CMS reconstruction improvements for the tracking in large pile-up events

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Abstract. 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 underwent a major upgrade deployed in two phases. It was needed 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. The improvements are described. Among the others, the iterative steps have been reorganized and optimized and an iterative step specialized for the reconstruction of photon conversion has been added. The overall impact on reconstruction performances is discussed and the prospects for future applications are given.

1. Introduction

The Compact Muon Solenoid, CMS, is one of the two general-purpose experiments installed at the Large Hadron Collider (LHC) at CERN [1]. The core of the CMS detector is the superconducting solenoid, 6 m in diameter and 13 m long, that produces a magnetic field of 3.8 T. The solenoid contains, from outside to inside, the calorimeter system and the silicon tracking system for the reconstruction of charged particles trajectories.

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x-axis pointing to the centre of the LHC, the y-axis pointing up (perpendicular to the LHC plane), and the z-axis along the anticlockwise-beam direction. The polar angle, θ, is measured from the positive z-axis and the azimuthal angle, ϕ, is measured in the x-y plane. Pseudo-rapidity is $\eta = -\log\tan\theta/2$.

The silicon tracking system, shown in figure 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. Pixel sensors feature single pixel size of $100 \times 150\,\mu m^2$ for a total of 66M channels. 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 detector layers, and a Tracker Outer Barrel (TOB), made of six detector layers. The TIB is complemented by three Tracker Inner Disks per side (TID). The forward and backward regions (120 cm $< |z| <$ 280 cm) are covered by nine Tracker End-Cap (TEC) disks per side thus
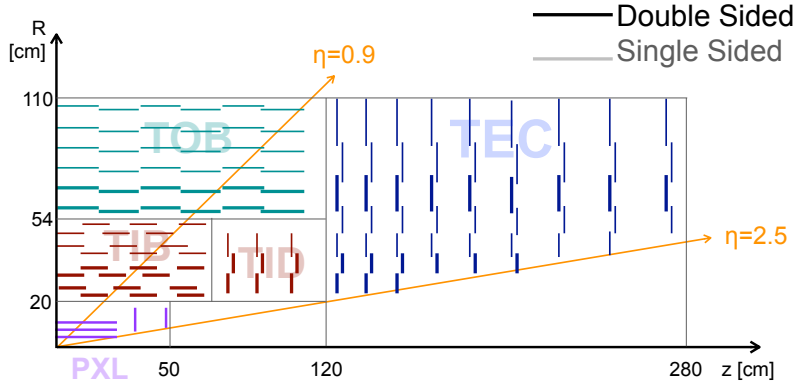
Figure 1. A simplified sketch of a quadrant of the Rz section of the CMS Tracker (bold lines represent double sided module assemblies).

extending the overall acceptance to cover the region $|\eta| < 2.5$. In some of the layers and in the innermost rings, special double-sided modules are able to provide accurate three-dimensional position measurement of the charged particle hits. The Silicon Strip Tracker is the world's largest silicon strip detector with a volume of approximately $23\,\mathrm{m}^3$, instrumented by about 15,000 modules with different strip pitches ranging from 80 to $180\,\mu\mathrm{m}$, for a total of $198\,\mathrm{m}^2$ of Silicon active area and about 9.6 million channels with full optical analog readout [1][2][3].
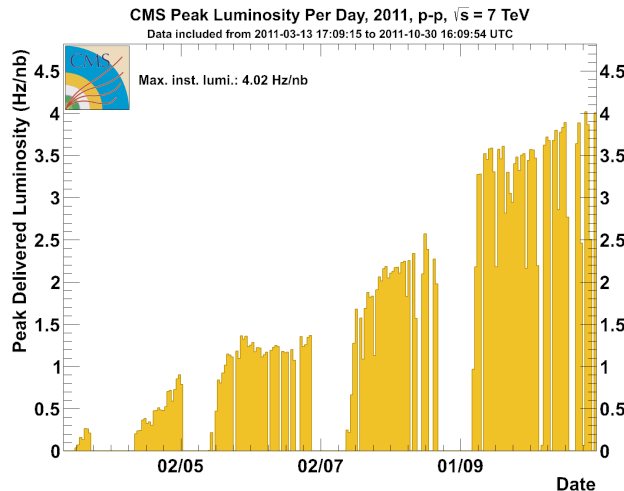
The CMS track reconstruction [4] starts with the appropriate grouping of the hits in the innermost layers to build up *seeds*. The seed is an initial track estimate and consists of a triplet or a pair of hits, sufficient for a basic prediction of the trajectory parameters if the primary vertex is also used. Starting from a given seed, pattern recognition using a Kalman Filter is performed to build inside-out trajectories. Then each identified track undergoes a procedure to reject possible outlier hits and is refitted, also using a Kalman Filter. Finally, a quality selection is performed. Reconstruction efficiency relies on several iterations (steps) of the tracking procedure; every step, except the first, works on the not-yet-associated hits surviving the previous step. Each step is optimized with respect to the seeding topology and to the final quality cuts. This recursive procedure is referred to as *iterative tracking*.

