LHC potential: Energy and Luminosity

W. J. Murray, CERN - STFC/RAL, Harwell Science and Innovation Campus, Didcot, Oxon., UK
On behalf of ALICE, ATLAS, CMS and LHCb

Abstract

The prospects for discovery physics in 2011 at LHC are reviewed. With 3.5 TeV per beam and 1 fb^{-1} per experiment the exclusion of the Standard Model Higgs boson by ATLAS and CMS combined is possible from 120 GeV up to over 600 GeV. Raising the beam energy to 4 TeV will gain 30% in the Higgs cross-section while for many other searches the gain is even larger.

THE SCENARIOS BEFORE US

The excellent performance of the LHC machine in its initial run in 2010 has encouraged speculation into the energy and integrated luminosity which might be achieved before the long shutdown. The influence on the physics potential of these is considered here, with the focus on ATLAS and CMS because the programmes of ALICE and LHCb are not as influenced by increasing energy, and their luminosity requirements do not press as hard upon the machine performance. In contrast, ATLAS and CMS essentially want as much luminosity as possible at the highest energy which can safely be reached.

The experiments are working remarkably well. The first 50 pb^{-1} delivered has been recorded with excellent efficiency and detector performance, and modelling are better than could have been hoped for. The detectors have reported the observation of all the fundamental SM particles (except the Higgs boson), usually with cross-sections and more measured too.

Searches for new physics have been made with sensitivity well beyond the Tevatron in many areas, which are changing and constraining our picture of the HEP world. So far most surprises in the p-p physics have been in details of QCD predictions, which are interesting but not paradigm-changing. The lead ion run produced good evidence that matter formed in these collisions is denser, hotter, and larger then that at RHIC, still having properties close to ideal liquid.

LHCB GOALS IN 2011

The principle requirement of LHCb is to run stably at about 2-3 10^{32} cm^{-2} s^{-1}, for as long as possible. Such a run should produce of order 1 fb^{-1} which will allow the possibility of discoveries in many channels. A few highlights are $B_s \rightarrow \mu\mu$, B_s CP-Violation (CPV) measurements, $B_s \rightarrow K^*\mu\mu$ studies, CPV search in the charm system and of course the unitary triangle angles, especially γ.

Each of these will have the worlds best sensitivity already with less than a third of the data discussed, and so there are exciting prospects for new physics. It should be noted that the beam energy plays a relatively minor role in those searches.

ALICE PROGRAMME

The instantaneous luminosity for p-p collisions in ALICE must be limited to 10^{30} cm^{-2} s^{-1}, (or possibly a little more), and the limitation of interpreting the Pb-Pb data often comes from the p-p statistics used for comparison. Therefore ALICE is interested in maximum stable running of p-p collisions. In addition, in pp collisions ALICE will be studying soft processes and charm production.

There is the need for a special p-p run of about 50M events with the beam energy reduced to 1.38 TeV to match the Pb-Pb energy per nucleon. This is to allow direct comparison between the two sorts of collisions, and will take a few days. There is no need to repeat this if the beam energy is changed to 4 TeV.

HIGH ENERGY FRONTIER

The main reason to wish to raise the beam energy is the increased production rate of heavy objects. This fractional increase is shown in Fig. 1 [1].

Standard Model

The 2011 data will be used to extend the suite of measurements, particularly in heavy gauge bosons, W and Z, and top quark studies. The production rate of these particles, and the quality of the detectors, gives good prospects for precise measurements such as the mass of the W boson, a key ingredient of the Standard Model. However it is top studies where the advantage of the LHC energy is most apparent. The first measurements of the top cross-section at LHC have been made on the first 3 pb^{-1} of data and have errors of order 40%. This helps to understand the gluon distribution inside the proton and hence better estimate the expected Higgs cross-section. The errors will be reduced enormously, but the top pair production would gain a 40% rate enhancement from 4 TeV operation, which would of course help greatly.

