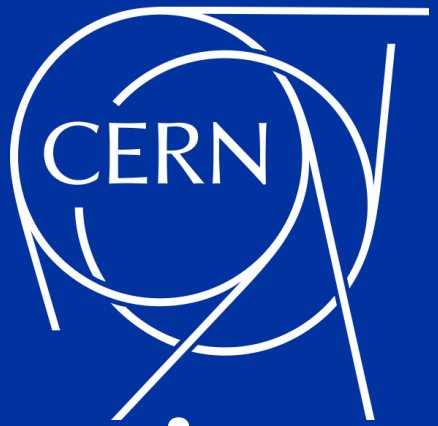


Performance estimates for the new HL-LHC baseline & variants

R. De Maria, S. Kostoglou, R. Tomas
H. Bartosik, I. Efthymiopoulos, L. Mether, N. Mounet, G. Sterbini

WP2 02/07/2024

Baseline

Input from new proposed DMR

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	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.

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 on the filling scheme
    II. Additional losses from unknown source based on LHC experience

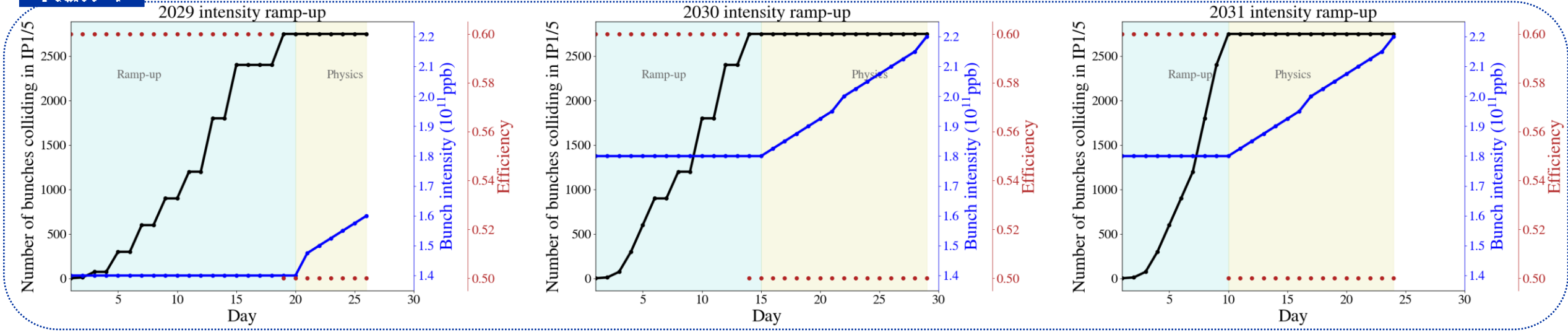
  - Luminosity:
    - Analytical and numerical integration of 4 integrals $L = N_1 N_2 n_b f_r \sqrt{(\vec{v_1} - \vec{v_2})^2 - \frac{(\vec{v_1} \times \vec{v_2})^2}{c^2}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho^{B1}\rho^{B2}\, dxdydzdt$ G. Sterbini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

