Beam Halo Measurements in Run2 and Run3 - Status and Prospects

C.E. Montanari, M. Giovannozzi, P. Hermes, M. Rakic, S. Redaelli

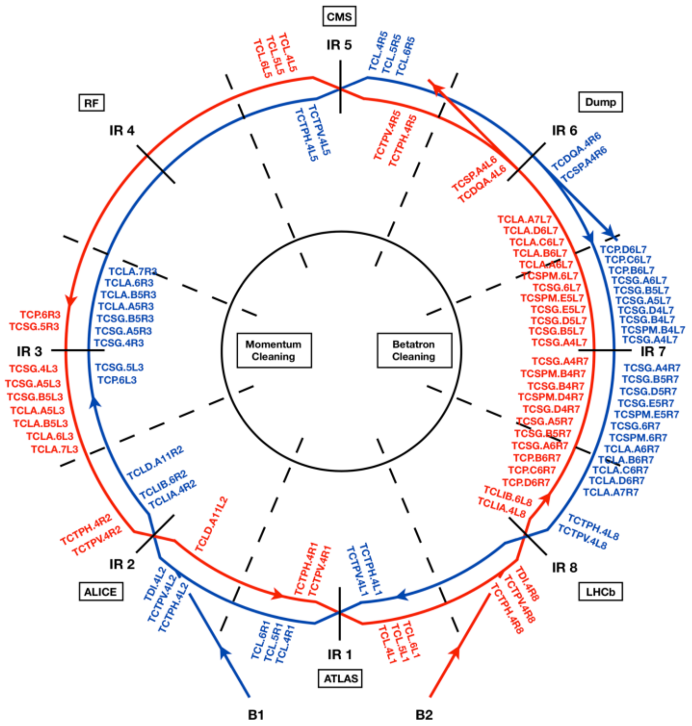
HL-LHC Beam Halo Monitor Review - 18 December 2024

Outline

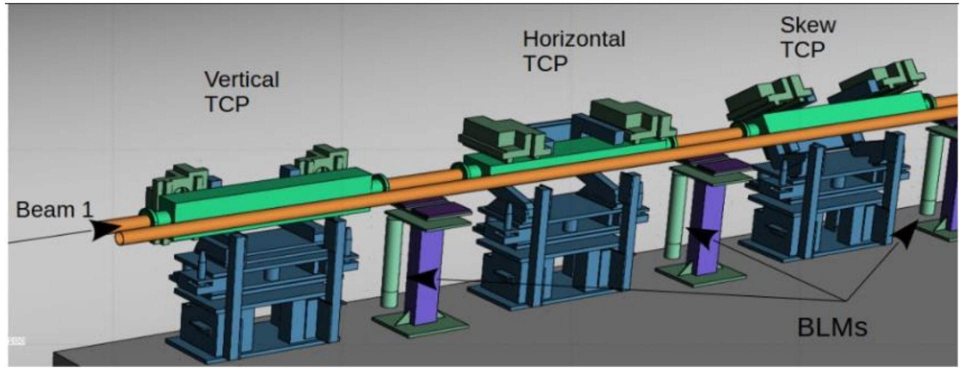
- **Introduction: LHC collimation and the halo problem**
- **Beam Halo - Measurement methodology**
  - Collimator scraping and calibrated BLM signal
  - Bunch-by-bunch visualization via fastBCT
- **Beam Halo - Recent observations**
  - Recall of Run2 and Run3
  - Correlation with e-cloud
  - Slow repopulation
  - Influence from BB effects and observed differences with BBCW
- **Ongoing modelling efforts**
  - Global diffusive models
  - Chaos indicators for single-particle tracking
  - Investigations at injection

The LHC collimator system

- **Multi-stage system**
  - Betatron cleaning in IR7
  - Momentum cleaning in IR3
  - Local protection of triplets and experiments
- **Critical for machine protection and background mitigation**
- **Multiple challenges for HL-LHC intensities**
  - Doubling of the bunch population
  - Total stored energy of 678MJ per beam
  - Higher impedance expected
  - No hollow electron lenses to mitigate the halo

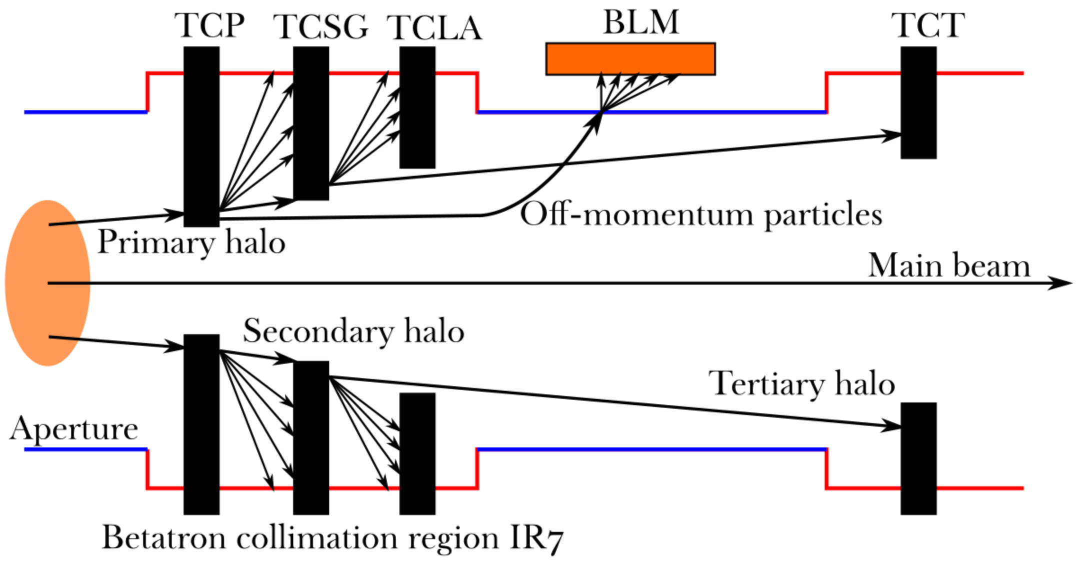


Overview of the LHC collimation system



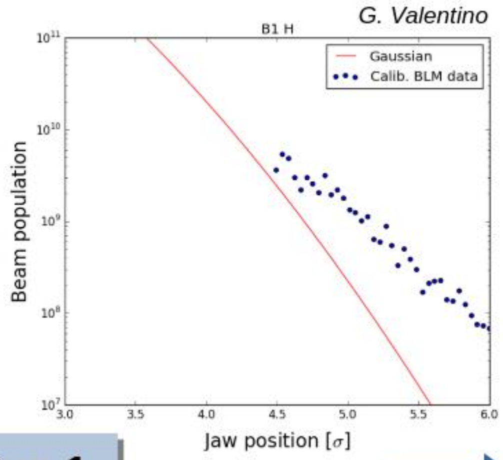
The LHC collimator system

- **Different collimation types for different purposes**
  - Primary collimators (TCP) – closest to main beam
  - Secondary and Tertiary collimators – remove particle showers, protect IPs, reduce background
- **Hierarchy designed around optics, aligned to beam centers, validated with dedicated runs**

