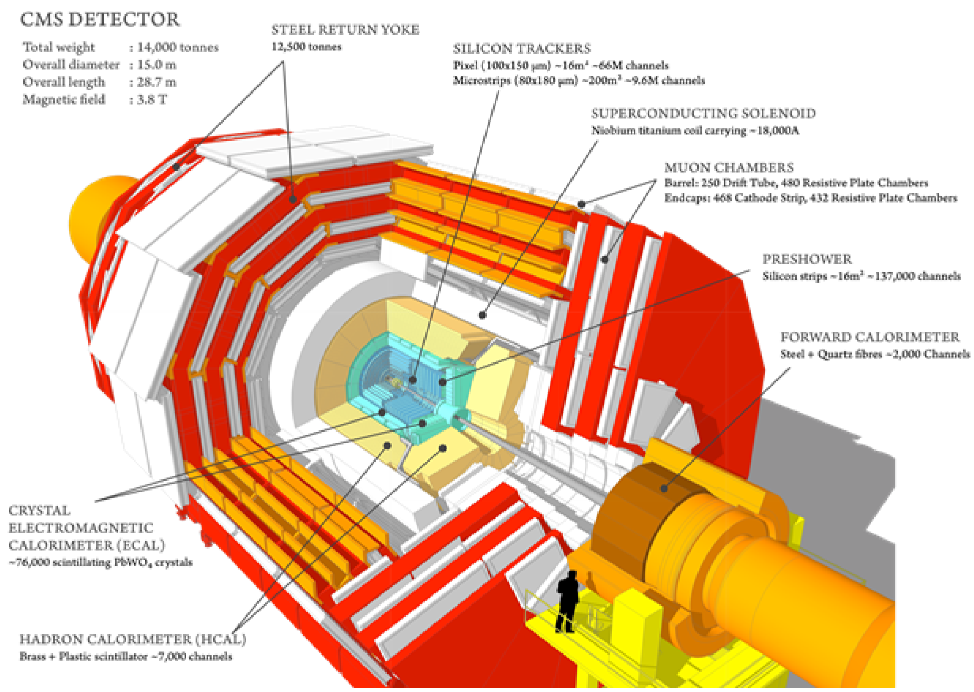
# U.S. CMS Compact Muon Solenoid Operations Program Quarterly Report for the Period Ending December 31, 2015

U.S. CMS Operations Program



# Program Manager's Summary

During this quarter, the 4th quarter of *calendar year 2015* (Oct – Dec 2015), the LHC completed its first running period in Run 2. The initial proton-proton physics run was completed, and after a set-up period, LHC collided heavy ions for a month. In mid December the LHC entered a "year end technical stop" (YETS) period with no beams in the machine, giving opportunity for repairs in the experiment areas.

During the run CMS data taking efficiency was high at an overall 90%. The total luminosity recorded in CMS during stable beams with $p-p$ collisions at 13 TeV center-of-mass energy was 3.81/fb. This number includes approximately 0.40/fb of data taken with the magnetic field off or below nominal value due to the problems with the magnet cryogenic system.

In November the run was turned over to the Heavy Ion (HI) physics program. LHC performed an initial reference proton collision run at the nucleon center-of-mass energy of 5 TeV, delivering 29.5/pb of which CMS recorded 27.9/pb. LHC then switched to lead-on-lead ion collisions, also at $\sqrt{s} = 5$ TeV/nucleon, delivering 0.60/nb, of which CMS recorded 0.56/nb.

At the end of the running period, during the HI run, CMS developed a water leak in the endcap muon system (YE+1) that impacted the operation of the detector and ultimately required to switch off power to the on-detector electronic. CMS ran without the whole Muon Endcap ME+1 station for the last few days of the HI run. Impact on HI data taking was only limited. A search for leaks and potential damages to detector electronics, as well as repairs are planned for the YETS. This work will impact the already tight schedule of the technical stop in the next quarter, as the CMS heavy elements will need to be opened to perform the repairs.

Scintillator light output in the HCAL is constantly monitored for the effect of radiation damage. We saw that the end cap HE signals continued to degrade due to significant radiation effects on scintillator tiles and wavelength-shifting fibers, and this is expected to continue at a rate that is possibly higher than anticipated. Working groups were formed in November to study the damage, assess its physics impact, and to develop mitigation strategies. HCAL also looks into the possibility of a partial replacement of HE mega-tiles during the Long Shutdown 2 (LS2).

Problems with operating the CMS magnet continued throughout the quarter. Since March the "Cold Box" (CB) that liquifies Helium for cooling the CMS superconducting solenoid has shown problems, following an incident where compressor oil contaminated the downstream CB circuits. There are now detailed plans for an overall cleanup to be preformed during next quarter's YETS. The oil separation system which is part of the Helium liquification plant will be replaced with a higher-capacity model, which has been ordered to arrive in time for installation during the YETS.

During the quarter the performance of the CB continued to be instable leading to insufficient production of liquid cold helium. Pressure-drops increasing over filters and adsorbers used to remove contaminants from the system, and variances in the temperature gradient across heat exchangers allowed to track the performance of the system. Breaks were needed to replace filters and regenerate adsobers and heat exchangers in the system, leading to down-times where the magnet could not be adequately cooled and thus had to be switched off. The CERN cryogenics group and CMS Technical Coordination managed to operate the CB with a reasonable duty cycle such that magnet down times could be to some extent synchronized with planned breaks in LHC physics operations. The impact on CMS data taking thus was minimized, and despite the ongoing difficulties with operating the CMS magnet, physics data taking was rather successful. Overall the CB issues resulted in loss of just about 10% of the total integrated luminosity during the run, and in the end only marginally effected CMS' physics productivity.

On going LHC and CMS activities determined the agenda for Software and Computing during the quarter. The end of the proton running allowed for a reprocessing pass for both data and simulation samples. A lot of work was done in software to be ready and to prepare the facilities and infrastructure systems for the data processing. The HI run with its higher data taking rate put particular strains on many aspects of the system, which required fast turnaround on a number of development efforts. These will be useful for the proton program as higher luminosities are reached. Finally, the start of the LHC technical stop allowed all computing facilities to focus on reprocessing activities.

The Resource Managers report section gives a detailed financial summary of the year 2015. The total spending for the U.S. CMS Operations Program in 2015 was $38,235K, of which $17,483K was spent on Software and Computing, $7,420K on Detector Operations and $4,015K on R&D for HL-LHC detector upgrades. A sum of $9,317K was spent on Common Operations, including $4,903K on CMS common cost for Cat-A maintenance and operations cost and the detector upgrade Common Fund for Phase 1. Management reserve funds totaling $700k were allocated over the year to deal with problems that required additional spending. The total cost variances were larger than that, as reported through change orders and in the quarterly reports. However, cost savings largely canceled out cost increases. In particular the exchange rate to Swiss Franc turned out to be favorable. A total of 27% of the spending was in Swiss Franc, at an average exchange rate of 0.96 CHF/USD, while the program had planned for a rate of 0.9 CHF/USD. A total of 109 SOWs (71 DOE and 38 NSF) were produced with U.S. universities and labs.

With the LHC "Data Jamboree"[1] on December 15 a challenging year ended with a real physics highlight. CMS presented[2] 33 different results using the initial Run 2 data at 13 TeV. The breadth of the physics and the fast turnaround to come to publishable results demonstrates the excellent operational performance of the detector, software, and computing systems. It is a testament to the success of all the operations tasks that are required to get from data to physics objects with which analysis can be performed.

[1] https://indico.cern.ch/event/442432/

[2] Slides of the CMS presentation are available here

# Report of the U.S. CMS Resource Manager

The funding provided by DOE and NSF to the U.S. CMS Operations Program for 2002 through 2015, as well as the funding guidance for 2016 through 2019, is shown in Figure 1.

