Tracking software in CMS
and first reconstruction results from
detector commissioning

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on behalf of CMS collaboration
Outline

• The challenge of track reconstruction at LHC

• Description of the CMS Tracker

• Software for track reconstruction
  - description of the algorithm
  - performance
  - recent improvements

• Results from Tracker commissioning at the Tracker Integration Facility
The challenges

pp-collisions at design luminosity \((10^{34}\text{cm}^{-2}\text{s}^{-2}, 14\text{TeV})\)

- 40 MHz crossing rate
- \(O(20)\) superimposed pileup (PU) events / crossing
- \(O(2000)\) charged tracks / crossing

Charged track density

Radiation hardness

Trigger

- Levels 2-3 (HLT) includes track reconstruction:
  - Reduction from 100kHz to \(~300\text{Hz}\)

Material budget

- high granularity and radiation hardness is obtained by means of a “heavy” tracker \((0.4-1.8\ X_0)\)
The detector
sub-structures of the full-silicon CMS tracker

- Pixels (barrel and disks)
- Tracker Inner Barrel & Disks (TIB & TID)
- Tracker Outer Barrel (TOB)
- Tracker End-caps (TEC)
The detector
sub-structures of the full-silicon CMS tracker

Endcaps
- 2 x 2 layers
- 672 modules
- $|z| = 34.5 / 46.5 \text{ cm}$
- Pixel size $100\mu\text{m} \times 150\mu\text{m}$
- 18 M pixels
- Tilted for Lorentz angle

Barrel
- 3 layers
- 768 modules
- $R = 4.4 / 7.3 / 10.2 \text{ cm}$
- Pixel size $100\mu\text{m} \times 150\mu\text{m}$
- 48 M pixels
- Lorentz angle 23°

Talk by Hans-Christian:
http://indico.cern.ch/contributionDisplay.py?contribId=7&sessionId=6&confId=30356
Strip lengths range from \(\sim 10 \text{ cm}\) in the inner layers to \(\sim 20 \text{ cm}\) in the outer layers.

Strip pitches range from \(80 \mu\text{m}\) in the inner layers to near \(200 \mu\text{m}\) in the outer ones.
material crossed by a primary track increases for a geometrical effect: \[ l = \frac{h}{\sin(\theta)} \]

most of the services are concentrated in this “barrel-endcap transition region”.

Path where many of the cables, fibers and services are.

Material is up to 1.8 radiation lengths
Because of inelastic nuclear interactions, many primary charged pions are detected only on the few innermost layers of the tracker: such particles can be reconstructed only as short tracks.
Strip and pixel signals are clustered. Positions and corresponding error matrices of each “hit” are evaluated.

Initial estimate of trajectory parameters from a small subset of tracker measurements (hits on seeding layers).

An iterative process which collects all the measurements associated to the same charged particle.

Estimate of final track parameters from the fit of the full set of measurements associated to the same charged particle.

Removal of “ghost” tracks + quality filter.
Two different general purpose tracking algorithms are currently implemented:

1. **Combinatorial Track Finder (CTF) is the default one:**
   - The seeding uses **innermost tracker’s layers**.
   - The pattern recognition uses a *track-following approach*: every time a new hit is associated to the track candidate, the parameters of the “partially reconstructed” trajectory are re-evaluated and the search window on the next tracker layer is narrowed, according to the smaller uncertainty on the track parameters themselves.
   - The final set of hits is fitted using a Kalman-Filter fitting/smoothing logic.

2. **Road Search (RS):**
   - The seeding is based on hits from modules on **inner and outer layers** of the tracker.
   - The pattern recognition initially uses a set of pre-calculated trajectory’s *roads* to collect *clouds* of hits along the direction of the seed. The final set of compatible hits is then obtained after a subsequent cleaning of the hits collection.
   - The final fit is identical to the one used by the CTF algorithm.
Tracking modules in CMS software

- hit collection
- seeds collection
- track candidates collection
- final tracks collection

Local Reconstruction

execution time

- hit creation
- pixel and strip clustering

seed finding

- hit collection
- seed finding

pattern recognition

- hit collection
- seeds collection
- track candidates collection

final fit

- hit collection
- seeds collection
- track candidates collection
- final tracks collection

module output

reconstruction modules

shared reconstruction "services"

- hit compatibility estimator
- trajectory updator
- track parameters propagator
- ..................
- Recent efforts to maximize the efficiency at high $\eta$: new seeder combining pixel and strip hits.
- Work in progress to fix remaining efficiency hole at $\eta \sim 0$.

- Because of inelastic nuclear interactions, around 10% of pions cannot be reconstructed: # available measurements < 3.
Resolution on transverse impact parameter is expected to be:

~50-60 microns for ~1 GeV particles

~10 microns for 100 GeV particles
In the barrel region, the resolution on transverse momentum is $\sim0.5\%$ for particles with $P_t = 10-100$ GeV.