Another interesting subject in top physics is the production of single top quarks. This is an important test of the model and detectors and was only first reported by the Tevatron in 2009. The expected error in two different production modes [2] can be seen in Table 1. A dataset of

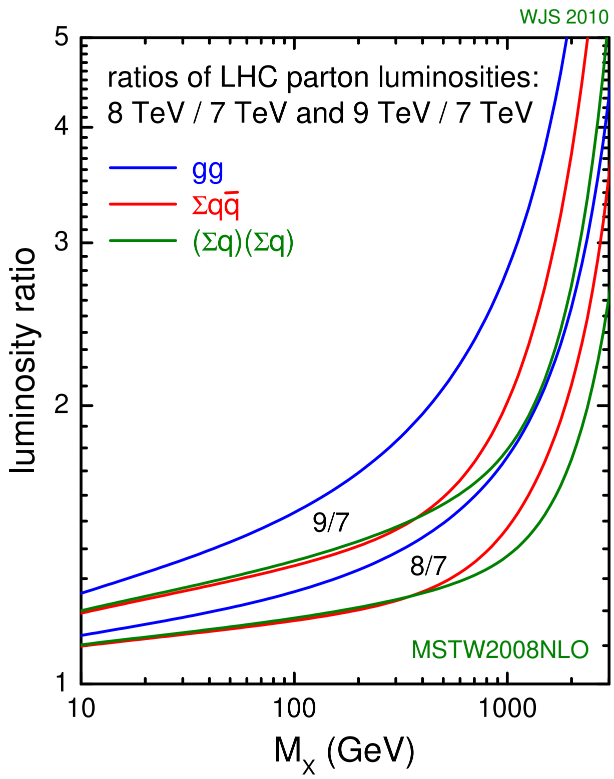

Figure 1: The effective gain in the rate of interactions from raising the centre-of-mass energy to 8 or 9 TeV.

around 5 fb^{-1} will be required to make meaningful measurements of the more difficult W plus top mode, but the signal rates in these channels increase 20-40% by raising the beam energy 0.5 TeV. This will be an important test of the experiments abilities to undertake searches for rare objects.

Table 1: Predicted error on the single top cross-section in two production modes as projected by the ATLAS experiment.

Mode	**1 fb^{-1}**	**5 fb^{-1}**
t-channel	32%	13%
Wt production	68%	32%

Exotics searches

There is a large range of exotic models which have been investigated with a large range of possible signatures. The example of the sensitivity of the search for a Z' [3] is used here. Figure 2 shows the sensitivity of the expected limits to the energy and luminosity available.

As the current data provides limits at just over 1 TeV, raising the E_{CMS} by 1 TeV roughly halves the amount of data required to set a new limit. For higher mass exotic scenarios, such as quark substructure or black hole production, the increased cross-section will in general give rise to

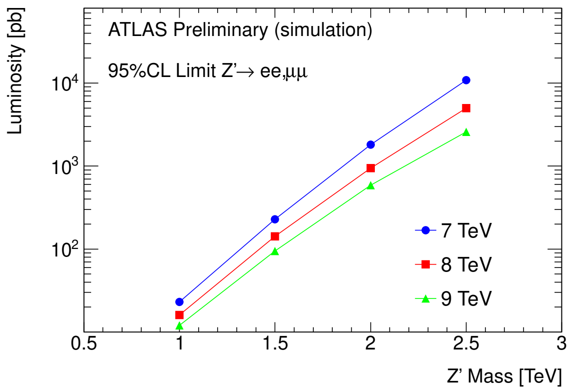

Figure 2: The estimated mass limits on a Z' from the ATLAS collaboration which can be obtained as a function of centre of mass energy and integrated luminosity.

a larger increase.

SUSY Searches

The search for supersymmetry is one of the key goals of LHC. CMS produced the first result on the total 2010 dataset [4], which placed limits on the CMSSM model using events with jets and missing energy. The results can be seen in Fig. 3. These are complemented by ATLAS results [5] showing that, in a very simplistic scenario where squarks and gluinos have the same mass, that mass scale is over 0.7 TeV.

