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ECFA EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

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Physics and Technology Challenges

Report submitted to ECFA
Prepared from inputs provided by the ALICE, ATLAS, CMS and LHCb Collaborations
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1. Introduction

The European Strategy for Particle Physics was published[1] earlier this year and adopted at the special European Strategy Session of CERN Council in Brussels on 30 May 2013. In that document, the priorities are set for European particle physics taking account of the Higgs boson discovery at the LHC in 2012 and of the global energy frontier research landscape. This contains a key message towards the accomplishment of the HL-LHC programme: "*Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma*." In this context, the ECFA High Luminosity LHC Experiments Workshop[2] was a first meeting of the four LHC experiments, together with the accelerator and theory communities, to address the challenges of the HL-LHC programme. The meeting held in Aix-les-Bains from 1st to 3rd October, 2013 gathered more than 300 physicists and engineers from these different communities.

[1] https://cds.cern.ch/record/1551933/files/Strategy_Report_LR.pdf?version=1

[2] https://indico.cern.ch/conferenceDisplay.py?confId=252045

The goal of the workshop was to initiate development of a common approach to the physics programme, to share experience among experiments and to look for synergies to streamline the work and the resources needed to prepare the detectors for best exploitation of the HL-LHC. Towards this end, eight groups were formed, involving members of the four collaborations as well as colleagues from theory and the accelerator, to prepare specific sessions with presentations across the experiments. All main areas of the programme were covered: physics goals; accelerator and beam conditions; overall experiment upgrades and sub-system performance requirements with associated technology R&D; as well as the schedule, logistics and scope of work during installation in the required Long Shutdowns (LS) of the accelerator.

This document contains a brief presentation of the LHC upgrade stages, of the ultimate physics goals and of the overall experimental projects. The main conclusions and proposals to consolidate cross-experiment activities are then presented. The following sections are discussions of the main detector sub-system challenges and associated R&D activities, prepared by each preparatory group. The summary of the physics studies performed for the workshop is attached to this report as an independent note.

2. LHC Upgrades

In its first period of operation from 2010 to 2012, the LHC has accumulated an integrated luminosity of about 30 fb^{-1} leading to the major discovery of the Higgs boson. Following the present long shutdown period (LS1) it will resume operation in 2015 at a centre of mass energy increased to close to 14 TeV and with an expected bunch spacing of 25 ns. A new scheme for the injection and the separation of the beam in bunches in the PS should allow increasing their brightness to raise the peak luminosity of the LHC from the nominal design value of $1 \times 10^{34}\ cm^{-2}s^{-1}$ to about $1.7 \times 10^{34}\ cm^{-2}s^{-1}$.

The current planning of upgrades then foresees two other long shutdowns LS2 and LS3. In LS2, starting in 2018, the injector chain[3] and the LHC will be both improved to potentially deliver a further increased luminosity of $2 \times 10^{34}\ cm^{-2}s^{-1}$ or slightly beyond. In LS3, starting in 2022, the LHC will be upgraded to HL-LHC to provide more populated and denser bunches at the collision regions of ATLAS and CMS, being able to reach virtual peak luminosities well in excess of $10^{35} cm^{-2}s^{-1}$ at the beginning of LHC fills.

With these upgrades, ATLAS and CMS will experience an average of about 25 to 40 inelastic interactions per bunch crossing (referred to as event pile-up) in the period before LS2 and possibly up to 60 to 70 afterwards. An integrated luminosity of over 300 fb^{-1} is expected by LS3. After LS3, the present HL-LHC operating scenario is to level the instantaneous luminosity at $\sim 5 \times 10^{34}\ cm^{-2}s^{-1}$, to contain the pile-up below 140 (and to cope with cryogenic limitations in the inner triplet quadrupoles) and to deliver an integrated luminosity of $\sim$ 250 fb^{-1} per year for a further 10 years of operation. Such extreme performance will require major LHC consolidation and upgrades, including replacement of the interaction region triplet quadrupoles using Nb_2Sn superconducting technology and the implementation of new devices to control the beam overlap, such as crab cavities[4].

Operation with increasing rates and pile-up will become more and more challenging for the experiments, and the performance degradations due to the integrated radiation dose will also need to be addressed for the HL-LHC era. ATLAS and CMS will therefore require substantial upgrades, tailored to the expected performance of the LHC accelerator chain. ALICE and LHCb do not require the LHC machine upgrades but the limits set by the detector constraints will need to be overcome to increase their integrated luminosities. LHCb will operate at a levelled luminosity of $\sim 2\times 10^{33}\ cm^{-2}s^{-1}$, a factor of 10 higher than the original plans, to

[3] See for example https://indico.cern.ch/conferenceDisplay.py?confId=260492

[4] See for example https://indico.cern.ch/conferenceDisplay.py?confId=257368

accumulate ∼50 fb^{-1} of data in 10 years of operation after LS2. ALICE will integrate a luminosity of ∼10 nb^{-1} of Heavy Ion collisions in several years of operation after LS2 and LS3.

In section 11 a more detailed description of the LHC upgrades is provided, along with a discussion of the beam loss risks and of the technical options to control the shape of the luminous region, which is especially important to control the pile-up density. In section 12 the implications of the accelerator modification in the experimental areas are discussed, together with the first estimates of the radiation and activation level that will occur in the HL-LHC era. The scope of work in these LS periods and their estimated durations to allow installation of the proposed upgrades are also presented.

3. Physics Programme

With 10 times more data than the LHC is expected to deliver by the end of this decade, the HL-LHC will be the unique worldwide facility to look for rare processes, study very high mass systems and make high precision measurements. For ATLAS and CMS, this gives unprecedented sensitivity for a large range of Higgs boson property measurements, as well as for searches of new particles and precision studies of a wide range of fundamental particles and processes. In case the 13-14 TeV running this decade leads to further new particle discoveries, the HL-LHC will also be essential to measure their properties. For ALICE and LHCb, much greater statistical precision can be achieved. For the heavy ion programme, 10 (triggerable probes) to 100 (minimum bias events) times larger statistics will significantly improve on the precision of measurements available before LS2, and allow for the exploration of rare probes of the QGP and permit key distributions to be extracted as a function of several variables simultaneously. For LHCb, a wide range of rare-decays can be explored with significantly extended sensitivity and the precision of many measurements will be greatly improved thereby increasing the reach of indirect searches for new physics. These will also benefit from the complementary studies that will be possible with the very high statistics samples recorded by ATLAS and CMS in both domains.

The HL-LHC physics programme and some preliminary performance reach projections were documented for the European strategy meeting in Cracow[5] and for the Snowmass workshop in the US[6]. The ECFA Workshop was a significant step forward to develop the physics goals and measurement requirements in collaboration with theorists; and to continue performance studies based on consistent assumptions for the generation of physics process and for the beam conditions, with common simulation methods, including improved descriptions of the proposed detector upgrades. These studies were organised along four major experimental lines of investigation: precision tests of the role of the observed Higgs boson in the Standard Model (SM), including searches for additional Higgs bosons, direct searches for other beyond-the-Standard Model (BSM) physics, precision tests of the SM in heavy flavour physics and rare decays, and precision measurements of the properties of the Quark-Gluon Plasma with heavy ion collisions. Below, only some major aspects of the physics programme are discussed, which are also representative of the motivation for a number of specific performance related detector upgrades.

A central component of the physics programme is to perform precision measurements of the properties of the 125 GeV Higgs boson discovered in 2012 and compare these to the predictions of the SM. This has been an

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[5] http://europeanstrategygroup.web.cern.ch/europeanstrategygroup/ (For HL-LHC projections see in particular: “Physics at a High-Luminosity LHC with ATLAS, ATL-PHYS-PUB-2012-001 (2012)” and “CMS at the High-Energy Frontier. Contribution to the Update of the European Strategy for Particle Physics”, CMS-NOTE-2012-006 (2012)).

[6] http://www.snowmass2013.org/tiki-index.php (For HL-LHC projections see in particular: “Physics at a High-Luminosity LHC with ATLAS (Snowmass Contribution)”, arXiv:1307.7292 [hep-ex] and “Projected Performance of an Upgraded CMS Detector at the LHC and HL-LHC: Contribution to the Snowmass Process”, arXiv:1307.7135 [hep-ph])

area of significant progress. The ATLAS and CMS experiments have validated their earlier projections, and have presented their updated results under consistent assumptions. Both experiments project comparable precision with an estimated uncertainty of a few % for many of the properties investigated, demonstrating that with an integrated luminosity of 3000 fb^{-1} the HL-LHC is a very capable precision Higgs physics machine. To fully benefit from the potential of high luminosity, however, progress will also be needed in the accuracy of theoretical calculations and precision Standard Model measurements. These findings are illustrated by the data in Table 1 where the estimated precision on the measurements of ratios of Higgs boson couplings is presented.

L(fb^{-1})	Exp.	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ/κ_Z	κ_W/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_Z/κ_g	κ_t/κ_g	κ_μ/κ_Z	$\kappa_{Z\gamma}/\kappa_Z$
300	ATLAS	[3,6]	[5,11]	[4,5]	N/a	[11,13]	[11,12]	[17,18]	[20,22]	[78,78]
	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,5]	[2,7]	[2,3]	N/a	[7,10]	[5,6]	[6,7]	[6,9]	[29,30]
	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

Table 1. Estimated precision on the measurements of ratios of Higgs boson couplings. These values are obtained at $\sqrt{s}$ = 14 TeV using an integrated dataset of 300 fb^{-1} at LHC, and 3000 fb^{-1} at HL-LHC. Numbers in brackets are % uncertainties on couplings for [no theory uncertainty, current theory uncertainty] in the case of ATLAS and [theoretical uncertainties scaled by a factor of 1/2, while other systematic uncertainties are scaled by the square root of the integrated luminosity, all systematic uncertainties are left unchanged] in the case of CMS.

The studies performed also demonstrate that the HL-LHC is at the same time a unique discovery machine. In addition to being sensitive to BSM physics via deviations from the SM in the Higgs sector, including the possibility of additional Higgs bosons, with the HL-LHC, ATLAS and CMS can continue the direct searches for other new particles that could shed light on one or more of the open questions in HEP and cosmology (such as the stabilisation of the Higgs mass or the nature of dark matter). ATLAS and CMS performed studies that illustrate the importance of the large dataset that HL-LHC will provide in making such a discovery in cases where the new physics is produced with a small cross section, small visible branching fraction, or experimentally challenging kinematics. Figure 1 shows the results of two such studies: electroweak production of charginos/neutralinos where masses up to above 650 GeV are discoverable with the HL-LHC and direct stop production, where masses up to 1200 GeV would be discoverable.

Preliminary studies of rare process only accessible at the HL-LHC, such HH decaying to $bb\gamma\gamma$, demonstrate the importance of tracking performance at high pile-up for mass resolution, primary and secondary vertex identification efficiency, and the rejection of fake photons. In addition, to improve the acceptance for Higgs decays particularly in the crucial rare channel H to $\mu\mu$, extensions of the pseudorapidity coverage of several detectors in both experiments is being very actively explored.

Other studies have also shown that a higher granularity calorimeter is also important for object recognition and isolation, in particular in the forward region. Moreover, processes that proceed by either vector boson fusion or vector boson scattering will be an important component of the HL-LHC physics programme. At the pile-up levels of the HL-LHC, VBF/VBS jet tagging efficiency will be significantly degraded unless forward calorimetry information is significantly improved. Studies carried out suggest that extending the tracker coverage to $|\eta|$~4, however, could dramatically improve the ability to reject fake jets and restore this efficiency. The relatively low mass of the Higgs means that its decay products often have momenta that are below the trigger thresholds required to contain the data bandwidth of accepted events. Improved precision in measuring trigger objects and more sophisticated algorithms can recover this lost trigger efficiency and thereby improve the precision of key Higgs measurements. Similarly, numerous BSM theories predict mass spectra that result in soft decay products that would evade detection unless sensitivity to low momentum objects is retained by the trigger system.

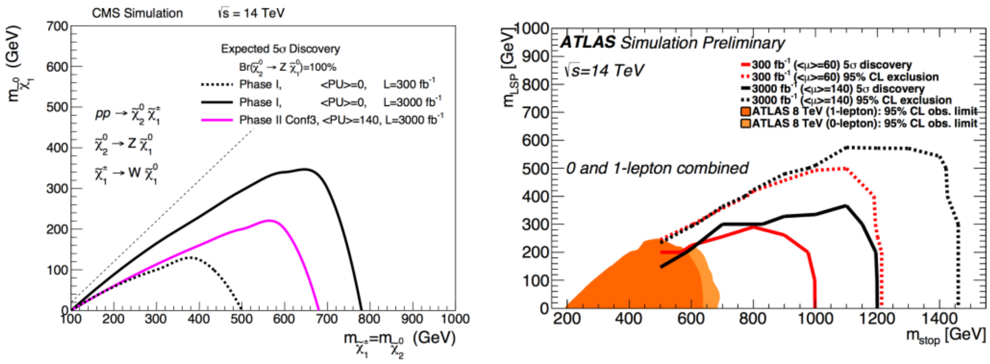

Figure 1. Left: Projections of the discovery reach for electroweak production of charginos/neutralinos that decay via W and Z bosons into the LSP. The magenta curve is the realistic reach obtainable under HL-LHC luminosity conditions. This can be compared with the black solid curve that shows what the reach would be if there were no pile-up effects, or equivalently pile-up effects were completely mitigated. This curve in turn can be compared with the black dashed curve in order to see the increase in reach due to the luminosity provided by the HL-LHC with respect to LHC. Right: The discovery reach for a simplified model of direct stop production for 300 fb^{-1} (solid red lines) and for 3000 fb^{-1} (solid black line). The corresponding 95% exclusion limits are shown as dashed lines.

The HL-LHC also provides exciting discovery potential through precision studies of the flavour sector. In particular, updated sensitivity studies from LHCb demonstrate that it will be the world-leading experiment for a wide range of important observables concerning rare decays and CP violation in charm and beauty hadrons. This capability is complemented by sensitivity from ATLAS and CMS in particular channels triggered by dimuon signatures, as well as in studies of the top quark.

Finally, the studies presented at this ECFA workshop for heavy ion physics, demonstrate that a dataset corresponding to more than 10 nb^{-1} of Pb-Pb collisions will allow the ALICE, ATLAS and CMS experiments to perform unique precision measurements of fundamental properties of the Quark-Gluon Plasma. To this purpose, several probes of the system conditions will be studied, including heavy-flavour particles, quarkonium states, real and virtual photons, jets and their correlations with other probes. The upgraded detectors and the 5-10 fold higher integrated luminosity will, in particular, provide access to new observables, characterized either by low cross sections (like heavy flavour baryons and b-jet correlations) or by low signal-to-background ratios (like low-mass dileptons).

In total, the physics performance of more than 30 searches and measurements was investigated. The theoretical motivations for these studies and all the results are presented in the note attached to this report. Some important channels, especially those with low statistics, need significant developments to optimize the analyses and the studies started for this workshop are continuing in many areas.

4. Experiment Upgrades

In order to operate correctly with continuously increasing luminosity beyond the nominal specifications, ATLAS and CMS have a staged upgrade programme through LS3. In LS1, both experiments will complete and consolidate their nominal detectors. In addition, ATLAS will install a new pixel detector layer and CMS will prepare for commissioning of a new trigger in 2015, and installation of a new pixel detector in the 2016 Year End Technical Stop. In LS2, the two experiments will complete their upgrades to allow operation up to $2.5 \times 10^{34}\ cm^{-2}s^{-1}$ and pile-up ∼ 70. ATLAS will upgrade the calorimeter read-out and trigger systems, including installation of the FTK hardware fast track finder, and will install new forward muon chambers, also for trigger purposes. CMS will complete the replacement of the front-end read-out of the hadron calorimeter to implement finer longitudinal segmentation. The opportunity to implement some infrastructure or other upgrades needed for the HL-LHC operation are also being considered to reduce the scope of work required during LS3. In LS3, major upgrades will take place to replace systems due to radiation damage or obsolescence, inability to read-out at HL-LHC data rates, or to maintain appropriate performance for physics in the very high pile-up environment. ALICE and LHCb upgrades, on the other hand, are driven by the goal to inspect all collisions. This involves a major redesign of all detector read-out electronics and also replacement of some sub-systems for improved precision measurements and due to longevity or performance issues at higher rates. These upgrades will already happen during LS2.

At the workshop, only the upgrades for higher luminosities were considered. All aspects of the experiments are affected to varying degrees and these were discussed in dedicated sessions, including one addressing common electronics issues.

All four experiments will require new trackers with improved granularities, rata capability, precision and radiation tolerance. For ATLAS and CMS, it will be essential to implement tracker information in the hardware selection of events (first level trigger) to ensure the required physics acceptance. Similar systems are proposed for this purpose and many other features of the detector designs are also common, this include silicon sensors, front-end read-out chips and data transfer technologies. In LHCb, and ALICE, the tracking systems have different requirements and constraints, however, technologies developed respectively for these two applications, such as the micro-channel CO_2 cooling of silicon sensors, monolithic active pixel sensors (MAPS on CMOS sensors) or Gas Electron Multiplier detectors, are of general interest to the community. Developments of light mechanical structures and new cooling and powering systems are as well addressing similar performance goals for all detectors. All these aspects and the related R&D activities are presented in section 6, which includes a discussion of the critical need for effective radiation and beam test facilities.

A second major common motivation of upgrades through all experiments is the improvement of the event selection for the data acquisition. This will require replacement of the front-end and back-end read-out electronics of most of the sub-systems, along with some detector upgrades in the most difficult regions. For ATLAS and CMS, the performance enhancement will be achieved at the hardware trigger level. In addition to implementing track information as mentioned above, the finest granularity of the calorimeters will be used for improved resolution, and new muon chambers will be added in the forward regions. With these changes, the acceptance rate capability will increase to more than 200 kHz in ATLAS and up to 1 MHz in CMS, with a latency to perform the event selection of 20 to 25 μs. A High Level Trigger (HLT) performed at the software level follows the hardware trigger pre-selection, the final rate of registered events could be increased up to 10 kHz to maintain similar reduction factors to those presently achieved. In ALICE and LHCb, all collision information will be read-out respectively at 50 kHz for Pb-Pb collisions and 40 MHz for p-p collisions, with the event selection being performed at the computing level. Even with improved selection in the first stages, the requirement to maximise the physics reach means much more data will be recorded, leading to significantly increased computing resource requirements. The evolution of electronics, computing and software environments over the timescales of the projects is expected to allow this. A significant effort in developing new programming techniques will however be needed. Trigger, software and computing issues are addressed in section 10.

Due to radiation damage in the most exposed regions, the CMS end-cap electromagnetic and hadronic calorimeters will need replacement in LS3. Different approaches are investigated to develop radiation tolerant solutions and also improved mitigation of pile-up effects, which are critical for physics in this forward regions. The calorimeter devices developed outside of the LHC community by the DREAM(RD52) and CALICE (ILC) collaborations are among the options considered. The other calorimeter upgrades mainly concern the read-out of the detectors, driven by the requirements for triggering capabilities. The summary of the motivations, requirements and on-going R&D activities for the calorimeter upgrades can be found in section 7.

Muon systems are less exposed to radiation and less sensitive to pile-up than other sub-systems. They are expected to sustain 3000 fb^{-1} without major upgrades. However, as for the calorimeters, most of the trigger electronics (both on and off detector) will need replacement. The main R&D programmes are related to the implementation of new chambers in the forward regions, where rates are approaching or exceeding the limits of the present detectors. These are described in section 8, as well as on-going studies and foreseen irradiation tests to mitigate operational issues and increase the lifetime of the detectors.

Finally, section 9 addresses the electronics issues, mostly common to all experiments and sub-systems. It covers all components of the read-out chain from the on-detector chips to the back-end boards and also discusses the powering of the detectors. Technology options are considered with their consequent needs for further developments and existing frameworks for common activities are also presented.

5. Conclusions and Follow-up Proposals

The ECFA High Luminosity LHC Experiments Workshop has been an important step in establishing a strong link among the communities that will develop the HL-LHC research programme for the many years to come. It has been an opportunity to form the basis for further collaborations, providing a clear assessment and documentation of the many challenges being faced, and of the on-going studies and R&D activities. Some examples of existing synergies and of possible consolidation of cross-experiment activities are given below.

For trackers, a number of aspects are already subject to joint activities. This is the case for development of radiation hard sensors, through CERN generic R&D programmes (RD42, RD50), and for electronics components, as mentioned later. However, there is also scope for possible cross-experiment activity on interconnects technologies (development of thin module assembly using through-silicon-via or 3D stacking techniques, identification of improved bump-bonding/flip-chip interconnections, …). The organization of the recent "Forum on Tracking Detector Mechanics 2013”[7] is another example of a common initiative in an area where significant synergies on mechanical support and cooling issues can also foster developments across the experiments.

For many detector and accelerator aspects, it was pointed out at the workshop that a common database with information on materials, glues and their radiation hardness, as well as thermo-dynamical properties such as heat transfer and pressure drop data could serve to reduce duplication of effort.

RD51 (Micro-Pattern Gas Detectors Technologies), RD52 (Dual Read-out Calorimetry), as well as some R&D undertaken by the CALICE collaboration for the ILC, also represent major detector development areas of interest for the HL-LHC programme. Other technology topics may benefit from a similar structure of shared R&D, for instance to develop high precision timing devices.

Access to adequately equipped test-beam facilities (with a range of particle types and momenta) and well characterised radiation sources for total ionising dose as well as high flux neutral and charged hadron exposure, are essential for all detector systems and their associated electronics. Such infrastructure items should ideally be provided centrally and managed with high availability for all the LHC experiments.

The recent RD53 proposal to collaborate on design of pixel detector front-end ASICs in deep sub-micron processes (65 nm) is a welcomed initiative. Many other electronics developments are federated by the CERN Electronics Systems for Experiments group, to develop microelectronics, high bandwidth links for data transfer (GBT and Versatile Link) and new powering systems. General pooling of microelectronics expertise across detector systems, and adoption of common standards for other electronic components, appears necessary to face the highly time demanding developments engendered by new technologies. For electronic

[7] https://indico.cern.ch/conferenceDisplay.py?confId=233332

developments and in many other areas, coordinated commercial approach through common orders could also give greater leverage with vendors to minimize R&D and future production costs.

The needs for storage and processing of the data at the HL-LHC will increase by more than an order of magnitude, requiring a new software approach and computing model. The Worldwide LHC Computing Grid project provides a framework for development of future solutions but a more structured and coordinated approach among the experiments could be effective to rationalize the required effort. New technologies, standards and computing paradigms will keep developing in the commercial sector and particle physics will need to keep track of these developments to be able to exploit improved performance against the backdrop of restricted budgets.

