The super-LHC, a luminosity upgrade

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The prospects for a long-term upgrade programme for the Large Hadron Collider, CERN's new proton-proton collider, are presented. While the final physics motivation and the exact schedule of operations depends on the coming LHC findings, it is clear today that a major consolidation and upgrade of the existing detectors and of the CERN accelerators complex will be necessary.

1 Motivation

The Large Hadron Collider (LHC) is the new particle accelerator which just started operations at CERN. It will collide protons on protons, at a centre-of-mass energy of 14 TeV. Its primary goal is to answer one of today's deepest questions of physics, namely what is the origin of the elementary particles' masses. The Higgs boson is a hypothised particle which, if it exists, would give the mechanism by which particles acquire mass. The mass of the Higgs boson is a free parameter in the Standard Model.

The design of the LHC [1] collider and of its two largest experiments, ATLAS [2] and CMS [3], has been tuned to enable the full exploration of this mass range, searching for a broad variety of the Higgs production and decay processes predicted by the Standard Model. The

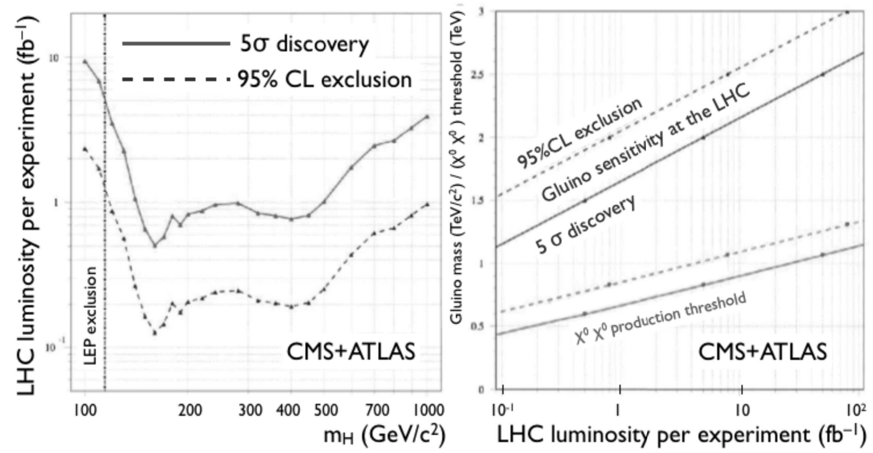

Figure 1: LHC Higgs and Gluino discovery potential at 10 fb^{-1} [4]

timeline for these searches is outlined in the left plot of figure 1. This shows the amount of data needed by each of the two experiments to establish a 5σ discovery, or a 95% CL exclusion, as a function of the Higgs mass. The present planning of LHC operations foresees the delivery of a few 100 pb^{-1} of data during 2010, which will not be enough to fulfill this task. Instead, with 10 fb^{-1} of delivered integrated Luminosity, the LHC will either discover or exclude the SM Higgs and this, probably, after 2-3 years of running at 14 TeV and at 10^{33} $cm^{-2}sec^{-1}$.
Whatever the results will be, we will be left with a lot of new questions and problems to solve [4]. There will be no limit to the need of accuracy after that! If the Higgs is discovered, among the possible open questions there is: Are there more particles in the Higgs sector? Is the Higgs boson elementary or composite? What is the origin of fermion masses?

Following the discovery, the main focus will become the quantitative study of the Higgs properties.

