Halo Studies Including Hierarchy Breakage

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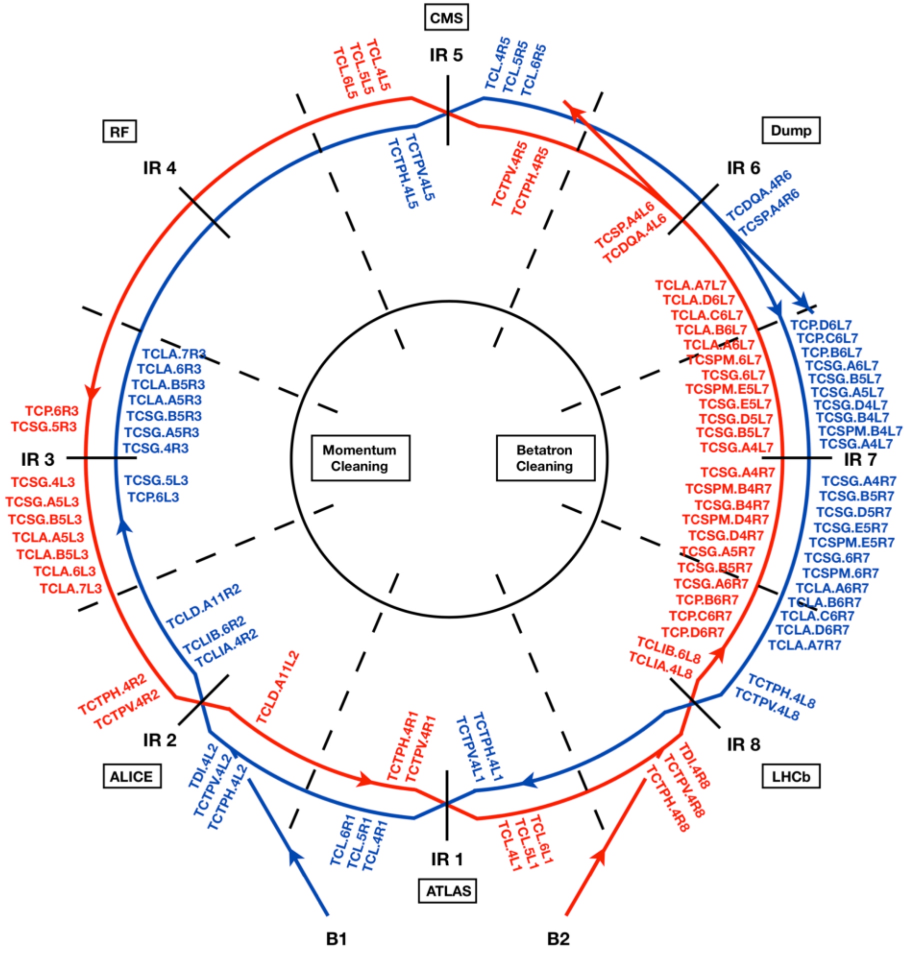
HL-LHC Collaboration Meeting - Genoa - 9 October 2024

Outline

- **Introduction: LHC collimation and hierarchy**
- **Beam Halo: definition, overview and measurements**
  - Collimator scraping overview
  - Update on recent observations
- **Ongoing modelling efforts**
  - Global diffusive models
  - Chaos indicators for single-particle tracking
- **Notes on Hierarchy Breaking**
  - Overview of the problem
  - Recent simulation efforts ongoing

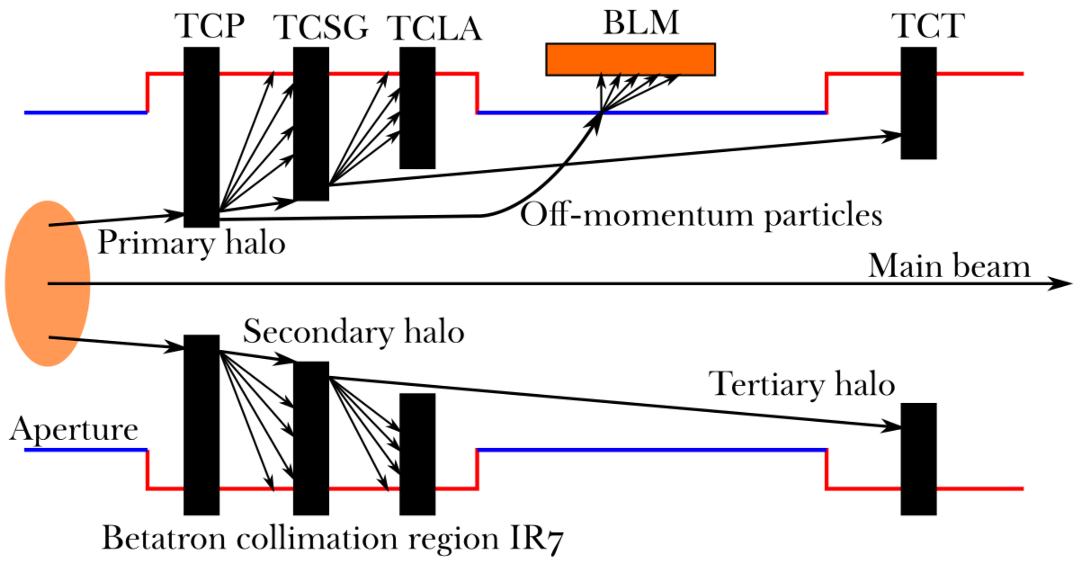
The LHC collimator system

- **Multi-stage system**
  - Betatron cleaning in IR7
  - Momentum cleaning in IR3
  - Nearby 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



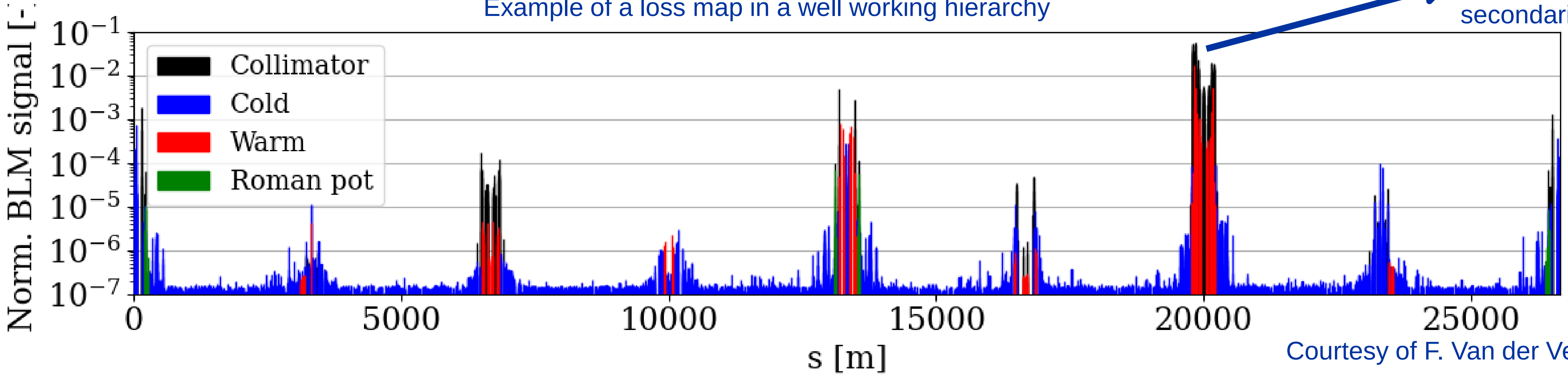
Overview of the LHC collimation system

A hierarchy to respect!



