Impact of beam-beam effects on the transverse LHC beam halo

ICFA mini workshop – Beam-Beam Effects in Circular Colliders

02 – 05.09.2024, EPFL, Lausanne, CH

Authors: M. Rakic, P. Hermes, C. E. Montanari, S. Redaelli, G. Sterbini

Thanks to LHC OP for the precious support!

Introduction

- **High stored energy of LHC particle beams (approx. 700MJ for HL-LHC!)**
- **LHC Collimation system**:
  - Multi-stage system, mainly located in IR7
  - Essential for machine protection
  - Different collimation types for different purposes
    - TCP: primary collimators – closest to main beam
    - Secondary and tertiary collimators – remove particle showers, protect IPs, reduce background
    - Collimation Hierarchy to be respected to ensure safe operation

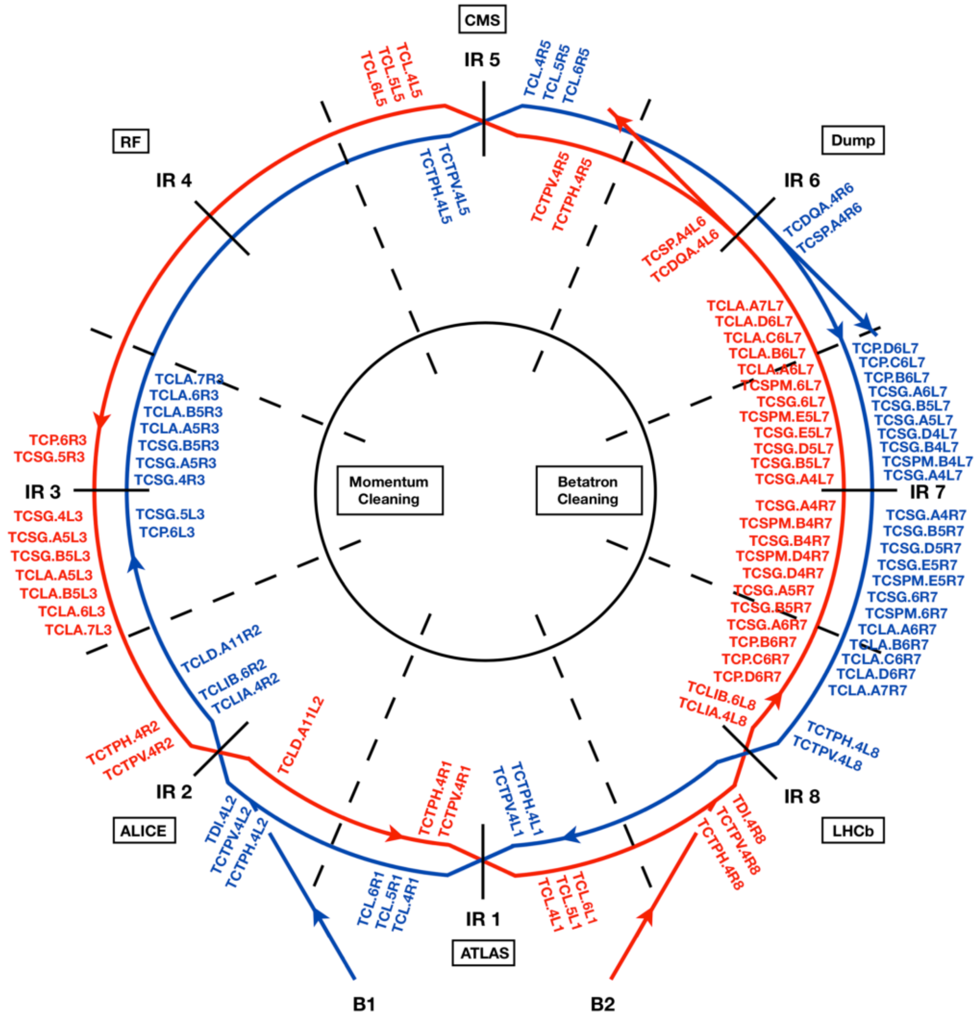


Figure – LHC collimation system layout [1]

LHC 2023 operation, a complex cycle!

$$\sigma_{\text{coll}} = \sqrt{\beta\epsilon}$$

	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

- Collision in four Interaction Points (IPs):
  - High Luminosity Experiments in IP1 (ATLAS) and IP5 (CMS)
  - Lower Luminosities in IP2 (ALICE) and IP8 (LHCb)
- Cycling through multiple optics, each yielding different challenges (and BB effects during levelling!)

LHC collimation along the cycle

		Betatron			Off-momentum			Dump		Triplet prot.				Physics debris		
		IR7 [σ]			IR3 [σ]			Dump [σ]		TCT [σ]				TCL [σ]		
		TCP	TCSG	TCLA	TCP	TCSG	TCLA	TCDQ	TCSP	1	2	5	8	4	5	6
Injection		5.7	6.7	10	8	9.3	12	8	7.5	13	13	13	13	-	-	-
Ramp		↓	↓	10	↓	↓	↓	↓	↓	↓	↓	↓	↓	-	-	-
Flat Top		5	6.5	10	15	18	20	7.3	7.3	18	37	18	18	-	-	-
Squeeze		5	6.5	10	15	18	20	7.3	7.3	↓	37	↓	18	-	-	-
LHCb Rotation		5	6.5	10	15	18	20	7.3	7.3	9.35	37	9.35	↓	-	-	-
Tune Change		5	6.5	10	15	18	20	7.3	7.3	9.35	37	9.35	11.5	-	-	-
Adjust		5	6.5	10	15	18	20	7.3	7.3	9.35	37	9.35	11.5	-	-	-
Levelling	120	5	6.5	10	15	18	20	7.3	7.3	↓	37	↓	11.5	↓	↓	↓
	60	5	6.5	10	15	18	20	7.3	7.3	8.5	37	8.5	11.5	↓	↓	↓
	30	5	6.5	10	15	18	20	7.3	7.3	8.5	37	8.5	11.5	17	42	30

- Collimator settings = functions of time synch-ed to the power converters, RF, orbit feedback,...
- Regular monitoring to detect early on potential deviations from reference performance
- All settings **beam-based**: dedicated alignment sections in initial commissioning

Beam halo and its importance

- **Transverse beam halo** defined as particle population above 3 σ_N
- Measured since LHC start: heavily populated halo, up to 5% [5]
- Halo and fast-failure scenarios:
  - Danger to collimation system
  - Danger of magnet quench
  - General concern on machine availability from loss spikes if halos too populated
- **Need to understand the mechanisms of halo formation and evolution**

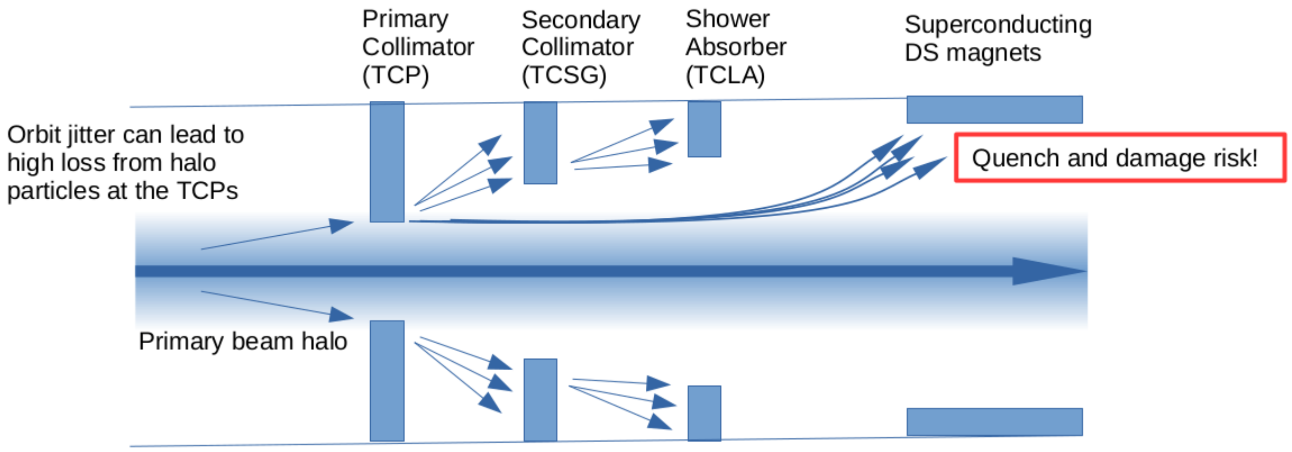


Figure – Beam halo interaction with collimator hierarchy [2]

