Integrated luminosity of the new HL-LHC baseline

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14th HL-LHC collaboration meeting

Overview

- The LHC Luminosity Model
- Luminosity projections for baseline scenario and variations
- Lessons learned from LHC Run3:
  - Emittance evolution at injection & collisions
  - Performance gain from BCMS in 2024
  - Losses, tails & DA during Adjust, start & during Stable Beams

Luminosity projections for HL-LHC

Summary of the LHC luminosity model

- Iterative algorithm that calculates evolution of beam & machine p
  collisions [1], [2]:
  - **Emittance evolution:**
    I. IntraBeam scattering
    II. Synchrotron radiation
    III. Crab cavity noise
    - Not included: extra emittance blowup from unknown source observed in LHC

Emittance blowup with unknown origin observed in the LHC both at injection and top energy, in both beams and planes, especially vertical plane cannot be explained with current models

Summary of the LHC luminosity model

- Iterative algorithm that calculates evolution of beam & machine parameters every 5 minutes during collisions [1], [2]:
  - **Emittance evolution:**
    - I. IntraBeam scattering
    - II. Synchrotron radiation
    - III. Crab cavity noise
    - ❖ Not included: extra emittance blowup from unknown source observed in LHC
  - **Intensity evolution:**
    - I. Burn-off decay due to collisions in ATLAS, CMS & LHCb depending on the filling scheme
    - II. Additional losses from unknown source based on LHC experience

Considering 110 mb instead of ~81 mb to account for losses beyond burn-off at the start of collisions based on LHC experience. Losses improved in 2024 thanks to DA optimizations & low-tail beams

Summary of the LHC luminosity model

- Iterative algorithm that calculates evolution of beam & machine parameters every 5 minutes during collisions [1], [2]:
  - **Emittance evolution:**
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  - **Intensity evolution:**
    - I. Burn-off decay due to collisions in ATLAS, CMS & LHCb depending on the filling scheme
    - II. Additional losses from unknown source based on LHC experience
  - **Luminosity:**
    - Analytical and numerical integration of 4 integrals
    - q-Gaussian PDF for the longitudinal plane with q=3/5 or Gaussian PDF
  - **Leveling to maximum pile-up or peak luminosity target:**
    - I. Continuous β^*-leveling for CMS & ATLAS with a lumi decay tolerance
    - II. Additional leveling by separation in ATLAS
    - III. Skew separation leveling in LHCb

Considering 110 mb instead of ~81 mb to account for losses beyond burn-off at the start of collisions based on LHC experience. Losses improved in 2024 thanks to DA optimizations & low-tail beams

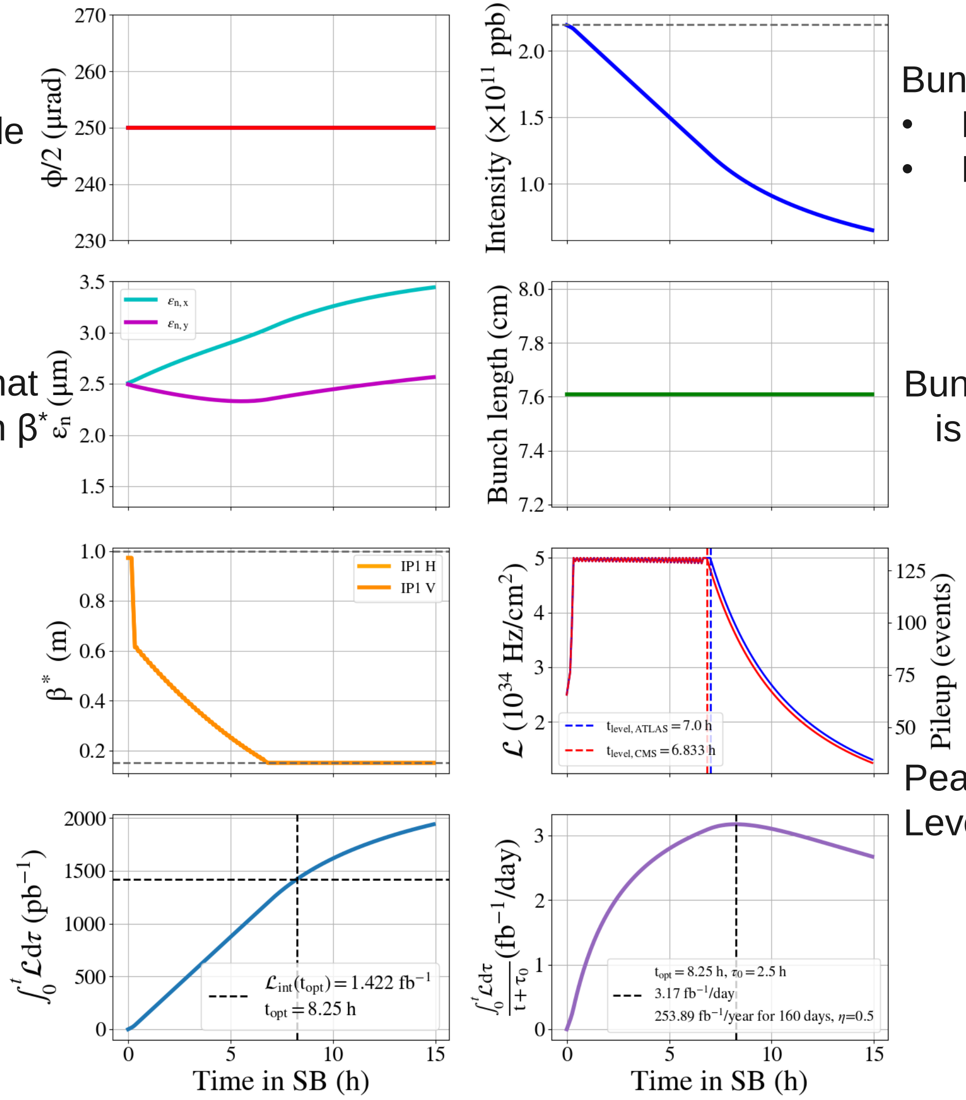
Evolution of beam & machine parameters in a nominal HL-LHC fill

Crossing angle

Emittance:
- IBS & SR
- CC noise that depends on β*

β*,
round optics

Integrated luminosity



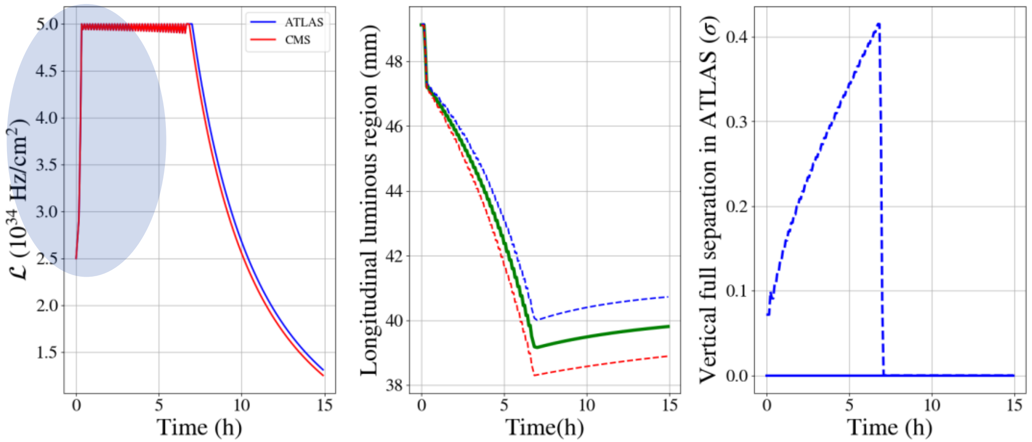
Bunch intensity:
- Burn-off
- Extra losses

Bunch length is leveled

Peak luminosity & pile-up:
Leveling on CMS

20-minute luminosity ramp due to cryogenics constraints

ATLAS vertical separation



Luminous region

Baseline

Run	Year	Efficiency	Bunch intensity (1e11 ppb)	$\beta_{//}^*$ (cm)	β_x^* (cm)	CC	PU_{max}	Days Intensity ramp-up	Days Proton physics [1]	# colliding IP1/5 bunches [2]	# colliding IP8 bunches	Emit start of SB (μm)	IP1/5 crossing plane	IP1/5 φ/2 (μrad)	LHCb L_{peak} (1e33 Hz/cm²) [3]
4	2029 (+1)	0.5	1.8	30	30	off	101	20	6	2748	2574	2.5	H/V	250	2
	2030	0.5	2.2	25	25	on	132	15	136	2748	2574	2.5	H/V	250	2
	2031	0.5	2.2	20	20	on	132	10	154	2748	2574	2.5	H/V	250	2
	2032	0.5	2.2	20	20	on	132	10	152	2748	2574	2.5	H/V	250	2
5	2035	0.5	2.2	15	15	on	132	15	152	2748	2574	2.5	H/V	250	2
	2036	0.5	2.2	15	15	on	132	10	195	2748	2574	2.5	H/V	250	2
	2037	0.5	2.2	15	15	on	132	10	198	2748	2574	2.5	H/V	250	2
	2038	0.5	2.2	15	15	on	132	10	198	2748	2574	2.5	H/V	250	2
6	2040	0.5	2.2	15	15	on	132	15	165	2748	2574	2.5	H/V	250	2
	2041	0.5	2.2	15	15	on	132	10	203	2748	2574	2.5	H/V	250	2

[1]: No ion operation beyond Run 4

[2]: 25ns_2760b_2748_2492_2574_288bpi_13inj_800ns_bs200ns

[3]: Not considering LHCb upgrade after LS4, up to 3% loss of integrated lumi for ATLAS/CMS.

Input from new proposed DMR M. Zerlauth

Baseline

Run	Year	Efficiency	Bunch intensity (1e11 ppb)	$\beta_{//}^*$ (cm)	β_x^* (cm)	CC	PU_{max}	Days Intensity ramp-up	Days Proton physics [1]	# colliding IP1/5 bunches [2]	# colliding IP8 bunches	Emit start of SB (μm)	IP1/5 crossing plane	IP1/5 φ/2 (μrad)	LHCb L_{peak} (1e33 Hz/cm²) [3]
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	2031	0.5	2.2	20	20	on	132	10	154	2748	2574	2.5	H/V	250	2
	2032	0.5	2.2	20	20	on	132	10	152	2748	2574	2.5	H/V	250	2
5	2035	0.5	2.2	15	15	on	132	15	152	2748	2574	2.5	H/V	250	2
	2036	0.5	2.2	15	15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	H/V	250	2
	2037	0.5	2.2	15	15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	H/V	250	2
	2038	0.5	2.2	15	15	on	132	10	[illegible]	2748	2574	2.5	H/V	250	2
6	2040	0.5	2.2	15	15	on	132	15	165	2748	2574	2.5	H/V	250	2
	2041	0.5	2.2	15	15	on	132	10	203	2748	2574	2.5	H/V	250	2

Starting from 1.4e11 ppb, will not be able to reach 1.8e11 ppb with days allocated to intensity ramp-up and physics

[1]: No ion operation beyond Run 4
[2]: 25ns_2760b_2748_2492_2574_288bpi_13inj_800ns_bs200ns
[3]: Not considering LHCb upgrade after LS4, up to 3% loss of integrated lumi for ATLAS/CMS.

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Variations

Run	Year	Efficiency	Bunch intensity (1e11 ppb)	$\beta_{//}^*$ (cm)	β_x^* (cm)	CC	PU_{max}	Days Intensity ramp-up	Days Proton physics [1]	# colliding IP1/5 bunches [2]	# colliding IP8 bunches	Emit start of SB (μm)	IP1/5 crossing plane	IP1/5 φ/2 (μrad)	LHCb L_{peak} (1e33 Hz/cm^2) [3]
4	2029 (+1)	0.5	1.8	**30**	**30**	off	101	20	6	2748	2574	2.5	**H/V→V/H**	250	2
	2030	0.5	2.2	**25**	**25**	on	132	15	136	2748	2574	2.5	**H/V→V/H**	250	2
	2031	0.5	2.2	**20→8**	**20→18**	on	132	10	154	2748	2574	2.5	**H/V→V/H**	250	2
	2032	0.5	2.2	**20→8**	**20→18**	on	132	10	152	2748	2574	2.5	**H/V→V/H**	250	2
5	2035	0.5	2.2	**15→8**	**15→18**	on	132	15	152	2748	2574	2.5	**H/V→V/H**	250	2
	2036	0.5	2.2	**15→8**	**15→18**	on	132	10	195	2748	2574	2.5	**H/V→V/H**	250	2
	2037	0.5	2.2	**15→8**	**15→18**	on	132	10	198	2748	2574	2.5	**H/V→V/H**	250	2
	2038	0.5	2.2	**15→8**	**15→18**	on	132	10	198	2748	2574	2.5	**H/V→V/H**	250	2
6	2040	0.5	2.2	**15→8**	**15→18**	on	132	15	165	2748	2574	2.5	**H/V→V/H**	250	2
	2041	0.5	2.2	**15→8**	**15→18**	on	132	10	203	2748	2574	2.5	**H/V→V/H**	250	2

“Flat 8/18 cm”: alleviate impedance from CC and increase integrated luminosity

Variations

Run	Year	Efficiency	Bunch intensity (1e11 ppb)	$\beta_{//}^*$ (cm)	β_x^* (cm)	CC	PU_{max}	Days Intensity ramp-up	Days Proton physics [1]	# colliding IP1/5 bunches [2]	# colliding IP8 bunches	Emit start of SB (µm)	IP1/5 crossing plane	IP1/5 φ/2 (µrad)	LHCb L_{peak} (1e33 Hz/cm^2) [3]
4	2029 (+1)	0.5	1.8	30	30	off	101	20	6	**2748→ 2440**	**2574→ 2240**	2.5	H/V	250	2
	2030	0.5	2.2	25	25	on	132	15	136	**2748→ 2440**	**2574→ 2240**	2.5	H/V	250	2
	2031	0.5	2.2	20	20	on	132	10	154	**2748→ 2440**	**2574→ 2240**	2.5	H/V	250	2
	2032	0.5	2.2	20	20	on	132	10	152	**2748→ 2440**	**2574→ 2240**	2.5	H/V	250	2
5	2035	0.5	2.2	15	15	on	132	15	152	**2748→ 2440**	**2574→ 2240**	2.5	H/V	250	2
	2036	0.5	2.2	15	15	on	132	10	195	**2748→ 2440**	**2574→ 2240**	2.5	H/V	250	2
	2037	0.5	2.2	15	15	on	132	10	198	**2748→ 2440**	**2574→ 2240**	2.5	H/V	250	2
	2038	0.5	2.2	15	15	on	132	10	198	**2748→ 2440**	**2574→ 2240**	2.5	H/V	250	2
6	2040	0.5	2.2	15	15	on	132	15	165	**2748→ 2440**	**2574→ 2240**	2.5	H/V	250	2
	2041	0.5	2.2	15	15	on	132	10	203	**2748→ 2440**	**2574→ 2240**	2.5	H/V	250	2

”Round hybrid”:
25ns_2452b_2440_1952_2240_248bpi_12inj_mixed

Variations

Run	Year	Efficiency	Bunch intensity (1e11 ppb)	$\beta_{//}^*$ (cm)	β_x^* (cm)	CC	PU_{max}	Days Intensity ramp-up	Days Proton physics [1]	# colliding IP1/5 bunches [2]	# colliding IP8 bunches	Emit start of SB (μm)	IP1/5 crossing plane	IP1/5 φ/2 (μrad)	LHCb L_{peak} (1e33 Hz/cm²) [3]
4	2029 (+1)	0.5	1.8	30	30	off	101	20	6	2748→ 2736	2574→2370	2.5→ 2.2	H/V	250	2
	2030	0.5	2.2	25	25	on	132	15	136	2748→ 2736	2574→2370	2.5→ 2.2	H/V	250	2
	2031	0.5	2.2	20	20	on	132	10	154	2748→ 2736	2574→2370	2.5→ 2.2	H/V	250	2
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	2036	0.5	2.2	15	15	on	132	10	195	2748→ 2736	2574→2370	2.5→ 2.2	H/V	250	2
	2037	0.5	2.2	15	15	on	132	10	198	2748→ 2736	2574→2370	2.5→ 2.2	H/V	250	2
	2038	0.5	2.2	15	15	on	132	10	198	2748→ 2736	2574→2370	2.5→ 2.2	H/V	250	2
6	2040	0.5	2.2	15	15	on	132	15	165	2748→ 2736	2574→2370	2.5→ 2.2	H/V	250	2
	2041	0.5	2.2	15	15	on	132	10	203	2748→ 2736	2574→2370	2.5→ 2.2	H/V	250	2

”Round BCMS”: Based on experience gained in LHC 2024 run

25ns_2744b_2736_2246_2370_240bpi_13inj_800ns_bs200ns_BCMS_5x48b

Variations

Run	Year	Efficiency	Bunch intensity (1e11 ppb)	β_x^* (cm)	β_y^* (cm)	CC	PU_{max}	Days Intensity ramp-up	Days Proton physics [1]	# colliding IP1/5 bunches [2]	# colliding IP8 bunches	Emit start of SB (μm)	IP1/5 crossing plane	IP1/5 φ/2 (μrad)	LHCb L_{peak} (1e33 Hz/cm^2) [3]
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	2031	0.5	2.2	20	20	on	132	10	154	2748	2574	2.5	H/V	250	2
	2032	0.5	2.2	20	20	on	132	10	152	2748	2574	2.5	H/V	250	2
5	2035	0.5	2.2	15	15	on	132	15	**152→130**	2748	2574	2.5	H/V	250	2
	2036	0.5	2.2	15	15	on	132	10	**195→172**	2748	2574	2.5	H/V	250	2
	2037	0.5	2.2	15	15	on	132	10	**198→175**	2748	2574	2.5	H/V	250	2
	2038	0.5	2.2	15	15	on	132	10	**198→175**	2748	2574	2.5	H/V	250	2
6	2040	0.5	2.2	15	15	on	132	15	**165→141**	2748	2574	2.5	H/V	250	2
	2041	0.5	2.2	15	15	on	132	10	**203→179**	2748	2574	2.5	H/V	250	2

"Nominal ions" → "Extended ions"

Yearly & total integrated luminosity

Run	Year	Baseline	Round hybrid	Round BCMS	Flat 8/18 cm	Vbaseline extended ions	Round hybrid extended ions	Round BCMS extended ions	Flat 8/18 cm extended ions
4	2029 (+1)	9.6	9.1	10	9.6	9.6	9.1	10	9.6
	2030	208	186.1	210.7	208	208	186.1	210.7	208
	2031	238.8	213.4	241	254.1	238.8	213.4	241	254.1
	2032	235.7	210.7	237.9	250.8	235.7	210.7	237.9	250.8
5	2035	248.5	222.6	250.2	256	213.8	191.6	215.3	220.3
	2036	311.7	278.6	313.7	320.5	275.4	246.2	277.2	283.2
	2037	316.4	282.9	318.4	325.3	280.1	250.5	281.9	288.1
	2038	316.4	282.9	318.4	325.3	280.1	250.5	281.9	288.1
6	2040	269.1	240.9	270.9	277	213.2	207.1	232.8	238.1
	2041	324.3	289.9	326.4	333.4	286.5	256.1	288.3	294.6
Total (fb^{-1})		2478.5	2217	2497.7	2560	2259.2	2021.2	2277.1	2334.9

- Approximately 6.5 hours of leveling & 7.5 h optimal fill length depending on the scenario.
- For Run 4, reaching 15 cm instead of 20 cm results in **+3.44%** increase of integrated luminosity per year
- Reducing crossing angle from 250 to 220 μrad with round optics and 210 μrad with flat results in gain of +**1.5% & +1%**

Realtive yearly & total integrated luminosity

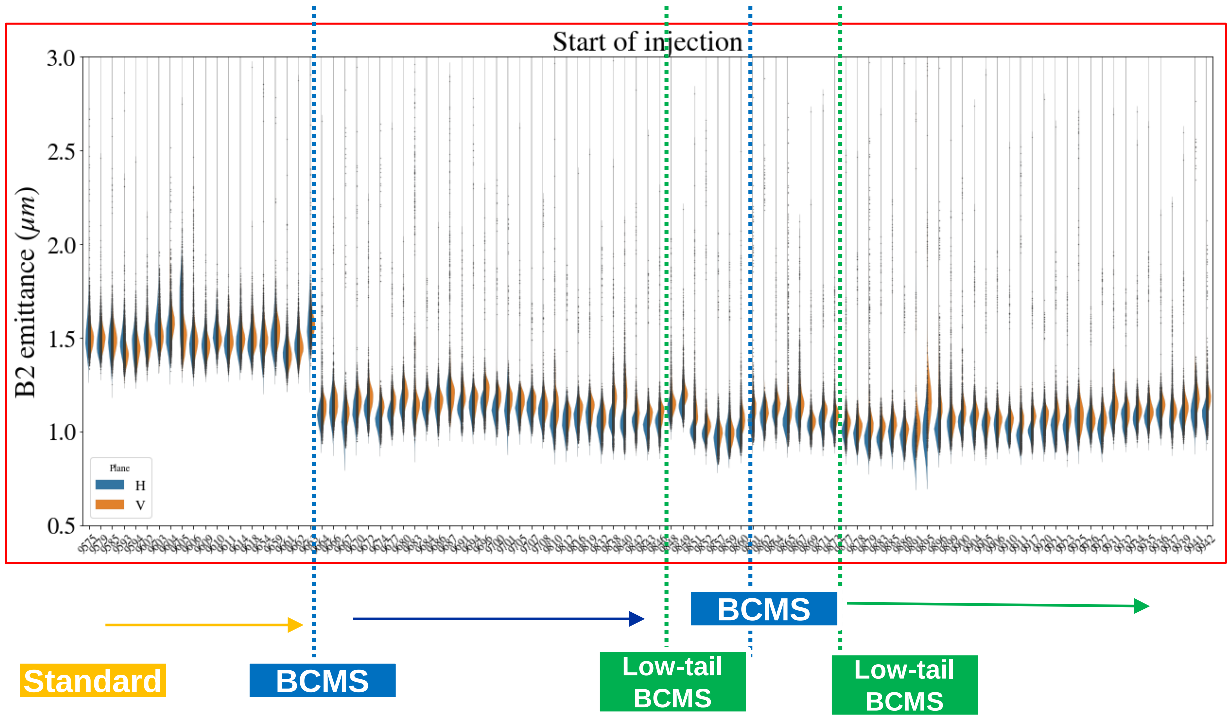
Run	Year	Baseline (fb-1)	Round hybrid	Round BCMS	Flat 8/18 cm	Vbaseline extended ions	Round hybrid extended ions	Round BCMS extended ions	Flat 8/18 cm extended ions
4	2029 (+1)	9.6	-5.21%	4.17%	0%	0%	-5.21%	4.17%	0%
	2030	208	-10.53%	1.30%	0%	0%	-10.53%	1.30%	0%
	2031	238.8	-10.64%	0.92%	6.41%	0%	-10.64%	0.92%	6.41%
	2032	235.7	-10.61%	0.93%	6.41%	0%	-10.61%	0.93%	6.41%
5	2035	248.5	-10.42%	0.68%	3.02%	-13.96%	-22.90%	-13.36%	-11.34%
	2036	311.7	-10.62%	0.64%	2.82%	-11.65%	-21.02%	-11.07%	-9.14%
	2037	316.4	-10.58%	0.63%	2.81%	-11.48%	-20.83%	-10.90%	-8.94%
	2038	316.4	-10.58%	0.63%	2.81%	-11.48%	-20.83%	-10.90%	-8.94%
6	2040	269.1	-10.48%	0.67%	2.94%	-20.78%	-23.04%	-13.49%	-11.52%
	2041	324.3	-10.60%	0.65%	2.81%	-11.66%	-21.03%	-11.10%	-9.15%
		2478.5	**-10.55%**	**0.77%**	**3.28%**	**-8.85%**	**-18.45%**	**-8.13%**	**-5.79%**

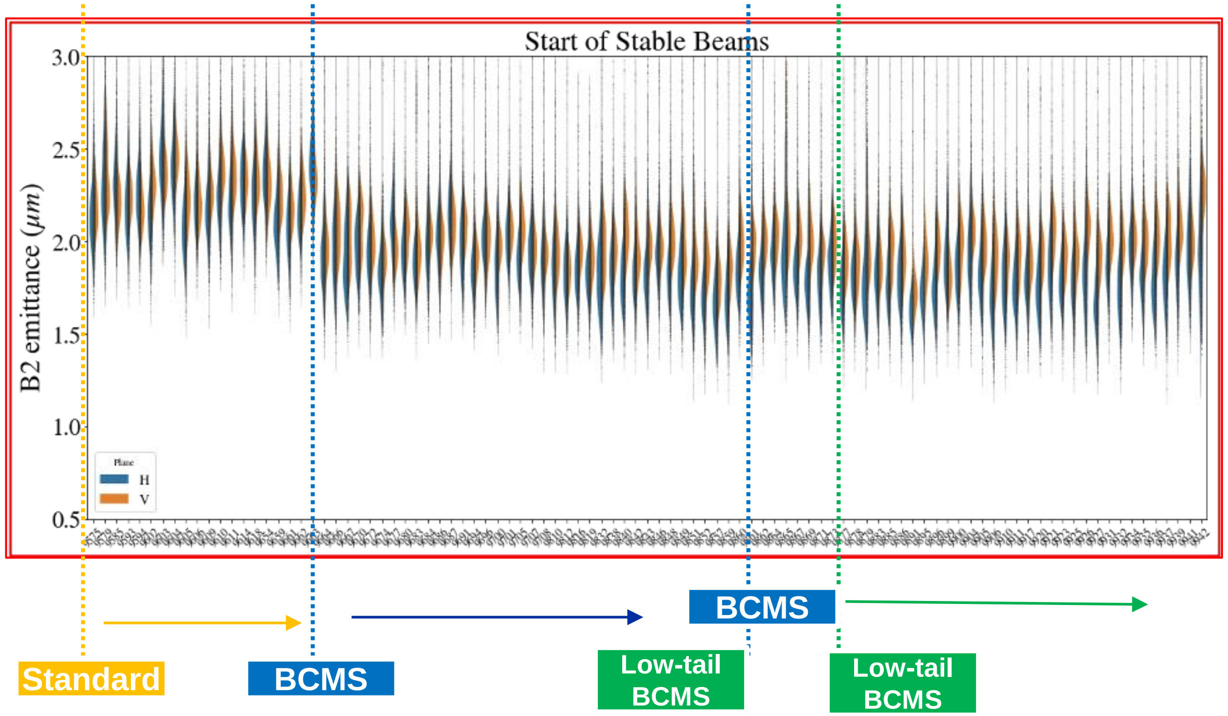
- Slight increase with BCMS **(+1%)** for HL-LHC: ~4% gain for 2029 where pile-up target & bunch intensity are smaller while β* limited to 30cm (similar to LHC) and then beneficial impact of lower initial emittance reduces to ~1%.
- **+3%** gain with flat optics
- **-9%** if ion runs extends beyond Run 4
- **-10%** with hybrid, -19% if hybrid + ion runs beyond Run 4
- Loss of performance due to ion runs beyond Run 4 can be partially mitigated with flat optics.
- Flat optics are clearly beneficial for performance but operational experience with flat optics is limited.

