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Physics at the Large Hadron Collider

Bruno Mansoulié
DAPNIA-SPP
CEA-Saclay
France

Abstract. The Standard Model of elementary constituants and interactions is a well tested theory, but we clearly see its limitations. In particular, the origin of the particle masses is now a central question. Several new theoretical frameworks are proposed to address it and answer it at least partially. All of them have the mechanism of ElectroWeak symmetry breaking as a cornerstone, and predict new phenomena at its typical energy scale: 1 TeV. The Large Hadron Collider, at Cern, will be the first accelerator to explore this energy scale directly.

Its construction is now in progress, together with the large experiments which will extract the physics out of the particle collisions. All the proposed models have been examined in great detail, and the detectors optimized accordingly. Physicists are confident that indeed LHC will bring crucial new informations and open a path beyond the Standard Model.

1 Introduction

The LHC at Cern is the most ambitious project in particle physics today. The machine and the experiments are huge technical challenges, and the experimental conditions are expected to be difficult in the best case. However, the motivation for this effort is unprecedented: physicists are convinced that LHC will bring key elements to answer the present questions in the field. Starting from the weaknesses of the Standard Model, many larger theories have been put forward, and a large amount of work has been devoted to studying the observable consequences of each of these new theories at LHC. A large part of this work was undertaken by the large collaborations which proposed, and now construct, experiments at LHC[1]. In this talk I will give a global survey of this work. At the same time I will go into some detail for a few cases, to underline the particular experimental conditions.

1.1 The Standard Model

The Standard Model is the theory which describes all the observations at the microscopic scale today. It assumes a number of input ingredients, namely the nature of the constituants of matter, the type of their interactions, and about 25 arbitrary parameters (mostly particle masses and interaction coupling strengths). Given this, the Standard Model offers a framework which we believe to be essential: quantum mechanics and special relativity, i.e. it is a quantum field theory.

For the experimentalist, the predictive power of quantum field theories comes mostly from the calculations of perturbation series, and renormalizability is the key criterion there. In the Standard Model, renormalizability, and hence an efficient use of perturbation series, is guaranteed by the structure of the model, based on local gauge symmetries.

For a non-insider, it is difficult to imagine how deeply the ideas of gauge invariance and renormalizability have modelled the entire landscape of experimental particle physics. We are now completely used to measuring properties of particles which were never produced in their real, on-shell state, but whose presence is seen through virtual effects. The most spectacular example was the measurement of the top quark mass at LEP ($m_t = 178 \pm 20\,\mathrm{GeV}$) before it was 'discovered' at FNAL in 1994 ($m_t = 174 \pm 5\,\mathrm{GeV}$). Internal and external radiation of real particles (photons, weak bosons, etc.) is routinely observed and taken into account in analyses, with detailed prescriptions for using experimental variables which make sense in the renormalization procedure and avoid divergences in the theoretical calculations.

The constituants are spin 1/2 fermions: leptons and quarks. We know three families of two leptons and two quarks each, with the second and third families replicating the first one in all aspects but the masses of the particles. The interactions are : the electro-weak (E-W) interaction, based on the gauge group SU(2)X U(1), and the strong interaction based on SU(3).

In a given family, the behaviour of the constituant fermions under an interaction is described by their location in the group multiplet representations:

Leptons and quarks are sensitive to the E-W interaction:

- left-handed states are doublets under SU(2).
- right-handed states are singlets under SU(2).
- One lepton has electric charge -1 (e, μ, τ) , the other is neutral (ν_e,ν_μ,ν_τ), the upper quark in the SU(2) doublet (u, c, t) has charge +2/3, the lower one (d,s,b) has charge -1/3 .
- Quarks are sensitive to the strong interaction: they are triplets under SU(3) (the strong charge is called 'color', and the strong interaction is referred to as Quantum Chromo Dynamics, in short QCD).

The number of families (3) is unexplained (but it is the minimal number which allows for CP violation, an effect with deep consequences, in particular for cosmology).

Although the particle masses are free parameters in the model, their sheer presence is central to the rationale behind the model. Indeed, the structure above would be easily realized if all particles were massless (or in the limit of very high energy where all masses would be negligible). But it is impossible to add masses 'by hand' to the constituants and keep the gauge symmetry structure, and consequently renormalizability. The question is to break gauge symmetry enough to get particle masses, while preserving it in depth. This is achieved by 'spontaneous symmetry breaking'.

In the SM, the ElectroWeak symmetry is broken down to separate weak and electromagnetic interactions. The standard way to achieve this breakdown is to introduce a scalar field (the Higgs boson) whose energy density is non-zero (positive) in the symmetrical vacuum. The value of this 'vacuum expectation value' determines the scale below which the symmetry appears as broken.

The system breaks the symmetry and choses a new fundamental state with minimum potential energy; then the fundamental fields are determined around this new vacuum. The messengers of the weak interaction (the W^+, W^-, Z^0 bosons) acquire a mass of the order of the Higgs vacuum expectation value, while the photon remains massless. Most importantly, the natural coupling of the constituant fermions with the Higgs provides them with a mass. The value of the masses are still free parameters, but now the theory with these masses is fully gauge invariant and renormalizable.

When the model was set-up, the W, Z and top quark had not been yet observed. Thus the experimental detection of the W and Z in 1983, precisely at the mass predicted by other previous measurements (neutrino scattering on nuclei), was a bright confirmation for the model. Since then, millions of Z's have been produced at LEP, and precision measurements have tested the whole scheme in great detail.

All the particles in the SM have now been observed, except the Higgs boson. The model does not predict its mass. For the standard Higgs boson, the LEP experiments have given a lower limit by direct search, $m_H > 113.5\,\mathrm{GeV}$, and an *upper limit* again through virtual effects : $m_H < 212\,\mathrm{GeV}$ at 95% confidence level. There is no real theoretical upper limit to the Higgs mass, but the natural range does not exceed $1\,\mathrm{TeV} = 1000\,\mathrm{GeV}$. For example, the width of a heavy Higgs is $\Gamma_H \sim 0.5 m_H^3$ (Γ_H, m_H in TeV) which shows that the Higgs is no longer a particle beyond $\sim 1\,\mathrm{TeV}$. More precisely, for Higgs masses larger than $\sim 800\,\mathrm{GeV}$, the interactions of W and Z bosons become strong and new structures must appear. We will see that LHC claims to explore completely this mass range. Nevertheless, it is interesting to study carefully the most unfavourable case, with a very heavy Higgs, and a new interaction which would turn on slowly, difficult to see experimentally.

1.2 Beyond the Standard Model

Although the Higgs mechanism is essential in the SM, its simplest implementation by the presence of a single scalar boson is far from satisfactory. The main concern is the 'naturalness' or 'fine-tuning' problem. We think that in the end the SM will be embedded in a more fundamental theory which will include larger mass scales. For example the unification of the strong and E-W interactions is thought to happen around 10^{16} GeV (from measurements of the evolution of their respective coupling strength with energy); even further, ultimately, a quantum gravity theory would be bring in its natural scale : the Planck mass (10^{19} GeV). Particles with these large masses would contribute to the Higgs self-energy, driving its mass up to the higher scale, unless a fortuitous cancellation occurs between these contributions. The required accuracy of this cancellation would be given typically by $m_i^2 - m_j^2 \sim m_W^2$, 28 orders of magnitude fine-tuning if $m_i \sim m_j \sim 10^{16}$ GeV, quite an unnatural coincidence.

