Status of software for track reconstruction in CMS

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on behalf of the Tracker DPG - Tracking group
Overview

Physics requirements and experimental challenges

The detector

Track reconstruction

• algorithm for general purpose tracking
• progresses and recent developments

Conclusions & Outlook
Physics requirements

**Highly efficient track reconstruction & low fake-track rate**

**Excellent momentum resolution**
- Mass reconstruction
- Energy flow
- Charge identification

**Excellent impact parameter resolution**
- Primary vertex reconstruction & separation of pileup vertices
- Secondary vertex reconstruction
- Heavy flavor tagging

**Combined reconstruction**
- Link to ECAL and Muon system for leptons identification and reconstruction
The challenges

pp-collisions at design luminosity ($10^{34}$ cm$^{-2}$s$^{-1}$, 14TeV)

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

Charged track density

- $2.5 / \text{cm}^2 / 25\text{ns}$ at $r = 4\text{cm}$

Trigger

- Level 1:
  Design rate 100kHz, no tracker
- Levels 2-3 (HLT):
  Reduction to $\sim 200\text{Hz}$
  Includes track reconstruction

Less demanding conditions during initial LHC running @ $10^{30}$-$10^{32}$cm$^{-2}$s$^{-1}$:

- PU: $\sim O(1-4)$ events/ crossing
- crossing rate: $< 1$ MHz

Higgs $\rightarrow$ ee $\mu\mu$ event with "Low Luminosity" PU
what special about CMS tracker:

- very high granularity (low occupancy even at High Luminosity)
- high resolution
- radiation hardness
- a lot of material

This “feature” has necessarily driven the design of the track reconstruction algorithms
The challenges

- **issue for general track reconstruction**: multiple scattering effects cannot be neglected.
- **issue for hadrons reconstruction**: particles can interact in-elastically after crossing few tracker layers. Therefore many of them can be reconstructed only as short tracks.
- **issue for electrons reconstruction**: bremsstrahlung radiation is massive and it needs a special handling.
- **general worry**: every time the previous two material budget plots are updated with a more accurate description of the tracker, the y axis range increases.

more dangerous: it kills tracks!
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 $80 \text{ µm}$ in the inner layers to near $200 \text{ µm}$ in the outer ones.
general purpose tracking

logical modularization

- hit reconstruction:
  strip and pixel signals are grouped (clustering) and finally hit positions and corresponding error matrices are evaluated.

- reconstruction of tracks:
  1) seed finding: a fast and rough estimate of the track’s parameters (+ errors) is obtained from a minimal amount of information.
  2) pattern recognition: an iterative process which, starting from the seed’s parameters, collects in the tracker all the hits which are compatible with a unique track.
  3) final fit: the positions of all the hits associated to the same charged particle are used to provide the best estimate of the track parameters and the corresponding errors.
Combinatorial Track Finder (CTF) is the default tracking algorithm for CMS

- **the seeding** uses measurements on the innermost tracker’s layers (whole pixel detector + some silicon sensors at high eta region). The in-out reconstruction has been chosen to not preclude reconstruction of inelastically interacting particles which don’t reach the outermost layers of the tracker.

- **the pattern recognition** is an iterative process based on a track-following approach which proceeds layer-by-layer: every time a new hit is associated to the track, the parameters of the partially reconstructed trajectory are re-evaluated and the search window on the next tracker layer is narrowed.

In order to maximize efficiency and not bias the reconstruction, **all the trajectories are built in parallel and there is not hit-removal**. Different track candidates can share one or more hits.

Ambiguities are resolved only after all the trajectories are built. A **trajectory cleaner** module is devoted to this operation.
- **the final fit** is based on Kalman filter + smoother technology.

This approach is indicated to properly handle multiple scattering effects and generally guarantees a precise estimate of track parameters for both the *innermost and the outermost state*.

The innermost state gives the parameters of the charged particle at the production vertex and has a clear impact on the physics: e.g. calculation of invariant masses from decay products.

