Beam-beam Effects and Compensation Techniques

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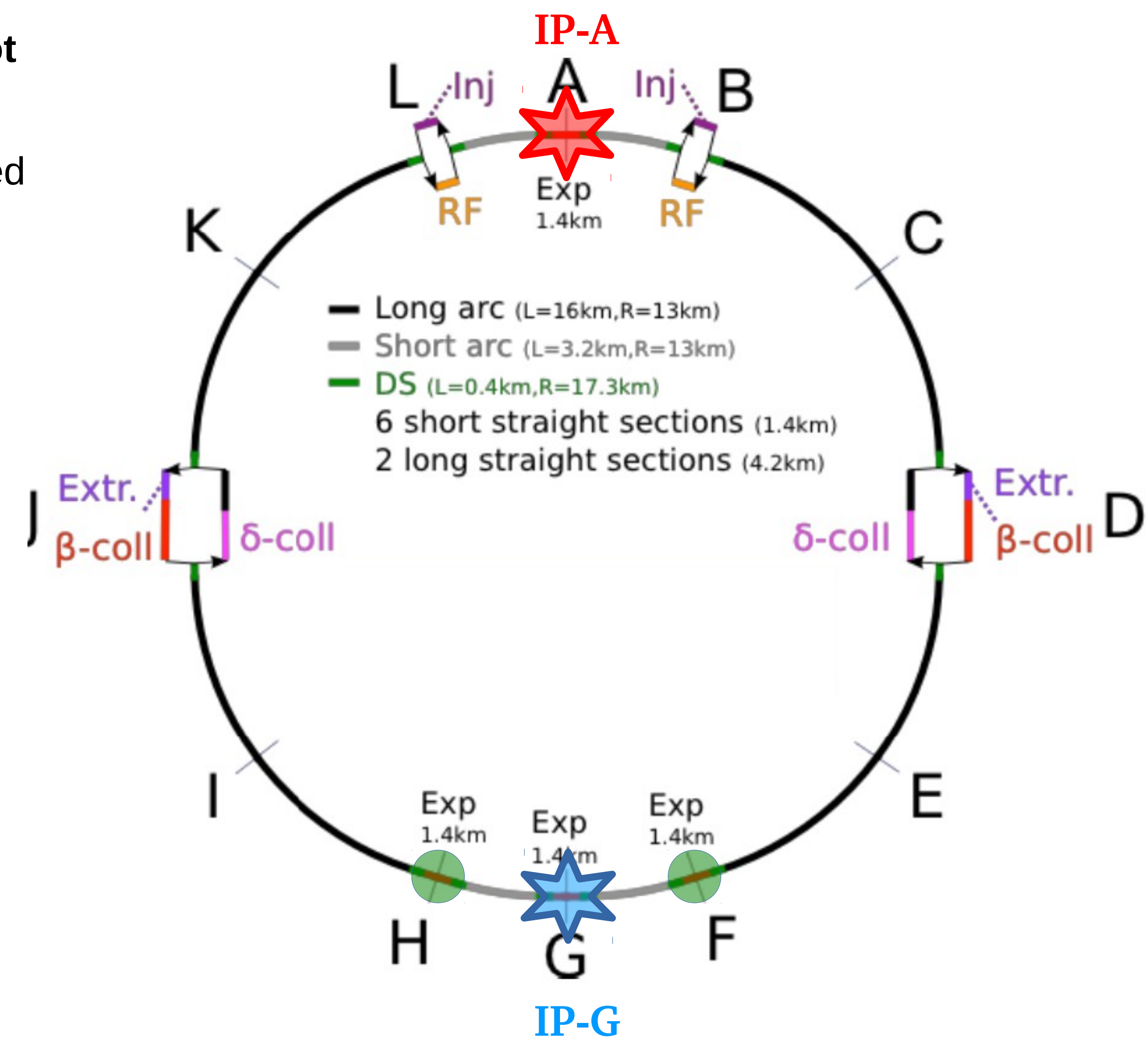
Collisions @ FCC-hh

- FCC-hh will collide in two high-luminosity experiments (**A** and **G** regions).
- Two other experiments (**F** and **H**) **not** considered in this study.
- Relevant FCC-hh beam-beam related parameters in the ultimate scenario.

