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# Upgrade of the CMS Tracker with tracking trigger

**D. Abbaneo**[1]
*CERN*
*Geneva, CH-1211, Switzerland*
*E-mail:* `Duccio.Abbaneo@cern.ch`

The planned upgrades of the LHC and its injector chain are expected to allow operation at luminosities around or above $5 \cdot 10^{34}$ $cm^{-2}s^{-1}$ sometimes after 2020, to eventually reach an integrated luminosity of 3000 $fb^{-1}$ at the end of that decade. In order to fully exploit such operating conditions and the delivered luminosity, CMS needs to upgrade its tracking detectors and substantially improve its trigger capabilities. To achieve such goals, R&D activities are ongoing to explore options and develop solutions that would allow including tracking information at Level-1. Some of the options considered are reviewed, discussing their potential advantages and disadvantages.

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1 Speaker, on behalf of the CMS Tracker Collaboration

 

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## 1. The CMS Tracker at the High-Luminosity LHC

The perspective of an increase of the LHC luminosity well above its original design figure of $10^{34}$ $cm^{-2}s^{-1}$ requires a substantial upgrade of the CMS tracking system, to cope with much more demanding requirements and to implement additional functionality.

The pixel detector is the first part of the tracking system that will show limitations in high-rate operation: for this reason an upgrade of this component is foreseen already in the middle of this decade. The new detector will feature 4 barrel layers and 3 forward discs, hence yielding on average one more coordinate per track compared to the present system, in the whole acceptance range. An optimized engineering of mechanics and services, together with the implementation of two-phase $CO_2$ cooling will provide a substantial reduction in the amount of material in the tracking volume, while upgraded front-end ASICs will enhance the robustness of the system at high-rate. The upgraded pixel detector together with the outer strip tracker will provide optimal tracking performance to CMS through 2020. The pixel detector upgrade is discussed in detail in another presentation at this conference [1].

The upgrade of the LHC accelerator complex, foreseen for the beginning of the next decade, will yield beams with substantially increased intensity and reduced emittance; such beams will allow to produce instantaneous luminosities of $5 \cdot 10^{34}$ $cm^{-2}s^{-1}$, that will be sustained for a large fraction of each fill through luminosity levelling, eventually collecting up to 3000 $fb^{-1}$ after several years of operation. The quoted instantaneous luminosity corresponds to approximately 100 pileup events per bunch crossing if the operating frequency is 40 MHz[1]. For such scenario, the tracking system has to be enhanced in three main aspects: (i) higher radiation resistance, with respect to both instantaneous and integrated levels; (ii) higher readout granularity, to keep the channel occupancy at an adequate level in the strip detector, and resolve tracks in high-energy jets in the pixel detector; (iii) ability to contribute information for the Level-1 trigger, to achieve the enhanced discrimination required by the increased pileup.

To cope with such requirements, the whole CMS Tracker will have to be replaced at the beginning of the next decade; such upgrade will involve the outer strip tracker, as well as a further upgrade of inner pixel detector. The implementation of the trigger functionality has been so far studied in the context of the outer tracker upgrade; this paper illustrates the options considered, discussing potential advantages and disadvantages.

## 2. Requirements for the Strip Tracker Upgrade

The upgraded tracker will have to provide improved tracking performance in a more challenging environment, while producing at the same time fast information for the Level-1 trigger. The basic requirements are summarized below.

- Robust tracking in operation with up to 200÷250 collisions per bunch crossing in the worst-case scenario of 20 MHz operation (to be compared to the original LHC design figure of 20

[1] The number of pileup events would be larger than 200 if the same luminosity was achieved with 20 MHz operation. Such option presents some advantages for the operation of the LHC complex, but clearly makes the collected statistics more difficult to exploit.

collisions per crossing); this can be achieved by maintaining the occupancy at the few % level, which requires increased granularity.

- Ability to provide satisfactory performance up to an integrated luminosity of ~ 3000 $fb^{-1}$, to be compared with the original figure of ~ 500 $fb^{-1}$; this requires the selection of more radiation hard silicon sensor material, especially for the innermost regions, as well as more stringent criteria in the qualification of electronics and mechanical assemblies.
- Reduced material in the tracking volume; the material is the most severe limitation of the performance of the present tracker (see Fig.1, and also Ref.[2]), and it is dominated by electronics and services (notably in the region between barrel and end-cap): a tracker upgrade cannot leave out a substantial reduction of the material.
- Ability to contribute information for the Level-1 trigger decision, in order to maintain the overall rate within 100 kHz[2], without compromising the physics performance of CMS. The trigger requirement is discussed in some more detail below.

