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Track reconstruction in CMS high luminosity environment

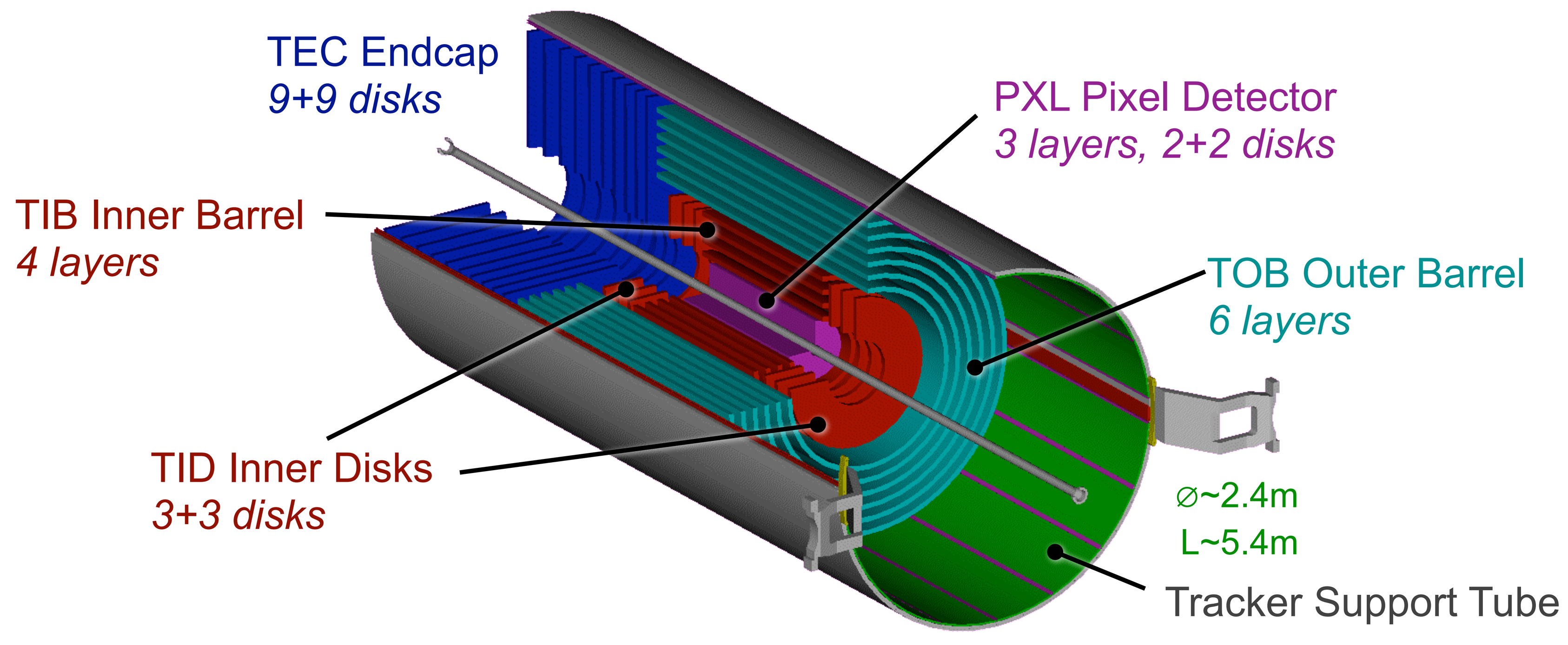
Giacomo Sguazzoni on behalf of the CMS Collaboration

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 1 and Run 2 physics program and within CMS future upgrades.

