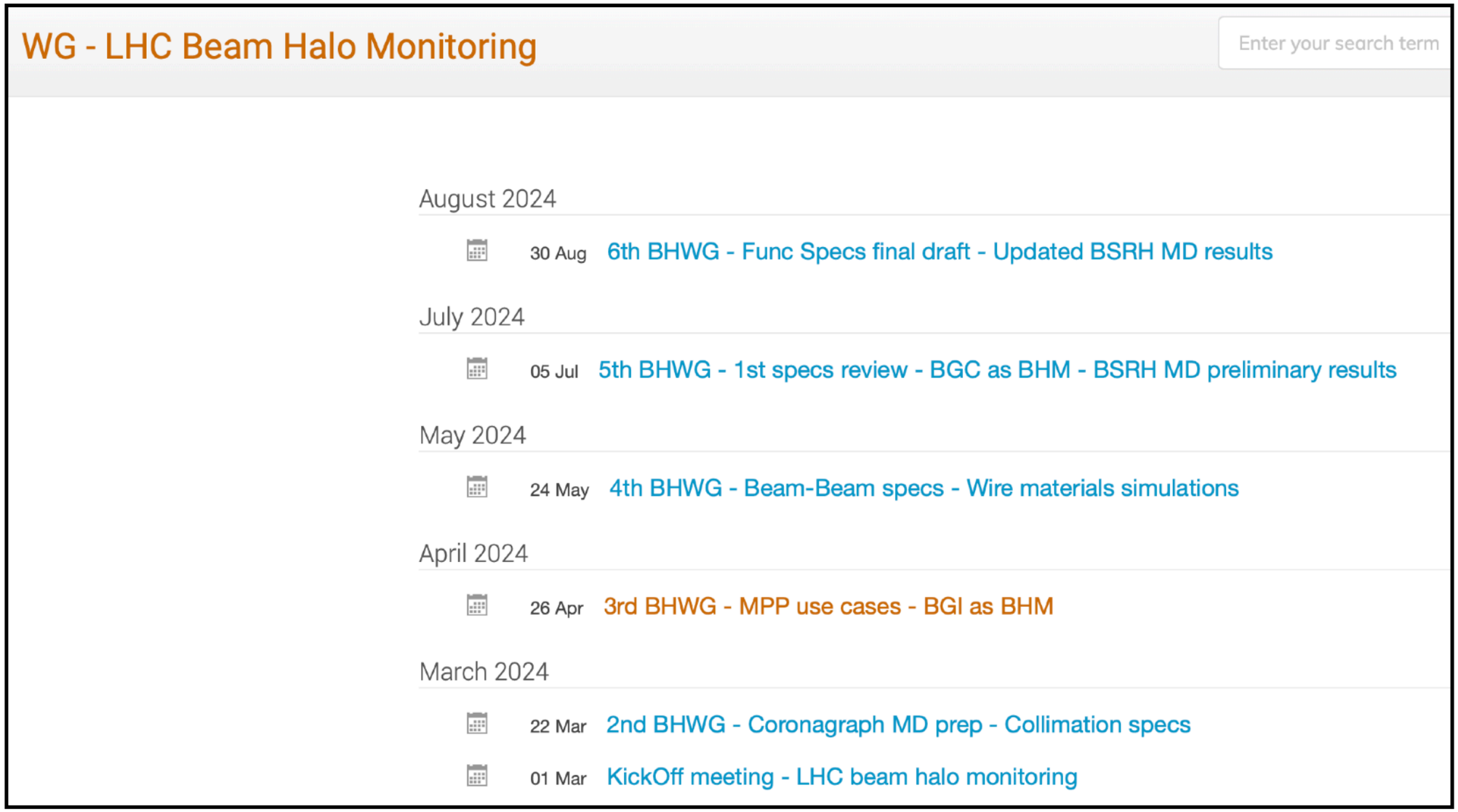
Overview of the beam-halo monitoring functional specifications

S. Redaelli with input from the LHC Beam Halo monitoring WG

Based on discussions with P. Hermes, M. Rakic, D. Wollmann, G. Sterbini, F. Roncarolo

HL-LHC Beam-Halo Monitor Review
18 December 2024
CERN, Geneva, Switzerland

Forum for halo discussions



…in addition to the long-lasting fora where measurements and simulations have been discussed: WP5 (ColUSM), WP7, non-linear beam dynamics (NLBD) WG, …

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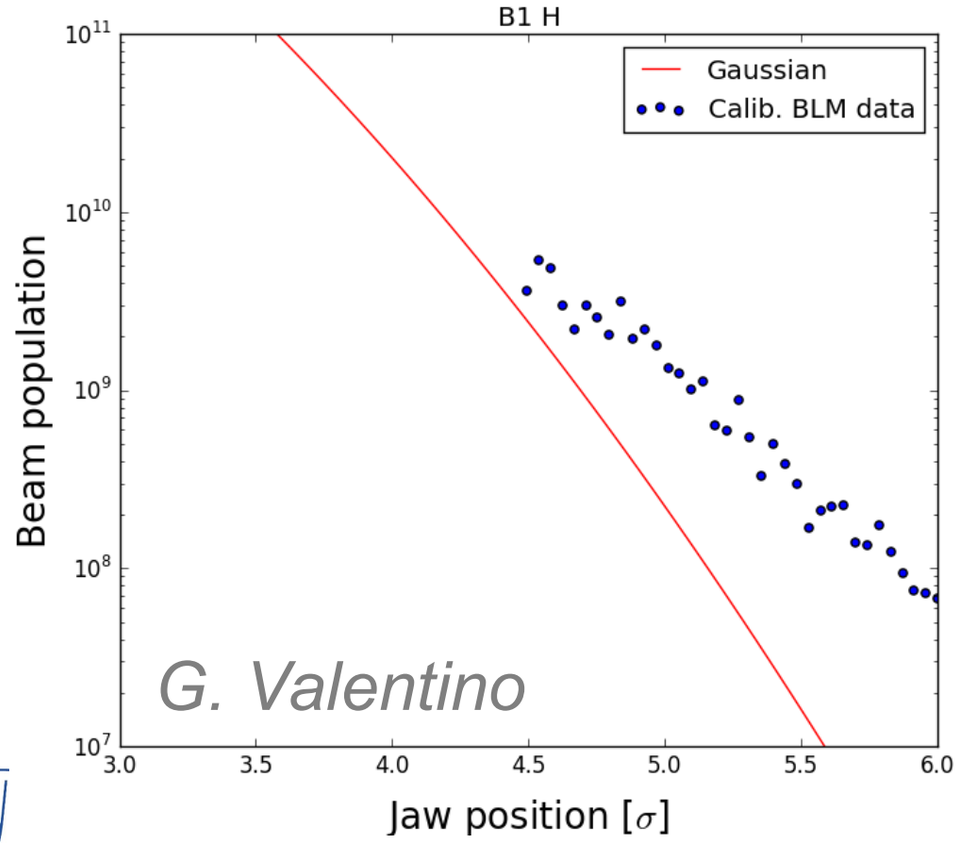
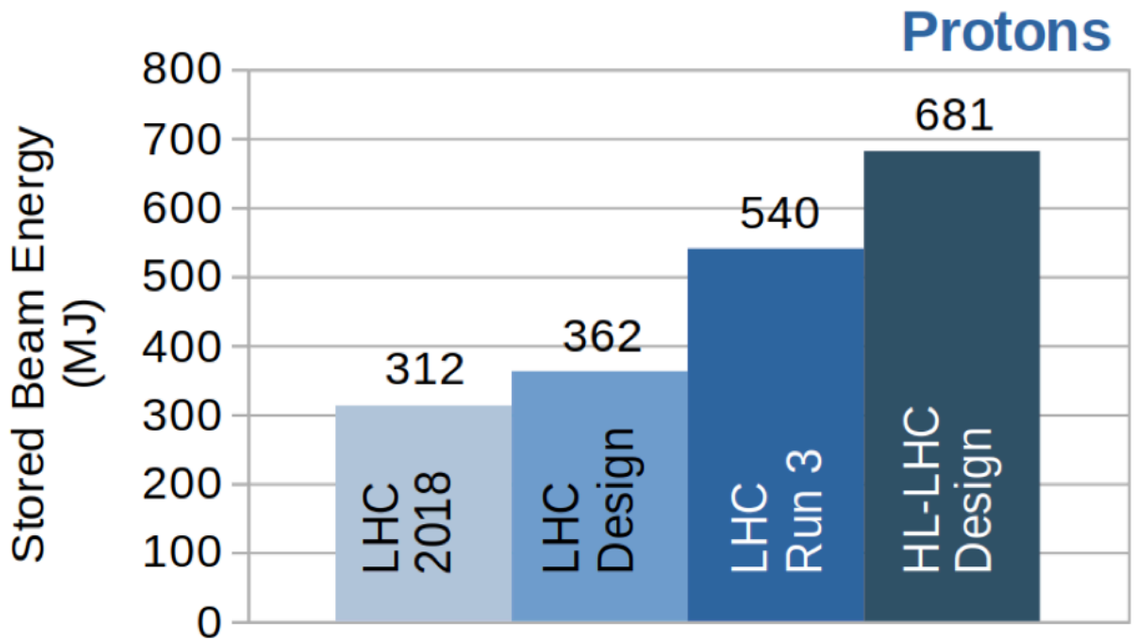
Introduction

