ATLAS Status and Physics Potential: an Overview

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Abstract

The ATLAS detector, currently under construction and scheduled to operate at the CERN LHC, is described briefly in its essentials. The physics capability of the detector is described using selected channels, particularly for 'discovery' physics. The current status of construction is reviewed, along with the LHC schedule. Finally, the prospects for physics in the first two years of operation is highlighted.

1 Introduction

ATLAS, shown in Figure 1, is a general purpose detector for use at the CERN LHC.

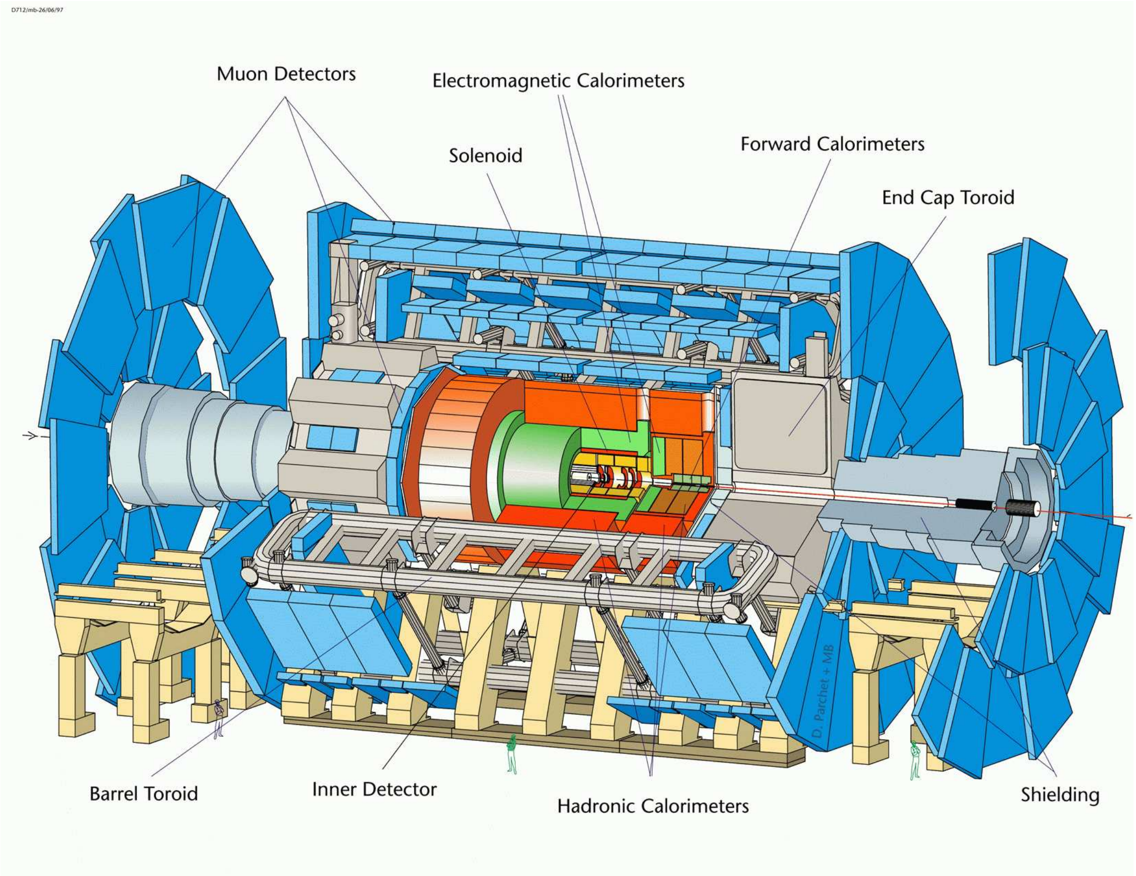

Figure 1: A schematic cutaway layout of the ATLAS detector

Currently under construction, its scale is formidable in all dimensions, time as well as space. A Letter of Intent was submitted to CERN in 1992 [1], and a Technical Proposal in 1994 [2]. At the time of writing the scheduled start-up of the machine is to be in 2006. Not only is the timescale long, but also the physical size, over 40m long and over 20m wide and high. The collaboration comprises 150 institutions with about 1850 authors. It represents a major part of the future of world Particle Physics.

It consists of a central tracking detector (silicon pixels, silicon strips and straw tubes) in a 2T solenoidal field, surrounded by an electromagnetic calorimeter made of lead and liquid argon, and a hadron calorimeter of iron-scintillator in the barrel region and copper-liquid argon in the forward region. Outside the calorimeter the muon spectrometer measures muon tracks in a magnetic field provided by open superconducting toroidal magnets.

The prime detector requirements are as follows:

- Good calorimetry with
  - electron and γ identification and measurement
  - full hermetic coverage in HCAL for jet and missing E_T
- High precision muon measurements over a wide range of rapidity
- Efficient tracking and good momentum measurement for high p_T particles, plus enhanced electron identification using transition radiation
- Secondary vertex identification for b and τ physics channels
- Efficient and fast trigger to select events of interest and reduce the dataflow to manageable proportions
- The ability to access and analyse a very large volume of data

2 The ATLAS detector

2.1 The Inner Tracker

The ATLAS Inner Tracker is shown in Figure 2. In the barrel region there are three pixel layers with cells 50 μm x 400 μm comprising 90M channels. The pixels improve the pattern recognition and are a special ingredient in the identification of displaced vertices. They are followed at larger radius by four double (back-to-back) silicon strip layers (the SCT) comprising 3.2M channels. Strips of 80 μm pitch and a stereo angle of 40 mrad between the back-to-back layers give a resolution of 16 μm in rϕ and 580 μm in z. The silicon detection is extended into the forward region by three layers of pixels and nine layers of SCT wheels at each end, comprising 50M pixels and 3M SCT strips.

