Swiss Accelerator Research and Technology

Beam-Beam and related effects at the Large Hadron Collider and FCC-hh

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Acknowledgements: M. Hostettler, S. Kostoglou, G. Sterbini, X. Buffat, R. Tomas, W. Herr, S. Redaelli

Beam-Beam Workshop 2-5th September 2024
EPFL, Lausanne

Outlook

- The Large Hadron Collider Beam-beam effects
  - Strong BB effects in 2012
  - Luminosity levelling
  - LHC 2012→2024 controlled BB
  - HL-LHC what is still missing?
  - Coherent effects and stability
  - Interplay, optics, collimation and modelling

- Far future FCC-hh

- Conclusions

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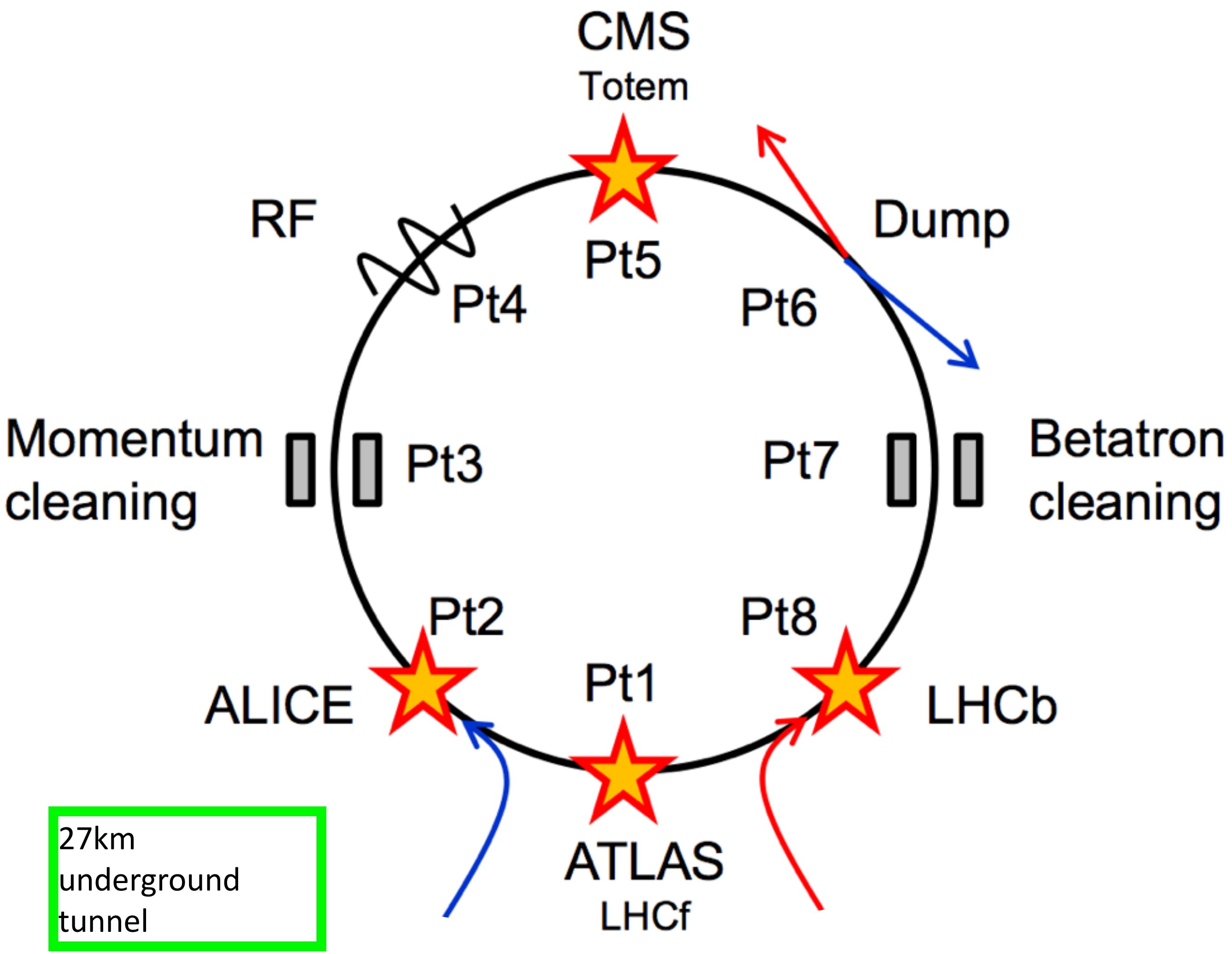
The Large Hadron Collider (LHC)



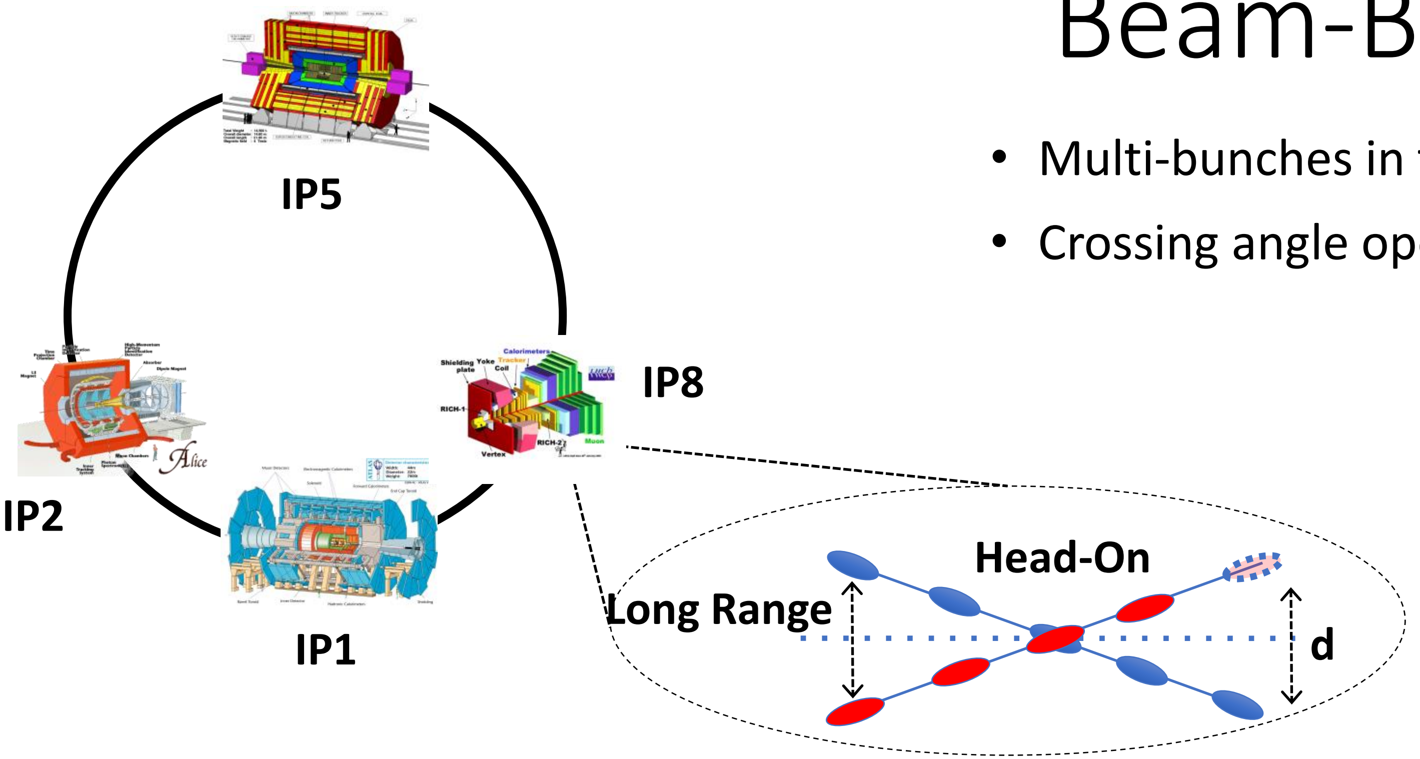
27km underground tunnel

- 8 arcs (~3 km)
- 8 straight sections (~700 m).
- Two-in-one magnet design
- 4 interaction points (IPs): IP1, IP2, IP5, IP8
- IP2 / IP8: beam injection
- IP6: beam dump region
- IP4: RF (acceleration)
- IP3 / IP7: beam cleaning systems

Synchrotron: proton beams accelerate from 450 GeV and collide at 4-6.8 TeV

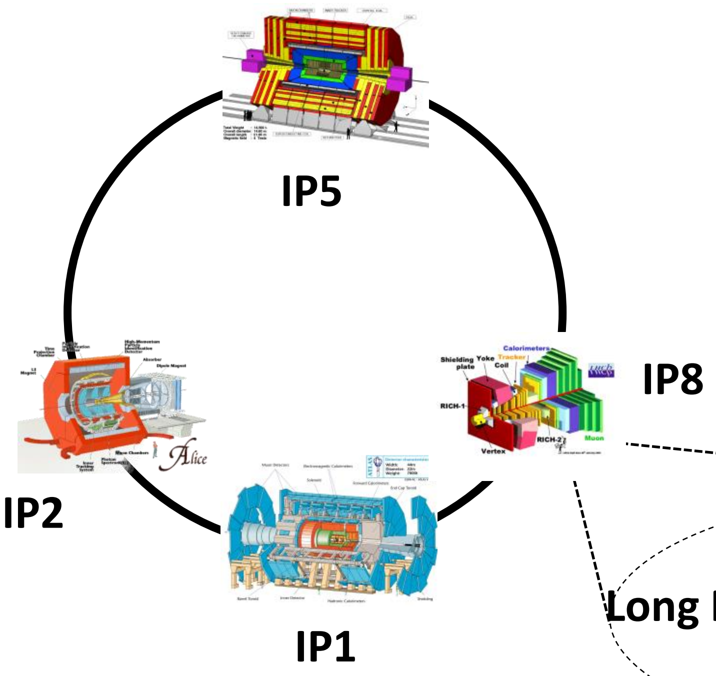
Beam-Beam effects

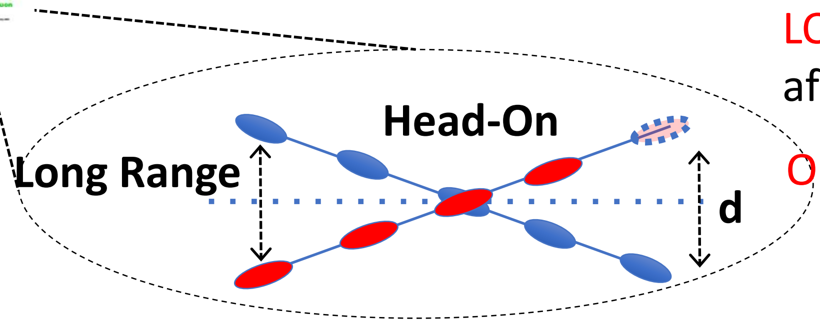
- Multi-bunches in train structure spaced by 50-25 ns
- Crossing angle operation needed to avoid multiple collisions



Beam-Beam effects

- Many interactions (~124 per turn for 25 ns spacing)
- Different types: Head-on, Offset and Long-Range collisions



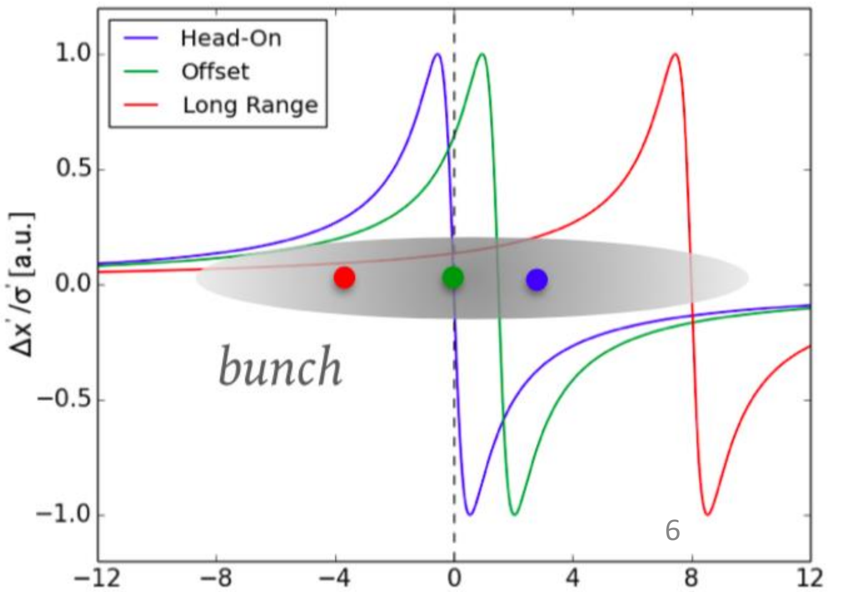


HEAD-ON beam-beam interaction (core particles mostly affected)

LONG-RANGE beam-beam interaction (tail particles affected)

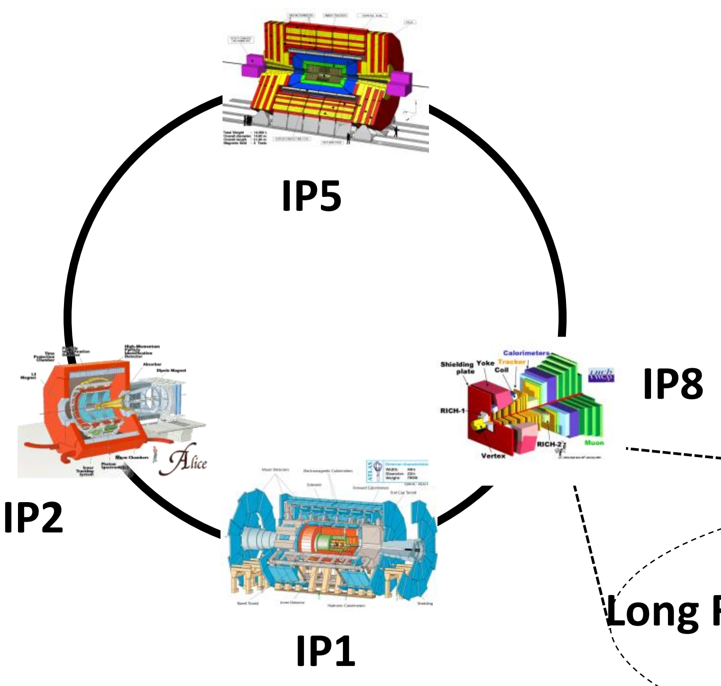
OFFSET beam-beam interaction (mixed state)

Beam-Beam force, highly non-linear

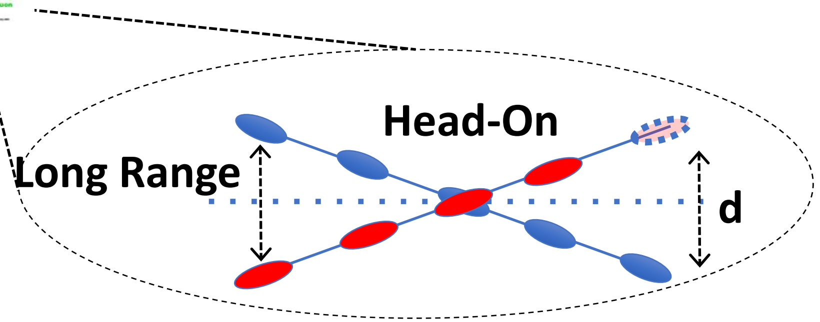


Changes:
- the OPTICS (tune shifts, spread, Q', beating, resonance excitation or enhancement, particle diffusion, distribution modification, reduced dynamic aperture)
- Interplays with the other collective effects (Impedance, electron cloud)

Beam-Beam effects



Complex problem with many parameters!



Luminosity key parameter for collider performance like the beam-beam force it depends on:

- β*
- ϕ
- beam intensities $N_{1,2}$
- emittances ε
- optics and non-linearities

Luminosity

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} W e^{\frac{B^2}{A}} \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2})^2}}$$

Beam-Beam effects

$$F \propto \frac{N_{1,2}}{\sigma_{x,y}} \cdot \frac{1}{r} \cdot \left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)$$

Best Performances is a trade off of the different parameters involved…plus the experiment requests!