The algorithms that build up the CMS event reconstruction software, CMSSW [5], output physics objects (e.g., tracks, electrons, jets, ...) from the raw data recorded by the detector. Ideally, all events collected by CMS are reconstructed by the CMS prompt reconstruction system quasi real-time, soon after being collected. The prompt reconstruction stream is of utmost importance for a discovery experiment and prompt reconstruction data samples have been the base of most of the CMS physics results so far. Clearly, they are also crucial for fast and accurate feedback on detector conditions.

The complexity and the granularity of the tracker system in connection with the large LHC instantaneous luminosity, resulting in a large number of interactions (pile-up, PU) per bunch crossing, make the track reconstruction largely dominating the entire reconstruction chain memory-wise and in terms of CPU time.

The LHC instantaneous luminosity is steadily growing since the beginning of the run in 2010. In figure 2 and figure 3 the maximum LHC instantaneous luminosity per day delivered to CMS is shown as a function of time for 2011 and 2012, respectively. During 2012 the LHC instantaneous luminosity is expected to reach a value of about $7 \cdot 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ that corresponds to a number of primary vertices per bunch crossing of about 25.

The other worsening factor that was not foreseen at the design level of LHC and consequently not taken into account in writing first versions of reconstruction software, is the bunch crossing frequency. LHC was supposed to run with 25ns between subsequent bunch crossings. But as a consequence of the LHC operating conditions and beam optics, it is preferable to run with 50ns between bunch crossings. This allows for fatter bunches in the machine and, eventually,

CMS Peak Luminosity Per Day, 2011, p-p, √s = 7 TeV
Data included from 2011-03-13 17:09:15 to 2011-10-30 16:09:54 UTC

Max. inst. lumi.: 4.02 Hz/nb

Figure 2. Maximum instantaneous luminosity per day delivered to CMS for pp running at 7 TeV centre-of-mass energy in 2011.
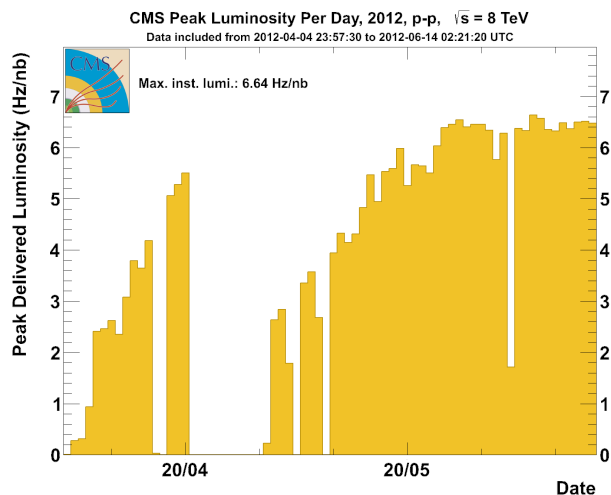
for a larger overall delivered luminosity. On the other hand, this results into a larger pile-up per bunch crossing and considerably increases the computing time per event that, being due to combinatorics, scales faster than with purely linear dependence. During 2011 it was soon clear that the current version of reconstruction software was not performing well enough to withstand prompt reconstruction for the last part of 2011 and 2012.

