

# Experiments: Session 1 Summary

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## Abstract

The European Strategy for Particle Physics (ESPP) has recently recommended the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors. Given this, the physics motivation for the upgrades is outlined. The limitations of the present detectors given the proposed medium term upgrades are recalled. The proposed HL-LHC performance parameters together with these detector limitations motivate the need for major upgrades. The required detector upgrades as foreseen at present are briefly sketched. Despite the upgrades the HL-LHC parameter space remains challenging and possible mitigation measures are discussed.

The requirements of ALICE and LHCb in the HL-LHC era are presented. Finally an attempt is made to sketch the long-term LHC schedule given the known constraints in the lead-up to the HL-LHC upgrades.

## INTRODUCTION

The first session of the RLIUP workshop was devoted to the experiments and the long-term schedule. The main goals were to: motivate the HL-LHC physics goals; examine the limits of the present detectors and to motivate the need for major experiment upgrades; to examine the challenges facing the proposed upgrades; and to attempt to sketch out a long-term post LS1 schedule taking into account the disparate requirements of machine and experiments.

The following presentations were given in the session.

- **Highlights from ECFA** (Austin Ball): Selection of highlights and topics of discussion from the ECFA HL-LHC Experiments Workshop (1-3 Oct) [1] which seemed (to the speaker) to be relevant to the workshop.
- **Physics landscape** (Fabiola Gianotti): The “physics landscape” from  $30 \text{ fb}^{-1}$  to  $300 \text{ fb}^{-1}$  to  $3000 \text{ fb}^{-1}$  and thus the physics potential of the HL-LHC.
- **Detector Limits** (Beniamino di Girolamo) The need to upgrade certain key detector elements of ATLAS and CMS for any programme beyond  $300 \text{ fb}^{-1}$ .
- **Performance parameters - experiments perspective** (Didier Contardo) The role of the upgrade changes to experiments in mitigating the high rate, high pile-up conditions of HL-LHC needed to reach the  $3000 \text{ fb}^{-1}$  target in a reasonable time-scale. The prospects for pile-up mitigation by tuning the luminous region were considered.
- **Plans and physics outlook for non-high luminosity experiments until and after LS3** (Richard Jacobs-

son) Physics motivation and realisation of the LHCb upgrade, plus the forward physics and ALICE proton-proton programmes.

- **Post LS1 schedule** (Mike Lamont) An attempt to fit the disparate requirements for operation and upgrade into a workable schedule, taking into account some constraints from accelerator consolidation and upgrade options.

The following summaries naturally draw heavily on the above presentations.

## REPORT FROM EFCA HL-LHC EXPERIMENTS WORKSHOP

The motivation of the workshop held 1-3 October 2013 in Aix-les-Bains was to address the implications of the ESPP document adopted by Council in May 2013.

A key passage from the document states:

*“The discovery of the Higgs boson is the start of a major programme of work to measure this particles properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier.”*

*The LHC is in a unique position to pursue this 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.”*

The strategy explicitly recommends a  $3 \text{ ab}^{-1}$  target. There is preliminary approval for the HL-LHC programme and it may assumed that the machine and experiments may proceed with serious consideration of the options. Further evaluation of: the physics reach; the technical feasibility for experiments; and machine time-line and cost estimates is needed for formal approval by Research Board, Council, Funding Agencies etc.

Given this, the stated objective of the workshop was to help define the upgraded HL-LHC detectors and physics program for many years to come. In particular:

- Develop a common approach to the HL-LHC program; identify synergies and possible common efforts;
- Provide a consistent presentation of physics goals, detector requirements and technology R&D needed, also accelerator interfaces, long shutdown constraints, and costing methods;

- Identify areas for further joint HL-LHC workshops;
- Provide a summary report to ECFA.

The outline conclusion was that 3 to 4 years of R&D followed by 5 to 6 years of construction are needed to complete the largest upgrades. R&D needs proper resources immediately. Long shutdown durations and schedule need further definition and consensus, especially to define clear profiles of resource needs versus time.