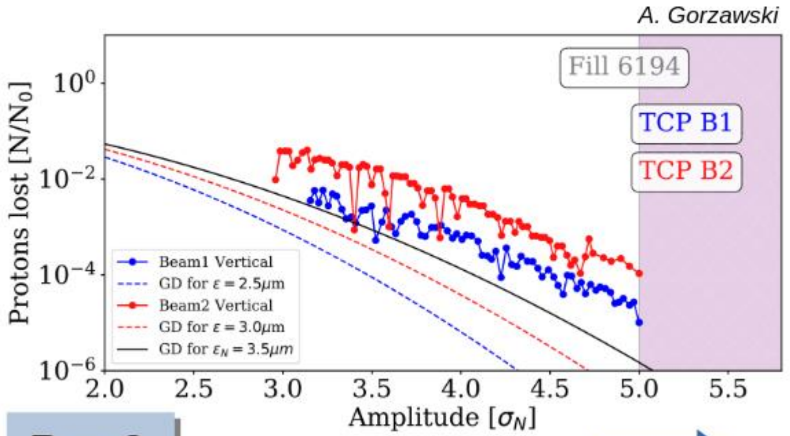


The Beam Halo Problem

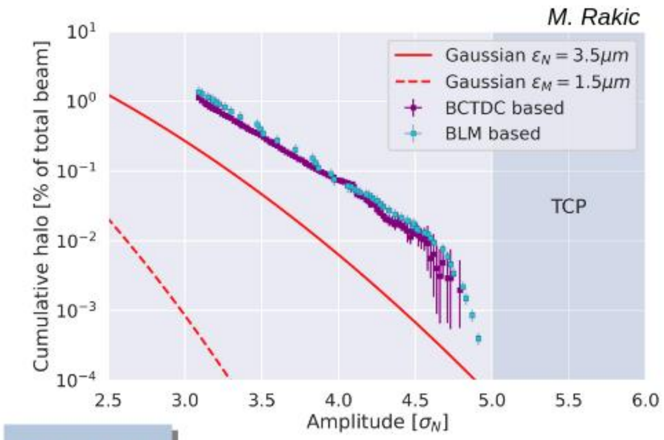
Assuming nominal σ with ε_N=3.5μm rad



Run 1

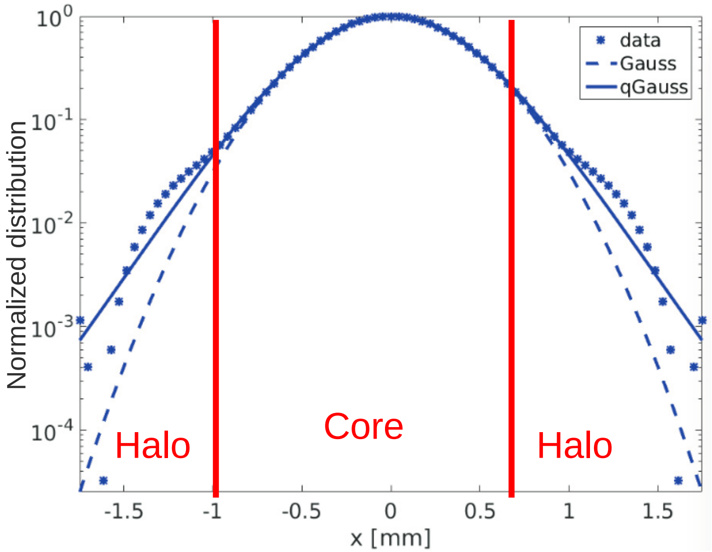


Run 2



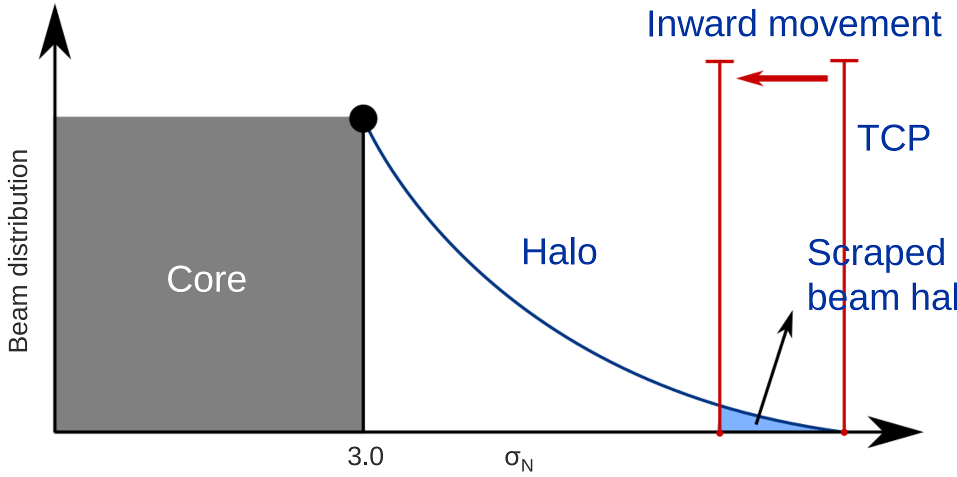
Run 3

- Transverse beam halo: **particle population above 3 σ_N**
- Measured since LHC start: **heavily populated halo**, up to 5% total intensity [ref.]
  - Risk for loss spikes, dumps, damage with orbit jitters
  - Threatening fast failure scenarios for HL if scales
  - Mitigation HW unavailable

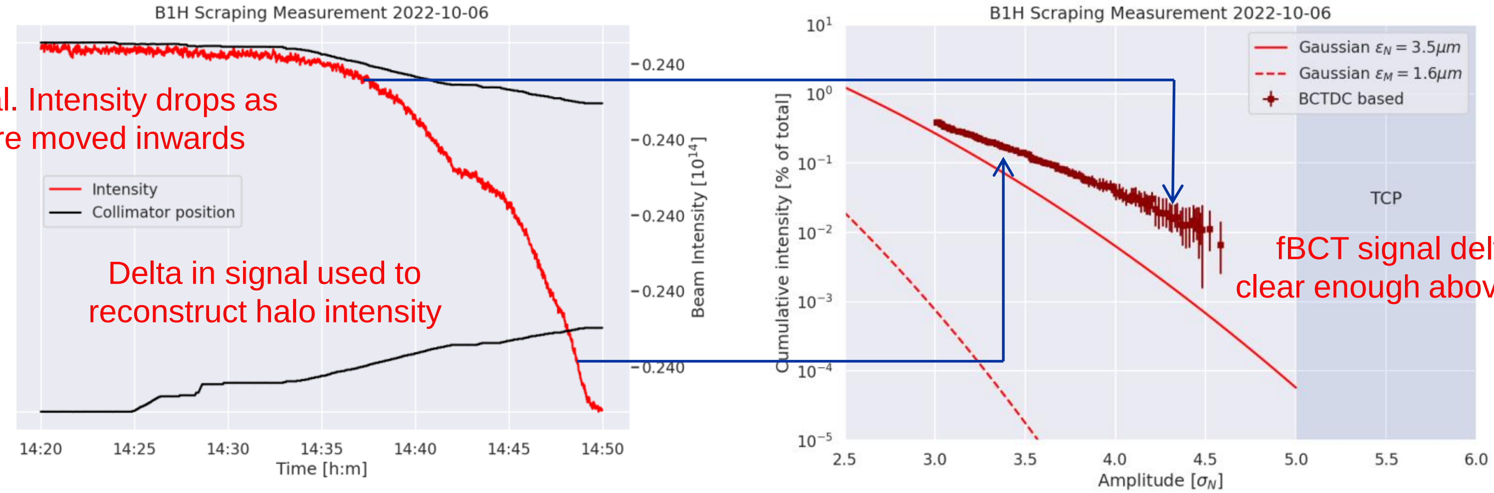


Halo measurement via collimator scraping

- Precise **indirect destructive** measurement via BLM/fBCT losses:
  - Perform BBA
  - Move TCP inwards
  - Measure induced losses
  - Integrate measured losses to reconstruct the scraped beam halo



BCT signal. Intensity drops as TCPs are moved inwards



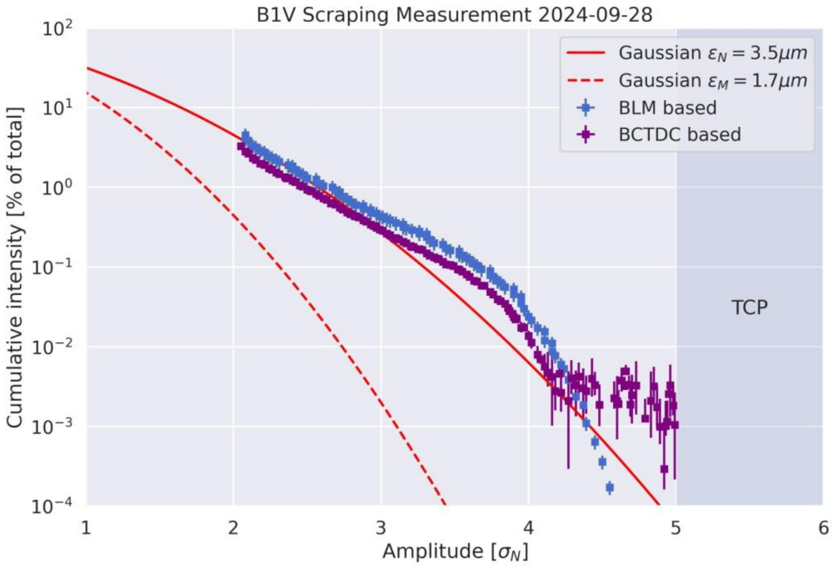
fBCT signal delta not clear enough above 4.5 σ_N

