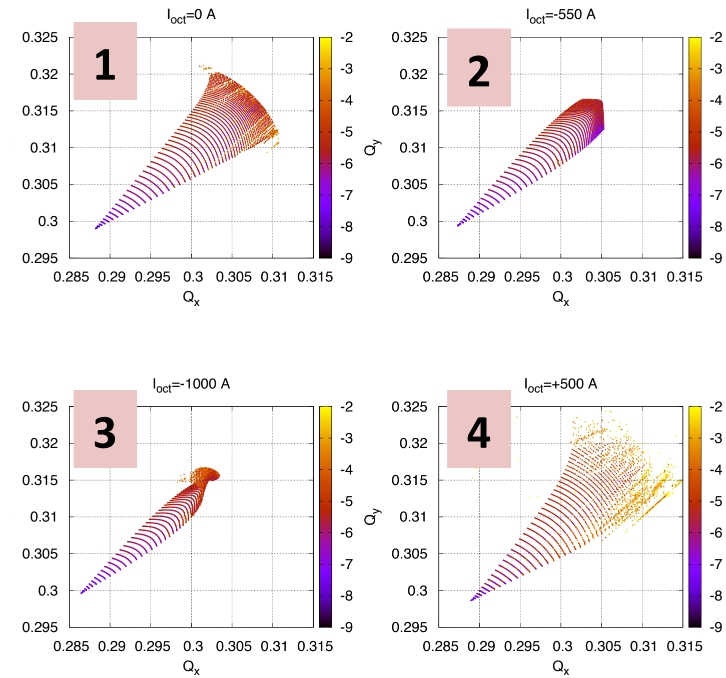
Global compensation with octupole magnets

