The LHC PHYSICS PROGRAM

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The physics program of the Large Hadron Collider is summarized.

1. Introduction

This presentation is intended to summarize the physics potential of the Large Hadron Collider (LHC) and explain the reasons why it is a crucial next step in our understanding of the behavior of nature. Despite the limited space available, it is hoped that the reader will be convinced that this physics potential is enormous. Among currently approved projects, the LHC is unique in that it is the only one that has sufficient energy and luminosity to probe in detail the energy scale relevant to electroweak symmetry breaking, while also enabling exploration of heavy flavor physics and quark-gluon plasma.

1.1. The Standard Model

The Standard Model (SM) is a very successful description of the interactions of the components of matter at the smallest scales ($\lesssim 10^{-18}$ m) and highest energies (~ 200 GeV) accessible to current experiments. It is a quantum field theory which describes the interaction of three generations of spin-$\frac{1}{2}$, point-like quarks and leptons, whose interactions are mediated by spin-1 gauge bosons.

In the SM the $SU(2)\times U(1)$ symmetry group (which describes the Electroweak interaction) is spontaneously broken by the existence of a (postulated) Higgs field with non-zero expectation value. This leads to the emergence of massive vector bosons, the $W^{\pm}$ and Z, which mediate the weak interaction, while the photon of electromagnetism remains massless. One physical degree of freedom remains in the Higgs sector, which should be manifest as a neutral scalar boson H^0, but which is presently unobserved. The basic elements of the Standard Model were proposed in the 1960's and 1970's [5]. Increasing experimental evidence of the correctness of the model accumulated through 1970's and 1980's:

- SLAC deep inelastic scattering experiments showed the existence of point-like scattering centers inside nucleons, later identified with quarks [6]
- observation of the c and b quarks [7]
- observation of neutral weak currents (Z exchange) [8]
- observation of jet structure and three-jet final states (gluon radiation) in e^+e^- and hadron-hadron collisions [9]
- direct observation of the W and Z at the CERN SPS collider [11]

Following these discoveries, an era of consolidation has been entered. Ever more precise experiments have been carried out at LEP and SLC which have provided verification of the couplings of quarks and leptons to the gauge bosons at the level of 1-loop radiative corrections ($\sim \mathcal{O}(10^{-3})$). The top quark was discovered at Fermilab in 1995, with a very large mass ($\sim 175\,\mathrm{GeV}$) [10].

Only two particles from the Standard Model have yet to be observed; ν_τ and the Higgs boson. Of these the latter is more important as it holds the key to the generation of W, Z, quark and lepton masses. Some of the SM parameters, particularly those of the CKM matrix are not well determined. Experiments over the next few years involving CP violation in the K[3] and B systems [4] should determine these parameters or demonstrate the SM cannot adequately explain CP violation.

1.2. Beyond the Standard Model

The success of the standard model[5] of strong (QCD), weak and electromagnetic interactions has drawn increased attention to its limitations. In its simplest version, the model has 19 parameters [12], the three coupling constants of the gauge theory $SU(3) \times SU(2) \times U(1)$, three lepton and six quark masses, the mass of the Z boson which sets the scale of weak interactions, and the four CKM (quark-mixing) parameters. All of these parameters are determined with varying errors. Of the two remaining, one, a CP violating parameter associated with the strong interactions, must be very small. The last parameter is associated with the mechanism responsible for the breakdown the electroweak $SU(2) \times U(1)$ to $U(1)_{em}$. This can be taken as the mass of the, as yet undiscovered, Higgs boson. The couplings of the Higgs boson are determined once its mass is given.

Unfortunately, within the model we have no guidance on the expected mass of the Higgs boson. The current (summer 1997) experimental lower bound is 77 GeV [19]. As its mass increases, the self couplings and the couplings to the W and Z bosons grow [13]. This feature has a very important consequence: either the Higgs boson must have a mass less than about 800 GeV or the dynamics of WW and ZZ interactions with center of mass energies of order 1 TeV will reveal new structure. It is this simple argument that sets the energy scale that must be reached to guarantee that an experiment will be able to provide information on the nature of electroweak symmetry breaking.

The presence of a single elementary scalar boson is distasteful to many theorists. If the theory is part of some more fundamental theory, which has some other larger mass scale (such as the scale of grand unification or the Planck scale), there is a serious "fine tuning" or naturalness problem. Radiative corrections to the Higgs boson mass result in a value that is driven to the larger scale unless some delicate cancellation is engineered ($m_0^2 - m_1^2 \sim M_W^2$ where m_0 and m_1 are order 10^{15} GeV or larger). There are two ways out of this problem which involve new physics on the scale of 1 TeV. New strong dynamics could enter that provide the scale of m_W, or new particles could appear so that the larger scale is still possible, but the divergences are cancelled on a much smaller scale. In any of the options, standard model, new dynamics or cancellations, the energy scale is the same; something must be discovered on the TeV scale.

Supersymmetry is an appealing concept for which there is, at present, no experimental evidence [14]. It offers the only presently known mechanism for incorporating gravity into the quantum theory of particle interactions and provides an elegant cancellation mechanism for the divergences provided that at the electroweak scale the theory is supersymmetric. The successes if the Standard Model (such as precision electroweak predictions) are retained, while avoiding any fine tuning of the Higgs mass. Some supersymmetric models allow for the unification of gauge couplings at a high scale and a consequent reduction of the number of arbitrary parameters. Supersymmetric models postulate the existence of superpartners for all the presently observed particles: bosonic superpartners of fermions (squarks $\tilde{q}$ and sleptons $\tilde{\ell}$), and fermionic superpartners of bosons (gluinos $\tilde{g}$ and gauginos $\tilde{\chi}_i^0$, $\tilde{\chi}_i^{\pm}$). There are also multiple Higgs bosons: h, H, A and $H^{\pm}$. There is thus a large spectrum of presently unobserved particles, whose exact masses, couplings and decay chains are calculable in the theory given certain parameters. Unfortunately these parameters are unknown. Nonetheless, if supersymmetry is to have anything to do with electroweak symmetry breaking, the masses should be in the region 100 GeV – 1 TeV.