The limits obtained with 35 pb^{-1} are a significant extension of the previous bounds. They represent a major constraint on SUSY model building, and are one of the most important LHC results to date. It can be seen that they approximately match the sensitivity which was estimated for 100 pb^{-1} [6]; there is a certain tendency to be conservative in making these estimations. ATLAS has provided some sensitivity projections showing how the discovery reach in the future evolves with energy and luminosity which are shown in Table 2. It can be seen that there is good discovery potential passing 1 TeV, provided 5 fb^{-1} at 7 TeV or 2 fb^{-1} at 8 TeV is available.

Table 2: The projected 5σ SUSY discovery ranges in TeV by ATLAS for different scenarios of energy and luminosity. Note that exclusion limits would be larger.

E$_{CMS}$	Integrated Luminosity			
	1 fb^{-1}	2 fb^{-1}	5 fb^{-1}	10 fb^{-1}
7 TeV	0.7	0.8	1.0	1.2
8 TeV	0.8	1.0	1.2	1.4
9 TeV	0.9	1.1	1.3	1.6

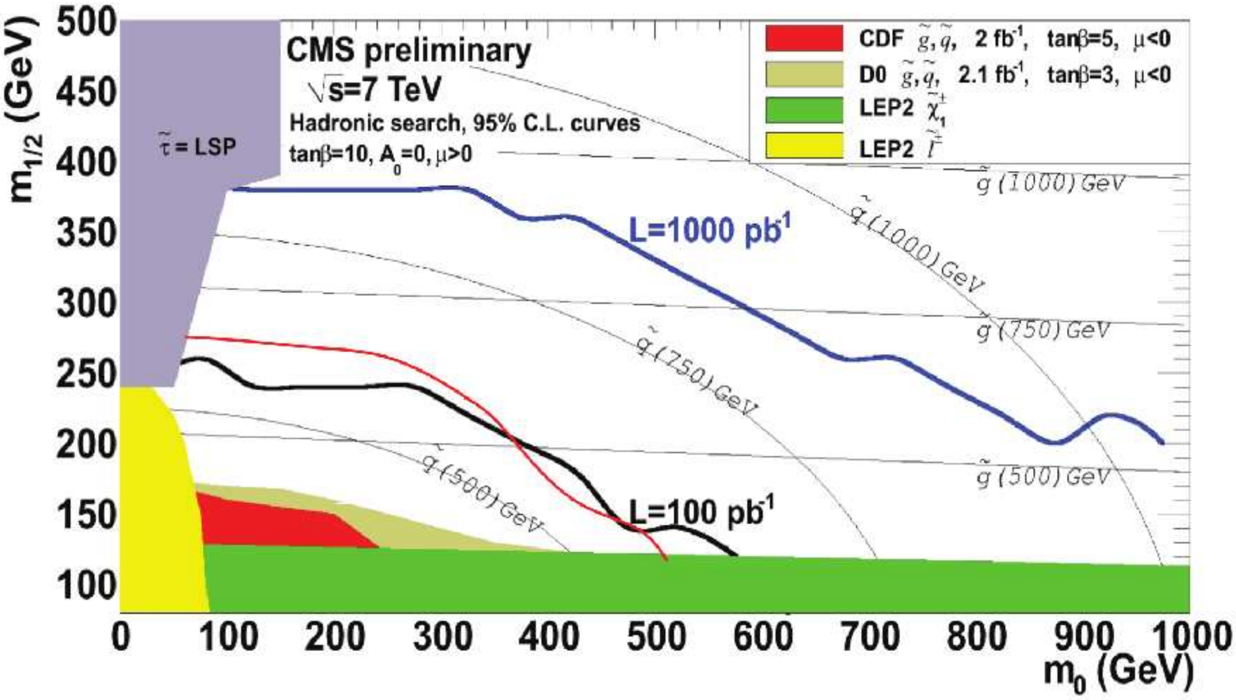

Figure 3: Limits on SUSY parameter space from the CMS experiment. The coloured (grey) lines show the expectations for sensitivity, calculated beforehand and the black is the actual limit obtained.

