Beam-Beam beta-beating effects and implication for the HL-LHC and FCC

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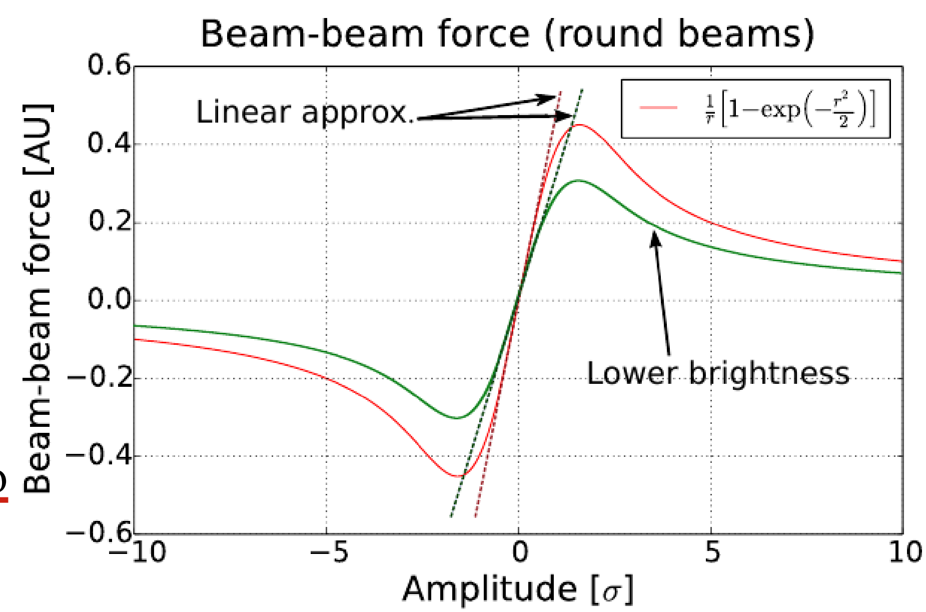
β-beating beam-beam induced

- 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:

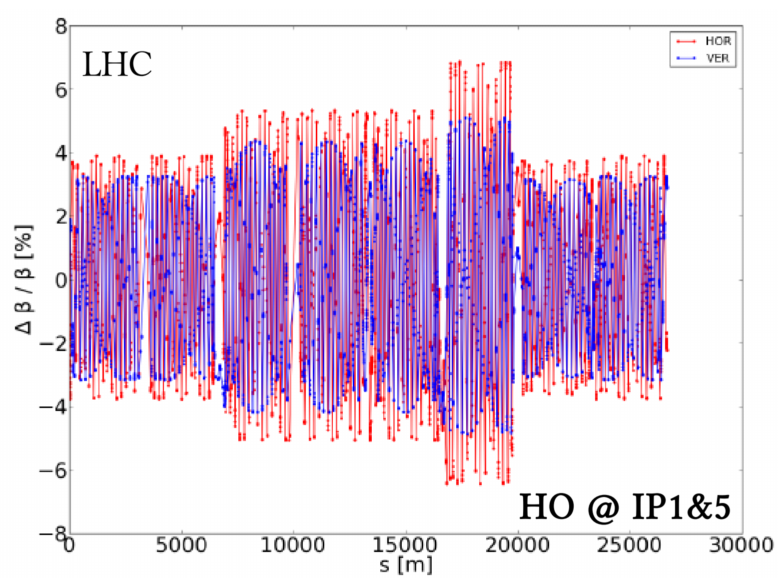


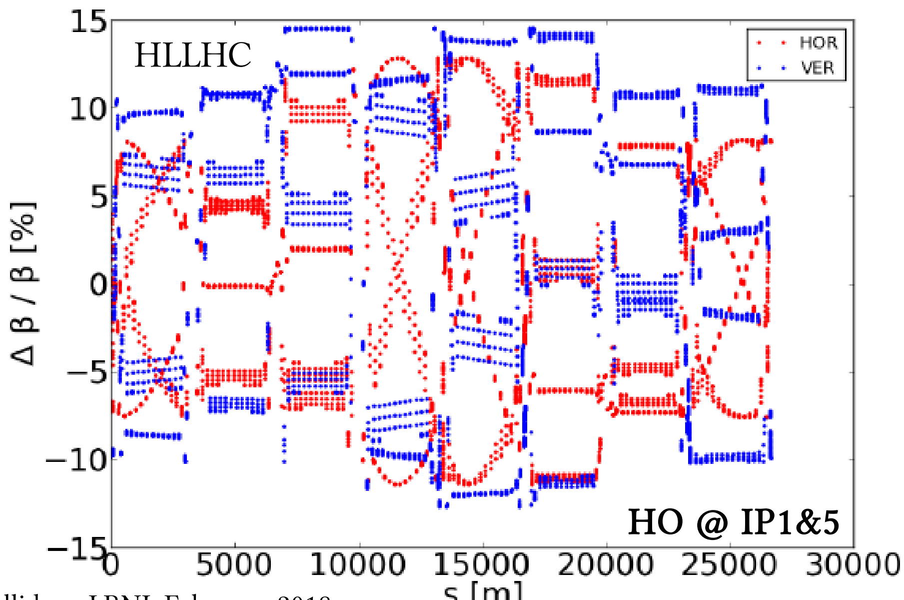
$$\frac{\Delta\beta(s)}{\beta_0(s)} = \frac{2\pi\xi}{\sin(2\pi Q_0)} \sum_{i=0}^{N} \cos(2\,|\mu_0(s) - \mu_0(s_i)| - 2\pi Q_0)$$

- 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.
- **Is the expected BB β-beating comparable with operational requirements? Linear vs Non-linear beating? Impact on machine protection? Luminosity?**

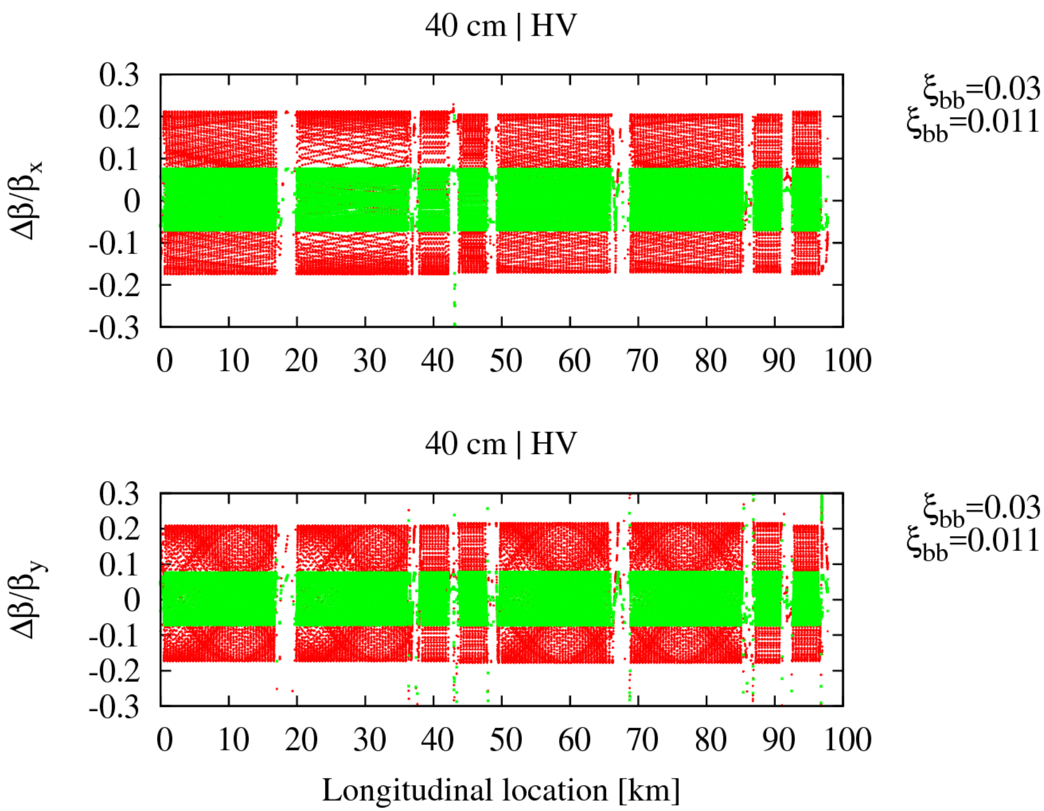
Linear BB β-beating Impact: LHC and HLLHC