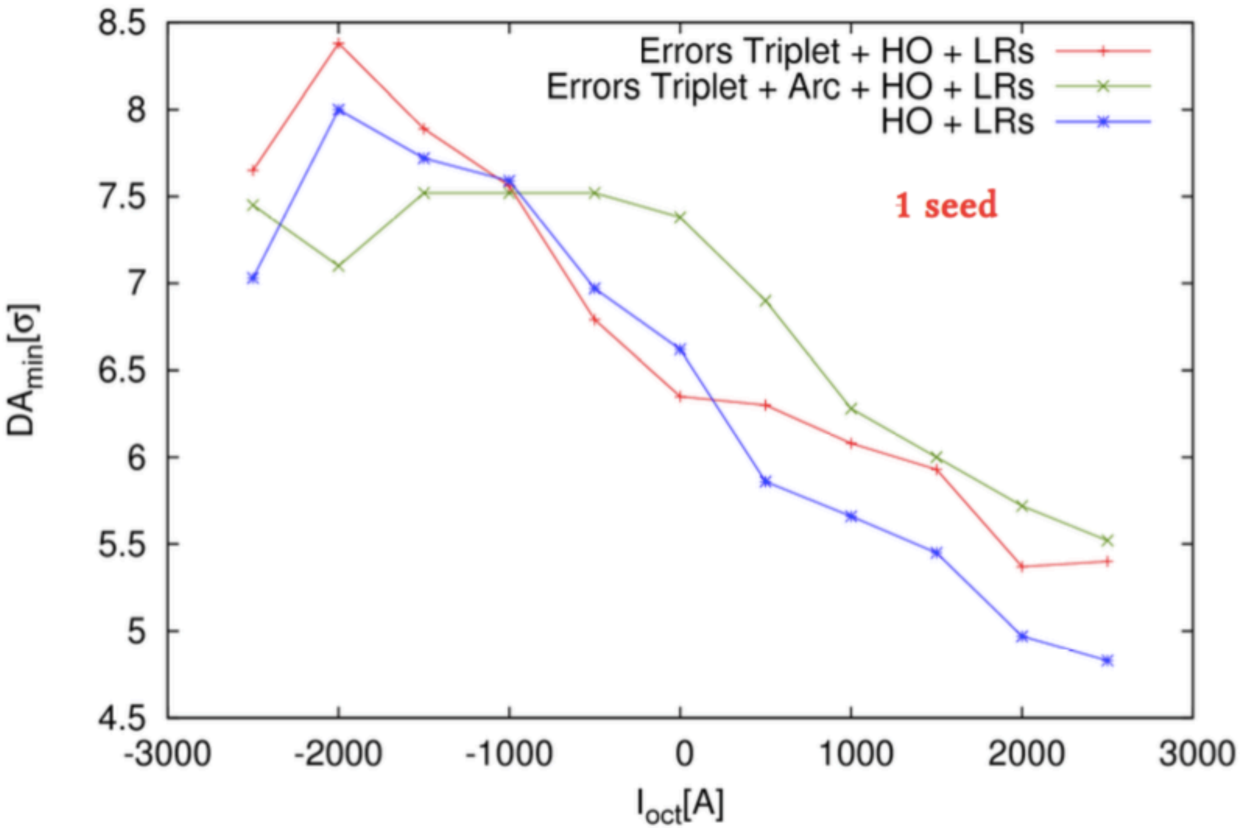




J. Shi et al. (2002)
HL-LHC study case
CERN-ACC-NOTE-2017-0035

- 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 lattice and beam-beam effects should be designed together to have this possibility of a global compensation (as studied for the LHC by Shi)**

Global compensation with octupole magnets



Eurocircle Meeting Oct2017

Octupole could have positive effect on dynamic aperture → will invest at early stage to define lattice properties such that we could use this compensation scheme!
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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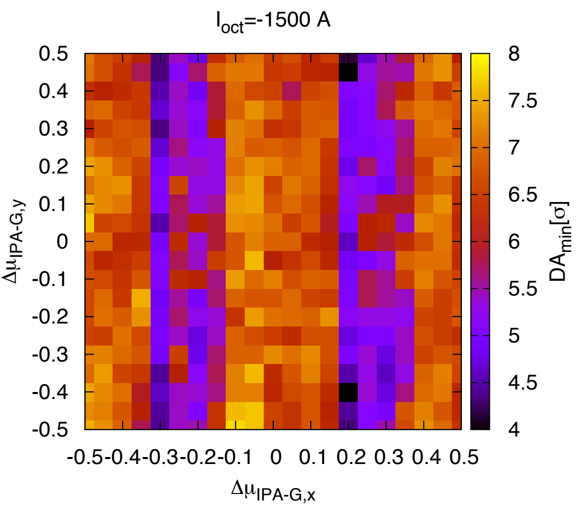
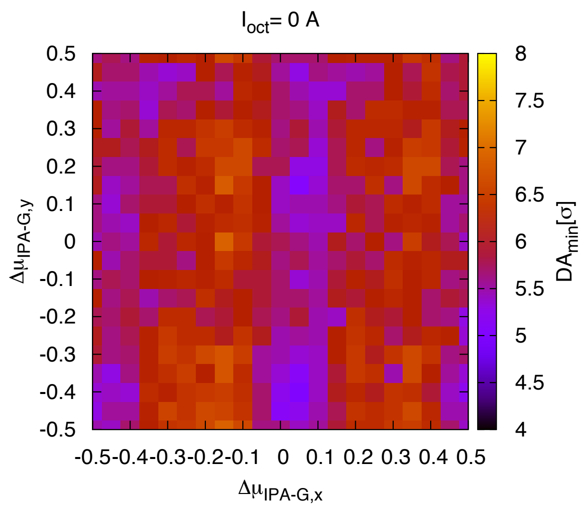
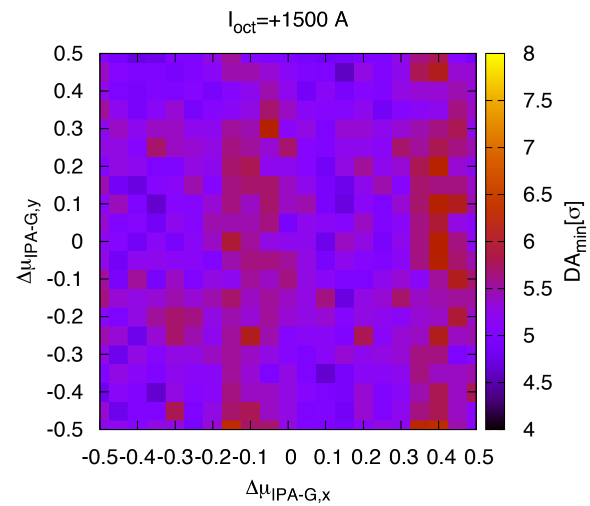
Global compensation with octupole magnets

