LHC Beam Operation Workshop 2016 - Evian

Long-range and head-on beam-beam interactions
What are the limits?

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Many thanks to the OP teams (LHC an injectors), as well as the ADT team, BI, J. Boyd and C. Schwick

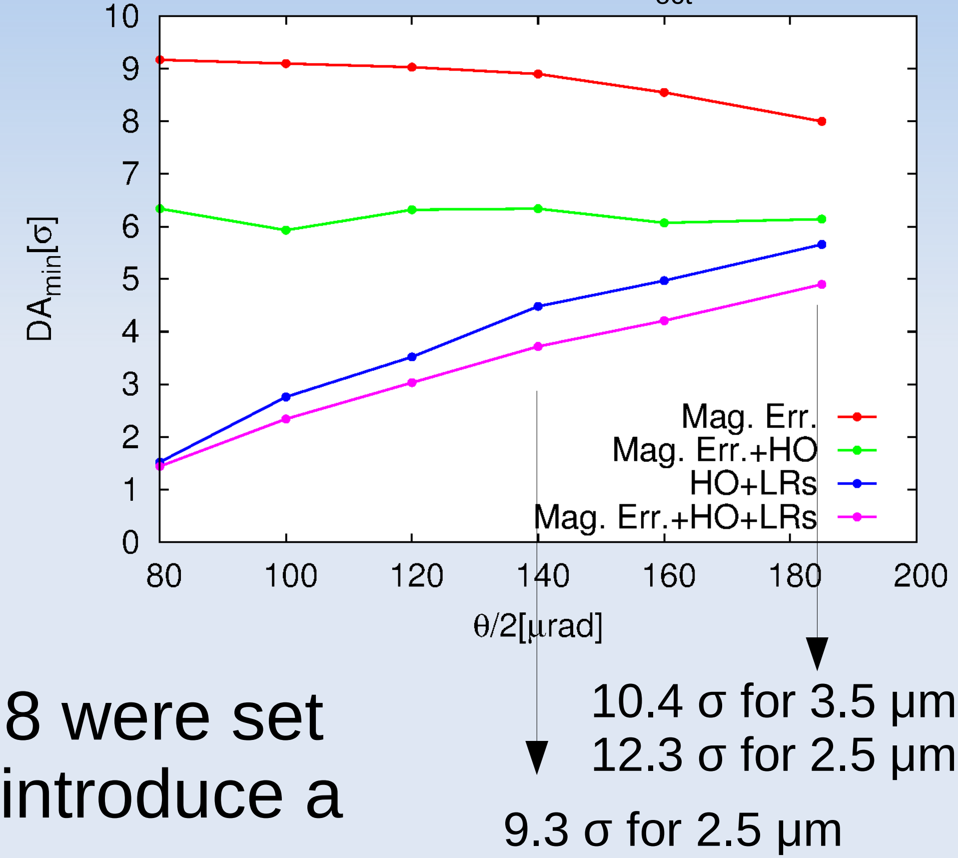
Content

- Limitations due to long-range beam-beam interactions
  - Experience in MDs
  - Experience in physics
- Levelling with a transverse offset
- Limitations due to head-on interactions
  - Observations
  - Emittance growth in collision
- Conclusion

2016 setup

- The crossing angles in IPs 1 and 5 were set based on experimental data from 2015 and DA simulations
  - Onset of long-range induced losses measured at 8.4 σ
  - Strong sensitivity to small tune shifts ($3{\cdot}10^{-3} \rightarrow -2$ σ DA)

$1.2{\cdot}10^{11}$, 2.5 μm, β*=0.4, beam-beam in IP1/5, Q'=15, I_{oct} = 500 A



- The crossing angles in IPs 2 and 8 were set such that long range interactions introduce a tune shift and spread ~10^{-4}

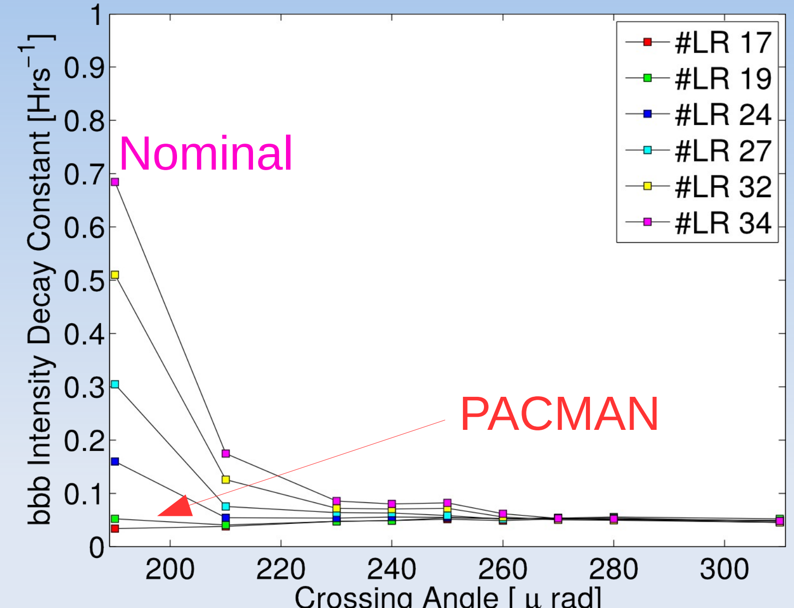
→ Head-on tune shift ($\sim 10^{-3}$) when levelling with a transverse offset might require compensation

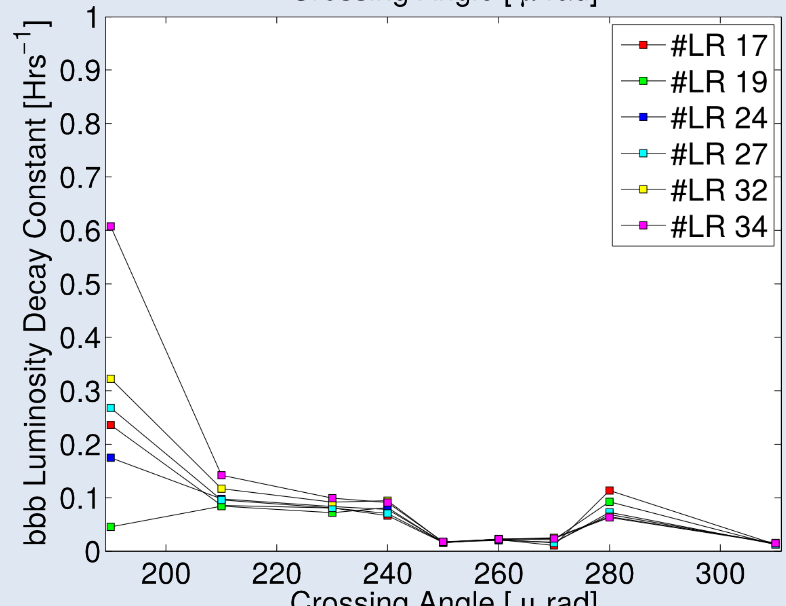
T. Pieloni, et al @ Evian 2015 and LMC 31.08.2016

Probing the long-range limitations

- Crossing angle scan with 3 trains of 48b (bunch intensity 1.2·10^{11} and emittance of 2.5 μm) colliding in all Ips :
  - Long-range driven losses were observed in B1 below 260 μrad → 8.6 σ
- No emittance growth was observed during the experiment
  - Slight emittance reduction (BSRT profiles) correlated with losses
  - Reduction of the luminosity lifetime

    → Particles in the core are lost

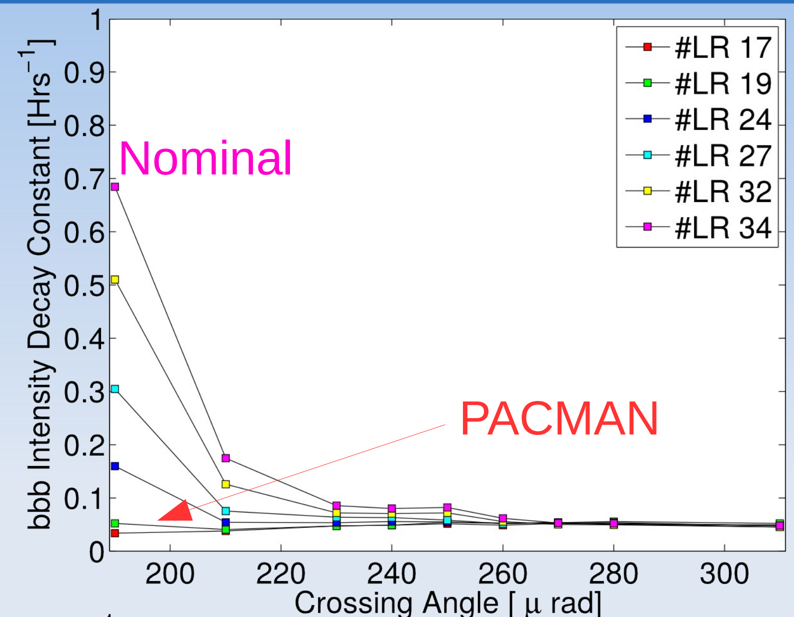


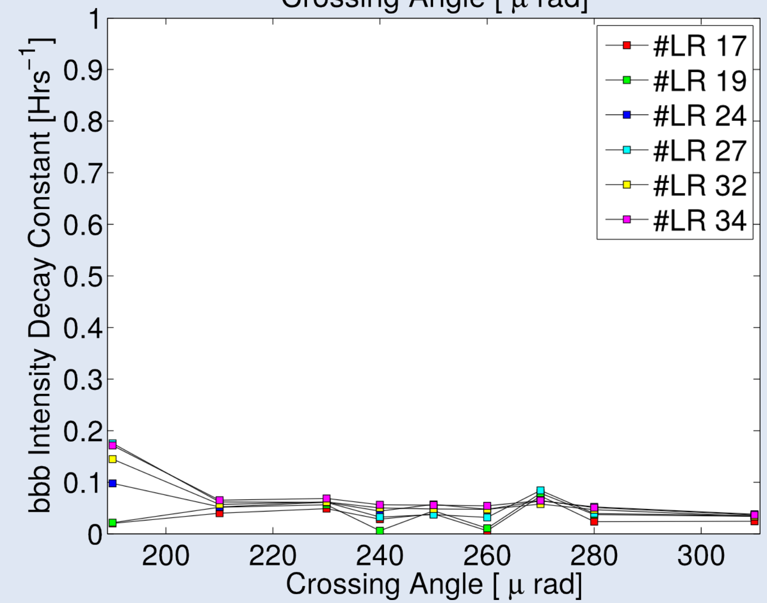


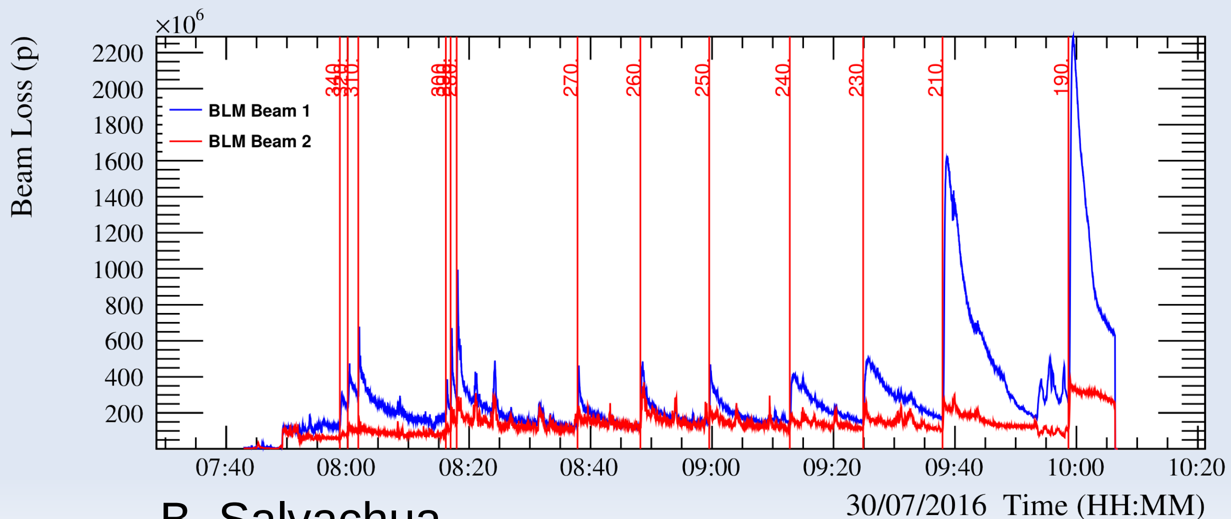
M. Crouch, et al @ Beam-beam and luminosity meeting 14.10.2016

B1-B2 difference

- Long-range driven losses became visible in B2 below 210 μrad → 7.0 σ
  - The difference between beam 1 and beam 2 was also visible in physics fills (see F. Antoniou)
- In similar experiments in 2015, beam 2 seemed more critical than beam 1
- Most losses are in the vertical plane of B1