- Linear beating from MADX (0σ particles) with head on (HO) interactions in IP1 and 5 and no lattice errors.
- For LHC: ξ_{bb}=0.0037/IP ⟹ Δβ/β~7% (2IPs)
- For HLLHC: ξ_{bb}=0.01/IP ⟹ Δβ/β~15 % (2IPs) or 24% (3IPs)
- In the **worst case** the beating from BB will **add up** to the beating due to lattice errors (5-7 %). Impossible to know a priori.
- In the HLLHC case since a full crab crossing scenario is considered so the beating is independent on the β*.
- Collimation experts request $\Delta\beta/\beta_{max}$ <10 % as in the LHC.





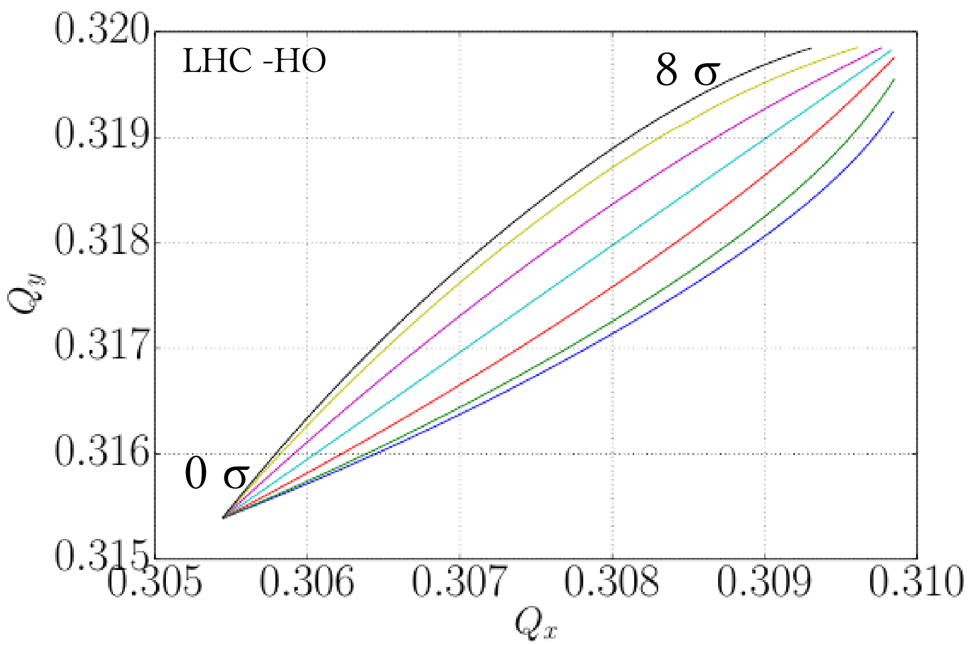
Linear BB β-beating Impact: FCC

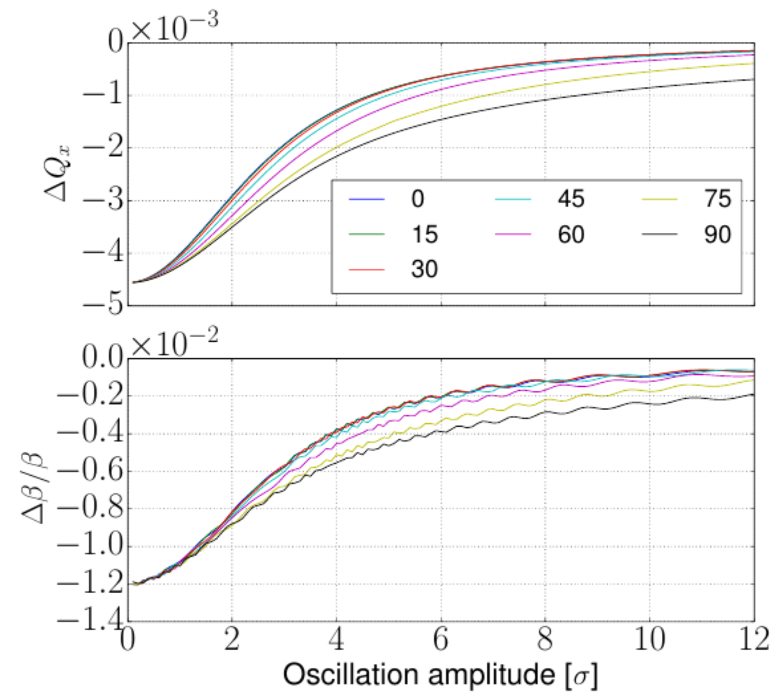


- Linear beating from MADX (0σ particles) with head on (HO) interactions in IPA and G and no lattice errors.
- Using L*=40m and β*=0.3m optics with full crab crossing.
- FCC adds new feature since the ξ_{bb} **changes over the fill** and so the beating.
  - $\xi_{bb,tot}$=0.011 (beg. Fill) - $\Delta\beta/\beta_{max}$=8 %
  - **$\xi_{bb,tot}$=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.

Non-linear β-beating impact: Head on

- MADX tracking for the LHC case plus SVD analysis (provides effective values for the twiss parameters).
- Limitations for amplitudes > 8.3σ where chaotic motion was found.
- The effective β beating from one IP follows the proportionality to the beam-beam tune shift.
- Beating vanishes asymptotically for large oscillation amplitudes ⟹ halo particles not affected.
- Challenging (impossible?) correction for all amplitudes due to the spread.