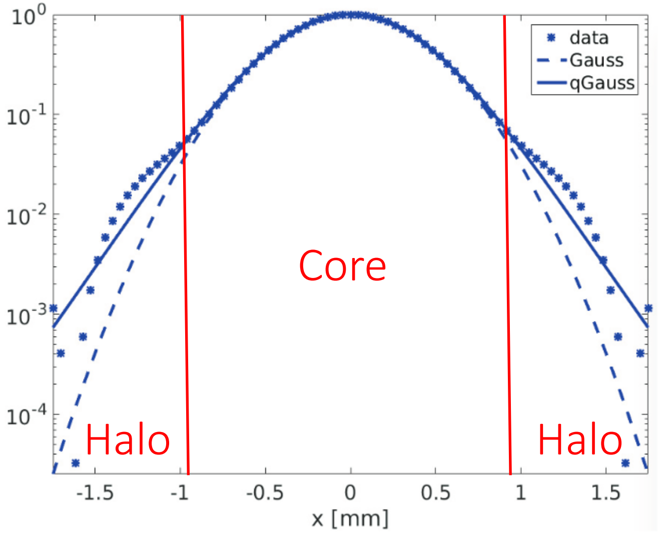


Figure – Transverse bunch profile measured by BSRT [3]

σ_N Tranverse beam size with nominal emittance

How is the halo measured in the LHC?

- Beam-based alignment
  - Precise collimator measurement of collimator gap when touching the beam
  - Important for positioning the beam centre
- Destructive scrapings with collimators:
  - Inward scraping in steps
  - Using TCPs
- Instruments used:
  - Beam current transformer (**BCT**) - beam intensity (per bunch or total)
  - Beam loss monitors (**BLM**) - local losses

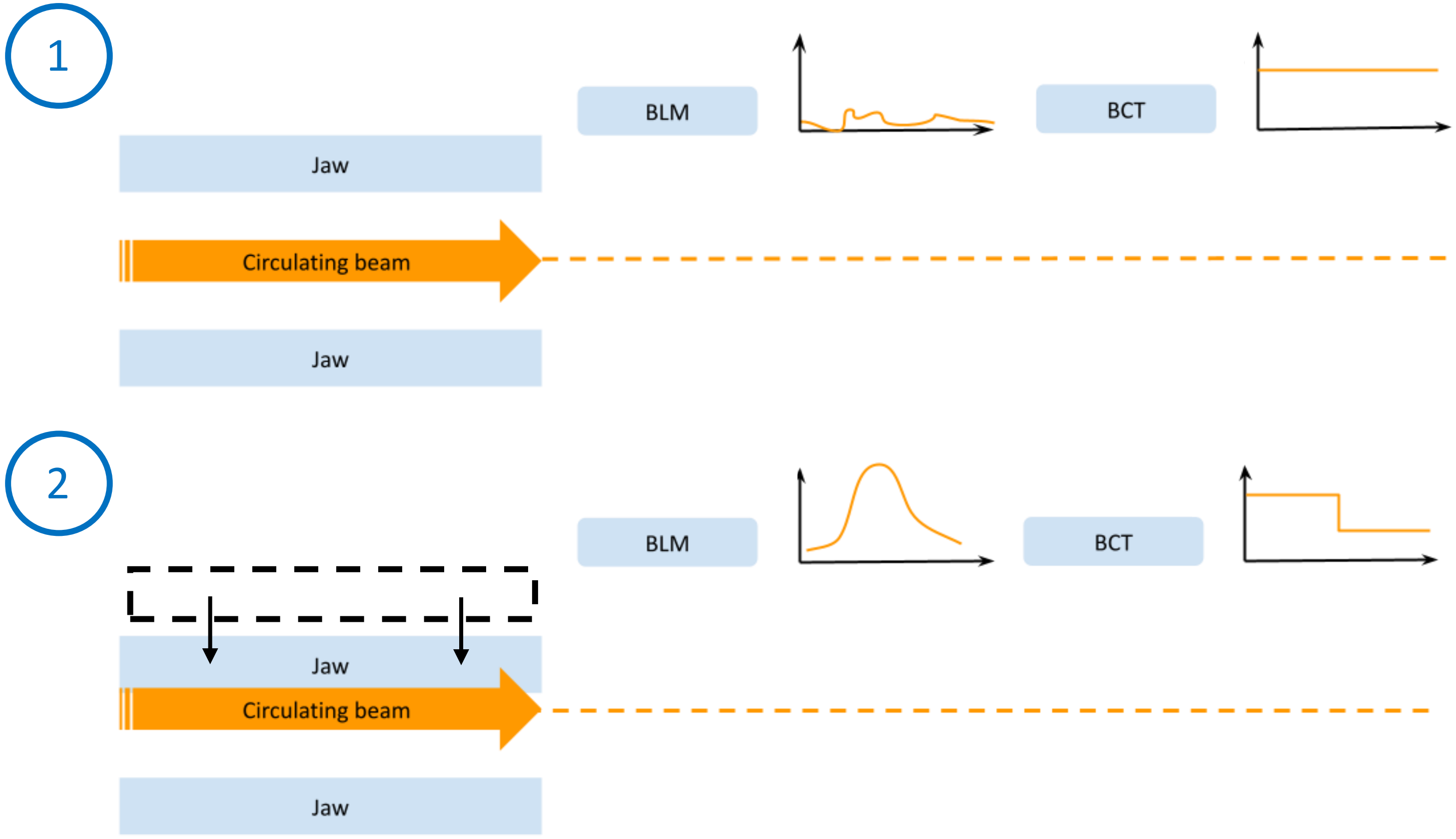


Figure – Illustration of halo scraping with TCPs and responses of BLM and BCT devices.

Measurement analysis

- Example: data from BCT ⟶ beam halo **[% total]** at fixed amplitude **[σ_N]**
- Emittances:
  - **M**easured: expected beam size
  - **N**ominal: by convention 3.5 µmrad in LHC and 2.5 µmrad in HL-LHC

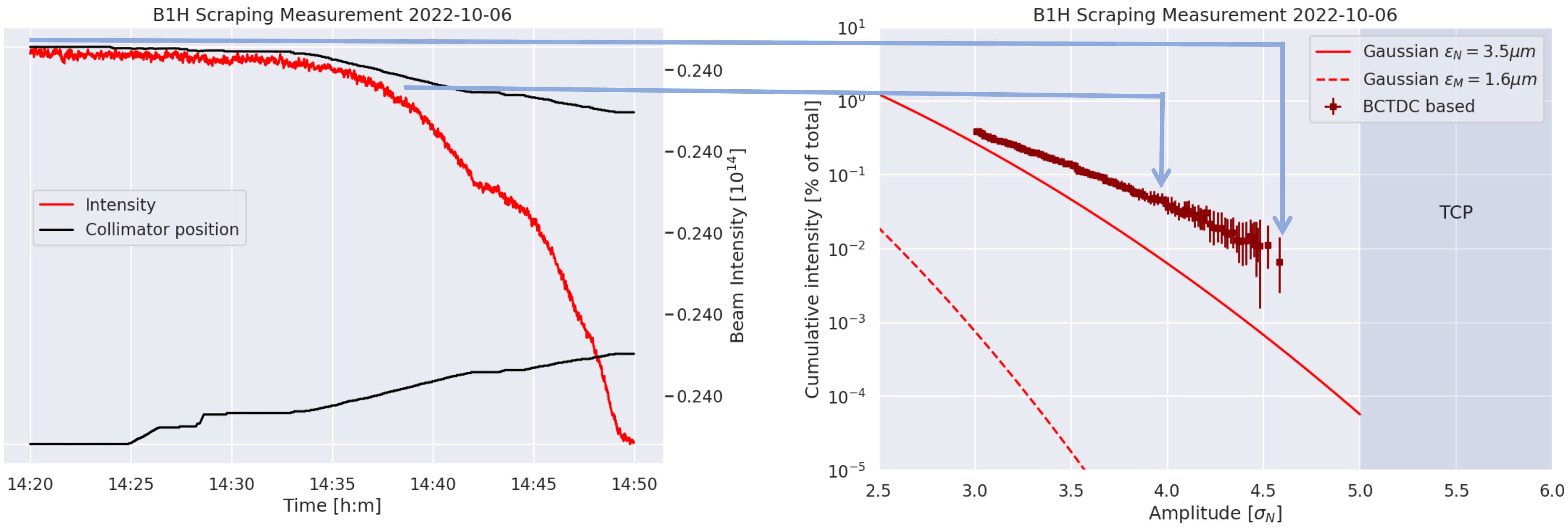


Figure – Extracting halo from the raw BCT signal and TCP positions.

