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# The CMS tracker upgrade for the high luminosity LHC

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ABSTRACT

The LHC machine is planning an upgrade program which will smoothly bring the luminosity to about $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ in 2028, to possibly reach an integrated luminosity of 4000 fb$^{-1}$ by the end of 2037. This High-Luminosity LHC scenario, HL-LHC, will require a preparation program of the LHC detectors known as Phase-2 upgrades. The current CMS Outer Tracker (OT), already running beyond design specifications, and CMS Phase1 Pixel Detector will not be able to survive the HL-LHC radiation conditions. Thus, CMS will need completely new devices, in order to fully exploit the delivered luminosity. The new OT should also have trigger capabilities. To achieve such demanding goals, there is ongoing R&D activity to explore the options for the Outer Tracker and for the pixel Inner Tracker. The developed solutions would allow including tracking information at the Level-1 trigger. The design choices for the Tracker upgrades have been documented in a dedicated Technical Design Report and will be reviewed along with some current highlights of the R&D activities.

**Contents**



## 1. Introduction

The Large Hadron Collider (LHC) will undergo a major upgrade program around 2024–2025 to reach an instantaneous luminosity of $5 - 7.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ in a so-called High-Luminosity phase of the LHC (HL-LHC) [1]. The HL-LHC could deliver around 300 fb$^{-1}$ a year to reach 3000 or even up to 4000 fb$^{-1}$ in its 10 years of planned lifetime.

This upgrade will offer great measurement possibilities for the CMS experiment, including percent precision on multiple Higgs Yukawa couplings, potential for many beyond the standard model searches and the expected feasibility of Higgs self-coupling measurement. However, the harsh HL-LHC conditions will be a real challenge for all of the experiments.

In order to maintain the outstanding performance of the detector, a major upgrade (known as Phase-2 upgrade) will be necessary. The entire silicon strip and pixel tracking system, also referred to as inner and outer tracker respectively, have to be replaced and meet the following requirements.

- *Radiation tolerance.* With a fluence expected to reach a total of $2.3 \times 10^{16}$ $n_{eq}/cm^2$ for the innermost regions, an order magnitude higher than for the current detector, the radiation hardness will be a key element to stay fully efficient during the whole data taking period.
- *Increased granularity.* With the peak number of simultaneous collisions per bunch crossing (pileup, PU) reaching 140 to 200, an increase in channel granularity will be necessary to keep the occupancy below or around a percent level to keep the tracking efficient.
- *Reduced material budget.* Studies have shown that the tracking performance of the detector would greatly benefit from a lighter tracker.

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- *Level-1 trigger contribution.* The selection of interesting physics event by the first level, hardware, trigger will be extremely challenging at the HL-LHC. In order to maintain reasonable cuts and acceptable acceptance rates, tracking information needs to be included into the trigger.

A full description of the tracker upgrade is available in the Tracker Technical Design Report [2]. This contribution will review the upgrade design with some highlights of the R&D activities for the inner and outer tracker and briefly describe the detector layout and the expected performance. Finally, the status and plans to include the tracking information to the Level-1 trigger will be discussed.

## 2. Inner tracker upgrade

Being so close to the beampipe and the given maximal expected total fluence of $2.3 \times 10^{16}$ $n_{eq}$ $cm^{-2}$, the radiation tolerance will be a key element for the inner tracker.

Two different silicon sensor designs are being considered, both n-in-p. They are either traditional thin planar sensors, with a thickness between 100 and 150 μm, or thicker 3 dimensional (3D) sensors. While 3D sensors have a higher intrinsic radiation tolerance due to a shorter charge collection path, the production process is more expensive and thus they are therefore only considered for the first layers of the detector.

The sensors will be segmented into pixels six times smaller than for the current detector, with either squares of 50 μm × 50 μm or rectangles of 100 μm × 25 μm aligned in the $z$ direction for the barrel and $r$ direction for the endcaps. Both geometries give similar tracking performance with a trade-off between primary vertex discrimination and $p_T$ resolution. In high $\eta$ regions, rectangular pixels would reduce the cluster size and allow for a higher charge collected per hit. As a result, the bandwidth consumption would be lowered while the signal to noise ratio would be increased.

The initial studies have been carried-out for both geometries, the results shown here will assume rectangular pixels.

The Pixel Read Out Chip (PROC) will need to meet multiple requirements, including low electronic noise, high radiation hardness and the ability to cope with hit rates approaching 3 GHz $cm^{-2}$. Such a chip is being developed within RD53 collaboration [3], which is a joint CMS-ATLAS collaboration.