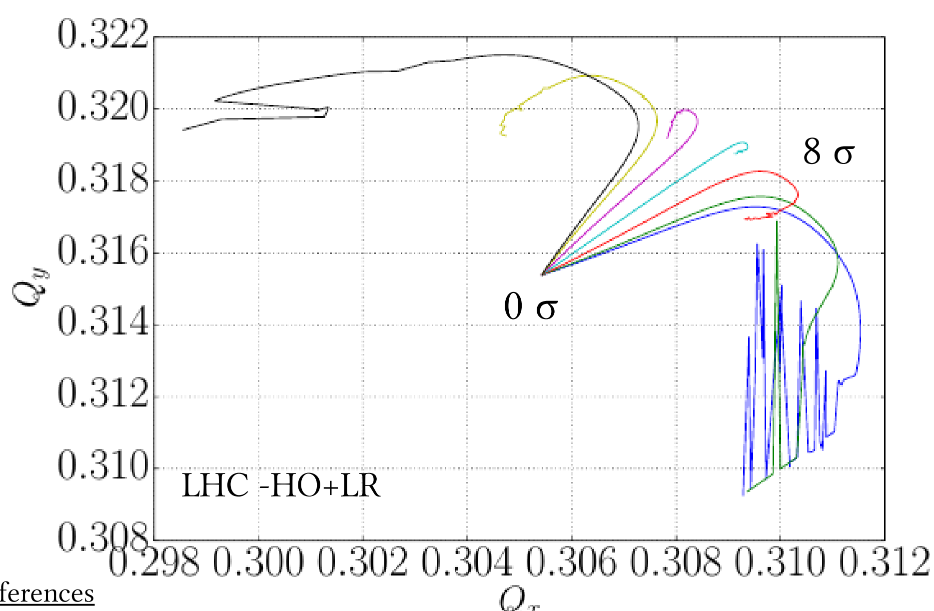


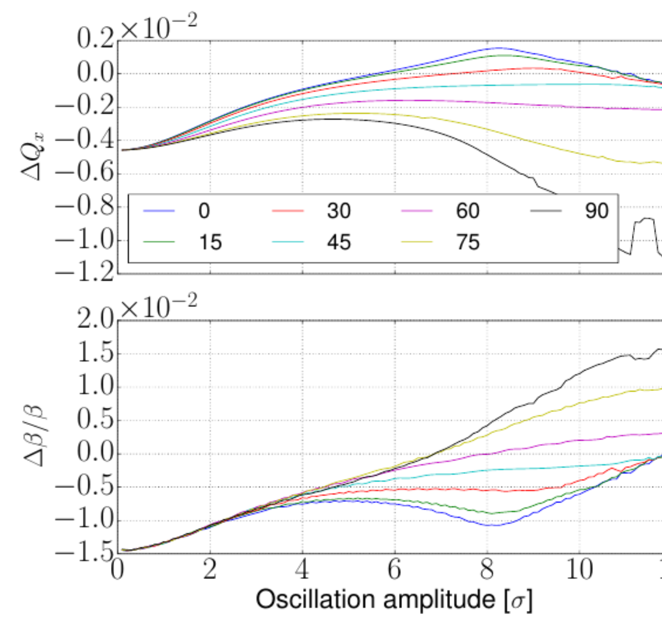


References
P.J. Gonçalves, Computation of Linear Optics Distortions due to Head-on Beam-Beam Interactions in Hadron Colliders, CERN-THESIS-2015-404
P.J. Gonçalves, Computation of Optics Distortions due to Beam-Beam Interactions in the FCC-hh, CERN-THESIS-2016-317

Non-linear β-beating impact: Long range

- MADX tracking for the LHC case plus SVD analysis (provides effective values for the twiss parameters).
- Unlike for the HO interactions the long-range (LR) are already strong in the LHC in comparison with HLLHC and FCC.
- During LHC operation no impact on cleaning inefficiency was observed at collision.
- The effective β beating does not follow a linear scaling with the tune shift.
- Passive compensation between two main IPs compensate shift from LRs. Not perfect cancellation and some β beating remains. Phase advance between the IPs can be optimized to minimized it.





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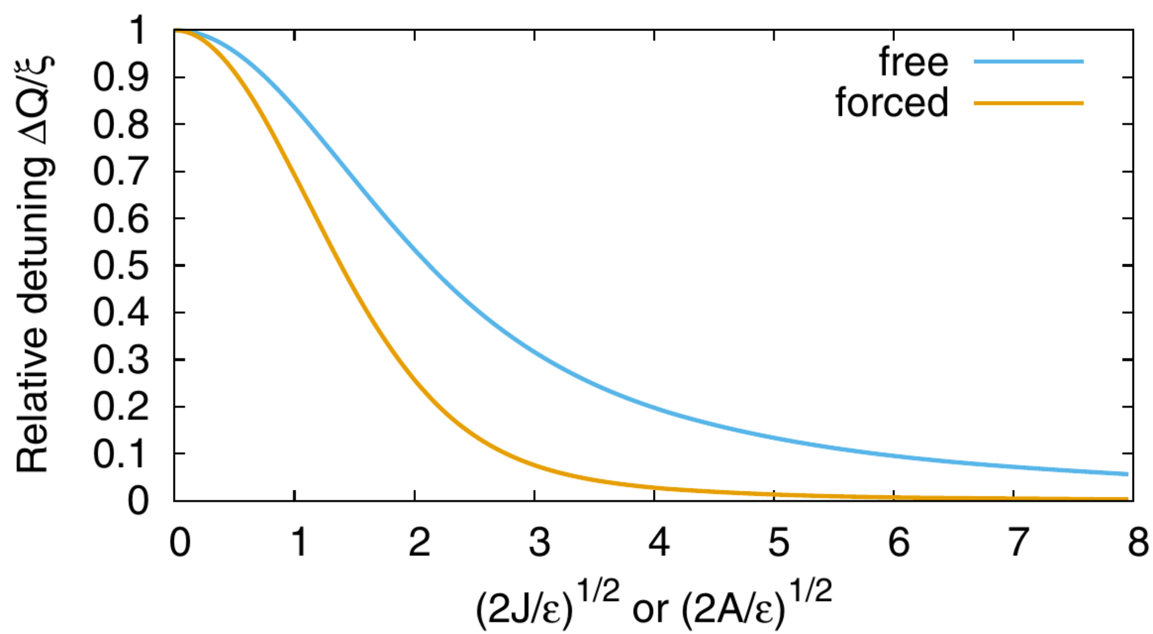
BB amplitude detuning with forced oscillations

- **Can be this effect measured in real operation?**
- Recently, some effort was devoted to extend forced oscillations (ADT or AC Dipole) based techniques to take into account the presence of beam-beam interactions (weak-strong regime).
- The free action refers to particles with an offset while for the forced is the oscillation amplitude.
- At small amplitude forced oscillations detune a **factor 2** faster than free.

Analytical Detuning

$$Q_x(A_x) = \xi\left[I_0\left(\frac{A_x}{2\epsilon}\right) - I_1\left(\frac{A_x}{2\epsilon}\right)\right]e^{-\frac{A_x}{2\epsilon}}.$$

$$Q_y(A_x) = \xi\left[I_0\left(\frac{A_x}{2\epsilon}\right) + I_1\left(\frac{A_x}{2\epsilon}\right)\right]e^{-\frac{A_x}{2\epsilon}}$$



References

R. Tomas *et al.*, Beam-beam amplitude detuning with forced oscillations, PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 101002 (2017).