This paper describes the actions that have been put in place to improve the tracking reconstruction software, the major responsible of the CPU load at the reconstruction level, in order to be compliant with the expected luminosity in 2011 and 2012. This improvement campaign took place in two phases: the first phase took place during 2011 and was completed in September 2011 (so-called *Fall 2011 campaign*), the second phase started at the beginning of 2012 and was completed in March 2012 (*Spring 2012 campaign*).

2. Fall 2011 campaign

The modifications put in place and optimized in the first phase of the improvement campaign have been developed on top of CMSSW version 4.2.x and implemented in the CMSSW version 4.4.x.

A first group of improvements are purely based on smarter coding and better algorithm

CMS Peak Luminosity Per Day, 2012, p-p, √s = 8 TeV
Data included from 2012-04-04 23:57:30 to 2012-06-14 02:21:20 UTC

Max. inst. lumi.: 6.64 Hz/nb

Figure 3. Maximum instantaneous luminosity per day delivered to CMS for pp running at 8 TeV centre-of-mass energy in 2012.

implementation and do not change the physics outcome of the tracking reconstruction workflow. They are mainly targeted to reduction and better handling of the memory and in fact they allow for a 40% cut of the memory budget. These modifications are described below in more detail.

Copy-less hit masking within the iterative tracking. Each step of the iterative tracking, but the first, works on the hits not yet associated to any track. Technically this was implemented by creating a new collection of surviving hits at each step. To save memory, a masking algorithm has been implemented adding to the hit object an appropriate data member for the masking bits. Results are unchanged with a major reduction of the allocated memory.

Batch cleaning of track candidates. The track candidate results from a seed that has been successfully propagated. Before being declared as a reconstructed track, the track candidate must undergo a filtering selection to reject fakes. To avoid storing too much track candidates in memory, the cleaning procedure is done once a subsample of 1000 track candidates has been accumulated with large benefit on the overall required memory.

Efficient quality assignment. Each step in the iterative tracking assigns tracks to a quality tier. Old implementation of the algorithm just created a copy of the same track per each quality tier it was belonging to; this has been modified by removing the copying and adding an appropriate data member to store the quality tier bits with an obvious advantage on the memory consumption.

Efficient track merging. After all iterative steps, the resulting track collections have to be merged and further cleaned from potential fake tracks and duplicated tracks. In fact, only hits associated to tracks with highest quality, know in CMS as *high purity tracks*, are not used in the following steps. But hits associated to lower quality tracks are retained, in the attempt to build better tracks out of them with different seed and propagation parameters. The old implementation of the merging algorithm compared the collection created by the various steps in pairs creating intermediate collections to be further compared with other collections up to the end of the process. In the updated version all track collections feed a merging module that works without creating any intermediate collection. This is pictorially shown in figure 4.