An example of the strong coupling this scenario is "technicolor" or models based on dynamical symmetry breaking[15]. Again, if the dynamics is to have anything to do with Electroweak Symmetry breaking we would expect new states in the region 100 GeV – 1 TeV; most models predict a large spectrum. An elegant implementation of this appealing idea is lacking. However, all models predict structure in the WW scattering amplitude at around 1 TeV center of mass energy.

There are also other possibilities for new physics that are not necessarily related to the scale of electroweak symmetry breaking. There could be new neutral or charged gauge bosons with mass larger than the Z and W; there could be new quarks, charged leptons or massive neutrinos; or quarks and leptons could turn out not to be elementary objects. While we have no definitive expectations for the masses of these objects, the LHC must be able to search for them over its available energy range.

The present comprehensive state of understanding the Standard Model stems in large part from our having a wide range of facilities which explore the interactions between the fermions at energy scales $\sqrt{\hat{s}}$ of order $m_{W,Z} \sim 100\,\mathrm{GeV}$ to $m_t \sim 180\,\mathrm{GeV}$. These are the Fermilab Tevatron collider, LEP (1 and 2), SLC, and HERA. While either LEP 2 or the Tevatron may be sufficiently lucky to discover new physics in the coming decade, there is *only one* facility under construction that will really enable us to address interactions at energy scales 250 GeV – 1 TeV: CERN's Large Hadron Collider. At present, this is our only sure window on to physics beyond the Standard Model.

2. The Large Hadron Collider

2.1. Machine parameters

THe LHC machine is a proton-proton collider that will be installed in the 26.6 km circumference tunnel currently used by the LEP electron-positron collider at CERN [16]. Superconducting dipole magnets with a field of 8.4 tesla, operated at 1.9 K, will allow a beam energy of 7 TeV to be achieved. The beams intersect at four points where experiments are placed. Two of these are high luminosity regions and house the ATLAS [1] and CMS [2] detectors. Two other regions house the ALICE detector [17], to be used for the study of heavy ion collisions, and LHC-B [18], a detector optimised for the study of B-mesons and B-Baryons. The bunches cross every 25 ns and the peak luminosity is

10^{34} cm^{-2} sec^{-1} at which there are an average $\sim 20pp$ interactions per bunch crossing. The machine will also be able to accelerate heavy ions resulting in the possibility of Pb-Pb collisions at 1150 TeV in the center of mass and luminosity up to 10^{27} cm^{-2} sec^{-1}.

2.2. Physics Goals

The fundamental goal is to uncover and explore the physics behind electroweak symmetry breaking. This involves the following specific challenges:

- Discover or exclude the Standard Model Higgs and/or the multiple Higgses of supersymmetry.
- Discover or exclude supersymmetry over the entire theoretically allowed mass range.
- Discover or exclude new dynamics at the electroweak scale

The energy range opened up by the LHC gives us the opportunity to search for other, possibly less well motivated, objects:

- Discover or exclude any new electroweak gauge bosons with masses below several TeV.
- Discover or exclude any new quarks or leptons that are kinematically accessible.

Finally we have the possibility of exploiting the enormous production rates for certain standard model particles to conduct the following studies:

- The decay properties of the top quark, limits on exotic decays such as $t \rightarrow cZ$ or $t \rightarrow bH^{+}$.
- b-physics, particularly that of B-baryons and B_s mesons.

2.3. ATLAS and CMS Detectors

An LHC experiment must have the ability to find the unexpected. New phenomena of whatever type will decay into the particles of the standard model. In order to cover the lists given above a detector must have great flexibility. The varied physics signatures for these processes require the ability to reconstruct and measure final states involving charged leptons (including the tau), the electroweak gauge bosons W, Z and γ, jets coming from the production at high transverse momentum of quarks and gluons (and to tag those jets that have b-quarks within them), and to determine missing transverse energy carried off by weakly interacting neutral particles such as neutrinos.

Two large, general-purpose pp collider detectors will be constructed for LHC: ATLAS [1] and CMS [2]. Both collaborations completed Technical Proposals for their detectors in December 1994, and were formally approved in January 1996. Though they differ in most details, the detectors share many common emphases which derive from the physics goals of LHC:

- they both include precision electromagnetic calorimetry;
- they both use a rather ambitious magnet (though of different geometries) in order to obtain good muon identification and precision momentum measurement;
- both have lepton identification and measurement over $|\eta| < 3$;
- they both incorporate ambitious multi-layer silicon tracker systems for heavy flavor tagging (the usefulness of this capability is an important lesson from the Tevatron);
- they both include forward calorimetry for large η coverage in order to obtain the required $\not{E}_T$ resolution.

Particle-identification such as what might be needed for B-physics (as opposed to b-tagging) is not part of ATLAS or CMS. The ATLAS and CMS detectors are described in the talk of C. Fabjan in these proceedings, and in their respective Technical Proposals [1, 2].

