HL-LHC performance and ramp-up scenarios

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- Proton performance and impact of:
  - LHCb upgrade II (not baseline)
  - Devoting 30 days/year for ion runs in Runs 5 & 6
  - Request from cryogenics to ramp-up fill luminosity
  - Blow-up from luminosity burn-off
  - Machine and crab cavity noise

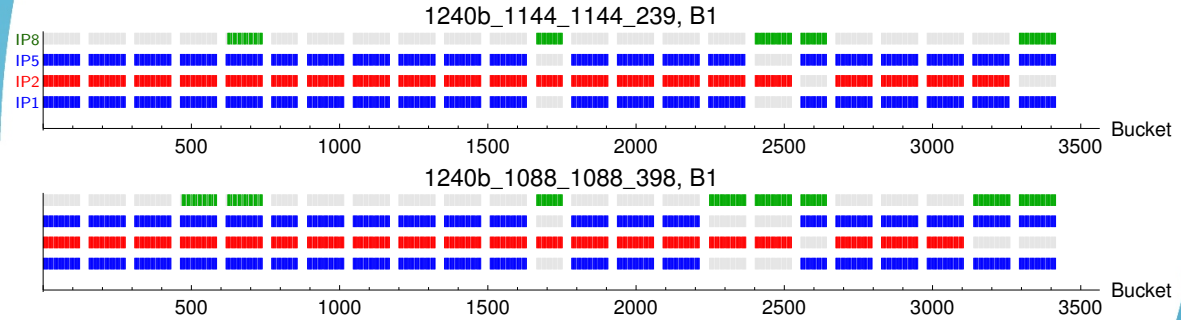
Heavy-ion operation

- Typically one short heavy-ion run per year until end of Run 4
- Updated targets for heavy-ion luminosity in WG5 yellow report:
  - **Pb-Pb goal (end of Run 4):** 13 nb^{-1} at IP1/2/5, 2 nb^{-1} in IP8
  - **p-Pb goal (end of Run 4):** 1200 nb^{-1} at IP1/5, 600 nb^{-1} in IP2/8
  - Note: New requests for more luminosity at LHCb
- Reviewed operational scenario and machine configuration for Pb-Pb and p-Pb: longitudinal parameters, collimation, impedance, ...

	injection	$\rightarrow$	collision
ipb $[10^8]$	1.9	95% transmission	1.8
ϵ_{ave} $[\mu\text{m}]$	1.5	10% blow-up	1.65
$N_{bunches}$	1240		

New heavy-ion filling schemes

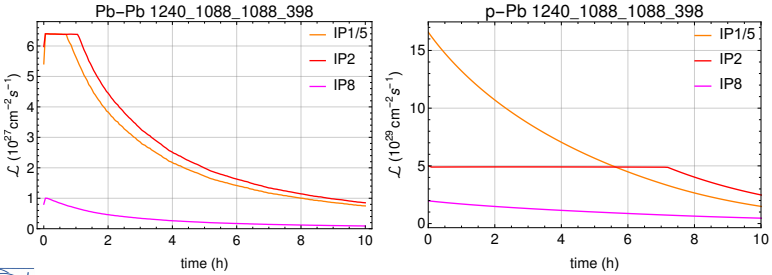
- Updated filling schemes for the Pb beam
  - Optimized abort gap keeper allows more colliding bunches at all IPs
  - Generated various new 50 ns schemes with more collisions at LHCb



See CERN report for details

New heavy-ion performance estimates

- Updated performance estimates for typical 1-month run
  - For Pb-Pb: 2.2–2.8 nb^{-1} at IP1/2/5, up to 0.5 nb^{-1} at IP8
  - For p-Pb: 530–690 nb^{-1} at IP1/5, 310 nb^{-1} at IP2, up to 150 nb^{-1} at IP8
- To reach targets need about 5 runs for Pb-Pb and 2 runs for p-Pb
  - Depending on filling scheme, targets fulfilled within 13%
  - except new LHCb p-Pb target, misses factor 2 - improvements under study
  - Need to also fit 3 p-p reference runs (few days each)



