Integrated luminosity of the new HL-LHC baseline

To include names

Luminosity projections for HL-LHC

Summary of the 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 o
    II. Additional losses from unknown source based on LHC experience

To mention that I am considering 110 mb for the simulation but this is greatly improved now in the LHC

  - Luminosity:
    - Analytical and numerical integration of 4 integrals $L = N_1 N_2 n_b f_r \sqrt{(\vec{v_1} - \vec{v_2})^2 - \frac{(\vec{v_1} \times \vec{v_2})^2}{c^2}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho^{B1}\rho^{B2}\ dx dy dz dt$ G. Sterbini python module
    - 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

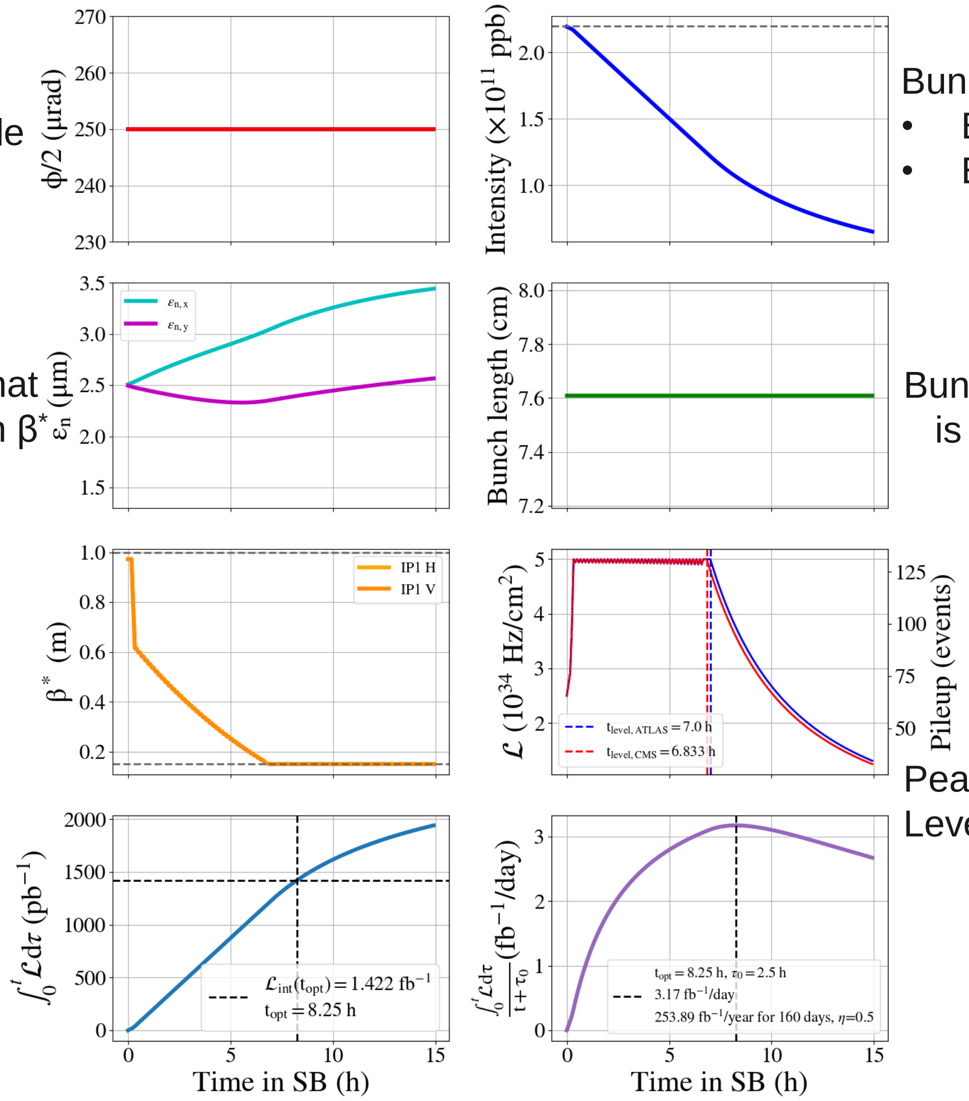
Evolution of beam & machine parameters for ATLAS/CMS in a nominal fill

Crossing angle

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

β*,
round optics

Integrated luminosity



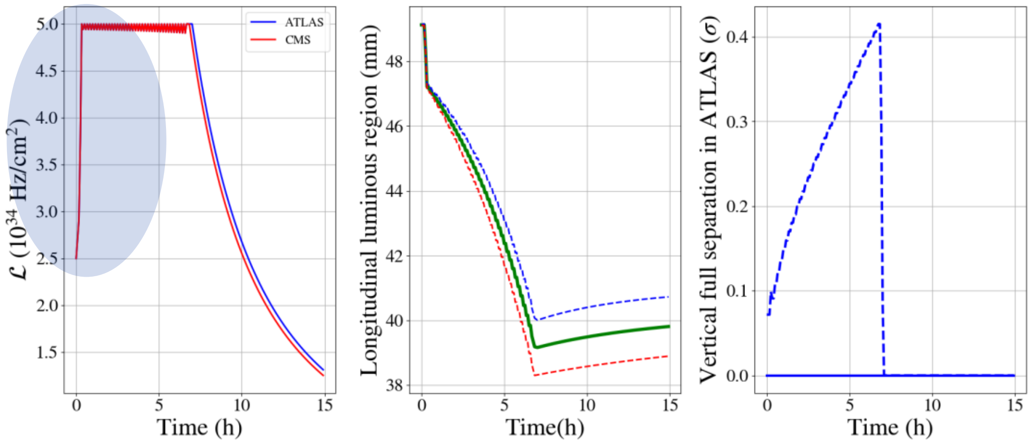
Bunch intensity:
- Burn-off
- Extra losses

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

To mention that there are not enough days in intensity rampup+proton physics for 2029+1 to ramp to 1.8e11 if we tart with 1.4e11, intensity ramp up plots in the backup

Run	Year	Efficien[illegible]	[illegible] (1e11 ppb)	[illegible] $_x$ [illegible]	[illegible] $_y$ [illegible]	[illegible]	[illegible] $_{max}$	[illegible] ramp-up	[illegible] physics [1]	[illegible] bunches [2]	[illegible]lliding [illegible]P8 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+1	0.5	2.2	25	25	on	132	15	136	2748	2574	2.5	H/V	250	2
	2031+1	0.5	2.2	20	20	on	132	10	154	2748	2574	2.5	H/V	250	2
	2032+1	0.5	2.2	20	20	on	132	10	152	2748	2574	2.5	H/V	250	2
5	2035+1	0.5	2.2	15	15	on	132	15	152	2748	2574	2.5	H/V	250	2
	2036+1	0.5	2.2	15	15	on	132	10	195	2748	2574	2.5	H/V	250	2
	2037+1	0.5	2.2	15	15	on	132	10	198	2748	2574	2.5	H/V	250	2
	2038+1	0.5	2.2	15	15	on	132	10	198	2748	2574	2.5	H/V	250	2
6	2040+1	0.5	2.2	15	15	on	132	15	165	2748	2574	2.5	H/V	250	2
	2041+1	0.5	2.2	15	15	on	132	10	203	2748	2574	2.5	H/V	250	2

Input from new proposed DMR M. Zerlauth

[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.

To mention I will show next some LHCb studies

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/cm²) [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+1	0.5	2.2	**25**	**25**	on	132	15	136	2748	2574	2.5	**H/V→V/H**	250	2
	2031+1	0.5	2.2	**20→8**	**20→18**	on	132	10	154	2748	2574	2.5	**H/V→V/H**	250	2
	2032+1	0.5	2.2	**20→8**	**20→18**	on	132	10	152	2748	2574	2.5	**H/V→V/H**	250	2
5	2035+1	0.5	2.2	**15→8**	**15→18**	on	132	15	152	2748	2574	2.5	**H/V→V/H**	250	2
	2036+1	0.5	2.2	**15→8**	**15→18**	on	132	10	195	2748	2574	2.5	**H/V→V/H**	250	2
	2037+1	0.5	2.2	**15→8**	**15→18**	on	132	10	198	2748	2574	2.5	**H/V→V/H**	250	2
	2038+1	0.5	2.2	**15→8**	**15→18**	on	132	10	198	2748	2574	2.5	**H/V→V/H**	250	2
6	2040+1	0.5	2.2	**15→8**	**15→18**	on	132	15	165	2748	2574	2.5	**H/V→V/H**	250	2
	2041+1	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"

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]
4	2029+1	0.5	1.8	30	30	off	101	20	6	2748→ 2440	2574→ 2240	2.5	H/V	250	2
	2030+1	0.5	2.2	25	25	on	132	15	136	2748→ 2440	2574→ 2240	2.5	H/V	250	2
	2031+1	0.5	2.2	20	20	on	132	10	154	2748→ 2440	2574→ 2240	2.5	H/V	250	2
	2032+1	0.5	2.2	20	20	on	132	10	152	2748→ 2440	2574→ 2240	2.5	H/V	250	2
5	2035+1	0.5	2.2	15	15	on	132	15	152	2748→ 2440	2574→ 2240	2.5	H/V	250	2
	2036+1	0.5	2.2	15	15	on	132	10	195	2748→ 2440	2574→ 2240	2.5	H/V	250	2
	2037+1	0.5	2.2	15	15	on	132	10	198	2748→ 2440	2574→ 2240	2.5	H/V	250	2
	2038+1	0.5	2.2	15	15	on	132	10	198	2748→ 2440	2574→ 2240	2.5	H/V	250	2
6	2040+1	0.5	2.2	15	15	on	132	15	165	2748→ 2440	2574→ 2240	2.5	H/V	250	2
	2041+1	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)	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/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+1	0.5	2.2	25	25	on	132	15	136	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2
	2031+1	0.5	2.2	20	20	on	132	10	154	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2
	2032+1	0.5	2.2	20	20	on	132	10	152	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2
5	2035+1	0.5	2.2	15	15	on	132	15	152	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2
	2036+1	0.5	2.2	15	15	on	132	10	195	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2
	2037+1	0.5	2.2	15	15	on	132	10	198	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2
	2038+1	0.5	2.2	15	15	on	132	10	198	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2
6	2040+1	0.5	2.2	15	15	on	132	15	165	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2
	2041+1	0.5	2.2	15	15	on	132	10	203	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2

”Round BCMS”: 25ns_2744b_2736_2246_2370_240bpi_13inj_800ns_bs200ns_BCMS_5x48b

To mention that I will show next lHC observations with BCMS

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/cm²) [3]
4	2029	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→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

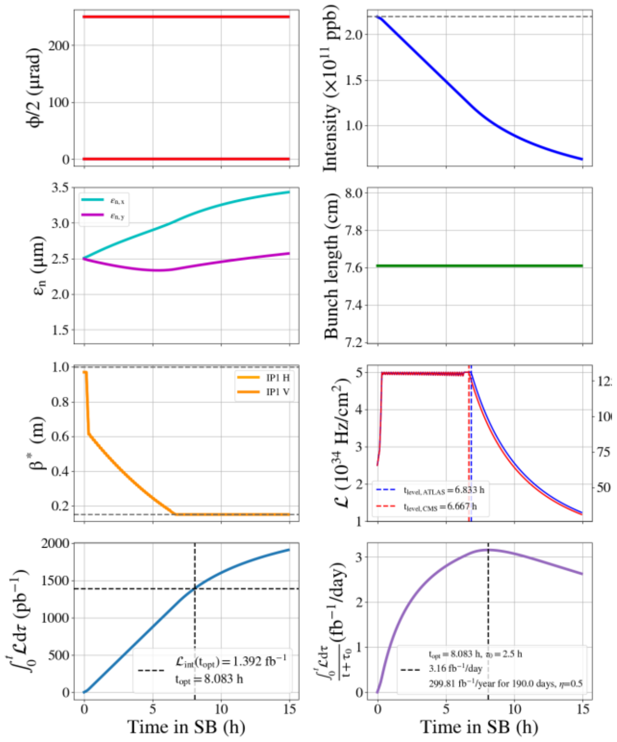
"Nominal ions" → "Extended ions"

Scenarios

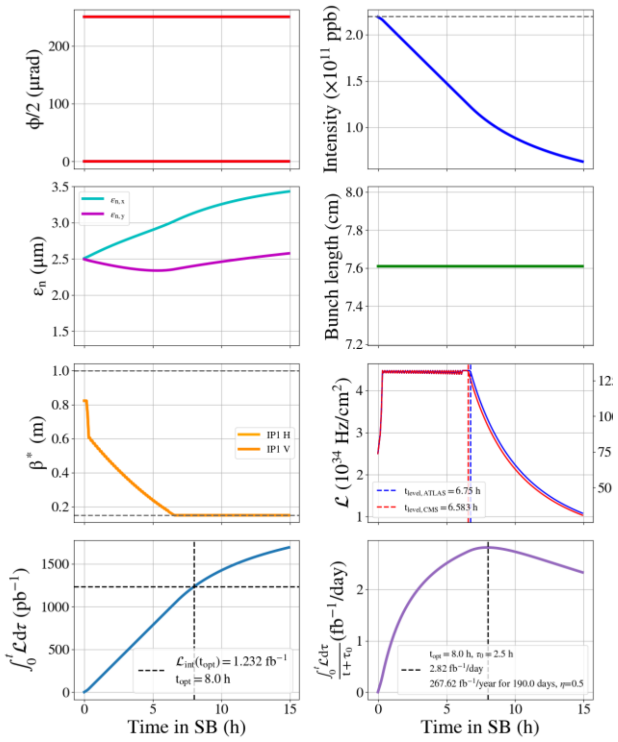
Scenario	Optics	Duration	Filling scheme
Baseline	Round Run4 20cm	Nominal ions	Standard
Round hybrid	Round Run4 20cm	Nominal ions	Hybrid
Round BCMS	Round Run4 20cm	Nominal ions	BCMS
Flat 8/18 cm	Flat 8/18 cm	Nominal ions	Standard
Vbaseline extended ions	Round Run4 20cm	Extended ions	Standard
Round hybrid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

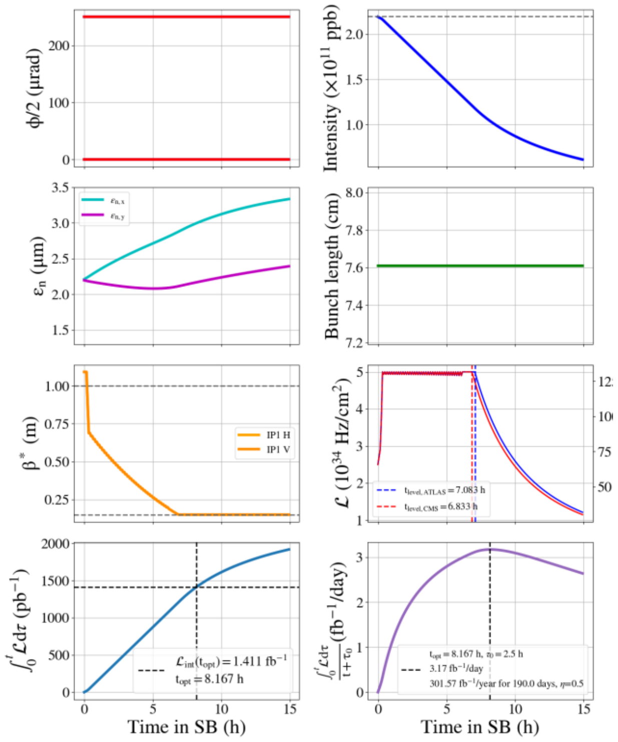
Baseline



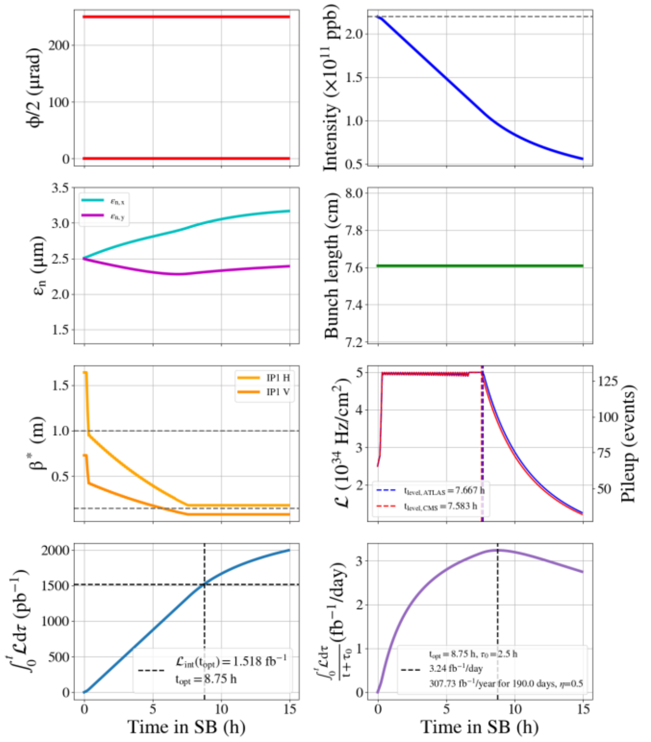
Round hybrid



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 lumi per year

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+1	208	186.1	210.7	208	208	186.1	210.7	208
	2031+1	238.8	213.4	241	254.1	238.8	213.4	241	254.1
	2032+1	235.7	210.7	237.9	250.8	235.7	210.7	237.9	250.8
5	2035+1	248.5	222.6	250.2	256	213.8	191.6	215.3	220.3
	2036+1	311.7	278.6	313.7	320.5	275.4	246.2	277.2	283.2
	2037+1	316.4	282.9	318.4	325.3	280.1	250.5	281.9	288.1
	2038+1	316.4	282.9	318.4	325.3	280.1	250.5	281.9	288.1
6	2040+1	269.1	240.9	270.9	277	213.2	207.1	232.8	238.1
	2041+1	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

- 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+1	208	-10.53%	1.30%	0%	0%	-10.53%	1.30%	0%
	2031+1	238.8	-10.64%	0.92%	6.41%	0%	-10.64%	0.92%	6.41%
	2032+1	235.7	-10.61%	0.93%	6.41%	0%	-10.61%	0.93%	6.41%
5	2035+1	248.5	-10.42%	0.68%	3.02%	-13.96%	-22.90%	-13.36%	-11.34%
	2036+1	311.7	-10.62%	0.64%	2.82%	-11.65%	-21.02%	-11.07%	-9.14%
	2037+1	316.4	-10.58%	0.63%	2.81%	-11.48%	-20.83%	-10.90%	-8.94%
	2038+1	316.4	-10.58%	0.63%	2.81%	-11.48%	-20.83%	-10.90%	-8.94%
6	2040+1	269.1	-10.48%	0.67%	2.94%	-20.78%	-23.04%	-13.49%	-11.52%
	2041+1	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%**

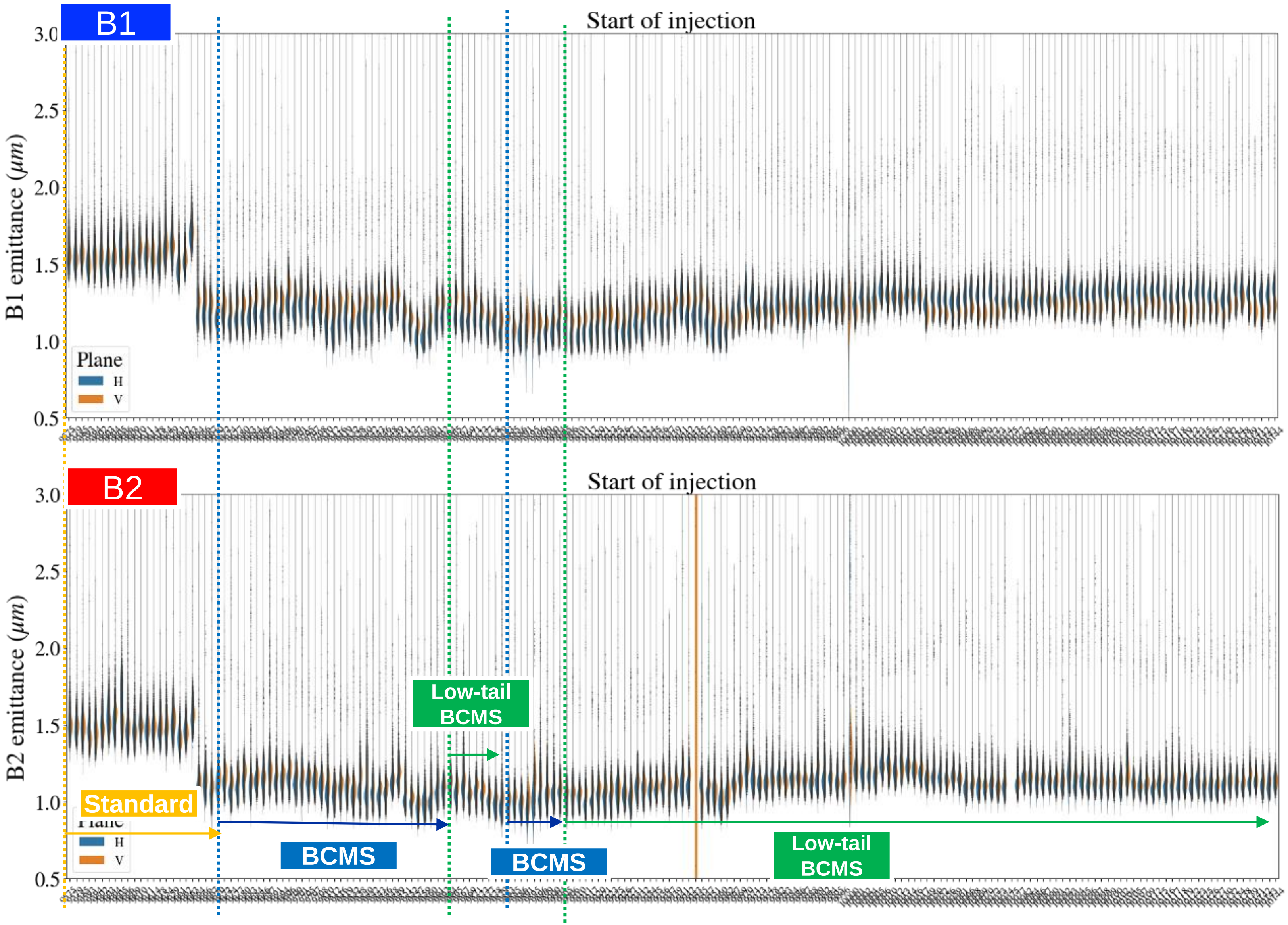
- Slight increase with BCMS (+1%) for HL-LHC
- +3% gain with flat optics
- -9% if ion runs beyond Run 4
- -10% with hybrid, -19% if hybrid + ion runs beyond Run 4
- Loss of performance due to ion runs beyond Run 4 can be partially mitigated with flat optics

Interesting observations from Run 3

Performance of BCMS in 2024

Fills	Beam type
9575-9663	Standard
9664-9847	Nominal BCMS
9848-9860	Low-tail BCMS
9861-9876	Nominal BCMS
9877-now	Low-tail BCMS

20% smaller emittance injected in the LHC with BCMS



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Fills	Beam type
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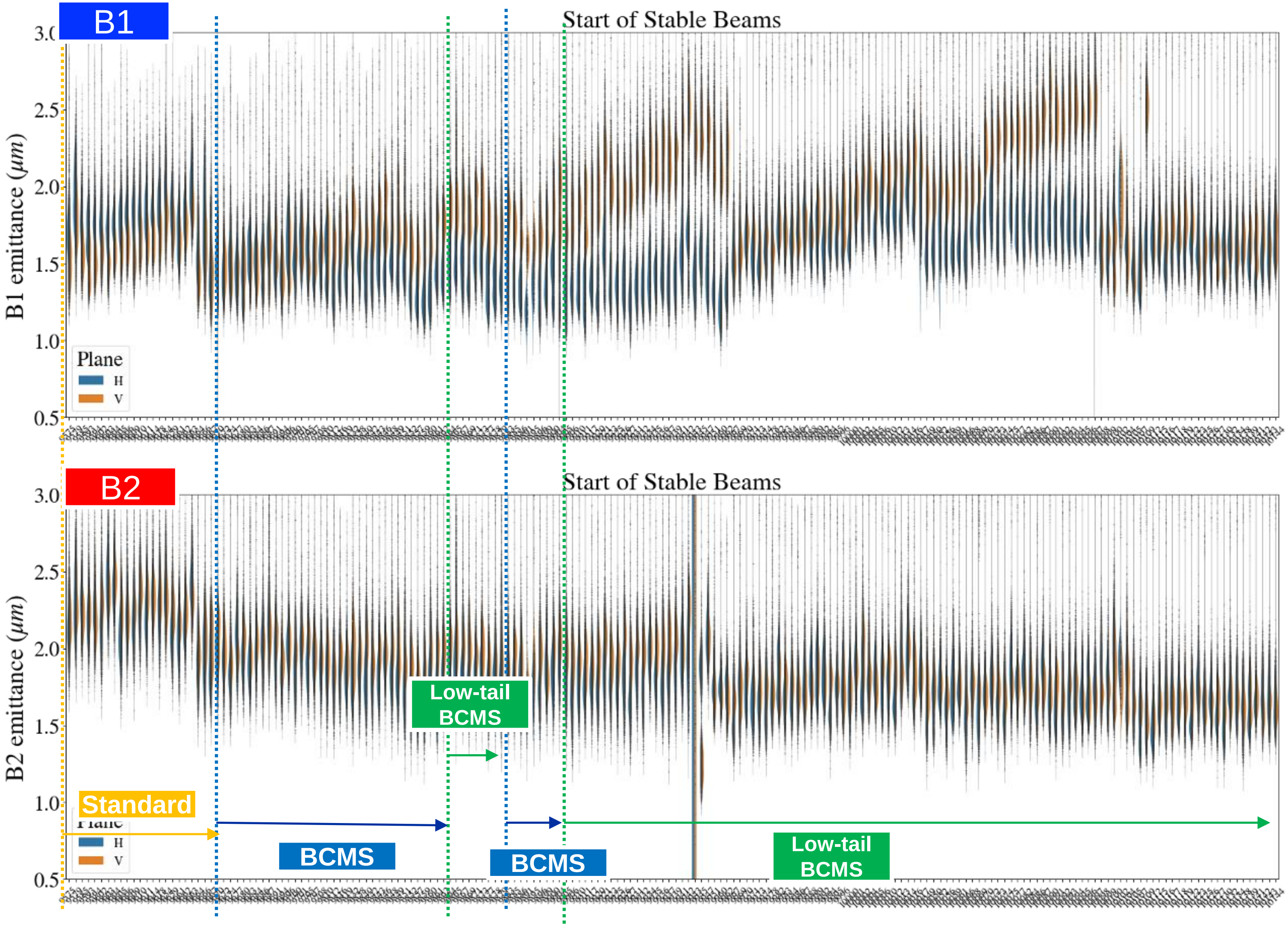
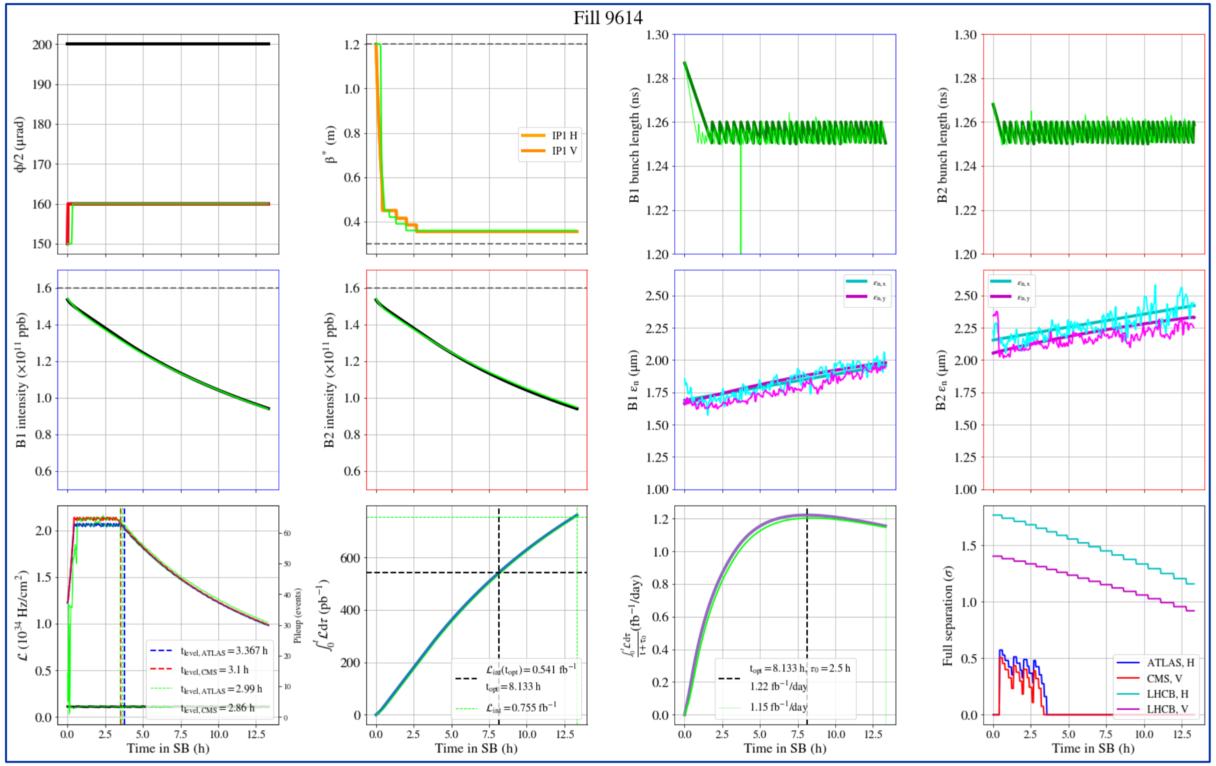
9861-9876	Nominal BCMS
9877-now	Low-tail BCMS

