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 75 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. With 13 layers crossed on average, transverse momentum resolution to the percent level 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

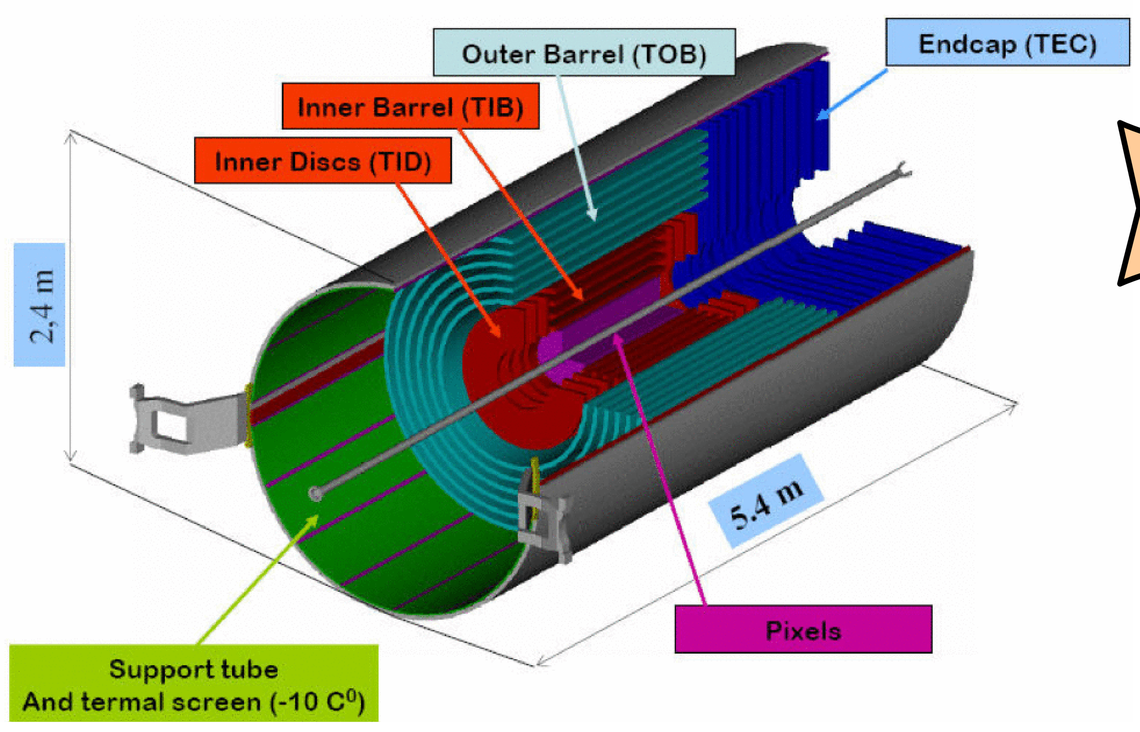
CMS inner tracker specification (see posters of G. Sguazzoni and J. Lamb for more details)

- Full Silicon detector for few but precise measurement points

The CMS inner tracking system consists solely of silicon sensors. It is embedded in a homogeneous solenoidal magnetic field of 4T. Innermost layers of pixels permit vertex reconstruction and precise trajectory seeding. Outer layers use micro-strip sensors partially mounted in stereo geometry.

- Pixel detector
  - 3 barrel layers
    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 million 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
  - 9.3 millions strips
    80 μm to 183 μm pitch
    320 μm and 500 μm thickness
  - 200 m^2 active area
  - 40% double sided layers with 5.7° stereo angle

