Status of Run3 and HL-LHC upgrade

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Contents

- Good physics data requires a good design of the system on accelerator and detector
- No perfect system however exists, so good physics data also requires;
  - A significant dedication on operations of accelerator and detectors for 24 hours
  - A significant effort on improvement of the systems every day
  - A strategy to maximize the amount of good data in many limitations on LHC/experiments

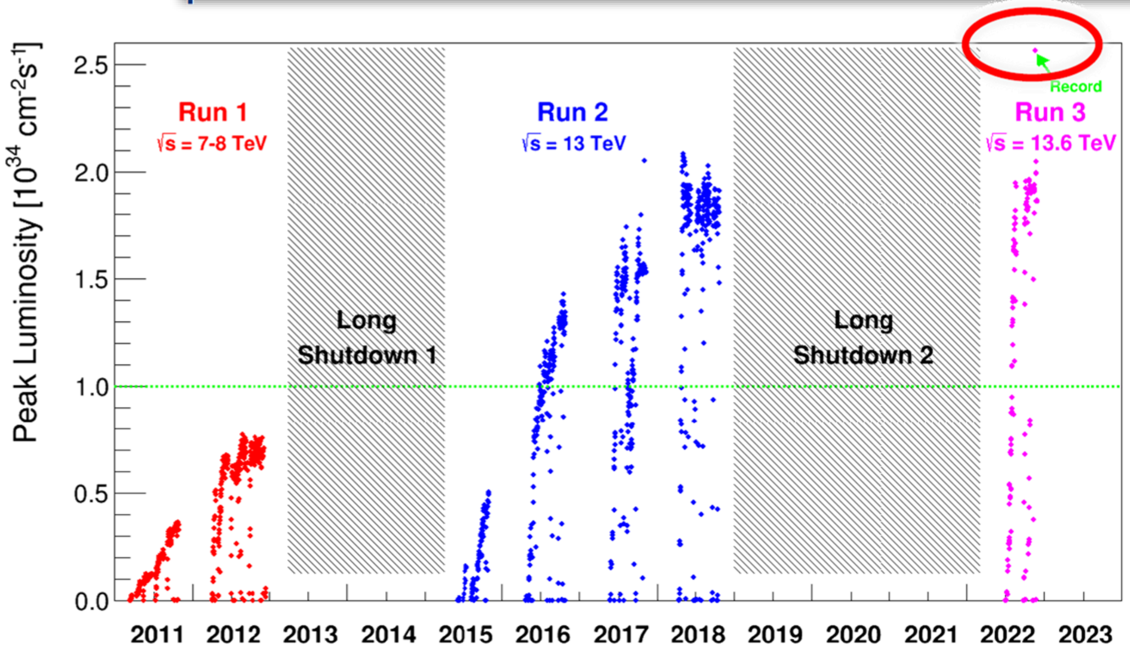
Recent information on LHC and experiments:
LHC Chamonix Workshop 2023, LHCC (7 June)

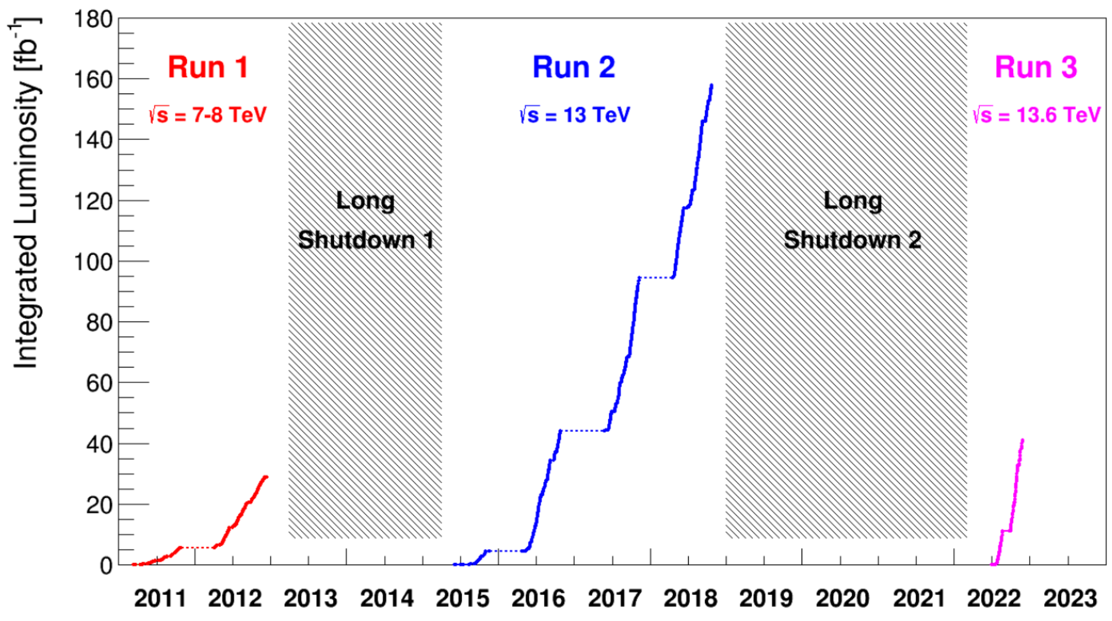
Recap of 2022 - 1st year of Run-3 -

Highlights of LHC in 2022

2022 was a very productive year

- Quick start after long shutdown of 2019-2021
- The highest energy ever reached : 13.6 TeV
- The highest peak luminosity ever reached : ~2.6 x 10^{34} $cm^{-2}s^{-1}$
  - Integrated luminosity delivered to ATLAS and CMS : ~40 fb^{-1}





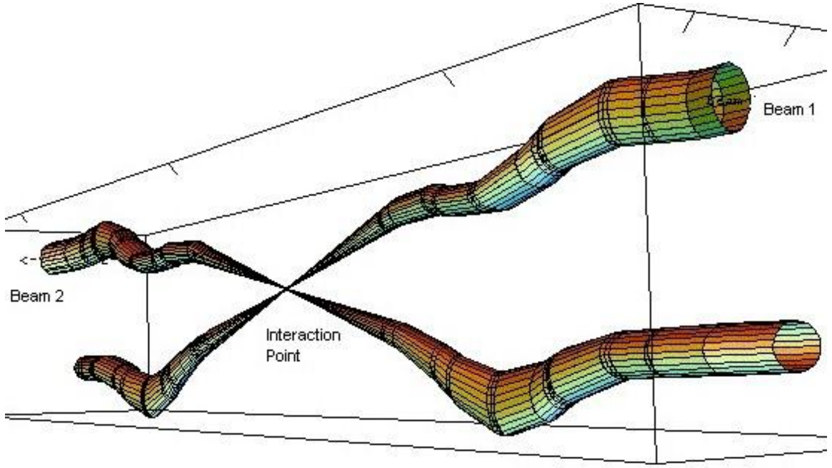
Inner triplet cooling for collision debris limits the peak luminosity

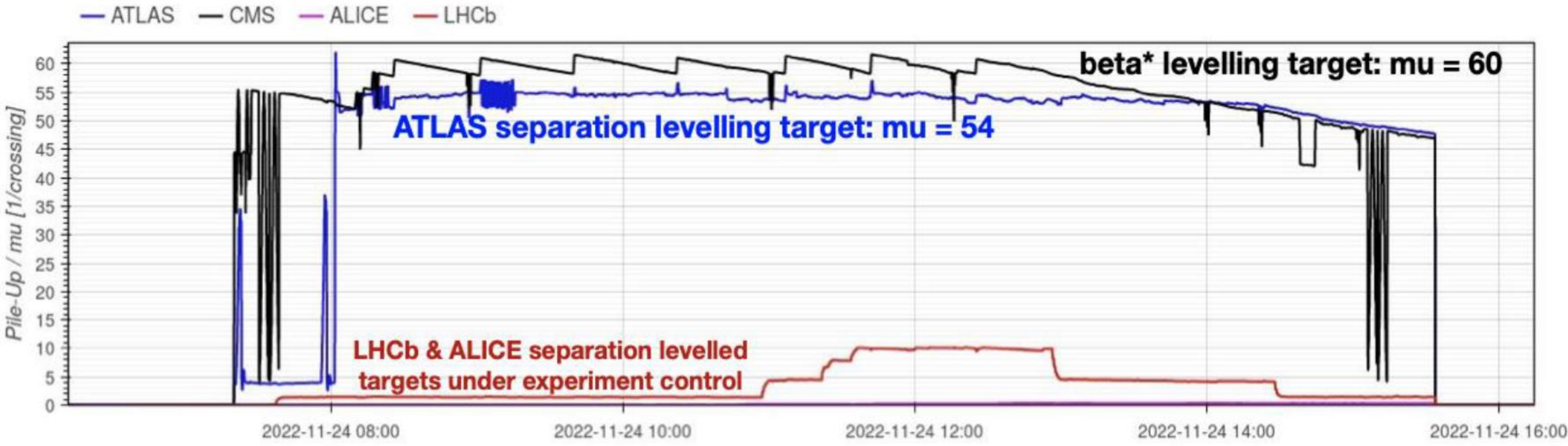
For maximizing integrated luminosity in 2022

In a limited operation time, sophisticated operations deployed to gently reduce the beam size (β* levelling) to keep the luminosity level at its maximum value for as long as possible

- Bunch intensity improved by LHC Injectors upgrade (1.5×10^{11} ppb in 2022, 1.1×10^{11} ppb in 2018)
- β* levelling routinely used for the first 5-6 hours of every fill
- Fully automated levelling of a specific <μ> for ATLAS and CMS
- High <μ> for much longer time than Run-2 ➜ Big challenge for ATLAS/CMS