More specific conclusions included:

- Experience and expertise from building and operating current experiment systems (including power, cooling, gas, beam-pipes, survey, magnets and cryogenics, planning, coordination etc.) must be retained and transmitted to those developing new systems.
- Modelling of radiation levels and radiation damage is clearly important, and in some cases more results are needed to identify where upgrades are required. Many systems would benefit from more common facilities for irradiations and beam tests as well as greater co-ordination for use of those already available. Tools for dealing with the very challenging environments at and after LS3 should be developed in common with the machine and realistic timescales presented for interventions that take full account of the overriding ALARA principle.
- In some areas common standards and a common CERN interface with industries developing key technologies of importance to several experiments would be beneficial to minimize development and procurement costs. Forums exist for interaction between the machine and the experiments, but always helpful to update a larger forum, to be sure key parameters are widely understood across experiments.

## PHYSICS LANDSCAPE

Three main results from LHC Run 1 were noted.

- We have consolidated the Standard Model with a wealth of measurements at 7-8 TeV, including the rare, and very sensitive to New Physics,  $B_s \rightarrow \mu\mu$  decay. It works beautifully!
- We have completed the Standard Model with Higgs boson discovery after almost 100 years of theoretical and experimental efforts! It is a Higgs boson.
- We have NO evidence of New Physics.

Note that the last point implies that, if New Physics exists at the TeV scale and is discovered at  $\sqrt{s} = 14$  TeV in 2015 onwards, its spectrum is quite heavy and it will require a lot of luminosity (for example  $3000 \text{ fb}^{-1}$  at the HL-LHC) and high energy to study it in detail. This has implications for future machines, for example, the New Physics - if it's there - is most likely not accessible at a 0.5 TeV linear collider.

On one hand, the LHC results imply that the SM technically works up to scales much higher than the TeV scale,

and limits on new physics seriously challenge the simplest attempts (e.g. minimal SUSY) to fix its weaknesses. On the other hand there is strong evidence that the SM must be modified with the introduction of new particles and/or interactions at some energy scale to address fundamental outstanding questions, including the following.

- Why is the Higgs boson so light (so-called “naturalness” or “hierarchy” problem)?
- What is the nature of the matter-antimatter asymmetry in the Universe?
- Why is Gravity so weak? Are there additional (microscopic) dimensions responsible for its “dilution”?
- What is the nature of Dark Matter and Dark Energy?

In addition the Higgs sector (and the Electroweak Symmetry Breaking mechanism) is the experimentally less well-known component of the Standard Model. A lot of work is still needed, for example, to understand if it is the minimal mechanism predicted by the Standard Model or something more complex (e.g. more Higgs bosons).

The HL-LHC can do a lot to address these (and other) questions given that answers to some of the above questions may be expected at the TeV scale. The strong physics case for the HL-LHC with  $3000 \text{ fb}^{-1}$  comes from the imperative necessity of exploring this scale as much as we can with the highest energy facility we have today (note: no other planned machine, except a 100 TeV proton-proton collider, has a similar direct discovery potential). It is likely, and perhaps more importantly, that the HL-LHC will also tell us what are the right questions to ask and how to continue.

## DETECTOR LIMITS

The following potential limits to detector operations and possible mitigations were enumerated and explored.

- Limits from radiation damage and ageing (detectors)
- Limits from pile-up
- Limits from ageing (infrastructure)
- Limits, corrective measures, upgrades

**Radiation damage and ageing** The silicon detectors will hit one or both of these limits at around 400 to 500  $\text{fb}^{-1}$ . The outer layers will follow with the rough scaling described in the presentation, here a missing layer has catastrophic effects: the detector needs to be upgraded. The calorimetry is also affected at the same threshold of around 500  $\text{fb}^{-1}$ .

**Limits from pile-up** The current detectors have been designed for a pile-up of 25 events. We surprisingly managed in 2012 to live with up to around 37 pile-up events. In the medium term (Run 2 and Run 3) we aim to equip ourselves to be able to survive up to around 50 pile-up events (not all detectors) and it is clear we won't be able to stand 140 pile-up events without a substantial upgrade.

Following the approach of the machine the expected upgrades may be divided into: essential upgrades; and “Nice

to have” upgrades. There are also the “performance improving consolidations (PICs)” and essential consolidation for the experiments.