Outside the SCT is an array of straw tubes, 0.42M channels in all, of diameter 4 mm. These are arranged as a short central barrel detector and an extended series of endcap wheels. A resolution of 170 μm per straw at 12 MHz has been obtained. The straws also have the capability of detecting transition radiation and thereby improving the electron identification. Tests have shown a π rejection of around 40 at p_T of 20 GeV/c with 90% electron efficiency.

The overall momentum resolution can be most easily characterised as 20% at a p_T of 500 GeV/c. Considerable progress has been made on developing these modules, as shown in Figure 3 and in Figure 4.

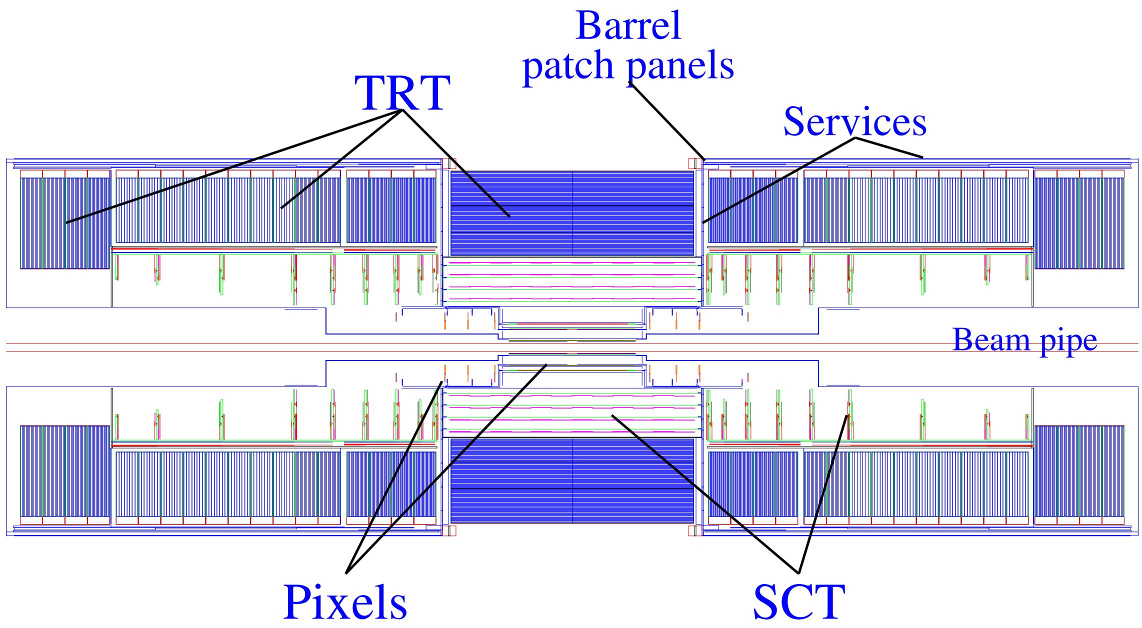

Figure 2: A section through the ATLAS inner tracker

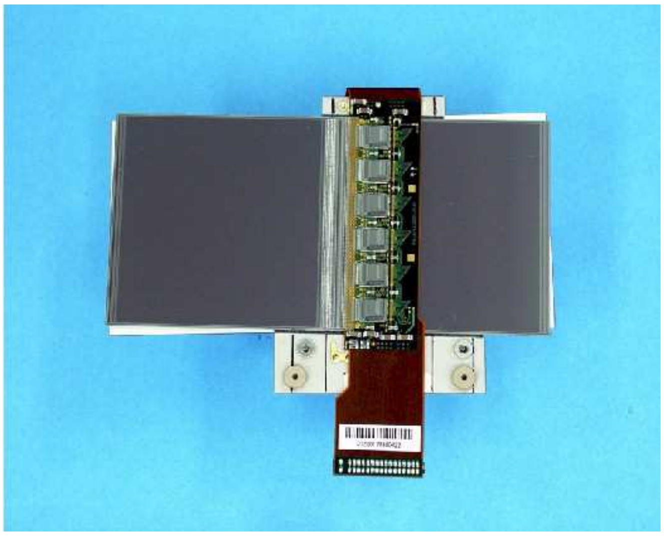

Figure 3: Prototype SCT silicon module

Figure 4: A TRT endcap wheel

2.2 Calorimetry

A schematic picture of the ATLAS calorimetry is shown in Figure 5. The electromagnetic part, outside the solenoid, is liquid argon read out using the 'accordion' method. It consists of three longitudinal samples plus, over most of the rapidity range, a presampler, which corrects for energy deposited upstream of the calorimeter. The granularity is typically 0.025 x 0.025 in $\Delta\eta$ x $\Delta\phi$ and is a very important feature of the performance.