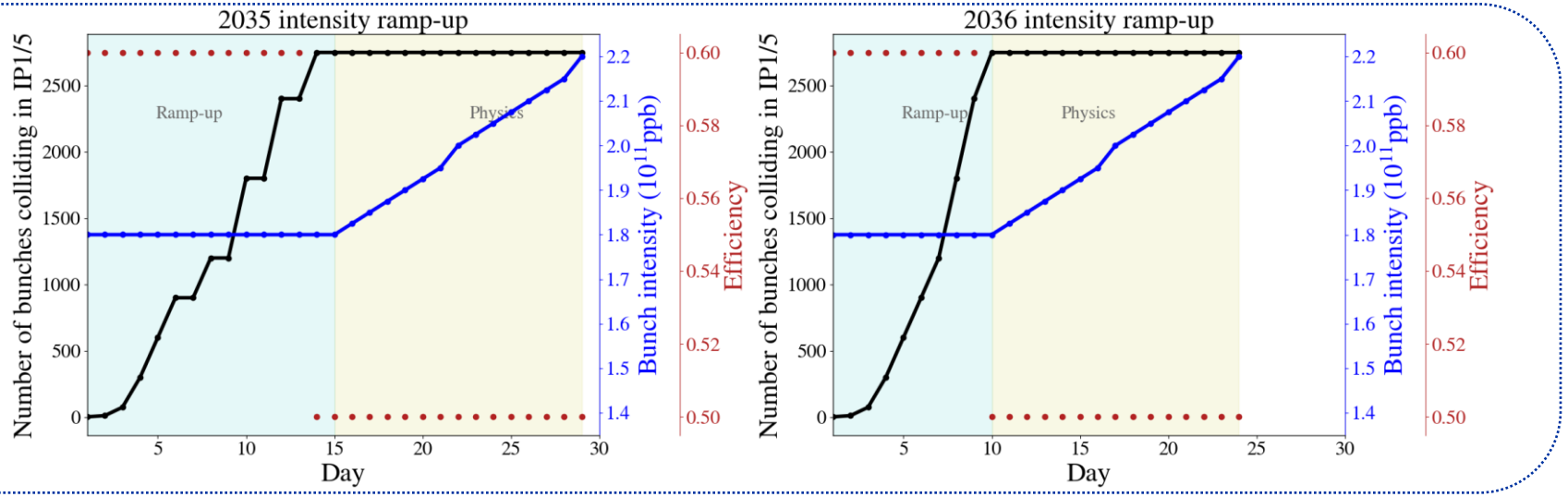
Intensity ramp up

Based on Riccardo's Chamonix 2024 talk

Run 4



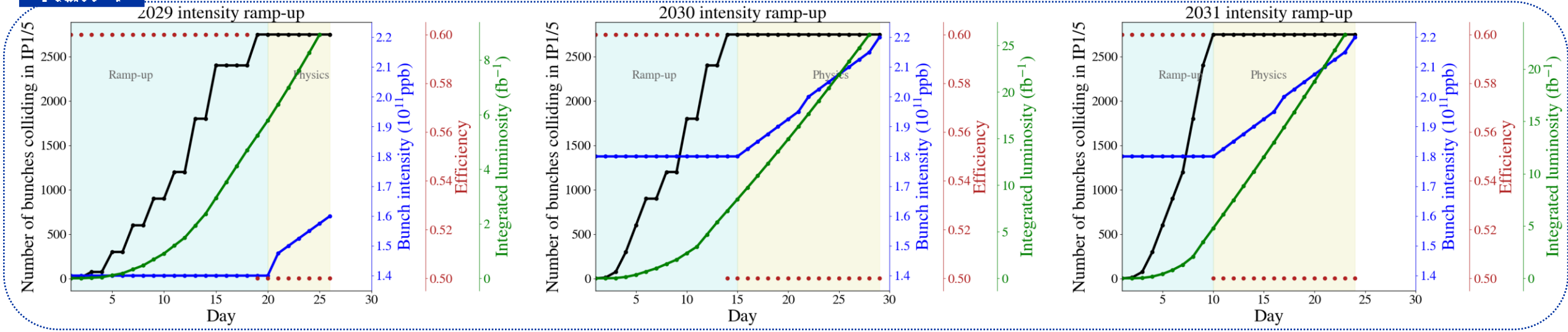
Run 5



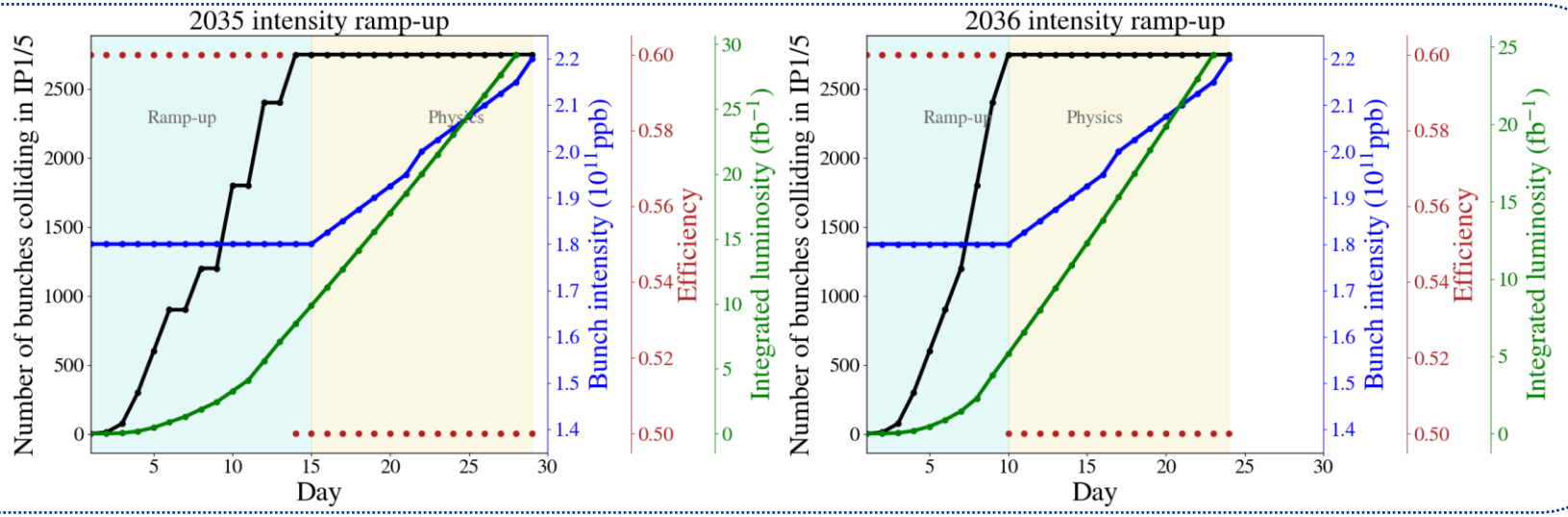
Intensity ramp up

Based on Riccardo's Chamonix 2024 talk

Run 4



Run 5



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→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”

