SLHC, EXPERIMENTS DESIDERATA

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Abstract

Even if the discovery potential of the LHC is not yet revealed, the physics community is making serious plans for running the LHC experiments up to the end of the next decade, aiming of collecting a large sample of statistics (~3000 fb^{-1}). The present detectors (ATLAS and CMS) will need a major upgrade once today's inner trackers will have been exposed to 300-600 fb^{-1} of integrated luminosity. The unprecedented peak luminosity needed to reach such a goal, will seriously challenge the detector performance. Various improvements, to most of the detector and its trigger system, will become necessary. Such a complex plan requires a well established upgrade project, which will span over this entire decade.

PHYSICS MOTIVATION

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

The timeline for these searches is outlined in the left plot of figure 1. It 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 1 fb^{-1} of data during 2011, which will not be sufficient 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. 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. At some point, with high statistics, rare decay modes of the SM Higgs will become accessible (H -> μ+μ−,H -> Zγ). Hb,Ht, HZ, HW couplings might be measured to 10% for mH < 200.

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 solve. 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

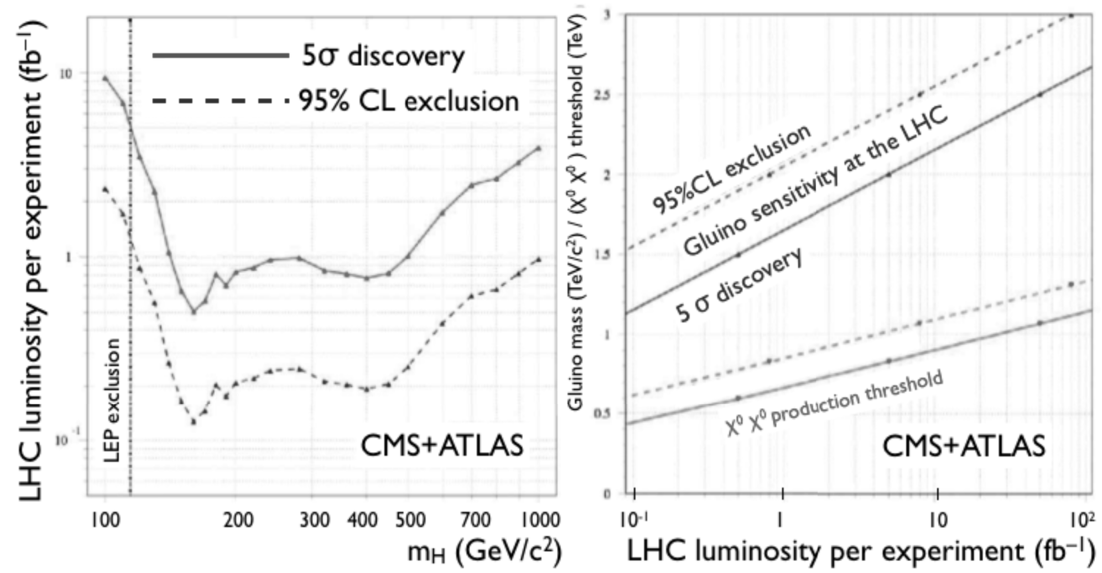

Figure 1: LHC Higgs and Gluino discovery potential at 10 fb^{-1}

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 (up to ~ 3000 fb^{-1}) 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 LHC luminosity upgrade will have a strong impact on physics.

DETECTORS REQUIREMENTS AND UPGRADE

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.

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, one of the scheme considered, the large Piwinski (LPA) angle scheme, allows for much more intense beams, at $10^{35}cm^{-2}s^{-1}$ requiring a longer bunch spacing of 50 ns and a larger crossing angle, limiting the geometric loss with a flat beam profile. The LPA 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 2 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 the pixel size, thr 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 (today labeled also as 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 running 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 (gaseous radiation transition) 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 upgrade shutdown (initially planned after 50-100 fb^{-1} delivered to the experiments around 2014-2015), 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 3. For both detectors this will represent on one side a real performance improvement (lower mass in the inner most region, better vertex tagging capability) and at the same time it will anticipate probable risks related to inefficiencies and aging effects which this detectors might already experience after having operated at 50-100 fb^{-1} integrated luminosity. After all, detectors of such complexity and placed in such a difficult radiation environment have never been operated up to now and both Collaborations, also supported by the LHCC committee, have judged this to be a reasonable and safe approach. Doing this, both ATLAS and CMS will require to operate the LHC with vacuum beam pipes smaller in diameter with respect to the one used today (-15-20%). This put an additional requirement on the optics of the beam in the interaction regions, to be analyzed and approved by the machine experts.

