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ATLAS Physics Performance and Commissioning

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Abstract

ATLAS, one of the two multi-purpose detectors at the proton-proton collider LHC, is scheduled to start taking data in 2007. This paper presents the physics performance of this experiment in studying one of the main topics of the LHC physics : the Higgs search. The use of the first data for the detector commissioning and the physics measurements that can be done in the early phase of the LHC operation are also reviewed.

1 Introduction

The ATLAS detector[1] has been mainly designed to search for new particles related to the symmetry breaking mechanism and to investigate theories beyond the Standard Model (SM). The physics program includes precise measurements of known particle properties (W, t and b) and the study of SM processes at a centre-of-mass energy $\sqrt{s} = 14$ TeV never explored before. To achieve the designed physics performance, an initial phase of commissioning *"in situ"* of the experiment is essential; it will take some time until the detector will be debugged and understood. The start-up procedure of LHC is well established [2]; nevertheless there are uncertainties on how the machine commissioning and performance will evolve. Two years before the date at which the first collisions are expected to occur, a reasonable assumption is that by the end of 2008, ATLAS will have recorded on tape an amount of data corresponding to an integrated luminosity of between 1 and 10 fb^{-1}. With this amount of data and even with a not perfectly calibrated detector, it is still possible to perform interesting SM studies and to search for those new phenomena which are expected to have so large cross-sections and so striking topologies that they could appear during the first days.

The first part of this paper (Sections 3, 4 and 5) reviews, after a very brief presentation of the ATLAS detector and of the expected luminosity at the LHC start-up (Section 2), the ATLAS discovery potential for the Higgs boson(s) in different scenarios: SM, Minimal Standard Model (MSSM) and little Higgs. The second part of this paper is devoted to the *"in situ"* detector commissioning (Sections 6) and to the physics (Sections 7 and 8) that can be studied with the data which will be collected at the beginning of the LHC running.

2 The ATLAS Detector at LHC

The ATLAS detector[3] is a general-purpose detector composed of an inner tracker in a 2T solenoidal magnetic field allowing to measure precisely the momentum of the charged particles, an electromagnetic sampling calorimeter using liquid argon (LAr) as sensitive media for photon and electron detection, hadron calorimeters for hadronic shower measurements and a muon spectrometer consisting of air core toroids with muon chambers. ATLAS will operate on the LHC collider being built at CERN, which will provide proton-proton collisions at $\sqrt{s}$=14 TeV with a design peak luminosity of L=10^{34} $\text{cm}^{-2}\text{s}^{-1}$. The collisions will occur every 25 ns. An initial period of lower luminosity to tune the machine parameters is needed. It is expected that the initial peak luminosity ranging between $3{\cdot}10^{28}$ and $2{\cdot}10^{31}$ $\text{cm}^{-2}\text{s}^{-1}$ will be brought up to $2{\cdot}10^{33}$ $\text{cm}^{-2}\text{s}^{-1}$ during the first year(s) and that in 2008 a six month physics run will take place. It is reasonable to assume that by the end of 2008 ATLAS will have recorder on tape an amount of data corresponding to an integrated luminosity of between 1 and 10 fb^{-1}.

3 The SM Higgs Search

The Higgs boson, essential ingredient of the SM, is the experimental missing element of the theory. Direct searches performed at LEP2[4], have established that if this particle exists, its mass should be above 114.4 GeV(at 95% CL). In the context of the SM, indirect searches[5] indicate that the Higgs mass is below 219 GeV at 95% CL. Model independent theoretical considerations put an upper limit on the SM Higgs mass of $\approx$ 1 TeV: if there is no fundamental scalar with mass below $\approx$ 1 TeV, new physics beyond the SM must exist to assure the unitarity of the vector boson scattering amplitude.

The search strategy depends on the expected production and decay processes. The dominant process of SM Higgs production at LHC is the gluon fusion, the second dominant process is the weak Vector Boson Fusion (VBF).

Because the Higgs to fermion coupling is proportional to the mass of the fermion, the Higgs particle decays into the heaviest available fermion pair until the thresholds for WW and ZZ production open.