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→ 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)	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→ 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
	2032	0.5	2.2	20	20	on	132	10	152	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2
5	2035	0.5	2.2	15	15	on	132	15	152	**2748→ 2736**	**2574→2370**	2.5→ **2.2**	H/V	250	2
	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”: 25ns_2744b_2736_2246_2370_240bpi_13inj_800ns_bs200ns_BCMS_5x48b

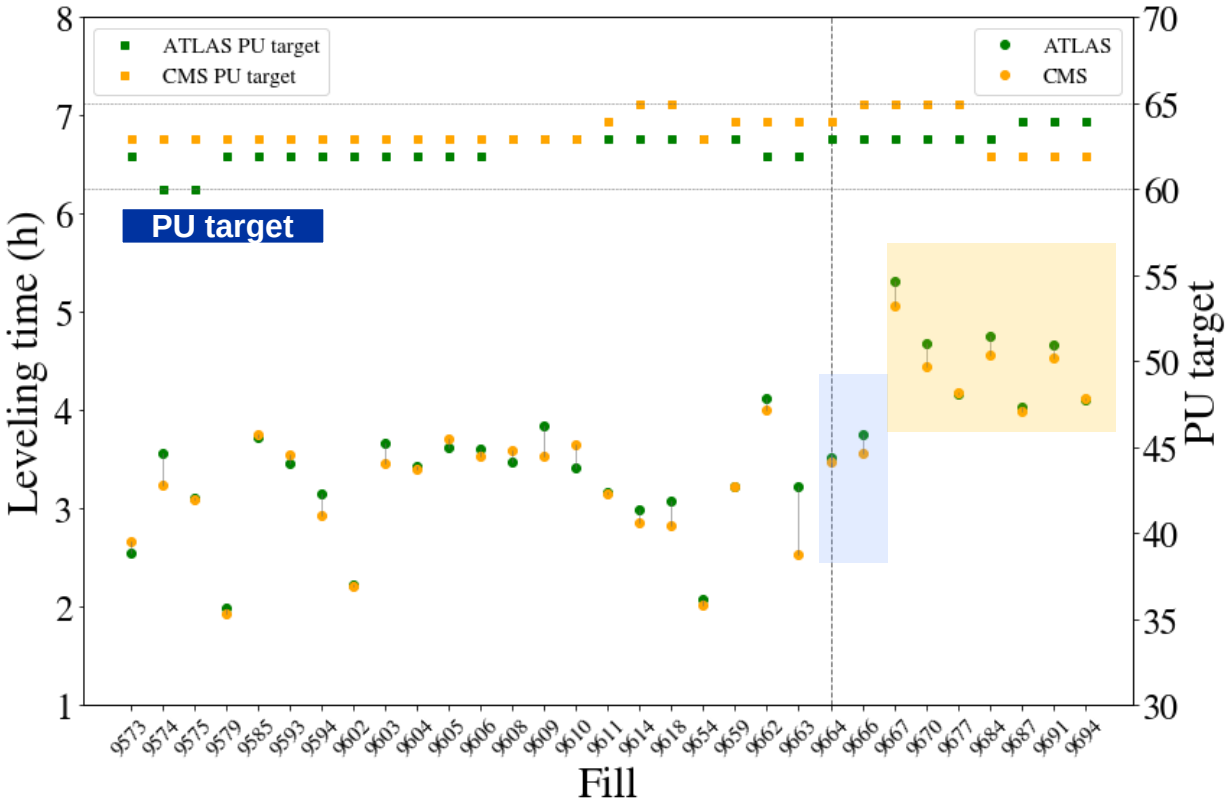
BCMS performance in 2024

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

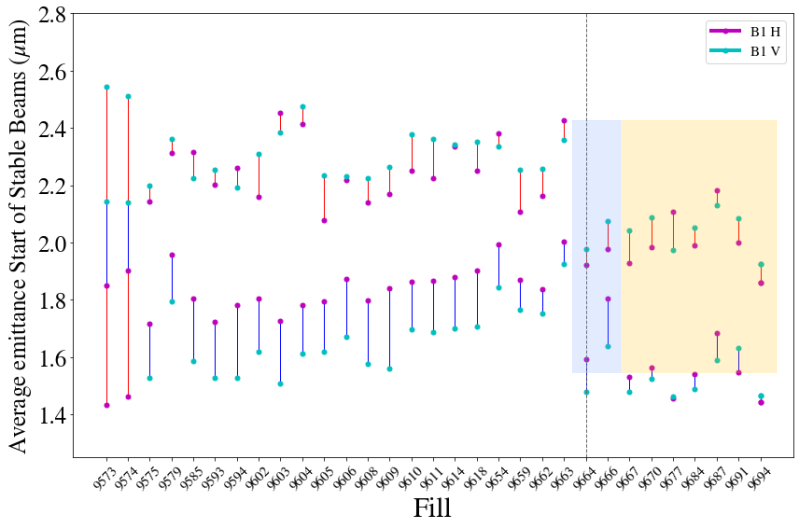
Bunch intensity (1e11 ppb)	B1 INJPHYS	B2 INJPHYS	B1 STABLE	B2 STABLE
Fills 9573-9663	1.59	1.59	1.56	1.55
Fills 9664-9694	1.62	1.62	1.59	1.57
%	+1.89	+1.89	+1.92	+1.29

