



The Compact Muon Solenoid Experiment  
**Conference Report**

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# Simulations and software tools for the CMS Tracker at SLHC

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## Abstract

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# Simulations and software tools for the CMS Tracker at SLHC

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**Abstract.** The CMS detector at the LHC features an all silicon tracking system, with a pixel detector at small radii and a silicon strip tracker surrounding it. It is expected that the pixel detector will have to be replaced after a few years of LHC operation due to radiation damage on the innermost barrel layer and disks. Furthermore, the tracker will need to provide trigger information in order to supplement calorimeter and muon triggers once SLHC upgrades increase the LHC luminosity towards  $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ . The current CMS tracking system is not expected to be capable of providing such trigger information, and thus a complete tracker replacement is being aimed at. This paper describes the status of the simulation studies performed in order to optimise the design of future CMS replacement tracking detectors.

## 1. Introduction

The Compact Muon Solenoid CMS [1] is a multi-purpose particle physics detector at the Large Hadron Collider LHC. It includes an all silicon tracking system comprising a three layer barrel pixel detector, two forward pixel disks on each side, an inner strip tracker consisting of four barrel layers plus three disks per side, and an outer strip tracker with six barrel layers and nine forward disks on each side. The silicon sensor area totals to more than  $200 \text{ m}^2$ . The tracker, an electromagnetic and a hadronic calorimeter are mounted inside a  $4 \text{ T}$  solenoid coil, the iron yoke of which is instrumented as a muon detector.

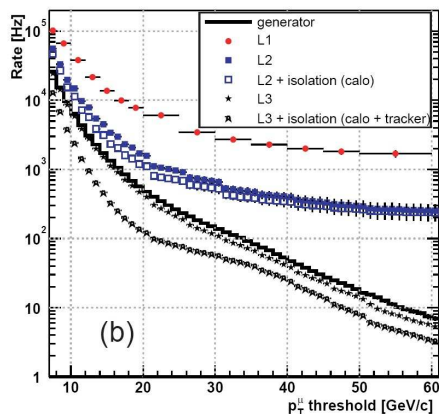
CMS is designed to record data from proton collisions at the LHC, where, at a nominal peak luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , an average of approximately 20 events are expected to pile up per bunch crossing every  $25 \text{ ns}$ . CMS employs a two level trigger system to reduce the amount of data for permanent storage. The level 1 trigger is designed to suppress the  $40 \text{ MHz}$  bunch crossing rate down to an event rate of at most  $100 \text{ kHz}$  to be passed on. The second trigger level reduces the rate further down to of the order of 100 events per second selected for permanent storage.

The LHC is expected to run below or at its design peak luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  for about four years [2] after its startup in late 2009. Upgrades to the collimation system, the linear accelerator and the interaction regions are expected to at least double the LHC peak luminosity in stages over the subsequent four or five years. Further interaction region upgrades and new LHC injectors planned for the late 2010s are expected to increase LHC luminosity to  $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$  by 2020.

No known tracking detector technology would survive the integrated radiation dose of the entire expected LHC and SLHC running period. Especially the innermost parts of the tracking

detector, i.e. the inner barrel pixel detector layer and the forward pixel disks, are likely to require replacement after about five years of LHC running [2]. The limited lifetime expectation of the pixel detector was taken into account during the design phase in the sense that the pixel detector is easily accessible and can be removed or inserted within days. While a replacement of the existing pixel detector by an identical model is considered a viable option, the CMS collaboration would like to take advantage of technological advances and insert an improved pixel detector system. In the following, this replacement will be referred to as the *phase I* tracker upgrade.

