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The Phase-2 Upgrade of the CMS Detector

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for the CMS Collaboration

The high-luminosity upgrade of the Large Hadron Collider (HL-LHC) will provide a unique opportunity to extend the physics reach of the CMS experiment by achieving unprecedented precision in the study of Standard Model (SM) processes and by increasing its discovery potential for physics beyond the SM to higher energy scales and rarer processes. The HL-LHC, however, will also bring experimental and instrumental challenges with its harsh environment: high radiation levels, high number of particle collisions per bunch crossing (pileup of 140-200), and extreme final state particle multiplicities. The CMS Collaboration has embarked on an ambitious upgrade program to improve the spatial granularity and timing resolution, to extend the coverage of precision detectors to higher absolute pseudorapidities (η), to increase the data rate that can be recorded, while using more robust and more radiation hard technologies.

In this paper, the main features of the CMS Phase-2 upgrade are reviewed. New high-granularity detectors will be installed: a silicon pixel and strip tracker with larger coverage ($|\eta| < 4$), an imaging endcap calorimeter ($1.5 < |\eta| < 3$), an extended muon system in the forward region ($|\eta| < 2.8$) including Gas Electron Multiplier detectors. The timing precision will also be significantly enhanced by dedicated timing detectors with 30-50 ps resolution ($|\eta| < 3$), supplemented by improved timing information from muon detectors and calorimeters with upgraded electronics. Fully reconstructed tracks with transverse momentum of $p_{\mathrm{T}} > 2$ GeV and particle-flow at the level-1 hardware trigger will enable more efficient online event selection, with an increased level-1 rate (750 kHz) and latency (12.5 μs). Trigger objects will be available at 40 MHz for monitoring and restricted data analysis through a Scouting System. The high-level trigger with a heterogeneous architecture will provide a 7.5 kHz output rate to benefit from the increased luminosity.

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1. Physics motivation

The HL-LHC – expected to start operation in 2029 – will allow precision studies of electroweak symmetry breaking and new physics via quantum loops [1]. Higgs boson couplings will be measured to a few percent precision, rare challenging Higgs decays (such as $\mathrm{H} \rightarrow \mathrm{c}\bar{\mathrm{c}}$), di-Higgs production and longitudinal vector boson scattering will become accessible (Fig. 1). With 14 TeV collision energy and 10-fold increase of integrated luminosity to 3000 fb^{-1} until the early 2040s, the mass reach for direct searches of exotic particles will be extended and blind spots (such as parameter regions leading to compressed supersymmetric partner mass spectra) can be uncovered. We might discover the particles responsible for the dark matter in the Universe, new resonances or long-lived particles predicted by various extensions of the SM featuring supersymmetry (SUSY), extra spatial dimensions or strong dynamics.

The next sections review the instrumentation that will allow to exploit the rich physics data delivered by the HL-LHC.

2. Silicon tracker

At the heart of CMS, Si pixel and strip detectors (Fig. 2) will measure the path of charged particles [2]. To cope with the higher particle rate, a 10 times more radiation hard, highly granular system (with 25 times as many output channels as the Phase-1 detector) is constructed. Certain subsystem (TEPX and the outermost layer of TB2S) will also serve as high-precision real-time luminometers.

Closest to the beam pipe, 2 billion hybrid micropixels of 25 μm $\times 100\mu$m size form the Inner Tracker (IT) and cover 4.9 m^2. The n-in-p type sensors of 150 μm thickness will be read out by a front-end ASIC produced in 65 nm radiation-hard CMOS technology.

The Outer Tracker (OT) consists of 43 million microstrip and 170 million macropixel n-in-p type sensors, covering 190 + 25 m^2. It will provide input at 40 MHz to the level-1 (L1) trigger [9] using a special module design. Transverse momentum discrimination is achieved by measuring hit coincidences (stubs) in sensors of double sided modules, where a flex hybrid allows to get data from both sensors to a single ASIC. For best performance, the sensor spacing is separately optimized for different detector regions, and the correlation window sizes for stub formation are tunable. Tracks