3. Standard Model Higgs Bosons

All the properties of the standard model Higgs boson are determined once its mass is fixed. The search strategy at LHC is therefore well defined. The current limit on the mass of the Higgs boson is $M_H > 77$ GeV for experiments at LEP[19]. Before the LHC gives data, masses up to 95 GeV will have been excluded or discovered by LEP[20]. There are several relevant production mechanisms; $gg \to H$ via an intermediate quark or gauge boson loop; $q\overline{q} \to WH$; $gg \to t\overline{t}H$; $gg \to b\overline{b}H$ and $qq \to qqH$. The relative importance of these processes depends upon the Higgs mass, the first dominates at small mass and the last at high masses. The branching ratios are shown in Fig. 1.

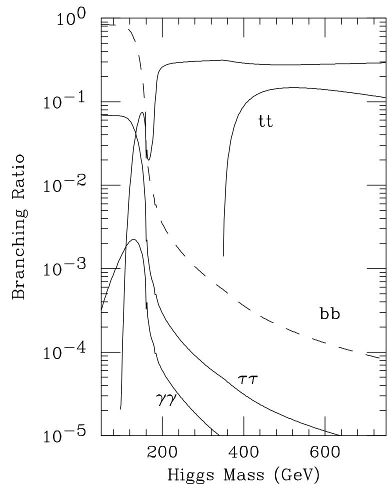

Figure 1: The branching ratios of the standard model Higgs boson as a function of its mass. The highest lying curve at large mass is the ZZ final state. Not shown is the WW rate which makes up almost all of the unaccounted for branching ratios.

3.1. $H \to \gamma\gamma$

At masses just above the range probed by LEP, the dominant decay of the Higgs boson is to the $b\overline{b}$ final state which is difficult to reconstruct. The decay to $\gamma\gamma$ is the most promising in this region. The branching ratio is very small and there is a large background from the pair production of photons via $q\overline{q} \to \gamma\gamma$, $gg \to \gamma\gamma$, and the bremsstrahlung process $qg \to q(\to \gamma)\gamma$. Excellent photon energy resolution is required to observe this signal, and this process is one that drives the very high quality electromagnetic calorimetry of both experiments. Fig.2 shows the background-subtracted signal in CMS corresponding to Higgs masses of 90, 110 and 130 GeV. This mode can discover the Higgs if its mass is between the maximum reach of LEP and about 140 GeV. Results of the ATLAS study are similar and the reach of the two experiments is similar.

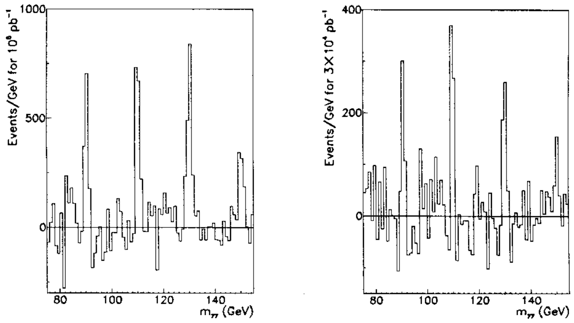

Figure 2: The invariant mass distribution of $\gamma\gamma$ pairs as simulated by the CMS collaboration. A smooth background has been fitted and subtracted to show signals for Higgs masses of 90, 110 and 130 GeV. The left (right) plot corresponds to low (high) luminosity running.

3.2. $H \to ZZ^* \to 4\ell$

The search for the Standard Model Higgs relies on the four-lepton channel over a broad mass range from $m_H \sim 130\,\text{GeV}$ to $m_H \sim 800\,\text{GeV}$. Below $2m_Z$, the event rate is small and the background reduction more difficult, as one or both of the Z-bosons are off-shell. In this mass region the Higgs width is small ($\lesssim 1\,\text{GeV}$) and so lepton energy or momentum resolution is of great importance in determining the significance of a signal[21].

For $m_H < 2m_Z$, the main backgrounds arise from $t\bar{t}$, $Zb\bar{b}$ and continuum $Z(Z/\gamma)^*$ production. Of these, the $t\bar{t}$ background can be reduced by lepton isolation and by lepton pair invariant mass cuts. The $Zb\bar{b}$ background cannot be reduced by a lepton pair invariant mass cut but can be suppressed by isolation requirements. The ZZ^* process is an irreducible background. Both CMS and ATLAS studied the process for $m_H = 130$, 150 and 170 GeV. The four-lepton mass distributions for ATLAS are shown in Fig. 3.

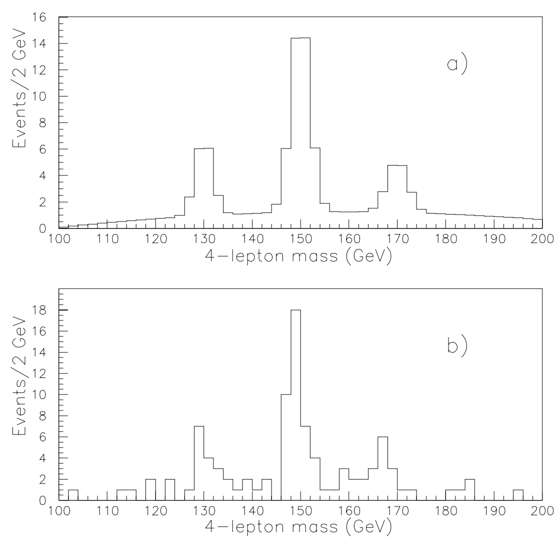

Figure 3: Reconstructed four-lepton mass above background, for $m_H = 130$, 150 and 170 GeV, and an integrated luminosity of $3 \times 10^4\,\text{pb}^{-1}$ (low luminosity) as simulated by the ATLAS collaboration. (a) indicates the expected average number of events; (b) shows the result of one experiment, obtained with randomized statistics in each mass bin.