Radiation and activation issues require further development of common simulation tools and the problems faced by the accelerator and experiments will require common solutions to be developed. In general, the relationship between the accelerator and the experiments should be strengthened. While the HL-LHC Coordination Group provides an official high-level forum for this, a more open contribution to experiment experts or an expanded forum could also be valuable to ensure rapid dissemination of common set of assumptions and parameters.

Developing a consistent schedule, to synchronize upgrades of the LHC and experiments, is essential to register a maximum integrated luminosity in the shortest operating time. This includes considerations on availability of technical solutions, time for construction and duration of the long shutdowns. Needs for the different upgrade steps from LS1 to LS3 were discussed at the workshop and it is expected that a new schedule will be proposed by the CERN management by the end of 2013. It was very clear at the workshop that reaching the HL-LHC integrated luminosity goal by 2035 will be challenging, and will need timely availability of funds. This is especially true to proceed rapidly with the critical R&D programmes needed to develop cost effective technical solutions.

In conclusion of the workshop, the interactions engendered in the preparatory groups which led to the different common presentations are seen as having been extremely fruitful to identify areas of common interest with potential for joint effort. A follow-up was seen to be very desirable, that can build on the present preparatory groups to provide discussion forums and to organize future topical meetings. In further developing the physics programme, the LHC physics centre at CERN (LPCC) could be an appropriate framework to expand the work initiated for the workshop, involving experiments and theoretical physicists. It is also proposed that in all areas, new event announcements and information of general interest are advertised in a common HL-LHC web page and on an open mailing list of the community.

Finally, it was strongly supported at the closing session of the meeting that a second “Aix-les-Bains” style workshop takes place in one year to present new studies and R&D progress.

6. Motivations and Requirements for Tracker Upgrades

Tracking detectors play a crucial role in all four LHC experiments, contributing to the identification and reconstruction of particles emerging from the collisions, especially allowing the reconstruction of short-lived particles such as charm and beauty mesons and taus. To preserve these capabilities during the higher luminosity phases, all four tracking systems need to be upgraded.

ALICE and LHCb will have to upgrade their tracking systems to cope with higher event rates. ALICE will read out data related to each individual interaction at a rate of 50 kHz for Pb-Pb collisions. This will require a new inner tracking system with higher rate capability and an upgrade to the rate capability of the TPC. Additionally the ALICE requirement for high efficiency tracking of low transverse momentum particles imposes a very low material budget (0.3% X_0 per inner tracker layer). The characterisation studies of the Quark-Gluon Plasma will greatly benefit from an improved impact parameter resolution and overall tracking efficiency (especially for low p_T heavy quarks). LHCb is targeting operation at $L=2\times10^{33}$ $cm^{-2}s^{-1}$, a factor of 10 higher than the original design figure, to reach an integrated luminosity of 7.5 fb^{-1} per year. In order to achieve good performance under these conditions, the detector will be read out at each bunch-crossing, with the trigger selection completely implemented in software: this is a major upgrade for the electronics of all sub-systems, and in particular for the tracking detectors, which will also feature higher granularity to cope with the higher track density. For the detector closest to the interaction point, the Vertex Locator (VELO), increased radiation tolerance is also required.

For ATLAS and CMS, the first and most fundamental reason for the upgrade is the longevity of the present trackers: the detectors were designed to operate efficiently up to an integrated luminosity of about 500 fb^{-1}, and the measurements of the critical parameters on the current detectors indicate that these design goals will be met. However, beyond 500 fb^{-1} the detectors will progressively degrade and become largely inoperable well before 1000 fb^{-1}, hence the high-luminosity programme requires new trackers, with substantially enhanced radiation tolerance. The second aspect that demands enhanced performance is related to the instantaneous rates. Some of the data links from the front-end electronics will already saturate at hit densities significantly below those anticipated at HL-LHC luminosities. With the LHC expected to produce an average of 140 p-p collisions per bunch crossing (to be compared with the original design pile-up figure of 25), efficient pattern recognition will not be possible without higher granularity throughout the tracking volume to cope with the high hit multiplicities. Furthermore, at high luminosity the selection of interesting events in the Level-1 trigger becomes more challenging, not only because of the rate increase, but also because selection algorithms become inefficient for high pile-up: to preserve the physics performance of the detectors, tracking information has to be used in the event selection, improving the overall event reconstruction at Level-1.

For all the trackers, the novel technologies that will be used to fulfil the above requirements will also enable improvement in the basic tracking performance, such as track reconstruction efficiency, transverse momentum and impact parameter resolution, and to reduce the amount of material in the tracking volume.

ALICE proposes to upgrade the detector during LS2 for higher precision in tracking and higher luminosity operation. The Inner Tracking System will be replaced with a new detector made of seven layers of monolithic pixel detectors of very small pixel size (20×20 μm^2), produced in a 0.18 µm CMOS process. This technology, well adapted to the relatively lower radiation environment of ALICE, is ideal to produce high-granularity low-mass sensors at an affordable cost. The same technology will be used for an additional tracker, the Muon Forward Tracker, consisting of 5 layers covering the acceptance of the muon spectrometer. In order to improve the rate capability of the TPC, it is planned to implement GEM Detectors in the read-out planes with corresponding new electronics.

LHCb does not require machine upgrades to receive higher luminosities but the current pile-up limits are set by detector constraints. This allows an upgrade during this decade. For the tracking system, the current pile-up limitations are resolved through implementing substantially higher granularity in the VELO and the Upstream Tracker. The VELO will adopt hybrid pixels, based on the Timepix chip, with thin sensors and small pixel size (55×55 μm^2), along with a novel cooling technique, using two-phase CO_2 in micro-channels embedded in silicon. For the large stations behind the magnet ("T stations") scintillating fibres with SiPM read-out are being considered as a possible technology.

The ATLAS and CMS Tracker upgrades will need to be implemented when the HL-LHC conditions are realised early in the next decade. The ATLAS and CMS trackers will be composed of pixel detectors made of hybrid pixel sensors with smaller pixel size, surrounded by large outer trackers also made of silicon sensors. For the outer trackers, both ATLAS and CMS have chosen n-in-p planar sensors as the baseline technology, while for the pixel detectors different options are still under study, including thin planar silicon and 3D silicon sensors. The extreme radiation environment of the pixel detector region represents a critical challenge for the development of sensors and electronics. The expected fluences for the innermost regions will amount to several 10^{16} cm^{-2} (normalised to the equivalent damage of 1 MeV neutrons, n_{eq}). The overall geometry of the detectors are similar, both experiments are considering extending the acceptance of the tracking system to η=4, and both will contribute information to the Level-1 trigger. Beyond these similarities, differences exist in the options chosen to address some of the requirements. In order to improve the robustness of the pattern recognition, ATLAS will expand the outer radius of the pixel detector up to about 30 cm, while CMS will keep the outer radius at 20 cm, and implement three layers of "Macro-Pixels" (about 1.5 mm × 100 μm^2) in the inner region of the Outer Tracker. For the trigger functionality, ATLAS will read out selected regions of the tracker (Regions Of Interest) identified by Level-0 triggers based on calorimeters and muons. Meanwhile CMS is developing modules for the entire outer tracker volume that can discard signals from low-p_T particles (with p_T below 2 GeV/c) by correlating hits in two closely-spaced sensors, and send out the selected pairs at each bunch crossing. ATLAS will implement optimized wedge-shaped modules in the end-cap, while CMS plans to use the same rectangular modules as in the barrel, to simplify the production at the cost of some additional overlap. Despite these implementation differences, the technological challenges are largely similar.

As mentioned above, p-type materials have been chosen as baseline option for the large area detectors (ATLAS and CMS outer trackers and LHCb upstream tracker) as they appear to offer the required radiation tolerance. Effort is required to optimize process and sensor design, and to qualify possible vendors. The option to produce such sensors on 8" wafers could lead to substantial savings, but requires a dedicated development. Identifying the most appropriate technology for the detectors with the highest radiation levels (ATLAS and CMS pixels) still requires substantial R&D (RD42, RD50). Optimized thin planar silicon and 3D silicon sensors are among the most promising options. Monolithic pixels are the optimal choice for detectors with lower read-out rate and radiation dose (ALICE ITS and MFT); recent developments have extended the range of applicability towards higher rates and radiation levels and such R&D is of general interest, since with such CMOS processing, there can be significant advantages in terms of lower cost and a larger number of potential vendors. A possible follow up workshop focused on CMOS sensor developments could ensure the continuation of common effort and exchange of information**.**

Low power electronics and ASICs are critical to build low mass trackers. ASICs for tracker upgrades are particularly complex chips in novel technologies that require large design teams that in HEP can typically only be found by combining efforts across multiple institutes with ASIC design experience. The personnel for this need to be identified early in the project phase as the front-end ASIC development can often drive the overall schedule. Deeper sub-micron ASIC technologies will be used in the upgraded trackers (130 nm and 65 nm). In particular, dedicated R&D (RD53) is required to qualify the 65 nm technology for use in the high radiation environment (up to 10MGy) of the ATLAS and CMS pixel detectors. The RD53 collaboration will also develop the ASIC building blocks needed for ATLAS/CMS pixels chips and appropriate tools to simulate and integrate very large complex mixed signal pixel chips. The final pixel chip(s) will most likely also be implemented within the RD53 framework. Advanced technologies are needed also for interconnections: high-density bump-bonding for inner pixels, low-density industrial bump-bonding for hybrid assemblies with flip chip (as an alternative to wire bonds), high-density low-mass substrates for hybrids and through silicon vias to optimise pixel design, (again removing the need for wire bonding and optimising active area). Substantial R&D is required to identify technology options and vendors suitable for the tracker upgrades which match the technical requirements, volume throughput and low cost production. In the back-end electronics, high-speed boards with high-density interconnections are required to handle the higher data volume, and in particular to process the tracking information at Level-1, in ATLAS and CMS. For this application, the further development of custom Associative Memory ASICs can be attractive. The ATLAS and CMS tracker upgrades also depend critically on the development of high-bandwidth low-power data links and efficient powering technologies.

Thermal management is more important than ever before in the LHC tracker upgrades, due to the high power densities and possible low operating temperatures down to -40°C. Materials and glues need to be qualified to operate in higher radiation environment and at lower temperatures compared to present trackers. Novel materials and technologies such as carbon foams, aluminium-carbon compounds, titanium cooling tubes (with evaporative CO_2) can help to realize lightweight assemblies fulfilling the more demanding requirements in thermal management while maintaining a low material budget. However, the use of such materials and technologies requires substantial R&D to develop assemblies that fulfil HL-LHC requirements. The complex geometry of the multiple cooling lines and their interaction on the tracker integral design needs to be evaluated at an early stage. To understand heat transfer and pressure drop mechanisms, R&D on 2-phase flow behaviour together with the development of models is necessary.

Two-phase CO_2 cooling is the technology of choice for most future trackers. Substantial development is needed to evolve from the current state of the art (LHCb VELO, ATLAS IBL and the 2x15 kW system for the "Phase-1" CMS pixel detector), to the ~100 kW range required for the ATLAS and CMS tracker upgrades. Such large projects also require the development of reliable and affordable lab-size systems, to support the detector design and production. A critical item that is still missing is access to laboratory scale reliable small liquid CO_2 pumps and substantial R&D on CO_2 pump development is urgently needed as a common activity.

A wide variety of facilities are required to prove sufficient radiation tolerance of all components. Such facilities are accessible through the RD50 collaboration with Karlsruhe, Ljubljana and CERN PS providing the most commonly used facilities for the silicon detector community. The upgraded irradiation facility at CERN East Area (24 GeV/c protons) will help to cover demands for studies on the radiation hardness of all necessary components, but further facilities are still required. A high intensity facility with a few hundred MeV pions, a reliable and easily accessible proton facility in the 100 MeV range, and a large area neutron source to complement the present irradiation test programme would all be extremely useful.

The on-going shutdown of the PS and SPS test beam facility at CERN creates difficult for detector upgrade communities as the overall particle beam availability is very limited. Most beam tests are currently performed at the electron facility at DESY. With the increasing R&D towards detectors for the higher luminosities, even more test beam time is needed. It is critical for the tracking groups that the available beam time is not further reduced. The tracking community is mostly interested in high-energy particles. Furthermore, a test beam facility with bunch structure of 25 ns, to determine the necessary timing precision for the read-out electronics and optimize timing through the entire read-out chain, is very important for detailed tests under experimental conditions. Also high rate tests, possibly with beam particles, are needed with intensities of the order of $2*10^8$ particles cm^{-2}. The Irrad4 facility at PS can partially address this, but the only fully suitable high rate facility is at Fermilab[8] and further facilities will be required.

Many groups have built high-resolution tracking telescopes for the use in test beam facilities, but these telescopes have not been conceived as common infrastructure. Within the European funded projects EUDET and AIDA, common tools have been developed and supported with two telescope types available. R&D groups from all four LHC experiments and many groups from other particle physics groups such as Belle-II and ILC are using these telescopes (with several currently at DESY). A complete reconstruction software is also available and widely used[9]. The Timepix telescope at the SPS also provides high resolution along with the possibility to cool the sample with two-phase CO_2. The continuation and development of such telescope systems is essential and further common infrastructure, such as cold boxes and CO_2 cooling is needed.

7. Motivations and Requirements for Calorimeter Upgrades

Calorimeters provide essential inputs for the precise measurement of basic physics objects and complex global event topologies, as well as being vital to the triggering capabilities of all the LHC experiments. For ATLAS and CMS, the very challenging HL-LHC environment imposes the need at the input of the Level-1 trigger

[8] http://www-ppd.fnal.gov/FTBF/M03/

[9] http://eutelescope.web.cern.ch/

system for more selective and sophisticated trigger algorithms based on high granularity and high precision calorimeter information. This requires both increased bandwidth and longer latency of the read-out systems. To address these requirements both ATLAS and CMS are planning electronics upgrades to allow full 40MHz read-out, and back-end buffering, of their calorimeter data. These upgrades will also ensure longevity of the calorimeter electronic systems through HL-LHC operation. The HL-LHC environment will also impact on the longevity of the calorimeter detector elements. Both the ATLAS and CMS barrel calorimeters are sufficiently radiation tolerant to operate at the HL-LHC. In addition, the ATLAS end-cap calorimeters are based on intrinsically radiation tolerant LAr technology. However, the ATLAS LAr Forward Calorimeter (FCAL) may suffer some response degradation at high instantaneous rates, and may therefore need to be augmented or replaced for this reason. The performance of both the CMS end-cap ECAL (EE) and the Hadronic Calorimeter (HE), on the other hand, would substantially degrade due to the radiation levels at the HL-LHC and both must be replaced. Different approaches are being evaluated, and some options are under study.

For the ALICE and LHCb experiments, on the other hand, operation of the experiments is not directly affected by the HL-LHC luminosity upgrade, and will be essentially an extension of the experimental programme established through upgrades this decade with no substantial further upgrades currently foreseen beyond this.

Table 2 summarizes the detector technologies employed by the four LHC experiments and their intrinsic longevity limitations due to either radiation doses and/or particle fluxes. A colour coded map indicates the risk level of a given technology for operations at the HL-LHC and the options and/or solutions under consideration by the respective collaborations. The upgrade plans are detector specific for the different experiments, as outlined in the following sections.

Experi -ment	detector	technology	Critical condition	maximal value for Phase2 of LHC	Expected degradation, considered mitigation
ALICE	PHOS	PbWO4	Hadron fluence	$< 10^{9}$ h/cm^{2}	OK
ALICE	EMCal/Dcal	Pb/Scint Shashlik	Radiation Dose	~ 0.1 kRad	OK
LHCb	ECAL	Pb/Scint Shashlik	Radiation Dose	~ 6 Mrad	will replace central cells during LS3 (spares exist)
LHCb	HCAL	TileCal	Radiation Dose	~ 1 Mrad	Not critical, accept the loss
ATLAS	ECAL Barrel	LAr	Inst. luminosity	OK up to 10^{35} cm^{-2}/s	OK
ATLAS	ECAL Endcap	LAr	Inst. luminosity	OK up to $5*10^{34}$ cm^{-2}/s	OK, re-calibrate if required
ATLAS	HCAL Endcap	LAr	Inst. luminosity	OK up to $8*10^{34}$ cm^{-2}/s	OK
ATLAS	HCAL Barrel	TileCal	Radiation Dose	~ 0.3 Mrad	Re-calibrate
ATLAS	Forward	LAr	Inst. luminosity	Possible degradation above $2*10^{34}$ cm^{-2}/s	May have to replace or add new detector during LS3
CMS	ECAL Barrel	PbWO4	Hadron fluence	$2*10^{12}$ h/cm^{2}	Re-calibrate
CMS	HCAL Barrel	Brass/Scint	Radiation Dose	~ 0.1 Mrad	Re-calibrate
CMS	ECAL Endcap	PbWO4	Hadron fluence	~ $2*10^{14}$ h/cm^{2}	Will be replaced during LS3
CMS	HCAL Endcap	Brass/Scint	Radiation Dose	~ 10 Mrad	Will be replaced during LS3
CMS	Forward	Steel/Quartz fibers	Radiation Dose	~ 500 Mrad	Re-calibrate

Detector degradation risk
LOW Low risk of detector degradation
ELEVATED Elevated risk of detector degradation
HIGH High risk of detector degradation
SEVERE Severe risk of detector degradation

Table 2: Calorimeter technologies deployed in the four LHC experiments and potential intrinsic limitations for operation at the HL-LHC, assuming luminosity levelled at $5*10^{34}$ and integrating a total $3000fb^{-1}$

ALICE is performing its major upgrades during this decade, including to the calorimeters and their read-out systems, to cope with their future data taking requirements. The calorimeter systems are not expected to undergo significant degradation over the course of HL-LHC running, so that no further upgrades for these are foreseen. ALICE is considering installing an additional electromagnetic calorimeter (FoCAL) to extend their coverage and improve γ, π^o identification in the forward region. The installation of the FoCAL system could be implemented during any later regular winter shutdown.

LHCb also plans its major upgrades this decade, in order to increase its data taking capability by an order of magnitude, implementing full 40MHz read-out of all its subsystems. The LHCb ECAL detector based on Pb/scintillator will eventually start suffering from total ionizing dose (TID) effects, in a small number of central cells near the beam pipe. The plan is to replace those modules with existing spares. In addition, the HCAL scintillating tiles will start to show degradation due to TID effects. However, this is not considered critical to the physics performance of the experiment

In ATLAS, the end-cap LAr detectors are intrinsically radiation hard and will not incur significant degradation during the HL-LHC operation. Limited space-charge effects due to the very high instantaneous rates are expected in the inner wheel of the end-cap ECAL ($2.4<\eta<3.2$), which will be compensated by offline corrections. In the FCAL, space-charge effects will be more significant and the HV resistive distribution network will further compound them, as the drift electric field in the LAr gaps will be reduced as a result of the higher ionization rate and consequent current drawn. Several possible options for mitigating this effect are being considered, including full replacement of the FCAL with another LAr detector with optimized geometry and HV distribution, or insertion of a new calorimeter in front. The on-going risk assessment and performance analysis may lead also to the conclusion that no upgrade is necessary. In addition, the longevity of the analogue preamplifiers of the end-cap HCAL, which are installed inside the LAr cryostat, is still under evaluation. Should these require replacement, this would have a substantial impact on the schedule and logistics for the HL-LHC upgrades.

The present CMS ECAL is a homogeneous ($PbWO_4$) detector, and the HCAL is a sampling detector based on plastic scintillating tiles. In the end-caps these would both suffer substantial performance degradation at the HL-LHC, and must be replaced. A targeted R&D programme is underway to meet all the challenges of replacing the CMS end-cap calorimeters early next decade for HL-LHC operation. Different approaches are being evaluated, and various options are under study. The first approach is to maintain the present tower-like geometry, as well as the emphasis on the electromagnetic resolution, with the hadronic resolution and jet response being lower priority. This essentially amounts to a replacement of the individual calorimeters with more radiation tolerant designs. The second approach is to consider an integrated calorimeter, which aims at maintaining adequate electromagnetic resolution, while substantially improving hadronic resolution and jet response. In both approaches, replacing the end-cap calorimeter system opens the possibility of extending its coverage beyond the present $|\eta| = 3$, out to $|\eta| = 4$, in order to provide a uniform response over the rapidity range containing most of the jets associated with VBF (which have a distribution peaked at $|\eta| = 3$). Furthermore, beyond $|\eta| = 4$ only limited transverse missing energy escapes the calorimeters.

For the first approach, the ECAL section would use radiation-hard, heavy scintillating crystals as the active medium. The crystals being considered, LYSO and CeF_3, are both very luminous, and can therefore be used in a sampling configuration, minimizing costs while maintaining the stochastic term of the resolution in the range of $10\% /\sqrt{E}$). The present design study has a Shashlik geometry with four read-out fibres and one calibration fibre running through a tower consisting of a lead-crystal sandwich. The Shashlik design aims to minimize the light path through materials that will darken under the effect of radiation, including both the crystal and the wavelength shifters of the read-out fibres. The light path through the wavelength shifter is kept very short by adopting a capillary design for the read-out fibres, where the wavelength shifter is inserted within a hollow quartz fibre. The quartz fibre, which will maintain good transparency even after the full HL-LHC exposure, collects light from the wavelength shifter, and transports it over the full length of the tower to the photo-detectors.

The photo-detectors would be installed close to the end of the towers in a region where the fluence is such that existing silicon Multi-Pixel Photon Counters (MPPCs) would suffer unacceptable noise degradation, due to the radiation induced increase in bulk leakage current. For this reason, CMS are developing the technology for

GaInP MPPCs, for which the radiation induced bulk leakage current is orders of magnitude lower than for silicon. In parallel with this, they continue to follow the trend towards smaller pixels for the Silicon MPPCs, which, together with operating temperatures well below 0^{o}C, can extend the useful lifetime of these devices in a high radiation environment. In this approach, the CMS hadron end-cap calorimeter would continue to provide similar performance to the present one, with replacement of the active element with either more radiation-hard plastic scintillator, or liquid scintillator. Closely spaced read-out fibers will ensure a short light path length, with the aim to maintain performance as the attenuation length in the scintillator reduces.

