

# Schedule and cost of CMS Phase II Upgrades

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# 1. Introduction

The LHC is the highest energy machine in the world and the **only** accelerator capable of investigating some of the highest priority fundamental physics topics for the foreseeable future. A 125 GeV boson compatible with the Standard Model Higgs was discovered in 2012; this is the beginning, not the end, of the programme which comprises searches for new physics and the detailed characterisation of discoveries.

The investment in the LHC programme has been immense; upgrades to CMS will extend its working lifetime considerably, and improve performance by taking advantage of technological progress. LHC operation is expected to continue for at least a decade longer than the experiments were designed for, allowing the harvest of about ten times more data, and extending searches and precision measurements considerably.

The very successful performance of the accelerator has already created challenges by exceeding some design specifications, which has a major impact on the physics capability of CMS unless addressed. Inevitable radiation damage to the tracking detector will require its replacement after 2023 and the new detector must be more granular and radiation hard. CMS must also perform better in an even harsher environment, especially the trigger, with even more events in each beam crossing, to meet required physics goals.

UK groups have played leading roles in crucial CMS sub-detectors and have undertaken highly successful R&D in recent years. The UK expects to provide new detector systems with substantial intellectual input and leadership roles.

This document summarises the present plans to contribute to the Phase II CMS upgrades and makes provisional estimates of the possible costs to the UK.

# 2. Overall LHC upgrade planning

The present machine schedule is indicated in fig. 1. There are inevitable uncertainties in the long term plan, but the recent update in November 2013 clarified plans up to the shutdown which begins in 2023. From the machine perspective, maintenance and access issues are also crucial, as well as development of major new components, such as Linac4 and the collimation and machine protection system.

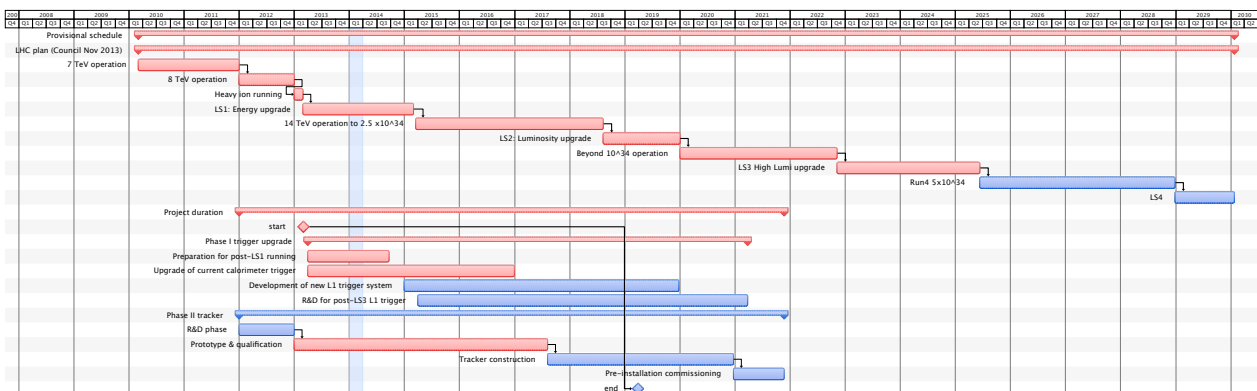


Fig. 1 Overall latest LHC schedule to the end of the next decade and the main elements of UK upgrade projects currently under way. (A larger version is appended)

CERN is now preparing for operation at the full energy of 7 TeV per beam during a Long Shutdown (**LS1**) in 2013 and 2014 which is on schedule for Run 2 data taking from March 2015. The second major shutdown (**LS2**), from mid-2018, will prepare for higher luminosities beyond  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$  (**Phase I** upgrade) starting in early 2020. The machine would run for a further three years and shut at the end of 2022 (**LS3**) for upgrade to very high intensity with an objective of a *levelled* peak luminosity of  $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , aiming to deliver up to  $3000 \text{ fb}^{-1}$ , the **Phase II** upgrade (**HL-LHC**). The timing of machine upgrades is largely determined by replacement of ageing and damaged components and new accelerator systems already in advanced preparatory stages.

What has already been achieved at the LHC is remarkable, and includes:

- confirmation of Standard Model (SM) predictions in the QCD and EW sectors at percent level
- observation of a Higgs boson with a mass of 125.7 GeV consistent with the SM
- observation at 3-5 $\sigma$  level of the major predicted SM decay modes
- strong evidence for 0<sup>+</sup> spin-parity assignment of the new boson
- measurement of rare decays such as B<sub>s</sub>- $\mu\mu$ , also consistent with the SM
- observation of other new particles, such as a new hyperon by CMS
- exclusion of a wide area of parameter space in Supersymmetry (SUSY) models
- exclusion of exotic heavy objects, with sufficiently strong couplings to quarks and gluons and sufficiently distinctive signatures, up to masses of 2-3 TeV.

There is a large physics programme envisaged for the next decade, which would be further enhanced by new discoveries, deeply investigating the Standard Model and deficiencies which must eventually emerge and can only be identified by experiment; they will be strongly enhanced by large improvements in statistics. Detector performance must remain as good as at LHC, but higher luminosity implies higher particle fluxes, detector occupancies, trigger rates, and radiation damage. Tracking detectors will have reached their design lifetime by LS3 and need complete replacement, adapted to the even harsher environment, while the remainder of the CMS detector should remain largely intact. The LS3 upgrades will coincide with major refurbishment of the LHC machine, especially the final focus quadruplet magnets which are expected to have reached their end of life.

