Chapter 1

Introduction

The CMS detector has been designed to detect cleanly the diverse signatures of new physics at the Large Hadron Collider. It will do so by identifying and precisely measuring muons, electrons, photons, and jets over a large energy range [1-1],[1-2],[1-3],[1-4]. Experience has shown that robust tracking and detailed vertex reconstruction within a strong magnetic field are powerful tools to reach these objectives.

The overall layout of the CMS detector is illustrated in Colour Figs. 1.i, 1.ii and 1.iii. In this chapter an overview of the tracking system is given, together with a discussion of the physics goals and the design considerations which motivate our basic approach and technological choices.

The subsequent chapters discuss in detail the three main sub-detector elements of the Tracker: the Pixel vertex detector system is described in Chapter 2, while the Silicon Strip (SST) and the Micro Strip Gas Chamber (MSGC) trackers are described in Chapters 3 and 4 respectively. Chapter 5 discusses the readout electronics of the Silicon Strip and MSGC detectors, the control and monitoring electronics and the low and high voltage power supplies. Chapter 6 describes the Tracker support structure, alignment, general engineering, services, beam pipe, installation and maintenance procedures. The safety aspects are also discussed in Chapter 6. In Chapters 7, 8 and 9 we discuss the detector simulation, the track and vertex reconstruction algorithms, and finally the performance of the Tracker in its important aspects. In Chapter 10 cost, funding, institutional responsibilities and management of the Tracker project are described. Chapter 10 ends with the construction schedule and planning. The radiation environment and the simulation methods to evaluate it are described in Appendix A.

1.1 Physics Objectives

Robust tracking and detailed vertex reconstruction are expected to play an essential role for an experiment designed to address the full range of physics which can plausibly be accessed at the LHC. The following considerations are illustrative of the performance requirements which the Tracker must satisfy.

The characterisation of events involving Gauge bosons, W and Z, will certainly be of primary importance at the LHC. In particular, their leptonic decays provide especially clean experimental signals. Indeed, possible heavier W' and Z' bosons in the TeV range are also best evidenced through leptonic decays. To fully exploit these signatures, the Tracker must be able to provide as good a momentum measurement for energetic leptons as can reasonably be achieved. Both the efficiency and resolution for isolated electrons are affected by the material in the Tracker, because of bremsstrahlung. This degradation in performance must be kept to a minimum. In CMS, Tracker measurements are combined with track segments reconstructed in the outer muon system to further extend the kinematic region over which a precise muon momentum measurement can be performed. This latter requirement will place stringent constraints on the alignment of the Tracker relative to the muon chambers.

Efficient isolated lepton reconstruction is also both necessary and sufficient to fulfil another of the important tasks for the Tracker, namely electron and photon identification for isolated electromagnetic clusters. However, not only must the Tracker be able to reconstruct and identify isolated leptons and photons efficiently, it must also establish that they are in fact isolated. For example, lepton isolation is required to suppress $t\bar{t}$ and $Zb\bar{b}$ backgrounds to a level which allows observation of $H \rightarrow ZZ^* \rightarrow 4l^{\pm}$ and $H \rightarrow ZZ \rightarrow 4l^{\pm}$ for the full mass range $120 \leq m_H \leq$ 800 GeV. Lepton isolation criteria also play an important role in SUSY particle searches, in particular for sleptons, charginos and neutralinos. The sensitivity to Higgs decay in the $\gamma\gamma$ channel is also greatly enhanced by Tracker isolation criteria applied to suppress the $\gamma - \pi^0$ (jet) and $\pi^0 - \pi^0$ (jet–jet) backgrounds to a level significantly below the irreducible $\gamma\gamma$ background. Effective isolation criteria rely on the efficient reconstruction of all hadronic tracks down to transverse momenta of approximately 2 GeV, and may be further improved by the reconstruction of tracks as low as 1 GeV in p_T.

The ability both to tag and to reconstruct in detail b jets, and B-hadrons within these jets, is also of fundamental importance. Indeed, not only are b jets particularly useful signatures for a broad spectrum of new physics, and essential tags for top quark physics, their detailed study may also yield fundamental insight into the question of CP violation. The latter requires the ability to identify unambiguously tracks coming from multiple vertices, the ability to reconstruct a variety of decay chains and the accurate determination of the b decay proper time, based on the characterisation of displaced vertices and the kinematics of the associated tracks.

As signals for new physics, b jets may result either from the decays of a new particle, or in associated production via gluon–gluon fusion mediated by b quark exchange. In the first case, sensitivity to heavy particles requires efficient b tagging for high momentum jets, resulting in severe constraints on two-track separation capability, while for the second case good b tagging efficiency is required over the full Tracker acceptance up to $\eta = 2.5$. In order to ensure satisfactory performance of b tagging algorithms based on displaced vertices, it is mandatory to control tails in the impact parameter measurement due to errors in pattern recognition, as well as hadronic interactions within the active volume of the Tracker.

In addition, a variety of plausible new physics channels including, for example, decay chains pertinent to a possible SUSY Higgs sector, result in τ leptons in the final state. Tau lepton identification requires the application of isolation criteria, and may also benefit substantially from displaced vertex information. Achieving the tracking performance required for b tagging and b physics studies will also ensure useful τ recognition capability.

Many of the most interesting physics questions require the highest luminosities achievable at LHC and therefore the stringent demands placed on the tracking system must continue to be satisfied for luminosities up to 10^{34} cm^{-2}s^{-1}. At the LHC, this implies the superposition of typically 20 to 30 unrelated minimum bias events within each bunch crossing, and puts a major additional burden on the task of correct pattern recognition.

