Research partly supported by the HL-LHC project

Exceeding high-luminosity LHC performance targets during the 2024 Pb-Pb ion run

R. Bruce, R. Alemany Fernández, F. Alessio, T. Argyropoulos, H. Bartosik, R. Cai, F. Carra, R. Denz, S. Fartoukh, P. Hermes, M. Hostettler, J.M. Jowett, S. Kostoglou, A. Lechner, K. Li, B. Lindstrom, E. Maclean, D. Mirarchi, S. Morales Vigo, T. Persson, L. Puddu, S. Redaelli, V. Rodin, B. Salvachua, M. Slupecki, M. Solfaroli, J. Steckert, G. Sterbini, H. Timko, R. Tomás, N. Triantafyllou, F. Van der Veken, E. Waagaard, J. Wenninger, C. Young, M. Zielińska

2025.06.03

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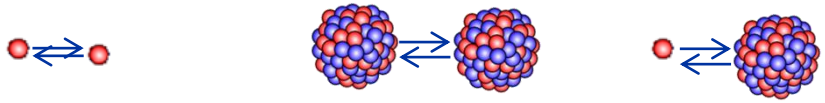
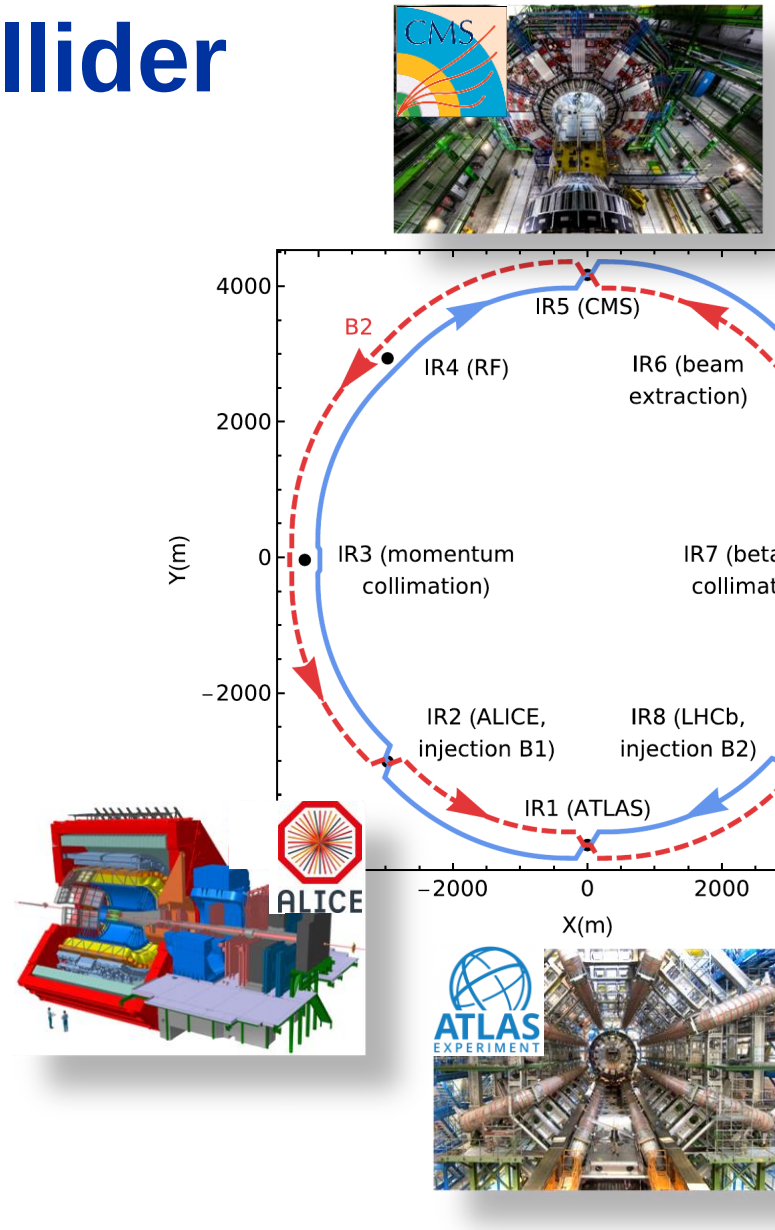
The CERN Large Hadron Collider



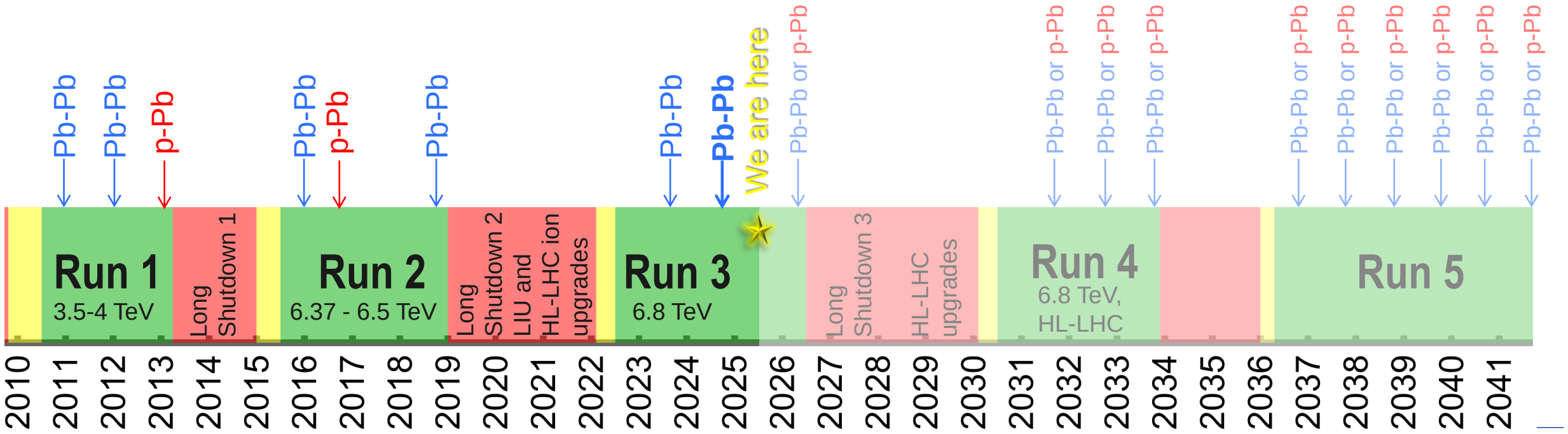
- **27 km ring, 2 counter-rotating beams**
- **Accelerates and collides protons and heavy ions at 6.8 Z TeV**
  - 4 main experiments
- **LHC heavy-ion programme**
  - Operation with fully stripped Pb ions typically one month per year
  - All main experiments take ion data
  - Mainly Pb-Pb, but also p-Pb



LHC heavy-ion programme

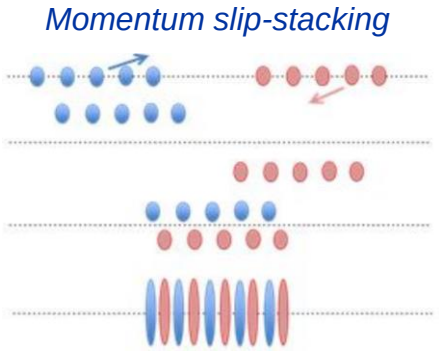
- **So far**
  - Pb-Pb (6 physics runs)
    p-Pb (2 physics runs)
  - Short pilot runs in other configurations
    - Past: p-Pb, Xe-Xe
    - Upcoming (2025): p-O, O-O, Ne-Ne
  - Yearly ion operation to continue

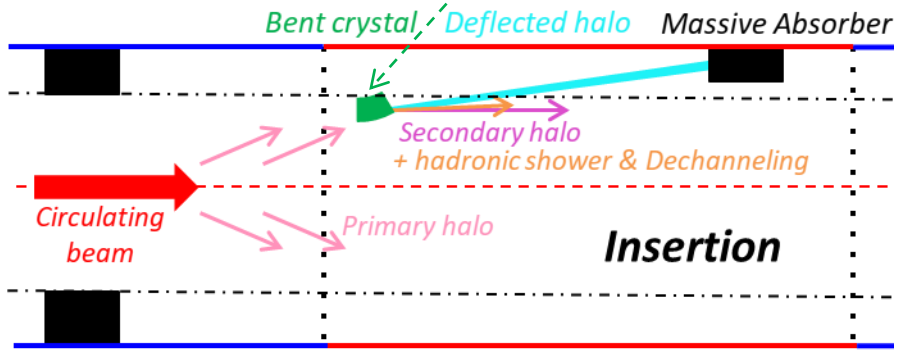
- **High-luminosity LHC (HL-LHC) + LHC Injector Upgrades (LIU)**
  - Goal: significantly increase LHC integrated luminosity
  - Protons: LHC implementation mainly in long shutdown 3
  - Pb ions: Upgrades already implemented in long shutdown 2
    - For Pb-Pb, all HL-LHC upgrades available since 2023!