<μ>: the number of interactions per bunch crossing



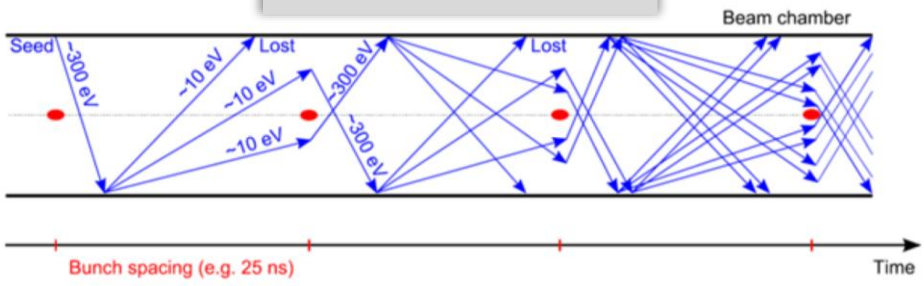


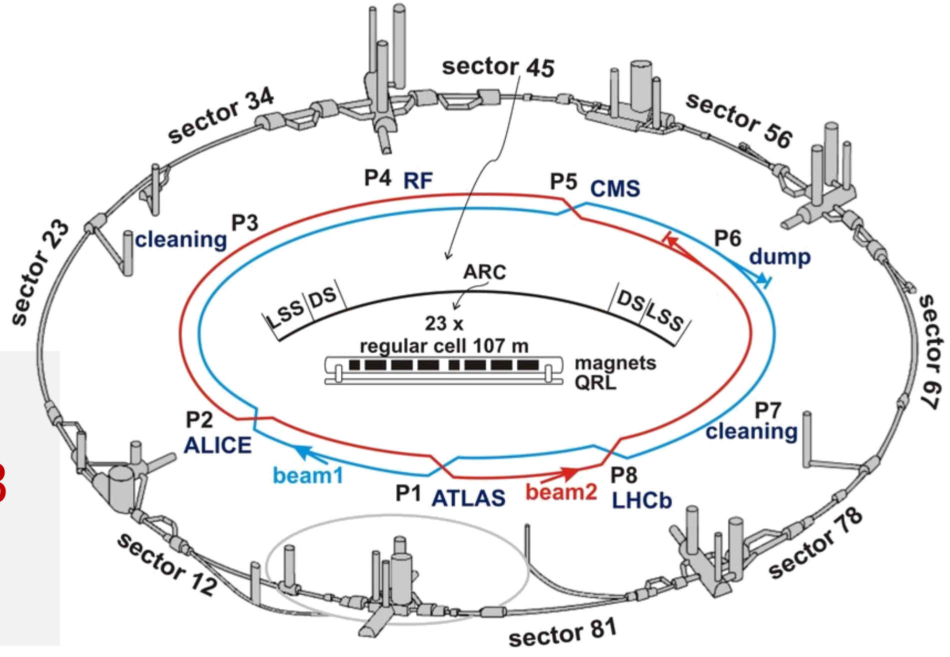
Electron-cloud issue in LHC operation

Issue of electron cloud head load

- An electron cloud in beam chamber cause the deposition of energy on their walls and a significant heat load
  - ➜ Significant decrease in the beam quality
- Especially in areas where bunches are denser such as inside the focusing triplet magnets surrounding the collision points
- Significant degradations of heat load in Sector 56/67/78 in 2022
  - S78 with the highest heat load

Electron cloud





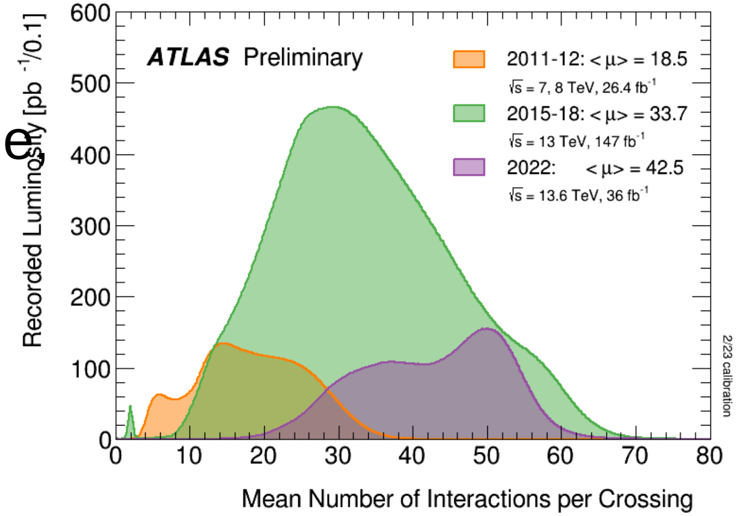
Dealing with electron cloud

- Bunch fill pattern adjusted to reduce the heat load of S78
- Bunch intensity increased slowly up to 1.5 x 10^{11} ppb

ATLAS and CMS operations in 2022

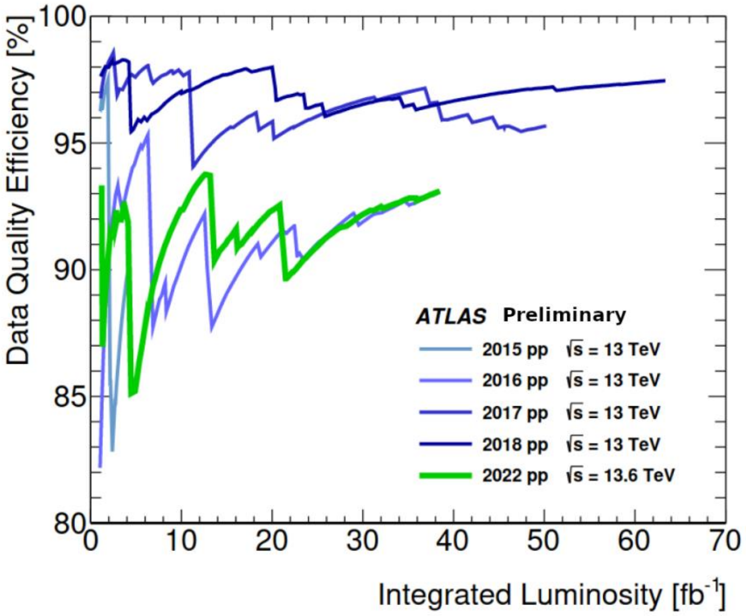
ATLAS and CMS struggled against high <μ> in the long levelling

- Limitation on <μ> below 50 at the start of Run-3 due to high deadtime, unstable readout, bandwidth and CPU limits
- Eventually both ATLAS and CMS running stably at <μ>~54



ATLAS

- Data taking at 93% efficiency at the end
- Limited to <μ>=55 due to HLT/DAQ bandwidth
  - Should be improved in 2023 by hardware replacement
- Commissioning on new Level-1 trigger systems/new muon detector



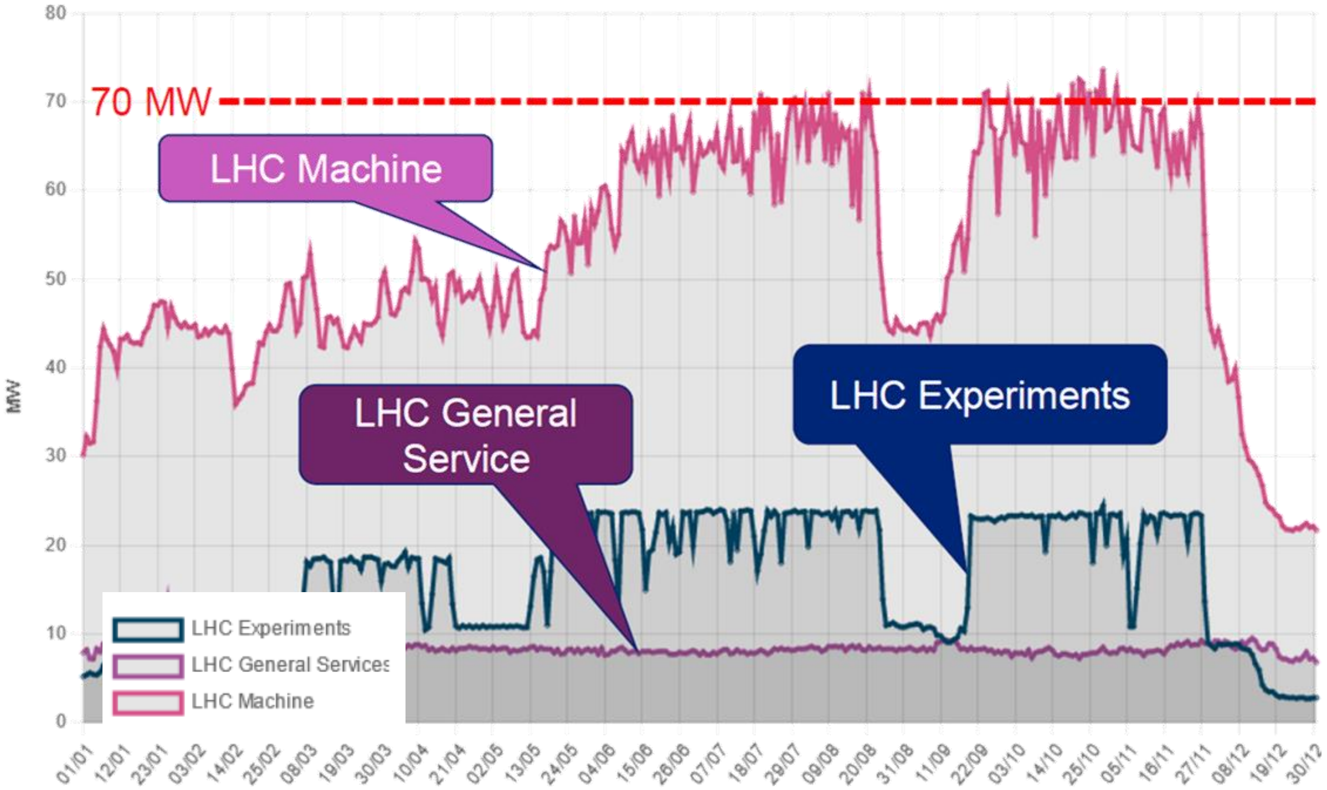
CMS

- Data taking at 92% efficiency at the end
- Limited by L1 rate and <μ> in Aug. Stable at <μ>=55 later.
- Commissioning of new detectors and new electronics

Sustainability: LHC energy consumption in 2022

As energy prices spike especially in Europe, CERN is not being spared

- CERN has massive energy consumption
  - Total Power ~ 100 MW
  - Main consumer is LHC
    - Cryogenics accounts for over half of LHC machine energy consumption