Measurement overview

- Overview of end-of-fill LHC Run 3 halo measurements:
  - Taken after beams spent hours in collision
- Range of measured halo populations

Date	Fill	B1H	B1V	B2H	B2V
		halo [% of total intensity] at **3.5σ_N**			
06/10/2022	8233	0.1%	0.1%	0.1%	0.3%
25/10/2022	8313	0.4%	0.6%	< 0.1%	1.5%
12/11/2022	8387	0.9%	0.6%	0.2%	0.7%
20/06/2024	9808	0.2%		0.1%	
23/08/2024	10048	0.5%	<0.1%	0.2%	0.2%

- **This talk**: focus on scraping done on Fill No. 8233

Measurement overview

- Beam conditions:
  - 200 bunches, 7×10^9 ppb
  - 10h in collisions - nominal LHC β*luminosity levelling
  - Reached nominal 2022 end of levelling (IP1/5 β*=30cm, IP2 β*=10m, IP8 β*=2m)
  - 350 A octupole currents
- **Different collision scheme for different bunches within trains**
  - Different head-on (HO) and long-range (LR) beam-beam forces
- Measurement at end of fill
  - FastBCT data for reconstructing **bunch-per-bunch** halo population

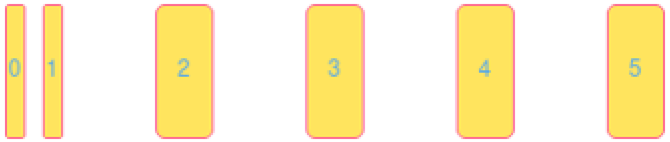
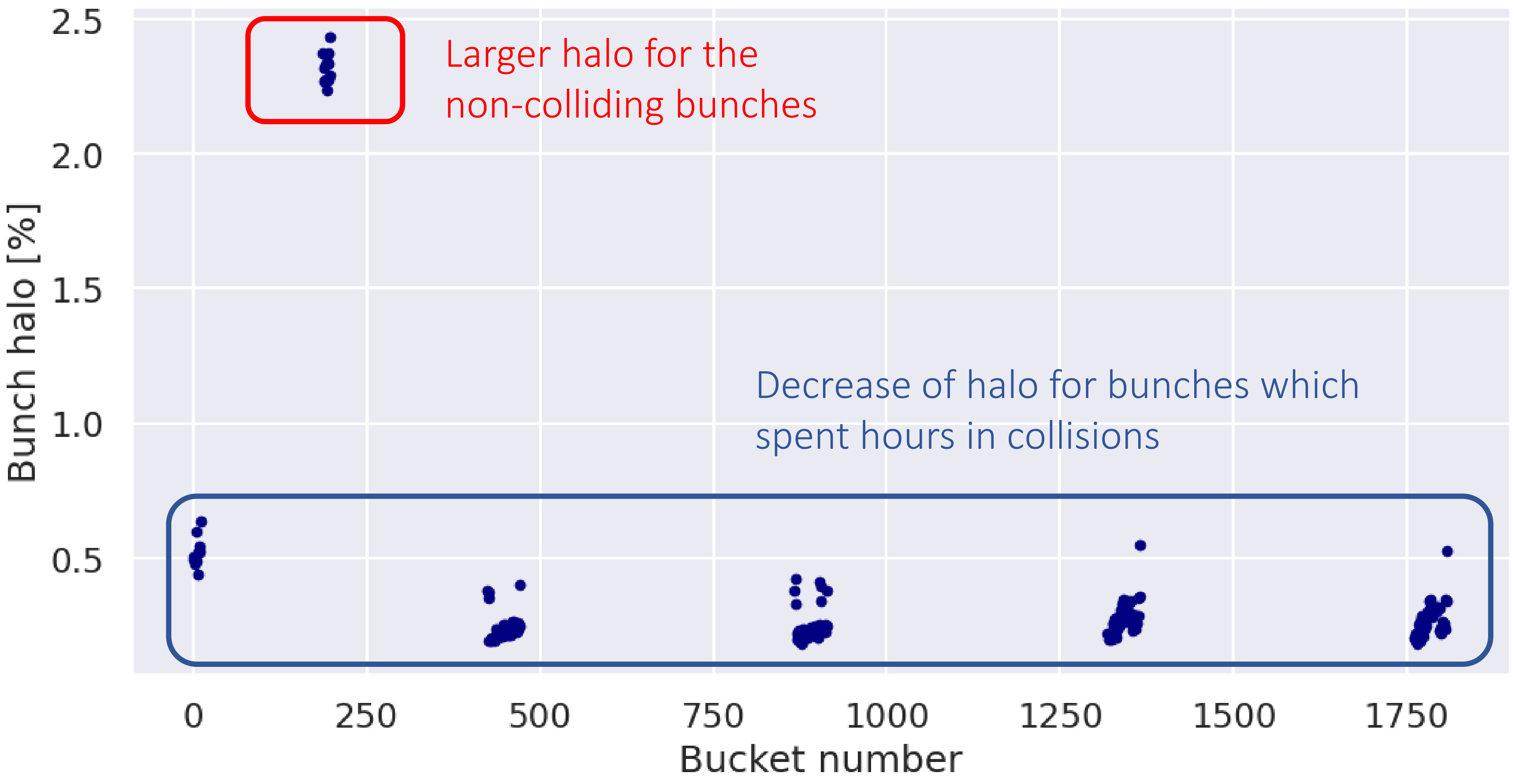


Figure – Fill scheme, 2 trains of 12b (0-1) and 4 trains of 48b (2-5).

Influence of collisions on halo

- B2H halo per bunch above 3.2 σ_N
- Expected behaviour: colliding vs non-colliding bunches
- Intra-train halo differences