3.3. $H \to ZZ \to 4\ell$

The $H \to ZZ \to 4\ell$ channel is sensitive over a wide range of Higgs masses from $2m_Z$ upwards: to about 400 GeV with $10^4\,\mathrm{pb}^{-1}$ and to about 600 GeV with $10^5\,\mathrm{pb}^{-1}$. For lower Higgs masses, the width is quite small and precision lepton energy and momentum measurements are helpful; for larger masses the natural Higgs width becomes large. The main background is continuum ZZ production. CMS 4-lepton invariant mass distributions are shown in Fig. 4. With $10^5\,\mathrm{pb}^{-1}$ a signal in excess of six standard deviations is visible over the entire range $200 < m_H < 600\,\mathrm{GeV}$. ATLAS obtains very similar results.

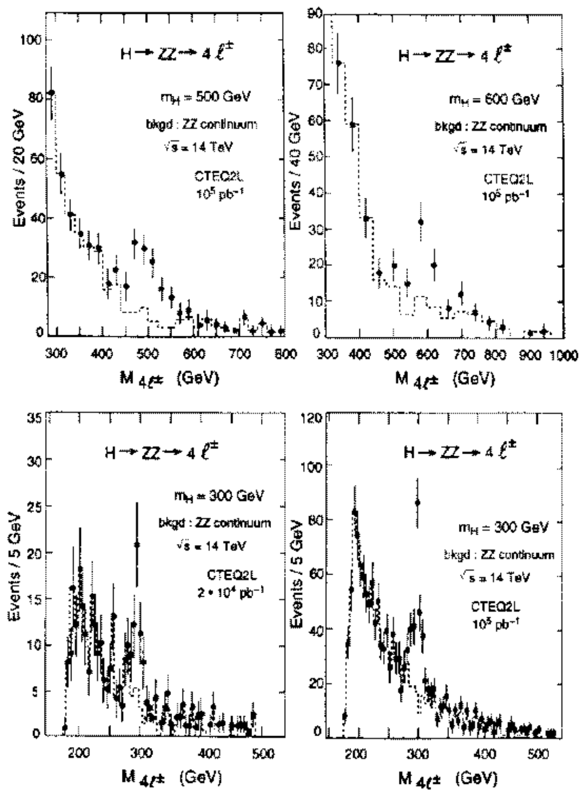

Figure 4: Mass distribution in $H \to ZZ \to 4\ell$ as simulated by CMS including all bremsstrahlung losses.

3.4. Higgs with mass ~ 1 TeV ($\ell\ell\nu\nu$, $\ell\ell$jj, $\ell\nu$jj, etc.)

As the Higgs mass is increased further, its width increases and the production rate falls and one must turn to decay channels that have a larger branching ratio.

The first of these is $H \to ZZ \to \ell\ell\nu\bar{\nu}$. Here the signal involves looking for a Z decaying to lepton pairs and a large amount of missing energy. The signal appears as a Jacobian peak in the missing E_T spectrum. There are more potentially important sources of background in this channel than in the 4ℓ final state. In addition to the irreducible background from ZZ final states, one has to worry about $Z+jets$ events where the missing E_T arises from neutrinos in the jets or from cracks and other detector effects that cause jet energies to be mismeasured. Figure 5 shows the Higgs signal in this channel from ATLAS. The statistical significance of the signal shown is large but depends on knowing the ZZ background well; hopefully this can itself be measured at the LHC. The CMS analysis of this process [24] uses a central jet veto (no jets with $E_T > 150$ GeV within $|\ \eta\ | < 2.4$) together with a forward jet tag (a jet with $E > 1TeV$ and $2.4 < |\ \eta\ | < 4.7$) to improve the signal to background ratio. This forward jet tag is only effective for high mass Higgs bosons where the $qq \to Hqq$ process, which gives jets at large rapidity, is significant, and it only becomes powerful at high luminosity. Nevertheless it will provide an unambiguous signal.

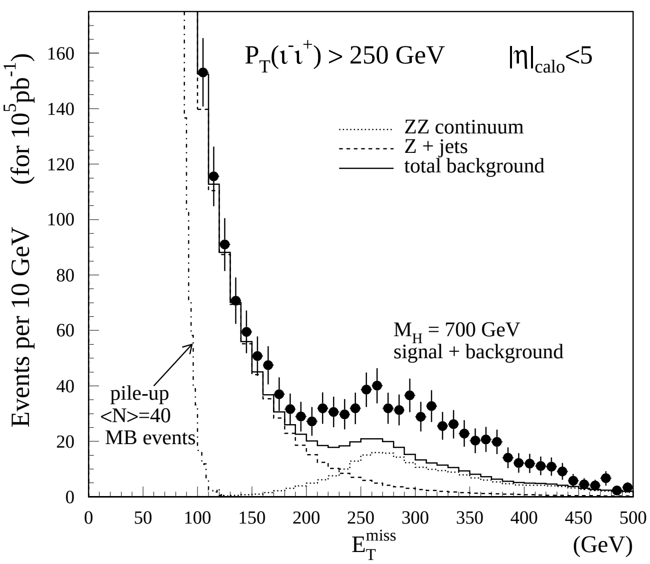

Figure 5: Missing E_T spectrum for the $H \to ZZ \to \ell\ell\nu\overline{\nu}$ process. The background contributions are shown separately; $Z+jets$ (dashed); ZZ (dotted) and minimum bias pile up (dot-dashed). The signal due to a Higgs boson of mass 700 GeV.

Substantially larger event samples are available if the decay modes $H \to WW \to \ell\nu + jets$ and $H \to ZZ \to \ell\ell + jets$ can be exploited efficiently. In order to do this one has to reduce the enormous $W + jets$ and $Z + jets$ background by kinematic cuts. Both ATLAS and CMS have investigated these processes, using a forward jet tag combined with a central jet veto to reduce the background from $t\bar{t}$. This technique looks promising, but finding relatively low-p_T jets in the forward direction at a hadron collider will not necessarily be straightforward.