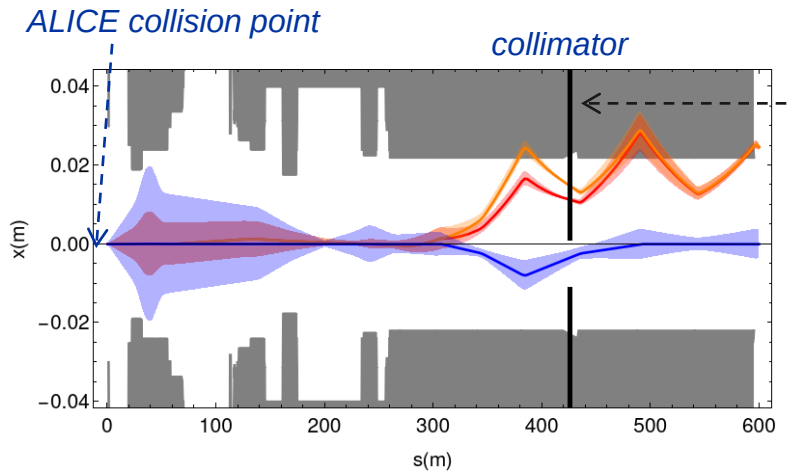


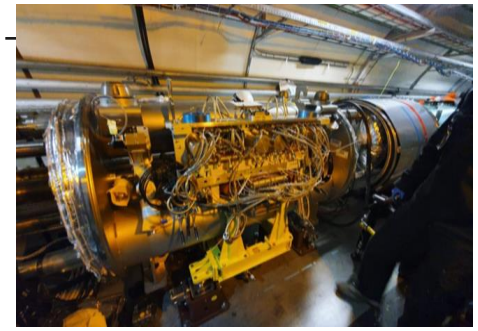
HL-LHC ion upgrades

- **Higher intensity from injectors (LIU)**
  - ~70% more bunches thanks to “slip-stacking”
- **Crystal collimation**
  - Bent crystals channel beam halo onto absorber
  - Needed to handle higher beam losses
- **Alleviation of collisional beam losses**
  - Orbit bumps + new collimators around ALICE
  - Needed to sustain higher luminosity
- **Upgraded ALICE detector**
  (not HL-LHC project)
  - Needed to tolerate higher event rate









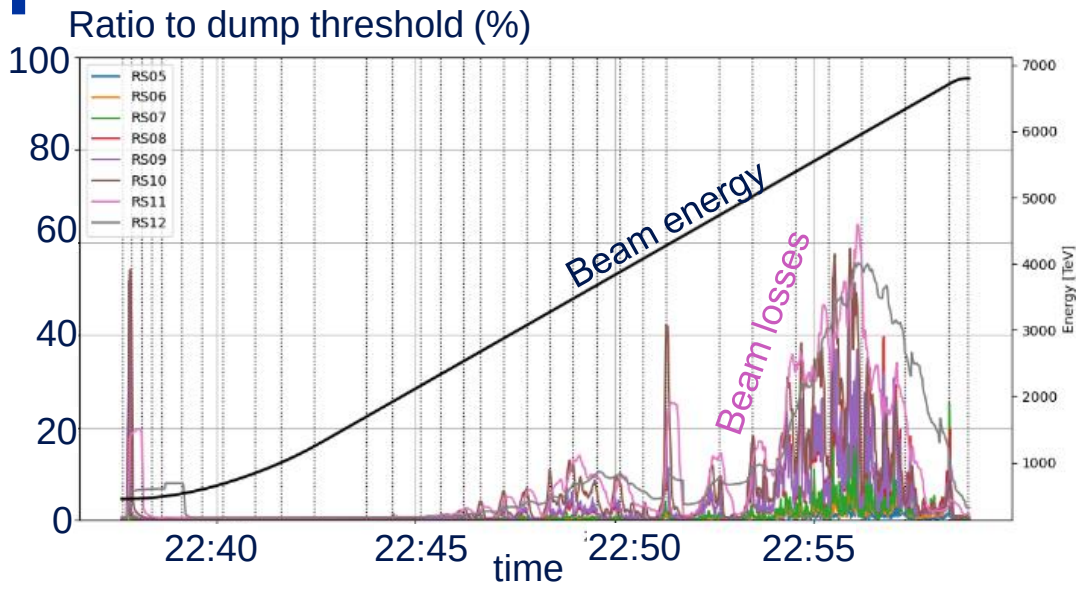
Outcome of the 2023 Pb-Pb run

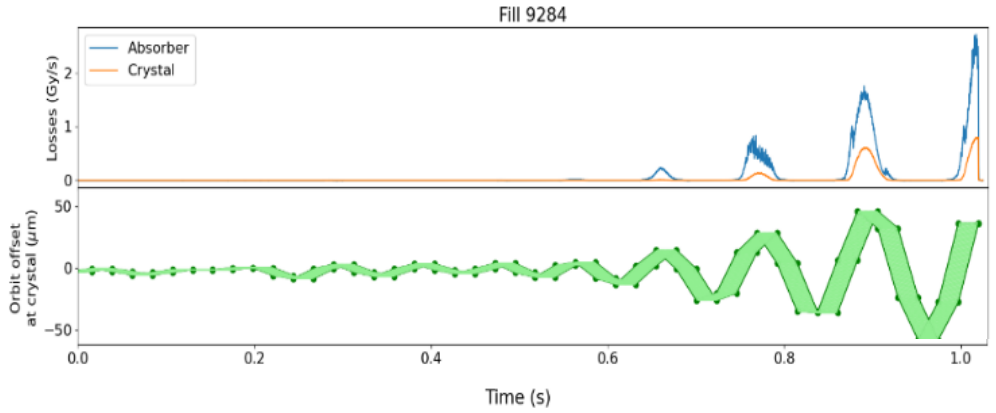
- **New HL-LHC concepts successfully put in operation**

- **Several problems encountered**
  - High beam losses caused unwanted beam aborts
    - Beam losses in the energy ramp
    - Beam losses due to 10 Hz orbit oscillations

    } Time lost and intensity limit
  - Intensity and emittance not reaching their targets
  - Limiting background in ALICE experiment
    - Mitigated in 2023, but lost significant time
  - Angular drifts of crystal collimators
    - Partly mitigated by automatic optimizations
  - Single event upsets on quench detection system
    - Triggered spurious firings of quench heaters → magnet quenches with long recovery time

- **Only 2/3 of integrated luminosity targets could be reached due to time lost and performance limits**





Considerations for the 2024 Pb ion run

- **Shorter ion run in 2024**
  - 18 days of physics operation - had 32 days in 2023

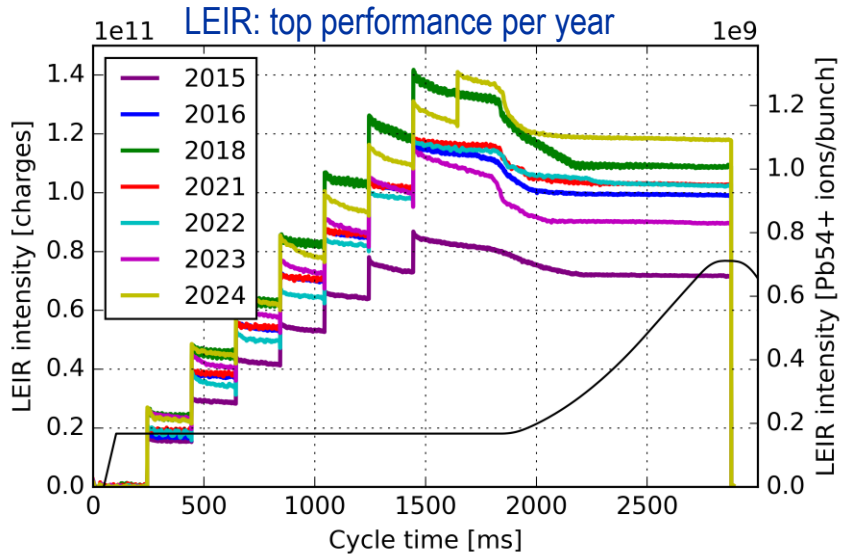
- **Target integrated luminosity anyway similar to total achieved in 2023**
  - For ALICE, ATLAS, CMS: of 1.9 nb^{-1} - reached 2 nb^{-1} in 2023
  - Crucial to significantly increase performance

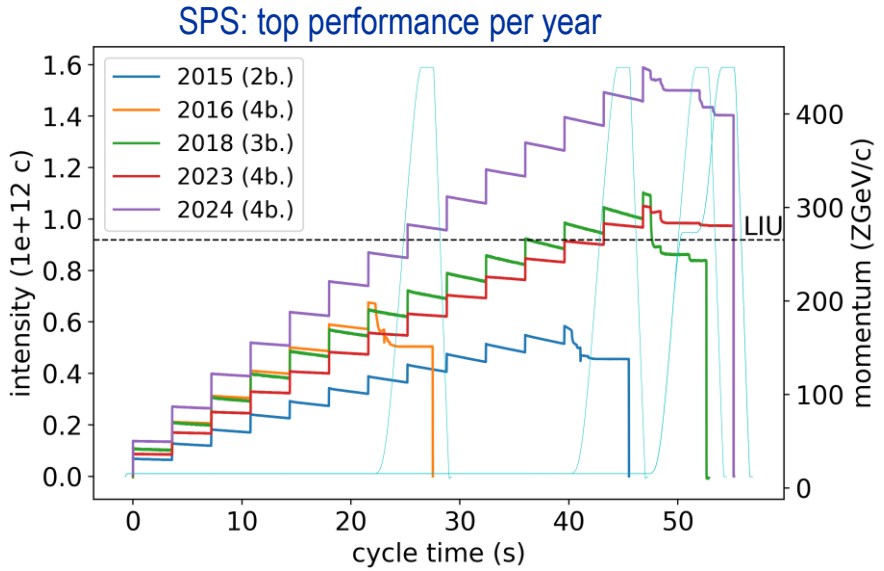
- **Main priority to mitigate 2023 problems → Action plan**
  - Improve machine availability and establish stable operation
  - Operate with higher intensity
    - Tolerate higher intensity in LHC and reduce losses
    - Produce higher intensity in injectors

