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Track reconstruction in CMS high luminosity environment

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Abstract

The CMS tracker is the largest silicon detector ever built, covering 200 square meters and providing an average of 14 high-precision measurements per track. Tracking is essential for the reconstruction of objects like jets, muons, electrons and tau leptons starting from the raw data from the silicon pixel and strip detectors. Track reconstruction is widely used also at trigger level as it improves objects tagging and resolution. The CMS tracking code is organized in several levels, known as 'iterative steps', each optimized to reconstruct a class of particle trajectories, as the ones of particles originating from the primary vertex or displaced tracks from particles resulting from secondary vertices. Each iterative step consists of seeding, pattern recognition and fitting by a Kalman filter, and a final filtering and cleaning. Each subsequent step works on hits not yet associated to a reconstructed particle trajectory. The CMS tracking code is continuously evolving to make the reconstruction computing load compatible with the increasing instantaneous luminosity of LHC, resulting in a large number of primary vertices and tracks per bunch crossing. This is achieved by optimizing the iterative steps and by using new software techniques. Tracking algorithms used in CMS are described; physics and computing performances are discussed with respect to Run I and Run II physics program and within CMS future upgrades.

Keywords: Track reconstruction, Tracking detectors

1. Introduction

The CMS Tracker [1] is composed of a Pixel Silicon detector with three barrel layers at radii between 4.4 cm and 10.2 cm and two endcap disks at each end. The Silicon Strip Tracker covers the radial range between 20 cm and 110 cm around the LHC interaction point. The barrel region ($|z| < 110$ cm) is split into a Tracker Inner Barrel (TIB) made of four layers, and a Tracker Outer Barrel (TOB) made of six layers. The TIB is complemented by three Tracker Inner Disks per side (TID). The forward and backward regions ($120\,\text{cm} < |z| < 280\,\text{cm}$) are covered by nine Tracker End-Cap (TEC) disks per side Part of the strip tracker is equipped with special double-sided (stereo) modules made up of two sensors with strips at an angle of 100mrad able to provide accurate three-dimensional position measurement of the charged particle hits.

The tracking procedure consists of the following tasks [2]: first *seeds* are searched in the innermost layers; they are proto-tracks consisting of hit pairs (plus the primary vertex) or three hits; the primary vertices are known thanks to the pixel-based upstream algorithm; then the Kalman filter based inside-out pattern recognition follows (*trajectory building*) and the trajectories are fit also using a Kalman Filter (*fitting*). Outlier hits, if any, are rejected based on a compatibility test with the final track and the track is refitted; finally, tracks are selected according to quality criteria.

2. Iterative Tracking

The CMS efficient tracking relies on several iterations (steps) of the tracking procedure; each step works on the hits that in the previous steps have not been associated to

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Table 1: Relevant parameters of the seven tracking iterative steps in 2012; P_T^{min} is in GeV$/c$ and σ represents the beam spot size along the z axis and d_0 and z_0 are the transverse (i.e. in the xy plane) and longitudinal impact parameters, respectively.

#	seed type	P_T^{min}	d_0 cut	z_0 cut
0	pixel triplet	0.6	0.03 cm	4.0σ
1	pixel triplet	0.2	0.03 cm	4.0σ
2	pixel pair	0.6	0.01 cm	0.09 cm
3	pixel triplet	0.2	1.0 cm	4.0σ
4	pixel+strip triplet	0.35-0.5	2.0 cm	10.0 cm
5	strip pair	0.6	2.0 cm	10.0 cm
6	strip pair	0.6	2.0 cm	30.0 cm

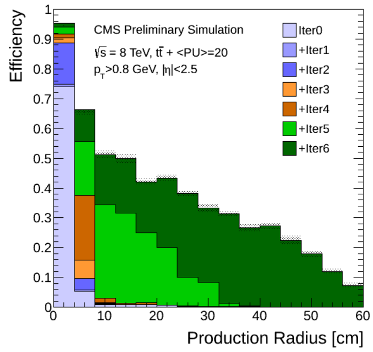

Figure 2: Efficiency as a function of the track production radius for the various iteration steps.

highest quality tracks. Specific steps can be introduced for speciality tracking (muons, electrons, jets).

The iterative tracking steps are configured to be complementary with respect to the subdetectors used for seeding and with respect to the track transverse momentum P_T and to the production vertex radius. The configuration used in 2012 is summarized in Table 1. Figure 1 and 2 show the complementarity of the different steps with respect to P_T and the production radius, respectively. Figures 3 and 4 show the tracking efficiency and the fake rate for simulated $t\bar{t}$ events as a function of the pseudorapidity η and demonstrate the excellent iterative tracking performance.

3. Outlook for Run II and beyond

The tracking algorithms are tuned to give the best performances within the limited computing resources allotted for reconstruction. Tracking occupies the largest chunk of CMS computing resources and needs to be continuously adapted for the increasing instantaneous luminosity of LHC. Run II, starting in 2015, makes no exception. In Run I the maximum pile-up (PU) was ∼20 events per bunch crossings but a PU up to 45 is expected for Run II. Moreover LHC will change bunch crossing frequency from 50 to 25ns yielding to hits due to out-of-time PU (+5% in pixel detector and +45% in silicon detector) thus largely affecting the combinatorial problem behind the track building with a factor two increase either in timing and fake rate. As visible in Fig. 5, the concept of iterative tracking (i.e. progressive removal of hits attached to tracks) is less evident for outermost and less granular detectors. In addition the number of ghost hits intrinsically generated by the strip stereo modules do increase with larger PU.