Moreover, the ability of the Tracker to characterise in detail these multiple event vertices may also play a crucially important role in CMS for the Higgs to $\gamma\gamma$ search. Indeed, the spectrum of charged particles recoiling against the Higgs provides a useful signature with which to differentiate the Higgs production vertex from the multitude of minimum bias event vertices. This will allow the required $\gamma\gamma$ mass resolution to be preserved at high luminosity.

In order to avoid significant loss of sensitivity in the Higgs to $\gamma\gamma$ channel, the fraction of such decays where neither photon converts should be close to 50%. This requirement, together with the need to minimise the effects on tracking performance of electron bremsstrahlung and hadronic interactions, impose severe constraints on the material budget allowed and are an important criterion for for the Tracker design.

As well as proton–proton collisions, the LHC will provide a unique opportunity to explore the physics of heavy-ion collisions at very high energy. These collisions give rise to extremely large charged particle multiplicites: up to 25 000 in the case of a central lead–lead collision. Although the CMS Tracker was not explicitly designed with such physics in mind, in conjunction with the CMS muon system it actually provides a useful tool for the reconstruction of muon-pair invariant masses even in this environment. This, in turn, is a powerful probe for the study of quark–gluon plasma physics which may be evidenced in heavy-ion collisions at the LHC.

1.2 CMS Tracker Performance

The requirements described in the previous section have led to the design of a Tracker for CMS with the following performance:

- As shown in Fig. 1.1, high p_T isolated tracks are reconstructed with a transverse momentum resolution of better than $\delta p_T/p_T \approx (15 \cdot p_T \oplus 0.5)\,\%$, with p_T in TeV, in the central region of $|\eta| \leq 1.6$, gradually degrading to $\delta p_T/p_T \approx (60 \cdot p_T \oplus 0.5)\,\%$, with p_T in TeV, as η approaches 2.5. This resolution is well suited to the reconstruction of narrow states decaying into charged particles, and is sufficient to ensure reliable charge assignment for muons and electrons up to the highest kinematically accessible momenta.
- From Fig. 1.2 it can be seen that, in combination with the outer muon chamber system, the muon momentum resolution above approximately 100 GeV can be parametrised as $\delta p/p \approx (4.5 \cdot \sqrt{p})\%$, with p in TeV, for rapidities extending up to at least $\eta = 2$ [1-4]. This results in a momentum resolution better than 10% even at 4 TeV.

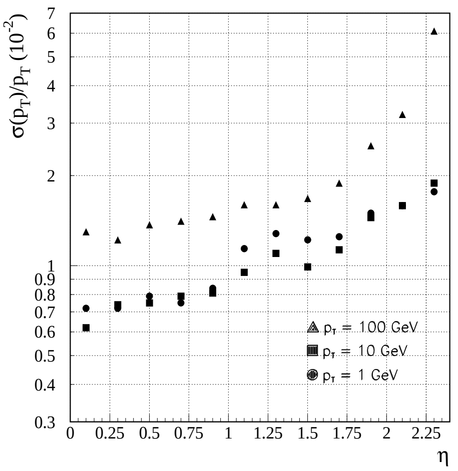

Fig. 1.1: CMS Tracker stand-alone transverse momentum resolution as a function η, for muons of $p_T = 1$, 10 and 100 GeV, without beam constraint.

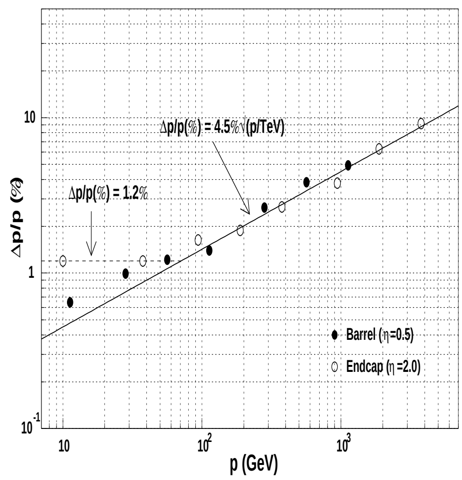

Fig. 1.2: Combined CMS Tracker and Muon Chamber momentum resolution as a function of momentum, in the central and forward rapidity regions.

- In dense jet environments, charged hadrons with p_T above 10 GeV are reconstructed with an efficiency approaching 95%, and even hadrons with p_T as low as 1 GeV are reconstructed with an efficiency better than 85%. The reconstruction efficiency for muons is better than 98% over the full η range, even for values of p_T as low as 1 GeV. High energy electrons are reconstructed with an efficiency above 90%.

- The impact parameter resolution in the plane perpendicular to the beams, shown in Fig. 1.3, is better than 35 μm over the full $|\eta| \leq 2.5$ range for particles with p_T above 10 GeV. The longitudinal impact parameter resolution, shown in Fig. 1.4, is significantly better than 75 μm over most of the rapidity range. At low luminosity it is possible to place the innermost Pixel layer closer to the beam line. This results in an appreciable improvement in impact parameter resolution, as can be seen from Figs. 1.5 and 1.6. These estimates do not take into account any degradation due to detector misalignement. Tails due to errors in track reconstruction are at a level well below the rate of displaced vertices due to long-lived particles.
- In the central rapidity region tagging efficiencies of 50% or better can be obtained for b jets ranging from 50 GeV to 200 GeV E_T, with a mistagging probability of around 1% to 2%. In the forward rapidity region, for equal mistagging probability, the tagging efficiency remains around 40%.