Influence of collisions on halo

Bunch-by-bunch halo above 3.2 σ_N

Influence of collisions on halo

- Visible decrease of halo when colliding in IP2

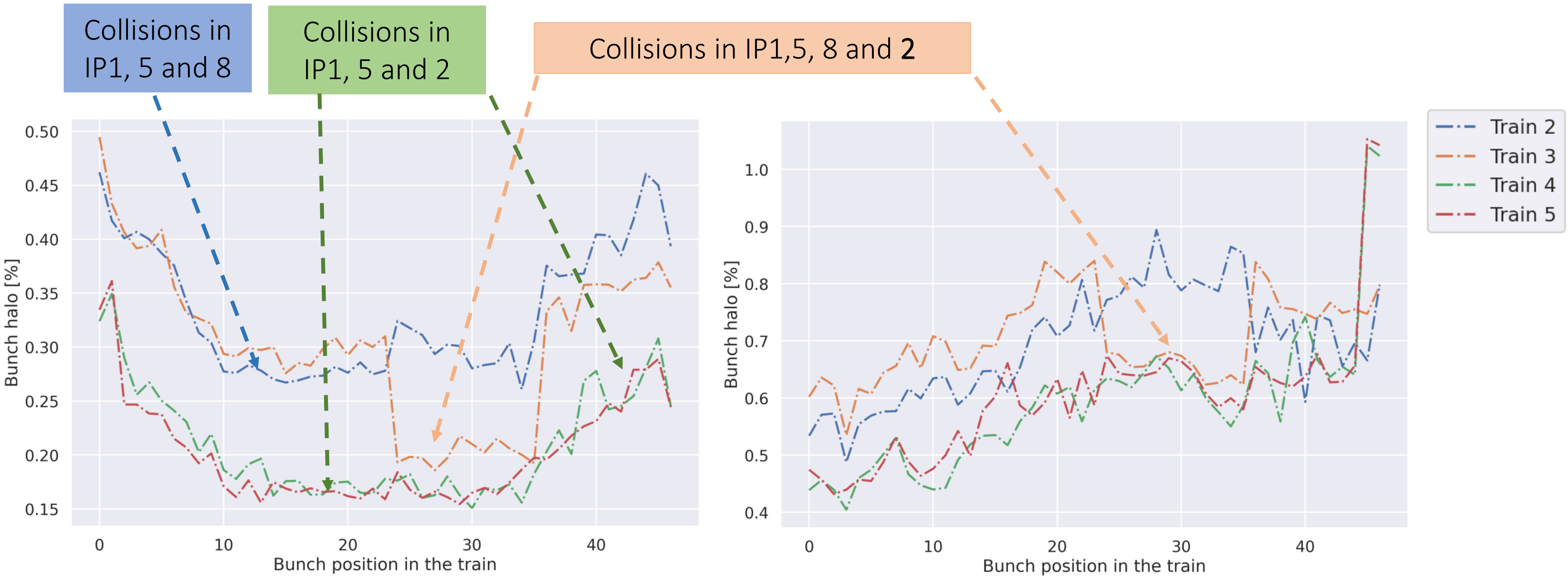
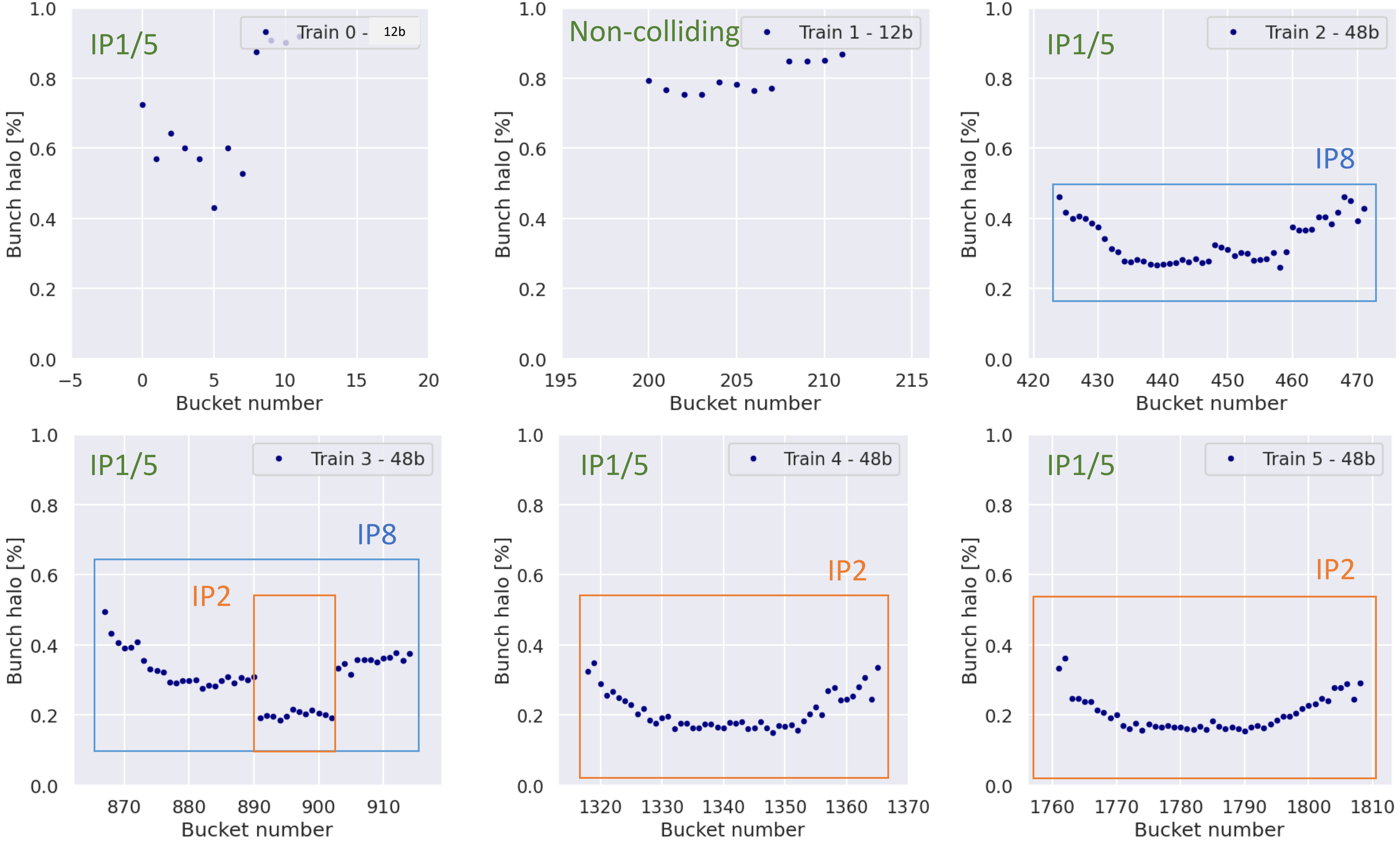


Figure – Bunch-by-bunch halo left in B2H and right in B2V.

Bunch-by-bunch halo and IP collision pattern - B2H

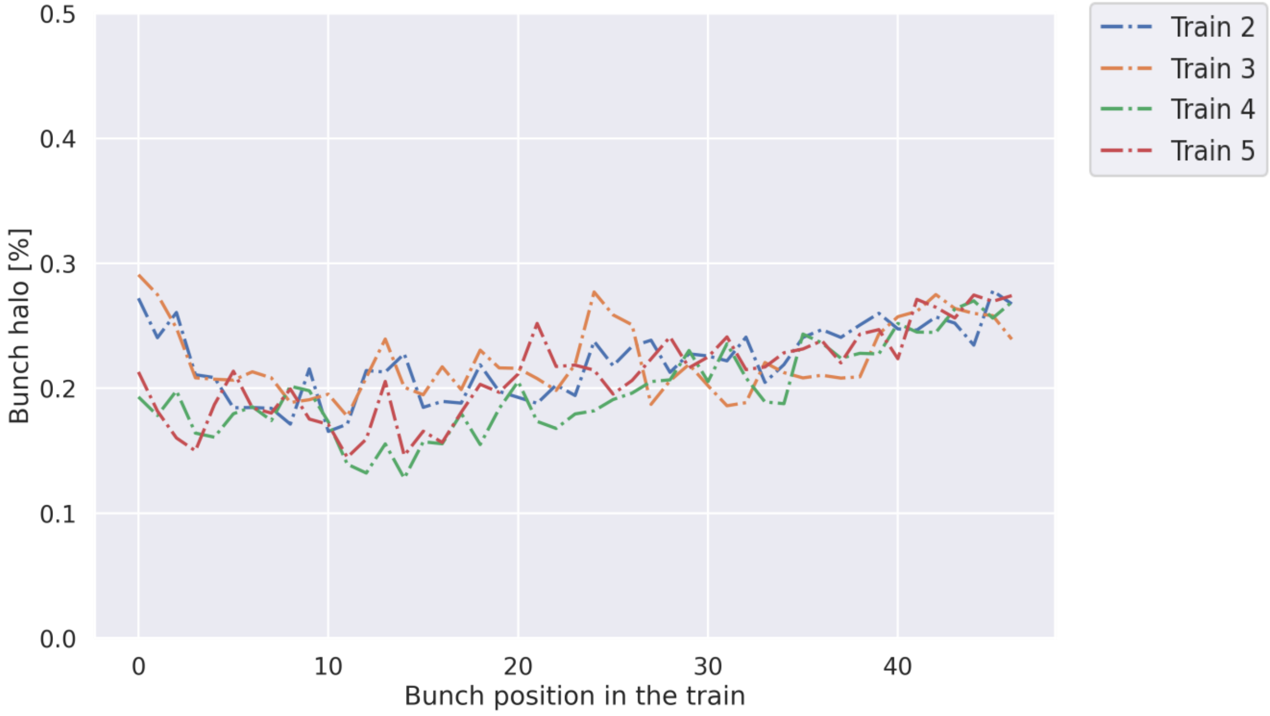


Is this visible also in B1?