**ATLAS and CMS PICs** Most PICs are concentrated before LS3 (and some even before LS2).

- ATLAS Pixel and Strips: must act on the back-end electronics to avoid link saturations and processing performance bottlenecks.
- ATLAS Pixel: performed PIC on services to restore the detector to 99% and to cure link saturations.
- CMS Pixel: performed PIC to eliminate some bottlenecks.
- ATLAS is installing a 4<sup>th</sup> layer (IBL) to fight against the ageing of the actual innermost layer.
- CMS will install a new Pixel detector to fight against the ageing and the pile-up increase.

We are forced to act on our Pixel and Strip detectors. We will have higher instantaneous luminosity than design, up to a factor 2.5 to 3 and quickly. By the time we will be at the LS3 threshold the inner detectors start to reach the 400 to 500 fb<sup>-1</sup> limit and they will be dead soon after LS3. It takes a long time to change them and a one year stop is not enough: ATLAS has 100 M channels, 92 M are from the Pixel detector - imagine the services.

#### **Infrastructure improvements and ageing effects**

Many examples were given at Aix-les-Bains workshop, only a few were reported here. For example, the back-end electronics is today based on VME standards. It will get old, obsolete, and difficult to maintain. New trends in telecommunications and higher speeds requires pushing towards different standards (xTCA) and/or commodity PCs. More speed means more power needed which in turn means more cooling will be needed. The current infrastructure already needs upgrades.

**Limits, corrective measures, upgrades** Here we have touched just the most important detector limits. For some of them corrective actions can be made: replacement of cabling, electronics, pipes; additional links to overcome saturations. For some other we really need upgrades. The detector layers will simply become non-operational with catastrophic effects on the physics already between 400 and 700 fb<sup>-1</sup>.

The radiation damage effects would deserve a lot more information (different effects at different radii, etc.), but a ball park number is sufficient. The ageing of both detectors and infrastructure plays a role on top of the radiation and activation effects. The bottom line is that to go beyond 500 to 700 fb<sup>-1</sup> upgrades of detectors and infrastructure are needed.

## **PERFORMANCE PARAMETERS: EXPERIMENTS’ PERSPECTIVE**

The challenge for the detectors of high luminosity operation and the impact of increasing pile-up were summarized. The main aims of the ATLAS and CMS upgrades were summarized.

### *LS1*

Complete original detectors and consolidate operations for nominal LHC beam conditions:

- 13 to 14 TeV,  $1 \times 10^{34}$  Hz/cm<sup>2</sup>, average pile-up ( $\langle \text{PU} \rangle$ ) of 25

Prepare for start of upgrades for higher  $\langle \text{PU} \rangle$ .

### *LS1 through LS2*

Prepare the detectors to maintain physics performance for:

- $1.6 \times 10^{34}$  Hz/cm<sup>2</sup>,  $\langle \text{PU} \rangle$  of 40,  $\leq 200$  fb<sup>-1</sup> by LS2
- $2.5 \times 10^{34}$  Hz/cm<sup>2</sup>,  $\langle \text{PU} \rangle$  of 70,  $\leq 500$  fb<sup>-1</sup> by LS3

### *LS2 through LS3*

Prepare for up to:

- $5 \times 10^{34}$  Hz/cm<sup>2</sup> with levelling,  $\langle \text{PU} \rangle$  of 140, a total of around 3000 fb<sup>-1</sup> in 10 years or so of operation.

One should: recognize the possible need to replace sub-systems that no longer function due to radiation damage or ageing; and the challenge of maintaining physics performance at very high pile-up.

The planned Phase 1 and Phase 2 upgrades for both ATLAS and CMS were presented, including the ATLAS and CMS Trigger upgrades from Phase 1 to Phase 2 (this includes upgrades of calorimeter and muon detectors) and details of the pile-up effects visible throughout detector and readout chain. In summary both ATLAS and CMS are designing Run 4 detectors to cope with mean pile-up  $\langle \text{PU} \rangle$  of 140 (25 ns,  $5 \times 10^{34}$  Hz/cm<sup>2</sup>) with “tails” up to 200 events per crossing.

The experiments are very interested in methods (for example crab kissing) that allow tuning the extent of the luminous region in time and space, to reduce the pileup density in either z or t dimensions. Although a reduction in line density of 1.2 events/mm to 0.6 events/mm does not automatically open up a door to accepting twice the instantaneous luminosity (the mean pile-up also has bad effects - for example neutrals in the calorimeters). The potential to exploit fast timing to mitigate pile-up still requires substantial R&D (but there is a dedicated community pursuing this).