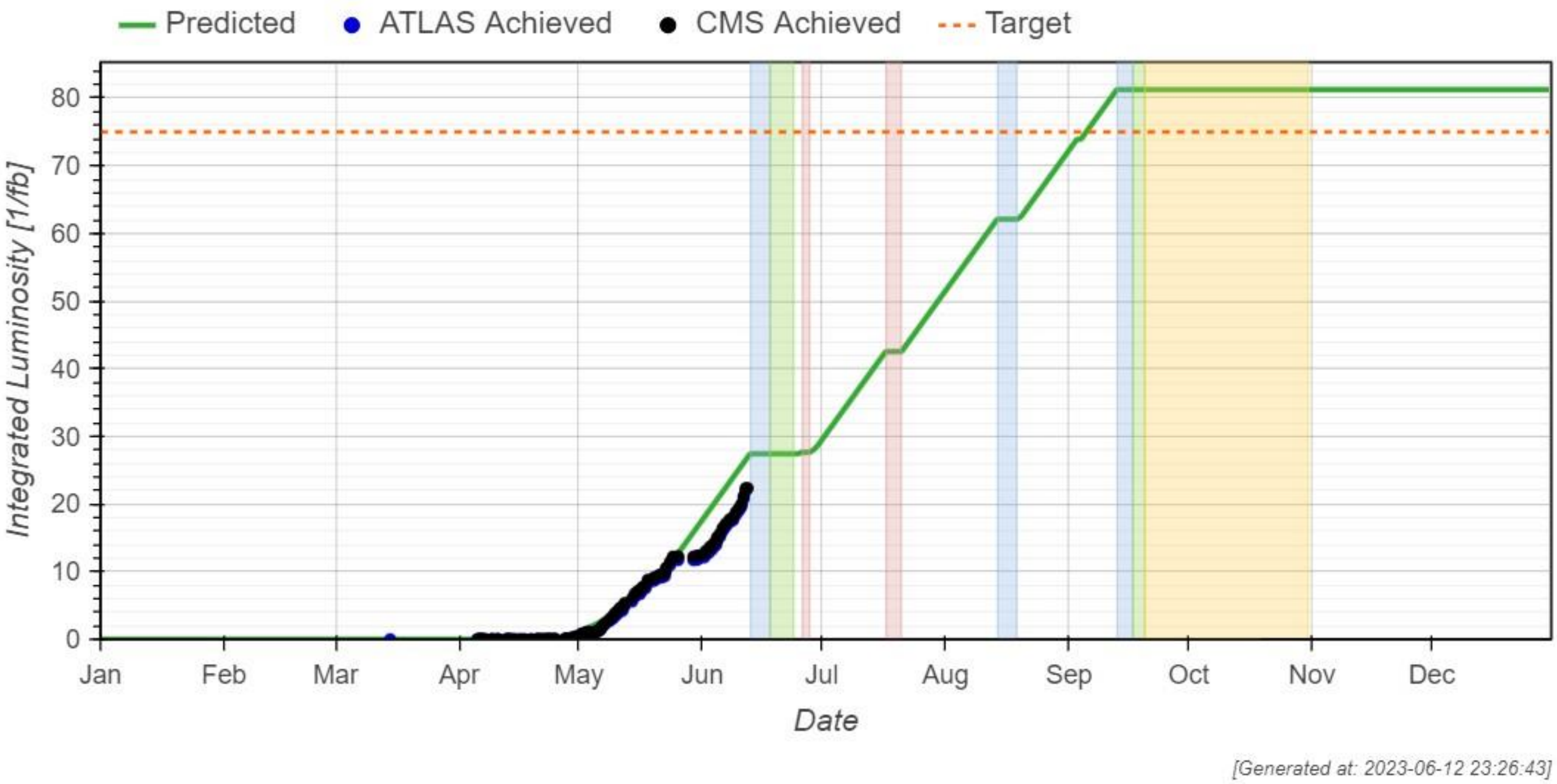


LHC has been actively working to reduce its electricity consumption

- Cryogenics: Energy economy mode developed to switch to a configuration with fewer active units and used for all compatible periods (commissioning, Ion run, long stops, …)

  ➜ Saving around 9 MW in 2022 (~37 MW for physics mode, ~28 MW for economy mode)

Run-3 operation in 2023



LHC operation in 2023, pushing the limits

LHC operation time is reduced in 2023 by 20% for saving energy costs

- Total operations for 2024/2025 remain unchanged (for the moment)
- Optimizing the running time can bring significant savings without impacting overall physics production time beyond that introduced in 2022 and 2023 measures

Main goal is physics production with increased bunch intensity

- Main differences for experiments between 2022 and 2023
  - Longer β^* levelling time from 1.2 m to 0.3 m (2022: 60-30 cm). Tuned for bunch intensities of 1.8 x 10^{11} ppb (limited by beam extraction system until HL-LHC upgrade)
  - Target pileup $\langle\mu\rangle = 60$

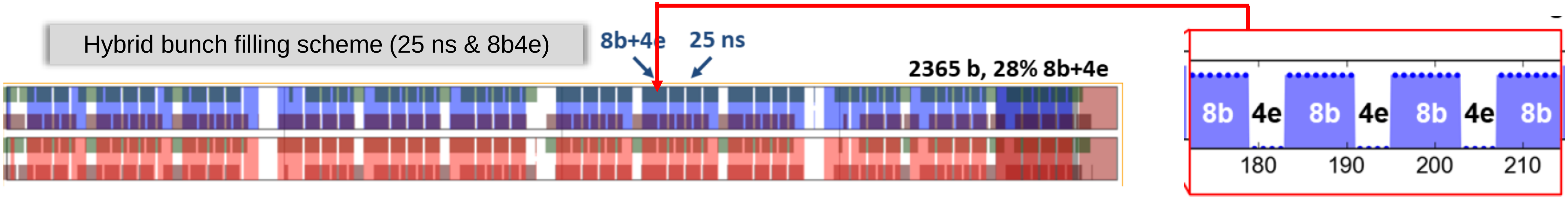
    ➜ Longer levelling time at higher $\langle\mu\rangle$. More challenging to ATLAS and CMS.
- Target integrated luminosity: ~75 fb^{-1}

Dealing with electron-cloud in 2023

Best compromise for maximizing performance while keeping heat loads within acceptable limits

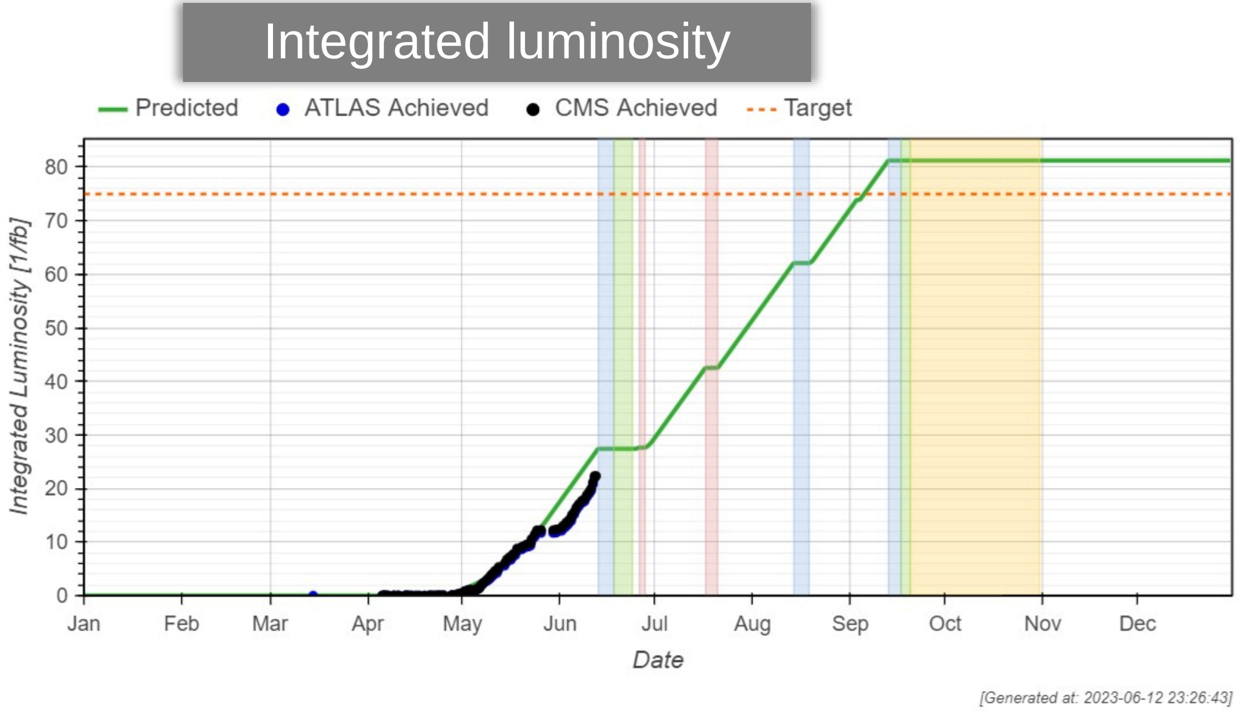
➜ Hybrid filling schemes with mixing 25 ns & 8b4e (8 bunches and 4 empty slots) beams