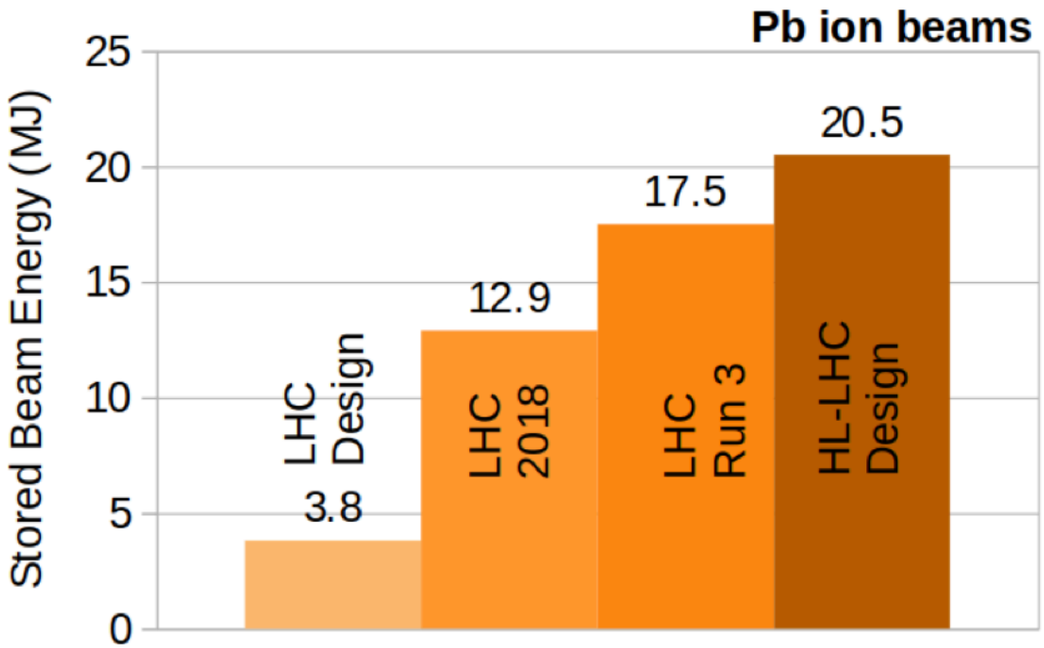
- The HL-LHC targets a **~700 MJ stored beam energy**
- LHC experience shows consistent indications of over-populated tails
  - *In particular, Run 1 and Run 2 showed the up to 5% of the total beam current is statically stored at amplitudes close to the primary collimators*
  - *Concerns for machine availability (dumps from loss spikes)*
  - *High potential of damage in case of fast failures*
- The monitoring of the halos at LHC and HL-LHC is of paramount importance for machine availability and safety: Strong interest from WP5!
- In addition, halo measurements offer unique opportunities to understand complex beam dynamics



Need for an <u>active tail control</u> at the HL-LHC was deemed <u>necessary</u>, however now descoped and — if still needed — only possible for Run 5 → halo measurements are even more important!

Target beam parameters

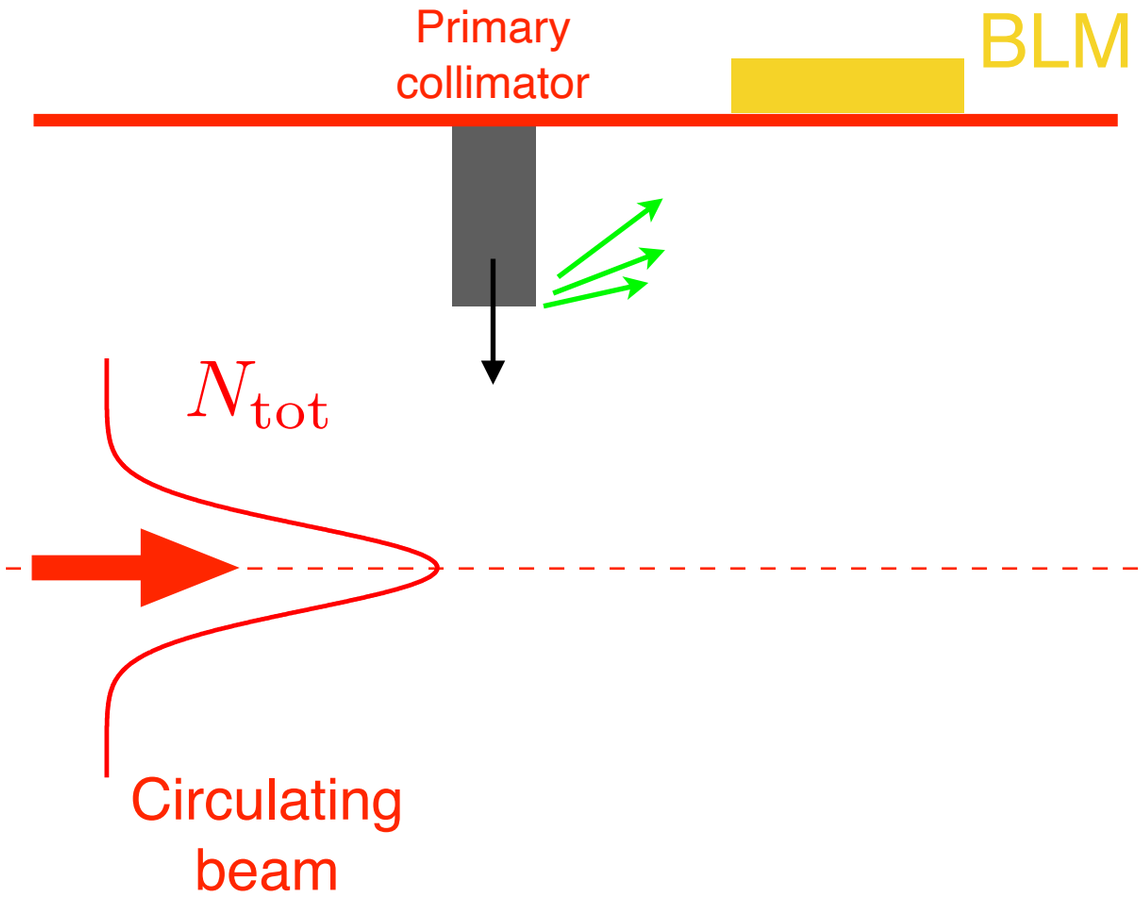


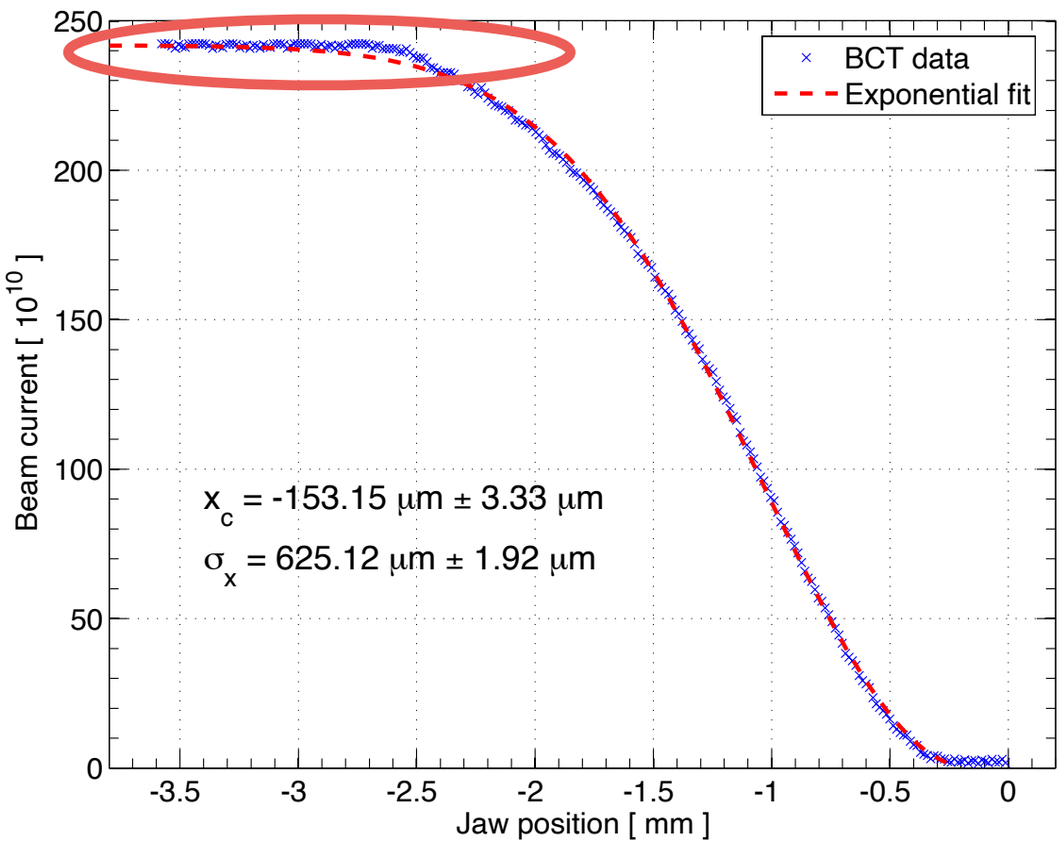


There is an interest in measuring halos also for ion beams, although the specs are driven by the proton beam challenges.

