THE GOALS AND POTENTIAL OF THE CERN LARGE-HADRON COLLIDER

MICHELANGELO L. MANGANO

Theoretical Physics Division, CERN, Geneva, Switzerland

I present a pedagogical introduction to the main ideas underlying the physics program of the Large Hadron Collider. I review the implications of the observation and study of the Higgs boson, in particular the relation between its mass and the possible, or necessary, existence of new physics. I introduce the main aspects of Supersymmetric models, and point out their relevance in the context of Higgs physics, as well as of other natural phenomena. I conclude with a short listing of SM studies that could possibly point toward the existence of new phenomena.

1. INTRODUCTION

The Large Hadron Collider (LHC), a proton–proton collider designed to operate at a center-of-mass energy of 14 TeV and with luminosities in the range of 10^{33-34} cm^{-2} s^{-1}, is expected to enter in operation at CERN towards the middle of the year 2007. This gigantic enterprise, involving over four thousand high-energy physicists working in the experiments as well as hundreds of machine physicists and engineers, is intended to provide the community of particle physicists with the ultimate tool to further the exploration of matter at the smallest possible distance scales. It is fair to anticipate that the outcome of the measurements to be carried out at the LHC will shape the directions of high-energy physics (HEP) for the rest of the XXI century. This comment reviews the ambitions and expectations of the LHC physics program, with particular emphasis on the studies of the electroweak symmetry breaking (EWSB) mechanism and implications for phenomena beyond the Standard Model (SM) of elementary particles.

The ability of the future LHC high-p_T experiments, ATLAS and CMS, to discover new particles has been firmly established on paper, after years

of beautiful work, documented for example in Refs. [1, 2, and 3]. In particular, the prospects for the observation and the study of the properties of the Higgs boson are very bright. Other important questions which should also be part of the global evaluation of the LHC potential are: what will the observation of new particles tell us about the new physics, how can these be correlated to phenomena possibly observable outside the LHC (e.g., in the cosmos, in B-factories, in low-energy precision measurements and searches for rare decays), and then what will be the best post-LHC machines to further pursue the frontier of physics. The ability to provide clear direction for the planning of future experimental facilities should be seen as a fundamental element in the physics program of the LHC. On our wish list for the LHC, we would therefore like to put the following items:

- The ability to formulate a post-SM paradigm for fundamental interactions (Supersymmetry perhaps? If so, which specific model of it?).
- The ability to provide concrete clues on the issues of EWSB and on the origin of flavor and family replication, as well as on the breaking of possible grand unified (GUT) symmetries and (in case it exists) of supersymmetry.
- Convincing proofs, or at least hints, of the existence of phenomena beyond the most common extensions of the SM.

In this contribution I then try to put the LHC discovery potential in a broader perspective, making reference to some recent theoretical developments in the area of SUSY, gravity, and to some long-standing issues in astrophysics and cosmology.

2. WHERE IS THE HIGGS?

2.1. Current Direct and Indirect Experimental Constraints

In the SM, omitting all $SU(2)$ indices, the Higgs potential is given by:

$$V(\phi) = -\frac{1}{2}\mu^2|\phi|^2 + \frac{\lambda}{4}|\phi|^4 \tag{1}$$

After minimization we obtain for the vacuum expectation value (vev) of the Higgs field $\langle\phi\rangle^2 = \frac{\mu^2}{\lambda} = (174 \text{ GeV})^2$. The numerical value follows

from the (tree level) relations between the vev v, the mass m_W and weak charge g of the W boson, and the Fermi constant G_F:

$$M_W^2 = \frac{1}{2}g^2v^2 \qquad G_F = \frac{\sqrt{2}g^2}{8M_W^2} \qquad (2)$$

giving $v^2 = 1/(2\sqrt{2}G_F)$. At the minimum of the potential, the mass of the Higgs particle is given by $m_H{}^2 = \mu^2 = \lambda v^2$. As λ is a free parameter, the value of m_H is not constrained, in spite of the known value of v.

The Higgs boson has been searched for directly through attempts to produce it as a real particle, and by seeking indirect evidence of its exchange as a virtual particle in higher-order corrections to precisely measured EW observables. Lower limits on m_H in the range of 113 GeV have been obtained by the LEP e^+e^- Collider [4, 5, 6]. Global SM fits [7] of EW precision observables [8, 9] give on the other hand:

$$m_H = 77 {}^{+69}_{-39} \text{ GeV} \qquad m_H < 215 \text{ GeV}(95\%CL) \qquad (3)$$

There is therefore a good chance that the Higgs boson is behind the corner. Tantalising evidence for this has recently emerged from the year 2000 data-taking of the LEP experiments [6, 10, 11], which provides a 2.9σ indication for the existence of a 115 GeV Higgs. The possible implications of a Higgs in this mass range will be reviewed below.

In addition to the experimental results, there are important theoretical constraints which arise from the overall consistency of the SM at the perturbative level. These considerations are based on the renormalization-group evolution (RGE) of the Higgs self-coupling λ, which at 1-loop reads:

$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left[\lambda^2 - 4\left(\frac{m_t}{v}\right)^2\right] \qquad (4)$$

Here $t = \log(Q/v)$, Q being the scale at which the coupling is evolved, and m_t is the top-quark mass. The first term in this equation arises from a 1-loop correction to the Higgs quartic self-interaction, with a Higgs boson circulating in the loop. The second term comes from a top quark going through the loop, the minus sign being due to Fermi statistics. Perturbativity of the Higgs interactions requires that $\lambda(Q)$ be at most of $\mathcal{O}(1)$ for all scales Q at which the theory is valid. Requiring that perturbativity holds up to some scale Λ (say the GUT or Planck scale)