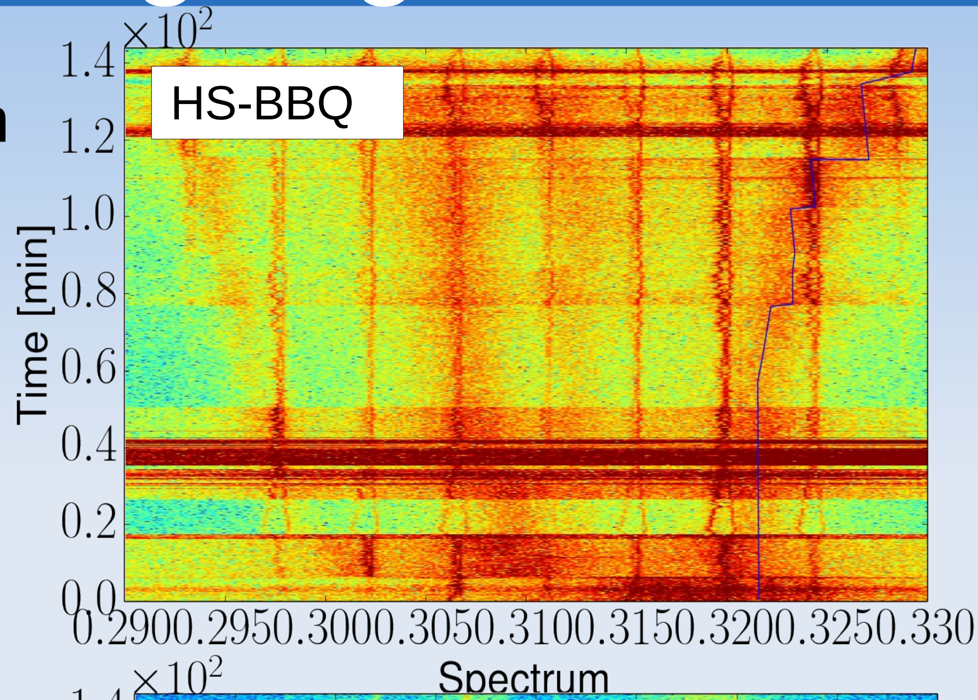


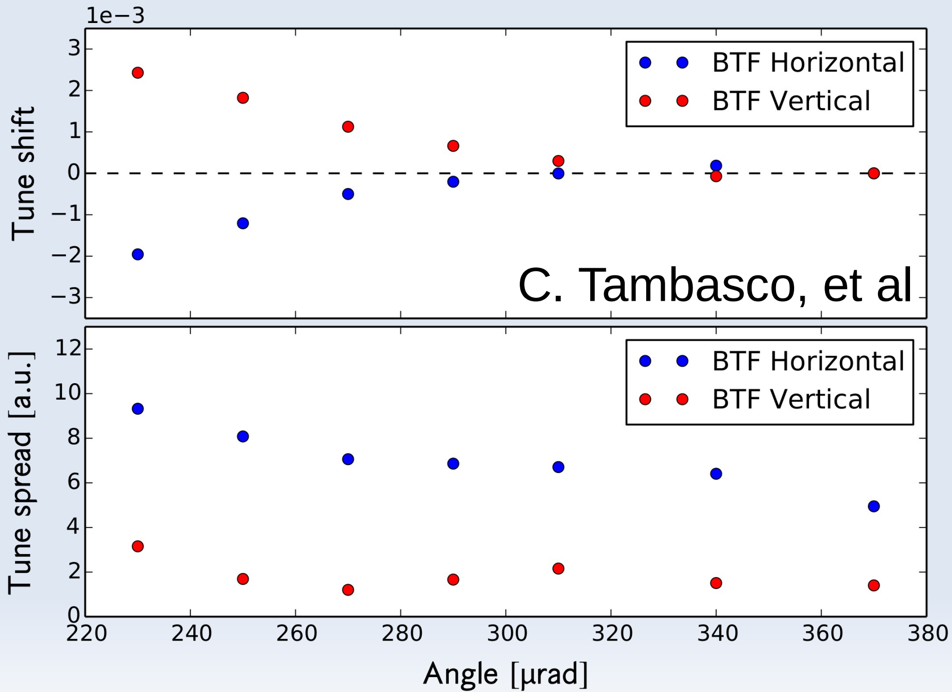
B. Salvachua

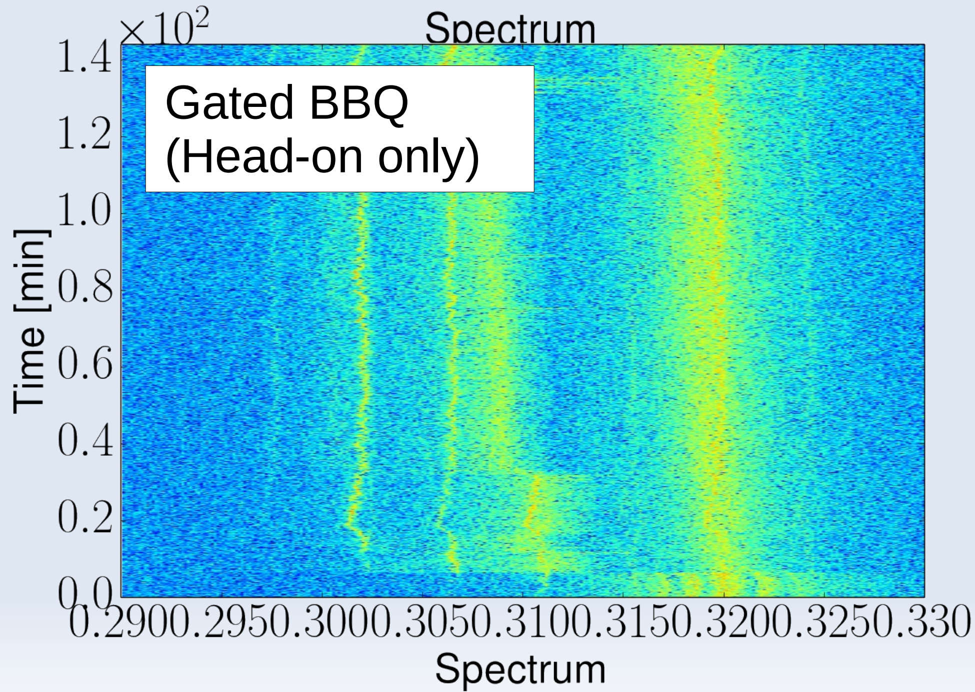
M. Crouch, et al @ Beam-beam and luminosity meeting 14.10.2016

Tune shift as a function of the crossing angle

- Unexpected tune shift as a function of the crossing angle, driven by long-range interactions
  - Beam transfer function MD in a weak-strong configuration (a single pilot against a trains of 48 nominal bunches) :



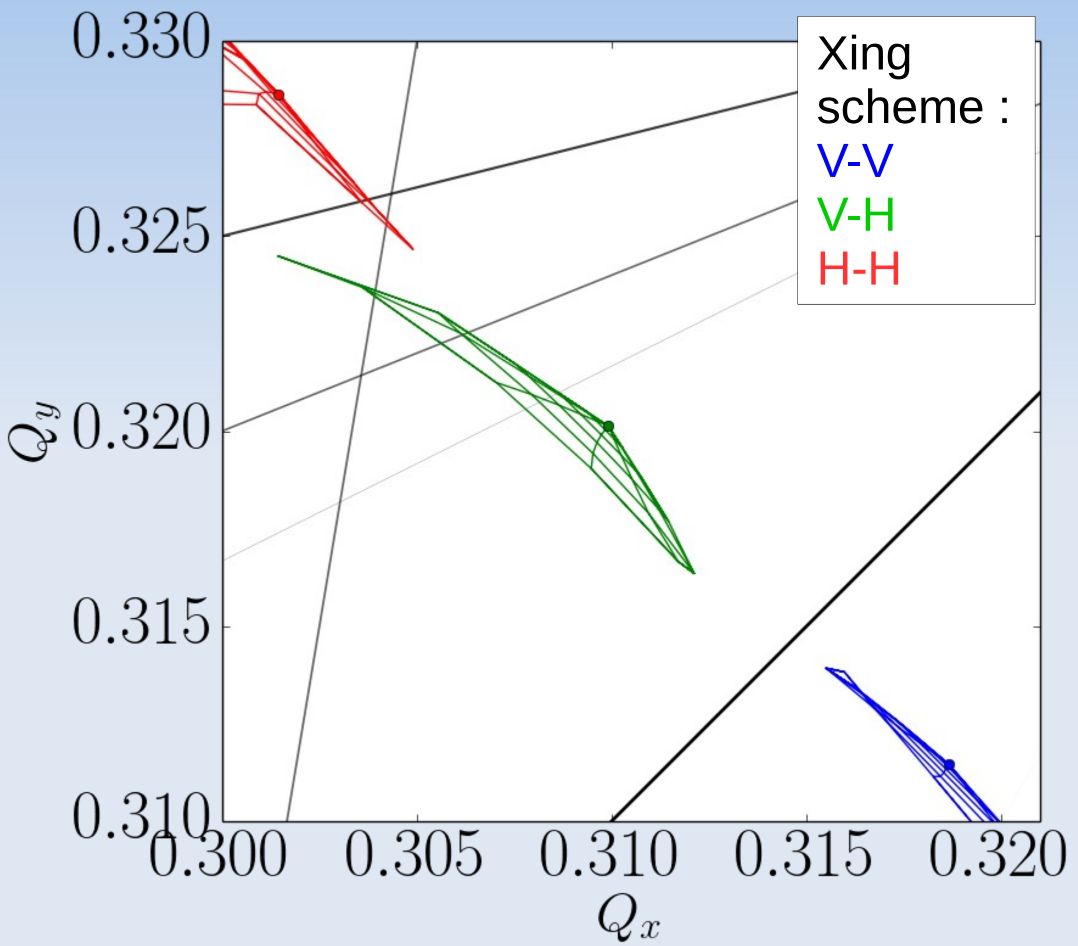




Possible mechanism

- The long-range interactions in IPs 1 and 5 induce tune shifts of opposite signs → passive compensation
- Asymmetries between the two main IPs (β*, Xing, local coupling, …) breaks the passive compensation
  - ΔQ up to $8 \cdot 10^{-3}$ (BCMS beams, 140 μrad)
  - PACMAN effects
  - Asymmetric tune spread (→ DA, Landau damping : see L. Carver)

  → Differences between the beams and plane

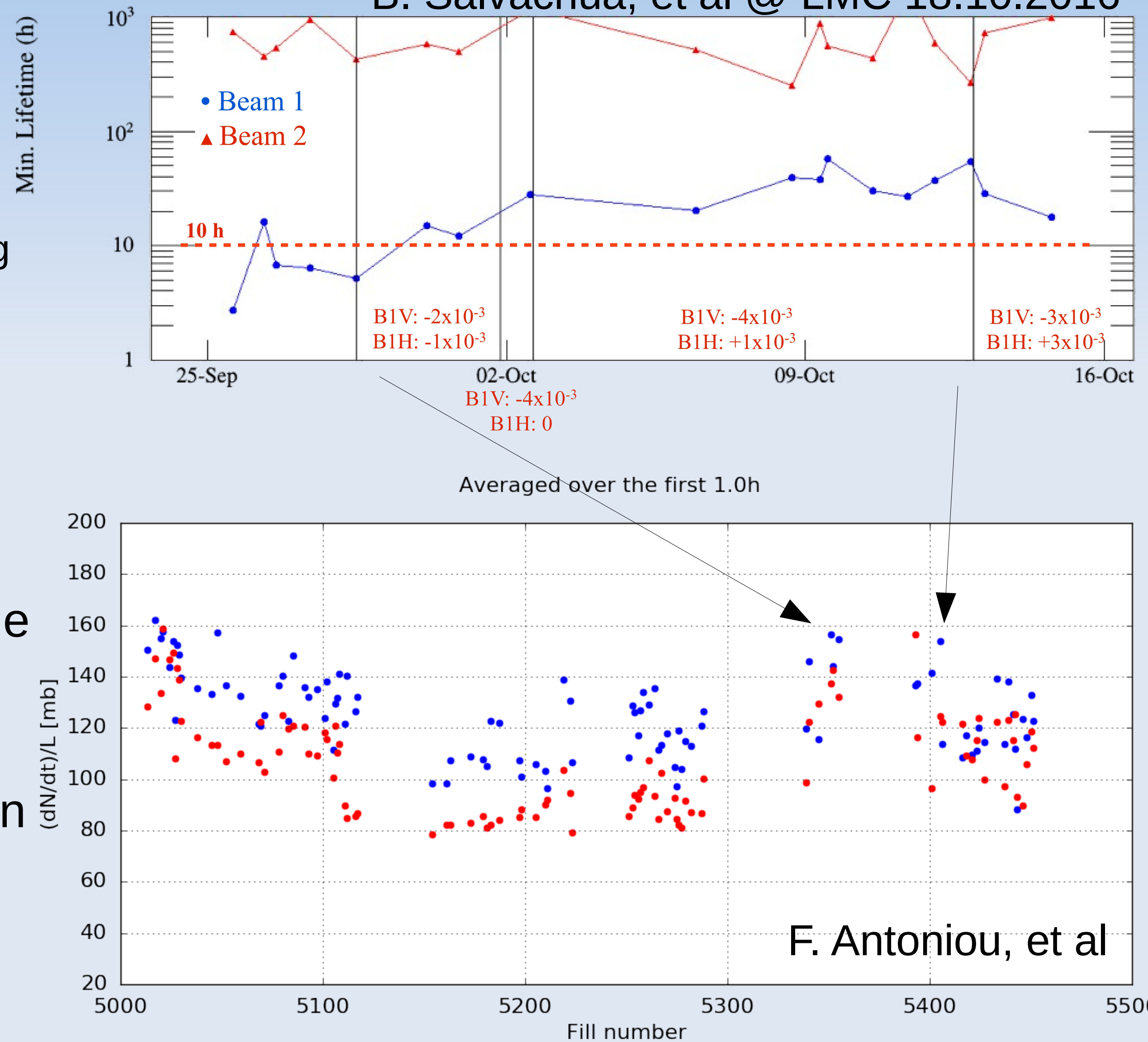


→ Need to measure and correct these effect during the setup, in order to avoid detrimental effect on DA and Landau damping