The number of pile-up events simultaneously recorded by CMS will increase from about 20 at  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  to above 200 at  $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$  if the bunch crossing rate remains at  $40 \text{ MHz}$ , or even 400, should the bunch spacing be doubled [3]. Major modifications of the CMS tracking system will be needed to accommodate this situation. The occupancy of the inner tracker will be at the level of a few percent even at nominal LHC luminosities. In order not to degrade pattern recognition in the tracker significantly, a new tracking detector is required with higher granularity. In addition, calorimeter and muon trigger rates are expected to increase with luminosity. Additional rejection will have to be introduced in the level 1 trigger to keep the data acquisition rates within the specifications of the higher level trigger and data processing and storage systems. For some triggers this might be achieved by increasing momentum or energy thresholds, but this is considered a very undesirable approach because it will reduce the ability to extend LHC physics measurements into the SLHC era. In some important cases raising trigger thresholds will not even suffice to increase rejection: as shown in Fig. 1, the level 1 muon trigger rate becomes almost independent of the trigger threshold above  $25 \text{ GeV}$ .



**Figure 1.** Simulated CMS muon trigger rates at a luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , as a function of muon transverse momentum [4].

The only viable solution to keep trigger rates manageable seems to be supplementing level 1 calorimeter and muon triggers with track information. Building a level 1 trigger system for the tracking detector, however, is challenging, and will require a redesign of the entire tracking system with trigger requirements in mind. A corresponding replacement tracker will in the following be referred to as a *phase II* tracker upgrade.

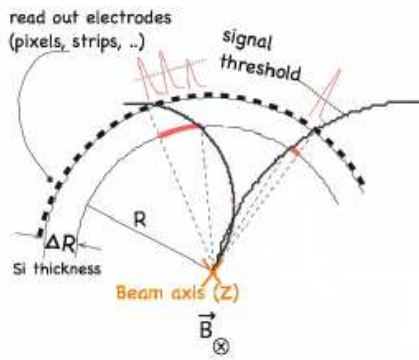
## 2. Track trigger concepts

The existing CMS level 1 trigger system runs at a latency of about  $3.2 \mu\text{s}$ . In order to avoid a redesign of the entire trigger system, a level 1 track trigger would have to provide track information on a similar time scale, possibly faster in order to allow for combinations of track candidates with calorimeter and muon objects at level 1. It is not considered feasible to do full track reconstruction of SLHC events at that time scale. Instead methods are investigated to extract information about only high  $p_t$  tracks. Two approaches are currently being studied,

both relying on identification of straight tracks among a large background of curved low-energy tracks.

### 2.1. Cluster width

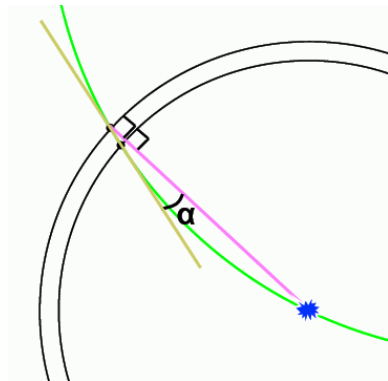
High  $p_t$  tracks from the interaction regions traverse silicon detectors in approximately perpendicular direction, leading to a comparatively narrow charge deposition and thus narrow cluster. Low energy tracks are expected to have incidence angles of significantly less than  $90^\circ$ , leading to a broader charge distribution. This general idea is somewhat more difficult in practice due to the Lorentz angle associated with the magnetic field in the tracking volume. It is possible to counter the magnetic field effects by using sensors that are tilted by the Lorentz angle. This track trigger approach will not be discussed in any further detail in this paper, see Ref. [5] for an overview.



**Figure 2.** Distinction of low- $p_t$  from high- $p_t$  tracks using cluster width [5].

### 2.2. Stacked layers

A different way of estimating track curvature quickly is the use of pairs of closely spaced sensors. On-detector electronics can then correlate hits with very similar  $\phi$  location on both layers of each such sensor stack. With suitable choice of pixel size and layer separation,  $p_t$  thresholds can be built into the detector. The status of simulation studies based on this idea as of CHEP2009 is described in this paper.