In the high $\eta$ regions of endcaps, the resolution on transverse momentum degrades to $\sim3\%$ because of the smaller lever arm used to evaluate the curvature of the tracks.
Track reconstruction performance

- reconstruction efficiency on multi-track events is dominated by pion reconstruction efficiency
- efficiency is lower in the barrel-endcap transition region (eta ~1.5) where the material budget has its maximum value.
Track reconstruction performance

Fake rate = \( \frac{(# \text{ tracks NOT associated to simulation})}{(# \text{ reconstructed tracks})} \)

A reconstructed track is associated to a simulated one if more than 75% of its hits are “matched” to the ones of the simTrack.

Most of the fakes are in:
- the low pt region
- barrel-endcap transition eta region
Timing optimization

Migration from CLHEP to Root matrix package + code profiling/optimization

new seed generator: ~same time, despite +65% reconstructed tracks

code profiling/re-optimization

More sophisticated reconstruction

all measurement done with:
- BJets_Pt_50-120 sample w/o PU
- 2.0 GHz E5335 Intel processor
- code compiled with gcc345
Iterative tracking

- around 10% of all trajectory seeds have to pass a loose primary vertex compatibility selection.

- short and low pt track candidates are accepted only if they pass a tight set of cuts on primary vertex compatibility.

- No vertex compatibility request for “many-hits” track candidates.

- Only luminous region compatibility for all trajectory seeds: no cut on primary vertex compatibility.

- loosen primary vertex compatibility cuts are allowed for track candidates.

Initial hits collection

First track collection

2nd hits collection

Second track collection

Final track collection

- up to 30-40% of innermost (pixel) hits are removed from the initial hit collection.

- The hit removal is flexible: only hits which are fully compatible with the reconstructed tracks are removed.
Iterative tracking
recovery of low pt particles

- +3-5% of tracks are recovered in the Pt > 1 GeV region thanks to the looser vertex compatibility cuts for seeds and short track candidates of the 2nd and 3rd iterations.
- up to +40% tracks in the pt < 0.5 GeV region are recovered thanks to the much looser vertex compatibility cuts for low pt tracks.
Runge-Kutta propagator  
reduction of bias on reconstructed \( pt \)

In the tracker endcaps the magnetic field cannot be considered homogeneous between 2 consecutive tracker layers.

A track parameters propagator based on Runge-Kutta methods takes into account magnetic field non-homogenity during the final fit of tracks.

Bias on reconstructed \( Pt \) is reduced from 1% to less than 0.1%
Other improvements to final track fit

- reconstruction software is using now a more accurate parameterization of material budget
- better handling of magnetic field non-homogenities (Runge-Kutta propagator)
- more advanced “cluster parameter estimator” for pixels (templates based)
- rejection tool for “outlier hits”

QCD 80-120 sample

average $\chi^2$/ndf vs $|\eta|$ before and after corrections

Talk by Vincenzo for pixel Templates:
CMS Tracker commissioning
at the Tracker Integration Facility

• **Opportunities**
  – First large-scale common test of all the strip sub-detectors.
  – A wealth of data:
    • More than 4 M “good“ events at different readout settings, temperatures and trigger configurations
  – Taken in conditions close to the final ones
  – Allowed for verification of HW, SW and calibration procedures

• **Challenges**
  – Cosmics on surface: weak constraints and low momentum
  – Code needed to be adapted: trigger conditions, partial readout of the tracker, no momentum measurement.
CMS Tracker commissioning
at the Tracker Integration Facility

Lead shield  Scintillators
CMS Tracker commissioning at the Tracker Integration Facility

3 reconstruction algorithms used for cosmic data taking:
- CTF with seeder for cosmic
- RS with seeder for cosmic
- Cosmic Track Finder (CosmicTF): ad-hoc algorithm for cosmic tracks

Result of the 3 algorithms were comparable.

Opportunity to debug and improve (80% of) the standard track reconstruction sequence ON REAL DATA
Hit efficiency

- Checks for hits if the (unbiased) track prediction is well within the fiducial area of a module
- Shows (fortunately!) the obvious result: very high and stable efficiency
CMS Tracker commissioning at P5

- almost complete silicon strip Tracker system has been readout simultaneously:
  - 97% TIB/TID/TOB
  - 95% TEC+

- ~200k cosmic tracks have been reconstructed and being used for alignment

- 81% TEC- readout separately

- Pixel detector being inserted during these days
Conclusions

- CMS tracker has been designed to cope with LHC conditions of radiation and track multiplicity.

- The material budget of the CMS tracking system is a challenge for track reconstruction concerning with efficiency and fake rate.

- The reconstruction software of CMS has been designed to:
  - be modularized and flexible
  - cope with “not negligible” tracker material budget

- Recent extensions of the tracking algorithms have increased the track efficiency (in particular at low pt), improved the quality of the reconstructed tracks and sensibly decreased the execution timing.

- Most of the offline tracking modules have been successfully used to reconstruct millions of cosmic tracks at TIF and P5.