Change of operational crossing angles

- After TS2 the crossing angle was reduced to 280 µrad
  - → 9.3 σ with BCMS emittance (wrt 10.4 σ with nominal emittance at the beginning of the year)
- Significant losses were observed and mitigated :
  - Correcting the long-range induced tune shift improved the losses during the change of Xing angle
  - Optimisation of the working point improved the lifetime in collision to similar levels as at the beginning of the year (with reduced intensity 1.1 wrt $1.2 \cdot 10^{11}$ at the beginning of the year)

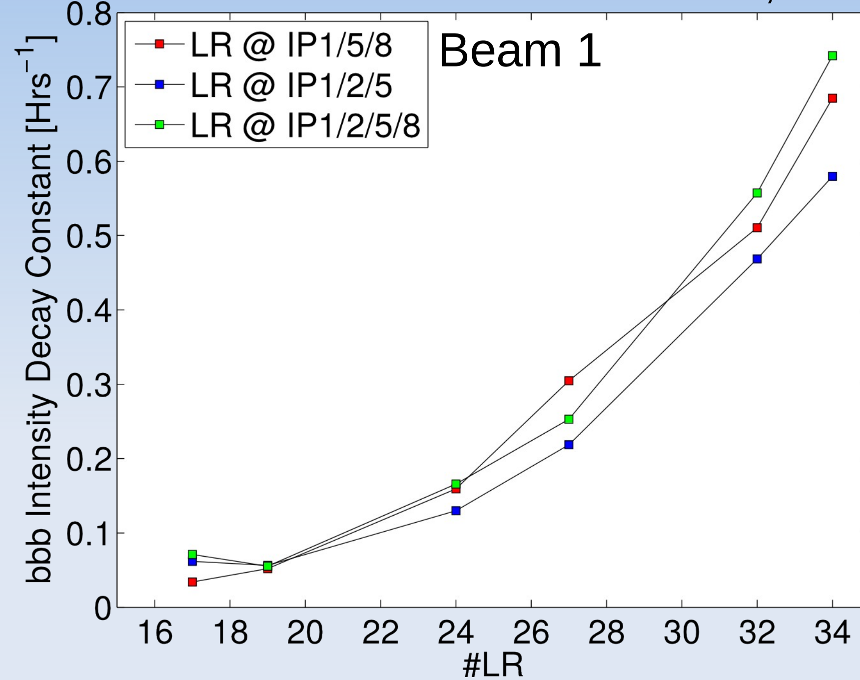
B. Salvachua, et al @ LMC 18.10.2016



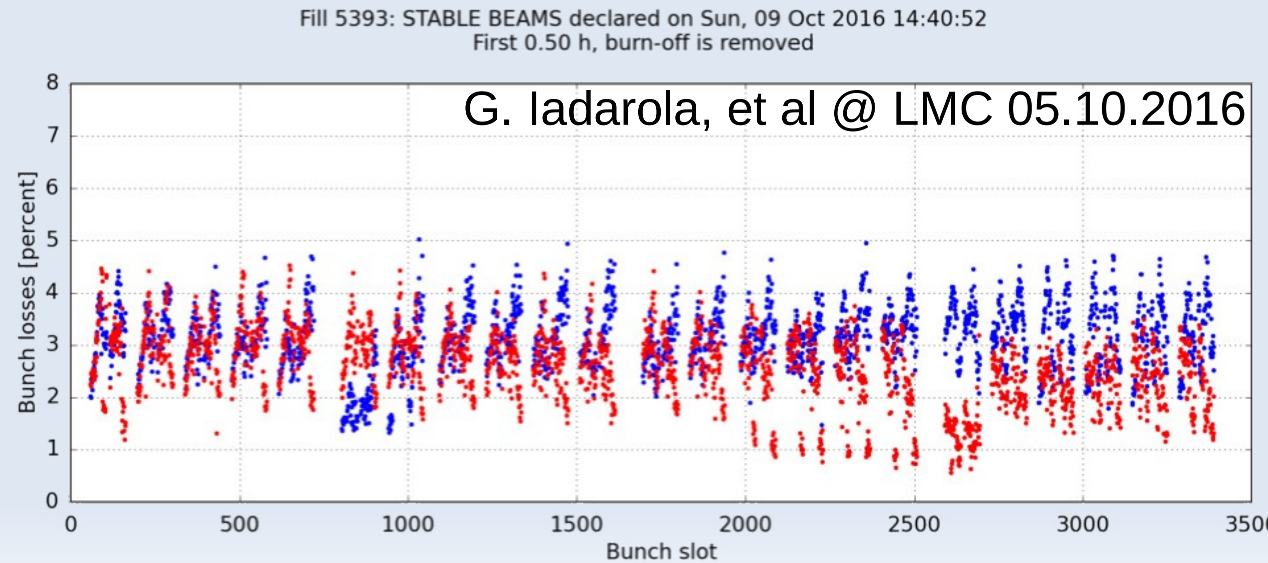
Impact of IPs 2 and 8

- No significant impact of IPs 2 and 8 observed at the smallest crossing angle (230 μrad) during the long-range MD
  - The train that does not collide in IP8 behaves slightly better
  - IP8 was separated by ~4σ, in physics levelling starts at ~2σ

M. Crouch, et al

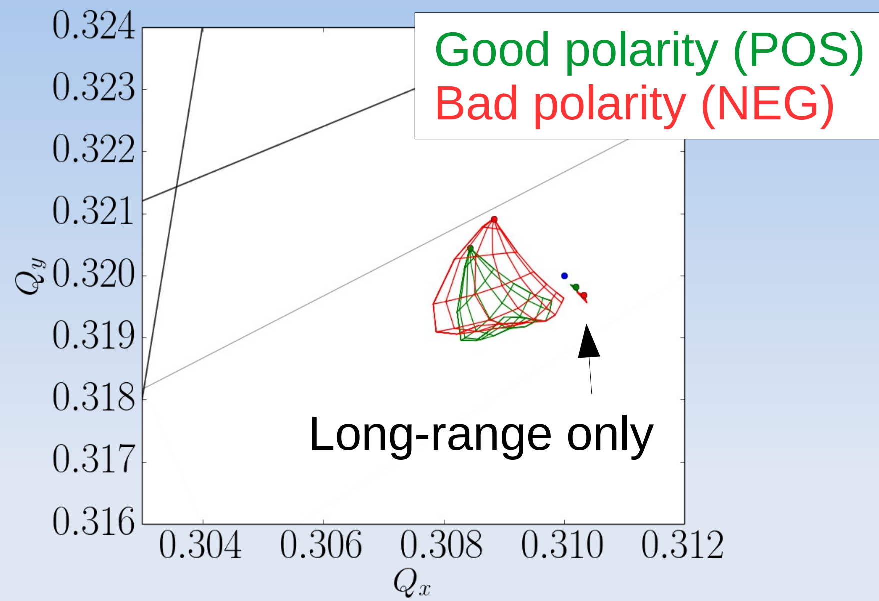


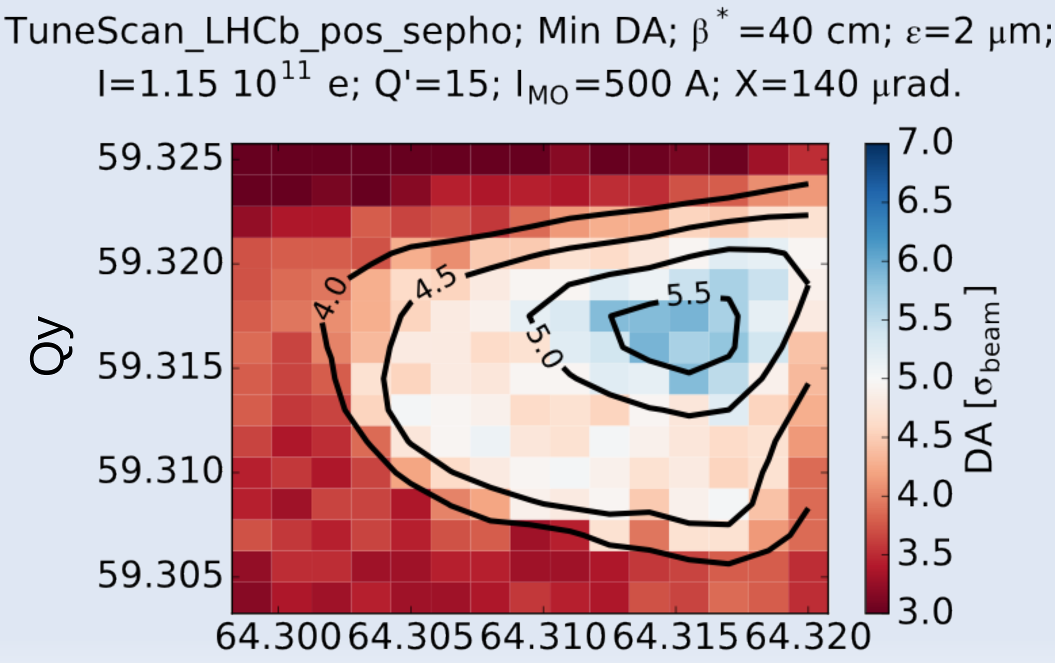
- During physics fills, the bunches colliding in IP8 experienced more losses than the others with the bad polarity of LHCb



Impact of IPs 2 and 8

- Long-range effects in IP8 are weak for both spectrometer polarities
- The *head-on* interaction can lead to a significant tune shift, varying during the levelling
  - Tune optimisation did mitigate the problem
  - If not sufficient, due to super-PACMAN bunches, levelling with a diagonal offset at the IP could mitigate this effect
- IP2 leveling started at ~ 4 σ separation at the IP, compared to 2 σ at IP8 → negligible tune shift