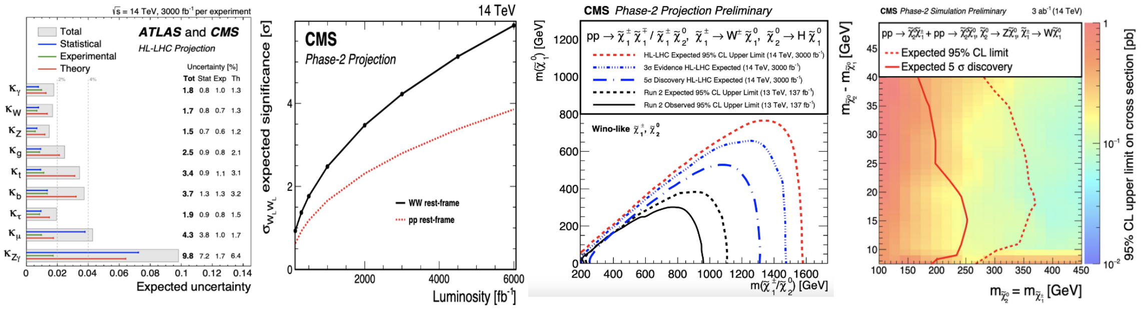

Figure 1: Expected sensitivity at HL-LHC: precision of Higgs coupling modifiers (left), significance of longitudinal WW scattering measurement (middle left), improvement for chargino exclusion (middle right) and cross-section upper limit for a SUSY scenario with compressed mass spectra (right).

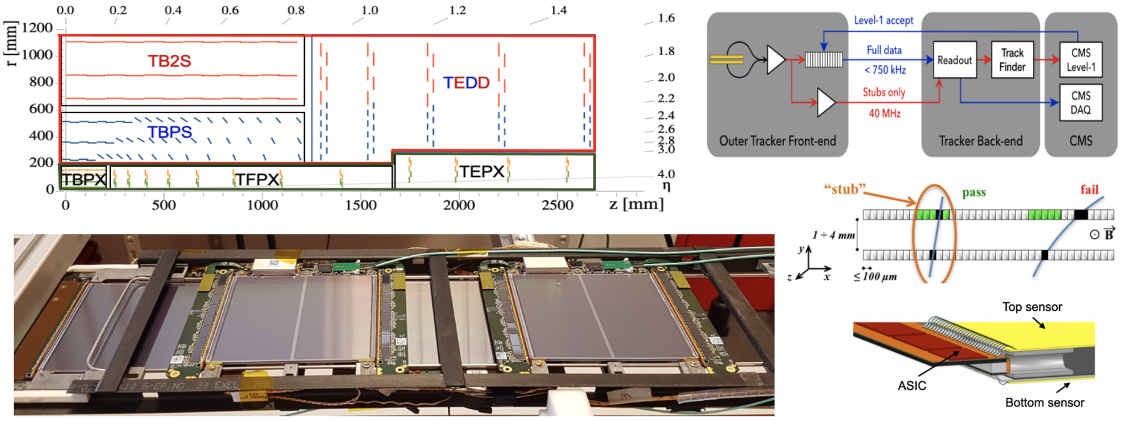

Figure 2: Phase-2 CMS Tracker geometry (top left), data paths of the Outer Tracker (top right) including stub (middle right) information, enabled by a special module design (bottom right), and prototype TB2S structure (bottom left).

are formed from stubs in the OT layers, and the transverse momentum is extracted and sent as input to the L1 trigger. Displaced track reconstruction is being studied.

3. Timing layer

To limit the effects of event pileup (PU) on reconstruction performance to Run 2 levels, 4D reconstruction of tracks and vertices with 30-50 ps time resolution is needed. Overlapping vertices at the same z coordinate can be then resolved using time stamps of tracks. Precision timing improves the calculation of lepton and photon isolation, the reconstruction of hadronic jets and missing transverse momentum, b-jet tagging and (especially in heavy ion collisions) π / K / p identification using time-of-flight measurement [4]. It can also extend the reach of long-lived particle searches.

The Barrel Timing Layer (BTL) [3] at an inner radius of 1148 mm covering $|\eta| < 1.5$ is constructed from Cerium-doped LYSO crystals read out by Silicon Photomultipliers (SiPMs) (Fig. 3). It is 40 mm thick and extends to 38 m^2 with a total of 332 thousand channels. Test beam results in late 2021 showed lower than expected light yield triggering a design re-optimisation. The main concern is performance (time resolution) degradation with radiation damage.