The CMS tracker, the world largest Silicon detector

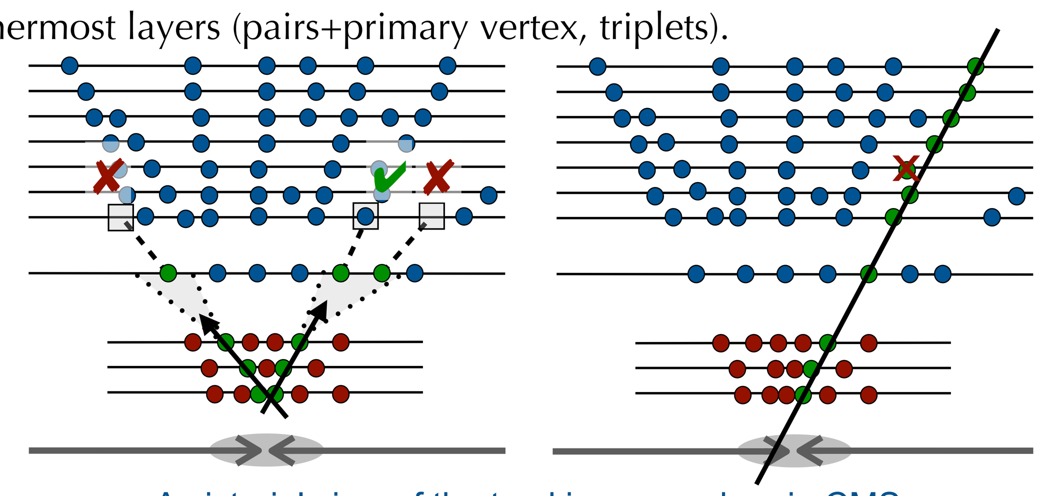
Pixel: ~66M channels, 100x150 μm² pixel / Strip: 15148 Strip modules, pitch in the range 80 to 200μm; ~200m² of Silicon active area; ~9M channels with full optical analog readout.



A sketch of the CMS Silicon Tracker and its subsystems.

CMS tracking procedure

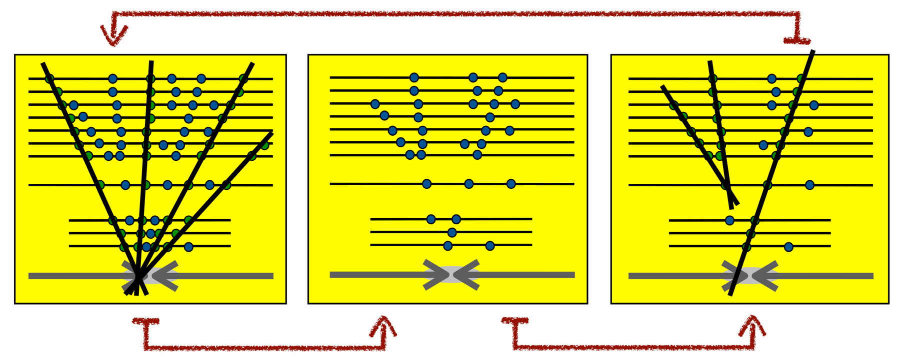
Seeding proto-tracks are searched for in the innermost layers (pairs+primary vertex, triplets).
Trajectory building Inside-out pattern recognition (based on Kalman Filter)
Rejection of outlier hits based on hit compatibility test with the trajectory
Final fit also based on Kalman Filter
Final selection of tracks quality cuts and/or MVA
Primary Vertex used in tracking is derived from pixel-based algorithm.



A pictorial view of the tracking procedure in CMS

Iterative tracking

The CMS efficient tracking relies on iterations (steps) of the tracking procedure; each step works on the remaining not-yet-associated hits. Each step is optimized with respect to the seeding topology and to the final quality cuts. The iterative tracking is largely configurable: Can be adapted to be used within High Level Trigger; specific iterations can be introduced for speciality tracking (muons, electrons, tracks in jets).

