Track Reconstruction with the CMS Tracking Detector

With proton-proton collision energy of 14 TeV at luminosity of 10^{34} cm^{-2} s^{-1}, the LHC environment poses challenges for the tracking system and for the tracking software. The system must reconstruct charged particles from the primary collision in the presence of up to 20 underlying events. CMS has built an all-silicon tracking system consisting of an inner pixel detector (1 m^2 active area) and an outer strip detector (200 m^2) with over 70 million readout channels. The CMS software has to master the dense track environment and also take into account multiple scattering due to the large amount of material (0.5 X0 on average). With 13 layers crossed on average, 0.7% to 5% transverse momentum resolution is achievable. An overview of the tracking system and the tracking software will be given. Both general and specialized tracking algorithms covering, for example, muon reconstruction will be discussed.

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For the CMS tracking group and the CMS Collaboration

CMS inner tracker specification (see poster of J.Lamb for more details)

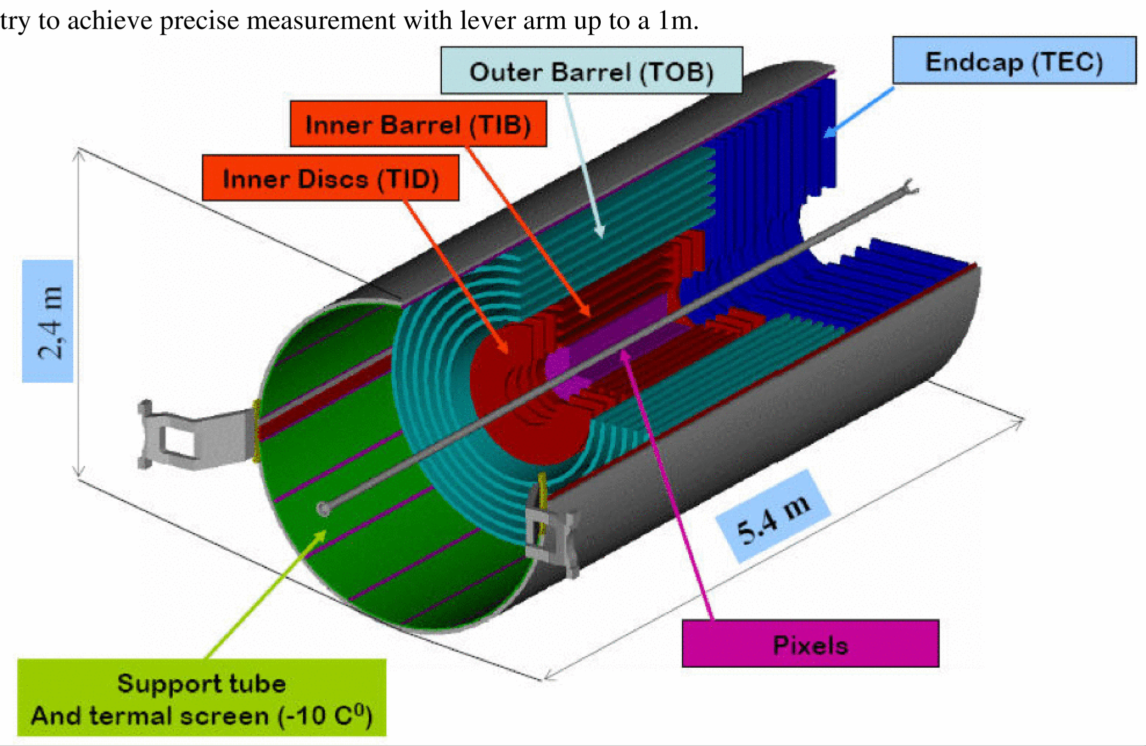
Full Silicon detector for few but precise measurement points

The CMS inner tracking system consist solely of Silicon based detectors. It is embended in a homogeneous longitudinal magnetic field of 4T. The inner most layers host silicon pixel wafers to achieve vertex reconstruction and precise trajectory seeding. Outer layers are made of silicon micro-strip sensors partially mounted in stereo geometry to achieve precise measurement with lever arm up to a 1m.