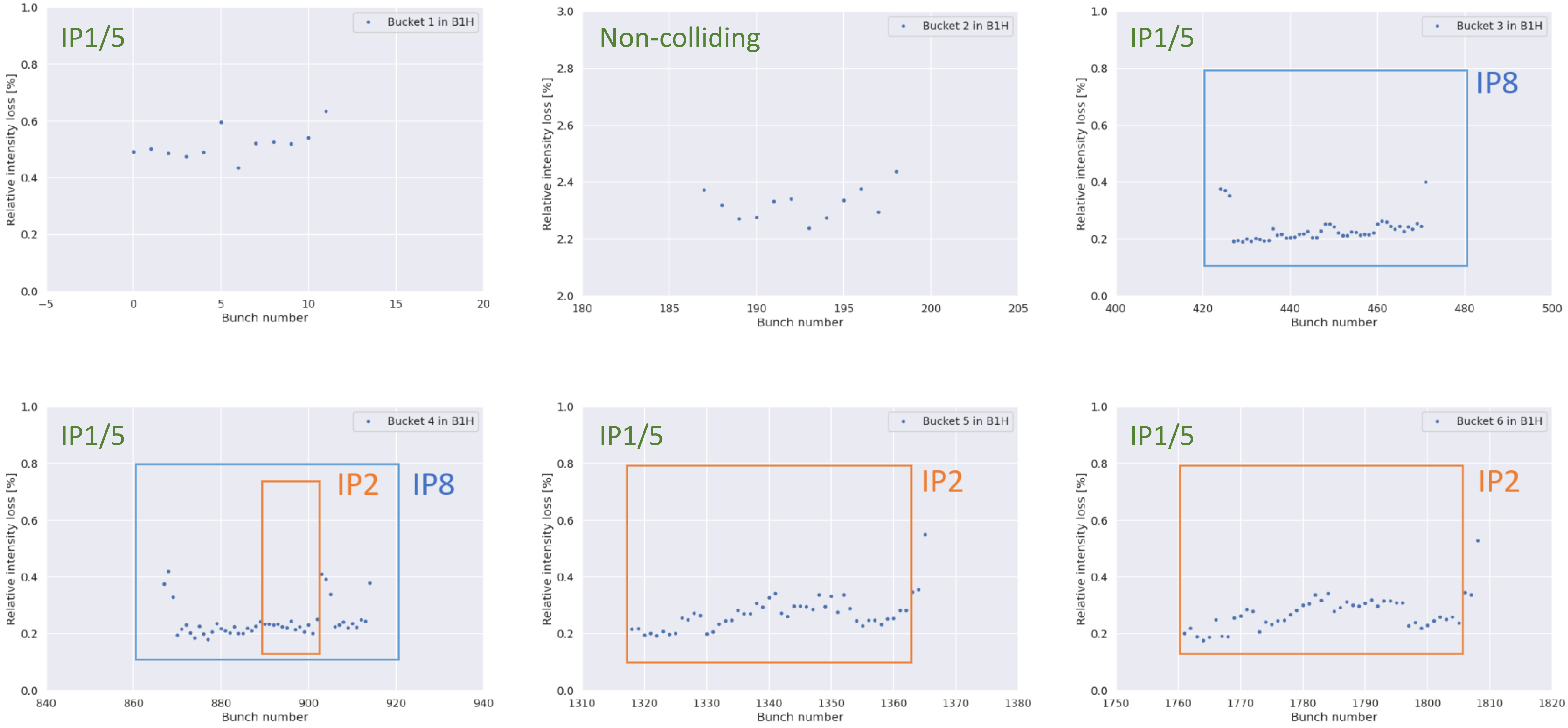
- Patterns observed in B2 are not present in B1
- Source of differences still uncertain

B1H

B1V



Bunch-by-bunch halo and IP collision pattern - B1H



Summary of key observations

- Difference in bunch halo population depending on collision pattern
- Unexpected differences between B1 and B2
- Possibly caused by different non-linear interaction with magnetic imperfections?
- Can we replicate this in simulations?

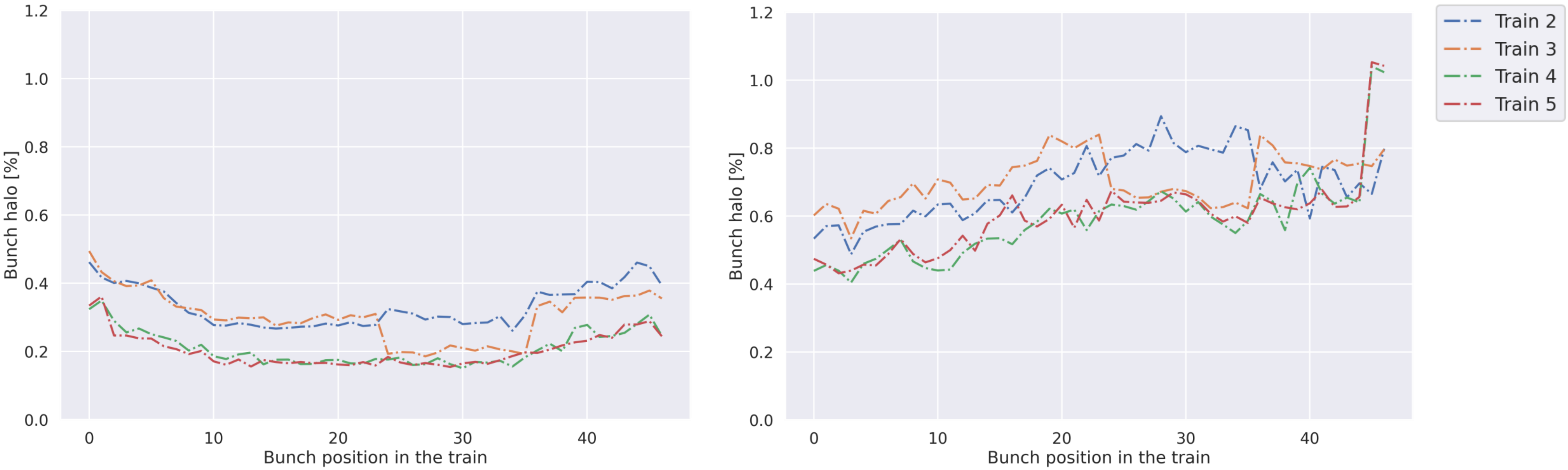
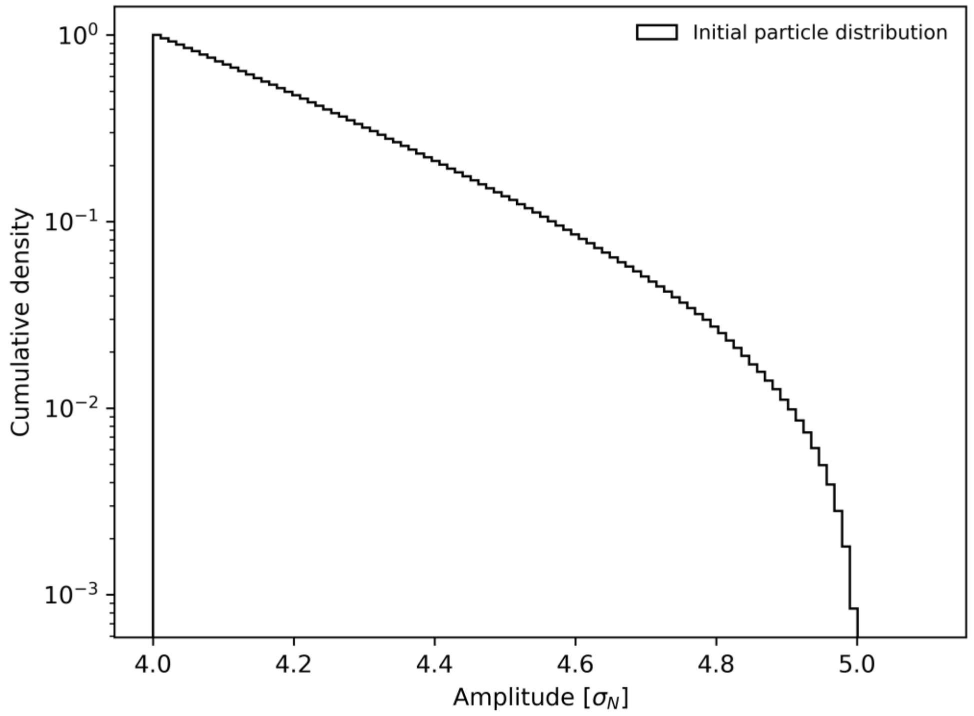