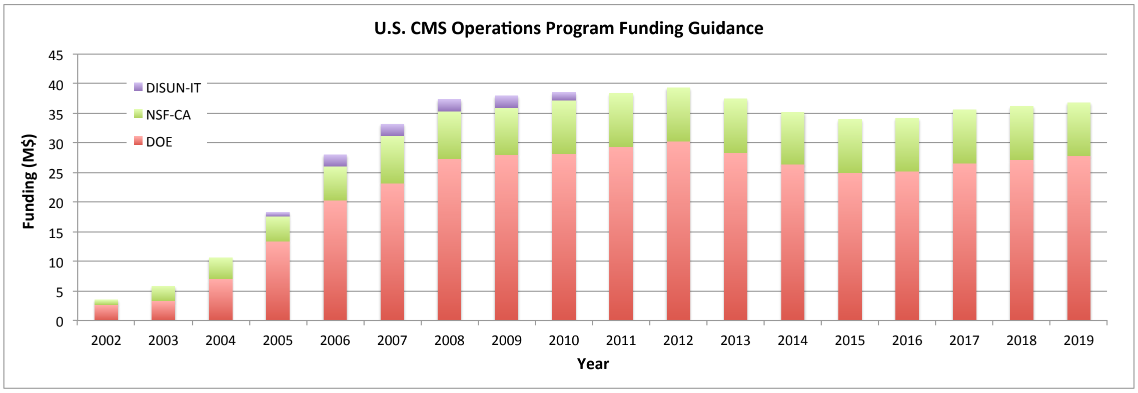



Figure 1: The annual U.S. CMS Operations Program funding provided by DOE and NSF. For 2002 through 2015 the chart shows the actual funding, while for 2016 onward the current funding guidance is shown.

Resources are distributed and tracked across the three areas through which the Operations Program is implemented: Detector Operations (DetOps), Software and Computing (S&C), and Common Operations (ComOps). ComOps is a category for items that would otherwise belong in both, or neither, of the other two categories.

Internal budget reviews for calendar year 2015 took place in August and September of 2014. Through this process, U.S. CMS Management developed a detailed spending plan. This plan was further refined through the March 2015 joint NSF/DOE Operations Program review.

Primarily during the first quarter of the calendar year, Statement of Work (SOW) agreements were established with each institution that is providing a deliverable in exchange for Operations Program funding. The SOWs specify the tasks to be carried out, as well as any portions of salaries, materials and services (M&S), travel funding, or cost of living adjustments (COLA) to be paid from the Operations Program budget. The SOWs must be approved by U.S. CMS Operations Program management, by the Fermilab Director Designee, and by representatives of the collaborating group and institution. In 2015, a total of 109 SOWs (71 DOE and 38 NSF) were produced and approved. After a SOW is approved, any additional changes are considered and, if approved, enacted through a Change Request procedure.

Table 2 shows the Spending Plan Change Log which captures revisions that were made prior to SOW approvals, as well as modifications implemented through Change Requests. The information is reported here down to the level-2 subsystem categories within DetOps, S&C, and ComOps. The CY15 spending plan, as of the end of Q4, is shown for DOE and NSF funds in Table 3. This represents the final status of the spending plan for CY15.

Once funds have been committed through purchase orders, in the case of DOE, and sub-awards, in the case of NSF, they are considered obligated. Figure 4 shows the obligations in the areas of DetOps, S&C, and ComOps, as compared to the spending plan, for DOE funds. The spending plan is plotted as if expenditures are carried out in even allocations each month, but this is intentionally not the

| U.S. CMS Detector Operations Change Control Activity | | | | | | |
|---|---|---|---|---|---|---|
| **WBS** | **Subsystem** | **Change Request Number** | **Description of Change** | **CY15Q4 Plan** | **Change $** | **CY15Q4 End** |
| 11 | Endcap Muon | | | $1,836,496 | $0 | $1,836,496 |
| 12 | Hardon Calorimeter | | COLA adjustment in CERN Team Account | $1,603,658 | $1,111 | $1,604,769 |
| 13 | Trigger | | | $926,141 | $0 | $926,141 |
| 14 | Data Acquisition | | | $780,208 | $0 | $780,208 |
| 15 | Electromagnetic Calorimeter | | | $841,815 | $0 | $841,815 |
| 16/17 | Tracker (Fpix&SiTrk) | | | $732,798 | $0 | $732,798 |
| 18 | Detector Support | CR-018 | Labor and materials for CT-PPS reference timing system | $258,262 | $51,000 | $309,262 |
| 19 | BRIL | | | $388,180 | $0 | $388,180 |
| 30 | Phase 2 Upgrade R&D | | | $4,014,955 | $0 | $4,014,955 |
| **11-18,30** | **Detector Operations** | | | **$11,382,513** | **$52,111** | **$11,434,624** |

| U.S. CMS Common Operations Change Control Activity | | | | | | |
|---|---|---|---|---|---|---|
| **WBS** | **Subsystem** | **Change Request Number** | **Description of Change** | **CY15Q4 Plan** | **Change $** | **CY15Q4 End** |
| 21.2 | Common Costs (M&OA, LS1, Loan) | | | $4,902,773 | $0 | $4,902,773 |
| 21.3 | RCMS | | | $554,413 | $0 | $554,413 |
| 21.4 | LHC Physics Center | | | $674,179 | $0 | $674,179 |
| 21.5 | Operations Support | CR-091 | U. of Florida L1 Trigger Project Manager travel support | $1,784,671 | $3,780 | $1,788,451 |
| 21.6 | Program Office | | | $1,049,394 | $0 | $1,049,394 |
| 21.7 | E&O | | | $345,480 | $0 | $345,480 |
| 21.8 | Collaboration Support | | | $2,500 | $0 | $2,500 |
| **21** | **Common Operations** | | | **$9,313,410** | **$3,780** | **$9,317,190** |

| U.S. CMS Software and Computing Change Control Activity | | | | | | |
|---|---|---|---|---|---|---|
| **WBS** | **Subsystem** | **Change Request Number** | **Description of Change** | **CY15Q4 Plan** | **Change $** | **CY15Q4 End** |
| 22.1 | Fermilab Facilities | | | $6,556,269 | $0 | $6,556,269 |
| 22.2 | University Facilities | | | $4,142,508 | $0 | $4,142,508 |
| 22.3 | Computing Operations | | | $1,129,031 | $0 | $1,129,031 |
| 22.4 | Computing Infrastructure and Services | CR-009 | Princeton SWF reduction | $2,106,931 | ($48,443) | $2,058,488 |
| 22.5 | Software and Support | | | $1,951,086 | $0 | $1,951,086 |
| 22.6 | Technologies & Upgrade R&D | CR-010 | Contractor support extension | $899,330 | $58,798 | $958,128 |
| 22.7 | S&C Program Management & CMS Coordination | CR-009 | Princeton COLA reduction | $694,276 | ($6,600) | $687,676 |
| **22** | **Software and Computing** | | | **$17,479,431** | **$3,755** | **$17,483,186** |
| | | | | | | |
| **U.S. CMS Operations Program Total** | | | | **$38,175,354** | **$59,646** | **$38,235,000** |

Figure 2: Spending Plan Change Log for CY15 Q4.

| WBS | Subsystem | DOE Funds | NSF Funds | Total |
|---|---|---|---|---|
| 11 | Endcap Muon | $1,501,776 | $334,720 | $1,836,496 |
| 12 | Hadron Calorimeter | $1,531,358 | $73,411 | $1,604,769 |
| 13 | Trigger | $778,331 | $147,810 | $926,141 |
| 14 | Data Acquisition | $780,208 | $0 | $780,208 |
| 15 | Electromagnetic Calorimeter | $841,815 | $0 | $841,815 |
| 16/17 | Tracker (Fpix-SiTrk) | $703,520 | $29,278 | $732,798 |
| 18 | Detector Support | $309,262 | $0 | $309,262 |
| 19 | BRIL | $115,300 | $272,880 | $388,180 |
| 30 | Phase 2 Upgrade R&D | $3,263,171 | $751,785 | $4,014,955 |
| **11-19,30** | **Detector Operations** | **$9,824,741** | **$1,609,884** | **$11,434,624** |
| 21.2 | Common Costs (M&OA,LS1,UpgrdLoan) | $3,894,968 | $1,007,805 | $4,902,773 |
| 21.3 | Run Coordination and Monintoring | $554,413 | $0 | $554,413 |
| 21.4 | LHC Physics Center | $674,179 | $0 | $674,179 |
| 21.5 | Operations Support | $1,595,945 | $192,506 | $1,788,451 |
| 21.6 | Program Office | $931,844 | $117,550 | $1,049,394 |
| 21.7 | Education and Outreach | $229,000 | $116,480 | $345,480 |
| 21.8 | Collaboration Support | $2,500 | $0 | $2,500 |
| **21** | **Common Operations** | **$7,882,849** | **$1,434,341** | **$9,317,190** |
| 22.1 | Fermilab Facilities | $6,556,269 | $0 | $6,556,269 |
| 22.2 | University Facilities | $111,217 | $4,031,291 | $4,142,508 |
| 22.3 | Computing Operations | $713,568 | $415,463 | $1,129,031 |
| 22.4 | Software and Support | $1,677,995 | $380,493 | $2,058,488 |
| 22.5 | Computing Infrastucture and Services | $1,694,841 | $256,245 | $1,951,086 |
| 22.6 | Technologies & Upgrade R&D | $264,989 | $693,139 | $958,128 |
| 22.7 | S&C Program Management and CMS Coordination | $464,016 | $223,660 | $687,676 |
| **22** | **Software and Computing** | **$11,482,895** | **$6,000,291** | **$17,483,186** |
| **U.S. CMS Operations Program Total** | | **$29,190,484** | **$9,044,516** | **$38,235,000** |

Figure 3: Spending plan at the end of CY15 Q4, for funds from DOE, NSF, and the total.

case due to equipment purchases and the larger of the transfers to CERN-based Team Accounts, the latter of which are targeted for when exchange rates are favorable.