Phase advance studies to tune the optics to the collisions and define the robustness of such scheme







A lot to be studied to have a robust and well understood evolving scenario, but simulations are faster and technology helps in addressing more details of the dynamic

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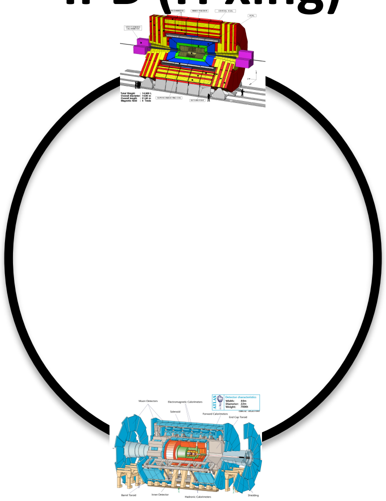
HE-LHC case

IPB (H xing)



IPA (V xing)

Preliminary assumptions

- 2 Interaction Points
- 25 ns bunch spacing (12.5 ns alternative)
- Fractional tune same as LHC (0.31,0.32)
- Alternating crossing to reduce Pacman (H crossing angle in IPA and V crossing angle in IPB)
- β^* 25 cm (most difficult scenario with maximum peak lumi with possibility to relax to 40cm with small loss in performance)
- 72 LR total before D1
- Crab Cavities to compensate geometric reduction of 60-70%

- First studies performed on Footprints and lattice checks (set-up of tools+optics available) + using all available studies from LHC and HL-LHC (similar BB effects)
- Room for further optimization of LR separation with optics colleaugues → could only make things better