The candidate theories to go beyond the SM essentially try to solve the fine-tuning problem in their own way.

1.2.1 Composite models/condensate models

In these models the Higgs is not elementary, hence solving the problem. In most implementations, quarks and leptons are also composite. Some of these models also try to explain the number of families as excited states of the same sub-constituants. Although being in the continuation of the 'russian doll' scheme for matter, no good model exists along these lines. Such signals of compositeness could anyway be observed at LHC.

1.2.2 Supersymmetry [2]

Supersymmetry is a symmetry between fermions and bosons. This theory has been developped since a long time, for a number of reasons: first it is the last possible type of symmetry among fields, not yet observed in nature, and up to now we have seen nature using all the symmetries we could think of. Second, it has a deep link with gravity. Our present understanding of gravity is general relativity, a classical field theory, and attempts at a quantum theory have been unsuccessful up to now. The most promising track is string theories, which make use of the connection between gravity and supersymmetry.

Last, supersymmetry solves the fine-tuning problem in an elegant way. The contributions to the Higgs mass, coming from the large mass fermions and bosons, cancel exactly in unbroken supersymmetry. The theory requires superpartners (s-particles) for each of the usual particles. As none of these partners has been observed, supersymmetry has to be broken at some scale. The naturalness argument leads to a supersymmetry breaking scale of the order of the E-W scale. In this scenario, a full spectrum of new particles could be there at masses of order ~ TeV, in the reach of LHC.

Supersymmetry is certainly the favored theory to go beyond the SM, despite the fact that no experimental sign has been found. An enormous amount of work has been devoted to evaluate the potential of LHC experiments on SUSY models. Many models can be constructed, with many free parameters. In order to study well defined cases, the physicists have defined a minimal supersymmetric standard model (MSSM). In this framework the Higgs sector is well defined, as we will see later, but for the other supersymmetric particles there are many variants, essentially in the precise way to implement the breaking of supersymmetry. An effort was brought to selecting the best defined models and exploring their parameter space consistently. The most popular one is the SUGRA model (SUper GRAvity inspired); the connexion to gravity is remote, but technically the model provides a 'reasonable' spectrum of all s-particles and Higgses, with only (!) 5 parameters.

An important aspect of supersymmetry is the link with cosmology, through the dark matter problem. Astrophysical measurements show that a large part of the matter in the universe does not radiate like ordinary matter (for a recent review, see for example [3]). In addition, this dark matter is believed to have a large non-baryonic part, and ordinary neutrinos can only contribute to a small amount. The whole scheme still has uncertainties, but taking it at face value, a large fraction ($\sim 20\%$) of the matter in the universe should be 'cold' dark matter, in the form of new particles, electrically neutral, stable, with a large mass. In many scenarios, the supersymmetric partner of the neutrino, called the neutralino ($\tilde{\chi}^0$), is the lightest supersymmetric particle (LSP), and is a good candidate for this particle. For a given model, one can crunch the usual big-bang scenario and calculate the relic density of neutralinos. In SUGRA models for example, requiring that the neutralino relic density be consistent with the cold dark matter selects a zone in the parameter space [4], which can be explored at LHC.

1.2.3 Extra dimensions

The idea that space-time could have more than 3+1 dimensions goes back to the Kaluza-Klein model, as early as 1919. These authors saw that writing general relativity in 5 dimensions, and 'compactifying' the 5th one on a small radius, one gets the classical theory of electromagnetism. This very appealing remark did not hold its promises, since noone succeeded in building a unified model of gravity and electromagnetism. In the eighties, the idea was revived because string theories, the candidate for a quantum theory of gravity, like to work in a higher-dimensional space-time. In this framework, our usual 4D space-time is what is left after 'compactification' of all other dimensions on a very small scale. It was first thought that this small scale was of the order of Planck's length (10^{-33} cm), or equivalently would be relevant for energies of the order of Planck's mass (10^{19} GeV). Recently, it was realized [5]that this needs not be the case.

In the simplest model[6], only gravity sees the extra dimensions, which could be as large as 1 mm, and the scale for quantum gravity is then $\sim$ 1 TeV. The extreme weakness of gravity at low energies comes from its 'dilution' in the extra dimensional volume, and the large value of Planck's mass is just an illusion: there is no mass scale higher than 1 TeV, which solves the fine-tuning problem. Again, for TeV scale quantum gravity, spectacular effects could be found at LHC.

2 The LHC

2.1 Machine [7] and experimental conditions

As soon as the LEP was approved, and well before its operation, physicists thought about putting a proton-proton collider in its tunnel. In the case of an electron accelerator like LEP, the beam energy is limited by synchrotron radiation losses: the loss must be compensated at each turn by accelerating cavities. The circumference of the LEP tunnel (27 km) was fixed to allow LEP to reach about 50 GeV per beam (100 GeV center of mass energy) with normal cavities, enough to produce on-shell Z^0 bosons, then 100 GeV per beam with superconducting cavities, enough to produce W pairs. In the case of proton beams, the energy is limited by the maximum field available in the bending (dipole) magnets. The design value for the field in the LHC superconducting magnets is 8.4 T, a ×1.8 increase from previous machines (and remember that the magnetic forces go like B^2). The 14 m long magnets operate in superfluid helium at 1.9 K. With this field value, the beam energy is 7 TeV, hence a proton-proton center of mass energy of 14 TeV.

Protons are not elementary: what really counts is the energy available in the collision of the point-like constituants (partons): quarks and gluons. As the quarks and gluons carry a fraction of the momentum of their parent proton, with a statistical distribution (structure function), there is a broad spectrum of collision energies at the constituant level. Of course the most interesting events are those with the highest collision energies: they are also the rarest, since they involve partons which carry an exceptionally large fraction of the proton momentum.

When the US physicists designed a machine to cover the same physics goal, namely explore exhaustively the E-W symmetry breaking mechanism, they chose a center of mass energy of 40 TeV and a circumference of 87 km (the SSC project, unfortunately discontinued in 1993). Limited by the pre-existing tunnel and by the attainable magnetic field, the LHC energy is 'only' of 14 TeV. To increase the discovery reach, the other handle is luminosity, the number of proton-proton encounters per second. The LHC luminosity will be $10^{34} cm^{-2} s^{-1}$, a factor of 10 larger than the SSC design. Typically a factor of 10 in luminosity provides the same rate of rare processes than a factor 1.5 to 2 increase in energy.

This very high luminosity will be achieved by storing a large number of intense proton bunches in each beam. The bunches are only 25 ns apart, and interactions occur at the 4 collision points every 25 ns. The interesting interactions between partons are rare, but the total collision rate between protons is enormous. The total p-p cross-section, from strong interactions, is expected to be about $8 \times 10^{-26} cm^2$, which means about 20 interactions per bunch crossing in average. Each of these interactions is an event with about 60 charged and 60 neutral particles in the acceptance of an experiment around the collision point. The experiment must deal with more than 1000 tracks and 2000 impacts every 25 ns, and yet extract rare signals at a rate of a few events per year. This pattern recognition problem calls for detectors with a very high number of cells or channels, a very fast response, and a large dynamic range.