For the integrated calorimeter approach, two different concepts are under evaluation:

- A fibre-based dual read-out calorimeter (DROC), with Cerenkov and scintillator light detection to identify the electromagnetic and hadronic components of the particle showers, as studied by the DREAM (RD52) collaboration. As well as enhanced particle identification capabilities, such a dual read-out system allows full compensation of individual hadronic showers, with excellent linearity and much improved hadronic energy resolution. For generating Cerenkov light, quartz fibers (which are currently available and sufficiently radiation hard) analogous to those already employed in the CMS forward calorimeter (HF) are used. They are investigating possible candidates for suitable scintillating fibres. The photo-detectors and read-out system considered are the same as those for the Shashlik design described above.
- A high granularity particle flow calorimeter (PFCAL), as developed by the CALICE, ILC and CLIC collaborations. The resolving power of tracking showers through a finely granulated and longitudinally segmented detector is an essential factor in the development of these detectors, and has the potential for improved particle identification and matching capability with the tracking detector. The present focus is on understanding whether the electromagnetic and hadronic sections instrumented with micro-patterns gas detectors (MPGDs) could provide a cost effective solution with adequate performance. Both GEMs and Micro-Megas have been used successfully in a range of experiments to date and are suitable for large-scale production. In order to ensure adequate response to the highest energy electrons and jets at high pile-up, the development of a 128 channel front-end read-out chip is under consideration, which will integrated a low power 10 bit ADC for each channel. Such a high granularity particle flow calorimeter will generate large amounts of data, and the development of high-speed (10Gbps) data links will be necessary to cope with the corresponding data rates.

The potential of these integrated options to provide improved performance for particle flow reconstruction in this particularly challenging but important region of the detector, and in the presence of the very high pile-up which will characterize operation at the HL-LHC, is under evaluation. Each of these schemes will require the development of specific physics object reconstruction as well as trigger architectures. CMS is also considering the development of a high precision timing system (~20ps resolution) to provide a time-of-arrival determination for charged particles and photons entering the ECAL, as a possible means to mitigate pile-up by associating calorimeter based objects to specific vertices.

The evolution of the calorimeter read-out systems shows common elements across the four experiments. A common goal is to provide the highest possible granularity and resolution information to the trigger processors to handle increasing pile-up, by streaming data off detectors at 40 MHz. LHCb is even planning a complete software-based trigger system, with full read out of all the detector subsystems at 40MHz.Three key technologies for enabling such an approach are: front-end signal analogue and digital processing, high throughput optical data transmission and high performance modular back-end electronics. Finally, system aspects related to power distribution (either as high power DC-DC converters and board local regulation in the front-end) and cooling will remain important factors to be taken into account in the development and the specification of the new read-out systems.

Calorimeter read-out systems are required to cover large dynamic ranges (up to 16-bits) while keeping high resolution. The very first elements of the analogue front-end are detector technology specific, but common functionality can be identified for the digital blocks (e.g. analogue-to-digital conversion, serialization, multiplexing, data reduction or compression in the front-end). Modern microelectronic technologies allow for the design of low power circuits, integrating analogue and complex digital functionalities in a single ASIC. Process feature sizes of 250nm and below are intrinsically radiation tolerant for the radiation levels expected in the locations of the front-end read-out, but with emerging technologies in 130 or 65 nm CMOS, single-event effect may become challenging for the calorimeter read-out. The experiments are pursuing several parallel developments using different technologies from different silicon foundries. The identification of synergies across experiments is desirable to rationalize globally the effort and the resources. Another important factor is that consumer electronics and telecommunication industries are pushing for a variety of existing custom off-the-shelf components (COTS) suitable for calorimetry applications in HL-LHC. It is clear that, wherever possible, the option of COTS should be considered if it can reduce the development costs associated with ASIC designs.

A strong convergence of interests across the four experiments toward technologies enabling 10 Gbps or higher data transmission has emerged. It is important that calorimeter groups make their requirements known, so that the specifications for the next generation of transceivers developed at CERN can reflect these. Fast links are extensively used commercially, and their possible use should be investigated given the relatively moderate radiation levels expected in the location of the front-end, for at least some of the calorimeter systems concerned. All four experiments require a high performance modular electronics, which processes the 40MHz incoming data, and all are developing solutions within the x-TCA framework (ATCA for ATLAS and LHCb, μ-TCA for CMS). Very recently, an interesting development using PCI boards in "commodity" PC to interface detector specific front-end to DAQ systems on a switched Ethernet network has been launched, which also may be relevant for the calorimeter read-out developments.

8. Motivations and Requirements for Muon System Upgrades

Muon identification and momentum measurement is key to the physics programmes of all 4 LHC experiments. These are large area systems which experience the least issues with integrated radiation doses except in the most forward regions. The issues to be addressed tend to be more rate related or follow from the needs for much greater precision information in the triggering systems to avoid requiring unacceptably high thresholds to fit within available Level-1 bandwidths. The most relevant parameter for the functioning of the muon systems is the maximum instantaneous luminosity, setting the scale for beam-induced and uncorrelated cavern background. In addition, the integrated luminosity sets the total accumulated radiation dose for the most forward detectors. Studies of the issues that the existing muon detectors will face after the HL-LHC upgrade have started, and possible actions to mitigate the problems have been investigated. The main challenges are from the chambers and front-end electronics reaching rate limits, suffering high occupancy and/or high dead time; and from aging due to high integrated radiation dose or accumulated charge.

High luminosity requires improved timing resolution and greater trigger sharpness to retain low trigger thresholds at sustainable rates, as well as good offline momentum and charge measurement accuracy. This is particularly critical in the forward regions of the ATLAS and CMS detectors where detector upgrades are mainly focused. At the HL-LHC, the expected trigger rates will exceed the capabilities of the present electronics. In addition, the accuracy of the p_T measurement for triggering purposes has to be improved by installing additional detectors: the new small wheel (NSW) with finer granularity detectors in the ATLAS case and a station of triple GEM detectors for CMS. Acceptance increases can also be envisaged and extensions to η =4 are under study by CMS.

ALICE and LHCb emphasize greater precision measurements and plan to maximizing the number of recorded events by going to continuous read-out, without a selective trigger, requiring upgraded muon electronics. An additional muon tracker, the MFT, near the vertex is proposed to improve the background rejection and mass resolution of the ALICE muon spectrometer.

The muon detectors of the four LHC experiments have shown excellent performance during the first LHC running. With the planned increases in the LHC luminosity, they will have to cope with a much higher background rate, raising concerns about their lifetime and performance. Detectors that were designed and built for a 10-year lifetime are now being required to operate for much longer. There are a large variety of technologies used in the muon systems of the LHC experiments, but they have many aspects in common. Nearly all of them are gaseous detectors either using wires (drift and wire chambers) or without wires (resistive-plate chambers). Potential issues due to high backgrounds at high luminosities include rate capability, occupancy and fake trigger rates. Also the detectors and front-end electronics all have a limited resistance to radiation, suffer from aging effects and components may become obsolete (and thus spares become unavailable).

It turns out that most of the existing muon detectors are expected to be able to work at HL-LHC luminosities (both instantaneous and integrated). Still, it will be important to continuously monitor the detector performance during running in order to verify their response under higher particle flux. This will be crucial to spot detector weaknesses and unexpected failures as early as possible, in order to be able to react timely and keep the system performance unaffected. In some limited detector regions, where particle and background rates are highest, replacing detectors and employing new technologies, will be unavoidable. Additional detectors can also be installed in a few strategic places to enhance the system performance (e.g. momentum resolution, trigger selectivity and sharpness, or angular coverage). An unforeseen problem to be considered is possible future restrictions on the use of tetrafluorethane, one of the components of the RPC gas mixture, due to its contribution to climate change. To solve this issue, working groups are now being formed in various LHC experiments which will surely benefit from possible synergies in this common research field. Common test facilities like GIF++ are essential to qualify present and future detector technologies and associated front-end electronics up to the highest luminosities expected at HL-LHC.

While most of the existing detectors are expected to be able to cope with the harsher operating conditions at the HL-LHC, much of the front-end read-out and trigger electronics will have to be replaced. The main reason for this is actually not radiation damage to electronics, but rather the fact that the triggering systems will need to be enhanced. For this, ATLAS and CMS take a very different approach to LHCb and ALICE. ATLAS and CMS will make their triggers more selective, aiming at enriching the fraction of muons above a given p_T threshold by sharpening the trigger turn-on curves. This will be done by increasing the complexity of the low-level trigger hardware, bringing in information from other parts of the system and from other detectors, which can require longer trigger latency and thus a re-design of the entire read-out and trigger electronics. In contrast, ALICE and LHCb are going towards a trigger-less scheme, where most of the functionality of the hardware trigger electronics will be taken over by software trigger algorithms. Thus, essentially the full data recorded by the detector will be transmitted to software algorithms running on high-level trigger computer farms. Common technologies employed for this by the different experiments are high-speed optical links (like the GBT), radiation-hard front-end ASICs, FPGAs with high-density serial links, and ATCA/μTCA cards and crates.

Given that new muon chambers are intended for end-caps and close to the beam pipe, full efficiency despite a high charged and neutral particle flux is essential. In addition, an improved spatial resolution for trigger detectors, ranging down to a few hundred microns, is mandatory, while a time resolution of around 100 ps could have additional applications. Finally, each of the possible candidate detector technologies should undergo an intense programme to assess radiation and aging effects, to quantify any performance deterioration and check this is within acceptable limits. An intense R&D effort over to five years has led to the proposal to equip two stations in the endcaps of the CMS experiment with triple Gas Electron Multipliers (GEMs). This has also profited from the experience accumulated by LHCb, the first experiment at the LHC to use GEMs (in the central part of the first station of its muon system), and where part of its second muon station is also planned to be instrumented with GEMs. Although not part of their muon system, ALICE also plan to replace MWPCs as the read-out system of their TPC with quadruple-GEM detectors, and GEMs are also considered for applications in the field of digital calorimetry. Common technological improvements, like single mask etching or stretched assembly were essential to assess the possibility of large scale use of these detectors.

Micromegas technology is used by the New Small Wheels (NSW) in ATLAS. The vulnerability of this chamber type to sparking has been solved by adding a layer of resistive strips on top of a thin insulator directly above the read-out electrodes. An additional technical improvement was the implementation of the floating-mesh configuration, in which the mesh is no longer integrated into the read-out structure. Moreover, the µTPC method, determining one coordinate by the drift time from the pair production point to the strip, gives spatial resolutions of the order of 0.1 mm. Small-strip Thin Gap Chambers (sTGC), technology is also adopted for the ATLAS NSW, as a further development of the TGCs already in use. In particular, a low surface resistivity cathode coating has been used, and the capacitance between the strips/pads and the cathode has been increased in order to keep the same transparency for fast signals, so that high efficiency at high rate is maintained.

The rate capability of Resistive Plate Chambers (RPCs) can be improved by lowering the electrode resistivity, or by changing the operating conditions and as a consequence transferring part of the required amplification from gas to front-end electronics, or by changing the detector configuration, in particular in terms of the gap thickness or number. Many groups are investigating these possibilities, among which new low resistivity glass RPCs for the CMS muon system upgrade, and Bakelite RPCs with an improved electronics and configuration for ATLAS should be mentioned.

Detector R&D greatly profits from cross-fertilization across different experiments and subsystems, a good example being GEMs and Micromegas in the RD51 framework, so similar collaborations could be considered for other areas such as improved RPCs or studies on novel gas mixtures.

9. Motivations for and Progress with Electronics Upgrades

Compared to current LHC experiments, the HL-LHC upgraded experiments will require significant enhancement, in particular improved impact parameter resolution, increased channel count, better hermeticity, lower tracker mass, ten times higher radiation hardness, better timing resolution, higher trigger and data read-out rates and more flexible data processing. Fulfilling these requirements necessitates R&D activities in electronics covering the following areas:

i) Very deep sub-micron technologies (e.g. 65 nm and lower)
ii) High density, low mass interconnect and hybrid technologies
iii) Radiation hardness
iv) High reliability design and qualification
v) Efficient power distribution systems and low power design techniques
vi) Low power, high speed electrical and optical links
vii) Modular electronics standards for high speed data back-end processing

In the last 25 years microelectronics has experienced impressive advances enabling the construction of higher performance and, of particular importance for inner trackers, lighter detectors for HEP experiments. In the LHC experiments the electronics is an integral part of each detector and advanced functionality built into the detector front-end systems extends their capabilities. In most cases, Commercial Off The Shelf components (COTS) cannot be used for front-end applications because of unique environmental (e.g. radiation) and functionality requirements.

Only a fraction of the possibilities offered by modern microelectronics has actually been exploited for the LHC experiments because of the access cost to modern advanced technologies and the engineering effort required mastering them. There are several areas that could benefit from the progress in microelectronics. A few are listed below:

i) Radiation hardness and reliability of the electronics located in inaccessible locations will require enhancement. Fine lithography technologies have shown to be robust to intense total ionizing dose and displacement damage, and solutions can be found to minimize the impact of single event upsets. However, qualification of new technologies at unprecedented radiation levels is still necessary[10].

ii) Hybrid pixel detectors for high rate applications require smaller pixel size and extra functionality within the pixel area (e.g. extra buffering). They are obvious candidates for introducing advanced technologies (65 nm CMOS or below)[11].

i) Pixel detectors for moderate rates and radiation levels are targeting improved spatial resolution and minimal material budget. Monolithic pixel detectors in advanced technologies are good candidates for these applications.

ii) Tracker detectors are aiming at increased functionality (e.g. first level tracking trigger) within a tighter material budget. This can be achieved with more advanced technologies and by a careful blend of microelectronics and integrated assembly techniques, such as advanced packaging and several forms of 3D integration.

iii) The amount of data to be read out will be higher than in the current experiments, either because of the requirement to read out the detector without a trigger or because of increased functionality and trigger rate. Data transmission at gigabit rates from tens of thousands of individual sources in heavily irradiated detector regions can be achieved by using custom ASICs in very deep-submicron technologies.

One must pursue sustained and significant R&D investments in these fields to cover the development costs in manpower, CAE tools, prototyping and qualification. However, the microelectronics industry has invested in equipment and human resources in this area at an exponentially increasing rate, while the HEP community has barely maintained a constant level of investment over the years. In addition, HEP relies on a small number of distributed chip designers while the development of large and complex systems on chip (SoC) requires large and well-organised engineering design teams.

New technologies open up many new possibilities in view of the HL-LHC. They can only be fully exploited with strengthened collaborative support and shared expertise and services inside the community, reuse of design and shared “IP blocks”, possibly subcontracting parts of the designs, and adapting and evolving design teams to the structures needed for managing complex projects.

Embedded front-end electronics in HL-LHC experiments will have significantly increased channel count and rate capability to reach the required performance. Deep-submicron CMOS technologies (130nm, 65nm or below) together with the use of low-power design techniques will enable such improvements, while maintaining total power consumption comparable to that in the current experiments. However, the lower power consumption per detector channel is largely achieved thanks to a lower power supply voltage (power $\propto V_{dd}^2$, V_{dd} ~1 V). Compared to the legacy systems operating at V_{dd} in the range 2.5 – 5 V, the total amount of current to be delivered to the front-end is hence increasing along with the losses in the distribution system if the V_{dd} ~1 V is directly distributed. New power distribution schemes using higher voltages for transport and

[10] 2012 JINST 7 P01015

[11] The RD53 collaboration on future pixel chips for ATLAS/CMS/LCD

local conversion will be needed. This can be obtained either using switching DC-DC converters[12] or a serial power distribution scheme[13].

Commercial switching DC-DC converters cannot be used in the inner trackers because of the high magnetic fields and radiation levels. Local power conversion based on switched air-core coils and/or switched capacitor circuits, using qualified radiation hard technology(ies) together with specialized circuit and layout techniques can potentially work in this environment. A DC-DC converter suitable for the upgrades this decade has been developed and is going to be produced. It has also been successfully demonstrated that noise can be maintained at low levels when careful EMI shielding is applied.

In the serial powering scheme, a chain of front-end modules is fed serially with a constant current slightly above the current required by one module. On each module, a local shunt regulator dynamically generates and regulates the appropriate local supply voltages for the front-end electronics. Several experimental front-end ASICs with built in shunt regulators have been successfully designed and small-scale system tests have shown encouraging results. This scheme, although more complicated at the system level, could be the only viable solution for powering pixel modules within the limits imposed on material mass.

Both powering schemes still need developments in order to meet the HL-LHC requirements as well as large-scale system tests. Grounding, shielding and local fault isolation are system considerations that need particular verification through prototyping with significant numbers of real detector modules.

Together with the distribution scheme, commercial "bulk" power supplies will be needed to feed the on-detector power and will have to be located in the experimental caverns in order to reduce the length of the power cables. This requires the development of radiation and magnetic field (albeit at moderate levels) tolerant power supplies and hence a combined R&D effort between the HEP community and industrial suppliers. This effort took several years for the current LHC experiments and should not be under-estimated in terms of time and resources. As the requirements are very similar in all HL-LHC experiments, a well-organized and continuous R&D effort is necessary and possible.

The LHC experiments deployed optical links to an unprecedented scale for their read-out systems. The lessons learned by ATLAS and CMS during the development, procurement, installation and commissioning of these systems have been summarized in a joint technical note[14], highlighting, among others, the need to increase link bandwidth (to better amortize system cost), to share R&D effort (to better use the limited resources available) and to enforce extensive and rigorous quality assurance programmes (to identify shortfalls as early as possible). Commercial optical data links have shown very rapid progress since the original LHC developments (10 Gbps has become the baseline data rate for Local Area Networks while 40 Gbps and 100 Gbps rates are being considered; 28 Gbps serialiser/deserialisers are now available in state-of-the-art FPGAs). However, the specific constraints on LHC detector front-ends (in particular radiation hardness) often make it difficult to directly and immediately benefit from these advances. A significant development effort is required in several areas, in view of the HL-LHC upgrades:

i) *High bit rate at low power:* reaching a bit rate of 10 Gbps with reasonable power consumption and qualifying the necessary technology is a challenge to be addressed with highest priority.

ii) *Radiation tolerance*: selected semiconductor lasers and photo-detectors have been demonstrated to dramatically degrade after fluences of 5×10^{15} particles/cm^2. For the inner parts of the HL-LHC detectors, new optoelectronic device types will need to be qualified, or low mass high speed electrical links developed to allow moving the optical devices outside the areas of intense radiation.

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[12] 2012 JINST 7 C01072

[13] 2011 JINST 6 C01019

[14] https://edms.cern.ch/document/882775/3.8

iii) *Packaging and interconnecting* electronic and opto-electronic components in a reliable fashion while meeting our density and mass constraints require a strong investment in development activities.

One common project addressing the above issues is *the "radiation hard optical link" project,*[15] bringing developments in the microelectronic (GBT project) and optoelectronic (Versatile Link project) areas under a common umbrella. Project completion for a 4.8 Gbps radiation hard link is expected in 2014 with the delivery of full component sets for the first upgrades (during LS2 or before).

Two flavours of optical links are under discussion for the HL-LHC era upgrades, one drastically reducing the chip-set power dissipation (still at 4.8 Gbps), and another one increasing the bit-rate to 10 Gbps. These developments will require switching to a new microelectronics technology (65nm), while trying to maintain in common as much of the design as possible.

There are locations in the experiments where *off the shelf commercial links* could be used. Being able to use standard FPGA transceivers for instance in detector areas with modest radiation hardness requirements would be a great advantage. A coordinated effort in the qualification of radiation-soft high speed links and in short-listing recommended components should be launched.

Silicon photonics is a potential paradigm shifting technology, bringing the promise of tightly integrating opto- and front-end electronics. Although a few groups have already started evaluating this technology for use in the particle physics community, a concerted R&D effort in this area will be needed, should it prove promising.

The development of common low power electrical links together with the support of the corresponding simulation tools will also be a key activity for HL-LHC.

The current LHC off-detector electronics is housed in VME crates (or "VME like" crates). This standard has been very successful for the last 30 years and the level of support and expertise available is considerable. However, off-detector electronic systems for HL-LHC will require higher bandwidth, power and increased density to handle efficiently the trigger tasks in counting rooms where rack space is at a premium while keeping the cost at a manageable level. Although it is difficult to make a safe statement about how technology will evolve in the next 10 years, and it could be an option to house the back-end electronics directly in read-out computers (PCs or similar devices), selecting one modular electronics standard to be used for the HL-LHC upgrades is necessary.

Most of the current upgrade development activities are based on the xTCA[16] (µTCA or ATCA) standards. They present a lot of advantages in terms of power distribution, cooling and high-speed data transfer and are capable of housing high power devices (e.g. FPGAs and modern optical engines). A common effort for defining standard crates, power supplies, cooling system, ancillary modules (shelf managers, IPMI components, etc.) and standard software must be made to achieve the same level of support as that today for VME equipment and should include procurement and maintenance contracts. This work should be done within the next two years in order to be ready for large installations during LS2. Attention must be given to scenarios in which the selected standard does not become as successful a long-term standard as VME has been and where the expertise and requirements from industry are assessed.

10. Motivation and Requirements for Triggering, Data Acquisition and Computing Upgrades

In order for ATLAS and CMS to reap the full physics harvest from the HL-LHC, it is necessary to maintain the physics acceptances of the key leptonic as well as hadronic and photon trigger objects such that the overall physics acceptances, especially for low-mass scale process like Higgs production, can be kept similar to those

[15] http://ph-dep-ese.web.cern.ch/ph-dep-ese/optical_link/optical_link.html

[16] http://www.picmg.org/v2internal/specifications.cfm

of the 2012 LHC running. In some cases, such as tau triggers, there is need for improvement. In order to achieve the needed acceptances, three strategies are applied. The first one is the addition of a L1 tracking trigger for identification of tracks associated with calorimeter and muon trigger objects at L1. The second is utilization of finer granularity information from the calorimeter and muon trigger systems. The third is a significant increase of L1 rate, L1 latency and HLT output rate.

The HL-LHC ATLAS and CMS strip trackers can provide L1 trigger information of four types: (1) the simple presence of a track match validates a calorimeter or muon trigger object, e.g. discriminating electrons from hadronic ($\pi^0 \rightarrow \gamma\gamma$) backgrounds in jets; (2) linking of precise tracker system tracks to muon system tracks in the fit improves precision on the p_T measurement, sharpening thresholds in the muon trigger; (3) the degree of isolation of an e, γ, μ or τ candidate; and (4) the primary z-vertex location within the 30 cm luminous region derived from projecting tracks found in trigger layers, providing discrimination against pile-up events in multiple object triggers, e.g. in lepton plus jet triggers. A L1 pixel trigger offers the opportunity to tag secondary vertices for identification of b-meson decays and improved electron identification from track matching and isolation.

The addition of a track trigger at L1 in ALTAS and CMS provides only limited improvement for photon triggers (except for track isolation) and hadronic trigger objects (except for requiring jets to have tracks pointing at the vertex), as well as missing energy triggers. Therefore efficient triggering on photon and important hadronic objects at the HL-LHC may require increasing the L1 acceptance rate substantially beyond the present constraint of about 100 kHz, possibly as high as 1 MHz. Furthermore, a significant increase of the present 3-4μs L1 latency would provide more time for tracking trigger calculations (including pixel tracking), for combination of calorimeter and muon trigger information with that of the tracking trigger and would provide additional flexibility which in turn could be used to facilitate the L1 decisions and thus to reduce the rate required on key trigger objects.

