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Analysis of the performance in the 2023 LHC Pb-Pb run

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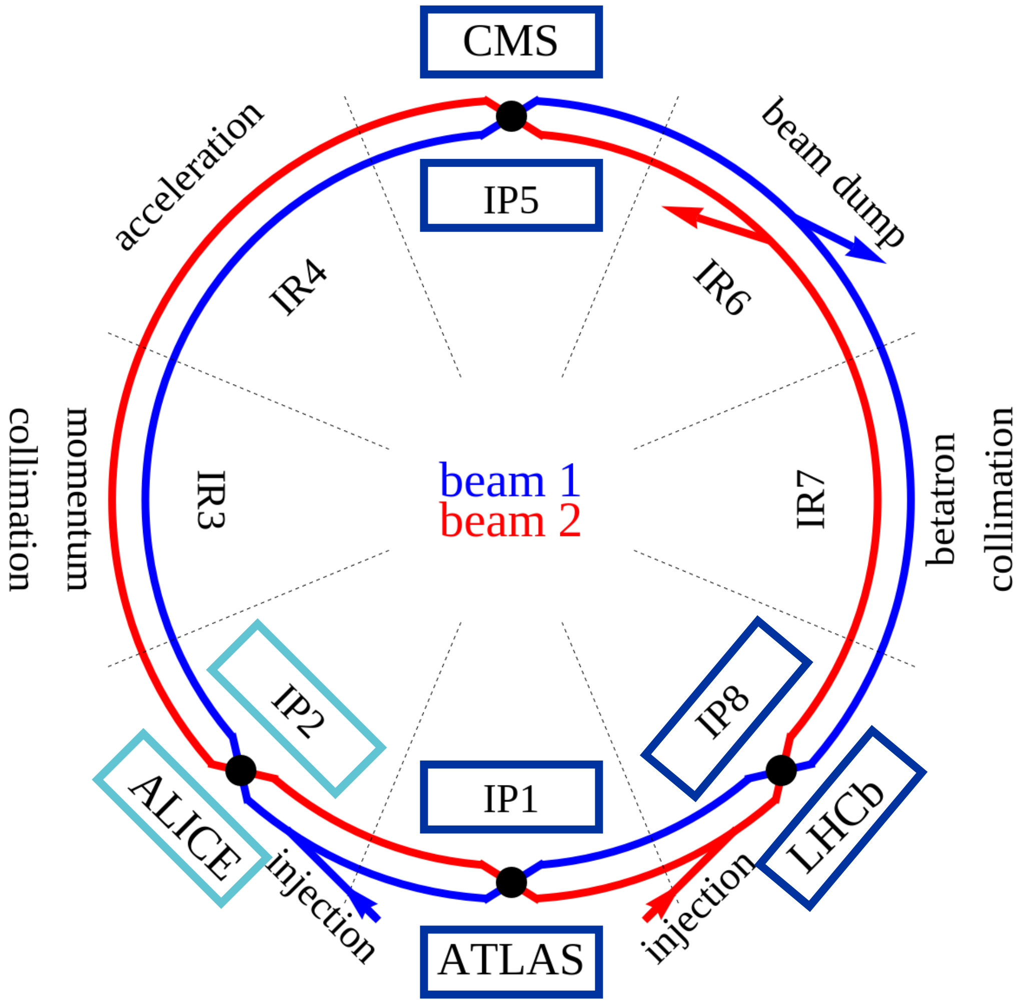
Outline

- Introduction
  - Heavy-ion program in the LHC
  - 2023 Pb-Pb run overview
- Achieved performance and challenges
- Performance comparison for configurations for future runs
- Summary and outlook

LHC and heavy ions

- The **LHC** accelerates and collides **2** counter-rotating **beams** in its **4 main experiments**
  - ATLAS / ALICE / CMS / LHCb

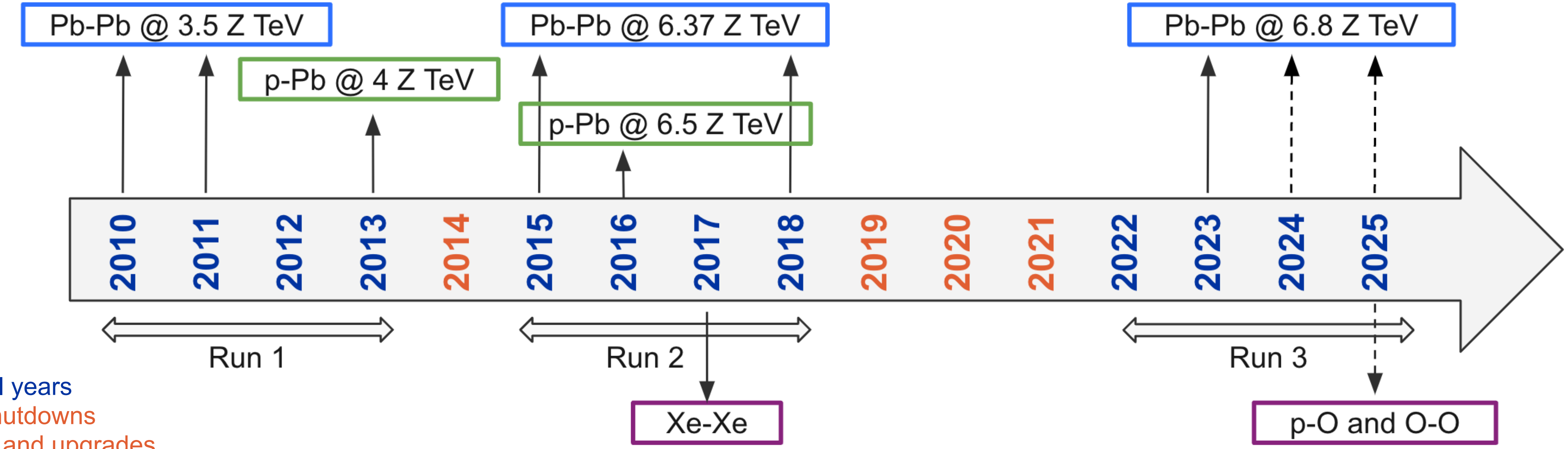
- Mainly protons but also heavy **ions**
  - Ion collisions **in all 4 experiments**
  - ALICE is specialised in ion collisions



Courtesy of B. Lindstrom

Ions in the LHC timeline

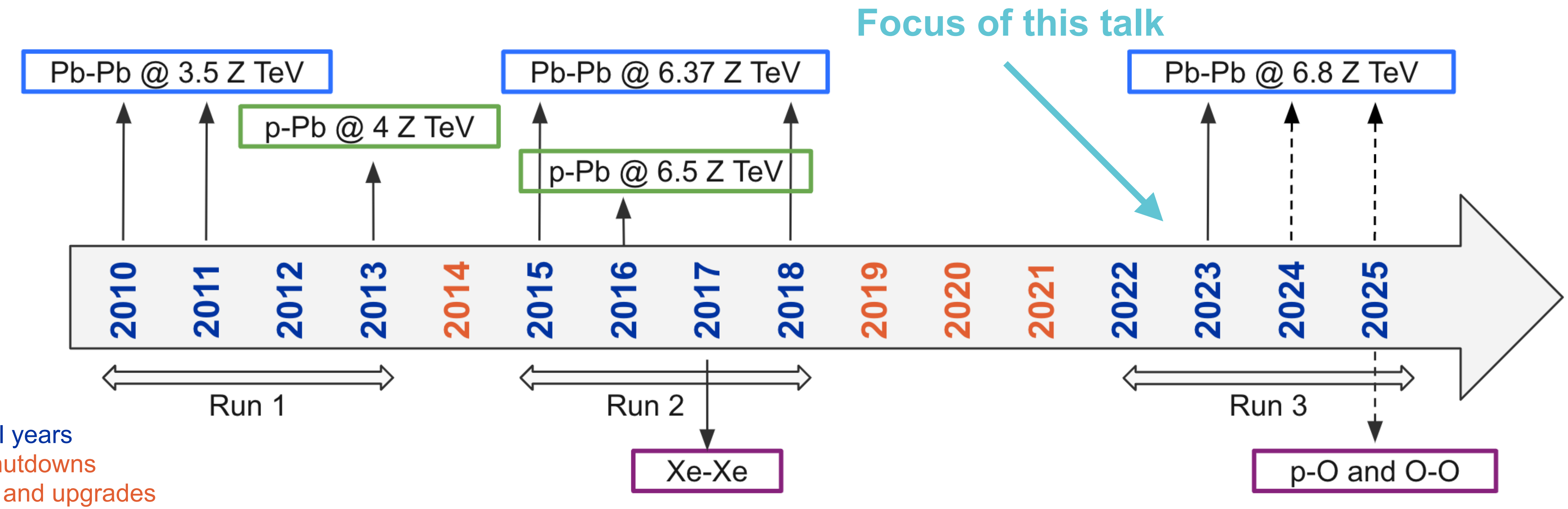
- **Ion run** typically at the **last month** of each **operational year**
- Initially fully stripped **Pb-Pb**; later **p-Pb**; but also short pilot runs with other species:
  - Xe-Xe (completed in 2017)
  - O-O and p-O (planned for 2025)