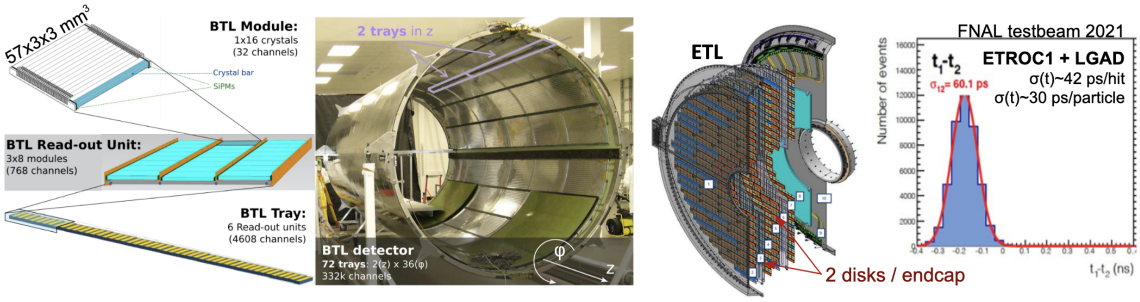

Figure 3: The design of the Barrel Timing Layer (left), the Endcap Timing Layer (middle right) and the ETL timing resolution based on testbeam data (right).

The Endcap Timing Layer (ETL), completing the geometrical coverage down to $|\eta| = 3$, utilizes ultrafast large-pitch Si Low-Gain Avalanche Detectors (LGADs) operated at -30 C. Its design is largely limited by the space available between the tracker and the calorimeters. On a total surface of 14 m^2, it has 8.5 million channels and provides two hits per track.

4. Calorimetry

In the barrel electromagnetic (EM) calorimeter [5], the $PbWO_4$ crystals read out by Avalanche Photodiodes (APDs) remain. The front-end (FE) electronics will be replaced to achieve 30 ps time resolution for electrons and photon of 30 GeV at 40 MHz. A new Very Front End (VFE) board removes spikes (anomalous signals due to particles hitting the APD directly). Cooling to 9 C (from 18 C in Run 3) mitigates APD aging effects. To harmonize the systems, the hadron barrel calorimeter back end (BE) will use the same ATCA boards for data read out, trigger primitive generation, clock distribution to the FE, as well as control and status monitoring.

The CMS Phase-2 endcap High Granularity Calorimeter (HGCal) will be the first imaging calorimeter at a high-PU hadron collider, designed (Fig. 4) to provide precision particle flow reconstruction improving the sensitivity for vector boson fusion and scattering and allowing more precise reconstruction of jet substructure, as well as – through its timing capability – to extend the reach for long-lived particle searches.

The system [6] uses mixed technology: 6 million Si sensor channels (120 μm x 0.5 cm^2 and 200/300 μum x 1.1 cm^2 cells) covering 620 m^2 in total in the region closer to the interaction point, and 250 000 scintillator tiles read out by SiPMs ("SiPM-on-Tile") covering 370 m^2 in the lower fluence hadronic region. CO_2 cooling ensure a temperature of -30 C to limit radiation damage of