## 3. Outer tracker upgrade

The ability to participate to the Level-1 trigger [4] is one of the driving principles for the Outer Tracker. Bandwidth limitations coupled with the necessity of sending out data at a 40 MHz rate will impose data reduction at the detector level. This is achieved through "$p_T$ modules" correlating hits from two sensors placed a few millimeters apart (see Fig. 1). Tracks from the charged particles will be curved in the transverse plane by the 3.8T magnetic field with the bending depending on the $p_T$ of the particle. Assuming the track originated from the primary vertex, the displacement of hits between the two sensors gives an indication of the transverse momentum. A "stub" is produced by correlating hits within a programmable window, and a data reduction of roughly an order of magnitude can be obtained for a window corresponding to a 2 GeV cut. The stubs are read out for every bunch crossing but the full hit information will only be sent upon receiving an accept signal from the triggering system, at a 750 kHz rate. Both data streams will be aggregated and sent asynchronously, with roughly 80% of the bandwidth used by the stub data (see Fig. 2).

Two different module types populate the outer tracker, both with 200 μm thick n-in-p sensors. For the outer layers, the modules will have two aligned strip sensors (2S). Both the sensors will be roughly 10 cm × 10 cm in size, with two rows of 1016 strips with 90μm pitch and 5 cm in length. The inner regions will be populated by modules with a macro pixel and a strip sensor (PS). The top sensor will consist of two rows of

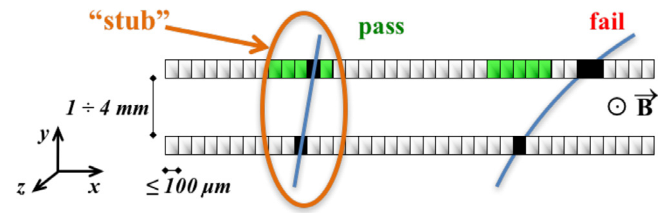


**Fig. 1.** Illustration of the $p_T$ module concept. Correlation of hits in the two closeby sensors allows to reject low $p_T$ particles. The channels in green represent the programmable acceptance window. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

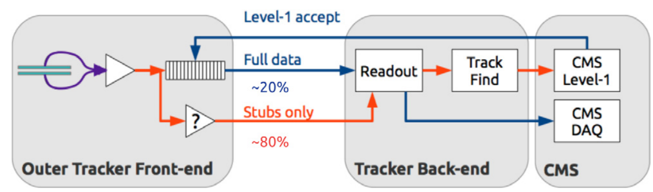


**Fig. 2.** Sketch of the read-out structure. Stubs (in orange) are read-out at 40 MHz, sent to the track finding system and the tracks are then sent to the CMS Level-1 trigger. For selected events (at 750 kHz), a Level-1 accept signal is sent and the full data is read-out from the detector. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

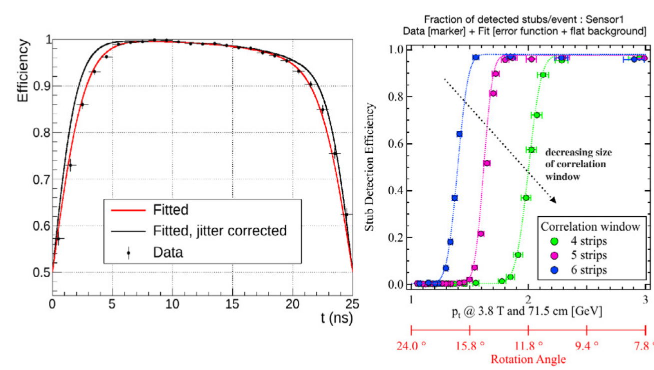


**Fig. 3.** Results from the beam test campaigns. On the left, the hit efficiency as a function of the phase between a 40 MHz clock and the particle arrival time for a PS prototype. On the right, the stub production efficiency as a function of angle or emulated $p_T$ in a 2S prototype.

960 2.5 cm length × 100 μm pitch strips and the bottom sensor of 960 rows of 32 macro pixels of 100 μm pitch and 1.5 mm length, for a total size of roughly 5 cm × 10 cm.

Both PS and 2S prototypes have been produced and thoroughly tested with the preliminary versions of the read-out chips and services. Beam test results show an efficiency of above 99.5%, and the stub concept has been validated by rotating a module with respect to the beam, thus emulating particles with different transverse momenta (Fig. 3).