### 3. Scope of Phase I upgrades

The CMS upgrades up to LS3 include improvements to the Hadron Calorimeter and installation of extra Muon systems, omitted for cost reasons from the present detector. DAQ improvements to keep pace with the expected data are foreseen, and investment in central systems, such as the magnet cryostat, infrastructure, including a new beam pipe, and safety systems. A new pixel detector will be installed in 2017, which will have a much reduced material budget but extra layers. The UK Phase I involvement will be in the upgraded L1 calorimeter trigger, which should be commissioned in 2015 and operating in 2016.

All the changes are to ensure CMS maintains optimal physics performance. During 8 TeV operation in 2012 the peak luminosity reached  $7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  with 50 ns bunch spacing, which doubles the pile-up (simultaneous events in a single bunch crossing) compared to the 25 ns design. After 2015, the LHC will operate with 13-14 TeV centre of mass energy, 25 ns bunch spacing and reach a luminosity of  $2.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , 2.5x the design and  $\sim 50$  events per beam crossing. Pileup could be a factor 2 larger if it is necessary to operate the LHC with 50 ns spacing, which might be required if electron cloud effects are hard to control.

These operating conditions have major repercussions for data quality and ability to discern rare signals in overwhelming backgrounds. The impact on the trigger is highly significant since rates are determined by energy thresholds in online selection of trigger objects. Upgrades have been driven by such factors as:

- offline event reconstruction is more difficult, time consuming and CPU-intensive,
- data are lost from the pixel detector, due to the size of on-detector buffers, weakening the ability to reconstruct short-lived decays from heavy quarks,
- basic trigger objects (*e*,  $\gamma$ ,  $\mu$ , *jets*, *event shape variables*) are harder to identify cleanly because of pileup of particles in calorimeters and muon detectors,
- Level-1 trigger rates would exceed the maximum level of 100kHz, owing to pileup in calorimeters and muon detectors.

Detector improvements should be sufficient to ensure efficient and high quality data until LS3, by which time over 300 fb<sup>-1</sup> of integrated luminosity are expected by LHC planners. This will allow further improvements in our understanding of the new boson: mass, spin, parity, couplings to vector bosons and fermions, possible compositeness. The physics objectives for the next decade remain

mainly unchanged: searches for partners to the new boson, other new particles and deviations from the Standard Model.

Supersymmetry is widely believed to be one of the most promising theories going beyond the Standard Model and potentially solves several major problems. It is premature to rule out SUSY although signals have not yet emerged; only the simplest models have been evaluated and although experimental results on (the absence of) sparticle observations put some SUSY models in an awkward position, many other scenarios for SUSY at the TeV scale are envisaged. Theoretical ideas are still evolving in response to the data and lack of SUSY sighting by LS3 may push searches into the next decade and instigate development of further models, requiring even higher statistics.

#### 4. Objectives of Phase II upgrades

By LS3, CMS will have operated for almost 15 years and will be running at an instantaneous luminosity of  $\sim 2.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  and  $\sim 50$  interactions per bunch crossing. From late-2022 a three year shutdown will increase the peak luminosity by a factor of  $\sim 5$  but using luminosity levelling the instantaneous value should be kept to  $\sim 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . This Phase II upgrade will provide  $\sim 300 \text{ fb}^{-1}$  per year leading to an integrated luminosity of about  $3000 \text{ fb}^{-1}$  over the following decade.

The exact scale of the entire upgrade has become clearer over the last year; it will depend on longevity issues in the sub-detectors and the physics objectives. It is certain that the tracking detectors must be replaced because of radiation damage and a new trigger is also essential. A Technical Proposal is foreseen in late 2014, with sub-detector Technical Design Reports from 2016, starting with the Tracker. (The proposed Tracker TDR date has not been reviewed since the new LHC schedule was announced and may be in 2017.) They will include evaluations of physics studies beyond what has been possible to date.

The main physics goals are clear:

- extend tests of the Standard Model, in particular measuring properties of the newly discovered particle and scattering of longitudinal components of the massive vector bosons with the highest possible precision, aiming to establish whether there are deviations from Standard Model predictions;
- confirm whether the Higgs is accompanied by other new particles at the TeV scale; not only additional resonances that might be evidence for an extended Higgs sector, but also other particles that may play a role in the global picture of electroweak symmetry breaking or the solution of the dark matter puzzle.

A very brief survey of the roadmap of physics at the HL-LHC is given below; it has changed dramatically with the discovery of the Higgs boson. There will be an unchallenged window for directly observable hypothetical heavy mass particles, indicators of new Beyond-Standard-Model (BSM) physics, and a clear task to investigate in great detail the properties of the new boson. This scenario will be enriched if 14 TeV data reveal BSM physics, which would then be exploited with higher available integrated luminosity.

SUSY searches will extend limits for generic squarks and gluinos up to 2.7 TeV and direct stop/sbottom production to 1.2 TeV. The sensitivity to direct stop/sbottom production will reach 1.2 TeV and EWKinos might be excluded up to about 800 GeV. Naturalness arguments suggest the top squark to be light, preferably below 1 TeV. At 14 TeV the direct stop pair production cross-section for 600 GeV (1 TeV) stops is 240 fb (10 fb). An increase in the luminosity from  $300 \text{ fb}^{-1}$  to  $3000 \text{ fb}^{-1}$  therefore increases sensitivity significantly for heavy stop in the interesting region or, if stop candidates are found, will enable their properties to be measured.

Heavy narrow resonances like  $Z^0$  will be probed up to typical values of 6.5 TeV (depending on models). Precise tests of the SM benefit from high statistics, especially top studies.