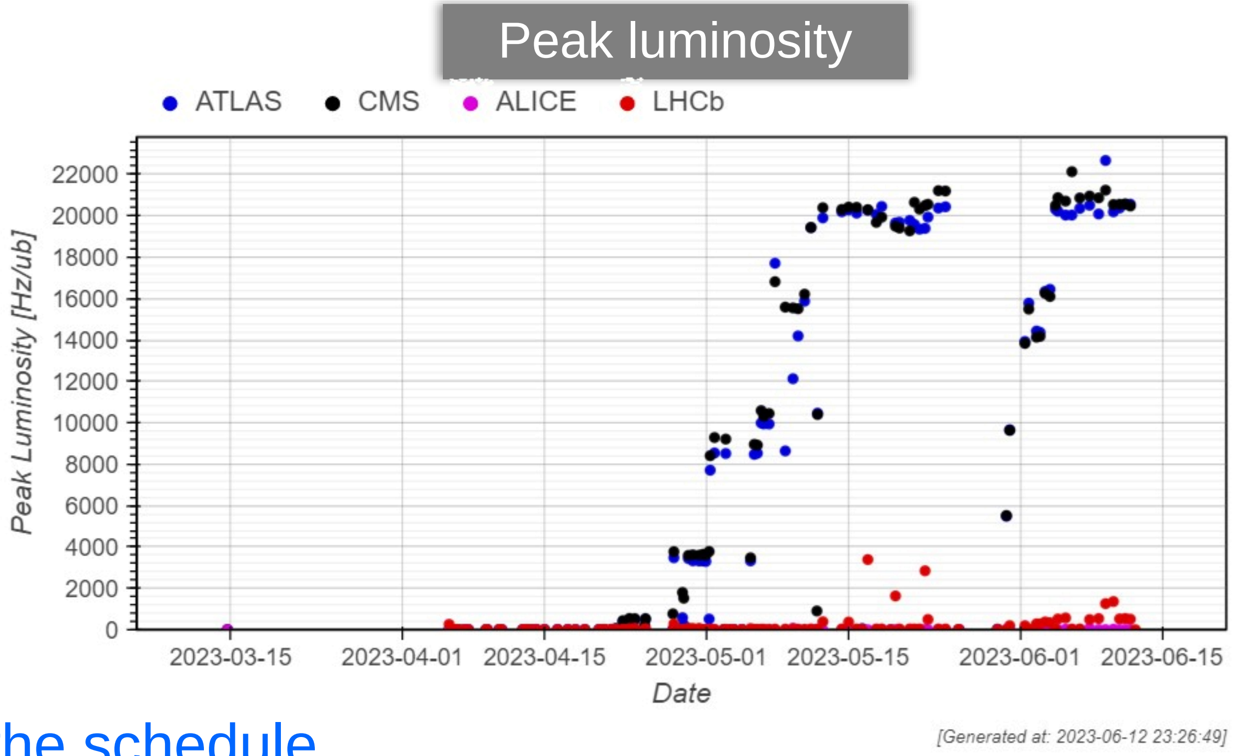
- Filling scheme combined with 8b4e bunch train inserts to mitigate the heat load due to the e-cloud
  - Added gaps on rising slope of the e-cloud building up so that e-could never reaches full saturation



- Fraction of 8b4e beam tuned to adapt to the cooling capacity to maximize the achievable number of bunches in the LHC ring
- A strong e-cloud reduction confirmed up to 1.7x10^{11} ppb in 2022 test

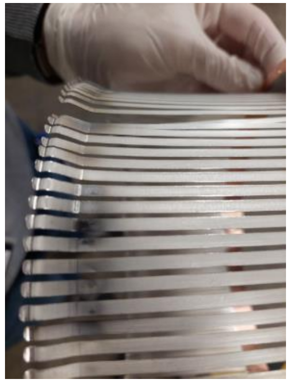
LHC performance in 2023





LHC had a good start with two weeks ahead of the schedule

- Only 21 days for beam commissioning until stable beam at 6.8 TeV
- But, beams dumped in ramp due to problem with vacuum module
  - Operation with 2400 bunches resumed on 4 June
- The target intensity is 1.8×10^{11} ppb (currently, 1.6×10^{11} ppb)



Clear signs of heating/sparks on outside of RF fingers and the transition tube

Experimental challenges in 2023

Higher pileup <μ> in 2023 ➜ Challenges for ATLAS and CMS

- CMS can cope with <μ> ~ 63, while ATLAS stayed at <μ> ~ 59 by the end of May
- CMS L1 trigger rate was increased to 110 kHz with only 2-3 % deadtime, while ATLAS stays below 100 kHz

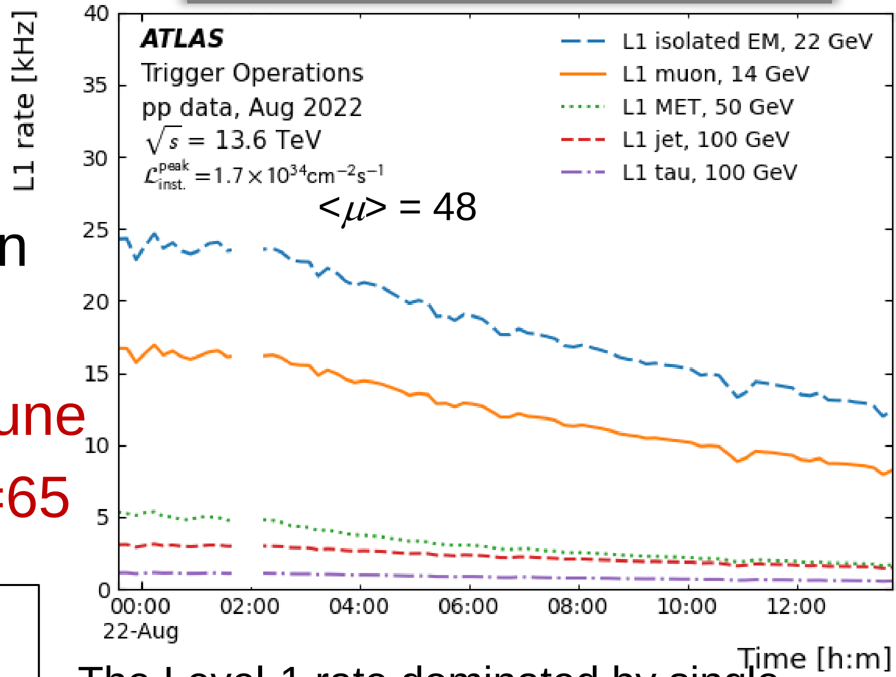
➜ Allowing more to be recorded at CMS than at ATLAS

100 kHz limit is due to protective deadtime for detector readout

ATLAS limitation: High deadtime (also HLT CPU exhaustion)

- The deadtime can be suppressed by L1 trigger rate reduction
- Full operation of upgraded L1 trigger systems necessary
- ATLAS pushing the limits and can cope with <μ>=61-62 in June
  - Actively working on further improvements, aiming for <μ>=65

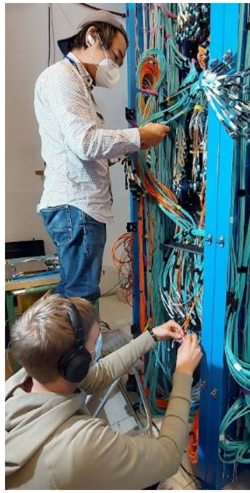
ATLAS Level-1 Trigger rate



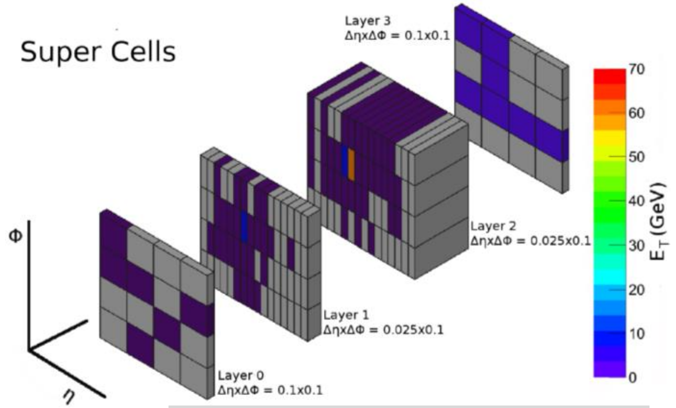
The Level-1 rate dominated by single electron/photon and muon triggers

The status of the new ATLAS L1 trigger system (L1Calo/L1Muon) are shown in next couple of slides. Japanese group heavily involved.

Level-1 Calorimeter trigger upgrade in Run3

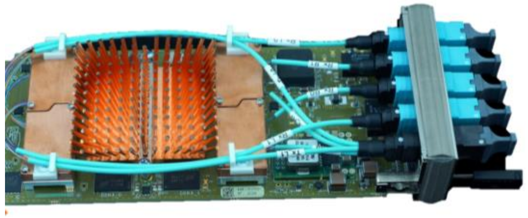


- High trigger rates induced by the large number of jets originating from *pp* collisions
- Finer-granularity readout to improve precision of energy measurement
  - enable better discrimination between photons, electrons, taus and jets
- New electronics in LAr calorimeter for energy measurement and in Level-1 trigger to reconstruct electromagnetic objects, etc