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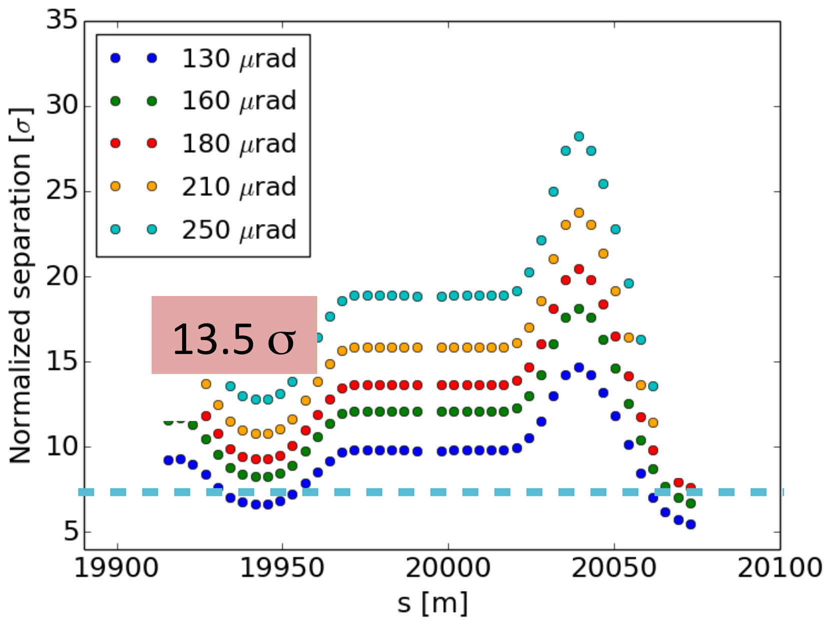
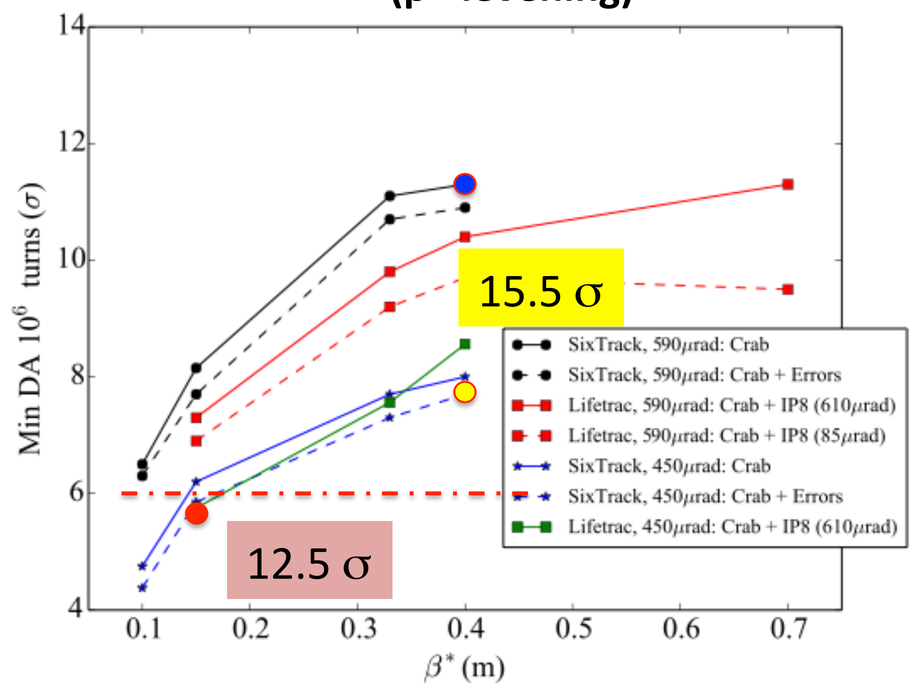
Beam-Beam Long Range separations



Dynamic Aperture simulations for HL-LHC (β* levening)



LR separation d_{sep} > 8.5 σ → x-angle/2 > 165 μrad (12.5 σ)

→ HL-LHC equivalent fully squeezed → Scaling from HL-LHC →Not enough from DA (below target) and still no margins