Layout

- Pixel detector
  - 3 barrel layer
    r = 4.4 cm to 10.2 cm ; L = 53 cm
  - 2 disks in each endcap
    r = 6 cm to 15 cm ; |z| = 34.5 cm, 46.5 cm
  - 66 millions 100×150 μm^2 pixels
  - 1 m^2 active area of 3D measurements
- Strip detector
  - 10 barrel layers
    r = 20 cm to 1.1 m ; L = 1.3 m, 2.2 m
  - 12 disks in each endcap
    r = 20 cm to 1.1 m ; |z| = 75 cm to 2.75 m
  - 9.6 millions strips
    80 μm to 183 μm pitch
    320 μm to 500 μm thickness
  - 200 m^2 active area
  - 40% double sided layers with 5.7° stereo angle

Ref. CMS Physics TDR Volume I, 2006

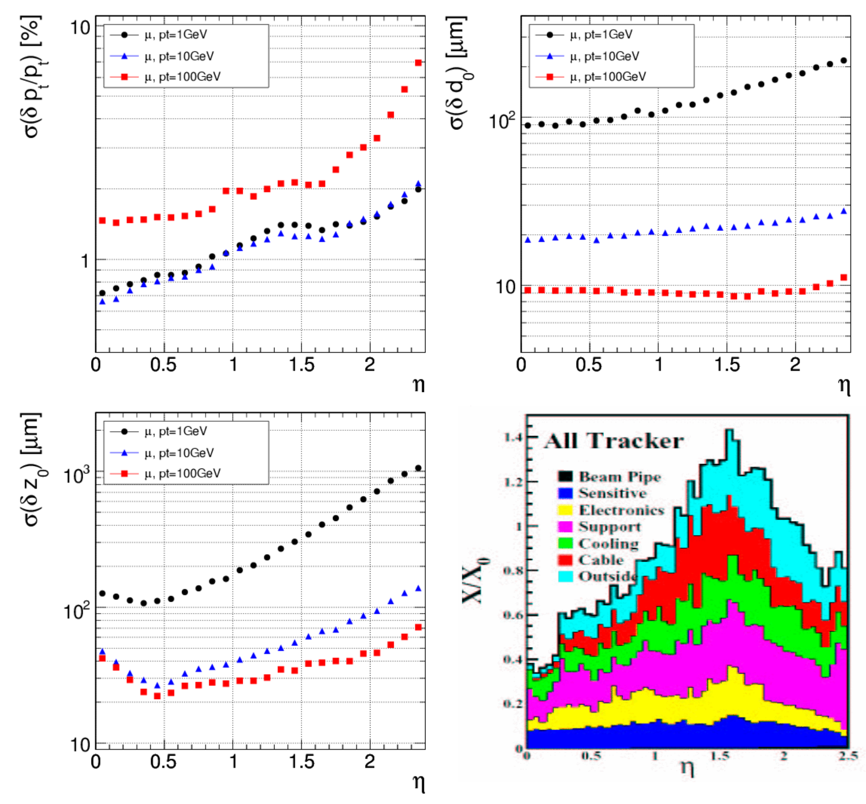


CMS tracking performance

- Kalman Fitting procedure taking into account material effect

The set of consecutive hits returned by the pattern recognition algorithm are forward fitted to un-bias the track parameters measurement from pattern recognition. The Kalman Fitting formalism is used, which is mathematically equivalent to a least-square minimization. It is then backward fitted in the smoothing step, providing optimal parameters measurement at each reconstructed hits. These procedure are taking into account material concentrated in the thin layer of the silicon detector. Analytical propagation from layer to layer thus possible and achieve a fast refitting step. The uncertainty from the amount of material and single measurement uncertainty lead to the shown resolution on track parameters. Uncertainty on impact parameters decreases with increasing momentum while transverse momentum uncertainty is optimum at the percent level on medium momentum track for which the of effects of multiple scattering and intrinsic curvature are balanced.