2024 Pb beams from the injectors

- **Following improvements, excellent intensity from injectors in 2024**
  - Optimization throughout injector complex → record performance
  - Very large improvement over 2023

- **2.6×10^8 Pb/bunch at LHC injection**
  - Intensity >30% above LIU/HL-LHC target
  - Almost factor 4 above LHC design from 2003
  - Emittance larger than spec, but LHC still gains significantly overall due to higher intensity



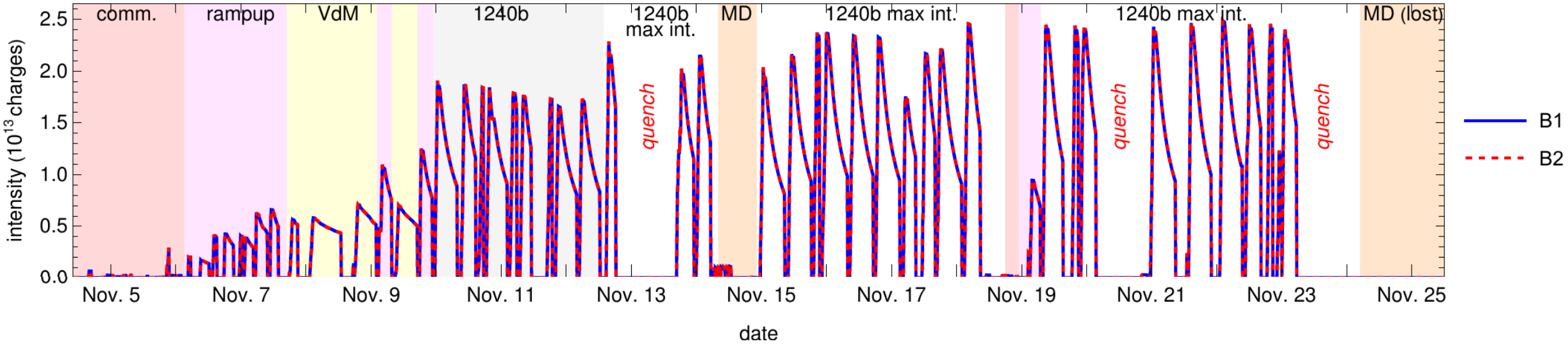


LHC machine configuration with Pb ions

- **Change as little as possible in 2024 to avoid new problems**

Parameter	2023	2024
Beam energy (Z TeV)	6.8	6.8
β* (m), ALICE, ATLAS, CMS	0.5	0.5
β* (m), LHCb	1.5	1.5
Net half crossing angle (μrad), ALICE	98	78
Net half crossing angle (μrad), ATLAS, CMS	170	150
Net half crossing angle (μrad), LHCb	-274	-71
Collimator cut (σ)	4.75	6.0

Overview of the LHC 2024 Pb-Pb run

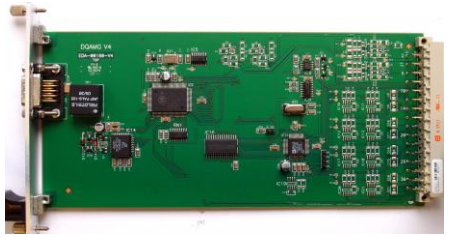


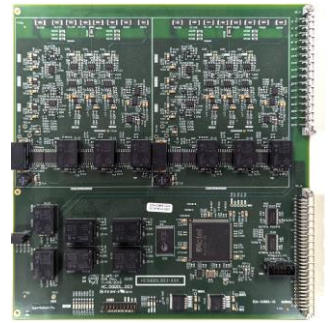
- **Intensity rampup after initial commissioning**
  - Uncertain if LHC could handle full intensity - initially decreased bunch intensity
  - Stable operation established → taking full bunch intensity from injectors
  - Stable operation demonstrated also with full intensity

- **Good availability in general, but 3 quenches caused by radiation to electronics**

2024 experience with 2023 problems (1)

- **Single event upsets on quench detection system**
  - 2023-type of events mitigated by new radiation-hard electronics cards
  - New type of event caused 3 quenches → further electronics updates in 2025





- **Beam losses from 10 Hz oscillations**
  - traced to opening of cryogenic valve** → opened only without beam in 2024 → no further events observed

** Acknowledgement: K. Paraschou, B. Bradu

2024 experience with 2023 problems (2)

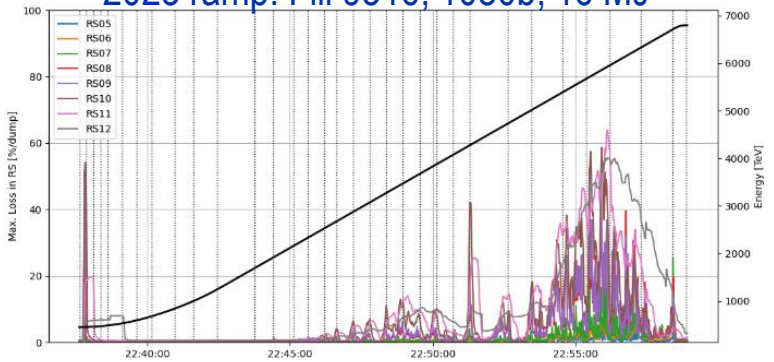
- **Beam losses in the ramp**
  - 2024 losses only at a low and tolerable level, even at high intensity
    - Cured by more open collimators, higher beam abort thresholds, less optics changes in ramp

- **Crystal channeling stability**
  - Relying on improved angular automatic optimization with controls upgrade
  - No longer a performance bottleneck, but would be good to mitigate root cause

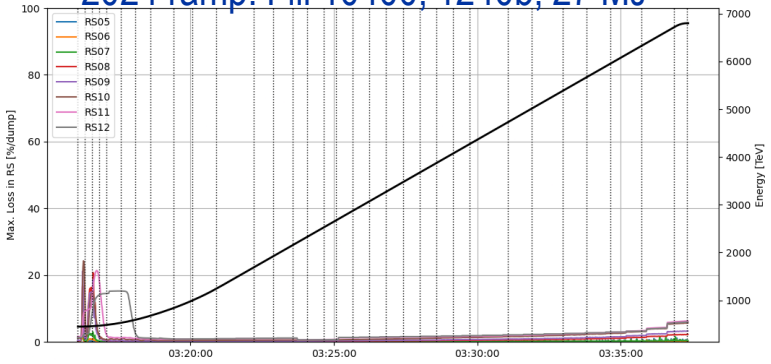
- **ALICE background**
  - Same mitigation as in 2023 (dispersion correction bump)
  - Some residual background remains, but acceptable for operation