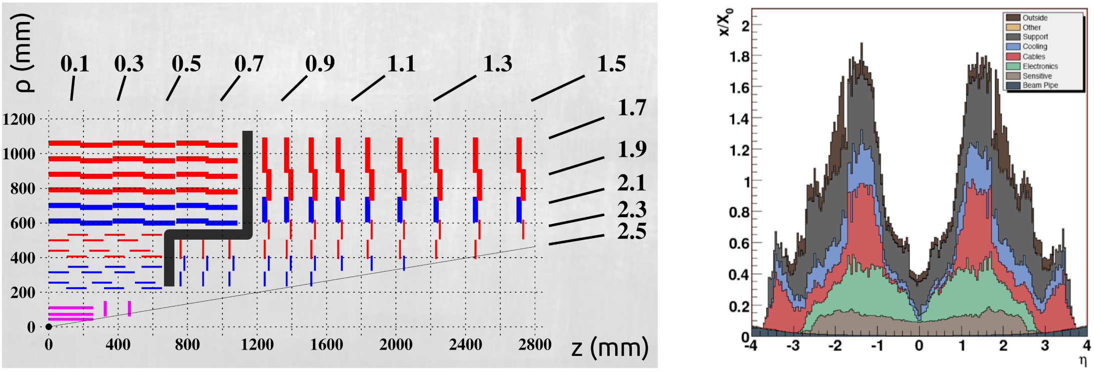



***Fig.1:*** *Sketch of the Silicon Strip Tracker layout (left), and distribution of radiation lengths as a function of pseudorapidity (right). The peak in the region $1<\eta<2$ contains an important contribution from the services routed between barrel and end-cap.*

## 2.1 Tracking information at Level-1

The event filtering at Level-1 becomes substantially more challenging in the High-Luminosity operation of the LHC (HL-LHC), not only because the rate of events passing a given selection scales with the instantaneous luminosity, but also because the performance of selection algorithms degrades with higher pile-up. For example, the single muon L1 rate has an irreducible tail due to poorly measured tracks that are compatible with straight trajectories, and therefore are not removed even increasing the $p_T$ threshold: such effect is aggravated at high luminosity by accidental coincidences. In the High-Level Trigger, where the information from the tracker is also added, the reconstruction is substantially improved and the rate of muon candidates follows closely the generator rate (see Fig. 2, left). Some improvements are expected with the "Phase-1" trigger upgrade (including the $4^{th}$ RPC and CSC stations, now under construction), which is expected to produce an acceptable rate for luminosities up to $\sim 2\cdot 10^{34}$ $cm^{-2}s^{-1}$, but the rate will saturate again the available quota for higher luminosities. Hence, a possible option to investigate is to anticipate the use of tracking information in the Level-1 selection, along the lines of what is done today in the High-Level Trigger (HLT).

[2] The limit at 100 kHz ensures compatibility with the electronics of subdetectors that will not be upgraded.

A similar problem is present in the single electron trigger, where high pile-up reduces the rejection power of isolation cuts on the calorimeter clusters.