Ref. CMS Physics TDR Volume I, 2006

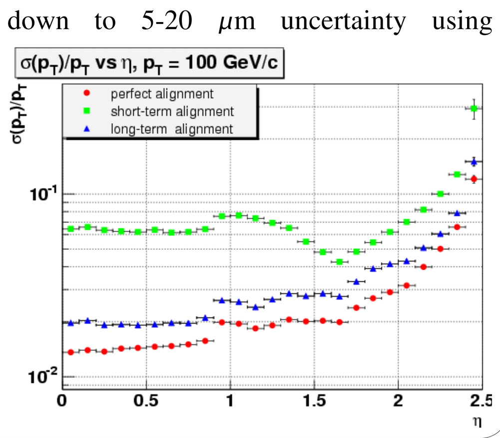


Detector Alignment

- Construction/Hardware/Software based alignment

Detector alignment is not only critical to measurement resolution, but also to track reconstruction efficiency. The alignment can be achieved in three steps. 1) Careful module position monitoring during assembly. 2) A laser system would provide mandatory alignment down to 100 μm uncertainty. 3) Three algorithms: *Millipede II, Kalman Filter* and *Hits and Impact Point* are expected to provide alignment down to 5-20 μm uncertainty using reconstructed tracks.

Ref. CMS Note 2006-11
Ref. CMS Note 2006-18
Ref. CMS Note 2006-22

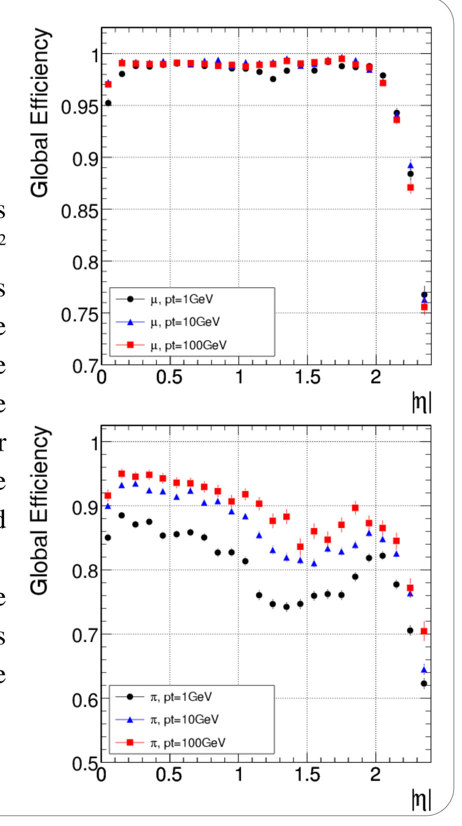


Combinatorial Track Finder

- Fast, inside-out, robust, Kalman combination of compatible hits into trajectory

The *CTF* algorithm grows a tree of possible trajectories from an initial trajectory seed. Based on a X^2 measurement at each layer, compatible measurements are added to the trajectories using the Kalman update formalism. Fast analytical extrapolation is possible due to the magnetic uniformity, however more precise extrapolation tools are available or under development. Trajectory duplicates are rejected base on the percentage of shared hits and a partial backward fitting provides an initial state to the track candidate. High efficiency is obtained for muon over a large range of pseudo-rapidity, while the efficiency on pions is worsen due to larger interaction with material. The *CTF* is used as a baseline pattern recognition.

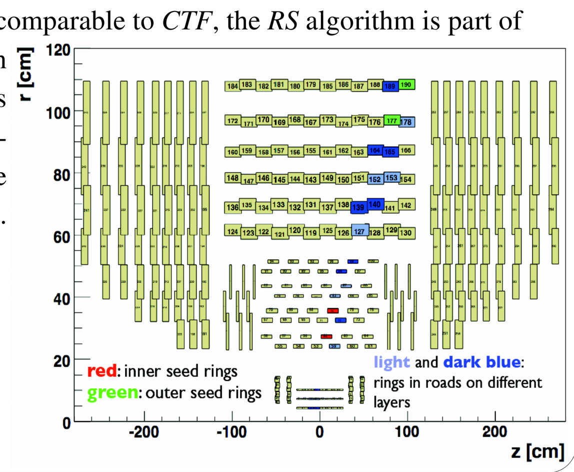
Ref. CMS Physics TDR Volume I, 2006
Ref. CMS Note 2006-41