10% smaller emittance with BCMS at start of SB (& 2% higher bunch intensity)

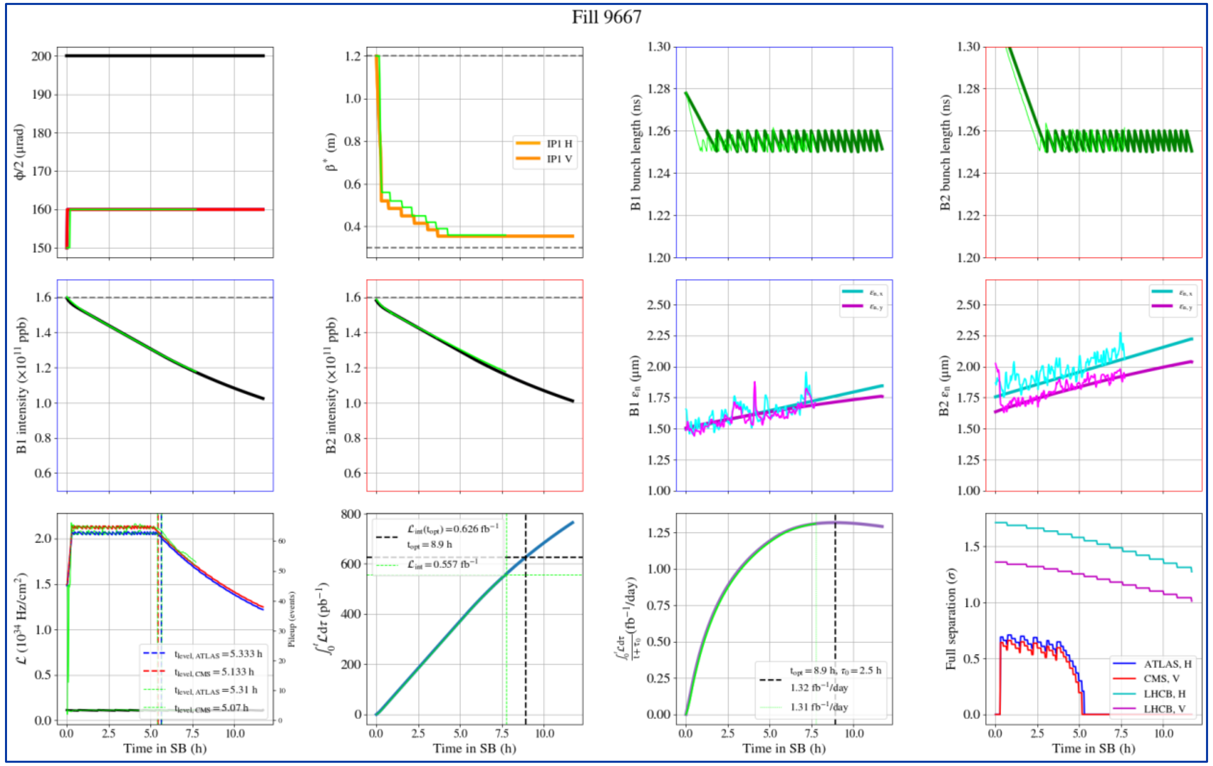


BCMS performance in 2024: Performance gain

Fill 9614, Standard



Fill 9667, BCMS

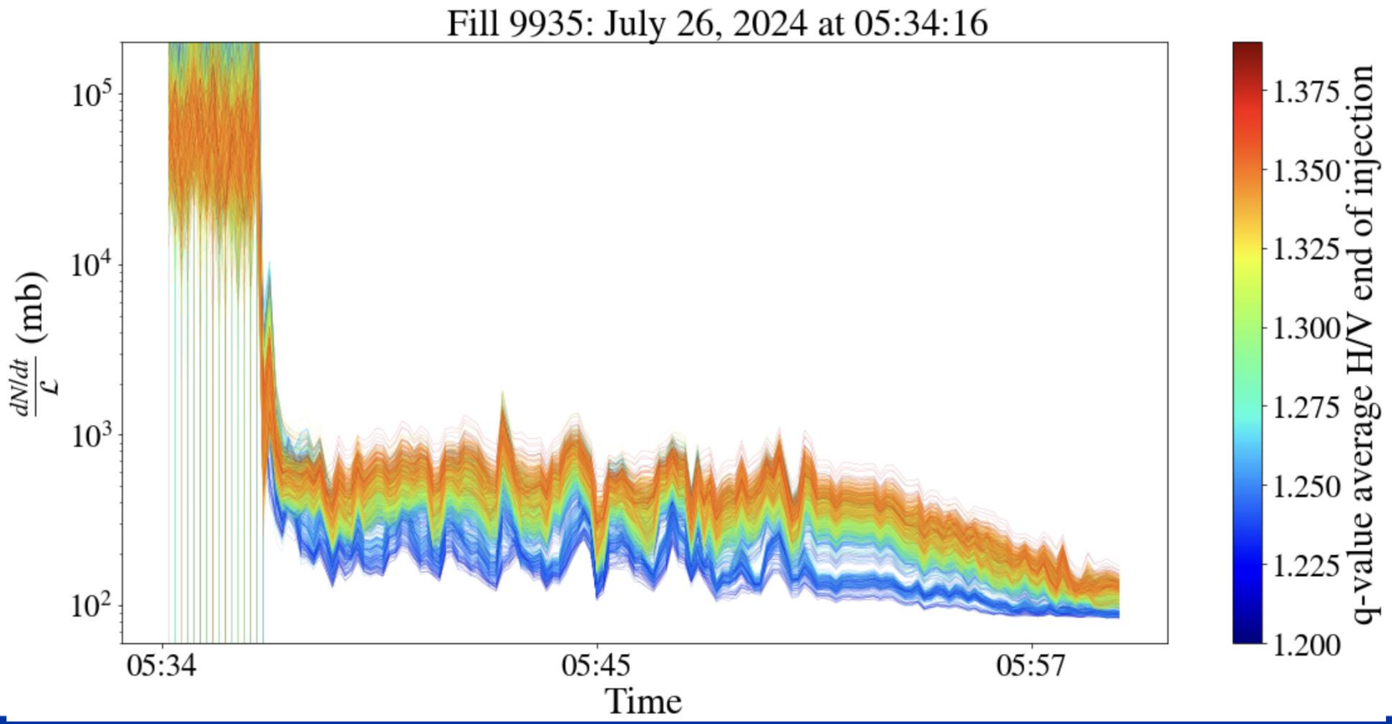


Considering a turn-around time of **2.5h**:

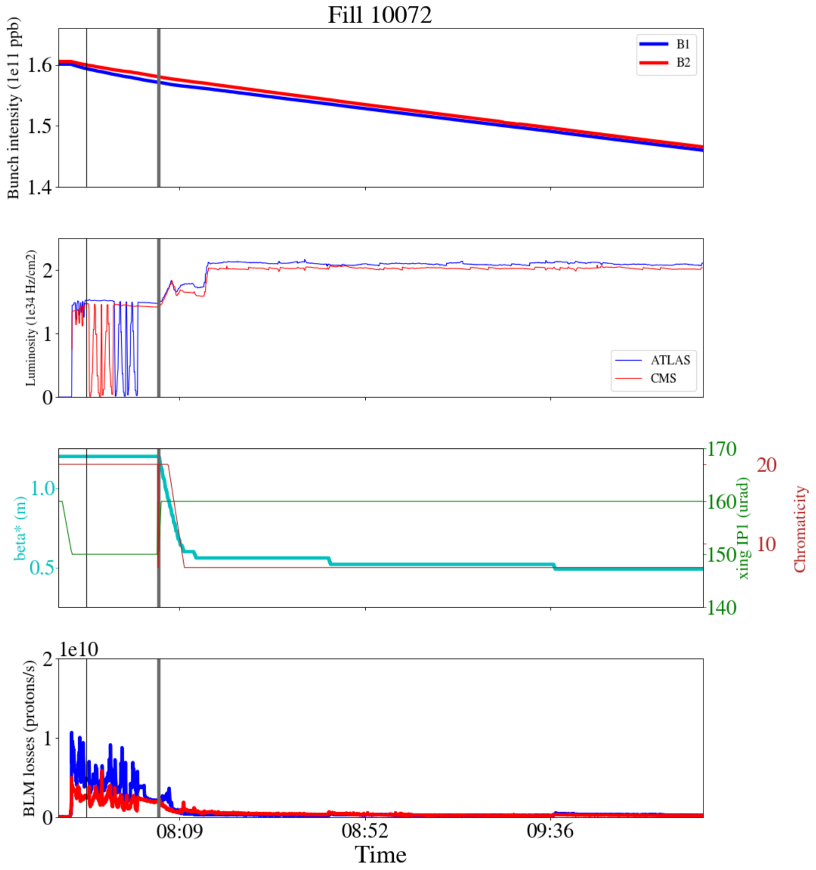
- From 1.22 fb^{-1}/day with standard to 1.32 fb^{-1}/day with BCMS: integrated luminosity for fills that make it to the optimal fill length (>8h), **+5%** due to the smaller emittance with BCMS

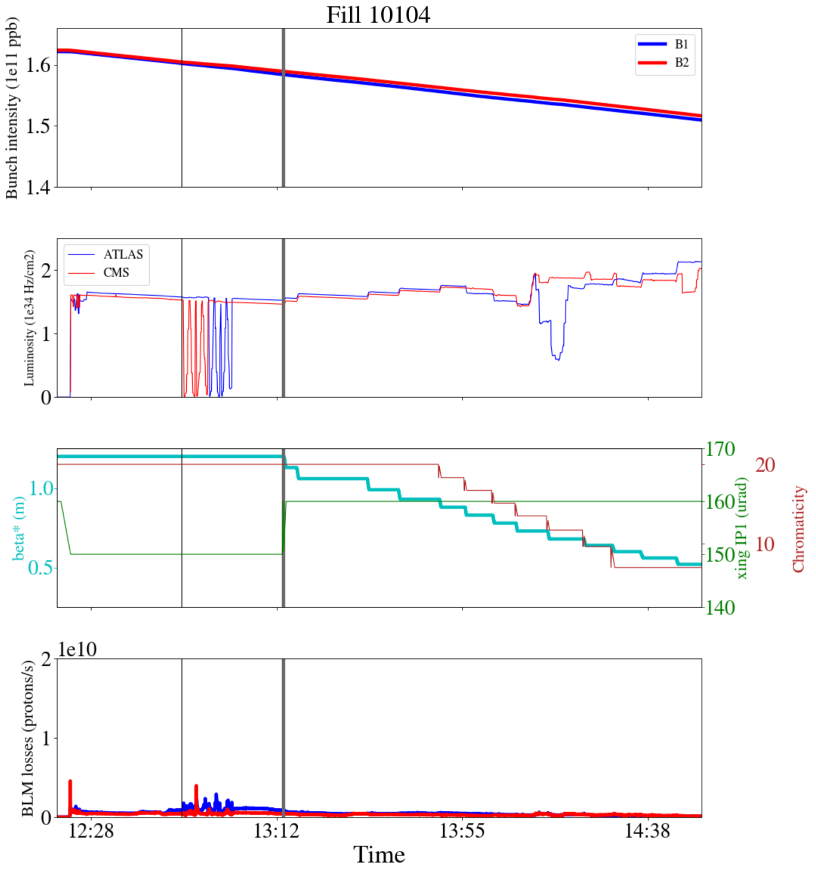
Losses at the start of collisions

- Bunch-by-bunch effective cross section from Adjust to 20 minutes into Stable Beams, color-coded with the bunch-by-bunch q-value (average between H/V) measured by the BSRT at the end of injection.
- No clear correlation with beam-beam effects (e.g. number of LR interactions).
- Correlation of losses with bunches with heavier tails.



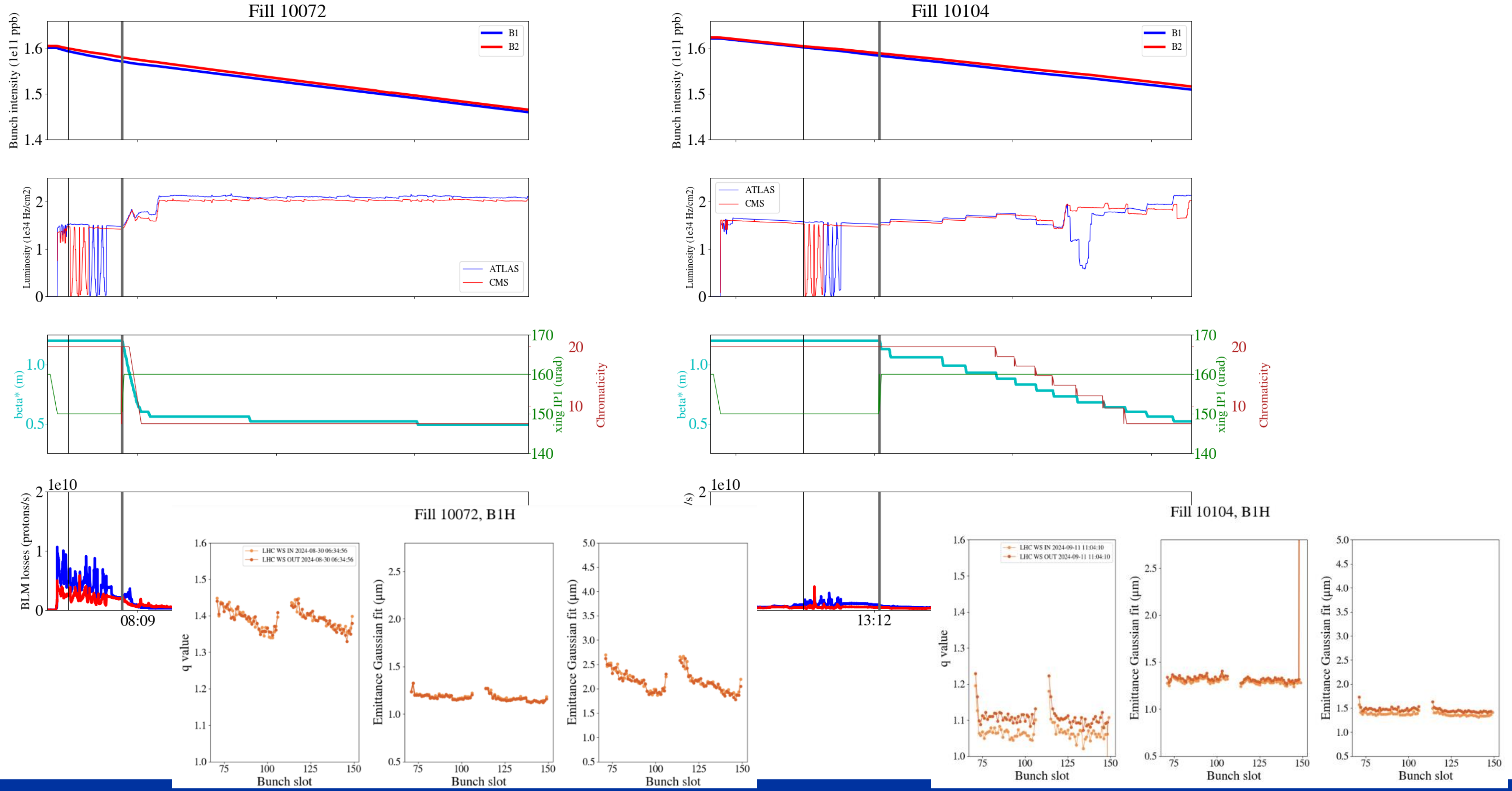
Losses at the start of collisions



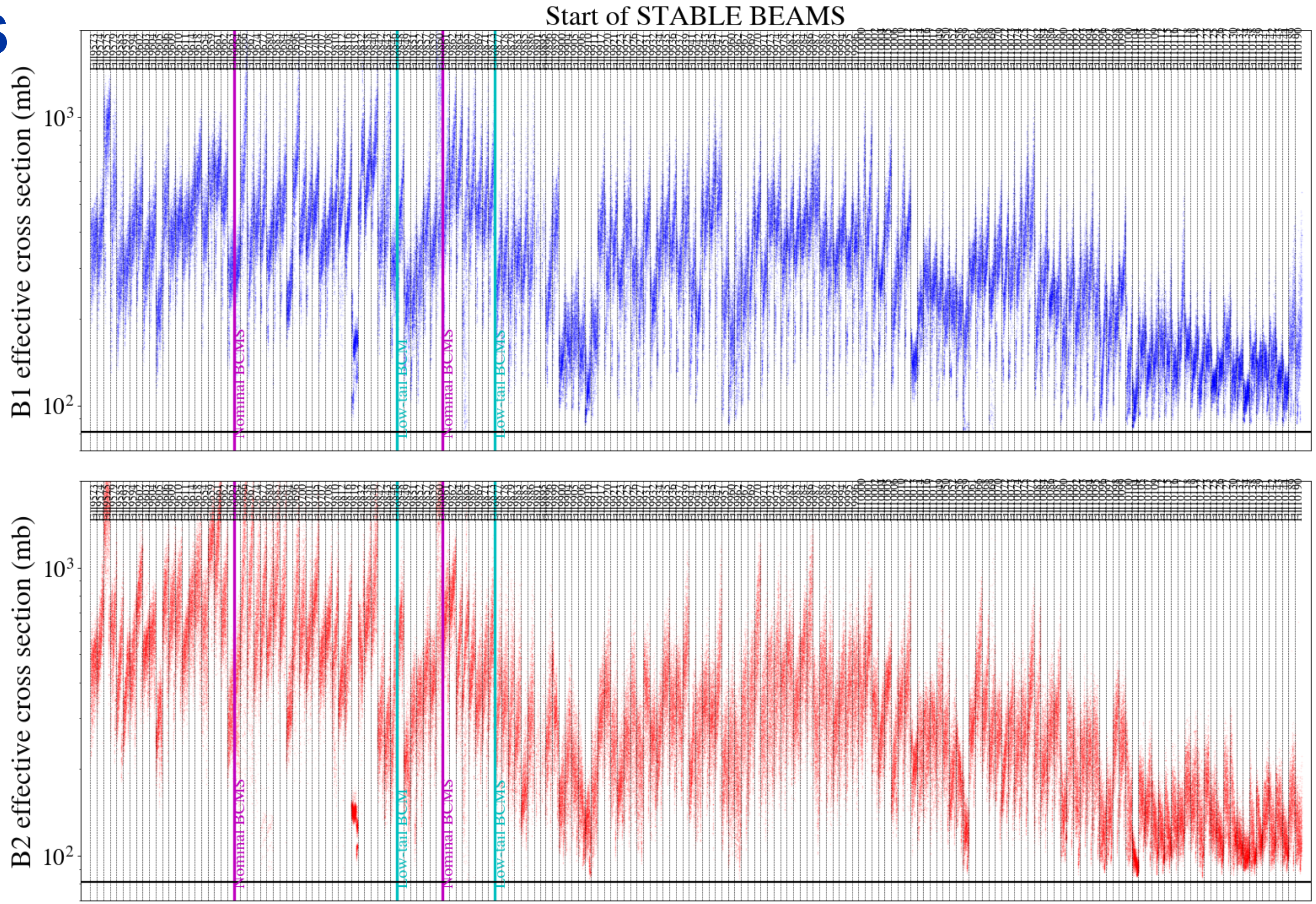


- Started observing lower losses in the latest fills

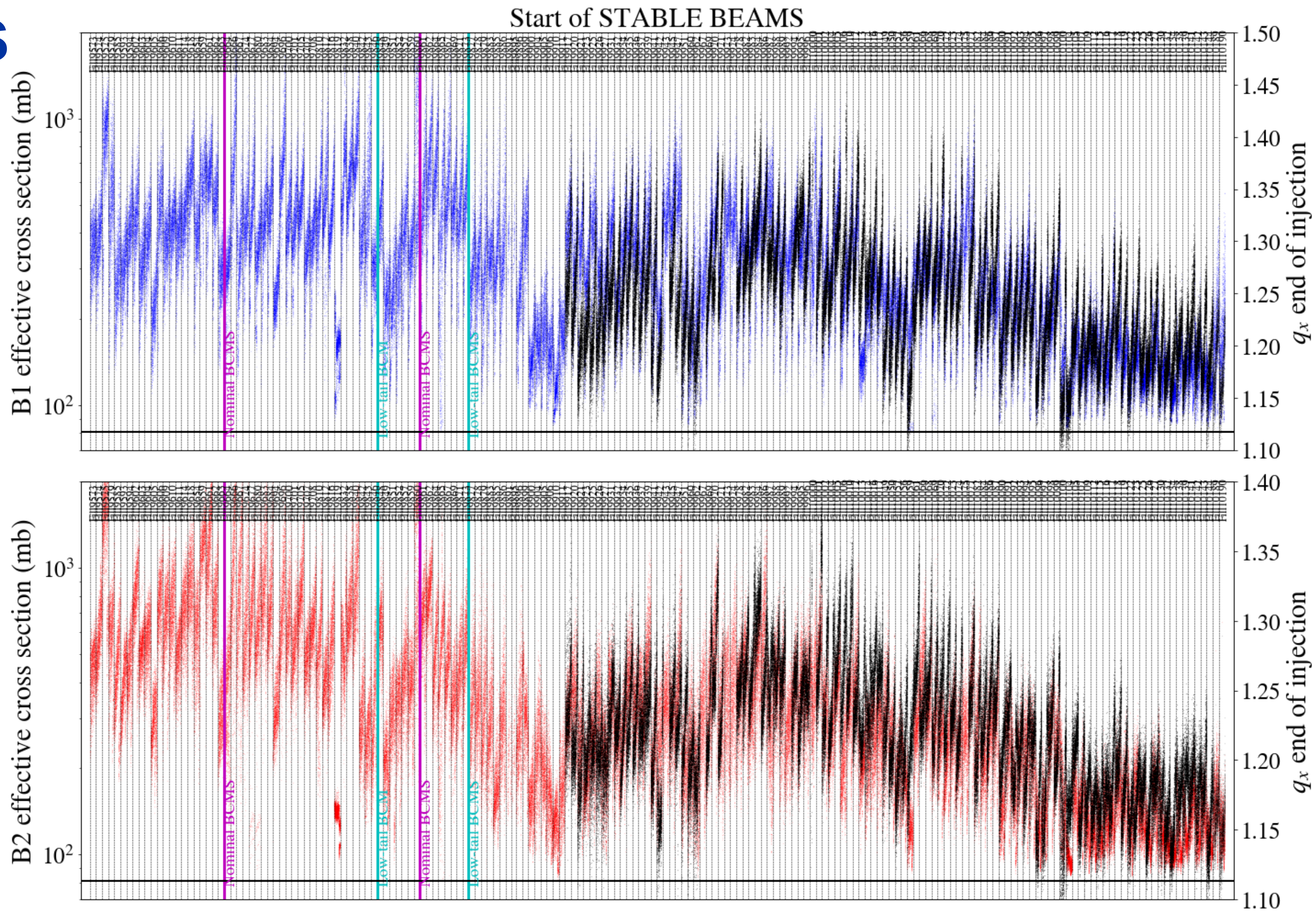
Losses at the start of collisions



Reduction of losses at the start of collisions with low-tails



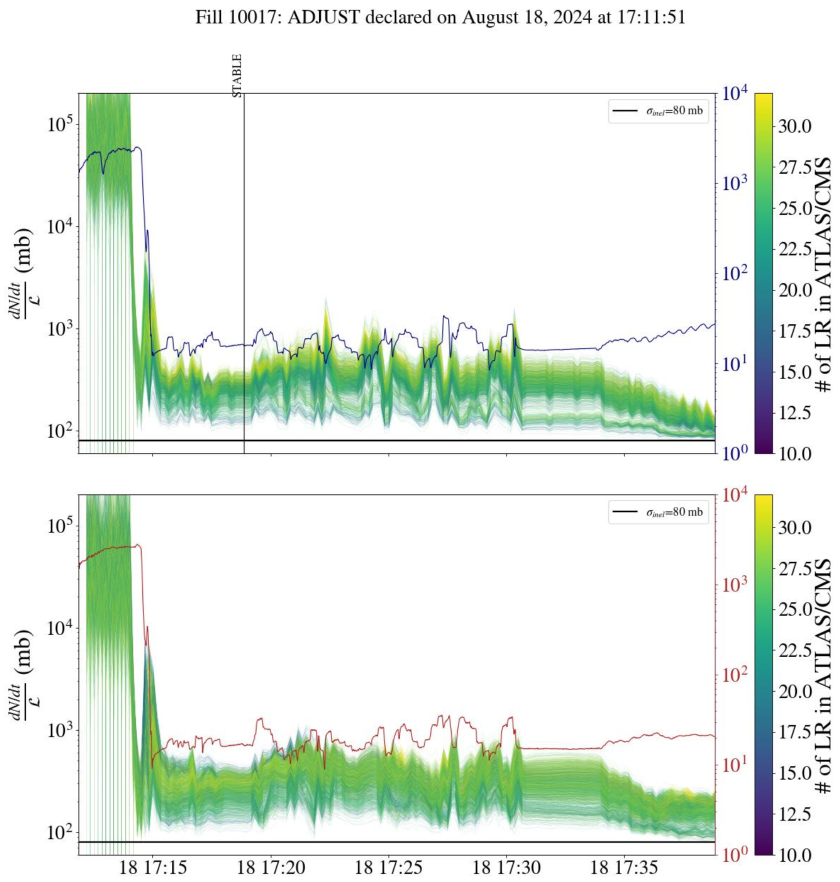
Reduction of losses at the start of collisions with low-tails



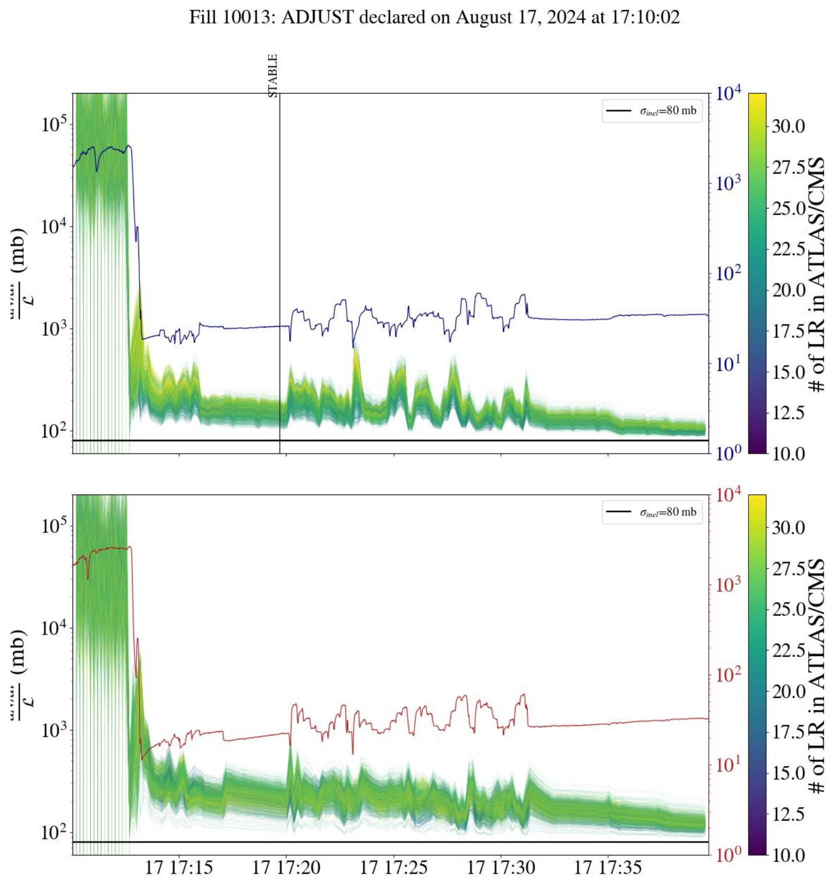
Losses during the collapse of the separation bump & start of collisions