Goals for proton operation

- **Nominal goal**: 250 fb^{-1}/year to reach 3000 fb^{-1}

	injection	$\rightarrow$	collision
ppb [10^{11}]	2.3	95% transmission	2.2
ϵ_{ave} [μm]	2.1	IBS+10% blow-up	2.5
$N_{bunches}$	2760		

  - Luminosity leveled with β^* @ 5×10^{34}cm^{-2}s^{-1}, PU=132
  - Injection with 4×72b.
  - Turn-around-time of 145 min
  - 50% machine efficiency (39% stable beam time)
- **Ultimate goal**: 320 fb^{-1}/year to reach 4000 fb^{-1}
  - leveling @ 7.5×10^{34}cm^{-2}s^{-1}, PU=200
  - 50% efficiency (34% stable beam time)
  - Turn-around-time of 150 min

HL-LHC performance ramp-up to baseline

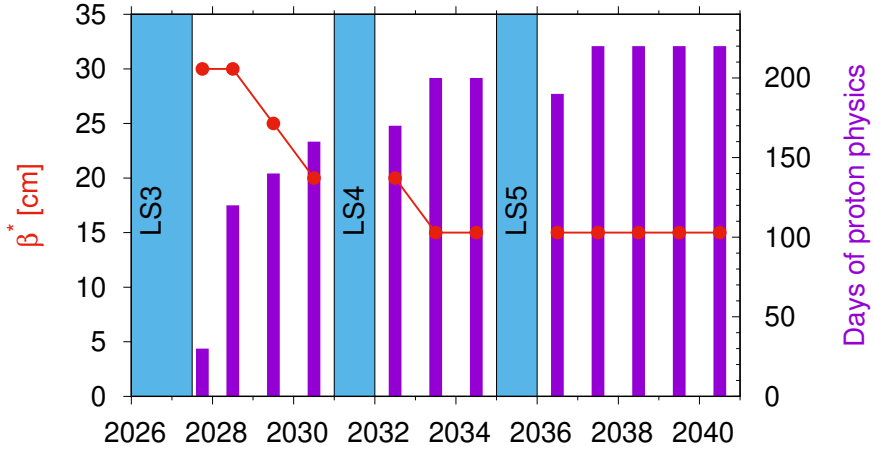
Year	ppb [10^{11}]	Virtual lumi. [10^{34}cm^{-2}s^{-1}]	Days in physics	θ [μrad]	β^*_{start} [cm]	β^*_{end} [cm]	HEL & crab cav.
2027	1.7	3.9	30	380	58	30	off
2028	1.7	3.9	120	380	58	30	off
2029	2.2	10.3	140	500	100	25	on
2030	2.2	13.5	160	500	100	20	on
2032	2.2	13.5	170	500	100	20	on
2033	2.2	16.9	200	500	100	15	on

Parameter or system being ramped-up or commissioned.

β^*_{start} provides initial luminosity of 2.5×10^{34}cm^{-2}/s as requested by cryo.