Road Search algorithm

- Alternate and complementary pattern recognition robust against mis-aligned detector

The *RS* algorithm computes pattern recognition on hits within pre-calculated roads. Roads are subsets of silicon modules consistent with a charge and transverse momentum assumptions. Pattern recognition is initiated by a trajectory seed from pair of hits sufficiently distant to provide a long lever arm. With a global timing comparable to *CTF*, the *RS* algorithm is part of the track reconstruction baseline. The efficiency is similar to *CTF* and further-more complementary in the very forward regions.

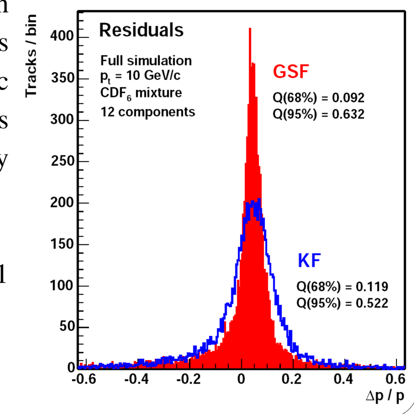


Alternative algorithms studied

Gaussian Sum Filter, Deterministic Annealing Filter and Multi Track Filter

Dedicated algorithms are developed to take into account more detailed model of energy loss. The GSF models the energy loss as a mixture of Gaussian, and is shown to give better momentum resolution than Kalman Fitting. DAF and MTF allows better hit combination region with high hit density like jets. However better performance and better pattern recognition in particular cases can be achieved, these specific algorithms are not used as baseline algorithms due to heavy computing requirements.

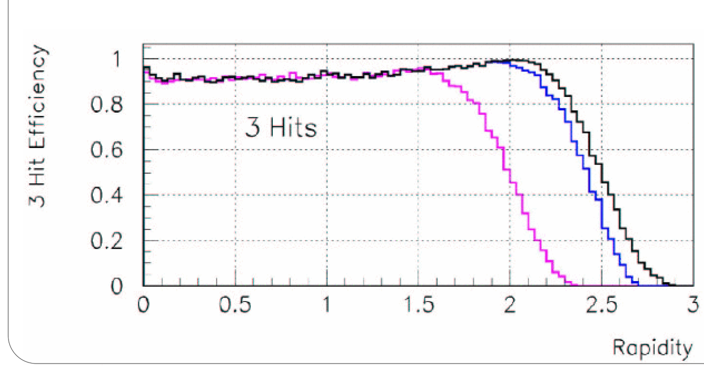
Ref. CMS Note 2005-14
Ref. CMS Note 2005-21

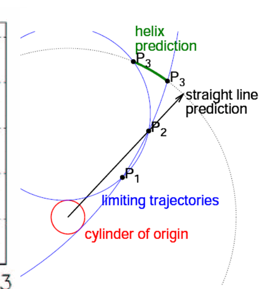


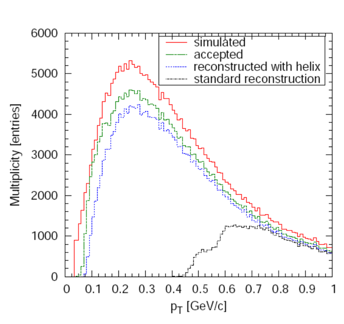
Pixel Hit Triplet Finding

- Low fake rate trajectory seed and fast track reconstruction

A charged particle trajectory in the central uniform magnetic field, neglecting material effects, is an helix which parameters can be constraint with 3 spatial measurements. The number of pixel layers crossed by a track is 3 up to pseudo rapidity of 2.2, allowing helix parametrization of tracks consistent with a given interaction region. Pixel triplets are build from pixel pairs (cf hit pair section) to which a consistent third hit can be found in the outer pixel layer. In the baseline reconstruction pixel triplet search is optimized for track with more than 1 GeV of PT and high efficiency is achieved at low momentum be dedicated algorithms.