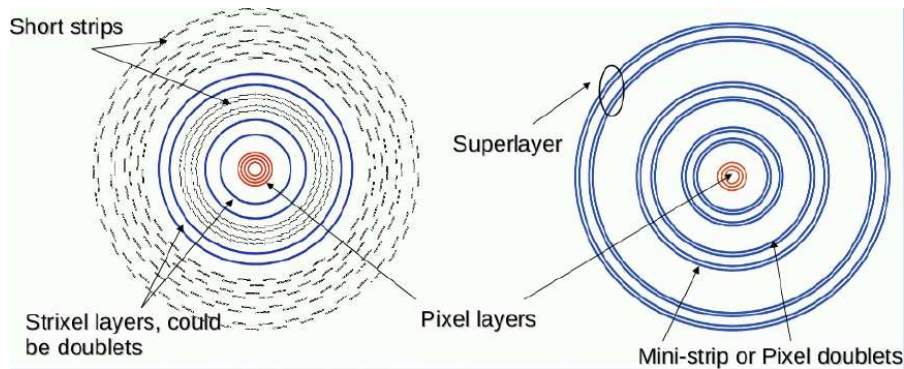
**Figure 3.** Distinction of low- $p_t$  from high- $p_t$  tracks using incidence angle derived from hits on stacked layers [6]. Hit pairs from high  $p_t$  tracks are expected to point back to the interaction point, whereas hit pairs caused by low  $p_t$  curved tracks are expected to be at an angle relative to the radial direction.

## 3. Detector concepts

The phase I upgrade for the pixel detector is relatively constrained due to the short time scale of the project — a replacement detector is possibly required in four years already. Therefore it is expected that the replacement detector will be based on the existing model in layout and

technology. It is considered to increase the number of barrel layers from three to four, and to replace the two endcap disks per side by three disks each. No attempts are currently being made to design a pixel detector with trigger capability.

The phase II upgrade will be a complete tracker replacement. No further design modifications beyond those of phase I are currently foreseen for the pixel detector. The main tracker, however, will need to be replaced by an improved version. The occupancy of the current silicon strip tracker will be too high in a situation with 200–400 pile-up events. Also, implementing track trigger capabilities in the tracker will require the use of dedicated track trigger layers with concepts as described above. Two main lines of thinking are being followed currently. One proposal is to keep the tracker layout similar to the existing design, but to replace a few silicon layers by trigger layers (the *Strawman A* series), the other suggestion is to use a radically different geometry consisting entirely of track trigger layers (the *Strawman B* series). The two strawman layouts as proposed originally are shown in Figure 4.



**Figure 4.** Cross-section of Strawman A (left) and B (right) proposals [8].

The strawman layouts are seen as starting points for more detailed studies that are meant to optimise number of layers, radii, lengths of barrel layers, and correspondingly for endcaps (if any). Pixel or strip pitch requirements need to be investigated, suitability for pattern recognition confirmed and realistic algorithms for track triggers developed.

#### 4. Simulation software

Simulation studies of CMS tracker upgrades are done at three levels:

- GEANT4-based full simulation based on standard CMS software,
- fast simulation based on standard CMS software,
- stand-alone four-vector simulation

Attempts are made to use as much of the standard CMS simulation and reconstruction framework as possible. Ideally, one would only have to introduce modified detector geometry descriptions. In practice, however, software changes are needed in other areas, e.g. taking measures to increase the code performance to reduce the penalty of running simulation and reconstruction in high pile-up scenarios corresponding to SLHC luminosity. Also, the flexibility of track reconstruction code is limited when tracker geometries are being used that differ significantly from the current design.