## 4. Layout and expected performance

A baseline tracker layout can be seen in Fig. 4, with a central "barrel" region completed by two "endcaps".

The inner tracker has four barrel layers and the endcaps have eight small and four large double disks. This design will allow a geometrical coverage of up to $|\eta| \sim 4$ (with respect to a current coverage of up to $|\eta| \sim 2.5$), which, besides the physics gain from the forward acceptance, also mitigates pileup particularly in the endcap calorimeters.

The outer tracker is composed of six barrel layers and five endcap double disks. The outer part ($r > 60$ cm) is populated with 2S modules

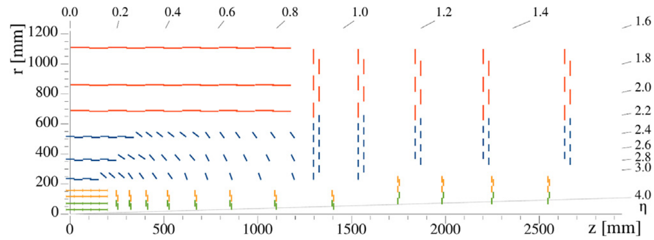


**Fig. 4.** Sketch of one quarter of the CMS phase 2 tracker in $r - z$ view. The green and yellow lines correspond to inner tracker modules with one and two read-out chips, while the blue and red lines represent the outer tracker PS and 2S modules. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

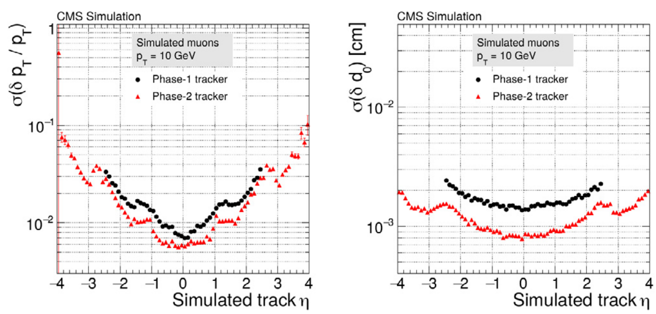


**Fig. 5.** Comparison of the resolution on the transverse momentum (left) and impact parameter (right) of isolated muons as a function of pseudo-rapidity between the phase-1 and phase-2 upgrade tracker.

and the inner part has the PS modules. The three first layers of the barrel are tilted in order to keep the sensors as perpendicular to the tracks originating from $z = 0$ as possible. Although mechanically challenging, this geometry maximizes the probability for a track to cross both sensors in the regions read by the same front end hybrid and therefore enhances stub finding efficiency.

The number of layers and wheels and their positioning as well as the service routing has been optimized in order to maintain a robust tracking while also minimizing the material budget. Using this geometry and prototyping results, full Monte Carlo studies have been performed in order to estimate the detector tracking performance. The resolution on transverse momentum and impact parameter as a function of pseudorapidity for single muons is shown in Fig. 5. The new geometry results in an improvement on both parameters for the whole $\eta$ range.

In order to evaluate the track reconstruction performance, $t\bar{t}$ events were generated with superimposed minimum-bias events. Fig. 6 shows the efficiency and fake rate for the tracks from the $t\bar{t}$ events under two pile-up scenarios. In both cases, the tracking efficiency is around 90% and the fake rate is kept under 2% for the 140 pileup scenario. The tracker geometry is still being optimized and the efficiency dip around $|\eta| \sim 1.2$ is being addressed.

## 5. Triggering

Tracking at the Level-1 trigger is a challenging task. With a fixed 12.5 μs trigger latency, tracks have to be produced within 5 μs after the collision. Two different FPGA-based approaches are being considered to meet these timing constraints.

In the first approach [5], pairs of stubs in adjacent layers/disks are combined to form a "tracklet". This tracklet is then extrapolated to the rest of the tracker and matched stubs are then collected (see Fig. 7). A track is then formed by performing a linearized chi squared fit. Since multiple tracklets can originate from a single track, a filtering process will remove duplicates.

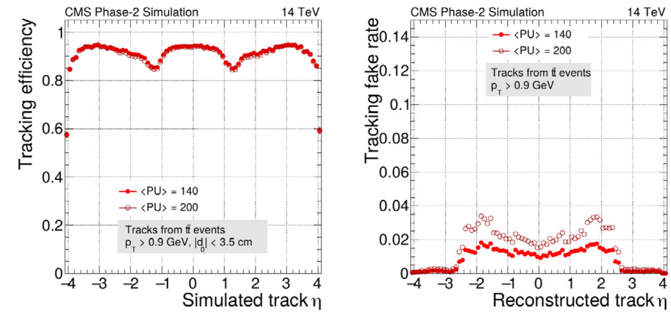


**Fig. 6.** Tracking efficiency (left) and fake rate (right) as a function of pseudorapidity for tracks originating from $t\bar{t}$ events with 140 and 200 superimposed minimum bias events.

