PROCEEDINGS OF SCIENCE

Status and Performance of CMS

Manfred Jeitler[*][†]
Institute of High Energy Physics of the Austrian Academy of Sciences, Nikolsdorfergasse 18,
1050 Vienna, Austria
E-mail: `manfred.jeitler@cern.ch`

Over the course of 2011, CMS reached cruising speed and collected over five inverse femtobarn of proton-proton collision data at a collision energy of 7 TeV. At the end of the year, a lead-lead run was taken. Technical aspects of running the experiment and preparing for future challenges are discussed and a few physics topics not described in dedicated presentations are shown.

LHC on the March,
November 16-18, 2011
Protvino, Moscow region, Russian Federation

---

[*] Speaker.
[†] For the CMS collaboration

PoS(IHEP-LHC-2011)012

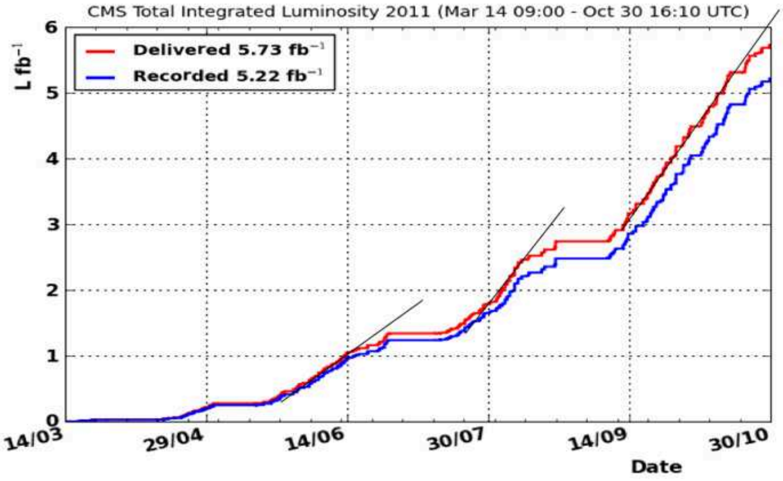


Figure 1: Integrated luminosity acquired by CMS over 2011. The flat sections correspond to technical stops of the LHC machine.

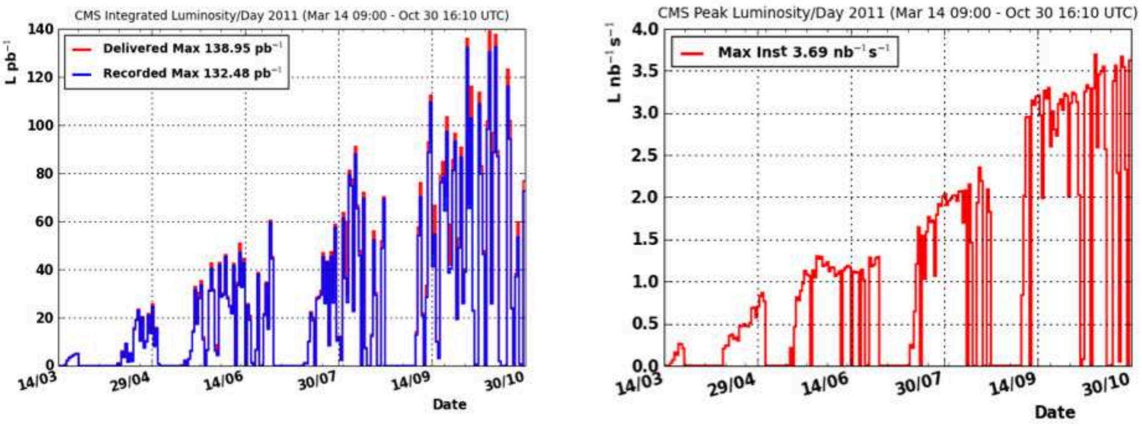


Figure 2: Integrated and peak luminosity per day seen at CMS over 2011.

1. LHC and CMS data taking in 2011

While in 2010 the LHC was being put into operation with much of the time being dedicated to accelerator development so that luminosity was accumulated rather slowly, in 2011 the accelerator reached cruising speed very soon and most of the time could be devoted to data taking for physics (see Figure 1). This allowed CMS to accumulate an integrated luminosity of over 5 fb^{-1} by the end of the year. At the same time, further work on the accelerator allowed to increase the instantaneous luminosity to 3.7×10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (see Figure 2). At this level of performance we may expect that in 2012 the experiments ATLAS and CMS will accumulate an integrated luminosity of 15 fb^{-1} each.