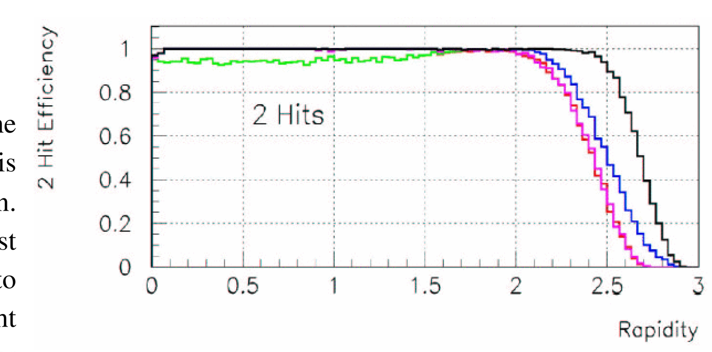


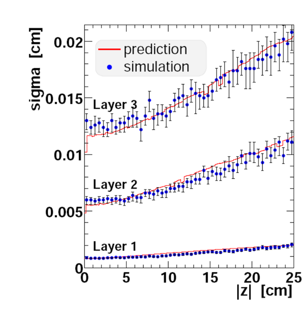
Hit Pairs Trajectory Seeding

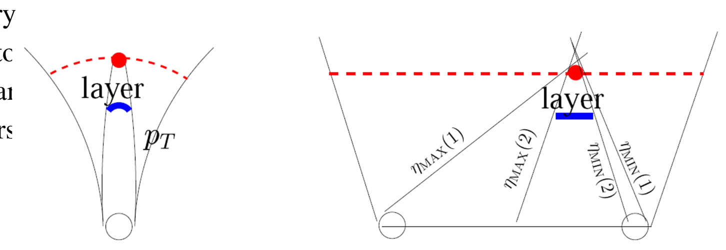
- High efficiency trajectory seeding

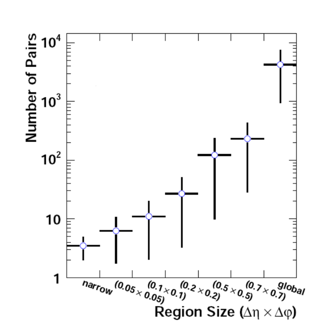
Redundant selection of pair of tracker layers are searched for hits compatible with the interaction region and furthermore, if required, to a specific $\eta\times\varphi$ region. The outer hit is found first so longer lever arm is used and the inner hit searched for in a narrowed region. Parametrized effect of material is used, so is computing optimization to achieve a very fast search. The seeding from hit pair if very efficient and its purity is low in the baseline due to loose constraints. Better purity, balanced by lower efficiency can be obtained with more tight constraints. The number of pixel layer crossed by a track is at least 2 up to CMS tracker maximum pseudo-rapidity. Pixel pairs can therefore be used as a very efficient trajectory seeding for inside-out pattern recognition. Strip pairs and mixed pairs seeding can be used to increase the track reconstruction efficiency, especially for tracks originating from nuclear interaction in tracker material, i.e with a very displaced vertex. Pair of non-consecutive layers far apart are used to seed the road search algorithm.

Ref. CMS Note 2006-26









High Level Trigger: trigger related

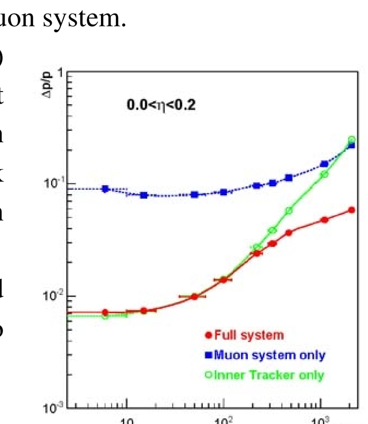
- Tracker optimum resolution used via local track reconstruction.

