Tracking, alignment and b-tagging performance and prospects in CMS

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on behalf on the CMS Collaboration

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Reconstruction of charged particle trajectories is a key ingredient of reconstructing the full event.

High efficiency and precision are mandatory to ensure overall performance of the experiment.

Contingent on good performance and alignment of the tracking detectors.

Identification of b-quark jets is crucial for the CMS physics programme and depends on optimal tracking performance.

CMS upgraded its pixel detector in 2017.

Additional layer improves track impact parameter resolution and vertexing performance, helpful especially for b-tagging.
Possible displacements and rotations of detector modules much larger than intrinsic hit position resolution on the sensor

Corrected for by track-based tracker alignment in two complementary approaches

- Simultaneously fit all track and alignment parameters in a global approach (MillePede II)
- Local fits, handling the correlations iteratively (HipPy)

Both are used to validate each other and best performing results is used in the event reconstruction

Needed to align the new pixel detector quickly in 2017 to ensure good detector performance from the start

Achieved using both cosmic ray data at 0 T and 3.8 T, as well as tracks from the first collision data
2017 Tracker Alignment Performance

- 2017 startup alignment derived on 0 T cosmic ray data
- Performed in two steps:
  - 1.: only the high level (HL) structures of the new pixel are considered
  - 2.: alignment is performed on module level (ML)

Track hit residuals show significant improvement in performance, correcting the overall offset and improving the resolution

CMS DP-2017/055
Alignment was updated with 3.8 T cosmic ray events
Updated again with tracks from collision data
Much larger track sample
Helps especially in FPix which is not illuminated well by cosmic ray tracks

With the final alignment the track hit residuals are significantly improved again, reaching a precision better than the intrinsic hit resolution of the detector
2017 Tracker Alignment Performance

- Alignment performance is monitored by studying higher level quantities.
- Biases in the alignment are visible in the mean track impact parameter, mostly cured by the final alignment.
- Using millions of Z boson events where the mass constraint can be used allows to control systematic deformation in the detector.

With this alignment, very good performance was achieved.

The same procedure of subsequently improving alignments has been applied successfully in the 2018 data taking.
Iterative Tracking in CMS

- Tracks are reconstructed iteratively to deal with the large combinatorial puzzle
  - Start with very tight criteria for track seeds and reconstruct tracks
  - Clear the detector of already used hits
  - Loosen the seed criteria and repeat

Tracking efficiency > 90% for $p_T > 1$ GeV

[Graphs showing tracking efficiency and vertex radius for different track conditions]

https://twiki.cern.ch/twiki/bin/view/CMSPublic/TrackingPOGPerformance2017MC

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Improvements in 2017

- Tracking seeded mostly by pixel hits → Update needed with new pixel detector
  - Pixel seeds found using Cellular Automaton technique
  - Hit pairs are formed between detector layers
  - Pair compatibility w.r.t. the interaction point is checked
  - Hit triplets or quadruplets used for seeing formed from compatible pairs

https://twiki.cern.ch/twiki/bin/view/CMSPublic/TrackingPOGPerformance2017MC

- Significantly improved efficiency and fake rate
Improvements in 2017 - Timing

- With the additional layers, conventional seed finding in the pixel detector would have significantly slowed down track seeding
- Use of CA reduces timing back to or below the 2016 performance
- Reduction in fake rate leads to reduction of time spent on pattern recognition, independent of seed algorithm

https://twiki.cern.ch/twiki/bin/view/CMSPublic/TrackingPOGPerformance2017MC
Future Tracking

- CMS will upgrade its tracking detectors in LS 3
- Major improvements, such as extending coverage to $|\eta|$ of 4, track triggering at the Level 1 trigger

- Development of tracking algorithm for the upgrade are in full swing
- Many further algorithmic improvements planned, but estimated performance already very good
- Same efficiency at PU 140 as with PU 35 in current setup
- Significantly improved resolution for key track properties
B-Tagging in CMS

- Identification of jets originating from heavy flavor quarks is essential for the CMS physics programme
- CMS has developed several algorithms over the years, using more sophisticated techniques to improve performance
- Two algorithms currently used for analysis:
  - **CSVv2** uses an artificial neural network to combine track and vertex information
  - **DeepCSV** Uses the same variables as CSV, but uses more tracks and a deep neural network to increase performance

DeepCSV currently gives 4% efficiency gain at 1% mis-tag rate
Impact of the Phase-I Pixel upgrade

- Upgrade of the pixel detector in 2017 improved track impact parameter resolution and vertexing
- Especially important for b-tagging performance
- Performance improvement illustrated for the example of DeepCSV
- Significant improvement out of the box
- Further small improvement with retraining of the neural network

- 7-8% better efficiency at 1% mis-tag rate
Future b-tagging developments

- Further developments on improved b-taggers ongoing
- DeepFlavour algorithm currently being commissioned
  - Includes more information from more tracks, neutral particle candidates and vertices are used to train a more complex deep neural network
- Further improves performance compared to DeepCSV
- Especially prominent gains for high $p_T$ jets

4% better efficiency at 1% mis-tag rate for low $p_T$ jets, about 20% at very high $p_T$
Summary

▶ Tracks and track-derived quantities are essential for the success of the CMS physics programme
▶ Depends on the performance of the detector as well as the algorithms used in the event reconstruction
▶ Good performance of the CMS tracking detectors, aligned by well established methods
▶ Tracking in CMS profits significantly from the Phase-I pixel detector upgrade and shows very good performance
▶ Running basically unchanged in 2018, with some added protection for potential detector issues
▶ Developments to make use of the Phase-II tracking detector in a very high PU environment well under way
▶ CMS b-tagging performance steadily improving, profiting both from the new pixel detector as well as constant algorithmically improvements