Blue: operational years
Orange: Long shutdowns
for maintenance and upgrades

Ions in the LHC timeline

- The **2023 Pb-Pb run** was the first in **LHC Run 3**
- At a record beam energy of **6.8 Z TeV** (557.6 TeV/Pb ion)
  - **Focus of this talk**
- Plans for future Pb-Pb runs in 2024, 2025 and in Run 4 (2029-2033)

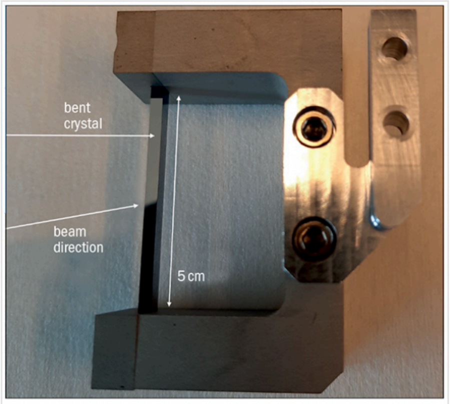


Blue: operational years
Orange: Long shutdowns for maintenance and upgrades

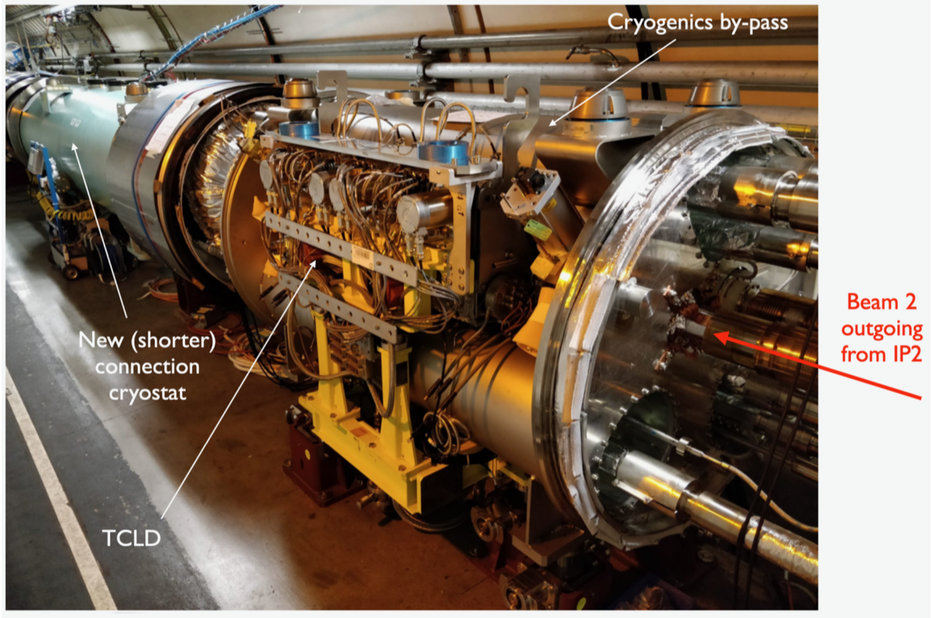
Key beam and machine upgrades

- **Increase of total number of bunches;**
  - 1240b vs 733b (50 ns vs 75 ns spacing)
  - This upgraded beam production scheme was achieved for the first time
- **Crystal collimation** to manage the higher intensity; Talk by S. Redaelli: **FRXN3**
- **New orbit bumps in IR2/8,** with **dispersion suppressor collimators** in IR2, to mitigate the risk of magnet quenches due to collisional losses
- **Major ALICE upgrades** in the last long shutdown to accept factor 6 higher luminosity

Silicon-strip crystal



Dispersion suppression collimator in LHC tunnel



** Deployed as a part of the High Luminosity LHC project*

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  - 1240b vs 733b (50 ns vs
  - This upgraded beam pro
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The 2023 ion run was the first one to include all foreseen ion upgrades for High Luminosity LHC

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  Talk by S. Redaelli: **FRXN3**

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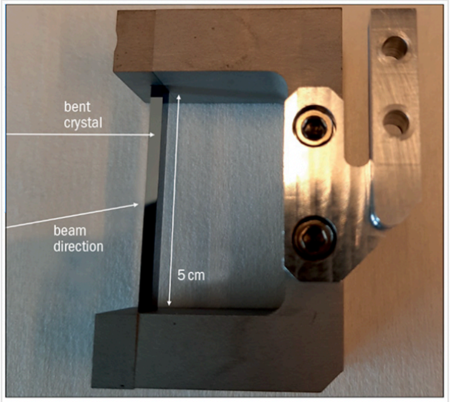
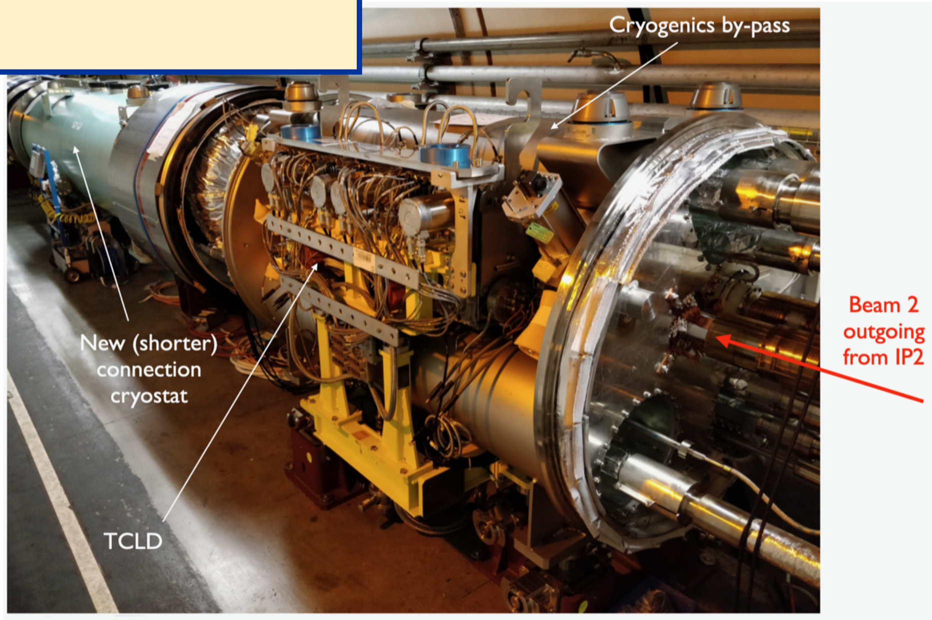


ion collimator in LHC tunnel



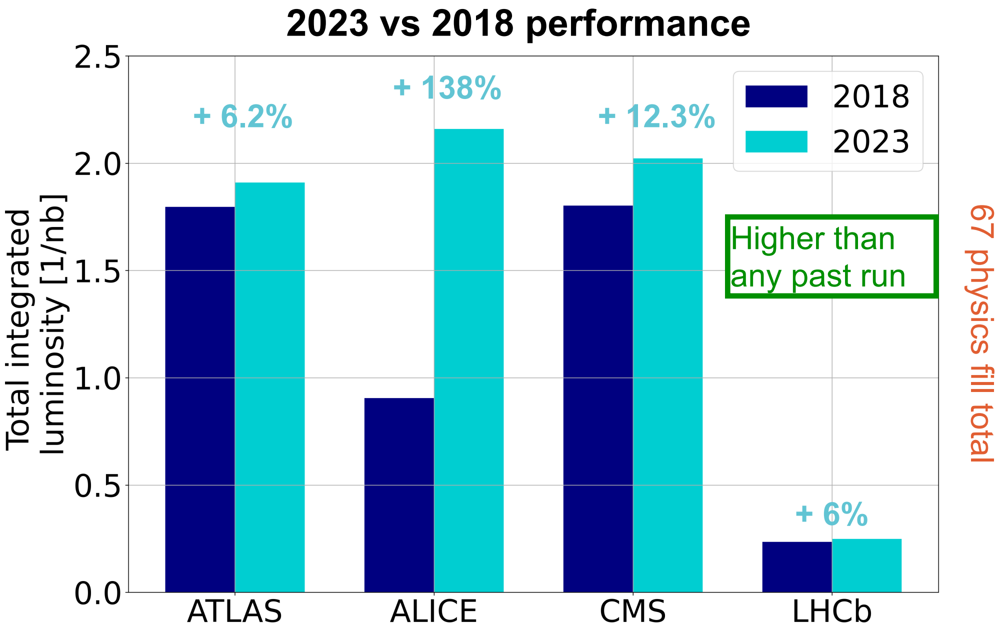
** Deployed as a part of the High Luminosity LHC project*