HiLumi HL-LHC PROJECT CERN

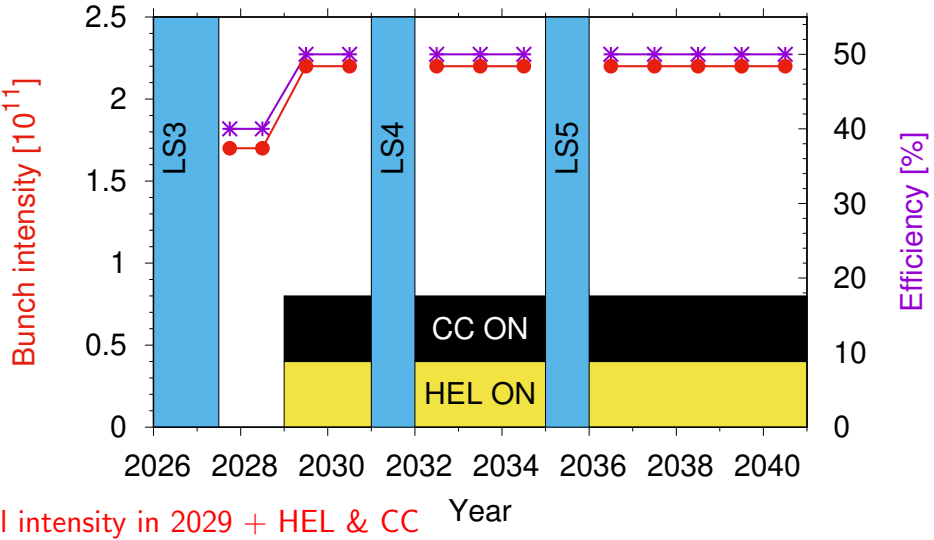
β^* and days of proton physics



Nominal β^* reached in 2033

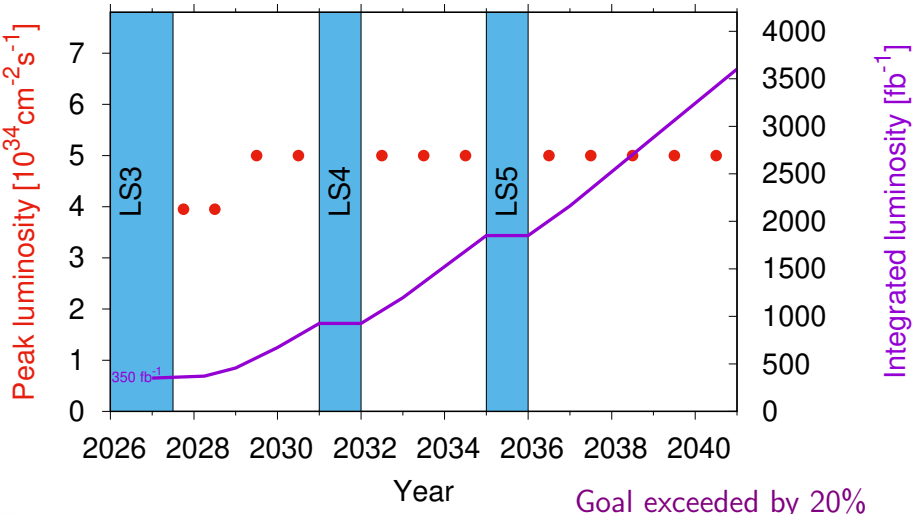
Total days of proton physics = 2090

Bunch intensity, efficiency, HEL and CC



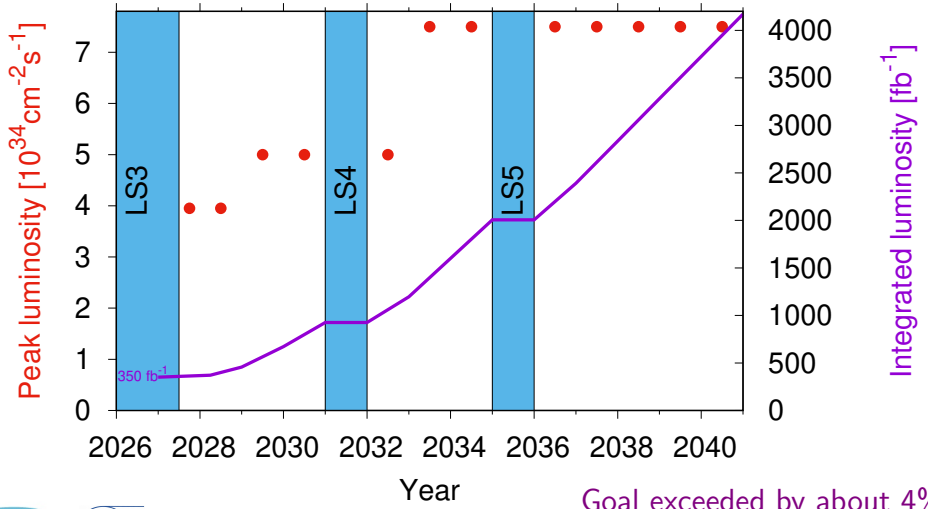
Nominal intensity in 2029 + HEL & CC

Baseline performance



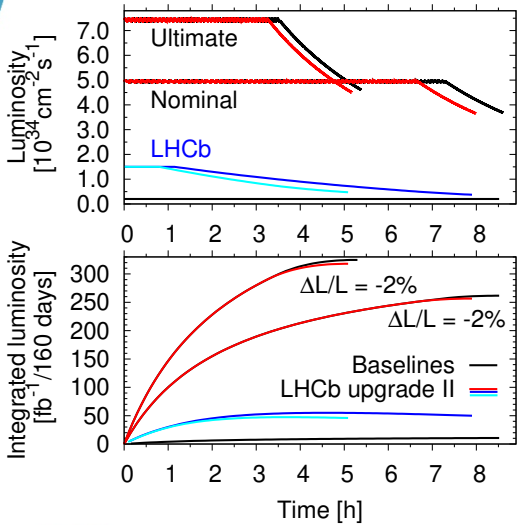
Goal exceeded by 20%

Ultimate performance



Goal exceeded by about 4%

Impact of LHCb upgrade II on ATLAS/CMS

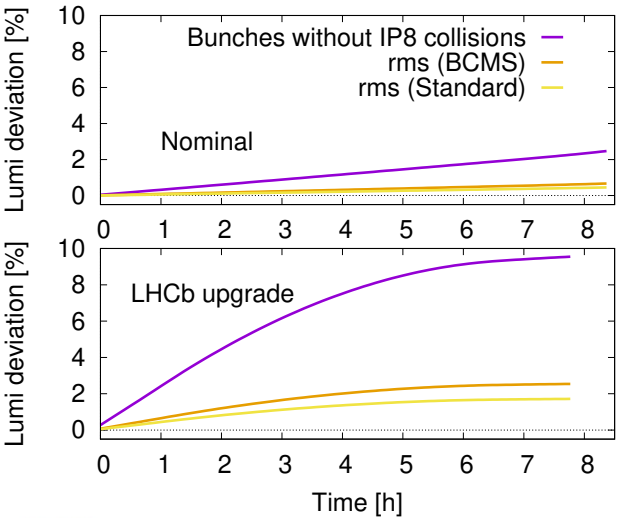


