CERN

Institute for Basic Science

ICFA

HiLumi
HL-LHC PROJECT

High-Intensity and High-Brightness Hadron Beams, Daejeon, Korea, 17-22 June, 2018

Beam-Beam Studies in Present and Future Hadron Colliders

Y. Papaphilippou

with contributions of

G. Arduini, S. Arsenyev, H. Bartosik, A. Bertarelli, O. Brüning, X. Buffat, F. Cerutti, R. de Maria, S. Fartoukh, S. Furuseth, G. Iadarola, N. Karastathis, S. Kostoglou, D. Pellegrini, A. Poyet, A. Rossi, L. Rossi, K. Skoufaris, D. Schulte, G. Sterbini, F. Zimmermann (CERN),

M. Fitterer (ex-FNAL), A. Valishev (FNAL), A. Patapenka (NIU), D. Shatilov (BINP) D. Kaltchev (TRIUMF),

J. Barranco, T. Pieloni, C. Tambasco (EPFL)

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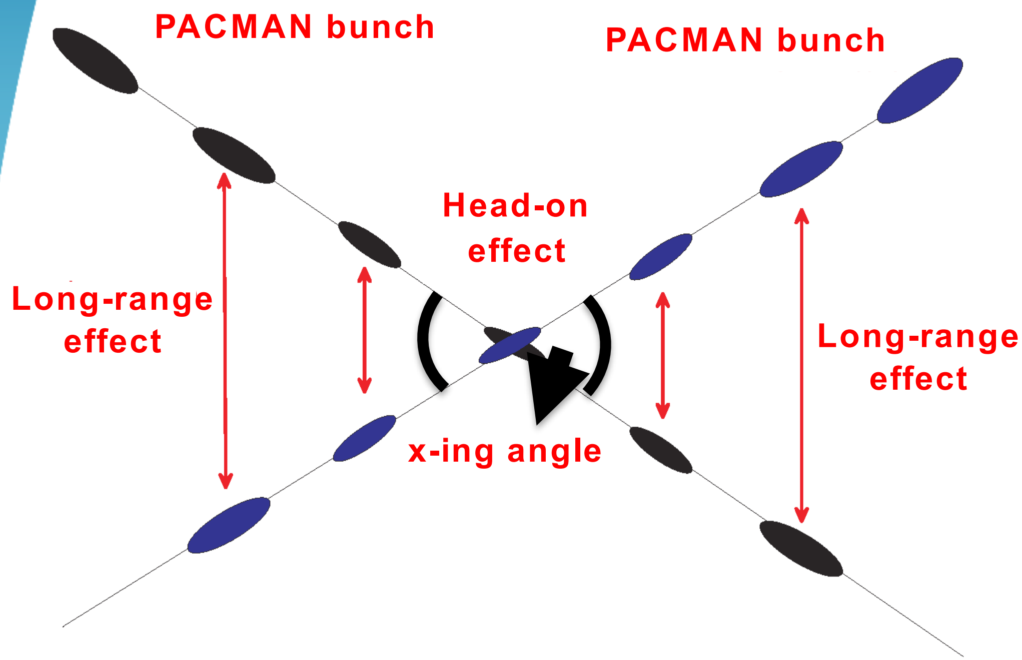
Outline

- **Incoherent beam-beam** effects
  - Head-on vs long range
- Optimising **beam lifetime** in the LHC
  - Correlation of **Dynamic Aperture** (DA) with lifetime
    - Measurements and simulations
  - Multi-parametric **DA scans**
    - **Working point** optimization, **chromaticity** sextupoles and Landau **octupoles**
    - **Crossing angle** anti-levelling
    - Tune **modulation**
- Dependence of **HL-LHC DA** during levelling on various **parameters**
    - **Adaptive x-ing angle** operational scenario
    - Impact of **multi-pole errors**
- **BBLR compensation** simulation and experiments
  - DC **wires** and **octupoles**
- Beam-beam studies for **FCChh** and **HE-LHC**

Beam-Beam interaction

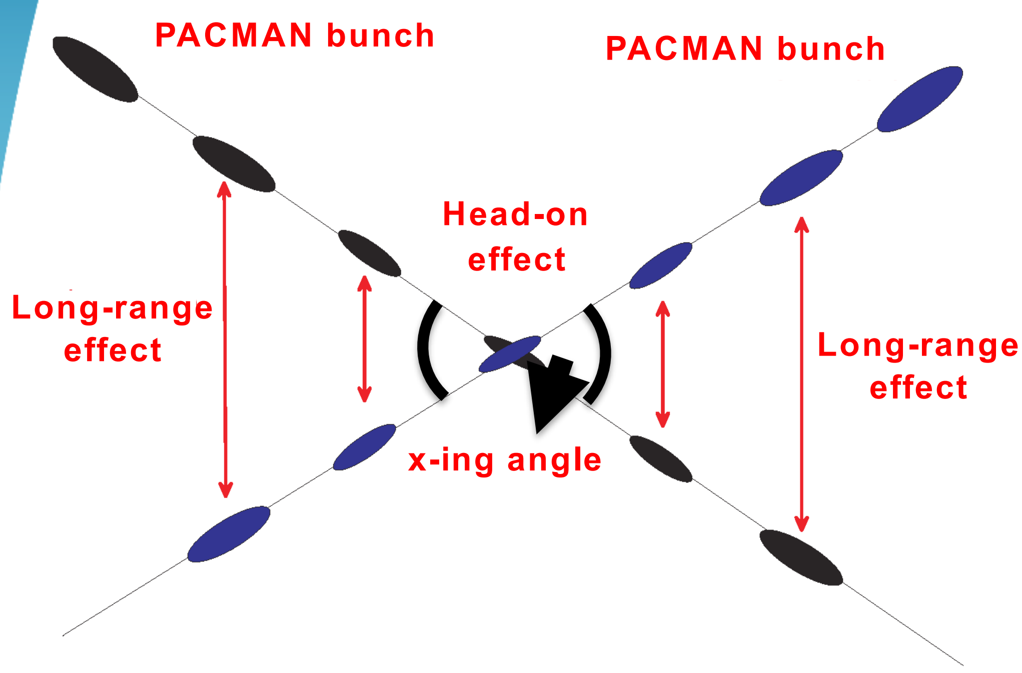


- Beam-beam kick (4D - round beams)

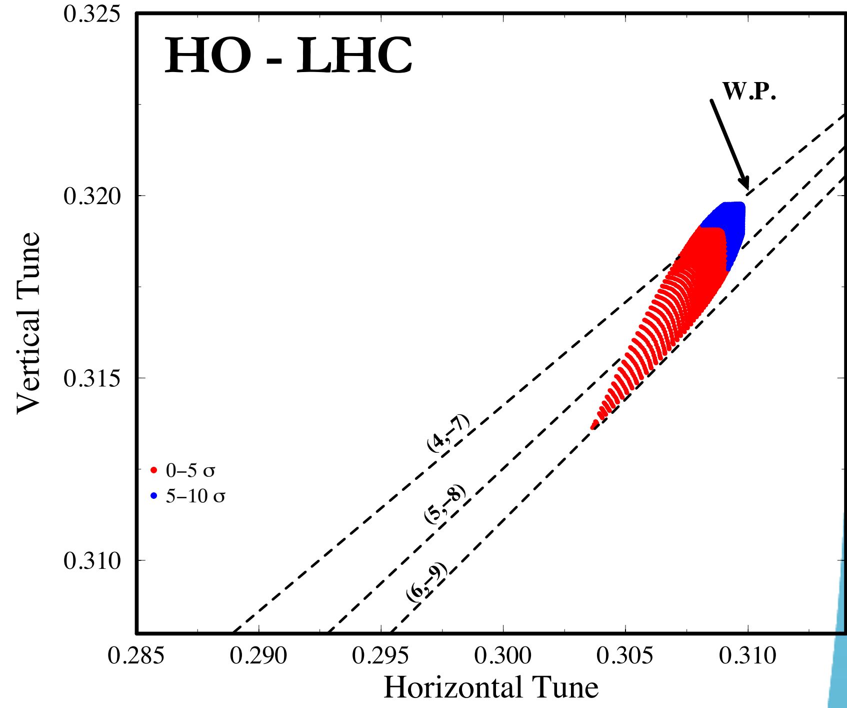
$$\Delta\{x',y'\} = -\frac{2N_b r_p}{\gamma}\frac{\{X,Y\}}{X^2+Y^2}(1-e^{-\frac{X^2+Y^2}{2\sigma^2}})$$

with $X = x + x_c, \quad Y = y + y_c$ beam separation

Beam-Beam for the LHC



YP and F.Zimmermann, PRSTAB, 1999



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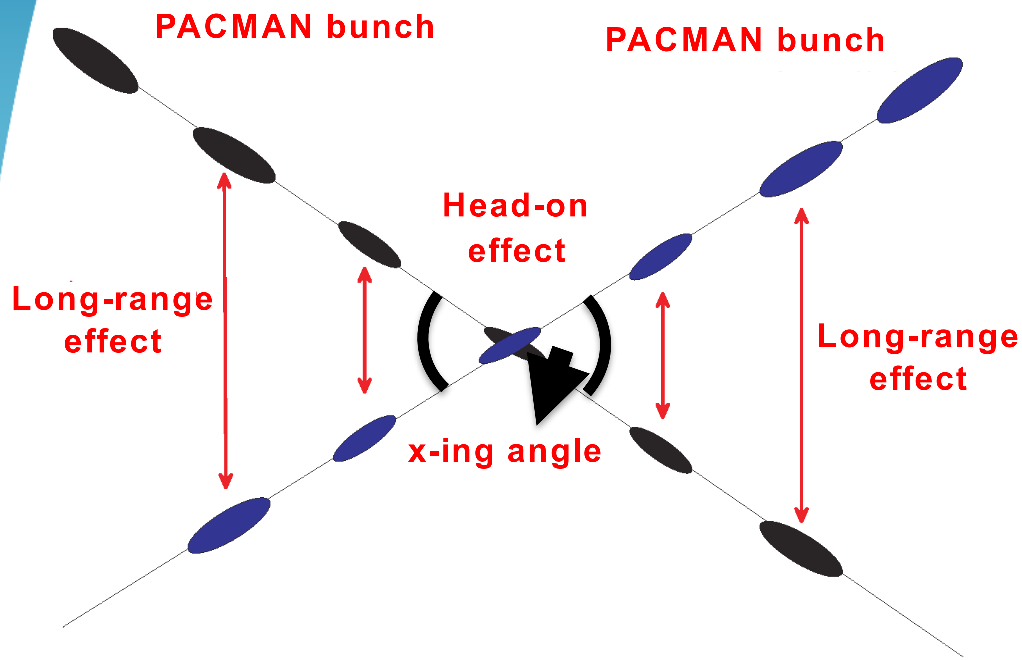

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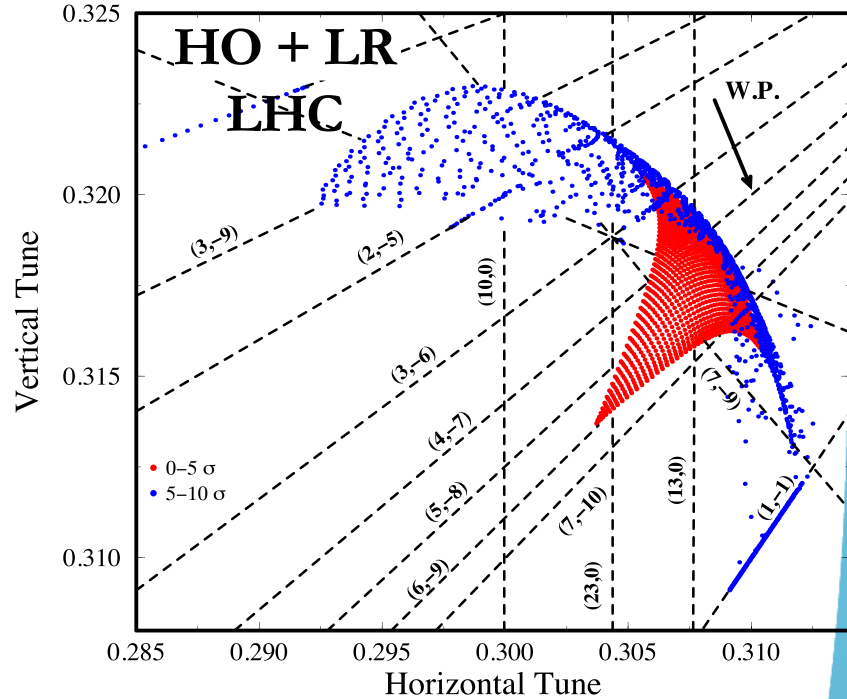

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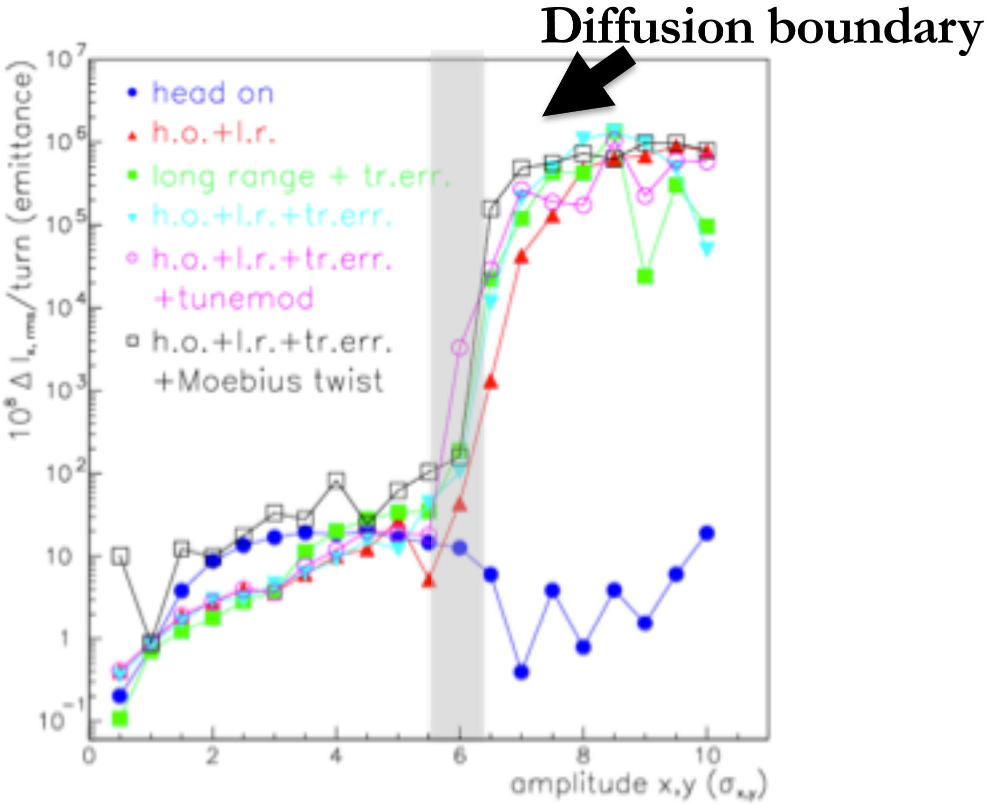
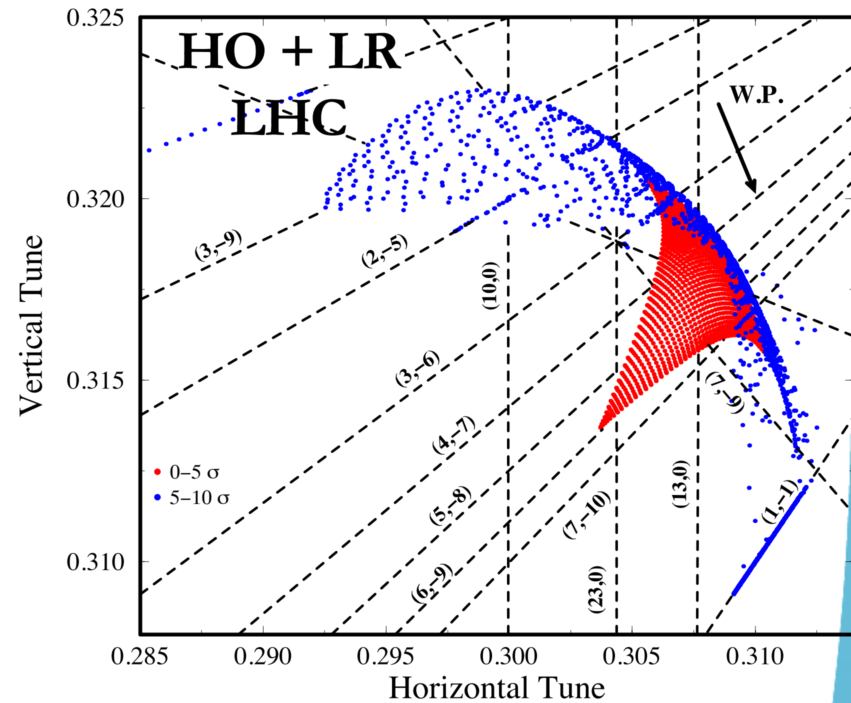