- **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**

Example of a loss map in a well working hierarchy

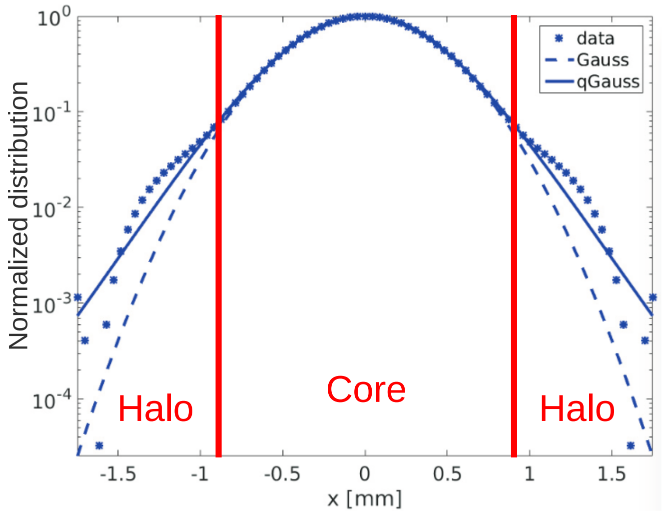


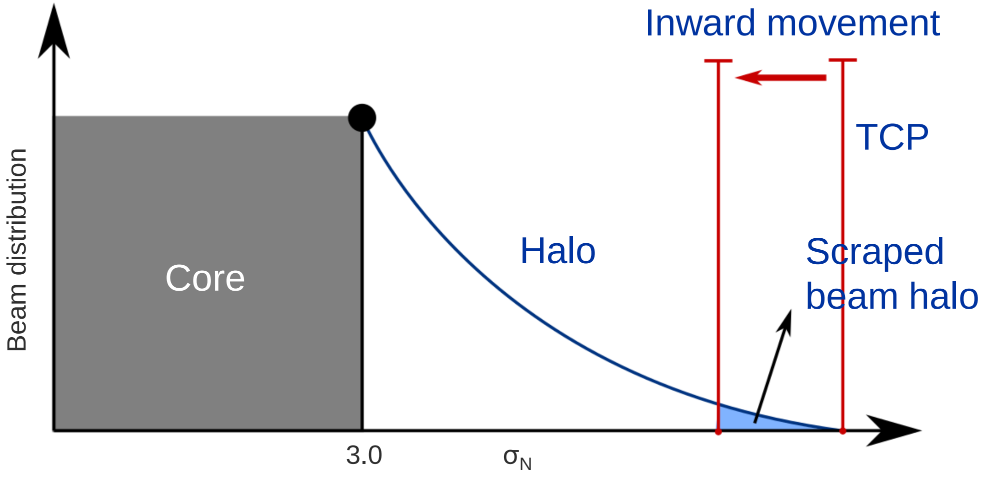
Peak losses at primaries, gradual descent along secondaries and tertiaries

Courtesy of F. Van der Veken

Beam Halo

- Transverse beam halo: defined as **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
- Precise measurements only possible with destructive **collimator scrapings**:
  - Move TCP inwards
  - Measure induced losses with
    - Beam Loss Monitors (BLMs)
    - Beam Current Transformers (BCTs)
  - Integrate measured losses to reconstruct the scraped beam halo
- Ongoing effort from BI in providing a **passive measurement** of beam halo by means of a **coronograph** (See talk by J. Pucek)

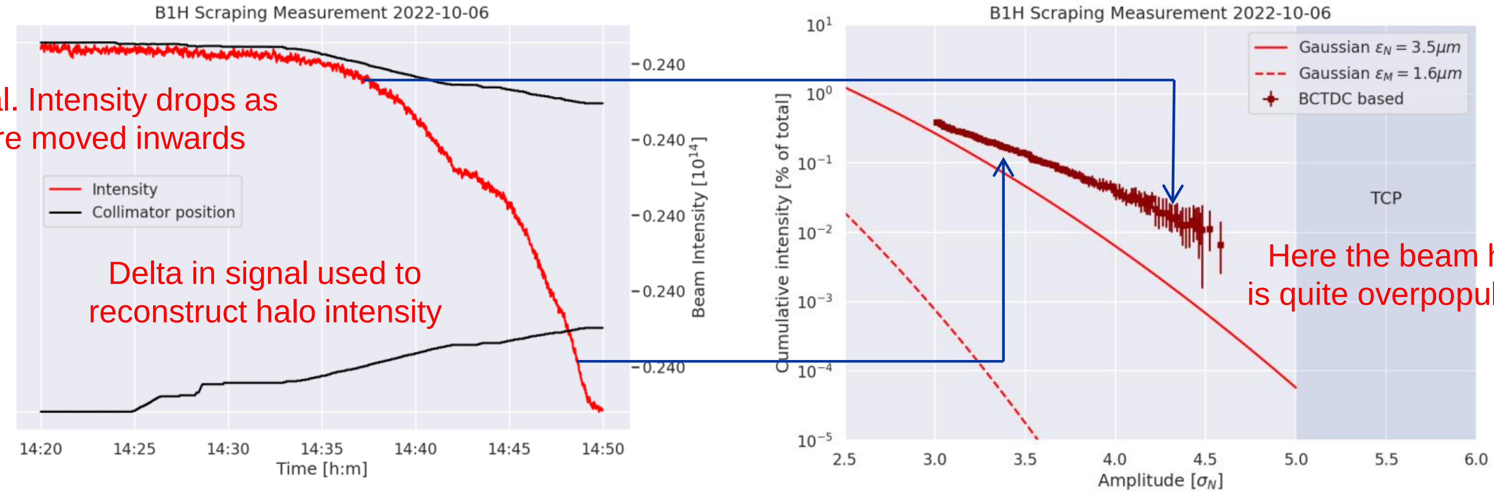




Examples of measurement

- **Cumulative beam halo intensity**

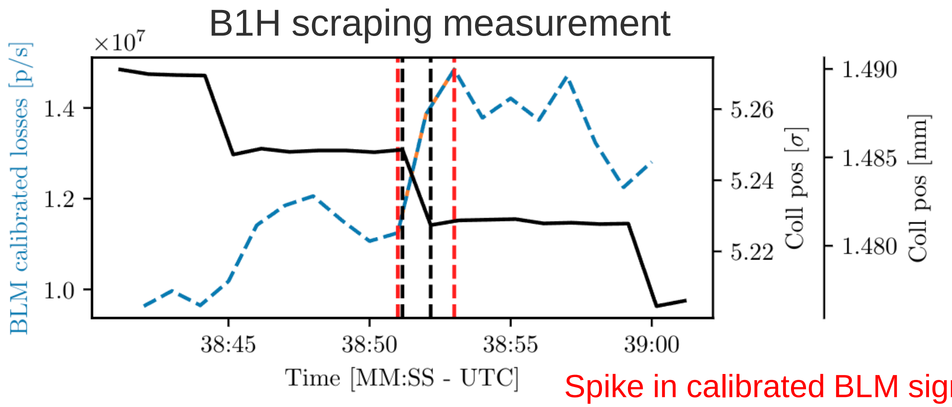
BCT signal. Intensity drops as TCPs are moved inwards



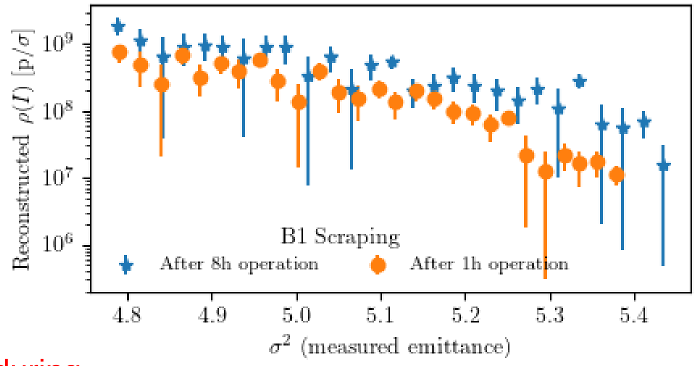
Courtesy of M. Rakic

- Metric of interest for operation
- Important to check when deploying new configurations
- A recent source on the topic