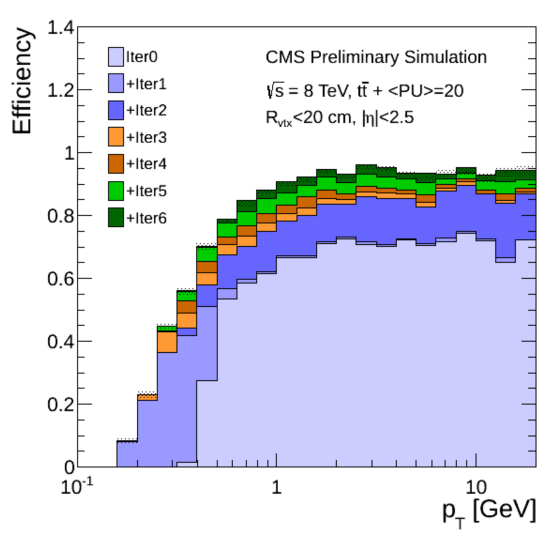


Pictorial view of the iterative tracking

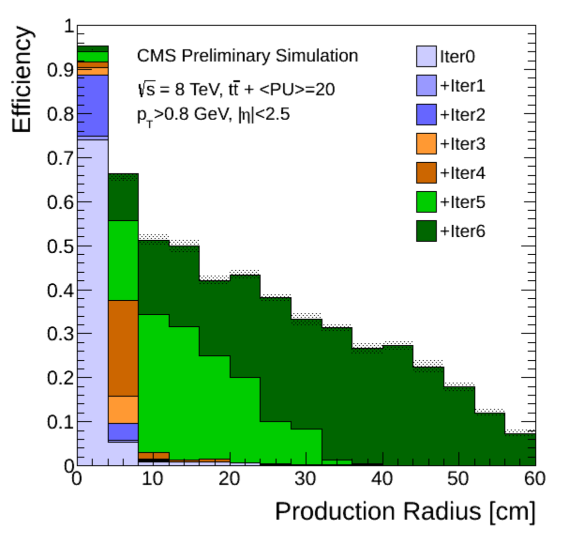
The iterative tracking steps are configured to be complementary with respect to the subdetectors used for seeding and the kind of tracks reconstructed.

#step	seed type	seed subdetectors	P_T^{min} [GeV/c]	d_0 cut	z_0 cut
0	triplet	pixel	0.6	0.03cm	4.0σ
1	triplet	pixel	0.2	0.03cm	4.0σ
2	pair	pixel	0.6	0.01cm	0.09cm
3	triplet	pixel	0.2	1.0cm	4.0σ
4	triplet	pixel/TIB/TID/TEC	0.35-0.5	2.0cm	10.0cm
5	pair	TIB/TID/TEC	0.6	2.0cm	10.0cm
6	pair	TOB/TEC	0.6	2.0cm	30.0cm

