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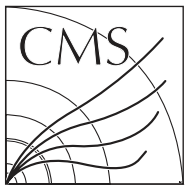

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

26 November 2013 (v2, 20 December 2013)

tkLayout: a Design Tool for Innovative Silicon Tracking Detectors

G. Bianchi for the CMS Collaboration

Abstract

A new CMS tracker is scheduled to become operational for the LHC Phase 2 upgrade in the early 2020's. tkLayout is a software package developed to create 3d models for the design of the CMS tracker and to evaluate its fundamental performance figures. The new tracker will have to cope with much higher luminosity conditions, resulting in increased track density, harsher radiation exposure and, especially, much higher data acquisition bandwidth, such that equipping the tracker with triggering capabilities is envisaged.

The design of an innovative detector involves deciding on an architecture offering the best trade-off among many figures of merit, such as tracking resolution, power dissipation, bandwidth, cost and so on. Quantitatively evaluating these figures of merit as early as possible in the design phase is of capital importance and it is best done with the aid of software models.

tkLayout is a flexible modeling tool: new performance estimates and support for different detector geometries can be quickly added, thanks to its modular structure. Besides, the software executes very quickly (about two minutes), so that many possible architectural variations can be rapidly modeled and compared, to help in the choice of a viable detector layout and then to optimize it. A tracker geometry is generated from simple configuration files, defining the module types, layout and materials. Support structures are automatically added and services routed to provide a realistic tracker description. The tracker geometries thus generated can be exported to the standard CMS simulation framework (CMSSW) for full Monte Carlo studies.

tkLayout has proven essential in giving guidance to CMS in studying different detector layouts and exploring the feasibility of innovative solutions for tracking detectors, in terms of design, performance and projected costs. This tool has been one of the keys to making important design decisions for over five years now and has also enabled project engineers and simulation experts to focus their efforts on other important or specific issues.

Even if tkLayout was designed for the CMS tracker upgrade project, its flexibility makes it experiment-agnostic, so that it could be easily adapted to model other tracking detectors. The technology behind tkLayout is presented, as well as some of the results obtained in the context of the CMS silicon tracker design studies.

Presented at *IPRD13 13th Topical Seminar on Innovative Particle and Radiation Detectors*

Preprint typeset in JINST style - HYPER VERSION

tkLayout: a Design Tool for Innovative Silicon Tracking Detectors

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ABSTRACT: A new CMS tracker is scheduled to become operational for the LHC Phase 2 upgrade in the early 2020's. tkLayout is a software package developed to create 3d models for the design of the CMS tracker and to evaluate its fundamental performance figures. The new tracker will have to cope with much higher luminosity conditions, resulting in increased track density, harsher radiation exposure and, especially, much higher data acquisition bandwidth, such that equipping the tracker with triggering capabilities is envisaged.

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Contents

1. Overview

1.1 Towards HL-LHC

Over the next ten years, LHC and its experiments have been earmarked for three technical stops (Long Shutdowns, or LS, 1, 2 and 3) during which maintenance and upgrade will be carried out to enable them to operate at higher performance (see Table 1). The CMS Tracker is a barrel-shaped detector sitting in the inner part of CMS, which features detecting units (*modules*) based on silicon sensors. Data from all the modules is then correlated so that a particle's track, as it leaves the Tracker, can be reconstructed. The CMS Tracker [1, 2, 3] is foreseen to last in the current configuration till 2022.

After LS3, LHC will start to operate under High-Luminosity regime (HL-LHC) thus entailing an instantaneous luminosity six times as high ($5 \times 10^{34} cm^{-2} s^{-1}$). This last scenario represents a challenge for the CMS detector due to the increased radiation dose [4] and amount of data. Therefore, a complete redesign of the tracker is envisaged (Phase 2 Tracker). In particular, the new CMS tracker is planned to be instrumented with Level-1 triggering capabilities, to aid the triggering system in coping with the increased event rate. However, adding functionality must not cause a loss in the tracking performance, due to the additional material. It is very important, therefore, to find the right trade-off between a multitude of parameters, such as the aforementioned tracking performance, the triggering performance, material, cost, and so on. This search for the optimal trade-off goes through a thorough analysis of several different tracker architectures and the variations on each architecture. It is evident that the size of the task calls for a computer-aided approach.