- **Beam halo population**



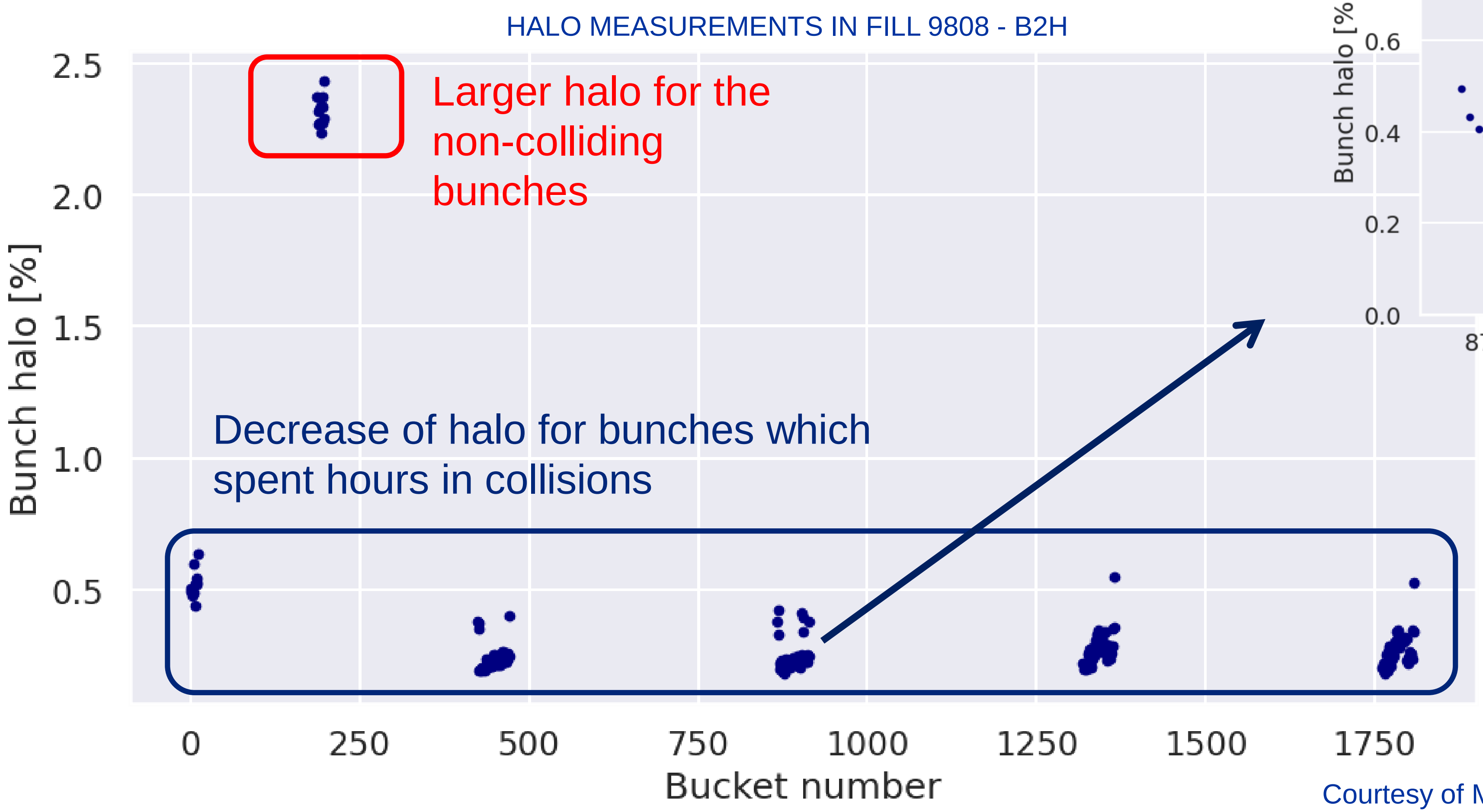
Spike in calibrated BLM signal during collimator movement considered

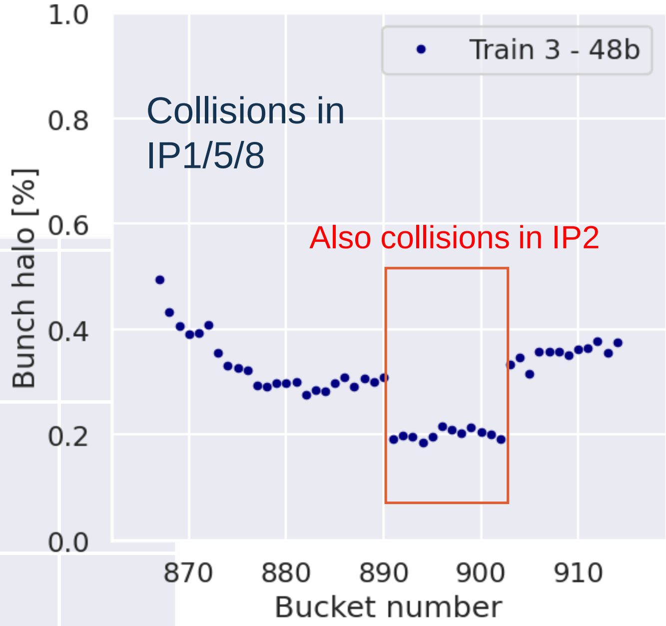


- Measure of interest for testing scale-law models (more on that later)

Visualizing the beam halo bunch-by-bunch

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





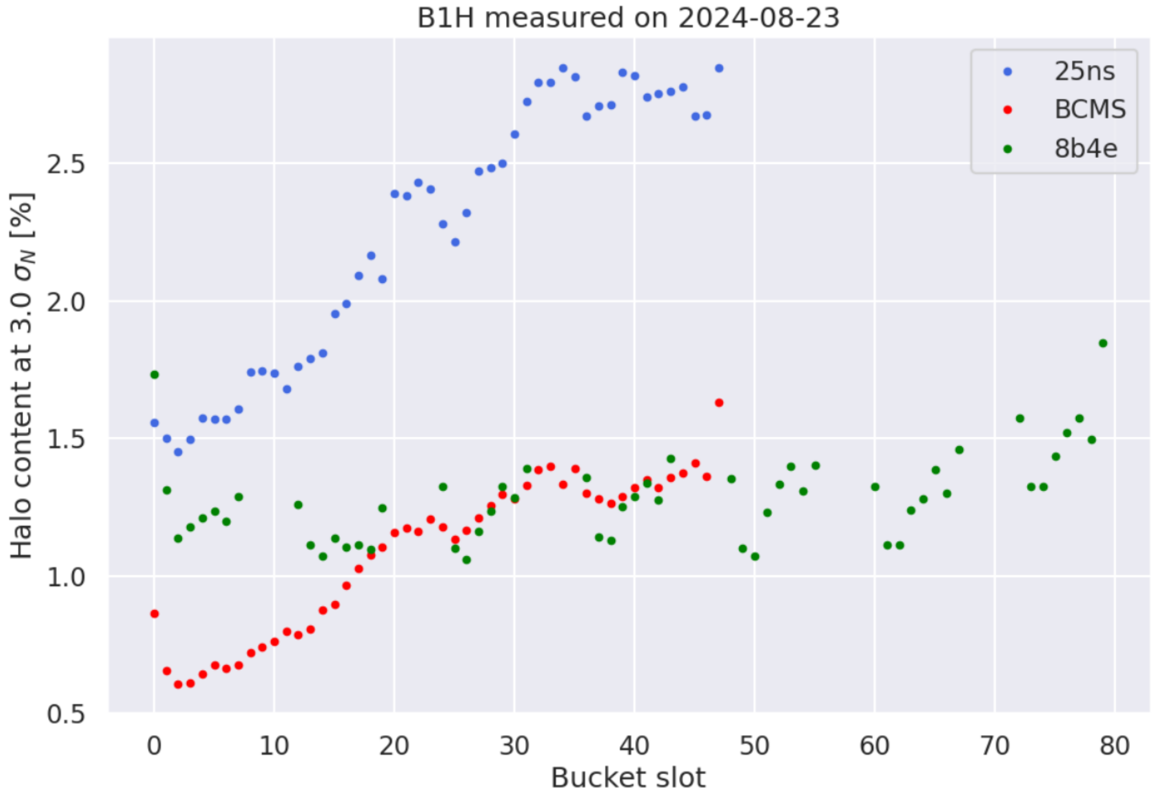
Clear view of the impact of beam-beam effects from different collision patterns!