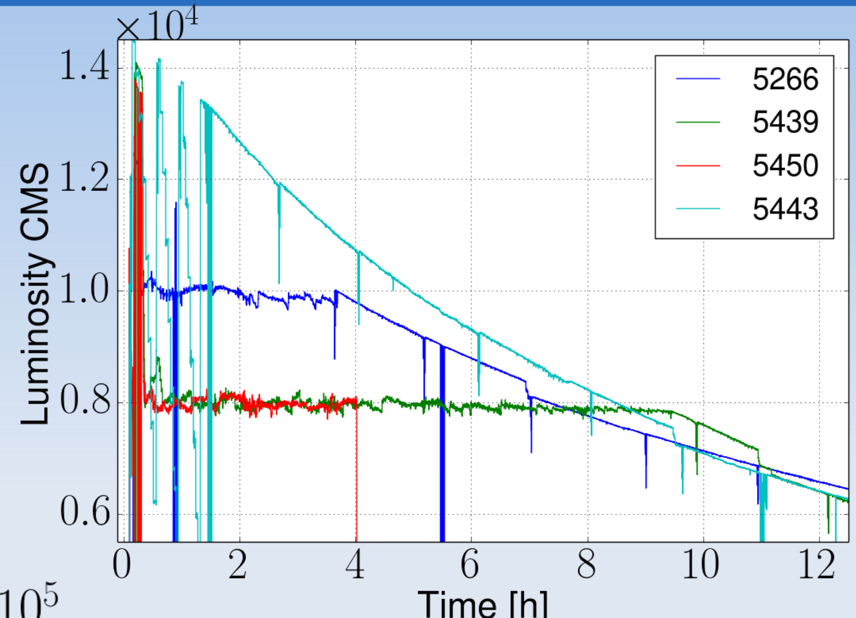


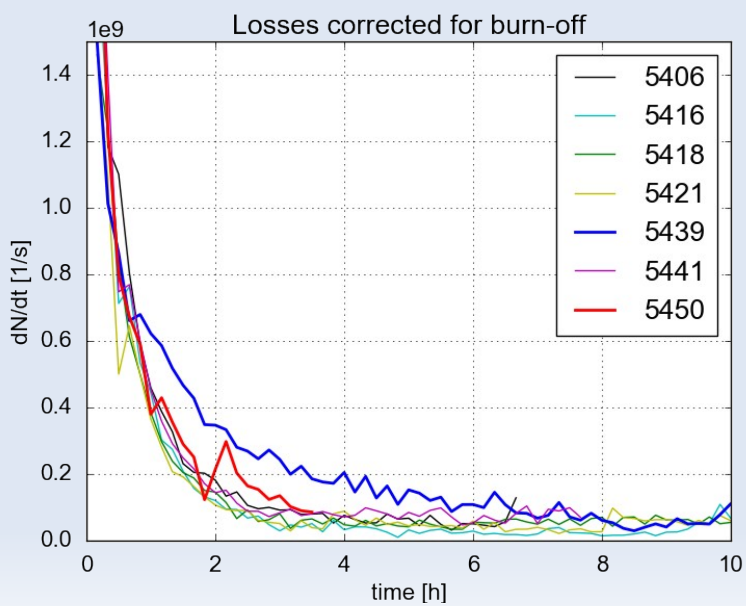
D. Pellegrini

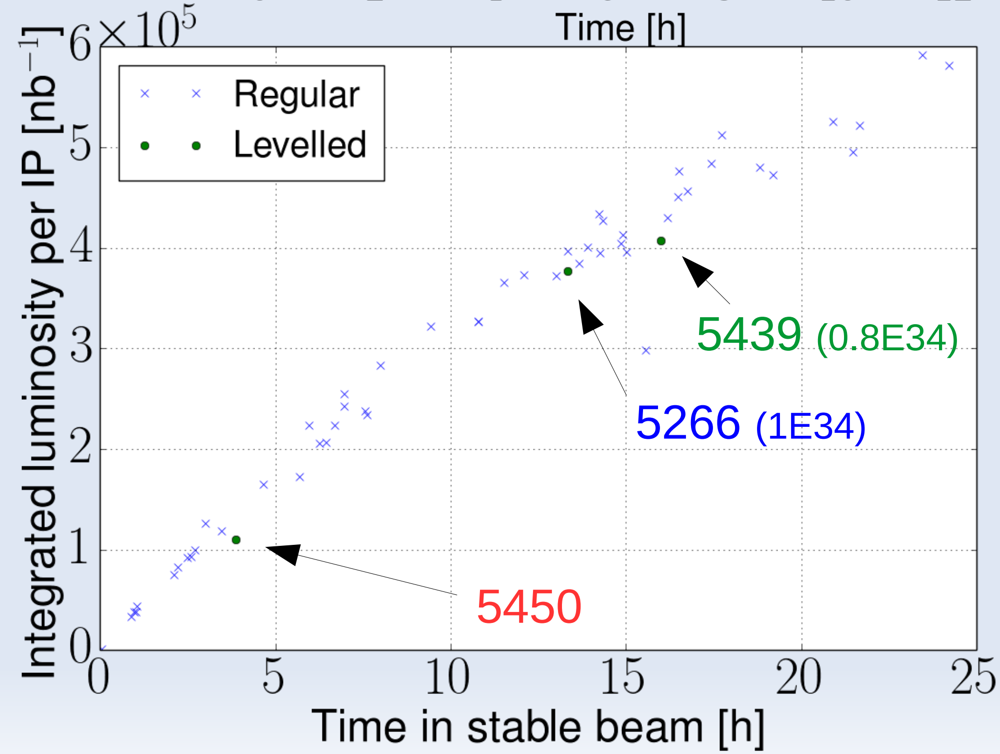
Offset levelling in IPs 1 and 5

- ~7% of the integrated luminosity was lost during a long fill levelled at $0.8 \cdot 10^{34}\ s^{-1}cm^{-2}$ wrt to regular fills in similar conditions
  - 10% is expected without beam quality degradation
  - Significant losses during the first levelling test → mitigated by reducing the octupoles from 470 to 220A, the chromaticity form 15 to 10 units and optimising the tunes (Fill 5450)

→ No show stopper due to beam-beam interactions with a transverse offset in IPs 1 and 5 with these parameters



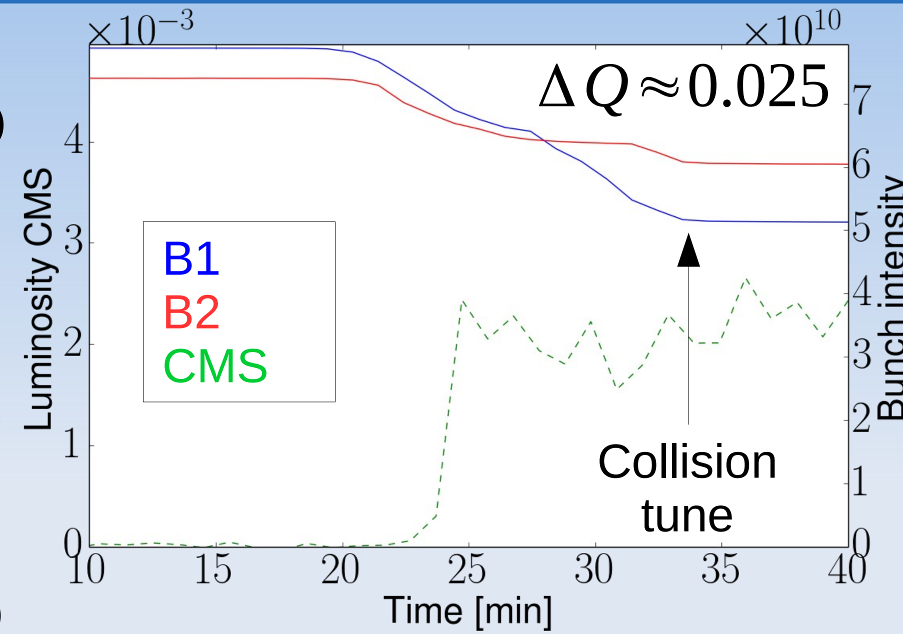


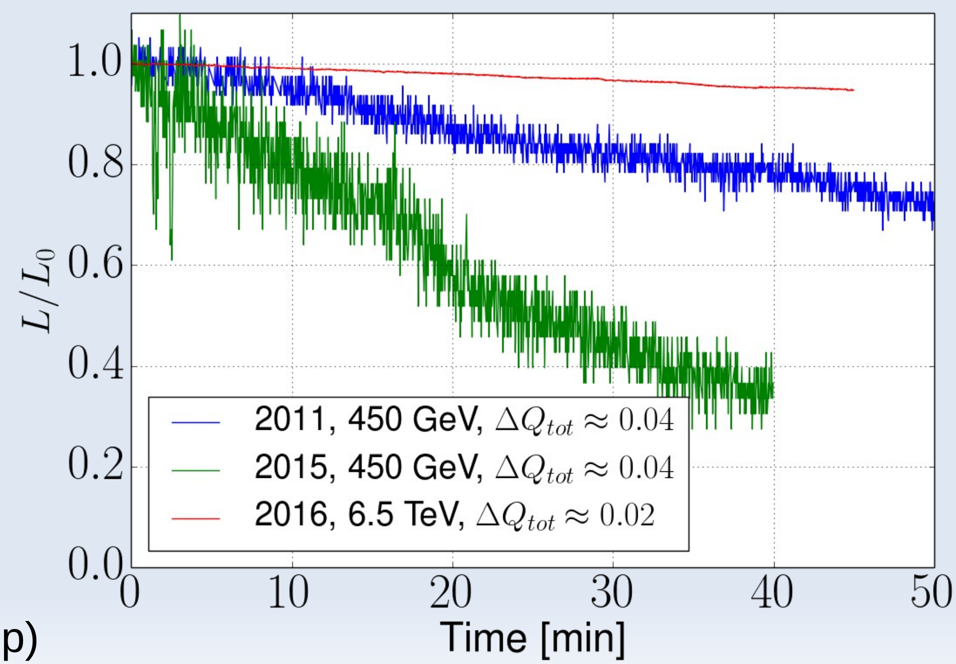


Do we observe limitations due to head-on beam-beam interactions ?

Large beam-beam tune shifts

- Strong losses were observed during the desqueeze with *colliding* beams (High β setup) with injection tunes
  - The effect was not observed with collision tunes
- The lifetime of colliding high brightness single bunches ($2{\cdot}10^{11}$ in 1.5 μm) was burn-off dominated at 6.5 TeV
  - Significant improvement with respect to previous MDs at injection (with collision tunes)
  - Promising results from the tune scan, but needs to be extended
  - A significant emittance blow up was observed (→ ADT high intensity settings)
  - More tests needed to assess HL-LHC tune shifts at top energy (remove the crossing angle / use a desqueezed optics, ADT setup)

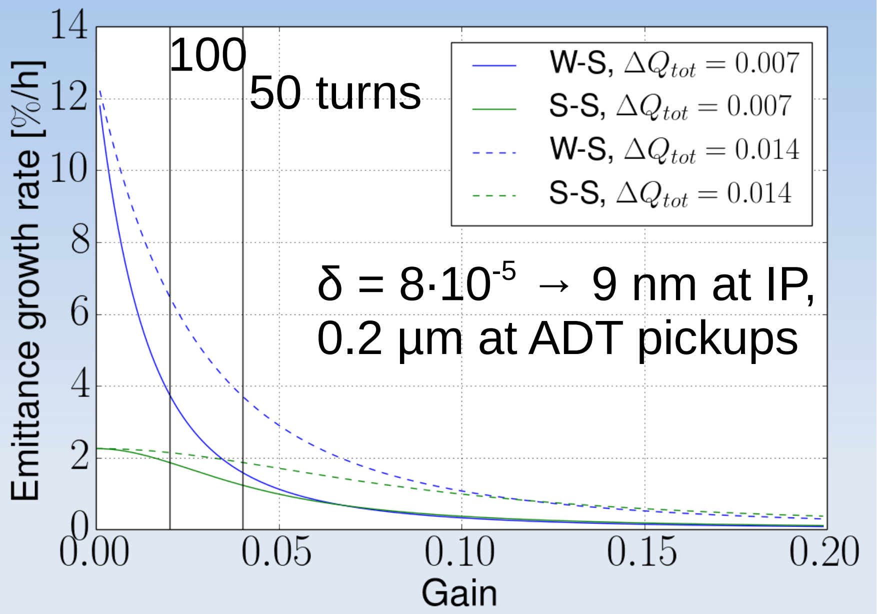




Do we observe limitations due to head-on beam-beam interactions ?