Ref. CMS Physics TDR Volume I, 2006

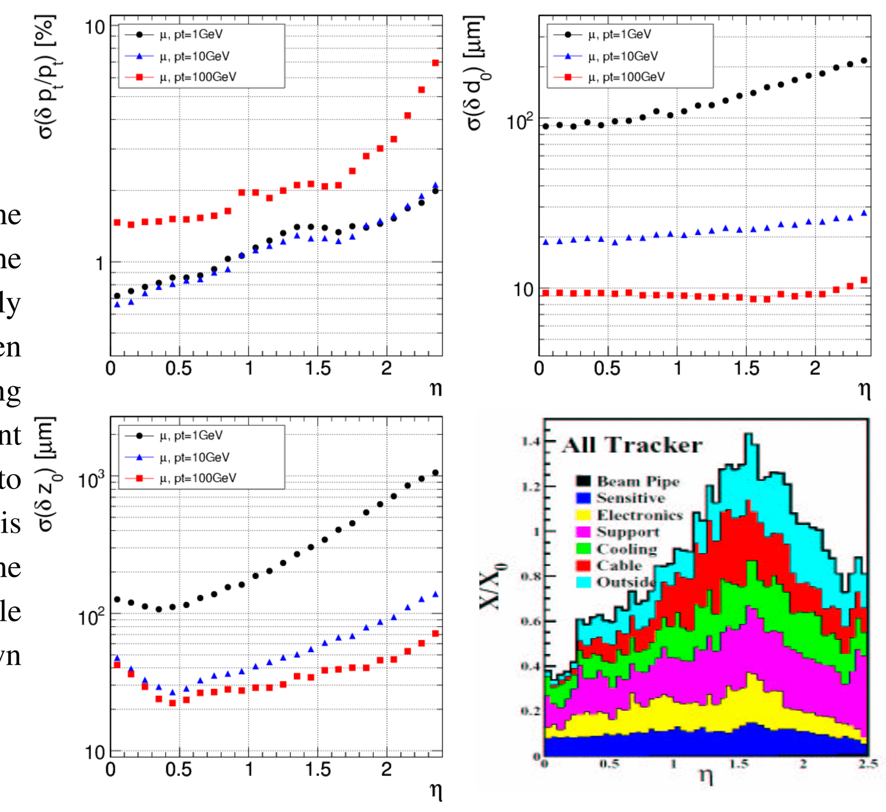


CMS tracking performance

- Kalman Fitting procedure taking into account the effect of material

The set of reconstructed hits obtained with the pattern recognition step are forward fitted using the Kalman Fitting formalism, which is mathematically equivalent to a least-squares minimization. It is then backward fitted in a smoothing step, providing optimal measurement of the impact-point parameters. Analytical propagation from layer to layer, modeling material in thin layers of detector, is used and achieve a fast track final fitting step. The uncertainty from the amount of material and single measurement uncertainty lead to the shown resolution on track parameters.

Ref. CMS Physics TDR Volume I, 2006

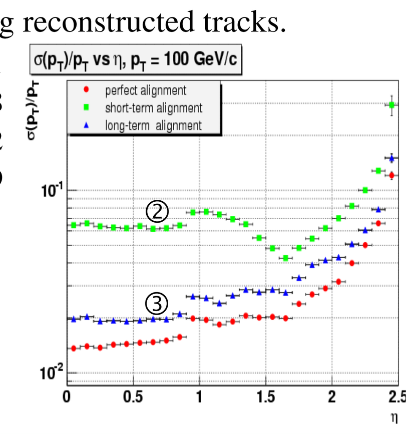


Detector Alignment

- Construction/Hardware/Software based alignment

Alignment is achieved in three steps. ① Sensor position monitoring during assembly. ② A laser system will provide alignment to 100 μm. ③ Algorithms: *Millipede II*, *Kalman Filter* and *Hits and Impact Point* are expected to provide alignment to 5-20 μm precision using reconstructed tracks.

Ref. CMS Note 2006-11
Ref. CMS Note 2006-18
Ref. CMS Note 2006-22
Ref. CMS Note 2006-29

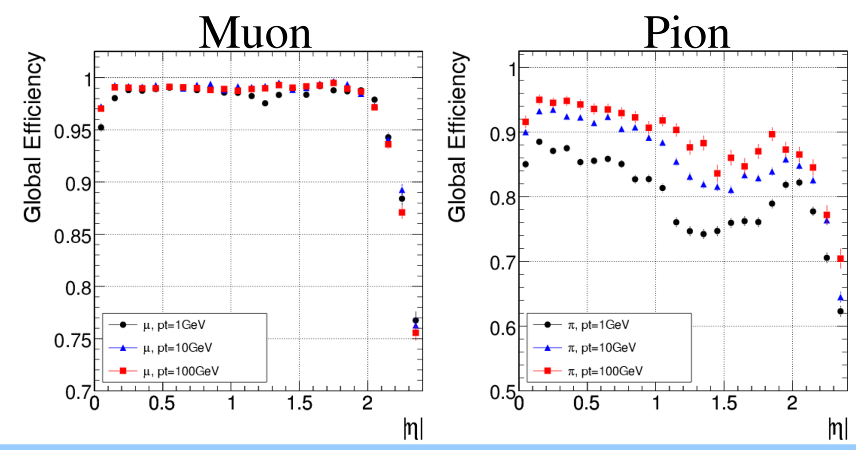


Combinatorial Track Finder

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

The *CTF* algorithm combines compatible measurements using the Kalman Filter formalism. Trajectory duplicates are rejected base on the percentage of shared hits. The *CTF* is used as a baseline pattern recognition.