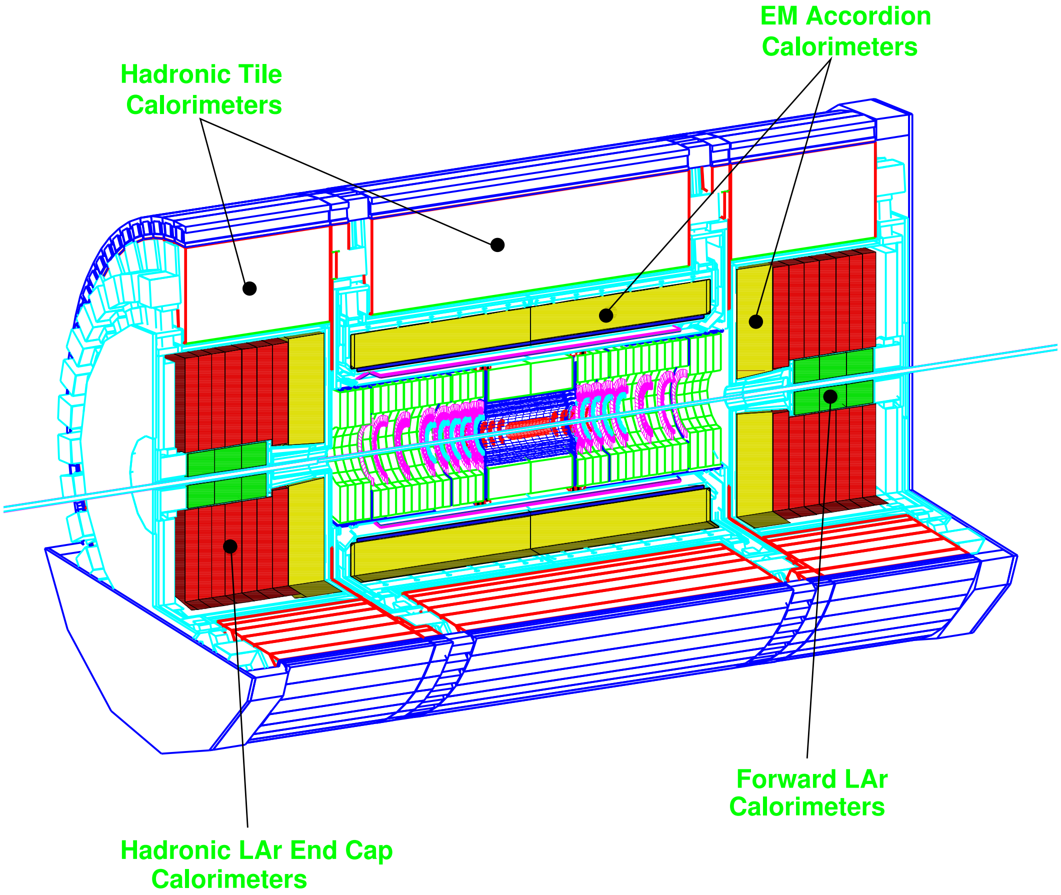

Figure 5: A schematic drawing of the ATLAS calorimeters

The hadron calorimetry in the barrel and 'extended barrel' regions is iron and scintillating tiles read out in three samples in depth with a granularity of about 0.1 x 0.1 in $\Delta\eta$ x $\Delta\phi$. In the endcap region liquid argon is used because of its greater radiation hardness. It takes the form of parallel plates of copper with readout electrodes arranged to give a granularity of 0.1 x 0.1 (except at the highest η) and three samples in depth.

The region between η=3.1 and η=4.9 is covered by the forward calorimeter, enclosed within the same vacuum vessel. Its construction is different (rods and tubes) and it has three depth samples (one copper and two tungsten) with a granularity of 0.2 x 0.2.

The calorimeter signals provide one element of the fast Level-1 trigger for the experiment.

The performance of the ATLAS calorimeter can be summarised in terms of energy

Figure 6: Liquid argon module being stacked

Figure 7: Tile calorimeter modules in storage area

resolution as follows:

•EM calorimeter	$10\%/\sqrt{E} \oplus 0.4\% \oplus$ 300 MeV (noise)
•Tilecal	combined with ECAL: $60\%/\sqrt{E} \oplus 3\%$
•Hadron LAr	standalone: $56\%/\sqrt{E} \oplus 4\%$
•FCAL	$100\%/\sqrt{E} \oplus 7\%$
•Jets	50-60%/$\sqrt{E} \oplus$ 1-2%
•Missing E_T	$\sigma(p_{xy}^{miss})$ of 40% x $\sqrt{\Sigma E_T}$

Progress on construction is shown in Figures 6 and 7

2.3 Muon Spectrometer

The ATLAS muon spectrometer provides a stand-alone measurement of muon trajectories through the toroidal magnetic field provided by barrel and endcap air-cored superconducting toroids (Figure 8).

Each toroid consists of eight racetrack 4-layer superconducting coils. Three layers of chambers provide accurate measurement of momentum: the technology is monitored drift tubes (MDT) in all regions except the first layer at large η (beyond 2.2) where rates are exceptionally high and cathode strip chambers (CSC) are used. The MDTs consist of cylindrical tubes of diameter 30 mm with a central sense wire and achieve a spatial resolution of 80 μm when operated at an absolute pressure of 3 bar. The momentum resolution achieved is typically around 10% at a p_T of 1 TeV/c. In addition to the precision chambers, trigger chambers with excellent timing resolution provide the second element of the fast first level trigger. Resistive plate chambers (RPC) are used in the barrel region, and thin gap chambers (TGC) in the forward region where rates are higher. Because of the openness of the spectrometer, the trigger threshold can be set to the low value of 6 GeV/c.

There has been good progress in the construction of the muon system, for example in the toroid coils (Figure 9) and the MDTs (Figure 10).