BCMS performance in 2024: Leveling time

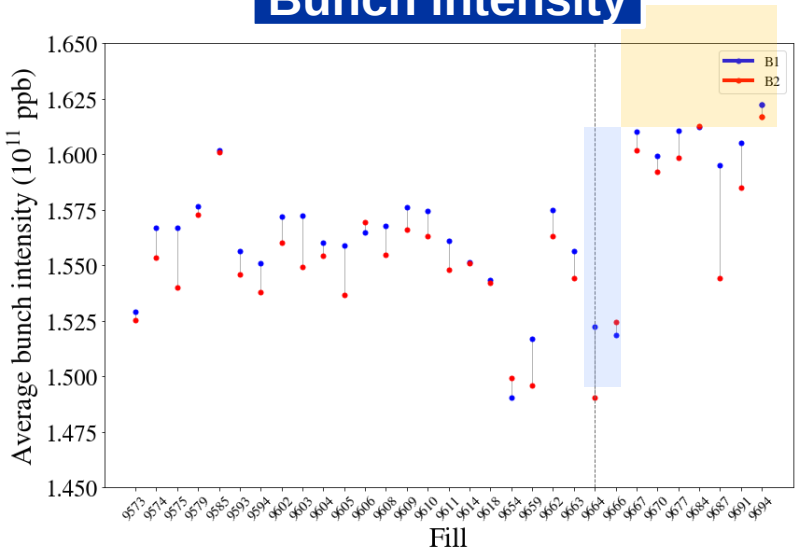
Leveling time



Emittance



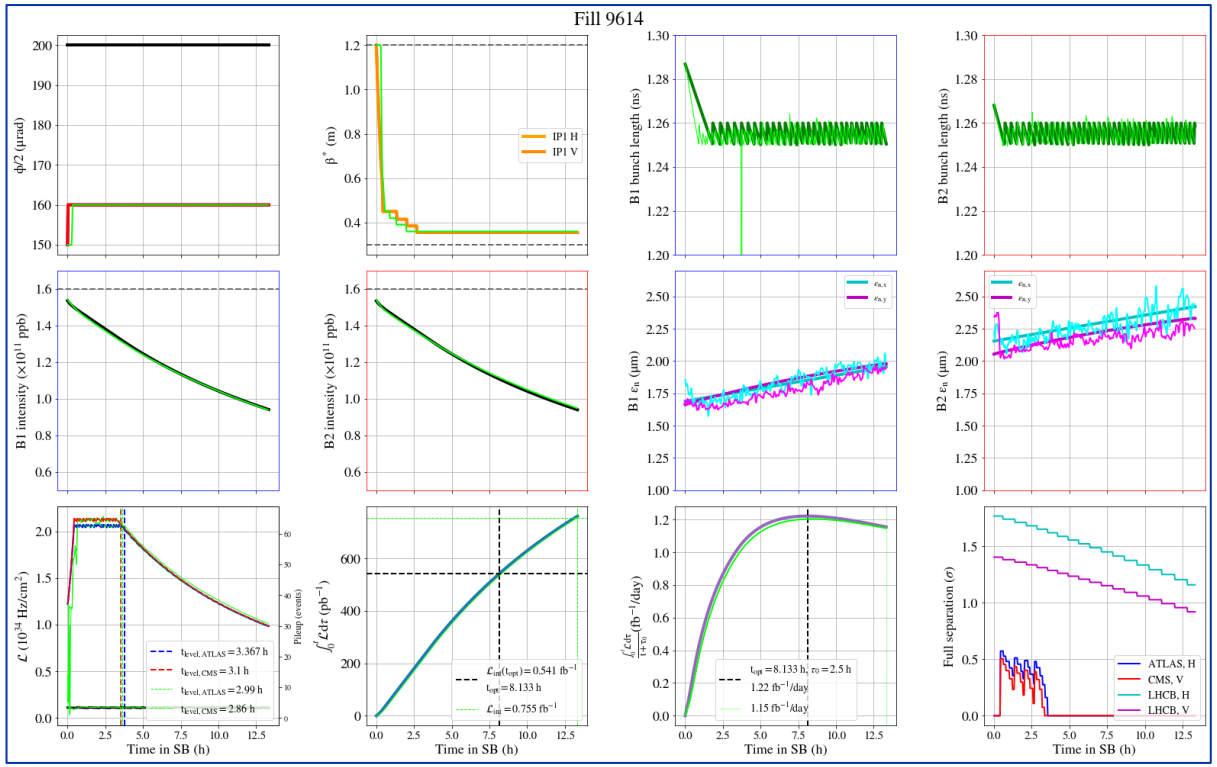
Bunch intensity



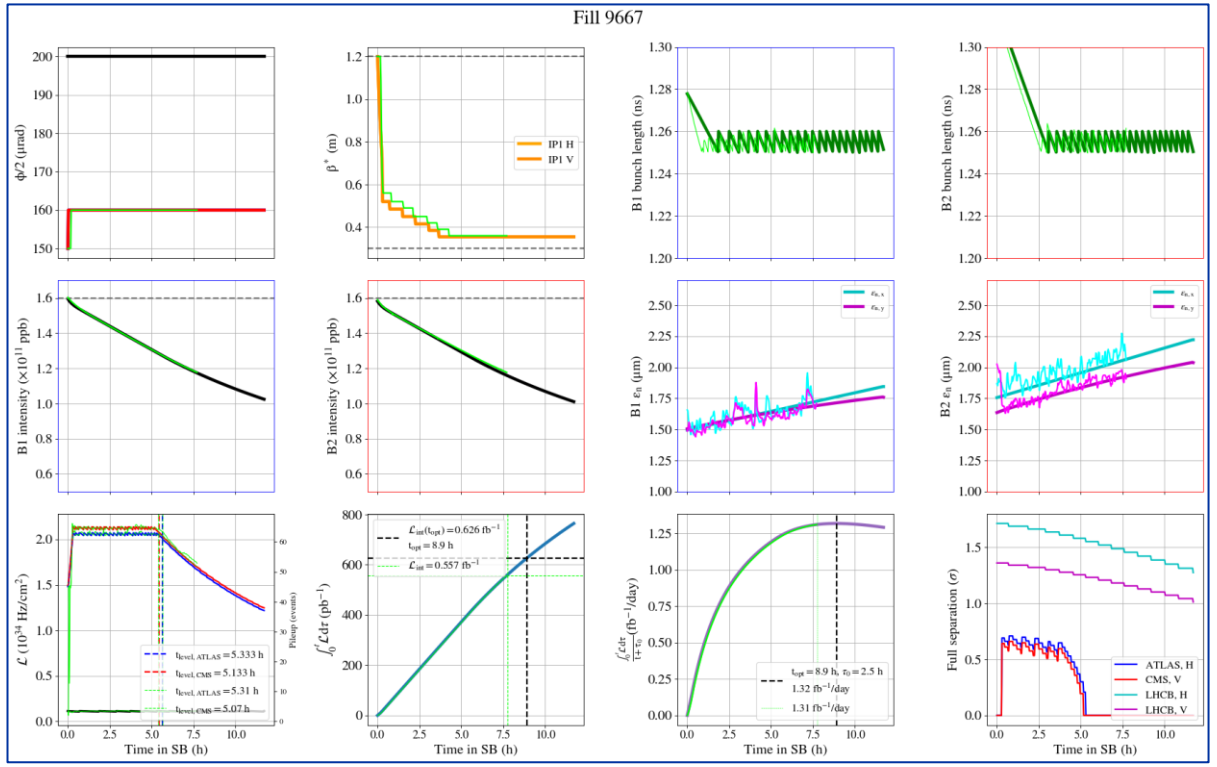
- Step in leveling time results from the