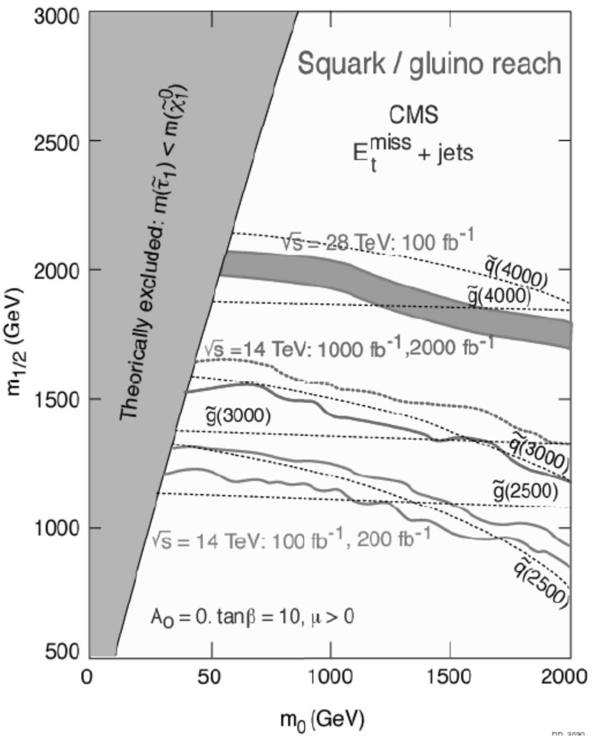

Figure 2: LHC SUSY mass reach for different luminosity and energy scenari

At some point, with high statistics, rare decay modes of the SM Higgs will become accessible ($H \rightarrow \mu_+\mu_-, H \rightarrow Z\gamma$). Hb,Ht, HZ, HW couplings might be measured to 10% for $m_H < 200$ GeV.

If the Higgs boson is not found, a radical departure from the Standard Model will be needed, and the searches to understand what other mechanism is responsible for the electroweak symmetry breaking will begin.

Dark matter is an additional puzzle that today's experimental particle physics tries to

reveal. Various models anticipate the existence of a higher level of symmetry in nature. In a theory with unbroken supersymmetry, for every type of boson there exists a corresponding type of fermion with the same mass and internal quantum numbers, and vice-versa. Once the discovery of supersymmetry is achieved, then it will be important to extend the mass reach for new particles. In general one will need to continue in the determination of SUSY masses and parameters.
An increase of a factor 5 to 10 in integrated luminosity will buy an additional 500 GeV on the mass reach. In the same way, the mass reach for new gauge bosons, or signatures of extra-dimension models will be increased by 30%.

All this has justified the need to start defining a project for running LHC for a longer period (at least until 2030). A luminosity upgrade (superLHC or sLHC [5]) will have a strong impact on the machine and on the experiments.

2 The CERN accelerator complex

In the LHC, at the interaction point the number of beam collision directly scales with the LHC luminosity (L), defined as :

$$L = \frac{f_r \cdot \gamma}{4\pi} \frac{N_b^2 \cdot n_b}{\epsilon_n \cdot \beta^*} \cdot F$$

Here f_r is the LHC revolution frequency, N_b is the number of protons per bunch, n_b is the number of bunches, β^* is the value of the betatron function at the interaction point (IP), and $F < 1$ is a factor measuring the geometric loss of overlap between two bunches as they cross at a given crossing angle. The luminosity can therefore be increased by increasing the bunch current (N_b), the number of bunches (n_b) and the geometric overlap (F), or by reducing the normalised emittance ϵ_n or β^*.

The LHC injector chain is shown in figure 3. The first stage of the acceleration takes place in the Linac2, a linear accelerator where protons reach an energy of 50 MeV. The proton-booster synchrotron (PSB) increases their energy up to 1.4 GeV, injecting them into the 51-years old proton synchrotron (PS). This one accelerates the beam to 25 GeV, and sends it into the super proton synchrotron (SPS), out of which 450 GeV protons are transferred to the LHC for the start of the ramp-up to the nominal energy of 7 TeV.

There are 2 fundamental parameters which define the characteristic and quality of the accelerator chain: the normalised emittance and the allowed number of protons per bunch. Both parameters enter into the definition of the beam brightness which is proportional to N_b/ϵ_n. The normalized emittance, $\epsilon_n = \beta \cdot \epsilon \cdot \gamma$, where β and γ are the relativistic functions, is constant across the full beam acceleration and storage path. Its value is defined at the earliest stage of the acceleration process, and is inherited by the high-energy components of the accelerator chain. The beam emittance is the extent of space and momentum phase space occupied by the particles as it travels, and in practice it determines, together with the β function, the transverse dimensions of the beam at a given point of its trajectory.