Pb ions 2023: record ~24MJ, above HL-LHC target

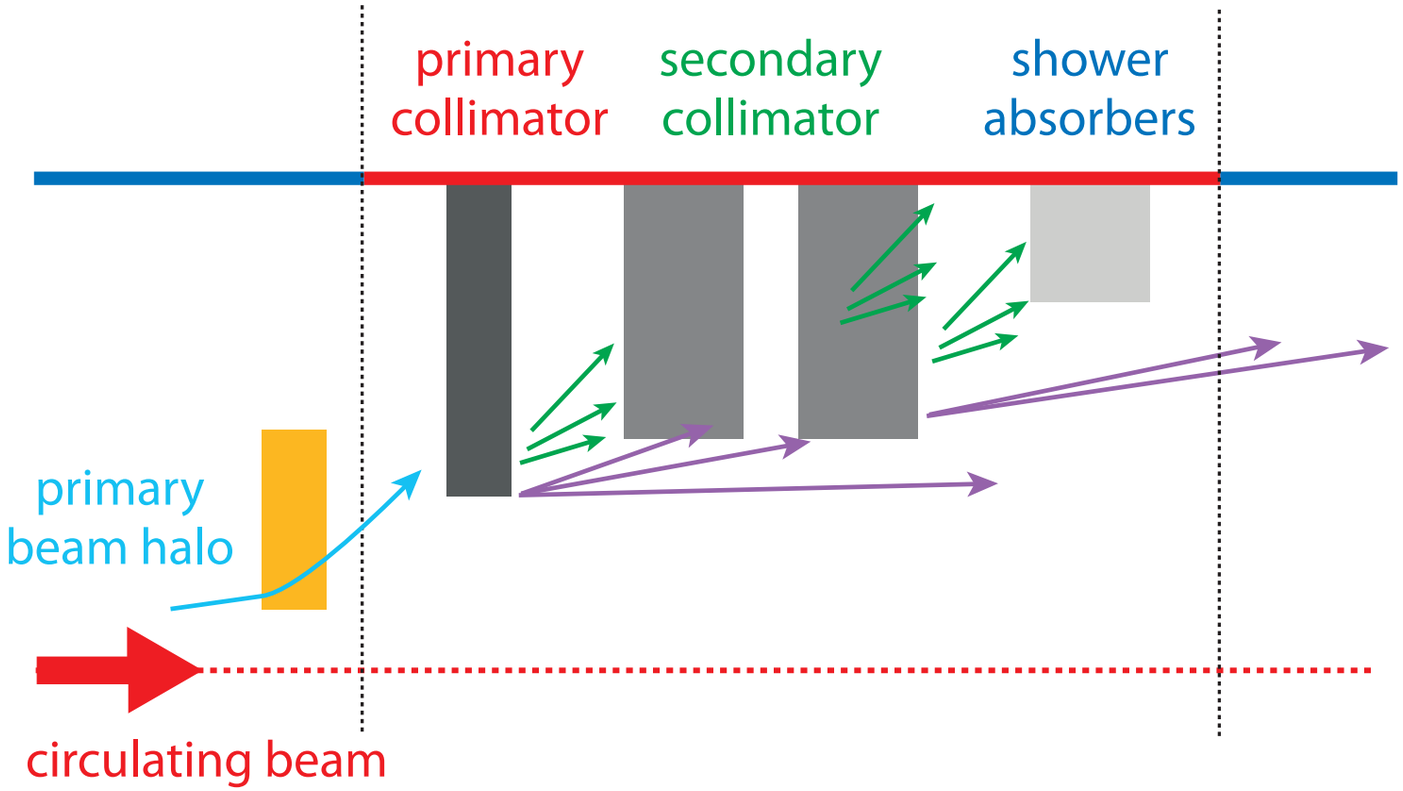
Collimator-based halo measurements

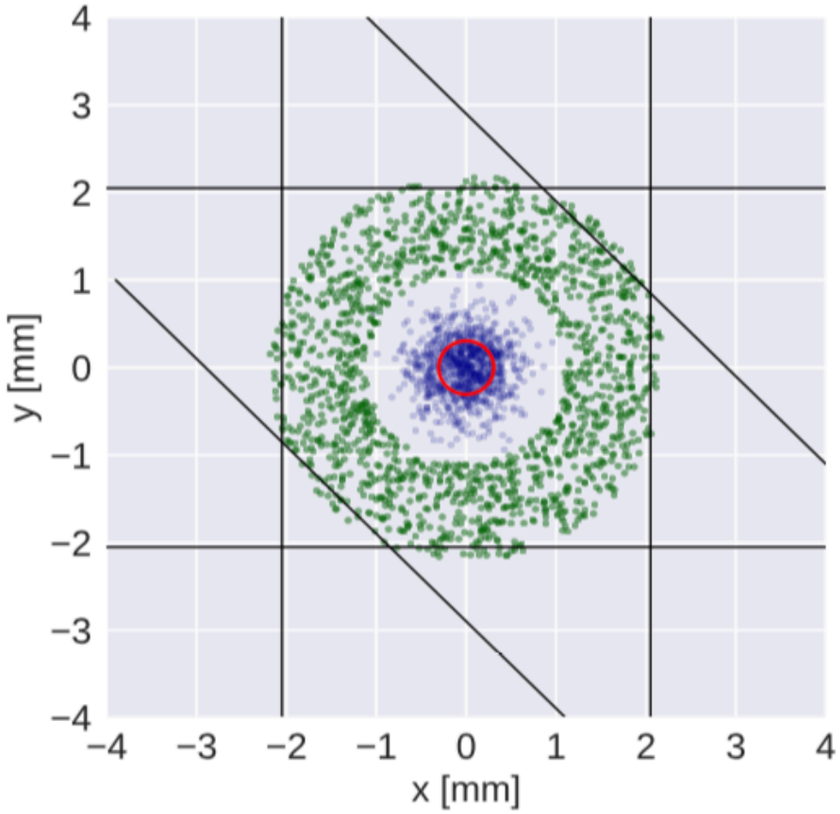




Idea: Move collimator jaw(s) into the beam while recording beam losses (local beam loss monitors [BLMs] + beam current).
We have experience from LHC, SPS, Tevatron, RHIC, …
Excellent dynamic range from the LHC BLM system!
Many drawbacks: time-consuming; destructive; generates losses; intensity limits; difficult for operational beams; …

The HEL-based collimation concept





Active halo depletion: control diffusion speed, selective by amplitude.

- Integrated in the hierarchy of the collimation system
- Various years of studies: WP2; WP7; integration; …

Baseline solution for halo monitoring: coronagraph to provide 2D imaged of the halo; we had started work on specs, seeing it as a tool to trigger the start of halo depletion.

Recent focus on the Beam Gas Curtain (BGC) monitor to centre hadron and electron beams.