Two examples that only become accessible quantitatively with the HL-LHC are:

- $WH/ZH, H \rightarrow \gamma\gamma$  and  $ttH, H \rightarrow \gamma\gamma$ : These channels have a low signal rate at the LHC, but more than 100 events at the HL-LHC can be expected. The  $ttH$  initial state gives the cleanest signal with a signal-to-background ratio ( $S/B$ ) of  $\sim 20\%$ . It also provides a measurement of the top-Yukawa coupling, which is not easily accessible elsewhere.

- $H \rightarrow \mu\mu$ : The  $S/B$  of this low-rate channel is only  $\sim 0.2\%$  but the narrow peak allows to extract a more than  $6\sigma$  signal for an inclusive measurement. The exclusive  $ttH, H \rightarrow \mu\mu$  would yield a clean ( $S/B > 1$ ) sample of 30 events providing information on both top- and  $\mu$ -Yukawa couplings.

The measurements of Higgs couplings to bosons ( $\gamma, Z/W, gluon$ ) and fermions ( $b, t, \tau$ ) will be greatly improved with HL-LHC data. The estimated precision attainable with  $3000 \text{ fb}^{-1}$  is 5-10% assuming unchanged systematic errors. Estimates of 1-4% can be obtained assuming an improvement of 50% in theoretical uncertainties and scaling experimental systematics as  $\sqrt{L}$ , where  $L$  is integrated luminosity. The coupling precisions estimated by CMS for  $300 \text{ fb}^{-1}$  and  $3000 \text{ fb}^{-1}$  assuming the two error scenarios are summarised in Table 1.

In order to fully determine the parameters of the SM and to establish the EW symmetry breaking mechanism, measurement of the Higgs self-coupling is important. A direct analysis of the Higgs trilinear self-coupling  $\lambda_{HHH}$  can be made via detection of Higgs boson pair production, through interference effects with the dominant pair production at LHC by gluon-gluon fusion. These are challenging measurements but the expectation is that 30% measurement precision on  $\lambda_{HHH}$  can be achieved by combining the HL-LHC measurements.

Table 1: Expected precision in % attainable by CMS with  $300 \text{ fb}^{-1}$  and  $3000 \text{ fb}^{-1}$  assuming the present systematic errors or scaling both theoretical and experimental errors as described.

| Coupling        | [%] @ $300 \text{ fb}^{-1}$ |               | [%] @ $3000 \text{ fb}^{-1}$ |               |
|-----------------|-----------------------------|---------------|------------------------------|---------------|
|                 | <i>present</i>              | <i>scaled</i> | <i>present</i>               | <i>scaled</i> |
| $\kappa_\gamma$ | 6.5                         | 5.1           | 5.4                          | 1.5           |
| $\kappa_V$      | 5.7                         | 2.7           | 4.5                          | 1.0           |
| $\kappa_g$      | 11                          | 5.7           | 7.5                          | 2.7           |
| $\kappa_b$      | 15                          | 6.9           | 11                           | 2.7           |
| $\kappa_t$      | 14                          | 8.7           | 8.0                          | 3.9           |
| $\kappa_\tau$   | 8.5                         | 5.1           | 5.4                          | 2.0           |

A broad variety of resonances and other exotic signatures are sought at the LHC. The reach for direct observations extends deep into the TeV mass scale; a typical example is searches for new sequential standard model bosons like  $Z'$  decaying into charged lepton pairs. As important as extending the mass range is the substantial improvement in probing smaller couplings than those assumed for a sequential SM  $Z'$ . The mass reach of typically 6.5 TeV with  $300 \text{ fb}^{-1}$  will increase to 7.8 TeV with  $3000 \text{ fb}^{-1}$ . This improved reach of about 20% is typical of many other searches.

A notable area of exotic physics that would benefit particularly from the HL-LHC is final states with top quarks. Strongly and weakly produced top-antitop resonances have been studied as an interesting benchmark. For example, strongly-produced Kaluza-Klein gluons in extra-dimension models could result in broad top-antitop resonance signals. The mass reach for them would increase very significantly from 4.3 TeV at  $300 \text{ fb}^{-1}$  to 6.7 TeV with  $3000 \text{ fb}^{-1}$ . The HL-LHC would provide huge samples of tops for searches of very rare top decays as a probe for new physics.

Efforts on simulation studies of the proposed detector are steadily increasing. The most recent summary was included in a document submitted to the RRB in October 2013<sup>1</sup>.

In summary, while experimentally challenging, very significant improvements in precision and extended physics reach can be expected from the HL-LHC. More detailed simulations are under way to evaluate all the opportunities quantitatively, which depend on the modelling of the future detector and assumptions about operating conditions. Further innovations in search strategies and analyses, as well additional model tests, can be expected.

## 5. Technical progress on upgrade R&D by the UK

The UK has made contributions to the overall physics motivation and ideas for hardware developments since upgrade activities began in about 2005. UK groups have a high standing in CMS,

<sup>1</sup> CMS-RRB-2013-124

based on delivery of much of the Tracker electronic readout system - much of which was later deployed in the ECAL - Endcap ECAL construction and delivery of the Level-1 Global Calorimeter Trigger, and have taken many leadership positions over the lifetime of CMS.

UK staff were early to contribute new concepts for the future Tracker and Trigger. Important new ideas have emerged from our work, notably “stacked tracker” modules, to suppress low transverse momentum hits on-detector to ensure that data can be transferred to the trigger processors within the available bandwidth, and the idea of the Time Multiplexed Trigger, which provides boundary-free processing of calorimeter trigger data within a single FPGA, allowing new algorithms to be implemented, which will be vital in the high pileup environment as the luminosity increases.