CERN is in the process of analysing the entire injection chain, trying to define possible bottlenecks that might limit the final LHC luminosity. Presently, the LHC brightness is limited by the characteristics of the Linac2 and of the PSB. For this reason CERN has already approved a new project, which consists in building a new linac accelerator (Linac4). The Linac4, whose construction has started and should be completed by 2014, will raise the injection energy into the PSB from 50 to 160 MeV. The factor of two gain in $\beta\gamma^2$ allows to double the beam intensity at constant tune shift, providing a better match to the space charge limitations of the PSB. The early stages of the acceleration make use of a H^- beam, whose two electrons will be eventually stripped off. This step eludes the constraints of the Liouville theorem, and reduces the beam emittance. Beam losses at the injection in the PSB will be reduced also via a chopper, which will remove the low-energy tail of the proton momentum distribution. Overall, the improved beam quality will allow to increase N_b from the nominal value of $1.15 \cdot 10^{11}$ to at least $1.7 \cdot 10^{11}$, leading to the so-called ultimate luminosity of $2.3 \cdot 10^{34} cm^{-2} s^{-1}$ in the LHC phase I upgrade.

The next steps in the chain are the PSB and the proton synchrotron. Higher energy out of the PS gives smaller transverse emittances and beam sizes, and therefore reduced injection losses in the next injection stage: the SPS.

A stage-2 upgrade project study was set up a few years ago with the goal of technically and financially defining the impact of constructing a new superconducting PS (PS2), with the goal of having it operational around 2020 -2022 (sLHC upgrade phase II). The PSB would then be replaced by a low-power superconducting linear accelerator (SPL), increasing the injection energy into the PS from 1.4 to 4 GeV thus greatly reducing the filling time. The increase in output energy of the SPL will allow to increase also the output energy of the PS2. The PS2 will deliver protons to the SPS at 50 GeV, well above the 22 GeV transition energy of the SPS, easing the handling of higher intensities. Injection into the SPS at 50 GeV will reduce the space-charge tune spread, to allow the bunch intensity to reach, if needed, $N_b = 4 \cdot 10^{11}$. Higher energy also gives smaller emittance, and less beam losses at injection. Shorter injection and acceleration times, finally, reduce the filling time, with a greater operational efficiency.

Recently this 1.3 billion CHF project has been questioned, given the uncertainties related to the real limitations of the SPS and of the LHC itself. Such a large investment makes sense if both accelerators will be able to accept the new delivered beam brightness or if it will serve