- 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



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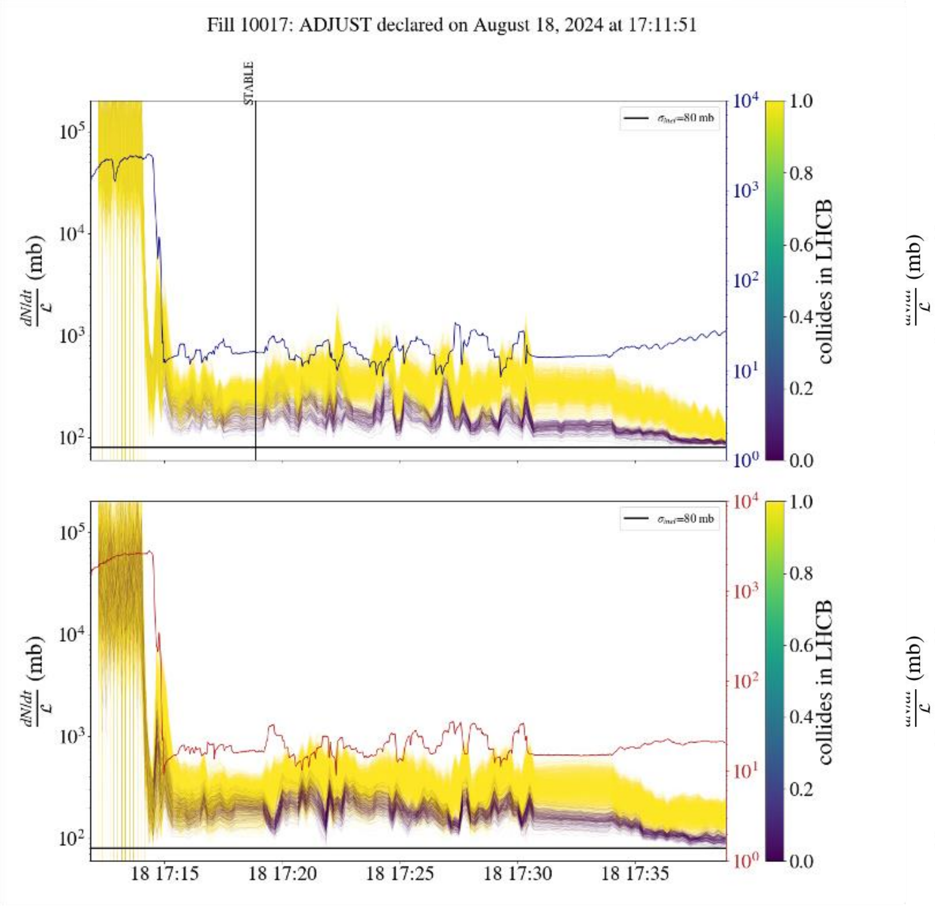
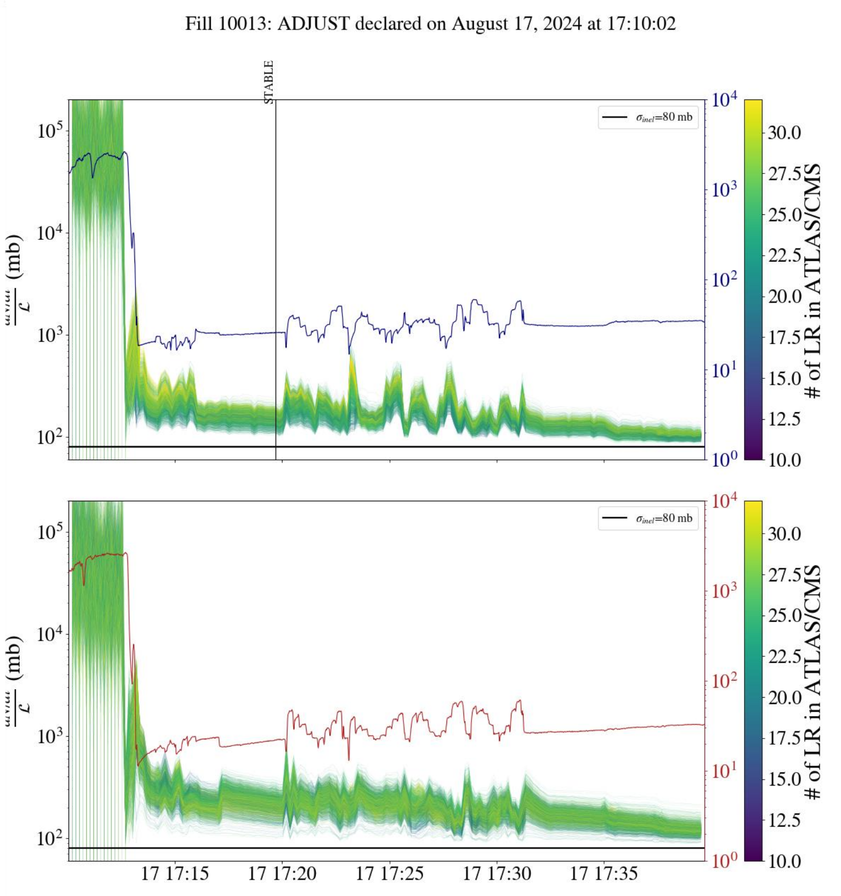
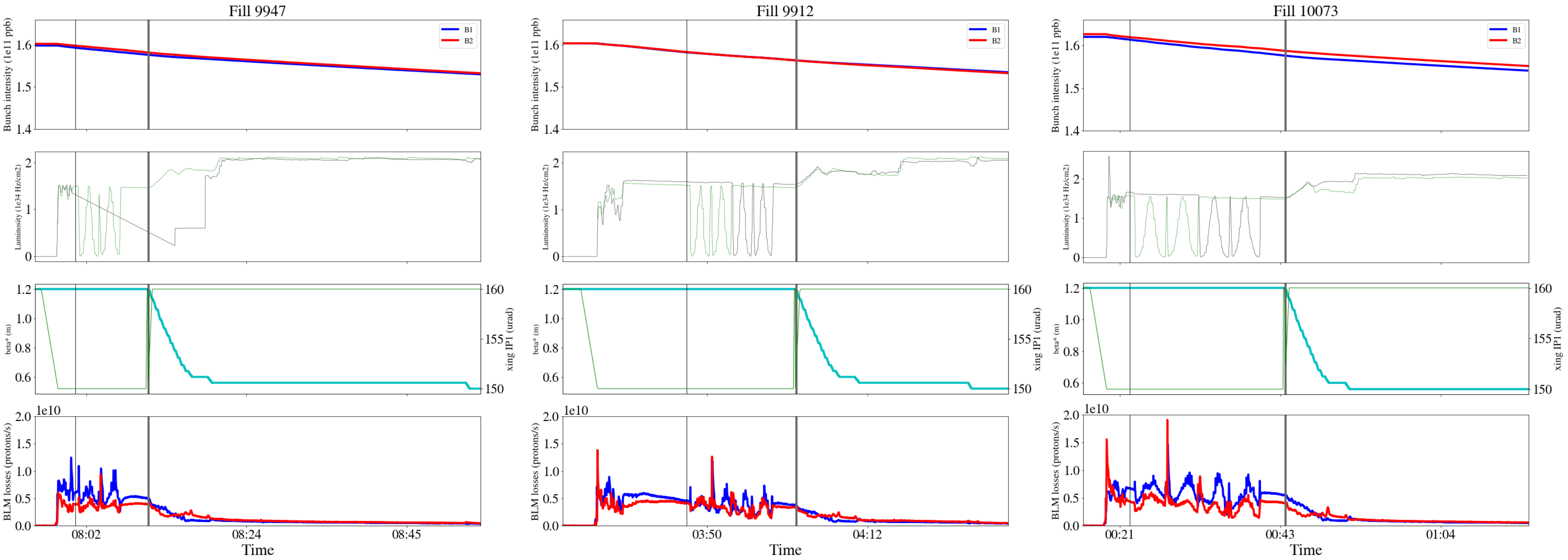


Collisions in IP1/2/5

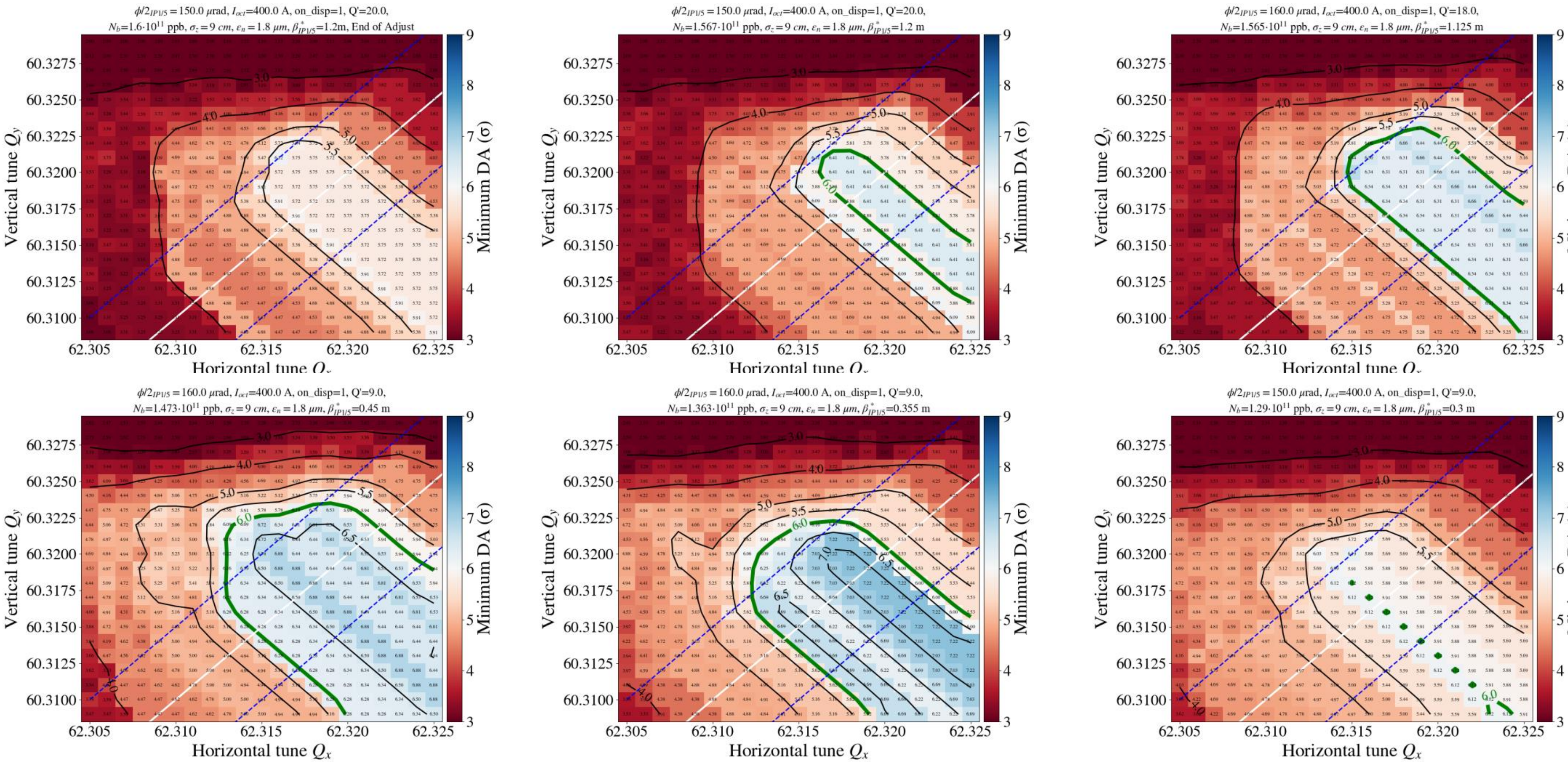


Losses during collisions



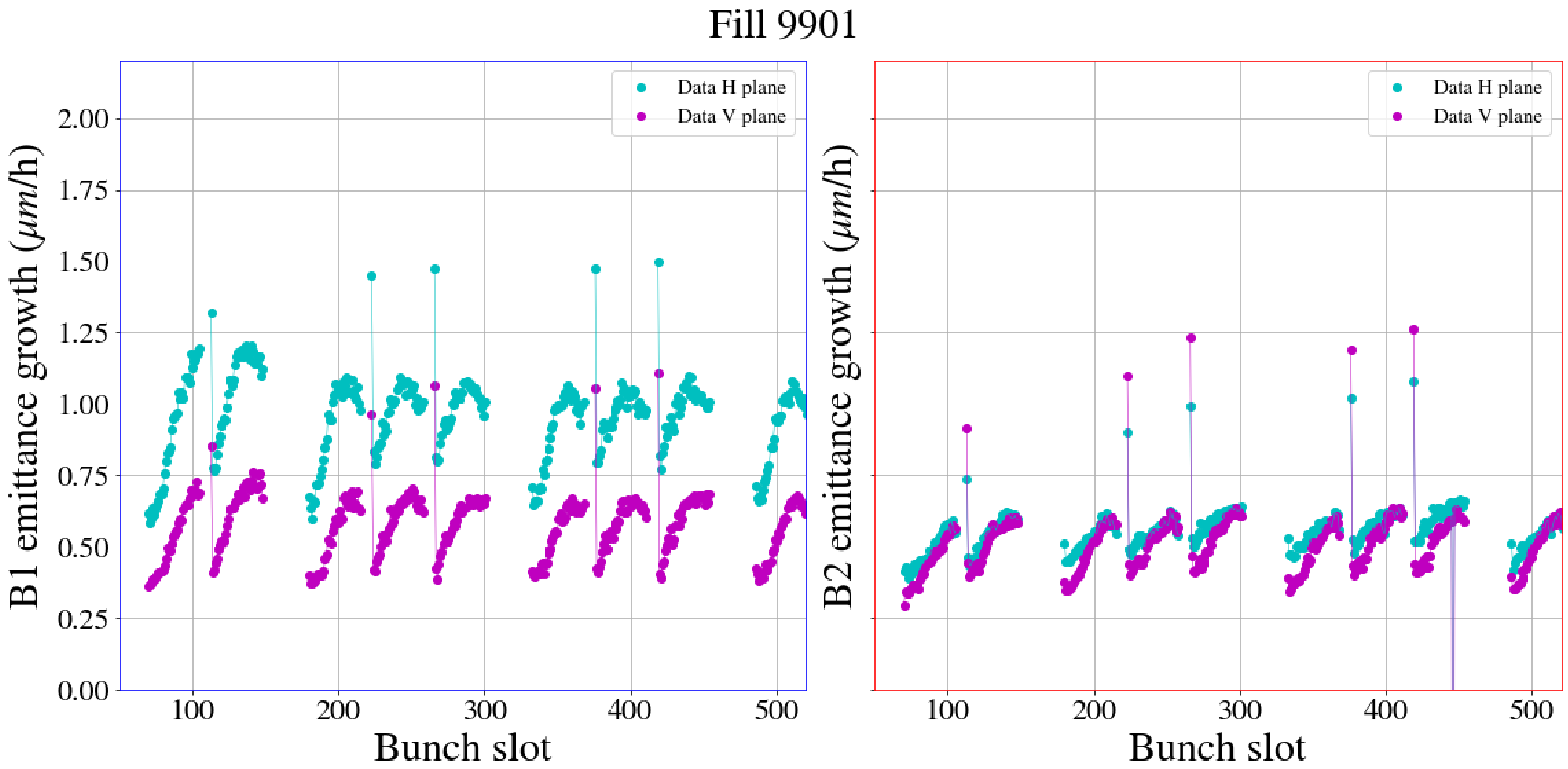
Reduction of losses as soon as leveling starts: pointing to small DA at the start?

DA for LHC Run 3



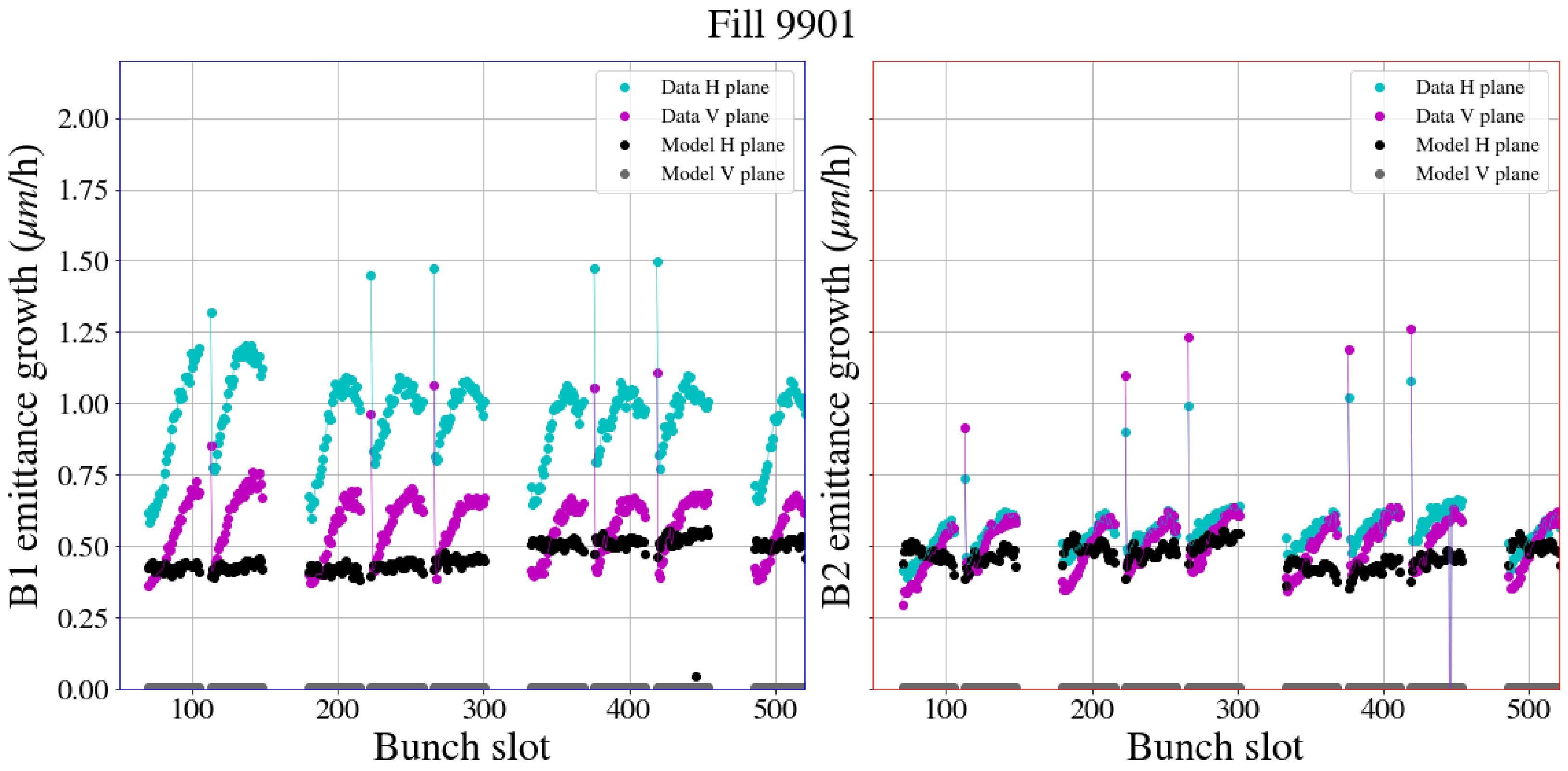
Emittance growth at injection

- **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.

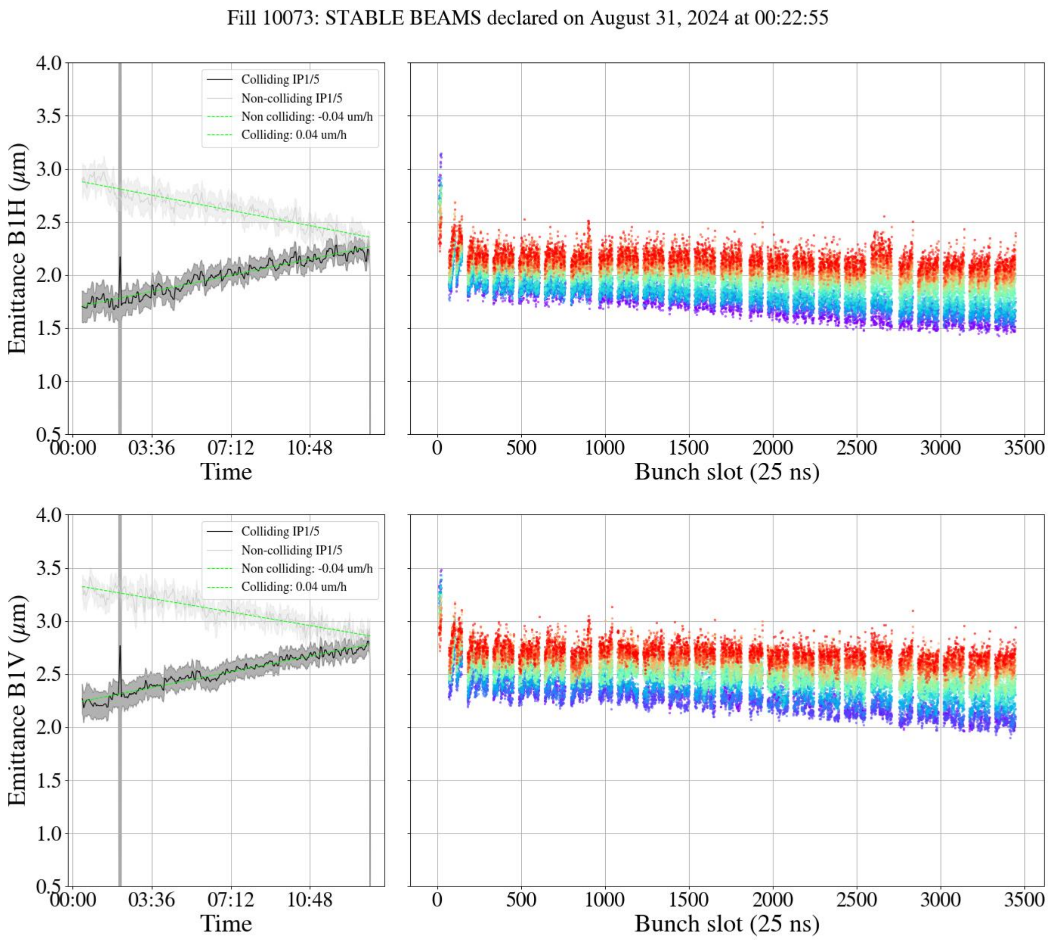


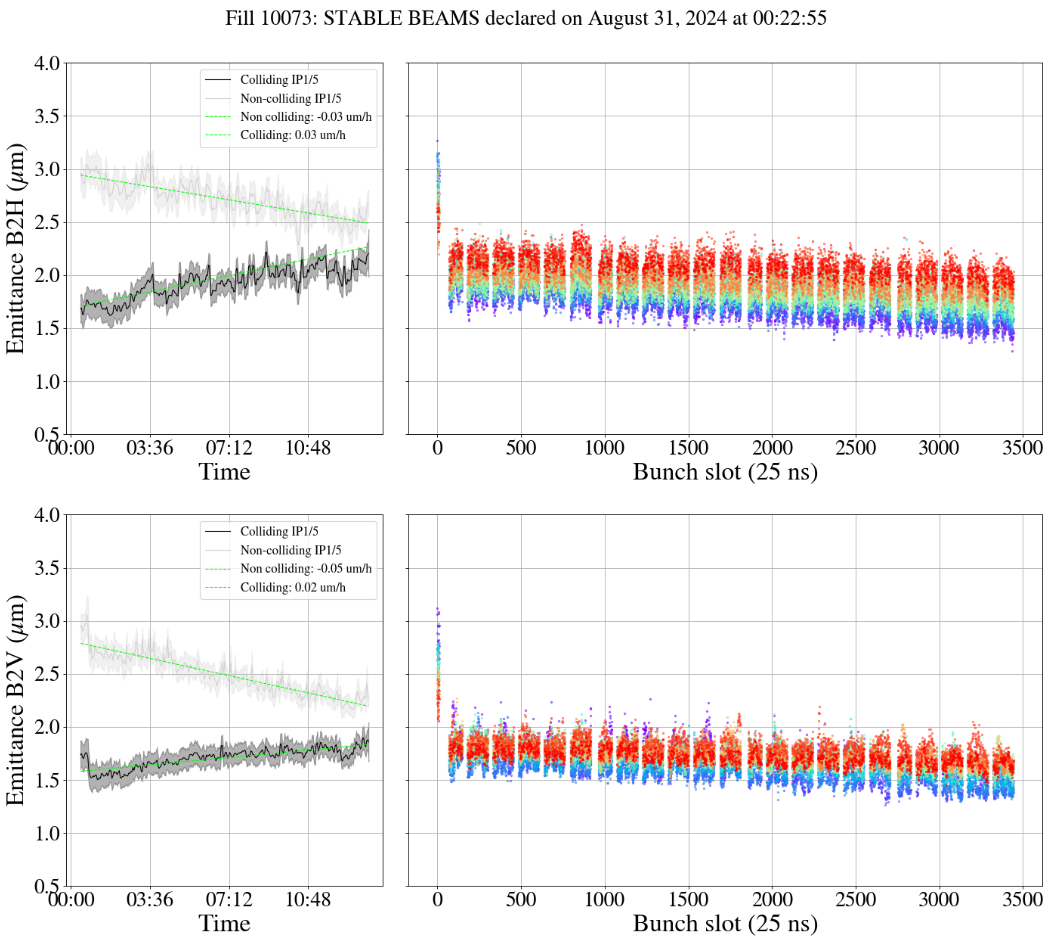
Emittance growth at injection

- **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.