Small beam-beam tune shifts

- Different analytical models exist to describe the emittance growth due to noise and beam-beam interactions in simple configurations (V. Lebedev / Y. Alexahin)
  - LHC data are compatible with ~ 2%/h emittance growth (See. F. Antoniou)
  - Using the most pessimistic model and assuming a noise-less ADT, one estimates a noise floor about $8{\cdot}10^{-5}$
- It is possible to mitigate effect of external sources of noise with the ADT, given a sufficiently low noise from the ADT itself at high gain
  - Gain (and therefore noise) requirements increases with the total head-on beam-beam tune shift



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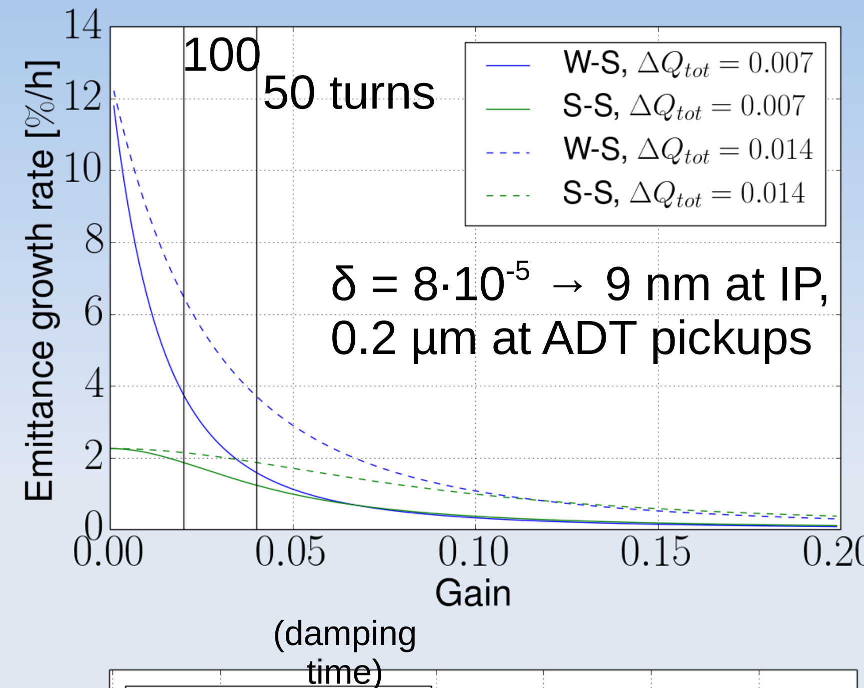
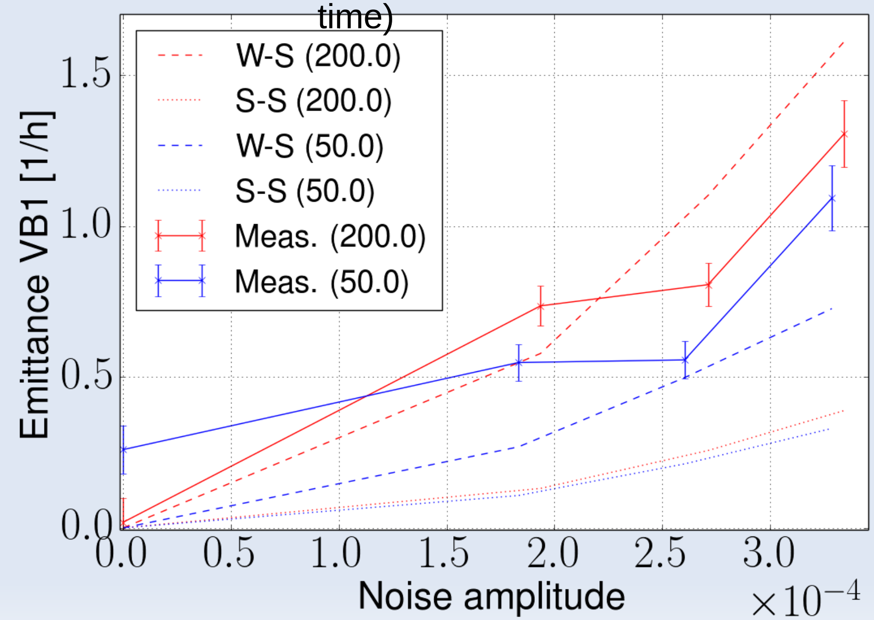
  - Gain (and therefore noise) requirements increases with the total head-on beam-beam tune shift
- MD results show a significant noise of the ADT with non-optimal high intensity settings
  - Yet the mitigation of the noise artificially introduced by the ADT was demonstrated with higher noise amplitudes





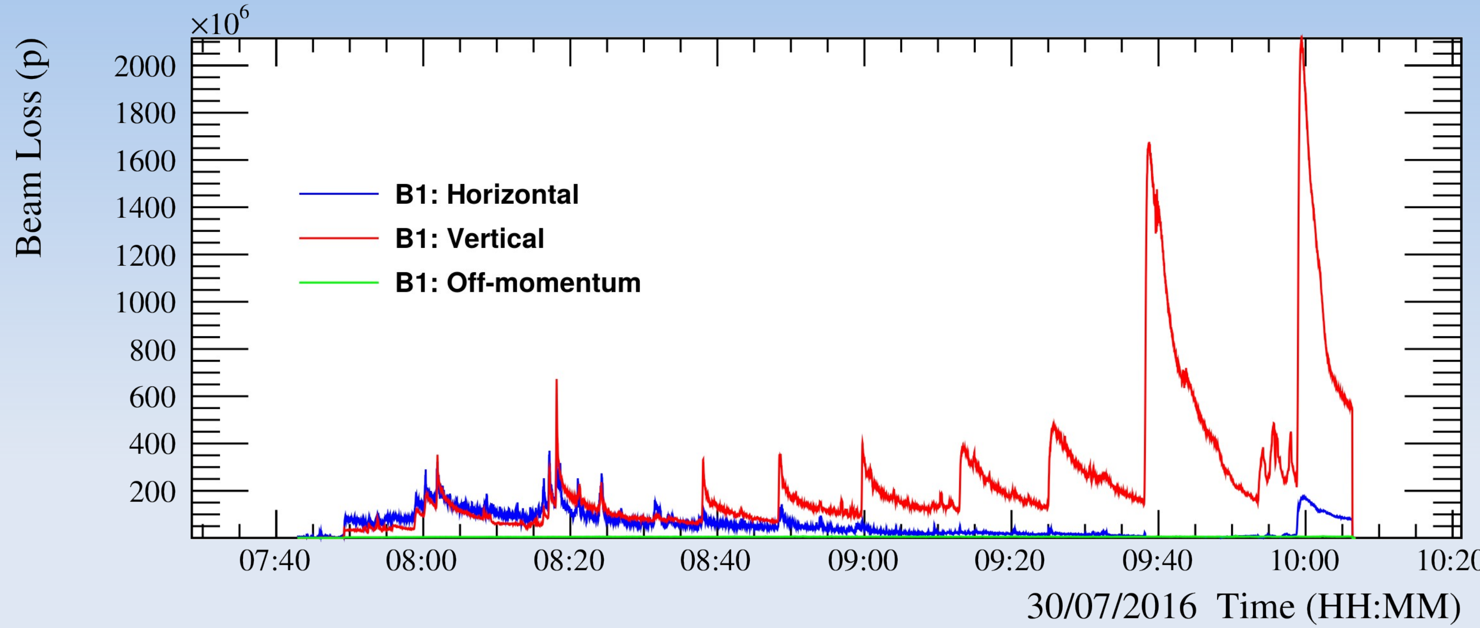
Conclusion

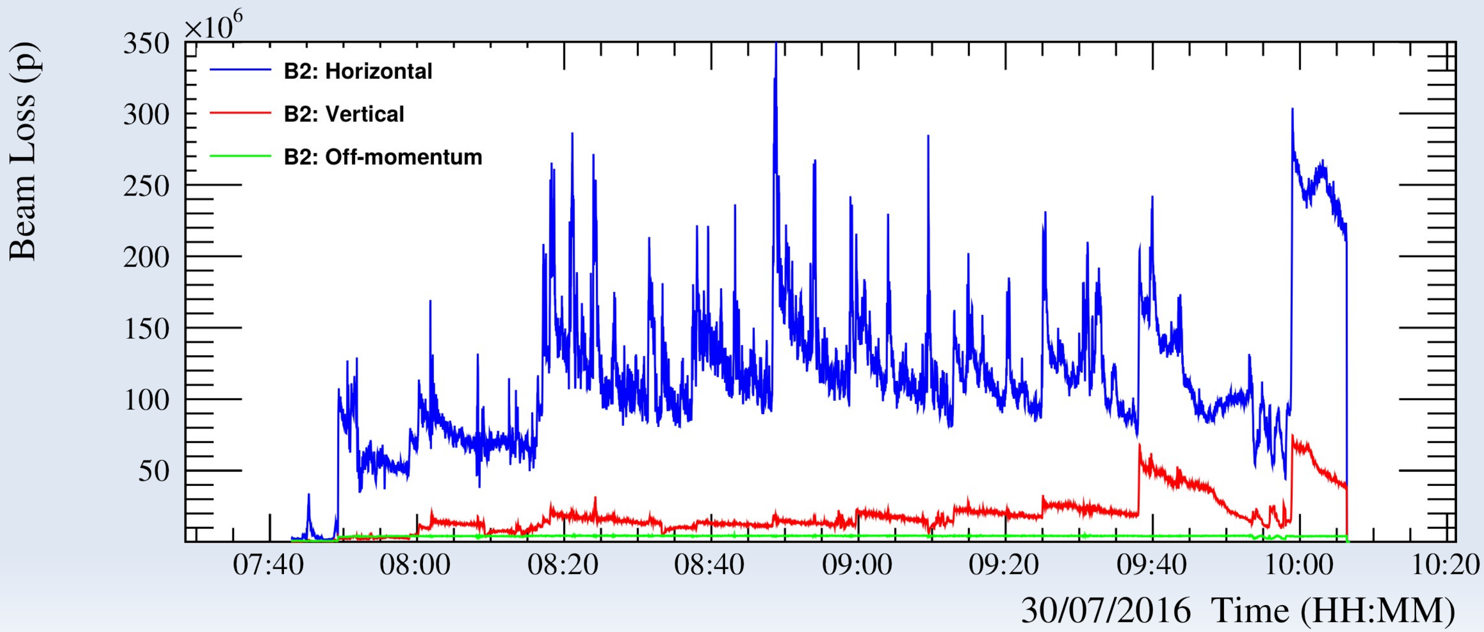
- Detrimental effects (losses, reduction of luminosity lifetime) due long-range beam-beam interactions were observed with physics beam (1) when reducing the normalised separation from 10.4 to 9.3 σ, that were mitigated by **tune adjustements**
  - In MDs, long-range induced losses were measured for crossing angles 8.6 σ for beam 1 and 7 σ for beam 2 (8.3 σ in 2015)
  - In dedicated experiments a tune shift due to the long-range interactions was observed, indicating an asymmetry between IPs 1 and 5 which needs to be understood and corrected during the setup to minimise the achievable crossing angle for both beams
  - The tune shifts due to the head-on beam-beam interaction with an offset at IP8 needs to be compensated (**tune adjustements** / diagonal levelling)
- No detrimental effect on the beam quality were observed during levelling tests in IPs 1 and 5
  - Detailed analysis is needed to fully understand why the losses increased before optimisation
- Head-on interactions are not limiting the performance with the current machine and beam parameters
  - The emittance growth observed in collision is compatible with a weak source of noise in the presence of the tune spread arising from head-on beam-beam interactions
  - Further optimisation of the ADT (gain / bandwidth / noise) could mitigate the ~2%/h emittance growth observed in stable beam
  - Further studies are needed to understand HL-LHC tune shifts