The second group of ameliorations directly affects the algorithms and thus the outcome on observables and has to be evaluated also with respect to performances on physics. These modifications target the CMSSW modules related to tracking that are dominating, in terms of CPU time, the entire reconstruction chain and are described in the following.
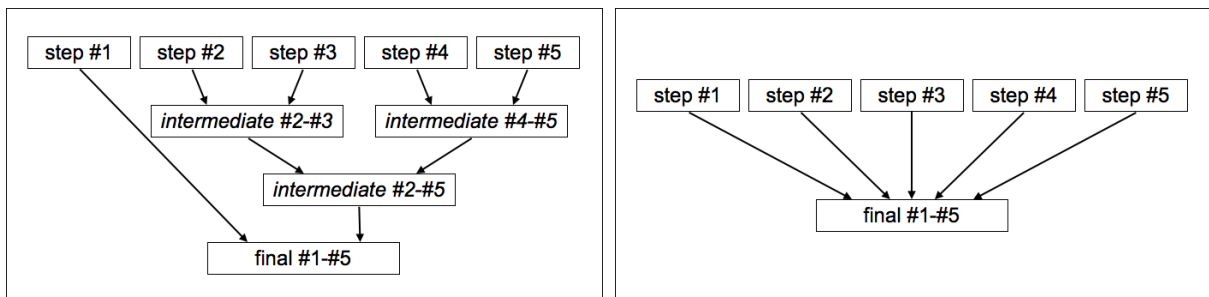
Figure 4. Schematical representation of the old (left) and the new (right) merging algorithm for an hypothetical iterative tracking with five steps; "intermediate" track collections are avoided in the new algorithm and this allows for consistent memory savings.

Iterative tracking. A factor 2.5 of improvement in the CPU time has been obtained by optimizing the iterative tracking, as detailed in table 2 to be compared with table 1 that summarizes the baseline configuration of CMSSW 4.2.x. As can be seen, the net effect is an increase of the effective P_T threshold for track reconstruction together with tighter constraint on impact parameter. This configuration results into a reduced efficiency for P_T lower than $300\,\mathrm{MeV}/c$ but an efficiency for P_T greater than $0.9\,\mathrm{GeV}/c$ larger by $\sim 1\%$ with a $\sim 8\%$ reduction of the fake rate.

Reconstruction of photon conversions. Reconstruction of photon conversion in the tracker volume is heavily affected by the higher P_T threshold and by the tighter impact parameter cuts since conversion tracks are typically soft and displaced. To recover this loss, a dedicated seeding has been deployed [6] and the photon conversion reconstruction has been further optimized resulting in a factor 12 improvement of the CPU time for conversion reconstruction.

Reconstruction of primary vertices. The reconstruction of primary vertices in the event has been optimized by integrating into the same module all the different reconstruction methods; the removal of the overhead due to the module split we had beforehand was enough to gain a factor two in CPU time in this specific context.

Reconstruction of nuclear interactions. Similarly to photon conversions, also nuclear interactions are reconstructed for tracker material studies and to correctly estimate

Table 1. Relevant parameters of the six iterative tracking steps in CMSSW 4.2.x, i.e. before the reconstruction improvement campaign described in this paper; 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.

#step	seed type	seed subdetectors	$P_T^{\min}$ [GeV/c]	d_0 cut	z_0 cut
0	triplet	pixel	0.8	0.2 cm	3.0σ
1	pair	pixel/TEC	0.6	0.05 cm	0.6 cm
2	triplet	pixel	0.075	0.2 cm	3.3σ
3	triplet	pixel/TIB/TID/TEC	0.25-0.35	2.0 cm	10.0 cm
4	pair	TIB/TID/TEC	0.5	2.0 cm	12.0 cm
5	pair	TOB/TEC	0.6	6.0 cm	30.0 cm

Table 2. Relevant parameters of the seven tracking iterative steps in CMSSW 4.4.x, after the first phase of the improvement campaign in fall 2011; in bold the parameters changed with respect to the corresponding steps in CMSSW 4.2.x (see table 1); step #1 is brand new with respect to CMSSW 4.2.x; see table 1 caption for symbol definitions.