YP and F.Zimmermann, PRSTAB, 1999



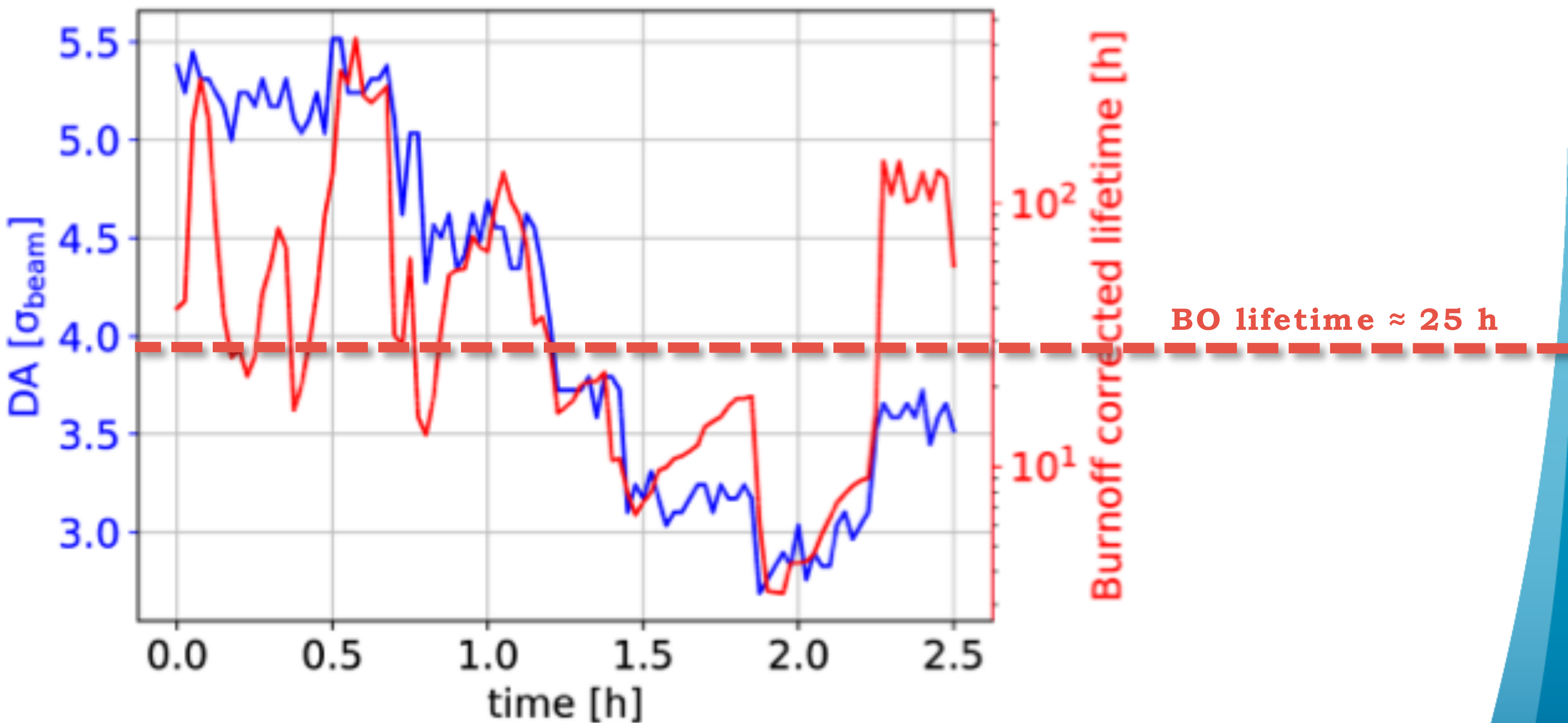
- **Beam-beam long-range** (BBLR) effect known to be a major limitation of the DA for the nominal LHC, at collision, since the design phase

Correlation of Dynamic Aperture with beam-lifetime from LHC experience

G. Iadarola, N. Karastathis, S. Kostoglou,
Y. Papaphilippou, **D. Pellegrini**, G. Sterbini (CERN)

Lifetime vs DA

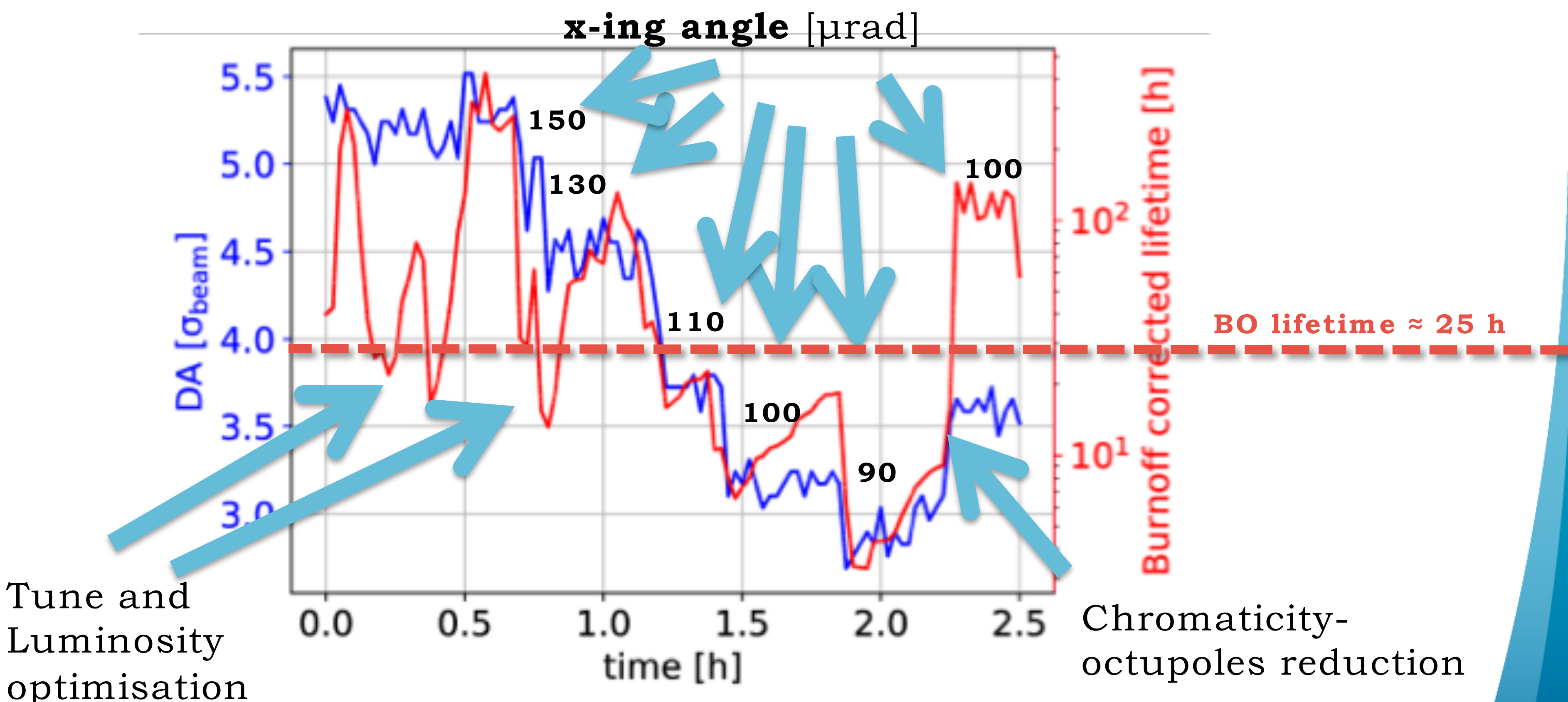
- Correlate **simulated DA** and measured **burn-off (BO) corrected lifetime** through x-ing angle scan **experiments** in the LHC



D. Pellegrini et al, Evian 2017

Lifetime vs DA

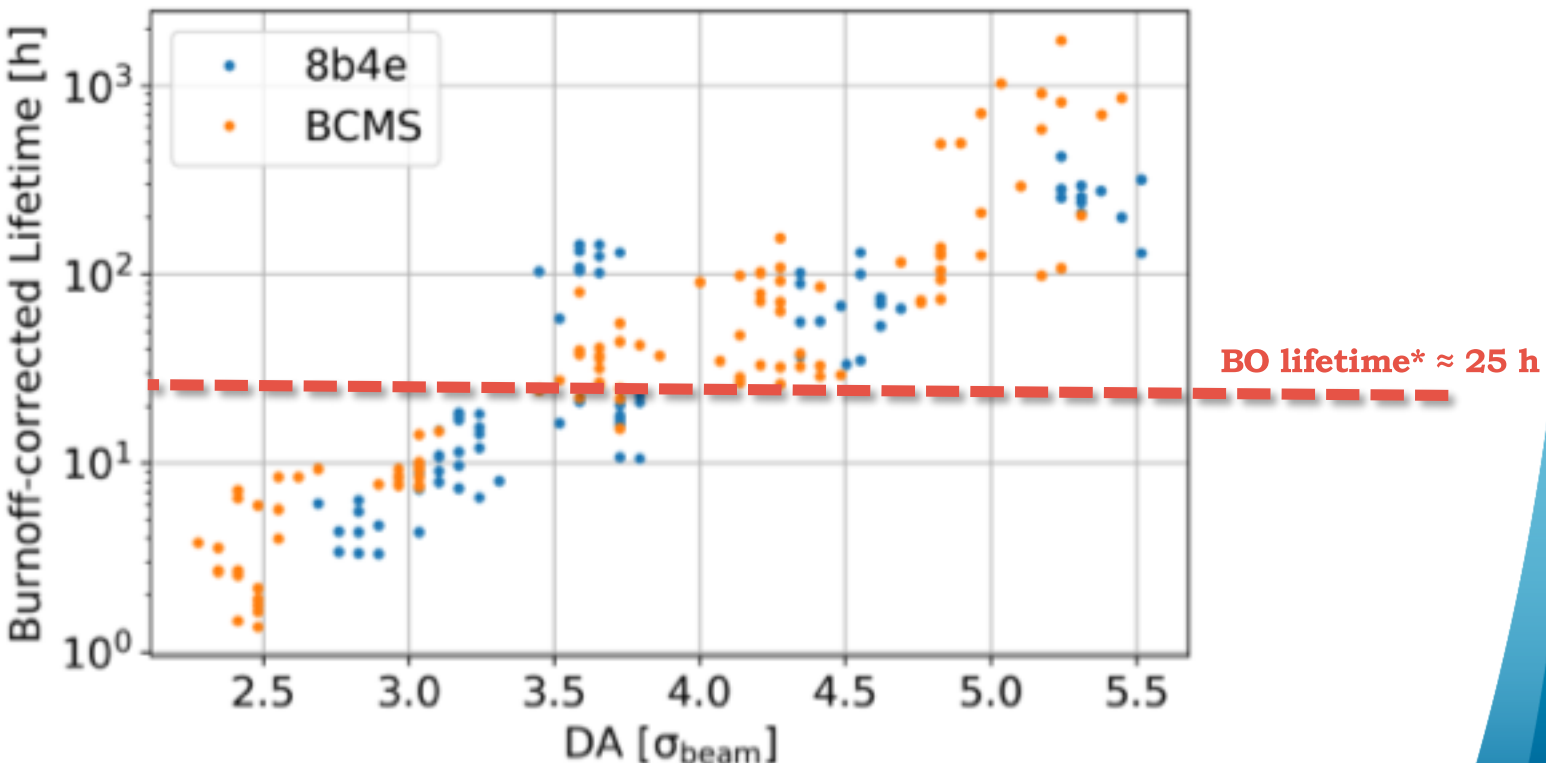
- Correlate **simulated DA** and measured **burn-off (BO) corrected lifetime** through x-ing angle scan **experiments** in the LHC
- Beam current decay follows $\frac{I(t)}{I_0} = -e^{-\frac{DA^2(t)}{2}}$ M. Giovannozzi, PRST-AB, 2012