The other consequence is that the radiation level coming from the interaction point is high, and imposes the use of radiation resistant technologies for most detectors.

2.2 Experiments

Two intersection regions are devoted to high-luminosity p-p collisions,with general purpose experiments: ATLAS and CMS. The other two regions are for the ALICE experiment, which studies ion-ion collisions, and the LHC-B experiment, which studies b-quark physics in medium luminosity p-p collisions. This talk will concentrate on physics at ATLAS and CMS.

When the first ideas of operation at high luminosity appeared (in 1984), the constraints coming from the event rate and radiation environment looked formidable, and it was first thought that the only possible experiment was an 'iron ball' around the interaction point, with only muon detection outside. Through a vigorous R and D program pursued in many labs around the world, it was shown that much more can be done, including precision measurements, detailed particle identification, and inclusive event reconstruction.

The experiments isolate the rare signals against the huge background by selecting processes with good signatures. As the background originates mostly from strong interactions, these signatures may involve the presence in the final state of:

- one or more lepton(s) : electrons, muons, and neutrinos (identified by the missing transverse energy).
- photons.
- b-quarks or c-quarks, identified by a displaced vertex.
- hadronic jets of high transverse momentum (from high momentum quarks and gluons).

Although the physics goals and the operation requirements are the same for both experiments, the technical choices for some of the detectors have been rather different, resulting in a real complementarity, as we can illustrate with a few examples:

The magnetic field in CMS is provided by a single, large superconducting solenoid (12 m long, 7 m diameter) with a high field (4T). In ATLAS, the magnet system includes a 'small' solenoid around the central region (7x3m) with a 2 T field, and a large (26m long, 20m diameter) system of 3 toroidal magnets for muon measurements. The CMS solution is conceptually simpler, but the ATLAS sytem should offer a safe measurement of muons in the outer spectrometer alone.

For the electromagnetic calorimeters, which measure the energy of electrons and photons, CMS has chosen scintillating crystals, while ATLAS has chosen a lead/liquid argon sampling technique. The CMS crystals have an excellent intrinsic energy resolution (typically 0.7% at 100 GeV), but it will be difficult to keep the calibration of their light output to the required accuracy (0.4%). On the opposite the ATLAS solution has only a fair intrinsic energy resolution (typ. 1.2% at 100 GeV), but should be very stable in time.

The number of electronic channels amounts to tens of millions in the central track detectors, and hundred of thousands for calorimeters and muons chambers. It is of course impossible to record all the read-outs for every bunch crossing: the trigger system selects interesting events for recording. The selection is made in several (usually 3) levels, the next level up analyzing events in more detail and being more selective. It is very important to establish 'trigger menus' large enough not to miss any new physics processes, but which keep the accepted rate inside the available bandwidth.

ATLAS and CMS are two large international collaborations, each with ~ 150 participating institutions and more than a thousand physicists. Both were approved in 1996, and are under construction now.

2.3 Simulation

An important part of the preparation work has been devoted to simulations. The collaborations have made exhaustive studies of the LHC physics, starting from available or customized event generators, and going sometimes to the finest detail of the experiment. These simulations have been used to optimize the detectors, design analysis algorithms, and in general evaluate the performance on every physics channel one could think of. Most of the material presented here comes from this work.

3 The Standard Model Higgs

Assuming a mass for the Higgs boson, one can calculate its production cross-section, and the probability for each of its decay modes. As the decay modes change strongly depending on the mass, the search involves different detectors and analyses. Thus the search for the Standard Model Higgs has quickly become the benchmark for detector optimization, and has been studied in great detail.

Several processes contribute to the production of Higgs bosons: $g\overline{g} \to H$ through a heavy quark loop, $qq \to qqH$ ("WWfusion"), $q\overline{q} \to WH$, $gg \to t\overline{t}H$, $gg \to b\overline{b}H$. The relative importance of these processes depends upon the Higgs mass, the first dominates at small mass and the first two become comparable for a Higgs mass of 1 TeV. The Higgs branching ratios are shown in Fig. 1.

3.1 $H \to \gamma\gamma, 115\,\mathrm{GeV} < \mathrm{m_H} < 140\,\mathrm{GeV}$

At low mass ($114\,\mathrm{GeV} < \mathrm{m_H} < 2 \times \mathrm{m_W}$) the main decay modes ($b\overline{b}$, $c\overline{c}$, $\tau^+\tau^-$) cannot be distinguished from the QCD background. One possibility is the decay mode $H \to \gamma\gamma$ which has a tiny branching ratio, but where two photons in the final state offer a rather good signature. This search is very demanding on the detector and has been used as a benchmark for the performance of electromagnetic calorimeters, hence it is interesting to look at it in some detail.

First, one has to identify the two photons. In the same invariant mass range (say, 120 GeV), the rate of jet pairs, coming from QCD processes like $gg \to gg, qg \to qg$,etc. is $\sim 10^6$ times larger than the signal; there are also $jet - \gamma$ events at a rate $\sim 10^3\times$ signal. It may seem obvious to discriminate a jet of particles from an isolated photon, but here we need a rejection of more than 1000 against each jet. Jets are made of charged particles (mostly charged pions) and neutral particles, mostly π^0's which decay instantaneously into two photons. Small detector inefficiencies can indeed fake single photons at a very low level. Particular jet configurations are also dangerous: in about 1 case in 1000 a quark hadronizes into a single π^0; with a π^0 momentum of 60 GeV, the two photons from the decay of this π^0 will be only 7 mm apart at the entrance face of the calorimeter, quite difficult to tell from a single photon. The ATLAS and CMS detectors devote 84000 (resp. 140000) read-out channels to a fine-grain section, whose main goal is to gain a factor of 3 rejection against π^0's in this particular search. To reject jets, analyses also require that the energy deposit associated to the photon be isolated, at the expense of a small (±10%) loss in efficiency on the signal.

Then there is a large irreducible background from processes like $q\overline{q} \to \gamma\gamma$, $gg \to \gamma\gamma$, $qg \to q\gamma\gamma$ which produce photon pairs with a continuous mass spectrum. The Higgs would appear as a peak in the photon pair invariant mass distribution, hence the signal to noise ratio depends directly on the mass resolution. The invariant mass is evaluated by $m^2 = 2E_1E_2 \times (1 - cos\theta)$, thus it depends on the energy resolution for each photon, and on the determination of the angle θ between the photons. The energy resolution is given by the performance of the electromagnetic calorimeter. The