Lessons learned from Run 3: emittance evolution

Performance in 2024 with BCMS beams: Emittance

- Different beam types from the injectors tested in 2024: BCMS → ~20% emittance reduction at the start of injection, ~10% at start of collisions (1.8 μm)



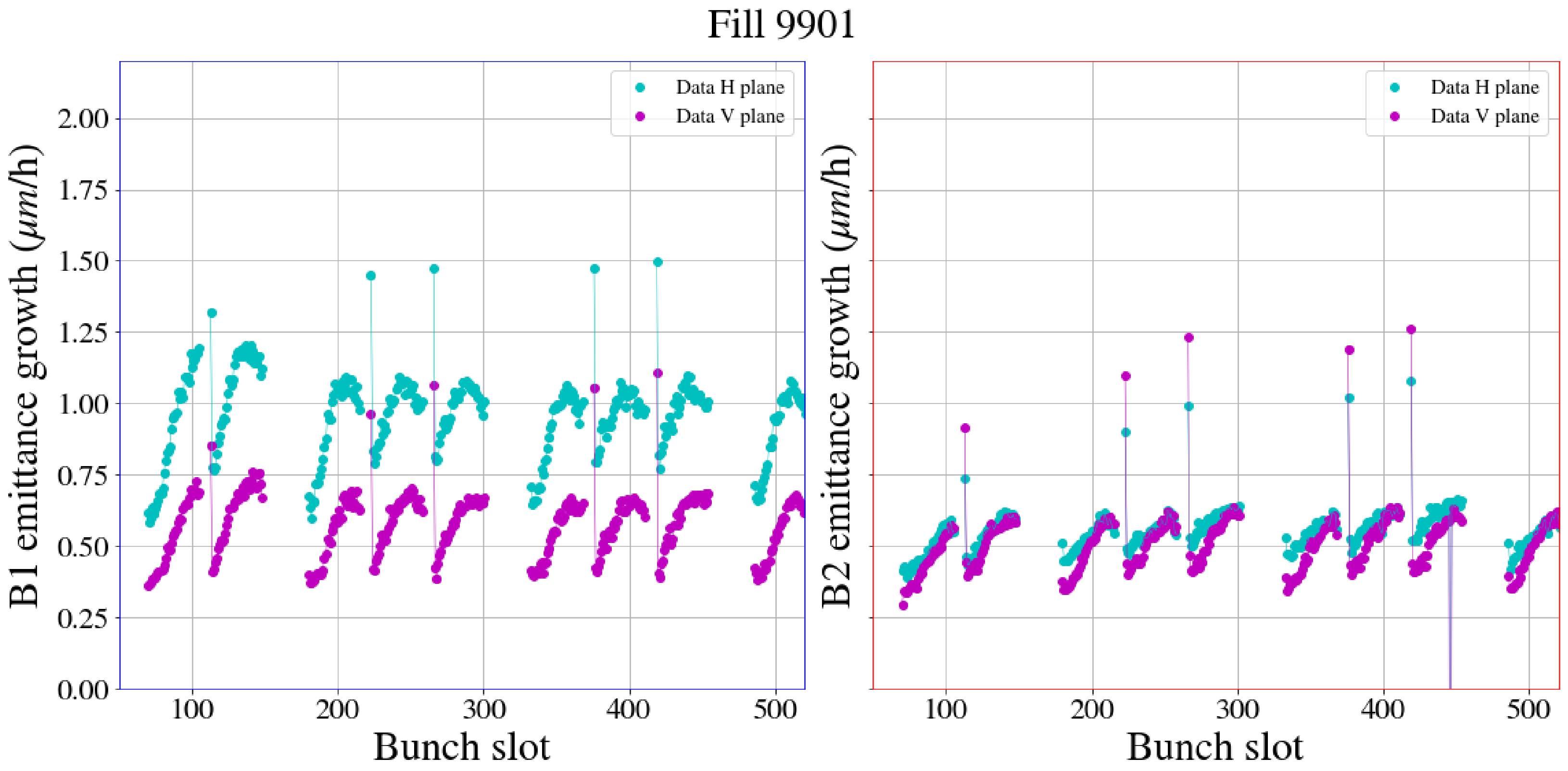


Emittance (μm)	B1H	B1V	B2H	B2V
Standard	1.56	1.58	1.5	1.5
BCMS	1.19	1.27	1.13	1.17
%	**-23.8**	**-19.84**	**-24.96**	**-22.33**

Emittance (μm)	B1H	B1V	B2H	B2V
Standard	1.84	1.67	2.25	2.3
BCMS	1.57	1.54	1.97	2.02
%	**-14.74**	**-7.38**	**-12.48**	**-12.06**

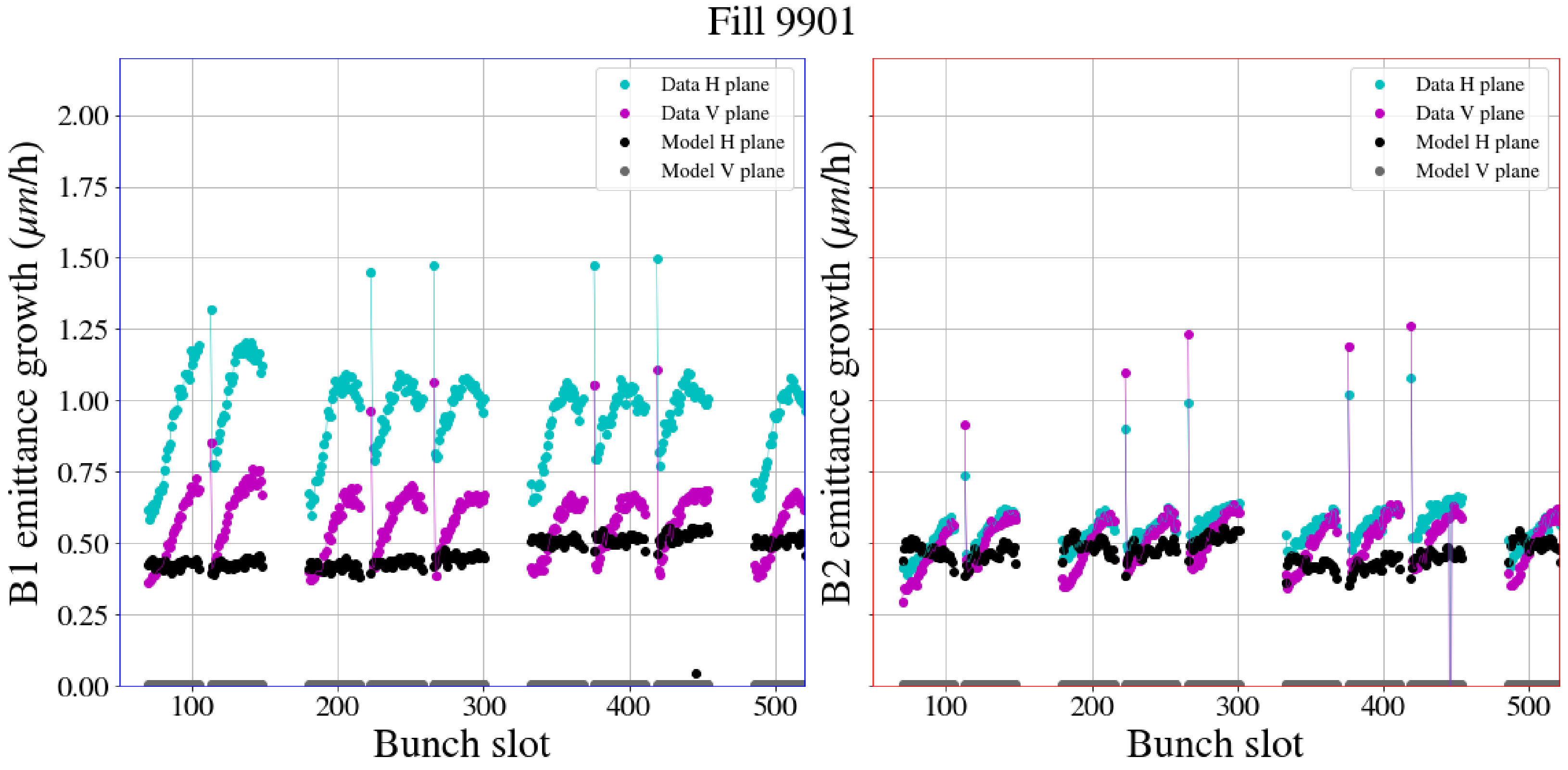
Emittance growth at injection

- **Emittance growth mechanism at injection not fully understood:**
  - Systematically larger in B1H: ~0.6 μm/h for B1H in addition to e-cloud.
  - ~0.35 μm/h in B2H/V & B1V in addition to e-cloud.



Emittance growth at injection

- **Emittance growth mechanism at injection not fully understood:**
  - Not consistent with IBS alone, especially for V plane, varies between fills.
  - Linear increase of emittance in time.



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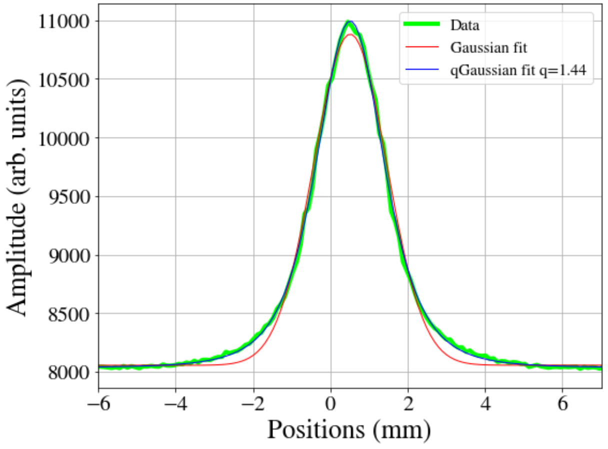
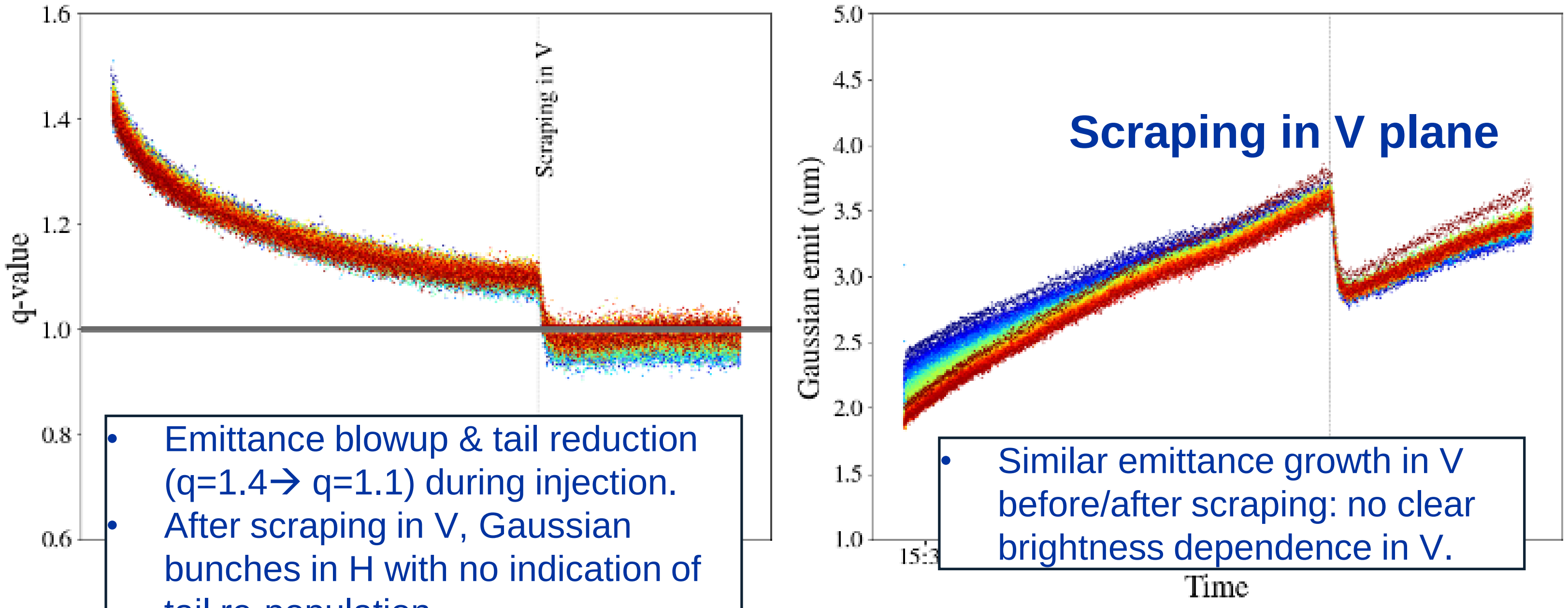


q-Gaussian fits:
q=1 Gaussian
q>1 heavy tails

Fill 10045, B1H, 36b BSRT



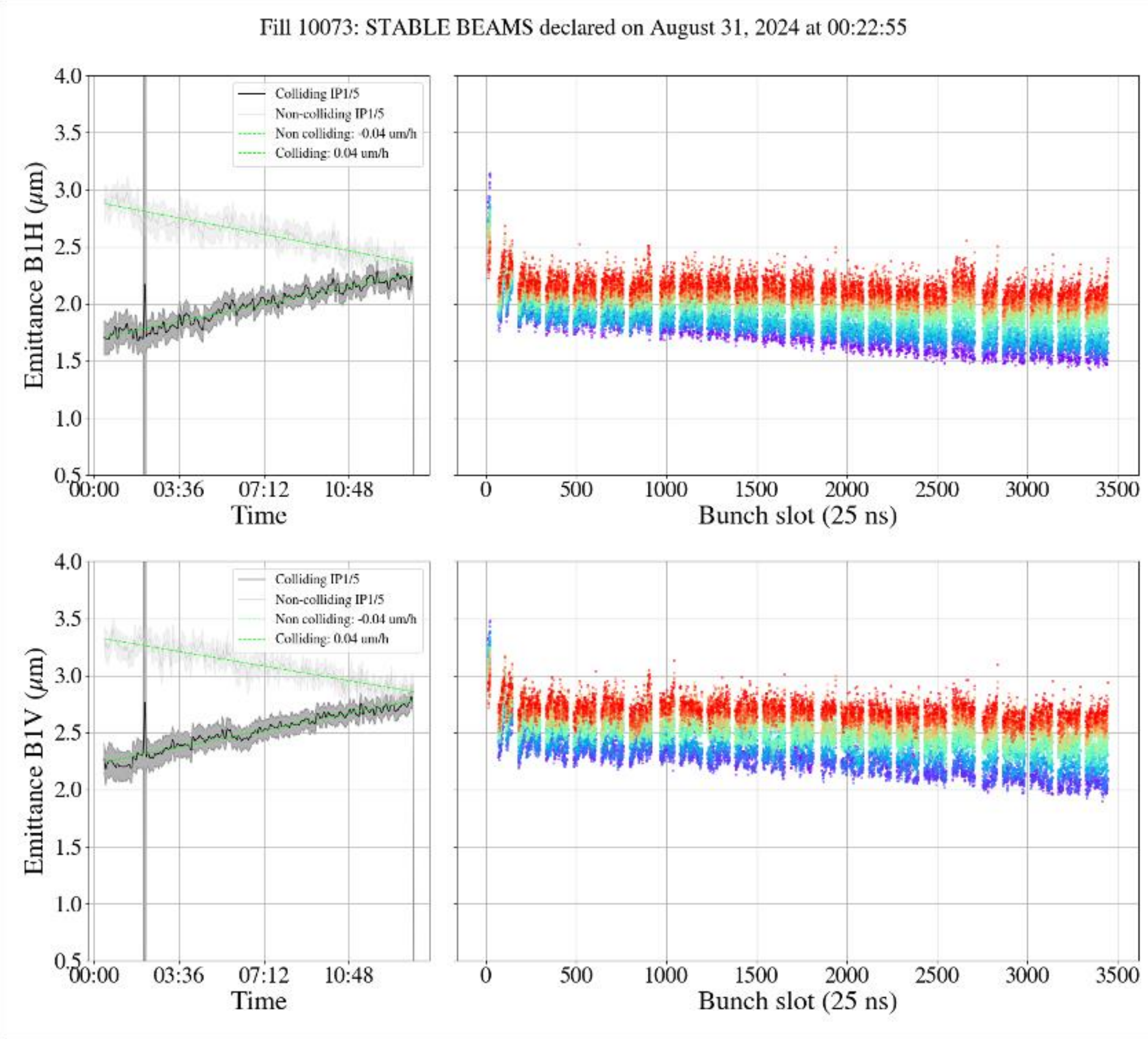
- Emittance blowup & tail reduction (q=1.4→ q=1.1) during injection.
- After scraping in V, Gaussian bunches in H with no indication of tail re-population.

Scraping in V plane

- Similar emittance growth in V before/after scraping: no clear brightness dependence in V.

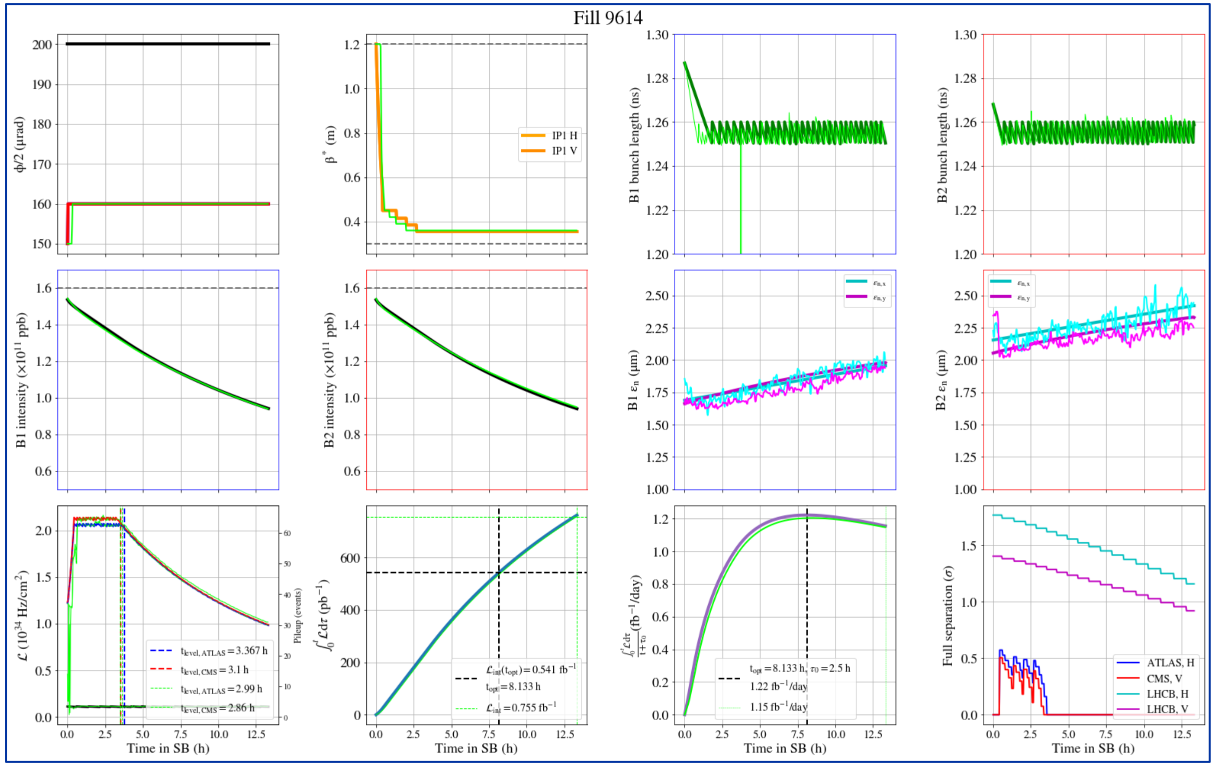
Emittance growth at collisions

- Emittance growth of unknown origin also during collisions:
  - Cannot be fully explained by IBS models.
  - Vertical emittance expected to be shrinking due to SR.