Table 1. The evolution of LHC performance through LS1 (2013-14), LS2 (2018), LS3 (2021).

	≤ 2012	2015-2017	2019-2021	≥ 2023
$E_{CM}[TeV]$	8	14	14	14
$L[cm^{-2}s^{-1}]$	8×10^{33}	$\leq 2 \times 10^{34}$	$\leq 2.5 \times 10^{34}$	$\simeq 5 \times 10^{34}$
$\int L[fb^1]$	≤ 30	≤ 50	≤ 50	≤ 3000

1.2 The tkLayout tool

tkLayout is a software package written in C++11, developed specifically to perform design studies of the new Phase 2 upgrade of the world's largest silicon tracker. Currently in its fifth year of active development, it started out as a simple calculation tool and over the years evolved into a comprehensive modeling and performance analysis solution, expanding its feature set to take on each new design challenge as it shaped up.

tkLayout creates a 3d model of the tracker from simple configuration files. Material is then added to the model automatically, but according to user-defined rules. Once an architecture has been modeled, its performance can be estimated in terms of, for example, tracking and triggering performance, trigger data rate or power dissipation after irradiation. The analyses are based on *a-priori* calculations or on *input parameterizations,* such as distributions of track properties coming from the current CMS tracker. For ease of consultation by tracker designers and engineers, the output of the tool is a mini-website.

Finally, the internal geometry and the associated material model can be exported to the CMS Geant4-based MC simulation framework CMSSW, for in-depth physics analysis.

1.3 tkLayout vs. full MC simulation

tkLayout adopts a non-simulative, parameterization-driven approach to tracker performance evaluation, going in the opposite direction of event-based Monte Carlo simulators. This has several advantages. Firstly, tkLayout shows the ideal performance figures of a tracker geometry, irrespective of the particular algorithm or technology used, for example, to perform track reconstruction. Once the final layout is decided, results from tkLayout can be used to benchmark different possible algorithms implemented in full simulations.

A second advantage to tkLayout's approach is performance: by avoiding complex calculations stemming from full event-by-event simulation of particle interactions, tkLayout runs in around two minutes on normal PC hardware (for comparison, CMSSW may need hours to run on a computing grid).

Another important difference with respect to a general-purpose simulator is tkLayout's *specificity*. tkLayout automatically creates a model for the non-sensitive elements of a tracker geometry such as supports and services, by making assumptions specific to the architecture CMS Phase 2 tracker (for example, the way cables are routed), making it possible to model complex geometries that would take weeks or months to be implemented from scratch in a general-purpose simulator.

For all these reasons, where a full Monte Carlo simulation allows a detailed later-stage physics analysis, tkLayout works well as a design tool, allowing quick setup, modeling and comparative evaluation of the many possible tracker layouts and their variations, as well as the iterative layout optimization once the best candidate has been found.

2. Tracker modeling with tkLayout

tkLayout models the tracker architecture at varying levels of abstractions. Active elements (modules), supports and services are modeled and material is added automatically to them, according to a set of rules defined by the user.

2.1 Module geometry

Detector modules are the main objects in tkLayout. tkLayout supports rectangular as well as wedge-shaped modules. Modules can have one or two sensor surfaces. Each sensor is independently defined and can feature a different topology in terms of number of sensing elements in the longitudinal and transverse direction.

Dual-sensor modules are fundamental to enable triggering in the CMS Tracker. On this kind of modules, specialized front-end electronics correlate the hits on the two sensors and measure their displacement to estimate the p_T of the track. The lower a track's p_T the farther away the two hits will be, due to the particle's trajectory bending in the CMS magnetic field. If the displacement between two hits is smaller than a configurable search window, a *stub* is formed and sent out to the L1 trigger system. For a track with a given p_T, increasing or reducing the spacing between the two sensors respectively increases or reduces the hit displacement.