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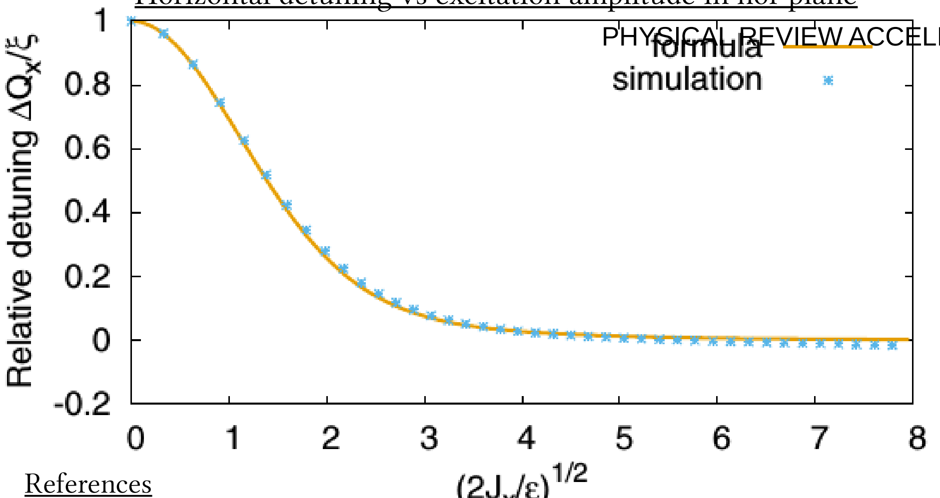
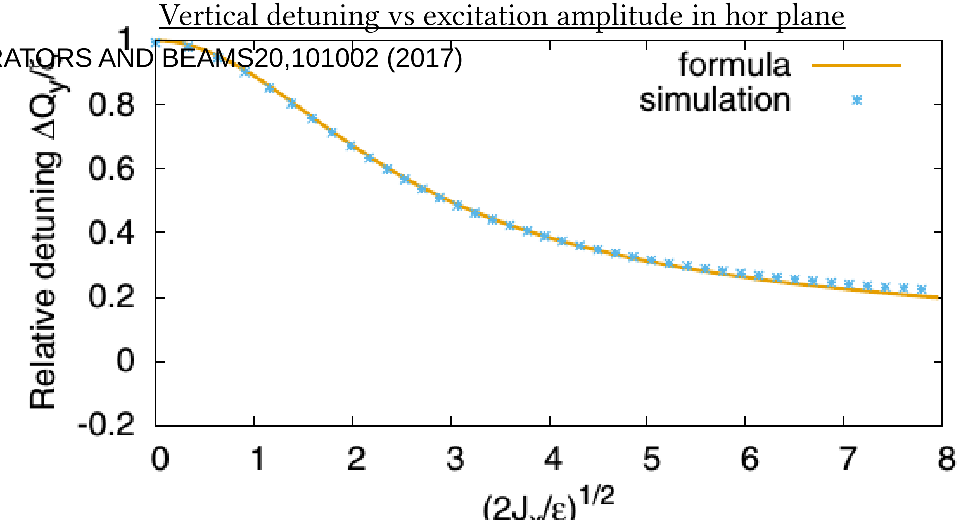
- The free action refers to particles with an offset while for the forced is the oscillation amplitude.
- At small amplitude forced oscillations detune a **factor 2** faster than free.
- The forced action is computed from the Fourier amplitude of the spectral line with the forced tune during the excitation plateau.
- Analytical detuning (single particle) benchmarked against MADX tracking (weak-strong) showing very good quantitative agreement for 0σ particles.

Horizontal detuning vs excitation amplitude in hor plane



Vertical detuning vs excitation amplitude in hor plane



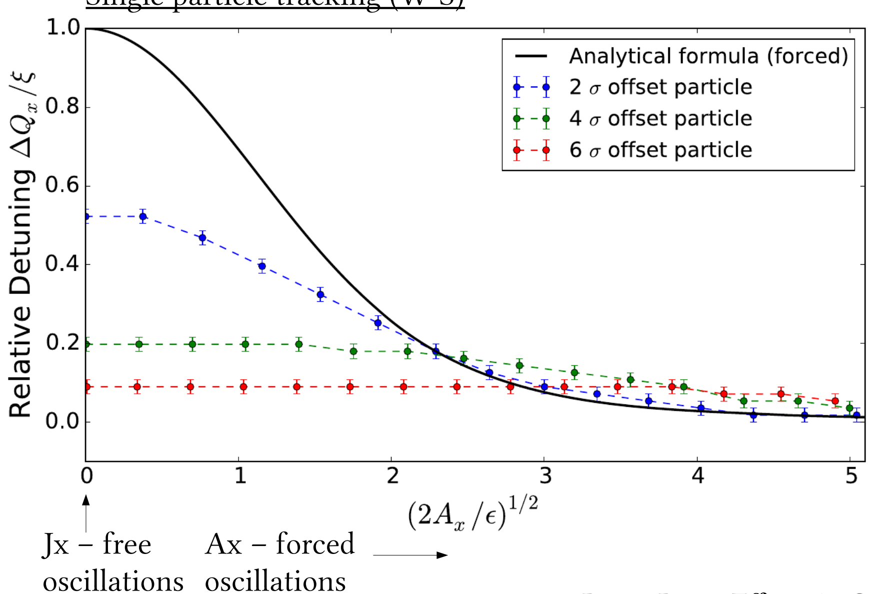
References

R. Tomas *et al.*, Beam-beam amplitude detuning with forced oscillations, PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 101002 (2017).

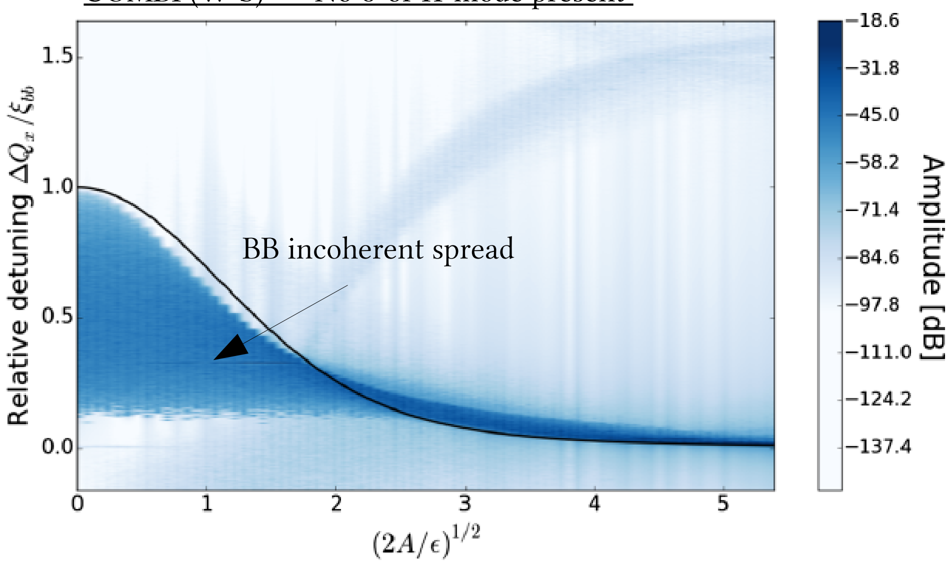
BB amplitude detuning with forced oscillations

- However the forced detuning is amplitude dependent. Particles with larger free action feature a weaker detuning versus the forced action.
- Between 2σ and 3σ non-zero amplitude cross the analytical formula ($J_x = 0$). This is explained from shape of the BB force since its derivative changes sign ~1.6σ.
- The analytical formula should represent the upper boundary of the incoherent spectrum below 2σ and the lower boundary for forced oscillations above 3σ (in the plane of excitation).
- In the non-excited plane the analytical formula represents always the upper boundary.
- Self-consistent simulations with COMBI (upgraded with an AC Dipole element) in weak-strong regime confirm the single particle tracking results.