LHC parameters 2012 versus design

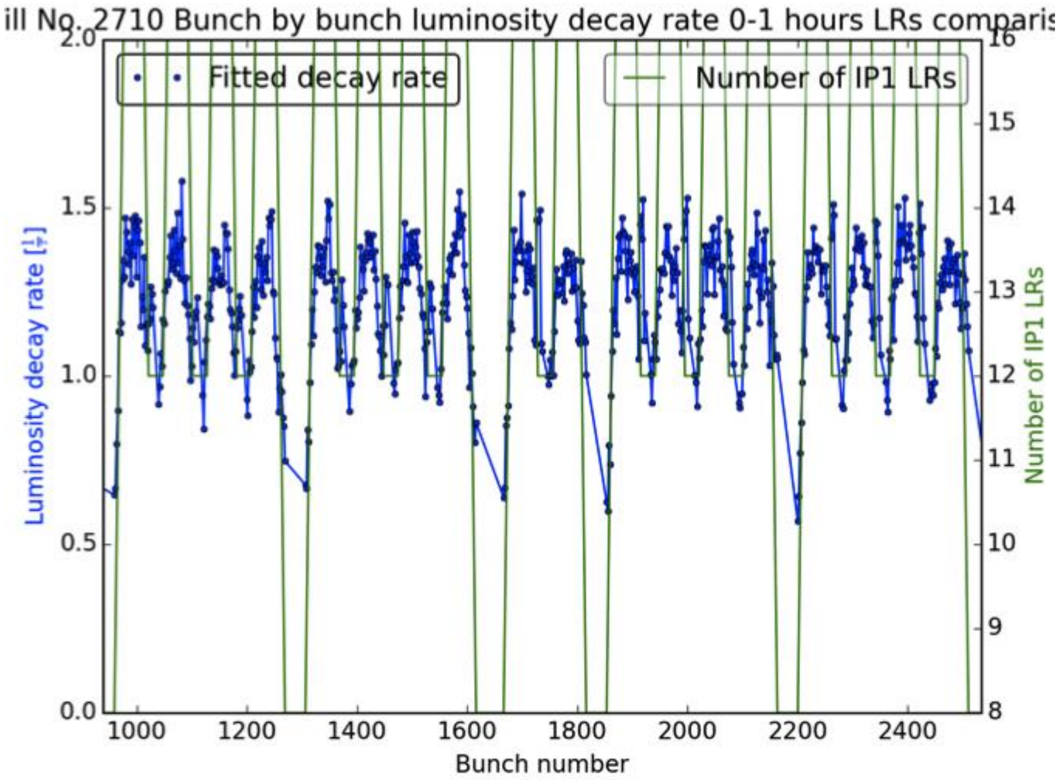
	2012	Design
Intensities protons per bunch	1.6-1.8 10^{11}	1.1
Normalized Emittances	2.5 μm	3.75 μm
ξ_{bb}	**0.008/IP**	**0.0034/IP**
Bunch spacing/ maximum # LR	50 ns / 60	25 ns/120
IP1/IP5 LR sep	**9.5 σ**	**9.8 σ**
IP2 LR sep	**> 12 σ**	**…**
IP8 LR sep	**> 10 σ**	**…**
Energy	4 TeV	7 TeV
Peak Luminosity	6.6 10^{33}	10^{34}
Octupole magnets	550 A	…
Chromaticity	>20 units	2 units

2012 Beam-Beam effects were strong!

- 2 HO 0.016 total tune shift (almost HL-LHC type)
- IP2 and IP8 with relevant efefcts
- Transverse Feedback at maximum gain
- Electron cloud signatures on train tails
- Strong Octupoles for Landau damping

Strong Beam-beam Observations 2012

Regular Physics Fill of 2012 LHC RUN

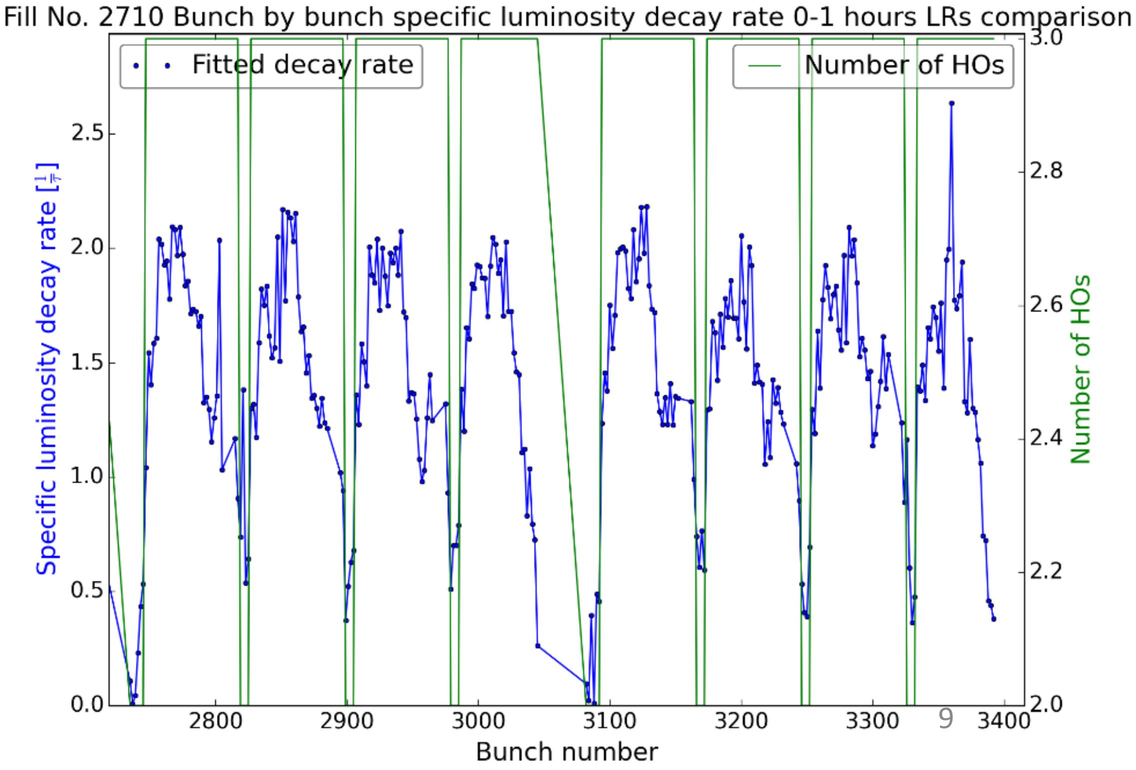


Intensity lifetimes reduction → losses in first 2 hours

Emittance blow-up → 20% in 1h

→Luminosity lifetime reduction

Increased beam brightness → no gain in Int Luminosity

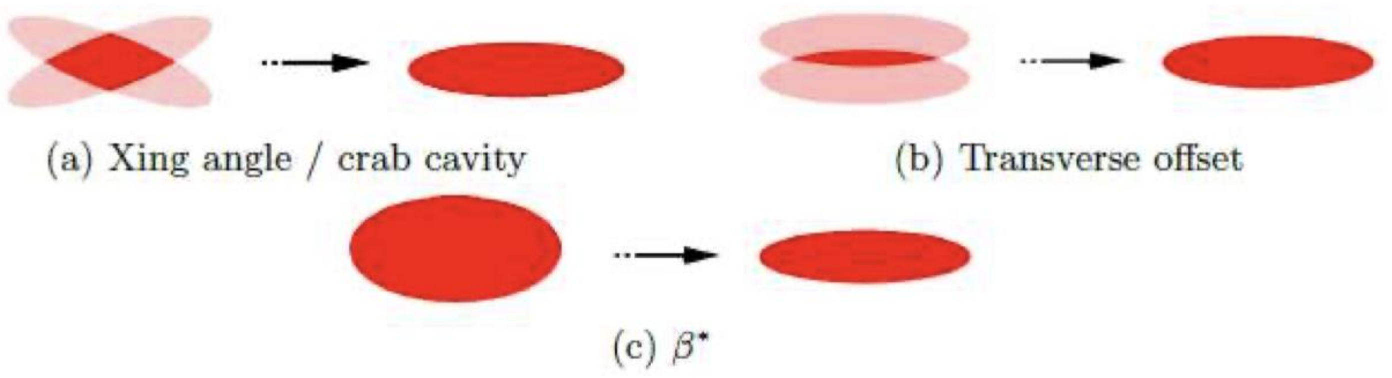


New regime: experiments require levelled luminosity

lumi constant at a fixed pile-up !

Game changer → allows to relax beam-beam effects!

Luminosity levelling : useful knobs to reduce limits



$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \quad SWC$$

$$W = e^{-\frac{1}{4\sigma_x^2}(d_2-d_1)^2}$$

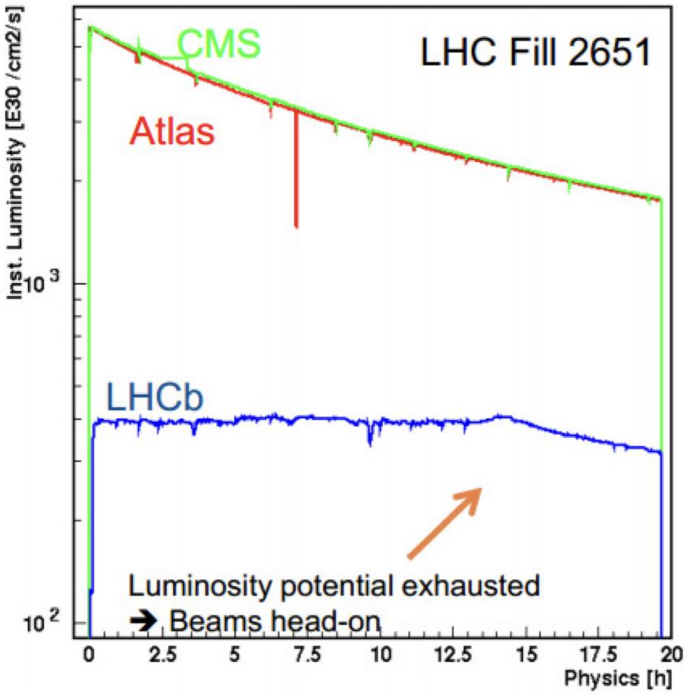
Separation factor

$$S = \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2})^2}}$$

Crossing Angle factor

Control luminosity using reduction factors (separation, beta*, angles) at a constant value while the beams intensity decays

Luminosity levelling : useful knobs to reduce limits



$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \quad SWC$$

$$W = e^{-\frac{1}{4\sigma_x^2}(d_2-d_1)^2}$$

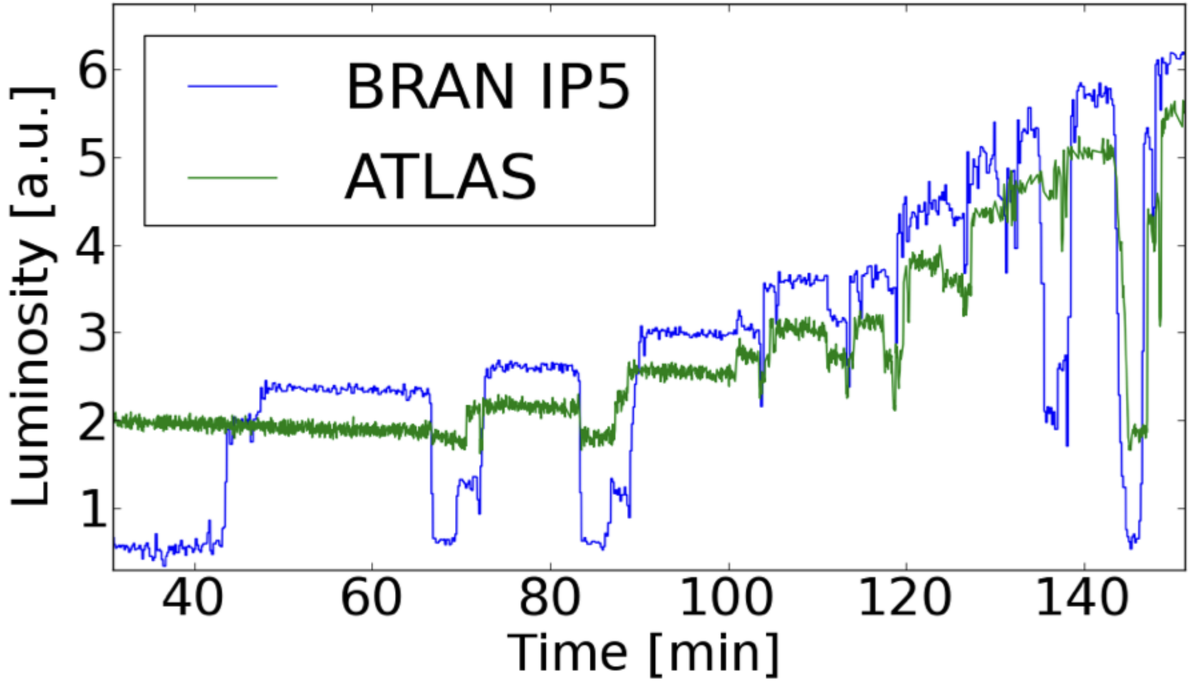
Separation factor

Separation Levelling: LHCb and Alice

Keep luminosity constant at a fixed value while reducing the beams separation (W factor) 2012

Luminosity levelling : useful knobs to reduce limits

1st b* leveling



$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \quad SWC$$

$$\sigma_{x,y} = \sqrt{\beta^*_{x,y}\epsilon_{x,y}}$$

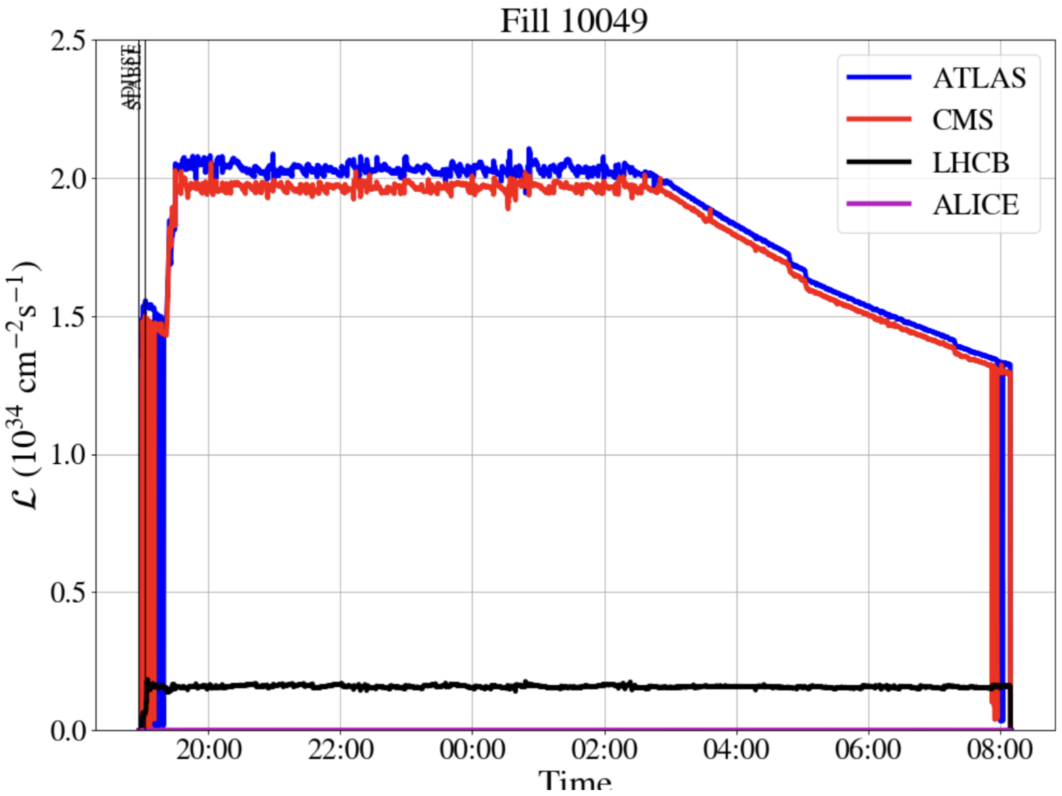
$$S = \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2})^2}}$$

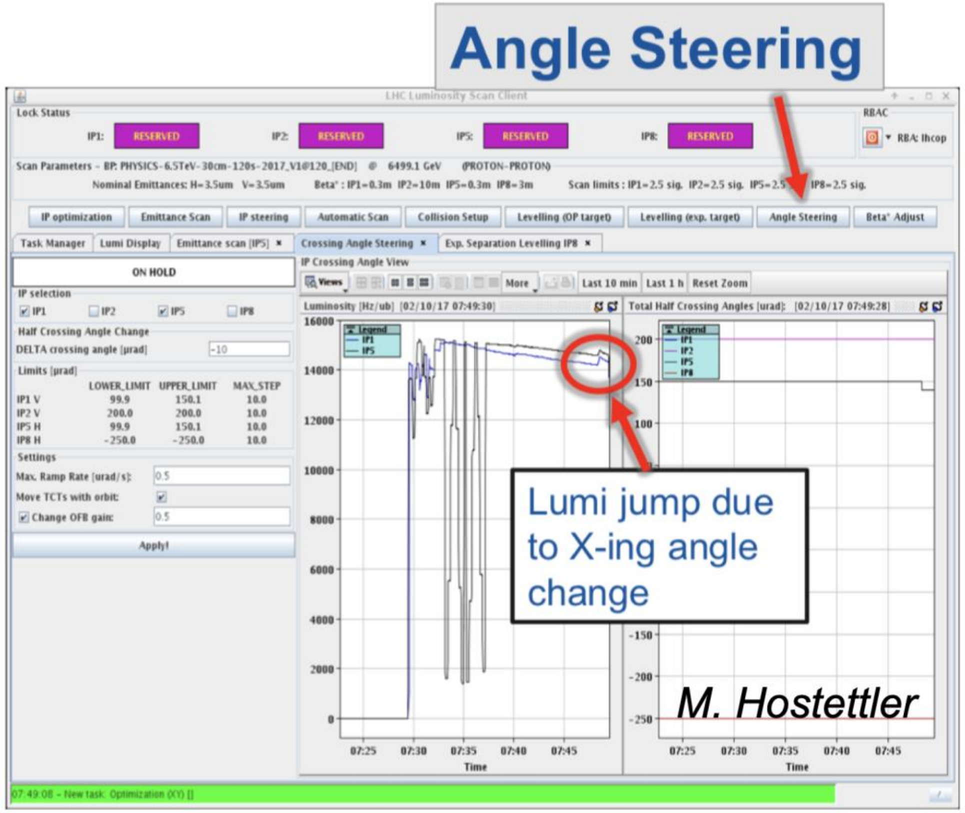
Crossing Angle factor

Redution of luminosity increasing the beta* and angles

Reduce beta* while intensity decays → larger Long Range BB separations !