LR separation larger than 8 σ → x-angle/2 > 180 μrad (13.5 σ) → DA around 7 σ

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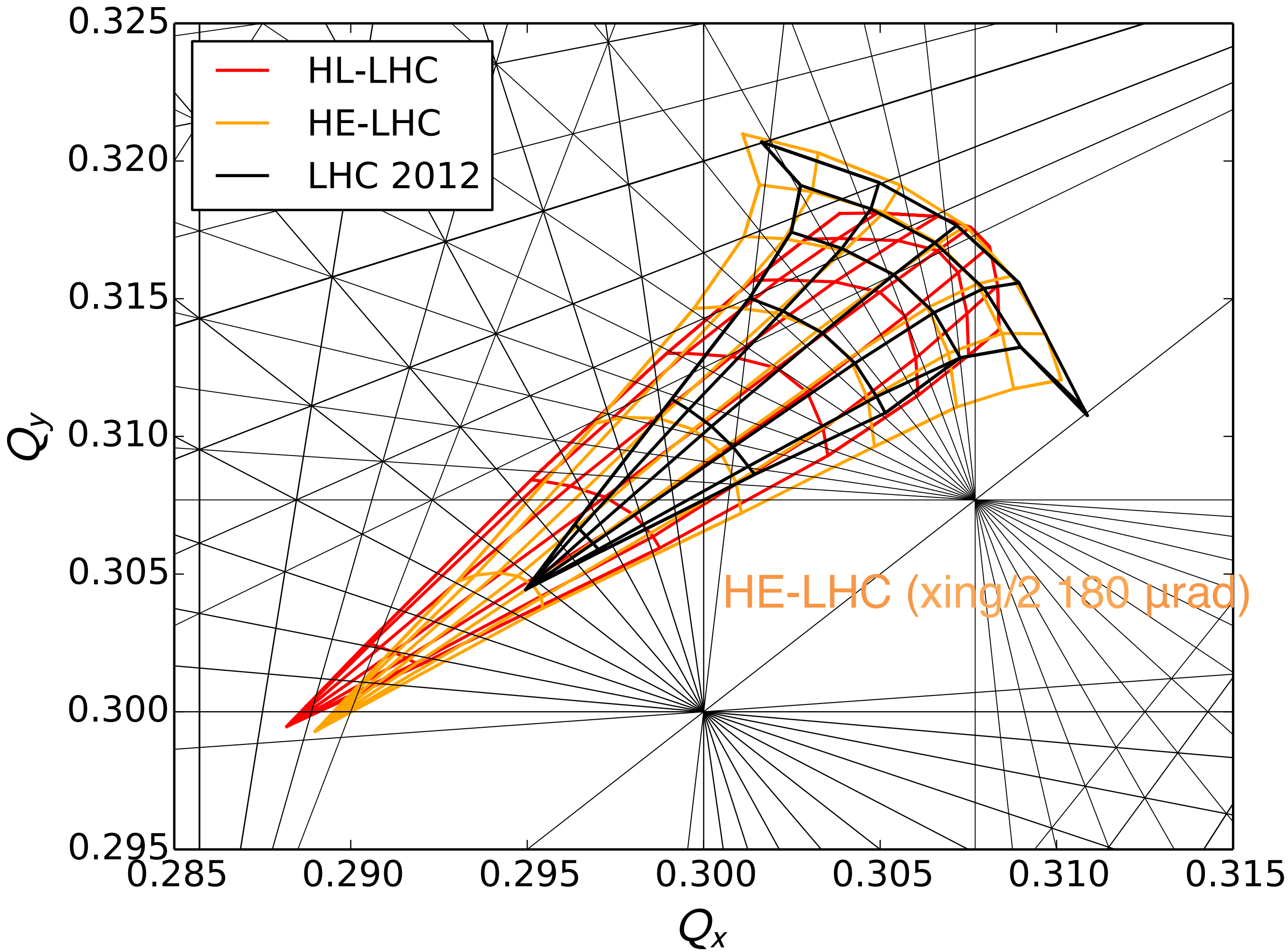
Head-on and long range interactions

X-angle/2 > 210 μrad at limit of aperture

Larger x-angle needed to have reduced LR contributions

Tool are in place !