Figure – Bunch-by-bunch halo left in B2H and right in B2V.

Single-particle tracking with Xsuite

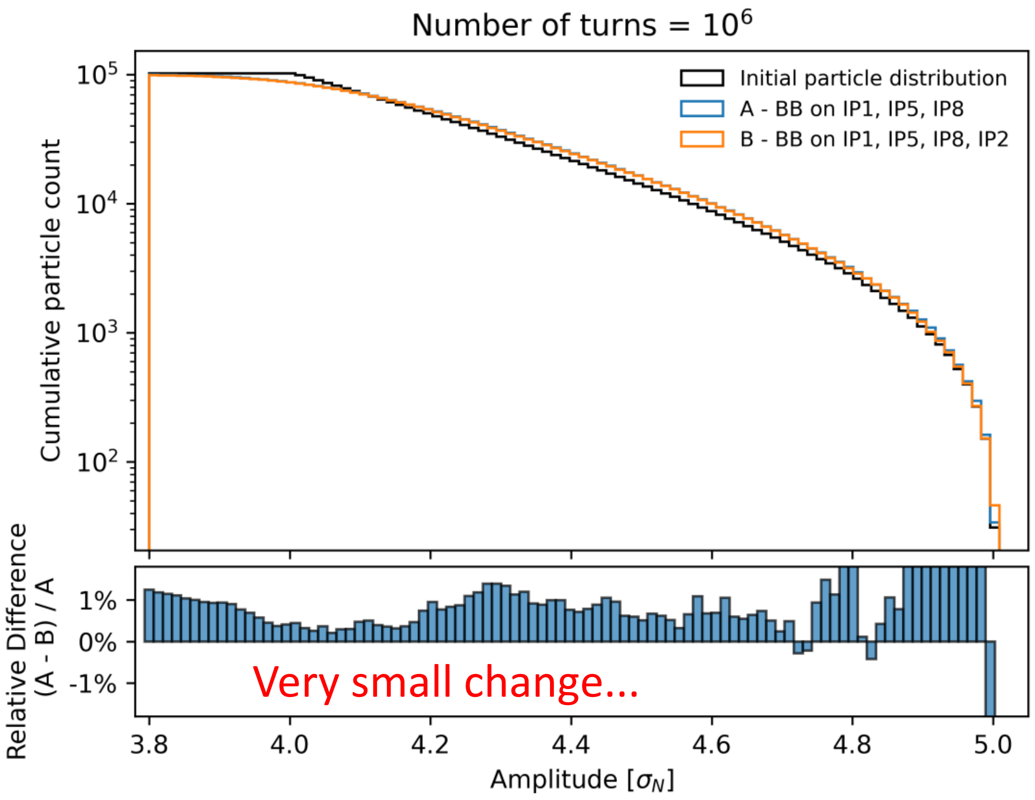
- Is the effect of IP2 BB effect in B2 visible in a single-particle tracking simulation?
- Xsuite weak-strong model used
- 2022 LHC optics, end of leveling, β*=30cm
- Octupoles @350 A
- Machine imperfections not included
- Different BB long-range and BB head-on setup
  A. All IPs except for IP2
  B. All IPs
- Nominal beam halo sampled between 4 and 5 σ_N as initial condition
- Betatron cut at 5 σ_N
- GPU tracking of 10^5 particles up to 10^6 turns (~90 seconds of LHC operation)

Not shown here: BB integration in full collimation simulations – F. Van der Veken talk



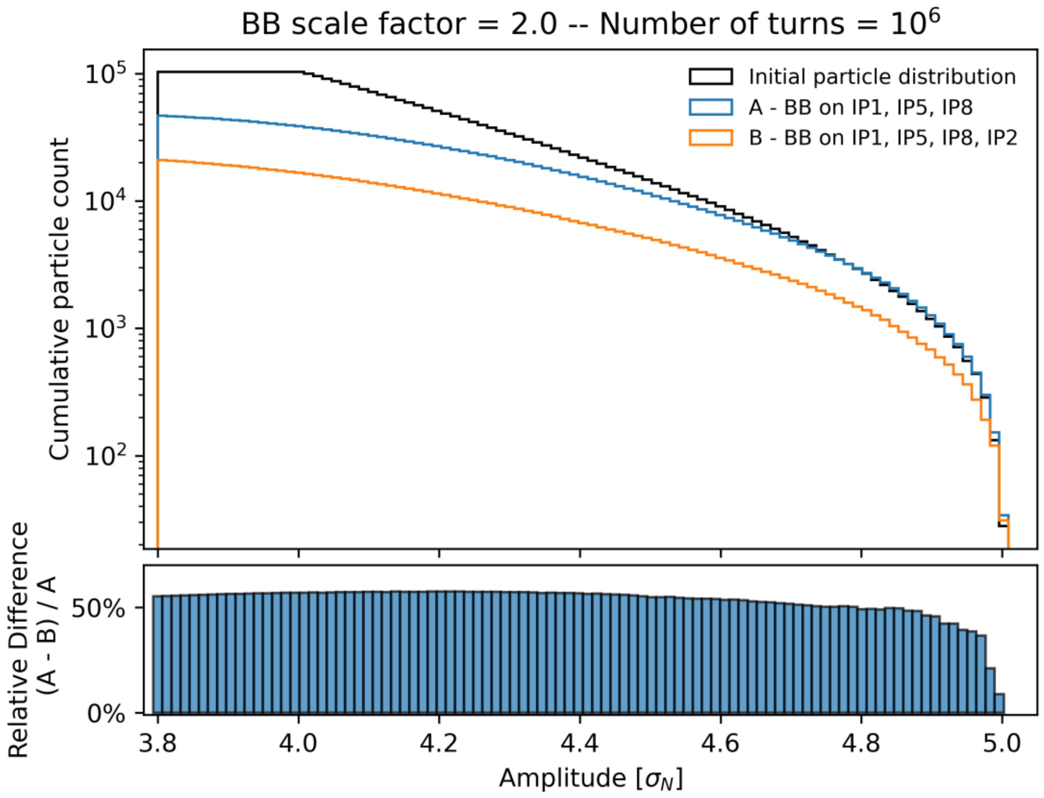
A difficult observation

- Beam halo dynamics simulation is an open challenge
- High statistics required
  - Achievable thanks to XSuite GPU implementation
  - Only requires deployment on more GPU hardware
- Longer simulation timescales required
  - Tracking took almost 2 days on a Nvidia A100
  - Scaling up to hours of LHC operation currently unfeasible



Amplify to observe

- Explorative attempt for visualizing IP2 BB effect
- Increase of BB intensity by factor 2 on all IPs
- Stronger degradation at reachable timescales
- Difference between resulting halo populations
- Possible next steps:
  - Increase number of turns in dedicated campaign
  - Focus on understanding differences between B1 and B2
  - Use extrapolation models / scale-laws to probe long-term dynamics