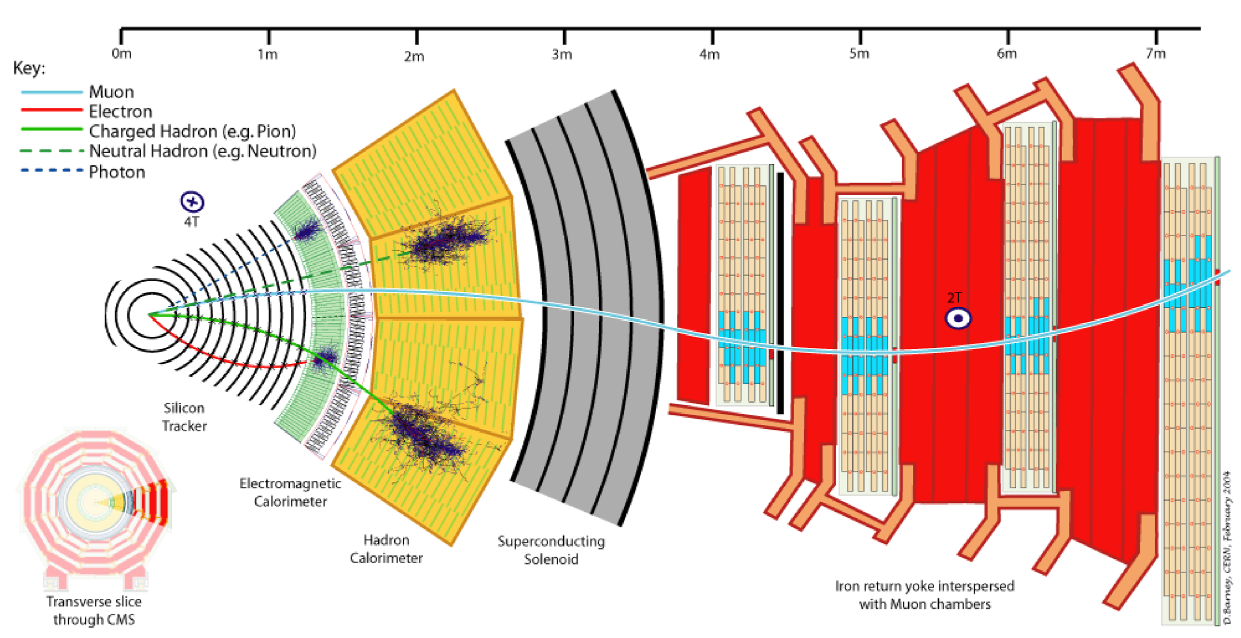
The CMS trigger has a hardware-based first level (*L1*) which task is to keep selected events from the bunch crossing frequency of 40 MHz down to 50-100 kHz. The next, and last level of trigger is fully software-based: it is called the High Level Trigger (*HLT*) which selection rate should not exceed 100 Hz. It contains several virtual levels to reject events as fast as possible. Partial reconstruction in sub-detectors is triggered by the *L1* system, however since the inner tracking detector is not part of the L1 decision, local track reconstruction has to be triggered from external *L1*/*HLT* primitives. Thus, local track reconstruction can be initiated by electron/photon from the *ECAL*, jets/tau from the *HCAL* or muon from the muon system.

As for muon seeded track reconstruction the baseline algorithm uses a L2-muon (see Riccardo Bellan's poster) reconstructed in the muon chambers only and constrain to originate from the interaction region. A region of interest is defined from the muon parameters and error matrix in order to search for hit pairs in the tracker. Pattern recognition and track fitting is then carried on from the regional seeds and hence provides the muon *HLT* with track parameters which resolution is up to 10 times better than the L2-muon: both measurement are combined to obtain optimum resolution. Other algorithm are under development

In addition to regional track reconstruction, pixel triplet can serve as low momentum track reconstruction and be used for primary/secondary vertex reconstruction. Vertex reconstruction at *HLT* stage is very important to significantly reconstruct b-jet and tau candidate at early trigger stages.