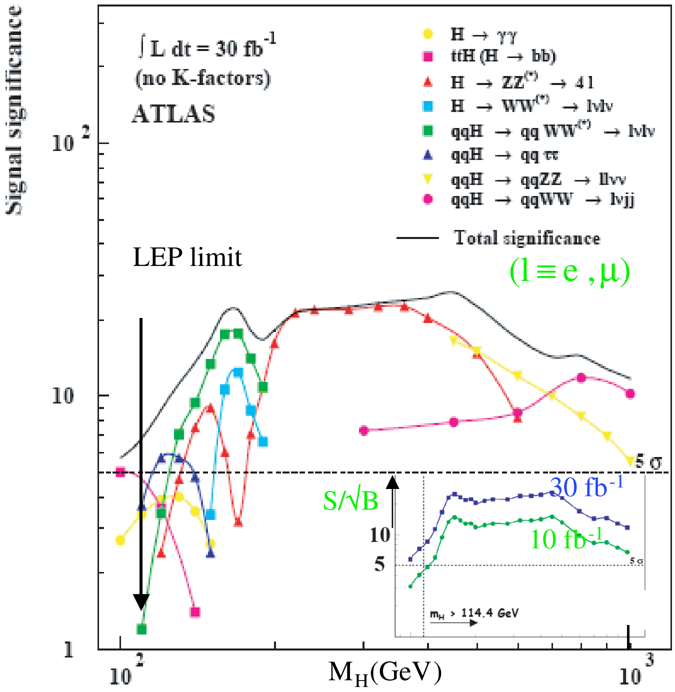

Figure 1: *Discovery potential of ATLAS at 5 σ level for the SM Higgs.*

Figure 1 shows that in ATLAS, combining all the studied channels, with an integrated luminosity of 30 fb^{-1}, a Higgs signal significance over the background larger that 5 σ is expected, for masses ranging between 100 GeV and 1 TeV. With 10 fb^{-1}, the Higgs discovery should be still relatively easy if its mass is above $\approx$ 180 GeV since the 'golden' channel $\mathrm{H}\rightarrow 4\ell$, essentially background free, can be used. Instead, the Higgs discovery will be much more difficult for Higgs masses below 180 GeV and in particular close to the LEP limit. In fact, for lower masses, the combination of three different decay channels ($\mathrm{H}\rightarrow 2\gamma$, $\mathrm{t\bar{t}H} \rightarrow \mathrm{t\bar{t}\ b\bar{b}}$, qq $\mathrm{H}\rightarrow$ qq $\tau\tau$) is necessary to extract a convincing Higgs signal. These channels are particularly challenging during the first year(s) of operation since they require a good understanding of the detector and of the background.

Assuming that SM Higgs boson analyses find a 5 σ evidence for the existence of a new neutral particle, the question if this particle is indeed the SM Higgs boson immediately arises. This question can be answered by measuring the new particle properties like its mass, production rate, width, branching ratios, spin and more generally its quantum number. In the following, the spin S and CP determination as well as the precision that can be achieved on the measurement of the Higgs width and couplings will be reviewed.

The SM predicts that the Higgs boson has S^{CP}=0^{++}. If there is evidence that the new particle is produced via the gluon fusion mechanism or if the decay into 2γ is observed, the S=1 hypothesis is ruled out. To prove the S and CP-eigenvalues of the new particle, angular correlations in the subsequent decay $H\rightarrow ZZ\rightarrow 4\ell$ can be used. It has been shown [6] that these correlations can be sufficiently well measured that consistency with the spin-CP hypothesis of the SM can be obtained for masses M_H above 250 GeV already with an integrated luminosity of 100 fb^{-1}. The full LHC luminosity (300 pb^{-1}) will be needed to rule out the non SM S=1 hypothesis, for all Higgs masses.

The Higgs width, Γ_H, can be directly obtained using the decay $H\rightarrow 4\ell$ from a measurement of the width of the reconstructed Higgs peak after unfolding the detector resolution. This, however, will only be possible for Higgs masses greater than $\approx$ 200 GeV, above which the instrinsic width of the resonance is comparable or larger than the expected experimental resolution. With 300 fb^{-1} the expected accuracy varies between 5% and 10% in the mass range between 300 and 700 GeV[1]. For masses smaller than $\approx$ 200 GeV, the Higgs width is too narrow to be measured with the direct method. Indirect measurements are based on a global maximum likelihood fit to the rates of the observed signals [7]. Theoretical assumptions are needed to extract Γ_H and the Higgs couplings. Assuming only one Higgs boson with S^{CP}=0^{++}, the ratios of the Higgs partial widths Γ_X/Γ_W (X= Z,γ,τ) can be extracted with an accuracy between 15 % and 60 % for $M_H > 120$ GeV and a luminosity of 30 fb^{-1}. With the additional assumption that only SM particles couple to Higgs, ratios of couplings (g_X^2/g_W^2, X=Z,γ,τ) can be measured with a precision ranging between 15 % and 60 % for M_H >125 GeV and a luminosity of 30 fb^{-1}. With high luminosity (300 pb^{-1}) a final accuracy of 30% on the top coupling ratio are expected.