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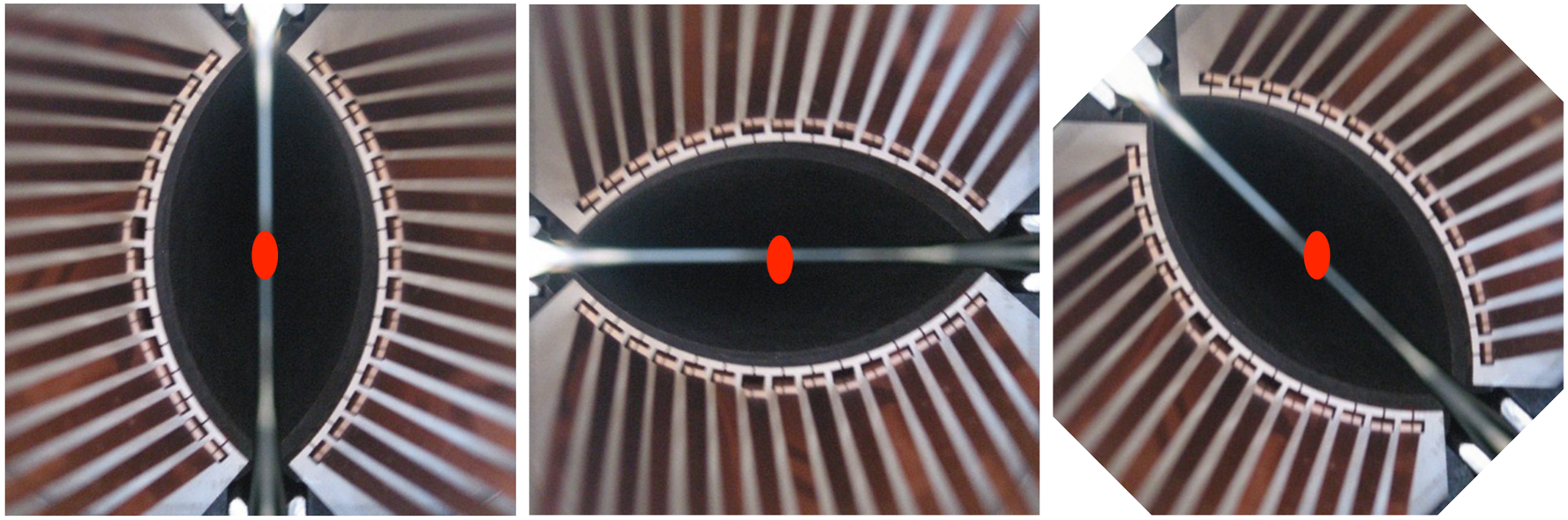
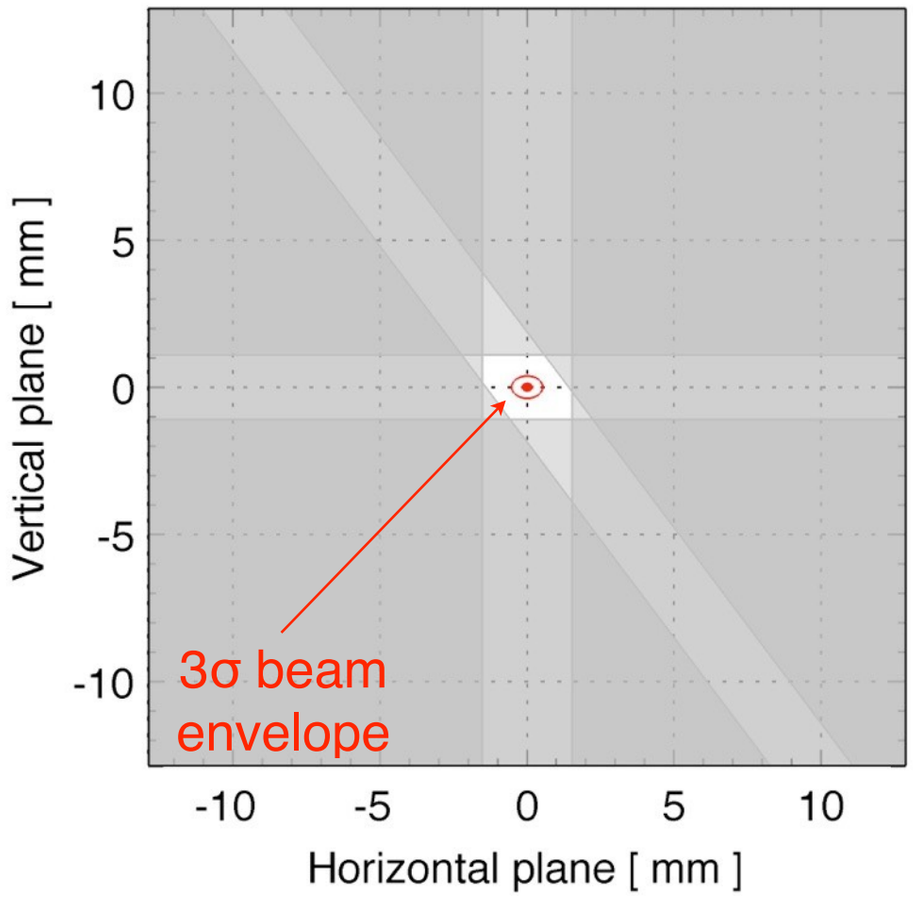
Betatron cuts by the TCPs

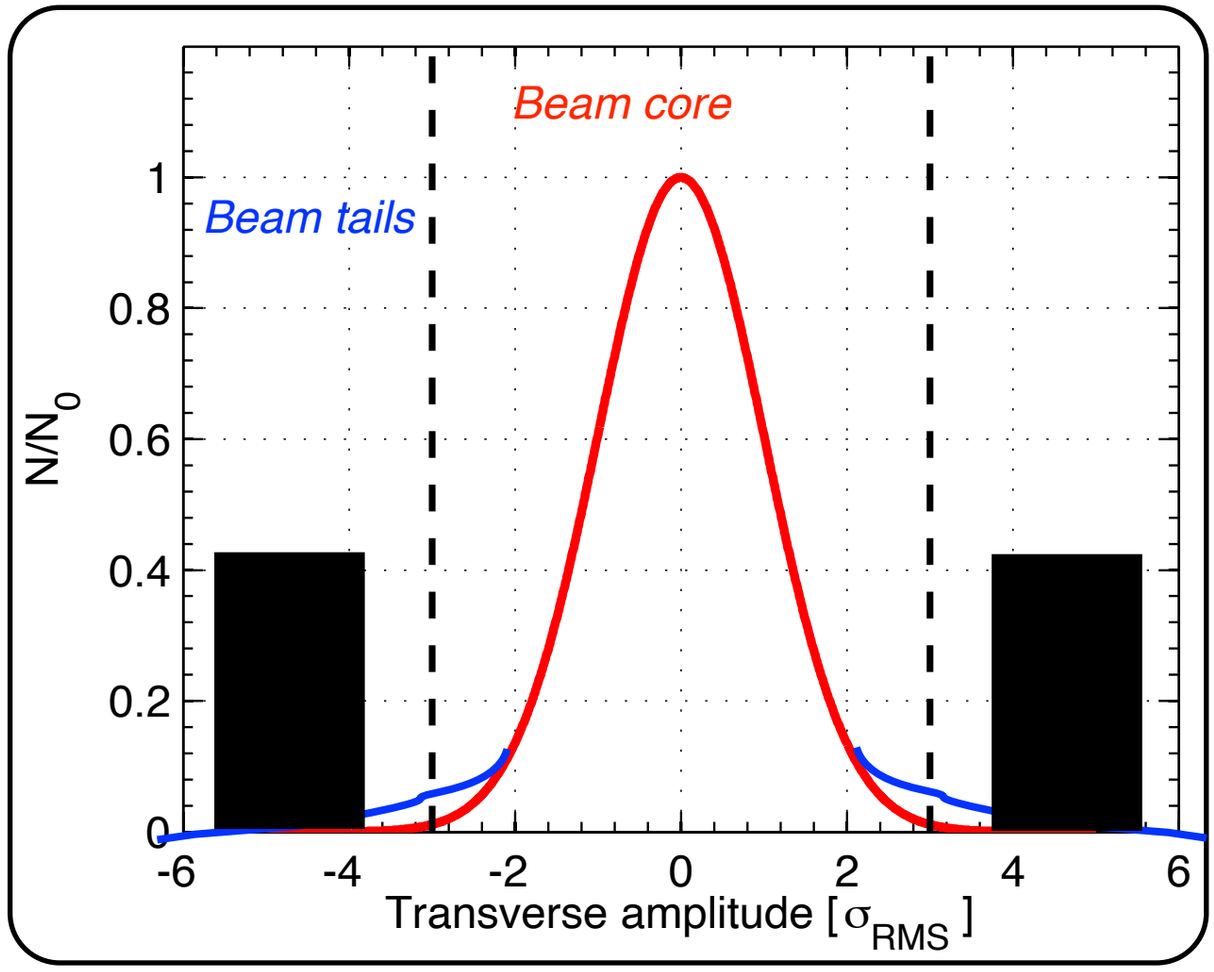
Horizontal **Vertical** **Skew**





- Symmetric primary betatron cuts of beam halos: H, V, S planes!
- Different beam dynamics H vs V…
- Different criticality of failures
  → typically, for the LHC more focus on H for asynchronous dump
  → HL-LHC fast failures (crab cavities, CLIQ) can be in both planes.
- Assume **same specs for both planes**