Courtesy of M. Rakic

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**

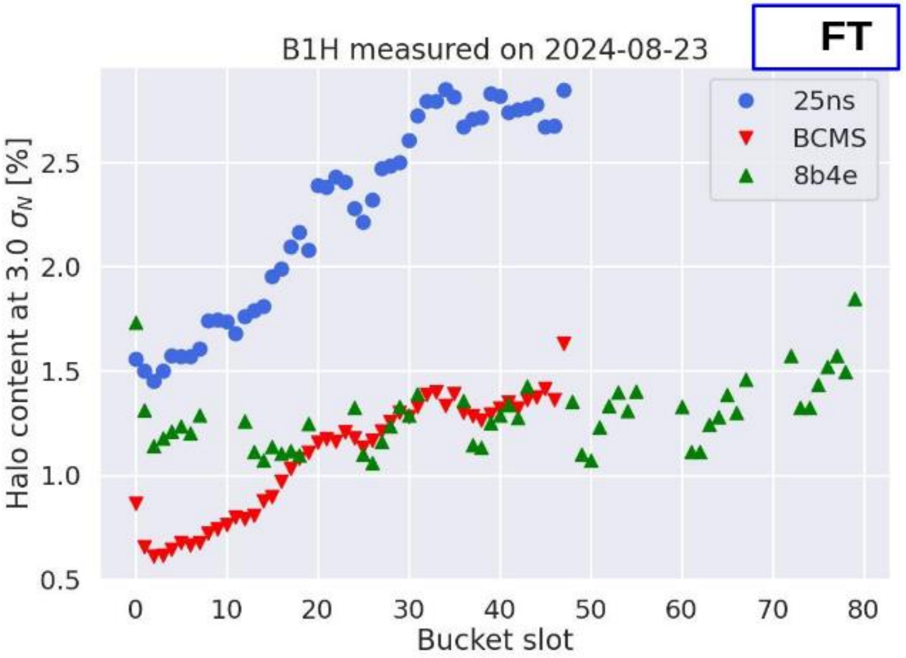
Collimator scraping @ Flat Top

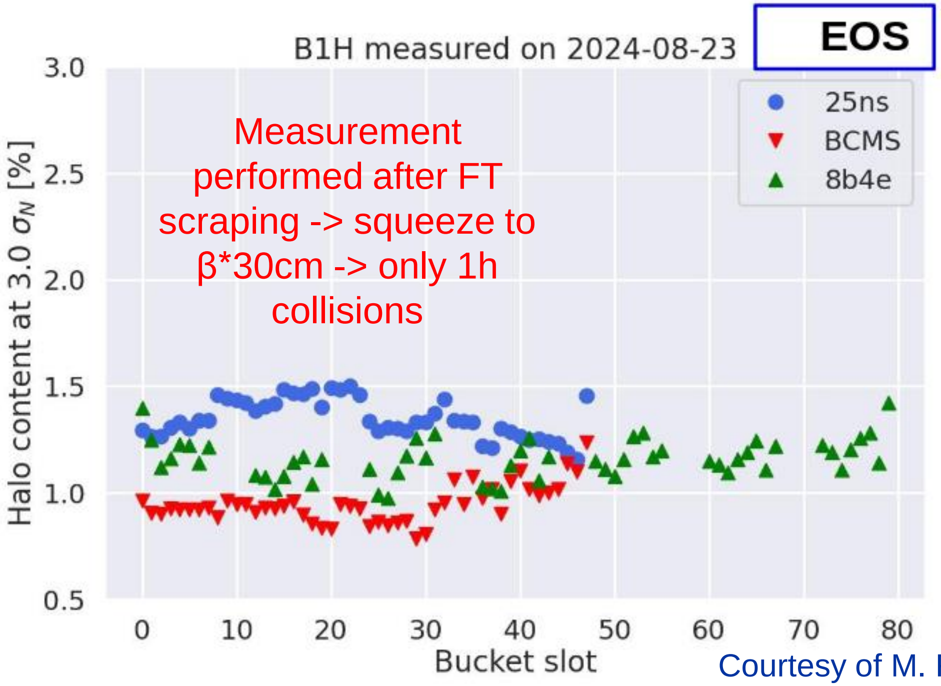


Courtesy of M. Rakic

Beam halo: 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!



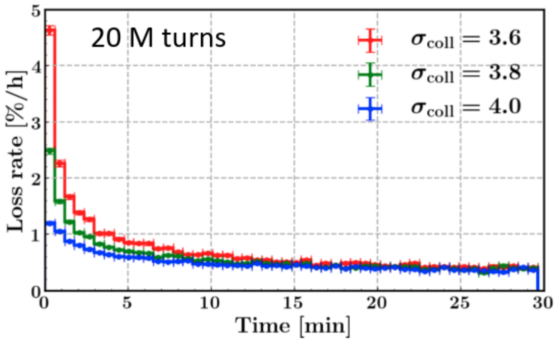


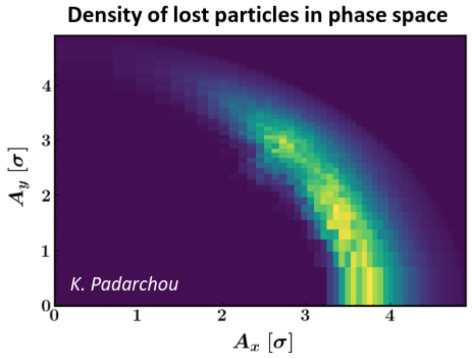
Courtesy of M. Rakic

Challenges in simulating the beam-halo

Beam halo formation simulation is an open challenge

- Plethora of effects at play
  - Beam halo clearly affected by multiple (modeled and still-to-be-modeled) elements
  - No direct reproducibility of quantities/differences achieved yet
- High statistics required
  - Achievable thanks to Xsuite GPU implementation
- Long simulation timescales required
  - Halo re-population after a scraping observed to take hours
  - Few minutes of LHC operation can be simulated
  - Latest promising direct simulations (10^4 particles, 30min of LHC, 3 days on V100 NVIDIA GPU) by K. Paraschou





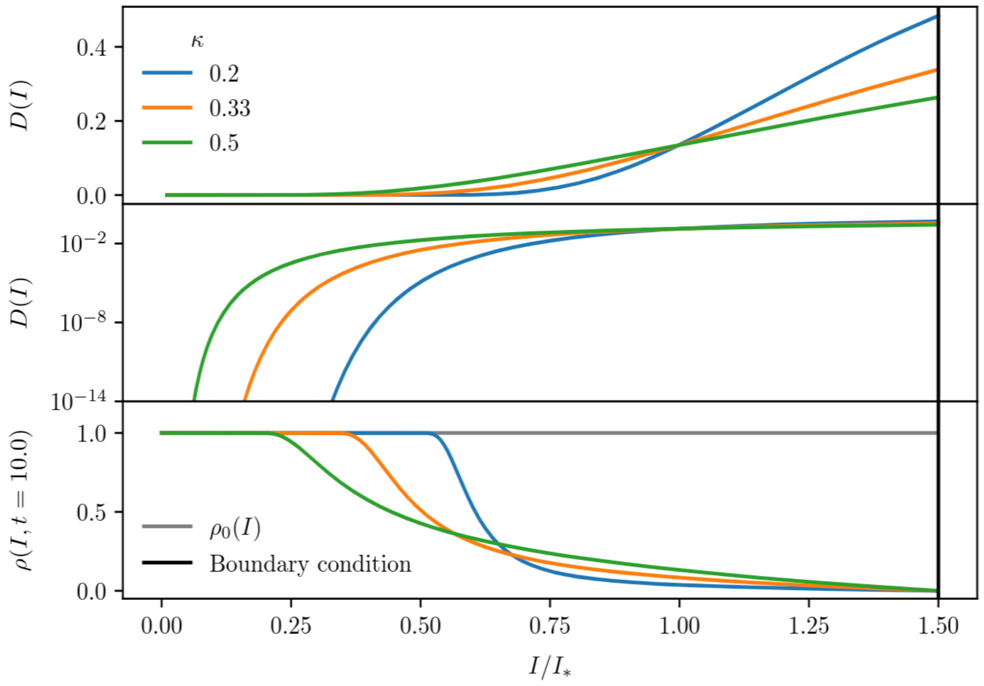
Investigating scale-laws: diffusion models