combination of smaller emittances at start of SB **and** increased bunch intensity.

BCMS performance in 2024: Performance gain

Fill 9614, Standard



Fill 9667, BCMS



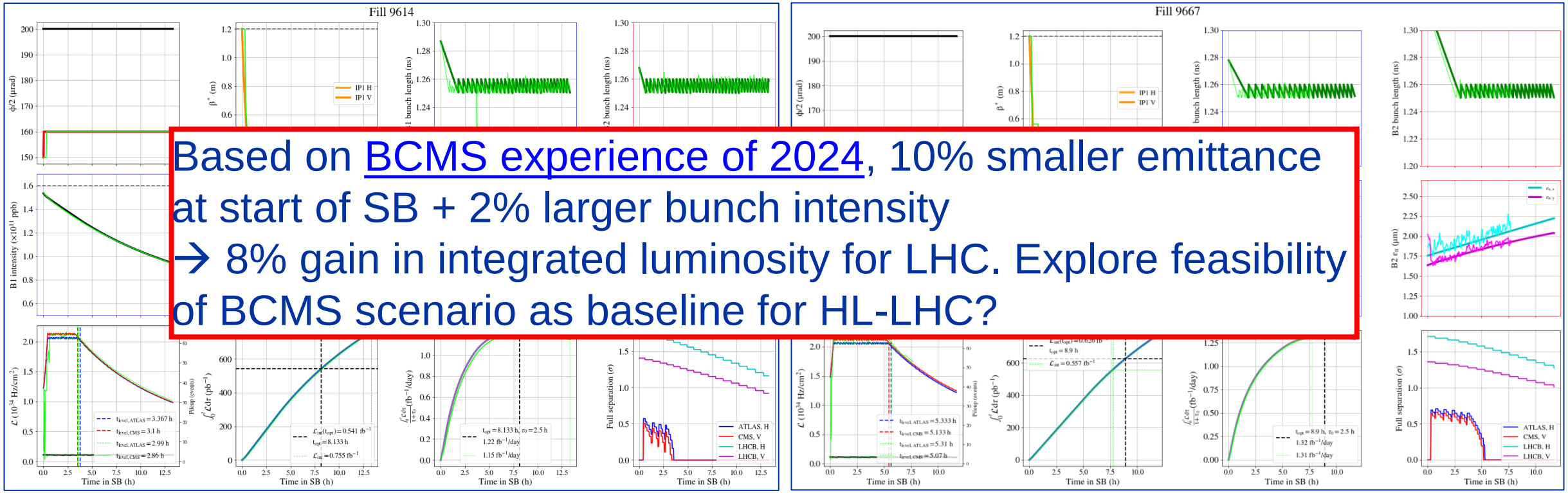
Considering a turn-around time of **2.5h**:

- From 1.22 fb^{-1}/day with standard to 1.32 fb^{-1}/day with BCMS: **+8.2%** integrated luminosity for fills that make it to the optimal fill length (>8h)

BCMS performance in 2024: Performance gain

Fill 9614, Standard

Fill 9667, BCMS



Based on BCMS experience of 2024, 10% smaller emittance at start of SB + 2% larger bunch intensity
→ 8% gain in integrated luminosity for LHC. Explore feasibility of BCMS scenario as baseline for HL-LHC?

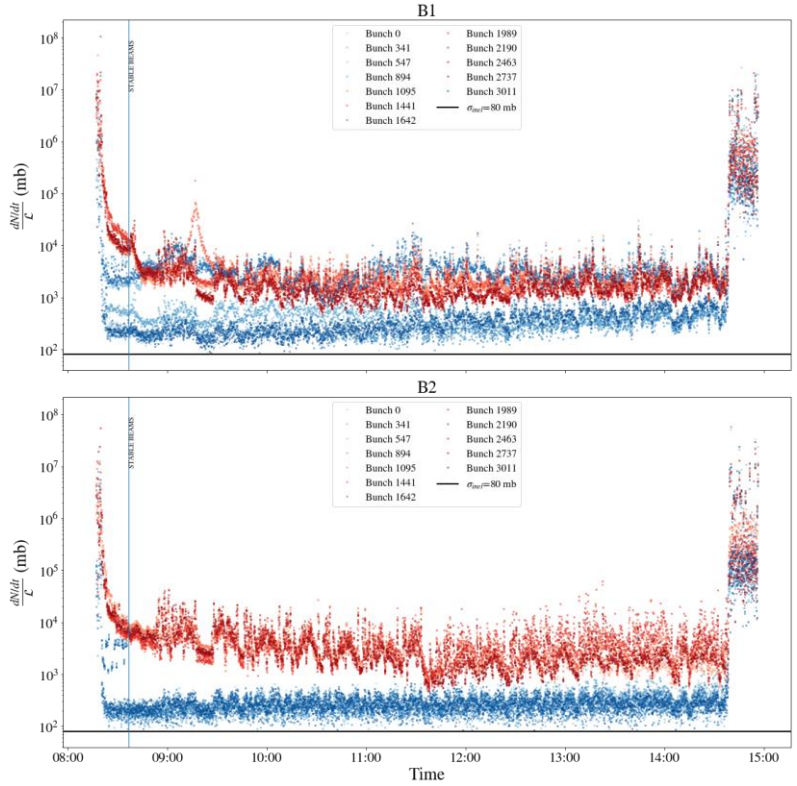
Considering a turn-around time of **2.5h**:

- From 1.22 fb^{-1}/day with standard to 1.32 fb^{-1}/day with BCMS: **+8.2%** integrated luminosity for fills that make it to the optimal fill length (>8h)

BCMS performance in 2024: Performance gain

- Impact of tails in the LHC to be considered and studied (“BCMS with reduced tails” from the injectors F. Asvesta, M. Bozatzis).

MD on non-factorization of VdM beams E. Lamb, G. Sterbini



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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

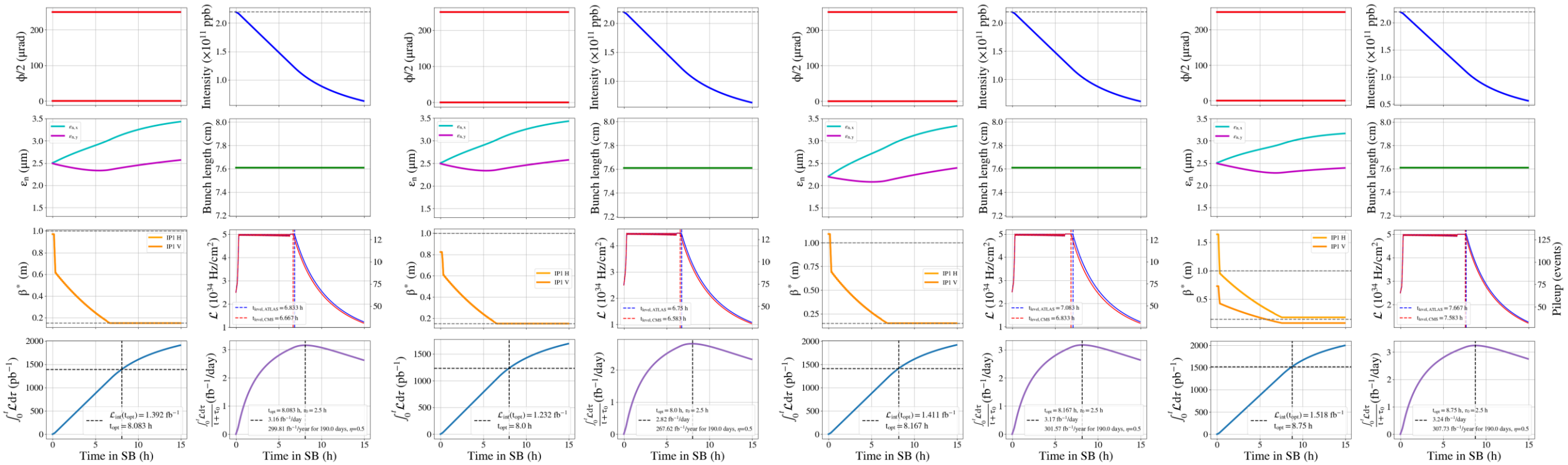
"Nominal ions" → "Extended ions"