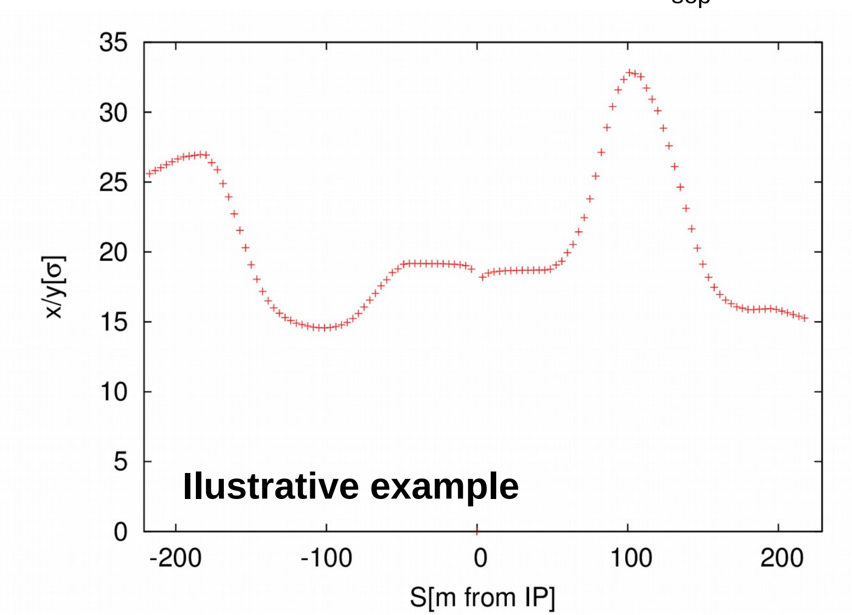
Parameter	Value
CMS energy [TeV]	100
Bunch distance [ns]	25
Bunch charge [10^{11} ppb]	1.0
Norm. emittance [µm]	2.2
RMS bunch length [cm]	8
IP β-function [m]	0.3
IP beam size [µm]	3.5
ξ_{bb} (2 IPs)	**0.011**
IR L^* [m]	45

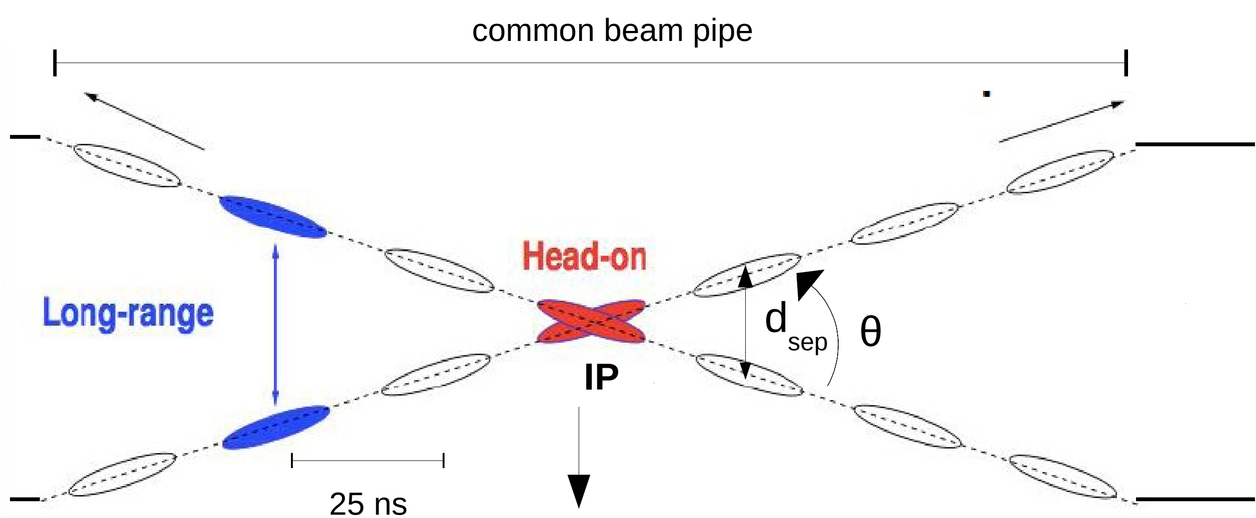


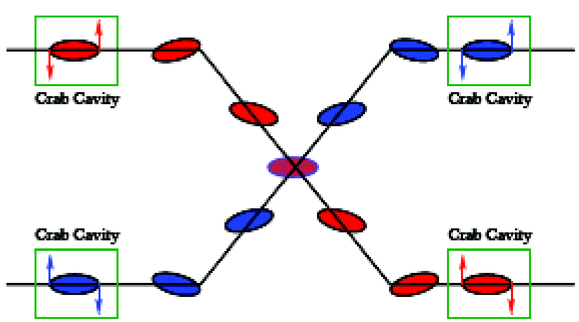
- The ultimate scenario relies on the use of **crab cavities** ensure full HO collisions.

Beam-beam interactions

- The two counter rotating beams will cross each other at the interaction regions (IRs). Two types of interaction:
  - *Head-on (HO)*: Two bunches colliding at the IP with **zero** or small separation.
  - *Long range (LRs)*: Bunches in the common beam pipe region will be affected by the opposite beam at a **separation**. These interactions are characterized by the separation of the **first encounter** (d_{sep}).