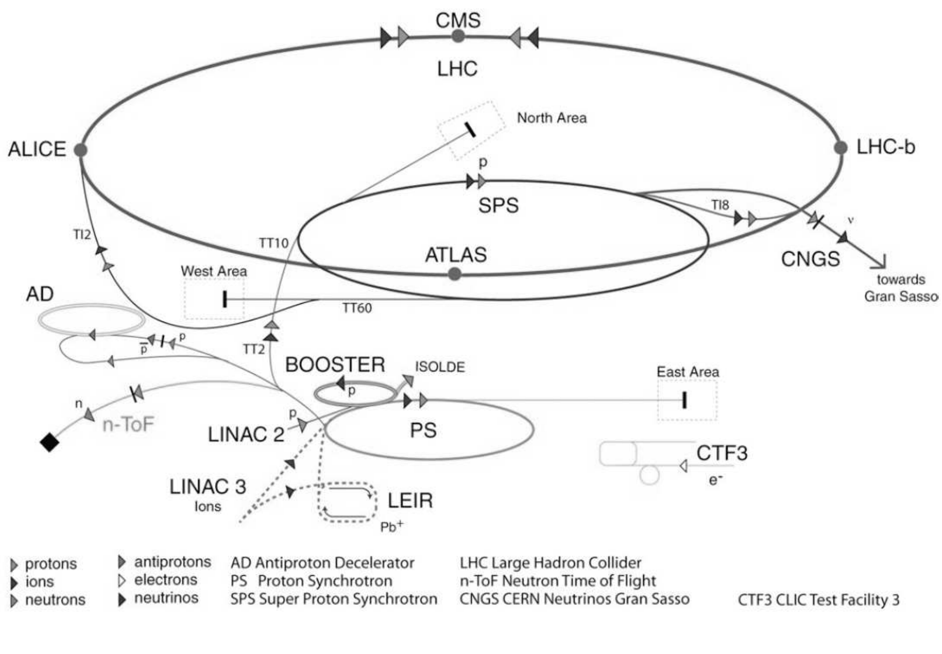

Figure 3: The CERN accelerator complex

the need of other projects at CERN beyond the sLHC. This debate is still open and mostly depends for its technical part from the knowledge of the limitations related to the SPS that will be gained over time. Today it is known that the SPS will need to be first upgraded to accept $1.7 \cdot 10^{11}$ protons per bunch. The electron cloud effect must be first mitigated. Beam losses which today account for about 10% of the total will have to be understood and reduced. The RF system will need a major upgrade to cope with high intensity beams. A study group has been set up and is operational since March 2007. Since then, progresses have been made on many fronts. The recent work has mainly focused on e-cloud mitigation, a-C coating of the vacuum chambers is the best candidate for implementation before 2014. E-cloud mitigation, impedance reduction and RF upgrade would help even for nominal and for sure for ultimate LHC beam operation and can be implemented earlier than in phase II.

If the SP2 phase II upgrade will not take place, the existing PS accelerator will need in any case to go through major consolidation work, to grant stability and reliability during the next 20 years of LHC operation.

3 The superLHC accelerator

Once enough beam brightness can be injected into the LHC, to obtain the necessary luminosity for sLHC, one has to optimise and upgrade the interaction regions (IRs).

Four schemes are presently under consideration: early separation (ES) of the beams, full crab crossing (FCC), large Piwinski angle (LPA) and low emittance (LE). The schematics of their layouts are shown in figure 4.

In the ES scheme, the relative positions of the quadrupoles and of the innermost dipole