Iterative tracking parameters in 2012

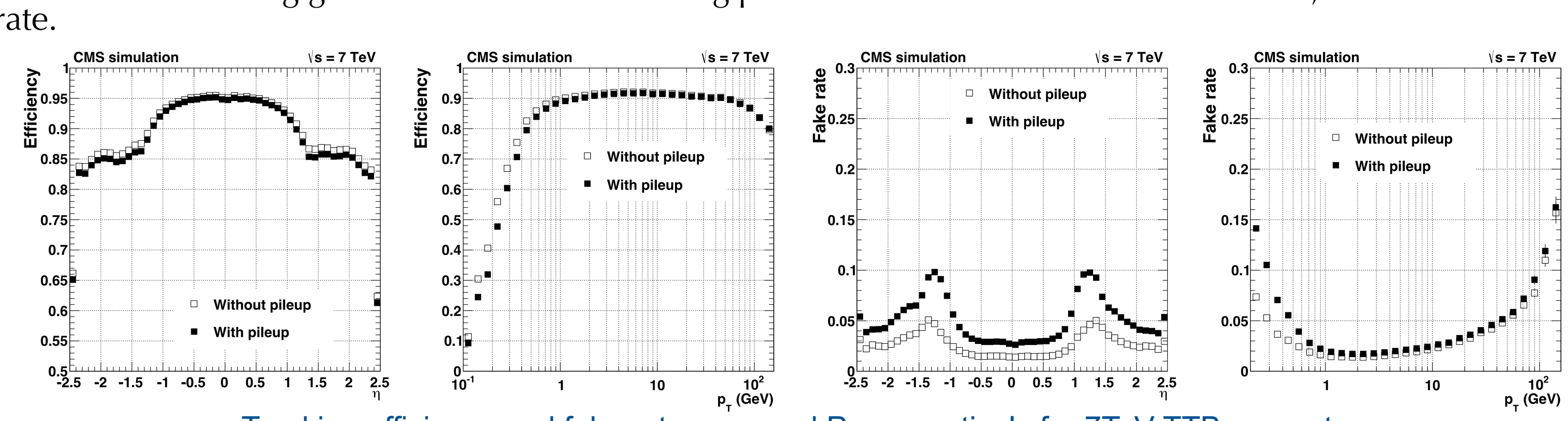


Step efficiency vs. P_T



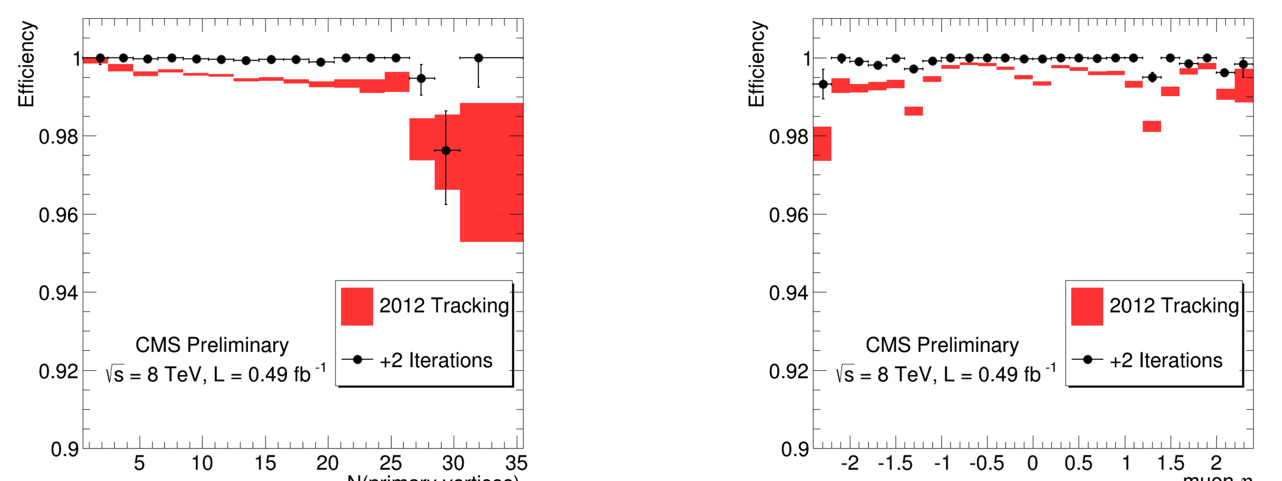
Step efficiency vs. production radius

The iterative tracking guarantees excellent tracking performances in the CMS environments, with low fake rate.



Tracking efficiency and fake rate vs. η and P_T respectively for 7TeV TTBar events

