

# Optimization of Silicon Pixel and Strip Detectors for High-Luminosity beyond Standard Model Physics Experiments

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**Abstract:** *The High-Luminosity Large Hadron Collider (HL-LHC) is expected to provide unprecedented opportunities for investigating physics beyond the Standard Model (BSM), including long-lived particles, dark-sector mediators, supersymmetric particles, and other hypothetical phenomena. The increased instantaneous luminosity and accumulated radiation exposure create significant challenges for silicon pixel and strip detectors, particularly in terms of radiation tolerance, spatial resolution, tracking efficiency, occupancy, electronic noise, and data acquisition. This research paper examines optimization strategies for silicon-based tracking systems designed for high-luminosity particle physics experiments.*

*It discusses sensor geometry, pixel dimensions, strip pitch, radiation-hard semiconductor technologies, detector material reduction, cooling, readout electronics, and track reconstruction. Particular attention is given to the relationship between detector performance and the reconstruction of displaced vertices, low-momentum charged particles, and unusual track signatures relevant to BSM searches. Drawing on experimental and technical literature published between 2010 and 2022, the paper presents a comparative framework for evaluating pixel and strip detector configurations. A structured optimization approach is proposed that integrates detector simulation, radiation-damage modeling, electronics characterization, and physics-level sensitivity studies.*

**Keywords:** Silicon pixel detectors, silicon strip detectors, high-luminosity LHC, beyond Standard Model physics, radiation damage, tracking efficiency, displaced vertices, detector optimization, particle tracking.

## I. INTRODUCTION

The Standard Model of particle physics provides a comprehensive description of elementary particles and their fundamental interactions, yet it does not fully explain several observed and theoretical phenomena, including the nature of dark matter, the matter–antimatter asymmetry of the Universe, and the origin of neutrino masses. These limitations motivate experimental investigations of physics beyond the Standard Model (BSM), in which collider experiments search for new particles, interactions, and deviations from established predictions. The Large Hadron Collider (LHC) has played a central role in these investigations by enabling high-energy proton–proton collisions and precision measurements of fundamental processes. However, the increasing luminosity planned for the High-Luminosity LHC introduces substantial detector challenges because higher collision rates increase radiation exposure, particle occupancy, and the complexity of event reconstruction. The HL-LHC upgrade programme consequently requires tracking systems with improved radiation tolerance, fine spatial granularity, efficient readout, and reliable operation under demanding environmental conditions (Apollinari et al., 2017).

## REVIEW OF LITERATURE

Research conducted during the period 2010–2022 established the importance of redesigning silicon tracking detectors to accommodate the higher collision rates and radiation levels anticipated at the HL-LHC. The ATLAS and CMS upgrade programmes investigated new detector layouts, radiation-resistant sensors, improved electronics, and more sophisticated tracking architectures. These developments were intended to maintain tracking and vertexing performance as the number of simultaneous proton–proton interactions increased. Apollinari et al. (2017) described the accelerator upgrade programme and its implications for the experimental infrastructure, while subsequent CMS upgrade studies discussed the integration of new inner and outer tracking systems with Level-1 trigger capabilities (La Rosa, 2021). The literature indicates that detector optimization must be considered as a system-level problem involving sensors, mechanical structures, electronics, cooling, and data processing.

Radiation damage is a major constraint on silicon sensors positioned close to the interaction point. High-energy particles create defects in the silicon crystal lattice, potentially changing effective doping concentration, increasing leakage current, reducing charge collection, and affecting depletion voltage. These effects can degrade detection efficiency and increase operational demands. Planar pixel sensors have been widely investigated because of their established manufacturing processes and compatibility with fine-pitch readout electronics.

## RESEARCH OBJECTIVES

The primary objective of this study is to develop a systematic framework for optimizing silicon pixel and strip detectors under the expected operating conditions of high-luminosity BSM experiments. The specific objectives are to examine the relationship between sensor geometry and spatial resolution, evaluate radiation tolerance and charge collection, investigate the effects of detector material and occupancy on track reconstruction, compare pixel and strip technologies for different tracking roles, and establish a multi-parameter optimization approach that links detector performance to BSM physics sensitivity. A further objective is to identify the principal trade-offs between detection efficiency, electronic power consumption, cooling requirements, channel count, and long-term operational reliability.

## RESEARCH METHODOLOGY

### 1. Research Design

This study adopts a literature-based technical analysis supported by a proposed simulation and optimization framework. The evidence base consists of detector-upgrade publications, sensor irradiation studies, and technical reports published between 2010 and 2022. The methodology separates documented experimental findings from proposed optimization procedures. Published results are used to establish the relevant detector constraints, while the proposed framework identifies how candidate configurations could be compared consistently. No new irradiation measurements, detector simulations, or experimentally measured BSM sensitivities are claimed in this paper.