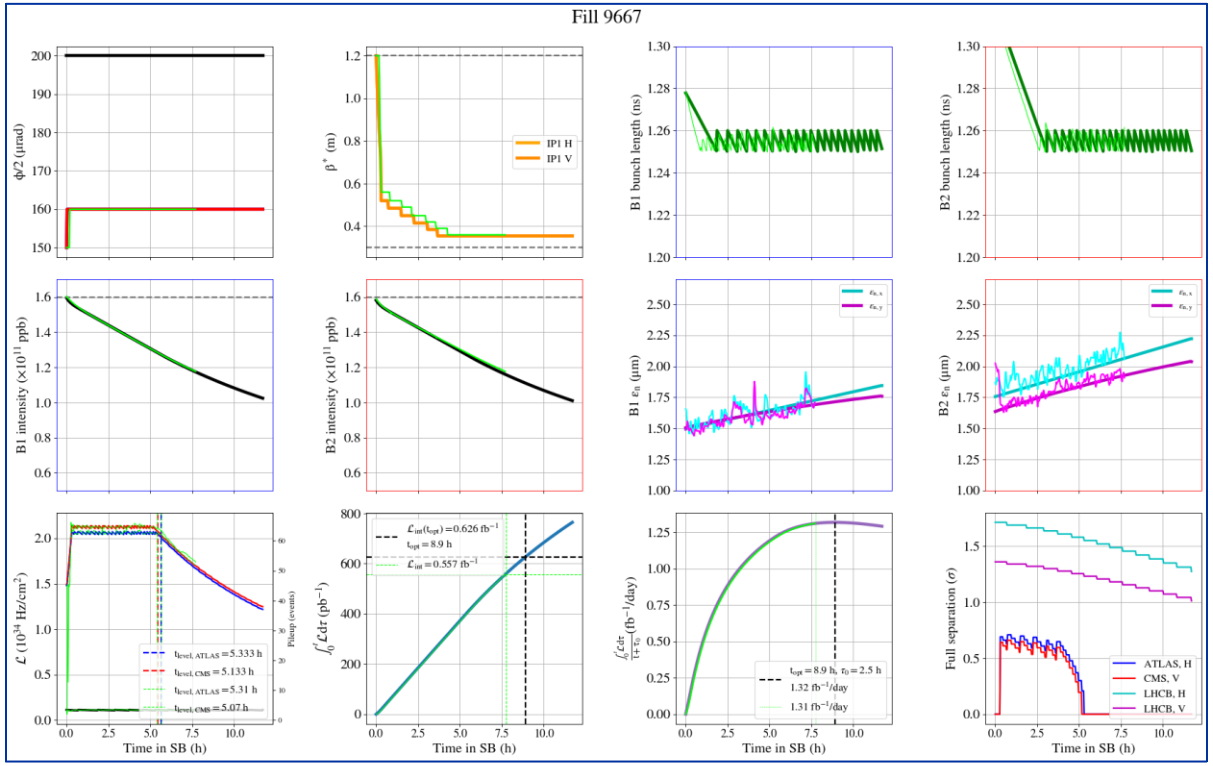


Performance gain from BCMS in 2024

Fill 9614, Standard



Fill 9667, BCMS



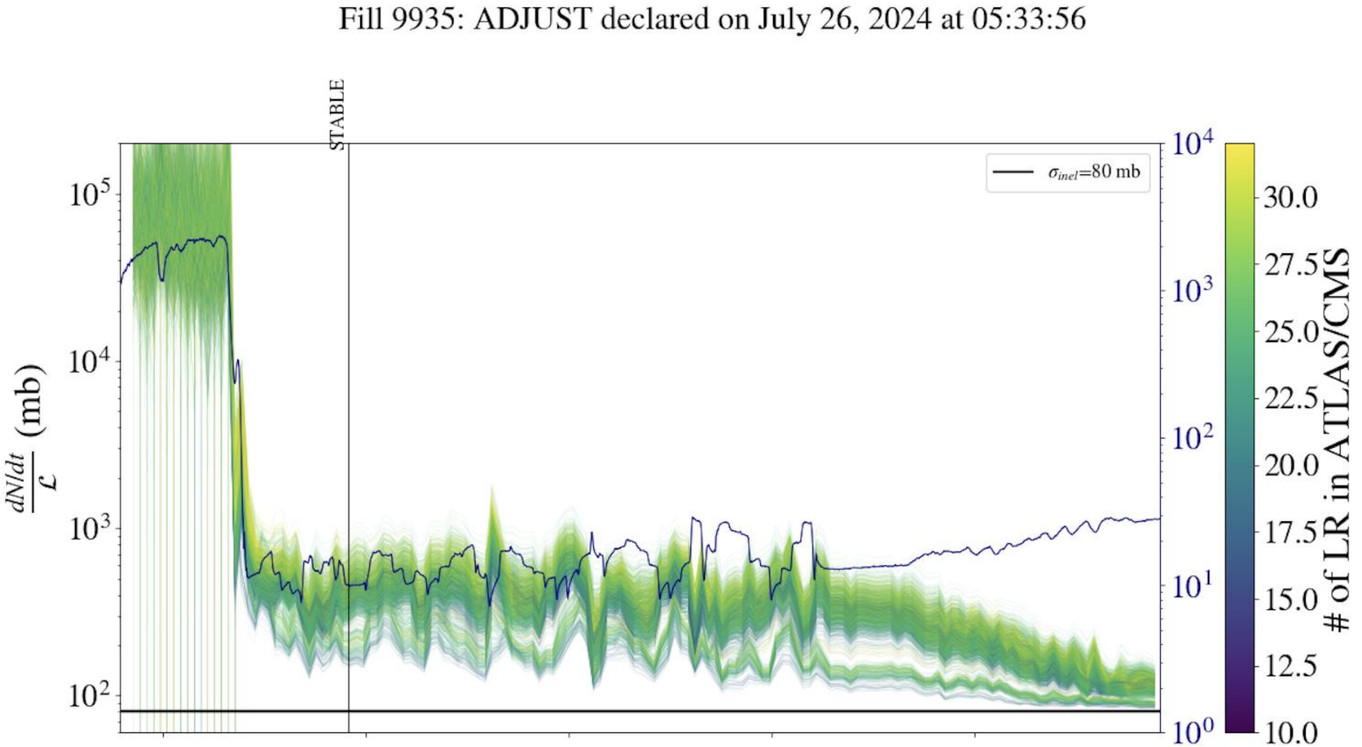
Considering a turn-around time of **2.5h**:

- From 1.22 fb^{-1}/day with standard to 1.32 fb^{-1}/day with BCMS:+8% of integrated luminosity for fills that make it to the optimal fill length (>8h), **+5%** due to the smaller emittance with BCMS

Lessons learned from Run 3: Losses

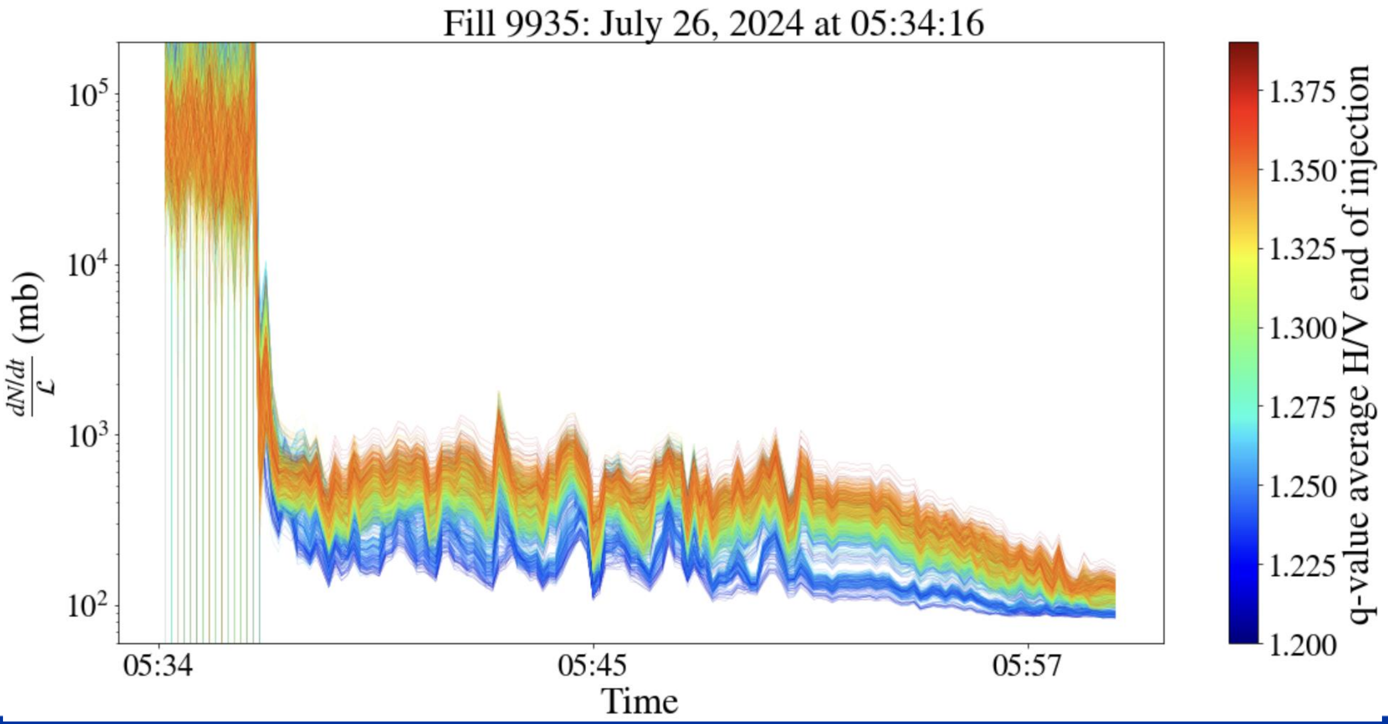
Losses in adjust

- Bunch-by-bunch effective cross section from Adjust to 20 minutes into Stable Beams.
- No clear correlation with beam-beam effects (e.g. number of LR interactions).

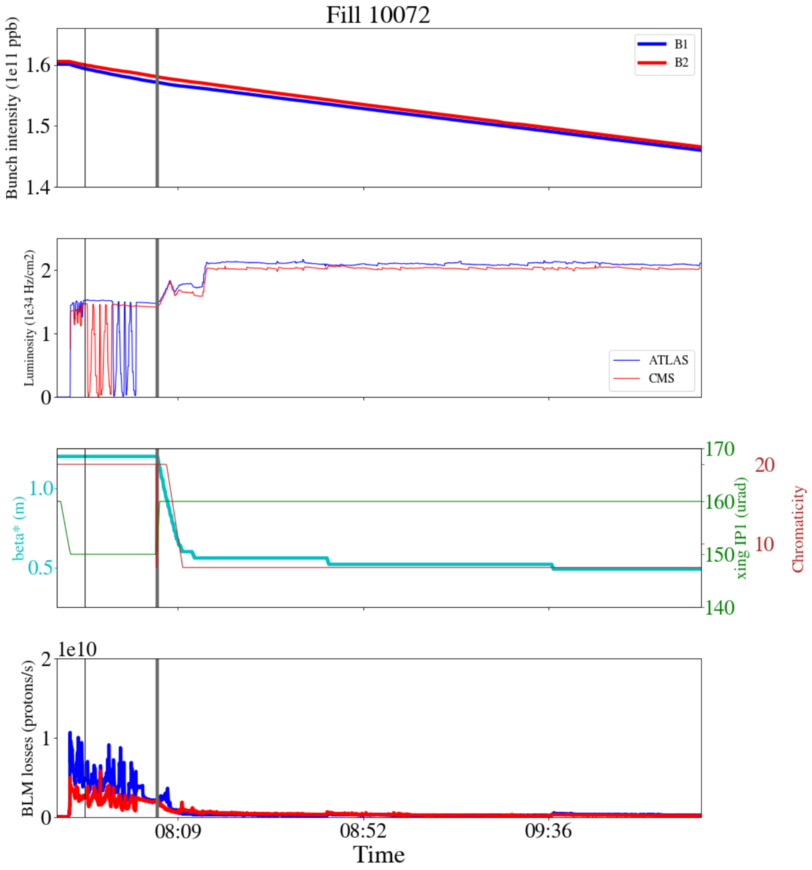


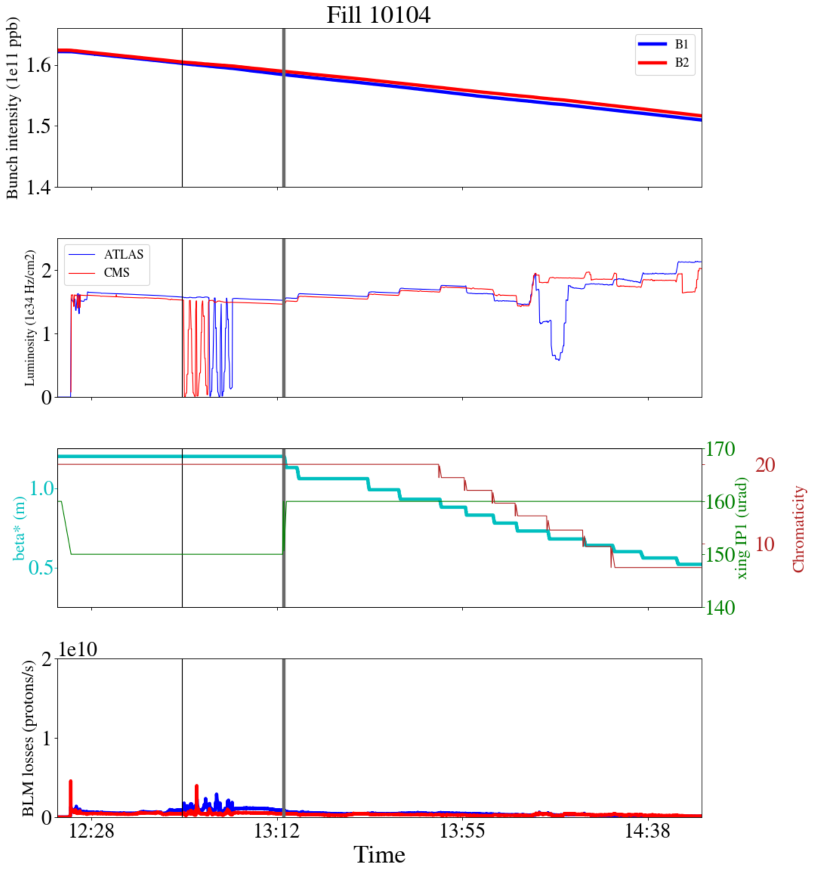
Losses in adjust

- Bunch-by-bunch effective cross section from Adjust to 20 minutes into Stable Beams.
- No clear correlation with beam-beam effects (e.g. number of LR interactions).
- Correlation of losses with bunches with heavier tails.



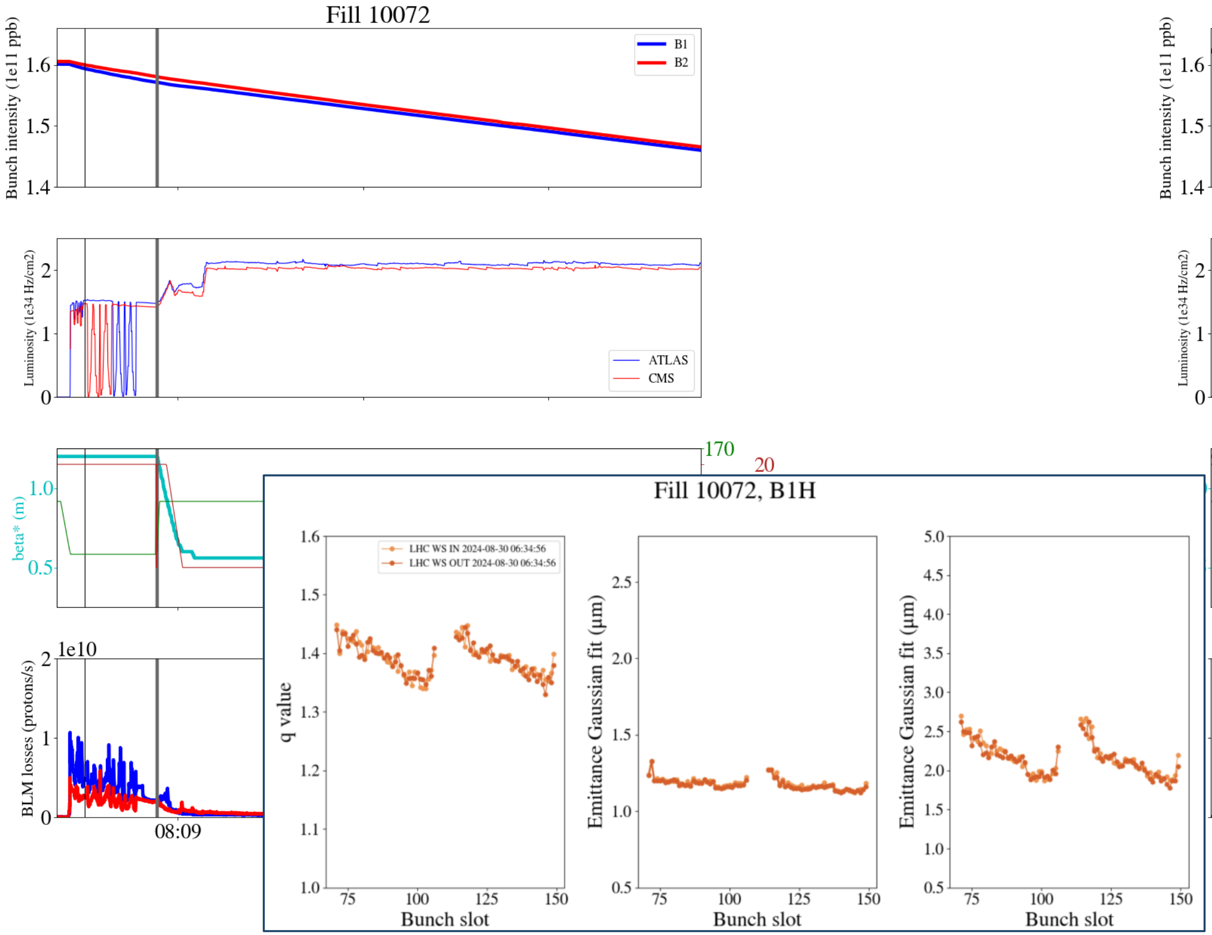
Losses at the start of collisions

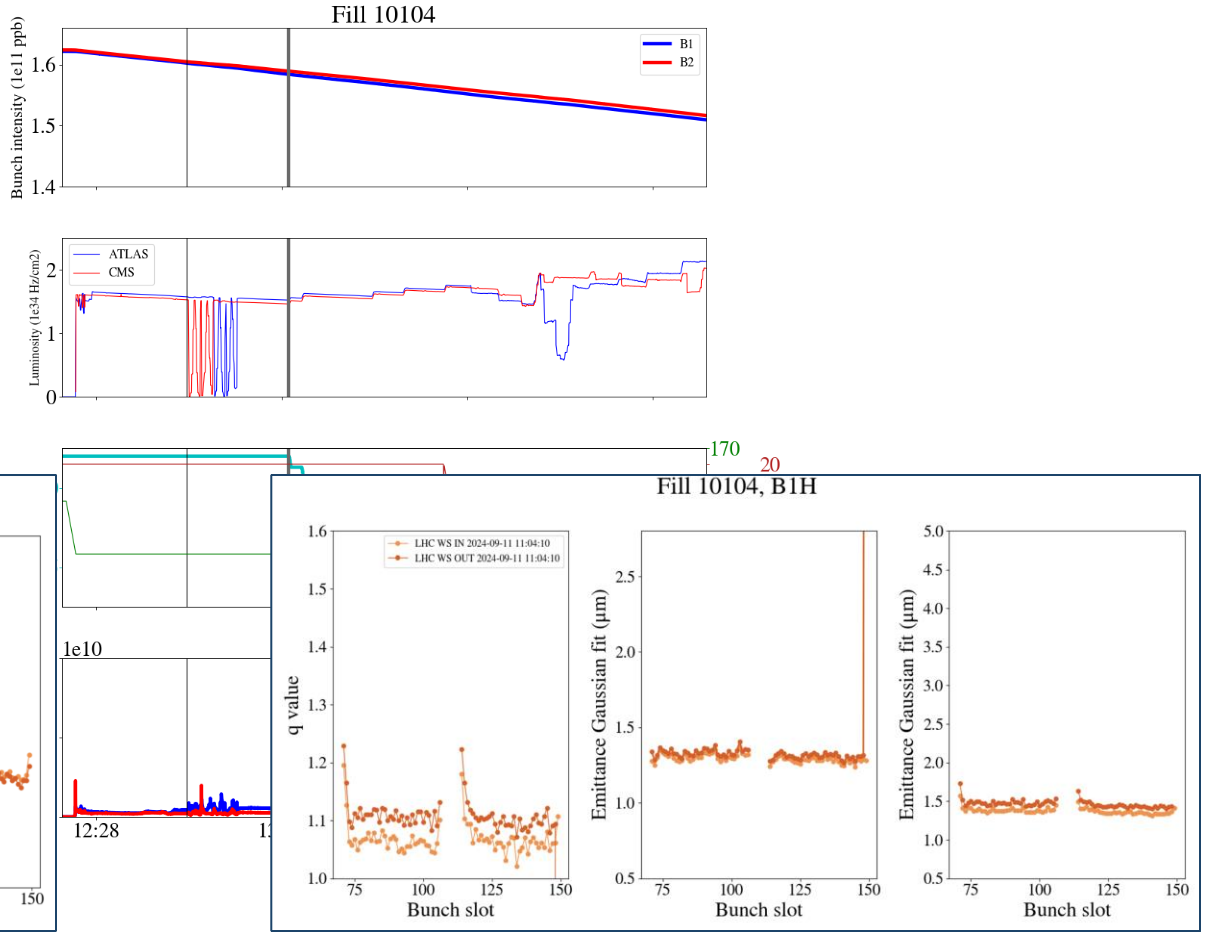




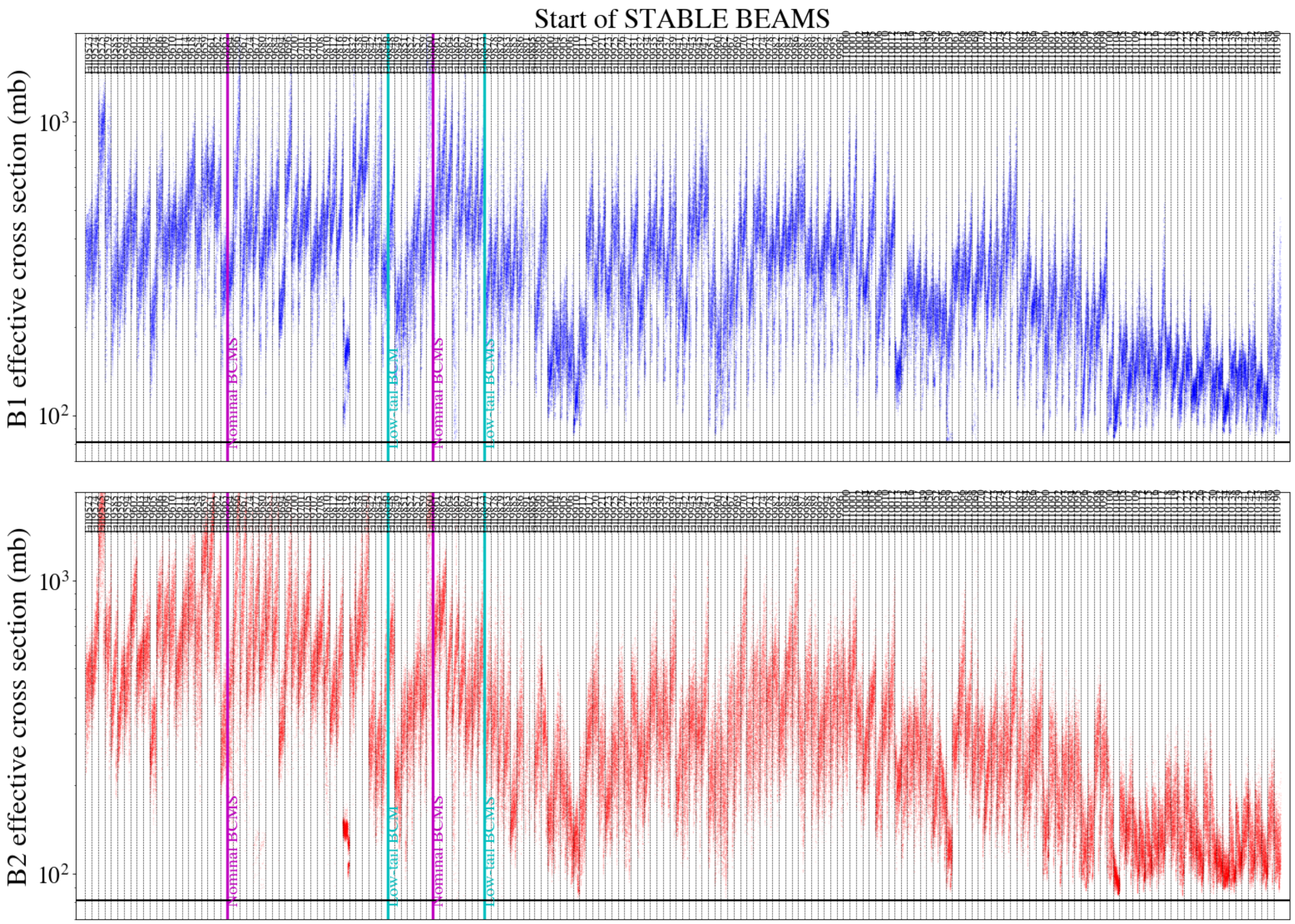
Losses reduction at the start of SB in the last LHC fills