| #step	seed type	seed subdetectors	$P_T^{\min}$ [GeV/c]	d_0 cut	z_0 cut
0	triplet	pixel	**0.6**	**0.03** cm	**4.0**σ
1	**triplet**	**pixel**	**0.2**	**0.03** cm	**4.0**σ
2	pair	**pixel**	0.6	**0.01** cm	**0.09** cm
3	triplet	pixel	**0.2**	**1.0** cm	**4.0**σ
4	triplet	pixel/TIB/TID/TEC	**0.35-0.5**	2.0 cm	10.0 cm
5	pair	TIB/TID/TEC	**0.6**	2.0 cm	**10.0** cm
6	pair	TOB/TEC	0.6	2.0 cm	30.0 cm
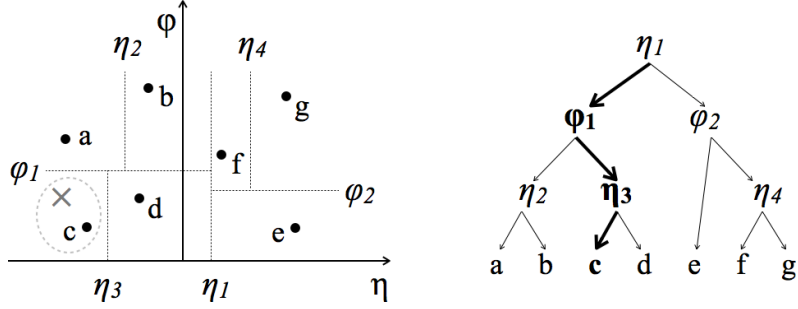
Figure 5. Pictorial representation of the kd-tree algorithm in the case of a very simple neighbor search problem in the (η, ϕ) plane: a track (represented by the "×" symbol) needs to be associated to one of the calorimetric clusters represented by the dots labelled with letters. On the left panel it is shown the way (η, ϕ) is split into domains and the resulting navigation tree is sketched on the right.

the hadronic energy fraction in jets within the Particle Flow, the global event reconstruction [7][8], that consists in reconstructing and identifying each single particle with an optimized combination of all subdetector information. To avoid consuming CPU time in the heavy vertex fit with candidates that are very likely to be fakes, a very simple preselection has been implemented: a nuclear interaction candidate track is kept only if P_T exceeds $800\,\mathrm{MeV}/c$, in case of primary tracks, or if the impact parameter in the xy plane is larger then $2\,\mathrm{mm}$ for secondary tracks; the vertex candidate must have at least three tracks (one primary and two secondaries or three secondaries) and, finally, candidates are discarded if the secondary vertex estimate falls within the beam pipe. These simple criteria are enough to reduce the combinatorics such that the nuclear interaction reconstruction gains a factor 5 in CPU time with no observable degradation in physics performances.

Particle flow links. The Particle Flow algorithm needs to link tracks to calorimetric clusters in the (η, ϕ) parameter space. This problem of nearest neighbor search over a large number of objects in CMSSW 4.2.x is implemented with nested loops and results to be rather time intensive. Moreover the complexity scales quadratically (N^2) as the object multiplicity N increases. In CMSSW 4.4.x the well known linearization technique known as *kd-tree* [9] has been introduced to replace nested loops. The method consists in an algorithm that, starting from a collection of objects (calorimetric cluster, for example), dynamically splits the (η, ϕ)
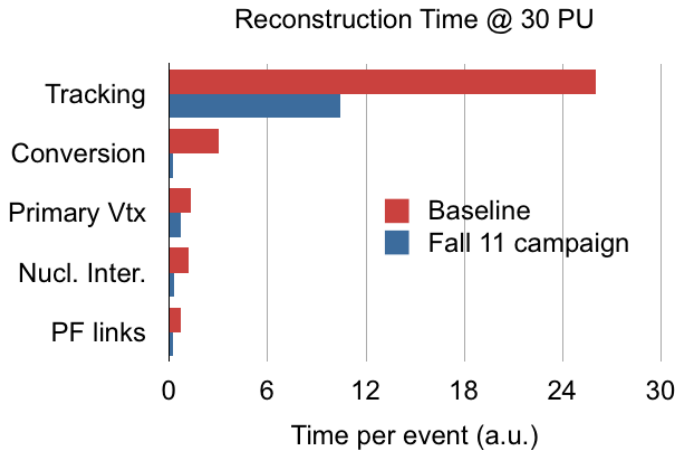
Figure 6. Breakdown of the average CPU time per event in arbitrary units before and after 'Fall 2011' for each improvement area of the tracking reconstruction software (simulated QCD events with 30 pile-up interactions).
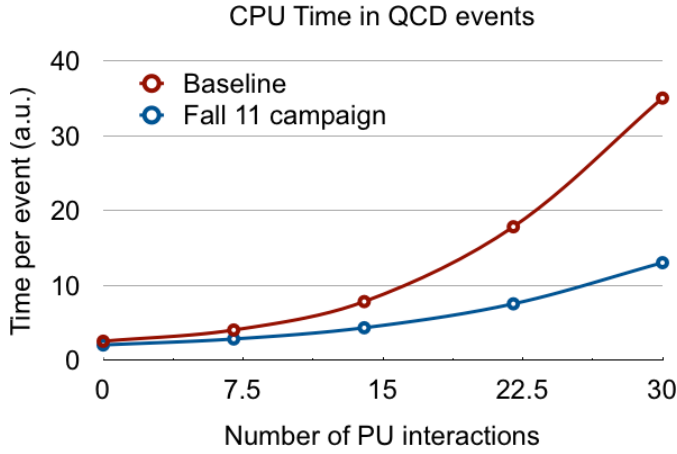
Figure 7. Total reconstruction CPU time per event (in arbitrary units) for as a function of pile-up events for simulated QCD events for the baseline CMSSW and the improved version.