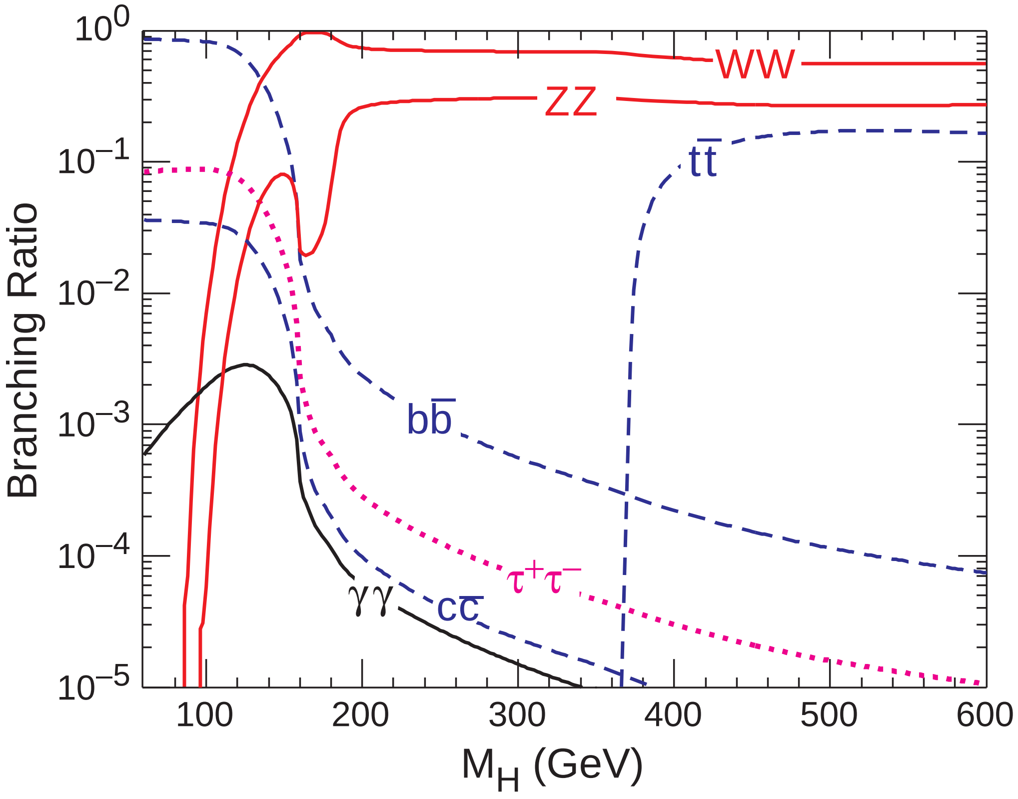

Figure 1: Standard Model Higgs branching ratios as a function of mass

measurement of the angle poses a challenge quite special to LHC: in an usual experiment, there would be only one interaction vertex, and the direction of a photon would be obtained simply by linking the impact point in the calorimeter to this vertex. At LHC, there are 20 interaction vertices per bunch crossing in average, distributed over 5.6 cm around the nominal crossing point. It is not so easy to associate the right vertex to the photon impact! The solution is to use the calorimeter for measuring not only the energy and position, but also the direction of the photon, and/or to select among all vertices the most probable good one, on other criteria like the multiplicity of tracks above some momentum.

Very detailed simulations have been performed on this channel. The result of such a simulation in CMS is shown in Fig. 2.

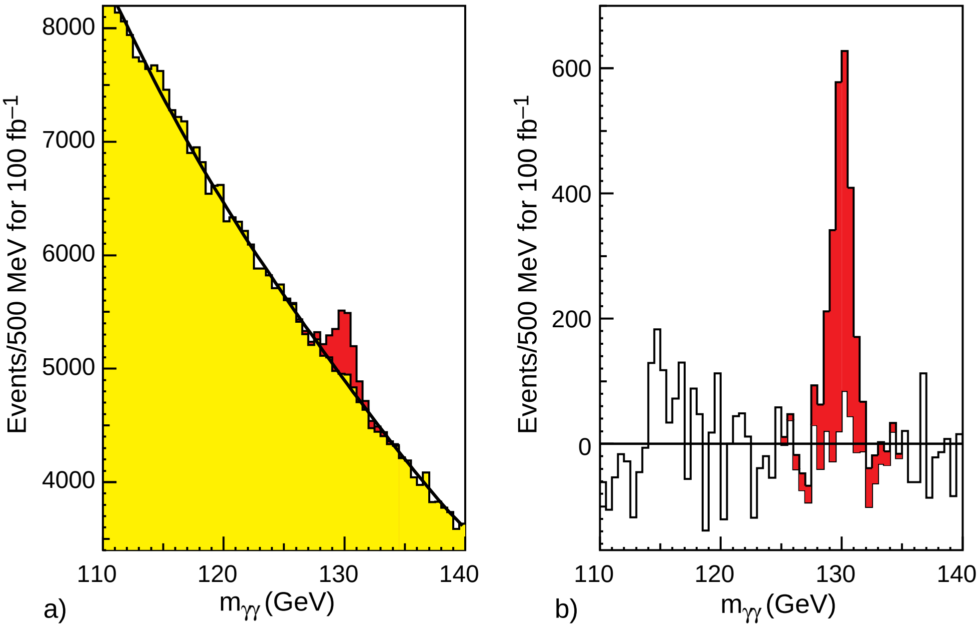

Figure 2: (a) The invariant mass distribution of $\gamma\gamma$ pairs for $M_h = 130\,\mathrm{GeV}$ as simulated by the CMS collaboration. (b) Same, with a smooth background fitted and subtracted. From Ref. [8].

3.2 W (or $t\bar{t}$) + $H \to b\bar{b}$, $115\,\mathrm{GeV} < \mathrm{m_H} < 130\,\mathrm{GeV}$

As we said above, it is impossible to extract a signal of a low mass Higgs in the dominant decay mode $H \to b\bar{b}$ if no other signature is present. However, there are processes where the Higgs is produced in association with a W or a $t\bar{t}$ pair. In this case, one can ask for a electron or muon from the W (top quark) decay, which reduces the background by a large amount. Then, the capacity of the detector in identifying b-quarks is essential. Mesons and baryons containing b-quarks are known to decay with a typical lifetime of $\sim$ 1.5 picosecond, hence they travel a small distance (hundreds of microns) away from the primary vertex, before decaying. Such displaced vertices can be measured by precision silicon strip track detectors with excellent results as demonstrated at LEP, Tevatron or B-factories. The question was if such precise measurements could be performed in the crowded environment of LHC, an if the silicon detectors, located close to the beam pipe, could survive the radiation.

Building and operating large silicon detectors and their electronics in a radiation environment is a whole field in technology. A lot of progress was done by the LHC experiments, in collaboration with teams interested in other uses, like electronics for space applications. For the pattern recognition problem, LHC vertex detectors have hundreds of times more channels than their predecessors. Again, detailed simulations predict that the b-tagging efficiency will be at least as good as that of the present CDF experiment at FNAL for example, despite the environment. In the end, a signal in this mode would be just visible, and would provide a confirmation of the $\gamma\gamma$ channel.

3.3 $H \to ZZ^* \to 4\,leptons$ (e **or** μ), $150\,\mathrm{GeV} < \mathrm{m_H} < 600\,\mathrm{GeV}$

If the Higgs mass exceeds $2 \times m_Z$, then the main decay modes are W^+W^- (70%) and ZZ (30%). The Z decays in an e^+e^- or $\mu^+\mu^-$ with a 3% branching ratio (each). $H \to ZZ \to 4\,leptons(e\,or\,\mu)$ are gold plated events, offering excellent signature and mass resolution. This mode allows an easy detection of a Higgs signal for $2 \times m_Z < m_H < 600\,\mathrm{GeV}$; for larger m_H, the Higgs production rate decreases, and at the same time its decay width increases, which spreads the mass peak over the background continuum. The study can be extended to m_H lower than $2 \times m_Z$ down to $\sim 150\,\mathrm{GeV}$: the Higgs can still decay to the same 4-lepton modes, although at least one of the intermediate Z's is off-shell. In this range, the study is more difficult and demands more on the detector resolution. Backgrounds such as $t\bar{t}$ and $Z + b\bar{b}$ contribute, in addition to the ZZ continuum (present at all masses).