Losses at the start of collisions



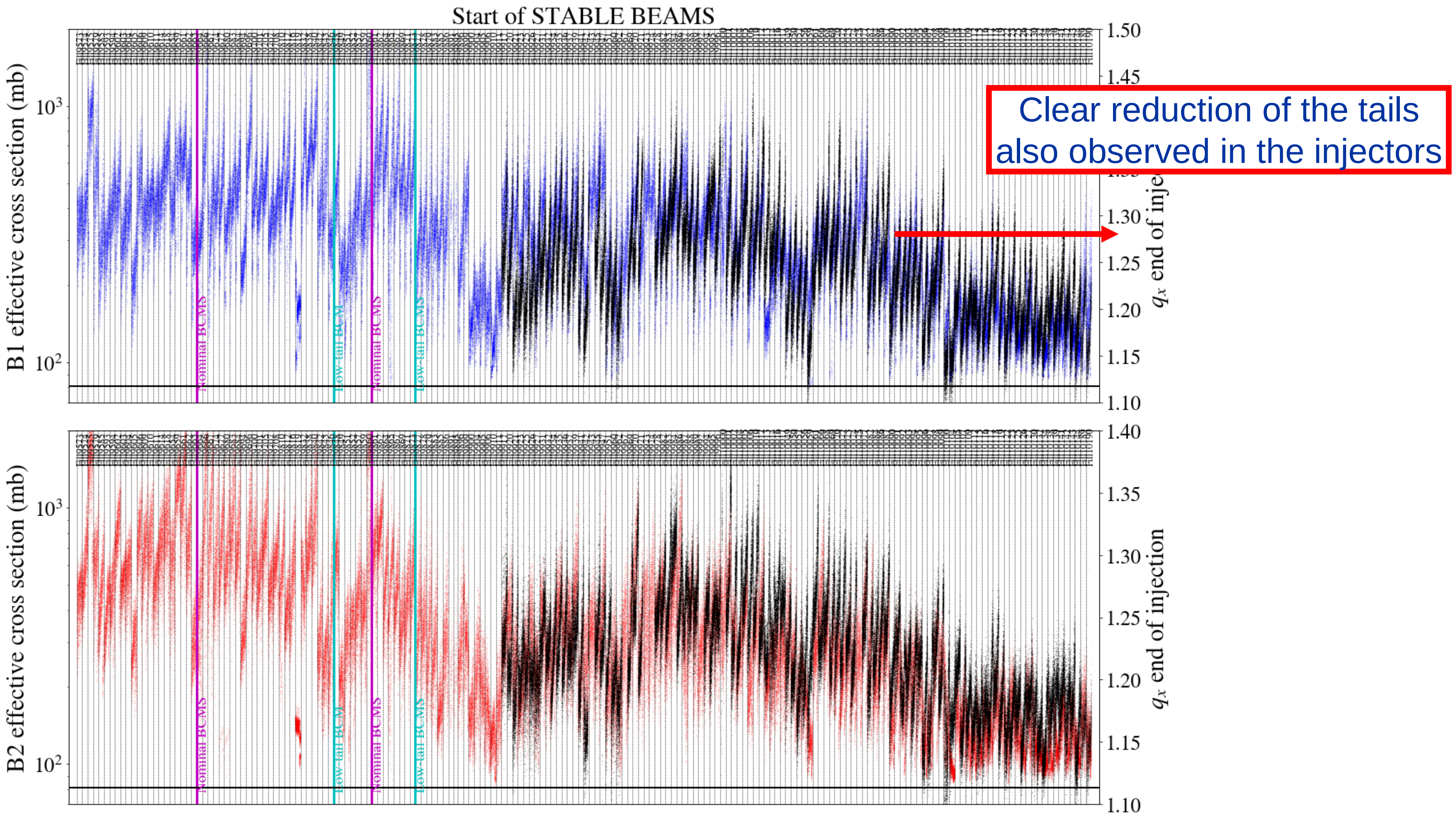


Losses at the start of collisions: correlation with tails



Losses at the start of collisions: correlation with tails

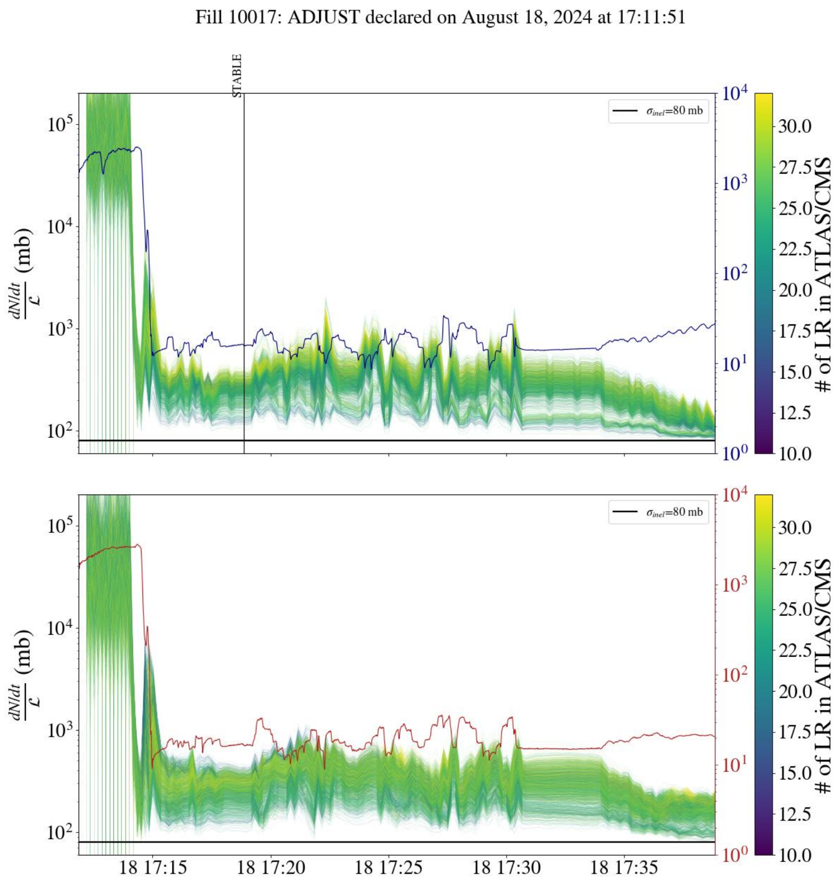
BSRT profiles systematically stored & published in NXCALS from fill 9912 onwards thanks to D. Butti



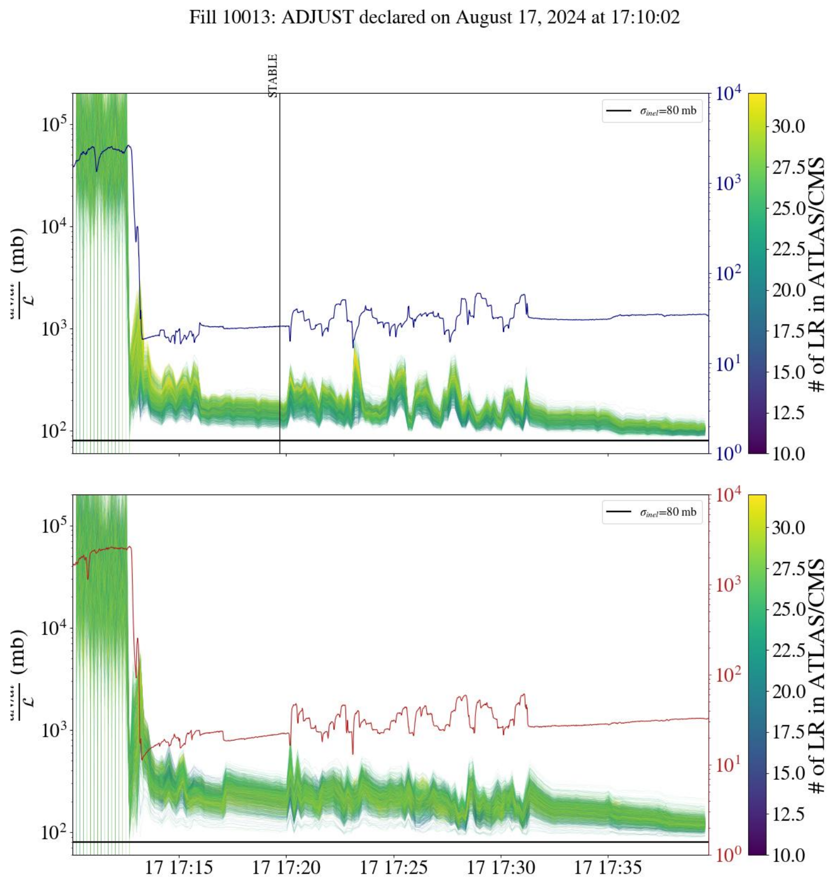
Losses during the collapse of the separation bump & start of collisions

- First year where we also observe impact from LHCb: LHCb luminosity 2e33 Hz/cm^2 while ATLAS/CMS 2e34 Hz/cm^2

Collisions in IP1/2/5/8



Collisions in IP1/2/5



Losses during the collapse of the separation bump & start of collisions

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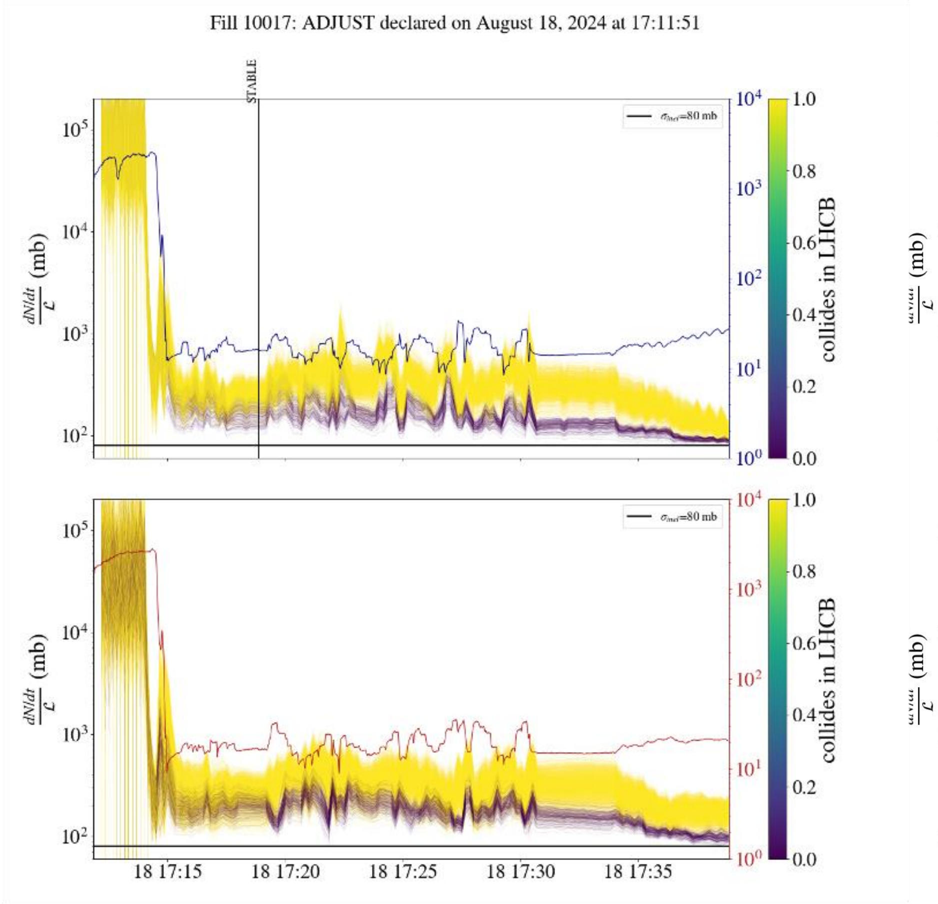
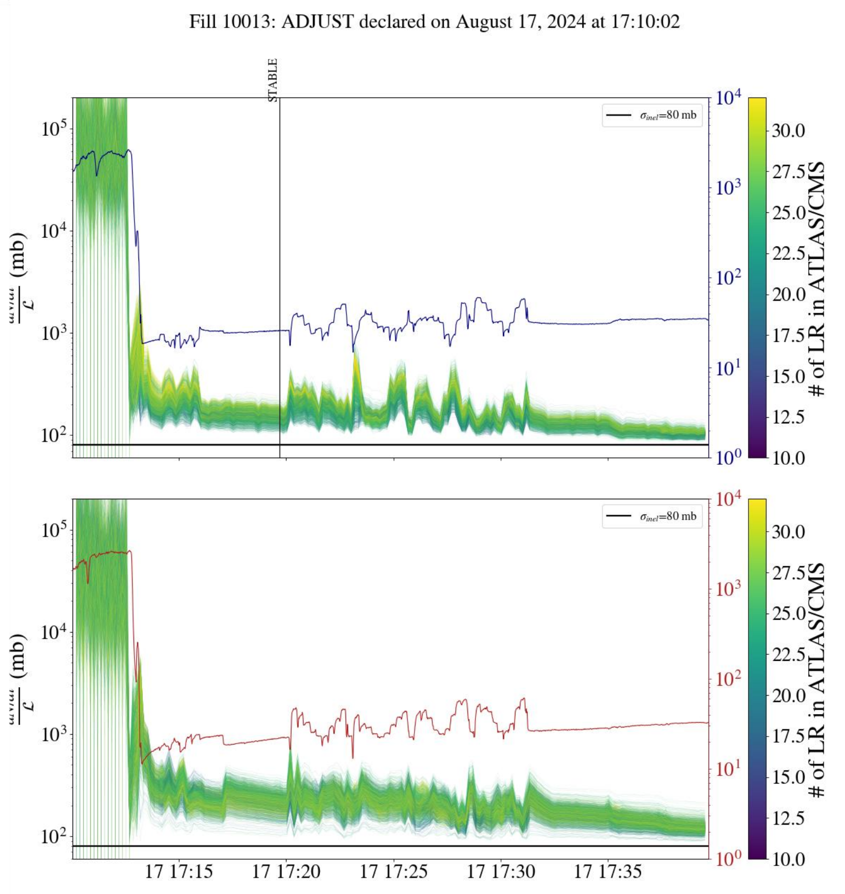
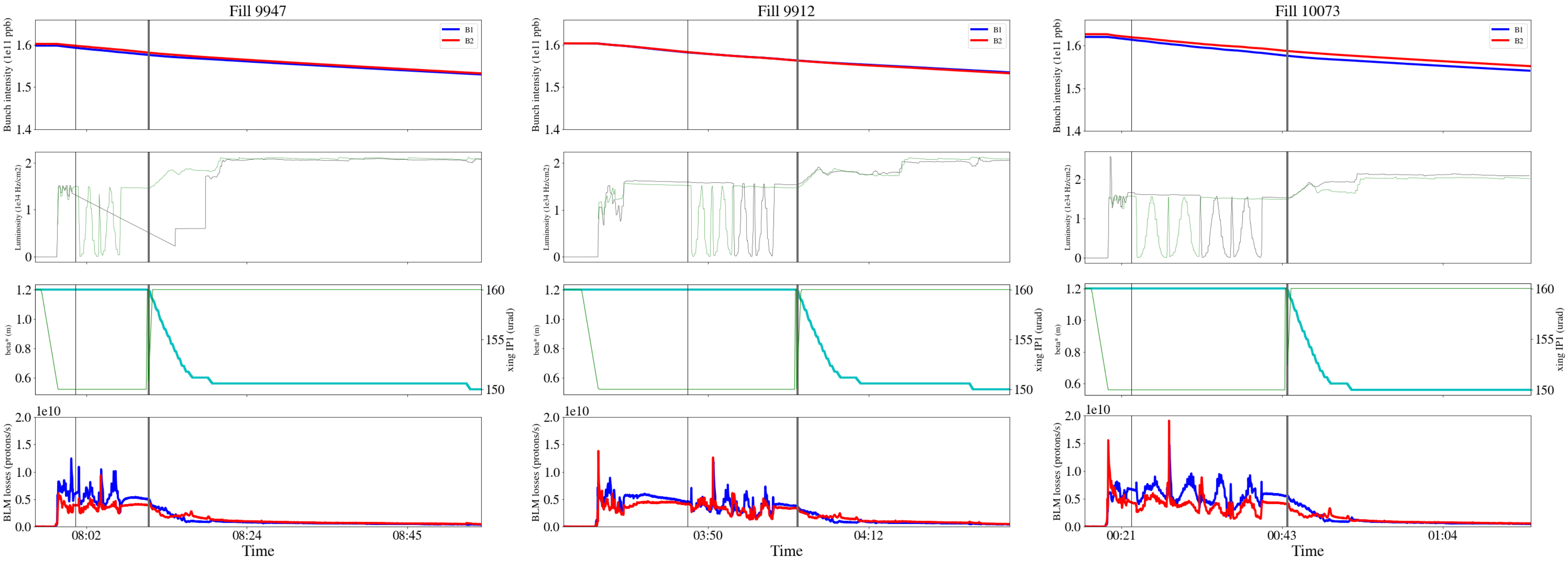


Collisions in IP1/2/5

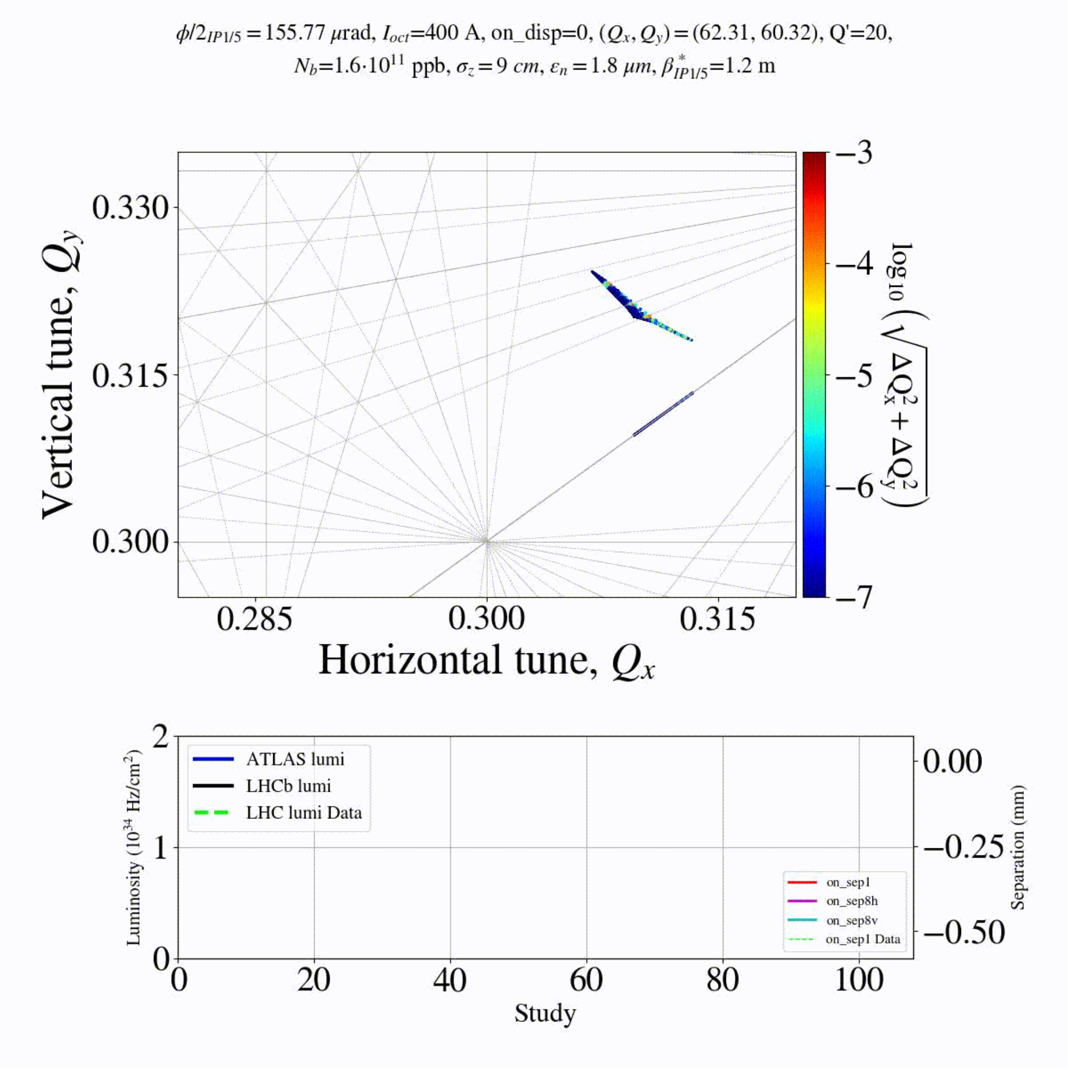


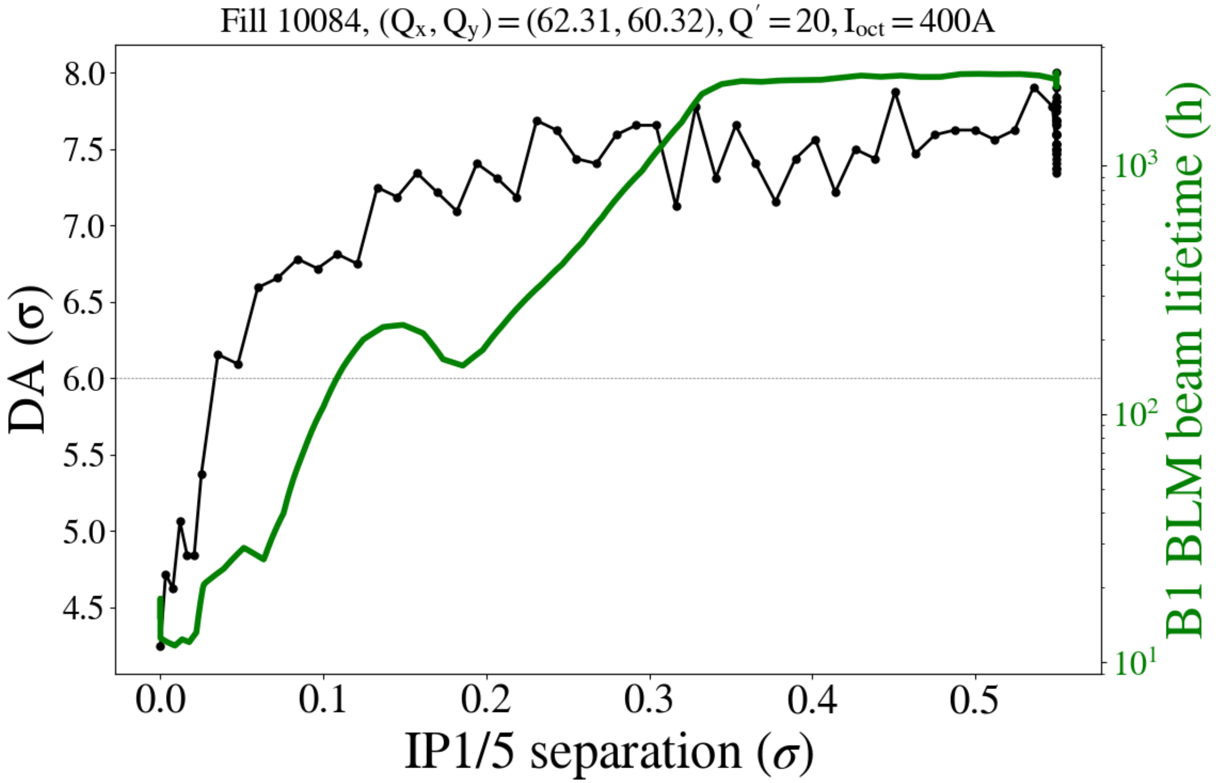
Losses during collisions



Reduction of losses as soon as leveling starts: pointing to small DA at the end of adjust/start of collisions.