D. Pellegrini et al, Evian 2017

DA vs Lifetime

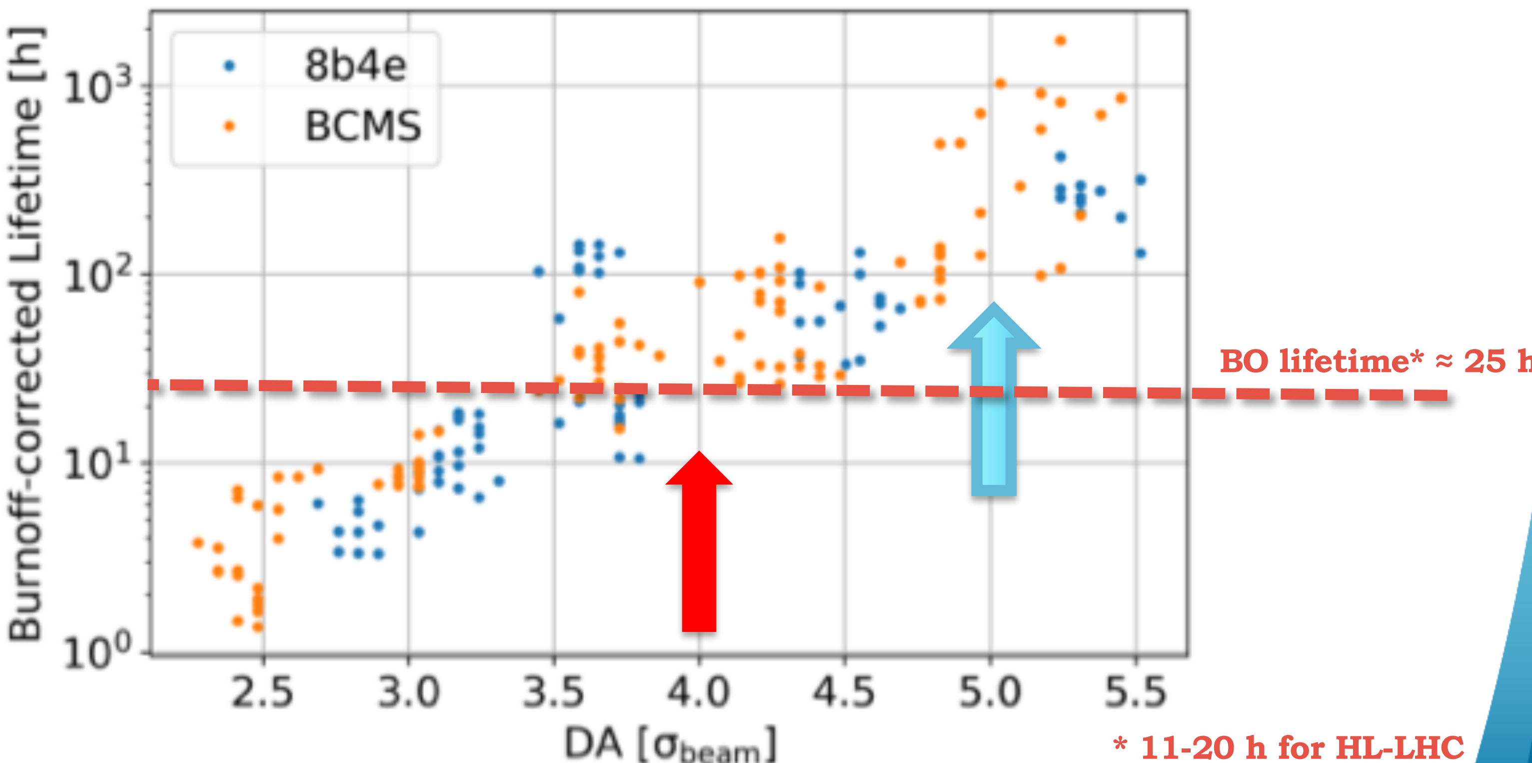
- Good **agreement** between high-intensity **8b4e** and **BCMS** (non-pacman):



D. Pellegrini et al, Evian 2017

DA vs Lifetime

- Good **agreement** between high-intensity **8b4e** and **BCMS** (non-pacman):
  - **4 σ:** corresponds to **lifetime** close to **BO**
  - **5 σ:** grants **lifetimes** above **~100 h**: **Minimum target** for **LHC operation**
  - **6 σ: target** for **studies** (HL-LHC) in presence of larger **uncertainties** (e.g. multi-pole errors, modulation, e-cloud,…)



* 11-20 h for HL-LHC

D. Pellegrini et al, Evian 2017

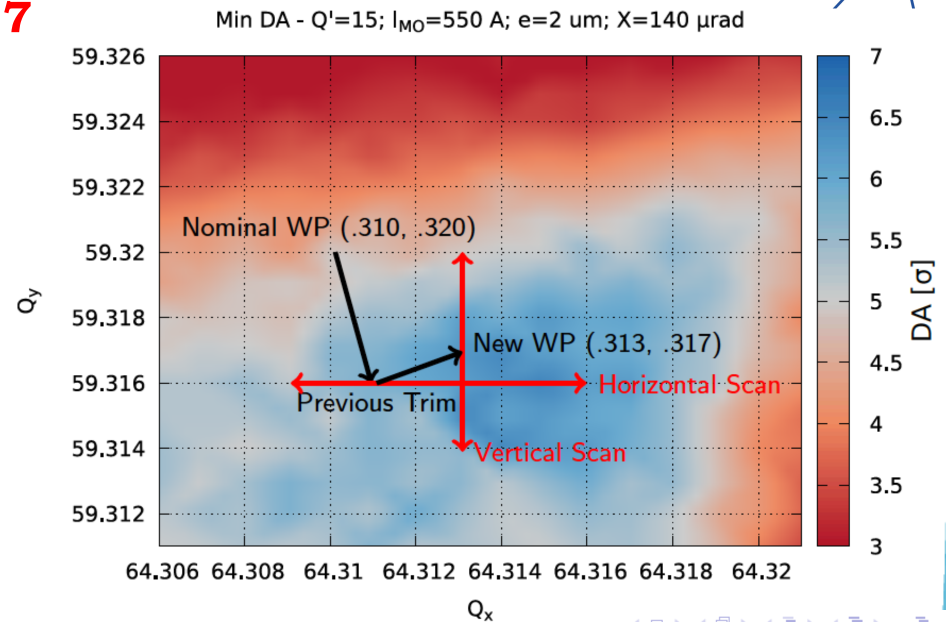
Multi-parametric DA scans for LHC

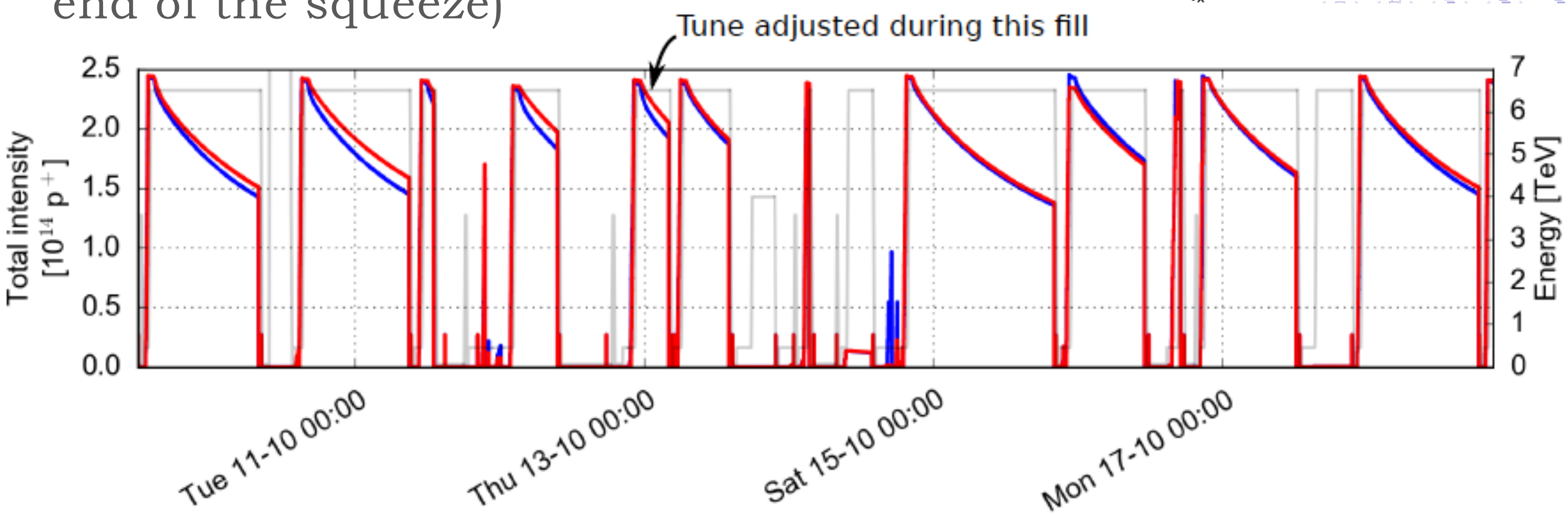
G. Iadarola, **N. Karastathis**, S. Kostoglou,
Y. Papaphilippou, **D. Pellegrini**, G. Sterbini (CERN)

DA guiding machine performance

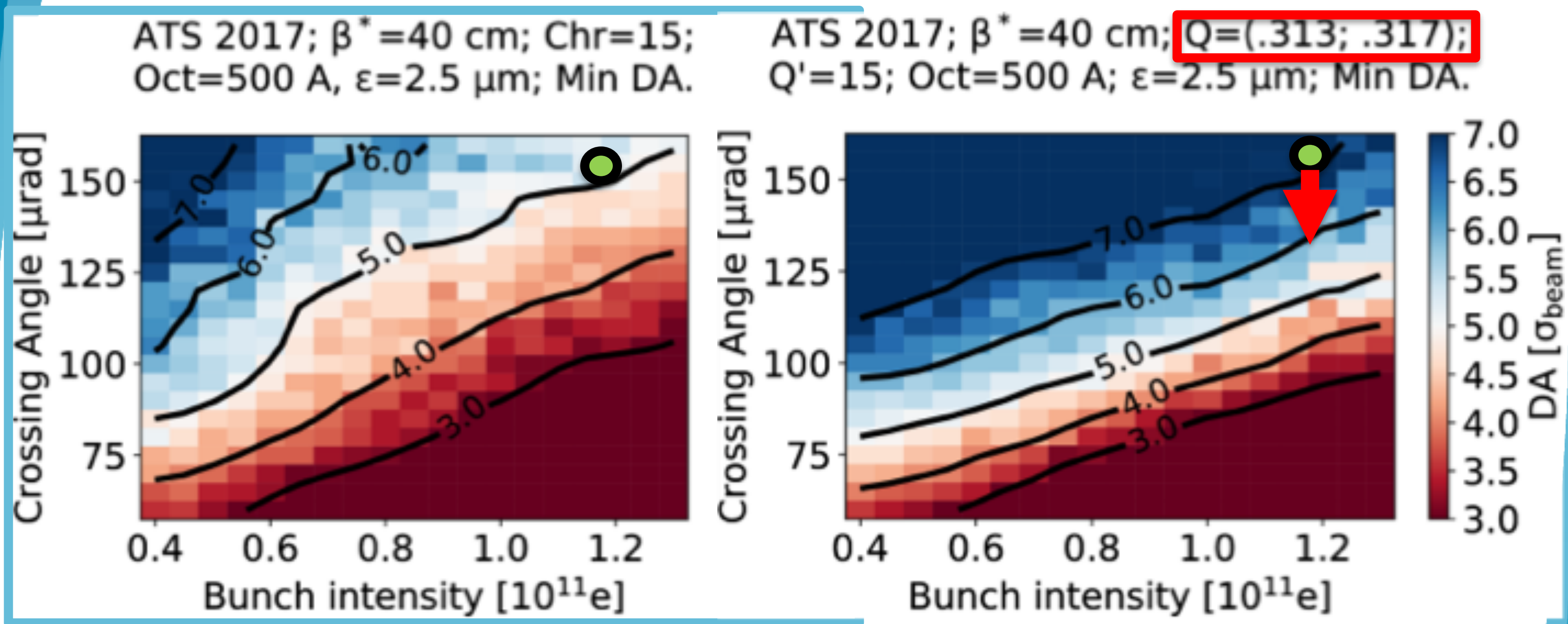
D. Pellegrini, et al., J. of Phys, 2017

- DA highly **sensitive** to **tune** (**1-2 σ** lost a few **10^{-3}** of tune-shift)
- First tests (guided by DA simulation) performed at end of **2016** with immediate **lifetime improvement**
- Tune optimisation **routinely** applied in Run II (even at the end of the squeeze)





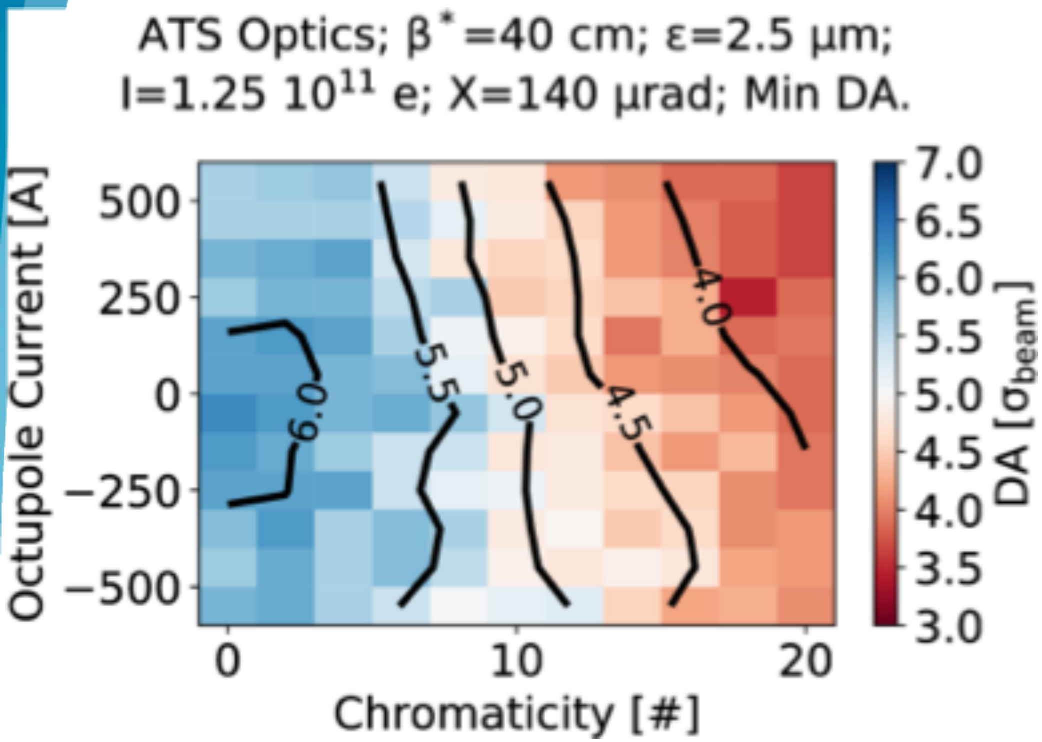
Impact of WP choice at collision



- Optimised tunes allow **30 μrad** reduction of half crossing angle (**2 σ** BB separation @ 40 cm) -> **10% increase** in **peak luminosity**