Notations and definitions



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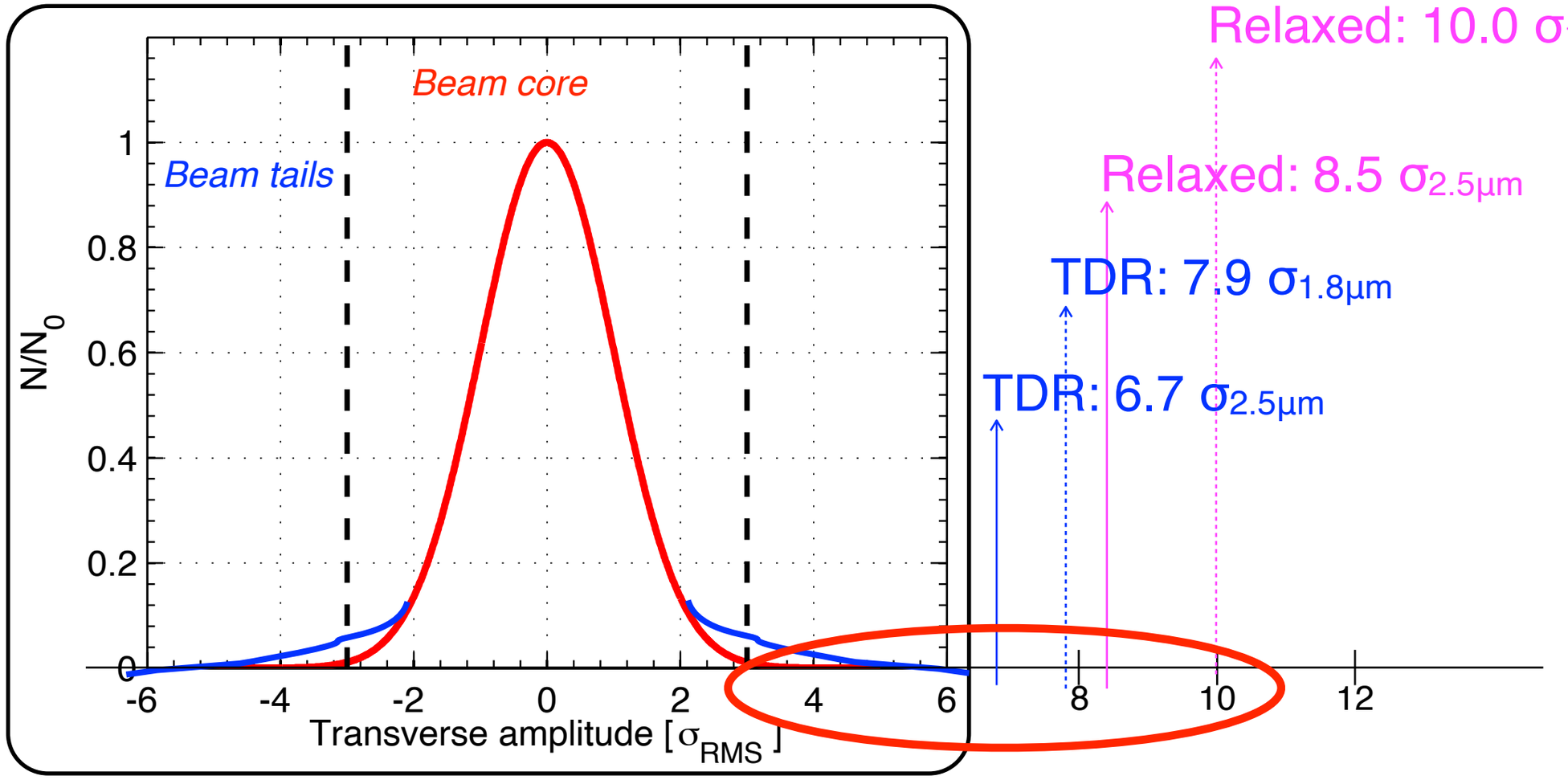

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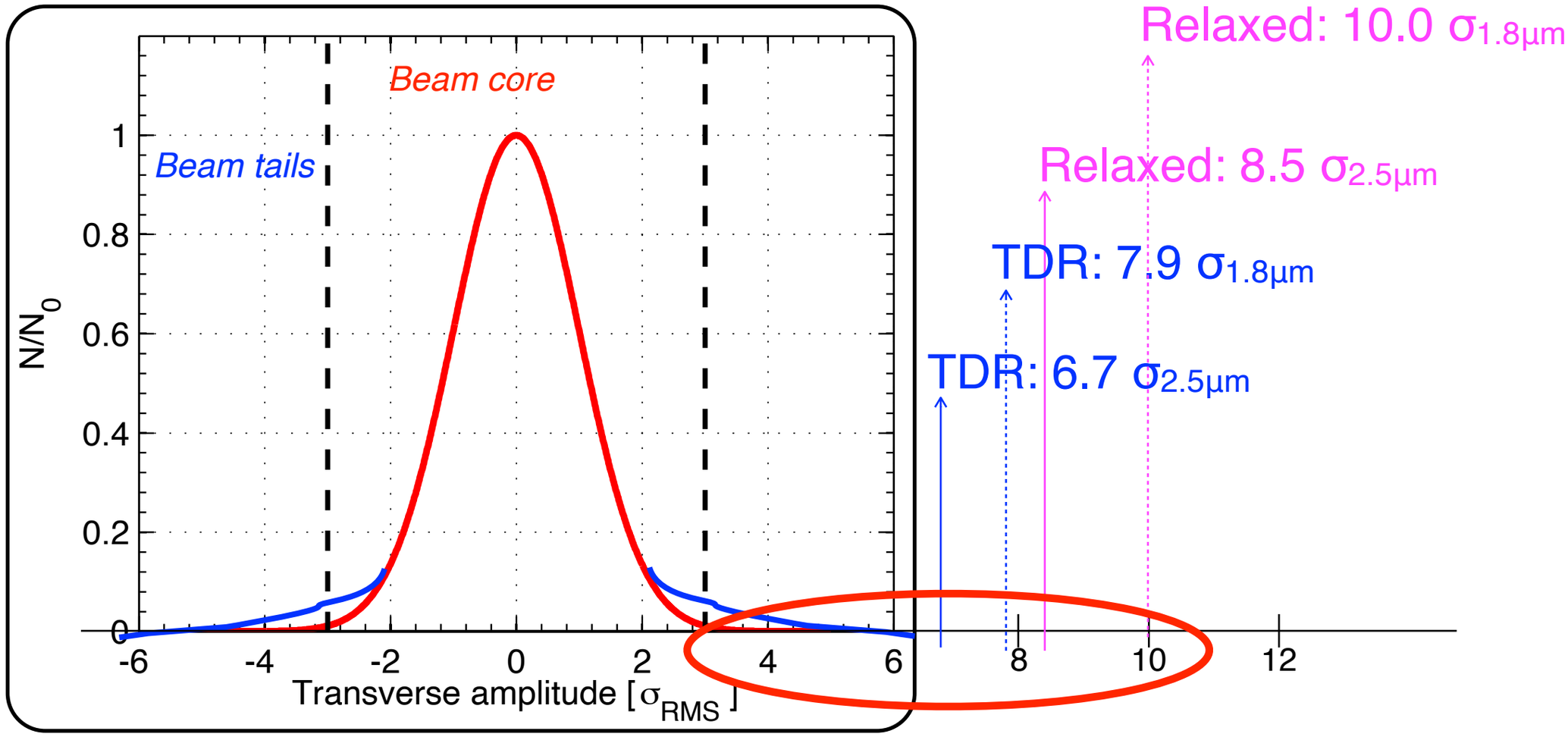
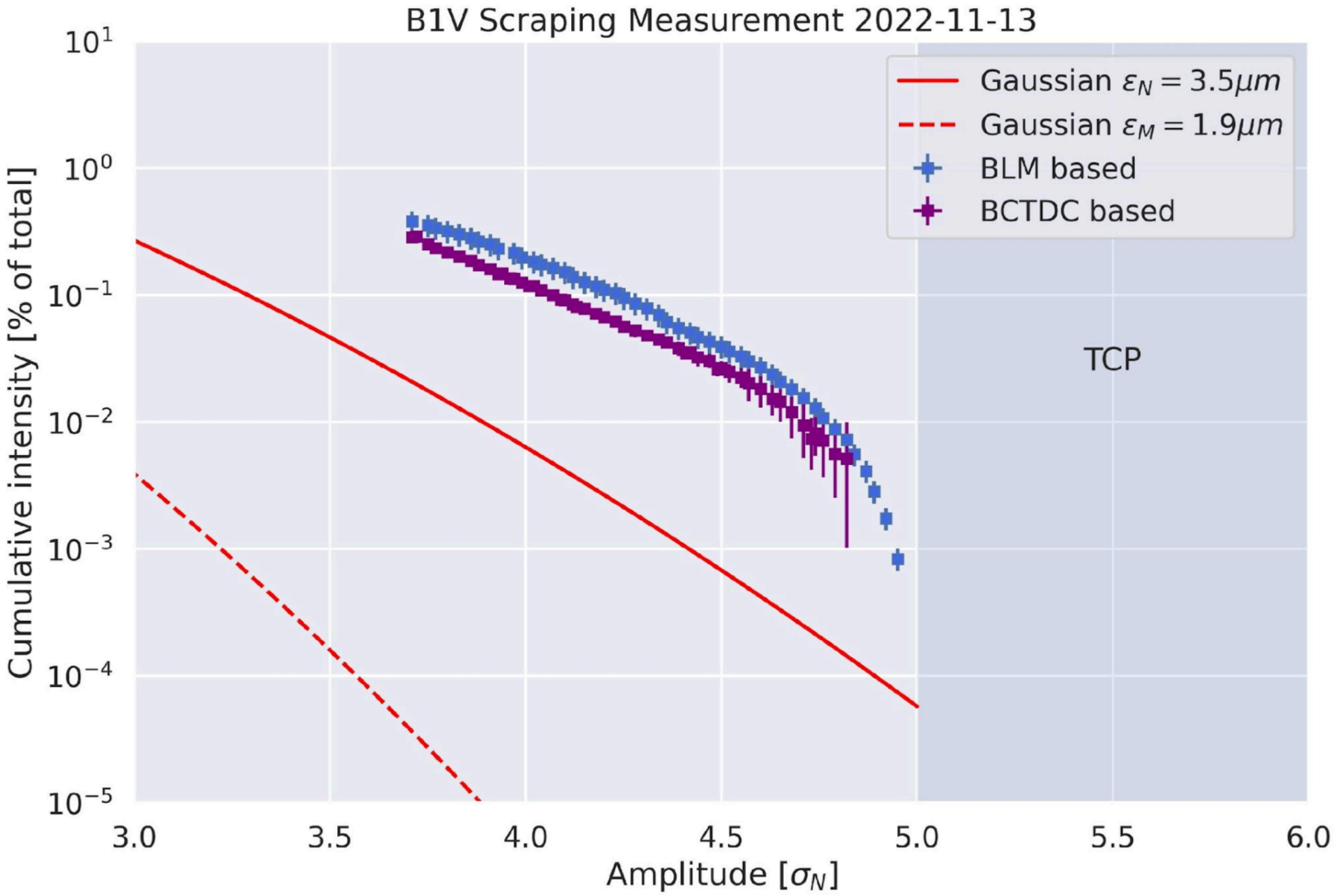