Spending through Universities and CERN Team Accounts is budgeted and tracked according to the calendar year, while spending at Fermilab has historically been budgeted according to the fiscal year. Of special note is that this year we have transitioned to reporting based on calendar year rather than based on fiscal year. There are two features of Figure 4 related to this transition. First, obligations for DOE spending at Fermilab in the last three months of calendar year 2014 have been included in the plotted obligations for 2015. Second, to accommodate the three month offset between fiscal year and calendar year, a buffer of $3M has been allocated this year, drawing from carry over from previous years. This is indicated by the difference between the solid and dashed blue lines. Figure 5 shows the total obligations and the spending plan, for NSF funds. Of the $9M in NSF funding, $1.1M in subawards went out this quarter, in addition to spending directly at Princeton.

Resources deployed at CERN, and paid directly in Swiss francs, account for approximately 28%

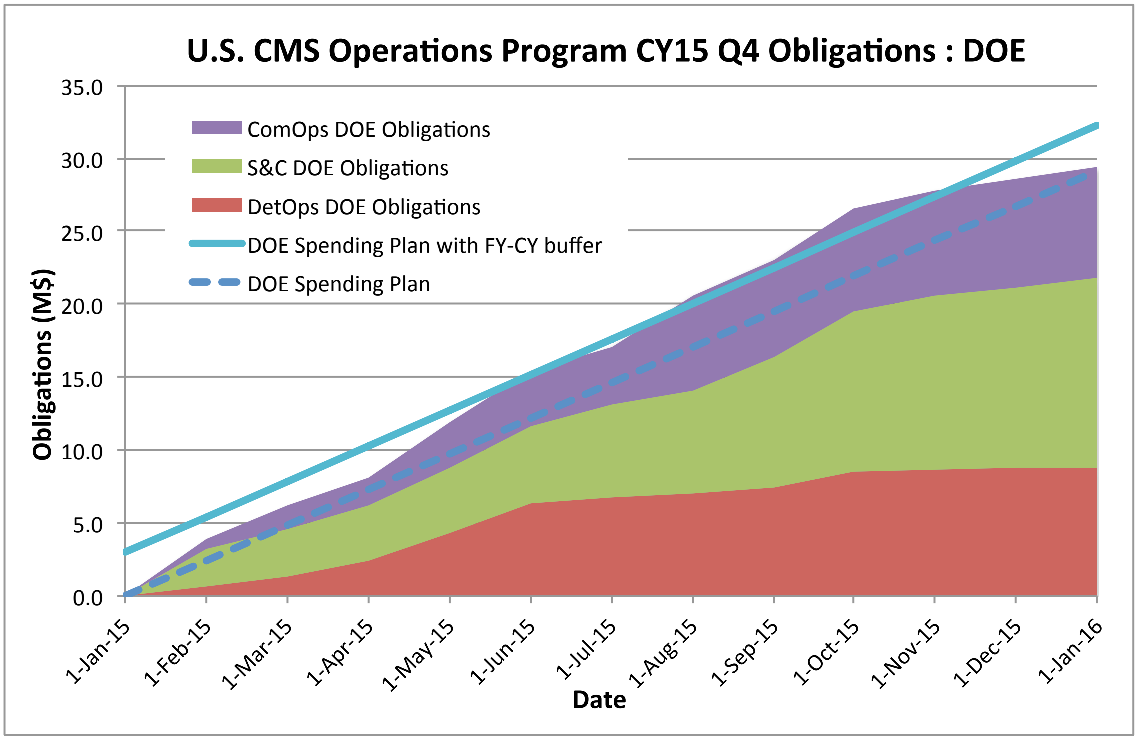



Figure 4: Obligations and spending plan for DOE funds. The spending plan is indicated with the assumption of equal monthly increments just as a rough guide. The lines show the spending plan with (solid) and without (dashed) a required buffer to bridge the difference between fiscal year and calendar year for funds spent at Fermilab, as described in the text.

of the 2015 spending plan. This carries considerable exposure to the exchange rate. A rate of 0.9 CHF/USD has been used for planning, while the actual rate in CY15 Q4 averaged 0.99 CHF/USD. Figure 6 shows the allocated budgets and year-to-date spending through the Team Accounts that are used for expenditures at CERN. Spending for labor and cost of living adjustments occurs at a fairly constant rate. Figure 6 does not include the last 823K CHF of the Upgrade Common Fund payments and the 3,827K CHF M&O-A payments, as these are each made through multiple payments to a separate Team Account.

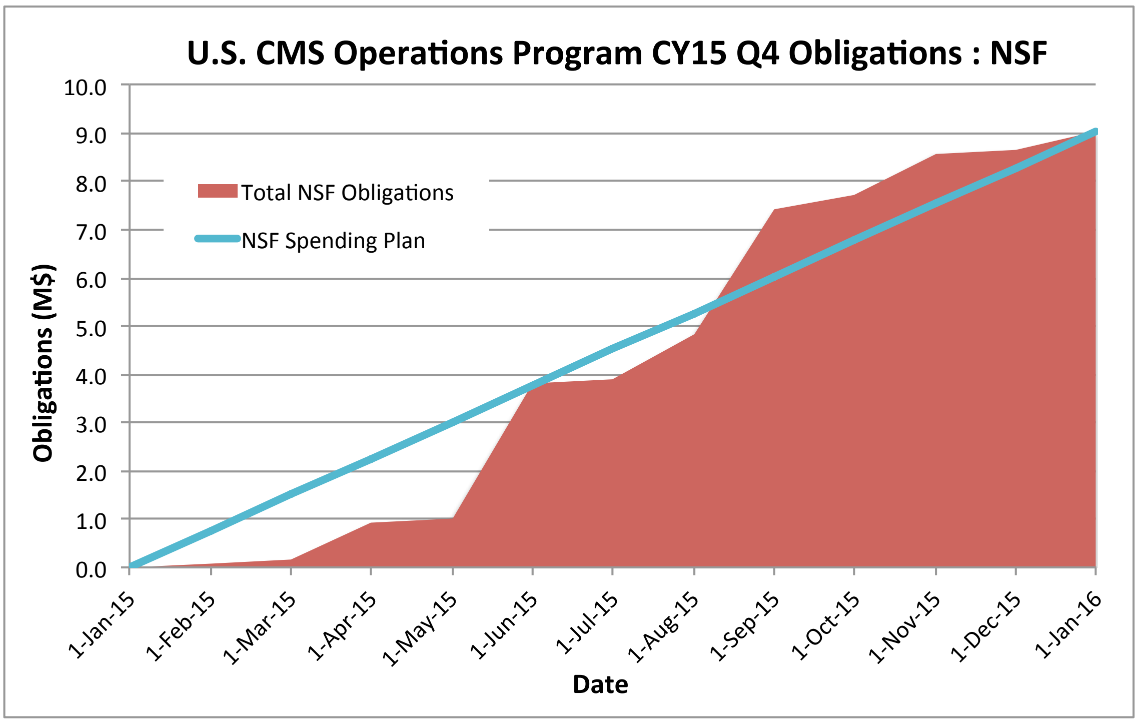



Figure 5: Obligations and spending plan for NSF funds. The spending plan is indicated with the assumption of equal monthly increments as a rough guide.