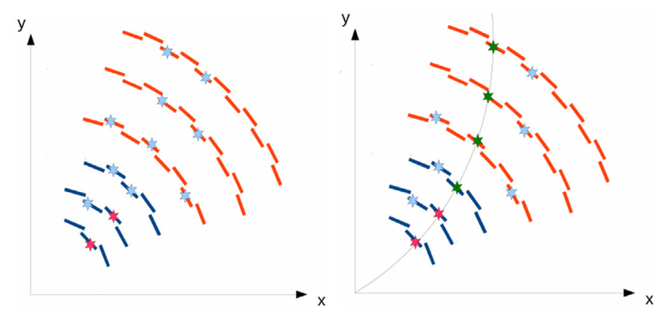

**Fig. 7.** Illustration of the tracklet concept [5]. Here, layers one and two of the barrel are used to form a tracklet and stubs from the next layers are added by extrapolating it.

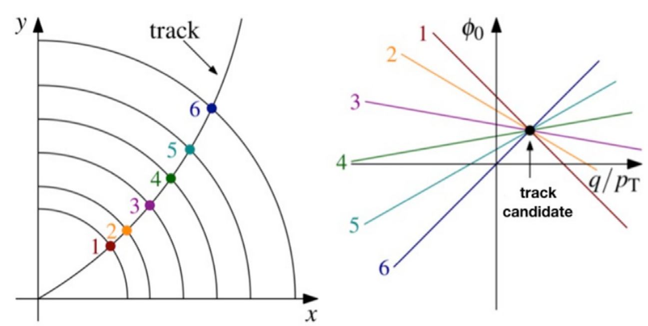


**Fig. 8.** Illustration of the track finding algorithm through Hough transform [6]. Stubs in the geometrical space are converted to lines in the parameter space. The intersection of those lines identifies a track and its parameters.

The second approach is based on Hough transform. Assuming particles of $p_T > 2$ GeV originating from the primary vertex, any given stub in the detector can be produced by a track that respects a specific linear relation between its parameters [6]. Combining multiple stubs, a track is detected at the intersection of these lines in the parameter space (see Fig. 8). The track parameters are then fitted through a Kalman filter before going through a duplicate removal process.

Hardware demonstrators were set up for both approaches and were fed with simulated $t\bar{t}$ events for different pile up scenarios. In both cases, tracks were produced within the required timing constraints with very similar results. The tracking efficiency and resolution on transverse momentum is shown on Fig. 9. An above 90% efficiency for high transverse momentum tracks even under high pile-up has been achieved, with a $p_T$ resolution between two and six percent depending on the particle pseudorapidity.

## 6. Conclusion

The Phase-2 upgrade of the CMS silicon tracker is needed in order to maintain the outstanding detector performance. The upgraded detector

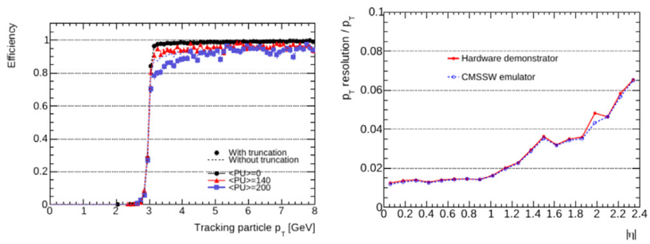


**Fig. 9.** Reconstruction efficiency for tracks from $t\bar{t}$ events as a function of transverse momentum under different pile-up assumptions in the tracklet demonstrators on the left. Transverse momentum resolution as of function pseudorapidity in the Hough transform approach is presented on the right.

will be able to maintain or outperform the current tracker under a high pile-up and radiation environment, while simultaneously participating to the Level-1 trigger.

The design is well advanced and many prototypes have been produced and tested, validating the concepts. Sensors with the appropriate granularity and radiation hardness have been produced. The detector layout will allow a lower material budget and enhanced tracking performance and tracking at 40 MHz was achieved. Mechanics, integration and installation concepts are also at an advanced state.

The CMS Tracker collaboration is now moving towards its final prototyping phase and the Engineering Design Report.

## Acknowledgment

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