Higgs searches

A major goal for the current run is to maximise sensitivity to the Standard Model Higgs boson. The LEP [7] lower limit of 114.4 GeV has been augmented by the Tevatron [8] exclusion of the region from 158-175 GeV. The consistency of fits to the electroweak data [9] points to an upper limit of 185 GeV, but this limit assumes no additions to the Standard Model. The LHC will be sensitive to a SM-like Higgs from the LEP bound to over 600 GeV.

The search strategy depends upon the Higgs boson mass and hence its decay modes, but it depends critically on the production cross-section. The gain in this from increasing the beam energy is shown in Fig. 4 for various production modes, of which the gluon fusion is probably the most important. The gain can be seen to be 30% for a light Higgs boson in this channel on raising the energy to 8 TeV.

The sensitivity of ATLAS and CMS has been assessed by the collaborations [10], [11], and is very similar. The sensitivity of the CMS experiment, combining several decay modes, can be seen in Fig. 5. With a baseline run of 1 fb^{-1} at 7 TeV the two sigma sensitivity region covers 130 to 600 GeV. 5 fb^{-1} at 8 TeV allows three sigma evidence across the entire region investigated.

The gain from higher energy can be assessed in terms of the amount of integrated luminosity at 8 or 9 TeV giving the same Higgs boson sensitivity as 1 fb^{-1} at 7 TeV. This is done in Fig. 6. If can be seen that for a low-mass Higgs, favoured by the electroweak fits, 20% less data is needed to have the same sensitivity at 8 TeV.

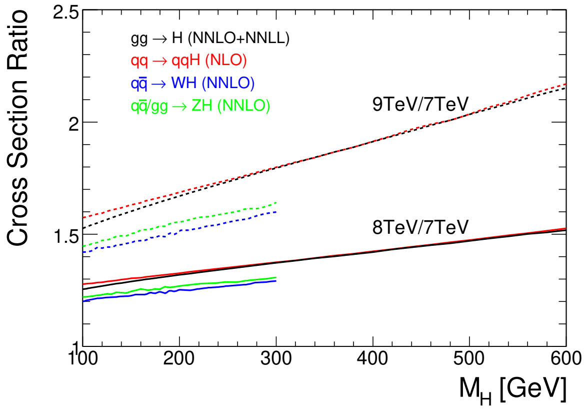

Figure 4: The ratio of the Higgs boson cross-section at 8 or 9 TeV to that at 7 TeV as a function of mass.

Table 3: Higgs mass range coverage at 8 TeV.

Mode	**2 fb^{-1}**	**5 fb^{-1}**	**10 fb^{-1}**
95% C.L.	Any	Any	Any
3σ	118-500+ GeV	Any	Any
5σ	130-200 GeV	120-500 GeV	Any

The Tevatron will continue to run through 2011 and produce new results. In the area of Higgs searches it will remain competitive for some while. The aim is to have 2.4 σ sensitivity for Higgs boson masses below 185 GeV. This is similar to the minimum sensitivity of the combined

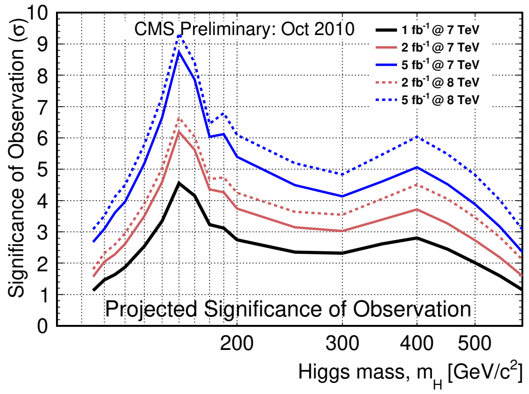

Figure 5: The significance of the expected observation of the Standard Model Higgs boson at 7 or 8 TeV for various assumed luminosity scenarios.