The performance of the level 1 trigger (LVL1) system, today fully based on hardware, will be the real challenge to face once we move into the sLHC regime. The real issue is to keep events rejection very efficient as a function of transverse momentum. The sharpness of such a trigger will be used as one of the main parameters to select new physics and therefore reject backgrounds. Two approaches have been looked at.
First one should better combine the information delivered at the trigger level by the calorimeters and the muon spectrometer. This requires to be able to use all the existing cell granularity in the calorimeters and pre-showers detectors and to improved the spatial resolution of the trigger information in the muon spectrometer. For the calorimeters this implies new front-end electronics, probably fully digital on the detector. For the muon spectrometer, in particular for ATLAS, this requires one additional layer of trigger chambers and probably the need to insert the existing drift tubes detector granularity at the trigger level. All this is under scrutiny in the detector community and might imply a sizable amount of work and investments on the detector itself (R&D and careful shutdowns plans). In both cases new radiation hard electronics will need to be designed and implemented on the detector.

The second approach will be to incorporate tracking information to supplement the reduced rejection power of muon and calorimeter triggers, and to maintain an acceptable efficiency and purity for electrons, affected by the degradation of the isolation criteria. LVL1 triggering at the inner trackers level was never done before. It requires new electronics and a novel strategy in the design of the various levels functionality of the new trackers. Both communities, and CMS in particular, are already very active on this, but a substantial level of R&D effort is still necessary.

In general planning for improved efficiency at the trigger selection level is manatory. One needs to plan to keep the stored event rate roughly the same as now : ~200 events per bunch crossing. The events are much bigger at high luminosity because of the increased detector granularity, 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 forwards in the chain some of what is today done in software at high level, such as combining trigger objects. All this requires new front-end and back-end electronics of a new generation, new trigger processors systems and a new generation of high level trigger farms.

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.

ATLAS AND CMS UPGRADE STRATEGY

Today both experiments foresee 3 distinct moments of detector consolidation and upgrade.

1) a first step of consolidation in the next 2-3 years, while the LHC finds its way to the design beam energy and explore a initial limited luminosity phase. Various detectors and infrastructure component will need to be debugged and consolidated to gain in efficiency and reliability. Components which in 2002

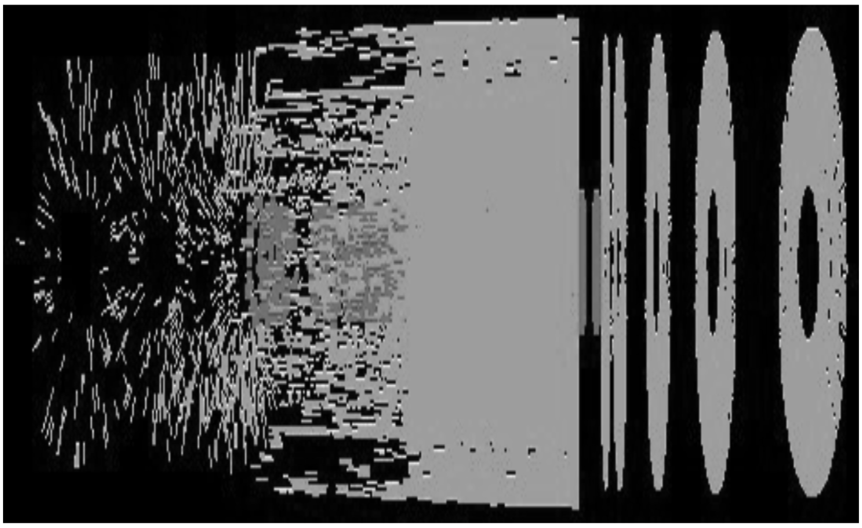

Figure 2: Picture shows hits in inner tracker from one bunch crossing with 400 pile up events; only tracks in forward half of detector were generated. The inner tracker gets about 15,000 tracks per bunch crossing.

were staged for financial reasons (CMS: forward muon trigger chambers and TDAQ computing power, …; ATLAS forward muon precision chambers second layer, shielding elements, CPU power,…) will need to be restored. All this should happen in the shadow of the LHC repairs. An effort will also be made to upgrade the forward vacuum beam pipe to light material one to prevent additional background induced problems and material activation (ALARA principle). ATLAS plans a major upgrade already in this phase of the external inner detector cooling plant, which is today problematic and need a lot of attention and care.

2) Before reaching the ultimate luminosity or just going beyond nominal, which could happen once the injector chain has been upgraded (Linac4, SPS consolidation,..), both detectors plan at least an upgrade of the pixel detectors or part of it (ATLAS: new insertable b-layer). Construction plans for this have been already presented to the LHCC and at least for ATLAS, internally this project has been launched already. This was done also within the logic presented few years ago by the LHC machine to the experiments and LHCC of having a substantial phase I upgrade. ATLAS will request at some point about 9 months of shutdown to insert this new pixel layer. If such a shutdown happens around 2016-2017, then there might be enough time and motivation to anticipate to that moment part of other components upgrade which is now foreseen for phase II. The ATLAS collaboration is already revisiting some plans in such a direction. Planning an upgrade/consolidation shutdown of 9-10 months just after the first 20-50 fb^{-1} of data have been acquired, might be a wise move. Anticipating problems and repairs that such complex detectors might be facing once in operation for 6-7 years is a realistic approach.