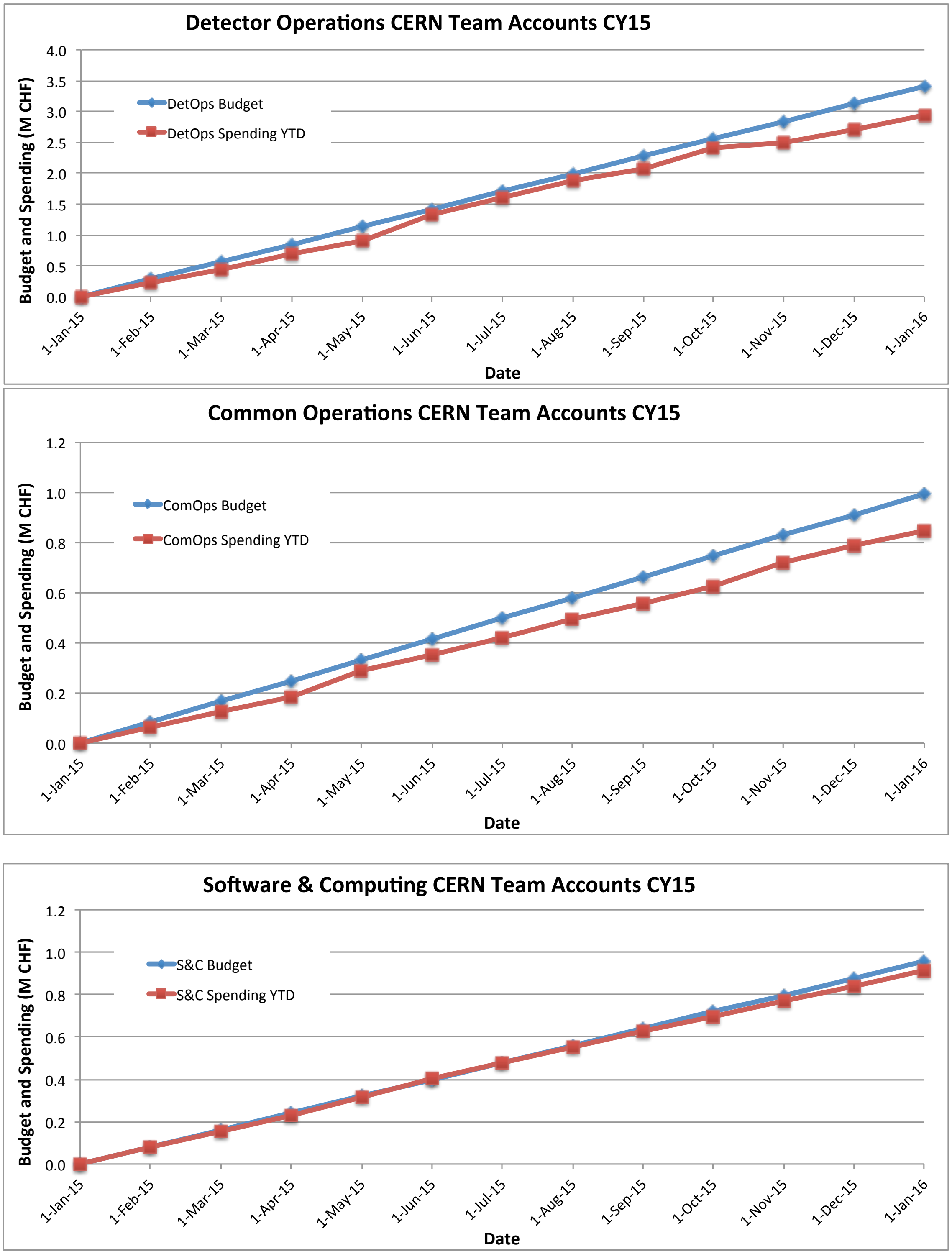



Figure 6: Budget plan and year-to-date spending, in Swiss francs, through DetOps (top), ComOps (middle), and S&C (bottom) Team Accounts.

## Detector Operations

Problems with the CMS magnet continued until the end of the year and the start of the technical stop. As reported last quarter, since March the Cold Box (CB) that produces liquid helium for cooling operation of the superconducting CMS magnet has shown problems, after an incident where compressor oil contaminated the CB circuit. For definitive recovery, the system requires an overall cleanup, which will takes several months and is now scheduled for the Year End Technical Stop starting at the end of this year. Meanwhile, the CERN cryo group, in collaboration with the CMS Technical Coordination, was able operate the CB with a reasonable duty cycle. In total, approximately 0.40/fb luminosity was with the magnetic field off or below nominal value. Figure 7 shows the luminosity delivered (blue) and recorded by CMS (orange) during 2015. The total luminosity recorded in CMS during stable beams with $p-p$ collisions at 13 TeV center-of-mass energy was 3.81/fb, taken with an overall efficiency of 90%.

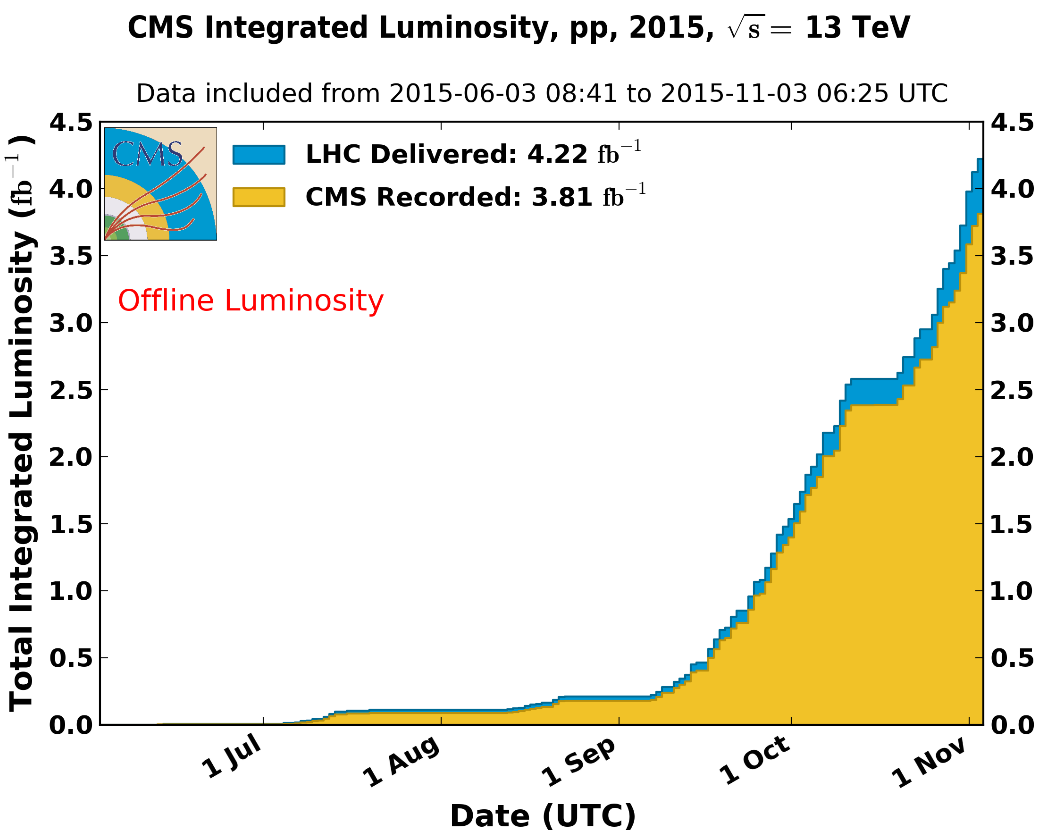



Figure 7: Cumulative offline luminosity versus day delivered to (blue), and recorded by CMS (orange) during stable beams and for $p-p$ collisions at 13 TeV center-of-mass energy in 2015. The delivered luminosity accounts for the luminosity delivered from the start of stable beams until the LHC requests CMS to turn off the sensitive detectors to allow a beam dump or beam studies. Given is the luminosity as determined from counting rates measured by the luminosity detectors after offline validation. This preliminary calibration is based on short van-der-Meer scans performed routinely by LHC in every fill.

In November the run was turned over to the Heavy Ion physics program. There was an initial reference proton collision run at 5 TeV center-of-mass energy, followed by lead-lead collisions at 5 TeV center-of-mass energy per nucleon. The LHC delivered 29.5/pb of proton collisions for the reference run, of which 27.9/pb were recorded. LHC delivered 0.60/nb of lead-lead collisions, of which 0.56/nb were recorded.

On December 15, at the so-called "Data Jamboree", the CMS experiment presented 33 different physics results from the 13 TeV data. This is a testament to the excellent operational performance of the detector, and the success of all the operations tasks that are required to get from data to physics objects with which analysis can be performed.