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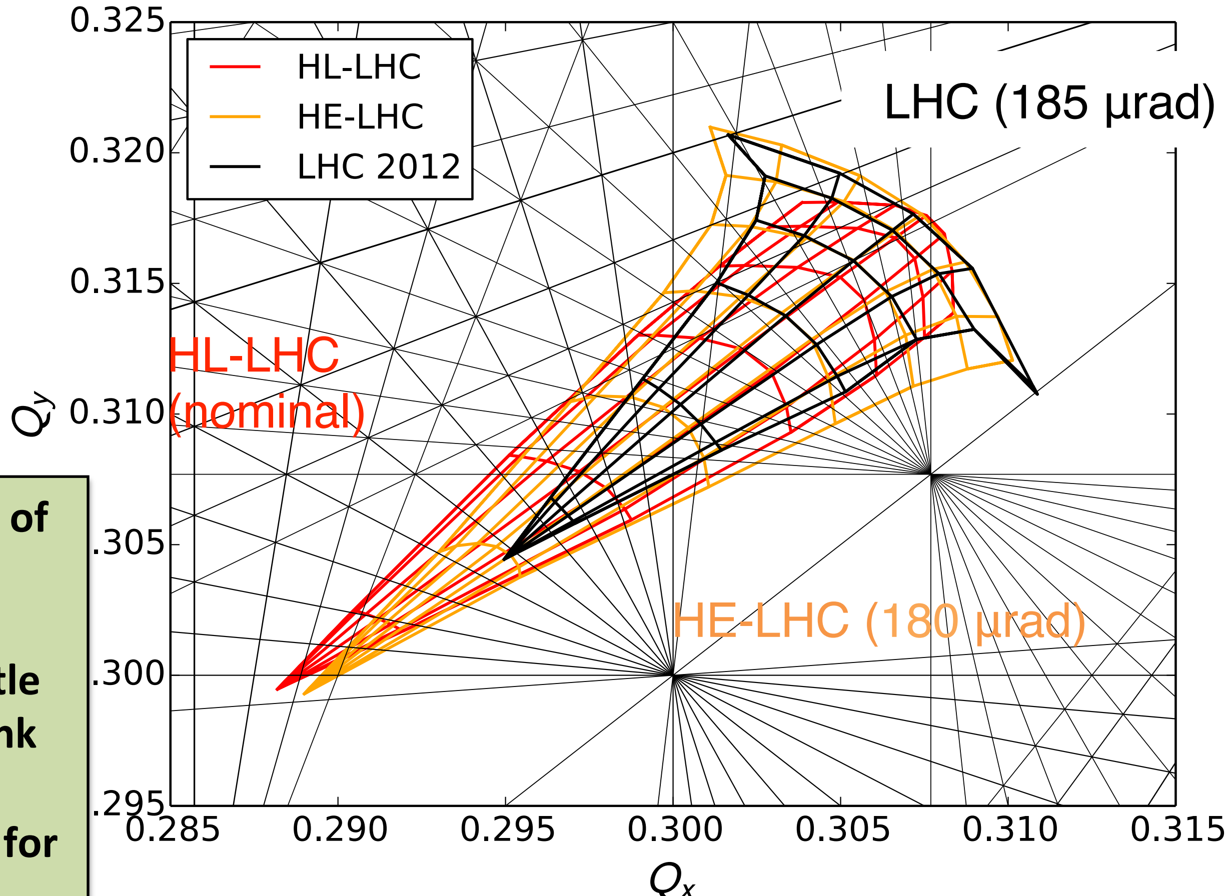
Head-on and long range interactions



X-angle/2 > 210 μrad at the limit of the aperture

→ Option is to increase β* → little loss in performances (see Frank talk)
β* = 40 cm → 15.8 σ separations for x-angle/ = 165 μrad

β* 25 cm → x-angle/2=180-210 μrad → 8.7-10 MV cavities

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FCC-hh 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 in luminosity model**

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

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

LHC@home
SixTrack

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

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FCC-hh Summary II

- **Orbit effects** do not represent a limit but should be studied in details over the different scenarios → **code extended and benchmarked to LHC data ready for the CDR in April.**
- **First models for predicting losses and emittance evolution are in place for FCC extrapolations**
- **Coherent instabilities and Landau damping are an important concern (C. Tambasco and X. Buffat talks)**
- **Beta-beating due to large beam-beam parameter could exceed the tolerances on beating defined by protection system and deteriorate the performances if not studied in details**
  - Need for correction: correction scheme of linear part testied on LHC or **e-lenses**!
- **Compensation techniques**
  - Global compensation using multiple 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 (flat optics, rotatable crossing planes)**

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HE-LHC Summary

- **The HE-LHC can profit of the several studies on going for FCC-hh**
- **Preliminary studies of beam-beam effects show no limitations and a set of parameters compatible with other constrains have been defined :**
  - Beam-beam separations have been defined scaling from LHC experience and from HL-LHC simulations studies
  - Alternatives are possible and simulation studies have started to open the possibilities and look for the most performing scenarios…

Future of the future…. ☺

- For FCC-hh robust baseline scenarios have been proposed and a big campaign of simulation studies has started to push for more challenging scenarios from the beam-beam point of view. FCC-hh Ultimate is not given but doesn't look out of reach if well defined with the help of the appropriate compensation schemes (i.e. e-lenses)

- HE-LHC studies just started, need more detailed evaluations

- **First draft of the Executive Conceptual Design Report submitted to review process**

- **Deadline for the first draft of the CDR is FCC week in April ! To be presented at the next update of the European Strategy for Particle Physics….**

Thank you!

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