Emittance growth during collisions





LHCb upgrade

Optics scenarios for LHCb

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:
  - Internal crossing angle in the horizontal plane: $\phi/2_{int,\ H}$ = spectrometer polarity x 135 µrad
  - External crossing angle in the vertical plane: $\phi/2_{ext,\ V}$ = 170 µrad

skew net crossing angle $|\phi/2_{net}|$ = 217 µrad and crossing at 51°

→ skew separation needed for luminosity leveling: orthogonal to crossing angle for round optics (51 + 90 = 161°)

- Flat optics can increase leveling time and push integrated luminosity. Issues from operating with flat optics and skew crossing will be discussed in next slides. **Flat optics configuration has not been verified yet with Dynamic Aperture studies.**

Luminosity scenarios for LHCb

Considering the following luminosity scenarios:

I. Low: $\mu_{max} = 28$

II. Medium-A: $\mu_{max} = 34$

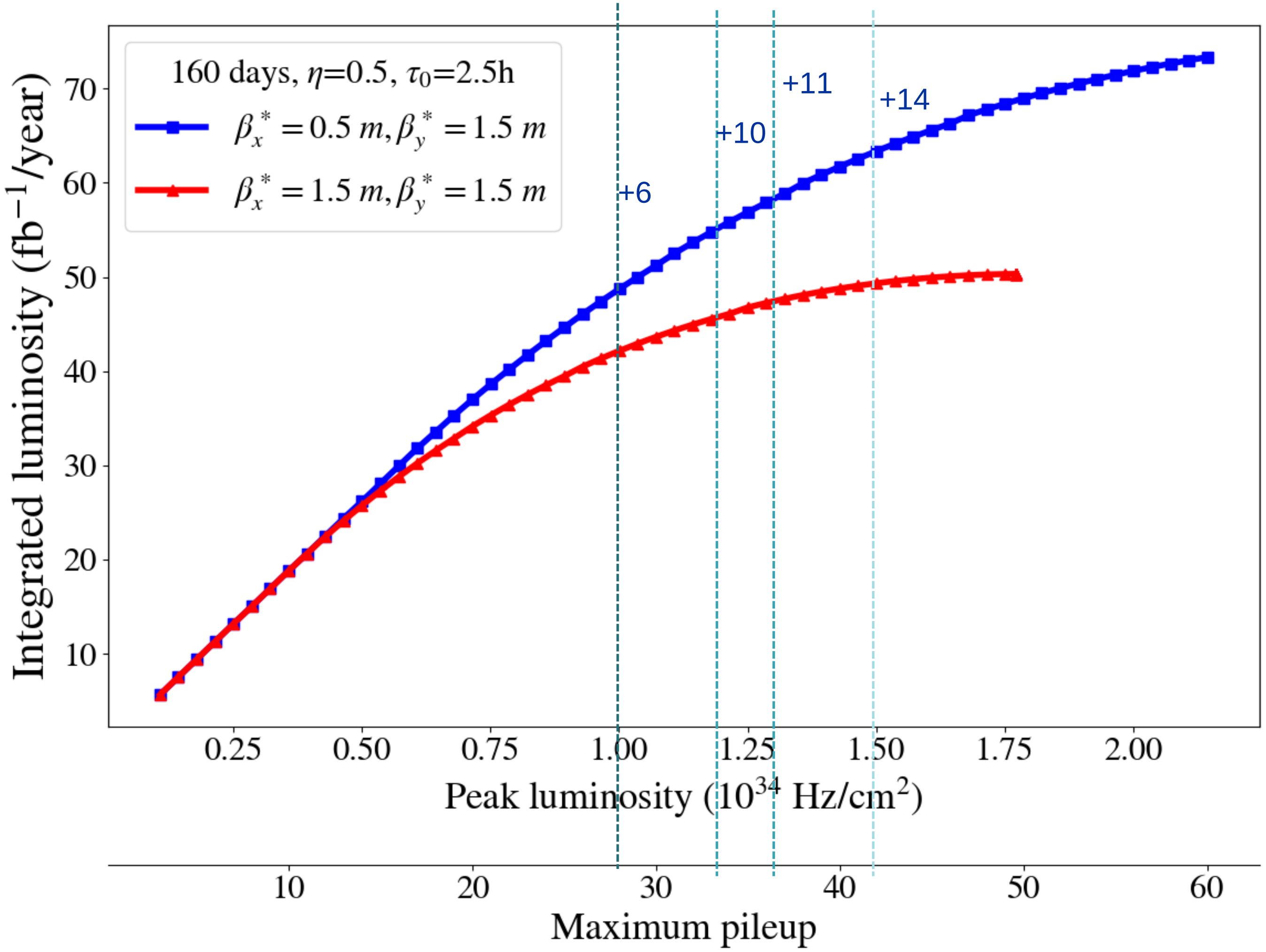
III. Medium-B: $\mu_{max} = 36$

IV. High: $\mu_{max} = 42$

For each scenario we estimate for both round and flat optics:

- Integrated luminosity per year
- Leveling time
- Impact on ATLAS/CMS performance,
- Luminous region & peak pile-up density

Performance projections: Yearly integrated luminosity



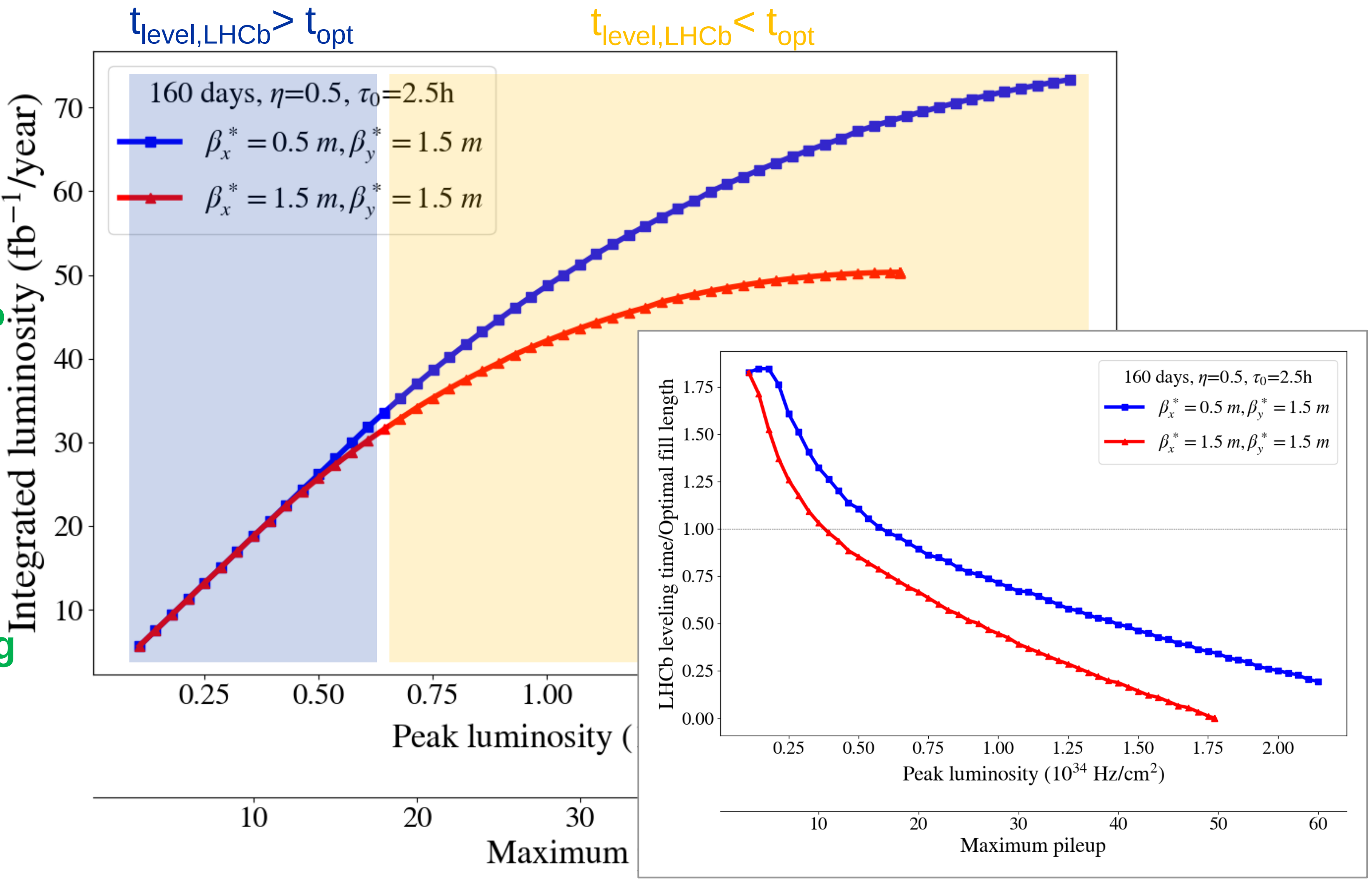
Performance projections: Yearly integrated luminosity

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

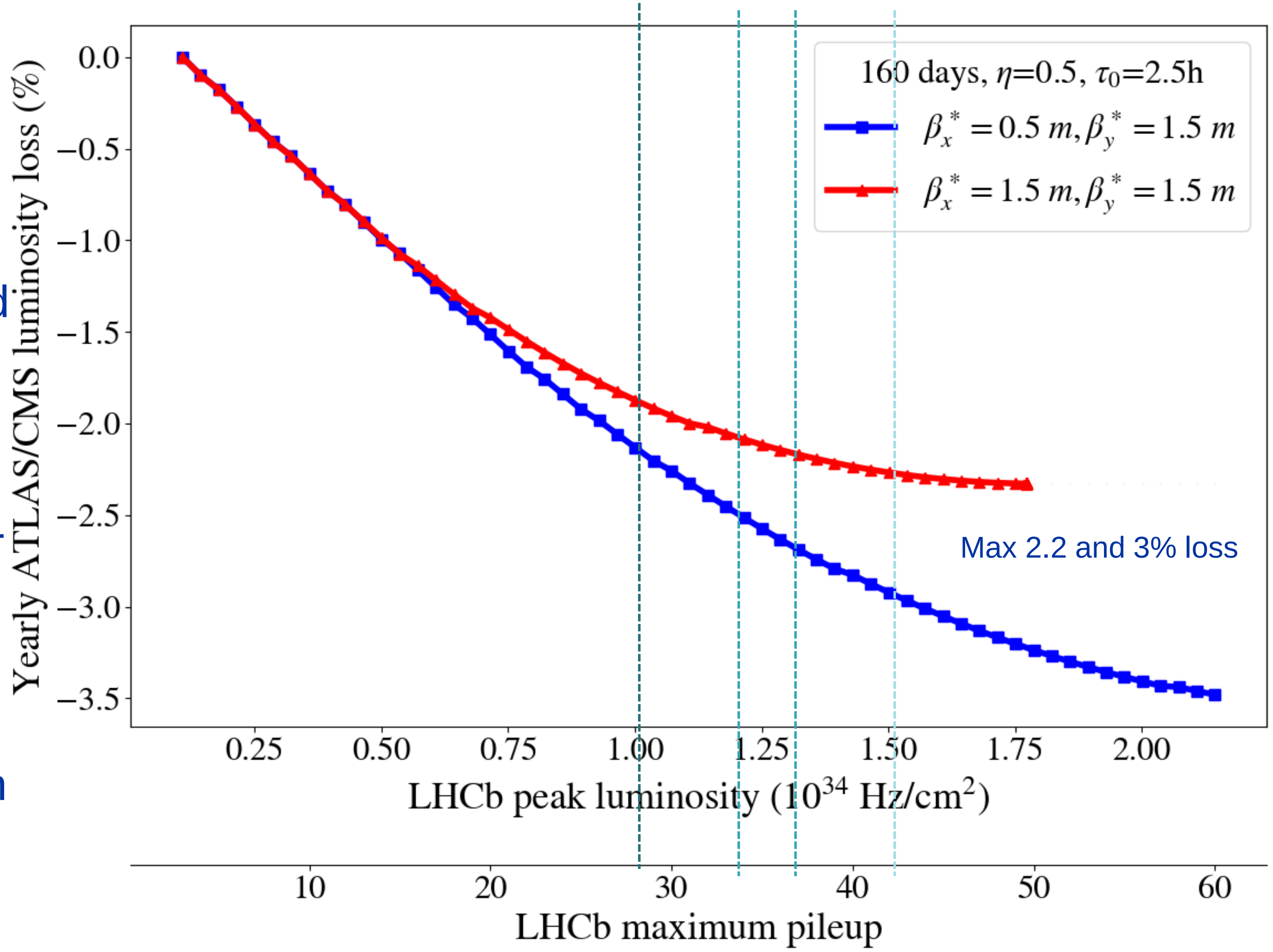


Performance projections: ATLAS/CMS loss of integrated luminosity

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°).

Conclusions for LHCb upgrade

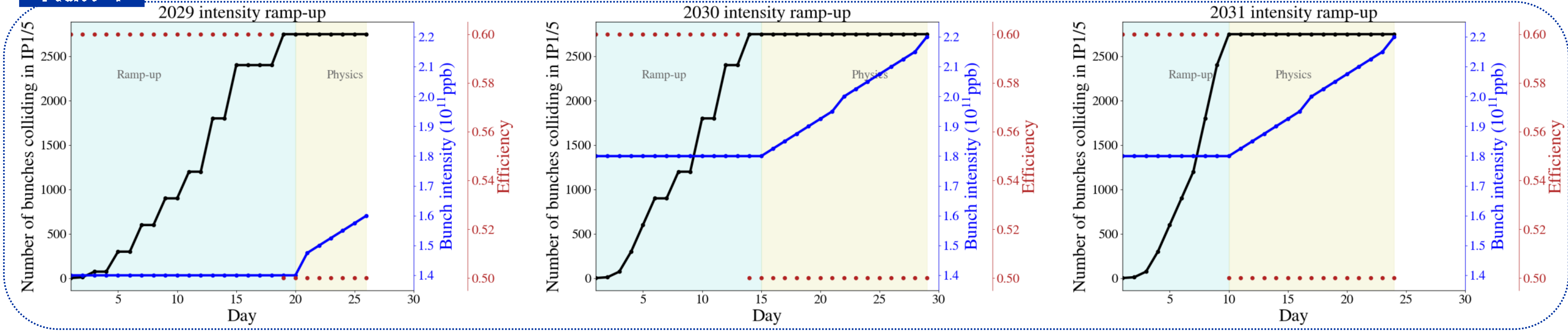
- Higher yearly integrated luminosity with flat optics:
  - **From +7 fb^{-1} or +13% (low scenario) to +14 fb^{-1} or +22% (high scenario) gain compared to round optics**
- Leveling time increase:
  - **~+2 hours of leveling time and higher ratio of leveling time to optimal fill length**
- Maximum loss 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°).

Backup slides

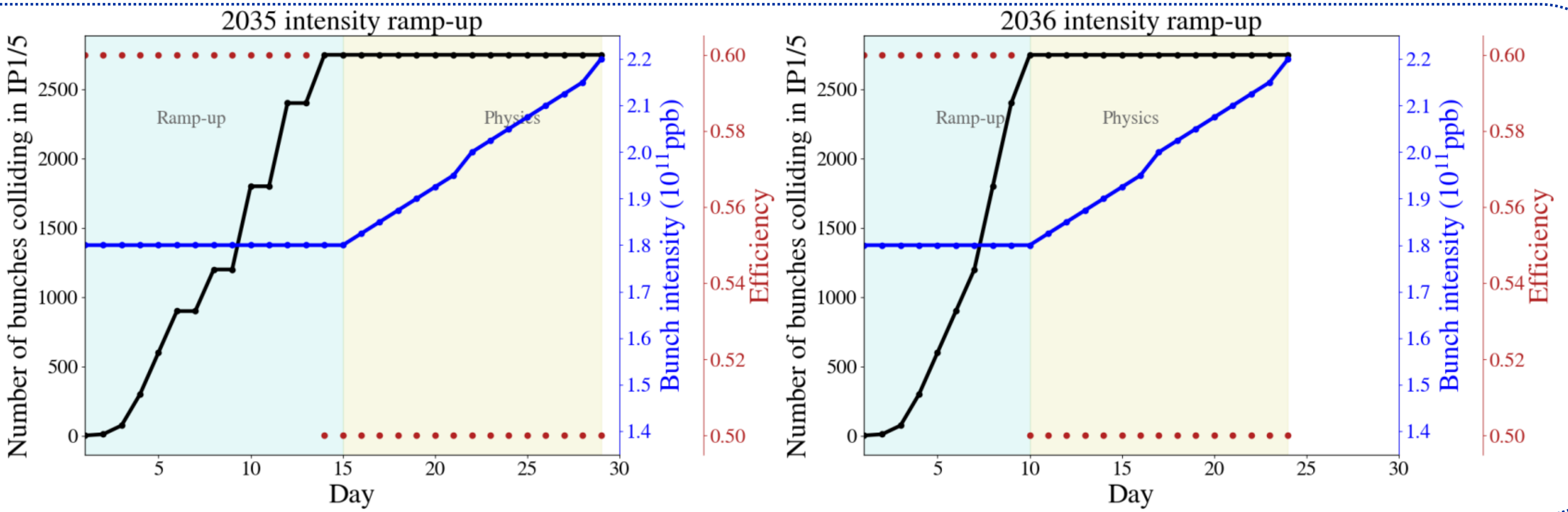
Intensity ramp up

Based on Riccardo’s Chamonix 2024 talk

Run 4



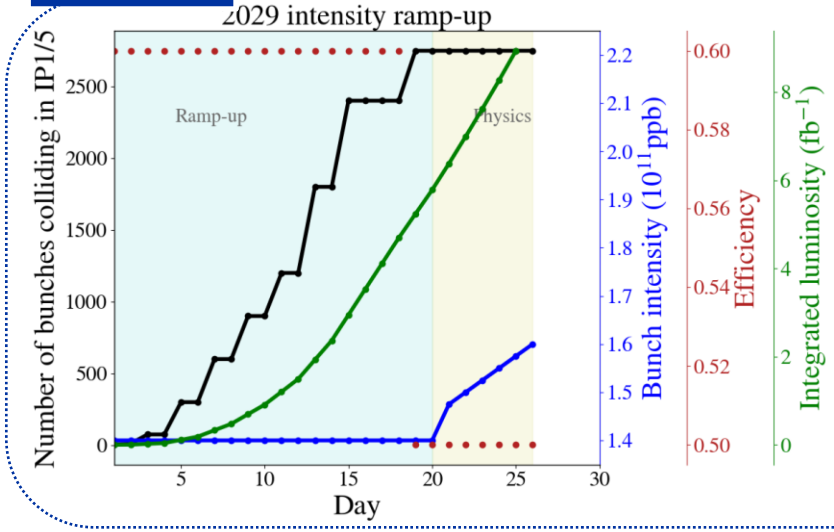
Run 5

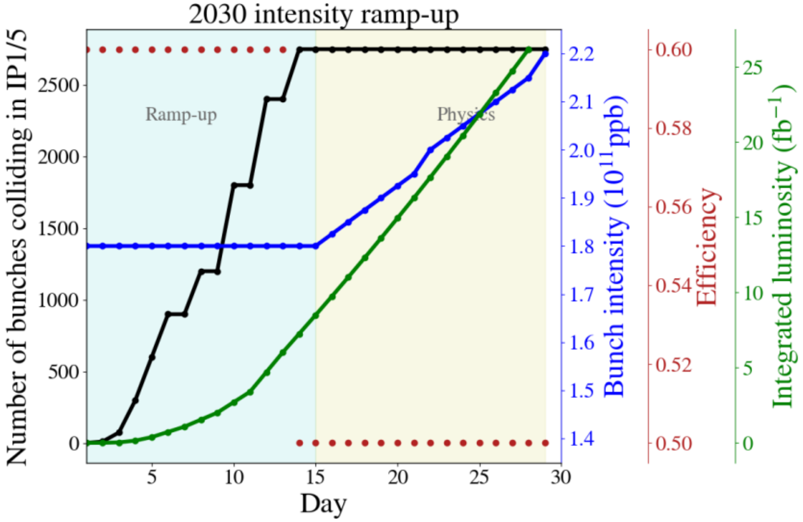


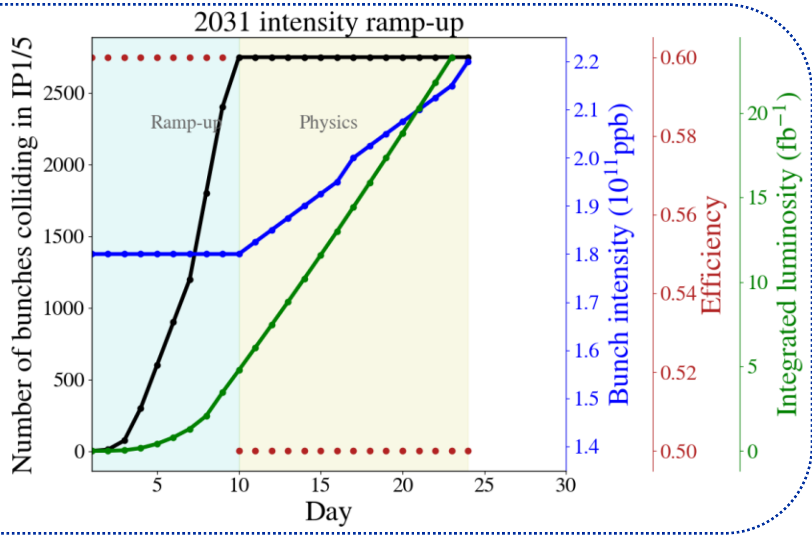
Intensity ramp up

Based on Riccardo’s Chamonix 2024 talk

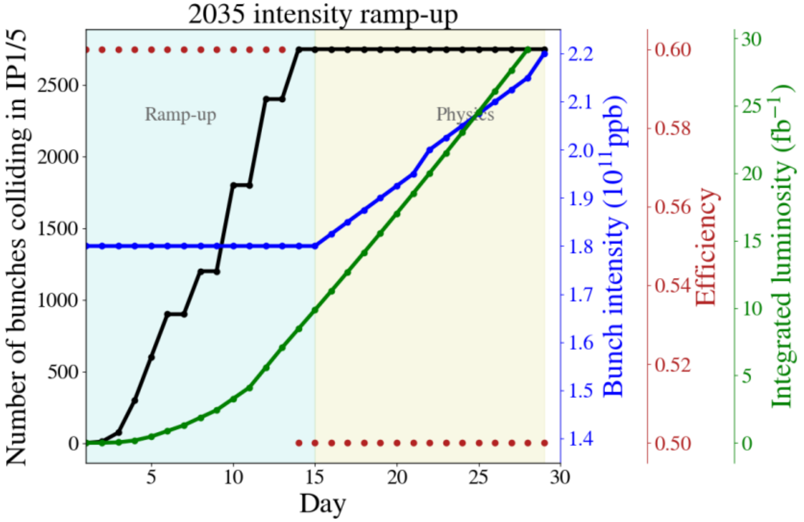
Run 4

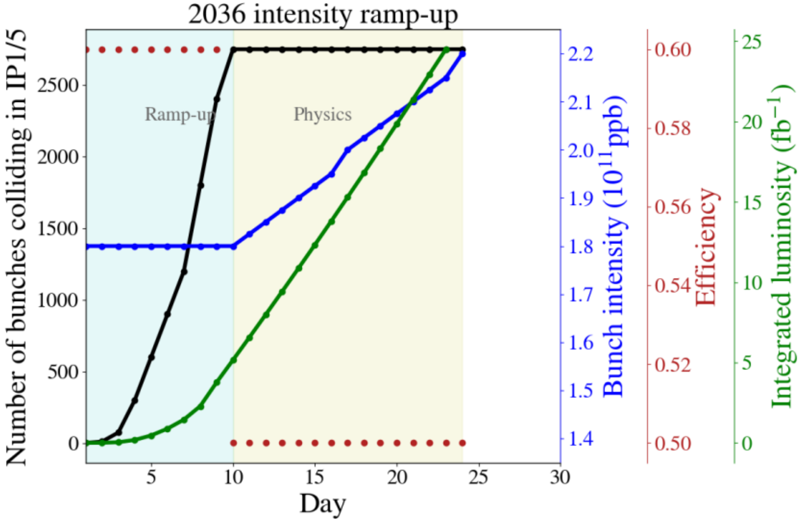






Run 5





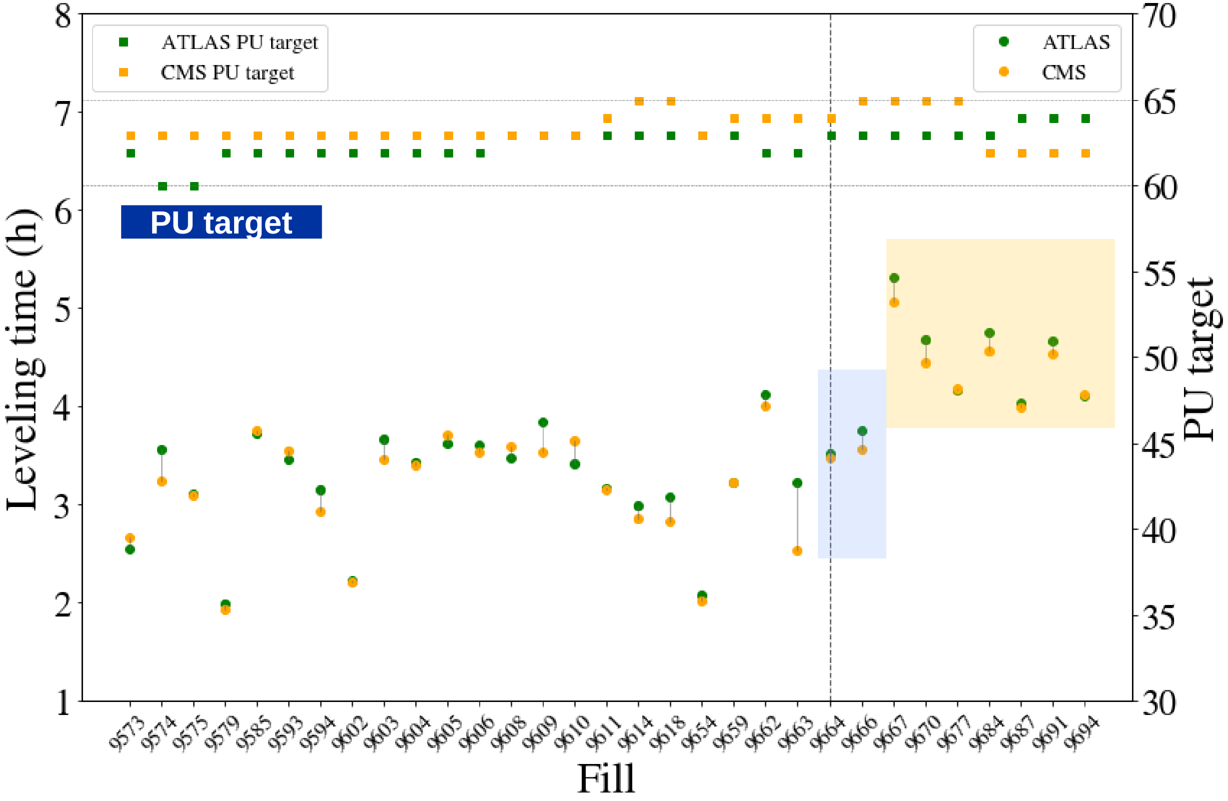
BCMS performance in 2024

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

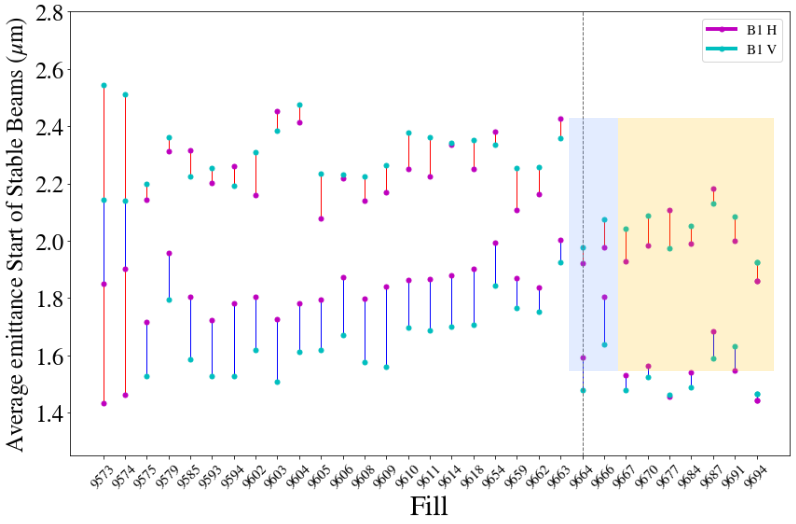
Bunch intensity (1e11 ppb)	B1 INJPHYS	B2 INJPHYS	B1 STABLE	B2 STABLE
Fills 9573-9663	1.59	1.59	1.56	1.55
Fills 9664-9694	1.62	1.62	1.59	1.57
%	+1.89	+1.89	+1.92	+1.29