3.4 $m_H > 600\,\mathrm{GeV}$

For large Higgs masses, one must search for more frequent decay modes of the W and Z's, at the expense of more difficult signatures. The first mode is $H \to ZZ \to ll\nu\overline{\nu}$, with one Z decaying into an electron or muon pair, and the other into a neutrino pair. Neutrinos are of course not detected individually, but their presence is marked by missing transverse energy when accounting for all the energies measured by the experiment (at a proton machine, the longitudinal momentum balance cannot be used, since the frame of the elementary collision between partons moves along the beam line). The background sources are the physical continuum of ZZ production, but also instrumental effects which can generate fake missing transverse energy, like inefficient areas in the detector. The detectors need to cover the full solid angle around the interaction point, in particular the forward region close to the beam pipe, eitherwise the statistical fluctuations of the other events occuring in the same bunch crossing ('pile-up events') would also contribute to the background.

Fig. 3 shows the missing transverse energy spectrum as simulated in ATLAS for a 700 GeV mass Higgs.

Then the modes $H \to WW \to l\nu + jets$ and $H \to ZZ \to l\bar{l} + jets$ have an even larger branching ratio. However, the background from ordinary production of $W + jets$ and $Z + jets$ is very large. In the signal the jet pair invariant mass is m_W or m_Z; the signal to noise ratio depends on the jet pair mass resolution which in turn depends on the performance of the hadronic calorimeter, and on the reconstruction algorithm.

For very high Higgs masses, the dominant production mode is $qq \to Hqq$, where the Higgs is produced in association with two jets in the forward and backward direction. The detectors have been optimized to measure these jets at small angle from the beam-line, a difficult region crowded with high-momentum particles and submitted to very high radiation levels. These modes should allow the detection of a Higgs up to a mass of 1 TeV.

3.5 Summary of Standard Model Higgs

Combining the analyses above, the mass range from the LEP limit to 1 TeV is covered. Fig. 4 shows for example in Atlas the statistical significance of a Higgs signal as a function of mass over the whole range.

We should not forget that the LEP results favor the low mass region: 114 GeVto $\sim 250\,\mathrm{GeV}$. From 114 to 160 GeV the detection of a Higgs at LHC relies on the mode $H \to \gamma\gamma$, the mode $W + H \to b\bar{b}$ and the lowest part of the mode $H \to ZZ^* \to 4\,leptons$, and requires all the detector capacity. Above 160 GeV the mode $H \to ZZ^* \to 4\,leptons$ allows for an easy detection.

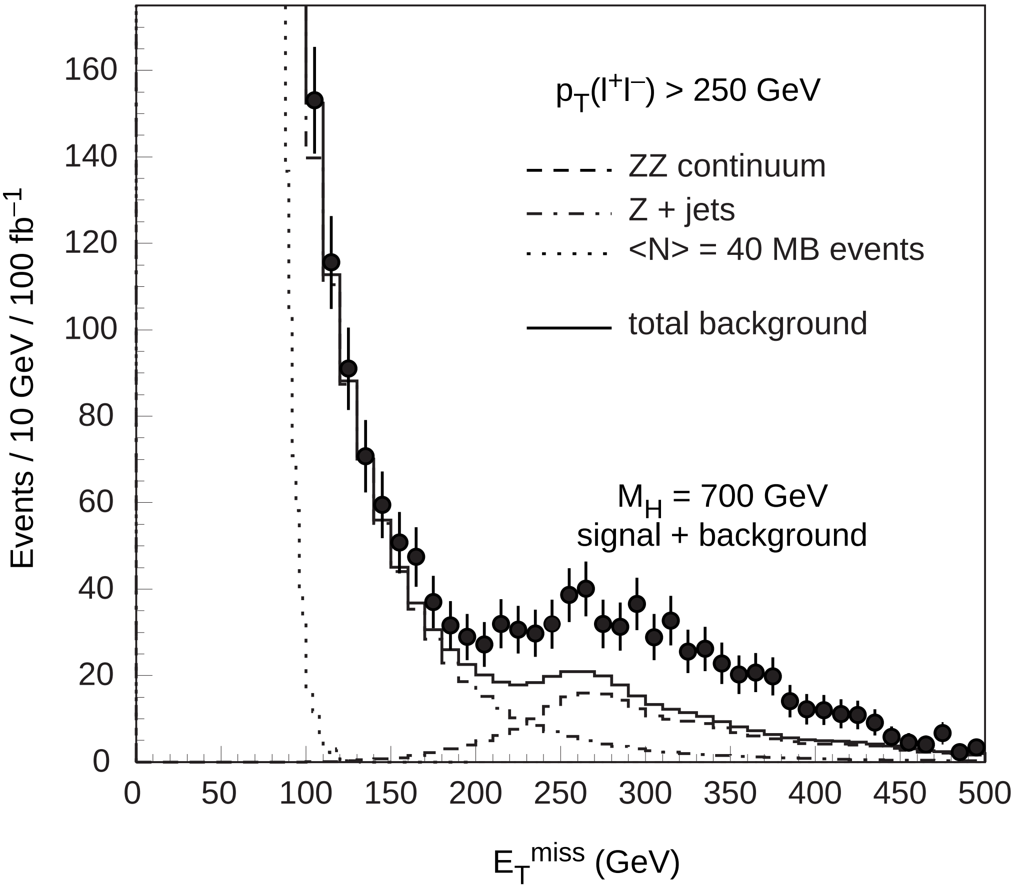

Figure 3: Missing E_T spectrum for the $H \to ZZ \to \ell\ell\nu\overline{\nu}$ process. The background contributions are shown separately; $Z + jets$ (dot-dashed); ZZ (dotted) and minimum bias pile up (dashed). The signal is due to a Higgs boson of mass 700 GeV. From Ref. [9].