- Several primary collimation settings under consideration (tight/relaxed)
- With a range of possible beam emittance values (reference: 2.5µm)
- Specifications must take this into account for the 7 TeV case (most critical)
- Two main regimes of interest for “tail population”: (1) within 2σ from the TCP jaws and (2) full amplitude range starting from the core edge.

LHC example from collimator scan



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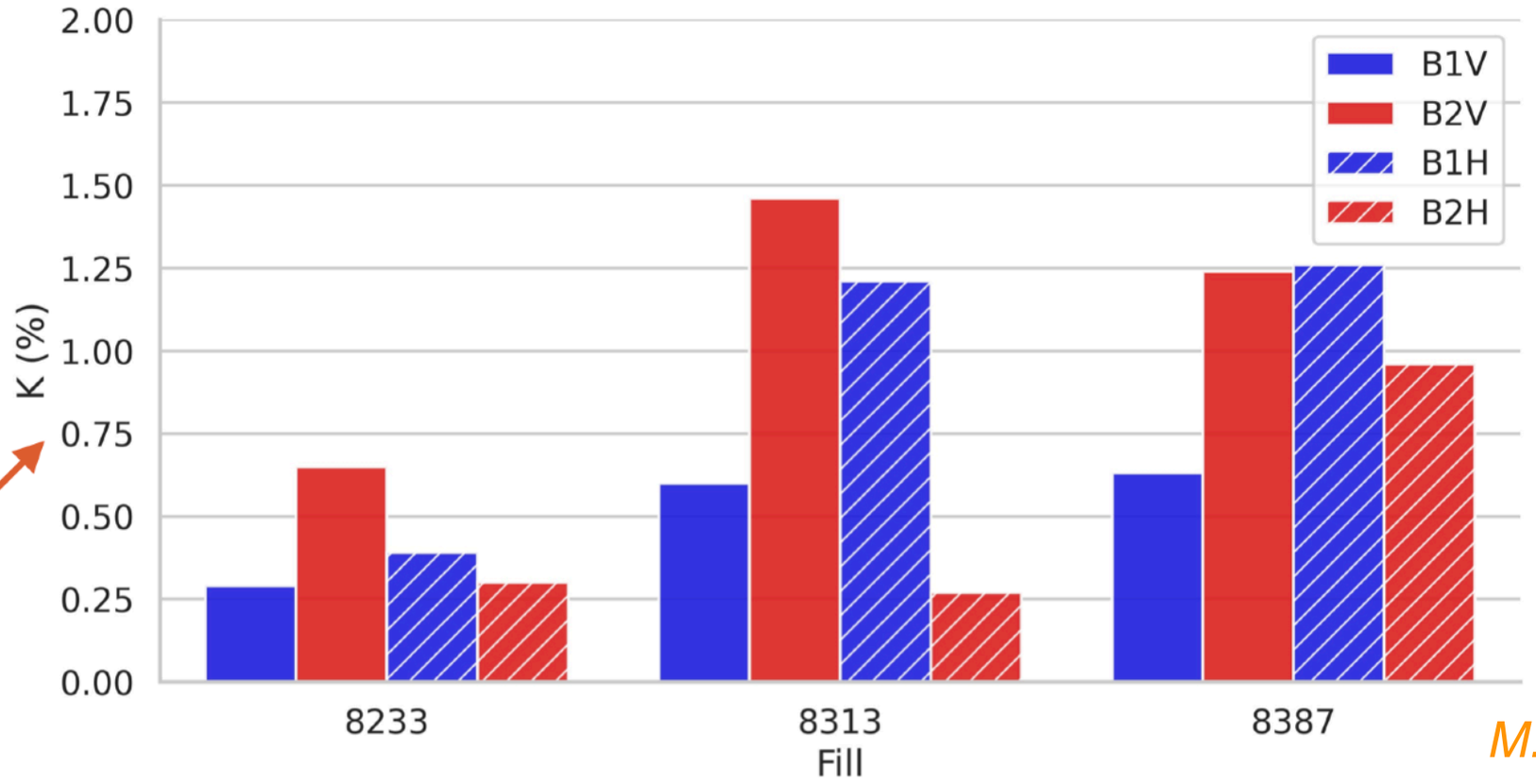
Update on measured halos

LHC reference:
ε = 3.5μm
TCPs at 5σ

Halo population in per cent of total beam intensity at final σ:

K (%)



M. Rakic

Final collimator position:

σ_N

3.1	3.1	3.0	3.2	3.5	3.6	3.1	3.0	3.7	3.4	3.5	3.7

- Could not always achieve the target -2σ from TCP jaws
- Significant variations in ranges observed halo populations: for different beam and planes and fill to fill
- Run 3 shows in general smaller tails than Run 2

Run 2 and Run 3 halos

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
4910	313	4.1	3.9	4.0	4.1				
		0.1	1.2	0.7	1.0				
5105	2076	3.8	3.1	3.1	3.4				
		0.0	1.7	0.9	0.2				
5834	900	3.0	3.0	3.1	3.1	4.6	2.5		1.4
		4.6	2.5	1.4	1.4				
5848	1741	3.2	/	3.1	/				
		8.7	/	8.1	/				
5849	2029	3.2	/	/	3.1				
		5.3	/	/	1.3				
6052	2550	3.7	3.3	3.5	2.8				2.8
		3.0	5.2	1.0	5.5				
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				
7221	2550	/	3.0	/	3.2		5.6		
		/	5.6	/	0.6				
7264	2550	2.9	3.1	3.3	2.8	1.5			1.0
		2.4	0.6	1.0	2.1				
7392	300	3.5	2.0	2.9	2.0		0.7	4.4	0.2
		10.0	9.4	5.7	2.5				