Single particle tracking (W-S)

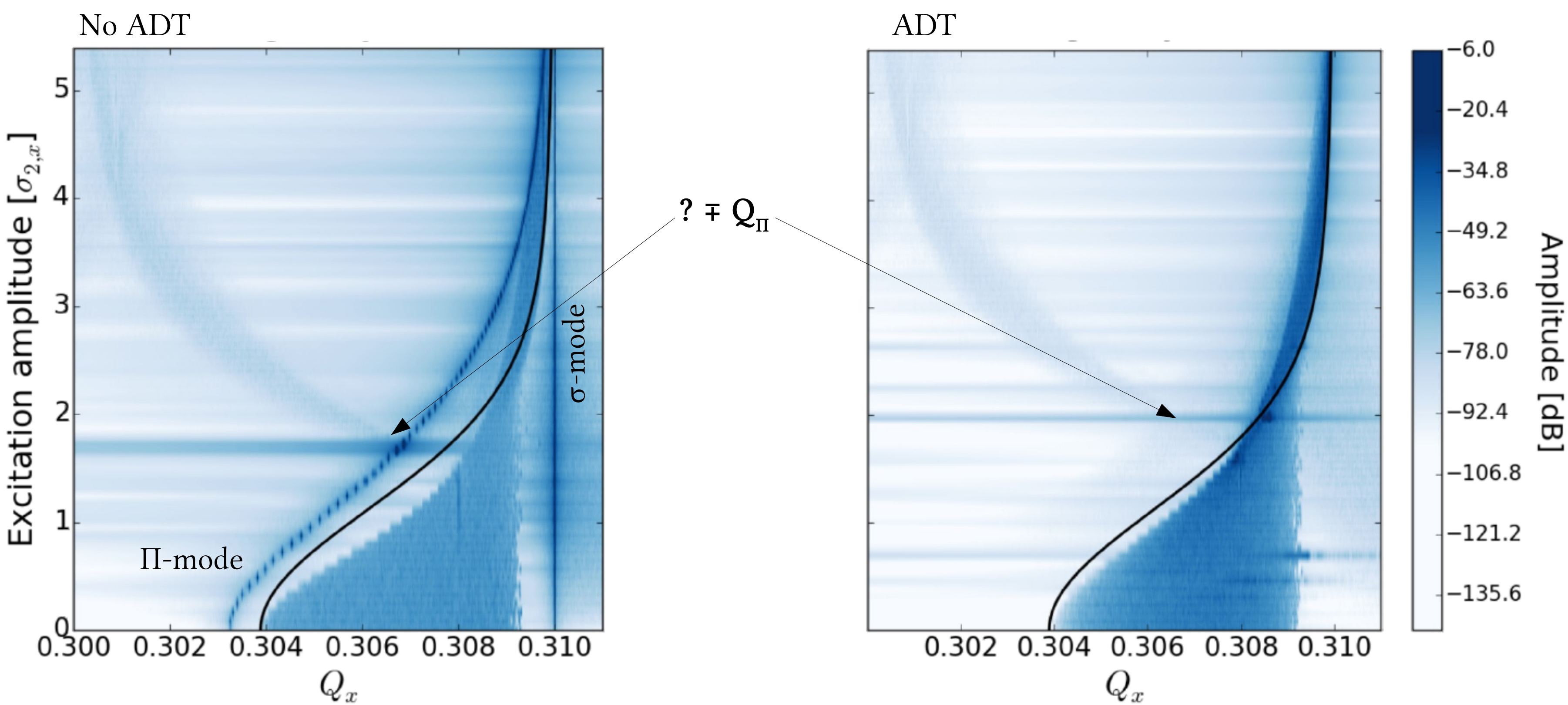


COMBI (W-S) ⟹ No σ or Π-mode present



BB amplitude detuning with forced oscillations

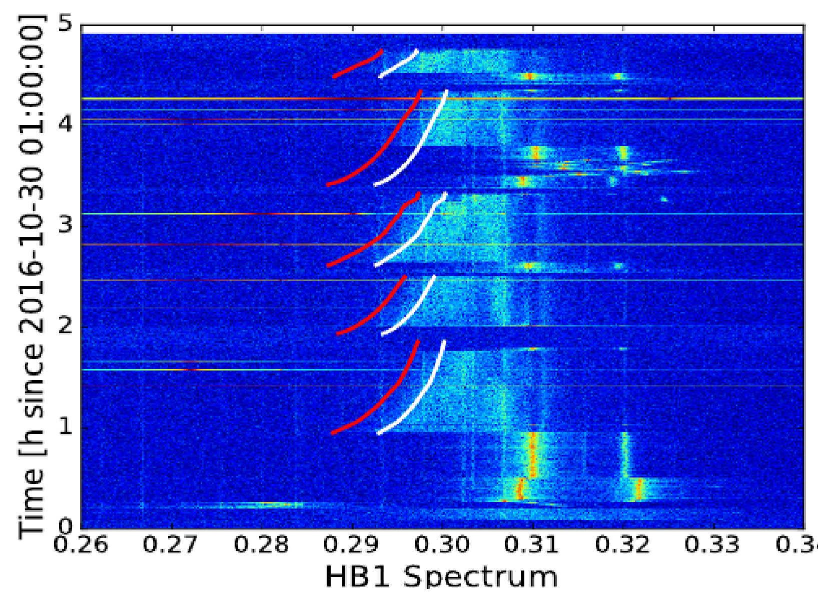
- Another way of forcing a weak-strong configuration is set up the ADT with strong gain.
- The coherent modes are clearly suppressed. However some modes are excited around 1.8σ apparently following the Π-mode. Still further analysis is needed.
- The presence of a large incoherent spread is not compatible with single particle models to compute the β beating from AC dipole measurements even in W-S regime. Only the boundary of low oscillation amplitude particles can be predicted.



Measurement of LHC HO β-beating

- **Is it possible to measure this effect on the LHC?**
- A 8h LHC MD was devoted to this purpose at the end of October 2016.
- Bunches were collided at injection energy with collision tunes.
- Weak-strong regime was chosen to avoid coherent effects. Large asymmetry on intensities.
- Collision tunes @ injection. β^*=11m and θ=340 μrad.
- Forced oscillations with ADT and AC dipole.
- The ADT allows to excite for longer periods (~ 5 times)
- Very small bunches were delivered by the injectors (ε< 1μm) to maximize ξ_{bb}, however wire measurements have 20% uncertainty in that range.
- BBQ plots show the effect of the underestimated emittance in terms of Δq_{bb}. Measurements (red) predicts larger shift than corrected (white).