Chromaticity and Octupoles

D. Pellegrini, et al., J. of Phys, 2017

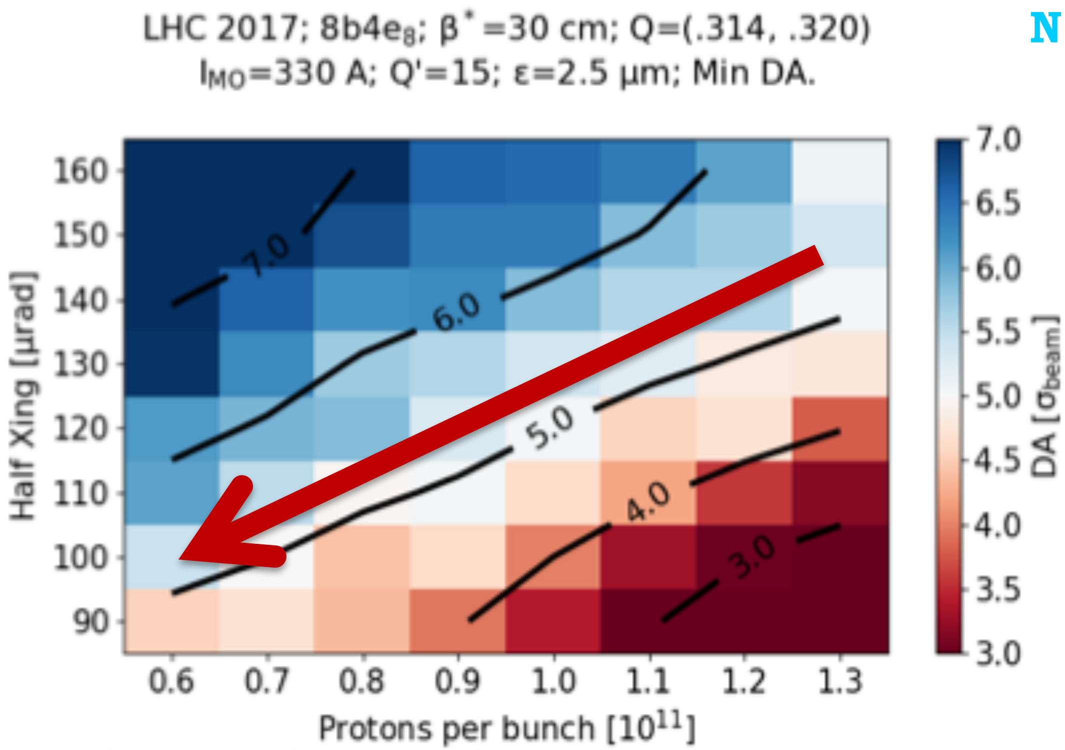


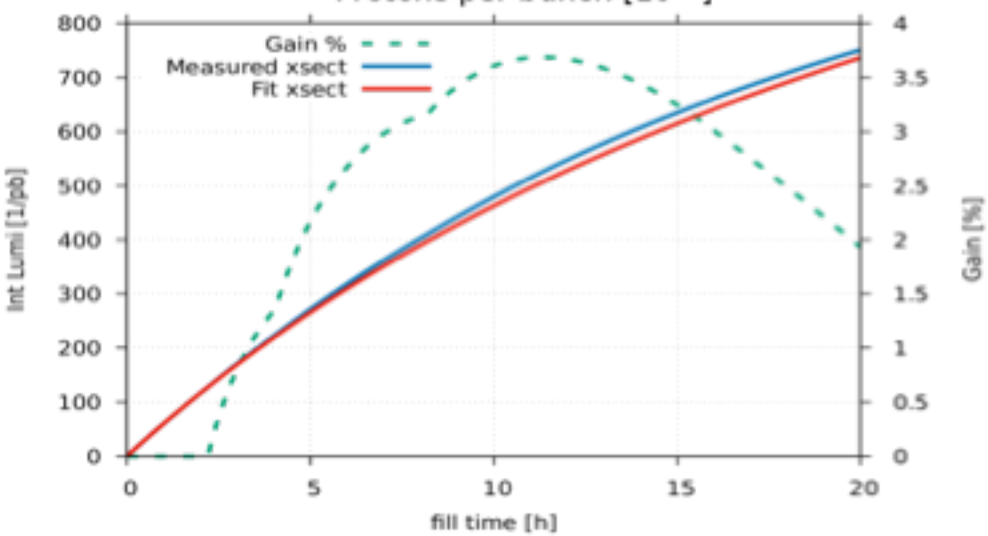
- **1 σ DA reduction** for **10 units** of chromaticity
- **Smaller impact** (< **0.5 σ**) of **octupoles** in the range 300-500 A
  - Demonstrated **lifetime improvement** for telescope-enhanced (ATS) **negative octupoles**

- **Reduce** steadily **chromaticity** (and **octupoles**) at **collision**, as allowed by stability margins, while improving performance

Crossing angle "anti-levelling"

N. Karastathis et al. IPAC 2018





- Follow **intensity decay** with the **crossing** (x-ing) **angle** along the iso-DA curve
- Reduce geometric factor -> gain a few % of integrated **luminosity**
- Careful **tuning** for not introducing extra losses
  - **Steps** too aggressive or too early
  - Emittance **growth**

Impact of tune modulation

H. Bartosik, G. Iadarola, **S. Kostoglou**,
Y. Papaphilippou, G. Sterbini (CERN)

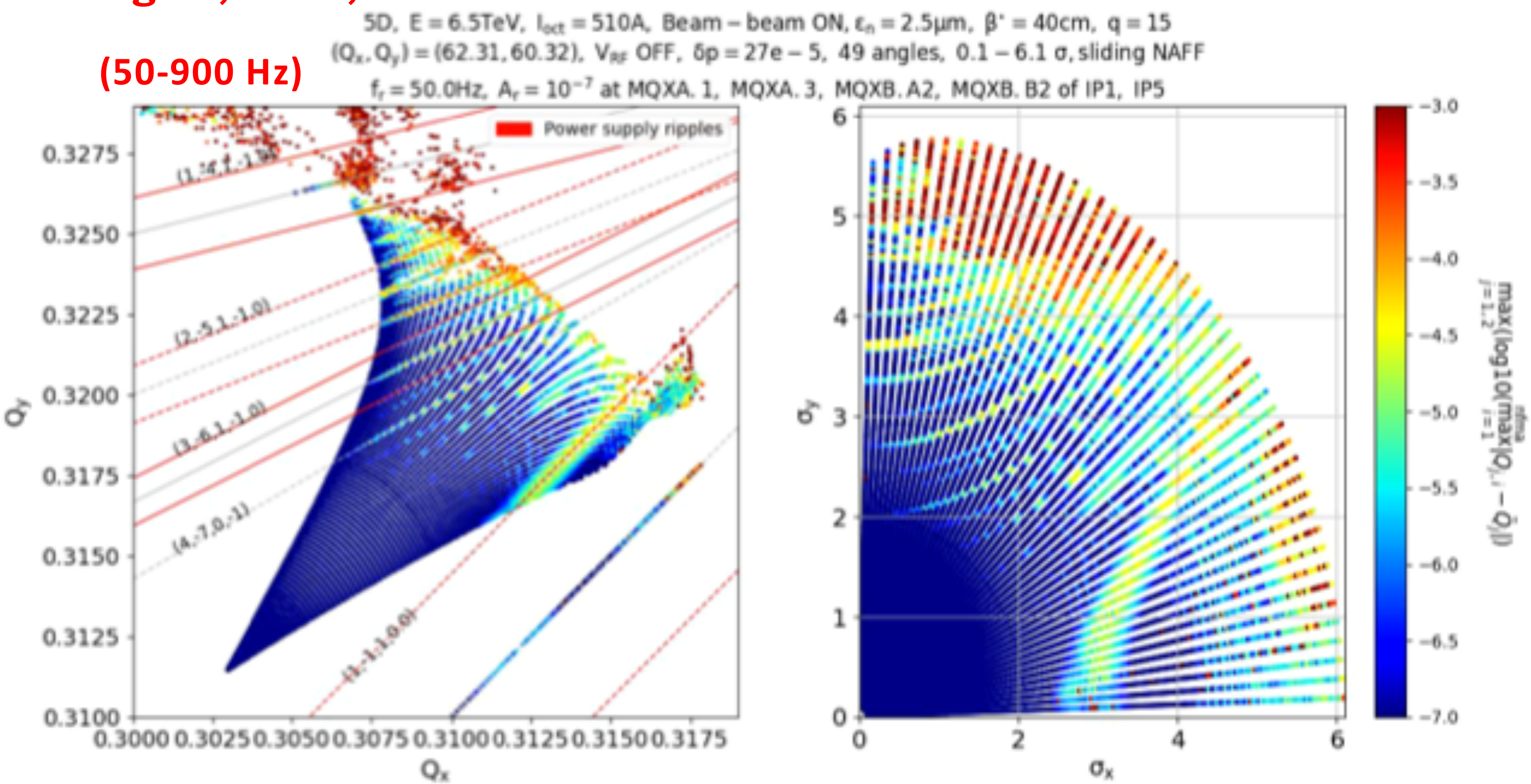
Impact of tune modulation

- Tune modulation induced by **power supply ripple** in inner triplet quads (IR1/5)
- Large β-functions increase the sensitivity to non-linear effects, different **modulation frequencies** enhance different **resonances**

$$aQ_x + bQ_y + c\frac{f_{modulation}}{f_{revolution}} = k \text{ for } a, b, c, k \text{ integers}$$

S. Kostoglou, et al., 2018

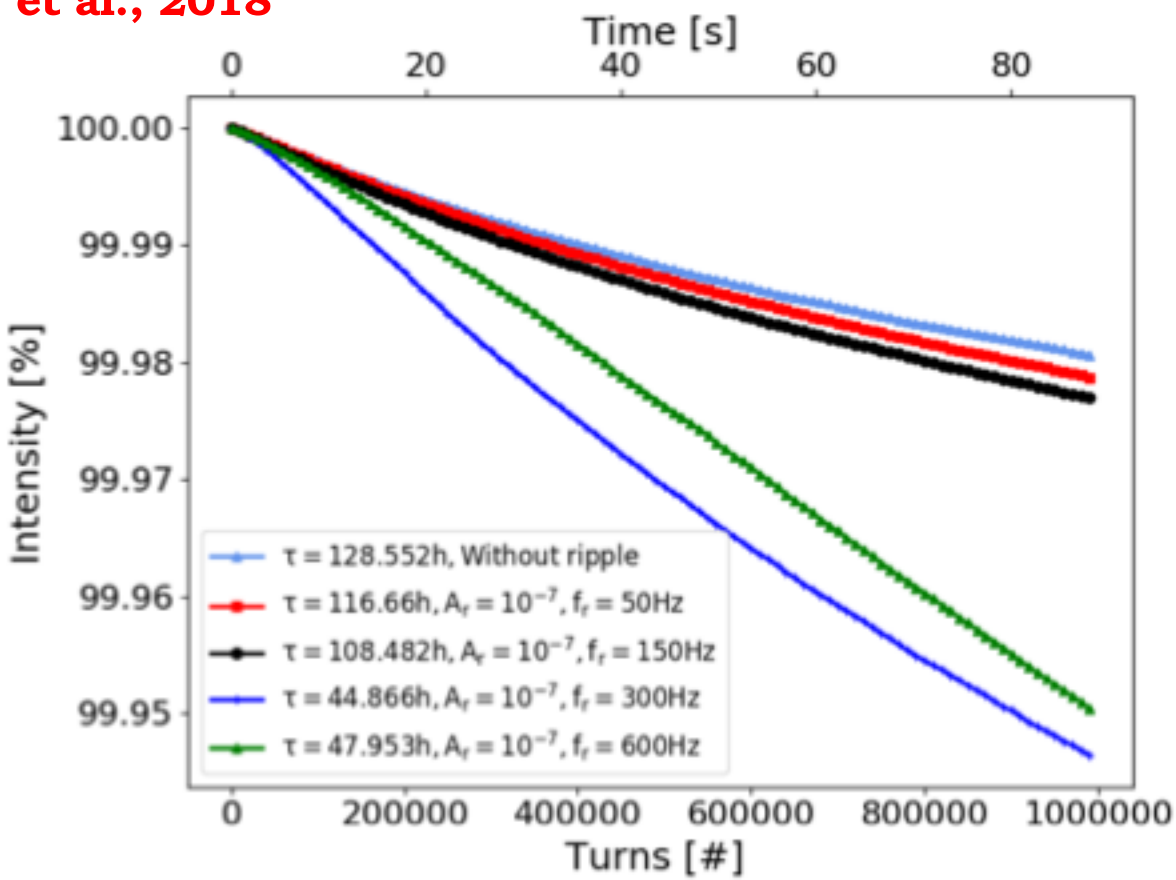
(50-900 Hz)



Impact of tune modulation

- SIXTRACK simulations show important lifetime degradation for **300** and **600 Hz** modulation frequencies, as inferred by FMAs

S. Kostoglou, et al., 2018



Dependence of HL-LHC DA during levelling on various parameters

G. Arduini, F. Cerruti, R. De Maria, S. Fartoukh,
N. Karastathis, Y. Papaphilippou,
D. Pellegrini (CERN), D. Kaltchev (TRIUMF)

HiLumi HL-LHC PROJECT

Adaptive Crossing Angle Levelling Scenario

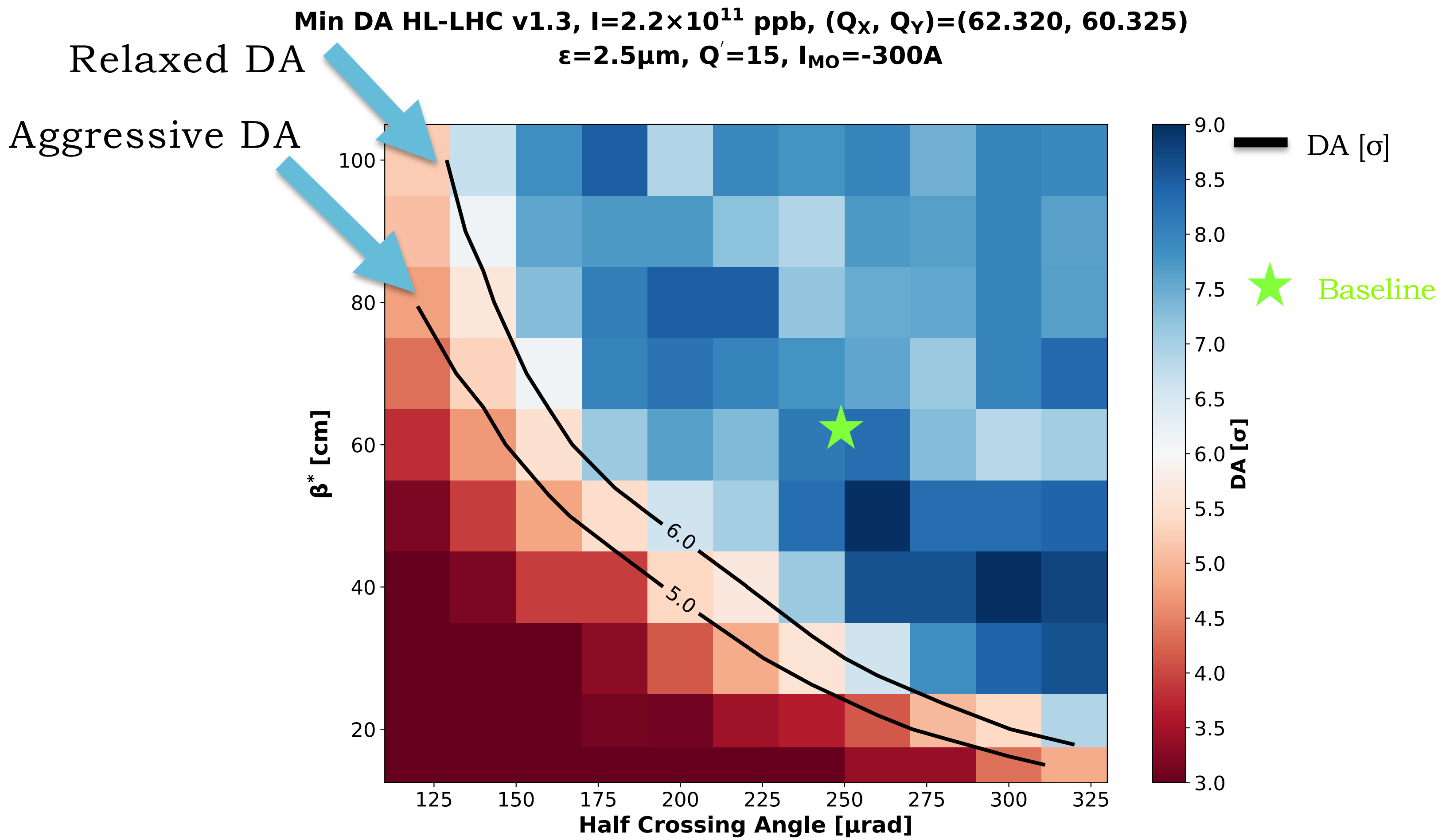
- **HL-LHC baseline** operational scenario
  - **β* levelling** during intensity decay at $5 \cdot 10^{34}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$ (**nominal**) or $7.5 \cdot 10^{34}\mathrm{s}^{-1}\mathrm{cm}^{-2}$ (**ultimate**)
  - **Fixed** half **x-ing angle** at **250 µrad**