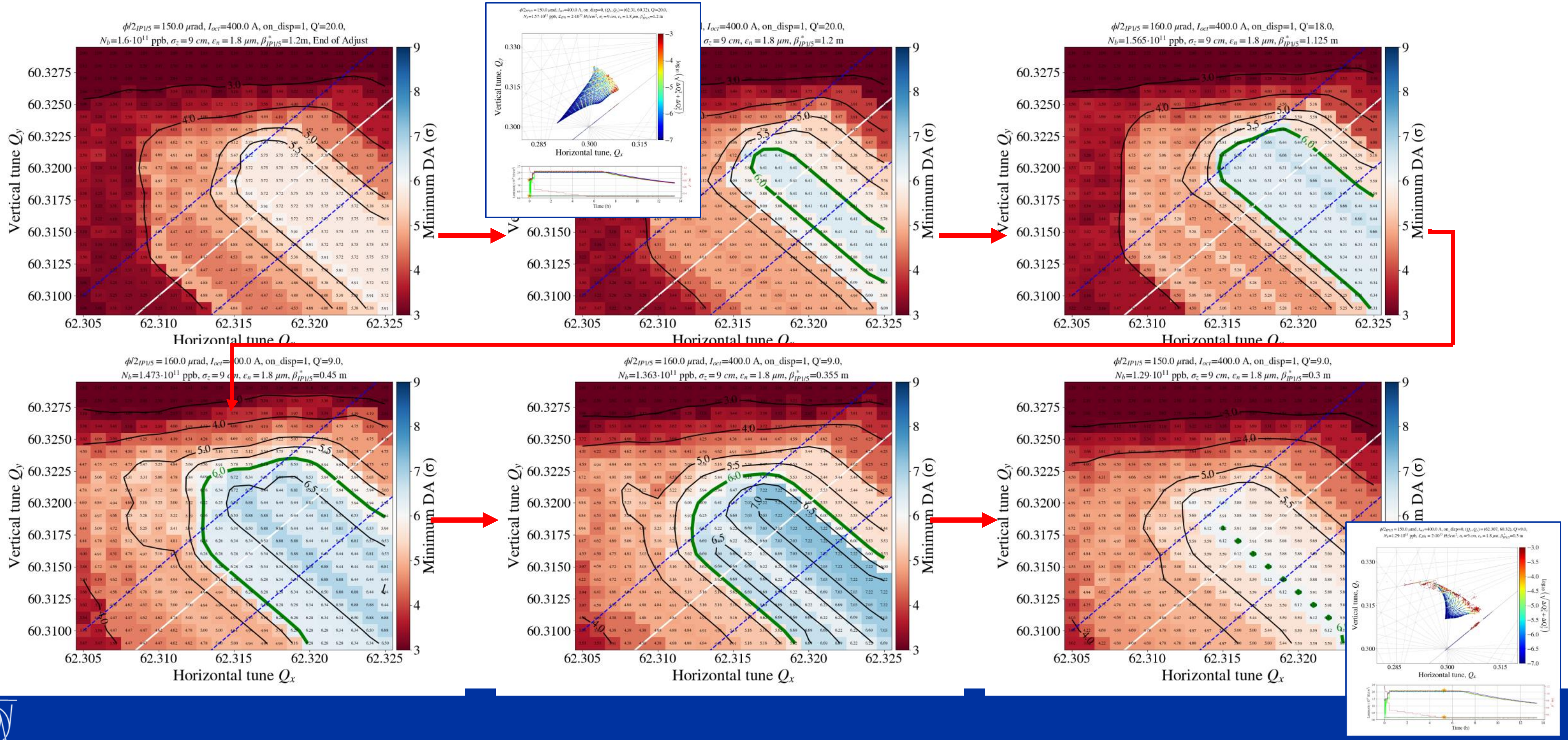
Losses during collapse and collisions





- Good correlation between DA and beam lifetime.
- Beam lifetime of ~10h indicates DA<4.5 σ

Losses during collisions: DA for 2024



Conclusions

- **Luminosity projections**
  - Extrapolating from BCMS 2024 performance (10% lower emittance at SB w r.t to standard, +5% gain in performance for the LHC) **gain of performance with BCMS for HL-LHC is only ~1%** based on present improvement.
  - **-10%** of integrated luminosity if hybrid filling scheme is needed due to e-cloud limitations instead of 25ns 4x72b baseline filling scheme.
  - **-9%** of integrated luminosity if ion run extends beyond Run 4.
  - **+3% gain** in integrated luminosity with flat optics. However, at the moment limited operational experience with flat optics.

Conclusions

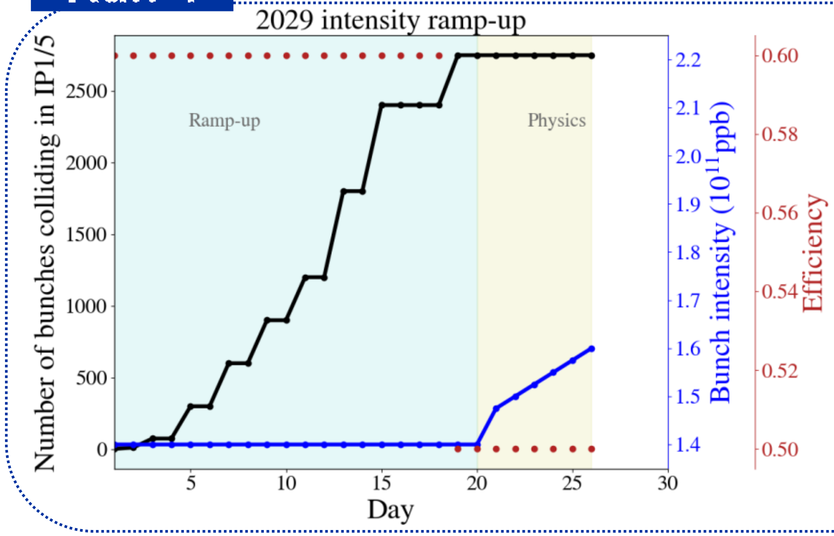
- **Lessons learned from the LHC:**
  - BCMS bunches reaching LHC with **20% lower emittance at the start of injection, 10% lower emittance with BCMS at start of Stable Beams.**
  - Source of **emittance blowup at injection & collisions** with unknown origin, affecting both beams and planes, especially V that does not agree with the present models.
  - Non-Gaussian bunch profiles injected in the LHC. **Clear correlation of losses at the end of collapse/start of collisions with tail population**: reduction of tails observed in the LHC in the last fills (also observed in injectors) resulted in reduction of losses at start of collisions.
  - **Clear impact of LHCb**, reaching 2e33 Hz/cm^2 in 2023, on losses. LHCb contribution on burn-off is considered in the luminosity model.
  - **DA below target at end of adjust & start of collisions**, DA impovement during leveling due to combined effects of intensity & chromaticity reduction until reaching 30 cm. **In agreement with experimental observations**: 1. validates the tracking tools and DA targets 2. allows to identify loss mitigation strategies.

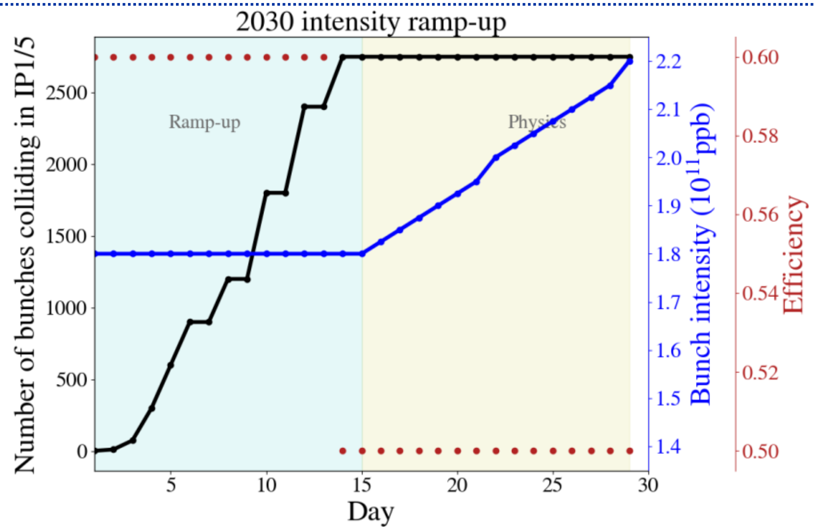
Backup slides

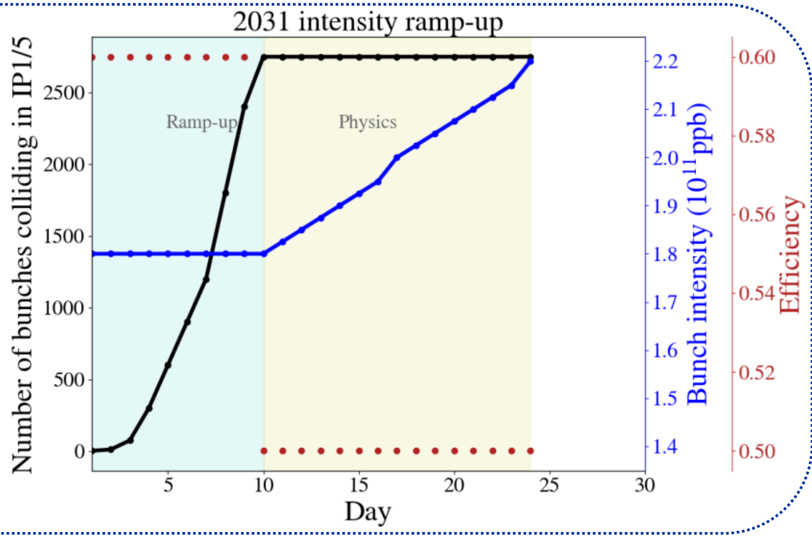
Intensity ramp up

Based on Riccardo's Chamonix 2024 talk

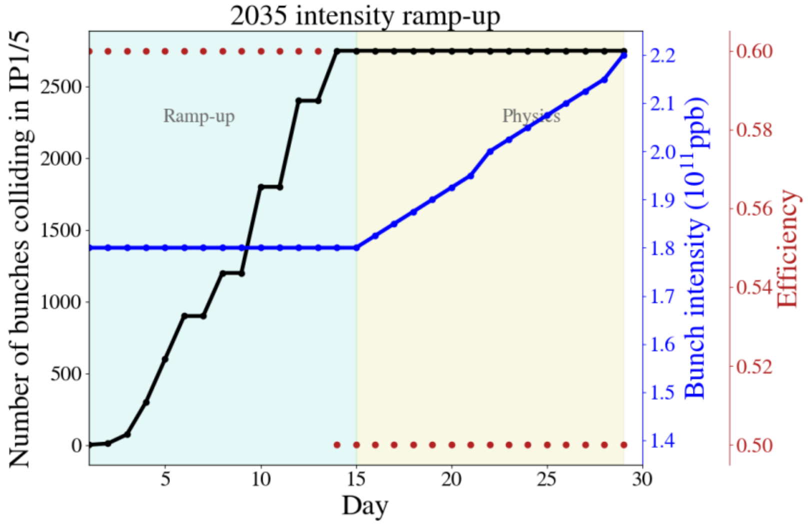
Run 4

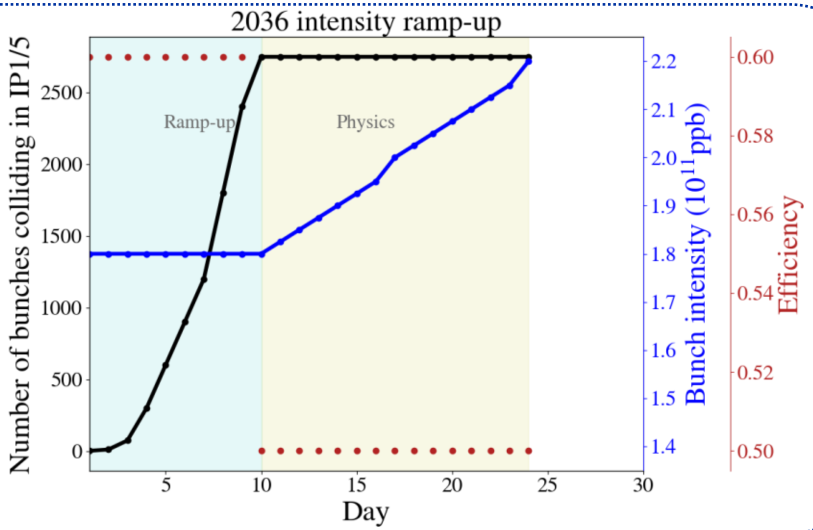






Run 5

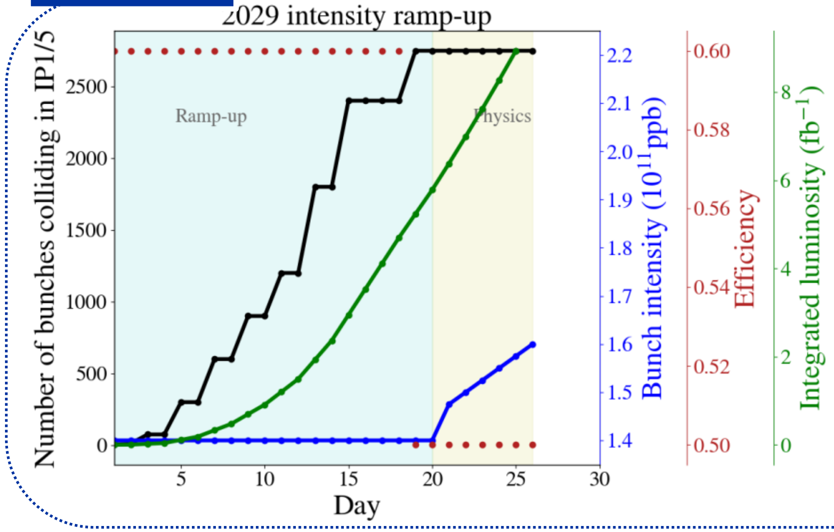


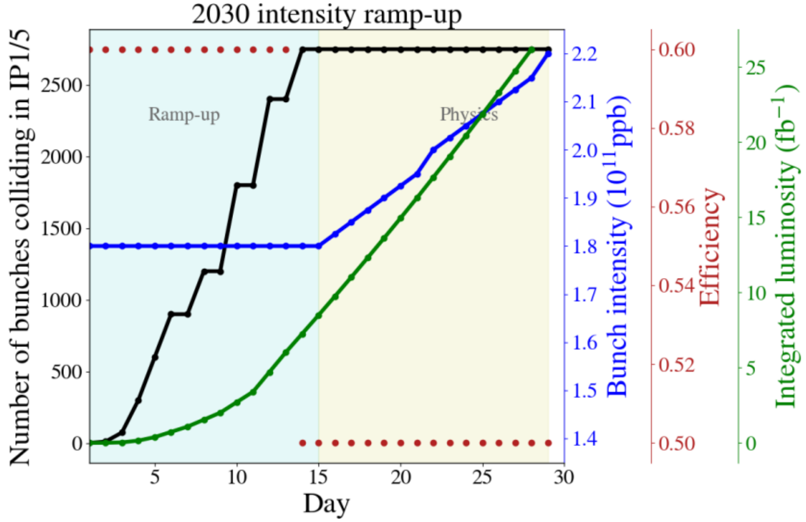


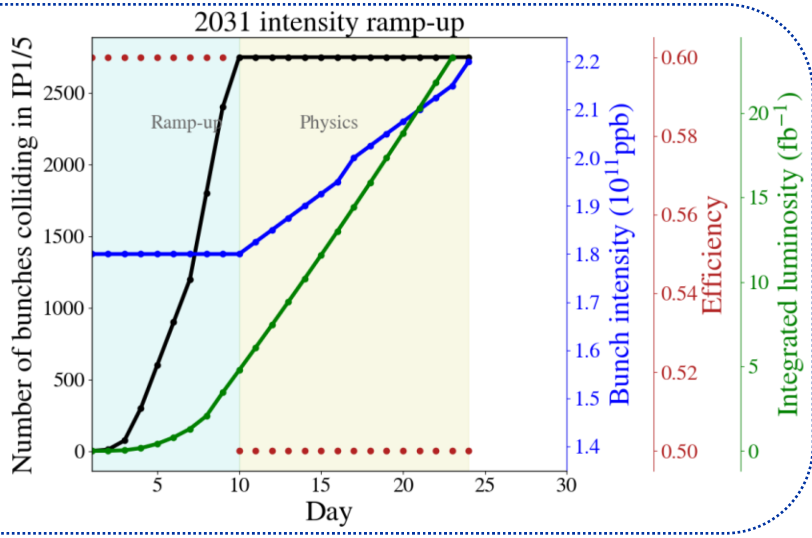
Intensity ramp up

Based on [Riccardo's Chamonix 2024 talk]

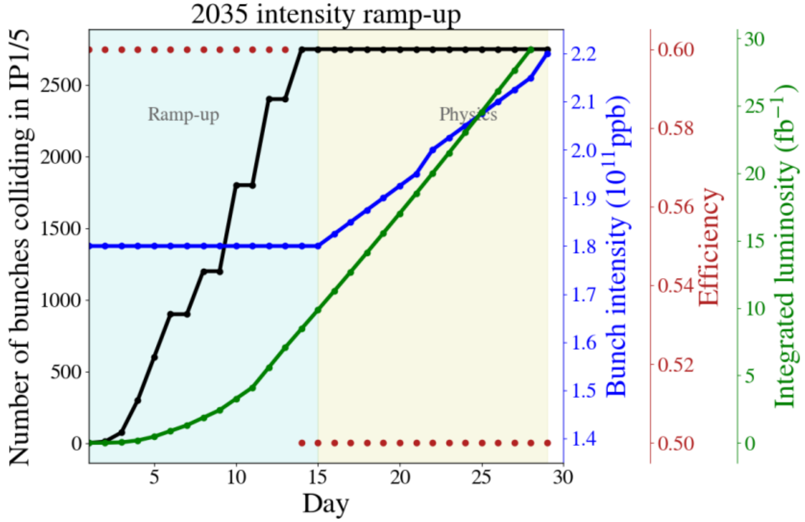
Run 4

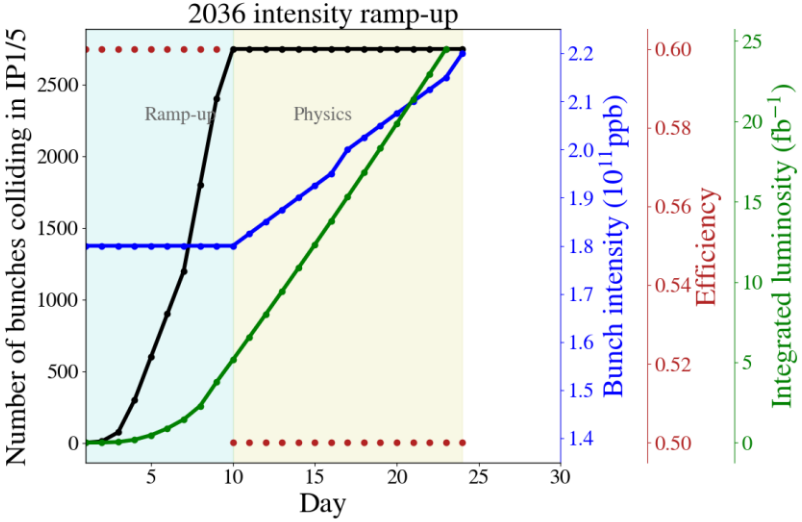






Run 5



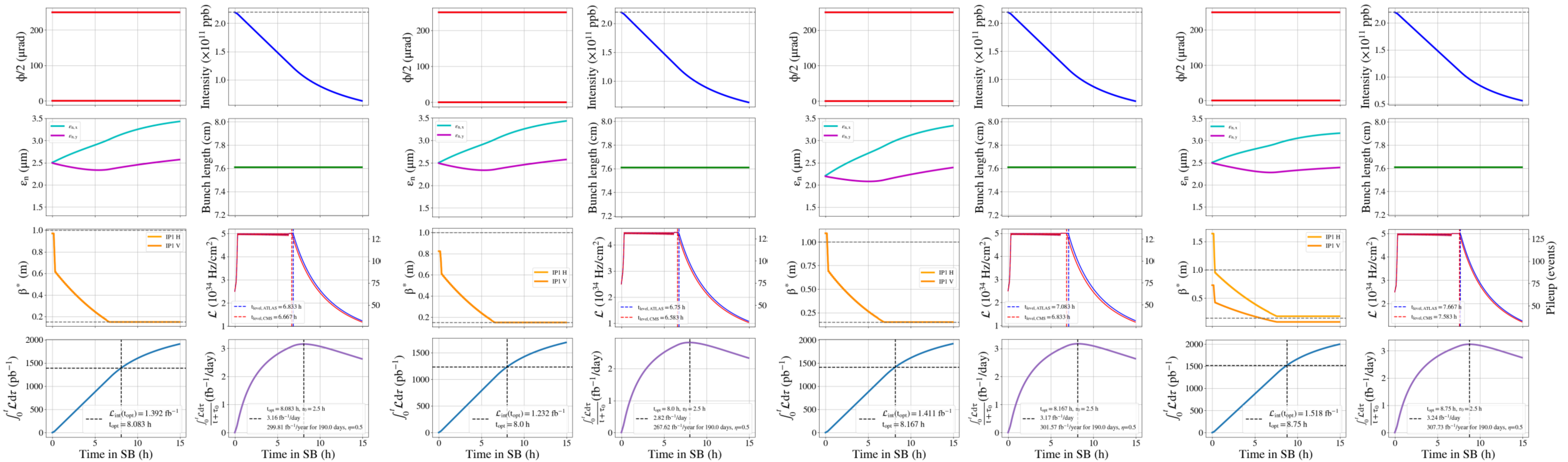


Scenarios

Scenario	Optics	Duration	Filling scheme
Baseline	Round Run4 20cm	Nominal ions	Standard
Round hybrid	Round Run4 20cm	Nominal ions	Hybrid
Round BCMS	Round Run4 20cm	Nominal ions	BCMS
Flat 8/18 cm	Flat 8/18 cm	Nominal ions	Standard
Vbaseline extended ions	Round Run4 20cm	Extended ions	Standard
Round hybrid extended ions	Round Run4 20cm	Extended ions	Hybrid
Round BCMS extended ions	Round Run4 20cm	Extended ions	BCMS
Flat extended ions	Flat	Extended ions	Standard