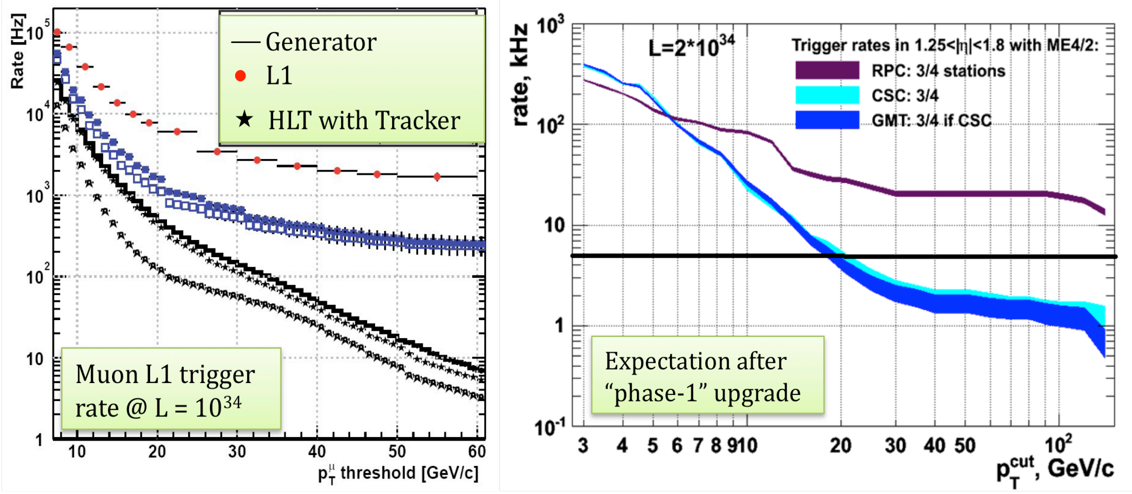



***Fig.2:*** *Expected L1 single muon rate (left) as a function of threshold for a luminosity of $10^{34}$ $cm^{-2}s^{-1}$, in the present system; the rate becomes almost flat for high $p_T$ cuts, due to poorly reconstructed tracks. The High-Level Trigger (HLT) rate, instead, follows closely the generator rate, thanks to the use of tracking information. With the planned "Phase-1" upgrade of the trigger system (right), it is expected to achieve a rate of 5 kHz for a target threshold of 20 GeV/c at $2\cdot10^{34}$ $cm^{-2}s^{-1}$. At higher luminosities further improvements are needed.*

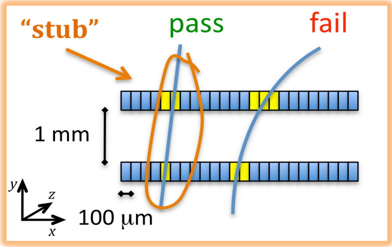
## 3. Implementation of tracking trigger

Two main architectures can be considered for the implementation of tracking trigger: (i) the "push" path, in which the Tracker provides Level-1 information that is combined with calorimeter and muon trigger data (with finer granularity than presently employed) to form "physics objects" that are transmitted to the Global Trigger, or (ii) the "pull" path, in which the present Level-1 calorimeter & muon triggers are used to produce a "Level-0" (within the current Level-1 latency of ~3µs), that is used to request tracking information from specific "regions of interest", at an expected rate of ~1 MHz; the tracking information would then be used to form a new combined Level-1 trigger, within the remaining latency of ~3µs.

The developments are focussing on option (i), which maintains the present CMS trigger architecture. Such option requires that rejection of low-$p_T$ tracks be performed locally in the module front-end electronics, in order to moderate the bandwidth needed in the data links. Possible implementations of local data reduction exploit the strong CMS magnetic field, as discussed below.

### 3.1 Modules with $p_T$ discrimination

The goal is to be able to reject locally signals from low-momentum particles, which are not interesting for the Level-1 reconstruction, while they generate the vast majority of the data. Rejecting particles below ~1÷2 GeV reduces the amount of data to be transmitted by one order of magnitude or more.




The basic concept consists in correlating signals in two closely spaced sensors: the distance between the hits in the x-y plane is correlated with the particle momentum, and allows the discrimination to be made (see sketch on the side). A pair of hits that fulfils the selection cut is called a "stub", and its coordinates are sent out for the Level-1 processing.

The options under study to realize a module with such $p_T$ discrimination capability ("$p_T$ module") are discussed below.

### 3.1.1 The "2S module"

The simplest $p_T$ module assembly is a sandwich of two strip sensors read out at the edges by the same set of front-end ASICs, that implement the correlation logic. In the model shown in Fig.3, two sensors of ~10×10 cm$^2$ are mounted on a mechanical structure that provides support and cooling, and connected at the edges on the two sides of a high-density substrate carrying the ASICs. The connection between sensors and substrate is realized by wirebonds, while the ASICs can be bump-bonded onto the substrate. The strip length has to be half of the module size, hence ~5 cm, and pitch can be 90 μm, corresponding to 2×1024 channels per sensor.

This concept results in a neat lightweight assembly, and it can be realized with commercial interconnection technologies. The estimated power consumption for the readout electronics, including the correlation logic, is below 2W, similar to the lowest values in the present tracker. The main limitation of this type of module is the lack of segmentation in the z direction: in order to be able to implement effective isolation cuts on calorimeter clusters, the L1 tracks are required to have a reasonable precision also in the z coordinate. In addition, the relatively long strips limit the use of this module in the radial region above ~50 cm, because of occupancy.