Adaptive Crossing Angle Levelling Scenario

- **HL-LHC** **baseline** operational scenario
  - **β* levelling** during intensity decay at $5 \cdot 10^{34}\ \mathrm{s^{-1}cm^{-2}}$ (**nominal**) or $7.5 \cdot 10^{34}\mathrm{s^{-1}cm^{-2}}$ (**ultimate**)
  - **Fixed** half **x-ing angle** at **250 μrad**
- **Adaptive x-angle** levelling scenario by using **DA margin** to enhance performance
  - As β*/intensity evolves for a certain levelled **luminosity**, trace alternative **x-ing angle** path corresponding to a **DA target**
    - **"Relaxed"** at **6 σ**
    - **"Aggressive"** at **5 σ**

N. Karastathis et al, IPAC 2018

Start of levelling: 2.2 x 10^{11} ppb



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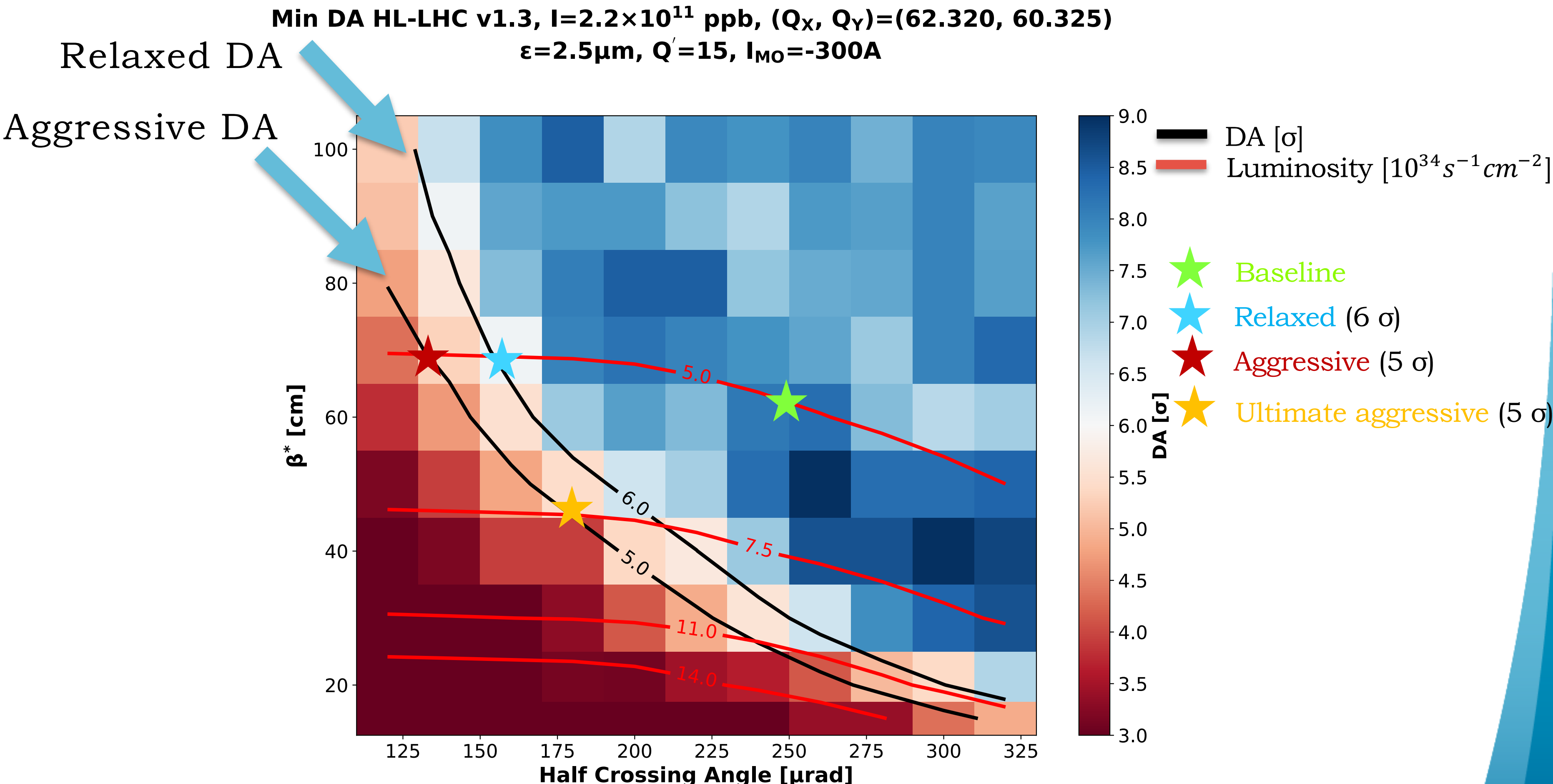
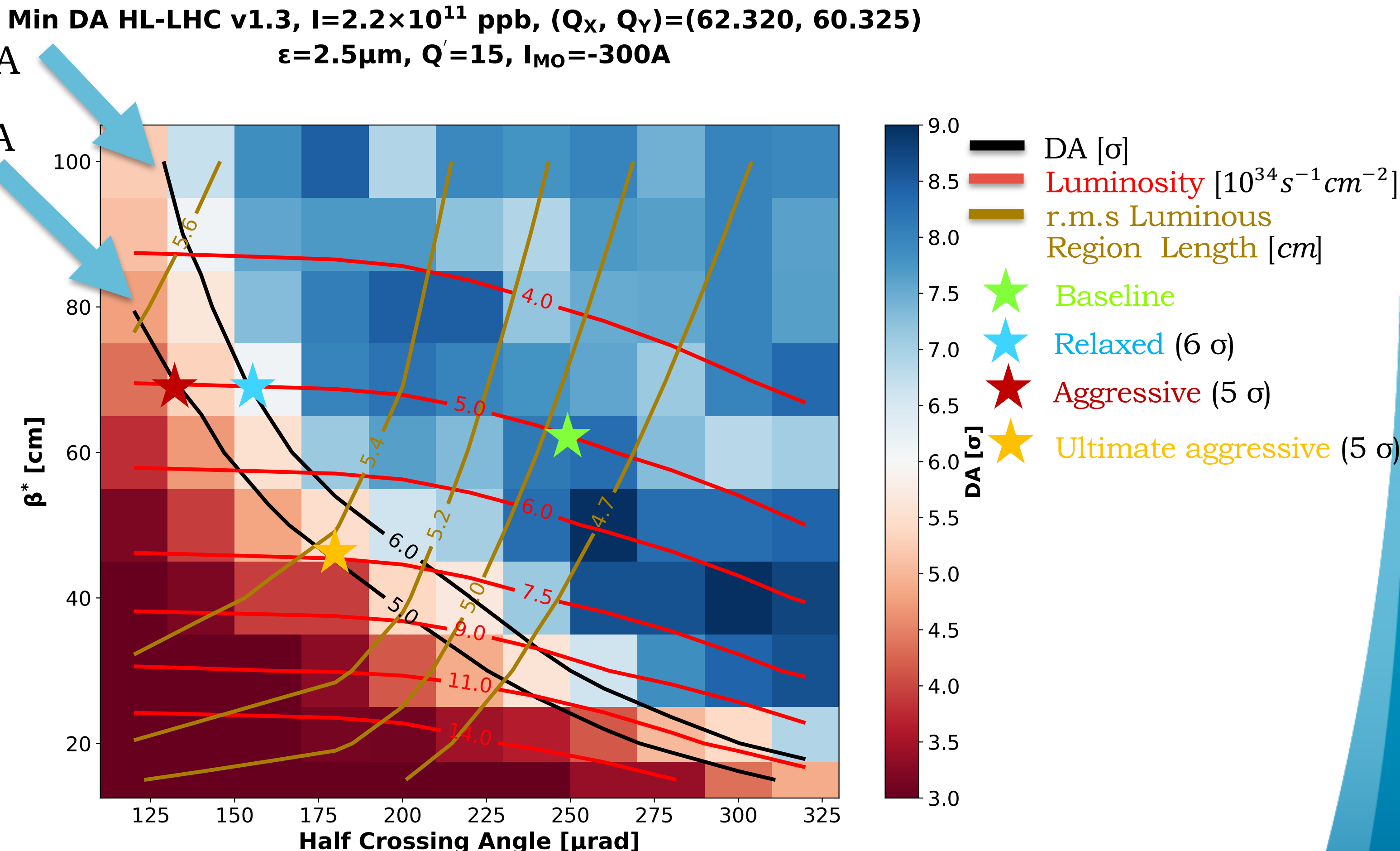


Start of levelling: 2.2 x 10^{11} ppb

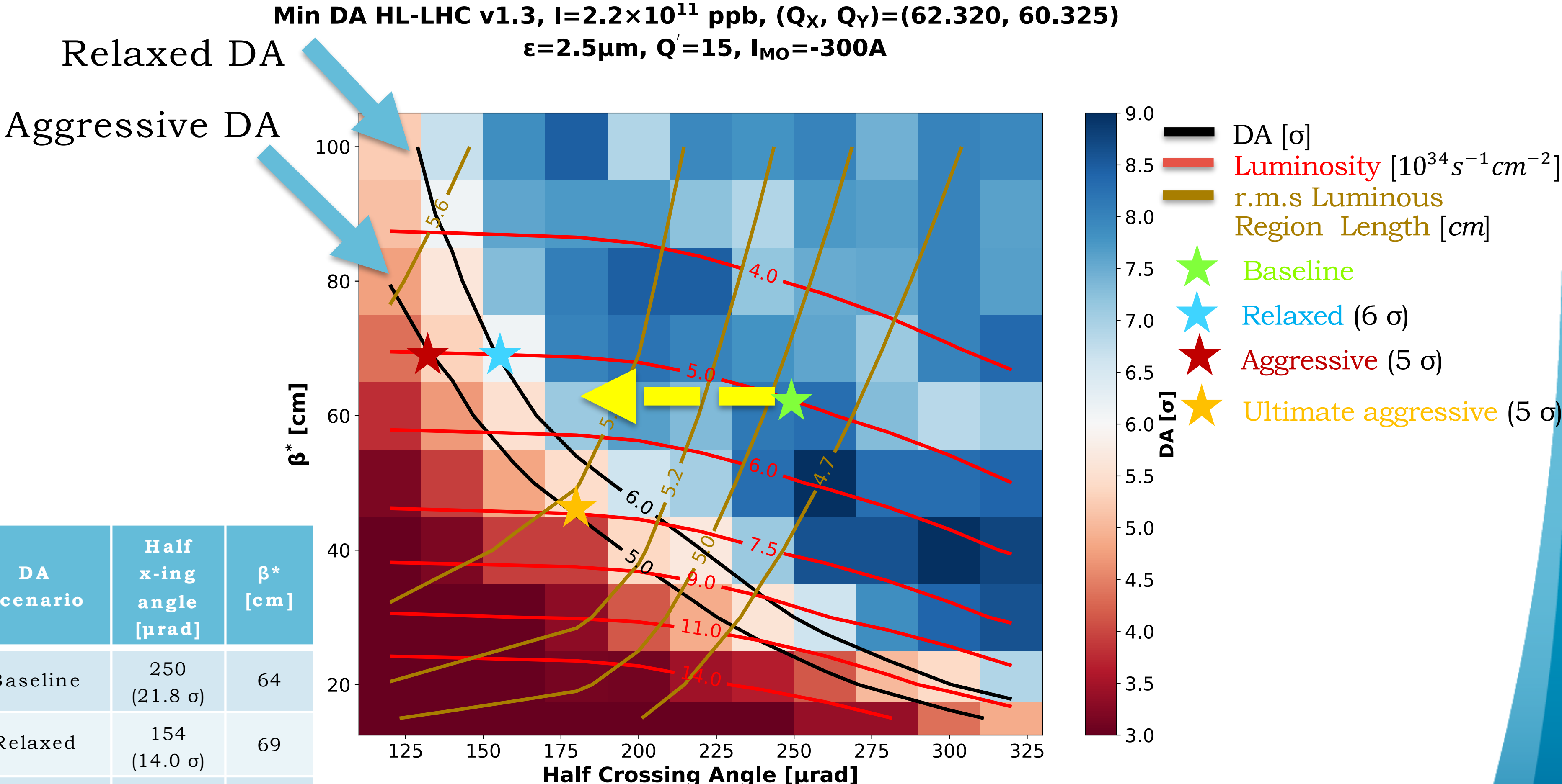
Relaxed DA

Aggressive DA



Start of levelling: 2.2 x 10^{11} ppb

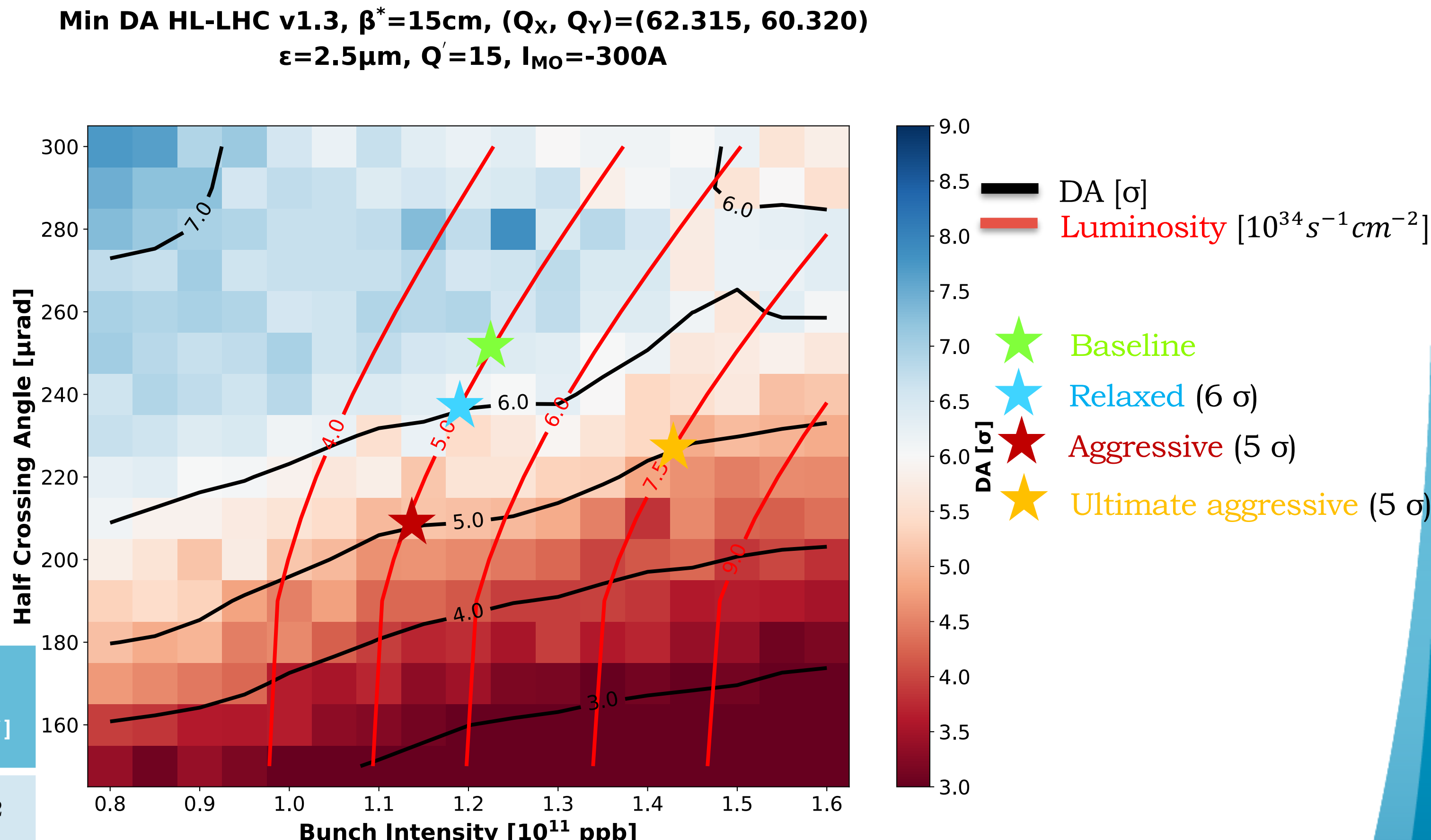
- Reduction of **crossing angle** at **constant luminosity**, reduces **pileup density** (by elongating the luminous region) and **triplet irradiation**