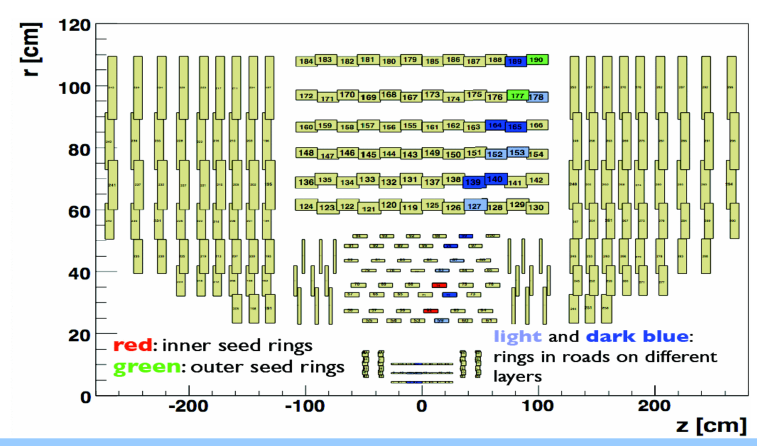
Ref. CMS Physics TDR Volume I, 2006
Ref. CMS Note 2006-41



Road Search algorithm

- Complementary pattern recognition, robust against mis-aligned detector

The *RS* algorithm recognizes patterns of hits within pre-calculated roads. Roads are subsets of silicon modules consistent with transverse curvature assumptions and pair of hits sufficiently distant to provide a lever arm. The *RS* algorithm is part of the baseline. The efficiency is similar to *CTF* and furthermore complementary in the very forward regions.

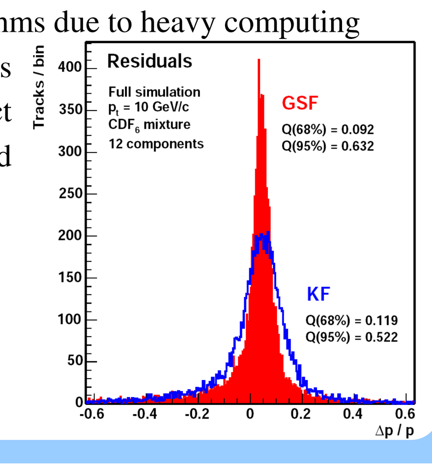


Alternative algorithms

- Gaussian Sum Filter, Deterministic Annealing Filter and Multi Track Filter

Dedicated algorithms have better model of material effects or more evolved hit combination. 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. *GSF* is used to reconstruct electron, while *DAF* and *MTF* are used in jets.