at which new physics may change the RGE, sets an upper limit on $\lambda(v)$, and therefore on m_H [12, 13]. The lower the scale Λ, the lower the upper limit on m_H. On the other hand, if $\lambda(v)$ is too small, the RGE will drive $\lambda(Q) < 0$ at some scale $Q = \Lambda$, and then lead to a potential unbounded from below. The larger the scale at which this is allowed to happen, the larger the lower limit on m_H. The large size of the top-quark mass, giving a large negative contribution to the RHS of the RGE equation, implies very strong constraints on the lower limit of m_H in the SM (for reviews, see [14, 15]). Requiring both scales Λ emerging from the two arguments to be of order 10^{16}GeV gives $130 \text{ GeV} \lesssim M_H^{SM} \lesssim 200 \text{ GeV}$. The impact of these constraints, as a function of Λ, is clearly illustrated by the two dark regions labeled *Triviality* and *Vacuum Stability* shown in Figure 1, from a
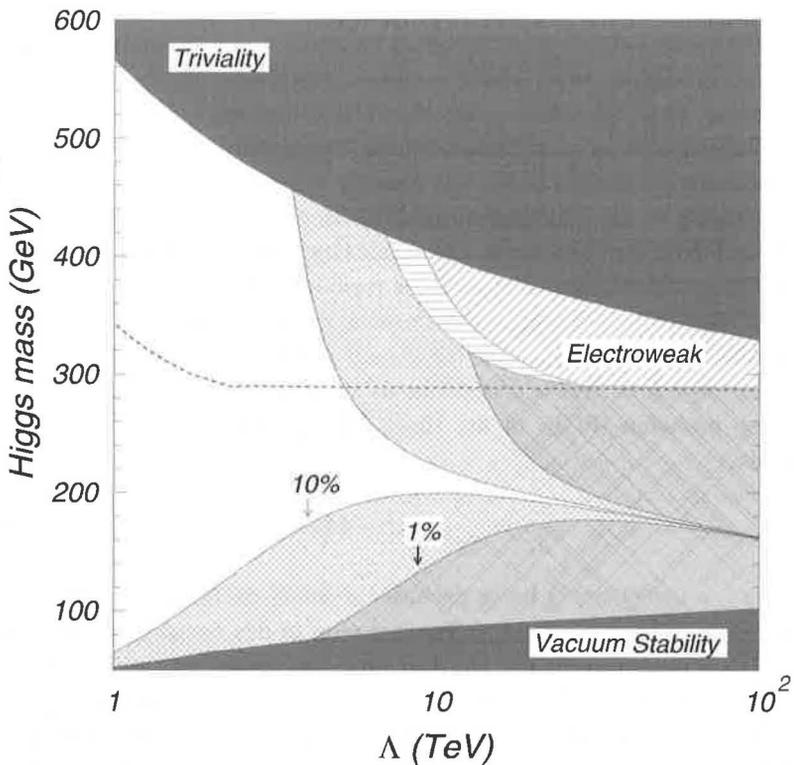

FIGURE 1. Theoretical constraints on the allowed value of m_H, as a function of the scale Λ at which new physics is assumed to appear [16]. The regions labeled 1% and 10% require corresponding values of fine tuning to ensure that radiative corrections to $m_H{}^2$ are not larger than $m_H{}^2$ itself (see text for details).

recent analysis of Kolda and Murayama [16]. Since the requirements of SM perturbativity and vacuum stability are not imposed on the SM fits, it is a remarkable success that the m_H window obtained from these theoretical considerations is totally consistent with the current experimental limits.

Should the Higgs satisfy the above SM constraints, it will be easy prey for the LHC. This is shown in Figure 2, which is the result of the combined efforts by the ATLAS and CMS collaborations [1, 2]. The different integrated-luminosity scenarios 10 (30) and 100 fb^{-1} correspond to a running period of 1 (3) year(s) at low luminosity (10^{33} cm^{-2} s^{-1}), and of 1 year at high luminosity (10^{34} cm^{-2} s^{-1}). From the theoretical viewpoint, discovering the Higgs in the mass range allowed and requested by the SM would perhaps be the least interesting possibility: yet one
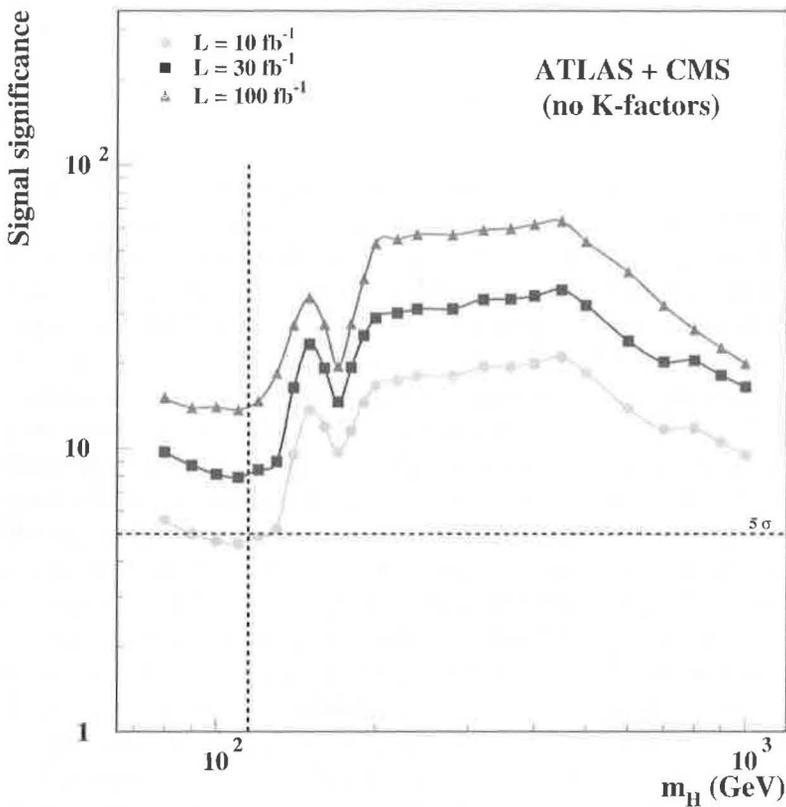

FIGURE 2. Signal significance (in standard deviations) for the observation of a SM Higgs at the LHC, as a function of m_H and for three values of the integrated luminosity.

more check of the SM would leave even less room for physics above the Fermi scale!

It is therefore interesting to explore possible way-outs from the above constraints, and study their possible consequences for the LHC. This is particularly worthwhile in view of the current LEP indications of a Higgs at 115 GeV, which, while consistent with the results of EW fits, would however violate the theoretical SM bounds from vacuum stability and perturbativity.

What is the price of evading the m_H limits set by SM EW fits and by the theoretical considerations within the SM? It is mandatory that new physics at energy scales below 10^{16} GeV be introduced: on one hand new particles with masses well below M_{GUT} should modify the RGE of the Higgs self-coupling, allowing for perturbativity and vacuum stability to be maintained. On the other, it is required that they modify the theoretical relations between the value of m_H and the EW observables used in the global EW fits, in order for the fits to be consistent with a value of m_H outside the range given in Eq. (3). How low can this new scale be? One can consider two separate cases. In one case new particles only appear at scales well above the TeV; LHC physics would be affected only indirectly through virtual effects. In the second case new particles appear at or below the TeV scale, and LHC could directly produce and study them.

