Track reconstruction in CMS high luminosity environment

Christophe Goetzmann on behalf of CMS collaboration

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Outline

- The CMS silicon tracker
  - Pixel detectors
  - Microstrip detectors
- Hit reconstruction performances under LHC conditions
  - Pixel efficiency vs occupancy
  - Pixel resolution vs irradiation
- Track reconstruction in high occupancy environment
  - Track reconstruction steps
  - Iterative tracking
  - Algorithm optimization: gain in CPU time and efficiency
- Conclusions
The CMS tracker

100 % silicon tracker
- Pixel detectors close to interaction point
- Microstrip detectors in the outer parts

Largest silicon tracker ever built
- Radius: 110 cm / Length: 540 cm
- Barrel: 13 cylinders (3 pixels)
- Endcaps: 14 disks (2 pixels) on each side

Reconstruction of charged particles tracks
- Measure charge and transverse momentum.
- Estimate the positions of interaction vertices using tracks informations
The pixel detector

Pixel size: 100 x 150 μm²
Each Read Out Chip (ROC) reads 80x52 pixels

Hit reconstruction
- Pixels with a charge above a configurable threshold are considered.
- Adjacent pixels (sharing a side or a corner) are grouped into clusters.
- *Projected-clusters* are obtained by projecting pixels charges onto local \( u \) and \( v \) perpendicular axis.

**First-Pass reconstruction**
- *Fast*, used in track reconstruction
- *Charge-weighted mean* used to estimate \( u \) and \( v \) position, corrected in transverse direction to account for Lorentz drift

**Template-Based reconstruction**
- *More accurate*, used in track final fit
- Projected distributions are *compared* with templates obtained from simulation
- Account for *aging*, *crossing angle*
The microstrip detector

9,3 millions microstrips in 15148 modules.

Characteristics adapted to the different regions:
- Pitch: from 80 to 205 μm
- Thickness: 320 or 500 μm

Hit reconstruction
- Signal is read by analogic chips (128 channels by chip) and sent to an electronic table
- Channels with S/N > 2 are kept for hit reconstruction
- Selected microstrips are grouped into clusters.
- Position estimated by charge-weighted mean, corrected for Lorentz drift.

Stereo layers (2 in TIB, TIDs, and TOB and 3 in TECs) associate back to back 2 microstrip detectors with a relative 100 mrad angle, providing 2D resolution
The LHC conditions

Tracker performances are impacted by instantaneous and integrated luminosity

**Instantaneous luminosity**

Higher **occupancy** could cause inefficiencies. At maximum luminosity, average number of « pile-up » vertices is \( \sim 25 \).

**Integrated luminosity**

The level of radiation received over time affect the performances of the sensors. Especially for **inner pixel layers**.
**Hit efficiency**: probability to reconstruct a hit when a charged particle crosses a sensor

- Increase temperature in ROCs: charge gain is lowered (right plot)
- Higher probability of ROCs buffer overflow
- Higher probability of charged particles flipping bits in electronics

**Particle flux in pixel layer 1**: 
\[ \sim 30 \text{ M/s/cm}^2 \]
*At max 2012 luminosity*
**Pixel resolution vs irradiation**

**Pixel thresholds increase** with integrated luminosity, reducing cluster size and affecting resolutions. **Recalibrations** are performed during LHC technical stops.

* $r\phi$ resolution of $\sim 9 \mu m$ is maintained in pixel barrel through 2012 data taking
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Tracking algorithm is composed of 4 steps:
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  First estimation of track parameters from minimal number of hits (3 hits, or 2 hits and a vertex constraint)
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  Propagate seed through tracker (inside-out propagation)
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  *ex: normalized $\chi^2$, number of layers with good hits...*
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Iterative tracking

- The tracking algorithm is run in several successive iterations.
- Each iteration is defined by the configuration of seed generation.
- Once an iteration is over, all hits affected to a track are removed from the hit collection.
- Next iteration is then launched, on a reduced number of hits.

<table>
<thead>
<tr>
<th>#step</th>
<th>seed type</th>
<th>seed subdetectors</th>
<th>$P_T^{\text{min}}$ [GeV/c]</th>
<th>$d_0$ cut</th>
<th>$z_0$ cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>triplet</td>
<td>pixel</td>
<td>0.6</td>
<td>0.02 cm</td>
<td>4.0$\sigma$</td>
</tr>
<tr>
<td>1</td>
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<td>pixel</td>
<td>0.2</td>
<td>0.02 cm</td>
<td>4.0$\sigma$</td>
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<tr>
<td>2</td>
<td>pair</td>
<td>pixel</td>
<td>0.6</td>
<td>0.015 cm</td>
<td>0.09 cm</td>
</tr>
<tr>
<td>3</td>
<td>triplet</td>
<td>pixel</td>
<td>0.3</td>
<td>1.5 cm</td>
<td>2.5$\sigma$</td>
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<td>triplet</td>
<td>pixel/TIB/TID/TEC</td>
<td>0.5-0.6</td>
<td>1.5 cm</td>
<td>10.0 cm</td>
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<tr>
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<td>0.6</td>
<td>2.0 cm</td>
<td>10.0 cm</td>
</tr>
<tr>
<td>6</td>
<td>pair</td>
<td>TOB/TEC</td>
<td>0.6</td>
<td>2.0 cm</td>
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Characteristics of the different iterations after spring 2012 improvements campaign.
Iterative tracking