Luminosity levelling : useful knobs to reduce limits





Luminosity constant at a fixed target value (optimal for detectors efficiency)
Knobs used: beta*, separation and angles in a combined way.
Optimizing integrated lumi → optimizing reducing BB effects!

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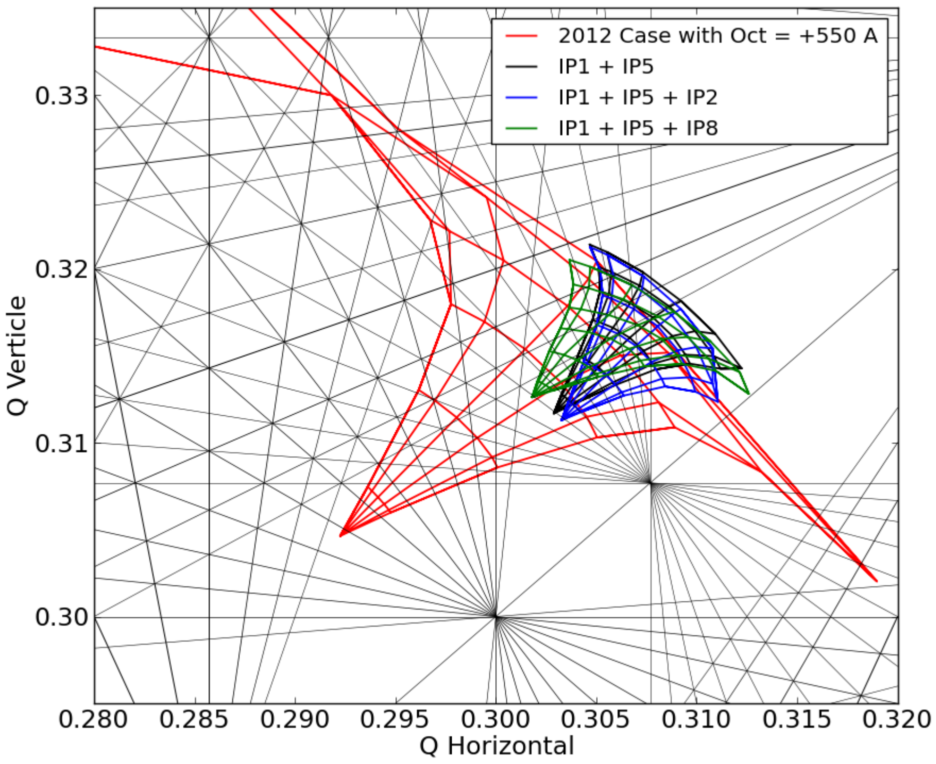
Footprint 2012 versus 2016



Footprints picture well the situation
A first try of a "global" optimization.
LHC simpler to optimize, keep margins for higher luminosity and to operate with high octupoles and chromaticity to stabilize beams

RUNI push for highest Lumi for higgs discovery pushed everything at the limit

- full squeeze to smallest beta*
- highest intensities 1.8-10^{11} ppb
- smallest crossing angles

RUN2 levelled luminosity: integrated versus peak → relax versus pushed. All methods developed and made operational as valuable knobs to relax limits!

IP8 and IP2 in shadow of high lumi experiments→ tune shifts and spread below 10^{-4} level

IP1 and IP5 beta* levelling at larger beta relaxes BB LR separations → reduce separations when intensity drops

The **LHC had a bright future toward 2*10^{34}** and beyond at peak for beta* of 30cm and injectors smaller emittances!

LHC parameters and RUN II strategy

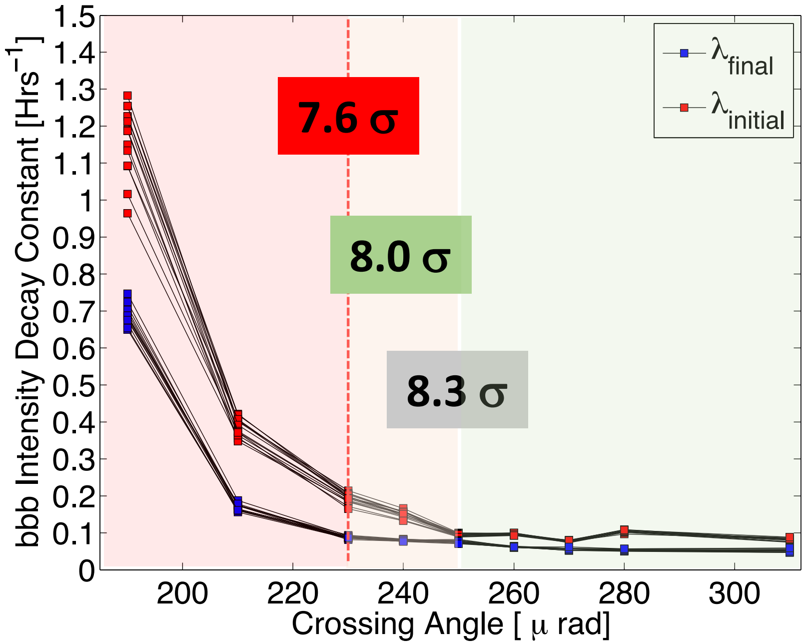
	2012	2015	2016
Intensities protons per bunch	1.6-1.7 10^{11}	1.2 10^{11}	1.1-1.25 10^{11}
Normalized Emittances	2.5 μm	3.5 μm	**3.5-2.5** μm
ξ_{bb}	**0.007/IP**	**0.0035/IP**	**0.003-0.004/IP**
Bunch spacing/ maximum # LR	50 ns / 60	25 ns / 120	25 ns / 120
IP1/IP5 LR sep	**9.5 σ**	**11.5 σ**	**10.5-12.3 σ**
IP2 LR sep	**> 12 σ**	**> 26 σ**	**> 26 σ**
IP8 LR sep	**> 10 σ**	**> 26 σ**	**> 26 σ**
Energy	4 TeV	6.5 TeV	6.5 TeV
Peak Luminosity	6.6 10^{33}	0.7 10^{34}	1.1-1.4 10^{34}
Octupole magnets	550 A	470 A	470 A

Potential to go to ~ 2 10^{34} at reduced BB separations after tests

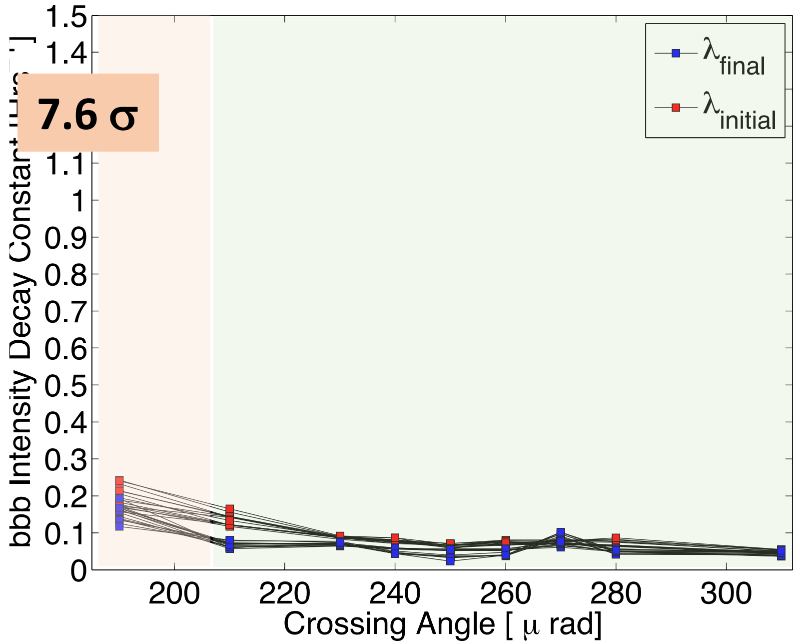
Long Range experiments 2016: LR limits

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

Beam 1



Beam 2



ϕ
310
280
270
260
250
240
230
210
190

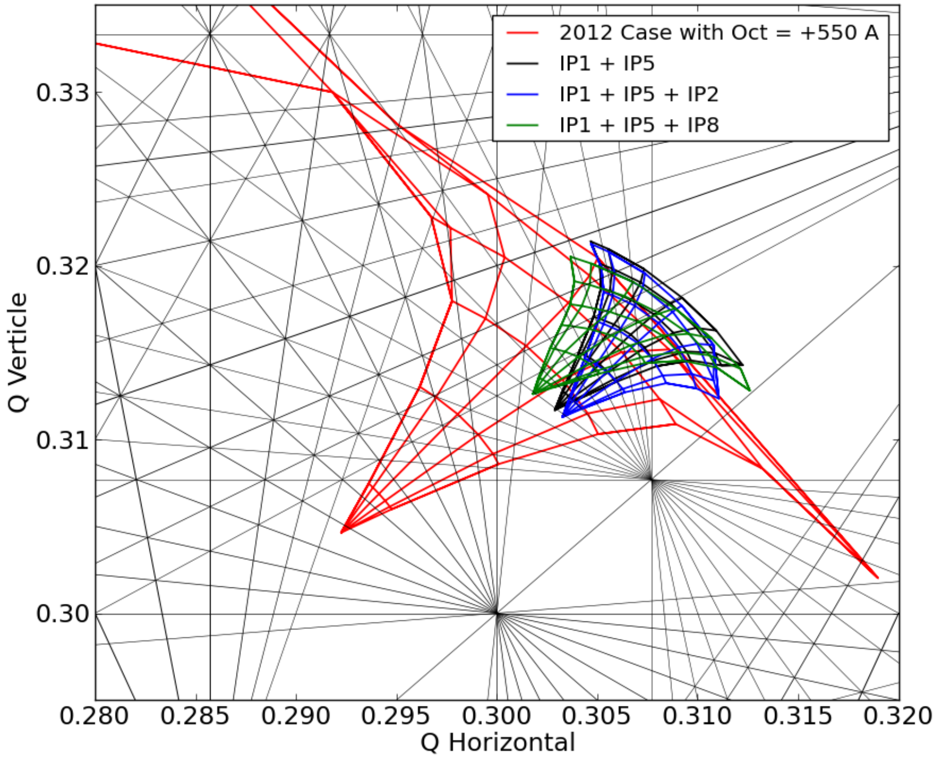
Intensities 1.2-1.35 10^{11}ppb:

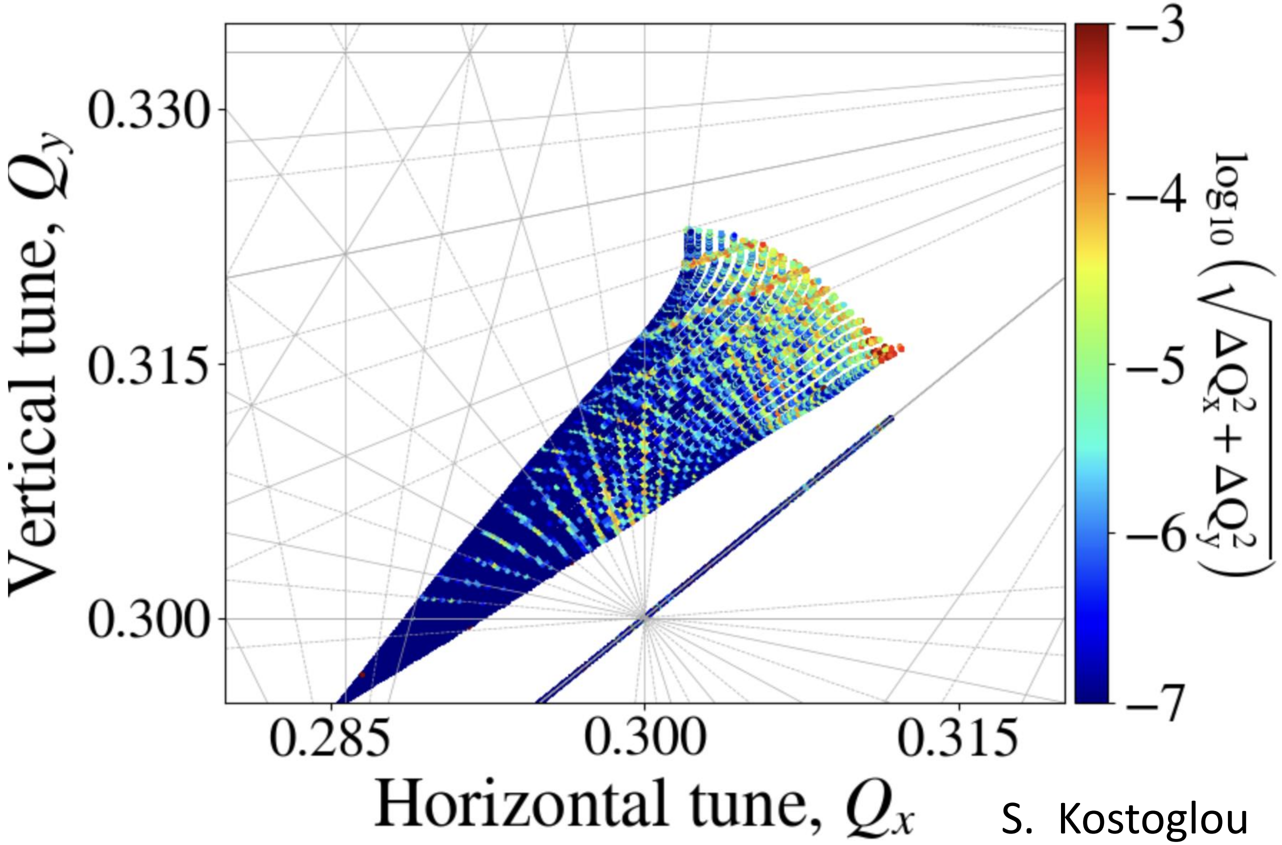
- **Fast losses at first time window of 5 min increases**
- **Slow losses increase and do not improve after 15 minutes**

  → Transient effect + strong deterioration of intensity lifetimes

Beam-beam effects visible with impact on losses 24%/hour
Two beam differences should be investigated

Footprint in 2024: past versus Present





S. Kostoglou

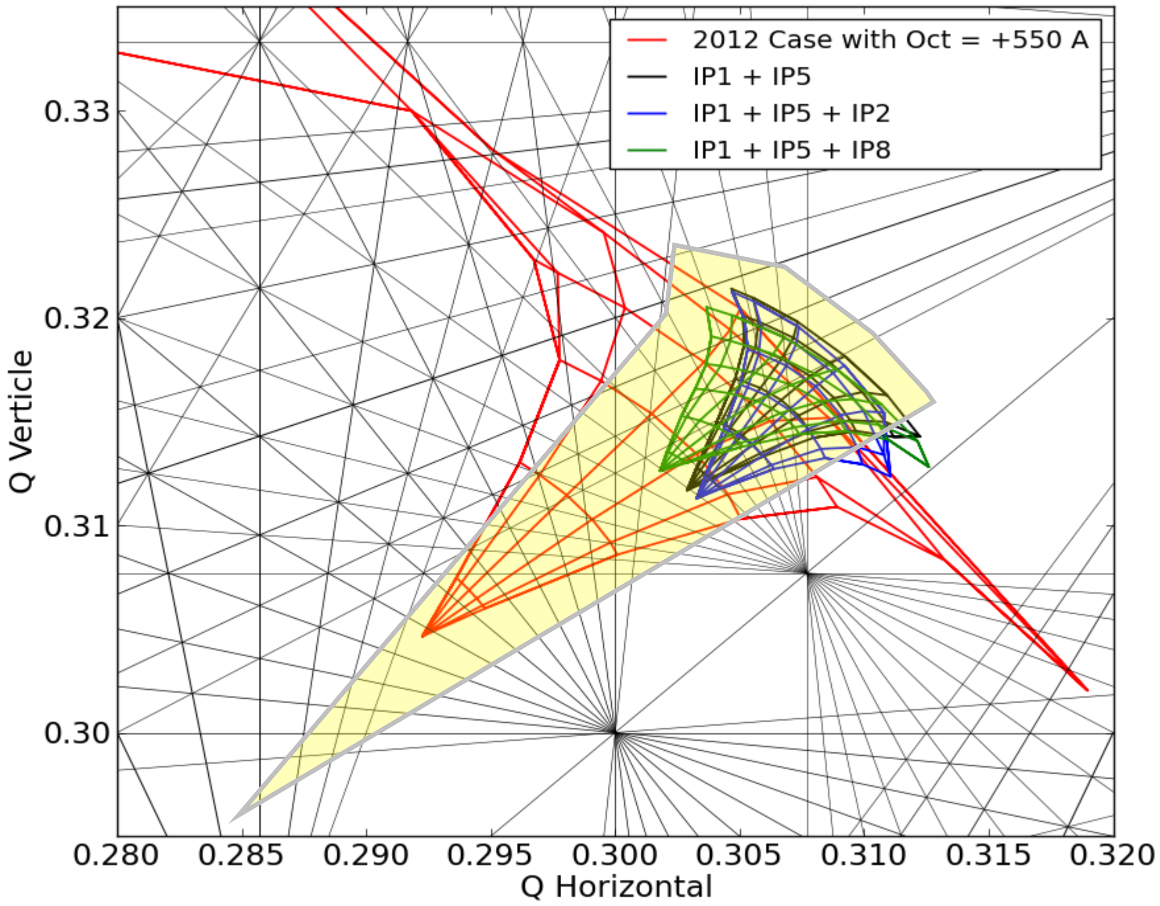
BB effects for LHCB and ALICE experiments are not negligible

LHCb at 1.5 σ separation HO!

β* levelling reduces long range effects of IP1 and IP5

Multiple knobs→ complex optimization!