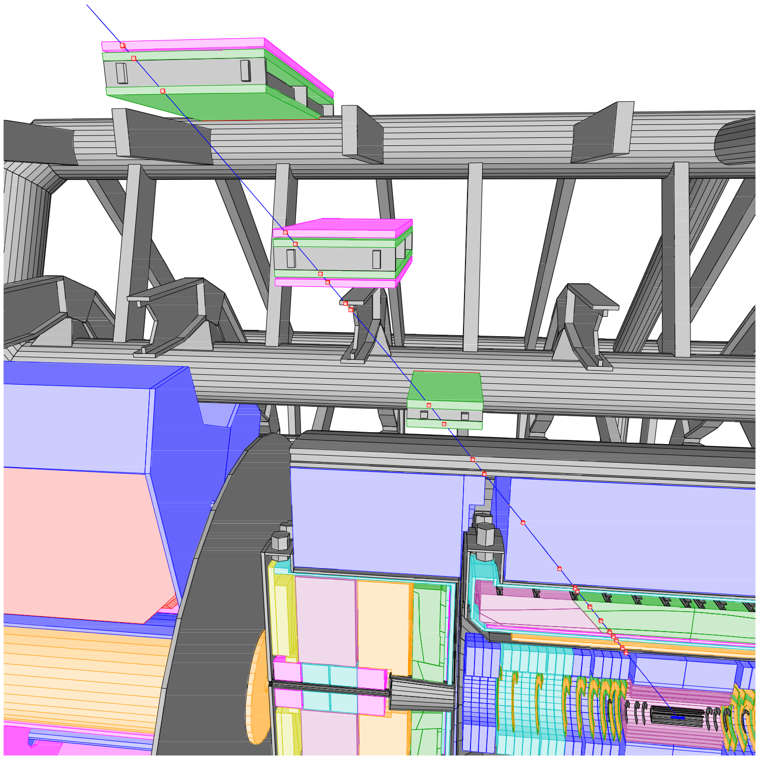

Figure 8: A schematic view of a muon trajectory in the barrel toroid

Figure 9: A barrel toroid coil under construction

Figure 10: Module zero of one series of MDTs

3 ATLAS Physics Studies

The ATLAS collaboration has made many studies of interesting physics channels, for the most part made with a fast simulation of the ATLAS detector which takes into account any resolution and distortion effects. These are summarised below:

- Higgs physics (both Standard Model Higgs and the minimal supersymmetric model)
- Supersymmetry (SUSY)
- W physics (mass, gauge couplings)
- B physics (CP violation, B_s^0oscillations, rare decays)
- t physics (mass,decays,couplings)
- QCD (including parton distribution functions, minimum bias events, diffractive scattering, jet production, photon production,Drell-Yan,...
- Technicolour
- Compositeness
- Extra dimensions
- Other exotica (4th generation, leptoquarks, new gauge bosons, Majorana neutrinos, magnetic monopoles,...)

There is time to consider only a few of these topics. A more detailed account can be found in the ATLAS Technical Design Report on the Detector and Physics Performance [3].

3.1 Standard Model Higgs

Fig 11 shows a simulation of the production of a Standard Model Higgs of mass 130 GeV. It decays into ZZ*, which in turn decays into $e^+e^-\mu^+\mu^-$. The tracking detectors show many tracks resulting from the superposition of minimum bias events, but the electron signals stand out in the calorimeter and the muons are visible.

It is very important to study the Higgs boson in a large number of decay channels in order to confirm its properties. The anticipated significance of a Higgs signal for luminosities of 30 fb^{-1} and 100 fb^{-1} are shown in Figure 12. The former represents two to three years running and the latter four years, provided that the machine delivers a progressively higher luminosity with time. The decay channels H$\rightarrow\gamma\gamma$, $t\bar{t}$H with H$\rightarrow b\bar{b}$, H$\rightarrow$ZZ$^*\rightarrow$4l, H$\rightarrow$WW$^{(*)}$ $\rightarrow$lνlν, H$\rightarrow$ZZ$\rightarrow$ll$\nu\nu$, H$\rightarrow$WW$\rightarrow$lνjj are shown on both figures. The significance achieved is somewhat pessimistic since no K-factors have been assumed for the production cross section. By combining all the channels it is possible to cover the whole range of Higgs mass up to 1 TeV at the 5σ level with just 30 fb^{-1}, whereas with 100 fb $^{-1}$ each channel can be seen at the 5σ level. In the intermediate mass range below the ZZ threshold the search is challenging: backgrounds must be evaluated carefully and detector performance is vital (calorimetry and jet identification for H$\rightarrow$ $\gamma\gamma$, displaced vertex detection for H$\rightarrow b\bar{b}$, good measurement of leptons for H$\rightarrow$ZZ*). In the H$\rightarrow$ WW$^{(*)}$ channel no mass peak appears and the presence of a Higgs is deduced from an excess of events. Hence the knowledge of the background is vital. It should be noted that ATLAS does not consider the channel WH with H$\rightarrow b\bar{b}$ to be a 'discovery' channel at LHC energies.

With the full luminosity it should be possible to reach 300 fb^{-1} in the running of the LHC over several years. It would then be possible to measure directly the Higgs width in