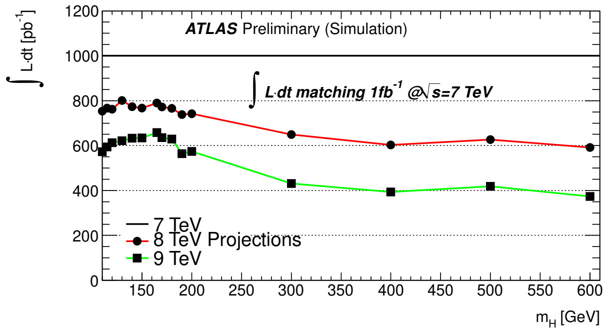

Figure 6: Effective luminosity, (see text)

LHC experiments given 2.5 fb^{-1} at 7 TeV each, however the LHC experiments would be more powerful everywhere other 115 GeV.

CONCLUSIONS

The LHC physics programme has got off to an excellent start in 2010, and we thank all the LHC team that have made it possible. There is an extremely exciting programme awaiting the LHC in 2011, in which we envisage two orders of magnitude more data and significant possibilities for a breakthrough in many areas. If the beam energy can be raised to 4 TeV there are important gains to be made. Some of these are itemised in Table 4.

Table 4: Gain from raising the E_{CMS} to 8 TeV for various analyses.

	Gain
SUSY	Needs 60% as much data
W′, Z′	Half the data needed
Black holes	Factor 5 increase in production
top	40% more top quarks
Higgs	Needs 80% as much data

It must be stressed that these projections have many assumptions. Typically the effects of pileup have not been completely included, which will degrade the results. However, the analyses used are generally rather simple and robust, and it is likely that the combined work of many highly motivated people will produced more finally-honed results.

Assuming 3.5 TeV beam energy, with about 2.5 fb^{-1} ATLAS and CMS can each independently exclude at 95% CL or more the Standard Model (SM) Higgs with every mass. With about 6 fb^{-1} ATLAS and CMS can each independently obtain at least a 3σ observation from the LEP bound at 114.4 GeV to about 500 GeV.

REFERENCES

[1] W.J. Stirling, private communication. `http://projects.hepforge.org/mstwpdf/`

[2] ATLAS collaboration, Aad, G. et al., "ATLAS top physics potential as a function of LHC integrated luminosity", ATL-PHYS-PUB-2011-004.

[3] ATLAS collaboration, Aad, G. et al., "Physics potential of Z' and W' searches with the ATLAS Detector as a function of the LHC center-of-mass energy", ATL-PHYS-PUB-2011-002.

[4] CMS collaboration, Khachatryan, Vardan et al., "Search for Supersymmetry in pp Collisions at 7 TeV in Events with Jets and Missing Transverse Energy", 2011, arXiv:1101.1628, submitted to Phys. Lett. B.

[5] ATLAS collaboration, Aad, G. et al., "Search for supersymmetry using final states with one lepton, jets, and missing transverse momentum with the ATLAS detector in $\sqrt{s}$ = 7 TeV pp", 2011, arXiv:1102.2357v2, accepted by Phys. Rev. Lett.

[6] The CMS collaboration, "The CMS physics reach for searches at 7 TeV" July 2010, CMS NOTE 2010/008.

[7] The LEP Higgs working group, 2003 Phys. Lett. B 565 61.

[8] CDF and D0 collaborations, "Combined CDF and D0 Upper Limits on Standard Model Higgs-Boson Production with up to 6.7 fb^{-1} of Data.", arXiv:1007.4587v1.

[9] The LEP Electro-weak working group, July 2010, http://lepewwg.web.cern.ch/LEPEWWG/

[10] The CMS collaboration, "Projected sensitivity for Standard Model Higgs boson searches at 7 and 8 TeV, and 1-10 fb^{-1}", `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIGStandardModelProjections`

[11] The ATLAS collaboration, "Further investigations of ATLAS Sensitivity to Higgs Boson Production in different assumed LHC scenarios", ATL-PHYS-PUB-2011-001.