4 The MSSM Higgs Search

Supersymmetry[8] is an appealing concept which offers the possibility of incorporating gravity into the quantum theory of particle interactions and provides an elegant cancellation mechanism that avoids a fine tuning of the Higgs mass. Two Higgs doublets are introduced in the MSSM scenario which is the Supersymmetric model with the minimal particle content. After symmetry breaking, five physical Higgs bosons are left : three neutral (h,H,A) and two charged ($H^{\pm}$). At the Born level the masses and the couplings of these particles depend on two parameters M_A (the mass of the CP-odd Higgs boson) and tanβ (the ratio of the vacuum expectation values of the two Higgs doublets). Quantum corrections introduce a dependence on the top mass and on five other unknown parameters. To establish the ATLAS discovery potential, the procedure is to fix these five parameters in bench-mark scenarios and scan the plane M_A vs tanβ. In this paper only CP conserving scenarios and Higgs decays in non SUSY particles are considered. All these scenarios put severe constraints on the h particle mass which is expected to be light, i.e. not very far from the LEP limit ($m_h < 135$ GeV). The decay channels h→WW and h→ $\tau\tau$ play an important role. For this reason a good reconstruction of the transverse missing energy (Etmiss) is a relevant experimental issue in these analyses. The main production mechanism of the h bosons which has been used in the ATLAS analyses is the VBF mechanism since it has a rather distinct signature (two forward jets and reduced hadronic activity in the central region) allowing QCD background discrimination. With 30 fb^{-1}, a 5 σ evidence for the h particle, can be achieved in ATLAS for almost all values of M_A - tanβ.

The heavy neutral Higgs has been searched in ATLAS in several channels and in particular in the associated production and subsequent decay ($b\bar{b}$ H/A)→ $b\bar{b}\tau\tau$. This channel is the main production process at large tanβ. To improve the signal significance in this region, hadronic decays of both τ have been recently considered[9] in addition to the previously considered leptonic decays. It has been shown that the ATLAS level-1 trigger based on τ- and jet-trigger with Etmiss signature doesn't reduce the signal significance. Finally, taking into account all studied channels, searches for the heavy MSSM Higgs (H,A $H^{\pm}$) in ATLAS have shown that with 300 fb^{-1}, the plane M_A - tanβ is not completely covered.

Fig. 2 shows that for high value of M_A and for intermediate values of tanβ only a h (SM-like) is observable. The observation of the full MSSM Higgs spectrum could require the construction of a high energy lepton collider ($\sqrt{s} > 2$ GeV).

To discriminate between the SM Higgs and the lightest MSSM Higgs, h, the ratio between the h branching ratio in W pairs and in τ pairs has been studied (R=Br(h→WW)/Br(h→ $\tau\tau$)). Very preliminary results indicate that with 30 fb^{-1}, if M_h=130 GeV and M_A >300 GeV the discrimination will be very difficult: in this region of the parameter space, the difference between the SM expected R value and the MSSM expected R value is less that 2 σ.