The pattern recognition performance and track reconstruction quality listed above are achieved at the highest luminosity foreseen for LHC operation.

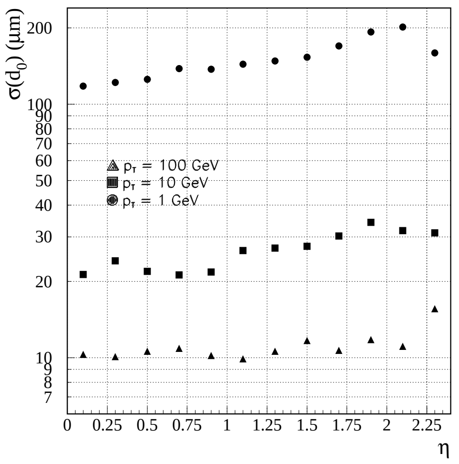

Fig. 1.3: Transverse impact parameter resolution as a function of η, for muons of $p_T = 1$, 10 and 100 GeV. High luminosity CMS Pixel configuration.

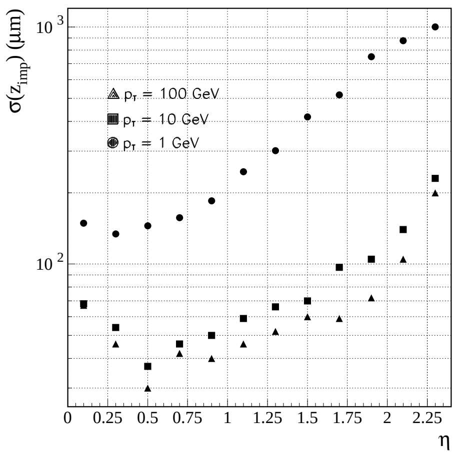

Fig. 1.4: Longitudinal impact parameter resolution as a function of η, for muons of $p_T = 1$, 10 and 100 GeV. High luminosity CMS Pixel configuration.

1.3 Overview and Layout of the CMS Tracking System

Momentum analysis in CMS makes use of a 4 T magnetic field, provided by a super-conducting solenoidal magnet around which the entire experiment is built [1-1]. The active envelope of the CMS Tracker extends to a radius of 115 cm, over a length of approximately 270 cm on each side of the interaction point. Momentum measurements of charged particles in the region $|\eta| \lesssim 1.6$ therefore benefit from the full momentum analysing power. In this region, a charged particle with p_T of 1000 GeV has a sagitta of 195 μm. The Tracker acceptance extends further to $|\eta|$ of 2.5, with a reduced radial lever arm of approximately 50 cm.

The very high magnetic field of CMS affects event topologies, by confining low p_T charged particles to small radius helical trajectories. Coupled with the steeply falling p_T spectrum

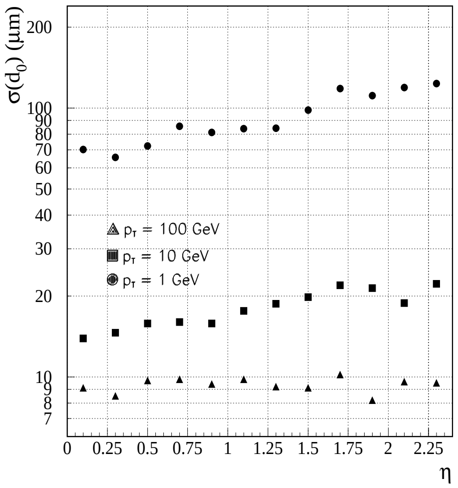

Fig. 1.5: Transverse impact parameter resolution as a function of η, for muons of $p_T = 1$, 10 and 100 GeV. Low luminosity CMS Pixel configuration.

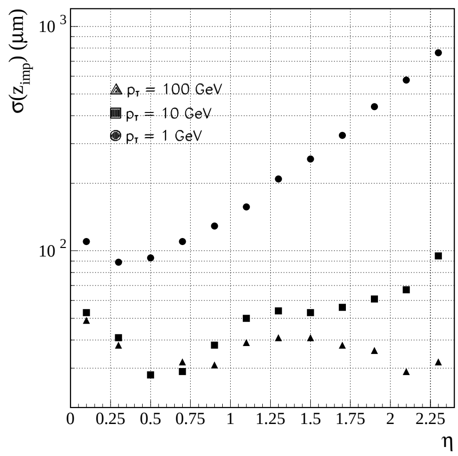

Fig. 1.6: Longitudinal impact parameter resolution as a function of η, for muons of $p_T = 1$, 10 and 100 GeV. Low luminosity CMS Pixel configuration.

characteristic of minimum bias events, this results in a track density which rapidly decreases with increasing radius.

This is illustrated in Fig. 1.7, where typical primary charged particle densities are shown for several different radii with 0 and 4 T solenoidal field, at $\eta = 0$. In the absence of a magnetic field, the charged track density simply falls off as $1/r^2$. Under the effect of the 4 T field, the decrease in charged track density with radius is initially more gradual, and then significantly more pronounced than $1/r^2$. It can be seen that, as a result, the charged particle rate at 20 cm is almost twice the value with no field, that at about 65 cm the rates are the same for both cases, and that the 4 T field reduces the charged particle rate at the outermost radius of the tracker by as much a factor of four. This has important implications for the architecture of the CMS Tracker.