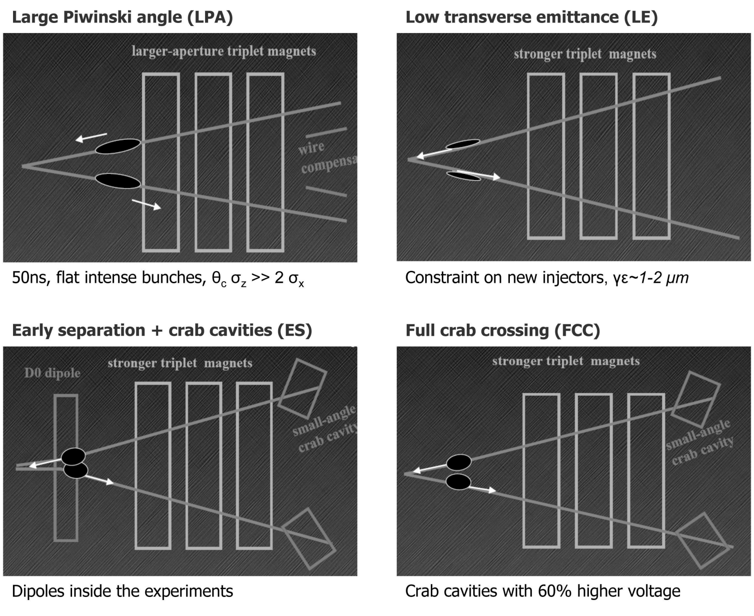

Figure 4: Four different and still possible interaction regions upgrade schemes

are swapped; the dipole is brought closer to the IP, and will reside within the detectors. This allows to keep the bunches separated up to the final dipoles. Small-angle crab cavities, located outside the quadrupoles, would allow for a total overlap at the collision. Introducing additional beam elements inside the detectors area is a major concern. It will complicate enormously the present detectors layout and might imply additional radiation background closer to the sensitive part of the detectors. The FCC scheme relies solely on crab cavities to maximise the bunch overlap (figure 5). The LPA scheme allows for much more intense beams, requiring a longer bunch spacing, of 50 ns, and a larger crossing angle, limiting the geometric loss with a flat beam profile. Long-range beam-beam interactions need to be screened with compensating wires. The LE scheme provides much thinner bunches, at a cost of a larger geometric loss. The LPA and LE schemes will require a full upgrade of the injector chain, including PS2 and SPL.

Certainly, the FCC scheme is the most attractive one. It does not require any major changes in the interface between machine and experiments, nor adds it requirements to the injection chain. RF crab cavities [6] deflect head and tail in opposite direction so that collisions are effectively "head on" for luminosity and tune shift. Bunch centroids still cross at an angle (easy separation). Crab cavities can increase the LHC luminosity without an accompanying increase in beam intensity, thereby avoiding negative side effects associated with high intensity and high stored beam energy.

Both "local" and "global" crabbing schemes are still under consideration for the LHC upgrade phase II. In the global solution a set of cavities is positioned at IR4, in the local solution crab cavities are placed on each beam around the ATLAS and CMS IR.

Over the last few years, major progresses have been made in the field of crab cavities. Recent KEK-B results have shown that crab cavities work and improve luminosity. Worries relate to machine protection, reliability and possible induced phase noise. A vigorous R&D program has started in various accelerator labs related to LHC. A test in the SPS could be prepared for 2012.

In addition, luminosity can be improved by a proper focusing of the beam around the interaction regions. While the overall behaviour of $\beta(s)$ around the full ring is constrained by global stability requirements, like the value of the tune, its value at a specific point (IP for

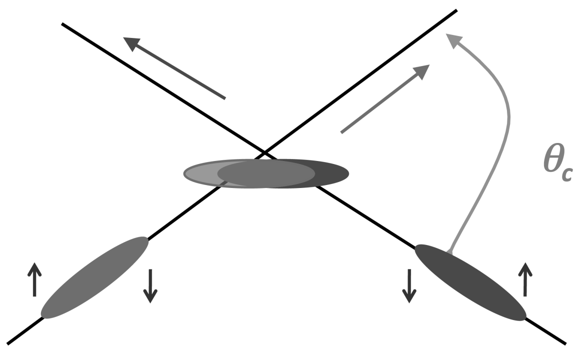

Figure 5: RF crab cavity scheme at the interaction point

example) depends on the local machine optics. The price to pay for a beam squeeze at the IP is a growth of the beam size before and after the minimum of β^*. The internal aperture of the quadruple magnets surrounding the IR must match this growth, to prevent the beam hitting their inner surface. An increase in the quadrupole aperture, on the other hand, requires a larger field, in order to maintain the constant field gradient necessary to focus the beam. Today the plan is to have new large aperture triplets already for phase I and high field ones based on Ni_3Sn technology for phase II. In both cases the installation of such devices in the straight sections in front of the experiments will require major shutdowns of the order of 9-12 months.

Recently it became evident that not just the value of the peak luminosity is a fundamental parameter for the sLHC, but also a decent life time of the beam luminosity is very important. What really counts, at the end, is to be able to maximise the integrated luminosity delivered to the experiments over a reasonable time span. Figure 6 shows that at a peak luminosity of $10^{35} cm^{-2} s^{-1}$, the typical life time, independently from the bunch intensity, is of the order of 3 to 4 hours. Its time evolution is exponential. Therefore it might not be optimal to continuously fill the machine to optimise the delivered integral luminosity. The drop in luminosity is proportional to the increase in interaction rate, and is just due to the loss of protons due to the collisions. With a bunch-bunch crossing every 25 ns, 300 or 400 pp collisions at each crossing, and two active experiments (ATLAS and CMS), a number of the order of 10^{14} p/h is simply disappearing, out of a total of about $5 \cdot 10^{14}$ stored in the initial beam.