The Phase II upgrade requires complete replacement of the present tracker with a higher granularity detector which must contribute information to the Level 1 trigger. The working design contains a pixel detector at small radii and an outer tracker ( $30\text{cm} < r < 120\text{cm}$  and end-caps) instrumented as two regions. The outermost region ( $60\text{cm} < r < 120\text{cm}$ , and outer end-cap disks) will be populated by so-called 2S-PT modules with two closely spaced microstrip sensor layers, providing L1 triggering information by correlating hits in the two layers to reject low transverse momentum track hits, and reduce the L1 data volume. The 2S designation refers to the 2 strip-sensor layers. A similar approach is adopted for the inner region of the outer tracker with increased segmentation in  $z$ , where one of the sensor layers is coarsely pixelated, hence known as PS modules. Both concepts originated from ideas developed by the UK.

UK R&D investment has led to our development of the CBC (CMS Binary Chip) ASIC to read out 2S-modules and shared development, mainly with CERN, of the 2S-modules themselves, recently demonstrated in successful beam tests.

The UK has proposed a novel, highly flexible processing architecture for the upgraded calorimeter trigger, which has been adopted for the Phase I upgrade. In a traditional trigger system, each module processes data from a small part of the detector using pipelined logic. Seamless coverage of the detector requires many cross-links between modules, and the dataflow architecture is fixed in the system design, for instance by the routing on crate backplanes. In the Time-Multiplexed Trigger (TMT), the system instead transfers all data corresponding to a given bunch-crossing into a single hardware module, with many identical modules working in parallel on different bunch-crossings. This approach is similar to that used by the CMS event builder.

The L1 trigger is designed with two layers. The first transfers data rapidly to the Layer 2 processing nodes where trigger algorithms run, but the system can be constructed with identical boards in both layers with advantages for maintenance, operation and overall cost. The current  $\mu\text{TCA}$  FPGA processor board is called the MP7, and is the most advanced of its kind in our field.

The UK has also recently produced another digital electronic board (FC7) which will be used for upgrade tracker DAQ, as well as wider applications throughout CMS, notably the new TCDS (TTC replacement) system and the Phase I pixel upgrade. In both trigger and tracker areas, the UK has a significant technological lead and expertise and the UK is one of a few funding agencies to have invested significantly for the long term future. We have significant influence and leadership responsibilities in both these areas.

Other new developments have emerged from UK studies, such as the pioneering of  $\mu\text{TCA}$  telecoms hardware, the hierarchical and expandable IPbus common firmware and software system to control and operate  $\mu\text{TCA}$  crates. The work has been supplemented by simulation studies and software developments, which have been essential to motivate the hardware initiatives and define the Technical Proposal now in preparation, and the Phase I Technical Design Reports.

UK electronics infrastructure and skills, especially in advanced ASIC and high speed FPGA board design and use in systems, are unique and world class – and, notably, have increased greatly in recent years. This partly resides in universities, and complements resources we use from RAL Technology. Other agencies have noticed our prominence in these important areas and have made efforts to emulate us. Italy, France and Germany, for example, at least in CMS, have little comparable strength in any of the electronic roles we have taken. UK ASIC and FPGA work within CMS is at least as important as anything contributed by the US and certainly of late in both areas greatly surpasses it.

Much of the UK planning for Phase II was described in the 2012 PPRP proposal, whose funding began in April 2013.

More recently, the scope of the CMS upgrade changed significantly with the relatively late realisation that changes to the calorimetry would be needed. After several years of aiming to maintain a 100 kHz L1 readout rate, with 6.4  $\mu$ s latency, it has been accepted that this presents too high a risk for the physics programme, since it is not certain that sufficiently low trigger thresholds can be maintained, even with inclusion of tracker data in the trigger. Increasing the latency (probably to 12.5  $\mu$ s, with a L1 rate of 0.5-1 MHz) necessitates changes to the ECAL electronics and therefore extraction of the barrel supermodules, during LS3. The impact of radiation damage on endcap calorimeters was also recognised to be more severe than hoped, especially affecting the most forward elements and necessitating replacement of the forward ECAL and HCAL systems, which are vital for Higgs physics. Since physics gains are believed to be significant, there is pressure to extend the future forward calorimeter coverage to higher  $\eta$ , and several alternative approaches are under urgent evaluation with the objective of narrowing down to two baseline options by early April 2014, to be pursued to the Technical Proposal.

The UK clearly has an interest in this subject, given our responsibilities for the Endcap ECAL, and involvement in Higgs physics. We are currently evaluating the potential to contribute to this R&D work and the implications for our commitments to CMS. CMS is reviewing several different options for the future forward calorimeter and expects to narrow them down to a single line by mid-2014. Among the options for UK contributions are development of VPT photo-sensors, innovative mechanical design of the new calorimeter, and electronic contributions, potentially deploying DAQ hardware developed for the new tracker and trigger. These are all areas where the UK has established expertise.

## 6. CMS Phase II Resource requirements

The overall cost scale of the upgrade is now reasonably clear, although will be further refined during the preparation of the Technical Proposal aimed for LHCC submission in September 2014. The potential extension of LHC operation beyond 2030 raises some difficult questions about the longevity of key components embedded in the experiment, especially in view of radiation exposure. The difficulties of containing trigger rates has led to proposals to revise crucial front-end electronics, e.g. in the ECAL, while the tracker is replaced; the costs are being evaluated. A balance must be found between high technology investments needed by the tracker and trigger and more modest, but effort intensive, improvements needed to ensure long term, high efficiency operation of outer, and mostly more accessible, parts of CMS. The UK was responsible for important parts of the ECAL, including some of the front-end electronics, and the endcap ECAL, which is more affected by radiation ageing but also important for some especially interesting physics studies.