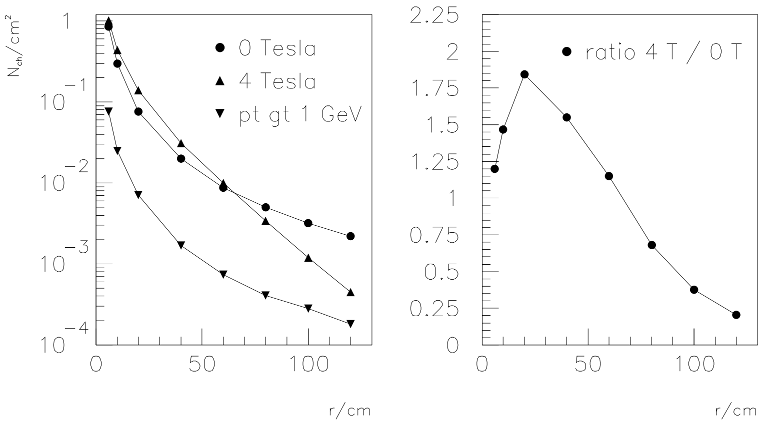

Fig. 1.7: Primary charged particle density per cm^2 at $\eta = 0$, for 20 minimum bias events superimposed (in units of %).

To satisfy the performance requirements and constraints outlined in the previous sections, we have adopted a strategy aimed at providing a set of coordinate measurements of sufficient precision and robustness so that track reconstruction can be reliably performed based on a relatively small number of measurements per track. To do this, we rely on sufficiently fine granularity such that typical single channel occupancy at high luminosity, for detectors with at least one hit in them, is kept between 1% and 3% everywhere in the Tracker. The required hit resolutions, at least in the transverse plane, are in the range of 15 μm to 40 μm at the inner and outer radii of the Tracker respectively.

We have chosen three detector technologies, each best matched to the task of satisfying our stringent resolution and granularity requirements in the high, medium and lower particle density regions. These are Pixels, Silicon Strip, and Micro Strip Gas Chambers (MSGCs) respectively. They are arranged in concentric cylindrical volumes, each corresponding to three occupancy regimes: the region below $\approx$ 20 cm, between $\approx$ 20 and $\approx$ 60 cm, and from $\approx$ 70 to 120 cm. The three detector types chosen are all fast on the scale of 25 ns, allowing event pile-up to be limited to a single bunch crossing for Pixels and Silicon and, for the MSGCs, to two bunch crossings.

The presence of a very large irreducible background due to minimum bias event pile-up at high luminosity challenges the pattern recognition capability of the Tracker. Therefore, strong emphasis is put on robust pattern recognition within each of the three sub-detectors. The unambiguous three-dimensional space points provided by the Pixels are essential for correct pattern recognition at these small radii. Each of the SST and MSGC volumes provides sufficient information to allow independent verification of the overall pattern recognition results, yielding a powerful measure of redundancy. This feature of the CMS Tracker is an essential tool to ensure tracking which is both efficient and ghost-free in the very high luminosity environment.

In the central rapidity region detectors are arranged in a barrel geometry, while at higher values of rapidity they are deployed as disks, organised into end-caps. In total there are 13 barrel layers, and the CMS Tracker geometry, shown in Fig. 1.8, has been defined so as to provide typically 13 distinct high resolution measurement planes for stiff tracks up to $|\eta|$ of about 2.0, gradually falling off to a minimum of 8 planes at $|\eta|$ of 2.5. This is shown in Fig. 1.9. The CMS tracker layout, as well as the overall mechanical structure, are also illustrated in Colour Figs. 1.iv and 1.v.

At the smallest radii (from 4 cm up to 7 cm at low luminosity and from 7 cm up to 11 cm at high luminosity) the interaction region is surrounded by two barrel layers of silicon Pixel detectors. Two end-cap disks cover radii from 6 cm to 15 cm. The cell size in the Pixel detectors is 150 μm by 150 μm. The CMS Pixel detectors are n-on-n devices so that, in the barrel, their response is strongly affected by the 32° Lorentz angle of the electrons. The barrel Pixel geometry is deliberately arranged such that this large Lorentz angle induces significant charge sharing across neighbouring cells and this results in expected hit resolutions of approximately 10 μm and 15 μm in the ϕ and z coordinates respectively. Similar resolutions, between 15 μm to 20 μm, are obtained in the end-cap Pixels, by rotating the sensors 20° around their central radial axis. In the high luminosity configuration, the Pixel detector will have an active surface of close to one square metre, instrumented with approximately 40×10^6 channels.

The intermediate region, from 22 cm up to 60 cm, is instrumented with a 5-layer Silicon Strip Barrel detector, complemented by 10 disks in each end-cap. Layers 3 to 5 of the Silicon Barrel are approximately 170 cm long. To avoid unfavourably shallow crossing angles, the length of the inner two layers is limited to 90 cm. The rest of the coverage is provided by incorporating 3 mini end-cap disks on each side. Barrel layers 1, 2 and 5 are double-sided layers, with stereo geometry for the longitudinal coordinate measurement. Correspondingly, the inner and outer radii of the end-cap disks are also instrumented with double-sided layers, where a stereo geometry is employed to measure the radial coordinate. The mini end-cap disks, closer to the interaction region, are fully double-sided.