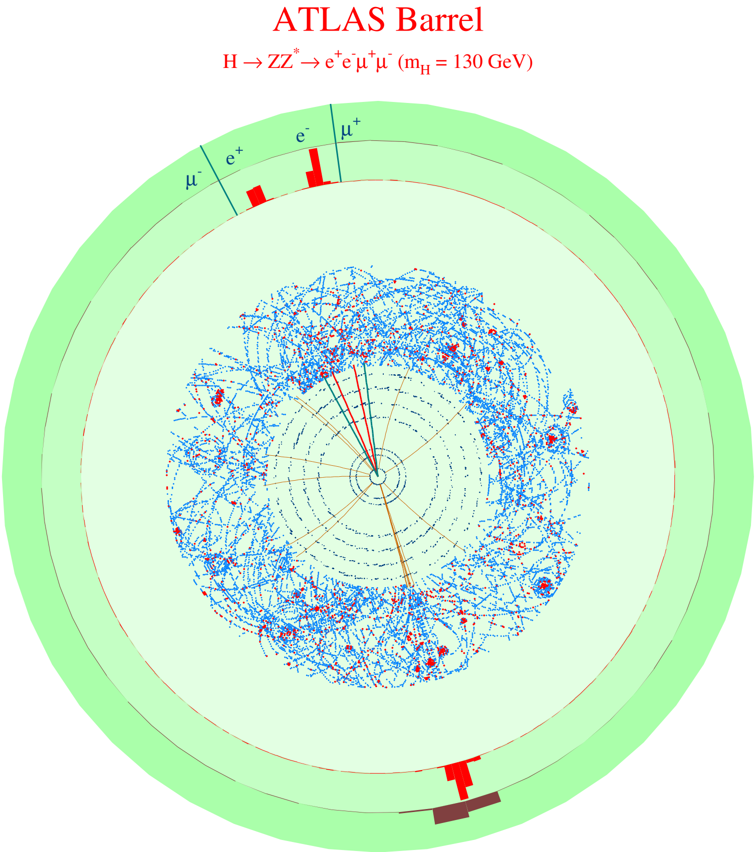

Figure 11: A simulated Higgs event at a luminosity of 5.10^{33}

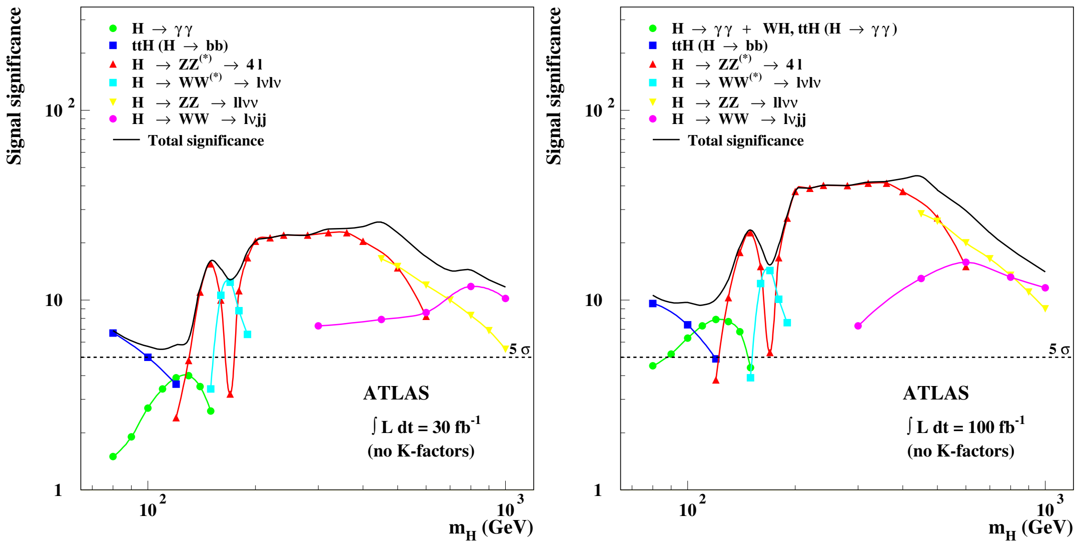

Figure 12: Higgs discovery limits for luminosities of 30 and 100 fb^{-1}

the decay channel H→ ZZ→4l if the Higgs mass is greater than 200 GeV. At lower values of M_H an indirect method must be used, in which ratios of branching ratios are measured and assumptions are made that some decays (such as $c\bar{c}$) are as expected. In this way the ratios of the Higgs coupling to different final states are measured and the Standard Model expectations can be checked [4].

3.2 MSSM Higgs

In the Minimal Supersymmetric Standard Model (MSSM) there exist more than just a single Higgs boson. There are three neutral bosons (h^0, H^0 and A^0) and two charged ($H^{\pm}$). The predictions of the model can be reduced to a dependence on m_A and tanβ (the ratio of the vacuum expectation values of the Higgs fields). Depending on the value of these parameters, different production methods are favoured. Some parts of the parameter space have already been eliminated by experiments at LEP. Assuming that the SUSY mass scale is large and that supersymmetric particles are not produced in Higgs decay, the full parameter space in the (m_A, tanβ) plane can be covered using the various decay modes shown in Figure 13. While for intermediate values of tanβ the SUSY Higgs particles may not be apparent at a luminosity of 30 fb^{-1}, for 300 fb^{-1} the whole plane can be covered. This statement is conservative in that it is independent of the mixing occurring in the stop-sbottom sector. The decay channels H/A→$\tau\tau$, $t\bar{t}H$ with H→$b\bar{b}$ and H→$\gamma\gamma$ are particularly important. Over much of the parameter space, more than one SUSY Higgs would be discoverable, although for intermediate tanβ only the Standard Model-like h^0 would be seen (Figure 14). For almost all cases the Standard Model and MSSM would be distinguishable.