In the case of new massive particles beyond the kinematical reach of the LHC, their exchange can still give rise at low energy to effective, higher-dimension operators connecting the SM fields. These operators can even describe more exotic scenarios [17], such as those emerging from theories in which large extra dimensions exist. The requirements of $SU(3) \times SU(2) \times U(1)$ invariance, and of flavor conservation, limit the number of possible operators. These interactions will shift the values of EW observables, and such a shift can compensate the shift induced by taking the Higgs mass away from the range determined by the SM fits. Barbieri and Strumia [18] classified 10 such objects of dimension 6, parameterized by a common scale Λ, such as $1/\Lambda^2 |\phi^* \partial_\mu \phi|^2$. Consistent fits with m_H very different from the SM fit value can be obtained if several operators are active at the same time, and if accurate fine tuning among Λ, m_H and the relative signs between operators is present. Only limited ranges of Λ can provide good fits for an arbitrary value of m_H. Probing the 2^{10} theories obtained by combining the 10 operators with all possible sign permutations, Ref. [18] found the distributions of limits on
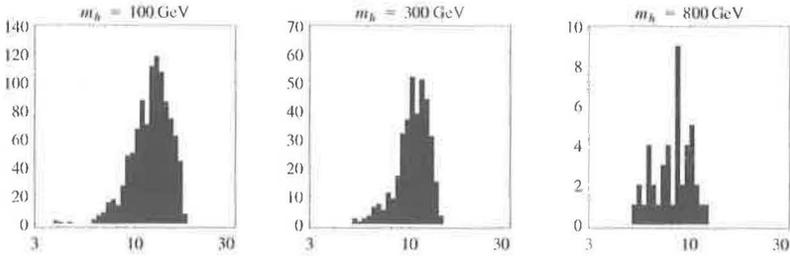
FIGURE 3. Distribution of 95%CL limits on Λ/TeV for those theories among the 1024 analysed in [18] returning acceptable ($|\chi^2 - \chi^2_{SM}| < 3.85$) fits of EW observables, for different values of m_H.

Λ for the acceptable models shown in Figure 3. Only 43/1024 models give acceptable fits for $m_H = 800$ GeV. Whether such a heavy Higgs is still visible at the LHC depends on the details of the models, which may affect the width and production cross-section [17]. If seen, such a Higgs would provide evidence for new physics at scales Λ between 5 and 10 TeV, and call for an explanation of the otherwise accidental and unlikely strong fine tuning of the model parameters. The issue of whether more direct manifestations of these dimension-6 operators are accessible at the LHC has not been studied as yet, but will deserve attention.

2.2. Fine-Tuning Constraints in the SM m_H Window

The objective criteria of theoretical consistency discussed earlier limit m_H within the 130–200 GeV window. A more subjective, but very intriguing, criterion exists which supports the existence of new physics at or just above the TeV scale even for m_H within that range.

This criterion calls for the absence of fine tuning in the renormalization of the Higgs mass. At one-loop, for example,

$$\mu_R^2 = \mu^2 - \frac{3\Lambda^2}{32\pi^2 v^2}(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \tag{5}$$

with Λ being the cutoff scale. Assuming that Λ is taken of the order of the GUT or Planck scale, a very accurate fine-tuning of μ and Λ is required to ensure that $\mu_R^2 \ll \Lambda^2$. This problem is often referred to as the "hierarchy" problem. It underscores the extreme instability of the renormalization

process for the Higgs mass, and points to the need of seemingly unnatural fine tuning of the bare Higgs mass in order to obtain a renormalized value of m_H in the range $m_H < 1$ TeV required by phenomenology. The fine-tuning problem is however reduced is one accepts to operate with values of m_H ensuring a strong cancellations among the terms in parenthesis, representing the coefficient of the 1-loop contribution [19]. For each value of Λ, and for a given amount of fine-tuning one is ready to accept, we are left with a range of acceptable m_H values. The results of the recent 2-loop study in [16] are shown in Figure 1. As anticipated, absence of fine tuning calls for the existence of new physics within the few-TeV scale even for m_H in the range allowed by the SM.

2.3. The Higgs in Supersymmetry

Supersymmetry [20] provides a BSM scenario in which all of the above issues find tantalizing solutions. To start with, the theoretical SM Higgs limits can be eluded, given the presence of new particles affecting the RGE evolution. Furthermore, the fits to EW observables maintain a high level of consistency, since SUSY relations among couplings and masses of the superpartners lead to generally strong cancellations in the contributions to EW observables, allowing the goodness of the current fits to LEP/SLC/Tevatron data to survive over wide regions of parameter space [8, 9]. Finally, the hierarchy problem is alleviated, as the quadratic divergences of the Higgs mass are replaced by a quadratic sensitivity to the mass splitting inside SUSY multiplets, weighted by a logarithmic divergence:

$$\delta m_H{}^2 \sim \frac{3m_{\tilde{f}}^2}{4\pi^2 v^2}\, m_{\tilde{f}}^2\, \log \Lambda \tag{6}$$

In addition to the above points, the implementation of the Higgs phenomenon in SUSY has the important feature that the Higgs quartic coupling λ is not a free parameter. The combination of gauge and supersymmetry invariance leads to the relation $\lambda = g^2 + g'^2$ and therefore $m_H{}^2 \sim m_Z^2$. The precise relation between m_H and m_Z depends on the details of the EW and SUSY breaking [20], but a general tree-level constraint forces the lighest among the 3 physical Higgs scalars to satisfy $m_H \leq m_Z$. Higher loop corrections extend the Higgs mass range up to at most ~ 130 GeV [21], just below the threshold of consistency for a

SM Higgs. An interesting accidental fact emerges from this: 130 GeV provides an approximate dividing line between the mass ranges where SM and SUSY respectively require the Higgs to be. This stresses once more the powerful value of the Higgs mass as a probe for physics beyond the SM.