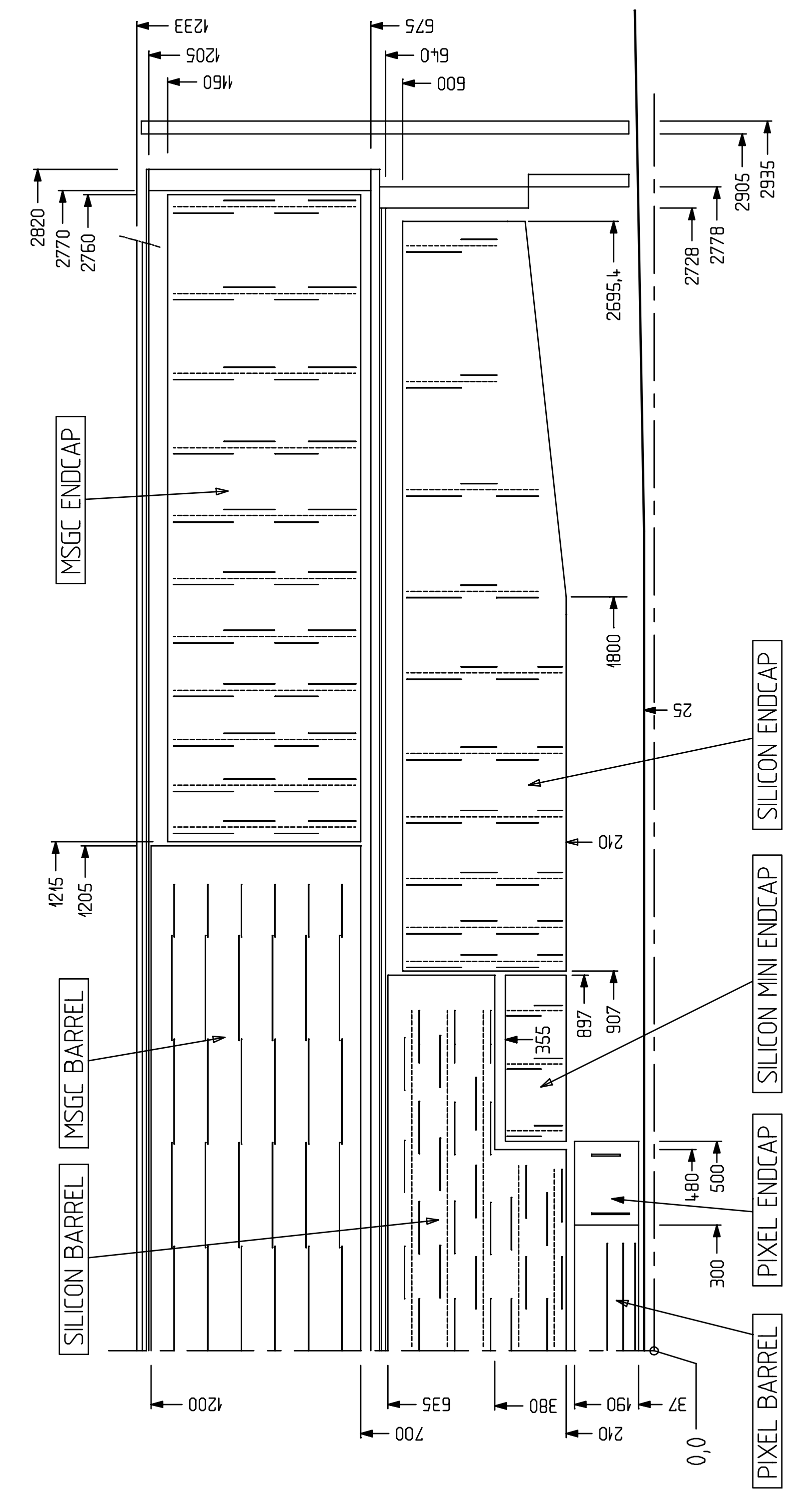

Fig. 1.8: A cut view of the CMS Tracker layout.

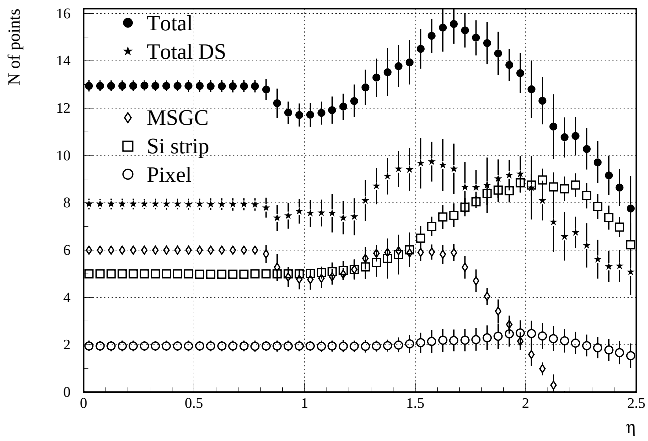

Fig. 1.9: Average number of measurement planes intersected by infinite momentum tracks, as a function of rapidity.

The outer volume of the Tracker, from 70 cm up to 120 cm, is instrumented with a 240 cm long barrel with 6 cylindrical layers of MSGCs, and by 11 discs of MSGCs for each end-cap. Layers 1, 4 and 6 of the barrel MSGC detector are double-sided, with a stereo geometry for the longitudinal coordinate measurement. Double-sided detectors with a stereo geometry are used at the inner and outer radii of the end-cap MSGC disks to provide measurements of the radial coordinate.

