Track reconstruction performance in CMS

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• LHC Tracking Challenges & the CMS Tracker
• Track finding and fitting
• Material effects
• Performances with single tracks
• Dealing with combinatorial fake tracks
• Iterative tracking
• Conclusions
Tracking challenges @LHC

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

- 40 MHz crossing rate
- ~20 superimposed pileup events / crossing
- ~2000 charged tracks / crossing

**Very high Charged track density**

- 2.5 / cm$^2$ / 25ns at $r = 4\text{cm}$
- 0.01 / cm$^2$ / 25ns at $r = 110\text{cm}$

**Inner Tracker must be**

- Highly granular
- Radiation hard
Tracking challenges @LHC

Track reconstruction

• High efficiency and low fake rate
• Excellent momentum resolution

(mass reconstruction, charge separation)

need:
1) large level arm L
2) large B field,
3) many independent measurements N
4) good detector resolution σ

• Excellent extrapolated resolution at the interaction region

(secondary vertex reconstruction, pile-up discrimination )

CMS Trigger

• Level 1
  » Design rate 100kHz, no tracker

• Levels 2-3: HLT
  » Reduction to 300Hz
    Includes (partial) track reconstruction
The CMS Tracker

Over 200 m² of silicon sensors. Strip lengths 10-20 cm. Strip pitches 80-200 μm. 60 Million pixels & 10 Million Silicon Strips

- TOB: 6 layers 5208 rect modules
- TIB: 4 layers 2724 rect modules
- TEC: 2X9 Disks 6400 wedge modules
- TID: 2X3 Disks 816 wedge modules

Single $r\phi$ sensor
Double $r\phi z$ sensor
A big Tracker with a lot of Silicon, electronics, services and support structures makes a lot of material.

The material seen by a track grows as a function of $\eta$ for geometrical reasons, and even more in the barrel-endcap transition region where a lot of services are concentrated.

Material reaches a maximum of 1.8 radiation lengths at $\eta\sim15$

Radiation lengths $\sim1.8X_0$
Nuclear interaction lengths $\sim0.8\lambda_0$

Effects on charged particles: radiation emission ($e^\pm$) & nuclear interactions ($\pi,K,p$)
A considerable fraction of pions sustain nuclear interactions while crossing the tracker material and only the initial (shorter) part of these charged tracks can be reconstructed.
The CMS track reconstruction is initiated by a **seeding in the innermost tracker layers**: both pixel and silicon strip hits.

Seeds are **compatible with the beam interaction region** and with a minimum track $p_T$.

Even if the track density is higher in the inner tracker layers the pixel hits are particularly useful since they carry full 3-D information, with a **low occupancy**.

The efficiency at high eta is maximized thanks to the bigger geometrical acceptance of the strip sub-detector.
Track Finding

The standard CMS track finding uses a **Combinatorial Kalman Filter** (CKF) approach. (see G. Cerati’s talk for alternative CMS track finding algorithms)

The Kalman filter is a statistically optimal refinement of **track following**

The Kalman Filter consists of a succession of alternating **prediction** and **filter** steps:

The progressive **track fitting works simultaneously with track finding**

Accuracy on the track state estimate increases after each new measurement is added
Trajectory fitting

Final estimate of the 5 track parameters from the fit of the set of measurements associated to the same particle as found with the CKF track finding procedure.

The track has to be known with the best precision near the interaction vertex.

The trajectory is refitted using a least-squares fit in two stages.

- **inside-out** forward fit removes approximations and biases of the finding stage

- **outside-in** smoother fit yields the final best estimates of the track parameters at the origin vertex
Because of nuclear interactions, 5-10% of single pions yield less than 3 measurements on the tracker layers and can’t be reconstructed.

For single muons the efficiency is close to 100% over the whole Tracker acceptance range.

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P. Azzurri - CMS Track Reconstruction
Momentum resolution on single tracks

In the central region the pT resolution is better than 1% for single muons with pT ≤ 10 GeV.

For larger |η| values the resolution worsens due to:
• Material effects
• Reduced lever arm
• Lower hit resolution
Vertex resolution
on single tracks

Resolutions on transverse impact parameter and longitudinal position at the point of closest approach to the beam line
Fake Tracks

In the case of more typical and dense LHC events with jets the standard CMS CKF track finder yields a significant fraction of fake reconstructed tracks (not associated to any real track).

In the case of short tracks that have crossed few layers (<7) the fake rate fraction is extremely large, up to 95% of all reconstructed tracks.

For long tracks that have crossed many layers the natural fake rates is very low, at the 0.1% level.
Rejection of fake tracks

The fake rate can be effectively reduced by applying quality cuts that keep only tracks with a good fit-$\chi^2$ and a good compatibility with the event interaction vertices.

Quality Cuts are applied on

- The track transverse compatibility with the beam line (using $d_0$, $\delta d_0$)
- The track longitudinal compatibility with the interaction vertices (using $\Delta z_i$, $\delta \Delta z_i$)
- The track fit-$\chi^2$ probability
Rejection of fake tracks

The **optimal** way to bring down the fake rate to an overall low level is to **adapt the cuts to the track** $p_T$, $\eta$ and mostly to the **number of hits**.

Basically **no quality cuts are needed for tracks with many hits** (≥10 crossed layers).

For track **with fewer hits progressively harder quality cuts are needed**, adapted to the **expected and measured resolutions** on the quality variables.

Fake rate remains higher in the **low $p_T$ region**.
Iterative tracking

An improvement is obtained with an iterative procedure so to perform the track reconstruction in stages, running different times the CKF reconstruction.

Initial hit collection

First CKF iteration

High purity filter

First track collection

Hit removal

Second hit collection

First CKF iteration

Second step filter

Second track collection

(higher fake rate level)

At each stage only hits which are fully compatible with the reconstructed tracks are removed.
Iterative tracking

Results with three iterations

The iterative procedure allows a better reconstruction and selection of short tracks with $p_T \leq 0.5$ GeV/c. It is now in the default CMS track reconstruction procedure.
Pile up effects

Low luminosity pile-up: small loss of efficiency with a visible rise in the fake rate.
Advanced tracking for electrons

To deal with possible bremsstrahlung emissions for \(e^\pm\) traversing the tracker material a minimal extension of the KF based on the sum of Gaussian components is used.

The Gaussian Sum Filter (GSF) resembles several Kalman Filters in parallel.

It is very CPU intensive and can be applied only to pre-selected tracks improving mean, resolution and residuals of the fit.
Conclusions

Track reconstruction at the LHC is a tough business.
CMS has the largest silicon Tracker ever built, with a 3.8 T inner field.

In an average dense LHC event, the charged particles interactions in the Tracker material complicate the track finding decreasing the finding efficiency and inflating the combinatorial fake rate.

Recent improvements with an optimal rejection of fake tracks and using an iterative tracking procedure allow to efficiently reconstruct tracks with pT down to 300 MeV/c and with as few as 3 crossed layers, with a fake fraction at the ~1% level.

Further development on alternative and complementary track reconstruction approaches is underway (outside-in track finding, ...), as well as work to improve track reconstruction efficiencies in critical situations (e.g. in the core of high p_T jets)

Stay tuned for Giuseppe’s talk on first CMS tracking results with real data