2.4. Prospects for Higgs Measurements at the LHC

As shown in Figure 2, one year at design luminosity should suffice for a combination of the 2 experiments to provide a 5σ evidence of the Higgs in the mass range 100 GeV $< m_H <$ 1 TeV. The accuracy with which m_H can be measured is shown in Figure 4, from Ref. [22]. In the case of a Higgs in the borderline region separating the SUSY from the SM Higgs, the 6–7% quoted precision may not be enough to firmly decide on the nature of the Higgs particle. Measurements of its properties will provide the only safe probe to understand more on the nature of EWSB. Recent studies have started addressing this important issue. A direct determination of the Higgs width Γ_H from the study of the resonance profile using (when allowed) the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ decays [1, 22] is shown for example on the right side of Figure 4. Information on the partial contributions to Γ_H requires the ability to observe a multitude of possible decay channels. It has recently been pointed out [23] that this is doable, provided use is made of the W-fusion production channel $q_i q_i' \rightarrow q_f q_f' H$ with $q_i \rightarrow q_f W^*$ and
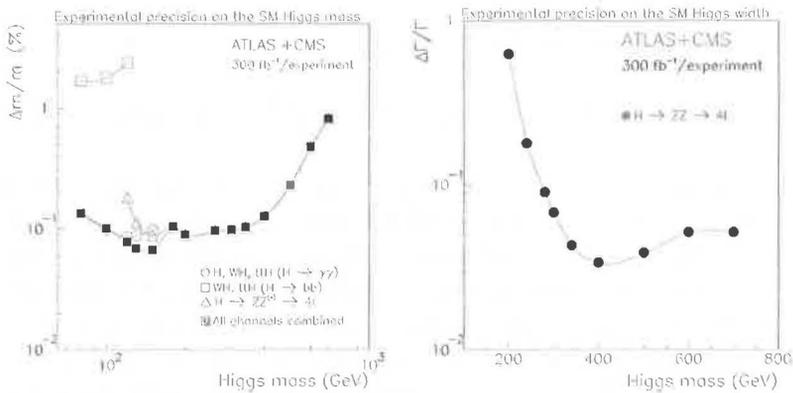

FIGURE 4. Experimental precision in the direct determination of the Higgs mass (left) and width (right) [1, 22].

$W^* W^* \rightarrow H$. The following quantities become then measurable through the determination of rates for the given processes [23]:

$$X_\gamma = \frac{\Gamma_W \Gamma_\gamma}{\Gamma} \qquad \text{from} \quad qq \rightarrow qqH, \ H \rightarrow \gamma\gamma \tag{7}$$

$$X_\tau = \frac{\Gamma_W \Gamma_\tau}{\Gamma} \qquad \text{from} \quad qq \rightarrow qqH, \ H \rightarrow \tau\tau \tag{8}$$

$$X_W = \frac{\Gamma_W^2}{\Gamma} \qquad \text{from} \quad qq \rightarrow qqH, \ H \rightarrow WW^{(*)} \tag{9}$$

These can be complemented with those extracted from the standard $gg \rightarrow H$ production channel: $Y_i = \Gamma_g \Gamma_i / \Gamma_H$, where $\Gamma_i = \Gamma(H \rightarrow ii)$ ($i = \gamma, W^{(*)}, Z^{(*)}$). These two sets of processes have common theoretical systematic errors of 5 and 20%, respectively. Expected accuracies in the determination of width ratios are given in Table 1.

A measurement with $H \rightarrow b\bar{b}$ final states would provide invaluable information as well. Additional detector-level studies will be necessary to assess its impact. In its absence, one can estimate the $Hb\bar{b}$ coupling using the expected relation (valid for most reasonable extensions of SM, c_{QCD} being a calculable QCD correction factor):

$$\frac{\Gamma_b}{\Gamma_\tau} = 3c_{QCD} \frac{g_{Hbb}^2}{g_{H\tau\tau}^2} = 3c_{QCD} \frac{m_b^2(m_H)}{m_\tau^2} \tag{10}$$

Assuming, as in the SM, that the decays $H \rightarrow b\bar{b}$, $H \rightarrow \tau^+\tau^-$, $H \rightarrow WW^{(*)}$, $H \rightarrow ZZ^{(*)}$, $H \rightarrow gg$, and $H \rightarrow \gamma\gamma$ saturate the full value of Γ_H, up to a correction of relative order ϵ for possible unknown decays, one can use the above observables to determine

$$\tilde{\Gamma}_W = \left(\Gamma_\tau + \Gamma_b + \Gamma_W + \Gamma_Z + \Gamma_\gamma + \Gamma_g \right) \frac{\Gamma_W}{\Gamma} = (1 - \epsilon)\Gamma_W \tag{11}$$

Theoretical knowledge of the weak-boson fusion cross-section ($\pm 5\%$) allows one then to measure the total H width, up to a $(1 - \epsilon)^2$ correction, with the accuracy shown in Figure 5. The above results are competitive with those obtained from the direct measurement of the Higgs width at the LHC, Figure 4, and therefore provide an important consistency check of the underlying assumptions. More work should however be done to extend this analysis to the region $m_H > 200$ GeV, where the Higgs width and couplings become a potentially sensitive probe of the new physics which allows the Higgs to evade the SM constraints.

TABLE 1. Statistical precision in the determination of relative Higgs branching ratios [23]

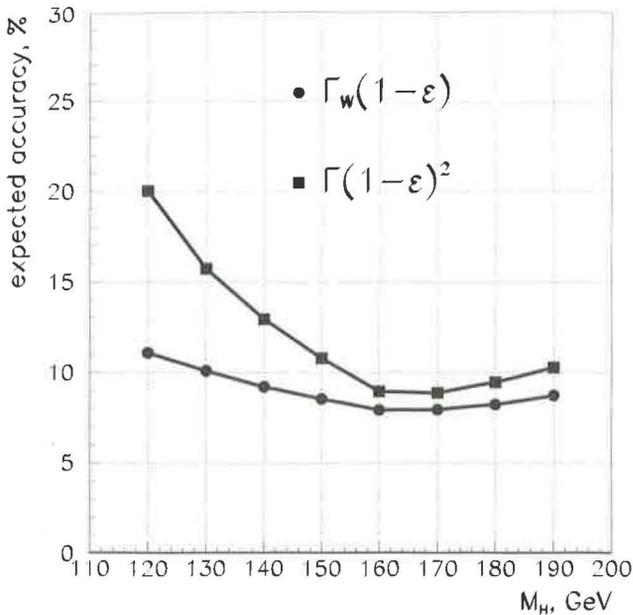| m_H		110	120	130	140	150	160	170	180
$z = \Gamma_Z/\Gamma_W$	Y_Z/Y_W		48%	29%	19%	17%	15%	20%	17%
	$\frac{Y_Z}{Y_\gamma}\frac{X_\gamma}{X_W}$		30%	21%	19%	23%			
	$\frac{Y_Z}{Y_W}\oplus\frac{Y_Z}{Y_\gamma}\frac{X_\gamma}{X_W}$		29%	19%	15%	14%	15%	20%	17%
Γ_γ/Γ_W	$\frac{Y_\gamma}{Y_W}\oplus\frac{X_\gamma}{X_W}$		16%	12%	11%	13%			
Γ_τ/Γ_W	$\frac{X_\tau}{X_W}$		15%	12%	14%	21%			
$\Gamma_\tau/\Gamma_\gamma$	$\frac{X_\tau}{X_\gamma}$	16%	15%	16%	18%	27%			
Γ_g/Γ_W	$\frac{Y_g}{X_\gamma}\oplus\frac{\Gamma_W}{X_W}$	18%	15%	13%	12%	13%	8%	9%	14%
	$\frac{Y_W}{X_\gamma}\oplus\frac{Y_W}{X_W}\oplus 21\%$	27%	25%	24%	24%	24%	22%	22%	25%