- **Mitigation measures largely very successful**

2023 ramp: Fill 9316, 1080b, 16 MJ



2024 ramp: Fill 10400, 1240b, 27 MJ

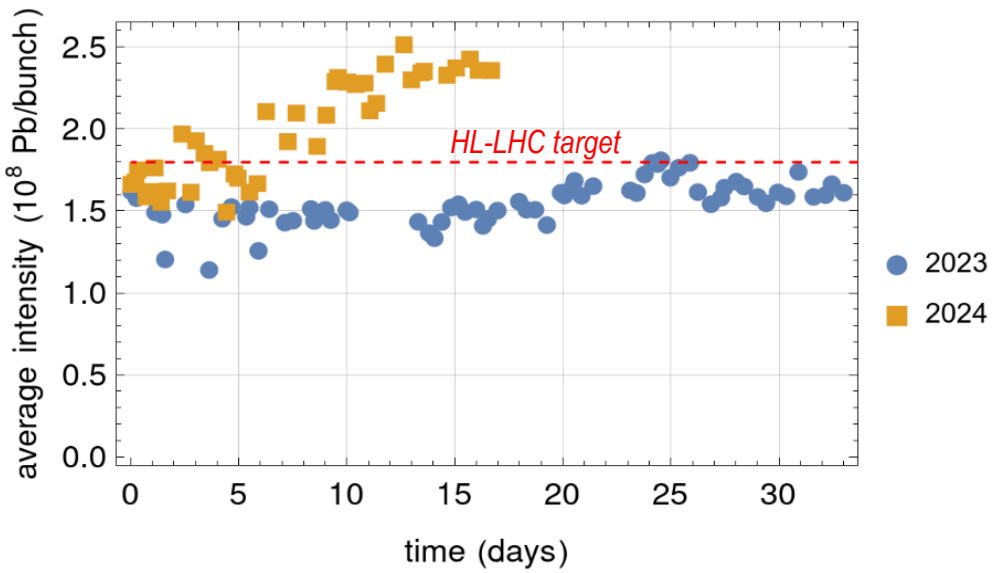


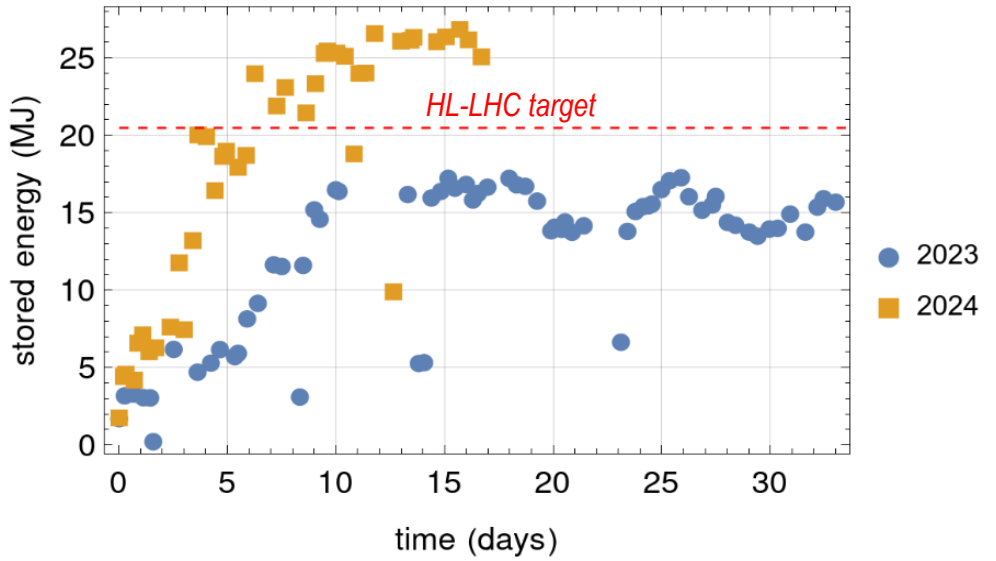
LHC Pb beam intensity

- **Bunch intensity (start of collisions)**
  - 2024 best fill 2.5×10^8 Pb/bunch, average 2.3×10^8 Pb/bunch
    - After taking full intensity from SPS
  - 2023: Average 1.6×10^8 Pb/bunch
  - Compare HL-LHC design: 1.8×10^8

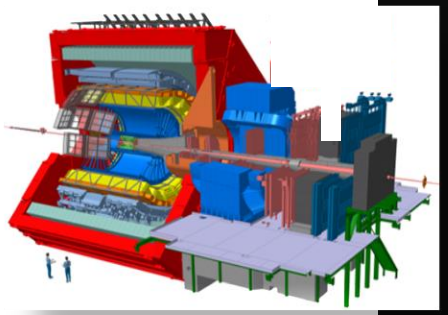
- **Stored beam energy (start of collisions)**
  - 2024: up to 26.9 MJ
    - In 2024, LHC could take this intensity without limitations from losses
  - 2023 up to 17.3 MJ
  - HL-LHC design: 20.5 MJ