The outermost state connects the trajectory reconstructed in the tracker with the other outer detectors of CMS. It is clearly important for electron and muon identification and for Energy flow.

There is an **alternative tracking algorithm developed at FERMILAB (Road Search)** which has similar reconstruction performance respect to CTF, but generally worse timing performance on complex multi-track events.

Rest of the talk will concentrate on the default tracking algorithm of CMS.
During 2006 and part of 2007, most of the efforts of the tracking group have been devoted to the porting of the tracking code from the previous software framework of CMS (the one used for the Physics TDR) to the current one (CMSSW):

- All the relevant features which were available have been ported. Many more have been added:

- The code has been modularized even more than it was in the past.

- The performance in terms of speed and resolutions are equal or better than before

**Very few exceptions:** particular performance degraded after the porting, but they will be fixed soon.
general purpose tracking
performance in CMSSW_1_6_0

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- Efficiency close to 99% up to |eta| = 2.0 for muons
- Pt resolution between 0.5% and 2% up to |eta| = 2
- Resolution on impact parameter around 10-100 microns

CTF tracking initiated by pixel/strip seeding

New respect to PTDR
general purpose tracking
performance in CMSSW_1_6_0

Pion (in-)efficiency reflects on general track
reconstruction efficiency in realistic multi-track events.

Most of the charged particles are pions indeed.
fake rate

Applying just a selection based on the minimum number of hits, the fraction of fake tracks is around 1% of the total number of tracks.

Accepting shorter tracks, the global reconstruction efficiency increases, but the fake rate increases as well.

**PTDR selection cut applied:** number of hits >= 8

\[
\text{fake rate} = \frac{\text{number of reconstructed tracks "not corresponding" to real charged particles}}{\text{total number of reconstructed tracks}}
\]
general purpose tracking
producer’s tracks selection

If a track is lost in the track producer, it is lost forever

Because tracking users can only filter the collection of tracks returned by the track producer, a very loose selection is applied by the producer itself:

- minimum number of hits is 5
- no cuts on the total chi2 of the tracks
- no primary vertex compatibility requested (only beam spot compatibility)
3 most important facts to know about track producer:

1) Users of the tracks collection (e.g. physics analysis or dependent reconstruction modules) have to be aware that the collection returned by the CTF producer is intended to maximize efficiency, in spite of minimize fake.

2) The proper trade-off between fake rate and efficiency has to be tuned according to the specific physics channels under investigation.

3) The track group can suggest a general purpose selection by means of an additional module external to the track producer (e.g. RecoTracker/FinalTrackSelectors), but will not force such a selection into the track producer module itself.
Recent studies (performed across tracking and particle flow groups) indicate that requesting the compatibility with the primary vertex and loosening the cut on the minimum number of hits, gives the same fake rate as in the PTDR together with a 10% higher reconstruction efficiency.

According to the same studies, the fake rate can be further reduced running the CTF algorithm iteratively and removing the hits associated to reconstructed tracks after each iteration. Such an approach may be included in the standard reconstruction sequence after the necessary validation (not yet planned for 1_8_0).
Recent progresses
use of Condition DB with tracker modules status

“Good” real tracks: they produce hits on each layer they cross (in a fully efficient tracker)

Fake track candidate: usually a set of accidentally aligned hits.

Lost hits are a clear signature for fake tracks.

If a track candidate has more than one lost hit, CTF producer rejects it.

Most powerful selection to kill fakes.
A good real track can have 2 or even more lost hits if it crosses 2 or more bad modules. This kind of track should be reconstructed and cannot be rejected: it is not a fake track!

CTF trajectory builder has been adapted to query condition DB information in order to exploit the knowledge on the status of tracker modules and not reject such kind of “good” tracks.

New respect to PTDR
During HLT the tracking has to be fast and **only one hit per tracker’s layer** per track is collected.