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FIGURE 5. Statistical precision in the determination of the total and $H \to W W^{(*)}$ Higgs decay widths [23].

3. SUPERSYMMETRY

In spite of its immense theoretical appeal, Supersymmetry [20, 24], with its doubling of the spectrum, namely, one bosonic (fermionic) partner for each SM fermionic (bosonic) degree of freedom, is often down-played as an academic complication of the already extended SM spectrum of fundamental particles and interactions. In a nice recent review of Supersymmetry [25], Murayama points out an interesting historical analogy with a previous circumstance in which the doubling of the particle spectrum turned out to be a key point in the evolution of the field: the introduction by Dirac of antiparticles. Similarly to the case of antiparticles, whose need arose from the consistency of quantum mechanics and of Lorentz symmetry, supersymmetric partners are the result of a space-time symmetry, extended in this case to the presence of fermionic coordinates [26]. With the introduction of the antiparticles, the electromagnetic self-energy of charged fermions, quadratically divergent

with the inverse of the particle charge radius in classical EM, was turned into a logarithmically divergent, and renormalizable quantity. The improvement in the behavior of perturbation theory caused by the introduction of antiparticles finds a close parallel in the removal of quadratically divergent corrections to the Higgs mass induced by the introduction of SUSY partners.

Furthermore, SUSY theories enjoy enchanced relations among couplings. To be extreme, a fully supersymmetric extension of the SM, however unrealistic, has less parameters than the SM itself, as the Higgs self-coupling λ, fully arbitrary in the SM, is related in SUSY to the EW gauge couplings, as we saw in the previous Section. It is SUSY breaking (SSB) which turns the Prince into a Frog! All complexity and parameter proliferation of SUSY are just a consequence of SSB. SUSY extensions of the SM with arbitrary patterns of spontaneous SUSY breaking, may have over 100 extra parameters [24] (mostly scalar and gauge-fermion masses and mixings). This is however not much worse than an arbitrary extension to leptons and hadrons of Fermi's theory of weak interactions, before the advent of the $V - A$ theory and of current algebra, or even before LEP/SLC firmly established the parameters of the SM. One could have needed parameters to describe non-$(V - A)$ couplings $(S, P, T, V + A)$, non-universal couplings to hadronic currents, and to μ and τ currents, more complex Higgs structures, or different realisations of EWSB. Parameter proliferation in SUSY is therefore the consequence of our current ignorance of the specific dynamics leading to SUSY breaking, and not an intrinsic shortcoming of the theory. This last statement allows us to define a benchmark goal for SUSY studies at the LHC: get clues on the mechanism of SSB. Will the measurement accuracy be sufficient to discriminate among different SSB models?

3.1. Constraints on Supersymmetry Breaking

In spite of the large multitude of possible parameters, very strong constraints can already be set on possible patterns of SSB [24]. In addition to the limits on SUSY particles coming from direct searches [24, 27], very strong indirect constraints exist, probing in some cases the multi-TeV mass scale. These indirect constraints arise from the tight limits set on flavor-changing neutral interactions. Generic SSB patterns, in fact, will induce flavor mixing among the scalar partners of the SM fermions, and

will allow flavor violation at unacceptable rates. For example, the current limits on $\mu \to e\gamma$ decays require $\sin^2 \theta_{\tilde{e}\tilde{\mu}}\, \Delta m^2_{\tilde{e}\tilde{\mu}}/m^2_{\tilde{e}} < 0.01$, where $\theta_{\tilde{e}\tilde{\mu}}$ and $\Delta m^2_{\tilde{e}\tilde{\mu}}$ are the mixing angle and the mass splitting between the scalar partners of electron and muon. A generic mixing angle and the current direct constraints on the scalar-electron mass [24] force the splitting to be of the order of few GeV at most. Likewise, contributions to the $K^0 - \bar{K}^0$ mixing parameter ϵ_K induce the following constraint on the imaginary part of the mixing among SUSY partners of down and strange quarks:

$$\left(\frac{100 \text{ TeV}}{m_{\tilde{q}}}\right)^2 \mathcal{I}m \left(\frac{\Delta m^2_{\tilde{d}_L \tilde{s}_L}}{m^2_{\tilde{d}}} \frac{\Delta m^2_{\tilde{d}_R \tilde{s}_R}}{m^2_{\tilde{d}}}\right) < 2 \cdot 10^{-3} \tag{12}$$

Generic SSB will lead to large effects also in $b \to s\gamma$, $\mathcal{CP}$, etc. Flavor conservation is therefore to SUSY what the GIM mechanism has been to the SM.