### 2. Detector Parameters and Optimization Variables

The optimization process considers a set of geometrical, electrical, thermal, and reconstruction variables. Pixel-related variables include cell dimensions, sensor thickness, electrode architecture, bias voltage, and hit-resolution characteristics. Strip-related variables include strip pitch, sensor thickness, stereo angle, strip length, and readout segmentation. System-level variables include material budget, power consumption, cooling capacity, occupancy, radiation fluence, and readout bandwidth. These variables interact: reducing pixel dimensions can improve hit separation but increases channel count, while increasing sensor thickness can improve signal generation under some conditions but may increase multiple scattering and cooling demands. Therefore, each configuration should be evaluated across the full set of relevant constraints rather than optimized according to a single isolated parameter.

### 3. Performance Evaluation

Candidate detector configurations should be evaluated using a combination of sensor-level, tracking-level, and physics-level metrics. Sensor-level metrics include charge collection efficiency, leakage current, depletion voltage, noise, and radiation-induced degradation. Tracking-level metrics include spatial resolution, hit efficiency, fake-track rate,

momentum resolution, and vertex reconstruction accuracy. Physics-level metrics include the efficiency for reconstructing displaced tracks, the probability of identifying displaced vertices, and the retention of signal events under realistic trigger and background conditions. Simulations should incorporate pile-up, detector geometry, magnetic fields, material interactions, and radiation-dependent sensor response. The final comparison should distinguish directly measured performance from simulation-based projections and clearly document the assumptions underlying each result.

## RESULTS AND DISCUSSION

### 1. Comparative Analysis of Silicon Pixel and Strip Detectors

Silicon pixel and strip detectors provide complementary capabilities within high-luminosity tracking systems. Pixel detectors offer two-dimensional spatial measurements and are particularly valuable in regions where charged-particle density is high. Strip detectors provide efficient coverage over larger surfaces, with fewer electronic channels than an equivalent fine-granularity pixel system. The CMS tracker upgrade programme incorporates both technologies in its planned tracking architecture, reflecting the need to balance spatial precision, radiation tolerance, and system-scale feasibility (La Rosa, 2021). Experimental studies of CMS outer-tracker sensors further demonstrate that material selection and sensor thickness are important variables when designing for the anticipated radiation environment (The Tracker Group of the CMS Collaboration, 2020).

### 2. Impact on Displaced-Track Reconstruction

The reconstruction of displaced particles depends on the detector's ability to measure track positions accurately while maintaining sufficient hit coverage. For long-lived BSM particles, the decay position may differ substantially from the primary interaction point, meaning that conventional track reconstruction assumptions may not always be suitable. Pixel detectors provide fine-grained measurements near the interaction region, while strip layers can extend the trajectory measurement beyond the innermost detector. Their combined measurements can constrain track parameters and support displaced-vertex reconstruction. However, performance depends on the distribution of tracking layers, available hit counts, detector material, and reconstruction algorithms. Therefore, the optimal configuration for a displaced-particle search may differ from the configuration that maximizes efficiency for prompt charged particles.

### 3. Occupancy, Readout, and Trigger Requirements

At high luminosity, a large number of simultaneous interactions creates challenges for hit assignment, data transmission, and event selection. Detector segmentation reduces the number of particles contributing to individual measurement channels, but finer segmentation also increases electronic complexity and power requirements. The CMS tracker upgrade programme includes trigger-related functionality intended to support event selection under increased collision rates (La Rosa, 2021). This demonstrates that sensor optimization cannot be separated from the readout and trigger architecture. A detector with excellent intrinsic spatial resolution may provide limited physics benefit if its data cannot be read out efficiently or if the trigger rejects relevant signal events. Consequently, readout latency, bandwidth, data reduction, and trigger efficiency should be treated as integral components of the optimization problem.

### 4. Comparative Table of Detector Optimization Parameters

The following table summarizes the principal design considerations. It is a qualitative synthesis of the cited technical literature, not a new experimental measurement or a numerical ranking of detector technologies.

| Optimization parameter | Silicon pixel detectors                                  | Silicon strip detectors                                                                           | Relevance to BSM experiments                         |
|------------------------|----------------------------------------------------------|---------------------------------------------------------------------------------------------------|------------------------------------------------------|
| Spatial measurement    | Two-dimensional position measurement                     | Primarily one-dimensional per sensor; stereo arrangements can provide two-dimensional information | Track separation and displaced-vertex reconstruction |
| Granularity            | Fine segmentation, especially near the interaction point | Larger measurement cells and strip lengths                                                        | Occupancy management and hit association             |
| Radiation              | Planar and 3D designs                                    | Material, thickness, and geometry                                                                 | Maintaining tracking                                 |

|                            |                                                         |                                                             |                                                            |
|----------------------------|---------------------------------------------------------|-------------------------------------------------------------|------------------------------------------------------------|
| tolerance                  | require radiation qualification                         | require radiation qualification                             | efficiency over detector lifetime                          |
| Material budget            | Depends on sensor, readout, support, and cooling design | Depends on sensor, support, and readout design              | Multiple scattering and track-parameter resolution         |
| Channel count              | Generally high for fine-pitch segmentation              | Generally lower for comparable large-area coverage          | Power, cost, and data-acquisition requirements             |
| Readout                    | High-density pixel electronics                          | Strip-specific amplification and readout architectures      | Timing, bandwidth, and trigger compatibility               |
| Principal design trade-off | Granularity versus power, cost, and material            | Coverage and channel economy versus measurement granularity | Maintaining sensitivity across different signal topologies |