BACKUP

Loss patterns during the long-range MD

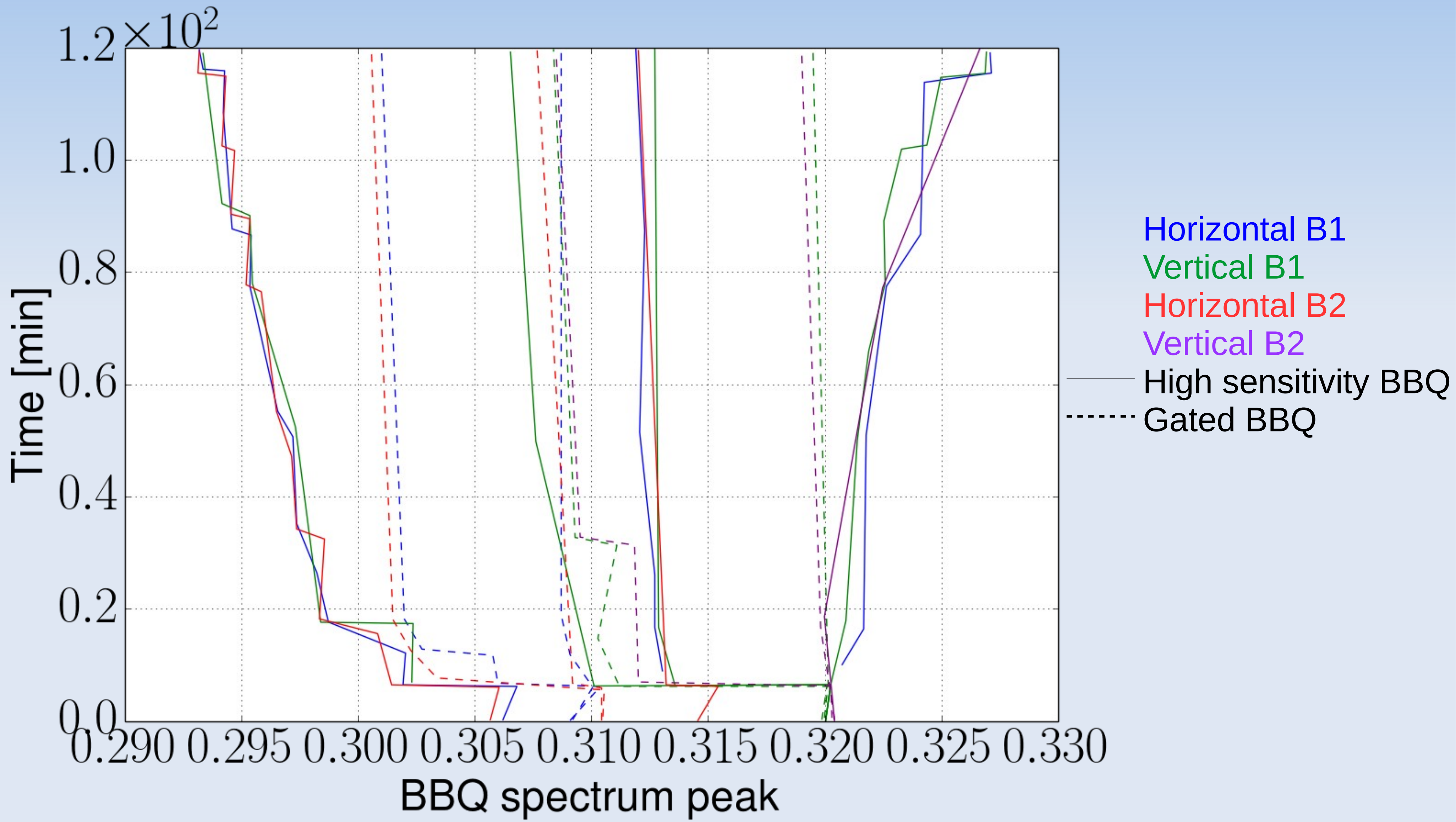
B. Salvachua





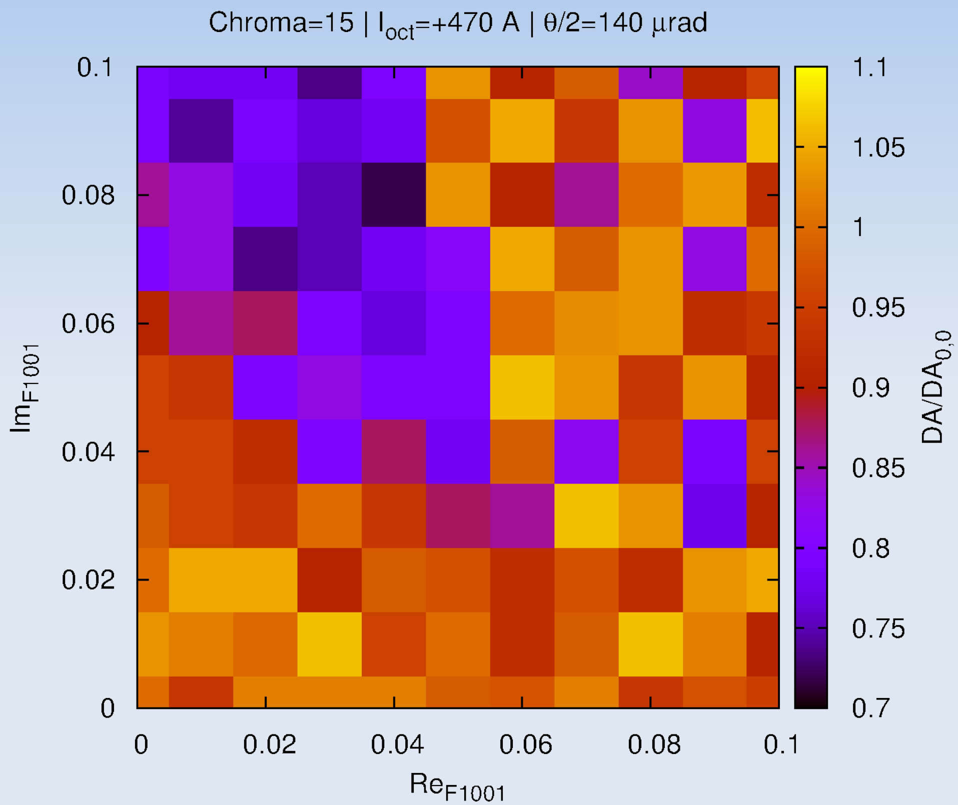
BACKUP

BBQ lines during the long-range MD



BACKUP

Dynamic aperture with a local coupling bump over IR1



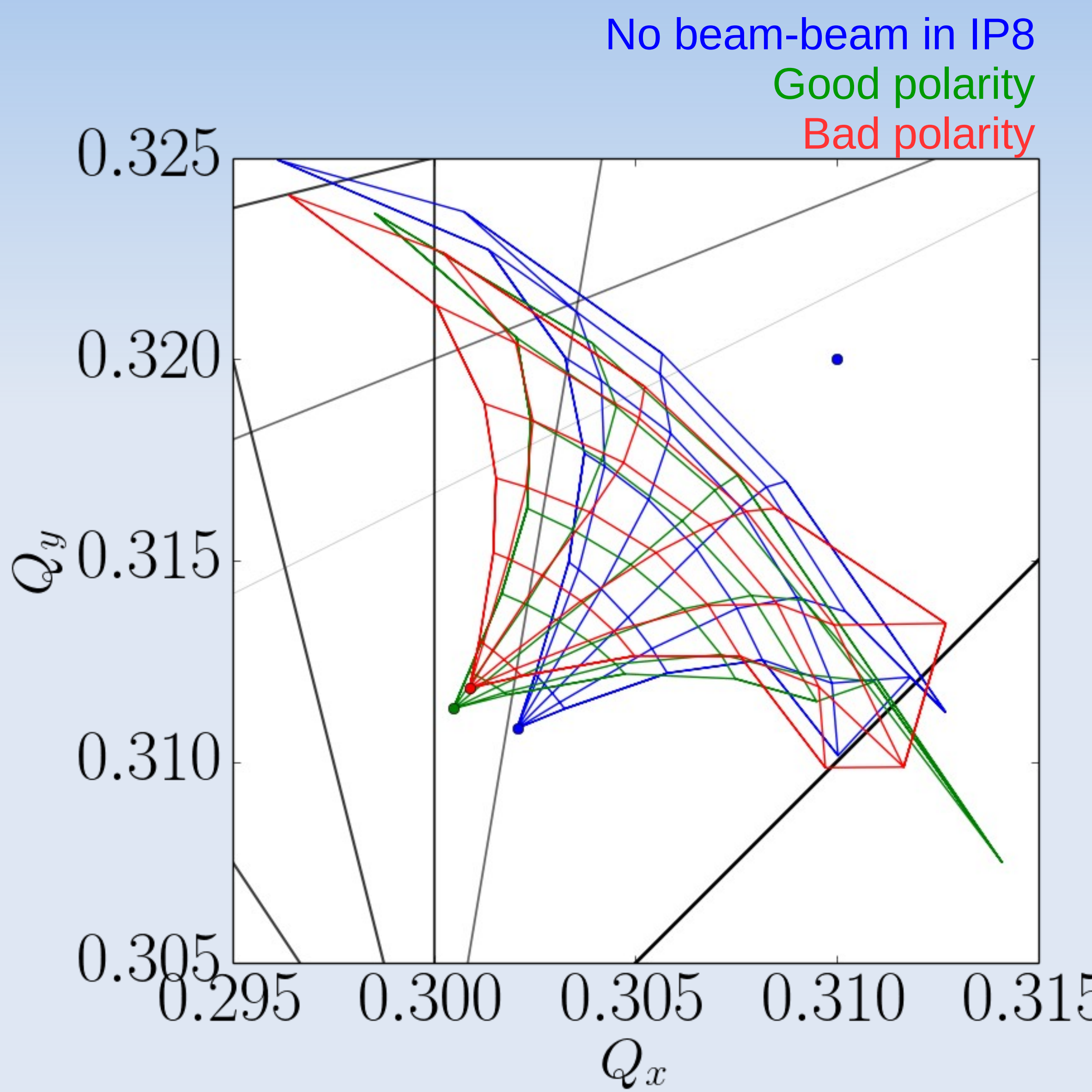
J. Barranco

- Asymmetries between IPs 1 and 5 can deteriorate the dynamic aperture
    - Local coupling bumps could explain differences in the tune shift, tune spread and lifetime

BACKUP

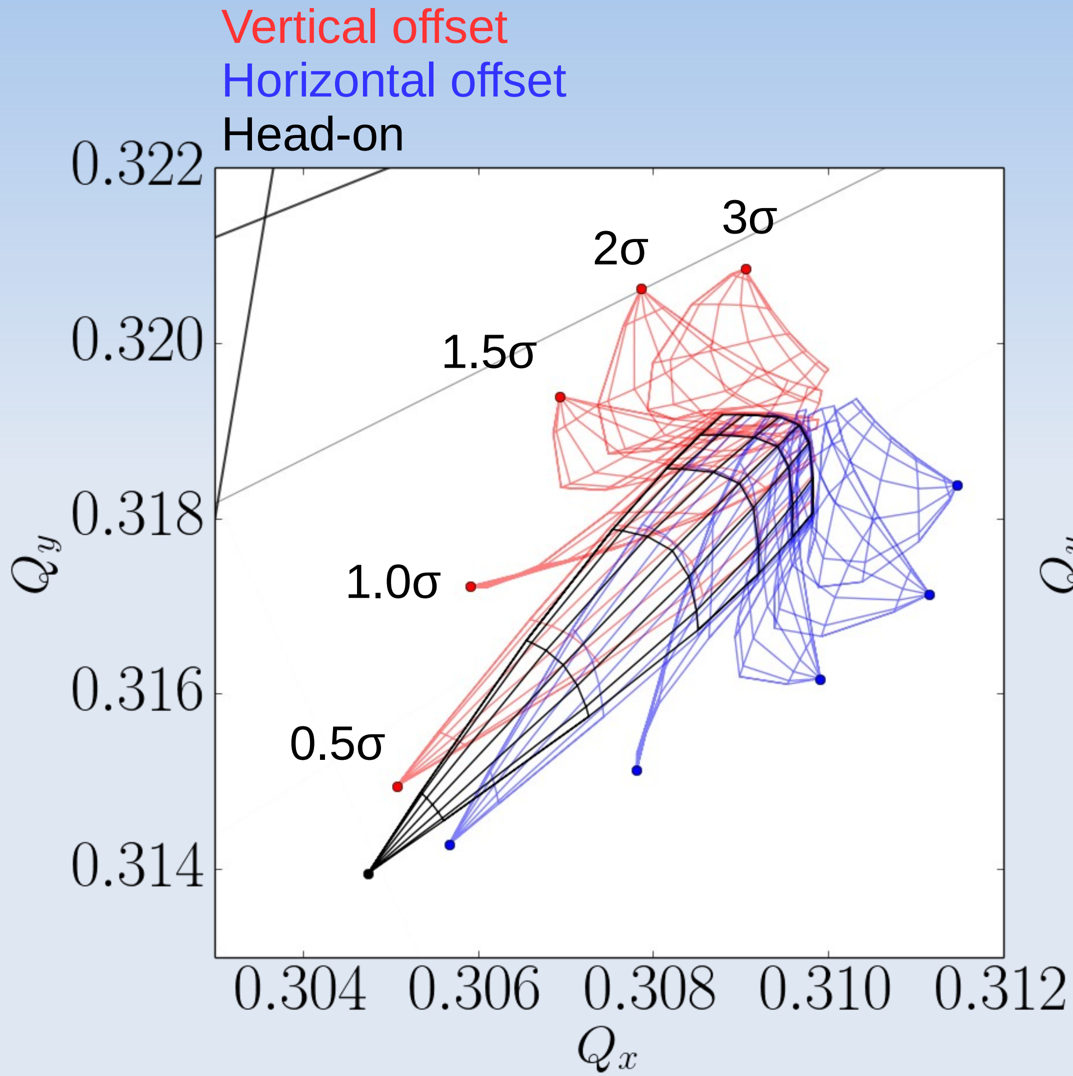
Effect of IP8 polarity on the footprint

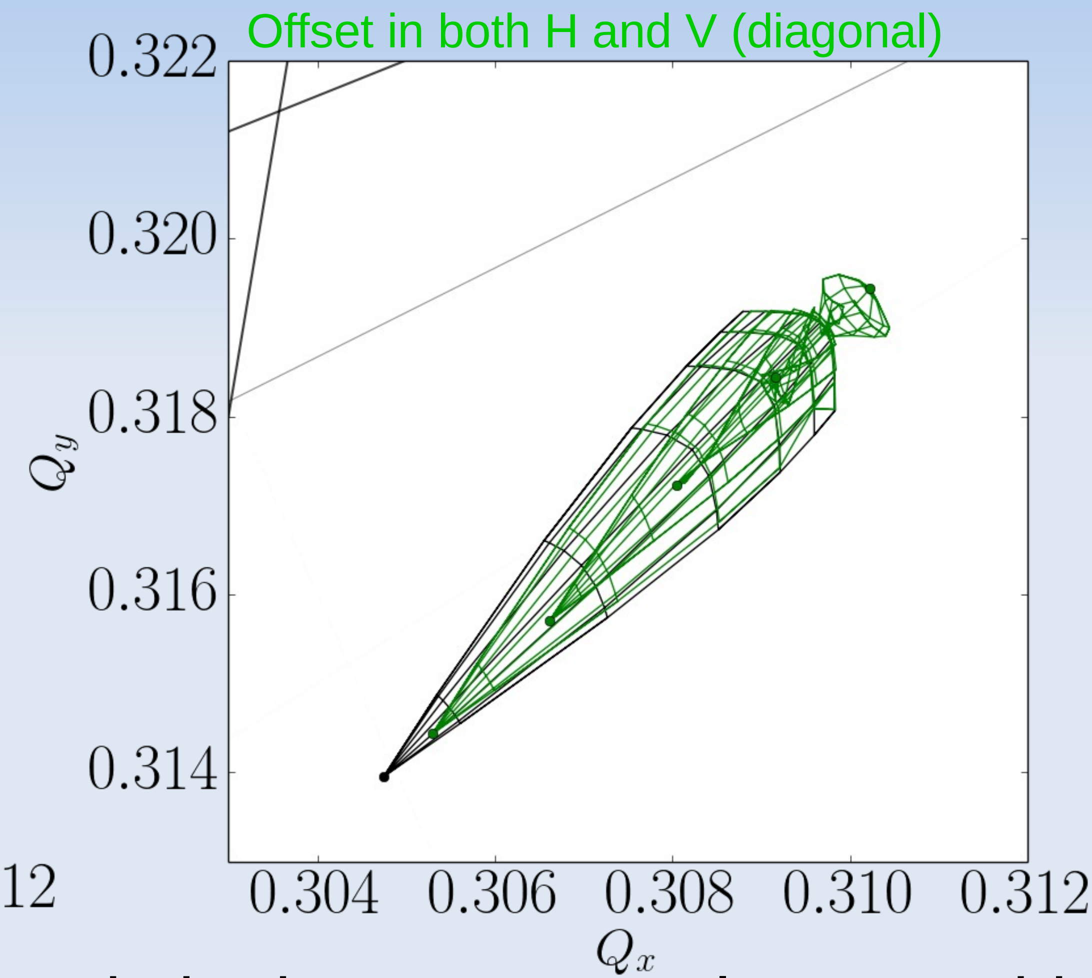
- The effect of LHCb polarity on the tune footprint seems small, yet it had an impact on the beam lifetime
  - Effect of specific resonances ?
  - Resonances excited by the offset collision ?