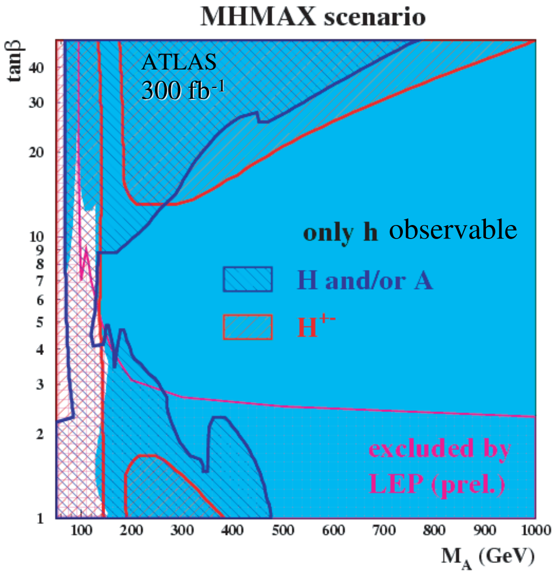

Figure 2: *Discovery potential of ATLAS at 5 σ level for the MSSM Higgs.*

5 Little Higgs Search

The "Little Higgs" model [10], proposed as a possible solution to the fine-tuning problem of the Higgs mass, embeds the SM inside a larger group with an enlarged symmetry. From the phenomenological point of view, the effect of this symmetry is to require the existence of new particles whose couplings assure that the large quantum contributions to the Higgs mass are cancelled. With this purpose, there must be three types of new particles. In particular in the "Littlest Higgs" model [11] a new charge 2/3 quark T, electroweak singlet, mixing with the top quark, decaying to Wb, Zt and th final states with mass below ≈ 200 GeV is predicted. The model predicts in addition four new gauge bosons $\mathrm{W}_\mathrm{H}^\pm$ A_H Z_H with masses below ≈ 600 GeV and new Higgs particles forming a $SU(2)_L$ triplet $(\phi^0, \phi^+, \phi^{++})$ with released constraints on the masses ($\mathrm{m}_\phi < 10$ GeV). The possibility of discovering such particles with the ATLAS detector have been investigated [12] and it has been found that the T quark is observable for masses up to ≈ 2 TeV via its decay to Wb with an integrated luminosity of 300 fb^{-1}. Fig. 3 shows the 5 σ discovery regions for Z_H and W_H decaying into various final states as function of cot θ[¶] and masses. One can see that ATLAS with 300 fb^{-1} is fully sensitive to new gauge bosons except for a very restricted range of cos θ. The new Higgs particles $(\phi^0, \phi^+, \phi^{++})$ may be out of reach.

[¶] θ is a parameter somewhat analogous to the Weinberg angle of the SM

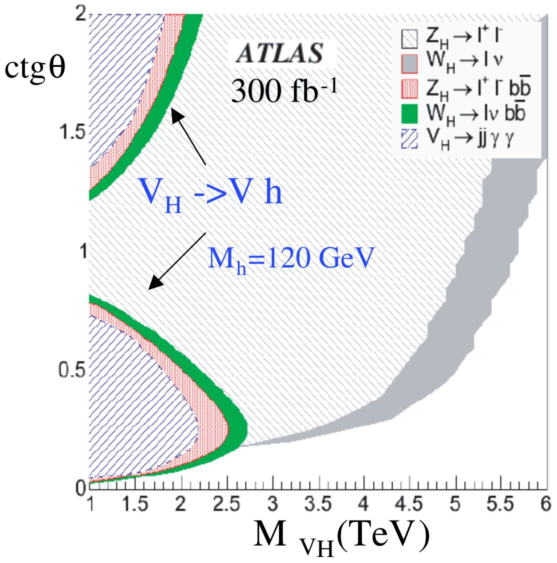

Figure 3: *Discovery potential of ATLAS at 5 σ level for Higgs in the Little Higgs Model.*

6 In situ Commissioning

In the first part of this paper the expected Higgs discovery potential of the ATLAS experiment has been reviewed. To achieve the described performance, stringent requirements and controls during the construction phase as well as measurements on prototypes and final modules in test beams were performed. The different components of the ATLAS detector are at the moment being installed in the experimental zone. The commissioning after installation in the pit (*"in situ"* commissioning) is an important phase of the preparation of the experiment since it allows to debug and to understand the detector as a whole. Before beam is circulating in LHC, cosmic muons[13] will allow to perform a first global debug: a search for dead and noisy channels, a preliminary detector alignment and signal synchronisation. The expected rate of cosmic muons passing close to the origin (i.e. ≈ 0.5 Hz for $|z| <60$ cm and $R <20$ cm from the interaction point) should be enough to align to tenths of microns some parts of the inner tracker and to perform useful studies of the LAr electromagnetic calorimeter like timing, signal shape and response uniformity. Beam-gas events (due to the interactions of 7 TeV protons on the residual gas at rest) and beam-halo events (straight tracks accompanying the beam) will also be used during the single beam period in spring 2007 to perform a preliminary alignment of the end cap-detectors[13].