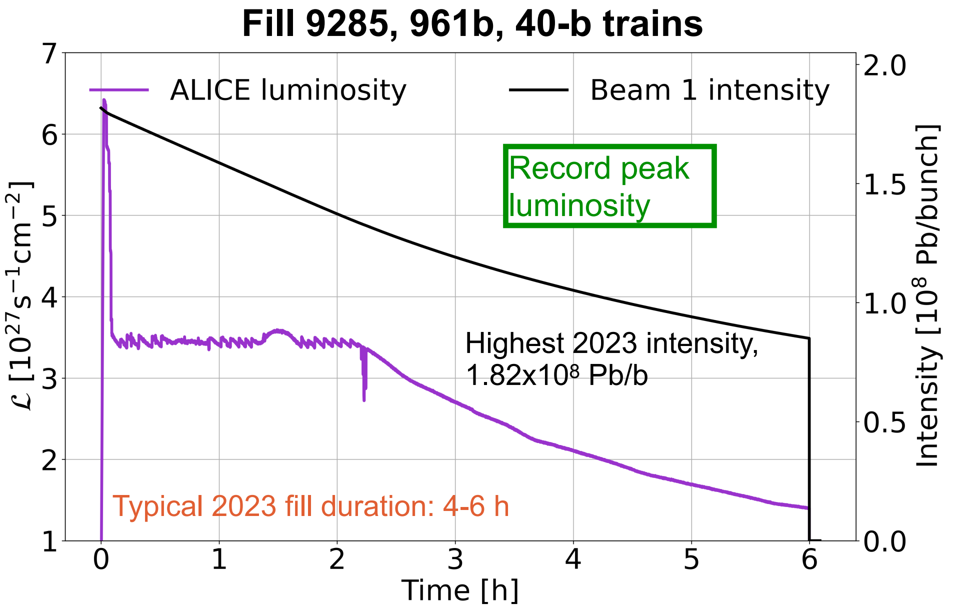
Performance highlights

- **Integrated luminosity:** key indicator of accelerator performance; ∝ to the number of collisions in a given amount of time
- **Integrated higher luminosity in 2023** than in any past run in **all experiments**
  - Similar performance for ATLAS/ALICE/CMS integrating ~2/nb
- Achieved more than a **factor 6** higher **peak luminosity** (6.4×10^{27} s^{-1} cm^{-2}) in **ALICE** than before
- $\mathscr{L}_{\text{daily}}$ **= 100/µb** in ATLAS/ALICE/CMS during periods w/o long faults

Collision optics in 2023

	IP1/5	IP2	IP8
$\beta^{\star}$ $[m]$	0.5	0.5	1.5
Net half crossing [urad]	170	± 98	-274





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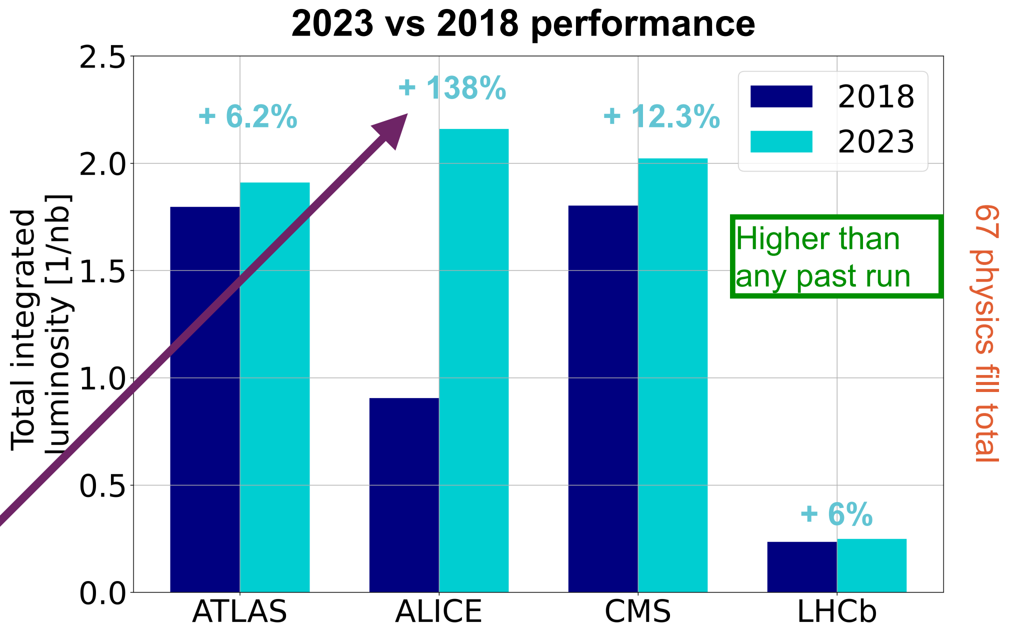
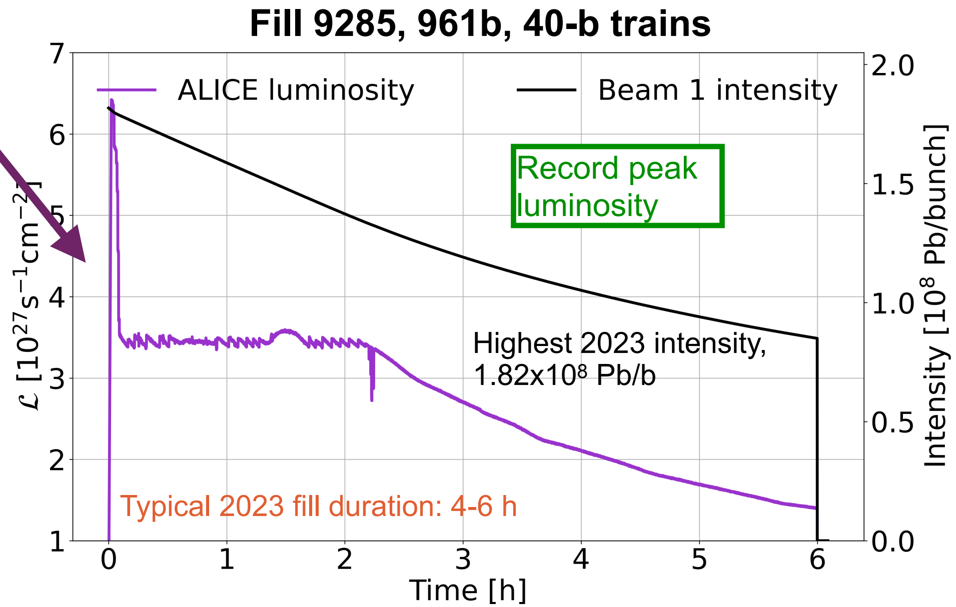
- Ac … ^{27} s-1

Clear benefits in ALICE from upgrades

- $\mathscr{L}_{\text{daily}}$ **= 100/μb** in ATLAS/ALICE/CMS during periods w/o long faults





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  - Similar performance for AT...

> The **performance** could have been even **higher** without several unforeseen **challenges**