3.5. Summary of standard model Higgs

The LHC at full luminosity will be **able to probe the entire range of allowed Higgs masses from the value reachable by LEP up to the value where it is no longer sensible** to speak of an elementary Higgs boson using final states that one is absolutely confident will be effective: $\gamma\gamma$, 4ℓ and $2\ell\nu\overline{\nu}$. Additional final states that afford an excellent chance of having a signal will be exploited to support these; $b\overline{b}$ and $\ell\nu + jets$, $\ell\ell + jets$. The failure to find a boson over this range would therefore enable the standard model to be ruled out. The Higgs sector then either consists of non-standard Higgs bosons or the electroweak symmetry breaking is via some strongly coupled process that will manifest itself in the study of WW scattering.

4. Supersymmetry

4.1. SUSY Higgs

The minimal supersymmetric standard model (MSSM) has three neutral and one charged Higgs bosons; h, H, A and $H^{\pm}$. These arise because supersymmetric models, unlike the standard model, need different Higgs bosons to generate masses for the up and down type quarks. In the standard model one parameter, the Higgs mass, is sufficient to fully fix its properties. In the Minimal supersymmetric model, two parameters are needed. These can be taken to be the mass of A which is unconstrained, and the ratio ($\tan\beta$) of the vacuum expectation values of the higgs fields that couple to up-type and down-type quarks.

ATLAS and CMS have studied a large number of Higgs decay modes, all of which can contribute in various regions of $(m_A, \tan\beta)$ parameter space, as shown in Fig. 6:

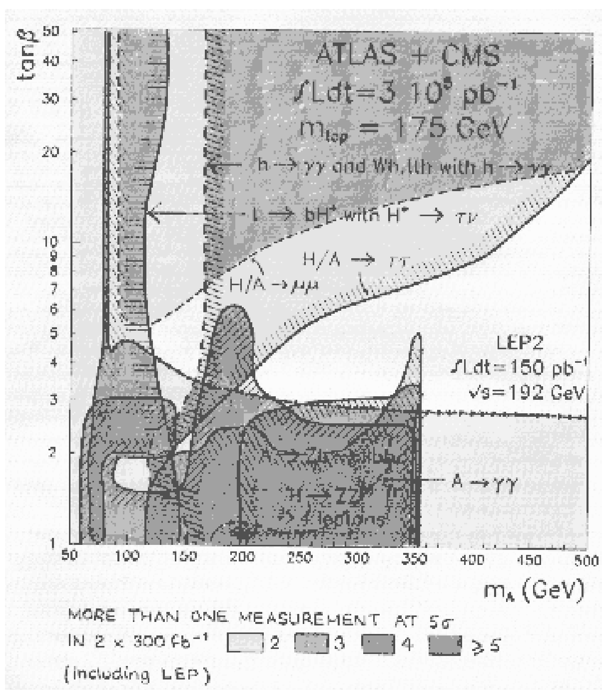

Figure 6: 5σ exclusion contours for the various processes used to search for Higgs bosons in the MSSM.

- $h, H, A \to \gamma\gamma$
- $h, H, A \to ZZ*, ZZ \to 4\ell$
- $h, H, A \to \tau\tau$ with $\tau\tau \to \ell^{\pm}h^{\pm} \not{E}_T$ or $\tau\tau \to e\mu$
- $h, H, A \to \mu\mu$
- $H^{\pm} \to \tau\nu$ in top decays
- $A \to Zh \to \ell\ell b\bar{b}$
- $H \to hh \to \gamma\gamma b\bar{b}$
- possibly $A, H \to t\bar{t}$ and $Wh \to \ell\nu b\bar{b}$.

Many of these modes are similar to those considered for the SM Higgs. The $\tau\tau$ decays are challenging to reconstruct, but appear feasible. This set of modes is sufficient for either experiment to *exclude* the entire $(m_A, tan\beta)$ plane at 95% confidence with 10^5 pb^{-1}. Ensuring a 5σ discovery over the entire $(m_A, \tan\beta)$ plane requires more luminosity. Figure 6 shows an indication of what can be achieved after a few years of running [25]. The entire plane is covered using the modes where one has great confidence. Over a significant fraction of the parameter space at least two distinct modes will be visible. For example, if h is observed at LEP II and M_A is small the LHC will see the H^+ in top quark decay, $H \to ZZ^*$, and possibly $H/A \to \tau\tau$. At large values of M_A, the decays $h \to \gamma\gamma$, $H \to ZZ^*$, and $A \to Zh$ will provide a third or fourth observation. If nothing is observed at LEPII, then over a significant fraction of the remaining phase space, $h \to \gamma\gamma$ and $H/A \to \tau\tau$ (and $H/A \to \mu\mu$) will be measured.

The decay of other supersymmetric particles will provide additional sources of h. Over a significant fraction of SUSY parameter space, there is a substantial branching fraction for squarks to decay to h. The rate is then such that decay $h \to b\bar{b}$ becomes clearly observable above background and this channel would then be the one where h is observed first at LHC.

4.2. Supersymmetric Particle Production

In addition to the extended Higgs sector discussed above, supersymmetry predicts the existence of partners for all the quarks, leptons and gauge bosons of the standard model. If supersymmetry is relevant to the electroweak symmetry breaking problem then most of these particles will be in a mass range that is observable at LHC [22].

Many supersymmetric models assume a discrete symmetry called R-parity that ensures that the lightest supersymmetric particle is absolutely stable. This particle must be electrically neutral and might pervade all of the current universe providing a substantial fraction of the dark matter. In most models this particle is the lightest neutralino χ_1^0 and it will exit the detector unmeasured, leading to one of the classic signals for supersymmetry at a hadron collider: missing E_T.