The expected performance of the ATLAS detector at the end of the pre-collision period and after final alignment and calibration is presented in Table

1. The aim of the commissioning with first collisions is to understand the trigger behaviour, to improve the detector calibration and alignment, to measure and understand SM processes, like QCD processes, Z, W and t$\bar{\text{t}}$ production at an energy never explored before. These studies are also important for the new physics searches since SM processes represent often background to the new physics. A large statistics, larger than the total statistics collected at previous colliders, is expected to be available already in the first two years. As an example, the expected number of t$\bar{\text{t}}$ events which will be recorded on tape for an integrated luminosity of 1 fb^{-1} is $\approx 10^5$, i.e. 10 times bigger than the total statistics collected at the Tevatron. Using the first collisions several studies can be performed. As an example:

Expected performance	End pre-collision period	Final
Tracker alignment	$\approx$ 20-200 μm in Rϕ	$\approx$ 5 μm
LAr em uniformity	$\approx$ 1%	$<$ 0.7 %
LAr em energy scale	$\approx$ 1-2%	$<$ 0.2%
Jet energy scale	$\approx$10%	$\approx$ 1%

Table 1: *Expected performance at the end of the pre-collision period and after final alignement and calibration of the ATLAS detector.*

- isolated tracks from τ and W decays can be used to cross-check and improve the pre-collision tracking alignment and to determine the E/p matching precision,
- the decay J/$\psi \rightarrow \ell\ell$ and especially Z$\rightarrow \ell\ell$ can be used to (inter)calibrate the LAr electromagnetic calorimeter and to align and set the μ momentum scale,
- the minimum bias events can be use to inter-calibrate the LAr electromagnetic calorimeter,
- the W mass constraint in W$\rightarrow$ jj decay from t$\bar{\text{t}}$ events and the events with Z/γ + 1 jet can be used to set the jet energy scale.

With more statistics it will be possible to set the b jet energy scale using Z/γ + b-jet and to measure the b-tagging efficiency with t$\bar{\text{t}}$ events.

As an example of the above described procedure, the case of the ATLAS LAr electromagnetic calorimeter[14] is discussed here. To observe a possible H $\rightarrow 2\gamma$ signal as a peak on top of the huge $\gamma\gamma$ background, one important performance issue for the electromagnetic calorimeter is to provide a 1% resolution on the 2 γ invariant mass in the hundred GeV range. This requirement puts an upper limit on the constant term of the energy resolution of the calorimeter: $c_{tot} < 0.7\%$. It has been verified with test beam data that stringent requirements on the mechanical accuracy during the calorimeter construction and a precise read-out electronics allow to get an energy constant term in each of the 448 regions ($\Delta\eta$x$\Delta\phi$= 0.2x0.4) of the calorimeter $c_{local} < 0.5\%$. As soon as first collider data will be available it will be possible to use Z→ e^+e^- events to correct long range non-uniformity, i.e to inter-calibrate the 448 regions. It has been shown[15] that with ≈ 170 000 events (corresponding to few days at a peak luminosity of 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$) it is possible to obtain a 'long range' constant term of ≈ 0.4% which translates to the required total constant term: $c_{tot} = c_{local} \oplus c_{long\ range} < 0.7\%$.

7 Early Physics

With an expected cross section of ≈ 70 mb, minimum bias (MB) events will be abundantly collected at LHC. The study of MB events will allow to tune the Underlaying Event (UE) models right from the beginning. The UE corresponds to the soft part of the proton-proton interaction which is not well described by perturbative QCD(PQCD).

At LHC the Z and W production cross sections can be computed precisely; in fact the NNLO calculations in PQCD result in a 1% theoretical uncertainty[16] and the input electroweak parameters are well known. The main uncertainties on Z and W production come from the knowledge of the parton distribution function (PDF) of the proton and from the machine luminosity. Interesting tests can be done already at the beginning of the data taking by looking at the ratio R=dσ/dy(W^-)/ dσ/dy(W^+) and at the W asymmetry which are less sensitive to PDF and luminosity and could allow at the same time to validate the analysis chain.

LHC will explore a region in the Q^2 vs x plane[¶] never explored before. In particular it will be possible to probe the low-x gluon PDF at $Q^2 = M_W^2$ by looking at the W→ $e\nu$ rapidity spectrum which is sensitive to the gluon shape parameter λ. Studies have shown that the inclusion of ATLAS data corresponding to one day at 10^{33} $\mathrm{cm}^2\mathrm{s}^{-1}$ would improve the precision on the λ parameter by 40%.