BACKUP

Leveling with diagonal offset in IP8



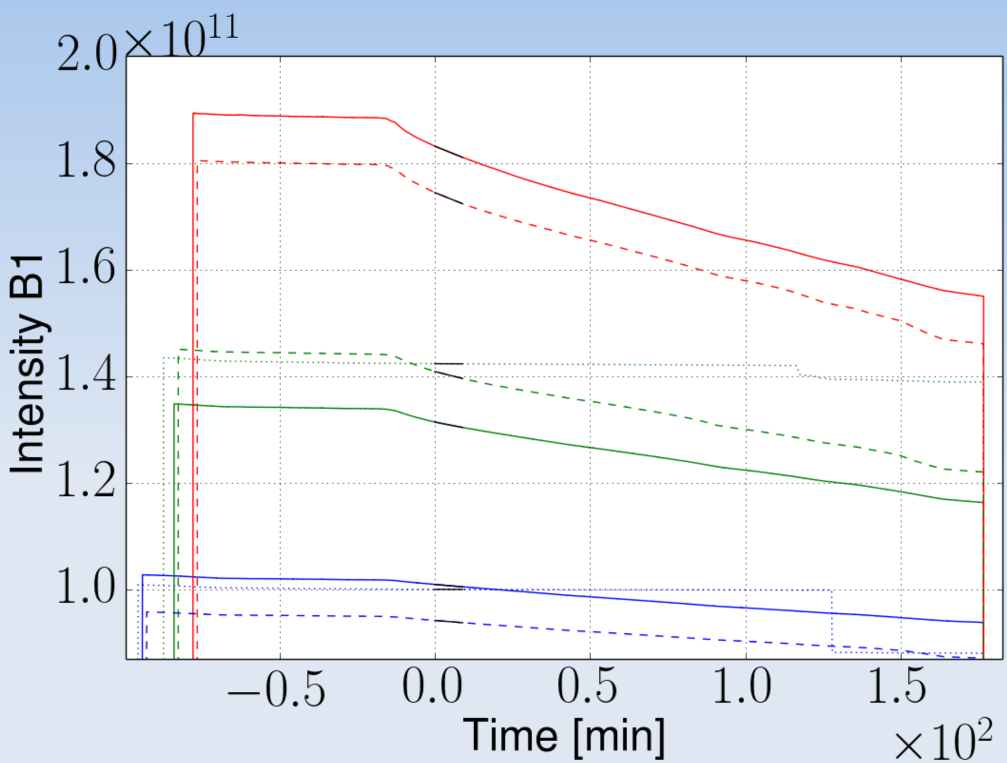


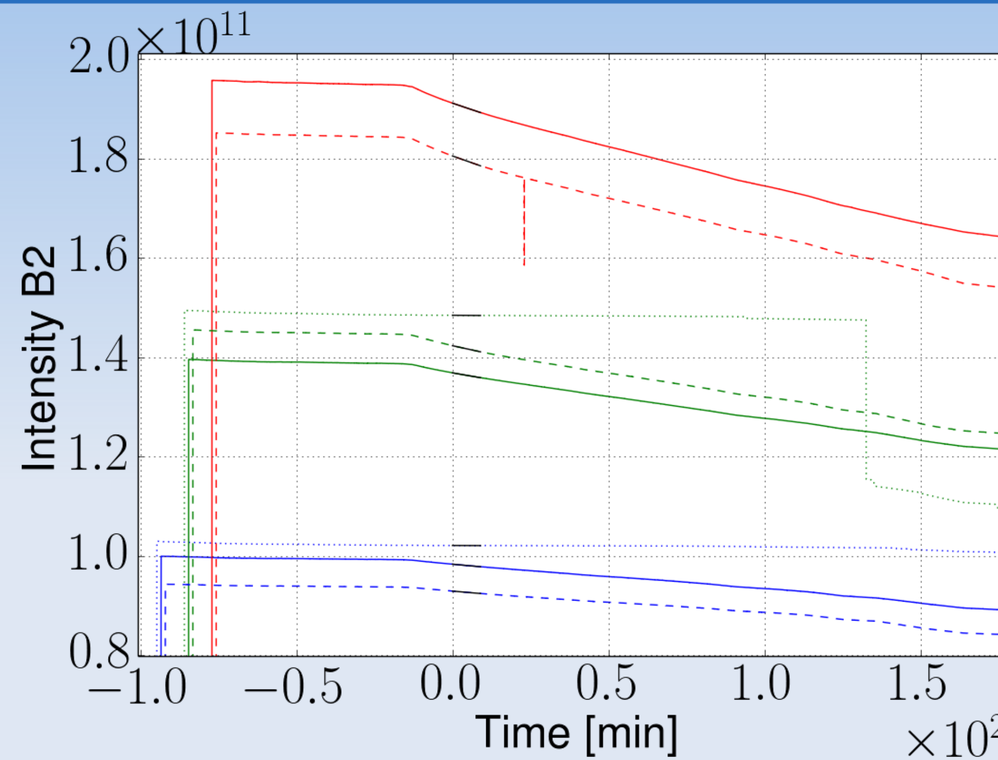
- Leveling with a transverse offset in both transverse planes avoids the tune shift normal to the diagonal

  → Need to study the impact on DA

BACKUP

Lifetime vs. burn-off during the high brightness MD





Solid : 50 turns / colliding — High
Dashed : 200 turns / colliding — Intermediate
Fine dashed : 50 turns / non-colliding — Low

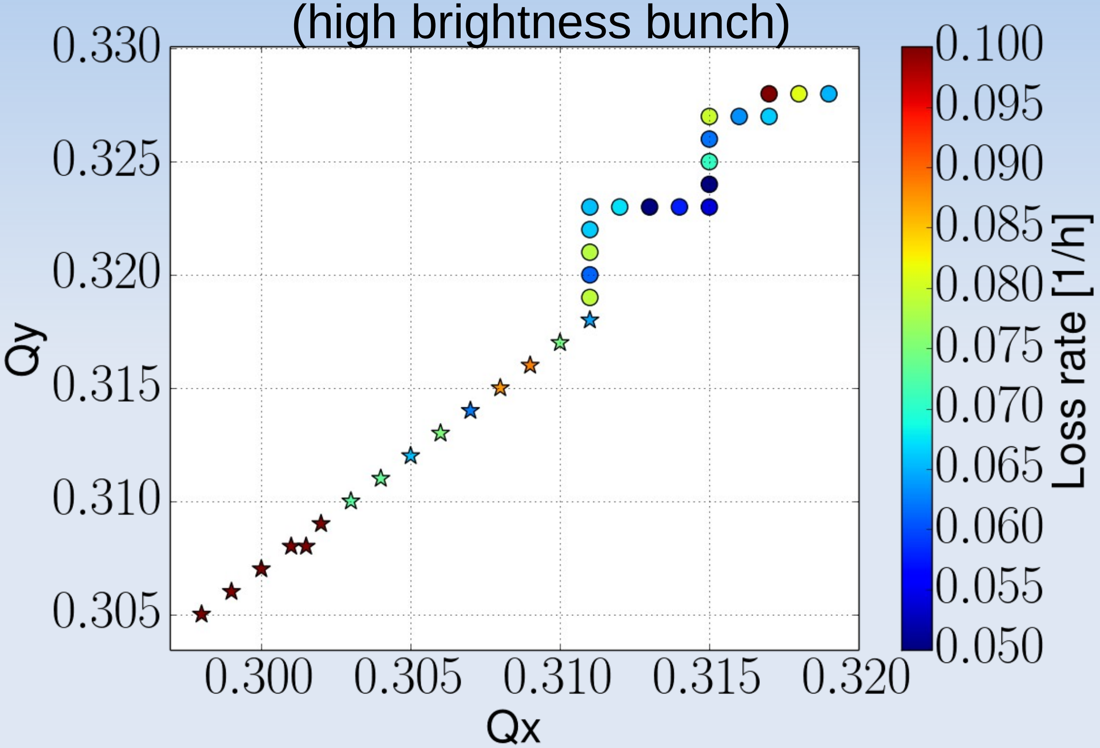
- Lifetime at the beginning of the study (highest beam-beam tune shift, without extra noise) is burn-off dominated

Tune shift	Measured loss rate [%/h]	Burn-off [%/h]
0.018±0.001	7.4±0.5	6.7±0.3
0.012±0.001	5.5±0.5	4.9±0.3
0.017±0.001	3.4±0.2	3.5±0.2

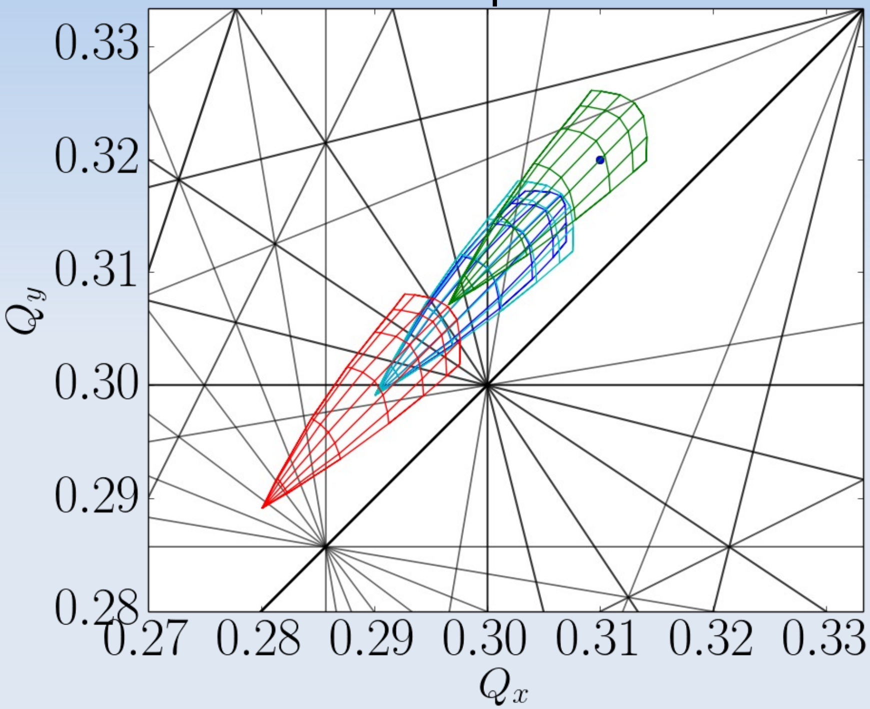
BACKUP

Tune scan with large beam-beam parameter

Beam 1 lifetime
(high brightness bunch)