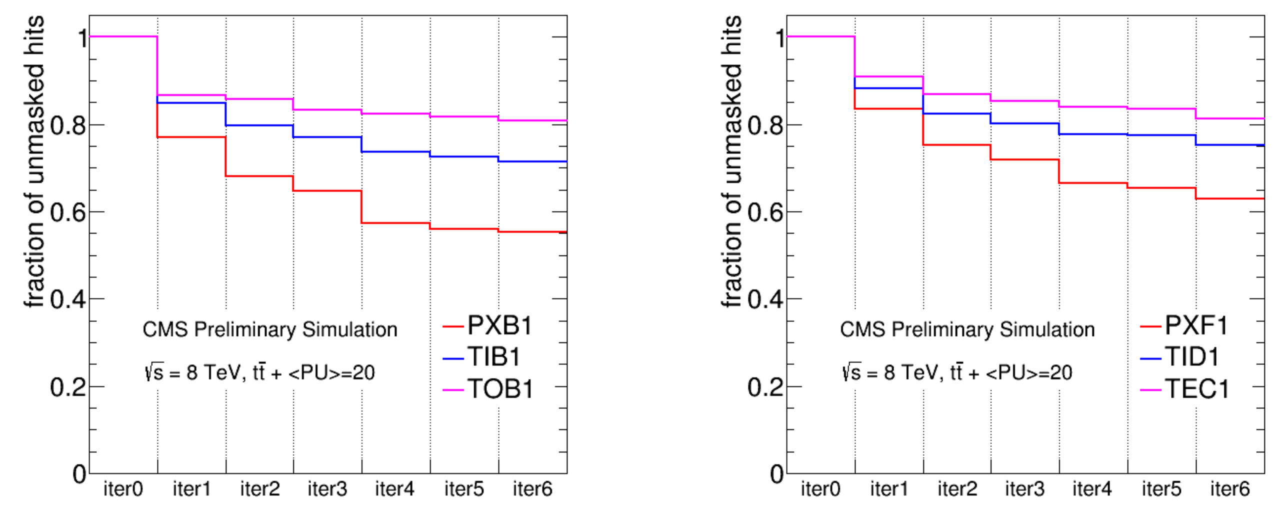
Tracking muon efficiency is already exceptionally good, but special iterative steps can be added to recover few percent of missing efficiency and make muon tracking more robust against the pileup expected in 2015. The extra steps are an OUT-IN iteration, seeded from the muon system, designed to recover the missing muon-track in the Tracker and an IN-OUT iteration designed to re-reconstruct muon-tagged tracks with looser requirements to improve the hit-collection efficiency. This is a perfect example of the power and flexibility of the iterative tracking concept.



Muon tracking *tag-and-probe* efficiency vs. the number of primary vertices η respectively for 8TeV with and without the new specialized iterations.

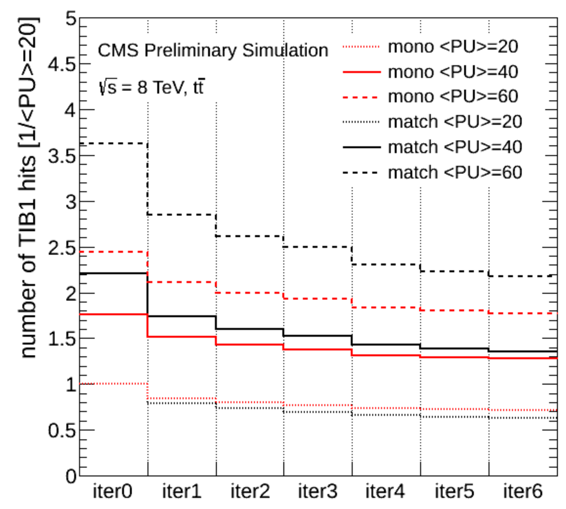
Outlook for Run2

The CMS tracking needs to be continuously adapted for increased instantaneous luminosity of LHC. Run2 starting in 2015 makes no exception. By definition the tracking is tuned to give the best performances within the limited computing resources allotted for reconstruction. Track reconstruction is the largest chunk of CMS reconstruction with respect to the computing resources. In 2012 maximum pile-up was ~20 events per bunch crossings. In 2015 up to 45 is expected. Moreover LHC will change bunch crossing frequency from 50 to 25ns yielding to hits due to out-of-time pile-up (+5% in pixel detector and +45% in silicon detector). The combinatorial problem behind the track building is largely increased. The concept of iterative tracking (i.e. progressive removal of hits attached to tracks) is less evident for outermost and less granular detectors.