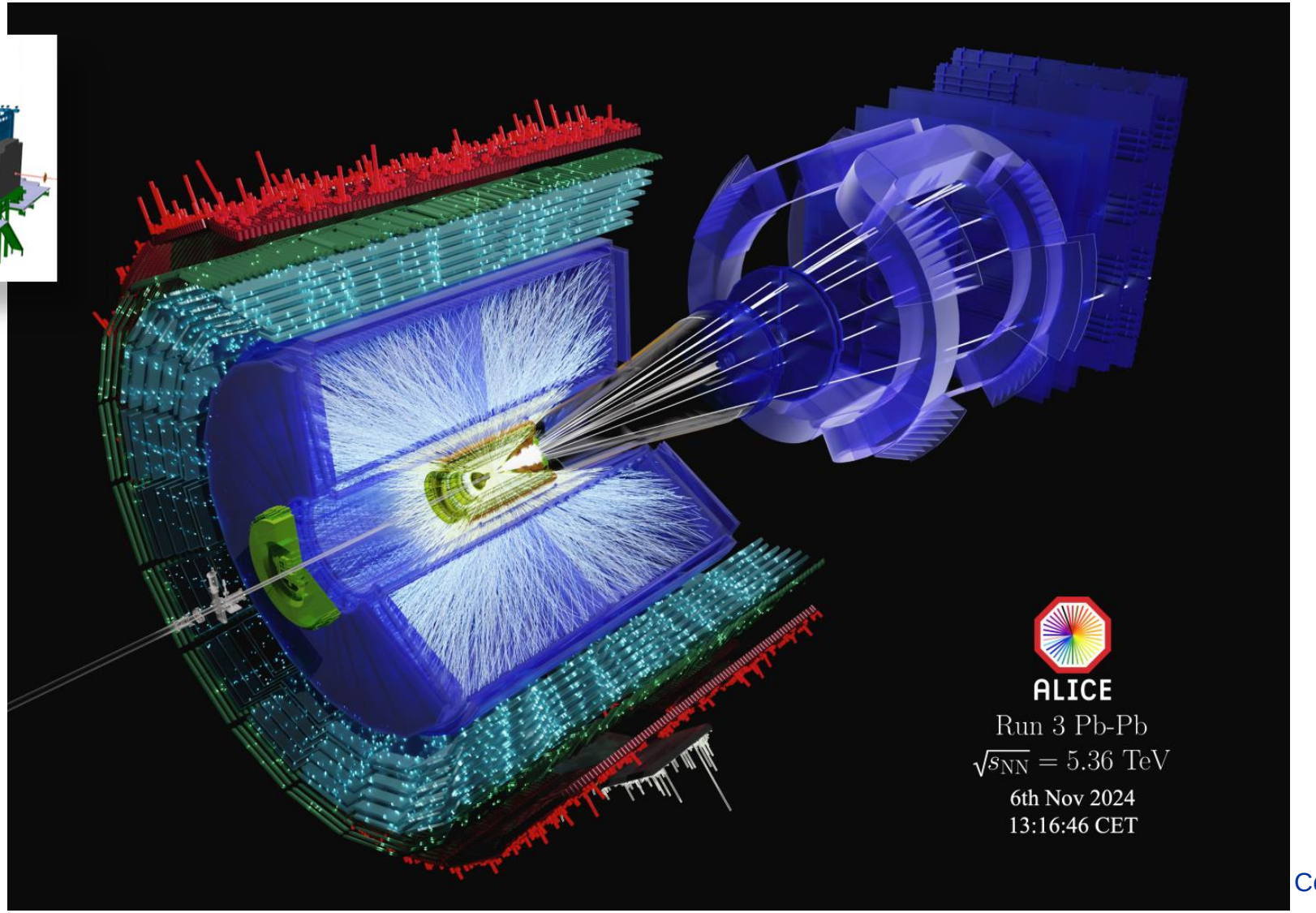
Bunch intensity at start of collisions





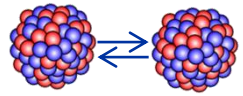
Pb ion collisions in the LHC

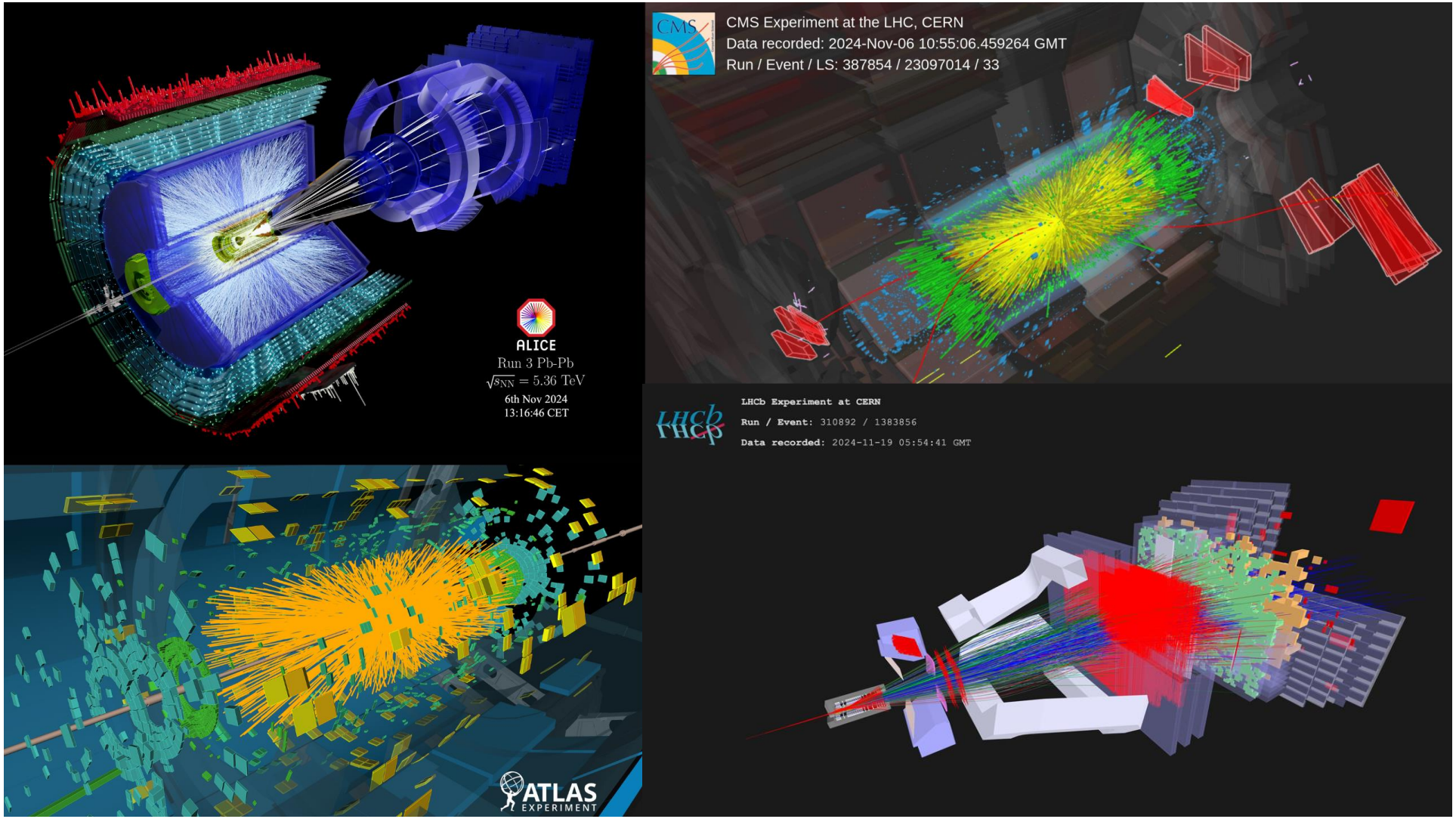




Courtesy ALICE- Image source

Pb ion collisions in the LHC



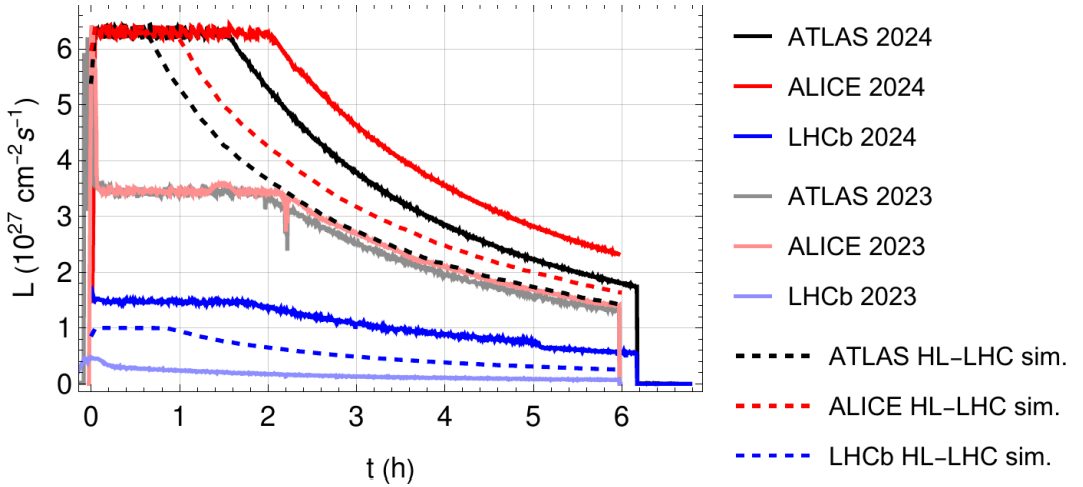


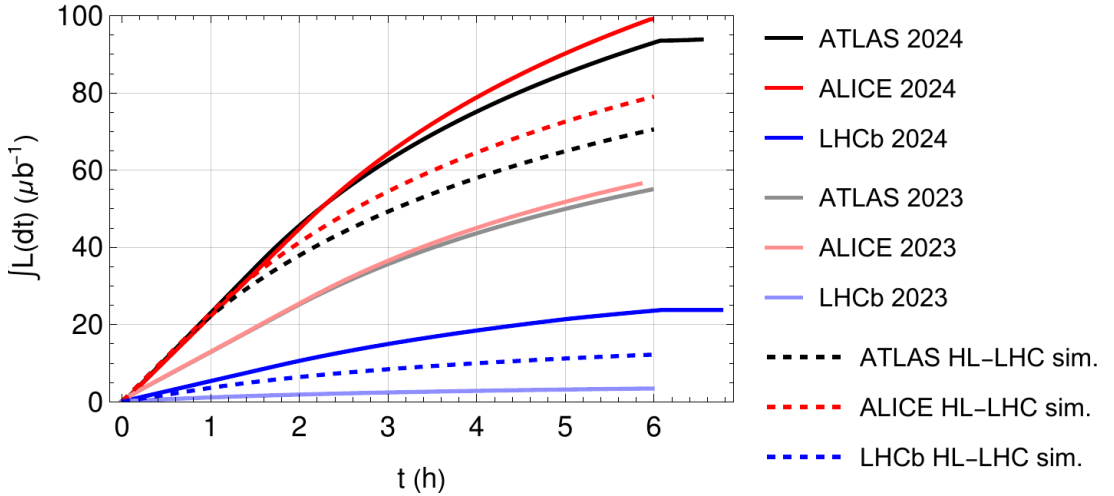
Images: Courtesy of LHC experiments

Luminosity performance in 2024 (single fills)

- **Luminosity levelled (separation)**
  - Limit on maximum event rate at ALICE
  - Limit from collisional losses at LHCb
- **Achieved levelling time**
  - ~2h at ALICE → factor ~2 above HL-LHC prediction
  - ~1.7h at LHCb → ~90% above HL-LHC prediction, *at higher levelling target*
    - Note: more colliding bunches at LHCb than in design scenario, and smaller crossing angle
- **Integrated luminosity**
  - 2024 fills surpassed by far 2023, and even HL-LHC
  - After 6h, ALICE has about 80% more data than in 2023 and 30% more than HL-LHC prediction
  - After 6h, LHCb has 80% more data than in HL-LHC prediction