The obvious solution is luminosity levelling, starting from an initial peak luminosity of $5 \cdot 10^{35} cm^{-2} s^{-1}$. The luminosity can be expressed as:

$$L \propto \frac{1}{\beta^* \sqrt{1 + \frac{\theta^2 \sigma^2}{4 \beta^* \epsilon}}}$$

Here the idea is to to tune the various parameters as a function of time to keep the luminosity constant as long as possible. Three possibilities in LHC, specific to crossing at an angle: 1)

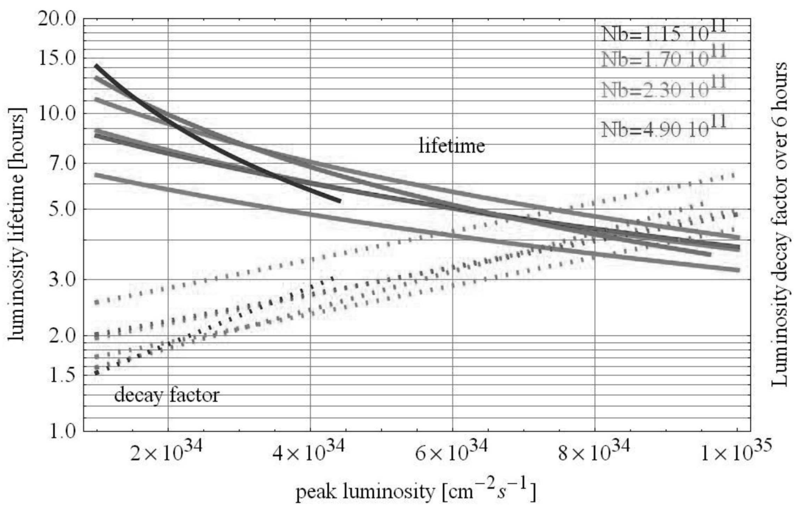

Figure 6: Luminosity lifetime as a function the peak luminosity, no levelling

levelling via dynamic β^* adjustments, 2) Levelling via dynamic crossing angle adjustments (θ) and 3) Levelling via dynamic bunch length adjustments (σ).

Levelling via the crossing angle (2) appears to have the best potential (performance, complexity) but requires the crab cavities solution to work. If the method works, one could keep an average luminosity of $5 \cdot 10^{35} cm^{-2}s^{-1}$ over 7 to 8 hours. This could be translated into a yearly integrated luminosity of $200 - 250 fb^{-1}$. Hence, luminosity levelling could be imposed as a requirement for all scenarios. Levelling is also useful for the machine in terms of peak energy deposition, beam-beam effect, operation efficiency.

4 Detectors requirement and detectors upgrade plans

The requirements on the experiments are driven by the nature of the observables that will be of interest at the sLHC. These will be defined by the discoveries or lack thereof that will emerge after the first few years of data taking and once the nature of any new phenomena will be more evident.

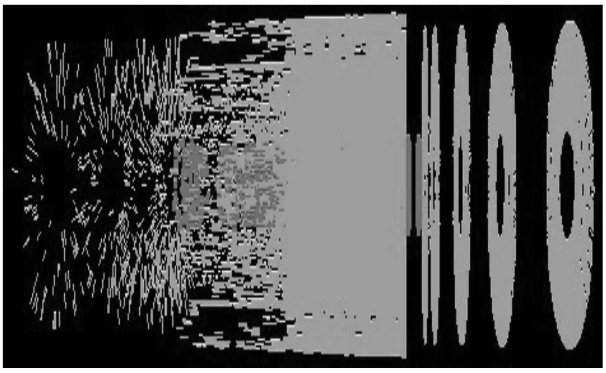

Figure 7: Tracks simulation in the new ATLAS inner tracker with 400 pile-up events

At this stage of the project, one can not relax any of the initial experimental requirements. Whatever the discovery scenario will be, the experiments will be required to perform lepton and photon identification down to rapidities of 3. Jet tagging in the very forward region will remain a must, in particular if the Higgs is not found. Missing energy will be a fundamental parameter for any search for new physics.