## *Performance parameters: conclusions*

Phase 1 upgrades are needed to maintain performance beyond  $1 \times 10^{34}$  Hz/cm<sup>2</sup>,  $\langle \text{PU} \rangle$  of 25. With these upgrades ATLAS and CMS will be able to operate with good performance up to  $\langle \text{PU} \rangle$  of 70 and integrated luminosity of up to 500 fb<sup>-1</sup>.

For Phase 2 HL-LHC physics program ATLAS and CMS are preparing for operation up to 140 to 200 pile-up but with luminosity levelling available depending on performance at high pile-up. Present simulations assume  $5 \times 10^{34}$  Hz/cm<sup>2</sup>, 140 pile-up with a Gaussian luminous region. A lot of work is ongoing to understand the limitations of Phase 1 detectors and the benefits of Phase 2 upgrades, and there is an important effort to develop and tune data reconstruction and physics analyses.

It is essential that Accelerator and Experiments investigate all opportunities to mitigate pile-up effects to fully profit from the LHC High Luminosity potential.

## **PLANS AND PHYSICS OUTLOOK FOR NON-HIGH LUMINOSITY EXPERIMENTS UNTIL AND AFTER LS3**

A concise run through of ALICE's and LHCb's physics motivation and upgrade plans was presented. Both ALICE and LHCb are going through major upgrades in LS2, which is assumed to be 18 months minimum. As regards the start of LS2, a delay of up to a year is advantageous. The scheduling of LS3 has little impact on ALICE and LHCb.

High luminosity programs of ALICE and LHCb are planned well into HL-LHC era. The principal targets being:

- ALICE 10 nb<sup>-1</sup> of ions, and proton-lead runs etc.
- ALICE proton-proton Run 2: continuous running at 13 TeV
- ALICE proton-proton Runs 3 and 4: concentrated periods at nucleon-nucleon equivalent energy to collect at least 6 pb<sup>-1</sup>. 1 to 2 months shadow data taking each year before the ion run.
- LHCb's target is 50 fb<sup>-1</sup>. Operation assumes levelled luminosities for efficiency and physics stability, and 25 ns proton-proton operation.
- (ATLAS and CMS have a preference for intermediate energy proton-proton reference data in short annual runs of a few days.)
- (Forward Physics in special conditions is assumed to be complete by end Run 3.)

## **POST LS1 SCHEDULE**

The constraints from experiments and machine were presented. Three main variations seemed possible.

Firstly a modified baseline would exclude the extended year end technical stop (EYETS), accept an extended LS2 of 18 months and keep the LS3 start in 2022. This is clearly

disfavours CMS, and given upgrade development and funding considerations unrealistically forces the pace.

The second option which was called "Slipped baseline+6" sees:

- a 19 week EYETS in 2017;
- an extended Run 2 to mid-2018;
- a 3 year Run 3 with LS3 starting in 2023.

The third option which called "Slipped baseline+12" sees:

- a EYETS in 2017;
- an extended Run 2 to end-2018;
- a slightly shortened Run 3 with LS3 starting in 2023.

A modified "Slipped baseline+6" was presented by Frederick Bordry and approved by CERN management and LHC experiments spokespersons and technical coordinators on Monday 2<sup>nd</sup> December 2013.

## **CONCLUSIONS**

- A strong physics case for the HL-LHC was presented.
- The detectors will have to work hard to maintain, and potentially improve, performance during Runs 2 and 3.
- The projected integrated luminosity in Runs 2 and 3 of around 300 fb<sup>-1</sup> will bring main sub-detectors near to the end of their lifetime.
- Major upgrades are required to deal with the planned luminosity of the HL-LHC era. There are considerable challenges, the lead-time is long, and work must start now.
- Foreseen pile-up and pile-up density make considerable demands on vertexing capabilities and any methods to alleviate these demands must be pursued.
- ALICE and LHCb have planned upgrades which will allow them to operate well into the HL-LHC era.
- An updated baseline schedule has been established.

## **REFERENCES**

- [1] ECFA High Luminosity LHC Experiments Workshop, <http://indico.cern.ch/conferenceDisplay.py?confId=252045>, Aix-les-Bains, October 2013.