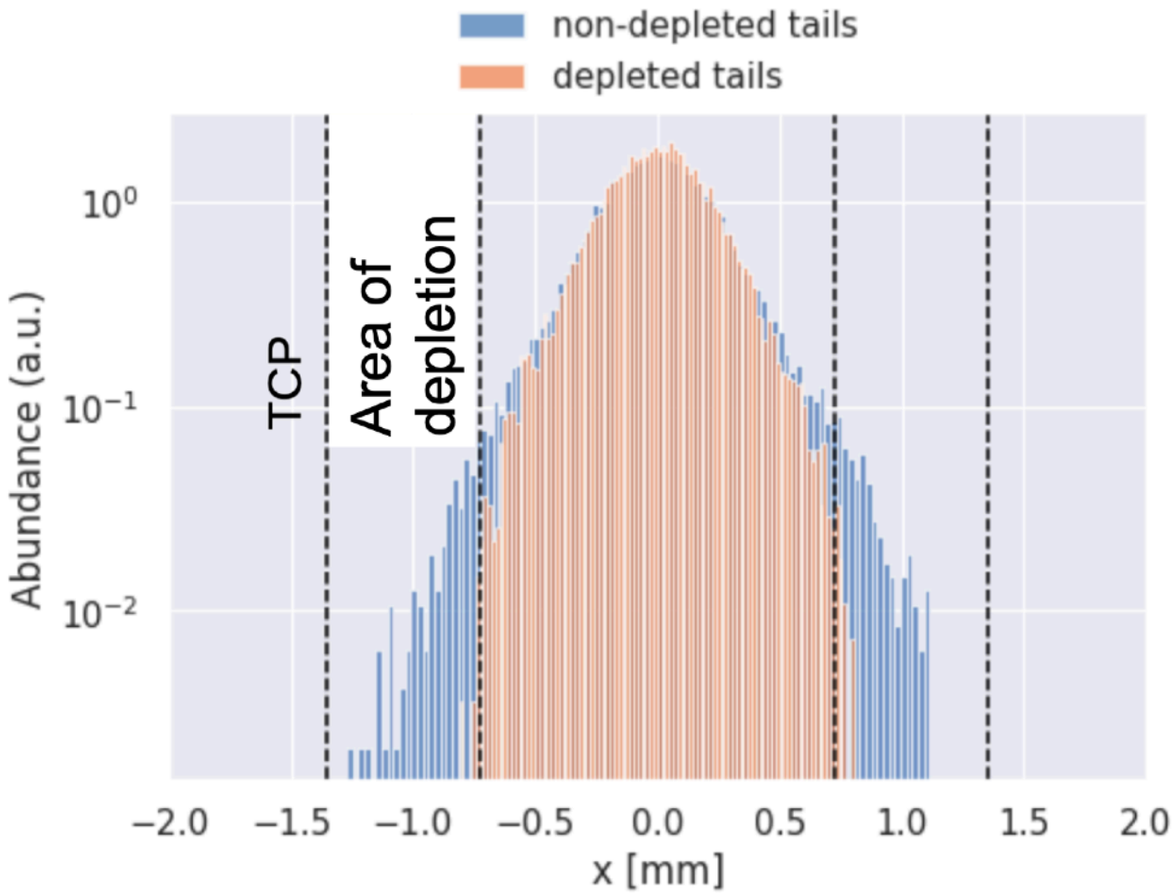
Fill number	Stage	No. of Bunches	Final collimator position [σ] Halo content [%] B1H	B1V	B2H	B2V	Halo content [%] at 3.0 [σ] B1H	B1V	B2H	B2V
8233	EOF	200	3.0	3.1	3.2	3.1	0.3	0.2	0.3	0.6
			0.4	**0.2**	**0.3**	**0.6**				
8313	EOF	1200	3.1	3.5	3.0	3.6	1.2		0.2	
			1.2	**0.6**	**0.3**	**1.4**				
8387	EOF	2462	3.5	3.7	3.7	3.4				
			0.9	**0.3**	**0.1**	**0.7**				
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**				
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**				
9808	EOF	1238	2.6	/	2.6	/	0.8		0.3	
			2.6	**/**	**1.1**	**/**				
9996	EOF	2351	3.1	3.2	3.2	3.5				
			0.7	**0.1**	**0.4**	**0.2**				
10045	INJ	96	/	1.7	/	1.5		1.3		1.3
			/	**26.5**	**/**	**31.5**				

M. Rakic

HL-LHC collimation requirements

TCP half gap (σ_N)	Radial range (σ_N)	Radial range to measure (mm)
6.7	4.7 — 6.7	1.2 — 1.7 (x) 1.6 — 2.3 (y)
8.5	6.5 — 8.5	1.7 — 2.2 (x) 2.3 — 3.0 (y)

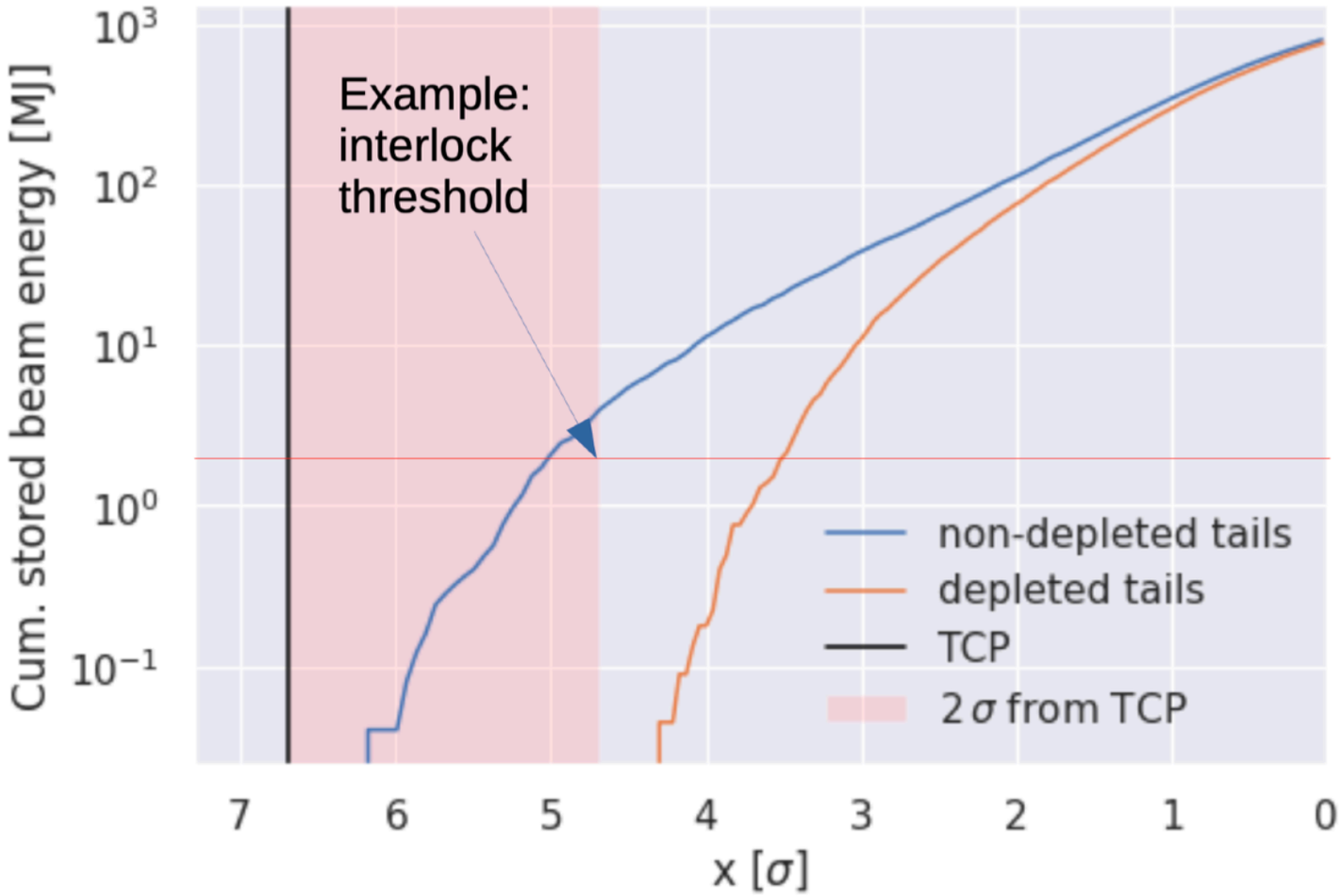
Example: corresponding mm range in IP4, BSRTR.5R4.B1location



$$\mathcal{T} > \int_{u_{\mathrm{TCP}}-2\,\sigma}^{u_{\mathrm{TCP}}} |\rho(u)|\,\mathrm{d}u$$

- Absolute halo content τ < damage level
- Indicative target for damage level 1MJ
- This value and the 2σ integration range are constantly being studied.

Halo monitoring for interlocking



- Halo measurement: initially thought as a trigger for starting HEL depletion, analogy with the abort gap cleaning at the LHC
- We still consider that this interlock functionality would be extremely useful
- Requires redundancy and reliability standards that pose additional challenges
- Some failure scenarios critical if not enough halo for BLM detection — warning if halos too low?

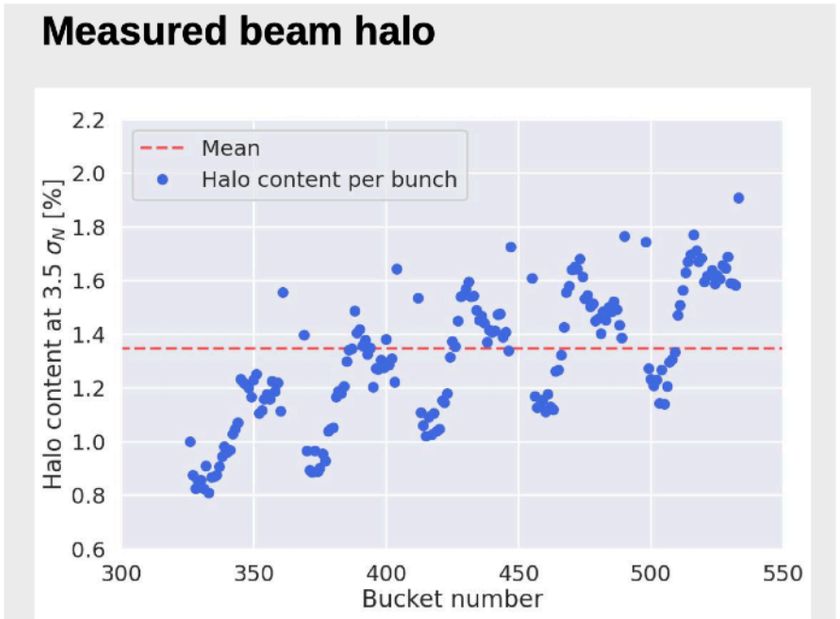
Other halo diagnostics requirements

Desiderata (1st iteration)

- We are mostly interested at **top energy** (but we assume that if have the information there we can have it during the full cycle (?), e.g. at injection (IBS effect) and during the ramp (evolution of the halo)).
- We would need **bunch-by-bunch** halo information (expect that the closed orbit will vary b-by-b up to 0.5 σ).
- We would like reach the precision of the tail distribution to be able to discriminate the q-Gaussian fit on the Δq=**0.02** for $0.8 < q < 1.4$.
- The ideal time sampling it is in the Hz (1/minute, i.e. **1/60 Hz**).