In addition to benefiting from an intrinsic response time shorter than the 25 ns bunch crossing interval, silicon sensors are especially well suited to the high and medium occupancy environment thanks to an active substrate thickness of only 300 μm and the very fine pitch which can thus be put to use. For the silicon detectors the typical strip length is 12.5 cm, and the pitch ranges from 61 μm to 122 μm and from 81 μm to 244 μm for the primary and stereo views, respectively. The hit resolution is around 15 μm for the 61 μm pitch, and approaches the digital limit (pitch/$\sqrt{12}$) for the larger pitches, where most of the charge is deposited on a single strip.

In the lower occupancy region of the Tracker, excellent resolution can be obtained with MSGCs with a significantly lower channel density. Here strip length ranges from 10 cm for the inner layers to 25 cm for the outer ones, and the pitches are around 200 μm and 400 μm for the primary and stereo views. The corresponding resolution is approximately 35 μm and 100 μm respectively. This lower channel density in the outer region of the Tracker is used to keep under control the overall cost of the Tracker, as well as to reduce the material in front of the electromagnetic calorimeter.

Overall, the CMS Silicon and MSGC trackers cover approximately 300 m^2 of active surface, consisting of more than ten thousand independent detector modules instrumented with 12×10^6 channels. The total active surface of the Silicon tracker is close to 75 m^2 and the total number of channels is 5.4×10^6, about equally distributed between barrel and end-caps. The total active area of the MSGC tracker is about 225 m^2 and the total number of channels 6.6×10^6, again approximately equally distributed between barrel and end-caps.

Silicon and MSGC detectors are not only natural complements in terms of their performance in the LHC environment, they also share basic technical characteristics. In particular, the same front-end electronics chain can be used for both, with only minor adaptations to best match the different pulse shapes of the two types of detector. This has proven to be a key advantage in the development of the electronics chain and is also expected to be an important factor in the production phase.

The readout of all the Tracker sub-detectors is analog. Analog information allows a better optimisation of the coordinate reconstruction, resulting in an improved resolution and more Gaussian error distributions, with respect to a digital scheme. Furthermore, analog information can be used to verify the pattern recognition in instances where clusters from distinct tracks appear to have been merged. Finally, analog readout lends robustness to the overall system, in particular by providing the means for efficient online common mode noise subtraction.

1.4 Progress Since the Technical Proposal

On account of its high centre of mass energy and unprecedented luminosity, the LHC will create a very hostile radiation environment for the Tracker (Section 1.7). Radiation damage will set a limit to the operational lifetime of detectors and requires the use of radiation-hard electronics everywhere in the Tracker volume. A vigorous R&D programme has been carried out on both the detectors and the front-end electronics chain, to ensure full functionality of the Tracker after exposure to 10 years of LHC operation or more.

The readout architecture has changed conceptually very little since the Technical Proposal [1-5] but has progressed considerably in design and implementation. The detailed implementation of the key components of our front-end analog readout chain, in radiation-hard technologies, is well advanced. The control system, involving a small number of ASICs which distribute clock, triggers and commands internally in the tracker, has been fully specified. The analog optical link, a cornerstone of the system, is now based on edge-emitting semiconductor lasers of the type extensively used for TELECOM and DATACOM applications.

Radiation effects on silicon Pixel and strip detectors are now much better understood. For Pixel detectors, the viability of silicon for the sensor material has been demonstrated, so that this is chosen instead of other more exotic materials. In the very extreme environment in which they must operate, the n-on-n architecture works best. The expected lifetime of the Pixel detectors and electronics is compatible with reasonable maintenance and upgrade scenarios.

For silicon strip detectors, both the sophistication of the devices and the quality of the technologies used in producing them have significantly advanced with respect to the state of the art as of a few years ago. The behaviour under irradiation of a broad spectrum of devices has been characterised in detail. It has been confirmed that both double-sided detectors as well as simple p-on-n truly single-sided sensors are viable at the LHC, provided they are of good quality. The latter devices, in particular, make use of essentially standard micro-electronics technologies, and can therefore be produced in large quantities and at relatively low cost. We have chosen to use single-sided devices throughout the SST, with double sided modules obtained by coupling two such sensors back-to-back.

The advances made in silicon strip detector technology, and the cost reductions these have resulted in, have made possible a far more extensive use of these devices than previously envisaged. At the time of the Technical Proposal, the SST provided only three detector layers, and was limited in radius to below 40 cm and in length to only ± 150 cm. In the present configuration the full region up to 60 cm in radius, where typical primary track densities are above 1 cm^{-2}, is covered by the SST.

An important milestone for the CMS Tracker has been the successful development of MSGC detectors with the demonstrated capability of stable and efficient operation in the LHC environment. To this end a new technique of ‘advanced passivation’ has been developed within CMS, which extends the safe operating regime of the MSGC to a range of gains well above the minimum required for efficient track finding. The effectiveness of this technique has been thoroughly studied in laboratory measurements and demonstrated in extremely high-intensity low-energy hadron beams (PSI) this past summer.

In addition, a great deal of progress has been made in both the mechanical engineering and system aspects of the Tracker. In the past year a series of large scale 'milestone' prototypes have been completed for each of the barrel and end-cap SST and MSGC sub-detectors, which have allowed detailed tests of the important aspects of their designs. The overall mechanical support structure, as well as the integration of services, has also been studied extensively. Comparisons between several alternative schemes resulted in the choice of a central cylindrical structure, which supports both the SST and MSGC trackers, on which our design is based.