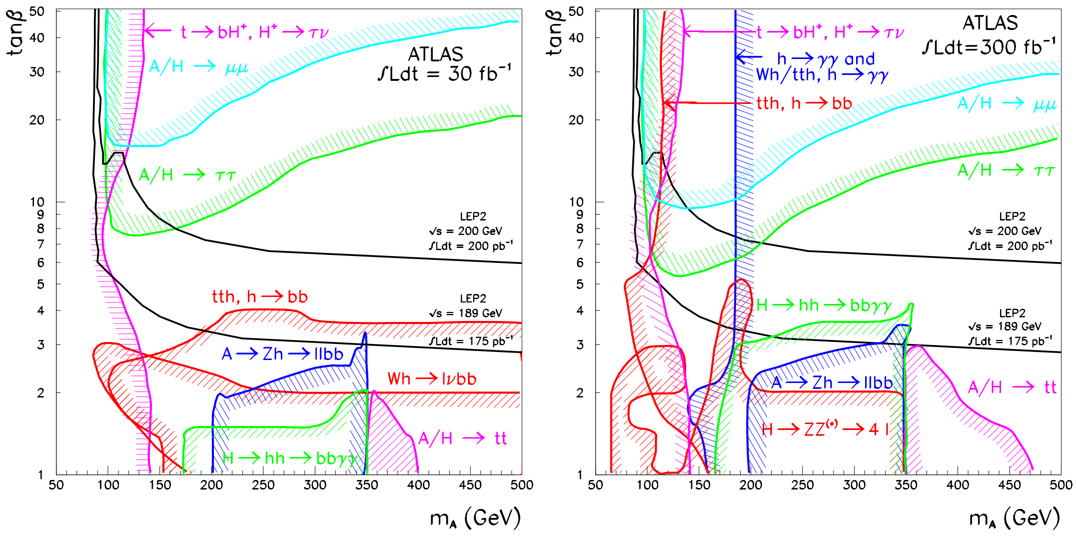

Figure 13: 5 σ discovery limits for SUSY Higgs

In the event that MSSM Higgs bosons (particularly H and A) decay into SUSY particles, the decay channel via neutralinos and charginos with leptons in the final state would be identifiable. Furthermore if h^0 were produced in the decay chain $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$, the h^0 would be observable in the ATLAS detector.

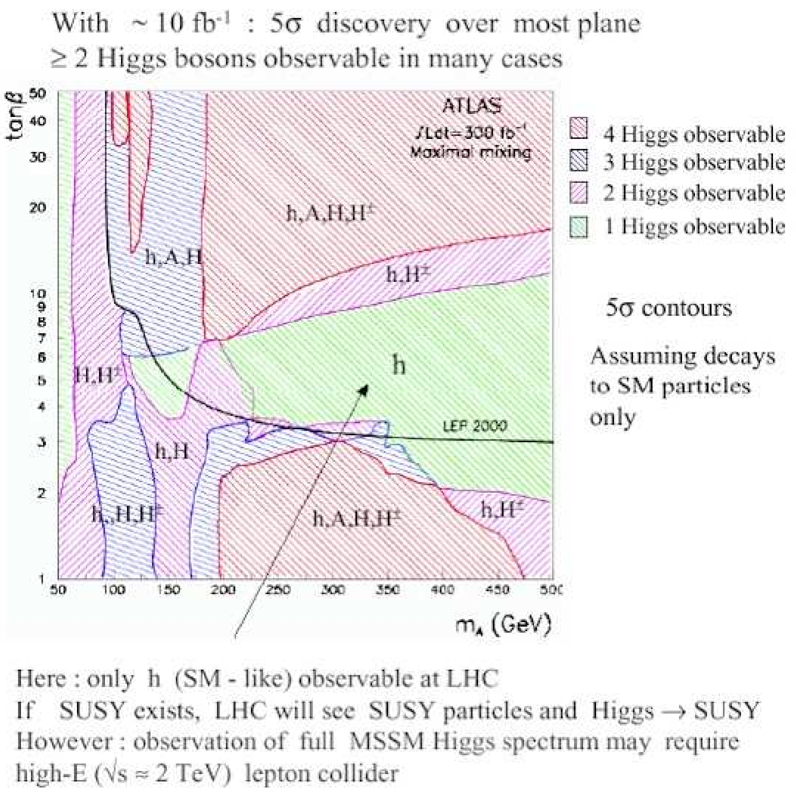

Figure 14: Regions of the m$_A$,tanβ plane where more than just one SUSY Higgs should be discovered

3.3 Extra dimensions

In some exciting new models, there can be new physics visible at the scale of 1 TeV, rather than at energies comparable to the Planck scale. This is achieved by setting the scale of gravity close to that of the electroweak scale, and introducing new extra dimensions curled up into a scale R, which is smaller than 1 mm for a gravity scale of 1 TeV, and at this distance the gravitational interactions have not been studied. Conventional particles are confined to the $3 + 1$ dimensions, whereas gravitons can propagate in the extra dimensions as well.

Two modes of detecting this have been studied. In the first, gravitons are emitted in particle collisions (qg$\rightarrow$q$\tilde{G}$) together with Kaluza-Klein excitations with mass differences $\sim 1/R$ which appear as a continuum. Gravitons interact very weakly with matter and there is an experimental signature of a jet plus missing energy, and also the possibility of single photon plus missing energy (Figure 15).

A second method is to look for the excitation of narrow graviton resonances through the processes $q\bar{q}, gg\rightarrow$G $\rightarrow$ e$^+$ e$^-$ [5]. The e$^+$e$^-$ mass shows a clear peak above a small SM background, and the angular distribution of the e$^+$e$^-$ pair can identify the resonance as spin-2 (Figure 16).

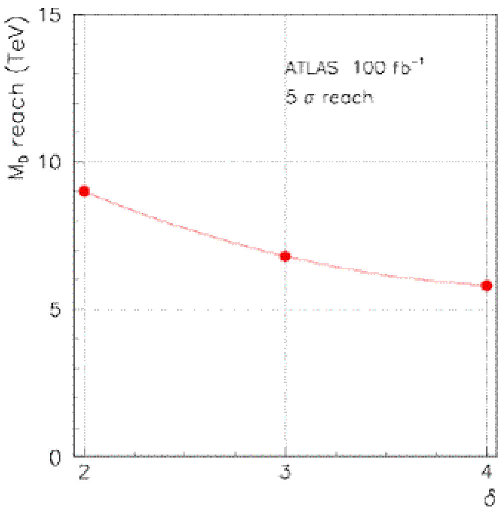

Figure 15: Continuum graviton excitation: the figure indicates the 5 σ reach in mass scale (in TeV) as a function of the number of extra dimensions δ for an ATLAS exposure of 100 fb^{-1}