This progress in data taking is reflected in the large scientific output of the LHC experiments. CMS has already published over 100 papers (see Figure 3) dedicated to detector performance and to the various physics processes that can be investigated in this experiment. The Standard Model has

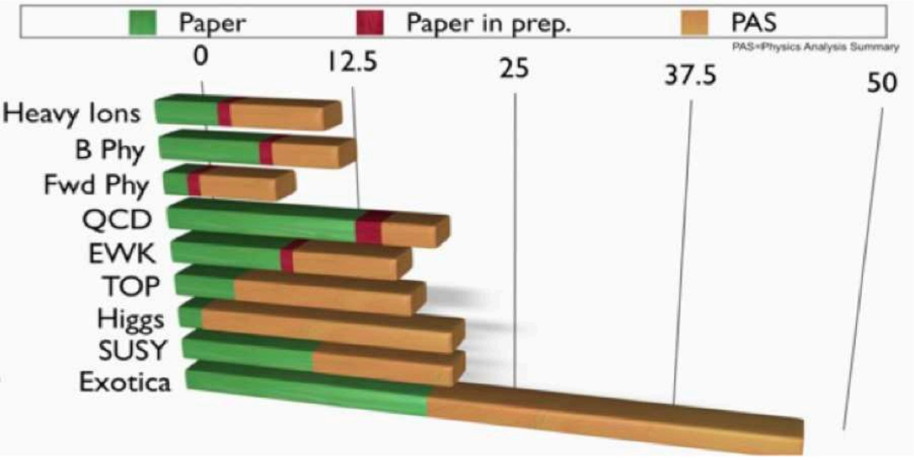


Figure 3: Number of CMS publications in the various fields.

been largely confirmed in the energy range open to LHC. So far, there are no unequivocal signs of the Standard Model Higgs particle or of "new physics" such as Supersymmetry, extra dimensions and the like.

However, there is good reason to believe that this will change over the next year. The Higgs particle has already been excluded over a significant mass range (see [1, 2]). By the end of 2012, with a total integrated luminosity of over 30 fb^{-1} at LHC, the Standard Model Higgs particle should either have been discovered, or else excluded over a very wide mass range. While a discovery of the Higgs particle would make it easier to explain the importance of LHC research to non-physicists, one should not forget that an exclusion of the Standard-Model Higgs boson would be just as important a finding and potentially yield even more important insight into our world.

For Supersymmetry, the picture will not be quite so clear (see [3]). We will only be able to exclude "minimal" SUSY models but theories have a large number of degrees of freedom, which will allow them to accommodate Supersymmetry even in the absence of a clear signal seen by the LHC experiments over the coming year 2012.

The 2011 data have not resulted in the discovery of new particles but have brought us a lot of "standard" physics, such as electroweak physics, QCD and top physics. The precision analysis of these known physics channels allows the experiments to have confidence into the performance and response of their detectors. At the same time it should be borne in mind that any possible deviation in precision measurements might yield hints of new and unexpected physics processes. New features in particle physics need not necessarily appear in the form of a salient and obvious signal but might be deduced indirectly from small numerical deviations from calculated values.

CMS is, like ATLAS, a "general purpose" experiment and can and must investigate a large range of physics topics (cf. Figure 3). A few of these which have not been covered by dedicated presentations at this Conference are discussed in the following sections.

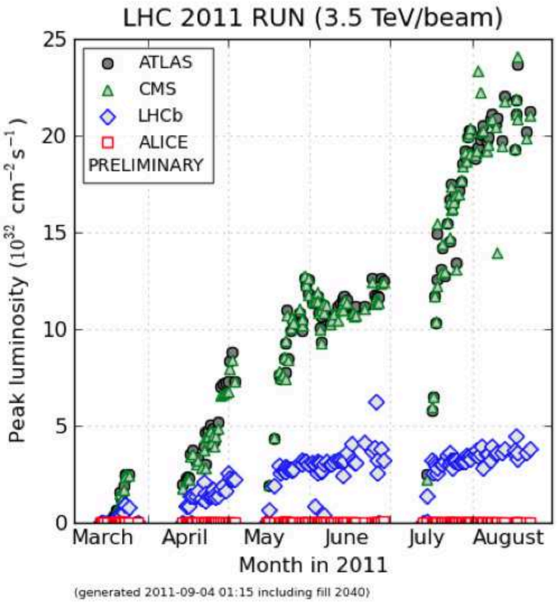


Figure 4: Rise of the peak luminosity in 2011 at ATLAS and CMS (limited only by accelerator performance) and at the specialized experiments LHCb and ALICE, which can run only at lower instantaneous luminosity.