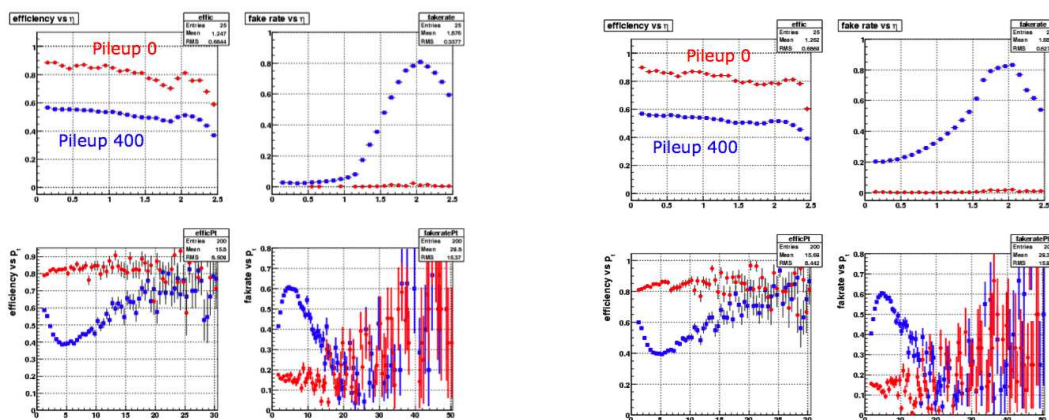
Both strawman models (with several revisions) are implemented in the full CMS simulation. But, while full simulation provides the reference for material interaction, its main application is currently limited to tuning fast simulation code. Simulating large samples of events with 200–400 pile-up interactions in the full tracking detector is not yet feasible.

number of pile-up events	0	10	100	200	400
CMS standard geometry	4.4	5.0	56.5	292	2350
Strawman A	6.2	6.7	104	272	1660
Strawman B	3.8	7.1	116	271	1720

**Table 1.** CPU time consumption (seconds per event) of the CMS fast simulation with full digitisation, full pattern recognition and track reconstruction, and including validation, as of February 2009 [9].

### Pileup 0 and 400 – Strawman A

### Pileup 0 and 400 – Strawman B



**Figure 5.** Tracking efficiency and fake rate as measured in simulations of the two original strawman proposals, in events with and without overlay of a large number of pile-up interactions [9]. The upper row of plots shows efficiency and fake rate as a function of pseudorapidity  $\eta$ , the lower row shows the dependence on transverse momentum  $p_t$ .

Fast simulation is the main workhorse for tracker upgrade studies. In order to obtain realistic results, the fast simulation is augmented by digitisation from the full simulation, and it is interfaced to full pattern recognition and track reconstruction. The main difference compared to the full simulation is thus the implementation of interaction of particles with detector material. The overall CPU consumption of this simplified simulation is therefore quite significant, as evident from Table 1. Even validation, such as the association of hits in reconstructed tracks with Monte Carlo particles from several hundred pile-up events, contributes a sizable fraction to the overall processing time.

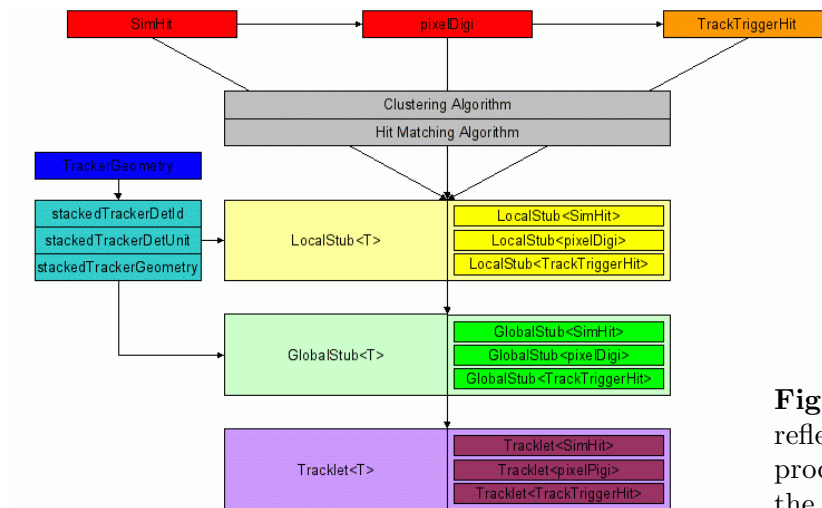
Various revisions of the phase II strawman proposals have been implemented with the CMS simulation framework, and also the phase I pixel upgrade is being integrated. Even before the geometries were available, it already became clear that work will be needed in various other parts of the CMS software to accommodate the SLHC simulation. For example, Figure 5 demonstrates a degradation of tracking efficiency and increase of track fake rate with the number of pile-up events increased significantly beyond the nominal LHC rate. It is evident that the track reconstruction will need to be retuned for a high pile-up environment.