$$F = \sqrt{1 + \left(\frac{\sigma_s \theta}{\sigma_{x,y} 2}\right)}$$

$$d_{sep} = \frac{\sqrt{\beta^*}\sqrt{\gamma}}{\sqrt{\epsilon_n}}\theta$$

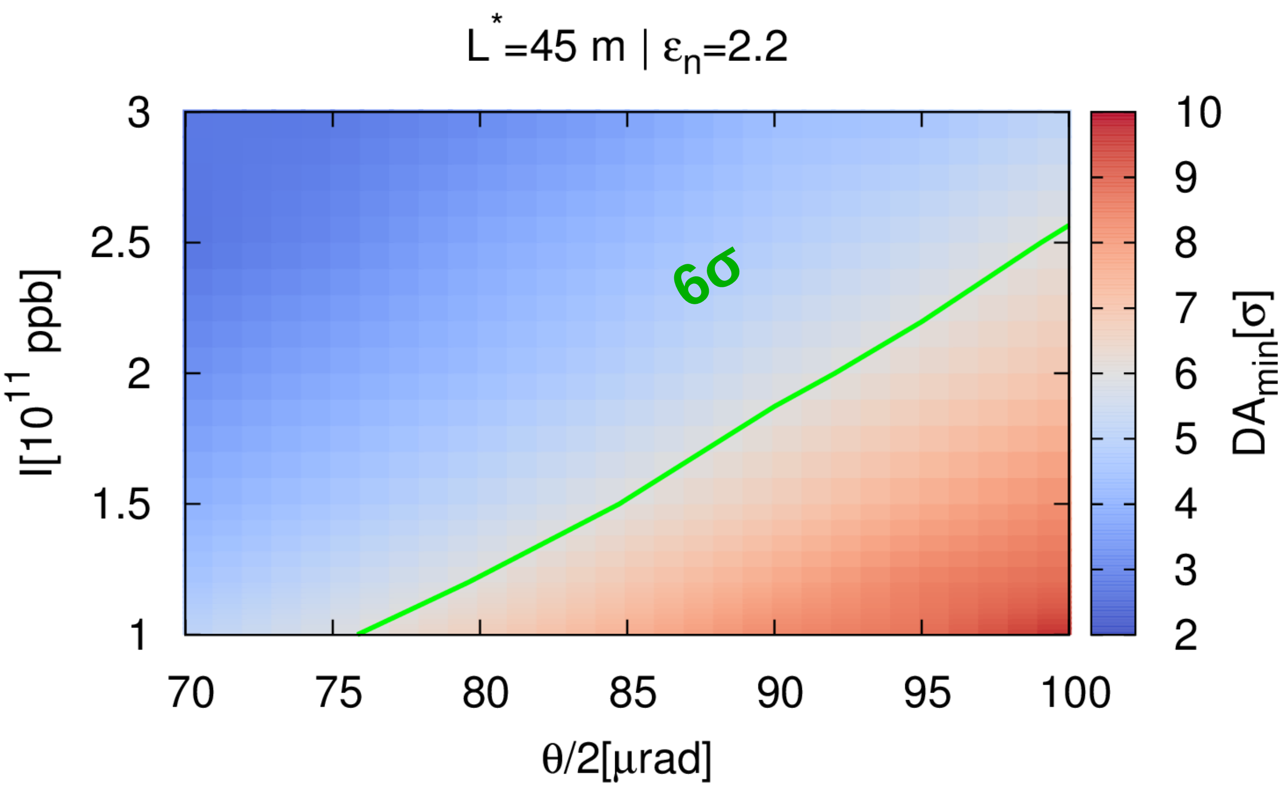
Simulations

- In order to validate the different scenarios from BB point of view we will use the **dynamic aperture** as figure of merit as done for the LHC design.
- The dynamic aperture refers to the **boundary for chaotic motion** in circular machines. This limit should be large enough to not interfere with aperture limitations (collimation system) and ensure adequate beam life time.
- DA criteria adopted: all particles stable up to initial 6σ.
- The simulations are done with the SixTrack code using the SixDesk environment.
- Parameters:
  - Tracking turns: 10^6
  - Phase space angles XY: 5 (to be increased in the future to improve resolution)
  - Normalized emittance: 2.2 μm (constant)
  - No magnets errors included (now ready to be included as next step)
  - 4D beam-beam head on interactions (crab crossing as 1 HO 4D)
  - Maximum number of BB encounters
- The results presented were obtained lxplus clusters at CERN, but possibility of using the BOINC platform if workload increases significantly.

LHC@home
SixTrack

Results. Baseline L^*=45 m

- For the baseline parameters (I=10^{11} ppb, see table before) a 6σ DA is ensured with a θ/2~76μrad, i.e. **d_{sep}= 12.95σ**.
- Large parameter space for more challenging scenarios.
- This is consistent with previous studies done with a FCC toy lattice (Xavier's presentation in Washington 2015) taking into account the differences in the IR region design.