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

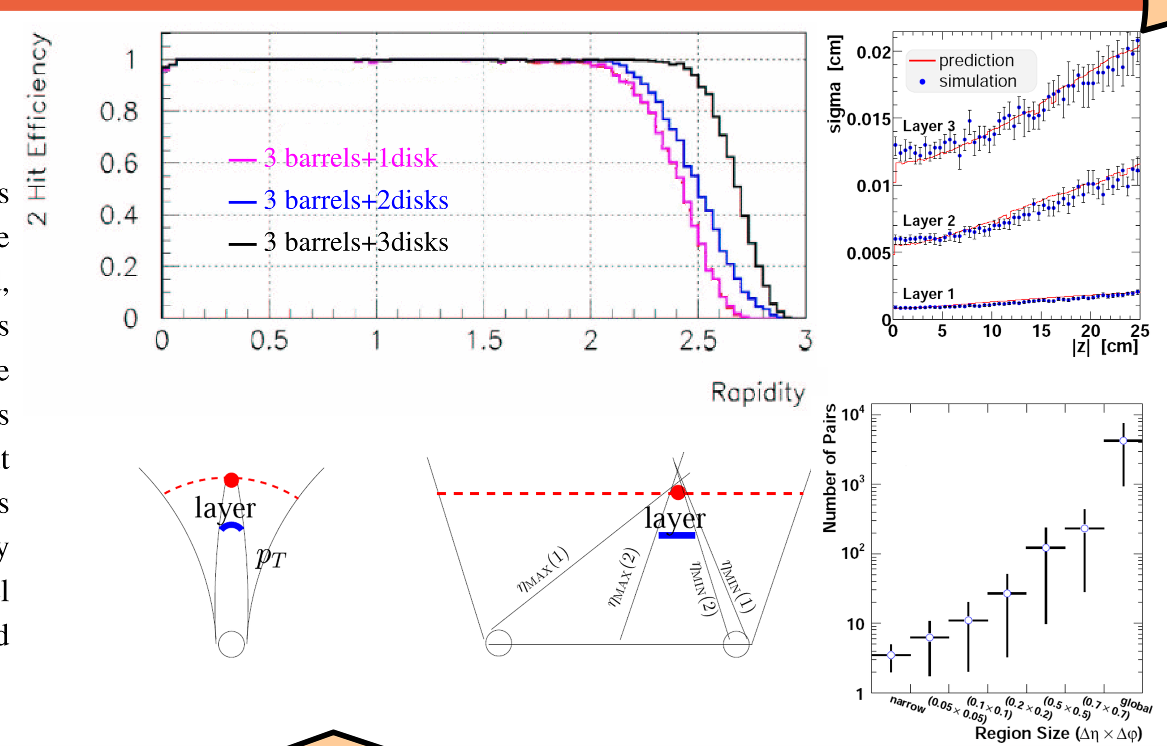


Hit Pairs Trajectory Seeding

- High efficiency trajectory seeding

Redundant selection of pairs of tracker layers are searched for hits compatible with the interaction region and furthermore, if required, to a specific $\eta\times\varphi$ region. Finding hit pair is fast, very efficient but low purity in the baseline due to loose constraints. Pixel pairs are used as trajectory seeding for inside-out pattern recognition. Strip pairs and mixed pairs seeding can be used to increase the efficiency on track originating further than the pixel detector volume. Inner/outer hit pair are used to seed the road search pattern recognition.

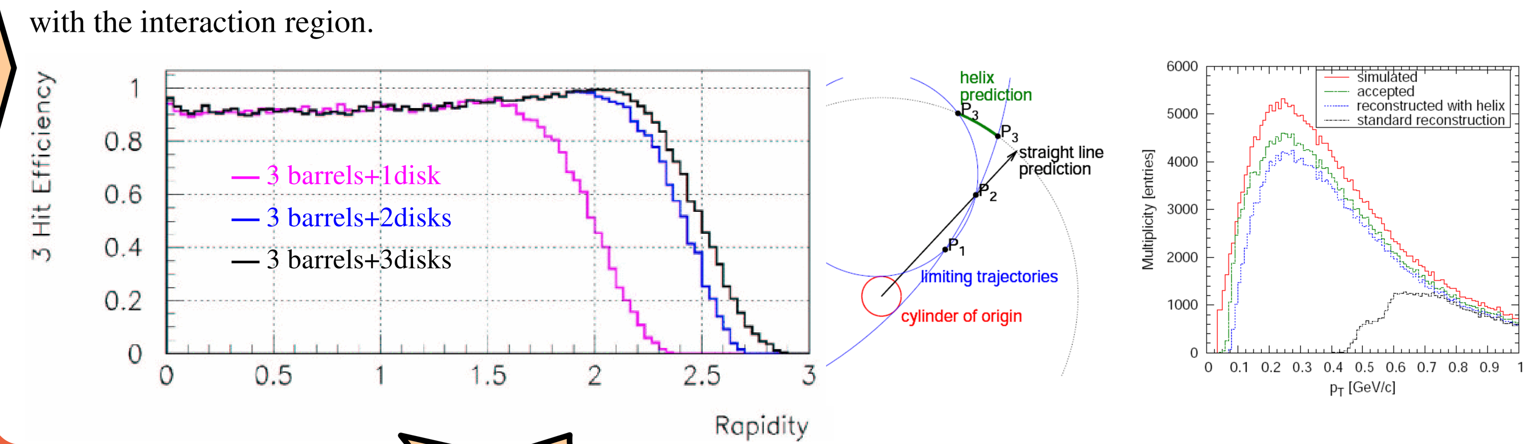
Ref. CMS Note 2006-26



Pixel Hit Triplet Finding

- Low fake rate trajectory seed and fast track reconstruction

Pixel triplets are built from pixel pairs (cf hit pair frame) for which a consistent third hit can be found in the outer pixel layer. As part of the baseline reconstruction, pixel triplet search is optimal above P_T=1 GeV. Higher efficiency is achieved at lower momentum with dedicated algorithms. Pixel triplet strongly constrains helix parameters consistent with the interaction region.