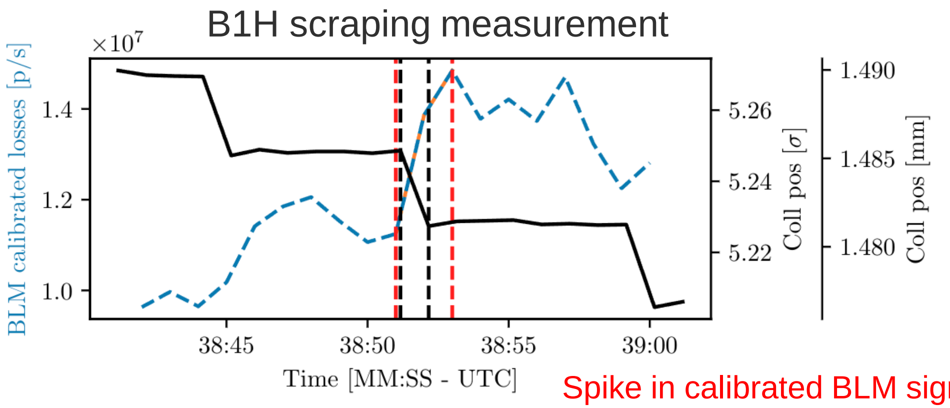
Courtesy of M. Rakic

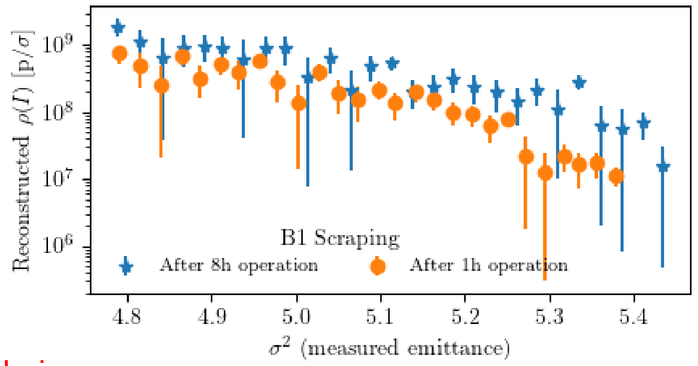
BLM calibrated signal for halo reconstruction

Courtesy of M. Rakic

- Leverage on BLMs large dynamic range
- Calibration of Gy/s signal on dedicated runs:
  - Induce high scraping losses, compare BCT intensity drop with BLM response
  - Construct Response Matrix
  - Apply inverse Response Matrix in nominal fills
- Further details here



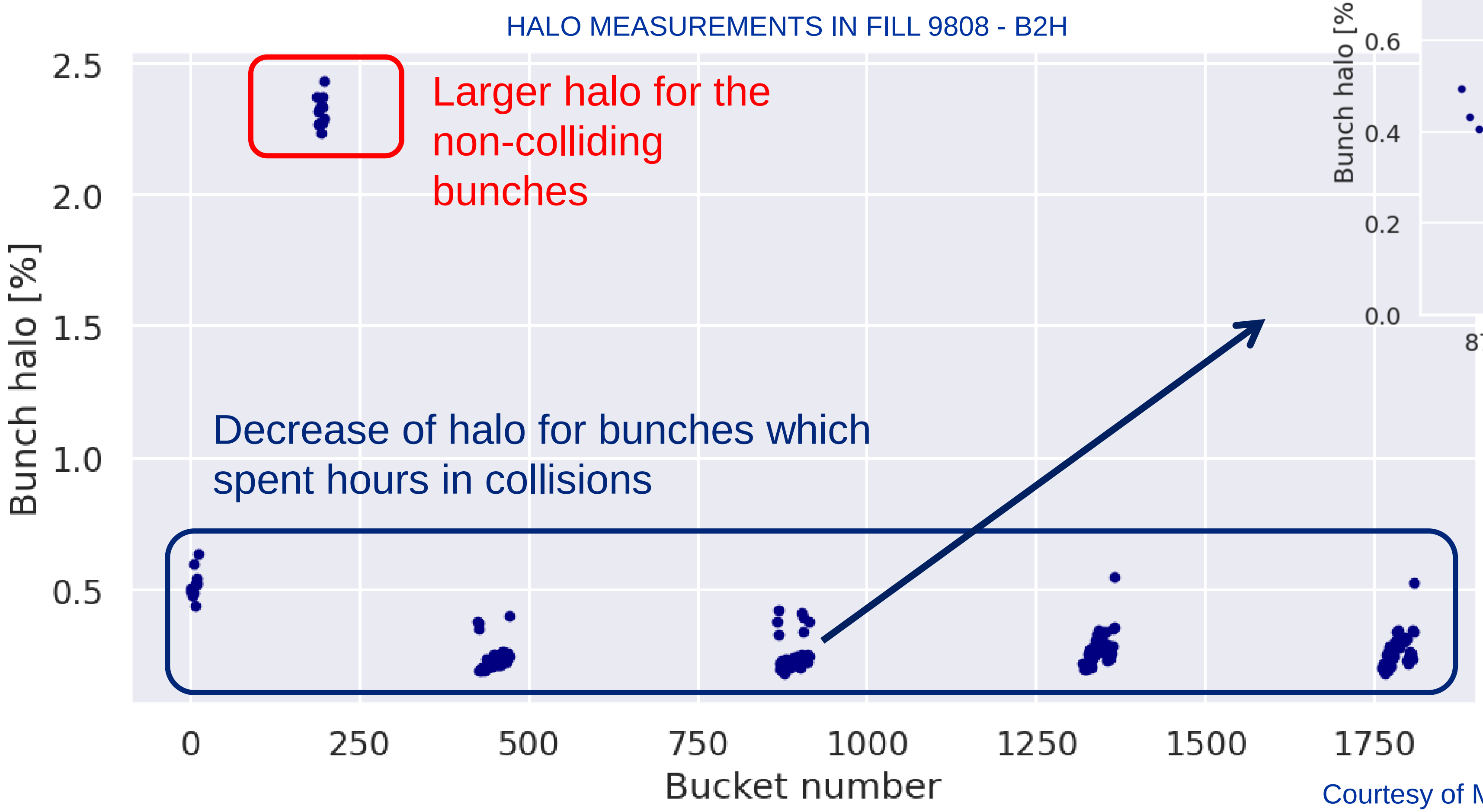


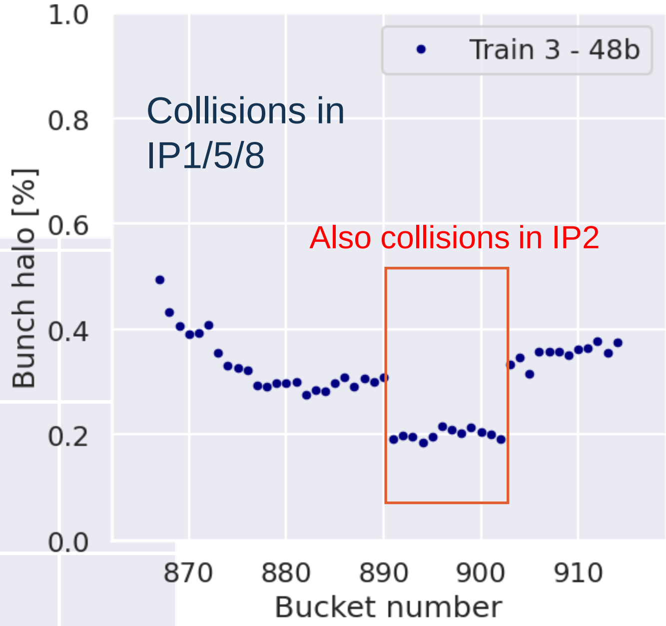


Spike in calibrated BLM signal during collimator movement considered

Visualizing the beam halo bunch-by-bunch

- **Fast BCT data enables bunch-by-bunch halo measurement**





Clear view of the impact of beam-beam effects from different collision patterns!

Courtesy of M. Rakic

Recall of Run2 Halo measurements

Date	Fill number	No. of Bunches	Final collimator position [σ] / Halo content [%] B1H	B1V	B2H	B2V	Halo content [%] at 3.0 [σ] B1H	B1V	B2H	B2V
10/05/2016	4910	313	4.1	3.9	4.0	4.1				
			0.1	1.2	0.7	1.0				
19/07/2016	5105	2076	3.8	3.1	3.1	3.4				
			0.0	1.7	0.9	0.2				
15/06/2017	5834	900	3.0	3.0	3.1	3.1	4.6	2.5		1.4
			4.6	2.5	1.4	1.4				
19/06/2017	5848	1741	3.2	/	3.1	/				
			8.7	/	8.1	/				
20/06/2017	5849	2029	3.2	/	/	3.1				
			5.3	/	/	1.3				
06/08/2017	6052	2550	3.7	3.3	3.5	2.8				2.8
			3.0	5.2	1.0	5.5				
13/09/2017	6194	224	2.3	2.4	2.1	2.2	6.2	1.5	0.1	1.8
			29.5	7.9	6.8	19.6				
25/09/2018	7221	2550	/	3.0	/	3.2		5.6		
			/	5.6	/	0.6				
06/10/2018	7264	2550	2.9	3.1	3.3	2.8	1.5			1.0
			2.4	0.6	1.0	2.1				
30/10/2018	7392	300	3.5	2.0	2.9	2.0		0.7	4.4	0.2
			10.0	9.4	5.7	2.5				