The increase in L1 output rate from 100 kHz to possibly as high as 1 MHz requires higher bandwidth into the ATLAS and CMS DAQ systems, more CPU power in the HLTs and higher performance read-out designs for the front-ends that use standard protocols to be able continue to exploit commercial high performance network technologies. Keeping approximately the same reduction factor at the HLT implies an output rate of 10 kHz. The addition of a tracking trigger and more sophisticated algorithms at L1 means that the purity of the sample of events passing the L1 trigger is higher and that many of the algorithms heretofore used by the HLT are deployed in the L1 trigger, requiring a higher sophistication and complexity of algorithms used at the HLT. However, this is somewhat mitigated by the availability of the L1 Tracking Trigger primitives in the data immediately accessible to the HLT. The DAQ hardware, HLT processing and computing (to process the HLT output) requirements are consistent with Moore's Law scaling taking into account estimates of reconstruction time and event sizes.

The LHCb detector upgrade plan for later this decade executes the whole trigger on their CPU farm with 40 MHz detector read-out (since 1 MHz read-out would deeply cut into the efficiency for hadronic final states). By reading out the detector and finding vertices, the flexible software trigger will reduce the 40 MHz input rate to a 20 kHz output rate, allowing LHCb to run at ~ 1-2 x 10^{33} cm^{-2} s^{-1}, about 10 times the nominal LHCb luminosity, and provide significant gains in signal efficiency. This would provide up to 7 times the present LHCb efficiency for hadronic modes.

The ALICE upgrade (also targeting this decade) requires running at much higher rates, e.g. 50 kHz Pb-Pb (luminosity of 6 x 10^{27} $cm^{-2}s^{-1}$), with a fully pipelined read-out for the main upgraded detectors, e.g. the TPC. This is a factor of 100 increase in studied luminosity over the present triggered ALICE read-out of 500 Hz minimum bias Pb-Pb collisions. The new combined DAQ and HLT online system will perform an event reconstruction including clustering and tracking. The results of this online reconstruction, e.g. for the TPC clusters not belonging to background tracks, will replace the raw data and be recorded to the mass storage system, reducing the peak data bandwidth of 1 TByte/s raw data from the detectors down to ~80 GByte/s into the local storage system.

In terms of offline processing[17], the installed CPU power increase per unit cost is expected to increase by 25% per year, and mass storage by 20% per year in the coming years. It is reasonable to expect this rate of increase to continue in the next 10 years, with no obvious technology wall until then. On the other hand, the increase in rate and in complexity of the events, especially for HL-LHC running in ATLAS and CMS, results in a much larger resource need than expected assuming constant budget. All possible efforts must therefore be made to improve software algorithms and the efficient use of available resources. The CPU architecture is also evolving: in the future there will be many more cores per processor, and likely different kind of cores, and in addition to use each core efficiently (even the ones available today) one has to exploit its micro level parallelism capabilities. Hence software improvements are needed following two strategies simultaneously.

The first strategy for the most CPU intensive calculations (e.g. tracking or simulation) is to write dedicated parallelized/vectorized software to maximize single core efficiency, by adapting particle physics programming models to operate on vector data types and redefining the experiment data models accordingly. A number of libraries make this easier, but it is a field under very active development. Writing efficient parallel software will be the task of a relatively few experts, who will concentrate on identified hot spots. The maintenance of the software through evolution of the underlying libraries, and of the hardware, is expected to be much more difficult than for current software (similar to that observed today with GPU technology, which has been successfully used in ALICE HLT). This effort has to be judged against potential gains in performance that could be achieved by using more specialized hardware such as GPUs and coprocessors, which could result in a need for frameworks capable of seamlessly adapting and using heterogeneous computing resources in order to optimize the overall cost.

The Geant4 and Root packages are being adapted and improved constantly in this respect and this needs to continue (e.g. a multi-threaded version of Geant4 is soon to be released, while, given the increase of disk capacity with unchanged disk access rate, optimization of the analysis data organization in Root remains necessary). Moreover, it is likely that more software can be shared, which would reduce the development and maintenance cost.

Today, the usual HEP jobs can run independently (generation, simulation, reconstruction, analysis) and using one core per job remains an efficient way to carry out high through-put computing, however, that this may not scale in the future due to contention access to shared resources (e.g. I/O) or memory. Hence the second strategy is to develop the software frameworks capable of efficiently using multiple-core processor capabilities. In this case one needs to give full control of a processor to an application, in contrast to the situation today where a typical processor on the grid is processing simultaneously different kinds of applications from different experiments. Such frameworks will be able to handle several events simultaneously, distributing algorithms (or modules) to cores in order to maximize the efficiency; access to I/O should be also pipelined to avoid collisions. This requires the software for individual algorithms and libraries to be thread-safe.

The Cloud model is based on sharing resources by presenting the physical multiple core systems as many single or multi-core virtual servers using the virtualization technology. Its commercial success and ability to provide a high quality of service at scale that is currently an order of magnitude larger than the current LHC Computing Grid should inspire and give direction for the future developments of the Grid.

The software used in the LHC experiments is more than 15 million lines of code in total, written by more than 3000 people. Some are very expert in software, but most are physicists with only ad-hoc software knowledge.

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17 I. Bird et al, “Update of the Computing Models of the WLCG and the LHC experiments”, LHCC document soon to be released

To meet the challenge for HL-LHC computing, a large fraction of the software will need to be rewritten or adapted by the same kind of people. For this to happen in time, the work has to start essentially now with substantial re-training of the physicists of the collaboration working on software. A forum[18] has been established in 2012 to aid the sharing of experience and software; its scope could be widened to cover additional aspects including algorithmic code such as tracking tools or calorimeter clustering, and the large training effort required.

11. Accelerator and Experiment Interface

The design of the High Luminosity-LHC machine impacts the design and physics performance of the detectors and vice versa. Thus a well-established interface and an excellent and frequent contact between the accelerator and the experiments is mandatory to optimize both accelerator and detector layout and operation.

The HL-LHC upgrade implies a major redesign of the layout of the interaction regions around IP5 and IP1, based on the upgrade of the inner triplet quadrupoles and of the separation/recombination dipoles which will allow a reduction of β^* by a factor 4. For the HL-LHC machine, the aperture of these magnets will more than double, entailing an increase of apertures of all element of these regions, namely the TAS[19] and TAN[20] absorbers. The TAS aperture is designed to protect the triplet magnets, and further studies between the machine and the experiments are recommended to understand if a larger TAS, in the presence of a small beam pipe, may present a problem for non-standard HL-LHC operation. The TAN is designed to protect the MS (matching section) magnets and, in future, the crab cavities, too. TAN aperture studies are less advanced and need to be pursued. The timely study of the interaction regions and its protections is indeed of very high priority as after agreeing on certain parameter sets, the work of the TAS/TAN replacements and modifications can already start, working towards the possibility of starting the work already at LS2 both to reduce the exposition of personnel to residual activation and in preparation of the work in later shutdowns.

The most relevant failure scenarios have been identified and simulated. These scenarios are: asynchronous beam dump and its impact on the experiments, falling objects in the vacuum or non-conformities (e.g. RF fingers) resulting in showers with local production of off-momentum and neutral particles around the experiments and failures of crab cavities. The results for crab cavity failures are rather encouraging and - despite of very fast growth of the envelope of the off-momentum particles around the interaction regions - failures seem to be manageable. These studies should be continued to confirm that crab cavity operation will be safe for the LHC. All relevant failure scenarios will need to be followed up.

Among the beam parameters, the size of the luminous region and the pile-up density play an important role for both the machine and experiment performance. Optimizing the design performance, various scenarios can be considered: the baseline design using crab cavities with a round optics acting on the beam in the crossing plane; flat optics without crab cavities but with long range beam-beam wire compensators (BBWCs) to minimize the crossing angle in the plane of highest beta*; or a new scheme which is a combination of both, the use of BBWCs and crab cavities both in the crossing and separation plane (crab kissing scheme). The first two will give a similar performance of 250 $fb^{-1/}$year and luminous region sizes of 4.4cm RMS at a peak pile-up density of 1.27 events per mm. The second may offer a variant with strong reduction of the time pile-up density (0.12 events/ps). Finally, the crab kissing scheme could give similar performance. However it would add flexibility for shaping and levelling the linear pile-up density, which may optimize the detector performance by reaching much smaller pile-up densities of 0.65 events per mm at 140 pile-up events, by

[18] http://concurrency.web.cern.ch

[19] TAS=Target Absorber Secondaries: Absorber for particles leaving the IP at large angle

[20] TAN=Target Absorber Neutral: Absorber for neutral particles leaving the IP

achieving a more rectangular distribution, at the possible cost of shrinking the collision time. With such a scheme, and partially also with the baseline scenario, a moderate increase of the level of pile-up above 140 would make it less difficult to reach the established goal of 250 fb^{-1}per year; a pile-up level of 200, with a line density still less than 1 events/mm would open the way for 300-350 fb^{-1} per year which could further increase the attractiveness of HL-LHC running. Studies are on-going to find an ideal scenario where both the time and line pile-up densities can be minimized, at constant integrated performance. The experiments should study impact and advantages of the various scenarios in detail to give timely feedback to the machine to support decisions on accelerator R&D.

12. Long Shutdowns, Radiation and Activation Effects

The HL-LHC project, planning to upgrade LHC to a five or more larger instantaneous luminosity is very challenging for the experiments and at the same time large parts of the infrastructure of the experimental sites will have to be upgraded, either due to end of lifetime or to cope with the new conditions of the HL-LHC. The upgrades will be complicated as parts of the detectors will be considerably activated after several years of LHC operation and furthermore all new components will have to be designed to withstand the harsh radiation environment at HL-LHC, and to stay maintainable after many years of operation.

After 15 years of operation, when the upgrade to HL-LHC will take place, many infrastructure systems will have to be replace or modified. These changes, in most cases, will require a considerable amount of time and resources, and will imply temporary access restrictions to the experimental or service caverns (eg: ventilation systems, 48V power network, lifts, …). The knowledge of the conditions to be expected in certain areas is still limited, and detailed studies have to be performed to determine the exact modifications required and their impact. It is important that these studies happen early as in some cases, they may demonstrate need for a change of technology, which requires time to select, validate and to install. (eg: detection systems, power distribution, local ventilation units, …).

Another important aspect of any infrastructure upgrade will be the maintenance. The more demanding conditions will require more frequent maintenance or much more robust (and therefore expensive) systems. Because of the harsh radiation environment the maintenance of many systems will require thorough preparation and strict procedures to minimize human exposure. The current infrastructure has been designed for operation of the existing detectors with reasonable but limited margins. All upgrades should be checked at an early stage to determine if their service demands fit within the capacity of the existing infrastructure. Increasing this capacity will require additional space to pass new pipes or new cables, and will interfere with other activities possibly happening in the same area.

It can be expected that some detectors will require full-time availability of a certain amount of the infrastructure also during the upgrade period. This will lead to very difficult constraints in the maintenance, consolidation and upgrade projects, which are already today very difficult to manage. As a consequence, as soon as the starting dates and durations of the LS will be updated, the attribution of the consolidation and upgrade projects to these different periods should be reviewed. To make sure that any upgraded infrastructure really will meet the needs of the experiments after LS3 it is important to start collaborating with Technical Departments already now, during the planning phase of the upgrades. New project that will last beyond 2030 will probably create new needs in terms of space and should be identified as soon as possible to be integrated in the full space management plan.

The High Luminosity LHC will generate many radiation and activation issues that the experiments have to start facing now to be ready for the start of the project. The most important source of radiation during shutdowns is material activation. Fluka based calculations were run in order to approximately quantify the dose rates for LS2, LS3, LS4, LS5 and after. The estimations were performed for the CMS and ATLAS detectors using the present detectors configurations. Normalizing to the same luminosity for both experiments the activation will be a factor 8.5-10 higher in LS3 with respect to LS1. This factor will go up to about 30 in

LS4 and beyond, leading to environmental dose rates in working areas of several hundreds of μSv/h and local peaks of tenth of mSv/h in the TAS regions. Such levels of environmental dose rates are higher than ever reached at the LHC experiments and safety mitigation measures need to be planned very much in advance.

The heavy ion programme for Run3 and Run4 for ALICE detector foresees a delivered Pb-Pb luminosity of >10 nb^{-1}. The radiation load of 10 nb^{-1} of Pb-Pb collisions @5.5TeV/nn corresponds to the radiation load of <100 pb^{-1} of p-p collisions@14TeV. Therefore activation will be only a minor issue for a few components very close to the beam pipe in ALICE.

The LHCb experiment is currently carrying out new calculations for LS2, when most of its upgrade will take place. High radiation levels are expected especially for accessing the area of the Vertex Locator very shortly after the beam stops with dose rates of a few hundred μSv/h.

A first estimation of the impact of HL-LHC on air activation, on access conditions and on the environment was performed. Air activation for LS4 and LS5 shutdowns were estimated for ATLAS, CMS and LHCb assuming proportionality with the peak luminosity. The values after 1 day of cooling for ATLAS and CMS will still be compatible with the CERN guidelines, requiring the effective dose by inhalation being less than 1μSv per hour of presence. More accurate calculations still have to be performed. Also the possible impact of air activation on the environment has to be carefully analysed, possibly requiring modifications of the ventilation system at some LHC access points. For some of the experiments (LHCb), the tightness between the experimental caverns, the services caverns and the LHC machine has to be consolidated. The radiation level in the service caverns during beam operation is under study. Probably some shielding will be required guaranteeing the services cavern remaining supervised radiation areas for HL-LHC. The same studies should be applied for surface buildings on top of the shafts.

A quantitative estimation of possible contamination problems for HL-LHC needs to be performed. The fluid activation calculations are to be updated for the 4 experiments for HL-LHC conditions to determine the risk of contamination and its impact on the environment. A regular fluid analysis for contamination is on-going and will be used to quantifying the problem for the HL-LHC. It also should be noted that corrosion of metallic structures might significantly increase the contamination by dust. Finally, the impact of possible contamination on all activities has to be carefully assessed. It could be very significant in terms of schedule and costs for required infrastructure upgrades.

A revision of the radioactive zoning for the 4 experiments taking into account the irradiation scenarios of the HL-LHC and the new detector layouts will be necessary and is partly already underway. Note that exemption limits (LE in Bq/kg) are under revision presently in Europe. Some of the LE values will be reduced significantly (in Switzerland probably in 2015) increasing the amount of material having to be declared radioactive. CERN will need to assess the quantity of radioactive material in the experiments, the composition of radioactive waste (nuclide inventory), the required space for cool down areas and storage, the needed radioactive workshops and the associated costs.

The CERN safety regulations and the **a**s **l**ow **a**s **r**easonably **a**chievable (ALARA) principle require a rigorous optimization of all working procedures to minimize the exposure of personnel. This includes a limitation of the collective dose for all people involved in a certain task. To comply with these rules, the design of new components and equipment must be optimized such that installation, maintenance, repair and dismantling work does not lead to an effective dose exceeding 2mSv per person and per intervention. In this context, for the selection of the material for any construction, the activation properties must be considered. For this purpose at CERN the web-based material selection tool ActWiz is available.

The present official LHC planning foresees LS2 to start end of 2017 for 14 months and a LS3 of 26 months starting end of 2021.

ALICE and LHCb foresee their major upgrades in LS2. For both, the upgrades require a single shutdown of 18 months, as the changes are so interleaved they cannot be distributed over several shutdowns. Both experiments prefer the start of LS2 to be delayed by 6 to a maximum of 12 months. In LS3, both experiments plan only maintenance, consolidation and maybe minor upgrades. ATLAS plans for LS2 fit into 14 months with the currently planned start date. CMS requests an extended year-end-technical-stop (YETS) 2016/17, requiring an additional 6 weeks compared to a standard YETS. The CMS LS2 programme also fits into 14 months.

At LS3, depending on the outcome of studies around the forward calorimeters, the required duration for ATLAS could vary between 27 and 35 months. For CMS, the estimated duration for planed upgrades is about 30 months. CERN is expected to release a new schedule taking into account these considerations by the end of this year. In case LS2 will become longer, it is being investigated if some work for ATLAS and CMS could be advanced from LS3 into LS2.

For the HL-LHC, the aperture of the TAS collimators close to the experiments has to be increased by about a factor of 2. Preliminary studies indicate that the outer diameter and shielding can remain unchanged. If this will be confirmed, the exchange of the TAS by a new one with a removable inner aperture should be advanced to the end of LS2 for ALARA reasons. Upgrades of parts of the beam-pipe work both for LHC and HL-LHC could also be advanced.

Considering all the upgrade plans for the LHC, experiments and general infrastructure, it is clear that an enormous programme has to be executed in a very limited time. It should be noted that the current planning of the experiments does not include possible delays due to the work on the infrastructure. To perform all this work it will be necessary to parallelize activities as much and as safely as possible. Therefore a common planning, establishing early resource loaded schedules, is mandatory. The CERN technical departments and services will be needed to support many installations, requiring a strong involvement of the management to provide the necessary manpower.

ECFA Report on the Physics Goals and Performance Reach of the HL-LHC *

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1 Introduction

The *Update of the European Strategy for Particle Physics*, adopted 30 May 2013 in a special session of CERN Council in Brussels, states that "the discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision . . . and to search for further new physics at the energy frontier . . . [HL-LHC] will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma." For the ECFA HL-LHC workshop that occurred 1-3 October 2013 in Aix-les-Baines, France, this "Physics Goals and Performance Reach" preparatory group has summarised a number of physics studies of the programme established by this directive.

It is foreseen that the HL-LHC will deliver proton–proton collisions with an integrated luminosity of 3000 fb^{-1} at a centre-of-mass energy of $\sqrt{s}$ = 14 TeV by around 2030, and Pb–Pb collisions with an integrated luminosity of at least 10 nb^{-1} at $\sqrt{s_{NN}}$=5.5 TeV. Relative to current LHC plans, these numbers correspond to a tenfold increase in statistics. The studies presented below aim to establish what can be achieved with this higher luminosity and with planned detector improvements. Four major experimental lines of investigation were considered:

1. Precision tests of the role of the observed Higgs boson in the Standard Model (SM), including searches for additional Higgs bosons.
2. Direct searches for other beyond-the-Standard Model (BSM) Physics

*Prepared from input provided by the ALICE, ATLAS, CMS and LHCb Collaborations

3. Precision tests of the SM in Heavy Flavour Physics and Rare Decays

4. Heavy Ion Collisions and the Physics of the Quark-Gluon Plasma

In order to deliver 3000 fb^{-1} by $\sim$ 2030, a sustained instantaneous luminosities of $L = 5\times10^{34}\,cm^{-2}\,s^{-1}$ is required. It is expected that this will result in a pile-up of about 130 events per crossing, with more than 10% of all bunch crossings having pile-up greater than 140 [1]. We have also investigated the impact of this high pile-up environment on the physics performance and the ability of the proposed upgrades to the experiments to mitigate this effect. The findings of each of these areas of inquiry are summarized in the following sections.

2 Theory perspectives on the HL-LHC

In this section, we review some of the theoretical motivations for the studies planned at the HL-LHC, as well as some of the needs for progress in theoretical calculations.

Let us start with the Higgs sector. The coupling of the Higgs to other elementary particles of the Standard Model is believed to be responsible for giving them mass. This picture, however, remains to be tested with precision. So far, a handful of couplings have been measured to tens of percent precision. With HL-LHC, they could be measured an order of magnitude better. A number of other couplings that are currently unconstrained will be measured for the first time. Among them, an important measurement is that of double Higgs production, which has the potential to probe the self-coupling of the Higgs boson, a key prediction of the Standard Model.

One of the motivations for the coupling measurements is that models of physics beyond the Standard Model often affect the Higgs sector: this is because many BSM models aim to resolve the problem of the instability of the Higgs mass under quantum corrections ("hierarchy problem"). In doing so, they predict the existence of new particles coupling to the Higgs boson. Even in cases where such new particles are hard to discover directly at foreseeable colliders, they still inevitably modify the Higgs boson kinematic distributions or loop-induced Higgs couplings, such as those to two photons, two gluons or a photon and a Z. There is also the potential to discover dark matter through invisible Higgs boson decays. Furthermore, double Higgs production can be strongly modified in models where the Higgs is composite rather than elementary.

Aside from the generation of mass, another important role of the Higgs boson within SM is that it protects the structure of this model at high energies. This can be tested in high-energy vector-boson scattering (VBS). If the Higgs is not that of the Standard Model, then the cross section for this process may grow significantly larger than the SM expectation. Currently there are no measurements of VBS, but this process is expected to be measured for the first time at the 14 TeV LHC with 300 fb^{-1}, and to be investigated with substantially higher precision and increased reach at the HL-LHC.

Turning to direct searches for physics beyond the standard model, a first remark is that the LHC has already probed significant new regions of BSM parameter space. Figure 1 provides an estimate of the scales that can be probed at $\sqrt{s} = 14\,TeV$ with 300 and 3000 fb^{-1}, as a function of the mass scales being probed in today's searches.[1] Broadly speaking, the centre-of-mass energies that can be studied increase by about 1 TeV thanks to the extra factor of 10 in integrated luminosity from HL-LHC relative to LHC. The relative gains are most significant for new physics objects where current searches exclude only low system masses, e.g. because of small production cross sections. With this in mind, let us now examine specific motivations and scenarios for new physics searches.

There are good theoretical arguments to suggest that a natural solution to the hierarchy problem should imply the existence of new particles at or around the TeV scale. Specifically, the leading quantum

[1]The results in this plot are expected to be a reasonable approximation under the following conditions: (a) adequeate mitigation of any potential performance degradation from the higher pileup and trigger rates; (b) that signals and backgrounds are driven by the same partonic channels (as is quite often the case); and (c) that the signature of the signal and characteristics of the background do not change substantially as one goes up in mass scale. Where actual simulation results differ substantially from the results in Fig. 1, it can be instructive to establish the exact cause.