The four-vector code mentioned at the beginning of this section is used exclusively for track trigger studies. The novelty of the track trigger approach requires tools that allow quick scans over many candidate geometries and parameter ranges in order to develop more detailed understanding of the potential performance of track trigger detectors.

## 5. Trigger simulation

Simulation of track triggers is performed within the full, fast and four-vector simulation software environments introduced in the previous section. CMS does not aim at developing a standalone track trigger. Instead, track triggers are expected to be used to augment trigger information from calorimeter and muon system. However, combined studies of SLHC track triggers with SLHC calorimeter and/or muon triggers are still under development. Therefore, a large fraction of track trigger studies is currently looking at low  $p_t$  track rejection power and high  $p_t$  track trigger efficiency only.

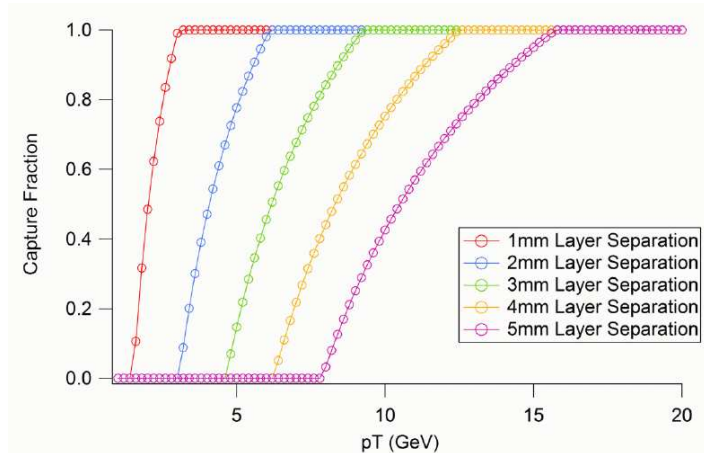
The track trigger simulation starts from hits or clusters on individual detector layers. Hits on stacked sensor layers are then combined into so-called stubs, using a suitable correlation algorithm for hit location on pixels (or strips) on the layers forming the stack. The resulting stubs are described by location and direction. Stubs from all stacks in the tracker are then combined to form tracklets. Figure 6 shows the software structure employed in full and fast simulation to reflect this concept.



**Figure 6.** Software structure reflecting the individual stages of processing of tracker hits through the track trigger [10].

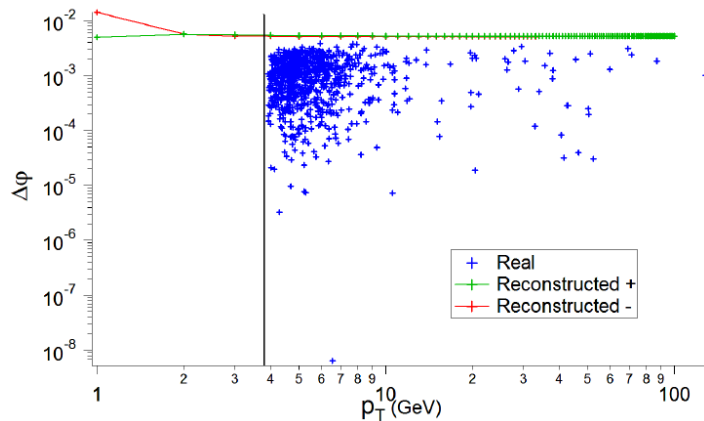
As outlined earlier, the purpose of the proposed CMS track trigger will be to tag high  $p_t$  tracks and match them spatially to calorimeter or muon system objects. The first task is thus a suppression of the abundance of low  $p_t$  tracks expected in SLHC events. Monte Carlo studies show that a  $p_t$  cut in the range of 5–10  $GeV/c$  will reduce the track rate by three to four orders of magnitude. One initial aim of track trigger studies was thus to show that a stacked layer approach would be able to provide  $p_t$  discrimination with a threshold in that region. The simplest possible trigger algorithm, used in these studies, would be to create a stub whenever two pixels with identical  $\phi$  coordinate on the two stack member layers are hit. In such a scenario the  $p_t$  threshold would be determined by pixel size in  $\phi$  and by the radial separation of the two sensors. Figure 7 demonstrates that reasonable values for the distance between sensors in a stack do indeed lead to thresholds in the desired range.