Recall of Run3 Halo measurements

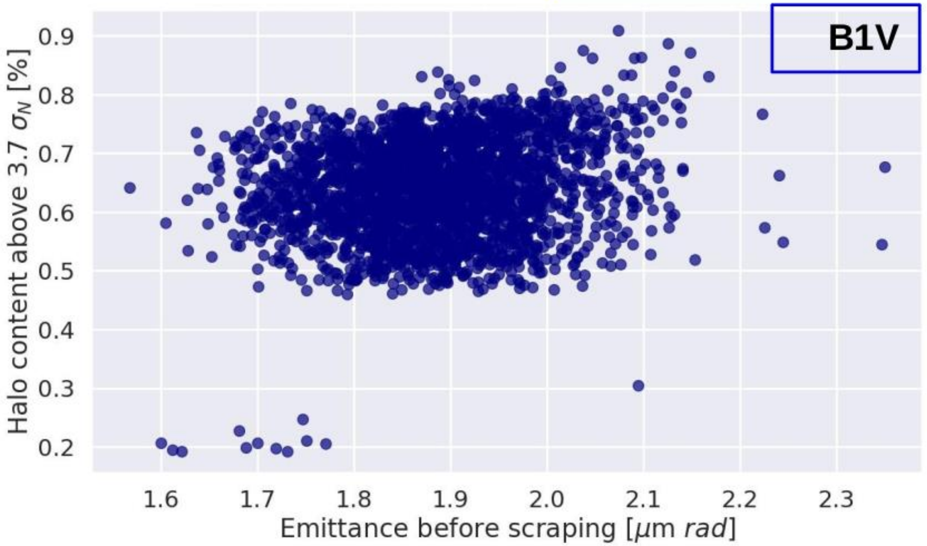
				Final collimator position [σ] Halo content [%]				Halo content [%] at 3.0 [σ]			
	Fill number	Stage	No. of Bunches	B1H	B1V	B2H	B2V	B1H	B1V	B2H	B2V
06/10/2022	8233	EOF	200	3.0	3.1	3.2	3.1	0.3	0.2	0.3	0.6
				0.4	**0.2**	**0.3**	**0.6**				
25/10/2022	8313	EOF	1200	3.1	3.5	3.0	3.6	1.2		0.2	
				1.2	**0.6**	**0.3**	**1.4**				
12/11/2022	8387	EOF	2462	3.5	3.7	3.7	3.4				
				0.9	**0.3**	**0.1**	**0.7**				
09/06/2024	9754	INJ	624	2.8	2.8	2.7	2.7	3.3	1.5	1.8	1.8
				4.7	**2.8**	**4.0**	**4.5**				
09/06/2024	9756	INJ	624	2.8	2.9	2.7	2.7	3.6	1.7	2.0	2.0
				5.0	**2.4**	**3.7**	**3.9**				
29/06/2024	9808	EOF	1238	2.6	/	2.6	/	0.8		0.3	
				2.6	/	**1.1**	/				
12/08/2024	9996	EOF	2351	3.1	3.2	3.2	3.5				
				0.7	**0.1**	**0.4**	**0.2**				
22/08/2024	10045	INJ	96	/	1.7	/	1.5		1.3		1.3
				/	**26.5**	/	**31.5**				

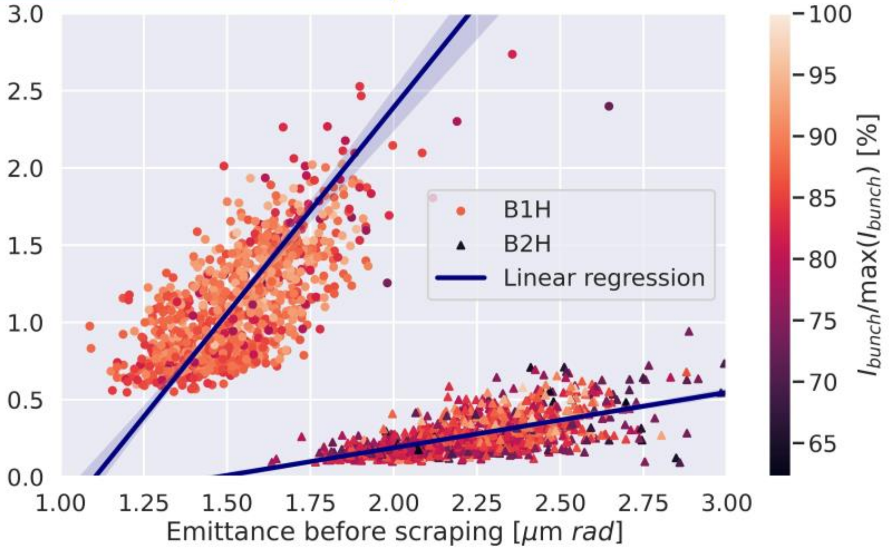
Correlation with initial emittance

- **Can beam halo population be related to initial beam emittance?**
- Spurious correlations have been observed, but no systematic relations so far
- More details available here

2022 measurements

Courtesy of M. Rakic

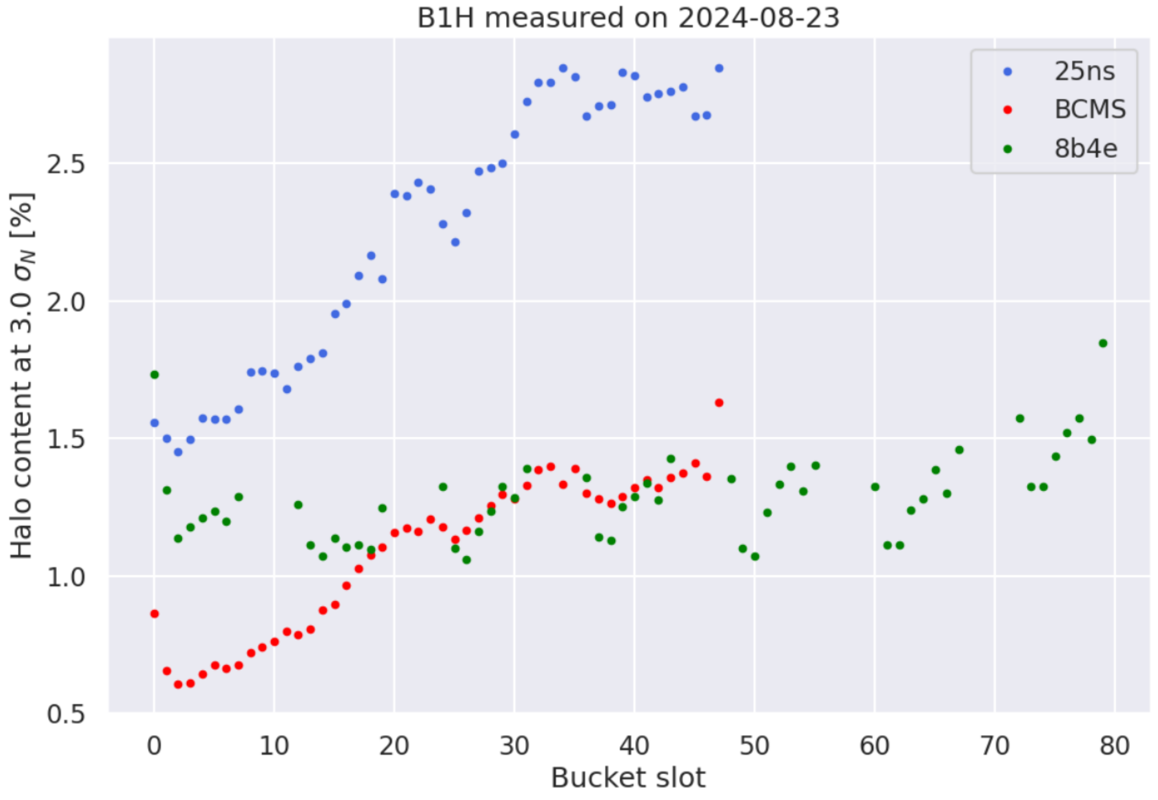




Electron cloud and beam halo

- **Recent halo measurements performed at Flat Top (@MD9325)**
- **Comparison of halo population intra-train between different train typologies**
  - 25ns: standard train
  - BCMS: 25ns batch compression, merging, and splitting train
  - 8b4e: train designed to minimize electron cloud presence
- **Strong correlation between halo population and electron cloud intensity**