2. Selected physics topics

2.1 B-physics

For B-physics, LHC has a dedicated experiment, LHCb (see [4]). This experiment has been designed to allow taking a large number of B-decay triggers at low energy thresholds. This is possible only at significantly lower pileup (number of proton-proton interactions per bunch crossing) and thus lower luminosity than allowed for by CMS or ATLAS. For the hadronic B-decay modes CMS cannot compete with LHCb because of the much higher trigger thresholds on transverse momentum CMS has to apply. However, for channels where muon triggers can be used this may be different: the CMS experiment was designed to allow for a highly efficient and pure muon trigger, and in the future the higher luminosity available to CMS might yield competitive results in selected decay channels.

While in 2010 the luminosity was still limited by the accelerator's performance for both CMS and LHCb, the picture changed in 2011 when LHC performance rose beyond the luminosity acceptable for LHCb and this experiment had to limit the number of interactions inside the LHCb detector. Figure 4 shows the rise of the instantaneous luminosity at the four LHC interaction points over part of the year 2011.

CMS is called the “Compact Muon Solenoid” for good reasons. A glance at the detector cutaway view reveals how much of the detector volume is taken up by muon chambers (see Figure 5). The superconducting solenoidal magnet with its strong field of 3.8 Tesla allows for very good muon momentum resolution.

There are three different kinds of muon chambers: Drift-Tube Chambers in the barrel, Cathode Strip Chambers in the endcaps, and Resistive Plate Chambers everywhere (see [5]). All of these are

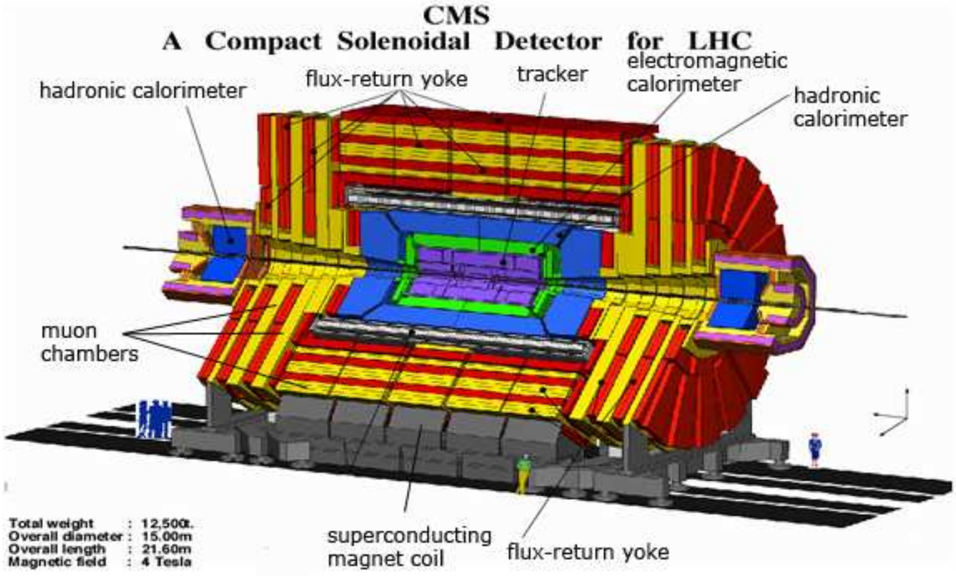


Figure 5: Cut-away view of the CMS detector with elements of the flux-return yoke (red), muon chambers (yellow), superconducting magnet coil (grey), hadronic calorimeter (blue), electromagnetic calorimeter (green) and tracker (magenta).

used not only for data readout but also in the first-level trigger. Tracks are determined separately for the barrel (Drift Tube Track Finder [6]) and endcaps (Cathode Strip Chamber Track Finder), with communication between these two systems in the overlap region. All muon trigger data are then combined and the four highest-quality muon candidates determined in the fast trigger electronics of the Global Muon Trigger, whose logic is implemented in FPGAs (Field Programmable Gate Arrays). The subsequent Global Trigger electronics [7] allows combining these muons with each other or with other trigger objects such as electron or jet candidates.