LHCb upgrade II, $L_{lev} = 1.5 \times 10^{34}$ cm^{-2}s^{-1} (not yet in the baseline) would reduce ATLAS/CMS integrated luminosity by 2% for both Nominal and Ultimate.

Reduced lifetime from increased beam-beam not included here.

Increased burn-off in IP8 causes bunch-by-bunch variations, under study.

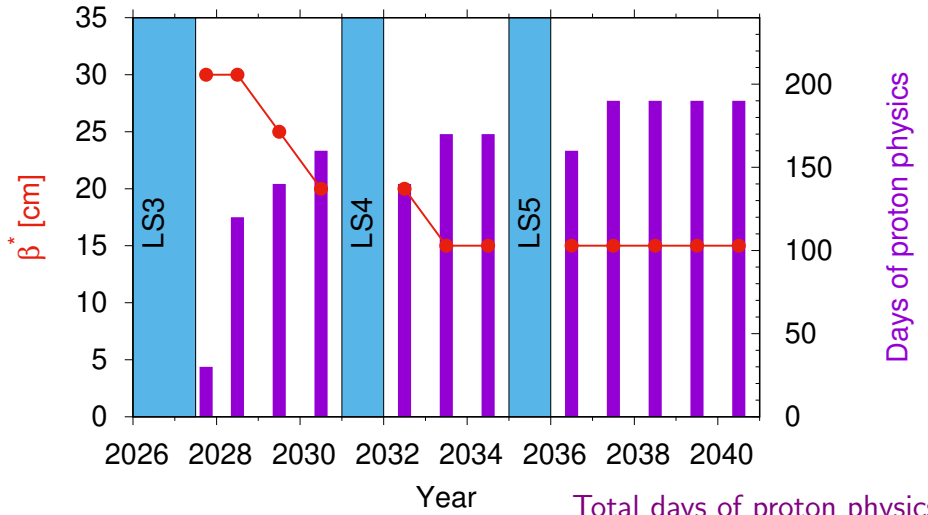
Bunch-by-bunch luminosity variations from IP8



Bunches not colliding in IP8 feature a 10% higher IP1/5 luminosity at the end of the fill for the LHCb upgrade II scenario.