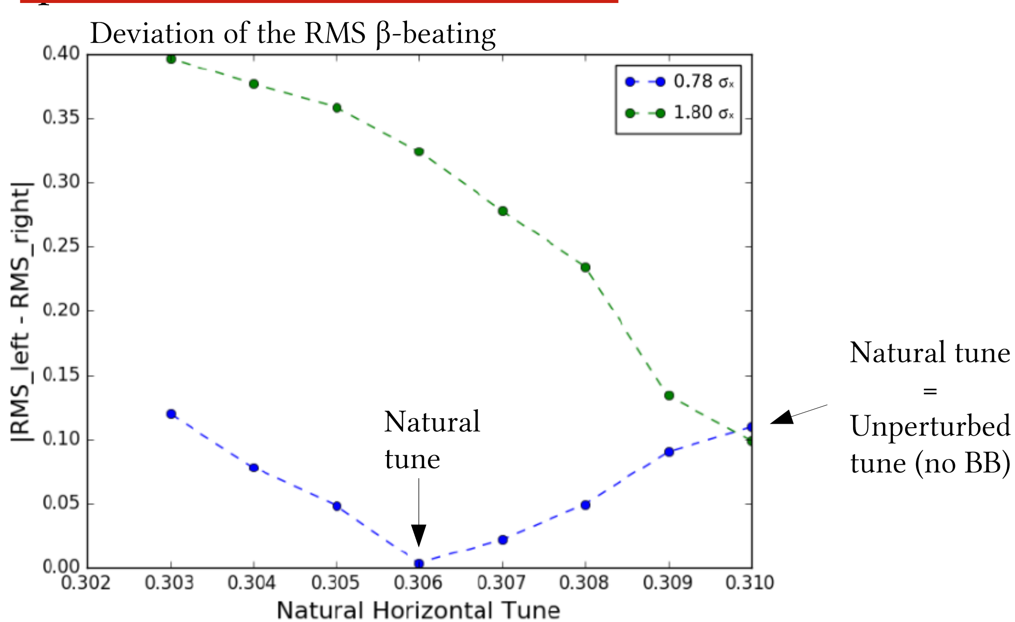
Parameter	Value
β^*[m]	11
θ[μrad]	340
E[GeV]	450
$Q_{x,y}$	0.31/0.32
$I_{1,2}$[10^{11} ppb]	0.07/1.05
ADT[turns]	29000
AC Dipole	6600

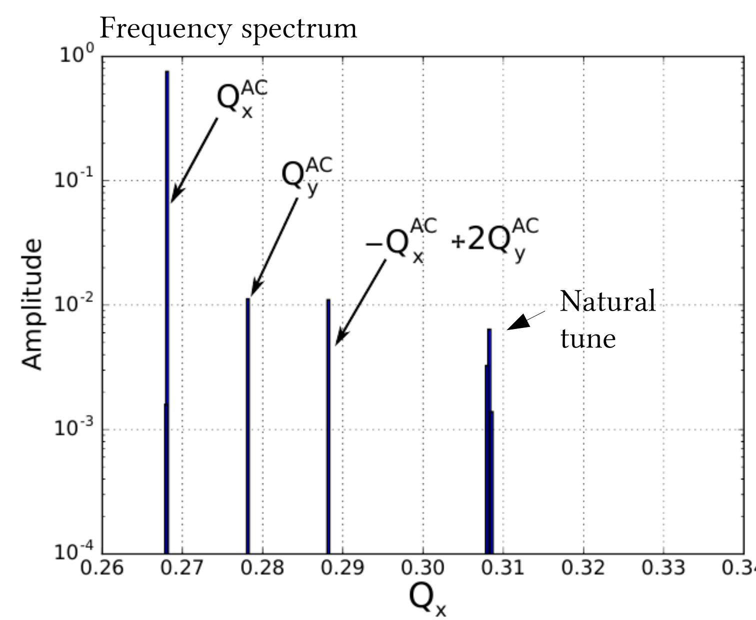


Measurement of LHC HO β-beating

- Optics reconstruction from measurements are based on the existence of a tune representative (natural tune) for the whole bunch. Not evident with BB since large spread of tunes is present.
- Three methods:
  - Direct observation of the natural tune in the frequency spectrum
  - Deviation of the RMS β-beating on both sides of the AC/ADT.
  - Minimize phase advance deviations from the AC/ADT location (OMC GUI segment-by-segment)

  } Scan tune until perturbation from ADT/AC is compensated for.
- However not conclusive for all measurements. Developments required take into account the tune spread from the BB interaction.