## BRIL

The main emphasis of the U.S. CMS hardware effort as part of the BRIL sub-detector group is the pixel luminosity telescope (PLT). The PLT provides fast triple-coincidences in 3-layer telescopes, and also has a readout of full hit-information at a lower rate. Based on the latter, detailed studies were performed that resulted in a first round of luminosity calculations for the 13 TeV data set by the time of the jamboree. The PLT also participated successfully in the Heavy Ion run at the end of 2015. All BRIL detectors have been shutdown for the year end technical stop.

During the quarter improvements were made to the online monitoring and DQM and these will be further improved during the technical stop to incorporate lessons learned from the running. Also during the shutdown, repairs will be made to two out of 16 telescopes that developed problems during the run. Parts for repair are ready and will be operated in a test stand that can be cooled down. The test stand has been moved to building 168 at CERN and is presently being recommissioned.

The pixel luminosity telescope was a very successful addition to the CMS detector in 2015, and it is expected to provide high-quality luminosity information with continuously improved certainty. The PLT's useful lifetime is predicted to to be 500/fb, and eventual radiation damage and efficiency is continuously monitored.

The PLT is now transition to regular operations, and that critically dependent on the presence of at least one senior researcher at CERN. Currently there is a concern as to how this support will be provided in the future, and U.S. CMS might have to re-evaluate the level of support.

Table 1: BRIL Milestones.

| Subsystem | Description | Scheduled | Achieved |
|---|---|---|---|
| BRIL | Hardware installed | Jan | Jan |
| BRIL | Ready to deliver Lum | March | March |
| BRIL | Ready to deliver bkg nums | May | May |

Table 2: BRIL Metrics.

| Metric | Performance |
|---|---|
| Fraction of telescopes operational | 14/16 |
| Efficiency of delivery of lumi histograms | $>$ 99 % |
| Uptime of lumi histogram production | $\sim$ 99 % |

## Tracker

The Tracker successfully shifted from proton-proton running to heavy ion running. The upcoming 2015-2016 YETS will be dominated by cooling system maintenance. We will also explore increasing the readout rate of the SLINK cards in the pixel DAQ. Work on the power issues in the BPiX will only commence once the magnet can again be energized towards the end of the technical stop.

**Pixels** In the last proton-proton running, pixels accounted for 13% of the CMS downtime. Heavy Ion data taking began with a modified proton-proton firmware that however resulted in a large (>10%) deadtime for CMS. A specifically developed new Heavy Ion firmware was installed on December 2 and worked well, reducing deadtime due to pixels well below 1%. During the Heavy ion running, pixels accounted for 11% of the CMS downtime. In total 98.6% of the pixel tracker channels are working, and for the FPiX alone 99.8% of channels are working.

**Strips** Towards the end of proton-proton running the Strips accounted for 8% of the CMS downtime. Heavy Ion data taking began with a new firmware that compresses the strip data. This firmware works well at rates below 10 kHz (typical rates were around 4-5 kHz). During the Heavy Ion running, Strips accounted for 21% of the CMS downtime. 97.3% of strip tracker channels are working.

Table 3: Tracker Milestones.

| Subsystem | Description | Scheduled | Achieved |
|---|---|---|---|
| Tracker | Installation and checkout | | Achieved |
| Tracker | Tracker operate -15C | | Achieved |
| Tracker | Pixel operate -10C | | Achieved |
| Tracker | Ready for proton beams | March | March |

Table 4: Tracker Metrics.

| Metric | Pixels | Strips |
|---|---|---|
| % Working channels | 98.6% | 97.3% |
| Fraction of deadtime attributed | 13% | 8% |

## ECAL Electromagnetic Calorimeter

The ECAL has performed excellently during the whole Run 2 period. The fraction of active channels is 99.07% in the barrel, 98.71% in the endcaps, and 96.9% in the preshower. ECAL has operated with very high data-taking and certification efficiency during the whole of 2015, causing no significant loss of recorded luminosity. A new pulse fit reconstruction technique has been deployed to mitigate the effects of out-of-time pileup. After a commissioning period this has been shown to improve resolution and identification efficiency of electrons and photons.

The stability of the new blue laser monitor has been excellent in Run 2. This has allowed the smooth computation of the laser monitoring corrections, to account for radiation-induced response changes. The laser corrections were also used to correct the energy scale at Level-1 and

HLT, both in the endcaps and in the barrel. This for the first time significantly improved trigger performance.

An intense program of work has been carried out in the summer and autumn to re-commission the three energy calibration methods ($\pi^0/\eta$, phi-symmetry in minimum bias events, and single electron events using the $E/p$ ratio), to understand the response of each calibration method at 13 TeV with respect to 8 TeV, and to evaluate any effects induced by the new reconstruction method. These were validated using $Z \rightarrow ee$ decays. They provide almost the same resolution as in 2012 for non-showering electrons in the barrel, and slightly worse in the endcaps, due to the smaller number of electron events recorded in 2015.

Table 5: ECAL Milestones.

| Subsystem | Description | Scheduled | Achieved |
|---|---|---:|---:|
| ECAL | Finish HV Install | Feb | May |
| ECAL | Baseline levels zero suppression | March | March |
| ECAL | Complete install HV calib system | April | May |
| ECAL | Selective readout | June | July |
| ECAL | Trigger thresholds | June | July |
| ECAL | Zero suppression thresholds | June | July |

Table 6: ECAL Metrics.

| Metric | Performance |
|---|---:|
| Fraction of channels operational: EB | 99.1% |
| Fraction of channels operational: EE | 98.9% |
| Fraction of channels operational: ES | 98.4% |
| Fraction of deadtime attributed | $< 1\%$ |
| Resolution performance | Equiv. to Run 1 |

## HCAL Hadron Colorimeter

During the final months of 2015, the HCAL project remained focused on two principal tasks: the operation of the HCAL detector for LHC collisions at 13 TeV in Run 2, and the development and preparation for the installation of the Phase 1 upgrades.

Since the beginning of Run 2, the entire HF detector has been read out with the new $\mu$TCA electronics, which also produce trigger primitives that are sent to the Regional Calorimeter Trigger (RCT). Operating the HF with new back-end electronics was not without challenges. Issues with a loss of synchronization in the HF readout and pipeline corruption in the new HF $\mu$HTRs affected approximately 490/pb of data of the 2.8/fb collected.

To accommodate this reduction, special MC datasets that reproduce the effect seen in collision data are being generated. Resolving these problems resulted in improvements in monitoring procedures and alarms, along with significant changes to online data quality monitoring plots, which are currently being implemented in preparation for 2016.

During the final four weeks of the 2015 $p - p$ run, data taking proceeded smoothly with a loss of less than 1% of the collected data due to HCAL problems (10.7/pb out of 1,184/pb). This good performance continued in the Heavy Ion running.

In Run 2, HE signals have continued to degrade due to radiation damage of the scintillator tiles and the wavelength-shifting fibers. As a result, working groups were formed in November to study the effect in detail and prepare for the possibility of a partial replacement of HE megatiles during Long Shutdown 2.

Table 7: HCAL Milestones.

| Subsystem | Description | Scheduled | Achieved |
|---|---|---|---|
| HCAL | Fully functional HCAL in CRAFT runs | March | March |
| HCAL | prepared to do HF Phase scan and $\phi$ symmetry calibration analysis | May | May |
| HCAL | New HBHE back-end operating in parallel with legacy system | July | July |

The status of the 2015 HCAL metrics is as follows:

- Fraction of channels working:
  - in HF, 1 channel out of 1728 dead
  - in HBHE, 7 channels out of 5184 dead
  - in HO all 2150 channels work.

In total $> 99.9\%$ of HCAL channels are working.

- Fraction of downtime attributable to HCAL with magnet on since LS1, 0.5%
- Intercalibration uniformity between individual HCAL towers
  - HB: 1–2%
  - HE: 1–2%
  - HF: 1–2%

### EMU Endcap Muon Systems

Data taking in this quarter was smooth with about 6% of the luminosity losses assigned to the CSC system.

In November, the CSCs began using recuperated CF_4. In 2015 the total volume of recuperated CF_4 was 60m$^3$ with a recuperation efficiency of 25%. This is lower than what expected (~50%) and will be corrected in 2016. The fraction of argon in the recuperated gas was relatively high (27%), thus requiring appropriate tuning of the mixer to maintain a stable mixture.

In December, a water leak in YE+1 caused HV trips in two CSC chambers, and caused CMS to run without the whole ME+1 station for the last few days of the heavy ion run. After the cooling circuit was turned off, the tripping chambers returned to normal functioning after a short time. A more through search for the leak and potential damages will be done during the YETS. Contrary to the initial plans for the YETS, the CMS heavy elements will need to be opened in order to perform the repairs.