The above described phenomena, mainly affecting the strips detector, have an important impact on tracking with large PU since the pixel detector suffers a dynamic inefficiency that increases with the instantaneous luminosity. This yields to a less effective pixel based seeding that results in an enlarged load on strip based iterative steps that are intrinsically less accurate (larger search windows in building) and prone to combinatoric.

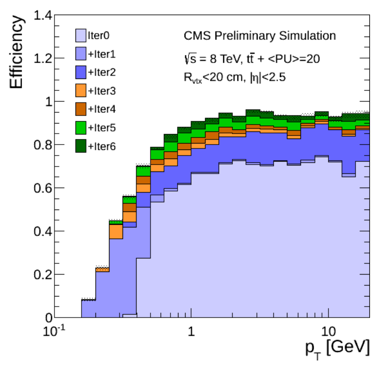

Figure 1: Efficiency as a function of P_T for the various iteration steps.

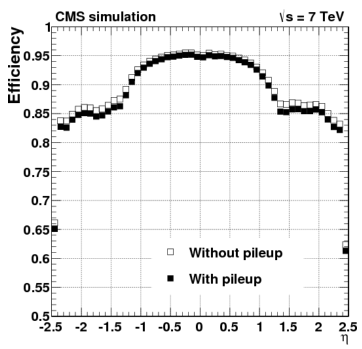

Figure 3: Tracking efficiency for simulated $t\bar{t}$ events as a function of the pseudorapidity η with and without a pile-up of 8 interactions.

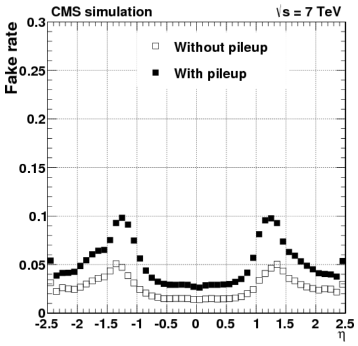

Figure 4: Rate of fake tracks for simulated $t\bar{t}$ events as a function of the pseudorapidity η with and without a pile-up of 8 interactions.

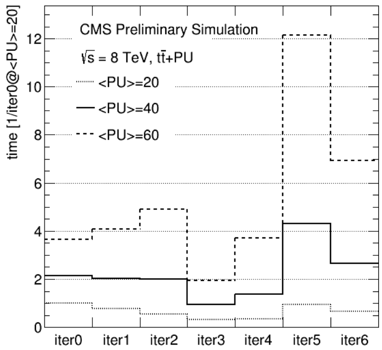

Figure 6: Absolute timing (in arbitrary units) per iteration step for various PU scenarios.

This is clearly visible in the tracking timing at different PU as shown in Fig. 6. The effect of PU is dramatic on iterations seeded by pairs of strip hits (iter#5 and #6), still problematic for steps seeded by pixel pairs (iter#2) and mixed triplets (iter#4). Pixel triplet seeded steps (iter#0, #1, #3) show an healthy behavior with respect to PU. This analysis clearly shows where to act to make CMS tracking more robust for high luminosity and, to get ready for Run II, the tracking is undergoing an extended optimization based on several actions.

A new triplet seeding algorithm is being developed to replace iterations #5 and #6; it is based on a χ^2 cut from a straight line fit of three points in the rz plane and on tigther beam spot constraints; half of the seeds are generated but the same number of tracks are reconstructed. At PU 40, the total time reduction on tracking is $\sim 40\%$ without performance loss, thanks to a timing improvement on iterations #5 and #6 larger than a factor two.

Clusters from out-of-time PU have low collected charge since they are due to tracks (loopers) that ionize not in time with respect to the sampling window. Cutting on the cluster charge largely suppresses out-of-time PU hits. A cut on cluster charge to be applied upfront, during seeding or during pattern recognition is foreseen for Run II. The cut accounts for sensor thickness and local crossing angle on sensor and is designed to be P_T dependent to preserve discovery potential for fractional charge BSM particles. On the detector side, it requires stable performance to be ensured by introducing tracker gain calibration in the automatic calibration procedure (Prompt Calibration Loop).

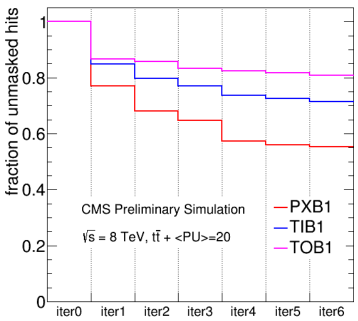

Figure 5: Fraction of unmasked hits per barrel subdetector.

Other optimizations are being implemented. Iter #3 is moved right after iter #0. Since iter #3 is faster (per track) than iter #1 and #2, this change reduces the load on the steps downstream iter #3. Iter #4 is simplified by removing redundant seed combinations, with lost tracks recovered in iter #5. The track selection is improved reducing the overlap between iterations for an overall better performance and, in addition, faster computations of the magnetic-field are being studied. These ameliorations, together with an improved architecture and the implementation of thread safety for event-level parallelization, result into a 10% gain in timing with no performance loss.

CMS tracking will need to be adapted also for the High Luminosity Phase of LHC. Complete software redesign will implement framework and algorithm vectorization and parallelization and innovative tracking algorithms.

References

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[2] S. Chatrchyan, et al., Description and performance of track and primary-vertex reconstruction with the CMS tracker-arXiv:1405.6569.