The examples of SSB breaking models most commonly studied in the context of LHC simulations are those of Minimal Supergravity (mSUGRA, [28]) and gauge-mediated SSB models (GMSB, [29]). In mSUGRA the SUSY breaking takes place at a scale intermediate between m_W and M_{Planck}:

$$M_{SSB} \sim \sqrt{m_W\, M_{\text{Planck}}} \sim 10^{11} \text{ GeV} \tag{13}$$

It is also assumed that at the SSB scale all scalar fields acquire the same SSB mass, and similarly for the fermionic partners of the gauge bosons (gauginos):

$$m_{\tilde{f}} = \mu_H = m_0 \quad \forall \text{ flavors } f \tag{14}$$

$$m_{\tilde{V}} = m_{1/2} \quad V = g, \gamma, W, Z \tag{15}$$

These assumptions have interesting phenomenological consequences: the mass splittings at the EW scale are only induced by RGE; they are small, and therefore induce no significant FCNC problems. The mass term of the Higgs field coupled to u-type quarks is driven negative at low energy by the large top mass, leading to a natural EWSB at the appropriate scale. Relations exist among the masses of the gluinos $\tilde{g}$ (fermionic partners of the gluons) and charginos $\chi^{\pm}$ or neutralinos χ^0 (the fermionic partners of the EW gauge bosons), $m(\tilde{g})/m(\tilde{\chi}) \sim \alpha_s/\alpha_W$, as well as

between $U(1)$ and $SU(2)$ gauge fermions: $m(\tilde{B}^0) = (5g'^2/3g^2)\,m(\tilde{W}) \sim 0.5m(\tilde{W})$. Accurate measurements of the SUSY spectrum at the LHC can therefore test the mSUGRA assumptions, and provide information on the parameters of the specific model implementing them. An example is given in Table 2 [1].

In GMSB, SUSY is broken in a strongly coupled sector at a scale M_{SSB} of $\mathcal{O}(1 - 100 \text{ TeV})$, and the breaking is transferred to the low energy sector only via gauge interactions Being mediated by gauge interactions, SSB is flavor independent and no FCNC problems arise. As in the case of mSUGRA, relations exist between some of the masses of the new states. They are determined by gauge couplings, and have patterns possibly different from those of mSUGRA. For example,

$$\frac{m(\tilde{q})}{m(\tilde{\ell})} \sim \frac{\alpha_S}{\alpha_W} \gg 1 \qquad \text{(unlike SUGRA)}$$

$$\frac{m(\tilde{g})}{m(\tilde{\chi})} \sim \frac{\alpha_S}{\alpha_W} \quad \text{(like SUGRA)},$$

$$(16)$$

$$m(\tilde{q}) \sim m(\tilde{g}) \qquad m(\tilde{\ell}) \sim m(\tilde{\chi}) \qquad m(\tilde{\chi}_1^{\pm}) \sim m(\chi_2^0) \qquad (17)$$

χ_2^0 here is the second heaviest neutralino, and $\chi_1^{\pm}$ the lighest chargino. In GMSB the lighest SUSY particle (LSP) is always the gravitino. The next-to-lightest, and therefore unstable, SUSY particle is usually the lightest neutralino or the fermionic partner of the τ lepton ($\tilde{\tau}$), leading to the possible striking experimental signatures $\chi^0 \to \tilde{G}\gamma$ or $\tilde{\tau} \to \tilde{G}\tau$ [29].

TABLE 2. Ability to reconstruct spectrum and parameters of a specific mSUGRA model in ATLAS [1]

Measurement	Expected value (GeV)	Error (%) 300 fb^{-1}	Measurement	Expected value (GeV)	Error (%) 300 fb^{-1}
m_0	100	± 3	$m_{1/2}$	300	$\pm 1,3$
$\tan\beta$	2.1	± 2	m_h	93	$\pm 0,2$
$m_{\ell^+\ell^-}^{end-point}$	109	± 0.2	$m_{\tilde{\ell}_R}$	157	± 0.3
$m_{\tilde{\ell}_L}$	240	± 1	$m_{\tilde{q}_L}$	690	± 1
$m_{\tilde{q}_R}$	660	± 1.5	$m_{\tilde{g}}$	770	± 1.5
$m_{\tilde{\tau}_1}$	490	± 10			

The exploration of the SUSY spectrum provides therefore invaluable information on the physics at scales much larger than the LHC's. Indications of a GMSB-like spectrum would indicate the existence of new phenomena at a scale of the order of 10-100 TeV, potentially accessible at a future "Very-large" hadronic collider. Indications of a mSUGRA-like spectrum would set the scale of SSB at $\sim 10^{11}$ GeV, and would provide no indication of interesting phenomena up to that scale. Nevertheless it is an intriguing coincidence that this scale coincides with the energy of the highest energy cosmic rays detected on earth. These cosmic rays are expected to be generated at distances no further away from us than 50 Mpc, to avoid the so-called GZK cut-off [30] induced by interaction with the cosmic microwave background photons. No galactic source has been identified for these events within the 50 Mpc bound, but solutions to this puzzle have been proposed [31] which assume that these cosmic rays are the result of the decay of metastable particles with masses in the range of $\sim 10^{12-13}$ GeV.

The most valuable information will come from the comparison of gaugino masses (gluino w.r.t. charginos and neutralinos) and scalar masses ($SU(2)$ doublet (L-type) vs singlet (R-type) scalars, squarks vs sleptons, first generation w.r.t. second and third). Of particular interest is the value of the $\tilde{t}$ mass, because of its connection with the Higgs mass (see Eq. (6)). The LHC is well armed to explore these issues in great detail, to point the direction for future experimental facilities, and to complement the information derived from the new generation of experiments aimed at accurate studies of flavor transitions (B factories, rare Kaon-decay experiments, $\mu \to e\gamma$ searches), and of astrophysical events.

3.2. Cosmological Implications of SUSY

There are several potential cosmological and astrophysical implications of SUSY. We review here some of these connections. In mSUGRA models the LSP, usually the lightest χ^0, is a potential candidate for Cold Dark Matter. This is detectable in terrestrial experiments [32]. In GMSB models the LSP is the gravitino, a potential candidate for Warm Dark Matter. No detection is possible in terrestrial experiments. In conjunction with the ongoing searches for Dark matter, the goal for the LHC is to firmly establish or disprove the connection between SUSY LSP and DM [32]. For example, the discovery of a mostly higgsino LSP would rule this out as a DM candidate if its mass is larger than M_W [33].

Another important connection comes from the problem of baryogenesis [34, 35]. This is not easily understood within the SM or generic GUT models

- CP violation (ℂP) from the CKM mixing is too weak.
- If the baryon number B is generated at the GUT scale, it is washed out at EW phase transition (EWPT).
- The EWPT itself is too weak to provide $B \neq 0$ if $m_H > 80$ GeV, which is nowadays a firmly established limit.

In presence of SUSY things improve:

- New sources of ℂP are available beyond the CKM mixing—for example, phases in the mass matrix of gauginos and squarks.
- A relatively light stop ($m_{\tilde{t}} \lesssim m_{top}$) strenghtens the EWPT. $B \neq 0$ can be then achieved for an extended Higgs mass range, up to $m_H \lesssim 115$ GeV [36], just at the edge of the current limits.