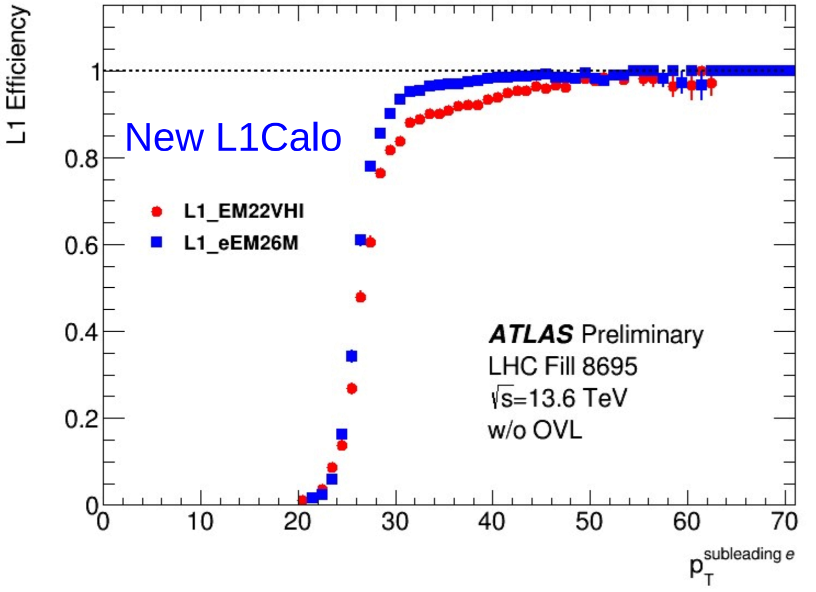
Ten-fold increase of data

New electronics in LAr calorimeter



New L1Calo electronics

Efficiency of electron/photon trigger

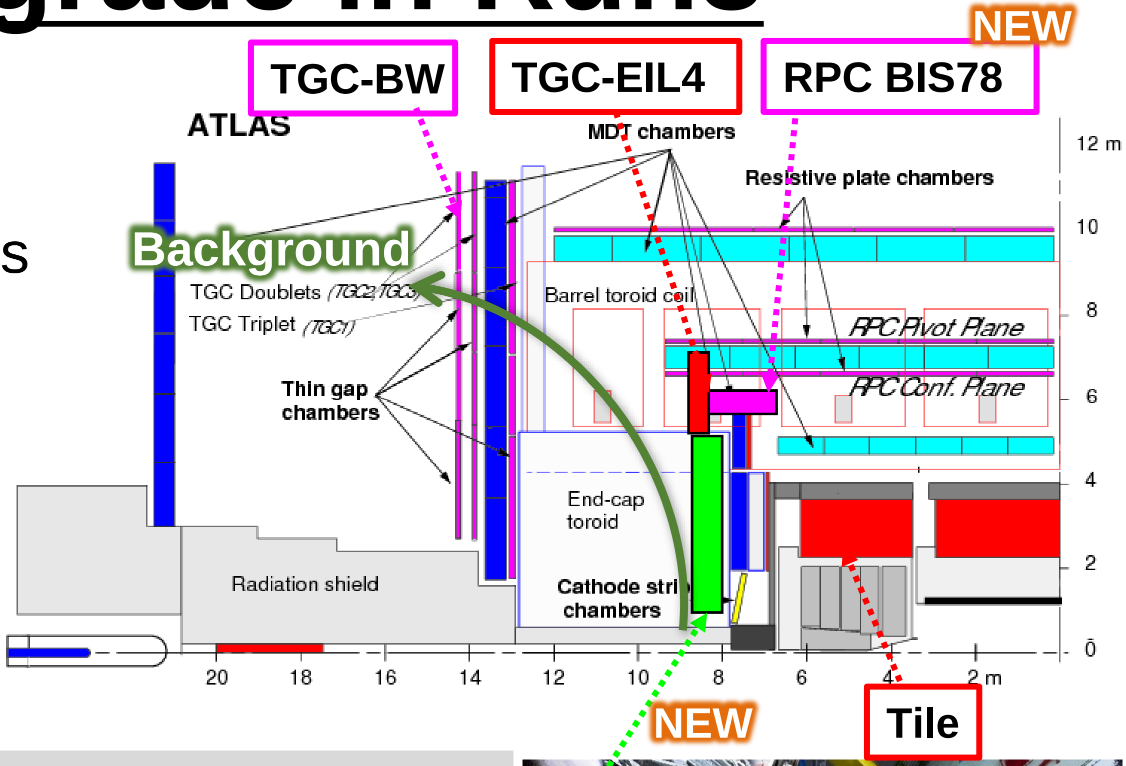


- New electron/photon triggers activated in May. ~5 kHz rate reduction. Jet triggers and topological triggers will follow

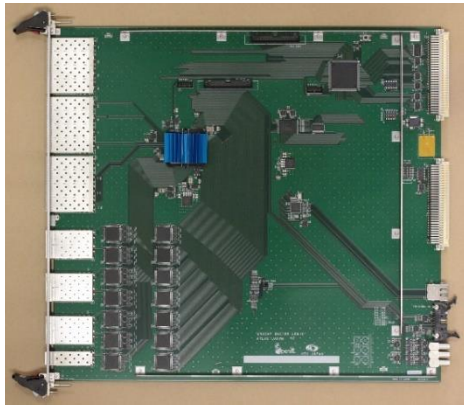
Level-1 Muon trigger upgrade in Run3

Muon finding and p_T measurement by TGC-BW

- The triggers still dominated by background particles not originated from IP
- The integrated algorithm with many detectors for better trigger decision
  - NSW, Tile, TGC-EIL4, RPC BIS78 complementarily used to cover the full endcap regions
- The new electronics successfully provided triggers by TGC-BW at day-1 of Run-3.
  - Rate reduction by TGC-EIL4 activated
- Integration of NSW and Tile calorimeter for L1 trigger rate reduction is in full swing



L1Muon trigger electronics



Level-1 Muon trigger upgrade in Run3

L1 trigger rate reduction started in June under a lot of pressures

L1 muon trigger rate reduction by Tile Calorimeter

- Final timing tuning and efficiency investigation
- Activated in the 1st week of June

➜ The rate successfully reduced by 1-1.5 kHz

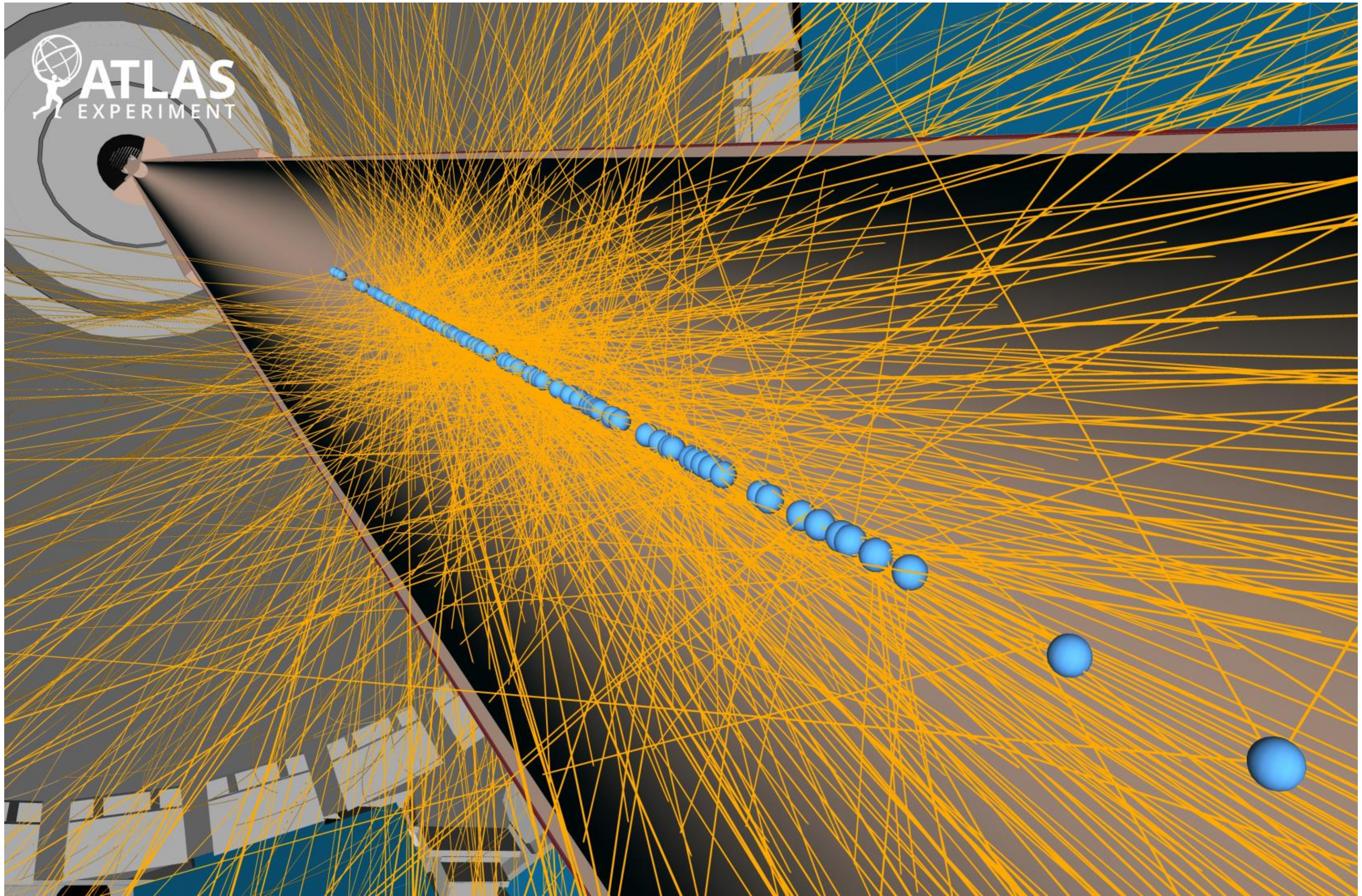
L1 muon rate reduction by NSW

- Final timing tuning and efficiency investigation
- Partially(~20%) activated in the 2nd week of June

➜ The rate successfully reduced by 1-1.5 kHz

Contribution to reducing deadtime and recording more data in ATLAS

HL-LHC (2029-)



HL-LHC technology

The High-Luminosity LHC will provide an order of magnitude more data starting from 2029

- Allowing precision tests of the properties of the Higgs boson and improved sensitivity to a wealth of new physics scenarios

New more powerful quadrupole magnets,

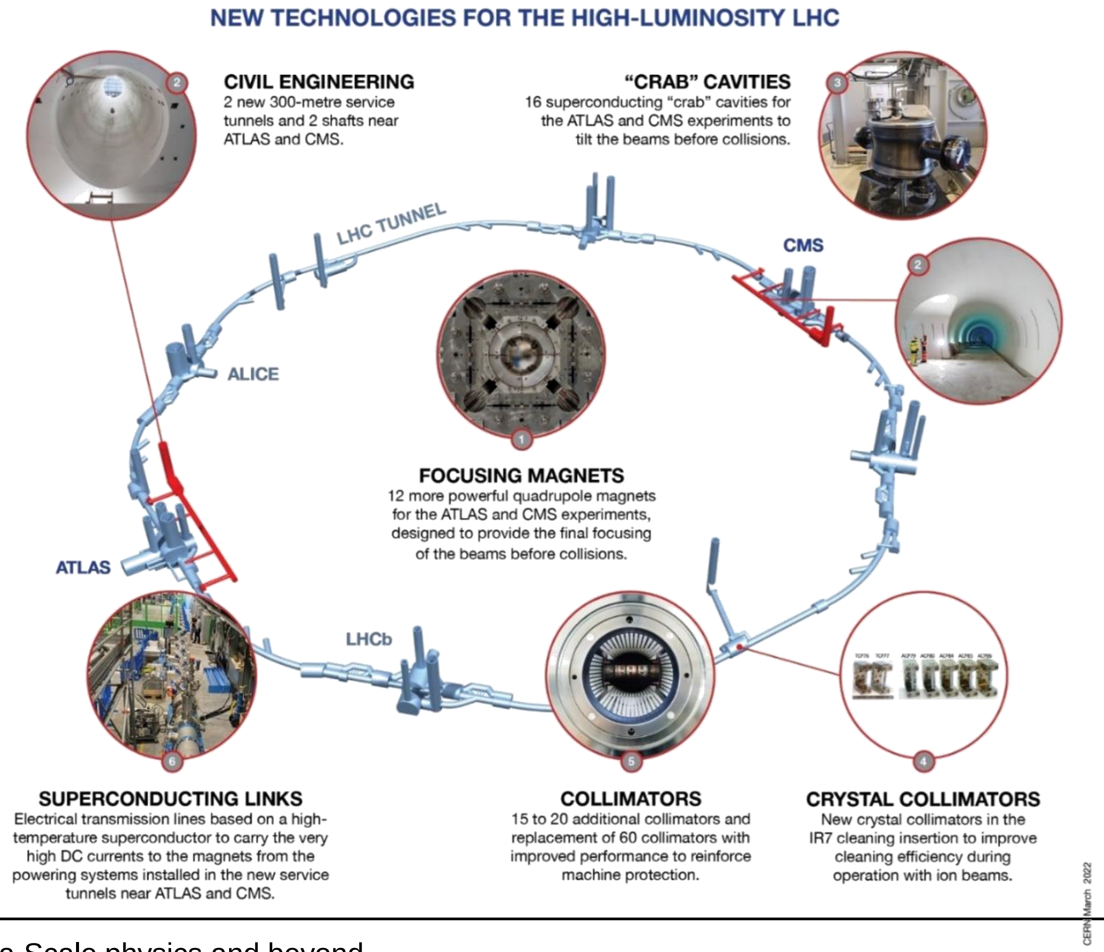
generating a 12 T magnetic field (8 T for LHC) to be installed either side of the ATLAS and CMS for the final focusing. More intense and concentrated beams.