CSC spatial resolutions were evaluated using the 2015 data. The results are consistent with earlier measurements from Run 2, and now have a statistical precision of about 0.04%. Note that systematic effects such as those from pressure variation are much larger. The analysis confirms the improvement of the spatial resolution of the innermost ME1/1a region ($2.1 < |\eta| < 2.4$) due to the new electronics and the 3-strips readout un-ganging.

Many plots and results on muon performance were approved for public release, including segment reconstruction efficiency, timing distributions, and event displays with muons in the CSCs and can be found here.

Table 8: EMU Milestones.

| Subsystem | Description | Scheduled | Achieved |
|---|---|---|---|
| EMU | CSC ready for collisions | May | April |
| EMU | Calibration for HLT and Offline included in DB | July | November |
| EMU | Fine timing adjustments with collision data completed | July | July |

Table 9: CSC Metrics.

| Metric | Performance |
|---|---|
| % Working channels | 99.0% |
| Fraction of deadtime attributed | 6% |
| Median spatial resolution | 129 $\mu$m |

## DAQ

The Main focus of the DAQ efforts during this quarter was on the preparation and then operation for Heavy Ion runs. During Heavy Ion collisions, the planned Level 1 trigger rate was ~10 kHz but due to non-zero suppressed readout, expected events sizes were ~17 MB. To handle this increased payload from the detector, the number of Readout Units (RU) were increased, the first stage of the Event Building (FEDBuilder) data network was expanded with a “FAT tree” architecture that provides full connectivity between all FrontEnd ReadOut Link (FEROL) modules and RU’s. Ten more Builder Units were also added to handle the larger event data. These modifications will also make it easier to handle the 2 MB events expected after the installation of additional Pixel layers and when the LHC reaches higher luminosities with larger pileup in 2016.

U.S. DAQ groups have led efforts for the Event Builder performance optimization and network routing and configurations for Heavy Ion conditions. The selection of High Level Triggers was relaxed during the Heavy Ion run with the goal of selecting as many events as the system could handle. In the end this resulted 6-7 k events/s corresponding to 5-6 GB/s aggregate archival rate to the Storage Manager.

Figure 8 contains a screen shot from File Based Filter Farm monitoring page from one of the last

Heavy Ion Runs. Total HLT output was 5.3 GB/s averaged over one Lumi Section. While there were a variety of issues that arose while stressing the system in this way, the data was successfully acquired at these rates and many valuable lessons were learned that can apply to future higher luminosity running.

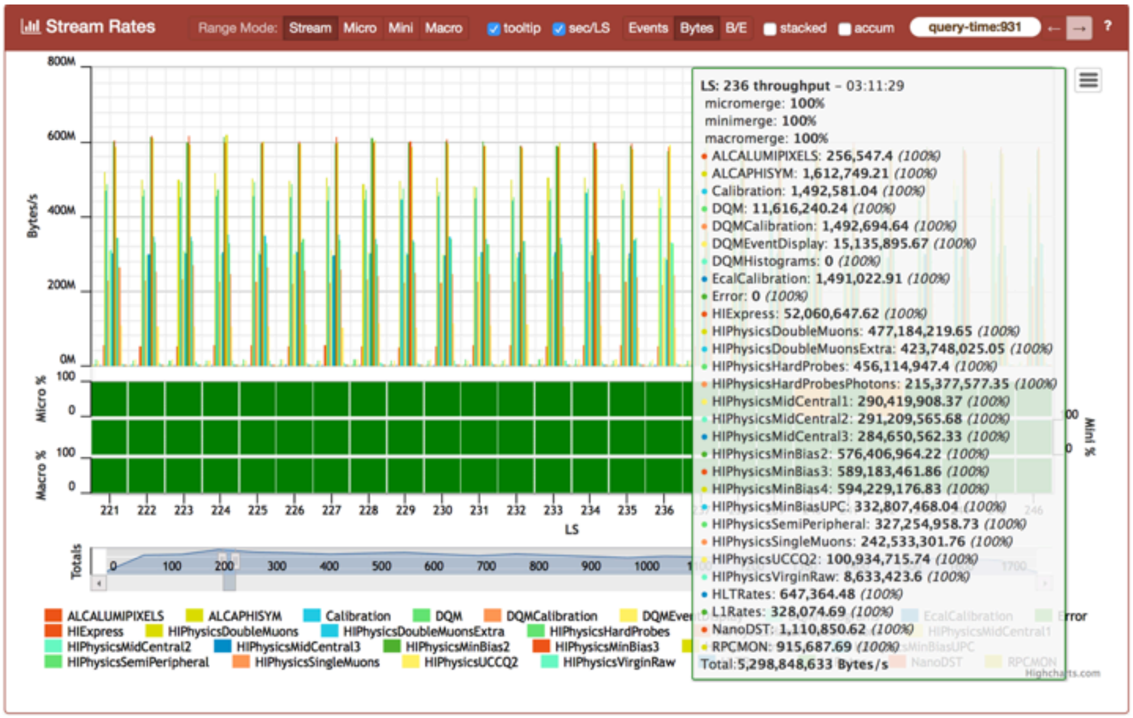



Figure 8: DAQ File Based Filter Farm Monitor page showing the merger status for each Lumi Section for one of the last runs of Heavy Ion running period. Total output from all HLT nodes was ~5.3 GB/s. The figure also lists the large number of different output streams HLT nodes produced.

Table 10: DAQ Milestones.

| Subsystem | Description | Scheduled | Achieved |
|---|---|---|---|
| DAQ | Hardware Installation of DAQ2. with new HLT nodes complete | April | April |
| DAQ | Complete DAQ2 is operational for collisions | July | May |
| DAQ | $\mu$TCA DAQ link commissioned for new trigger and HCAL FEDs | July | June |
| DAQ | DAQ2 with Run 1 design performance | Sept. | Sept. |

Table 11: DAQ Metrics.

| Metric | Performance |
|---|---|
| Dead time due to trigger throttling | $< 1\%$ |

| Metric | Performance |
|---|---|
| Downtime due to DAQ | negligible |

## Trigger

During this quarter U.S. groups continued their work on the regional calorimeter (RCT) and the endcap muon triggers.

### Regional Calorimeter Trigger

During the previous three months, the CMS RCT has participated in the 25 ns LHC proton-proton collisions and the Pb-Pb Heavy Ion program. During the entire time, the calorimeter triggered with the RCT and Stage-1 MP7. Some minor interventions were required, in a couple of instances this required replacing receiver cards, but others involved reloading firmware on oRMS by cycling crate power between fills, and one remote firmware reload of an oRSC, the first time this has been required since the oRSCs were commissioned.

The entire Stage-2 Layer-1 Calorimeter trigger was added to the RCT DAQ partition. This included moving the Layer-1 AMC13's to the RCT TCDS partition (including returning TTS states), adding 3 FEDS to be readout, and a new Layer-1 worker cell in the RCT Trigger Supervisor. The worker cell has limited functionality, mainly responding to CMS CDAQ state transitions. The Layer-1 input links can be monitored in real-time using a script.

To analyze the new Layer-1 data, an unpacker has been developed and is in use. Currently, we are comparing the e/g and sums emulated with Trigger Primitives (TPs) received by Layer-1 to those read out. ECAL has excellent agreement (the source is the same, ECAL TCCs) and there are issues at about the 10% level with the HB/HE, thought to be due to incorrect timing.

### Endcap Muon Trigger

The Rice University, Northeastern, and University of Florida groups have successfully maintained on-call coverage of the CSC Track-Finder during the reporting period, which included the end of proton collision operations in 2015 and the heavy-ion running period. Only a few instances needed intervention such as an MPC replacement after errors were observed in DQM coming from some chambers. A few minor interventions were required on the B904 test stand during this period as well to keep it up-to-date and functional. Additional plots have been added to the CSCTF DQM to aid in identifying any CSCs sending data out of range, which indicates a problem, and when synchronization error flags are sent with CSC trigger primitive data. The plots streamline the identification and diagnosis of the problems for the CSC experts.