Ref. CMS Physcis TDR Volume I, 2006
Ref. CMS Data Acquisition & HLT TDR, 2002





Hit Reconstruction in the CMS Inner Tracking System

- Few but precise measurements points

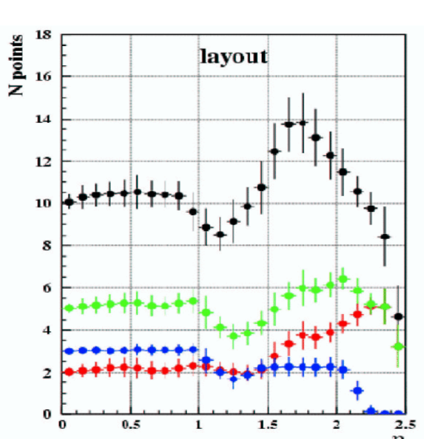
Charged particles energy deposition in the silicon sensor are collected in each pixel or strip channel. Pixel and strip signals are clustered with nearest neighbor independent algorithm using variable S/N thresholds.

- Pixel cluster position is determined from relative charge on the edges of the cluster and position resolution ranges from 15 μm to 30 μm and is favored by the charge sharing due to the Lorentz drift. Position uncertainty in the pixel detector highly depends on the irradiation fluence and is expected to degrade by a factor of two over time even with adjustment of bias voltage.
- Strip cluster position is calculated from the charge centroid. The cluster edges weight method cannot be trivially used due to inter-channel couplings on small cluster is however used on large cluster. Strip position resolution ranges from 10% to 35% of the strip pitch, i.e 8 μm to 64 μm.

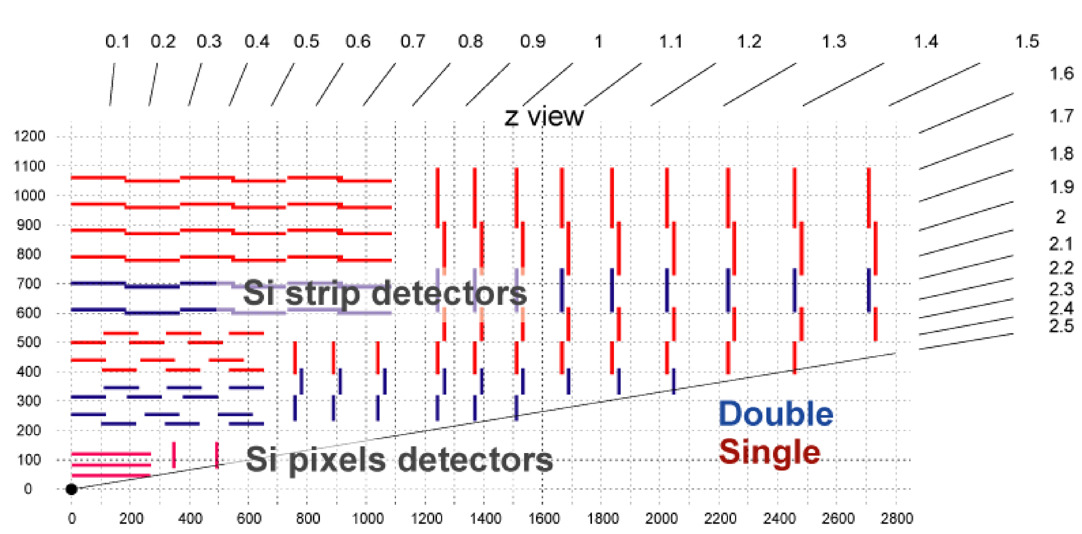
Estimated track crossing angle is used in pixel hits and strip stereo-hits reconstruction. Charged particles emerging from the interaction points are expected to cross 10 strip layers, with a peak at 14 where barrel and disk region overlap most. 50% of the measurement points are expected to be 3D measurements. In addition 3 layers of pixel are crossed up to pseudo rapidity of 2.2.

The fine granularity of the pixel and strip detectors allows for low occupancy from tracks per bunch crossing: 10^{-4} in the pixel detector and 1% to 3% in the strip detector.

Ref. CMS Physics TDR Volume I, 2006



- Total strip points
- Double sided hits
- Thin detector • thick detector



The layout of the CMS inner tracker