Nevertheless, during offline reconstruction, the full available information has to be exploited. So, a special trajectory builder for CTF has been developed to recover additional hits inside the regions of a layer where 2 or more tracker’s sensors overlap.

The **final hit collection efficiency** is therefore increased.

**Recent progresses**

**new CTF trajectory builder in CMSSW_1_7_0**

Since CMSSW_1_7_0, the new builder is the **default one for offline track reconstruction**
Recent progresses
more accurate transverse momentum reconstruction

More accurate propagator of track parameters (which is based on Runge-Kutta method) takes better into account the magnetic field inhomogeneities during the final fit of tracks.

1.0-1.5% bias in the reconstructed transverse momentum is almost completely removed

Available in 1_6_X and 1_7_0 releases, but it has not activated by default yet.

Target to be the default fitter for 1_8_0 release
Open issue after porting material budget description and cluster position error parametrization

To be fair, let’s show also some performance which degraded respect to PTDR: normalized chiSquared of final fitted reconstructed tracks

- material description used during reconstruction has been re-written for 1_7_0
- use of cluster parameter errors by the track fitter is under review

Expected to return to the old (or even better) performance in time for CMSSW_1_8_0.
Conclusions & Outlook

• The original CMS tracking algorithm (CTF) and a new one (RS) have been successfully ported/implemented inside the new software framework of CMS.

• The tracking code is highly modularized in order to:
  - facilitate the interaction with the rest of the reconstruction code
  - share common resources and facilitate debugging/maintaining of the code

• The collection of tracks returned by the producer is intended to maximize efficiency in spite of minimize fake rate. Physics analysis has to take into account this and perform the necessary actions.

• Important improvements to the track reconstruction algorithm have been added recently. New changes are planned for the coming 1_8_0 release and next ones.

• All results shown have been the product of an (intercontinental) collaboration.

Some important recent developments have been not shown because of lack of space. People interested in all the major activities of the tracking group can have a look at the group web page (under development as well):

https://twiki.cern.ch/twiki/bin/view/CMS/TrackerDpgTracking
special tracking and interaction with other reconstruction modules

**Specific seed generators**

- tracking without pixels: default solution for the run without pixel data and backup solution for the physics run

- tracking for cosmic muon: tested on real data during integration tests of the CMS tracker (no B-Field)

  seer: [http://indico.cern.ch/contributionDisplay.py?contribId=264&sessionId=21&confId=3580](http://indico.cern.ch/contributionDisplay.py?contribId=264&sessionId=21&confId=3580)

- tracking for alignment of the tracker with cosmic and beam-halo muon tracks.

**CTF regional seed generator module**

- regional tracking for Trigger reconstruction

CTF regional seed generator module + rest of the CTF tracking sequence
Service for track parameters propagation with electron mass hypothesis

+ Final fit module based on a *Guassian Sum Filter*

(it takes properly into account bremsstrahlung and subsequent kinks in the electron’s trajectory)

+ rest of the CTF tracking sequence

see:
http://indico.cern.ch/contributionDisplay.py?contribId=193&sessionId=21&confId=3580
BACKUP SLIDES
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)

volume 24.4 m³
~ 10 millions of read-out channels only for silicon strip sub-detector
**BACKUP SLIDES**

**the reconstruction sequence implementation**

- **hit collection**
  - pixel and strip clustering

- **seed finding**
  - hit creation
  - RS SeedFinder

- **pattern recognition**
  - Global Mixed Seed Generator

- **final tracks collection**
  - RS Cloud Maker
  - RS Track Candidate Maker
  - Kalman-Filter final Fit

- **local reconstruction**

- **CTF**
  - CTF Track Candidate Maker

- **execution time**

- **reconstruction modules**
  - hit compatibility estimator
  - trajectory updator
  - track parameters propagator
  - ....................

- **shared reconstruction “services”**
  - hit compatibility estimator
  - trajectory updator
  - track parameters propagator
  - ....................

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Tracking Status – US CMS First Physics Workshop, October 2007  
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