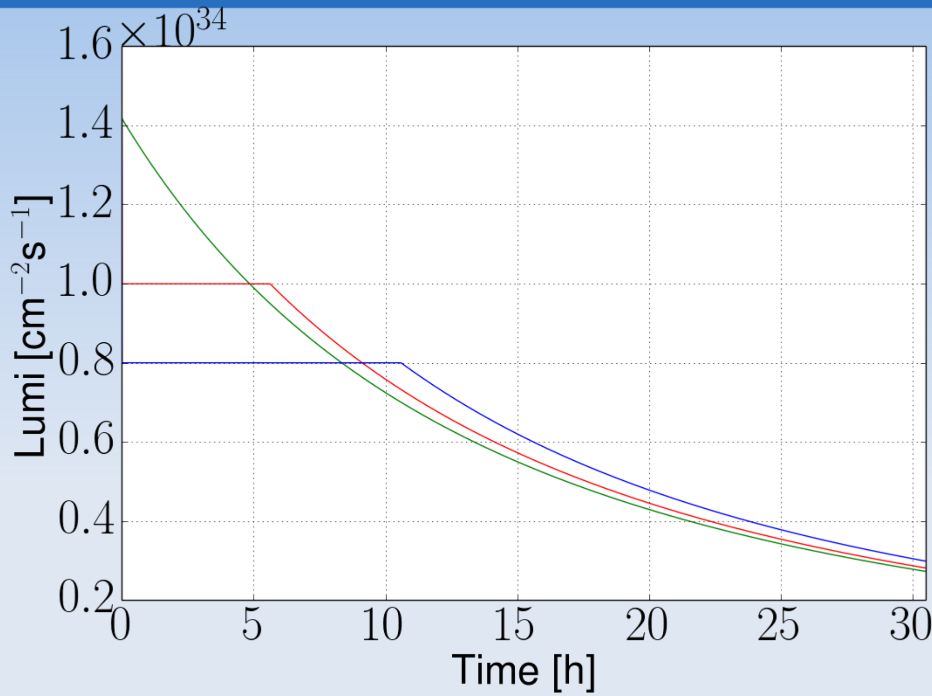
Resonances up to 14th order*

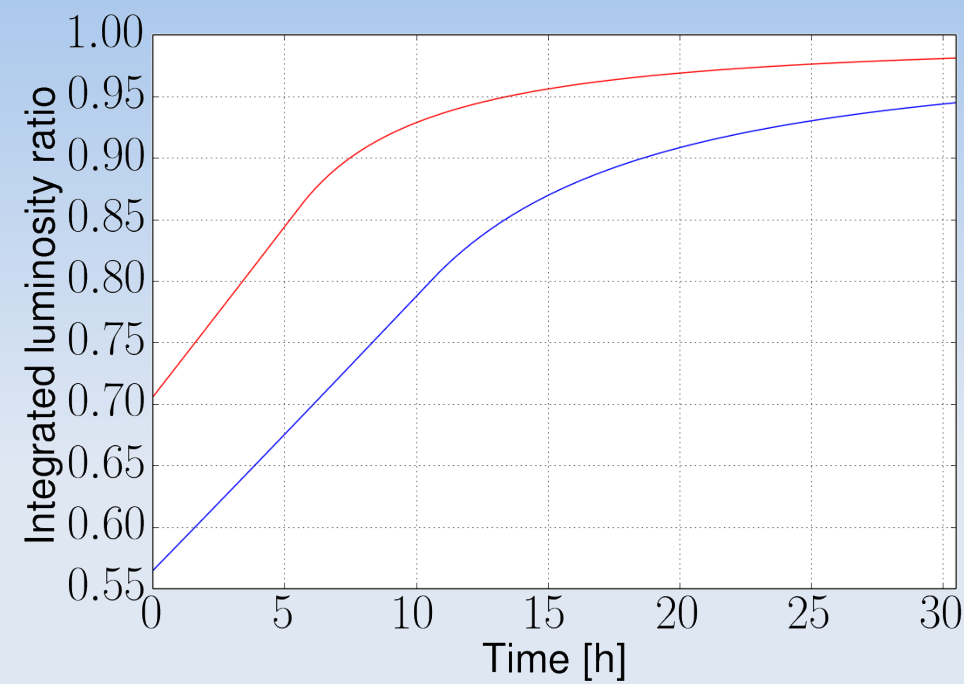


- B2 data is not representative due to issues with the RF loop during the MD
- Possibly the impact of the 10th and 14th order resonances on tail particles result in respectively the lower and higher limit for the tunes machine tune

BACKUP

Impact of levelling on performance





- A 'Simple' luminosity model (i.e. only burn off losses, constant transverse and longitudinal emittances) shows that the integrated luminosity of a levelled fill goes asymptotically to the non-levelled one

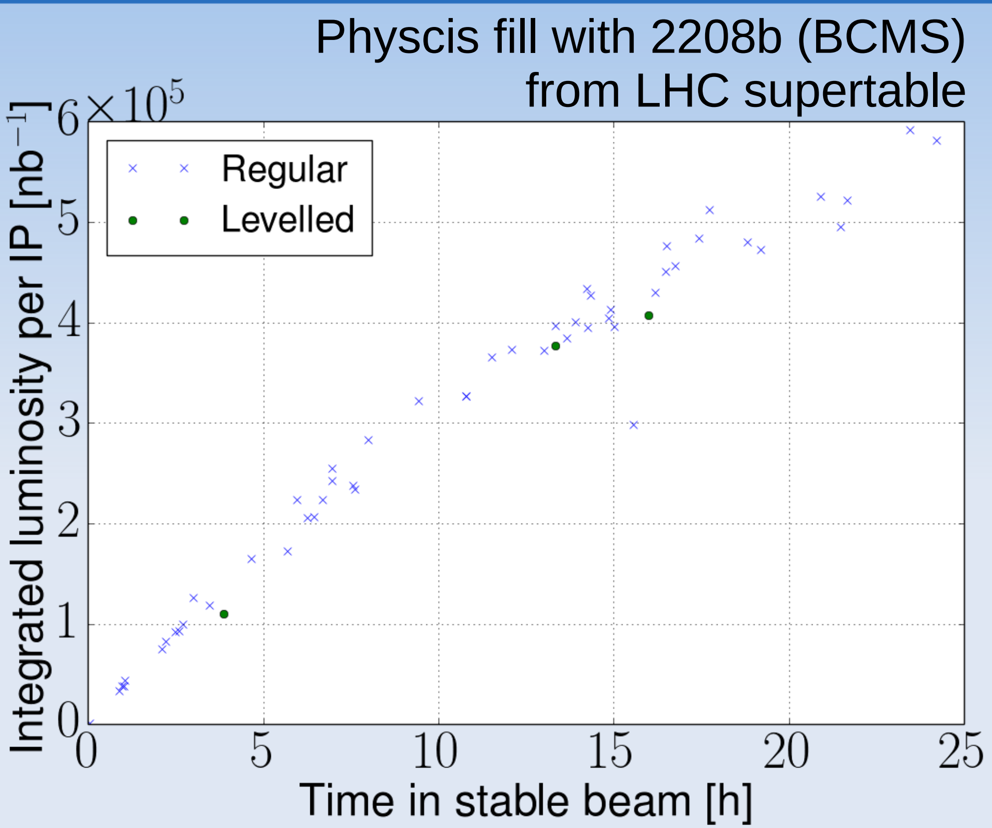
- However, in a reasonably short (i.e. optimal for overall performance) fill length, the collider performance is reduced :

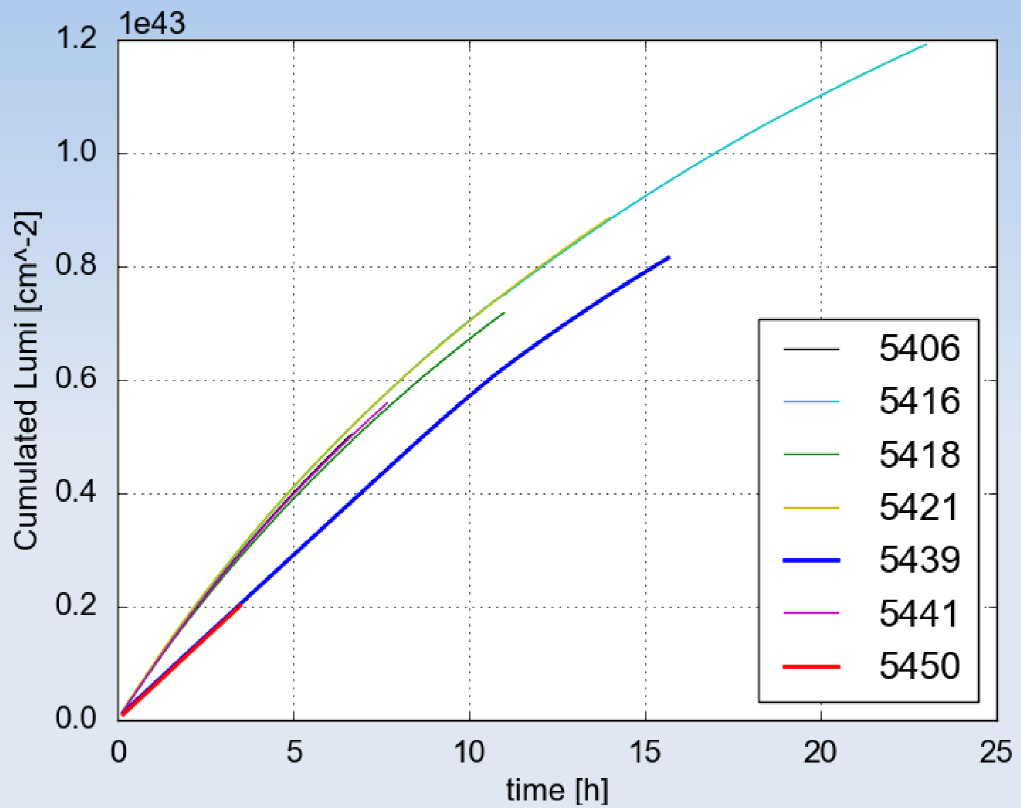
  *Assumed turn around : 4h

Peak Lumi. [10^{34} Hz/cm^2]	Levelled Lumi. [10^{34} Hz/cm^2]	Optimal fill time [h]	Average luminosity production* [fm^{-1}/day]	Loss due to levelling
1.4	1.4	10	0.63	0%
1.4	1.0	12	0.59	6%
1.4	0.8	15	0.53	16%

BACKUP

Measured integrated luminosity

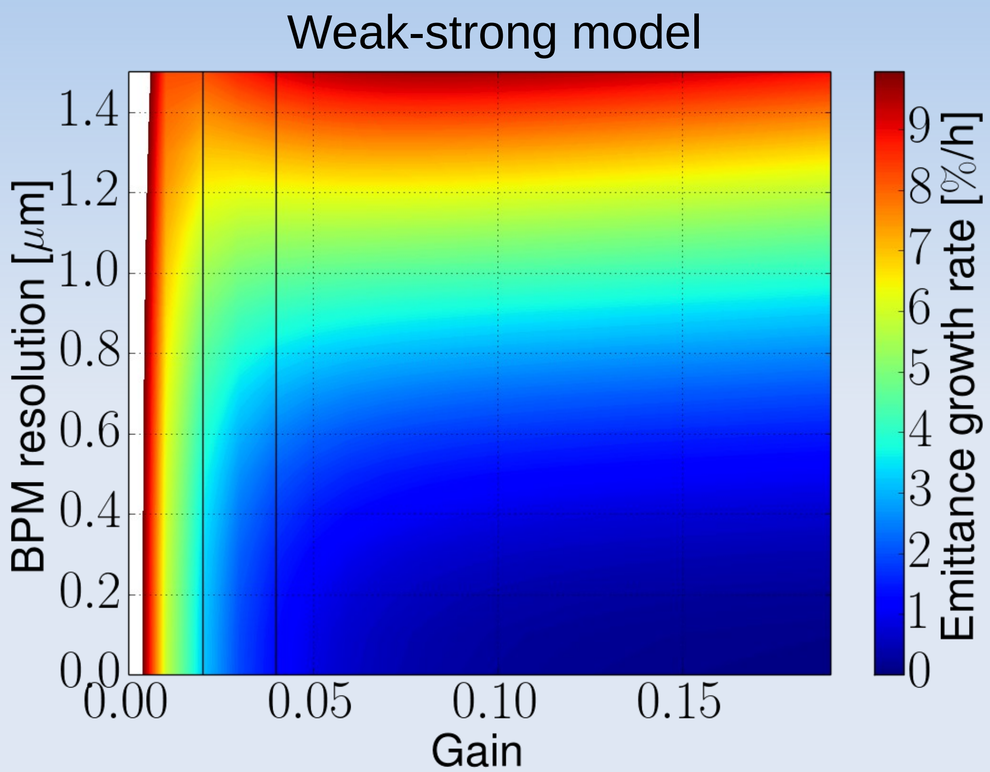




- Levelled fill systematically performed less than the average regular fill
  - The long fill levelled at 0.8E34 has about 7% less integrated luminosity wrt to the average regular fill of the same length (~10% expected)

BACKUP

Mitigation of the emittance growth with the ADT



- For large intrinsic noise of the ADT (modelled by the BPM resolution), low gain minimise the emittance growth
- For low intrinsic noise, the effect of other external sources of noise are mitigated by the ADT