- 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)

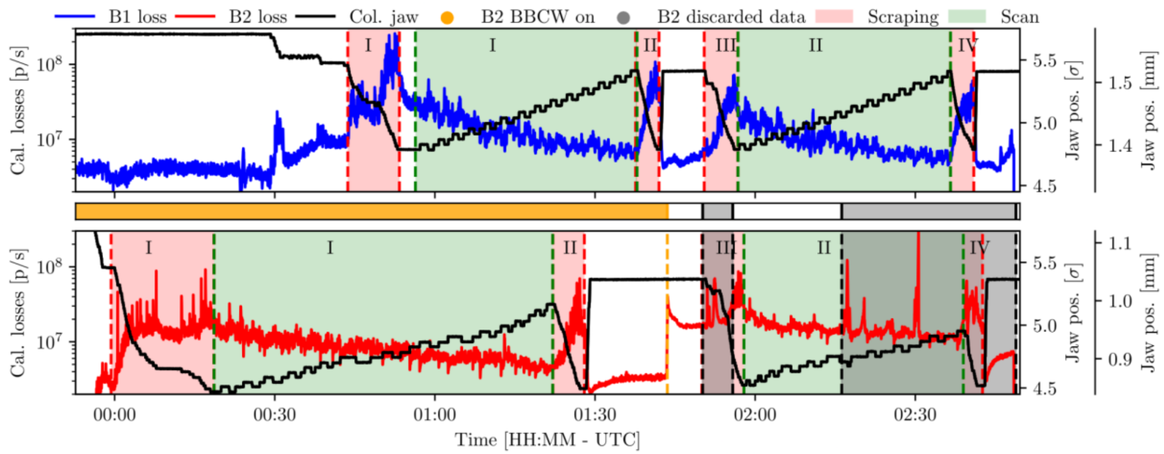
Observable from our diffusive model

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

- Collimator jaw initially at I_a;
- Multiple fast inward steps to scrape the beam;
- Integral of beam-loss signal during inwards steps yields beam-halo population.



BEAM-LOSS SIGNAL AT DIFFERENT AMPLITUDES

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

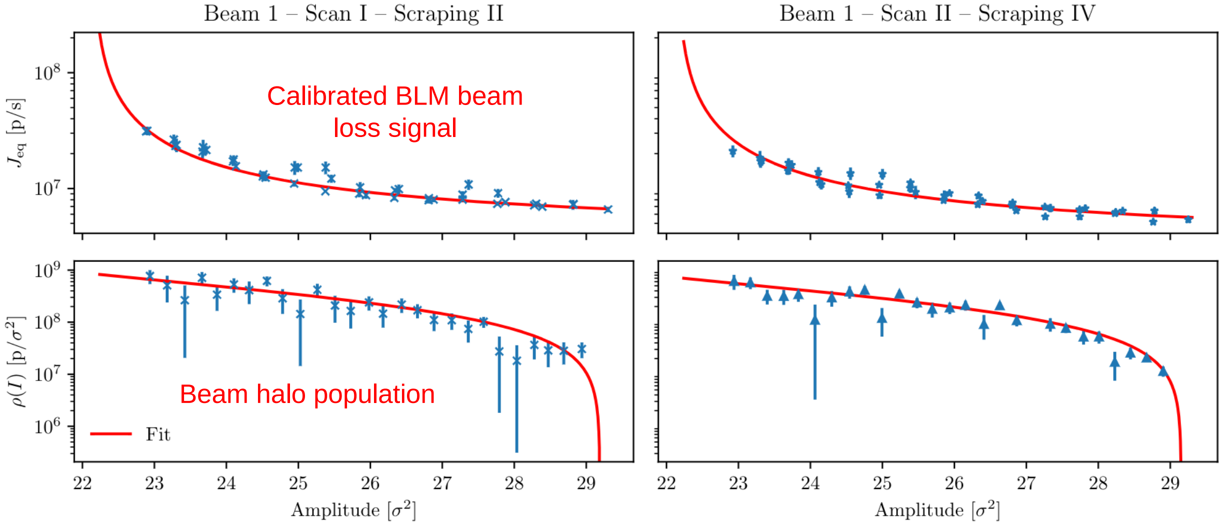
Measured while retracting the collimator

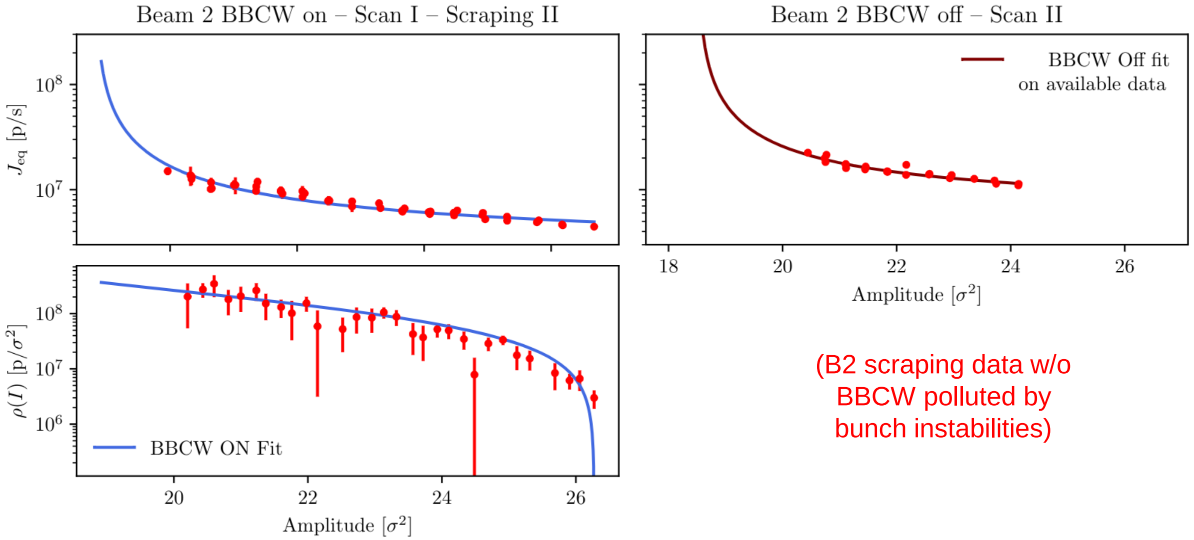
- Collimator jaw at low sigma;
- Outward movements or alternation of outward and inward movements **with pauses in between**;
- J_{eq}; is the stabilized beam-loss signal

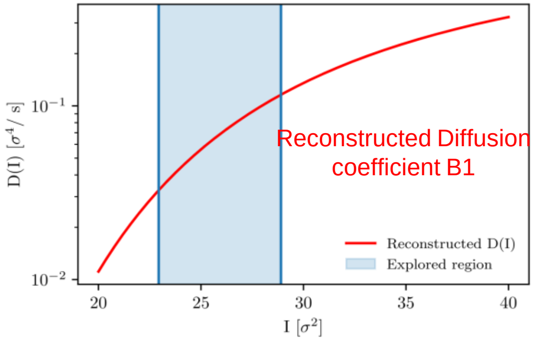
Measurement performed at the end of Beam-Beam wire compensation MD in 2022