2.2 Trigger window and sensor spacing dimensioning

It is desirable to find a combination of trigger window and sensor spacing that achieve good triggering efficiency (meaning as many as possible high-p_T tracks are detected) but also good low-p_T rejection. The *hit occupancy* on each sensor puts a limit to the window size: if a window is made too large it will likely result in the erroneous correlation of hits belonging to two different tracks, thus creating *fake* stubs. Additionally, sensors cannot be arbitrarily spaced apart, due to structural constraints.

The following formula relates hit displacement (s) with p_T:

$$s(p_T) = \frac{d_r}{\sqrt{a-1}} \quad a = \left(\frac{2p_T}{B \cdot r \cdot 0.3 \frac{GeV}{T \cdot m}} \right)^2$$

where r is the radial coordinate of the module center and d_r is the radial distance between the lower-sensor and upper-sensor hits, which is proportional to the sensor spacing.

This formula is used for the error propagation computation of the measurement of a track's p_T by the module itself. After assigning a window and spacing value, tkLayout can compute the probability of stubs being found as a function of p_T. This hinges on two hypotheses: (1) *high-p_T* (i.e. passing the threshold) particles are mainly primaries, (2) the amount of *low-p_T* particles detected by a module is much higher, due to combinatorics between the hit on the inner sensor and the hits within the search window on the outer sensor, and can be extracted from the predicted occupancy.

To quantify the average number of high-p_T particles traversing a module, tkLayout uses the following function:

$$f(x) = \exp(a_0 + a_1 x + a_2 x^{-0.1} + a_3 x^2)$$

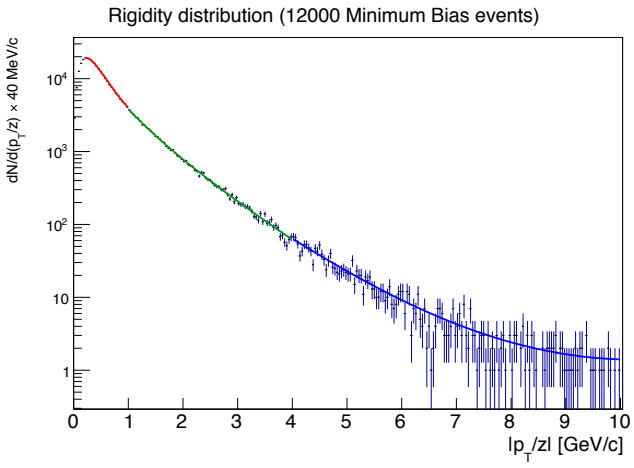

Figure 1. Distribution of particle rigidity (p_T/Z), fitted with 3 different sets of parameters (see Table 2).

Table 2. Parameter set for the function fitting the rigidity distribution

Range (p_T)	a_0	a_1	a_2	a_3
$0.22 < x \leq 1$	25.2523	−6.84183	−12.0149	1.89314
$1 < x \leq 4$	0.727638	−1.04041	8.56495	6.52714×10^{-3}
$4 < x \leq 10$	46.6514	−2.88910	−37.8716	0.126635

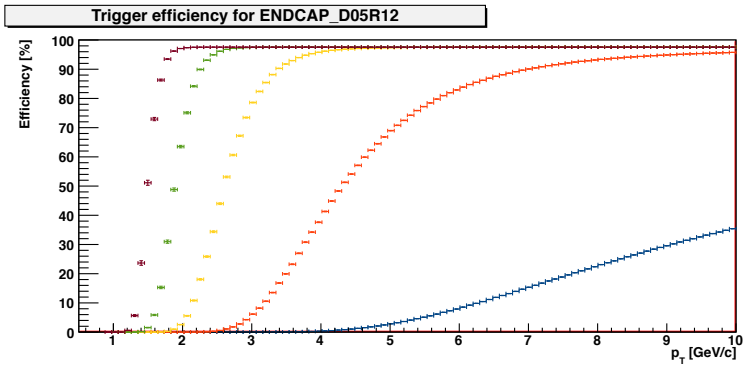

Figure 2. Example of a module turn-on curve. The curve becomes sharper as the window size (W) increases (here depicted W = 1, 3, 5, 7, 9 strips).