G. Sterbini, Beam Halo meeting, May 2024.

Demonstrated correlation halo / e-cloud



Courtesy of M. Rakic

- Strong synergy between different teams within ABP on halo measurements for beam-beam and performance characterisation. See also talk C.E. Montanari.
  Non-linear dynamics, beam-beam and e-cloud drive diffusion mechanisms and losses at top energy — non-destructive measurements would support a better understanding!
- "Dream specs" for precise bunch-by-bunch measurements of halos!
  Interest in tail populations close to the core, q-Gaussian analysis — promising results in 2024 with the LHC synchrotron light monitor.

Considerations on time structure

- Ideally, we want “bunch-by-bunch everything”
- Collimation/machine protection require the knowledge of the total population above 4.7σ. Measurement times: seconds to minutes
  More studies needed to refine these numbers
- Requirement to resolve injected batched of 36b to 72b
  HEL specs for batch-by-batch depletion to leave “witness batches”

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- Some definitions
- Review of requirements
- **Funct. specifications summary**
- Conclusions

REFERENCE

LHC-EQCOD-ES-XXXXX

Date: December 16, 2024

FUNCTIONAL SPECIFICATIONS

Beam halo monitor

ABSTRACT:
This document presents the reference functional specifications of the Beam Halo monitor for the High-Luminosity Large Hadron Collider project.

DOCUMENT PREPARED BY:	DOCUMENT TO BE CHECKED BY:	DOCUMENT TO BE APPROVED BY:
F. Roncarolo (SY-BI) J. Pucek (SY-BI)	beam-halo-WG-invited	S. Redaelli (BE-ABP) T. Lefevre (SY-BI) D. Wollmann (TE-MPE) M. Zerlauth (ATS-DO)

DOCUMENT SENT FOR INFORMATION TO:

beam-halo-WG-for-info egroup

Some highlight of specs. document

1. **Relative integral**, as the ratio between the beam profile (image) integral from $\bar{\sigma}$ to ∞ and the beam profile (image) integral from 0 to ∞.
2. **Contrast**, defined as the ratio between the beam profile (image) intensity at $\bar{\sigma}$ and the beam profile (image) maximum.
3. **Q-value** of the q-Gaussian model of the charge distribution.

All of the quantities above are linked together as long as an assumption holds true – the proton bunch is reasonably well represented by a q-Gaussian model at all times. To complement the definitions with a graphical representation, the figures 2.1,2.2 demonstrate the relation between contrast and relative integral.

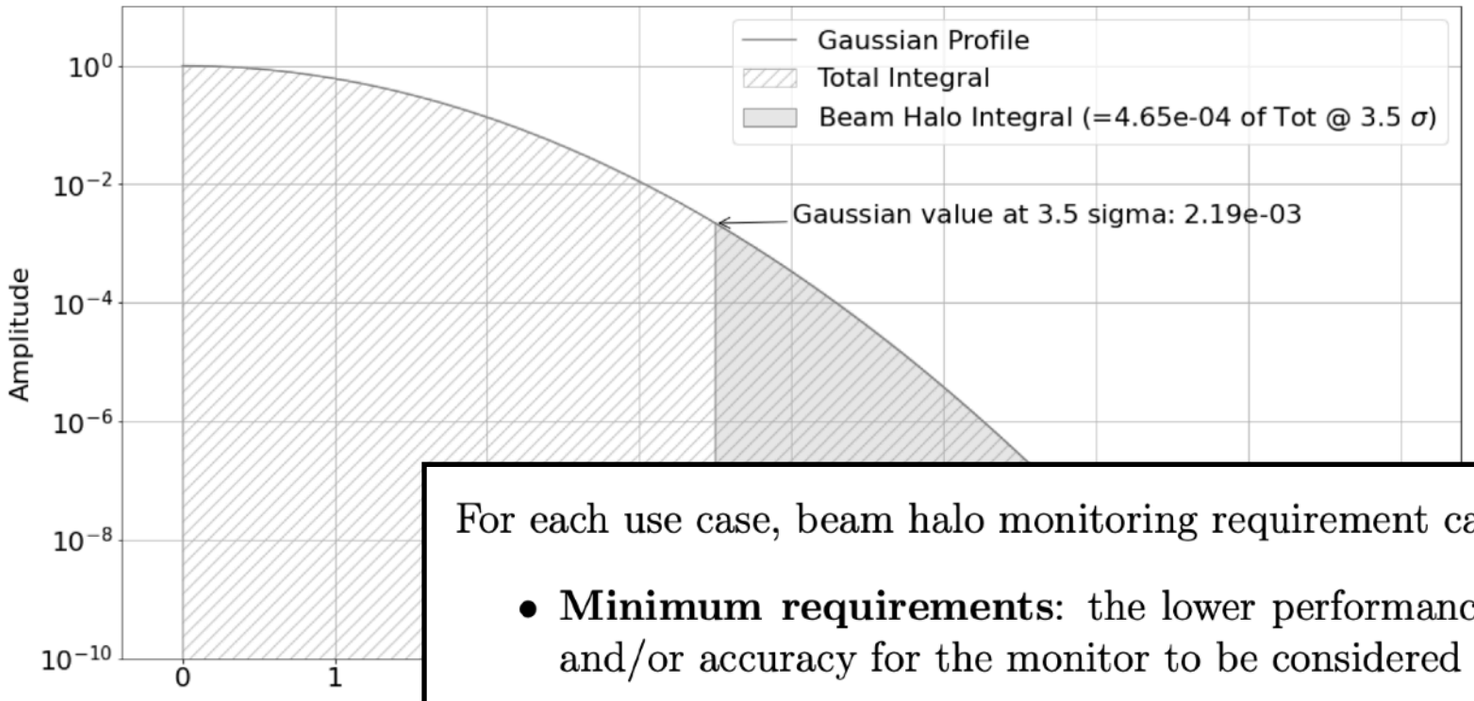

Figure 2.1 – The relati

For each use case, beam halo monitoring requirement can be categorised as:

- **Minimum requirements**: the lower performance range in terms of sensitivity, resolution and/or accuracy for the monitor to be considered useful
- **Ultimate requirements or desiderata**: more demanding performance levels that would enhance halo monitoring effectiveness in optimising the LHC's overall protection and/or physics reach
- **Warning or Interlocking functionalities** implying high availability and reliability to avoid spurious beam dumps.

Summary table with specifications

Parameter	Remarks	Unit	Collimation	MP	Beam-Beam
ROI	e.g. 3.5 to $+\infty$	Sigmas $\epsilon_n = 2.5\mu m$	4.7 to 6.7, 6.5 to 8.5	4.7 to 6.7, 6.5 to 8.5	3.5 to 8.5
Contrast Required	Resolve halo at xx sigma / core-peak=1e-4	-	10^{-4} at upper bound	10^{-6} at 6.7σ	5×10^{-5} at 7σ
Relative Integral	(Halo/total) measurement range for ROI	# of p	5% to 0.5%	1.4% to 0.2%	
Absolute Integral	# of p in ROI	# of p	1.5×10^{12}	$(1-4) \times 10^{10}$	
Charge Required	Yes / No	-	Yes	Yes	No
Profile Required	Yes / No	-	No	No	Yes (complementary to BWS)
Profile Desirable	Yes / No	-	Yes	Maybe	-
2D Image Required	Yes / No	-	No	No	Yes
2D Image Desirable	Yes / No	-	Yes	No	-
Acq. Rate	for full machine	Seconds	≈ 60	≈ 10	≈ 60
Gating and Integration	Bunch per Bunch / Trains / other	-	Beam	Train of 48b	bunch per bunch
Integration over Multi Turns Acceptable	Yes/No	Yes	Yes	Yes	Yes
Interlocking Desired	Yes / No (=monitoring only)	-	No	Yes	No

Conclusions

- The functional specifications for a halo monitoring system at the HL-LHC are being finalised
  - The beam halo monitoring WG collected consistently the requirements
  - "Minimum functionality" driven by collimation/machine protection
  - A plethora of requirements is out there, which reflects the strong interest
  - Funct. specs should also be compatible with a future deployment of HELs
- Halo matters will remain important for the HL-LHC operation, in particular during Run 4 without active halo control
  - Crucial to continue studying these topics with the final HL-LHC beam parameters — not accessible in Run 3 — to decide promptly of HEL deployment
- Measurements must continue in Run 3 with high priority!
  - Not-ideal method based on collimator scans is still extremely useful!
  - Important to understand the full potential of the coronagraph, in particular for the updated specs about requirements of critical tails in the TCP jaw vicinity
- Looking forward to seeing various methods under study