Footprint RUN1 → RUN2 →RUN3

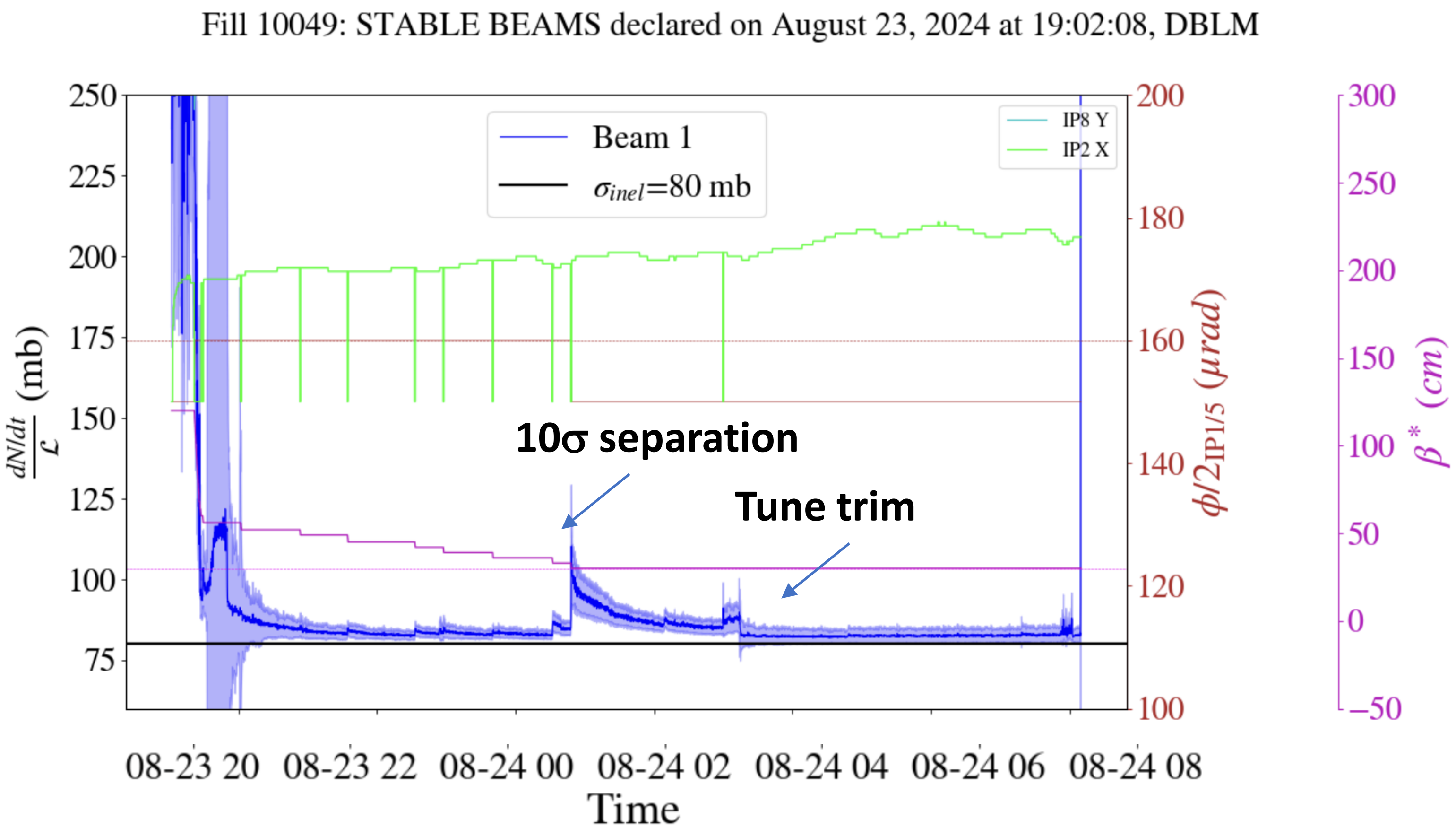


Footprint dominated by head-on collisions, maximum tune shift ~0.025

2024 observations: losses and levelling

- Losses during 1st hour of collisions, no signature of long range
- Beam lifetimes 20-10 h all along the fills

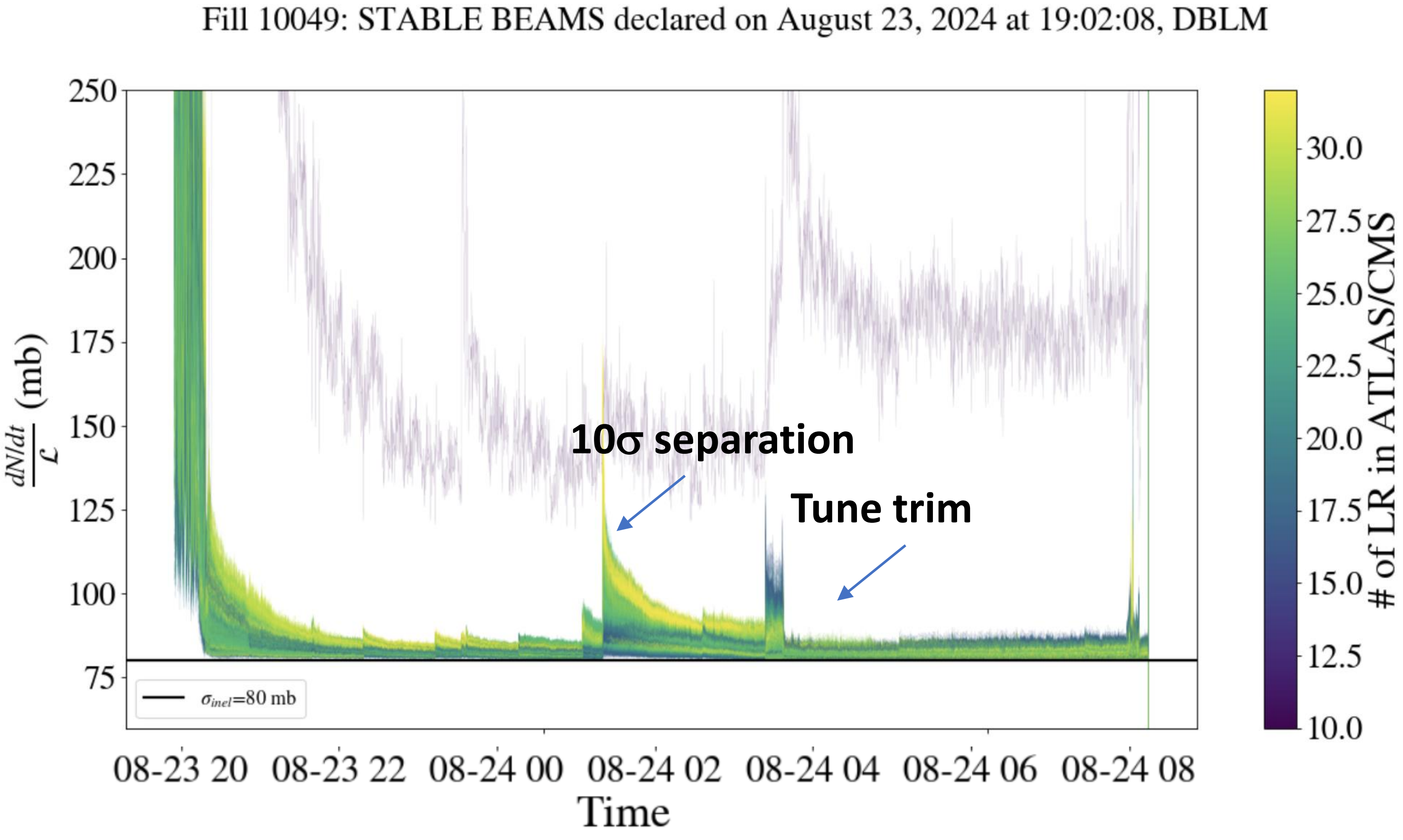
Minor emittance blow-up, losses under control



talks S. Kostoglou

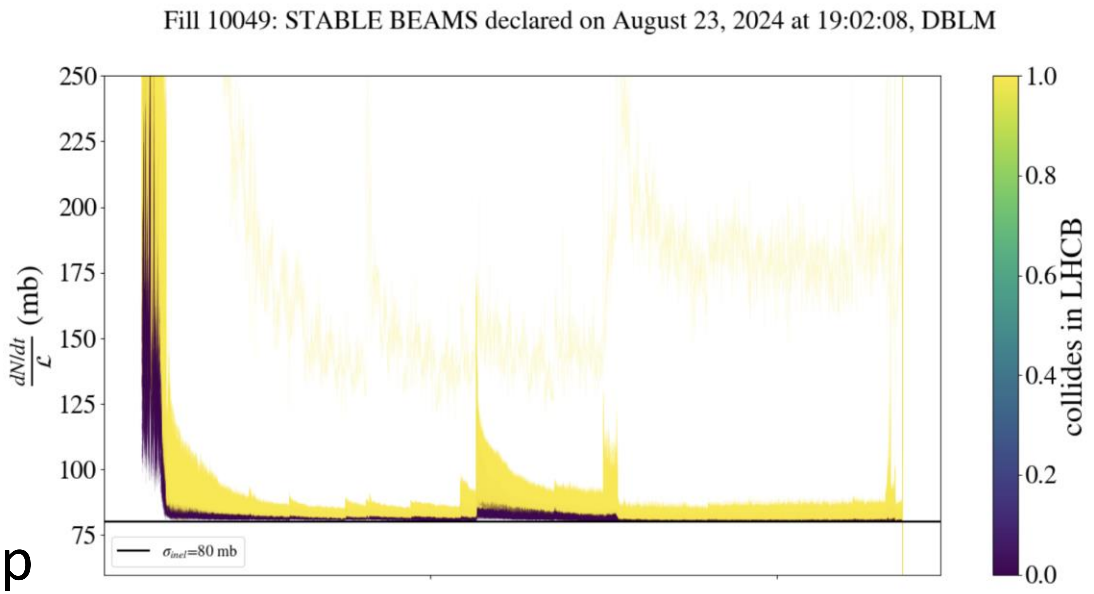
2024 observations: Bunch by bunch signatures?

- At smaller separations (reduction of crossing angles IP1 and IP5) signature of LR
- Lifetimes still above 10 h (tune trim seems even mitigating the effects)
- Development of Wire compensation scheme in the LHC (**talks G. Sterbini and P. Belanger**)



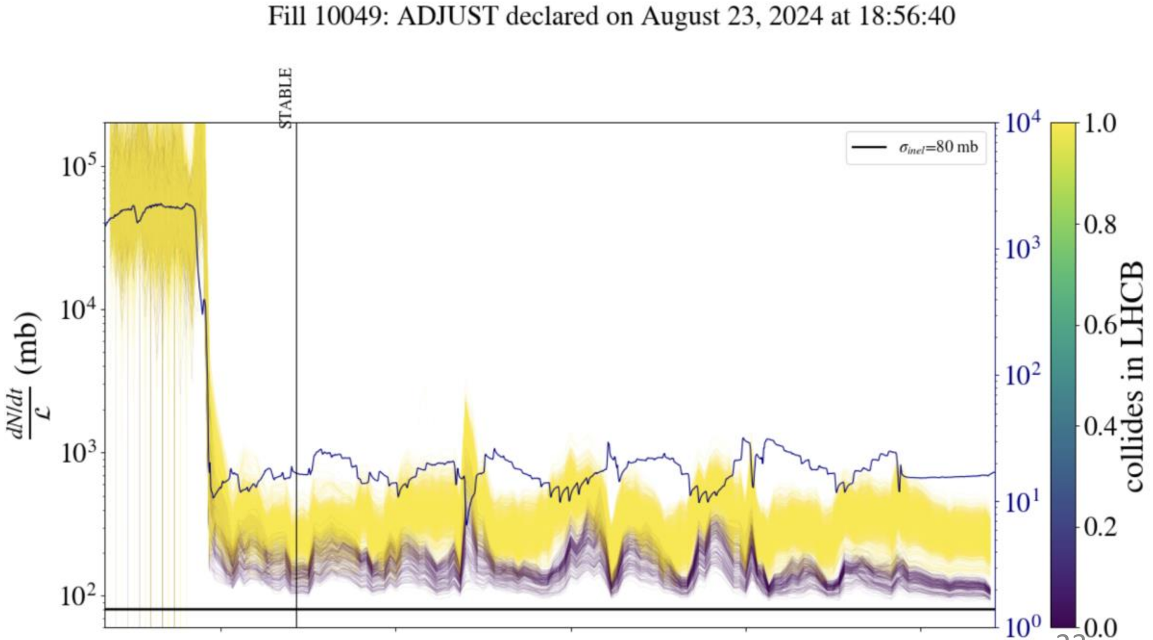
LR act as scrapers but lifetime is good

2024 observations: IP8



Bunches colliding in IP8 have larger losses

- Contribution to HO not negligible at 1.5 σ sep
- Offset collision shifts particles tunes



HO collision at 1.5 σ shows its effect

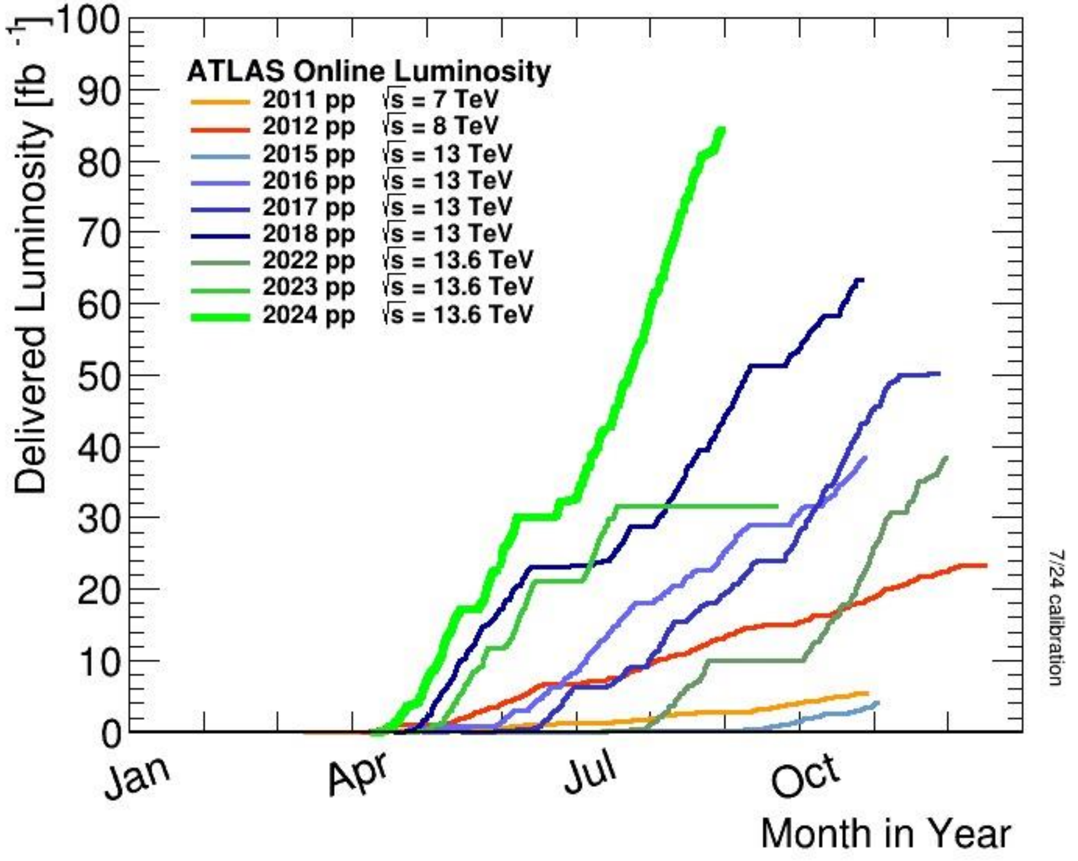
What is causing the effect? Need to improve understanding!

Separation levelling in IP and IP5 visible in lifetimes

S. Kostoglou, G. Sterbini

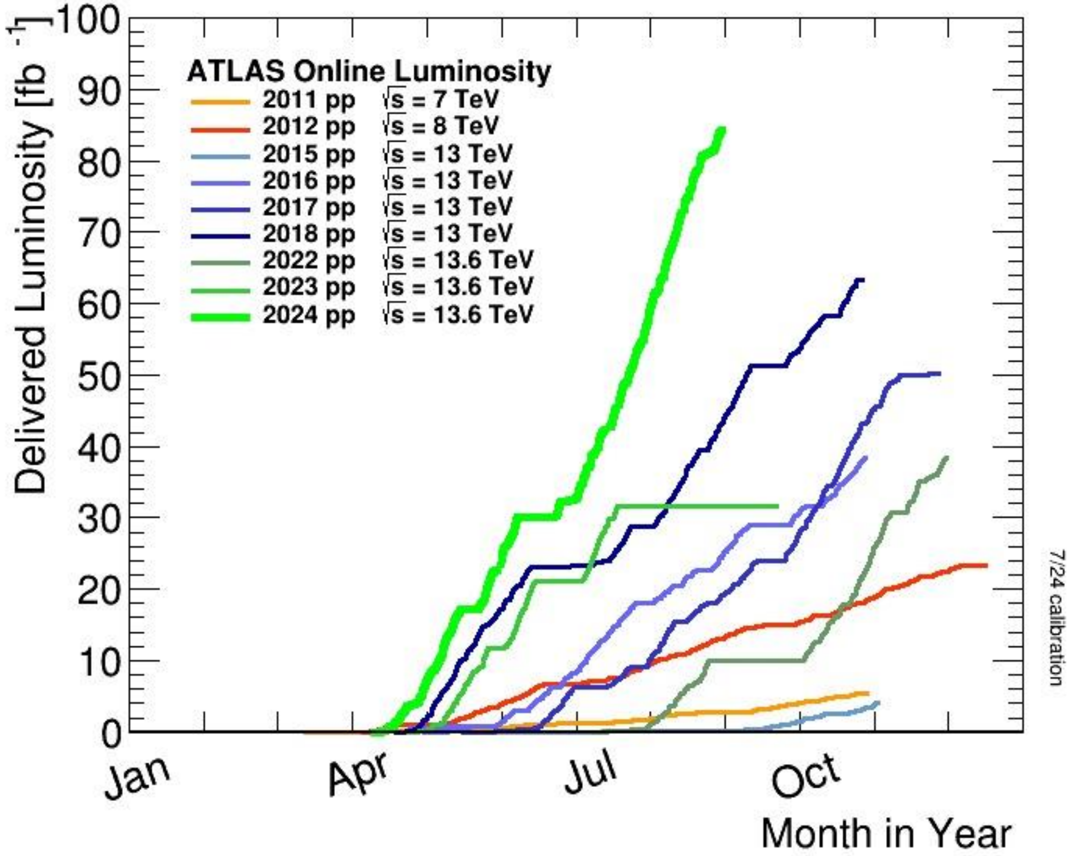
Where are the limits?