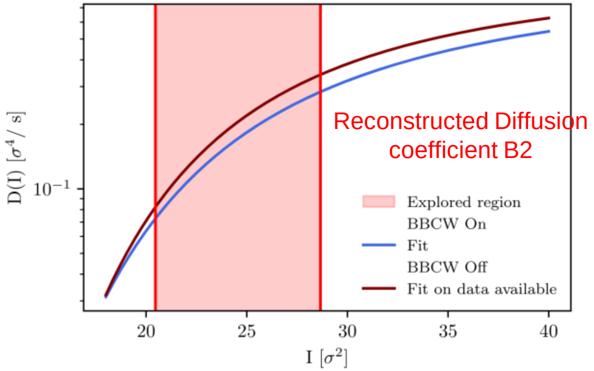
- Special configuration dominated by BB effects
- Wire compensation available in B2

An example of diffusion reconstruction









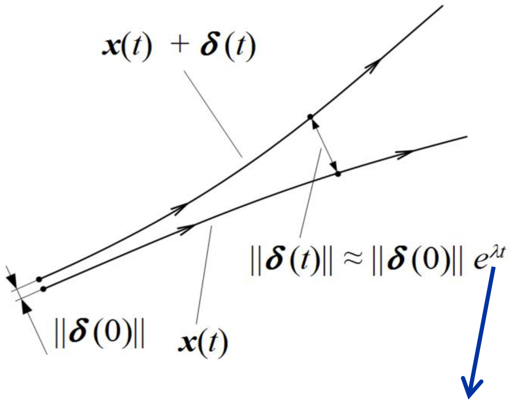
- **Overall great fit reconstruction**
- **Able to relate both beam-halo and equilibrium beam loss signal**
- **Lower diffusion reconstructed with Beam-Beam wire compensators on**

- Initial analysis of B1 presented at IPAC'23
- Complete work currently under peer-review @ C.E. Montanari et al. "Measurement of the nonlinear diffusion of the proton beam halo at the CERN LHC"

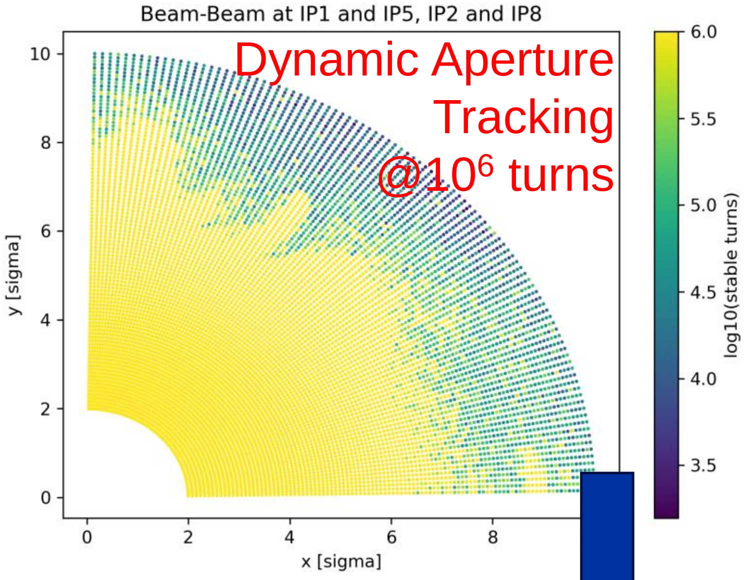
Enhancing single-particle tracking: Chaos Indicators

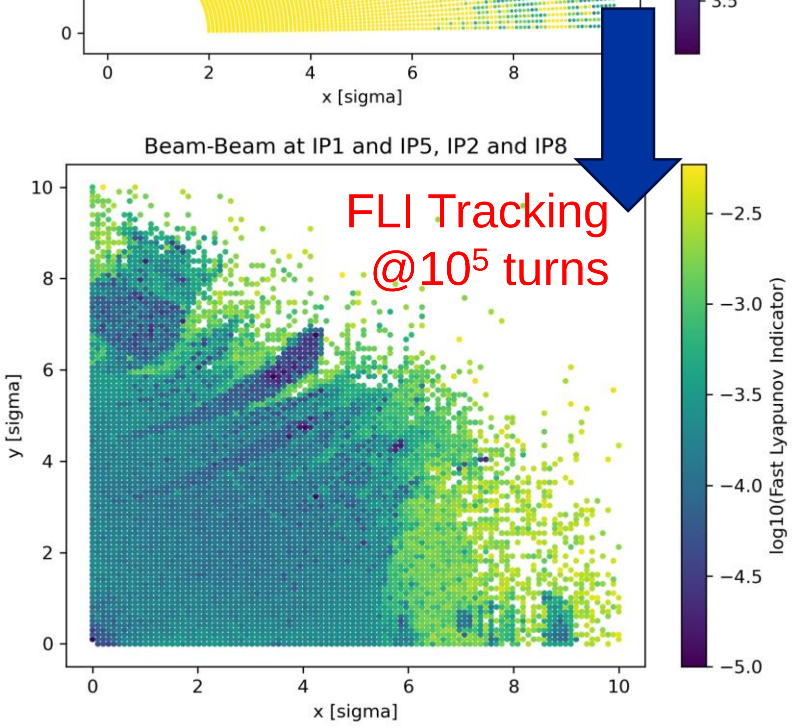
- Chaos: sensitivity of a particle orbit to initial perturbations
- Vast literature in mathematical physics and astrophysics

- In accelerator physics, some performance studies based on chaos have been performed in the past with, e.g., the Fast Lyapunov Indicator (FLI)
- We are currently studying further applications of more advanced chaos indicators
- Implementation (CPU/GPU) on Xsuite