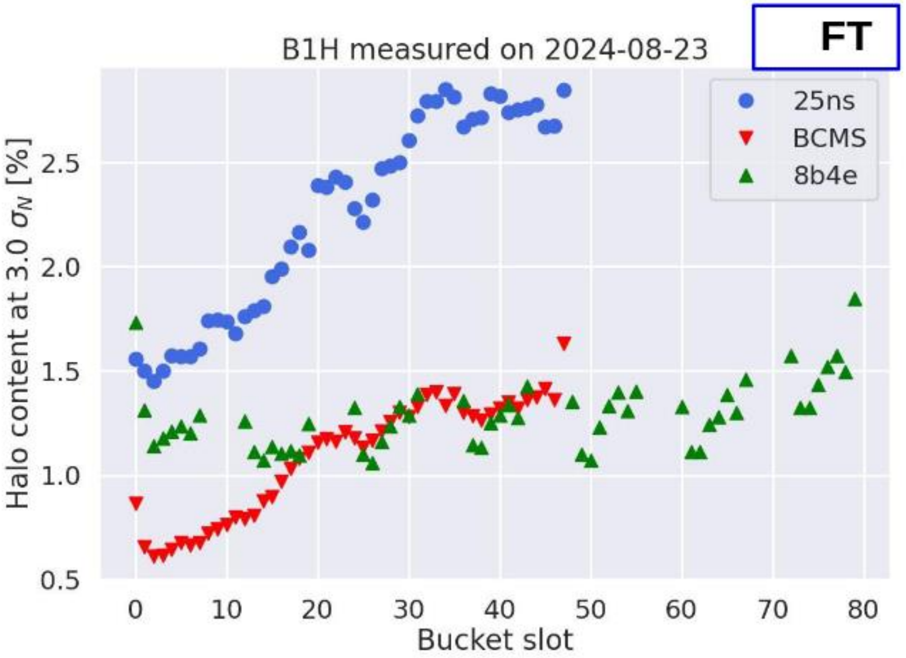
Collimator scraping @ Flat Top

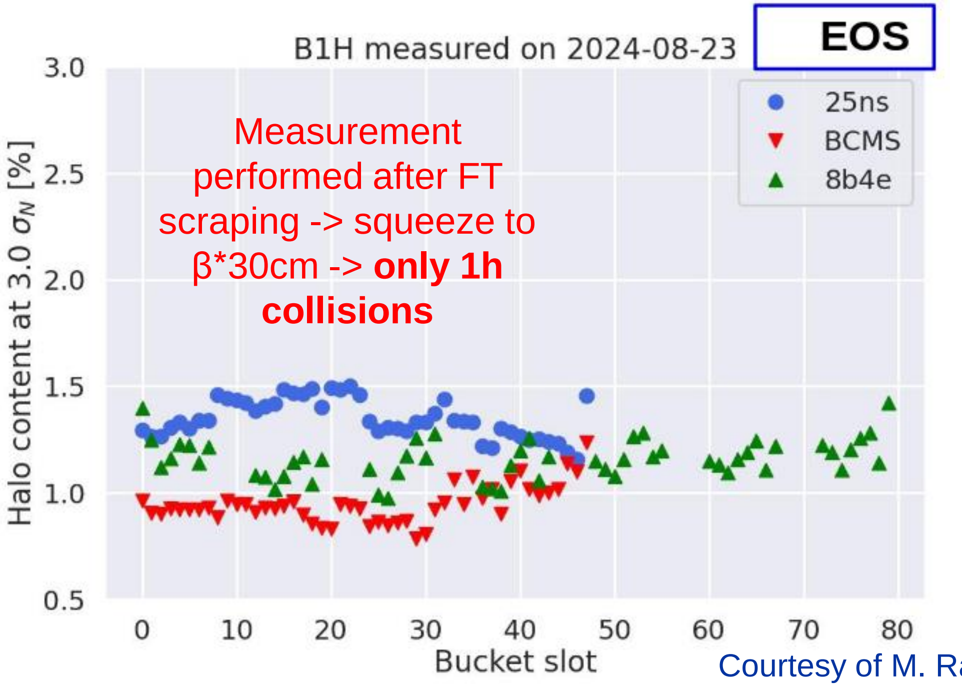


Courtesy of M. Rakic

A slow repopulation

- A collimator scraping removes the beam halo
- Repeated measurements in same fill suggest long repopulation times (order of hours)
- Huge challenge for making comparable measurements!





Courtesy of M. Rakic

Halo distribution and wire compensator impact

- **Two EOF scrapings:**
  - Fill 9808: wire kept **OFF 1h before** scraping, **10 min between** OFF/ON,
  - Fill 9996: wire kept **ON 5.5h before** scraping, **10 min between** ON/OFF

On nominal settings, no visible impact of wires on halo population between

Fill	No. bunches	Scraping no.	Wire state	B1H	B1V	B2H	B2V
9808	1238	1	OFF	0.8	/	0.3	/
		2	ON	0.15	/	< 0.1	/
9996	2351	1	ON	0.7	0.1	0.4	0.2
		2	OFF	0.15	0.01	/	/

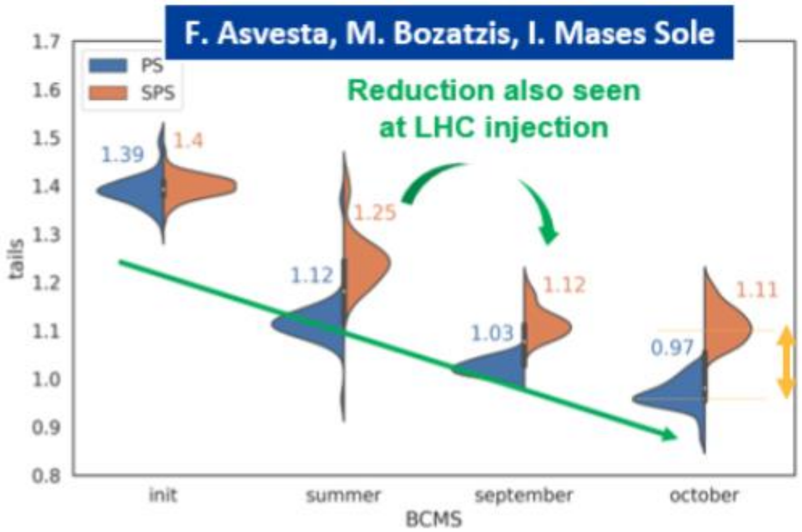
Table: Measured halo content in [%] at 3σ.

Need for a comparative study with wires kept ON/OFF equal amount of time

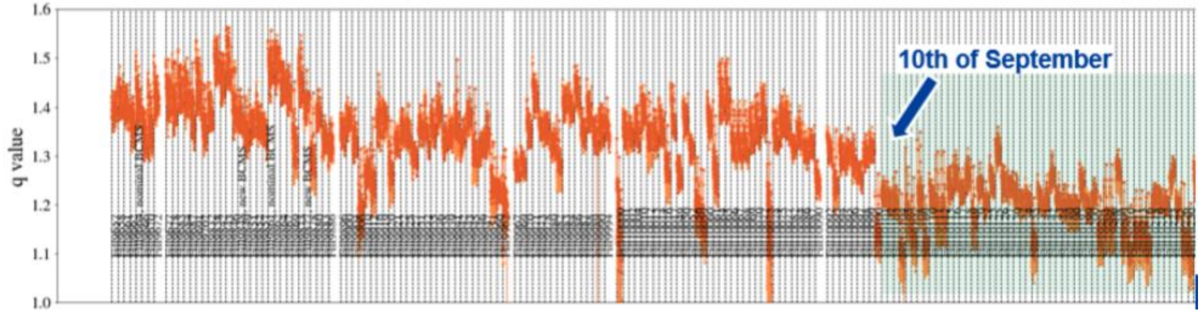
BB-dominated configurations show more visible effects (in later slides)

Open investigation - halo induced at injection

- Slow repopulation times suggest main halo source **may come from injection**
- This checks out with observed improvements after LIU
- Overview on the topic presented by S. Kostoglou at recent JAPW



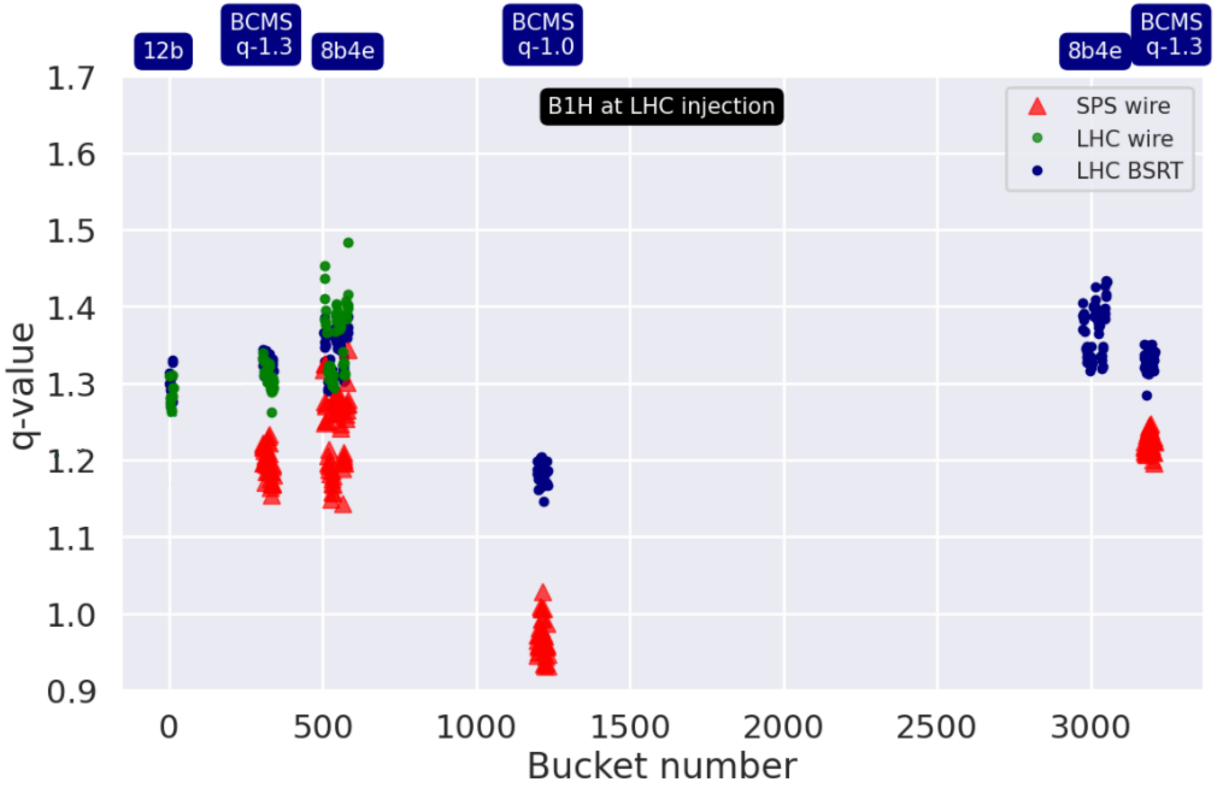
- Modeling of beam tails/halo by means of q-gaussian distributions
- Degradations in beam-halo populations can be traced back up to the PS!
- Main improvements achieved with last iteration of BCMS
- **Still an open chalenge relating beam profiles to beam halo scraping measurements!**