Another point on the wish-list for the LHC is therefore to firmly establish or disprove the viability of $B \neq 0$ at the EW phase transition, by mapping out the spectrum of the Higgs and stop sectors, and to extract hints of complex phases in the gaugino and squark mixings.

4. STRONG GRAVITY AT THE LHC?

A recent intriguing idea [37] to solve the hierarchy problem involves the existence of extra dimensions compactified on a large scale of the order of a millimiter, and with gravitational interactions becoming strong at scales $\mathcal{O}$(few TeV). In this case, physics would change so dramatically that all corrections to low-energy observables (including m_H) would necessarily be cut off at the scale of strong gravity. One is therefore replacing the hierarchy problem with the problem of the naturalness of such a large scale for gravitational interactions: what guarantees the stability of such large-radius compactifications? Nevertheless this idea provides a very exciting new framework to study these questions. It may well be that rephrasing the fine-tuning problem in terms of gravity will provide the proper dynamical setup to eventually find an answer. Interestingly enough, this idea is also suitable to testing at the LHC, as we now shortly review.

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Gauss's law gives the gravitational potential in $4 + d$ dimensions as:

$$V(r) \sim \frac{m_1 m_2}{M_{Pl,d}^{d+2}} \frac{1}{r^{d+1}} \tag{18}$$

If the d extra dimensions are compactified with a size R, the flux at $r \gg R$ scales like $1/r^2$, and

$$V(r) \sim \frac{m_1 m_2}{M_{Pl,d}^{d+2} R^d} \frac{1}{r} \equiv \frac{m_1 m_2}{M_{Pl}^2} \frac{1}{r} \tag{19}$$

with the 4-dimensional Planck mass given by $M_{Pl}^2 = M_{Pl,d}^{d+2} R^d$. Choosing $M_{Pl,d}$ of the order of the EW scale (m_{EW}) gives:

$$R \sim 10^{\frac{30}{d} - 17} \, \text{cm} \times \left(\frac{1 \, \text{TeV}}{m_{EW}} \right)^{1 + \frac{2}{d}} \tag{20}$$

For $d = 1$, $R \sim 10^{13}$ cm (ruled out by astronomical observations), while for $d \geq 2$, $R \lesssim 1$ mm, at the edge of current limits, but testable in new ongoing laboratory gravity experiments [38].

The introduction of these large extra dimensions opens a set of challenging questions. Several succesfull predictions valid in scenarios where gravity has its influence only above the Planck scale would call for new explanations. For example, the very successful results of Bing Bang nucleosynthesis is based on the standard cosmological evolution of the Universe. The unification of gauge couplings at the GUT scale, valid with great accuracy in SUSY GUT models, would appear to be an accident in models in which extra dimensions appear at the TeV scale. It has been suggested however [39] that in these scenarios the running of couplings is power-like instead of logarithmic, and faster convergence is therefore possible. Finally, the presence of nearby extra-dimensions allows for possible alternatives to the Higgs mechanism [40]. Non-perturbative gauge couplings at the unification point in extra dimensions lead to confinement of higher-dimensional fermions, and to the natural formation of Higgs-like scalars. In these models the observed value of m_t can be predicted with a ± 30 GeV accuracy, and a strong correlation is found between the value of m_t and m_H.

In the simplest implementations of these models, the Kaluza-Klein modes of the graviton are separated by $\delta m \sim R^{-1}$, and although each

TABLE 3. LHC discovery reach [42] for the existence of δ extra dimensions, given in terms of the maximum strong-gravity scale M_D which is detectable at the 5σ level through jet+E_T^{miss} final states; R is the corresponding compactification radius

δ	M_D (TeV)	R
2	7.5	10 μm
3	5.9	0.3 μm
4	5.3	10^{-3} μm

one of them is weakly coupled for $E < M_{Pl,d}$, their large multiplicity gives potentially large emission rates [41]. These gravitons, produced in a partonic collision and recoiling against a jet, would leave the detector as invisible particles, and give rise to missing tranverse-energy (E_T^{miss}) signatures. The LHC reach from this measurement of jet+E_T^{miss} final states has been studied with complete detector simulations in [42], with the results for an integrated luminosity of 100fb^{-1} shown in Table 3. While these results are not enough to conclusively observe or rule out these models, the energy reach of the LHC will allow to probe these ideas in much more depth than is possible today.

5. STANDARD MODEL STUDIES AS PROBES FOR NEW PHYSICS

While the main goals of the LHC will be the exploration of the EW symmetry breaking mechanism and the search for exciting and unexpected new phenomena, the LHC will also be in the position to significantly improve our knowledge of the fundamental parameters and dynamics of the SM [3]. These measurements could ultimately lead to indirect evidence for phenomena beyond the SM itself. The production rates at the LHC for most SM particles and processes are mindboggling. Huge statistics of final states nowadays totally unaccessible at the current accelerators will be available, and will allow measurements of unprecedented accuracy and depth. Table 4 contains a condensed summary of the cross-sections for some of the most relevant processes. For low luminosity (10^{33} cm^{-2} s^{-1}), cross-sections of 1 nb correspond to 1 event per second of data taking.

The huge lever arm in energy available through the measurement of high transverse-energy (E_T) jets [43] will allow to probe the smallest distance

TABLE 4. Benchmark cross-sections for key SM processes at the LHC;
in the case of jets and photons, we assume a $|\eta| < 1$ rapidity cut

Process	σ (nb) $\equiv$ evts/s	Process	σ (nb) $\equiv$ evts/s
Jets ($E_T > 100\text{GeV}$)	10^3	Jets ($E_T > 2\text{TeV}$)	1×10^{-4}
$W^\pm \to e\nu_e$	20	$Z \to e^+e^-$	2
Photons ($E_T > 60\text{GeV}$)	20	$c\bar{c}$	8×10^6
$b\bar{b}$	5×10^5	$t\bar{t}$	0.8

scales ever accessed. One year of high-luminosity running will give tens of events with jets with $E_T > 3$ TeV. Compared to the Tevatron, where jets up to 600 GeV will be observed, this is an a factor of 5 reduction in the scale at which the quark form factor can be explored.