This sophisticated system allows for a very clean selection of decays into muons. For B-physics, one particularly interesting channel is the rare decay of B-mesons into two muons: $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \mu^+\mu^-$, for which the predicted Standard-Model branching ratios are 3.4×10^{-9} and 1×10^{-10}, respectively. These channels are highly suppressed in the Standard Model but would be very sensitive to enhancement due to new physics. Triggering on two muons reveals a multitude of known particles and can be used to search for this signal (Figure 6).

For the decay $B_s \rightarrow \mu^+\mu^-$, based on part of the data from the 2011 run, CMS established a rate limit of 1.9×10^{-8} [8] (at an expected background contribution of 1.8×10^{-8}). This is only slightly worse than the LHCb limit of 1.5×10^{-8} [9] and constitutes an important ingredient in the combined limit from both experiments (1.1×10^{-8}). Over the next few years, observation would allow to approach the Standard Model prediction and be highly sensitive to new physics. Both CMS and LHCb will make important contributions to lowering the limit.

For the $B_d \rightarrow \mu^+\mu^-$ decay, measurements will have to continue for many years (the observed limits are now 4.6×10^{-9} for CMS [8] and 5.1×10^{-9} [9] for LHCb) but the eventual value to be measured will yield important insight into the Standard Model and its possible extensions.

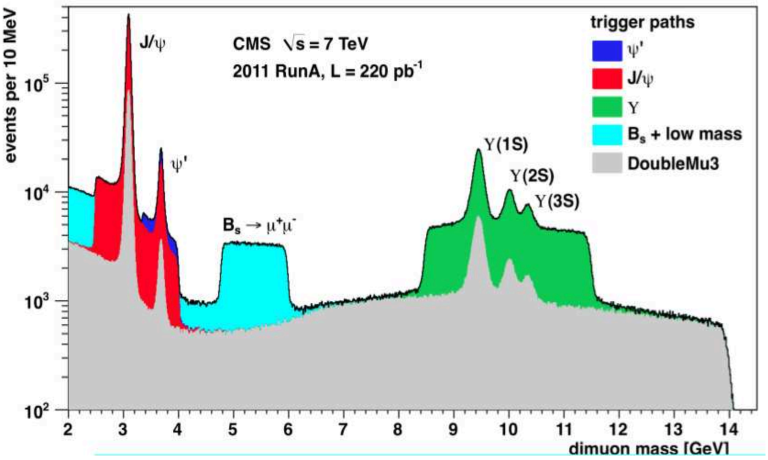


Figure 6: Spectrum of the invariant mass of di-muon events taken in CMS. The various trigger paths open windows around known particles such as J/ψ, ψ' and Υ and in the region where the decay $B_s \rightarrow \mu^+\mu^-$ should appear.

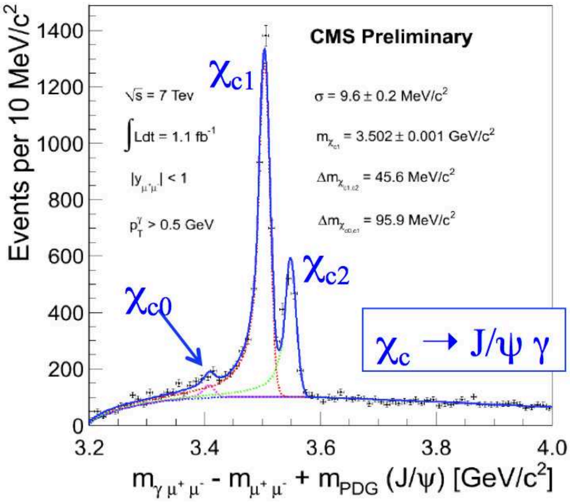


Figure 7: Invariant-mass spectrum for the decay $\chi_c \rightarrow J/\psi\ \gamma$. Events were reconstructed using the electron and positron tracks from converted photons in the CMS silicon tracker.

2.2 Quarkonia

Quarkonia studies at CMS also benefit from the detector's good di-muon mass resolution, which allows not only to achieve very sharp mass peaks but also to use efficient triggers at low thresholds in transverse momentum (p_T) while still keeping the rates under control. For decays involving photons (such as $\chi_c \rightarrow J/\psi\ \gamma$) it is particularly important that these can be seen not only as showers in the electromagnetic calorimeter (ECAL) but that photons may convert and the resulting electron and positron tracks in the inner tracker can be used to reconstruct the event with much higher accuracy (see Figure 7). The CMS silicon tracker contains somewhat more inactive material (support structure, cooling pipes, cabling) than one might ideally wish for but for this analysis this actually appears as a benefit because it gives rise to a larger fraction of converted photons. The silicon tracker also allows to determine secondary decay vertices and thus to distinguish decays such as $B \to J/\psi\, X$ from non-prompt contributions $B \to \psi'\, X$.