Comparison with SPS halo population

- Comparison of q-value evolution from SPS measurement to LHC at flat bottom

- Clear increase in q-value along the SPS-LHC transfer line
- Biggest relative increase for the case BCMS q-1.0 (most scraped at SPS level)



Courtesy of M. Rakic

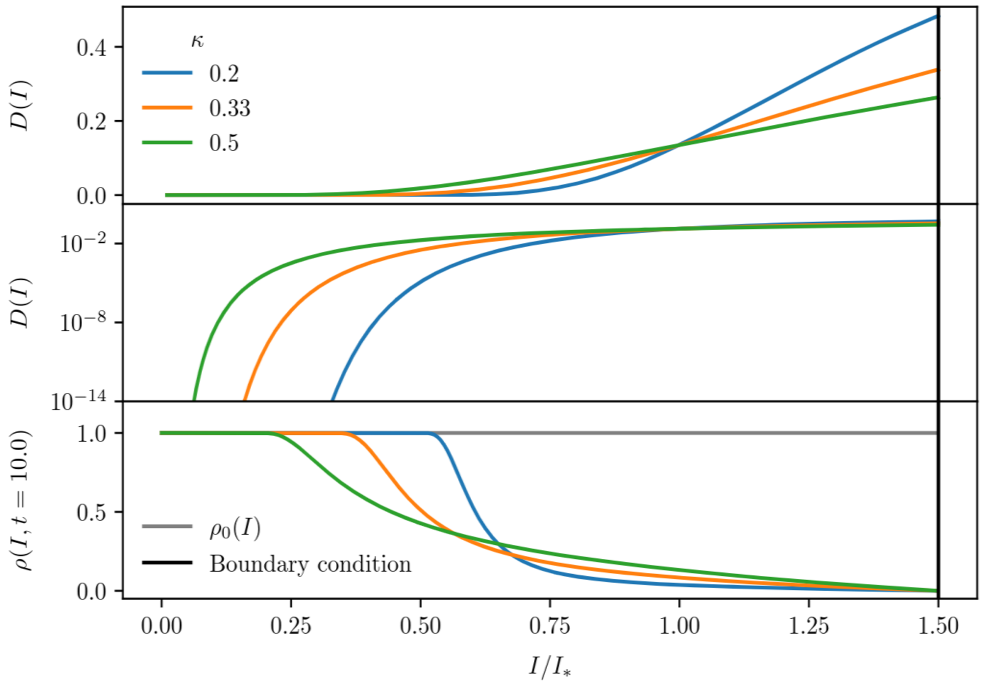
Investigating scale-laws: diffusion models

- Natural extension of established Dynamic Aperture scale-laws [A. Bazzani et al.] and local diffusion measurements performed in the LHC [A. Gorzawski et al.]
- Description of beam distribution as solution of a Fokker-Plank equation

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

where perturbations are summarized by the diffusion coefficient with functional form:

$$D(I) \propto \exp\left[-2\left(\frac{I_*}{I}\right)^{\frac{1}{2\kappa}}\right]$$



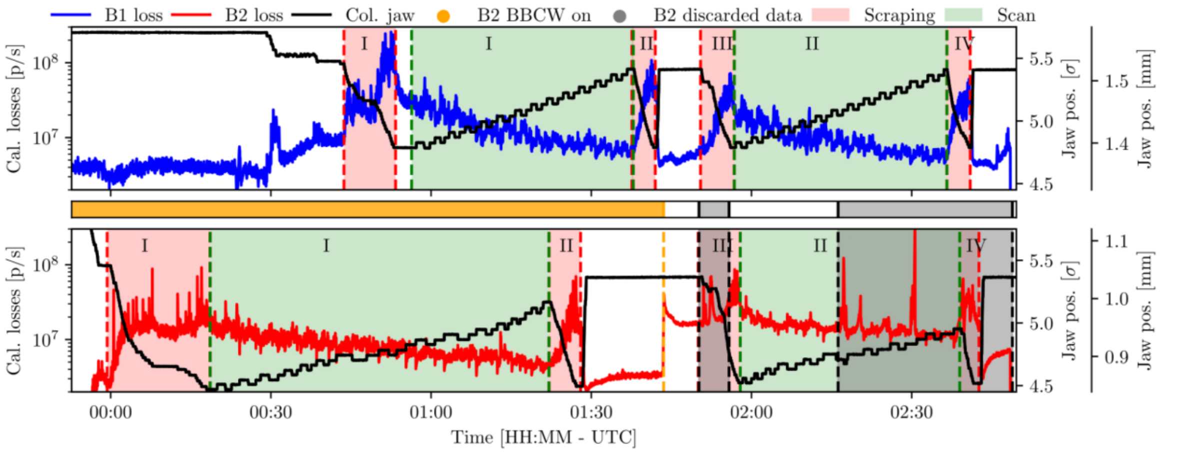
- I is the action variable
  - σ^2 evaluated with measured beam emittance
- Equation valid only for the beam-halo!
- Beam core expected to follow a separate regime (mostly due to Beam-beam head-on effects)

Observable from our diffusive model

BEAM-HALO POPULATION

$$\rho_{\mathrm{eq}}\left(I, I_{\mathrm{a}}\right)=\alpha\left(I_{\mathrm{a}}\right) \int_{I}^{I_{\mathrm{a}}} \frac{\mathrm{d} x}{D(x)}$$

Measured by means of Collimator Scrapings



BEAM-LOSS SIGNAL AT DIFFERENT AMPLITUDES

$$J_{\mathrm{eq}}\left(I_{\mathrm{a}}\right)=D\left(I_{\mathrm{a}}\right) \left.\frac{\partial \rho_{\mathrm{eq}}(I)}{\partial I}\right|_{\left(I_{\mathrm{a}}\right)}$$

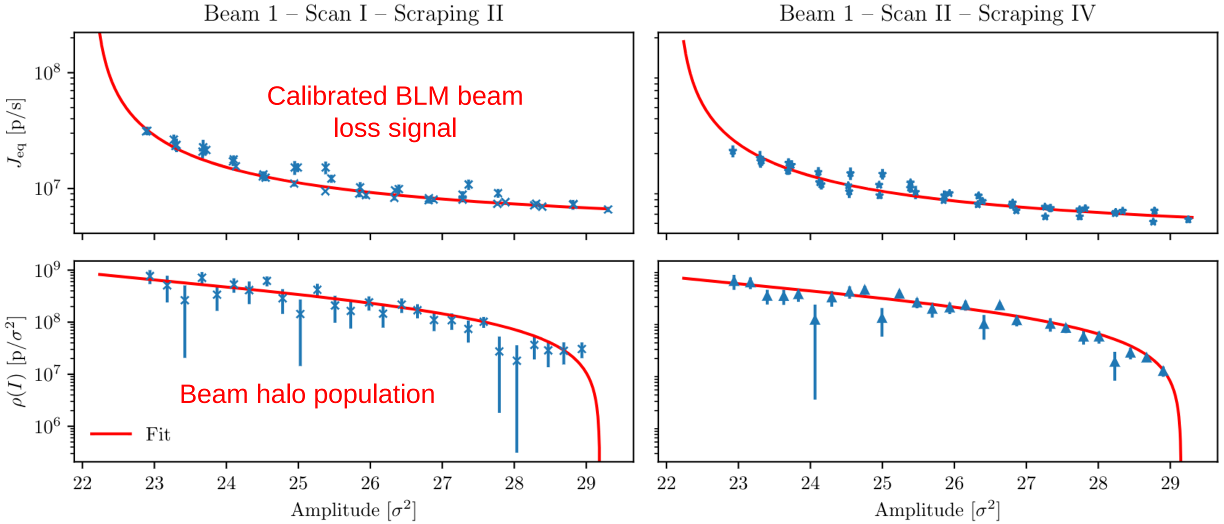
Measured while retracting the collimator