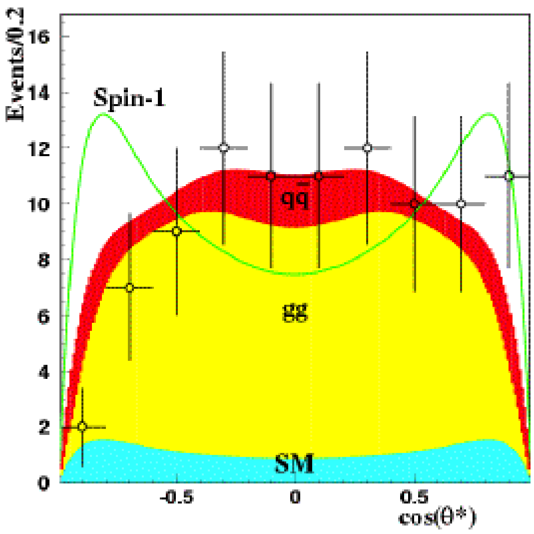

Figure 16: The angular distribution in $G \to e^+e^-$ showing the sensitivity to spin 2

4 Progress on the LHC

Significant progress has been made on the preparation for the LHC, as shown in Figure 17 and Figure 18. The civil engineering work on the machine pits and transfer tunnels is well advanced, and the excavation of the ATLAS cavern is most impressive.

The LHC machine schedule was updated during 2001 and is shown in Figure 19. It envisages a pilot run in April 2006, with a first main physics run of proton-proton collisions from August 2006 to February 2007, with luminosity of at least 2.10^{33} cm^{-2} sec^{-1}. This would provide an integrated luminosity in the range of around ten inverse femtobarns.

5 ATLAS physics with the initial luminosity

When the LHC machine first turns on the luminosity is not expected to be at its nominal value of 10^{34}cm^{-2}sec^{-1} immediately. Indeed, the scenarios envisage an initial exposure of 10 fb^{-1}. I give a brief account here of some of the physics which can be expected from ATLAS during this initial period.

5.1 Supersymmetry

Because supersymmetric quarks and gluons (squarks and gluinos) respond to the strong interaction, their production cross section (in pairs) is very high above the threshold for their production, around 1 pb. For a squark or gluino mass of around 1 TeV, one would expect 100 events per day at a luminosity of 10^{33}. Even with only 1 fb^{-1} of data the

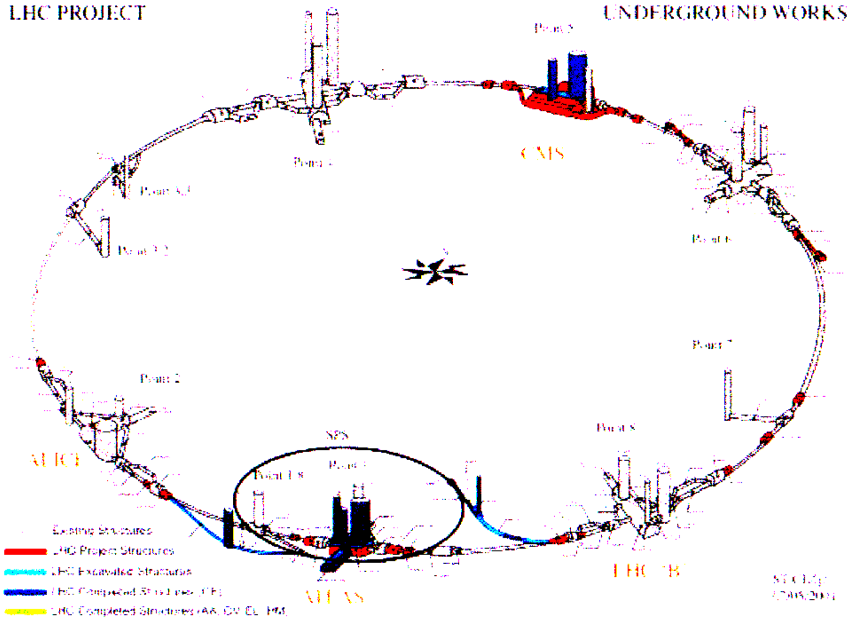

Figure 17: LHC layout showing the progress on civil engineering

Figure 18: The ATLAS cavern: progress on excavation

Jan 2004 – Sept 2004	Octant test	
2005 March	Last dipole delivered	
Dec 2005	Ring closed and cold	Full access to experimental caverns
Jan 2006	Machine commissioning Beam pipes in place	Full access to experimental caverns
Feb-Mar 2006	Single beam	Restricted access to experimental caverns
Apr-2006	First collisions 4 week pilot run	Luminosity between 5.10^{32} and 2.10^{33}.
May-July 2006	Shutdown	Full access to experimental caverns
Aug 2006 – Feb 2007	Physics run; 7 months	Luminosity >= 2.10^{33} Integrated >= 10 fb^{-1}
Mar – Apr 2007	Lead ion run, 6 weeks	

Figure 19: The LHC schedule announced in February 2001

signal stands out clearly (Figure 20) using a signature of jets plus missing transverse energy. Of course, the calorimetry must be working satisfactorily over the whole rapidity range for this to be achieved. This scenario of course assumes R-parity conservation and the presence in SUSY decays of the lightest supersymmetric particle, an invisible, weakly interacting neutralino.

5.2 Higgs searches

For low Higgs masses, close to the LEP limit of around 115 GeV, a significant Higgs signal from 10 fb^{-1} will have to be obtained by combining ATLAS and CMS and using both H$\rightarrow\gamma\gamma$ and $t\bar{t}$H$\rightarrow$ $t\bar{t}b\bar{b}$. The signal significances (S/$\sqrt{}$B) are 3.4 and 3.2 respectively, giving 4.7 for the two channels combined, ignoring any K-factors. The 5σ discovery is just obtainable in 10 fb $^{-1}$ and a very clear indication should be seen. For higher SM Higgs masses the discovery is faster,and the whole range of Higgs masses up to 1 TeV could be excluded at 95% CL with one month of running at a luminosity of 10^{33} (Figure 21).