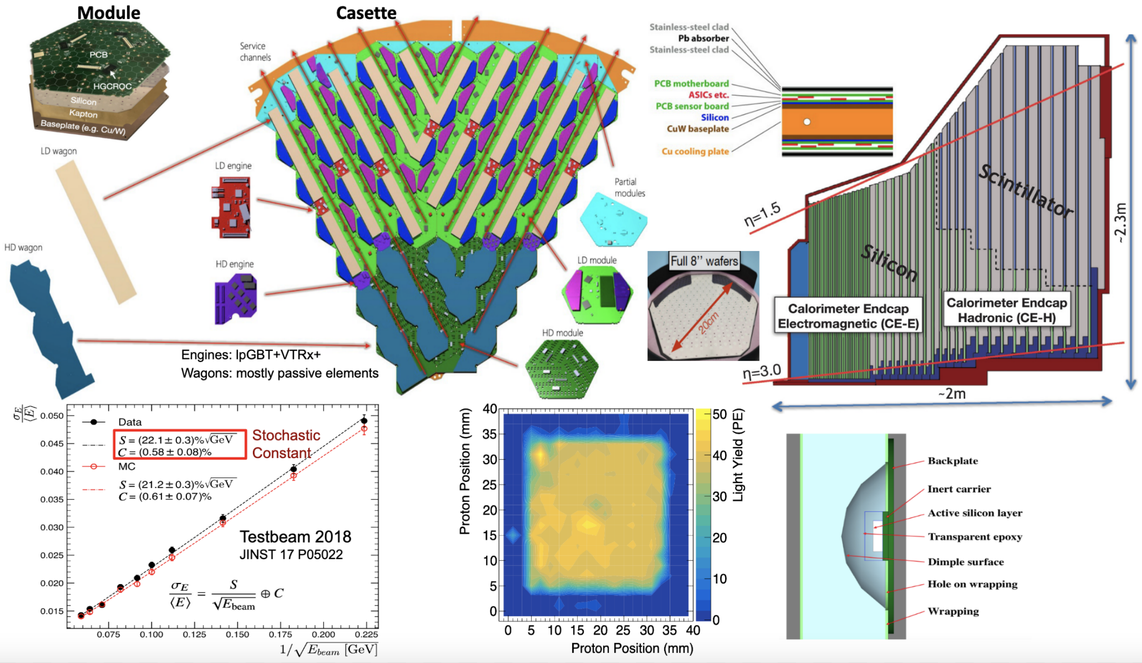

Figure 4: HGCal calorimeter design (top), energy resolution in testbeam data (bottom left), response uniformity of the SiPM-on-Tile detector (bottom center), and its with a dimple in the tile (bottom right).

sensors. In the EM section (CE-E) Pb, Cu, Cu-W absorbers, while in the hadronic section (CE-H) steel is used, resulting in a total weight of 215 t per endcap. The steel absorbers – now in production – achieve a flatness of 1 mm. Longitudinal sampling has been recently re-optimised to stay within space limitations while preserving calorimetric depth. CE-E features 26 layers (down from 28) with a total depth of 27.7 radiation length (X_0) and about 1.5 hadronic interaction length (λ). CE-H has 7 all-Si layers (down from 8) and 14 mixed layers (down from 16). The total depth corresponds to more than 10λ.

HGCal has 26 000 large 8 hexagonal Si modules of 12 different types, consisting of a rigid Cu/W baseplate, a gold-plated kapton foil, a Si sensor, a printed circuit board (PCB) housing the HGCROC FE read-out ASIC. 20% of the modules located at the inner and outer border regions are not fully hexagonal to minimise dead space. Modules mounted on a cooling plate with electronics and absorbers form the casettes.

The HGCROC chip features a large dynamic range to read out MIP signals as well as those of high-energy photons. Lower energy values are digitised by a 10-bit Analog-to-Digital Converter (ADC), while higher energies are reconstructed using the time over threshold (ToT). The time of arrival (ToA) has a resolution of about 50 ps using 10-bit Time-to-Digital Converter (TDC). The data is forwarded to the ECON-D (data) and ECON-T (trigger) concentrator chips, which send the data over optical fibers to the off-detector electronics. The trigger signals (3D clusters of energy deposits) are formed in two stages of FPGAs. The per channel power consumption is about 20 mW, reaching 125 kW/endcap by the end of the HL-LHC era. Online and offline processing uses highly sophisticated pattern recognition and machine learning assisted algorithms to achieve the best particle flow reconstruction.

In the low-radiation part of the hadronic section the SiPM-on-Tile technology offers a cost-effective solution. To equalize the response across the tile, a dimple is formed around the SiPM into the scintillator. Cast and machined PVT-based material is used in the front, while in the back, where lower radiation tolerance is needed, PS-based scintillators. The areas of the tiles and SiPMs are optimized depending on the expected fluence. Reflective wrapping increases the light yield and cooling limits the noise of the SiPMs.

5. Muon system

In the muon system [7] (Fig. 5), the existing Drift Tube (DT), Cathode Strip Chamber (CSC), and Resistive Plate Chamber (RPC) detectors will be enhanced with upgraded electronics to cope with the 10 times higher rates and to improve their performance. The time resolution of the RPC trigger signal will decrease from 25 ns to 1.5 ns. The CSC on-detector electronics have been modernized in the long shutdown after Run 2 (LS2), as well as a slice of the barrel DTs received the new on-board electronics to test the performance in real operating conditions.