3) Once the detectors have been exposed to 300 to 600 fb^{-1}, the inner detector trackers of both, CMS and ATLAS, will need to be replaced. This is a major operation, which will require at least 18 months of shutdown (detectors request). The old inner detectors will need to be removed, the services (cabling , piping, …) upgraded in situ, the new inner detector installed and commissioned. Given the fact that such devices will require new technology and therefore an important R&D effort to be mature for construction, given the fact that it will be difficult to justify the new choices without knowing the new physics potential, it will be reasonable and realistic to assume that in today's scenario, green light for construction will not come before 2012-2013. The construction time, if we compare it to what was done initially for both experiments, will take at least 7-8 years. Therefore this phase of the upgrade (phase II in the LHC plans) should happen at the beginning of the next decade. It is implicit that the 2 detectors will have to face at the same time a major upgrade of all the front-end and back end electronics and the online computing systems.

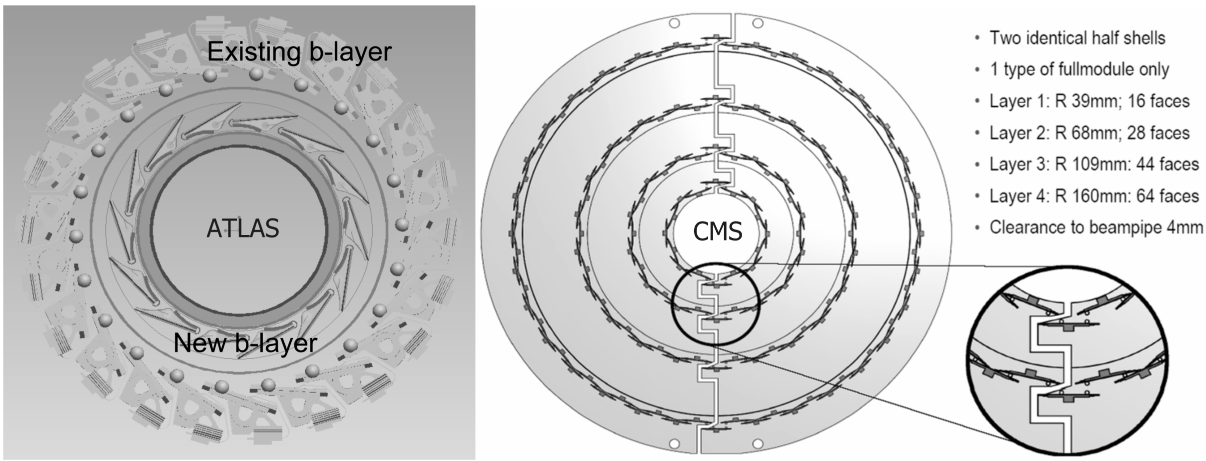

Figure 3: ATLAS (left) and CMS (right) new phase I pixel detectors

ALICE AND LHCB UPGRADE STRATEGY

The case of ALICE and LHCb is slightly different from the 2 major LHC detectors.

ALICE plans on the long term to increase its statistics through an effective peak luminosity increase in Pb+Pb by factor five to $5*10^{27}$ $cm^{-2}s^{-1}$ (still compatible with the TPC detector operation).

For the 'Phase II' operation one assumes the typical scheme of a yearly ion run together with a (short) period of p+p running necessary for data comparison and detector startup. For the pp running mode, the luminosity has to stay below few 10^{31} cm $^{-2}$s^{-1}. This might be achieved with displaced beams and/or short dedicated low luminosity runs.
ALICE also plans a major detector upgrade for phase II: a 2nd generation vertex detector, also using a smaller beam pipe; new detectors for forward physics (in particular, forward calorimetry); particle ID for p_T in the range 5 to 20 GeV; increased rate capability of the TPC (faster gas, increased R/O speed); upgraded DAQ & HLT.

The LHCb plans, on the long term, aim at increasing the collected statistics by a factor 10.
The strategy is to first collect ~10 fb^{-1}, then upgrade the detector read-out to 40MHz (it requires a ~8-10 months shutdown) and then collect ~100 fb^{-1}. This requires running LHC at a luminosity of $5*10^{33}$ at Point 8. LHC and sLHC operation schemes must be designed to allow the running of LHCb after 2020 with L=$5*10^{33}$ cm $^{-2}$s^{-1}.

In general the compatibility of running ALICE and LHCb while ATLAS and CMS are running at high luminosity regime must be addressed, and clear solutions must be presented to the community, before going to far in the upgrade plans. The same reasoning is valid for the upgrade which might become necessary to these two interaction points (compatibility of triplets in IP8 with higher luminosity, at present no TAS in P8, as an example).

OUTLOOK

All experiments need to define a plan and a strategy towards sLHC. The lead time for major detector upgrades can take several years of construction once the green light is given. This means that decisions have to be taken in a very early stage of the LHC project. The experiments are eager to enter now in such discussions and plans, in order to be ready once the discovery landscape of the LHC will be clear.

It is also evident that such complex and unprecedented detectors will need a continuous consolidation and upgrades to cope with the challenges they will face once the LHC luminosity evolves towards its design value, the ultimate reach and later to the sLHC scenario. All this will go through a series of installation shutdowns that both, machine and experiments, will have to face and optimize together, the final goal being the optimal use of the resources to best pursue new physics discoveries.

REFERENCES

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