Both ATLAS and CMS investigated a number of supersymmetry signals within the MSSM for the 1996 LHCC Workshop [23]. The MSSM parameter space was explored, and five chosen points were studied in more detail.

The sparticles with the largest production rates at LHC are those with strong interaction couplings, the squarks and gluinos. The maximum mass reach for discovery is achieved in the lepton(s) + jets + missing E_T channel, and (as shown for CMS in Fig. 7) can reach squark and gluino masses up to ~ 2 TeV.

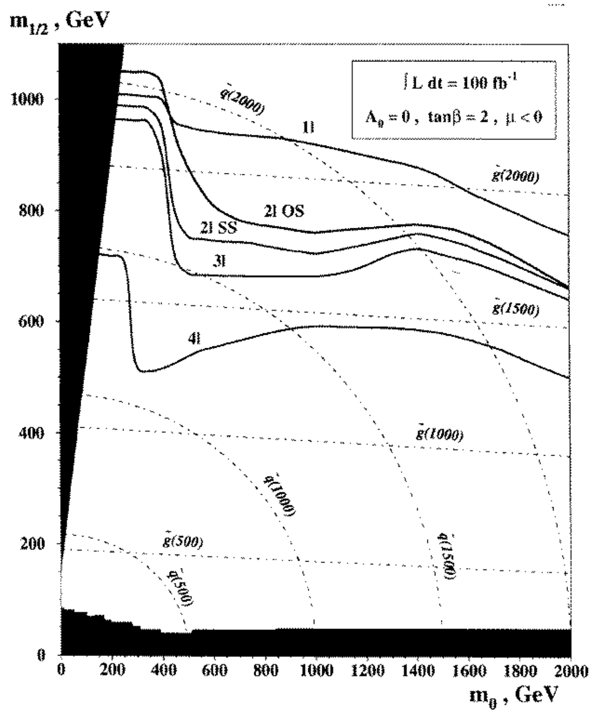

Figure 7: The plane $(m_0, m_{1/2})$ of parameter space in the MSSM, with $\tan\beta = 2$, $\mu < 0$ and $A_0 = 0$, showing discovery reach in CMS for squarks and gluinos in various channels: jets and $\not{E}_T$ plus 1ℓ = single lepton,2ℓOS(SS)= two leptons, opposite (same) sign, 3ℓ = three leptons, etc. Dashed lines indicate contours of constant squark and gluino mass.

Pair production of sleptons and gauginos has much lower cross sections, but these particles would still be detectable in particular regions of parameter space in multilepton + missing E_T final states. A jet veto is also needed to reduce the background from cascade decays of squarks and gluinos.

Besides the discovery of supersymmetry, the LHC will be capable of making some quite precise mass measurements and determining parameters of the model. As an example, Fig. 8 (taken from [23]) shows, for ATLAS, the dilepton invariant mass distribution after cuts designed to select supersymmetry events; it is dominated by the decay $\chi_2^0 \to \ell^+\ell^-\chi_1^0$. From the position of the kinematic "edge" near 110 GeV one may infer very precisely the mass difference between the lightest and second-lightest neutralino.

5. Other New Physics

5.1. New Gauge Bosons

A generic prediction of superstring theories is the existence of additional $U(1)$ gauge groups. There is thus motivation to search for additional W' and Z' bosons. The best sensitivity appears to be in the electron decay modes; a mass reach of 6 TeV for W' and 5 TeV for Z' is achievable with 100 fb^{-1}[30]. Figure9 shows the signal in ATLAS for a 4 TeV W'.

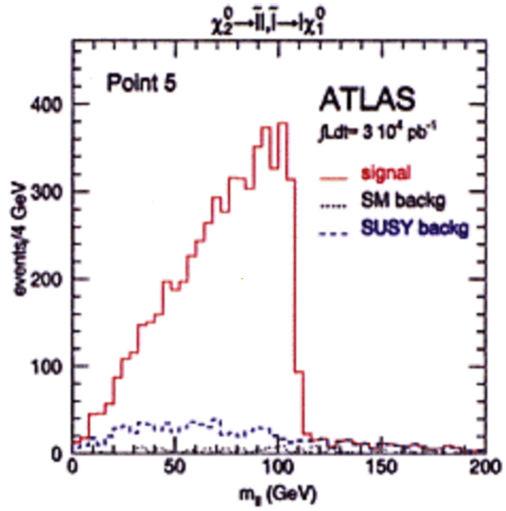

Figure 8: Invariant mass distribution for dilepton pairs at point 5 in MSSM parameter space from the LHCC SUSY workshop, as reconstructed by ATLAS after cuts. The kinematic "edge" from the decay $\chi_2^0 \to \ell^+\ell^-\chi_1^0$ is prominent above SUSY and SM backgrounds.

5.2. Technicolor

Many models of strong electroweak symmetry breaking (technicolor, topcolor-assisted technicolor, BESS [29]) predict resonances which decay into vector bosons (or their longitudinal components). These signals are very striking since they are produced with large cross sections and may be observed in the leptonic decay modes of the W and Z where the backgrounds are very small.

ATLAS have studied a techni-rho, $\rho_T \to WZ$, with $W \to \ell\nu$, $Z \to \ell\ell$, for $m_{\rho_T} =$ 1.0 TeV and also a techni-omega, $\omega_T \to Z\gamma$, with $Z \to \ell\ell$, for $m_{\omega_T} = 1.46$ TeV. The backgrounds due to $t\bar{t}$ and continuum vector-boson pair production are small as can be seen in Fig.9.