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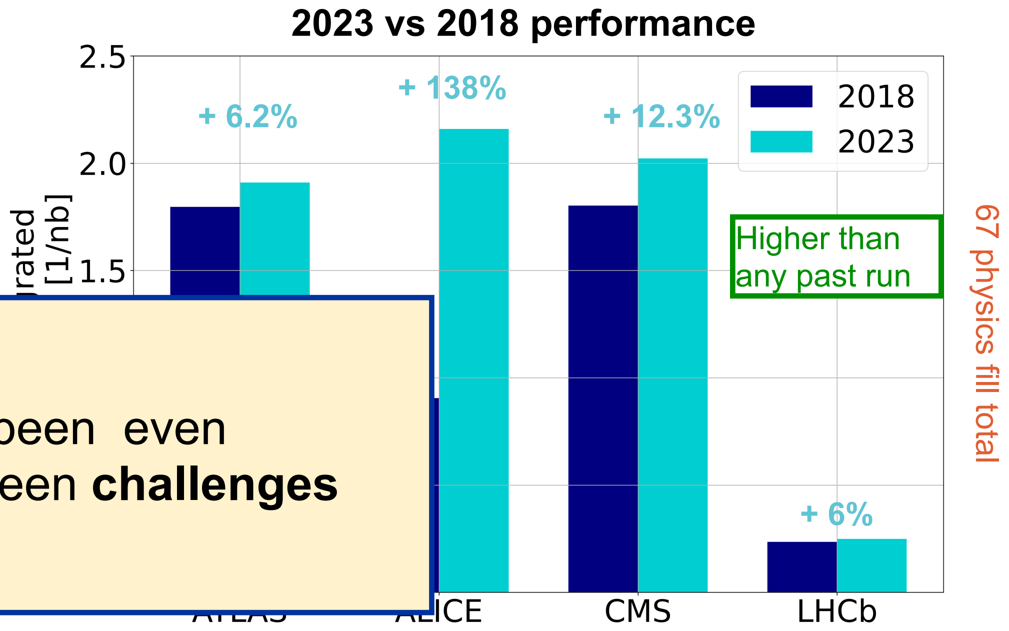
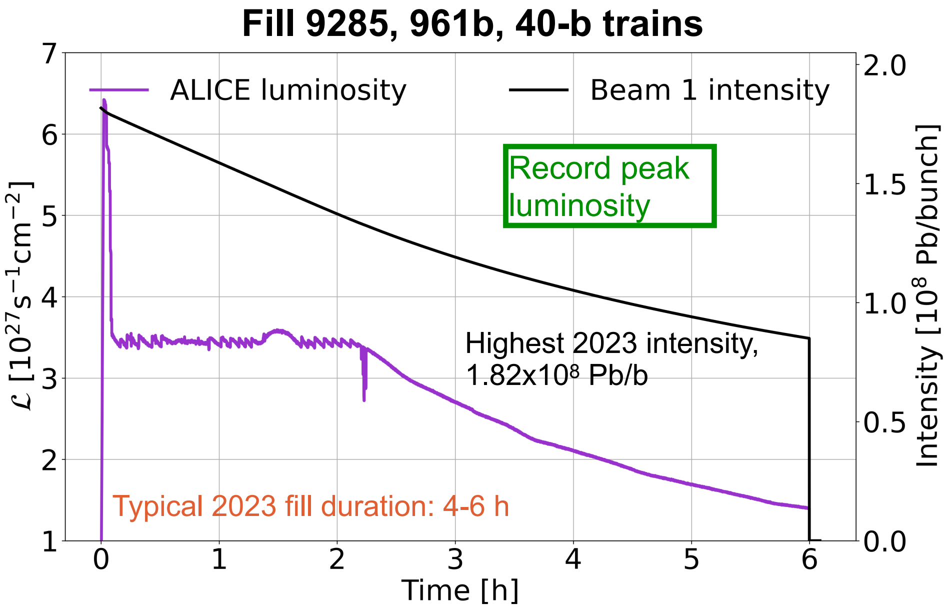
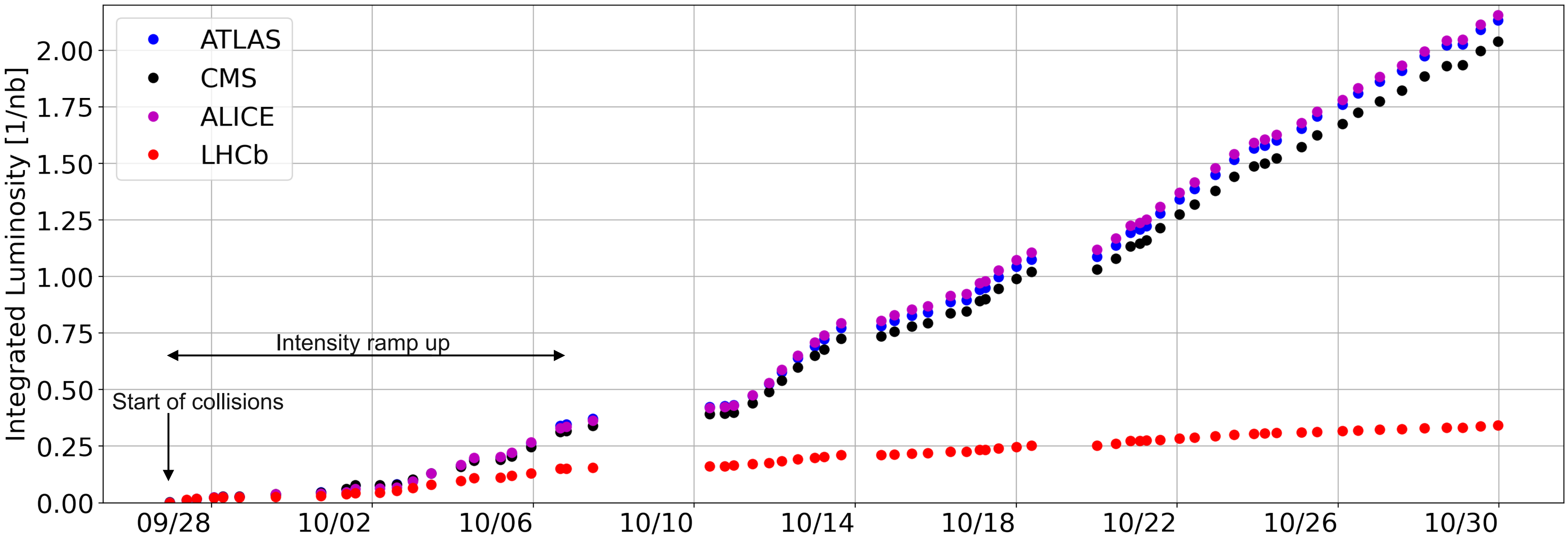


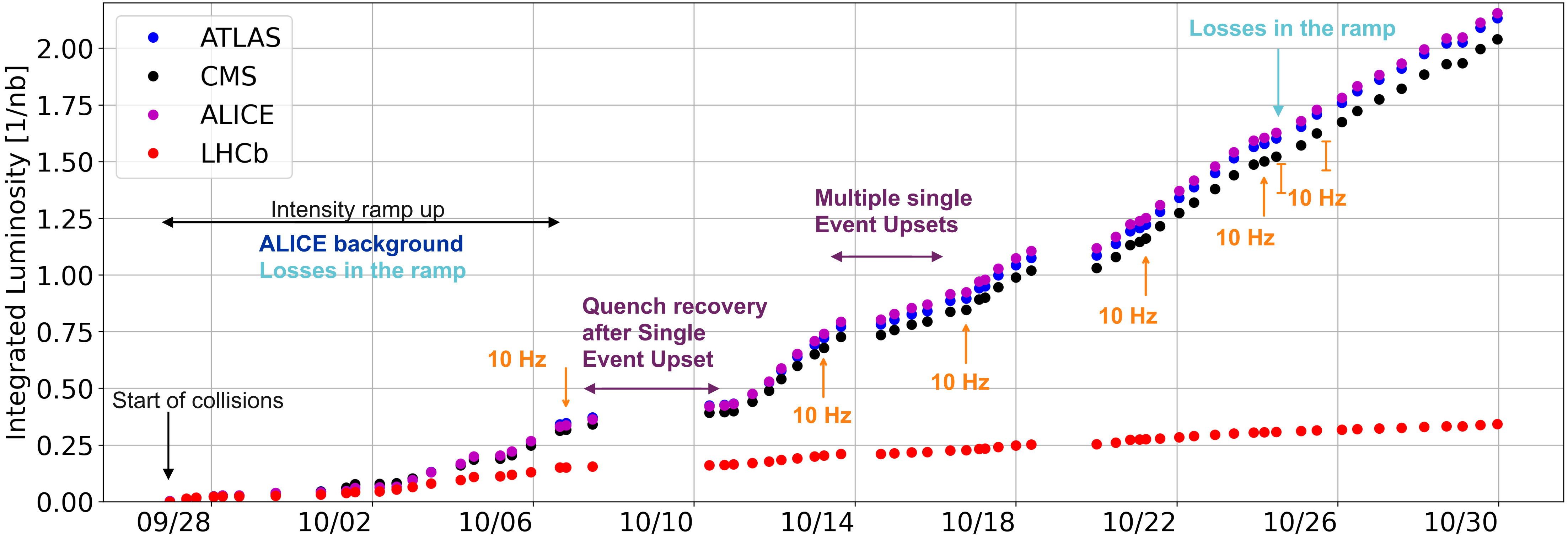


Run overview



Unforeseen challenges

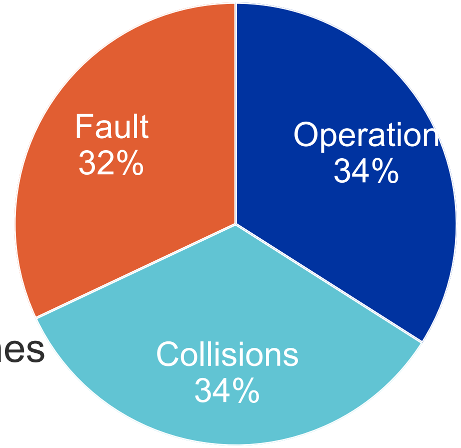
- Significant **time lost** due to:
  - **Strong background in ALICE** → 1.6 days mitigation campaign
  - **Transverse losses in the ramp** (6.1-6.7 Z TeV) → beam dumps
  - **Single Event Upsets** on quench protection system, likely from collisional radiation → beam dumps, quenches
  - **Horizontal orbit oscillations** in beam 1 at ~10 Hz for high-intensity beams → beam dumps