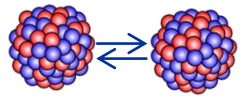
Best fills in 2023 and 2024



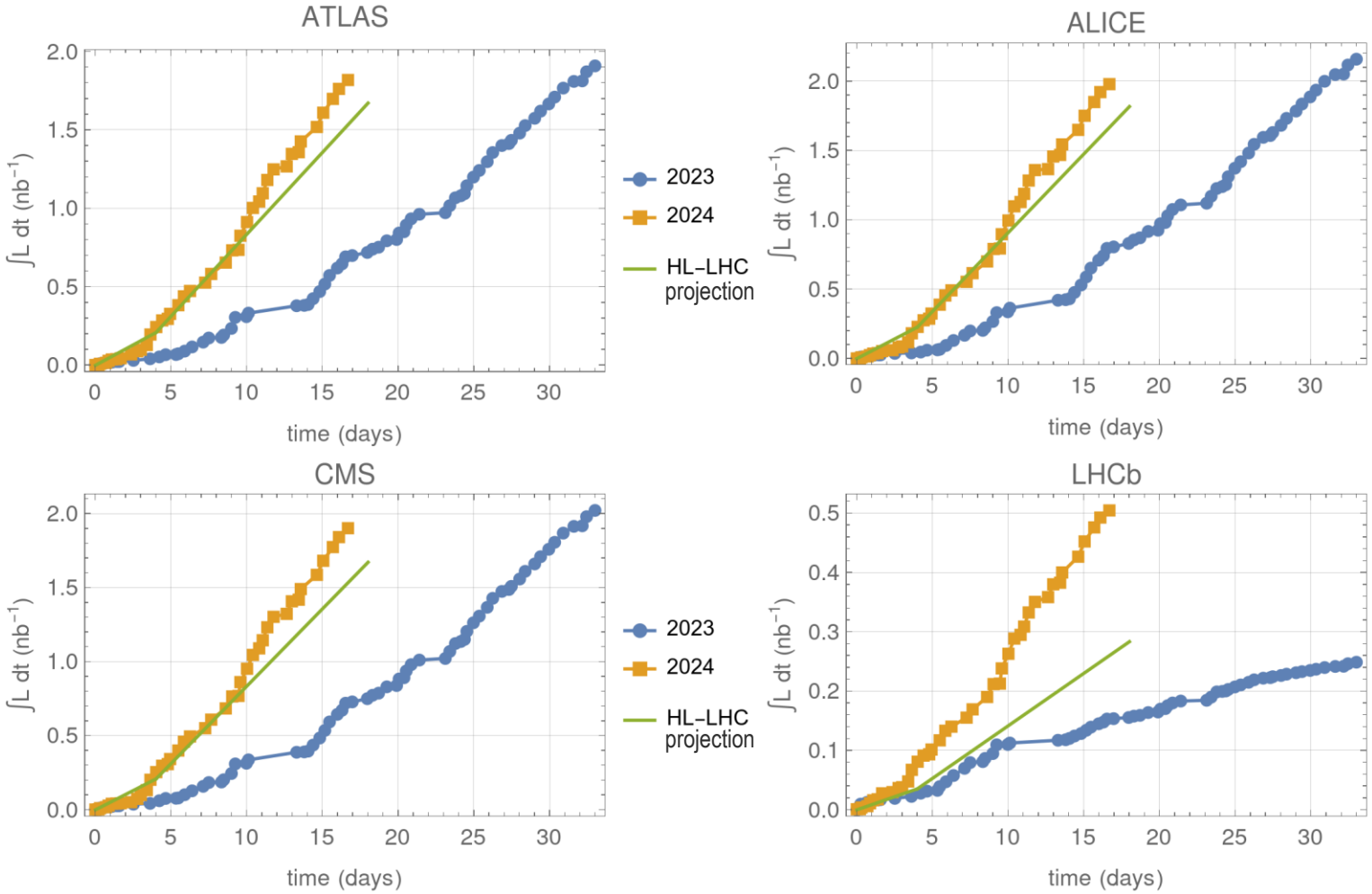


Luminosity modelling and projections described in EPJ plus paper

Integrated luminosity production



- **ALICE, ATLAS CMS**
  - Almost same luminosity in 2024 as 2023, in about half the time
  - 142 μb^{-1} mean daily production (with max. no. bunches)
    - 118 μb^{-1} projected for HL-LHC
  - Reached target of 1.9 nb^{-1}
- **LHCb**
  - About double in 2024 the 2023 luminosity in about half the time
  - 37 μb^{-1} mean daily production (with max. no. bunches)
    - 20 μb^{-1} projected for HL-LHC



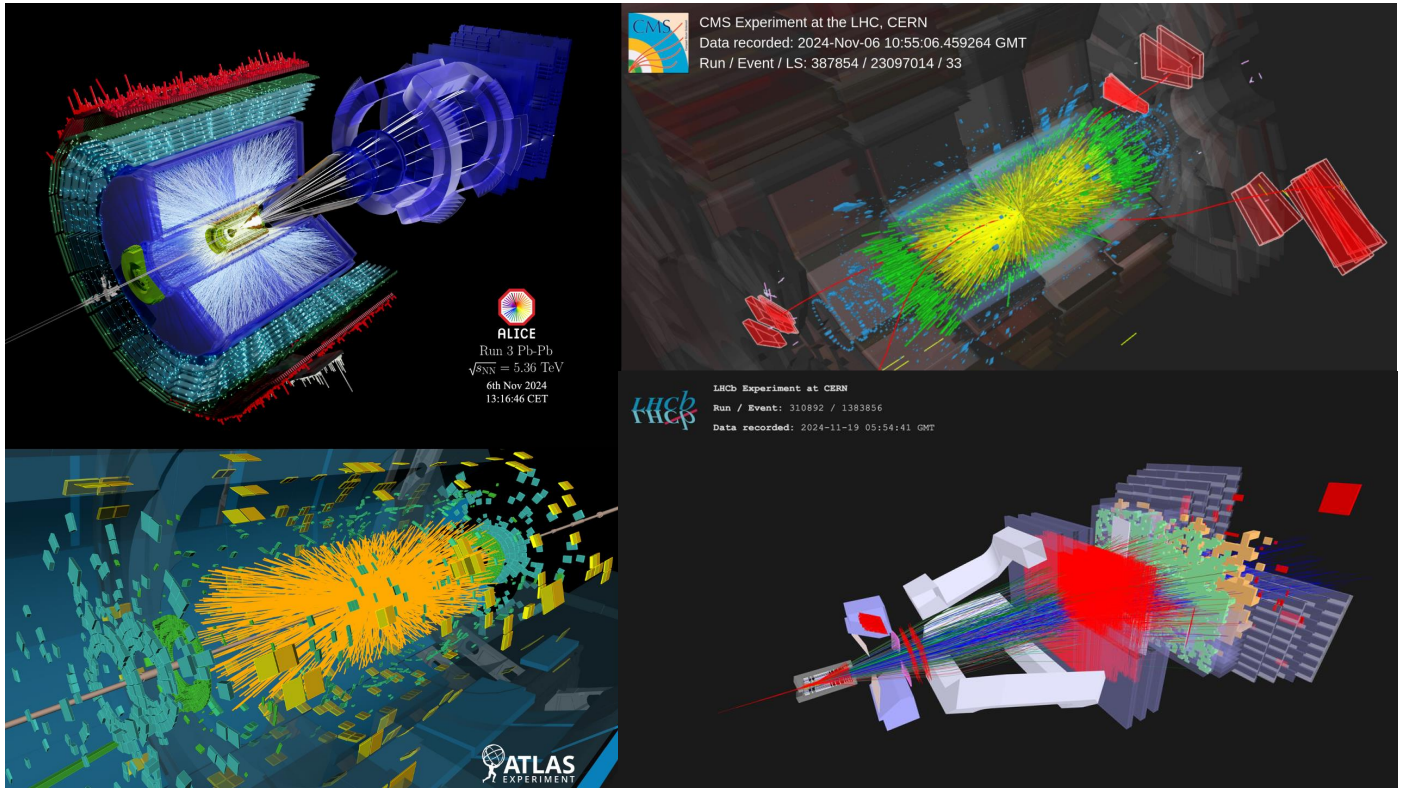
Summary and outlook

- **In 2024, for the first time, reached and significantly surpassed the projected HL-LHC Pb-Pb luminosity performance thanks to**
  - Successful mitigation of limitations encountered in 2023 (beam losses, availability, ….)
  - Excellent performance from injectors with intensity >30% above target

- **All HL-LHC upgrades for Pb ion operation are already implemented and luminosity production with Pb-Pb has entered HL-LHC era!**

- **Ion operation at LHC will continue**
  - Yearly runs with Pb-Pb or p-Pb
  - Upcoming Pb-Pb run in November 2025
  - Upcoming short low-intensity run in July 2025 with O-O, p-O and Ne-Ne

Thanks for the attention!



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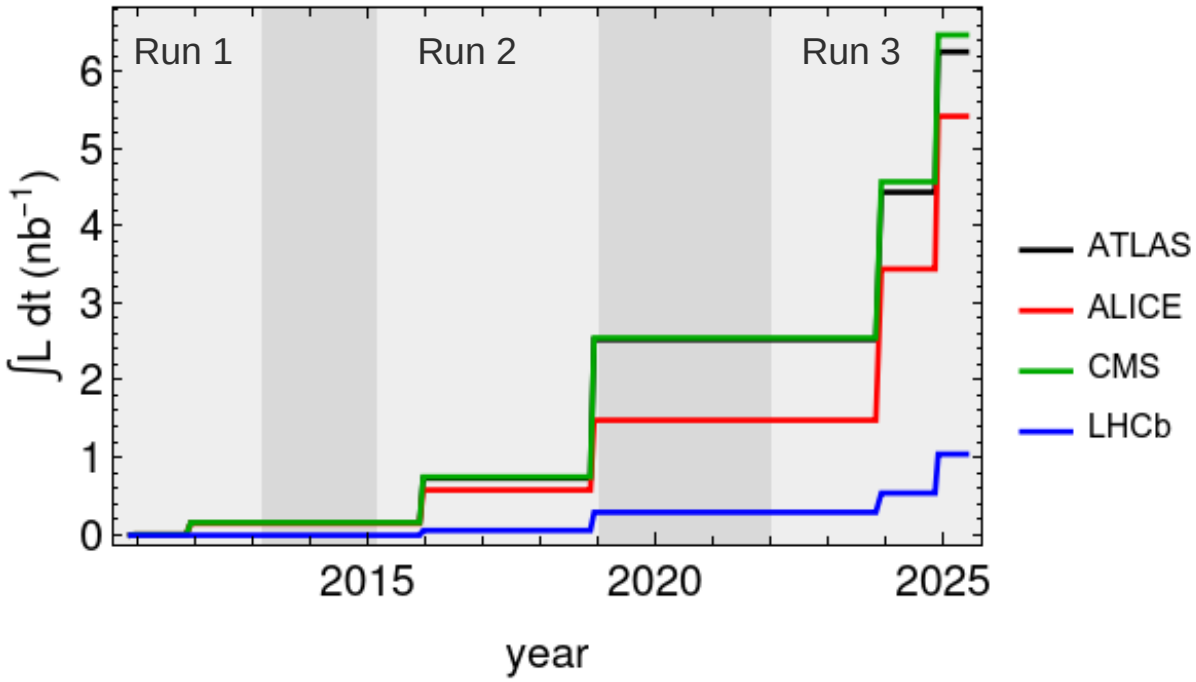
Backup

Physics targets for Pb-Pb

- **Initial target for Run 1 + Run 2 of 1 nb^{-1}**
  - Surpassed in 2018
- **Target for Run 3 + Run 4**
  - For ALICE, ATLAS, CMS : 13 nb^{-1}
  - LHCb: 2 nb^{-1} initially, now requesting more
  - Relies on improved HL-LHC performance
- **So far in Run 3**
  - ALICE, ATLAS, CMS (mean): 3.9 nb^{-1}
  - LHCb: 0.75 nb^{-1}