The quarkonia group has determined the differential cross sections by bins in p_T for the J/ψ, ψ' and the several Υ states (for J/ψ and ψ' also subdivided into rapidity bins) and compared with theoretical calculations. Agreement has been found with NLO NRQCD (next-to-leading order non-relativistic QCD calculations). S-wave states have been analyzed and currently work is in progress on P-wave states and polarization measurements.

2.3 Heavy-Ion physics

For some part of the data-taking time the LHC runs with heavy ions, producing Pb-Pb (lead-lead) collisions. While the ALICE experiment has been particularly optimized for this kind of physics [10], heavy-ion data are also taken by ATLAS and CMS.

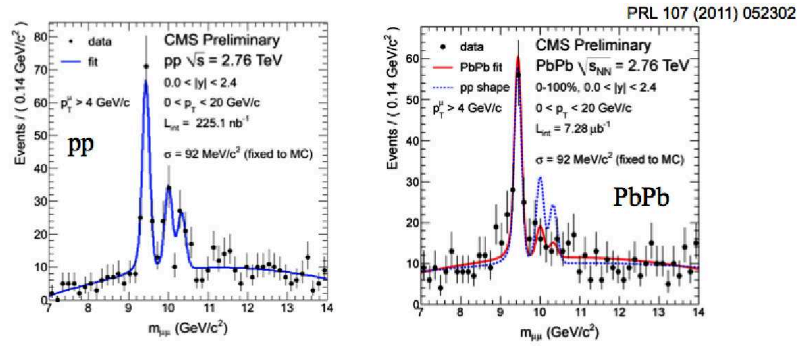
Obviously, luminosity and triggering conditions in heavy-ion running are very different from the conditions for proton-proton collisions. Heavy-ion data in 2010 and 2011 were taken at a beam energy of 2.76 TeV per nucleon, which corresponds to the same magnetic field in the LHC dipoles as for 3.5 TeV protons. While for proton-proton collisions CMS operates by design at a Level-1 trigger rate of up to 100 kHz, for heavy-ion running this trigger rate must be limited to a few kHz to allow for enough time for reading out the much bigger heavy-ion events from the detector (in this mode, the CMS silicon tracker runs without zero suppression to avoid distortions caused by the much higher occupancy of the detector). Just as for proton running, also for heavy-ion running there has been remarkable progress in the performance of the LHC accelerator and the experiments. While in 2010 the integrated Pb-Pb luminosity recorded by CMS was slightly below 10 $\mu\mathrm{b}^{-1}$, in 2011 this value was over 140 $\mu\mathrm{b}^{-1}$.

For understanding the physics of heavy-ion collisions it is important to compare results with those for proton-proton collisions to see where differences appear and where things remain unchanged. So, CMS has observed vector boson production by heavy ions by looking at $Z \to \mu^+\mu^-$ events and seen no modification with respect to the proton-proton reference measurements. On the other hand, in the production of Υ-states the expected suppression of excited states has been observed in comparison with proton-proton collisions (see [11] and Figure 8).

2.4 Forward physics

The CMS experiment is also in a good position for investigating forward physics by making use of a number of specialized subdetectors. A wide range in pseudorapidity (η) is almost hermetically covered by calorimeters: HF (Hadronic Forward Calorimeter) at $3 < \eta < 5$, the CASTOR ("Centauro And STrange Object Research") calorimeter at $5.2 < \eta < 6.6$ and the ZDC (Zero Degree Calorimeter) at even higher pseudorapidities. The ZDC η range is also covered by Forward Shower Counters (FSC) which allow to look for rapidity gaps in decays.

In addition, adjacent to the CMS detector there are the various tracking detectors of the TOTEM ("TOTal Elastic and diffractive cross section Measurement") experiment: detectors T1 ($3.1 < \eta < 4.7$) and T2 ($5.3 < \eta < 6.5$) near the CMS main detector as well as the TOTEM Roman



$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$ $\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

Figure 8: Suppression of excited ϒ-states (ϒ(1S) and ϒ(2S)) in lead-lead collisions as opposed to proton-proton collisions.