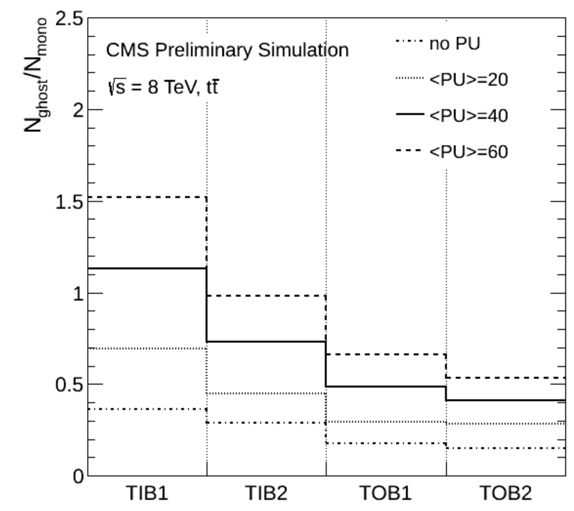


Fraction of unmasked hits per tracking stage in barrel and forward detectors

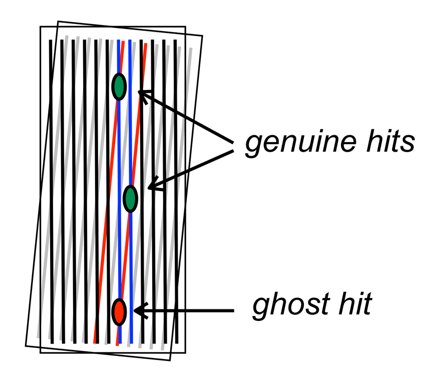
Some strip layers provide 3D hit information: to serve such purpose, the detector module is made up of two sensors with strips at an angle of 100mrad (stereo module). With increasing PU the number of ghost hits intrinsically generated by this approach increases.



Number of unmasked hits per iteration of the first TIB layer (relative to hits at <PU>=20) for rphi strip hits (mono, red) and double-sided strip hits (matched, black). The latter increases more with PU due to ghost hits.

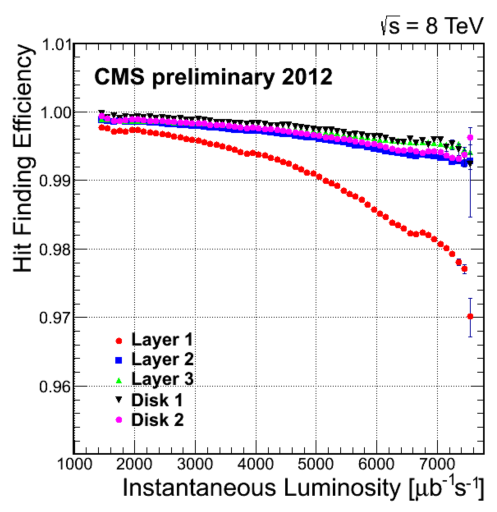


Ratio of ghost matched hits and rphi hits in double-sided barrel layers. In TIB1 (where the occupancy is higher) for PU≥40, the number of ghost hits exceeds the number of true (mono) hits.