to fit a distribution of primaries coming from a MC simulation (see Figure 1 and Table 2). Stubs originating from low-p_T particles are instead estimated by a pure combinatorial of hits: $S_L = n \cdot W \cdot \nu^2$, where ν is the module occupancy (from a parameterization of the current tracker occupancies), n is the number of sensing elements on the lower sensor and W is the window size.

To help in the choice of the appropriate values for spacings and windows, tkLayout can plot stub-generation efficiency graphs in the form of turn-on curves (see Figure 2) and several figures of merit such as: fake stubs rate, true stubs rate, purity (the ratio of true stubs over the total).

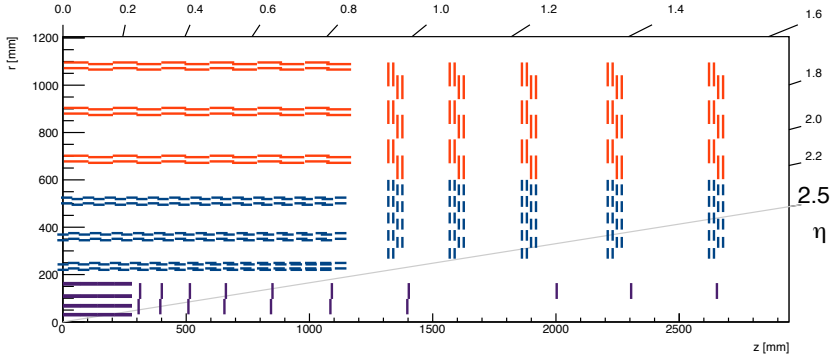

Figure 3. Longitudinal section of a CMS Phase 2 tracker layout modeled with tkLayout. The beam pipe runs along the z axis.

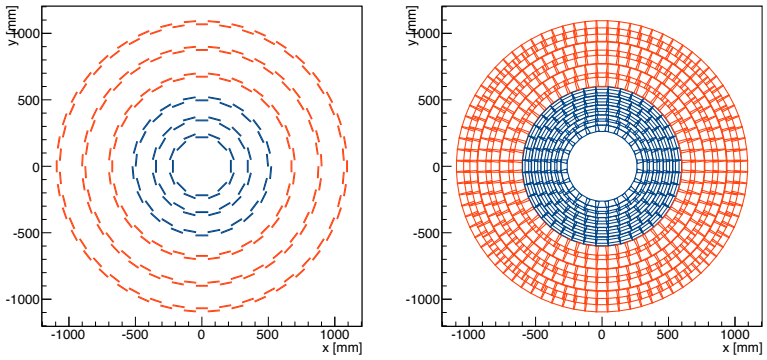

Figure 4. Transverse section of a CMS Phase 2 tracker barrel (left) and endcap (right)

2.3 Module positioning

The CMS Tracker is inherently symmetric around the axis formed by the beam pipe, so, to take advantage of this feature, layouts are traditionally composed of *barrel* and *endcap* sections. In a barrel section modules cover the surface of concentric cylindrical *layers* around the beam axis and, within a layer, they are hierarchically arranged in *rods* - strings of modules running along a layer's length. An endcap section is instead composed by *disk*s, acting as a "lid" for the barrel. Disks are composed of concentric *rings* of detector modules (see Figures 3 and 4).