Pots detectors at 140 meters and 220 meters from the interaction point, covering a pseudorapidity range of $9.5 < \eta < 13$. So far, CMS and TOTEM have been operated completely separately but now good progress is being achieved for future joint operation allowing to look at the same events both in the forward region at very high pseudorapidity and in the central region (perpendicular to the beam) as well.

For diffractive measurements trying to observe a rapidity gap it is essential to avoid pileup. So, most of the forward physics measurements must be carried out a lower luminosities than LHC core physics topics such as Higgs and SUSY searches where the highest achievable luminosities are required to accumulated the necessary statistics and where pileup may be 20 or more (i.e., 20 or more collisions of individual protons per bunch crossing). For the time being, this is achieved by taking special low-luminosity runs (data taking periods where the accelerator operates at high β^*, the value of the accelerator's beta function at the interaction point). In the future it might also be envisaged to use both high- and low-luminosity bunches in the same accelerator fill. For more details on CMS forward physics results see [12].

2.5 Heavy Stable Charged Particles

Some models of "new physics" predict meta-stable (comparatively long-lived) particles that could be produced in proton-proton collisions but decay at a later time. The LHC experiments are clocked at 40 MHz so that their natural timing units are time slices of 25 ns, the minimum bunch spacing that can be achieved in the LHC machine. The CMS detector is kept active also during gaps in the LHC proton bunch structure to look for events caused by collisions at a somewhat earlier time (see Figure 9).

Upon receiving a Level-1 trigger, CMS reads out the corresponding time slice. Some subdetectors also read out a few preceding and subsequent time slices but this is not possible for the inner tracker because of the large data volume. When receiving a muon trigger signal from a "long-lived" particle decaying in the outer detector it would be interesting to examine the preceding bunch crossing where this particle may have been produced and see the tracks of all the other products produced in the corresponding proton-proton collision. For this, CMS uses a special scheme that

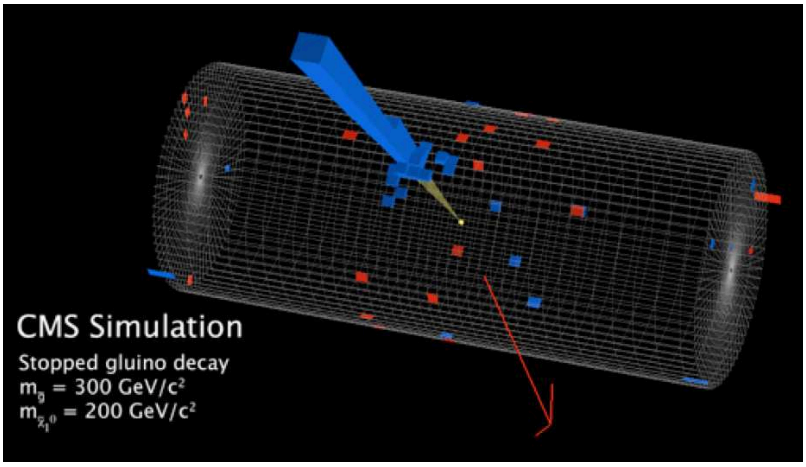


Figure 9: Simulation of the decay of a metastable particle in CMS, showing a large signal in the calorimeter without any tracks in the central detector for the same time slice.

allows triggering on collision bunch crossings that would not give rise to a trigger signal by themselves but are followed by a high-momentum muon trigger in the next bunch crossing. In 2011, the bunch spacing used was 50 ns, so only every second "bunch crossing" was actually filled with protons; see Figure 10.

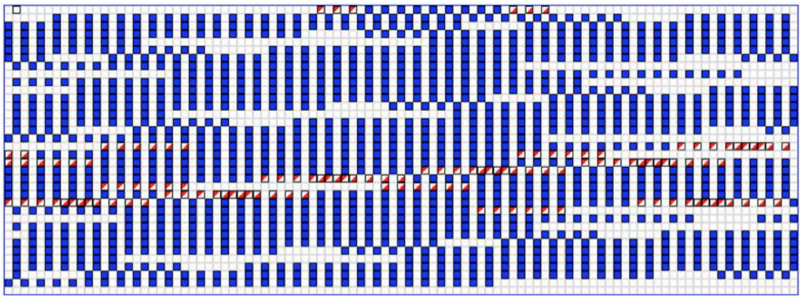


Figure 10: The LHC bunch structure as seen by the CMS detector. Most bunches (blue) collide at CMS (and also at ATLAS). Some bunches collide at LHCb or ALICE only but do not collide with another bunch inside CMS (red and white). Unfilled spaces in the structure due to the used 50-ns bunch filling scheme and the gaps from the accelerator structure are shown in white.