- Over the last years several knobs developed to improvement and optimize the physics cycle reducing beam-beam effects all along
- Good optimization of integrated lumi!
- Beam-beam effects seem to be undercontrol and with margins!No real limits



Where are the limits?

- Very little exploration of the limits in terms of HO and LR
  - → Understand the margins (reproducibility, optimization, B1 and B2 differences)
  - →Models benchmark to get confidency on observations and simulation results
  - →Prepare the future if HO or LR limited one needs different mitigations
- HL-LHC is coming!

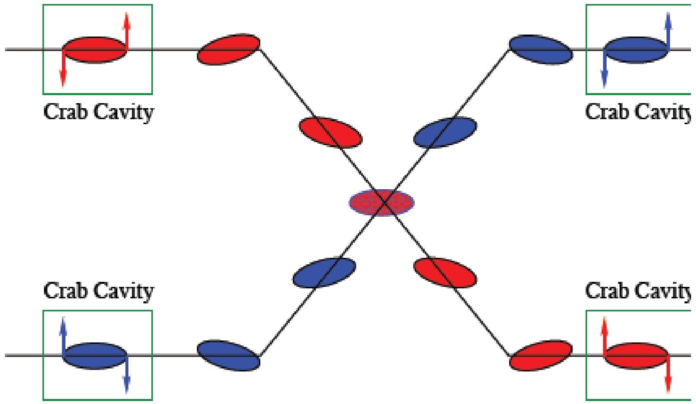


The High-Luminosity LHC

- The main objective of the HL-LHC is to determine and build a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

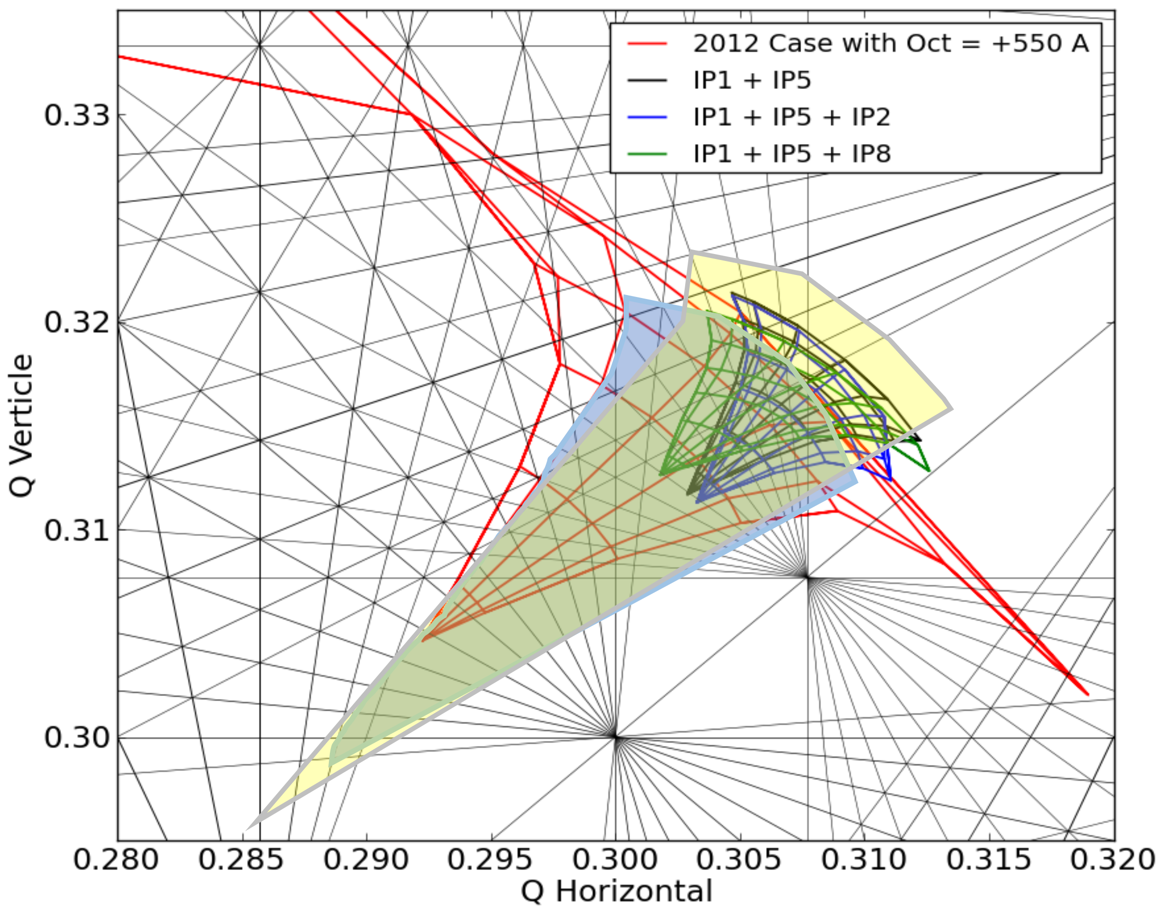
- Prepare machine for operation beyond 2025 and **up to the early 2040s**
- Devise beam parameters and operational scenarios for:
  - Enabling at total integrated luminosity of **3000 fb^{-1}**
  - Implying an integrated luminosity of **250 fb^{-1} per year**,
  - Design for **pile-up ≤ 140** (➔ peak luminosity 5 x 10^{34}cm^{-2}s^{-1})

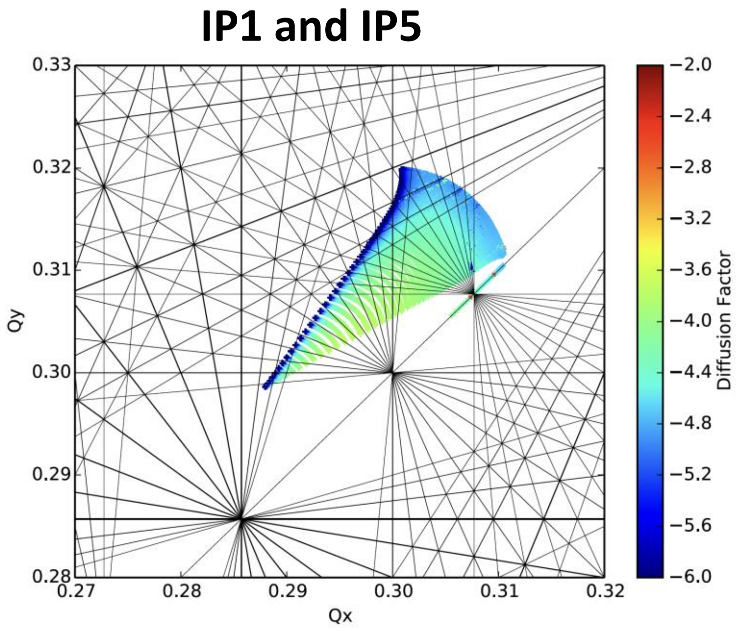
$$S = \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x} \tan \frac{\phi}{2})^2}}$$



Crab Cavities to compensate for geom loss reduction (LHC24 down to 0.6)

Footprint RUN1 → RUN2 →RUN3→HL-LHC





HL-LHC larger beam charges 2.2 10^{11}
IP8 will become a high luminosity exp
Experiments will explore higher pile-ups
Relys on Beta* levelling and Crab crossing scheme

→ Need to be ready!

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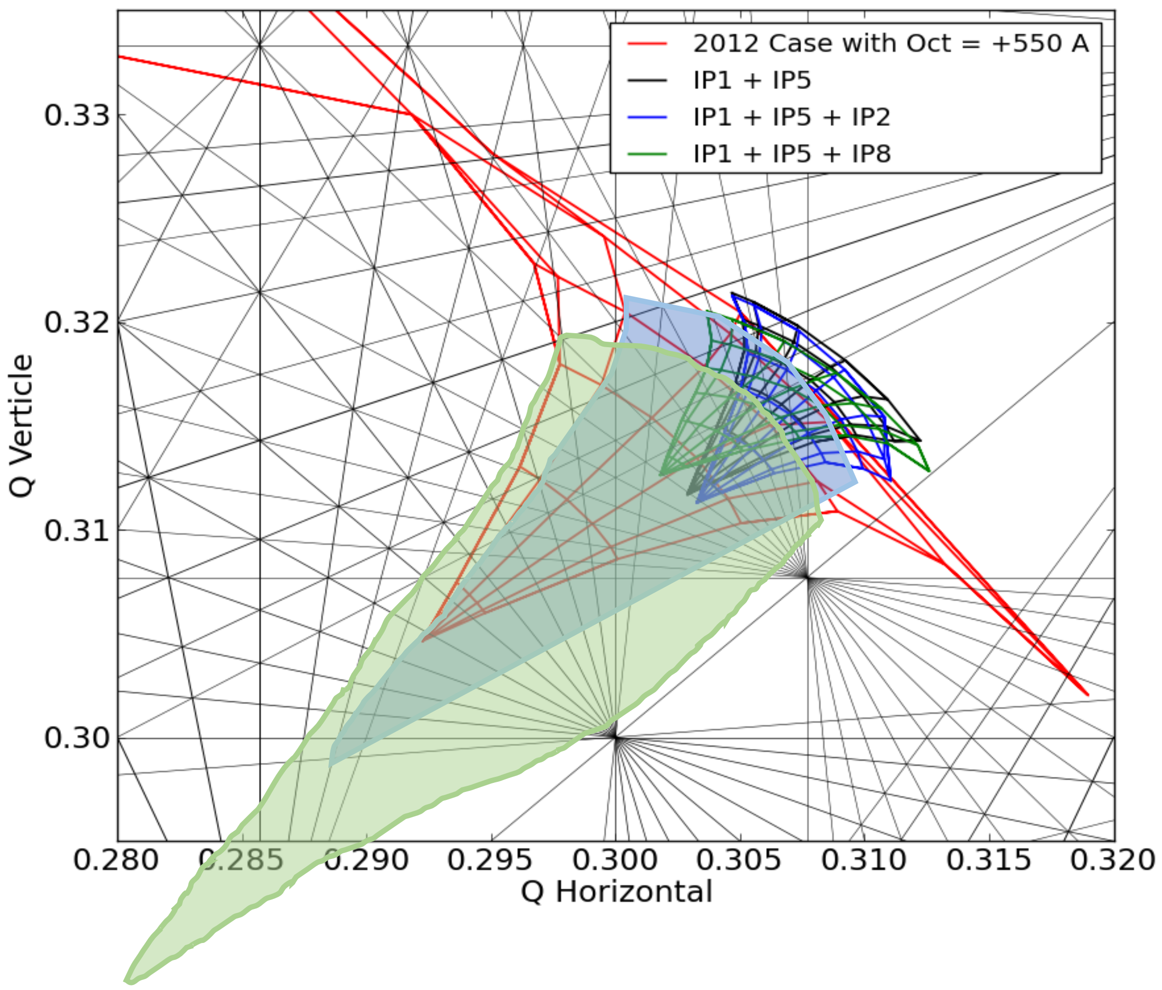
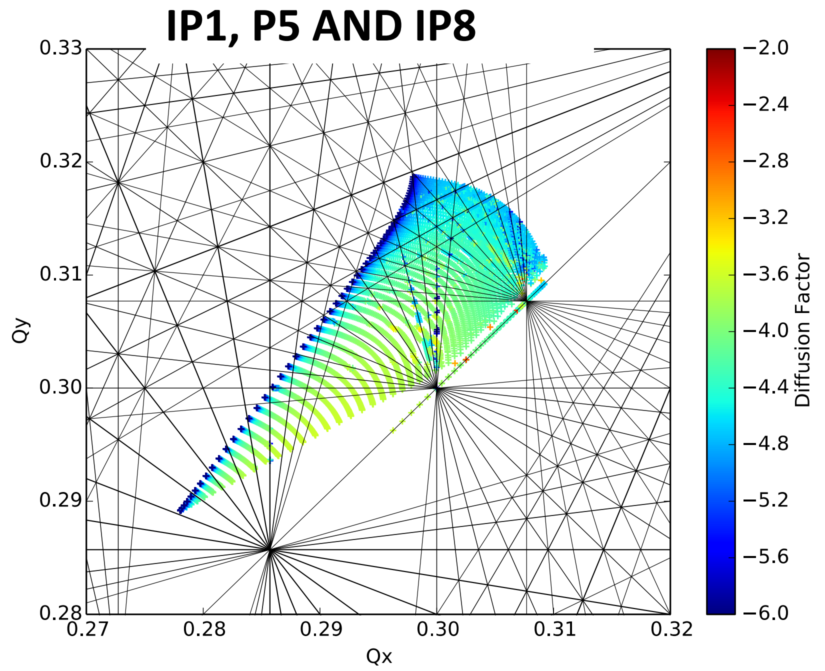
Footprint RUN1 → RUN2 →RUN3→HL-LHC





IP1,5 and 8 in HO collision

Separation levelling for IP1 and 5 might be reconsidered to help reducing HO limit?!

Stability needs to be mantained

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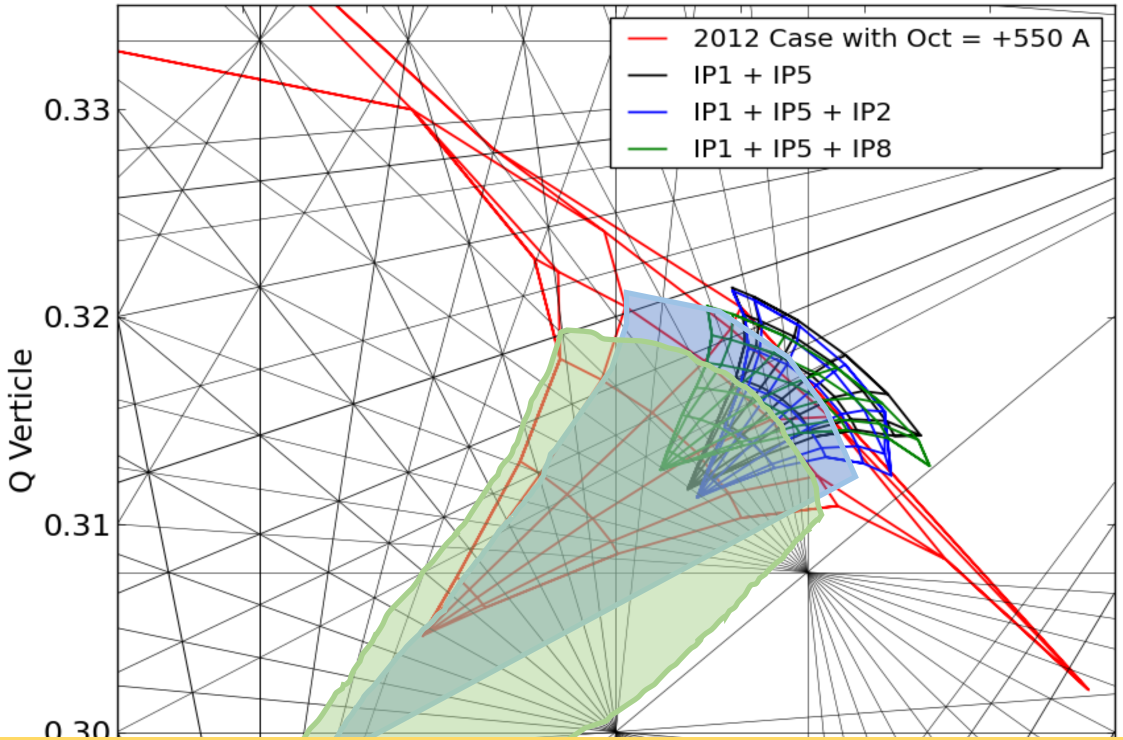
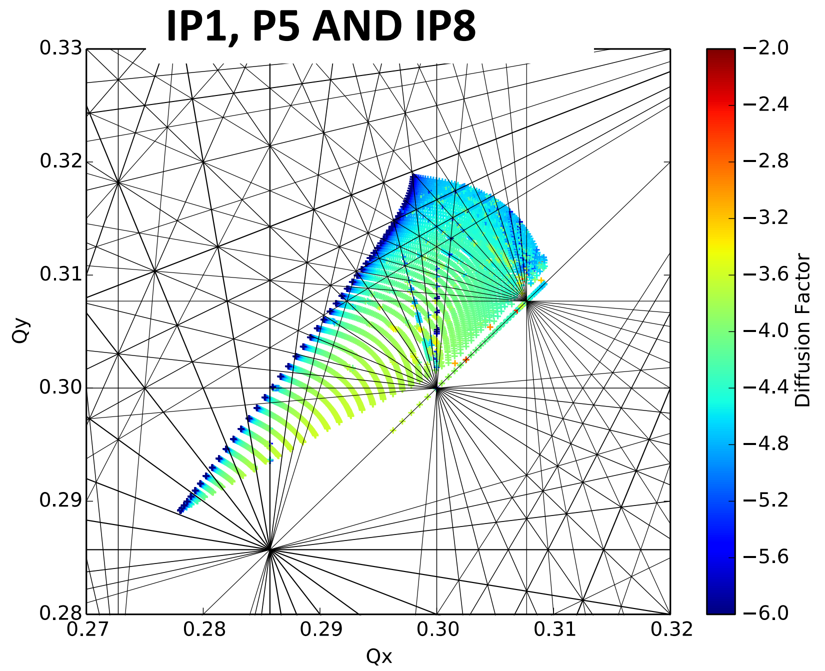
Footprint RUN1 → RUN2 →RUN3→HL-LHC





IP1,5 and 8 in HO collision
Tunes might need adjustment in collision
LR contribution very small
ight
O

We have to explore the limits of HO and LR to be ready for HL-LHC!
Pushed tests and extensive benchmark of models versus observations
Need observations ahead of time to understand and improve models!