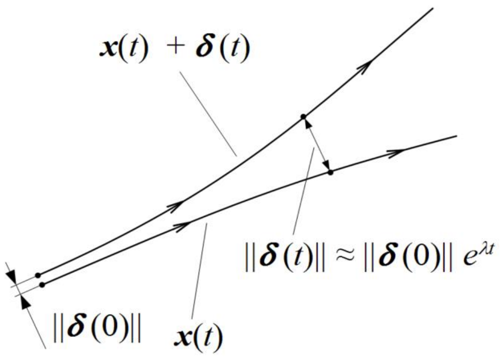
Faster depletion of (B)

Approaches under consideration: Chaos Indicators

- Lyapunov exponent: measurement of an orbit’s reaction to an initial perturbation

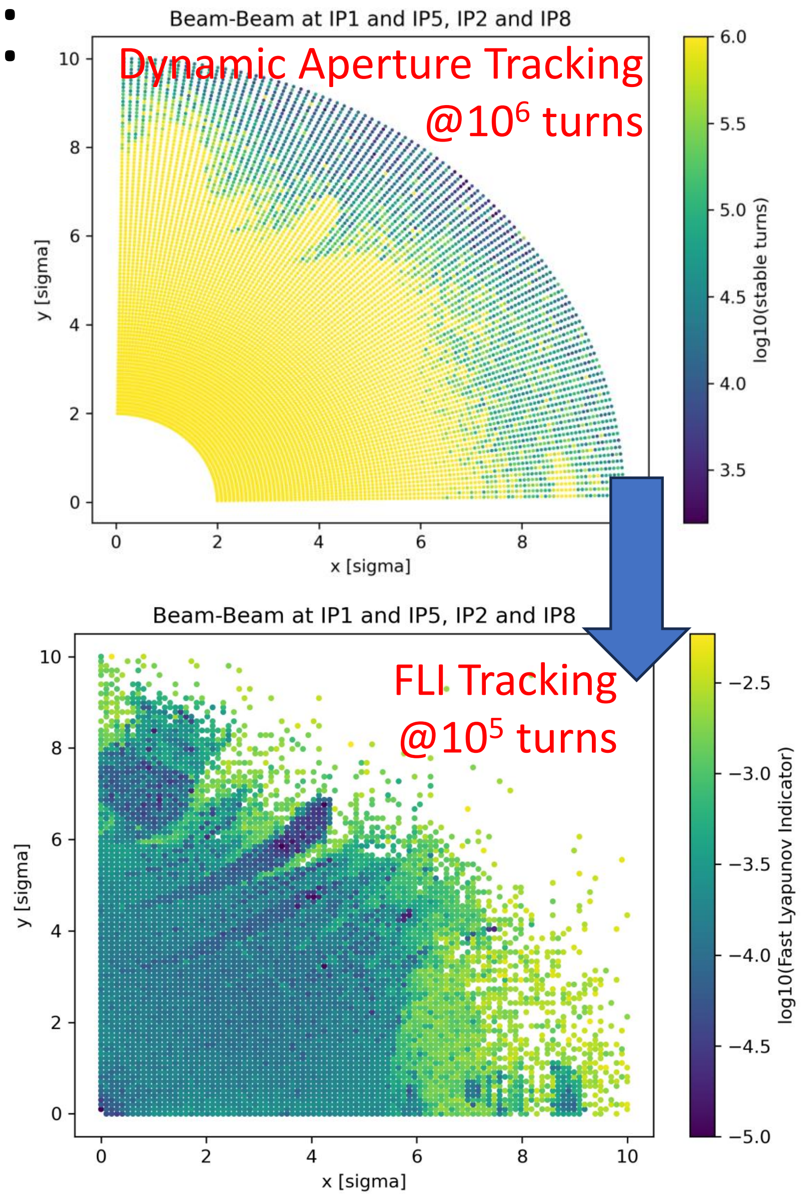
$$\lambda = \lim_{t\to\infty} \lim_{|\delta \mathbf{Z}_0|\to 0} \frac{1}{t} \ln \frac{|\delta \mathbf{Z}(t)|}{|\delta \mathbf{Z}_0|}$$

  - λ = 0 - Non-chaotic
  - λ > 0 - Chaotic



- Can be probed via Choas Indicators (e.g. Fast Lyapunov indicator FLI)

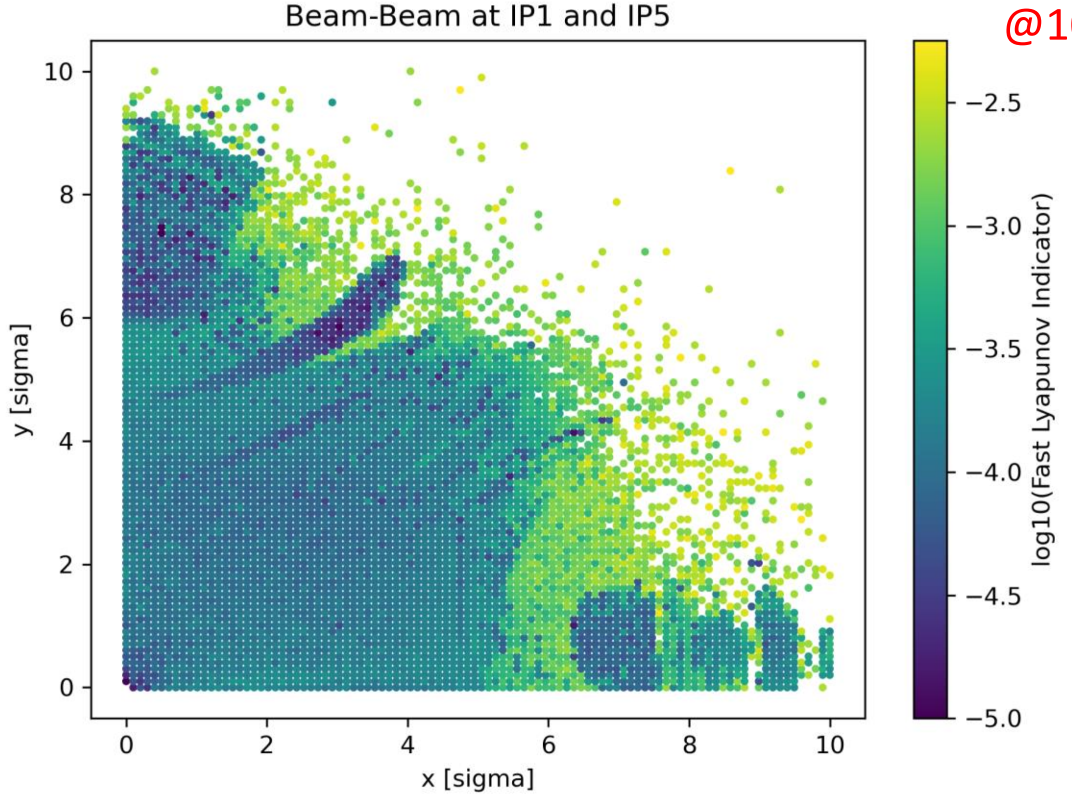
- Possible extension of "standard" dynamic aperture simulations
- Good observables for constructing extrapolation models