Leveling time & optimal fill length

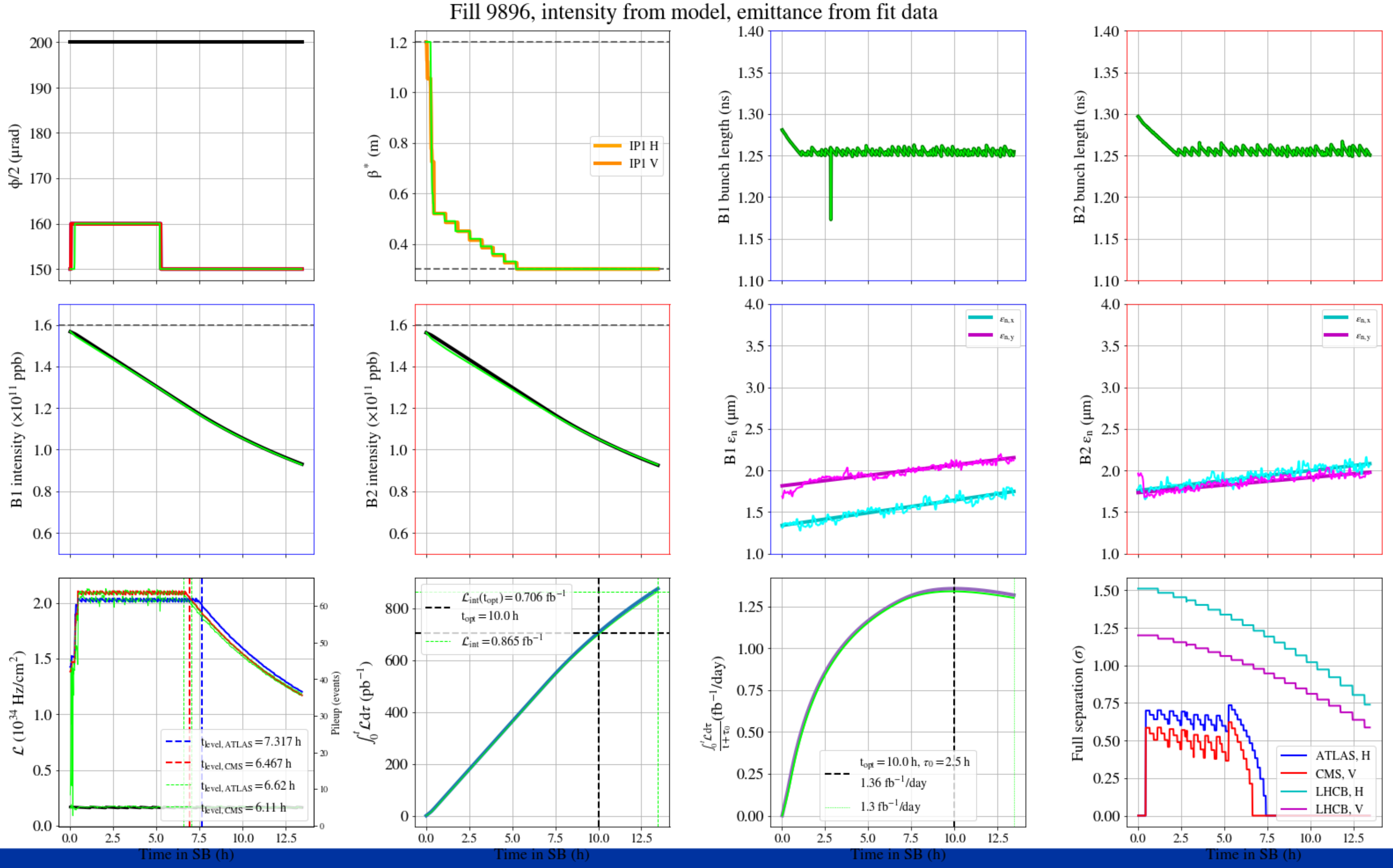
Baseline | **Round hybrid** | **Round BCMS** | **Flat 8/18 cm**



Run 6	Baseline	Round hybrid	Round BCMS	Flat 8/18 cm
Run 6 leveling time (h)	6.7	6.5	6.8	7.5
Run 6 optimal fill length (h)	8.1	8	8.2	8.8
Yearly integrated lumi (fb-1)	269.1	240.9	270.9	277

- For Run 4, reaching 15 cm instead of 20 cm results in 3.44% increase of integrated luminosity per year

Luminosity model example in Run 3



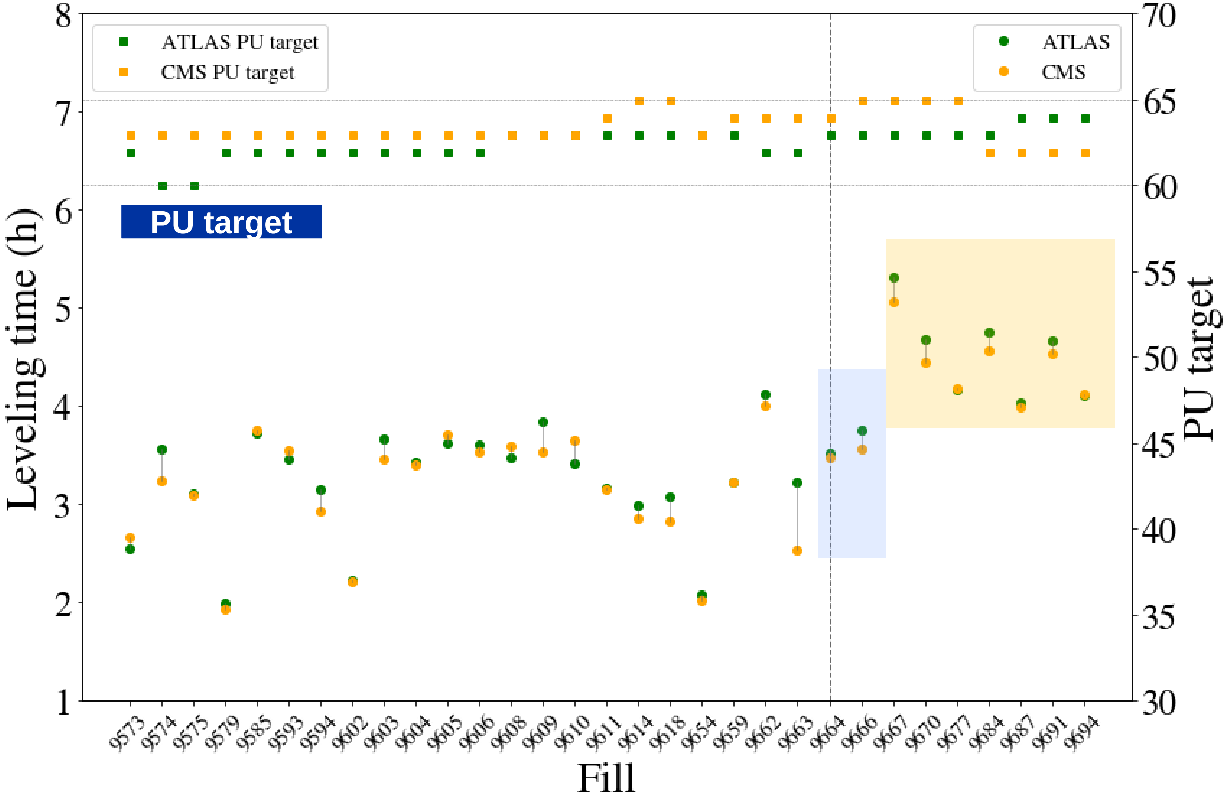
BCMS performance in 2024

Emittance start of injection (µm)	B1H	B1V	B2H	B2V
Fills 9575-9663	1.57	1.59	1.5	1.5
Fills 9664-9694	1.19	1.27	1.13	1.16
%	-24.2	-20.1	-24.7	-22.7
Emittance end of injection (µm)				
Fills 9575-9663	1.77	1.71	1.63	1.62
Fills 9664-9700	1.49	1.44	1.32	1.31
%	-15.7	-16	-18.7	-18.8
Emittance start of SB (µm)				
Fills 9575-9663	1.84	1.66	2.25	2.3
Fills 9664-9694	1.57	1.53	1.99	2.04
%	-14.67	-7.83	-11.56	-11.3

Bunch intensity (1e11 ppb)	B1 INJPHYS	B2 INJPHYS	B1 STABLE	B2 STABLE
Fills 9573-9663	1.59	1.59	1.56	1.55
Fills 9664-9694	1.62	1.62	1.59	1.57
%	+1.89	+1.89	+1.92	+1.29

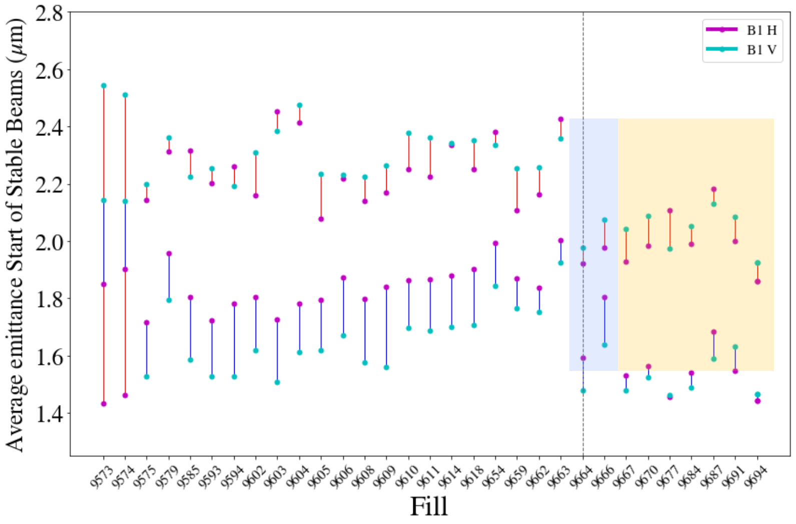
BCMS performance in 2024: Leveling time

Leveling time

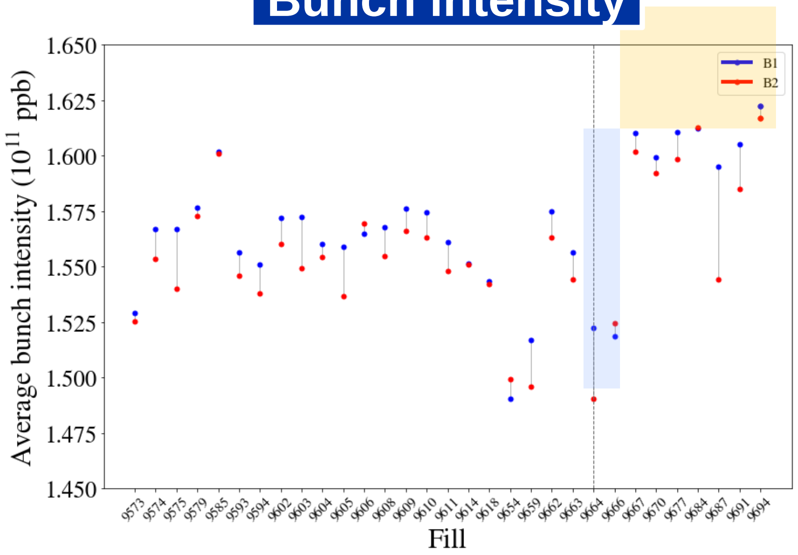


- Step in leveling time results from the combination of smaller emittances at start of SB **and** increased bunch intensity.

Emittance

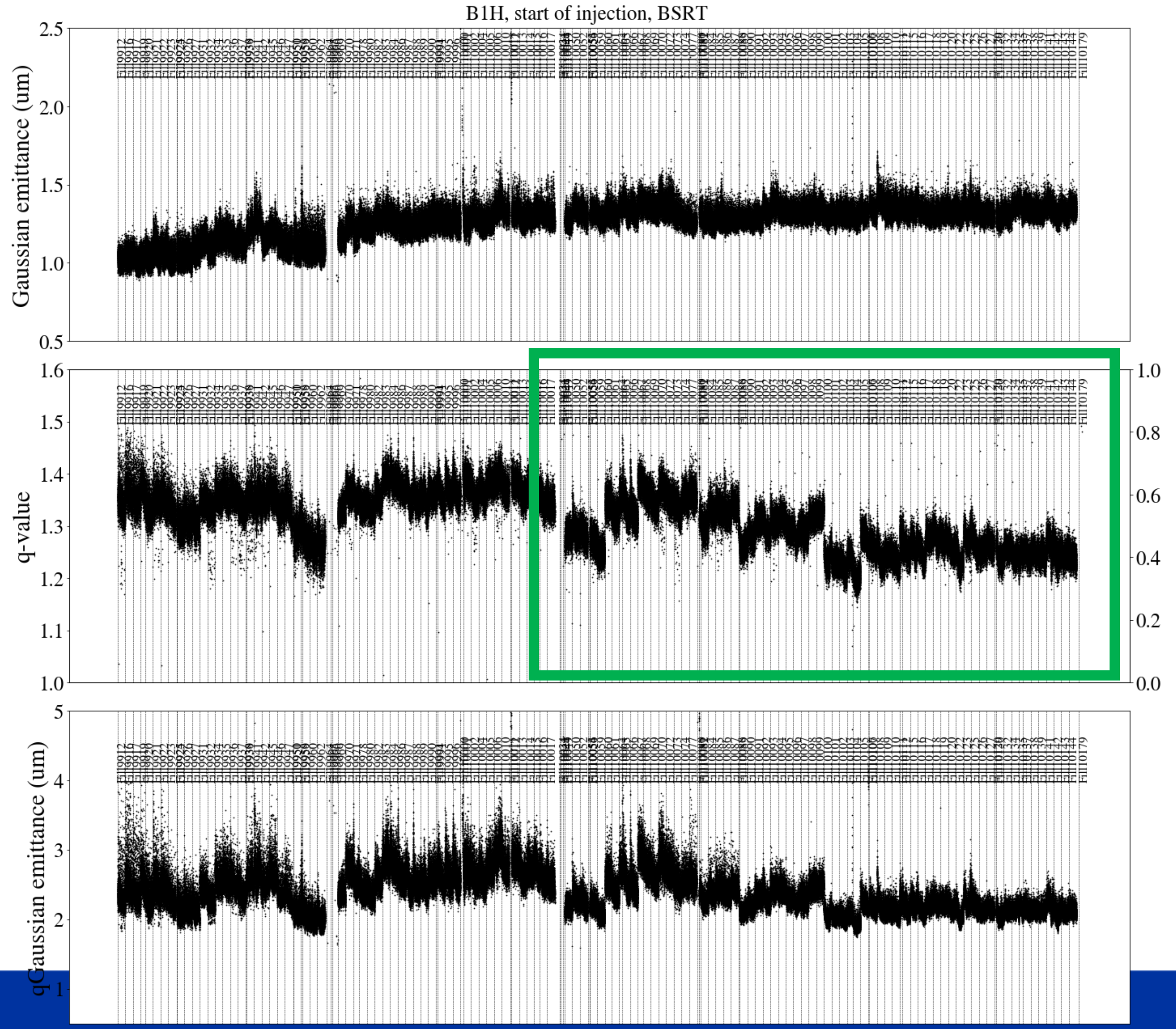


Bunch intensity



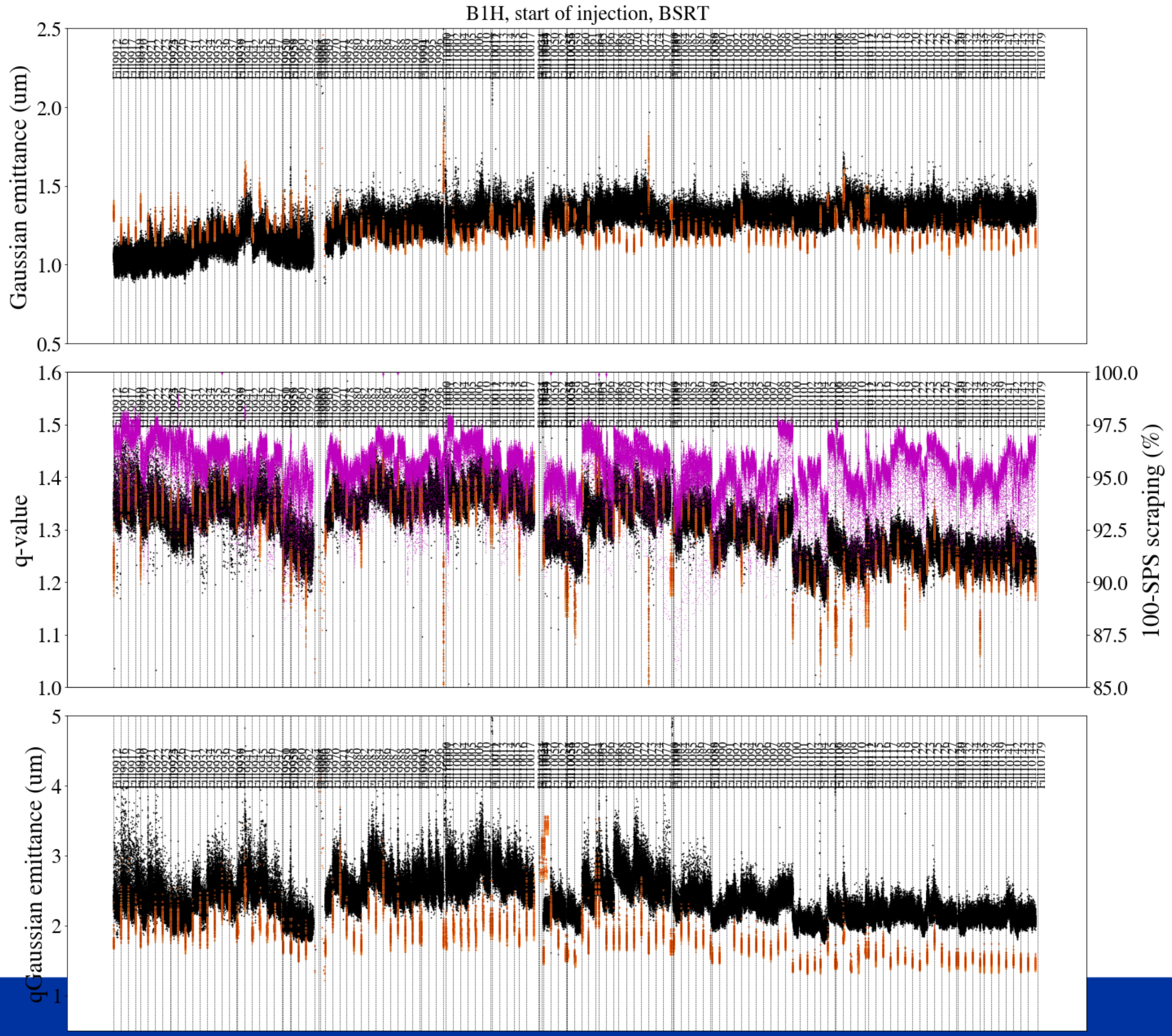
Transverse bunch profiles at injection

- **Clear tail reduction** when injected in the LHC in the last fills.



Transverse bunch profiles at injection

- **Clear tail reduction** when injected in the LHC in the last fills.
- **SPS scraping did not change**, usual fill-to-fill variation. However, with the same SPS scraping, q injected in the LHC is lower.

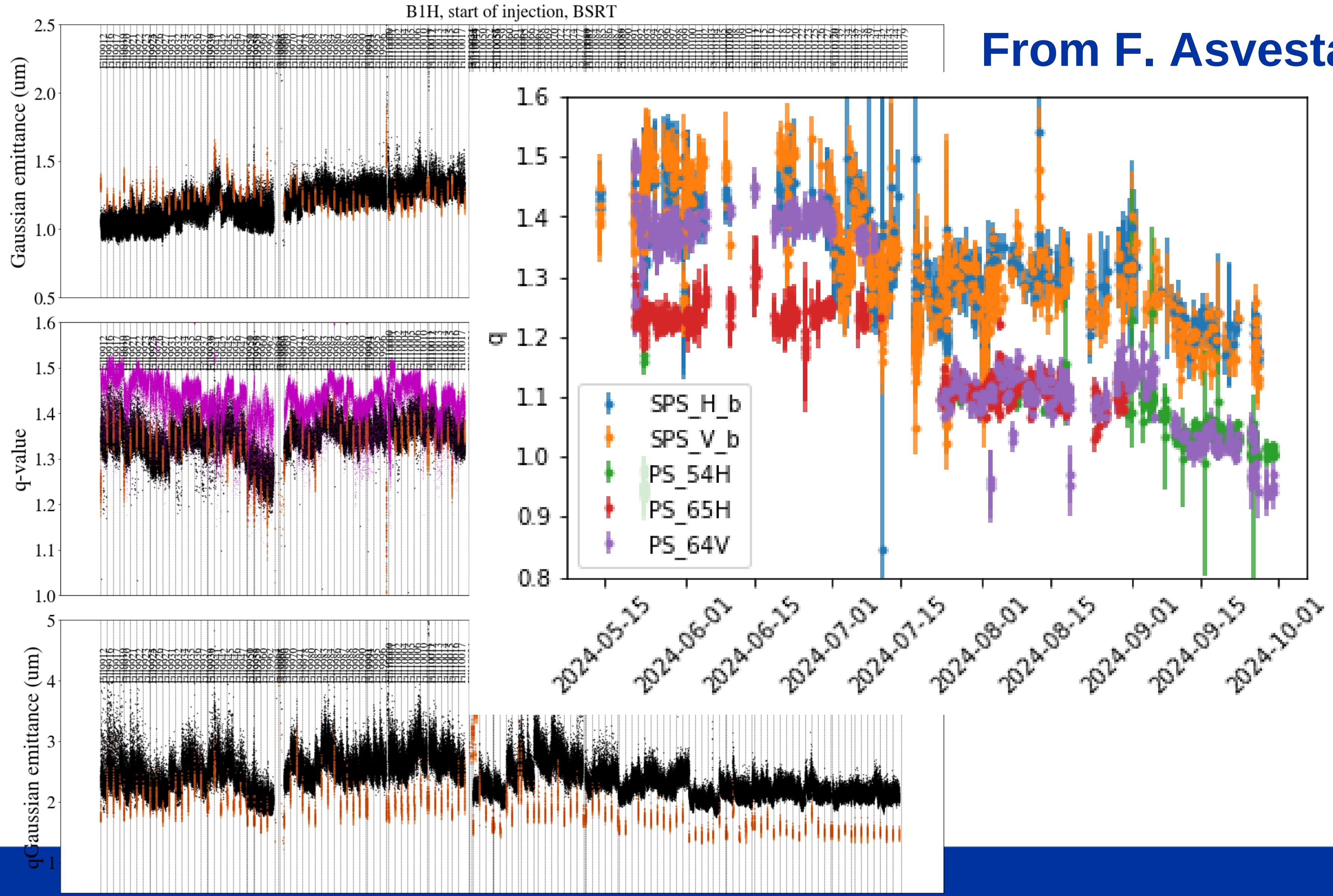


Plotting (100-SPS scraping %) which is correlated with q (larger scraping, lower tails)