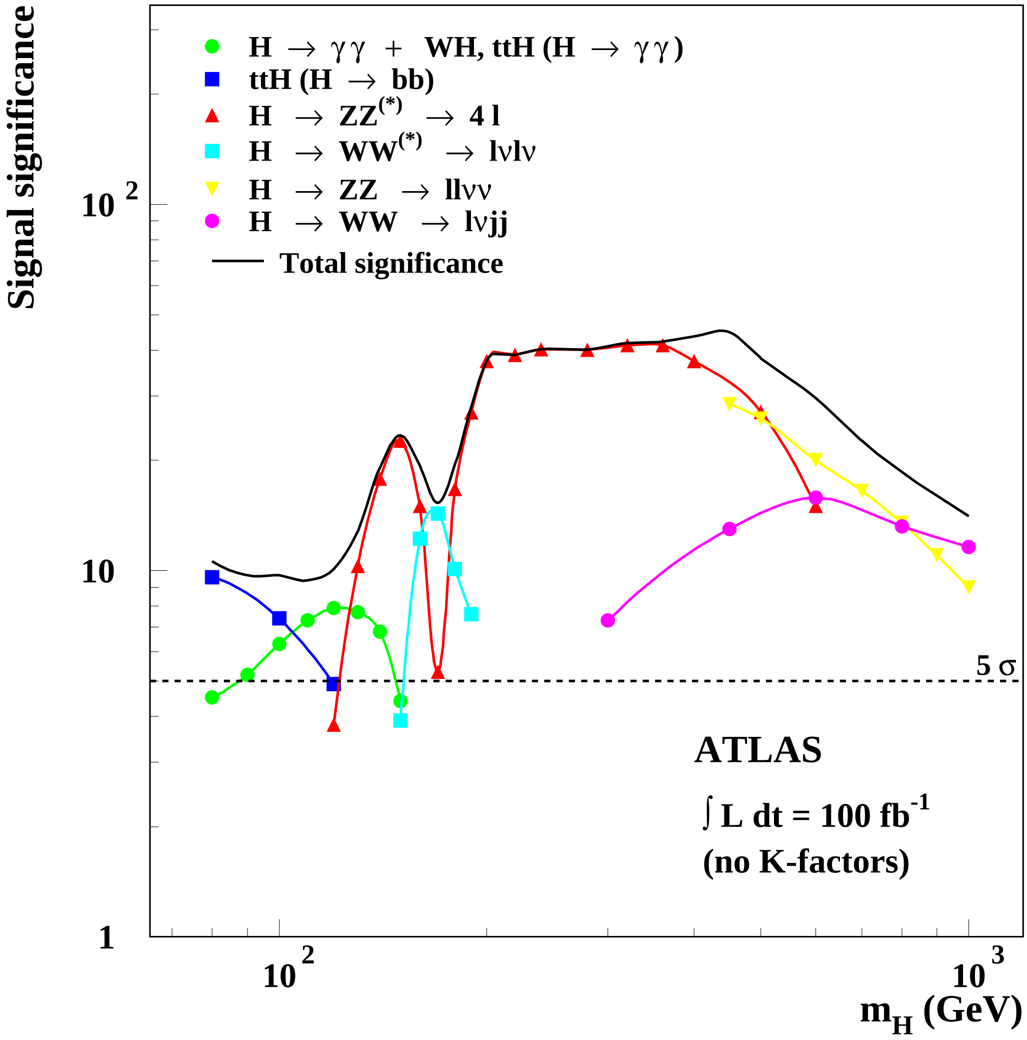

Figure 4: ATLAS experiment sensitivity for the discovery of a Standard Model Higgs boson From Ref. [9].

4 The Higgs sector in Supersymmetry

In supersymmetric theories, the Higgs sector is more complex than in the SM. In the MSSM, there are two different Higgs fields with two vacuum expectation values. The analysis of the physical states turn up two charged ($H^{\pm}$) and three neutral (h, H, A) scalar particles. Their masses and couplings are basically determined by two parameters, usually taken as the mass of the A (m_A) and $tan\beta$, the ratio of the two vacuum expectation values. Radiative corrections from loops containing ordinary or supersymmetric particles modify the values of masses and couplings, sometimes substantially. For example, without these corrections, one of the neutral Higgses, the h, would have a mass always *lower* than m_Z, but with corrections, this upper limit can reach 150 GeV for large values of m_A and $tan\beta$.

To limit the parameter space to just these two, we first assume that all supersymmetric partners of usual particles have large masses (TeV); in this case the Higgses can only decay into ordinary particles. The production cross-sections of the 5 Higgses, and their different branching ratios to ordinary particles, vary across the $m_A, tan\beta$ plane. The study of the experiment potential for one particular decay mode of one of the Higgses is expressed as a contour in this plane, inside which a statistically significant signal (5σ) would be observed. Fig. 5 shows the compilation of all these studies in ATLAS. It would be too long to go into the detail of each study, but a few remarks may be made.

The first important message is that the entire plane is covered by the reunion of all contours, meaning that in all cases at least one supersymmetric Higgs would be observed. The main features of this coverage go as follows:

- At large m_A, the h behaves like a Standard Model Higgs with a mass lower than 150 GeV. Thus it can be detected in the $h \rightarrow \gamma\gamma$ mode as we have seen. However it would be impossible to tell that this is a *supersymmetric* Higgs and not the Standard one.
- At large $tan\beta$, the branching ratios of H and A into $\tau^+\tau$ (tau lepton pair) is high, and this mode can be detected. This does not have an equivalent in Standard Model studies, and was looked at carefully. The reconstruction of the H or A mass is difficult because the τ decays always contain neutrinos which go undetected. The critical ingredient is the missing transverse energy resolution of the detector.

At lower values of m_A and $tan\beta$, several modes can be observed. The observation of more than one mode would bring redundancy and confirm the supersymmetric nature of the Higgses.

More precise studies must take into account the possibility that the Higgses decay into s-particles or couple to them. There are much too many parameters in the general MSSM, so this can only be attempted in a restricted model as SUGRA. The main conclusions are:

- The overall observability of the h boson through $\gamma\gamma$ or $b\overline{b}$ decays is unaffected.
- In a substantial part of the parameter space, the H boson decays to s-particles (namely neutralinos $\tilde{\chi}^0$ and charginos $\tilde{\chi}^{\pm}$) and this can be detected, although not easily. This would be very important as it would allow to discriminate between a SM Higgs (only seen in $h \rightarrow \gamma\gamma$) and a supersymmetric one.
- In a large region of the parameter space, the h can be produced in the cascade decays of s-particles, together with other particles with a very characteristic signature. It can then be detected in its dominant decay mode $b\overline{b}$, which increases the overall sensitivity to the Higgs sector.

5 Supersymmetric particles

In the early searches of supersymmetry at existing machines, or studies for LHC, there were no precise models, and the only signature which people thought of was missing energy. Indeed, if s-particles are produced, their decay products must contain the LSP which would go undetected. The most visible processes would then be of the type $qq \rightarrow \tilde{q}\overline{\tilde{q}} \rightarrow q + \tilde{\chi}_0 + \overline{q} + \tilde{\chi}_0$. The cross-section