On top of that, luminosity above or equal $4 \cdot 10^{34} cm^{-2}s^{-1}$ implies many overlapping hard collisions in the same bunch crossing (pile-up). For example, the PA scheme at $10^{35} cm^{-2}s^{-1}$ implies a pile-up of about 400 hard collisions in the same bunch crossing.

This imposes a very high density of tracks and photons in the inner detector regions, far beyond what the existing ATLAS and CMS trackers can effort. The detector occupancy would be very high, the challenge being to find all the tracks, without also finding many fake tracks from random combinations of hits. Picture 7 shows hits in the newly designed sLHC ATLAS inner tracker from one bunch crossing with 400 pile-up events; only tracks in the forward half of the detector were generated. The inner tracker gets about 15,000 tracks per bunch crossing and a similar number of photons which can produce e+e- pairs. A sufficient number of hits per tracks must be recorded, the detector granularity will be increased by almost a factor 10 to keep occupancy at the $1-2\%$ level for an efficient pattern recognition. This can be achieved by reducing pixel size, strip dimensions for silicon counters, and by adding more detector layers to increase the number of precision points per track. The ability to reconstruct displaced vertices will also deteriorate, with a reduced efficiency to tag b quarks and leptons and a larger rate of fake tags.

In any case, before one moves to the sLHC regime (upgrade phase II), the existing ATLAS and CMS inner detectors will need to be replaced, because fully damaged by the accumulated radiation dose during the initial LHC discovery period (600-700 fb^{-1} acquired on tape). Whatever the sLHC scenario will be, beyond this integrated luminosity, both experiments will require new inner detector trackers. ATLAS in particular will have to abandon the concept of a TRT tracker detector and fully rely on semiconductor sensors.

Other components might not survive beyond the agreed LHC luminosity period. ATLAS might loose the front-end electronics placed on the forward hadron calorimeter. The functioning of the forwards calorimeters might be compromised. As an example, the ATLAS LAr forward calorimeter might suffer from space charges which might break down the original ionization signal and even cause boiling of the liquid at the innermost radii. Similarly, the CMS endcap and forward calorimeters might suffer from radiation damage.

ATLAS has estimated the need for at least 18 months of shutdown before moving to phase II, to replace and commission its new inner detector and eventually upgrade its forward calorimeter and change the hadronic calorimeter front-end electronics.

Even before worrying about physics performance, the experiments will have to worry about the operability of their innermost detectors. Already during the phase I shutdown, needed to install the Linac4 and the new large aperture triplets, ATLAS and CMS plan to upgrade their pixel detectors. ATLAS will add a new pixel layer, built around a new beam pipe, sliding inside the previous pixel detector. CMS will replace the entire pixel detector with a new low-mass, 4-layers one. Layout drawings of both pixel detectors are shown in figure 8.

The performance of the level 1 trigger (LVL1) system, fully based on hardware today , will be the real challenge. The emphasis will therefore be on the first trigger levels, where one may need to incorporate tracking information to supplement the reduced rejection power of muon and calorimeter triggers, and to maintain acceptable efficiency and purity for electrons, affected by the degradation of isolation criteria.