CMS presented a summary of its provisional plan to the LHCC and RRB<sup>2</sup> in October 2013, to inform funding agencies. The cost of the Phase 2 upgrade is anticipated to be approximately 270 MCHF (Table 2).

Dismantling costs are either included in the total or will be covered by M&O income; at present we assume those costs will remain roughly unchanged. In CMS planning, installation and commissioning costs are also included, except for those costs involved in providing effort in CERN which would usually originate with outside institutes taking responsibility for commissioning their own hardware and sharing common efforts on the sub-detectors to which they contribute. In the case of the UK, we would expect to follow past practice and cover such expenditure from the CMS travel budget. Some further comments on costs which concern the UK directly follow later.

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<sup>2</sup> CMS-RRB-2013-124

| Item  | Sub-item                                   | Estimated CORE Cost<br>(MCHF 2013) |
|---|--|------------------------------------|
| <b>Tracker</b>                                  | Silicon Tracker                            | 94                                 |
|   | Pixel Detector                             | 34                                 |
|   |  | <b>127</b>                         |
| <b>Calorimeters</b>                             | Endcap Calorimeter Upgrade: EM & HAD       | 67                                 |
|   | HF upgrade to 4-channels per PMT           | 2                                  |
|   |  | <b>69</b>                          |
| <b>Muon System</b>                              | DT Electronics                             | 7                                  |
|   | Endcap Muon System Upgrade                 | 12                                 |
|   | High Eta Muon Tagging Station              | 6                                  |
|   |  | <b>25</b>                          |
| <b>Trigger System and Front-end Electronics</b> | L1-Trigger                                 | 7                                  |
|   | EB Frontend Electronics                    | 11                                 |
|   |  | <b>18</b>                          |
| <b>DAQ and HLT</b>                              | DAQ system: Clock, Readout, Network        | 5                                  |
|   | HLT  | 6                                  |
|   |  | <b>11</b>                          |
| <b>Infrastructure and Common Systems</b>        | Tooling, rail systems, cranes for LS3 work | 5                                  |
|   | Common Systems and Installation            | 9                                  |
|   |  | <b>19</b>                          |
| <b>Total</b>                                    |  | <b>269</b>                         |

Table 2: Summary of CORE costs for the CMS Phase 2 Upgrade

## 7. Possible cost to the UK

CMS Phase II upgrade financial or technical plans are not so well advanced that the UK share of the upgrade costs can be stated with great precision, which in any case also depends on the UK approval process as well as that in CERN and other agencies. However, a realistic appraisal of the costs which would be incurred, based on our most likely contributions to the upgrade, can be made, which ought to provide a planning envelope.

Two sets of assumptions are needed, which are explained below:

- The technical areas where the UK would contribute to construction, based on our current planning. Given our R&D progress to date, and roles in the upgrade planning, much of this is at quite an advanced stage.
- A cost-sharing model for CMS upgrade construction. This is still in its early stages so must be regarded as a plausible scenario, pending further evolution.

### 7.1 UK construction contributions

In view of the progress explained above in section 5, the two most natural areas for UK contributions to upgrade construction are in the tracker, to 2S-modules, and in the trigger, where the UK could provide the two processing layers needed for a TMT implementation of the track-trigger. However variants of this scenario are certainly possible to adapt as well as possible to available funding, or to proposed shared contributions from CMS collaborators.

For the outer tracker, since the CBC chip has no competitor, meets CMS requirements and is at an advanced stage, UK contributions to the 2S-module construction are essential and unchallenged.

In the trigger, the TMT architecture will be fully established in CMS with the Phase I upgrade and can be deployed widely in future, in the future tracking readout and track-trigger, and in the calorimeter trigger, and probably elsewhere. The MP7 has been adopted by several trigger sub-systems and it is quite likely, and highly desirable, that a single board could provide most of the trigger functionality throughout CMS in future. However, this is not yet certain and more advanced processing

boards will certainly be required for Phase II, most likely building on the MP7 design using future generations of FPGAs and optical links.

In view of the flexibility of the MP7 and its successors, such boards could be adopted for many DAQ and trigger tasks, which implies that the UK could collaborate with other groups in several different areas of CMS. The size of the track-trigger is likely to be so great (400-500 boards) that a multi-national CMS team will be assembled to operate it, in a way not dissimilar to the present Silicon Tracker DAQ, where we constructed 500 9U-VME Front End Driver boards (with spares) but share the online software tasks and operations load. Much of the future work will be dedicated to algorithm development and their implementation in FPGA firmware, an area where there are few experts and where we have a core team with significant expertise, and with a strong physics impact.

The situation with the forward calorimetry is at present too uncertain to be confident about construction contributions. However, the UK team is not so large that we would wish to be overextended and would strive to ensure any calorimeter activity would complement, and preferably build on, expertise and effort elsewhere in the UK project. Therefore, our planning is based on the assumption that our principal construction contributions will be in the two areas outlined above and that, should circumstances permit and CMS require it (for example, if crucial expertise is identified from the UK, which has been the case in the past in the ECAL and elsewhere), we would reconfigure our activities within the same cost envelope to adapt.