With a production cross section $\sigma \approx 830$ pb, $t\bar{t}$ events are abundantly produced at the LHC. The top signal can be used to validate the detector performance during the initial phase of data taking. As an example the W mass constraint in the hadronic decays of W bosons produced in top decays

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[¶] $Q^2$is the momentum transferred from the initial to the final quark in the hard scattering and x is the fraction of the proton momentum carried by the quark allows to set the jet energy scale. In addition top events represent an excellent sample to understand the b-tagging performance. A top signal should be visible in ATLAS in a few days. Figure 4 shows the reconstructed top signal in the gold-plated semileptonic channel $t\bar{t} \rightarrow bjj\, b\ell\nu$ for an integrated luminosity of 150 pb^{-1}, corresponding to less than a week of data taking at a peak luminosity of $L=10^{33}$ $cm^{-2}s^{-1}$.

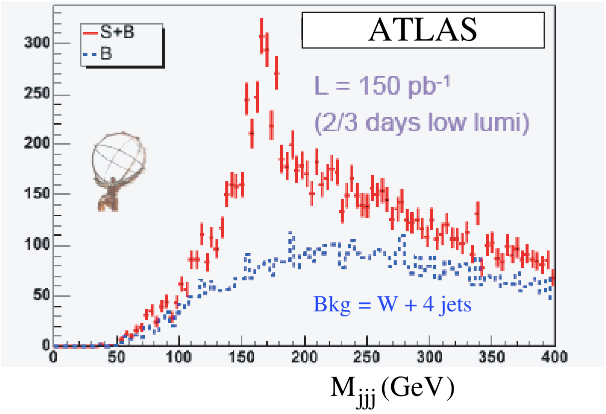

Figure 4: *Invariant mass distribution of the three highest p_T jets in the events selected as described in the text for the top analysis.*

To produce the three jet mass distribution presented in Figure 4 a very simple analysis was used requiring an isolated electron or muon with transverse momentum $p_T > 20$ GeV and 4 jets with $p_T > 40$ GeV. No kinematic fit was applied, no b-tagging was required since it was assumed that these procedures would be not yet understood at the beginning of the data taking. The signal is cleraly visible on top of the backgoound; it can be used to to verify the jet energy scale. Top physics is an important topic for several reasons: in particular an accurate measurement of the top mass allows to put stringent constraints on the Higgs mass. With 10 fb^{-1} ATLAS should be able to measure the top mass with an uncertainty of ≈ 1 GeV dominated by the systematic error arising from the imperfect knowledge of the b-jet energy scale and the effects of the final state radiation. At present the preliminary measurement of the top mass performed at Tevatron gives 172.0 ± 2.9 GeV.

8 Early Discoveries

Several theories beyond the SM (Grand Unified Theories, Little Higgs Model, Extra Dimensions) predict the existence of at least a new massive neutral particle decaying into fermion pairs. Lower limits on its mass have been established by direct search and at present vary between 600 and 700 GeV depending on the assumed model[17]. At LHC a new neutral particle with mass in the TeV region, decaying into pairs of leptons of opposite sign ($e^+ e^-$ or $\mu^+\mu^-$) should be easily found, if it exists, since in all cases the number of expected events after all experimental cuts is relative large and the dominant background, consisting in Drell-Yann lepton pairs, is small in the TeV region. For these reasons the signal has a striking signature appearing as a resonant peak on top of a low background and could be found already in the first years of running when the detector will have non-ultimate performance and the design machine luminosity is not yet achieved. As an example the integrated luminosity which is necessary to find a neutral gauge boson of mass $M_Z = 1$ TeV predicted by the Grand Unified Theories, using the decay to electron-positron pairs ranges between 0.07 and 0.7 fb^{-1} depending on the assumed gauge group structure[18]. Much more statistics is needed to distinguish among the different models.

9 Conclusions

The ATLAS detector performance allows to find the Higgs boson(s) of the SM, of the MSSM and of the Little Higgs Model over a very wide range of masses. ATLAS is getting ready for the LHC startup in 2007. The understanding of the detector and of the background will need a lot of data and time. The LHC offers the possibility for doing interesting physics and discoveries right from the beginning when the detector is not yet perfectely calibrated. To exploit the full LHC potential, efficient commissioning with physics data is important for several reasons; among them the fact that the future of our discipline will benefit from a quick feedback from LHC detectors, since LHC results could better guide the planning of future facilities.

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