If we use the cylindrical coordinates r (cylindrical radius), ϕ (rotation angle around z) and z (beam axis), barrel modules are alternately staggered in r to avoid collisions, by requiring a small radial gap d_1 between modules within a rod and rods themselves are staggered by a larger d_2 in the same layer.

tkLayout, given a set of parameters, such as the aforementioned d_1 and d_2, the number of layers (n), their length, and the inner and outer radius of the barrel (r_m and r_M), creates and positions the modules automatically.

Given a certain radius r, the theoretical (non-integer) number of rods in ϕ to guarantee complete coverage can be calculated as $N(r) = 2 \cdot \lceil \pi/\alpha(r) \rceil$, where $\alpha(r)$ is the rods' ϕ-aperture, depending on the layer radius, the inter-rod radial stagger d_2, the module width and the rod ϕ-overlap

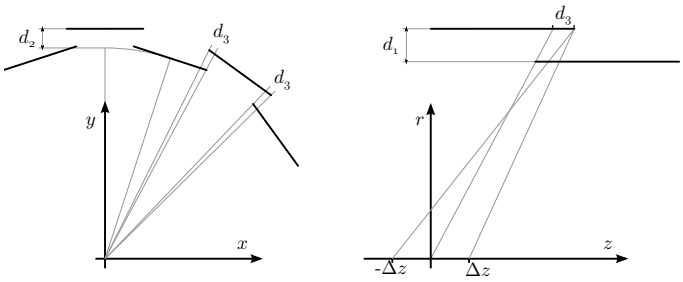

Figure 5. Placement of modules in the transverse (left) and longitudinal (right) planes. Figure is not to scale.

d_3. The first layer is always placed at r_m with $N(r_m)$ rods, while, similarly, the last layer is at r_M with $N(r_M)$ rods. The radius and number of rods of the middle layers is instead determined according to one of the following heuristics, selected by the user:

1. *Enlarge* causes layer $k = \{1,2...n-1\}$ to be tentatively placed at radius $r_k = r_m + k \cdot (r_M - r_m)/n$, with $N(r_k)$ rods, then enlarged until the overlap between rods decreases to d_3;

2. *Shrink* uses the same initial layer placement as Enlarge, but the number of rods is calculated as $N^* = 2 \cdot \lfloor \pi/\alpha(r_k) \rfloor$, so the layer radius is shrunk until the rods overlap by d_3;

3. *Fixed* forces the layer to be built at a user-specified radius;

4. *Auto* chooses Enlarge or Shrink on the basis of which is closer to the layer's tentative radius

To prevent particles from finding a gap between two adjacent modules from which to escape the barrel undetected, tkLayout positions the modules hermetically in z so that no gap would be seen from $(0,0,\pm\Delta z)$, where Δz is the expected variance of the z coordinate of the primary interaction points. Additionally, tkLayout imposes that an overlap of at least d_3 be seen from the origin $(0,0,0)$. This is to make sure that two adjacent modules both register a hit on their overlapping edges, to help software module alignment (see Figure 5).

Endcap modules can be either rectangular or wedge-shaped and are staggered alternately in z within their ring by a small gap d_1. Rings are staggered in z between each other by a larger gap d_2 and they are placed with an overlap in r calculated with the same criterion as the z-overlap for barrel modules.

Modules can be rotated around their longitudinal axis by a *skew angle* α. This effectively increases the resolution seen by tracks by a factor $\cos(\alpha)$, but, on the other hand, reduces the ϕ-aperture by the same amount.

tkLayout also supports rotating barrel modules around their transverse axis by a *tilt angle* β, in a layout called "tilted barrel" (see Figure 6), where barrel modules are increasingly tilted the further they are on the z axis (up to $\beta = \pi/2$ when they effectively become endcap modules). The advantage of the tilted layout is that the modules' aperture in θ (the angle relative to the beam axis) is increased, so the number of modules to cover the same volume is reduced, to the benefit of material amount and cost.