## 7.2 Cost-sharing model

CMS is engaged in wide ranging discussions on how the construction costs might be shared in future. In an ideal world, a formula relating share to relative size in CMS, as is done with M&O A costs, might be appropriate but this is practically very difficult to achieve. Both technical and scientific interests drive the distribution of effort between projects, as well as historic factors (the US is the major player in the HCAL and Switzerland in pixels, for example). Not all agencies are able to contribute in the areas where upgrade activities will take place. High technology electronic and sensor developments require specialist expertise and facilities, there are export restrictions on the use of radiation-hard ASIC technology imposed by the US, and some activities require long term commitments in CERN, as well as financial constraints, so achieving an acceptable balance is a challenge. Some agencies have been able to contribute more than a proportionate share of finance in the past, and this may well happen again, or be expected from some non-member state agencies which do not share in the CERN subscription costs.

Nevertheless, a potential starting point as a target for the total UK contribution might be as a fraction of the PhD author list, which is currently 4%, so  $\sim 7.4$  MCHF. We expect a Common Fund to be defined. This should certainly cover the 19 MCHF foreseen for Infrastructure and Common Systems but could justifiably include the 11 MCHF DAQ and High Level Trigger, which is what we assume. This represents 11% of the total upgrade construction cost, so the UK share would be 0.44% or 1.2 MCHF.

The UK CORE construction cost estimates are explained below in section 7.4.

## 7.3 Schedule

The detailed construction schedule is not yet defined and is expected to be done for the Tracker TDR which may be in mid-2017. However, a plausible tracker construction schedule has been widely discussed in CMS and the main parts can be reasonably well predicted (fig. 2), which allows a cost profile of UK spending on the tracker and track-trigger to be forecast. The costs have been distributed over the construction period in a way which plausibly matches the likely production rate.

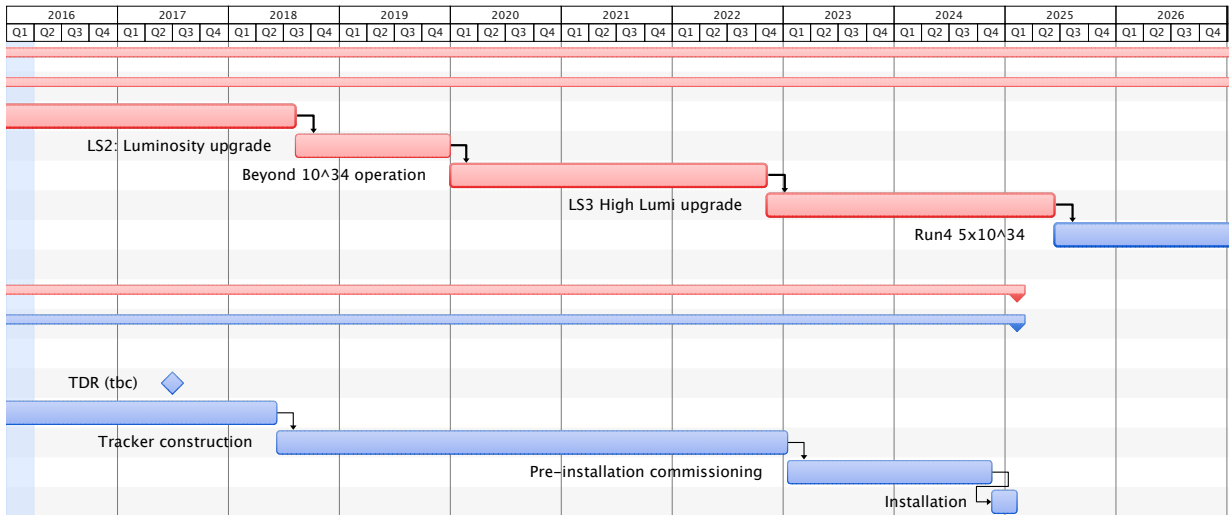


Fig. 2 The post-2016 LHC schedule and possible main elements of the tracker schedule.

## 7.4 UK costs

The estimated costs of possible CORE contributions to the tracker and trigger budgets are listed in Table 3 based on known prices in 2013, in the currencies and at the exchange rates indicated. In fact most of them originate in US \$.

|                                     |                  |      |  |
|-------------------------------------|------------------|------|--|
| <b>ASIC manufacture</b>             |                  |      | Comment                                  |
| NRE                                 | 500,000          | \$   | Final mask set                           |
| No CBC chips                        | 135,000          |      | Present layout                           |
| CBC/wafer                           | 450              |      |  |
| No wafers                           | 300              |      |  |
| Cost per wafer                      | 3,500            | \$   |  |
| Actual wafers required              | 360              |      | Allow 20% factor for losses              |
| Cost/chip (inc spare/NRE)           | 13.0             | \$   |  |
| No modules                          | 8,500            |      |  |
| CBC hybrids required                | 20,400           |      | 2 CBC hybrids per module with factor 20% |
| Cost/hybrid inc assembly            | 125              | CHF  |  |
| Total cost hybrids                  | 2,550,000        | CHF  |  |
| Total ASIC cost                     | 1,760,000        | \$   |  |
| Exchange rate                       | 1.65             | £/\$ |  |
| ASIC cost                           | 1,066,667        | £    |  |
| Hybrid cost                         | 1,758,621        | £    |  |
| Total cost                          | <b>2,825,287</b> | £    |  |
| <b>Processing board manufacture</b> |                  |      |  |
| No boards                           | 360              |      |  |
| Spares & preproduction              | 72               |      | 20% spares                               |
| Total boards                        | 432              |      |  |
| Cost per board                      | 15,000           | \$   | including optics                         |
| NRE & preproduction                 | 250,000          | \$   |  |
| No crates                           | 37               |      | 12 boards /crate                         |
| Cost per crate/utilities            | 15,000           | \$   |  |
| Crate and infrastructure            | 555,000          | \$   |  |
| Total cost                          | 7,285,000        | \$   |  |
| Total board costs                   | 4,078,788        | £    |  |
| Total crates & infrastructure cost  | 336,364          | £    |  |
| Total cost                          | <b>4,415,152</b> | £    |  |
| <b>Common fund</b>                  |                  |      |  |
| Total CMS cost                      | 270,000,000      | CHF  |  |