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Beam-beam coherent effects

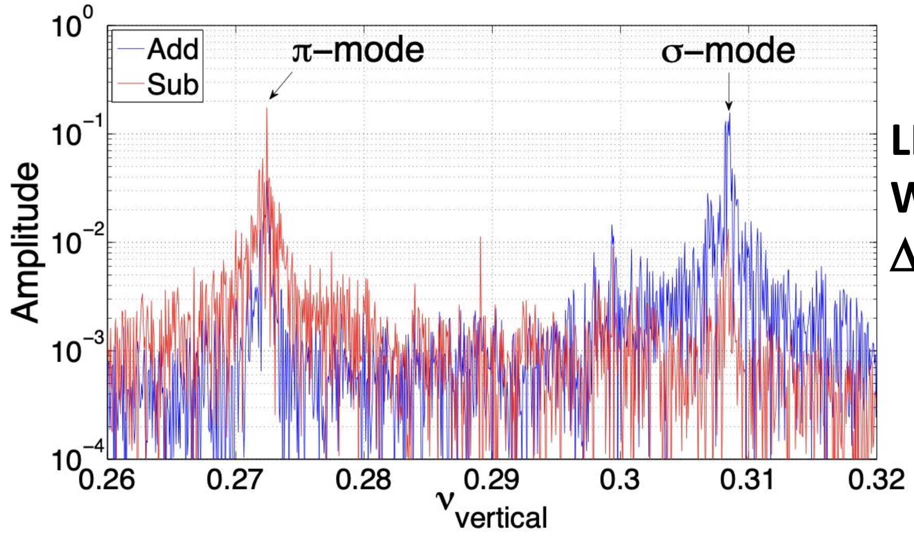
Talk X. Buffat

- Coherent modes
- Landau damping of impedance driven modes
- High feedback operation → Noise + beam-beam
- Beam-beam + Impedance mode coupling
- Orbit effects
- Optics and collimation

Any effect visible is an opportunity to benchmark models!

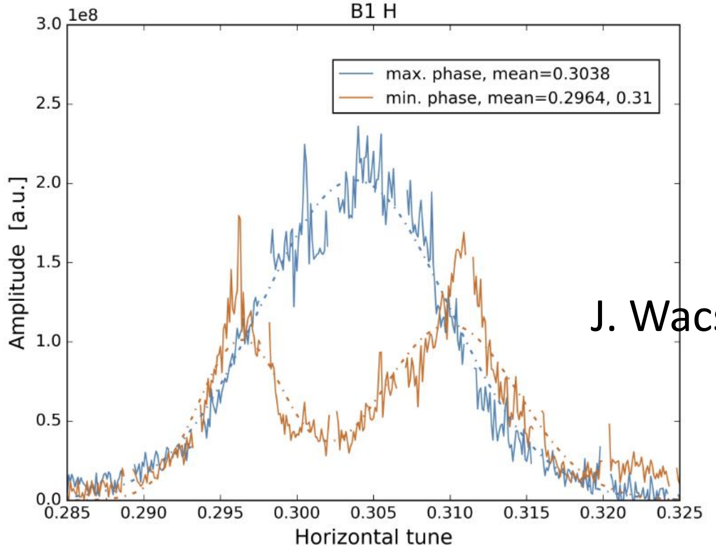
Beam-beam coherent modes

- Measured several times in the LHC, well reproduced
- No bad impact to performances
- No instabilities due to only coherent BB modes
- Most of the time due to strong non-linearities, many long-ranges and strong transverse feedback → they are suppressed
- Proved very large beam-beam tune shift not impossible but limits are in incoherent effects→ lifetimes, losses, emittance blow-up.
- Recently experimentally proved one can suppress them with optics corrections → possible improvement of spectra, disentagling coherent from incoherent effects. (test to be prepared)



(c) Collision in IP1 and IP5

LHC test 2011
W. Herr and Co.
ΔQ~-0.04



J. Wacsky EPFL Thesis

Beam-beam and Landau damping

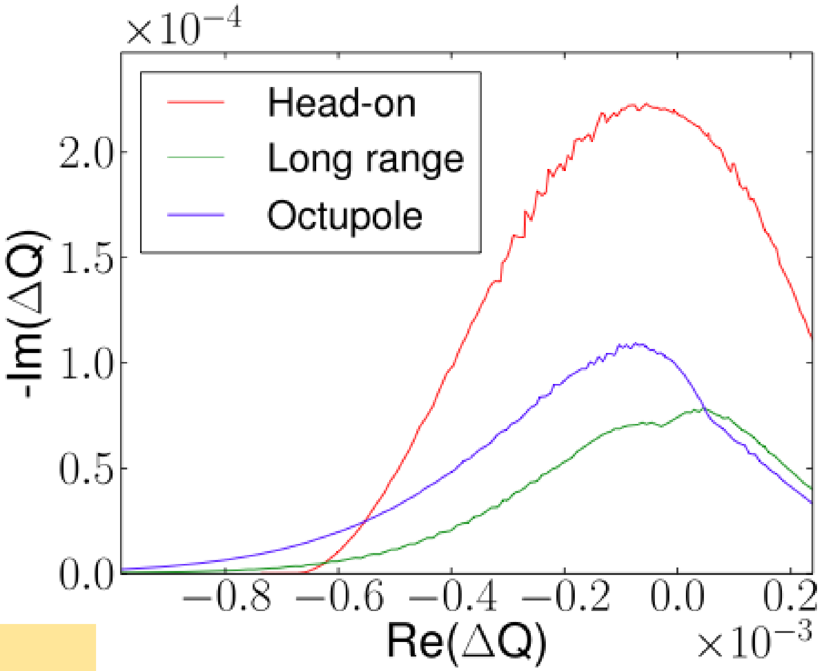
HO beam-beam spread very effective in stabilizing coherent instabilities (impedance driven)→ Landau damping contribution

Larger frequency spread → Stronger Landau damping

A way to quantify the Landau damping is by use of the Stability Diagram

Several references Prof. Vaccaro, Berg-Ruggiero

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

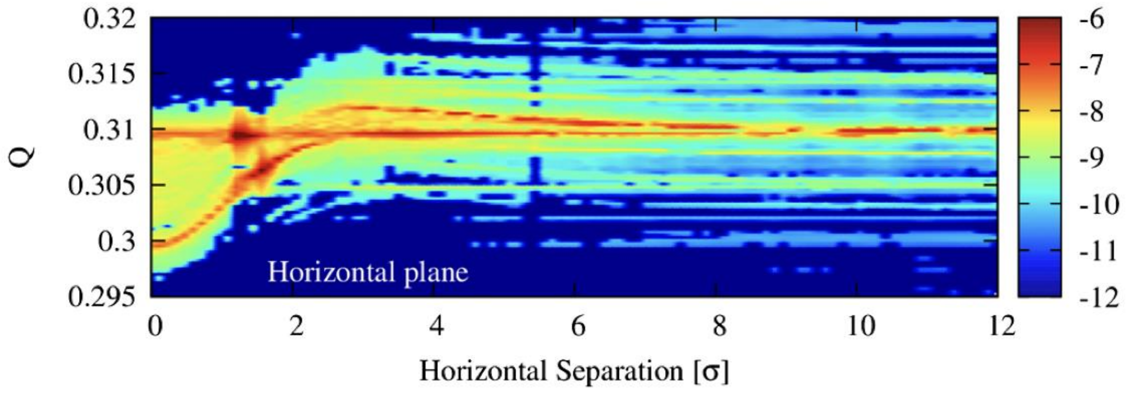


Beam-beam effects do contribute to stability!
Quote by A. Chao from BB2013 “Colliding beams will never become unstable”

X. Buffat EPFL PhD Thesis

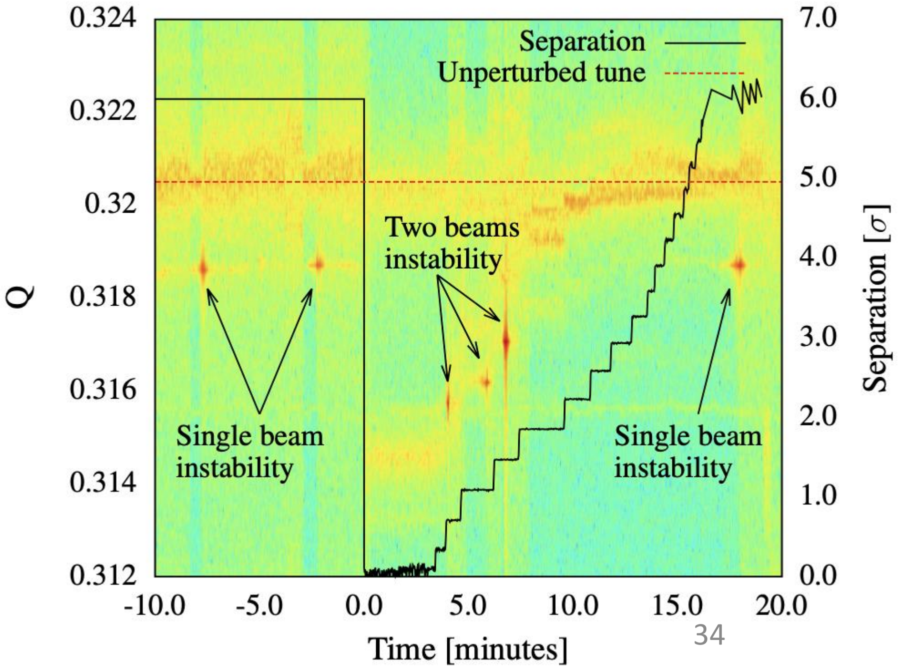
Coherent instabilities and noise

[Transverse Mode Coupling BB](#) and impedance has been proved experimentally and in simulations but fully cured by transverse feedback



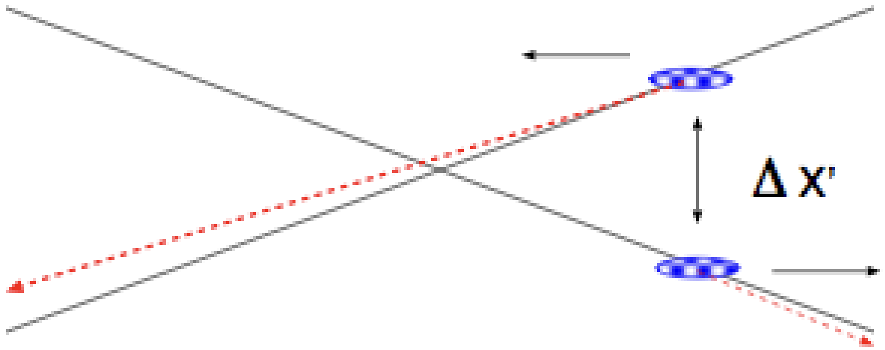
Transverse feedback intrinsic Noise and high gain operation

- Extensive use of feedback to damp coherent instabilities → drive emittance blow-up due to intrisic noise
- Larger Beam-beam parameter → larger emittance growth
- LHC 2024 emittance growth minor thanks to optimized transverse feedback noise level and gain



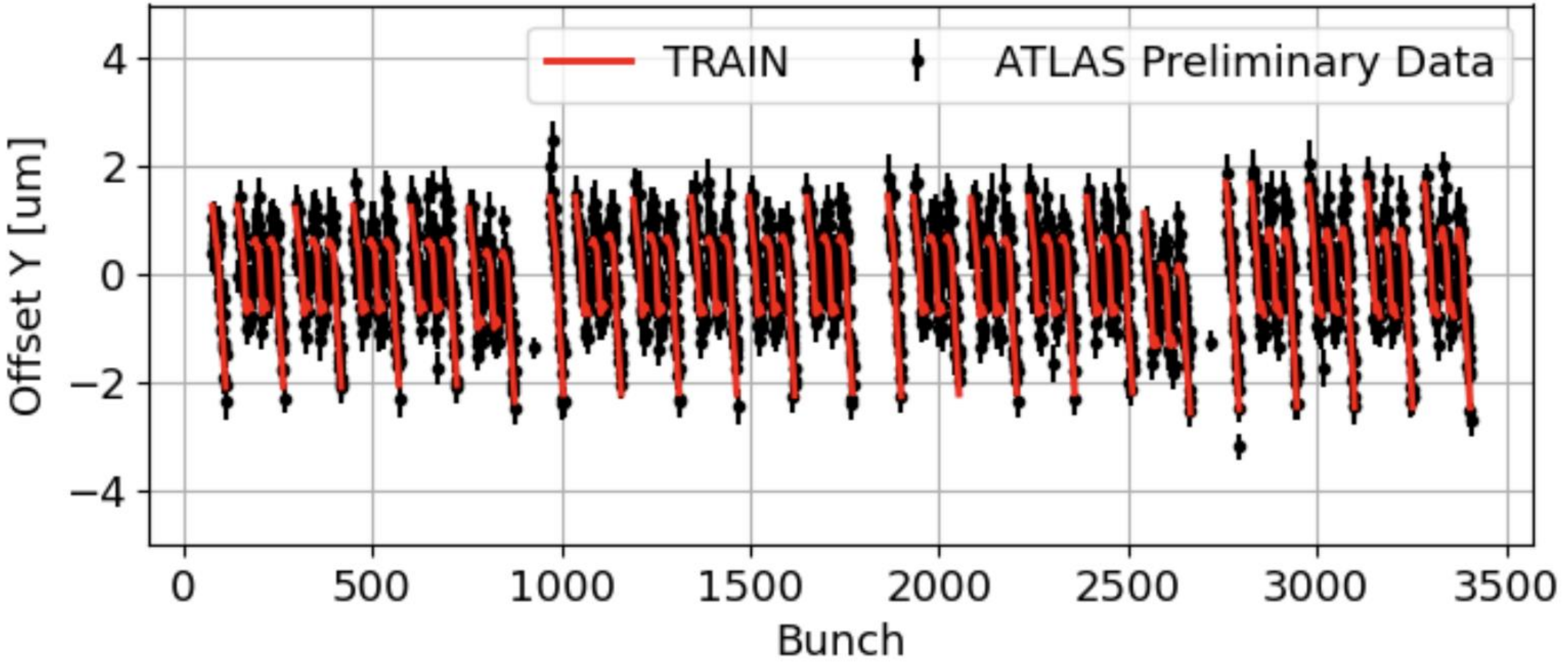
2017 CERN-ACC-NOTE-2017-0044 CERN-ACC-NOTE-2017-0030

Beam-beam orbit effects



- Long range beam-beam interactions will modify the closed orbit → offsets at the collision points

- Self consistent calculations are used to compute the orbit changes (PyTRAIN)



- Benchmark of model to detectors measurements show excellent agreement between orbit model and reality

- Minor impact to luminosity

New observable luminous regions from detectors

Talk by M. Hostettler

Beam-beam effects: modelling, collimation, optics

- Even if LHC seems not to be BB limited “yet”