Pb-Pb integrated luminosity



Total integrated Pb-Pb luminosity so far

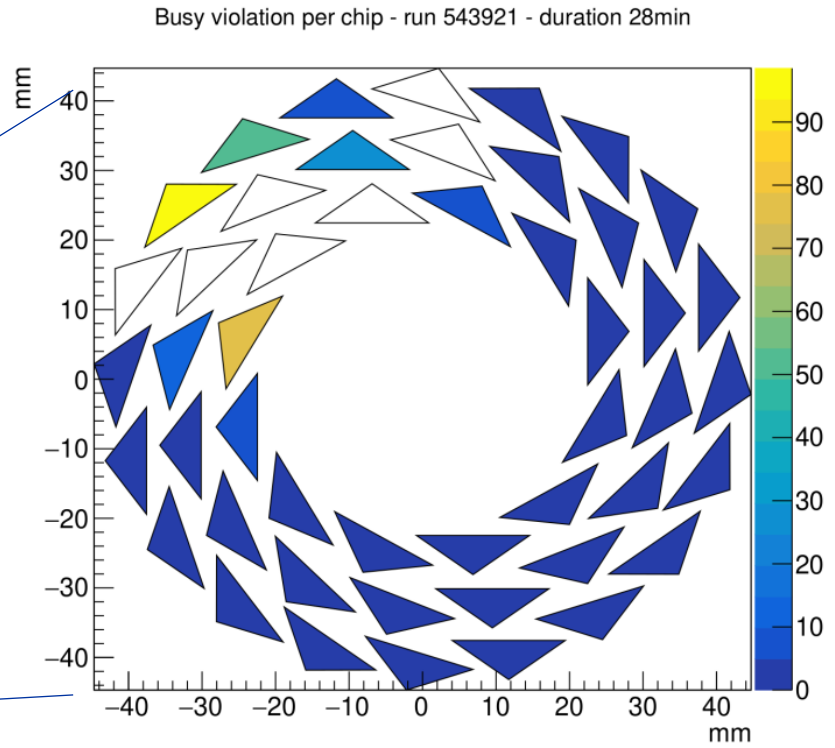
- ATLAS: 6.3 nb^{-1}
- ALICE: 5.4 nb^{-1}
- CMS: 6.5 nb^{-1}
- LHCb: 1.05 nb^{-1}

Observations of background in ALICE

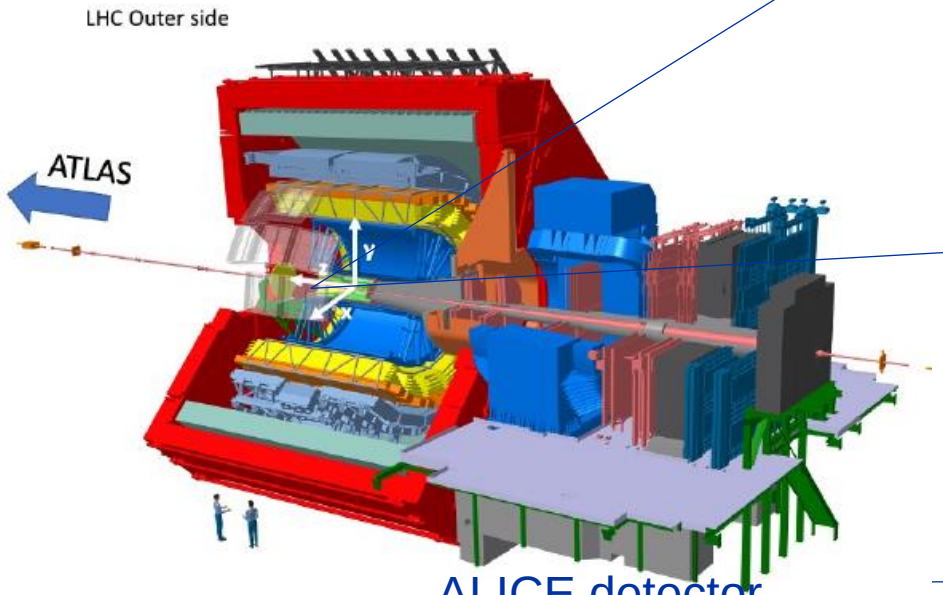
- **Strong background observed in ALICE from the start of the ion run**
  - Some chips of ITS fully saturated
  - About 25% of inner barrel acceptance affected
  - Possibly observed only in 2023 due to smaller radius of upgraded detector compared to Run 2

- **Crash effort to find mitigation**
  - 5 fills devoted to machine studies
  - Campaign of simulation studies in parallel

Outside of the ring



ITS inner layer during 899b-fill
In white: fully saturated chips, not sending signals



ALICE detector

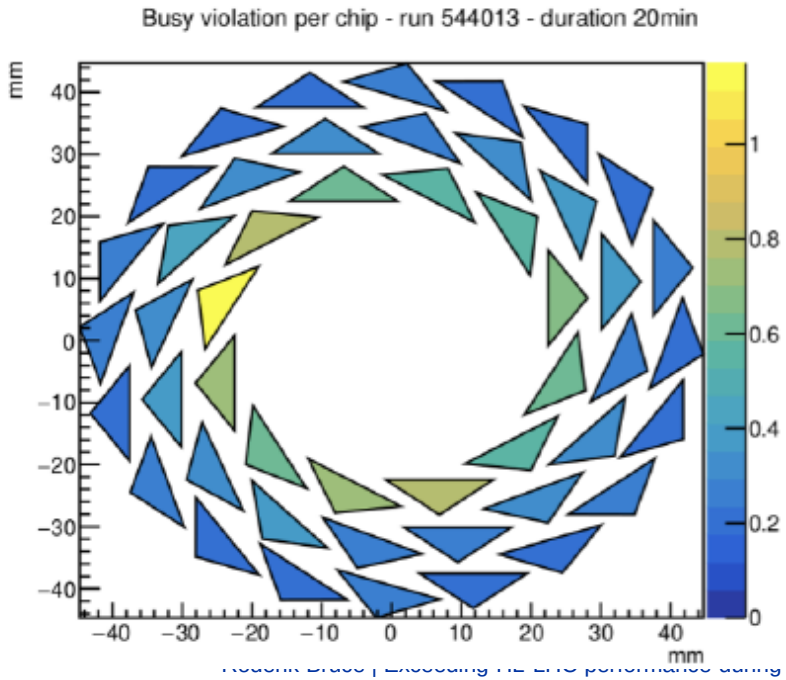
Courtesy of ALICE. From talk by S. Porteboef

Mitigation of ALICE background

- **Main source likely identified**
  - $^{207}Pb^{82+}$ produced by halo hitting vertical crystal in IR7
  - Simulations show outscattered $^{207}Pb^{82+}$ ions pass all the way from IR7 to IR2 and hit TCTPV.4L2.B1

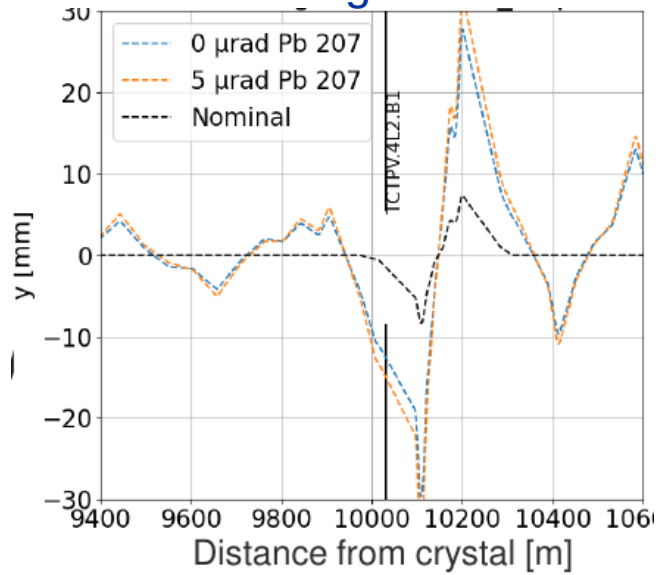
- **Mitigation: used orbit bump around IR1 to modify vertical dispersion**
  - Simulations show $^{207}Pb^{82+}$ dispersive trajectory steered differently and misses the TCTPV.4L2.B1

- **With this knob, ALICE background acceptable even with full machine**
  - Bump added to the machine configuration in physics