|                      |                  |       |                                 |
|----------------------|------------------|-------|---------------------------------|
| Exchange rate        | 1.45             | CHF/£ |                                 |
| Common fund fraction | 11.0%            |       |                                 |
| CMS Common Fund      | 29,700,000       | CHF   | DAQ/HLT & Common items = 30MCHF |
| UK share             | 4.0%             |       |                                 |
| UK Common Fund       | 1,188,000        | CHF   |                                 |
| UK Common Fund       | <b>819,310</b>   | £     |                                 |
| Total UK CORE cost   | <b>8,059,749</b> | £     |                                 |

Table 3: Possible UK CORE costs for the Phase II tracker and trigger

To estimate potential staff costs (Table 4), we have relied on the **approved** PPRP proposal produced in 2012 which began in April 2013. A possible scenario is that Consolidated Grant and RAL PPD core staff numbers remain constant over the next few years, with a similar profile of skills as at present, which would be appropriate for the projects outlined earlier. Having looked at the effort currently available, it appears possible that one extra FTE in RAL PPD might be available, for example from the ECAL, so this has been added but the university CG numbers have remained unchanged.

Similarly, the new staff (and three project student, or 10.5 FTE) requests have remained virtually unchanged from what was approved, on the assumption that this would be affordable and should deliver the projects we have in mind. In view of the R&D and Phase I trigger construction presently under way, we can be confident that this amount of effort can deliver the intellectual leadership and much of the construction effort to provide and implement our hardware. It is certain that other CMS teams would wish to collaborate and share the effort but, since there are other major items – such as sensors, mechanics and other electronics - which must be provided we do not assume that they share these costs.

No working allowance has been included, given the stage we are at. The new staff costs and university overheads should be regarded as reasonable approximations based on earlier submissions but have not been otherwise revised.

Costs are to STFC, i.e. 80% of staff and other minor costs, but assuming construction costs are funded at 100% under the Instrument Development Exception.

Travel for upgrades has been estimated, based on the assumption that there will be a need for several LTAs in CERN which will increase during construction, as the track-trigger system is commissioned. The budget is about 80% larger than the present upgrade travel budget for a similar period, but much of it at present covers R&D activities. We know that a sustained effort in CERN is required during the final stages of development, construction and installation of these complex systems, as well as for operation, for which the trigger is a crucial component required for 24-hour operation over long periods. The distinction between the regular CMS travel budget, allocated via the PPGP and assumed to continue, and upgrade construction travel may evolve in future. Institute expenses have been estimated on the assumption that this will cover some infrastructure for construction tasks, which is not eligible for CORE costs, such as crates, computers, consumables, and other expenses.

RAL TD effort has been estimated assuming some effort to finalise the masks for the CBC production will be needed but remaining effort will be assigned to ASIC acceptance work.

The nature of the work is such that it can also be distributed reasonably well over the construction period, with the ASIC production coming relatively early and the track-trigger relatively late, so avoiding a large spending peak early, or mid-way through the project. It is possible that the peak which does occur could be smoothed by agreements with other agencies or CERN.

## 7.5 M&O expenditure

At this stage the overall planning is not so precise that it is possible to describe in detail how dismantling and installation of new parts of CMS will be carried out, and some parts of the upgrade, such as the forward calorimetry, are not yet fully defined. However, it is probably possible to make realistic estimates of the impact on the UK and to assess if there is double counting regarding M&O.

The UK currently contributes ~520 kCHF annually as its share of M&O A, which is paid by STFC directly to CERN, not out of the experiment allocations. This covers many common costs which are not

attributable to individual sub-detectors, including the magnet, cooling and cryogenics, safety systems, control rooms and general technical support, as well as online and central computing, test beam facilities, clean areas and other items. The budgets are planned for about three years ahead but it is probably realistic to assume those costs would remain roughly constant. However, in shutdown periods some of them are likely to be used to cover detector operations carried out by the central Technical Coordination team, as was the case during LS1. Beam pipe installation is a typical example, and refurbishment of major cooling and powering systems. Hence it is most probable that many of the dismantling costs would be covered from within this budget.

The UK currently pays ~200 kCHF in M&O B costs for the ECAL, trigger and tracker subsystems with some additional common UK expenses, such as van hire or CERN consumables. Presently for the tracker, as an example, M&O B covers common cooling and dry gas systems, mechanics, power supply and other electronics maintenance contracts and some hired support staff costs. Eventually, during LS3, the present cooling systems will be replaced but it is most likely that the dismantling and installation costs of a new system would be largely covered by M&O B, while the purchase costs of the replacement are expected to form part of the construction budget. Hence there should be no double counting.

The UK would expect to be responsible for dismantling its own hardware so removing our own trigger electronics and tracker FED boards and crates would be part of our contribution. In our estimates of Consolidated Grant and RAL PPD core staff effort, some is attributed to upgrades but a fraction is considered to be operations. Those staff on LTA in CERN, along with short term travellers as required, would expect to carry out the dismantling and installation of the new system, as was done previously for the Global Calorimeter Trigger, the Tracker FED system and the imminent Phase I trigger upgrade. While the future track-trigger system is large, it can be compared with the present 440 large-VME board Tracker FED system and the GCT, which comprises ~70 boards of different sizes.