→ Beam-Beam still defines the dynamics of colliding beams

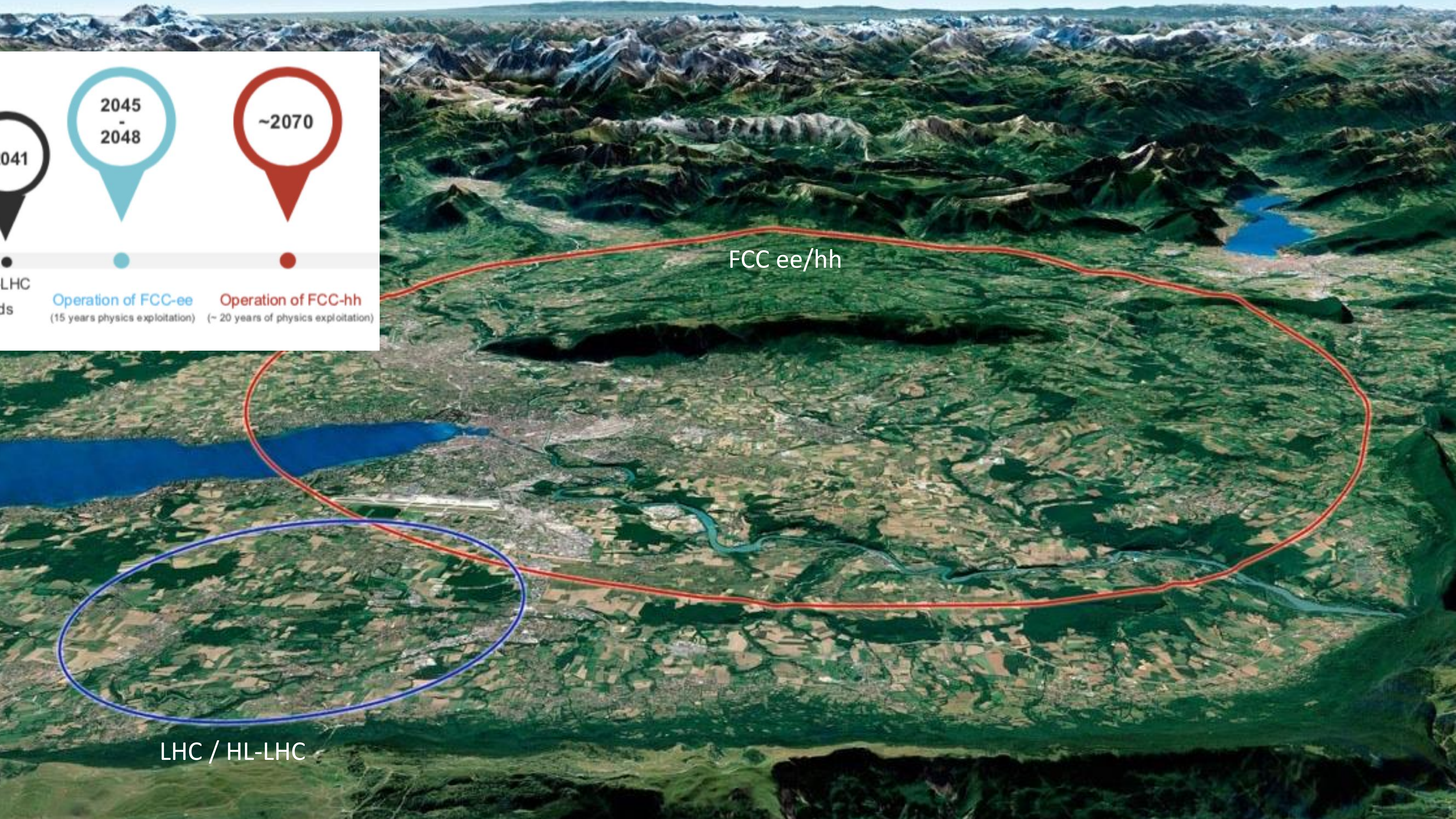
  - Collimation hierarchy breakage and observations on protection system (**C.E. Montanari, F. van der Veken**) → Models with BB and collimation tracking
  - Non-linear dynamics: BB and Optics (**T. Carlier, E. Maclean**)
  - Beam-beam and electron cloud interferences (Pop-corn instabilities at end of fill)

→ Modeling → XSUITE (Ji’s talk)

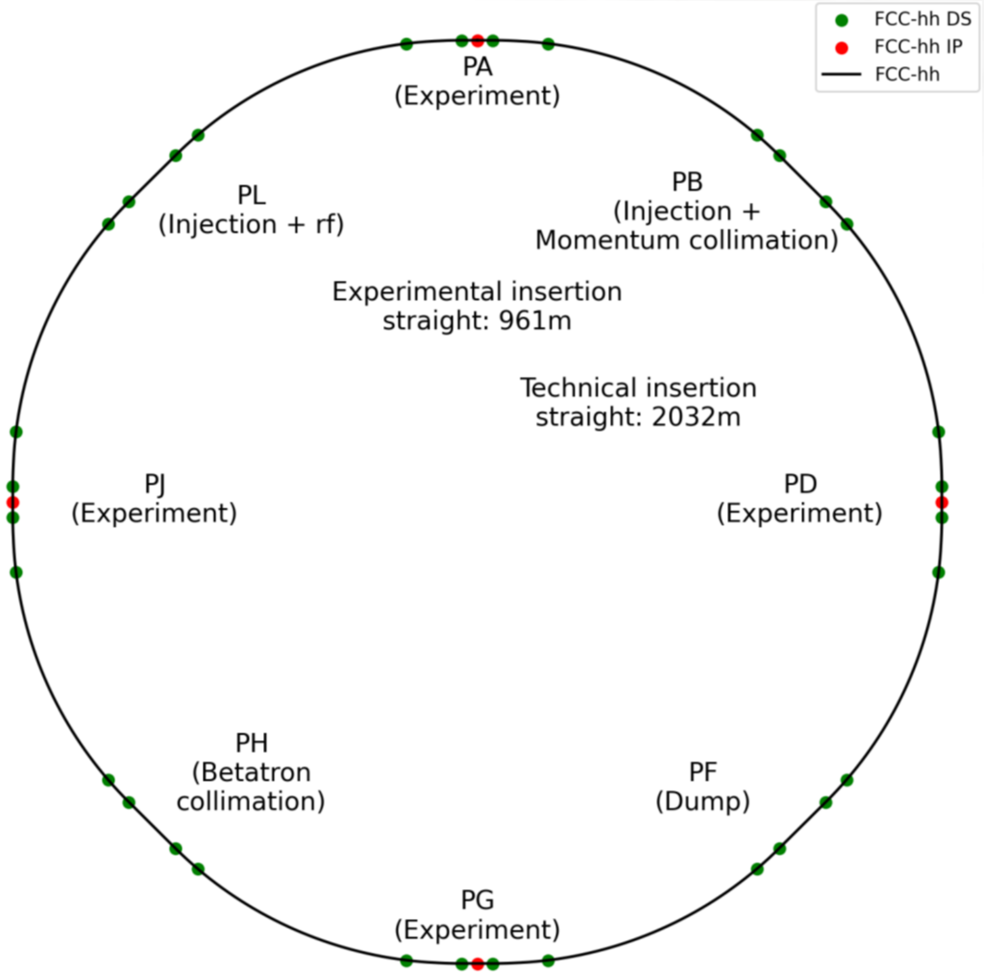
Fundamental to model all effects together and benchmark to reality ! (**talk G. Iadarola**)

Outlook

- The Large Hadron Collider Beam-beam effects
  - Strong BB effects in 2012
  - Luminosity levelling
  - LHC 2012→2024 controlled BB
  - HL-LHC what is still missing?
  - Coherent effects and stability
  - Interplay, optics, collimation and modelling
- Far future FCC-hh
- Conclusions

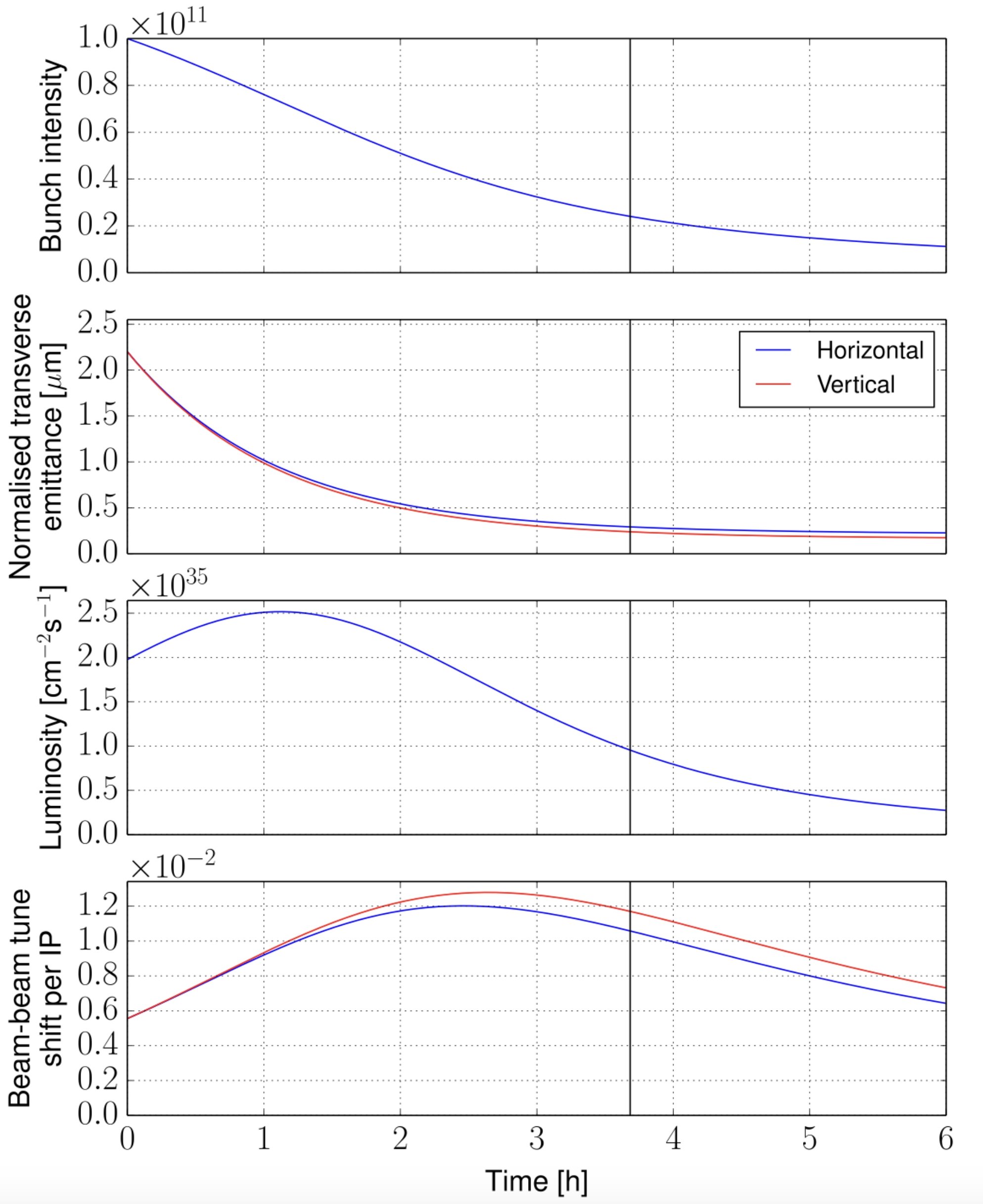

2045
-
2048
~2070
Operation of FCC-ee
(15 years physics exploitation)
Operation of FCC-hh
(~ 20 years of physics exploitation)
FCC ee/hh
LHC / HL-LHC

FCC-hh



- 4-fold symmetry with 4 experimental interaction points
- Target for centre of mass energy is 90 TeV @ 14T
- **Main area of R&D for FCC-hh is high field superconducting magnets**
- Low temperature, high temperature or hybrid

G. P. Segurana and M. Giovannozzi



FCC-hh

Beam-beam effects will be even different:

- HO dominated maximum tune shift of 0.024 (LHC today) 2IPs
- 2 secondaries at separation levelling
- Relevant damping large BB tune shift middle fill
- Long range effects negligible (beta* levelling)

LHC has to explore all the effect to make future colliders designed on solid foundations!

Need to explore experimentally where possible, develop more realistic models and benchmark extensively present machines!

Outlook

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Conclusions (I)

- **Several Beam-beam effects** have been observed in the LHC and mitigated resulting in a collider with excellent performances and not limited by BB
  - This was possible thanks to luminosity levelling requests by the experiments → knobs exsist to **reduce lumi and consequently the BB effects** (relaxed beta, separations, angles)
  - **Losses observed seem to show the head-on** effects to be more dominant today
  - **No long-range limitations** seem to be present

- **Very little experimental tests** have been made in the last 8 years: head-on and long range **limits have not be explored and studied sistematically**
  - Fundamental to **understand the limits** and where the margins are
  - Prepare possible **mitigation strategies and compensation schemes** for the future: HO? LR?
  - **Benchmark models as much as possible in systematic manner→** bridge simulations/observables

Conclusions (II)

- **HL-LHC** will have $2.2*10^{11}$ppb and crab cavities → **will reserve some observations we need to be ready**
  - LHC today is alredy showing what HL-LHC with 2 collisions will be, exploring will prepare us for the RUN4

- **FCC-hh** will have beam-beam effects very similar to HL-LHC but with relevant radiation damping (~1h damping time).
  - LHC will be the last hadron collider ever built till FCC-hh.
  - Everything learned at the LHC will represent an unvaluable source of knowledge for who will have to design such collider
  - We need to explore limits in MDs pushing the limits and learning beyond the operational needs

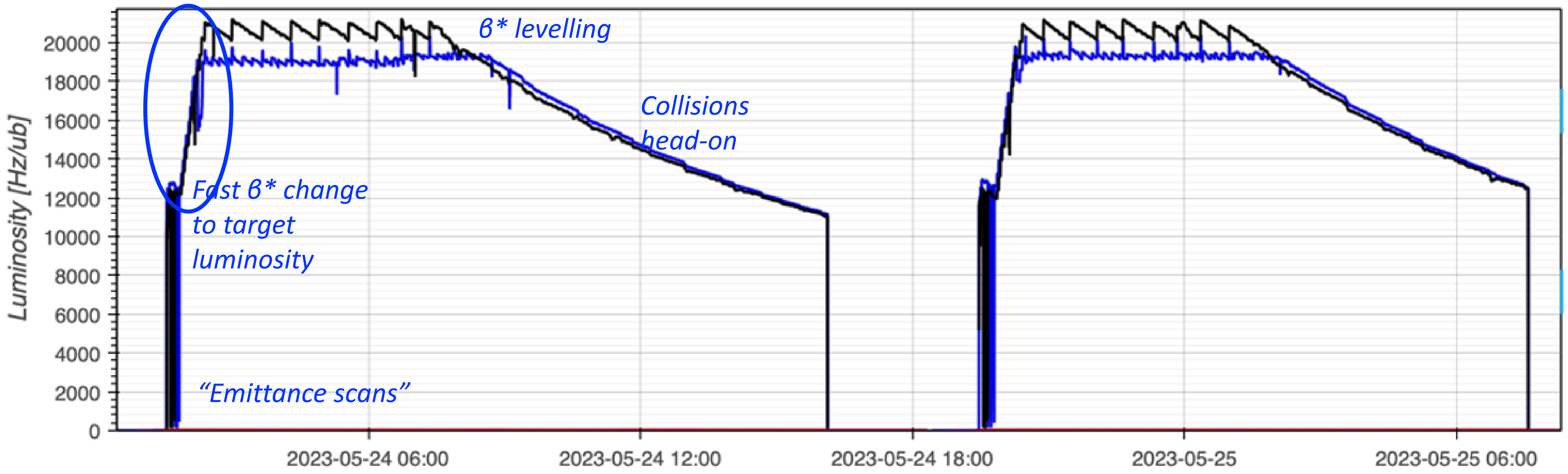
Thank you!

Operational configurations 2023 — challenging!

	E [GeV]	Optics	ß* 1/5 [m]	ß* 2 [m]	ß* 8 [m]	X 1 [µrad] V	X 5 [µrad] H	X 2 [µrad] V	X 8 [µrad] H →V
Injection	450	1	11	10	10	-170	170	170	-170
Ramp	450-6800	1-20	11 → 2	10	10 → 2	-170 → -135	170 → 135	170 → 200	-170 → -200
Flat Top	6800	20	2	10	2	-135	135	200	-200
Squeeze	6800	20-22	2 → 1.2	10	2	-135	135	200	-200
LHCb Rotation	6800	22	1.2	10	2	-135	135	200	H: -200 → 0 V: 0 → 200
Tune Change	6800	22	1.2	10	2	-135	135	200	200
Adjust	6800	22	1.2	10	2	-135	135	200	200
Large Levelling	6800	23-34	1.2 → 0.6	10	2	-135 → -145	135 → 145	200	200
Levelling	6800	34-43	0.6 → 0.3	10	2	-145 → -160	145 → 160	200	200

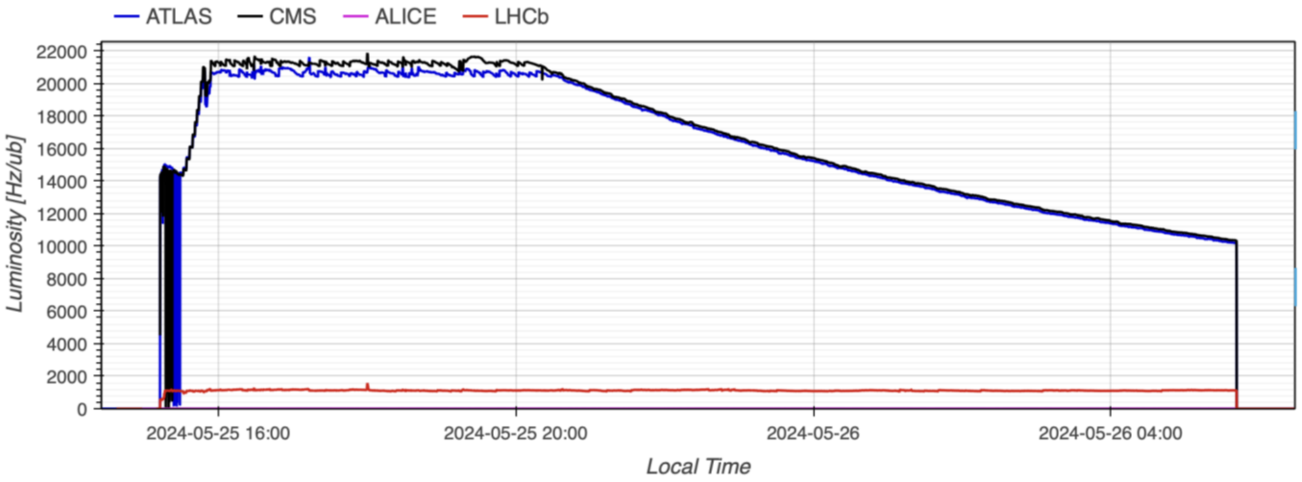
- Deployed already some key features required for the HL-LHC operation!
- Smoothly put in operation in 2023 and 2024 despite the complexity!