Unforeseen challenges

1/3 of the time spent in physics **collisions**

2023 availability



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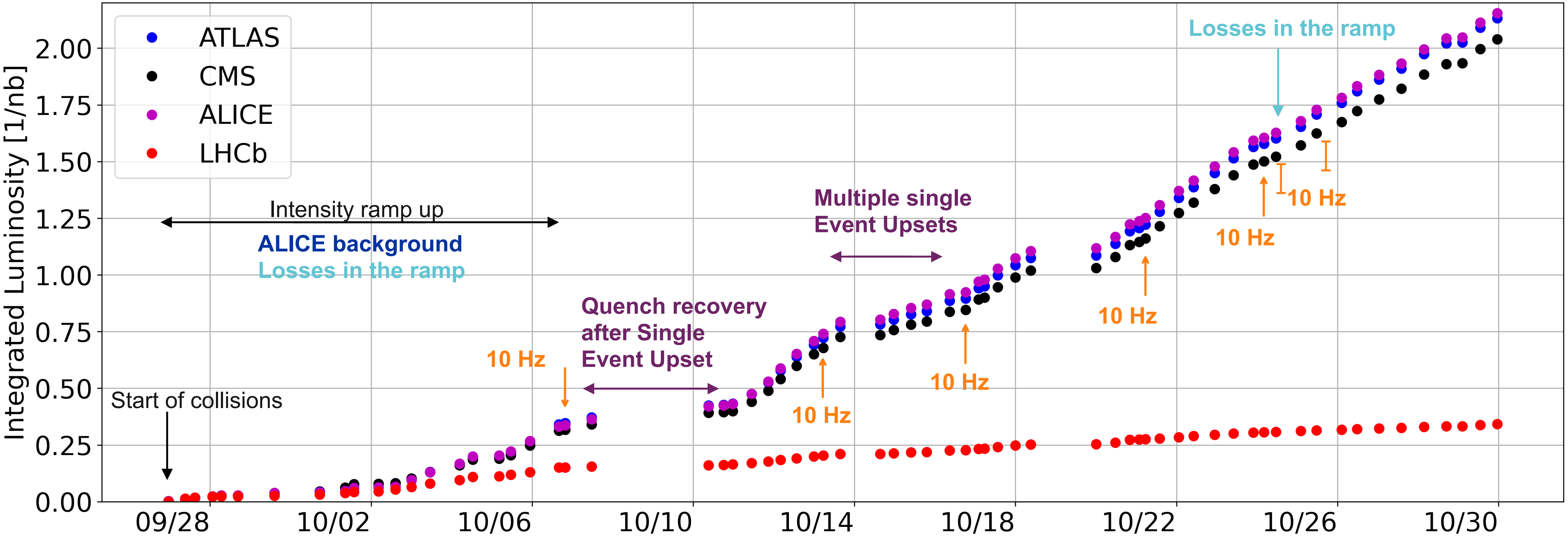
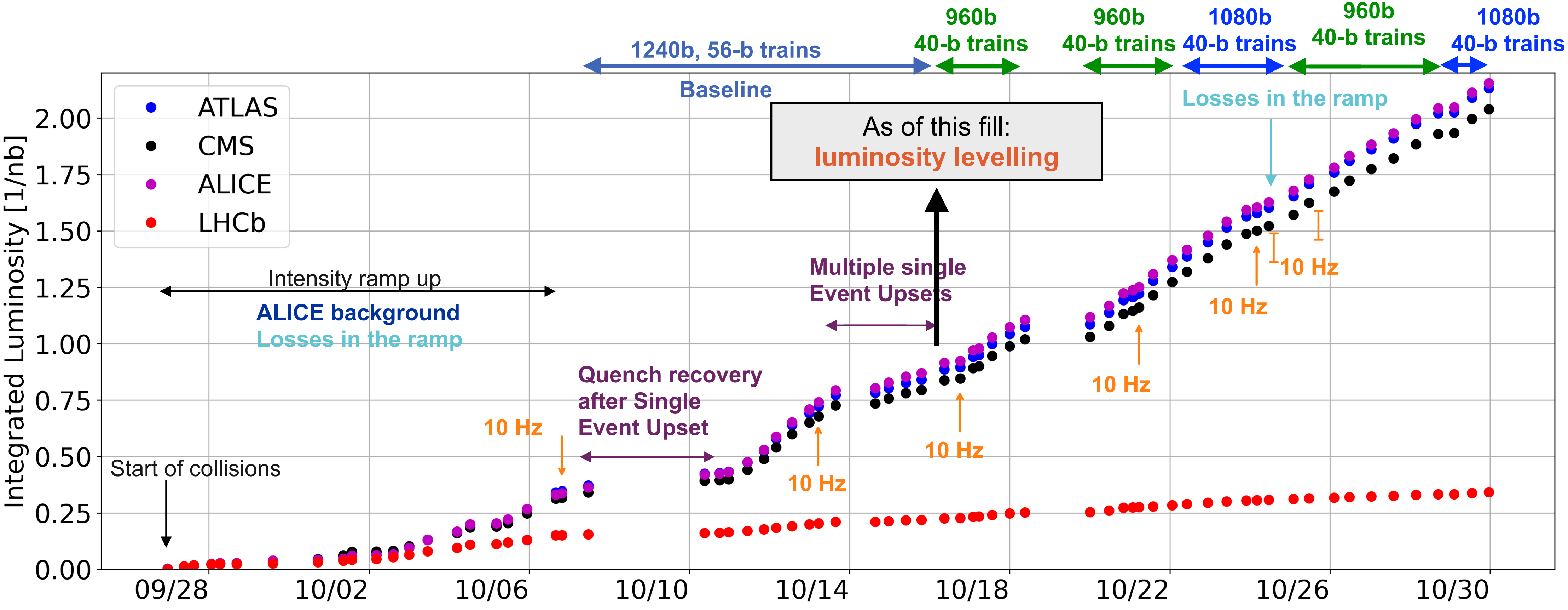


Mitigation measures impacting performance

- **Luminosity levelling @ 3.5x10^{27} s^{-1} cm^{-2}** to mitigate the Single Event Upsets from collisional losses
- **Different filling schemes** with 40-b trains I/o 56 b-trains to lower total intensity and intensity per injection



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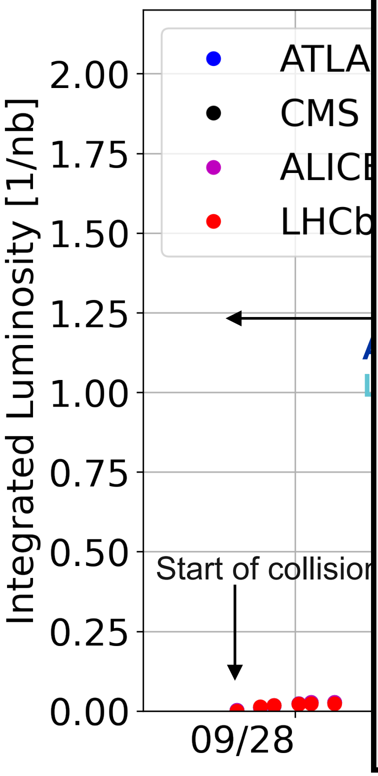
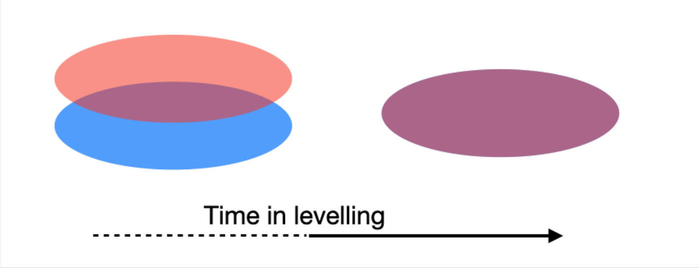


Luminosity levelling: used to **control** peak luminosity / number of collisions per bunch

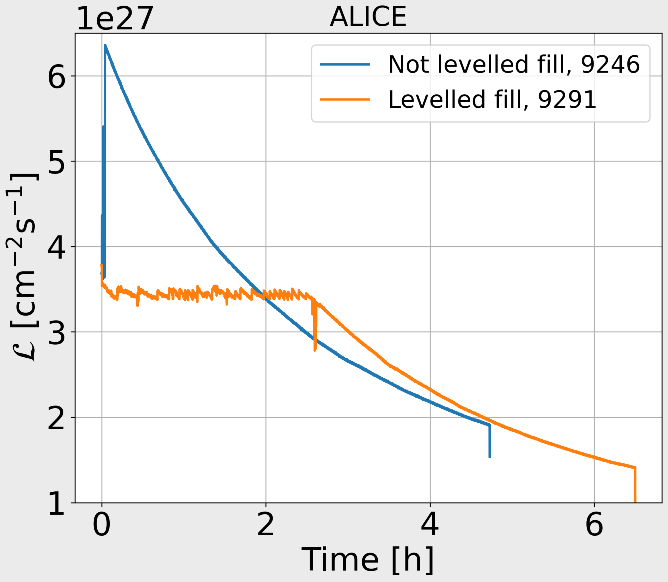
Achieved with **transverse offset** between the two **colliding beams**

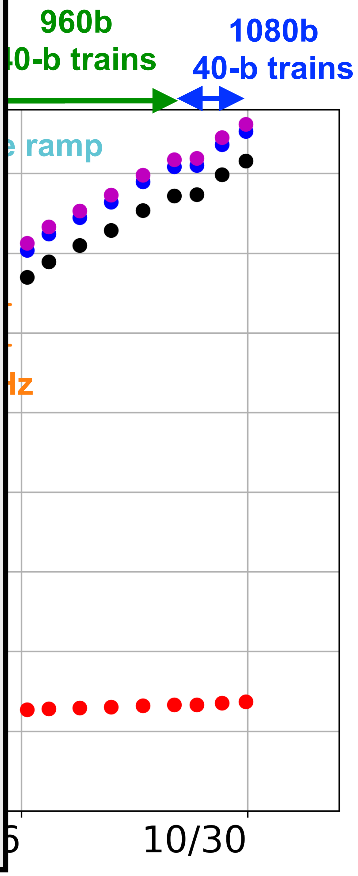
- **Local** orbit bump
- Applied **independently** in all interaction points