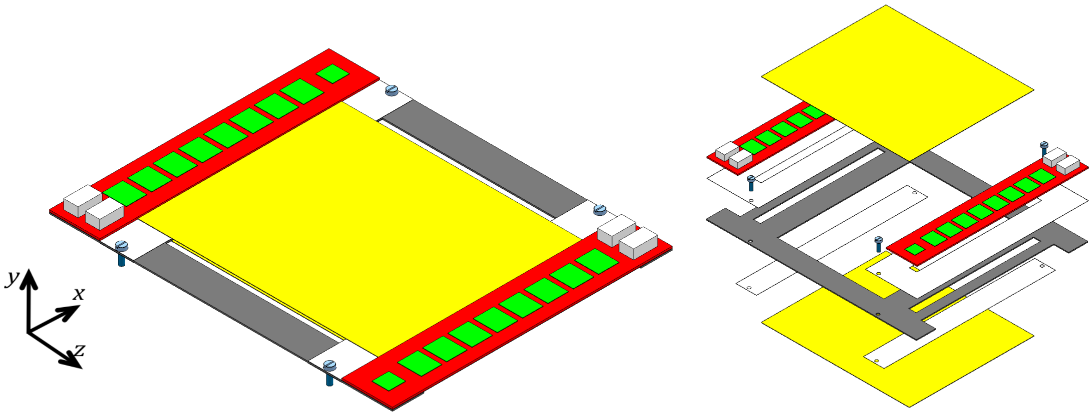



***Fig.3:*** *Model of a "2S module", made of 2 Strip sensors read out at the edges by a common set of ASICs. The connection between the sensors and the substrate carrying the ASICs is realized by wirebonds. A lightweight frame provides support and cooling to sensors and electronics, featuring a "window" to allow wirebonding on both sides of the substrate.*

### 3.1.2 The "PS module"

In order to overcome the limitations of the 2S module, while retaining as much as possible its positive features, another $p_T$ module concept is under study, based on the assembly of one strip and one pixel sensor. The module has a size of ~ 5×10 $cm^2$, the strip sensor is segmented in of 2×1024, hence featuring ~2.5 cm long strips, while the pixel sensor has pixels of ~ 1.5×0.1 $mm^2$ (Fig. 4). The shorter dimension along the z coordinate is driven by the need of covering the entire length with two pixel chips, while at the same time the shorter strips make the module suitable for operating in regions with higher particle densities. As for the 2S module, strips are read out at the edges, and the connectivity between the top and bottom sensors is realized through wirebonds on the two sides of the substrate. In this case, the correlation logic is implemented in the pixel ASIC. A detailed discussion of this module is given in another presentation at this conference [3].

Compared to the 2S module, this concept offers a sufficiently precise measurement of the z coordinate from the pixellated sensor, while the ~2.5 cm long strips allow the module to be used down to 20÷25 cm radius. On the other hand the power consumption is expected to be ≥ 4W, dominated by the pixel ASICs: a four times higher power density compared to the 2S module, which translates to a significantly higher estimated density of material.

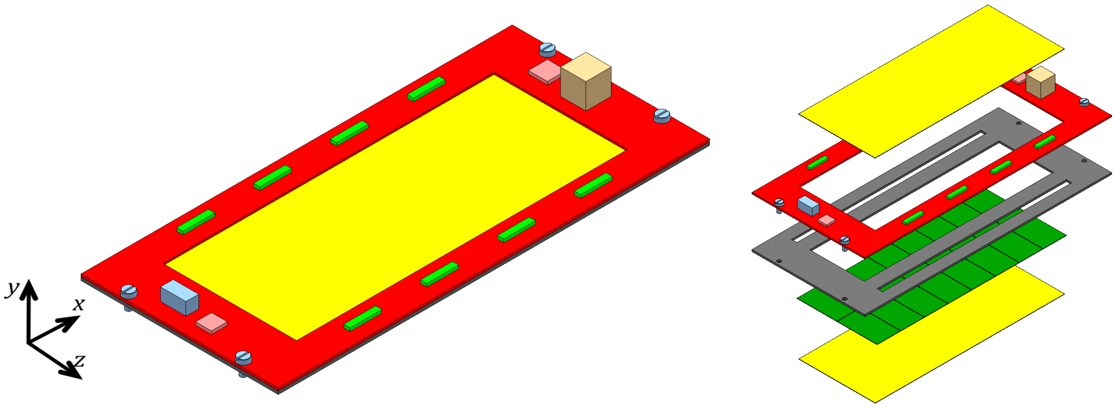



***Fig.4:*** *Model of a "PS module". The assembly and the connectivity follow the same logic as for the 2S module. In this sketch a single substrate (in red) serves the whole module, carrying the front-end ASICs for the strip sensor, as well as all the auxiliary electronics for powering and data transmission. The feasibility of such an option is under investigation.*