space into appropriate domains, each containing one single object, organized in a tree. The closest cluster to a given track can be found by exploring the (η, ϕ) space with a very fast binary search that ends up in the closest neighbor domain. This algorithm, schematically represented in figure 5, has a complexity that scales as $N \cdot \log N$, thus more convenient with respect to standard nested loops especially for large multiplicity, and allows to gain a factor 4 in CPU time in this specific application. Its extension to other modules of CMSSW is being studied.

The results of the improvements just described are graphically represented in figure 6 and figure 7. In the former the breakdown of the CPU time for each improvement area before and after each improvement is reported for simulated QCD events with 30 pile-up interactions per event; in the latter the total CPU time is shown as a function of the number of pile-up interactions for simulated QCD events.

The CMSSW 4.4.x releases derived from the "fall 2011" campaign have been fully validated and have been accepted for production since changes in performaces are minor with respect to physics outcome.

3. Spring 2012 campaign

The modifications put in place in the second phase of the improvement campaign have been developed on top of CMSSW version 4.4.x and implemented in the CMSSW version 5.2.x. Again a group of improvements are based on better coding and technological improvements and do not change the physics outcome. More in detail, these modifications are described below.

Change of compiler version. The implementation of CMSSW 5.2.x has been accompanied by the switch from `gcc` 4.3.4 to `gcc` 4.6.2 to produce binaries. This latter compiler version allows for faster code to be generated also thanks to some compiler specific optimizations. The net gain is up to 10% as shown in figure 8 where the reduction in CPU time is shown as a function of the number of pile-up vertices for simulated QCD events. Other features that came along the new compiler version are the C++11 standard support and autovectorization flags on by default.

JEMalloc. The concurrent malloc implementation JEMalloc, highly performant and able to better redeem memory, has been implemented in place of the standard malloc.

Switch to improved ROOT version. The ROOT package version has been changed from 5.27 to 5.32 that features several improvements, especially in I/O with less memory required.

Several design modifications to improve speed and memory consumption. The code has been again carefully reviewed and many improvements have been implemented. Several

of those are related to track reconstruction classes. For example, the devirtualization of the BasicTrajectoryState class (an ancillary class for track reconstruction) resulted into a 10% gain in speed and in some 100MB of resident set size (RSS) saved per event. Similarly the stereo hit class (the class that stores the double sided module hits) has been considerably slimmed down (a factor three in size) with a net decrease of RSS memory from 50MB to 150MB, depending on the event occupancy.

Another set of modifications directly affects the outcome on physics output. These are described in the following.