New detectors will be installed in the challenging (high rate, high background) forward region to increase redundancy and extend the geometric coverage to $|\eta| = 2.4 - 2.8$, enhance tracking performance and allow bending angle measurement at the trigger level. Three rings of Gas Electron Multiplier (GEM) chambers per endcap will be installed, instrumenting 50+100 m^2 by 2-layer triple-GEM, and 60 m^2 by 6-layer triple-GEM detectors. The first ring (GE1/1) was installed in LS2, the second (GE2/2) is scheduled for end-of-year technical stops (YETs) during Run 3, the last

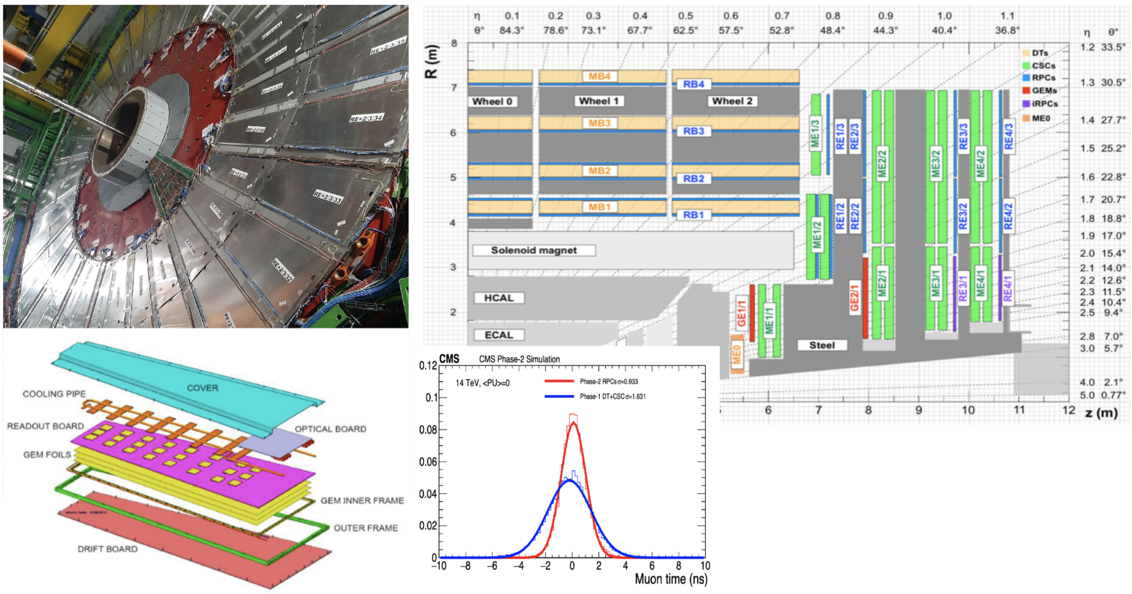

Figure 5: CMS Phase-2 muon system (right), first installed GE2/1 chamber (top left), structure of the GEM detectors (bottom left) and improved time resolution with the upgraded RPC electronics (bottom center).

(ME0) for LS3. Two layers of improved RPCs (RE3/1, RE4/1) will also be placed in the outer region. One slice of the endcap is equipped by new GE2/1, RE3/1, and RE4/1 chambers.

6. Beam instrumentation and luminosity

The Beam Radiation Instrumentation and Luminosity (BRIL) project is responsible for 14 technical systems to provide beam timing, beam loss monitoring and beam abort to protect sensitive instrumentation, beam-induced background (BIB) and luminosity measurements, as well as radiation monitoring in the CMS cavern [8].

To reach the 1% precision target for luminosity determination at HL-LHC, required for example by the most precise Higgs cross-section measurements, luminometry will be both a consumer of CMS subsystem data and rely on a new dedicated bunch-by-bunch luminometer, the Fast Beam Condition Monitor (FBCM). The system design relies on maximum commonality, and introduces for some of its components the concept of luminosity triggers. At the heart of the luminosity instrumentation, the BRIL Trigger Board (BTB) will provide a special clocking scheme for independent operation of FBCM and the outermost smallest radius ring (disk 4 ring 1, D4R1) of the Tracker Endcap Pixel Detector (TEPX). At all times when beam is present in the accelerator (even during the ramping phase of the LHC cycle when the clock frequency changes), they can thus provide feedback on BIB. The BTB will also encode the beam signals to be sent from the Beam Pickup Timing Experiment (BPTX) to the Global Trigger (GT), and utilize them to generate independent triggers for D4R1 and for the rest of the TEPX to measure luminosity based on real-time pixel cluster counting, implemented on FPGA. All system (Fig. 6) will use a common histogramming firmware integrated to their backend boards.