## PROPOSED MULTI-OBJECTIVE OPTIMIZATION FRAMEWORK

### 1. Constraints and Feasibility

The optimization must satisfy practical constraints on radiation tolerance, cooling, mechanical stability, data throughput, and electronic power. A candidate design must remain operational under the anticipated radiation fluence and must provide acceptable performance after irradiation. Thermal requirements should be evaluated together with leakage current and sensor bias, since cooling and electrical operation are coupled. The selected design must also provide sufficient readout capacity for the expected occupancy and collision rate. These constraints imply that the solution should be selected from a feasible design region rather than by maximizing a single unconstrained performance metric.

### 2. Simulation and Validation Strategy

A practical implementation would begin by generating candidate sensor layouts and modeling their response under representative irradiation and collision conditions. Detector simulation would then provide hit distributions, track parameters, occupancy, and vertex reconstruction performance. The configurations would be evaluated against a common set of physics benchmarks, including prompt-track reconstruction and displaced-particle signatures. Laboratory measurements and test-beam results would be used to validate sensor-response assumptions, while full detector simulations would be used to evaluate system-level effects. The final design comparison should report uncertainties, operating assumptions, and the range of signal models considered.

## CHALLENGES AND LIMITATIONS

The optimization of silicon detectors for high-luminosity BSM experiments involves several interacting technical limitations. Radiation damage can alter sensor response during operation, while increased leakage current and electronic power can intensify cooling requirements. High channel density increases the complexity of readout, cabling, and data processing. In addition, reducing detector material may conflict with mechanical stability, cooling, and service requirements. These engineering trade-offs make it difficult to identify a universally optimal pixel or strip configuration.

A further limitation concerns the diversity of BSM signatures. A detector configuration optimized for prompt tracks may not provide the same efficiency for highly displaced particles, low-momentum tracks, or unusual ionization signatures. Physics-level optimization therefore requires a representative collection of signal and background models. The literature reviewed here establishes important design constraints and demonstrates selected sensor-performance results, but it does not provide a single common dataset from which all detector configurations can be quantitatively ranked. The proposed framework should consequently be regarded as a methodology for future simulation and experimental studies rather than a claim that a globally optimal design has already been established.

## II. CONCLUSION

The optimization of silicon pixel and strip detectors is an essential component of preparing high-luminosity particle physics experiments for searches beyond the Standard Model. The expected increase in collision rates and radiation exposure requires tracking systems that combine radiation-resistant sensors, suitable spatial granularity, reliable electronics, effective cooling, and efficient data acquisition. Pixel detectors provide fine-grained position measurements that are particularly important in dense tracking environments, whereas strip detectors offer efficient coverage over larger areas. Their complementary characteristics support a combined tracking architecture capable of addressing a wide range of particle trajectories.

The reviewed literature demonstrates the importance of radiation-hard sensor development, including the investigation of 3D silicon pixel geometries and systematic comparisons of silicon strip sensor materials and thicknesses. These developments establish a technical foundation for maintaining tracking performance under HL-LHC conditions. For BSM searches, the optimization process must extend beyond conventional prompt-track efficiency to include displaced-track reconstruction, vertex resolution, occupancy, and the retention of unusual event topologies. A multi-objective approach incorporating sensor-level measurements, detector simulation, and physics-level validation provides a structured way to assess these requirements.

In conclusion, effective detector optimization requires a coordinated design strategy that balances radiation tolerance, spatial resolution, material budget, power consumption, readout capability, and physics sensitivity. Future studies should apply this framework to detailed detector simulations and experimentally validated sensor models, with particular attention to the differing requirements of long-lived-particle searches and other BSM signatures.

## REFERENCES

1. M., Rossi, L., & Tavian, L. (Eds.). (2017). High-Luminosity Large Hadron Collider (HL-LHC): Technical design report V. 0.1 (CERN Yellow Reports: Monographs, Vol. 4). CERN.
2. ATLAS Collaboration. (2010–2022). ATLAS detector and tracking performance publications. CERN Document Server. CERN Document Server .
3. ATLAS Collaboration. (2017). Technical design report for the ATLAS Inner Tracker pixel detector. CERN. CERN Document Server .
4. CMS Collaboration. (2010–2022). CMS tracking, pixel detector, and silicon sensor performance publications. CERN Document Server. CERN Document Server .
5. CMS Collaboration. (2017). The Phase-2 Upgrade of the CMS Tracker. CERN. CERN Document Server .
6. M., Lange, J., & Rummler, A. (2022). Radiation hard 3D silicon pixel sensors for use in the ATLAS detector at the HL-LHC. arXiv.
7. La Rosa, A. (2021). The upgrade of the CMS tracker at HL-LHC. arXiv.
8. Migliore, E. (2019). The CMS tracker upgrade for the High-Luminosity LHC. arXiv.
9. The Tracker Group of the CMS Collaboration. (2020). Experimental study of different silicon sensor options for the upgrade of the CMS Outer Tracker. arXiv.