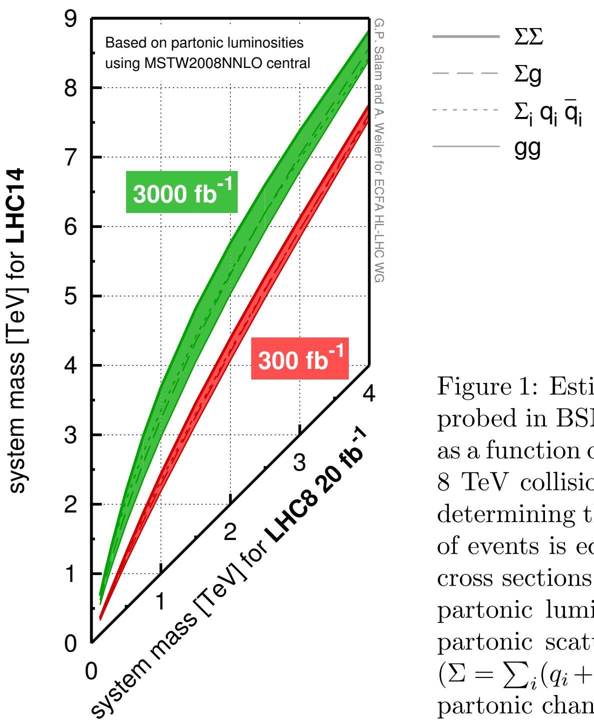

Figure 1: Estimate of the system mass (e.g. $m_{Z'}$ or $2m_{\tilde{g}}$) that can be probed in BSM searches at the 14 TeV LHC with 300 or 3000 fb^{-1}, as a function of the system mass probed so far for a given search with 8 TeV collisions and 20 fb^{-1}. The estimate has been obtained by determining the system mass at $\sqrt{s} = 14$ TeV for which the number of events is equal to that produced at $\sqrt{s} = 8$ TeV, assuming that cross sections scale with the inverse squared system mass and with partonic luminosities. The exact results depend on the relevant partonic scattering channel, as represented by the different lines ($\Sigma = \sum_i (q_i + \bar{q}_i)$), and the bands cover the spread of those different partonic channels.

instability, due to the top quark, suggests light top partner particles, either as equal spin partners in composite Higgs models or as fermionic partners ("stops") in supersymmetric models. Typically production cross sections for top partners are small, and so searches benefit substantially from the HL-LHC.

Supersymmetry of course brings a number of other classes of new particle. Among them, one can mention additional scalar particles that extend the standard-model Higgs doublet, which also have small production cross sections. Such extended Higgs sectors are not unique to supersymmetry, being present in non-minimal composite Higgs models, or own their own, for example in the two Higgs doublet extension of the SM.

A generically important class of processes with low cross sections is those involving electroweak couplings, leading to cross sections two to three orders of magnitude smaller than generic QCD cross-sections. In particular, EW BSM processes could see large relative increases in mass reach at high luminosity. The most important candidate particles are supersymmetric EW gauge- and Higgs-boson partners and EW spin 1 resonances. Such processes may also cast light on the nature of dark matter which could manifest itself as missing energy at the LHC. Dark matter particles can be produced as the lightest stable BSM particles at the end of a decay chain, or through effective higher-dimensional interactions in the case of heavy messengers. The HL-LHC therefore provides an opportunity to complement direct and indirect detection strategies by significantly increasing the sensitivity to dark matter production.

A complementary window on BSM physics is provided by flavour studies. The masses and mixings of quarks and leptons exhibit large and unexplained hierarchies — unlike in the gauge and Higgs sector where all couplings are of similar order. Further, in BSM models, the flavour sector is generally only approximately aligned with the SM mass matrices, and one therefore expects deviations in precision flavour observables. Flavour probes are 'indirect': they test the virtual effects of new particles, which can be observable even for particle masses much above the TeV scale. Past measurements have shown good agreement within SM predictions and theoretically clean processes are of high importance. HL-LHC allows measurements of clean ratios of flavour changing neutral current (FCNC) processes which together with future advances in lattice QCD calculations will significantly increase the BSM reach. Additionally, HL-LHC will be able to directly probe flavour properties of the top quark using FCNC decays, which are tiny in the SM but can be enhanced to measurable rates in the presence of new physics.

For maximum benefit to be obtained from the HL-LHC it will be crucial for the Higgs studies and new physics searches to be accompanied by more precise Standard Model measurements and calculations. For example, one potentially limiting factor on the extraction of certain Higgs couplings at the LHC is our incomplete knowledge of the expected Higgs production cross section: uncertainties on parton distribution functions and on the intrinsic gluon-fusion Higgs cross section each enter at the 7–10% level.

Differential measurements of top-quark, single vector-boson, di-boson and jet production will provide important high-precision inputs for parton distribution function determinations, and will also play an important role in validating and constraining state-of-the-art simulation tools. These measurements are also of intrinsic interest, complementary to searches, as we explore the physics of the TeV scale, for example with di-boson production sensitive to anomalous triple gauge-boson couplings.

In parallel to new measurements, advances in QCD and electroweak theory computations are to be expected. For example, with technology that is currently being developed, one extra order of the perturbative QCD is just becoming available (e.g. [2, 3]) or will do soon (e.g. [4, 5, 6]) for many key processes, helping to significantly reduce the uncertainties in the theoretical predictions.

Beyond the studies mentioned above, the HL-LHC will also investigate strongly-interacting matter at very high temperature and density. This matter is believed to exist in a state called the Quark-Gluon Plasma (QGP), in which quark and gluon degrees of freedom are liberated and chiral symmetry is partially restored. The second generation of LHC heavy-ion studies following *LS2* will focus on precise and multi-differential measurements of many different probes of this special state of matter, including heavy-flavour particles, quarkonium states, real and virtual photons, jets and their correlations with other probes. The upgraded detectors and the 10-fold higher integrated luminosity will, in particular, provide access to several new observables, characterized either by low cross sections (like heavy flavour baryons and b-jet correlations) or by low signal-to-background ratios (like low-mass dileptons).

To summarise, as we shall see in more detail below, the sensitivity gains at higher luminosity will give us a historical chance to elucidate the mechanism of electroweak symmetry breaking, to discover new particles relevant for the quantum stabilisation of the Higgs potential, and to provide insights into unsolved problems of the Standard Model.

3 Simulation methods

The expected performance of searches and measurements using the data that would be provided by the HL-LHC is estimated using two approaches based on *parametric simulations* of detector effects and *projections* based on existing measurements. These estimates assume a center-of-mass energy of $\sqrt{s} = 14$ TeV, a sustained instantaneous luminosity of $L = 5 \times 10^{34}$ cm^{-2}s^{-1} and 25 ns bunch spacing.

For its parametric approach, ATLAS establishes "smearing" functions using a full detector simulation, including the effects of event pile-up, from which corresponding resolutions, detection and reconstruction efficiencies, and the rejection of fakes produced by jets are extracted. These functions are then applied to the Monte Carlo truth event information. Performance studies of the Phase II ATLAS detector upgrade are summarized in the Letter of Intent [7]. These studies assumed up to 200 pileup events and a new all-silicon inner tracker. Expected performance of the upgraded ATLAS detector and nominal HL-LHC conditions are summarized in Ref. [8]. CMS on the other hand establishes the response, efficiency and misidentification rates in low pileup conditions, where the reconstructions and identification algorithms have been tuned. Different detector configurations for the CMS Phase II upgrade are then configured using Delphes [9, 10]. The tool is also used to overlay minimum bias collisions to match the expected pile-up scenario. The performance of the parametrization is confirmed using full simulation of the CMS Phase I upgrade detector at the nominal HL-LHC luminosity.

The projection approach consists in the extrapolation to $\sqrt{s} = 14$ TeV and $L = 5 \times 10^{34}$ cm^{-2}s^{-1}

of the current results from data taken at $\sqrt{s} = 8$ TeV and $L = 0.7 \times 10^{34}$ cm^{-2}s^{-1}. The underlying assumption of the extrapolations is that future upgrades will provide the same level of detector and trigger performance achieved with the current detector in the 2012 data taking period. Naturally, these extrapolations do not take into consideration those channels that were not utilized in the currently available dataset, and there is no attempt to optimize measurements in order to minimize uncertainties or to maximize sensitivity. CMS presents extrapolations under two uncertainty scenarios. In Scenario 1, all systematic uncertainties are left unchanged. In Scenario 2, the theoretical uncertainties are scaled by a factor of 1/2, while other systematic uncertainties are scaled by the square root of the integrated luminosity (including the uncertainty on luminosity). The comparison of the two uncertainty scenarios indicates a range of possible future measurements. Extrapolation without theoretical uncertainties is also presented (in the case of ATLAS studies), to illustrate the importance of reducing those uncertainties in the future. It should be noted that systematic uncertainties are inputs to the fits and can be further constrained by the data when extracting observables.

In most cases, one or other of these approaches have been been used to study two scenarios: one corresponding to L = 300 fb^{-1} taken at $L = 2{\times}10^{34}$ cm^{-2}s^{-1} as planned for the LHC physics programme and another corresponding to L = 3000 fb^{-1} taken at an instantaneous luminosity of $L = 5{\times}10^{34}$ cm^{-2}s^{-1} as planned for the HL-LHC physics programme. The parametric approach has been adopted also by ALICE for Pb–Pb analyses, validated by full simulation studies.

4 Higgs boson precision measurements

In 2012 the experiments ATLAS and CMS at the Large Hadron Collider announced the discovery of a new resonance with mass of about 125 GeV, using a data sample of proton-proton collisions collected mostly at $\sqrt{s}$=8 TeV, and corresponding to an integrated luminosity L=25 fb^{-1} [11][12]. The sample analyzed represents less than 1% the total integrated luminosity that can be collected with HL-LHC, at a center-of-mass-energy that is about half of what can be achieved by this collider.

This particle, discovered with the analysis of $\gamma\gamma$, $ZZ^{(*)}$ and $WW^{(*)}$ final states, is compatible within current experimental and theoretical uncertainties with the properties of the Higgs boson predicted by Standard Model. It is of paramount importance to clarify the nature of this new object and its role in EWSB. Deviations of physics properties from those predicted in the Standard Model would unambiguously indicate new physics beyond this theory. Hence, the precise measurement of this particle's properties represent a major goal of the LHC experiments. Of fundamental importance are the determinations of the couplings of the particle to elementary fermions and bosons, the strength of the self-coupling, and its CP composition. The data that will be delivered by HL-LHC will allow measurements with a precision sufficient to test the Standard Model predictions of Higgs boson couplings at the level of a few % [13, 14, 15]. In addition to continuing direct searches for new particles, it will also facilitate the indirect search for new physics in rare SM (or BSM) physics processes [13, 16].

The results summarised here present the updated conclusions of studies, the earlier results of which were initially reported to the *Update of the European Strategy for Particle Physics* Symposium held in Krakow in September 2012 [17][18].

4.1 Higgs boson couplings to elementary fermions and bosons

4.1.1 Rare and "invisible" Higgs boson decays

We present here the main results on $H \to \mu^+\mu^-$ and $H \to Z\gamma$ final states. Searches in these channels are challenged by the low branching fraction (e.g., B.R. $H \to \mu^+\mu^- \sim 2.2 \times 10^{-4}$); a high luminosity collider such as HL-LHC is an ideal machine for the production rate measurement of these final states. Results on Higgs boson decays to invisible final states, which would contribute to the missing transverse energy measurement, are also summarized.

In SM, both $H \to \gamma\gamma$ and $H \to Z\gamma$ are loop induced decays with the important difference that $H \to Z\gamma$ is sensitive to the chiral nature of the particle in the loop. New particles beyond the SM can affect their relative amplitudes, where $H \to Z\gamma$ can be sensitive to effects invisible in $H \to \gamma\gamma$. Therefore, a simultaneous measurement of their production rates will be important in understanding the nature of the newly observed Higgs particle. Events are selected online with a single-lepton or dilepton trigger with threshold of the order of 20 GeV p_{T}. The offline analysis is based on the selection of lepton pairs with high invariant mass, produced in association with a high-p_{T} isolated photon. The dilepton-photon invariant mass spectrum is studied to separate the Higgs boson signal from the background made by the irreducible contribution from Zγ production, as well as Drell-Yan plus jet processes where the jet is mis-identified as a prompt photon. Results have shown that a precision on the rate of this process between 20% and 55% can be obtained with 3000 fb^{-1}, which represents an improvement by a factor of three with respect to that expected at LHC.

The study of the $H \to \mu^+\mu^-$ decay channel is of particular importance as it allows the investigation of the Higgs boson coupling to second generation fermions, and can contribute to the final mass measurement. It offers the best experimental mass resolution for fermionic final states, comparable to the one of $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to l^+l^-l^+l^-$. The dimuon signature is experimentally very robust. By requiring opposite charge isolated high-p_{T} muons, more than 15K signal events are expected. The large background, more than 5M events, can be measured precisely, with a systematic uncertainty below the statistical fluctuations. The study has been performed both in the gluon-gluon and VBF channels. The production of the SM Higgs boson in the decay $H \to \mu^+\mu^-$ is expected to be measured with an accuracy of about 12% with 3000 fb^{-1}, a factor three better than expected at LHC.

Even with 3000 fb^{-1}, the results on the $H \to \mu^+\mu^-$ and $H \to Z\gamma$ final states will be limited by statistical uncertainties, implying that a combination of results from ATLAS and CMS will yield even more precise measurements. Figure 2 shows the dimuon mass and $m_{ll\gamma} - m_{ll}$ distribution for 3000 fb^{-1}.

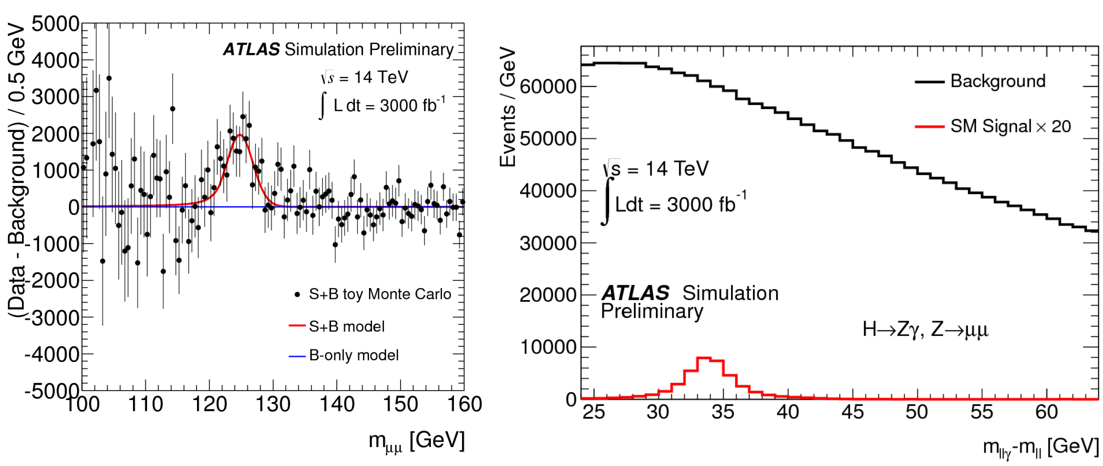

Figure 2: Toy MC samples generated under the signal-plus-background hypothesis for the background subtracted distribution of the dimuon mass in the $H \to \mu^+\mu^-$ analysis (left) and distribution of $m_{ll\gamma} - m_{ll}$ (x20) for $H \to Z\gamma$ and background in the inclusive Z$\to \mu^+\mu^-$ channel (right) for 3000 fb^{-1}.

A further key study is the search for decays of the Higgs boson to particles that leave the experimental apparatus without being detected, e.g. to dark matter WIMPs. The process considered in the study performed is the associated ZH production, with Z$\to l^+l^-$ and the Higgs boson decaying invisibly. The event selection is based on the reconstruction of the Z-boson in the dielectron or dimuon channels; the signal would manifest itself in the production of events with large missing transverse energy, in addition to those expected from SM processes such as diboson production, Z+jets, top quark. Limits on the "invisible final state" branching ratio of the Higgs boson at the level of 6-8% can be set at the 95% confidence level; in a more conservative scenario this limit would degrade by about a factor of two. Measurements using the VBF and gluon fusion production modes can further improve the results.

4.1.2 Higgs boson signal strength

The HL-LHC will provide sensitivity to numerous Higgs boson production and decay channels. These include gluon-gluon fusion (ggF), vector-boson fusion (VBF) production mechanisms, as well as production of the SM Higgs boson in association with vector bosons (VH, V = W or Z) or $t\bar{t}$ pairs. Higgs boson decay modes studied include $H \to \gamma\gamma$, $H \to WW^{(*)} \to l\nu l\nu$, $H \to ZZ^{(*)} \to l^+l^-l^+l^-$, $H \to \tau^+\tau^-$, $H \to b\bar{b}$, as well as $H \to Z\gamma$, $H \to \mu^+\mu^-$and searches for invisible decays discussed above. As stated in the previous section, deviations from expectations would provide clear evidence of new physics beyond the SM.

Table 1 shows the expected relative uncertainties on the determination of the Higgs boson signal strengths, $\mu = \sigma/\sigma_{SM}$. The results are given for two scenarios, with different assumptions for the evolution of systematic uncertainties. The comparison of the two uncertainty scenarios indicates the range of expectations for possible future measurements. For ATLAS the lower bound is extracted neglecting theoretical uncertainties, while for CMS the lower bound follow the strategy called Scenario 2 described earlier. The upper bounds assume the present theoretical uncertainties. For CMS all experimental systematic uncertainties are unchanged with respect to the 8 TeV analyses, following Scenario 1. These systematic uncertainties are input to the fits and are further constrained by the data. Many of the ATLAS analyses take the reduction of experimental systematic uncertainties directly into account, considering the very large statistics available in background control samples, and the better knowledge of the biases introduced by the detector measurements again thanks to the large data samples that will be produced by HL-LHC. The results for ATLAS and CMS compare well. Exceptions are the τ and the $Z\gamma$ final states. The former discrepancy is due to a conservative and partial analysis, and the latter due to different assumptions on the performance of photon identification at high pileup (with ATLAS adopting a more conservative approach).

Table 1: Precision on the measurements of the signal strength for some key decay modes of a SM-like Higgs boson. These values are obtained at $\sqrt{s} = 14$ TeV using an integrated dataset of 300 fb^{-1} at LHC, and 3000 fb^{-1} at HL-LHC. Numbers in brackets are % uncertainties on the measurements estimated under [no theory uncertainty, current theory uncertainty] for ATLAS and [Scenario2, Scenario1] for CMS as described in the text.

L(fb^{-1})	Exp.	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	Zγ	$\mu\mu$
300	ATLAS	[9, 14]	[8, 13]	[6, 12]	N/a	[16, 22]	[145, 147]	[38,39]
	CMS	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]
3000	ATLAS	[4, 10]	[5, 9]	[4, 10]	N/a	[12, 19]	[54, 57]	[12,15]
	CMS	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[14,20]

4.1.3 Higgs boson coupling fit

Higgs boson couplings can be measured at the HL-LHC making some model assumptions, in particular on the total intrinsic width of this scalar. Almost fully model independent measurements can be performed using coupling ratios for which the total width cancels.

Only modifications of coupling strengths are considered, while the tensor structure of the Lagrangian is assumed to be the same as in the Standard Model. This implies in particular that the observed state is a CP-even scalar. The coupling scale factor κ_i are defined in such a way that the cross sections $\sigma_{i,j}$ and the partial decays widths Γ_j associate to the SM with $\kappa_i^2 \cdot \kappa_j^2$ [19]. With this formulation, defining

κ_H^2 as the scale factor for the total Higgs boson natural width Γ_H, the ratio of the cross sections for the $gg \to H \to \gamma\gamma$, for example, can be written as $\frac{\sigma \cdot BR(gg\to H\to\gamma\gamma)}{\sigma_{SM} \cdot BR_{SM}(gg\to H\to\gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$.

Table 2 shows the expected relative uncertainties on the determination of these coupling uncertainties for the LHC (L=300 fb^{-1}) and HL-LHC (L=3000 fb^{-1}). The experimental uncertainties are reduced by a factor of two or more for almost all couplings, and reach a precision of a few % for most of the cases. These results have been obtained in a minimal coupling fit where only n independent scale factors k_i are analyzed with no BSM contributions to loops or to the total width. These uncertainties are summarised also in Figure 3 (left), based on the CMS findings for HL-LHC.

The possibility of Higgs boson decays to beyond-Standard-Model (BSM) particles, with a partial width Γ_{BSM}, can be accommodated in the coupling fit. The likelihood scan versus $BR_{BSM} = \Gamma_{BSM}/\Gamma_{tot}$ yields a 95% CL of the BSM branching fraction of 14 and 7 % for LHC and HL-LHC, respectively and complements direct search for invisible Higgs decays.

ATLAS results on Higgs decays to b-quarks are not available yet. Hence, the additional assumption of $\kappa_b = \kappa_\tau$ is made in the coupling fit. The uncertainties of coupling measurements depend on how well the final state and the total width can be constrained. As a consequence, all measurements of κ_i received a penalty from the measurement of κ_τ. In the case of CMS, $H \to b\bar{b}$ projections at HL-LHC are available, and this allows a significantly better measurement of the Higgs couplings under the assumptions mentioned above.

Table 2: Precision on the measurements of κ_γ, κ_W, κ_Z, κ_g, κ_b, κ_t, κ_τ, $\kappa_{Z\gamma}$, and $\kappa_{\mu\mu}$. These values are obtained at $\sqrt{s}$ = 14 TeV using an integrated dataset of 300 fb^{-1} at LHC, and 3000 fb^{-1} at HL-LHC. Numbers in brackets are % uncertainties on couplings for [no theory uncertainty, current theory uncertainty] for ATLAS and [Scenario2, Scenario1] for CMS as described in the text.

L(fb^{-1})	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	ATLAS	[8,13]	[6, 8]	[7, 8]	[8, 11]	N/a	[20, 22]	[13, 18]	[78, 79]	[21, 23]
	CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	ATLAS	[5, 9]	[4, 6]	[4, 6]	[5, 7]	N/a	[8, 10]	[10, 15]	[29, 30]	[8, 11]
	CMS	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

4.1.4 Higgs boson coupling ratio measurements

Almost fully model independent measurements can be achieved if coupling ratio measurements are performed. Because of the cancellation of the total width, ratios avoid introducing cross-dependencies between couplings, notably that related to κ_b. Table 3 shows the expected relative uncertainties. Results for ATLAS, summarised in figure 3 (right), and CMS compare well. Coupling ratios can be determined with an uncertainty of a few % for many of the cases investigated.

4.2 Higgs boson pair production

The measurement of the Higgs boson self-coupling and subsequent reconstruction of the Higgs potential is a fundamental test of the Higgs mechanism described in the Standard Model. At hadron colliders, the dominant production mechanism is gluon-gluon fusion, and at the HL-LHC is estimated to be $34^{+37\%}_{-30\%}$ fb [20], assuming the Higgs boson mass $m_H = 125$ GeV. Due to the destructive interference of the diagrams involving di-Higgs production, this cross section is modified to be 71 (16) fb if the self-coupling is assumed to be zero (twice the SM prediction). Recent calculation of next-to-next-to-leading order (NNLO) QCD corrections suggests an increase of the SM cross-section by a factor O(20%) [3], thus enhancing its value to about 40 fb.