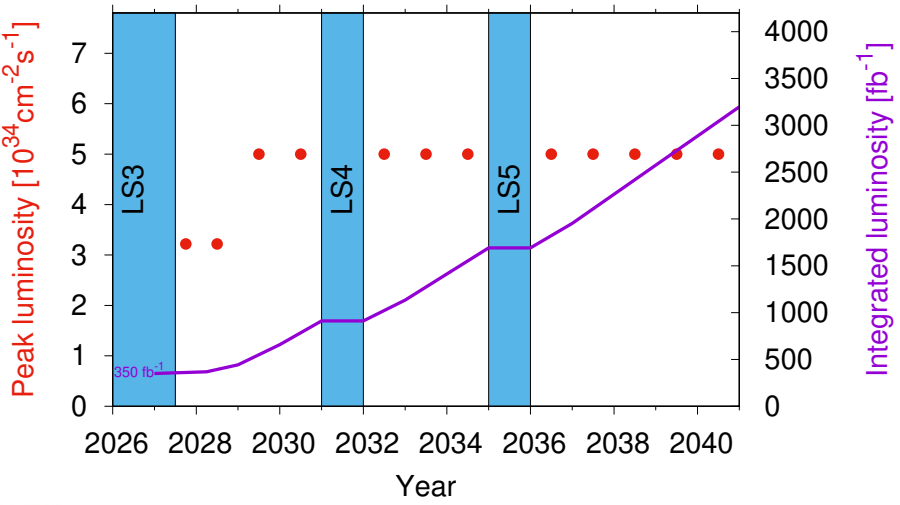
Impact on bunch-by-bunch rms luminosity is about 2%, which is OK compared to the 10% rms tolerance set by detectors. To be monitored with performance from injectors.