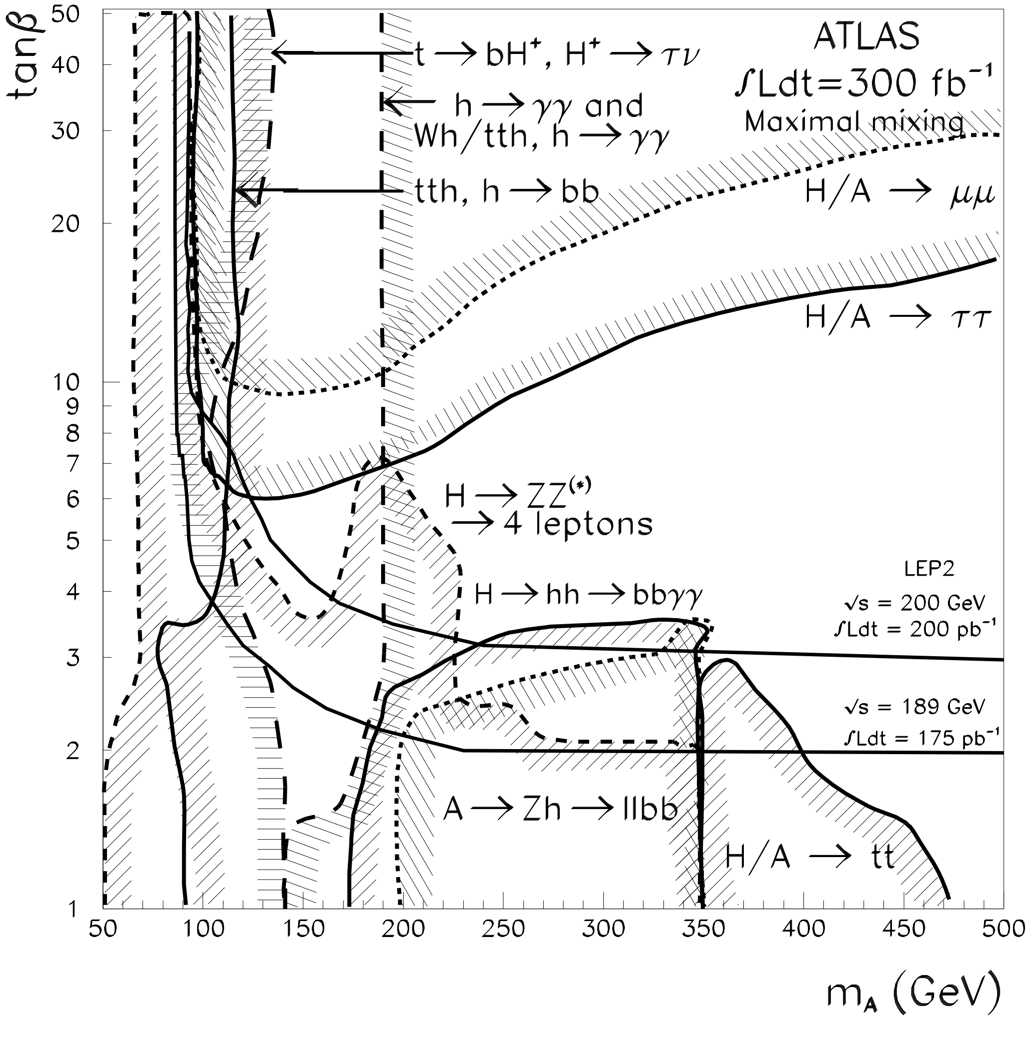

Figure 5: ATLAS experiment sensitivity for the discovery of a Supersymmetric Higgs boson: 5 σ discovery contours in the plane $m_A, tan(\beta)$ From Ref. [9].

for such processes is high because the s-quarks are produced by strong interactions, and the event contains two very hard jets recoiling against nothing, a case with no equivalent in the Standard Model (hence no background).

This simple picture is still valid if we assume very high masses for the s-particles: then the discovery reach is just rate limited. For s-quarks and gluino masses of 2 TeV, we expect a few spectacular events, which would be unambiguous signs of supersymmetry, but would not bring much information beyond this fact.

The studies of the last few years have brought in a different picture, with precise models which give the complete spectrum of s-particles masses and couplings. For a large domain in the parameter space (s-particle masses of the order of, or below, 1 TeV), we now expect a rich phenomenology, with the production of many particle types, complex and beautiful cascade decays, allowing for precision measurements. In fact, the problem would not be to show evidence for supersymmetry as a whole, but to separate the different channels, and discriminate between models. In many cases, the background behind the studied signal comes from other supersymmetric processes!

Let us look at one of these scenarios: a SUGRA model with the parameters chosen to be 'cosmologically' correct. As in the simple case above, the strongest reactions produce squarks and gluinos (which then decay to a squark $\tilde{q}$ and a normal quark q).

Now the decay chain for each squark can be much more complex, and far more interesting:

$$\tilde{q} \to \tilde{\chi}_2^0 q \to \tilde{\ell}^{\pm}\ell^{\mp} q \to \tilde{\chi_1}^0 \ell^+ \ell^- q$$

As two squarks were produced, this would give an event with 4 leptons (e or μ), 2 jets, and missing transverse energy. A lot of information can be extracted from such events; in particular the analysis of the event kinematics allows for a determination of the neutralino mass to about 10%, which would be of great importance for cosmology (this was not possible in the early inclusive studies).

Many more studies were performed on SUSY models, which would be too long to report here. Let us mention the GMSB (Gauge mediated symmetry breaking) models, where the LSP is not the neutralino but the gravitino (the s-partner of the graviton). These models have a rather different phenomenology which can be challenging for the detector.

As a summary I would take Fig. 6. This plot is in the plane of the two most important parameters of SUGRA, for a 'reasonable choice' of the other 3 parameters. The figure shows the 'cosmological' area, (where the LSP relic density is between 10% and 30% of the critical density), the reach of LHC in an inclusive squark or gluino search ($m_{\tilde{q}}, m_{\tilde{g}} < 2\,\mathrm{TeV}$), and the area where the cascade decay above allows for precision measurements and an estimate of the LSP mass. The inclusive search covers all the the cosmologically allowed domain, and it it is tantalizing that in a large part of it the most interesting studies are possible.

6 Extra dimensions

Since the appearance of the idea that extra-dimensions could be as close as the TeV scale, the number of publications on this topic has exploded: at least 50 papers published each month since year 2000! For the phenomenology at LHC, there are two main classes of models: 'factorizable' and 'non-factorizable' geometries. In factorizable geometries, the extra (compactified) dimensions are just added to the metric, without changing the usual part. Then one can decide which particles have access to all dimensions (the 'bulk') and which remain in our good old world (the 'brane'). In every model, the graviton has access to the bulk, in order to 'dilute' gravity and make it very weak in our world.

In the earliest model [6], only the graviton was allowed to propagate in the bulk. The parameters of the model are the number of extra dimensions n_D and the fundamental mass scale M_D . Planck's mass as it appears to us is related to M_D by the relation: $M^2_{Planck(4D)} = r^{n_D} M_D^{n_D+2}$, where r is the size of the extra dimensions. Taking M_D of order 1 TeV, we see that $n_D = 1$ is obviously excluded as it would make $r \sim 10^{13}$m, and modify gravity in the solar system. $n_D = 2$ and $M_D \sim$ TeV is just allowed, as it would modify gravity at a distance of less than 1 mm. This model appeared because it was realized that we did not have a good measurement of the gravitational force