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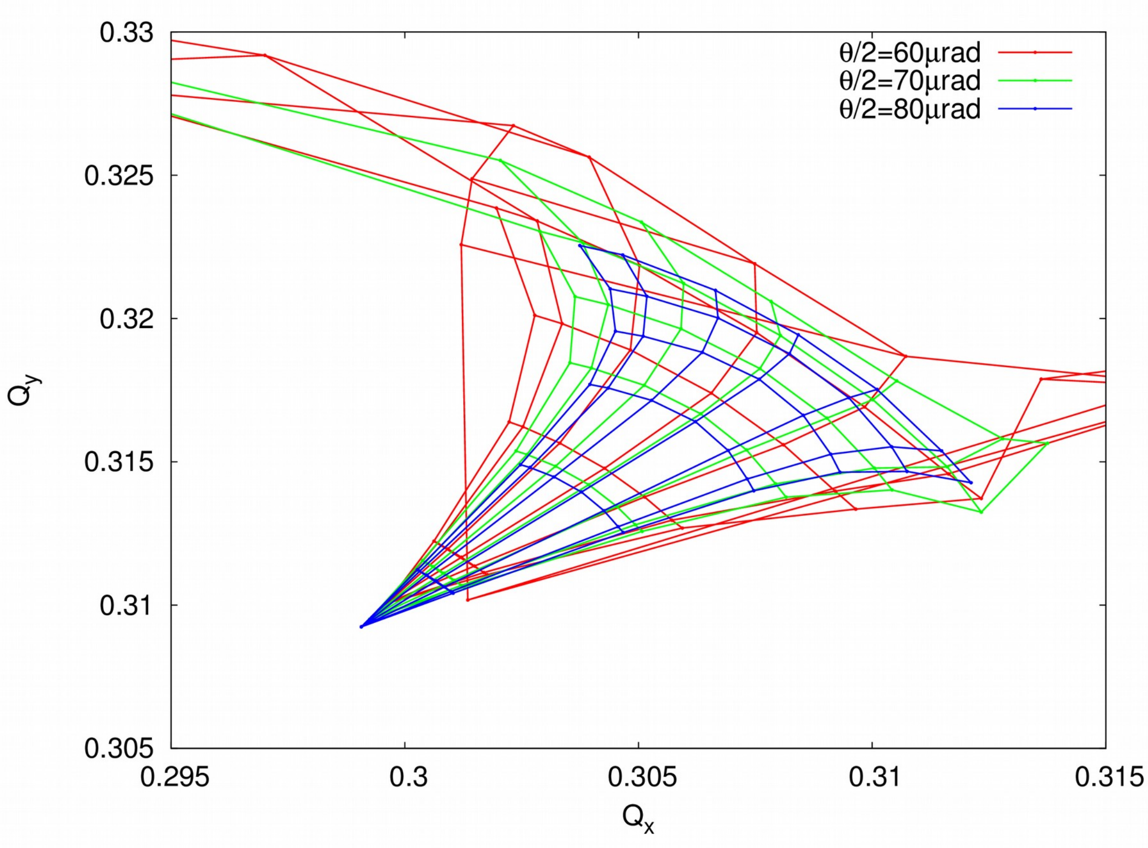

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- This is consistent with previous studies done with a FCC toy lattice (presented in Washington 2015) considering the differences in the IR region design.
- Scaling from the LHC case using laws in [1],

$$\frac{I_b n_{LR}}{d_{sep}^2} \propto \Delta Q_{LR} \;\Rightarrow\; d_{sep} \approx 14\,\sigma$$

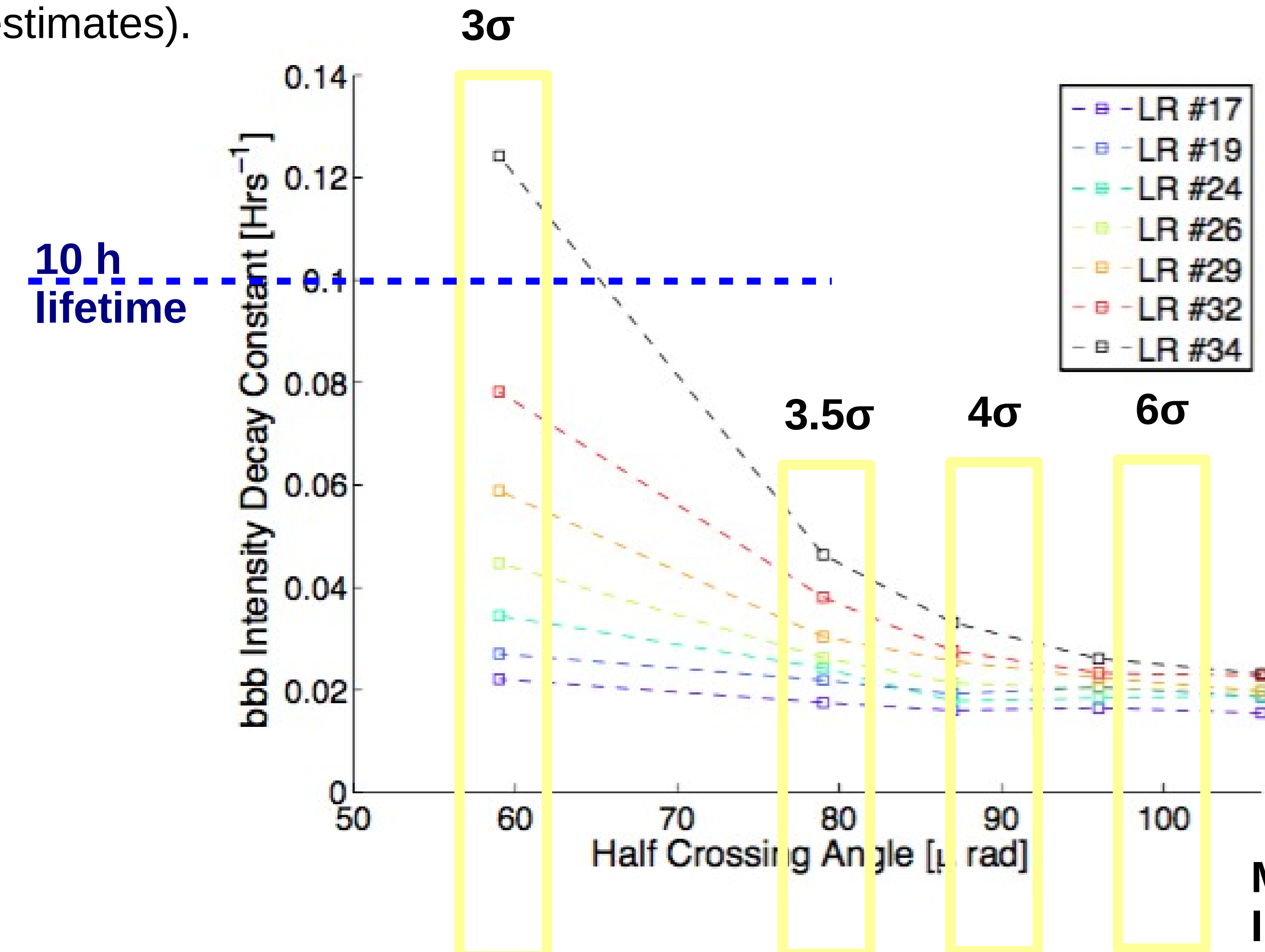
$$\frac{I_b n_{LR}}{d_{sep}^4} \propto \text{Tune Spread} \;\Rightarrow\; d_{sep} \approx 12\,\sigma$$