Luminous region during levelling



Example fills with / without levelling





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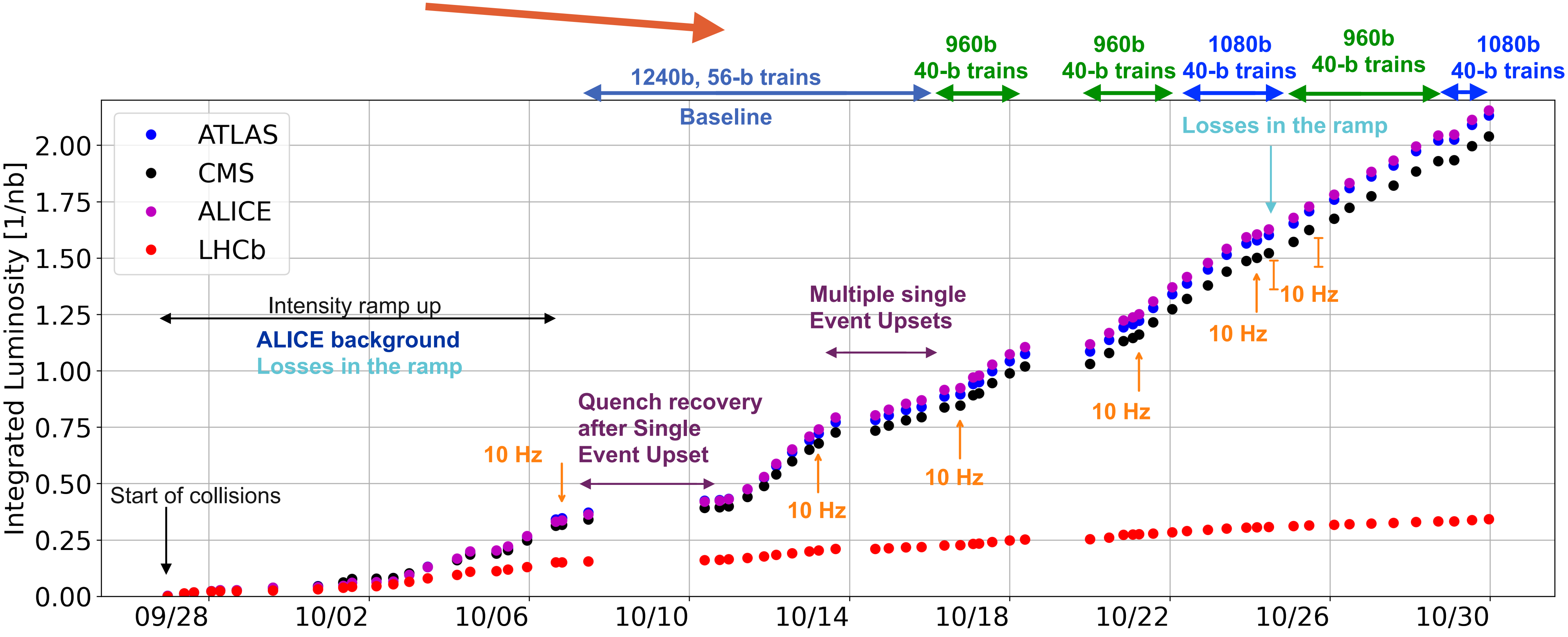
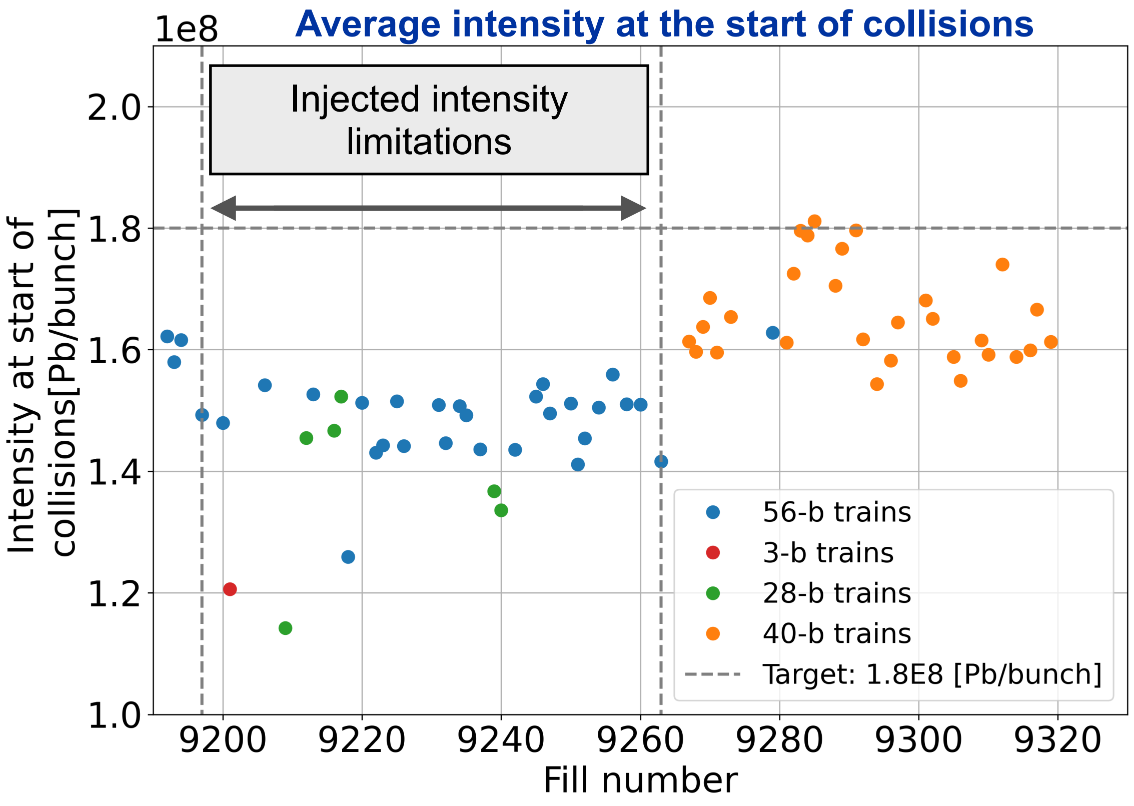


Beam quality

- **Bunch intensity** at the start of collisions
  - **56-b trains: 1.5x10⁸ Pb/bunch**; limitations on injected intensity*2 for machine protection reasons
  - **40-b trains: 1.67x10⁸ Pb/bunch**; no limitations on injected intensity
  - **Target 1.8x10⁸ Pb/bunch** achieved only in a few fills with 40-b trains

- **Emittance** similar for **56-b** vs **40-b** trains ~2 μm at the start of collisions
  - Computed from ATLAS luminous region
  - **Higher than** the **target value** 1.65 μm, mainly in horizontal



*1 *3-b, 28-b trains used for special fills, out of scope here*

*2 *Intensity limitations for 56-b trains to protect injection protection absorber operating in degrading mode due to vacuum leaks, 1 less injection in LEIR*

Quantifying the performance

- To **understand** the encountered limitations and **further increase** the **performance** in future runs a **detailed analysis** of the performance impact will be shown
- For issues that mainly resulted in **lost time** we estimated the impact on performance as $\mathscr{L}_{\text{daily}} \times T_{\text{lost}}$
- For other factors such as **levelling** and **beam quality** we estimated the performance impact using **simulations**

Luminosity evolution in simulations

- **Simulations** with **CTE*** (Collider Time Evolution) tracking code:

1.	**Tracking** of macroparticle bunches **influenced** by **several physical effects** such as betatron motion, IBS, radiation damping, luminosity burnoff etc
2.	After the **initial conditions** are generated, the simulation **evolves independently,** without further input from data

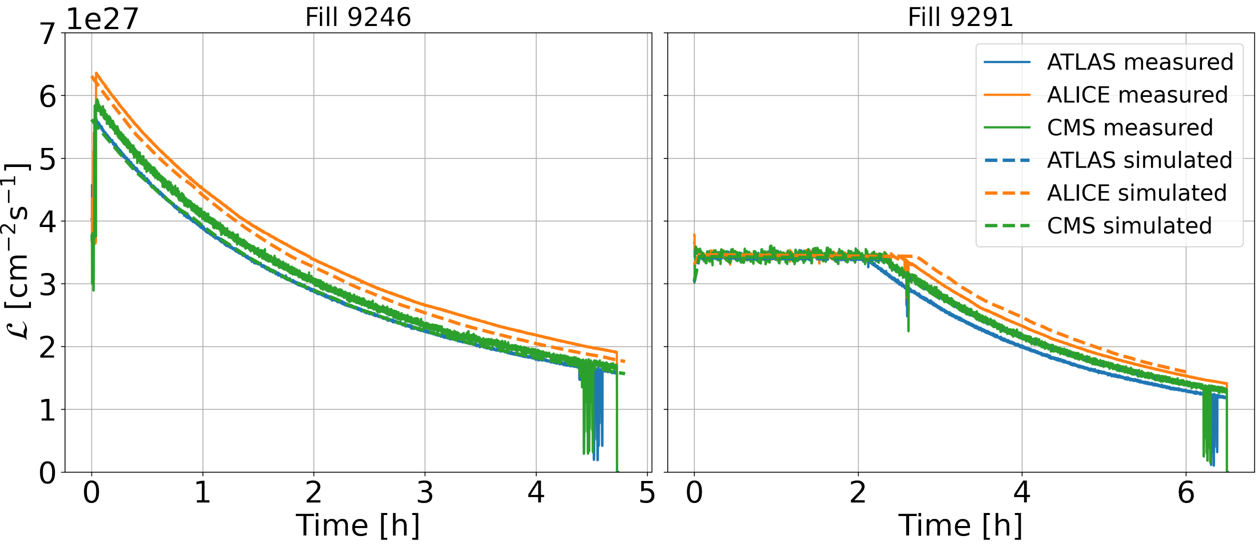
- **Simulations** used as initial conditions the **typical** (average) **parameters measured in 2023**

* *"Performance and luminosity models for heavy-ion operation at the CERN Large Hadron Collider", R. Bruce et al, EPJ Plus* *link*