With extra ion runs in Runs 5 & 6

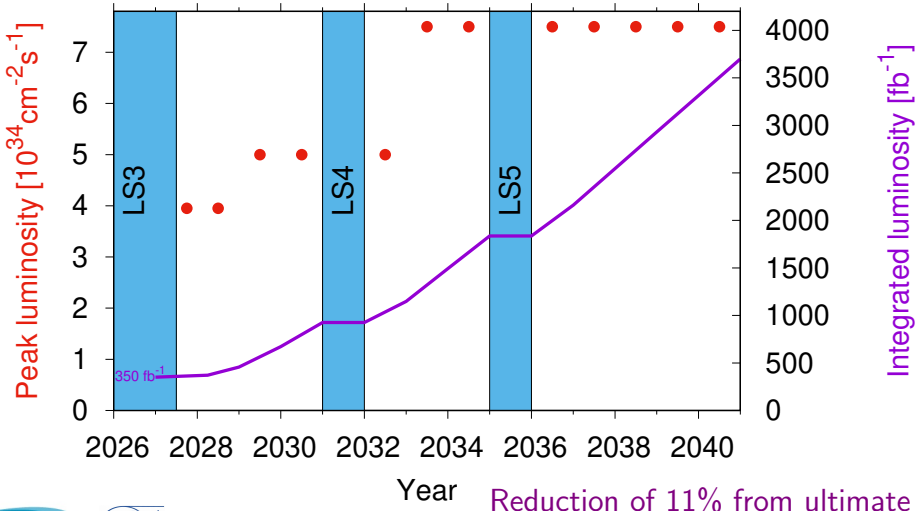


Total days of proton physics = 1850

Baseline performance – With extra ion runs

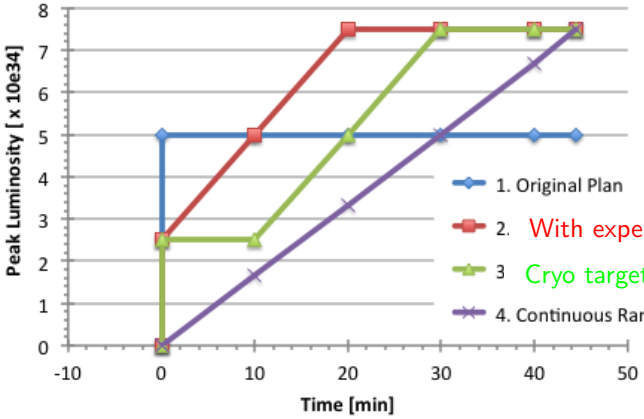


Ultimate performance – With extra ion runs



Reduction of 11% from ultimate operation

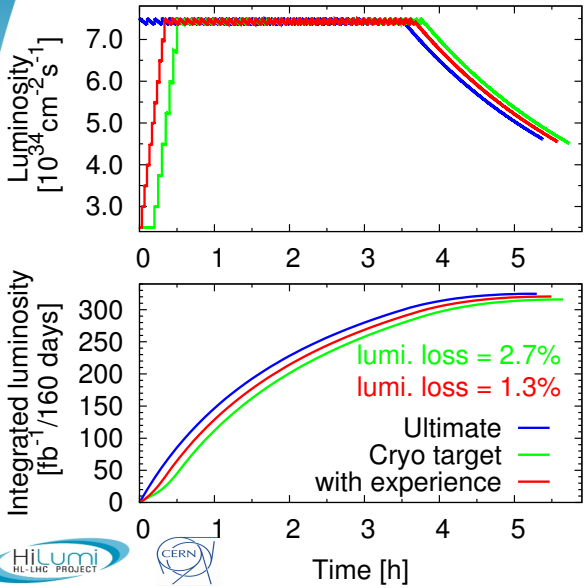
Request of slow luminosity ramp-up from cryogenics



Serge Claudet

Need to start collisions at $\beta^* = 1$ m to provide L=2.5×10^{34}cm^{-2}/s with crab cavity off.

Fill luminosity ramp-up for cryo. (Ultimate)



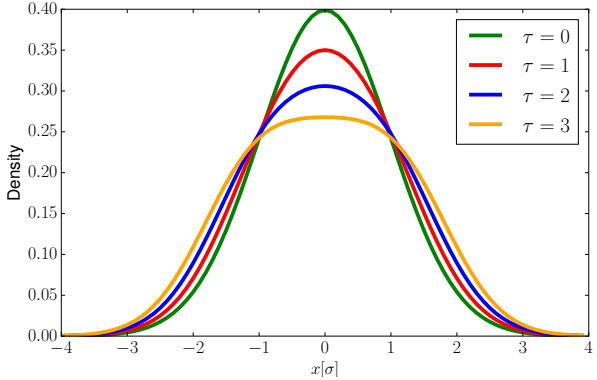
Cryo target: 2.7% lumi loss.

With experience: 1.3% lumi loss.

1% integrated luminosity in HL-LHC is not negligible

Emittance blow-up from luminosity burn-off

Luminosity burn-off removes relatively more particles from the core than from the tails, producing an effective emittance blow-up:

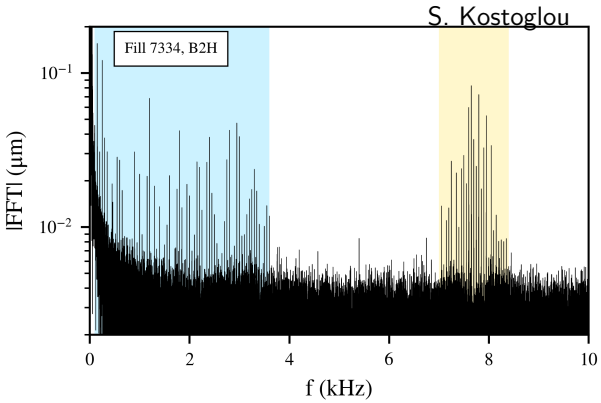


τ represents time in collision

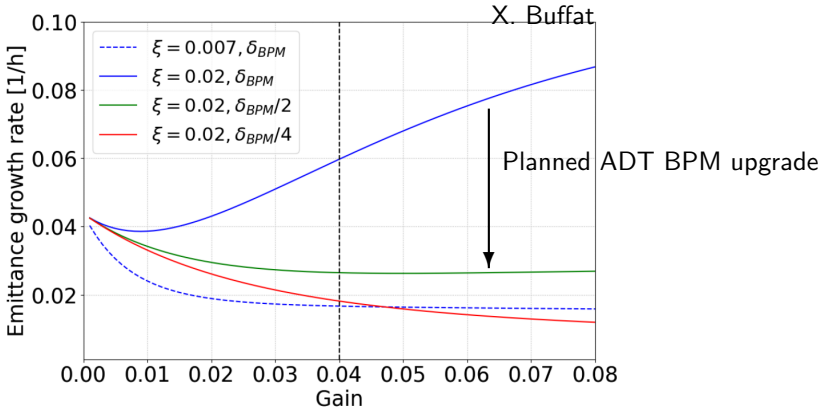
R. Tomas et al, "Emittance growth from luminosity burn-off in future hadron colliders" Phys. Rev. Accel. Beams **23**.

Machine noise: recent finding

- Two clusters of 50 Hz harmonics on the transverse beam spectrum: low-f cluster and high-f cluster (7-8 kHz).
- Based on measurements, UPS is a potential candidate for the high-f cluster. ADT and UPS beam and HW tests in Run 3.
- Ideally, source is identified and mitigated to avoid emittance blow-up, else rely on feedback.

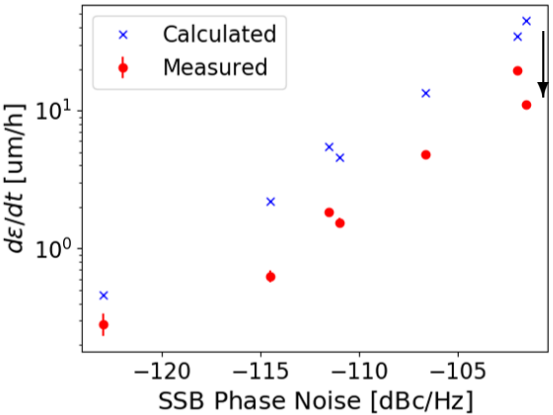


Fighting noise with the ADT feedback



Further optimisation: S. Furuseth, X. Buffat *et al*, "Emittance growth suppression with a multibunch feedback in high-energy hadron colliders: Numerical optimization of the gain and bandwidth"

Crab cavity noise: SPS measurements Vs model



This factor 2 discrepancy is being reviewed by doing bunch-by-bunch studies since there was a large spread

In HL-LHC feedback should partially mitigate impact of CC phase noise.

Known potential sources of lumi loss in IP1/5

	$-\Delta L/L$ [%]
Cryo lumi. ramp-up	0-3
Blow-up from burn-off	1
Blow-up from machine noise	1-2
Blow-up from CC noise	0-2
LHCb upgrade II	2
Extra ion runs in Runs 5&6	11
Total	2-21

Some of these items will be incorporated in baseline figures.

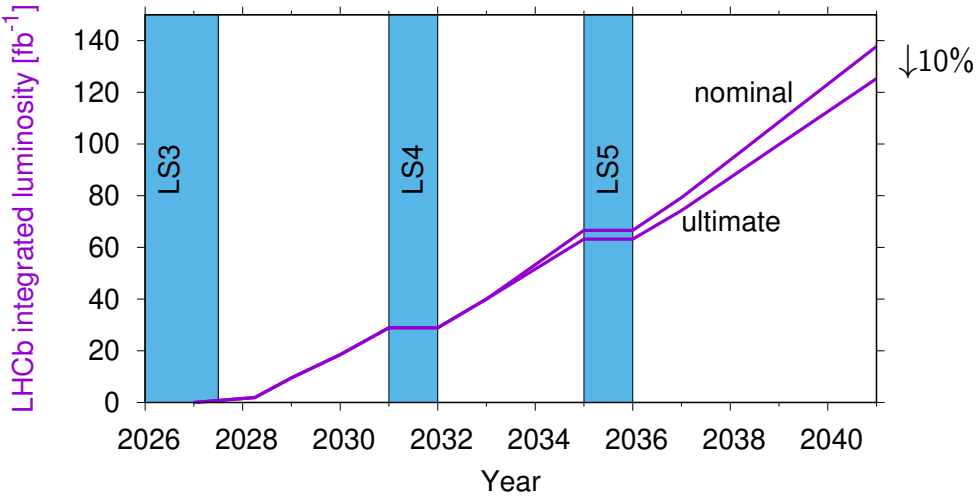
Unknown sources not accounted: Blow-up in ramp, poor lifetime, etc.