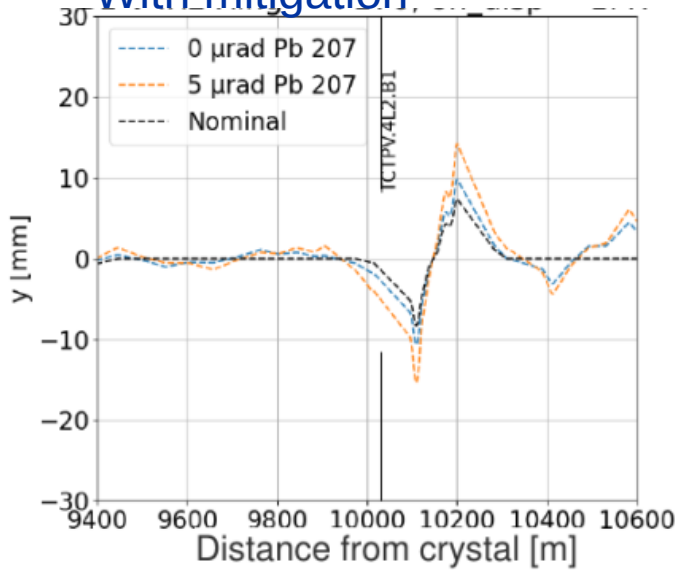


R. Cai

Without mitigation

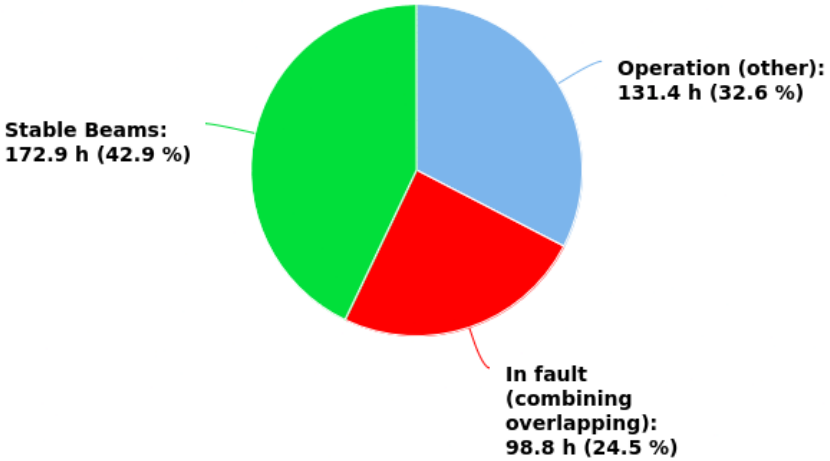


With mitigation

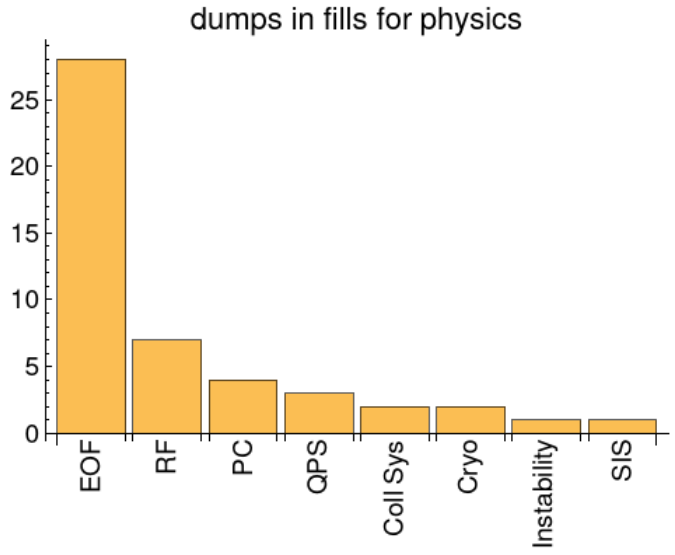


2024 availability and statistics

- **In physics period 2024:**
  - 75% availability
  - 43% of time spent with colliding beams
    - 33% in 2023
  - 25% of time in fault
    - 33% in 2023

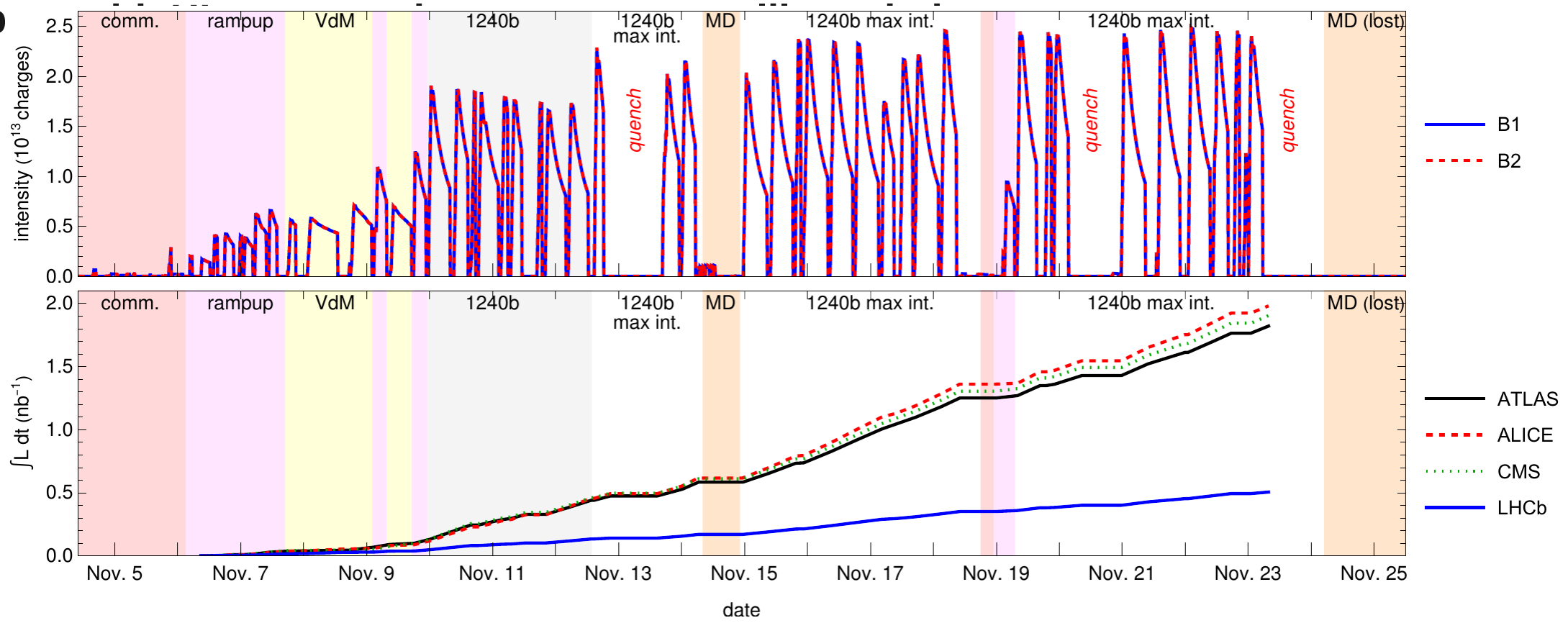
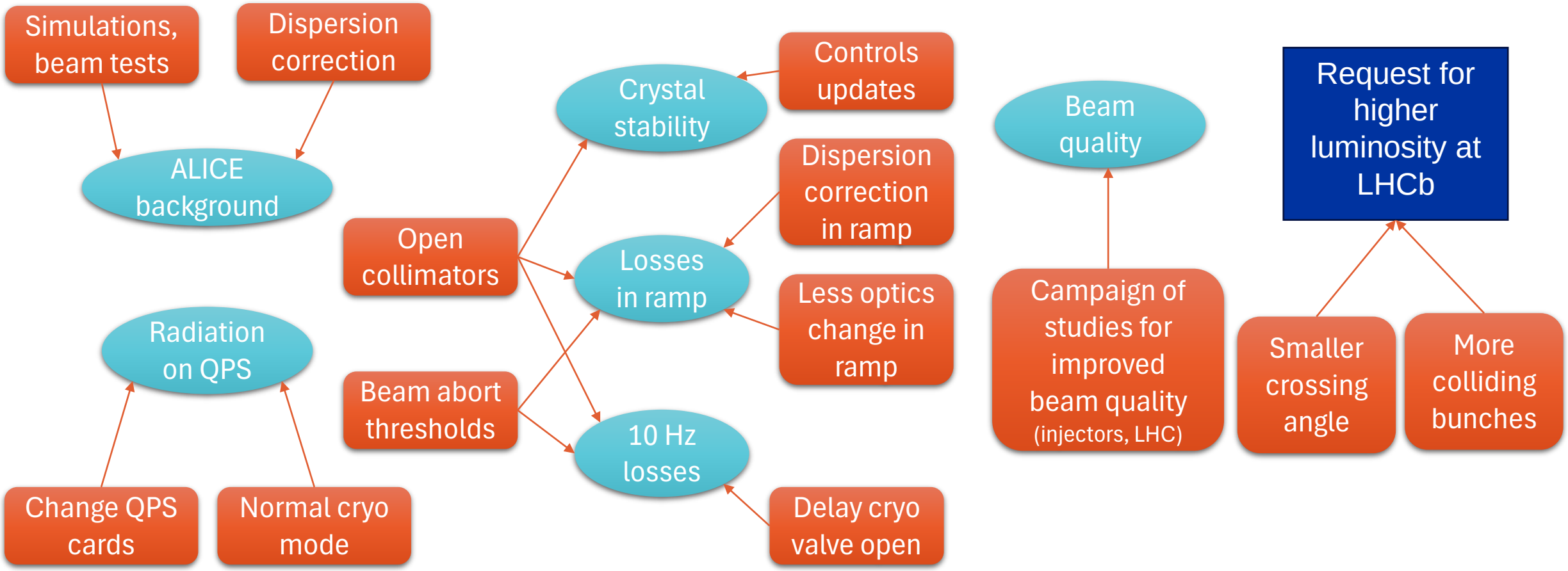


- **Fill statistics**
  - 48 physics fills attempted
  - 45 made it to collision
  - 28 dumped by operator



Total integrated luminosity

- **In 2024, and so far in Run 3**
- **Comp**



Plans to mitigate 2023 problems