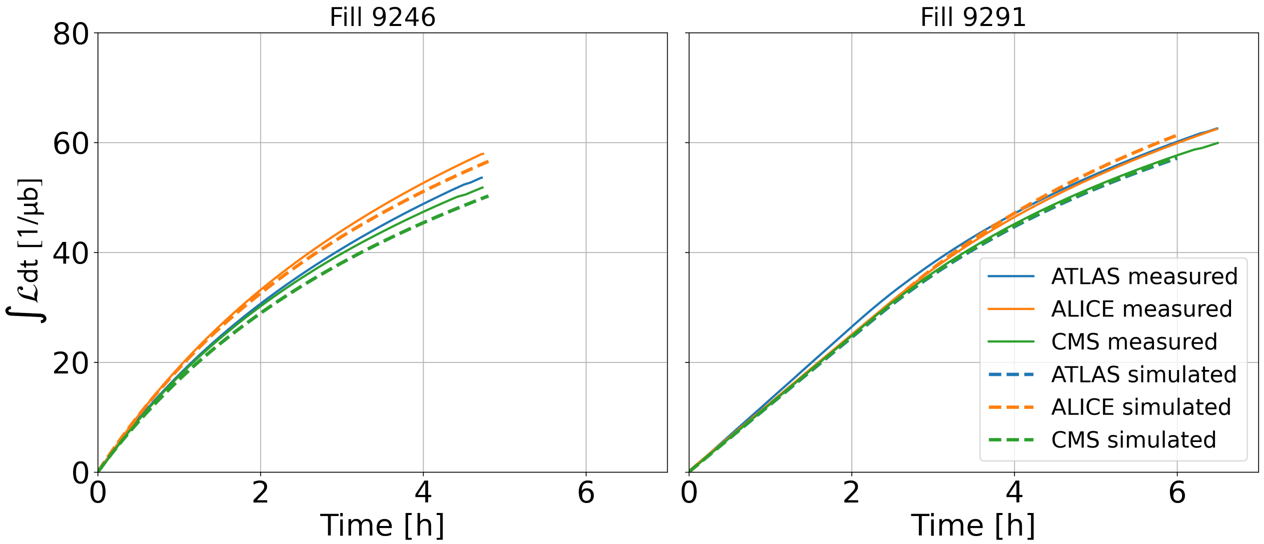
Simulations vs measurements in 2023

- **Good agreement** between **measurements** and **CTE** for ATLAS/ALICE/CMS, for the different fills with and without levelling

Instantaneous luminosity



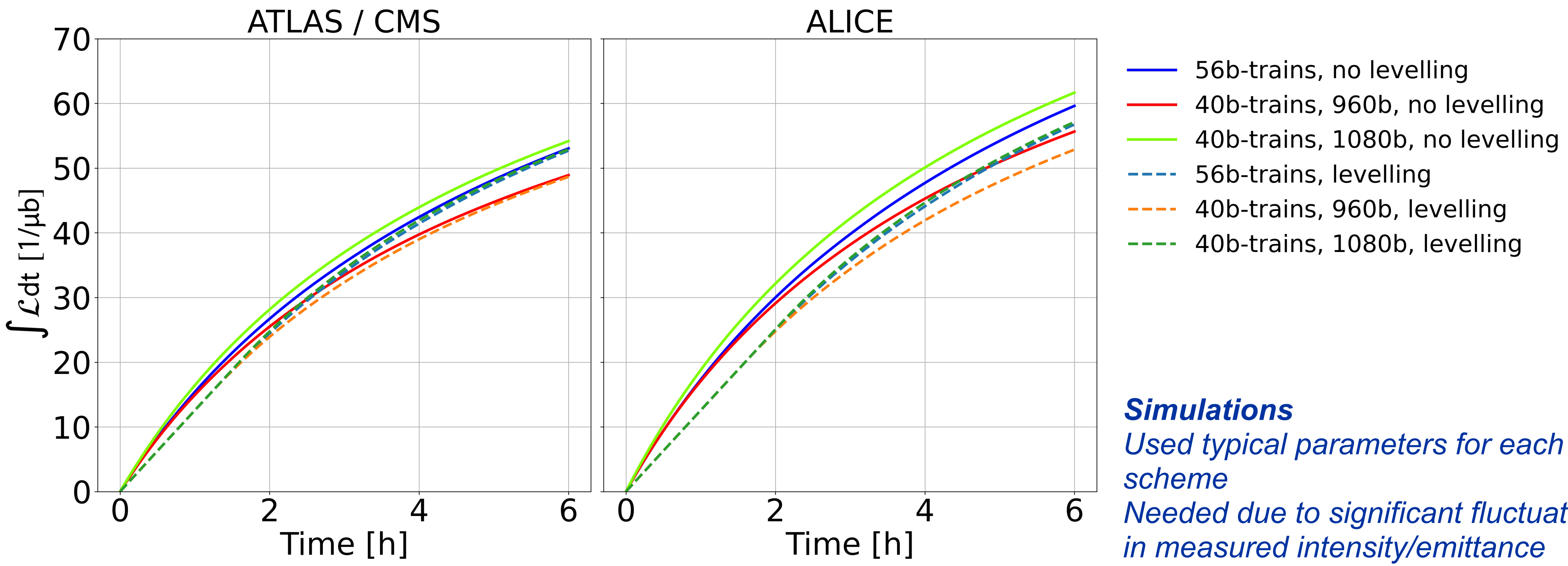
Integrated luminosity



Fill 9246: 1240b, 56-b trains
Fill 9291: 1080b, 40-b trains

Impact on performance from levelling

- **No impact** on integrated luminosity from the levelling for **ATLAS/CMS** after **5-6h**; but ~2-4% for fills lasting <4h
- **For ALICE a 7-10%** loss per fill is predicted even for 5h fills



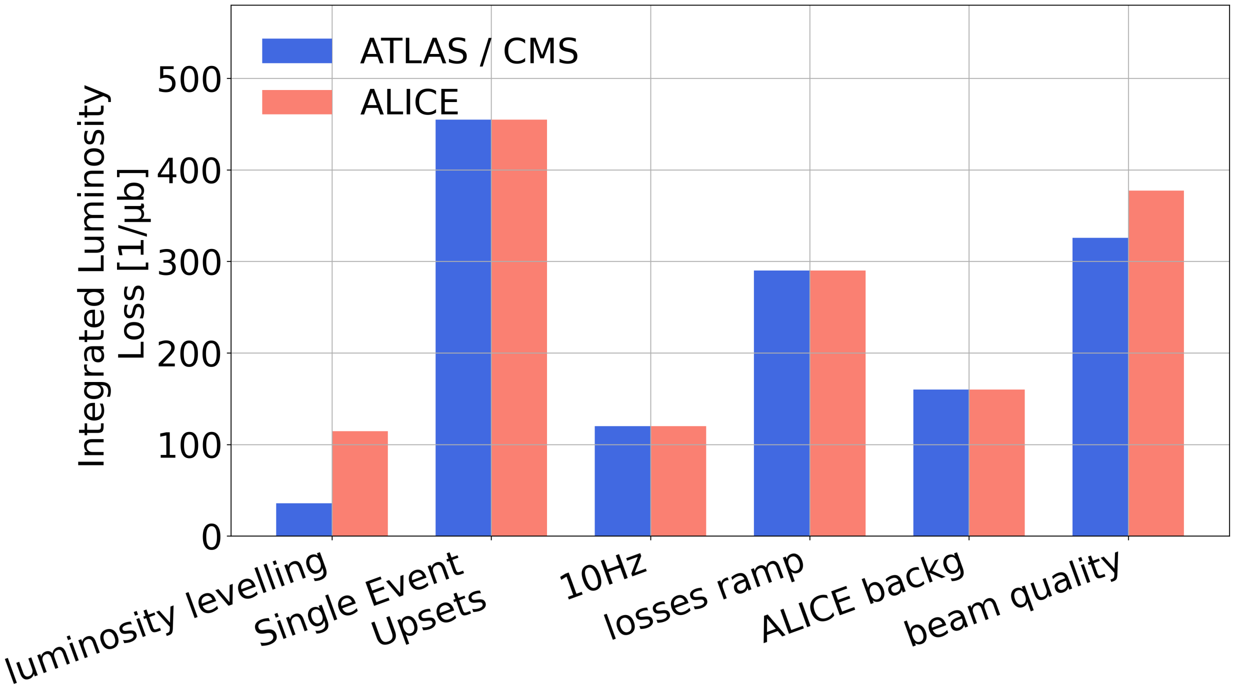
Simulations
Used typical parameters for each scheme
Needed due to significant fluctuations in measured intensity/emittance