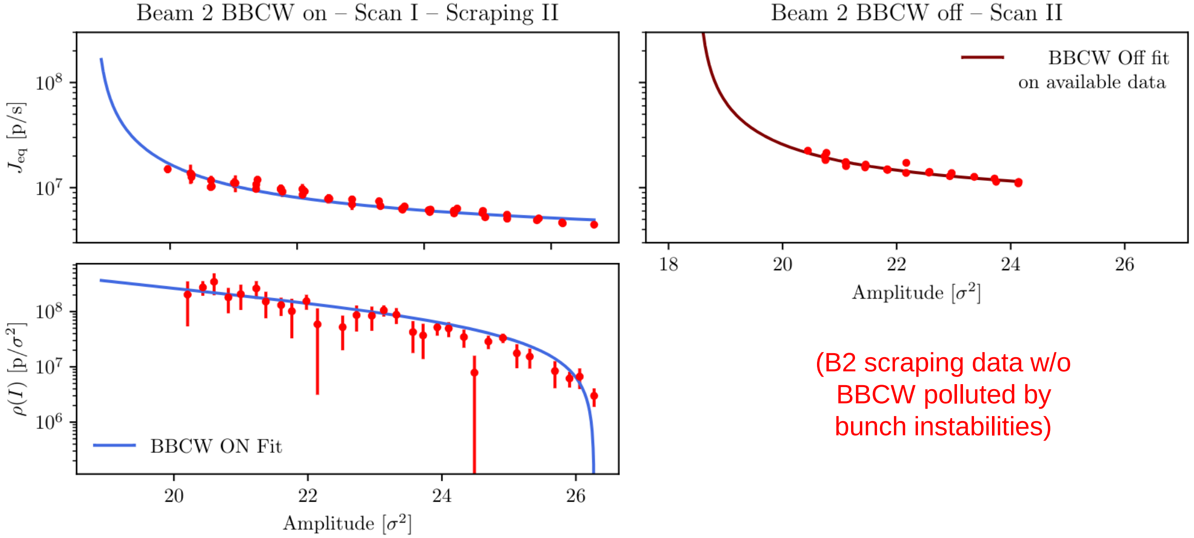
- Outward movements or alternation of outward and inward movements **with pauses in between**;
- J_{eq}; is the stabilized BLM beam-loss signal

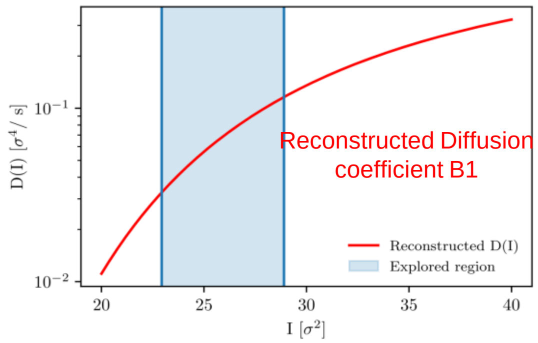
Measurement performed at the end of Beam-Beam wire compensation MD in 2022

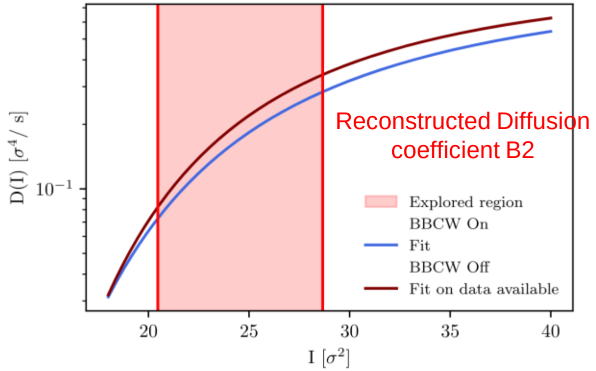
- Special configuration dominated by BB effects
- Wire compensation available in B2

An example of diffusion reconstruction







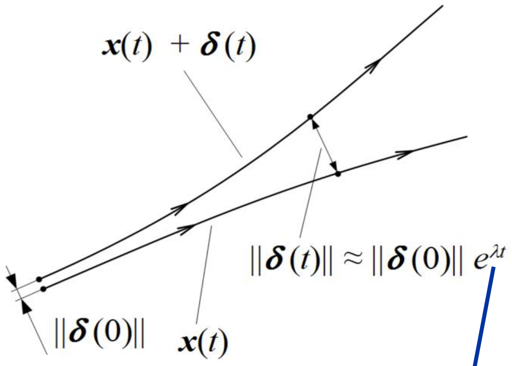


- **Overall great fit reconstruction**
- **Able to relate both beam-halo and equilibrium beam loss signal**
- **Lower diffusion reconstructed with Beam-Beam wire compensators on**

- Initial analysis of B1 presented at IPAC'23
- Complete work to be published on EPJ Plus @ C.E. Montanari et al. "Measurement of the nonlinear diffusion of the proton beam halo at the CERN LHC"

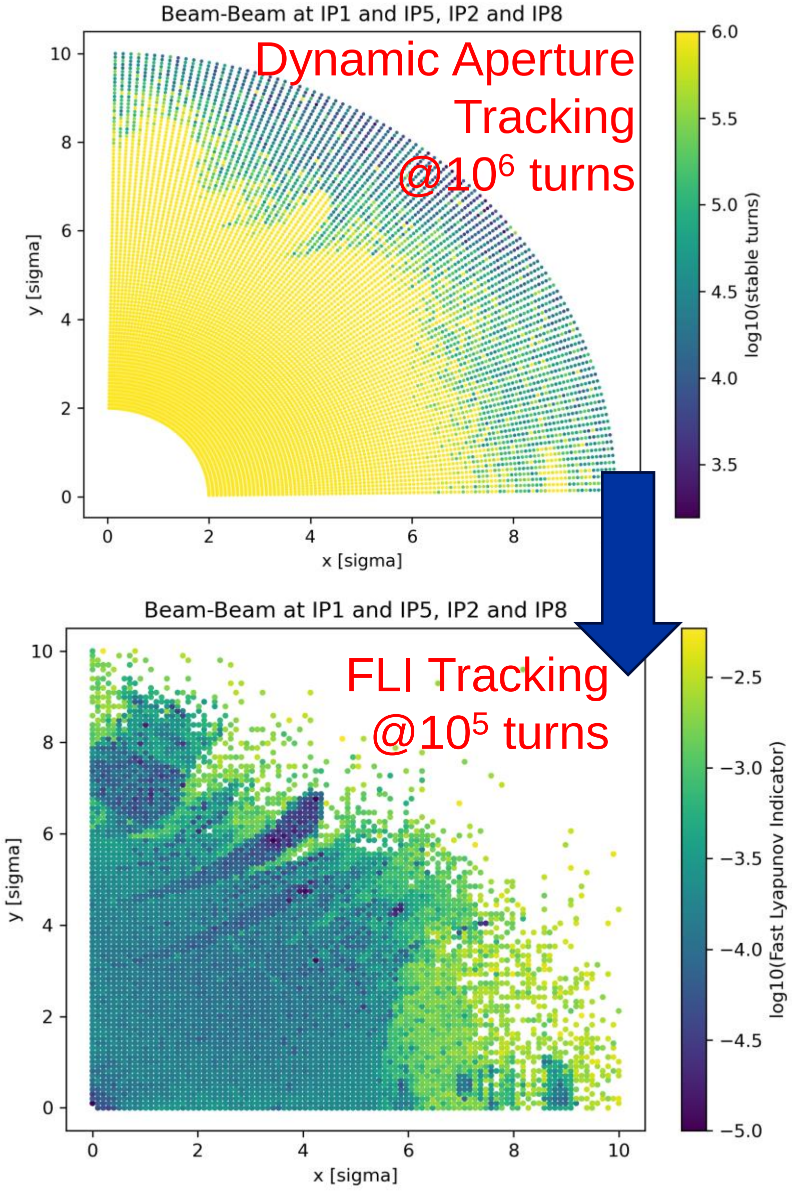
Enhancing single-particle tracking: Chaos Indicators