Transverse bunch profiles at injection

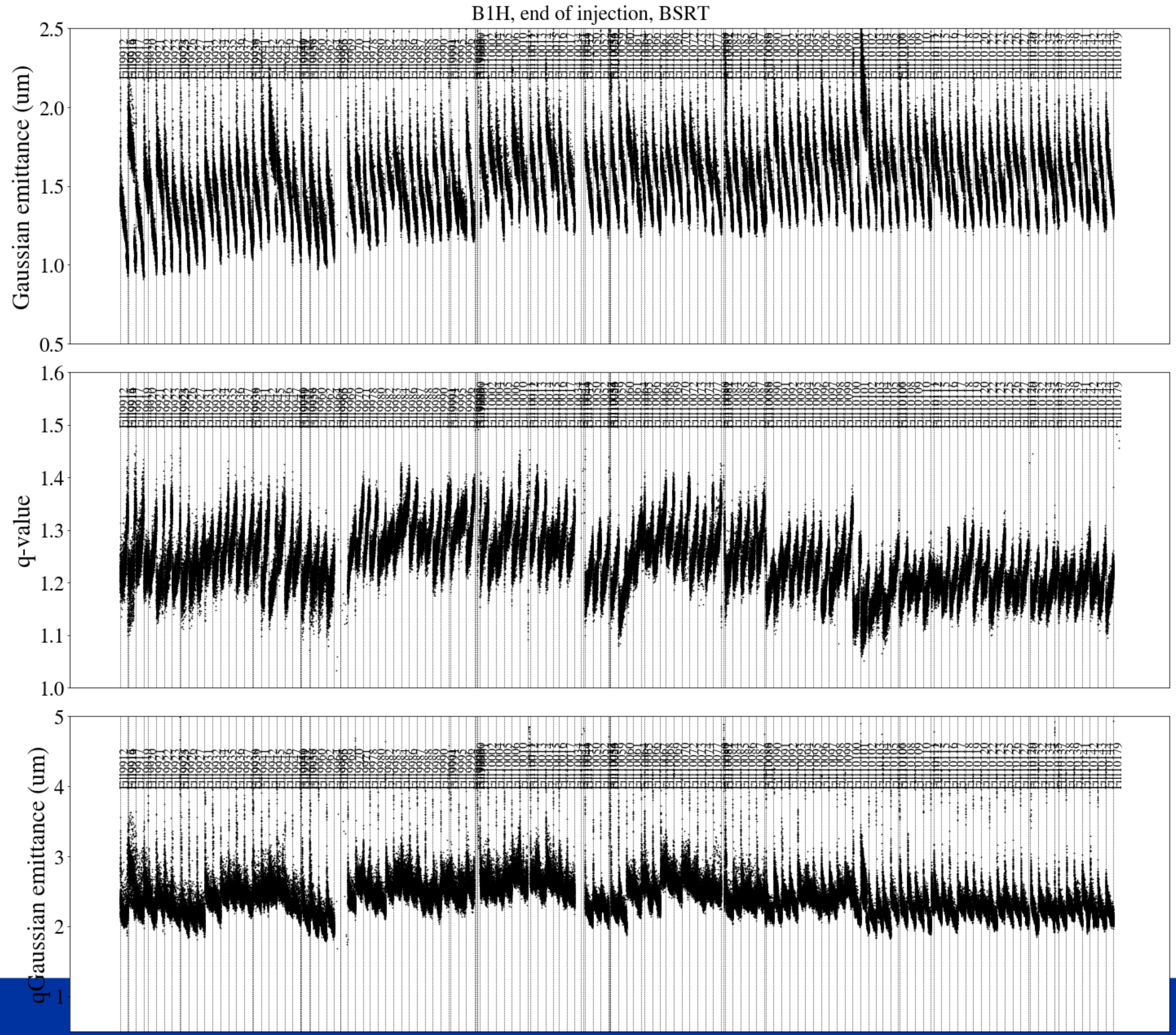
- **Clear tail reduction** when injected in the LHC in the last fills.
- **SPS scraping did not change**, usual fill-to-fill variation. However, with the same SPS scraping, q injected in the LHC is lower.
- **Tail step also observed in injectors**, no impact on emittance. Source of improvement still unknown but possibly originating from PS.

From F. Asvesta



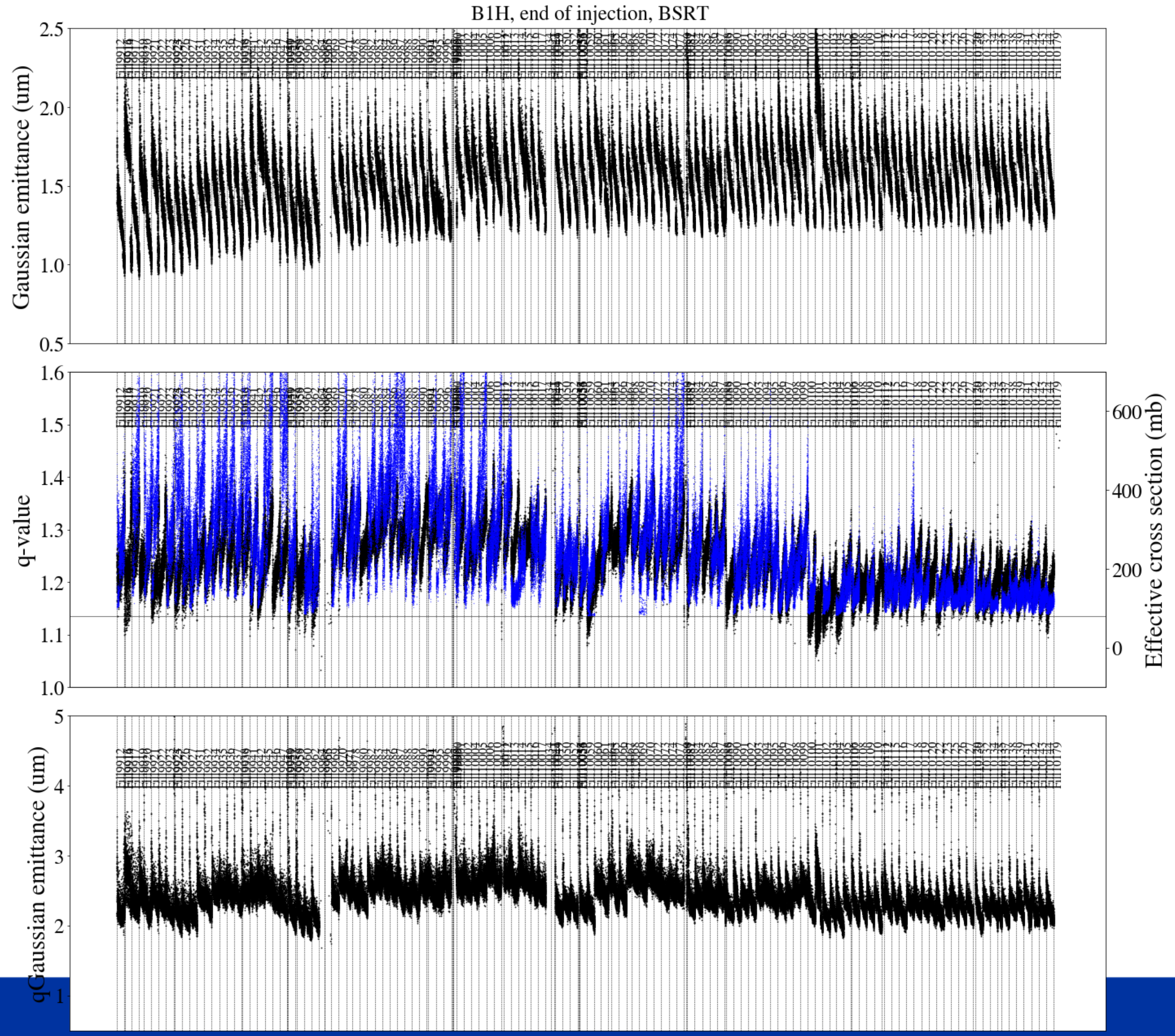
Transverse bunch profiles at end of injection

- **Clear tail reduction also at the end of LHC injection for the last fills.**



Transverse bunch profiles at injection

- **Clear tail reduction also at the end of LHC injection for the last fills.**
- **Clear correlation with improvement of losses at the start of collisions.**



Transverse bunch profiles at injection

- **Clear tail reduction also at the end of LHC injection for the last fills.**
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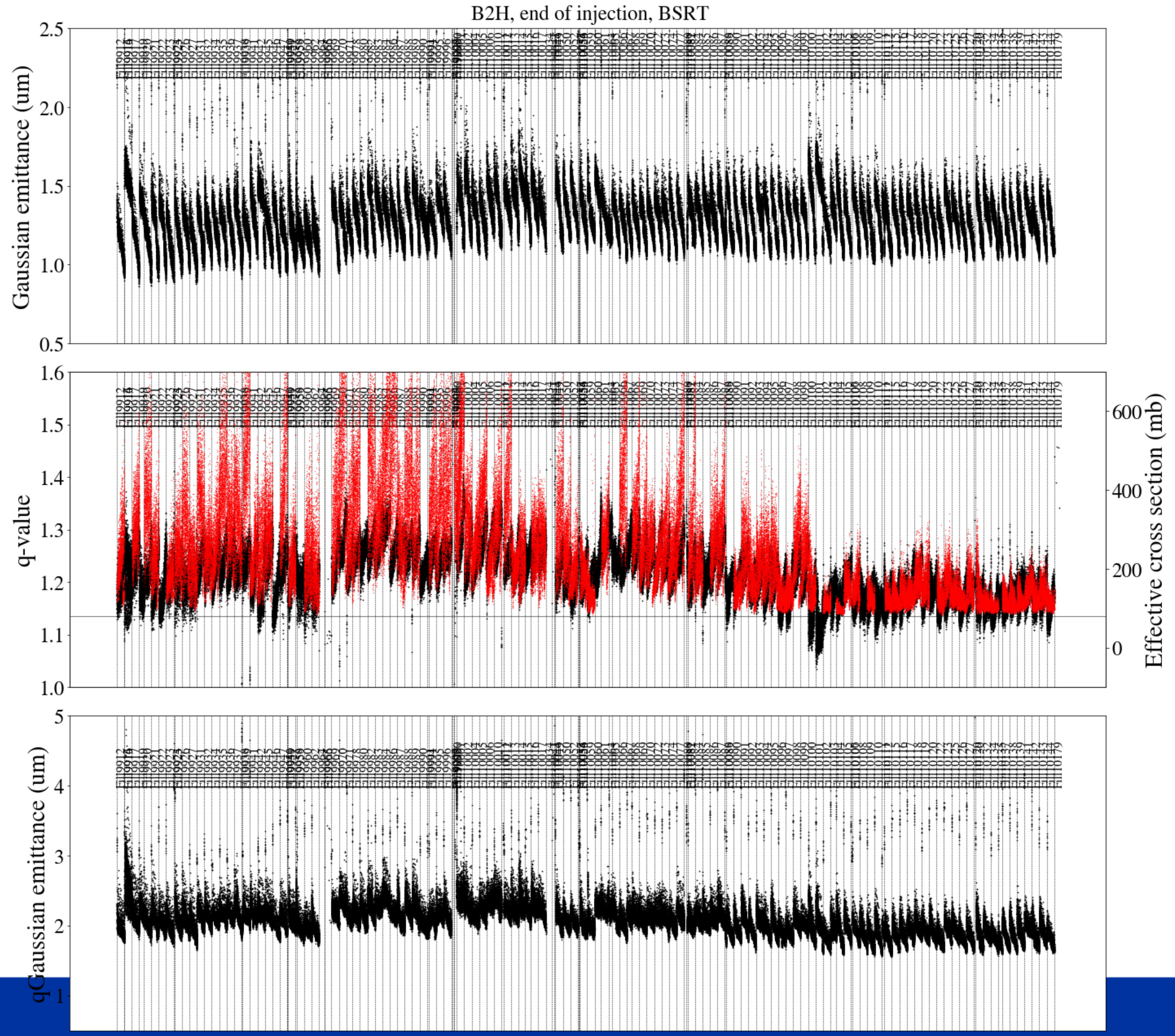
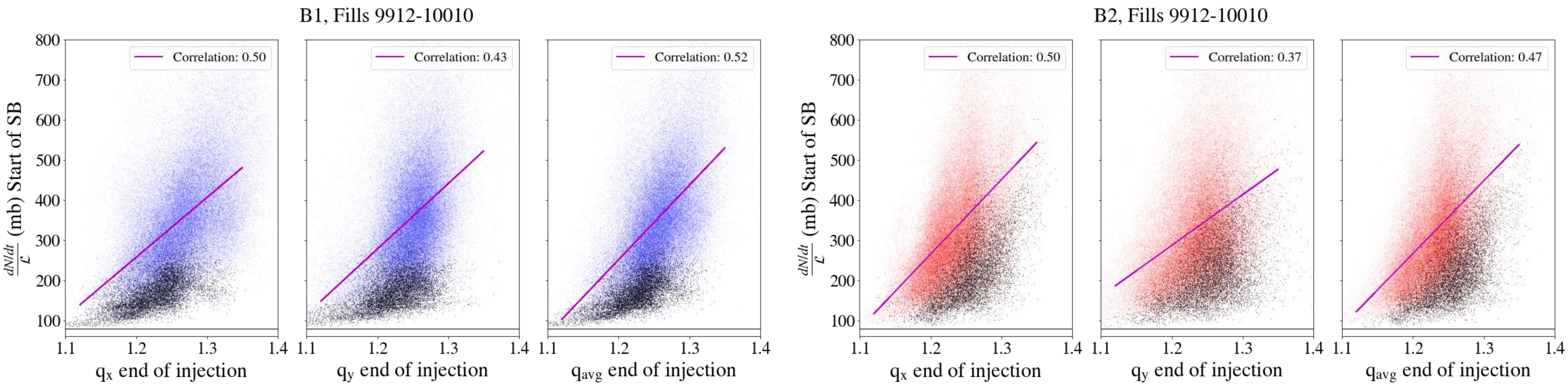


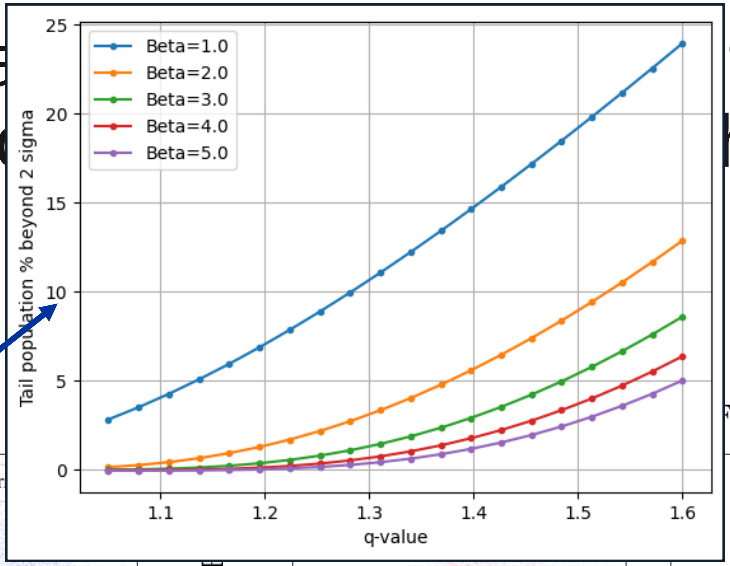
Losses at the start of collisions

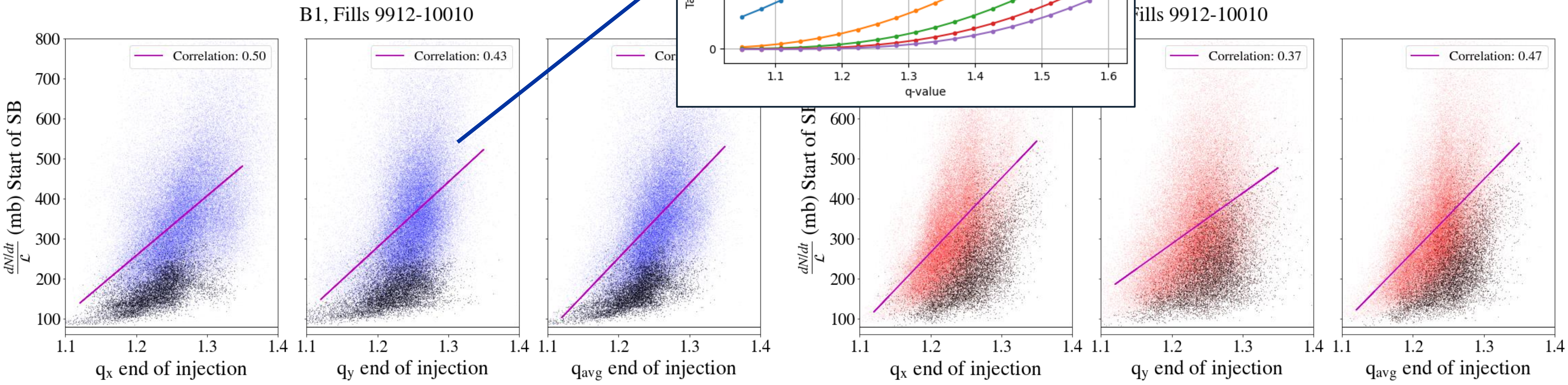
- Correlation of losses at the start of Stable Beams with the q-value measured at the end of injection: Larger tails → Higher losses



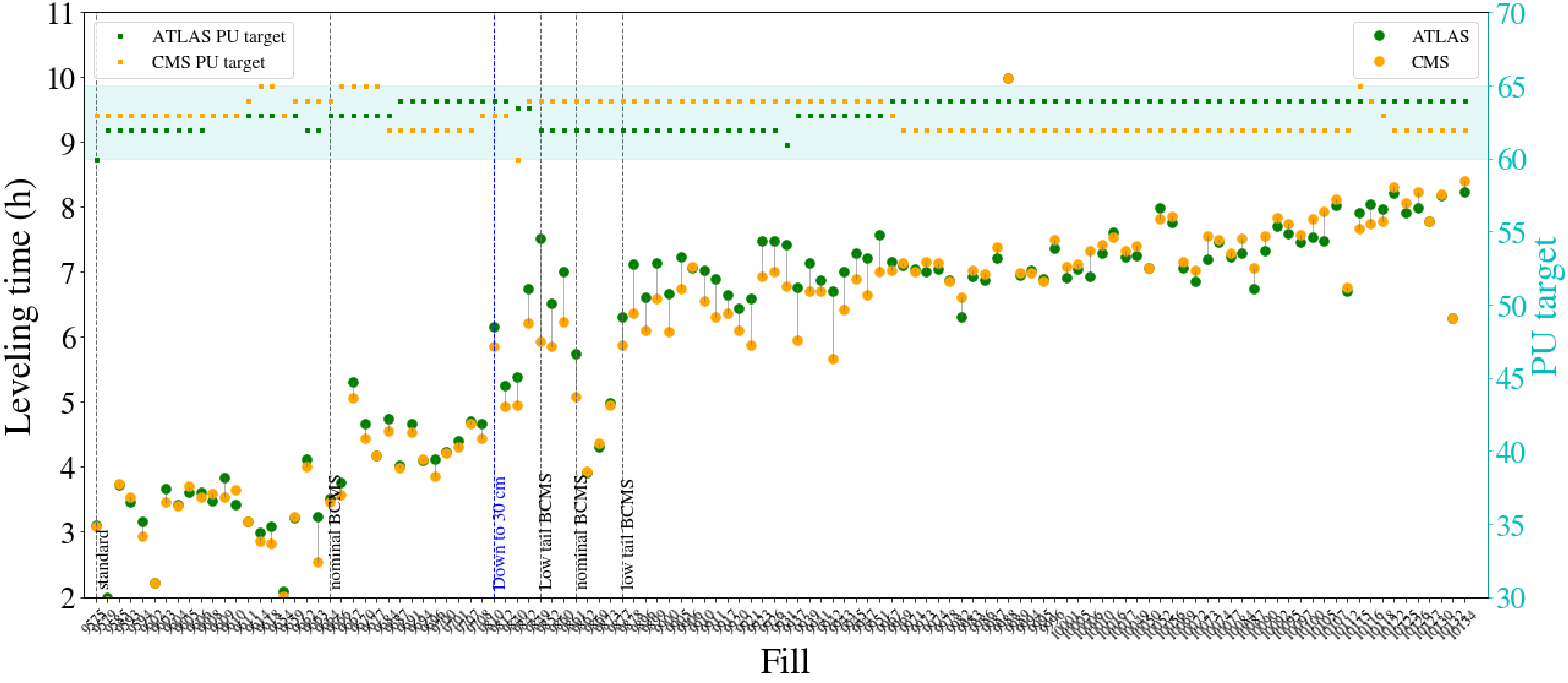
Losses at the start of collisions

- Correlation of losses at the sta th the q-value measured at the end of injecti her losses

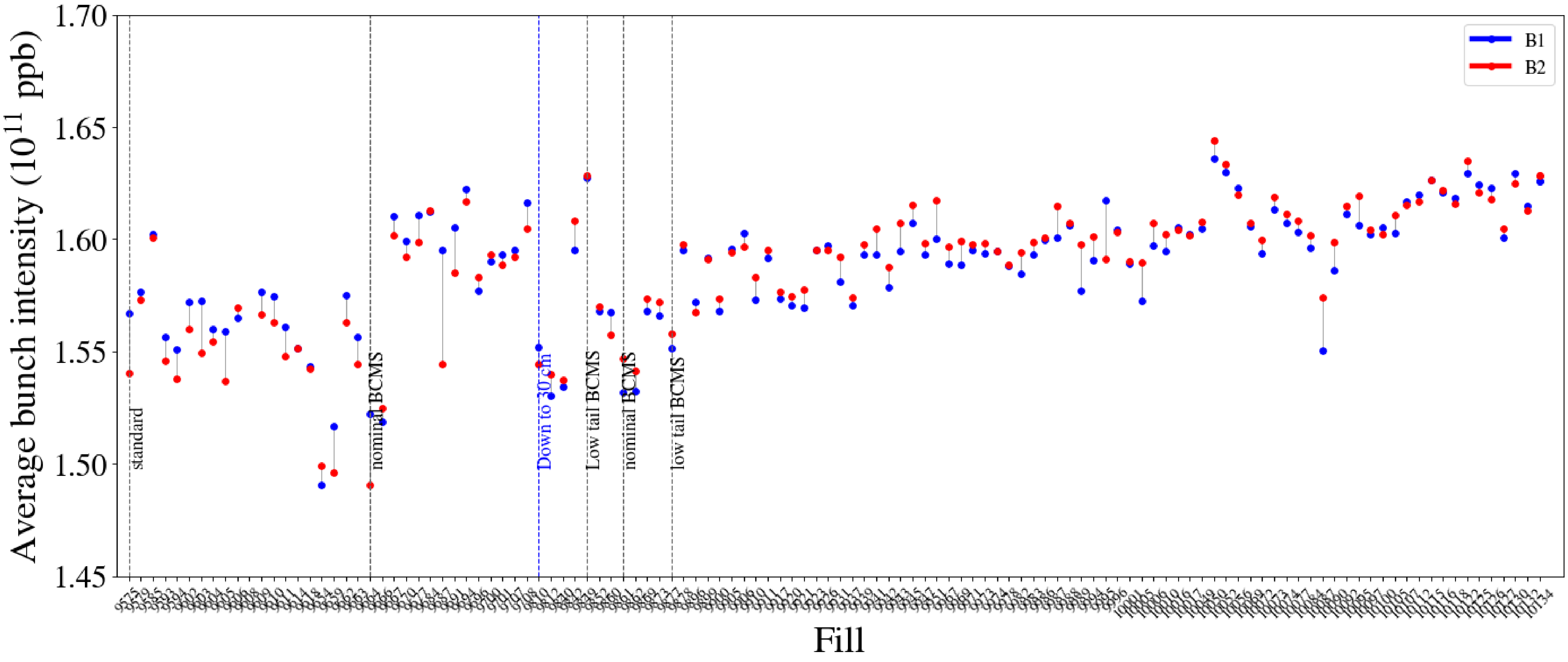




Leveling time in 2024



Bunch intensity in 2024



HL-LHC luminosity for reduced crossing angles

Run	Year	Baseline	Baseline 220 urad	Flat 8/18 cm	Flat 8/18 cm 210 urad
4	2029	9.6	10.32	9.6	9.6
	2030	208	212.1	208	208
	2031	238.8	242.8	254.1	257.2
	2032	235.7	239.7	250.8	253.9
5	2035	248.5	252.3	256	259.2
	2036	311.7	316.2	320.5	324.3
	2037	316.4	321	325.3	329.2
	2038	316.4	321	325.3	329.2
6	2040	269.1	273.1	277	280.5
	2041	324.3	329	333.4	337.4
Total (fb^{-1})		2478.5	2517.5	2560	2588.5

+1.55 %

+1%

LHCb upgrade

- LHCb upgrade II in LS4 will allow reaching higher peak luminosity in Run 5.
- Based on aperture studies, two possible optics scenarios:
  - β^*_x and β^*_y :
    I. Round 1.5 and 1.5 m
    II. Flat 0.5 and 1.5 m
  - Crossing angle: Skew net crossing angle as in Run 3 to remove dependence on spectrometer polarity
- Considering the following luminosity scenarios:

I. Low: μ_{max} = 28
II. Medium-A: μ_{max} = 34
III. Medium-B: μ_{max} = 36
IV. High: μ_{max} = 42

- Flat optics can increase leveling time and push integrated luminosity also for LHCb.