Renovated injector accelerator chain

To provide beams with more intensity and brightness for LHC. A major step was achieved before Run3 (Linac4 replaced Linac2)

Crab cavities for tilting the beams

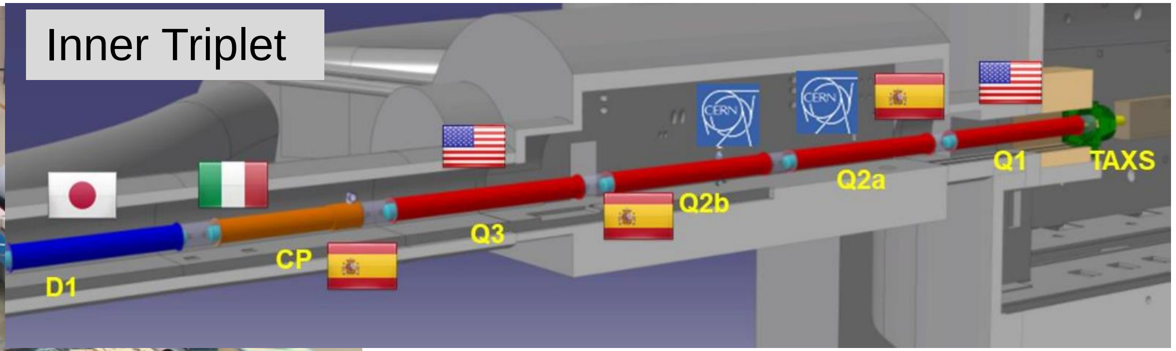
The crab cavities give opposite deflections to the head and the tail of the bunches, to get a better overlap of the colliding bunches

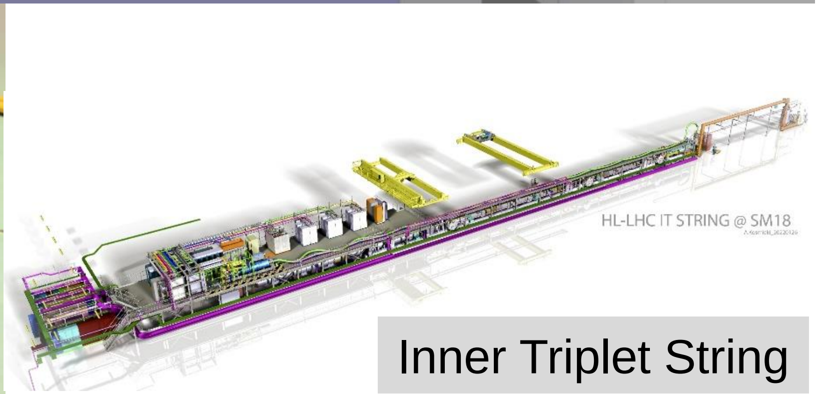


Japanese contribution to HL-LHC D1 magnets

A prototype of 7 m beam separation dipole (D1) delivered from KEK to CERN on 4 Apr 2023

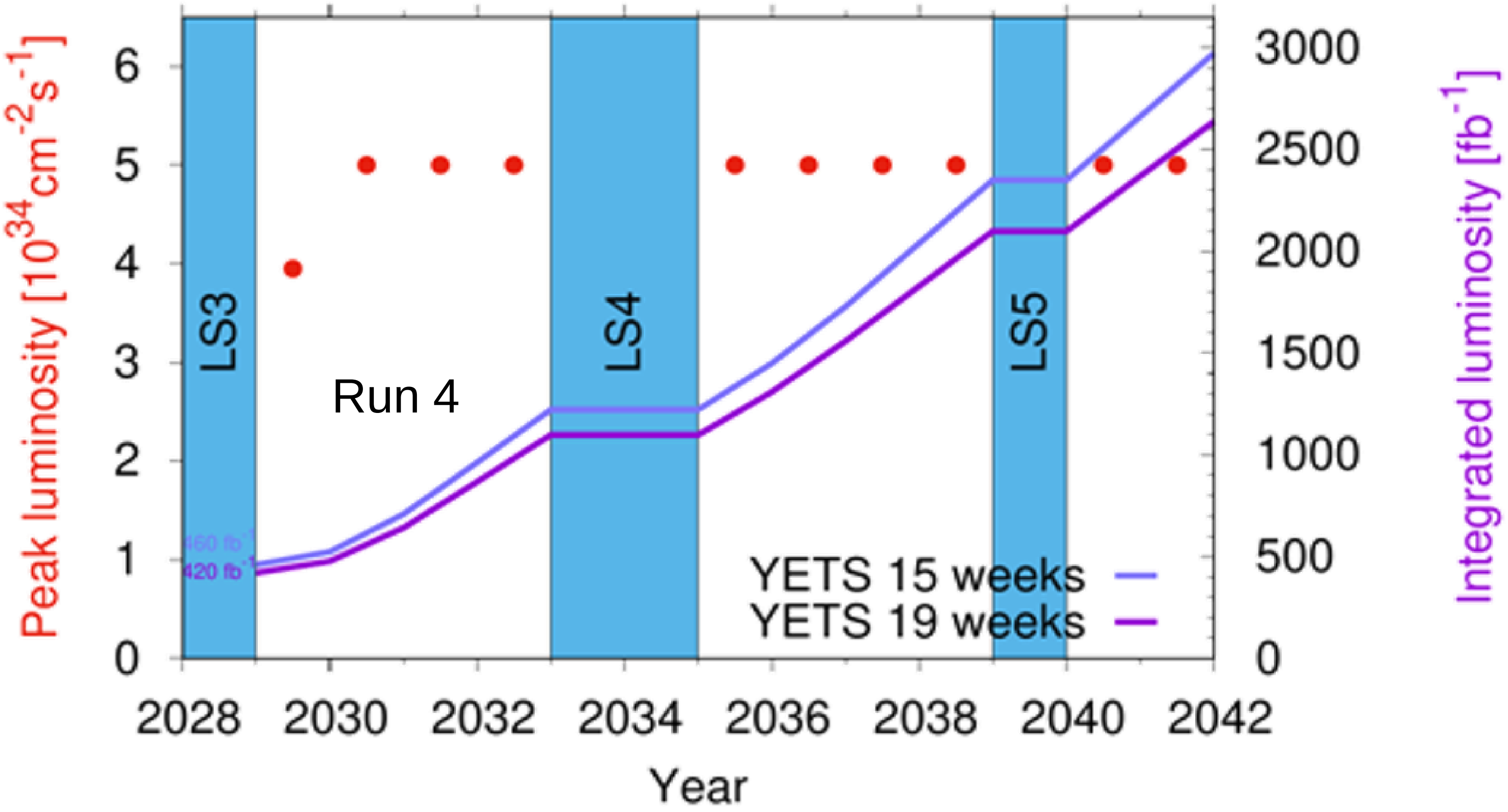
- 8 inner triplets, two of which are located at each of the 4 detectors. Inner triplets tighten the beam.





- The prototype used for Inner Triplet string test, which serves a testbed for matters that cannot be tested as part of the components, to study and validate the integrated system of the key technologies of the HL-LHC

HL-LHC schedule



Current baseline:
- 2748 bunches,
- $2.3x10^{11}$ ppb,
- 2.5h turn-around,
- 40% stable-beam efficiency for 7h stable beam duration

- Run 4 aims at approaching 250 fb^{-1} in the last year after ramping up for a total of 750 fb^{-1}
- But, unless effective mitigation is established, the maximum number of bunches in Run4 will be limited by e-cloud heat load

Challenges of Run-4: Electron cloud limitation

The production of denser beams for HL-LHC makes the issue of e-clouds even more pressing