BCMS performance in 2024: Leveling time

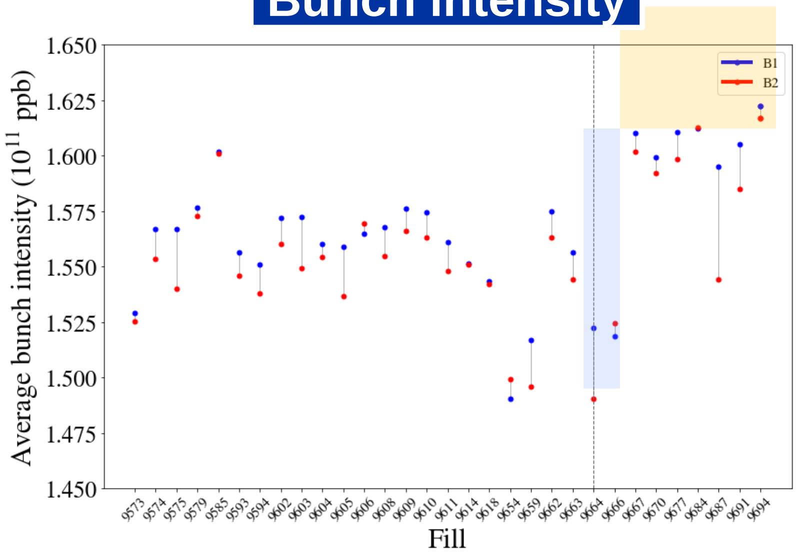
Leveling time



Emittance



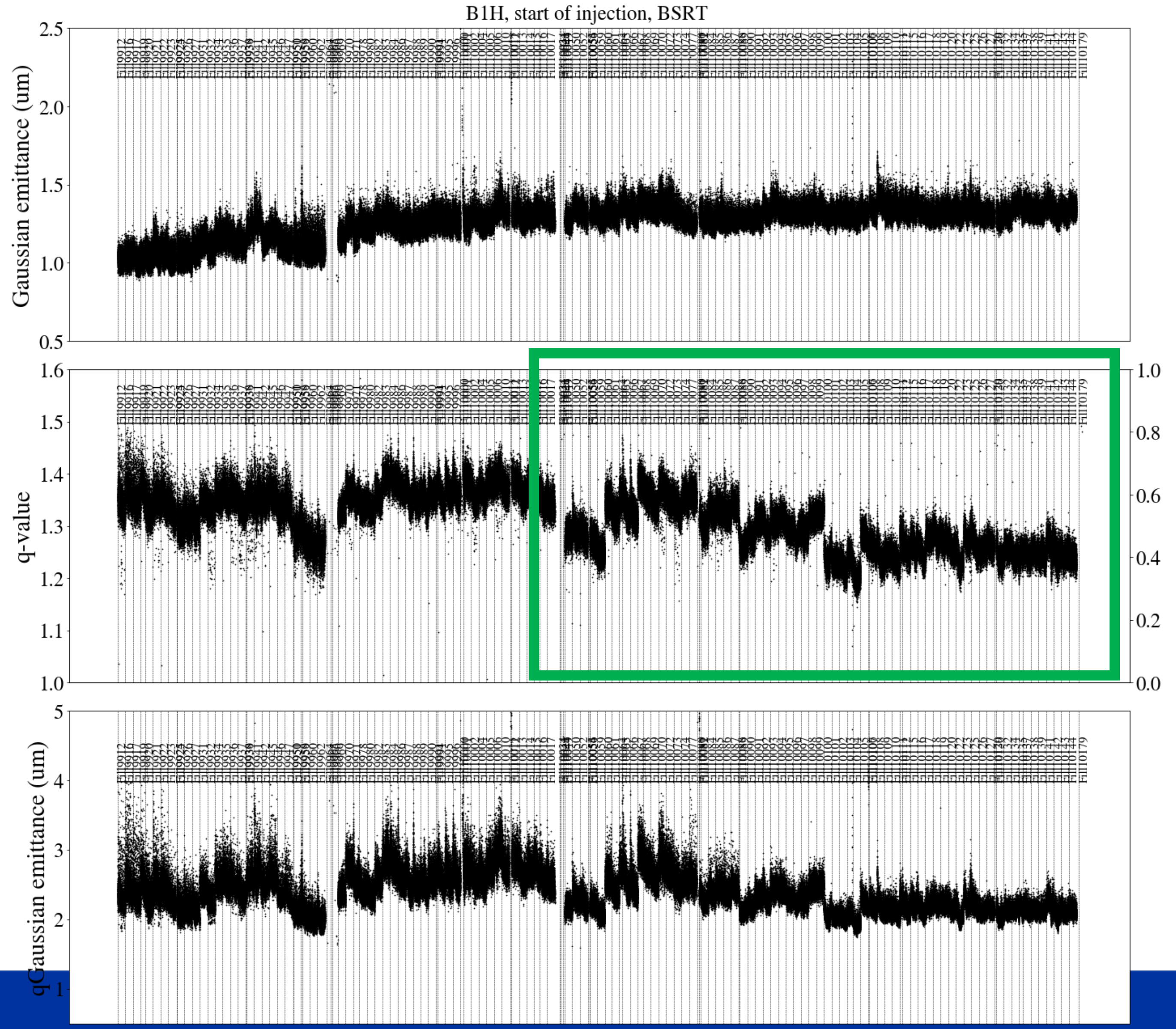
Bunch intensity



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

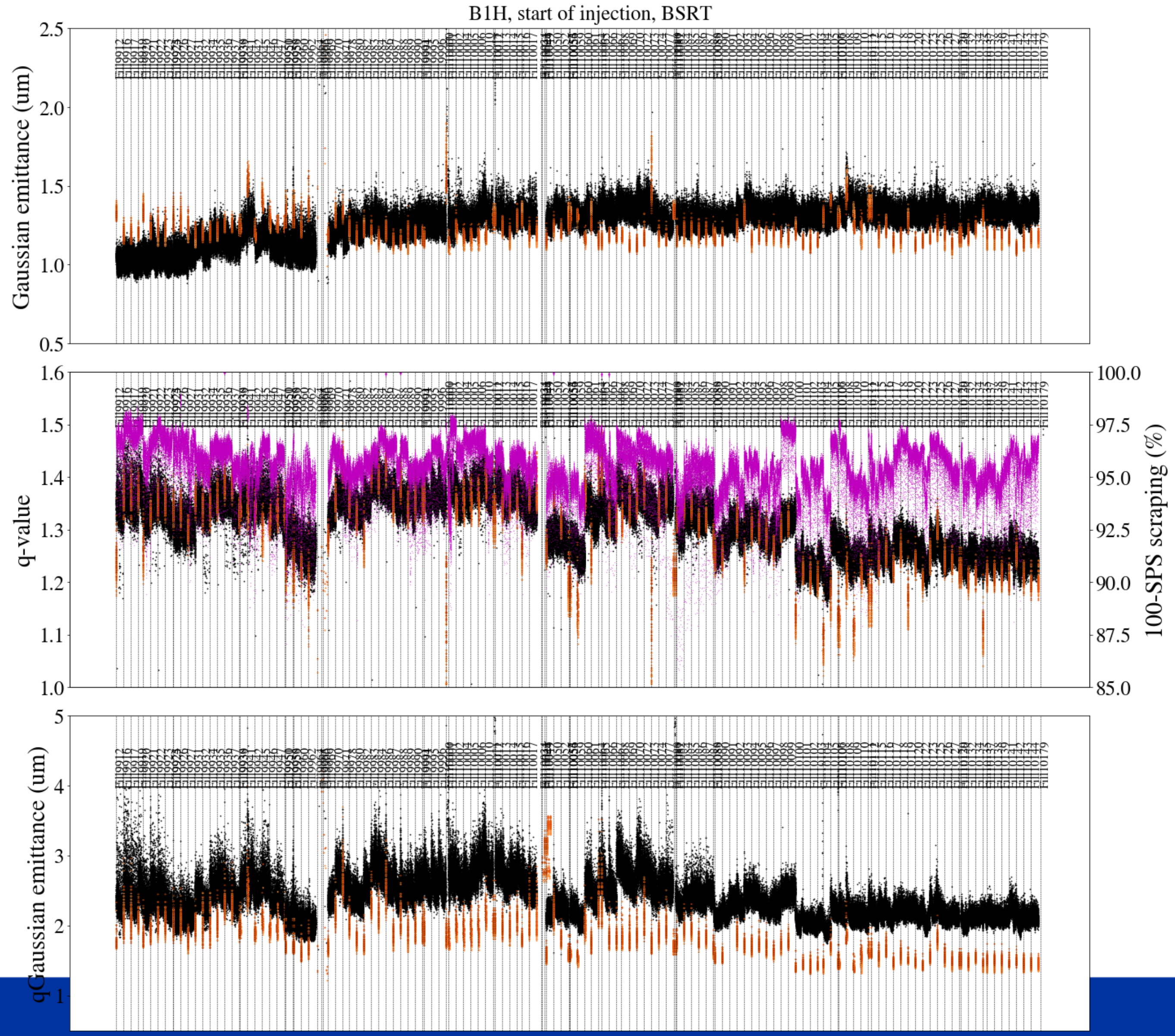
Transverse bunch profiles at injection

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



Transverse bunch profiles at injection

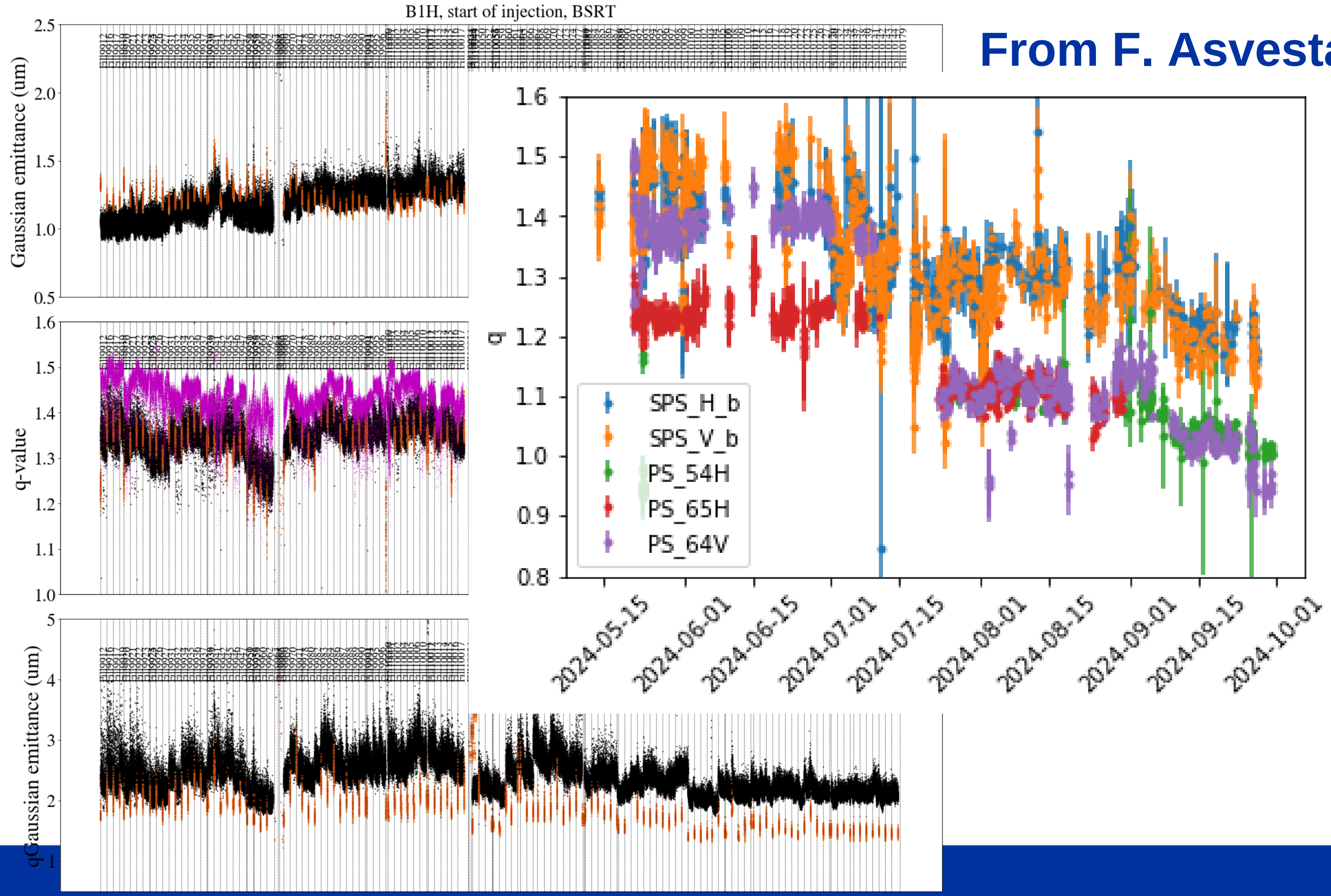
- **Clear tail reduction** when injected in the LHC in the last fills.
- **SPS scraping did not change**, usual fill-to-fill variation. However, with the same SPS scraping, q injected in the LHC is lower.



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

Transverse bunch profiles at injection

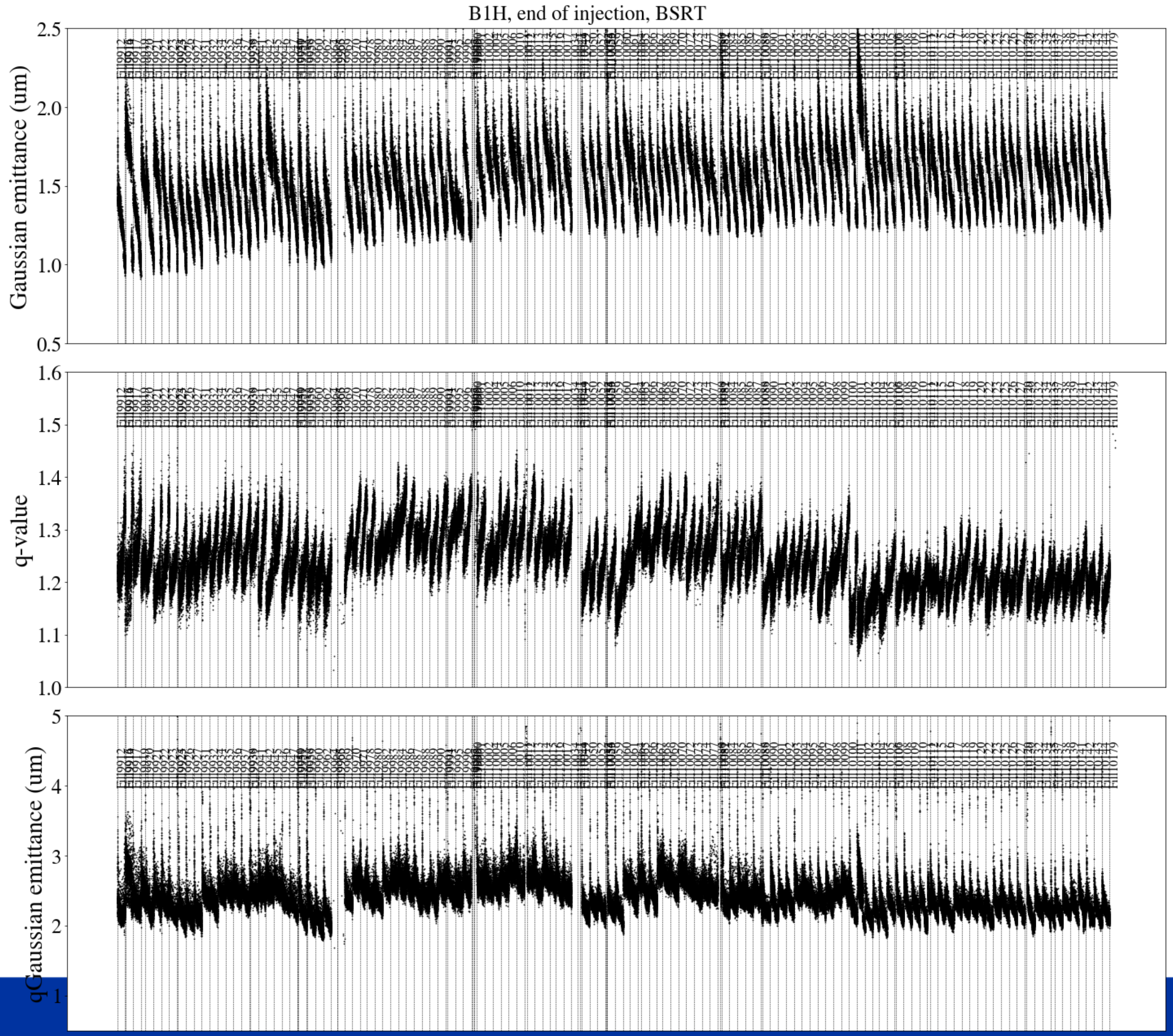
- **Clear tail reduction** when injected in the LHC in the last fills.
- **SPS scraping did not change**, usual fill-to-fill variation. However, with the same SPS scraping, q injected in the LHC is lower.
- **Tail step also observed in injectors**, no impact on emittance. Source of improvement still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



From F. Asvesta

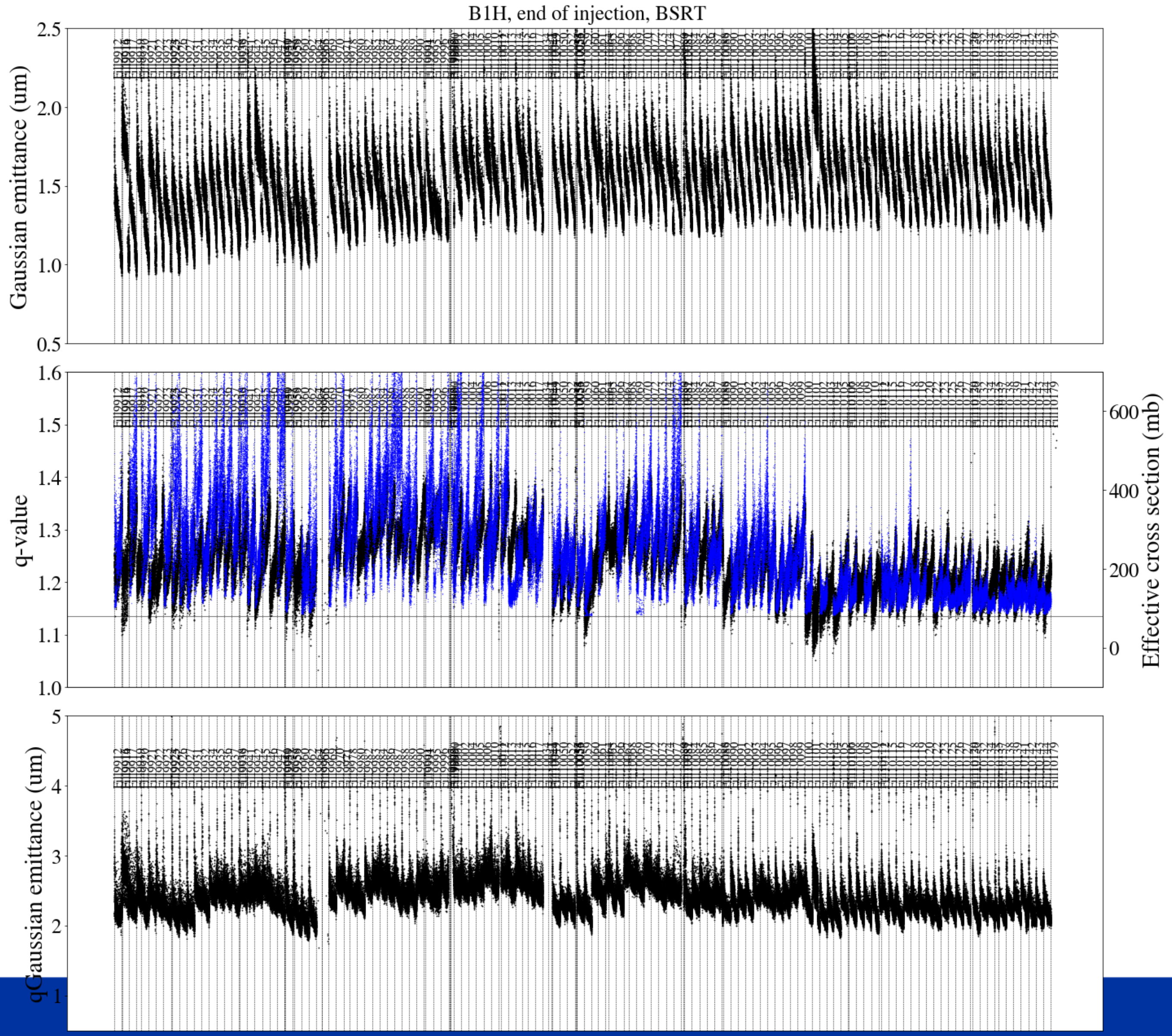
Transverse bunch profiles at end of injection

- **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.**
- Can also explain discrepancy between B1 and B2 observed in some fills: B1H has systematically larger tails already at LHC injection due to mismatch between SPS and LHC. MD showed that this can be partially mitigated with optimized transfer function in transfer line from ABT.



Transverse bunch profiles at injection

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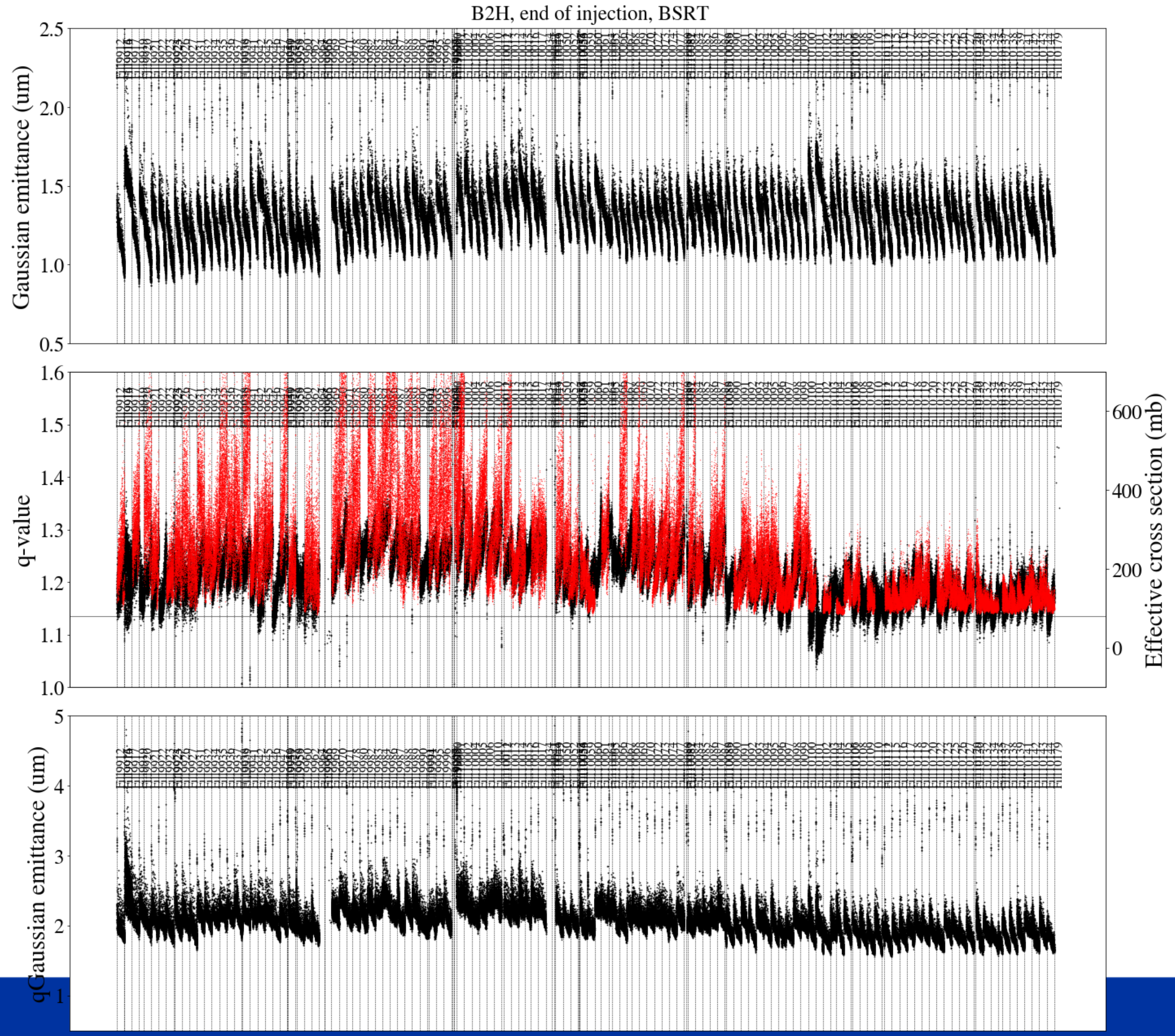
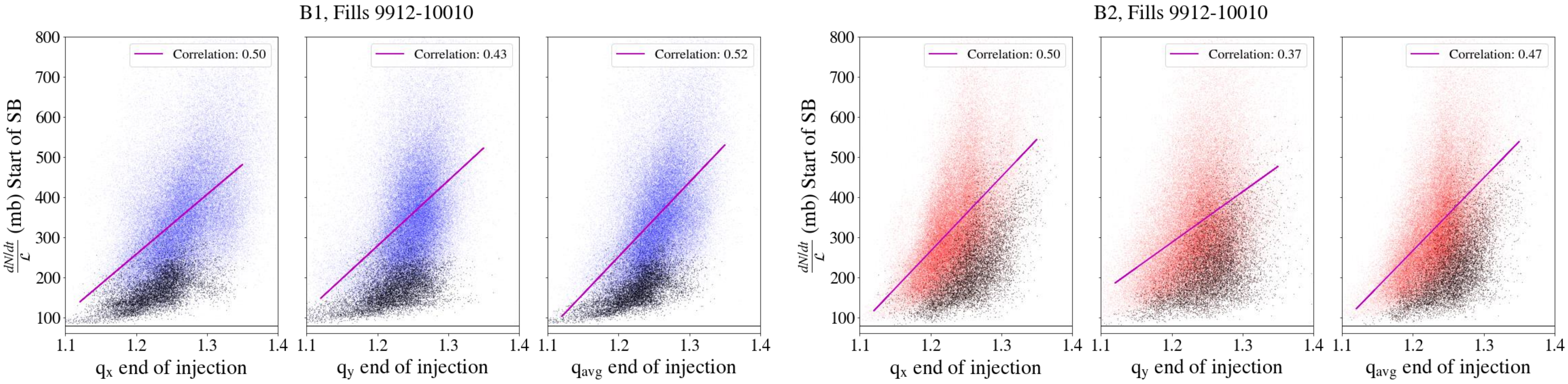


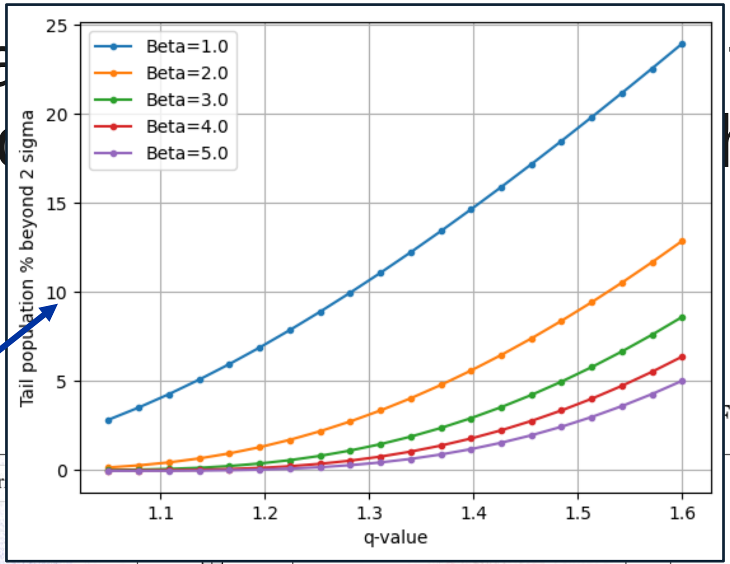
Losses at the start of collisions

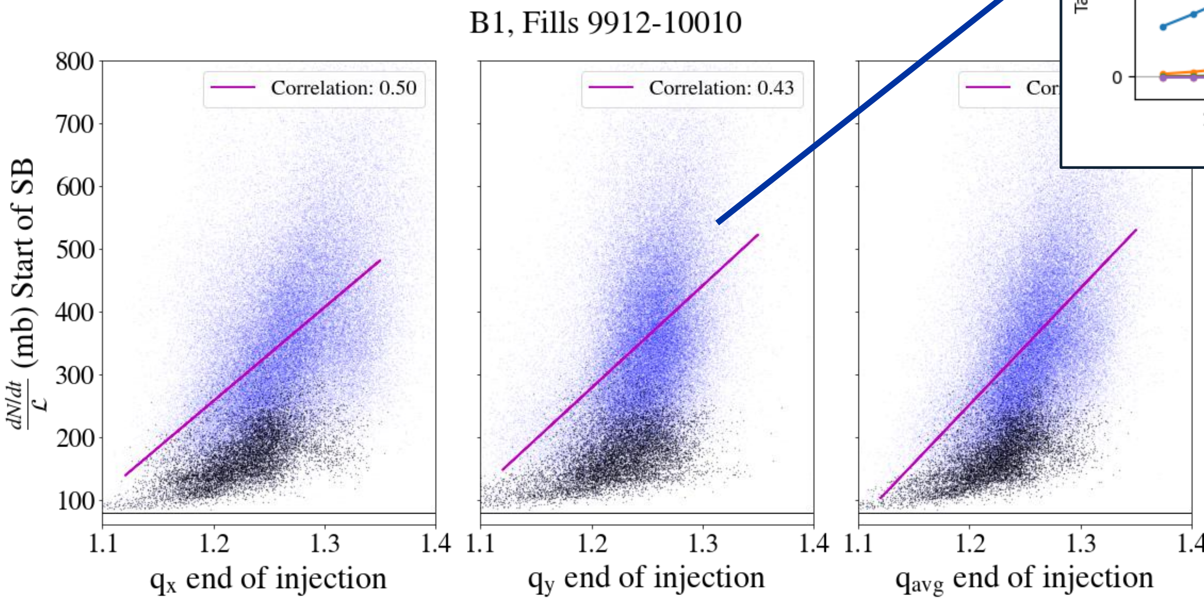
- Correlation of losses at the start of Stable Beams with the q-value measured at the end of injection: Larger tails → Higher losses