Summary

- Proton and ion goals are at reach in new baselines.
- New p-Pb request for LHCb missed by factor 2, being investigated.
- Tight margin for proton ultimate goal
- Need to include known sources of luminosity loss in baseline, which might need improved models
- New results from the impact of pile-up density on detector performance being analyzed within the EDQ WG

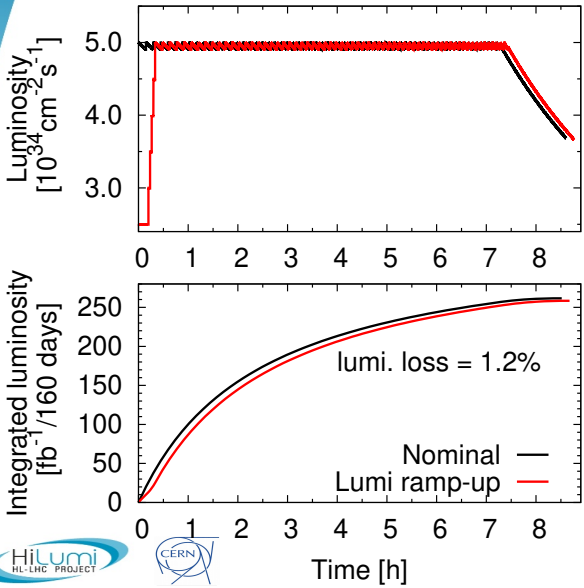
Extra slides

LHCb, $L_{lev} = 2 \times 10^{33}$ cm^{-2}s^{-1}



For ALICE $L_{lev} = 1.4 \times 10^{31}$ cm^{-2}s^{-1}

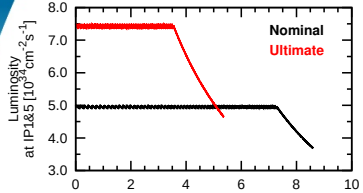
Luminosity ramp-up for Nominal

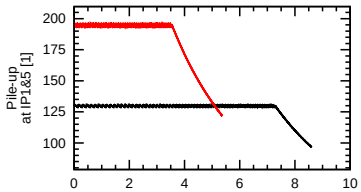


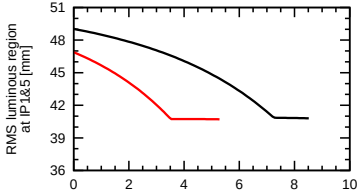
Cryo Target is shown in red.

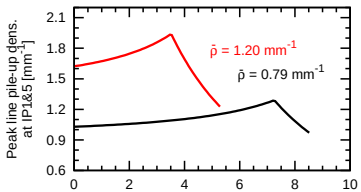
1.2% lumi. loss at the end of the fill, but larger loss for shorter fills.

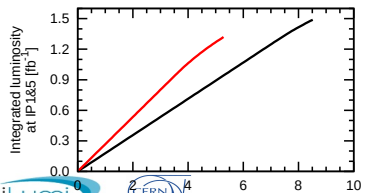
With experience: 0.4% loss.

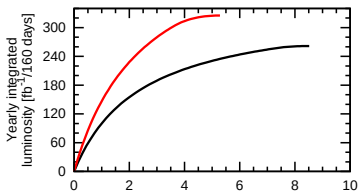

Luminosity at IP1&5 [10^34 cm^-2 s^-1]
Nominal
Ultimate


Pile-up at IP1&5 [1]


RMS luminous region at IP1&5 [mm]


Peak line pile-up dens. at IP1&5 [mm^-1]
ρ̃ = 1.20 mm^-1
ρ̃ = 0.79 mm^-1


Integrated luminpsity at IP1&5 [fb^-1]
Time [h]


Yearly integrated luminosity [fb^-1/160 days]
Time [h]