Good agreement between 'detailed' simulations and coarse estimations.

[1] S. Peggs and B. Neuffer, "Beam-beam tuneshifts and spread in the SSC – Head on, long range and PACMAN conditions", April 1986, SSC-63, Dallas, USA.

Why a 6σ DA criteria?

- Extensive experimental studies since 2010 to validate the LHC DA scaling laws vs BB parameters (crossing angle, β*, intensities) to identify the minimum BB separation (BB pattern in the losses).
- 2015 DA vs beam and luminosity lifetime as a function on the crossing angle (quantitative estimates).



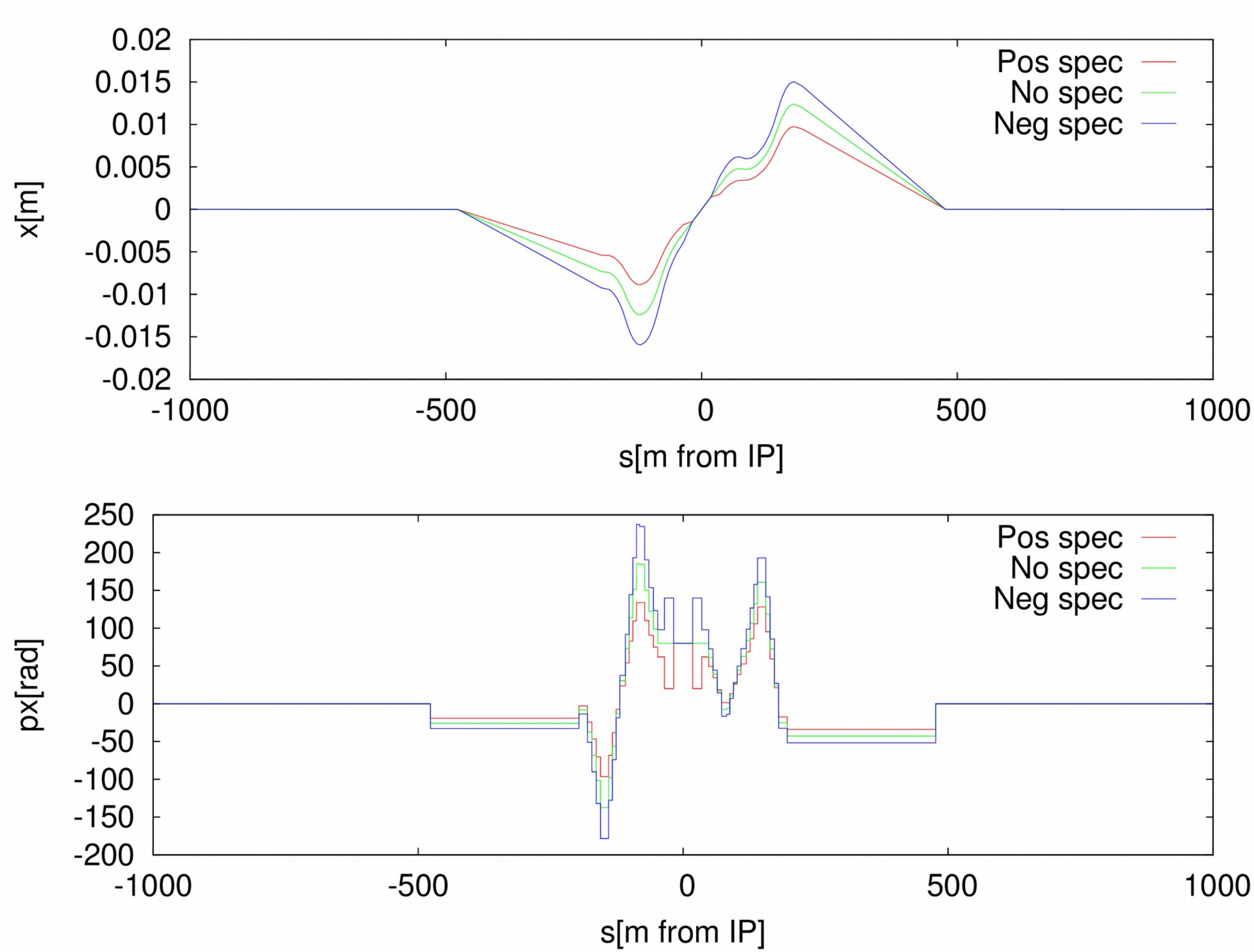
Several studies by W. Herr *et al.*

M. Crouch *et al.* IPAC16

6σ criteria is robust as it gives 2σ margin from observables BB LR effects on beam and luminosity lifetime.