Offline vertexing. The offline reconstruction of primary vertices is based on a deterministic annealing algorithm to find the z coordinate of the vertices. Major improvements have been deployed for CMSSW 5.2.x: loops have been autovectorized (thanks to the introduction of the new compiler) but, to further profit of autovectorization capabilities, the exponential functions heavily used in the algorithm have been replaced with a fast, autovectorizable inlined double precision version. Eventually the deterministic annealing algorithm has been further made more efficient by optimizing some configuration parameters with essentially no change in physics performances. The net increase in CPU time amounts to a factor 3 for large PU events.

Cluster shape based seed filtering The large CPU time needed by the track reconstruction is to be ascribed to the huge number of seeds due to hit combinatorics; in fact a propagation has to be attempted for each of them. A way to keep this number under control is to implement filters able to reject fake seeds. One of the most effective is based on the cluster shape. For example a track impinging a sensor with a large angle will generate a cluster wider than a track with normal incidence. This can be used to evaluate seed compatibility with the track hypothesis. Such a filter was used only in steps #0 and #1 in CMSSW 4.4.x (see table 2); for CMSSW 5.2.x it has been extended also to steps #2, #4 and #5 (see table 3) with a substantial CPU time benefit. For example, the step #2, particularly prone to combinatorics since seeds are made up of hit pairs, sees a CPU time reduction of a factor 2.7. Overall the improvement in CPU time is of a factor 1.5. As a side effect of the filter also the fake rate is reduced by $\sim 20\%$.

Iterative tracking. After all the modifications described above, also the iterative tracking has been further optimized for CMSSW 5.2.x. Nevertheless the differences, summarized in table 3, are tiny, which demonstrates that upstream improvements are already almost sufficient to make CMSSW compliant with requirements. There is no need to modify deeply the iterative tracking, i.e. to reduce combinatorics and to match performance target by increasing effective P_T thresholds and/or by reducing efficiency for displaced tracks. A relevant change introduced as part of the optimization consist of the upgrade of the final
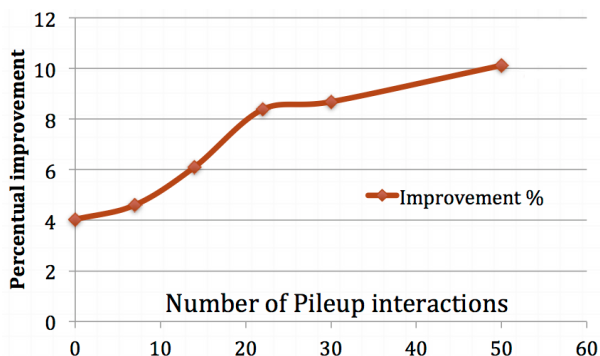
Figure 8. Relative CPU time reduction to be ascribed to the introduction of gcc 4.6.2 as a function of the number of PU vertices for simulated QCD events.

Table 3. Relevant parameters of the seven tracking iterative steps in CMSSW 5.2.x, after the second phase of the improvement campaign in 2012; in bold the parameters changed with respect to the corresponding steps of CMSSW 4.4.x in table 2; see table 1 caption for symbol definitions.

| #step	seed type	seed subdetectors	$P_T^{\min}$ [GeV/c]	d_0 cut	z_0 cut
0	triplet	pixel	0.6	**0.02** cm	4.0σ
1	triplet	pixel	0.2	**0.02** cm	4.0σ
2	pair	pixel	0.6	**0.015** cm	0.09 cm
3	triplet	pixel	**0.3**	**1.5** cm	**2.5σ**
4	triplet	pixel/TIB/TID/TEC	**0.5-0.6**	**1.5** cm	10.0 cm
5	pair	TIB/TID/TEC	0.6	2.0 cm	10.0 cm
6	pair	TOB/TEC	0.6	2.0 cm	30.0 cm

track cleaning and selection criteria. Eventually the efficiency for prompts tracks with P_T larger than 0.9 GeV/c is not affected but the fake rate is reduced by about $\sim 35\%$.