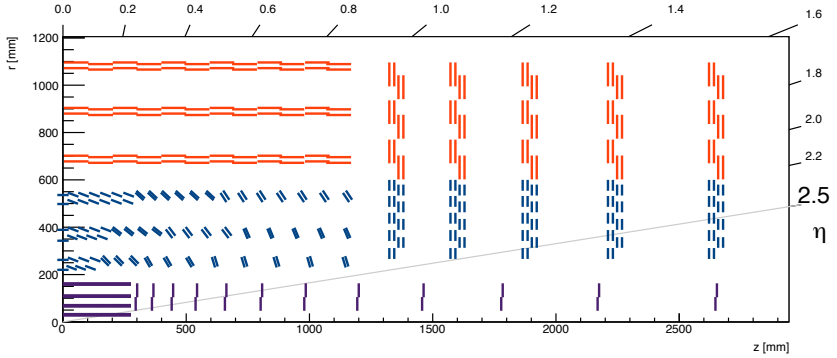

Figure 6. Longitudinal section of the "tilted barrel" geometry

2.4 Material

For efficiency reasons, tkLayout models a module's components (for example sensors, power converters or support mechanics) only in terms of the amount of material with which they contribute to the module's volumetric material budget and never as true geometric objects placed on the module. Therefore, each component is defined only by its material composition (1g Copper + 0.5g PVC...).

Furthermore, services running inside the detector to and from the end-flange (like power cables, cooling pipes or optical fibers) are also modeled as material assigned to the modules' volumes, as these hermetically cover the detector volume. The actual assigned material depends on its position in the supporting structure: for example, for a barrel module on a given layer the amount of material M is:

$$M(n) = n \cdot \sum_i A_i + \sum_j B_j$$

where n is the module position on the rod ($n = 0$ for modules at $z = 0$), A_i are the materials composing the services running through the rod and B_j those composing a module's components. This parameterization takes into account the accumulation of running services towards the end of a barrel layer: a module next to the end-flange will contain in its volume as many service lines as the number of modules before itself.

A similar computation is done for endcap modules across rings, with a scaling factor applied to A_i, such that the material amount for a module on ring n ($n = 0$ for the innermost ring) is:

$$M(n) = \sum_{k=0}^{n} \frac{N_k}{N_n} \cdot \sum_i A_i + \sum_j B_j$$

with N_k being the number of modules on ring k. This factors in the reduction in service density as they spread outward from one concentric ring to the next.

Additionally, each material A_i and B_j can be flagged as "local" if it only contributes to the material inside the layers or disks (like support mechanics or silicon sensors) or "exiting" if it implies the presence of other services coming from outside the detector (like cooling pipes or power lines).

Once the material for *local* modules and services is in place, additional volumes representing *exiting* services and their support structures are created. Materials for exiting services are automatically created depending on the amount of module material previously flagged as such with several

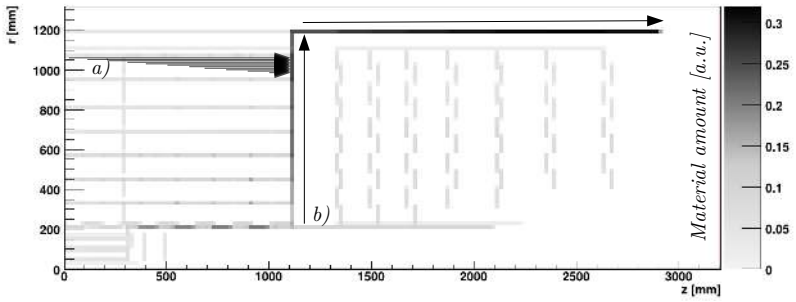

Figure 7. Distribution of material in an (r,z) section of a tracker model. The accumulation of material along the barrel layers (a) is indicated by the big arrow. The accumulation of routed services (b) is shown by the line becoming increasingly dark.

configurable conversion rules (for example, many small cooling pipes running inside a rod will join through a manifold into fewer larger exiting pipes). Part of these services are automatically routed up to the edge of the tracking volume with the same material accumulation mechanism described for services inside the detecting volumes (for example, the cooling pipes will be propagated, while the material of their manifolds will not). Furthermore, an additional fixed amount of material can be added to the service volumes to represent specific objects. The routing procedure is shown in Figure 7.