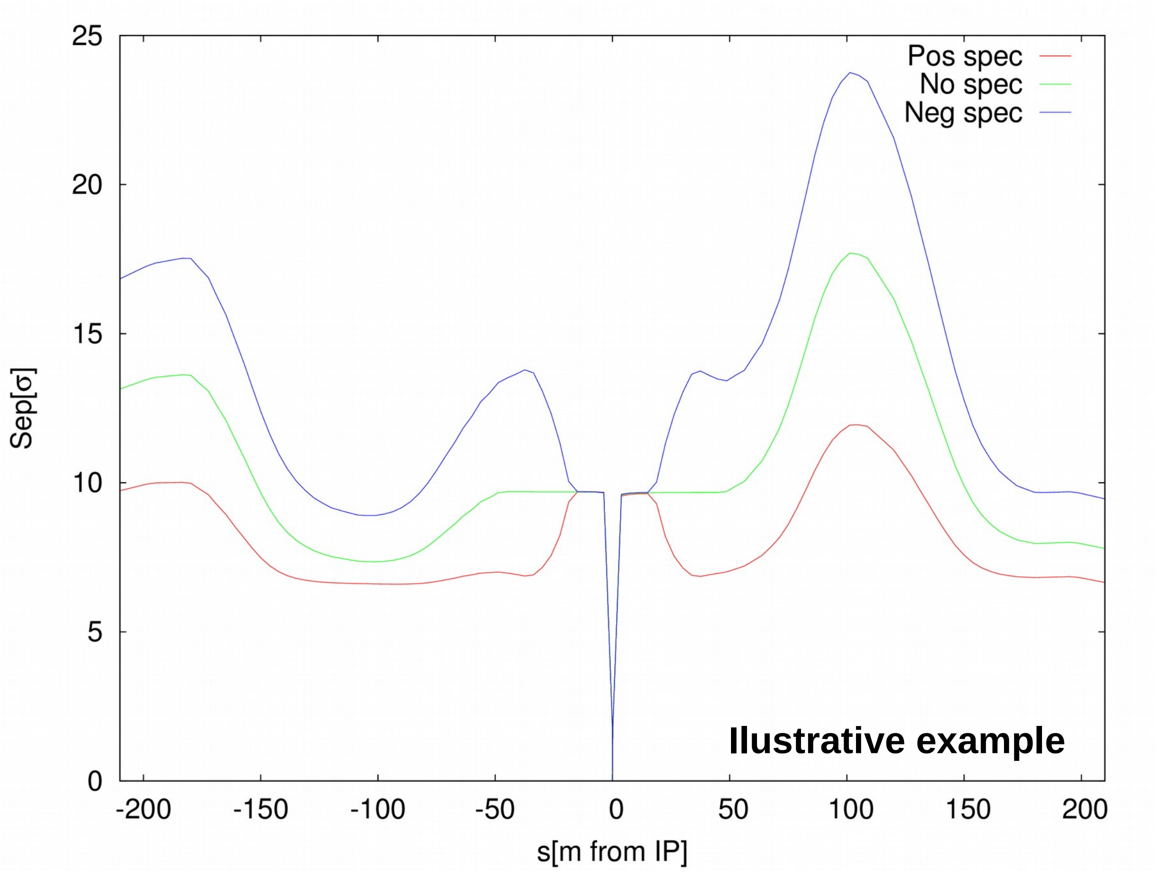
Spectrometer Magnet in the IRs

- Requested by the experiments. Dipole inside the experiment to bend particles trajectories.
- Two angles now: effective (luminosity) and external (aperture) crossing angle.
- Negative polarity pushes away the long ranges interactions while positive brings them closer to the opposite beam.