- Chaos: sensitivity of a particle orbit to initial perturbations



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

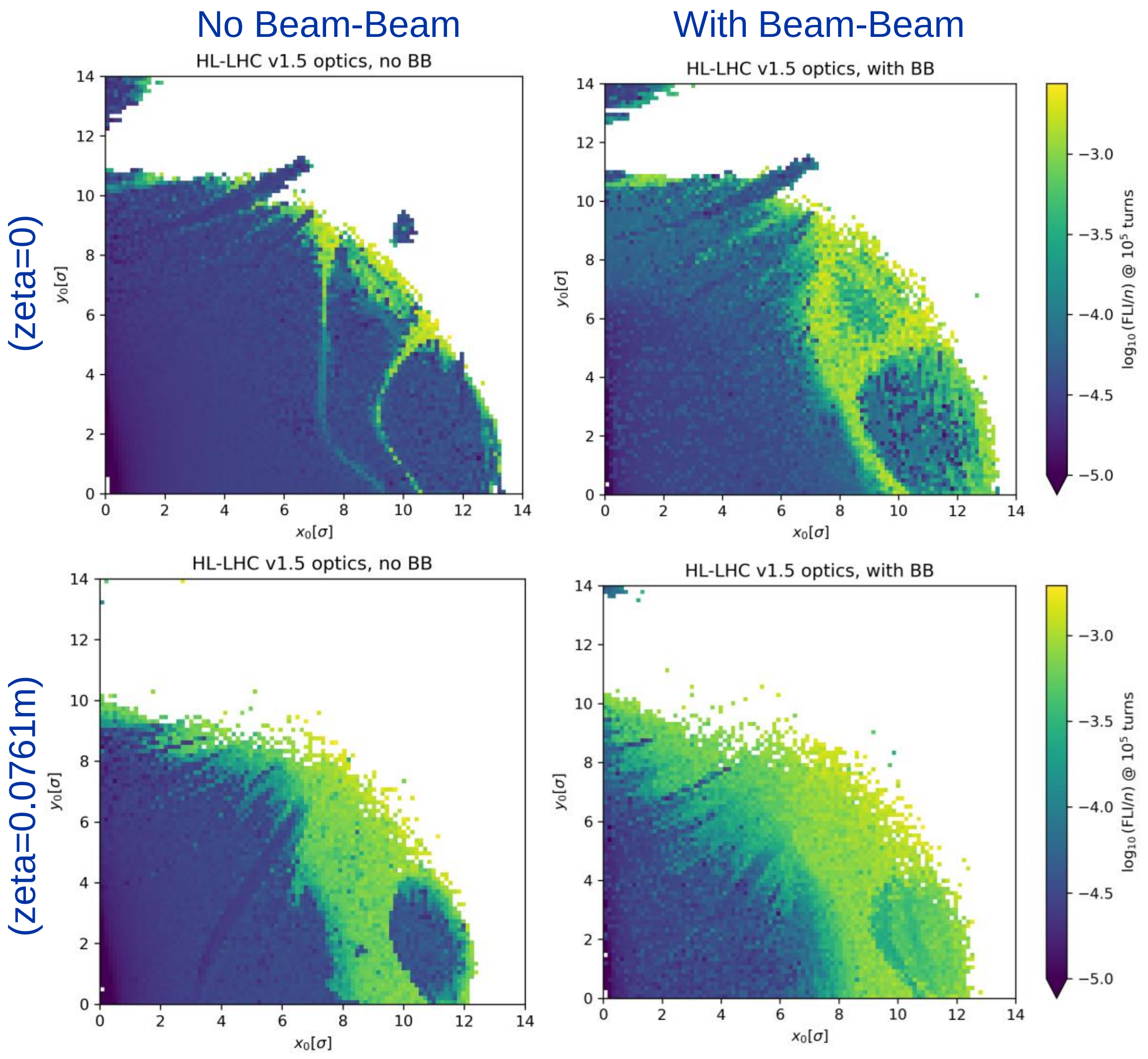
- Performance studies based on chaos have been performed in the past with, e.g., the Fast Lyapunov Indicator (FLI)
- We are studying applications of more advanced chaos indicators
- Implementation (CPU/GPU) on Xsuite under the package Xnlbd



Example of FLI evaluation on HL-LHC lattice

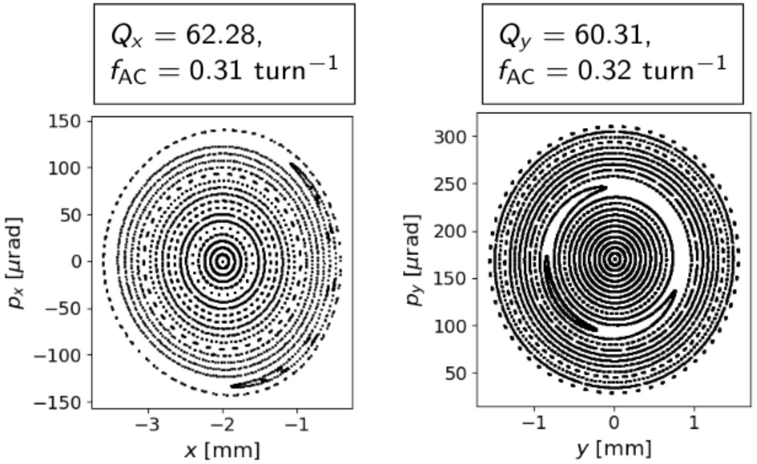
- **Lattice considered with and without Beam-Beam effects**
- **Different chaos topology with BB weak-strong**
  - Thin chaotic border and resonance-like lines without BB
  - Large regions of chaos appearing with BB long-range;
- **Light chaos can be observed up to the core region of the beam due to head-on BB;**
- **Chaos topology reflects interplay of nonlinear contributions (beam-beam, longitudinal motion, etc.)**

- **Ongoing work: connect observed chaos timescales to diffusion presence/halo population**



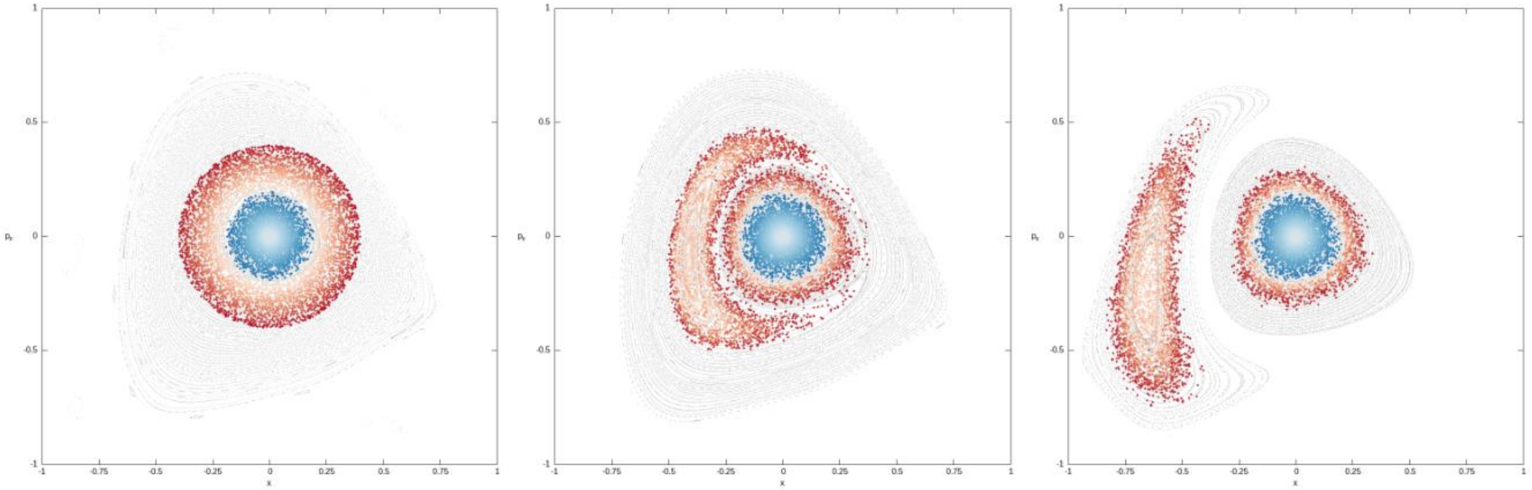
Novel halo depletion approach under study: halo cleaning via AC magnets

- **Island trapping & transport could be a solution to halo cleaning**
- **Adiabatic changes ideally via AC multipoles**
- **Theoretical approach by F. Capoani et al.**
- **Initial simulation attempts with LHC AC dipoles under study by D. Veres**



Courtesy of D. Veres

- **For more information!**



Courtesy of F. Capoani

Conclusions and outlook

- **Influencing factors on halo population**
  - E-cloud effects
    - Observed clear correlation between e-cloud and halo population
  - Long-Range Beam-Beam (LRBB) wire compensators
    - Impact on halo population is unclear
    - Requires studies with extended configuration times for halo relaxation and re-population
    - Better observations achieved on BB-dominated settings
- **Halo evolution across LHC stages**
  - Halo increases from SPS to LHC
  - Energy ramp in the LHC does not appear to be the main driver of halo re-population
- **Ongoing and future efforts**
  - Relating beam profile measurements to observed beam halo measurements
  - Developing diffusive models to predict and extrapolate long-term halo behavior
  - Enhancing insights from single-particle tracking simulations using chaos indicators
  - Exploration of alternative depletion methods based on AC magnets ongoing!

Thank you!