5.3 W physics

There will be a very large production of Ws at the LHC: ATLAS would see 10^8 W$\rightarrow e\nu$ events in a year at a luminosity of 10^{33}, giving a statistical error of only 2 MeV on the W mass in this channel. Clearly the systematic errors are going to dominate, such as the energy- momentum scale and the knowledge of parton distribution functions. Despite these caveats, it is hoped to keep systematic errors below 25MeV. Good measurements of the triple gauge coupling will need 30 fb^{-1}.

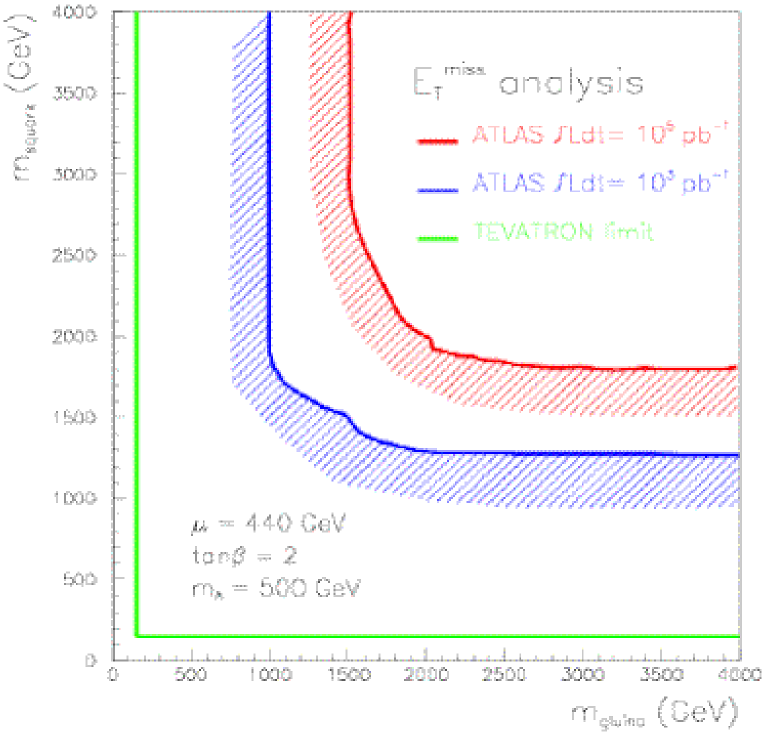

Figure 20: 5 σ limits for 1 fb^{-1} and 100 fb^{-1} in ATLAS with the SUSY parameters tan β=2, μ=440 GeV, M_A=500 GeV

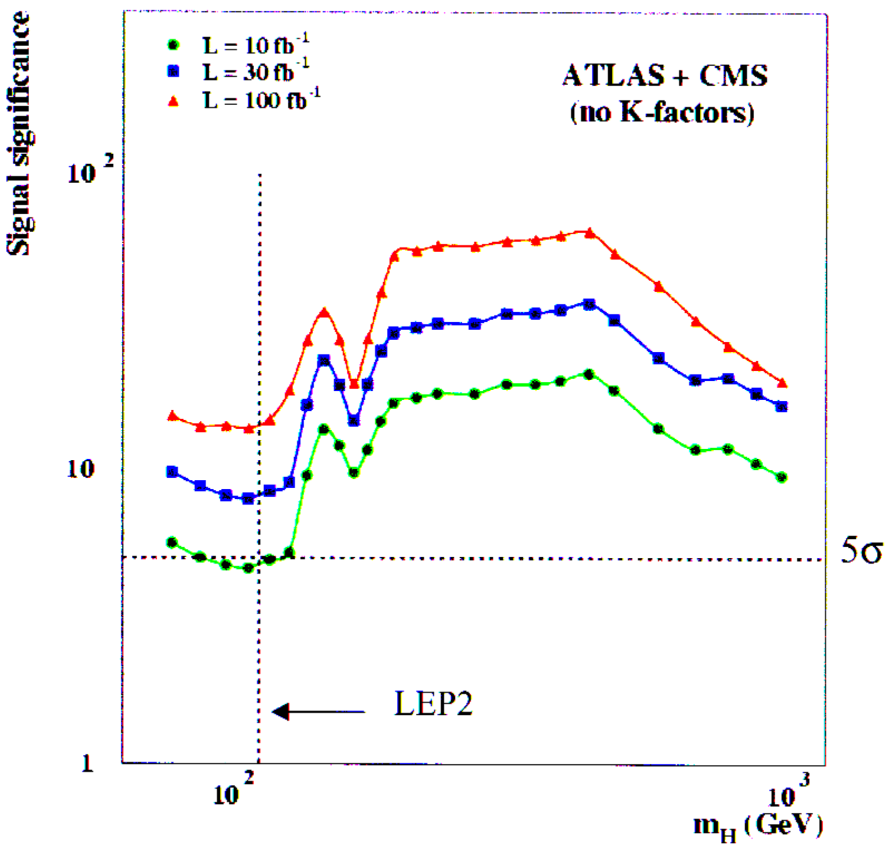

Figure 21: Higgs discovery limits for ATLAS and CMS combined at various luminosities

5.4 Top physics

Top quarks will be produced in abundance in ATLAS (10^7 events per year), and it is expected that the uncertainty on the mass will be reduced to around 2 GeV, again dominated by systematic uncertainties (the statistical error should be smaller than 100 MeV). This measurement, combined with the W mass, constrains the mass of the SM Higgs. The production cross section will also be measured well, but its accuracy will be limited by the 5-10% uncertainty in the determination of the luminosity. Other important studies of top, such as limits on FCNC and $t \to bH^+$ will require more integrated luminosity.

6 Summary

Physics at the LHC will be exciting as well as challenging. Discoveries could be made in days and months rather than years provided that the apparatus works well and we understand it. This gives us confidence that we are on the brink of new physics.

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