Table 12: Trigger Milestones.

| Subsystem | Description | Scheduled | Achieved |
|---|---|---|---|
| TRIG | Legacy RCT ready for physics | June | June |
| TRIG | MPC ready for physics | June | June |
| TRIG | CSCTF Ready for physics | June | June |
| TRIG | Stage-1 Layer-1 calorimeter trigger | | |

| Subsystem | Description | Scheduled | Achieved |
|---|---|---|---|
| | ready for physics | Sept | . Sept. |

Table 13: Trigger Metrics.

| Metric | Performance |
|---|---|
| Frac legacy RCT channels | 100% |
| Frac of deadtime attributed legacy RCT | 0.6% |
| Frac of MPC Channels | 98.3% |
| Frac of EMUTF Channels | 100% |
| Frac of deadtime attributed to legacy EMUTF | 0% |
| Frac of Stage-1 Layer-1 Channels | 100% |
| Frac of deadtime attributed to Stage 1 Layer 1 | 0% |

## Software and Computing

LHC activities set the agenda for Software and Computing this quarter. The end of the proton running allowed for a reprocessing pass for both data and simulation samples. A lot of work was done in the software to be ready for that, and to prepare the facilities and infrastructure systems for the processing. The heavy-ion run with its higher data taking rate put particular strains on many aspects of the system, which required fast turnaround on a number of development efforts. These will be useful for the proton program as higher luminosities are reached. Finally, the start of the LHC technical stop allowed all facilities to focus on reprocessing activities.

All computing facilities showed good performance during this period, with a record number of CPU hours delivered by the Fermilab Tier-1 facility (despite a few operational difficulties described below, which unfortunately impacted the measured Tier-1 availability metric), and rather heavy use of the Tier-2 centers. The operations team used these facilities to deliver a large number of data samples that are needed for data analysis to show new physics results at the upcoming winter conferences. Ongoing development efforts supported these activities, and this quarter included the first scale tests of the Fermilab HEPCloud elastic facility, in preparation of major use expected for the coming quarter.

Table 14: Major milestones achieved this quarter

| Date | Milestone |
|---|---|
| October 2015 | Tier0 2.0.0 released |
| October 2015 | CMSSW_7_6_0 released with features needed for end-of-year reprocessing |
| November 2015 | CMSSW_7_5_0 deployed in the Tier-0 facility for HI data taking |
| November 2015 | Tier 1 FY15 CPU and disk purchases deployed |
| December 2015 | WMAgent 1.0.12 released |
| December 2015 | End-of-year reprocessing begins |

### Fermilab Facilities

During Run 2 the Fermilab facility collected almost 4 PB of collision and simulated data. Over 8,000 cores of additional CPU resources from the FY15 purchase cycle were deployed this quarter. As soon as they were deployed the new resources were fully utilized due to the increase in CPU demands by CMS in preparation for winter conferences.

Fermilab site readiness metrics were impacted by the many changes in deploying these resources. Two periods of failing metrics are seen in Figure 9. The first, in October was due to a controller failure on one of the older storage nodes, leading to failed test jobs and transfer failures until recovery. In November a mis-configuration of the new CPU nodes deployed at that time impacted performance metrics. The mis-configuration primarily affected the test jobs themselves. Despite these incidents FNAL provided over 33 million successful wall hours to CMS in the quarter, more than any quarter prior.

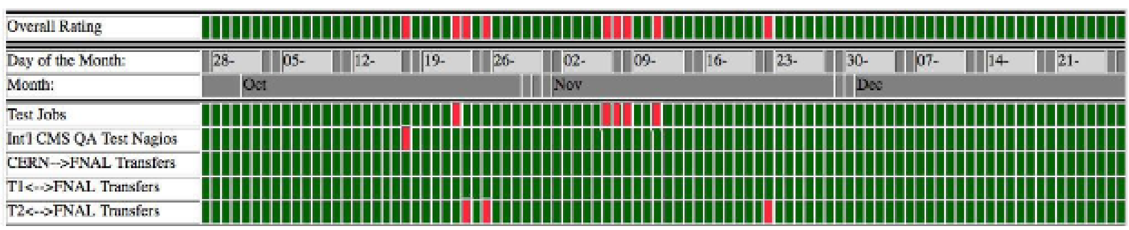



Figure 9: Fermilab readiness metrics for 2015Q4. Green indicates a passing metric, red a failed metric. Blue indicates a scheduled downtime. The Fermilab facility was 91% available during the quarter.

Late in this quarter the Tier-1 facility began working toward upgrading the dCache disk and tape storage pools to the latest supported version, and transitioning its support to the Data Management Services department within Fermilab Scientific Computing Division. That department also supports the Fermilab public dCache storage and the lab's Enstore tape archive (including that for CMS), so this move is both a consolidation of effort and working toward a service model of support for CMS. The 8 PB of disk storage purchased in 2015 is being used to facilitate this upgrade by providing a separate pool to thoroughly test the targeted version for the dCache upgrade.

### University Facilities

This quarter saw a continuing increase in the usage of the U.S. CMS Tier-2 facilities, as seen in Figure 10. This increase was largely due to running the CMS data reconstruction at the U.S. Tier-2 sites. This workflow has been possible at Tier-2 sites since May 2015, thanks in part to development work undertaken during the shutdown. These workflows place a heavy strain on the internal networking capabilities of the sites, but the U.S. sites are all able to handle the increased load. Physics analysis with CRAB3 and other production activities are also increasing.

The seven U.S. sites have finalized their hardware deployments for 2015 and are starting to plan hardware procurements for 2016. The connection of the Tier-2 sites to the LHCONE VPN by ESNet is proceeding in an orderly manner and is approaching completion. All sites have deployed the HTCondor-CE computing element, and over half of the sites have retired their old GRAM

CEs. The rest are planning to do so soon. The motivation for this transition is better stability and scalability as well as easier support.

All of the U.S. CMS Tier-2 sites have operated successfully this quarter. On our two official performance metrics based on CMS test jobs, all sites were at least 82.5% available and 93% ready. The CMS goal for each of these metrics is 80%. The U.S. CMS Tier-2 centers delivered 42.9% of all measured computing provided by Tier-2 sites in CMS (our commitment to global CMS is > 25%), making them seven of the eight most-used Tier-2 sites in all of global CMS.

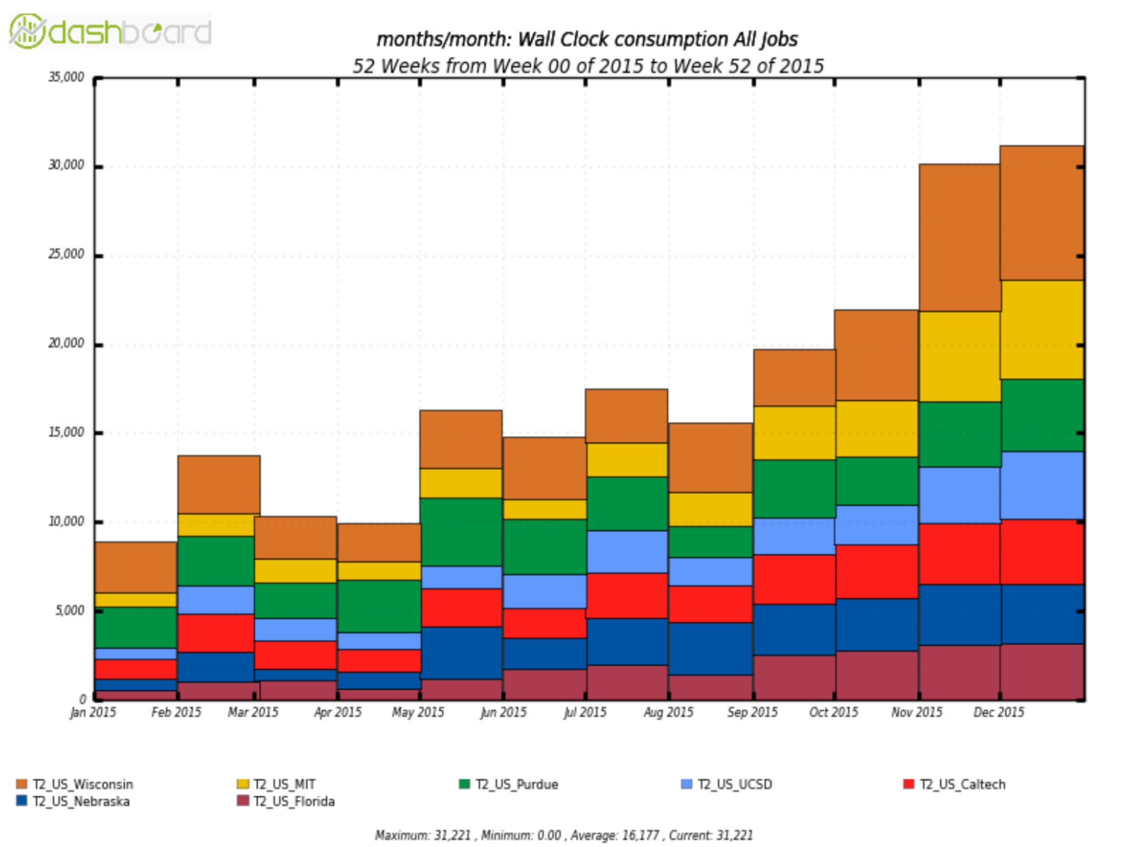



Figure 10: Wall clock time consumption of CMS workflows at the U.S. CMS Tier-2 sites by month.