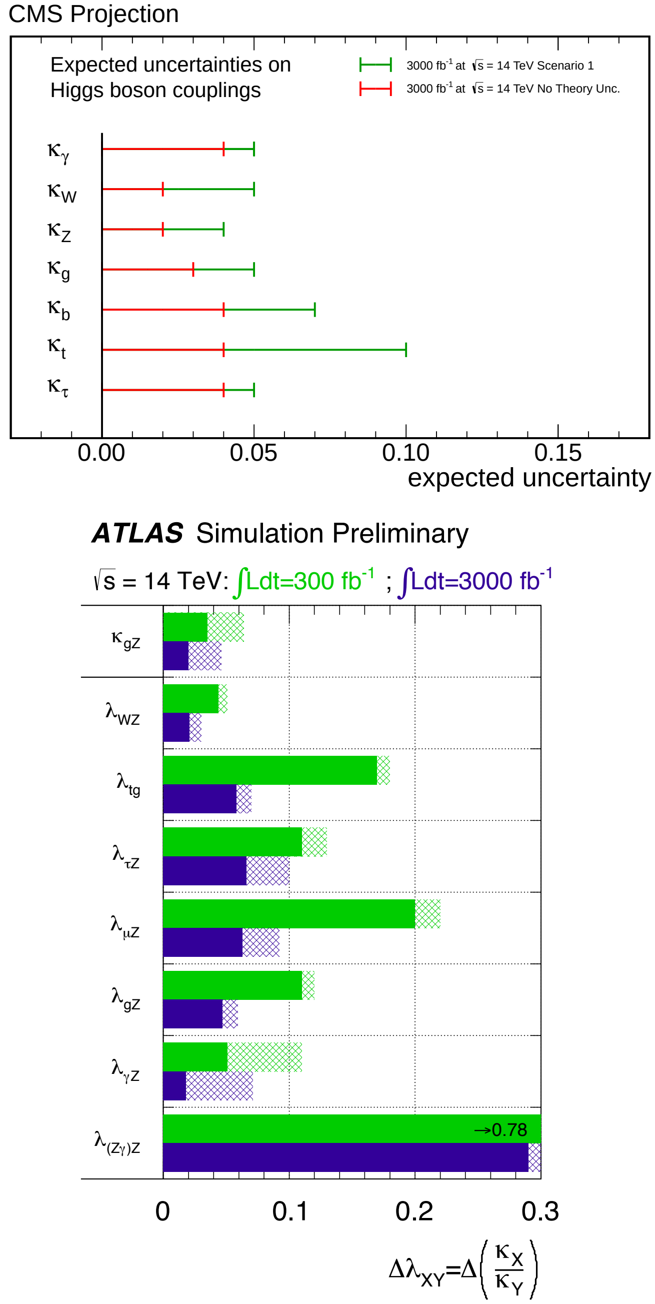

Figure 3: Top: Estimated precision on coupling modifiers. The projection assuming $\sqrt{s} = 14$ TeV an integrated dataset of 3000 fb^{-1}, and Scenario 1 are compared with a projection neglecting theoretical uncertainties. Bottom: Relative uncertainty on the expected precision for the determination of coupling scale factor ratios λ_{XY} in a generic fit without assumptions, assuming a SM Higgs Boson with a mass of 125 GeV and LHC at 14 TeV, 3000 fb^{-1}. The hashed areas indicate the increase of the estimated error due to current theory systematics uncertainties.

Table 3: Estimated precision on the measurements of ratios of Higgs boson couplings. These values are obtained at $\sqrt{s} = 14$ TeV using an integrated dataset of 300 fb^{-1} at LHC, and 3000 fb^{-1} at HL-LHC. Numbers in brackets are % uncertainties on couplings for [no theory uncertainty, current uncertainty] for ATLAS and [Scenario2, Scenario1] for CMS as described in the text.

L(fb^{-1})	Exp.	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ/κ_Z	κ_W/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_Z/κ_g	κ_t/κ_g	κ_μ/κ_Z	$\kappa_{Z\gamma}/\kappa_Z$
300	ATLAS	[3,6]	[5,11]	[4,5]	N/a	[11,13]	[11,12]	[17,18]	[20,22]	[78,78]
	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,5]	[2,7]	[2,3]	N/a	[7,10]	[5,6]	[6,7]	[6,9]	[29,30]
	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

The effect of the Higgs self-coupling is probed studying the production of Higgs boson pairs. Studies of di-Higgs boson production in the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ final states are ongoing. The measurement of this process is very challenging, but is nevertheless anticipated to be accessible at HL-LHC.

4.3 Higgs boson spin/CP properties

Studies on the prospects of measuring properties of the Higgs boson decay vertex $H \to ZZ^{(*)} \to l^+l^-l^+l^-$ in 14 TeV proton-proton collisions have been performed. Though this channel has much reduced sensitivity to mixed CP states in the MSSM, where the decay to ZZ projects out the CP-even component, this does not apply to general BSM studies. The expected sensitivities on the measurement of the HZZ vertex tensor couplings are reported for a data sample equivalent to an integrated luminosity of 3000 fb^{-1} taken at the HL-LHC. These results are compared to those expected by LHC 300 fb^{-1}. More specifically, under the spin-zero assignment for the Higgs boson with the mass of 125.5 GeV, the parametrization of the general scattering amplitude in terms of its four complex couplings g_1, g_2, g_3 and g_4 [19] have been considered. To measure the values of the real and imaginary parts of the couplings g_1 - g_4, the specific kinematical variables and the full information of the event obtained from the analytical calculation of the corresponding matrix elements are used. The result of the study shows that with 3000 fb^{-1} we can exclude at 95% Confidence Level (CL) the values for the couplings g_4 and g_2 reported in Table 4, substantially improving our knowledge of the tensor structure of the HZZ vertex.

Table 4: Expected values excluded at 95% CL for the real and imaginary part of g_4/g_1 and g_2/g_1 couplings, assuming the Standard Model. These values are obtained at $\sqrt{s} = 14$ TeV using an integrated dataset of 3000 fb^{-1} at HL-LHC.

$\Re(g_4)/g_1$		$\Im(g_4)/g_1$		$\Re(g_2)/g_1$		$\Im(g_2)/g_1$	
$<$-0.34	$>$0.26	$<$-0.34	$>$0.48	$<$-0.30	$>$0.11	$<$-0.71	$>$0.68

For the alternative parametrization in terms of the two cross-section fractions (f_{g_2} and f_{g_4}) and the relative phases (ϕ_{g_2} and ϕ_{g_4}) [19] this translates into the exclusion limits $f_{g_4} < 0.037$, $f_{g_2} < 0.12$, at 95% CL. The results of the study are also presented in terms of contour regions in (f_{g_4}, ϕ_{g_4}), (f_{g_2}, ϕ_{g_2}), and similar two-dimensional planes. Further information can be found in Ref. [21].

4.4 Direct and indirect searches for BSM Higgs bosons

Extended Higgs sectors are predicted by many BSM theories, including supersymmetric extensions of the SM and various types of composite models. They can be tested through coupling measurements of the observed Higgs boson and direct searches for new particles. Two Higgs doublet models (2HDM) provide an effective description for many such extensions. They provide relations between the couplings of the observed Higgs boson and the event yields and properties of additional new scalars. 2HDMs contain five physical Higgs bosons, two CP-even scalars h and H, a CP-odd pseudo-scalar, and a pair of charged Higgs bosons $H^{\pm}$.

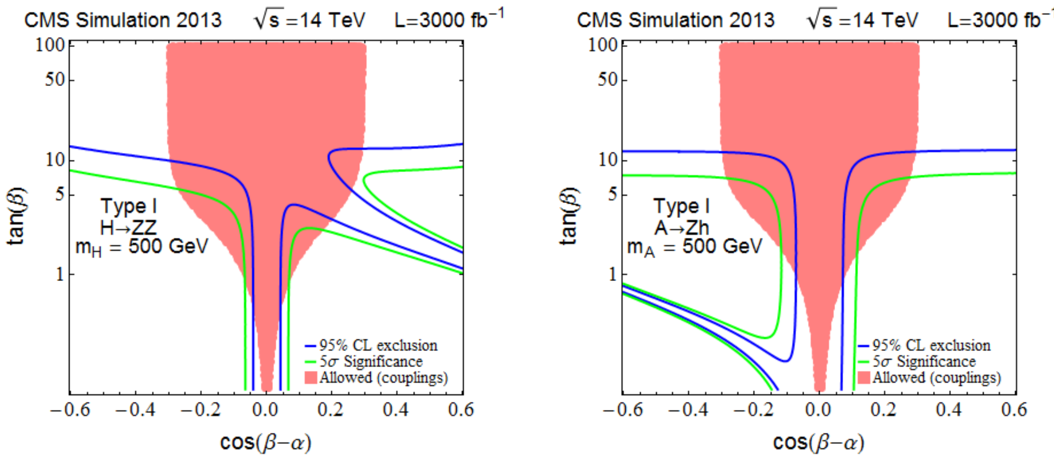

Figure 4: The region of parameter space for which 500 GeV H (left) and A (right) bosons could be excluded at 95% CL (blue), and the region of parameter space which could yield a 5σ observation (green), in the context of Type I 2HDMs. The red colored regions correspond to the expected 95% CL allowed region from Higgs precision measurements with 3000 fb^{-1}.

Assuming that the observed Higgs boson is the lighter of the two CP-even scalars h, it is possible to constrain the 2HDM parameter space of $\tan\beta$ and $\cos\beta-\alpha$, where $\tan\beta$ is the ratio of vacuum expectation values and α the CP-even mixing angle. Direct searches for H$\to$ZZ and A$\to$Zh extend the sensitivity obtained through precision measurements. ATLAS and CMS studied the performance of direct and indirect Higgs searches in the context of 2HDM models [22, 23, 24].

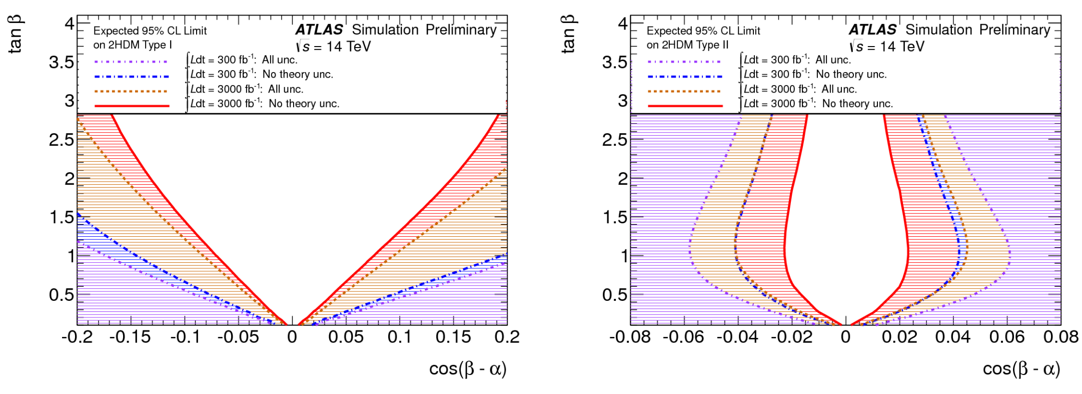

Figure 5: The regions of parameter space expected to be excluded with 300 and 3000 fb^{-1} at $\sqrt{s} = 14$ TeV, each shown with and without the inclusion of theoretical uncertainties in the coupling measurements. These are determined for Type I (left) and Type II (right) 2HDMs using fits to the expected rates and their precision.

Figure 4 shows the regions of parameter space for which 500 GeV H and A bosons could be excluded at 95% CL or discovered with 5σ significance. Figure 5 shows the regions expected to be excluded with and without the inclusion of theoretical uncertainties in the coupling measurements. By pursuing both strategies, the direct and indirect searches, the regions are improved significantly, and in the event of a discovery the studies are greatly enhanced.

5 Search for signatures of physics beyond the Standard Model

The SM describes an impressive variety of experimental data over a very large energy range. Nonetheless, for numerous reasons (e.g. the absence of a description of the gravitational interaction), it is postulated that the SM may be a low energy effective theory. One particular important shortcoming of the SM given the recent discovery of a relatively low mass Higgs boson is that the mass of a scalar particle such as the Higgs receives large radiative corrections, on the order of M_{Planck}, i.e. the hierarchy problem described previously. One of the most pressing questions in particle physics is, therefore, whether or not there exists a "natural" solution to this problem that stabilises the Higgs mass against these quadratic divergences.

Supersymmetry (SUSY) is a hypothetical new symmetry of nature which relates fermions and bosons. SUSY particles with masses at the electroweak scale could represent the new degrees of freedom that cancel the quadratic divergences in the Higgs sector. Figure 6 shows the cross sections for the pair production of SUSY particles. As noted in Section 2, while production cross sections for strongly produced sparticles are relatively large, cross sections for electroweak particles like neutralinos and charginos are several orders of magnitude smaller and thereby benefit significantly from the large integrated luminosity provided by the HL-LHC.

There are also non-supersymmetric solutions that could cancel these divergences. The search for these will continue with the HL-LHC; the sensitivity for discovering a heavy vector like quark is studied as a benchmark. In addition to the question of naturalness, the HL-LHC will also provide an opportunity to study further the electroweak symmetry breaking mechanism of the SM, e.g. by verifying that vector boson scattering cross sections are damped by the Higgs boson as expected.

If a signal of new physics is found in Runs 2 or 3 of the LHC, the HL-LHC will be essential to determine the detailed properties of the BSM physics and a large programme of measurements will be undertaken in order to reach this physics goal. This is not the subject of this report though which focuses on the discovery reach of a few most interesting benchmark scenarios.

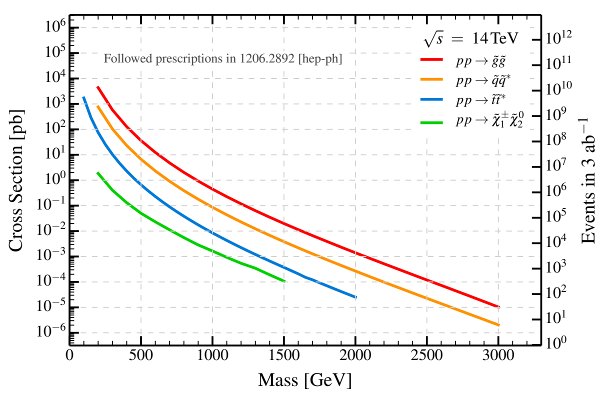

Figure 6: Next-to-leading order cross-sections for the production of supersymmetric particles at the LHC as a function of the average mass of the pair-produced supersymmetric particles. The $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ are assumed to be wino-like.

5.1 Search for neutralinos and charginos

One of the processes with a low production cross section, and therefore strongly dependent on high luminosity, is the direct production of the supersymmetric partners of the electroweak gauge bosons. The SUSY partner of the Higgs particle, the higgsino, is bound by the Higgs mass parameter μ to be close to the Higgs mass. The higgsino mixes with the partner particles of the other bosons to mass eigenstates, called neutralinos ($\tilde{\chi}_1^0$ to $\tilde{\chi}_4^0$) and charginos ($\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$). At least a few of these particles are expected to be light (of the order of several hundred GeV) in natural supersymmetry [25, 26].

Weak gauginos can originate in cascade decays from squark and gluino production or can be directly produced via weak interactions. In scenarios with heavy gluinos and squarks, the direct pair production of weak gauginos can become the dominant SUSY process at the LHC. The decays of $\tilde{\chi}_1^\pm \to W^{\pm(*)}\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to Z^{(*)}\,\tilde{\chi}_1^0$, can lead to clean final states with three leptons and missing transverse momentum. The $\tilde{\chi}_1^0$ is in this model the lightest SUSY particle (LSP), which is stable, and a viable dark matter candidate. The search for direct production of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ with decays as described above is interpreted in the context of a simplified SUSY model where a branching ratio $\mathrm{BR}(\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to \mathrm{W}^{(*)}\,\tilde{\chi}_1^0\mathrm{Z}^{(*)}\,\tilde{\chi}_1^0)$ of 100% is assumed. The corresponding Feynman diagram is shown in Fig 7(left). Nature might well have a lower BR and several other decays, e.g. $\tilde{\chi}_2^0 \to h\,\tilde{\chi}_1^0$, which are then expected to become observable.

With an integrated luminosity of 3000 fb^{-1} neutralinos ($\tilde{\chi}_2^0$) and charginos ($\tilde{\chi}_1^\pm$) up to a mass of 700 GeV for $\tilde{\chi}_1^0$ masses of up to 200 GeV can be discovered with a significance of 5σ, as shown in Fig. 7(right). Further information can be found in Ref. [27, 16].

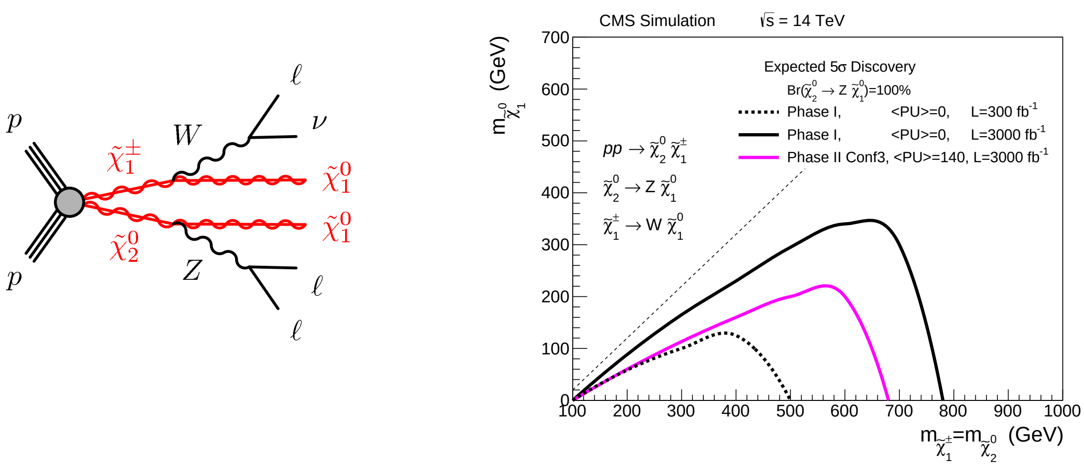

Figure 7: Left: The Feynman diagram for the $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ simplified model. Right: Projections of the discovery reach for electroweak production of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ that decay via W and Z bosons into $\tilde{\chi}_1^0$. The magenta curve is the realistic reach obtainable under HL-LHC luminosity conditions. This can be compared with the black solid curve that shows what the reach would be if there were no pileup effects, or equivalently pileup effects were completely mitigated. This curve in turn can be compared with the black dashed curve in order to see the increase in reach due to the luminosity provided by the HL-LHC with respect to LHC.

On the other hand, the above analysis is not very sensitive to very compressed spectra. In these cases, vector-boson-fusion (VBF) processes provide a unique opportunity to search for new physics with electroweak couplings [28, 29]. Also here, the low production cross section for VBF channels demands high luminosity. The sensitivity to detect supersymmetric dark matter produced directly at the HL-LHC in VBF processes has been investigated for a model in which $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ are mainly Wino and nearly mass-degenerate, so that both are invisible in the detector. They could be produced directly in VBF processes, which are selected by requiring two jets in the forward direction in opposite hemispheres and missing energy due to the undetected LSPs. Such events suffer from pileup which could be mitigated with enlarged tracking in the forward region up to a pseudorapidity of 4, as currently under discussion for CMS. In this case the background from SM processes could be reduced by a factor 3–10.

5.2 Direct stop production

Naturalness arguments require the light top squark mass eigenstate to be below 1-1.5 TeV [25, 26]. While stops are the lightest colored SUSY particles, the cross section for direct stop pair production is only about 1 fb for 1.5 TeV. Such searches are therefore expected to benefit from the large luminosity of the HL-LHC and are studied in this section.

Stops can decay in a variety of modes which are very much dependent on the parameters of the SUSY model assumed. Typically, SUSY final state events contain top or b-quarks, W/Z or Higgs bosons, and an LSP. Pair production signatures are thus characterized by the presence of several jets, including b-jets, large missing transverse momentum and possibly leptons. In some cases (e.g. the loop-dominated $\tilde{\mathrm{t}} \to \mathrm{c} + \tilde{\chi}_1^0$ decay in the very compressed scenario) the dominant decay chains will be difficult to separate from the SM background and dedicated analyses must be employed. For the discovery of such scenarios high luminosity is a key factor.

The search presented here aims for the discovery of pair-produced stops that are assumed to decay to a top quark and the LSP ($\tilde{\mathrm{t}} \to \mathrm{t} + \tilde{\chi}_1^0$), as shown in Fig. 8(left). Here it is required that the produced top quark is on shell, $m(\tilde{\mathrm{t}}) - m(\tilde{\chi}_1^0) > m(\mathrm{t})$. The final state for such a signal is characterized by a top quark pair produced in association with large missing transverse momentum from the undetected LSPs.

Two studies are carried out as counting experiments targeting the scenario described above, a zero lepton selection requiring jets, b-jets and a large missing transverse momentum and a one lepton selection with stringent requirements on missing transverse momentum. For the calculation of the discovery reach, shown in Fig. 8(right), the zero lepton and one lepton channels are statistically combined. Further information can be found in Ref. [27].

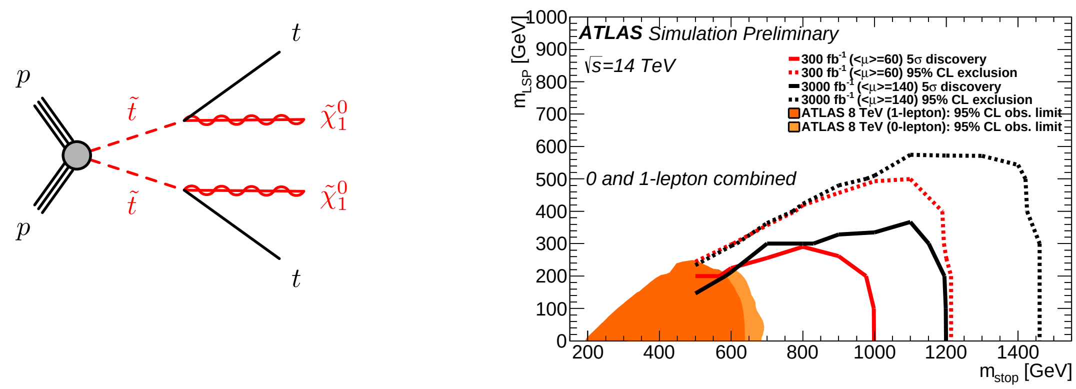

Figure 8: Left: The Feynman diagram for the simplified model of direct stop production. Right: The 5σ discovery reach (b) for 300 fb^{-1} (solid red lines) and for 3000 fb^{-1} (solid black line). The corresponding 95% exclusion limits are shown as dashed lines.