Fully configurable software: optimize iterative tracking for high luminosity

Baseline configuration

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<tr>
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<td>0.2 cm</td>
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<td>0.05 cm</td>
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<td>3</td>
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<td>pixel/TEB/TEC</td>
<td>0.25-0.35</td>
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<td>4</td>
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<td>TEB/TEB/TEC</td>
<td>0.5</td>
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Fall 2011 improvements

At 30 pile-up, optimization improves tracking CPU time by a factor 2.5
New iterations can be added to improve efficiency. Here 2 new iterations for muons:

- Outside-In tracking: seeds from muon chambers
- Inside-Out tracking: to re-reconstruct tracks tagged as muons, with looser requirements

Efficiency estimated via Tag and probe method: use muons chambers to select muons from $Z^0$ to $\mu\mu$ events.
Conclusions and Perspectives

- LHC run 1 lasted from 2010 to 2013

- The CMS tracker has maintained satisfying performances through 7 TeV and 8 TeV proton-proton collisions

- Robustness up to an average value of 25 pile-up vertices per event

- Luminosity will still increase: future upgrades
  - Phase 1 (2017): new pixel detector with 4 barrels and 3 disks.
Thank you for your attention
Backup slides
**Hit efficiencies**

**Hit efficiency**: probability to reconstruct a hit when a charged particle cross a sensor

Measured for each layer using well reconstructed tracks with hits on previous and next layer.

![Graphs showing hit efficiencies for Pixel and Microstips](image)

- **Pixel**: (bad modules excluded)
- **Microstips**

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Christophe Goetzmann  
TIPP Amsterdam – June 3, 2014
**Hit resolutions**

Hit resolutions are measured from residuals: differences between expected hit position (from track fit), and measured hit position (from hit reconstruction) on a given layer.

**Pixel, barrel, layer 2:**
- 9.4 μm in $r\phi$ (transverse plan)
- 20 to 46 μm in $z$

**Microstrip, barrel:**
- 10 to 42 μm in $r\phi$
- Resolution in $z$, from stereo layers, is typically 10 times larger
Pixel hit resolutions depends on the crossing angle of the incoming charged particle
Five parameter are needed to describe a track. A possible set is:

- $d_0$: Transverse impact parameter (signed)
- $z_0$: Longitudinal impact parameter
- $\phi$: track direction in transverse plane
- $\cot \theta$: angle between track and beam line
- $p_T$: transverse impulsion
Each iteration enables the reconstruction of tracks produced in different region of the tracker.

Contribution of the different iterations to tracking efficiency with respect to the radius of track origin.

Results are shown for a previous algorithm configuration (before fall 2011).
Iterative tracking

Once an iteration is over, hits associated to high quality tracks are masked, and the next iteration is run on a reduced number of hits.

![Graph showing fraction of unmasked hits across iterations](image-url)
Iterative tracking

The CPU time needed for each iteration is strongly pile-up dependent.

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Spring 2012
tracking configuration

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Tracking improvements

2011 improvements campaign:
- Iterative tracking
- Photon conversions
- Primary vertices
- Nuclear interactions
- Particle Flow links
Efficiency from Monte-Carlo studies

A track is considered as **efficiently reconstructed** if 75% of its hits come from the same generated charged particle. Otherwise it is considered as a « fake track »

2 types of Monte-Carlo events are used:
- **Single particle** events: only one isolated muon, electron or pion
- **High occupancy** events: $t\bar{t}$ events, with or without pile-up vertices

Efficiency from data

The information from muon chambers are used to select $Z^0$ to $\mu\mu$ events. Efficiency are then estimated with a « **Tag and Probe** » method.

Efficiency is the probability that the second muon was well reconstructed in tracker.
Efficiencies from Monte Carlo: $t\bar{t}$ events with and without pile-up (7 TeV conditions)

Number of pileup vertices is randomly generated from a Poisson distribution peaking at 8.
Tracking efficiency

Efficiency from Monte Carlo: isolated muons and pions

Efficiency as a function of the pseudo-rapidity $\eta$.  

![CMS Simulation](chart)

- Muons, $p_T = 1$ GeV
- Muons, $p_T = 10$ GeV
- Muons, $p_T = 100$ GeV

- Pions, $p_T = 1$ GeV
- Pions, $p_T = 10$ GeV
- Pions, $p_T = 100$ GeV
Tracking efficiency

Efficiency from 2011 data: estimated from muons

Tag and probe method: use muons chambers to select muons from $Z^0$ to $\mu\mu$ events.

Robust tracking efficiency under 2011 pile-up conditions
**Track resolutions**

**Resolutions from Monte Carlo**: isolated muons and pions

Obtained by comparing generated and reconstructed track parameters.

![Graph showing resolutions in transverse impact parameter as a function of η for muons and pions](image)

Resolutions in transverse impact parameter as a function of η. Obtained from half-width of an interval containing 68% (solid symbols) and 90% (open symbols) of residuals distribution.

~ 10 μm for 100 GeV particles
Track resolutions

Resolutions from Monte Carlo: \( t\bar{t} \) events with pile-up

About 20 \( \mu m \) for 100 GeV particles in central and transition regions

Minimum \( p_T \) resolution obtained in central region is 1.5 %