1.5 Tracker Material Budget

Great care has been taken throughout the design of the Tracker to ensure that it meets stringent material budget constraints. Indeed this consideration limits the total number of active layers which can be usefully deployed and motivates the choice of materials used.

In some respects, however, we have been forced to accept inevitable compromises. In particular, for stable long term operation in the LHC environment, the Silicon tracker and Pixel vertex detectors must be operated at -10 °C, whereas the MSGC Tracker will be operated at 18 °C. This requirement for a thermal separation and screening of the SST and MSGC volumes has important consequences on the mechanics of the Tracker, and especially on the organisation and routing of services within it. Indeed, all services for the Silicon tracker must be removed axially to the Tracker end-flanges at a radius of 60 cm, not an optimum configuration in terms of the effect on material budget. Similarly, the constraints imposed on the installation of the Pixel detector require their services to be removed axially to the end-flanges at a radius below 20 cm.

This situation clearly results in an undesirable local peak in the material density, in particular between the SST and MSGC volumes. The ability of each of the Pixel + Silicon and MSGC Trackers to verify independently the pattern recognition results provides a powerful means with which to address this problem.

We have performed a thorough analysis of the material budget of the CMS Tracker design. A detailed accounting has been made of all the Tracker components and implemented within a GEANT simulation. This tool allows us both a general overview of the situation, as well as a detailed breakdown of the effect of individual components on the material budget. Figure 1.10 summarises the situation.

In Chapter 9 it is shown that pattern recognition even for low p_T hadrons remains very good, and the effects of bremsstrahlung on electrons can be controlled at a satisfactory level. A Monte Carlo study of Higgs to $\gamma\gamma$ decays propagated through the detailed detector geometry shows that in 46% of such decays both photons leave the Tracker volume without converting. Most of the events where photon conversions do take place are still well reconstructed. It has been shown that, with this rate of conversions, the loss of efficiency in CMS for the Higgs to $\gamma\gamma$ search does not exceed other irreducible inefficiencies [1-2].

We consider that, as our detailed understanding of the critical engineering issues continues to improve, we will be able to further reduce the overall material budget without compromising the integrity of the detector.

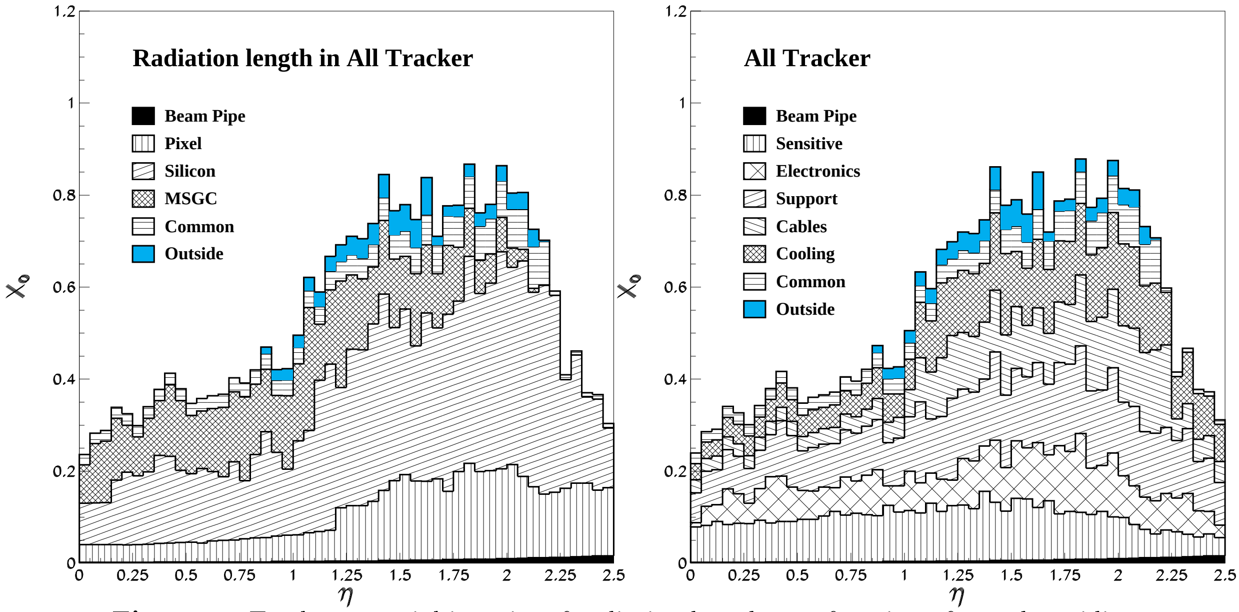

Fig. 1.10: Tracker material in units of radiation length as a function of pseudorapidity.

1.6 Staged Deployment of the CMS Tracker

The extremely high rate of interactions (up to 10^9 Hz) and the 25 ns bunch crossing frequency characteristic of the LHC environment greatly complicate the task of achieving the required level of performance. As discussed above, this mandates a certain level of redundancy in the detector design and sets the scale for the number of precision measurements required to define tracks, as well as their organisation in Pixel, Silicon and MSGC volumes. Together with considerations of two track resolution required to reconstruct tracks in high energy jets, this also basically defines the total number of readout channels.