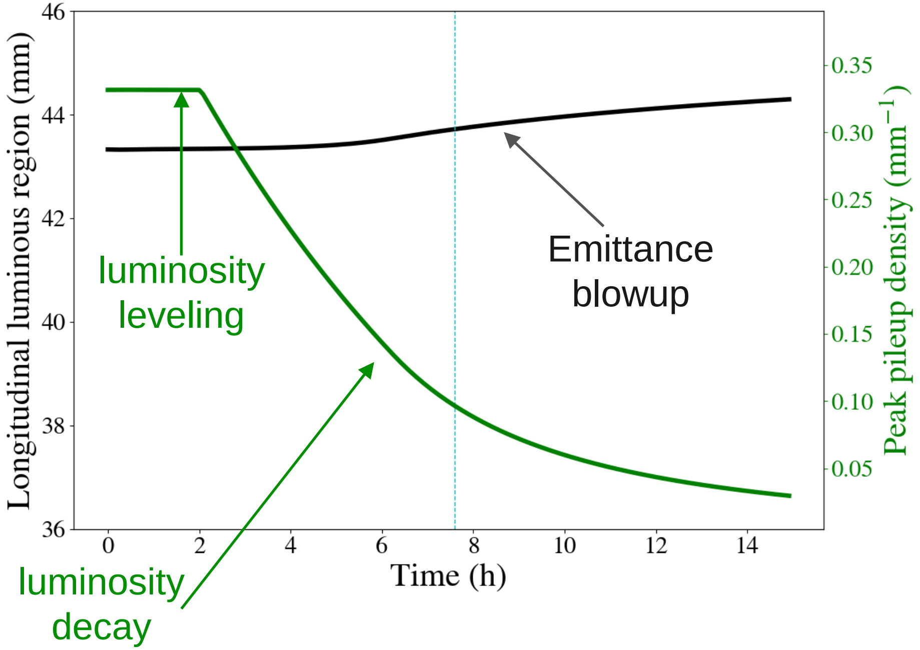
Conclusions for LHCb upgrade

- Higher yearly integrated luminosity with flat optics:
  - **From +7 fb^{-1} or +13% (low scenario) to +14 fb^{-1} or +22% (high scenario) gain compared to round optics**
- Leveling time increase:
  - **~+2 hours of leveling time and higher ratio of leveling time to optimal fill length**
- Maximum loss of ATLAS/CMS integrated lumi around 2.5% for round and 3% for flat
- Longitudinal luminous region around **43 mm** (round) and **38 mm** (flat) or -12% between flat and round
- Peak pile-up density increase by ~25% between flat and round
- Flat optics configuration **must be verified with Dynamic Aperture studies and MDs**.
- **Increased peak-pile up density and shortened luminous region** results from the reduction of β^*=1.5 m (round) to 0.5 m (flat) in H-plane while crossing plane is skew.
- Shift of pile-up density maximum can be mitigating by **replacing orthogonal separation with separation at 61 °** w.r.t crossing plane (51°).

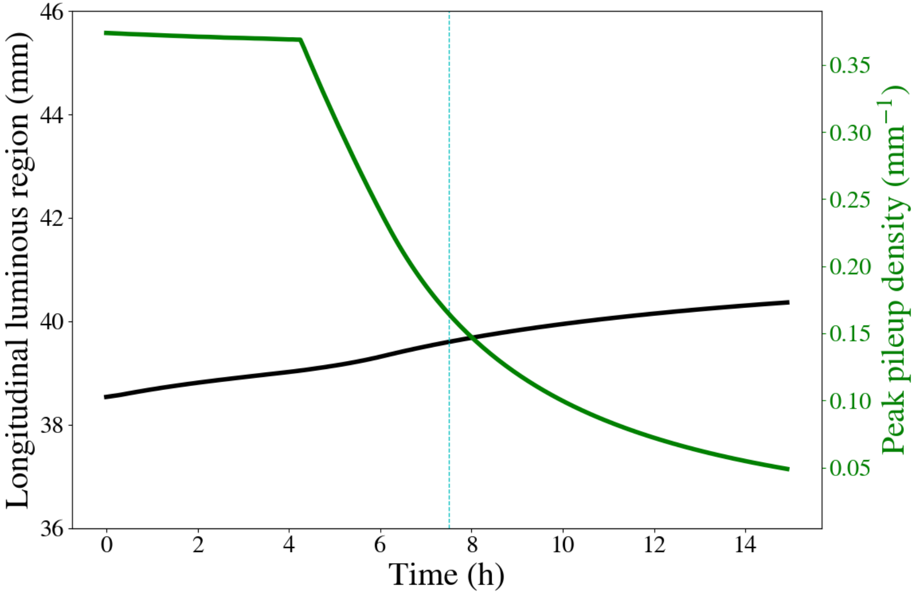
LHCb upgrade: Example for round and flat optics

- Luminous region and peak pile-up density from pile-up density $\frac{\sigma_{inel}L(z)}{f_{rev}N_b}$

Round

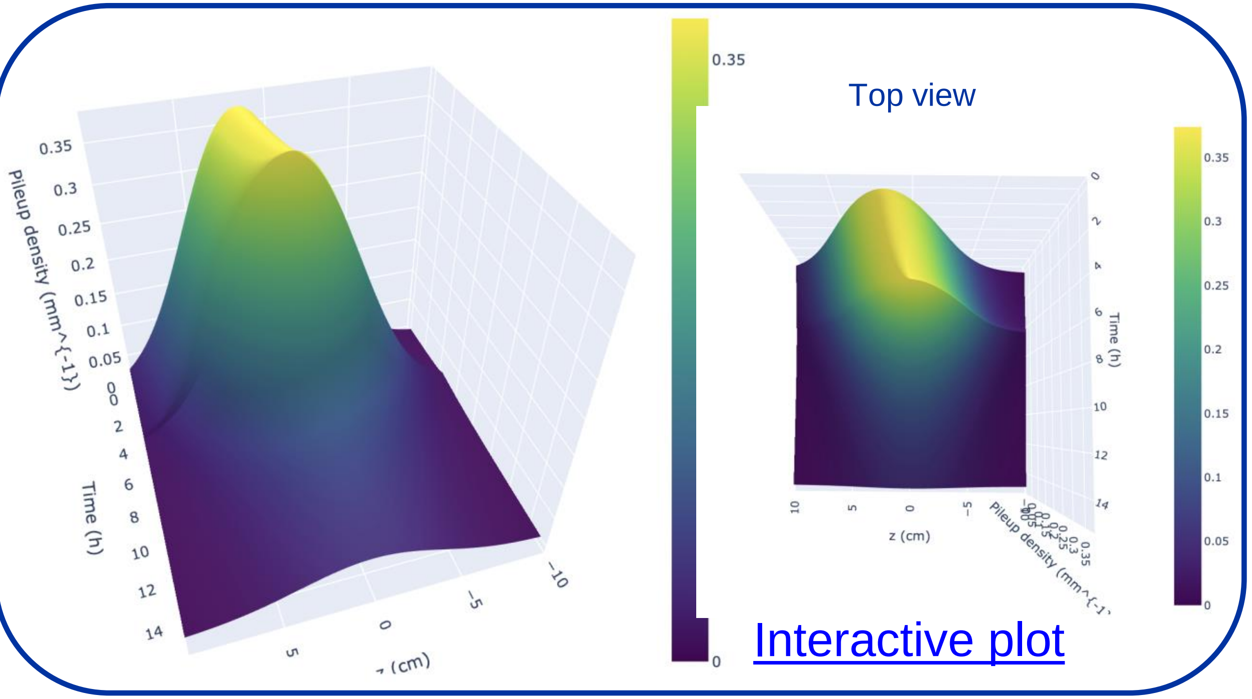


Flat

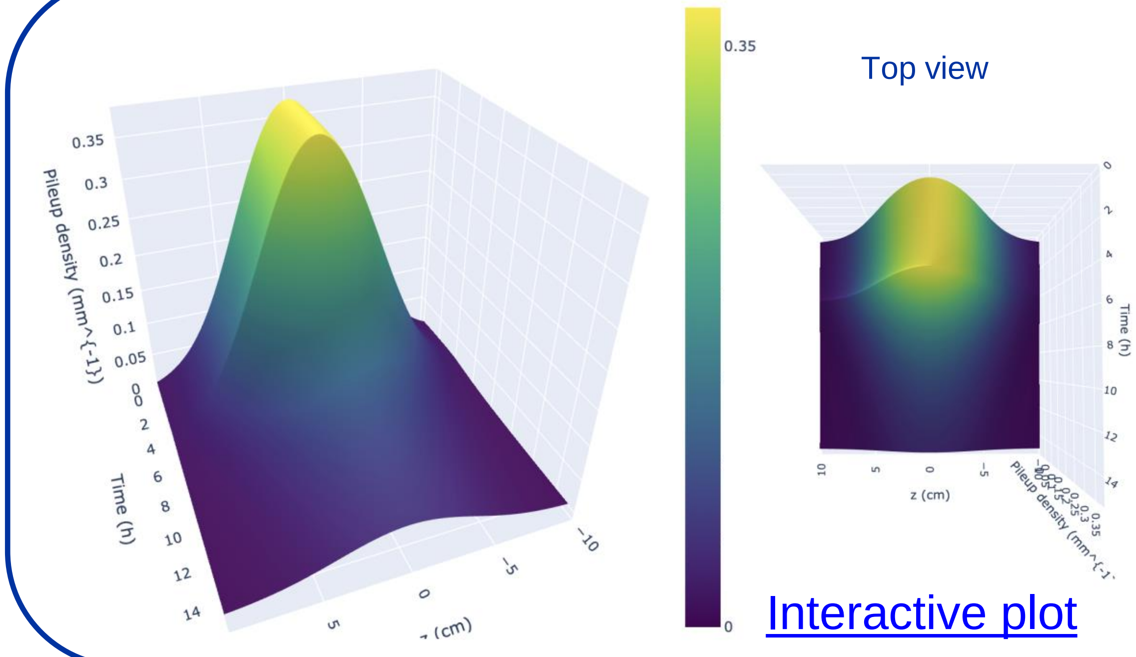


- Possible issue for the detector 1: Shortest luminous region and maximum peak pile-up density with flat optics during leveling.

LHCb upgrade: Mitigating peak pile-up density z-shift

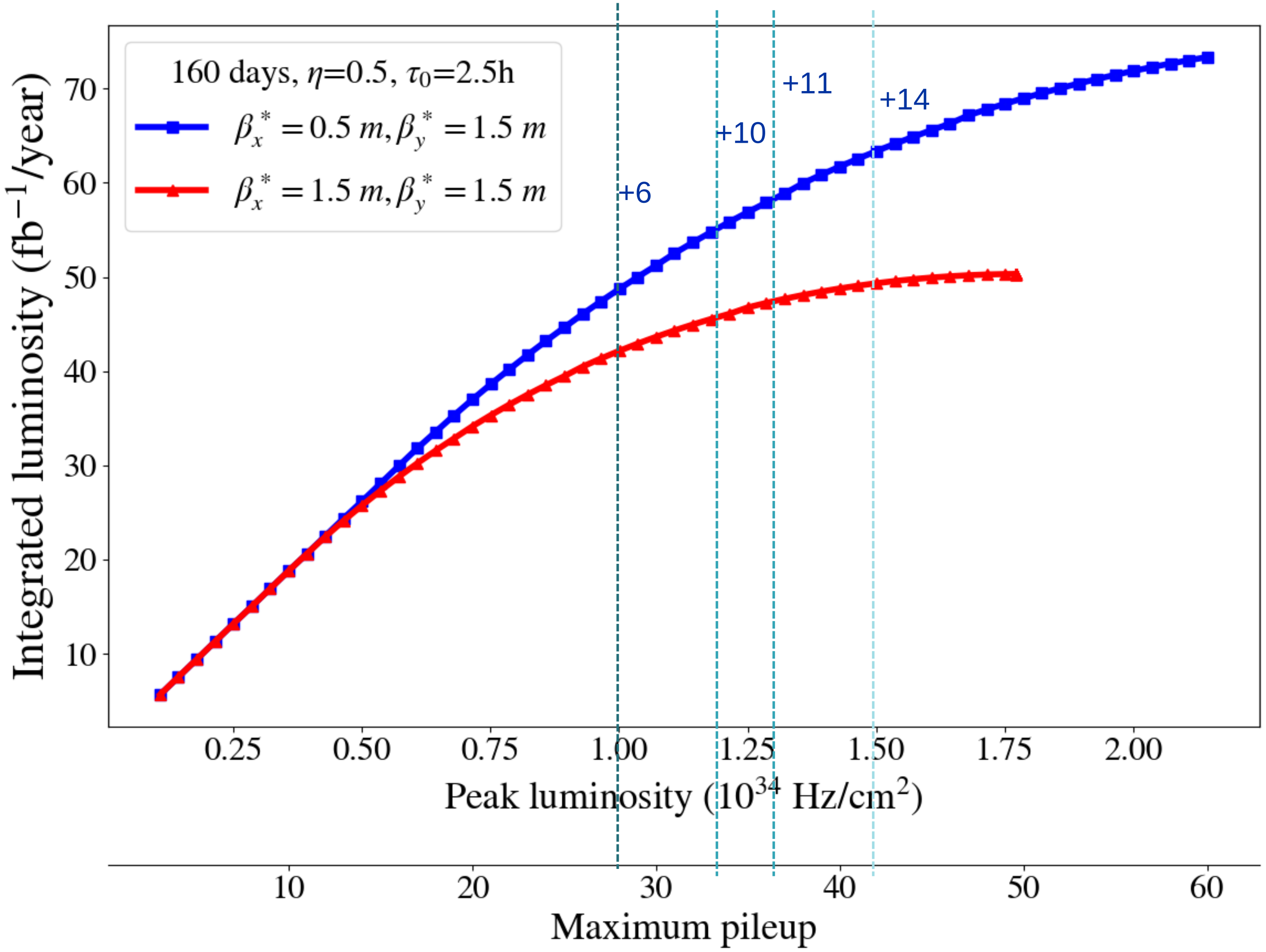


[Interactive plot]

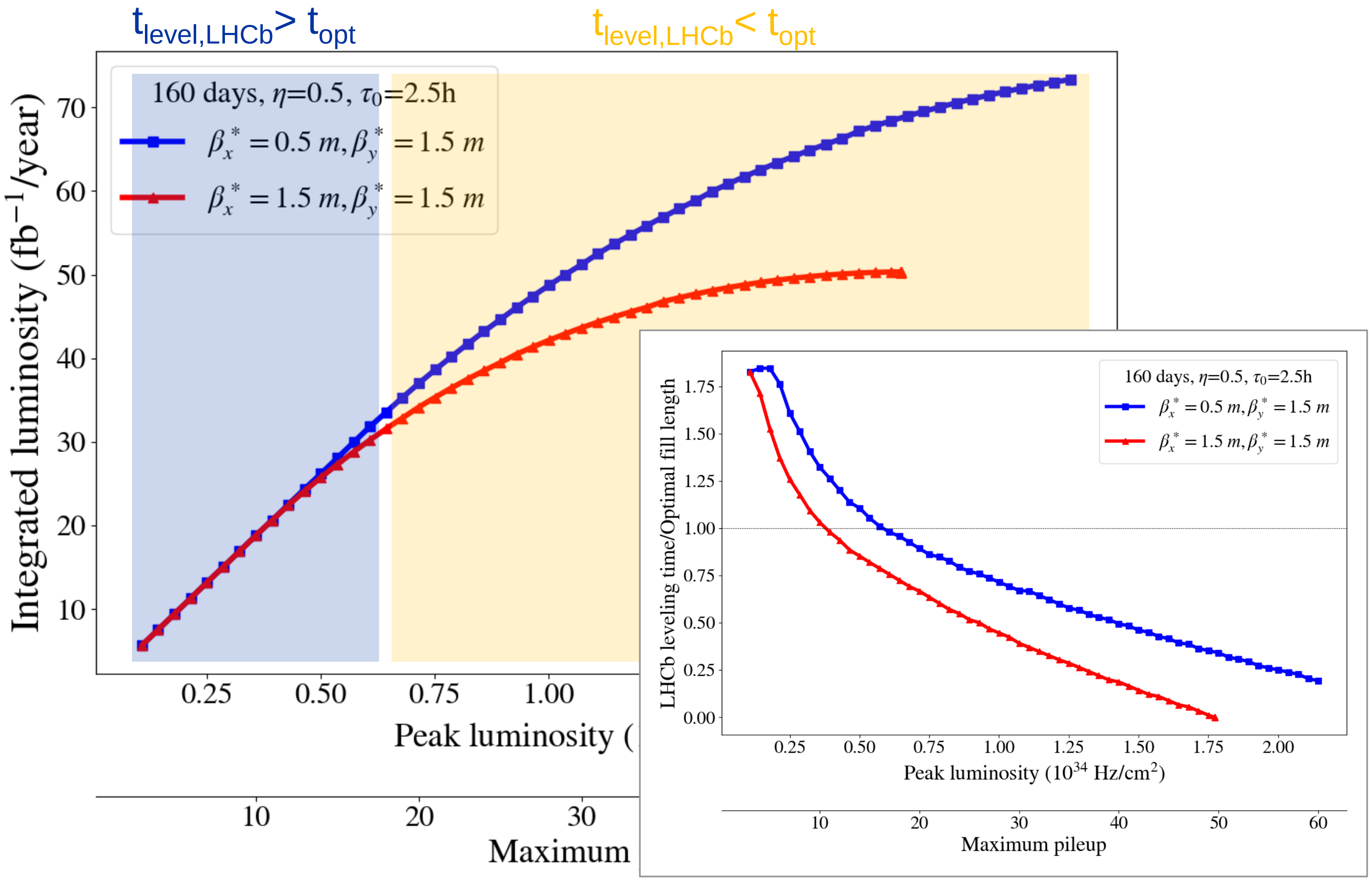


[Interactive plot]

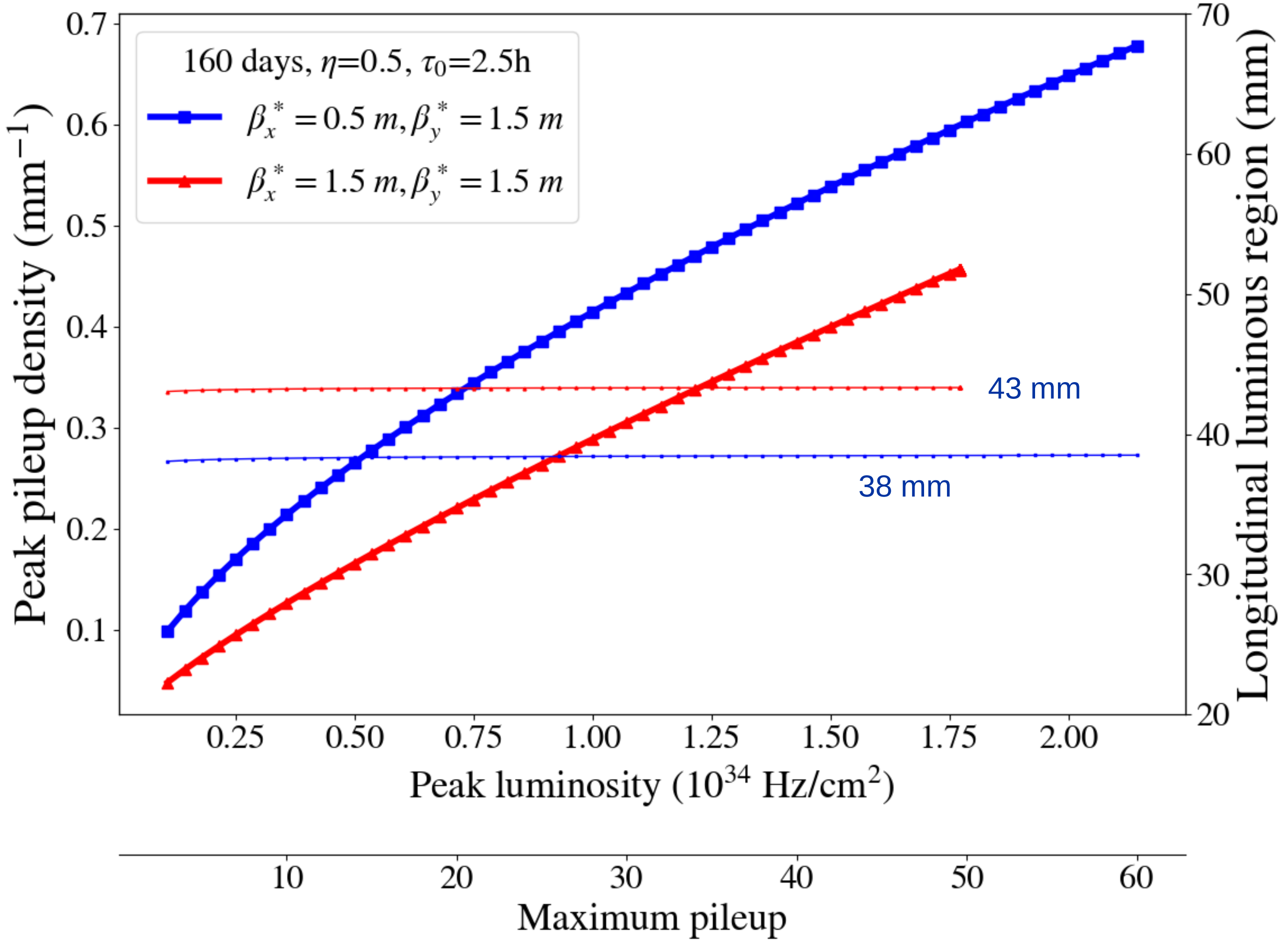
Performance projections: Yearly integrated luminosity



Performance projections: Yearly integrated luminosity



Performance projections: Luminous region & peak pile-up density



Performance projections: ATLAS/CMS loss of integrated luminosity