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

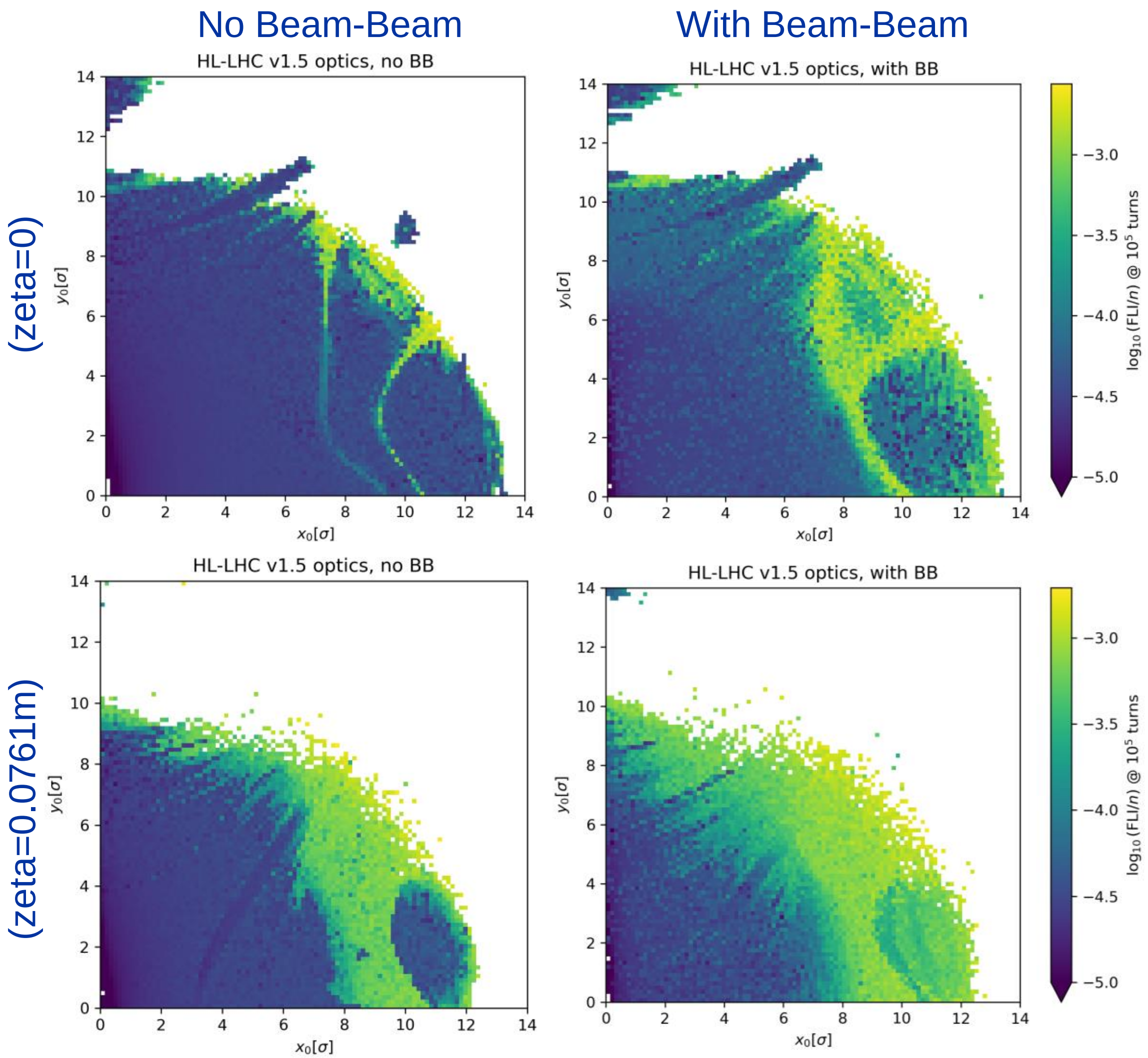




Example of FLI evaluation on HL-LHC lattice

- **Lattice considered with and without Beam-Beam effects**
- **Possible to observe the chaos topology with the insertion of BB weak-strong lenses**
  - Very thin chaotic border and resonance-like lines for the case without BB
  - Large regions of chaos appearing for the case 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.)**

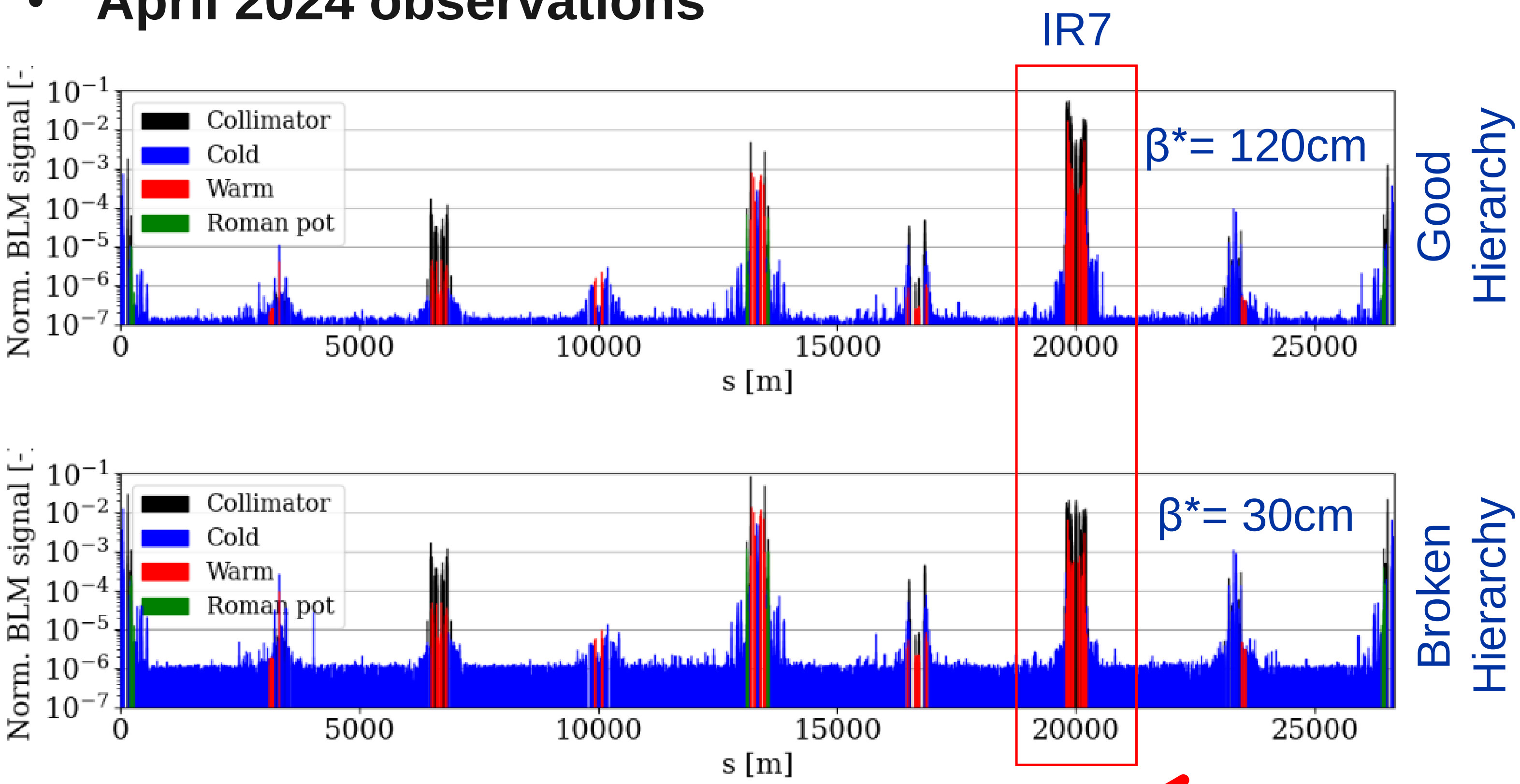
- **Ongoing work: connect observed chaos timescales to diffusion presence/halo population**



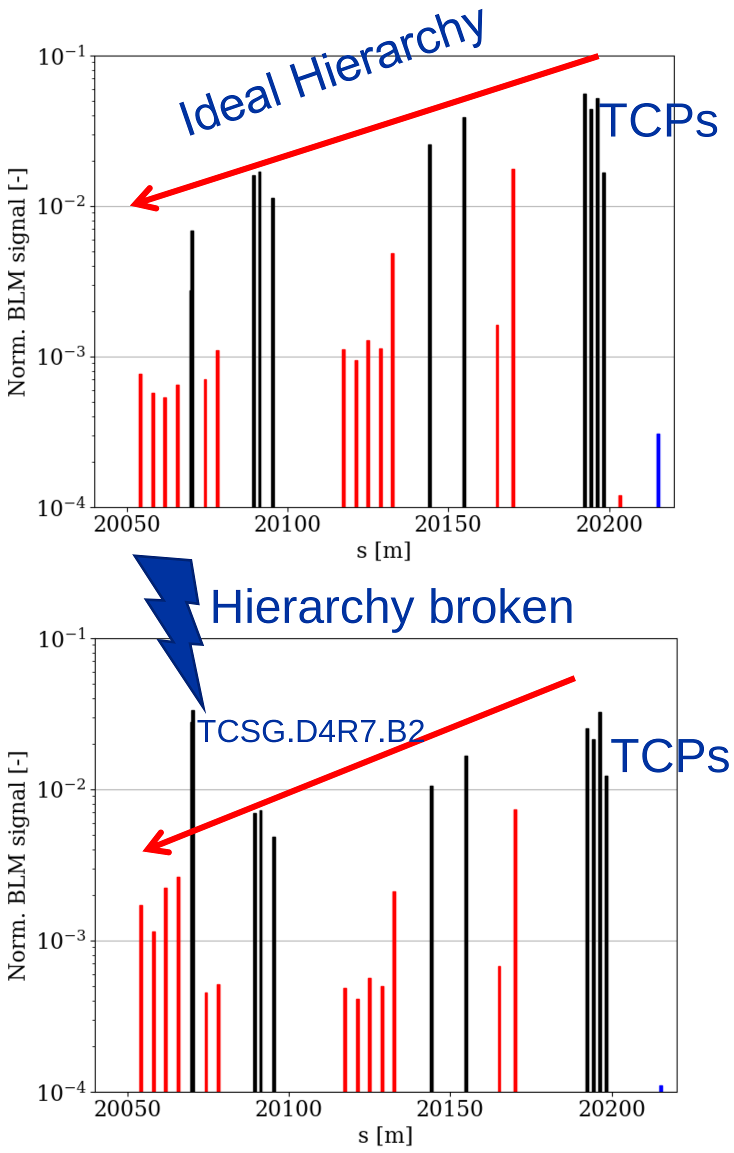
Hierarchy breaking: observations and ongoing work