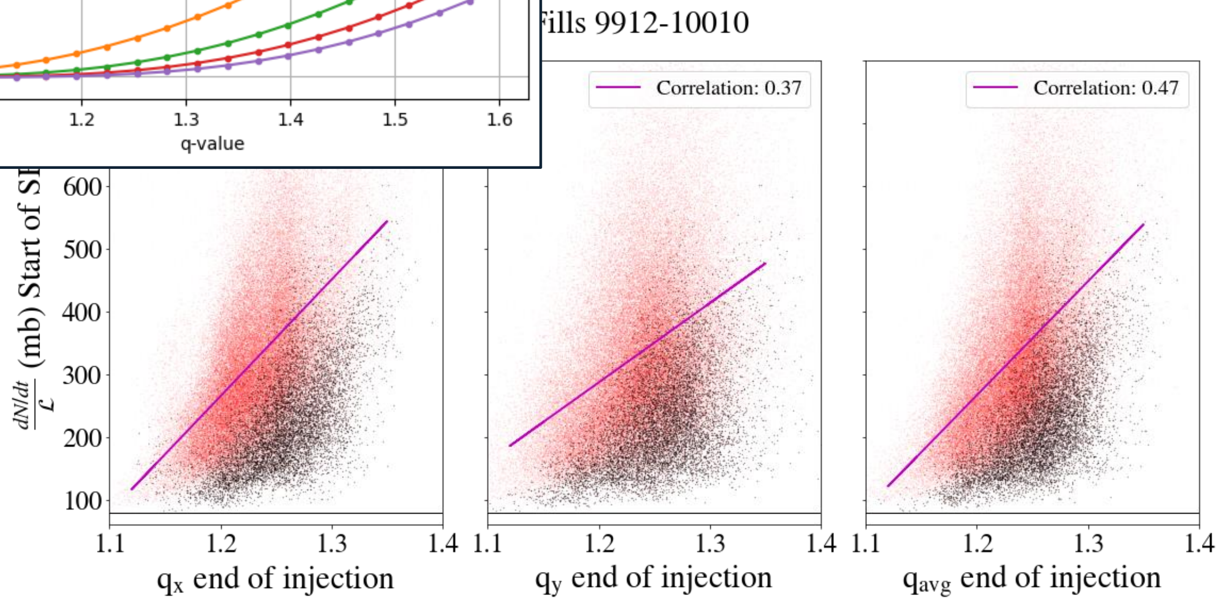


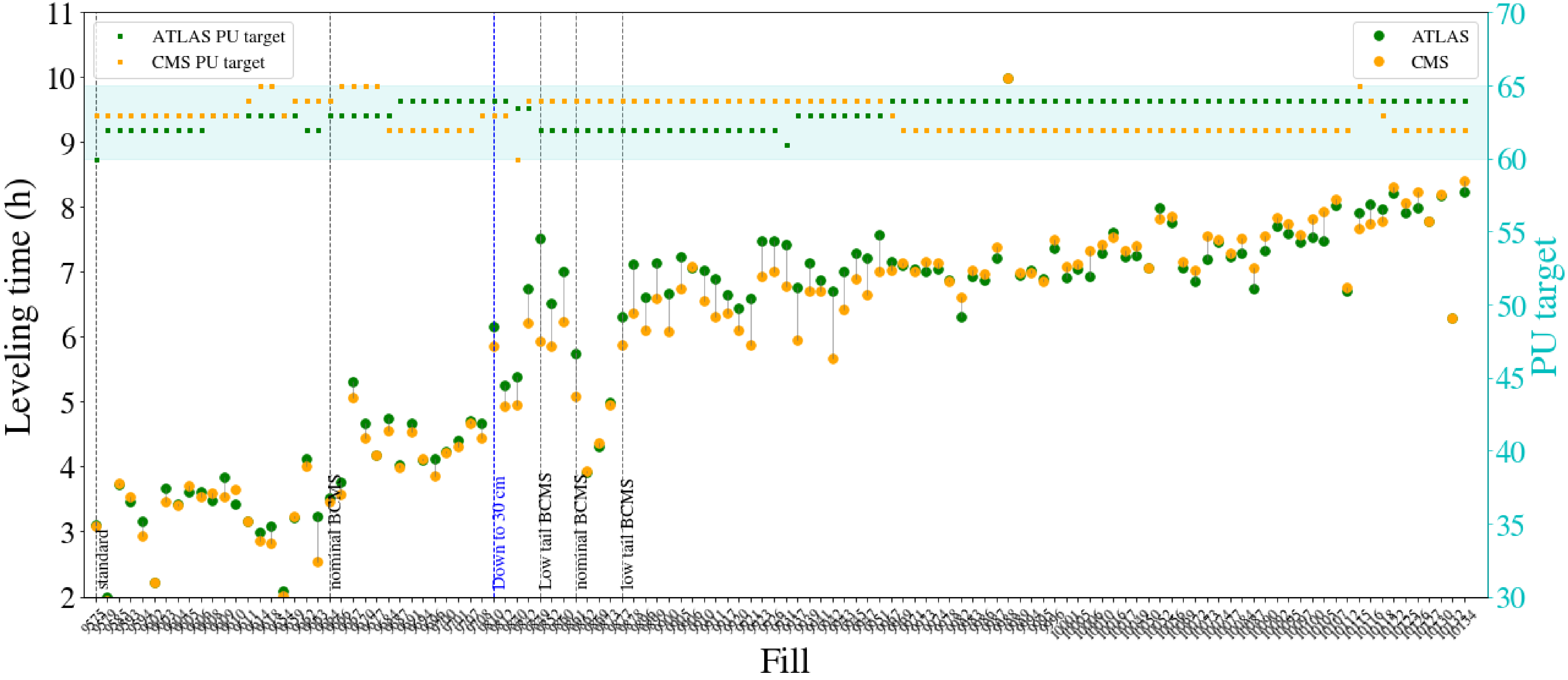
Losses at the start of collisions

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

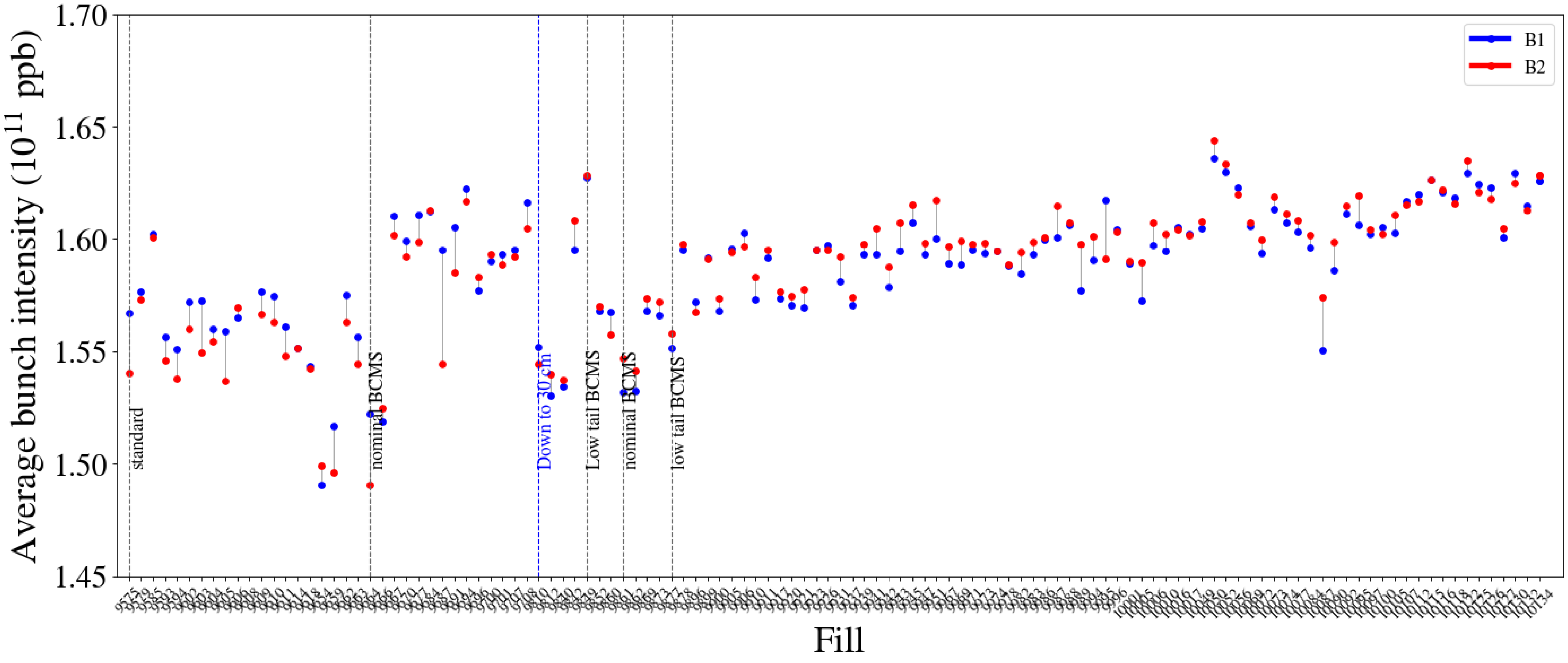


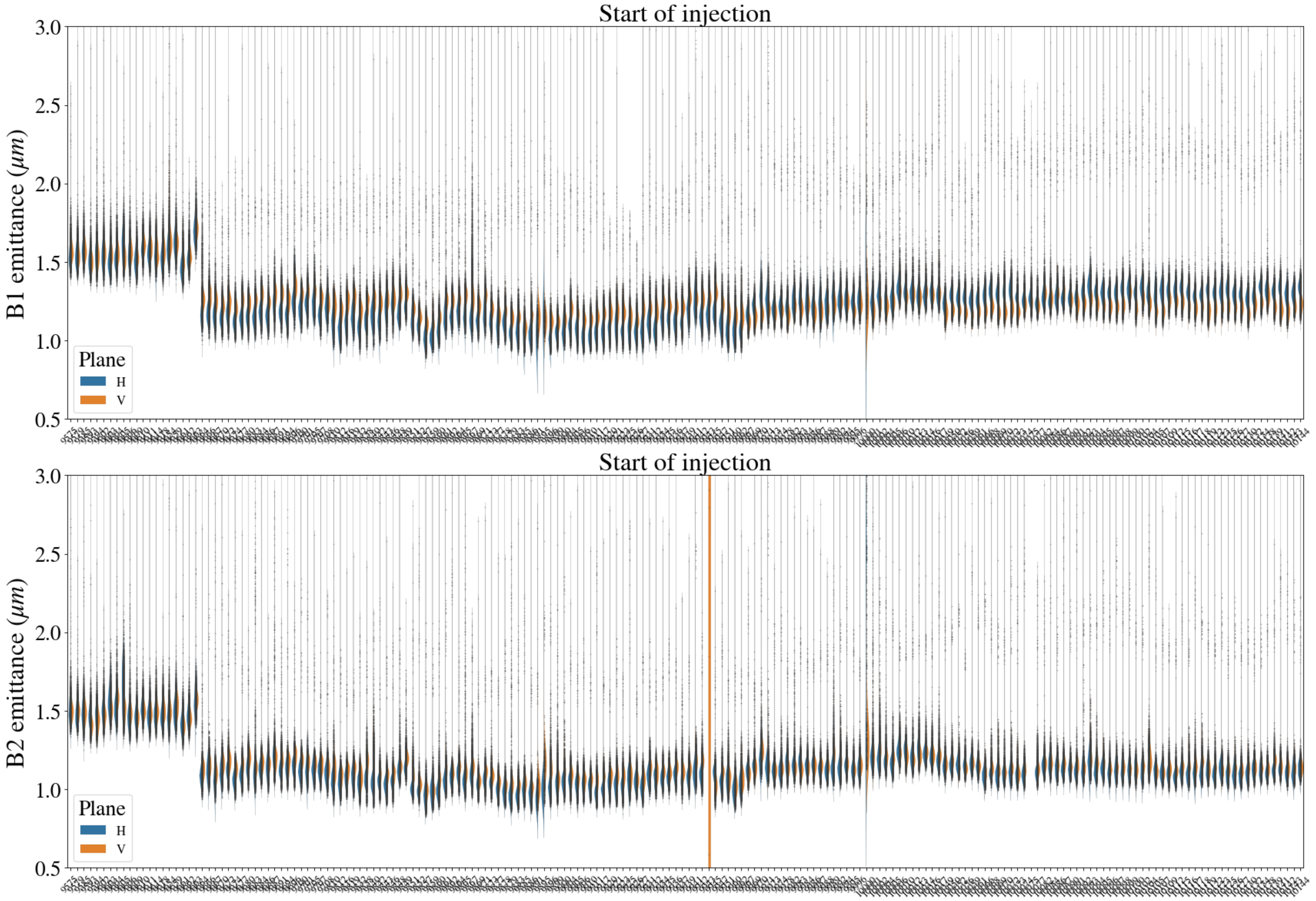


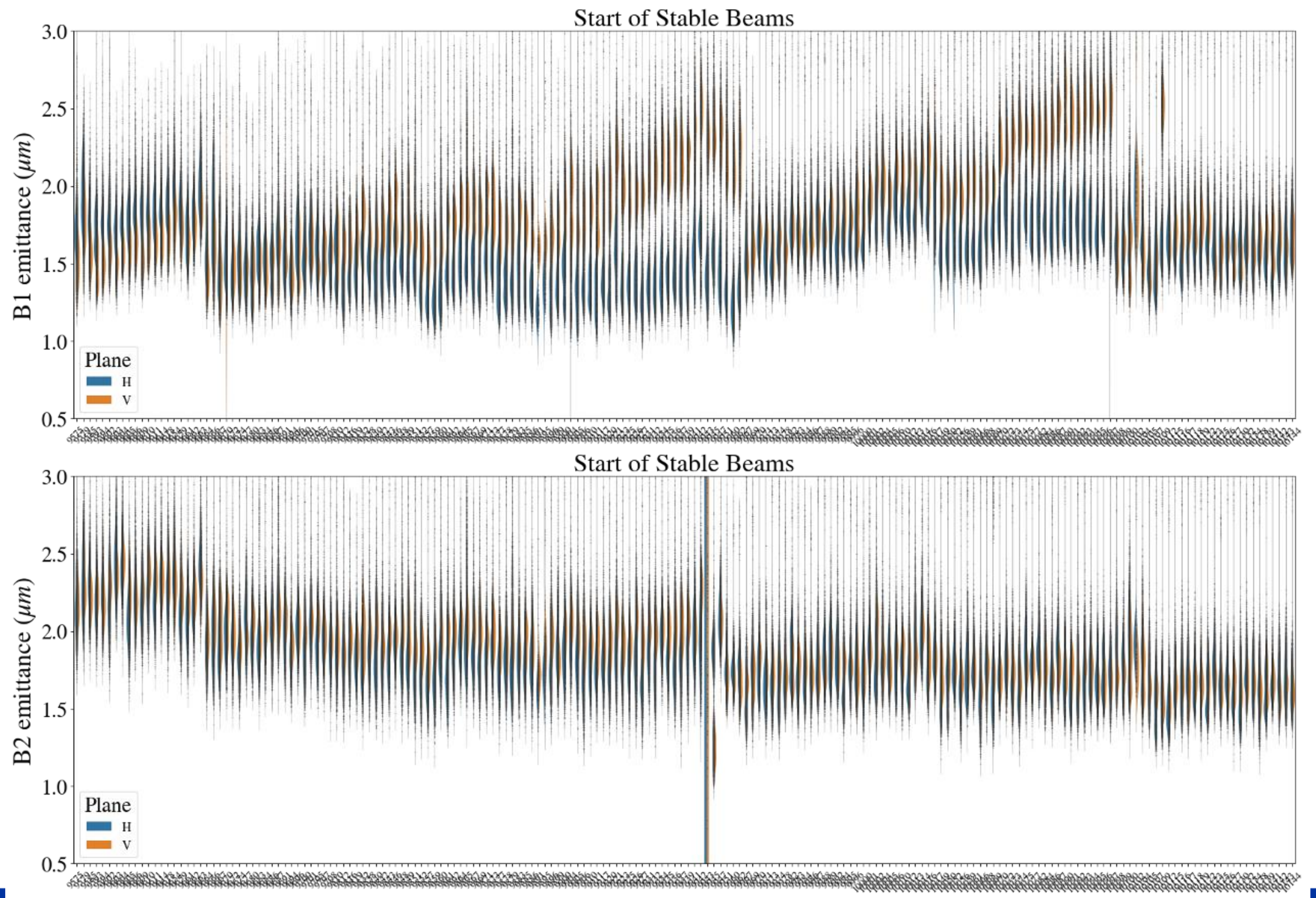




ATLAS PU target
CMS PU target
ATLAS
CMS
Leveling time (h)
PU target
Fill
standard
nominal BCMS
Down to 30 cm
Low tail BCMS
nominal BCMS
low tail BCMS


Average bunch intensity (10^{11} ppb)
1.70
1.65
1.60
1.55
1.50
1.45
Fill
B1
B2
standard
nominal BCMS
Down to 30 cm
Low tail BCMS
nominal BCMS
low tail BCMS


Start of injection
B1 emittance (μm)
3.0
2.5
2.0
1.5
1.0
0.5
Plane
H
V
Start of injection
B2 emittance (μm)
3.0
2.5
2.0
1.5
1.0
0.5
Plane
H
V


Start of Stable Beams
B1 emittance (μm)
3.0
2.5
2.0
1.5
1.0
0.5
Plane
H
V
Start of Stable Beams
B2 emittance (μm)
3.0
2.5
2.0
1.5
1.0
0.5
Plane
H
V

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/cm²) [3]
4	2029	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→ 15	20 → 15	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

”Round Run4 20 cm”→ “Round Run4 15cm”

Yearly & total integrated luminosity

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

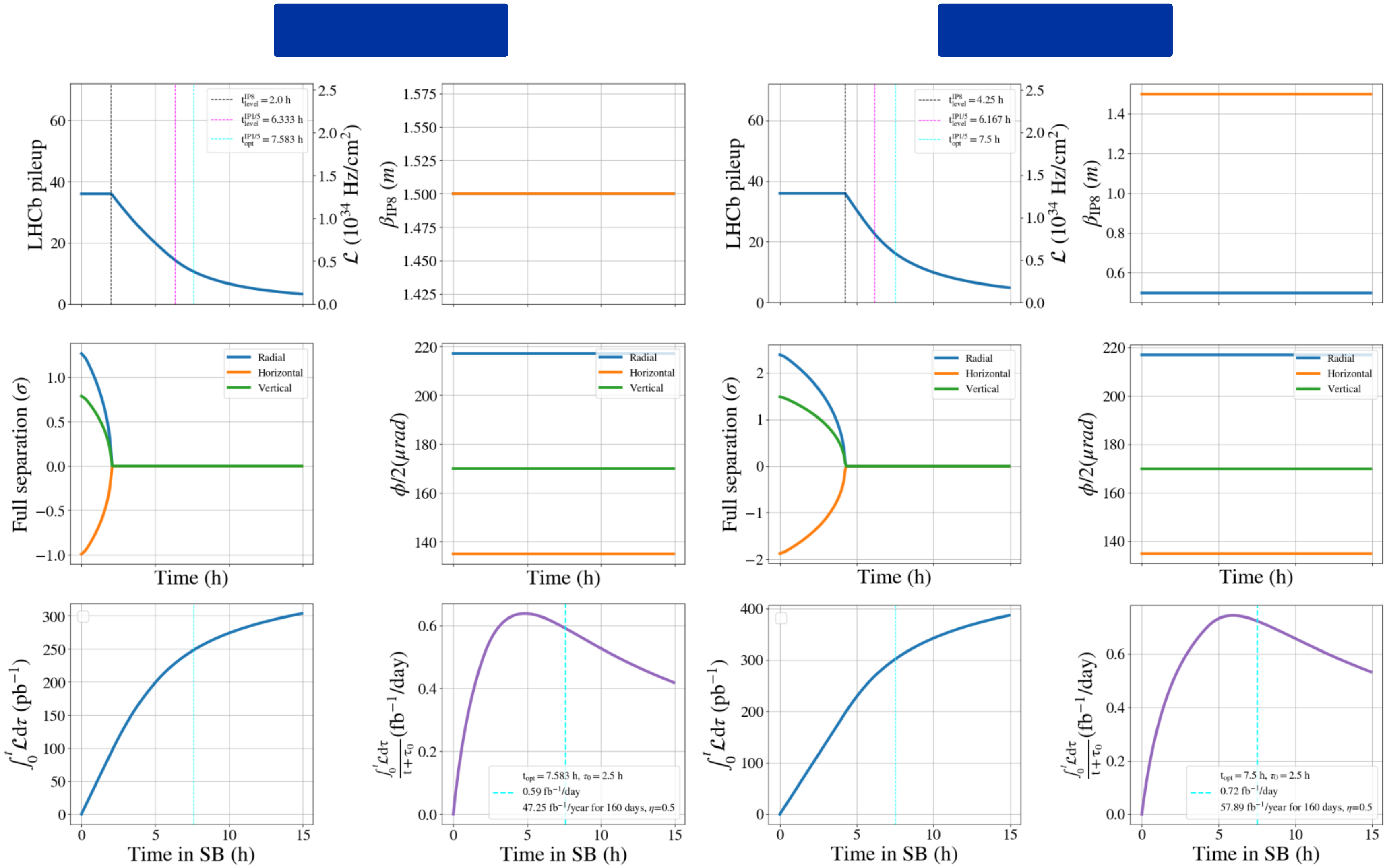
+1.55 %

+1%

Example for round and flat optics

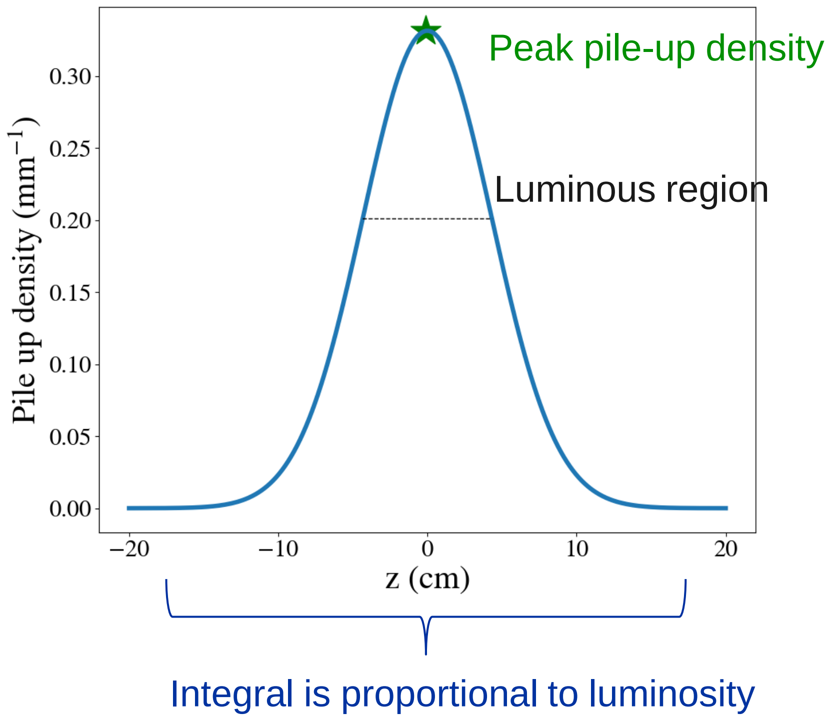
Medium-B case:

- leveling time increase from 2 to 4.25 hours with flat.
- Integrated luminosity increase from 47 fb^{-1} /year to 58 fb^{-1}/year with flat.



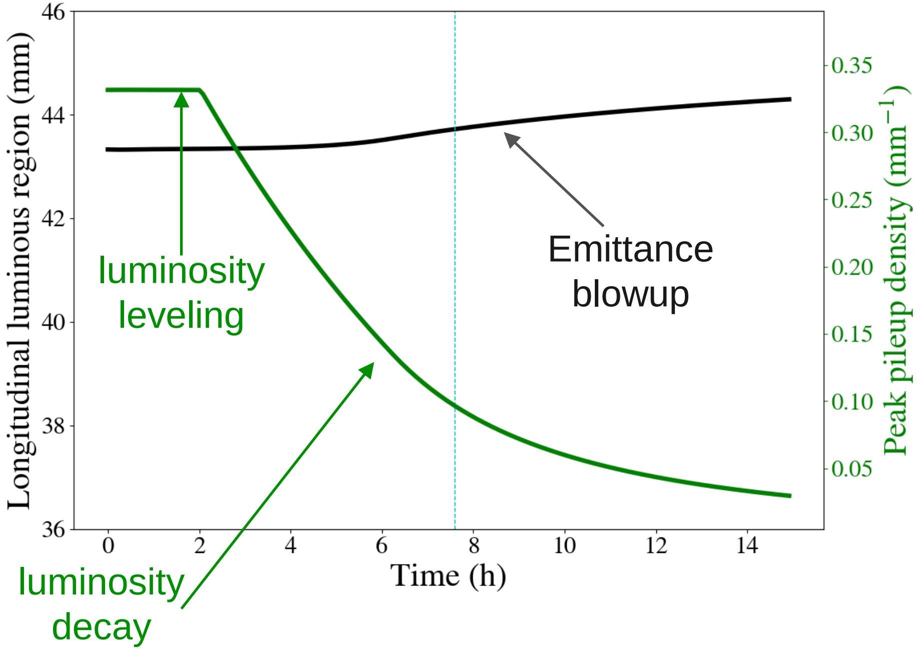
Example for round and flat optics

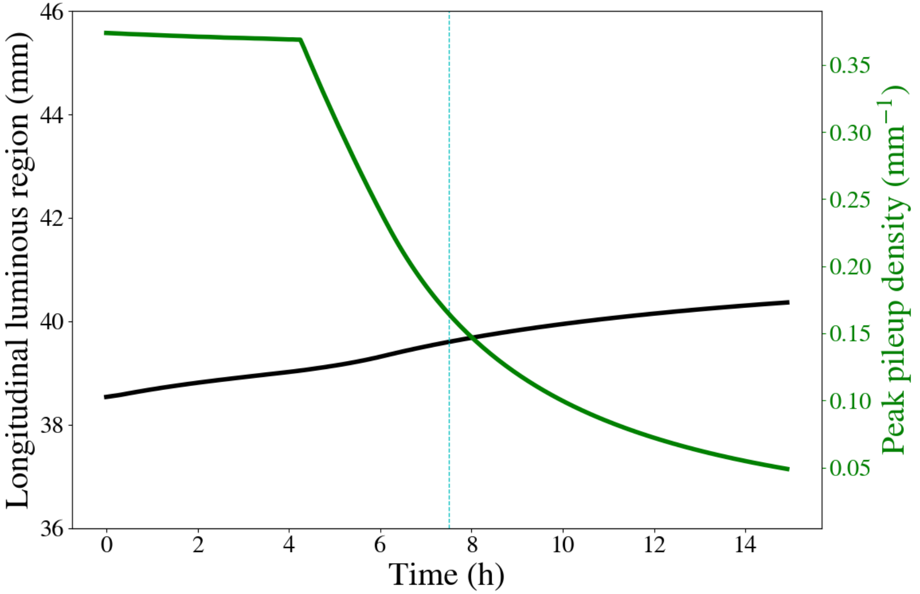
- Luminous region and peak pile-up density from pile-up density $\frac{\sigma_{inel} L(z)}{f_{rev} N_b}$



Example for round and flat optics

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



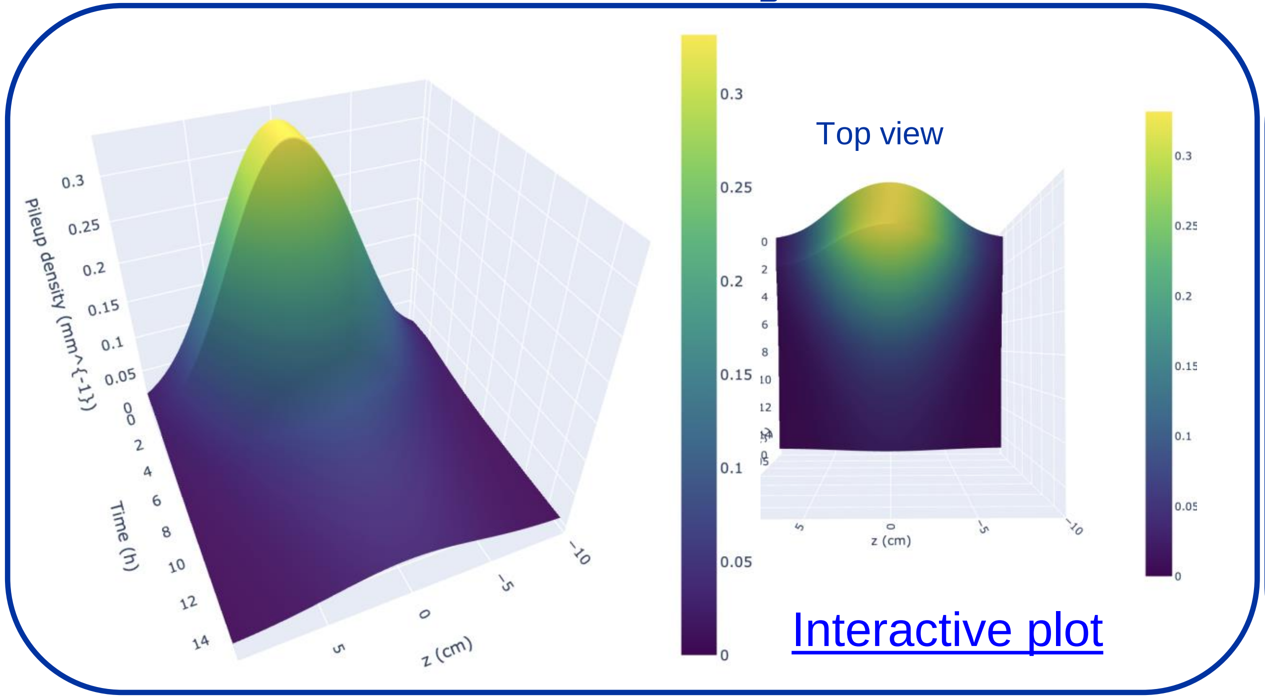


- Possible issue for the detector 1: Shortest luminous region and maximum peak pile-up density with flat optics during leveling.