### 3.1.3 The "VPS module"

A different approach to the construction of a $p_T$ module made of a pixellated sensor and of one sensor with short strips is based on vertical interconnections. One same 3-d chip reads out the pixellated sensor and the short-strip sensor, connected by analogue paths through an interposer (see Fig.4), and implements the correlation logic. The use of vertical connectivity removes all constraints between module dimensions and sensors segmentation: such a module can in principle be realized in 10×10 $cm^2$ size, and, if needed, the strip length can be reduced to further reduce the occupancy (e.g. ~1 cm).

Compared to the PS module, the realization of a module of larger surface offers some advantages for the integration of hermetic surfaces and for the optimization of the services. On the other hand, the interconnection technologies are challenging: feasibility, reliability and yield for large-surface assemblies need to be verified, also considering the demanding operating conditions inside CMS. In addition, in this concept a ~1 mm thick interposer covers the entire surface of the module, defining the spacing between the two sensors, providing the top-to-bottom connectivity and carrying at the same time power lines and readout signals: the realization of lightweight interposer with the necessary electrical and mechanical properties is a key issue to realize a module with an acceptable material density.

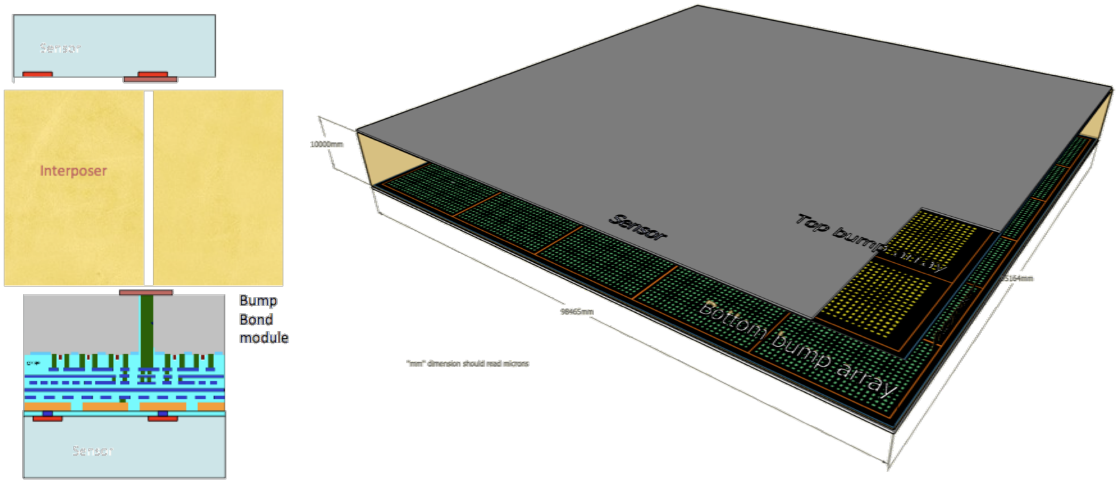



***Fig.4:*** *Sketch of the connectivity for a "VPS module" (left): a 3-d ASIC reads out at the same time the pixellated sensor and, through analogue paths in the interposer, the short-strip sensor on the other side. The interposer defines the spacing between the two sensors, carries at the same time power lines and readout signals. The module can in principle be realized in 10×10 cm² size (right).*

## 4. Evaluation of tracker options and geometries

In order to evaluate quantitatively different options and geometries for the tracker upgrade, a standalone software package has been developed (tkLayout) to generate detector layouts starting from a reasonably small set of parameters, and to implement in a simple and flexible way estimates of the material densities for active and inactive volumes, including the routing of the services. The software calculates, as a function of pseudorapidity, the expected tracking precision and the performance potential for the L1 track reconstruction, as well as the fraction of converted photons and interacting pions. Besides, it generates summary statistics for the considered layout, such as number of modules, readout channels, active surface, power consumption, estimated total weight, etc. The validation of the package with the modelling of the present tracker has demonstrated an excellent agreement between the predicted performance and the one measured on the real detector. Some examples of the studies that have been carried out are shown below.