Hit Reconstruction in the CMS Inner Tracking System

- Few but precise measurement points

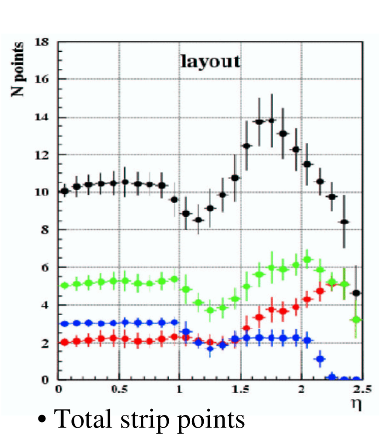
Pixel and strip signals are clustered with nearest neighbor independent algorithms using variable S/N thresholds

- Pixel cluster position is determined from relative charge on the edges of the cluster; position resolution ranges from 15 μm to 30 μm, favored by charge sharing. Position uncertainty in the pixel detector depends on the irradiation 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 on small clusters and cluster edges weight method is used on large cluster. Strip position resolution ranges from 8 μm to 64 μm.

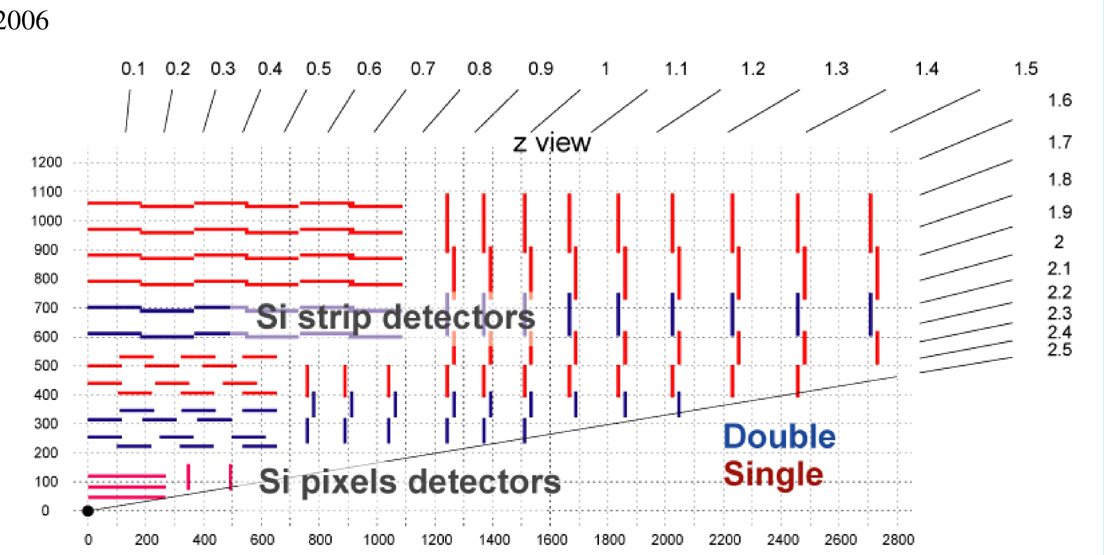
Estimated track crossing angle is used in pixel hits and strip stereo-hits reconstruction.

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
- Hits on double sided layer
- Thin detector • thick detector



The layout of the CMS inner tracker

High Level Trigger: tracker related

- Tracker optimum resolution used via local track reconstruction.

The CMS trigger has a hardware-based first level (*L1*) whose task is to reduce input event stream from *LHC* frequency (40 Mhz), to 50-100 kHz. The next, and last level of triggering is fully software-based: the High Level Trigger (*HLT*) which rate is 100 Hz. The inner tracking detector is not part of the L1 decision and regional track reconstruction has to be triggered from external *L1*/*HLT* primitives. Thus, electron/photon from the *ECAL*, jets/tau from the *HCAL* or muon from the muon system are used.

As for muon seeded track reconstruction the baseline algorithm uses a L2-muon (see poster of R. Bellan) constrained to originate from the interaction region. A region of interest is defined around the object to construct pixel pairs. Pattern recognition and track fitting is then carried on and hence provides the muon *HLT* with track parameters of better resolution. Other algorithms are under development to have a robust muon reconstruction at *HLT* for LHC start-up. The best balance of timing, efficiency and purity has to be found between different approaches to regional reconstruction.

In addition to regional tracking, pixel triplets can serve as fast track reconstruction and be used for finding vertexes. Vertexing at the *HLT* stage is important for triggering on b-jet, tau candidate,... at early trigger stages.

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