The problem

- **April 2024 observations**



Beam direction (B2)



Beam direction (B2)

Courtesy of F. Van der Veken

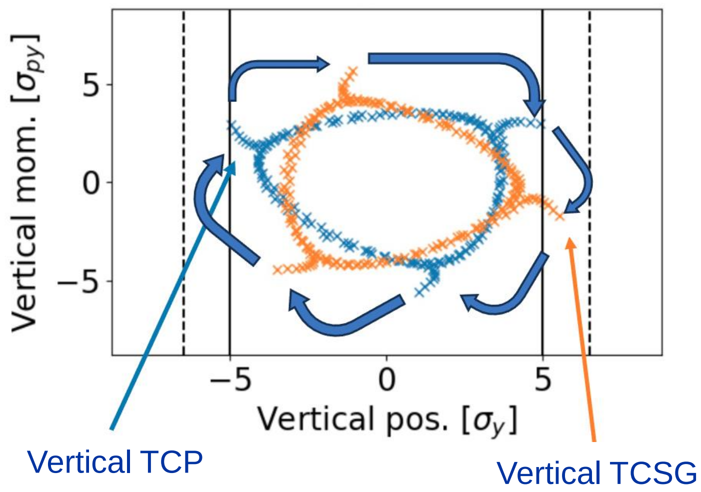
Visible only with colliding beams!

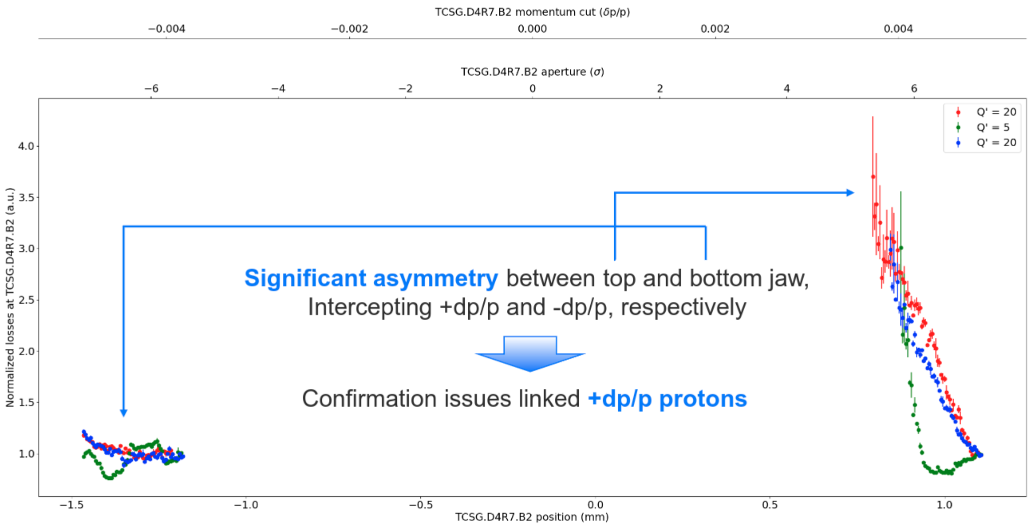
Multiple elements at play

Ultimately, the problem was related to **various contributions**:

- **Not related to collimation alignment**
- Long-range beam-beam effects (stronger at low **β***) inducing changes in tune and orbit
- Derivative tune-shift, exciting 3Qy resonance, inducing stronger losses at the secondary collimator (K. Paraschou and X. Buffat)
  - Mitigations of RDTs under development (E. Maclean)
- Vertical dispersion drastically reducing the collimator margin (D. Miriarchi)
  - Issue solved with review of dispersion correction strategy at IR7

K. Paraschou





D. Miriarchi

Ongoing work: beam-beam (and more) in Xcoll!

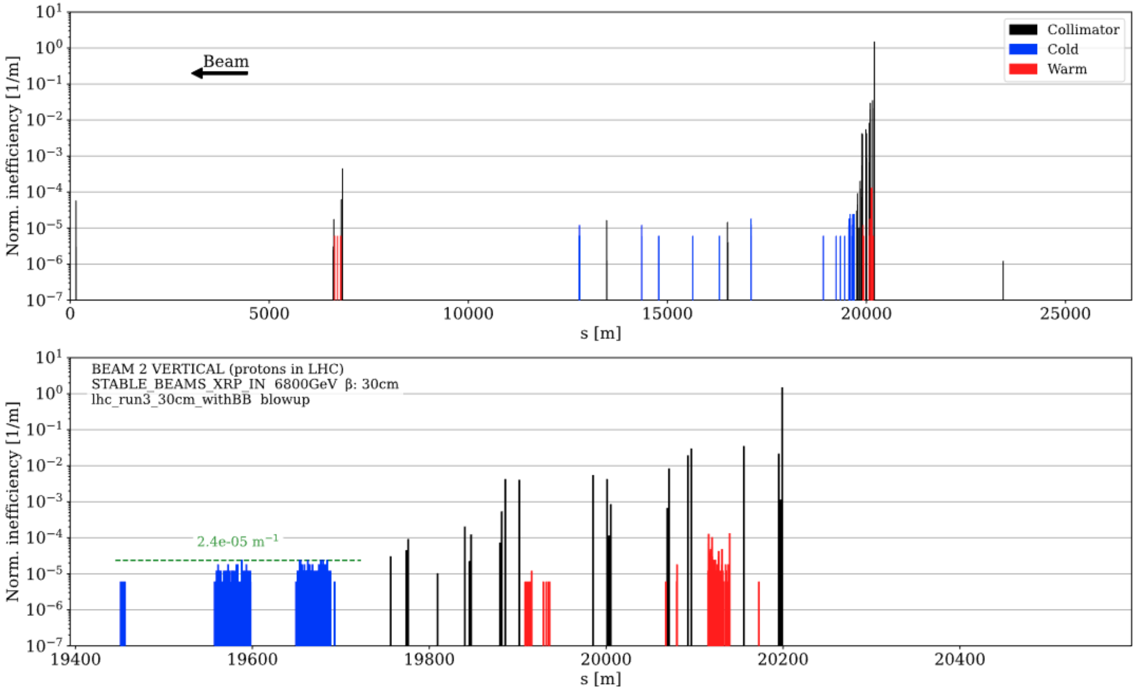
Beam-beam simulations through Xsuite: Xfields

Collimation simulations via Xsuite: Xcoll

- Incorporates native scattering capabilities (Everest) derived from the established SixTrack tool
- Offers potential to utilize FLUKA and Geant4

Modular development of Xsuite makes complex simulations more and more approachable!

Development ongoing by F. Van der Veken (recent talk)



Conclusions

- **Measurement and characterisation of beam halo is a critical open challenge for HL-LHC operation**
  - Beam halo interacts with everything in its path, responds to every influence, and requires specialized techniques for precise measurement and assessment
  - Recent measurements offer quantitative assessments on beam halo features in diverse LHC configurations
  - Simulation and modeling efforts for beam-halo are ongoing, considering multiple promising paths
- **Recent hierarchy breaking problem highlights how advanced LHC configurations interlinks various phenomenons, usually treated as isolated**
  - Simulation tools are being updated accordingly to better incorporate more phenomena, such as beam-beam in collimation simulations

Thank you!

Recall of Run2 Halo measurements

			Final collimator position [σ] Halo content [%]				Halo content [%] at 3.0 [σ]			
	Fill number	No. of Bunches	B1H	B1V	B2H	B2V	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

Date	Fill number	Stage	No. of Bunches	Final collimator position [σ] / Halo content [%] B1H	B1V	B2H	B2V	Halo content [%] at 3.0 [σ] 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**				