Sketches of two layouts that have been studied in detail are shown in Fig.5: the one on the left implements 2S modules in the outer part, down to R~ 50 cm, complemented with stereo modules without trigger functionality (not discussed in this paper) in the region between 20 and 50 cm; the layout on the right implements modules with $p_T$ discrimination in the whole tracking volume, 2S module in the outer half of the radial range, and PS modules in the inner half. It should be mentioned that the use of modules with $p_T$ discrimination in the end-cap configuration is not fully proven, as it may require tuning the spacing between the two sensors according to the (R,z) position, to obtain an adequate discriminating power.

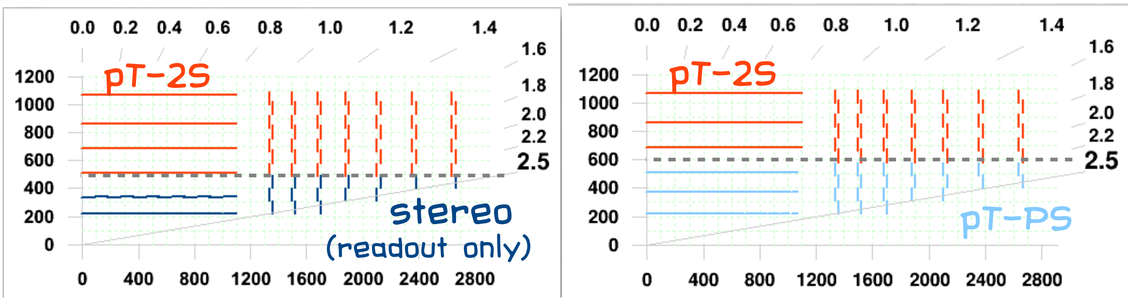



***Fig.5:*** *Left: sketch of a possible Outer Tracker layout implementing 2S modules with $p_T$ discrimination in the region R >50 cm, complemented with stereo modules without trigger functionality in the inner part. Right: layout implementing 2S modules in the outer half of the radial range, and PS modules in the inner half.*

In Fig. 6 the expected tracking precision and fraction of interacting particles of these two layouts are compared with the present tracker and with an upgraded tracker without trigger functionality (not discussed in this paper). The results show that the technological advancements that will be exploited in the upgraded tracker offer the possibility to achieve substantial improvements in tracking precision and reduced fraction of interacting hadrons and converted photons (A vs B). The performance of the layout implementing 2S modules is very close to "B", demonstrating that the use of 2S modules with trigger functionality has minimal impact on the tracker performance. A larger difference is observed for the layout with PS modules, because of the larger amount of material mostly due to the higher power density. A more detailed and quantitative comparison between the two layouts is given in Fig. 7: the use of PS modules substantially improves the performance potential for the L1 reconstruction.