These measurements have allowed CMS to exclude the existence of such metastable particles over 10 orders of magnitude in lifetime, ranging from microseconds to hours (see [13]).

3. Luminosity measurements

For precision measurements at hadron colliders, accurate determination of luminosity is essential. This has been made even clearer by a slight mismatch in the luminosities measured by ATLAS and CMS. The basic method of luminosity determination used in CMS is "zero counting", where the luminosity is derived from the probability that a "tower" of the hadronic forward calorimeter

(HF) sees zero hits in a collision. This method becomes increasingly problematic at high instantaneous luminosity resulting in high pileup, where such events become very rare. Therefore, CMS has been looking into alternative methods of measuring the instantaneous luminosity.

One such method is "Pixel Cluster counting": it has been seen that there is a good correlation between the luminosity and the number of clusters in the Silicon Pixel detector at the center of CMS. Due to their tiny size the individual pixels have a small occupancy and this allows to use this method also at very high luminosities. A heavily prescaled zero-bias trigger (where only a crossing of the LHC beams but no signals in the CMS detector are required) is used to collect a representative subsample of bunch crossings for this measurement. In this context it is important to note that the luminosities of the individual LHC bunch crossings differ significantly. In order to avoid large statistical fluctuations and get a meaningful measurement within a short time span while keeping trigger rates at a reasonable level only a representative subset of bunch crossings is selected by the trigger system (see [14]).

To further improve the accurate and fast measurement of luminosity, a "Pixel Luminosity Telescope (PLT)" consisting of dedicated diamond detectors inside the Pixel detector system is under development. These diamond detectors will be placed close to the beam on either side of the CMS interaction point at a distance of 1.75 meters. The measurement of 3-fold coincidences within each bunch crossing will allow for accurate online determination of the luminosity.

4. Beam background studies

Residual gas in the beam pipe hit by beam protons may constitute an important contribution to the event background. A good way to monitor such effects is by using a certain number of "unpaired" bunches used to produce collisions in ALICE or LHCb but which do not collide in CMS or ATLAS (in ATLAS and CMS, exactly the same bunches collide). Experience has shown that high-luminosity bunch trains of many bunch collisions following one after the other result in significant induced short-term activity in the detector (dubbed "albedo") that makes it hard to see effects from the collisions of protons with beam gas atoms. Therefore, a triggering scheme was worked out which allows to trigger only on unpaired bunches before but not after a bunch train by asking for a certain "quiet" period before the trigger.

5. The future

5.1 Plans for 2012

5.1.1 LHC bunch structure

The original LHC design foresaw running at a bunch crossing spacing of 25 ns, in other words with collisions occurring at a frequency of 40 MHz (except for the gaps between the bunch trains due to the accelerator structure). The CMS detector and trigger have been set up to cope with this frequency. So far, the bunch spacing used was mostly 50 ns (see Figure 10), mainly to cope with "electron clouds" developing in the accelerator that are getting worse at 25 ns bunch spacing. Although successful tests of running at 25 ns have been carried out, for the time being luminosity can be better optimized at a bunch spacing of 50 ns and it is very likely that in 2012 LHC will also run in this mode. Obviously, running at a wider bunch spacing results in more pileup at the same luminosity, which makes data analysis harder. Studies have shown, however, that the CMS detector and analysis approach are well suited to cope with this.

5.1.2 Energy

So far, LHC has been running at a proton beam energy of 3.5 TeV, corresponding to a center-of-mass collision energy of $\sqrt{s} = 7$ TeV. During the long shutdown in 2013 and 2014 it is planned to carry out extensive work to allow the accelerator running at the original design energy of $\sqrt{s} = 14$ TeV for proton collisions.

Much work is needed to reach this ambitious goal but it appears likely that for 2012 the beam energy can at least be increased slightly to 4 TeV, resulting in proton collisions at $\sqrt{s} = 8$ TeV. Although this increase may seem tiny, when running at the same luminosity it would actually be very beneficial for CMS because of the rise in production cross sections, in particular for heavy objects. So, the cross section for the production of a hypothetical supersymmetric particle of a mass of 2.5 TeV produced by gluon-gluon fusion would go up by more than three times when increasing the collision energy from $\sqrt{s} = 7$ to $\sqrt{s} = 8$.