5.3 Search for gluinos

Gluinos correct the Higgs mass at two-loop level and similar naturalness arguments therefore also favour lower gluino masses [26]. Two searches for gluinos are performed. A generic search is based on the observation of large amount of hadronic energy and missing transverse momentum. This search is interpreted in a model describing gluino pair production, where each gluino decays to two quarks and the LSP. Here the discovery reach for gluinos is enhanced to 2.2 TeV, while the LSP masses can be probed up to 500 GeV at a luminosity of 3000 fb^{-1}. The other search focuses on final states with four top quarks and two LSPs, and requires exactly one electron or muon in the final state. With a luminosity of 3000 fb^{-1} gluino masses of up to 2.2 TeV and LSP masses of up to 1.2 TeV can be discovered. Further information can be found in Ref. [16].

5.4 Search for heavy vector-like quarks

Vector-like quarks differ from SM quarks in their electroweak couplings: while SM quarks have V-A coupling to the W leading to different couplings of the left- and right-handed states to the W, vector-like quarks have only vector-coupling to the W. The vector-like mass term does not violate gauge invariance without the need for a Yukawa coupling to the Higgs boson and is predicted, for example, by little Higgs models. As noted above, the existence of vector-like quarks could also provide a natural solution to cancel the diverging contributions of top quark loops to the Higgs boson mass.

Searches for a vector-like charge 2/3 quark have been performed in single- and multi-lepton channels, which have been statistically combined for a common result. With 3000 fb^{-1}, vector-quark masses of up to 1.5 TeV can be probed. Further information can be found in Ref. [30].

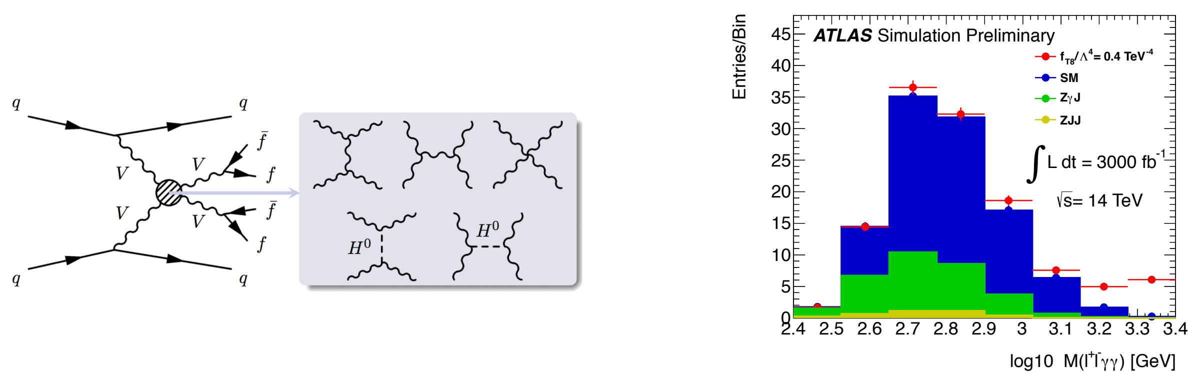

Figure 9: Left: The Feynman diagram for vector boson scattering. Right: The reconstructed mass spectrum for the charged leptons and photons in selected $Z\gamma\gamma$ events.

5.5 Anomalous couplings in vector boson scattering

A major reason for the expectation of new physics to occur at around the TeV energy scale has been the realization that an untamed rise of the vector boson scattering (VBS) cross section in the longitudinal mode would violate unitarity at this scale. In the SM it is the Higgs particle that is responsible for its damping (through negative interference), as shown in Fig. 9(left). Alternate models such as Technicolor and little Higgs have been postulated which encompass TeV scale resonances and a light scalar particle. Other mechanisms for enhancing VBS at high energy are possible, even after the SM Higgs mechanism is established. The measurement of the energy dependence of the VBS cross section is therefore a task of principal importance, which could also lead to unexpected new physics. The SM VBS production of a W and a Z boson is expected to be observed with about 185 fb^{-1} (if the cross section is calculated including the destructive interference by the Higgs). Depending on the nature of possible BSM contributions, they might already start to become visible with 300 fb^{-1}. At the HL-LHC the coefficients of these couplings could then be measured up to a precision of 5%, yielding new insights into the nature of electroweak symmetry breaking. In addition, the HL-LHC offers access to rare events with very high transverse momentum, enhancing the sensitivity to anomalous gauge couplings by a significant amount.

We show in Fig. 9(right) an example for a BSM signal at very high reconstructed mass from the charged leptons and photons in selected $Z\gamma\gamma$ events, which is only possible to observe with 3000 fb^{-1}. More results can be found in Ref. [31, 32, 33].

6 Physics requirements on the detectors and trigger systems

The detector and trigger upgrades at each stage of the LHC+HL-HLC program are designed to maintain or improve on the performance already achieved in Run 1. Some requirements are driven by the basic need to remain operational despite the increasing accumulated radiation dose and to deal with higher occupancies from pile-up. Others are motivated more directly by the need to trigger on and measure the physics channels of interest, and are the topic of this section. There is a need to gradually move more refined object selection algorithms upstream, from the offline to the high-level trigger or from the high-level trigger to the hardware trigger(s). Specific final state topologies also lend themselves to selection by multi-object triggers, which will complement lower threshold lepton, jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers.

The largest single change for ATLAS and CMS is to replace their tracking detectors so as to maintain track reconstruction efficiency and resolution, impact parameter resolution, and primary and secondary vertex finding. Specific examples of use cases at HL-LHC include $H \to \mu^+\mu^-$, where tracks are of low enough p_{T} that the tracker makes an important contribution to the resolution, identification of the correct primary vertex for $H \to \gamma\gamma$, and algorithms using tracking to reject fake jets and correct jet energy (particle flow or other).

A higher granularity calorimeter is important for object recognition, in particular for isolation. In the case of ATLAS, higher granularity and higher precision readout will be available earlier in the trigger decision. CMS will add the ability to read out its calorimeters with longitudinal segmentation and will replace the end cap calorimeters for HL-LHC. For both detectors the importance of maintaining adequate performance of the forward calorimetry is also under study. Improved granularity of parts of the muon system is also planned. Some of these improvements are part of the Phase I upgrade, but are already being designed such that they are "Phase II ready".

The emphasis so far has been to demonstrate that the upgraded systems are necessary and fit for purpose. In the following, the trigger improvements are discussed in more detail. The potential benefit of extending the tracking and other detector elements to $|\eta| < 4$ are discussed further in section 6.2.

6.1 Trigger level

The detailed study of Higgs properties and Standard Model physics processes that comprise a major focus of the HL-LHC physics program sets the characteristic energy scale for objects selected online. The trigger thresholds used throughout the first LHC run must be maintained in order to preserve the physics sensitivity of the experiments. The instantaneous luminosity increase to 5×10^{34} $\text{cm}^{-2}\text{s}^{-1}$, coupled with a substantial increase in pileup collisions per bunch crossing, will easily saturate the current trigger bandwidth.

6.1.1 Lepton triggers

The $H \to WW, ZZ$, and $\gamma\gamma$ decays are favored as isolated lepton and photon decay products provide distinctive signatures for Higgs reconstruction. The p_{T} scale of the Higgs decay products is low, so Higgs trigger efficiency is maximized by setting isolated lepton thresholds as low as possible.

Fake and non-isolated lepton signatures make up a significant fraction of the hardware (L1) lepton trigger bandwidth. At HL-LHC the overall lepton trigger rate must be controlled in order to avoid raising trigger thresholds and losing physics sensitivity. This can be accomplished through the introduction of tracking information in the hardware trigger.

The combined information from the tracker and the muon systems will provide a more precise measurement of muon momentum at L1, allowing a strong rejection of very low $p_{\rm T}$ muons. The electron selection efficiency can also be improved as the matching of charged tracks to electromagnetic calorimeter energy deposits will dramatically reduce triggering on fake signatures.

Improved trigger granularity also helps reject fake signatures and will help control the L1 trigger rate while maintaining physics efficiency. Increasing calorimeter granularity, for example, it will be possible to identify neutral pion signatures and thus improve the photon L1 trigger purity.

Tracking information will also be used in the hardware trigger system to identify isolated leptons. Current calorimeter isolation algorithms will be ineffective at identifying isolated electrons and muons due to the abundance of low $p_{\rm T}$ particles from HL-LHC pileup collisions. By counting tracks in a cone surrounding the lepton track, isolated leptons can be identified at L1.

Tau trigger performance will also be dramatically improved by the addition of tracking information, as shown in Figure 10 (reproduced from Ref. [7]). Hadronic tau decays are difficult to identify in the trigger with calorimeter information alone, and calorimeter thresholds must be increased to control the rate of fake tau signatures. Matching tracks to calorimeter signatures recovers tau efficiency at reasonable trigger rates by rejecting fake tau backgrounds.

Further adaptation of online algorithms will progress as offline criteria are moved upstream to the high-level trigger. By continually moving selection criteria upstream, more detailed algorithms can be employed with improve both the purity and selection efficiency for physics objects.

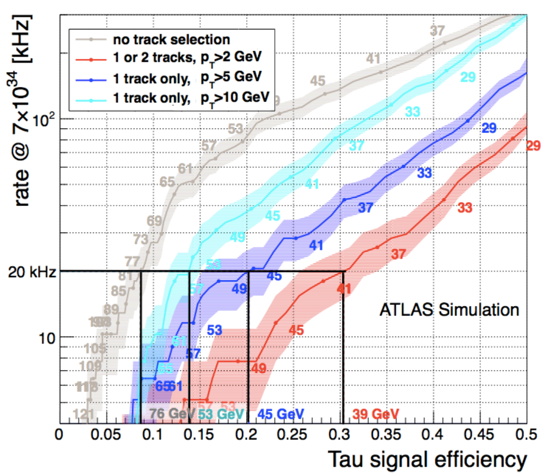

Figure 10: Rate vs. tau finding efficiency curves for taus from the decay of a 120 GeV Higgs boson for the inclusive tau trigger at a luminosity of 7×10^{34} cm^{-2}s^{-1} for different track multiplicity and minimum track $p_{\rm T}$ requirements. The bands show the rate vs. efficiency parametrised for different L1 cluster transverse energy thresholds, shown as the small numbers next to the corresponding points on each band. The thresholds for each band, such that the integrated rate from the trigger is 20 kHz, are shown at the bottom of the plot. The rates are estimated using simulated minimum bias events at 3×10^{34} cm^{-2}s^{-1} and extrapolated to 7×10^{34} cm^{-2}s^{-1}.

6.1.2 Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers and b-jets

Pileup mitigation will be essential to maintain sensitivity to hadronic signatures online. Failure to do so will result in multiple fake jets and poor missing energy resolution. Both of these effects can be controlled by raising trigger thresholds at the cost of physics sensitivity.

Hardware track trigger information can reduce the impact of pileup on hadronic triggers. By matching jets to a collision vertex using the track constituents, jets from multiple pp interactions can be rejected. This allows lower thresholds to be placed on mulitjet triggers at L1 as long as the jets can be associated with a single collision vertex. This same procedure can be used to improve the missing energy resolution by rejecting energy signatures associated with charged tracks from pileup vertices. Tracking information will also provide for early identification of b-jets in the trigger, allowing for early separation of heavy flavor and light jets.

More advanced pileup mitigation techniques will be possible in the high-level trigger than in the hardware trigger as algorithms will be adapted to closely resemble offline selection criteria. In order to achieve optimal performance for online selection, the hadronic trigger output rate from L1 should be maximal. Increasing the hardware trigger output rate allows relaxed thresholds to be placed on hadronic triggers which increases signal efficiency. The high-level trigger processing, with access to more information and more complicated algorithms, can be used to increase the purity of online selection of events with a purely hadronic signature.

6.2 Physics Motivation for Increased Detector Acceptance

As discussed above, the study of processes that proceed by either vector boson fusion or vector boson scattering will be an important component of the HL-LHC physics program. It is important that the upgraded detectors remain sensitive to the distinctive high p_{T} forward jets and rapidity gap associated with these events. The jets are typically produced with $|\eta| \sim 3$. Although the majority of these jets are reconstructed outside of the current tracker acceptance, the low level of pileup in LHC Run 1 facilitated relatively easy calorimetric jet identification.

At the pileup levels of the HL-LHC, the forward jet signature from scattering processes will be overwhelmed by pileup jets in the forward region. For VBF/VBS jets outside the tracker acceptance, unless forward calorimetry is significantly improved, raised p_{T} thresholds will be the only means of pileup jet rejection. Any increase in jet p_{T} requirements will rapidly erase signal efficiency.

Extending the tracker coverage to include the forward region, however, could dramatically improve the ability to reject pileup jets as illustrated by Figure 11 (left) (see Ref. [34]). By reducing the number of pileup jets in the forward region, forward jet thresholds can be kept low enough to maintain efficiency for VBF/VBS processes. The performance and planned upgrade for CMS of the forward calorimeters is currently under study in order to verify VBF/VBS forward jet acceptance for the HL-LHC.

Physics sensitivity can also be improved through an extension of muon coverage. This is illustrated by a study of $H \to ZZ \to 4\mu$ events, as shown in Figure 11 and described in Ref. [15], where an increase of the CMS tracker and muon acceptance to $|\eta| < 4.0$ adds nearly 50% to the $H \to 4\mu$ signal acceptance. This conclusion places a design goal on the extension such that low momentum forward muons from Higgs decay can be measured with a p_{T} resolution of 5-10% using the tracker, with the extended muon chambers acting in a tagging capacity.

7 Heavy Flavour physics in the HL-LHC era

The large production cross-sections for heavy flavoured particles in LHC *pp* collisions provide excellent opportunities for heavy flavour physics. In particular, precision measurements of rare decays and *CP* violation allow studies of effects of virtual particles that can contribute to the quantum loops. Certain observables can be predicted with low uncertainty in the Standard Model (SM), and provide sensitivity to new physics even if it occurs at energy scales far above those that can be directly probed by the LHC.

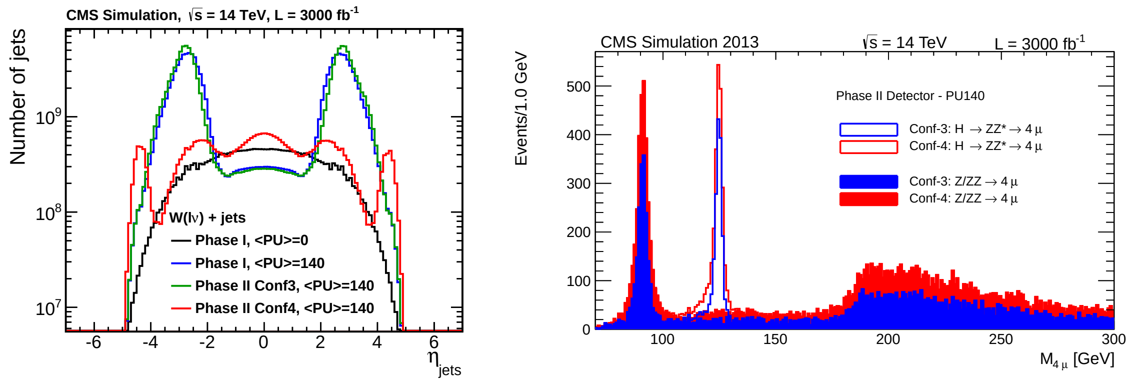

Figure 11: Left: Pseudorapidity distribution for jets with $p_{\mathrm{T}}>$ 30 GeV for various pileup scenarios and detector configurations from a simulated sample of $W(\ell\nu)$+jets events. Extending CMS tracking acceptance to $|\eta| < 4.0$ (Phase II, configuration 4) rejects pileup jets beyond $|\eta| < 2.5$ where the current tracker acceptance ends [3]. Right: Four muon mass distributions for the $H \to ZZ \to 4\mu$ signal sample (solid lines) and for the irreducible $ZZ \to 4\mu$ background (filled histograms). Both processes were simulated with (configuration 4) and without (configuration 3) the proposed extension to the tracker and muon systems.

Since the effects of new physics in flavour observables depend on the complex coupling coefficients as well as the energy scale, these measurements are complementary to the energy frontier searches, and thus increase the discovery potential of the LHC.

The use of the LHC to make precision measurement in the heavy flavour sector has been definitively proved by the results from Run 1 data. The dedicated heavy flavour experiment LHCb has produced a range of world-leading results for B and D meson oscillations, CP violation and rare decays [35]. The results from ATLAS and CMS in the beauty sector are limited mainly to final states containing dimuons, due to their stringent trigger constraints, but in those areas very significant contributions have been made. In addition, the large samples of top quarks available at ATLAS and CMS have brought studies of the heaviest flavour into the precision domain.

In order to exploit fully the flavour physics potential of the LHC, an upgrade to the LHCb detector has been proposed [36, 37] and approved. The upgraded LHCb detector will be installed during LS2 and commence operation in 2019. LHCb will then record data at an instantaneous luminosity of 1–$2 \times 10^{33}\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$, levelled using a scheme similar to that deployed during Run 1. The LHCb upgrade design is qualified for an integrated luminosity of $50\,\mathrm{fb}^{-1}$ but it is anticipated that LHCb will continue to be operational throughout the HL-LHC era, which is defined to commence after LS3 when the "Phase II" upgrades for ATLAS [38] and CMS will take place. The upgrades will significantly enhance also the heavy flavour physics capability of ATLAS and CMS through, in particular, improvements to the tracking and muon detectors and triggers. Table 5 gives the estimated accumulated luminosity during each run period for LHCb, ATLAS and CMS. The Belle II experiment at the SuperKEKB e^+e^- collider in Japan will also accumulate large samples of beauty and charm hadrons, and pursue an extensive programme of flavour physics measurements with complementary sensitivity to the LHC experiments [39]. Indicative

[3]The pileup subtraction performed in this plot was carried out using a pileup contamination estimate that was effectively averaged over all rapidities. From a particle-level study performed independently for this report, it appears that certain detailed features would change if one takes into account the pileup's rapidity dependence: the impact of the extended tracking on the central jet rate would largely be eliminated; and the very large jet rate at $|\eta| \simeq 3.0$ for the Phase I and Phase II Conf3, $\langle \mathrm{PU} \rangle = 140$ curves would be somewhat reduced, though it remains very substantially above the 0-pileup rate. The main conclusion from the plot is, however, confirmed in the particle-level study, i.e. extended tracking does significantly reduce the impact of high pileup on the forward-jet rate.

estimates for the amounts of data expected to be recorded by Belle II by the end of each period are also given. Note that the relative efficiencies for particular modes of interest can vary dramatically between experiments at e^+e^- and hadron colliders, so that a direct comparison of integrated luminosities is not useful.

Table 5: Estimated integrated luminosities that will be recorded by ATLAS & CMS, LHCb during the different LHC runs. The approximate amount of e^+e^- collision data that is expected to be recorded by Belle II by the end of each period is also given (the $\sim 1\,\mathrm{ab}^{-1}$ of data recorded by Belle prior to the KEKB upgrade is not included).

	LHC era			HL-LHC era	
	Run 1 (2010–12)	Run 2 (2015–17)	Run 3 (2019–21)	Run 4 (2024–26)	Run 5+ (2028–30+)
ATLAS & CMS	$25\,\mathrm{fb}^{-1}$	$100\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$	$\longrightarrow$	$3000\,\mathrm{fb}^{-1}$
LHCb	$3\,\mathrm{fb}^{-1}$	$8\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$46\,\mathrm{fb}^{-1}$	$100\,\mathrm{fb}^{-1}$
Belle II	—	$0.5\,\mathrm{ab}^{-1}$	$25\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$	—

Although a very wide range of interesting observables of the b and c hadrons, the τ lepton and the top quark can be studied with the HL-LHC, a small subset has been chosen to provide an illustrative range of sensitivity studies. These are each briefly described below.

7.1 Selected key observables

7.1.1 The ratio of branching fractions of the rare B decays $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$

The dimuon decays of B mesons are highly suppressed and have excellent sensitivity to physics beyond the SM. The SM predictions of their branching fractions are known to about 10% precision, with further improvement possible as lattice QCD calculations are refined [40]. Results from CMS [41] and LHCb [42] based on LHC Run 1 data have provided the first observation of the $B_s^0 \to \mu^+\mu^-$ decay, and the corresponding branching fraction is now known to about 25% precision. ATLAS have also presented results of searches for B meson decays to dimuons [43], but do not currently have the mass resolution to distinguish the B^0 and B_s^0 signals.

In the HL-LHC era, one of the most interesting observables will be the relative branching fractions of the B^0 and B_s^0 dimuon decays. This will be measured by CMS and LHCb, and also by ATLAS if the improvement in mass resolution necessary to separate the B^0 and B_s^0 peaks can be achieved (sensitivity studies from ATLAS are not available at this time). When large $B_s^0 \to \mu^+\mu^-$ samples are available, it will also be possible to go beyond branching fraction measurements and use additional handles on possible new physics contributions, such as the effective lifetime.

The sensitivities quoted in Table 6 are extrapolated from current results, assuming the SM value of the ratio of branching fractions. For the LHCb extrapolation [44], the measured branching fractions are uncorrelated, to a good approximation, so the uncertainty on the ratio is obtained trivially. In the case of CMS [45], upgrades to the detector are expected that will improve the mass resolution and hence the separation of the B^0 and B_s^0 peaks. The extrapolation also takes into account some expected loss of efficiency due to the high pile-up conditions, and assumes that the trigger thresholds and analysis procedures will remain the same as those used for existing data. Systematic uncertainties which arise, for example, from the lack of knowledge of background decay modes containing misidentified hadrons, are expected to be controlled to better than the level of statistical precision.

7.1.2 Angular observables in the decay $B^0 \to K^{*0}\mu^+\mu^-$

The $B^0 \to K^{*0}\mu^+\mu^-$ decays provide a wide range of angular observables, many of which are predicted with low theoretical uncertainty in the SM. These observables probe the helicity structure of the SM and can be used not only to search for new physics effects, but – if observed – to understand which operators are affected by the new physics. The latest results from LHCb [46, 47] show an interesting tension with the SM predictions. ATLAS [48] and CMS [49] have both also reported studies of $B^0 \to K^{*0}\mu^+\mu^-$ decays. One of the many interesting observables that can be studied in these decays is the point where the forward-backward asymmetry as a function of the dimuon invariant mass-squared, q^2, crosses zero, $q_0^2\ A_{\rm FB}(K^{*0}\mu^+\mu^-)$. This will be determined by ATLAS, CMS and LHCb in the HL-LHC era. Sensitivity studies from ATLAS and CMS are, however, not available. Belle II will also be able to determine this parameter

The expected sensitivities presented in Table 6 are based on extrapolating the yields of the current measurements while assuming the SM distribution of $A_{\rm FB}$ as a function of q^2. In the Belle II case [39], the expected sensitivities are for $K^*\ell^+\ell^-$, where $\ell = e$ or μ and K^* includes both K^{*0} and K^{*+} mesons. LHCb can also study the $K^{*+}\mu^+\mu^-$ channel, but treats it separately, in order to determine the so-called isospin asymmetry [50].