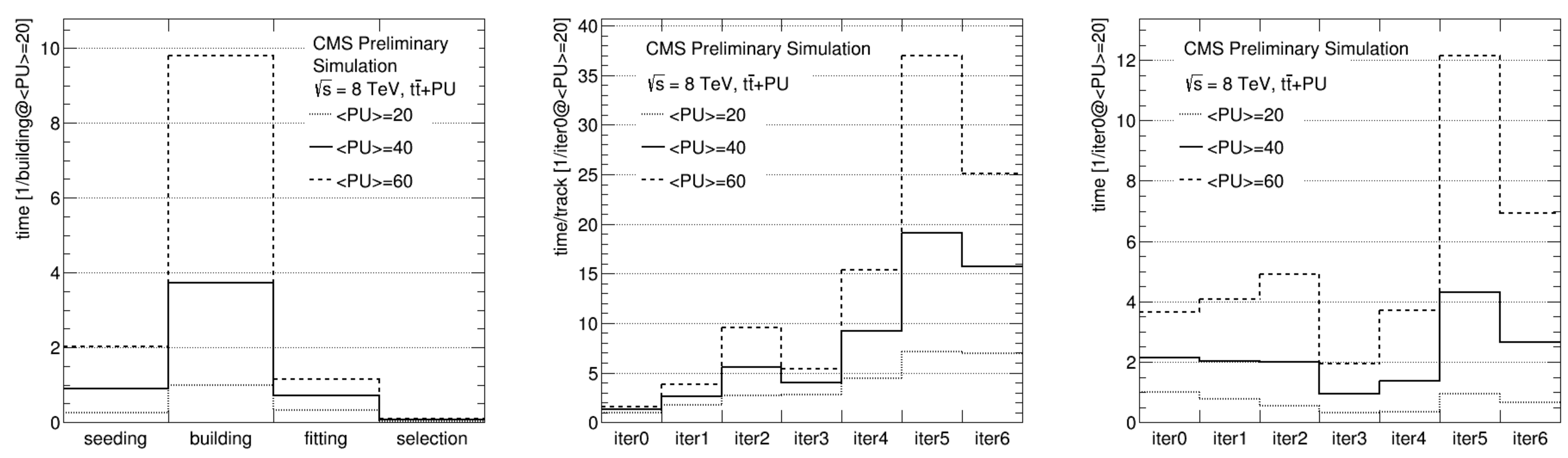


Sketch of a stereo module and the ambiguity yielding to ghost hits.

These 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 more prone to combinatorics. This is clearly visible in the tracking timing plots at different PU. The effect of pile-up is dramatic on iterations seeded by pairs of strip matched 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.



Pixel Hit finding efficiency vs. instantaneous luminosity.



Tracking timing plots (in arbitrary units) for various PU scenarios: vs. tracking task (left), per track vs. iteration step (center), absolute vs. iteration step (right).

To get ready for Run2, the tracking is undergoing an extended optimization based on several cornerstones.

Extended usage of Triplet Base Seeding

Development of a new triplet algo to replace iter #5 and iter #6 pair strip-seeded steps; the new algo is based on a χ^2 cut from straight line fit of 3 points in the rz plane and profits also from a 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 ~40% with negligible effciency, thanks to an timing improvment on iter5 and iter6 alone larger by a factor 2.

Strip Cluster Charge cut

With 25 ns bx, the increase in occupancy du to out-of-time PU for the strip detector induce an increase by 2x both on timing and fake rate; however clusters from out-of-time PU are characterized by low collected charge since it is induced by tracks (loopers) that deposit charge not in time with respect to the sampling window. Cutting on the cluster charge largely suppresses the hits due to out-of-time PU. A cut on cluster charge to be applied upfront, during seeding or during pattern recognition is foreseen for Run2. The cut accounts for sensor thickness and local crossing angle on sensor and is designed to be P_T dependent to preserve potential signal from fractional charge particles foresees by some BSM models. On the detector side, it requires stable performance to be ensured by introducing tracker gain calibration in the automatic calibration procedure (Prompt Calibration Loop).

Other Tracking Optimization

Faster first! Since iter#3 is faster (per track) than iter #1 and #2. By moving iter #3 right after iter #0.
Iter #4 was simplified by removing redundant seed combinations, but lost tracks are recovered in iter #5.
Optimization of track selection Less iteration-specific track selection removes overlaps between iterations and improves overall performances.
Code optimizations Better use of magnetic-field, improved architecture and thread safety for event-level parallelization.
These improvements allow for a 10% gain in timing with no performance loss.

A glimpse into the future...

CMS tracking will need to be adapted for the High Luminosity Phase of LHC from 2014 on. Complete software redesign will implement framework and algorithm vectorization and parallelization and innovative tracking algorithms.

Giacomo Sguazzoni | INFN Sezione di Firenze | giacomo.sguazzoni@cern.ch