5.2 CMS upgrade projects

Although the CMS detector has been showing a very good performance there is a number of reasons why upgrade work will be necessary. One factor included in the design plans since the very beginning is that after a certain number of years of operation the silicon tracker will have to be replaced due to radiation damage. Obviously, this occasion will also allow to make use of technological progress. Another reason is obsolescence: big experiments such as CMS necessitate a very long preparation time. Over this period, technology changes, and it becomes harder and harder to maintain outdated equipment, in particular electronics.

Apart from these technical reasons, there are also reasons linked to the physics performance of the system. The LHC accelerator has been approaching its luminosity goal successfully and will subsequently be upgraded, first to reach the design energy but then also to exceed the design luminosity. To cope with these conditions, detector upgrades are also needed. One important step will be to include the silicon tracker into the first-level trigger to reduce the rate of candidate events before reading out the whole detector. At the moment, the tracking information enters the trigger only at the stage of the computer-farm based high-level trigger.

The present time schedule for the upgrade foresees a first long shutdown of the accelerators in 2013-2014 during which LHC will be upgraded to the design collision energy of $\sqrt{s} = 14$ TeV. CMS will replace part of the first-level trigger electronics during this period. After three more years of data taking in 2015-2017, there will be a second long shutdown during which the CMS inner detector (tracker) will be replaced.

6. Conclusions

The LHC accelerator, the CMS experiment and the other LHC experiments have shown very good performance during the first two years of data taking and no major problems have been encountered. There is good reason to believe that 2012 will give us important new insight into physics.

The Standard Model Higgs mechanism should be either confirmed or rejected based on the data to be collected in 2012. However, other physics questions will require far more integrated luminosity. CMS is looking ahead at a long future of data taking with a detector that will be continually upgraded.

Acknowledgments

Both the construction and operation of CMS and the analysis of the physics data have been possible only due to the work of thousands of physicists, engineers and technicians. I gratefully acknowledge the help of many colleagues who generously supplied me with information and graphical material.

References

[1] Artur Kalinowski, *Higgs search by CMS*, this volume.

[2] Nansi Andari, *Higgs searches in ATLAS (SM and MSSM)*, this volume.

[3] Mirjam Lena Fehling, *SUSY searches in ATLAS*, this volume.

[4] Oleg Yushchenko, *B_c production at LHCb*, this volume.

[5] CMS Collab., JINST **3**, S08004 (2008).

[6] J. Erő *et al.*, *The CMS Drift Tube Trigger Track Finder*, JINST **3**, P08006 (2008).

[7] M. Jeitler *et al.*, *The level-1 global trigger for the CMS experiment at LHC*, JINST **2**, P01006 (2007).

[8] CMS Collab., *Search for B(s) and B to dimuon decays in pp collisions at 7 TeV*, Phys. Rev. Lett. **107**, 191802 (2011).

[9] Marc-Olivier Bettler, *Search for $B_{s,d} \to \mu\mu$ at LHCb with 300 pb^{-1}*, arXiv:1110.2411v2 [hep-ex] (2011).

[10] ALICE Collab., *The ALICE Experiment at the CERN LHC*, JINST **3**, S08002 (2008).

[11] CMS Collab., *Indications of Suppression of Excited Υ States in Pb-Pb Collisions at $\sqrt{s_{NN}}$=2.76 TeV*, Phys. Rev. Lett. **107**, 052302 (2011).

[12] Igor Katkov, *QCD and forward results from CMS*, this volume.

[13] CMS Collab., *Search for new physics with long-lived particles decaying to photons and missing energy*, CMS PAS EXO-11-067, CERN, Geneva, 2011; http://cdsweb.cern.ch/record/1394286?ln=en; CMS Collab., *Search for Heavy Resonances Decaying to Long-Lived Neutral Particles in the Displaced Lepton Channel*, CMS-PAS-EXO-11-004, CERN, Geneva, 2011; http://cdsweb.cern.ch/record/1380311?ln=en

[14] CMS Collab., *Absolute Calibration of Luminosity Measurement at CMS: Summer 2011 Update*, CMS-PAS-EWK-11-001, CERN, Geneva, 2011; https://cdsweb.cern.ch/record/1376102?ln=en.