7.1.3 *CP* violation in B_s^0 oscillations: $\phi_s(B_s^0 \to J/\psi\phi)$ and $\phi_s(B_s^0 \to \phi\phi)$

The *CP* violating phase in B_s^0 oscillations, labelled ϕ_s or $-2\beta_s$, is very small in the SM ($\phi_s^{\rm SM} = -0.0364 \pm 0.0016$ rad [51]) but can be enhanced in new physics models. The benchmark channel for the measurement is $B_s^0 \to J/\psi\phi$, which has been used by LHCb [52] and ATLAS [53] to measure ϕ_s. CMS have also performed an untagged analysis of $B_s^0 \to J/\psi\phi$ [54]. Significant improvement in the precision is warranted not only in this channel, but also in the loop-dominated $B_s^0 \to \phi\phi$ decay (a first measurement with this channel has been performed by LHCb [55]).

All of ATLAS, CMS and LHCb expect to continue studies of $B_s^0 \to J/\psi\phi$ in the HL-LHC era. ATLAS have performed a detailed analysis [56] extrapolating from existing data and taking into account the increased cross-sections for signal and background at $\sqrt{s} = 14$ TeV, improvements in the decay time resolution arising from upgrades of the inner tracker, and the impact of the increased pile-up on resolution parameters. The effective tagging efficiency is assumed to remain the same as in existing data, and the measurement is assumed to remain statistically limited as the main systematic uncertainties is expected to scale with increased data samples. Another key parameter which affects the sensitivity is the $p_{\rm T}$ threshold used in the trigger for the online event selection.

The sensitivity projections for $B_s^0 \to J/\psi\phi$ at LHCb [44] assume similar performance to the current detector, with a modest improvement in the effective tagging efficiency. The systematic uncertainty in the current analysis is at the level of 0.01 rad, and is expected to be reduced further as larger data samples are accumulated. The projections for the hadronically-triggered $B_s^0 \to \phi\phi$ mode include also a factor due to the improved trigger efficiency expected with the high-level trigger of the LHCb upgrade [44]. Similar sensitivity will also be achieved for the $B_s^0 \to K^{*0}\bar{K}^{*0}$ mode, which probes similar physics.

Table 6 summarizes the perspectives on the mesurement of the angle ϕ_s at LHC and HL-LHC.

7.1.4 The CKM unitarity triangle angle γ from $B \to DK$ decays

The angle γ of the CKM unitarity triangle, when determined from decays such as $B \to DK$ that contain only tree amplitudes, provides a SM benchmark measurement of *CP* violation with negligible theoretical uncertainty [57]. Its precision determination is therefore one of the main goals of current and future flavour physics experiments including LHCb and Belle II. The latest results from LHCb [58, 59] give uncertainties of $\pm 12°$, while Belle obtain $\pm 15°$ [60]. Improvements in the determination of γ will be a major goal for LHCb. This includes not only improving the precision of the observables that are currently used in the combinations, but also adding additional channels that may make significant contributions when sufficiently large data samples are available. The expected sensitivities for LHCb and Belle II presented in Table 6 are based on extrapolating from current measurements. It is expected that it will be possible to control systematic uncertainties at better than the 1° level in both experiments.

7.1.5 CP violation in the charm sector: $A_\Gamma(D^0 \to K^+K^-)$

The charm system provides excellent opportunities to search for new physics affecting flavour-changing neutral-currents of up-type quarks. One of the most interesting observables being pursued by experiments is referred to as A_Γ and quantifies the difference in the inverse effective lifetimes between D^0 and $\bar{D}^0$ decays to CP eigenstates such as K^+K^- and $\pi^+\pi^-$. A non-zero value of A_Γ would point to CP violation in charm mixing, which is expected to be at the $\mathcal{O}(10^{-4})$ level in the SM. A difference between $A_\Gamma(D^0 \to K^+K^-)$ and $A_\Gamma(D^0 \to \pi^+\pi^-)$ would indicate direct CP violation.

The most precise measurements of A_Γ to date have recently been presented at Charm 2013 [61]. Based on the 2011 data, for the first time LHCb measures A_Γ separately for the K^+K^- and $\pi^+\pi^-$ final states, and reaches a precision of $\sim 6 \times 10^{-4}$ ($\sim 11 \times 10^{-4}$) in the K^+K^- ($\pi^+\pi^-$) channel. This represents an improvement of more than a factor of three compared to the previous best measurement from Belle [62].

The expected sensitivities for these observables are presented in Table 6, and they are based on extrapolating the uncertainties of the current measurements. The Belle II projections include estimates of the limiting systematic uncertainties. The LHCb projections [44] include statistical uncertainties only. The systematic uncertainties in the current analysis are at the level of 1×10^{-4}, and are evaluated in data. Careful studies will be needed to control systematic uncertainties at very low level, and this can be achieved with direct precise measurements of detector effects possible with the large data samples that will be available with HL-LHC.

Table 6: Expected sensitivities that can be achieved on key heavy flavour physics observables, using the total integrated luminosity recorded until the end of each LHC run period. Discussion of systematic uncertainties is given in the text. Uncertainties on ϕ_s are given in radians. The values for flavour-changing neutral-current top decays are expected 95% confidence level upper limits in the absence of signal.

		LHC era			HL-LHC era	
		Run 1	Run 2	Run 3	Run 4	Run 5+
$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s^0\to\mu^+\mu^-)}$	CMS	> 100%	71%	47%	...	21%
	LHCb	220%	110%	60%	40%	28%
$q_0^2\ A_{\rm FB}(K^{*0}\mu^+\mu^-)$	LHCb	10%	5%	2.8%	1.9%	1.3%
	Belle II	—	50%	7%	5%	—
$\phi_s(B_s^0 \to J/\psi\phi)$	ATLAS	0.11	0.05–0.07	0.04–0.05	...	0.020
	LHCb	0.05	0.025	0.013	0.009	0.006
$\phi_s(B_s^0 \to \phi\phi)$	LHCb	0.18	0.12	0.04	0.026	0.017
γ	LHCb	7°	4°	1.7°	1.1°	0.7°
	Belle II	—	11°	2°	1.5°	—
$A_\Gamma(D^0 \to K^+K^-)$	LHCb	3.4×10^{-4}	2.2×10^{-4}	0.9×10^{-4}	0.5×10^{-4}	0.3×10^{-4}
	Belle II	—	18×10^{-4}	$4–6 \times 10^{-4}$	$3–5 \times 10^{-4}$	—
$t \to qZ$	ATLAS	...	...	23×10^{-5}	...	$4.1–7.2 \times 10^{-5}$
	CMS	100×10^{-5}	...	27×10^{-5}	...	10×10^{-5}
$t \to q\gamma$	ATLAS	...	...	7.8×10^{-5}	...	$1.3–2.5 \times 10^{-5}$

7.1.6 Flavour-changing neutral-current top decays

The large samples of top quarks produced at ATLAS and CMS enable increasingly precise searches for flavour-changing neutral-current decays, $t \to qZ$, $t \to q\gamma$, $t \to qg$ and $t \to qH$ (where $q = u, c$). These have unobservably small ($< 10^{-12}$) branching fractions in the SM, but can be significantly enhanced in various new physics models.

Results on $t \to qZ$ on subsets of the Run 1 data have been presented by ATLAS [63] and CMS [64, 65], and CMS have in addition set limits on $t \to qg$ [66]. ATLAS have also presented estimates of the sensitivity in the HL-LHC era to both $t \to qZ$ and $t \to q\gamma$ channels [31], as well as $t \to cH$ [67], where ranges of potential upper limits that can be reached in the absence of signal are given, depending on the analysis techniques used. CMS have studied the sensitivity to $t \to qZ$ [68]. Table 6 presents the expected 95% confidence level upper limits on the analysed branching fractions in absence of signal.

8 Heavy Ion physics prospects at the HL-LHC

The programme of the ALICE, ATLAS, CMS and LHCb[4] experiments for the heavy-ion campaigns of Run 3 and Run 4 at the LHC is outlined in this section. As for the case of Heavy Flavour, the period starting after LS2 is considered, for two main reasons: a) the prospected substantial increase of the LHC instantaneous luminosity for ion collisions; b) the major detector upgrades of the ALICE, ATLAS, CMS and LHCb during LS2. Both aspects will open new perspectives for heavy-ion measurements.

The goal of the experiments is to integrate, for Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV, an integrated luminosity $L_{\rm int}$ exceeding[5] 10 nb^{-1} after LS2. This represents an increase by an order of magnitude with respect to the expectation for Run 2 (between LS1 and LS2). In the case of the ALICE experiment, the upgrade of the detector read-out capabilities will allow for the recording of all interactions with a minimum bias trigger, up to a rate of 50 kHz. This will allow for an increase in the data sample by two orders of magnitude, which is crucial for the main points of the ALICE upgrade programme, as illustrated below.

In the second generation of LHC heavy-ion studies following LS2, the investigation of strongly-interacting matter at high temperature and energy density will focus on rare probes, and on the study of their coupling with the medium and of their hadronization processes. These include heavy-flavour particles, quarkonium states, jets and their correlations with other probes, as well as real and virtual photons. The collaborations are developing second-generation heavy-ion physics programmes with a high level of complementarity, which will allow us to exploit at best the increased LHC luminosity for ion beams (see [69, 70, 71, 72, 73]).

The main items of these programmes are listed in the following. Most of them will be addressed by all experiments, with focus on different kinematic regions.

Heavy flavour: precise characterization of the quark mass dependence of in-medium parton energy loss; study of the transport and possible thermalization of heavy quarks in the medium; study of heavy quark hadronization mechanisms in a partonic environment. These require measurements of the production and azimuthal anisotropy of several charm and beauty hadron species, over a broad momentum range, as well as of b-tagged jets. ALICE will focus mainly on the low-momentum region, down to zero $p_{\rm T}$, and on reconstruction of several heavy flavour hadron species. ATLAS and CMS will focus mainly on b-tagged jets and B-decay J/ψ. LHCb will contribute with precise measurements of initial-state effects in p–Pb collisions.

Quarkonia: study of quarkonium dissociation and possible regeneration as probes of deconfinement and of the medium temperature. ALICE will carry out precise measurements, starting from zero $p_{\rm T}$, of J/ψ yields and azimuthal anisotropy, ψ' and Υ yields, at both central and forward rapidity. ATLAS and CMS will carry out precise multi-differential measurements of the Υ, Υ', Υ'' states to map the dependencies of their suppression pattern. They will also extend charmonium measurements to high transverse momentum. LHCb will contribute with precise measurements of initial-state effects in p–Pb collisions.

Jets: detailed characterization of the in-medium parton energy loss mechanism, that provides both a testing ground for the multi-particle aspects of QCD and a probe of the QGP density. The relevant observables are: jet structure and di-jet imbalance at TeV energies, b-tagged jets and jet correlations

[4] The LHCb experiment will participate in the proton–nucleus runs.

[5] For example, the ALICE upgrade physics programme requires 10 nb^{-1} at the nominal barrel magnetic field of 0.5 T and 3 nb^{-1} at reduced field of 0.2 T [69].

with photons and Z^0 bosons (unaffected by the presence of a QCD medium). These studies are crucial to address the flavour dependence of the parton energy loss and will be the main focus of ATLAS and CMS, which have unique high-p_T and triggering capabilities. ALICE will complement them in the low-momentum region, and carry out measurements the flavour dependence of medium-modified fragmentation functions using light flavour, strange and charm hadrons reconstructed within jets.

Low-mass dileptons and thermal photons: these observables are sensitive to the initial temperature and the equation of state of the medium, as well as to the chiral nature of the phase transition. The study will be carried out by ALICE, which will strengthen its unique very efficient electron and muon reconstruction capabilities down to almost zero p_T, as well as the read-out capabilities for recording a very high statistics minimum-bias sample.

Figures 12 and 13 present the projected performance in Pb–Pb collisions ($L_\mathrm{int} = 10$ nb^{-1}) for a selection of benchmark measurements. Several other studies are reported in [69, 74, 73].

The left-hand panel of Fig. 12 shows the projected ALICE performance for the measurement of the nuclear modification factors of charm (via $D^0 \to K^-\pi^+$) and beauty (via non-prompt $J/\psi \to e^+e^-$). The precision of the measurement and the broad p_T coverage will allow for a detailed characterization of the quark mass dependence of parton energy loss and, in conjunction with the elliptic flow measurements, of the diffusion coefficients for c and b quarks in the medium. The other investigated measurements include Λ_c and D_s reconstruction, beauty via non-prompt D mesons and via b-tagged jets.

The right-hand panel of Fig. 12 shows the projected ALICE performance on the ratio of the nuclear modification factors of J/ψ and ψ', integrated from $p_\mathrm{T} = 0$, as a function of Pb–Pb collision centrality [74]. The measurement will provide discrimination between two models that describe the production of charmonium in terms of the competing effects of dissociation and regeneration in a deconfined medium. In the bottomonium sector, the large expected yields (e.g. $2.7 \cdot 10^5$ Υ, $4 \cdot 10^4$ Υ', $7 \cdot 10^3$ Υ'' in CMS with 10 nb^{-1} [73]) will allow for precise measurements to map the sequential suppression pattern as a function of p_T, rapidity, collision centrality and in-medium path-length.

The left-hand panel of Fig. 13 shows the projected CMS performance for the study of jet–Z^0 momentum imbalance [73]. Jet–Z^0 (and jet–photon) events constitute a unique tool to study the in-medium interactions of hard partons, because the boson escapes unaffected by the strongly-interacting medium and so provides a measure of the initial energy of the jet. The figure shows the momentum imbalance ratio $x_{jZ} = p_\mathrm{T}^{jet}/p_\mathrm{T}^{Z} \approx p_\mathrm{T}^{jet,measured}/p_\mathrm{T}^{jet,produced}$. A similarly good performance is expected for jet–photon, jet–jet and b-jet–b-jet imbalance.

The right-hand panel of Fig. 13 shows the projected ALICE performance for the measurement of the low-mass dielectron spectrum in central Pb–Pb collisions. This measurement will be carried out in dedicated run of 3 nb^{-1} with a reduced value of the central barrel magnetic field (0.2 T), in order to maximize the acceptance for low-p_T electrons. The figures shows statistical and systematic uncertainties on the mass spectrum after background subtraction, with the two signal components from resonances (the ρ meson spectral function is sensitive to chiral symmetry restoration) and thermal dileptons (the $\gamma \to e^+e^-$ continuum is sensitive to the temperature of the system). The estimated statistical uncertainty on the slope of the continuum is of about 10%.

All experiments stress the importance of having pp collisions at the Pb–Pb energy $\sqrt{s} = 5.5$ TeV during Runs 3 and 4. The availability of reference data at the same nucleon–nucleon collision energy as for Pb–Pb is crucial for most of the measurements. For heavy flavour and quarkonia production, the energy scaling or interpolation of the reference introduces substantial systematic uncertainties, in particular in the low momentum region, where scaling factors from perturbative QCD calculations are not robust. For jet measurements, several sources of systematic uncertainty, related to the jet flavour composition and the jet energy scale corrections, cancel to a large extent only in the comparison of Pb–Pb and pp observables at the same nucleon–nucleon collision energy. The following considerations were used to define the requirements in terms of integrated luminosity for pp collisions at $\sqrt{s} = 5.5$ TeV.

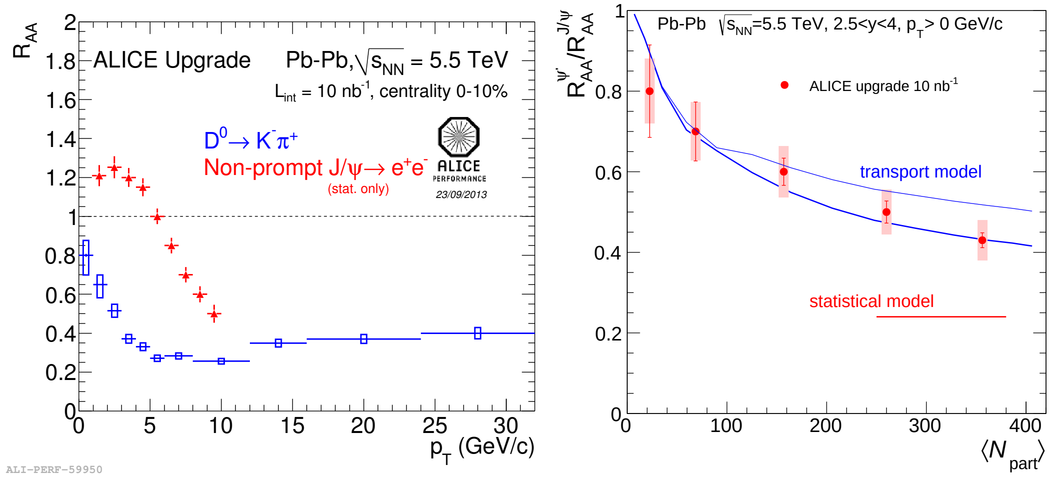

Figure 12: Left: ALICE performance on the nuclear modification factors of charm and beauty. Right: ALICE performance on the ratio of the nuclear modification factors of J/ψ and ψ'. See text for details.

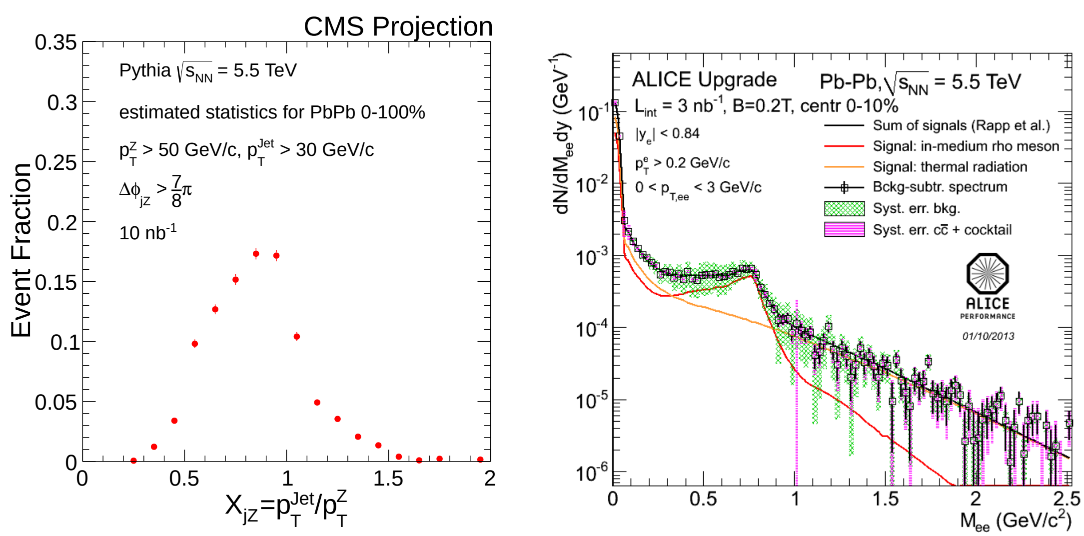

Figure 13: Left: CMS performance on the jet–Z^0 transverse momentum imbalance. Right: ALICE performance on the low-mass dielectron spectrum. See text for details.

For low-p_{T} and low signal-to-background measurements (charm and charmonia, di-leptons), the required pp integrated luminosity is of a few pb^{-1}, to make the pp statistical uncertainty subdominant with respect the one from 10 nb^{-1} of Pb–Pb data.

For high-p_{T} and low-background measurements (e.g. jets), the requirement is more demanding, in order to compensate for the largely increased yields in Pb–Pb, that scale with the number of binary nucleon–nucleon collisions, i.e. up to 1600 in central collisions. ATLAS and CMS studies suggest that a pp sample of about 300 pb^{-1} would be needed, in order to match the signal statistics expected in 10 nb^{-1} of Pb–Pb data.

A high luminosity p–Pb run has been requested by the experiments for the period after LS2. Proton–nucleus collisions provide a crucial reference to study initial-state effects on hard probes production and to single-out the hot medium effects in nucleus–nucleus collisions. Further motivation is provided by the intriguing results from the recent p–Pb run — namely, the observation, in high multiplicity events, of several effects that resemble those that in Pb–Pb collisions are attributed to the collective expansion of the system.

Finally, the experiments suggest to keep the possibility open for high-luminosity run with light ions (e.g. p–Ar and Ar–Ar), with a priority that will be defined on the basis of the results from the Pb–Pb and p–Pb samples collected in Run 2.

9 Conclusion

In this report, we have summarized the studies presented on behalf of the "Physics Goals and Performance Reach" preparatory group during the ECFA HL-LHC workshop that occurred 1-3 October 2013 in Aix-les-Baines, France. This workshop provided a focal point for the LHC experiments to work together to establish HL-LHC physics goals and assess detector performance. The resultant presentations explored the HL-LHC physics programme as outlined by the *Update of the European Strategy for Particle Physics*.

A central component of this program is to perform precision measurements of the properties of the 125 GeV Higgs boson and compare these to the predictions of the SM. This has been an area of significant progress. The ATLAS and CMS experiments have validated their earlier projections, and have presented their updated results under consistent assumptions. Both experiments project comparable precision with an estimated uncertainty of a few % for many of the properties investigated demonstrating that with an integrated luminosity of 3000 fb^{-1} the HL-LHC is a very capable precision Higgs physics machine. To fully benefit from the potential of high luminosity, however, progress will also be needed in the accuracy of theoretical calculations and precision Standard Model measurements.

The studies performed also demonstrate that HL-LHC is at the same time a unique discovery machine. In addition to being sensitive to BSM physics via deviations from the SM in the Higgs sector, including the possibility of additional Higgs bosons, with HL-LHC, ATLAS and CMS will continue the direct search for other new particles that could shed light on one or more of the open questions in HEP and cosmology such as the stabilisation of the Higgs mass or the nature of dark matter. ATLAS and CMS performed studies that illustrate the importance of the large dataset that HL-LHC will provide in making such a discovery in cases where the new physics is produced with a small cross section, small visible branching fraction, or experimentally challenging kinematics.

The HL-LHC also provides exciting discovery potential through precision studies of the flavour sector. In particular, updated sensitivity studies from LHCb demonstrate that it will be the leading experiment for a wide range of important observables concerning rare decays and CP violation in charm and beauty hadrons. This capability is complemented by sensitivity from ATLAS and CMS in particular channels triggered by dimuon signatures, as well as in studies of the top quark. Lastly, in addition to high luminosity proton operation, the HL-LHC will provide a substantial integrated luminosity of heavy ion collisions. In the studies presented at this ECFA workshop, the ATLAS, CMS and ALICE experiments demonstrated the impact that a dataset of 10 nb^{-1} of Pb–Pb collisions will have on the precision of a variety of physics observables that will be used to further our understanding of the quark-gluon plasma.

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