Finally, the material assignment results in several summary plots, such as distribution of material, photon conversion and nuclear interaction probabilities, etc.

2.5 Tracking performance

The tracking performance analysis is the most important performance metric to qualify a tracker layout. It offers several figures of merit to estimate the accuracy achieved by a layout in reconstructing a track's parameters: transverse momentum (p_T), longitudinal impact parameter (z_0), transverse impact parameter (d_0), polar angle (θ) and azimuthal angle (ϕ_0). p_T is expressed also in terms of the particle curvature radius (R): $p_T = B \cdot R \cdot 0.3 \frac{GeV}{T \cdot m}$.

In tkLayout the tracking resolution is calculated taking into account the precision of the measurement points and the multiple scattering. The method is based on treating a particle's trajectory in the CMS magnetic field independently as a circle in the (r,ϕ) plane and a straight line in the (r,z) plane. This approximation was proven to be valid - a-posteriori - by modeling the current tracker and comparing it with the results from a full MC simulation [5]. These calculations will closely follow those published by Karimäki [6, 7] with two main differences: first multiple scattering is taken into account here, while the author explicitly neglects it in the cited article; second we are only interested in the general solution of the problem, as tkLayout performs the computation for each particular case.

In the (r,ϕ) plane, tracks are fitted with a circle, yielding a measurement $\widehat{\alpha}_i$ of the track parameters $\alpha_i = \{\varphi_0, d_0, \rho\}$ ($\rho = 1/R$), from the set of N measured points $P_i = (r_i, \varphi)$.

If r_i is the module radial position, the error ε_i of the i-th measurement point is:

$$\varepsilon_i = \frac{1}{2}\rho r_i^2 - (1+\rho d_0) r_i sin(\phi_i - \phi_0) + \frac{1}{2}\rho d_0^2 + d_0$$

tkLayout builds the covariance matrix $U_{ij} = cov[\widehat{\alpha}_i, \widehat{\alpha}_j]$. The measurement errors are $\sigma(\widehat{\alpha}_i) = \sqrt{U_{ii}}$.

If we rotate the reference frame by ϕ_0, the coordinate measured by the modules becomes x. Furthermore, if we assume the sensor radial positions r_i to be known and errorless and, for high-p_T tracks, $\rho \cdot d_0 \ll 1$, we have that: $d\varepsilon_i \simeq dx_i$ (approximation valid only for non-tilted and non-skewed modules, see below for other cases).

It is assumed here that the best fit of the trajectory to the measured points will be given by minimizing χ^2: $\chi^2 = \sum_{i,j} \varepsilon_i W_{ij} \varepsilon_j$ where $W = U^{-1}$ is the weight matrix. This is given by $W = D^T C^{-1} D$ where D is the matrix of derivatives $D_{ij} = \partial\varepsilon_i/\partial\alpha_j \simeq \partial x_i/\partial\alpha_j$ and C is the covariance matrix of the N measured points: $C_{ij} = [\varepsilon_i, \varepsilon_j] \simeq [x_i, x_j]$.

Since tkLayout treats multiple scattering as a measurement error, considering it as a deviation from the track's ideal trajectory, C can be written as a sum of two components: $C^M + C^R$, where C^M is the covariance matrix of the multiple scattering and $C^R_{ij} = \delta_{ij}\sigma(x_i)$ is the covariance matrix due to the intrinsic resolution of the N measurement points (due to the sensor characteristics).