DA Scenario	Half x-ing angle [μrad]	β* [cm]
Baseline	250 (21.8 σ)	64
Relaxed	154 (14.0 σ)	69
Aggressive	133 (12.1 σ)	69
Ultimate Aggressive	179 (13.1 σ)	45

End of leveling

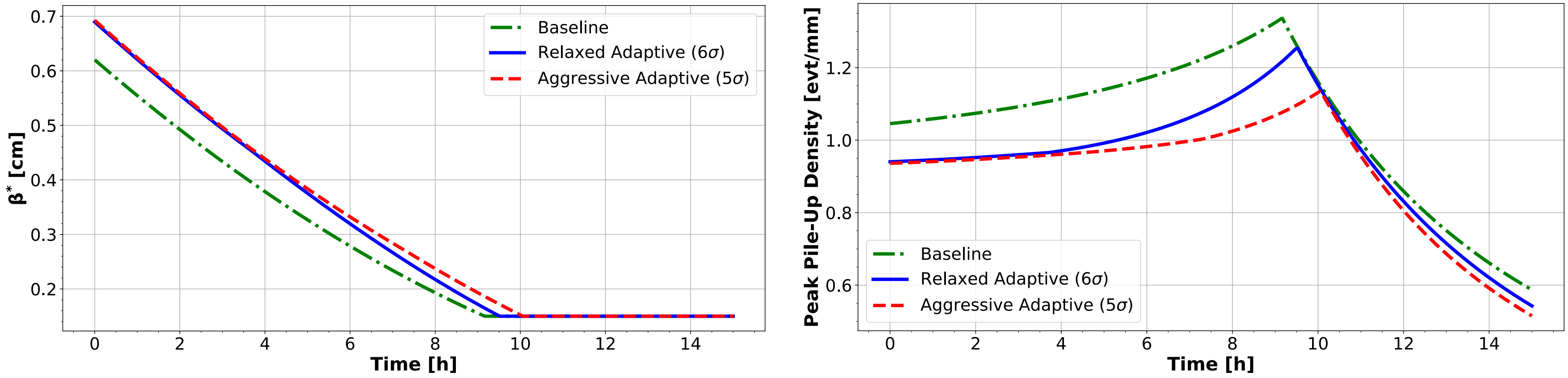
- Exit of leveling determined by **intensity** and associated **crossing angle** @ $\beta^* = 15$ cm



DA Scenario	Half x-ing angle [μrad]	I [10^{11}]
Baseline	250 (10.5 σ)	1.22
Relaxed	235 (9.9 σ)	1.19
Aggressive	207 (8.8 σ)	1.13
Ultimate Aggressive	225 (9.5 σ)	1.42

Evolution of parameters

- **Small increase** on **levelling time** and integrated luminosity
- Luminous region increase of ~15% leads to **peak pile-up density reduction** of **~7%**



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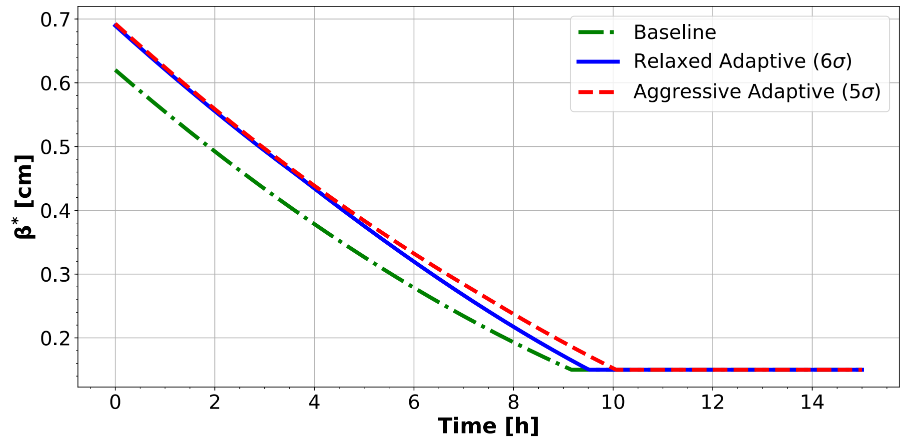
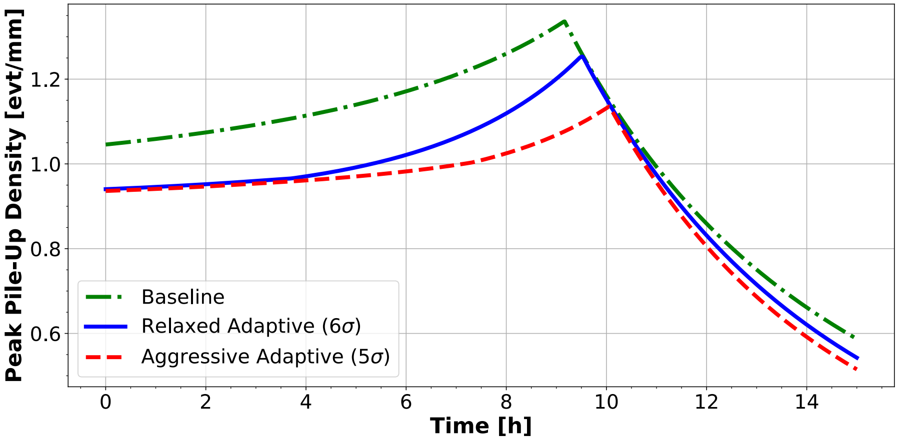
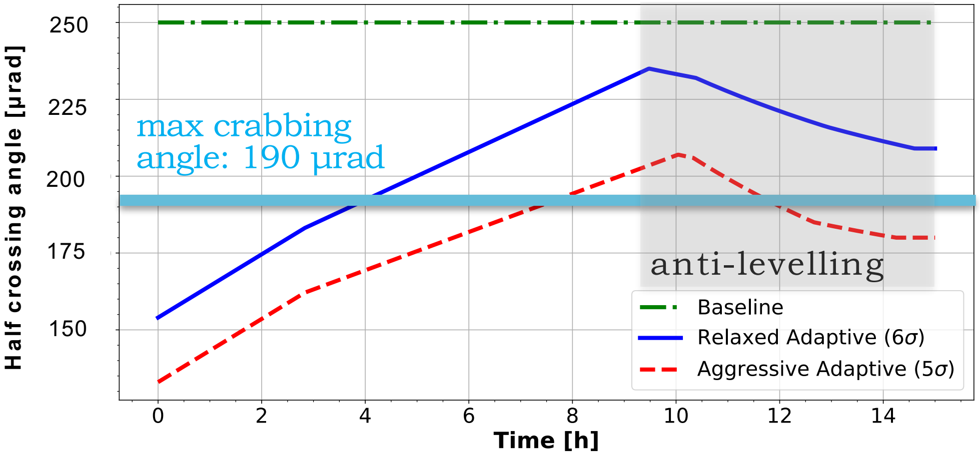






- Include **x-ing angle "anti-levelling"** *à la* LHC after the end β* levelling
- Average reduction of the half **x-ing angle** by **40-50 μrad** leads to **reduction** of **triplet peak dose** by **~10 %**

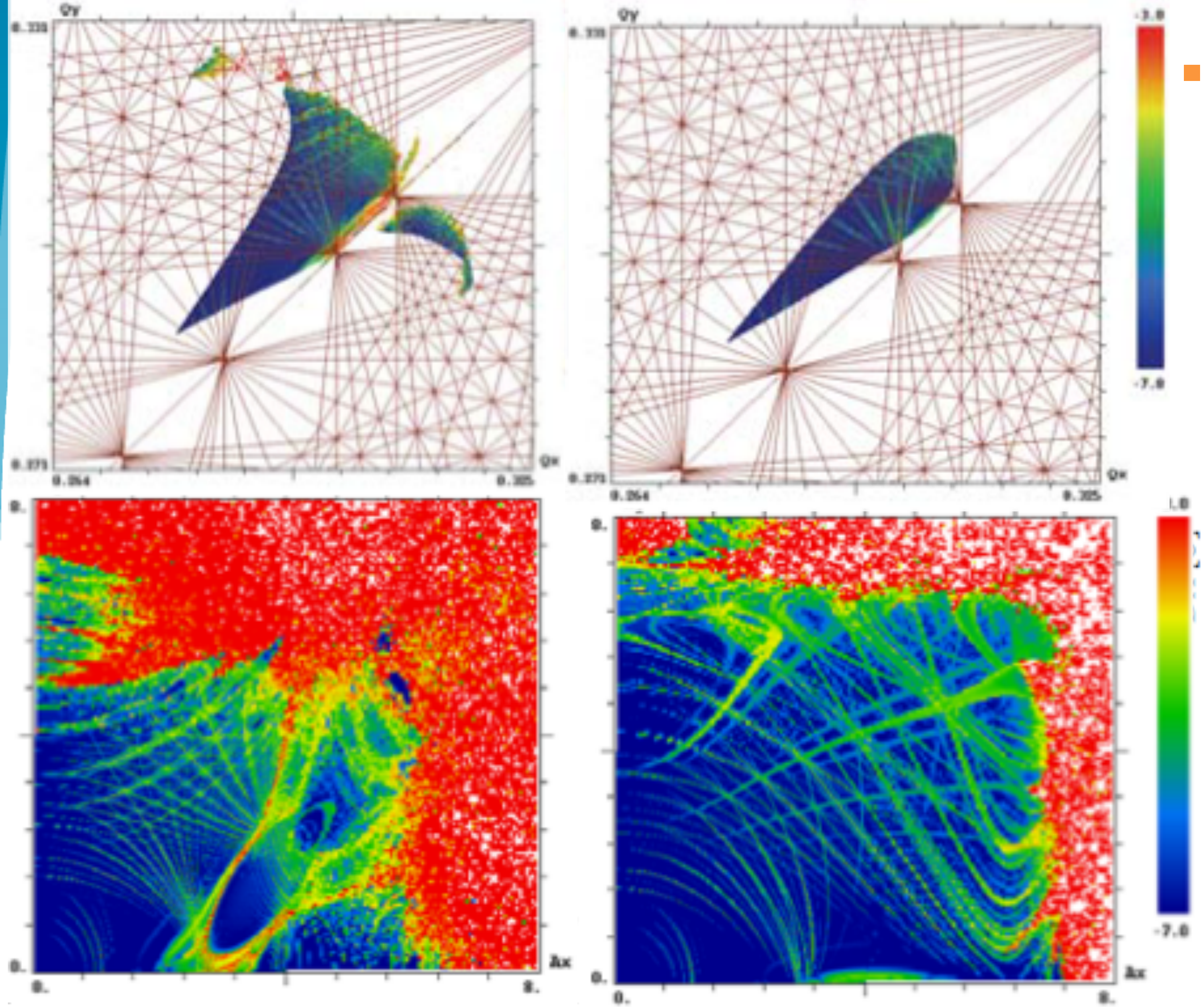
BBLR mitigation measures - DC wires and octupoles

G. Arduini, **A. Bertarelli**, O. Brüning, **S. Fartoukh**, N. Karastathis, Y. Papaphilippou, D. Pellegrini, **A. Poyet, A. Rossi**, L. Rossi, **K. Skoufaris**, **G. Sterbini**, F. Zimmermann (CERN),