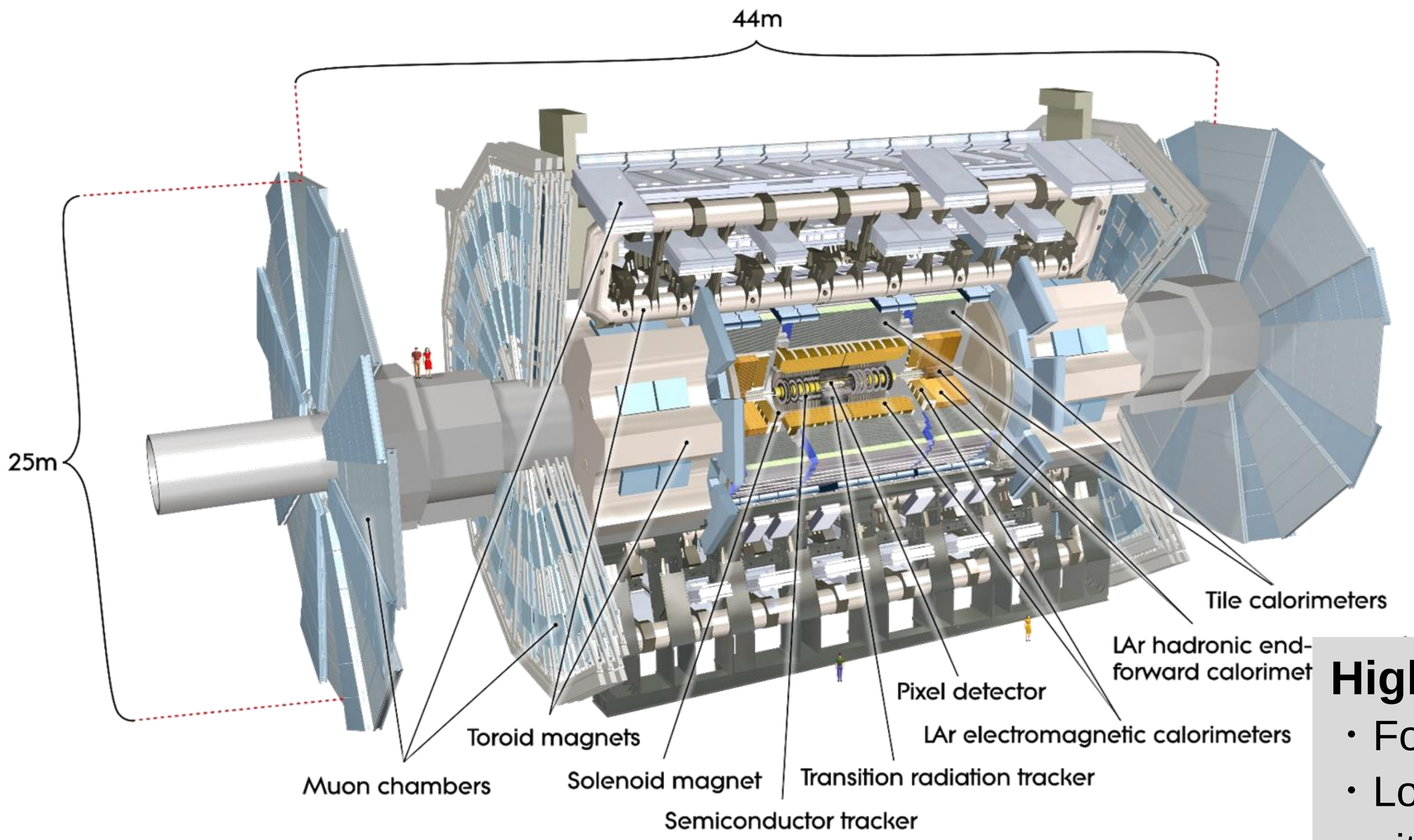
- The beam induced heat loads in LHC cryogenic with some arcs being close to the cooling capacity
- Further degradation of head load cannot be excluded for HL-LHC
  - The different degradation of the sectors is still not clear.
  - The degradation is likely due to combination of several factors (Surface reactivity of beam screens etc)
- Investigation on possible treatments of beam screen ongoing to mitigate the e-cloud

# of bunches	PU	Integrated Lumi [1/fb] (Δ[%])	Feasibility from		
			e-cloud	Beam Dynamics	Experiments
2748 (25ns)	132	257 (0%)	No	Yes	Yes
	200	318 (+23%)	No	To be studied	From Run 5
2200 (hybrid)	140	217 (-16%)	Maybe	Yes	Yes
	160	234 (-9%)	Maybe	Yes	Probable
	200	257 (0%)	Maybe	Studies ongoing	From Run 5
1972 (8b+4e)	140	194 (-24%)	Yes	Yes	Yes
	160	209 (-19%)	Yes	Yes	Probable
	200	230 (-10%)	Yes	Studies ongoing	From Run 5
1972 2.5×10^{11}	200	253 (-1%)	Exceeding LIU and HL-LHC goals, but worth investigating if possible		

250 fb^{-1} per year will be unreachable without the e-cloud mitigation.

HL-LHC performance critically depends on how the e-could mitigation will evolve.

ATLAS upgrade for HL-LHC



Trigger and DAQ
- Level-0 trigger at 1 MHz
- Improved high-level trigger (150 kHz full-scan tracking)

Electronics upgrade
- LAr and Tile Calorimeters and Muon

New Muon Chambers
- Inner barrel region with new RPC and sMDT detectors

High Granularity Timing Detector (HGTD)
- Forward region ($2.4 < |\eta| < 4.0$)
- Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

New Inner Tracking Detector (ITk)
- All silicon, up to $|\eta|=4$

This presentation only covers ITk and Muon trigger electronics

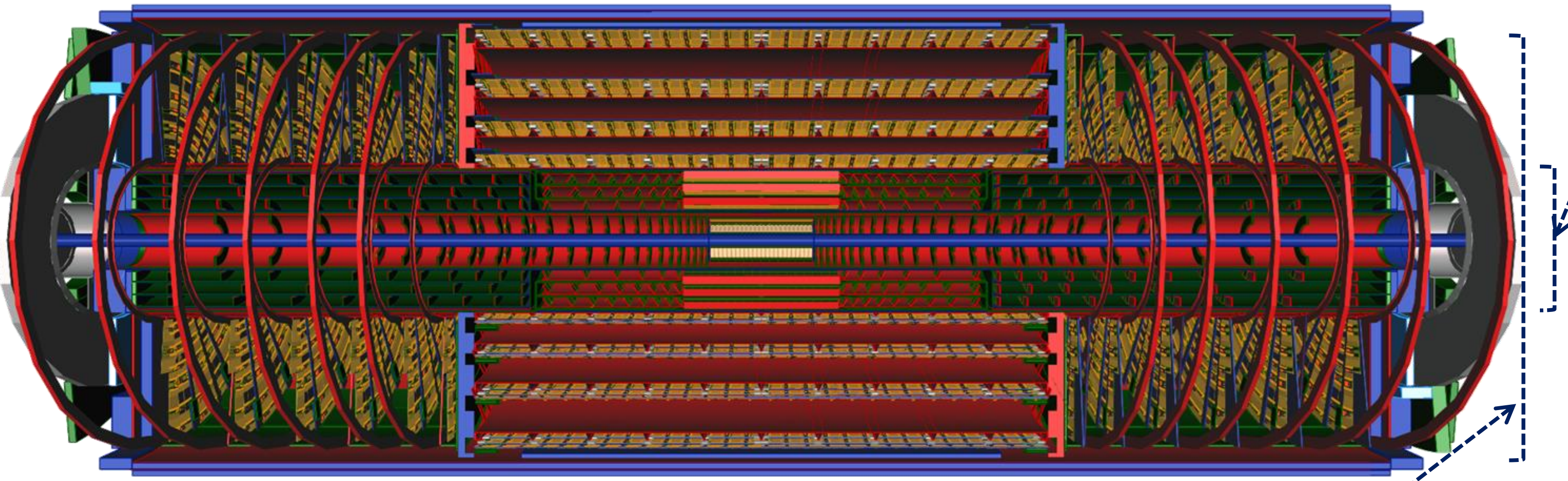
Inner Tracker (ITk)

Inner detector will be replaced by a new all-silicon Inner Tracker (ITk) designed to face the challenging for the high number of collisions per bunch crossing

- The ITk features higher granularity, increased radiation hardness and readout electronics that allow higher data rates and a longer trigger latency.

Pixel:

- 5 barrel cylindrical layers and multiple ring-shaped endcap disks up to $|\eta|$=4.0
- Pixel pitch: 50x50μm (Run-3: 50x250μm). Smaller pitch in z for pileup mitigation.
- Inclined modules in barrel for lower material (Severe requirement in mechanical precision)

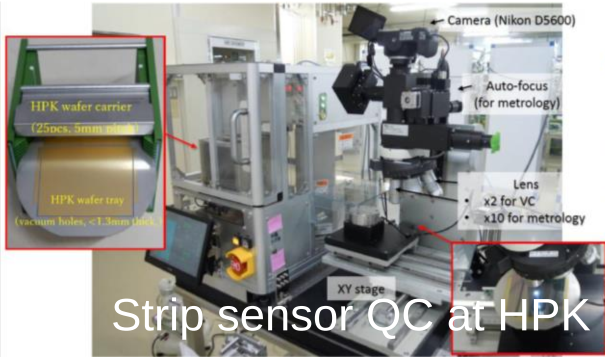


Strip: 4 strip double-module layers in the barrel region and six endcap disks up to $|\eta|$=2.7

Significant progress in transitioning from design to production

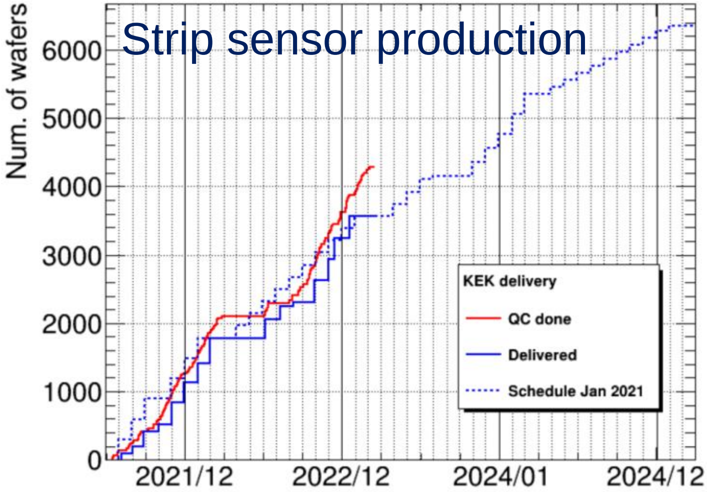
ITk production status

Japan has a big responsibility on ITk production.
A significant part of strip sensors and pixel modules are produced in Japan