Potential additional performance

Computation of performance impact

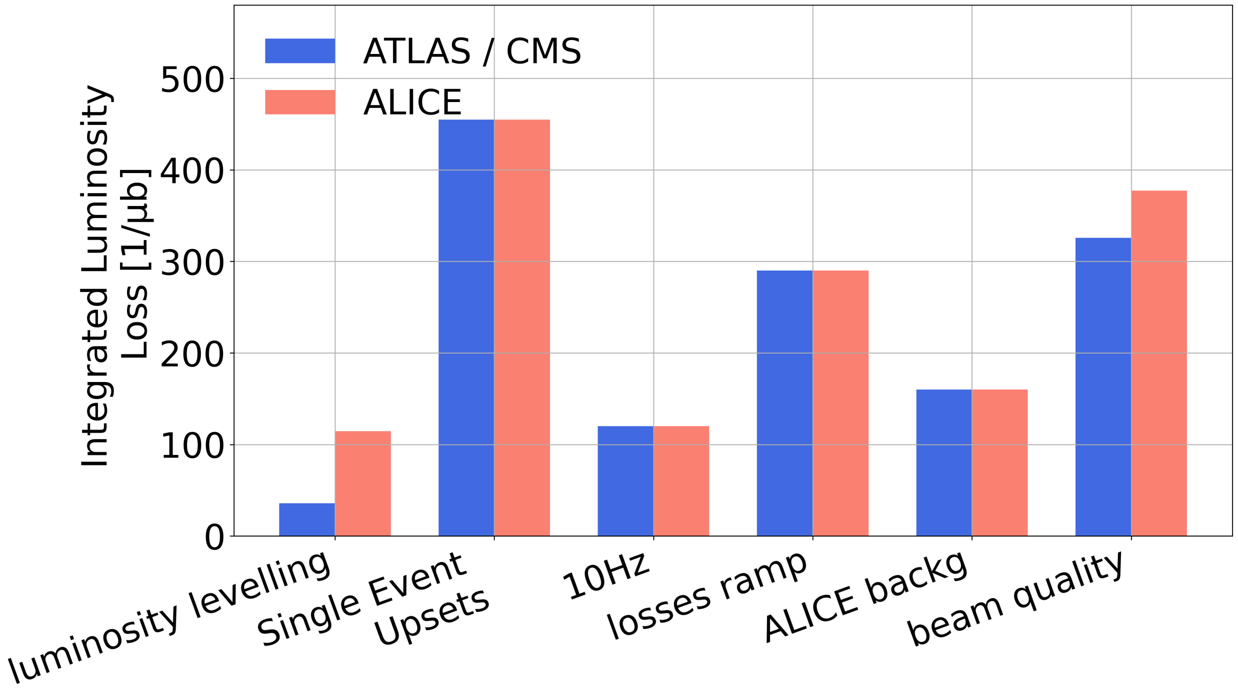
- Single Event Upsets, 10 Hz, losses in ramp, ALICE background $\mathscr{L}_{daily} \times T_{Loss}$

- Levelling, beam quality from **simulations** considering actual fill times and achieved parameters, independent of other performance loss factors



Potential additional performance

- Possible total additional gain ~**1.5/nb**
- Dominant factors: **Single Event Upsets, sub-optimal beam quality** and **losses in the ramp**
  - Focus of mitigation campaign

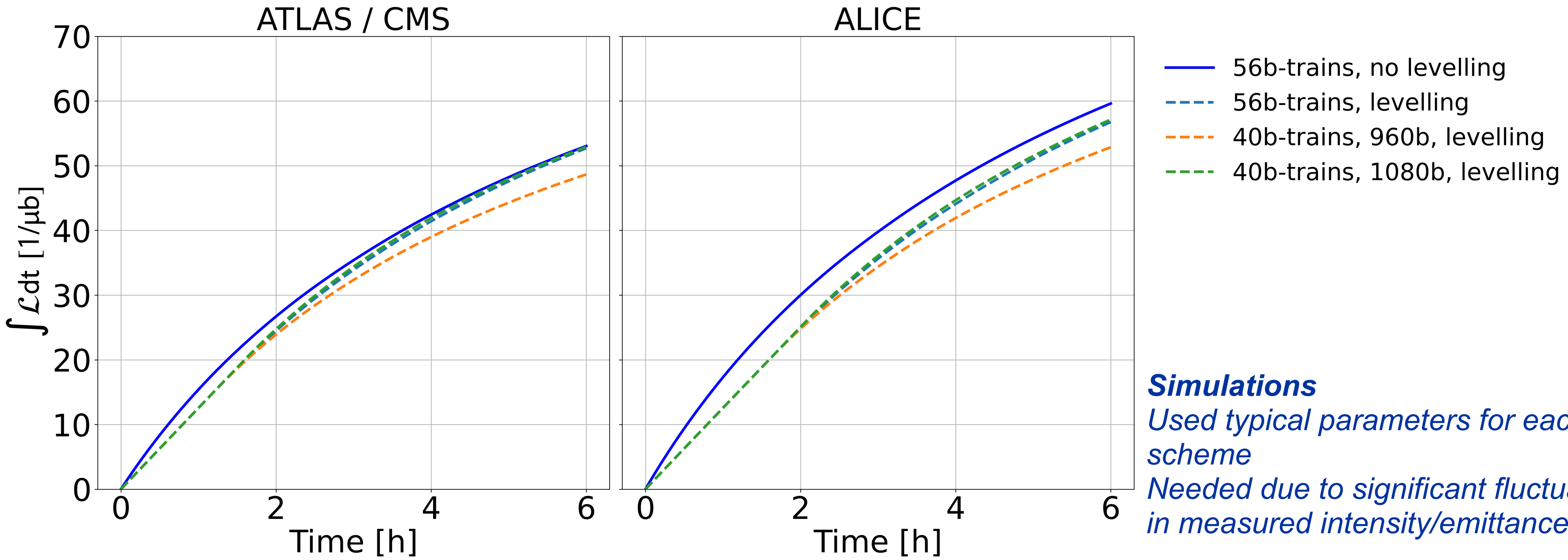


Performance comparison of different configurations

With 2023 operational configurations

luminosity levelling and injected intensity limitations for 56-b trains

- **Very similar** performance for **all filling schemes**
- **For ALICE best: 56-b trains w/o levelling**
- Worse performance predicted for 40-b trains
  - Achieved the **highest luminosity** of the 2023 run due to better beam quality by chance



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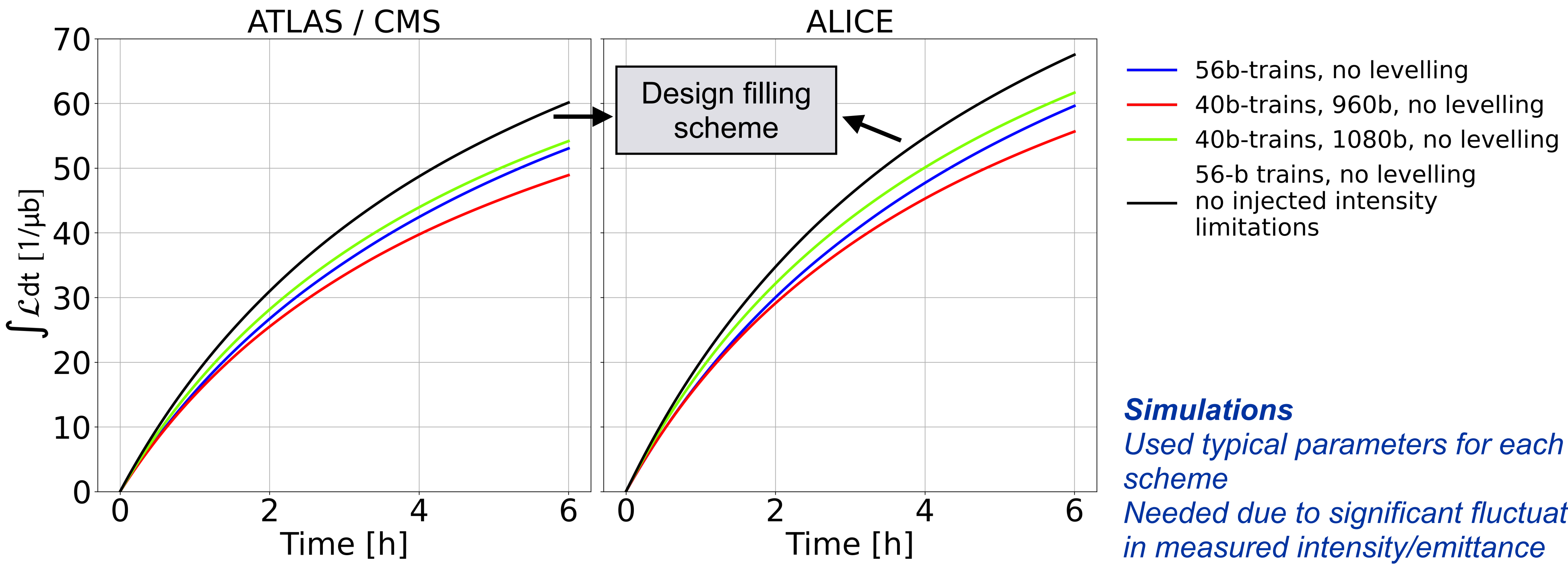
Performance comparison of different configurations

Without 2023 limitations

On luminosity and injected intensity for 56-b trains

- **Best performance for 56-b trains; design case**
  - **Baseline for 2024** assuming successful mitigations of 2023 challenges



Simulations

Used typical parameters for each scheme

Needed due to significant fluctuations in measured intensity/emittance

Summary and outlook

- The **2023 Pb-Pb run** relied on several **new concepts** that were **successfully deployed**
- **Higher luminosities** were recorded **than in any previous run**
- **Performance** could have been **even higher** without several **unforeseen challenges**
  - **Highest impact** on 2023 performance: **Single Event Upsets** and **sub-optimal beam quality**
  - Ongoing campaigns to mitigate the 2023 limitations
- **Filling schemes** with **different train lengths**, **40-b vs 56-b**, were used
  - **Similar operational efficiency was observed**
  - Assuming successful mitigation of the 2023 limitations, better performance is predicted with **56-b trains; baseline for 2024**
- These results are **crucial** for **selecting machine configuration** to **optimise** integrated luminosity in the **2024 ion run** and **future ion operations**

Thank you for your attention!

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