To evaluate C^M, tkLayout generates a number of sample tracks traveling in a straight line (mimicking high-p_T tracks) and registers all the M impact points tracks encounter on their way out of the detector, including inactive surfaces such as services and support structures. Hence, a larger covariance matrix $\widetilde{C}^M_{mn} = \mathrm{cov}\,[\widetilde{\mathrm{x}}_\mathrm{m}, \widetilde{\mathrm{x}}_\mathrm{n}]$ is computed. Then, the $M - N$ lines and columns corresponding to the multiple scattering contributions from non-sensitive elements are dropped to obtain in fact C^M.

Given the radial positions of interactions $r_n = r_1, r_2, \ldots, r_M$ and the associated scattering angles $\vartheta_n = \vartheta_1, \vartheta_2, \ldots, \vartheta_M$, the deviation from the ideal path $\widetilde{x}_n$ is $\widetilde{x}_n \simeq \sum_{i=1}^{n} (r_n - r_i)\,\vartheta_i$ and, since the scattering angles ϑ_n are uncorrelated:

$$\widetilde{C}_{mn} = \langle \widetilde{x}_m, \widetilde{x}_n \rangle \simeq \sum_{i=1}^{min(n,m)} (r_m - r_i)\,(r_n - r_i)\,\left\langle \vartheta_i^2 \right\rangle$$

Finally, the expected resolution of the track parameters can be obtained from the covariance matrix $U = [D^T C^{-1} D]^{-1}$.

In the (r,z) plane, assuming again $\rho \cdot d_0 \ll 1$, tracks are fitted with straight lines to obtain the measurements of the last two parameters θ and z_0. Thus, the track equation is:

$$r_i = \frac{z_i - z_0}{ctg(\theta)}$$

The resolutions of θ and z_0 can be evaluated with the same method described above on the simpler linear fit.

The methods described above assume that r_i is known and (x_i, y_i) are the only source of uncertainty, respectively, in the transverse and longitudinal planes. While this is a good approximation for regular, non-tilted, non-skewed barrel modules, this is not the case for modules with more complex placement. To tackle the latter, tkLayout performs a projection of the intrinsic measurement errors on a *virtual* barrel module centered on the hit, such that, if (x,y) are, respectively, the local transverse and longitudinal coordinates on the original module and (a,b), respectively, the transverse and longitudinal coordinates on the virtual module, the variances σ_a^2 and σ_b^2 of the projected

measurements are:

$$\sigma_a^2 = (sin(\alpha)cos(\beta)+cos(\alpha))^2\sigma_x^2+(B\cdot sin(\beta))^2\sigma_y^2$$
$$\sigma_b^2 = ((D\cdot cos(\beta)+sin(\beta))sin(\alpha))^2\sigma_x^2+(D\cdot sin(\beta)+cos(\beta))^2\sigma_y^2$$

with $B = A/\sqrt{1-A^2}$, $D = ctg(\theta)/\sqrt{1-A^2}$ and $A = r_i/(2R)$. This hinges on the assumption that the errors on x_i and y_i can be treated as uncorrelated. It can be demonstrated that this assumption holds true for the range of track p_T's and module geometries we are interested in. Hence, the measurement covariance matrix can be built as if the module were a regular barrel module and the method described above for them can be used for modules placed at any tilt and/or skew angles.

3. Conclusions

Designing a new tracker is a very complex endeavor. It requires making quantitative comparisons between many different architectures, in terms of their tracking and triggering performance, material amount, cost, etc. It involves seeking the right trade-off between different parameters and optimizing the final architecture. tkLayout was developed specifically to provide tracker designers with an easy and rapid way to evaluate the performance of layouts. tkLayout executes very quickly, so that performance-tuning a layout can be done in a trial-and-error, incremental manner. The accuracy of the a-priori, non-simulative approach the tool adopts has been proven to be within 20% with respect to a Full MC simulation [5].

tkLayout was built to design the CMS tracker, but, since the vast majority of silicon trackers have similar defining characteristics, support for other trackers could easily be added.

Over the last 5 years, tkLayout has been a key tool in the design of the Phase 2 CMS tracker and geometries generated with it have made their way into the CMSSW simulation framework for physics analysis.

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