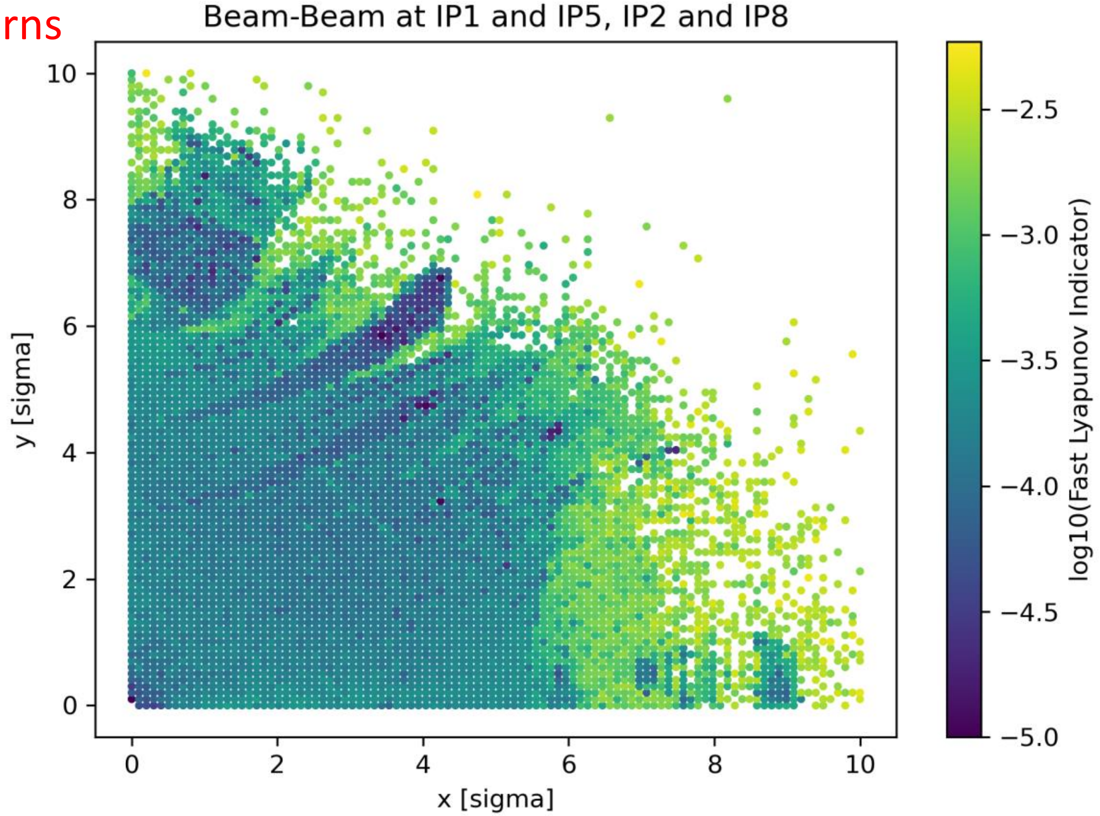


Approaches under consideration: Chaos Indicators

- Small differences in chaotic structures in the phase space may be used as base for long-term extrapolation models/scale-laws

FLI Tracking
@10^5 turns





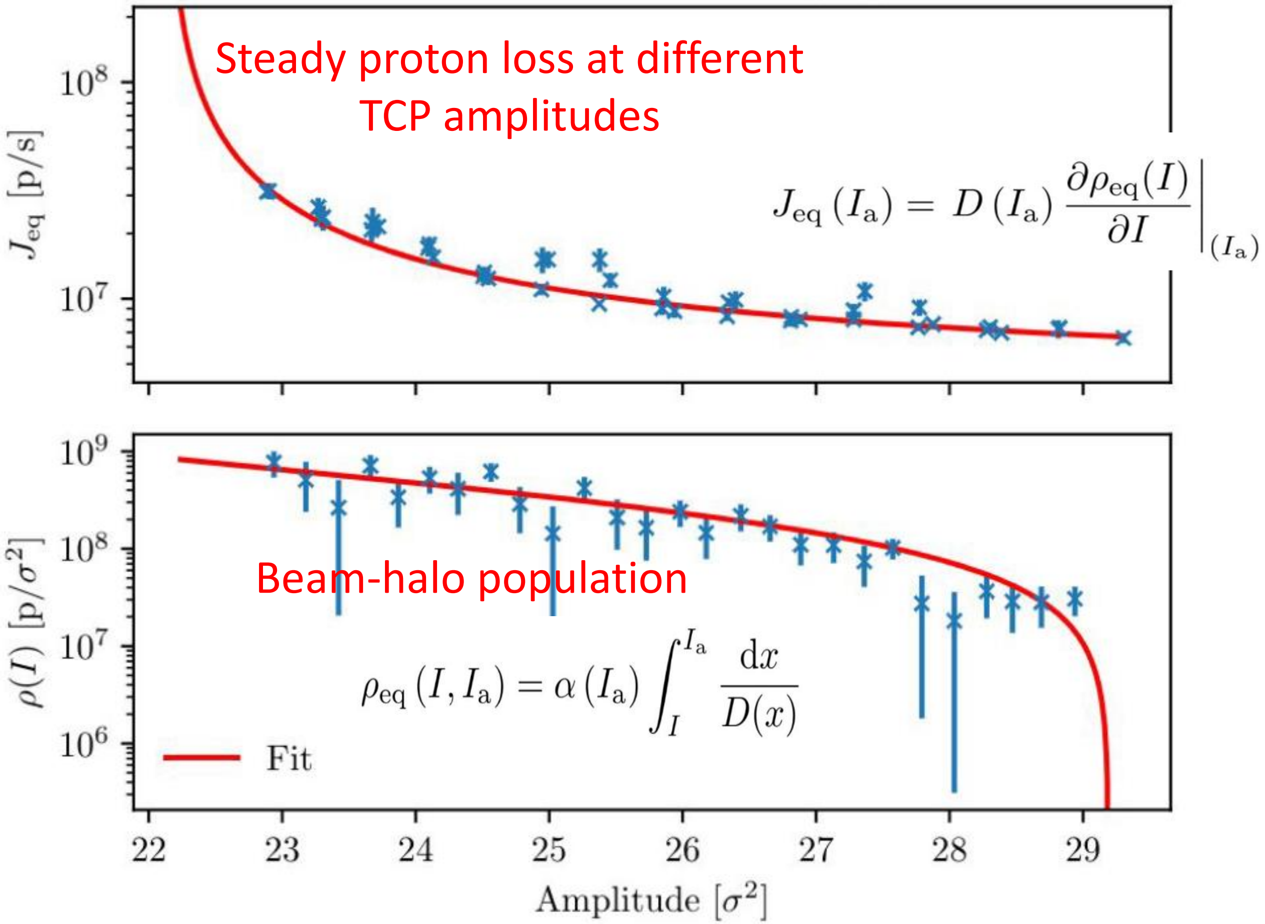
Approaches under consideration: Non-linear diffusive models

- Describe the transverse beam distribution evolution as a Fokker-Plank model:

$$\frac{\partial \rho(I,t)}{\partial t} = \frac{1}{2}\frac{\partial}{\partial I} D(I) \frac{\partial}{\partial I} \rho(I,t)$$

- Physics-based functional shape for the diffusion coefficient
- (Ideally) relate the presence of chaoitc regions to diffusion-like dynamics observed in experiments

Diffusion Measurements and Fit @Fill 8348



Conclusions

- Understanding of beam-halo dynamics is an open problem, critical for present and future LHC operation
- Multiple measurements of beam-halo correlate halo depletion to different BB effects
- Measurements of halo differences with and without various BB contributions offer great experimental data
- BB-halo interaction will become of more interest in HL-LHC when considering, e.g. Crab-cavity failure scenarios

- Simulation efforts ongoing, open to suggestions!

References

[1] - **Data-driven cross-talk modelling of beam losses in LHC collimators**, G. Azzopardi, B. Salvachua and G. Valentino, Phys. Rev. Accel. Beams, 2019.

[2] - **Optimization of tail depletion efficiency in pulsed operation of the hollow electron lens**, P. Hermes, Non-Linear Beam Dynamics WG Meeting, 24.06.2021.

[3] - **Modelling and measurements of bunch profiles at the LHC,** S. Papadopoulou et al., J. Phys.: Conf. Ser. 874/1, 2016.

[4] - **A study of beam-beam effects in hadron colliders with a large number of bunches**, T. Pieloni, Ecole Polytechnique, Lausanne, 2008

[5] - **Probing LHC halo dynamics using collimator loss rates at 6.5 TeV**. A. Gorzawski, et al., Phys. Rev. Accel. Beams 23, 044802 – Published 27 April 2020.

[6] - **Recent measurements and analyses of the beam-halo dynamics at the CERN LHC using collimator scans.** C. E. Montanari, et al. in Proc. IPAC'23, Venice, Italy, May 2023

[7]- **Performance analysis of indicators of chaos for nonlinear dynamical systems.** A. Bazzani, et al. Physical Review E 107.6 – Published 22 June 2023