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

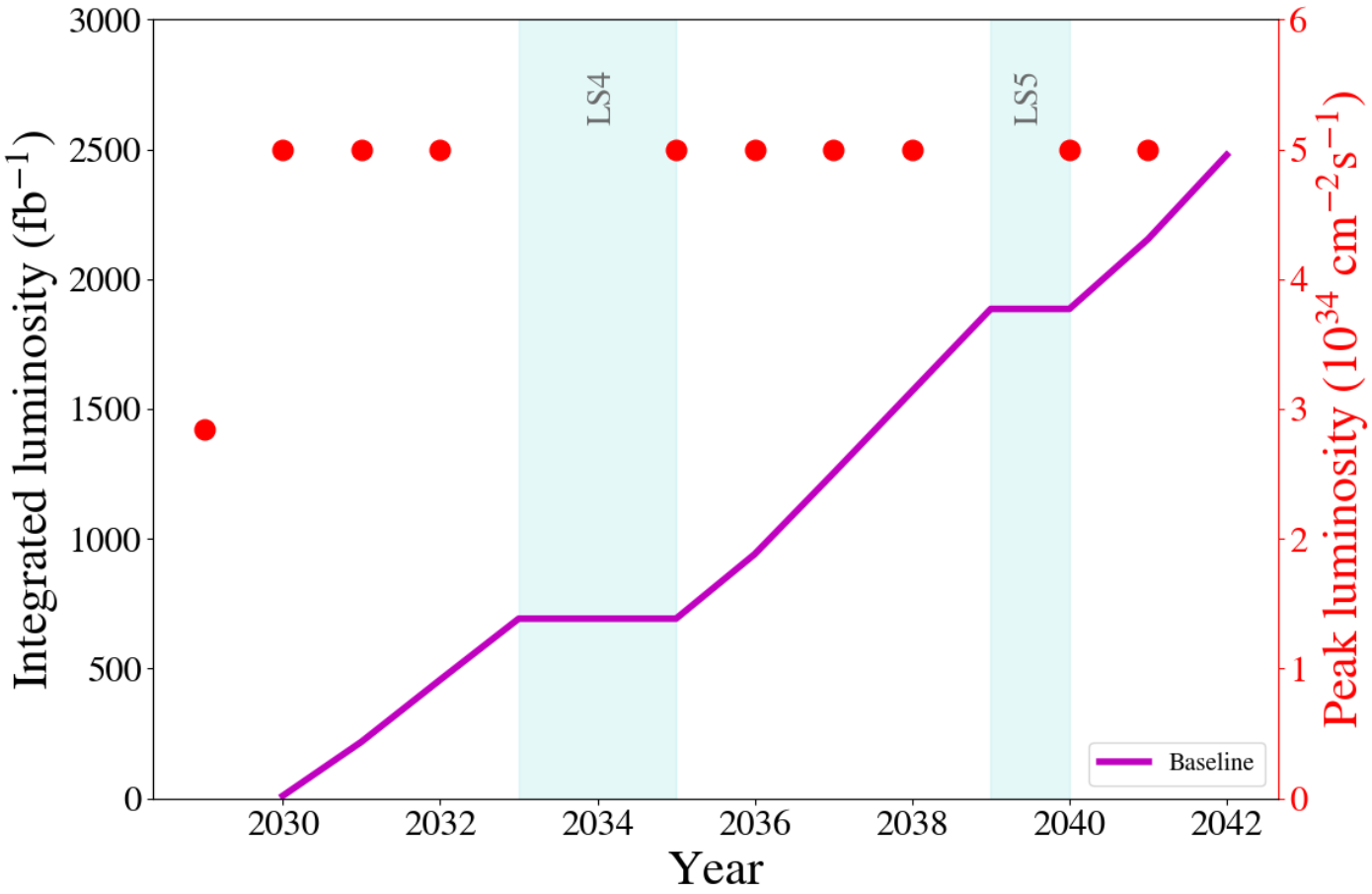
Run	Year	Baseline	Round hybrid	Round BCMS	Flat 8/18 cm	Vbaseline extended ions	Round hybrid extended ions	Round BCMS extended ions	Flat 8/18 cm extended ions
4	2029	9.6	9.1	10	9.6	9.6	9.1	10	9.6
	2030	208	186.1	210.7	208	208	186.1	210.7	208
	2031	238.8	213.4	241	254.1	238.8	213.4	241	254.1
	2032	235.7	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