The immense samples of EW gauge bosons will enable high-precision measurements of the W mass (± 15 MeV) and of the gauge bosons self-couplings [44]. The study of Drell-Yan final states will be sensitive to several possible new phenomena. For example, possible contact interactions mixing light quarks with leptons will be probed up to scales of the order of 25–30 TeV, well in the region where new strongly interacting phenomena related to the EWSB may take place. New $U(1)$ gauge bosons with Z-like couplings will be observed up to masses of the order of 4–5 TeV. s-channel graviton exchange, in the context of the low-scale gravity models described in the previous Section, will induce DY-like reactions such as $gg \to \ell^+\ell^-$, and probe scales up to 5 TeV. The large statistics will also allow measurements of the W and Z total cross sections with accuracies significantly better than 1%, providing luminosity monitors which are only limited by the precision of the theoretical predictions for these rates (predictions currently estimated to be around 5%, being dominated by uncertainties in the knowledge of the partonic densities of the proton [43]).

Top quark pairs will be produced in great abundance, at a rate of approximately 1 pair/sec. With this large sample of events, precise determinations of the top mass (m_t) and of the top decay properties will be possible [45]. It is estimated that m_t will be measured with an accuracy just above 1 GeV. When combined with the expected precision on m_W, this knowledge of m_t will lead to a very stringent prediction for the Higgs mass. Once the Higgs mass will be known, its combination with EW measurements, m_W and m_t will enable to predict the mass of possible particles BSM, as shown in the case of stop quarks in Figure 6.
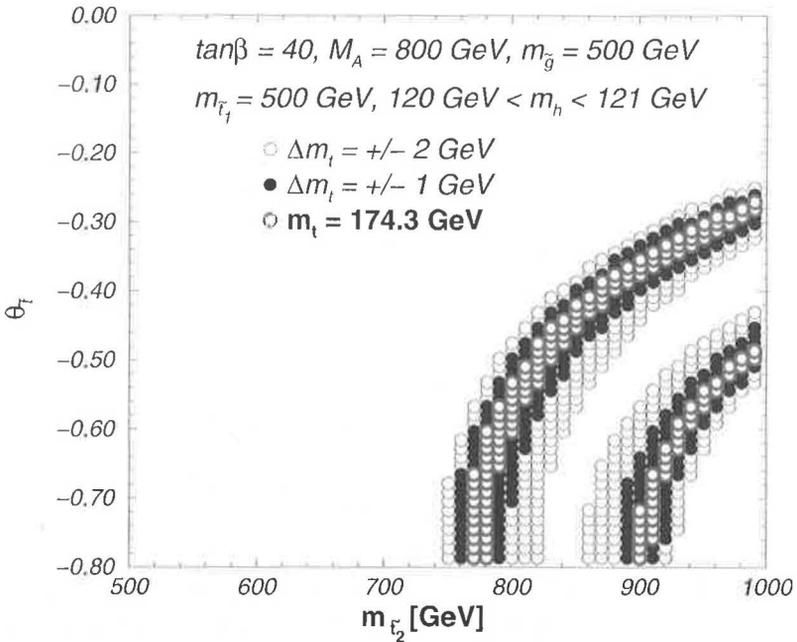
FIGURE 6. Indirect constraints on the mass of the heavier scalar top in the MSSM, given the measurement of other parameters at the LHC. The effect of the experimental error in m_t is shown for $\Delta m_t = 2$ GeV and $\Delta m_t = 1$ GeV [45]. The two bands correspond to two possible sets of solutions.

The production of single tops, via decay of a virtual W or via Wg fusion, will allow a direct measurement of the CKM matrix element V_{tb} with a 5% accuracy, providing an important test of the 3-family unitarity of the CKM matrix. Given the large top mass, which makes the 3rd generation rather special compared to the first two, the exploration of FCNC processes involving the top is a very important objective for the LHC. Rare decays of the top quark (such as FCNC transitions like $t \rightarrow uZ$) will be explored down to branching ratios of $\mathcal{O}(10^{-4 \div -5})$. Far away from the SM expectations, any signal at this level would clearly indicate the presence of new flavor physics. The study of flavor physics will be enriched by a thorough b-physics program [46] at ATLAS, CMS and at the dedicated experiment LHCb [47]. The tens of billions of bottom quarks produced [48], will allow to pin down with great accuracy and redundancy the CKM matrix elements, to probe in full detail the parameters of $\mathcal{CP}$ in

the B_q systems ($q = u, d, s$), and to study rare decays with branching ratios at the level of 10^{-9}. For example, the standard $\sin 2\beta$ parameters will be determined with a 0.01 accuracy within 3 years of running, a factor of 5 improvement over the expectations of $e^+ e^-$ B factories. A combined analysis of $B_d \rightarrow \pi^+ \pi^-$ and $B_s \rightarrow K^+ K^-$ final states will determine the angle γ with an accuracy of $2° - 4°$, depending on the value of the mixing parameter x_s. The $B_s / \bar{B}_s$ mass difference will be measured with a 1% accuracy, and will lead to a determination of the $|V_{td} / V_{ts}|$ ratio limited only by the theoretical knowledge of the ratio of B_d and B_s decay constants and bag factors.

6. CONCLUSIONS

The observation and study of the Higgs boson at the LHC will provide key clues on the question of "what's next." The observation of $m_H \lesssim 130$ GeV will be a strong indication for the existence of SUSY, and the discovery of SUSY would become very likely at the LHC. On the other hand, $m_H \gtrsim 200$ GeV would be a strong clue for the existence of new interactions at scales in the range of $1 - 10$ TeV, possibly outside LHC's reach. Most, if not all, of SUSY models would be ruled out. More complete information on the nature of this new physics will require the LHC's ability to map in detail the couplings of the Higgs, through the study of the branching ratios into as many channels as possible, as well as of the Higgs self-interactions. Should the Higgs lie within the region allowed by the SM constraints, $130 \lesssim m_H \lesssim 200$ GeV, the fine-tuning problem would be the only clue in favor of possible new physics. SUSY would however be seriously challenged, certainly in its more common realisations.

If SUSY is observed, the next big question facing HEP is the clarification of the SUSY breaking phenomenon. While understanding EWSB leads us to a clarification of dynamics at the TeV scale, understanding SSB takes us to the much larger energies where gravity is thought to play a role. The understanding of SSB would most likely be linked to the understanding of the flavor structure of the SM, and the thorough experimental investigation of the flavor-violating phenomena would become one of the leading priorities. As an alternative, or even perhaps as an interesting extra possibility, the LHC has still a margin to explore potential scenarios with nearby strong gravitational interactions. This, by all criteria, would be the most important discovery of HEP so far!

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