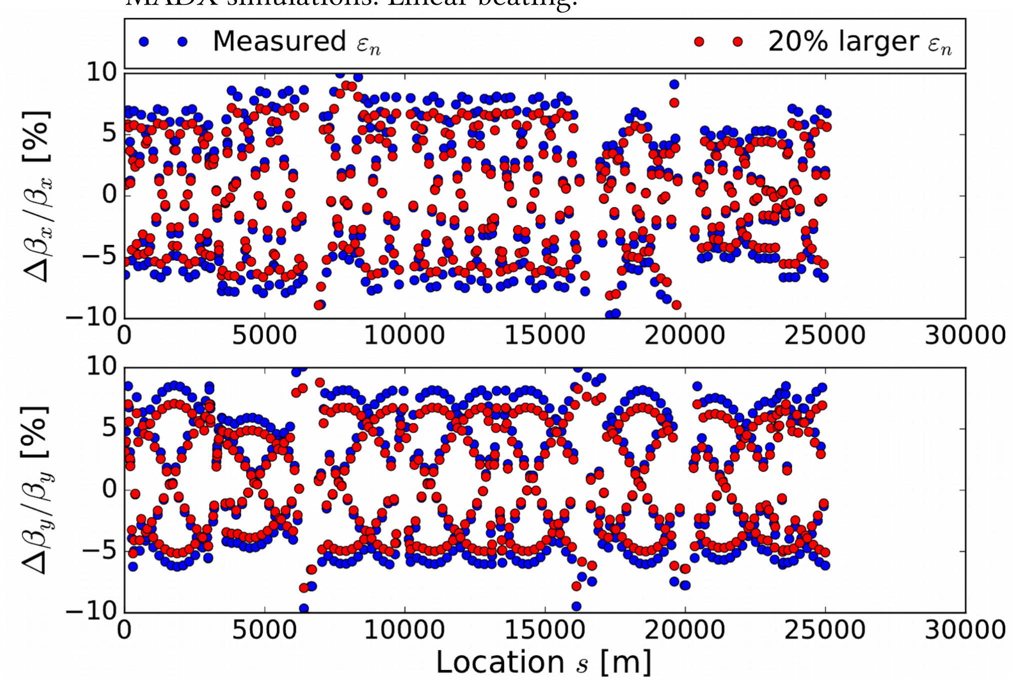




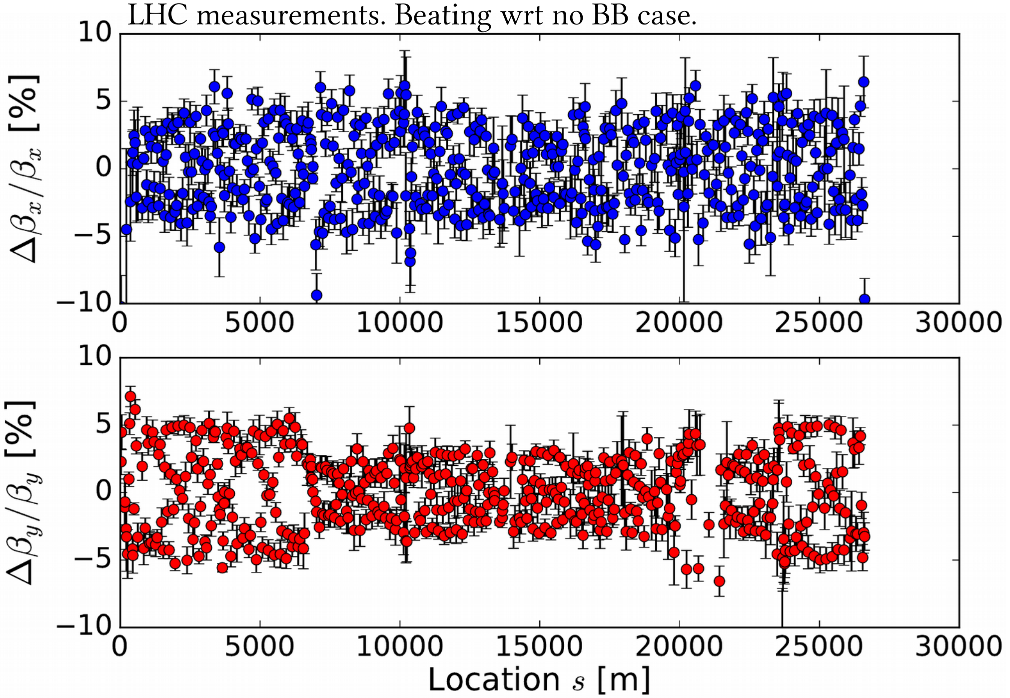
Measuring β-beating in the LHC

- First successful BB induced β-beating measurement ever.
- Measurements (beating wrt no BB case) and MADX simulations (linear beating wrt perfect machine) agreed qualitatively.
- Reconstruction methods have to be revisited with BB spread and MD should be repeated with correction schemes in the future.

MADX simulations. Linear beating.



LHC measurements. Beating wrt no BB case.

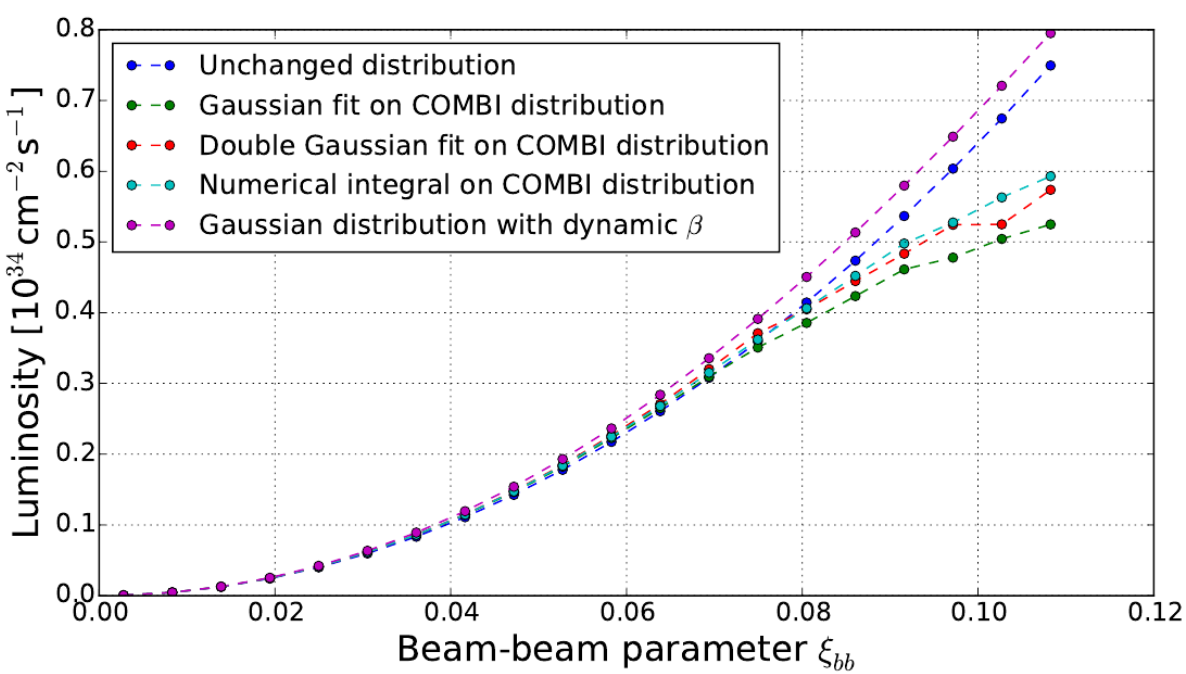


1IP | ΔQ~0.013 | Q_{AC} = (0.268,0.278) | A_{AC} = 1.8 σ

P.J. Gonçalves, *"Observations and measurements of dynamic effects due to beam-beam interactions in the LHC and extrapolation to the FCC-hh"*, EPFL Master thesis, 2017.

Impact on the 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 $\forall\ \xi_{bb}$

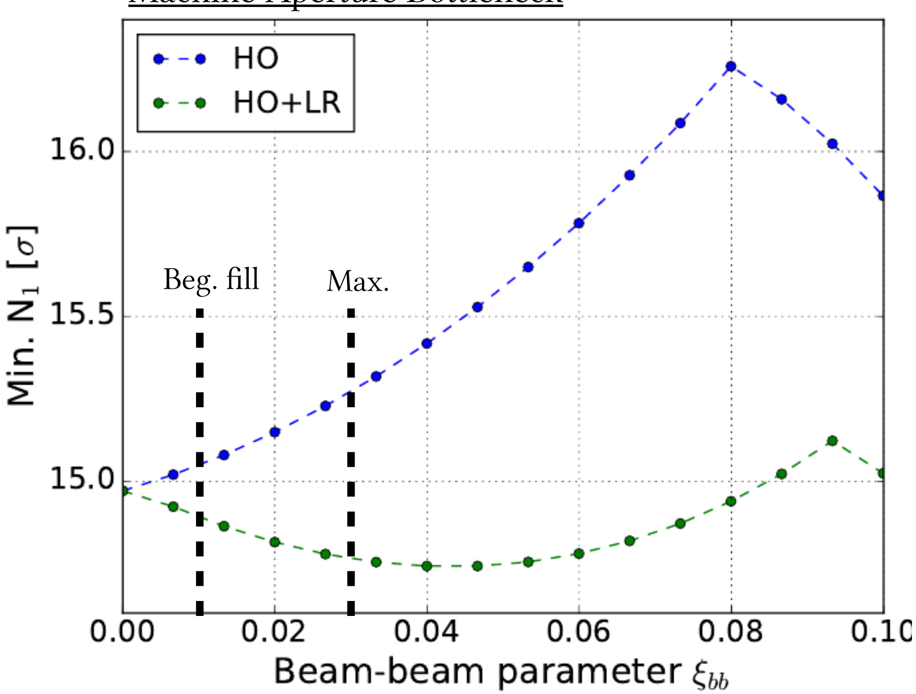


Beam-Beam Effects in Circular Colliders, LBNL February 2018.