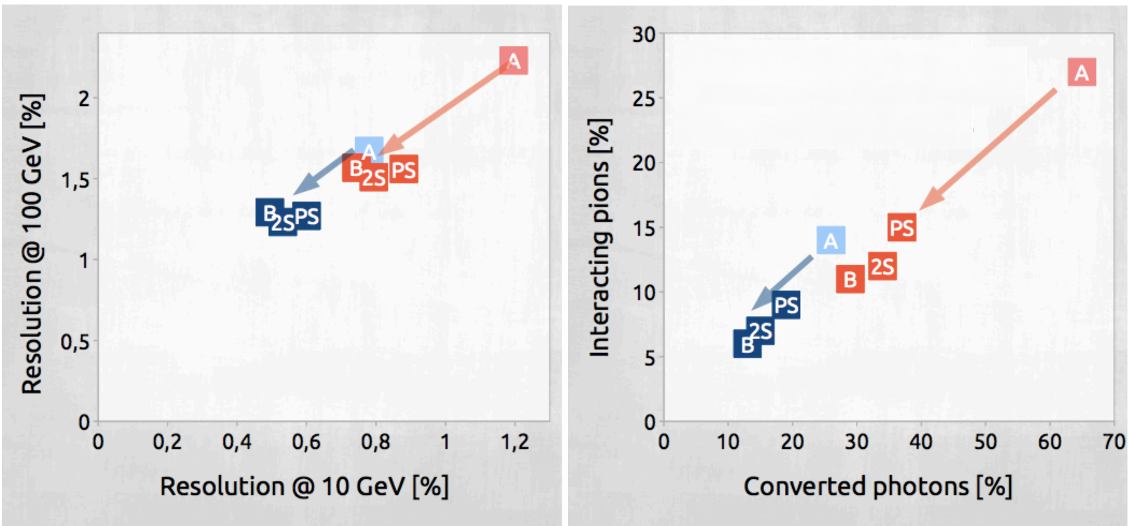



***Fig.6:*** *Comparison of momentum resolution for 10 GeV and 100 GeV tracks (left), and fraction of interacting pions and converted photons (right) for 4 tracker layouts, namely A: the present tracker, B: an upgraded tracker without trigger functionality (not discussed in this paper), 2S: the layout of Fig.5 (left), PS: the layout of Fig.5 (right). The blue and orange markers correspond to the central and intermediate rapidity regions, respectively, as defined below in Fig. 7.*

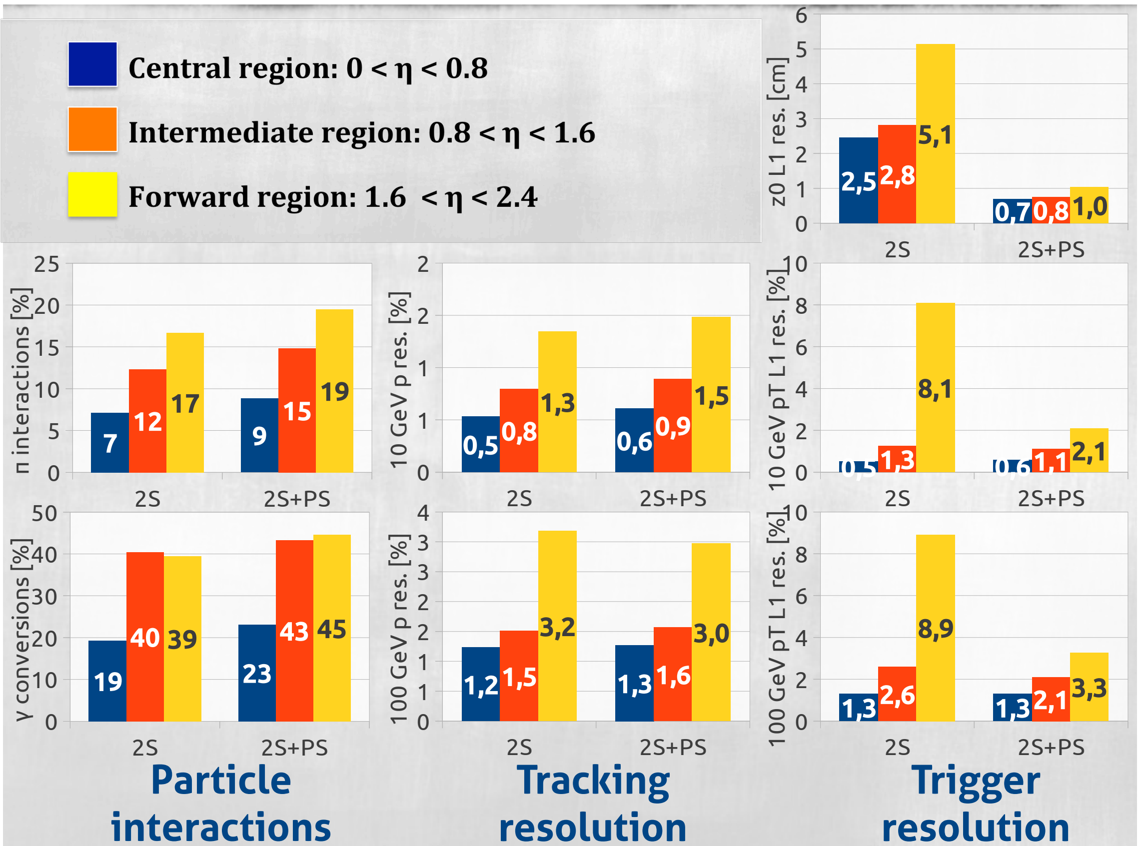



***Fig.7:*** *Comparison of the expected performance of the two layouts shown in Fig 5, in three rapidity ranges. The two layouts have very similar momentum resolution, the layout with PS modules has somewhat larger probability of particle interaction, but the performance potential for the L1 reconstruction is substantially improved, notably the momentum resolution in the forward region, and the d0 resolution in the whole rapidity range. The d0 resolution is expected to be relevant to be able to discriminate between the different collision points.*