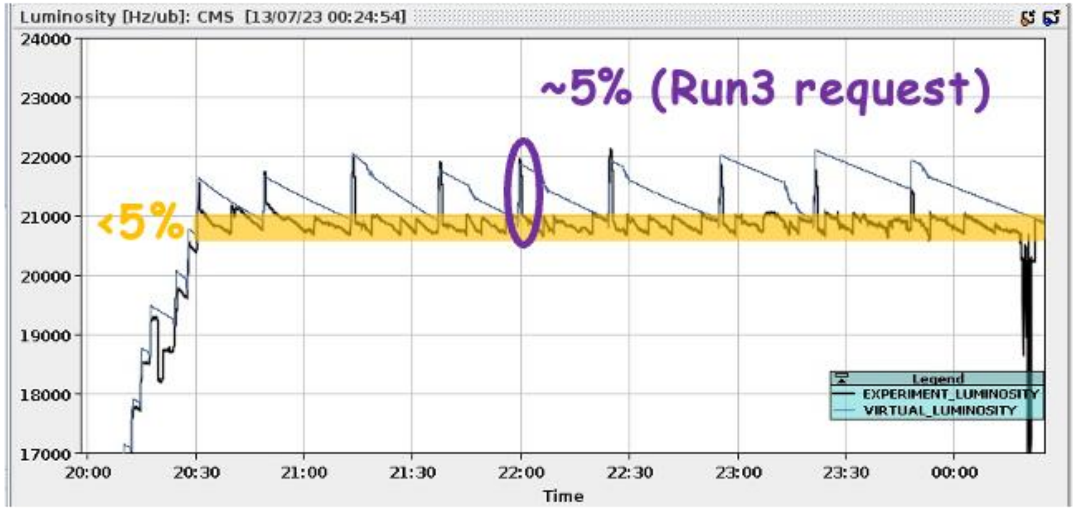
Luminosity levelling at the LHC



- Levelling range 120cm-30cm initially optimised for bunch intensities up to 1.8×10^{11}p
- Most complex operations were deployed starting in 2023 with changes at the same time of the β* functions, the separation bumps and crossing angle.
  IR's tertiary and physics-debris collimators changing gaps and positions!
- Target lumi step size ~5% — can do much better by combining separation and β*!
- Separation levelling in LHCb and ALICE

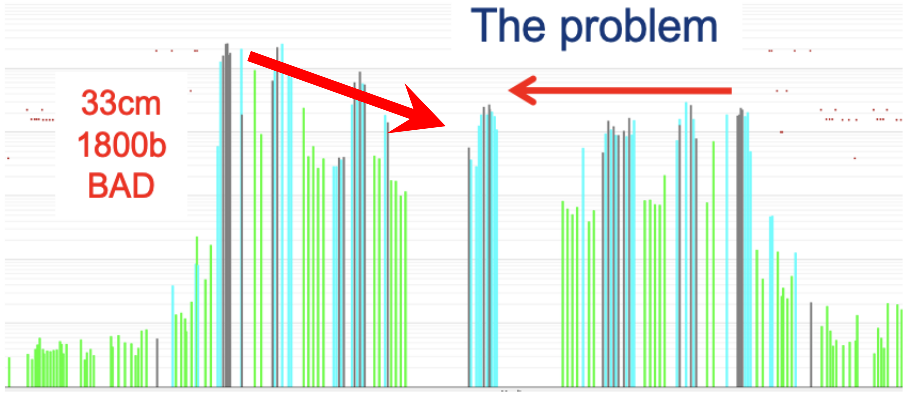
Further improvements in 2024

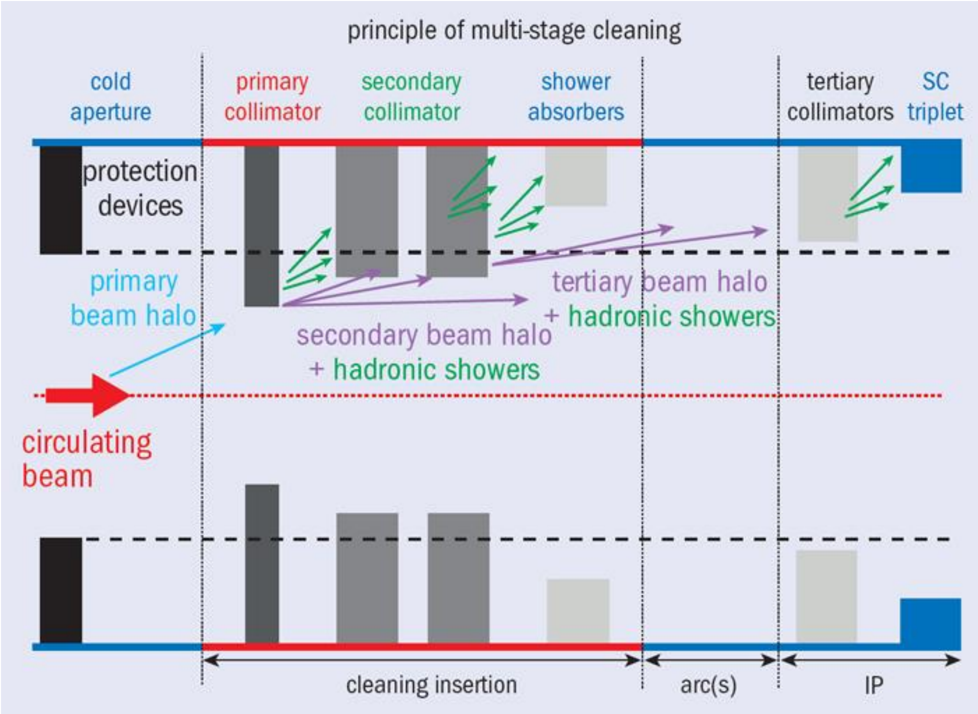




- Fast levelling to peak luminosity, reached at around 60cm
  Branch 120cm-60cm kept in case of larger bunch currents are accessible later in the year
- Finer tuning of pile-up, independently for ATLAS and CMS: new tools to combine separation and β* levelling
  Larger-than-needed "virtual" luminosity done with a step in β, then fine tuning with separation*

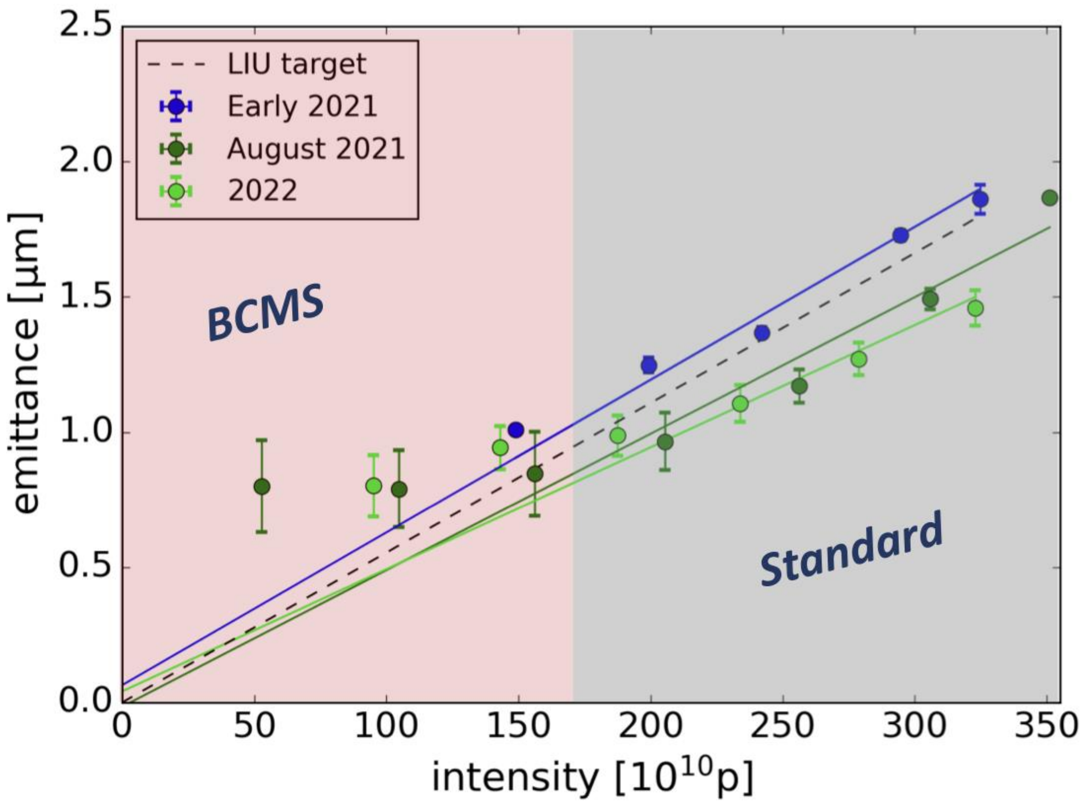
Collimator Hierarchy





On 17 April a first breakage in the collimator hierarchy was observed:
With 1800 bunches per beam
Losses on the secondary collimators increased more than the losses on the primary collimators during the β^* squeeze from 36 to 30 cm
The squeeze halted at 36 cm for machine protection reasons → **~ 2% loss in luminosity**
Studies and tests indicate that off-momentum halo particle with a large vertical betatron amplitude are responsible for the breakage

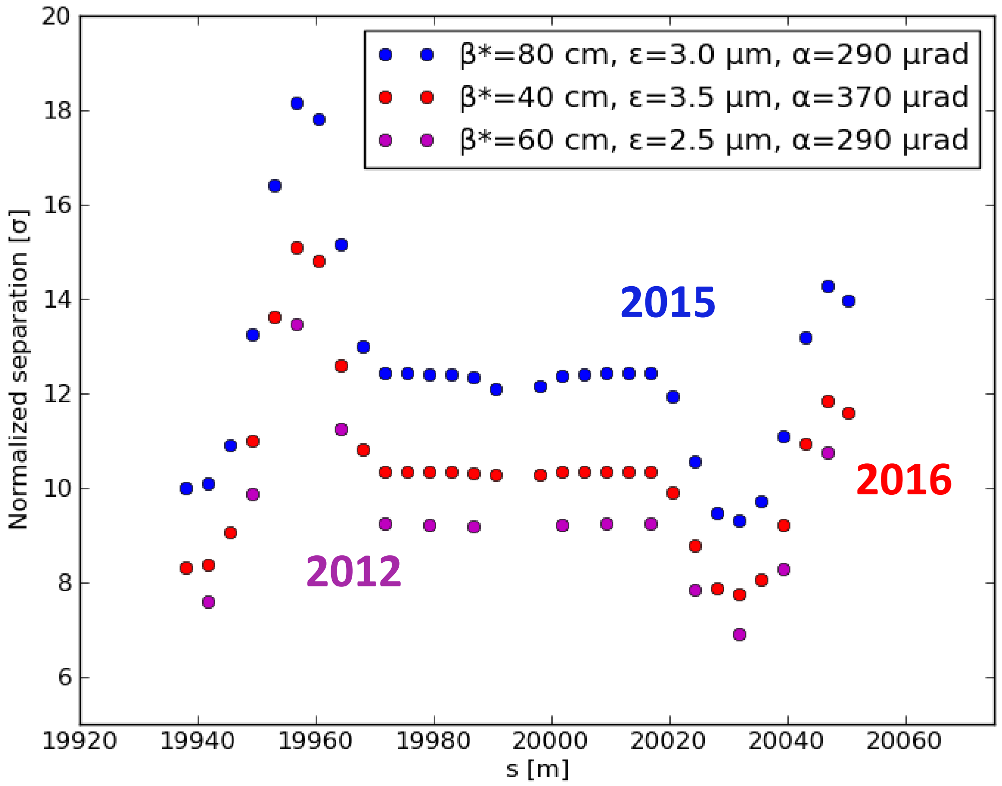
Standard vs BCMS in the Injectors



- Splitting factor Standard beam = 12
- Splitting factor BCMS beam = 6
- BCMS beam requires less protons per bunch injected in the PSB
- Transverse emittance is preserved during longitudinal bunch splitting
- Therefore, BCMS beam has higher brightness

LHC configuration RUN I→RUN II

- Move from **50 to 25 ns spacing** → **double long-range numbers**
- **Electron cloud effects** → big uncertainty on final **emittances in collision**
- **Instabilities** during squeeze → allow for safe **High chromaticity and high octupoles operation**
- **β*** → to probe potential **luminosity reach** commissioning the final optics



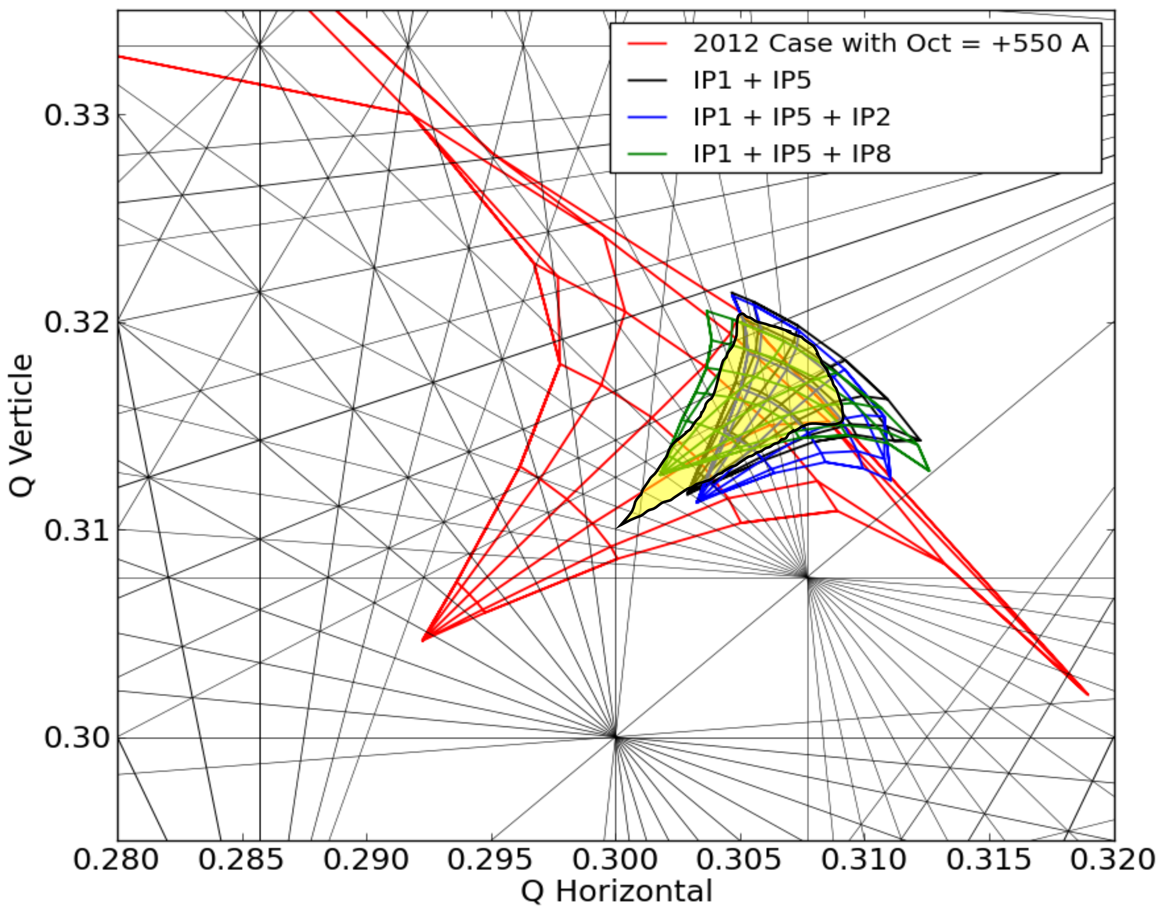
IP1 IP5

IP1 and IP5 at 10 σ beam-beam separation for emittance of 3.75 μm → relaxed configuration

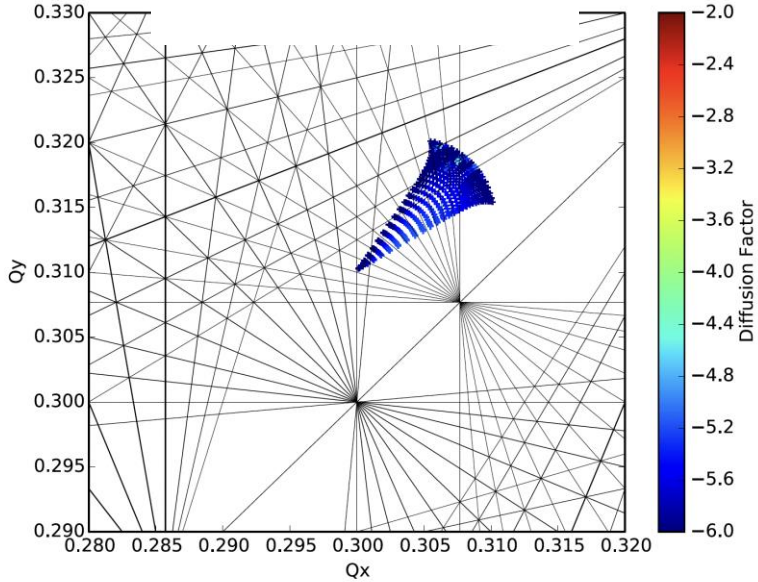
Dynamic Aperture from 4 to 5-6 σ

When emittances stable and at the smallest values → room for reducing crossing angles!

Footprint RUN1 → RUN2 →RUN3→HL-LHC



IP1 and IP5



2 IPS end of Fill 10^{11}ppb

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