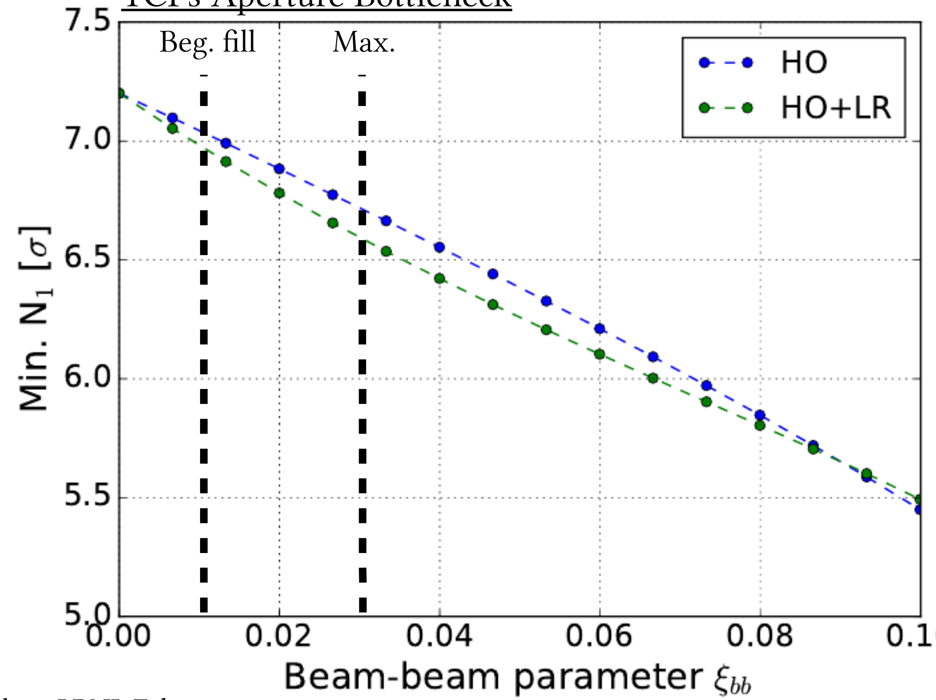
Impact on Machine aperture

- 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.

Machine Aperture Bottleneck



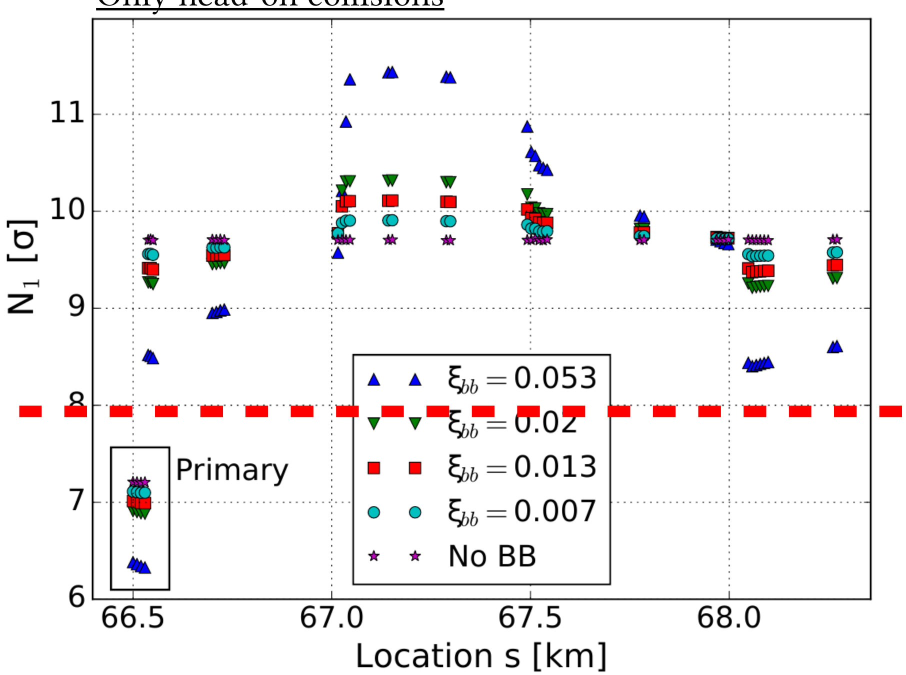
TCPs Aperture Bottleneck



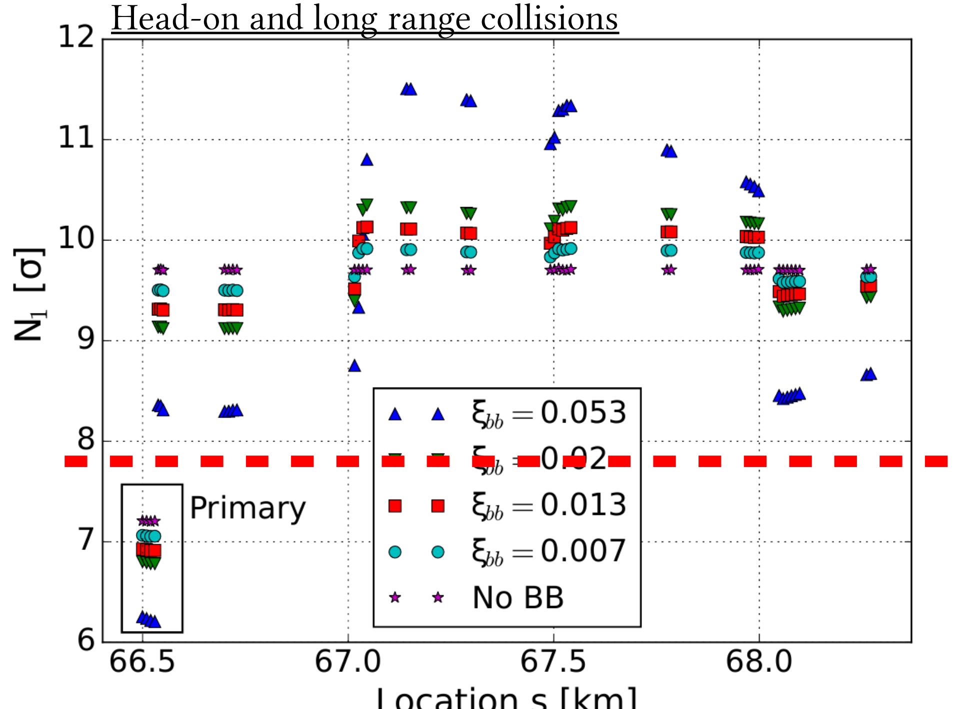
Collimation hierarchy

- We explore the impact on machine and collimator apertures for various ξ_{bb}. Only linear beating is considered (worst case).
- Primaries set @ 7.2σ and secondaries @9.7 σ. Only betatron collimation considered.
- The collimation hierarchy is preserved, even for high ξ_{bb}. However apertures are strongly perturbed.
- The usual beam loss maps including BB are needed to evaluate the impact of these distorted apertures.
- Simulations with SixTrack and BB are under discussion with FCC collimation experts. The tracking should be realistic in terms of amplitude detuning from BB.

Only head-on collisions



Head-on and long range collisions



Summary and Outlook

- The distortion of the linear optics due to beam-beam interactions will be non-neglilible for the HL-LHC and FCC. Correction is possible (see L. Medina IPAC17), however they only apply to small amplitude particles increasing β beating for particles in the tail.
- Single particle approach does not provide a recipe for determining the "natural tune" for optics reconstruction. Theoretical developments are needed to take into consideration BB tune spreads.
- First AC dipole measurements at injection with large ξ_{bb} and only HO show qualitative agreement with MADX simulations.
- Preliminary studies with linear β-beating shows no loss of hierarchy in the collimation system even for very large ξ_{bb}.
- Realistic beam loss maps including beam-beam interaction and collimation system with SixTrack are being planned with the FCC experts.

The possibility to use an e-lens to compensate the β-beating is considered and will be investigated