In principle, a single stacked layer with two closely spaced sensors provides sufficient information to perform an extrapolation to calorimeter and muon system: assuming that a track originates from the interaction point in the centre of the detector, one gets three points (primary vertex and the hits on both stack members) that define a helical trajectory. However, studies have shown that the extrapolation precision of a single stack will not be sufficient to match trigger tracks to calorimeter or muon system objects. At least two stacks are needed, with a radial distance that represents a trade-off between extrapolation precision and reliability of pattern recognition. The total number of stacks needs to be determined considering material



**Figure 7.** Dependence of  $p_t$  threshold on layer separation within a stack, for a pixel size of  $20 \mu m \times 50 \mu m$  [11].

budget, pattern recognition capabilities and cost.



**Figure 8.** Uncertainty of  $\phi$  coordinate of track parameters extrapolated from *two* stacked layers to the inner surface of the CMS electromagnetic calorimeter [7]. The uncertainty assigned to electrons (positrons) is shown in red (green); the actual errors encountered in a single particle event sample are indicated in blue.

## 6. Conclusion

Even before the beginning of LHC data taking, plans for LHC upgrades need to be made. Simulation studies are being performed for replacement options for the CMS tracking detectors. Integrated luminosity of about four years of LHC running at nominal luminosity will require a replacement of at least the innermost pixel detector layer and the forward pixel disks. It is planned to make cautious use of technological advances when replacing the pixel detector, and to insert an improved pixel system as a *phase I* tracker upgrade. The geometry of the baseline pixel detector proposal is being implemented in the CMS full and fast simulations.

The CMS silicon strip tracker will not be able to perform efficient track reconstruction in the SLHC era due to excessive occupancy. The current muon and calorimeter trigger systems will also be degraded. CMS therefore intends to replace the tracking detector by a new system that is capable of supporting electron and muon triggers with matched high  $p_t$  track information. This requires a significant redesign of the tracking system, and a wider range of options needs to be studied. Full and fast simulation of various baseline scenarios has been put into place based on standard CMS simulation code. This software is used to evaluate pattern recognition and track reconstruction performance of proposed detector layouts, and it is being interfaced to calorimeter and muon trigger simulation to allow studies of the full intended SLHC trigger system. In addition to these simulation options integrated into the CMS software framework,



a simple stand-alone four-vector simulation software is available for quick scans over a broad range of detector options.

Some pieces of software are not yet fully available, such as parts of the interfaces between track, calorimeter and muon trigger simulation, but the CMS tracker upgrade simulation studies are already providing valuable input for and strong constraints on proposals for future CMS tracker upgrades.

## 7. Acknowledgments

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## References

- [1] G. L. Bayatian *et al.* [CMS Collaboration], *J. Phys.* G34:995-1579, 2007.
- [2] G. Hall, “The Upgrade of the CMS Tracker for Super-LHC,” *Proceedings of TIPP09, Tsukuba, Japan.*
- [3] F. Gianotti *et al.*, *Eur. Phys. J. C* **39** (2005) 293 [arXiv:hep-ph/0204087].
- [4] G. L. Bayatian *et al.* [CMS Collaboration], “CMS Data Acquisition and High-Level Trigger Design Report,” CERN/LHCC-02-26, 2006.
- [5] F. Palla, *JINST* **2**, P02002 (2007).
- [6] J. Jones
- [7] J. Jones *et al.*, “Stacked tracking for CMS at Super-LHC,” *Proceedings of LECC 2006, Valencia, Spain.*
- [8] Strawman A: A. Tricomi, C. Civinini; Strawman B: H. Cheung, M. Pesaresi.
- [9] J. Ellison, A. Chandra
- [10] A. Rose
- [11] J. Jones *et al.*, “A Pixel detector for Level-1 triggering at SLHC,” arXiv:physics/0510228.