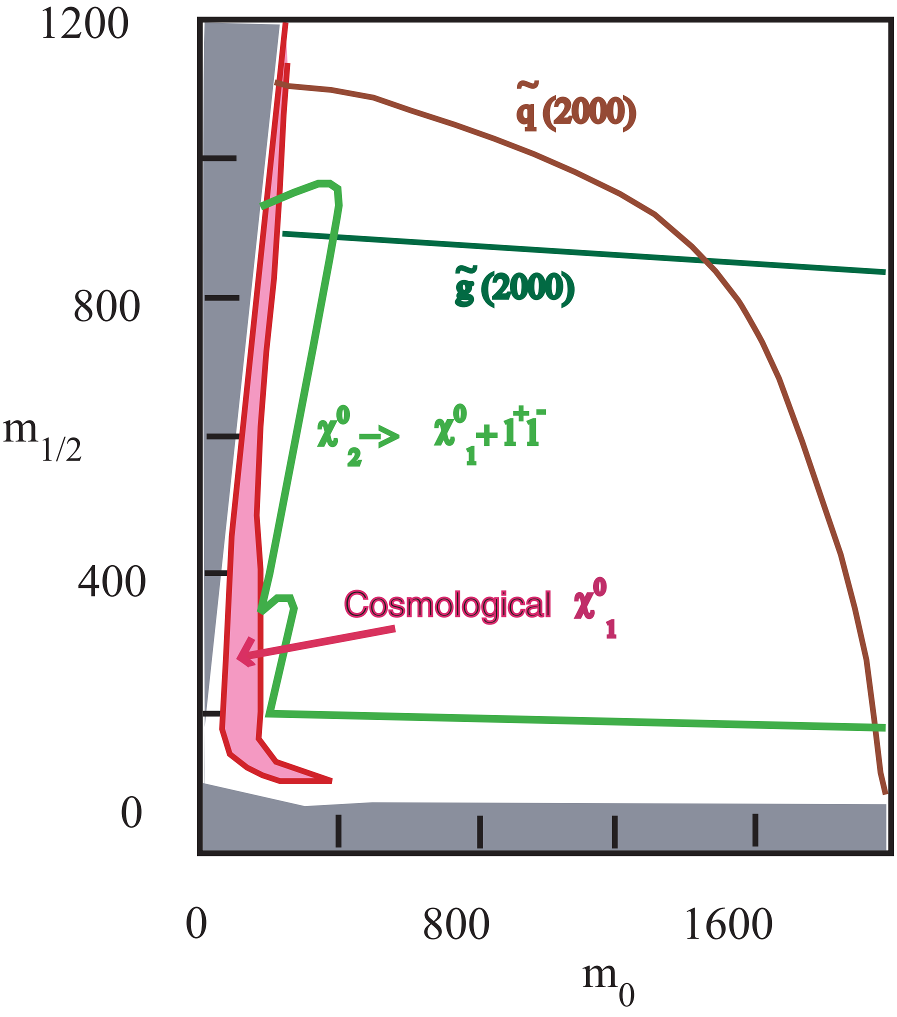

Figure 6: In the plane of the SUGRA parameters, the zone where the neutralino is the cosmologically preferred cold dark matter, with the reach of LHC experiments for $\tilde{q}$ and $\tilde{g}$ discovery (below the curves), and the area where a cascade decay is observable (below the curve, see text).

in $1/r^2$ below 1 mm! Since then several laboratory experiments (Cavendish-type) have been started to improve this knowledge, see for example [10]; present limits are $r < 0.2mm$ and $M_D > 4\,\mathrm{TeV}$ for $n_D = 2$. The graviton has many 'Kaluza-Klein excitations', essentially modes around the extra dimensions compactified on a circle. Take a process like $quark + gluon \rightarrow quark + Graviton$. At low energies, this cross-section would be extremely small: in ordinary terms the right part (graviton/quark coupling) is just the gravitational mass of the quark. In terms of coupling it is suppressed by $1/M_{Planck}$, a very small number indeed. But now, when the energy becomes of the order of M_D, gravity becomes strong and it becomes highly probable to emit a graviton or one of its excitations, which then vanishes into the extra dimensions. Seen in the lab, this appears as an event where an invisible particle has been emitted, and this particle has a continuous spectrum of masses, a very unusual signal. For $n_D = 2$, LHC could see such events for M_D up to 9 TeV.

As an extension of this model, one can allow for example the gauge bosons to propagate in the bulk, a rather natural prescription if m_D is at the weak scale. Then these bosons acquire Kaluza-Klein excitations, with masses given by an harmonic formula such as $m_i^2 = m_0^2 + i^2 m_D^2$. The first states would just look like a W' or a Z', i.e. a heavy W or Z, with the same decay modes as the W and Z. Heavy W' or Z's appear in several other theories, and the potential for their discovery was studied as such. The reach of LHC is about 5 TeV for a Z' and 6 TeV for a W'.

In the other important class of models, non-factorizable geometries, the metric is no longer the simple superposition of extra and normal dimensions; the original model [11] is with 5 dimensions: there is the usual 4D 'brane' of our world, and another similar brane, parallel to the first one and separated from it by some distance in the 5th dimension, and the 4D metric is intricated into the 5D one. Gravity is mainly located on the other brane, and what remains on ours is exponentially weak. All the fields are sensitive to the extra dimension, and have Kaluza-Klein excitations, which appear as new particles. The spacing of these partners is different from the case of factorizable geometry, and would be a strong indication. The graviton also has TeV-scale excitations, which would decay into jets, leptons or photons. Note that the angular distribution of these decays would show the spin-2 nature of the particle, quite an unambiguous sign for a graviton.

In summary, extra-dimensions theories are highly speculative. But the same argument is true, that if they have anything to do with ElectroWeak symmetry breaking, a sign should show up at LHC.

7 And if?

The question is often asked : What if there is no Supersymmetry, no extra-dimensions, and even no Standard Model Higgs below 1 TeV? If the Higgs mass goes beyond 1 TeV, then the interaction between W's would become strong for W momenta of $\sim$ 1 TeV, and ultimately the diffusion process of two W's would violate unitarity (i.e. get an interaction probability greater than 1). So something must happen. One way out is to invoke a strong interaction between W's, which would more or less cancel the problem. There are candidates for such an interaction, like compositeness models or Technicolor models (a kind of new strong force) but as we said above none is really satisfactory. However, one can design phenomenological models without a fundamental basis, just to see what an experiment would detect in such a case. Quite naturally, most phenomenological models involve resonances between W's, which would be seen as large signals at LHC. Now if one really wants to be nasty, it is possible to construct a phenomenological model which removes the unitarity problem 'a minima', without any resonance and with as smooth a behaviour as possible [12]. Then the only possible sign to look at is an abnormal rise of the WW cross-section at the extreme end of the WW mass spectrum. We must admit that this would be very difficult to observe at LHC (a 4σ excess over a large background). Indeed the 40 TeV of the former SSC were chosen to give a clear answer even in this case. Upgrades of the LHC luminosity or energy are being considered to face this very unfavorable situation.

8 Standard Model physics

Besides all the new physics we can dream of discovering, there are many measurements in the Standard Model which will be improved at LHC. As an example the top quark mass can be determined to an accuracy better than ±2 GeV. Jet and direct photon measurements will be used to test QCD, the theory of strong interactions, into a new domain. A rich program of B-physics will also be possible, with for example a measurement of the CP-violation parameter $sin2\beta$, to ±0.02.

9 Conclusion

The Standard Model provides a very operative description of what we know about the elementary bricks of nature and their interactions. It is rather frustrating that particle masses (may be the simplest characteristic of a particle) are free parameters in the model. However, we know that there is a deep connection between particle masses and the ElectroWeak symmetry breaking mechanism. This connection was already seen in virtual effects in previous accelerators, like LEP, but LHC will have the potential for studying it at its natural energy scale. It is not surprising that all theories put forward today to subtend the EW breaking mechanism, predict measurable or even spectacular signals at LHC. This is the motivation of hundreds of experimentalists, who devote ten or fifteen years to this very challenging project, and look forward to the first collisions in 2007.

Acknowledgments

I thank all my ATLAS and CMS colleagues who have carried out most of the work presented here. A good guide to this work can be found in the review by J.G. Branson, D.Denegri, I. Hinchliffe, F. Gianotti, F.E. Paige and P. Sphicas [13].

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