More challenging are the possible decays into non-leptonic modes such as $\rho_T \to W(\ell\nu)\pi_T(b\bar{b})$, which has a signature like associated WH production with $H \to b\bar{b}$; $\eta_T \to t\bar{t}$, for which the signature is a resonance in the $t\bar{t}$ invariant mass; and $\rho_{T8} \to$ jet jet, for which the signature is a resonance in the dijet invariant mass distribution. The cross sections are high and the masses of the new particles should lie in the range 100 GeV – 1 TeV so it will be hard for technicolor to escape detection at the LHC.

5.3. Strongly interacting W's

The couplings of longitudinally polarized gauge bosons to each other are fixed at low energy by the nature of the spontaneously broken electro-weak symmetry and are independent of the details of the breaking mechanism. Scattering amplitudes calculated from these couplings will violate unitarity at center of mass energies of the WW system around 1.5 TeV. New physics must enter to cure this problem. In the minimal standard model and its supersymmetric version, the cure arises from the perturbative couplings of the Higgs bosons. If no Higgs-like particle exists, then new non-perturbative dynamics must enter in the scattering amplitudes for WW, WZ and ZZ scattering at high energy. Therefore if no new physics shows up at lower mass scales one must be able to probe $W_L W_L$ scattering at $\sqrt{\hat{s}} \sim 1$ TeV.

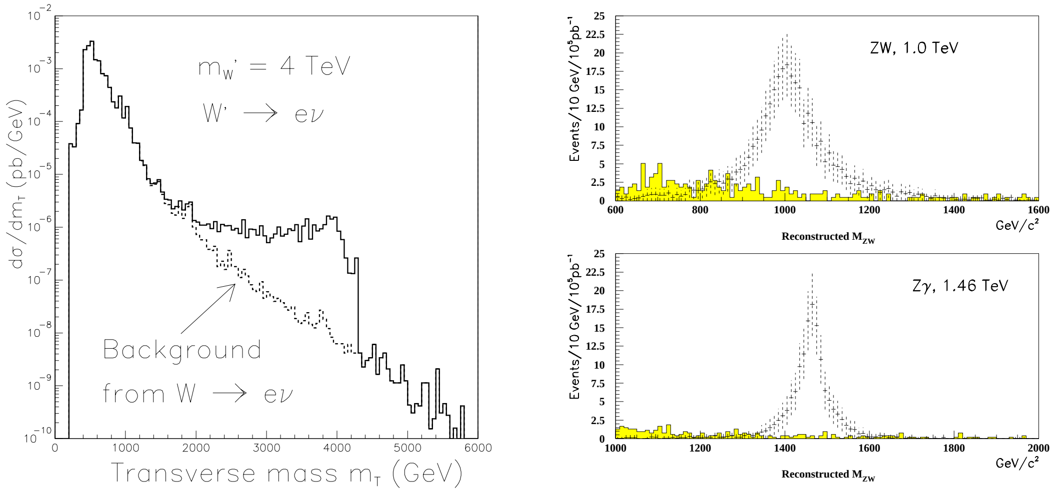

Figure 9: (Left) Expected electron-neutrino transverse mass distribution in ATLAS for $W' \to e\nu$ decays with $m_{W'} = 4$ TeV above the dominant background from $W \to e\nu$ decays. (Right) Reconstructed masses for high-mass resonances decaying into gauge boson pairs a simulated by ATLAS: (a) ρ_T of mass 1.0 TeV decaying into WZ and subsequently into 3 leptons; and (b) ω_T of mass 1.46 TeV decaying into $Z\gamma$ with $Z \to 2$ leptons.

Various models exist that can be used as benchmarks for this physics [26]. The basic signal in all of them is an excess of events over that predicted by the standard model for gauge boson pairs of large invariant mass. In certain models resonant structure can be seen (as in the previous subsection). In the standard model, the W^+W^+ final state is the only one where there is no process $q\overline{q} \to WW$ and therefore has the best signal-to-background ratio.

ATLAS [27] studied this channel, using leptonic W decays, a central jet veto, and forward jet tagging in order to extract a signal (modelled as a 1 TeV Higgs in Fig. 10) The analysis is challenging but appears possible will the full LHC luminosity. CMS[28] reach a similar conclusion.

5.4. Compositeness

There is no *a priori* reason for quarks to be elementary. If they have substructure it will be revealed in the deviations of the jet cross-section from that predicted by QCD. The deviation is parameterized at low energies by an effetive interaction of the form $4\pi q\gamma^\mu \overline{q} q\gamma^\mu \overline{q}/\Lambda^2$, which has a scale Λ. ATLAS has investigated a search for substructure in the jet cross-section at high p_T, as shown in Fig. 10. It indicates sensitivity up to $\Lambda \sim 20$ TeV, though systematic effects (both theoretical uncertainties and detector effects) will need to be well understood. A better reach in Λ may be obtained from Drell-Yan dilepton final states, if leptons are also composite.