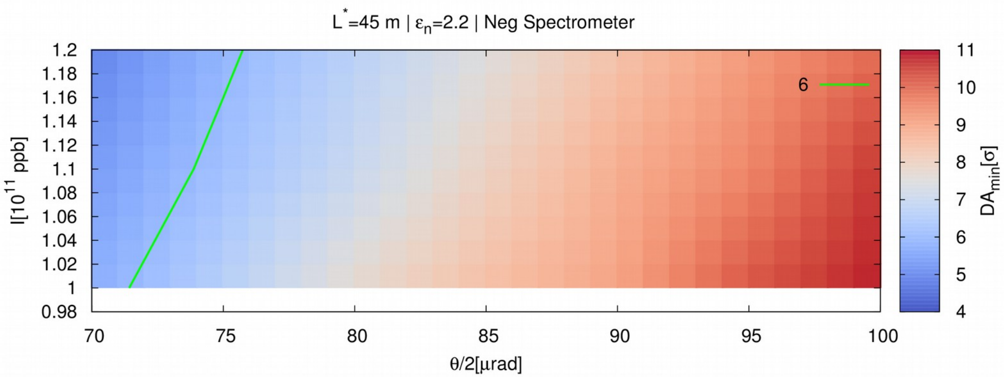


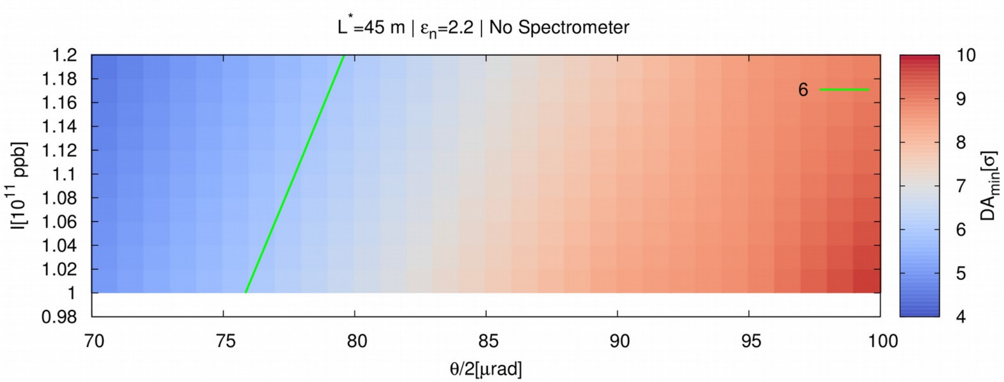
Spectrometer Polarity

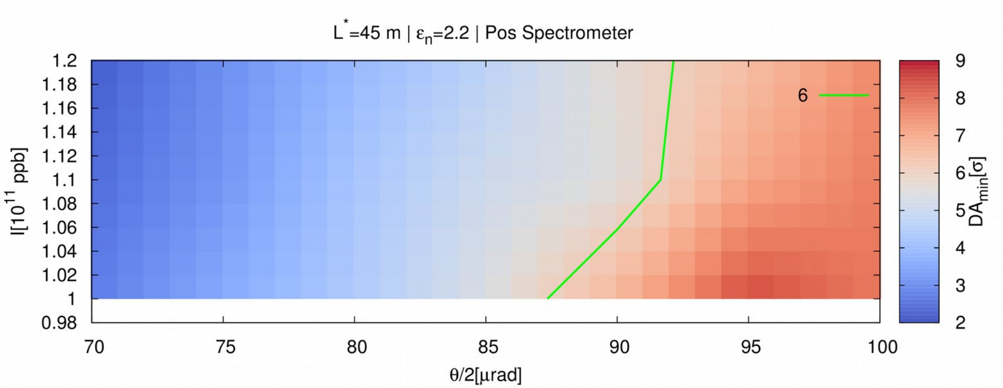
- Requested by the experiments. Dipole inside the experiment to bend particles trajectories.
- Introduces a new concept: effective (luminosity) and external (aperture) crossing angle.
- Negative polarity pushes away the long ranges interactions while positive brings them closer to the opposite beam.



DA vs spectrometer polarity







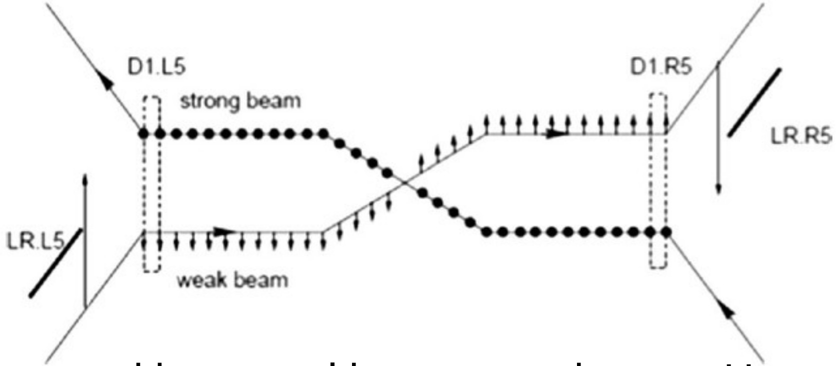
As expected negative polarities provides better DA for a given internal crossing angle.

The 6σ limit gives the following **effective** angles:

- Neg. polarity →θ/2~71 μrad
- No spectr. →θ/2~76 μrad
- Pos. polarity →θ/2~87 μrad

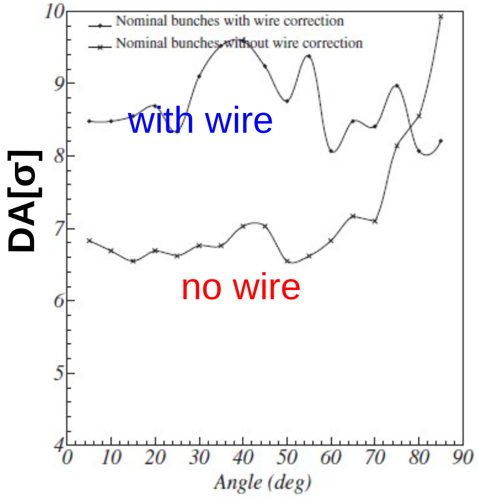
LR compensation: Wires,e-lens

- It is possible to compensate locally the kick by the long range interactions using an electrostatic wire[1].