Five Tier-3 sites required assistance from the Tier-3 support team this past quarter. Most sites have transitioned to OSG 3.2 so support efforts are primarily focused on helping sites that are rebuilding their sites (primarily Rice, FSU, and UMD). TAMU became the first U.S. Tier 3 site to implement the submission for local users via GlideinWMS/CRAB3; this allows physicists to use the exact same tools for submitting jobs both to the grid and to local resources. Support was also provided for updating PhEDEx parameters and keys.

This quarter, the CMS Connect Integration Test Bed factory hosted at CERN. The final software developments required to begin beta testing have been completed. Beta testers have been recruited to give feedback during the current quarter.

## Operations

Operations during the quarter was dominated by three main activities: finishing up the data processing for the 13 TeV pp run, closing the CMSSW_74x DIGI-RECO processing, and processing the 2015 heavy-ion data. The very end of the quarter was dedicated to the preparation of the CMSSW_76x re-reconstruction of all data, which finally got started on December 18 and ran well throughout the end-of-year break. In the first quarter of FY16 we have completed 3.6 Billion DIGI-RECO events (including some CMSSW_76x re-reconstruction), 8.9 Billion GEN-SIM events, and redone 3.9 Billion MINIAOD and 3.7 Billion data events re-reconstructed. This is a substantial increase with respect to the production activity during the year as shown in Figure 11.

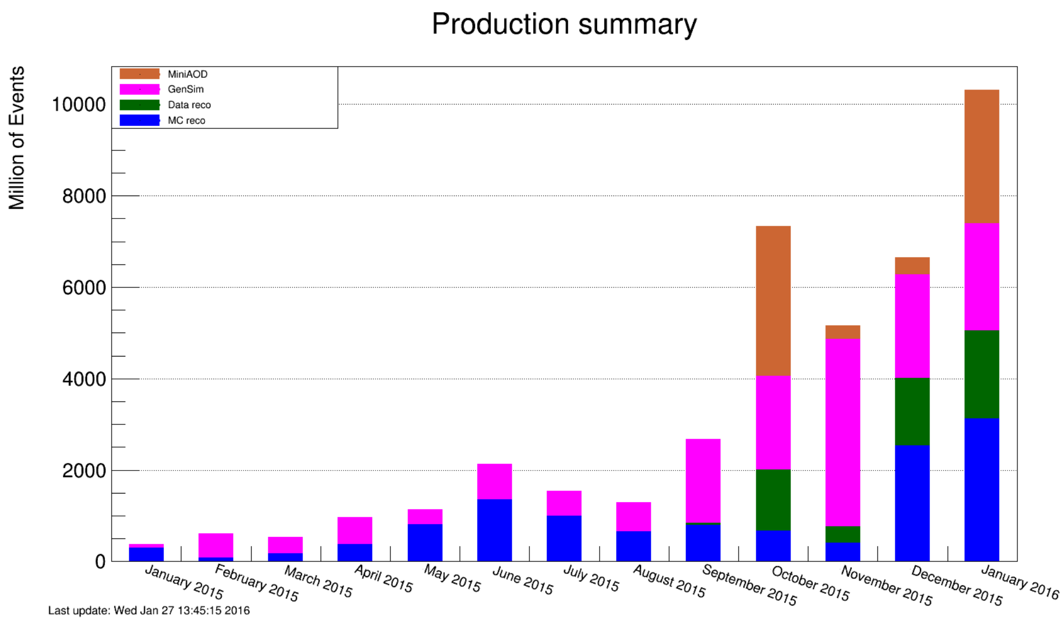



Figure 11: Production summary for the last 13 months. A steep increase of the production rate in this quarter is due to re-doing the MINIAOD, the data re-reconstruction, and the MC re-processing with version CMSSW_76x.

The Computing Operations project has transitioned into the new organizational structure of the CMS Offline Software and Computing project. The "Central Services" and the "Facilities and Infrastructure" groups in Computing Operations have been replaced with a single Liaison to new level-2 organization "Facilities and Services". A new Computing Operations group, "Tools and Integration" is being established to better address the topics of integration of our tools.

## Computing Infrastructure and Services

This quarter came to a close with the LHC heavy-ion running. This was a challenge for the CMS Tier-0, as the facility was pushed beyond its design limits to maximize the amount of data collected. However, due to improvements made during the quarter to WMAgent and the Tier-0, particularly performance enhancements and increased robustness of data publication and injection, the Tier-0 performed well under this extreme load.

Among numerous improvements to WMAgent, the developers added settings to allow workflows to overflow into opportunistic resources. Planning has begun for a needed refactoring of WMAgent to make better use resources available only for a limited time, and to reduce operational effort. The WMArchive project to store all the performance and monitoring data as well as provide access to debugging data from WMAgent made good progress, in outlining the project plan and finalizing the architecture.

All projects have finished modernizing their Python code in preparation for the move to Python 3. Enhancements to DBS and WMAgent to improve the memory performance of the applications went into production.

Towards our long-term goal of "elastic scale out," we made considerable progress in collaboration with the Fermilab HEPCloud project. We have an allocation on the Amazon Web Services (AWS) cloud, to establish sustained operations at a level of 50,000 simultaneous cores. We use the standard CMS production infrastructure to submit workflows to the Fermilab Tier-1, and augment its resources by elastically scaling out to AWS via HEPCloud. During this quarter we successfully achieved initially a 1% and then a 10% scale, that is 5000 cores sustained operations. The 100% scale operations planned for the next quarter will produce actual simulation requests at AWS that are directly used and needed for the CMS science program.

### Software and Support

During this quarter significant effort went into understanding the detector response to the extra out-of-time pileup at 25 ns bunch spacing relative to the previous running conditions at 50 ns bunch spacing. The knowledge gained was captured in the code and calibrations delivered in the CMSSW 7_6_0 release, which was used to reprocess all of the data collected in 2015.

The commissioning of the heavy-ion data taking required many modifications to the CMSSW 7_5_0 release that was used to acquire the data. Thanks in part to being able to run the heavy-ion HLT and Tier-0 applications in multi-threaded mode, the data was collected and processed at unprecedented rates and operations were considered very successful.

### Technologies and Upgrade R&D

The R&D area has continued work on evolving and scaling the CMS computing system, as well as prototyping new technologies for future use.

During this quarter, significant improvements in the HTCondor negotiator service were delivered. These improve the speed of the central daemons sufficiently to keep up to 130k cores occupied while allowing the central daemons to limit the number of concurrent jobs that utilize the AAA data federation. Within the production system "global pool" we prototyped and delivered a mechanism for utilizing data federations (and otherwise reroute jobs to other sites). This was extensively used to run jobs on the CERN HLT farm over the end-of-year shutdown. To further improve accessibility of data, we have started to integrate machine learning techniques to predict dataset popularity for initial placement.

Beyond the CMS-owned computing facilities, we have further developed the capability to run at DOE supercomputing facilities (namely, NERSC). We have managed the NERSC allocation of 2.5M CPU hours for U.S. CMS. As NERSC is transitioning to new hardware, the focus has been on continued benchmarking via the Docker-like "Shifter" interface provided by the NERSC team.

On the software side we have migrated all production and experimental CMSSW architectures to GCC 5.3.0 and a single branch. In this quarter, we were able to get CMSSW functioning on the POWER8 architecture. The ARM work was presented at the Linaro Connect SFO 2015 conference ("ARM64/AArch64 for Scientific Computing at the CERN/CMS Particle Detector"). There has been continuous background activity with Intel on Intel C++ Compiler and CMSSW; a number of issues have been reported, confirmed and resolved for future releases. This will improve our ability to quickly deploy on new platforms, such as the upcoming Xeon Phi KNL.

For the tracking software prototype, this quarter has focused on code consolidation and cleanup to establish a baseline as well as a common development platform for different architectures. We are utilizing Intel VTUNE to try and explore and understand the outstanding issues observed with the baseline (with respect to vectorization and parallelization efficiencies).