M. Fitterer (ex-FNAL), **A. Valishev** (FNAL), A. Patapenka (NIU), D. Shatilov (BINP)

BBLR Wire compensation

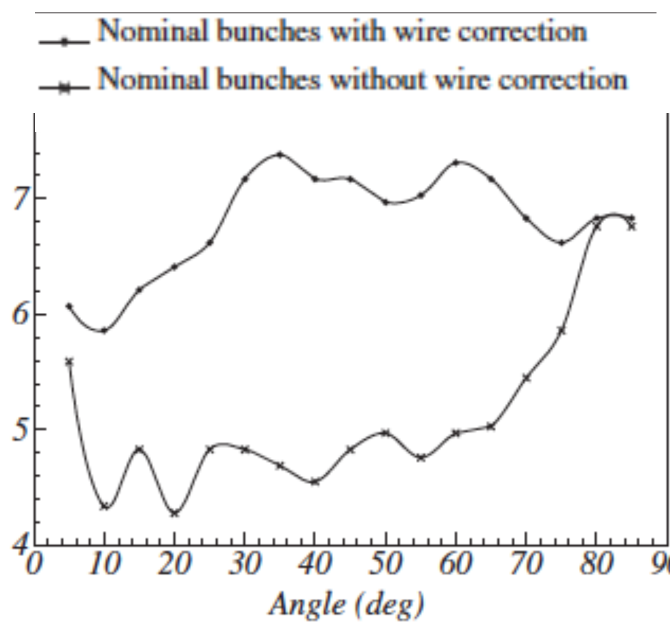
Without correction   With correction



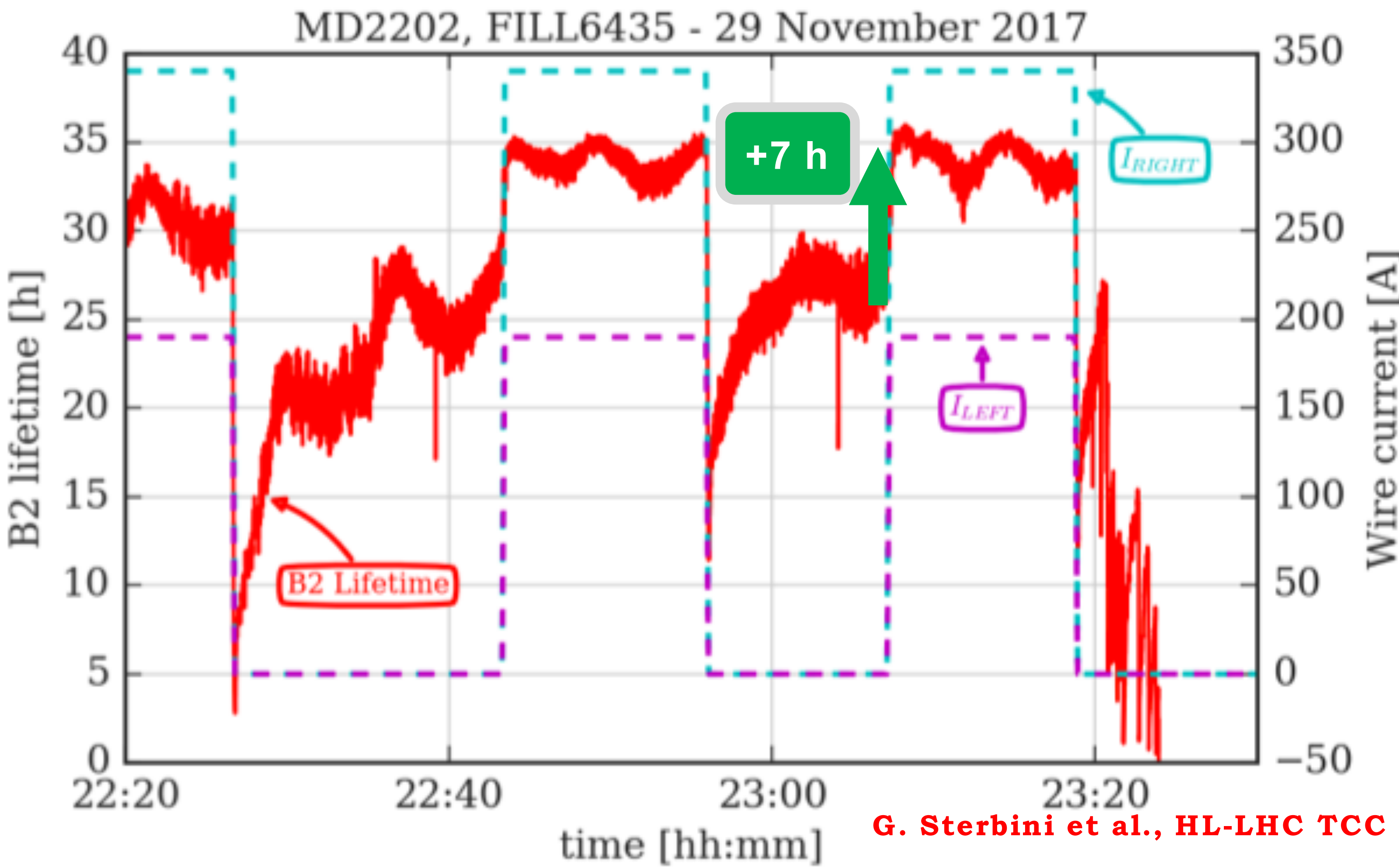
- Current baring wire can **improve DA by 1-2 σ**
- Tests in the LHC during 2017-2018

Reduced crossing angle of 450μrad @ 15cm

S. Fartoukh, et al., PRSTAB, 2015



Experimental results with partial compensation (IP5)



G. Sterbini et al., HL-LHC TCC 2017

- Wire current @ 340/190 A and collimator jaw at 5.5 σ_{coll}
- **Compensating effect** of the wires visible on beam **lifetime**

Experimental results with partial compensation (IP5)

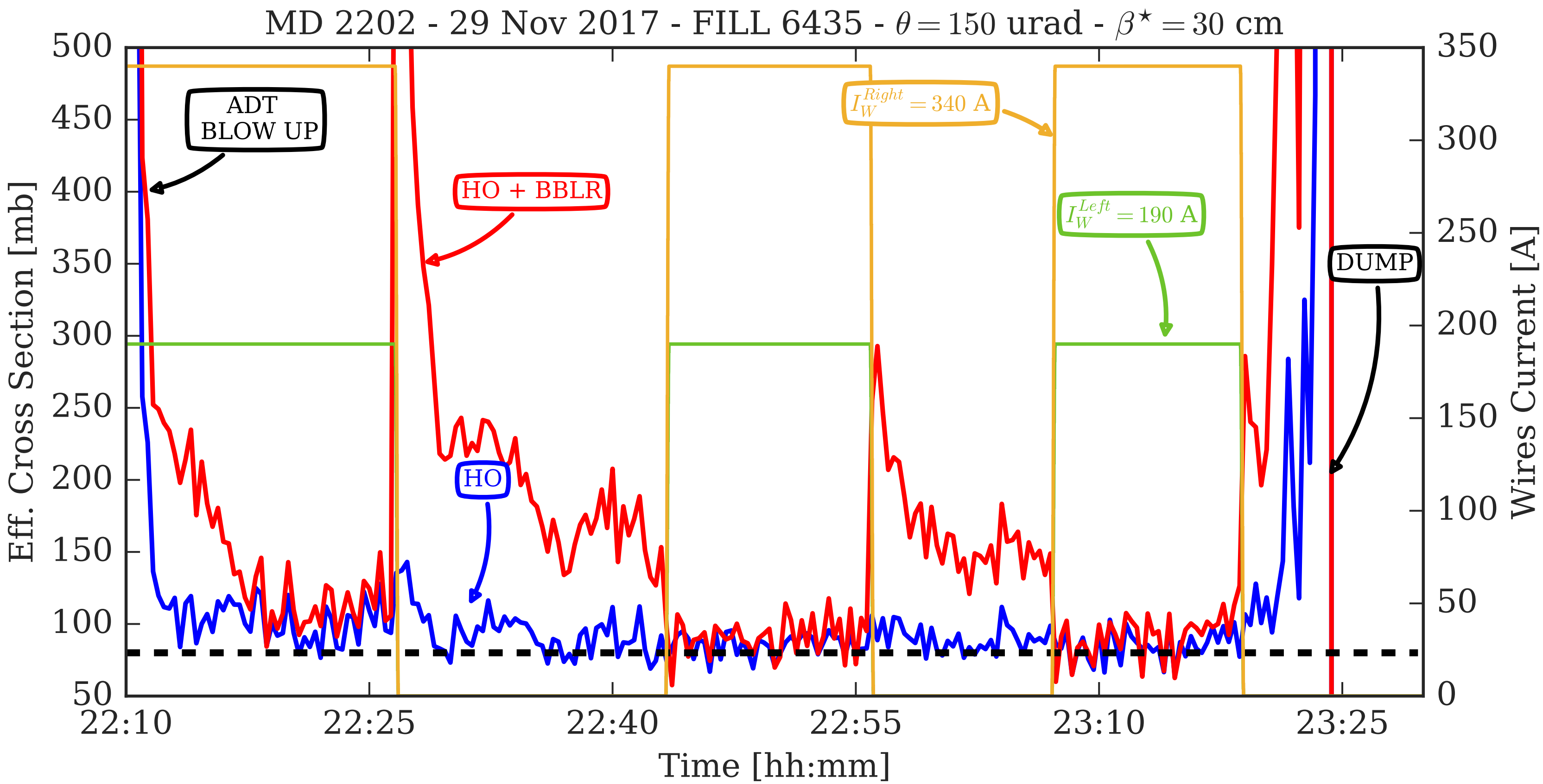
- **Compensating effect** of the wires visible on **effective x-section**

$$\sigma_{EFF} = -\frac{1}{\boxed{\sum_{IP} L_{IP}}}\frac{\boxed{dN}}{dt}$$

Instantaneous luminosity

Intensity loss-rate

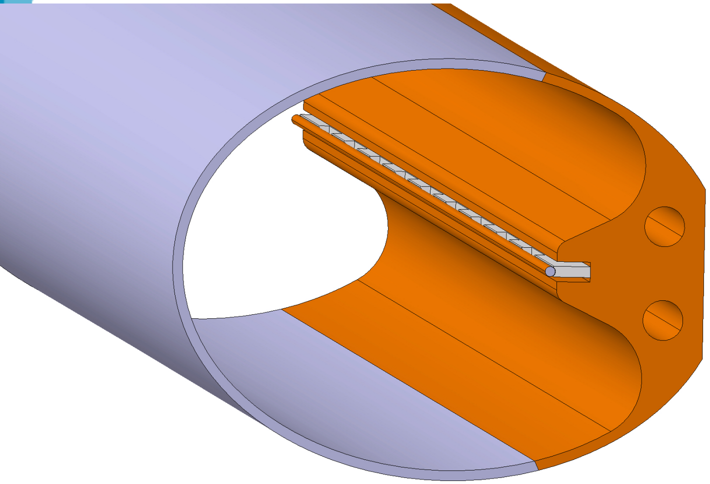
G. Sterbini et al., HL-LHC TCC 2017

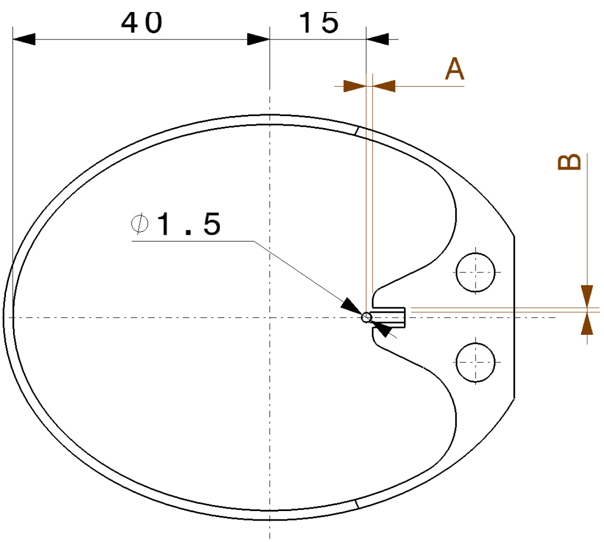


DA simulation wire current vs distance

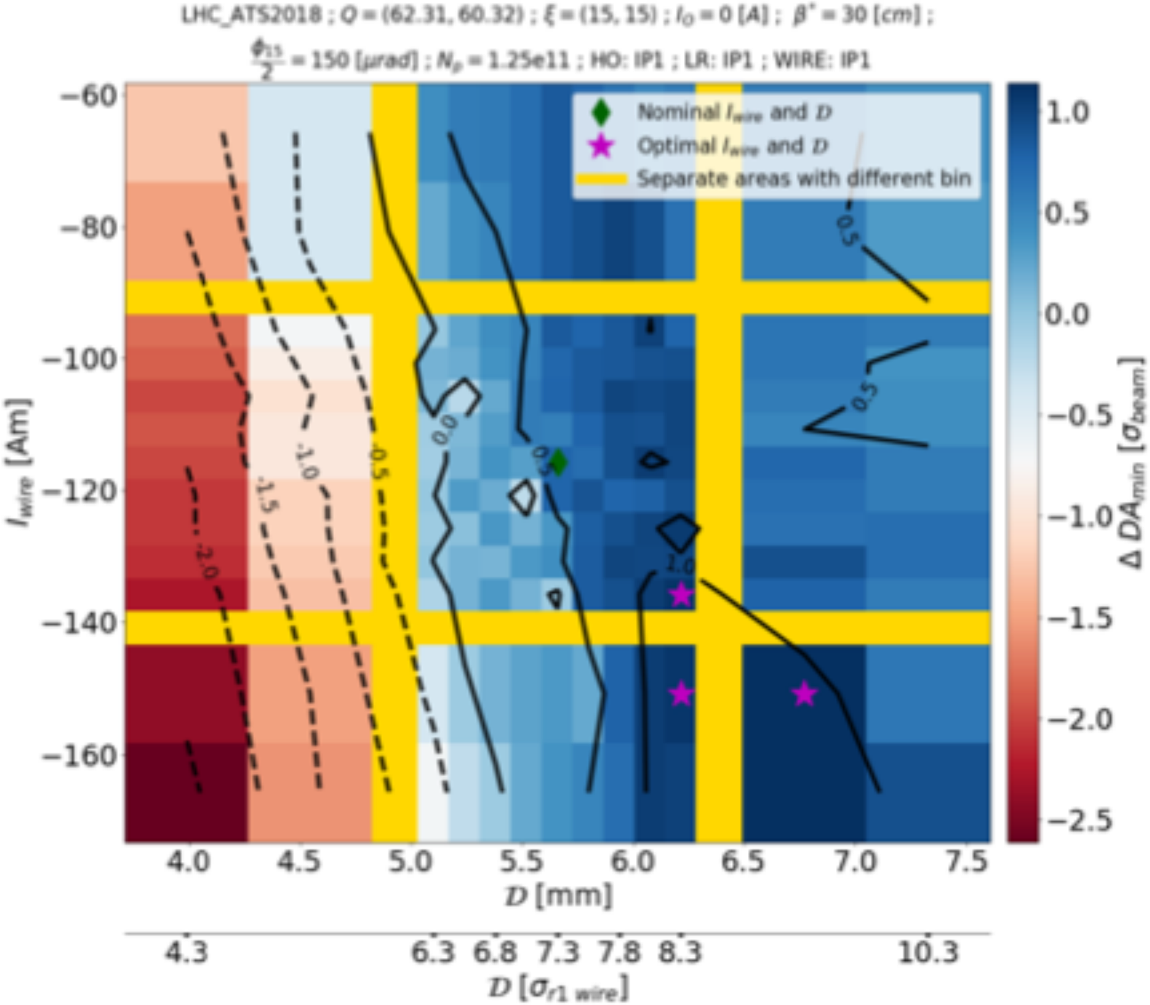
- DA **improvement** for higher **distances** and moderate **current**
- Opens the route for a **solid wire HW** solution for HL-LHC