- These devices has been tested in several beam experiments. However its location, current settings, distance to the circulating where always an iterative
- In [2] a new semi analytic approach was developed showing that the compensation is maximized for a given ratio between β at the location of the wire.

$$r_w \equiv \frac{\beta_x^{w.R}}{\beta_y^{w.R}} = \frac{\beta_y^{w.L}}{\beta_x^{w.L}} = 2$$

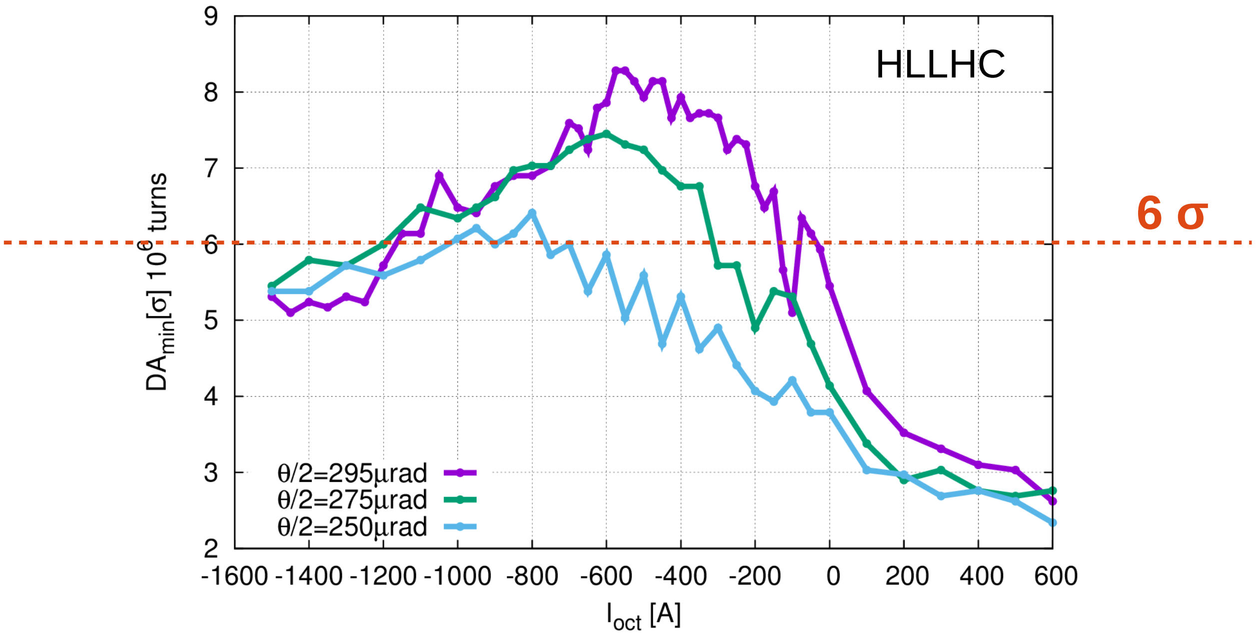


- Test of wires in the LHC in near future. Lots of feedback and experience expected (H. Smickler and Y. Papaphilippou)

[1]J. P. Koutchouk, *"Principle of a Correction of the Long-Range Beam-Beam Effect in LHC using Electromagnetic Lenses"*, LHC Project Note 223, April 2000.
[2]S. Fartoukh *et al., "Compensation of the long-range beam-beam interactions as a path towards new configurations for the high luminosity LHC",* PRSTAB 18, 121001 (2015).

LR compensation: Octupoles

- Past studies show that it is possible to recuperate significant DA levels in the HL-LHC by **powering octupoles at collision** (T. Pieloni and D. Banfi WP2 HLLHC January 2015)
- Resume the studies recently.
- However it has to be fully understood since the results cannot be reproduced in the LHC case so far. **Design differences** between the two cases could explain it.
- FCC we should explore this type of compensation.



HO compensation: e-lens

- Electron lenses can be considered as “electron cloud” that can be fully controlled (charge density, diameter, length…).
- Recent studies and development at RHIC show the feasibility of compensating HO BB effects with elens[1].
- E-lens operational used at RHIC for compensating half HO spread.

W. Fischer, *“RHIC electron lenses upgrades”*, IPAC15.

If HO is a limit then,

Need of explore e-lens compensation

Upgrade of our tools/model to allow this studies and,

collaborations with RHIC team would be essentail.

Conclusions & Outlook

- Models and simulations were successfully set up for the FCC ultimate.
- The dynamic apertures is used as figure of merit to **characterize and validate** the different scenarios.
  - Intensity and crossing angles to determine limits.
  - Preliminary results shows 12.9 σ for the ultimate scenario (consistent with previous FCC studies as well with scaling laws from the LHC)
  - Studies with spectrometer show need of 10% increase of effective needed. Negative decreases 5% the angle.
- Different compensation techniques initial locations and values have to be set up. Proper simulations with updated codes will be needed.
- Next simulations steps
  - Include magnets errors and corrections.
  - 6D head on interactions with crab cavities.
  - Evaluate flat beams, flat optics.
  - Alternate crossing schemes HH, intermediate angles (?).
  - Parameters evolution during the fill (snapshots)