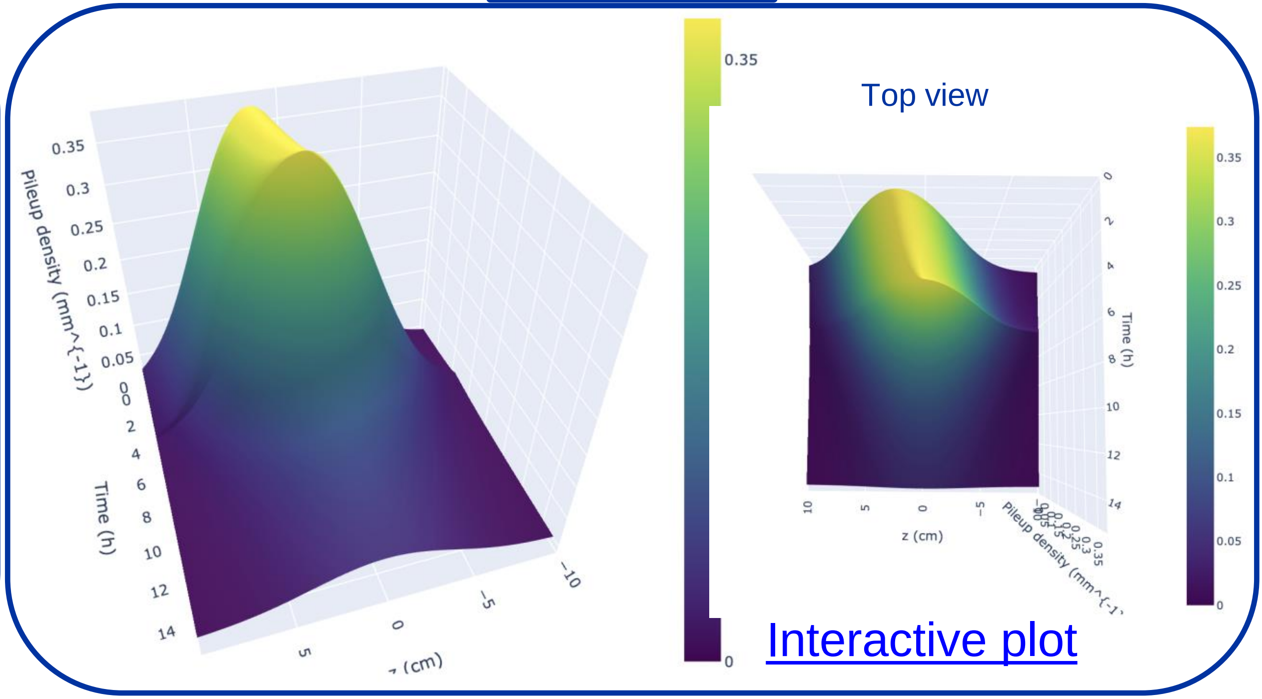
Example for round and flat optics

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

[redacted]



[redacted]



- Possible issue for the detector 2: Peak pile-up density not centered around z=0 in the presence of skew crossing, flat optics & orthogonal offset. Shift not observed with round optics or with flat when there is no orthogonal separation.

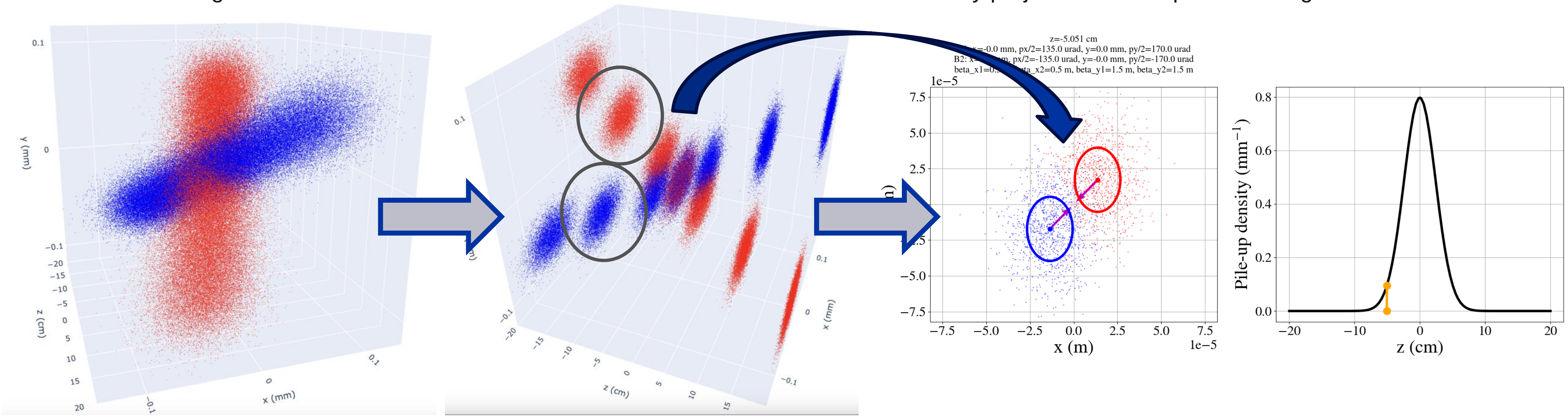
Flat optics & skew crossing

- To understand and address these issues we plot the x-y projections as a function of z

Colliding bunches in 3D

3D in z-slices

x-y projections for a specific z integrated in t

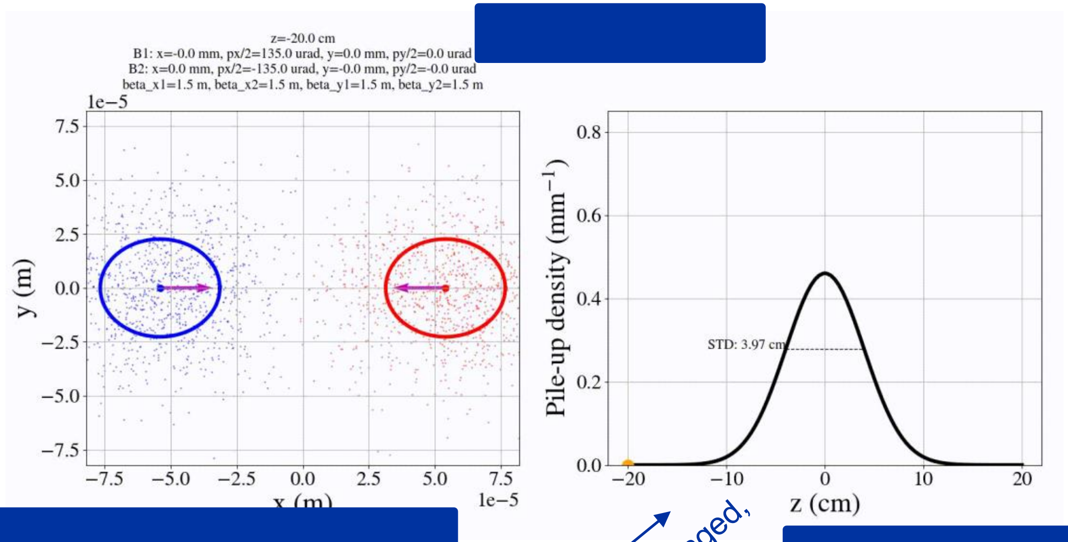


[Interactive plot]

[Interactive plot]

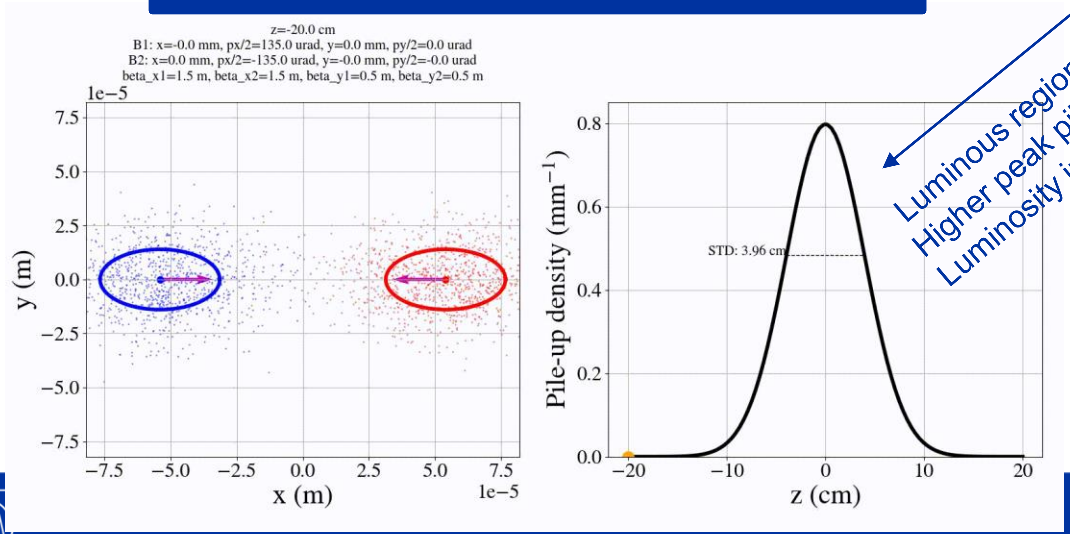
Flat optics & skew crossing

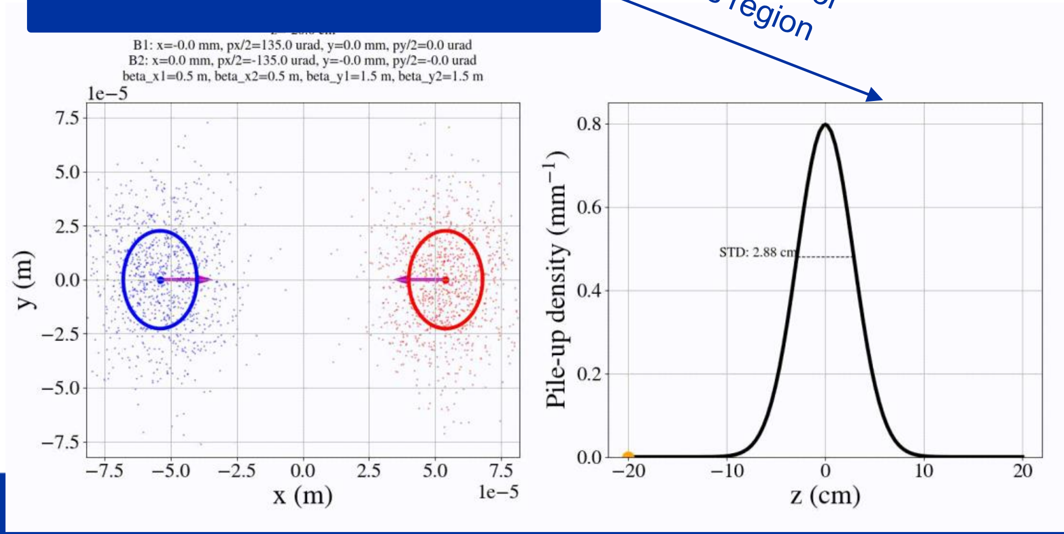
- Example of pure horizontal crossing (similar to LHCb configuration in Run 2/ Run 3 2022)



Reduction of geometric factor
Reduction of luminous region

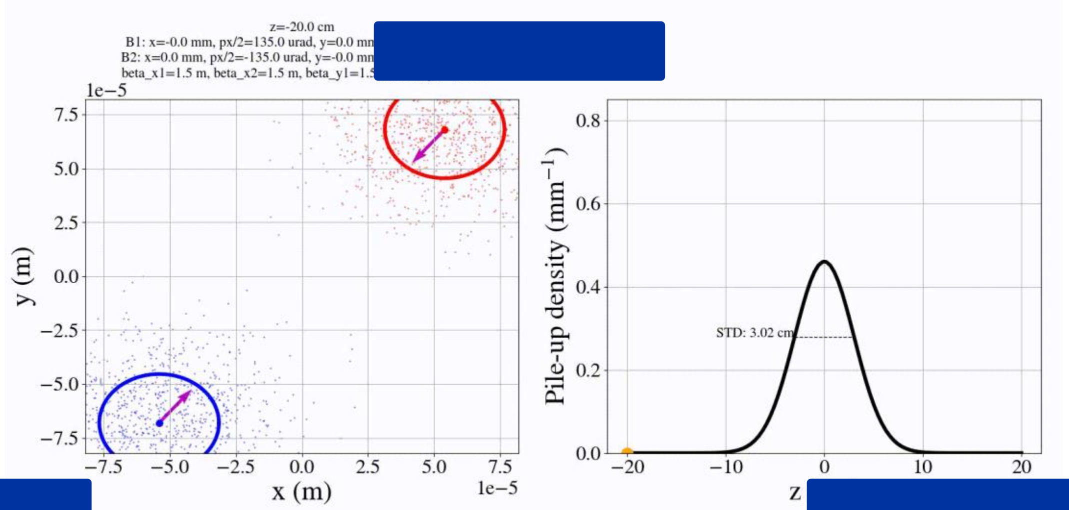
Luminous region unchanged,
Higher peak pile-up density
Luminosity increase

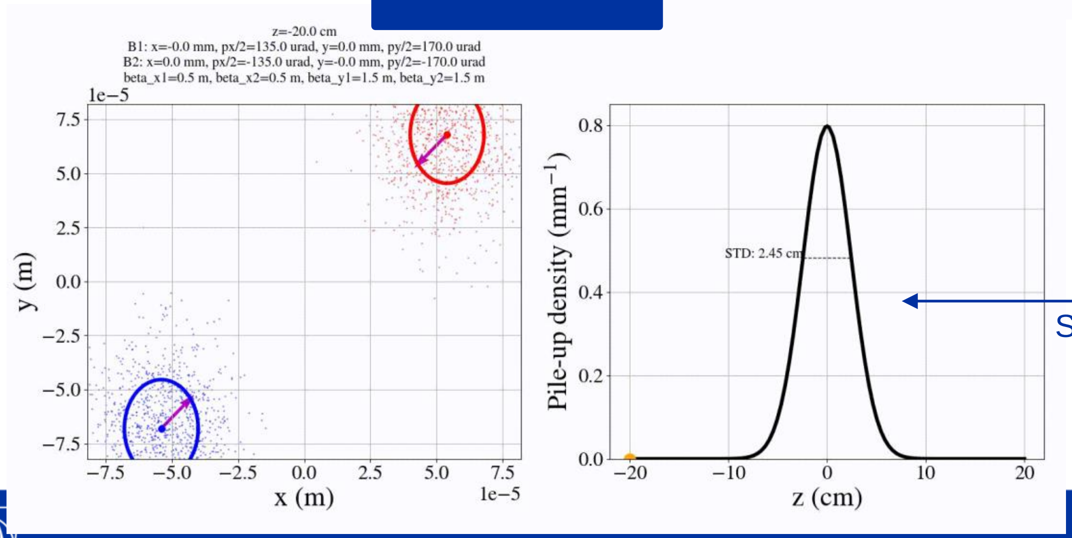




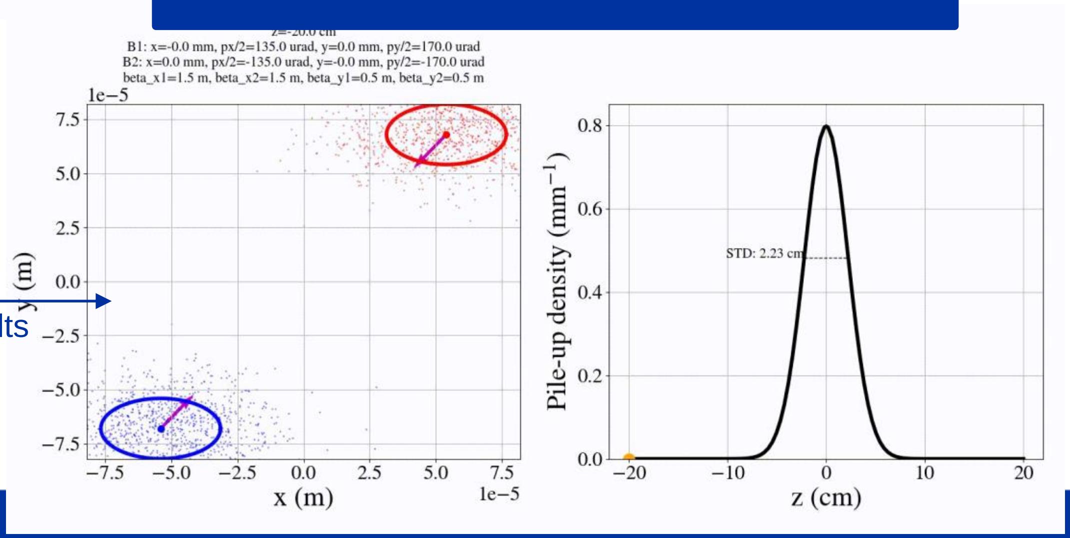
Flat optics & skew crossing

- Example of skew crossing: flattening from β_x^*1.5 to 0.5 m affects the crossing plane as there is skew crossing



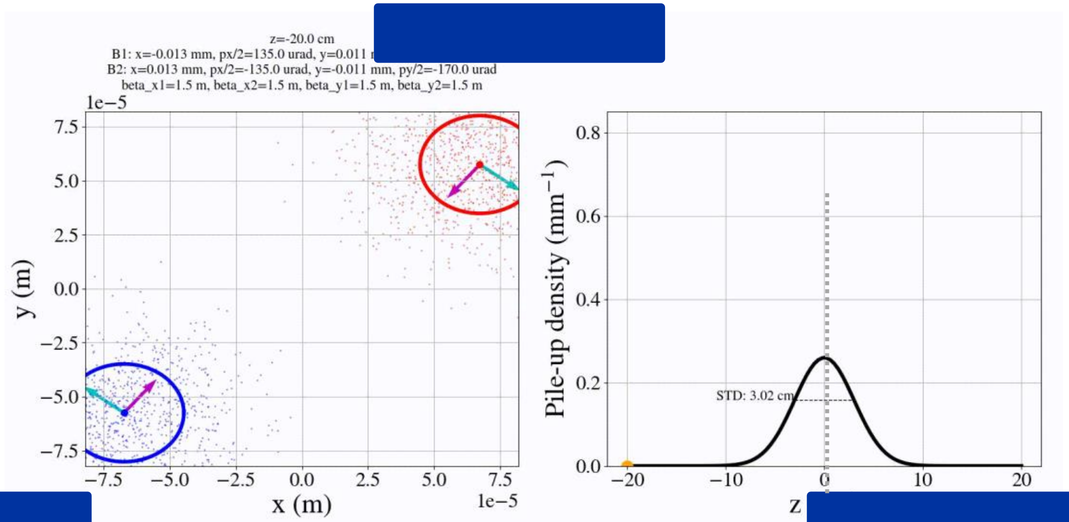


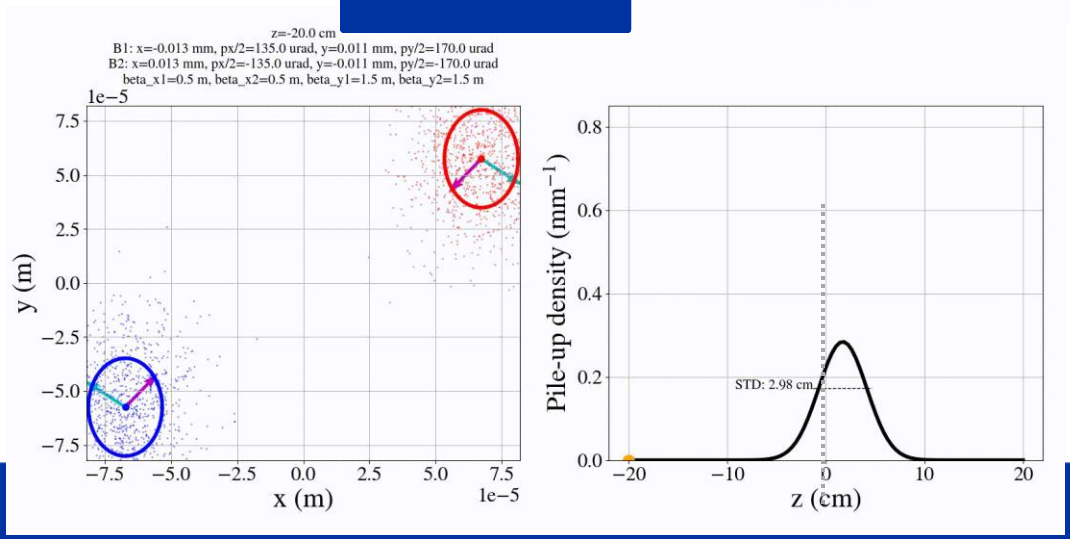
Similar results

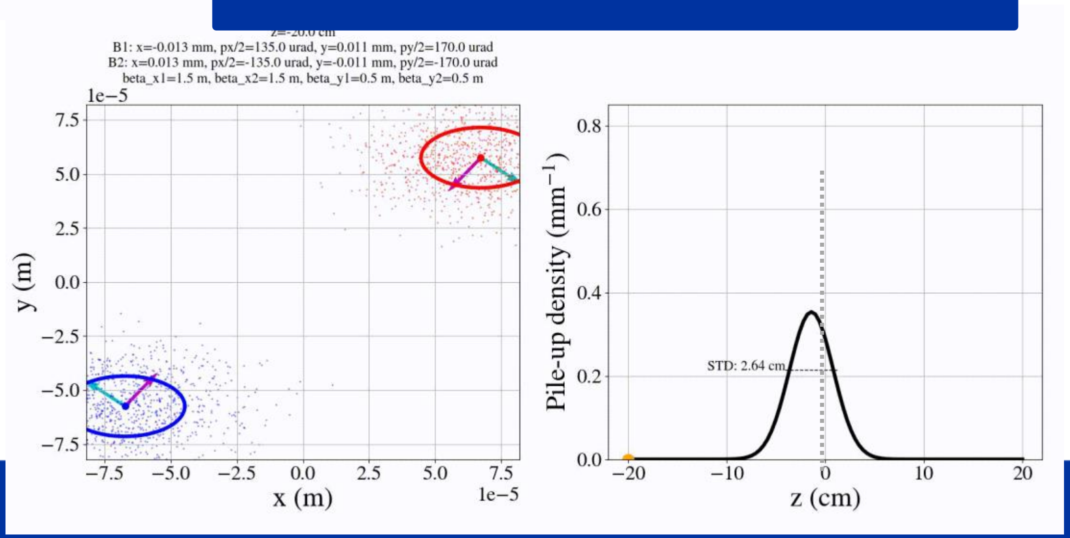


Flat optics, skew crossing & orthogonal separation

- Skew crossing and orthogonal offset: shift of peak pile-up density from z=0 with flat





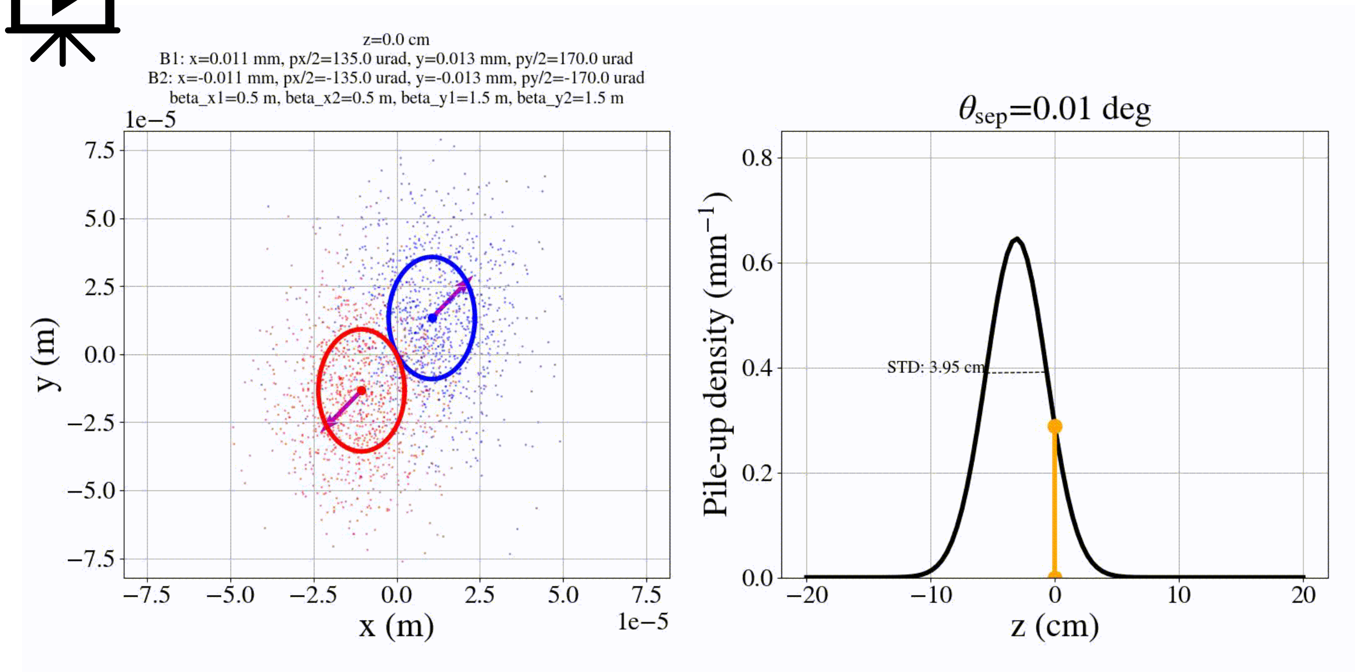


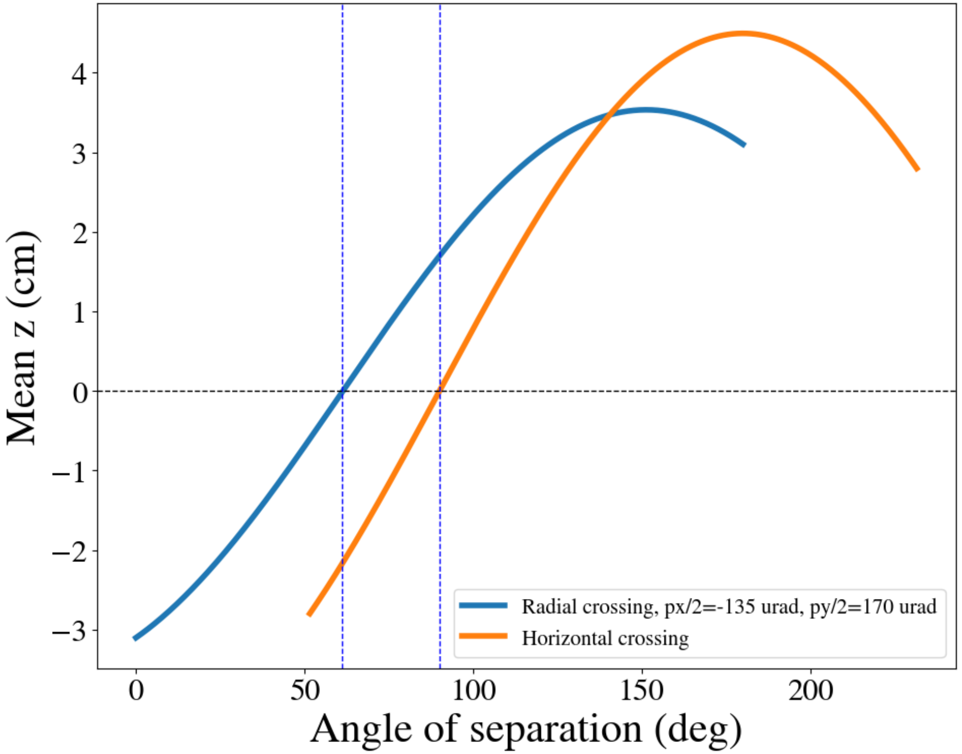
Mitigating peak pile-up density z-shift

- Solving analytically the integrals for the pile-up density, maximum pile-up density for z=0:

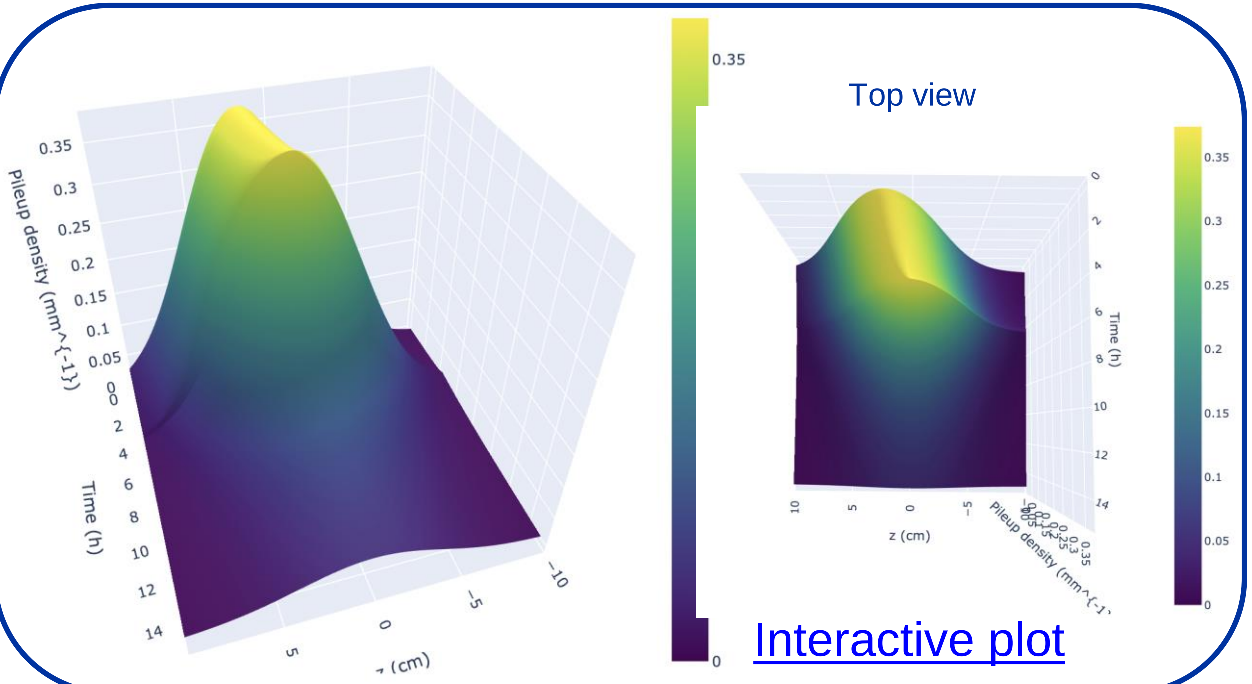
$$\frac{sep_x}{sep_y} = -\frac{\varepsilon_y}{\varepsilon_x}\frac{\beta_y^*}{\beta_x^*}\frac{\varphi_x}{\varphi_y}$$

For flat optics 0.5/1.5: $angle(sep_r) = 112°$, $\boldsymbol{angle(\varphi_r \rightarrow sep_r) = 61°}$

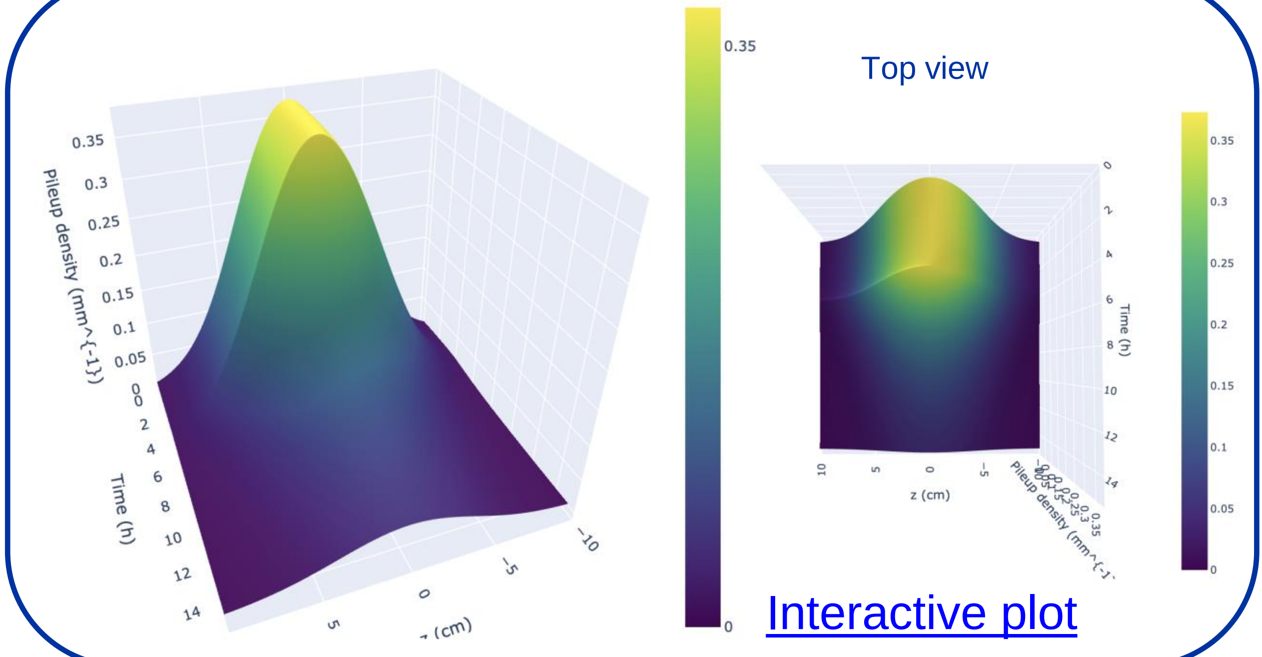




Mitigating peak pile-up density z-shift

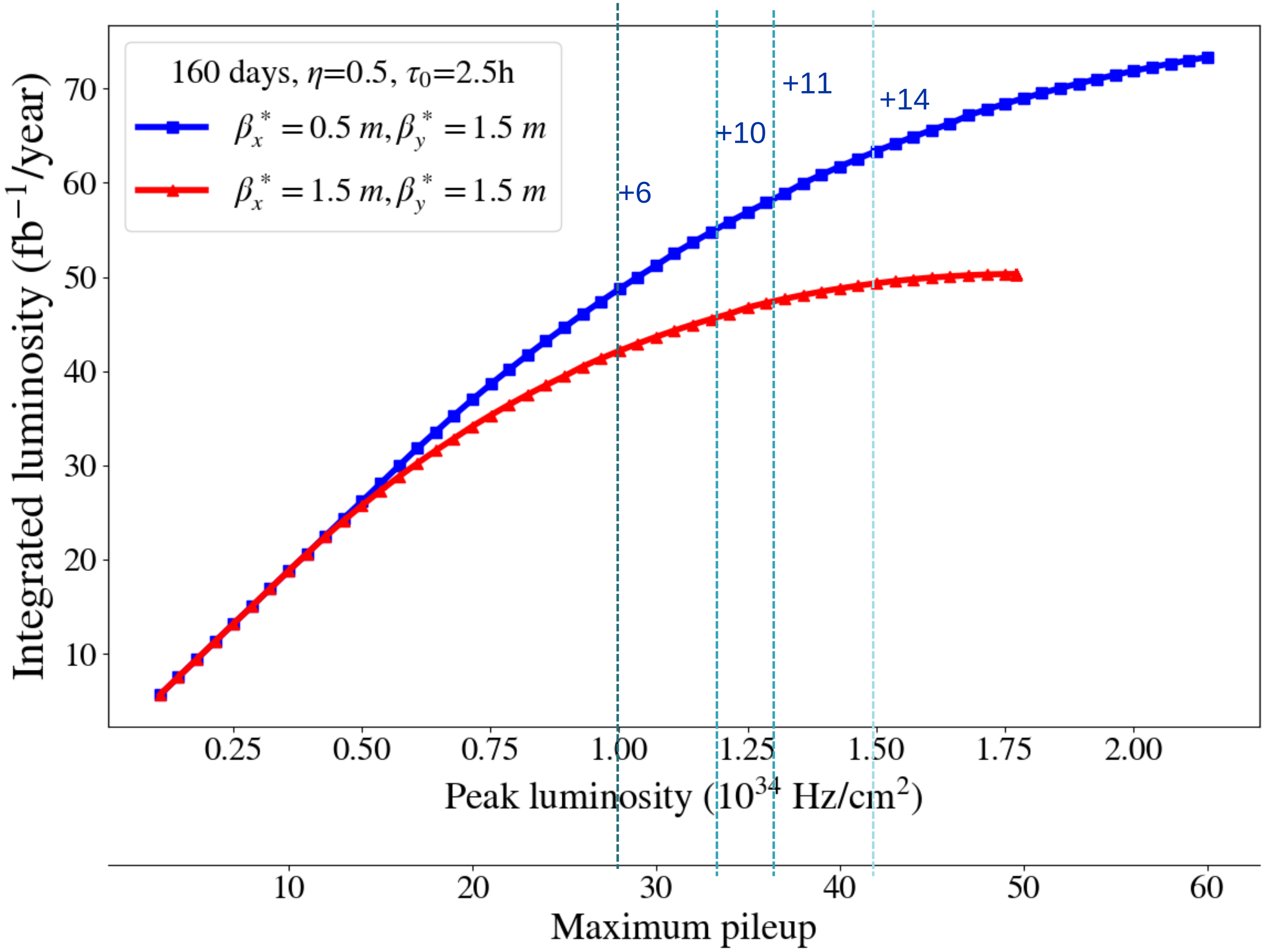


[Interactive plot](#)



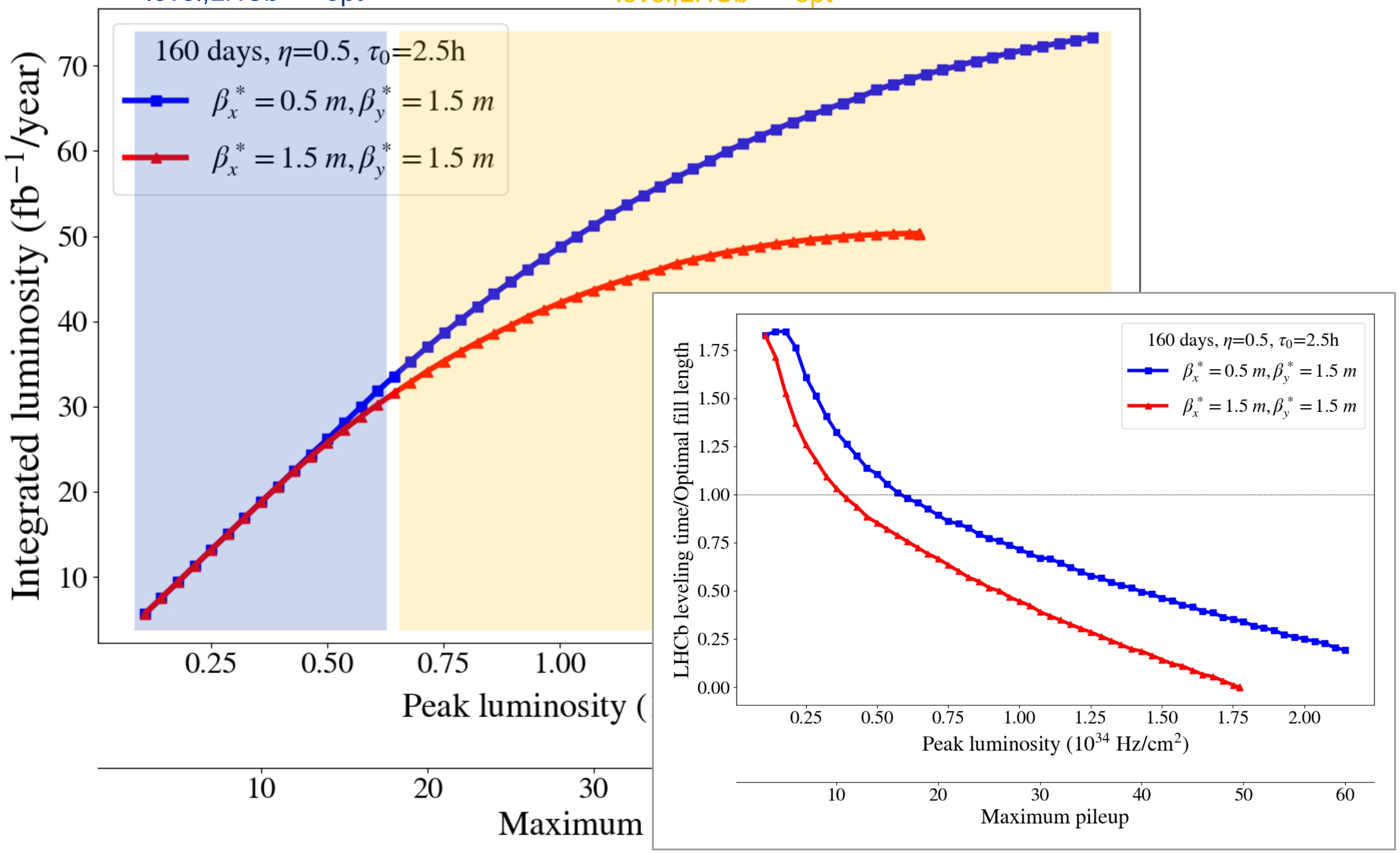
[Interactive plot](#)

Performance projections: Yearly integrated luminosity

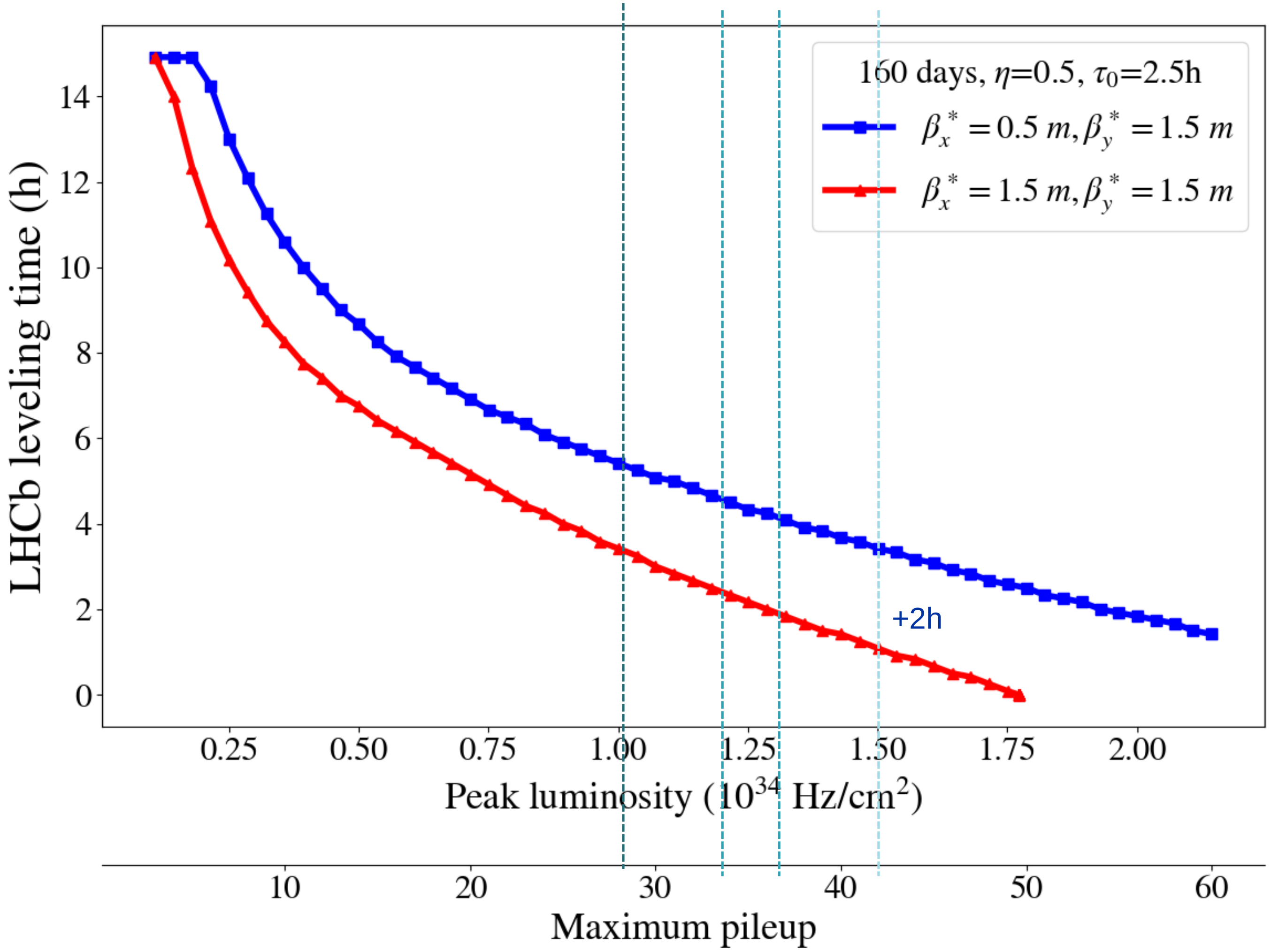


Performance projections: Yearly integrated luminosity

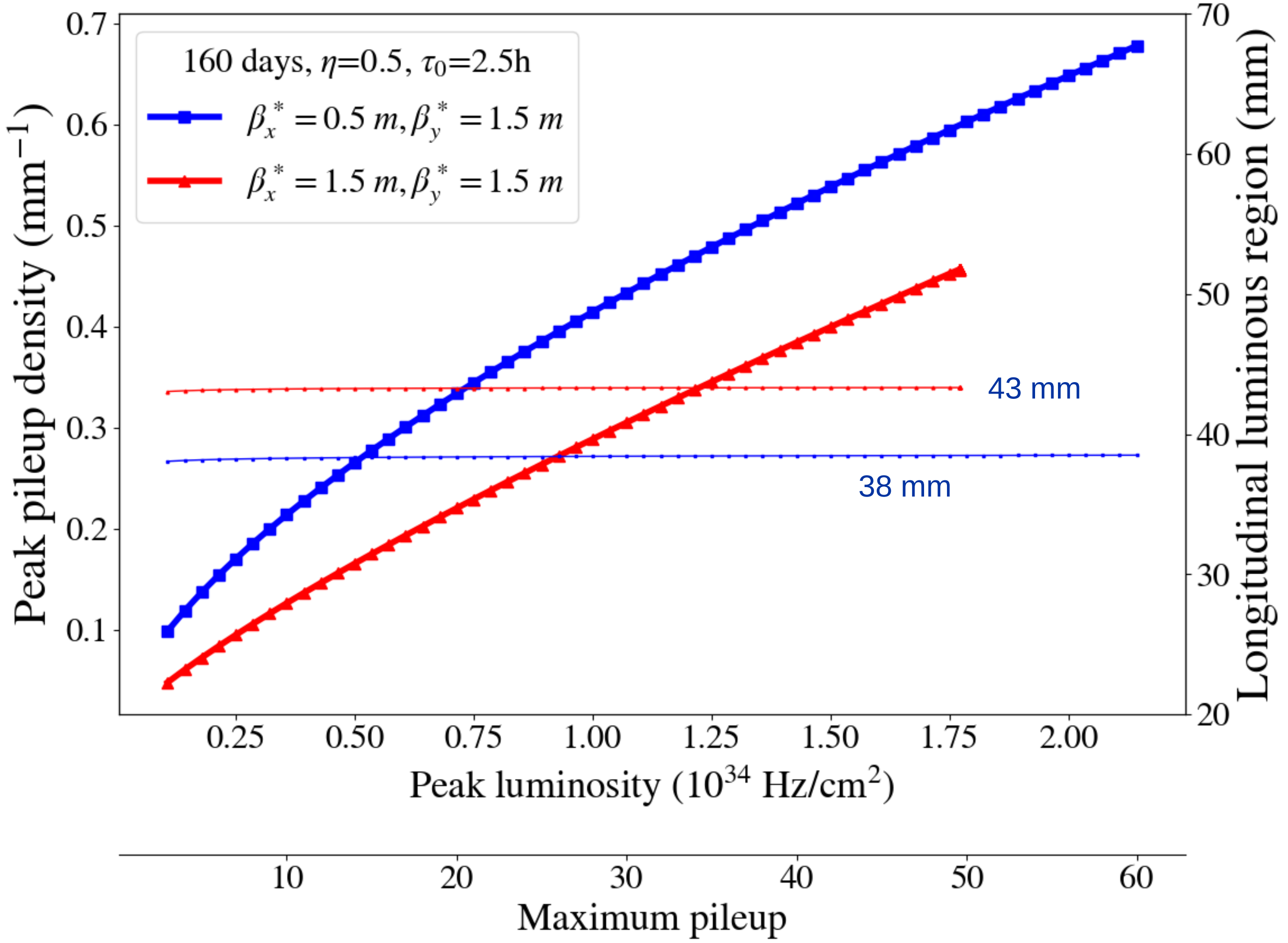
$t_{level,LHCb} > t_{opt}$ $t_{level,LHCb} < t_{opt}$



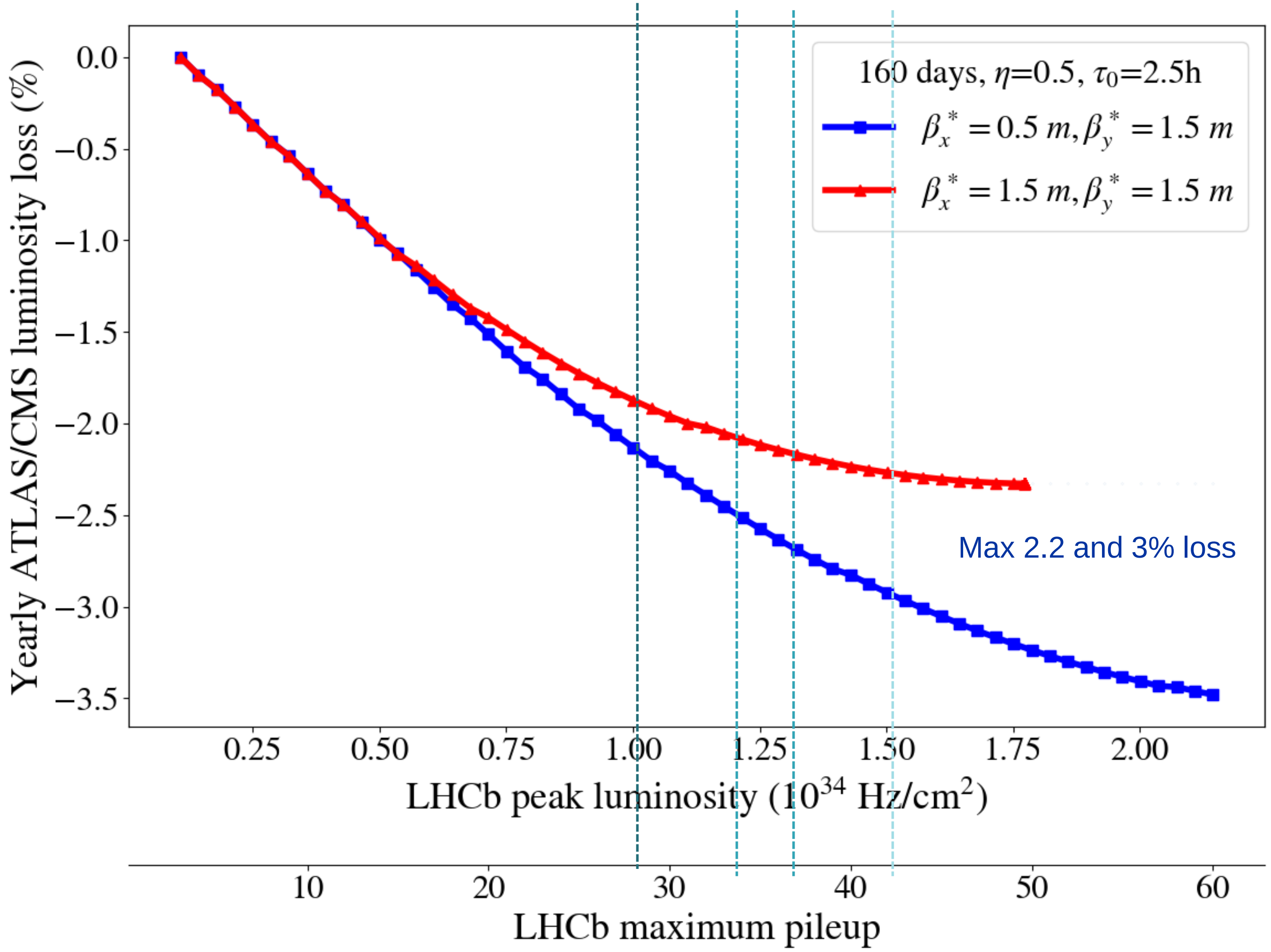
Performance projections: Leveling time



Performance projections: Luminous region & peak pile-up density



Performance projections: ATLAS/CMS loss of integrated luminosity



Performance projections: Summary

	Round optics					Flat optics				
	Low	Medium-a	Medium-b	High	Virtual	Low	Medium-a	Medium-b	High	Virtual
L_{peak} (10^{34} Hz/cm^2)	1	1.22	1.29	1.5	1.77	1	1.22	1.29	1.5	2.72
Maximum pile-up	28	34	36	42	49.5	28	34	36	42	76.1
L_{int} per year (fb^{-1})	**42.16**	**46.09**	**47.25**	**49.34**	50.32	**48.73**	**55.85**	**57.89**	**63.36**	76.24
Leveling time (h)	3.42	2.33	2	1.083	0	5.42	4.5	4.25	3.42	0
Optimal fill length (h)	7.67	7.67	7.58	7.58	7.58	7.58	7.5	7.5	7.42	7.25
Leveling time/Optimal fill length	0.45	0.3	0.26	0.14	0	0.71	0.6	0.57	0.46	0
Loss of ATLAS/CMS integrated lumi (%)	-1.87	-2.09	-2.14	-2.27	-2.33	-2.16	-2.54	-2.66	-2.95	-3.67
Luminous region (mm) at t=0	**43.3**	43.3	43.31	43.31	43.32	**38.41**	38.43	38.44	38.45	38.51
Peak pile-up density (mm^{-1}) at t=0	0.29	0.34	0.35	0.4	0.46	0.41	0.47	0.49	0.54	0.79

Flat optics scenario is **not** yet verified with Dynamic Aperture studies,
MD validation will also be needed

Conclusions

- 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°).