Preliminary design
A. Bertarelli et al., 2018



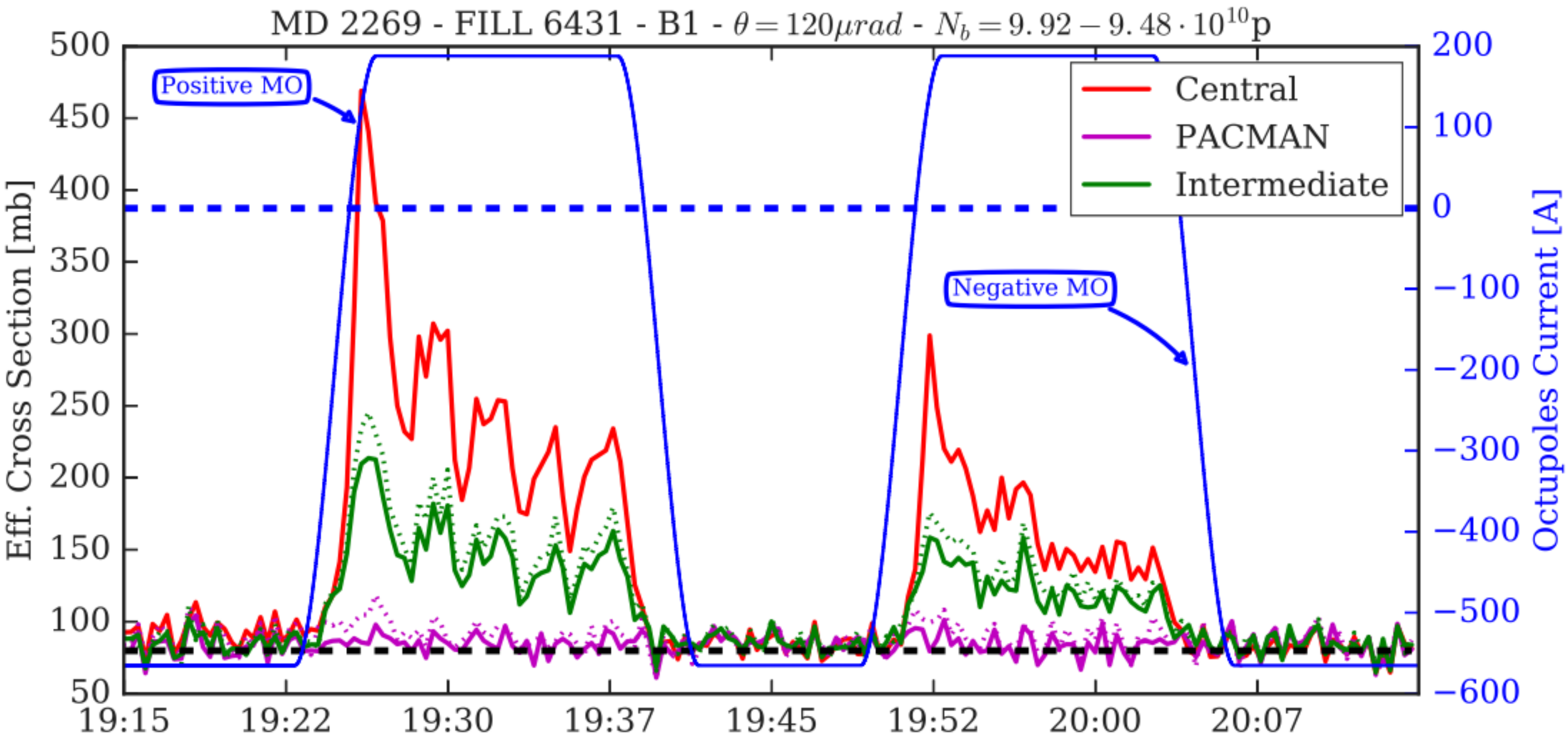


K. Skoufaris et al., 2018



BBLR compensation with octupoles

- Through arc β-function enhancement through the Achromatic Telescopic Squeeze (**ATS**) optics, Landau octupoles (negative polarity) used to reduce **BBLR tune-spread**
- Experimentally proven **lifetime improvement**

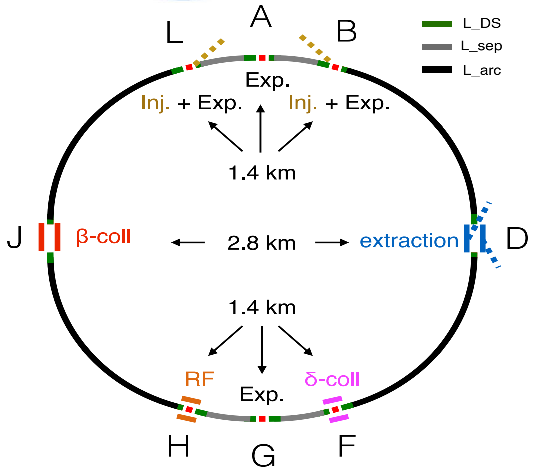


S. Fartoukh, et al., Chamonix workshop 2018

Beam-beam studies for FCChh and HE-LHC

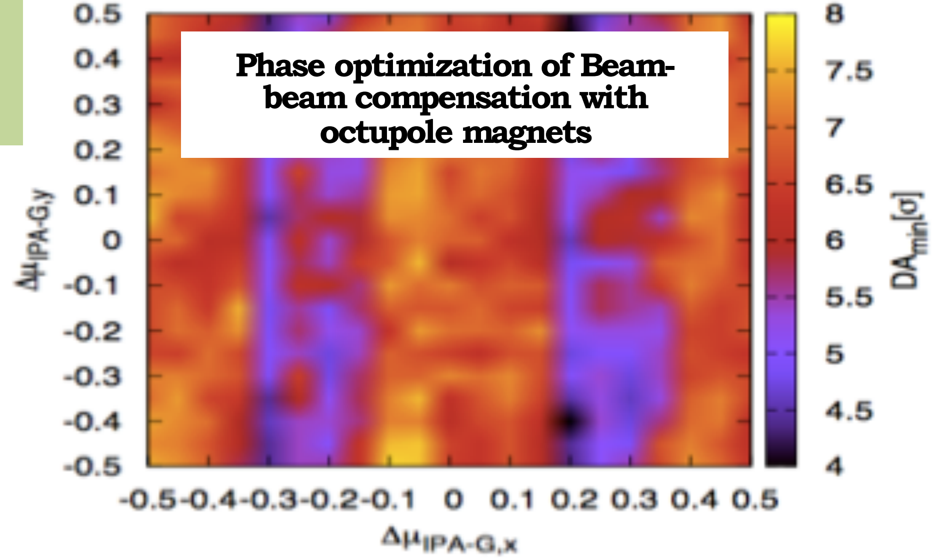
S. Arsenyev, X. Buffat, S. Furuseth, D. Schulte (CERN),
J. Barranco, **T. Pieloni,** C. Tambasco (EPFL)

Future Circular Collider Studies

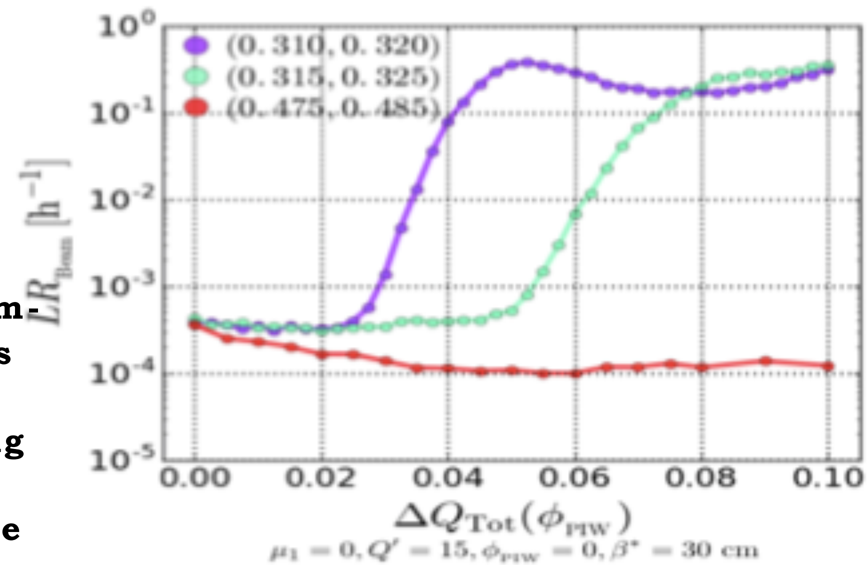


FCC-hh and HE-LHC Studies summarized in CDR

IPAC 2017 TUPVA026
IPAC2018 MOPMF069



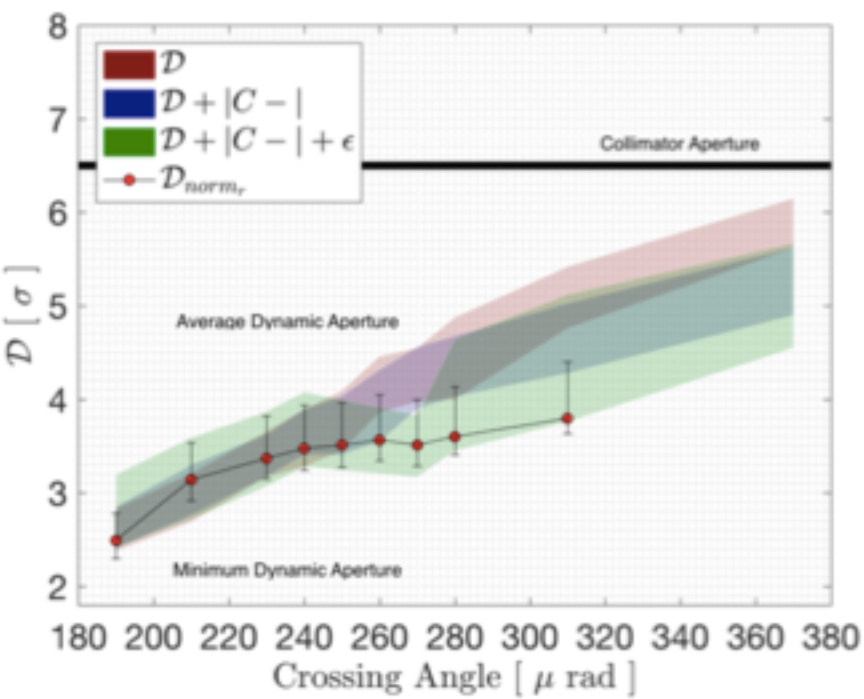
	FCC-hh Baseline-Ultimate	FCC-hh Ultimate
Luminosity[10^{34}cm^{-2}s^{-1}]	5	20-30
Bunch distance	25 (5) [ns]	
Bunch charge	1 (0.2) 10^{11}protons	
Norm. emitt.	2.2 (0.44) [μm]	
ξbb per IP	0.01 (0.02)	0.03
IP beta-function	1.1 [m]	0.3 [m]
IP beam size [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length	8 [cm]	



1. **Lattice design with global compensation of beam-beam long-range effects with multipole magnets in place**
2. **Head-on limit studies fundamental due to strong radiation damping**
3. **Coherent stability and interplay with impedance**

CERN-THESIS-2017-279 (2017)

Beam-beam effects FCC challenges



LHC Experiments data 2016 versus simulations IPAC THPAB056

LHC benchmark of dynamic aperture and losses very positive for beam-beam effects but we have learned some lessons:

- Much larger number of tracked particles needed in phase space to describe full beam-beam dynamics of LHC
- Multipolar errors in model with beam-beam
- Number of tracked turns has to be increased to compare to observations 10^6 turns only

LHC case for 1 configuration:
LXBATCH (300-1000 CPUs) → 8.3-2.5 days
LHC@HOME (4000 CPUs) → 0.63 days

FCC-hh and HE-LHC factor 3&5 complexity :
LXBATCH (300-1000 CPUs) → 41-22.5 days
LHC@HOME (4000 CPUs) → 3.15 days

Designing for the future with lesson learned from LHC is today impossible!

Projects on going to apply machine learning techniques to predict long term dynamic aperture!

Summary

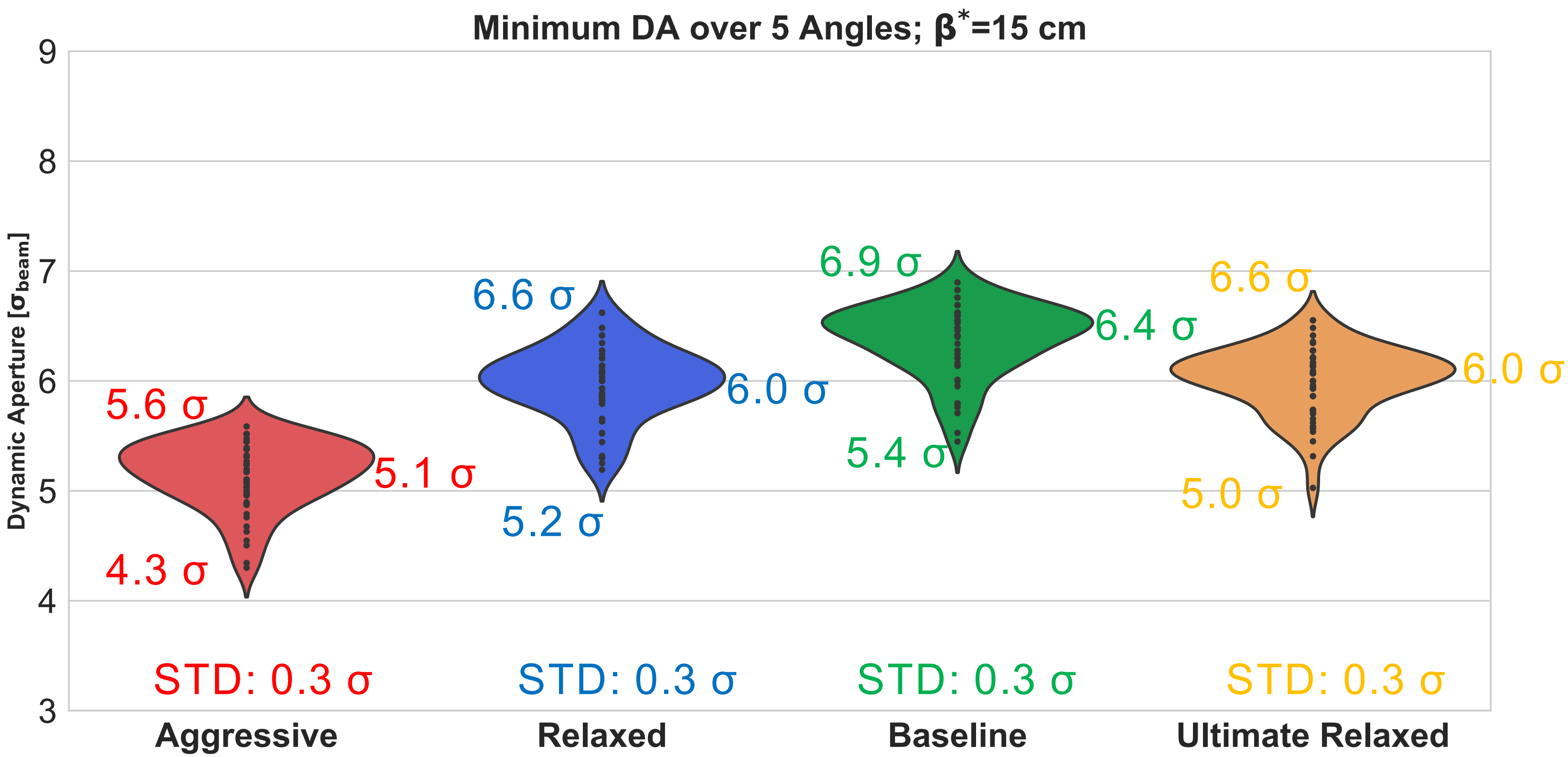
- Guiding LHC machine operation with **multi-parametric beam-beam DA** scans
  - Measured and simulated **correlation** with beam **lifetime**
- **HL-LHC operational scenario** guarantying **6 σ DA** for **high chromaticity** (15) and **octupole** current (-300 A)
  - Adaptive crossing angle levelling scenario reduces **pile-up density** and **triplet irradiation** (increasing their **lifetime** by **~10 %**)
- First observations in LHC of a direct compensation of the BBLR effect with **DC wires** and **octupoles**
  - Studying **HW solutions** for BBLR compensation in the HL-LHC era
- On-going studies for impact of **tune modulation** on **lifetime** (tail population evolution)

HiLumi
HL-LHC PROJECT

Thank you for your attention

Field Errors at the End of Levelling

- Focus on a few interesting configurations at **end** of the levelling:
  - Aggressive, Relaxed Adaptive Scenarios
  - Baseline Nominal and Ultimate relaxed Scenarios



- Average **spread** of the various realizations of **0.3 σ**
- Justifies the **6 σ DA target** for beam-beam **without errors**