The overall result obtained with the "spring 2012" campaign improvements implemented in CMSSW 5.2.x is shown in figure 9 where the dependence of RSS memory as a function of running time is plotted in CMSSW 4.4.x and CMSSW 5.2.x for a reconstruction job of 100 real data events from the 2011 special run with high PU. The substantial reduction both in memory load as well as in total running time is clearly evident.

The CMSSW 5.2.x releases have been fully validated and have been accepted for production since changes in performaces are minor with respect to physics outcome.

4. A glimpse into the future
The challenge for the CMS reconstruction cannot be considered over with the deployment of the software for 2012 data taking, currently ongoing. After the first long shutdown, foreseen for almost two years in 2013 and 2014, LHC will increase center-of-mass energy and instantaneous luminosity as well. This will require a major reengineering of the entire reconstruction software and of the tracking.
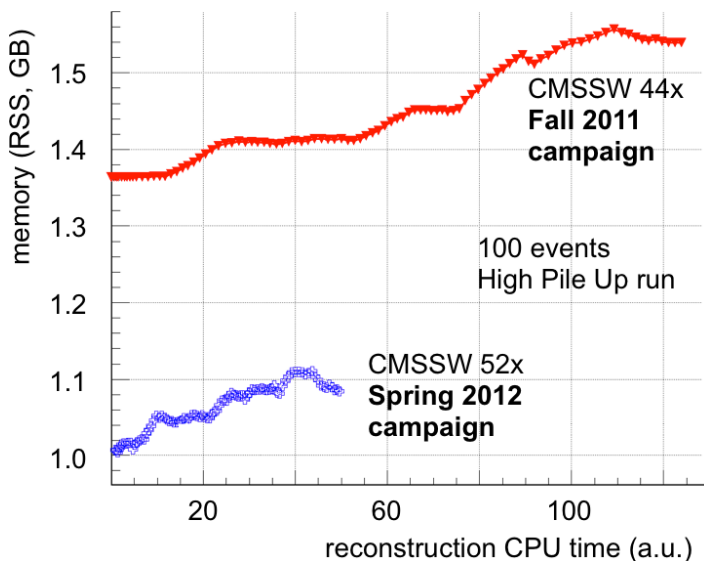
Figure 9. RSS memory as a function of running time in CMSSW 4.4.x and CMSSW 5.2.x for a reconstruction job of 100 real data events from the 2011 special run with high PU.

Two major areas of improvements are being considered: implementation of tracking techniques never used in CMS up to now (like Hough transforms tracking); exploitation at any possible level of parallelization techniques. The latter, in particular, turns out to be necessary to better profit from the actual trend of increase of the computing power that is realized by an increase of the number of cores in the same monolithic CPU.

Parallelization can be implemented in several ways. At the level of the framework by allowing different modules to run in parallel taking appropriately into account all dependencies; this would be almost transparent for the final user and developer, i.e. it would require minor or no changes to user and reconstruction module code. Nevertheless this is not optimal as some modules of CMSSW need much longer time to run with respect to the others; track reconstruction is the typical example. In this case it is worthwhile to implement parallelization at the module and algorithm level. This requires code modifications but is also much more effective. Prototype implementations are already being studied and are very promising [10].

5. Conclusions

The CMS track reconstruction has recently been streamlined to allow for quasi real-time prompt reconstruction to be performed with the available computing resources during 2011 and 2012 data taking, despite the steady increase of instantaneous luminosity delivered by the LHC thanks to its impressive performance.

This goal has been achieved by a number of actions taken at any level of the track reconstruction workflow by means of smarter coding techniques and by using technological improvements as well. The overall gain is approximately a factor 2 reduction of memory load and a factor 7 reduction of CPU time for the typical 2012 event.

The LHC operating conditions after the long shutdown, foreseen in 2013-2014, requires further performance improvements that will be object of future activities. New tracking techniques and parallelization will be implemented. Prototype applications are already being investigated.

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