## 5. Tracking trigger: from stubs to tracks

The coordinates of stubs selected by the $p_T$ modules have to be combined in the trigger electronics to form L1 tracks. The goal is to reconstruct with high efficiency the tracks of particles with $p_T > 2$GeV, which should allow to perform isolation cuts on calorimeter clusters. The two concepts considered so far are briefly discussed below.

### 5.1 Hierarchical processing in FPGA

The possibility of processing the coordinates of the selected stubs in a dedicated set of FPGAs has been studied in some detail, using a detector geometry optimized for trigger reconstruction. Layers are arranged in closely-spaced pairs (“double-stack” geometry) in order to mitigate the combinatorial problem, and pairs of stubs are first combined to form “tracklets”, that have sufficient precision to extrapolate to the next double stack (see sketches of Fig. 8). Tracklets and remaining un-associated stubs are then combined to form L1 tracks. The geometry is also tuned to have well-defined sectors in the φ view.

Good progress has been made in exploring this option, with barrel geometry.

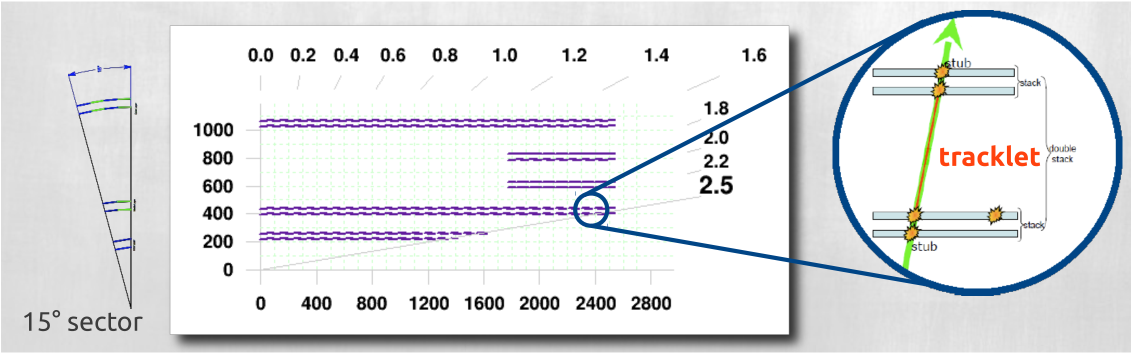



***Fig.8:*** *Hierarchical processing of stub coordinates. In a detector geometry where layers are arranged in closely spaced pairs, pairs of stubs are first combined to form "tracklets" which are then used as seeds for the L1 track finding. The modularity in φ is tuned to have self-contained 15° sectors. The concept has been studied in barrel geometry.*

### 5.2 Parallel processing in Associative Memories

Parallel processing in Associative Memories is considered as an alternative approach, which could allow to process stub coordinates in a generic detector geometry, by comparing the collected coordinates with pre-stored patterns, corresponding to the high-$p_T$ tracks. This approach was successfully used in the CDF trigger, and is been considered for the ATLAS trigger upgrade. However the application in CMS would be of unprecedented size and complexity, and feasibility studies have just started.

## 6. Conclusions

Module concepts that offer the potential for precise tracking at Level-1 in the planned upgrade of the CMS Tracker have been discussed. Modelling studies at the detector system level show that the trigger functionality can be implemented with an acceptable impact on tracking performance. Compared to the present CMS Tracker, an improvement between 30% and 50% in momentum resolution seems to be achievable, while the rate of particles (hadrons or photons) interacting in the detector material can be reduced by almost a factor of two.

The study of options to process the trigger information to form L1 tracks has also started.

The set of software tools developed to qualify the different options in terms of the expected detector performance will be an asset to achieve an optimal tracker design.

## References

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[2] G. Sguazzoni, *Performance of the CMS silicon tracker*, these proceedings.

[3] A. Marchioro, *A hybrid module architecture for a prompt momentum discriminating tracker at SLHC*, these proceedings.