Realtive yearly & total integrated luminosity

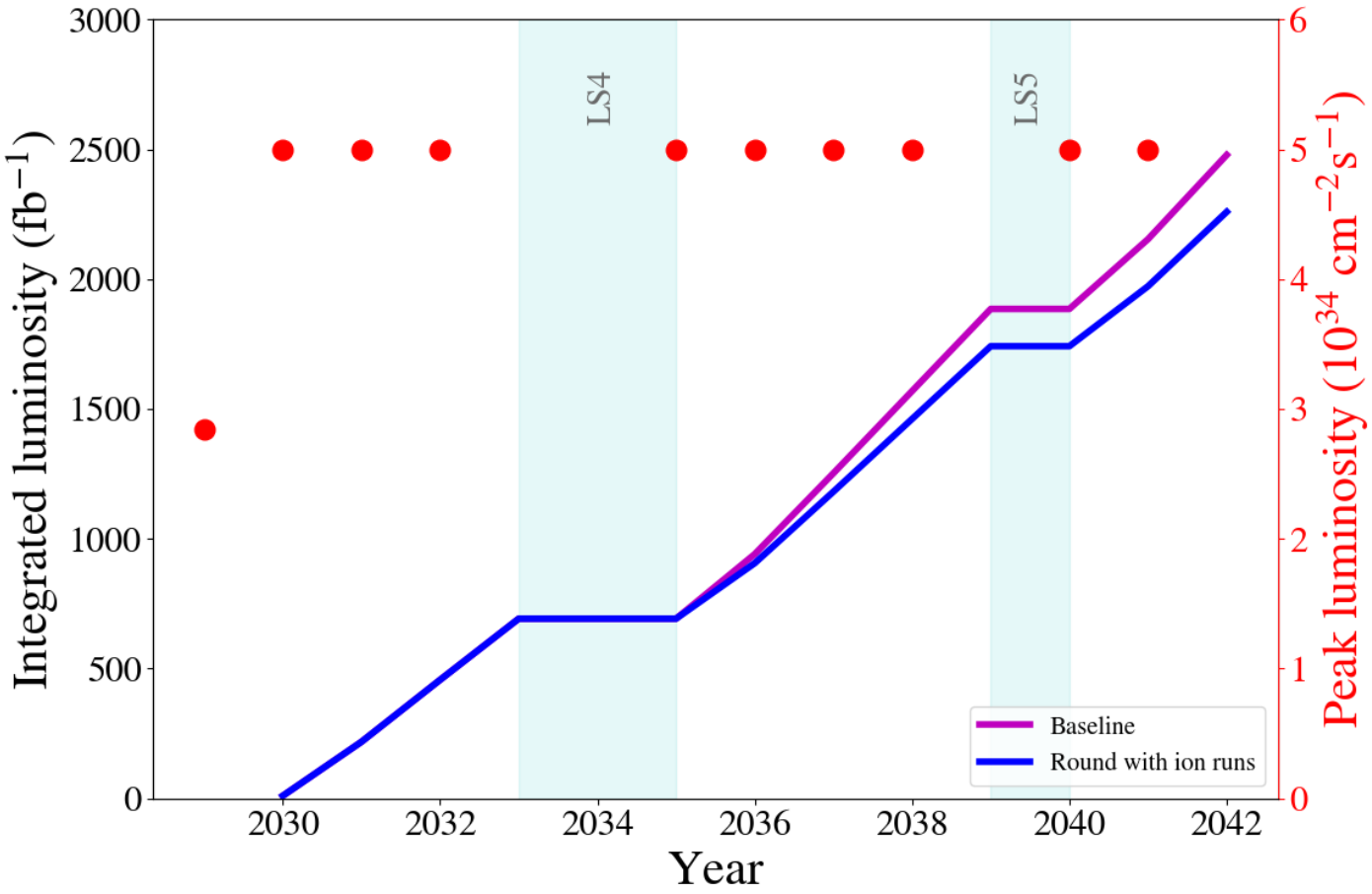
Run	Year	Baseline (fb^{-1})	Round hybrid	Round BCMS	Flat 8/18 cm	Vbaseline extended ions	Round hybrid extended ions	Round BCMS extended ions	Flat 8/18 cm extended ions
4	2029	9.6	-5.21%	4.17%	0%	0%	-5.21%	4.17%	0%
	2030	208	-10.53%	1.30%	0%	0%	-10.53%	1.30%	0%
	2031	238.8	-10.64%	0.92%	6.41%	0%	-10.64%	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%**

- Reaching 15 cm in Run 4 results in 3.44% increase of integrated lumi per year
- 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

Summary


3000
2500
2000
1500
1000
500
0
Integrated luminosity (fb^{-1})
6
5
4
3
2
1
0
Peak luminosity (10^{34} cm^{-2}s^{-1})
LS4
LS5
Baseline
2030
2032
2034
2036
2038
2040
2042
Year

Summary


Integrated luminosity (fb^{-1})
Peak luminosity (10^{34} cm^{-2}s^{-1})
Year
LS4
LS5
Baseline
Round with ion runs
0
500
1000
1500
2000
2500
3000
0
1
2
3
4
5
6
2030
2032
2034
2036
2038
2040
2042

Backup slides

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”