At low luminosity, the performance requirements in terms of two-track resolving power, momentum and impact parameter resolution remain as stringent as in the high luminosity environment. The absence of minimum bias event pile-up, however, allows to relax significantly the redundancy which is an essential feature of the high luminosity layout. Because the highest luminosities will be attained only after several years of LHC running, and due to a shortage of currently available financial resources, we propose to install the detector in two stages.

We have identified an initial 'Phase I' configuration, consisting of a subset of the fully instrumented detector, which is well matched to the much cleaner environment expected for the low luminosity operation of the LHC. For the Phase I Silicon tracker we omit the fourth, single-sided, Silicon Barrel layer as well as two complete disks in each end-cap. For the MSGC tracker we omit the fourth, double-sided, barrel layer and, once again, two complete disks in each end-cap. The position of the end-cap disks is modified so that, on average, 11 distinct measurement points are ensured for $|\eta|$ less than about 2.0, falling off to 6 points at $|\eta|$ of 2.5. This reduced configuration still preserves the required performance of the Tracker at low luminosity and is matched to the currently available funding for the Tracker project.

Full deployment of the Tracker will follow as 'Phase II', to be completed in time for the high luminosity LHC running. The support mechanics are designed so as to allow the later installation of the missing barrel layers and end-cap disks. Furthermore, we plan to include all services for these detectors in the initial installation phase, from the counting rooms to the Tracker patch panel inside the magnet coil. The transition from the Phase I to the Phase II configuration, which ensures full functionality of the Tracker to the high luminosity LHC conditions, should thus be possible within a regular LHC shutdown period.

1.7 The LHC Radiation Environment

The radiation field within the Tracker is characterised by two distinct sources. Secondaries from the *pp* interaction, the products of their interactions in the Tracker structures and some decay products, give the dominating contribution to the fluences at the inner layers of the Tracker. This component of the fluence is almost independent of the z-coordinate and behaves roughly as $1/r^2$, where r is the distance from the beam-line. Almost all of the charged hadron fluence originates from the vertex. On the other hand, most of the neutrons observed in the Tracker region are due to albedo from the surrounding electromagnetic calorimeter. The most intense source of albedo neutrons is the end-cap ECAL. While the fluence originating from the vertex is irreducible, a neutron moderator lining of the ECAL is shown to efficiently reduce the neutron albedo, which is particularly intense for the heavy $PbWO_4$ crystals.

Figure 1.11 shows approximate values for the absorbed dose, which is to some extent material dependent, as well as the fast neutron and charged hadron (and neutral kaon) fluences at different radii in the Tracker region. A more detailed analysis, as well as a thorough discussion of the methods used for estimating the radiation levels, can be found in Appendix A.

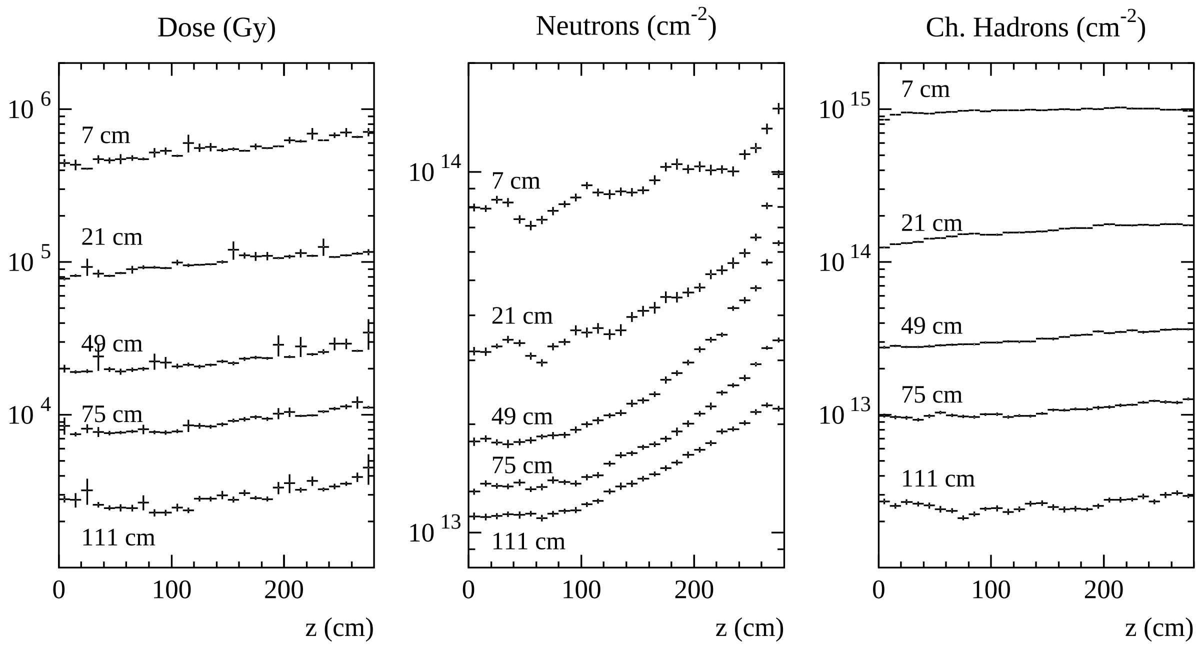

Fig. 1.11: Radiation levels at selected radii in the CMS Tracker region. All values correspond to an integrated luminosity of 5×10^5 pb^{-1}. The error bars indicate only the statistics of the simulations. The neutron fluences include only the part of the spectrum above 100 keV.