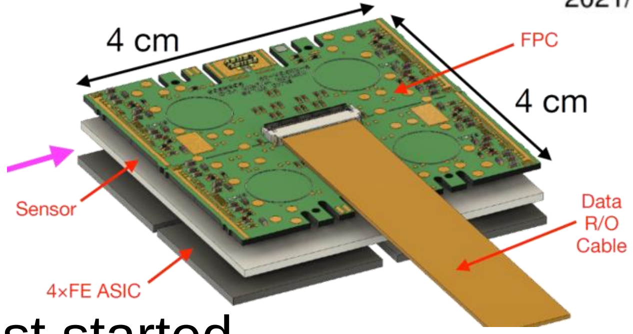
Strip sensor production

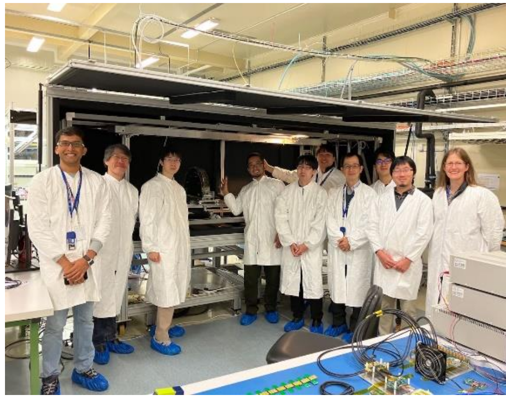
- 6350 sensors to be produced in Japan (out of 22,080)
- Production in progress (started from 2021)
  - Production at HPK going well
  - ~60% done as scheduled



Pixel module production

- 2800 modules to be produced in Japan (out of 8372)
- Pre-production in progress: important step to validate and optimize the long production process
  - Sensor production completed. Module assembly just started
- Production to be started in 2024

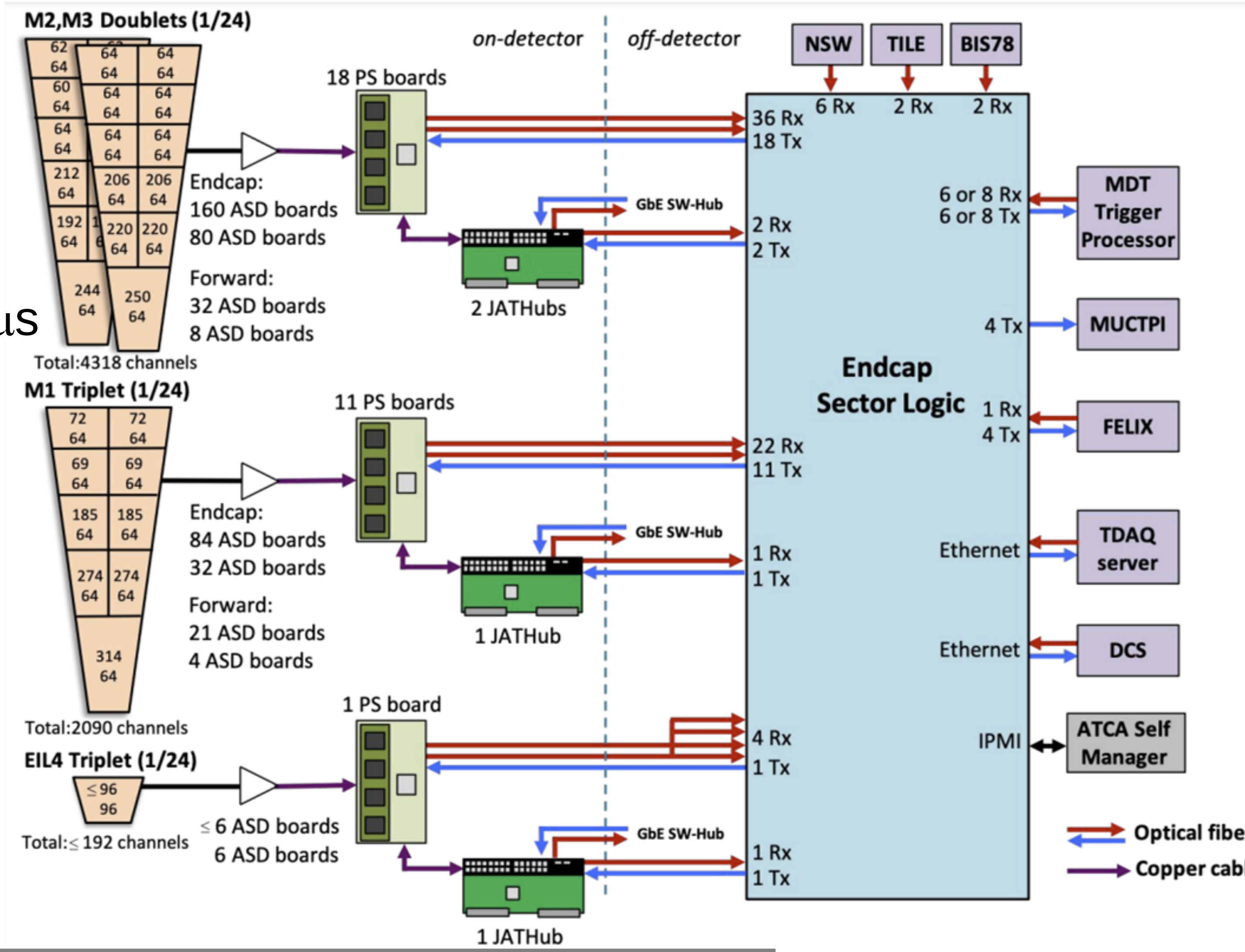




Muon trigger electronics upgrade

Muon trigger needs to be upgraded to cope with higher luminosity

- It will need to cope with a trigger rate of 1 MHz (10 times higher) with latency of 10 μs
- TGCs responsible for triggering on muons in the endcap region
- The electronics upgrade will allow all hit data to be sent to the back-end, removing the need for readout buffers on the detector.
- All hits in the detector will be used to perform trigger logic in hardware



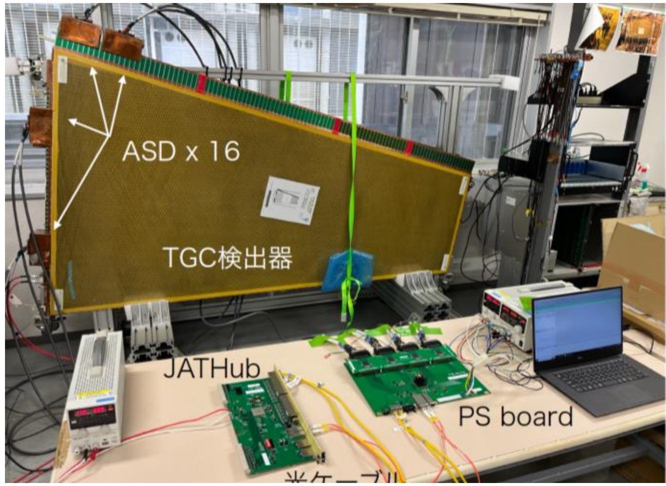
The upgrade being carried out under the responsibility of Japanese group

Muon trigger electronics upgrade status

Front-end electronics

- **PS board**: 16 boards produced in pre-production
  QA/QC ongoing. ~1500 to be produced in 2024
- **JATHub**: 16 boards production and QA/QC completed in pre-production. 180 boards to be produced.
- **TAM**: 2nd prototype being tested. Production in 2024

Integration work at Nagoya Univ.

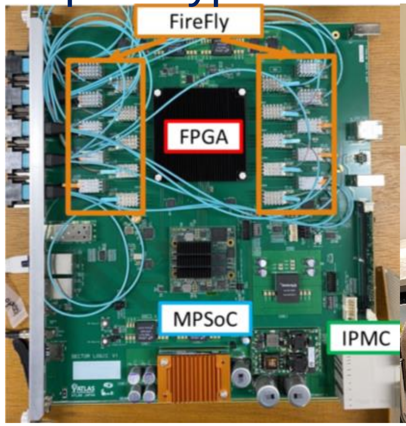


Back-end electronics (Sector Logic)

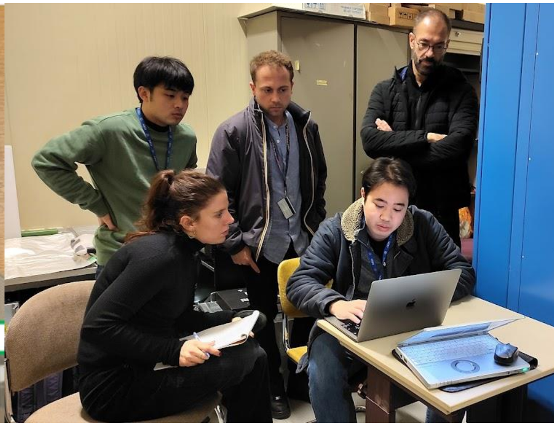
- The board designed and tested by Japanese group
  - Used for the endcap (Japan) and the barrel (Italy)
- 1st prototype test completed
  - some modifications for 2nd prototype (the power sequence, reference clock distributions for transceivers, DC/DC converters)
- 2nd prototype production in coming months

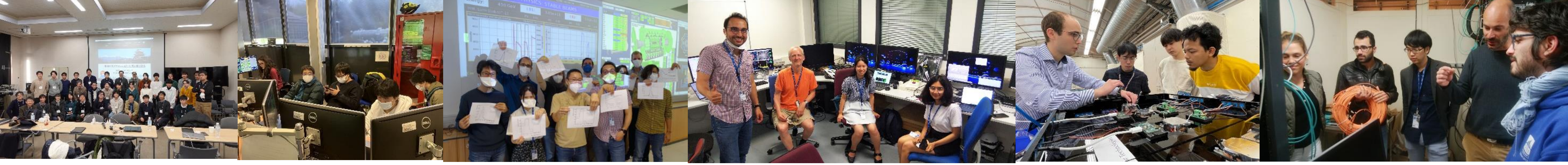
Production, QA/QC and integration in full swing

1st prototype SL



Collaboration work on 1st prototype SL with Italian group at CERN





Summary

Run-3 LHC and experiments

- LHC had a good start in 2023 with higher intensity
- CMS running with L1 rate of 110 kHz and pileup of ~63.
- ATLAS catching up beyond the limitations and running with pileup of 62 in June

HL-LHC upgrades on LHC and experiments

- HL-LHC preparation under way
  - A prototype of the beam separation dipole (D1) delivered from KEK to CERN in Apr 2023
  - The HL-LHC run scenario critically depends on how the e-could mitigation will evolve.
- ATLAS upgrade: Significant progress in transitioning from design to production
  - ITk/Muon trigger electronics upgrades being carried out under the responsibility of Japanese group