FBCM, a stand-alone luminometer under full control of BRIL, will be independent of central CMS services (such as data acquisition [10], timing and control distribution system, run control,

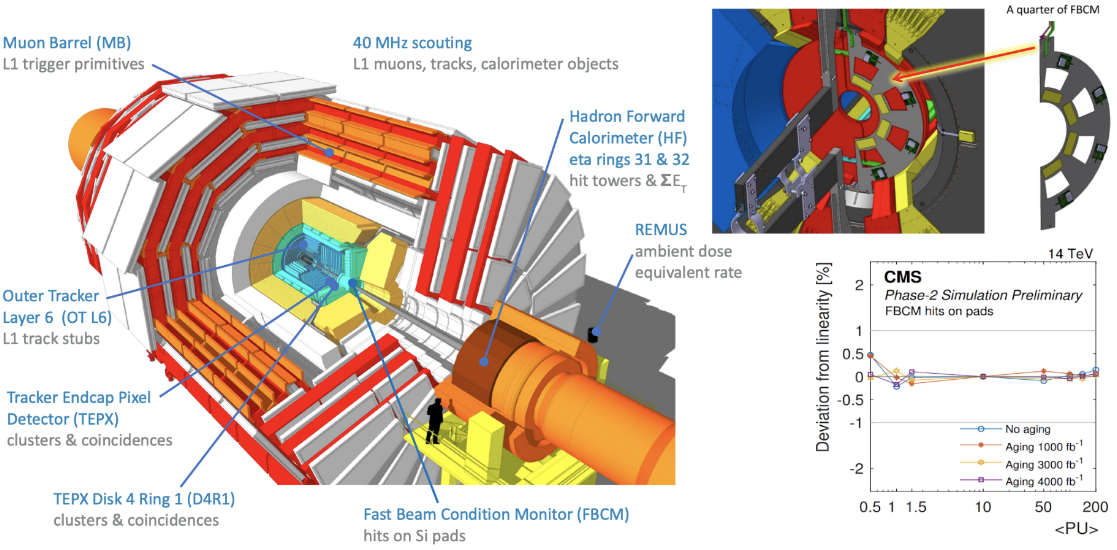

Figure 6: CMS Phase-2 luminosity system (left), stand-alone FBCM luminometer (top right), and expected residual non-linearity of FBCM (bottom right).

magnet status) and available outside stable beams, providing prompt feedback on beam conditions to the LHC and input to the operation of sensitive CMS instrumentation. Its pragmatic design is inspired by the Run 2 BCM1F concept [11] and is based on Si-pad sensors with a fast FE ASIC. The asynchronous readout with sub-bunch-crossing time resolution will allow a better understanding of the time structure of the beams and the measurement of beam-induced background. The electronics system adapts as much as possible the Phase-2 Inner Tracker components. In the baseline design, 288 Run 2 BCM1F Si sensors of 2.89 mm^2 x 300 μm (utilizing already Phase-2 technology) are placed at r = 14.5 cm arranged on 4 half-disks, using a modular design. It will be located Disk 4 of the TEPX in the Tracker cold volume. Detailed simulation studies show a good statistical precision, excellent linearity, and no significant performance degradation with aging.

7. Outlook

The Phase-2 CMS detector upgrades employ novel technologies at an unprecedented scale. As the projects move from the prototyping phase to the final verification before (pre-)production, the last technical challenges are being worked out. The schedules have been adjusted to the new HL-LHC time line with first beams in 2029.

For the success of the industrial size production, automatisation is key. The integration of the complex, large scale systems require a lot of attention and vigilance, as well as extensive system tests in realistic conditions. The first phase-2 muon detector (GE1/1) and all planned muon GEM and RPC, as well as BRIL demonstrator systems have been installed and will provide valuable data for design verification.

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