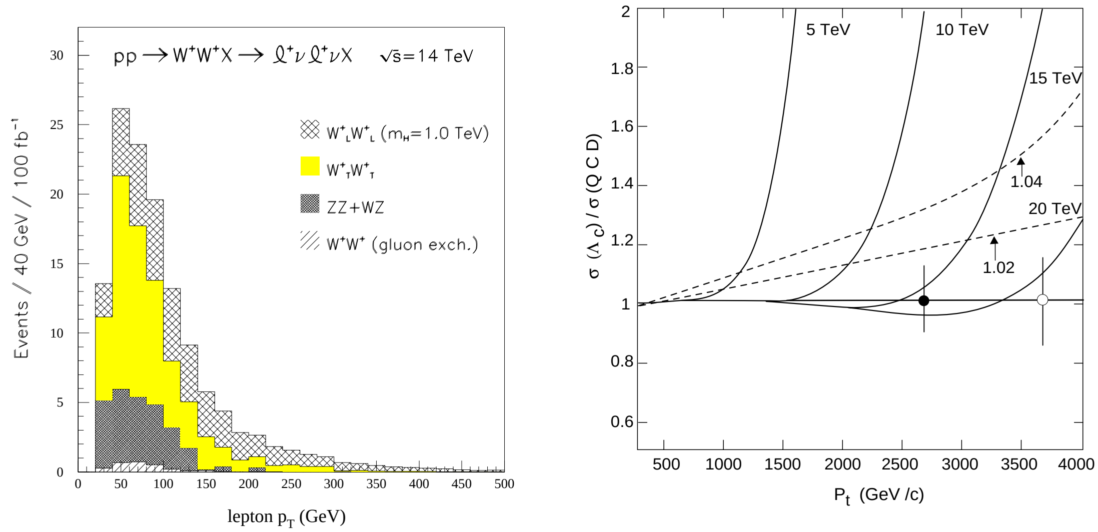

Figure 10: (Left) The p_T spectrum for same sign dileptons in the search for a strongly coupled WW sector as simulated by ATLAS. The signal corresponds to a 1 TeV Higgs boson. (Right) Deviation from QCD for various values of the compositeness scale Λ. The error bars correspond to statistical sensitivities at 100 fb^{-1} (open circle) and 10 fb^{-1}. The dotted lines refer to the errors induced by possible nonlinearities in the ATLAS calorimeter.

6. B Physics and the LHC-B Experiment

The preceding sections have shown the importance of b-tagging in addressing many of the high-p_T physics goals of the LHC. Both major detectors will consequently have the capability to tag heavy flavor production through displaced vertices and enable them to pursue a targeted but interesting program of b-physics.

To fully exploit the physics potential offered by the large b-quark production cross-section at the LHC (10^{12} $b\bar{b}$ pairs produced per year even at "low" luminosity, 10^{32} cm^{-2}s^{-1}), a dedicated experiment for b-physics is foreseen, called LHC-B[18].

LHC-B will use a forward geometry, which exploits the Lorentz boost of the $b\bar{b}$ system while sacrificing little acceptance (since the quark pair tends to lie close in rapidity). The detector includes particle-identification capabilities and has excellent mass resolution. An optimized trigger system is an important part of the detector.

It can be assumed that CP violation in the $b-$quark system will have been observed before the LHC gives data. Nevertheless the enormous rate and precision resolution of LHC-B will enable a precise determination of $\sin 2\beta$ using the decay $B^0 \to \psi K_S$; determination of $\sin 2\alpha$ using $B_d^0 \to \pi\pi$; determination of γ using $B_d^0 \to D^0 K^0$; study of $B^0 \to \psi\phi$; study of $B_s \overline{B}_s$ mixing; and study of B-baryons, B_c mesons, rare decays, etc. The technical proposal for LHC-B is currently in preparation and will be presented in early 1998.

7. FELIX

A group is studying the option of an additional pp collider detector, optimized for forward and diffractive physics. The goals of this detector, called FELIX[31], would be to study elastic scattering, and measure the total pp cross section; single, double, and higher order diffraction; multiparticle production and correlation studies; hard diffraction, including electroweak processes; rapidity gap tags for new physics; the unexpected, such as new physics suggested by cosmic ray anomalies; and two-photon interactions in heavy-ion collisions. A technical proposal for FELIX is in preparation though it should be noted that limited resources may mean that its approval will not be straightforward.

8. Heavy Ion Collisions and ALICE

The LHC will offer the potential to collide beams of heavy ions with atomic number as high as lead, resulting in the possibility of Pb-Pb collisions at 1150 TeV in the center of mass and luminosity up to 10^{27} cm^{-2} sec^{-1}. To explore this environment, a dedicated heavy ion experiment, ALICE [17] as been approved. ALICE will make use of the existing L3 solenoid and collision hall, and will incorporate a tracking system, particle-identification, EM calorimetry and a forward muon spectrometer. Physics interest focuses on production of quark-gluon plasma; signals include global features such as particle and E_T flow (which help determine the initial conditions); charged particle p_T spectra and jet quenching; particle correlations and fluctuations; flavor composition of events; direct photon production; lepton pairs (continuum Drell-Yan and vector meson resonances); and production of exotica such as strangelets. The multipurpose detectors also have some capability of interest for heavy ion collisions (such as E_T flow measurement and muon detection) and will contribute to the study of this physics.

9. Summary and Conclusions

The LHC is unique among accelerators currently existing or under construction. It will have sufficient energy and luminosity to enable vital discoveries to be made and will lead to insight into the mass generation mechanism of the standard model. The very detailed simulation studies carried out by the experimental collaborations enable us to be sure that:

- If the minimal standard model is correct and the Higgs boson is not discovered at LEP II, it will be found at LHC.
- If supersymmetry is relevant to the breaking of electroweak symmetry, it will be discovered at LHC and many details of the particular supersymmetric model will be disentangled;
- If the Higgs sector is that of the minimal supersymmetric model, at least one Higgs decay channel will be seen, no matter what the parameters turn out to be. In many cases, several Higgs bosons or decay channels will be seen;
- If the electroweak symmetry breaking proceeds via some new strong interactions, many resonances and new exotic particles will almost certainly be observed;
- Precision measurements of standard model parameters such as the b-sector will be made;
- Signals of quark-gluon plasma will be unambiguously detected (or ruled out).

A great opportunity and a vast amount of excitement is promised to those physicists fortunate enough to be part of an LHC experiment.

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