Therefore, while it is difficult to be precise about the exact value of dismantling and installation costs, it is believed that they should be covered in the estimates which have been made. The M&O obligations taken by the UK should be maintained within the staff complements foreseen.

## 8. Conclusions

The plans for the Phase II upgrade of CMS are still evolving but the 270 MCHF cost envelope is intended to be one of the constraints to which further technical developments are subject. The exact contribution by the UK to the Phase II upgrade is also not precisely defined but can develop in areas where we have a highly significant technical presence and leadership roles, based on our previous contributions to CMS and very successful R&D to date, and which are coherent with our physics interests.

| Institution                     | Cost to STFC      |             |                   |             |                   |             |                   |              |                   |             |                   |             | Total              |              |
|---------------------------------|-------------------|-------------|-------------------|-------------|-------------------|-------------|-------------------|--------------|-------------------|-------------|-------------------|-------------|--------------------|--------------|
|                                 | Y1                |             | Y2                |             | Y3                |             | Y4                |              | Y5                |             | Y6                |             |                    |              |
|                                 | Cost              | FTE         | Cost              | FTE         | Cost              | FTE         | Cost              | FTE          | Cost              | FTE         | Cost              | FTE         | Cost               | FTE          |
| <b>New staff</b>                |                   |             |                   |             |                   |             |                   |              |                   |             |                   |             |                    |              |
| Bristol                         | £76,571           | 2.5         | £87,344           | 3.0         | £89,478           | 3.0         | £91,670           | 3.0          | £76,556           | 2.0         | £78,836           | 2.0         | £500,455           | 15.5         |
| Brunel                          | £22,230           | 0.5         | £22,230           | 0.5         | £22,230           | 0.5         | £22,230           | 0.5          | £22,230           | 0.5         | £22,230           | 0.5         | £133,380           | 3.0          |
| Imperial                        | £178,503          | 4.8         | £201,971          | 5.8         | £215,275          | 6.3         | £218,948          | 6.3          | £193,953          | 5.1         | £178,703          | 4.1         | £1,187,352         | 32.3         |
| RAL PPD                         | £69,200           | 1.0         | £69,200           | 1.0         | £69,200           | 1.0         | £69,200           | 1.0          | £69,200           | 1.0         | £69,200           | 1.0         | £415,200           | 6.0          |
| RAL TD                          | £172,815          | 1.6         | £119,559          | 1.1         | £66,302           | 0.6         | £50,325           | 0.45         | £39,674           | 0.25        | £10,651           | 0.1         | £459,326           | 4.1          |
| <b>Total new staff</b>          | <b>£519,319</b>   | <b>10.4</b> | <b>£500,304</b>   | <b>11.4</b> | <b>£462,484</b>   | <b>11.4</b> | <b>£452,373</b>   | <b>11.25</b> | <b>£401,612</b>   | <b>8.8</b>  | <b>£359,620</b>   | <b>7.7</b>  | <b>£2,695,713</b>  | <b>60.9</b>  |
| <b>Common Fund</b>              | £100,000          |             | £120,000          |             | £140,000          |             | £150,000          |              | £160,000          |             | £150,000          |             | <b>£820,000</b>    |              |
| <b>Institute expenses</b>       | £63,000           |             | £63,000           |             | £53,000           |             | £42,000           |              | £40,000           |             | £40,000           |             | <b>£301,000</b>    |              |
| <b>CORE costbook</b>            | £480,000          |             | £650,000          |             | £1,050,000        |             | £2,270,000        |              | £2,490,000        |             | £350,000          |             | <b>£7,290,000</b>  |              |
| <b>Travel</b>                   | £70,000           |             | £80,000           |             | £90,000           |             | £100,000          |              | £100,000          |             | £100,000          |             | <b>£540,000</b>    |              |
| <b>Other costs</b>              |                   |             |                   |             |                   |             |                   |              |                   |             |                   |             |                    |              |
| Other DI                        |                   |             |                   |             |                   |             |                   |              |                   |             |                   |             |                    |              |
| Other DA                        | £3,946            |             | £3,946            |             | £3,946            |             | £3,946            |              | £3,946            |             | £3,946            |             | <b>£23,677</b>     |              |
| <b>Indirect costs</b>           | £201,903          |             | £201,903          |             | £201,903          |             | £201,903          |              | £201,903          |             | £201,903          |             | <b>£1,211,419</b>  |              |
| <b>Estates costs</b>            | £80,019           |             | £80,019           |             | £80,019           |             | £80,019           |              | £80,019           |             | £80,019           |             | <b>£480,112</b>    |              |
| <b>Total 'new' cost</b>         | £1,518,187        |             | £1,699,172        |             | £2,081,353        |             | £3,300,241        |              | £3,477,480        |             | £1,285,488        |             | <b>£13,361,922</b> |              |
| <b>Existing grant resources</b> | £831,046          | 11.1        | £829,936          | 11.2        | £824,228          | 10.9        | £853,752          | 10.1         | £859,113          | 10.1        | £849,969          | 10.0        | <b>£5,048,043</b>  | <b>63.4</b>  |
| <b>Grand total</b>              | <b>£2,349,233</b> | <b>21.5</b> | <b>£2,529,108</b> | <b>22.6</b> | <b>£2,905,581</b> | <b>22.3</b> | <b>£4,153,993</b> | <b>21.4</b>  | <b>£4,336,593</b> | <b>18.9</b> | <b>£2,135,457</b> | <b>17.7</b> | <b>£18,409,965</b> | <b>124.3</b> |

Table 4: Estimated resource requirements for a six year construction programme.