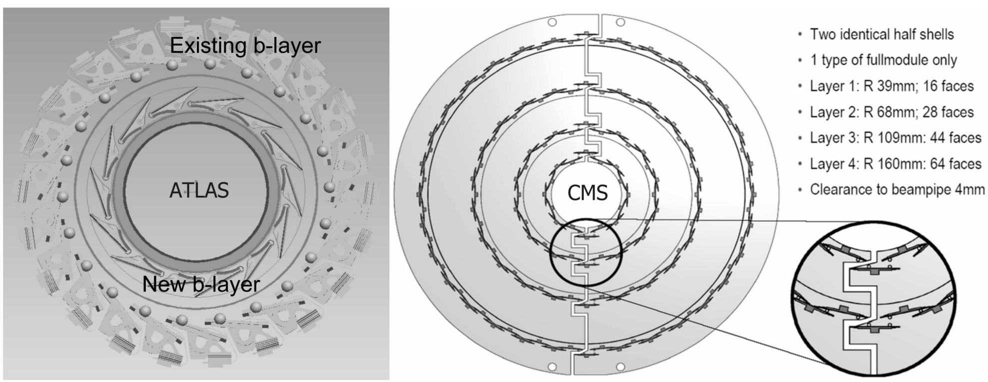

Figure 8: ATLAS (left) and CMS (right) new phase I pixel detectors

One needs to keep the stored event rate roughly the same as now : ~ 200 events per bunch crossing. The events are much bigger at high luminosity, so this is quite a challenge. It means rejecting 10 to 20 times as many events as now, each of which is about 10 times as big. To meet this challenge, one can increase the latency at level-1 and move some of what is done in software at high level, such as combining trigger objects.

Today ATLAS and CMS consider introducing new elements at LVL1, including a track-trigger. First studies in this direction are just starting, but the community is lacking experience in this field.

Full granularity of the calorimeters at trigger level will allow better particle identification.

The muon trigger needs better resolution to allow higher momentum thresholds to reduce the muon trigger rate. Adding some new chambers can achieve this, or at least trying to use the existing precision chambers granularity at the trigger level.

It is not known how the very important forward calorimeter trigger will perform at these sLHC high rates.

The upgrade of the LHC experiments will require major R&D and construction work, with a likely time line of at least 8-9 years for construction and integration. The planning has to assume the worst possible scenarios in terms of pile-up and radiation environment. While getting the financial green light for this new enterprise will probably take a few years and will be triggered by the first LHC discoveries, the detector community has to act now, preparing technology, making choices, testing prototypes and going deeply into the engineering design.

5 Outlook

Whatever the LHC will discover, it will set the path of future research in particle physics. After the first moments of assessments of the new landscape, the next step will be the precise measurement of the spectra, mixings and couplings of the new particles. The existence of supersymmetry, if confirmed, will open a completely new world of mass spectroscopy at high masses. For years one will be far from the dominance of systematics, and statistics will undoubtedly remain the most important factor.

Defining from now on a programme of high luminosity, beyond the initial LHC mandate, remains the only logical solution. It will take time until more dedicated machines, like linear colliders or more energetic hadron colliders, will become a reality.

Planning from now on a LHC luminosity upgrade program is a must.

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Discussion

Majid Hashemi (Antwerp University): One of the main concerns of SLHC would be the amount of the pile up. Are the current physics results shown in the talk based on rescaling or simulation including pile-up?
Answer: Not all. Today it is still very difficult to work with 400 pile-up events in full simulation. For the moment we have that just for special optimization studies related to the inner tracker detector.
Joel Feltesse (IRFU, CEA): We all know how old is the PS. Reliability is more and more a problem. Have you already an estimate of the cost and the schedule of a new PS?
Answer: I did not give a number. But I forwarded the question to the CERN DG, who was better qualified. The number was not given, but today (end of 2009) we know that the estimation is of the order of 1.2BCHF
Dimitri Denisov (FNAL): Energy is in many cases more important than luminosity for physics reach: 1. Are there any substantial upgrades expected to be needed to reach 14 TeV?
Answer: More then upgrade we speak about consolidation work, to repair the warm splices and retune the dipole magnets. This is part of the plans of CERN for the next few years. It is a major piece of work.
: What are options to go above 14 TeV?
Answer: We speak about DLHC. Here the possible idea is to double the field strength of the dipoles by using new superconducting material (Ni3Sn). This technology is no yet at the stage to be rescaled to mass production. A substantial R&D would need to be launched.